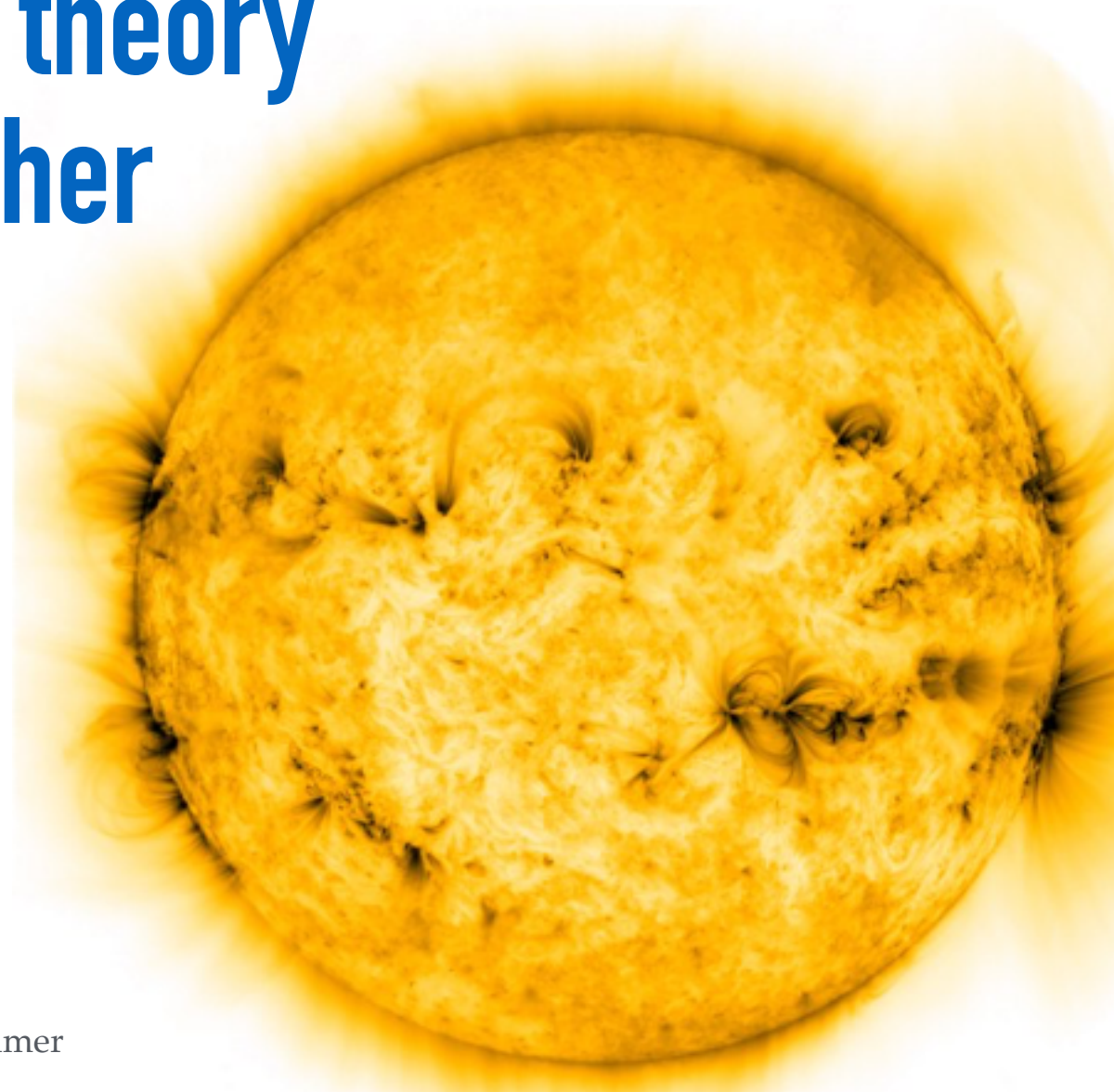
Solar and stellar magnetism:

From dynamo theory to space weather

Antoine Strugarek

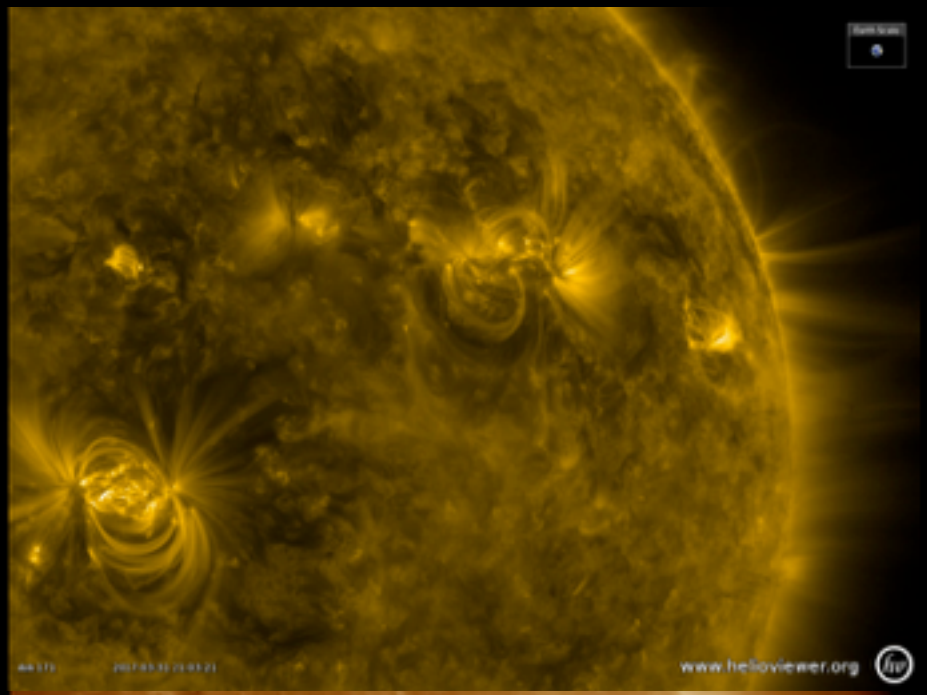


With P. Beaudoin, R. Barnabé, A.S. Brun,
P. Charbonneau, J. Do Nacimento Jr,
V. Réville, S. Matt, P. Smolarkiewicz, N. Vilmer

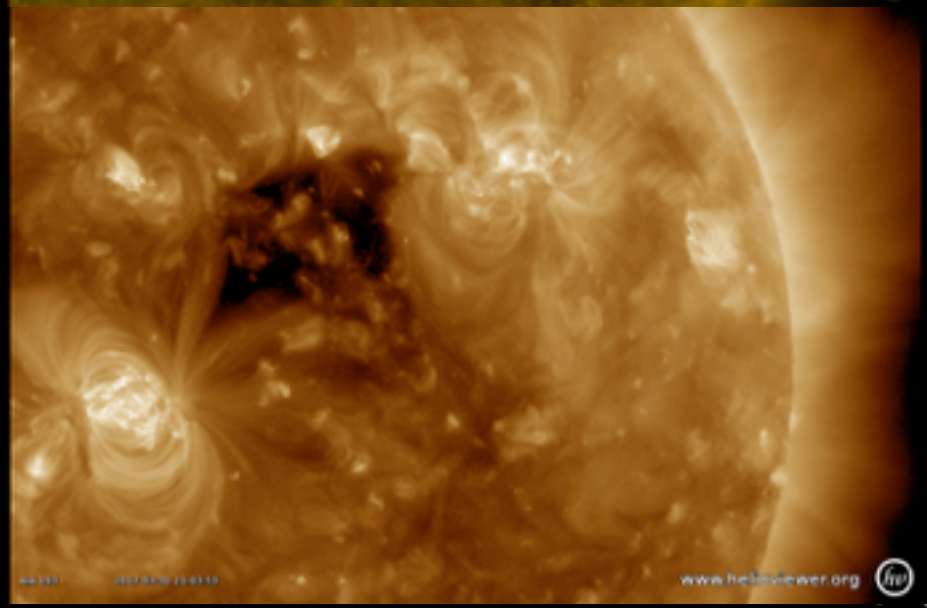
Understanding couplings in stellar systems

Manifestations of solar magnetism: solar flares (April 1st 2017)

AIA 171
$6\ 10^5$ K



AIA 193
10^6 K



Manifestations of solar magnetism: solar flares (April 1st 2017)

