How an active region works

Loukas Vlahos

History

- More than 10 years ago Miller et al. wrote a nice review which is highly cited in the literature even today. The main goal in this review was to contrast the known acceleration mechanisms (E-fields, Turbulence, shocks) with observations. The energy release (magnetic reconnection and flows) during the eruption was hided on the background of the analysis.
- In the Miler et al. review you left with the impression that turbulence is the wining mechanism

History

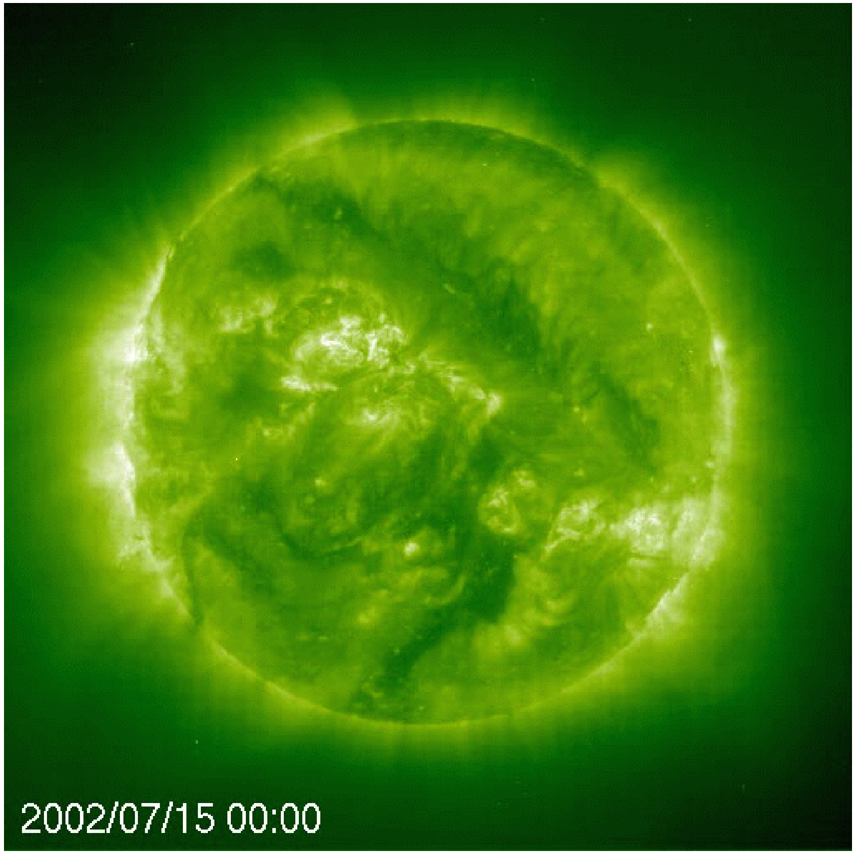
- A long list of outstanding problems were mentioned and open observational issues were listed.
- The recent observations added to the Miller list even more constrains, the most important been that “if the energy carried by the high energy particles reaches as high as 30-40% of the total energy… acceleration should be part of the energy release picture.
- So let us try to place the accelerator on the framework of things discussed yesterday.

Outline

- Active regions as driven non linear systems
- Spatially self-similar, small-scale energy release
- Power-law statistics
- The solar atmosphere as an externally driven turbulent system
- Turbulent self-organization: Critical or non-critical?
- Formation of stable and unstable current sheets
- Particle dynamics in fractal current sheets
- Active regions as particle accelerators
- Summary

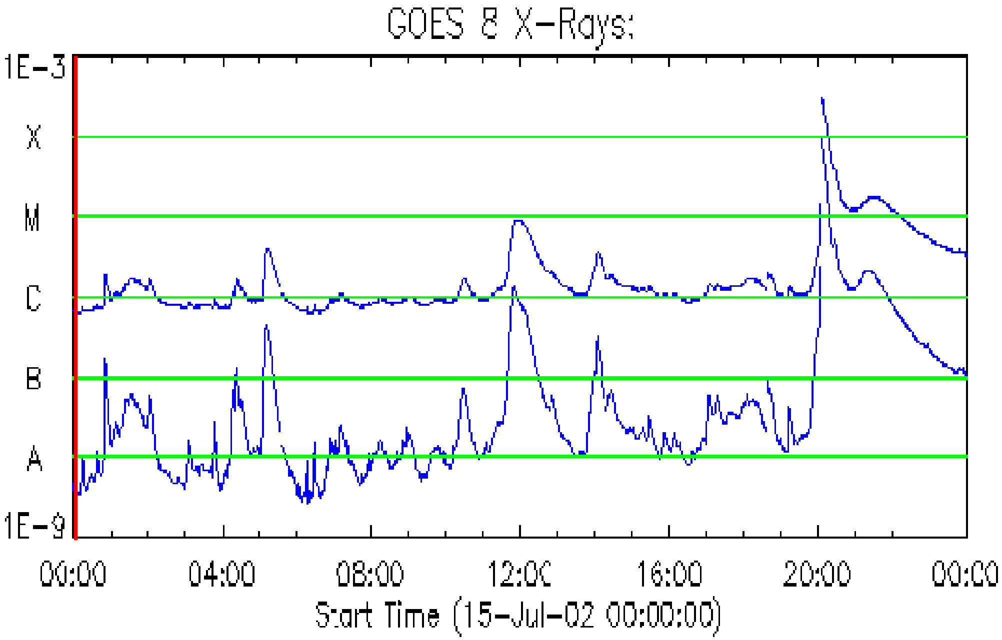
Solar eruptions – intermittent phenomena

Activity on the Sun



Source: SoHO / EIT

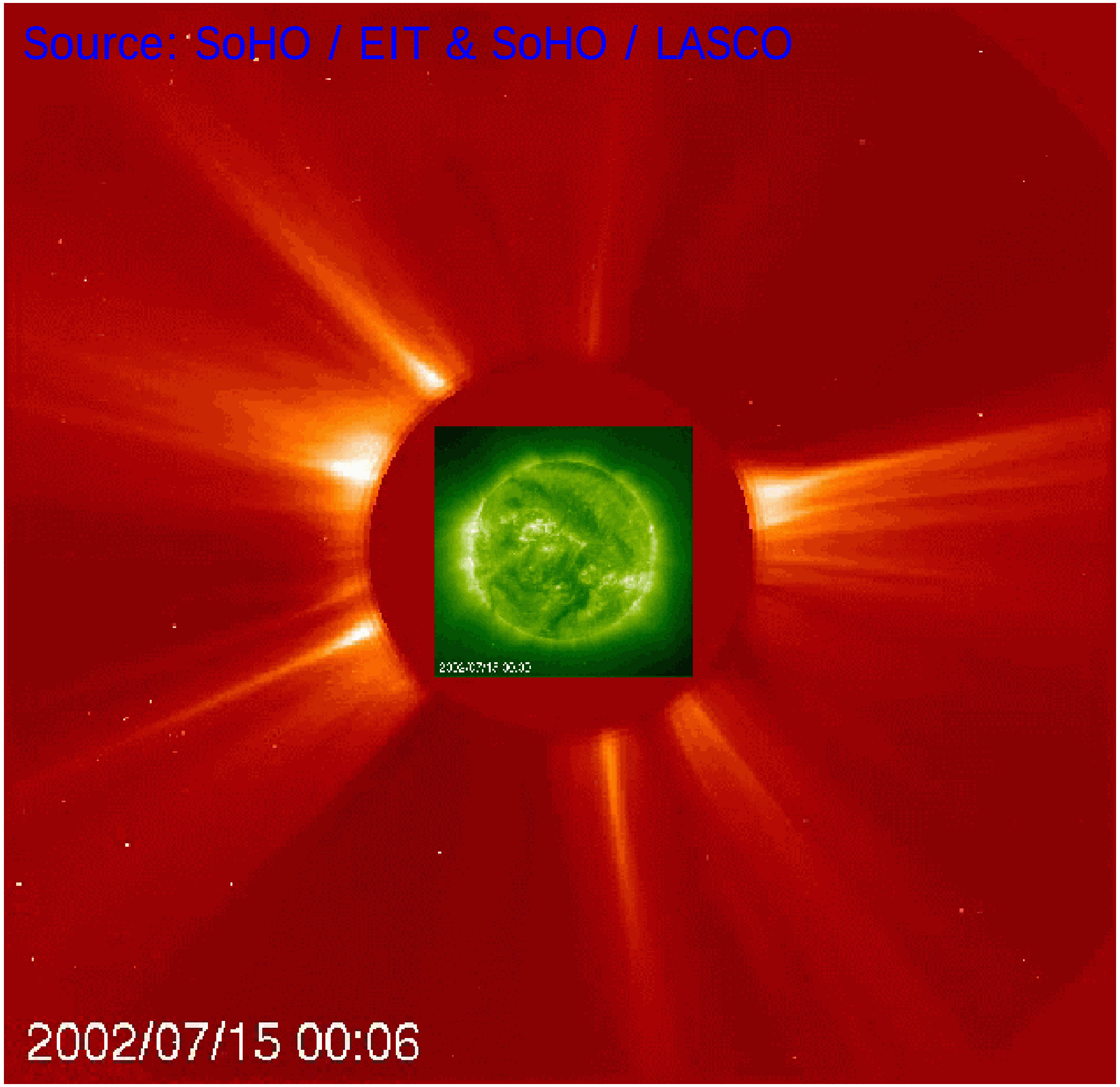
The response at 1 AU



Source: NOAA / GOES

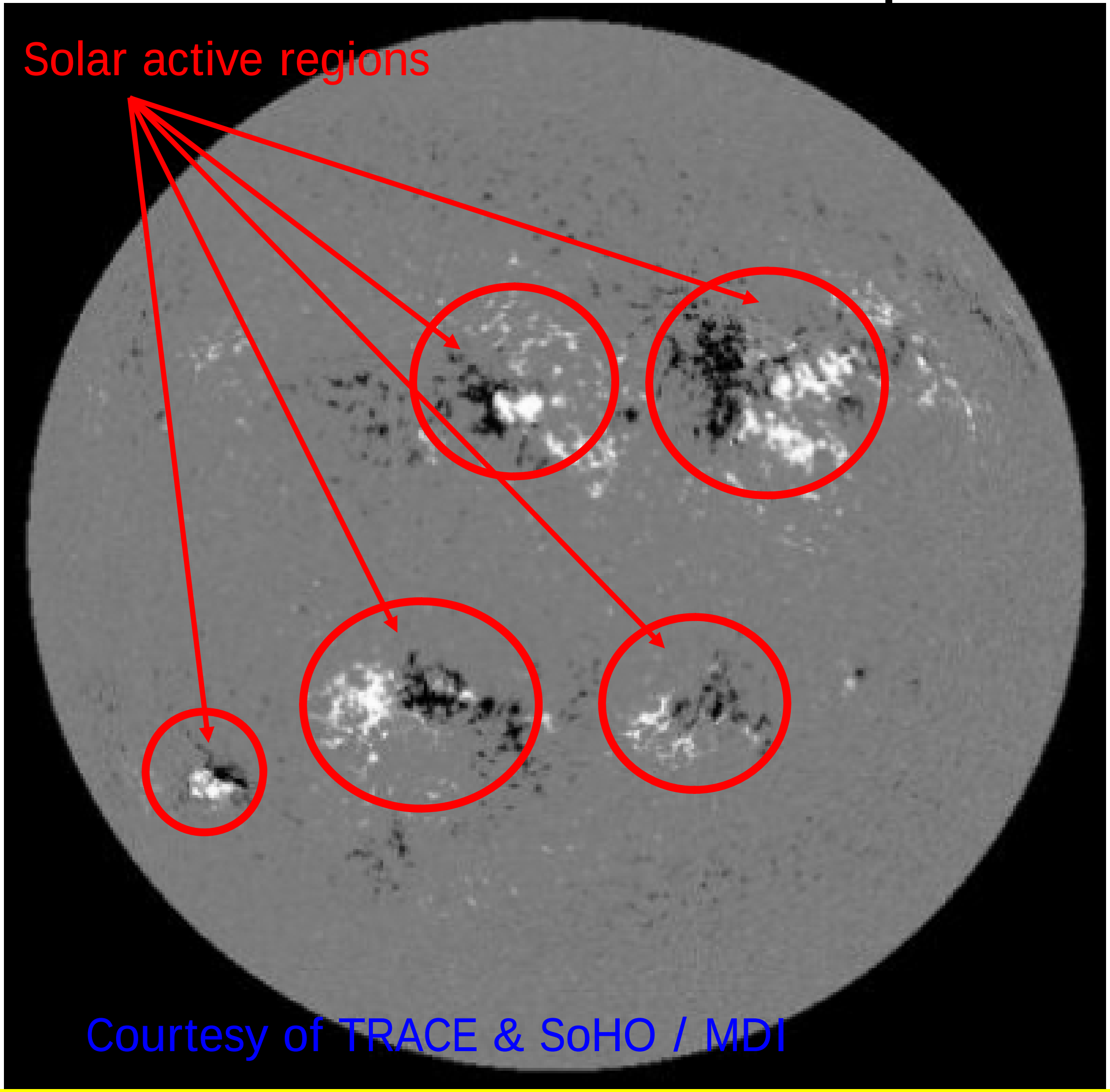
The time scale of solar eruptions is much shorter than the lifetime of their magnetic sources

The building blocks of solar eruptions


Source: SoHO / EIT & SoHO / LASCO

solar eruption = flare + coronal mass ejection (CME)

Active regions: the sources of solar eruptions

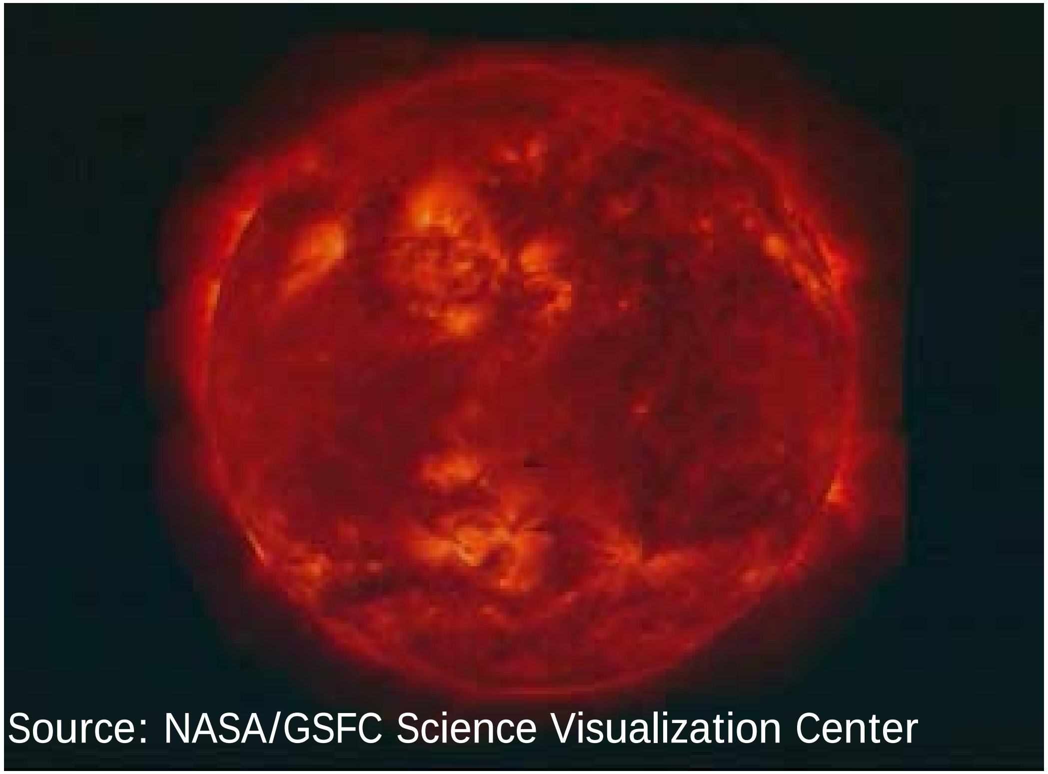


Courtesy of TRACE & SoHO / MDI

Instabilities in active regions are a generally accepted eruption cause. But what is the nature of these instabilities?

