

Bayesian inference in time-varying parameter models with global-local shrinkage process priors

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Plan for the talk

- Setting the stage: Bayesian inference in state-space models
- Motivation: Time-varying multi-seasonal AR models with dynamic shrinkage process prior
- Challenge: Algorithms for Bayesian inference based on Gaussian approximations
- Slides: <http://mattiasvillani.com/news>
- Paper: [arXiv: 2409.18640](https://arxiv.org/abs/2409.18640) (ARMA extension + paper on near unstable processes soon on arXiv)

Time-varying parameter models

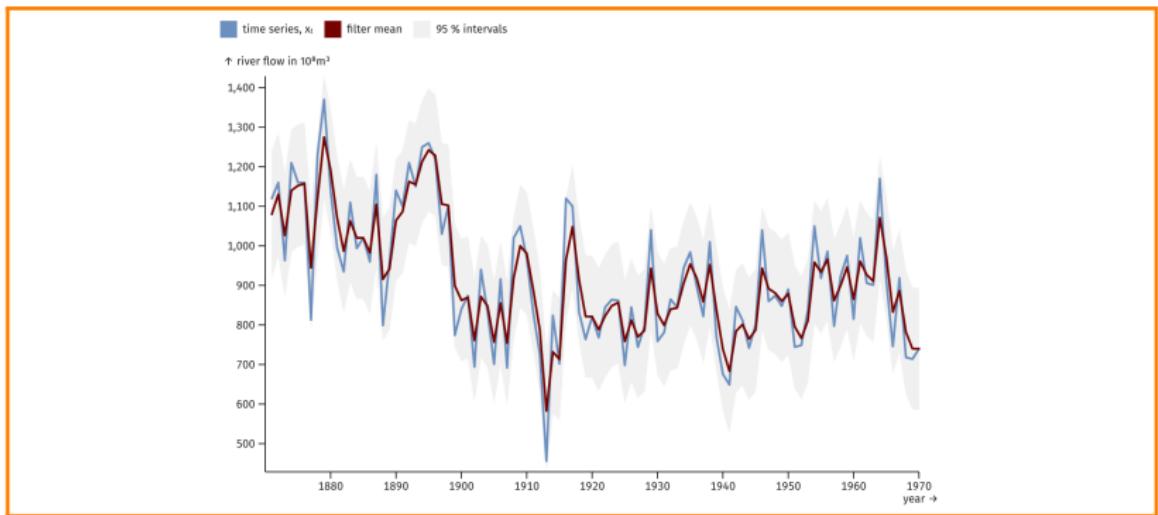
■ Regression with time-varying parameters

Measurement model: $y_t = \mathbf{x}_t^\top \boldsymbol{\beta}_t + \varepsilon_t, \quad \varepsilon_t \stackrel{\text{iid}}{\sim} N(0, \sigma_\varepsilon^2)$

Transition model: $\boldsymbol{\beta}_t = \boldsymbol{\beta}_{t-1} + \boldsymbol{\nu}_t, \quad \boldsymbol{\nu}_t \stackrel{\text{iid}}{\sim} N(\mathbf{0}, \boldsymbol{\Sigma}_\nu)$

- Linear Gaussian **state-space model** with state: $\mathbf{z}_t = \boldsymbol{\beta}_t$
- **Filtering posterior:** $p(\mathbf{z}_t | y_{1:t})$. Instantaneous posterior.
- **Smoothing posterior:** $p(\mathbf{z}_t | y_{1:T})$. Retrospective posterior.
- **Joint smoothing posterior:** $p(\mathbf{z}_{1:T} | y_{1:T})$.

Local level model for the Nile data



Parameter evolutions matter

■ Regression with time-varying parameters

Measurement model: $y_t = \mathbf{x}_t^\top \boldsymbol{\beta}_t + \varepsilon_t, \quad \varepsilon_t \stackrel{\text{iid}}{\sim} N(0, \sigma_\varepsilon^2)$

Transition model: $\boldsymbol{\beta}_t = \boldsymbol{\beta}_{t-1} + \boldsymbol{\nu}_t, \quad \boldsymbol{\nu}_t \stackrel{\text{iid}}{\sim} N(\mathbf{0}, \boldsymbol{\Sigma}_\nu)$

- Homoscedastic Gaussian parameter innovations
 $\boldsymbol{\nu}_t \stackrel{\text{iid}}{\sim} N(\mathbf{0}, \boldsymbol{\Sigma}_\nu)$ often a problem. Over- and under-smoothing.
- Ideal: parameters can stand still, move rapidly and jump. [1]
- **Dynamic global-local priors** is a great step forward. [2, 3, 4]
- ... but can be tricky computationally.

Taxonomy of state-space models

■ Linear Gaussian models

Measurement model: $\mathbf{y}_t = \mathbf{C}\mathbf{z}_t + \boldsymbol{\varepsilon}_t, \quad \boldsymbol{\varepsilon}_t \stackrel{\text{iid}}{\sim} N(\mathbf{0}, \boldsymbol{\Sigma}_{\varepsilon})$

Transition model: $\mathbf{z}_t = \mathbf{A}\mathbf{z}_{t-1} + \boldsymbol{\nu}_t, \quad \boldsymbol{\nu}_t \stackrel{\text{iid}}{\sim} N(\mathbf{0}, \boldsymbol{\Sigma}_{\nu})$

■ Non-linear (additive) Gaussian models

Measurement model: $\mathbf{y}_t = \mathbf{c}(\mathbf{z}_t) + \boldsymbol{\varepsilon}_t, \quad \boldsymbol{\varepsilon}_t \stackrel{\text{iid}}{\sim} N(\mathbf{0}, \boldsymbol{\Sigma}_{\varepsilon})$

Transition model: $\mathbf{z}_t = \mathbf{a}(\mathbf{z}_{t-1}) + \boldsymbol{\nu}_t, \quad \boldsymbol{\nu}_t \stackrel{\text{iid}}{\sim} N(\mathbf{0}, \boldsymbol{\Sigma}_{\nu})$

■ General distribution (non-linear and non-Gaussian) models

Measurement model: $\mathbf{y}_t \sim p(\mathbf{y}_t | \mathbf{z}_t)$

Transition model: $\mathbf{z}_t \sim p(\mathbf{z}_t | \mathbf{z}_{t-1})$

■ Hybrids: nonlinear measurement + linear Gaussian transition.

