The challenge of building agent-based models of the economy

Dutch National Bank

Amsterdam, November 3, 2011

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Outline

- Why do we need agent-based models?
- What have agent-based models already done?
- What can they do?
- What are the key steps that need to be taken to realize potential? What resources are required?

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. Makes it possible to incorporate behavioral assumptions.
- 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

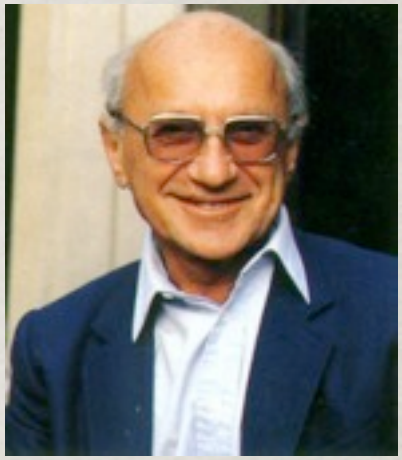
Ric Mishkin, Sept 2007: Fortunately, the overall financial system appears to be in good health, and the U.S. banking system is well positioned to withstand stressful market conditions,"

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

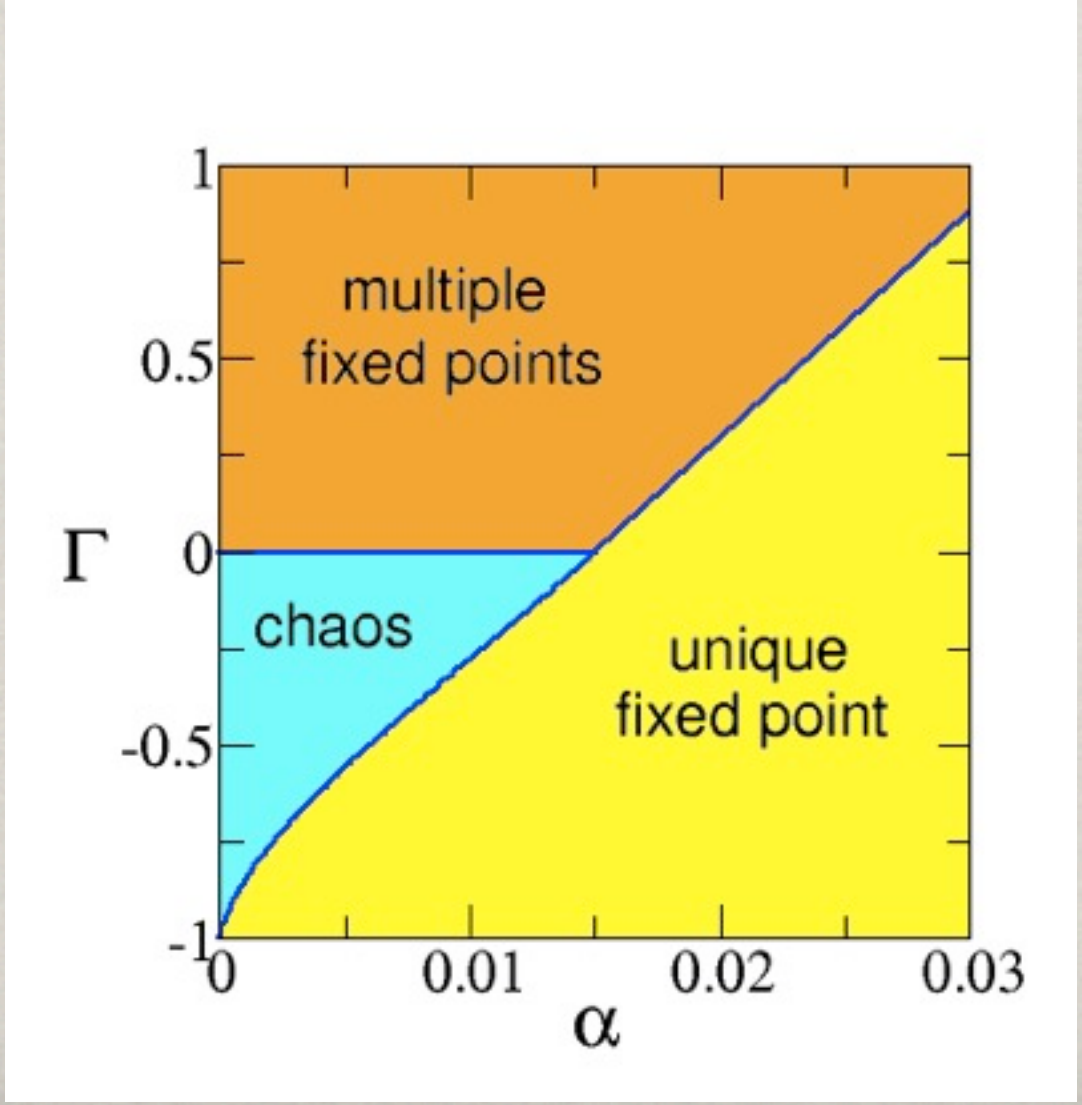
- Reinforcement learning: Players learn strategies based on actions that were successful in the past.

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

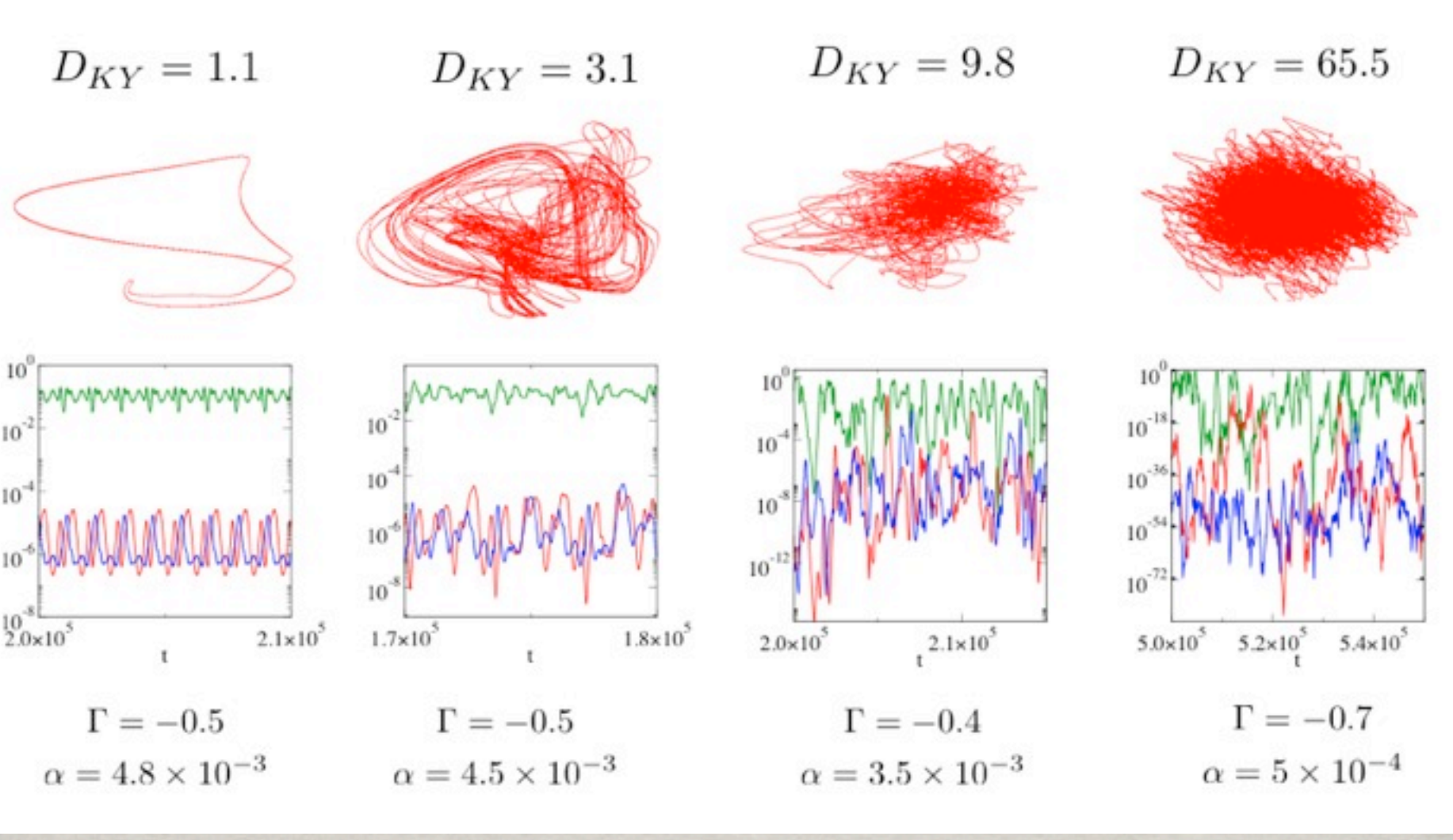
$$Q_i^A(t+1) = (1-\alpha)Q_i^A(t) + \alpha \sum_j \Pi_{ij}^A x_j^B$$