Active regions and flares

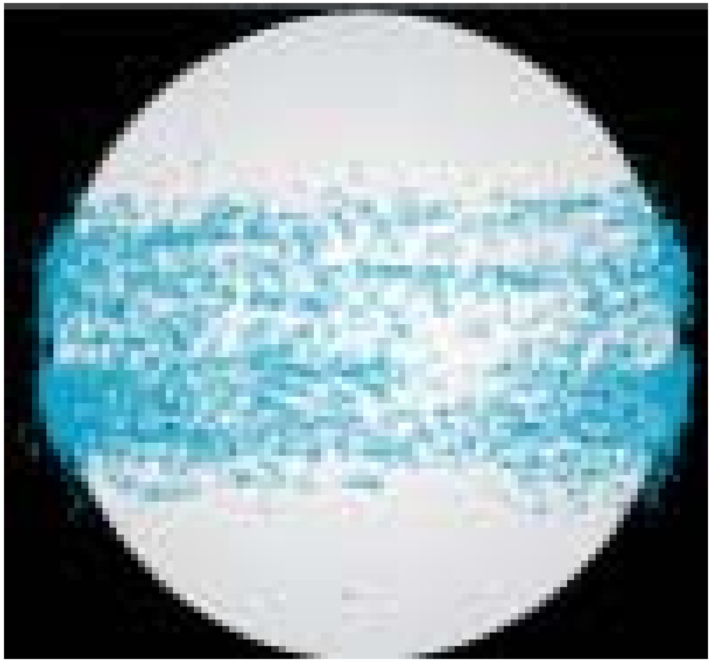
The 2nd Bastille Day flare, 07/14/00 (NOAA AR 9077)



Source: NASA/GSFC Science Visualization Center

Big flares are an exclusive characteristic of active regions

- Not all flares are accompanied by CMEs
- CMEs are not necessarily triggered in active regions

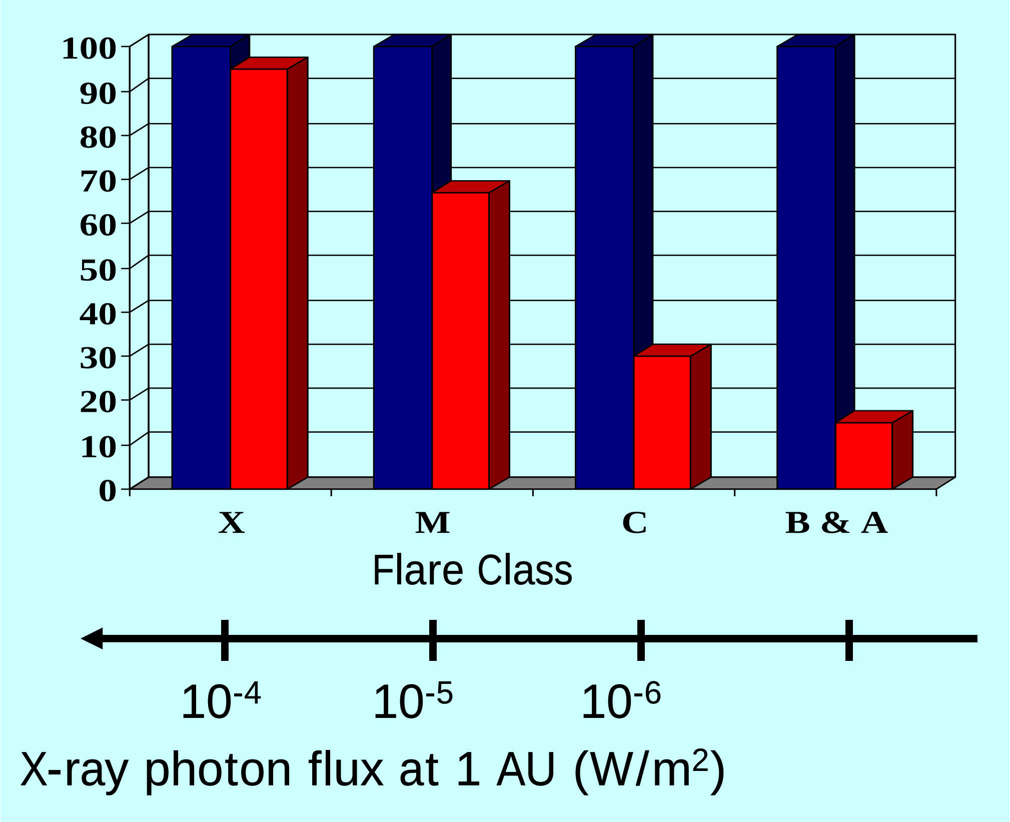


RHESSI Science Nugget, 05/20/07, by I. Hannah & S. Christe

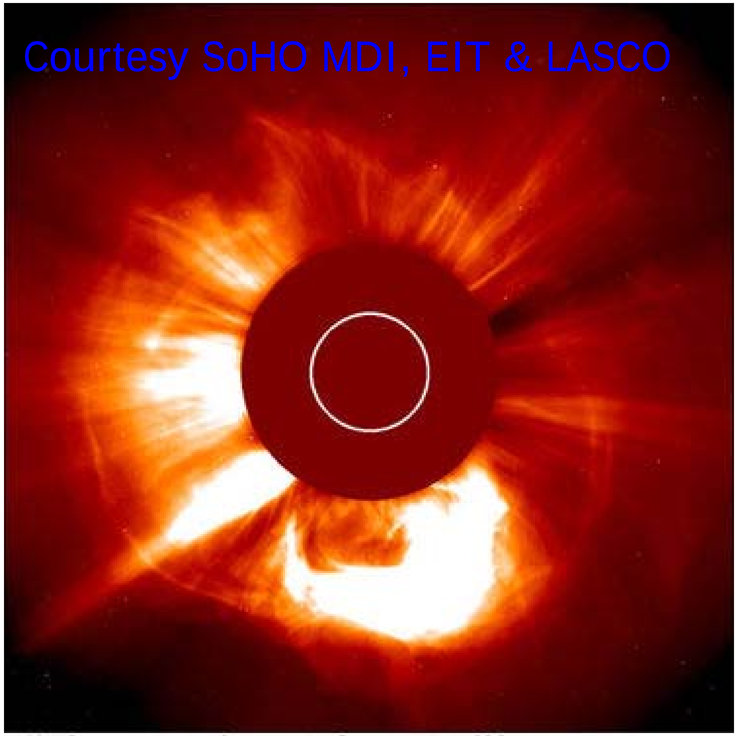
The same appears to be the case with microflares (the locations of ~25000 of these events are given above)

What is the relation between flares and CMEs?

Flares vs. coronal mass ejections

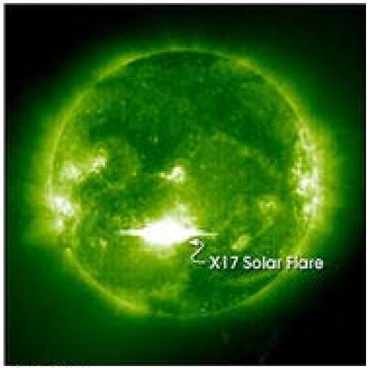


- The probability of an eruptive flare depends on the intensity of the flare
- For the strongest (NOAA X-class) flares, the correlation with a CME is almost one-to-one
- However, the physics of this correlation remains <u>elusive</u>

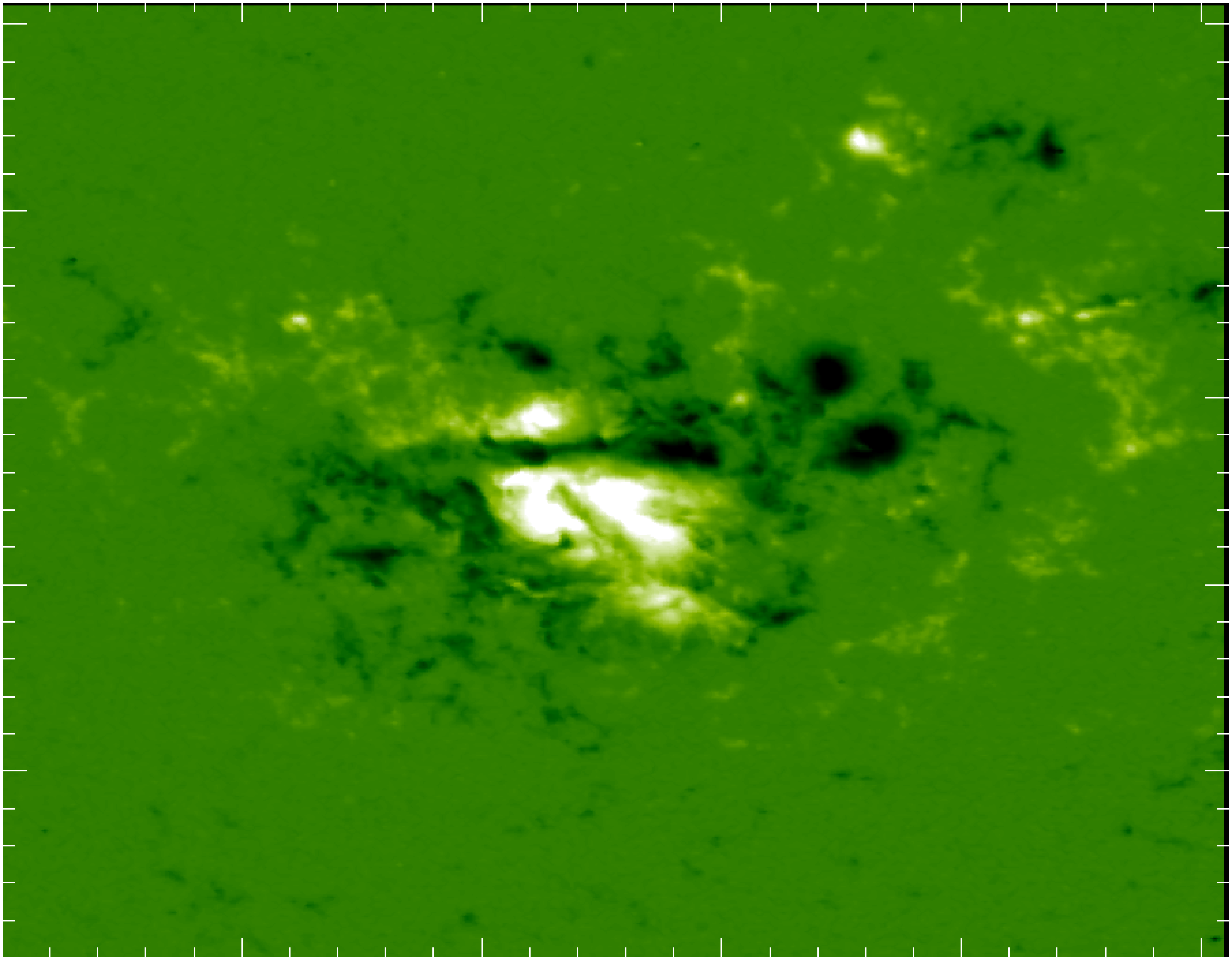

Courtesy SoHO MDI, EIT & LASCO

11:30 UTC Large Angle and Spectrometric Coronagraph (LASCO)

14:24
Michelson Doppler Imager (MDI)



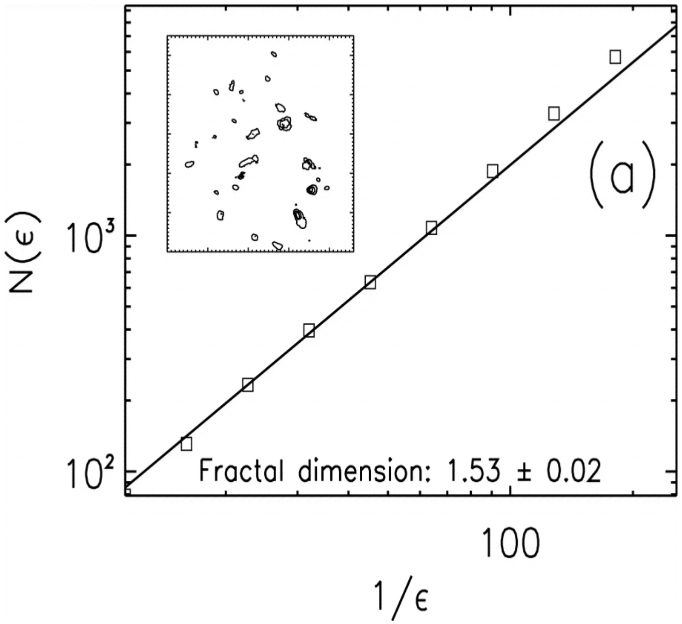
11:12 UTC
Extreme Ultraviolet Imaging Telescope (EIT)



