Complexity in solar and stellar active regions

Loukas Vlahos

History

- More than 20 years ago on the skylab workshops (Vlahos et al.) and then ten years ago Miller et al. wrote a nice review which is highly cited in the literature even today. In both reviews, the main goal was to contrast the known acceleration mechanisms (E-fields, Turbulence, shocks) with observations. The energy release (magnetic reconnection and flows) 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

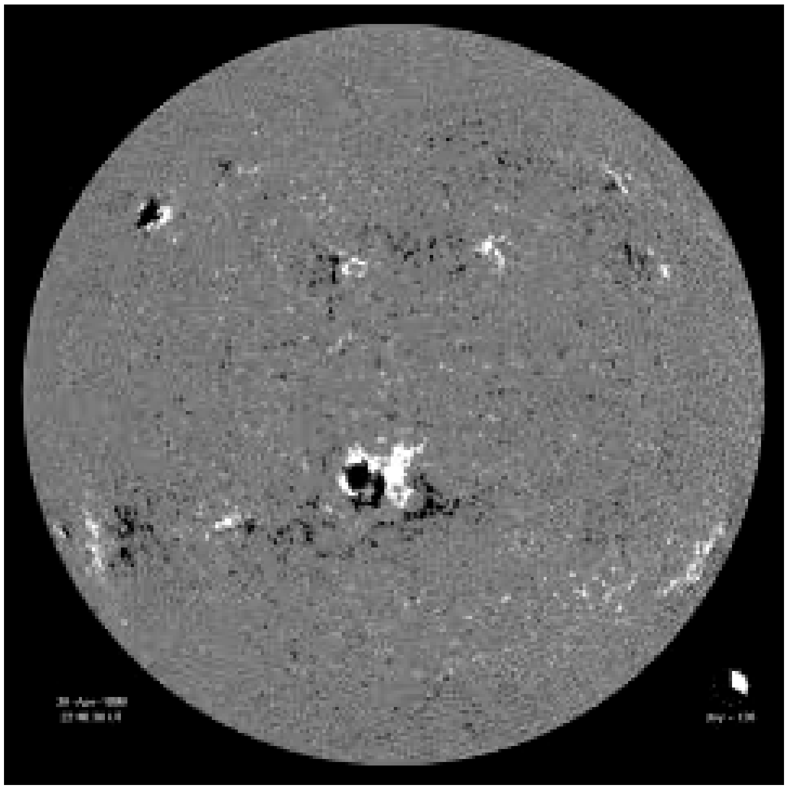
- A long list of outstanding problems were mentioned and open observational issues were listed.
- The recent observations added to the Miller list even more constrains, the most important been that “if the energy carried by the high energy particles reaches as high as 30-40% of the total energy… acceleration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

Outline

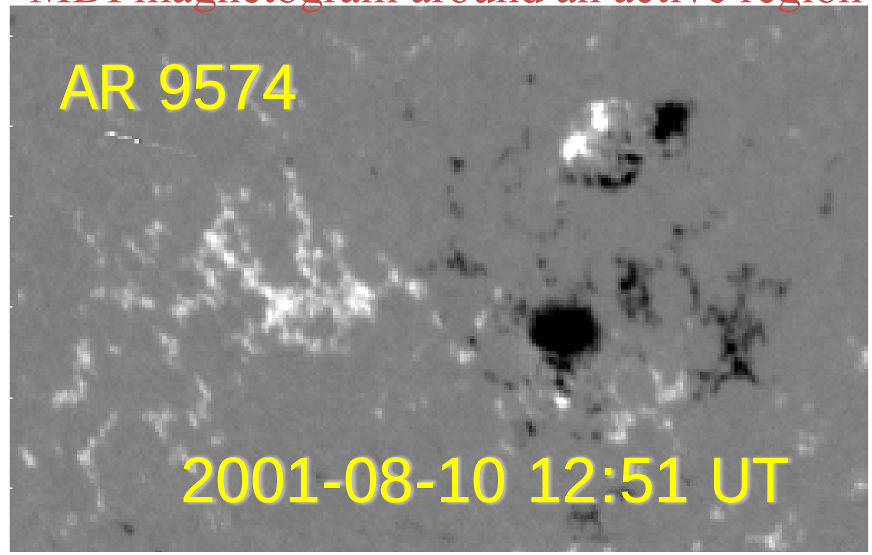
- Active regions as driven non linear systems
- Spatially self-similar, small-scale energy release
- Power-law statistics
- The solar atmosphere as an externally driven turbulent system
- Turbulent self-organization: Critical or non-critical?
- Formation of stable and unstable current sheets
- Particle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

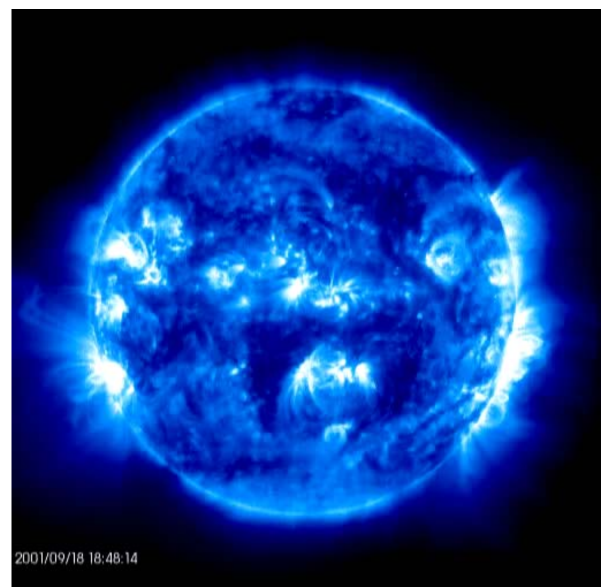
Sunspots and active regions

Sunspots in a full disk magnetogram



MDI magnetogram around an active region

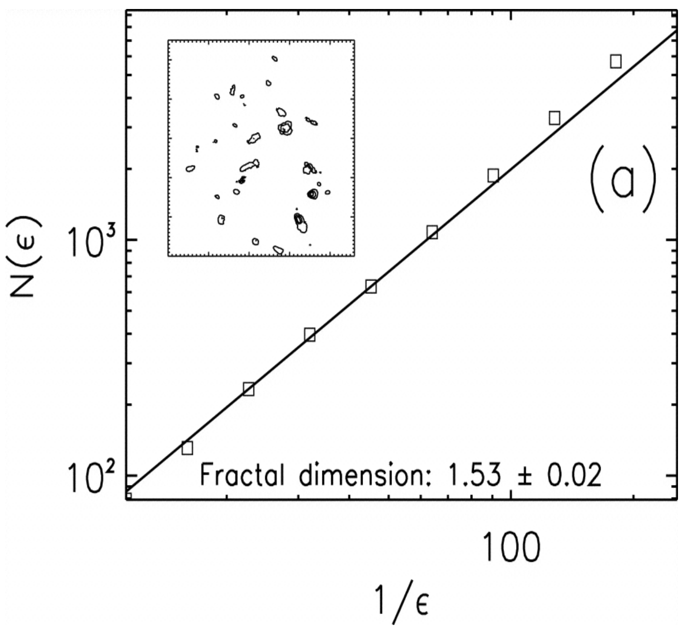




Multi-scale diagnostics of solar structures

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

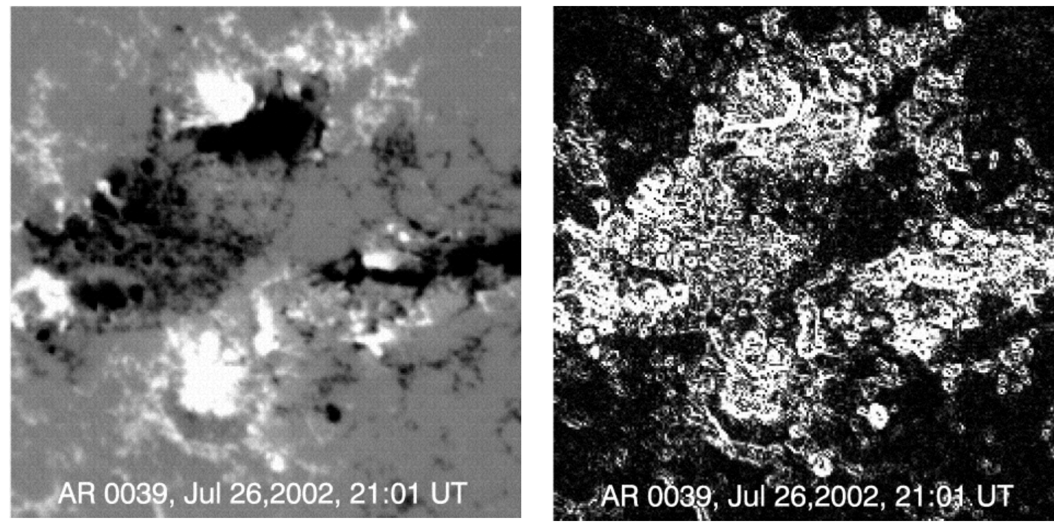
Georgoulis et al. (2002)



The fractal dimension:

EBs are fractal structures

Abramenko et al. (2003)



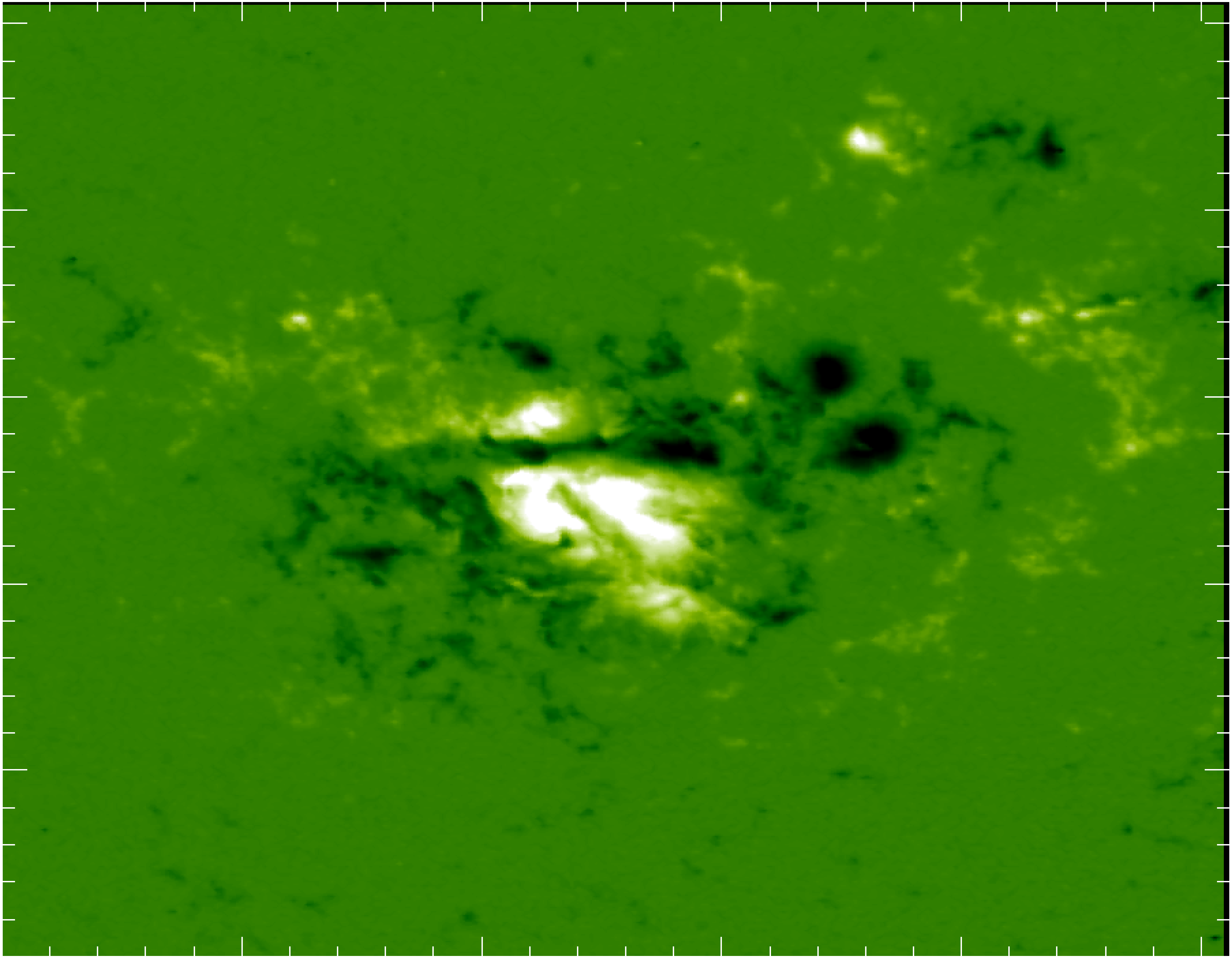
Structure functions:

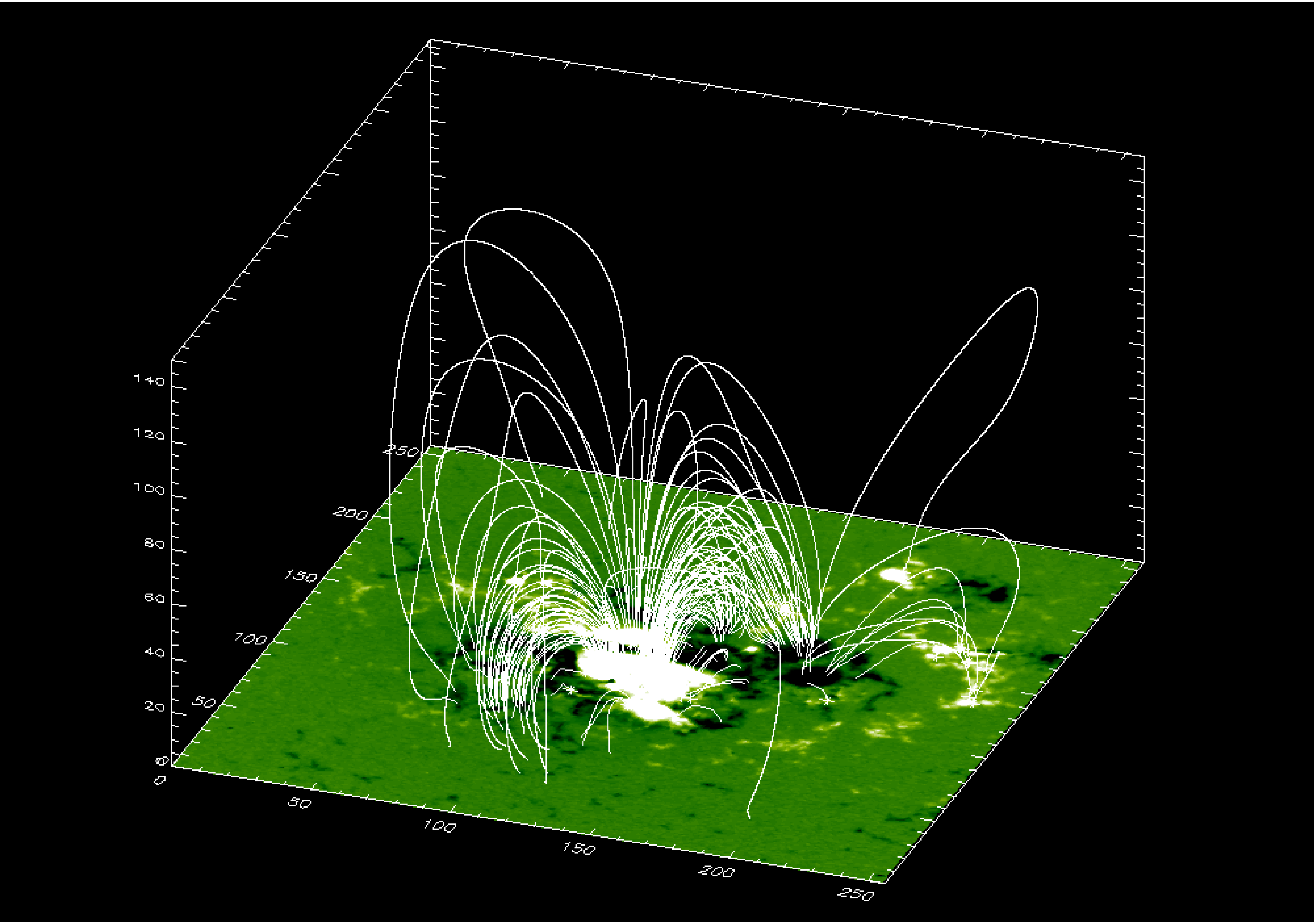
$$S_q(r)=\left\langle \left|B_z(\bar{x}+\bar{r})-B_z(\bar{x})\right|^q \right\rangle \sim (r)^{\zeta(q)}$$

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





140
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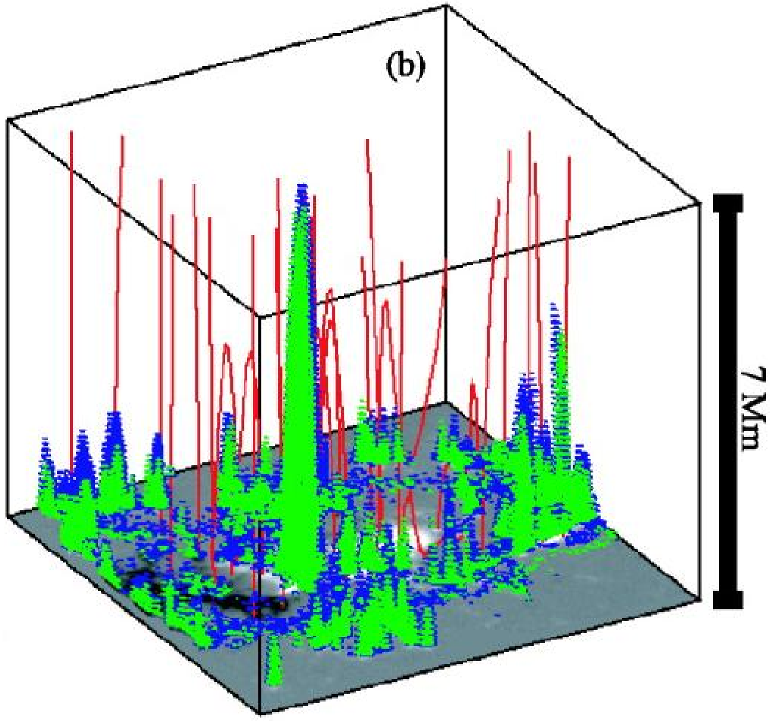
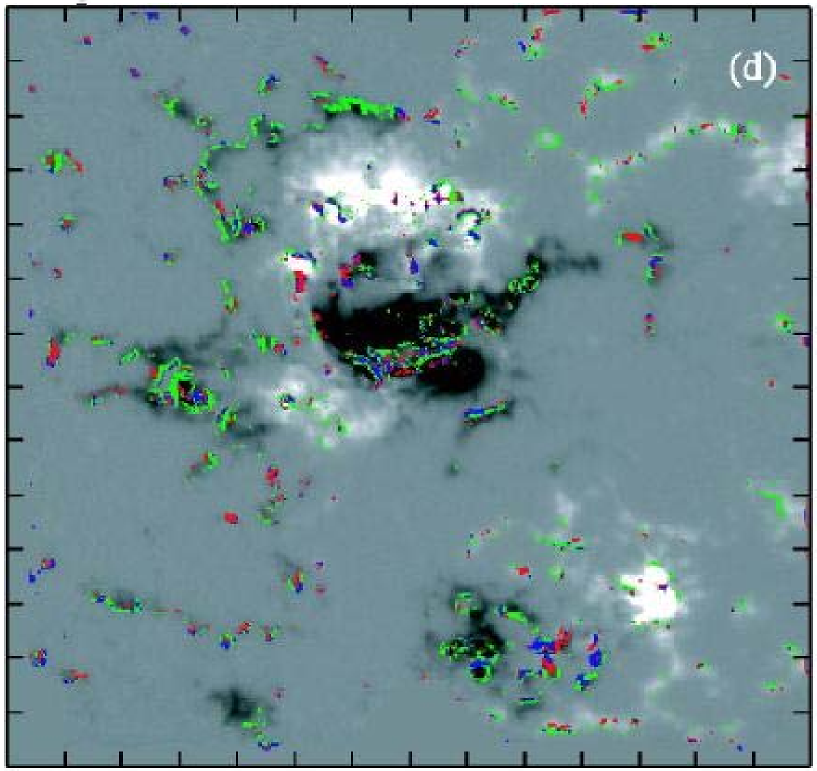
Pre-flare / Quiescent evolution of solar ARs

Vlahos & Georgoulis (2004)

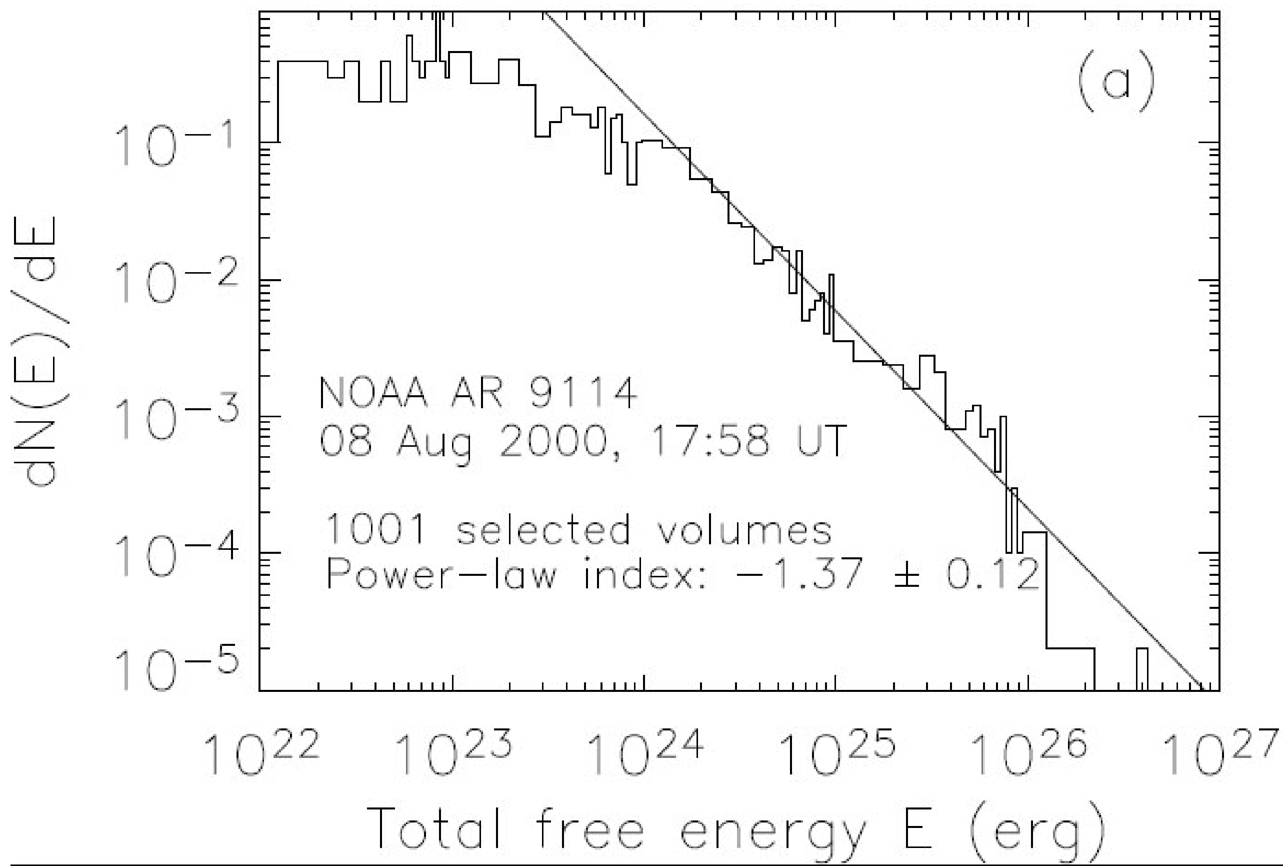




- A large number of likely unstable <u>fractal</u> volumes at low altitudes $\left(\leq 10\mathrm{Mm} \right)$
- Free energies showing power-law distribution; index nearly <u>insensitive</u> to the critical threshold
- Free energies of the order $10^{24} - 10^{26} erg$ - An <u>avalanche</u> necessary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

Statistical properties of Thin Current Layers (TCL)



Numerical method

Three dimensional time-dependent resistive MHD equations

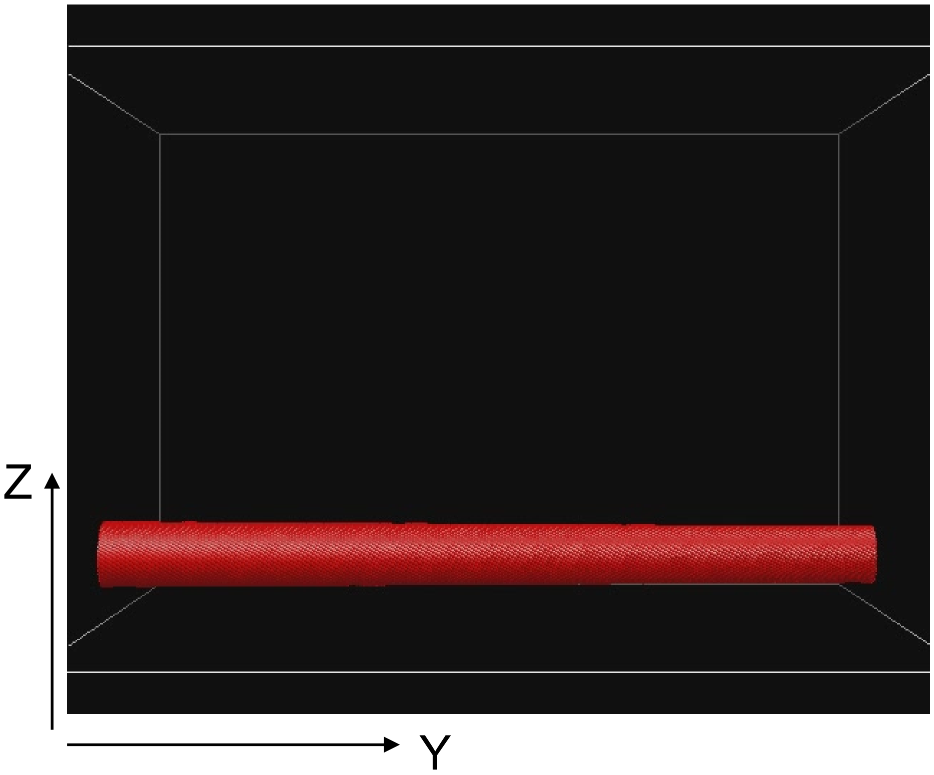
$$
\begin{aligned}
\frac{\partial \rho}{\partial t} &= -\nabla \cdot (\rho \mathbf{u}), \\
\frac{\partial (\rho \mathbf{u})}{\partial t} &= -\nabla \cdot (\rho \, \mathbf{u} \otimes \mathbf{u} + \underline{\underline{\tau}}) - \nabla p + \rho \, \mathbf{g} + \mathbf{J} \times \mathbf{B}, \\
\frac{\partial e}{\partial t} &= -\nabla \cdot (e \mathbf{u}) - p \, \nabla \cdot \mathbf{u} + Q_{\text{Joule}} + Q_{\text{visc}}, \\
\frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E}, \\
\mathbf{E} &= -(\mathbf{u} \times \mathbf{B}) + \eta \mathbf{J}, \\
\mathbf{J} &= \nabla \times \mathbf{B}, \\
p &= \rho T \, \frac{\mathcal{R}}{\tilde{\mu}},
\end{aligned}
$$

- 6th order - partial derivatives
- 5th order - interpolation
- 3rd order - predictor-corrector - time stepping
- Stretched staggered grid 1d, 3d
- Periodic and closed BC
- Damping zone top-bottom

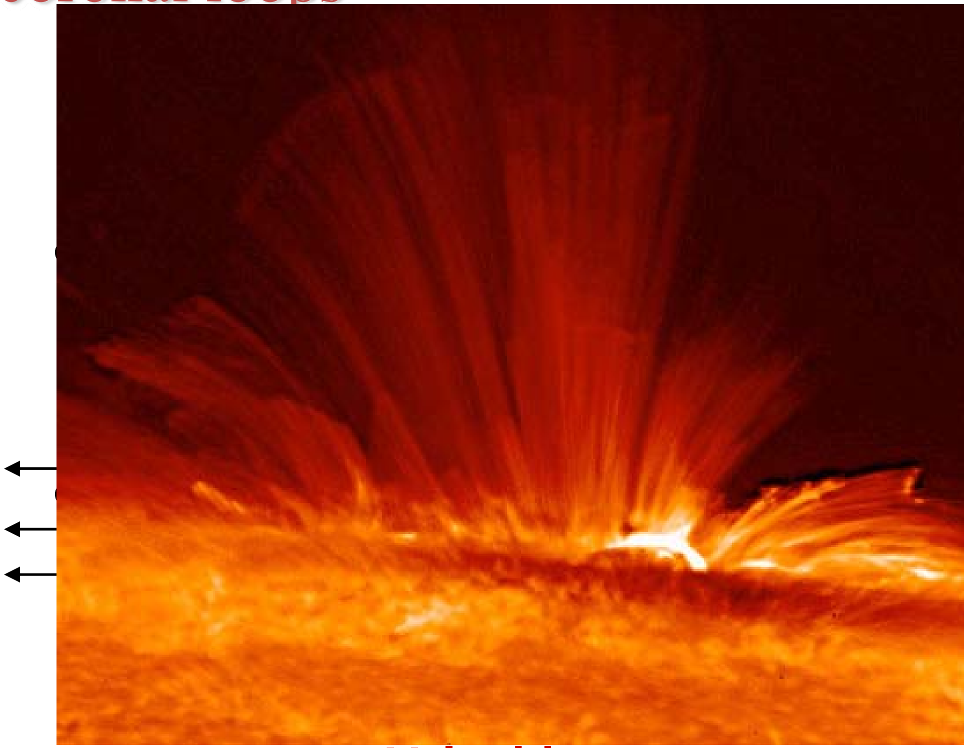
. Hyperdiffusive scheme, 4th order quenced diffusion operators

Emergence into a null corona

Formation of coronal loops



- The tube is more buoyant in the middle
- Fieldlines expand in three directions
- Strongly azimuthal nature at the top
- Fan-like shape of the expanding field.