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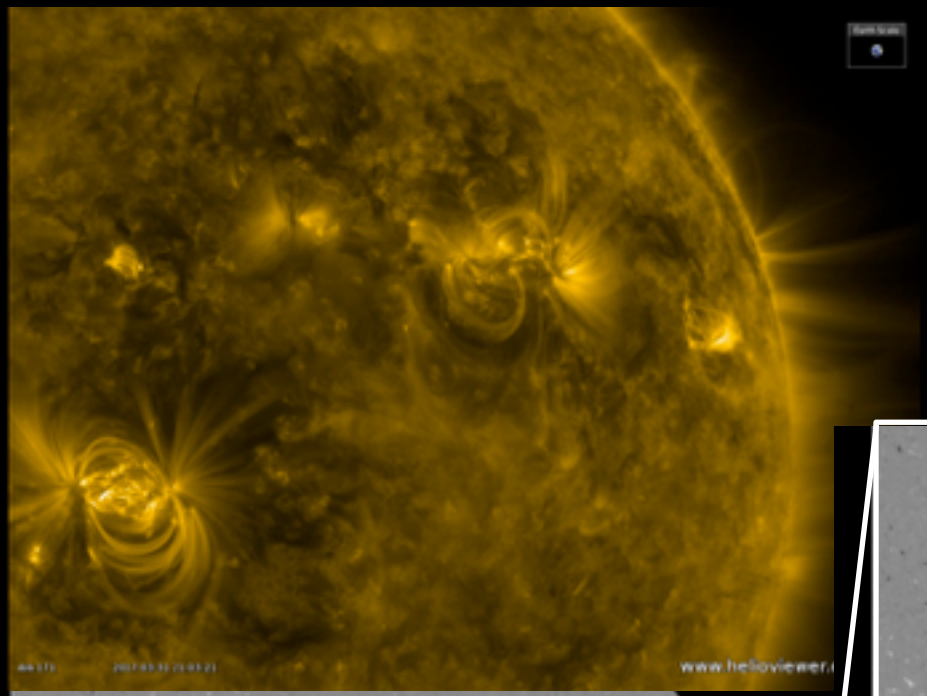
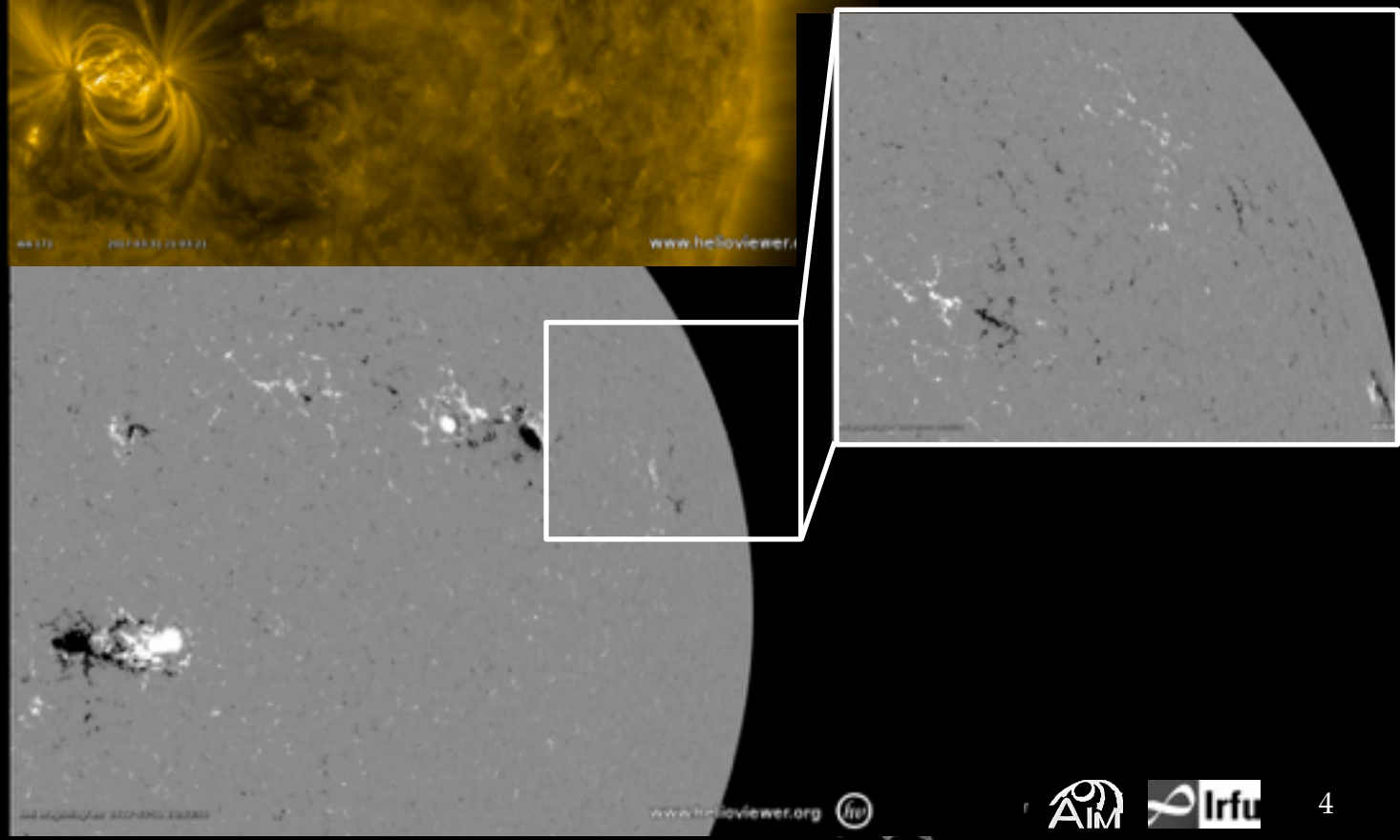
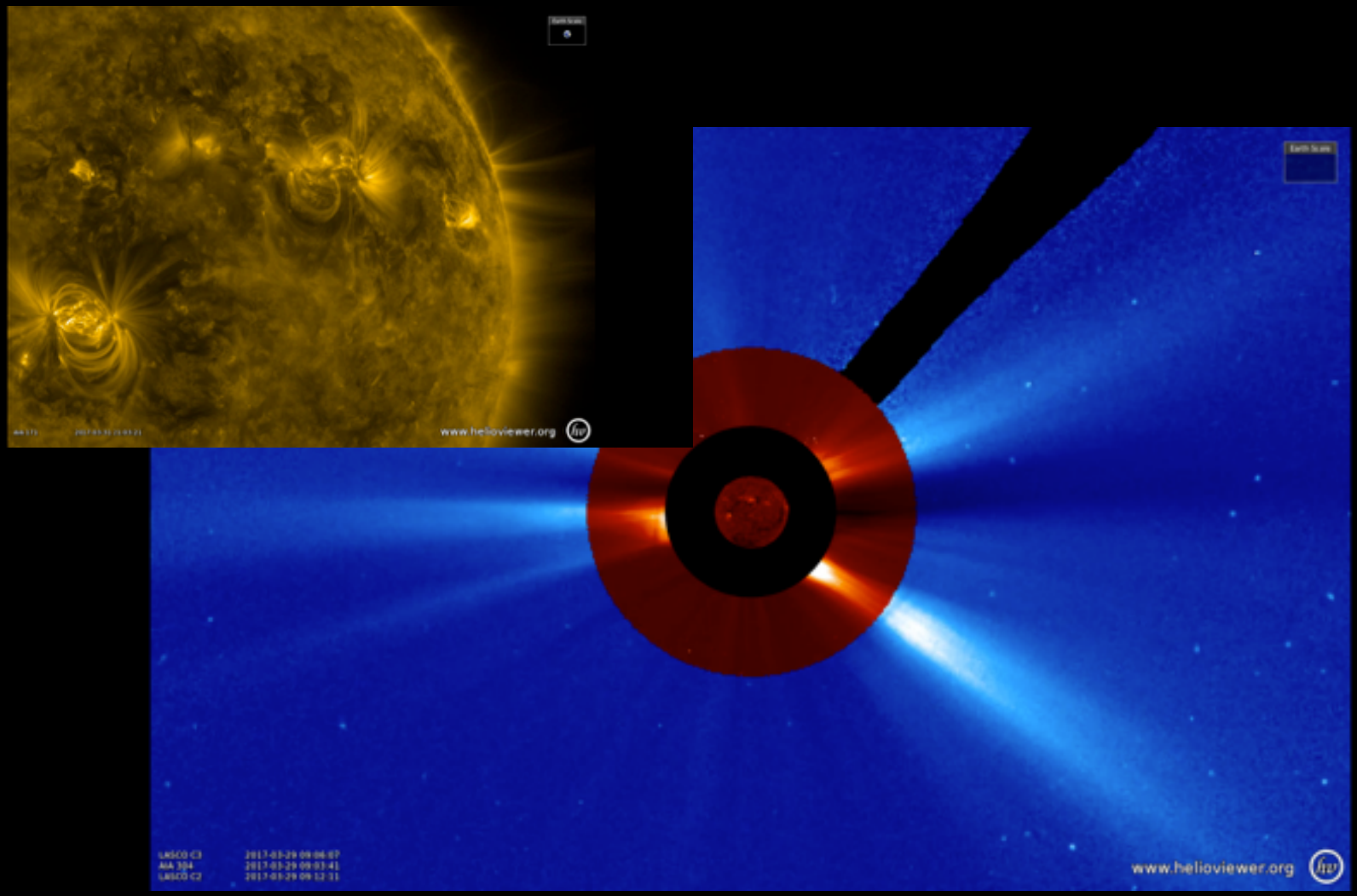


Magnetogram

White/black = mag. polarity

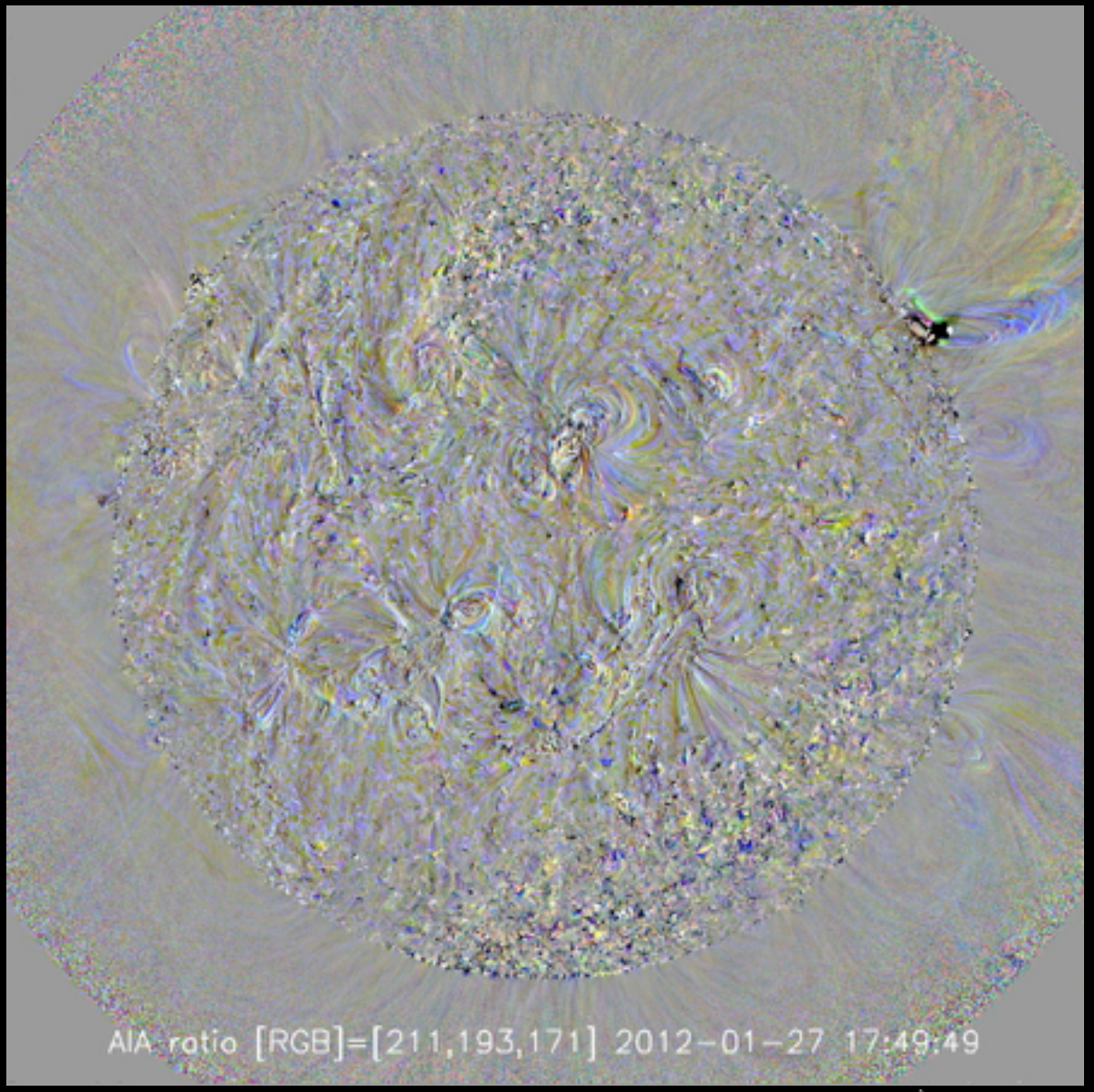


Manifestations of solar magnetism: solar flares (April 1st 2017)

