The challenge of building agent-based models of the economy

European Central Bank
Frankfurt, June 10, 2011

J. Doyne Farmer
Santa Fe Institute

Agent-based models

- Use a computer to simulate decisions of heterogeneous individual agents
  - households, firms, banks, government, ...
  - ground with behavioral knowledge
- Can include: Real estate, capital markets, taxes, foreign exchange, liquidity, stock market, ...
- Can ground with micro-data. Potentially allows rich calibration and validation.
- Key: Can model complexity of a real economy

Krugman on ABM
(Nov. 30, 2010)

- This WSJ article about economists in search of a model takes it as given that all our models have failed completely in the crisis — which is a gross exaggeration.

- "… those of us who hadn't forgotten Keynes, who paid attention to things like Japan's lost decade and developing-country financial crises, aren't feeling all that at sea."

- "Oh, and about ~~Roger~~Doyne Farmer (sorry, Roger!)and Santa Fe and complexity and all that: I was one of the people who got all excited about the possibility of getting somewhere with very detailed agent-based models — but that was 20 years ago. And after all this time, it's all still manifestos and promises of great things one of these days."

Contrasting statements

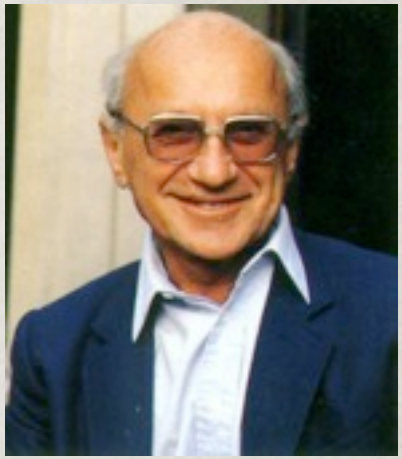
Ric Mishkin, Sept 2007: Fortunately, the overall financial system appears to be in good health, and the U.S. banking system is well positioned to withstand stressful market conditions,"

Paul Krugman: (NYT, Sept 2009): Macro of the past 30 years "spectacularly useless at best, and positively harmful at worst."

Jean-Claude Trichet: "In the face of the crisis, we felt abandoned by conventional tools".

Why do we need agent-based models?

Lucas Critique



- Recession of 70's. "Keynesian" econometric models.
- Phillips curve: Rising prices ~ rising employment
- Following Keynesians, Fed inflated money supply
- Result: Inflation, high unemployment = stagflation
- Problem: People can think
- Conclusion: Macro economic models must incorporate human reasoning
- Solution: Dynamic Stochastic General Eq. models

What happens when we have complicated strategic interactions? (with Tobias Galla)

- Consider a "complicated game", i.e. one where the number of possible moves is large.
- E.g. a 2 player game with (fixed) random payoffs.
- Assume players learn strategies with reinforcement learning
- What happens?

Γ = correlation of payoff to player 1 vs. player 2

Learning: Experience weighted attraction

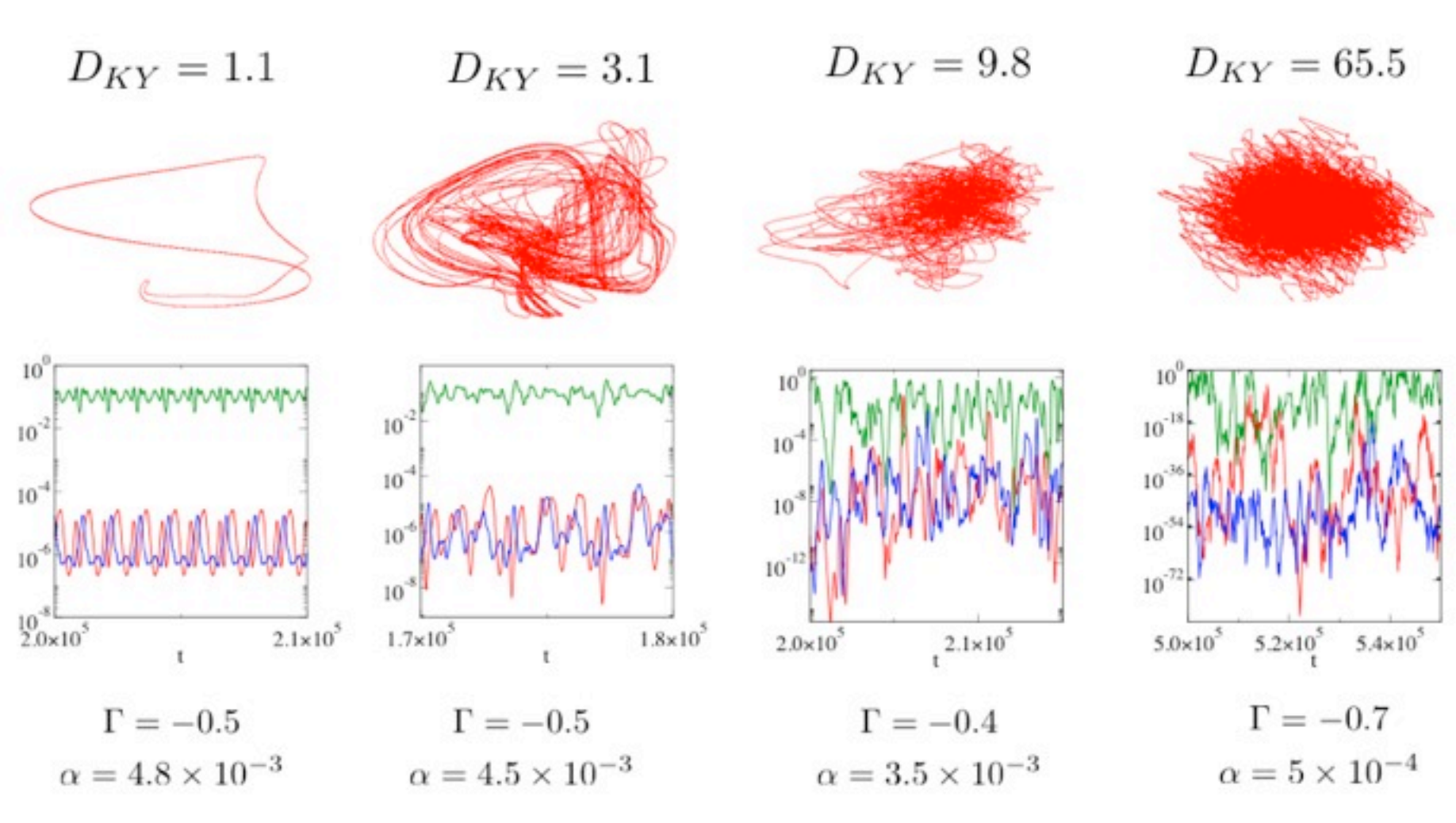
- Reinforcement learning: Players learn strategies based on actions that were successful in the past.

