Energy Storage and Release in Solar Active Regions

(How an Active Region works?)

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Outline

- **Active regions: Multi scale laboratories**
- **Large scales: Formation of Active regions (100-1000Mm, 3D MHD????)**
- Emerging Flux is behind the formation of AR
- The driver of the active regions is the convection zone
- Active regions are driven non linear systems
- **MESO SCALES (1m<L<1000Mm) Storage or ideal MHD instabilities**
- **Small scales(<m): Energy release (3D Kinetic phenomena)**
- Formation of stable and unstable current sheets
- Spatially self-similar, small-scale energy release
- Power-law statistics
- Turbulent self-organization: Critical or non-critical?
- **Kinetic Effects: Particle acceleration and radiation**
- Summary: **The Integrated Flare Model**

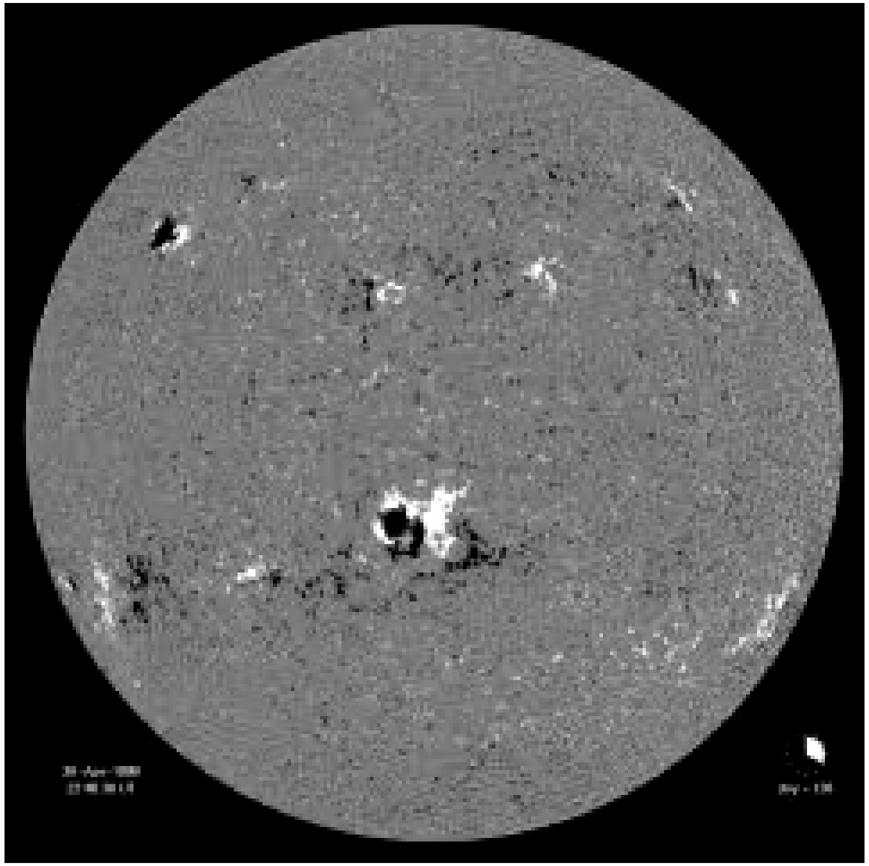
Large scales:

- Formation of Active regions

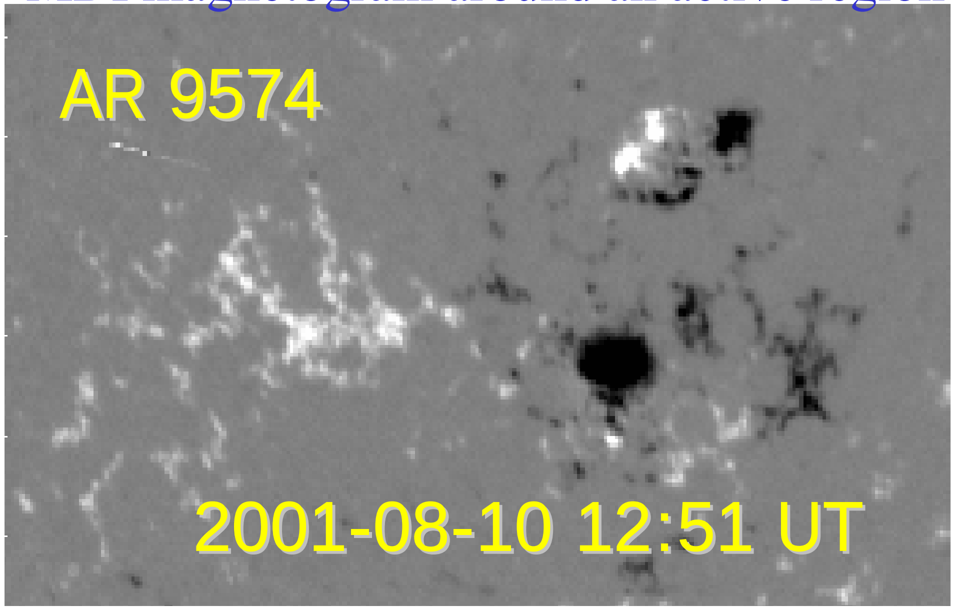
The rise and fall of MHD simulations?

