The (unfortunate) complexity of the economy

15 years of 'Econophysics': a personal view*

see: Nature (30 Oct 2008)
& Physics World (April 2009)

J.P. Bouchaud, Capital Fund Management

*Note: arXiv/q-fin since Dec. 2008; ca. 1000 papers

Why and how do market prices move?

- Crucial question in theoretical Economics and Finance:

  what is the information reflected by prices & to what extent (if any) can markets be trusted?

- Crucial question for investment strategies:

  is there any way to predict how prices will move?

- Crucial question for risk control/regulation:

  understanding why and how prices move allows one to devise efficient risk models and useful regulation (well, maybe)

The Sacred Answer of Theoretical Economics

- Efficient market theory: Agents are rational and Markets are in equilibrium

- Prices reflect faithfully the Fundamental Value of assets and only move because of exogeneous unpredictable news.

- Platonian markets which merely reveal fundamental values without influencing them – or is it a mere tautology??

  Note 1: if we had a way to check, we would not need markets

  Note 2: markets can be (nearly) unpredictable but not necessarily efficient

  Note 3: Black's definition of efficiency: price right to within a factor 2!

- Crashes can only be exogenous, not induced by markets dynamics itself – oh really??

The Aftermath...

- *As I see it, the economics profession went astray because economists, as a group, mistook beauty, clad in impressive-looking mathematics, for truth.* – Paul Krugman, How Did Economists Get It So Wrong, September 2009

- *Research tended to be motivated by the internal logic (...) and esthetic puzzles of established research programs rather than by a powerful desire to understand how the economy works - let alone how the economy works during times of stress and financial instability.* – Willem Buiter, The unfortunate uselessness of most 'state of the art academic monetary economics, March 2009

...and the defenders

- *I'm less convinced that we require a major paradigm shift. Despite suggestions to the contrary, I've yet to see the evidence that progress requires moving beyond the intellectual boundaries in which most economists already live.* – David Altig, Atlanta Fed, September 2009

- *I think that calls for a radical reworking of the field go too far. [...] The financial crisis did not discredit the usefulness of economic research and analysis by any means*,

  still: *The crisis should motivate economists to think further about their modeling of human behavior. Most economic researchers continue to work within the classical paradigm that assumes rational, self-interested behavior and the maximization of expected utility*,

  and: *Another issue brought to the fore by the crisis is the need to better understand the determinants of liquidity in financial markets. The notion that financial assets can always be sold at prices close to their fundamental values is built into most economic analysis...*

  – Ben Bernanke, Princeton, September 2010

Indeed...

- Agents (us humans) do make errors and have regrets, (cognitive or sensorial biases, imperfect or superabundant information, overconfidence, urgency, negligence, etc.)

- Problems can be algorithmically so complex that we have to make suboptimal decisions based on heuristic rules

  – Agents are deeply influenced by the behaviour of others (who might have more information)

  – Agents are deeply influenced by past patterns (that might repeat)

- Flimsy information, on which investors trade and by doing so randomly impact prices – on short to medium time scales, prices are weakly anchored by fundamentals

Indeed...

- Flimsy liquidity: Even silly trades do impact market prices and the above mechanims lead to positive feedback loops

The trouble with Financial Engineering

- Rooted in the idea that dynamics is exogenous and markets are efficient, Financial Engineering takes prices at face value and:

- (1) postulate any process that
  - is tractable
  - looks vaguely similar to real data – or not even

- (2) brute force calibrate, on "liquid" markets (supposed to be efficient)

- Examples: Brownian motion (Black-Scholes), GARCH, Heston, Local vol., Lévy, Multifractal, etc. , etc., etc.

BUT

- NONE of these models are justified by "first principles", or agent based models, such that parameters can be *computed*, e.g. Navier-Stokes from molecules

- Uncontrolled brute force calibration are often

  – based on models absurdly remote from reality (e.g. local volatility models, Archimedean copulas, etc.)

  – can be dangerous: errors and biases are amplified in a non-linear way – cf. the BS feedback loop in 1987...

  – A perfect fit is not a theory – often a red-herring; models can be worse than no-models!

- Let's try to undestand what's going on at the micro level

Some questions with empirical answers

- Financial markets offer Terabytes of information (weekly) to try to investigate why and how prices move, and offer an ideal test bed for some fundamental questions in economics, e.g.:

- A) Are news really the main determinant of volatility? Exogenous vs. endogenous dynamics