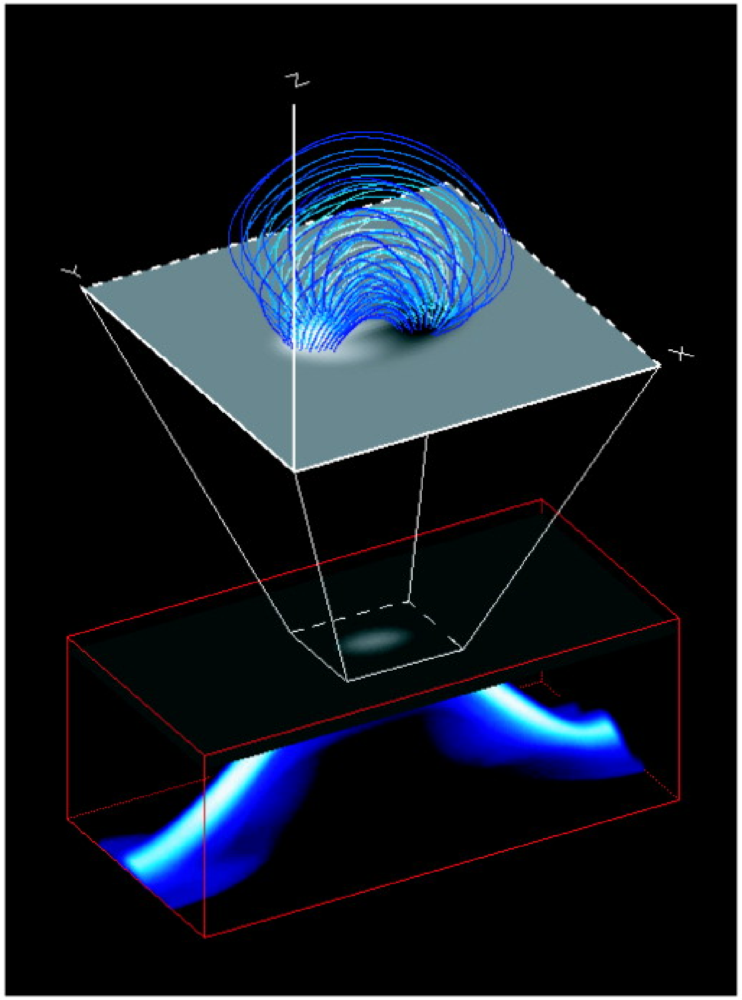


Hinode Solar Optical Telescope

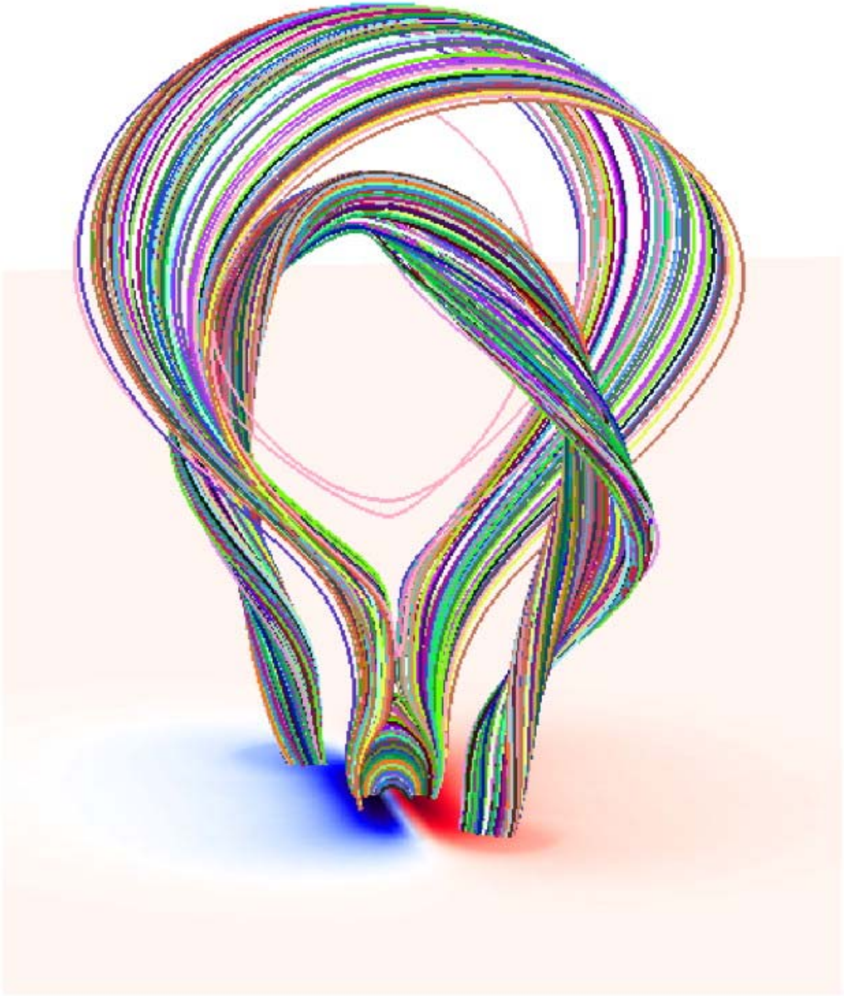
Solar magnetic field rises vertically from a sunspot and adopts a fan-like shape.

