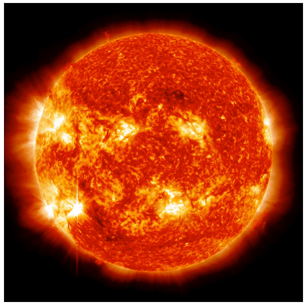
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

IfB
Institut für Baustoffe
Institute for Building Materials

Modeling the influence of photospheric turbulence on solar flare statistics

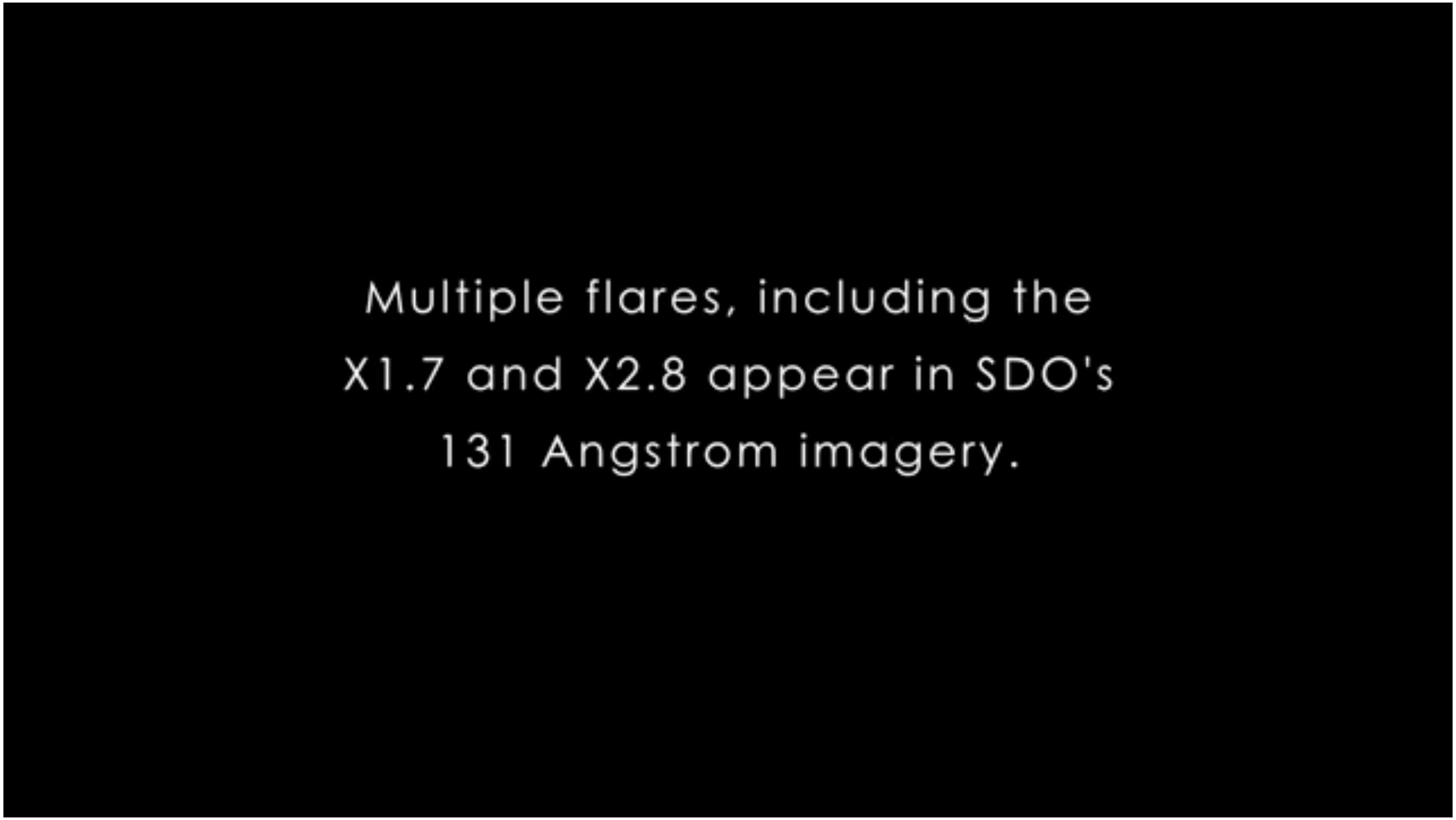


Miller Mendoza Jiménez

Collaborations: A. Kaydul, T. Koskamp, L. de Arcangelis, J. S. Soares Jr., H. J. Herrmann

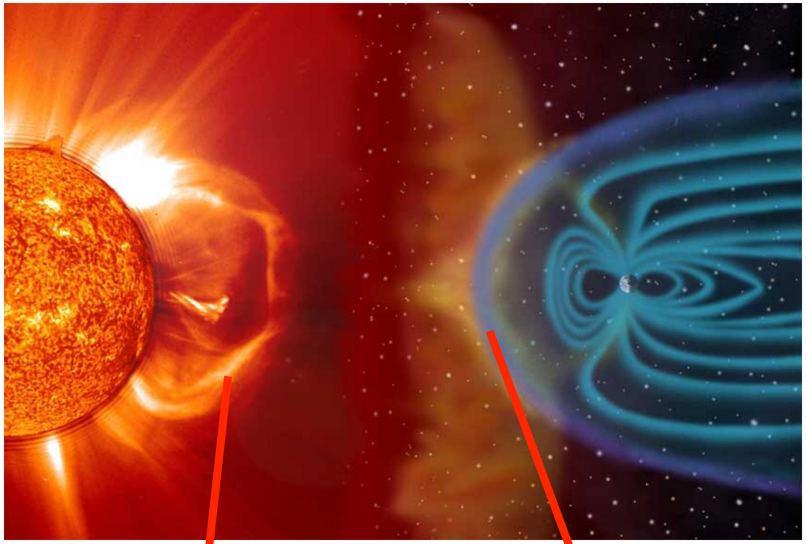
What are solar flares??

X-ray video of the Sun



Why is it important?

Impact on our lives



CME: Coronal Mass Ejections

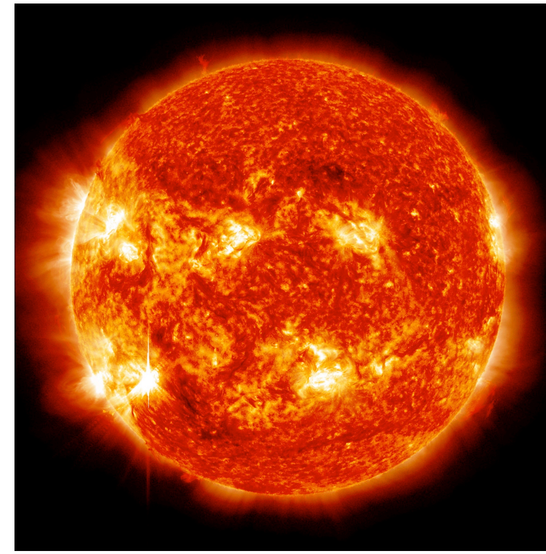
Magnetic Storms

Magnetohydrodynamics

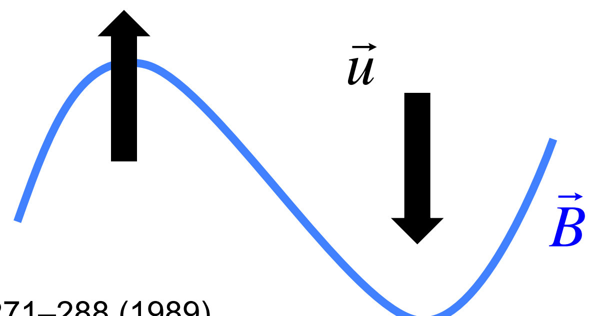
$$\rho\frac{\partial\vec{u}}{\partial t}+\rho\vec{u}\cdot\nabla\vec{u}=-\nabla P+\vec{J}\times\vec{B}+\eta\nabla^2\vec{u}$$

$$\frac{\partial\vec{B}}{\partial t}=\nabla\times\left(\vec{u}\times\vec{B}\right)+\eta_m\nabla^2\vec{B}$$

$$\vec{J}=\frac{1}{\mu_0}\nabla\times\vec{B}$$

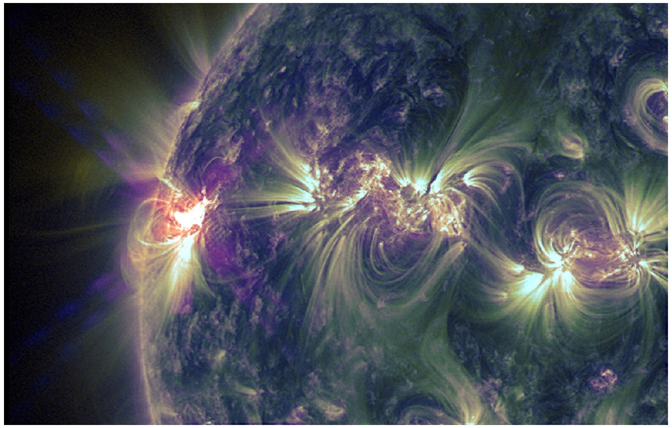


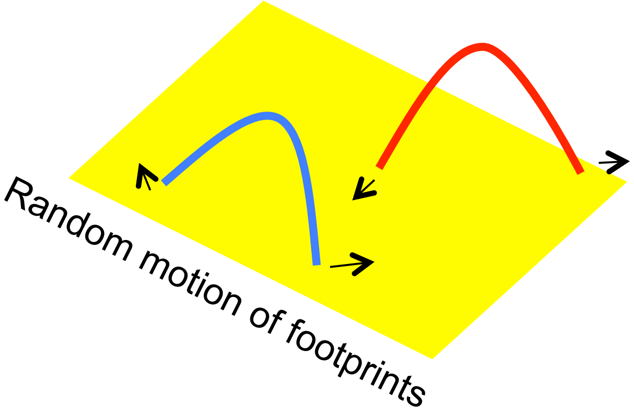
Magnetic lines are frozen in a highly conductive plasma

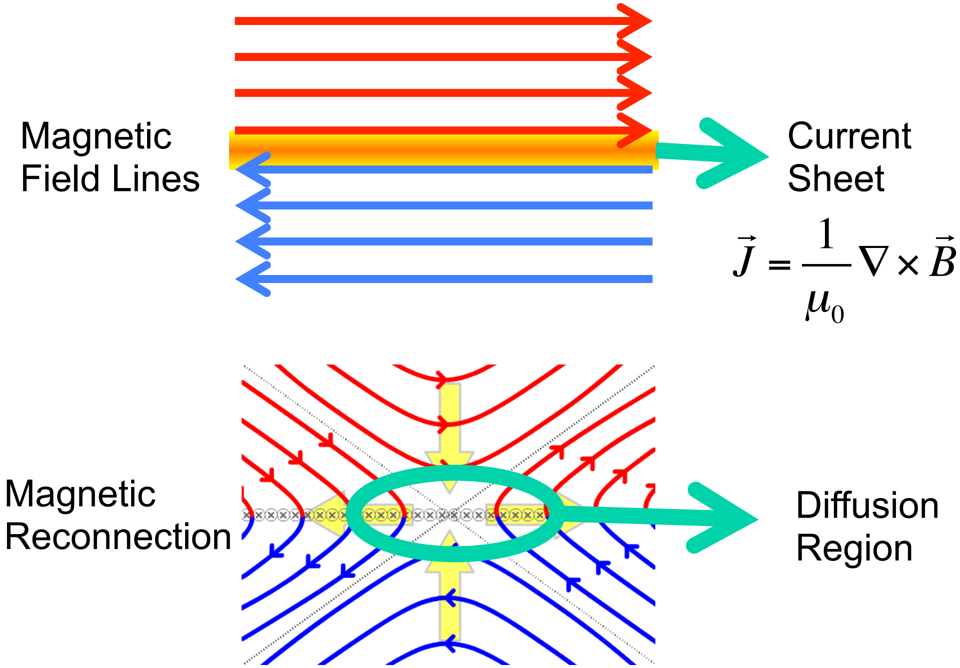


Parker, E., Theory. Solar Phys. 121, 271–288 (1989).