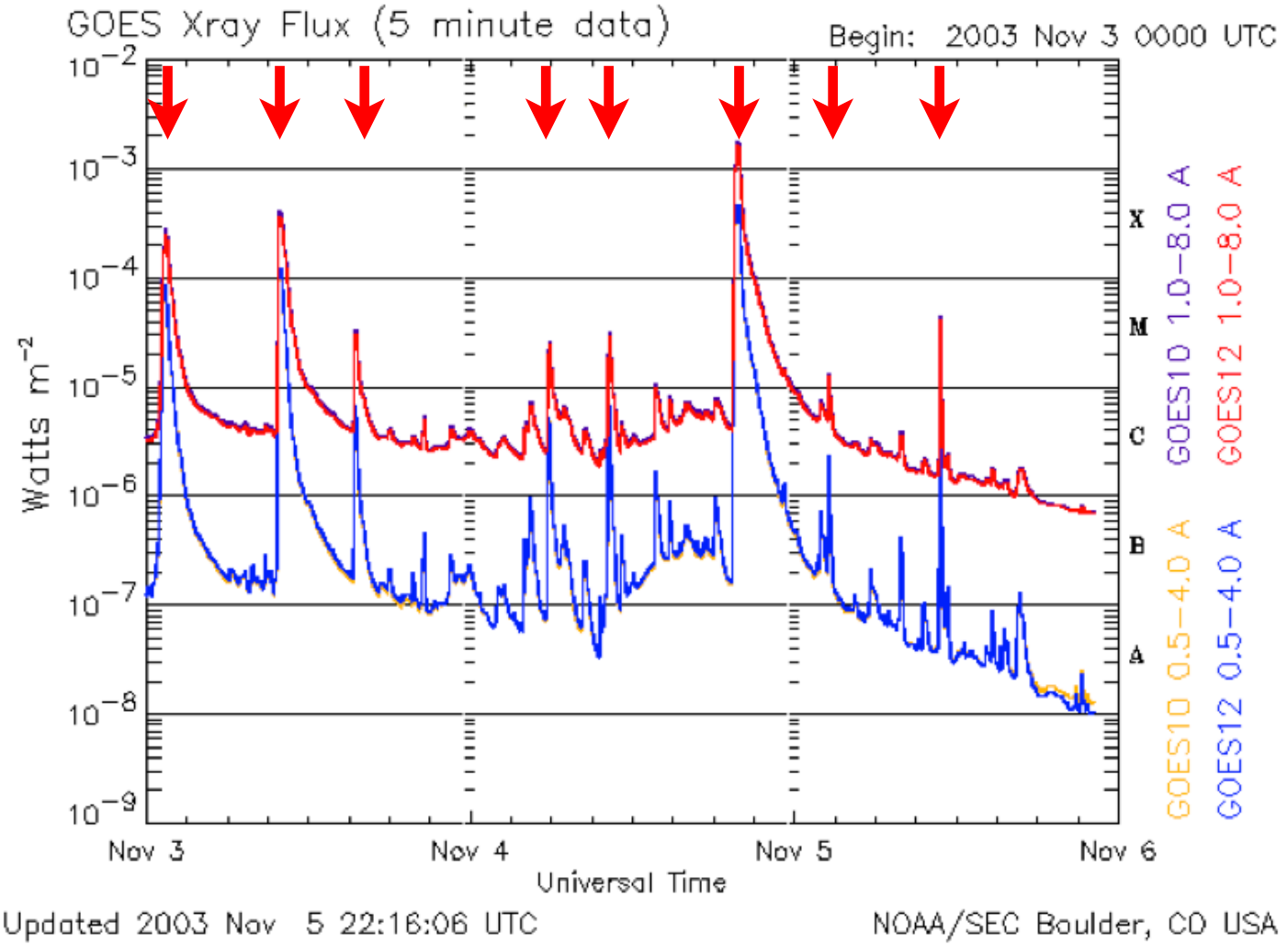


View of the solar corona

Coronal mass ejections and sympathetic flares



Detection of solar flares in X-rays

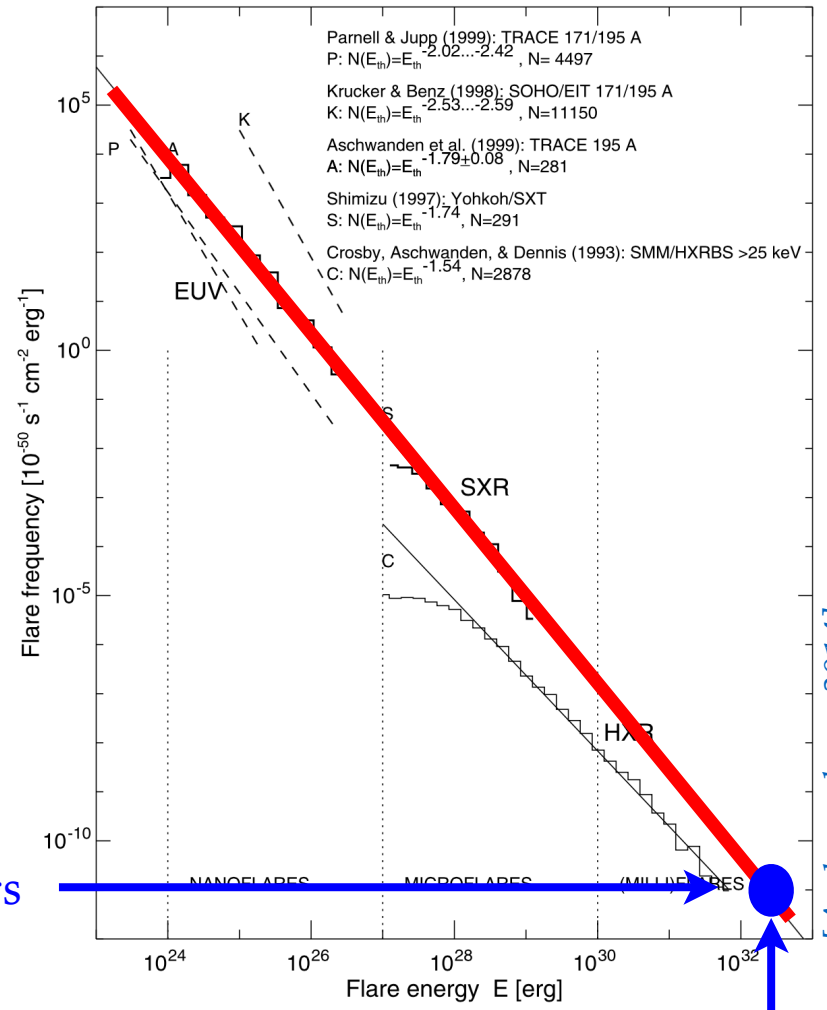


Flare classification and statistics

[Bhatnagar & Livingston 2005]

Hα classification			Radio flux at 5000 MHz in s.f.u.	Soft X-ray class	
Importance Class	Area (Sq. Deg.)	Area 10^{-6} solar disk		Importance class	Peak flux in 1-8 Å w/m^2
S	2.0	200	5	A	10^{-8} to 10^{-7}
1	2.0–5.1	200–500	30	B	10^{-7} to 10^{-6}
2	5.2–12.4	500–1200	300	C	10^{-6} to 10^{-5}
3	12.5–24.7	1200–2400	3000	M	10^{-5} to 10^{-4}
4	>24.7	>2400	3000	X	>10^{-4}

1 s.f.u. = 10^4 jansky = 10^{-2} W m^{-2} Hz^{-1}



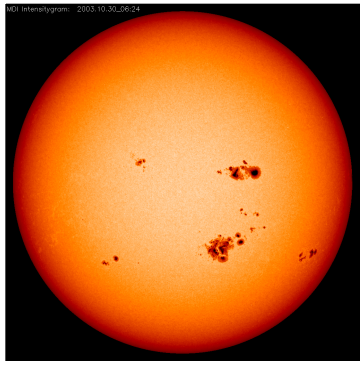
[Aschwanden+, 2014]

Largest recorded solar flare is of class >X10
('Carrington event' in 1859) ~ 1 in 100 years

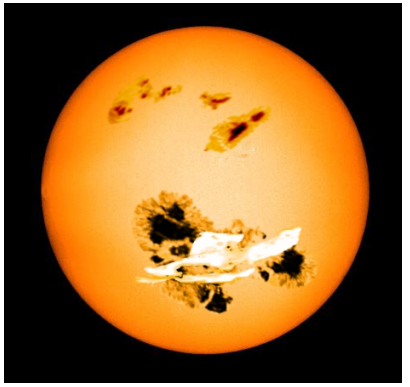
Largest solar flare to date ~ 10^{32}-10^{33} ergs

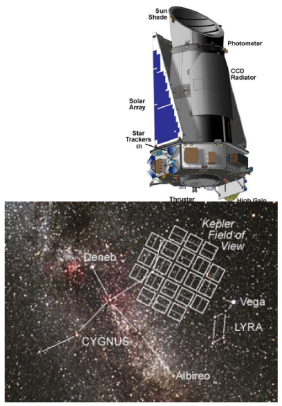
Super-flares on other solar-type stars with Kepler

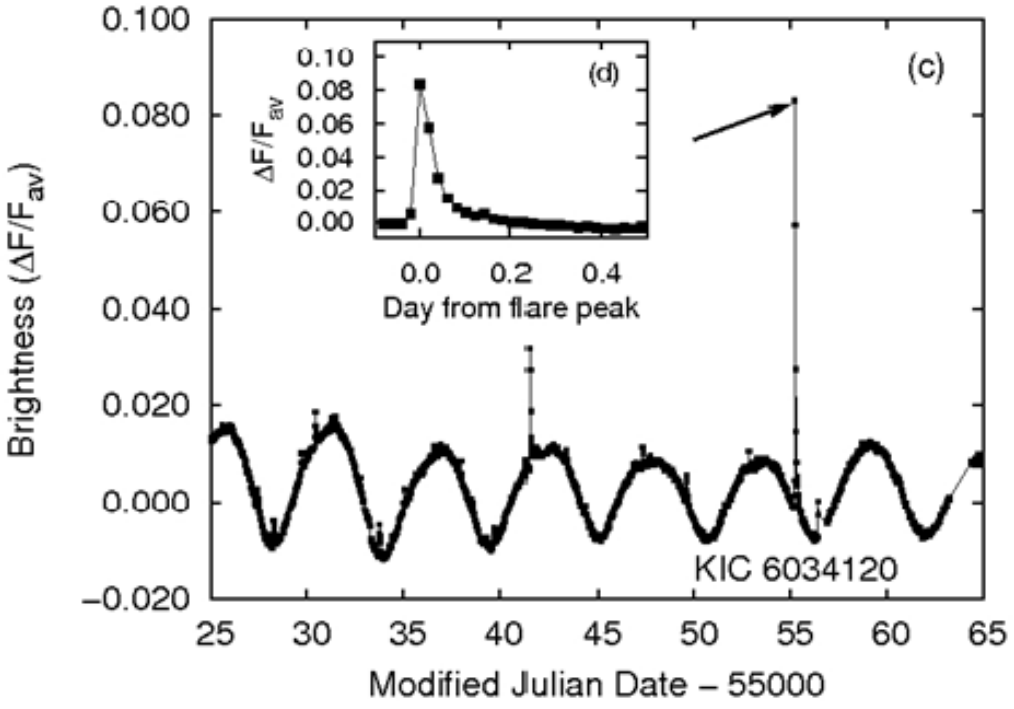
Active Sun



Super-active star
(artist view)







Total energy
~ 3x10^{35} erg !!
(> by three orders of magnitude than Carrington event)

[Mahera+ 2012]

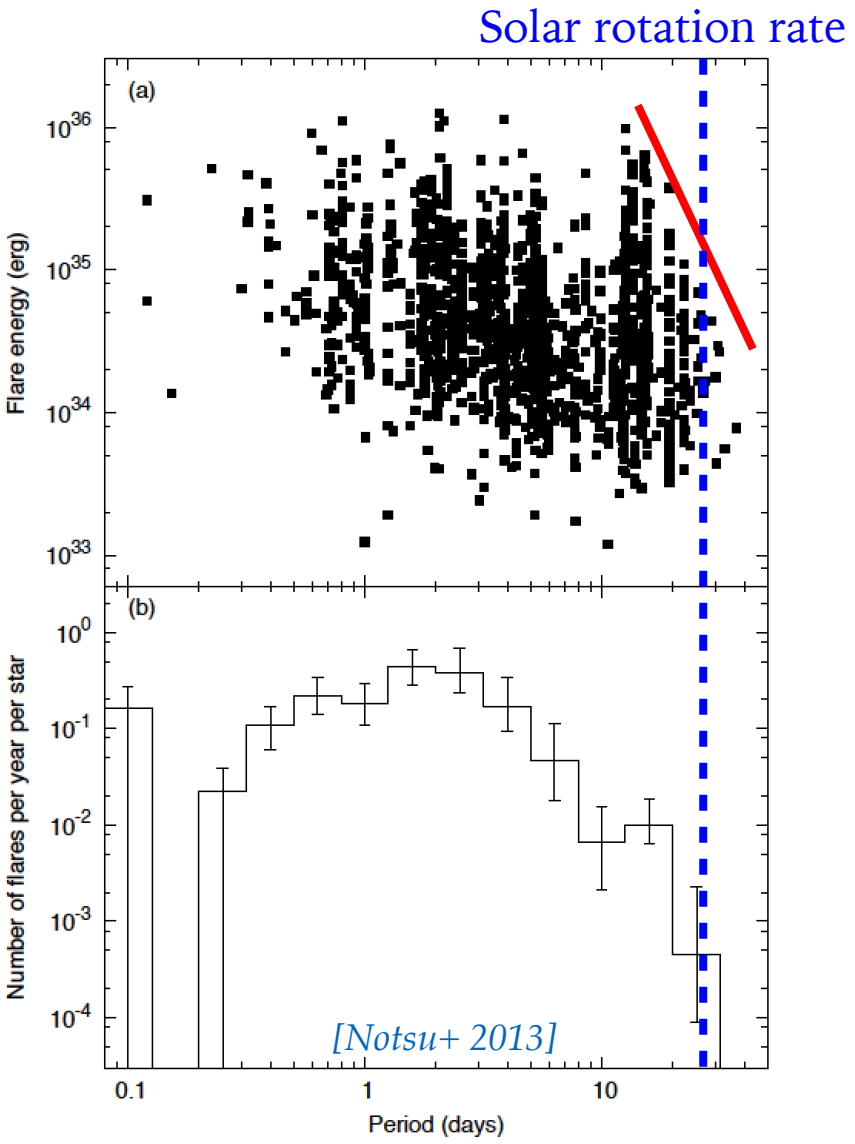
Super-flares on other solar-type stars with Kepler

Kepler found 365 super flares (10^{33} - 10^{36} ergs) on 148 solar-type stars (sample of ~83000), including slowly rotating stars

