References with abstracts for QWIM project: machine learning (and more) applied to market regimes, changepoints, bubbles and crashes in quantitative wealth and investment management

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Abstract

This document includes the list of references (including abstracts) for this QWIM project

Contents

1 Motivation for the project

There is much evidence that crash and bubble periods display much different patterns than normal markets, suggesting that forecasting models (and investing approaches) ought to be based on multiple regimes.

It was shown that asset performance over long time periods can be separated into distinctive periods, called regimes, which display common characteristics. Regime-based asset allocation has been shown to add value over rebalancing to static weights and, in particular, reduce potential drawdowns by reacting to changes in market conditions. regime based asset allocation can effectively respond to changes in financial regimes at the portfolio level, in an effort to provide better long-term results than more static approaches can offer.

Baltas and Karyampas ("Forecasting the equity risk premium: The importance of regime-dependent evaluation," 2018):

"Is superior econometric predictability across the business cycle synonymous with predictability at all times?"

It appears that recently introduced forecasting models for equity risk premium ERP, which have been shown to generate econometrically superior ERP forecasts, have forecasting ability which is regime-dependent. They give rise to significant relative losses during market downturns, when it matters the most for asset allocators to retain assets and their client base intact. Conversely, any economic benefit occurring during market upswings is diminished for high risk-averse and leverage-constrained investors.

1.1 Market states in $\mathbb{QWIM}$

It was observed empirically that there are two separate market states:

- low uncertainty (relatively stable and resilient) market
- high uncertainty (relatively chaotic and fragile) market

Markets in **"low uncertainty"** state:

- statistically well behaved
- can be modeled using standard statistical tools
- volatility is stable and low
- correlations relatively stable
- tail events ($\geq$3 std deviations in either direction) quite rare.

Markets in **"high uncertainty"** state:

- not statistically well behaved
- vols and correlations change significantly on regular basis
- Tail events happen with much more regularity

To account for the two market states, practitioners use a relatively similar concept of **"risk on, risk off"**:

The **"high uncertainty"** state can incorporate multiple instances and multiple types of significant changes in time series:

- market regimes
- changepoints
- bubbles and crashes

1.2 Structural breaks: market regimes

Regime changes, some transitory, some recurring (recessions versus expansions) some permanent (structural breaks), are prevalent across a wide range of financial markets and in behavior of many macro variables. Examples of regimes considered in academia and/or practitioners:

- bull vs. bear market regimes
- inflationary vs. recessionary regimes
- high vs. low volatility regimes
- mean reverting vs. trending regimes

Regime shifts are challenging for investors because they cause portfolio performance, risk and behavior to depart significantly from ranges implied by long-term averages of means and covariances. Regime-based asset allocation was shown to deliver improved performance and risk profile

Goof performance of investment strategies greatly enhanced with introduction of regime switching models $\mathbb{RSM}$s . $\mathbb{RSM}$s characterize market states using estimates of parameters of some underlying model, and use a transition matrix to quantify probability of moving from one state to another.

$\mathbb{ML}$ may be effective at detecting change (even in chaotic system), for example through robust anomaly detection. It can be enhanced to compute probability of observation in previously observed "market regimes" (defined as clusters in $\mathbb{ML}$). Thus clustering algorithms can identify regimes in datasets. What they have in common with regular regime switching models is ability of producing probabilities of "switching" into another regime. $\mathbb{ML}$ can also feed on large amounts of data to detect preconditions of a break

1.3 Structural breaks: bubbles and crashes

Chaotic systems of the real world are comparable to stock market indices evolution.Llog-periodic power law singularity (LPPLS) model captures well bubbles and crashes LPPLS framework successfully captures, ex-ante, most prominent bubbles across different time scales (Black Monday, Dot-com, and Subprime Crisis).

1.4 Structural breaks: changepoints

Change point detection (CPD) is the problem of finding abrupt changes in data when a property of the time series changes . Segmentation, edge detection, event detection, and anomaly detection are similar concepts within $\mathbb{ML}$ space.

Traditional changepoint detection methods only look for statistically-detectable boundaries that are defined as abrupt variations in the generative parameters of a data sequence. . However, it is observed that breakpoints occur on more subtle boundaries non-trivial to detect with these statistical methods, but detectable using deep learning

2 Relevant references

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Smug et al. ("Predicting Financial Market Crashes Using Ghost Singularities," 2017)
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2.2.7 Forecasting under data regimes

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2.2.8 Numerical methods, models and their implementations to model and analyze data regimes

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Bazzi et al. ("Time-Varying Transition Probabilities for Markov Regime Switching Models," 2017)

Bergmeir et al. ("Time Series Modeling and Forecasting Using Memetic Algorithms for Regime-Switching Models," 2012)

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Jochmann and Koop ("Regime-switching cointegration," 2015)

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Ou et al. ("Whats for dynr: A Package for Linear and Nonlinear Dynamic Modeling in R," 2019)

Zheng et al. ("Regime switching model estimation: spectral clustering hidden Markov model," 2021)

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Ahelegbey, D. F., Billio, M., and Casarin, R. (2020). "Modeling Turning Points In Global Equity Market." In: *SSRN e-Print*.

Turning points in financial markets are often characterized by changes in the direction and/or magnitude of market movements with short-to-long term impacts on investors' decisions. This paper develops a Bayesian technique to turning point detection in financial equity markets. We derive the interconnectedness among stock market returns from a piece-wise network vector autoregressive model. The empirical application examines turning points in global equity market over the past two decades. We also compare the COVID-19 induced interconnectedness with that of the global financial crisis in 2008 to identify similarities and the most central market for spillover propagation.

Ahmad, W., Bhanumurthy, N. R., and Sehgal, S. (2015). "Regime dependent dynamics and European stock markets: Is asset allocation really possible?" In: *Empirica* 42(1), pp. 77–107.

In this study, we examine the regime shifts and volatility in stock market returns of eighteen European stock markets and the USA and utilize these regimes in asset allocation and risk management contexts. Using a Markov regime switching model, the study finds strong evidence of regime switching characterized by two regimes over the sample period from February, 1996 to January, 2012. Smoothed probabilities and time-varying conditional volatilities also highlight the meaningful turning points including the recent global financial crisis (2008) and Eurozone crisis (2009). Analyzing the market synchronization and Sharpe ratios, the study finally concludes that sample markets provide very limited scope of asset allocation and risk diversification.

Ahmad, W. and Sehgal, S. (2015). "Regime shifts and volatility in BRIICKS stock markets: an asset allocation perspective." In: *International Journal of Emerging Markets* 10(3), pp. 383–408.

This paper examines the regime shifts and stock market volatility in the stock market returns of seven emerging economies popularly called as BRIICKS which stands for Brazil, Russia, India, Indonesia, China, South Korea and South Africa, over the period from February, 1996 to January, 2012 by applying Markov regime switching in mean-variance model. The employed model finds two regimes in each of these markets. The identified regimes are further utilized in formulating the asset allocation strategies based on market synchronization and Sharpe ratio. The results suggest that BRIICKS is not a homogeneous asset class and each market should be independently evaluated in terms of its regime switching behavior, volatility persistence and level of synchronization with other emerging markets. The study finally concludes that Russia, India and China as the best assets to invest within this emerging market basket which can be pooled with a mature market portfolio to achieve further benefits of risk diversification.

Akioyamen, P., Tang, Y. Z., and Hussien, H. (2021). "A Hybrid Learning Approach to Detecting Regime Switches in Financial Markets." In: *arXiv e-Print*.

Financial markets are of much interest to researchers due to their dynamic and stochastic nature. With their relations to world populations, global economies and asset valuations, understanding, identifying and forecasting trends and regimes are highly important. Attempts have been made to forecast market trends by employing machine learning methodologies, while statistical techniques have been the primary methods used in developing market regime switching models used for trading and hedging. In this paper we present a novel framework for the detection of regime switches within the US financial markets. Principal component analysis is applied for dimensionality reduction and the k-means algorithm is used as a clustering technique. Using a combination of cluster analysis and classification, we identify regimes in financial markets based on publicly available economic data. We display the efficacy of the framework by constructing and assessing the performance of two trading strategies based on detected regimes.

Alberico, S., Coche, J., Sahakyan, V., and Zulaica, O. (2018). "Regime identification for sovereign bond portfolio construction." In: *Advances in the practice of public investment management: portfolio modelling, performance attribution and governance*. Ed. by N. Bulusu, J. Coche, A. Reveiz, F. Rivadeneyra, V. Sahakyan, and G. Yanou. Springer International Publishing, pp. 247–274.

Traditional asset allocation algorithms do not typically incorporate regime-specific information to construct optimal portfolios. In this chapter, we introduce a state-dependent investment strategy based on a set of indicators that we believe are useful in identifying economic and financial regimes and apply it to a universe consisting of four of the most important and liquid developed government bond markets: the United States, the United Kingdom, Germany, and Japan. The results show that portfolios optimised across regimes have properties markedly different from those optimised using conventional asset allocation approaches. The findings may indicate that

the regime-optimised allocations are exposed to an additional risk factor that, when priced, could give rise to an expected excess return over standard mean-variance portfolios.

Allaj, E. and Sanfelici, S. (2022). "An Early Warning System for Identifying Financial Instability." In: *SSRN e-Print*.
Financial crises prediction is an essential topic in finance. Designing an efficient Early Warning System (EWS) can help prevent catastrophic losses resulting from financial crises. We propose different EWSs for predicting potential market instability conditions, where market instability refers to large asset price declines. A logit regression EWS is employed to predict future large price losses and Early Warning Indicators (EWIs) based on the realized variance (RV) and price-volatility feedback rate are considered. The latter EWI is supposed to describe the ease of the market in absorbing small price perturbations. Our study reveals that, while RV is important in predicting future price losses in a given time series, the EWI employing the price-volatility feedback rate can improve prediction further.

Amini, M. and Bayat, A. (2022). "hhsmm: An R package for hidden hybrid Markov/semi-Markov models." In: *arXiv e-Print*.
This paper introduces the hhsmm, which involves functions for initializing, fitting and predication of hidden hybrid Markov/semi-Markov models. These models are exible models with both Markovian and semi-Markovian states, which are applied to situations where the model involves absorbing or macro states. The left-to-right models and the models with series/parallel networks of states are two models with Markovian and semi-Markovian states. The hhsmm also includes the residual useful lifetime estimation in the predict function. The commercial modular aero-propulsion system simulation (C-MAPSS) data-set is also included in the package, which is used for illustration of the application of the package features.

Ang, A. and Bekaert, G. (2004). "How do Regimes Affect Asset Allocation." In: *Financial Analysts Journal* 60(2), pp. 86–99.
International equity returns are characterized by episodes of high volatility and unusually high correlations coinciding with bear markets. We develop models of asset returns that match these patterns and use them in asset allocation. First, the presence of regimes with different correlations and expected returns is difficult to exploit within a framework focused on global equities. Nevertheless, for all-equity portfolios, a regime-switching strategy dominates static strategies out-of-sample. Second, substantial value is added when an investor chooses between cash, bonds and equity investments. When a persistent bear market hits, the investor switches primarily to cash. There are large market timing benefits because the bear market regimes tend to coincide with periods of relatively high interest rates.

Ang, A. and Timmermann, A. (2012). "Regime Changes and Financial Markets." In: *Annual Review of Financial Economics* 4(1), pp. 313–337.
Regime-switching models can match the tendency of financial markets to often change their behavior abruptly and the phenomenon that the new behavior of financial variables often persists for several periods after such a change. Although the regimes captured by regime-switching models are identified by an econometric procedure, they often correspond to different periods in regulation, policy, and other secular changes. In empirical estimates, the means, volatilities, autocorrelations, and cross-covariances of asset returns often differ across regimes in a manner that allows regime-switching models to capture the stylized behavior of many financial series including fat tails, heteroskedasticity, skewness, and time-varying correlations. In equilibrium models, regimes in fundamental processes, such as consumption or dividend growth, strongly affect the dynamic properties of equilibrium asset prices and can induce nonlinear risk-return trade-offs. Regime switches also lead to potentially large consequences for investors' optimal portfolio choice.

Angelini, G., Bacchiocchi, E., Caggiano, G., and Fanelli, L. (2019). "Uncertainty across volatility regimes." In: *Journal of Applied Econometrics* 34(3), pp. 437–455.
We propose a nonrecursive identification scheme for uncertainty shocks that exploits breaks in the volatility of macroeconomic variables and is novel in the literature on uncertainty. This approach allows us to simultaneously address two major questions in the empirical literature: Is uncertainty a cause or effect of decline in economic activity? Does the relationship between uncertainty and economic activity change across macroeconomic regimes? Results based on a small-scale vector autoregression with US monthly data suggest that (i) uncertainty is an exogenous source of decline of economic activity, and (ii) the effects of uncertainty shocks amplify in periods of economic and financial turmoil.

Ansari, A. F., Benidis, K., Kurle, R., Turkmen, A. C., Soh, H., Smola, A. J., Wang, Y., and Januschowski, T. (2021). "Deep Explicit Duration Switching Models for Time Series." In: *arXiv e-Print*.

Many complex time series can be effectively subdivided into distinct regimes that exhibit persistent dynamics. Discovering the switching behavior and the statistical patterns in these regimes is important for understanding the underlying dynamical system. We propose the Recurrent Explicit Duration Switching Dynamical System (RED-SDS), a flexible model that is capable of identifying both state- and time-dependent switching dynamics. State-dependent switching is enabled by a recurrent state-to-switch connection and an explicit duration count variable is used to improve the time-dependent switching behavior. We demonstrate how to perform efficient inference using a hybrid algorithm that approximates the posterior of the continuous states via an inference network and performs exact inference for the discrete switches and counts. The model is trained by maximizing a Monte Carlo lower bound of the marginal log-likelihood that can be computed efficiently as a byproduct of the inference routine. Empirical results on multiple datasets demonstrate that RED-SDS achieves considerable improvement in time series segmentation and competitive forecasting performance against the state of the art.

Arago, V. and Salvador, E. (2013). "Non-linear Tradeoff between Risk and Return: A Regime-switching Multi-factor Framework." In: *Modeling and Simulation in Engineering, Economics, and Management*. Ed. by M. Fernandez-Izquierdo, M. Munoz-Torres, and R. Leon. Vol. 145. Lecture Notes in Business Information Processing. Springer Berlin Heidelberg, pp. 64–74.

This study develops a multi-factor framework where not only the market risk is considered but also potential changes in the investment opportunity set. Although previous studies find no clear evidence about a positive and significant relation between return and risk, favourable evidence can be obtained if a non-linear relation is established. The positive and significant tradeoff between return and risk is essentially observed during low volatility periods suggesting a procyclical risk aversion of investors. Different patterns for the risk premium dynamics in low and high volatility periods are obtained, both in risk prices and risk (conditional second moments) patterns.

Astill, S., Harvey, D. I., Leybourne, S. J., Sollis, R., and Taylor, A. M. R. (2018). "Real-Time Monitoring for Explosive Financial Bubbles." In: *Journal of Time Series Analysis* 39(6), pp. 863–891.

We propose new methods for the real-time detection of explosive bubbles in financial time series. Most extant methods are constructed for a fixed sample of data and, as such, are appropriate only when applied as one-shot tests. Sequential application of these tests, declaring the presence of a bubble as soon as one of these statistics exceeds the one-shot critical value, would yield a detection procedure with an unknown false-positive rate likely to be far in excess of the nominal level. Our approach sequentially applies the one-shot tests of Astill et al. (2017), comparing sub-sample statistics calculated in real time during the monitoring period with the corresponding sub-sample statistics obtained from a prior training period. We propose two procedures: one based on comparing the real-time monitoring period statistics with the maximum statistic over the training period, and another that compares the number of consecutive exceedances of a threshold value in the monitoring and training periods, the threshold value obtained from the training period. Both allow the practitioner to determine the false-positive rate for any given monitoring horizon, or to ensure that this rate does not exceed a specified level by setting a maximum monitoring horizon. Monte Carlo simulations suggest that the finite-sample false-positive rates lie close to their theoretical counterparts, even in the presence of time-varying volatility and serial correlation in the shocks. The procedures are shown to perform well in the presence of a bubble in the monitoring period, offering the possibility of rapid detection of an emerging bubble in a real-time setting. An empirical application to monthly stock market index data is considered.

Bae, G. I., Kim, W. C., and Mulvey, J. M. (2014). "Dynamic asset allocation for varied financial markets under regime switching framework." In: *European Journal of Operational Research* 234(2), pp. 450–458.

Asset allocation among diverse financial markets is essential for investors especially under situations such as the financial crisis of 2008. Portfolio optimization is the most developed method to examine the optimal decision for asset allocation. We employ the hidden Markov model to identify regimes in varied financial markets; a regime switching model gives multiple distributions and this information can convert the static mean-variance model into an optimization problem under uncertainty, which is the case for unobservable market regimes. We construct a stochastic program to optimize portfolios under the regime switching framework and use scenario generation to mathematically formulate the optimization problem. In addition, we build a simple example for a pension fund and examine the behavior of the optimal solution over time by using a rolling-horizon simulation. We conclude that the regime information helps portfolios avoid risk during left-tail events.

Bahrami, A., Shamsuddin, A., and Uylangco, K. (2019). "Are advanced emerging market stock returns predictable? A regime-switching forecast combination approach." In: *Pacific-Basin Finance Journal* 55, pp. 142–160.

Advanced emerging markets (AEMs) transitioning into developed markets experience far-reaching economic and institutional changes. Developing predictive models of stock returns in AEMs involves challenges of parameter instability and model uncertainty. This study uses Markov regime switching (MRS) models to address parameter instability and a combination forecast approach to mitigate model uncertainty. We find that the MRS model better captures the effects of predictor variables on returns compared to models with time-invariant parameters and produces statistically and economically significant return forecasts. Combining return forecasts from different MRS models further improves return predictability in AEMs. Consequently, employing MRS models in conjunction with the combination forecast approach goes a long way to improving forecast accuracy in AEMs.

Baitinger, E. and Flegel, S. (2021). "The better turbulence index? Forecasting adverse financial markets regimes with persistent homology." In: *Financial Markets and Portfolio Management*.
Persistent homology is the workhorse of modern topological data analysis, which in recent years becomes increasingly powerful due to methodological and computing power advances. In this paper, after equipping the reader with the relevant background on persistent homology, we show how this tool can be harnessed for investment purposes. Specifically, we propose a persistent homology-based turbulence index for the detection of adverse market regimes. With the help of an out-of-sample study, we demonstrate that investment strategies relying on a persistent homology-based turbulence detection outperform investment strategies based on other popular turbulence indices. Additionally, we conduct a stability analysis of our findings. This analysis confirms the results from the previous out-of-sample study, as the outperformance prevails for most configurations of the respective investment strategy and thereby mitigating possible data mining concerns.

Balcerak, M. and Schmelzer, T. (2020). "Constructing trading strategy ensembles by classifying market states." In: *arXiv e-Print*.
Rather than directly predicting future prices or returns, we follow a more recent trend in asset management and classify the state of a market based on labels. We use numerous standard labels and even construct our own ones. The labels rely on future data to be calculated, and can be used a target for training a market state classifier using an appropriate set of market features, e.g. moving averages. The construction of those features relies on their label separation power. Only a set of reasonable distinct features can approximate the labels. For each label we use a specific neural network to classify the state using the market features from our feature space. Each classifier gives a probability to buy or to sell and combining all their recommendations (here only done in a linear way) results in what we call a trading strategy. There are many such strategies and some of them are somewhat dubious and misleading. We construct our own metric based on past returns but penalising for a low number of transactions or small capital involvement. Only top score-performance-wise trading strategies end up in final ensembles. Using the Bitcoin market we show that the strategy ensembles outperform both in returns and risk-adjusted returns in the out-of-sample period. Even more so we demonstrate that there is a clear correlation between the success achieved in the past (if measured in our custom metric) and the future.

Baltas, N. and Karyampas, D. (2018). "Forecasting the equity risk premium: The importance of regime-dependent evaluation." In: *Journal of Financial Markets* 38(March), pp. 83–102.
Asset allocation is critically dependent on the ability to forecast the equity risk premium (ERP) out-of-sample. But, is superior econometric predictability across the business cycle synonymous with predictability at all times? We evaluate recently introduced ERP forecasting models, which have been shown to generate econometrically superior ERP forecasts, and find that their forecasting ability is regime-dependent. They give rise to significant relative losses during market downturns, when it matters the most for asset allocators to retain assets and their client base intact. Conversely, any economic benefit occurring during market upswings is diminished for high risk-averse and leverage-constrained investors.

Baltas, N. and Karyampas, D. (2020). "Forecasting the Equity Risk Premium: The Importance of Regime-Dependent Evaluation." In: *SSRN e-Print*.
Asset allocation is critically dependent on the ability to forecast the equity risk premium (ERP) out-of-sample. But, is superior econometric predictability across the business cycle synonymous to predictability at all times? We evaluate recently introduced ERP forecasting models, which have been shown to generate econometrically superior ERP forecasts, and find that their forecasting ability is regime-dependent. They give rise to significant relative losses during market downturns, when it matters the most for asset allocators to retain assets and their client base intact. Conversely, any economic benefit occurring during market upswings is diminished for high risk averse and leverage constrained investors.

Bansal, R., Miller, S., Song, D., and Yaron, A. (2021). "The term structure of equity risk premia." In: *Journal of Financial Economics*.

We estimate a regime-switching model for the equity term structure with Bayesian methods. Our approach accounts for the data sample being unrepresentative of the population distribution of regimes. We find that the term structure of expected equity dividend strip returns is downward sloping in recessions and upward sloping in expansions, and the unconditional term structure of expected equity returns is positively sloped. Our estimation shows that the sample unrepresentativeness induces a downward bias in the estimate of the equity term structure slope. We present a regime-switching consumption-based asset-pricing model that matches the empirical findings.

Barkai, I., Shushi, T., and Yosef, R. (2021). "A Cryptocurrency Risk-Return Analysis for Bull and Bear Regimes." In: *The Journal of Alternative Investments* 24(1), pp. 95–118.
In this article, the authors develop a new analytical lens through which to examine the risk-return profiles of bitcoin, litecoin, ripple, and ethereum. Their focus is to understand better the price behavior of individual cryptocurrencies and their influence on one another. To achieve this, they segment each cryptocurrency's time series of returns into disparate bull and bear regimes. They then examine the nature and extent of overlap between these regimes and whether they change over time. They also collect and plot several indicative distributed-denial-of-service attacks against the time series to investigate their possible impact on regime change episodes. Their findings shed light on previously unexplored systemic risk indicators within the cryptomarket as a whole and on the relationship between specific cryptocurrency pairs. These findings enhance the risk management toolkit for investors by revealing potential price behavior contagion patterns between cryptocurrencies pertinent to blended portfolio management. Furthermore, the authors' approach serves as a blueprint for additional research into regime-type overlap within the cryptomarket.

Bazzi, M., Blasques, F., Koopman, S. J., and Lucas, A. (2017). "Time-Varying Transition Probabilities for Markov Regime Switching Models." In: *Journal of Time Series Analysis* 38(3), pp. 458–478.
We propose a new Markov switching model with time-varying transitions probabilities. The novelty of our model is that the transition probabilities evolve over time by means of an observation driven model. The innovation of the time-varying probability is generated by the score of the predictive likelihood function. We show how the model dynamics can be readily interpreted. We investigate the performance of the model in a Monte Carlo study and show that the model is successful in estimating a range of different dynamic patterns for unobserved regime switching probabilities. We also illustrate the new methodology in an empirical setting by studying the dynamic mean and variance behaviour of US industrial production growth.

Beccarini, A. (2019). "Testing for the omission of relevant variables and regime-switching misspecification." In: *Empirical economics* 56(3), pp. 775–796.
This article shows that the interpretation of statistical evidence of regime-switching is not unambiguous. The usual interpretation is that some parameters switch according to the values of a predefined latent variable. An alternative interpretation is that regime-switching, as a statistical evidence, is also possible when the linear model is underspecified and the omitted variable bias emerges. A formal test is proposed to verify a potentially spurious regression with regime-switching. Through this test, it is evident that regime-switching estimates presented in an academic paper, should be interpreted as a consequence of the misspecification considered here.

Bel, K. and Paap, R. (2016). "Modeling the impact of forecast-based regime switches on US inflation." In: *International Journal of Forecasting* 32(4), pp. 1306–1316.
Forecasts of key macroeconomic variables may lead to policy changes by governments, central banks and other economic agents. Such policy changes in turn lead to structural changes in macroeconomic time series. We describe this phenomenon in US inflation by introducing a logistic smooth transition autoregressive model where the regime switches depend on the Michigan Inflation Expectation Series. Our results show that (i) forecasts lead to regime changes and have an impact on the level of inflation; (ii) the absorption time of shocks in the forecast of inflation is about four quarters; and (iii) a positive (negative) shock in the forecast results in actions which increase (decrease) the inflation rate.

Benhamou, E., Ohana, J.-J., Saltiel, D., and Guez, B. (2021a). "Explainable AI (XAI) Models Applied to Planning in Financial Markets." In: *SSRN e-Print*.
Regime changes planning in financial markets is well known to be hard to explain and interpret. Can an asset manager ex-plain clearly the intuition of his regime changes prediction on equity market ? To answer this question, we consider a gradi-ent boosting decision trees (GBDT) approach to plan regime changes on S&P 500 from a set of 150 technical, fundamental and macroeconomic features. We report an improved accuracy of GBDT over other machine learning (ML) methods on the S&P 500 futures prices. We show that retaining fewer and carefully selected features provides improvements across all ML approaches. Shapley values have recently

been intro-duced from game theory to the field of ML. This approach allows a robust identification of the most important variables planning stock market crises, and of a local explanation of the crisis probability at each date, through a consistent features attribution. We apply this methodology to analyse in detail the March 2020 financial meltdown, for which the model of-fered a timely out of sample prediction. This analysis unveils in particular the contrarian predictive role of the tech equity sector before and after the crash.

Benhamou, E., Ohana, J.-J., Saltiel, D., and Guez, B. (2021b). "Planning in Financial Markets in Presence of Spikes: Using Machine Learning GBDT." In: *SSRN e-Print*.
lanning in financial markets is a difficult task as the method needs to dramatically change its behavior when facing very rare black swan events like crises that shift market regime. In order to address this challenge, we present a gradient boosting decision trees (GBDT) approach to predict large price drops in equity indexes from a set of 150 technical, fundamental and macroeconomic features. We report an improved accuracy of GBDT over other machine learning (ML) methods on the S&P 500 futures prices. We show that retaining fewer and carefully selected features provides improvements across all ML approaches. We show that this model has a strong predictive power. We train the model from 2000 to 2014, a period where various crises have been observed and use a validation period of 3 years to find hyperparameters. The fitted model timely forecasts the Covid crisis giving us a planning method for early detection of potential future crises.

Benhamou, E., Saltiel, D., Ohana, J.-J., and Atif, J. (2021c). "Detecting and Adapting to Crisis Pattern with Context Based Deep Reinforcement Learning." In: *SSRN e-Print*.
Deep reinforcement learning (DRL) has reached super human levels in complex tasks like game solving (Go, StarCraft II, Atari Games), and autonomous driving. However, it remains an open question whether DRL can reach human level in applications to financial problems and in particular in detecting pattern crisis and consequently dis-investing. In this paper, we present an innovative DRL framework consisting in two subnetworks fed respectively with portfolio strategies past performances and standard deviations as well as additional contextual features. The second sub network plays an important role as it captures dependencies with common financial indicators features like risk aversion, economic surprise index and correlations between assets that allows taking into account context based information. We compare different network architectures either using layers of convolutions to reduce network's complexity or LSTM block to capture time dependency and whether previous allocations is important in the modeling. We also use adversarial training to make the final model more robust. Results on test set show this approach substantially over-performs traditional portfolio optimization methods like Markovitz and is able to detect and anticipate crisis like the current COVID one.

Berger, T. and Gencay, R. (2020). "Short-run wavelet-based covariance regimes for applied portfolio management." In: *Journal of Forecasting* 39(4), pp. 642–660.
Decisions on asset allocations are often determined by covariance estimates from historical market data. In this paper, we introduce a wavelet-based portfolio algorithm, distinguishing between newly embedded news and long-run information that has already been fully absorbed by the market. Exploiting the wavelet decomposition into short- and long-run covariance regimes, we introduce an approach to focus on particular covariance components. Using generated data, we demonstrate that short-run covariance regimes comprise the relevant information for periodical portfolio management. In an empirical application to US stocks and other international markets for weekly, monthly, quarterly, and yearly holding periods (and rebalancing), we present evidence that the application of wavelet-based covariance estimates from short-run information outperforms portfolio allocations that are based on covariance estimates from historical data.

Bergmeir, C., Triguero, I., Molina, D., Aznarte, J. L., and Benitez, J. M. (2012). "Time Series Modeling and Forecasting Using Memetic Algorithms for Regime-Switching Models." In: *IEEE Transactions on Neural Networks and Learning Systems* 23(11), pp. 1841–1847.
In this brief, we present a novel model fitting procedure for the neuro-coefficient smooth transition autoregressive model (NCSTAR), as presented by Medeiros and Veiga. The model is endowed with a statistically founded iterative building procedure and can be interpreted in terms of fuzzy rule-based systems. The interpretability of the generated models and a mathematically sound building procedure are two very important properties of forecasting models. The model fitting procedure employed by the original NCSTAR is a combination of initial parameter estimation by a grid search procedure with a traditional local search algorithm. We propose a different fitting procedure, using a memetic algorithm, in order to obtain more accurate models. An empirical evaluation of the method is performed, applying it to various real-world time series originating from three forecasting competitions. The results indicate that we can significantly enhance the accuracy of the models, making them competitive to models commonly used in the field.

Bernhart, G., Hocht, S., Neugebauer, M., Neumann, M., and Zagst., R. (2011). "Asset Correlations in Turbulent Markets and the Impact of Different Regimes on Asset Management." In: *Asia-Pacific Journal of Operational Research* 28(01), pp. 1–23.
In this article, the dependence structure of the asset classes stocks, government bonds, and corporate bonds in different market environments and its implications on asset management are investigated for the US, European, and Asian market. Asset returns are modelled by a Markov-switching model which allows for two market regimes with completely different risk-return structures. Using major stock indices from all three regions, calm and turbulent market periods are identified for the time period between 1987 and 2009 and the correlation structures in the respective periods are compared. It turns out that the correlations between as well as within the asset classes under investigation are far from being stable and vary significantly between calm and turbulent market periods as well as in time. It also turns out that the US and European markets are much more integrated than the Asian and US/European ones. Moreover, the Asian market features more and longer turbulence phases. Finally, the impact of these findings is examined in a portfolio optimization context. To accomplish this, a case study using the mean-variance and the mean-conditional-value-at-risk framework as well as two levels of risk aversion is conducted. The results show that an explicit consideration of different market conditions in the modelling framework yields better portfolio performance as well as lower portfolio risk compared to standard approaches. These findings hold true for all investigated optimization frameworks and risk-aversion levels.

Bhansali, V. and Holdom, J. (2021). "Good States, Bad States: What Do Options Tell Us About Schizophrenic Behavior of Mr. Market and What Can We Do About It?" In: *Journal of Investment Strategies* 19(4), pp. 79–91.
Option prices theoretically encapsulate participants' expectations about good state (bullish) and bad state (bearish) market outcomes. By using a mixture of distributions and reasonable assumptions, the authors extract time series of expected returns, volatilities and mixture probabilities of these outcomes surrounding the current US elections. The bimodality of asset return distributions suggests important modifications for asset allocation and risk management.

Bianchi, D. and Guidolin, M. (2014). "Can Linear Predictability Models Time Bull and Bear Real Estate Markets? Out-of-Sample Evidence from REIT Portfolios." In: *The Journal of Real Estate Finance and Economics* 49(1), pp. 116–164.
A recent literature has shown that REIT returns contain strong evidence of bull and bear dynamic regimes that may be best captured using nonlinear econometric models of the Markov switching type. In fact, REIT returns would display regime shifts that are more abrupt and persistent than in the case of other asset classes. In this paper we ask whether and how simple linear predictability models of the vector autoregressive (VAR) type may be extended to capture the bull and bear patterns typical of many asset classes, including REITs. We find that nonlinearities are so deep that it is impossibile for a large family of VAR models to either produce similar portfolio weights or to yield realized, ex-post out-of-sample long-horizon portfolio performances that may compete with those typical of bull and bear models. A typical investor with intermediate risk aversion and a 5-year horizon ought to be ready to pay an annual fee of up to 5.7 percent to have access to forecasts of REIT returns that take their bull and bear dynamics into account instead of simpler, linear forecast.