$$x_i^\mu(t) = \frac{e^{\beta Q_i^\mu(t)}}{\sum_k e^{\beta Q_k^\mu(t)}}$$

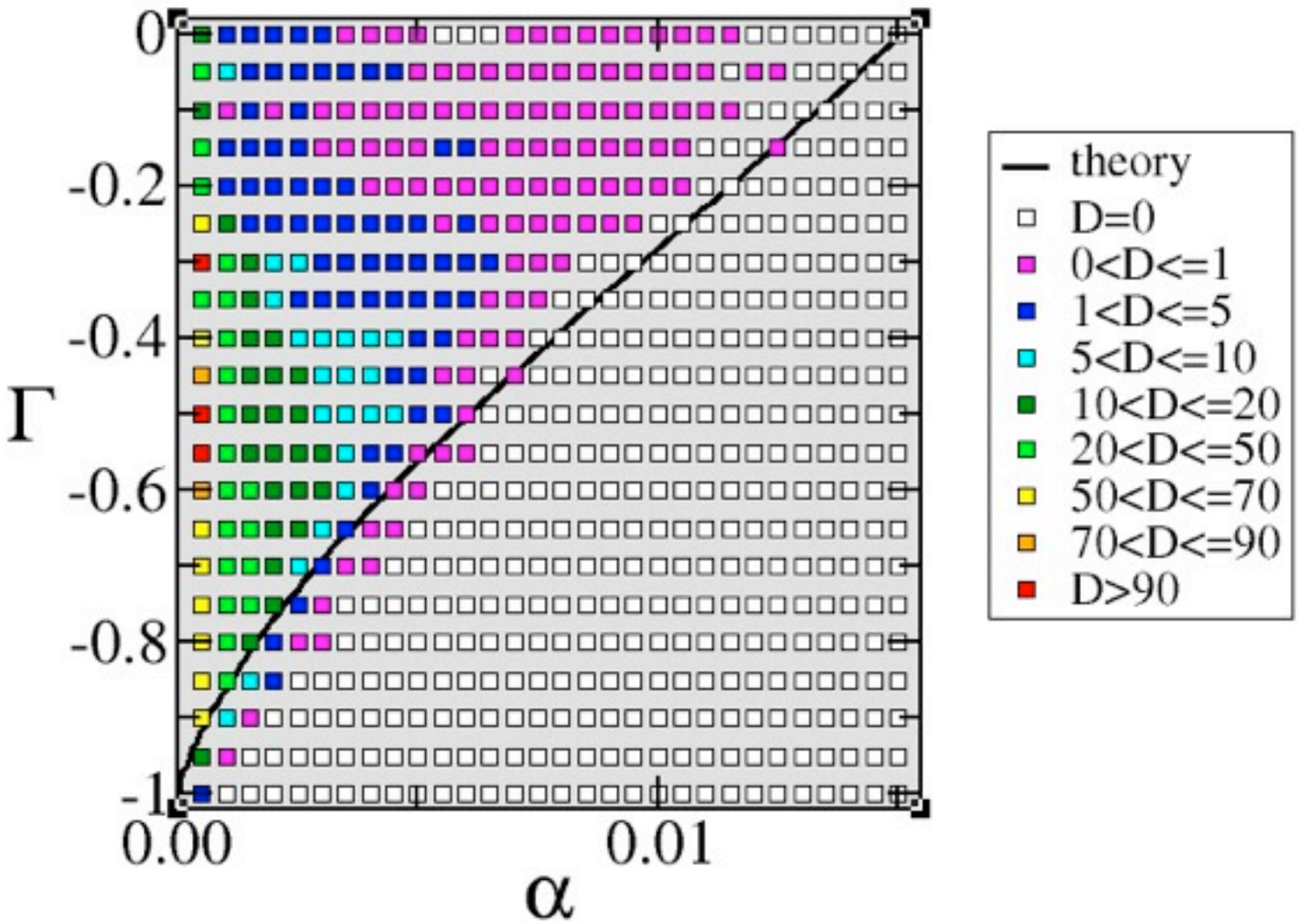
$$Q_i^A(t+1) = (1-\alpha)Q_i^A(t) + \alpha \sum_j \Pi_{ij}^A x_j^B$$