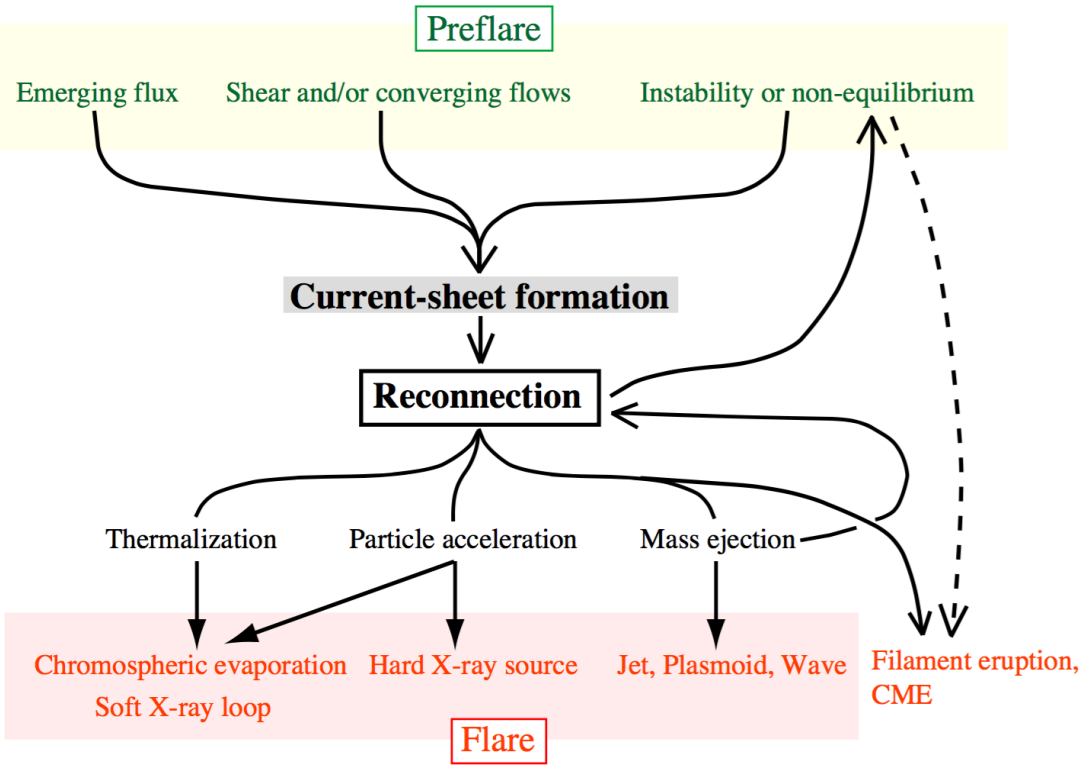
Super-flares occur on solar type stars, and flares with energy between 10^{34}-10^{35} ergs could occur typically every 800 to 5000 years on the Sun

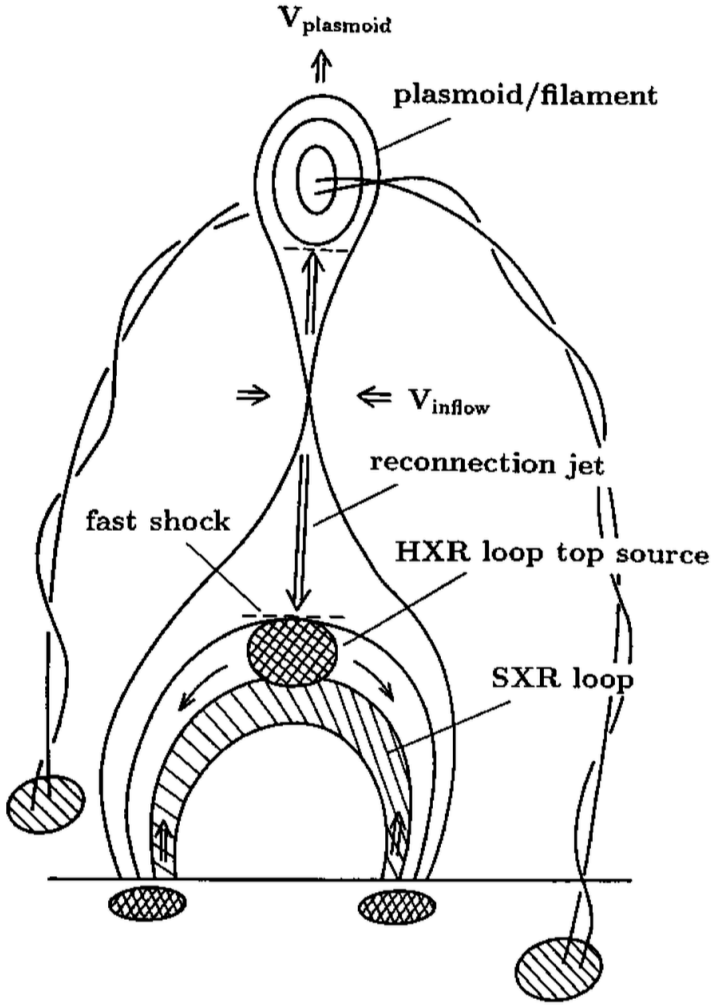
What **physical mechanism(s)** drive solar and stellar flares?

Can we predict their occurence?



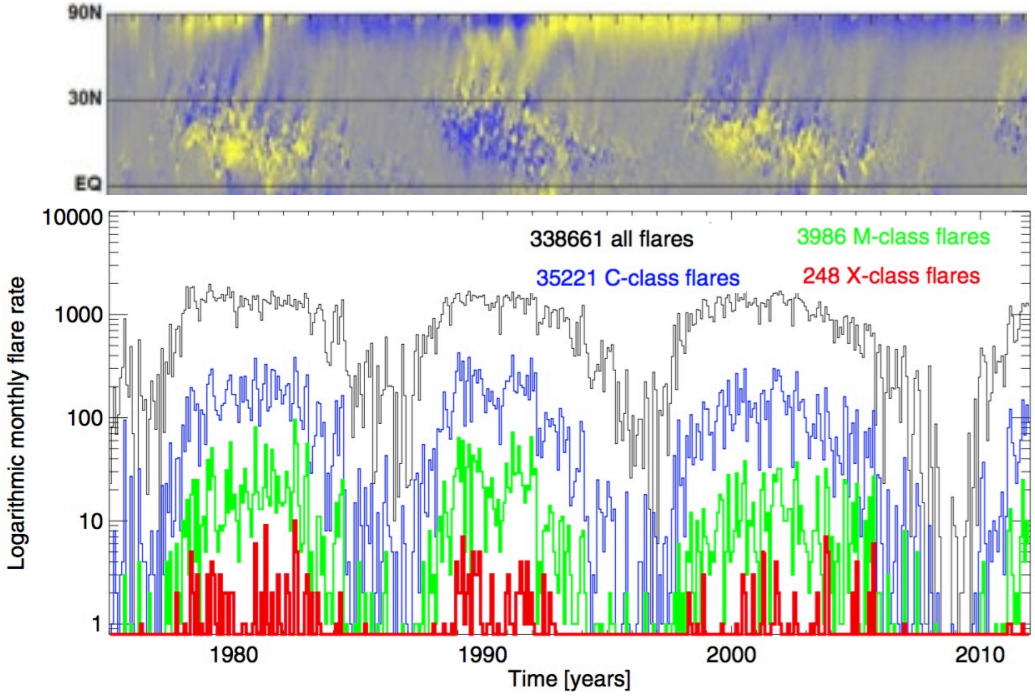
A standard model for solar eruptions





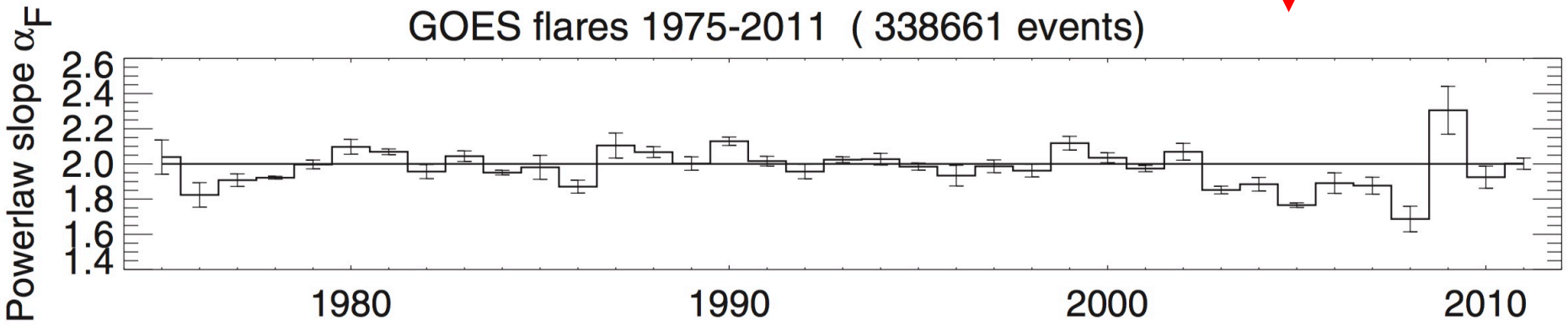
[Shibata 2011]

The number of flares strongly varies during the solar cycle



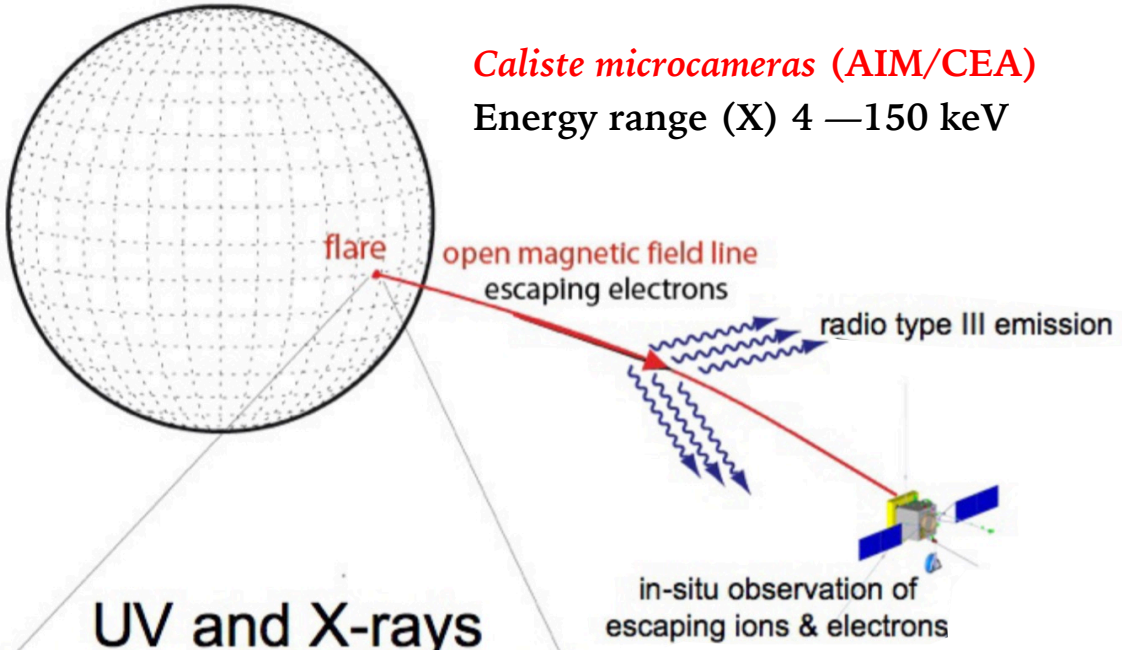
Line of sight magnetic field in the north hemisphere of the Sun

But no correlation of the power-law slope of the peak X-ray flux during flares



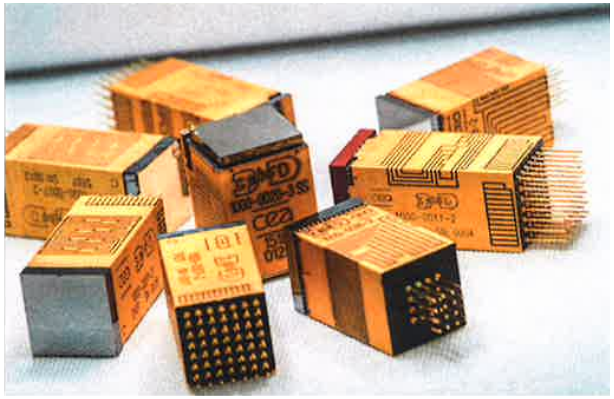
[Aschwanden & Freeland 2012]

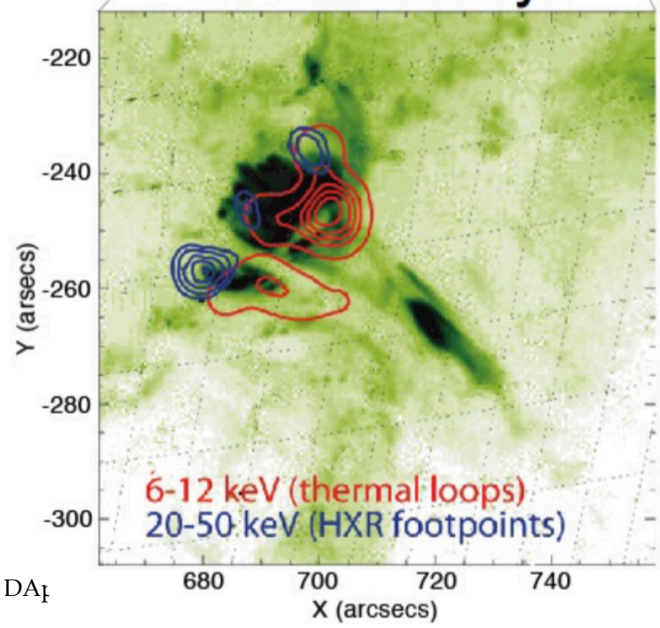
Flares and Solar Orbiter



Caliste microcameras (AIM/CEA)