Common Bayesian computational approaches

- Kalman filtering and **FFBS sampling** for linear Gaussian models. [5, 6]
- **Particle MCMC** and **SMC** [7]
- **Hamiltonian Monte Carlo** (Stan/Turing.jl)
- **Variational approximations** [8]
- **INLA** [9]
- **Gaussian approximations** [10]

Multi-seasonal AR models

- Seasonal AR(p, P) with season s

$$\phi_p(L)\Phi_P(L^s)y_t = \varepsilon_t, \quad \varepsilon_t \stackrel{\text{iid}}{\sim} N(0, \sigma^2)$$

- Seasonal AR can be written as a **non-linear regression**:

$$(1 - \phi_1 L)(1 - \Phi_1 L^s)y_t = (1 - \phi_1 L - \Phi_1 L^s + \phi_1 \Phi_1 L^{1+s})y_t$$

$$y_t = \mathbf{x}_t^\top \tilde{\boldsymbol{\phi}} + \varepsilon_t$$

- ▶ covariates $\mathbf{x}_t = (y_{t-1}, y_{t-s}, y_{t-(1+s)})^\top$ and
- ▶ regression coefficients $\tilde{\boldsymbol{\phi}} = (\phi_1, \Phi_1, \phi_1 \Phi_1)^\top$.

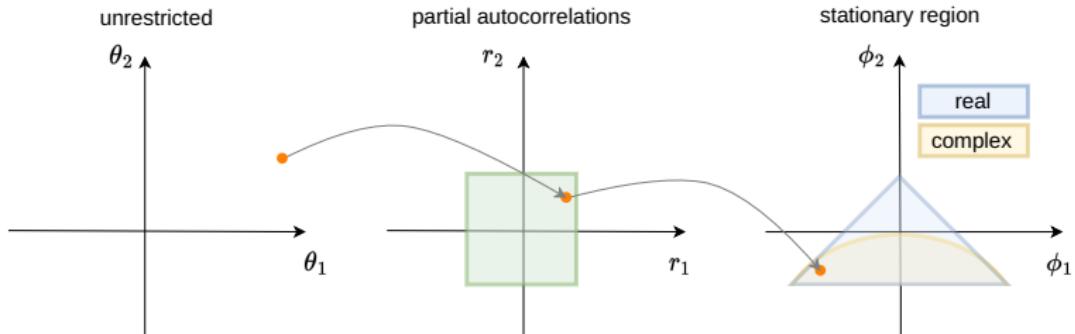
- **Multiple seasonal periods**, e.g. hourly data with daily, weekly and yearly cycles.

- **Multi-seasonal AR** models with M polynomials

$$\prod_{j=1}^M \phi_j(L^{s_j})(y_t - \mu) = \varepsilon_t$$

- Extension to **ARMA**. Exact likelihood. Need to infer the ε_t .

Enforce stability/invertibility in ARMA models



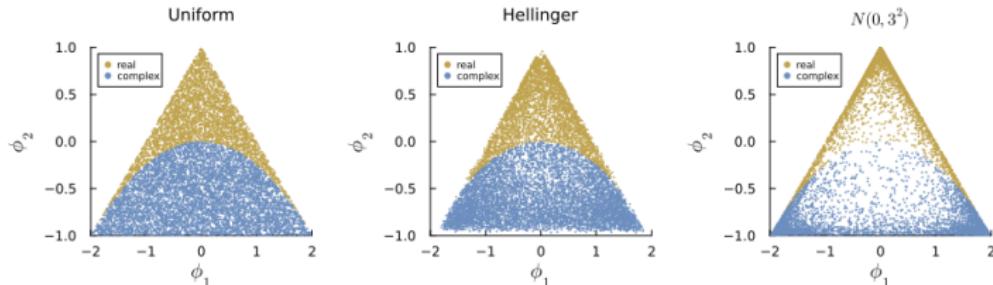
- $\phi = \mathbf{g}(\theta)$ composite map: [11, 12]

unrestricted $\theta \rightarrow$ partial autocorr $r \rightarrow$ stable AR ϕ

- Same parameterization for all polynomial factors.
- For seasonal models $\tilde{\phi}_t = \tilde{\mathbf{g}}(\theta_t)$ is the nonlinear mapping from
 - 1 stability restrictions
 - 2 multiplication of polynomials
- **Invertibility in MA** by the same parameterization.

Uniform distribution over stability region

- Unrestricted parameters θ_k have no interpretation. Priors?
- Uniform distribution over stability region \mathbb{S}_p for ϕ .



- Lemma: If, independently,

$$\theta_k \sim \begin{cases} t(k+1, 0, \frac{1}{\sqrt{k+1}}) & \text{if } k \text{ is odd} \\ t_{\text{skew}}\left(\frac{k}{2}, \frac{k+2}{2}, 0, \frac{1}{\sqrt{k+1}}\right) & \text{if } k \text{ is even,} \end{cases}$$

then $\phi = (\phi_1, \dots, \phi_p)^\top$ is uniformly distributed over \mathbb{S}_p .