Bianchi, F. (2016). "Methods for measuring expectations and uncertainty in Markov-switching models." In: *Journal of Econometrics* 190(1), pp. 79–99.
I develop methods to analyze multivariate Markov-switching models. Formulas for the evolution of first and second moments are derived and then used to characterize expectations, uncertainty, impulse responses, sources of uncertainty, and welfare implications of regime changes in general equilibrium models. The methods can be used to capture the link between uncertainty and the state of the economy. Campbell's present value decomposition is generalized to allow for parameter instability. Taking into account regime changes is shown to be important for expectations, welfare, and uncertainty. All results are derived analytically and are therefore suitable for structural estimation.

Bianchi, F. (2020). "The Great Depression and the Great Recession: A view from financial markets." In: *Journal of Monetary Economics* 114, pp. 240–261.
Similarities between the Great Depression and the Great Recession are documented with respect to the behavior of financial markets. A Great Depression regime is identified by using a Markov-switching VAR. The probability of this regime has remained close to zero for many decades, but spiked for a short period during the most recent financial crisis, the Great Recession. The Great Depression regime implies a collapse of the stock market, with small-growth stocks outperforming small-value stocks. A model with financial frictions and uncertainty about policy makers' intervention suggests that policy intervention during the Great Recession might have avoided a

second Great Depression. A multi-country analysis shows that the Great Depression and Great Recession were not like any other financial crises.

Billio, M., Ferrara, L., Guegan, D., and Mazzi, G. L. (2013). "Evaluation of Regime Switching Models for Real-Time Business Cycle Analysis of the Euro Area." In: *Journal of Forecasting* 32(7), pp. 577–586.
In this paper, we aim at assessing Markov switching and threshold models in their ability to identify turning points of economic cycles. By using vintage data updated on a monthly basis, we compare their ability to date ex post the occurrence of turning points, evaluate the stability over time of the signal emitted by the models and assess their ability to detect in real-time recession signals. We show that the competitive use of these models provides a more robust analysis and detection of turning points. To perform the complete analysis, we have built a historical vintage database for the euro area going back to 1970 for two monthly macroeconomic variables of major importance for short-term economic outlook, namely the industrial production index and the unemployment rate.

Bilokon, P., Jacquier, A., and McIndoe, C. (2021). "Market regime classification with signatures." In: *arXiv e-Print*.
We provide a data-driven algorithm to classify market regimes for time series. We utilise the path signature, encoding time series into easy-to-describe objects, and provide a metric structure which establishes a connection between separation of regimes and clustering of points.

Blazquez-Garcia, A., Conde, A., Mori, U., and Lozano, J. A. (2022). "A review on outlier/anomaly detection in time series data." In: *ACM Computing Surveys* 54(3), pp. 1–33.
Recent advances in technology have brought major breakthroughs in data collection, enabling a large amount of data to be gathered over time and thus generating time series. Mining this data has become an important task for researchers and practitioners in the past few years, including the detection of outliers or anomalies that may represent errors or events of interest. This review aims to provide a structured and comprehensive state-of-the-art on outlier detection techniques in the context of time series. To this end, a taxonomy is presented based on the main aspects that characterize an outlier detection technique.

Blin, O., Ielpo, F., Lee, J., and Teiletche, J. (2017). "A Macro Risk-Based Approach to Alternative Risk Premia Allocation." In: *Factor Investing*. Elsevier, pp. 285–316.
Alternative risk premia are encountering growing interest from investors. The vast majority of academic literature has been focusing on describing the alternative risk premia (typically, momentum, carry and value strategies) individually. In this chapter, we investigate the question of the allocation across a range of cross-asset alternative risk premia. For this, we design an active macro risk-based framework that notably aims to exploit alternative risk premia's varying behavior in different macro regimes. We build long-term strategic portfolios across economic regimes, which we dynamically tilt based on point-in-time signals related to regimes nowcasting and current carry. We perform back tests of the allocation strategy in an out-of-sample setting.

Blitz, D. and Van Vliet, P. (2009). "Dynamic Strategic Asset Allocation: Risk and Return Across Economic Regimes." In: *SSRN e-Print*.
We propose a practical investment framework for dynamic asset allocation across different economic regimes, which we illustrate using a sample of U.S. data from 1948 to 2007. We identify four regimes in the economic cycle and find that these regimes capture pronounced time-variation in the risk and return properties of asset classes. Time-variation is also observed in the risk of a traditional, static strategic asset allocation portfolio . In order to stabilize risk across the economic cycle we propose a dynamic strategic asset allocation approach, which has the potential to enhance expected return as well. The proposed approach is found to be robust to variations in the variable composition of the regime model and can easily be extended with different economic variables and/or additional assets.

BNYMellon Research (2013). *Great expectations: regime based asset allocation seeks higher return, lower drawdowns*. Tech. rep. BNY Mellon.
Our research finds that dynamically adjusting asset class exposures as growth and inflation expectations shift has the potential to significantly improve risk-adjusted returns and reduce drawdowns. We analyzed more than 40 years of economic and market performance to achieve a more granular understanding of the complex pattern of macroeconomic regime transitions and the role growth and inflation expectations play in driving asset prices. Based on this research, we used growth and inflation expectations data to create a model that could offer insight into the probability of certain macroeconomic regimes. Changes in these expectations pointed to macroeconomic regimes in which assets have distinct performance characteristics. These regimes have varying lengths and occur at varying frequencies. Our model seeks to provide a roadmap to the probabilities of future regimes based on the evolution of our factors, and we explore structuring portfolios to take advantage of probable transitions

among them. We extend this framework to allow clients to see which regimes their own portfolios are currently positioned for, and provide a structure for analyzing how portfolios are aligned with the convictions of their managers.

Boot, T. (2017). "Macroeconomic Forecasting under Regime Switching, Structural Breaks and High-dimensional Data." PhD thesis. Tinbergen Instituut.
In the first two chapters of this thesis, we consider the bias-variance trade-off in models subject to regime switches and structural breaks. The non-linearities pose a challenge to find an optimal trade-off as the variance term is not easily tractable. The final two chapters discuss the trade-off in (high-dimensional) linear models, in which we consider estimators for which explicit bounds on their performance can be provided.

Bordalo, P., Gennaioli, N., Kwon, S. Y., and Shleifer, A. (2021). "Diagnostic bubbles." In: *Journal of Financial Economics* 141(3), pp. 1060–1077.
We introduce diagnostic expectations into a standard setting of price formation in which investors learn about the fundamental value of an asset and trade it. We study the interaction of diagnostic expectations with learning from prices and speculation (buying for resale). With diagnostic (but not with rational) expectations, these mechanisms lead to price paths exhibiting three phases: initial underreaction, then overshooting (the bubble), and finally a crash. With learning from prices, the model generates price extrapolation as a by-product of beliefs about fundamentals, lasting only as the bubble builds up. When investors speculate, even mild diagnostic distortions generate substantial bubbles.

Botte, A. and Bao, D. (2021). *A Machine Learning Approach to Regime Modeling*. Tech. rep. Two Sigma.
The authors offer a data-driven approach to modeling market regimes by applying a Gaussian Mixture Model (a machine learning method) to the factors in the Two Sigma Factor Lens.

Bradrania, R. and Neghab, D. P. (2022). "State-dependent asset allocation using neural networks." In: *The European Journal of Finance*.
Changes in market conditions present challenges for investors as they cause performance to deviate from the ranges predicted by long-term averages of means and covariances. The aim of conditional asset allocation strategies is to overcome this issue by adjusting portfolio allocations to hedge changes in the investment opportunity set. This paper proposes a new approach to conditional asset allocation that is based on machine learning; it analyzes historical market states and asset returns and identifies the optimal portfolio choice in a new period when new observations become available. In this approach, we directly relate state variables to portfolio weights, rather than firstly modeling the return distribution and subsequently estimating the portfolio choice. The method captures nonlinearity among the state (predicting) variables and portfolio weights without assuming any particular distribution of returns and other data, without fitting a model with a fixed number of predicting variables to data and without estimating any parameters. The empirical results for a portfolio of stock and bond indices show the proposed approach generates a more efficient outcome compared to traditional methods and is robust in using different objective functions across different sample periods.

Braei, M. and Wagner, S. (2020). "Anomaly Detection in Univariate Time-series: A Survey on the State-of-the-Art." In: *arXiv e-Print*.
Anomaly detection for time-series data has been an important research field for a long time. Seminal work on anomaly detection methods has been focussing on statistical approaches. In recent years an increasing number of machine learning algorithms have been developed to detect anomalies on time-series. Subsequently, researchers tried to improve these techniques using (deep) neural networks. In the light of the increasing number of anomaly detection methods, the body of research lacks a broad comparative evaluation of statistical, machine learning and deep learning methods. This paper studies 20 univariate anomaly detection methods from the all three categories. The evaluation is conducted on publicly available datasets, which serve as benchmarks for time-series anomaly detection. By analyzing the accuracy of each method as well as the computation time of the algorithms, we provide a thorough insight about the performance of these anomaly detection approaches, alongside some general notion of which method is suited for a certain type of data.

Bucci, A. and Ciciretti, V. (2021). "Market Regime Detection via Realized Covariances: A Comparison between Unsupervised Learning and Nonlinear Models." In: *arXiv e-Print*.
There is broad empirical evidence of regime switching in financial markets. The transition between different market regimes is mirrored in correlation matrices, whose time-varying coefficients usually jump higher in highly volatile regimes, leading to the failure of common diversification methods. In this article, we aim to identify market regimes from covariance matrices and detect transitions towards highly volatile regimes, hence improving tail-risk hedging. Starting from the time series of fractionally differentiated sentiment-like future values, two

models are applied on monthly realized covariance matrices to detect market regimes. Specifically, the regime detection is implemented via vector logistic smooth transition autoregressive model (VLSTAR) and through an unsupervised learning methodology, the agglomerative hierarchical clustering. Since market regime switches are unobservable processes that describe the latent change of market behaviour, the ability of correctly detecting market regimes is validated in two ways: firstly, randomly generated data are used to assess a correct classification when regimes are known; secondly, a naïve trading strategy filtered with the detected regime switches is used to understand whether an improvement is showed when accounting for regime switches. The results point to the VLSTAR as the best performing model for labelling market regimes.

Bybee, L., Kelly, B. T., and Su, Y. (2022). "Narrative Asset Pricing: Interpretable Systematic Risk Factors from News Text." In: *SSRN e-Print*.

We seek fundamental risks from news text. Conceptually, news is closely related to the idea of systematic risk, in particular the "state variables" in the ICAPM. News captures investors' concerns about future investment opportunities, and hence drives the current pricing kernel. This paper demonstrates a way to extract a parsimonious set of risk factors and eventually a univariate pricing kernel from news text. The state variables are reduced and selected from the variations in attention allocated to different news narratives. As a result, the risk factors attain clear text-based interpretability as well as top-of-the-line asset pricing performance. The empirical method integrates topic modeling (LDA), latent factor analysis (IPCA), and variable selection (group lasso).

Campani, C. H., Garcia, R., and Lewin, M. (2021). "Optimal portfolio strategies in the presence of regimes in asset returns." In: *Journal of Banking & Finance* 123, p. 106030.

This paper analyzes optimal portfolio and consumption strategies in a regime-switching economy with unobservable states and predictability of risky asset returns. We develop approximate analytical solutions to the unconstrained dynamic problem. The approximation is shown to be fast and accurate in a four-regime setting with an allocation to four assets compared to the numerical solution developed in Guidolin and Timmermann (2007). The computation time of the approximate solution is shown to be practically independent of the number of assets when no predictors are present and only marginally affected by the number of predictors. While the portfolio policy strongly depends on the current state of the economy, the consumption-to-wealth ratio is roughly state-independent. Predictability considerably changes the optimal portfolios. Hedging demands are negligible with regimes and no predictability, but are important with predictability. On the other hand, the consumption-to-wealth ratio is not very impacted by the predictor. We provide an out-of-sample statistical assessment of the returns provided by a multi-regime strategy with respect to a single-regime and to a strategy.

Can, H. (2019). "To Switch or Not to Switch: Return Prediction and financial cycles." MA thesis. Erasmus University.

This paper emphasizes the importance of identifying changes in financial cycles when predicting monthly US excess stock returns for the period 1977 - 2017. Incorporating regime switching into the predictive models improves the quality of the excess return forecasts in terms of market timing ability, economic value and stability. The Markov Switching models consisting of predictor variables selected based on their performance during bull and bear markets performs especially well. A mean-variance investor would be willing to pay several hundreds basis points to switch from the static benchmark portfolios to one of these portfolio strategies.

Chabi-Yo, F., Huggenberger, M., and Weigert, F. (2022). "Multivariate Crash Risk." In: *Journal of Financial Economics*.

This paper investigates whether multivariate crash risk (MCRASH), defined as exposure to extreme realizations of multiple systematic factors, is priced in the cross-section of expected stock returns. We derive an extended linear model with a positive premium for MCRASH, and we empirically confirm that stocks with high MCRASH earn significantly higher future returns than stocks with low MCRASH. The premium is not explained by linear factor exposures, alternative downside risk measures, or stock characteristics. Extending market-based definitions of crash risk to other well-established factors helps to determine the cross-section of expected stock returns without further expanding the factor zoo.

Chalapathy, R. and Chawla, S. (2019). "Deep Learning for Anomaly Detection: A Survey." In: *arXiv e-Print*.

Anomaly detection is an important problem that has been well-studied within diverse research areas and application domains. The aim of this survey is two-fold, firstly we present a structured and comprehensive overview of research methods in deep learning-based anomaly detection. Furthermore, we review the adoption of these methods for anomaly across various application domains and assess their effectiveness. We have grouped state-of-the-art research techniques into different categories based on the underlying assumptions and approach adopted. Within each category we outline the basic anomaly detection technique, along with its variants and present key assumptions, to differentiate between normal and anomalous behavior. For each category, we present we also

present the advantages and limitations and discuss the computational complexity of the techniques in real application domains. Finally, we outline open issues in research and challenges faced while adopting these techniques.

Chalapathy, R., Khoa, N. L. D., and Chawla, S. (2020). "Robust Deep Learning Methods for Anomaly Detection." In: *Proceedings of the 26th ACM SIGKDD International Conference on Knowledge Discovery & Data Mining*. ACM.

Anomaly detection is an important problem that has been well-studied within diverse research areas and application domains. A robust anomaly detection system identifies rare events and patterns in the absence of labelled data. The identified patterns provide crucial insights about both the fidelity of the data and deviations in the underlying data-generating process. For example a surveillance system designed to monitor the emergence of new epidemics will use a robust anomaly detection methods to separate spurious associations from genuine indicators of an epidemic with minimal lag time. The key concept in anomaly detection is the notion of "robustness", i.e., designing models and representations which are less-sensitive to small changes in the underlying data distribution. The canonical example is that the median is more robust than the mean as an estimator. The tutorial will primarily help researchers and developers design deep learning architectures and loss functions where the learnt representation behave more like the "median" rather than the "mean." The tutorial will revisit well known unsupervised learning techniques in deep learning including autoencoders and generative adversarial networks (GANs) from the perspective of anomaly detection. This in turn will give the audience a more grounded perspective on unsupervised deep learning methods. All the methods will be introduced in a hands-on manner to demonstrate how high-level ideas and concepts get translated to practical real code.

Chalkis, A., Christoforou, E., Dalamagkas, T., and Emiris, I. Z. (2021). "Modeling of crisis periods in stock markets." In: *arXiv e-Print*.

We exploit a recent computational framework to model and detect financial crises in stock markets, as well as shock events in cryptocurrency markets, which are characterized by a sudden or severe drop in prices. Our method manages to detect all past crises in the French industrial stock market starting with the crash of 1929, including financial crises after 1990 (e.g. dot-com bubble burst of 2000, stock market downturn of 2002), and all past crashes in the cryptocurrency market, namely in 2018, and also in 2020 due to covid-19. We leverage copulae clustering, based on the distance between probability distributions, in order to validate the reliability of the framework; we show that clusters contain copulae from similar market states such as normal states, or crises. Moreover, we propose a novel regression model that can detect successfully all past events using less than 10% of the information that the previous framework requires. We train our model by historical data on the industry assets, and we are able to detect all past shock events in the cryptocurrency market. Our tools provide the essential components of our software framework that offers fast and reliable detection, or even prediction, of shock events in stock and cryptocurrency markets of hundreds of assets.

Chang, Y., Choi, Y., and Park, J. Y. (2017). "A new approach to model regime switching." In: *Journal of Economics* 196(1), pp. 127–143.

This paper introduces a new approach to model regime switching using an autoregressive latent factor, which determines regimes depending upon whether it takes a value above or below some threshold level. In our approach, the latent factor is allowed to be correlated with the innovation to the observed time series. If the latent factor becomes exogenous, our approach reduces to the conventional Markov switching. We develop a modified Markov switching filter to estimate the mean and volatility models with Markov switching that are frequently analyzed, and find that the presence of endogeneity in regime switching is indeed strong and ubiquitous.

Chapman, J.-L. and Killick, R. (2020). "An assessment of practitioners approaches to forecasting in the presence of changepoints." In: *Quality and Reliability Engineering International* 36(8), pp. 2676–2687.

A common challenge in time series is to forecast data that suffer from structural breaks or changepoints which complicate modeling. If we naively forecast using one model for the whole data, the model will be incorrect, and thus, our forecast error will be large. There are two common practices to account for these changepoints when the goal is forecasting: (1) preprocess the data to identify the changepoints, incorporating them as dummy variables in modeling the whole data, and (2) include the changepoint estimation into the model and forecast using the model fit to the last segment. This article examines these two practices, using the computationally exact Pruned Exact Linear Time (PELT) algorithm for changepoint detection, comparing and contrasting them in the context of an important Software Engineering application.

Chen, J. M., Rehman, M. U., and Vo, X. V. (2021). "Clustering commodity markets in space and time: Clarifying returns, volatility, and trading regimes through unsupervised machine learning." In: *Resources Policy* 73, p. 102162.

Unsupervised machine learning can interpret logarithmic returns and conditional volatility in commodity markets. This article applies machine learning in order to visualize and interpret log returns and conditional volatility in commodities trading. We emphasize two classes of unsupervised learning methods: clustering and manifold learning for the reduction of dimensionality. We source daily prices from September 18, 2000 through July 31, 2020, for precious metals, base metals), energy commodities and agricultural commodities. Our results highlight that at the very least, returns-based clusters conform more closely to traditional boundaries between precious metals, base metals, fuels, temperate-climate agricultural commodities, and tropical agricultural commodities. On the other hand, volatility-based clustering succeeds in identifying periods of extreme market distress, such as the global financial crisis of 2008-09 and the Covid-19 pandemic.

Chen, J. (2019). "Studying Regime Change using Directional Change." PhD thesis. University of Essex.

Financial markets reflect what is the collective trading behaviour of traders. Such behaviour is often affected by financial crisis or political events. The term regime change is used to describe such significant change of collective behaviour. This thesis studies how regime change can be measured and detected in financial markets. The traditional ways to detect regime changes are based on analysis of the statistical properties of time series. For example, researchers may have used significant changes in means, volatilities, autocorrelations and cross-covariances of asset returns to conclude regime changes. In this thesis, we study regime change detection using indicators developed in Directional Change (DC). DC is an alternative way to sample financial data. Unlike time series, which samples transaction prices at regular time intervals, DC samples prices at peaks and troughs of the market. We propose a new method to detect regime changes under the DC framework. DC data is fed into a Hidden Markov Model (HMM), a machine learning model, which aims to discover the hidden state of the market. To evaluate our method, we apply it to the Forex market over a time period of uncertainty, namely the Brexit referendum period. The timing of regime changes detected by this method is consistent with the political developments taking place at the time. While regime changes detected by DC and time series agree with each other most of the time, some regime changes found under DC were not found under time series. That means our DC approach complemented the time series approach by the provision of supporting and additional information. With the method developed, we then went on to detect normal and abnormal market regimes (which represent regimes before and after significant events took place) in other assets. Through observation of regimes detected in ten different markets at different times using different thresholds, we discovered that normal and abnormal regimes are clearly separable from each other in the DC indicator space. This allowed us to generalise and characterise what are the features of normal and abnormal market regimes using DC indicators. We then showed that the regime characteristics established above can be used for regime tracking. As a proof of concept, we showed that, based on the market data observed so far, one can use a simple Bayes model to compute the probability of the current market being in the normal or abnormal regime. Preliminary results suggested that the proposed method managed to detect regime change signals accurately and promptly. Finally, we examined the usefulness of the detected regime change signals. Two trading algorithms are proposed to demonstrate the practical implication of the regime tracking information. To summarise: this thesis pioneers a new method for regime change detection under the DC framework. It showed that normal and abnormal regimes can becharacterised using DC indicators. Once such characteristics are clearly established, this could be used for effective market tracking, which potentially lays the foundation for a practical financial early warning system. The regime tracking signals can be used to established valuable trading algorithms.

Chen, J. and Tsang, E. P. K. (2020). *Detecting regime change in computational finance: data science, machine learning and algorithmic trading*. Boca Raton: CRC Press, Taylor & Francis Group. 164 pp.

Based on interdisciplinary research into "Directional Change", a new data-driven approach to financial data analysis, Detecting Regime Change in Computational Finance: Data Science, Machine Learning and Algorithmic Trading applies machine learning to financial market monitoring and algorithmic trading. Directional Change is a new way of summarising price changes in the market. Instead of sampling prices at fixed intervals (such as daily closing in time series), it samples prices when the market changes direction ("zigzags"). By sampling data in a different way, this book lays out concepts which enable the extraction of information that other market participants may not be able to see.

The book explores the following topics:

1) Data science: as an alternative to time series, price movements in a market can be summarised as directional changes
2) Machine learning for regime change detection: historical regime changes in a market can be discovered by a Hidden Markov Model

3) Regime characterisation: normal and abnormal regimes in historical data can be characterised using indicators defined under Directional Change

4) Market Monitoring: by using historical characteristics of normal and abnormal regimes, one can monitor the market to detect whether the market regime has changed

5) Algorithmic trading: regime tracking information can help us to design trading algorithms

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Chen, P. and Yang, H. (2011). "Markowitz's Mean-Variance Asset-Liability Management with Regime Switching: A Multi-Period Model." In: *Applied Mathematical Finance* 18(1), pp. 29–50.
This paper considers an optimal portfolio selection problem under Markowitz's mean-variance portfolio selection problem in a multi-period regime-switching model. We assume that there are n + 1 securities in the market. Given an economic state which is modelled by a finite state Markov chain, the return of each security at a fixed time point is a random variable. The return random variables may be different if the economic state is changed even for the same security at the same time point. We start our analysis from the no-liability case, in the spirit of Li and Ng (2000 Li, D. and Ng, W. L. 2000. Optimal dynamic portfolio selection: Multi-period mean-variance formulation. Mathematical Finance, 10: 387-406. [Crossref], [Web of Science] , [Google Scholar]), both the optimal investment strategy and the efficient frontier are derived. Then we add uncontrollable liability into the model. By direct comparison with the no-liability case, the optimal strategy can be derived explicitly.

Cheng, E., Kostyuchyk, N., Lee, W., Liu, P., and Ma, C. (2021). "Trending Fast and Slow." In: *The Journal of Portfolio Management*.
This article develops a methodology to combine fast and slow time-series momentum signals using machine learning techniques based on market volatility. Starting with the US equity market, the authors find that the performance of a time-series momentum strategy is determined by both its responsiveness and the market volatility regime, among other factors. A decision tree gives a simple and insightful way to determine the threshold in characterizing low- and high-volatility regimes. A slow time-series momentum strategy tends to outperform a fast time-series momentum strategy when market volatility is low. The opposite tends to occur when volatility is high. This pattern of relative performance can be attributed to market-timing alpha and exists in most global equity markets, including both developed and emerging markets.

Chiappa, S. (2011). "Unified Treatment of Hidden Markov Switching Models." In: *arXiv e-Print*.
Many real-world problems encountered in several disciplines deal with the modeling of time-series containing different underlying dynamical regimes, for which probabilistic approaches are very often employed. In this paper we describe several such approaches in the common framework of graphical models. We give a unified overview of models previously introduced in the literature, which is simpler and more comprehensive than previous descriptions and enables us to highlight commonalities and differences among models that were not observed in the past. In addition, we present several new models and inference routines, which are naturally derived within this unified viewpoint.

Chollete, L., Heinen, A., and Valdesogo, A. (2009). "Modeling International Financial Returns with a Multivariate Regime-switching Copula." In: *Journal of Financial Econometrics* 7(4), pp. 437–480.
In order to capture observed asymmetric dependence in international financial returns, we construct a multivariate regime-switching model of copulas. We model dependence with one Gaussian and one canonical vine copula regime. Canonical vines are constructed from bivariate conditional copulas and provide a very flexible way of characterizing dependence in multivariate settings. We apply the model to returns from the G5 and Latin American regions, and document three main findings. First, we discover that models with canonical vines generally dominate alternative dependence structures. Second, the choice of copula is important for risk management, since it modifies the Value-at-Risk (VaR) of international portfolios and produces a better out-of-sample performance. Third, ignoring asymmetric dependence and regime-switching in portfolio selection leads to significant costs for an investor.

Chowdhury, M. S. R., Damianov, D. S., and Elsayed, A. H. (2021). "Bubbles and Crashes in Cryptocurrencies: Interdependence, Contagion, or Asset Rotation?" In: *SSRN e-Print*.
Using a quantile vector autoregressive model to capture return dynamics in extreme market conditions, we find that the cryptocurrency market exhibits a high level of market connectedness. Bitcoin is a net transmitter of return spillovers during busts and a net receiver during booms. Analysis of the timing of bubble and crash periods uncovers the presence of interdependence and contagion effects. There is only limited evidence for asset rotation,

and it involves mostly Ripple. Bubbles in Ripple occur simultaneously or are followed by crashes in other major cryptocurrencies which highlights its unique role as a portfolio diversifier in extreme market conditions.

Chuffart, T. (2017). "An Implementation of Markov Regime Switching GARCH Models in Matlab." In: *SSRN e-Print*.
MSGtool is a MATLAB toolbox which provides a collection of functions for the simulation and estimation of a large variety of Markov Switching GARCH (MSG) models. Currently, the software integrates a method to select the best starting values for the estimation and a post-estimation analysis to ensure the convergence. The toolbox is very flexible a user-friendly with a large number possible options. In this paper, we give some illustrative examples.

Clacher, I., Freeman, M., Hillier, D., Kemp, M., and Zhang, Q. (2015). "A Practical Guide to Regime Switching in Financial Economics." In: *Quantitative Financial Risk Management: Theory and Practice*. Ed. by C. Zopounidis and E. Galariotis. John Wiley and Sons, Inc, pp. 71–97.
In this chapter, we introduce the principles and applications of Markov Regime Switching Models in financial economics. Real world asset return dynamics are complex and do not follow the standard assumptions of being independently and identically normally distributed (i.i.n.d.). As a result, standard models with logarithmic returns often fail to capture the underling processes in the data and the presence of time-varying correlations. One way in which academics and practitioners can better model these dynamics is through Markov Regime Switching Models. We therefore introduce some of the basic concepts in this area; provide an overview of some of the economic contexts where this modelling has been applied; and finish by providing a discussion around the challenges in properly implementing these models in a real world context.

Corbelli, R., Vellasco, M., and Veiga, A. (2020). "Investigating Optimal Regimes for Prediction in the Stock Market." In: *IEEE Congress on Evolutionary Computation (CEC)*. IEEE.
Forecasting stock prices in the market its known to be an extremely difficult task, where even the predictability of the series itself is a controversial matter. The present study investigates the existence of periods within the series more suitable for prediction, and whether the identification and exploitation of those periods could be learned from data. In order to do that, the Predictability Crawler (P-Craw) framework is proposed. The technique uses optimizations routines such as the Particle Swarm optimization (PSO) or Genetic Algorithms (GA) to select subsets of historical data where statistical learning algorithms can be more efficiently trained. When tested against simulated data, The P-Craw is able to reliably identify the optimal subsets in scenarios ranging from 40% to 100% of predictable samples in the data. To access if the framework brings any improvement when used in a real world scenario, it is tested in a dataset containing intraday data from the Brazilian stocks exchange (BOVESPA). When benchmarked against training with all the samples for the series in the BOVESPA dataset the use of the framework is able to significantly raise the Correct Directional Changes (CDC) of the trained models while reducing the Mean Absolute Error (MAE) in up to 19%.

Costa, G. and Kwon, R. H. (2019). "Risk parity portfolio optimization under a Markov regime-switching framework." In: *Quantitative Finance* 19(33), pp. 453–471.
We formulate and solve a risk parity optimization problem under a Markov regime-switching framework to improve parameter estimation and to systematically mitigate the sensitivity of optimal portfolios to estimation error. A regime-switching factor model of returns is introduced to account for the abrupt changes in the behaviour of economic time series associated with financial cycles. This model incorporates market dynamics in an effort to improve parameter estimation. We proceed to use this model for risk parity optimization and also consider the construction of a robust version of the risk parity optimization by introducing uncertainty structures to the estimated market parameters. We test our model by constructing a regime-switching risk parity portfolio based on the Fama-French three-factor model. The out-of-sample computational results show that a regime-switching risk parity portfolio can consistently outperform its nominal counterpart, maintaining a similar ex post level of risk while delivering higher-than-nominal returns over a long-term investment horizon. Moreover, we present a dynamic portfolio rebalancing policy that further magnifies the benefits of a regime-switching portfolio.

Costa, G. and Kwon, R. H. (2020). "A regime-switching factor model for mean-variance optimization." In: *Journal of Risk* 22(4), pp. 31–59.
We formulate a novel Markov regime-switching factor model to describe the cyclical nature of asset returns in modern financial markets. Maintaining a factor model structure allows us to easily derive the asset expected returns and their corresponding covariance matrix. By design, these two parameters are calibrated to better describe the properties of the different market regimes. In turn, these regime-dependent parameters serve as the inputs during mean-variance optimization, thereby constructing portfolios adapted to the current market envi-

ronment. Through this formulation, the proposed model allows for the construction of large, realistic portfolios at no additional computational cost during optimization. Moreover, the viability of this model can be significantly improved by periodically rebalancing the portfolio, ensuring proper alignment between the estimated parameters and the transient market regimes. An out-of-sample computational experiment over a long investment horizon shows that the proposed regime-dependent portfolios are better aligned with the market environment, yielding a higher ex post rate of return and lower volatility than competing portfolios.

Cram, R. G. (2020). "Late to Recessions: Stocks and the Business Cycle." In: *SSRN e-Print*.
I find that returns are predictably negative for several months after the onset of recessions, and only become high thereafter. I identify business-cycle turning points by estimating a state-space model using macroeconomic data. Conditioning on the business cycle further reveals that returns exhibit momentum in recessions, whereas in expansions they display the mild reversals expected from discount rate changes. A market timing strategy that optimally exploits this business-cycle pattern produces a 60% increase in the buy-and-hold Sharpe ratio. I find that a subset of hedge funds add value for their clients in part by avoiding stock market crashes during recessions.

Dai, M., Jin, H., Kou, S., and Xu, Y. (2021). "Robo-Advising: A Dynamic Mean-Variance Approach." In: *SSRN e-Print*.
In contrast to traditional financial advising, robo-advising needs to elicit investors' risk profile via several simple online questions and provide advice consistent with conventional investment wisdom, e.g., rich and young people should invest more in risky assets. To meet the two challenges, we propose to do the asset allocation part of robo-advising using a dynamic mean-variance criterion over the the portfolio's log-returns. The model yields analytical and time-consistent optimal portfolio policies under jump-diffusion models and regime-switching models.

Dal Pra, G., Guidolin, M., Pedio, M., and Vasile, F. (2018). "Regime Shifts in Excess Stock Return Predictability: An Out-of-Sample Portfolio Analysis." In: *The Journal of Portfolio Management* 44(3), pp. 10–24.
The authors analyze the out-of-sample performance of asset allocation decisions based on financial ratio predictability of aggregate stock market returns under linear and regime-switching models. The authors adopt both a statistical perspective to analyze whether models based on valuation ratios can forecast excess equity returns, and an economic approach that turns predictions into portfolio strategies. These consist of a portfolio switching approach, a mean-variance framework, and a long-run dynamic model. The authors find a disconnect between the statistical perspective, whereby the ratios yield a modest forecasting power, and a portfolio approach, by which a moderate predictability is often sufficient to yield significant portfolio outperformance, especially before transaction costs and when regimes are taken into account. However, also when regimes are considered, predictability gives high payoffs only to long horizon, highly risk-averse investors. Moreover, different strategies deliver different performance rankings across predictors.