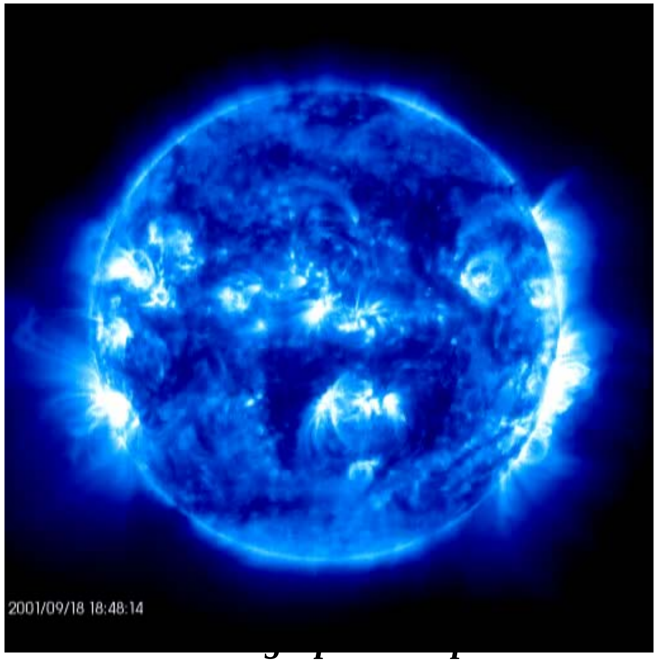
Sunspots and active regions

Sunspots in a full disk magnetogram



MDI magnetogram around an active region





Numerical method

Three dimensional time-dependent resistive MHD equations

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

· 6th order - partial derivatives

· 5th order - interpolation

· 3rd order - predictor-corrector - time stepping

· Stretched staggered grid 1d, 3d

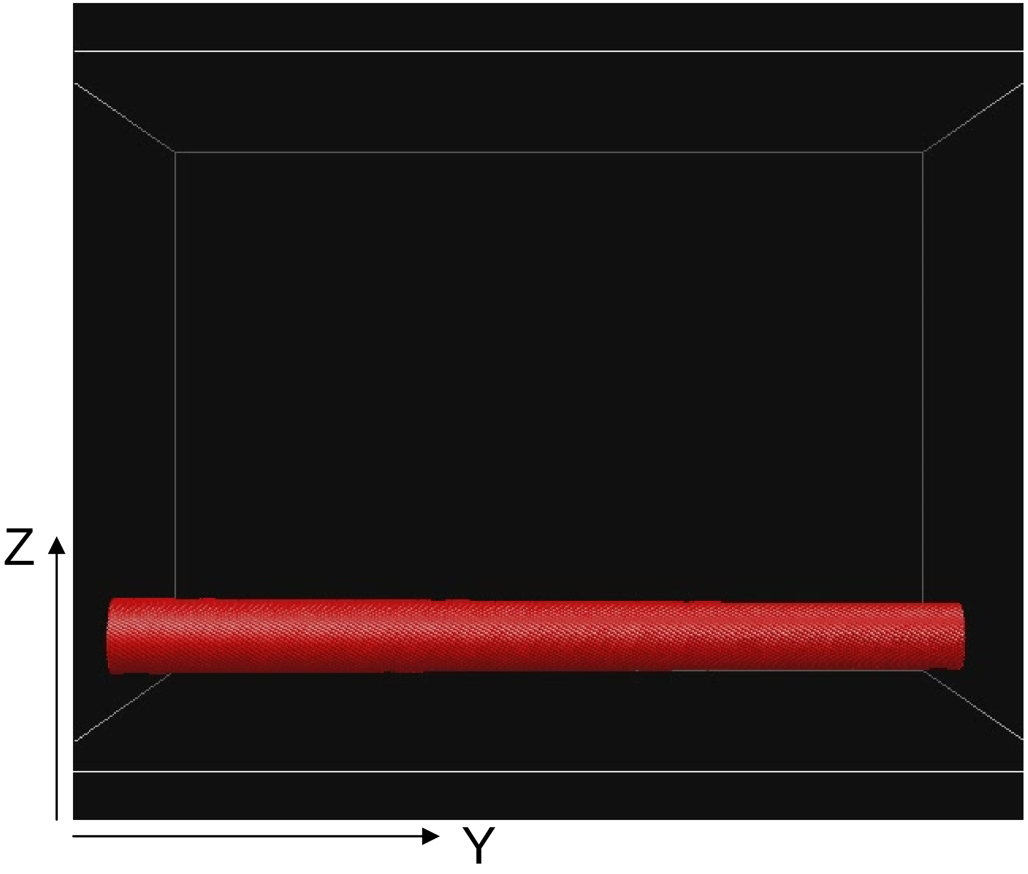
· Periodic and closed BC

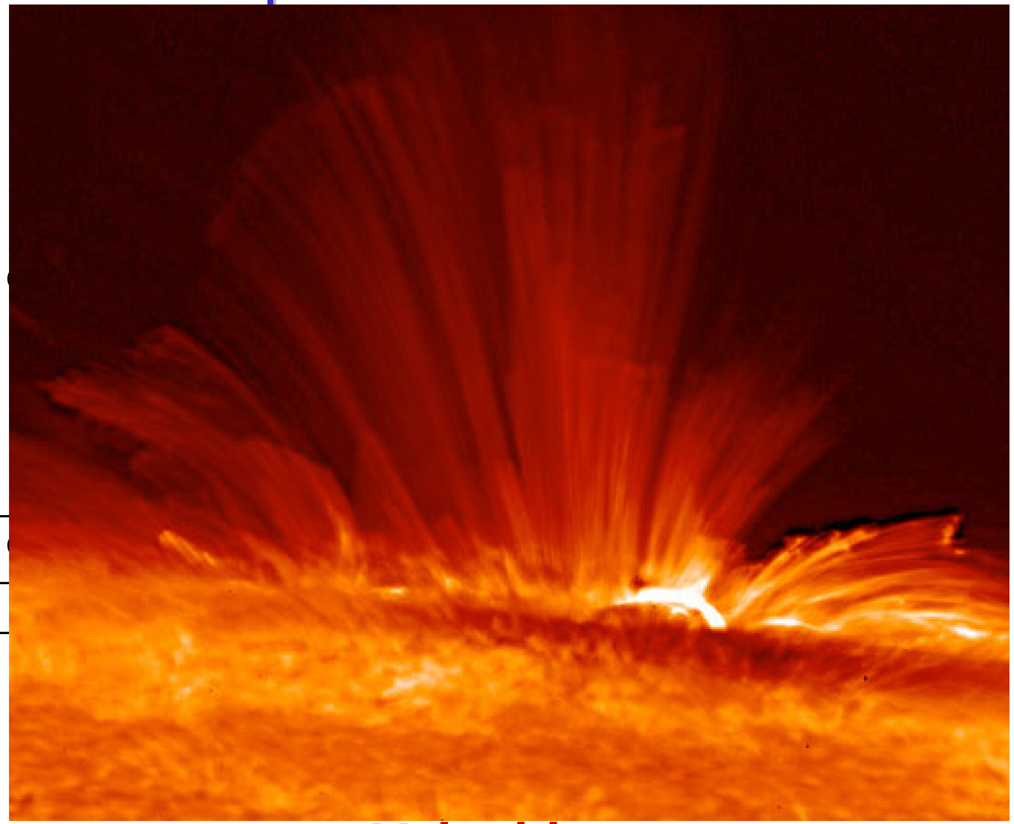
· Damping zone top-bottom

. Hyperdiffusive scheme, 4^{th} order quenced diffusion operators

Emergence into a null corona

Formation of coronal loops



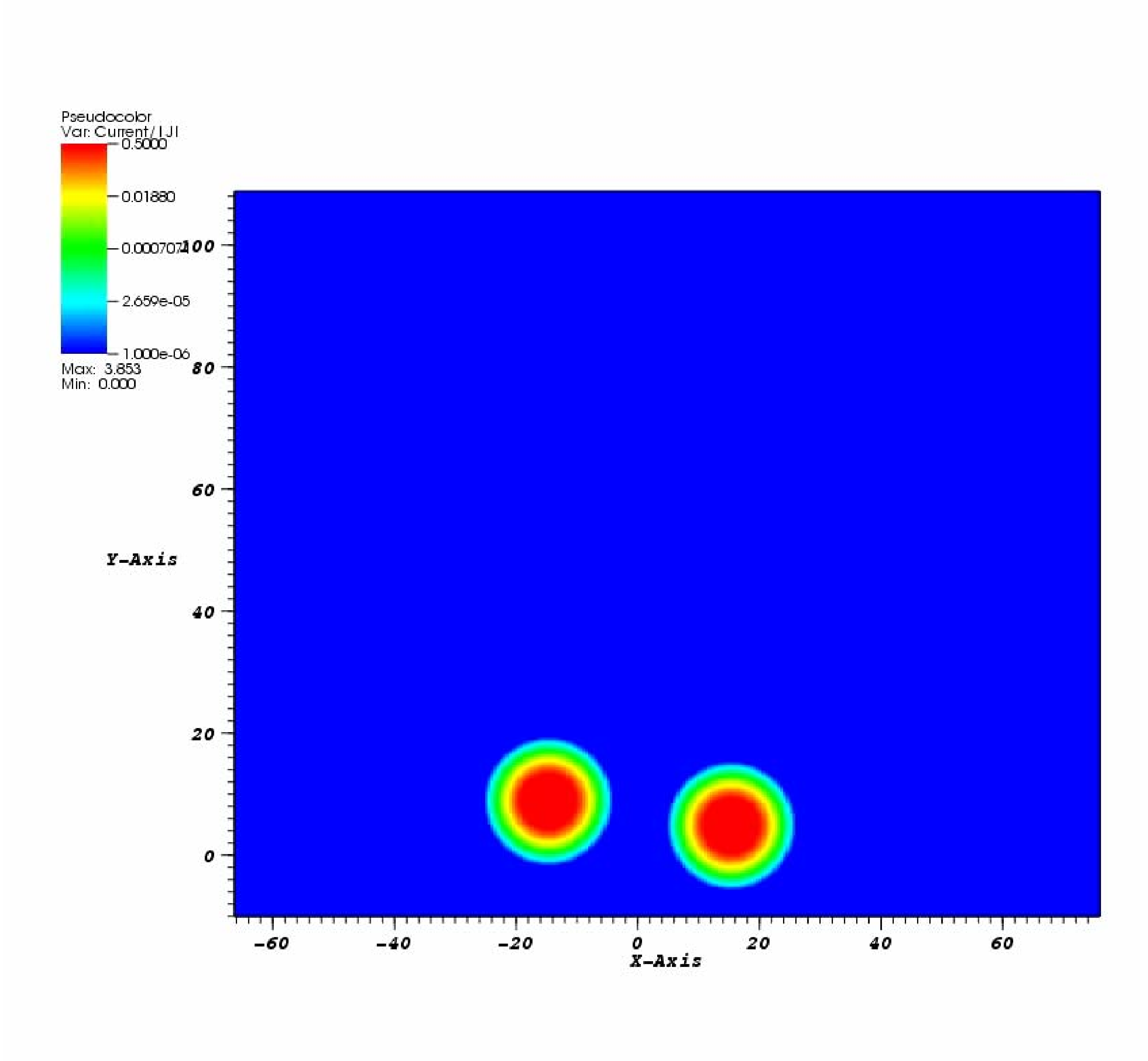


- The tube is more buoyant in the middle
- Fieldlines expand in three directions
- Strongly azimuthal nature at the top
- Fan-like shape of the expanding field.

Hinode Solar Optical Telescope

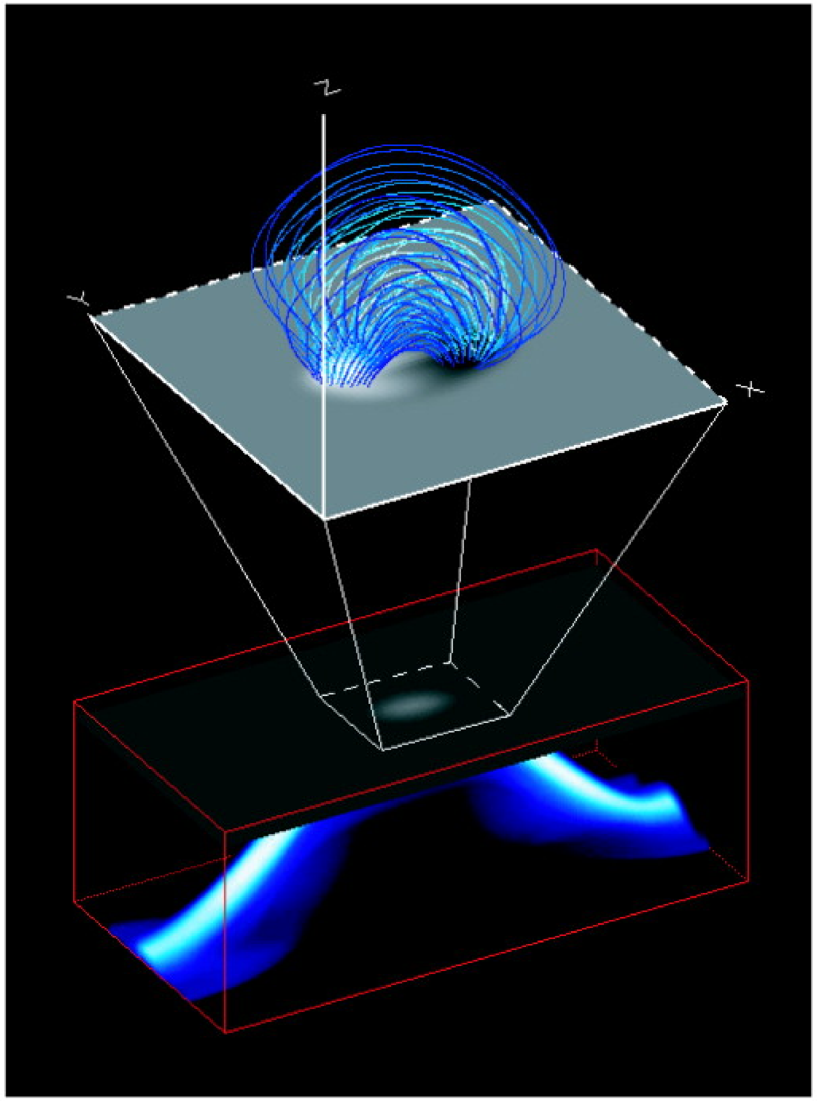
Solar magnetic field rises vertically from a sunspot and adopts a fan-like shape.

Formation of current sheet + collapse

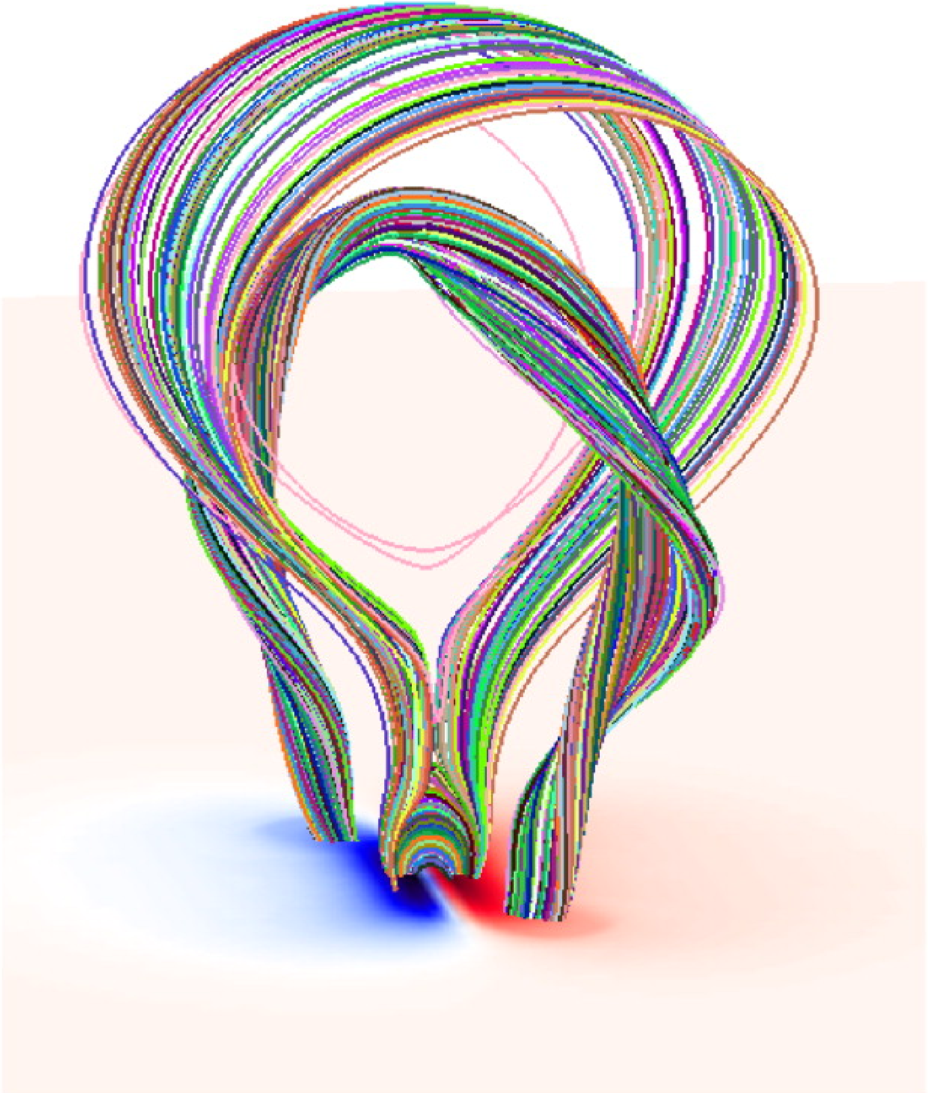


The solar corona

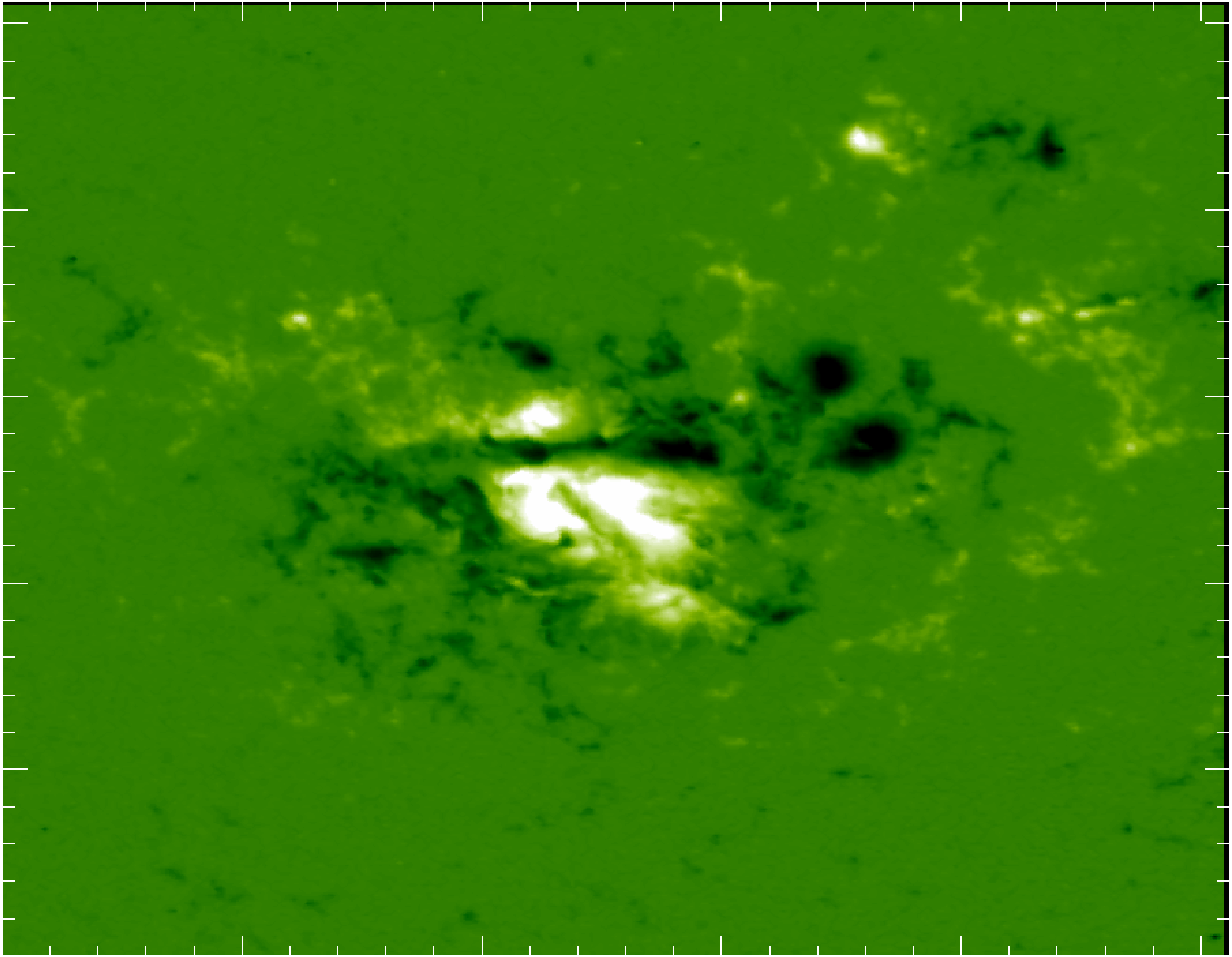
- An externally driven, non-linear dynamical system



