



PROBABILISTIC MARKET ECOSYSTEM ANALYZER: AN INTEGRATED FRAMEWORK FOR FINANCIAL MARKET ANALYSIS USING REGIME DETECTION AND ECOLOGICAL MODELING

- FINAL REVIEW -

22AIE301: PROBABILISTIC REASONING

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INTRODUCTION TO STOCK MARKET

- **What is a Stock?**
 - A share of ownership in a company.
 - Its price changes based on supply (sellers) and demand (buyers).
- **Key Market "Moods" (Regimes)**
 -  **Bull Market:** Prices are rising, investor confidence is high.
 -  **Bear Market:** Prices are falling, investor confidence is low.
 -  **Stable Market:** Prices are moving sideways with low volatility.
- **Key Concepts**
 - **Volatility:** Price fluctuation intensity
 - **Liquidity:** How easily stocks can be bought/sold
 - **Market Sentiment:** Overall investor attitude

PROBLEM STATEMENT

- Financial markets are complex, adaptive systems with non-linear dynamics and regime changes.
- Traditional tools (technical/fundamental analysis) often fail to capture this complexity.
- **Key Gaps:**
 - **Fragmented Analysis:** Tools are either too simple or too complex and inaccessible.
 - **Ignores Uncertainty:** Point forecasts ignore probabilistic nature of markets.
 - **Misses Interactions:** Treats assets in isolation, not as part of an ecosystem.

SUMMARY OF LITERATURE REVIEW

1. Complex Quantitative Models

- **Examples:** Hidden Markov Models (HMMs), Advanced Monte Carlo methods, Regime-switching models
- **Strengths:** High theoretical accuracy, comprehensive risk modeling
- **Limitations:**
 - Computationally expensive for real-time analysis
 - Require significant expertise to implement and interpret
 - Often inaccessible to portfolio managers and traders

2. Simple Practical Tools

- **Examples:** Basic technical indicators, Traditional charting platforms
- **Strengths:** User-friendly, fast decision-making, widely adopted
- **Limitations:**
 - Lack probabilistic foundation and uncertainty quantification
 - Ignore market regime changes and structural breaks
 - Limited risk management capabilities

3. Theoretical Frameworks

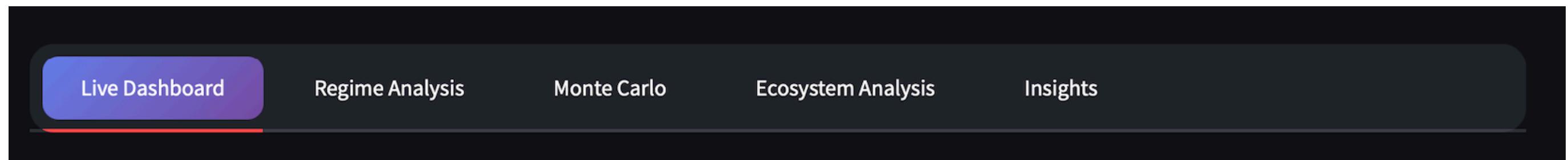
- **Examples:** Agent-based models, Ecological finance concepts, Predator-prey dynamics
- **Strengths:** Provide deep insights into market microstructure and participant behavior
- **Limitations:**
 - Rarely implemented in practical trading tools
 - Parameter estimation challenges in real-world settings
 - Limited validation with actual market data

THE CRITICAL GAP IDENTIFIED

- **Fragmentation:** Each approach exists in isolation without integration
- **Accessibility Barrier:** Sophisticated models remain confined to academic research
- **Practical Void:** No unified platform that combines mathematical rigor with user-friendly implementation
- **Ecological Blindspot:** Market participant interactions largely ignored in commercial tools

OUR SOLUTION: AN INTEGRATED FRAMEWORK

- We built a single, cohesive system that combines three powerful analytical models:
 - **Lotka-Volterra Ecological Model:** Models market dynamics as a predator-prey system.
 - **Markov Regime Detection:** Identifies Bull, Bear, and Stable market states.
 - **Enhanced Monte Carlo Simulation:** Provides probabilistic forecasts with realistic constraints.
- **Key Benefit:** Provides complementary perspectives for a more robust analysis.



DATASET

- **Source:** Yahoo Finance API (via yfinance Python library)
- **Period:** January 1, 2015 – December 31, 2023
- **Rationale:** Covers bull runs, corrections, COVID-19 crash & recovery
- Selected Assets (Diverse Market Representation)

AAPL (Apple Inc.)

GOOGL (Alphabet Inc.)

MSFT (Microsoft Corp.)

GSPC (S&P 500 Index)