Dapena, J. P., Serur, J. A., and Siri, J. R. (2020). "Risk On-Risk Off: A Regime Switching Model for Active Portfolio Management." In: *SSRN e-Print*.
Unlike passive management, where investors almost do not buy and sell securities, active management involves a set of trading rules that govern investment decisions regarding mainly market timing. In this paper, we take the basics of active management and the two fund separation approach, to exploit the fact that an investor can switch between the market portfolio and the risk free asset according to the perceived state of the nature. Our purpose is to evaluate if there is an active management premium by testing performance with our own non-conventional multifactor model, constructed with a Hidden Markov Model which depending on the market states signaled by the level of volatility spread. We have documented that effectively, there is present a premium for actively manage the strategies, giving evidence against the idea that managers destroy capital. We then propose the volatility spread as the active management factor into the Carhart's model used to evaluate trading strategies with respect to a benchmark portfolio.

Das, S. R., Ostrov, D. N., Casanova, A., Radhakrishnan, A., and Srivastav, D. (2021). "Optimal Goals-Based Investment Strategies For Switching Between Bull and Bear Markets." In: *SSRN e-Print*.
We apply dynamic programming to solve a long-horizon fund choice problem, given that the underlying market can switch between different regimes. The objective function is based on reaching a target level of wealth, following the paradigm of goal-based investing. In a world with a good regime (e.g., a bull market) and a bad regime (e.g., a bear market), we find that an investor who is cognizant of regime switching can potentially do much better over time than an investor who assumes there is only one regime. However, there is a caveat—an investor must be able to predict the regime they are in with reasonable levels of confidence, and if not, they are in fact worse off than an investor who assumes just one regime. Using data from recent history, we find that

investors may be better off not switching from existing single-regime models to more complex multiple-regime models.

Das, S. R., Ostrov, D. N., Casanova, A., Radhakrishnan, A., and Srivastav, D. (2022). "Optimal Goals-Based Investment Strategies For Switching Between Bull and Bear Markets." In: *The Journal of Wealth Management* 24(4), pp. 8–36.
We solve a dynamic, long-horizon, goals-based wealth management problem, given different investment regimes. In a world with a good regime (bull market) and a bad regime (bear market), an investor who is cognizant that regime switching occurs has the potential to do better than an investor who assumes only one regime. However, models with more than one regime incur the additional risk of regime uncertainty. Investors must be able to predict which regime is governing the market with reasonable levels of confidence, or they can be worse off than investors who assume just one regime. Using data from recent history, we develop a framework that determines how accurate regime prediction needs to be to achieve gains from a regime-cognizant goals-based investing approach.

Das, S., Islam, M. R., Jayakodi, N. K., and Doppa, J. R. (2019). "Active Anomaly Detection via Ensembles: Insights, Algorithms, and Interpretability." In: *arXiv e-Print*.
Anomaly detection (AD) task corresponds to identifying the true anomalies from a given set of data instances. AD algorithms score the data instances and produce a ranked list of candidate anomalies, which are then analyzed by a human to discover the true anomalies. However, this process can be laborious for the human analyst when the number of false-positives is very high. Therefore, in many real-world AD applications including computer security and fraud prevention, the anomaly detector must be configurable by the human analyst to minimize the effort on false positives. In this paper, we study the problem of active learning to automatically tune ensemble of anomaly detectors to maximize the number of true anomalies discovered. We make four main contributions towards this goal. First, we present an important insight that explains the practical successes of AD ensembles and how ensembles are naturally suited for active learning. Second, we present several algorithms for active learning with tree-based AD ensembles. These algorithms help us to improve the diversity of discovered anomalies, generate rule sets for improved interpretability of anomalous instances, and adapt to streaming data settings in a principled manner. Third, we present a novel algorithm called GLocalized Anomaly Detection (GLAD) for active learning with generic AD ensembles. GLAD allows end-users to retain the use of simple and understandable global anomaly detectors by automatically learning their local relevance to specific data instances using label feedback. Fourth, we present extensive experiments to evaluate our insights and algorithms. Our results show that in addition to discovering significantly more anomalies than state-of-the-art unsupervised baselines, our active learning algorithms under the streaming-data setup are competitive with the batch setup.

Demos, G. and Sornette, D. (2017). "Birth or burst of financial bubbles: which one is easier to diagnose?" In: *Quantitative Finance* 17(5), pp. 657–675.
Abreu and Brunnermeier (2003) have argued that bubbles are not suppressed by arbitrageurs because they fail to synchronise on the uncertain beginning of the bubble. We propose an indirect quantitative test of this hypothesis and confront it with the alternative according to which bubbles persist due to the difficulty of agreeing on the end of bubbles. We present systematic tests of the precision and reliability with which the beginning t1 and end tc of a bubble can be determined.For this, we use a specific bubble model, the log-periodic power law singularity (LPPLS) model, which represents a bubble as a transient noisy super-exponential price trajectory decorated by accelerated volatility oscillations. Generalising the estimation procedure to endogenise the beginning of the fitting time interval, we quantify the uncertainty on the calibrated t1 and tc (as well as the other model parameters) via the eigenvalues of the Hessian matrix, which characterise the shape of the calibration cost function in the different directions in parameter space, on many synthetic data and four historical bubble cases. We find overwhelming evidence that the beginning of bubbles is much better constrained that their end. Our results are robust over all four empirical bubbles and many synthetic tests, as well as when changing the time of analysis (the present) during the development of the bubbles. As a bonus, we find that the two structural parameters of the LPPLS model, the exponent m controlling the super-exponential growth of price and the angular log-periodic frequency omega describing the log-periodic acceleration of volatility, are very rigid according the Hessian matrix analysis, which supports the LPPLS model as a reasonable candidate for describing the generating process of prices during bubbles.

Dette, H., Eckle, T., and Vetter, M. (2021). "Multiscale change point detection for dependent data." In: *Scandinavian Journal of Statistics*.

In this article we study the theoretical properties of the simultaneous multiscale change point estimator (SMUCE) in piecewise-constant signal models with dependent error processes. Empirical studies suggest that in this case the change point estimate is inconsistent, but it is not known if alternatives suggested in the literature for correlated data are consistent. We propose a modification of SMUCE scaling the basic statistic by the long run variance of the error process, which is estimated by a difference-type variance estimator calculated from local means from different blocks. For this modification we prove model consistency for physical-dependent error processes and illustrate the finite sample performance by means of a simulation study.

Dette, H., Wu, W., and Zhou, Z. (2019). "Change Point Analysis of Correlation in Non-stationary Time Series." In: *Statistica Sinica* (29), pp. 611–643.
A restrictive assumption in change point analysis is "stationarity under the null hypothesis of no change-point", which is crucial for asymptotic theory but not very realistic from a practical point of view. For example, if change point analysis for correlations is performed, it is not necessarily clear that the mean, marginal variance or higher order moments are constant, even if there is no change in the correlation. This paper develops change point analysis for the correlation structures under less restrictive assumptions. In contrast to previous work, our approach does not require that the mean, variance and fourth order joint cumulants are constant under the null hypothesis. Moreover, we also address the problem of detecting relevant change points.

Dias, J. G., Vermunt, J. K., and Ramos, S. (2015). "Clustering financial time series: New insights from an extended hidden Markov model." In: *European Journal of Operational Research* 243(3), pp. 852–864.
In recent years, large amounts of financial data have become available for analysis. We propose exploring returns from 21 European stock markets by model-based clustering of regime switching models. These econometric models identify clusters of time series with similar dynamic patterns and moreover allow relaxing assumptions of existing approaches, such as the assumption of conditional Gaussian returns. The proposed model handles simultaneously the heterogeneity across stock markets and over time, i.e., time-constant and time-varying discrete latent variables capture unobserved heterogeneity between and within stock markets, respectively. The results show a clear distinction between two groups of stock markets, each one characterized by different regime switching dynamics that correspond to different expected return-risk patterns. We identify three regimes: the so-called bull and bear regimes, as well as a stable regime with returns close to 0, which turns out to be the most frequently occurring regime. This is consistent with stylized facts in financial econometrics.

Ding, Z. (2012). "An Implementation of Markov Regime Switching Model with Time Varying Transition Probabilities in Matlab." In: *SSRN e-Print*.
This memo explains how to use the MATLAB code for estimating a Markov Regime Switching Model with time varying transition probabilities. The code is developed by Zhuanxin Ding based on the original code by Marcelo Perlin for estimating a Markov Regime Switching Model with constant transition probability matrix.

Dou, P. Y., Gallagher, D. R., Schneider, D., Walter, T., and Berkman, H. (2014). "Cross-region and cross-sector asset allocation with regimes." In: *Accounting and Finance* 54(3), pp. 809–846.
Cross-region and cross-sector asset allocation decisions are one of the most fundamental issues in international equity portfolio management. Equity returns exhibit higher volatilities and correlations, and lower expected returns, in bear markets compared to bull markets. However, static mean-variance analysis fails to capture this salient feature of equity returns. We accommodate the nonlinearity of returns using a regime switching model across both regions and sectors. The regime-dependent asset allocation potentially adds value to the traditional static mean-variance allocation. In addition, optimal allocation across sectors provide greater benefits compared to international diversification, which is characterized by higher returns, lower risks, lower correlations with the world market and a higher Sharpe ratio.

Douady, R. and Kornprobst, A. (2018). "An Empirical Approach to Financial Crisis Indicators Based on Random Matrices." In: *International Journal of Theoretical and Applied Finance* 21(03), p. 1850022.
The aim of this work is to build a class of financial crisis indicators based on the spectral properties of the dynamics of market data. After choosing an appropriate size for a rolling window, the historical market data inside this rolling window are seen every trading day as a random matrix from which a correlation matrix is obtained. Our goal is to study the correlations between the assets that constitute this market and look for reproducible patterns that are indicative of an impending financial crisis. A weighting of the assets in the market is then introduced and is proportional to the daily traded volumes. This manipulation is realized in order to give more importance to the most liquid assets. Our financial crisis indicators are based on the spectral radius of this weighted correlation matrix. The idea behind this type of financial crisis indicators is that large eigenvalues are a

sign of dynamic instability. The out-of-sample predictive power of the financial crisis indicators in this framework is then demonstrated, in particular by using them as decision-making tools in a protective put strategy.

Duprey, T. and Klaus, B. (2017). "How to Predict Financial Stress? An Assessment of Markov Switching Models." In: *SSRN e-Print*.

This paper predicts phases of the financial cycle by combining a continuous financial stress measure in a Markov switching framework. The debt service ratio and property market variables signal a transition to a high financial stress regime, while economic sentiment indicators provide signals for a transition to a tranquil state. Whereas the in-sample analysis suggests that these indicators can provide an early warning signal up to several quarters prior to the respective regime change, the out-of-sample findings indicate that most of this performance is due to the data gathered during the global financial crisis. Comparing the prediction performance with a standard binary early warning model reveals that the MS model is outperforming in the vast majority of model specifications for a horizon up to three quarters prior to the onset of financial stress.

Edirisinghe, C. and Zhao, Y. (2020). "Smart Indexing Under Regime-Switching Economic States." In: *Applied Mathematical Finance* 27(5), pp. 422–456.

Index funds that track a benchmark, such as the market cap-weighted S&P 500 index, tend to have portfolio holdings biased towards slower-growth large-cap equities that result in the fund's under-performance, especially in economic downturns. We develop a rigorous quantitative framework that allows dynamic-rebalancing of the allocations such that portfolio exposure in a market segment can change periodically based on economic activity, measured via a set of macro-economic and financial indicators. The method incorporates potential shifts in the economic state, and the likelihood thereof, to determine the fund's risk orientation optimally in tracking or not tracking the benchmark index. That is, the greater the likelihood of a stronger economic state, the higher the degree of tracking the market index; however, a lack of confidence in the economic state results in a more index-neutral portfolio composition. The proposed smart indexing optimal strategy generates superior risk-adjusted returns consistently in out-of-sample testing, relative to (pure) index tracking. We test several variants and present sensitivity analyses that support our actively-managed smart indexing approach.

Elkamhi, R., Lee, J., and Salerno, M. (2021). "Portfolio Tilts using Views on Macroeconomic Regimes." In: *SSRN e-Print*.

Long-term investors rebalance their portfolios given their views on the investment landscape. Portfolio tilting is often implemented using investors' views on point estimates of asset expected returns which are notoriously difficult to estimate and lead to unstable portfolio weights. We avoid such shortcomings by providing a methodology that incorporates views on the likelihood of economic regimes (e.g., growth and inflation). Using data on equities, bonds and commodities, we show - both in simulation and empirically - that our approach generates stable portfolio weights and a performance that is minimally affected by forecast errors.

Elkind, D., Kaminski, K., Lo, A. W., Siah, K. W., and Wong, C. H. (2022). "When Do Investors Freak Out? Machine Learning Predictions of Panic Selling." In: *The Journal of Financial Data Science* 4(1), pp. 11–39.

Using a novel dataset of 653,455 individual brokerage accounts belonging to 298,556 households, the authors document the frequency, timing, and duration of panic sales, which they define as a decline of 90% of a household account's equity assets over the course of one month, of which 50% or more is due to trades. The authors find that a disproportionate number of households make panic sales when there are sharp market downturns, a phenomenon they call freaking out. The authors also show that panic selling and freak-outs are predictable and fundamentally different from other well-known behavioral patterns such as overtrading or the disposition effect.

Elliott, G. and Timmermann, A. (2005). "Optimal forecast combination under regime switching." In: *International Economic Review* 46(4), pp. 1081–1102.

This article proposes a new forecast combination method that lets the combination weights be driven by regime switching in a latent state variable. An empirical application that combines forecasts from survey data and time series models finds that the proposed regime switching combination scheme performs well for a variety of macroeconomic variables. Monte Carlo simulations shed light on the type of data-generating processes for which the proposed combination method can be expected to perform better than a range of alternative combination schemes. Finally, we show how time variations in the combination weights arise when the target variable and the predictors share a common factor structure driven by a hidden Markov process.

Elouai, H. M., Lambinet, R., and Morel, T. (2013). "Bubbles and Regimes: Two Complementary Approaches." In: *SSRN e-Print*.

The financial risk associated with financial bubbles (both large and small) is difficult to analyse using traditional risk models. The ability to detect bubbles before they burst represents a major challenge in itself. We believe

that the issue raised by financial bubbles can contribute to discussions on the risk-on/risk-off theory as identified by the various regime switches. In addition to a signal indicating the presence of bubbles, we need a second signal to help us determine the theoretical date that the bubble will burst in order to determine the optimal exit time. Our approach is built on a combination of two quantitative models: a bubble detection model and a Markov regime-switching model. These signals offer two benefits: generating absolute performance and limiting extreme risk (the tail-risk hedging strategy). Although we only illustrate the results with the SandP 500, the approach should be generalised to all asset classes.

Endres, S. and Stubinger, J. (2019). "A flexible regime switching model with pairs trading application to the S&P 500 high-frequency stock returns." In: *Quantitative Finance*, pp. 1–14.
This paper develops the regime classification algorithm and applies it within a fully-fledged pairs trading framework on minute-by-minute data of the SandP 500 constituents from 1998 to 2015. Specifically, the highly flexible algorithm automatically determines the number of regimes for any stochastic process and provides a complete set of parameter estimates. We demonstrate its performance in a simulation study algorithm achieves promising results for the general class of Levy-driven Ornstein-Uhlenbeck processes with regime switches. In our empirical back-testing study, we apply our regime classification algorithm to propose a high-frequency pair selection and trading strategy. The results show statistically and economically significant returns with an annualized Sharpe ratio of 3.92 after transaction costs remain stable even in recent years. We compare our strategy with existing quantitative trading frameworks and find its results to be superior in terms of risk and return characteristics. The ...

Engle, R. F. and Ruan, T. (2019). "Measuring the probability of a financial crisis." In: *Proceedings of the National Academy of Sciences* 116(37), pp. 18341–18346.
This study develops quantitative estimates of the level of systemic risk in the financial sector that precipitates a financial crisis. When financial firms are undercapitalized, they face difficulty in covering losses in a downturn. The natural response to such vulnerability, reducing leverage through asset sales, can start a financial crisis. Perilous excessive credit growth is reflected in the undercapitalization of the financial sector. Market-based indicators of systemic risk such as SRISK, which stands for systemic risk, measure such weakness in real time. We develop a probability of crisis measure and an SRISK capacity measure for 23 developed countries. Our analysis highlights the important global externality whereby the risk of a crisis in one country depends on the undercapitalization of the rest of the world.

Erlwein, C., Mitra, G., and Roman, D. (2012). "HMM based scenario generation for an investment optimisation problem." In: *Annals of Operations Research* 193(1), pp. 173–192.
The Geometric Brownian motion (GBM) is a standard method for modelling financial time series. An important criticism of this method is that the parameters of the GBM are assumed to be constants; due to this fact, important features of the time series, like extreme behaviour or volatility clustering cannot be captured. We propose an approach by which the parameters of the GBM are able to switch between regimes, more precisely they are governed by a hidden Markov chain. Thus, we model the financial time series via a hidden Markov model (HMM) with a GBM in each state. Using this approach, we generate scenarios for a financial portfolio optimisation problem in which the portfolio CVaR is minimised. Numerical results are presented.

Erlwein-Sayer, C., Grimm, S., Sass, J., and Sayer, T. (2016). "Portfolio Strategies and Estimation in a Hidden Markov Model Using State Dependent, State Independent or No Correlation." In: *SSRN e-Print*.
We consider portfolio optimization in a regime-switching market. The assets of the portfolio are modeled through a hidden Markov model (HMM) in discrete time, where drift and volatility are allowed to switch between different states. We consider different parametrizations of the involved asset covariances namely state-wise uncorrelated assets, which are though linked through the common Markov chain, assets correlated in a state-independent way, and assets where the correlation varies from state to state. As a control model, we also consider a model without regime switches. We utilize a filter-based EM-algorithm to obtain optimal parameter estimates within this multivariate HMM and develop parameter estimators in all three HMM settings. We discuss the impact of these different models on the performance of several portfolio strategies. Our findings show that for simulated returns our strategies often outperform naive investment strategies, like the equal weights strategy. Information criteria can be used to detect the best model for estimation as well as for portfolio optimization. A second study using real data confirms these findings.

Filimonov, V., Demos, G., and Sornette, D. (2017). "Modified profile likelihood inference and interval forecast of the burst of financial bubbles." In: *Quantitative Finance* 17(8), pp. 1167-11861–20.

We present a detailed methodological study of the application of the modified profile likelihood method for the calibration of nonlinear financial models characterized by a large number of parameters. We apply the general approach to the Log-Periodic Power Law Singularity (LPPLS) model of financial bubbles. This model is particularly relevant because one of its parameters, the critical time signalling the burst of the bubble, is arguably the target of choice for dynamical risk management. However, previous calibrations of the LPPLS model have shown that the estimation of is in general quite unstable. Here, we provide a rigorous likelihood inference approach to determine , which takes into account the impact of the other nonlinear (so-called ?nuisance?) parameters for the correct adjustment of the uncertainty on . This provides a rigorous interval estimation for the critical time, rather than the point estimation in previous approaches. As a bonus, the interval estimates can also be obtained for the nuisance parameters (, damping), which can be used to improve filtering of the calibration results. We show that the use of the modified profile likelihood method dramatically reduces the number of local extrema by constructing much simpler smoother log-likelihood landscapes. The remaining distinct solutions can be interpreted as genuine scenarios that unfold as the time of the analysis flows, which can be compared directly via their likelihood ratio. Finally, we develop a multi-scale profile likelihood analysis to visualize the structure of the financial data at different scales (typically from 100 to 750 days). We test the methodology successfully on synthetic price time series and on three well-known historical financial bubbles.

Fischer, E. O. and Murg, M. (2015). "A combined regime-switching and Black Litterman model for optimal asset allocation." In: *Journal of Investment Strategies* 4(3), pp. 1–36.

Traditionally, portfolios are optimized with a single-regime Markowitz model, using volatility as the risk measure and historical return as the expected return. This paper shows what effects a regime-switching framework, alternative risk measures (modifiedvalue-at-risk and conditional value-at-risk) and return measures (capital asset pricing model estimates and Black Litterman estimates) can have on asset allocation as well as the absolute and relative performance of portfolios. We show that the combination of alternative risk and return measures within the regime-switching framework gives significantly better results in terms of performance and a modified Sharpe ratio. The use of alternative risk and return measures also mitigates the issue that asset returns are not often normally distributed or serially correlated. To eliminate the empirical shortcomings of asset returns, an unsmoothing algorithm in combination with the Cornish-Fisher expansion is used.

Flint, E., Seymour, A., and Chikurunhe, F. (2021). "Defining and measuring portfolio diversification." In: *South African Actuarial Journal* 20(1), pp. 17–48.

It is often said that diversification is the only 'free lunch' available to investors; meaning that a properly diversified portfolio reduces total risk without necessarily sacrificing expected return. However, achieving true diversification is easier said than done, especially when we do not fully know what we mean when we are talking about diversification. While the qualitative purpose of diversification is well known, a satisfactory quantitative definition of portfolio diversification remains elusive. In this research, we summarise a wide range of diversification measures, focusing our efforts on those most commonly used in practice. We categorise each measure based on which portfolio aspect it focuses on: cardinality, weights, returns, risk or higher moments. We then apply these measures to a range of South African equity indices, thus giving a diagnostic review of historical local equity diversification and, perhaps more importantly, providing a description of the investable opportunity set available tofund managers in this space. Finally, we introduce the idea of diversification profiles. These regime dependent profiles give a much richer description of portfolio diversification than their single-value counterparts and also allow one to manage diversification proactively based on one's view of future market conditions.

Flint, E. and du Plooy, S. (2018). "Extending risk budgeting for market regimes and quantile factor models." In: *Journal of Investment Strategies* 7(4), pp. 51–74.

We combine several disparate avenues in the literature to create a novel, unified risk- based optimization framework. Specifically, we extend an existing risk-budgeting approach to allow for changing market regimes and factor dependence as well as a nonlinear, asymmetric market structure. We show that the existing framework can be readily extended to include a factor-dependent return process using standard models available in the literature. Structural changes in the market conditions are then incorporated into the framework via the use of a regime-switching turbulence index, and the nonlinear and asymmetric market dependence structure is accounted for by using quantile factor models. Most importantly, this extended framework is comprised of a series of linear models only and is thus simple to understand and to implement. We consider two applications of the extended framework, namely, scenario analysis and parameter uncertainty analysis, by way of a simple empirical case study. Finally, we introduce the concept of risk maps, which provide managers with a graphical approach for estimating and evaluating risk optimality in a multiobjective, multiscenario setting.

Flint, E. J. and Mare, E. (2019). "Regime-Based Tactical Allocation for Equity Factors and Balanced Portfolios." In: *South African Actuarial Journal* 19(1), pp. 27–52.
It is now an accepted fact that the majority of financial markets worldwide are neither normal nor constant, and South Africa is no exception. One idea that can be used to understand such markets and has been gaining popularity recently is that of regimes and regime-switching models. In this research, we consider whether regimes can add value to the asset allocation process. Four methods for regime identification – economic cycle variables, fundamental valuation metrics, technical market indicators and statistical regime-switching models – are discussed and tested on two asset universes – longonly South African equity factor returns and representative balanced portfolio asset class returns. We find several promising regime indicators and use these to create two regime-based tactical allocation frameworks. Out-of-sample testing on both the equity factor and balanced asset class data shows very promising results, with both regime-based tactical strategies outperforming their respective static benchmarks on an absolute return and risk-adjusted return basis. We also turn our attention to a potentially major recent development in the local fund management space; namely, the introduction of Capped Shareholder-Weighted indices as new benchmarks. We provide comparative analysis between the capped and uncapped Shareholder-Weighted indices in terms of sector weights, stock concentration, currency exposure and factor risk contributions.

Fons, E., Dawson, P., Yau, J., Zeng, X.-j., and Keane, J. (2021). "A novel dynamic asset allocation system using Feature Saliency Hidden Markov models for smart beta investing." In: *Expert Systems with Applications* 163, pp. 113720+.
The financial crisis of 2008 generated interest in more transparent, rules-based strategies for portfolio construction, with smart beta strategies emerging as a trend among institutional investors. Whilst they perform well in the long run, these strategies often suffer from severe short-term drawdown (peak-to-trough decline) with fluctuating performance across cycles. To manage short term risk (cyclicality and underperformance), we build a dynamic asset allocation system using Hidden Markov Models (HMMs). We use a variety of portfolio construction techniques to test our smart beta strategies and the resulting portfolios show an improvement in risk-adjusted returns, especially on more return-oriented portfolios (up to 50% of return in excess of market adjusted by relative risk annually). In addition, we propose a novel smart beta allocation system based on the Feature Saliency HMM (FSHMM) algorithm that performs feature selection simultaneously with the training of the HMM, to improve regime identification. We evaluate our systematic trading system with real life assets using MSCI indices; further, the results (up to 60% of return in excess of market adjusted by relative risk annually) show model performance improvement with respect to portfolios built using full feature HMMs.

Foorthuis, R. (2021). "On the Nature and Types of Anomalies: A Review." In: *arXiv e-Print*.
Anomalies are occurrences in a dataset that are in some way unusual and do not fit the general patterns. The concept of the anomaly is generally ill-defined and perceived as vague and domain-dependent. Moreover, no comprehensive and concrete overviews of the different types of anomalies have hitherto been published. By means of an extensive literature review this study therefore offers the first theoretically principled and domain-independent typology of data anomalies, and presents a full overview of anomaly types and subtypes. To concretely define the concept of the anomaly and its different manifestations the typology employs four dimensions: data type, cardinality of relationship, data structure and data distribution. These fundamental and data-centric dimensions naturally yield 3 broad groups, 9 basic types and 61 subtypes of anomalies. The typology facilitates the evaluation of the functional capabilities of anomaly detection algorithms, contributes to explainable data science, and provides insights into relevant topics such as local versus global anomalies.

Francis, N., Owyang, M. T., and Soques, D. (2021). *Business Cycles Across Space and Time*. Tech. rep. SSRN e-Print.
We study the comovement of international business cycles in a time series clustering model with regime-switching. We extend the framework of Hamilton and Owyang (2012) to include time-varying transition probabilities to determine what drives similarities in business cycle turning points. We find four groups, or "clusters", of countries which experience idiosyncratic recessions relative to the global cycle. Additionally, we find the primary indicators of international recessions to be fluctuations in equity markets and geopolitical uncertainty. In out-of-sample forecasting exercises, we find that our model is an improvement over standard benchmark models for forecasting both aggregate output growth and country-level recessions.

Fulop, A. and Yu, J. (2017). "Bayesian analysis of bubbles in asset prices." In: *Econometrics* 5(4), p. 47.
We develop a new model where the dynamic structure of the asset price, after the fundamental value is removed, is subject to two different regimes. One regime reflects the normal period where the asset price divided by the

dividend is assumed to follow a mean-reverting process around a stochastic long run mean. The second regime reflects the bubble period with explosive behavior. Stochastic switches between two regimes and non-constant probabilities of exit from the bubble regime are both allowed. A Bayesian learning approach is employed to jointly estimate the latent states and the model parameters in real time. An important feature of our Bayesian method is that we are able to deal with parameter uncertainty and at the same time, to learn about the states and the parameters sequentially, allowing for real time model analysis. This feature is particularly useful for market surveillance. Analysis using simulated data reveals that our method has good power properties for detecting bubbles. Empirical analysis using price-dividend ratios of SandP500 highlights the advantages of our method.

Gallagher, L. A., Hutchinson, M. C., and O'Brien, J. (2020). "Using Smooth Transition Regressions to Model Risk Regimes." In: *Handbook of Financial Econometrics, Mathematics, Statistics, and Machine Learning*. World Scientific, pp. 4281–4311.

The smooth transition regression (STR) methodology was developed to model nonlinear relationships in the business cycle. We demonstrate the methodology can be used to analyse return series where exposure to financial market risk factors depends on market regime. The smooth transition between regimes inherent in STR is particularly appropriate for risk models as it allows for gradual transition of risk factor exposures. Variations in the methodology and tests its appropriateness are defined and discussed. We apply the STR methodology to model the risk of the return series of the convertible arbitrage (CA) hedge fund strategy. CA portfolios are comprised of instruments that have both equity and bond characteristics and alternate between the two depending on market level (state). The dual characteristics make the CA strategy a strong candidate for nonlinear risk models. Using the STR model, we confirm that the strategy's risk factor exposure changes with market regime and, using this result, are able to account for the abnormal returns reported for the strategy in earlier studies.

Gao, G., Ho, K.-Y., and Shi, Y. (2018). "Long memory or regime switching in volatility? Evidence from high-frequency returns on the U.S. stock indices." In: *Pacific-Basin Finance Journal*.

Recent research suggests that long memory and regime switching can be effectively distinguished, if the cause of the confusion between them is properly controlled for. Motivated by this idea, our study aims to distinguish between them in modelling stock return volatility. We firstly model long memory and regime switching in volatility via the Long-Memory GARCH (LMGARCH) and Markov Regime-Switching GARCH (MRS-GARCH) models, respectively. A theoretical cause of the confusion between those processes is proposed with simulation evidence. Adopting the ideas of existing studies, an MRS-LMGARCH framework is further developed to control for this cause. Our Monte Carlo studies show that this model can effectively distinguish between the pure LMGARCH and pure MRS-GARCH processes. Finally, empirical studies of NASDAQ and SandP 500 index returns are conducted to demonstrate that our MRS-LMGARCH model can provide potentially more reliable estimates of the long-memory parameter, identify the volatility states and outperform both the LMGARCH and MRS-GARCH models.

Gatumel, M. and Ielpo, F. (2014). "The Number of Regimes Across Asset Returns: Identification and Economic Value." In: *International Journal of Theoretical and Applied Finance* 17(06), pp. 1450040+.

A shared belief in the financial industry is that markets are driven by two types of regimes: bull markets, characterized by high returns and low volatility, and bear markets, characterized by low returns coupled with high volatility. Modeling the dynamics of different asset classes (stocks, bonds, commodities and currencies) with a Markov switching (MS) model and using a density-based test, we reject the hypothesis that two-regimes are enough to capture asset return evolutions for many of the investigated assets. Once the accuracy of our test methodology has been assessed through Monte Carlo experiments, our empirical results point out that between two and five regimes are required to capture the features of each asset's distribution. Moreover, we show that only a part of the underlying number of regimes is explained by the distributional characteristics of the returns such as kurtosis. A thorough out-of-sample analysis provides additional evidence that there are more than just bulls and bears in financial markets. Finally, we highlight that taking into account the real number of regimes allows both improved portfolio returns and density forecasts.

Geiger, A., Liu, D., Alnegheimish, S., Cuesta-Infante, A., and Veeramachaneni, K. (2020). "TadGAN: Time Series Anomaly Detection Using Generative Adversarial Networks." In: *arXiv e-Print*.

Time series anomalies can offer information relevant to critical situations facing various fields, from finance and aerospace to the IT, security, and medical domains. However, detecting anomalies in time series data is particularly challenging due to the vague definition of anomalies and said data's frequent lack of labels and highly complex temporal correlations. Current state-of-the-art unsupervised machine learning methods for anomaly

detection suffer from scalability and portability issues, and may have high false positive rates. In this paper, we propose TadGAN, an unsupervised anomaly detection approach built on Generative Adversarial Networks (GANs). To capture the temporal correlations of time series distributions, we use LSTM Recurrent Neural Networks as base models for Generators and Critics. TadGAN is trained with cycle consistency loss to allow for effective time-series data reconstruction. We further propose several novel methods to compute reconstruction errors, as well as different approaches to combine reconstruction errors and Critic outputs to compute anomaly scores. To demonstrate the performance and generalizability of our approach, we test several anomaly scoring techniques and report the best-suited one. We compare our approach to 8 baseline anomaly detection methods on 11 datasets from multiple reputable sources such as NASA, Yahoo, Numenta, Amazon, and Twitter. The results show that our approach can effectively detect anomalies and outperform baseline methods in most cases (6 out of 11). Notably, our method has the highest averaged F1 score across all the datasets. Our code is open source and is available as a benchmarking tool.