Causes of Solar Flares







$$\vec{J} = \frac{1}{\mu_0} \nabla \times \vec{B}$$

However, still an open Question !!

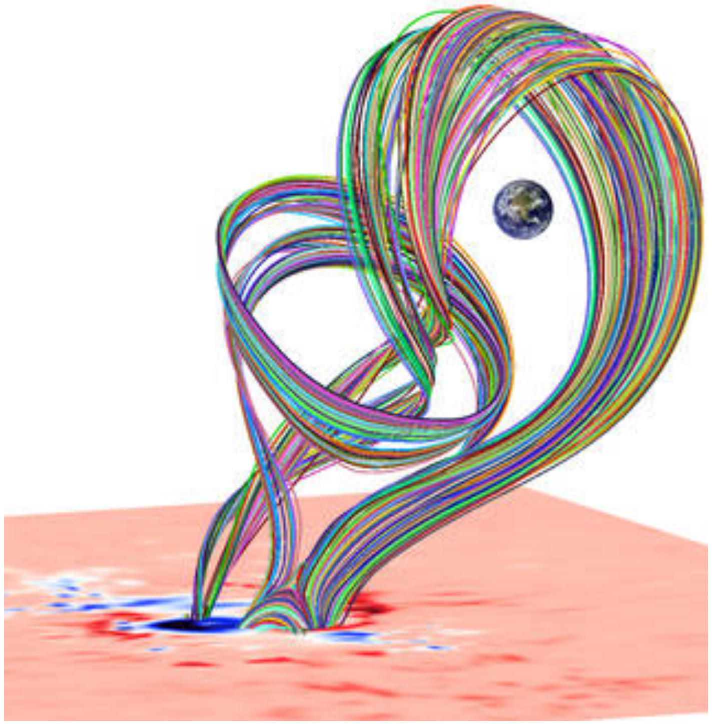
Parker, E., Theory. Solar Phys. 121, 271–288 (1989).

First principles simulations in 3D

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho \vec{u} \cdot \nabla \vec{u} = -\nabla P + \vec{J} \times \vec{B} + \eta \nabla^2 \vec{u}$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{u} \times \vec{B} \right) + \eta_m \nabla^2 \vec{B}$$

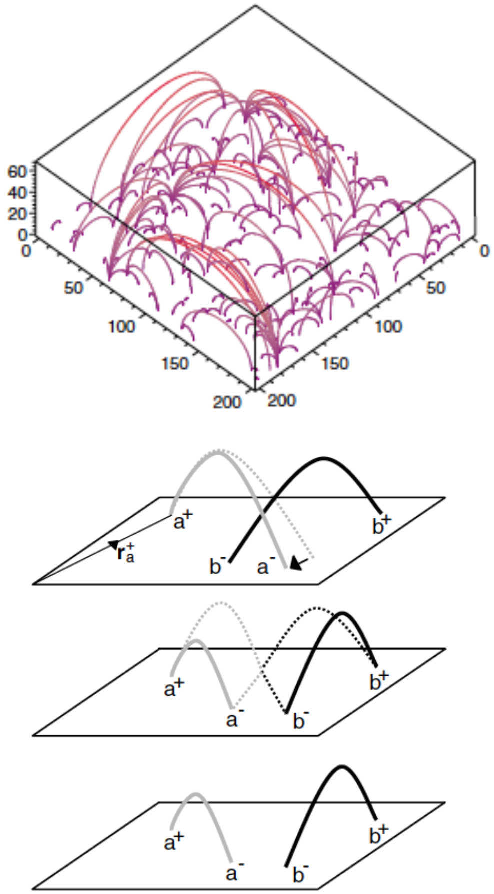
$$\vec{J} = \frac{1}{\mu_0} \nabla \times \vec{B}$$

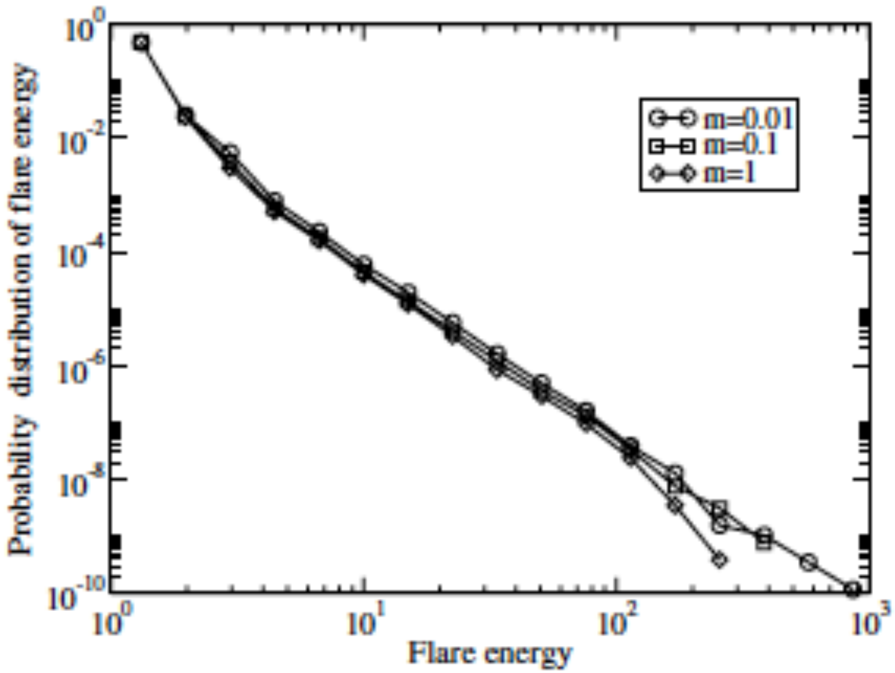


Requires tooooooo much computational power!!

Parker, E., Theory. Solar Phys. 121, 271–288 (1989).

Model based on self-organized criticality (SOC)





Exponent = -3. Expected value ~ 1.68
Inter-time distribution: Poisson (not expected)

D. Hughes, et al. Phys. Rev. Lett. 90, 131101 (2003)

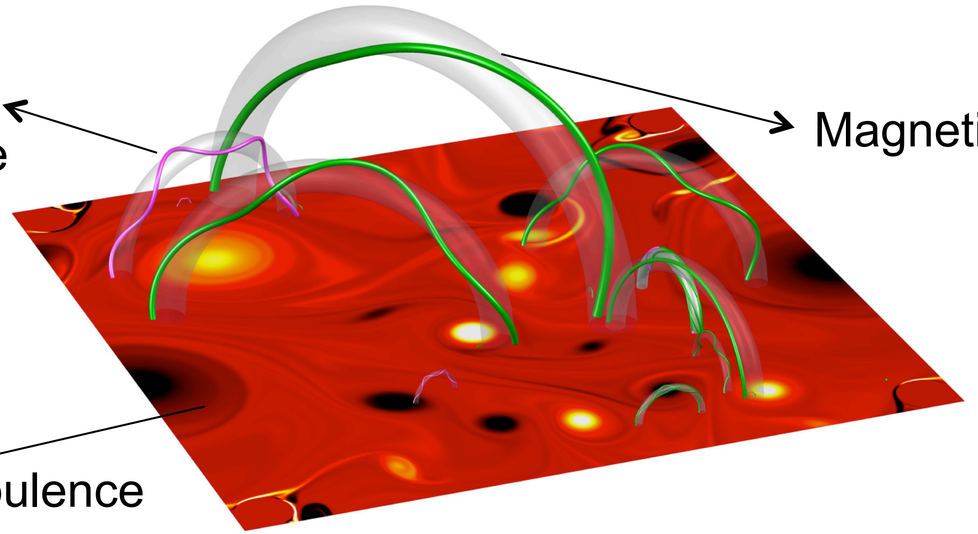
There are many more works studying this phenomenon.

Model Description

Exponent of the distribution of peak energy of solar fares ~ -1.68

Exponent of power spectrum of turbulence flow = 5/3 ~ -1.67

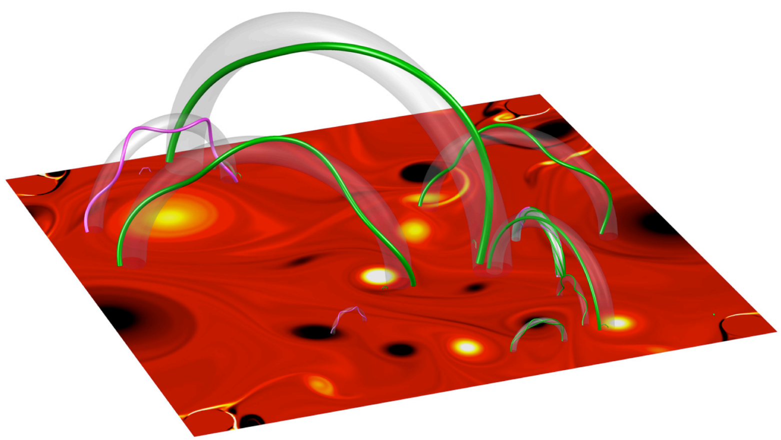
Model Description



1. Photospheric Turbulent Plasma
2. Footprints follow the velocity field (as track particles)
3. Twist is controlled by vorticity
4. Flare event affects neighboring magnetic flux tubes

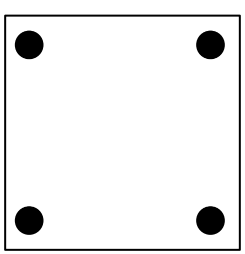
Mendoza, M., et al. *Nature communications* 5 (2014).