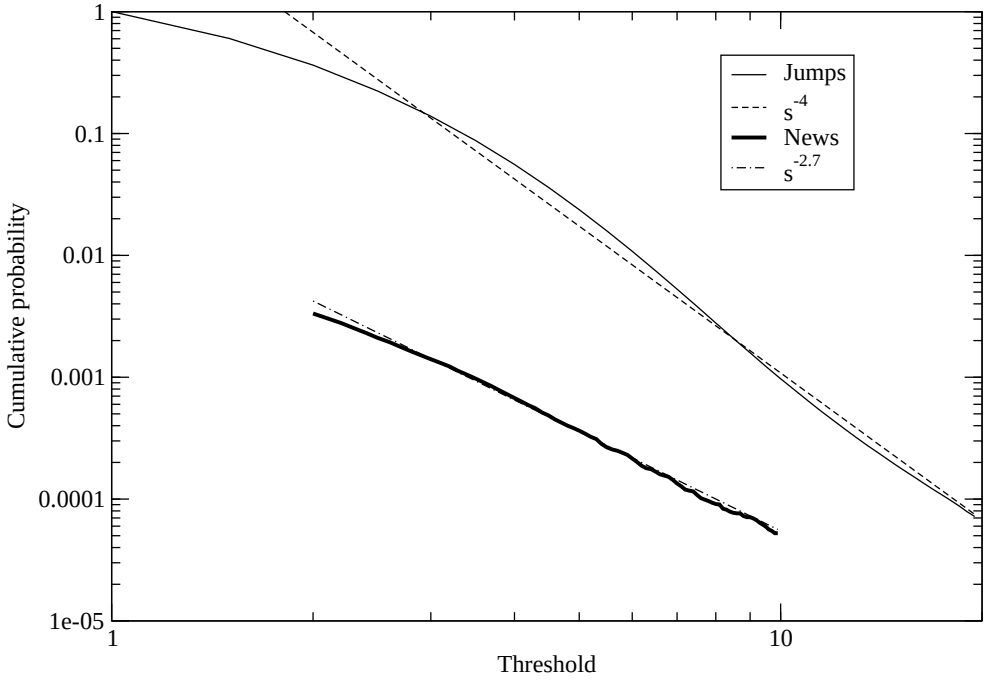
- B) Are price really such that supply instantaneously equals demands? Are markets "in equilibrium"?

- C) How do trades impact prices? How is information included in prices?

A) Exogenous or endogenous dynamics?

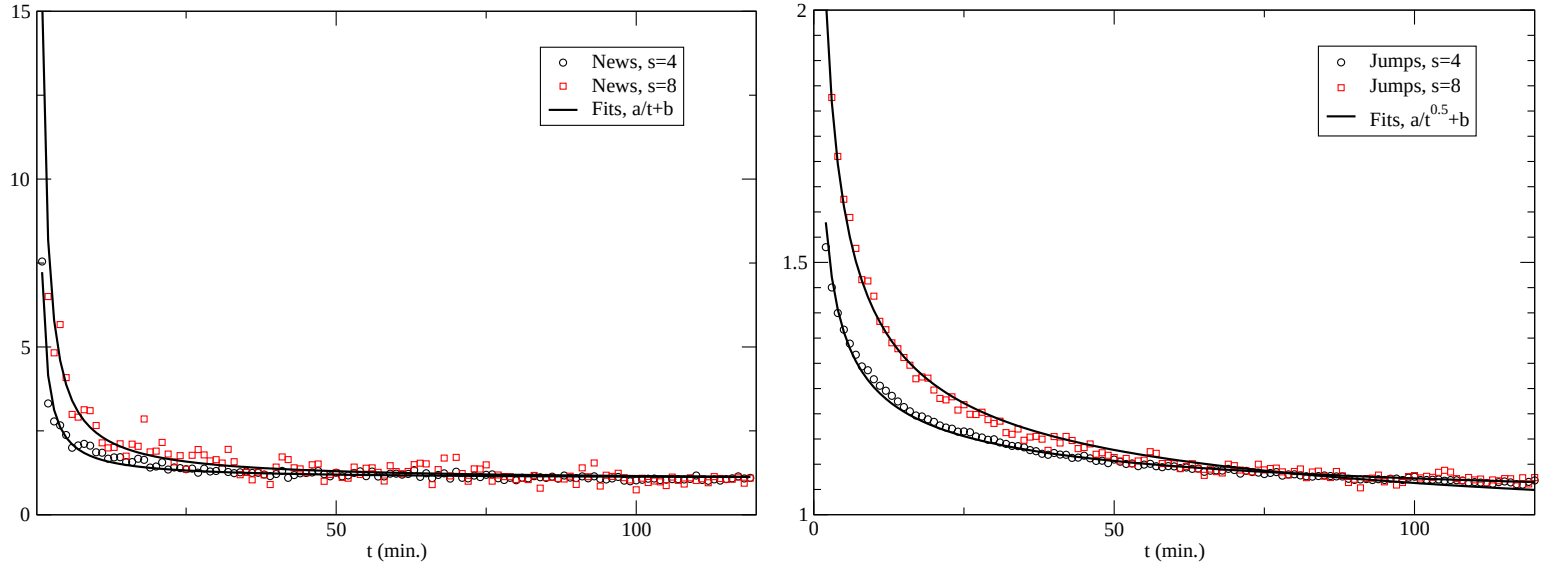
- HF version of the seminal paper of Cutler, Poterba, Summers
- Yes, some news make prices jump, sometimes a lot, but jump freq. is much larger than news freq.
- On stocks, only $\sim 5\%$ of $4-\sigma$ jumps can be attributed to news, most jumps appear to be endogeneous
- News induced jumps and No-news jumps have markedly different statistics, in particular 'aftershocks' that follow the analogue of the "Omori law" for earthquakes
- Private information should not make prices jump ! (See Kyle)