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

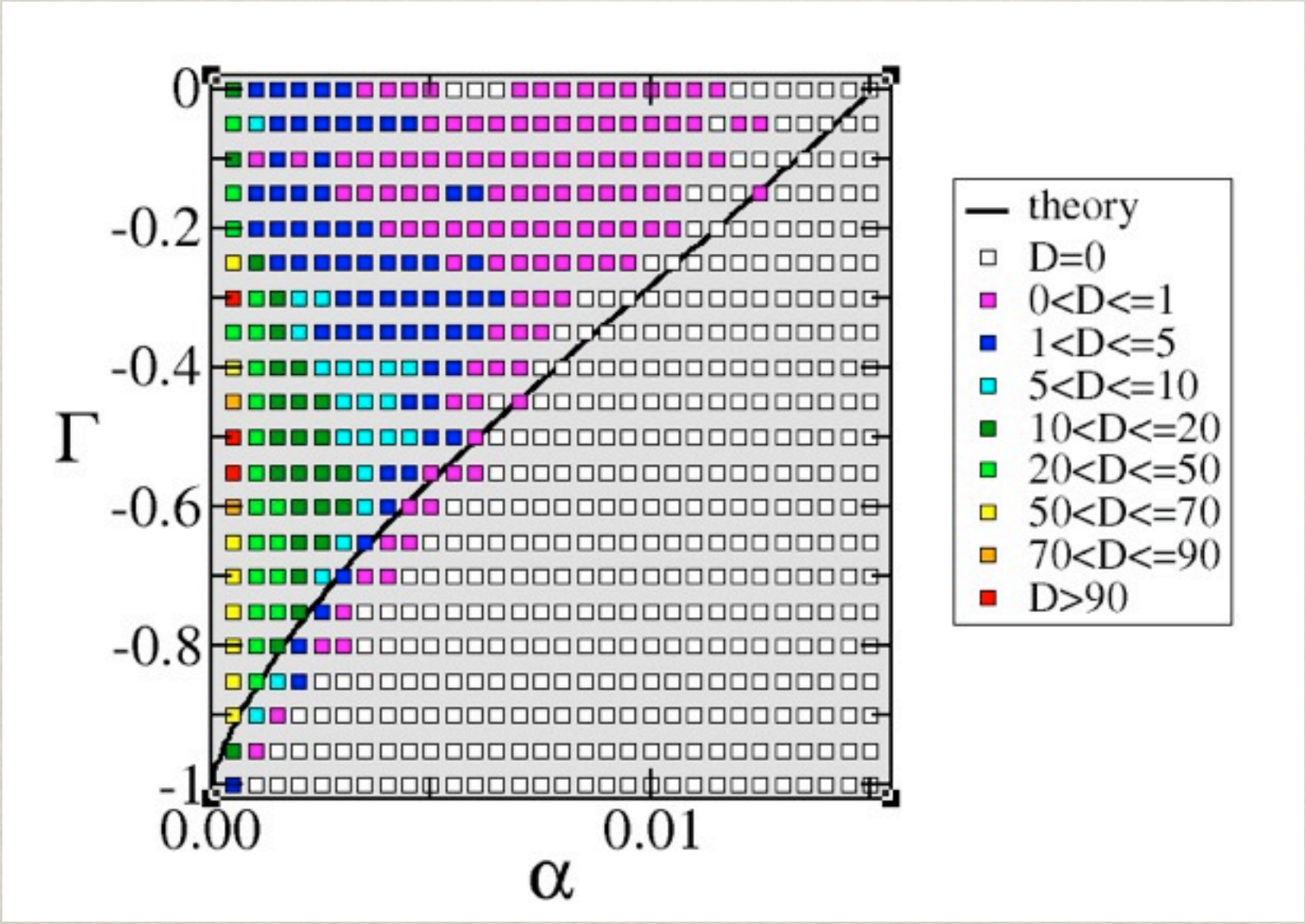
Phase diagram



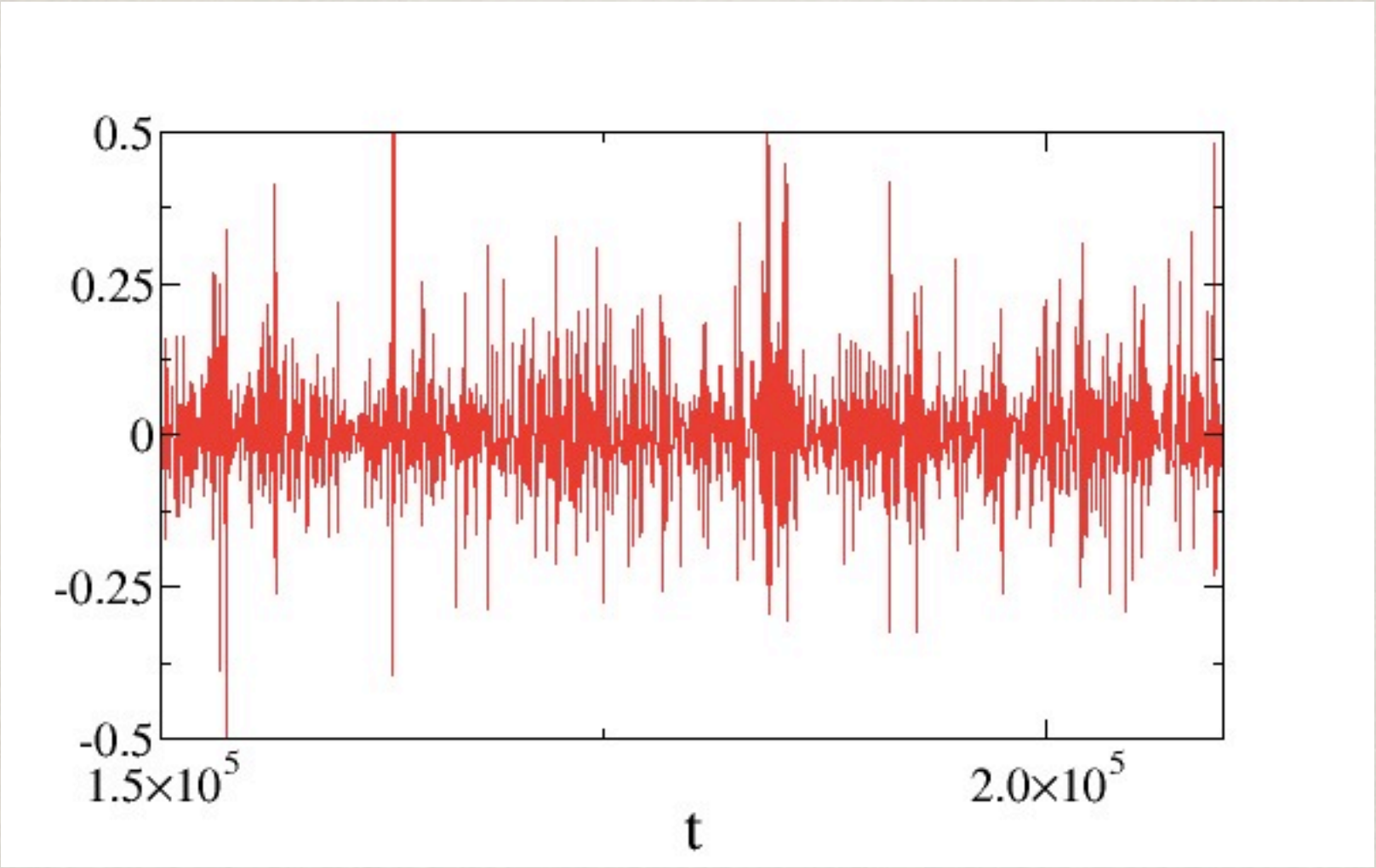
Strategy dynamics



Dimensionality of attractors



TOTAL PAYOFF VS. TIME

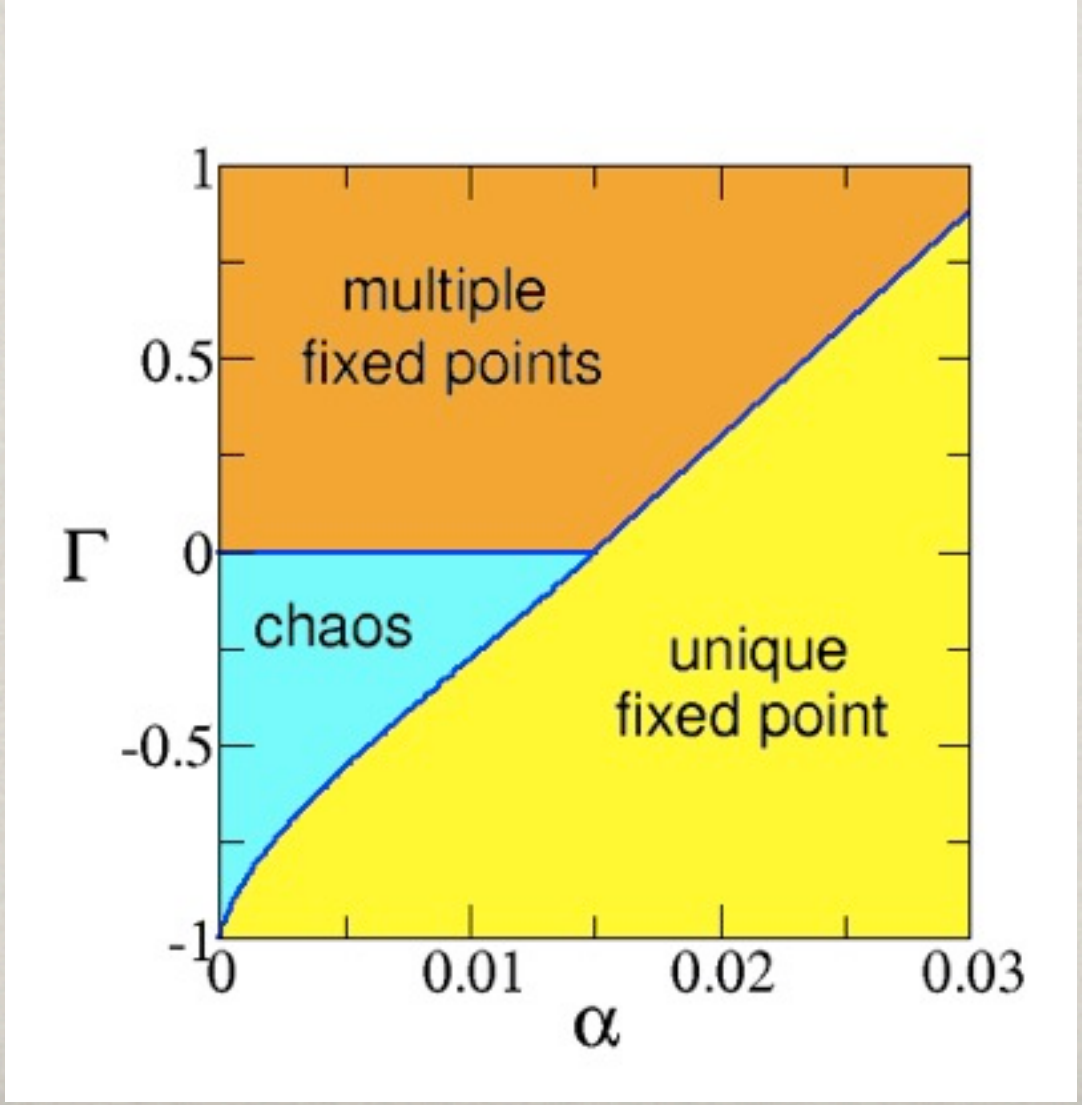


Also leads to heavy tails.

Conclusion

- If real world is in upper - left half of parameter space, standard equilibrium models for resolving Lucas critique are sure to fail.

Phase diagram



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 and feedbacks that are pervasive in economic phenomena.
  -

EXAMPLES OF WHAT AGENT-BASED MODELS HAVE ALREADY ACCOMPLISHED

Engineering successes of agent-based modeling elsewhere

- Traffic: Study of city of Portland, Oregon. Has become powerful tool for city planning.