Time-varying multi-seasonal AR

■ Time-varying multi-seasonal AR (TVSAR)

$$\prod_{j=1}^M \phi_{jt}(L^{s_j})(y_t - \mu_t) = \varepsilon_t \quad \varepsilon_t \stackrel{\text{iid}}{\sim} N(0, \sigma_t^2)$$

■ Dynamic shrinkage process prior [3] for TVSAR

$$\tilde{\phi}_t = \tilde{\mathbf{g}}(\boldsymbol{\theta}_t)$$

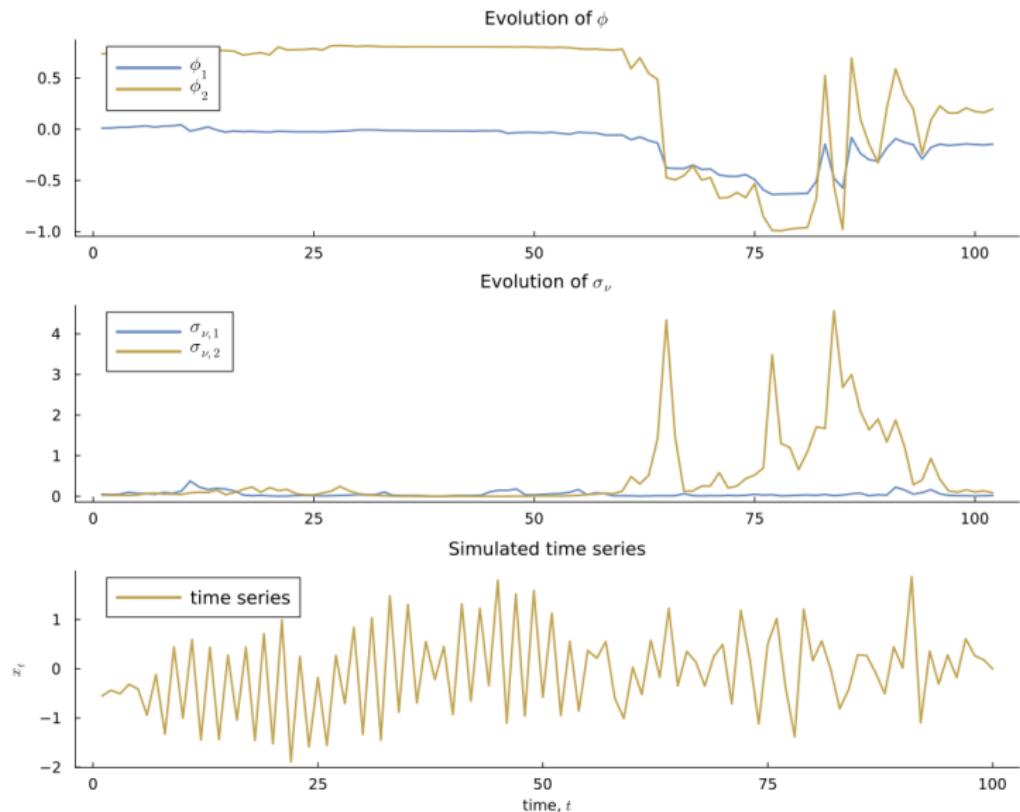
$$\theta_{kt} = \theta_{k,t-1} + \nu_{kt}, \quad \nu_{kt} \stackrel{\text{indep}}{\sim} N(0, \exp(h_{kt}))$$

$$h_{kt} = \mu_k + \kappa_k(h_{k,t-1} - \mu_k) + \eta_{kt}, \quad \eta_{kt} \stackrel{\text{iid}}{\sim} Z(1/2, 1/2, 0, 1)$$

■ Global log-variance μ_k and local log-variance η_{kt} .

- Constant periods, periods of rapid change and jumps.
- Time-series extension of the horseshoe prior [13].

Dynamic shrinkage process priors for TVAR(2)



Bayesian inference for TVSAR

- Aim: posterior conditional on time series $y_{1:T}$

$$p(\theta_{0:T}, \mathbf{h}_{1:T}, \boldsymbol{\mu}, \boldsymbol{\kappa}, \sigma_{1:T} | y_{1:T})$$

- Gibbs sampling by data augmentation:
 - ▶ Mixture of normal for $\log \chi_1^2$ for volatility $\mathbf{h}_{0:T}$ [14]
 - ▶ Polya-Gamma augmentation for Z-distribution. [3]
- Conditional on $\mathbf{h}_{1:T}$, the TVSAR is a state-space model with:
 - ▶ **nonlinear additive Gaussian measurement** model
 - Nonlinearity 1: multiplicative seasonality
 - Nonlinearity 2: stability restrictions
 - ▶ **linear** (heteroscedastic) **Gaussian transition** model

Sampling from conditional posterior for $\theta_{0:T}$

■ Particle Gibbs with Ancestor Sampling (PGAS) [15]

- ▶ simulation consistent
- ▶ slow
- ▶ **particle degeneracy when model is near-degenerate**
(parameters standing still for extended periods).
- ▶ Adding an offset fixes particle degeneracy, but parameters can then no longer stand still. [16]

■ FFBSx - FFBS with extended Kalman filter

- ▶ **Local linearization** of transition and measurement functions.
- ▶ fast
- ▶ robust to near-degeneracy
- ▶ approximate, but generally accurate for TVSAR
- ▶ **automatic differentiation** of $\tilde{\phi}_t = \tilde{\mathbf{g}}(\theta_t)$ makes it beautiful.