Abbet & Fisher, ApJ, 2002



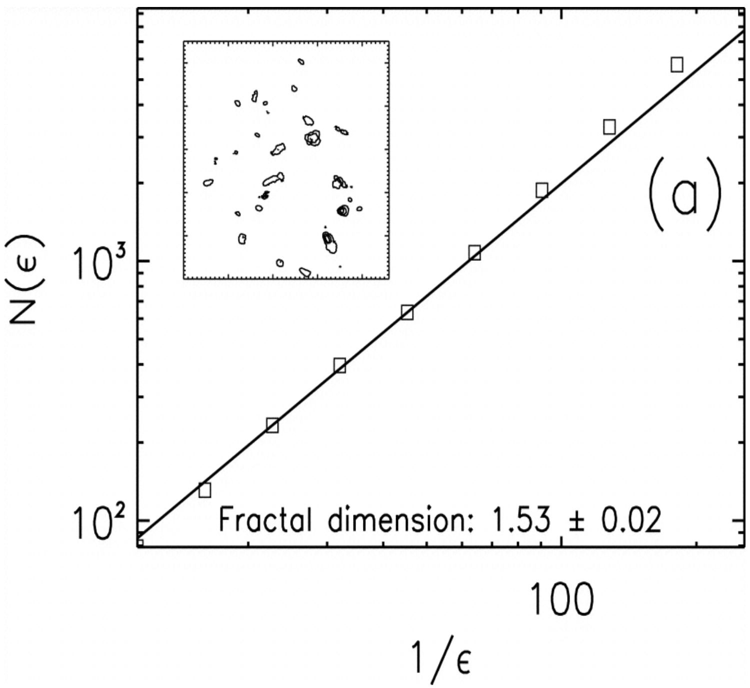
Amari *et al.,* ApJ, 2003



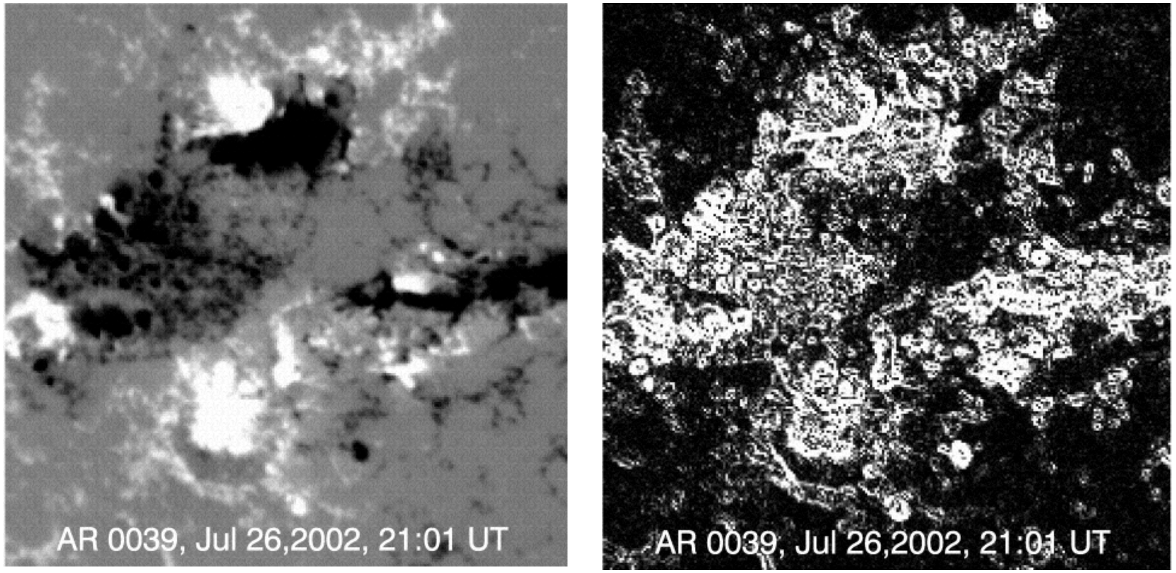
Multi-scale diagnostics of solar structures

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

Georgoulis et al. (2002)



Abramenko et al. (2003)



The fractal dimension:

Structure functions:

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

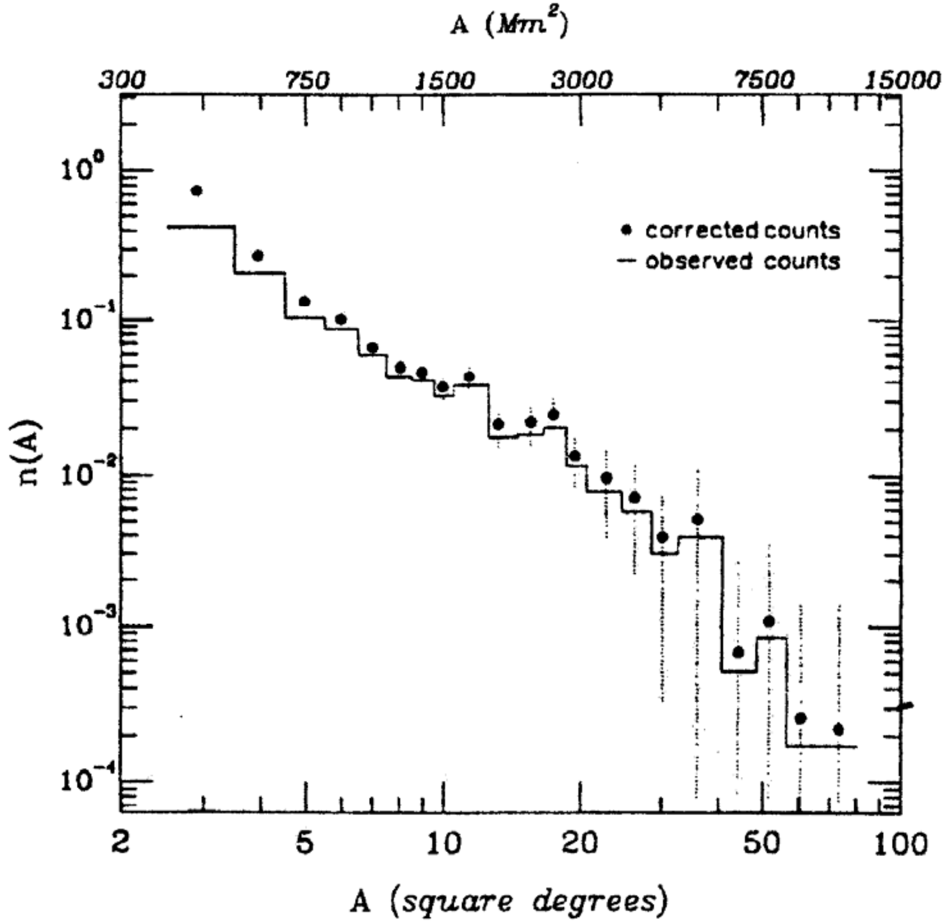
EBs are fractal structures

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

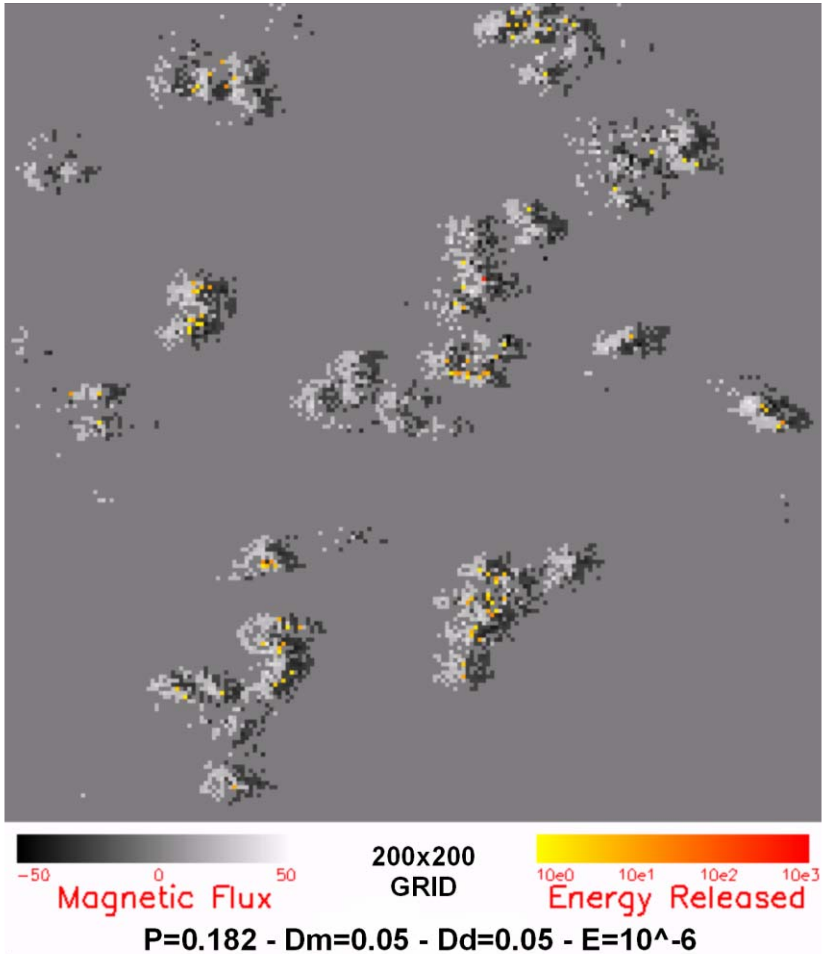
Size distribution

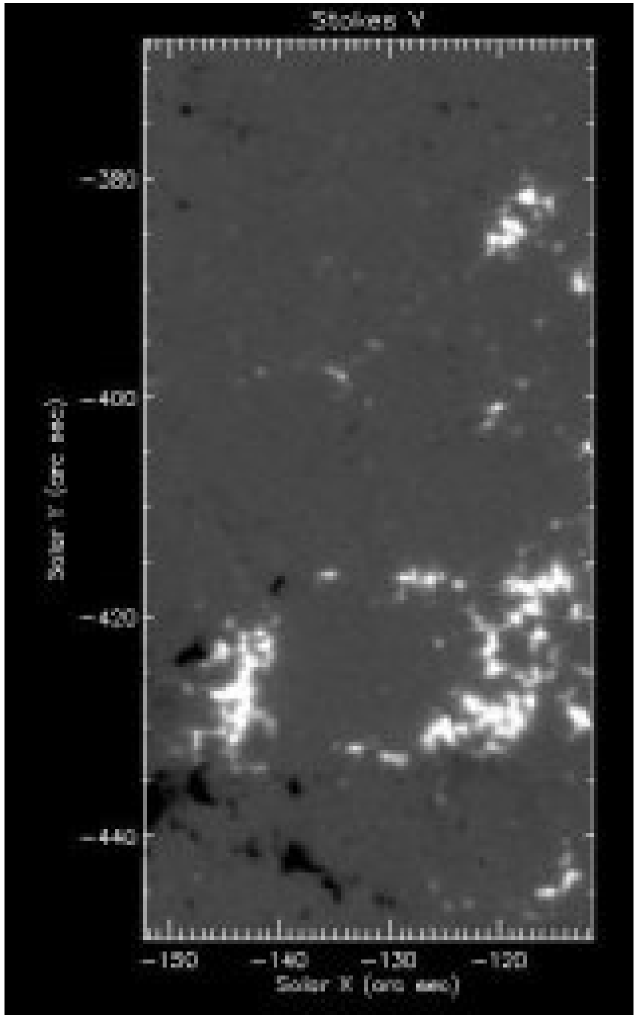


The basic rules for a Percolation model for the formation of active regions (Vlahos, et al ApJL, 2002)

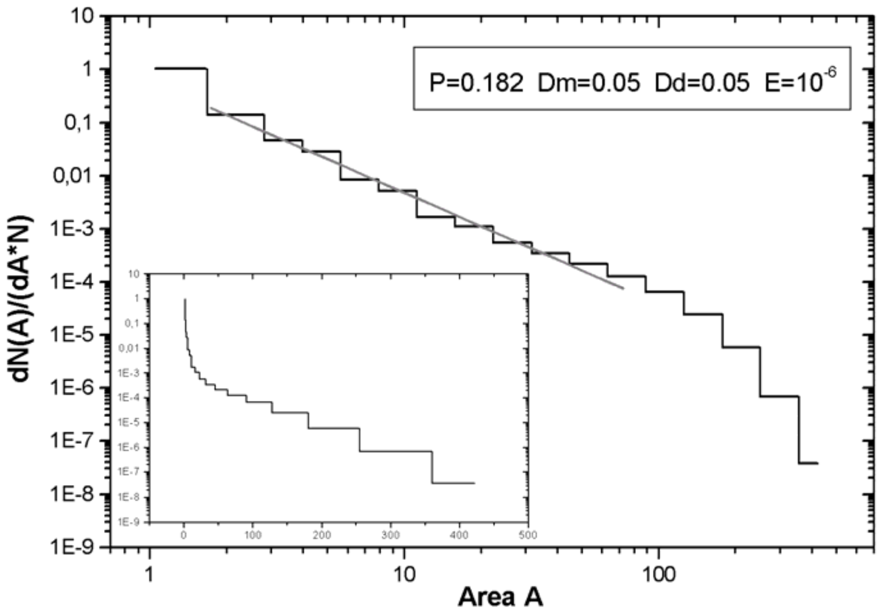
- We use a 200x1000 square grid with no magnetic flux (0)
- We star by filling 0.5 % (+1)positive magnetic flux a 0.5% (-1) negative.
- Stimulation probability P: Any active point for one time step stimulate the emergence of new flux in the neighborhood. Newly emerged flux appear in dipoles.
- Diffusion due to unrestricted random walk D_m:(mobility) free motion on the grid.
- Diffusion due to submergence D_d: (submergence of flux) Fast disappearance if the neighboring points are non-active.
- Spontaneous generation of new flux E: (its value is not important) to keep the process going