- Epidemiology: Best method of predicting spread of epidemics. Can test policies, such as selective vaccination.
- Common feature: Constraints due to "institutions" are large, limited role of human decision making. Good data.
- Economics is more challenging because of increased dependence on decision making.

AGENT-BASED MODELS IN ECONOMICS

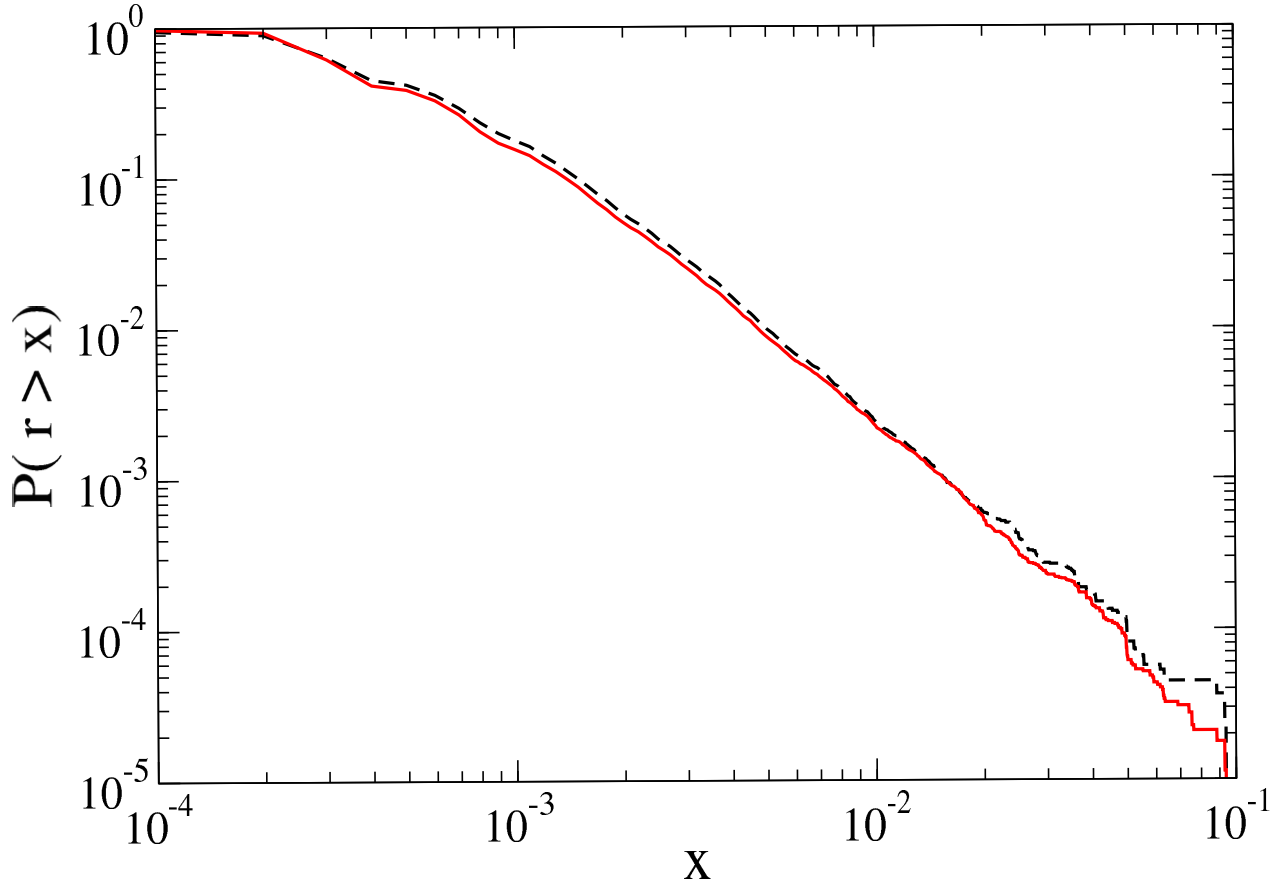
- Firm size: Axtell
- Financial markets: LeBaron, Lux, SFI stock mkt, ...
- Credit markets: Gallegati, Delligati, ...
- Labor market: Clower and Howitt
- Mortgage prepayment (Geanakoplos et al.)
- Leverage in real estate: Khandahani, Lo, Merton
- Energy markets: Tesfatsion
- Labor market decision making: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