Extended Kalman filter

■ State-space model

$$\theta_t = A\theta_{t-1} + Bu_t + \eta_t, \quad \eta_t \sim N(0, \Sigma_\eta)$$
$$y_t = C(\theta_t) + \varepsilon_t, \quad \varepsilon_t \sim N(0, \Sigma_\varepsilon)$$

Standard Kalman filter

```
# Prior propagation step
```

$$\bar{\mu} = A*\mu .+ B*u$$

$$\bar{\Omega} = A*\Omega*A' + \Sigma_n$$

```
# Measurement update
```

$$K = \bar{\Omega}*C' / (C*\bar{\Omega}*C' .+ \Sigma_e)$$

$$\mu = \bar{\mu} + K*(y .- C*\bar{\mu})$$

$$\Omega = (I - K*C)*\bar{\Omega}$$

Extended Kalman filter

```
# Prior propagation step
```

$$\bar{\mu} = A*\mu + B*u$$

$$\bar{\Omega} = A*\Omega*A' + \Sigma_n$$

$$\bar{C} = \partial C(\bar{\mu}, \text{Cargs})$$

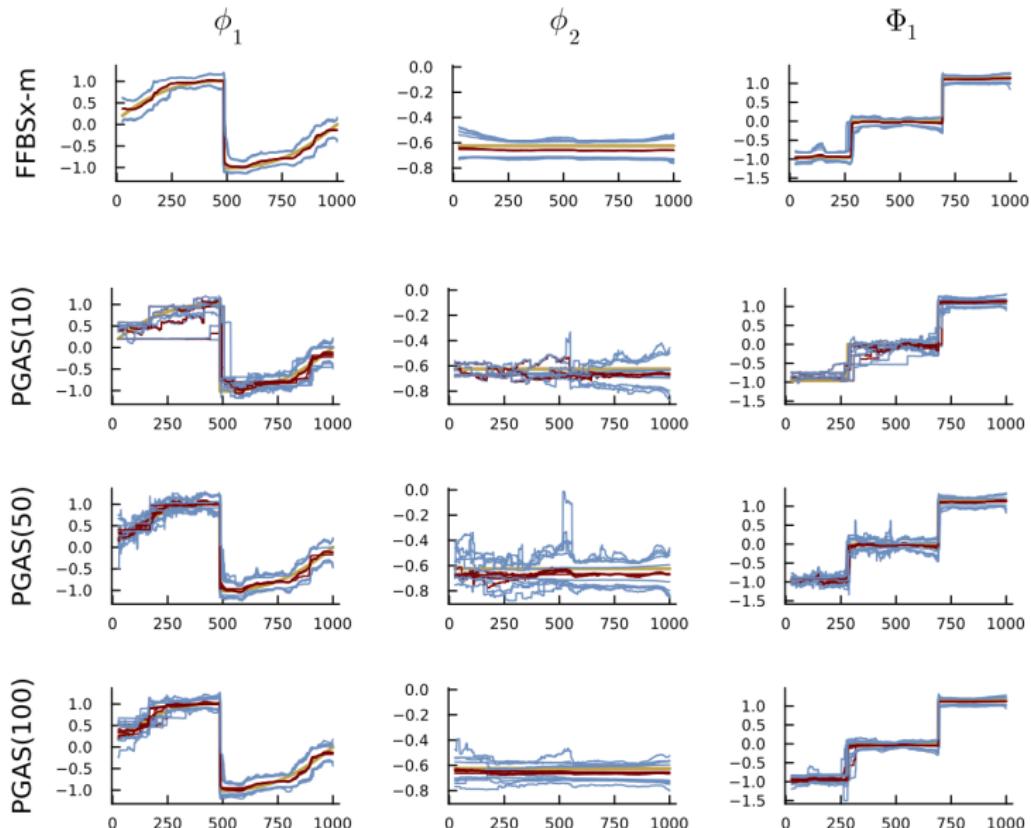
```
# Measurement update
```

$$K = \bar{\Omega}*\bar{C}' / (\bar{C}*\bar{\Omega}*\bar{C}' .+ \Sigma_e)$$

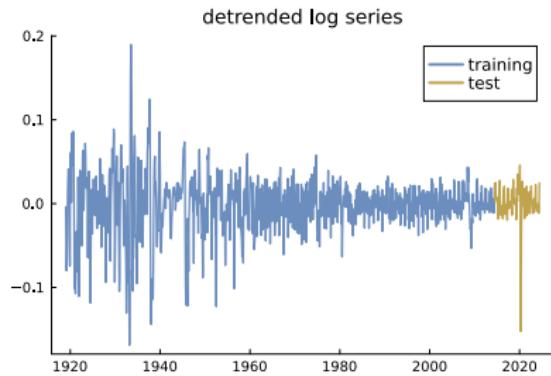
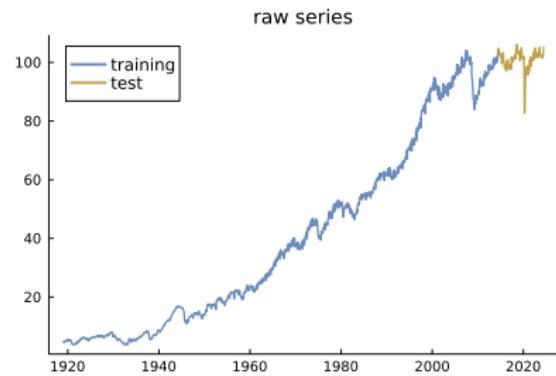
$$\mu = \bar{\mu} + K*(y .- C(\bar{\mu}, \text{Cargs}))$$

$$\Omega = (I - K*\bar{C})*\bar{\Omega}$$

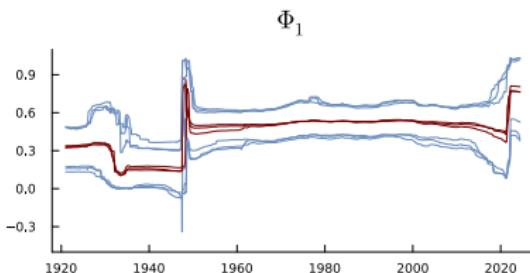
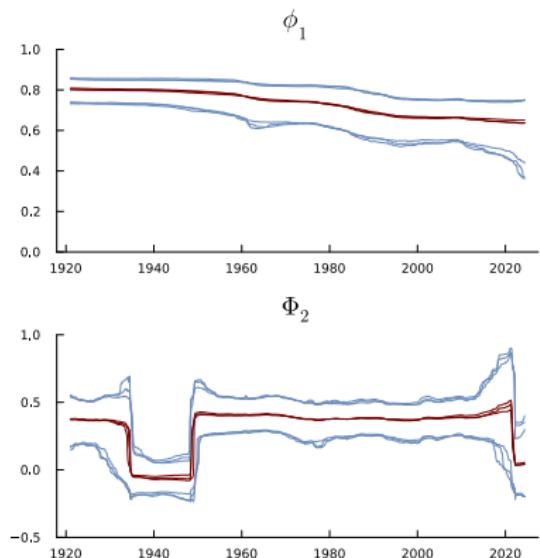
Simulation TVSAR with $p = (2, 2)$ and $s = (1, 12)$