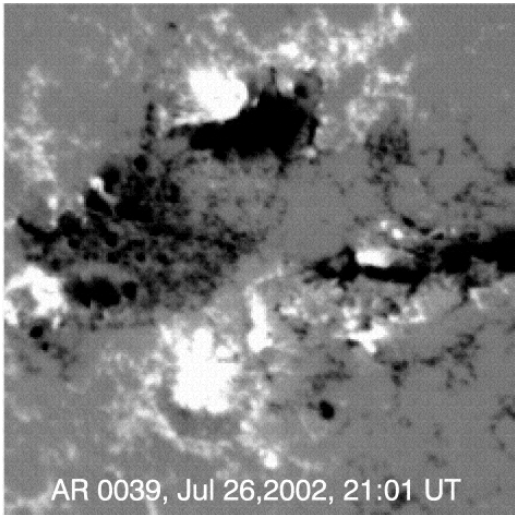
Multi-scale diagnostics of solar structures

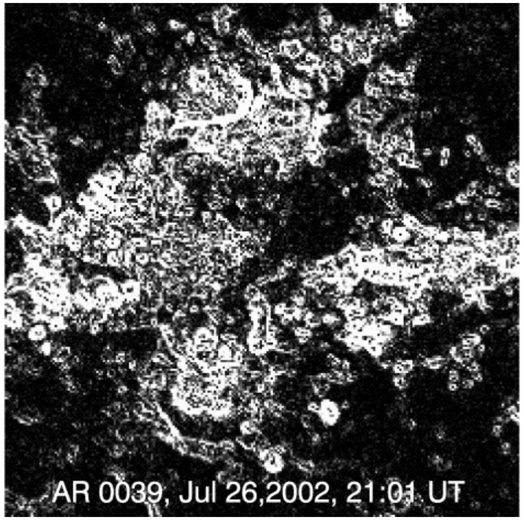
Fractal and multi-fractal methods in the hunt for a tale-telling pattern:

Georgoulis et al. (2002)



Abramenko et al. (2003)





The fractal dimension:

EBs are fractal structures

Structure functions:

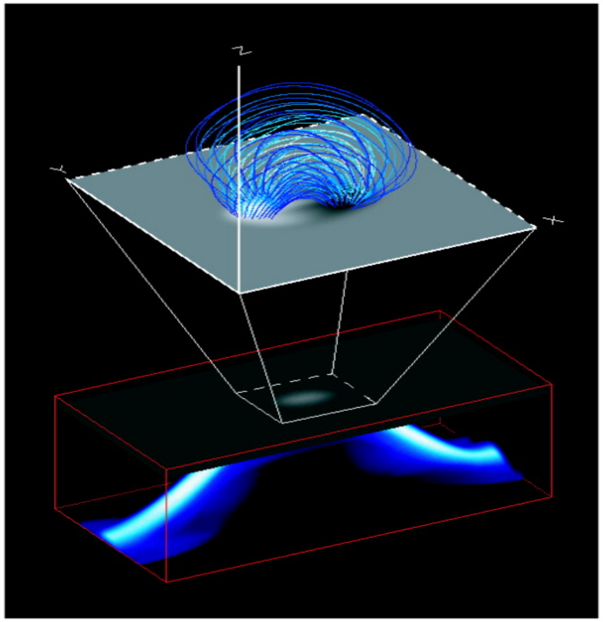
$$S_q(r) = \left\langle \left| B_z(\bar{x}+\bar{r}) - B_z(\bar{x}) \right|^q \right\rangle \sim (r)^{\zeta(q)}$$

AR magnetic fields are multi-fractal structures

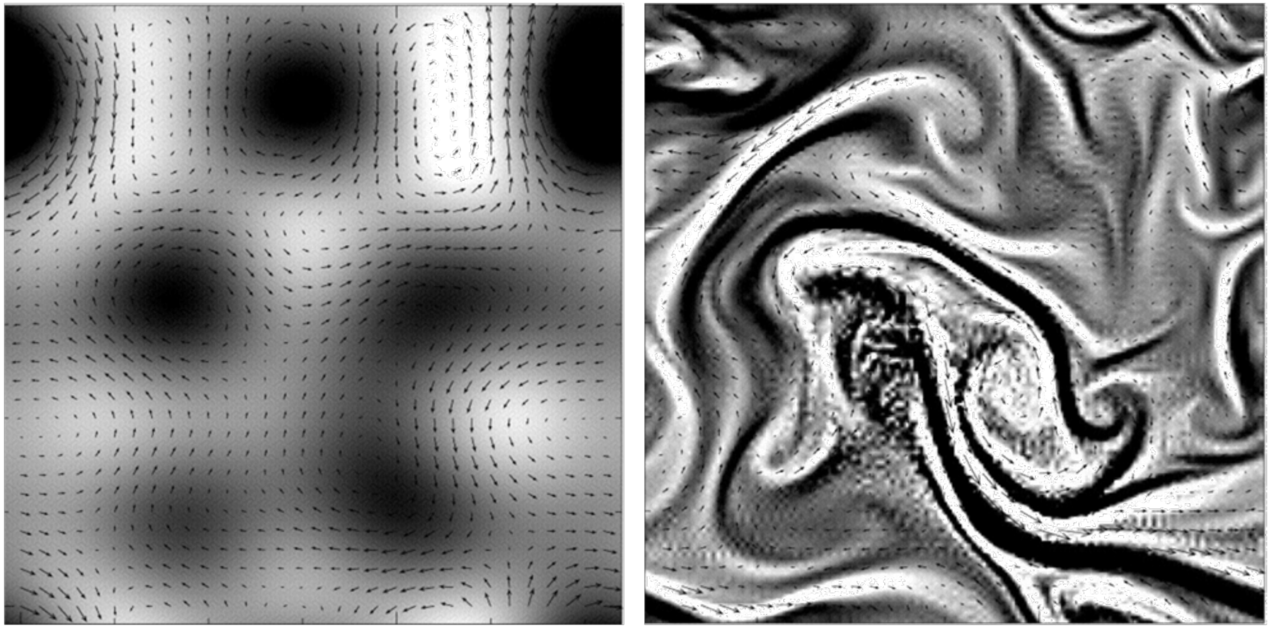
Wavelets, shapelets, automatic pattern recognition, phase diversity, deconvolution techniques, applied to magnetograms, EUV and X-ray images, CMEs, etc.

Significant focus / an arsenal of novel tools

Envisioned situation in the solar atmosphere



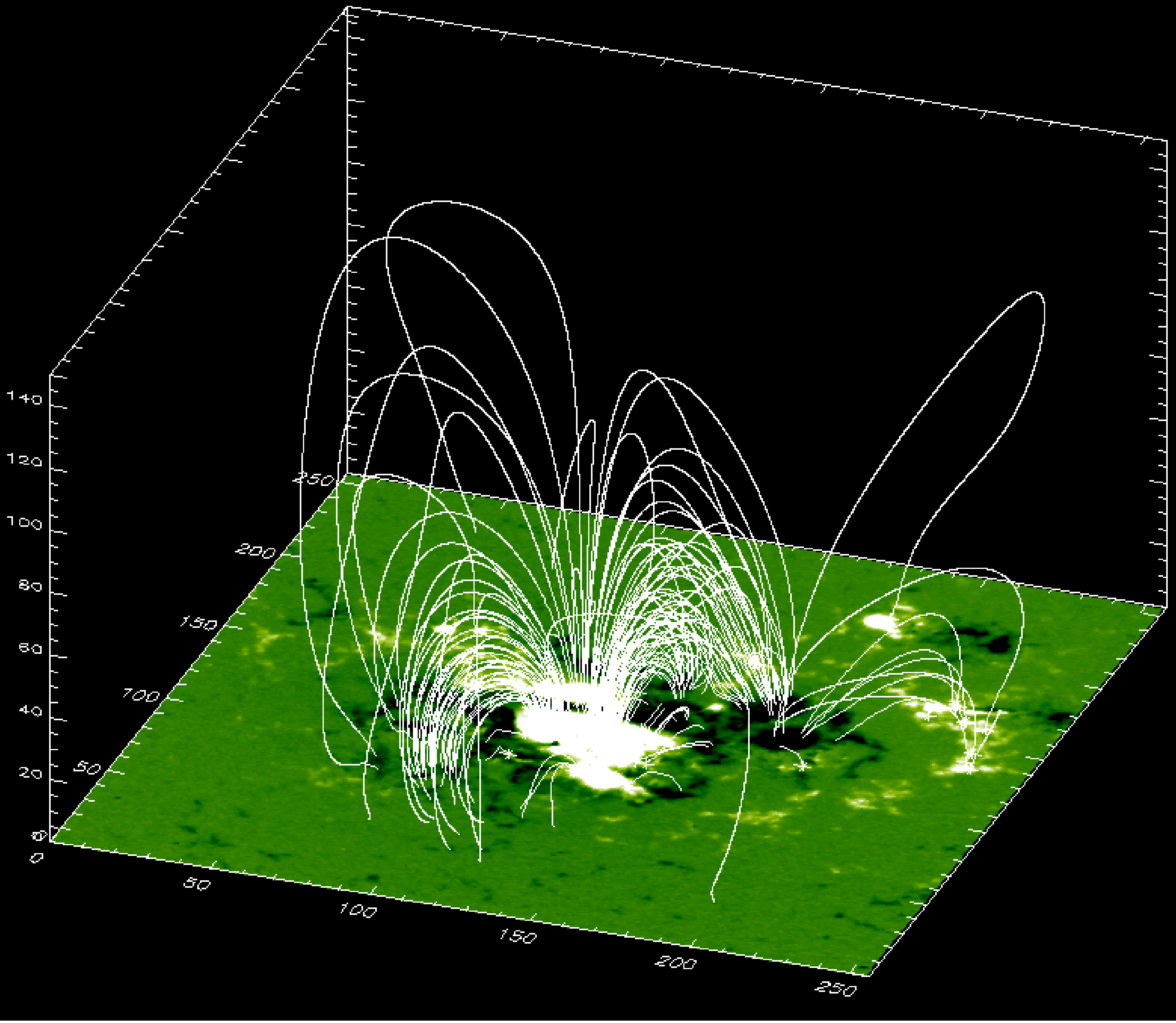
Abbett & Fisher (2002)



Dmitruk et al. (2002)

- The solar atmosphere: An externally driven, dissipative, non-linear dynamical system
- Vector potential / Velocity field : A few coherent, large-scale structures (inverse cascade)
- Free magnetic energy / Vorticity: Numerous small-scale structures (direct cascade)
- Dissipation (flares): Triggered locally, [rapidly spreading over the AR (domino effect)]

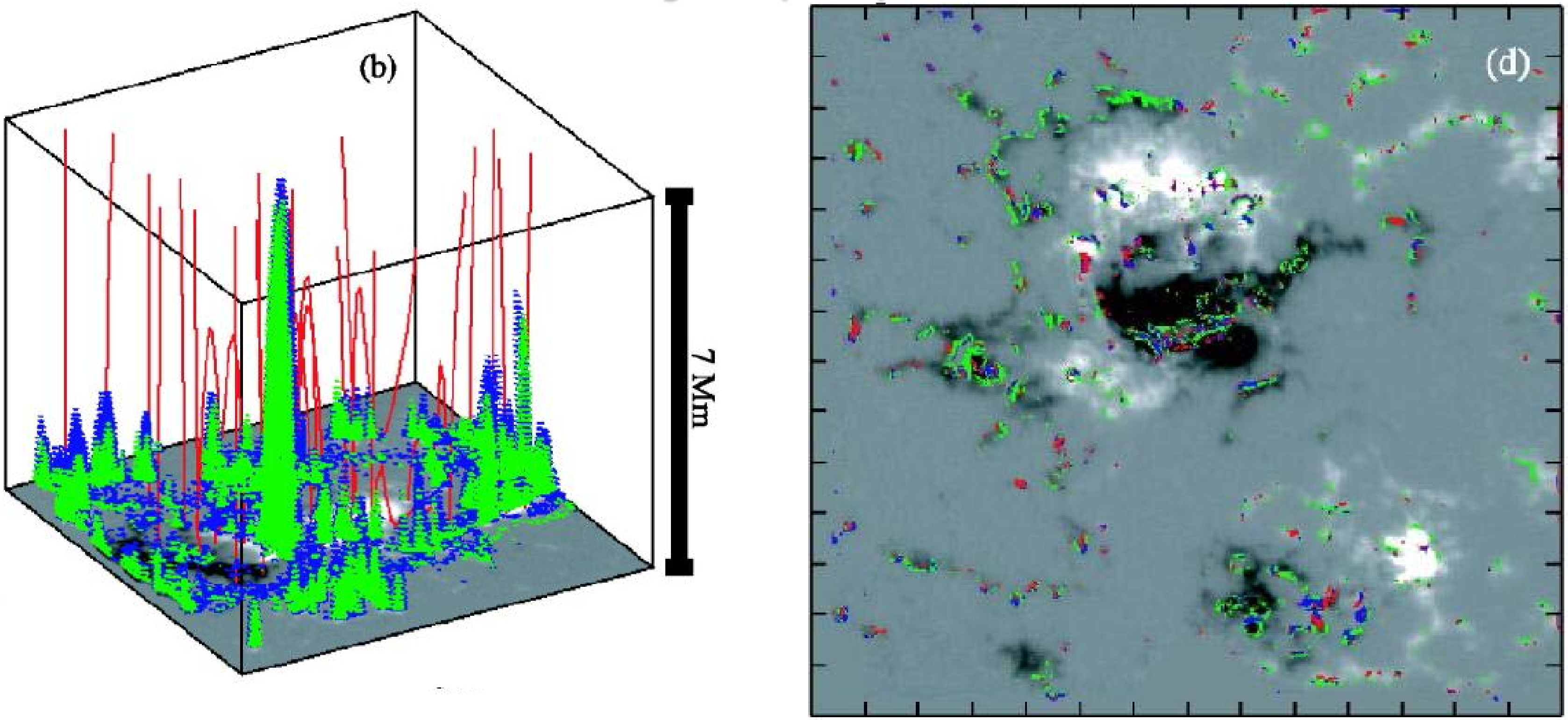
Turbulence !