The solar corona

- **An externally driven, non-linear dynamical system**

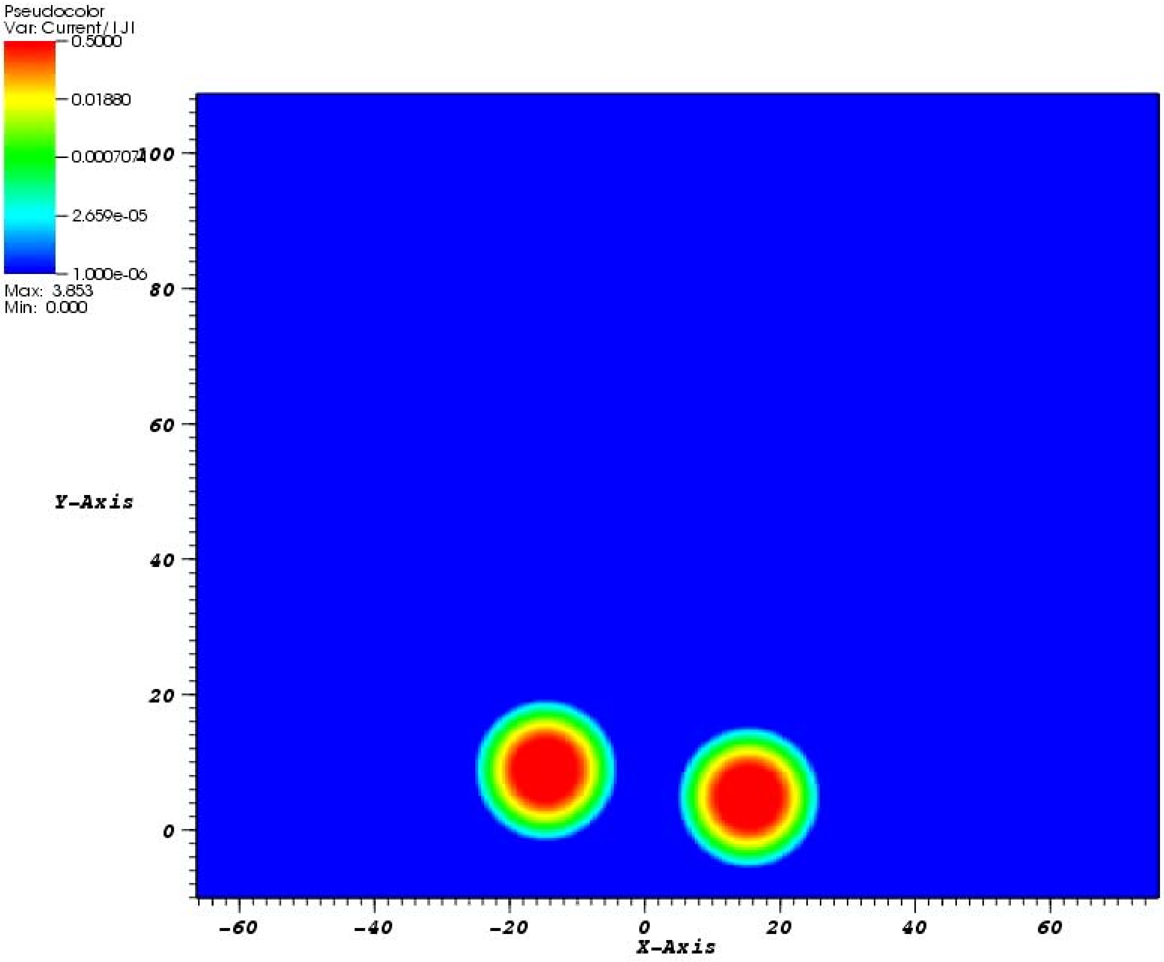


Abbet & Fisher, ApJ, 2002



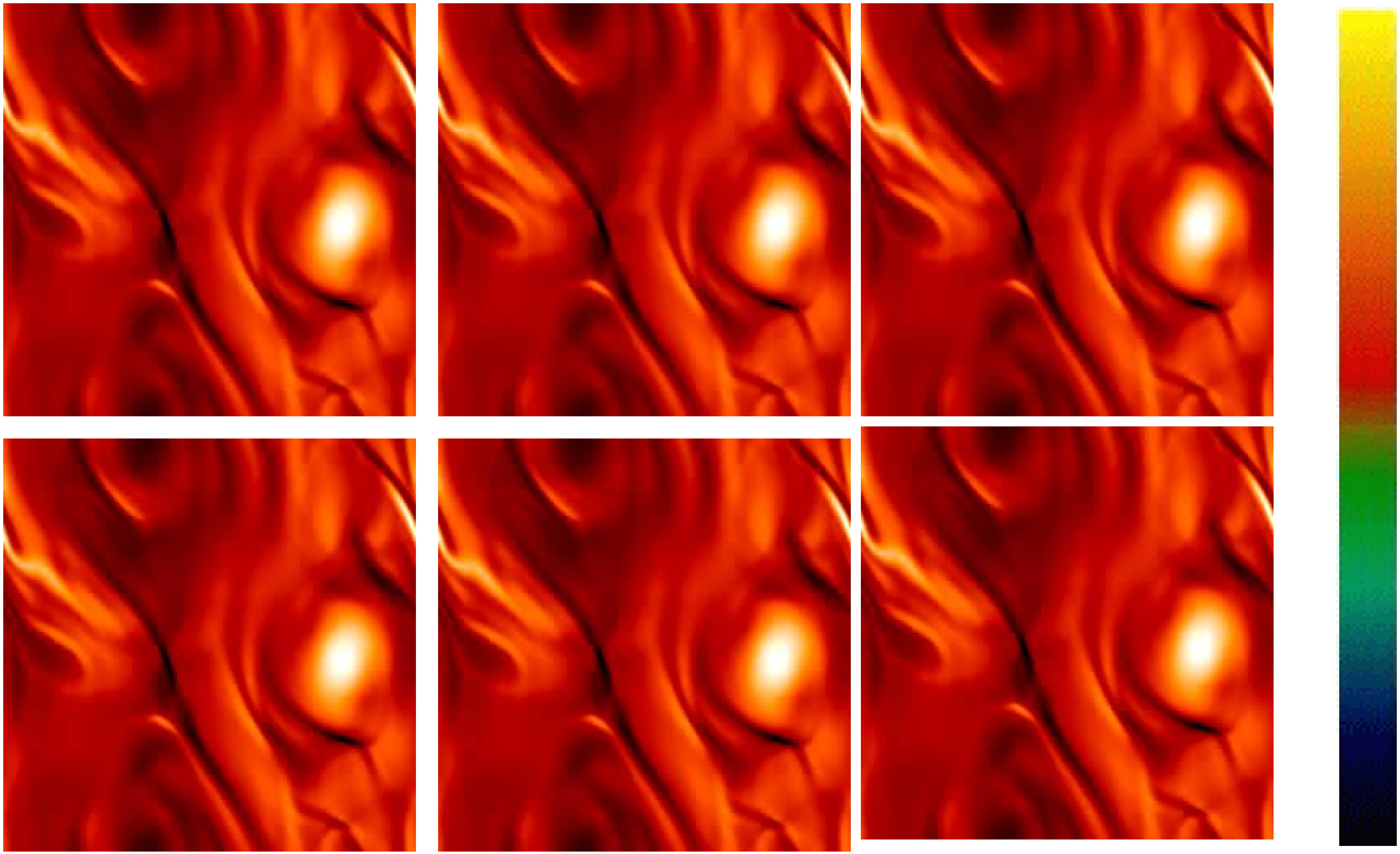
Amari *et al.,* ApJ, 2003

Formation of current sheet + collapse



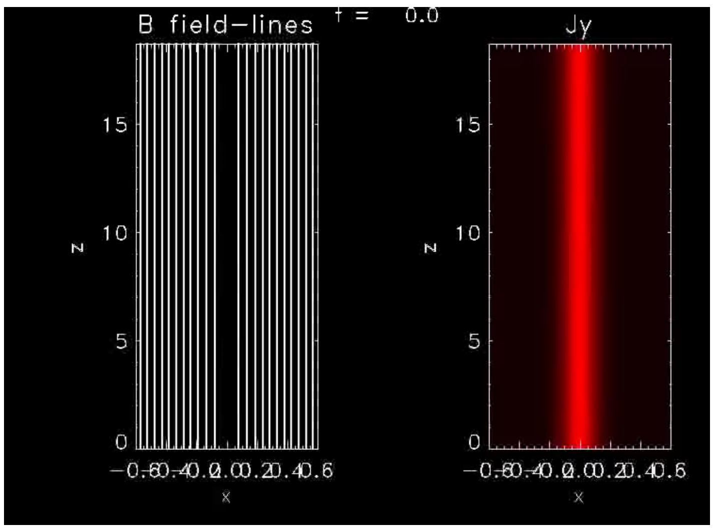
Statistics of the MHD models

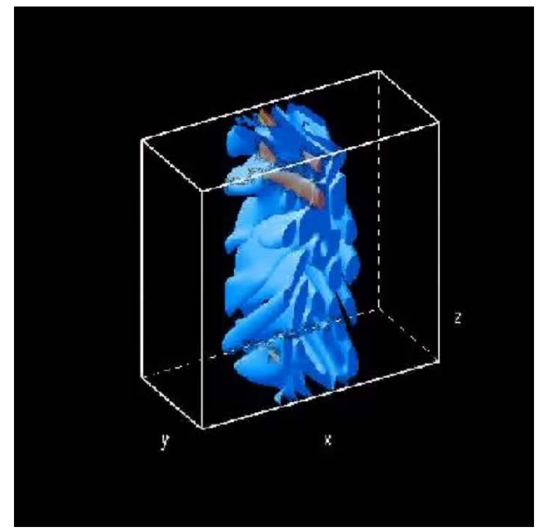
- MHD models with a turbulent evolution exhibit complexity, spatio-temporal intermittency, and self-similarity in the resulting distributions



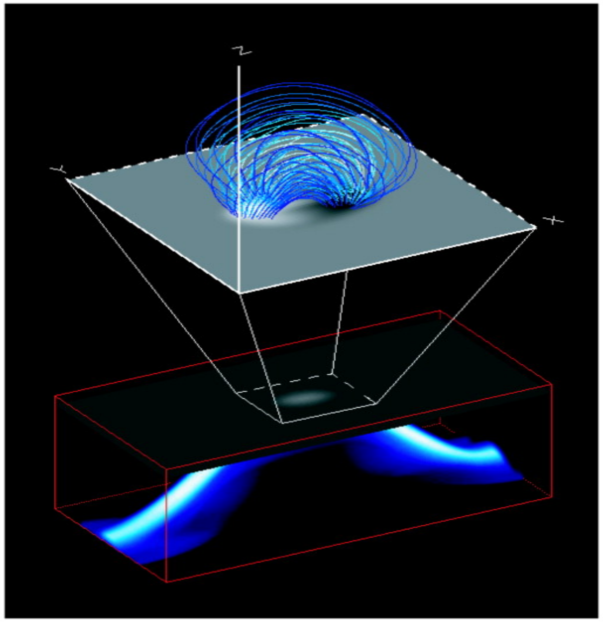
Georgoulis *et al.*, ApJ, 1998

Inside a collapsing current sheet

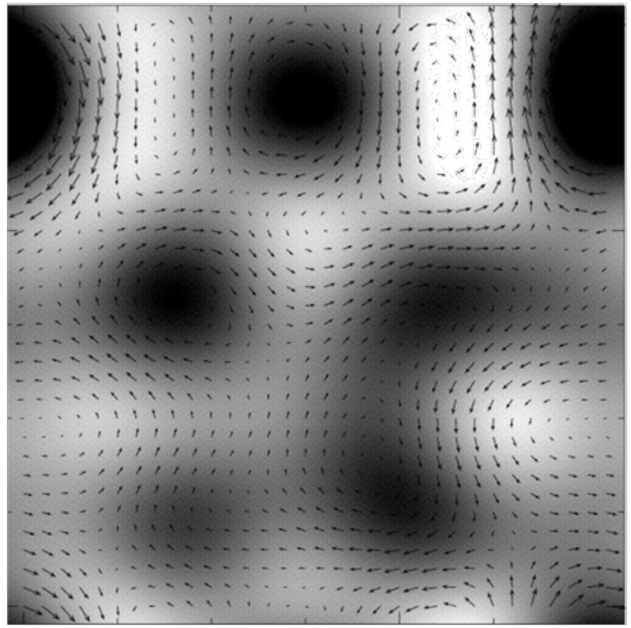


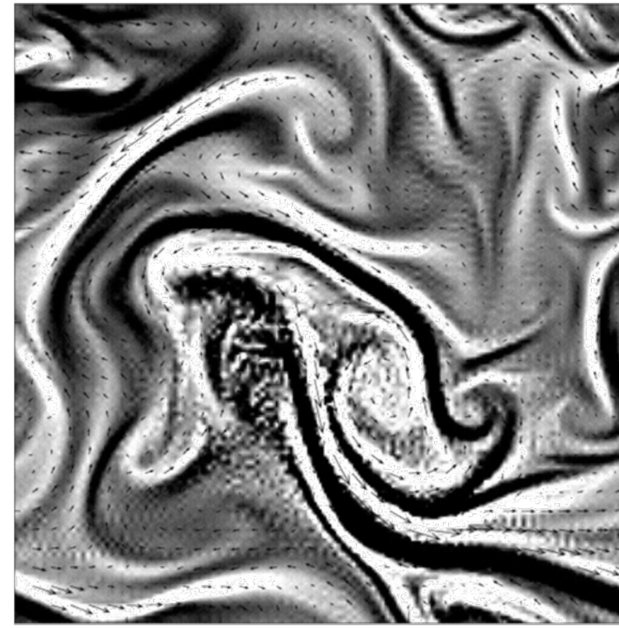


Envisioned situation in the solar atmosphere



Abbett & Fisher (2002)





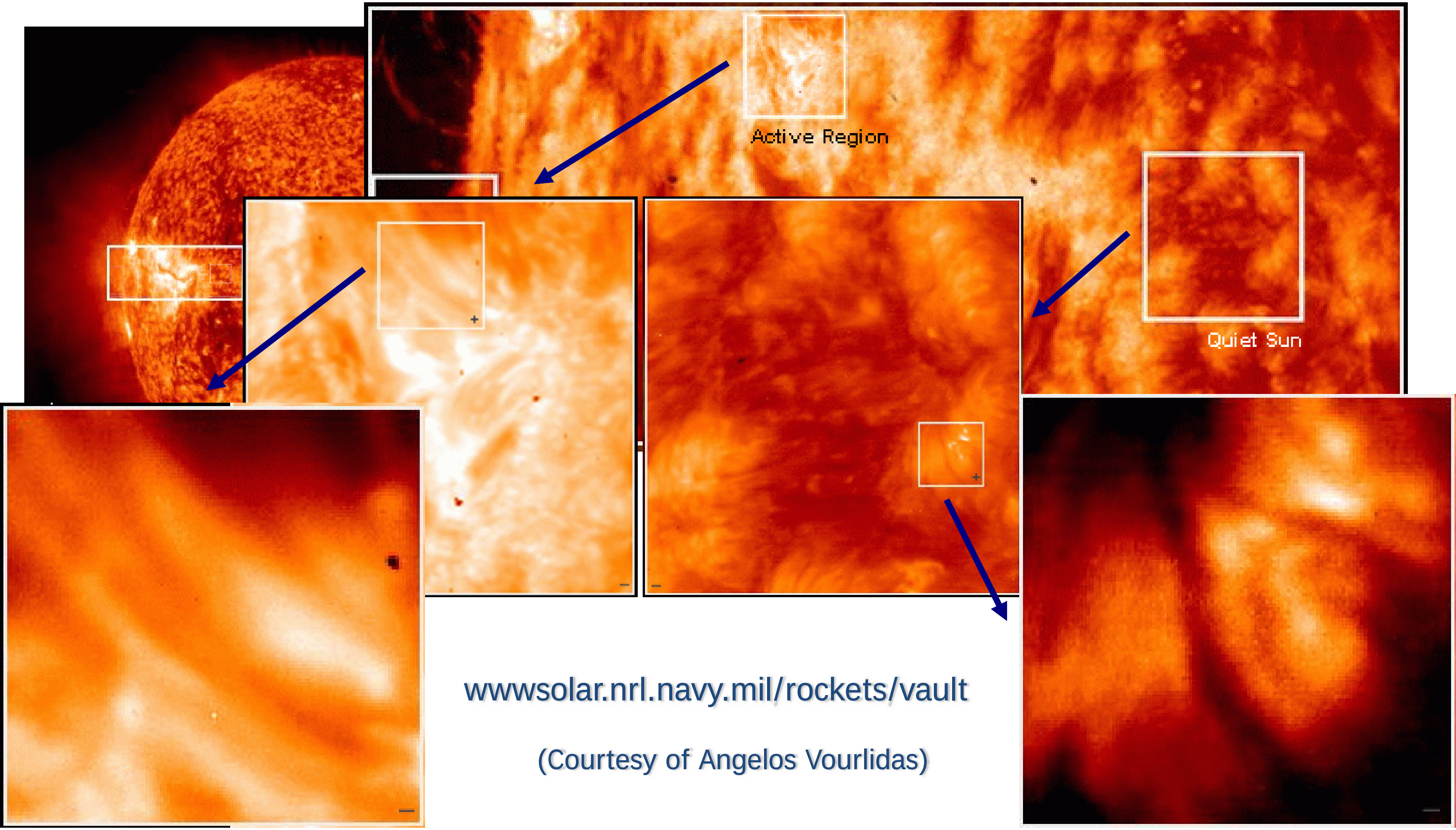
Dmitruk et al. (2002)

- 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 !

Activity in all spatial scales / Scale invariance

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



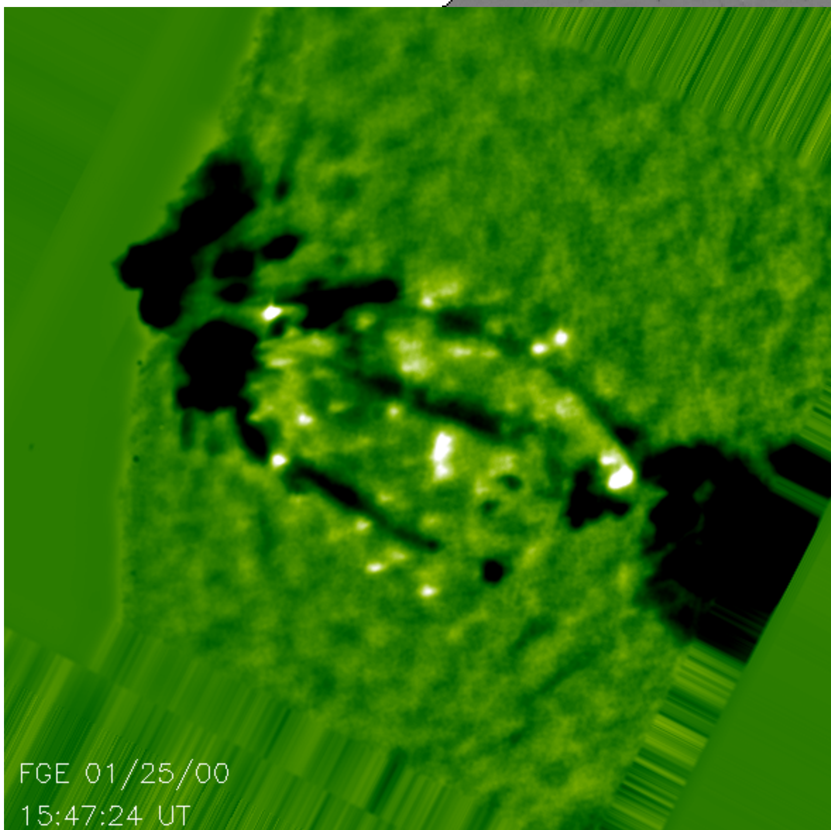
wwwsolar.nrl.navy.mil/rockets/vault

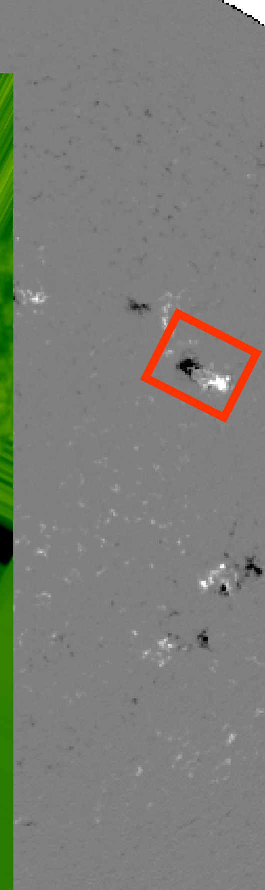
(Courtesy of Angelos Vourlidas)