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?

Why do prices have clustered volatility and heavy tails?

- Market returns have power law tails.
- The need to explain this has not been appreciated by the majority of 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!


10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
P(r > x)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x

Largest S&P index moves 1946-87

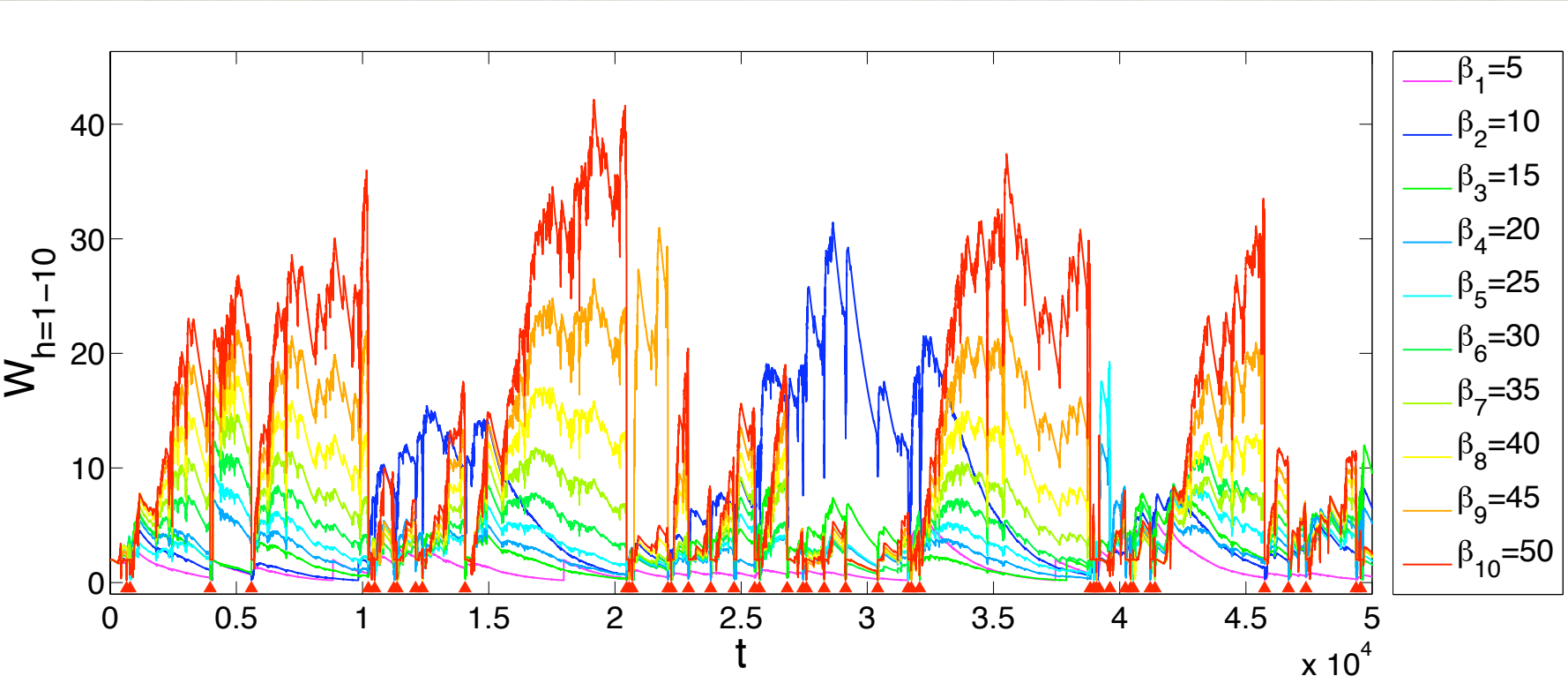
(Cutler, Poterba, Summers 1989)

Rank	Date	%	NY Times explanation
1	Oct 19, 1987	-20.5	Worry over dollar decline and rate deficit Fear of US not supporting dollar
2	Oct 21, 1987	9.1	Interest rates continue to fall Deficit talks in Washington Bargain hunting
3	Oct 26, 1987	-8.3	Fear of budget deficits Margins calls Reaction to falling foreign stocks
4	Sep 3, 1946	-6.7	"No basic reason for the assault on prices"
5	May 28, 1962	-6.7	Kennedy forces rollback of steel price hike
6	Sep 26, 1955	-6.6	Eisenhower suffers heart attack
7	Jun 26, 1950	-5.4	Outbreak of Korean War
8	Oct 20, 1987	5.3	Investors looking for quality stocks
9	Sep 9, 1946	-5.2	Labor unrest in maritime and trucking
10	Oct 16, 1987	-5.2	Fear of trade deficit Fear of higher interest rates Tension with Iran
11	May 27, 1970	5.0	Rumors of change in economic policy "stock surge happened for no fundamental reasons"
12	Sep 11, 1986	-4.8	Foreign governments refuse to lower interest rates Crackdown on triple witching announced