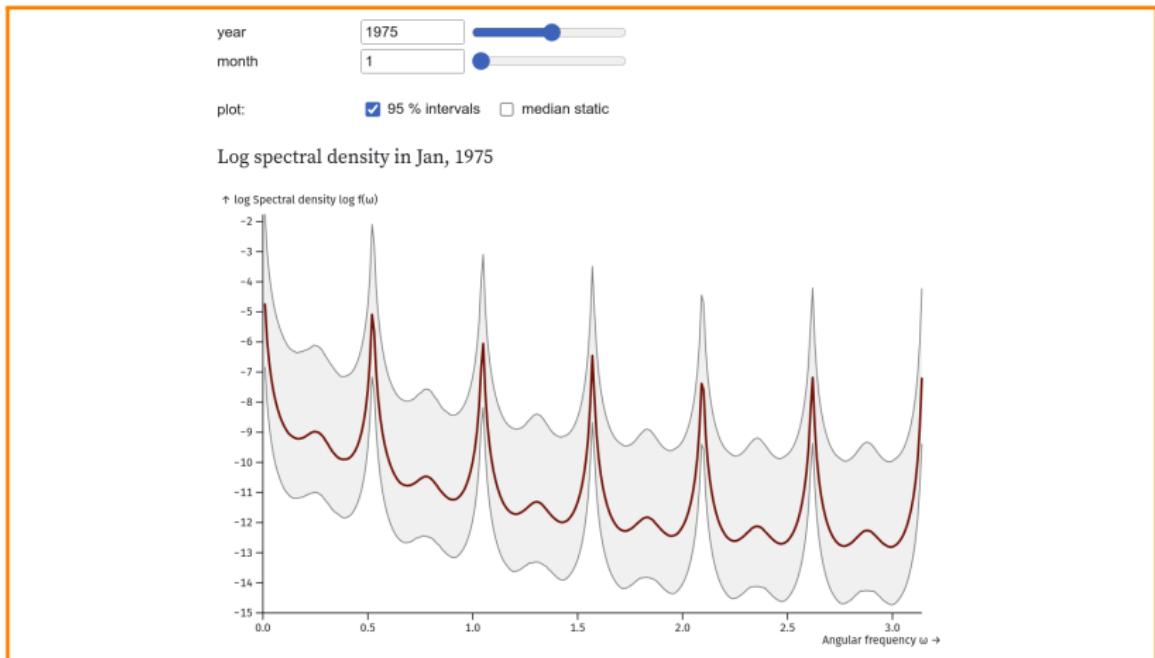
US industrial production 1919-2024



SAR(1,2) - FFBSx three random initial values



SAR(1,2) spectral density snapshots



Approximate Gaussian Kalman-based samplers

- Key for **prior propagation update**: approximate the joint distribution $p(\mathbf{z}_t, \mathbf{z}_{t-1} | \mathbf{y}_{1:t-1})$

$$\begin{pmatrix} \mathbf{z}_t \\ \mathbf{z}_{t-1} \end{pmatrix} | \mathbf{y}_{1:t-1} \stackrel{\text{approx}}{\sim} N \left[\begin{pmatrix} \mathbb{E}(\mathbf{z}_t) \\ \mathbb{E}(\mathbf{z}_{t-1}) \end{pmatrix}, \begin{pmatrix} \mathbb{V}(\mathbf{z}_t) & \mathbb{C}(\mathbf{z}_t, \mathbf{z}_{t-1}) \\ \mathbb{C}(\mathbf{z}_t, \mathbf{z}_{t-1})^\top & \mathbb{V}(\mathbf{z}_{t-1}) \end{pmatrix} \right]$$

- Key for **measurement update**: approximate the joint distribution $p(\mathbf{y}_t, \mathbf{z}_t | \mathbf{y}_{1:t})$

$$\begin{pmatrix} \mathbf{y}_t \\ \mathbf{z}_t \end{pmatrix} | \mathbf{y}_{1:t} \stackrel{\text{approx}}{\sim} N \left[\begin{pmatrix} \mathbb{E}(\mathbf{y}_t) \\ \mathbb{E}(\mathbf{z}_t) \end{pmatrix}, \begin{pmatrix} \mathbb{V}(\mathbf{y}_t) & \mathbb{C}(\mathbf{y}_t, \mathbf{z}_t) \\ \mathbb{C}(\mathbf{y}_t, \mathbf{z}_t)^\top & \mathbb{V}(\mathbf{z}_t) \end{pmatrix} \right]$$

- **Extended Kalman filter (EKF)**

- ▶ linearizes transition model around posterior mean at $t - 1$.
- ▶ linearizes measurement model around prior mean at t .