"Quiet" Sun indistinguishable from active regions in small spatial scales

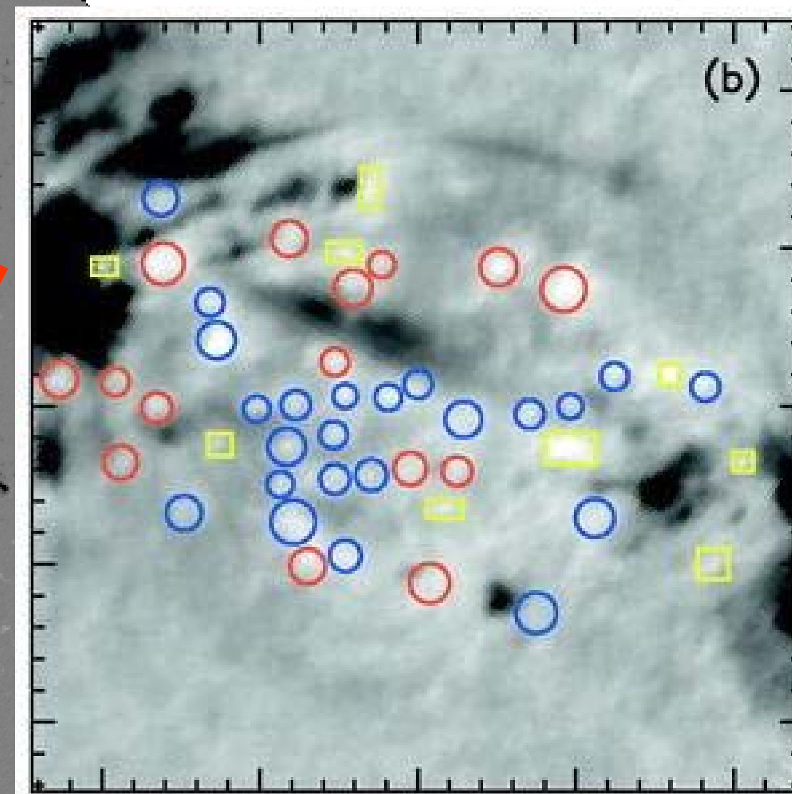
Ubiquitous small-scale energy release

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





Courtesy of Pariat et al. (2004)



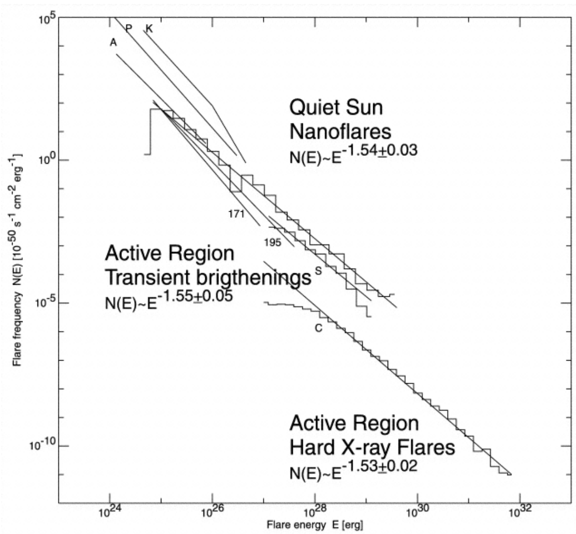
Hundreds of small-scale, short-lived brightenings (Ellerman bombs) over a 3-hr period

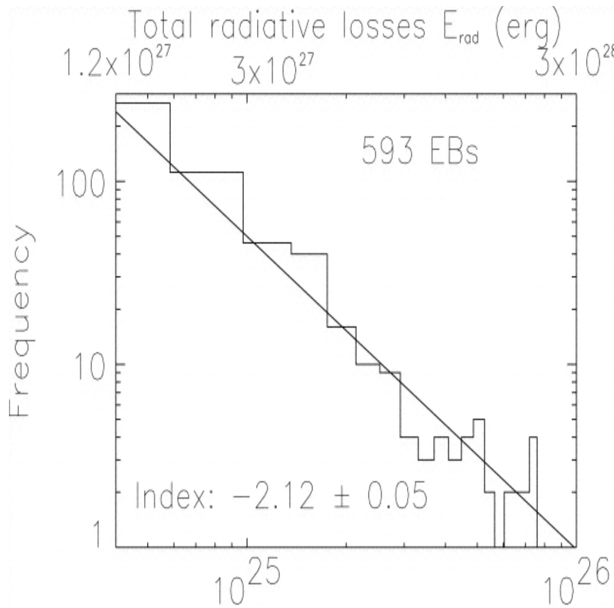
Approx. 81% (38/47) of EBs associated with magnetic bald patches, separatrices or QSLs

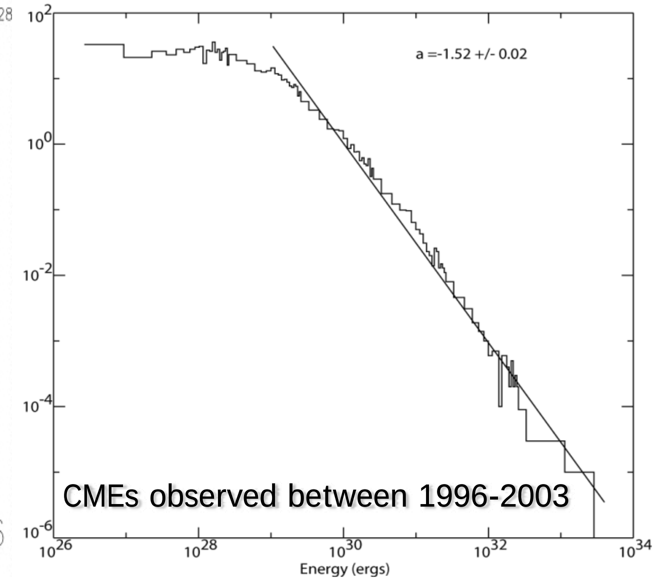
Evidence of <u>self-similarity</u> in small-scale energy dissipation processes

Quantifying the statistics of solar activity

Power laws everywhere:







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

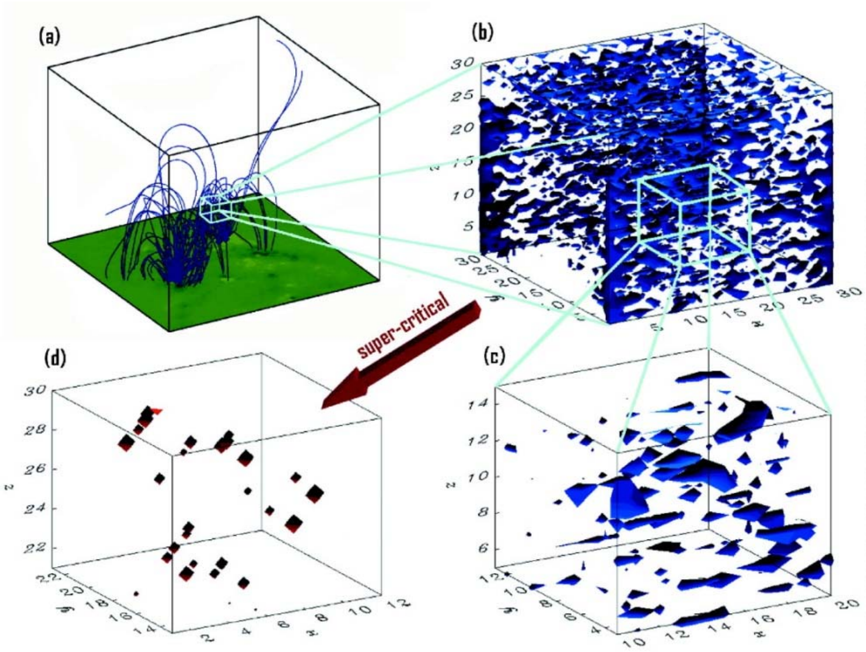
Ellerman bombs (Georgoulis et al. 2002)

Kinetic Energy of CMEs (Courtesy of A. Vourlidas)

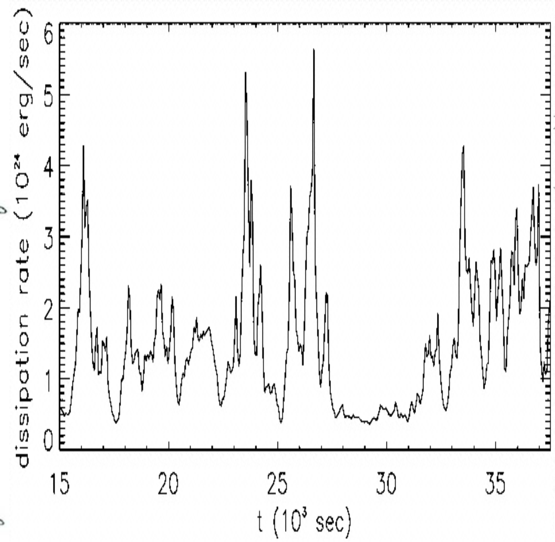
Moreover, power laws are found in the events' peak activity, total duration, rise and decay times, area coverage, inferred volumes, etc.

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

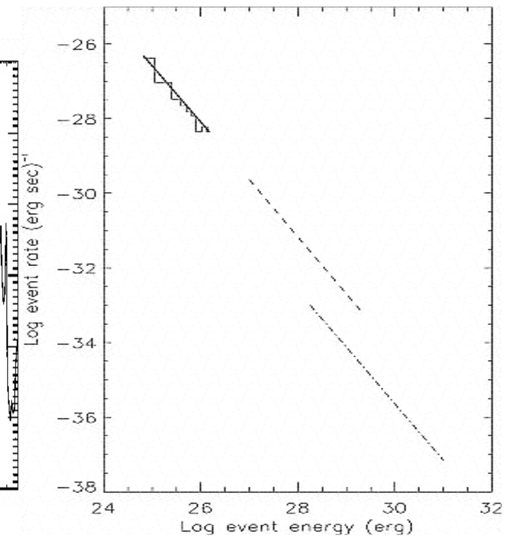
Expected consequences of turbulence



Vlahos et al. (2004)



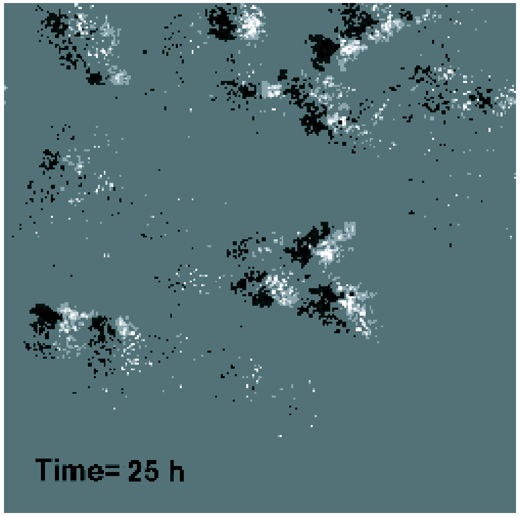
Dmitruk et al. (1998)

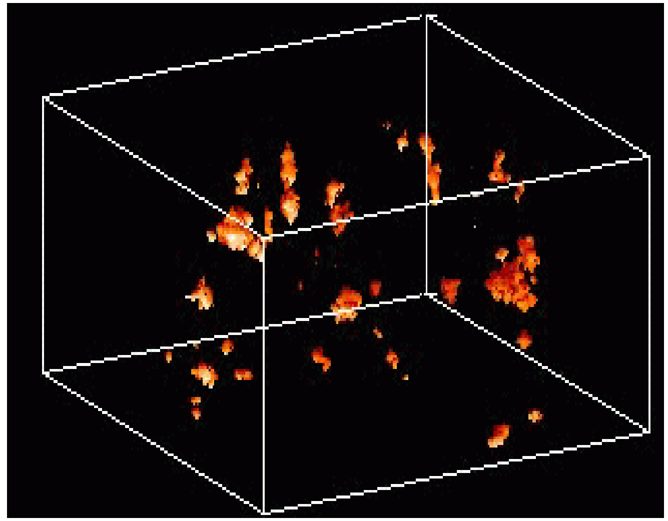


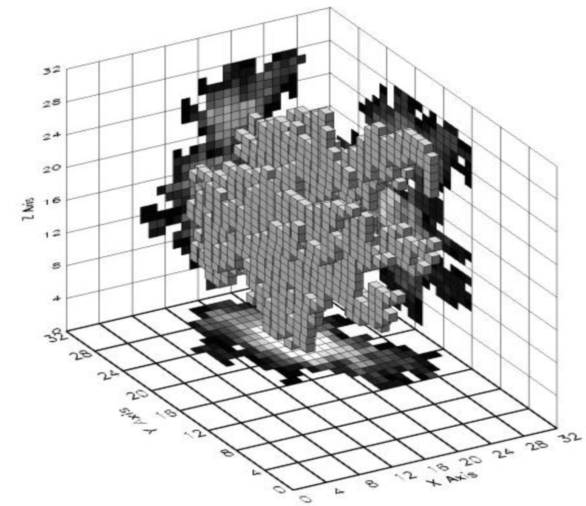
Dmitruk & Gomez (1997)

- 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

Self-Organization: deterministic or stochastic?







Fragos et al. (2004)

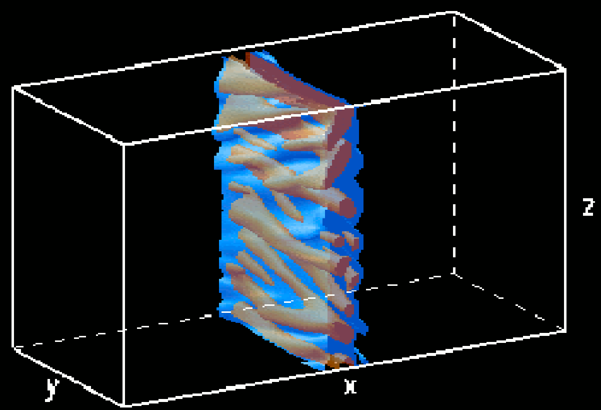
McIntosh & Charbonneau (2001)

- 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

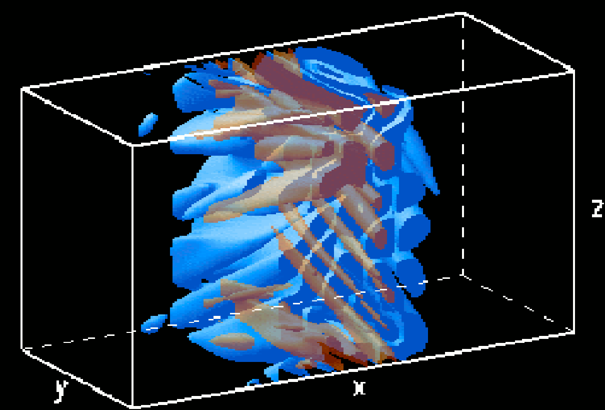
But what is the nature of the critical threshold, if any?