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

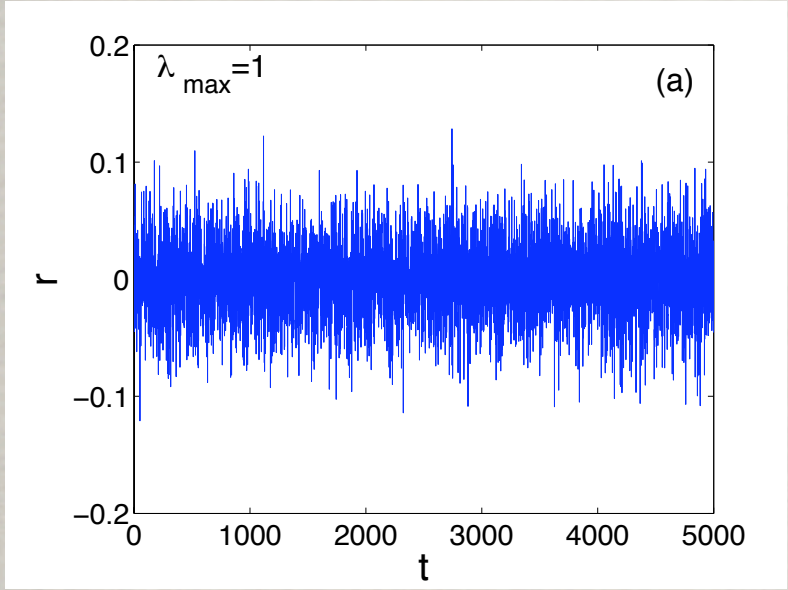
Wealth vs. time, 10 funds

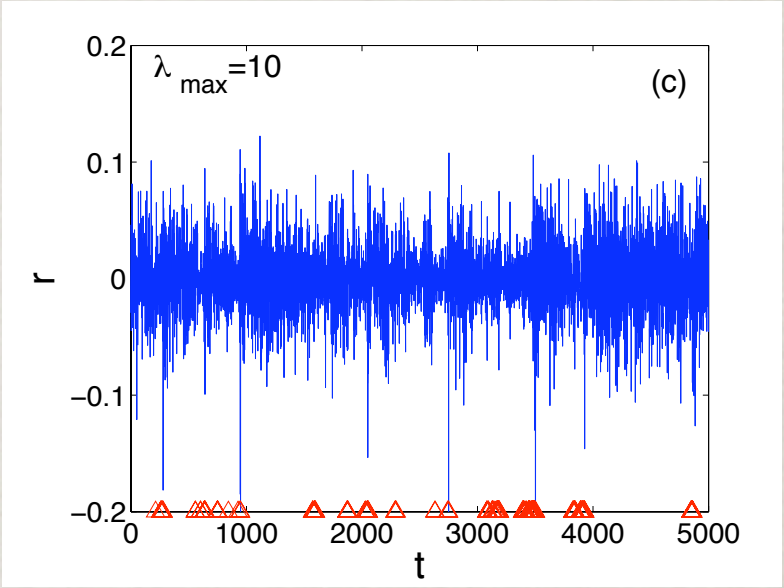


- Hedge fund wealth fluctuates
- There are crashes
- Evolutionary pressure favors more aggressive funds, but not exclusively

Leverage and volatility

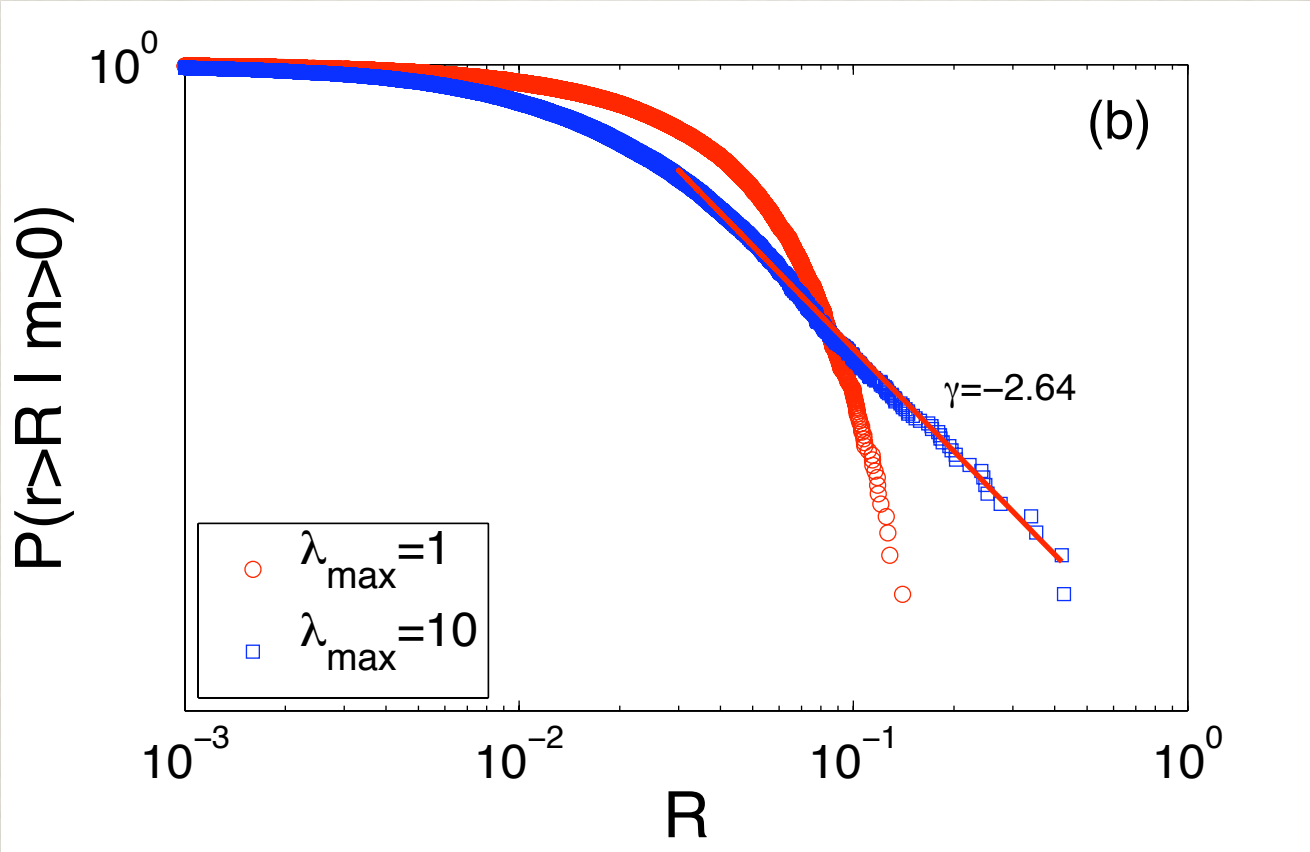
Asset returns vs. time





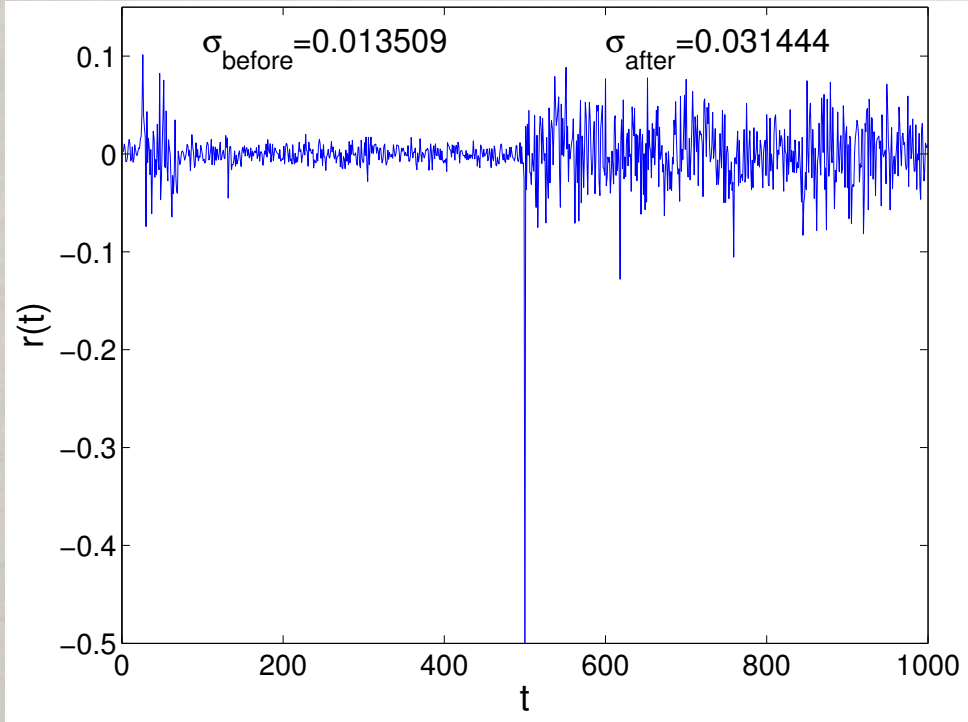
- When mispricing is small, funds lower volatility
- When mispricing is large funds use max leverage, sell into falling market, amplify volatility.
- Extreme events caused by attempt to control risk.
- Leverage tends to increase with time!