Energy range (X) 4 —150 keV

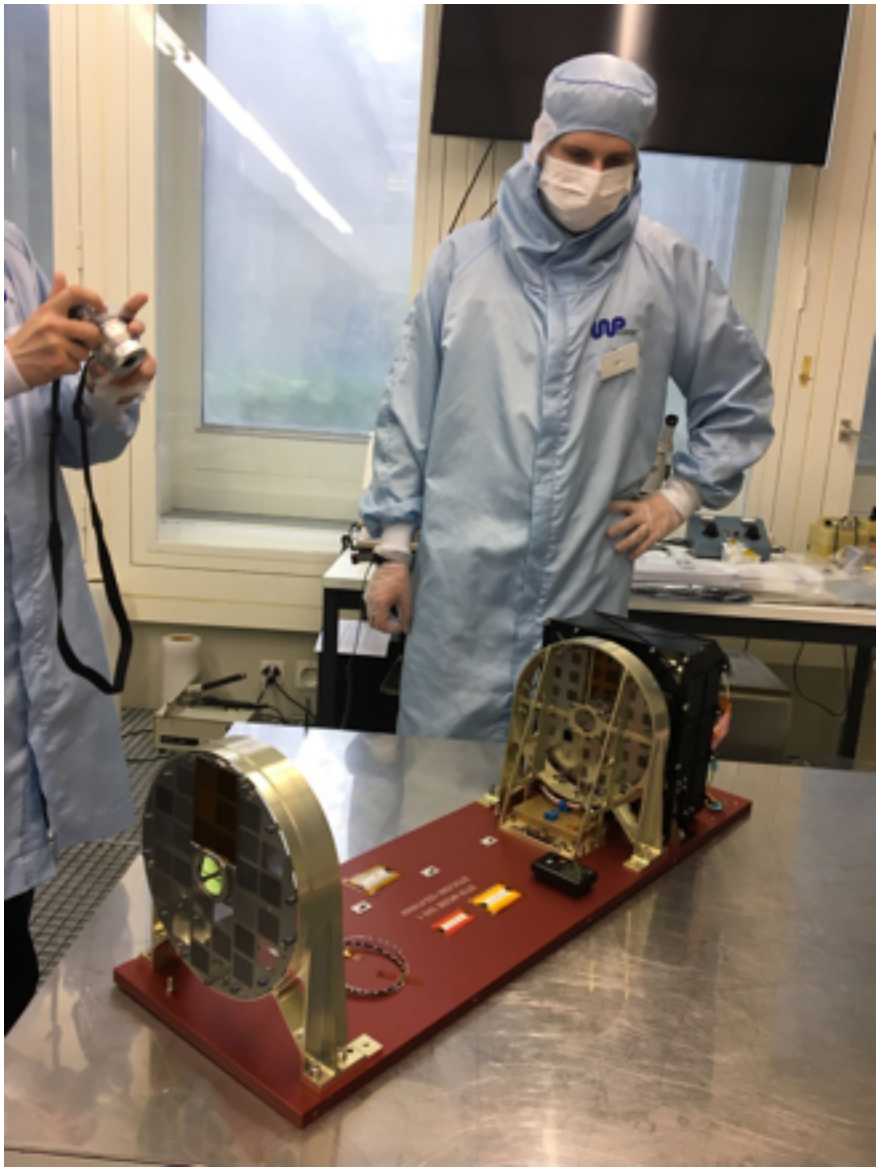


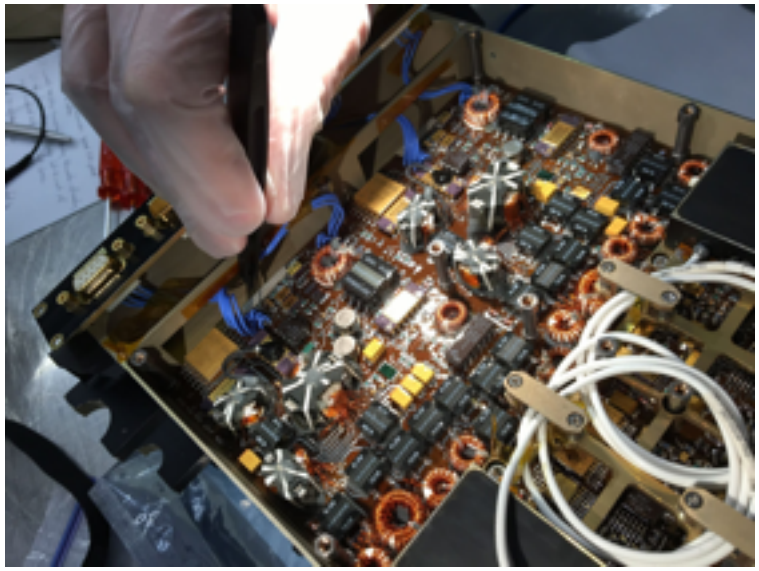


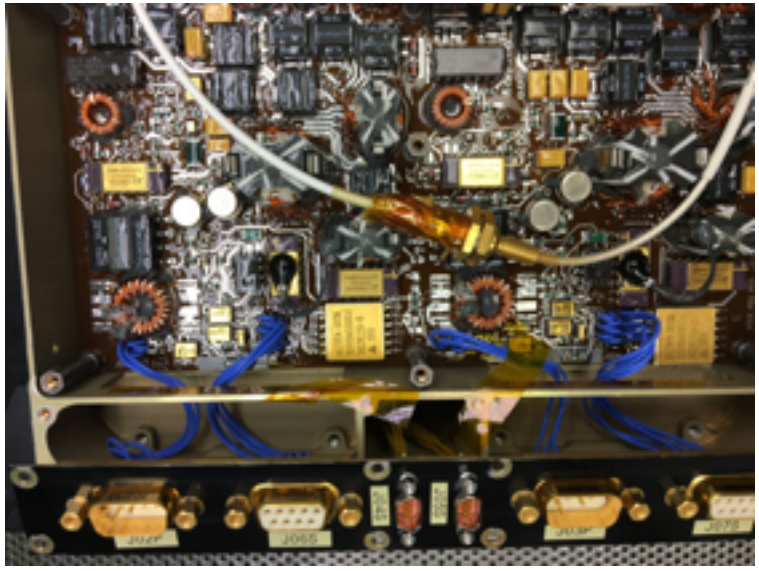
Scientific Objectives of Solar Orbiter/STIX

- Understand **electrons acceleration** and **propagation** during eruptions
- Determine the **magnetic connectivity** between the Sun and Solar Orbiter

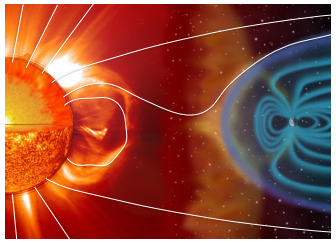
SolO/STIX: latest news from last week (delivery: end of May)







Outline



I. A physically-based sandpile model to predict solar flares

- Sandpile model and solar flares
- Data assimilation: towards the Solar Orbiter era

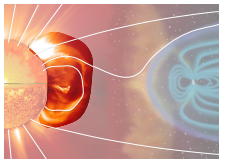
Strugarek+ 2014, Solar Physics
Strugarek & Charbonneau 2014, Solar Physics
R. Barnabé's PhD thesis (AIM)

II. The solar dynamo cycle

- *Ab initio* modelling of the solar magnetic cycle
- Unified mechanism for cycles in solar-like stars

Strugarek+ 2013, ApJ
Strugarek+ 2016, Adv. Space Research
Strugarek+ 2017, to appear in Science

Basics of sandpile models (I)



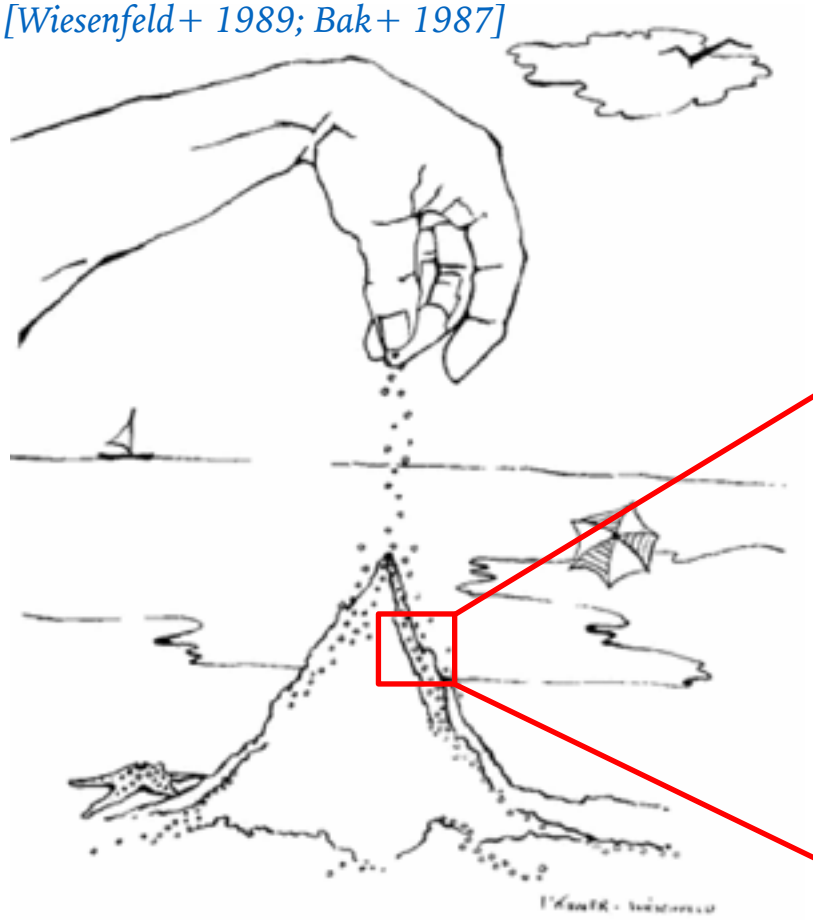
Basic model ingredients:

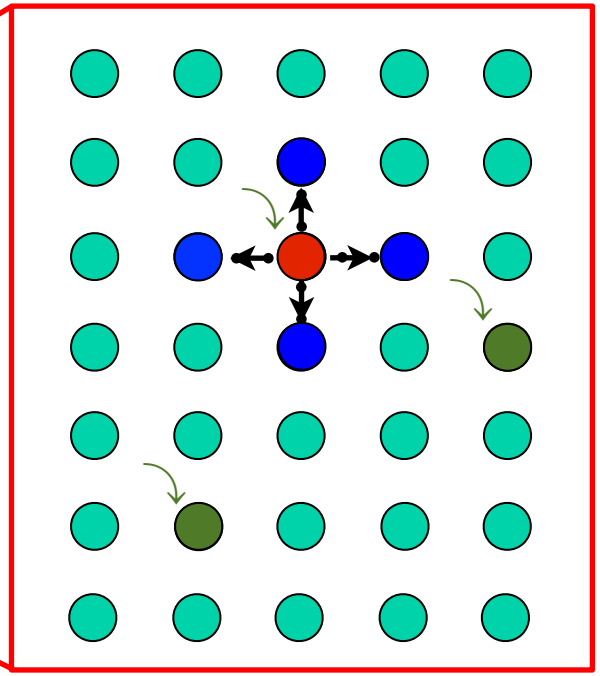
Driver

Threshold

Redistribution rule

[Wiesenfeld+ 1989; Bak+ 1987]