Model Description. Photospheric Plasma



$$\vec{F} = A_0 \left(\sin(k_f x)\cos(k_f y), -\sin(k_f y)\cos(k_f x) \right)$$

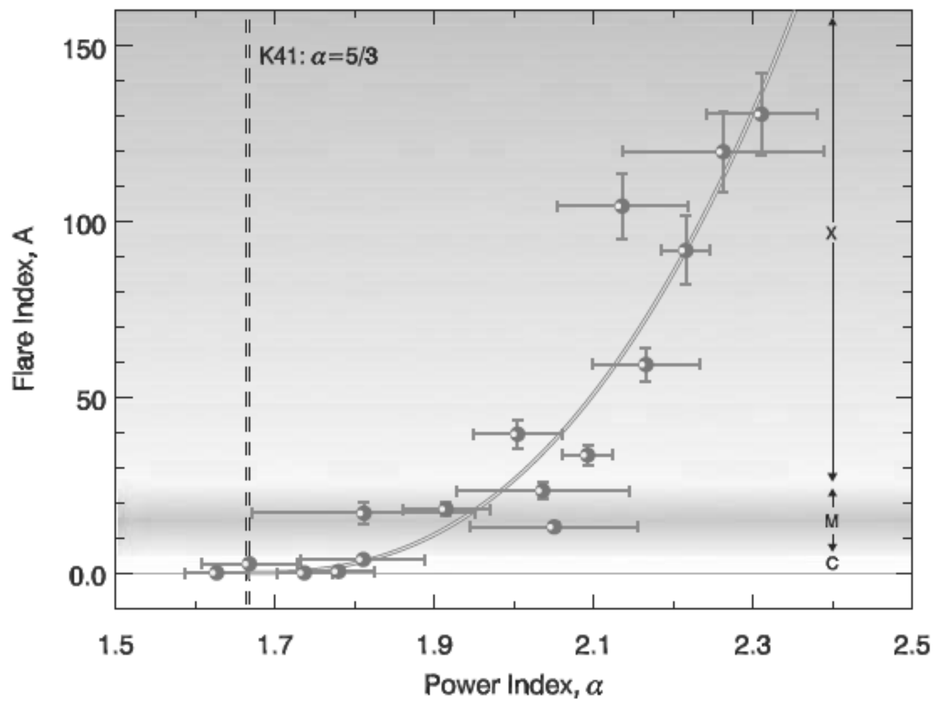
Large-scale dissipation mechanism to avoid vortex condensation.



$$-\mu \vec{u}$$

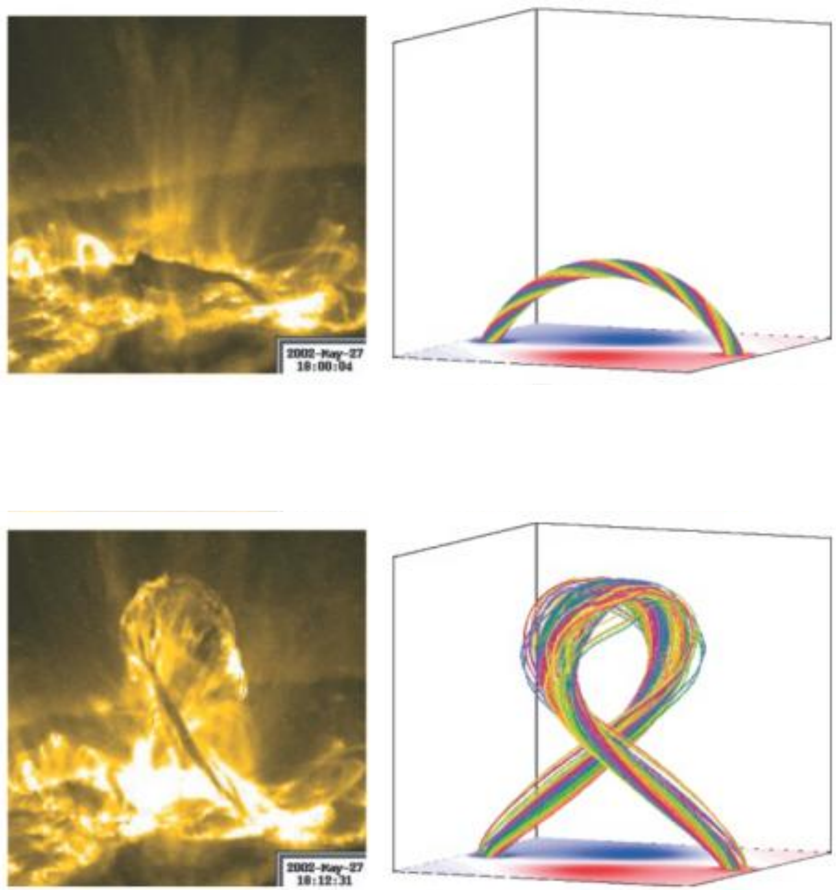
Ekman friction

Photosphere can be approximated as a two-dimensional system. Thickness ~ 500 km, Solar radius ~ 10^6 km.



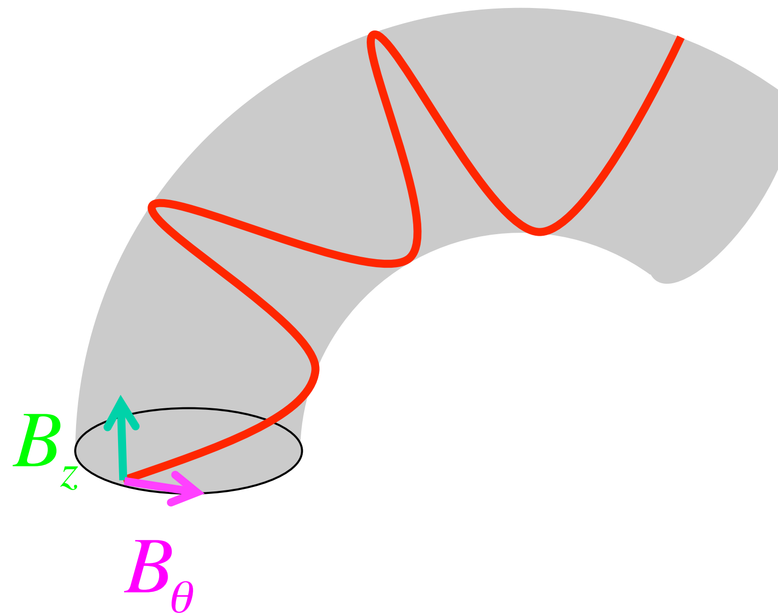
Abramenko, V. I. The Astrophysical Journal 629.2 (2005).
Mendoza, M., et al. *Nature communications* 5 (2014).

Kink Instability



Hanlon, Paul. Nature Physics (2005)

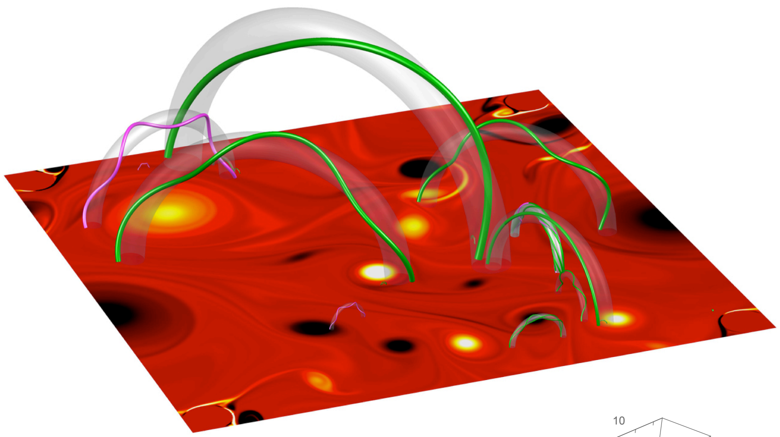
$$\phi = \frac{\pi R B_\theta}{r_c B_z}$$



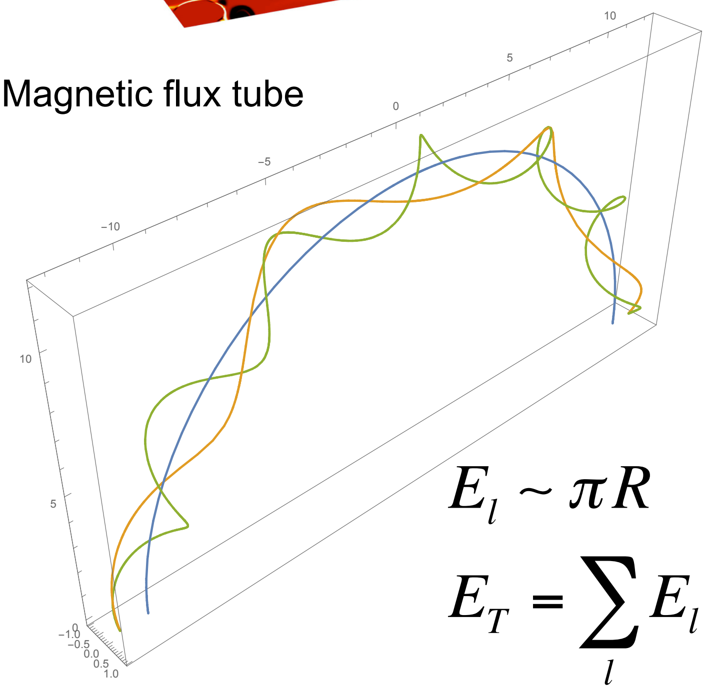
$$\boxed{\phi_c = 2\pi - 12\pi}$$

Török, T. & Kliem, B. *Astrophys. J. Lett.* **630**, L97 (2005).
Kliem, B., Titov, V. S. & Trk, T. *Astron. Astrophys.* **413**, (2004).

Model Description. Magnetic Flux Tubes



Magnetic flux tube



$$E_l \sim \pi R$$

$$E_T = \sum_l E_l$$

Due to the freezing of the magnetic flux tubes in the photospheric flow, we move the footprints according to:

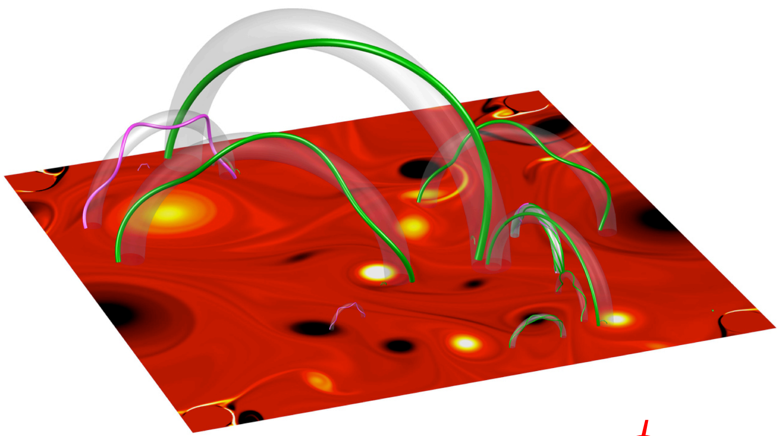
$$\vec{x}_\pm(t+\delta t) = \vec{x}_\pm(t) + \vec{u}(\vec{x}_\pm, t)\delta t$$

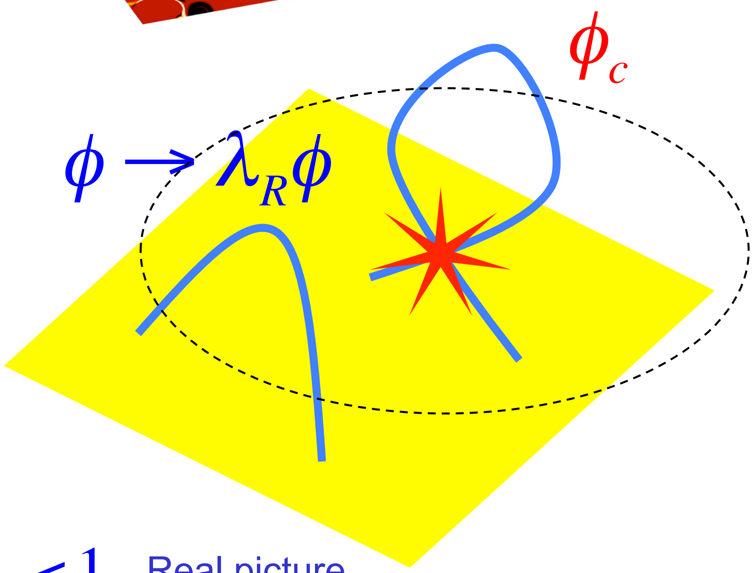
$$w_\pm(t+\delta t) = w_\pm(t) + \left(\nabla \times \vec{u}\right)_{z;\ (\vec{x}_\pm, t)} \delta t$$

$$\phi = \frac{\pi R(w_+ + w_-)}{2r_c + R}$$

Mendoza, M., et al. *Nature communications* 5 (2014).