Three-dimensional structure of the electric field

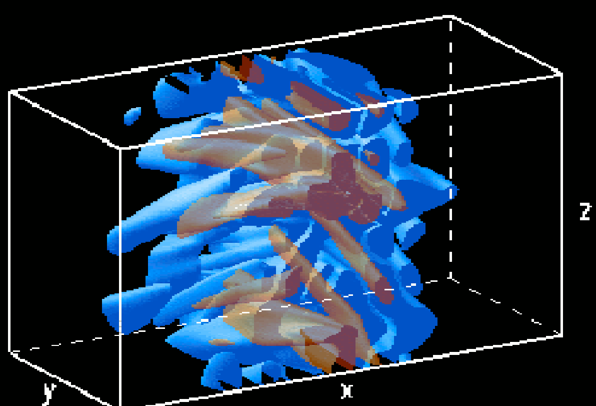
Isosurfaces of the electric filed at different times



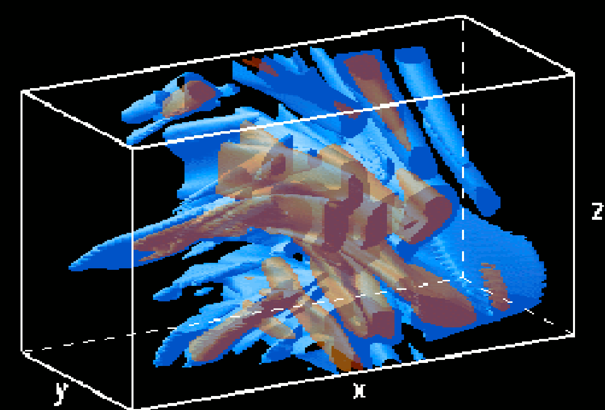
t=50



t=200

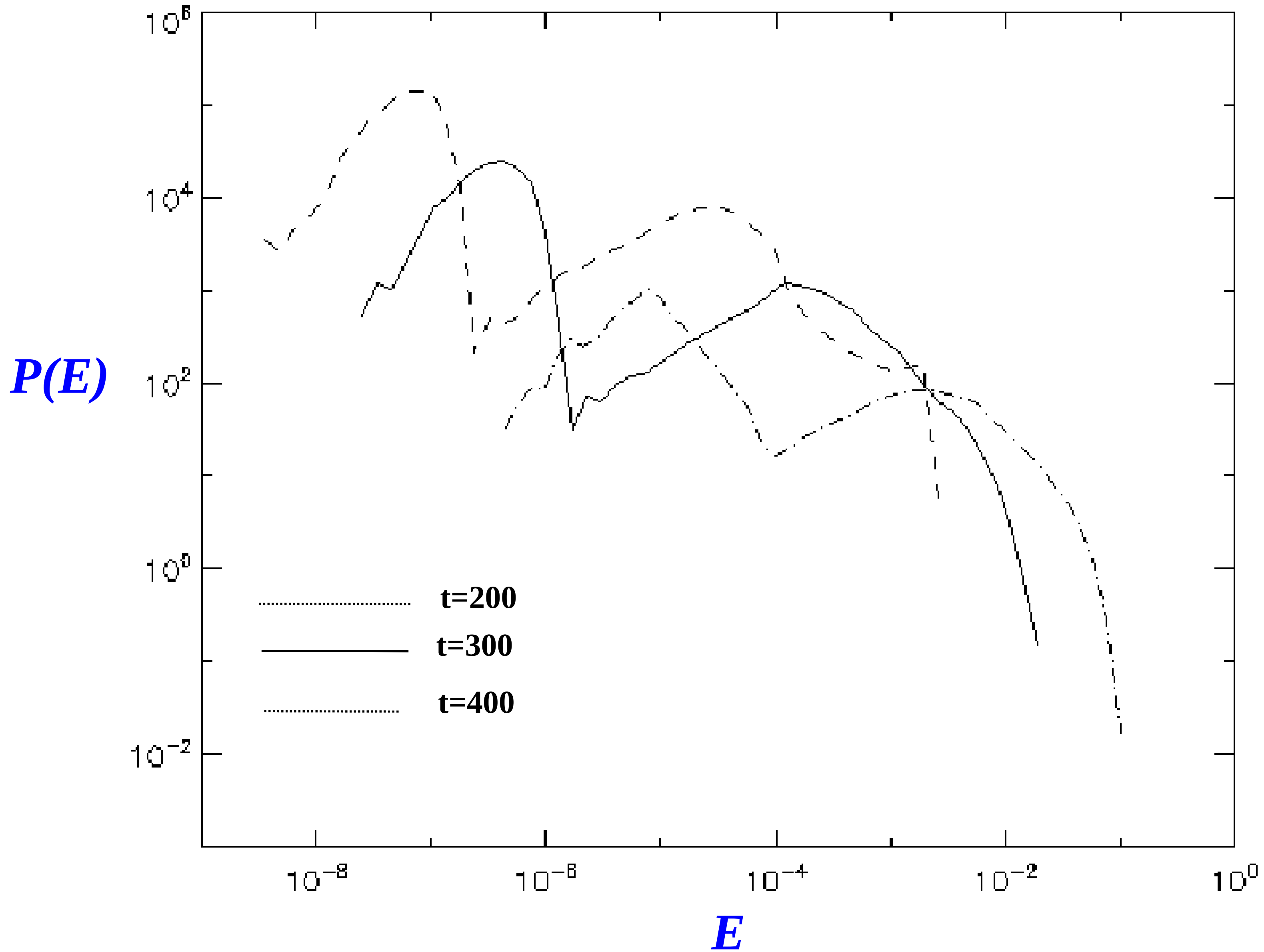


t=300



t=400

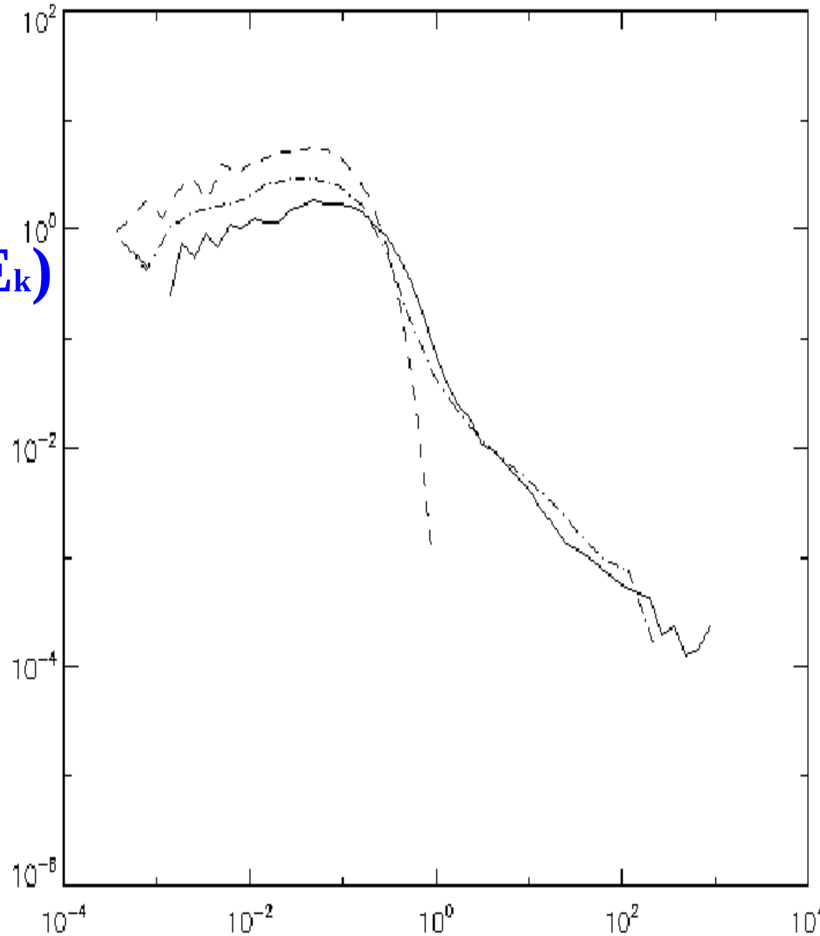
Distribution function of the electric field



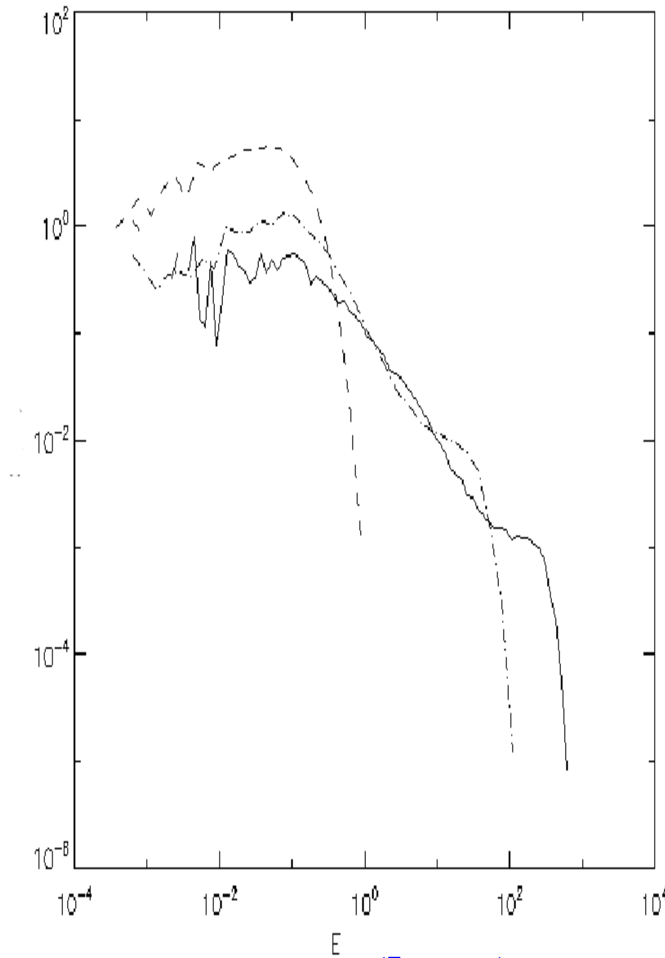
Kinetic energy distribution function of electrons

$t=50\ T_A$ $\qquad$ $T=400\ T_A$

$P(E_k)$



E_k (keV)



E_k (keV)

A ‘**Turbulent**’ Field Model
(stochastic but not resonant accelerator)
(Azner+Vlahos, APJL, 2004)

$\mathbf{A} = \Sigma_{\mathbf{k}}\, \mathbf{a}_{\mathbf{k}} \cos(\mathbf{k}\cdot\mathbf{x} - \omega(\mathbf{k})t + \phi_{\mathbf{k}})$

$\langle|\mathbf{a}_{\mathbf{k}}|^2\rangle \sim (1+ \mathbf{k}^T S \mathbf{k})^{-\nu}$