Jump statistics



Power-law distribution of news jumps and no-news jumps. With A. Joulin, D. Grunberg, A. Lefevre

Two jump types: Aftershocks



Volatility relaxation after news (t^{-1}, left) and endogenous jumps ($t^{-1/2}$, right). With A. Joulin, D. Grunberg, A. Lefevre

A) Exogenous or endogenous dynamics?

- Power-law distribution of price changes for anything that is traded

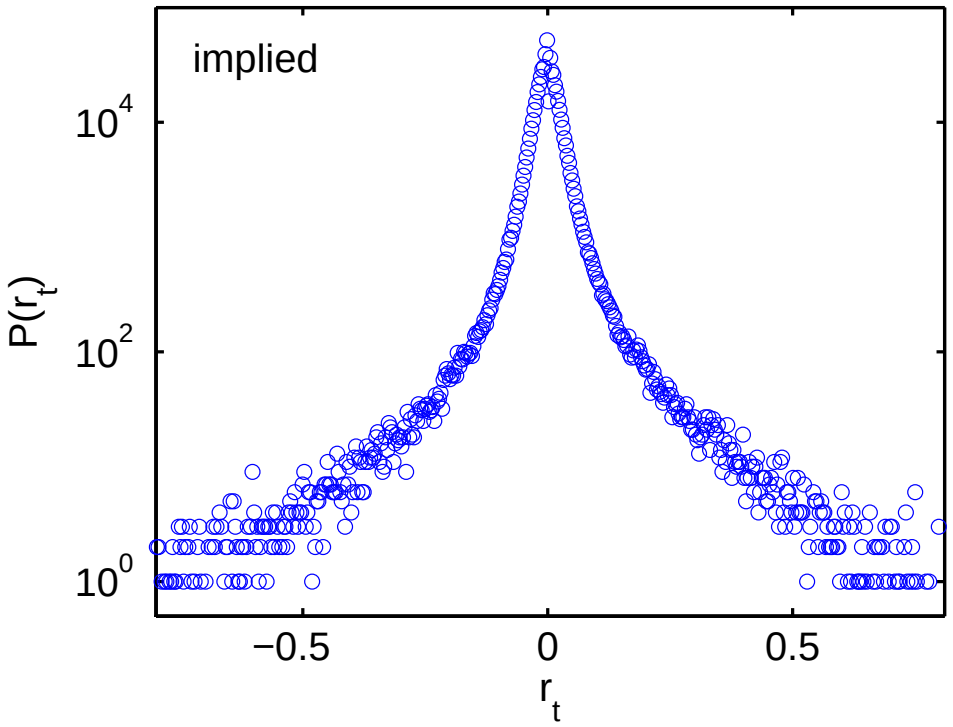
  $\longrightarrow$ There is a full continuum between 'micro-crises' and crashes

  – like for earthquakes

- Excess volatility, with long range memory – looks like endogeneous intermittent noise in complex systems (turbulence, Barkhausen noise, earthquakes, etc.)