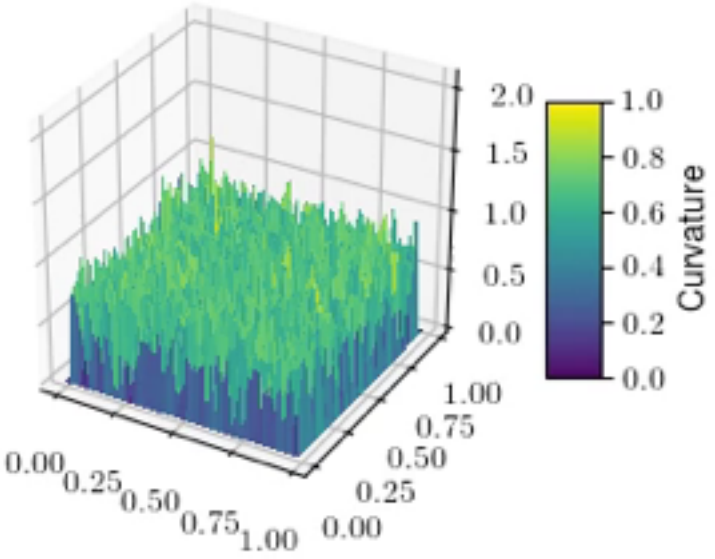


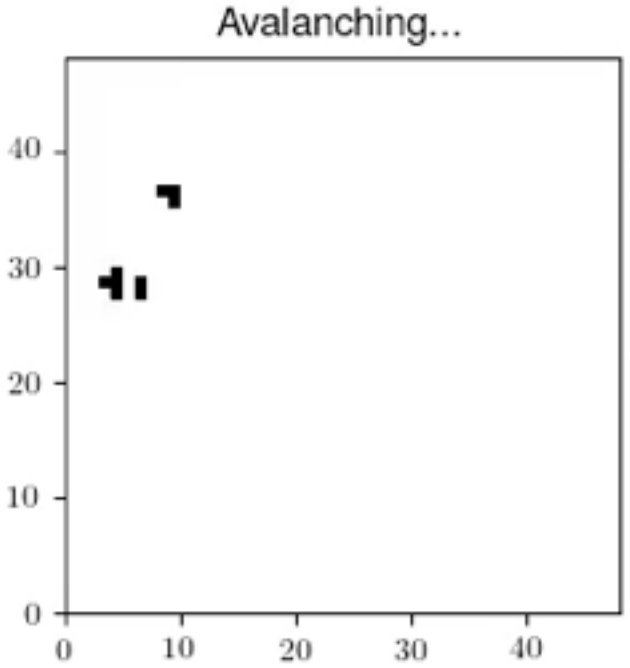


[Lu & Hamilton 1993]

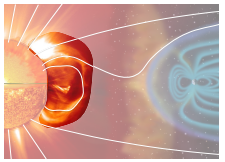
'Self-Organized Criticality'

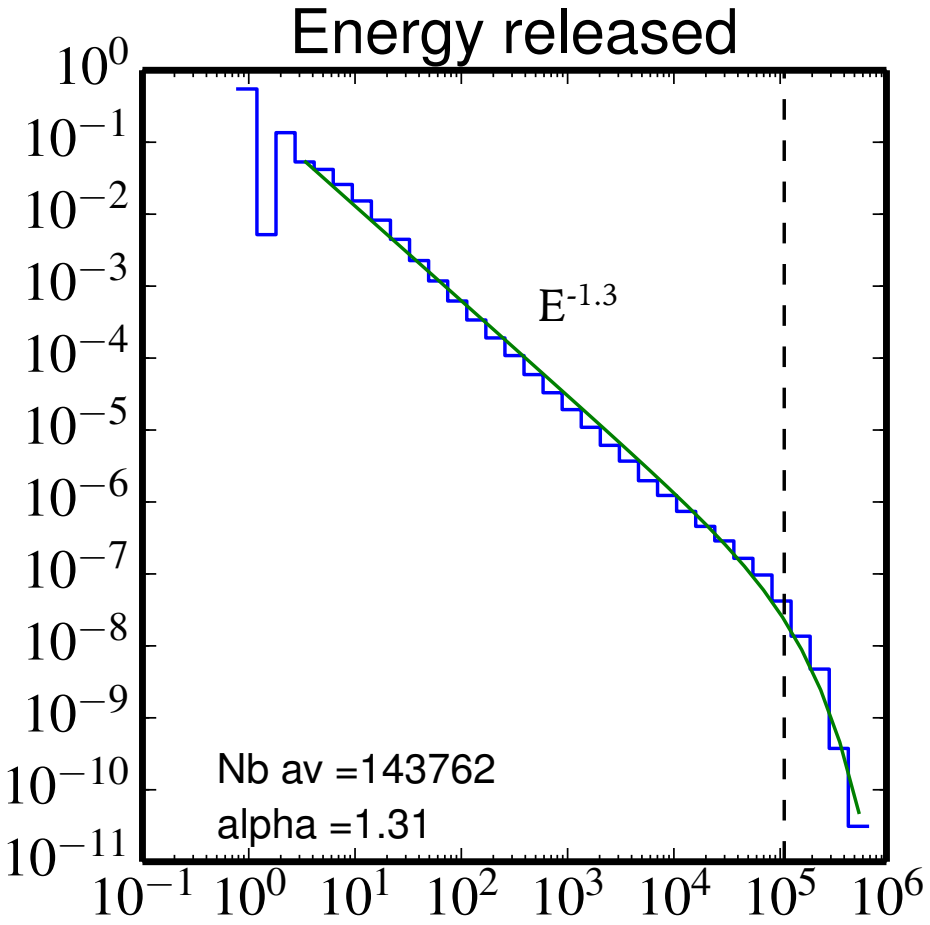
Basics of sandpile models (II)





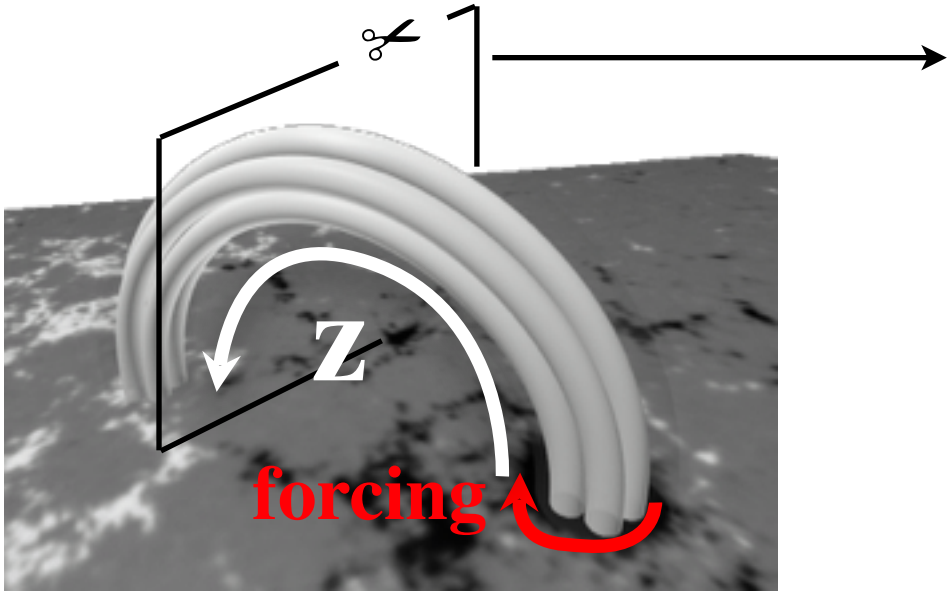
Basics of sandpile models (III)

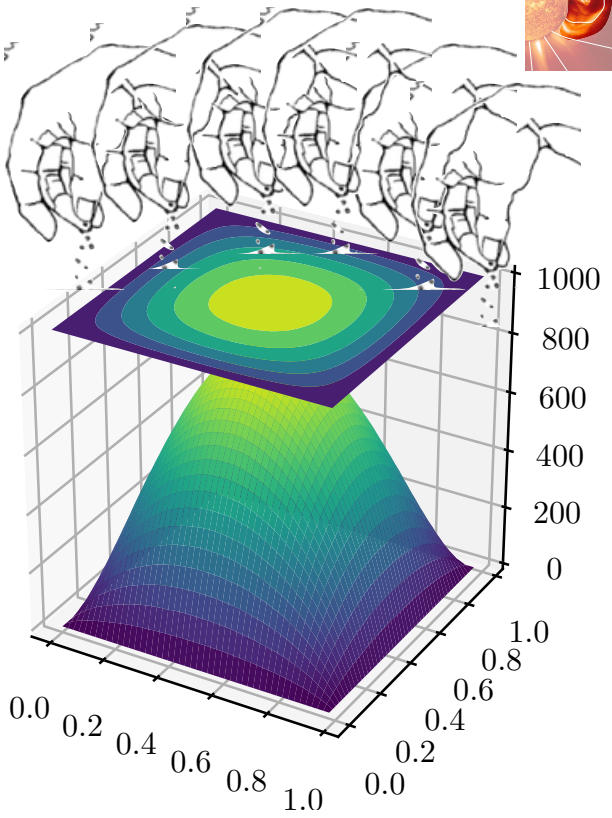


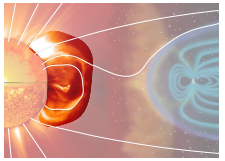


Power law obtained for the **energy release**, **peak energy** during the avalanche, and also **duration** and **area** covered by the avalanche

A physical interpretation of sandpiles

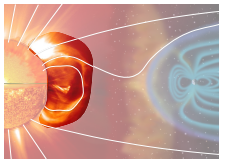


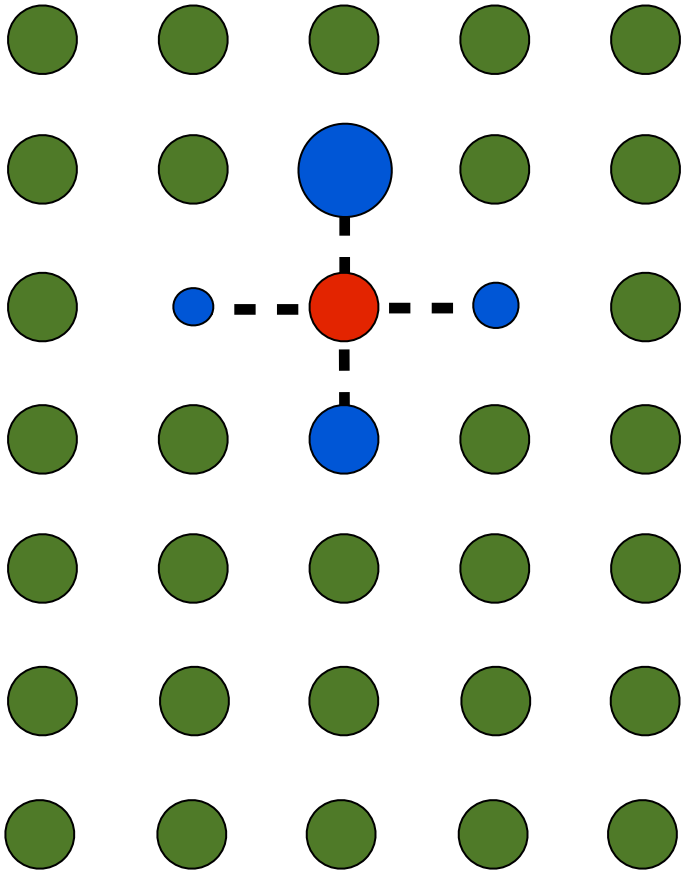




Coronal Loop	Sandpile
Magnetic potential A_z	Height
Turbulent twisting of loop	Homogenous forcing
Currents	Curvature
Magnetic reconnection	Stochastic redistribution