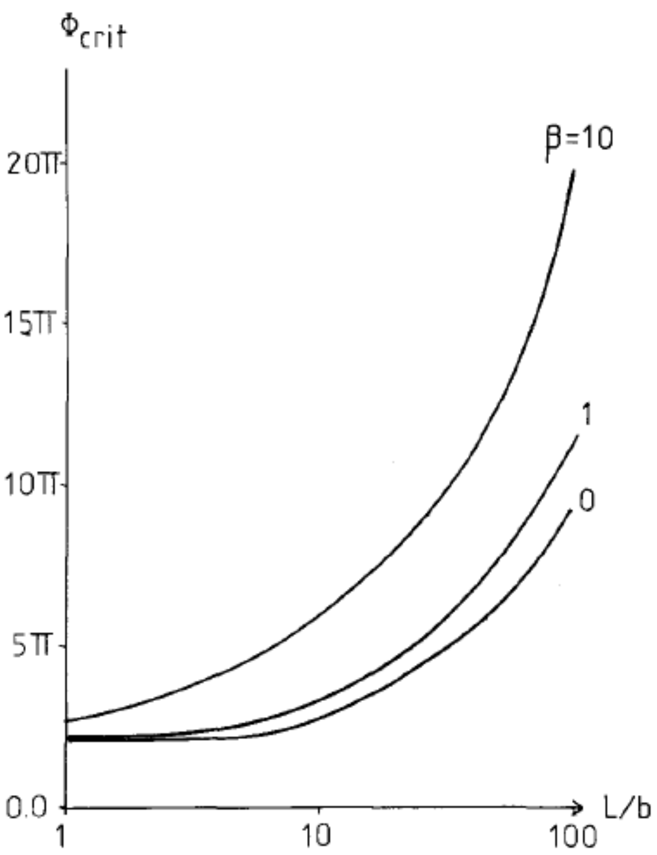
Model Description. Loop Interaction





$\lambda_R < 1$ Real picture

$\lambda_R > 1$ Avalanching process: SOC



Hood, A. W., and E. R. Priest. *solar physics* 64.2 (1979)
Mendoza, M., et al. *Nature communications* 5 (2014).

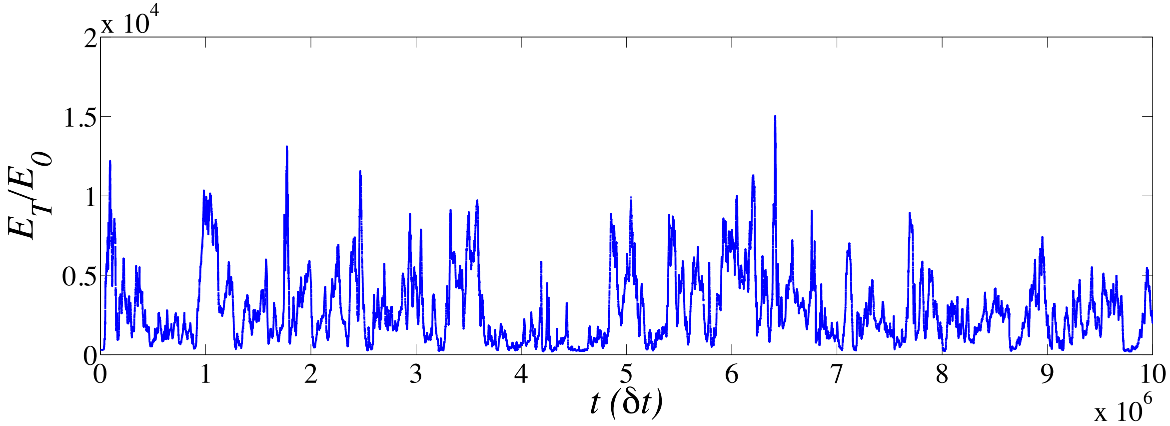
Simulation Parameters and Total Energy

L	Re	N	N_e
128	9×10^3	100	200000
256	1.7×10^4	200	200000
512	3.5×10^4	400	200000
1024	6.0×10^4	800	175100
2048	1.1×10^5	1600	150000

Simulation parameters

$$\tau = \frac{1}{2} + 0.003 \quad \rightarrow \quad \nu \approx 10^{-3}$$

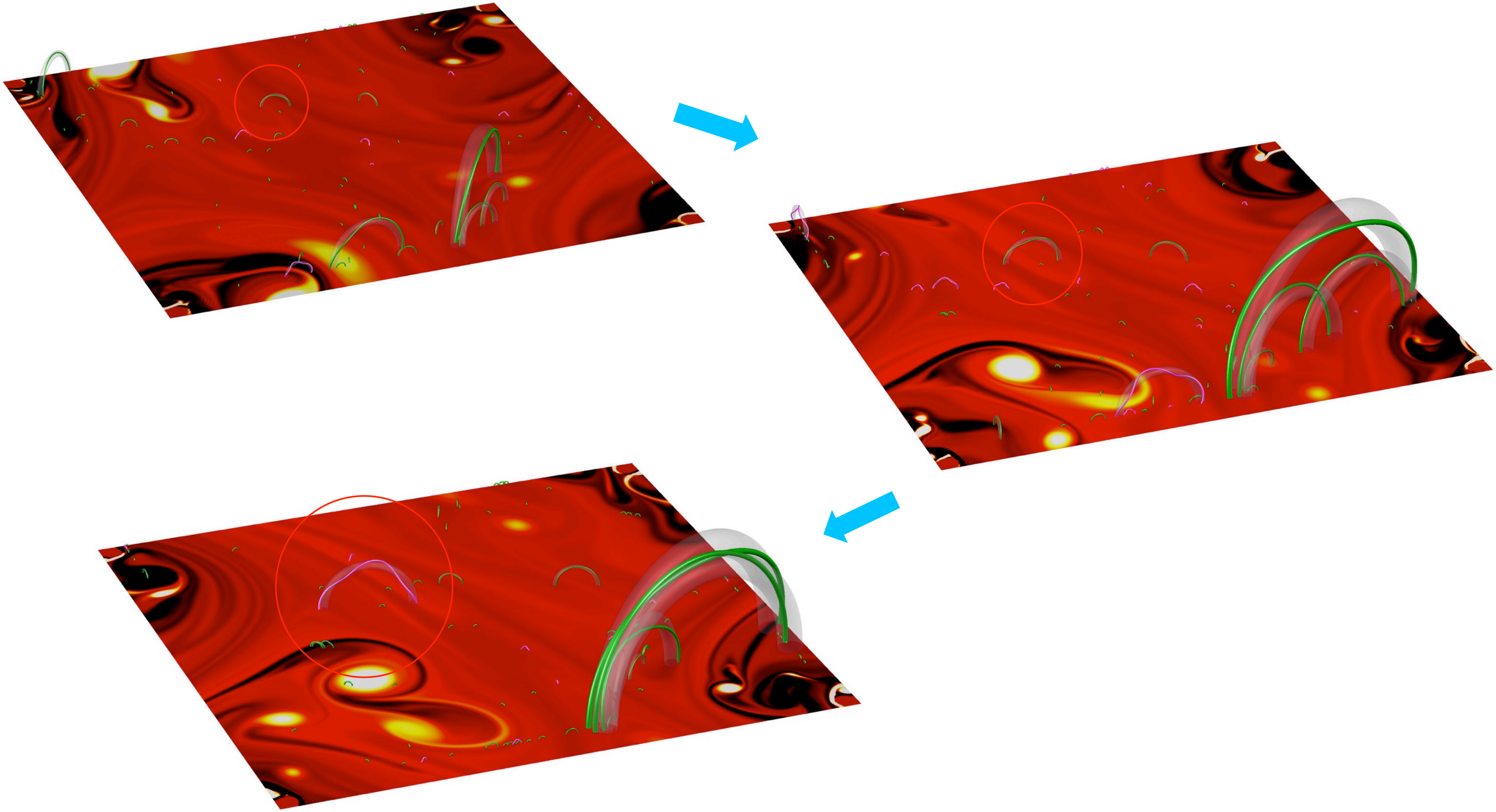
$$\mathrm{Re} = \frac{u_{rms} L}{\nu}$$



Total Magnetic Energy

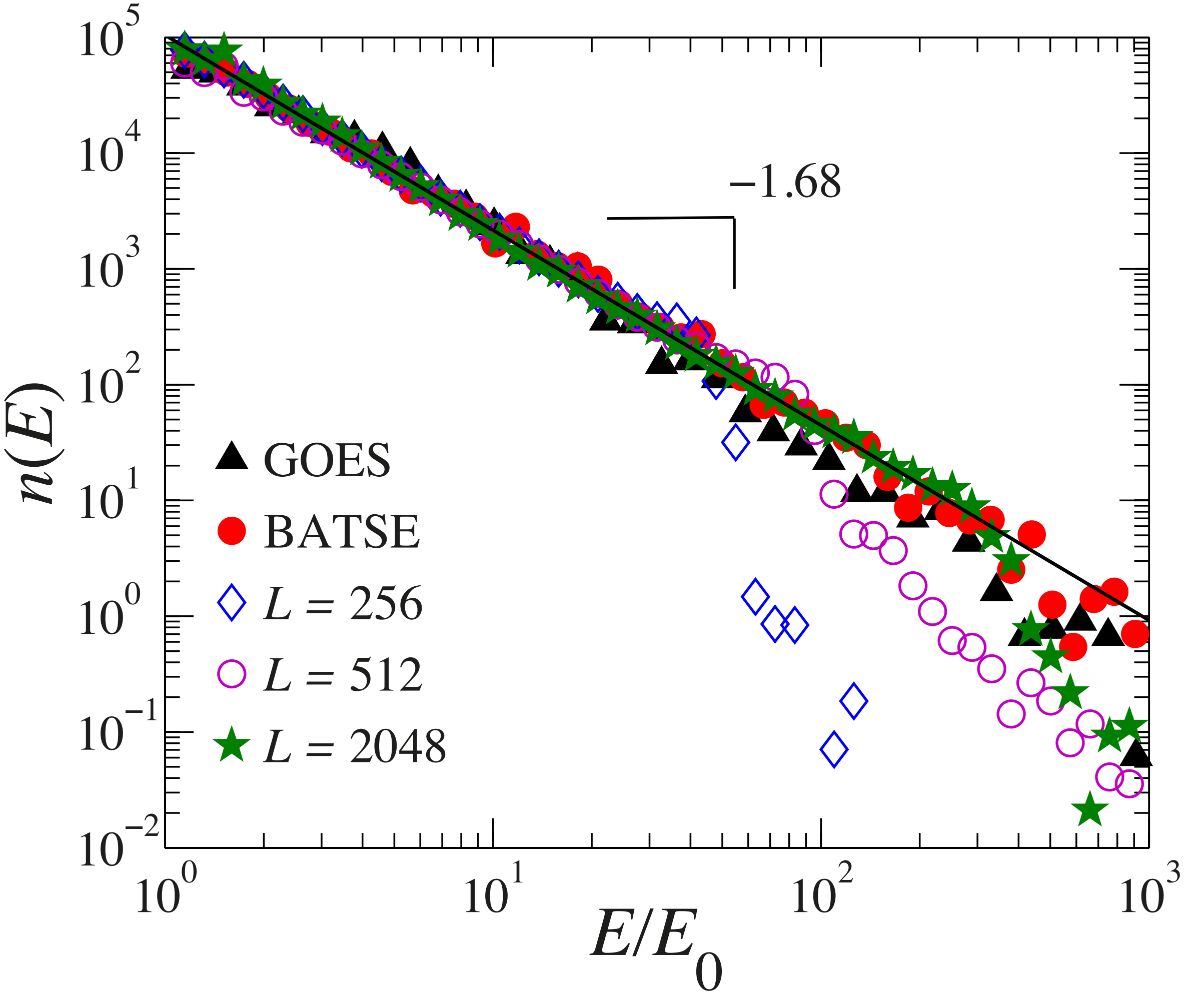
Mendoza, M., et al. *Nature communications* 5 (2014).