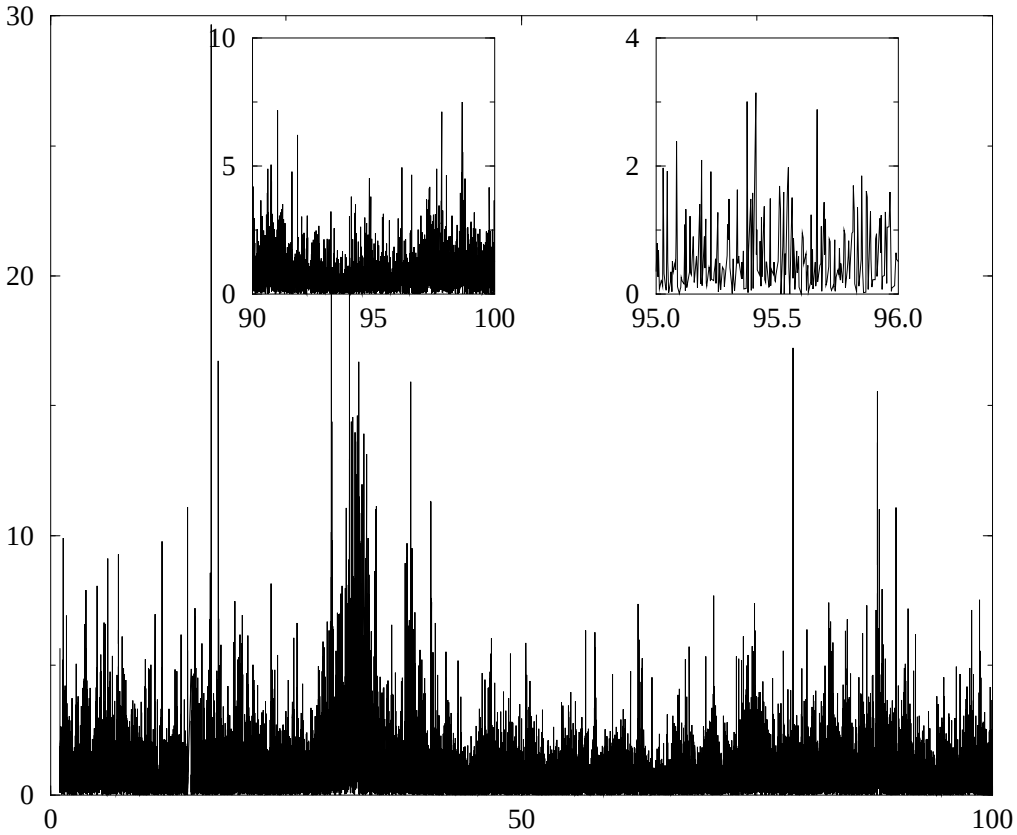
- To a large extent: Universal observations in time, space & assets

Power-law tails



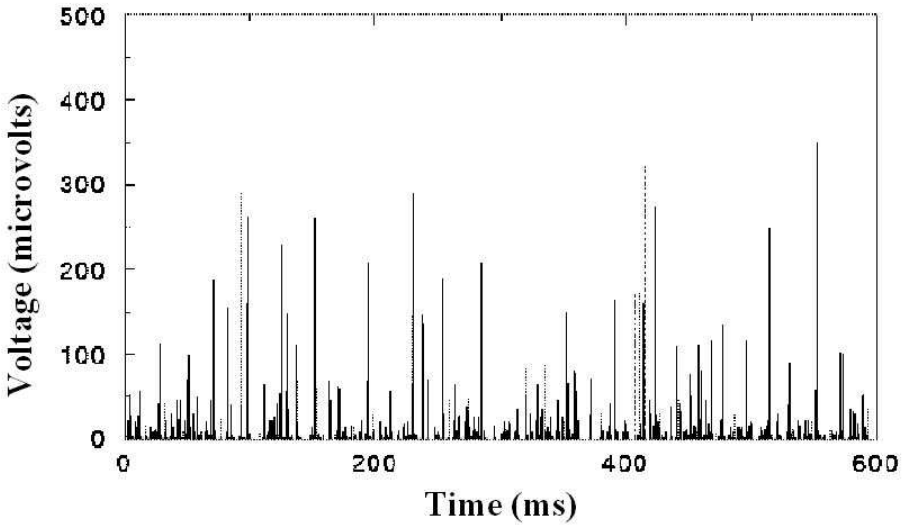
Distribution of daily volatility moves on option markets or *any other traded stuff*: inverse cubic law

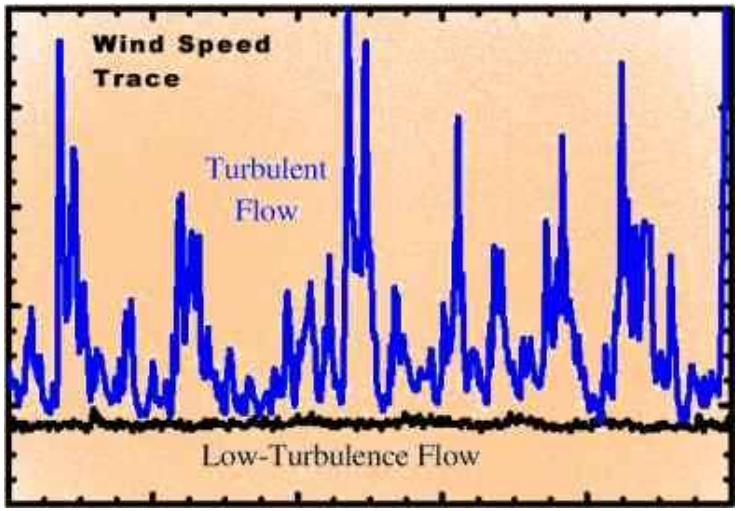
Multiscale intermittency



Excess volatility, with long range memory – looks a lot like endogeneous noise in complex systems

Intermittency: Barkhausen noise, Turbulence





Slow, regular and featureless exogeneous drive but intermittent endogeneous dynamics

Exogenous or endogenous dynamics?