Leverage causes power law tail for stock returns



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

What causes clustered volatility?



- Prior to crash:
  - Funds get wealthier
  - Volatility is damped
  - Leverage builds
- After crash:
  - Funds are poor
  - Volatility not damped
  -

Conclusion

- Agent-based model show that two possible mechanisms reproduce basic phenomena:
  - clustered volatility
  - power law tails with tail exponent in range 2-4.
- Not clear how much each of these operates in real market. May be other causes as well.
- Both suggest key is nonlinear feedback in price formation.
- Leverage model generates systemic risk: Bank's risk control is source of problem.
  - "more sophisticated" risk control makes it worse

What can agent-based models do?

Different levels of understanding

- 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
- Alternative policies

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
  - tax policy, monetary policy, fiscal stimulus, macro-prudential rules,
- Participatory simulation (joystick for decision makers)
- Post mortem analysis
- Early warning indicators
- Macro from micro
- Provide narratives
- Provide feedback to subfields: Where are bottlenecks?

Current agent-based models are only weakly quantitative

- Lots of models that are useful for qualitative understanding of interactions.
- Some qualitatively reproduce stylized facts.
- A few reproduce some quantitative properties.
- None are capable of convincing skeptics they match reality.
- Must make useful time series forecasts (like what Hommes group has done in experiments)

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 (when possible)
  - Microcalibrate against micro-data
  - Make full use of domain experts
  - Time series forecasts
- Build in incentives, moral hazard
- Carefully explore model sensitivities
- Dialogue with end-users
- Plug and play
- Standardized interface (facilitate inter-group collaboration)
- Industrial code, software standards, open source

Example: INET project

- Agent-based model of house prices.
- Must model house quality.
- "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, U.S. census, IRS, HUD, several mortgage sources, Case-Shiller, ...
- On each step, model matches buyers and sellers.

Objective

- Develop a housing market model for Washington, DC metro
- Explore major factors causing the bubble
- Intended output targets of the model
  - Case-Shiller Index
  - Days on Market (DOM)
  - Foreclosure/Delinquency Rates
- Take all other variables as exogenous inputs and make conditional forecasts and analysis

Model Overview

- Agents
  - Households
  - (exogenous: banks, houses, ...)
- Basic Algorithm
  - Update housing stock
  - Update agent population (lifecycle, migration,...)
  - Agents do non-interactive behaviors
    - receiving income and consuming
    - deciding whether to default
    - whether to buy or sell; etc.
  - Execute the housing market matching algorithm

Update Housing Stock

- Add or remove houses according to the data.
- Currently perform calculation using vacancy rate & # of households.
- CoreLogic data on residential housing stock
- Quality of home decreases when foreclosed.

Update Agent Population

- Add appropriate number of agents to account for changing demographics.
  - IRS Data - Estimate of households based upon tax returns (1/97 - 12/2009).
  - CoreLogic Data - Total Households (1/2000 - 6/2011)
- Increase agent's age allowing for mortality
  - Dead agents are removed
  - If agent owned a house, the house is listed for sale

Agent Non-Interactive Behaviors

- Receives income - AGI from IRS tax forms
- Expends wealth on non-housing consumption
- If a homeowner with a loan
  - Consider strategic default
  - If not, make monthly payment provided wealth large enough.
  - If not in default, list house for sale?
  - If not listing, consider refinancing.

Agent Non-Interactive Behaviors

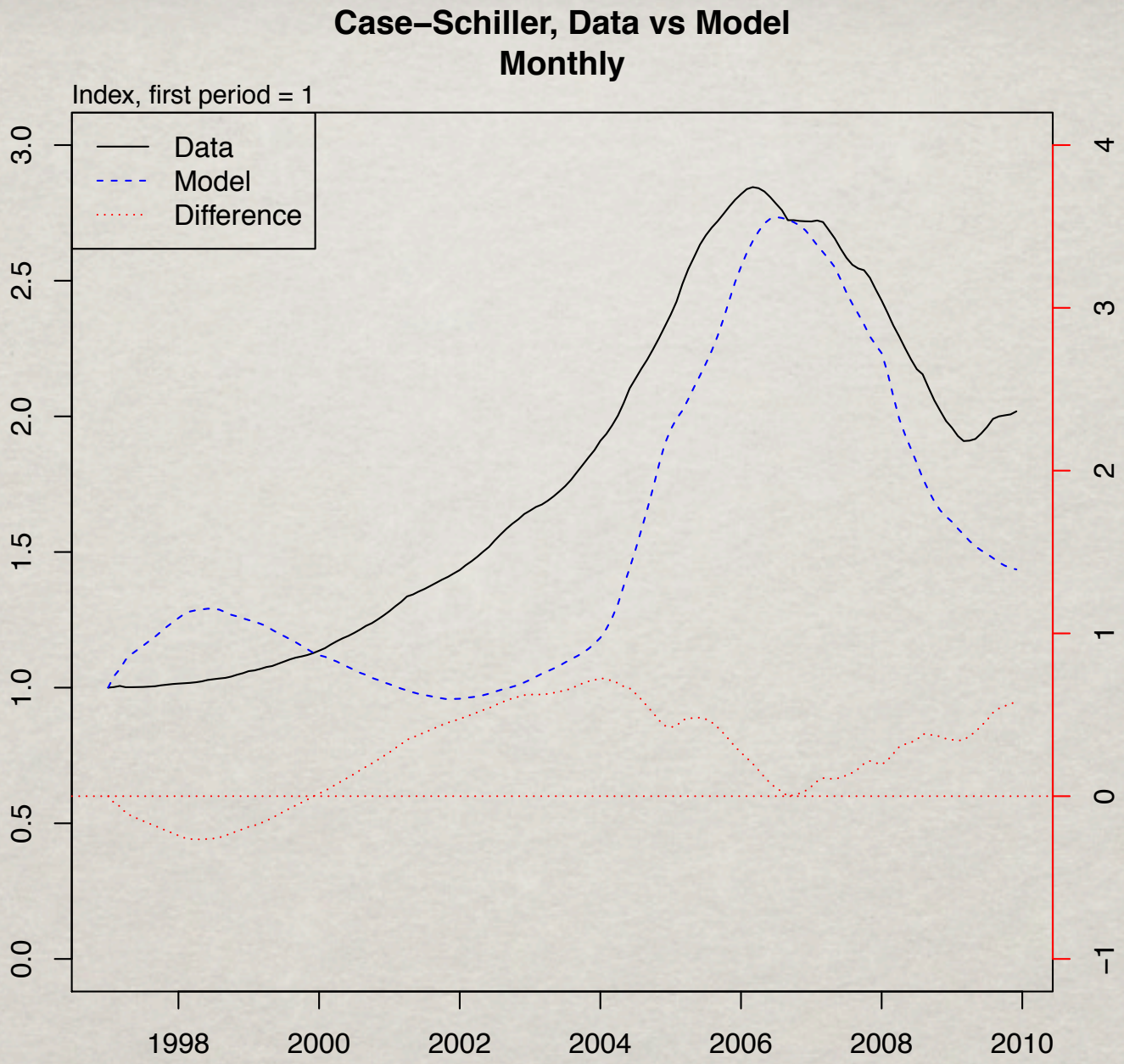
- If a renter
  - Check whether lease is up
  - If so, switch to buyer?
  - If so, perform home purchase algorithm
- If owner who just sold a house
  - Perform home purchase algorithm

Home Purchase Algorithm

- Pick a desired expenditure

$$E = \frac{Y * \epsilon}{3(r + \tau - a\Delta P + b * d)}$$

- Pick a desired downpayment
- Apply for a loan
  - Loan type and interest rates set by banks
  - If necessary, change desired downpayment so that downpayment and monthly payments satisfy banks's constraints.
- Find home meeting financial & quality constraints


Case–Schiller, Data vs Model
Monthly
Index, first period = 1
Data
Model
Difference
3.0
2.5
2.0
1.5
1.0
0.5
0.0
4
3
2
1
0
−1
1998
2000
2002
2004
2006
2008
2010

What resources are required to make agent-based models a useful tool for central bank policy analysis?