Gerlach, J.-C., Kreuser, J. L., and Sornette, D. (2020). "Crash-sensitive Kelly Strategy built on a modified Kreuser-Sornette bubble model tested over three decades of twenty equity indices." In: *SSRN e-Print*.
We present a modified version of the super-exponential rational expectations "Efficient Crashes" bubble model of (Kreuser and Sornette, 2019) with a different formulation of the expected return that makes clearer the additive nature of corrective jumps. We derive a Kelly trading strategy for the new model. We combine the strategy with a simplified estimation procedure for the model parameters from price time series. We optimize the control parameters of the trading strategy by maximizing the return-weighted accuracy of trades. This enables us to predict the out-of-sample optimal investment, purely based on in-sample calibration of the model on historical data. Our approach solves the difficult problem of selecting the portfolio rebalancing time, as we endogenize it as an optimization parameter. We develop an ex-ante backtest that allows us to test our strategy on twenty equity asset indices. We find that our trading strategy achieves positive trading performance for 95% of tested assets and outperforms the Buy-and-Hold-Strategy in terms of CAGR and Sharpe Ratio in 60% of cases. In our simulations, we do not allow for any short trading or leverage. Thus, we simply simulate allocation of 0-100% of one's capital between a risk-free and the risky asset over time. The optimal rebalancing periods are mostly of duration around a month; thus, the model does not overtrade, ensuring reasonable trading costs. Furthermore, during crashes, the model reduces the invested amount of capital sufficiently soon to reduce impact of price drawdowns. In addition to the Dotcom bubble, the great financial crisis of 2008 and other historical crashes, our study also covers the most recent crash in March 2020 that happened globally as a consequence of the economic shutdowns that were imposed as a reaction to the spread of the Coronavirus across the world.

Gerstenberger, C. (2021). "Robust discrimination between long-range dependence and a change in mean." In: *Journal of Time Series Analysis* 42(1), pp. 34–62.
In this article we introduce a robust to outliers Wilcoxon changepoint testing procedure, for distinguishing between shortrange dependent time series with a change in mean at unknown time and stationary longrange dependent time series. We establish the asymptotic distribution of the test statistic under the null hypothesis for L1 near epoch dependent processes and show its consistency under the alternative. The Wilcoxontype testing procedure similarly as the CUSUMtype testing procedure (of Berkes I., Horvath L., Kokoszka P. and Shao Q. 2006. Ann.Statist. 34:1140-1165), requires estimation of the location of a possible changepoint, and then using pre and postbreak subsamples to discriminate between short and longrange dependence. A simulation study examines the empirical size and power of the Wilcoxontype testing procedure in standard cases and with disturbances by outliers. It shows that in standard cases the Wilcoxontype testing procedure behaves equally well as the CUSUMtype testing procedure but outperforms it in presence of outliers. We also apply both testing procedure to hydrologic data.

Gkatzilakis, G.-X. and Sivasubramanian, S. (2014). "Active Allocation of Smart Beta Indices based on Factor Timing and Regime Switching." MA thesis. EDHEC Risk Institute.
There has been significant evidence on the forecasting ability of Regime switching regression models. Smart beta or alternative beta indices are gaining wide popularity among investment community. Smart beta indices constructed based on fundamental weighing are proven to outperform cap-weighted portfolios in the long run. At the same time, smart beta indices have significant exposure to risk factors such as size, value, momentum and volatility. The risk factors exhibit different behaviour in different regimes. In this research we examine and present evidence of the presence of regimes in smart beta indices. We also examine the possibility of adding value to a portfolio by switching between regime dependent portfolios of smart beta indices exploiting factor exposures.

Glasserman, P., Mamaysky, H., and Shen, Y. (2021). "Dynamic information regimes in financial markets." In: *SSRN e-Print*.
We develop a model of investor information choices and asset prices where the availability of information about fundamentals is time-varying. A competitive research sector produces more information when more investors are willing to pay for that research. This feedback, from investor willingness to pay for information to more information production, generates two regimes in equilibrium, one having high prices and low volatility, the other the opposite. The low-price, high-volatility regime is associated with greater information asymmetry between informed and uninformed investors. Information dynamics move the market between regimes, creating large price drops even with no change in fundamentals. In our calibration, the model suggests an important role for information dynamics in financial crises.

Glocker, C. and Wegmueller, P. (2020). "Business cycle dating and forecasting with real-time Swiss GDP data." In: *Empirical Economics* 58(1), pp. 73–105.
We develop a small-scale dynamic factor model for the Swiss economy allowing for nonlinearities by means of a two-state Markov chain. The selection of an appropriate set of indicators utilizes a combinatorial algorithm. The model's forecasting performance is as good as that of peers with richer dynamics. It proves particularly useful for a timely assessment of the business cycle stance, as the recessionary regime probabilities tend to have a leading property. The model successfully anticipated the downturn of the 2008-2009 recession and promptly indicated a fall in GDP growth following the discontinuation of the exchange rate floor of the Swiss Franc.

Gobel, M. and Araujo, T. (2020). "Indicators of economic crises: a data-driven clustering approach." In: *Applied Network Science* 5(1) (44).
The determination of reliable early-warning indicators of economic crises is a hot topic in economic sciences. Pinning down recurring patterns or combinations of macroeconomic indicators is indispensable for adequate policy adjustments to prevent a looming crisis. We investigate the ability of several macroeconomic variables telling crisis countries apart from non-crisis economies. We introduce a self-calibrated clustering-algorithm, which accounts for both similarity and dissimilarity in macroeconomic fundamentals across countries. Furthermore, imposing a desired community structure, we allow the data to decide by itself, which combination of indicators would have most accurately foreseen the exogeneously defined network topology. We quantitatively evaluate the degree of matching between the data-generated clustering and the desired community-structure.

Goswami, B., Boers, N., Rheinwalt, A., Marwan, N., Heitzig, J., Breitenbach, S. F. M., and Kurths, J. (2018). "Abrupt transitions in time series with uncertainties." In: *Nature Communications* 9(1) (48).
Identifying abrupt transitions is a key question in various disciplines. Existing transition detection methods, however, do not rigorously account for time series uncertainties, often neglecting them altogether or assuming them to be independent and qualitatively similar. Here, we introduce a novel approach suited to handle uncertainties by representing the time series as a time-ordered sequence of probability density functions. We show how to detect abrupt transitions in such a sequence using the community structure of networks representing probabilities of recurrence. Using our approach, we detect transitions in global stock indices related to well-known periods of politico-economic volatility. We further uncover transitions in the El Nino-Southern Oscillation which coincide with periods of phase locking with the Pacific Decadal Oscillation. Finally, we provide for the first time an 'uncertainty-aware' framework which validates the hypothesis that ice-rafting events in the North Atlantic during the Holocene were synchronous with a weakened Asian summer monsoon.

Gu, J. and Mulvey, J. M. (2021). "Factor Momentum and Regime-Switching Overlay Strategy." In: *The Journal of Financial Data Science* 3(4), pp. 101–129.
Investors are faced with challenges in diversifying risks and protecting capital during crash periods. In this article, the authors incorporate regime information in the portfolio optimization context by identifying regimes for historical time periods using an l1-trend filtering algorithm and exploring different machine learning techniques to forecast the probability of an upcoming stock market crash. They then apply a regime-based asset allocation to nominal risk parity strategy. Investors can further improve their investment performance by implementing a dollar-neutral factor momentum strategy as an overlay in conjunction with the core portfolio. The authors demonstrate that the time-series factor momentum strategy generates high risk-adjusted returns and exhibits pronounced defensive characteristics during market crashes. A volatility scaling approach is employed to manage the risk and further magnify the benefits of factor momentum. Empirical results suggest that the approach improves risk-adjusted returns by a substantial amount over the benchmark from both the standalone perspective and the contributory perspective.

Guérin, P., Leiva-Leon, D., and Marcellino, M. (2020). "Markov-Switching Three-Pass Regression Filter." In: *Journal of Business & Economic Statistics* 38(2), pp. 285–302.
We introduce a new approach for the estimation of high-dimensional factor models with regime-switching factor loadings by extending the linear three-pass regression filter to settings where parameters can vary according to Markov processes. The new method, denoted as Markov-switching three-pass regression filter (MS-3PRF), is suitable for datasets with large cross-sectional dimensions, since estimation and inference are straightforward, as opposed to existing regime-switching factor models where computational complexity limits applicability to few variables. In a Monte Carlo experiment, we study the finite sample properties of the MS-3PRF and find that it performs favorably compared with alternative modeling approaches whenever there is structural instability in factor loadings. For empirical applications, we consider forecasting economic activity and bilateral exchange rates, finding that the MS-3PRF approach is competitive in both cases. Supplementary materials for this article are available online.

Guidolin, M. (2011). "Markov Switching in Portfolio Choice and Asset Pricing Models: A Survey." In: *Advances in Econometrics*. Emerald Group Publishing, pp. 87–178.
I survey applications of Markov switching models to the asset pricing and portfolio choice literatures. In particular, I discuss the potential that Markov switching models have to fit financial time series and at the same time provide powerful tools to test hypotheses formulated in the light of financial theories, and to generate positive economic value, as measured by risk-adjusted performances, in dynamic asset allocation applications. The chapter also reviews the role of Markov switching dynamics in modern asset pricing models in which the no-arbitrage principle is used to characterize the properties of the fundamental pricing measure in the presence of regimes.

Guidolin, M., Orlov, A. G., and Pedio, M. (2018). "How good can heuristic-based forecasts be? A comparative performance of econometric and heuristic models for UK and US asset returns." In: *Quantitative Finance* 18(1), pp. 139–169.
This paper systematically investigates the sources of differential out-of-sample predictive accuracy of heuristic frameworks based on internet search frequencies and a large set of econometric models. The volume of internet searches helps gauge the degree of investors' time-varying interest in specific assets. We use a wide range of state-of-the-art models, both of linear and nonlinear type (regime-switching predictive regressions, threshold autoregressive, smooth transition autoregressive), extended to capture conditional heteroskedasticity through GARCH models. The predictor variables investigated are those typical of the literature featuring a range of macroeconomic and market leading indicators. Our out-of-sample forecasting exercises are conducted with reference to US, UK, French and German data, both stocks and bonds, and for 1- and 12-months-ahead horizons. We employ several forecast performance metrics and predictive accuracy tests. Internet-search-based models are found to perform better than the average of all of the alternative models. For several country-asset-horizon combinations, particularly for UK bond returns, our heuristic models compare favourably with sophisticated econometric methods. The heuristic models are also shown to perform well in forecasting realized volatility. The baseline results are supported by several extensions and robustness checks, such as using alternative search keywords, controlling for Fama-French and Cochrane-Piazzesi factors, and implementing heuristic-based trading strategies.

Guidolin, M. and Timmermann, A. (2008). "International asset allocation under regime switching, skew, and kurtosis preferences." In: *The Review of Financial Studies* 21(2), pp. 889–935.
This paper investigates the international asset allocation effects of time-variations in higher-order moments of stock returns such as skewness and kurtosis. In the context of a four-moment International Capital Asset Pricing Model (ICAPM) specification that relates stock returns in five regions to returns on a global market portfolio and allows for time-varying prices of covariance, co-skewness, and co-kurtosis risk, we find evidence of distinct bull and bear regimes. Ignoring such regimes, an unhedged US investor's optimal portfolio is strongly diversified internationally. The presence of regimes in the return distribution leads to a substantial increase in the investor's optimal holdings of US stocks, as does the introduction of skewness and kurtosis preferences.

Haase, F. and Neuenkirch, M. (2021). "Predictability of Bull and Bear Markets: A New Look at Forecasting Stock Market Regimes (and Returns) in the U.S." In: *SSRN e-Print*.
The empirical literature of stock market predictability mainly suffers from model uncertainty and parameter instability. To meet this challenge, we propose a novel approach that combines the documented merits of diffusion indices, regime-switching models, and forecast combination to predict the dynamics in the S&P 500. First, we aggregate the weekly information of 115 popular macroeconomic and financial variables through an interaction

of principal component analysis and shrinkage methods. Second, we estimate one-step Markov-switching models with time-varying transition probabilities using the diffusion indices as predictors. Third, we pool the forecasts in clusters to hedge against model risk and to evaluate the usefulness of different specifications. Our results show that we can adequately predict regime dynamics. Our forecasts provide a statistical improvement over several benchmarks and generate economic value by boosting returns, improving the certainty equivalent return, and reducing tail risk. Using the same approach for return forecasts, however, does not lead to a consistent outperformance of the historical average.

Hallac, D., Nystrup, P., and Boyd, S. (2019). "Greedy Gaussian segmentation of multivariate time series." In: *Advances in Data Analysis and Classification* 13(3), pp. 727–751.
We consider the problem of breaking a multivariate (vector) time series into segments over which the data is well explained as independent samples from a Gaussian distribution. We formulate this as a covariance-regularized maximum likelihood problem, which can be reduced to a combinatorial optimization problem of searching over the possible breakpoints, or segment boundaries. This problem can be solved using dynamic programming, with complexity that grows with the square of the time series length. We propose a heuristic method that approximately solves the problem in linear time with respect to this length, and always yields a locally optimal choice, in the sense that no change of any one breakpoint improves the objective. Our method, which we call greedy Gaussian segmentation (GGS), easily scales to problems with vectors of dimension over 1000 and time series of arbitrary length. We discuss methods that can be used to validate such a model using data, and also to automatically choose appropriate values of the two hyperparameters in the method. Finally, we illustrate our GGS approach on financial time series and Wikipedia text data.

Hammerschmid, R. and Lohre, H. (2018). "Regime Shifts and Stock Return Predictability." In: *International Review of Economics and Finance* 56, pp. 138–160.
Identifying economic regimes is useful in a world of time-varying risk premia. We apply regime switching models to common factors proxying for the macroeconomic regime and show that the ensuing regime factor is relevant in forecasting the equity risk premium. Moreover, the relevance of this regime factor is preserved in the presence of fundamental variables and technical indicators which are known to predict equity risk premia. Based on multiple predictive regressions and pooled forecasts, the macroeconomic regime factor is deemed complementary relative to the fundamental and technical information sets. Finally, these forecasts exhibit significant out-of-sample predictability that ultimately translates into considerable utility gains in a mean-variance portfolio strategy.

Hao, H. (2019). "A Regime-Aware Agent-Based Framework for Financial Planning." PhD thesis. Princeton University.
The vulnerability of individuals planning for retirement has been growing due to the conversion from defined-benefit plans to defined-contribution plans, the steady increase in life longevity, and the uncertainty of asset returns under an ever-changing global environment. A serious problem is the lack of appropriate planning for retirement. How much should an individual save beyond the Social Security tax in order to maintain a reasonable lifestyle after retirement? This paper designs a framework to facilitate the process of setting realistic goals for financial planning, featuring the concept of agent-based simulations. The framework also provides policy-rule guidelines for the agent to search for an optimal strategy. Additionally, a micro-macro analysis enables us to analyze a cohort of representative agents and aggregate the individual results on the macro-level. The simulation module employs a regime-based Monte Carlo simulation of multiple asset categories, a factor-based diversifying asset allocation approach, and a collection of dynamic policy-rule-based investment strategies. Empirical results, consisting of a downside risk simulation for university endowments, a sustainability assessment for the Social Security fund, and a personal goal-based retirement planning, demonstrate stylized applications of the planning framework.

Harvey, D. I., Leybourne, S. J., Sollis, R., and Taylor, A. M. R. (2021). "Real-Time Detection of Regimes of Predictability in the U.S. Equity Premium." In: *Journal of Applied Econometrics* 36, pp. 45–70.
We propose new real-time monitoring procedures for the emergence of end-of-sample predictive regimes using sequential implementations of standard (heteroskedasticity-robust) regression t-statistics for predictability applied over relatively short time periods. The procedures we develop can also be used for detecting historical regimes of temporary predictability. Our proposed methods are robust to both the degree of persistence and endogeneity of the regressors in the predictive regression and to certain forms of heteroskedasticity in the shocks. We discuss how the monitoring procedures can be designed such that their false positive rate can be set by the practitioner at the start of the monitoring period using detection rules based on information obtained from the data in a training period. We use these new monitoring procedures to investigate the presence of regime changes in the

predictability of the US equity premium at the 1-month horizon by traditional macroeconomic and financial variables, and by binary technical analysis indicators. Our results suggest that the 1-month-ahead equity premium has temporarily been predictable, displaying so-called "pockets of predictability," and that these episodes of predictability could have been detected in real time by practitioners using our proposed methodology.

Hauptmann, J., Hoppenkamps, A., Min, A., Ramsauer, F., and Zagst, R. (2014). "Forecasting market turbulence using regime-switching models." In: *Financial Markets and Portfolio Management* 28(2), pp. 139–164.

We propose an early warning system to timely forecast turbulence in the US stock market. In a first step, a Markov-switching model with two regimes (a calm market and a turbulent market) is developed. Based on the time series of the monthly returns of the SandP 500 price index, the corresponding filtered probabilities are successively estimated. In a second step, the turbulent phase of the model is further specified to distinguish between bullish and bearish trends. For comparison only, a Markov-switching model with three states (a calm market, a turbulent bullish market, and a turbulent bearish market) is examined as well. In a third step, logistic regression models are employed to forecast the filtered probabilities provided by the Markov-switching models. A major advantage of the presented modeling framework is the timely identification of the factors driving the different phases of the capital market. In a fourth step, the early warning system is applied to an asset management case study. The results show that explicit consideration of the models' signals yields better portfolio performance and lower portfolio risk compared to standard buy-and-hold and constant proportion portfolio insurance strategies.

Heckens, A. J. and Guhr, T. (2022). "A new attempt to identify long-term precursors for endogenous financial crises in the market correlation structures." In: *Journal of Statistical Mechanics: Theory and Experiment* 2022(4), p. 043401.

Prediction of events in financial markets is every investor's dream and, usually, wishful thinking. From a more general, economic and societal viewpoint, the identification of indicators for large events is highly desirable to assess systemic risks. Unfortunately, the very nature of financial markets, particularly the predominantly non-Markovian character as well as non-stationarity, make this challenge a formidable one, leaving little hope for fully fledged answers. Nevertheless, it is called for to collect pieces of evidence in a variety of observables to be assembled like the pieces of a puzzle that eventually might help to catch a glimpse of long-term indicators or precursors for large events-if at all in a statistical sense. Here, we present a new piece for this puzzle. We use the quasi-stationary market states that exist in the time evolution of the correlation structure in financial markets. Recently, we identified such market states relative to the collective motion of the market as a whole. We study their precursor properties in the US stock markets over 16 years, including two endogenous crises, the dot-com bubble burst and the pre-phase of the Lehman Brothers crash. We identify certain interesting features and critically discuss their suitability as indicators.

Hollstein, F., Prokopczuk, M., and Voigts, V. (2022). "How Robust are Empirical Factor Models to the Choice of Breakpoints?" In: *SSRN e-Print*.

We comprehensively investigate the robustness of well-known factor models to altered factor-formation breakpoints. Deviating from the standard 30th and 70th percentile selection, we use an extensive set of anomaly test portfolios to uncover two main findings: First, there is a trade-off between specification versus diversification. More centered breakpoints tend to result in less (idiosyncratic) risk. More extreme sorts create stronger exposures to the underlying anomalies and, thus, higher average returns. Second, the models are robust to different degrees. The Hou, Xue, and Zhang (2015) model is much more sensitive to changes in breakpoints than the Fama-French models.

Horvath, B., Issa, Z., and Muguruza, A. (2021). "Clustering Market Regimes Using the Wasserstein Distance." In: *SSRN e-Print*.

he problem of rapid and automated detection of distinct market regimes is a topic of great interest to financial mathematicians and practitioners alike. In this paper, we outline an unsupervised learning algorithm for clustering financial time-series into a suitable number of temporal segments (market regimes). As a special case of the above, we develop a robust algorithm that automates the process of classifying market regimes. The method is robust in the sense that it does not depend on modelling assumptions of the underlying time series as our experiments with real datasets show. This method – dubbed the Wasserstein k-means algorithm – frames such a problem as one on the space of probability measures with finite p^{th} moment, in terms of the p-Wasserstein distance between (empirical) distributions. We compare our WK-means approach with a more traditional clustering algorithms by studying the so-called maximum mean discrepancy scores between, and within clusters. In both cases it is shown that the WK-means algorithm vastly outperforms all considered competitor approaches.

We demonstrate the performance of all approaches both in a controlled environment on synthetic data, and on real data.

Horváth, L., Li, H., and Liu, Z. (2022). "How to identify the different phases of stock market bubbles statistically?" In: *Finance Research Letters* 46 (Part A) (102366).
Eugene Fama once mentioned in 2016 that people have not come up with ways of identifying bubbles statistically. This paper presents the nonparametric change-point method to identify different stages of stock bubbles, and we derive its asymptotic distribution under the null hypothesis. By simulation, we obtain the corresponding critical value. In the empirical analysis, we employ this test and binary segmentation method to the 1990s Nasdaq bubble and get the same result as Phillips et al. (2011). We also apply this test to the S&P 500 index, the Shanghai stock index, the Nikkei 225 index, the FTSE 100 index, and the CAC 40 index respectively, and successfully identify the bubbles' different phases in each stock market.

Hu, Y., Shi, X., and Xu, Z. Q. (2022). "Mean variance asset liability management with regime switching." In: *arXiv e-Print*.
This paper is concerned with mean variance portfolio selection with liability, regime switching and random coefficients. To tackle the problem, we first study a general non-homogeneous stochastic linear quadratic (LQ) control problem for which two systems of backward stochastic differential equations (BSDEs) with unbounded coefficients are introduced. The existence and uniqueness of the solutions to these two systems of BSDEs are proved by some estimates of BMO martingales and contraction mapping method. Then we obtain the optimal state feedback control and optimal value for the stochastic LQ problem explicitly. Finally, closed form efficient portfolio and efficient frontier for the original mean variance problem are presented.

Huang, D., Jiang, F., Tu, J., and Zhou, G. (2017). "Forecasting Stock Returns in Good and Bad Times: The Role of Market States." In: *SSRN e-Print*.
This paper proposes a two-state predictive regression model and shows that stock market 12-month return (TMR), the time-series momentum predictor of Moskowitz, Ooi, and Pedersen (2012), forecasts the aggregate stock market negatively in good times and positively in bad times. The out-of-sample R-squares are 0.96% and 1.72% in good and bad times, or 1.28% and 1.41% in NBER economic expansions and recessions, respectively. The TMR predictability pattern holds in the cross-section of U.S. stocks and the international markets. Our study shows that the absence of return predictability in good times, an important finding of recent studies, is largely driven by the use of the popular one-state predictive regression model.

Iqbal, J. (2018). "Application of Regime Switching and Random Matrix Theory for Portfolio Optimization." PhD thesis. University of Essex.
Market economies have been characterized by boom and bust cycles. Since the seminal work of Hamilton (1989), these large scale fluctuations have been referred to as regime switches. Ang and Bekaert (2002) were the first to consider the role of regime switches for stock market returns and portfolio optimisation. The key stylized facts regarding regime switching for stock index returns is that boom periods with positive mean stock returns are associated with low volatility, while bear markets with negative mean returns have high volatility. The correlation of asset returns also show asymmetry with greater correlation being found during stock market downturns. In view of the large portfolio losses from correlated negative movements in asset returns during the recent 2007 financial crisis, it has become imperative to incorporate regime sensitivity in portfolio management. This thesis forms an extensive application of regime sensitive statistics for stock returns in the management of equity portfolios for different markets. Starting with the application to a small 3 asset portfolio for UK stocks (in Chapter 4), the methodology is extended to large scale portfolio for the FTSE-100. In chapters 5 and 6, respectively, using stock index data from the subcontinent (India, Pakistan and Bangladesh) and for the Asia Pacific, optimal regime sensitive portfolios have been analysed with the MSCI AC Index (for Emerging and Asia Pacific Markets) being taken as the benchmark index. Portfolio performance has been studied using a dynamic end of month rebalancing of the portfolio on the basis of regime indicators given by market index and relevant regime dependent portfolio statistics. The cumulative end of period returns and risk adjusted Sharpe Ratio from this exercise is compared to the simple Markowitz mean-variance portfolio and market value portfolio. The regime switching optimal portfolio strategy has been found to dominate non-regime sensitive portfolio strategies in Asia Pacific and 3 asset portfolio for UK stocks cases but not in Subcontinent case (for the first half of out-sample period). In the case of the relationship of the sub-continental indexes vis-a-vis the MSCI benchmark index, the latter has negligible explanatory power for the former especially for the first half of out-sample period. Hence, the regime indicators based on MSCI emerging market index have detrimental effects on portfolio selection based on the sub-continental indexes. As regime sensitive variance-

covariance matrices have implications for the selection of optimal portfolio weights, the final Chapter 7 uses the FTSE-100 and its constituent company data to compare and contrast the implications for optimal portfolio management of filtering the covariance matrix using Random Matrix Theory (RMT). While it is found that filtering the variance-covariance matrix using Marchenko-Pasteur bounds of RMT improves optimal portfolio choice in both non-regime and regime dependent cases, remarkably in the latter case for Regime 2 determined variance-covariance matrix, the RMT filter was least needed. This result is given in Chapter 7, Table 7.5-1. This confirms the significance of using Hamilton (1989) regime sensitive statistics for stock returns in identifying the 'true' non-noisy variance-covariance relationships. The RMT methodology is also useful for identifying the centrality, based on eigenvector analysis, of the constituent stocks in their role in driving crisis and non-crisis market conditions. A fully automated suite of programs in MATLAB have been developed for regime switching portfolio optimization with RMT filtering of the variance-covariance matrix.

Jacob, V., Song, F., Stiegler, A., Diao, Y., and Tatbul, N. (2021). "Exathlon: A Benchmark for Explainable Anomaly Detection over Time Series." In: *arXiv e-Print*.

Access to high-quality data repositories and benchmarks have been instrumental in advancing the state of the art in many experimental research domains. While advanced analytics tasks over time series data have been gaining lots of attention, lack of such community resources severely limits scientific progress. In this paper, we present Exathlon, the first comprehensive public benchmark for explainable anomaly detection over high-dimensional time series data. Exathlon has been systematically constructed based on real data traces from repeated executions of large-scale stream processing jobs on an Apache Spark cluster. Some of these executions were intentionally disturbed by introducing instances of six different types of anomalous events (e.g., misbehaving inputs, resource contention, process failures). For each of the anomaly instances, ground truth labels for the root cause interval as well as those for the extended effect interval are provided, supporting the development and evaluation of a wide range of anomaly detection (AD) and explanation discovery (ED) tasks. We demonstrate the practical utility of Exathlon's dataset, evaluation methodology, and end-to-end data science pipeline design through an experimental study with three state-of-the-art AD and ED techniques.

Jacquier, A., Bilokon, P., and McIndoe, C. (2021). "Market regime classification with signatures." In: *SSRN e-Print*.

We provide a data-driven algorithm to classify market regimes for time series. We utilise the path signature, encoding time series into easy-to-describe objects, and provide a metric structure which establishes a connection between separation of regimes and clustering of points.

James, N. (2021). "Evolutionary correlation, regime switching, spectral dynamics and optimal trading strategies for cryptocurrencies and equities." In: *arXiv e-Print*.

This paper uses new and recently established methodologies to study the evolutionary dynamics of the cryptocurrency market, and compares the findings with that of the equity market. We begin by applying random matrix theory and principal components analysis (PCA) to correlation matrices of both collections, highlighting clear differences in the eigenspectra exhibited. We then explore the heterogeneity of both asset classes, studying the time-varying dynamics of underlying sector behaviours, and determine the collective similarity within each collection. We then turn to a study of structural break dynamics and evolutionary power spectra, where we quantify the collective affinity in structural breaks and evolutionary behaviours of underlying sector time series. Finally, we implement two algorithms simulating 'portfolio choice' dynamics to compare the effectiveness of stock selection and sector allocation in cryptocurrency portfolios. There, we highlight the importance of both endeavours and comment on noteworthy implications for cryptocurrency portfolio management.

Jewell, S., Fearnhead, P., and Witten, D. (2021). "Testing for a Change in Mean After Changepoint Detection." In: *arXiv e-Print*.

While many methods are available to detect structural changes in a time series, few procedures are available to quantify the uncertainty of these estimates post-detection. In this work, we fill this gap by proposing a new framework to test the null hypothesis that there is no change in mean around an estimated changepoint. We further show that it is possible to efficiently carry out this framework in the case of changepoints estimated by binary segmentation and its variants, ℓ_0 segmentation, or the fused lasso. Our setup allows us to condition on much less information than existing approaches, which yields higher powered tests. We apply our proposals in a simulation study and on a dataset of chromosomal guanine-cytosine content. These approaches are freely available in the R package ChangepointInference at `https://jewellsean.github.io/changepoint-inference`.

Jiang, H., Li, J., and Li, Z. (2020). "Determining the number of change-point via high-dimensional cross-validation." In: *Stat* 9(1) (e284).

In multiple changepoint analysis, one of the major challenges is the determination of the number of change points, which is usually cast as a model selection problem. However, for model selection methods based on the Schwarz information criterion (SIC), it is typical that different penalization terms are required for different changepoint problems and the optimal penalization magnitude usually varies with the model and error distributions. In order to estimate the number of change points in high dimension, we develop a highdimensional datadriven crossvalidation selection criterion. First, we define a goodnessoffit measure by incorporating the dimensionality into the quadratic prediction error function. Second, the highdimensional crossvalidation (hCV) procedure is applied based on an orderpreserved samplesplitting strategy. Simulation studies show that the proposed hCV criterion has more robust performance compared with a highdimensional SIC criterion tailored for the highdimensional changepoint problem. The selection property is also established under some mild conditions.

Jiang, P., Liu, Q., and Tse, Y. (2015). "International Asset Allocation with Regime Switching: Evidence from the ETFs." In: *Asia-Pacific Journal of Financial Studies* 44(5), pp. 661–687.
We develop a dynamic investment strategy with Markov regime switching (MRS) in asset allocation with international iShares exchange-traded funds (ETFs). Using daily ETF data, we show that a portfolio based on the dynamic MRS strategy outperforms one based on static mean-variance strategies after transaction costs. This dynamic investment strategy not only captures the regime shifts in the highly frequent trading process but also can be practically used with tradable ETFs. We investigate the reasons for predictive misjudgments and assess the contribution of each regime's investment strategy, providing insight into the characteristics of the MRS model and modifying our views on why the MRS strategy outperforms traditional strategies.

Jochmann, M. and Koop, G. (2015). "Regime-switching cointegration." In: *Studies in Nonlinear Dynamics and Econometrics* 19(1).
We develop methods for Bayesian inference in vector error correction models which are subject to a variety of switches in regime (e.g., Markov switches in regime or structural breaks). An important aspect of our approach is that we allow both the cointegrating vectors and the number of cointegrating relationships to change when the regime changes. We show how Bayesian model averaging or model selection methods can be used to deal with the high-dimensional model space that results. Our methods are used in an empirical study of the Fisher effect.

Kabran, F. B. and Unlu, K. D. (2021). "A two-step machine learning approach to predict S&P 500 bubbles." In: *Journal of Applied Statistics* 48(13-15), pp. 2776–2794.
In this paper, we are interested in predicting the bubbles in the S&P 500 stock market with a two-step machine learning approach that employs a real-time bubble detection test and support vector machine (SVM). SVM as a nonparametric binary classification technique is already a widely used method in financial time series forecasting. In the literature, a bubble is often defined as a situation where the asset price exceeds its fundamental value. As one of the early warning signals, prediction of bubbles is vital for policymakers and regulators who are responsible to take preemptive measures against the future crises. Therefore, many attempts have been made to understand the main factors in bubble formation and to predict them in their earlier phases. Our analysis consists of two steps. The first step is to identify the bubbles in the S&P 500 index using a widely recognized right-tailed unit root test. Then, SVM is employed to predict the bubbles by macroeconomic indicators. Also, we compare SVM with different supervised learning algorithms by using k-fold cross-validation. The experimental results show that the proposed approach with high predictive power could be a favourable alternative in bubble prediction.

Kaihatsu, S. and Nakajima, J. (2015). *Has Trend Inflation Shifted? An Empirical Analysis with a Regime-Switching Model*. Tech. rep. Bank of Japan.
This paper proposes a new econometric framework for estimating trend inflation and the slope of the Phillips curve with a regime-switching model. As a unique aspect of our approach, we assume regimes for the trend inflation at one- percent intervals, and estimate the probability of the trend inflation being in each regime. The trend inflation described in the discrete manner provides for an easily interpretable explanation of estimation results as well as a robust estimate. An empirical result indicates that Japan's trend inflation stayed at zero percent for about 15 years after the late 1990s, and then shifted away from zero percent after the introduction of the price stability target and the quantitative and qualitative monetary easing. The U.S. result shows a considerably stable trend inflation at two percent since the late 1990s.