random $\phi_{\mathbf{k}}$

$\mathbf{B} = \nabla \times \mathbf{A}$

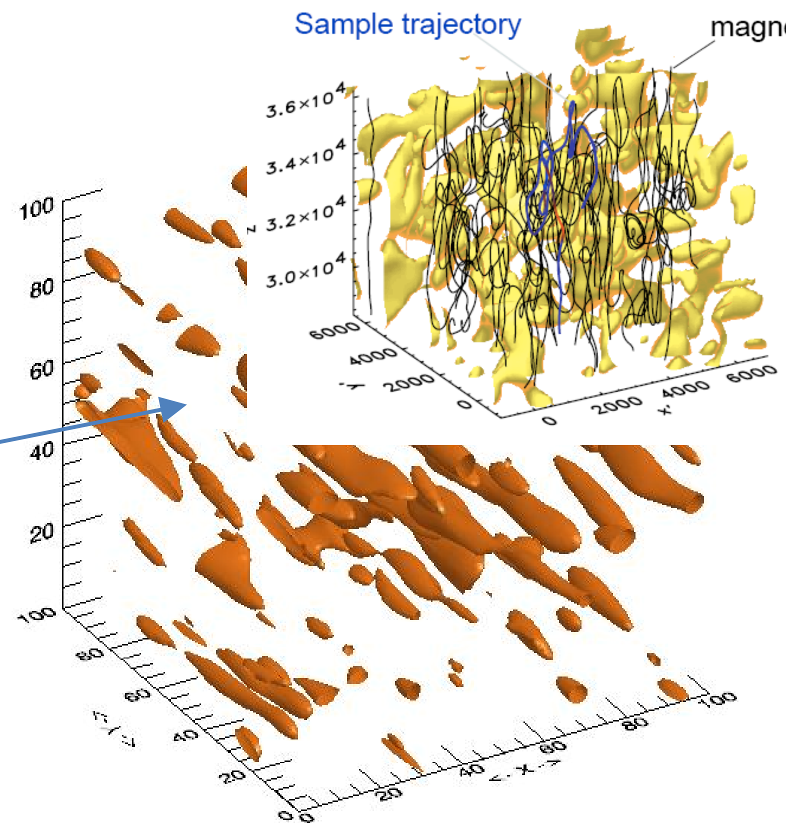
threshold

j_c

$\mathbf{E} = -\,\partial_t \mathbf{A} + \eta(\mathbf{j})\, \mathbf{j}$

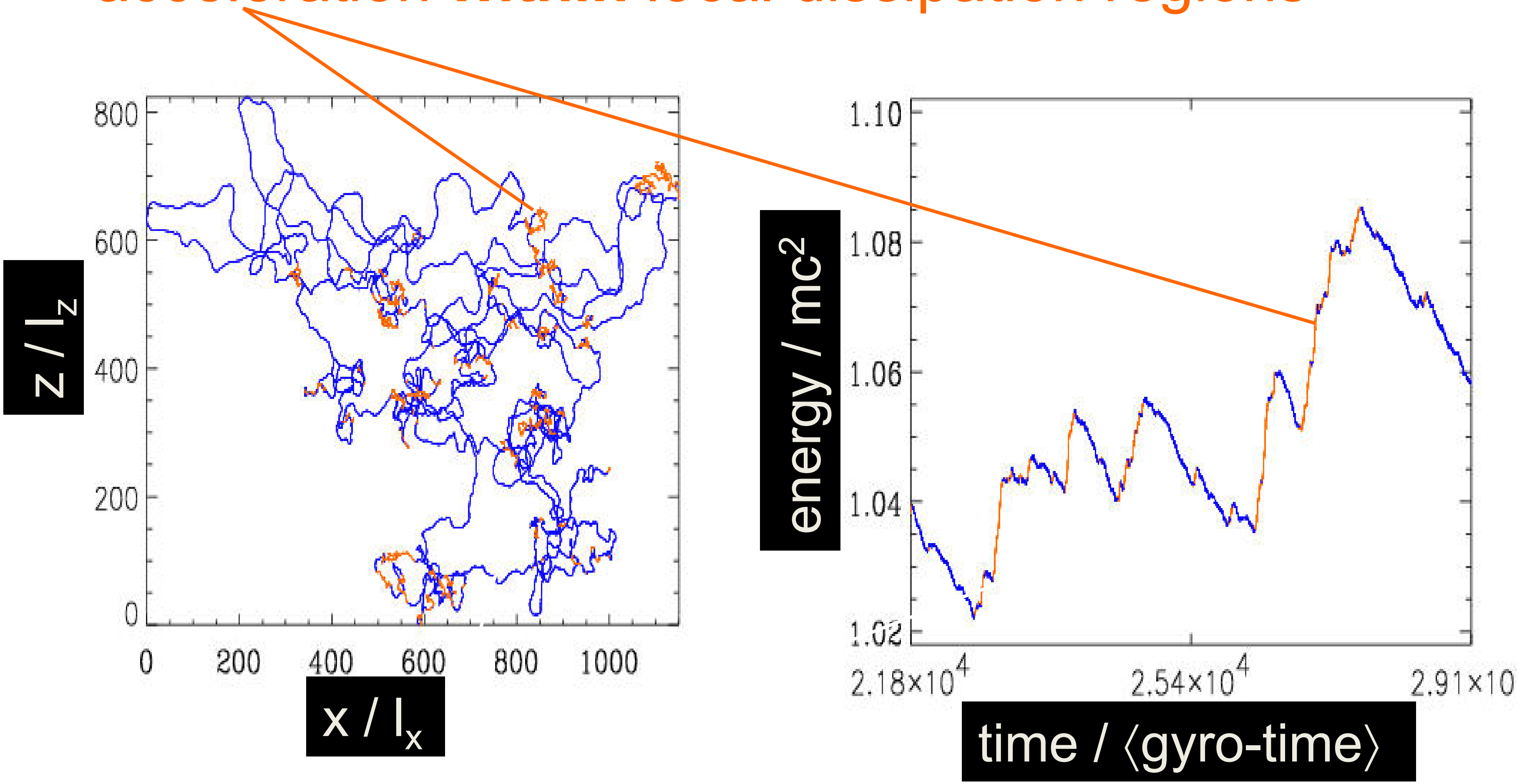
$\partial_y << \partial_x , \partial_z$

$v_{ph} << |\mathbf{v}_{ptcl}|$

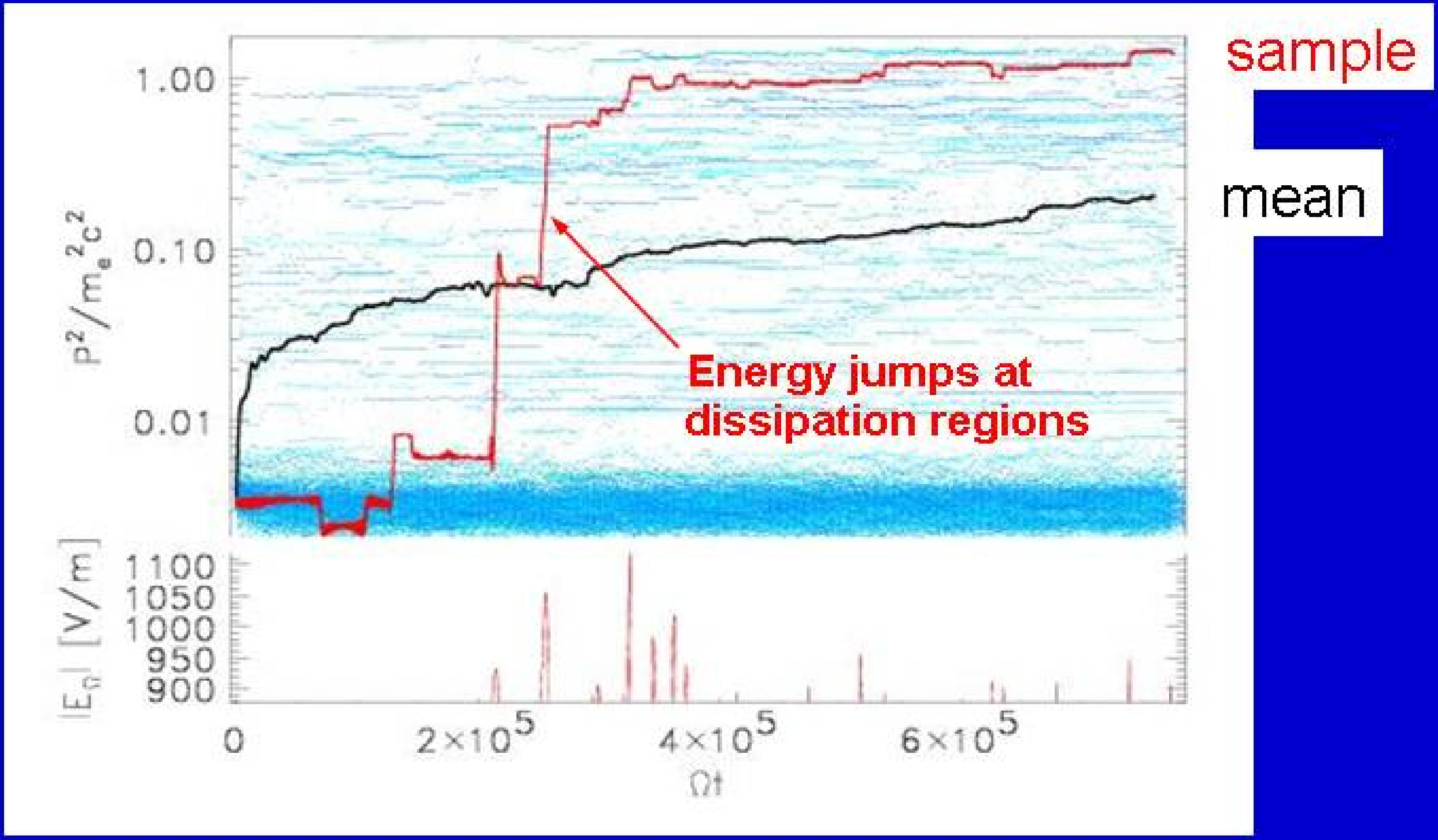


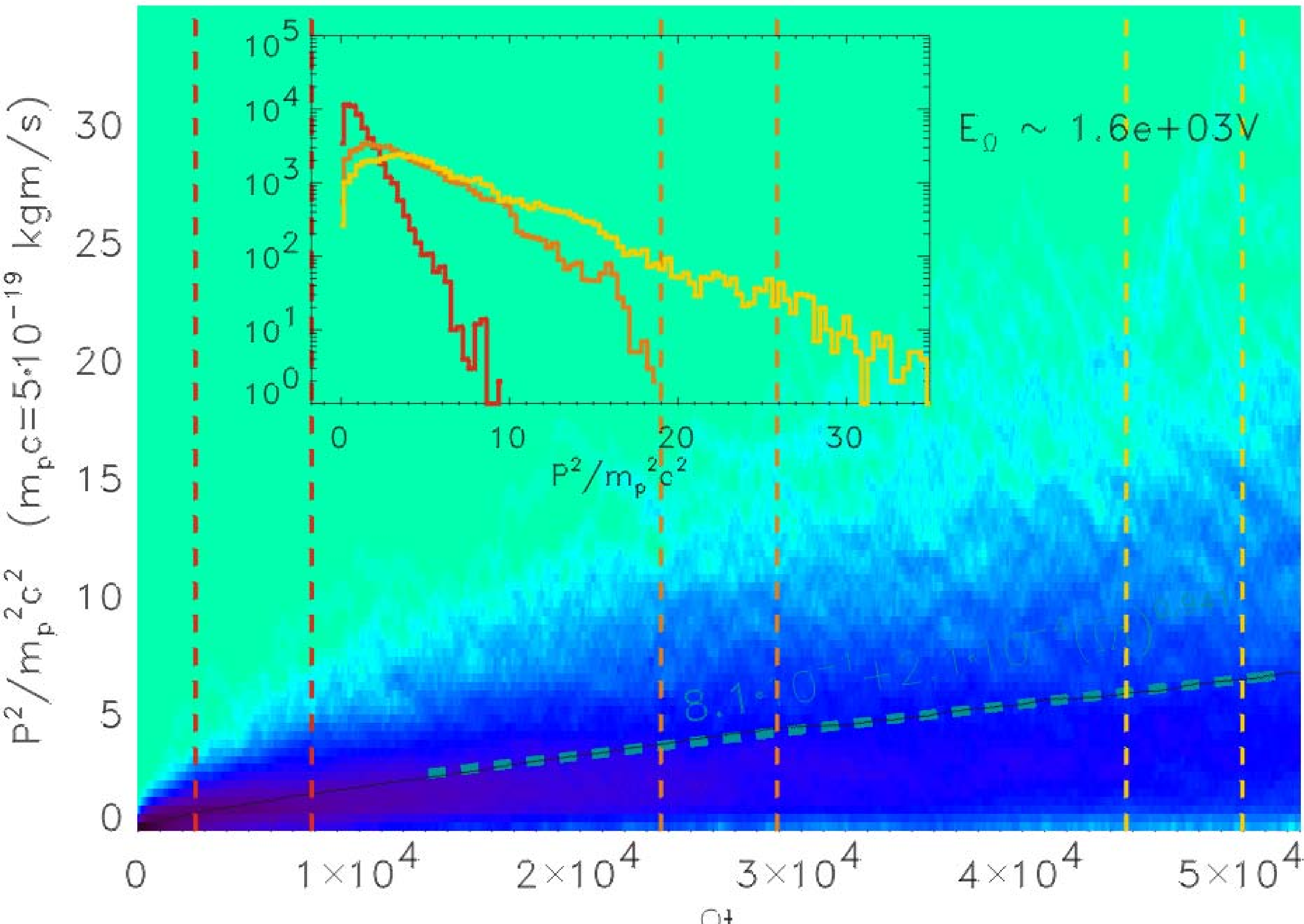
Finding: intermittent particle orbits

acceleration **within** local dissipation regions



Electron Acceleration




$P^2/m_p^2c^2$ $(m_pc=5\cdot10^{-19}$ kgm/s$)$
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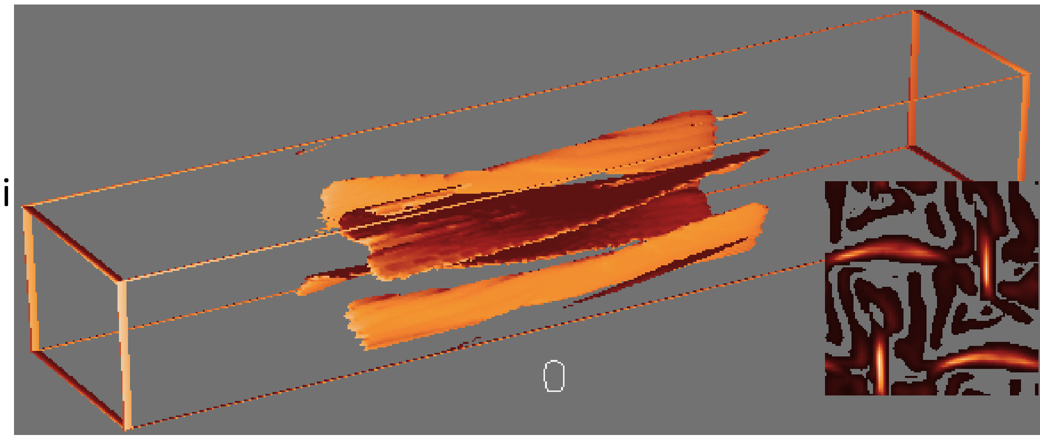
5
10
15
20
25
30
0
1×10^4
2×10^4
3×10^4
4×10^4
5×10^4
Ωt
$E_\Omega \sim 1.6e+03V$
10^0
10^1
10^2
10^3
10^4
10^5
0
10
20
30
$P^2/m_p^2c^2$

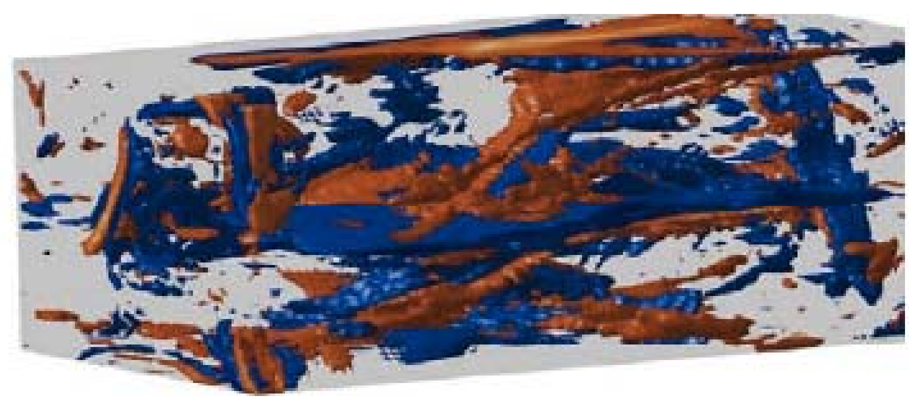
Particle acceleration in stochastic current sheets