A basic portrait



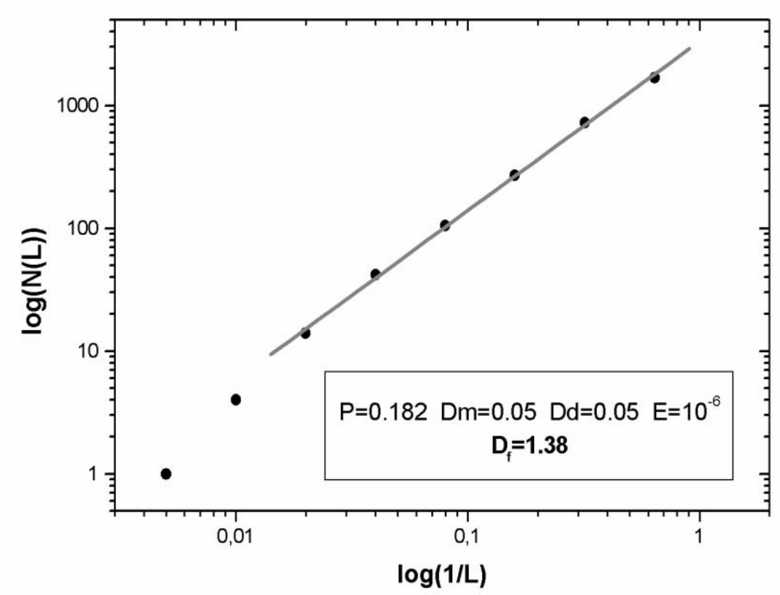


Size distribution

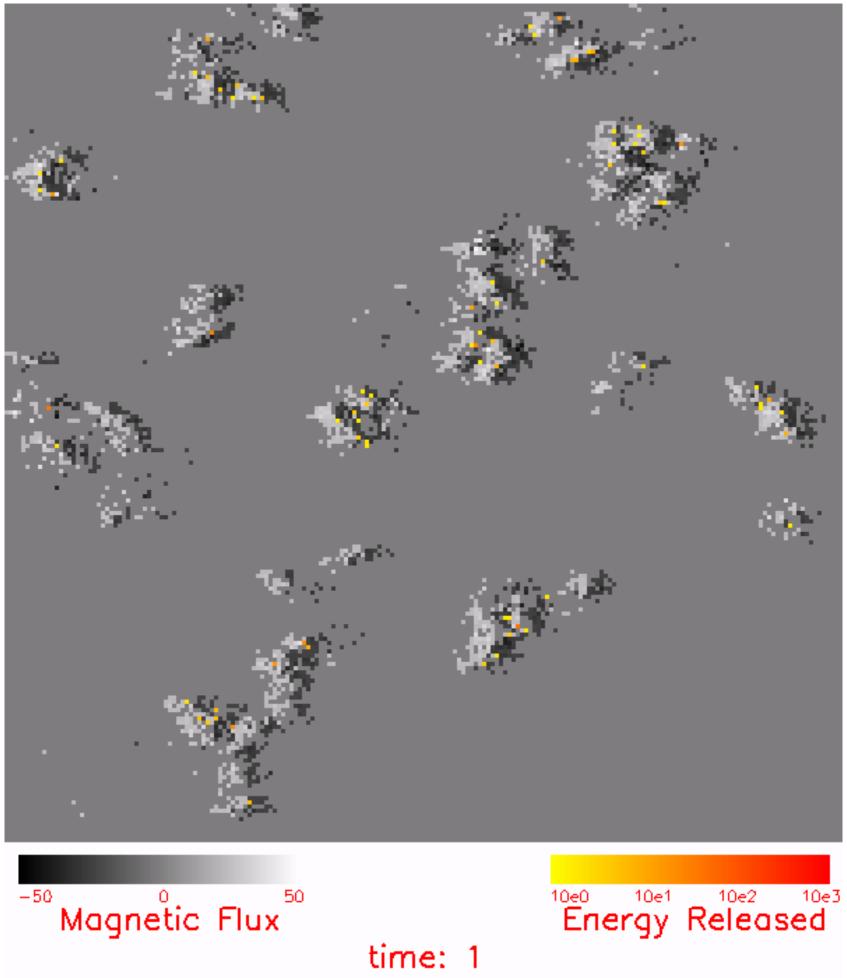


Fractal correlation dimension

- See also Meunier 1999 for similar results using a variant of Wentzel and Seiden model.



A movie on the active region evolution and magnetic field cancellation

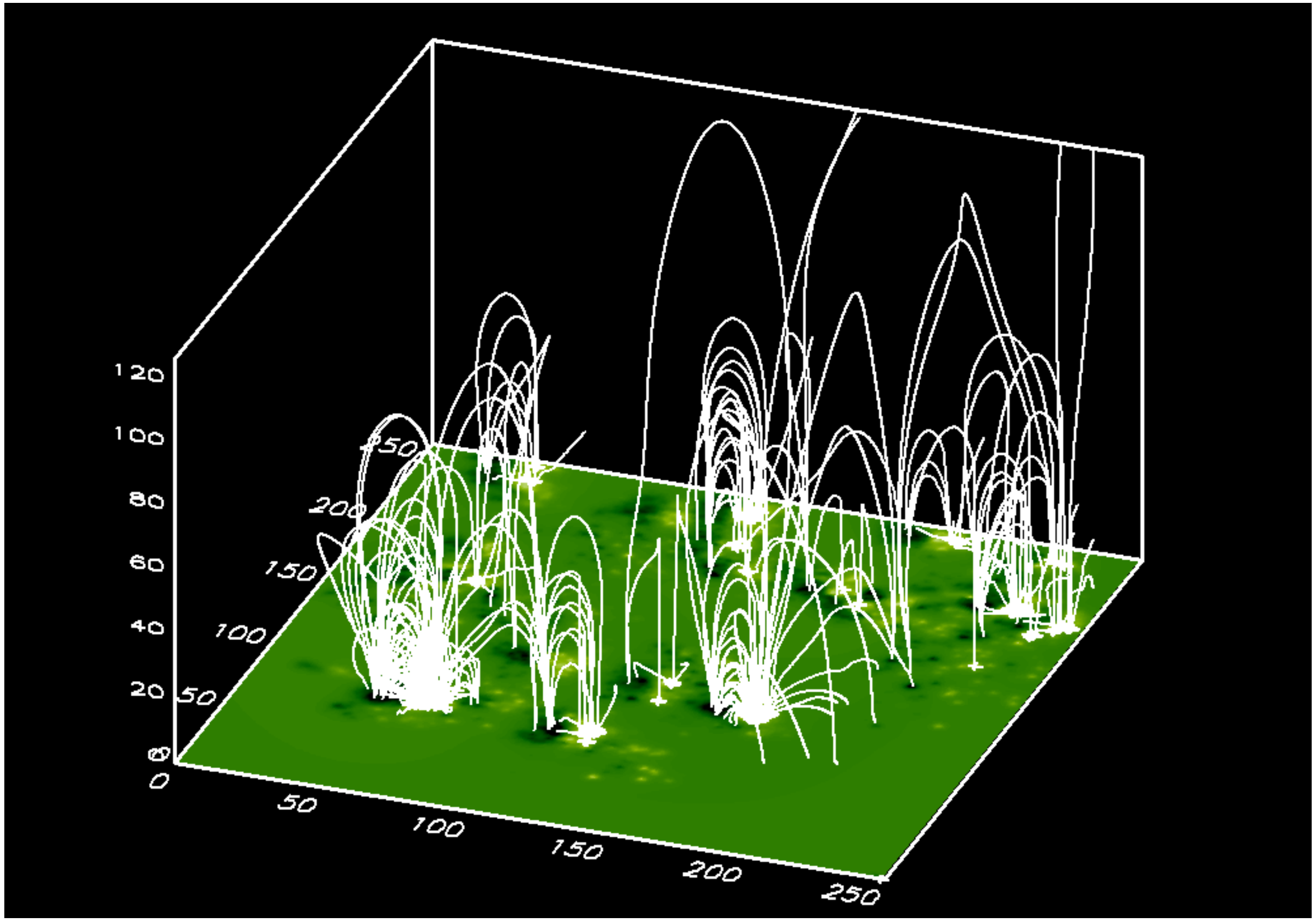


Magnetic Field extrapolation

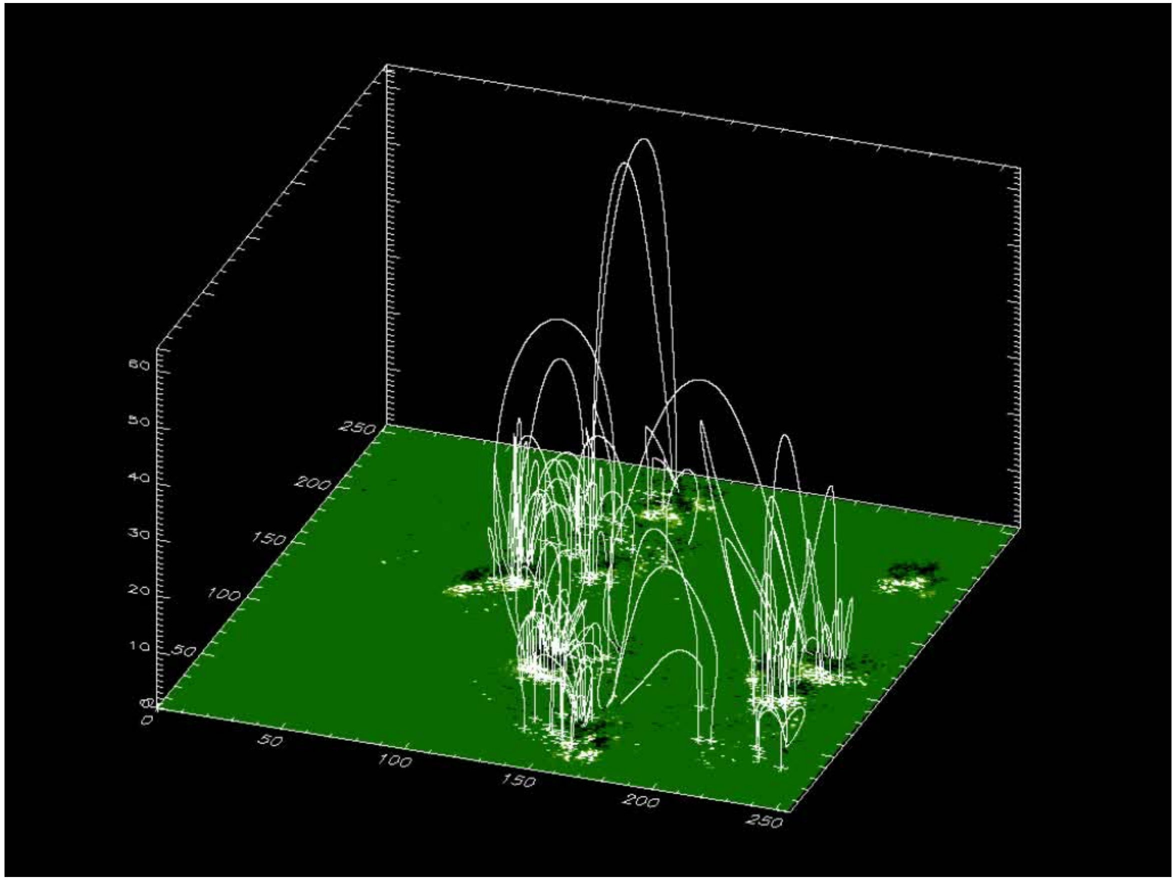
(from the magnetogram to the 3D active regions)

- Linear force free extrapolation is simple but has many uncertainties
- Non- linear extrapolation solves some of the problems but creates others (this is an open a challenging scientific problem)
- For my work in the rest of the talk… I will proceed with linear force free extrapolation to make my main points…

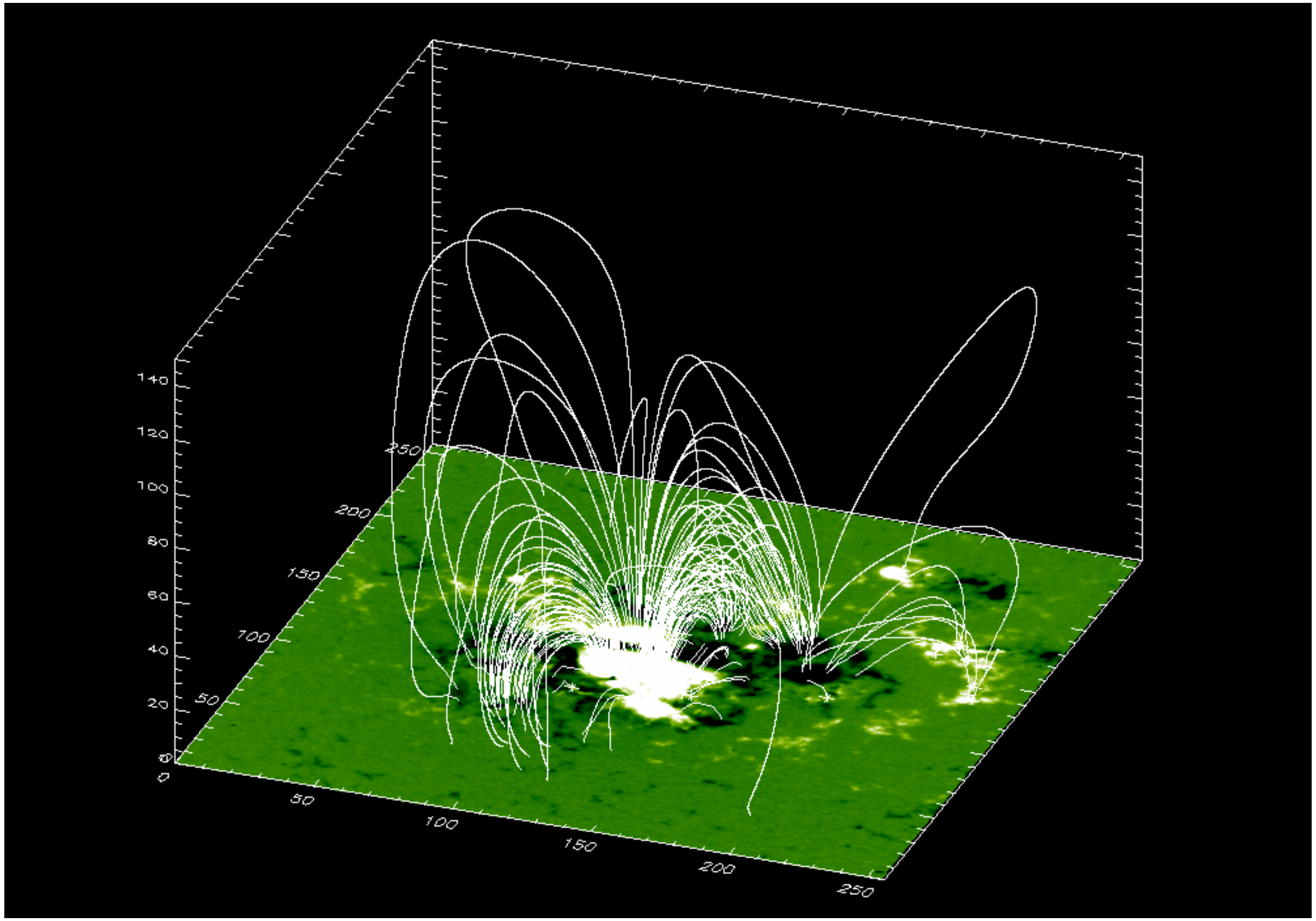
Extrapolating the CA generated magnetic field