Simulation Results



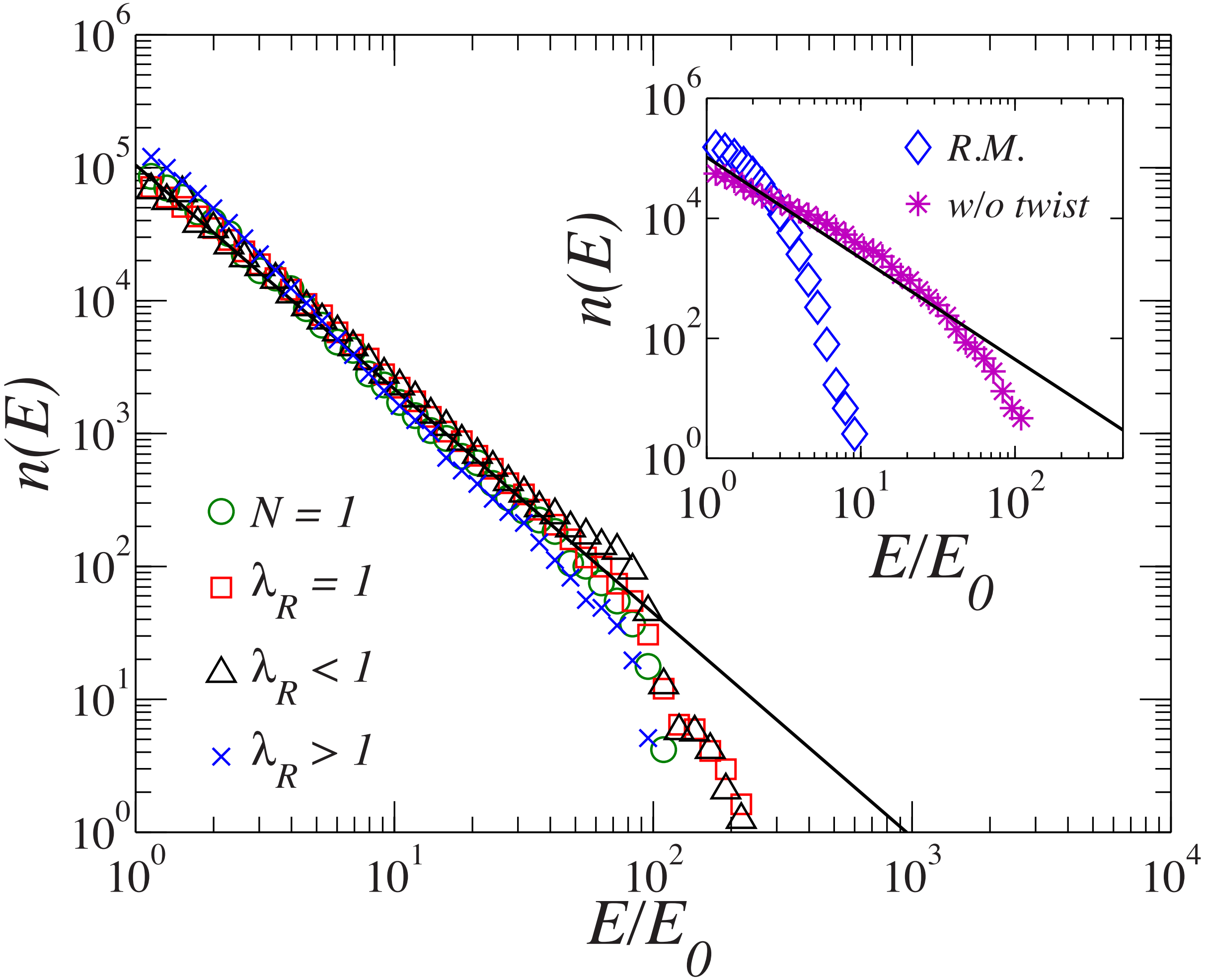
Mendoza, M., et al. *Nature communications* 5 (2014).

Energy Distribution of Flares



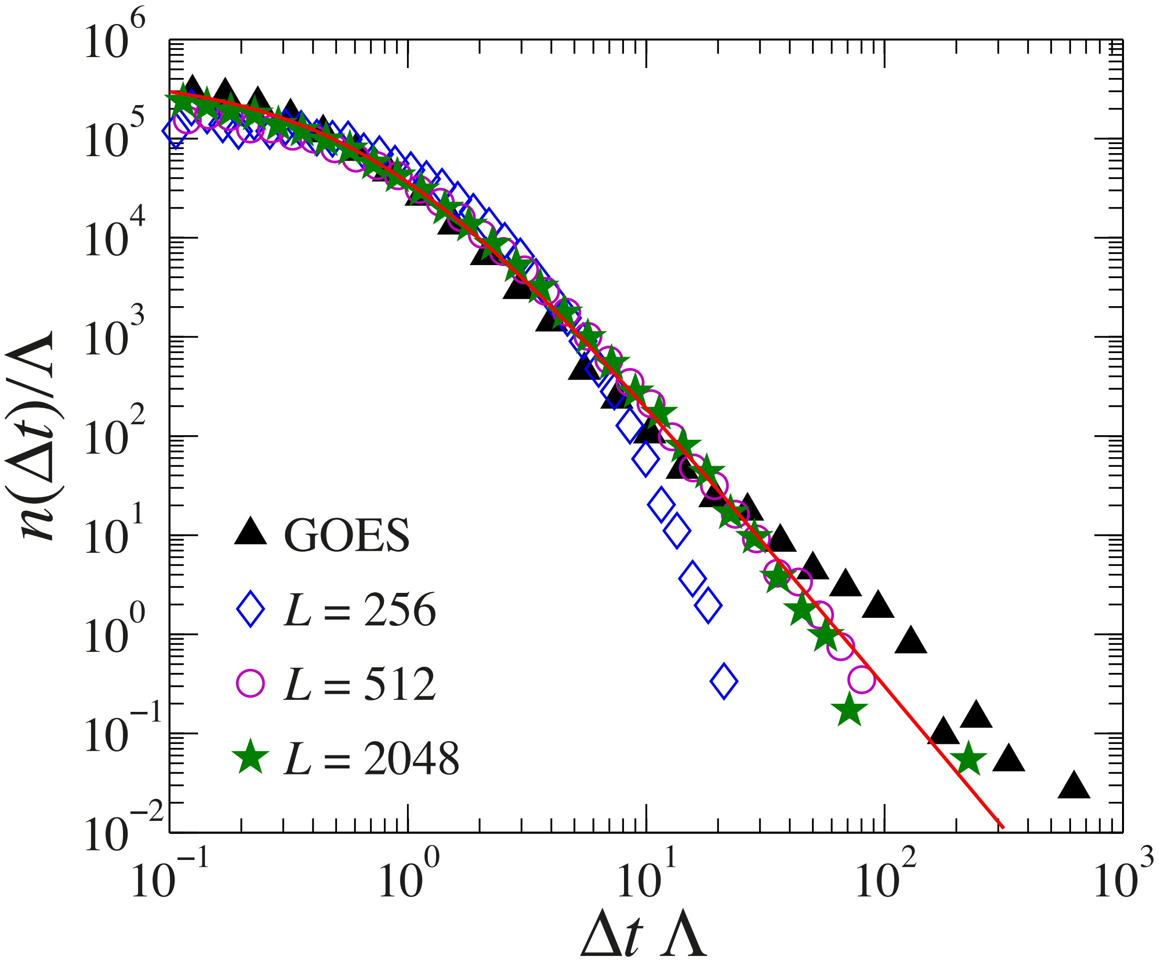
Mendoza, M., et al. *Nature communications* 5 (2014).

Energy Distribution: A closer look



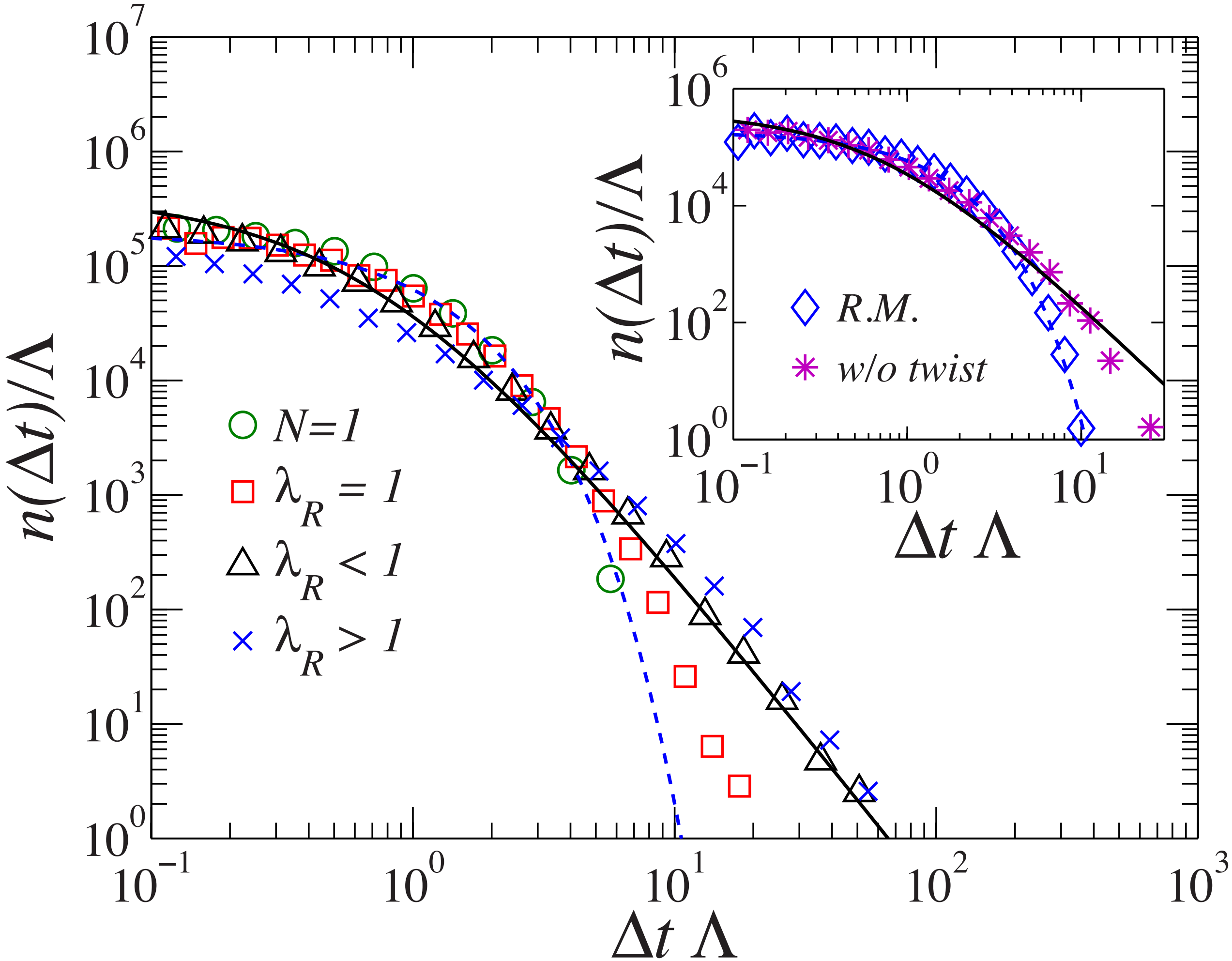
Mendoza, M., et al. *Nature communications* 5 (2014).