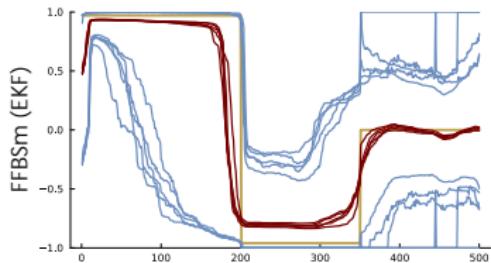
Alternative Gaussian Kalman-based samplers

- **Moment matching** by numerical integration. [10]
- **Unscented Kalman Filter (UKF)**: map sigma points through nonlinear transition and measurement functions. [17]
- **Iterated EKF** and **Iterated UKF**: expands around posterior mean instead of prior mean. [18, 19]
- Iterated EKF/UKF with **line search**. [18, 19]
- **Prior Linearization filter**. Linearizes $\mathbf{y} = \mathbf{g}(\mathbf{x})$ by minimizing $\mathbb{E}_{\text{prior}} \left(\|\mathbf{g}(\mathbf{x}) - (\mathbf{a} + \mathbf{Cx})\|^2 \right)$. [20]
- **Posterior linearization filter** minimizes $\mathbb{E}_{\text{post}} \left(\|\mathbf{g}(\mathbf{x}) - (\mathbf{a} + \mathbf{Cx})\|^2 \right)$ by iterating. [20]
- **Laplace approximation**: approximates by posterior mode and inverse negative Hessian. [21]

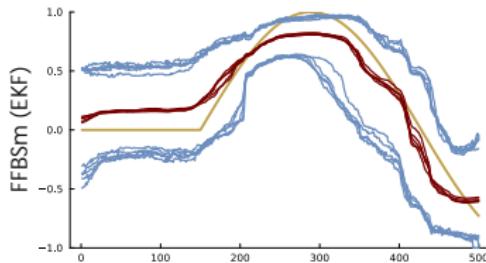
FFBS-EKF - at the boundary of the stable region

Mohanam transformation

Φ_1

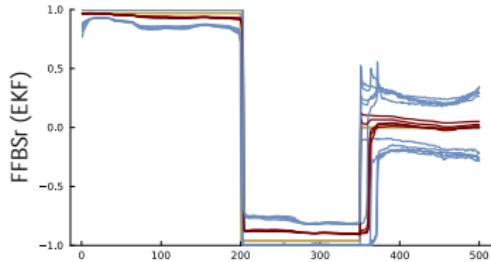


Φ_1

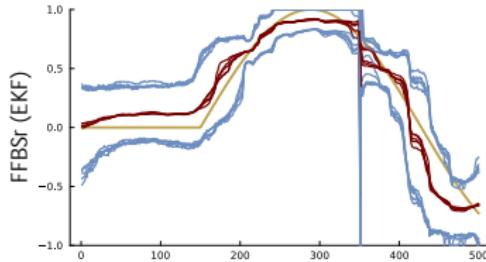


RELU transformation

Φ_1



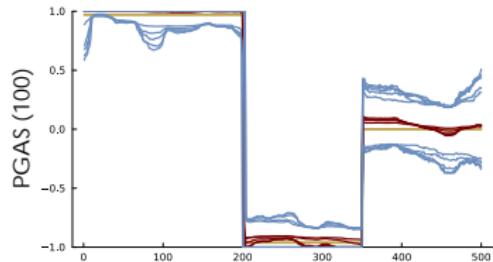
Φ_1



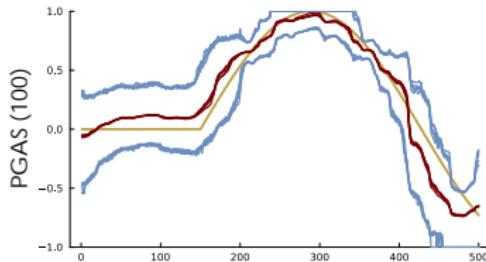
FFBS-EKF - at the boundary of the stable region