Assume they play enough rounds before updating to get rid of statistical uncertainty

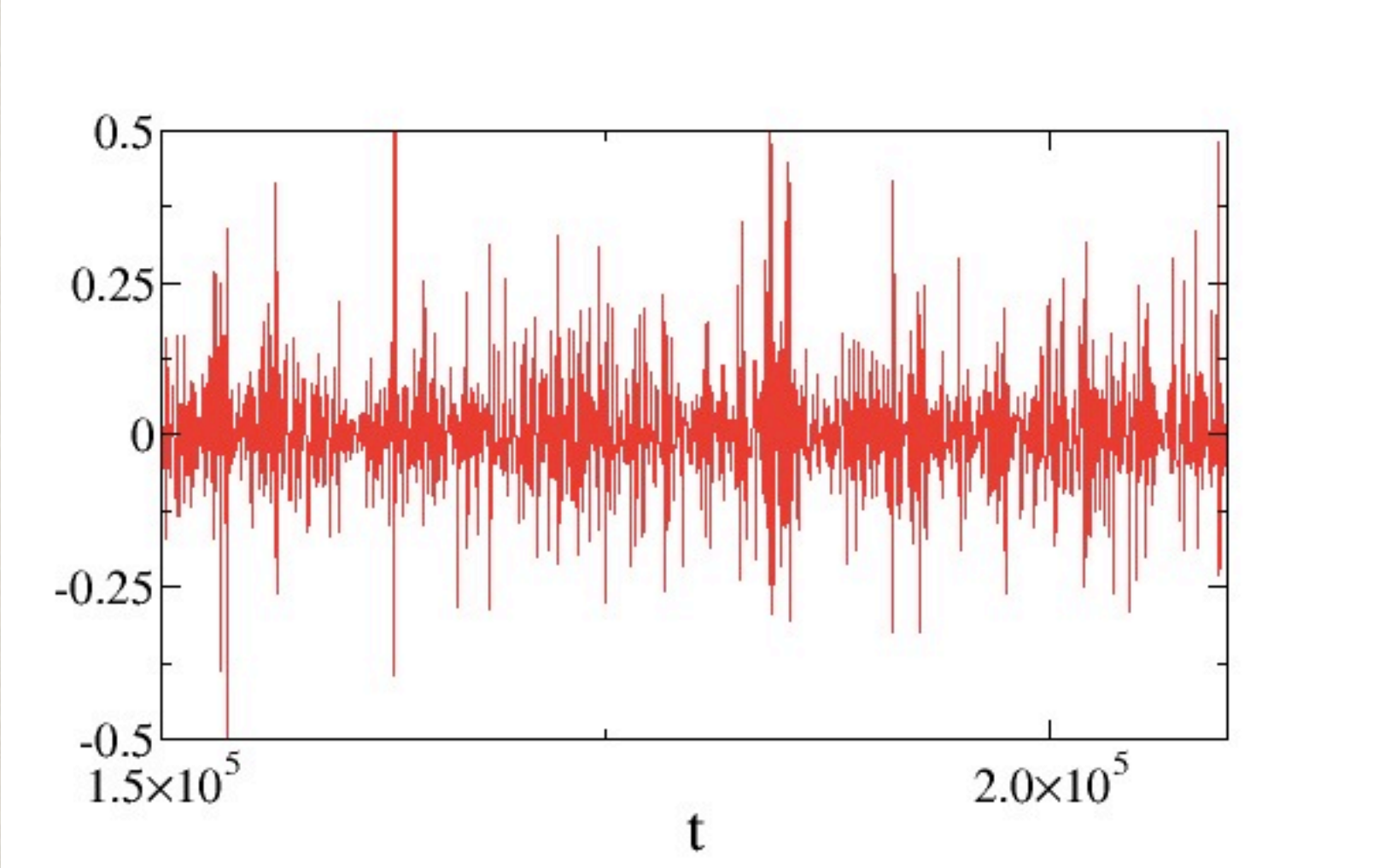
Strategy dynamics



Dimensionality of attractors



TOTAL PAYOFF VS. TIME



Also leads to heavy tails.

What is the key innovation needed?