140
120
100
80
60
40
20
0
250
200
150
100
50
0
50
100
150
200
250

Pre-flare / Quiescent evolution of solar ARs

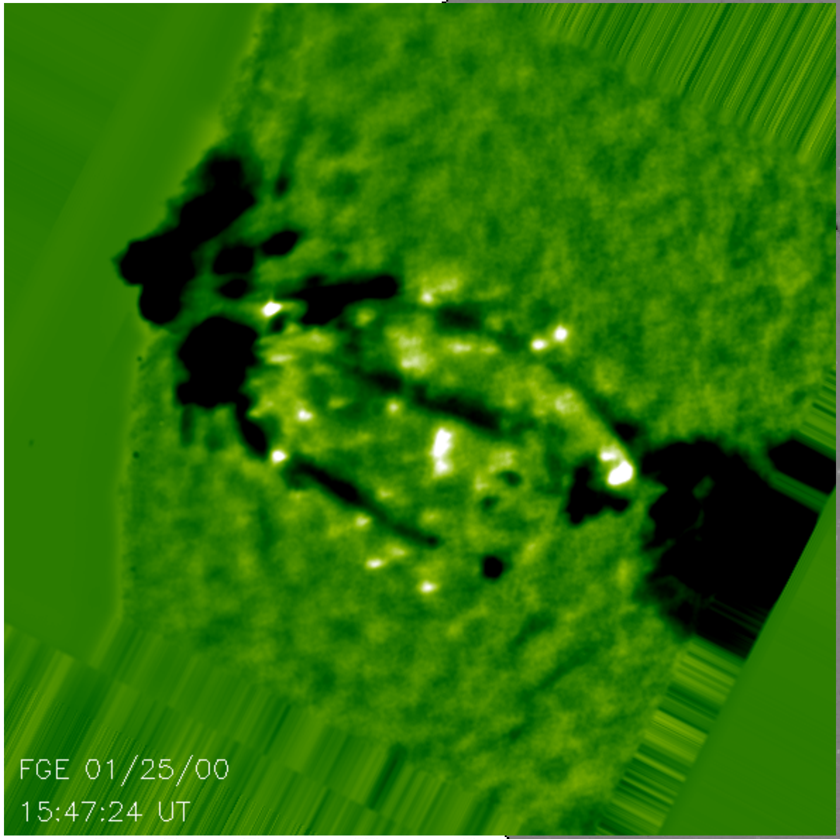
Vlahos & Georgoulis (2004)



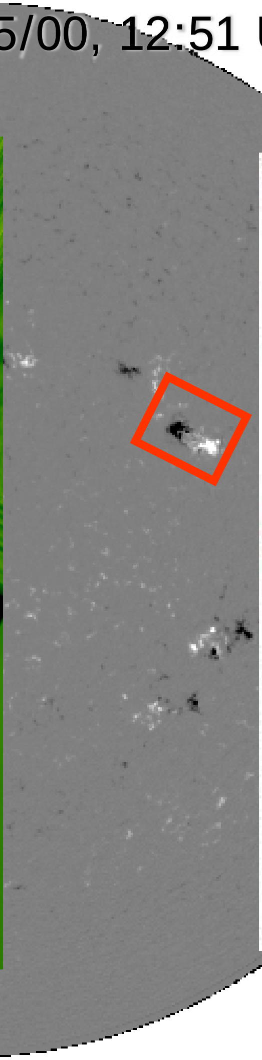
- A large number of likely unstable fractal volumes at low altitudes $\left(\leq 10\mathrm{Mm}\right)$
- Free energies showing power-law distribution; index nearly insensitive to the critical threshold
- Free energies of the order $10^{24} - 10^{26} erg$ - An avalanche necessary to achieve a flare

Turbulent-driven self-organization appears as an inherent feature in solar ARs irrespectively of whether these ARs are quiescent or flare/CME -prolific

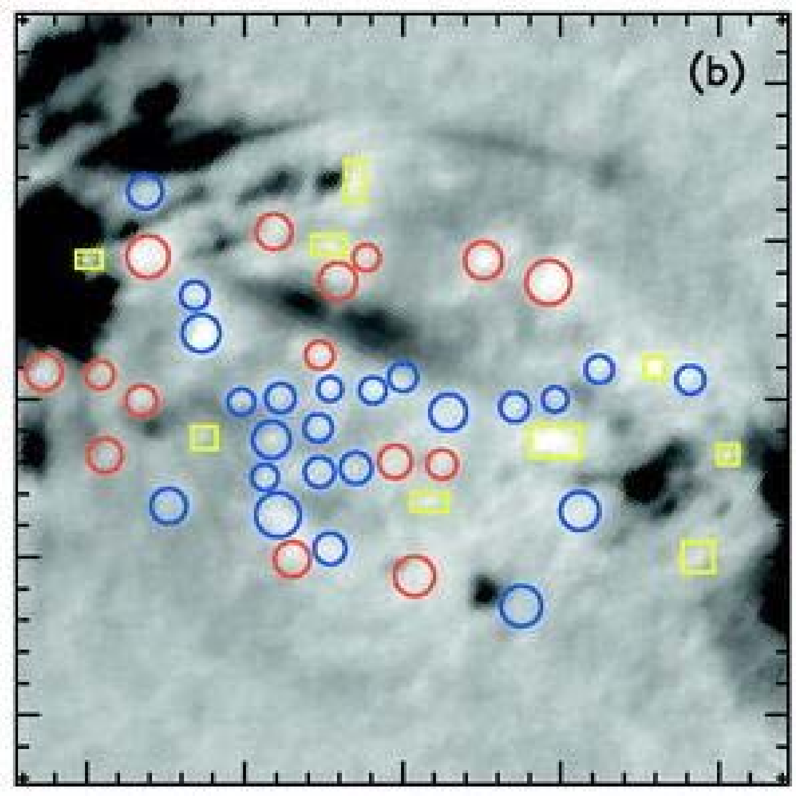
Ubiquitous small-scale energy release



SoHO/MDI 01/25/00, 12:51 UT



Courtesy of Pariat et al. (2004)

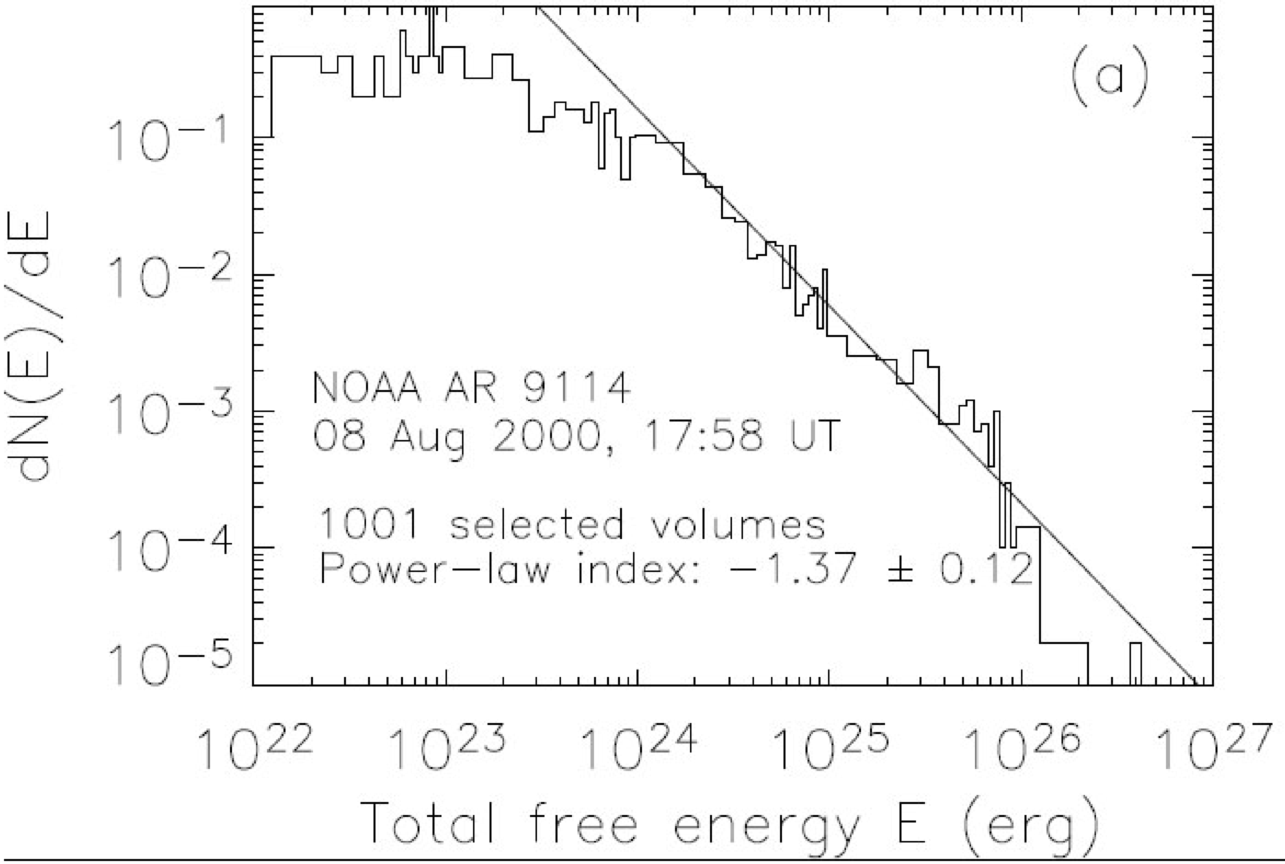


Hundreds of small-scale, short-lived brightenings (Ellerman bombs) over a 3-hr period

Approx. 81% (38/47) of EBs associated with magnetic bald patches, separatrices or QSLs

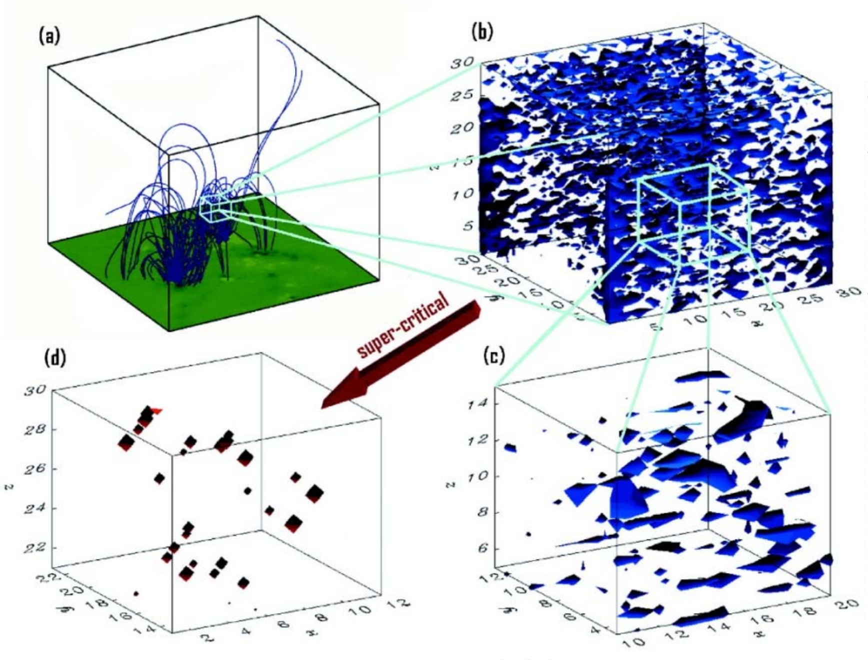
Evidence of self-similarity in small-scale energy dissipation processes

Statistical properties of Thin Current Layers (TCL)

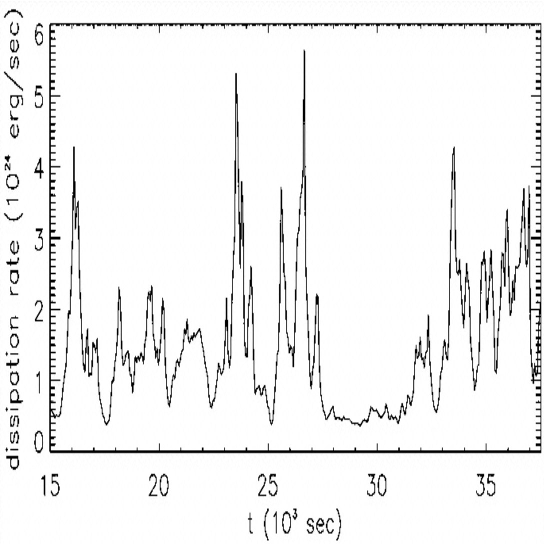


Time evolving magnetogram

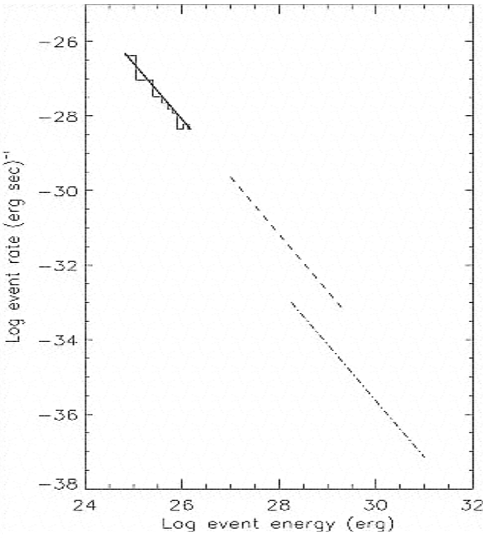
Expected consequences of turbulence



Vlahos et al. (2004)



Dmitruk et al. (1998)

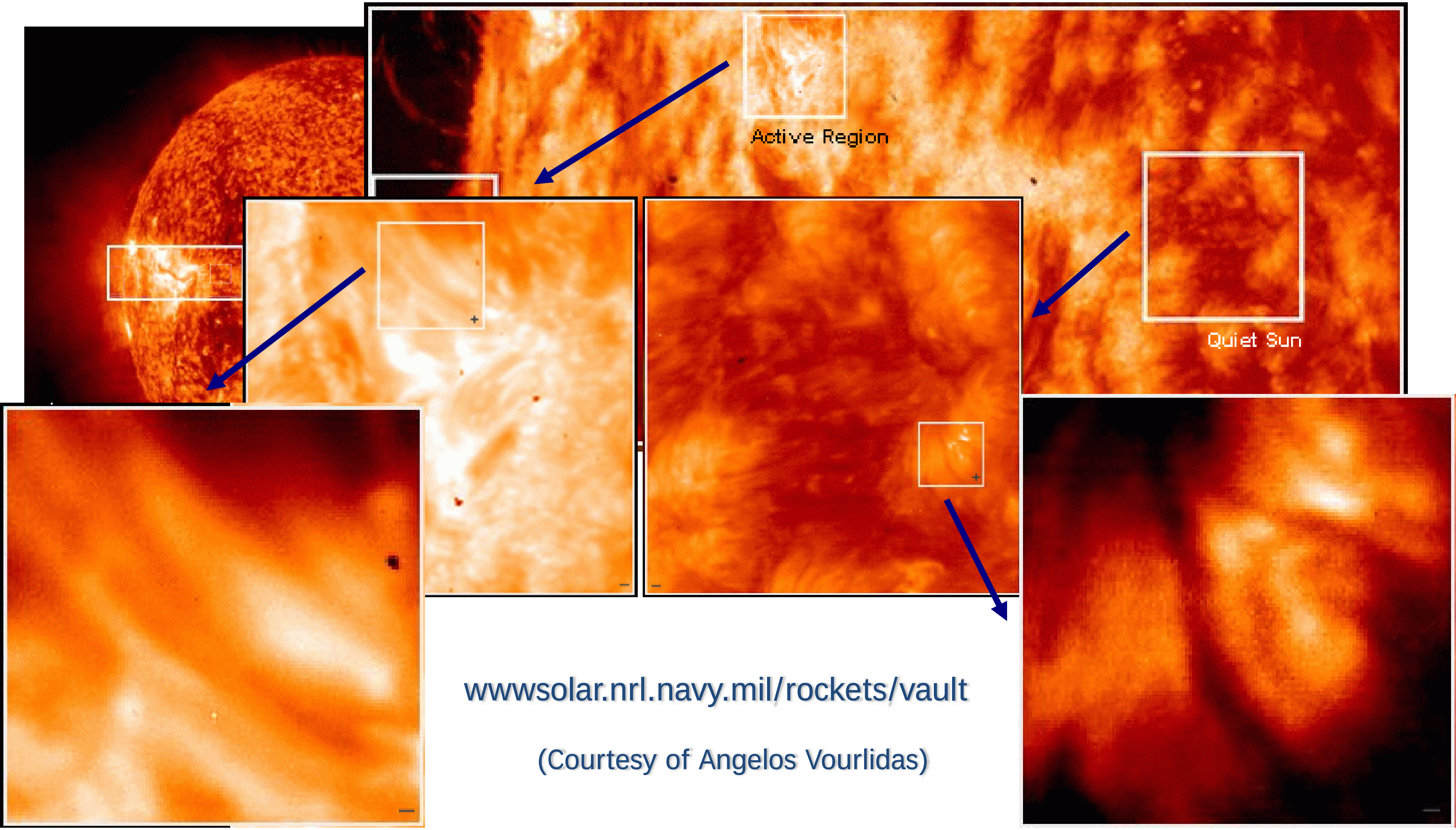


Dmitruk & Gomez (1997)