- To a large extent: Universal observations in time, space & assets

- These observations and analogies strongly suggest that endogeneous dynamics is the solution to the excess volatility puzzle – not due to fundamentals

Questions with possible empirical answers

- A. Are news the main determinant of volatility?: clearly no
- B. Are price such that supply instantaneously equals demands? How fast information is included in prices?
- C) How do trades impact prices?

B. Are markets in "equilibrium?"

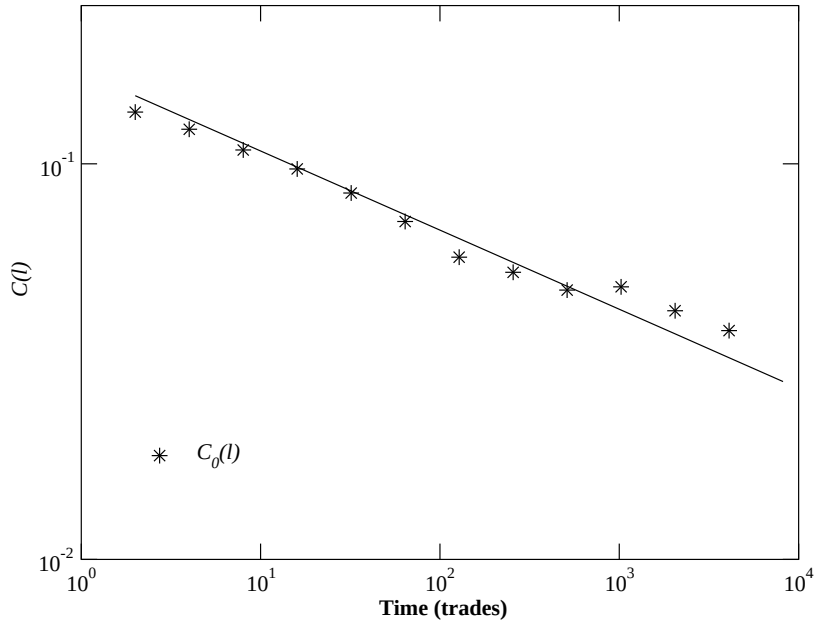
- UHF data allows one to understand the microscopics of order flow and price formation

- One can distinguish buy orders from sell orders

- Surprise: the autocorrelation of the sign of trades is long-range correlated $C(\tau) \sim \tau^{-\gamma}$, $\gamma < 1$, over several days or weeks

- A Paradox: Sign of order flow very predictable and orders impact the price – but no predictability in the sign of price changes – see below

Trade correlations



Correlations extend to several days! (Chordia et al., Hopman, etc.)

B. Are markets in "equilibrium?"

- Flimsy liquidity: even "liquid" markets offer a very small immediate liquidity (10^{-5} for stocks) – buyers/sellers have to fragment their trades over days, weeks or even months

- "Information" can only be *slowly incorporated into prices*, latent demand does not match latent supply

- Markets are hide and seek games between buyers and sellers and *cannnot* be in equilibrium

Conclusion

- A) Are news really the main determinant of volatility?
  - No, endogenous dynamics more likely, through impact – see below
- B) Are price really such that supply instantaneously equals demands?
  - No, "information" is only very slowly incorportated into prices
- C) How do trades impact prices?

C. Impact

- Using high frequency data, one can measure impact accurately:

$$\mathcal{I}_+ = E[p_{n+1} - p_n | \epsilon_n = +1], \qquad \mathcal{I}_- = -E[p_{n+1} - p_n | \epsilon_n = -1]$$

- Empirical finding (1):

$$\mathcal{I}_+ \approx \mathcal{I}_- > 0$$

- Trading, even uninformed and with relatively small volumes in usual market conditions, strongly influences prices and leads to measurable effects – even "liquid" markets are not that liquid

  (1% of the daily volume moves the price by 5% of the daily volatility!!)

C. What is impact?

- Efficient market story: Informed agents successfully forecast short term price movements and trade accordingly. This results in correlations between trades and price changes, but uninformed trades have no price impact – prices stick to "Fondamental Values"

- A more plausible story: since there is no easy way to distinguish "informed" from "non informed" traders, all trades statistically impact prices since other agents believe that some of these trades might contain useful information – a mechanism for feedback loops and avalanches