- Popular idea: Behavioral economics
- Bigger problem: Economy is a complex system.
  - intractability of rationality blocks complexity
  - biggest virtue of behavioralism: It permits more focus on complex, nonlinear interactions
- Need to make entirely new kind of models

Some examples of what agent-based models have already accomplished in economics

Past agent-based models

- Firm size: Axtell
- Financial markets: LeBaron, Lux, SFI stock mkt, ...
- Credit markets: Gallegati, Delligati, ...
- Labor market: Clower and Howitt
- Mortgage prepayment (Geankoplos et al.)
- Leverage in real estate: Khandahani, Lo, Merton
- Energy markets: Tesfatsion
- Gintis, Kirman, ... (many more)
- Whole economy:
  - EURACE project

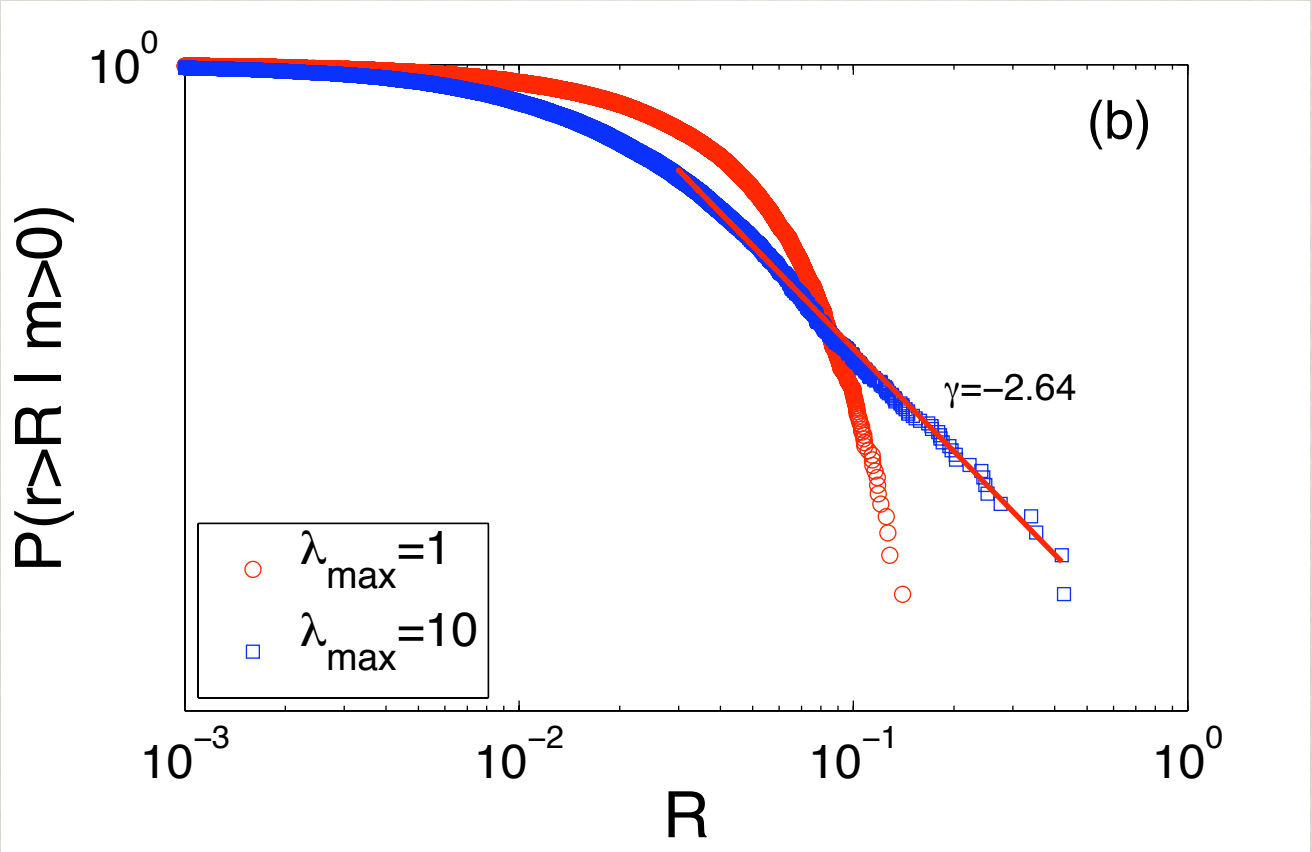
Why do prices have clustered volatility and heavy tails?

- Market returns have power law tails.
- This elementary fact, and the need to explain it, has not been appreciated by economists.
- Standard explanation by mainstream economists:
  - ~ exogenous information arrival
- Explanation by "alternative economists" using agent-based modeling:
  - ~ trend followers + value investors (SFI stock market, Brock & Hommes, Lux & Marchesi, ...)
  - ~ Key difference: Extreme events generated endogenously!

Value investor leverage model

- With Stefan Thurner and John Geanakoplos
- Agents
  - funds (long only value investors)
  - noise traders reverting to a fundamental value
  - investors choosing between fund and cash; base decisions on trailing performance of funds
  - bank lending to funds
- Results
  - clustered volatility, heavy tails
  - "better" risk control can make things worse
- Explanation: Leverage causes positive feedback, banks recall loans, generating adverse price pressure