Active regions as driven systems

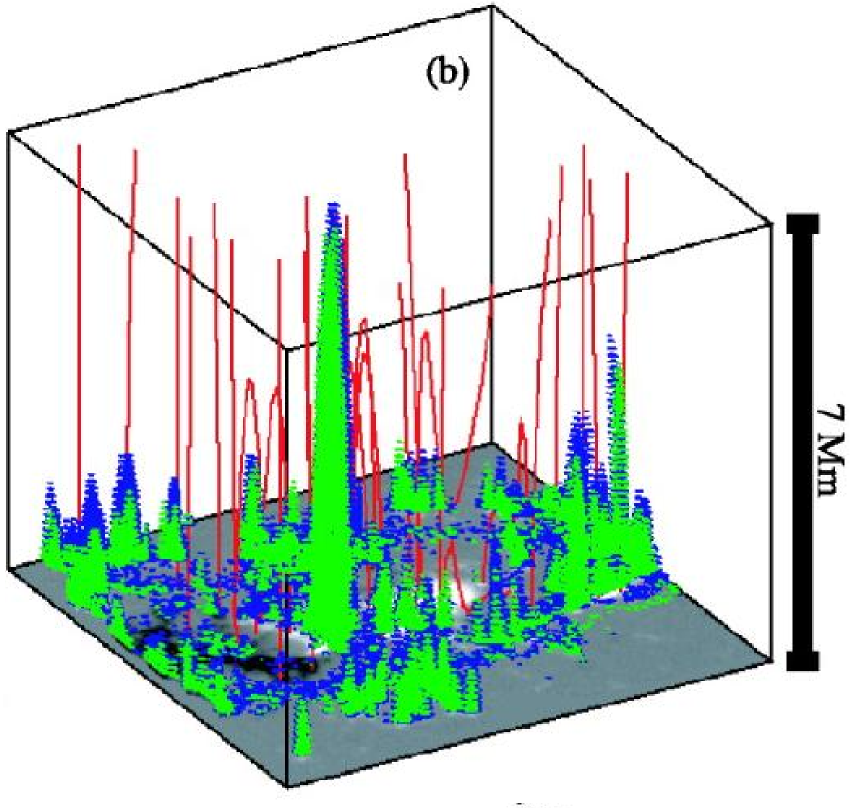


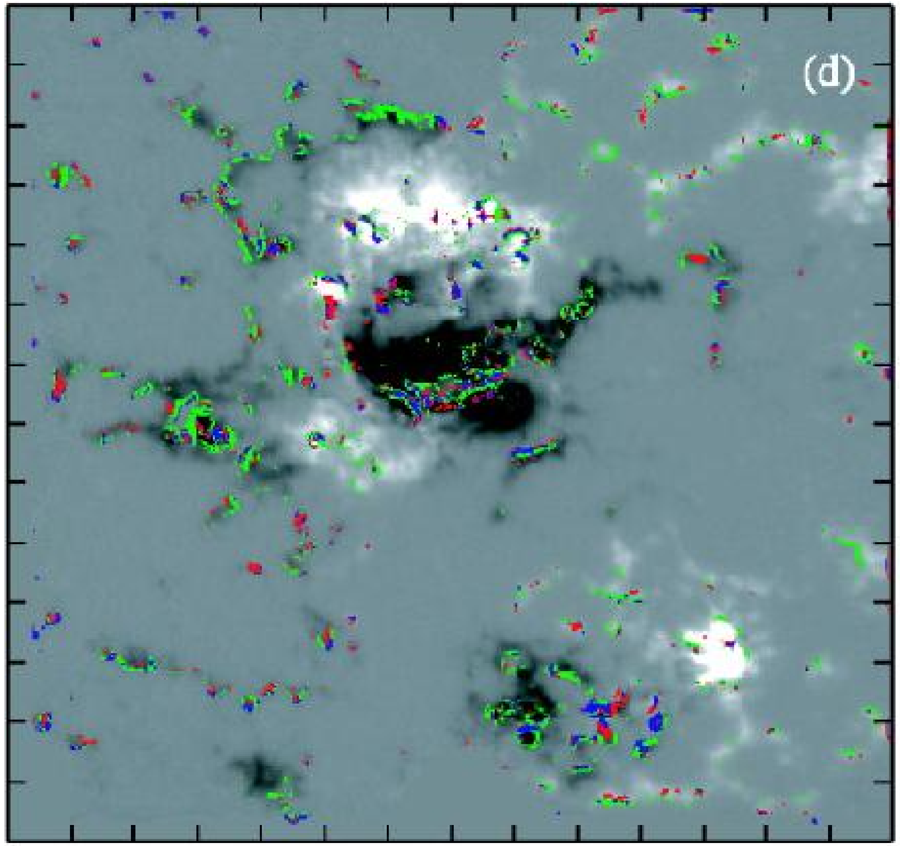
Extrapolating a magnetogram



Pre-flare / Quiescent evolution of solar ARs

Vlahos & Georgoulis (2004)

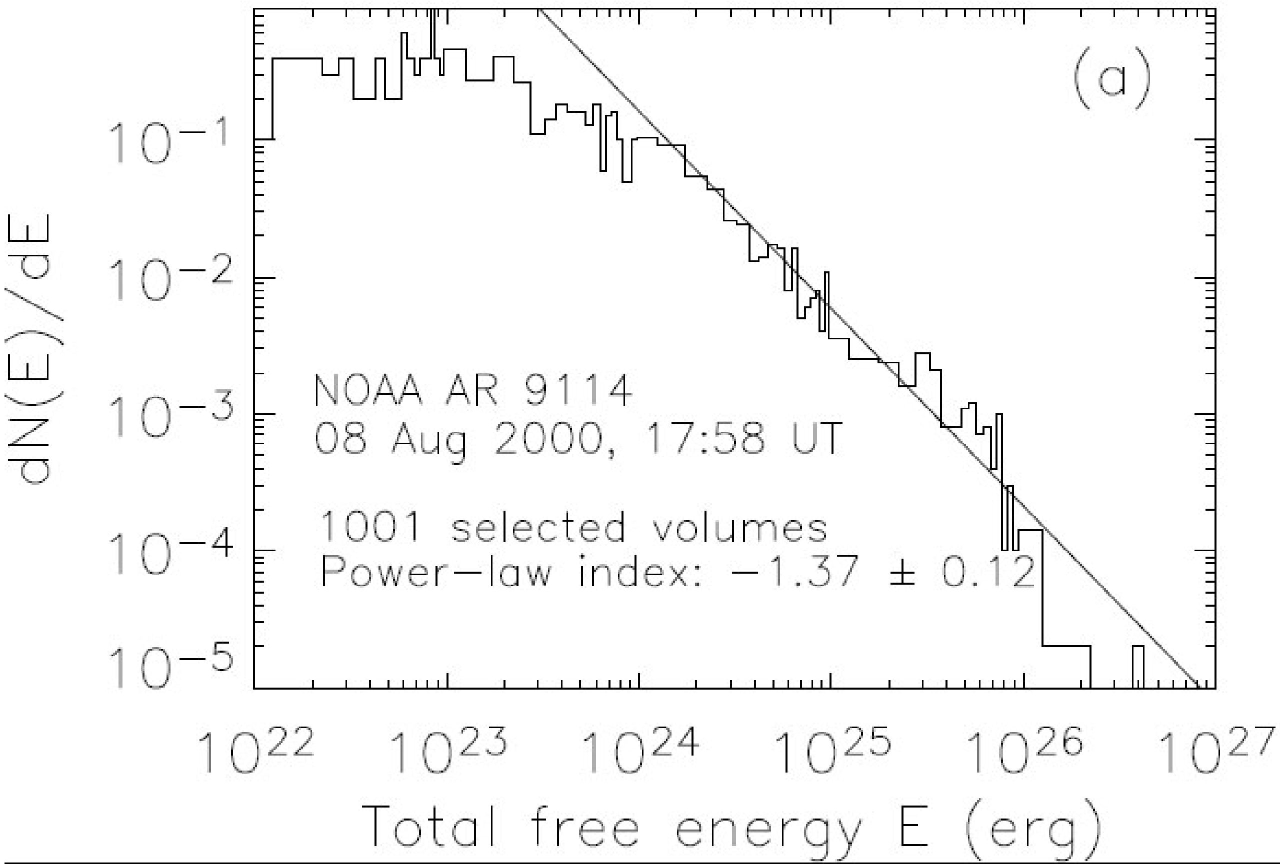




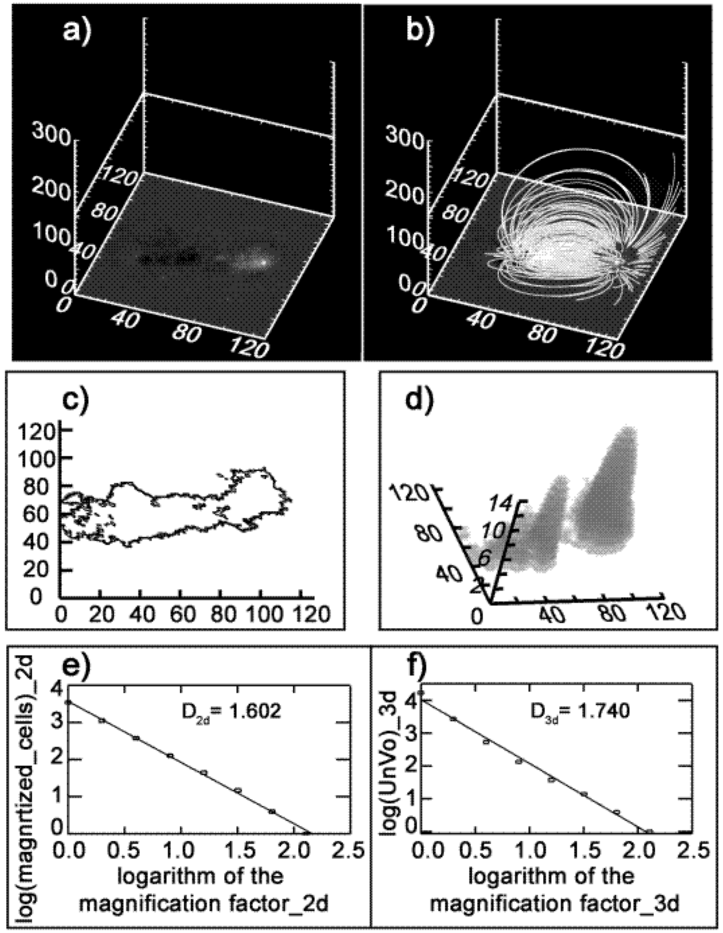
- A large number of likely unstable <u>fractal</u> volumes at low altitudes $\left(\leq 10\mathrm{Mm}\right)$
- Free energies showing power-law distribution; index nearly <u>insensitive</u> to the critical threshold
- Free energies of the order $10^{24} - 10^{26} erg$ - An <u>avalanche</u> necessary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