- Hierarchical self-organization, which gives rise to tremendous spatial complexity
- Spatial self-similarity (scale invariance & fractal structures)
- Intermittency in the energy release process
- Power laws in the statistical behavior of the system

Activity in all spatial scales / Scale invariance

Results from the Very high Angular Resolution Ultraviolet Telescope (VAULT)



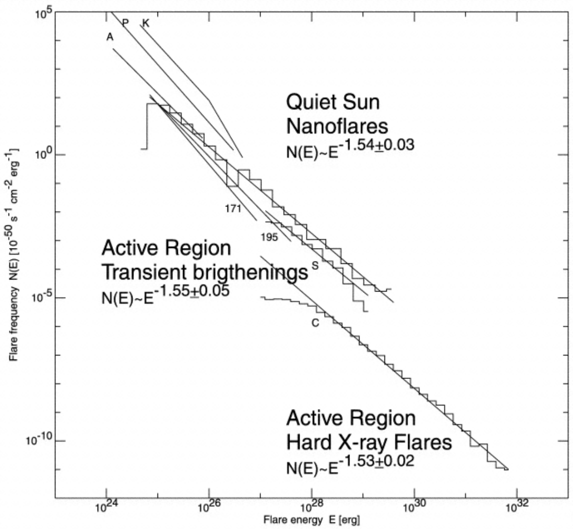
wwwsolar.nrl.navy.mil/rockets/vault

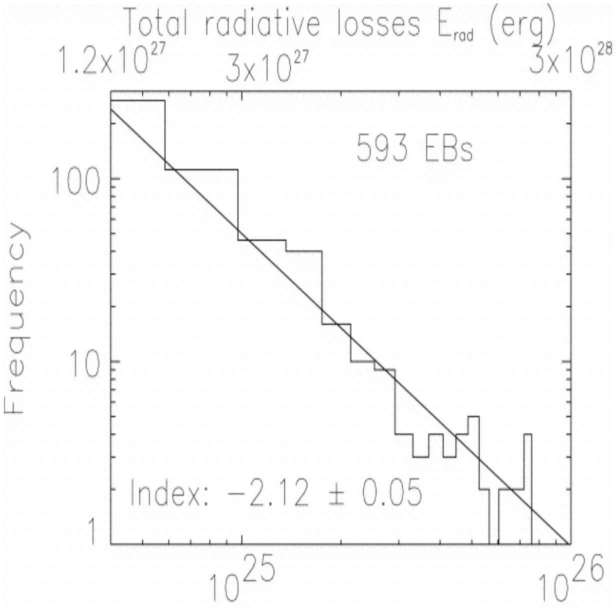
(Courtesy of Angelos Vourlidas)

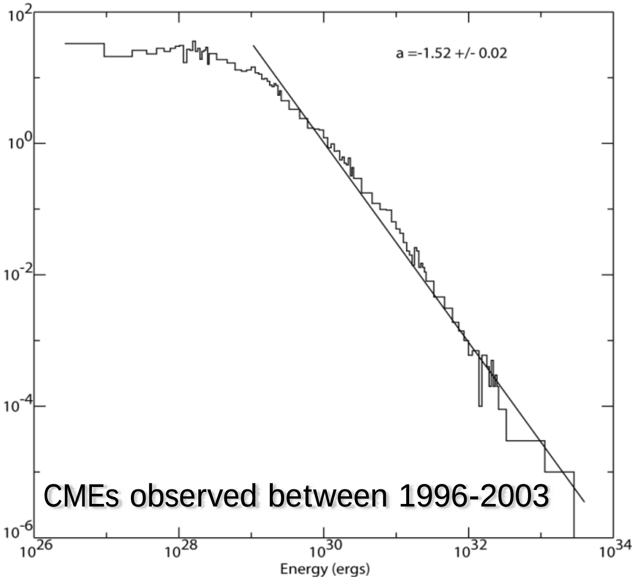
“Quiet” Sun indistinguishable from active regions in small spatial scales

Quantifying the statistics of solar activity

Power laws everywhere:







ATRBs, nanoflares, hard X-ray flares
(Aschwanden & Parnell 2002)

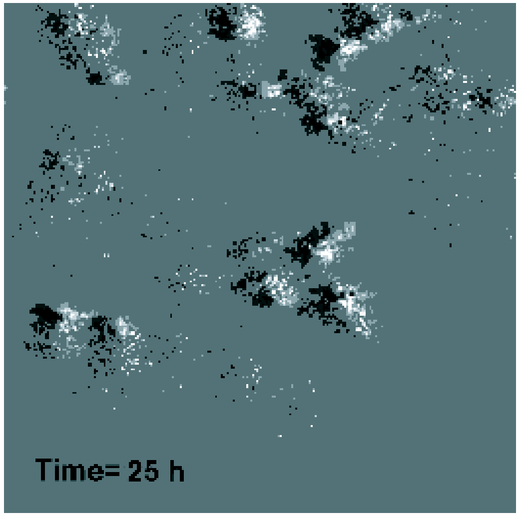
Ellerman bombs
(Georgoulis et al. 2002)

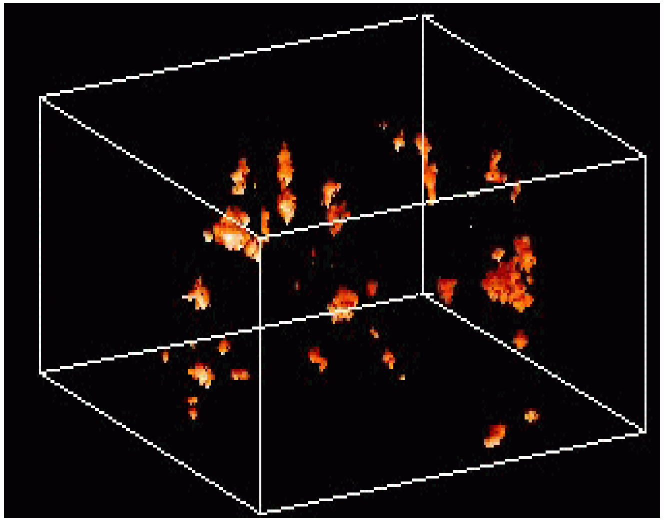
Kinetic Energy of CMEs
(Courtesy of A. Vourlidas)

Moreover, power laws are found in the events' peak activity, total duration, rise and decay times, area coverage, inferred volumes, etc.

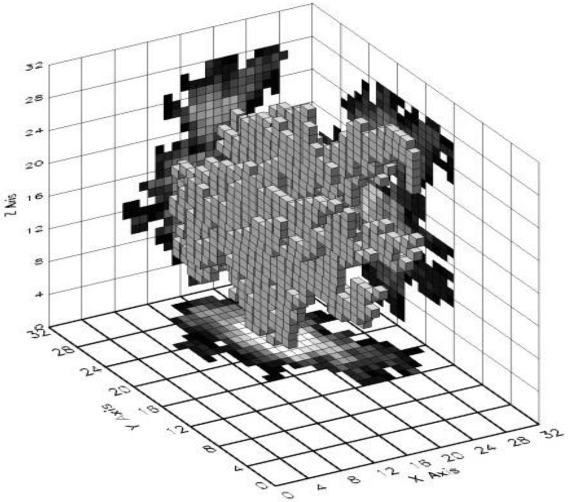
- Intermittency and self-similarity (scale invariance) evident in space and time
- What is the cause of the observed complexity ?

Self-Organization: deterministic or stochastic?





Fragos et al. (2004)

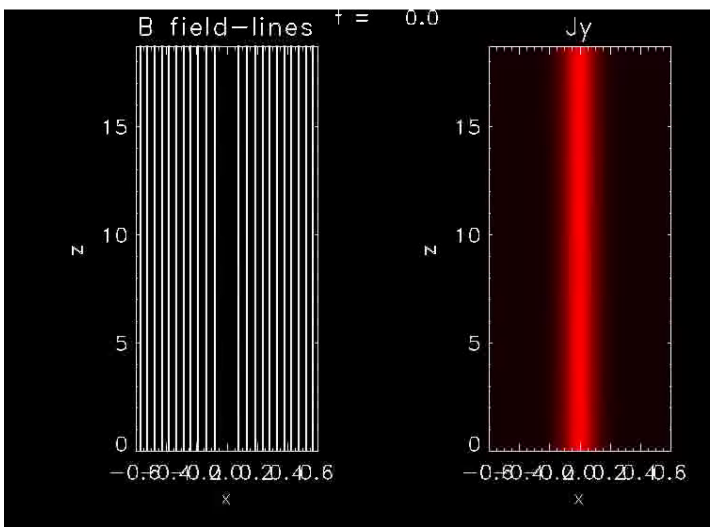


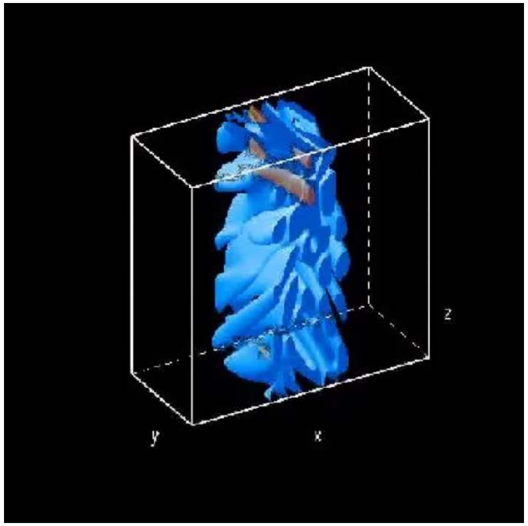
McIntosh &
Charbonneau (2001)

- Both seem to be at work:
  - Stochastic self-organization (percolation) reproduces emergence of magnetic flux
  - Deterministic self-organization (SOC) reproduces the triggering of dissipative events
- Spatiotemporal fractality and multi-fractality evident in both cases
- Cascades (avalanches) in the energy release process
- A critical loss of equilibrium possibly responsible for avalanches

But what is the nature of the critical threshold, if any?