Kamenshchikov, S. (2016). "Bifurcation patterns of market regime transition." In: *Quantitative Finance* 16(11), pp. 1631–1636.

In this paper mechanisms of reversion - momentum transition are considered. Two basic nonlinear mechanisms are highlighted: a slow and fast bifurcation. A slow bifurcation leads to the equilibrium evolution, preceded by stability loss delay of a control parameter. A single order parameter is introduced by Markovian chain diffusion, which plays a role of a precursor. A fast bifurcation is formed by a singular fusion of unstable and stable equilibrium states. The effect of a precatastrophic range compression is observed before the discrete change of a system. A diffusion time scaling is presented as a precursor of the fast bifurcation. The efficiency of both precursors in a currency market was illustrated by simulation of a prototype of a trading system.

Kasahara, H. and Shimotsu, K. (2017). "Testing the Number of Regimes in Markov Regime Switching Models." In: *Canadian Econometric Study Group (CESG)*.
Markov regime switching models have been widely used in numerous empirical applications in economics and finance. However, the asymptotic distribution of the likelihood ratio test statistic for testing the number of regimes in Markov regime switching models is an unresolved problem. This paper proposes the likelihood ratio test of the null hypothesis of M0 regimes against the alternative hypothesis of M0 + 1 regimes for any M0 >= 1 and derives its asymptotic distribution.

Kasahara, H. and Shimotsu, K. (2019). "Testing the Order of Multivariate Normal Mixture Models." In: *arXiv e-Print*.
Finite mixtures of multivariate normal distributions have been widely used in empirical applications in diverse fields such as statistical genetics and statistical finance. Testing the number of components in multivariate normal mixture models is a long-standing challenge even in the most important case of testing homogeneity. This paper develops likelihood-based tests of the null hypothesis of M0 components against the alternative hypothesis of M0 + 1 components for a general M0 1. For heteroscedastic normal mixtures, we propose an EM test and derive the asymptotic distribution of the EM test statistic. For homoscedastic normal mixtures, we derive the asymptotic distribution of the likelihood ratio test statistic. We also derive the asymptotic distribution of the likelihood ratio test statistic and EM test statistic under local alternatives and show the validity of parametric bootstrap. The simulations show that the proposed test has good finite sample size and power properties.

Kashif, M. and Leirvik, T. (2021). "Regime Switching Stock Returns and Hybrid Tail Risk." In: *SSRN e-Print*.
We investigate the relationship between hybrid tail covariance risk (HTCR) and expected return over the last four decades. Despite a significant positive HTCR-expected return relationship in Bali et al. (2014) , we find that this relationship is not significant at least during average market conditions. However, if we control for market regime the relationship starts to appear. We find a strong link between market volatility and the relationship between HTCR and expected returns. We analyze this relationship during two market regimes, calm and noisy, depending on the return and return-volatility. We find that these market regimes pose as a catalyst to HTCR pricing in the cross-section of expected returns because HTCR-expected return relationship exists only during the calm regime and it ceases to exist during the noisy regime. Firm level cross-sectional regressions show significant positive relation (no relation) between HTCR and expected returns during calm (noisy) regime even after controlling for other relevant priced factors.

Kaya, H. (2017). "Managing ambiguity in asset allocation." In: *Journal of Asset Management* 18(3), pp. 163–187.
This paper is about the issue of input parameter uncertainty in portfolio optimization in a discrete setting with finite states (such as the case in a world with different macroeconomic regimes). In such a setting, being unable to assign reliable point estimates to the probabilities (or frequencies) of the states creates the ambiguity. We first describe how this ambiguity can be modeled probabilistically. Then, we show how this added uncertainty can be dealt with in optimal asset allocation problems. In simple-yet-realistic example applications we demonstrate that without sacrificing much of the upside, ambiguity managed portfolios may enhance the uniformity of returns across different states when compared to portfolios constructed by traditional methods. We stress that a key conclusion to be taken from these methods builds the case for insurance-like and potentially negative-yielding investments such as bonds and commodities so as to hedge the unforeseeable macrouncertainties for a smoother portfolio performance. Finally, we offer a variety of problem domains in which ambiguity management can be nested including macroeconomic scenario-based asset allocation, investing with regime-switching models, momentum investing, and risk-based investing.

Kelliher, C., Hazrachoudhury, A., and Irving, B. (2022). "A Novel Approach to Risk Parity: Diversification across Risk Factors and Market Regimes." In: *The Journal of Portfolio Management* 48(3).
In this article, the authors describe a robust approach to portfolio diversification that balances risk contributions across risk factors and market regimes. After identifying four compensated macro risk factors-growth, inflation, real rates, and liquidity-the authors construct a factor portfolio for each based on a broad set of asset classes,

including proxies for private equity and private real estate. Next, the authors identify five distinct market regimes characterized by unique asset class behaviors. The factor portfolios are then combined such that the risk contributions to the resulting total portfolio are as balanced as possible, regardless of which market regime materializes. By combining regime-aware correlations with dynamic volatility estimates for each factor and applying standard 1.5x to 2x leverage, the authors demonstrate a risk-parity portfolio with 10% ex ante volatility and attractive absolute and risk-adjusted returns. Compared with a traditional 60/40 portfolio, the proposed risk-parity portfolio displays greater diversification, more consistent factor-risk contributions, and greater resilience to economic shocks.

Khalili, A., Chen, J., and Stephens, D. A. (2016). "Regularization in Regime-Switching Gaussian Autoregressive Models." In: *Advanced Statistical Methods in Data Science*. Springer Singapore, pp. 13–34.
Regime-switching Gaussian autoregressive models form an effective platform for analyzing financial and economic time series. They explain the heterogeneous behaviour in volatility over time and multi-modality of the conditional or marginal distributions. One important task is to infer the number of regimes and regime-specific parsimonious autoregressive models. Information-theoretic criteria such as aic or bic are commonly used for such inference, and they typically evaluate each regime/autoregressive combination separately in order to choose the optimal model accordingly. However, the number of combinations can be so large that such an approach is computationally infeasible. In this paper, we first use a computationally efficient regularization method for simultaneous autoregressive-order and parameter estimation when the number of autoregressive regimes is pre-detertermined. We then use a regularized Bayesian information criterion (rbic) to select the most suitable number of regimes. Finite sample performance of the proposed methods are investigated via extensive simulations. We also analyze the U.S. gross domestic product growth and the unemployment rate data to demonstrate this method.

Kim, E.-c., Jeong, H.-w., and Lee, N.-y. (2019). "Global Asset Allocation Strategy Using a Hidden Markov Model." In: *Journal of Risk and Financial Management* 12(4), p. 168.
This study uses the hidden Markov model (HMM) to identify the phases of individual assets and proposes an investment strategy using price trends effectively. We conducted empirical analysis for 15 years from January 2004 to December 2018 on universes of global assets divided into 10 classes and the more detailed 22 classes. Both universes have been shown to have superior performance in strategy using HMM in common. By examining the change in the weight of the portfolio, the weight change between the asset classes occurs dynamically. This shows that HMM increases the weight of stocks when stock price rises and increases the weight of bonds when stock price falls. As a result of analyzing the performance, it was shown that the HMM effectively reflects the asset selection effect in Jensen's alpha, Fama's Net Selectivity and Treynor-Mazuy model. In addition, the strategy of the HMM has positive gamma value even in the Treynor-Mazuy model. Ultimately, HMM is expected to enable stable management compared to existing momentum strategies by having asset selection effect and market forecasting ability.

Kim, Y. M. and Kang, K. H. (2022). "Bayesian Inference of Multivariate Regression Models with Endogenous Markov Regime-Switching Parameters." In: *Journal of Financial Econometrics*.
This study introduces a multivariate regression model with endogenous Markov regime-switching parameters, in which the regression disturbances and regime switches are allowed to be instantaneously correlated. For the estimation and model comparison, we develop a posterior sampling algorithm for the parameters, regimes, and marginal likelihood calculation. We demonstrate the reliability of the proposed method using simulation and empirical studies. The simulation study shows that neglecting the endogeneity leads to inaccurate parameter estimates, and that our marginal likelihood comparison chooses a correctly specified model. In the business cycle application, we find that the joint dynamics of the U.S. industrial production index (IPI) growth and unemployment rates are subject to three-state endogenous regime shifts. Another application to stock and bond return data suggests that negative shocks to the stock return seem to cause regime shifts from a low volatility state to a high volatility state of the financial markets.

Koki, C., Leonardos, S., and Piliouras, G. (2022). "Exploring the predictability of cryptocurrencies via Bayesian hidden Markov models." In: *Research in International Business and Finance* 59, p. 101554.
In this paper, we consider a variety of multi-state hidden Markov models for predicting and explaining the Bitcoin, Ether and Ripple returns in the presence of state (regime) dynamics. In addition, we examine the effects of several financial, economic and cryptocurrency specific predictors on the cryptocurrency return series. Our results indicate that the non-homogeneous hidden Markov (NHHM) model with four states has the best one-step-ahead forecasting performance among all competing models for all three series. The dominance of the predictive densities over the single regime random walk model relies on the fact that the states capture

alternating periods with distinct return characteristics. In particular, the four state NHHM model distinguishes bull, bear and calm regimes for the Bitcoin series, and periods with different profit and risk magnitudes for the Ether and Ripple series. Also, conditionally on the hidden states, it identifies predictors with different linear and non-linear effects on the cryptocurrency returns. These empirical findings provide important benefits for portfolio management and policy implementation.

Kole, E. and van Dijk, D. (2016). "How to Identify and Forecast Bull and Bear Markets?" In: *Journal of Applied Econometrics* 32(1), pp. 120–139.

Because the state of the equity market is latent, several methods have been proposed to identify past and current states of the market and forecast future ones. These methods encompass semi-parametric rule-based methods and parametric Markov switching models. We compare the mean-variance utilities that result when a risk-averse agent uses the predictions of the different methods in an investment decision. Our application of this framework to the S&P 500 shows that rule-based methods are preferable for (in-sample) identification of the state of the market, but Markov switching models for (out-of-sample) forecasting. In-sample, only the mean return of the market index matters, which rule-based methods exactly capture. Because Markov switching models use both the mean and the variance to infer the state, they produce superior forecasts and lead to significantly better out-of-sample performance than rule-based methods. We conclude that the variance is a crucial ingredient for forecasting the market state.

Komatsu, T. and Makimoto, N. (2015). "Dynamic Investment Strategy with Factor Models Under Regime Switches." In: *Asia-Pacific Financial Markets* 22(2), pp. 209–237.

A model for dynamic investment strategy is developed where assets' returns are represented by multiple factors. In a mean variance framework with factor models under regime switches, we derive a semi-analytic solution for the optimal portfolio with transaction costs. Due to the existence of transaction costs, the optimal portfolio is characterized as a linear combination of current and target portfolios, the latter of which maximizes the value function in the current regime. For some special cases of interest, we also derive simplified analytical solutions. To see the effect of regime switches, the proposed model is applied to US equity market in which small minus big and high minus low are employed as factors. Investment strategy based on our model demonstrates empirically that the regime switching models exhibit superior performance over the single regime model for such performance measures as realized utility and Sharpe ratio which are of particular interest in practice. Taking a close look at the time series of portfolio returns, the result shows the usefulness of the regime switching model as investors flexibly optimize asset allocations depending on the state of the market.

Kreuser, J. and Sornette, D. (2019). "Super-Exponential RE bubble model with efficient crashes." In: *The European Journal of Finance* 25(4), pp. 338–368.

We propose a dynamic Rational Expectations (RE) bubble model of prices, combining a geometric random walk with separate crash (and rally) discrete jump distributions associated with positive (and negative) bubbles. Crashes tend to efficiently bring back excess bubble prices close to a "normal" process. Then, the RE condition implies that the excess risk premium of the risky asset exposed to crashes is an increasing function of the amplitude of the expected crash, which itself grows with the bubble mispricing: hence, the larger the bubble price, the larger its subsequent growth rate. This positive feedback of price on return is the archetype of super-exponential price dynamics. We use the RE condition to estimate the real-time crash probability dynamically through an accelerating probability function depending on the increasing expected return. After showing how to estimate the model parameters, we obtain a closed-form approximation for the optimal investment that maximizes the expected log of wealth (Kelly criterion) for the risky bubbly asset and a risk-free asset. We demonstrate, on seven historical crashes, the promising outperformance of the method compared to a 60/40 portfolio, the classic Kelly allocation, and the risky asset, and how it mitigates jumps, both positive and negative.

Kritzman, M., Page, S., and Turkington, D. (2012). "Regime Shifts: Implications for Dynamic Strategies." In: *Financial Analysts Journal* 68(3).

Regime shifts present significant challenges for investors because they cause performance to depart significantly from the ranges implied by long-term averages of means and covariances. But regime shifts also present opportunities for gain. The authors show how to apply Markov-switching models to forecast regimes in market turbulence, inflation, and economic growth. They found that a dynamic process outperformed static asset allocation in backtests, especially for investors who seek to avoid large losses.

Kunjal, D., Peerbhai, F., and Muzindutsi, P.-F. (2021). "The performance of South African exchange traded funds under changing market conditions." In: *Journal of Asset Management* 22(5), pp. 350–359.

Despite the soaring popularity of exchange-traded funds (ETFs), ETFs may find it difficult to replicate the returns of their underlying index under changing market conditions. The objective of this study is to examine the performance of South African ETFs under bullish and bearish market conditions. This paper employs a single index Markov Switching model to examine the tracking efficiency of a sample of ETFs tracking the FTSE/JSE Top 40 (J200) index from 27 November 2000 until 31 July 2019. The findings suggest that, on average, ETFs are more responsive to fluctuations in their underlying index during bullish market conditions and they display a higher tracking error during bearish market conditions. Thus, our findings support the notion that ETF performance differs across market regimes, implying that ETF fund managers should disclose their betas across different market conditions so that ETF investors and traders can adequately evaluate their risk exposures in each market condition.

Lattanzi, C. and Leonelli, M. (2019). "A changepoint approach for the identification of financial extreme regimes." In: *arXiv e-Print*.
Inference over tails is usually performed by fitting an appropriate limiting distribution over observations that exceed a fixed threshold. However, the choice of such threshold is critical and can affect the inferential results. Extreme value mixture models have been defined to estimate the threshold using the full dataset and to give accurate tail estimates. Such models assume that the tail behavior is constant for all observations. However, the extreme behavior of financial returns often changes considerably in time and such changes occur by sudden shocks of the market. Here we extend the extreme value mixture model class to formally take into account distributional extreme changepoints, by allowing for the presence of regime-dependent parameters modelling the tail of the distribution. This extension formally uses the full dataset to both estimate the thresholds and the extreme changepoint locations, giving uncertainty measures for both quantities. Estimation of functions of interest in extreme value analyses is performed via MCMC algorithms. Our approach is evaluated through a series of simulations, applied to real data sets and assessed against competing approaches. Evidence demonstrates that the inclusion of different extreme regimes outperforms both static and dynamic competing approaches in financial applications.

Lee, M.-C., Lin, J.-C., and Gran, E. G. (2020a). "ReRe: A Lightweight Real-time Ready-to-Go Anomaly Detection Approach for Time Series." In: *arXiv e-Print*.
Anomaly detection is an active research topic in many different fields such as intrusion detection, network monitoring, system health monitoring, IoT healthcare, etc. However, many existing anomaly detection approaches require either human intervention or domain knowledge, and may suffer from high computation complexity, consequently hindering their applicability in real-world scenarios. Therefore, a lightweight and ready-to-go approach that is able to detect anomalies in real-time is highly sought-after. Such an approach could be easily and immediately applied to perform time series anomaly detection on any commodity machine. The approach could provide timely anomaly alerts and by that enable appropriate countermeasures to be undertaken as early as possible. With these goals in mind, this paper introduces ReRe, which is a Real-time Ready-to-go proactive Anomaly Detection algorithm for streaming time series. ReRe employs two lightweight Long Short-Term Memory (LSTM) models to predict and jointly determine whether or not an upcoming data point is anomalous based on short-term historical data points and two long-term self-adaptive thresholds. Experiments based on real-world time-series datasets demonstrate the good performance of ReRe in real-time anomaly detection without requiring human intervention or domain knowledge.

Lee, S., Liao, Y., Seo, M. H., and Shin, Y. (2020b). "Factor-Driven Two-Regime Regression." In: *arXiv e-Print*.
We propose a novel two-regime regression model where regime switching is driven by a vector of possibly unobservable factors. When the factors are latent, we estimate them by the principal component analysis of a panel data set. We show that the optimization problem can be reformulated as mixed integer optimization, and we present two alternative computational algorithms. We derive the asymptotic distribution of the resulting estimator under the scheme that the threshold effect shrinks to zero. In particular, we establish a phase transition that describes the effect of first-stage factor estimation as the cross-sectional dimension of panel data increases relative to the time-series dimension. Moreover, we develop bootstrap inference and illustrate our methods via numerical studies.

Lee, S., Liao, Y., Seo, M. H., and Shin, Y. (2021). "Factor-driven two-regime regression." In: *Annals of Statistics* 49(3).
We propose a novel two-regime regression model where regime switching is driven by a vector of possibly unobservable factors. When the factors are latent, we estimate them by the principal component analysis of a panel data set. We show that the optimization problem can be reformulated as mixed integer optimization,

and we present two alternative computational algorithms. We derive the asymptotic distribution of the resulting estimator under the scheme that the threshold effect shrinks to zero. In particular, we establish a phase transition that describes the effect of first-stage factor estimation as the cross-sectional dimension of panel data increases relative to the time-series dimension. Moreover, we develop bootstrap inference and illustrate our methods via numerical studies.

Lezmi, E., Malongo, H., Roncalli, T., and Sobotka, R. (2019). "Portfolio Allocation with Skewness Risk: A Practical Guide." In: *SSRN e-Print*.
In this article, we show how to take into account skewness risk in portfolio allocation. Until recently, this issue has been seen as a purely statistical problem, since skewness corresponds to the third statistical moment of a probability distribution. However, in finance, the concept of skewness is more related to extreme events that produce portfolio losses. More precisely, the skewness measures the outcome resulting from bad times and adverse scenarios in financial markets. Based on this interpretation of the skewness risk, we focus on two approaches that are closely connected. The first one is based on the Gaussian mixture model with two regimes: a normal regime and a turbulent regime. The second approach directly incorporates a stress scenario using jump-diffusion modeling. This second approach can be seen as a special case of the first approach. However, it has the advantage of being clearer and more in line with the experience of professionals in financial markets: skewness is due to negative jumps in asset prices. After presenting the mathematical framework, we analyze an investment portfolio that mixes risk premia, more specifically risk parity, momentum and carry strategies. We show that traditional portfolio management based on the volatility risk measure is biased and corresponds to a short-sighted approach to bad times. We then propose to replace the volatility risk measure by a skewness risk measure, which is calculated as an expected shortfall that incorporates a stress scenario. We conclude that constant-mix portfolios may be better adapted than actively managed portfolios, when the investment universe is composed of negatively skewed financial assets.

Li, L. (2021). "Risk of investing in volatility products: A regime-switching approach." In: *Investment Analysts Journal* 50(1), pp. 1–16.
Volatility indexes provide a tool for investors to speculate and trade on market sentiment regarding future volatility. The risk of trading on volatility indexes can be measured by their second moments, namely, variance and correlation. This study considers the four representative volatility indexes published by the CBOE: stock market volatility index (VIX), crude oil volatility index (OVX), foreign exchange rate volatility index (EVZ), and gold price volatility index (GVZ). To examine their risk, we develop an extended multivariate Markov switching ARCH (MSARCH) model in which regime-switching variances, correlations, and variance-correlation relations are designed. Our empirical sample consists of the four volatility indexes from June 2008 to April 2020 for 612 weekly observations (Wednesday to Wednesday). For the conditional variances, we find evidence of regime-switching processes (switching between low and high volatility regimes) for the individual volatility index returns, with the exception of the GVZ. The estimated probability of the high volatility regime may be used to track economic distress and uncertainty shocks. These results provide evidence for volatility-of-volatility risk. For the conditional correlations, we find a regime-switching relation between variances and correlations. That is, the highest correlation appears when the paired volatility markets are simultaneously experiencing a state of high volatility. By contrast, when the paired volatility markets are encountering different volatility states, the correlation is weaker. These results indicate that the volatility-of-volatility risk is a factor affecting the dynamics of correlations between volatility indexes.

Li, X. and Mulvey, J. M. (2021). "Portfolio Optimization Under Regime Switching and Transaction Costs: Combining Neural Networks and Dynamic Programs." In: *INFORMS Journal on Optimization* 3(4), pp. 398–417.
Multiperiod financial models provide superior capabilities over single-period myopic approaches but, in general, suffer from the curse of dimensionality. Prominent features include transaction costs, rebalancing gains, intermediate cashflows, and short- versus long-term trade-offs. In this paper, we propose and test an algorithm combining dynamic programming with a recurrent neural network. The dynamic program provides advanced starts for the neural network. Empirical tests show the benefits of this novel strategy with optimizing a hidden Markov model in the presence of linear transaction costs. Test problems with 50-250 time steps and up to 11 risky assets are solved efficiently, relative to stand-alone dynamic programs or neural networks. The recurrent neural network addresses transaction costs within difficult multiperiod optimization models in polynomial run time.

Li, X. and Zakamulin, V. (2020). "Stock volatility predictability in bull and bear markets." In: *Quantitative Finance* 20(7), pp. 1149–1167.

The recent literature on stock return predictability suggests that it varies substantially across economic states, being strongest during bad economic times. In line with this evidence, we document that stock volatility predictability is also state dependent. In particular, in this paper, we use a large data set of high-frequency data on individual stocks and a few popular time-series volatility models to comprehensively examine how volatility forecastability varies across bull and bear states of the stock market. We find that the volatility forecast horizon is substantially longer when the market is in a bear state than when it is in a bull state. In addition, over all but the shortest horizons, the volatility forecast accuracy is higher when the market is in a bear state. This difference increases as the forecast horizon lengthens. Our study concludes that stock volatility predictability is strongest during bad economic times, proxied by bear market states.

Liszewski, O. (2016). "Asset allocation under multiple regimes." MA thesis. Erasmus University.
In this paper we examine the performance of the Markov Switching model with intra-regimes changes such as the bull market correction and bear market rallies. We accommodate this short time rehearsals by imposing restrictions on the transition probability matrix. We compare the model with classic mean-switching and dynamic VAR models in an asset allocation problem with different number of regimes, initial states choices and asset distributions used in the estimation process. In an out-of-sample and bootstrap verification we give evidence that the constrained model outperforms other models in terms of risk-adjusted returns in the long horizon above 2 years.

Liu, L., Chen, C., and Wang, B. (2022). "Predicting financial crises with machine learning methods." In: *Journal of Forecasting*.
Countries must establish an effective early warning system to predict financial crises in order to avoid their catastrophic effects. To this end, we construct early warning systems based on the logistic model and seven machine learning methods, and we also use the Shapley value decomposition and Shapley regression to explore the causality of the machine learning methods. By comparing the performance of different early warning models in out-of-sample tests, we find that the machine learning models, especially the random forest, gradient boosting decision tree, and ensemble models, outperform the logistic model in terms of providing early predictions of financial crises. In addition, the Shapley value can be used to find more effective predictive indicators and analyze the causes of risks in different countries to a certain extent, enabling policymakers to supplement the policy toolbox to deal with such crises. Thus, we suggest that machine learning methods should be considered when establishing early warning systems to predict financial crises in the future.

Ma, Y., MacLean, L., Xu, K., and Zhao, Y. G. (2011). "Portfolio optimization model with regime-switching risk factors for sector exchange traded funds." In: *Pacific Journal of Optimization* 7, pp. 455–470.
This paper develops a portfolio optimization model with a market neutral strategy under a Markov regime-switching framework. The selected investment instruments consist of the nine sector exchange traded funds (ETFs) that represent the U.S. stock market. The Bayesian information criterion is used to determine the optimal number of regimes. The investment objective is to dynamically maximize the portfolio alpha (excess return over the T-Bill) subject to neutralization of the portfolio sensitivities to the selected risk factors. The portfolio risk exposures are shown to change with various style and macro factors over time. The maximization problem in this context can be established as a regime-dependent linear programming problem. The optimal portfolio constructed as such is expected to outperform a naive benchmark strategy, which equally weights the ETFs. We evaluate the in-sample and out-of-sample performance of the regime-dependent market neutral strategy against the equally weighted strategy. We find that the former generally outperforms the latter.

Malevergne, Y., Sornette, D., and Wei, R. (2021). "A model of financial bubbles and drawdowns with non-local behavioral self-referencing." In: *SSRN e-Print*.
We propose a novel class of models in which the crash hazard rate is determined by a function of a non-local estimation of mispricing. Rooted in behavioral finance, the non-local estimation embodies in particular the characteristic of "anchoring" on past price levels and the "probability judgment" about the likelihood of a crash as a function of the self-referential mispricing, enabling us to disentangle the risk-return relationship from its instantaneous connection. By describing drawdowns and crashes as market regimes with correlated negative jumps clustering over a finite period of time, our model provides a solution to the problem plaguing most crash jump models, which are in general rejected in calibrations of real financial time series because they assume that crashes occur in a single large negative jump, which is counterfactual. The model estimation is implemented on synthetic time series and real markets, shedding light on the estimation of the "true" expected return, which is usually confounded by the entanglement between volatility and jump risks. Estimated from the daily time series

of three stock indexes, the hidden expected return exhibits a secular increase over time and tends to be larger than the realized return, suggesting that financial markets have been overall underpriced.

Martirosyan, A. and Simonian, J. (2021). "Emerging Market Stock Momentum Returns during US Economic Regimes." In: *The Journal of Portfolio Management* 47(7), pp. 27–45.
In this article, the authors investigate the momentum exhibited by emerging market (EM) stocks in US macroeconomic regimes. Although EM markets are often viewed and invested in as a basket, they comprise countries that are distinct in terms of their response to macroeconomic dynamics. The unique behavior of EM countries can in turn be expected to affect the momentum behavior of EM stocks. To investigate the latter hypothesis, the authors analyze the momentum of a selection of EM markets during expansionary and contractionary regimes in the US economy. Because the United States is arguably the anchor economy for the global economic system, it is reasonable to assume that its dynamics influence investment strategies in EM markets. The goal of the present article is to examine the nature and extent of that influence. The authors frame their study using Hamilton's well-known regime-switching model. Momentum returns are measured over different holding periods and are further adjusted using the CAPM and Fama-French asset pricing models. The results show that there is a high degree of variation in the degree to which individual EM momentum profits are generated in different macroeconomic states. The results may therefore provide some insight into the potential efficacy of using macroeconomic information to drive investment decisions in the EM space.

Massacci, D. (2014). "Multivariate Regime Switching Model with Flexible Threshold Variable." In: *SSRN e-Print*.
This paper proposes a novel multivariate regime switching model that allows the threshold variable to be a linear combination of covariates with unknown coefficients: the model is likely to be more suitable to analyze time series of data in which regimes dynamics are driven by multiple covariates rather than by just one single threshold variable. The paper considers least squares estimation of the model and it proposes a test for the number of regimes based on theoretical results from multivariate statistics. Finite sample results from Monte Carlo analysis strengthen the methodological contribution of the paper. An application to measuring regime-specific cross-sectional dependence in the U.S. stock market illustrates the usefulness of the proposed model for applied work.

Massacci, D. (2021). "Testing for Regime Changes in Portfolios with a Large Number of Assets: A Robust Approach to Factor Heteroskedasticity." In: *Journal of Financial Econometrics*.
We develop a new test for threshold-type regime changes in the risk exposures in portfolios with a large number of financial assets whose returns exhibit an approximate factor structure. Unlike existing procedures to detect discrete shifts in factor models, our test is robust to regime-specific second moment of the common factors. We rely on an auxiliary threshold regression: we take a weighted cross-sectional average of the cross-sectional units; we estimate the factors from the original model under the null hypothesis of no regime changes; we construct a Lagrange multiplier statistic to test for threshold effect in the auxiliary regression. Numerical results show the good finite sample properties of our procedure. The empirical analysis uncovers the dynamics of portfolio weights and diversification benefits in factor mimicking portfolios across different regimes.

Massacci, D. and Kapetanios, G. (2021). "Forecasting in Factor Augmented Regressions under Structural Change." In: *SSRN e-Print*.
Factor augmented regressions are widely used to produce out-of-sample forecasts of macroeconomic and financial time series. However, these series are subject to occasional breaks. We study the effect of neglected structural instability on the forecasts produced by factor augmented regressions when the latent factors are estimated by cross-sectional averages from a large panel of variables. Our results show that neglecting structural instability can be very costly in terms of forecasting performance. We derive analytical results to show that both instability in the factor model and in the forecasting equation have an impact on the produced forecasts. We further provide numerical results showing that conditioning upon the most recent break tends to produce more accurate forecasts than unconditional estimation methods based on expanding or rolling windows, although the actual gain depends on the location and the magnitude of the breaks.

McGee, R. (2021). "Can Market Regimes Really be Timed with Historical Volatility?" In: *SSRN e-Print*.
Recent research findings suggest long-term investor utility benefits through scaling expected returns by recent realized volatility. We test for utility gains to volatility timing using a utility regime-based methodology to classify investor-specific market investment regimes based solely on recent realized volatility levels. Under this framework we find limited informational content in using recent realized volatility to forecast utility regimes for the market index. To reconcile our findings we replicate work by Moreira and Muir (2017) and find that their reported Sharpe ratio gains through volatility-managing the US market factor do not appear to be statistically

significant. We find that their scheme under-performs buy and hold in terms of Sharpe ratio over 30 of the 70 twenty year sub-periods in our sample (58 out of 70 for an un-leveraged investor). Furthermore, the historical out-performance of volatility management for the market index is highly sensitive to the timing of re-balancing within a month, suggesting that the strategy may not be robust to the precise timing of key market events relative to volatility changes. Strategy adopters should be aware that this timing is not guaranteed to line up favorably over future investment periods.

McIndoe, C. (2020). "A Data Driven Approach to Market Regime Classification." MA thesis. Imperial College.
We provide a novel algorithm which attempts to classify market regimes in US equities time series. As far as possible, manual intervention is avoided, preferring a data-driven approach. The path signature is utilised as a central tool; the application of which is justified. We discuss the connection between market regimes and distributions of path signatures, and provide a metric space structure on the latter which allows for a clustering to be formulated. The code both to reproduce the results and to develop further the clustering algorithms presented is provided on GitHub - mcindoe/regime-detection.

McQuarrie, E. F. (2021). "New Lessons from Market History: Sometimes Bonds Win." In: *SSRN e-Print*.
When Jeremy Siegel published his Stocks for the Long Run thesis, little information was available on stocks before 1871 or bonds before 1926. But today, digital archives have made it possible to compute real total return on stock and bond indexes back to 1793. This paper presents that new market history and compares it to Siegel's narrative. The new historical record shows that over multi-decade periods, sometimes stocks outperformed bonds, sometimes bonds outperformed stocks, and sometimes they performed about the same. More generally, the pattern of asset returns in the modern era, as seen in the Ibbotson SBBI and other datasets that begin in 1926, emerges as distinctly different from what came before. Contrary to Siegel, the pattern of asset returns seen in the 20th century does not generalize to the 19th century. A regime perspective is introduced to make sense of the augmented historical record. It argues that both common stocks and long bonds are risk assets, capable of outperforming or underperforming over any human time horizon. [This July revision adds more international data.]

Mehta, P. (2020). "The Mechanism behind the Bursting of Financial Bubbles and Market Crashes." In: *SSRN e-Print*.
This article proposes to deliver an algorithm to envisage the distribution of the critical points of bubbles, may it be a financial bubble or an asset bubble. The study comprehensively examines the use of Log periodic Power law in various articles from renowned authors from the first paper that was published by Didier Sornette in 1996 to the present day. The paper scrutinizes the prerogatives and robustness of the LPPL for large market falls and the anti-bubbles that build in a market. The LPPL fit has been attempted to fit into various crashes in different stock markets that were predicted previously to establish the smooth working of the model.