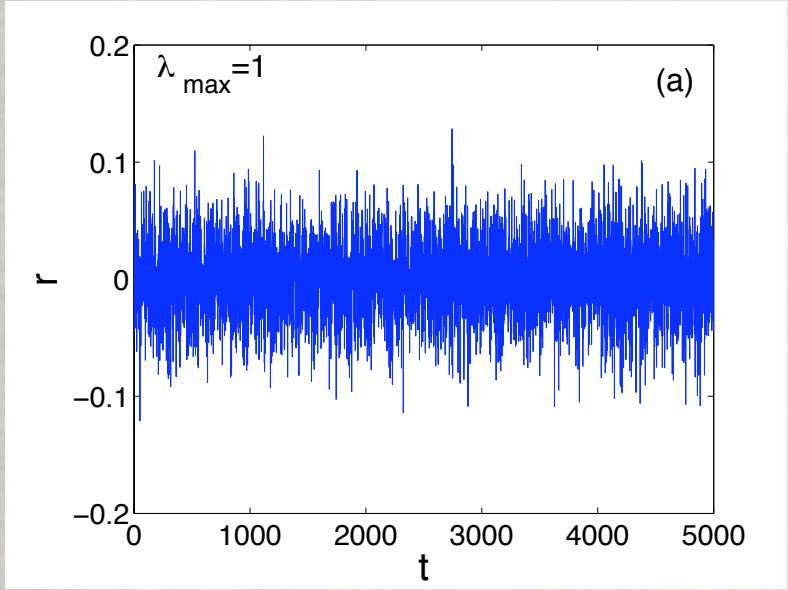
Leverage causes power law tail for stock returns

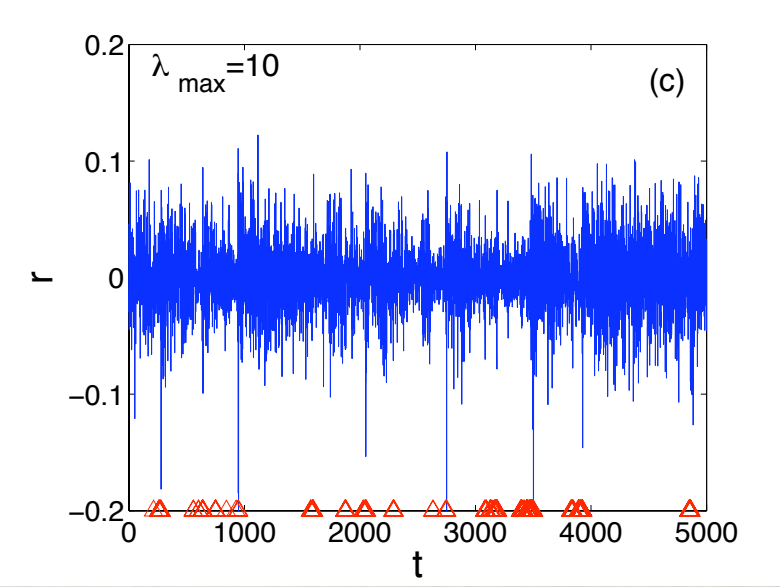


$$P(r > R) \sim R^{-\gamma}$$

Leverage and volatility

Asset returns vs. time





- When mispricing is small, funds lower volatility
- When mispricing is large funds use max leverage, sell into falling market, amplify volatility.
- Extreme events caused by attempt to control risk.
- Leverage tends to increase with time!

What can agent-based models do?

- Qualitative understanding of interactions.
- Reproduce stylized facts
  - ~ Qualitative properties (e.g. heavy tails)
  - ~ Correct functional form (e.g. power law)
  - ~ Correct quantitative properties (e.g. tail exponent, moments of distribution)
- Time series forecasting
  - ~ Caveat: Conditional forecasts of inefficient variables
- Regulatory experiments

Current agent-based models are at best weakly quantitative

- Lots of models that are useful for qualitative understanding of interactions.
- Some qualitatively reproduce stylized facts.
- A few reproduce some quantitative properties.
- Well calibrated models?
- Useful time series forecasts? (Hommes group)

Goals for agent-based modeling

- Quantitative scenario analysis
  - generate crises we haven't seen yet
  - Reproduce current crisis
  - Propagation of sector-specific shocks
- Robustness testing
- Policy testing
  - efficacy of tax policy
  - efficacy of monetary policy
  - efficacy of different approaches to economic stimulus
- Participatory simulation (joystick for decision makers)
- Post mortem analysis
- Early warning indicators

Goals (continued)

- Understanding of distributional properties and how policies may impact them.
- Forecasting
  - conditional vs. unconditional
- Provide explanations and narratives
  - not a black box!
- Ability to test theories about each component
- Provide feedback on level of knowledge in each sub-field
- Crashes, growth: Do booms and bust slow down or speed up the overall growth rate of the economy?
- Macro from micro
- Both positive and normative

Challenges

- Little prior art.
- Gathering micro-data. Need system level view, ideally with identity information. Market ecologies.
- Good agent decision rules
- Developing appropriate abstractions for agents and institutions. What to include, what to omit?
- How to calibrate models?
- Limits to prediction, e.g. stock market.
- Resistance by establishment

Note: Computation is not bottleneck

Design philosophy

- As simple as possible (but no more)
- Design model around available data
- Calibrate each module independently (insofar as possible)
- Standardized historical data sets for testing
- Make full use of domain experts
- Dialogue with end-users
- Plug and play
- Standardized interface so multiple groups can contribute
- Industrial code, modern software standards, open source

Design philosophy

- Systemic investigation of factor sensitivity.
- Should capture moral hazards.
- Could be extremely useful, even if it fails
- To achieve goals need ability to initialize model in current economic state.
- Build model around available data

Example: INET project

- Narrowed scope to build a model of house prices
- "Clamped model", conditional on many exogenous factors:
  - demography (age, income)
  - immigration and emigration
  - interest rates
  - mortgage policy
  - construction
- Requires processing 16 distinct data sets, including real estate records, census, IRS, HUD, mortgage, Case-Shiller, ...
- On each time step, model matches buyers and sellers. Must model house quality.