C. Impact & volatility

- Empirical finding (2): volatility per trade is proportional to impact

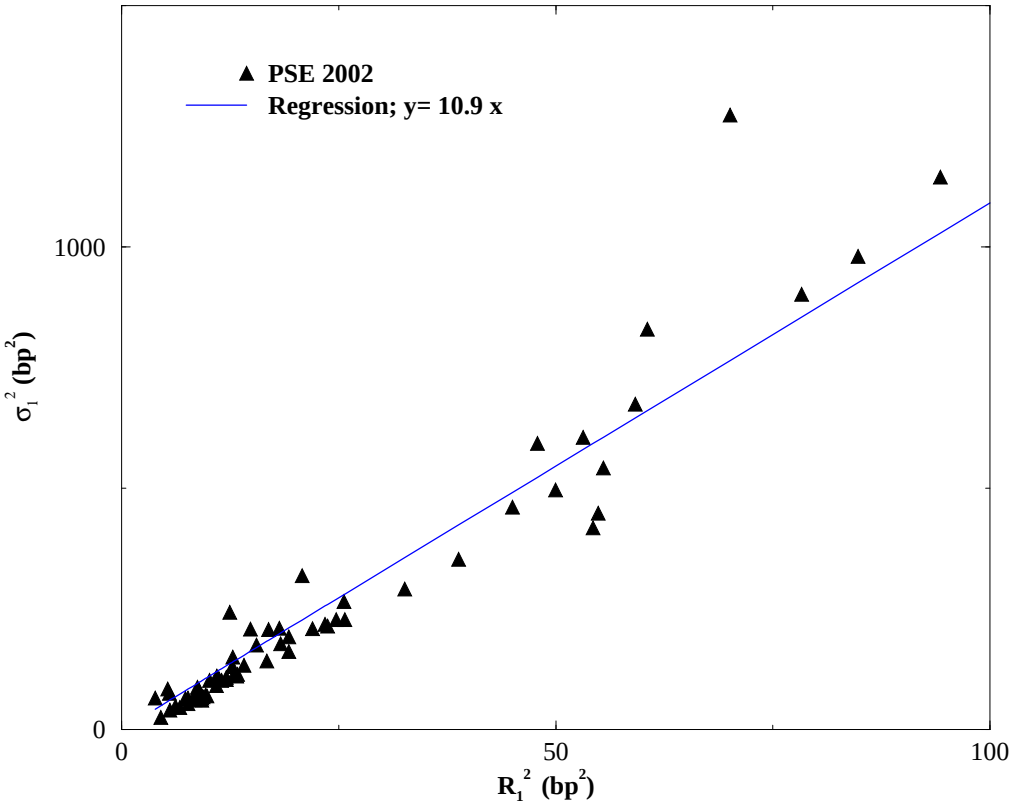
$$\sigma_1^2 = A\mathcal{I}^2 + BJ^2, \qquad B \approx 0$$

(impact component + "news" component)

- Volatility is indeed mostly due to impact of trades – very little to quote jumps J without trades ("news")

- Volatility is slaved to spread and vice-versa: $\sigma_1 = cS$

C. Volatility: impact + news?



Very little contribution from quote jumps J without trades ("news")

– with J. Kockelkoren, M. Potters, M. Wyart

C. Impact: non linear and transient

- Impact is both non-linear and non local in time

$$p_t = p_{-\infty} + \lambda \sum_{t'=-\infty}^{t} G(t-t')\,\epsilon_{t'} \cdot S_{t'} \cdot V_{t'}^{\psi} + \text{Jumps},$$

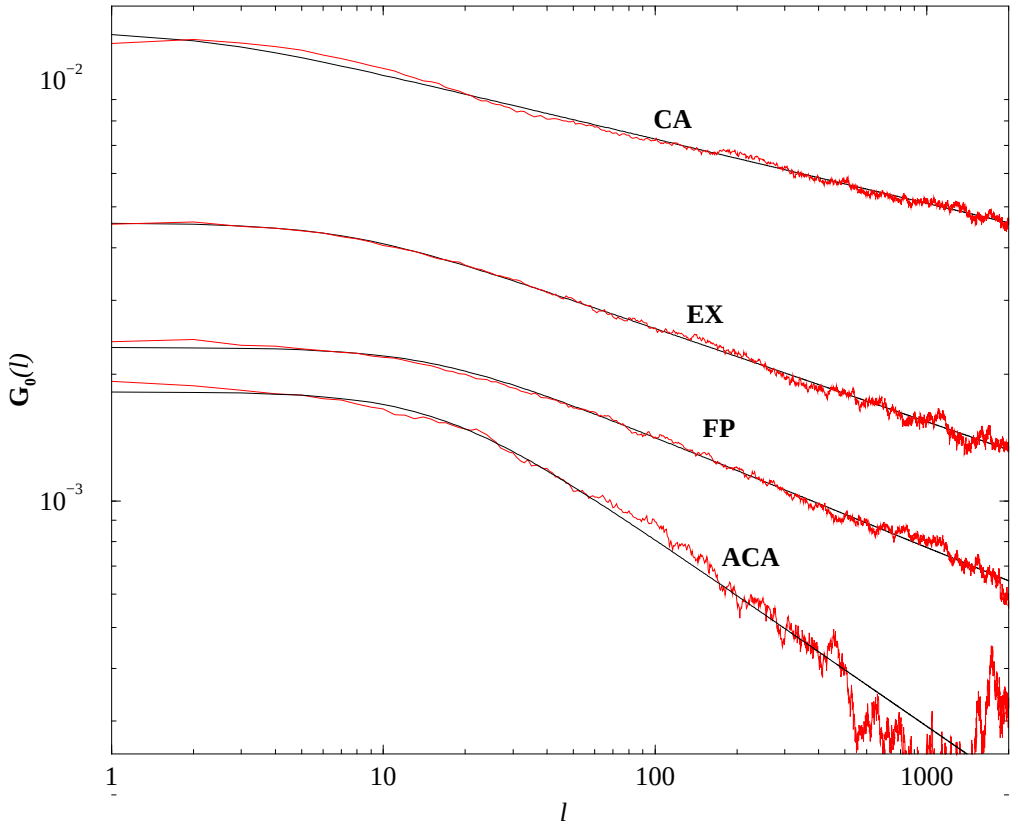
- $\psi \approx 0.2$: very concave impact – trades are more important than volume (Hasbrouck, Jones)