- **Data Preprocessing & Validation Pipeline**

- **Data Cleaning:**

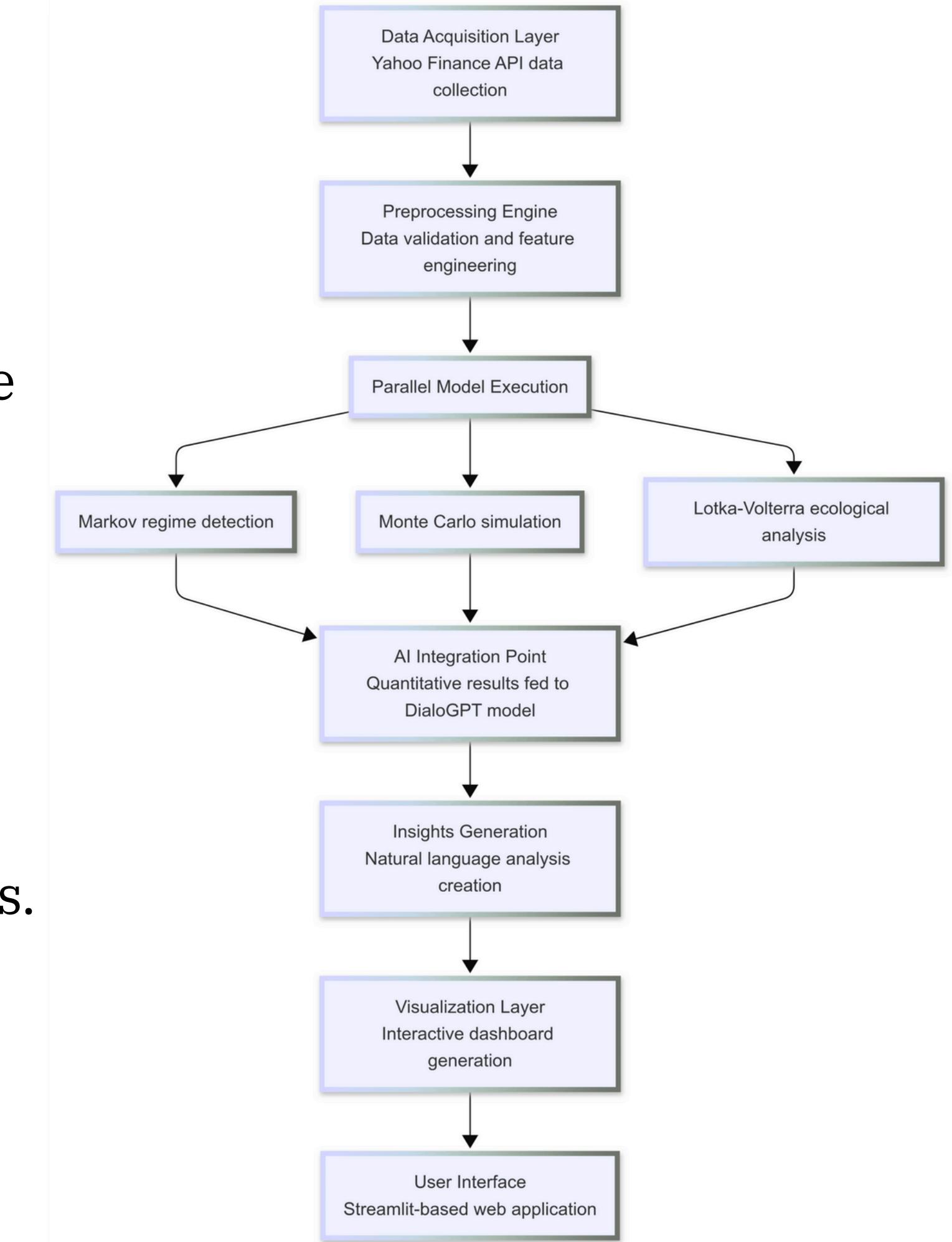
- Handled missing values using limited forward-filling.
 - Outlier detection using rolling Z-score analysis.

- **Feature Engineering:**

- **Log Returns:** $rt=\log(Pt/Pt-1)$ (Used for regime detection and GBM)
 - **Simple Returns:** For intuitive analysis.
 - **Rolling Volatility** (60-day annualized): For risk assessment.
 - **Relative Strength Index** approximations: For momentum-based features.

SYSTEM ARCHITECTURE OVERVIEW

- **Data Acquisition:** Fetch data from Yahoo Finance (e.g., AAPL, MSFT).
- **Data Validation & Feature Engineering:** Clean data and calculate indicators (returns, volatility).
- **Parallel Model Execution:** All three models run simultaneously.
- **Result Integration & AI Insights:** Combine results and generate natural language summaries.
- **Interactive Visualization:** Display results on a web dashboard.



MARKOV REGIME DETECTION

- **Goal:** Automatically classify the market into Bull, Bear, or Stable regimes.
- **Method:** Uses a rolling Z-score of log returns to identify significant price movements.
 - Z-score $> 0.5 \rightarrow$ Bull
 - Z-score $< -0.5 \rightarrow$ Bear
 - Else \rightarrow Stable
- **Output:** A timeline showing historical regimes and a transition probability matrix.

MATHEMATICAL LOGIC

Identifying Market States with Rolling Z-Score

1. Calculate Log Returns:

$$r_t = \log \left(\frac{P_t}{P_{t-1}} \right)$$

2. Compute Rolling Z-Score (Window W):

$$z_t = \frac{r_t - \mu_t}{\sigma_t}$$

where,

$$\mu_t = \frac{1}{W} \sum_{i=t-W+1}^t r_i, \quad \sigma_t = \sqrt{\frac{1}{W-1} \sum_{i=t-W+1}^t (r_i - \mu_t)^2}$$

3. Regime Classification Rule:

$$\text{Regime}_t = \begin{cases} \text{Bull} & \text{if } z_t > 0.5 \\ \text{Bear} & \text{if } z_t < -0.5 \\ \text{Stable} & \text{otherwise} \end{cases}$$

4. Transition Matrix: Estimates probability P_{ij} of switching from regime i to j .

$$\begin{pmatrix} P_{\text{Bull} \rightarrow \text{Bull}} & P_{\text{Bull} \rightarrow \text{Bear}} & P_{\text{Bull} \rightarrow \text{Stable}} \\ P_{\text{Bear} \rightarrow \text{Bull}} & P_{\text{Bear} \rightarrow \text{Bear}} & P_{\text{Bear} \rightarrow \text{Stable}} \\ P_{\text{Stable} \rightarrow \text{Bull}} & P_{\text{Stable} \rightarrow \text{Bear}} & P_{\text{Stable} \rightarrow \text{Stable}} \end{pmatrix}$$

localhost

MSFT Regime Details

MSFT - Market Regime Timeline

Apr 2018 May 2018 Jun 2018 Jul 2018 Aug 2018 Sep 2018 Oct 2018 Nov 2018 Dec 2018 Jan 2019
Date

Transition Probability Matrix

	Bull	Bear	Stable
Bull	23.7%	30.5%	45.8%
Bear	40.4%	29.8%	29.8%
Stable	25.6%	25.6%	48.8%

GOOGL Regime Details

GOOGL - Market Regime Timeline

Apr 2018 May 2018 Jun 2018 Jul 2018 Aug 2018 Sep 2018 Oct 2018 Nov 2018 Dec 2018 Jan 2019
Date

Transition Probability Matrix

	Bull	Bear	Stable
Bull	27.3%	23.6%	49.1%
Bear	31.5%	35.2%	33.3%
Stable	25.8%	23.7%	50.5%

^GSPC Regime Details

^GSPC - Market Regime Timeline

Apr 2018 May 2018 Jun 2018 Jul 2018 Aug 2018 Sep 2018 Oct 2018 Nov 2018 Dec 2018 Jan 2019
Date

Transition Probability Matrix

	Bull	Bear	Stable
Bull	25.9%	18.5%	55.6%
Bear	29.1%	32.7%	38.2%
Stable	25.8%	29.0%	45.2%

LOTKA-VOLTERRA ECOLOGICAL MODEL

- **Core Idea:** Markets as a Living Ecosystem
 - Model markets using predator-prey equations from biology

Prey = Buying Pressure (Retail Traders)

Emotional trading decisions

Often follow trends (buy high, sell low.)