Meitz, M. and Saikkonen, P. (2021). "Testing for observation-dependent regime switching in mixture autoregressive models." In: *Journal of Econometrics* 222(1), pp. 601–624.
Testing for regime switching when the regime switching probabilities are specified either as constants ('mixture models') or are governed by a finite-state Markov chain ('Markov switching models') are long-standing problems that have also attracted recent interest. This paper considers testing for regime switching when the regime switching probabilities are time-varying and depend on observed data ('observation-dependent regime switching'). Specifically, we consider the likelihood ratio test for observation-dependent regime switching in mixture autoregressive models. The testing problem is highly nonstandard, involving unidentified nuisance parameters under the null, parameters on the boundary, singular information matrices, and higher-order approximations of the log-likelihood. We derive the asymptotic null distribution of the likelihood ratio test statistic in a general mixture autoregressive setting using high-level conditions that allow for various forms of dependence of the regime switching probabilities on past observations, and we illustrate the theory using two particular mixture autoregressive models. The likelihood ratio test has a nonstandard asymptotic distribution that can easily be simulated, and Monte Carlo studies show the test to have good finite sample size and power properties.

Messer, M. (2021). "Bivariate change point detection: joint detection of changes in expectation and variance." In: *arXiv e-Print*.
A method for change point detection is proposed. We consider a univariate sequence of independent random variables with piecewise constant expectation and variance, apart from which the distribution may vary periodically. We aim to detect change points in both expectation and variance. For that, we propose a statistical test for the null hypothesis of no change points and an algorithm for change point detection. Both are based on a bivariate moving sum approach that jointly evaluates the mean and the empirical variance. The joint

consideration helps improve inference as compared to separate univariate approaches. We infer on the strength and the type of changes with confidence. Nonparametric methodology supports the analysis of diverse data. Additionally, a multi-scale approach addresses complex patterns in change points and effects. We demonstrate the performance through theoretical results and simulation studies. A companion R-package jcp (available on CRAN) is discussed.

Min, S., Song, R., and Zhu, W. (2021). "The 2021 Bitcoin Bubbles and Crashes – Detection and Classification." In: *SSRN e-Print*.

In this study, we adopted the Log-Periodic Power Law Singularity (LPPLS) model for real-time identification and monitoring of Bitcoin bubbles and crashes using different time scale data and proposed the modified Lagrange regularization method to alleviate the impact of potential LPPLS model over-fitting to better estimate bubble start time and market regime change. We also aimed to determine the natures of the bubbles and crashes - be it endogenous due to its own price evolution or exogenous due to external market and/or policy influences. We performed a systematic market event analysis and correlated which to Bitcoin bubbles detected. Based on the daily LPPLS confidence indictor from December 1, 2019 to June 24, 2021, we found that the Bitcoin boom from November 2020 to mid-January 2021 is an endogenous bubble, stemming from the self-reinforcement of cooperative herding and imitative behaviors of market players, while the price spike from mid-January 2021 to mid-April 2021 is likely an exogenous bubble driven by extrinsic events including a series of large-scale acquisitions and adoptions by well-known institutions such as Visa and Tesla. We have also demonstrated the utilities of multi-resolution LPPLS analysis in revealing both short-term changes and long-term states.

Mizuno, T., Ohnishi, T., and Watanabe, T. (2020). "Detecting Stock Market Bubbles Based on the Cross-Sectional Dispersion of Stock Prices." In: *Proceedings of the 23rd Asia Pacific symposium on intelligent and evolutionary systems*. Ed. by H. Sato, S. Iwanaga, and A. Ishii. Vol. 12. Springer International Publishing, pp. 194–202.

A statistical method is proposed for detecting stock market bubbles that occur when speculative funds concentrate on a small set of stocks. The bubble is defined by stock price diverging from the fundamentals. A firm financial standing is certainly a key fundamental attribute of that firm. The law of one price would dictate that firms of similar financial standing share similar fundamentals. We investigate the variation in market capitalization normalized by fundamentals that is estimated by Lasso regression of a firm financial standing. The market capitalization distribution has a substantially heavier upper tail during bubble periods, namely, the market capitalization gap opens up in a small subset of firms with similar fundamentals. This phenomenon suggests that speculative funds concentrate in this subset. We demonstrated that this phenomenon could have been used to detect the dot-com bubble of 1998-2000 in different stock exchanges.

Moreno-Pino, F., Sukei, E., Olmos, P. M., and Artes-Rodriguez, A. (2022). "PyHHMM: A Python Library for Heterogeneous Hidden Markov Models." In: *arXiv e-Print*.

We introduce PyHHMM, an object-oriented open-source Python implementation of Heterogeneous-Hidden Markov Models (HHMMs). In addition to HMM's basic core functionalities, such as different initialization algorithms and classical observations models, i.e., continuous and multinoulli, PyHHMM distinctively emphasizes features not supported in similar available frameworks: a heterogeneous observation model, missing data inference, different model order selection criterias, and semi-supervised training. These characteristics result in a feature-rich implementation for researchers working with sequential data. PyHHMM relies on the numpy, scipy, scikit-learn, and seaborn Python packages, and is distributed under the Apache-2.0 License. PyHHMM's source code is publicly available on Github `https://github.com/fmorenopino/HeterogeneousHMM` to facilitate adoptions and future contributions. A detailed documentation `https://pyhhmm.readthedocs.io/en/latest`, which covers examples of use and models' theoretical explanation, is available. The package can be installed through the Python Package Index (PyPI), via 'pip install pyhhmm'.

Muller, S. and Preissler, F. (2021). "In Good and in Bad Times? The Relation between Anomaly Returns and Market States." In: *SSRN e-Print*.

We evaluate the relation between the size of 138 return anomalies and market states using a sample of 56 countries from 1981 to 2019. We find that the vast majority of anomalies (51 of 138 statistically significant at the 5% level) perform better if the country's stock market index trades below its 200-day moving average, our definition of a bad market state; 10 anomalies perform significantly better in good market states. On average, the value-weighted four-factor alpha amounts to 46.7 (31.2) bps per anomaly-month in bad (good) times. In relative terms, abnormal anomaly returns are 49.8% higher in bad times. Our findings are consistent across regions and different anomaly classifications. They are robust to alternative market state classifications and additional

controls for investor sentiment. The evidence suggests that risk or data-mining cannot entirely explain anomaly returns.

Mulvey, J. M., Hao, H., and Li, N. (2018). "Machine learning, economic regimes and portfolio optimisation." In: *International Journal of Financial Engineering and Risk Management* 2(4), p. 260.
In portfolio models, the depiction of future outcomes depends upon a representative accounting of economic conditions. There is much evidence that crash periods display much different patterns than normal markets, suggesting that forecasting models ought to be based on multiple regimes. We apply two techniques from machine learning in our empirical study to improve robustness: 1) trend-filtering - to distinguish regimes possessing relatively homogeneous patterns; 2) a shrinkage/cross validation approach within a factor analysis of performance. A scenario-based portfolio model is proposed and designed to address multiple regimes. The worst-case events are well described within the framework, as compared with mean-variance Markowitz models that treat equally all historical performance.

Navarro, M., Allen, G. I., and Weylandt, M. (2021). "Network Clustering for Latent State and Changepoint Detection." In: *arXiv e-Print*.
Network models provide a powerful and flexible framework for analyzing a wide range of structured data sources. In many situations of interest, however, multiple networks can be constructed to capture different aspects of an underlying phenomenon or to capture changing behavior over time. In such settings, it is often useful to cluster together related networks in attempt to identify patterns of common structure. In this paper, we propose a convex approach for the task of network clustering. Our approach uses a convex fusion penalty to induce a smoothly-varying tree-like cluster structure, eliminating the need to select the number of clusters a priori. We provide an efficient algorithm for convex network clustering and demonstrate its effectiveness on synthetic examples.

Neto, A. E. D., Gonzalo, J., and Pitarakis, J.-Y. (2021). "Uncovering regimes in out of sample forecast errors." In: *Oxford Bulletin of Economics and Statistics* 83(3), pp. 713–741.
We introduce a set of test statistics for assessing the presence of regimes in out of sample forecast errors produced by recursively estimated linear multiple predictive regressions. These predictive regressions can accommodate multiple predictors that are highly persistent with potentially different degrees of persistence. Our method is also designed to be robust to the chosen starting window size so as to avert data mining concerns. Our tests are shown to be consistent and to lead to null distributions that are free of nuisance parameters and hence robust to the degree of persistence of the predictors.

Nystrup, P. (2014). "Regime-Based Asset Allocation: Do Profitable Strategies Exist?" MA thesis. Technical University of Denmark.
Regime shifts present a big challenge to traditional strategic asset allocation, demanding a more adaptive approach. In the presence of time-varying investment opportunities, portfolio weights should be adjusted as new information arrives. Regime-switching models can match the tendency of financial markets to change their behavior abruptly and the phenomenon that the new behavior often persists for several periods after a change. They are well suited to capture the stylized behavior of many financial series including skewness, leptokurtosis, volatility persistence, and time-varying correlations. This thesis builds on this empirical evidence to develop a quantitative framework for regime-based asset allocation. It investigates whether regime-based investing can effectively respond to changes in financial regimes at the portfolio level in an effort to provide better long-term results when compared to more static approaches. The thesis extends previous work by considering both discrete-time and continuous-time models, models with different numbers of states, different univariate and multivariate state-dependent distributions, and different sojourn time distributions. Out-of-sample success depends on developing a way to model the non-linear and non-stationary behavior of asset returns. Dynamic asset allocation strategies are shown to add value over strategies based on rebalancing to static weights with rebalancing in itself adding value compared to buy-and-hold strategies in an asset universe consisting of a global stock index, a global government bond index, and a commodity index. The tested strategies based on an adaptively estimated two-state Gaussian hidden Markov model outperform a rebalancing strategy out of sample after accounting for transaction costs, assuming no knowledge of future returns, and with a realistic delay between the identification of a regime change and the portfolio adjustment.

Nystrup, P., Hansen, B. W., Larsen, H. O., Madsen, H., and Lindstrom, E. (2018a). "Dynamic Allocation or Diversification: A Regime-Based Approach to Multiple Assets." In: *The Journal of Portfolio Management* 44(2), pp. 62–73.

This article investigates whether regime-based asset allocation can effectively respond to changes in financial regimes at the portfolio level in an effort to provide better long-term results when compared to a static 60/40 benchmark. The potential benefit from taking large positions in a few assets at a time comes at the cost of reduced diversification. The authors analyze this trade-off in a multi-asset universe with great potential for static diversification. The regime-based approach is centered around a regime-switching model with time-varying parameters that can match financial markets' behavior and a new, more intuitive way of inferring the hidden market regimes. The empirical results show that regime-based asset allocation is profitable, even when compared to a diversified benchmark portfolio. The results are robust because they are based on available market data with no assumptions about forecasting skills.

Nystrup, P., Hansen, B. W., Madsen, H., and Lindstrom, E. (2015). "Regime-Based Versus Static Asset Allocation: Letting the Data Speak." In: *The Journal of Portfolio Management* 42(1), pp. 103–109.
Regime shifts present a big challenge to traditional strategic asset allocation. This article investigates whether regime based asset allocation can effectively respond to changes in financial regimes at the portfolio level, in an effort to provide better long-term results than more static approaches can offer. The authors center their regime-based approach around a regime-switching model with time-varying parameters that can match financial markets' tendency to change behavior abruptly and the fact that the new behavior often persists for several periods after a change. In an asset universe consisting of a global stock index and a global government bond index, they show that, even without any level of forecasting skill, holding a static portfolio may not be optimal.

Nystrup, P., Lindstrom, E., and Madsen, H. (2020). "Learning hidden Markov models with persistent states by penalizing jumps." In: *Expert Systems with Applications* 150, p. 113307.
Hidden Markov models are applied in many expert and intelligent systems to detect an underlying sequence of persistent states. When the model is misspecified or misestimated, however, it often leads to unrealistically rapid switching dynamics. To address this issue, we propose a novel estimation approach based on clustering temporal features while penalizing jumps. We compare the approach to spectral clustering and the standard approach of maximizing the likelihood function in an extensive simulation study and an application to financial data. The advantages of the proposed jump estimator include that it learns the hidden state sequence and model parameters simultaneously and faster while providing control over the transition rate, it is less sensitive to initialization, it performs better when the number of states increases, and it is robust to misspecified conditional distributions. The value of estimating the true persistence of the state process is illustrated through a simple trading strategy where improved estimates result in much lower transaction costs. Robustness is particularly critical when the model is part of a system used in production. Therefore, our proposed estimator significantly improves the potential for using hidden Markov models in practical applications.

Nystrup, P., Madsen, H., and Lindstrom, E. (2018b). "Dynamic portfolio optimization across hidden market regimes." In: *Quantitative Finance* 18(1), pp. 83–95.
Regime-based asset allocation has been shown to add value over rebalancing to static weights and, in particular, reduce potential drawdowns by reacting to changes in market conditions. The predominant approach in previous studies has been to specify in advance a static decision rule for changing the allocation based on the state of financial markets or the economy. In this article, model predictive control (MPC) is used to dynamically optimize a portfolio based on forecasts of the mean and variance of financial returns from a hidden Markov model with time-varying parameters. There are computational advantages to using MPC when estimates of future returns are updated every time a new observation becomes available, since the optimal control actions are reconsidered anyway. MPC outperforms a static decision rule for changing the allocation and realizes both a higher return and a significantly lower risk than a buy-and-hold investment in various major stock market indices. This is after accounting for transaction costs, with a one-day delay in the implementation of allocation changes, and with zero-interest cash as the only alternative to the stock indices. Imposing a trading penalty that reduces the number of trades is found to increase the robustness of the approach.

Nystrup, P., William Hansen, B., Madsen, H., and Lindstrom, E. (2016). "Detecting change points in VIX and S&P 500: A new approach to dynamic asset allocation." In: *Journal of Asset Management* 17, pp. 361–374.
The purpose of dynamic asset allocation (DAA) is to overcome the challenge that changing market conditions present to traditional strategic asset allocation by adjusting portfolio weights to take advantage of favorable conditions and reduce potential drawdowns. This article proposes a new approach to DAA that is based on detection of change points without fitting a model with a fixed number of regimes to the data, without estimating any parameters and without assuming a specific distribution of the data. It is examined whether DAA is most profitable when based on changes in the Chicago Board Options Exchange Volatility Index or change points

detected in daily returns of the S&P 500 index. In an asset universe consisting of the S&P 500 index and cash, it is shown that a dynamic strategy based on detected change points significantly improves the Sharpe ratio and reduces the drawdown risk when compared with a static, fixed-weight benchmark.

O'Cinneid, R. (2019). "Applications of machine learning in finance: analysis of international portfolio flows using regime-switching models." PhD thesis. University College Cork.
Recent advances in machine learning are finding commercial applications across many sectors, not least the financial industry. This thesis explores applications of machine learning in quantitative finance through two approaches. The current state of the art is evaluated through an extensive review of recent quantitative finance literature. Themes and technologies are identified and classified, and the key use cases highlighted from the emerging literature. Machine learning is found to enable deeper analysis of financial data and the modelling of complex nonlinear relationships within data. The ability to incorporate alternative data in the investment process is also enabled. Innovations in backtesting and performance metrics are also made possible through the application of machine learning. Demonstrating a practical application of machine learning in quantitative finance, regime-switching models are applied to analyse and extract information from international portfolio flows. Regime-switching models capture properties of international portfolio flows previously found in the literature, such as persistence in flows compared to returns, and a relationship between flows and returns. Structural breaks and persistent regime shifts in investor behaviour are identified by the models. Regime-switching models infer regimes in the data which exhibit unique characteristic flows and returns. To determine whether the information extracted could aid in the investment process, a portfolio of global assets was constructed, with positions determined using a flowbased regime-switching model. The portfolio outperforms two benchmarks, a buy & hold strategy and the MSCI World Index in walk-forward out-of-sample tests using daily and weekly data.

Odendahl, F., Rossi, B., and Sekhposyan, T. (2020). "Comparing Forecast Performance with State Dependence." In: *SSRN e-Print*.
We propose a novel forecast comparison methodology to evaluate models' relative forecasting performance when the latter is a state-dependent function of economic variables. In our benchmark case, the relative forecasting performance, measured by the forecast loss differential, is modeled via a threshold model. Importantly, we allow the threshold that triggers the switch from one state to the next to be unknown, leading to a non-standard test statistic due to the presence of a nuisance parameter. Existing tests either assume a constant out-of-sample forecast performance or use non-parametric techniques robust to time-variation; consequently, they may lack power against state-dependent predictability. Importantly, our approach is applicable to point forecasts as well as predictive densities. Monte Carlo results suggest that our proposed test statistics perform well in finite samples and have better power than existing tests in selecting the best forecasting model in the presence of state dependence. Our test statistics uncover "pockets of predictability" in U.S. equity premia forecasts; the pockets are a state-dependent function of stock market volatility. Models using economic predictors perform significantly worse than a simple mean forecast in periods of high volatility, but, in periods of low volatility, the use of economic predictors may lead to small forecast improvements.

Ohana, J.-J., Ohana, S., Benhamou, E., Saltiel, D., and Guez, B. (2021). "Explainable AI Models of Stock Crashes: A Machine-Learning Explanation of the Covid March 2020 Equity Meltdown." In: *SSRN e-Print*.
We consider a gradient boosting decision trees (GBDT) approach to predict large S&P 500 price drops from a set of 150 technical, fundamental and macroeconomic features. We report an improved accuracy of GBDT over other machine learning (ML) methods on the S&P 500 futures prices. We show that retaining fewer and carefully selected features provides improvements across all ML approaches. Shapley values have recently been introduced from game theory to the field of ML. They allow for a robust identification of the most important variables predicting stock market crises, and of a local explanation of the crisis probability at each date, through a consistent features attribution. We apply this methodology to analyze in detail the March 2020 financial meltdown, for which the model offered a timely out of sample prediction. This analysis unveils in particular the contrarian predictive role of the tech equity sector before and after the crash.

Oliveira, A. B. and Valls Pereira, P. L. (2018). "Asset Allocation With Markovian Regime Switching: Efficient Frontier and Tangent Portfolio With Regime Switching." In: *SSRN e-Print*.
Asset allocation is important for diversifying risk and realizing gains in the financial market. It involves decisions taken under uncertainty based on statistical methods. Returns on financial assets generally present regime switching and there are different distributions of returns in bull and bear markets. Regime switching in the data generating process for returns makes it necessary to reformulate the asset allocation problem. This paper develops asset allocation models with regime switching. Due to the comparative study of asset allocation, portfolios with

regime switching enable the space of risk and return to be increased, reduce the risk for each level of return at the mean variance efficient frontier, and have the best risk-return relationship over time.

Omerovic, S., Friedl, H., and Grun, B. (2021). "Modelling Multiple Regimes in Economic Growth by Mixtures of Generalised Nonlinear Models." In: *Econometrics and Statistics*.
The new model class of mixtures of generalised nonlinear models (GNMs) is introduced. The model is specified, identifiability issues discussed, the fitting in a maximum likelihood framework using the expectation-maximisation (EM) algorithm outlined and an appropriate computational implementation introduced. The new model class is applied to capture cross-country heterogeneity when considering the augmented Solow model including human capital accumulation as underlying model structure. The inherent heterogeneity is attributed to multiple regimes being present within the selected country data set. The results highlight that country-specific differences lead to distinct components. Countries belonging to the same component exhibit convergence to a homogeneous steady state. The components differ in the initial technological endowment and the contribution of the economic variables to economic growth.

Oprisor, R. and Kwon, R. (2021). "Multi-Period Portfolio Optimization with Investor Views under Regime Switching." In: *Journal of Risk and Financial Management* 14(1), p. 3.
We propose a novel multi-period trading model that allows portfolio managers to perform optimal portfolio allocation while incorporating their interpretable investment views. This model's significant advantage is its intuitive and reactive design that incorporates the latest asset return regimes to quantitatively solve managers' question: how certain should one be that a given investment view is occurring? First, we describe a framework for multi-period portfolio allocation formulated as a convex optimization problem that trades off expected return, risk and transaction costs. Using a framework borrowed from model predictive control introduced by Boyd et al., we employ optimization to plan a sequence of trades using forecasts of future quantities, only the first set being executed. Multi-period trading lends itself to dynamic readjustment of the portfolio when gaining new information. Second, we use the Black-Litterman model to combine investment views specified in a simple linear combination based format with the market portfolio. A data-driven method to adjust the confidence in the manager's views by comparing them to dynamically updated regime-switching forecasts is proposed. Our contribution is to incorporate both multi-period trading and interpretable investment views into one framework and offer a novel method of using regime-switching to determine each view's confidence. This method replaces portfolio managers' need to provide estimated confidence levels for their views, substituting them with a dynamic quantitative approach. The framework is reactive, tractable and tested on 15 years of daily historical data. In a numerical example, this method's benefits are found to deliver higher excess returns for the same degree of risk in both the case when an investment view proves to be correct, but, more notably, also the case when a view proves to be incorrect. To facilitate ease of use and future research, we also developed an open-source software library that replicates our results.

Ou, L., Hunter, M. D., and Chow, S.-M. (2019). "Whats for dynr: A Package for Linear and Nonlinear Dynamic Modeling in R." In: *The R Journal*.
Intensive longitudinal data in the behavioral sciences are often noisy, multivariate in nature, and may involve multiple units undergoing regime switches by showing discontinuities interspersed with continuous dynamics. Despite increasing interest in using linear and nonlinear differential/difference equation models with regime switches, there has been a scarcity of software packages that are fast and freely accessible. We have created an R package called dynr that can handle a broad class of linear and nonlinear discreteand continuous-time models, with regime-switching properties and linear Gaussian measurement functions, in C, while maintaining simple and easy-to learn model specification functions in R. We present the mathematical and computational bases used by the dynr R package, and present two illustrative examples to demonstrate the unique features of dynr.

Pang, Z., Hu, Z., Tokmakov, P., Wang, Y.-X., and Hebert, M. (2021). "Unlocking the Full Potential of Small Data with Diverse Supervision." In: *arXiv e-Print*.
Virtually all of deep learning literature relies on the assumption of large amounts of available training data. Indeed, even the majority of few-shot learning methods rely on a large set of "base classes" for pretraining. This assumption, however, does not always hold. For some tasks, annotating a large number of classes can be infeasible, and even collecting the images themselves can be a challenge in some scenarios. In this paper, we study this problem and call it "Small Data" setting, in contrast to "Big Data". To unlock the full potential of small data, we propose to augment the models with annotations for other related tasks, thus increasing their generalization abilities. In particular, we use the richly annotated scene parsing dataset ADE20K to construct our realistic Long-tail Recognition with Diverse Supervision (LRDS) benchmark by splitting the object categories

into head and tail based on their distribution. Following the standard few-shot learning protocol, we use the head classes for representation learning and the tail classes for evaluation. Moreover, we further subsample the head categories and images to generate two novel settings which we call "Scarce-Class" and "Scarce-Image", respectively corresponding to the shortage of samples for rare classes and training images. Finally, we analyze the effect of applying various additional supervision sources under the proposed settings. Our experiments demonstrate that densely labeling a small set of images can indeed largely remedy the small data constraints.

Papenbrock, J. and Schwendner, P. (2015). "Handling risk-on/risk-off dynamics with correlation regimes and correlation networks." In: *Financial Markets and Portfolio Management* 29(2), pp. 125–147.
In this paper, we present a framework for detecting distinct correlation regimes and analyzing the emerging state dependences for a multi-asset futures portfolio from 1998 to 2013. These correlation regimes have been significantly different since the financial crisis of 2008 than they were previously; cluster tracking shows that asset classes are now less separated. We identify distinct risk-on and risk-off assets with the help of correlation networks. In addition to visualizing, we quantify these observations using suitable metrics for the clusters and correlation networks. The framework will be useful for financial risk management, portfolio construction, and asset allocation.

Perikos, I., Kardakis, S., and Hatzilygeroudis, I. (2021). "Sentiment analysis using novel and interpretable architectures of Hidden Markov Models." In: *Knowledge-Based Systems* 229, p. 107332.
Sentiment analysis aims to formulate automated methods to recognize sentiments, opinions and emotions in text. Many methods and approaches have been utilized but most of them do not disclose the way that decisions are made and operate as black boxes. Hidden Markov Models (HMMs) constitute a quite suitable and potent approach for sentiment analysis, since they can utilize the sequential nature of the text, a piece of information that machine learning methods cannot properly utilize. However, little attention has been paid to formulating and applying sophisticated HMM-based methods and advanced training approaches for accomplishing sentiment analysis tasks. In this article, we introduce novel, interpretable HMM-based methods for recognizing sentiments in text and we examine their performance under various architectures, training methods, orders and ensembles. The introduced models possess interpretability, they can indicate the sentimental parts of a sentence and illustrate the way that the overall sentiment evolves from the start to the end of it. A concrete experimental study is conducted and the results show that the introduced HMMs methods and the training approaches are quite competitive with machine learning methods and that they outperform traditional HMMs. Furthermore, the designed HMMs methods possess great interpretability and can be an efficient approach for sentiment analysis.

Peters, E. (2015). "Stable vs. Unstable Markets: A Tale of Two States." In: *SSRN e-Print*.
One of the bedrocks of modern capital market theory is that market risk and related statistics are stable over the long run. Nobel prizes have been won for this insight, and it is taught in the best business schools. Regulations have also been written based upon this assumption. Yet, experience does not support this idea. We know that often markets have periods of relative stability, but they can also be followed by years where it seems that all is chaos (and not in the physics sense of the word). In academia, there are theories that compete with the Capital Asset Pricing Model (CAPM), the main proponent of stable markets, but these competing theories are generally considered impractical since they don't lend themselves to easy solutions. The answers we often receive from the usable models, however, go horribly wrong when markets go south. Could it be that we're using those models simply because the light is better here? But how can we use the models that are impractical? In this paper, we show convincing evidence that there are actually two separate market states, each corresponding to these competing models. In essence, the CAPM and its critics are both right, but only part of the time. The implications from this for asset allocation and plan management are profound. There will be periods where using standard techniques for asset allocation or investment management will work well. When the environment changes, however, those processes may no longer work with reliability. This is particularly true of diversifi cation because assets that diversify one another in one state fail in the other state when they are truly needed. The rules change, and if investors hope to adapt successfully, they will need to know the new rules when the change occurs. This paper offers an explanation for that problem - two different market states causing assets to behave very differently. A subsequent paper will provide a roadmap to help asset owners anticipate and navigate deftly through the changes in market states.

Pharasi, H. K., Seligman, E., Sadhukhan, S., and Seligman, T. H. (2020a). "Dynamics of market states and risk assessment." In: *arXiv e-Print*.
Based on previous developments of the concept of market states using correlation matrices, in the present paper we address the dynamical evolution of correlation matrices in time. This will imply minor modifications to

the market states themselves, due to increased attention to the transition matrix between the states. We will introduce trajectories of the correlation matrices by considering one day shifts for the epoch used to calculate the correlation matrices and will visualize both the states and the trajectories after dimensional scaling. This approach using dynamics improves the options of risk assessment and opens the door to dynamical treatments of markets and shows noise suppression in a new light.

Pharasi, H. K., Seligman, E., and Seligman, T. H. (2020b). "Market states: A new understanding." In: *arXiv e-Print*.
We present the clustering analysis of the financial markets of S&P 500 (USA) and Nikkei 225 (JPN) markets over a period of 2006-2019 as an example of a complex system. We investigate the statistical properties of correlation matrices constructed from the sliding epochs. The correlation matrices can be classified into different clusters, named as market states based on the similarity of correlation structures. We cluster the S&P 500 market into four and Nikkei 225 into six market states by optimizing the value of intracluster distances. The market shows transitions between these market states and the statistical properties of the transitions to critical market states can indicate likely precursors to the catastrophic events. We also analyze the same clustering technique on surrogate data constructed from average correlations of market states and the fluctuations arise due to the white noise of short time series. We use the correlated Wishart orthogonal ensemble for the construction of surrogate data whose average correlation equals the average of the real data.

Pinto, J. M. and Castle, J. (2021). *A machine learning dynamic switching approach to forecasting when there are structural breaks*. Tech. rep. University of Oxford.
Forecasting economic indicators is an important task for analysts. However, many indicators suffer from structural breaks leading to forecast failure. Methods that are robust following a structural break have been proposed in the literature but they come at a cost: an increase in forecast error variance. We propose a method to select between a set of robust and non-robust forecasting models. Our method uses time-series clustering to identify possible structural breaks in a time series, and then switches between forecasting models depending on the series dynamics. We perform a rigorous empirical evaluation with 400 simulated series with an artificial structural break and with real data economic series: Industrial Production and Consumer Prices for all Western European countries available from the OECD database. Our results show that the proposed method statistically outperforms benchmarks in forecast accuracy for most case scenarios, particularly at short horizons.

Platanakis, E., Sakkas, A., and Sutcliffe, C. (2017). "Portfolios in a Regime Shifting Non-Normal World: Are Alternative Assets Beneficial?" In: *European Financial Management Association Annual Meeting Athens*.
Adding five alternative assets to equity and bond portfolios is harmful for US investors. We use nineteen portfolio models in conjunction with dummy variable regression, and measure out-of-sample performance by both certainly equivalent ratios and Sharpe ratios. The presence of harmful diversification is robust to different estimation periods and levels of risk aversion, and to the use of two regimes. Harmful diversification is not primarily due to transactions costs or non-normal returns, but to estimation risk. Large estimation errors during the credit crisis (2007-09) account for the harmful diversification of three of the five alternative assets over the 1997-2015 period.

Prakash, A., James, N., Menzies, M., and Francis, G. (2021a). "Structural Clustering of Volatility Regimes for Dynamic Trading Strategies." In: *Applied Mathematical Finance* 28(3), pp. 236–274.
We develop a new method to find the number of volatility regimes in a nonstationary financial time series by applying unsupervised learning to its volatility structure. We use change point detection to partition a time series into locally stationary segments and then compute a distance matrix between segment distributions. The segments are clustered into a learned number of discrete volatility regimes via an optimization routine. Using this framework, we determine the volatility clustering structure for financial indices, large-cap equities, exchange-traded funds and currency pairs. Our method overcomes the rigid assumptions necessary to implement many parametric regime-switching models while effectively distilling a time series into several characteristic behaviours. Our results provide a significant simplification of these time series and a strong descriptive analysis of prior behaviours of volatility. Finally, we create and validate a dynamic trading strategy that learns the optimal match between the current distribution of a time series and its past regimes, thereby making online risk-avoidance decisions at present.

Prakash, A., James, N., Menzies, M., and Francis, G. (2021b). "Structural clustering of volatility regimes for dynamic trading strategies." In: *arXiv e-Print*.
We develop a new method to find the number of volatility regimes in a nonstationary financial time series by applying unsupervised learning to its volatility structure. We use change point detection to partition a time series into locally stationary segments and then compute a distance matrix between segment distributions. The

segments are clustered into a learned number of discrete volatility regimes via an optimization routine. Using this framework, we determine a volatility clustering structure for financial indices, large-cap equities, exchange-traded funds and currency pairs. Our method overcomes the rigid assumptions necessary to implement many parametric regime-switching models, while effectively distilling a time series into several characteristic behaviours. Our results provide significant simplification of these time series and a strong descriptive analysis of prior behaviours of volatility. This empirical analysis could be used with other regime-switching implementations, justifying the parametric structure encoded in any candidate model. Finally, we create and validate a dynamic trading strategy that learns the optimal match between the current distribution of a time series and its past regimes, thereby making online risk-avoidance decisions in the present.

Procacci, P. F. and Aste, T. (2019). "Forecasting market states." In: *Quantitative Finance* 19(9), pp. 1491–1498.
We propose a novel methodology to define, analyze and forecast market states. In our approach, market states are identified by a reference sparse precision matrix and a vector of expectation values. In our procedure, each multivariate observation is associated to a given market state accordingly to a minimization of a penalized Mahalanobis distance. The procedure is made computationally very efficient and can be used with a large number of assets. We demonstrate that this procedure is successful at clustering different states of the markets in an unsupervised manner. In particular, we describe an experiment with one hundred log-returns and two states in which the methodology automatically associates states prevalently to pre- and post-crisis periods with one state gathering periods with average positive returns and the other state periods with average negative returns, therefore discovering spontaneously the common classification of "bull" and "bear" markets. In another experiment, with again one hundred log-returns and two states, we demonstrate that this procedure can be efficiently used to forecast off-sample future market states with significant prediction accuracy. This methodology opens the way to a range of applications in risk management and trading strategies in the context where the correlation structure plays a central role.