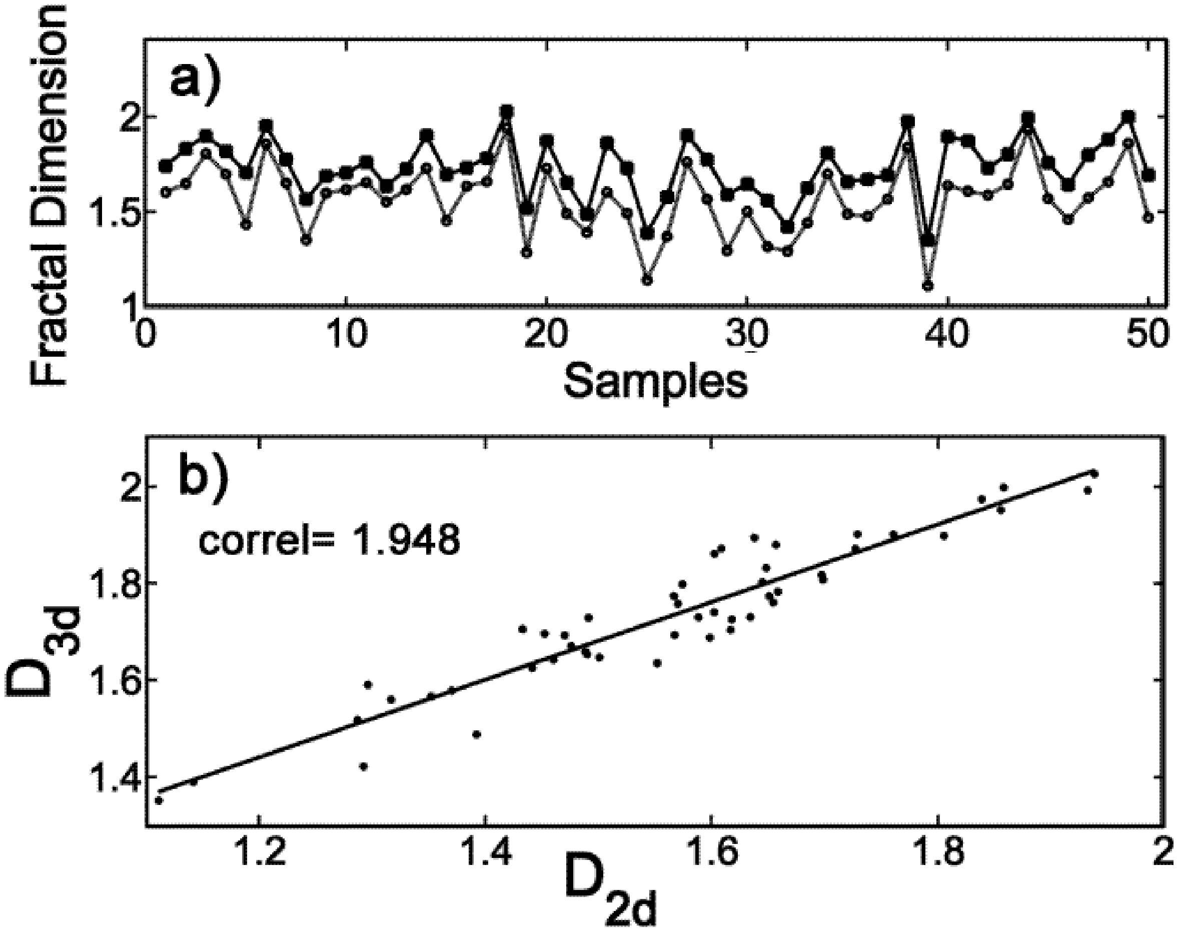
Statistical properties of Thin Current Layers (TCL)



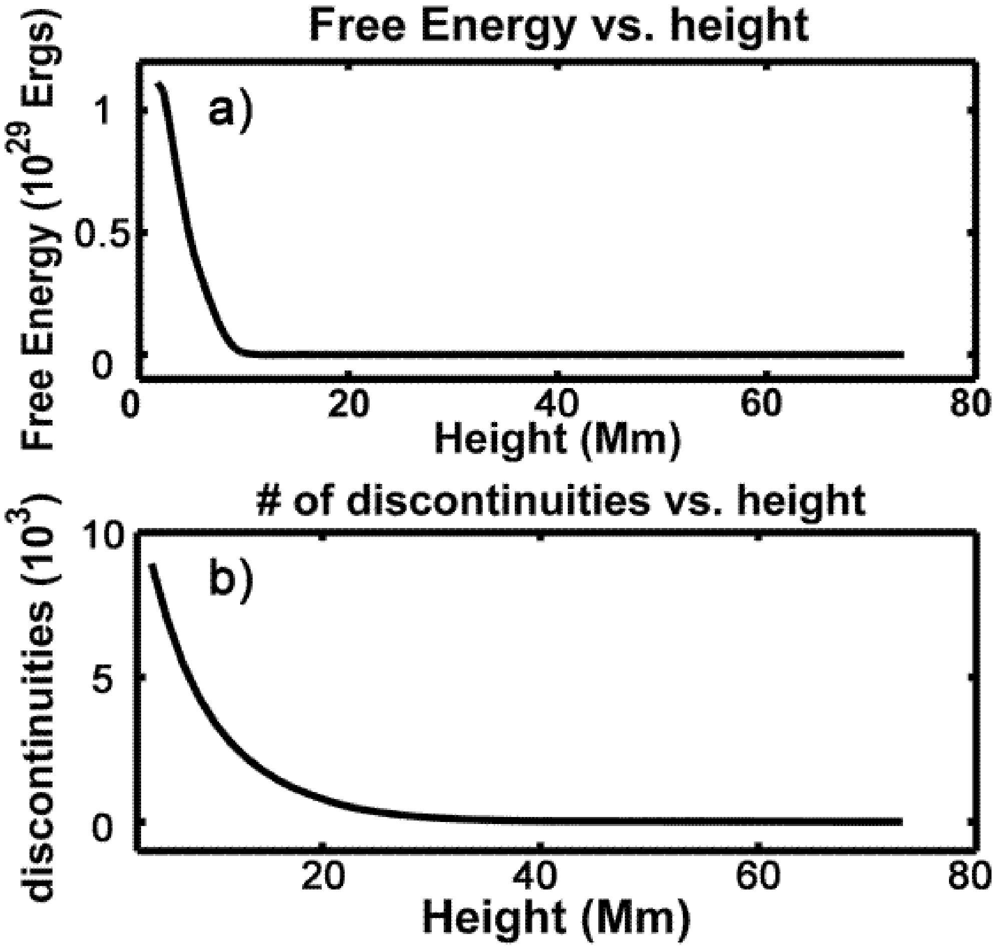
Complexity on magnetograms is mapped on AR (Dimitropoulou et al (in preparation))



Convection zone (Photosphere) drives locked to the corona (Dimitropoulou et al (in preparation))



Where is all the free energy stored?



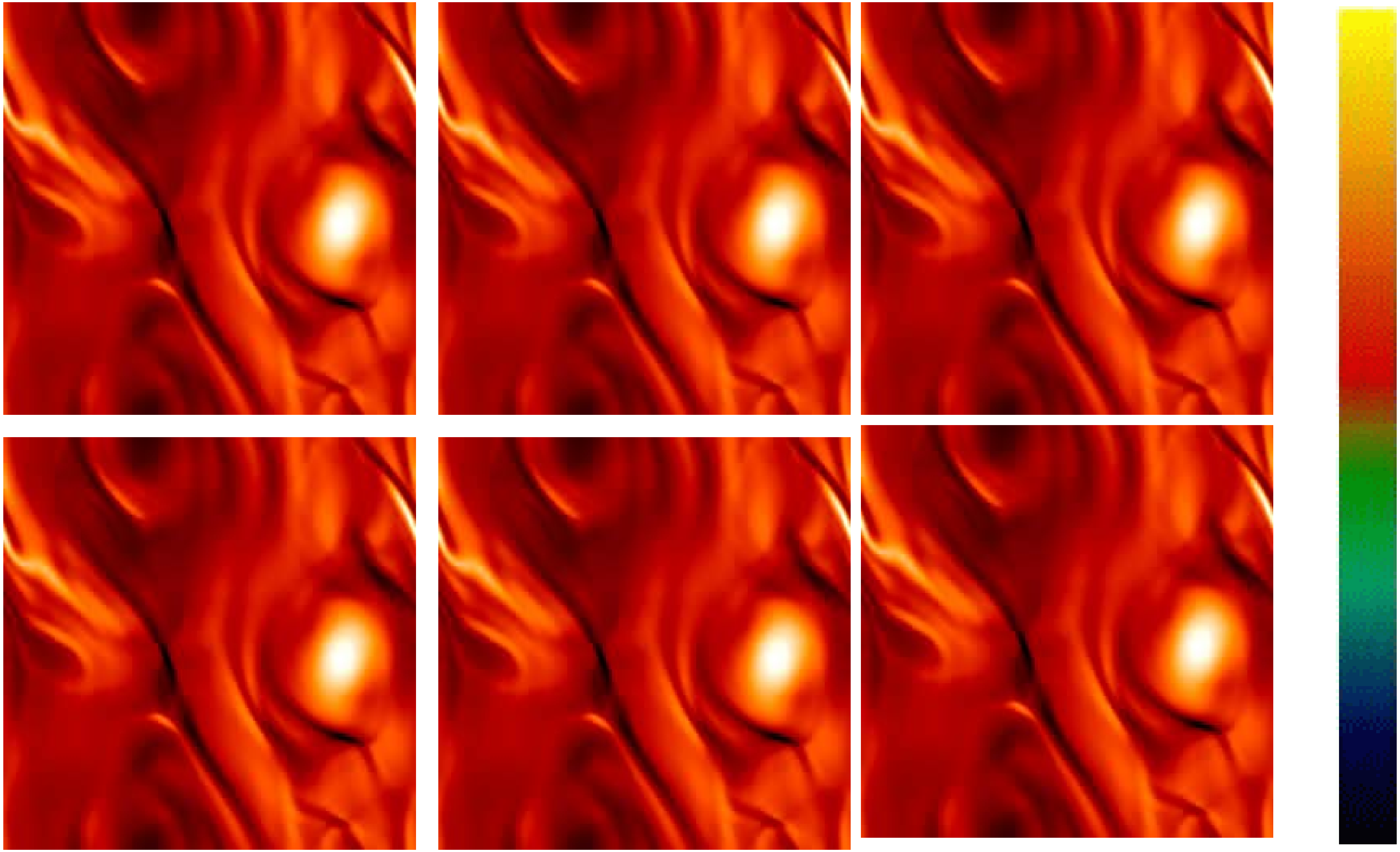
3D dynamics of Current sheets

- Energy dissipation: The Current Sheet and reconnection

(A 3d kinetic problem)

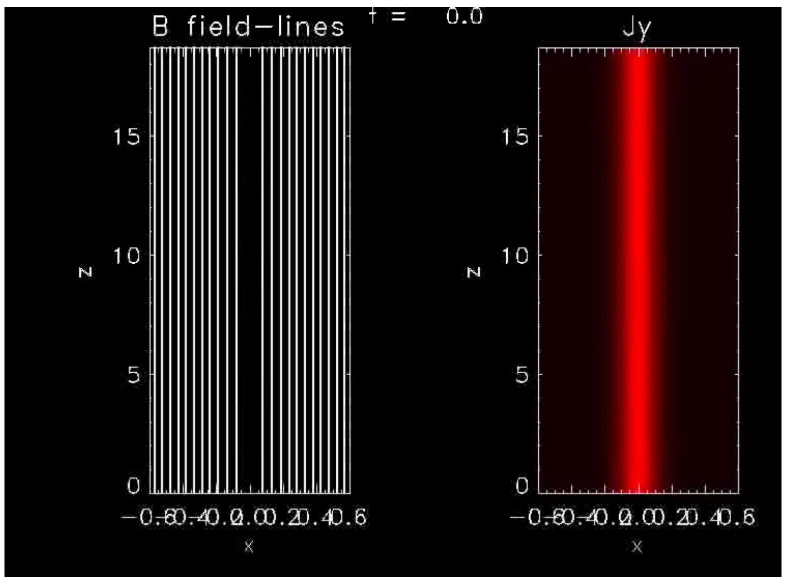
Statistics of the MHD models

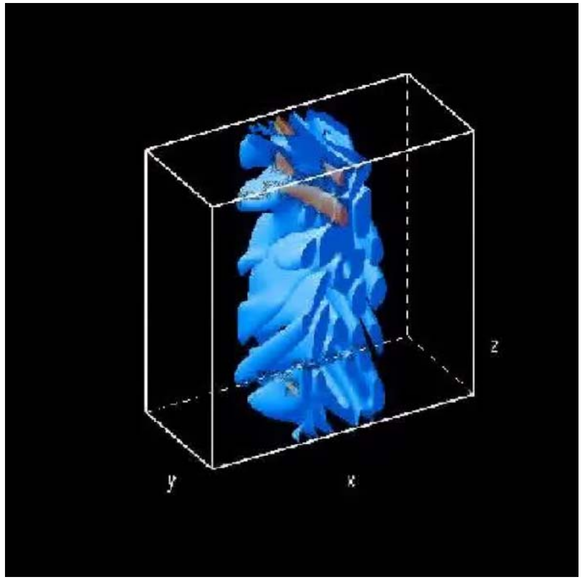
- MHD models with a turbulent evolution exhibit complexity, spatio-temporal intermittency, and self-similarity in the resulting distributions