- The impact function $G(\ell)$ must decay as $\ell^{-\beta}$ to exactly offset the correlation of trades and remove predictability of returns!

$$\beta = \frac{1-\gamma}{2}, \qquad 0 \leq \gamma \leq 1$$

Critical long term market resiliency (with J. Kockelkoren, M. Potters, M. Wyart)

Critically resilient markets



Decay of $G(\ell)$ for different stocks: impact is transient – with J. Kockelkoren, M. Potters

C. Impact: non linear and transient

- Bachelier's legacy: the random walk nature of prices results from a subtle balance between trending order flow (liquidity takers) and mean-reverting impact (liquidity providers)

- Think of the dynamical equilibrium between the two forces as a "tug of war": sometimes one side yields...leading to a microliquidity crisis

  Liquidity is a coward, it is never there when one needs it

Mechanism: Feedback loops/instabilities

- Unstable feedback loops pervade financial markets and can and do lead to crises – to name a few:
  - *) Model induced feedback loops: e.g. the BS feedback loop in 1987, the CDO feedback loop in 2008,...
  - Regulation induced feedback loops: mark to market, Value at Risk...
  - *) The volatility – liquidity feedback loop (see above)
  - Pattern following: trends feed trends (*learn history – it might repeat*)
  - * Crowd following: panic feeds panic (*imitate others – they might have some information*)

C. Impact and feedback loops

- Example: Portfolio Insurance & the 1987 crash
- Remember the Black-Scholes model: zero risk means perfect replication
- Forget buying a true insurance protecting against a fall of the market: follow the replicating strategy
- Sell when the market goes down!
- LOR: 80 B$ "insured" like that in 1987 – for a daily market liquidity of 5 B$....

C. Impact and feedback loops

- Example: Portfolio Insurance & the 1987 crash
- This did not cause the crash but amplified it tremendously
- By neglecting the crash probability, B&S contributed in creating one!
- After 1987: very slow, incomplete evolution away from Black & Scholes – still the textbook standard, with very little caveats.
- Cf. *Les marchés dérivés: pour une pédagogie du risque*, JPB, Le Monde, Mars 1995.

C. Impact and feedback loops

- History repeating: Credit Derivatives & the 2008 crash

- Absurd models for correlation between obligors $\longrightarrow$ Huge underestimation of the risk of credit derivatives (CDOs, etc)

- Feedback loops: a) Mark to market accounting rules – inspired by efficient market theory; b) CDSs

- Lost of confidence in the models $\longrightarrow$ overreaction and unjustified write-downs $\longrightarrow$ Banks technically bankrupt (Lehmann)

- By neglecting global systemic risk, faulty models created it

Other important missing ingredients

- I. Imperfect Liquidity cf. above
- II. Imperfect Rationality: noisy decisions but not necessarily of strong distortions
- III. Heterogeneity & Interaction/Competition: The Random Field Ising Model, Spin-Glasses
- IV. Pattern following, leverage, etc., etc.

III. Cartoon model of collective decisions

- Collective behaviour is often irreducible to individual dynamics – at variance with the "representative agent theory"

- People do not make decision in isolation but rely on the choice of others: this is an empirical fact...

  (cf. Artificial culture market by Salganik et al.)

- Many important situations in practice: vaccines, hygiene, smoking, driving, crime, technology, etc.

- Sometimes very strong distortion/amplification phenomena due to imitation: fads & fashion (Louis XIV's wig), bubbles, etc.

Starlings in Rome

A. Cavagna et al.

III. Cartoon model of collective decisions

- Binary decision of agent i: $S_i = \pm 1$ (to buy/sell/lend or not to buy/sell/lend, to join or not to join a riot, etc.)