Pruser, J. (2021). "Forecasting US inflation using Markov dimension switching." In: *Journal of Forecasting* 40(3), pp. 481–499.
This study considers Bayesian variable selection in the Phillips curve context by using the Bernoulli approach of Korobilis (Journal of Applied Econometrics, 2013, 28(2), 204-230). The Bernoulli model, however, is unable to account for model change over time, which is important if the set of relevant predictors changes. To tackle this problem, this paper extends the Bernoulli model by introducing a novel modeling approach called Markov dimension switching (MDS). MDS allows the set of predictors to change over time. It turns out that only a small set of predictors is relevant and that the relevant predictors exhibit a sizable degree of time variation for which the Bernoulli approach is not able to account, stressing the importance and benefit of the MDS approach. In addition, this paper provides empirical evidence that allowing for changing predictors over time is crucial for forecasting inflation.

Rebonato, R. and El Aouadi, A. (2021). "How Do the Volatilities of Rates Depend on Their Level? The "Universal Relationship" Revisited." In: *The Journal of Fixed Income* 30(4), pp. 17–31.
The authors present a straightforward extension valid in the current negative-rate regime of the "universal relationship" uncovered in De Guillaume, Rebonato, and Pogudin (2013) between the level of rates and their volatility. They also provide an explanation of the origin of this relationship by showing the existence of two sharply distinct regimes for the volatility of real rates as a function of real rate levels, and by linking periods of high inflation with periods of high real rates. Finally, they provide evidence that the "volatility of volatility" also displays a "universal" behavior, with a significant linear dependence on the level of rates (and of the volatility itself).

Reher, G. and Wilfling, B. (2015). "A nesting framework for Markov-switching GARCH modelling with an application to the German stock market." In: *Quantitative Finance*, pp. 1–16.
In this paper, we establish a generalized two-regime Markov-switching GARCH model which enables us to specify complex (symmetric and asymmetric) GARCH equations that may differ considerably in their functional forms across the two Markov regimes. We show how previously proposed collapsing procedures for the Markov-switching GARCH model can be extended to estimate our general specification by means of classical maximum-likelihood methods. We estimate several variants of the generalized Markov-switching GARCH model using daily excess returns of the German stock market index DAX sampled during the last decade. Our empirical study has two major findings. First, our generalized model outperforms all nested specifications in terms of (a) statistical fit (when model selection is based on likelihood ratio tests) and (b) out-of-sample volatility forecasting performance.

Second, we find significant Markov-switching structures in German stock market data, with substantially differing volatility equations across the regimes.

Ren, D. (2016). "Essays in Asset Pricing and Financial Econometrics." PhD thesis. University of Guelph.
In the first chapter, we compare the finite sample power of short and long-horizon tests in nonlinear predictive regression models of regime switching between bull and bear markets, allowing for time varying transition probabilities. As a point of reference, we also provide a similar comparison in a linear predictive regression model without regime switching. Overall, our results do not support the contention of higher power in longer horizon tests in either the linear or nonlinear regime switching models. Nonetheless, it is possible that other plausible nonlinear models provide stronger justification for long-horizon tests. Using finite sample simulation methods, we assess the power of long-horizon predictive tests and compare them to their short-run counterparts, when the true underlying model contains financial asset bubbles. Our results indicate that long-run predictive test using valuation predictors – specifically the dividend price ratio– do pick up the return predictability inherent in the asset bubbles. However, after size-adjustment, the long-run predictive framework has a small advantage over its short-run counterpart when the predictor is highly persistent and provides a larger, yet still modest power improvement when the predictor is moderately persistent. The third chapter proposes a simple Bayesian learning framework to assess leverage ratios in the presence of parameter uncertainty about mean log cash flow. In particular it can explain why firm's leverage ratios have been observed to increase with firm age. Market values are increasing in uncertainty about mean cash flow and leverage ratios are decreasing with market values. Over the life period of firm, the managers and investors rationally learn from realized cash flows. Due to the convex relationship between cash flow and firm value, ceteris paribus, this results in a decrease in market value and an increase in the leverage ratio. Firm level panel data provides empirical evidence consistent with the model predictions after correcting for the endogeneity of the book to market and profitability control variates. The empirical results suggest that the firm leverage ratio increases over firm age due to learning.

Reus, L. and Mulvey, J. M. (2016). "Dynamic allocations for currency futures under switching regimes signals." In: *European Journal of Operational Research* 253(1), pp. 85–93.
Exchange carry trade returns can be classified in regimes by a Hidden Markov Model. Regime identification allows to construct outstanding carry trade strategies. Optimal mean-semivariance currency portfolio enhances carry trade strategies. Over the last decades, speculative investors in the FX market have profited in the well known currency carry trade strategy (CT). However, during currencies or global financial crashes, CT produces substantial losses. In this work we present a methodology that enhances CT performance significantly. For our final strategy, constructed backtests show that the mean-semivolatility ratio can be more than doubled with respect to benchmark CT. To do the latter, we first identify and classify CT returns according to their behavior in different regimes, using a Hidden Markov Model (HMM). The model helps to determine when to open and close positions, depending whether the regime is favorable to CT or not. Finally we employ a mean-semivariance allocation model to improve allocations when positions are opened.

Ruff, L., Kauffmann, J. R., Vandermeulen, R. A., Montavon, G., Samek, W., Kloft, M., Dietterich, T. G., and Muller, K.-R. (2021). "A Unifying Review of Deep and Shallow Anomaly Detection." In: *arXiv e-Print*.
Deep learning approaches to anomaly detection have recently improved the state of the art in detection performance on complex datasets such as large collections of images or text. These results have sparked a renewed interest in the anomaly detection problem and led to the introduction of a great variety of new methods. With the emergence of numerous such methods, including approaches based on generative models, one-class classification, and reconstruction, there is a growing need to bring methods of this field into a systematic and unified perspective. In this review we aim to identify the common underlying principles as well as the assumptions that are often made implicitly by various methods. In particular, we draw connections between classic 'shallow' and novel deep approaches and show how this relation might cross-fertilize or extend both directions. We further provide an empirical assessment of major existing methods that is enriched by the use of recent explainability techniques, and present specific worked-through examples together with practical advice. Finally, we outline critical open challenges and identify specific paths for future research in anomaly detection.

Samal, A., Pharasi, H. K., Ramaia, S. J., Kannan, H., Saucan, E., Jost, J., and Chakraborti, A. (2021). "Network geometry and market instability." In: *Royal Society Open Science* 8(2).
The complexity of financial markets arise from the strategic interactions among agents trading stocks, which manifest in the form of vibrant correlation patterns among stock prices. Over the past few decades, complex financial markets have often been represented as networks whose interacting pairs of nodes are stocks, connected by edges that signify the correlation strengths. However, we often have interactions that occur in groups of

three or more nodes, and these cannot be described simply by pairwise interactions but we also need to take the relations between these interactions into account. Only recently, researchers have started devoting attention to the higher-order architecture of complex financial systems, that can significantly enhance our ability to estimate systemic risk as well as measure the robustness of financial systems in terms of market efficiency. Geometry-inspired network measures, such as the Ollivier-Ricci curvature and Forman-Ricci curvature, can be used to capture the network fragility and continuously monitor financial dynamics. Here, we explore the utility of such discrete Ricci curvatures in characterizing the structure of financial systems, and further, evaluate them as generic indicators of the market instability. For this purpose, we examine the daily returns from a set of stocks comprising the USA S&P-500 and the Japanese Nikkei-225 over a 32-year period, and monitor the changes in the edge-centric network curvatures. We find that the different geometric measures capture well the system-level features of the market and hence we can distinguish between the normal or 'business-as-usual' periods and all the major market crashes. This can be very useful in strategic designing of financial systems and regulating the markets in order to tackle financial instabilities.

Sarwar, G., Mateus, C., and Todorovic, N. (2017). "A tale of two states: asymmetries in the UK small, value and momentum premiums." In: *Applied Economics* 49(5), pp. 456–476.
This article performs comparative analysis of the asymmetries in size, value and momentum premium and their macroeconomic determinants over the UK economic cycles, using Markov switching approach. We associate Markov switching regime 1 with economic upturn and regime 2 with economic downturn. We find clear evidence of cyclical variations in the three premiums, most notable being that in the size premium, which changes from positive in expansions to negative in recessions. Macroeconomic indicators prompting such cyclicality the most are variables that proxy credit market conditions, namely the interest rates, term structure and credit spread. Overall, macro factors tend to have more significant impact on the three premiums during economic downturns. The results are robust to the choice of information variable used in modelling transition probabilities of the two-stage Markov switching model. We show that exploiting cyclicality in premiums proves particularly profitable for portfolios featuring small cap stocks in recessions at a feasible level of transaction costs.

Satchell, S. (2011). "Regime-switching in financial markets." In: *Journal of Asset Management* 12(5), p. 309.
This issue looks at a number of studies of regime-switching in financial markets; a hardy perennial of a research topic, much loved by academics and central bankers, but rather underused by practitioners. The reasons for this unpopularity are many. These reasons are not based on ignorance but on very real difficulties in implementation. Furthermore, the structure of these models sits uncomfortably with the assumptions made by conventional optimisers. Converting these regime structures into global stock selection models with universes of, say, 5000 stocks seems not to be currently feasible. The first paper, by Bulla and co-authors, looks at a Markov-switching asset allocation model, which uses current information on volatility to adjust the market exposure. They show that, compared with buy-and-hold, there are increased returns and reduced volatility. The second paper, by Guidolin and Ria, converts regime-switching in first and second moments into regime-switching in mean variance frontiers. The data used here are Morgan Stanley investable indices for five countries/regions. The third article, by Haque, provides a theoretical contribution, in that it generalises the famous Barberis and Shleifer model of style switching. It is known that this model leads to small order ARMA models in relative style returns and current research looks at this structure as a way of forecasting when the switch may occur. This paper, by focusing on leaders and followers, may help in forecasting style switching and lead to new implementations of dynamic style allocation. The final paper, by van Vliet and Blitz, looks at asset allocation across different phases in the business cycle and identifies four phases, expressible in terms of time variation and risk and returns. Concluding this issue provides a thorough examination of current research ideas on regime-switching. A point that comes through three of the papers very clearly is that, if we can implement regime-switching successfully, it is going to be with respect to asset classes or a small number of factors. For those of our readers who may wish to apply these ideas to stock selection models, it is clear that the only way forward is to regime-switch some of the key factors in the model. If a typical model has as factors market indices, style variables and possibly statistical factors, then it is not clear as yet which of these should be the most important ones for regime-switching. This may be a good topic for future research.

Schatz, M. (2020). "Financial Modeling of Bubbles and Crashes." PhD thesis. ETH Zurich.
The aim of this thesis is to develop and study mathematical models of financial markets experiencing bubbles and crashes. Our study is based on a model structure that combines increasingly positive returns (the build-up of a bubble) with a sudden reversal and an accumulation of large negative returns (the crash). The occurrence of financial crashes, fueled by bubbles, are widely recognized as disruptive events that have significant adverse

effects on the performance of mathematical tools in many financial problem settings. However, models that explicitly incorporate the stylized features of bubble-and-crash dynamics are yet to permeate most areas of (mathematical) finance.

To address this shortcoming, in the first part of the thesis we develop a general stochastic model framework based on the dialectic view that build-up and implosion of financial bubbles are inherently linked. We show that the framework encompasses a wide range of models from the bubble literature in (financial) economics that focus on market failure as a driver of financial distress. As such, it functions both as a tool to compare the various assumptions underlying such models and as a good starting point to robustify financial problem settings that are affected by bubbles and crashes. Based on this general framework, we pick several specific models combining (possibly explosive) diffusions and single jump processes, study their stochastic and statistical properties and show how they can be applied to a common problem in mathematical finance, the pricing and hedging of European options. Where indicated, we apply our methods to financial data sets.

The second part of the thesis introduces a class of point processes that combines two wellestablished cluster mechanisms, a self-exciting structure commonly referred to as Hawkes process, and a shot-noise structure known as Neyman-Scott process. As such, these processes are useful in modeling the accumulation of points - for example, the clustering of negative returns during financial crashes within the framework mentioned above. However, given that such point processes transcend the mostly diffusive setting of the first part and show a similarity to ARMA time series of counts, which confirms their wide potential applicability beyond finance, this line of work deserves a distinct part in this thesis. In many cases, missing data complicates statistical estimation for this type of process, and explicit mathematical expressions exist only for (Markovian) special cases. To address this, we derive an Expectation-Maximization (EM) algorithm that allows us to estimate general inhomogeneous and non-parametric specifications and marks. We test the algorithm in a range of simulation and case studies.

Scherer, B. and Apel, M. (2020). "Business cycle-related timing of alternative risk premia strategies." In: *The Journal of Alternative Investments* 22(4), pp. 8–24.

Time variation in risk premia is not a violation of market efficiency but rather a reflection of time-varying economic rewards. By analyzing macroeconomic sensitivities (proxying for good and bad times), the authors show that time-varying returns of certain alternative risk premia strategies are significantly related to economic conditions. On the basis of identified return patterns, the authors construct a risk premia timing strategy that adds statistically significant marginal performance with low turnover. They confront data mining concerns by successfully cross validating their model across various investment universes.

Seidl, I. (2012). "Markowitz versus Regime Switching: An Empirical Approach." In: *The Review of Finance and Banking* 04(1), pp. 033–043.

This article discusses an adjusted regime switching model in the context of portfolio optimization and compares the attained portfolio weights and the performance to a classical mean-variance set-up as introduced by Markowitz (1952). The model postulates different asset price dynamics under different regimes, and jumps between regimes are driven by a Markov process. For examples, 'bear' and 'bull' markets could be such regimes. Given a particular regime, portfolio weights are set based on the conditional means and variance-covariance structure of the asset dynamics. The model is evaluated in an out-of-sample period of the last three years with a moving window and a forecast of only one period. It is found that with the adjusted regime switching portfolio selection algorithm as applied here, the performance of the optimal portfolio is highly improved even where portfolio weights are constrained to realistic values.

Sharaiha, Y. M. and Johansson, K. K. (2014). "The state-dependent time variation in the value premium." In: *Journal of Asset Management* 15(2), pp. 150–161.

It is well documented that asset and strategy returns are generally exposed to identifiable risk factors. Moreover, the exposure to these systematic risk factors tends to be time varying. Examples of strategies that exhibit such regime-dependent variability include value investing in equity markets and carry in foreign exchange markets. The literature proposes several macro-based explanations for this time variation such as liquidity or cyclicality risk depending on the strategy and horizon under consideration. This project relies on developments in the academic literature in the area of state-dependent asset pricing models (see, for example, survey by van Dijk et al, 2002). Under such a framework, a strategy return is modelled using a multi-factor asset pricing equation where the risk sensitivities (or betas) to the pre-defined factors are allowed to vary according to one or multiple state variables. The approach considered here uses a logistic smooth transition regression methodology applied to the value strategy, where the state variables have an economic meaning (see Christiansen et al, 2011 application to foreign exchange carry strategy). By distinguishing between low and high state regimes (in a continuous

space), the aim is to first investigate improvements in the explanatory power of the model relative to the linear (no-state dependency) approach. In particular, we study the performance of the value factor during turbulent periods, and identify economic variables driving its time-varying behaviour. We also present an algorithm that allocates dynamically to a long short value overlay portfolio conditioned on regime transitions. We show that the performance of this dynamic portfolio is superior to a portfolio with a static value overlay.

Sheikh, A. Z. and Sun, J. (2012). "Regime Change: Implications of Macroeconomic Shifts on Asset Class and Portfolio Performance." In: *The Journal of Investing* 21(3), pp. 36–54.
It is a well-recognized empirical observation that different asset classes respond differently to different economic drivers. It is also well recognized that asset class behavior can vary significantly over shifting economic scenarios. This article builds on this empirical evidence to develop a quantitative framework for regime-based asset allocation. It investigates whether regime-based investing can effectively respond to changes in economic regimes at the portfolio level in an effort to provide better long-term results when compared to a more static approach. Results indicate that it is both possible and practical to develop a regime-based investing approach that can potentially add value over time. Success depends on identifying key factors that influence asset class performance, and then developing a way to model those non-linear relationships. Regime-based investing also requires a healthy degree of economic forecasting skill, which need not be perfect to add value. Based on the authors' analysis, regime based investing can offer investors a compelling alternative to a more static approach.

Shi, X. (2020). "A Survey of Changepoint Techniques for Time Series Data." PhD thesis. Clemson University.
Changepoint analysis has played an important role in modern time series study. Detection of changepoints helps modelling and prediction of time series and is found in applications of many fields. This dissertation focuses on the detection of mean structure changes in correlated time series. It consists of the results of three research projects on changepoint problems: (1) the comparison of changepoint techniques; (2) autocovariance estimation of an AR(p) time series with changepoints; and (3) L1-regularization in changepoint analysis. In chapter 2 the single changepoint techniques, or At-Most-One-Changepoint (AMOC) tests are reviewed. A new AMOC test, Sum of Squared CUSUMz is developed and is shown to be the most powerful AMOC test through simulation studies on the time series with various ARMA(p,q) structures. Multiple changepoint techniques that are applicable to correlated time series are discussed in chapter 3, which includes an in-depth discussion on the wild binary segmentation. A new distance metric is also proposed in this chapter for comparing the multiple changepoint techniques. Next in the chapter 4 a Yule-Walk moment estimator based on the first order difference is proposed for autocovariance estimation of an AR(p) time series with a small number of changepoints. The last chapter simply reviews the L1- regularization and its application to changepoint analysis.

Shi, X., Gallagher, C., Lund, R., and Killick, R. (2021). "A Comparison of Single and Multiple Changepoint Techniques for Time Series Data." In: *arXiv e-Print*.
This paper describes and compares several prominent single and multiple changepoint techniques for time series data. Due to their importance in inferential matters, changepoint research on correlated data has accelerated recently. Unfortunately, small perturbations in model assumptions can drastically alter changepoint conclusions; for example, heavy positive correlation in a time series can be misattributed to a mean shift should correlation be ignored. This paper considers both single and multiple changepoint techniques. The paper begins by examining cumulative sum (CUSUM) and likelihood ratio tests and their variants for the single changepoint problem; here, various statistics, boundary cropping scenarios, and scaling methods (e.g., scaling to an extreme value or Brownian Bridge limit) are compared. A recently developed test based on summing squared CUSUM statistics over all times is shown to have realistic Type I errors and superior detection power. The paper then turns to the multiple changepoint setting. Here, penalized likelihoods drive the discourse, with AIC, BIC, mBIC, and MDL penalties being considered. Binary and wild binary segmentation techniques are also compared. We introduce a new distance metric specifically designed to compare two multiple changepoint segmentations. Algorithmic and computational concerns are discussed and simulations are provided to support all conclusions. In the end, the multiple changepoint setting admits no clear methodological winner, performance depending on the particular scenario. Nonetheless, some practical guidance will emerge.

Shu, M., Song, R., and Zhu, W. (2021). "The 2021 Bitcoin Bubbles and Crashes – Detection and Classification." In: *SSRN e-Print*.
In this study, we adopted the Log-Periodic Power Law Singularity (LPPLS) model for real-time identification and monitoring of Bitcoin bubbles and crashes using different time scale data and proposed the modified Lagrange regularization method to alleviate the impact of potential LPPLS model over-fitting to better estimate bubble start time and market regime change. We also aimed to determine the natures of the bubbles and crashes -

be it endogenous due to its own price evolution or exogenous due to external market and/or policy influences. We performed a systematic market event analysis and correlated which to Bitcoin bubbles detected. Based on the daily LPPLS confidence indictor from December 1, 2019 to June 24, 2021, we found that the Bitcoin boom from November 2020 to mid-January 2021 is an endogenous bubble, stemming from the self-reinforcement of cooperative herding and imitative behaviors of market players, while the price spike from mid-January 2021 to mid-April 2021 is likely an exogenous bubble driven by extrinsic events including a series of large-scale acquisitions and adoptions by well-known institutions such as Visa and Tesla. We have also demonstrated the utilities of multi-resolution LPPLS analysis in revealing both short-term changes and long-term states.

Siliverstovs, B. and Wochner, D. (2021). "State-Dependent Evaluation of Predictive Ability." In: *Journal of Forecasting* 40(3), pp. 547–574.

This study systematically broadens the relevance of possible model performance asymmetries across business cycles in the spirit of the recent state-dependent forecast evaluation literature (e.g. Chauvet and Potter, 2013) to hundreds of macroeconomic indicators and deepens the forecast evaluation of the recent factor model literature on hundreds of target variables (e.g. Stock and Watson, 2012b) in a state-dependent manner. Our results are consistent with both strands of the literature and generalize the former to over 200 macroeconomic indicators and differentiate the latter across three levels of temporal granularity: We document systematic model performance differences in both absolute and relative terms across business cycles (longitudinal) as well as across variable groups (cross-sectional) and find these performance differences to be robust across several alternative specifications. The cross-sectional prevalence and robustness of state-dependency shown in this article encourages economic forecasters to complement model performance assessments with a state-dependent evaluation of predictive ability.

Silveira, D. and Oscar, R. B. L. M. (2021). "Inflation Targeting Regimes in Emerging Market Economies: To Invest or Not to Invest?" In: *SSRN e-Print*.

We propose a stochastic learning rule through an Agent-based Model (ABM) to understand how emerging market economies (EMEs) can achieve high levels of investment, given the announced inflation target rate. The central banks act as a pseudo-player, choosing between the pursued target inflation rate or a negative inflation rate. By taking this action as given, bounded-rational firms and workers iteratively play a two-population well-mixed evolutionary game to make investment decisions. Our findings show that when inflation converges to its target, less the central planners' effort to reach the steady-state with investment coordination. When central banks target a negative inflation rate, it can speed up the EMEs' convergence to a steady-state with agents coordinating their investment strategies. It shed some light on central banks' transparency and credibility to avoid the so-called debt-deflation spiral, which typically increases the uncertainty in EMEs, limiting the investments in the economy.

Simonian, J. (2020). "Mixed Ag: A Regime-Based Analysis of Multi-Asset Agriculture Portfolios." In: *The Journal of Portfolio Management* 46(6), pp. 135–146.

For some time now, the prospect that the world is entering a new epoch of elevated prices for agricultural commodities has been a focus of both policymakers concerned with the food security of their citizens and investors looking to benefit from a potential secular uptrend in the demand for food. Investors most commonly access agriculture in public markets through funds that invest in agricultural commodity futures or the common stock of companies that engage in agribusiness. In general, funds that invest in agricultural commodities are either dedicated equity or futures managers. However, there are potentially significant performance benefits to investing in agricultural commodities through a single multi-asset vehicle composed of both agricultural commodity futures and agribusiness stocks. To that end, in this article the author examines the performance of a multi-asset agriculture portfolio in periods of high and low economic growth and compares it with the performance of its individual equity and futures components, as well as the broader stock market and investment-grade bonds. The author finds that in terms of return generation, risk mitigation, and diversification potential relative to core stocks and bonds, the multi-asset agriculture strategy makes a compelling case for inclusion alongside traditional strategies within institutional investors portfolios.

Simonian, J. and Wu, C. (2019a). "Factors in Time: Fine-Tuning Hedge Fund Replication." In: *The Journal of Portfolio Management* 45 (3), pp. 159–164.

Hedge fund replication has become a cottage industry in investing. Among the most popular hedge fund replication frameworks are factor models based on ordinary least squares (OLS) regression, a development that is no doubt due to its simplicity and familiarity among investment practitioners. Despite their widespread use, the OLS regression-based factor models that form the basis for many hedge fund replication programs are often overfitted to a single sample, severely undercutting their predictive effectiveness. As a remedy to the latter

shortcoming, in this article the authors apply the regularization method known as regression to the replication of hedge fund strategies. Ridge regression works by formally imbuing a regression with additional bias in exchange for a reduction in the variance between training and test samples. Using a simple yet robust methodology, the authors show how to dynamically calibrate the predictively optimal level of bias without significantly reducing the backward-looking explanatory power of a given model. In doing so, the authors demonstrate that ridge regression can help produce generalizable models that are useful in both the ex post risk analysis and ex ante replication of hedge fund strategies.

Simonian, J. and Wu, C. (2019b). "Minsky vs. Machine: New Foundations for Quant-Macro Investing." In: *The Journal of Financial Data Science* 1(2), pp. 94–110.
Systematic macro investors use of the regime-switching models that have been developed in academia over the last several decades is infrequent at best and, when used, generally tangential to their core investment process. The roots of this less-than-enthusiastic uptake can be found in two familiar sources: models that possess an overly complex formal structure and poor predictive ability. As a remedy to the current state of affairs, the authors present a new foundation for regime-based investing, one based on spectral clustering, a graph theoretic approach to classifying data. Drawing inspiration from the work of Hyman Minsky and John Geanakoplos, the authors present a macro framework that uses measures of growth, inflation, and leverage to define regimes and drive portfolio decisions. To the latter end, the authors show how the framework can be used to build portfolios using information about regimes as defined, to outperform a no-information equal-weight portfolio both out-of-sample and in bootstrapped and cross-validated simulations. The authors thus show that spectral clustering can provide both an elegant mathematical description of the leverage cycle and a robust foundation for quant-macro investing.

Singh, A. and Singh, M. (2016). "Risk-Return Relationship in BRIC Equity Markets: Evidence from Markov Regime Switching Model with Time-varying Transition Probabilities." In: *Metamorphosis : A Journal of Management Research*.
A rich literature supports the existence of both positive and negative relationship between the risk and return in the developed equity markets. However, the present study attempts to capture the risk-return relationship in the most promising and opportunities-instilled emerging market club, the "BRIC" equity markets, by employing a Markov regime switching model with time-varying transition probabilities, further taking St. Louis Fed Financial Stress Index (the US financial market stress) as an economic variable. The weekly benchmark index values are used in the analysis, spanning from the year 2004 to 2013. The results report the existence of time-varying transition probabilities with respect to the Brazilian and Indian markets only and fixed transition probabilities for the other countries undertaken. The Markov results support the existence of two regimes, wherein regime-1 reports a positive risk-return relationship, and regime-2 reports a negative relationship between the risk and return. Ironically, the Chinese equity market is found to be the riskiest but a perfect hedge instrument amongst others, considering its risk-return interactions in both the regimes. Furthermore, a lower level of financial stress in the US financial market is associated with a higher probability of remaining in the "Bullish" regime-1 in the Indian market as well as Brazilian market. Moreover, there is a positive co-movement between the US financial stress and the expected time-varying duration of remaining in the "Bearish" regime. This shows that due to the growing interdependence among the worldwide economies, a financial stress in one economy does have an impact on the other markets and risk-return relationship in their equity markets. An understanding of the risk-return dynamics coupled with the impact of exogenous variables is an imperative task that a portfolio manager must undertake so as to justify and manage the investments made in the equity markets.

Smith, S. (2021). "International Stock Return Predictability and Asset Pricing Models." In: *SSRN e-Print*.
We propose a new methodology for predicting international stock returns and evaluating international asset pricing models. Our Bayesian framework performs probabilistic selection of predictors and factors that can shift at multiple unknown structural break dates. The approach generates significantly more accurate forecasts of international stock returns than a range of popular models that are economically meaningful for a risk-averse mean-variance investor. Allowing for regime-specific variable selection reduces considerably the international diversification of an unhedged U.S. investor's portfolio. Our framework improves the ability of international asset pricing models to explain the cross-section of expected returns.

Smith, S. C., Bulkley, G., and Leslie, D. S. (2020). "Equity Premium Forecasts with an Unknown Number of Structural Breaks." In: *Journal of Financial Econometrics* 18(1), pp. 59–94.
Estimation of models with structural breaks usually assumes a pre-specified number of breaks. Previous models which do allow an endogenously determined number of breaks require a simple structural model, and rarely

allow for information transfer across the break. We introduce a methodology that allows the number of breaks to be determined endogenously and including an economically motivated model of transition regimes between each break. We demonstrate the usefulness of our approach for forecasts of the equity premium. We find the demonstrated success of the historical average can be improved upon by an economic model with theory informed priors estimated using our methodology.

Smith, S. C. and Timmermann, A. (2021). "Break Risk." In: *The Review of Financial Studies* 34(4), pp. 2045–2100.
We develop a new approach to modeling and predicting stock returns in the presence of breaks that simultaneously affect a large cross-section of stocks. Exploiting information in the cross-section enables us to detect breaks in return prediction models with little delay and to generate out-of-sample return forecasts that are significantly more accurate than those from existing approaches. To identify the economic sources of breaks, we explore the asset pricing restrictions implied by a present value model which links breaks in return predictability to breaks in the cash flow growth and discount rate processes.

Smug, D., Ashwin, P., and Sornette, D. (2017). "Predicting Financial Market Crashes Using Ghost Singularities." In: *SSRN e-Print*.
We analyse the behaviour of a non-linear model of coupled stock and bond prices exhibiting periodically collapsing bubbles. By using the formalism of dynamical system theory, we explain what drives the bubbles and how foreshocks or aftershocks are generated. A dynamical phase space representation of that system coupled with standard multiplicative noise rationalises the log-periodic power law singularity pattern documented in many historical financial bubbles. The notion of 'ghosts of finite-time singularities' is introduced and used to estimate the end of an evolving bubble, using finite-time singularities of an approximate normal form near the bifurcation point. We test the forecasting skill of this method on different stochastic price realisations and compare with Monte Carlo simulations of the full system. Remarkably, the former is significantly more precise and less biased. Moreover, the method of ghosts of singularities is less sensitive to the noise realisation, thus providing more robust forecasts.

Sornette, D. (2014). "Dragon-kings and Predictions: Diagnostics and Forecasts for the World Financial Crisis." In: *SSRN e-Print*.
We develop the concept of "dragon-kings" corresponding to meaningful outliers, which are found to coexist with power laws in the distributions of event sizes under a broad range of conditions in a large variety of systems. These dragon-kings reveal the existence of mechanisms of self-organization that are not apparent otherwise from the distribution of their smaller siblings. We present a generic phase diagram to explain the generation of dragon-kings and document their presence in six different examples (distribution of city sizes, distribution of acoustic emissions associated with material failure, distribution of velocity increments in hydrodynamic turbulence, distribution of financial drawdowns, distribution of the energies of epileptic seizures in humans and in model animals, distribution of the earthquake energies). We emphasize the importance of understanding dragon-kings as being often associated with a neighborhood of what can be called equivalently a phase transition, a bifurcation, a catastrophe (in the sense of Rene Thom), or a tipping point. The presence of a phase transition is crucial to learn how to diagnose in advance the symptoms associated with a coming dragon-king. Several examples of predictions using the derived log-periodic power law method are discussed, including material failure predictions and the forecasts of the end of financial bubbles.

Sornette, D., Andraszewicz, S., Murphy, R. O., Rindler, P. B., and Sanadgol, D. (2016). "Resolving Persistent Uncertainty by Self-Organized Consensus to Mitigate Market Bubbles." In: *SSRN e-Print*.
We propose a new paradigm to study coordination in complex social systems, such as financial markets, that accounts for fundamental uncertainty. This new context has features from prediction markets that have been shown previously to mitigate price bubbles in classical asset market experiments. Our setup is more realistic as it offers multiple securities that are continuously traded over days and, importantly, there is no true underlying price. Nonetheless, the market is designed such that its rationality can be evaluated. Quick consensus emerges early yielding pronounced market bubbles. The overpricing diminishes over time, indicating learning, but does not disappear completely. Traders' price estimates become progressively more independent via a collective realization of communal ignorance, pushing the market much closer to rationality, with forecasts that are close to the realized outcomes.

Sornette, D. and Cauwels, P. (2014). "Financial bubbles: mechanisms and diagnostics." In: *arXiv e-Print*.
We define a financial bubble as a period of unsustainable growth, when the price of an asset increases ever more quickly, in a series of accelerating phases of corrections and rebounds. More technically, during a bubble phase, the price follows a faster-than-exponential power law growth process, often accompanied by log-periodic oscillations.

This dynamic ends abruptly in a change of regime that may be a crash or a substantial correction. Because they leave such specific traces, bubbles may be recognised in advance, that is, before they burst. In this paper, we will explain the mechanism behind financial bubbles in an intuitive way. We will show how the log-periodic power law emerges spontaneously from the complex system that financial markets are, as a consequence of feedback mechanisms, hierarchical structure and specific trading dynamics and investment styles. We argue that the risk of a major correction, or even a crash, becomes substantial when a bubble develops towards maturity, and that it is therefore very important to find evidence of bubbles and to follow their development from as early a stage as possible. The tools that are explained in this paper actually serve that purpose. They are at the core of the Financial Crisis Observatory at the ETH Zurich, where tens of thousands of assets are monitored on a daily basis. This allow us to have a continuous overview of emerging bubbles in the global financial markets. The companion report available as part of the Notenstein white paper series (2014) with the title "Financial bubbles: mechanism, diagnostic and state of the World (Feb. 2014)" presents a practical application of the methodology outlines in this article and describes our view of the status concerning positive and negative bubbles in the financial markets, as of the end of January 2014.