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

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 is uncontroversial
- Led to climate modeling
  - learning through failure
  - power of micro-validation

Inadequate funding for economics

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!
- NSF Economics: $30 million; median project $75K
- Europe is funding agent-based modeling, but only through technology programs.

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, Fabrizio Lillo, Stefan Thurner)
- $120K: Sloan funding for data analysis of systemic risk (Dan Rockmore)
- 3.3M euro (pending) CRISIS project. (Delli Gatti, Beinhocker, Bouchaud, Carvalho, Diks, Gallegati, Gulyas, Hommes, Iori, Lillo, Thurner)
- FuturICT?

Summary

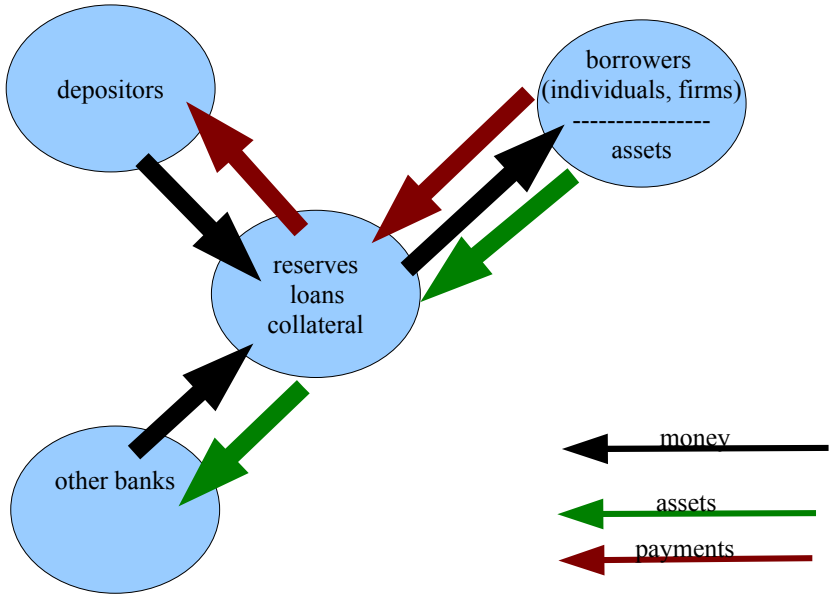
- Building quantitative agent-based models, capable of time series forecasting, is a daunting project. Dirty job. Must keep empirical focus.
- Controversy should be resolved by head-to-head quantitative empirical comparison.
- DSGE vs. Agent-based: Balinese tunnel digging.
- Prediction: Agent-based modeling will become a major component of economists' toolkit.

How to define success?

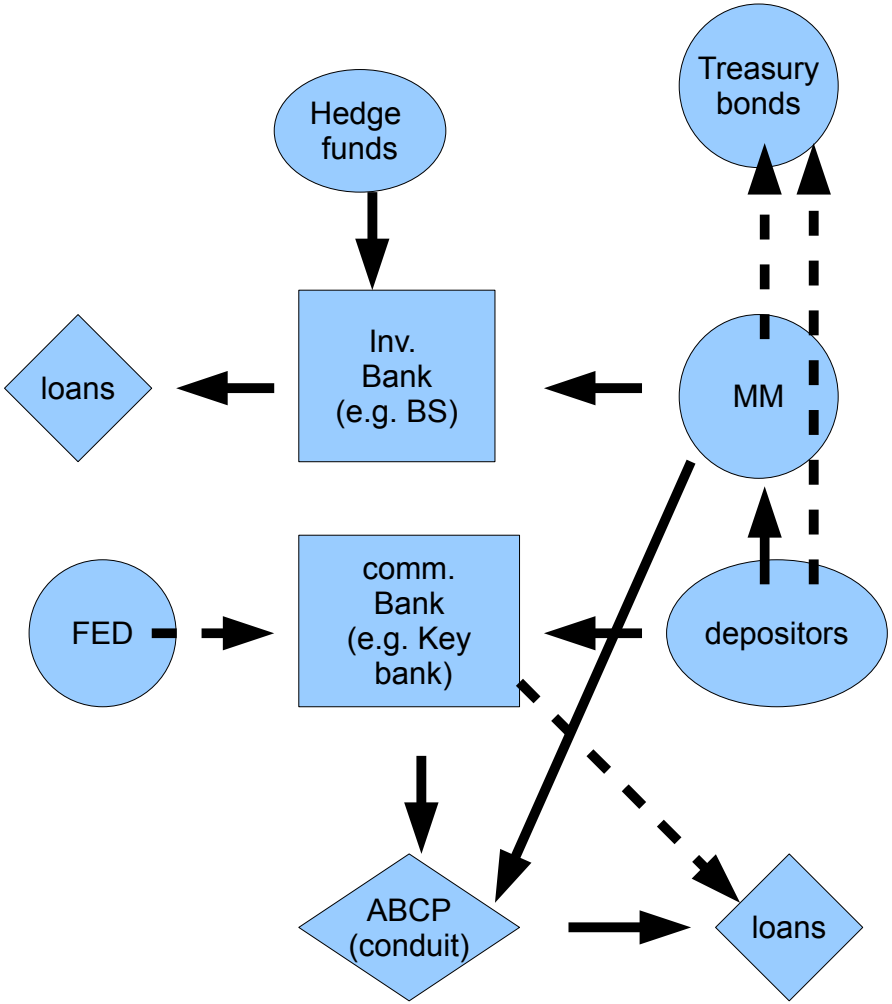
- Reproduce correct stylized macro-economic facts
- Exceed performance of DSGE and econometric models in at least some categories
- Ability to reproduce past events (crises and bubbles)
- Ability to reproduce cross-sectional statistical measures
- Reproduce key time series behavior
  - e.g. business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

Model of bank

- Key state variables are:
  - cash reserves
  - securities (collateral)
  - loans
- Focus on maturity transformation, interbank lending, leverage