Predators = Selling Pressure (Market Makers)

Profit from bid-ask spreads

"Consume" retail flow for profit

• Ecological Market Cycles & Trading Signals:

- Rising prices → attract more buyers → prices rise further (prey multiplication)
- High prices → attract profit-takers → selling pressure increases (predator response)
- Falling prices → trigger more selling → prices fall further (predator dominance)
- Low prices → attract value buyers → buying resumes (prey recovery)

• Key Application

- Provides early warnings for regime changes
- Identifies unsustainable market conditions
- Enhances timing for entries and exits

MATHEMATICAL LOGIC

- **Core Dynamic Equations (The Theory)**

- Describes how pressures influence each other:

$$\frac{dx}{dt} = \alpha x - \beta xy$$

--> Prey Population (x): Buying Pressure

$$\frac{dy}{dt} = \delta xy - \gamma y$$

→ Predator Population (y): Selling Pressure

Parameter Interpretation

--> α : Buying momentum rate

→ β : Selling pressure impact on buyers

--> δ : Selling response to buying opportunities

→ γ : Natural selling decay rate

- **Discrete Calculation (Our Implementation)**

- Buying Pressure Proxy (x_t): Normalize ($RSI_{bullish} \times \log(Volume_t)$)

- Combines bullish momentum with volume confirmation.

- Selling Pressure Proxy (y_t): Normalize ($RSI_{bearish} \times \log(Volume_t)$)

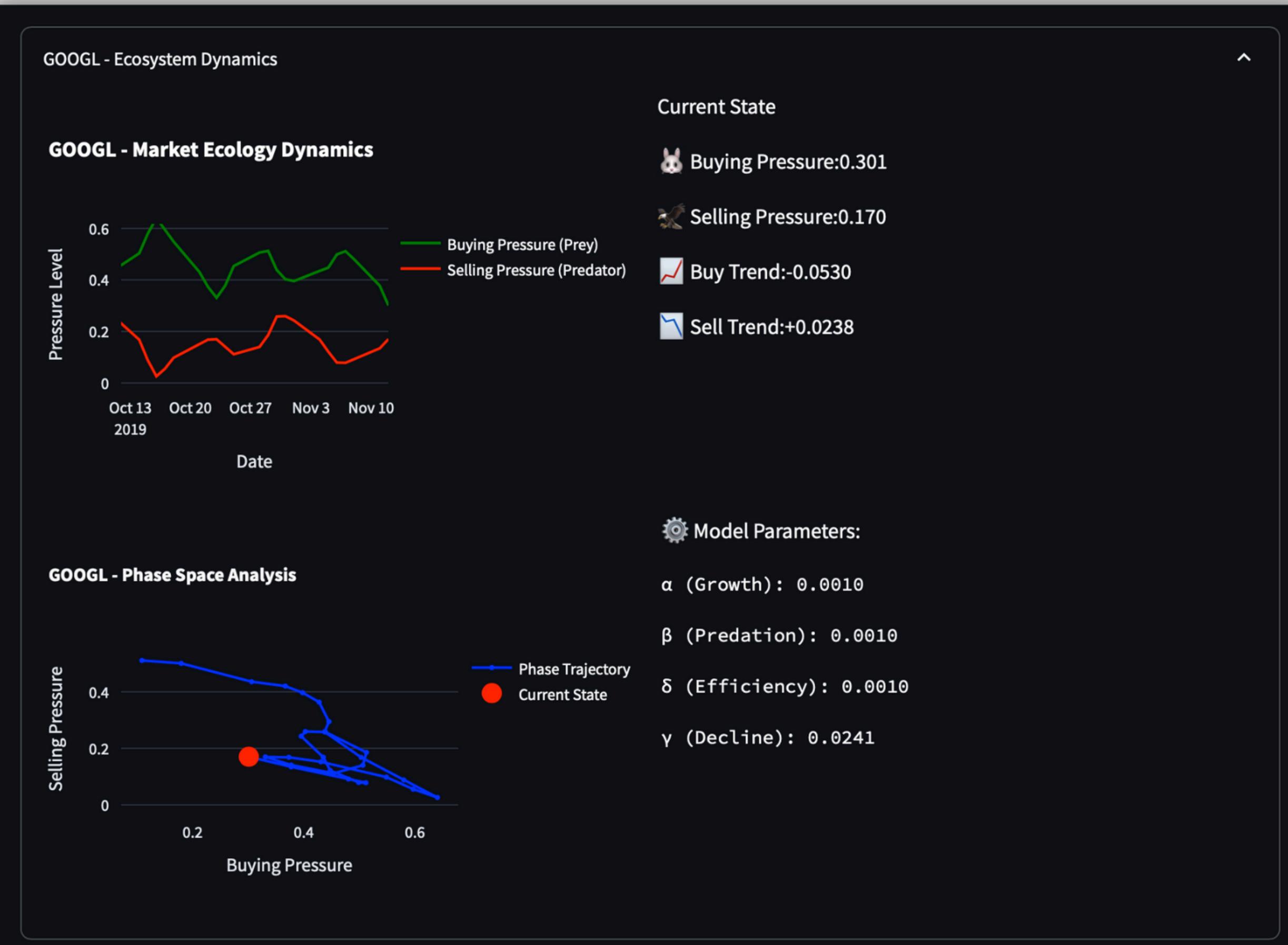
- Combines bearish momentum with volume confirmation.