Sornette, D., Cauwels, P., and Smilyanov, G. (2017). "Can We Use Volatility to Diagnose Financial Bubbles? Lessons from 40 Historical Bubbles." In: *SSRN e-Print*.

We inspect the price volatility before, during, and after financial asset bubbles in order to uncover possible commonalities and check empirically whether volatility might be used as an indicator or an early warning signal of an unsustainable price increase and the associated crash. Some researchers and finance practitioners believe that historical and/or implied volatility increase before a crash, but we do not see this as a consistent behavior. We examine forty well-known bubbles and, using creative graphical representations to capture robustly the transient dynamics of the volatility, find that the dynamics of the volatility would not have been a useful predictor of the subsequent crashes. In approximately two-third of the studied bubbles, the crash follows a period of lower volatility, reminiscent of the idiom of a "lull before the storm". This paradoxical behavior, from the lenses of traditional asset pricing models, further questions the general relationship between risk and return.

Sornette, D., Demos, G., Zhang, Q., Cauwels, P., Filimonov, V., and Zhang, Q. (2015). "Real-time prediction and post-mortem analysis of the Shanghai 2015 stock market bubble and crash." In: *Journal of Investment Strategies* 4(4).

The authors assess the performance of the real-time diagnostic, available to the public on the website of the Financial Crisis Observatory (FCO) at ETH Zurich, of the bubble regime that began developing in Chinese stock markets in mid-2014 and started to burst in June 2015. The analysis is based on (i) the economic theory of rational expectation bubbles; (ii) the behavioral mechanisms of imitation and the herding of investors and traders; (iii) the mathematical formulation of the log-periodic power lawsingularity (LPPLS), which describes the critical approach toward a tipping point in complex systems. The authors document how the real-time predictions were presented in the automated analysis of the FCO, as well as in their FCO Cockpit report of June 2015. A complementary post-mortem analysis of the nature and value of the LPPLS methodology in diagnosing the Shanghai Composite Index bubble and its termination is also given.

SSgA Research (2015). *Optimizing asset allocations to market regimes*. Tech. rep. State Street Global Advisors.

One of the greatest challenges investors face is finding an investment strategy that provides competitive returns while reducing downside risk in both stable and changing market environments. The past two decades have shown the limitations of traditional, static portfolio approaches and the weakness of diversification alone as a loss protection strategy. Many investors found that their supposedly diversified portfolios had correlations that moved to one in times of crisis and fell in lockstep. On the other hand, excessive caution over asset allocation in more favorable markets may well equate to less upside participation, also leading to a less than optimal return. But what if a strategy could help reduce a portfolio's risk exposure before a downside event took place? What if a strategy could continually and dynamically re-allocate assets for optimal returns? Is there a reliable way of determining safer market conditions in which it makes more sense to invest more heavily in aggressive assets, providing optimized growth? We think there is. Look Forward, Not Backward We've found that recent crises have caused many investors to ask what they could have done differently and to consider if there were signals, triggers or data points that may have foreshadowed the chaos that followed. They're looking to avoid damaging downsides but also to time increasing their market participation at the most favorable times. We recognized that retro-fitting signals from previous crises and opportunities may not mean that we will spot the next ones. So, we set out to build a framework that had effective signaling power across a number of prior events, while also recognizing the need to continually adjust its influences over time. Our goal was to develop and design a market-

aware framework and dynamic investment process that would give us a systematic approach for identifying market environments and which used forward-looking factors to indicate which type of environment the market was moving into.

Stillwagon, J. and Sullivan, P. (2020). "Markov switching in exchange rate models: will more regimes help?" In: *Empirical Economics*, pp. 413–436.
This paper examines the performance of Markov switching models of the exchange rate using a data-driven approach to determine the number of regimes rather than simply assuming two states. The analysis is conducted for the British pound, Canadian dollar, and Japanese yen exchange rates against the US dollar over the last 30 years with alternative specifications including a simple segmented trends model and Markov switching autoregressive models with monetary fundamentals. A noteworthy finding is that the number of regimes that minimizes mean square forecast errors tends to correspond to the number of regimes selected by Bayesian information criteria (but not Markov-switching-specific information criteria). For the monetary models, the number of regimes that minimizes forecast errors also tends to correspond to the most parsimonious model with well-behaved residuals. Although allowing for more regimes yields forecasting improvement over single- or two-regime models, the Markov switching model is still unable to outperform a random walk. This suggests that exchange rate models need to allow for novel, as opposed to repetitive or predetermined, structural change.

Sueppel, R. (2021). *Classifying market regimes*. Tech. rep. Systematic Risk and Systematic Value.
Market regimes are clusters of persistent market conditions. They affect the relevance of investment factors and the success of trading strategies. The practical challenge is to detect market regime changes quickly and to backtest methods that may do the job. Machine learning offers a range of approaches to that end. Recent proposals include [1] supervised ensemble learning with random forests, which relate the market state to values of regime-relevant time series, [2] unsupervised learning with Gaussian mixture models, which fit various distinct Gaussian distributions to capture states of the data, [3] unsupervised learning with hidden Markov models, which relate observable market data, such as volatility, to latent state vectors, and [4] unsupervised learning with Wasserstein k-means clustering, which classifies market regimes based on the distance of observed points in a metric space.

Tachibana, M. (2020). "Flight-to-quality in the stock-bond return relation: a regime-switching copula approach." In: *Financial Markets and Portfolio Management* 34, pp. 429–470.
This paper examines the existence, intensity and international dependence of flight-to-quality from stocks to government bonds. To this end, we develop a two-state regime-switching bivariate copula model and apply it to the domestic and cross-country stock-bond return pairs of six developed countries (France, Germany, Japan, Switzerland, the UK and the US) over the period 1999-2019. We find that US and UK government bonds have played a primary role of safe-haven assets during stock market downturns. The remaining government bond markets show the evidence of flight-to-quality, but its intensity is relatively weak. Further, we find that although flight-to-quality tends to occur simultaneously in multiple countries, the frequency of the joint occurrence varies across government bond markets.

Tajeuna, E. G., Bouguessa, M., and Wang, S. (2022). "Modeling Regime Shifts in Multiple Time Series." In: *arXiv e-Print*.
We investigate the problem of discovering and modeling regime shifts in an ecosystem comprising multiple time series known as co-evolving time series. Regime shifts refer to the changing behaviors exhibited by series at different time intervals. Learning these changing behaviors is a key step toward time series forecasting. While advances have been made, existing methods suffer from one or more of the following shortcomings: (1) failure to take relationships between time series into consideration for discovering regimes in multiple time series; (2) lack of an effective approach that models time-dependent behaviors exhibited by series; (3) difficulties in handling data discontinuities which may be informative. Most of the existing methods are unable to handle all of these three issues in a unified framework. This, therefore, motivates our effort to devise a principled approach for modeling interactions and time-dependency in co-evolving time series. Specifically, we model an ecosystem of multiple time series by summarizing the heavy ensemble of time series into a lighter and more meaningful structure called a *mapping grid*. By using the mapping grid, our model first learns time series behavioral dependencies through a dynamic network representation, then learns the regime transition mechanism via a full time-dependent Cox regression model. The originality of our approach lies in modeling interactions between time series in regime identification and in modeling time-dependent regime transition probabilities, usually assumed to be static in existing work.

Tran, B.-H., Rossi, S., Milios, D., Michiardi, P., Bonilla, E. V., and Filippone, M. (2021). "Model Selection for Bayesian Autoencoders." In: *arXiv e-Print*.
We develop a novel method for carrying out model selection for Bayesian autoencoders (BAEs) by means of prior hyper-parameter optimization. Inspired by the common practice of type-II maximum likelihood optimization and its equivalence to Kullback-Leibler divergence minimization, we propose to optimize the distributional sliced-Wasserstein distance (DSWD) between the output of the autoencoder and the empirical data distribution. The advantages of this formulation are that we can estimate the DSWD based on samples and handle high-dimensional problems. We carry out posterior estimation of the BAE parameters via stochastic gradient Hamiltonian Monte Carlo and turn our BAE into a generative model by fitting a flexible Dirichlet mixture model in the latent space. Consequently, we obtain a powerful alternative to variational autoencoders, which are the preferred choice in modern applications of autoencoders for representation learning with uncertainty. We evaluate our approach qualitatively and quantitatively using a vast experimental campaign on a number of unsupervised learning tasks and show that, in small-data regimes where priors matter, our approach provides state-of-the-art results, outperforming multiple competitive baselines.

Tu, J. (2010). "Is Regime Switching in Stock Returns Important in Portfolio Decisions?" In: *Management Science* 56, pp. 1198–1215.
The stock market displays regime switching between upturns and downturns. This paper provides a Bayesian framework for making portfolio decisions that takes this regime switching into account, together with asset pricing model uncertainty and parameter uncertainty. The findings reveal that the economic value of accounting for regimes is substantially independent of whether or not model and parameter uncertainties are incorporated: the certainty-equivalent losses associated with ignoring regime switching are generally above 2 percent per year, and can be as high as 10 percent. These results suggest that the more realistic regime switching model is fundamentally different from the commonly used single-state model, and hence should be employed instead in portfolio decisions irrespective of concerns about model or parameter uncertainty.

Uysal, A. S. and Mulvey, J. M. (2021). "A Machine Learning Approach in Regime-Switching Risk Parity Portfolios." In: *The Journal of Financial Data Science* 3(2), pp. 87–108.
The authors present a machine learning approach to regime-based asset allocation. The framework consists of two primary components: (1) regime modeling and prediction and (2) identifying a regime-based strategy to enhance the performance of a risk parity portfolio. For the former, they apply supervised learning algorithms, including the random forest, based on a large macroeconomic database to estimate the probability of an upcoming recession or a stock market contraction. Out-of-sample tests show the reliability of these predictions, especially for recessions in the United States, over the period 1973 to 2020. The probability estimates are linked to a dynamic investment overlay strategy. The combined approach improves risk-adjusted returns by a substantial amount over nominal risk parity in two-asset and multi-asset test cases, even during rising interest rates in the late 1970s.

Uysal, S. (2021). "Risk Budgeting Portfolios Under a Modern Optimization and Machine Learning Lens." PhD thesis. Princeton University.
The mean-variance optimization framework has been the traditional approach to decide portfolio allocations based on return-risk trade-offs. However, it faces practical drawbacks, including sensitivity to estimated input parameters and concentration of portfolio risk. Risk budgeting portfolio optimization is a popular risk-based asset allocation technique where risk budgets are assigned to each assets' risk contribution, and equalizing all risk budgets in the portfolio is known as risk parity strategy. Unlike mean-variance, the risk parity strategy provides a balanced risk concentration in the portfolio and does not require expected asset return estimates as input. However, its performance can depend on the selected asset universe. Furthermore, its mathematical formulation imposes some computational challenges due to the non-convex structure. In this thesis, the risk budgeting problem is studied with modern optimization and machine learning approaches to enhance the portfolio model and address the aforementioned challenges. The second chapter introduces regime-switching risk parity portfolios with two primary components: regime modeling and prediction with supervised learning methods and identifying a regime-based strategy to improve the performance of a nominal risk parity portfolio. In the third chapter, we formulate a multi-period risk parity portfolio optimization problem in a transaction cost environment with a model predictive control approach. We provide a successive convex program algorithm that provides faster and more robust solutions. Lastly, we present an end-to-end portfolio allocation method by embedding the risk budget optimization problem as an implicit layer in a neural network. This approach combines prediction and optimization tasks in a single decision-making pipeline and constructs dynamic risk budgeting portfolios.

Furthermore, we introduce a novel asset selection property with stochastic gates that protects the risk budgeting portfolio against the unprofitable assets.

van den Burg, G. J. J. and Williams, C. K. I. (2022). "An Evaluation of Change Point Detection Algorithms." In: *arXiv e-Print*.

Change point detection is an important part of time series analysis, as the presence of a change point indicates an abrupt and significant change in the data generating process. While many algorithms for change point detection exist, little attention has been paid to evaluating their performance on real-world time series. Algorithms are typically evaluated on simulated data and a small number of commonly-used series with unreliable ground truth. Clearly this does not provide sufficient insight into the comparative performance of these algorithms. Therefore, instead of developing yet another change point detection method, we consider it vastly more important to properly evaluate existing algorithms on real-world data. To achieve this, we present the first data set specifically designed for the evaluation of change point detection algorithms, consisting of 37 time series from various domains. Each time series was annotated by five expert human annotators to provide ground truth on the presence and location of change points. We analyze the consistency of the human annotators, and describe evaluation metrics that can be used to measure algorithm performance in the presence of multiple ground truth annotations. Subsequently, we present a benchmark study where 14 existing algorithms are evaluated on each of the time series in the data set. This study shows that binary segmentation (Scott and Knott, 1974) and Bayesian online change point detection (Adams and MacKay, 2007) are among the best performing methods. Our aim is that this data set will serve as a proving ground in the development of novel change point detection algorithms.

van Vliet, P. and Blitz, D. (2011). "Dynamic strategic asset allocation: Risk and return across the business cycle." In: *Journal of Asset Management* 12(5), pp. 360–375.

We propose a practical investment framework for dynamic asset allocation across different phases in the business cycle, which we illustrate using a sample of US data from 1948 to 2007. We identify four phases in the business cycle and find that these capture pronounced time variation in the risk and return properties of asset classes. Time variation is also observed in the risk of a traditional, static strategic asset mix. In order to stabilize risk across the business cycle, we propose a dynamic strategic asset allocation approach, which has the potential to enhance expected return as well. The proposed investment framework is found to be robust to variations in the variable composition of the business cycle indicator and can easily be extended with different economic variables and/or additional assets.

Viebig, J. (2020). "Exuberance in Financial Markets: Evidence from Machine Learning Algorithms." In: *Journal of Behavioral Finance* 21(2), pp. 128–135.

Motivated by Campbell and Shiller (1998), we show that the probability that abnormally low returns over long-term investment horizons occur in the future is disproportionately high when equity markets trade at extremely high valuation levels. Support vector machines are able to learn patterns from fundamental data with high precision rates. Decision boundaries calculated with machine learning algorithms can help investors to detect irrational exuberance in financial markets followed by abnormally low returns.

Vo, H. T. and Maurer, R. (2013). "Dynamic Asset Allocation under Regime Switching, Predictability and Parameter Uncertainty." In: *SSRN e-Print*.

This paper solves the dynamic asset allocation problem under stock return predictability based on the dividend price ratio with regime shifts and parameter uncertainty in a fully Bayesian framework. Intertemporal hedging demands are simultaneously induced by predictability, regime shifts, parameter uncertainty, and learning about the regimes. Optimal policies display non-monotonic horizon effects whereby regime shifts tend to induce negative hedge demands in the short-run, while predictability induces positive hedge demands in the long-run. The economic costs of ignoring regime switching and predictability are high even in the light of regime and parameter uncertainty.

Wang, J., Ma, F., Liang, C., and Chen, Z. (2022). "Volatility forecasting revisited using Markov-switching with time-varying probability transition." In: *International Journal of Finance & Economics*.

This study proposes a novel model, Markov-switching Heterogeneous Autoregressive (MS-HAR) model with jump-driven time-varying transition probabilities (TVTP), to forecast the future volatility in Chinese stock market. The in-sample results show that MS-HAR models are more powerful than HAR-RV-type models; furthermore, the high-volatility regime is short-lived. Moreover, the out-of-sample results indicate that the MS-HAR with TVTP model can achieve a superior forecasting performance and increase the economic value than the competing models including the simple HAR model and the MS-HAR with fixed transition probabilities (FTP)

model. The results are robust to several robustness checks including alternative forecast window, alternative evaluation method, alternative predictive model, sub-sample analysis and alternative representative index.

Wang, P. and Zong, L. (2020). "Are Crises Predictable? A Review of the Early Warning Systems in Currency and Stock Markets." In: *arXiv e-Print*.

The study efforts to explore and extend the crisis predictability by synthetically reviewing and comparing a full mixture of early warning models into two constitutions: crisis identifications and predictive models. Given empirical results on Chinese currency and stock markets, three-strata findings are concluded as (i) the SWARCH model conditional on an elastic thresholding methodology can most accurately classify crisis observations and greatly contribute to boosting the predicting precision, (ii) stylized machine learning models are preferred given higher precision in predicting and greater benefit in practicing, (iii) leading factors sign the crisis in a diversified way for different types of markets and varied prediction periods.

Wang, R., Nie, K., Chang, Y.-J., Gong, X., Wang, T., Yang, Y., and Long, B. (2020). "Deep Learning for Anomaly Detection." In: *Proceedings of the 26th ACM SIGKDD International Conference on Knowledge Discovery & Data Mining*. ACM.

Anomaly detection has been widely studied and used in diverse applications. Building an effective anomaly detection system requires researchers and developers to learn complex structure from noisy data, identify dynamic anomaly patterns, and detect anomalies with limited labels. Recent advancements in deep learning techniques have greatly improved anomaly detection performance, in comparison with classical approaches, and have extended anomaly detection to a wide variety of applications. This tutorial will help the audience gain a comprehensive understanding of deep learning based anomaly detection techniques in various application domains. First, we give an overview of the anomaly detection problem, introducing the approaches taken before the deep model era and listing out the challenges they faced. Then we survey the state-of-the-art deep learning models that range from building block neural network structures such as MLP, CNN, and LSTM, to more complex structures such as autoencoder, generative models (VAE, GAN, Flow-based models), to deep one-class detection models, etc. In addition, we illustrate how techniques such as transfer learning and reinforcement learning can help amend the label sparsity issue in anomaly detection problems and how to collect and make the best use of user labels in practice. Second to last, we discuss real world use cases coming from and outside LinkedIn. The tutorial concludes with a discussion of future trends.

Wang, X. and Hsieh, F. (2021). "Unraveling S&P500 stock volatility and networks – An encoding-and-decoding approach." In: *arXiv e-Print*.

Volatility of financial stock is referring to the degree of uncertainty or risk embedded within a stock's dynamics. Such risk has been received huge amounts of attention from diverse financial researchers. By following the concept of regime-switching model, we proposed a non-parametric approach, named encoding-and-decoding, to discover multiple volatility states embedded within a discrete time series of stock returns. The encoding is performed across the entire span of temporal time points for relatively extreme events with respect to a chosen quantile-based threshold. As such the return time series is transformed into Bernoulli-variable processes. In the decoding phase, we computationally seek for locations of change points via estimations based on a new searching algorithm in conjunction with the information criterion applied on the observed collection of recurrence times upon the binary process. Besides the independence required for building the Geometric distributional likelihood function, the proposed approach can functionally partition the entire return time series into a collection of homogeneous segments without any assumptions of dynamic structure and underlying distributions. In the numerical experiments, our approach is found favorably compared with parametric models like Hidden Markov Model. In the real data applications, we introduce the application of our approach in forecasting stock returns. Finally, volatility dynamic of every single stock of S&P500 is revealed, and a stock network is consequently established to represent dependency relations derived through concurrent volatility states among S&P500.

Wehrli, A. and Sornette, D. (2022). "Classification of flash crashes using the Hawkes(p,q) framework." In: *Quantitative Finance* 22(2), pp. 213–240.

We introduce a novel modeling framework-the Hawkes(p,q) process-which allows us to parsimoniously disentangle and quantify the time-varying share of high frequency financial price changes that are due to endogenous feedback processes and not exogenous impulses. We show how both flexible exogenous arrival intensities, as well as a time-dependent feedback parameter can be estimated in a structural manner using an Expectation Maximization algorithm. We use this approach to investigate potential characteristic signatures of anomalous market regimes in the vicinity of 'flash crashes'-events where prices exhibit highly irregular and cascading dynamics. Our study covers some of the most liquid electronic financial markets, in particular equity and bond futures, foreign

exchange and cryptocurrencies. Systematically balancing the degrees of freedom of both exogenously driving processes and endogenous feedback variation using information criteria, we show that the dynamics around such events are not universal, highlighting the usefulness of our approach: (i) post-mortem, for developing remedies and better future processes-e.g. improving circuit breakers or latency floor designs-and potentially (ii) ex-ante, for short-term forecasts in the case of endogenously driven events. Finally, we test our proposed model against a process with refined treatment of exogenous clustering dynamics in the spirit of the recently proposed autoregressive moving-average (ARMA) point process.

Werge, N. (2021). "Predicting Risk-adjusted Returns using an Asset Independent Regime-switching Model." In: *arXiv e-Print*.
Financial markets tend to switch between various market regimes over time, making stationarity-based models unsustainable. We construct a regime-switching model independent of asset classes for risk-adjusted return predictions based on hidden Markov models. This framework can distinguish between market regimes in a wide range of financial markets such as the commodity, currency, stock, and fixed income market. The proposed method employs sticky features that directly affect the regime stickiness and thereby changing turnover levels. An investigation of our metric for risk-adjusted return predictions is conducted by analyzing daily financial market changes for almost twenty years. Empirical demonstrations of out-of-sample observations obtain an accurate detection of bull, bear, and high volatility periods, improving risk-adjusted returns while keeping a preferable turnover level.

Wheatley, S., Sornette, D., Huber, T., Reppen, M., and Gantner, R. N. (2018). "Are bitcoin bubbles predictable? combining a generalized metcalfe's law and the LPPLS model." In: *SSRN e-Print*.
We develop a strong diagnostic for bubbles and crashes in bitcoin, by analyzing the coincidence (and its absence) of fundamental and technical indicators. Using a generalized Metcalfe's law based on network properties, a fundamental value is quantified and shown to be heavily exceeded, on at least four occasions, by bubbles that grow and burst. In these bubbles, we detect a universal super-exponential unsustainable growth. We model this universal pattern with the Log-Periodic Power Law Singularity (LPPLS) model, which parsimoniously captures diverse positive feedback phenomena, such as herding and imitation. The LPPLS model is shown to provide an ex-ante warning of market instabilities, quantifying a high crash hazard and probabilistic bracket of the crash time consistent with the actual corrections; although, as always, the precise time and trigger (which straw breaks the camel's back) being exogenous and unpredictable. Looking forward, our analysis identifies a substantial but not unprecedented overvaluation in the price of bitcoin, suggesting many months of volatile sideways bitcoin prices ahead (from the time of writing, March 2018).

Wolchover, N. (2018). "Machine Learning's 'Amazing' Ability to Predict Chaos." In: *Quanta Magazine*.
In new computer experiments, artificial-intelligence algorithms can tell the future of chaotic systems. Researchers have used machine learning to predict the chaotic evolution of a model flame front.

Wood, K., Giegerich, S., Roberts, S., and Zohren, S. (2022). "Trading with the Momentum Transformer: An Intelligent and Interpretable Architecture." In: *arXiv e-Print*.
We introduce the Momentum Transformer, an attention-based deep learning architecture which outperforms benchmark momentum and mean-reversion trading strategies. Unlike state-of-the-art Long Short-Term Memory (LSTM) architectures, which are sequential in nature, the attention mechanism provides our architecture with a direct connection to all previous time-steps. Our architecture enables us to learn longer-term dependencies, improves performance when considering returns net of transaction costs and naturally adapts to new market regimes, such as during the SARS-CoV-2 crisis. The Momentum Transformer is inherently interpretable, providing us with greater insights into our deep learning momentum trading strategy, including how it blends different classical strategies and the past time-steps which are of the greatest significance to the model.

Wu, R. and Keogh, E. J. (2021). "Current Time Series Anomaly Detection Benchmarks are Flawed and are Creating the Illusion of Progress." In: *arXiv e-Print*.
Time series anomaly detection has been a perennially important topic in data science, with papers dating back to the 1950s. However, in recent years there has been an explosion of interest in this topic, much of it driven by the success of deep learning in other domains and for other time series tasks. Most of these papers test on one or more of a handful of popular benchmark datasets, created by Yahoo, Numenta, NASA, etc. In this work we make a surprising claim. The majority of the individual exemplars in these datasets suffer from one or more of four flaws. Because of these four flaws, we believe that many published comparisons of anomaly detection algorithms may be unreliable, and more importantly, much of the apparent progress in recent years may be illusionary. In addition to demonstrating these claims, with this paper we introduce the UCR Time Series Anomaly Datasets.

We believe that this resource will perform a similar role as the UCR Time Series Classification Archive, by providing the community with a benchmark that allows meaningful comparisons between approaches and a meaningful gauge of overall progress.

Wu, Y. (2020). "On the Predictive Performance of the Stock Returns by Using the Markov-Switching Models." MA thesis. University of Uppsala.
This paper proposes the basic predictive regression and Markov Regime-Switching regression to predict the excess stock returns in both US and Sweden stock markets. The analysis shows that the Markov Regime-Switching regression models out perform the linear ones in out-of-sample forecasting, which is due to the fact that the regime-switching models capture the economic expansion and recession better.

Yan, C. and Huang, K. X. D. (2020). "Financial cycle and business cycle: An empirical analysis based on the data from the U.S." In: *Economic Modelling* 93, pp. 693–701.
In this paper, we first study the relationship between the financial cycle and the business cycle in the time and frequency domain. Then we also explore the interactions and dynamic mechanisms of the financial cycle, the business cycle, real interest rate and exchange rate by the VAR model. The empirical results show that the financial cycle is closely related to the business cycle, especially at medium-term frequencies (8-30 years), the business cycle leads the financial cycle with a high positive correlation. However, the relationship between them is not significant during the Great Moderation at business-cycle (2-4 years). In addition, the financial cycle not only becomes a main driver of real interest rate, the financial cycle and the business cycle, but also serves as an important source of the business cycle fluctuations. In general, our results lay some theoretical foundation for the policy practice of financial and economic stability.

Yao, C.-Z. and Li, H.-Y. (2021). "A study on the bursting point of Bitcoin based on the BSADF and LPPLS methods." In: *The North American Journal of Economics and Finance* (101280).
We aim to reveal the characteristics and mechanism of the Bitcoin bubble in 2019. First, we identify the period during which two important Bitcoin bubbles occurred based on the generalized supremum augmented Dickey-Fuller (GSADF) method. There are two significant bubble cycles. The first bubble lasted approximately 26 days from November 25, 2017, to December 21, 2017, while the second bubble lasted approximately one week from June 22 to June 29, 2019. The occurrence of the first bubble was related to the considerable expansion of initial coin offerings (ICOs) in 2017, while the formation of the second bubble was affected by the release of Libra. Second, as the GSADF method cannot be used to accurately infer the time at which a bubble bursts, we employ the log-periodic power law singularity (LPPLS) model for this purpose. We verify that the LPPLS method can not only infer the timing of a bubble burst but also shows stable results. Finally, we demonstrate the implications of the 2019 bubble. During the 2019 bubble, due to the increased supervision of European and American governments and the impact of hedging assets, the bubble's duration was shorter, and the positive feedback mechanism was not as strong as that of the 2017 bubble. In addition, the oscillating frequency of the bubble in 2019 was low and unstable, which means that it would be more beneficial for investors to hold the currency for a long time.

Zakamulin, V. (2020). "Not All Bull and Bear Markets Are Alike: Insights From a Five-State Hidden Semi-Markov Model." In: *SSRN e-Print*.
This paper employs the hidden semi-Markov model and a novel model selection procedure to detect different states in the US stock market. The empirical results suggest that the market is switching between five states that can be classified into three bull states and two bear states. The three bull states are categorized as a low volatility bull market, a high volatility bull market, and a stock market bubble. One of the bear states represents a regular bear market, while the other one corresponds to either a stock market crash or a market correction. The paper demonstrates that the five-state model is consistent with a number of stylized facts and provides many valuable insights into the dynamics of the US stock market. Besides, the five-state model has clear implications for the success of some active strategies that aim to enhance returns and reduce losses.

Zaremba, A., Czapkiewicz, A., and Kambouris, G. D. (2020). "A Tale of Two States: An Application of a Markov Switching Model to Anomaly Returns." In: *Eurasian Studies in Business and Economics*. Springer International Publishing, pp. 227–240.
The time-varying profitability of equity anomalies calls for a useful tool to select the winning investment strategies from the loser investment strategies. We offer a new framework for dynamic asset allocation across the anomalies based on a Markov regime switching model. Using a sample of eleven equity anomalies from the US equity market from the years 1963 to 2016 we demonstrate the predictability of their performance. The anomalies forecasted to

be profitable significantly outperform the remaining anomalies by 0.15-0.43% per month. The results are robust to many considerations.

Zhang, Q., Sornette, D., Balcilar, M., Gupta, R., Ozdemir, Z. A., and Yetkiner, H. (2016). "LPPLS bubble indicators over two centuries of the S&P 500 index." In: *Physica A: Statistical Mechanics and its Applications* 458, pp. 126–139.

Novel tests for early causal diagnostic of bubbles in the US S&P 500 index. Large testing period of more than two hundred years. Construction of efficient end-of-bubble signals. Horse-race between LPPLS versus exponential curve fitting and generalized sup ADF test approaches. Detection of eight positive bubbles and two negative bubbles from January 1814 to August 2014. The aim of this paper is to present novel tests for the early causal diagnostic of positive and negative bubbles in the S&P 500 index and the detection of End-of-Bubble signals with their corresponding confidence levels. We use monthly S&P 500 data covering the period from August 1791 to August 2014. This study is the first work in the literature showing the possibility to develop reliable ex-ante diagnostics of the frequent regime shifts over two centuries of data. We show that the DS LPPLS (log-periodic power law singularity) approach successfully diagnoses positive and negative bubbles, constructs efficient End-of-Bubble signals for all of the well-documented bubbles, and obtains for the first time new statistical evidence of bubbles for some other events. We also compare the DS LPPLS method to the exponential curve fitting and the generalized sup ADF test approaches and find that DS LPPLS system is more accurate in identifying well-known bubble events, with significantly smaller numbers of false negatives and false positives.

Zhao, D. and Sornette, D. (2022). "Bubbles for Fama from Sornette." In: *SSRN e-Print*.

Galvanized by the claims of Greenwood et al. in Bubbles for Fama that "a sharp price increase of an industry portfolio does not, on average, predict unusually low returns going forward", and Fama's quote (June, 2016) that "Statistically, people have not come up with ways of identifying bubbles", we present significant evidence to the contrary of both statements. Using a methodology called logperiodic power law singularity (LPPLS), which has been developed by the Sornette group over more than two decades, we show that a LPPLS-based "bubble confidence indicator" allows one to diagnose ex-ante the presence of a bubble. Using superposed epoch analysis, we find an excellent timing performance of price regime shifts, and more so, the larger the bubble confidence indicator. Moreover, we identify two classes of regime shifts following an accelerated price growth qualified by LPPLS: (i) bubbles followed by a large drawdown or crash, and (ii) price catch-up followed by a plateau, associated with the convergence to a stable price level. Indiscriminately mixing these two types of accelerated transient price increases may explain in part previous failures to diagnose bubbles and their aftermath. While the existence of the first class of transient accelerated price increases followed by crashes is a long-standing puzzle, the existence of the second class of transient accelerated price increases followed by a plateau poses a challenge to the efficient market hypothesis, thus constituting a new puzzle: the convergence to a stable price level, while accelerating, is slow, with investors and the market taking weeks to months to digest available information and to progressively converge to the final higher valuation consensus.

Zheng, K., Li, Y., and Xu, W. (2021). "Regime switching model estimation: spectral clustering hidden Markov model." In: *Annals of Operations Research* 303(1-2), pp. 297–319.

We propose a novel method for Markov regime switching (MRS) model estimations by spectral clustering hidden Markov model (SC-HMM). The proposed SC-HMM exploits the Markov property of hidden states and utilizes pairwise feature similarities for latent state identifications. It can be applied to general hidden Markov models (HMMs) with continuous observations. In contrast to the maximum likelihood estimation (MLE), SC-HMM predicts latent states and yields conditional distribution statistics without knowledge of types of conditional distributions. To illustrate, SC-HMM is first applied to a simple HMM with discrete observations. We consider the MRS model estimation with continuous observations to further demonstrate SC-HMM. Specifically, based on local observations, we propose a set of features for the MRS estimation. A similarity matrix is determined from derived features and spectral clustering predicts latent states. Conditional distribution statistics and transitional probabilities are estimated based on identified latent states. By conducting simulation studies on both two-state and three-state MRS estimations, we demonstrate that, in comparison with MLE, the proposed SC-HMM is more robust. Furthermore, we demonstrate the validity of SC-HMM by estimating a two-state MRS from the S&P/TSX Composite Index daily and monthly data from 1977 to 2014.