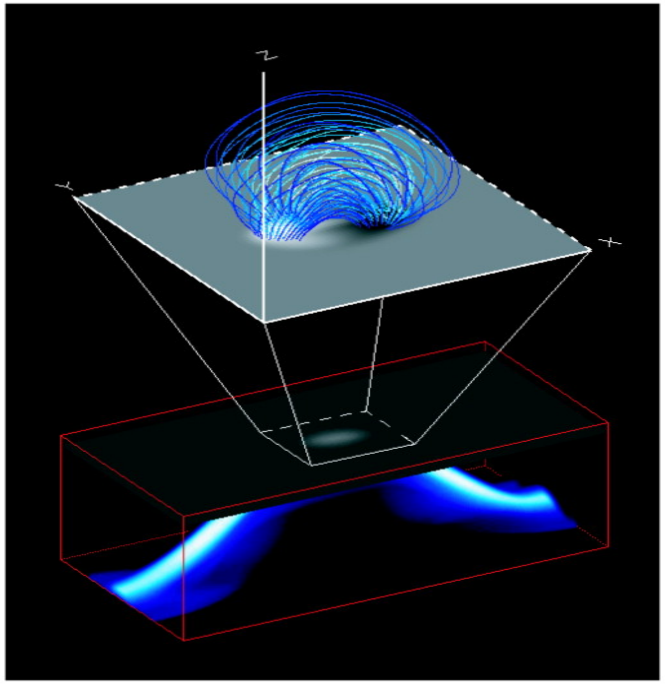
Georgoulis *et al.*, ApJ, 1998

Inside a collapsing current sheet

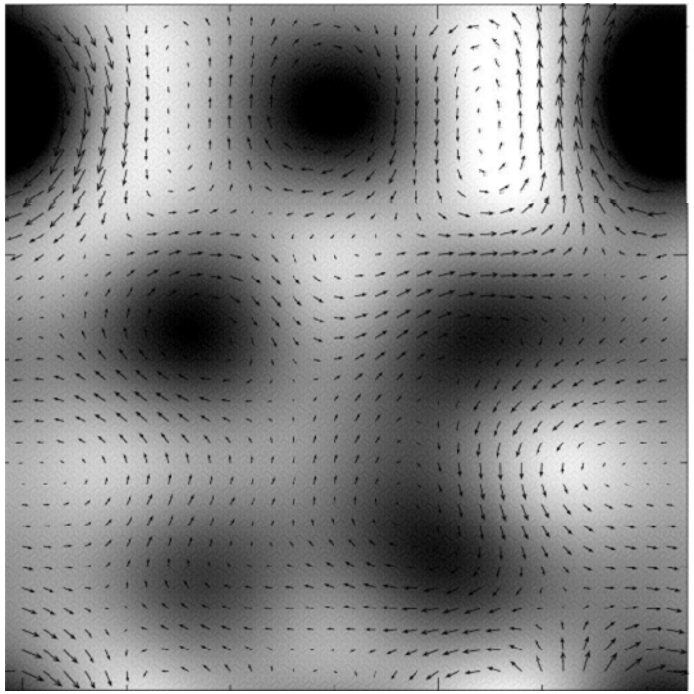


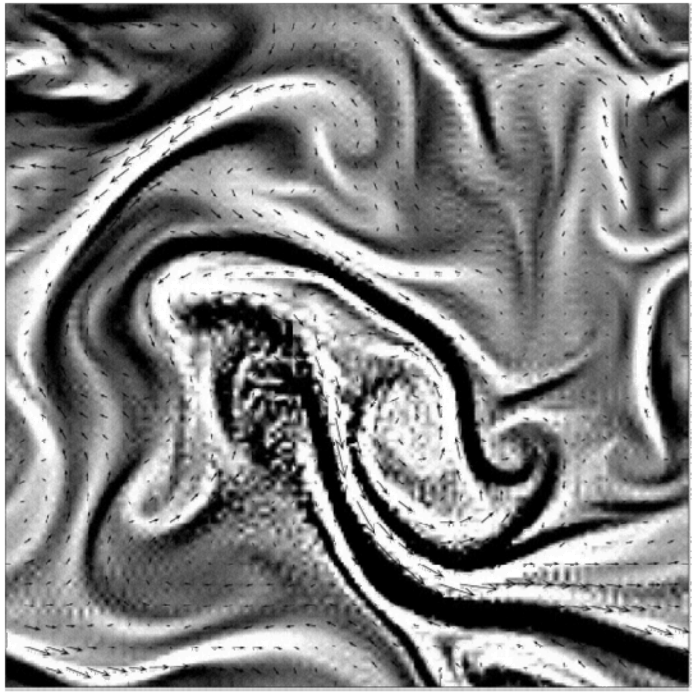


Envisioned situation in the solar atmosphere



Abbett & Fisher (2002)





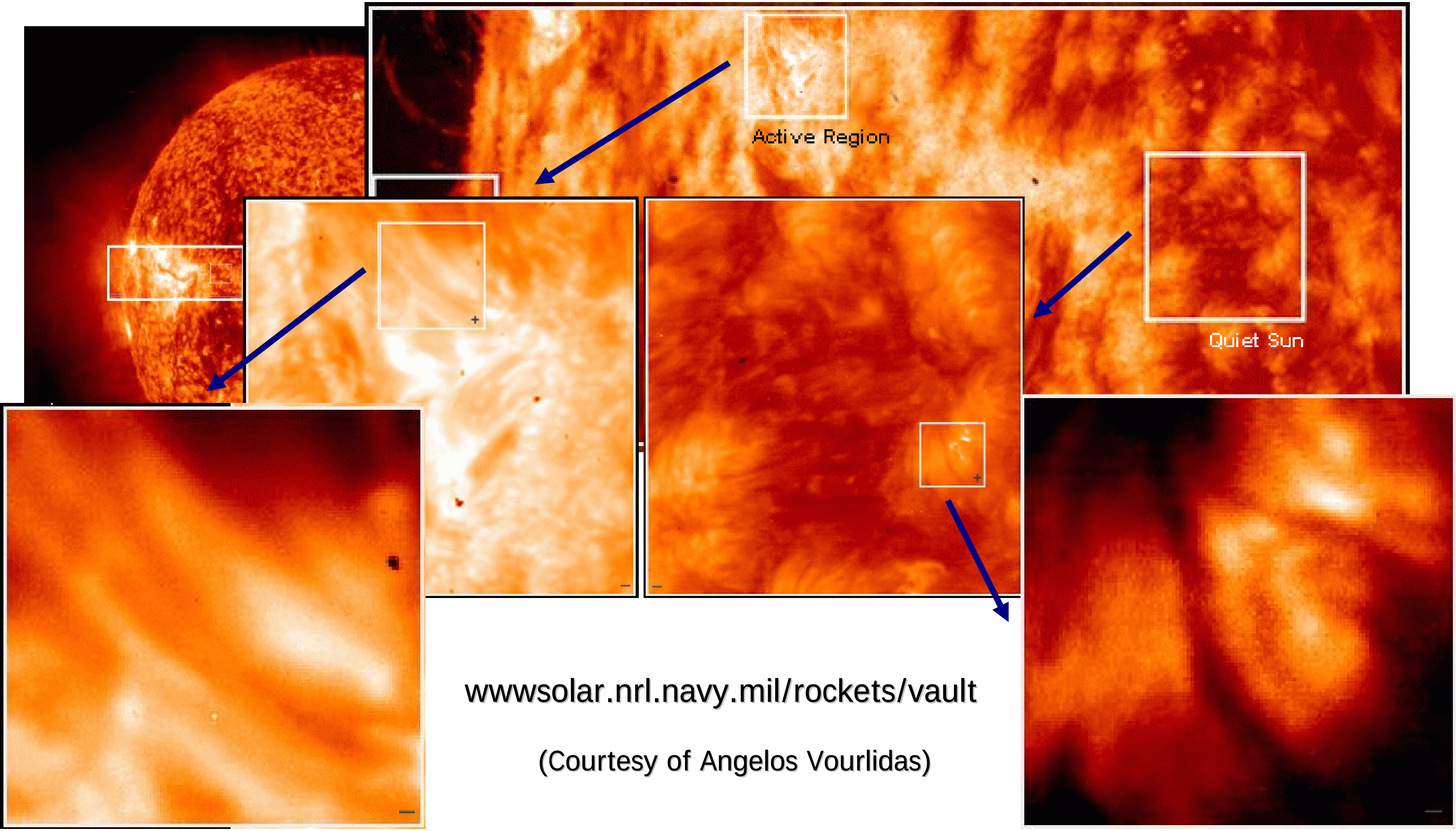
Dmitruk et al. (2002)

- 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)



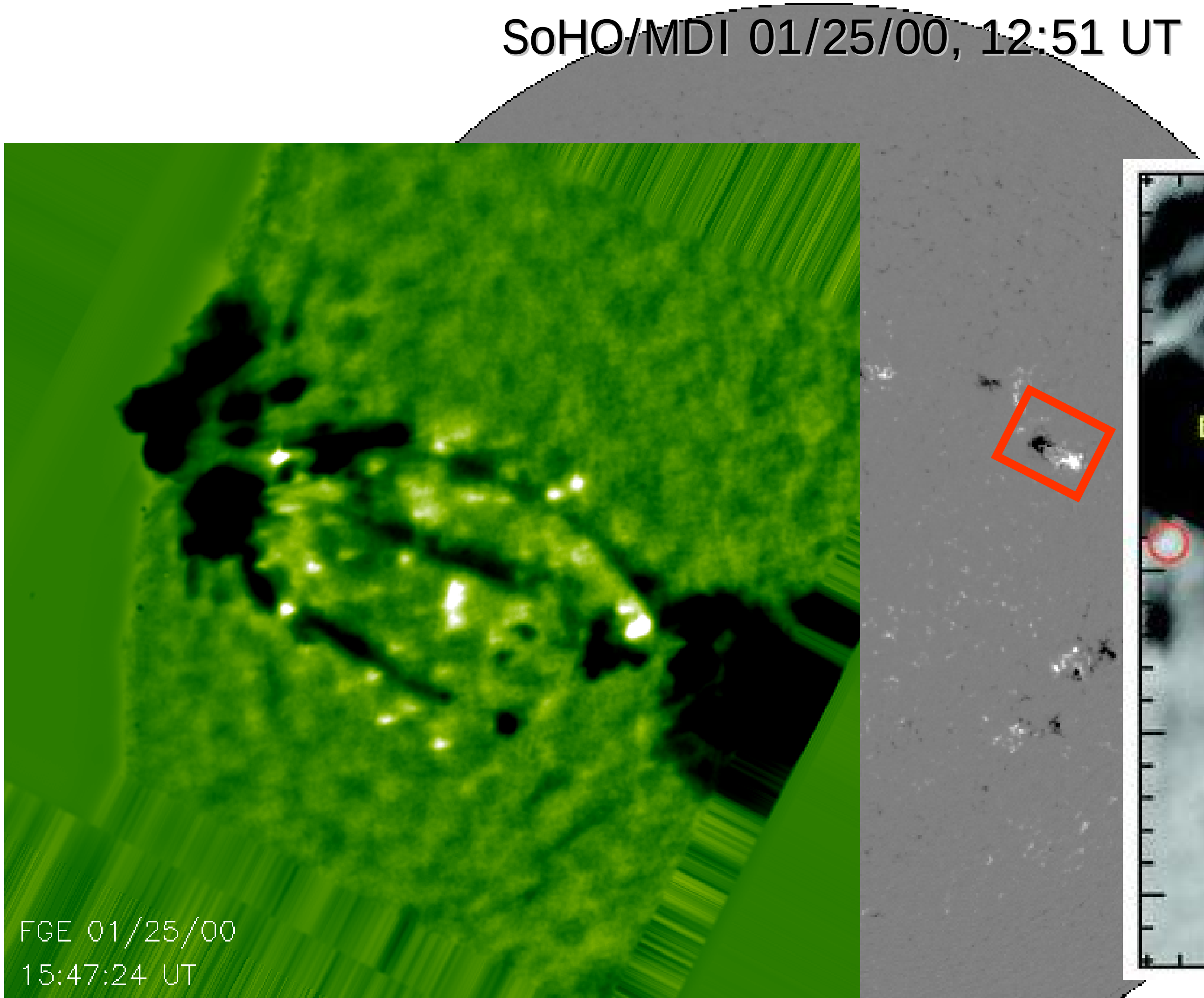
wwwsolar.nrl.navy.mil/rockets/vault

(Courtesy of Angelos Vourlidas)

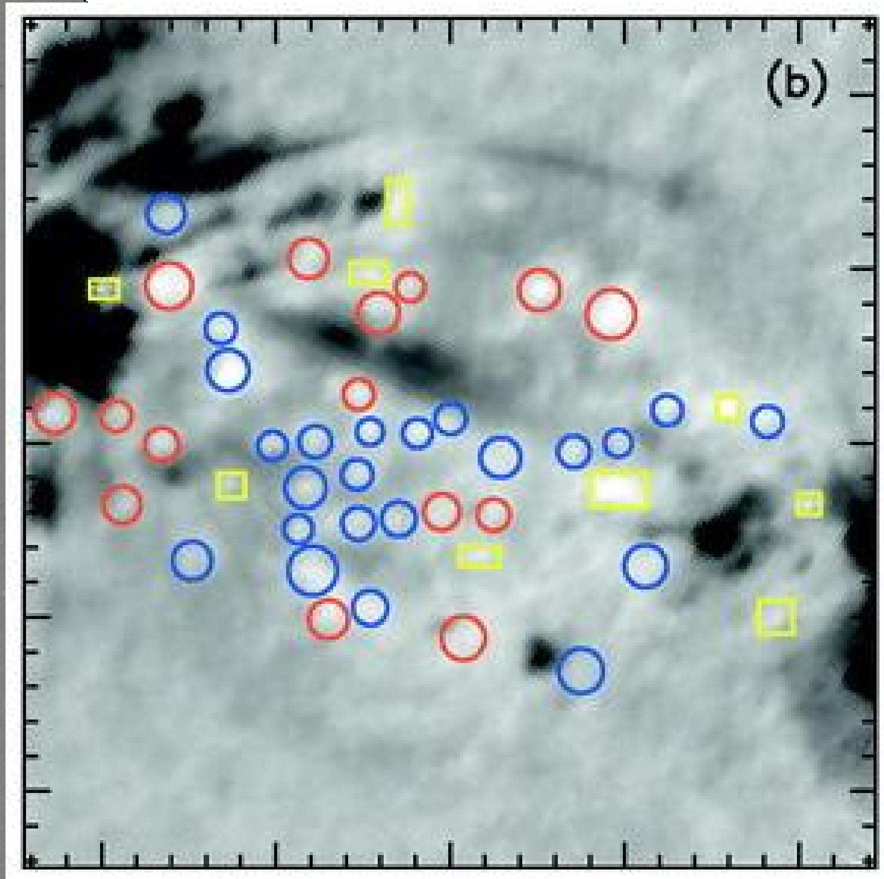
"Quiet" Sun indistinguishable from active regions in small spatial scales

Ubiquitous small-scale energy release

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



Courtesy of Pariat et al. (2004)