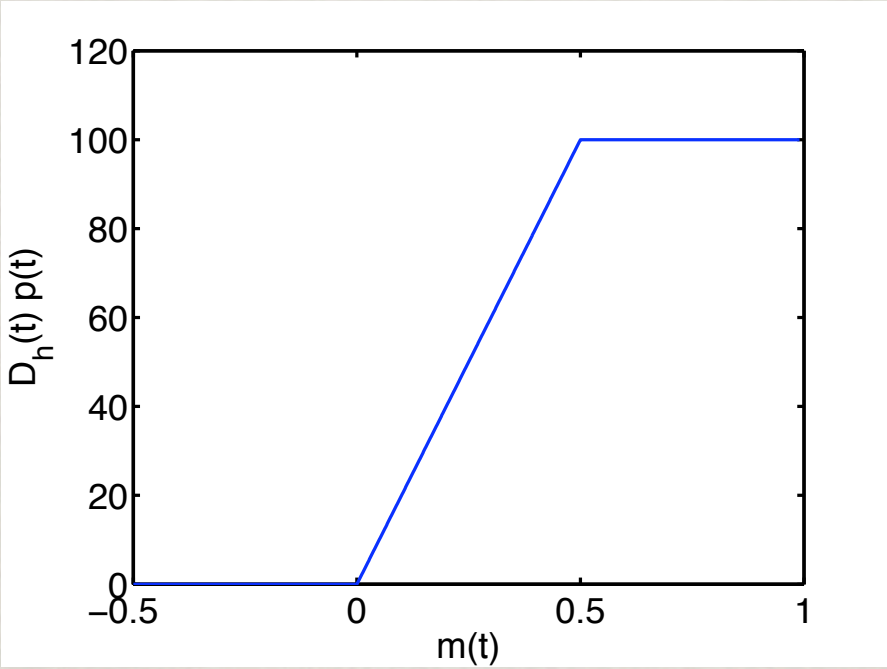


Shadow banking system



Fund demand function

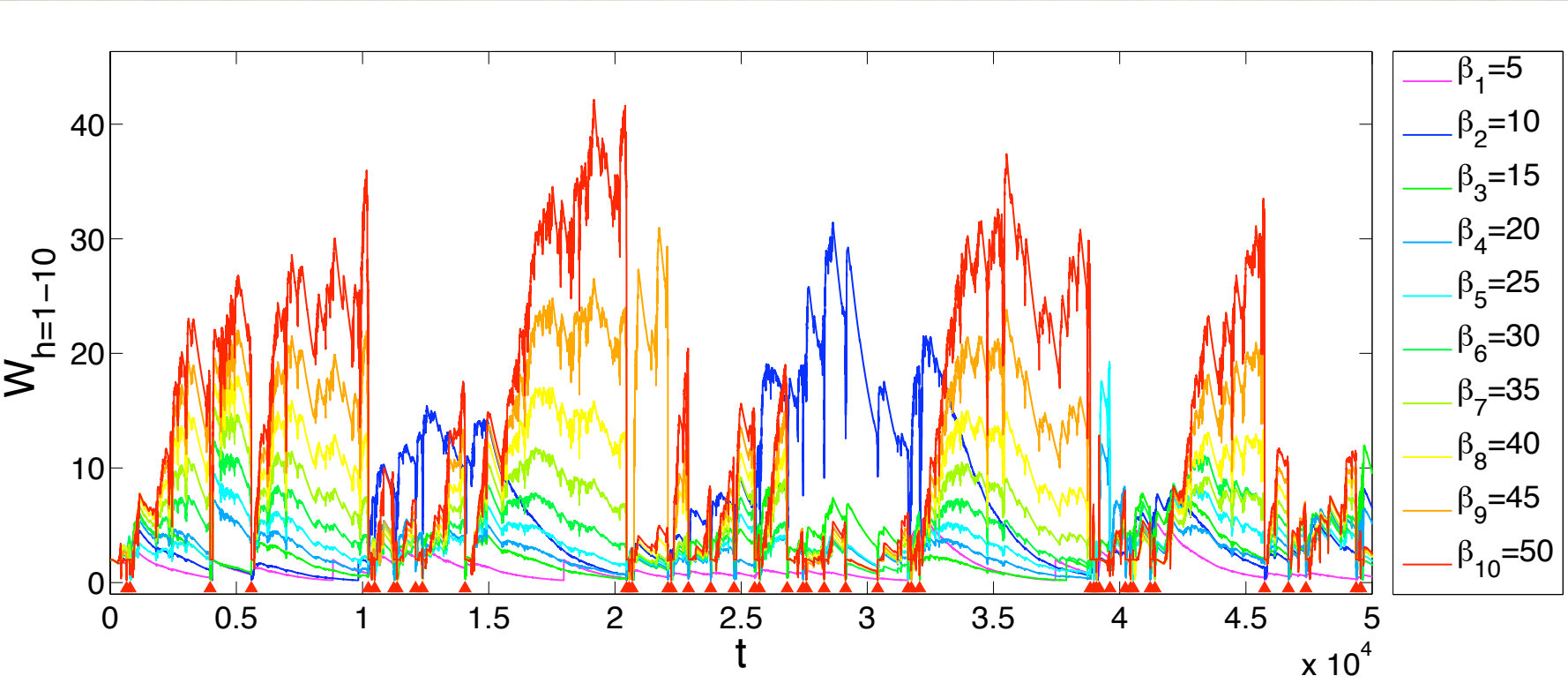
fund demand



mispricing

- Hedge funds can use *leverage*, defined as ratio of value of holdings to their wealth. Maximum leverage is key parameter
- Hedge funds differ in their aggression, i.e. how much they buy for a given mispricing (slope)

Wealth vs. time, 10 funds



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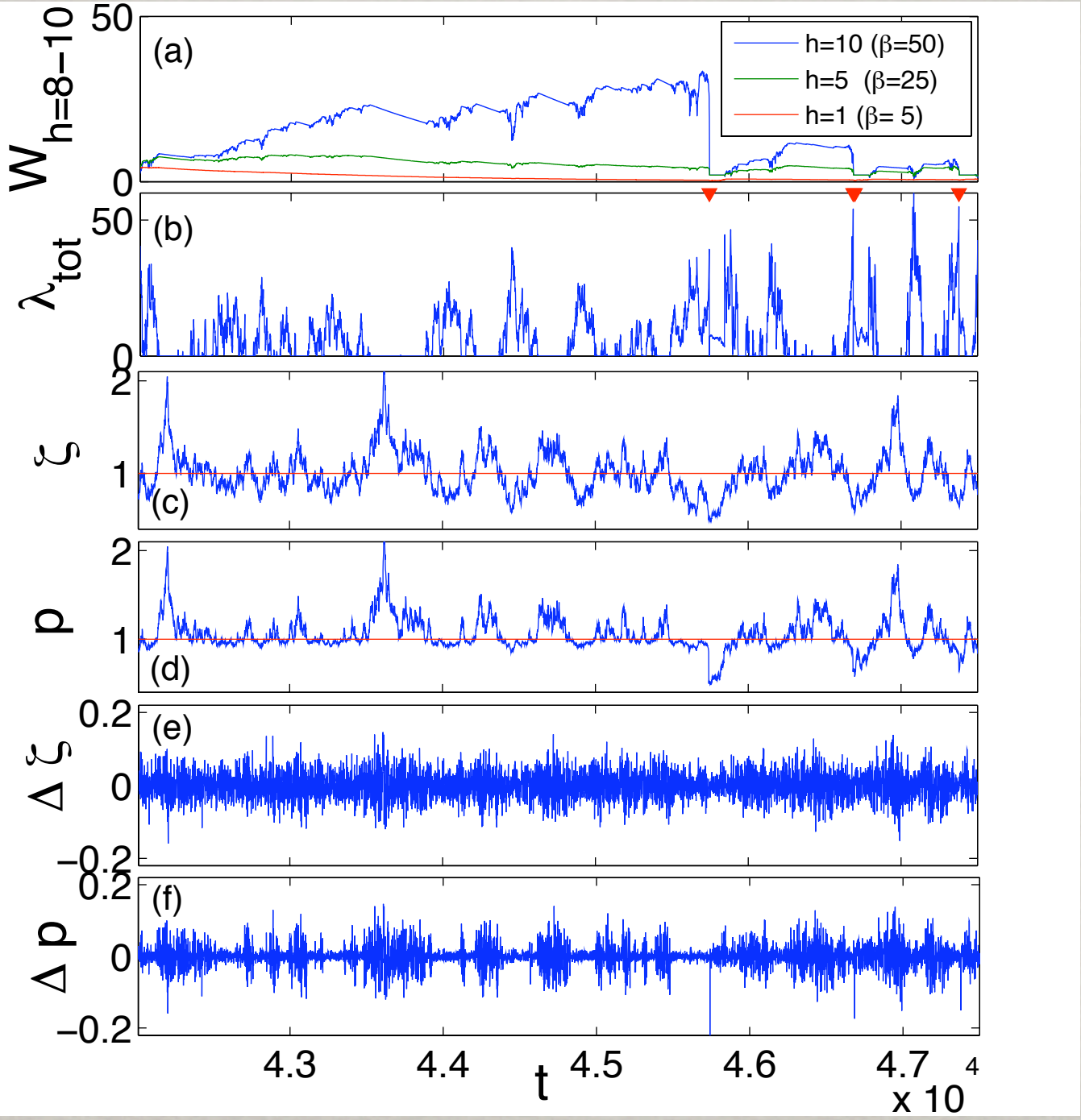
(a)
h=10 (β=50)
h=5 (β=25)
h=1 (β= 5)
W h=8–10
50
0
(b)
λ tot
50
0
(c)
ζ
2
1
(d)
p
2
1
(e)
Δ ζ
0.2
0
–0.2
(f)
Δ p
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0
–0.2
4.3
4.4
4.5
4.6
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t
x 10 4