Threshold for success

- We believe there is a threshold level of effort to achieve success
- Estimate that we need a budget of several million/year for five years.

Comparison: Prediction Company

- Developed successful automated trading strategy for US equities, sold to UBS
- Made so far ~ $500M
- 7 people -> 50 people over 10 year period
  - budget: $1M/year -> $15M/year
- 2 full time data experts, 25 software developers
- Built comprehensive data, modeling, testing infrastructure
- Five years before successful trading model

How to define success?

- Reproduce correct stylized macro-economic facts
- Exceed performance of DSGE and econometric models in at least some categories
- Ability to reproduce past events (crises and bubbles)
- Ability to reproduce cross-sectional statistical measures (M40)
- Reproduce key time series behavior
  - e.g. business cycle with correct magnitude, lag structure
- Provide useful feedback to sub-domains
  - e.g. eliminate some existing theories
- Establish a community of users

Comparison to weather prediction

- Weather prediction has improved dramatically in my lifetime. How was this achieved?
- Prior to 1950: Method of analogues
- 1950: Physics-based weather simulation on ENIAC.
- Overtook method of analogues circa 1980.
- Required: better data, faster computers, better numerical algorithms, better science. Global circulation models directed these efforts.
- At least 100,000 person-years, $50B
- Had support of mainstream. Physics was on their side.

Inadequate funding

The crisis cost the world $5-30 trillion. Compare to US funding levels for other branches of science:

- NSF: SBE budget is $250 million, SES is $100 million
  - SES includes decision science, political science, sociology, law and economics
- $500 million on Polar programs, $375 on ocean programs
- FY 2009 increment in the physics/math ≈ SBE budget!
- Budget for Office of CyberInfrastructure ≈ SBE budget
- Anthropology, archaeology and political science NSF is the only source of Federal research money; sociology + social psychology, NSF is 1/2 of Federal funding
- Economics: $30 million; median project $75K (w/overhead)
- Europe is funding agent-based modeling more aggressively.

Time investment in 3 methods so far?

- Econometric models: 30,000 person-years?
- DSGE models: 20,000 person-years?
- Agent-based models: 500 person-years?

Current funding
(my projects only)

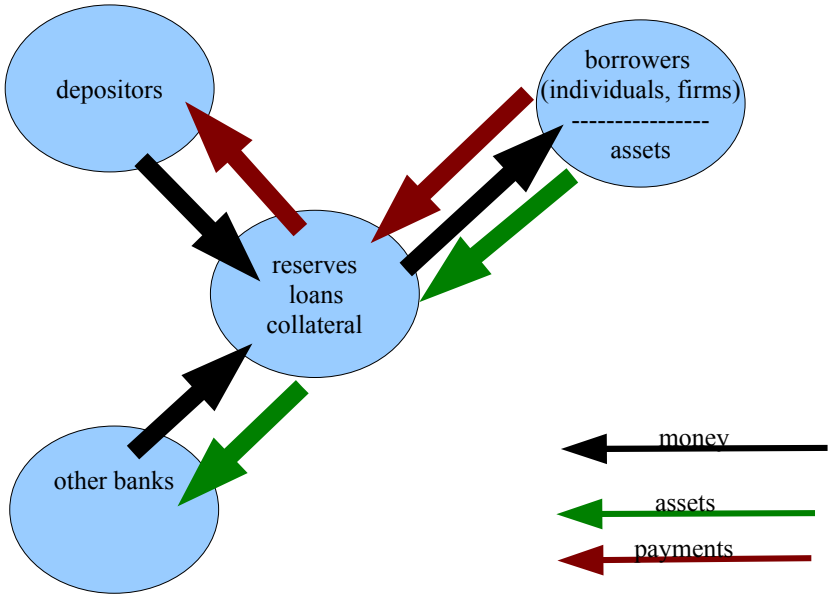
- $375K: INET project to fund crisis from an American point of view: (Rob Axtell, John Geanakoplos, Peter Brown)
- $450K: NSF project to develop agent-based models of systemic risk. (John Geankoplos, Fabrzio Lillo, Stefan Thurner)
- $120K: Sloan funding for data analysis of systemic risk (Dan Rockmore)
- 3.3M euro (pending) CRISIS project. (Delli Gatti, Bouchaud, Hommes, Gallegati, ...)

Summary

- Building quantitative agent-based models, capable of time series forecasting, is a daunting project. A dirty job.
- Nonetheless, it will inevitably become a major component of economists' toolkit.