RELU transformation - PGAS

φ_1

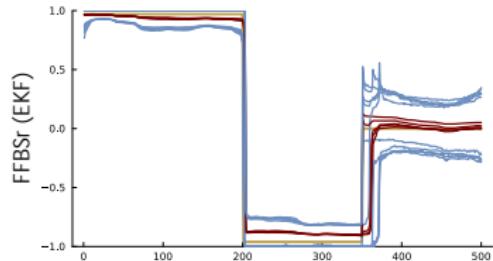


ϕ_1

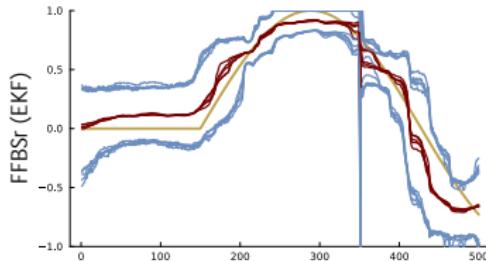


RELU transformation - EKF

φ_1



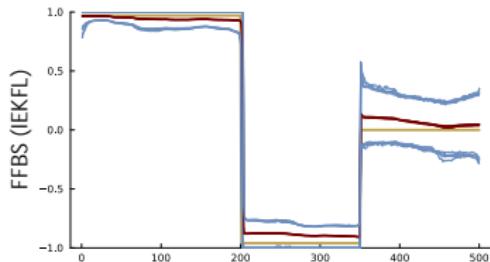
ϕ_1



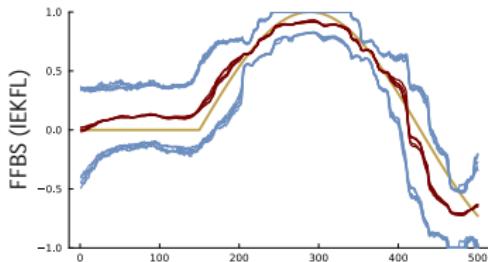
Iterated EKF/UKF may help

Iterated EKF with line search

φ_1

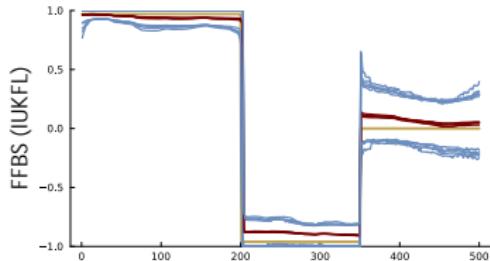


Φ_1

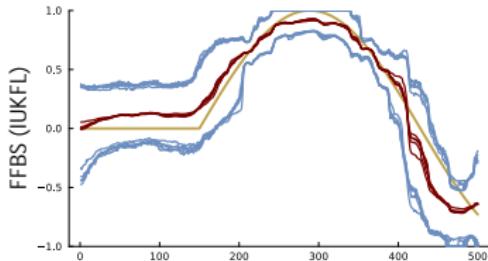


Iterated UKF with line search

φ_1



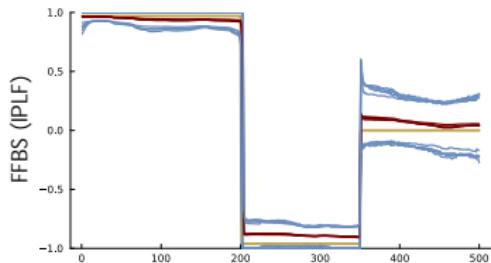
Φ_1



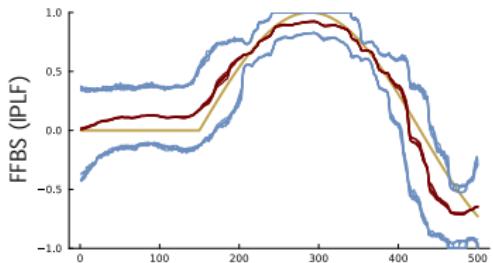
Posterior linearization filter

IPLF

φ_1



Φ_1



Summary

- Dynamic global-local shrinkage priors have interesting parameter evolutions.
- The near-constancy of parameters makes particle methods problematic.
- Gaussian approximations work well in many settings.
- Multi-seasonal ARMA models with time-varying parameters following a dynamic shrinkage process
 - ▶ can be made stable at every time period
 - ▶ the extended Kalman filter works well in many settings
 - ▶ large changes in seasonality in US industrial production data
 - ▶ Julia package for arbitrary number of polynomials is coming
- Ongoing: Non-Gaussian models with dynamic global-local shrinkage priors (VR 2026-2028).

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Bayesian inference TVSARMA

■ **TVSARMA** with exact likelihood:

$$y_t = \mathbf{x}_t^\top \tilde{\phi}_t + \mathbf{z}_t^\top \tilde{\psi}_t + \varepsilon_t, \quad \varepsilon_t \stackrel{\text{indep}}{\sim} N(0, \sigma_t^2)$$
$$(\tilde{\phi}_t, \tilde{\psi}_t) = \tilde{\mathbf{g}}(\boldsymbol{\theta}_t)$$
$$\boldsymbol{\theta}_t = \boldsymbol{\theta}_{t-1} + \boldsymbol{\nu}_t, \quad \boldsymbol{\nu}_t \stackrel{\text{indep}}{\sim} N(0, \text{Diag}(\exp(\mathbf{h}_t)))$$
$$\mathbf{h}_t = \boldsymbol{\mu} + \boldsymbol{\kappa}(\mathbf{h}_{t-1} - \boldsymbol{\mu}) + \boldsymbol{\eta}_t, \quad \boldsymbol{\eta}_{kt} \stackrel{\text{iid}}{\sim} Z(1/2, 1/2, 0, 1)$$

■ Add Gibbs update steps for

- ▶ past disturbances: $\mathbf{z}_t = (\varepsilon_{t-1}, \varepsilon_{t-s}, \varepsilon_{t-(1+s)})^\top$
- ▶ pre-sample lags: $y_0, y_{-1}, y_{-2}, \dots$

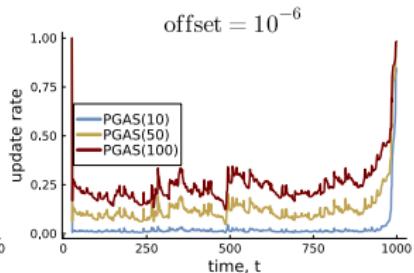
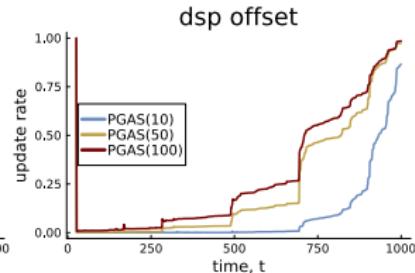
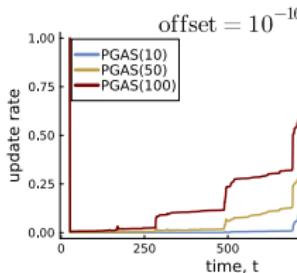
PGAS - larger offset improves convergence