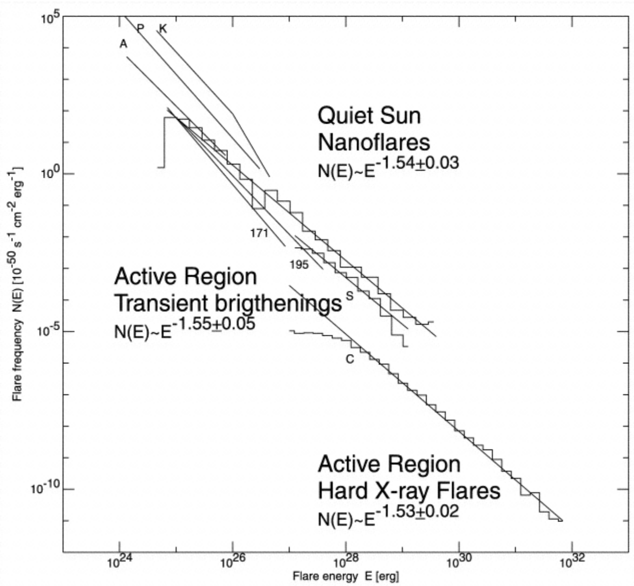
Hundreds of small-scale, short-lived brightenings (Ellerman bombs) over a 3-hr period

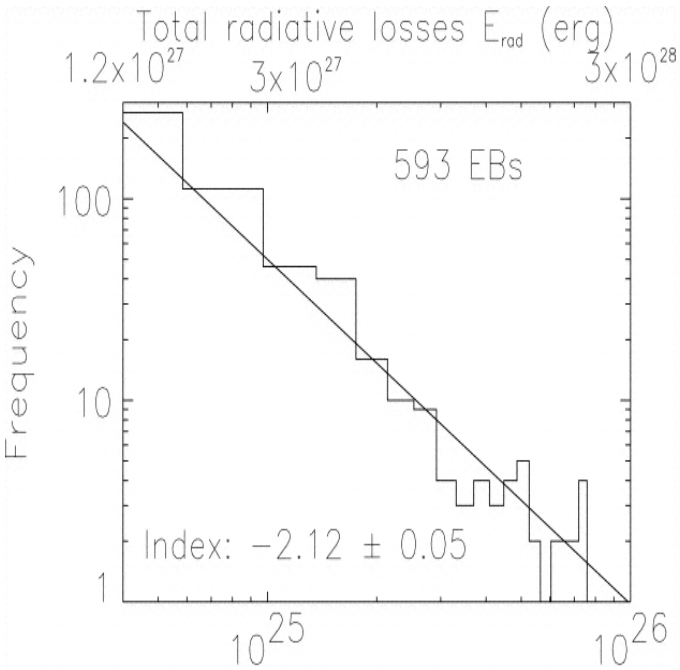
Approx. 81% (38/47) of EBs associated with magnetic bald patches, separatrices or QSLs

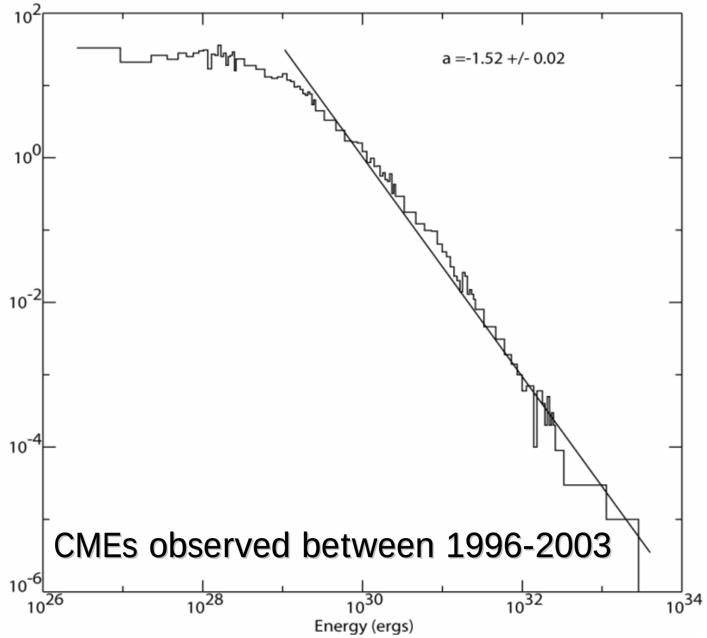
Evidence of self-similarity in small-scale energy dissipation processes

Quantifying the statistics of solar activity

Power laws everywhere:







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

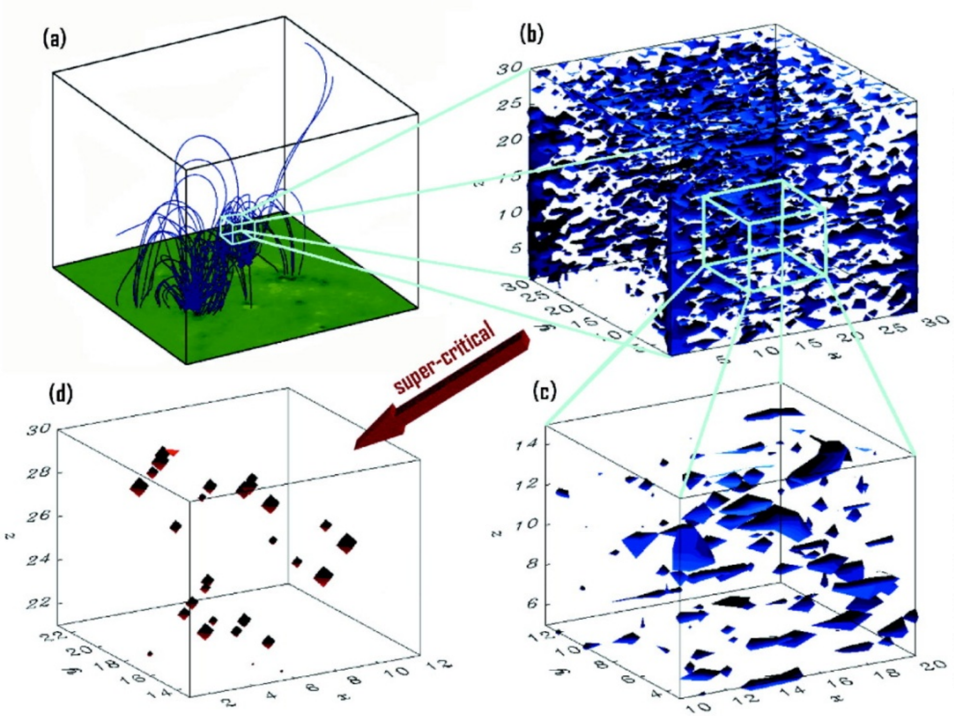
Ellerman bombs
(Georgoulis et al. 2002)

Kinetic Energy of CMEs
(Courtesy of A. Vourlidas)

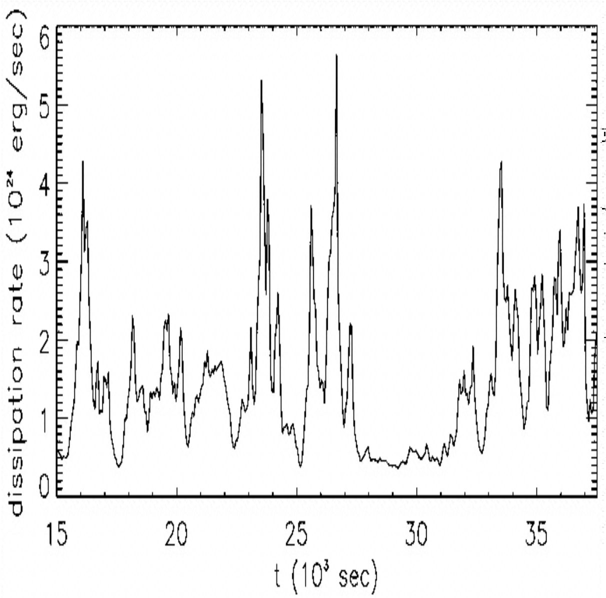
Moreover, power laws are found in the events' peak activity, total duration, rise and decay times, area coverage, inferred volumes, etc.

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

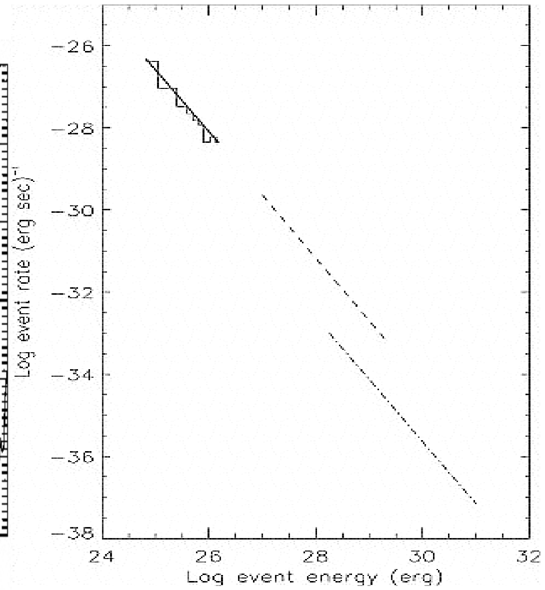
Expected consequences of turbulence



Vlahos et al. (2004)



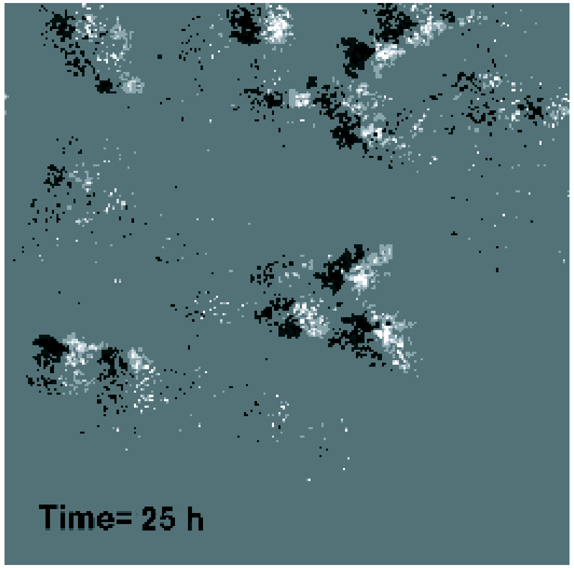
Dmitruk et al. (1998)



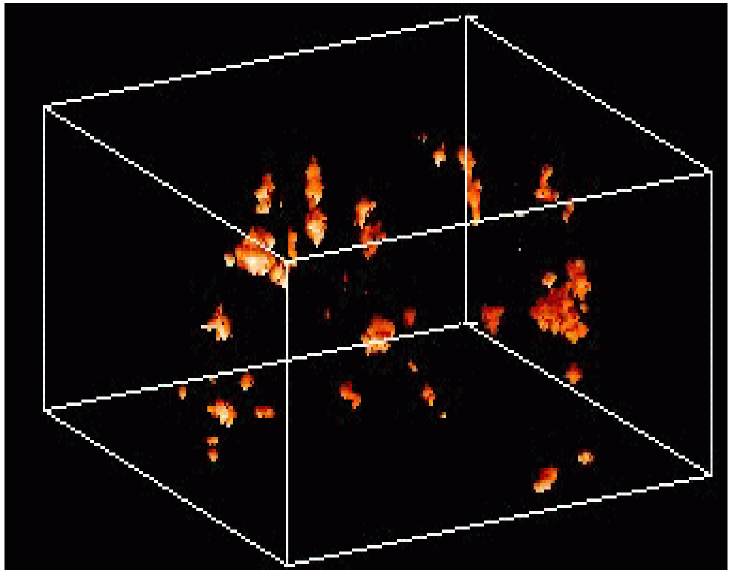
Dmitruk & Gomez (1997)

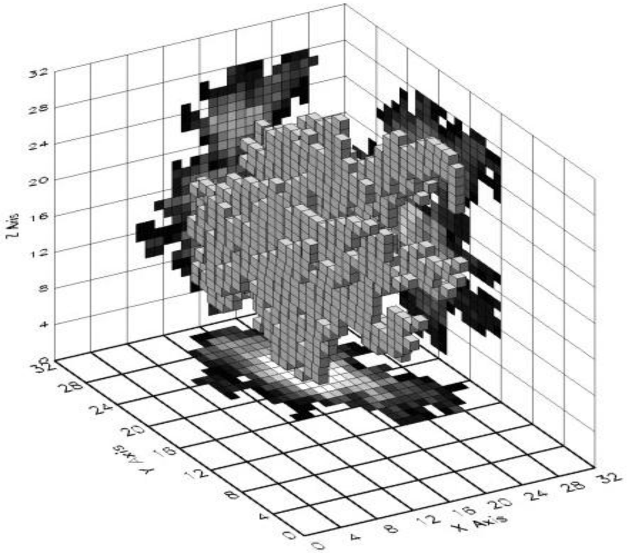
- Hierarchical <u>self-organization</u>, which gives rise to tremendous spatial complexity
- Spatial self-similarity (scale invariance & fractal structures)
- Intermittency in the energy release process
- Power laws in the statistical behavior of the system

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?

No time to discuss other issues

- There are two more levels of sophistication which time limits did not allow me to present
  - Particle acceleration on stochastic e-fields
  - High energy emission
  - Coronal Heating

The Integrated Flare Model

- In the area of grid physics a new question can be posed: We can lunch a new very ambitious project.
- Can we stuck a number of codes
  - Extrapolation of a dynamic photosphere (the driver) (code 1)
  - Search of small scales discontinuities (code 2)
  - Energy release (flares) and magnetic field rearrangement (code 3)
  - Is the new magnetic topologies stable or the arcade system will explode (code 4 CME)
  - Particle acceleration on the unstable nodes by stochastic electric fields (code 4)
  - Radiation from the accelerated particles but on the extrapolated magnetic topologies (code 5)

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