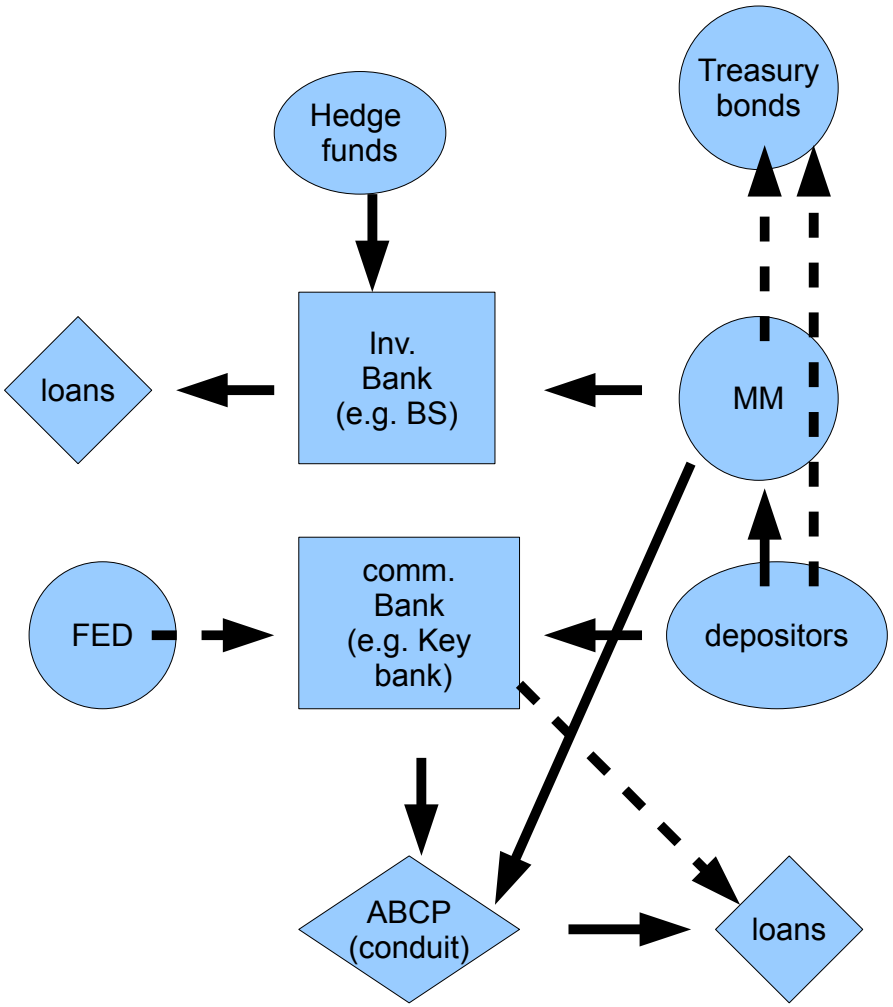
Model of bank

- Key state variables are:
  - cash reserves
  - securities (collateral)
  - loans