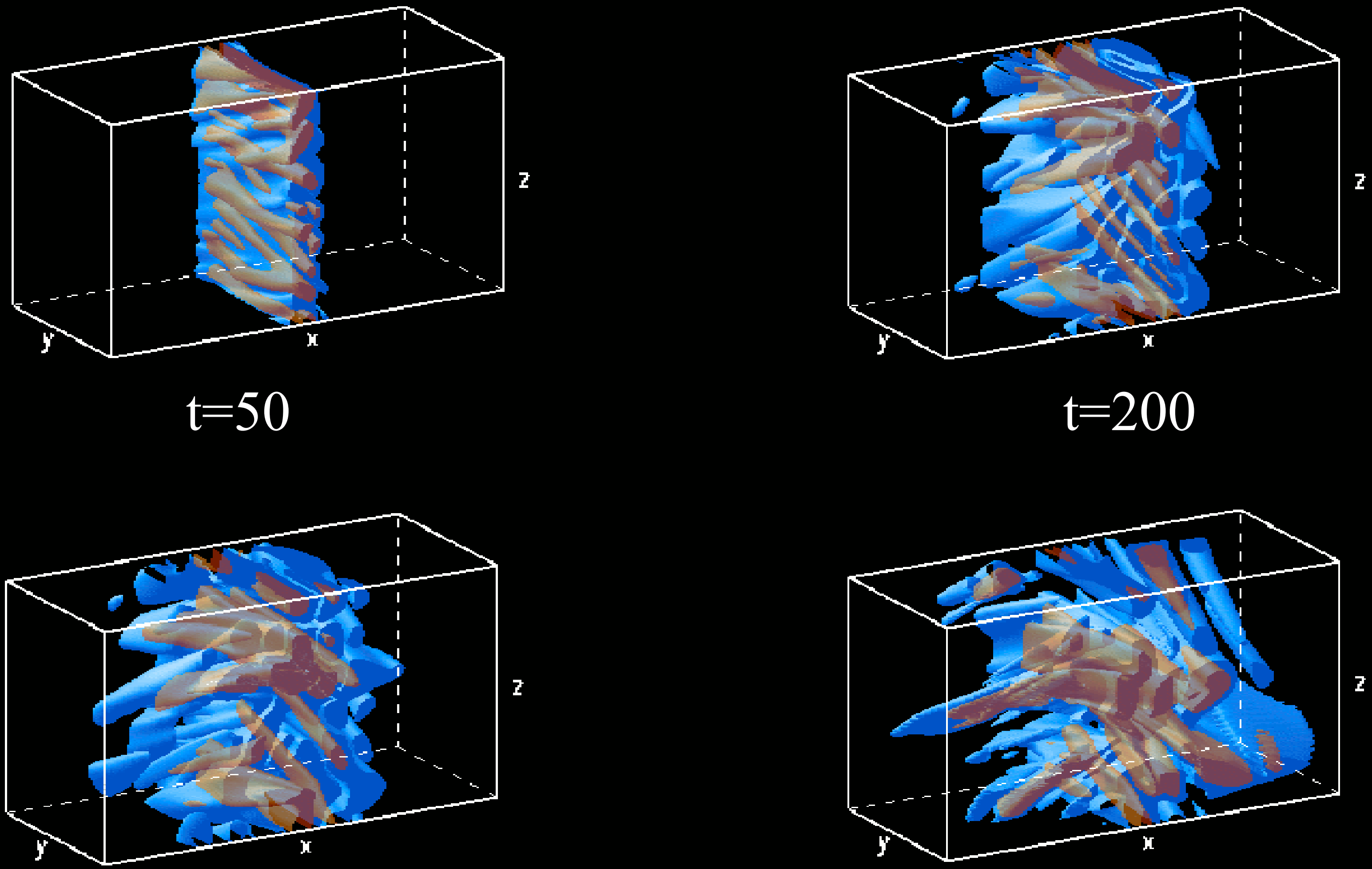
Inside a collapsing current sheet





Three-dimensional structure of the electric field

Isosurfaces of the electric filed at different times



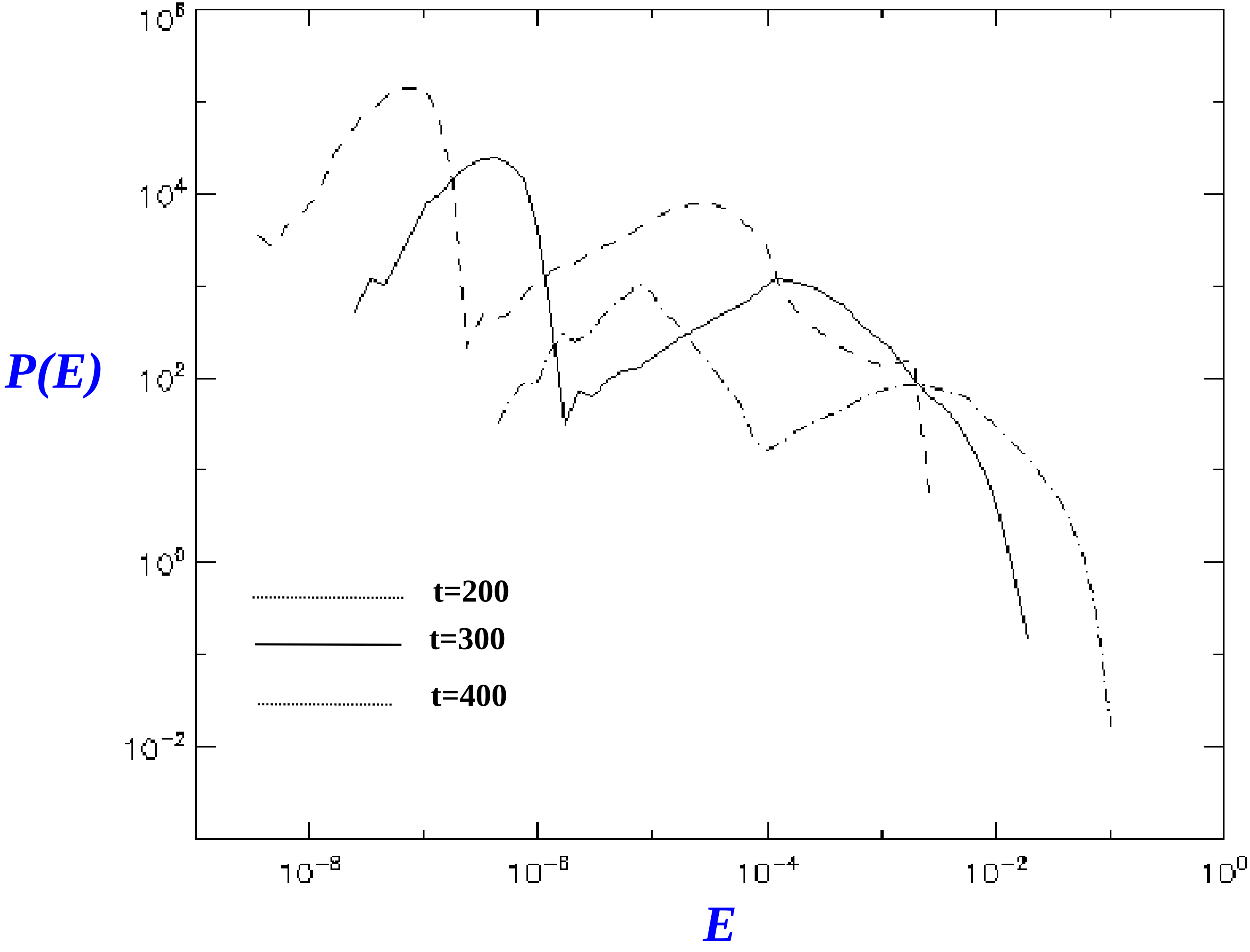
t=50

t=200

t=300

t=400

Distribution function of the electric field

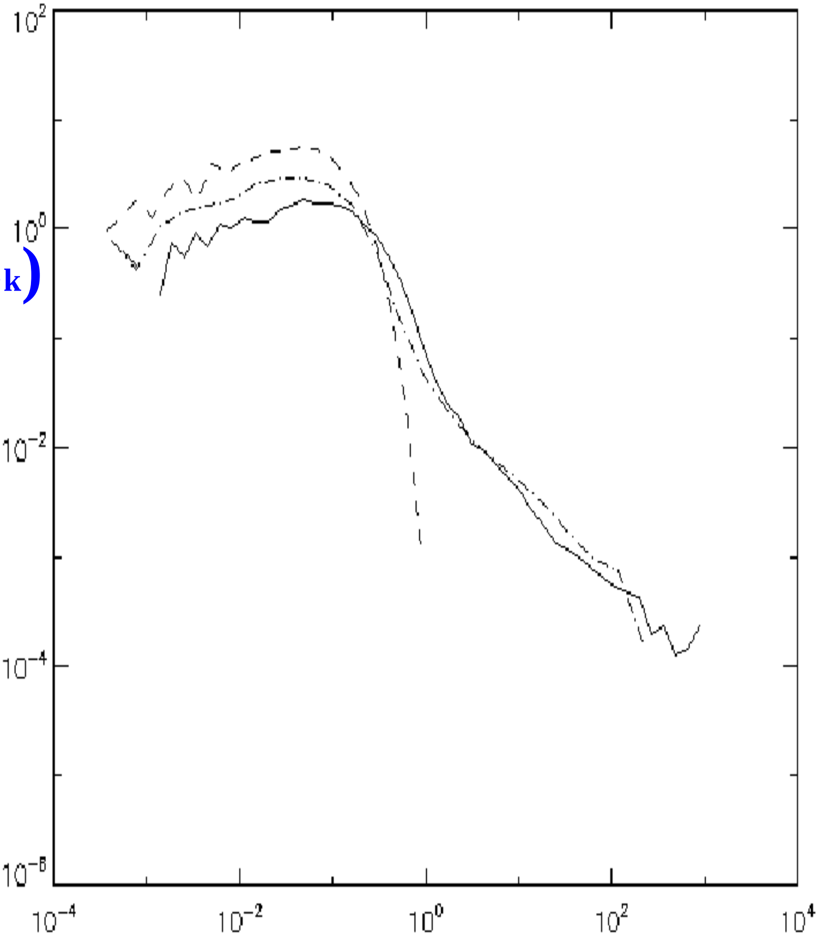


Kinetic energy distribution function of electrons

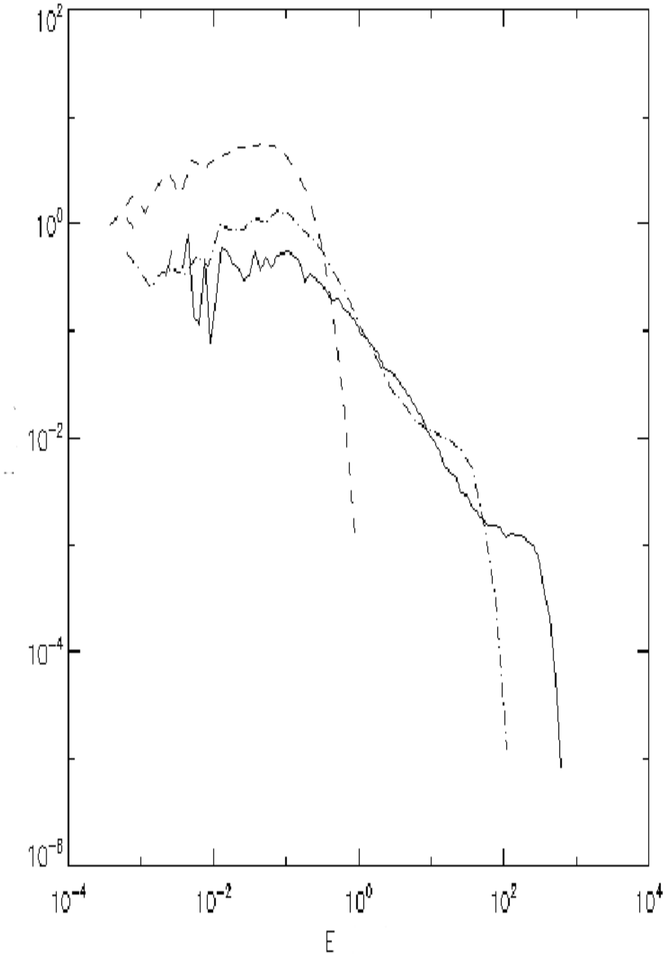
t=50 T_A

T=400 T_A

$P(E_k)$



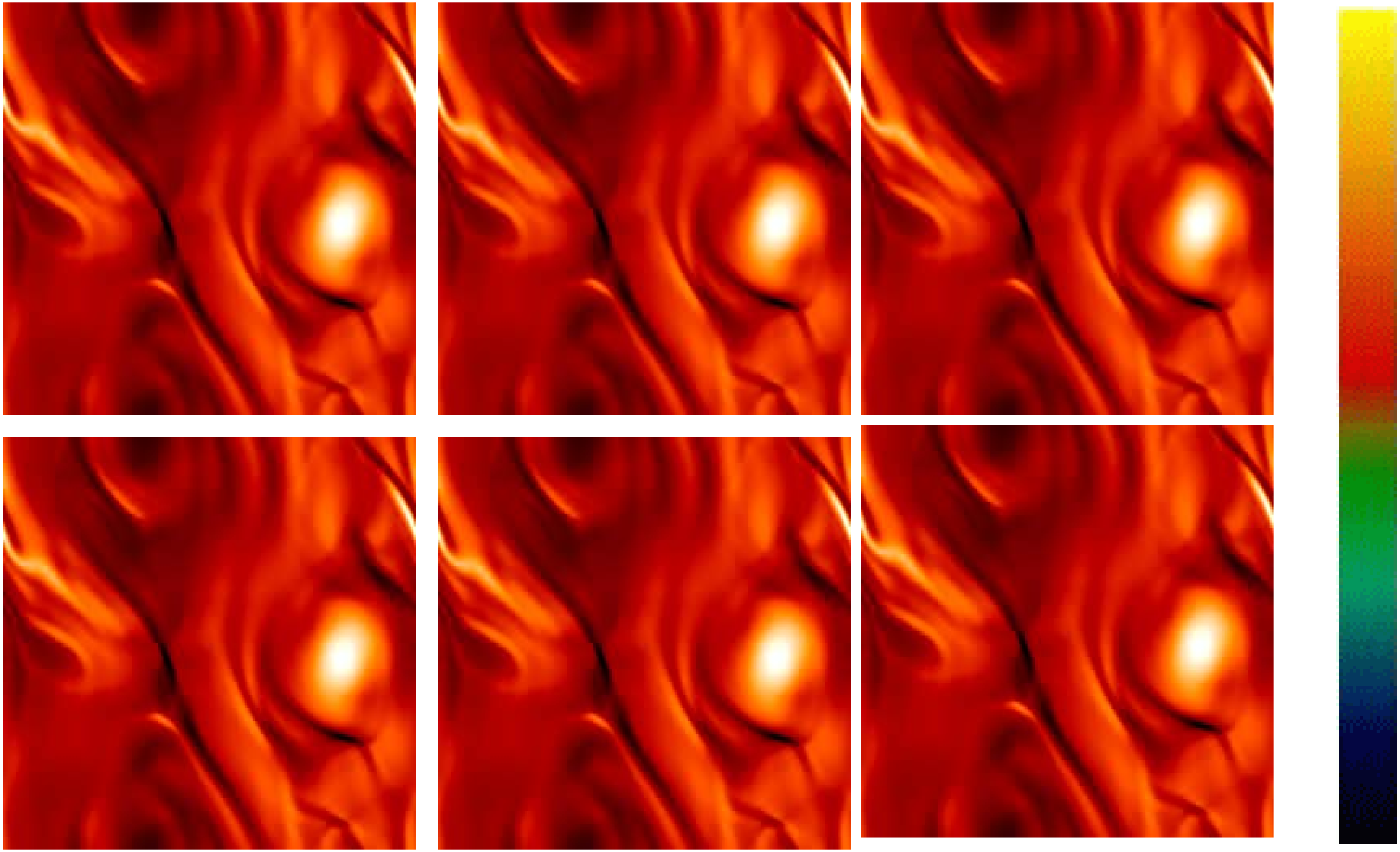
E_k (keV)



E_k (keV)