(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

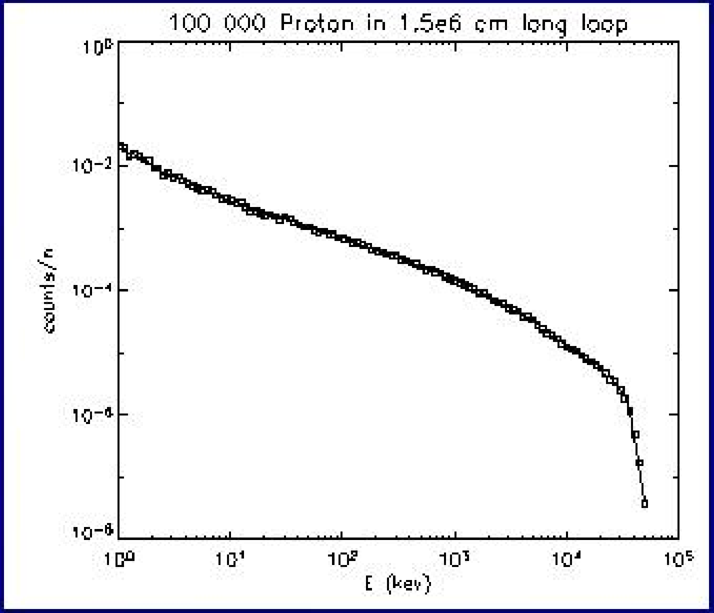


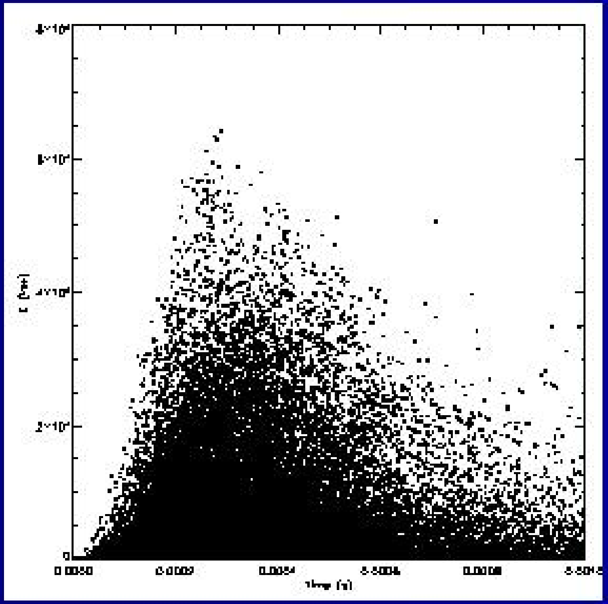
- Acceleration time scale much shorter than MHD time scale
- B and E are scaled;
- initial values:
  - B: Mean ~ 1.0 (0.89 – 1.08)
  - E: Mean ~ 7e-4 (e-5 – e-2)



Distribution Functions

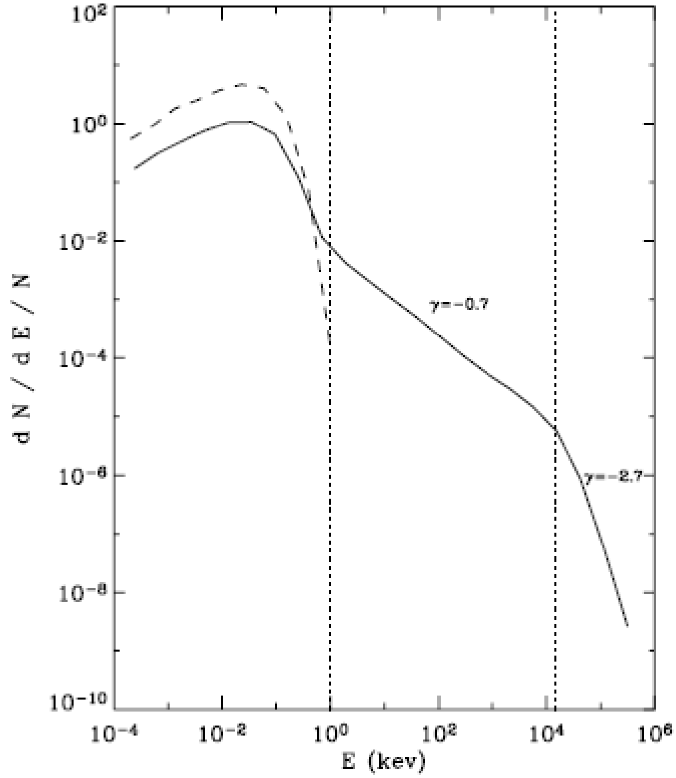
- 100,000 proton in 100 G magnetic field run for 1 ms



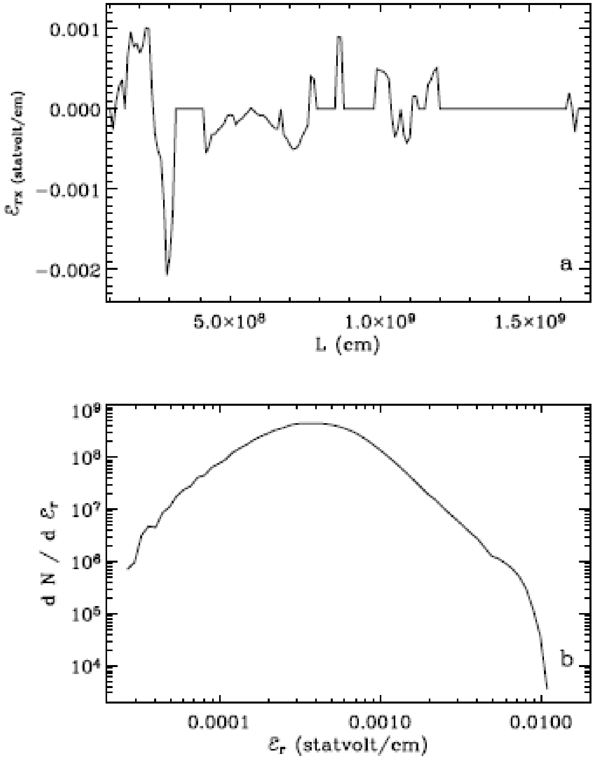


- Two parts power law
- ~ 60 Mev in 0.3 ms

Turkmani et al

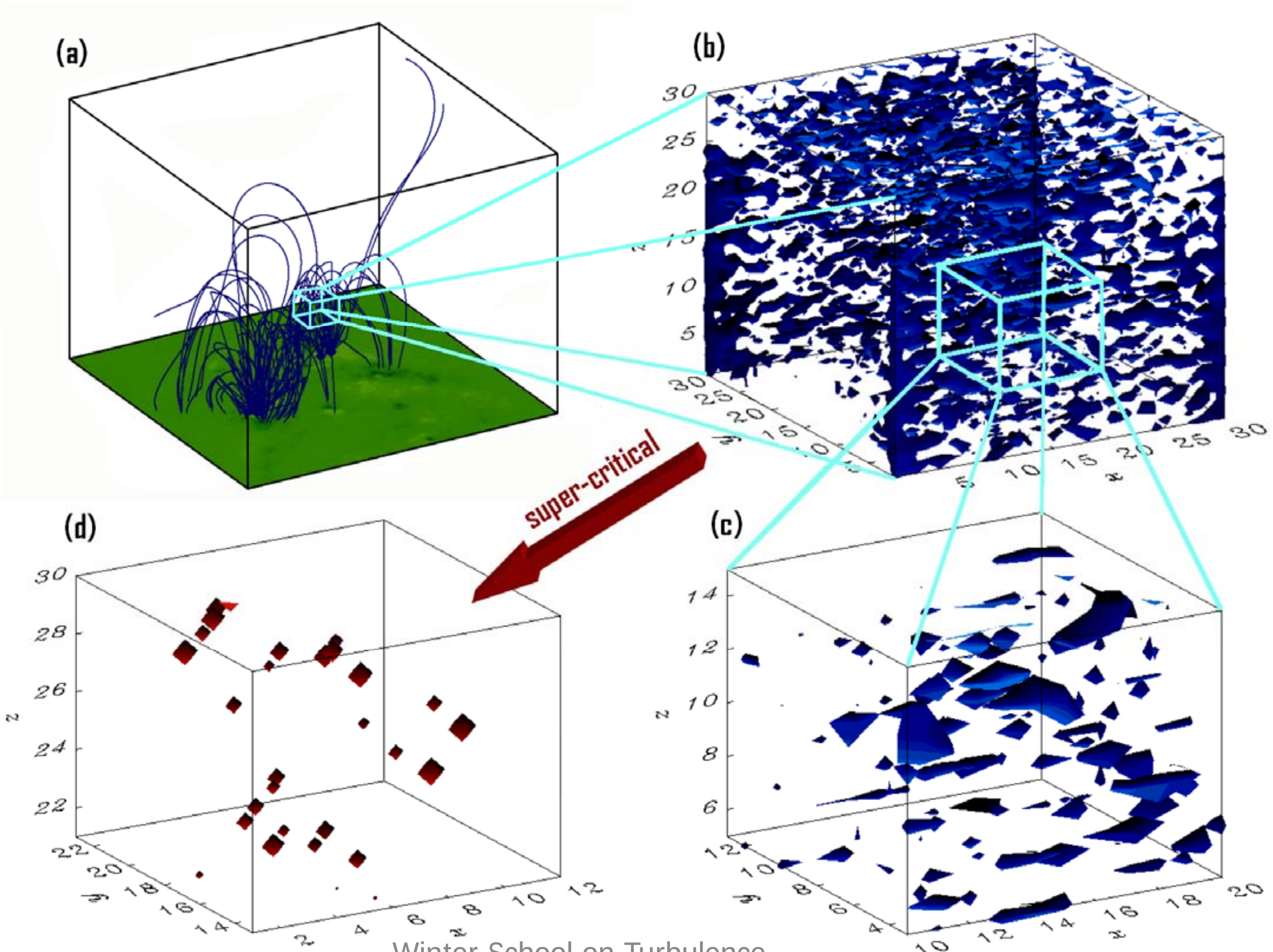


- Velocity distribution



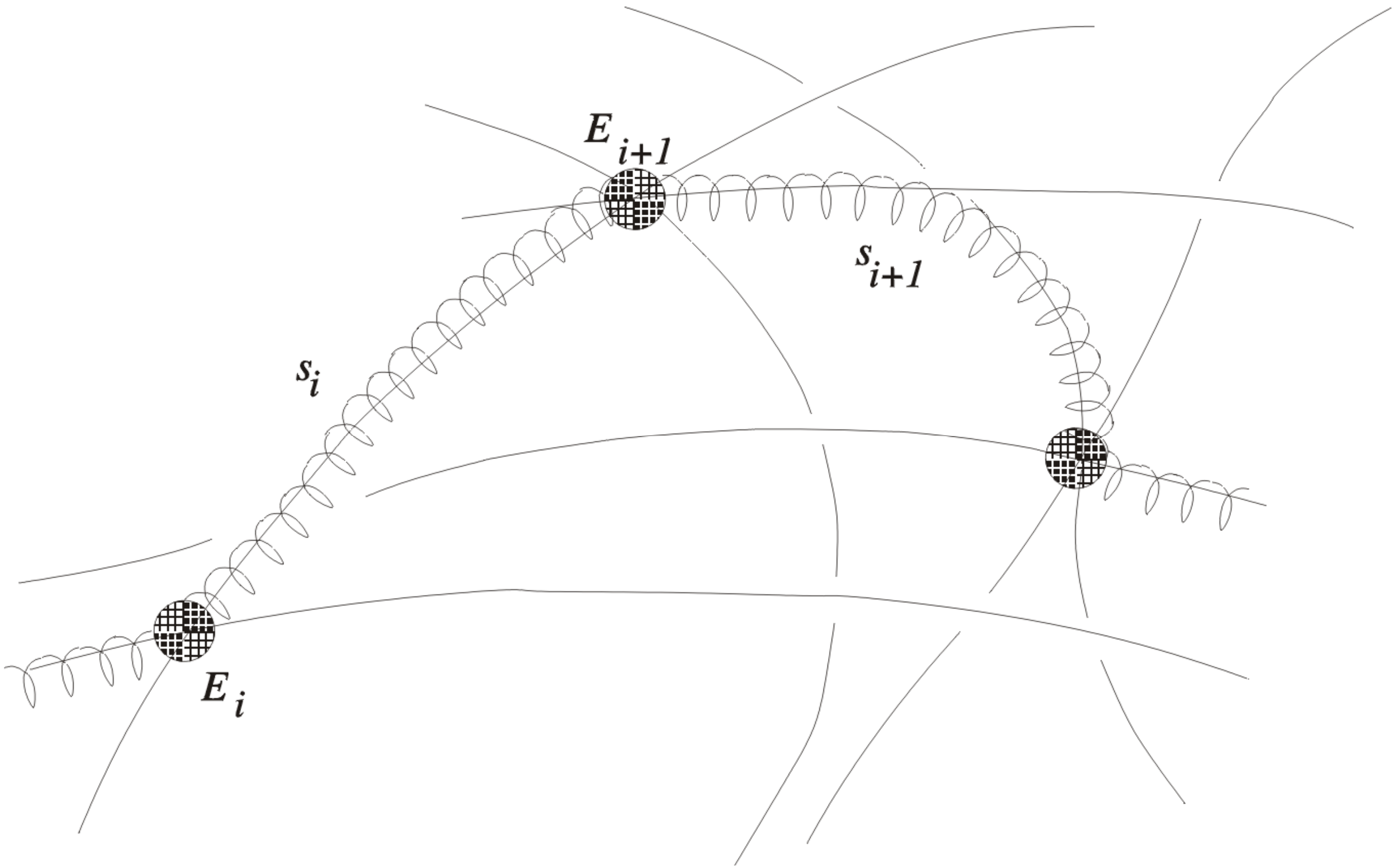
Using the X-CA model

- From



Winter School on Turbulence,
Montegufon, Firenze, 3-7 October, 2005

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



Sporadic formation of current sheets
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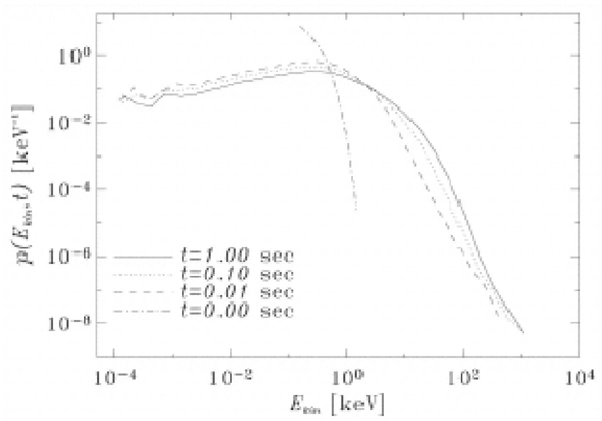

Conclusions

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 sheet-
- Self organized critical state of active regions
- Collapse of current sheets
- Network of current sheets
- Fully developed turbulence in active region
- Particle dynamics on unstable current sheets
- Very good correlation with observations