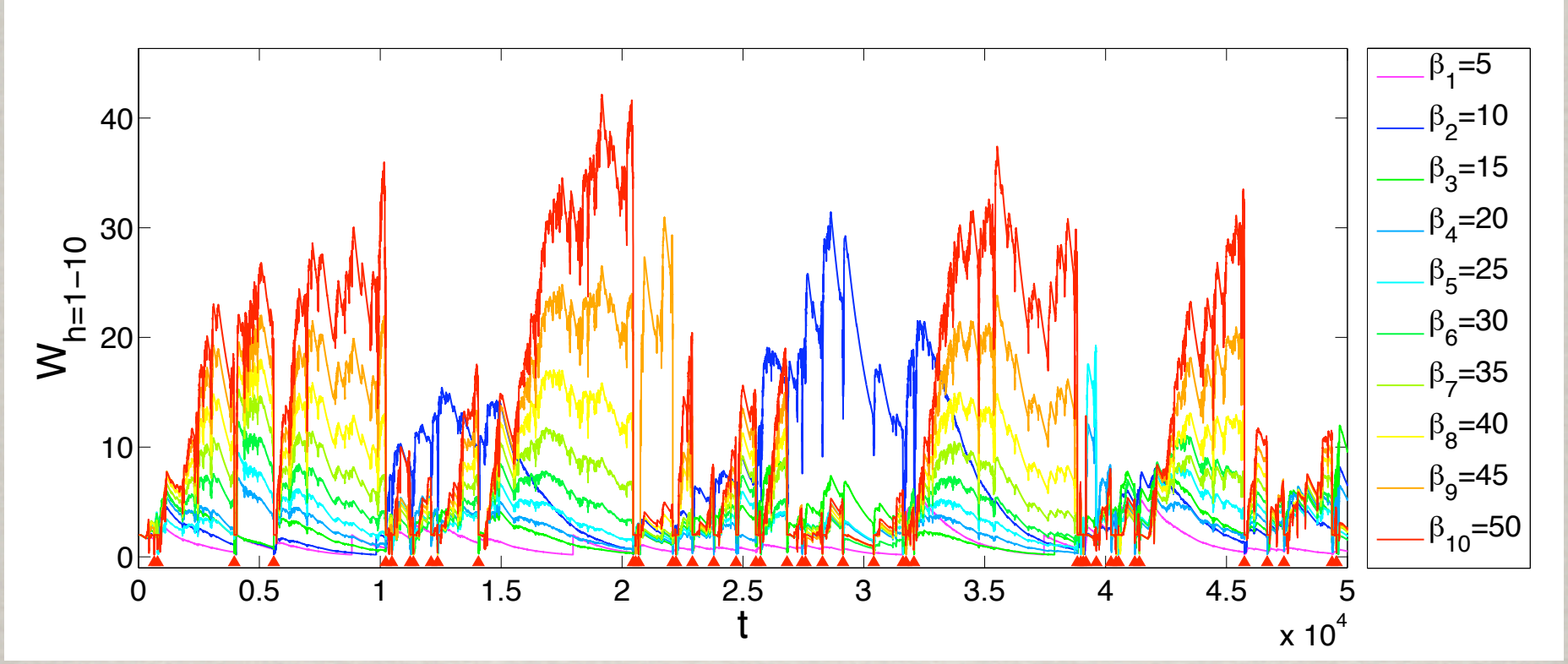


- Focus on maturity transformation, interbank lending, leverage

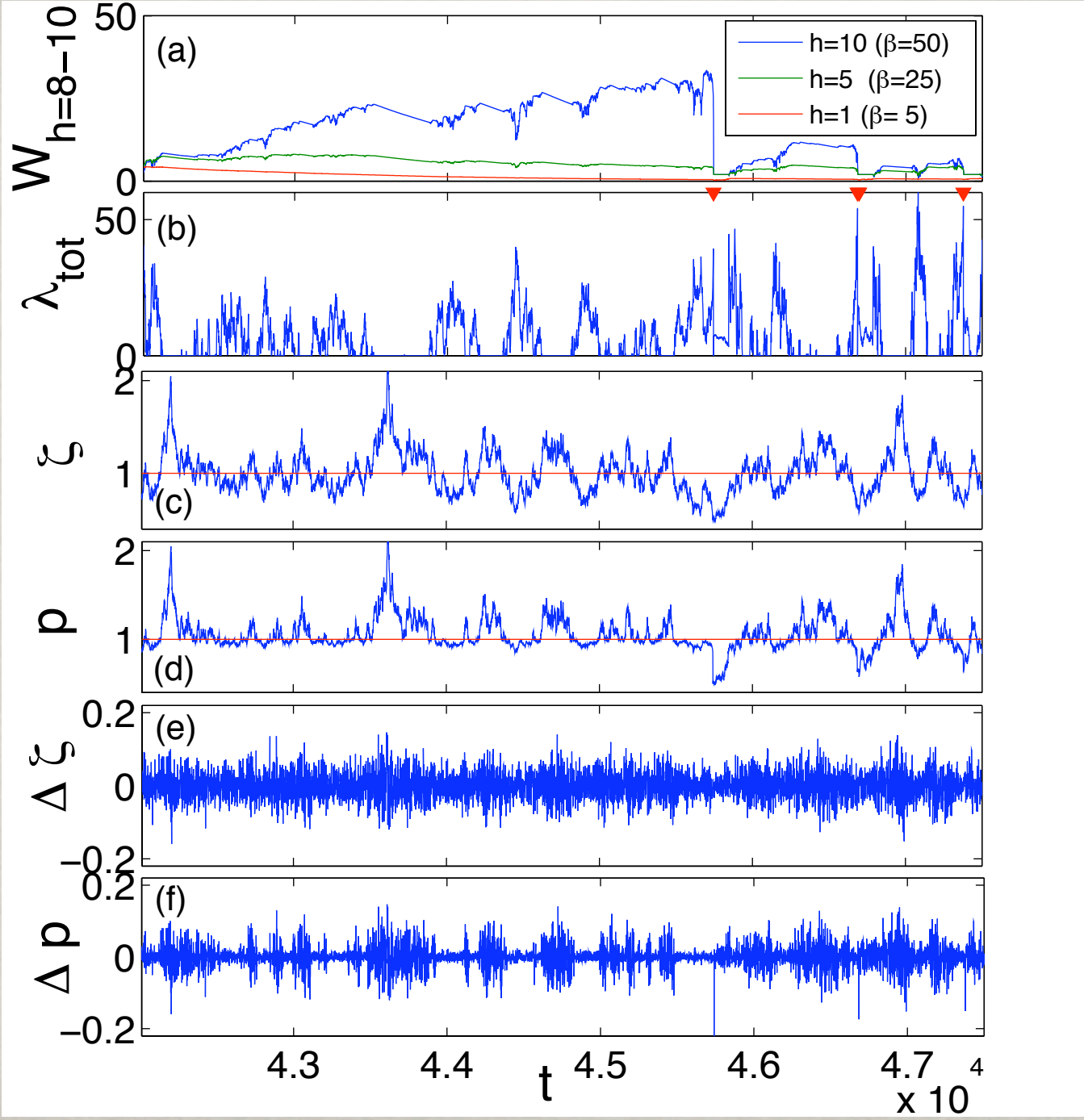
Shadow banking system



Wealth vs. time, 10 funds



- Hedge fund wealth fluctuates
- There are crashes
- Evolutionary pressure favors more aggressive funds, but not exclusively


(a)
h=10 (β=50)
h=5 (β=25)
h=1 (β= 5)
W h=8−10
50
0
(b)
λtot
50
0
(c)
ζ
2
1
(d)
p
2
1
(e)
Δ ζ
0.2
0
−0.2
(f)
Δ p
0.2
0
−0.2
4.3
4.4
4.5
4.6
4.7
t
x 10 4