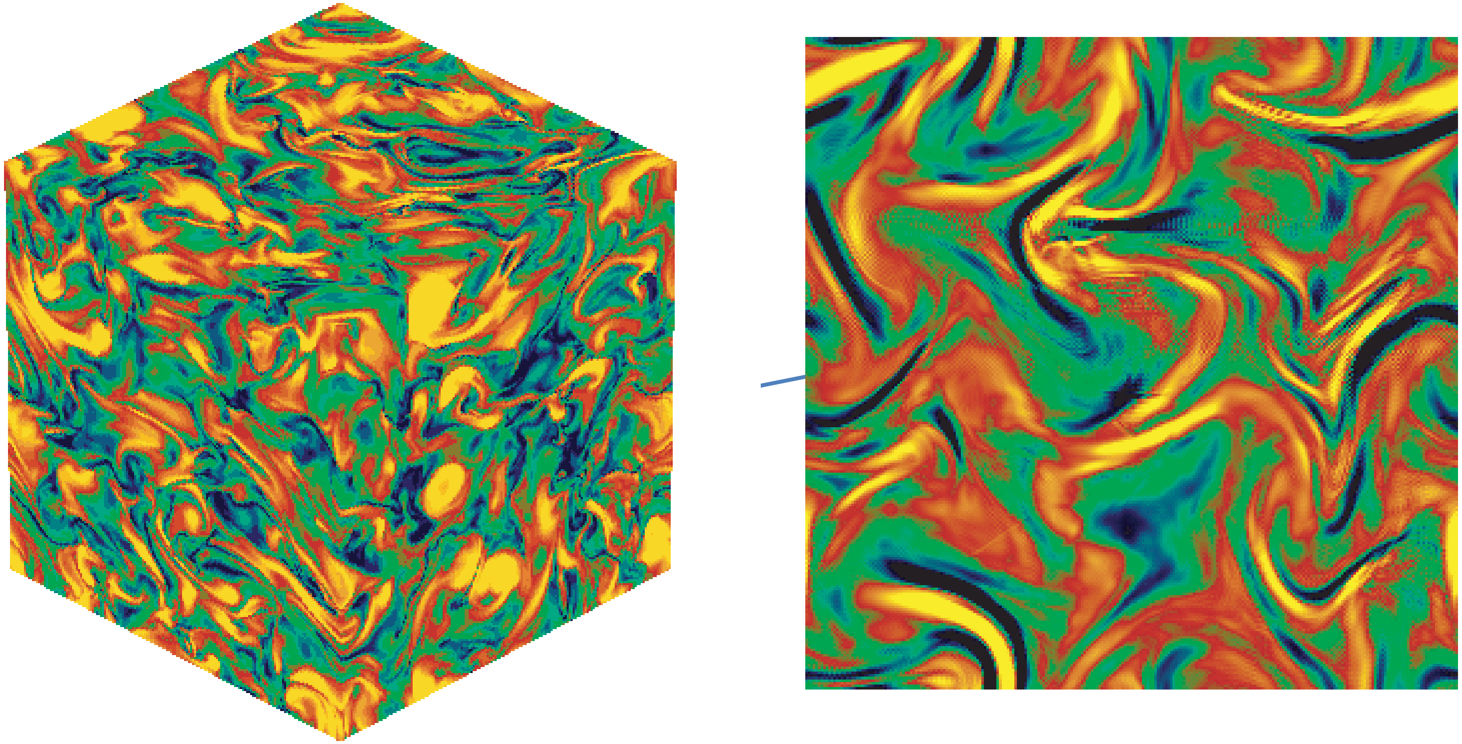
Statistics of the MHD models

- MHD models with a turbulent evolution exhibit complexity, spatio-temporal intermittency, and self-similarity in the resulting distributions



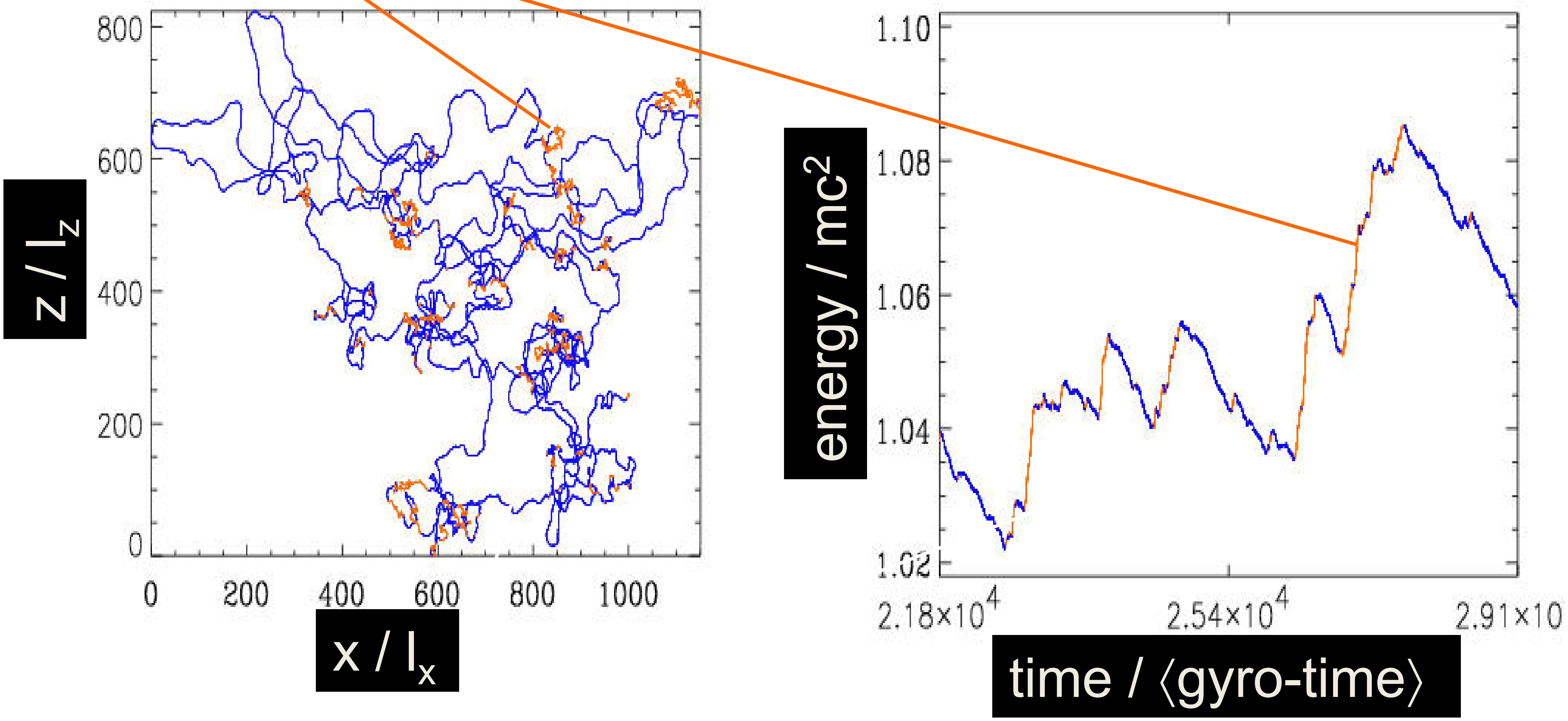
Georgoulis *et al.*, ApJ, 1998

A ‘**Turbulent**’ Field Model
(stochastic but not resonant accelerator)
(Dmitruk et al, 2003, Azner and Vlahos, 2004)

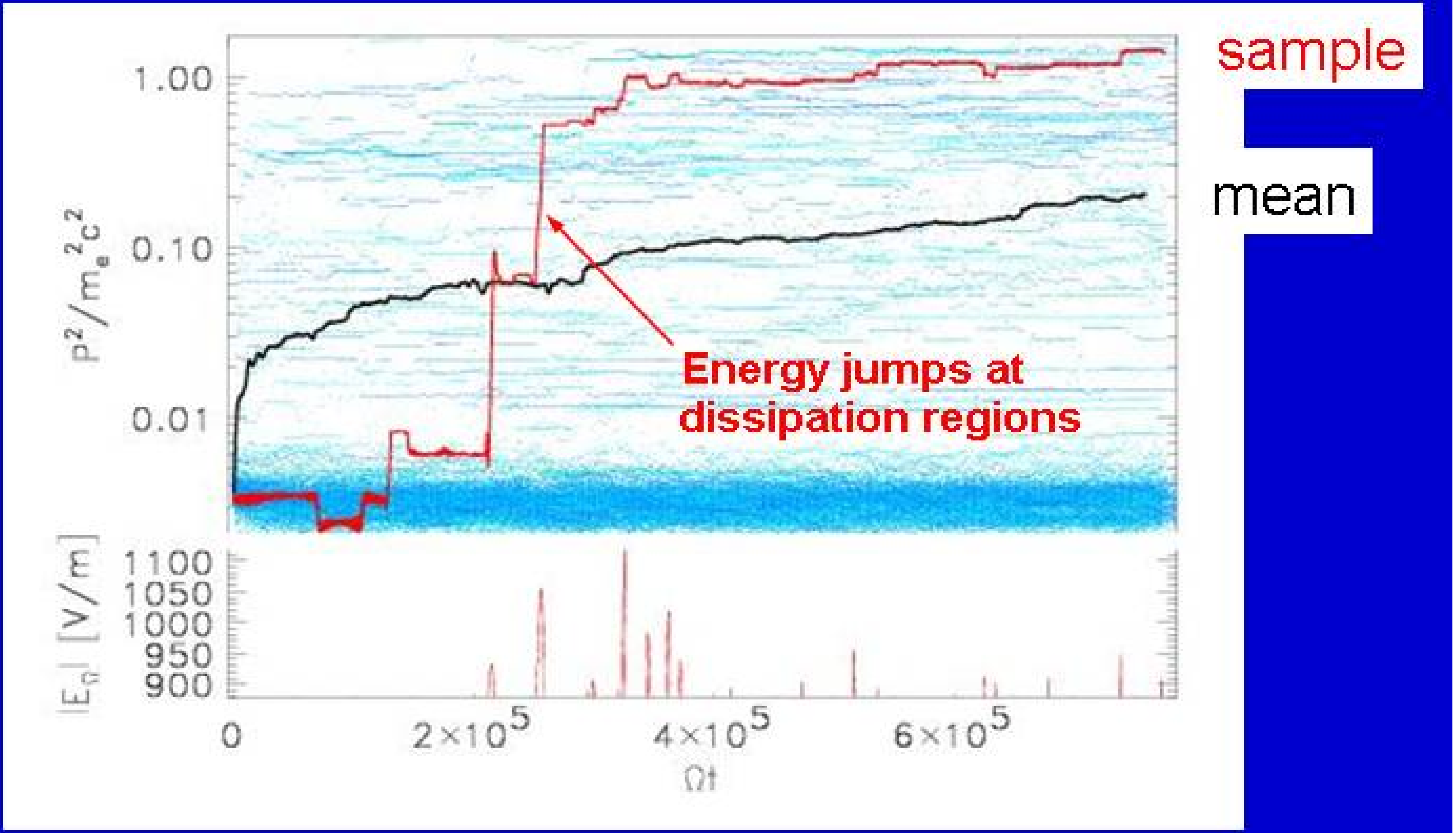


Finding: intermittent particle orbits

acceleration **within** local dissipation regions



Electron Acceleration



sample

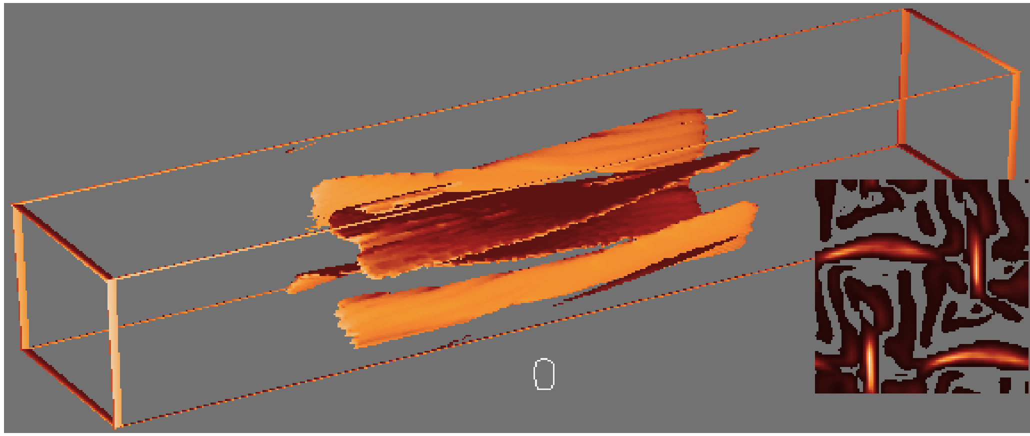
mean

Energy jumps at dissipation regions

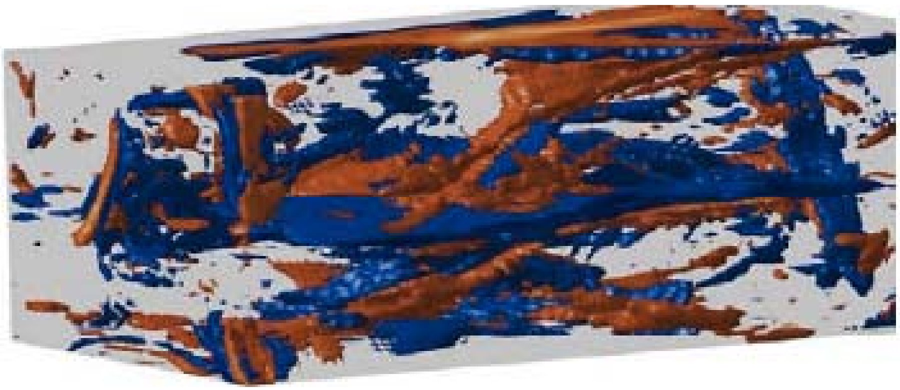
Particle acceleration in stochastic current sheets

(Rim Turkmani et al, ApJL2004, AA 2005)

- Particles injected at random positions within an MHD box
  - Protons 0.027 kev
  - Electron 1.16 kev
- Initial velocity fixed in amplitude, random i direction

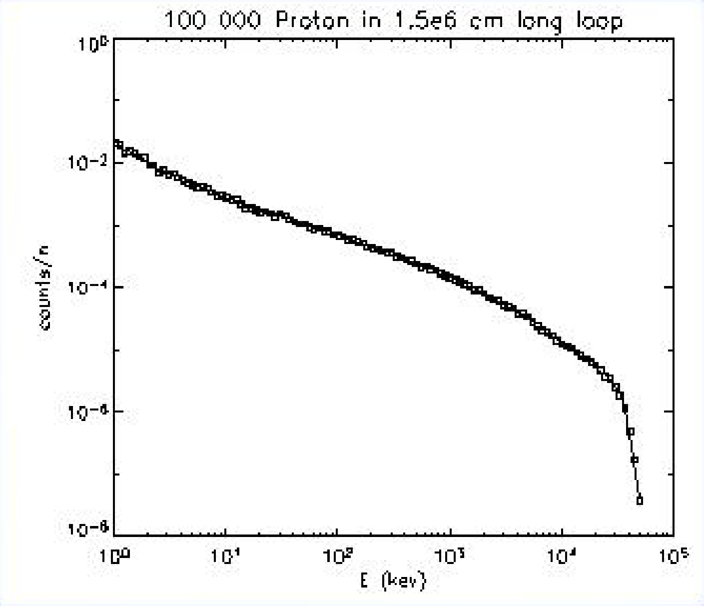


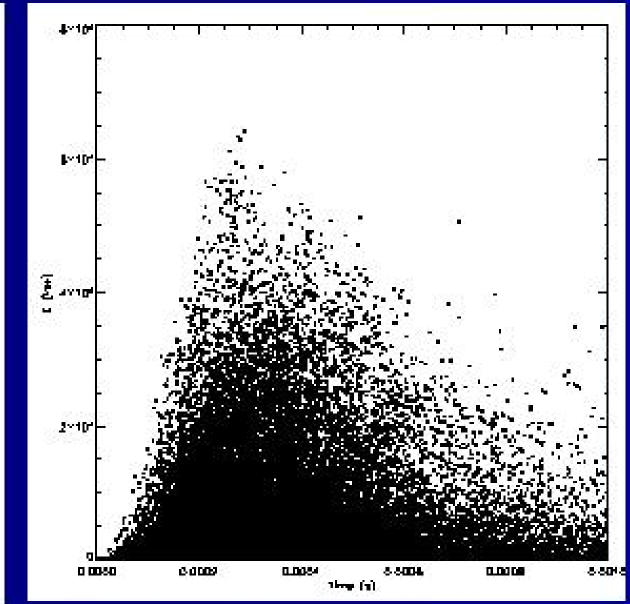
- **Acceleration time scale much shorter than MHD time scale**
- **B and E are scaled;**
- **initial values:**
  - **B: Mean ~ 1.0 (0.89 – 1.08)**
  - **E: Mean ~ 7e-4 (e-5 – e-2)**