Deterministically-driven models



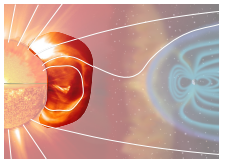


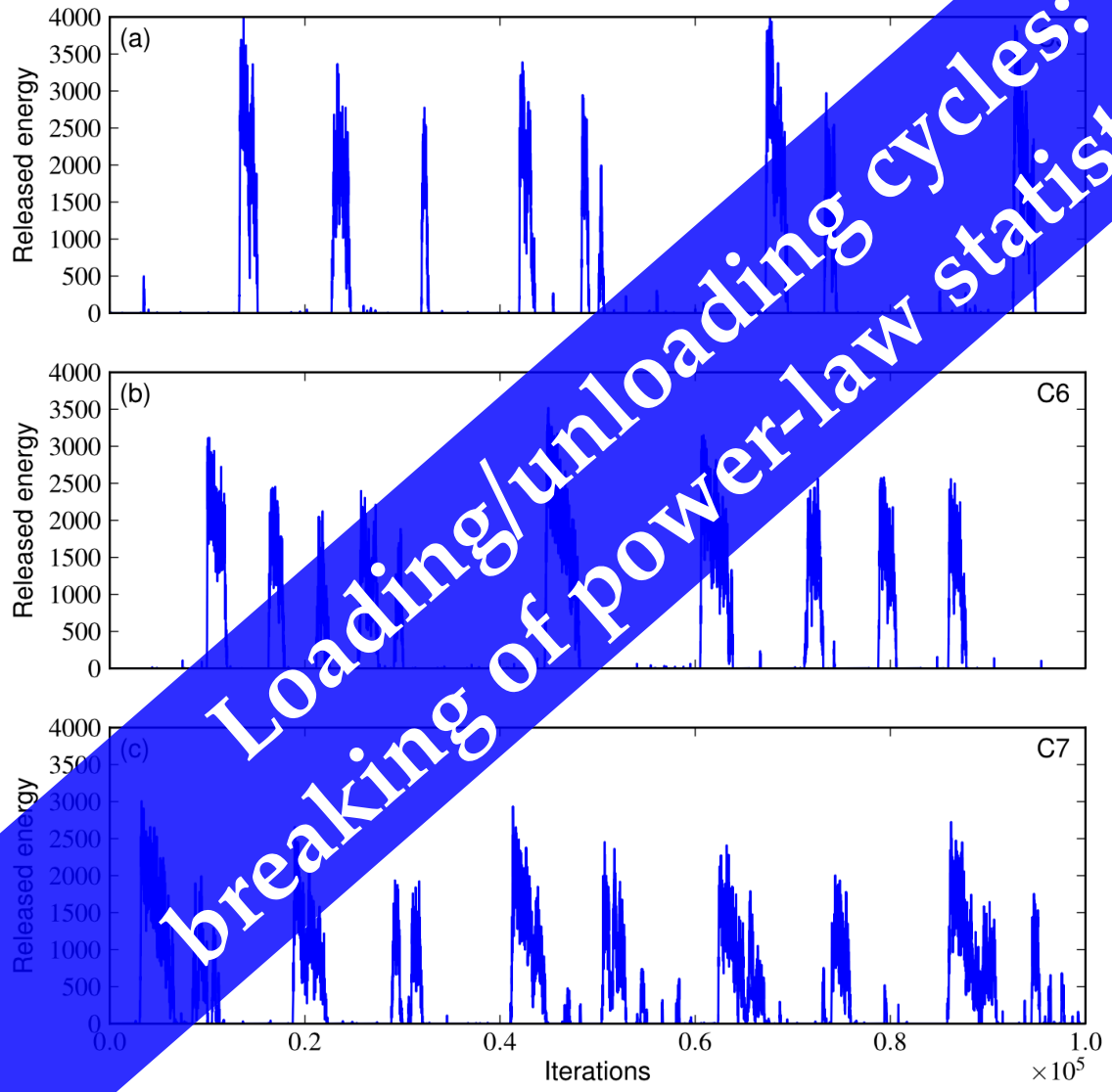
Deterministic driving on **all nodes**

(**Non)-Conservative** redistribution rule

Random process in **threshold**, **redistribution** and/or **extraction**

Conservative models do not reach the 'SOC' state





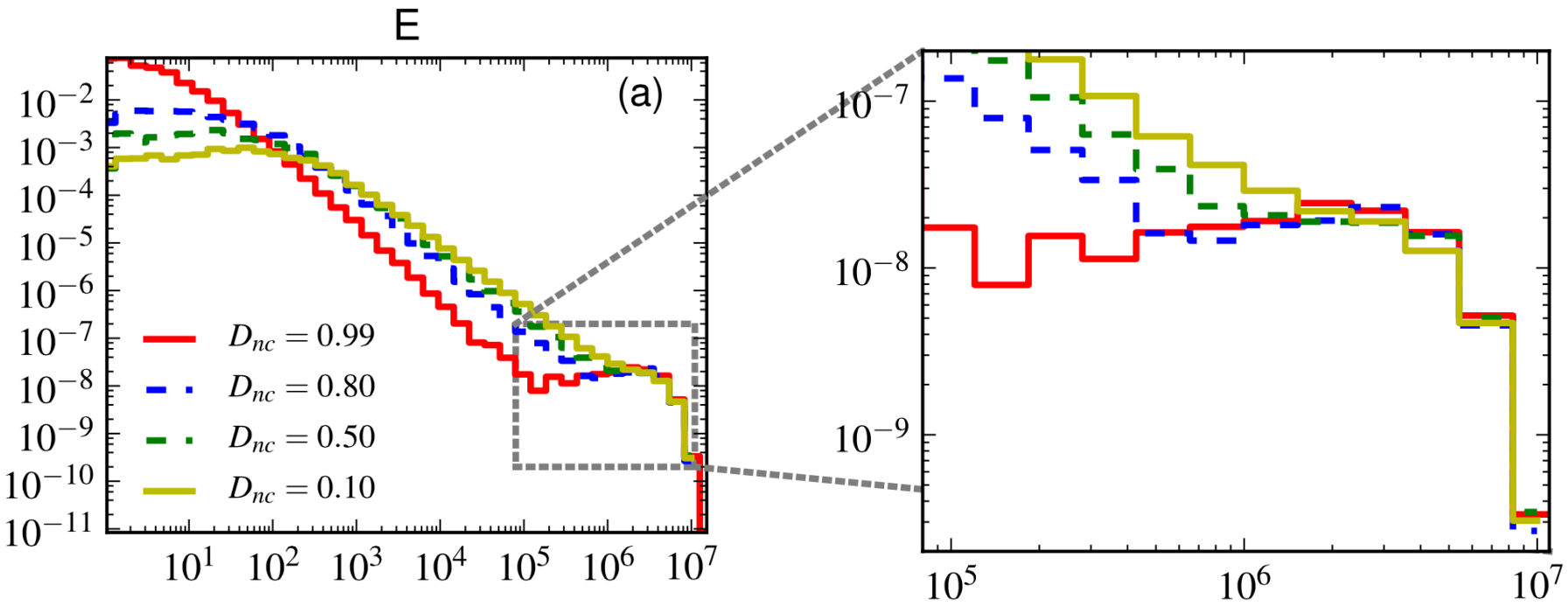
Loading/unloading cycles:
breaking of power-law statistics…

Random extraction

Random extraction
+
Random redistribution

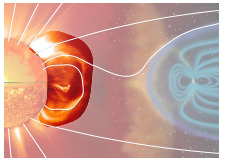
Random extraction
+
Random redistribution
+
Random threshold

Non-conservative models manage to recover SOC



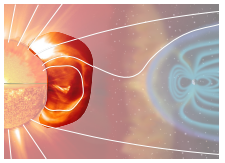
D_{nc} = Non-conservation parameter

(D_{nc}=1 for conservative model)

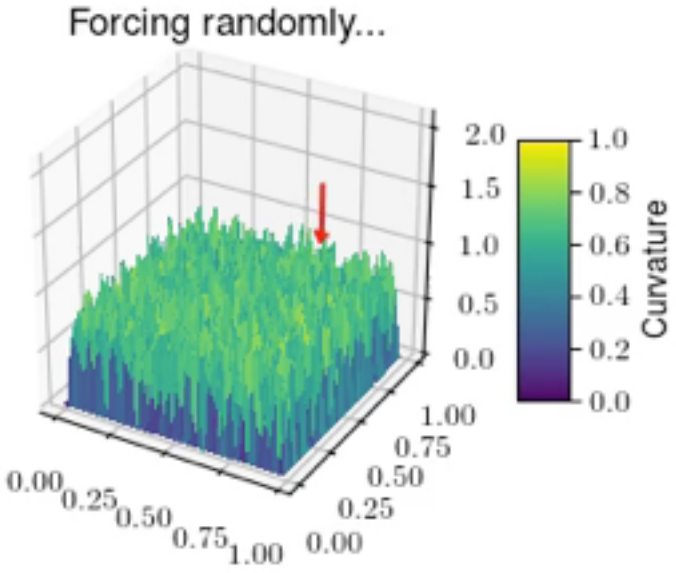


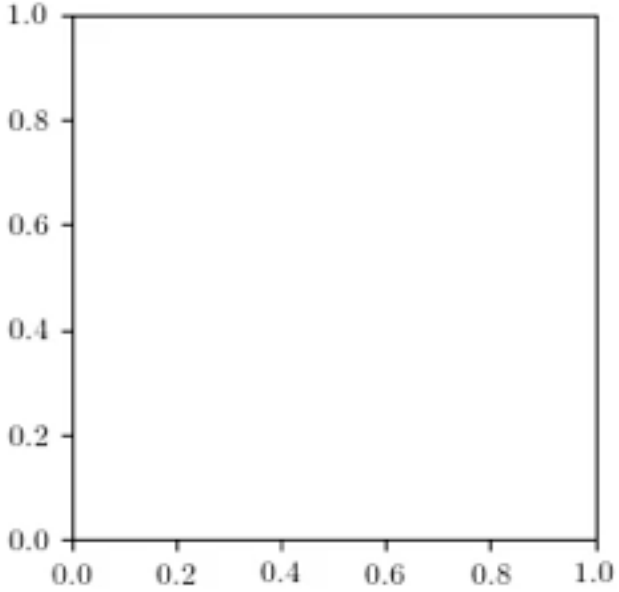
Could these models be used to predict individual events?