- **Parameter Estimation**

- We find $\alpha, \beta, \delta, \gamma$ that best fit the calculated x_t and y_t to the LV model by minimizing:

$$\sum_t [(x_{t+1} - x_t - (ax_t - \beta x_t y_t) \Delta t)^2 + (y_{t+1} - y_t - (\delta x_t y_t - \gamma y_t) \Delta t)^2]$$

- with constraints: $\alpha, \beta, \delta \in [0.001, 1.0]$, $\gamma \in [-0.5, 1.0]$



ENHANCED GEOMETRIC BROWNIAN MOTION

- **Goal:** Generate probabilistic forecasts of future prices, not just a single guess.
- **Method:** Enhanced Geometric Brownian Motion (GBM).
- **Our Innovation:**
 - **Robust Parameter Estimation:** Clips drift (μ) and volatility (σ) to realistic bounds to prevent unrealistic simulations.
 - **Comprehensive Risk Metrics:** Calculates Value at Risk (VaR) and Conditional VaR.

MATHEMATICAL LOGIC

- Stochastic Differential Equation:

$$dS_t = \mu S_t dt + \sigma S_t dW_t$$

- Euler-Maruyama Discretization:

$$S_{t+\Delta t} = S_t \exp \left[\left(\mu - \frac{\sigma^2}{2} \right) \Delta t + \sigma \sqrt{\Delta t} Z_t \right], \quad Z_t \sim \mathcal{N}(0, 1)$$

- Key Enhancement: Robust Parameter Estimation

- Drift (μ): $\mu_{\text{annual}} = \text{clip}(252 \cdot \text{mean}(r_t), -0.5, 0.5)$

- Volatility (σ): $\sigma_{\text{annual}} = \text{clip}(\sqrt{252} \cdot \text{std}(r_t), 0.05, 0.8)$

- The clip() function ensures realistic, stable simulations.

- Risk Metrics:

- Value at Risk (VaR): $\text{VaR}_\alpha = S_0 \cdot \Phi^{-1}(1 - \alpha) \cdot \sigma \sqrt{T}$

- Conditional VaR (Expected Shortfall): $\text{CVaR}_\alpha = \frac{1}{1-\alpha} \int_\alpha^1 \text{VaR}_u du$



AI-POWERED FINANCIAL INSIGHTS

- **LLM Architecture**

- **Model:** Microsoft's DialoGPT-medium
- **Integration:** Hugging Face Transformers library

- **What It Does**

- Translates complex math into simple English
- Acts as "Financial Analyst in a Box"
- Provides instant, actionable insights

- **Key Benefits**

- Makes analytics accessible to all
- Bridges gap between models and practical decisions
- Explains regime changes, risks, and opportunities clearly