Inter-time Distribution of Flares



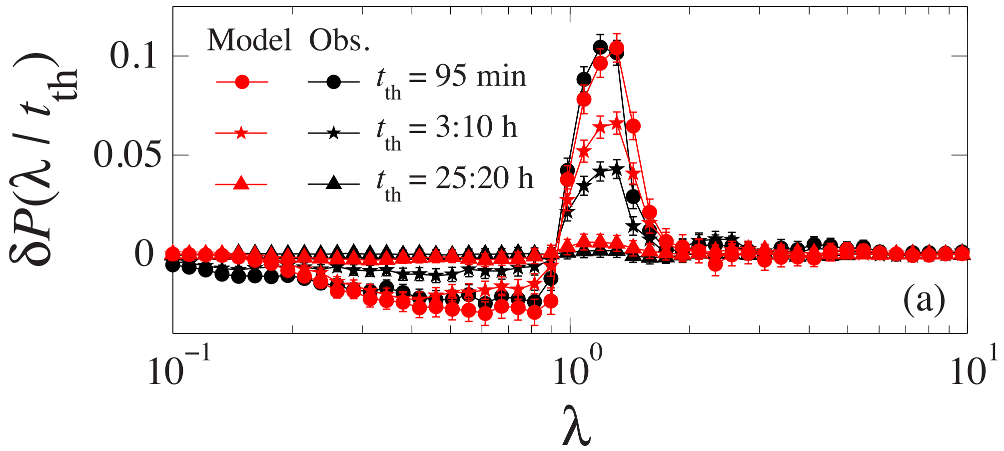
Mendoza, M., et al. *Nature communications* 5 (2014).

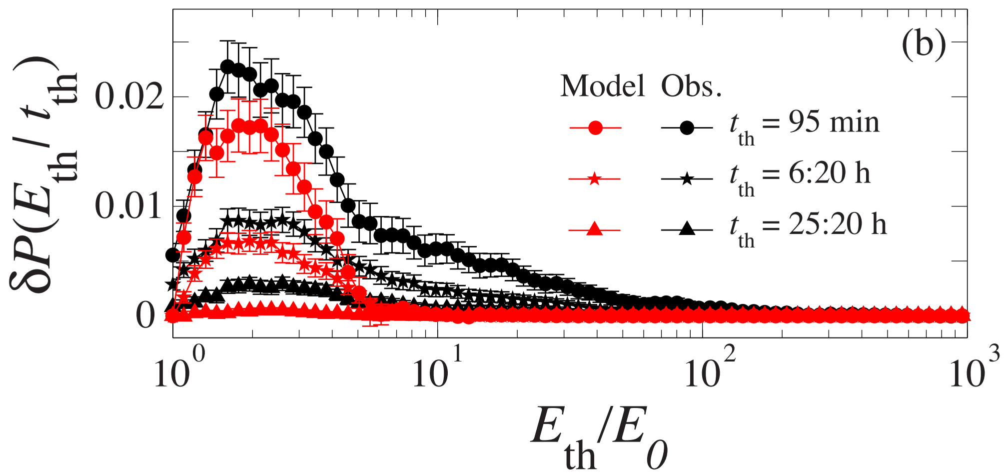
Inter-time Distribution: A closer look



Mendoza, M., et al. *Nature communications* 5 (2014).

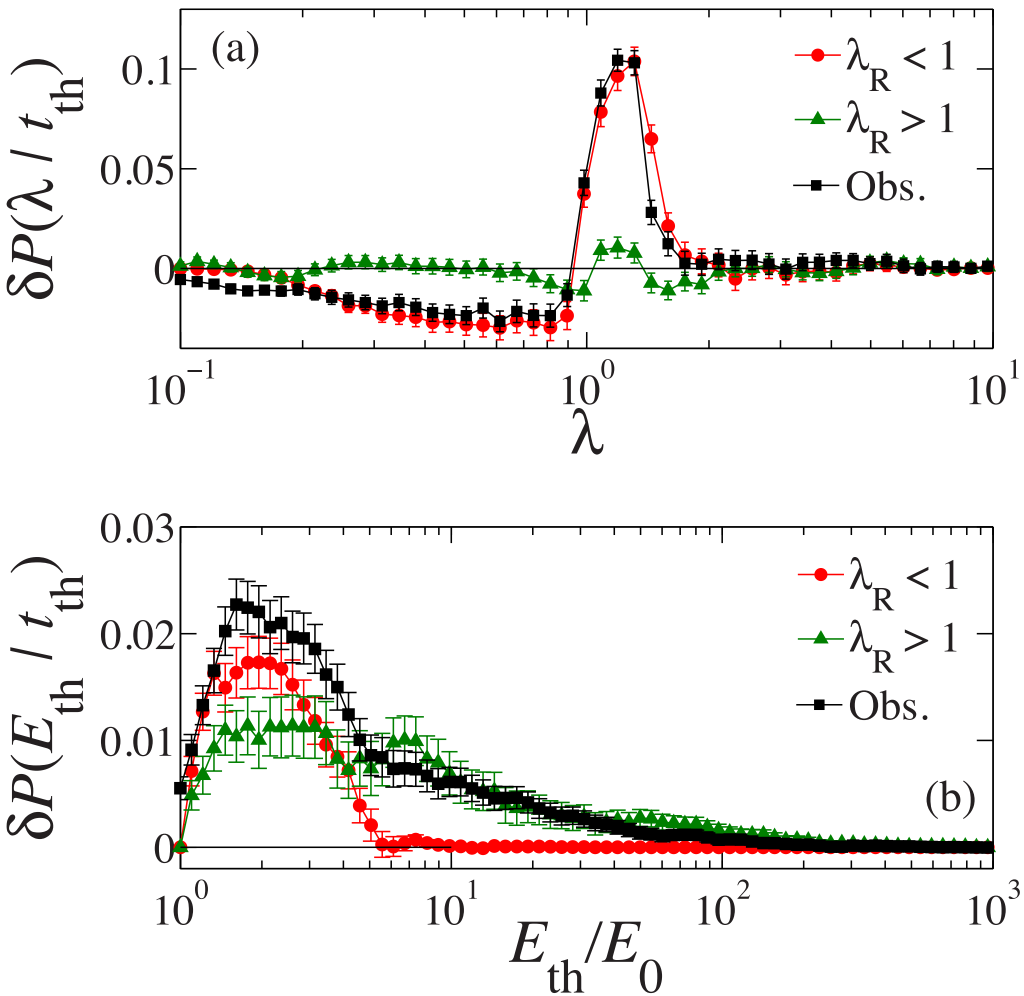
Energy-Time Correlations





Mendoza, M., et al. *Nature communications* 5 (2014).

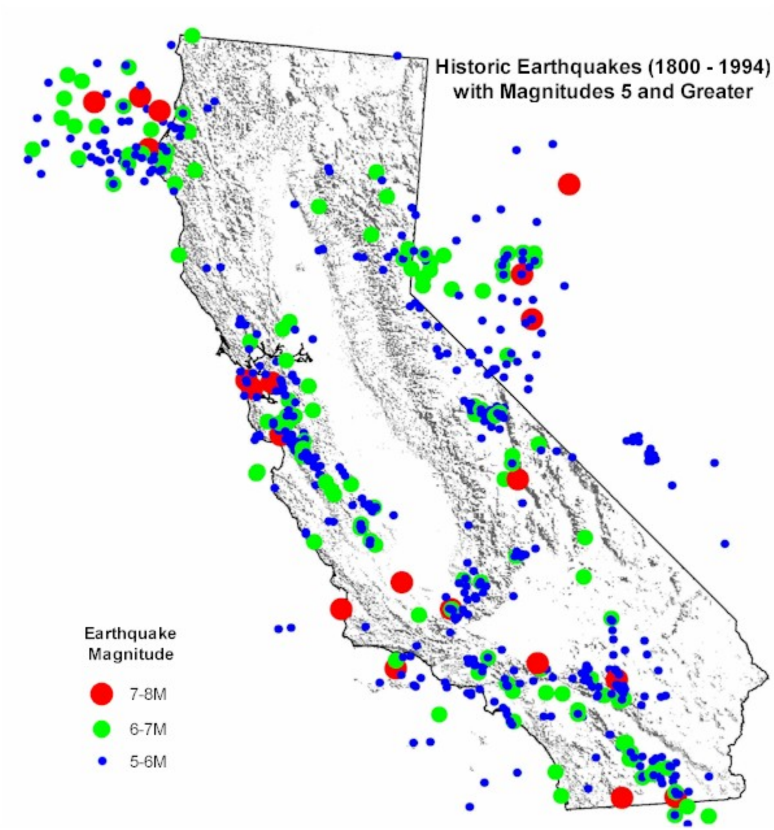
Energy-Time Correlations. A closer look

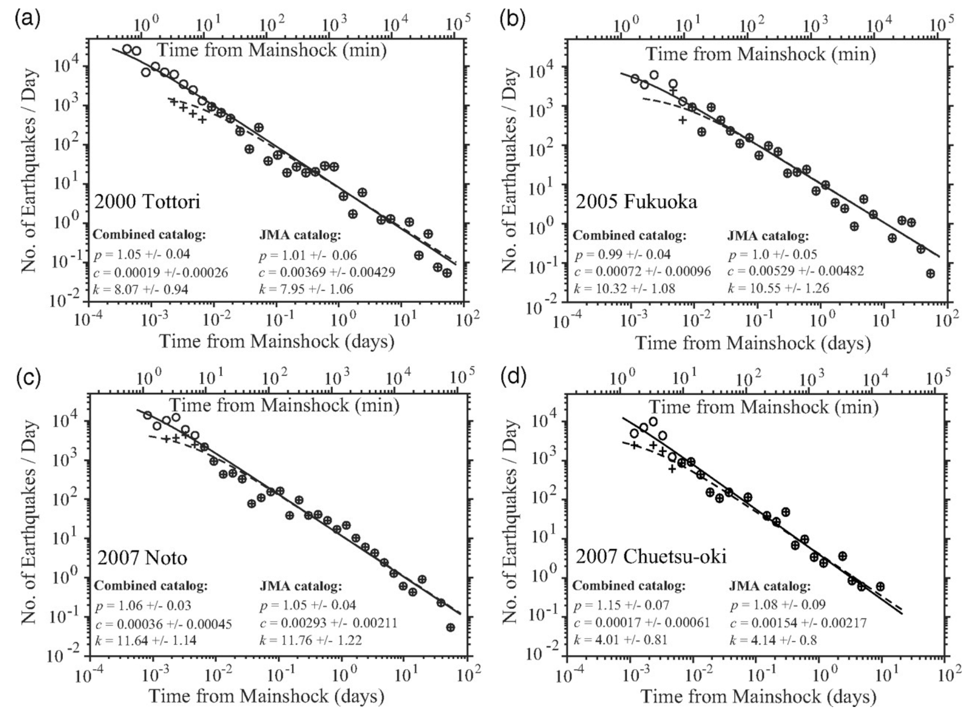


Mendoza, M., et al. *Nature communications* 5 (2014).