- Volatility models

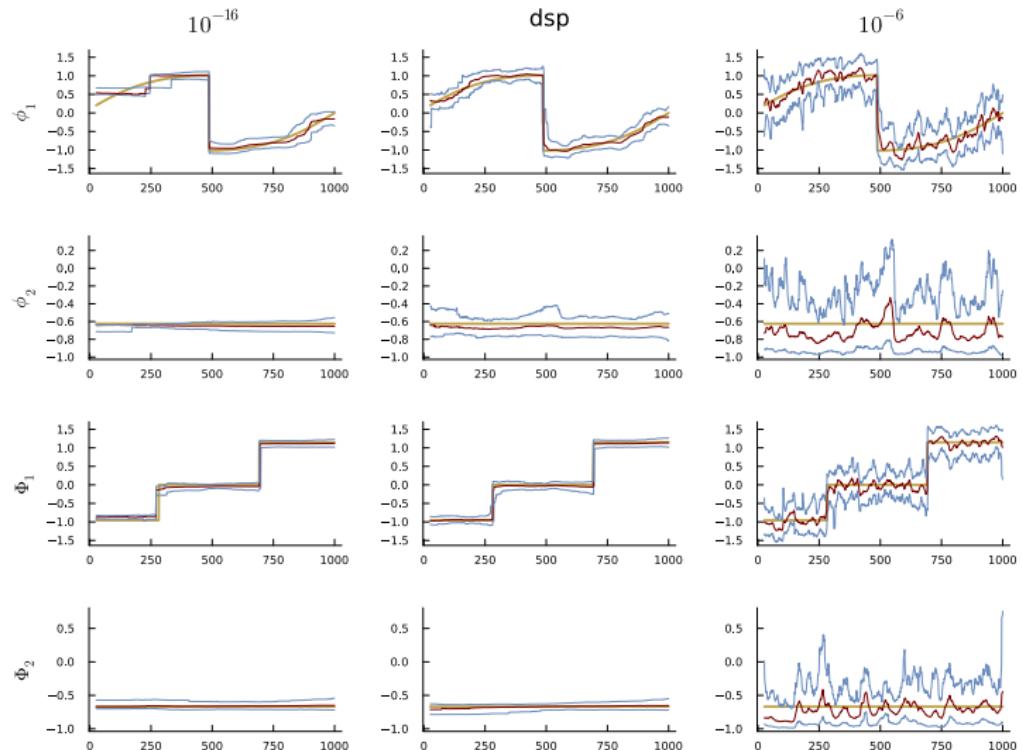
$$\nu_t = \exp(h_t/2)\epsilon_t, \quad \epsilon_t \sim N(0, 1)$$

- The usual **square-and-log trick**

$$\log(\nu_t^2 + \text{offset}) = h_t + \log \epsilon_t^2$$



... but makes parameters more “wiggly”



Spectral density Seasonal ARMA

Spectral density ARMA(p,q)×(P,Q)

seasonal period

no. of AR

no. of MA

no. of seasonal AR

no. of seasonal MA

Parameter settings

ϕ_1

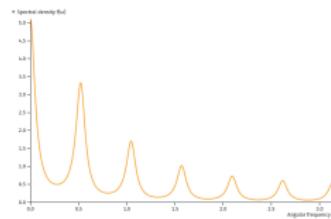
No regular MA

Φ_1

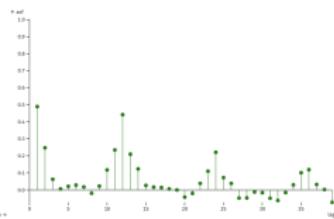
No seasonal MA

plot log f(u)

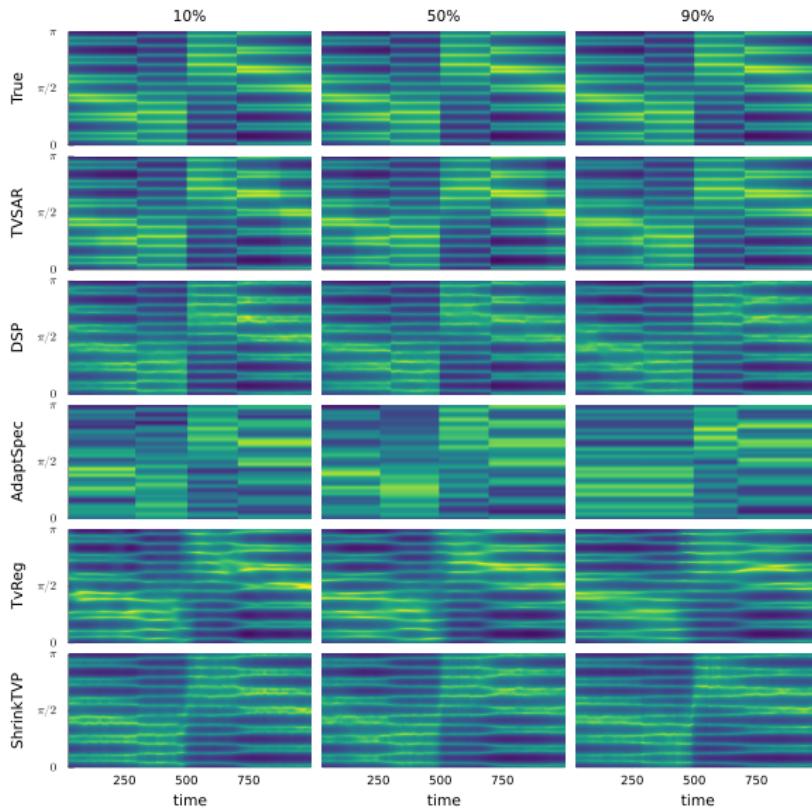
Spectral density of an ARMA(1,0)×(1,0) process with season s=12



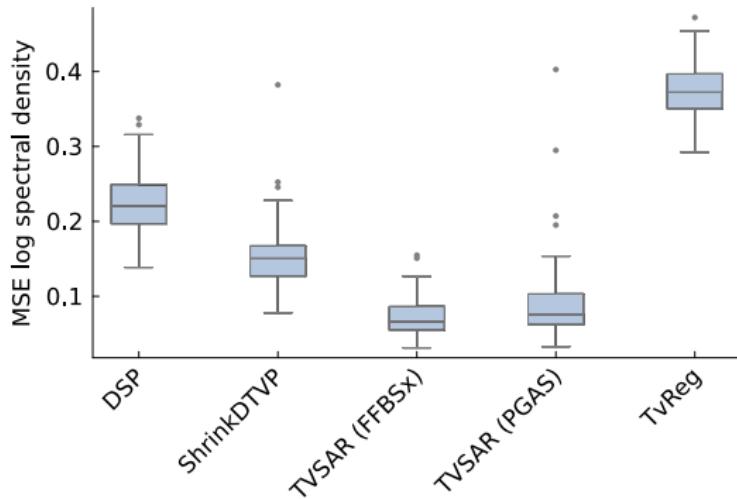
Estimated ACF of ARMA(1,0)×(1,0) process with season s=12



Fitted log spectrogram



Quantifying the spectral density fit



Gaussian approximations to bivariate log-normal