Hugging Face



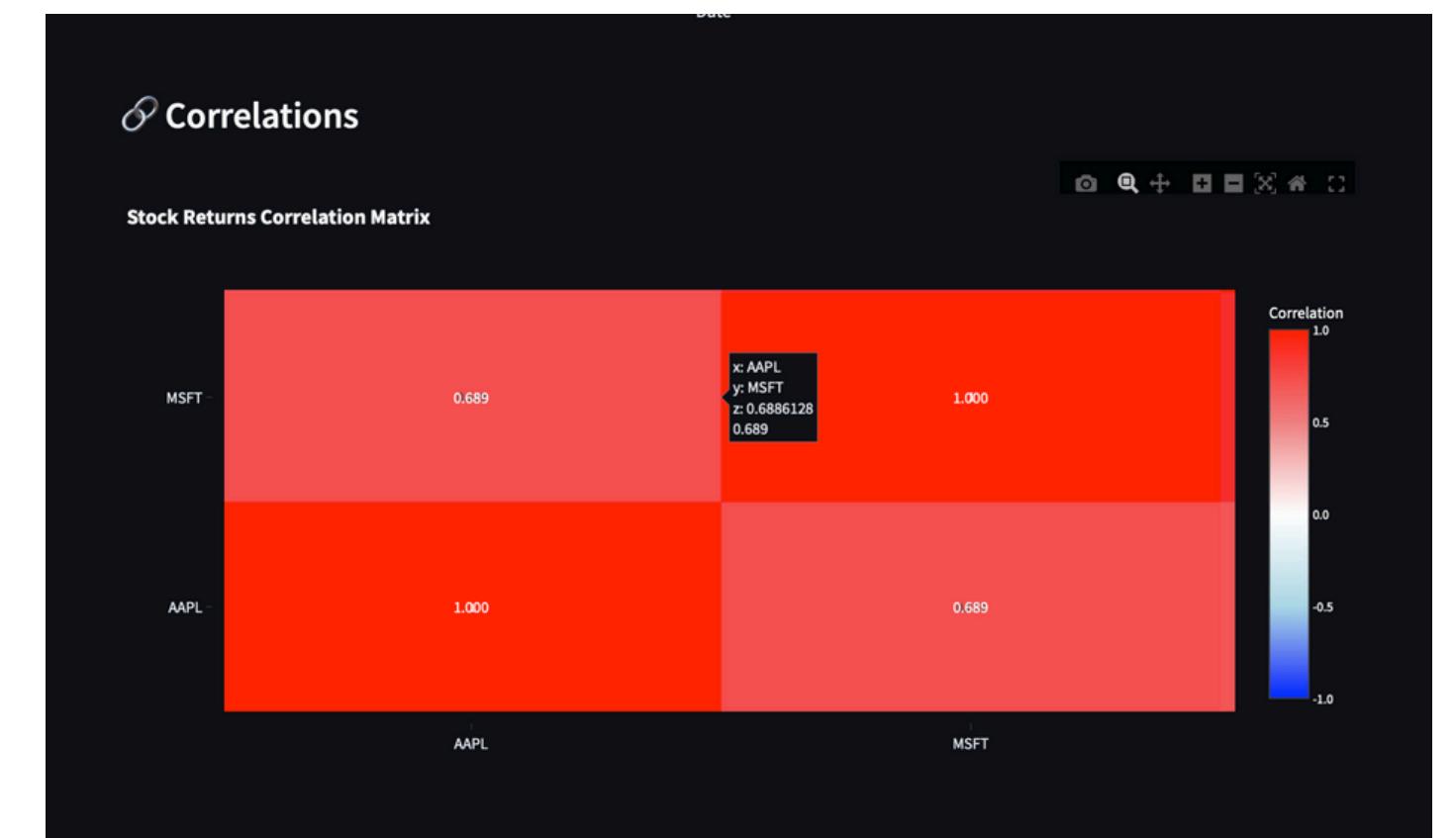
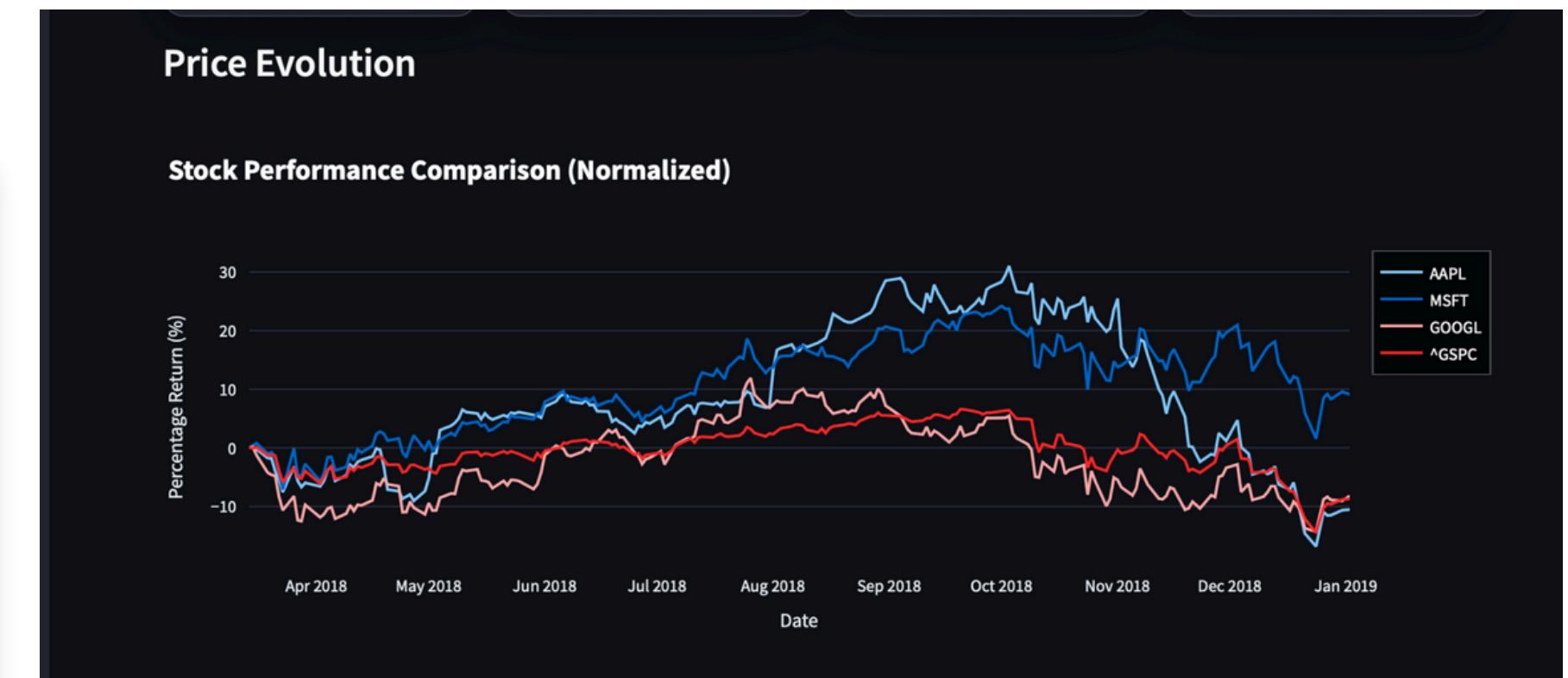
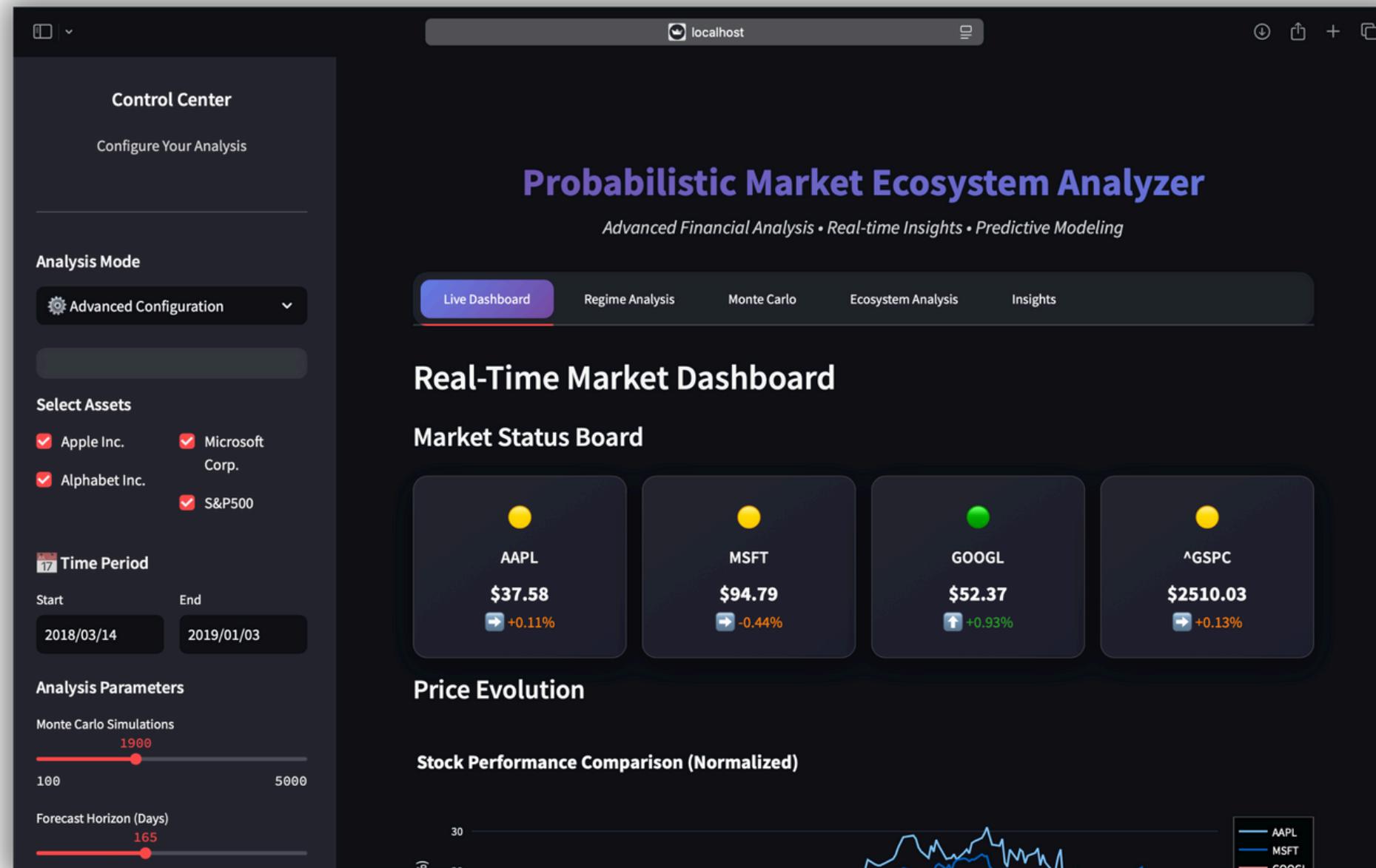
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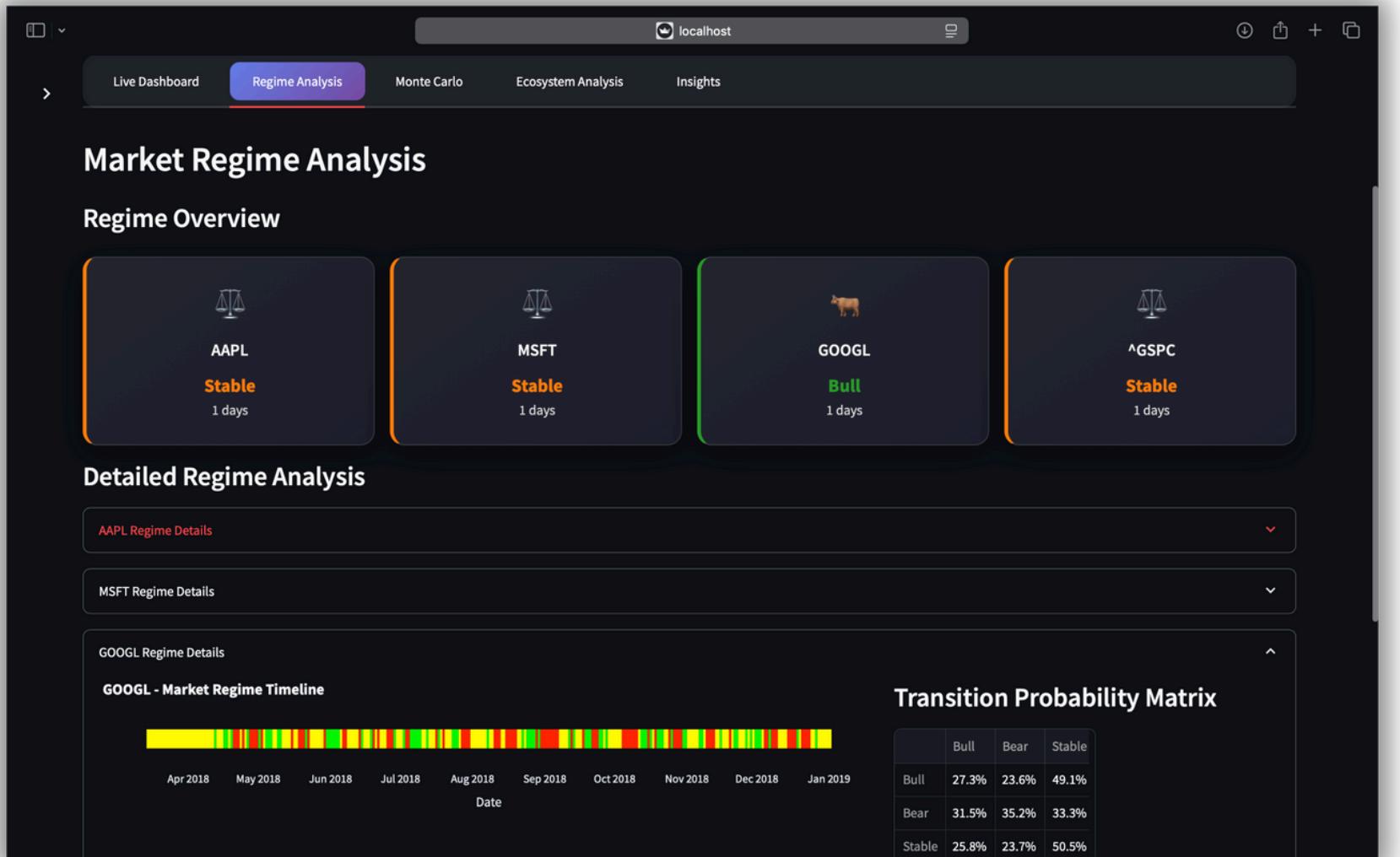
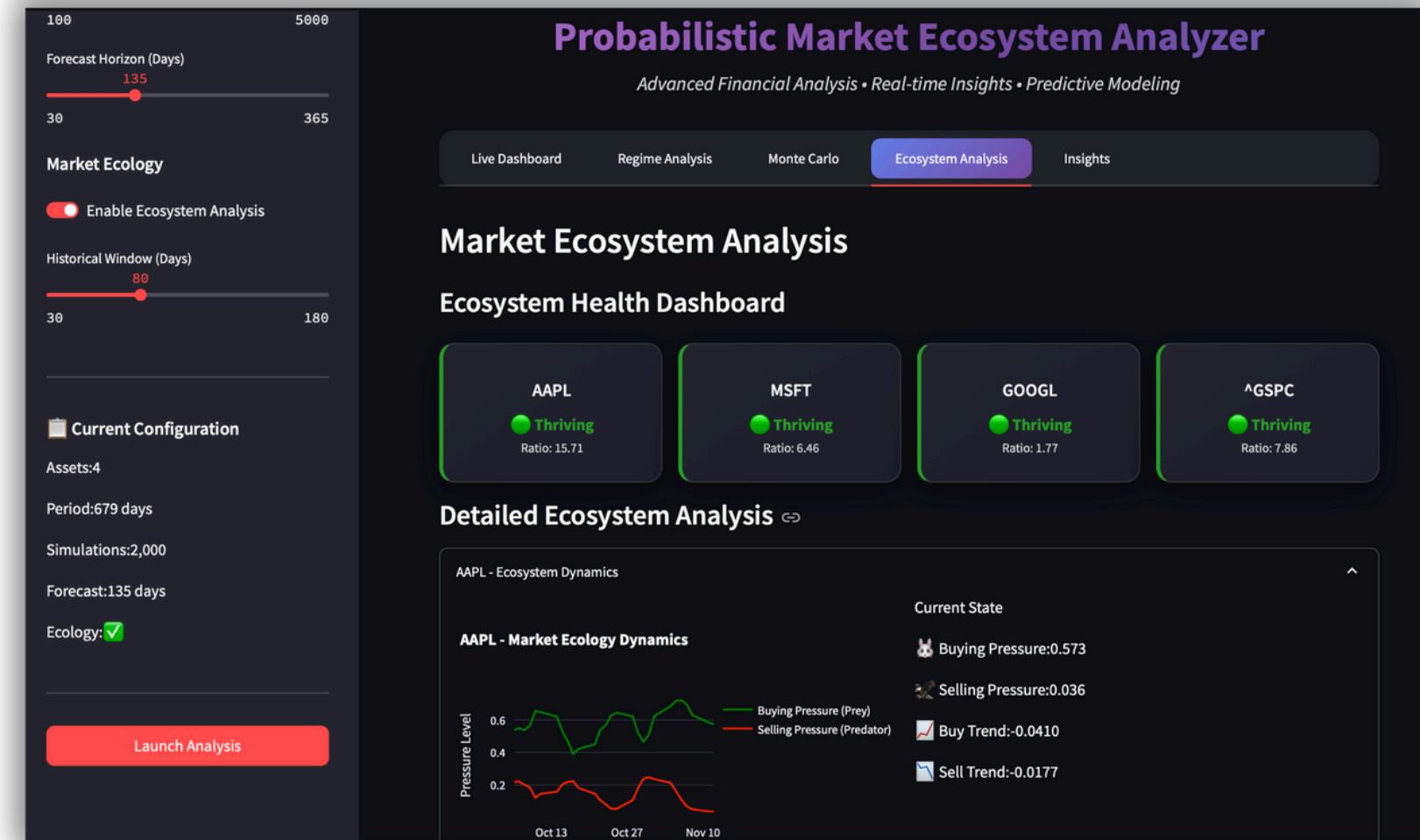
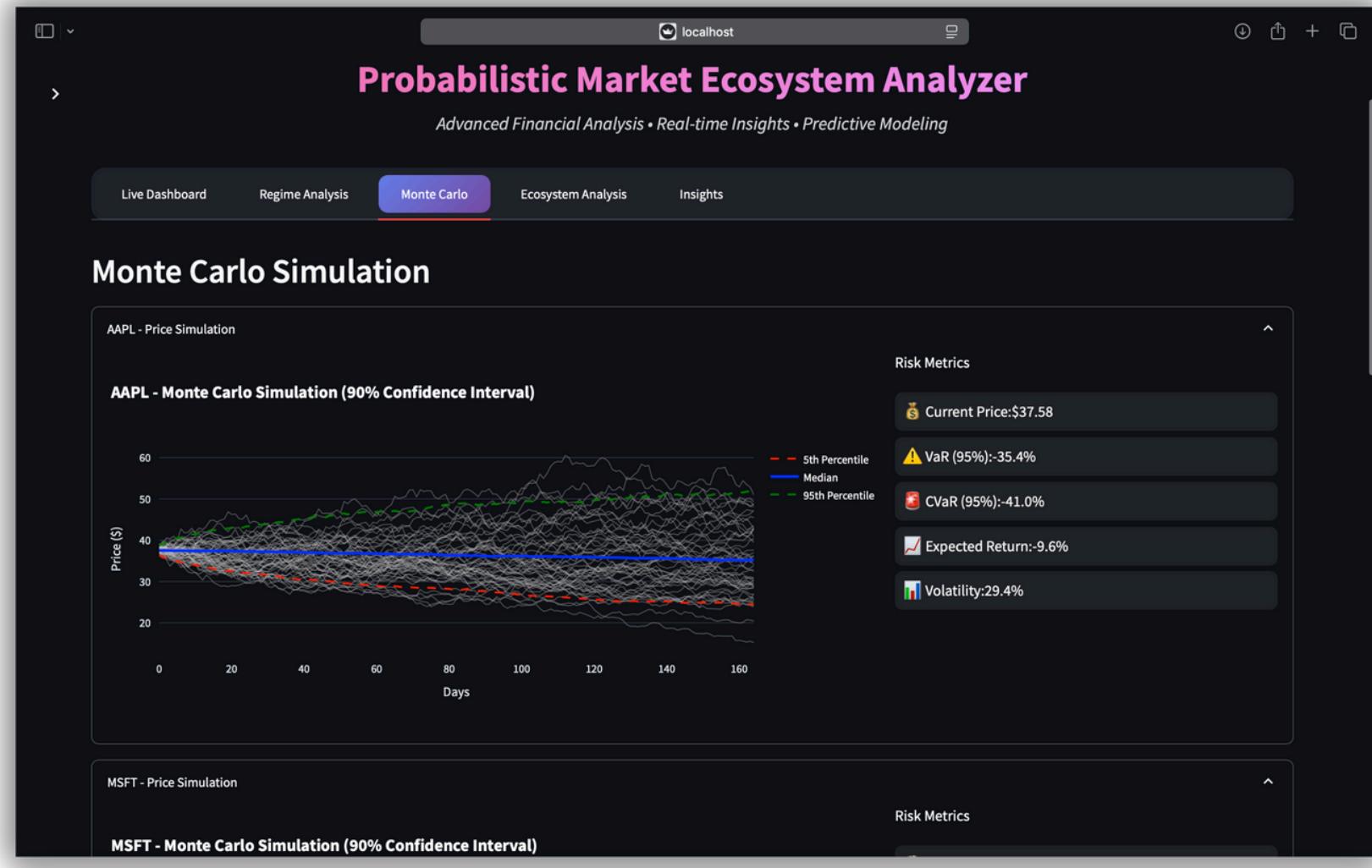
The screenshot shows a web browser window with the URL `localhost` in the address bar. The page title is **Probabilistic Market Ecosystem Analyzer**, described as *Advanced Financial Analysis • Real-time Insights • Predictive Modeling*. The main navigation menu includes **Live Dashboard**, **Regime Analysis**, **Monte Carlo**, **Ecosystem Analysis**, and **Insights** (which is currently selected). Below the menu, there are two buttons: **AI Raw Insights** (highlighted with a red underline) and **Formatted Insights**. The main content area features a section titled **AI Market Insights** with a **Generate Insights** button. The **Key Findings** section lists the following market observations:

- AAPL is stable. Current price \$37.58 indicates consolidation.
- MSFT is stable. Current price \$94.79 indicates consolidation.
- GOOGL is in a bullish trend. Current price \$52.37 shows positive momentum.
- ^GSPC is stable. Current price \$2510.03 indicates consolidation.

Overall market sentiment: Cautious (1/4 assets in uptrend)

RESULTS





Probabilistic Market Ecosystem Analyzer

Advanced Financial Analysis • Real-time Insights • Predictive Modeling

- Live Dashboard
- Regime Analysis
- Monte Carlo
- Ecosystem Analysis
- Insights**

AI Raw Insights | **Formatted Insights**

AI Market Insights

Key Findings

- AAPL is stable. Current price \$37.58 indicates consolidation.
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Probabilistic Market Ecosystem Analyzer

Advanced Financial Analysis • Real-time Insights • Predictive Modeling

- Live Dashboard
- Regime Analysis
- Monte Carlo
- Ecosystem Analysis
- Insights**

AI Raw Insights | **Formatted Insights**

Formatted Market Insights

Overall Market Summary

Bullish Stocks	Bearish Stocks	Avg Regime Duration
1/4 ↑ 25.0%	0/4 ↑ 0.0%	1.0 days

Market Sentiment: ⚡ Moderately Bullish - Cautious optimism recommended

Individual Stock Analysis

AAPL - Detailed Analysis

Price Analysis	Regime Analysis
Current Price \$37.58	Current Regime Stable

GOOGL - Detailed Analysis

Price Analysis

- Current Price
\$52.37
- Weekly Change
+0.65%
- Monthly Change
-5.53%
- 30D Volatility
35.5%
- 90D Volatility
31.7%

Monte Carlo Projections

- Expected Price
\$51.32
- VaR (95%)
\$34.29
- Projected Return
-2.0%
- Drawdown Risk
34.5%
- VaR (99%)
\$29.41
- Extreme Risk
43.8%

Regime Analysis

- Current Regime
Bull
- Duration
1 days
- Regime Frequency:
 - Stable: 45.8%
 - Bull: 27.6%
 - Bear: 26.6%

Early Stage - Monitor for confirmation

⚠ Risk Assessment

Portfolio Risk Analysis

stock	volatility	sharpe	max_drawdown	regime	regime_duration
0 AAPL	29.48%	-0.47	45.43%	Stable	1
1 MSFT	28.47%	0.38	20.12%	Stable	1
2 GOOGL	27.99%	-0.38	26.66%	Bull	1
3 ^GSPC	16.61%	-0.68	22.04%	Stable	1

Moderate Volatility - Standard risk management required | Moderate Drawdown Risk - Standard precautions needed

Trading Recommendations

Trading Strategy Recommendations

Stock	Regime	Duration	Recommendation	Confidence
0 AAPL	Stable	1 days	Range-bound trading - wait for breakout	Medium
1 MSFT	Stable	1 days	Range-bound trading - wait for breakout	Medium
2 GOOGL	Bull	1 days	Monitor for confirmation - early bullish phase	Low
3 ^GSPC	Stable	1 days	Range-bound trading - wait for breakout	Medium

Overall Portfolio Bias: ⚡ Bullish - Favor long positions

CONCLUSION & FUTURE WORK

- **Summary of Contributions:**

- Integrated Multi-Model Framework unifying regime detection, probabilistic forecasting, and ecological analysis.
- Novel Mathematical Application of Lotka-Volterra equations to practical equity market analysis.
- Enhanced GBM with robust parameter constraints for stable, realistic simulations.
- Accessible Platform bridging sophisticated mathematics and practical usability via an AI-powered web interface.

- **Future Work:**

- **Short-Term:** Extend to cryptocurrencies, integrate real-time news sentiment.
- **Medium-Term:** Develop multi-asset Lotka-Volterra models, incorporate LSTMs for regime prediction.
- **Long-Term:** Real-time risk monitoring system and macroeconomic integration.

THANK YOU

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