Omori's law in Earthquakes

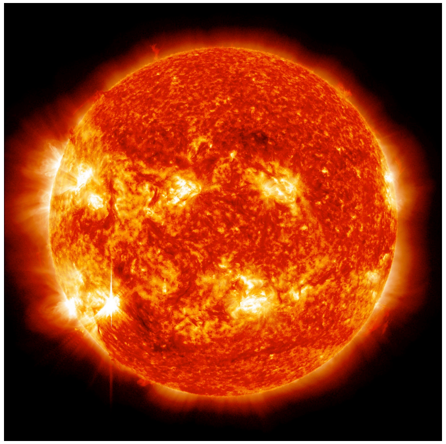
$$n(t) = \frac{A}{(t+c)^{\alpha}}$$





Bulletin of the Seismological Society of America April 2009 vol. 99 no. 2A 884-891

Omori's law for Solar flares



No declustering: We do not know where main flares occur!!

Assuming:

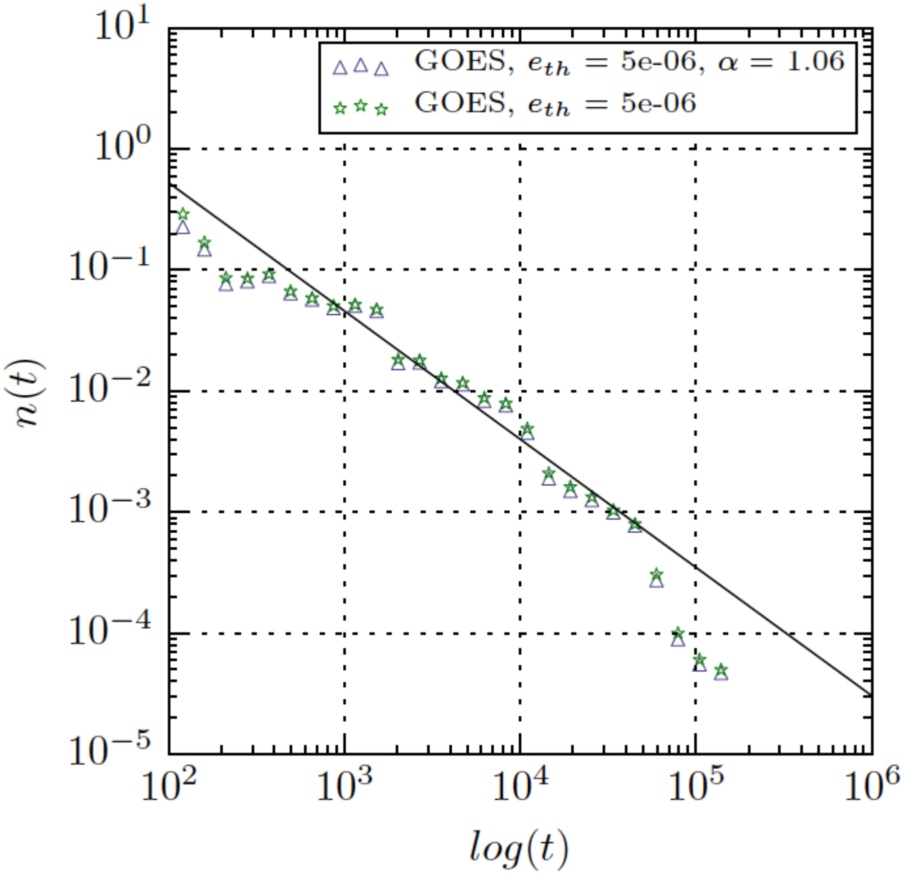
$$n(t) = \frac{A}{t^{\alpha}}$$

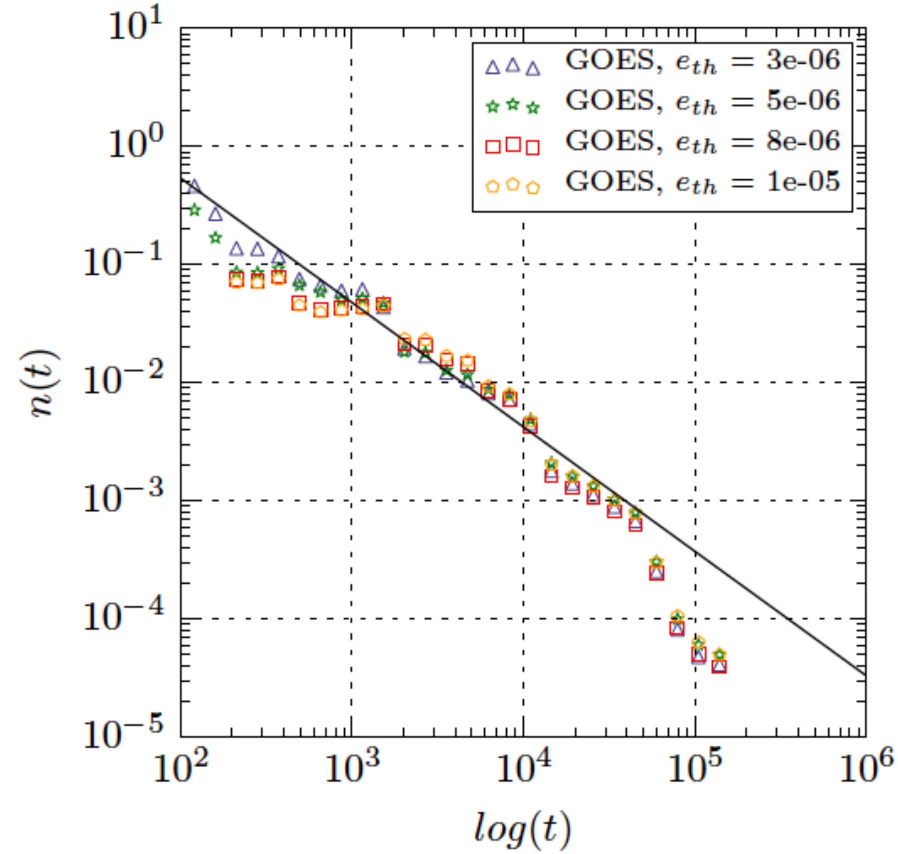
$$N_i(t) = \frac{A}{(t-t_i)^{\alpha-1}}\Theta(t-t_i)$$

$$N_T(t) = \sum_i \frac{A}{(t-t_i)^{\alpha-1}}\Theta(t-t_i) = n(t)\sum_i \frac{1}{t\left(1-t_i/t\right)^{\alpha-1}}\Theta(t-t_i)$$

$$n(t) = \frac{N_T(t)}{t\sum_i \left(1-t_i/t\right)^{1-\alpha}\Theta(t-t_i)} \approx \frac{N_T(t)}{t\sum_i \Theta(t-t_i)}$$