- Influence factors:

  - personal opinion, propensity or utility ϕ_i – heterogeneous with probability P

  - public information (price, technology level, zeitgeist) $F(t)$, smooth

  - social pressure or imitation effects $\sum_j J_{ij} S_j$

III. Cartoon model of collective decisions

- The RFIM update rule:

$$S_i(t) = \text{sign}\left[\phi_i + F(t) + \sum_{j \in \mathcal{V}_i} J_{ij} S_j(t-1)\right],$$

- Aggregate demand: $\mathcal{O} = N^{-1} \sum_i S_i$

- Some concrete applications: Birth rates, Cell phones, Clapping...(with Q. Michard)

- Similar ideas in sociology (Granovetter, Galam), economics (Brock, Durlauf)

III. Cartoon model of collective decisions

- $J < J_c$: personal choices dominate, smooth demand curve

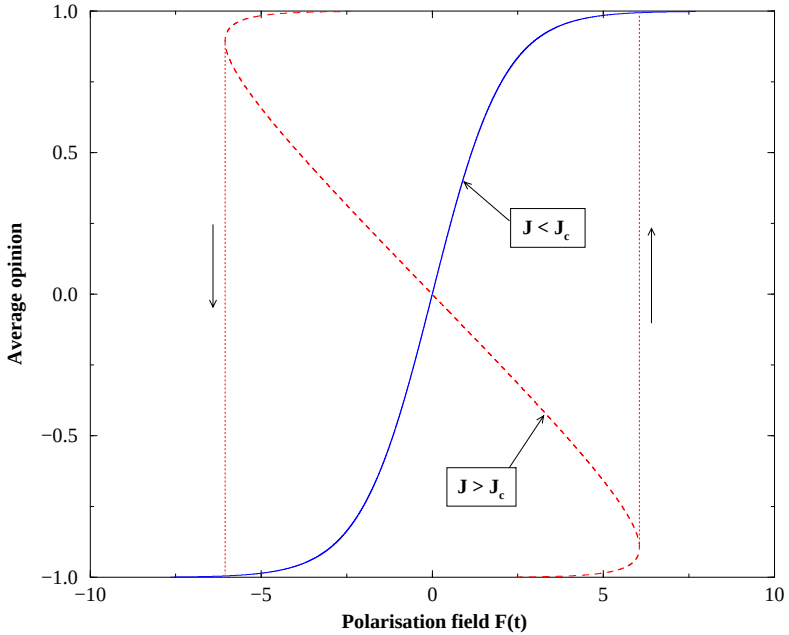
- $J > J_c$: herding dominates, strong deformation of the fundamental demand curve: discontinuities appear at the macro level – imitations induced panic/crashes

- $J \approx J_c$: avalanche dynamics with power-law distribution of sizes

- Example: Clapping, but also Contagion: Pessimism, Trust, Default, etc.

- Hysteresis in and out of the crisis

III. Cartoon model of collective decisions



In the collective phase, anecdoctal fluctuations trigger crashes

Heterogeneity + interactions = Discontinuities & Breakdown of the representative agent theory

III. Metaphoric models of complexity

- Generically, a system such that its individual elements are heterogeneous and interacting (competing) is in the "spin-glass" class – cf. also pinned domain walls, vortices, fracture fronts, etc. (P.W. Anderson)

  – Multiple equilibria – actually exponential!

  – Intermittent dynamics – with long stasis in quasi-equilibrium

  – Critical fragility to external perturbations – more efficiency lead to more vulnerability !

- New methods from physics to deal with these heterogeneous and interacting problems – "cavity" theory (1985, 2009)

Conclusion: Second generation models

- Markets are complex systems (i.e. made of *heterogeneous, interacting elements*) $\longrightarrow$ rich endogenous dynamics, with intrinsic discontinuities and intermittency, and little anchor to fundamentals

  – Feedback loops and instabilities are numerous and are probably at the origin of excess volatility and market turbulence

- "Second generation" market models should start from:

  – realistic agent based models,

  – high frequency microstructure data,

  – a proper theory of *impact* (non-linear, transient,...)

  – identify interactions, feedback loops and contagion mechanisms

Second generation models – Finance

- Coarse-graining *should* lead to the emergence of some regularities (universality, power-laws and intermittency) – but how, precisely? – and allow one to understand the value and dynamics of the parameters (volatility, correlations, etc.)

- Help identify systemic instabilities and liquidity (micro-) crises

  (e.g. spread $\rightarrow$ vol. $\rightarrow$ spread and May 6th "flash crash")

- Think about rules and regulations that engineer endogeneous stability

  (e.g. mark-to-market with liquidity discount, dynamic make/take fees, etc.)

Second generation models – Economics

- Collective effects are of paramount importance and one should shun away from the utility maximizing, single representative agent framework

  $\longrightarrow$ Promote realistic Agent Based simulations with millions of heterogeneous, interacting agents?

  – cf. D. Farmer, D. Foley, Nature, August 2009

- A major scientific program, where recent ideas/methods from statistical physics should help – i.e. inferring macro-laws from micro-rules, or "macro behaviour from micro-motives" (cf. Schelling)