Distribution Functions

- 100,000 proton in 100 G magnetic field run for 1 ms

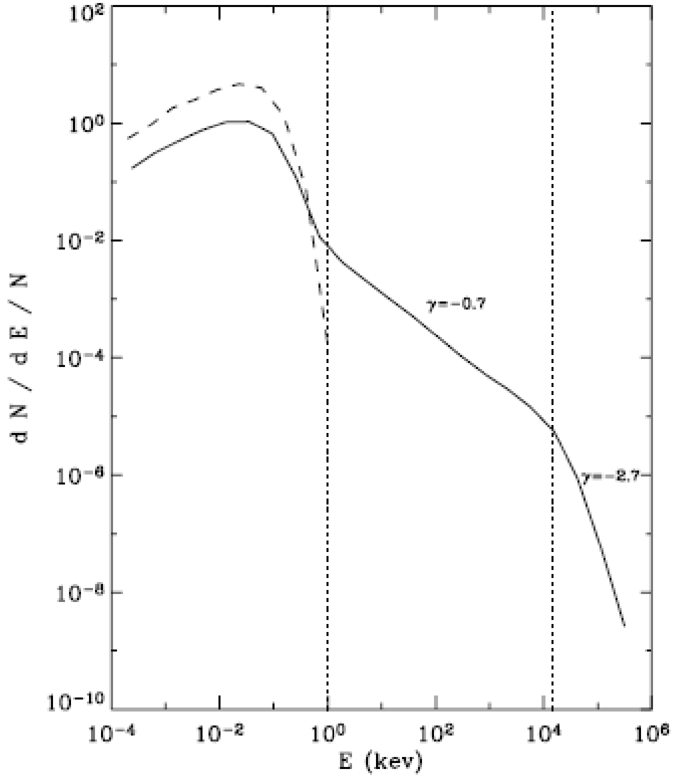


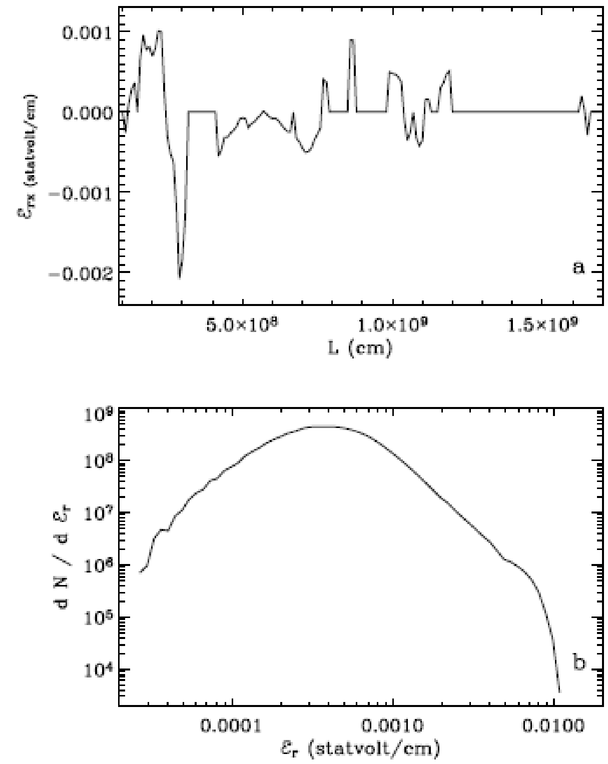


- Two parts power law
- ~ 60 Mev in 0.3 ms

Turkmani et al

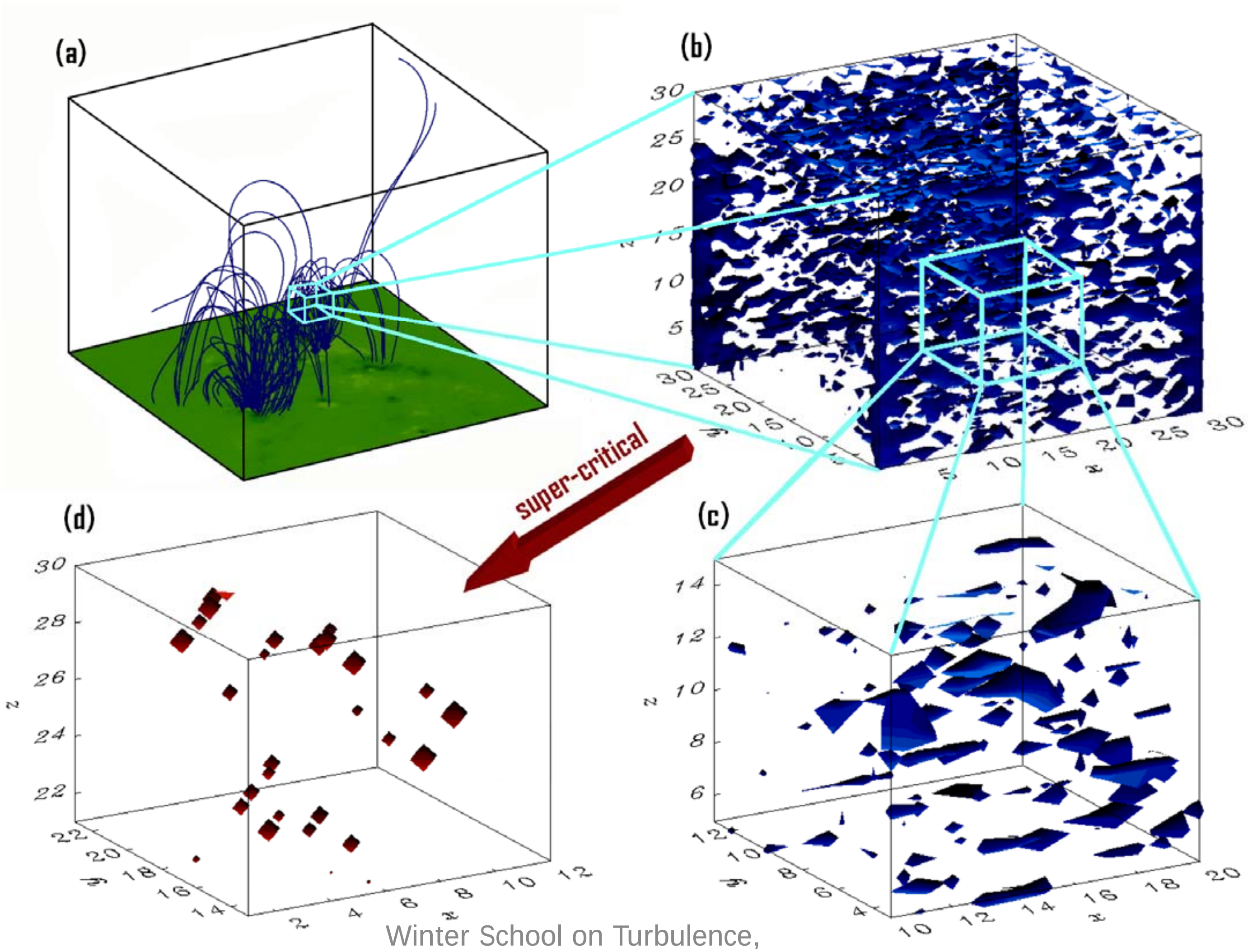
- Velocity distribution



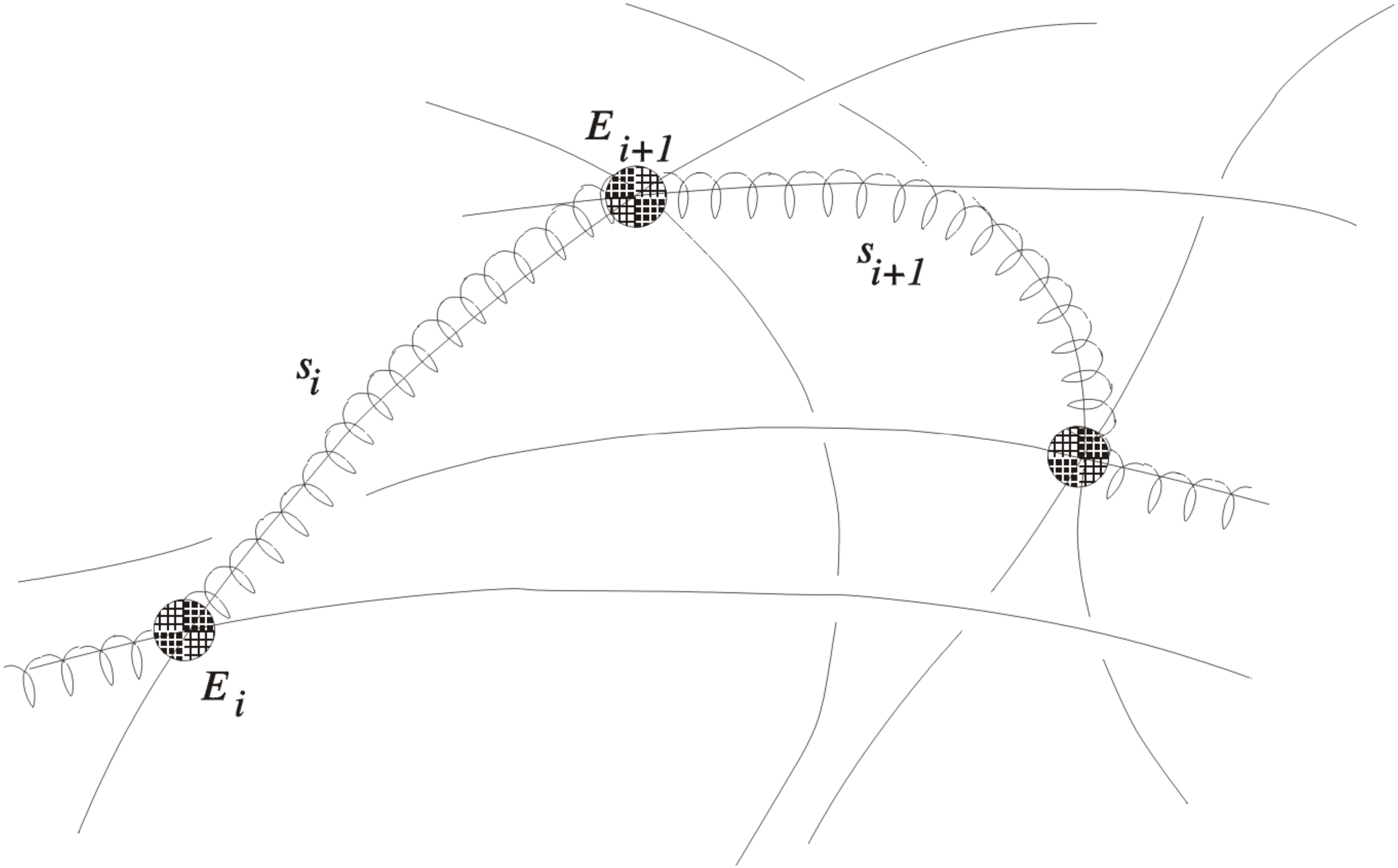


Using the X-CA model

- From



Sporadic formation of current sheets
Vlahos, Isliker and Lepreti (ApJ, June 10,2004)



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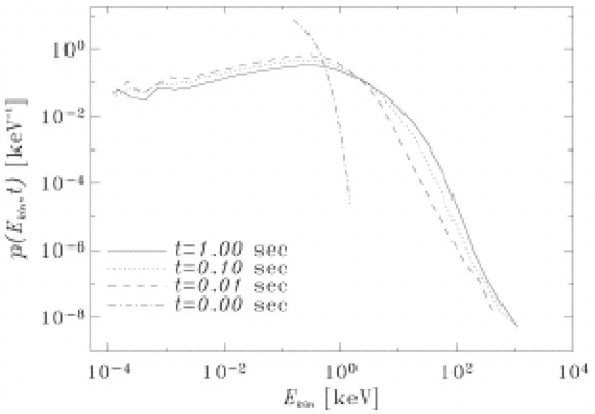
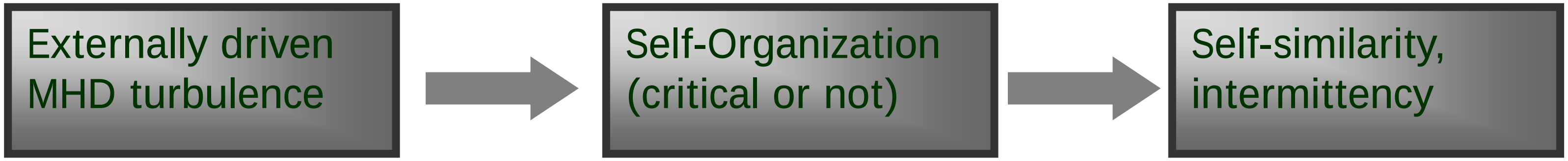


Conclusions


Externally driven MHD turbulence

Self-Organization (critical or not)

Self-similarity, intermittency

- The driver: convection zone
- Spontaneous or driven formation of current sheets
- Threshold for stable and unstable current sheets
- Self organized critical state of active regions
- Collapse of current sheets and avalances
- Network of current sheets
- Fully developed “strong” turbulence in active region
- Particle dynamics inside “strong” turbulence
- Very good correlation with observations

Role of Theory ? (E. Priest, 2005)

- Not -- reproduce images
- Nor explain every observation
- ***Understand Basic Processes**
  -- step-by-step -- simple ->
  sophisticated model
- ***Listen to Observers** -- clues
- Diff. Types Theory -- complement
  -- analytical -- computational -- data interp.