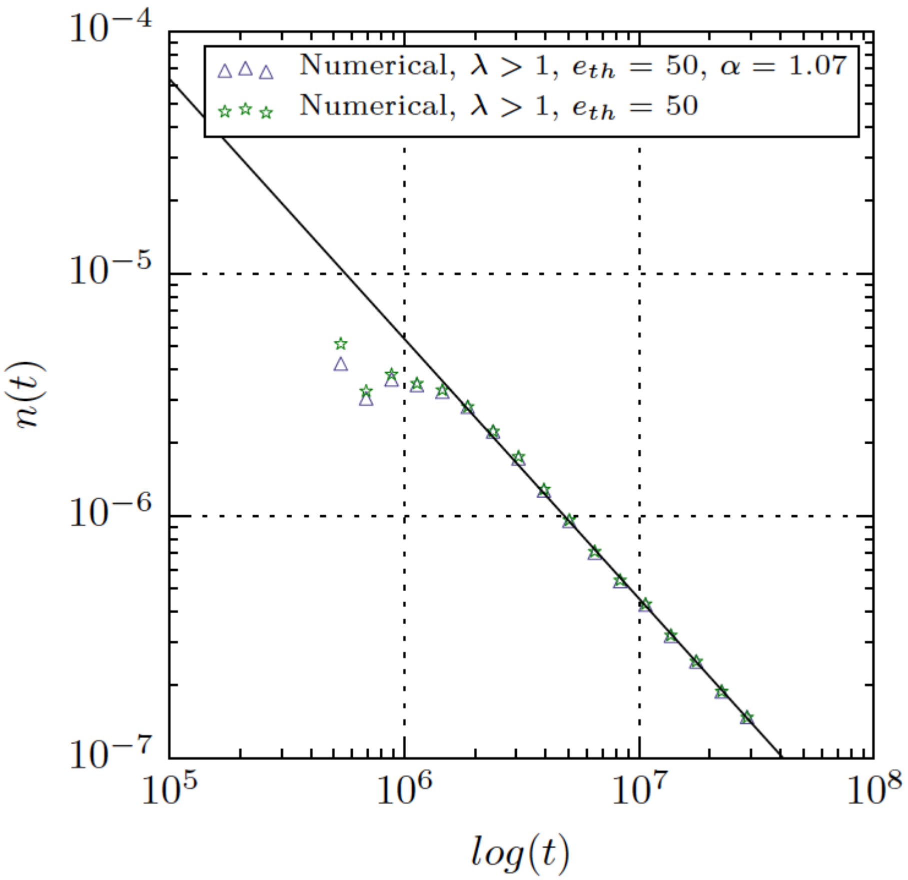
Omori's law for Solar flares

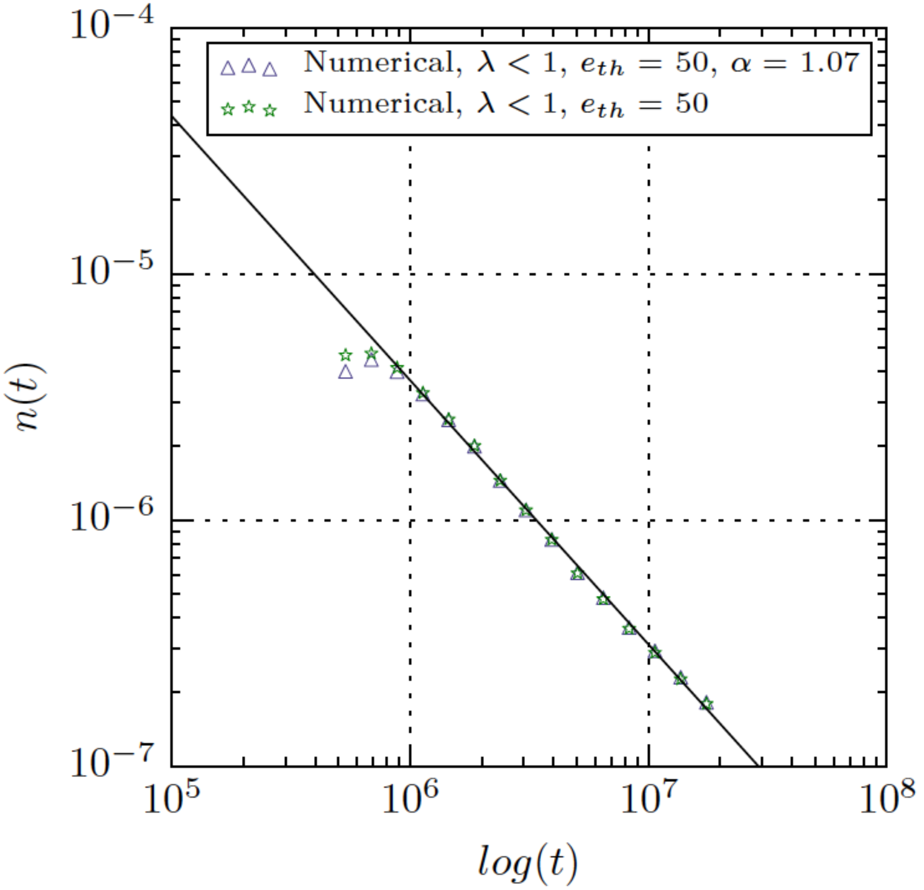




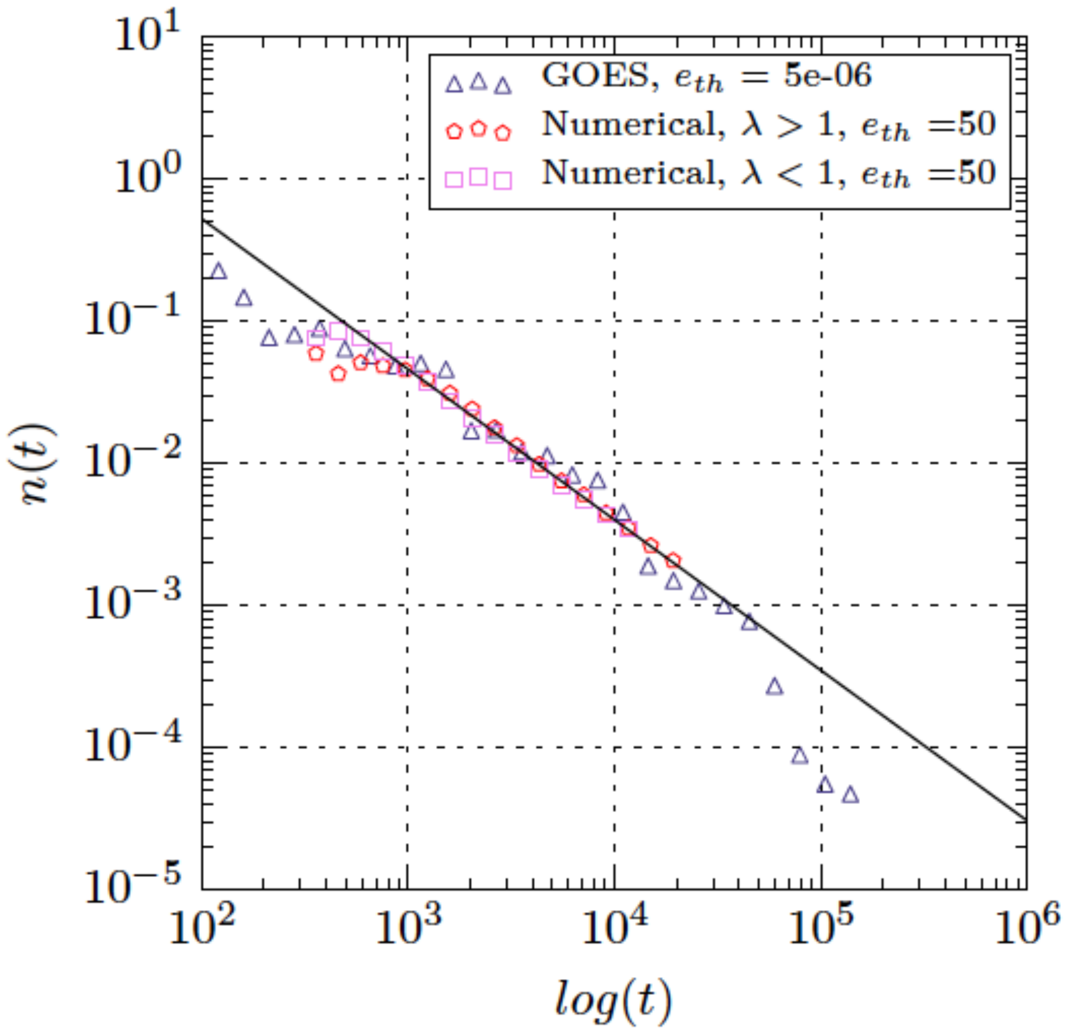
Units:
Energy: W/m^2
Time: Hours

Omori's law for Numerical Catalogues

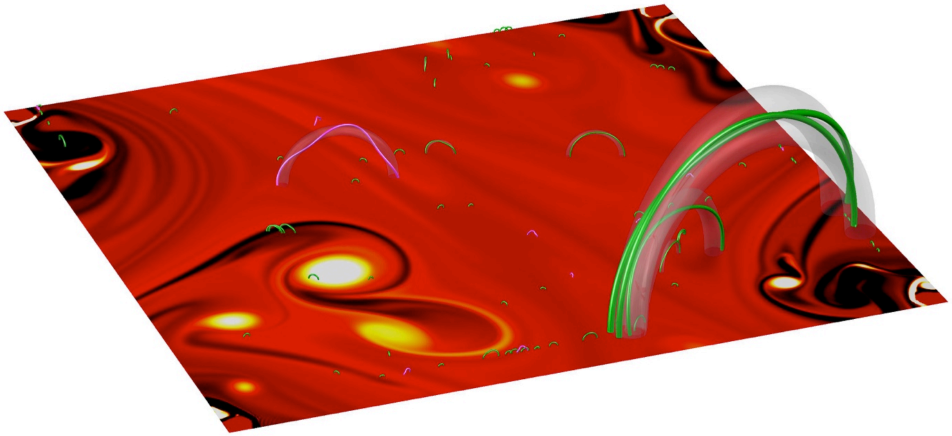




Omori's law all together



Numerical Catalogues: One step forward



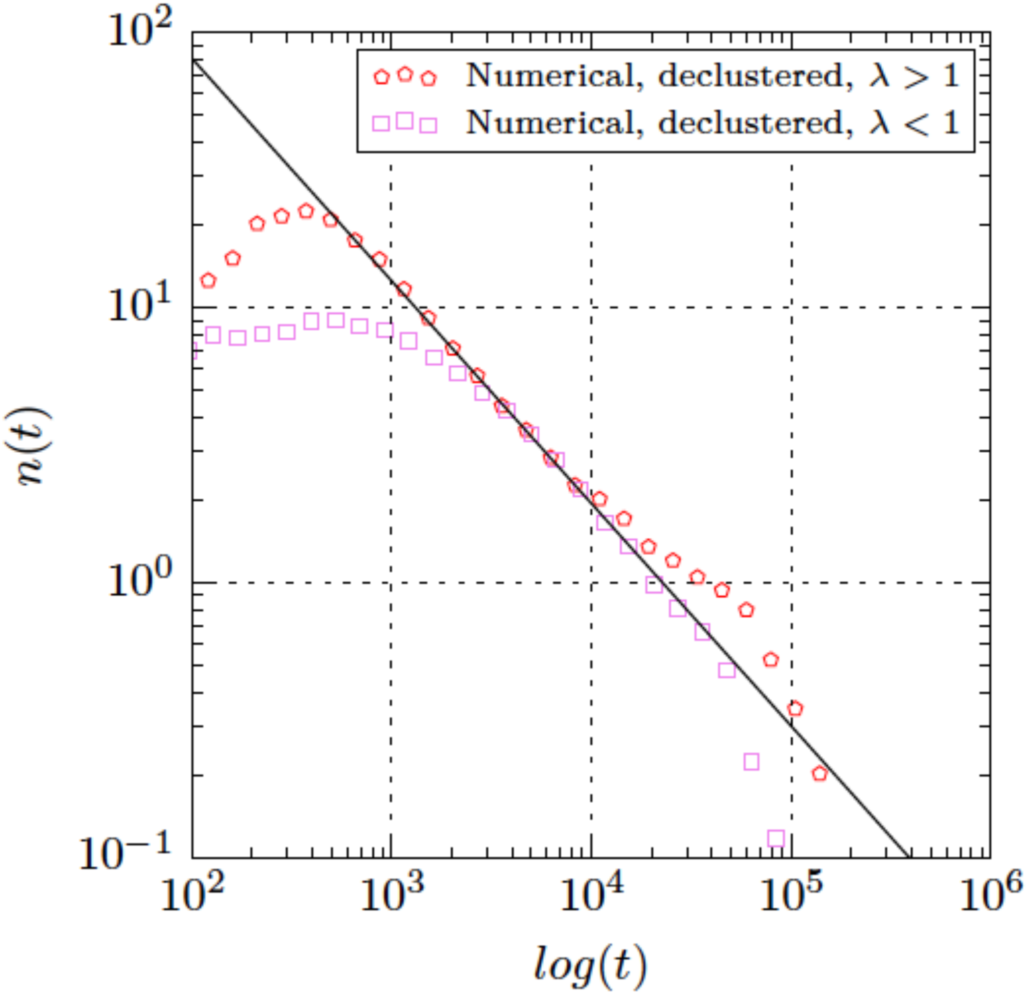
Main Event

After-event

After-event

After-after-event

Omori's law for declustered catalogues



$$\alpha = 0.81 \pm 0.01$$

Summary

1. Turbulence is the responsible for the scale free energy distribution of solar flares.

2. Loop-Loop interactions are responsible for the inter-time distribution.

3. Energy-time correlations are recovered due to loop-loop interaction and turbulence.

4. It is the first model capable to describe in good agreement the full statistics of solar flares, and suggest that SOC might not be the main leading mechanism in flare emission.

5. Omori's law for earthquakes is also recovered. Although when one performs a declustering of the data, one finds a different exponent.

6. Based on our results, we make a step forward into the prediction of solar flares.

Thank you for your attention!