Stochasticity vs memory: the issue with classical sandpile



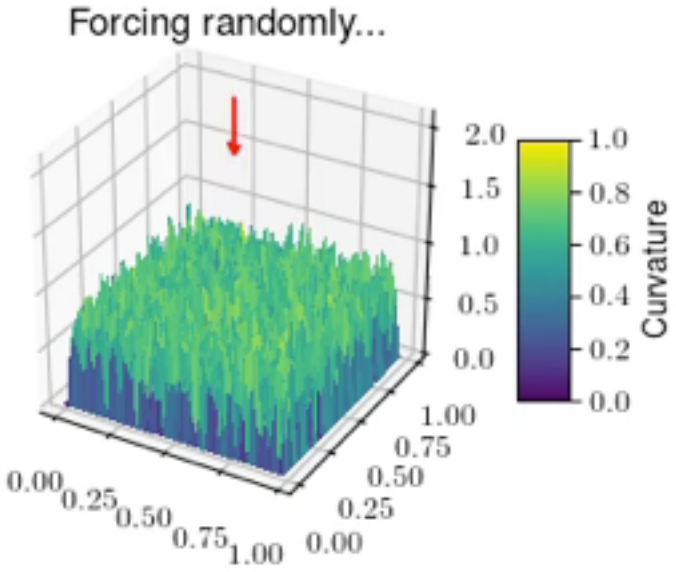
Random seed #1

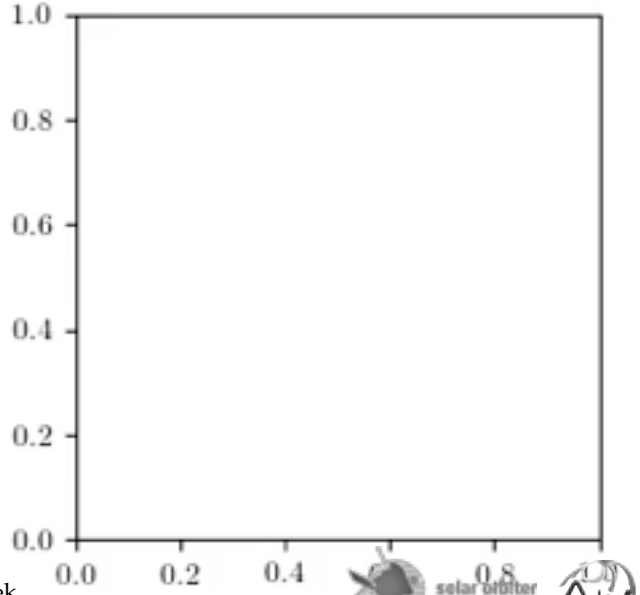




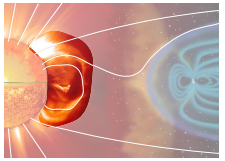
Standard sandpile model

Random seed #2

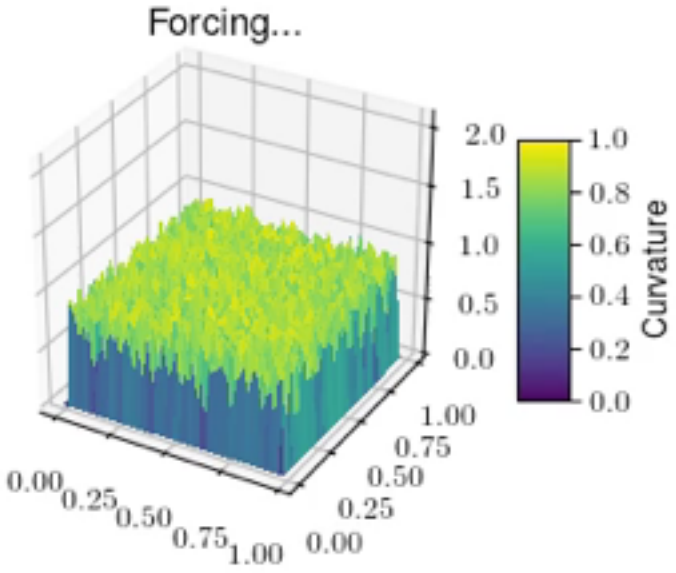


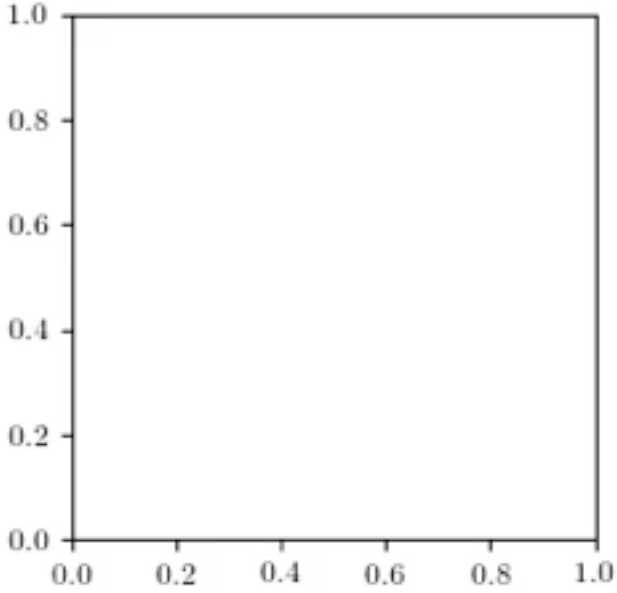


Stochasticity vs memory: the issue with classical sandpile



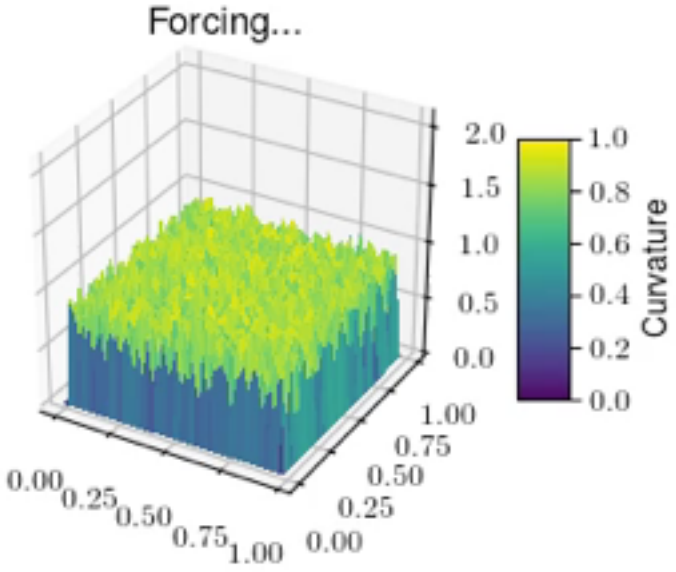
Random seed #1

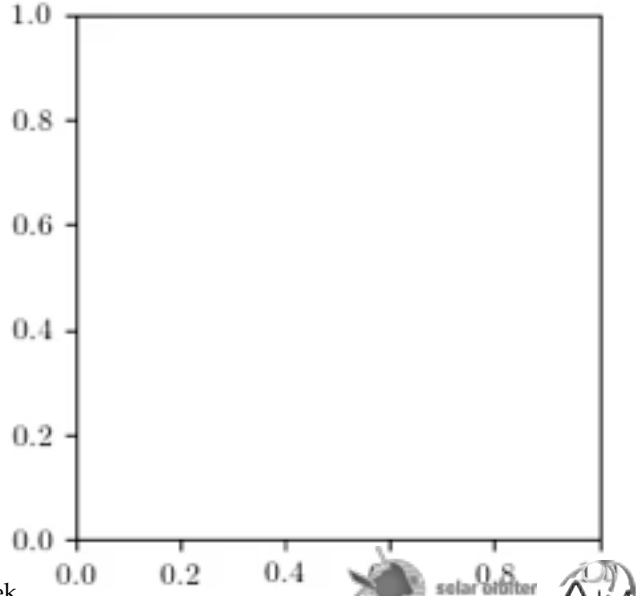




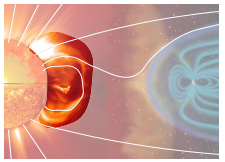
Non-Conservative sandpile model

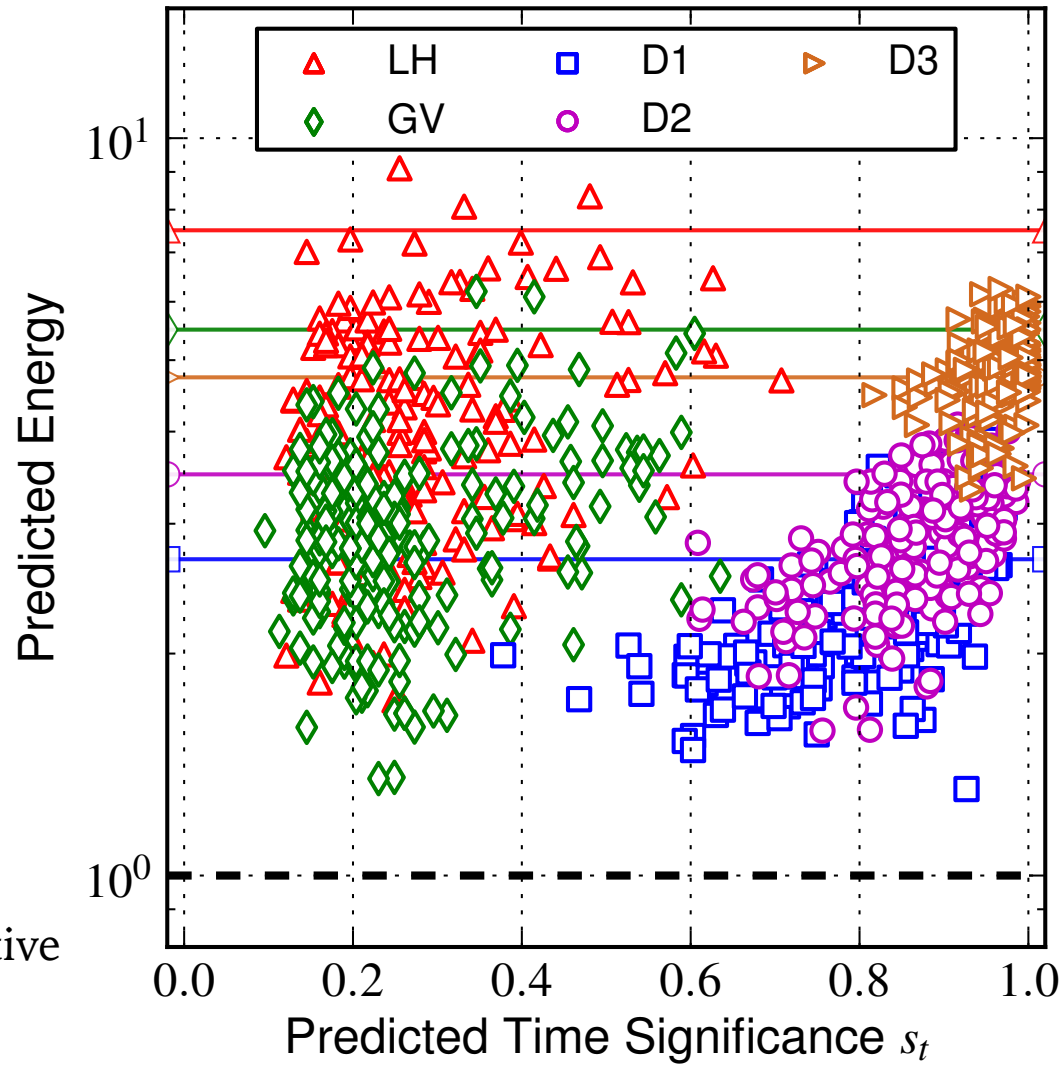
Random seed #2





Predictive performance of sandpile models

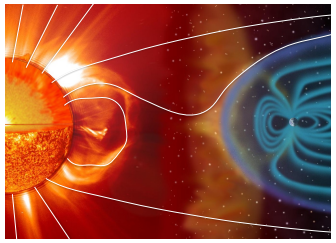




Good predictive capabilities

Bad predictive capabilities

Outline



I. A physically-based sandpile model to predict solar flares

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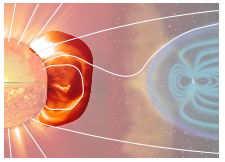
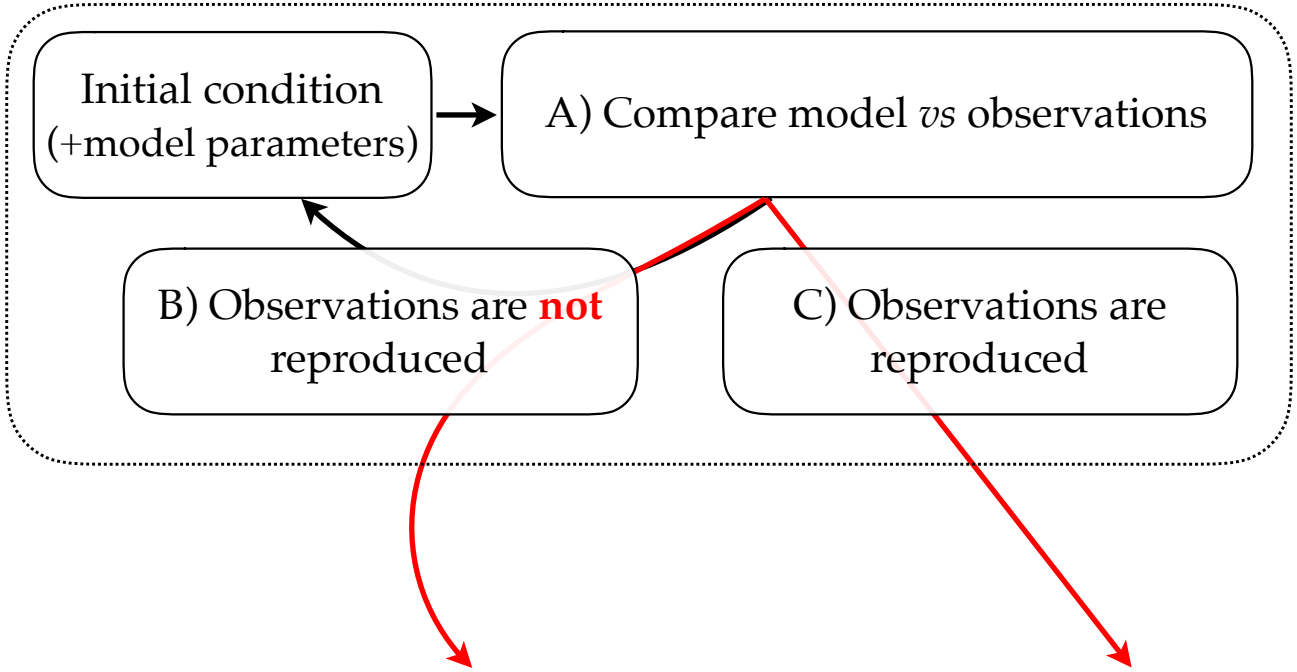
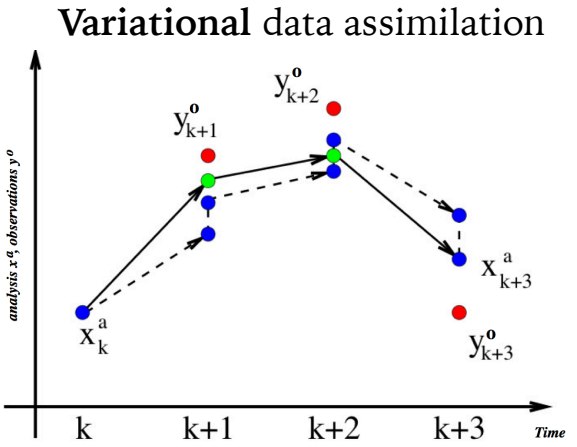
Strugarek+ 2017, to appear in Science

Data assimilation in sandpile models: FlarePredict



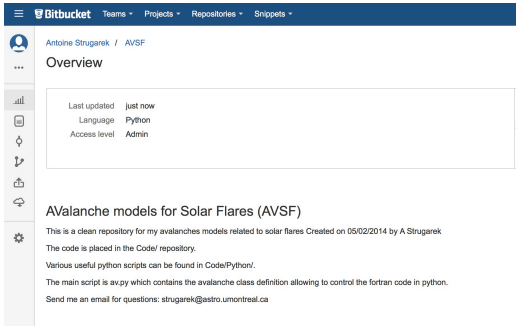




Promising technique: **simulated annealing**

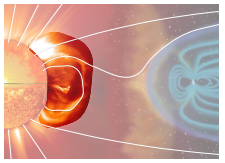
Determine eruptive probability (prediction)

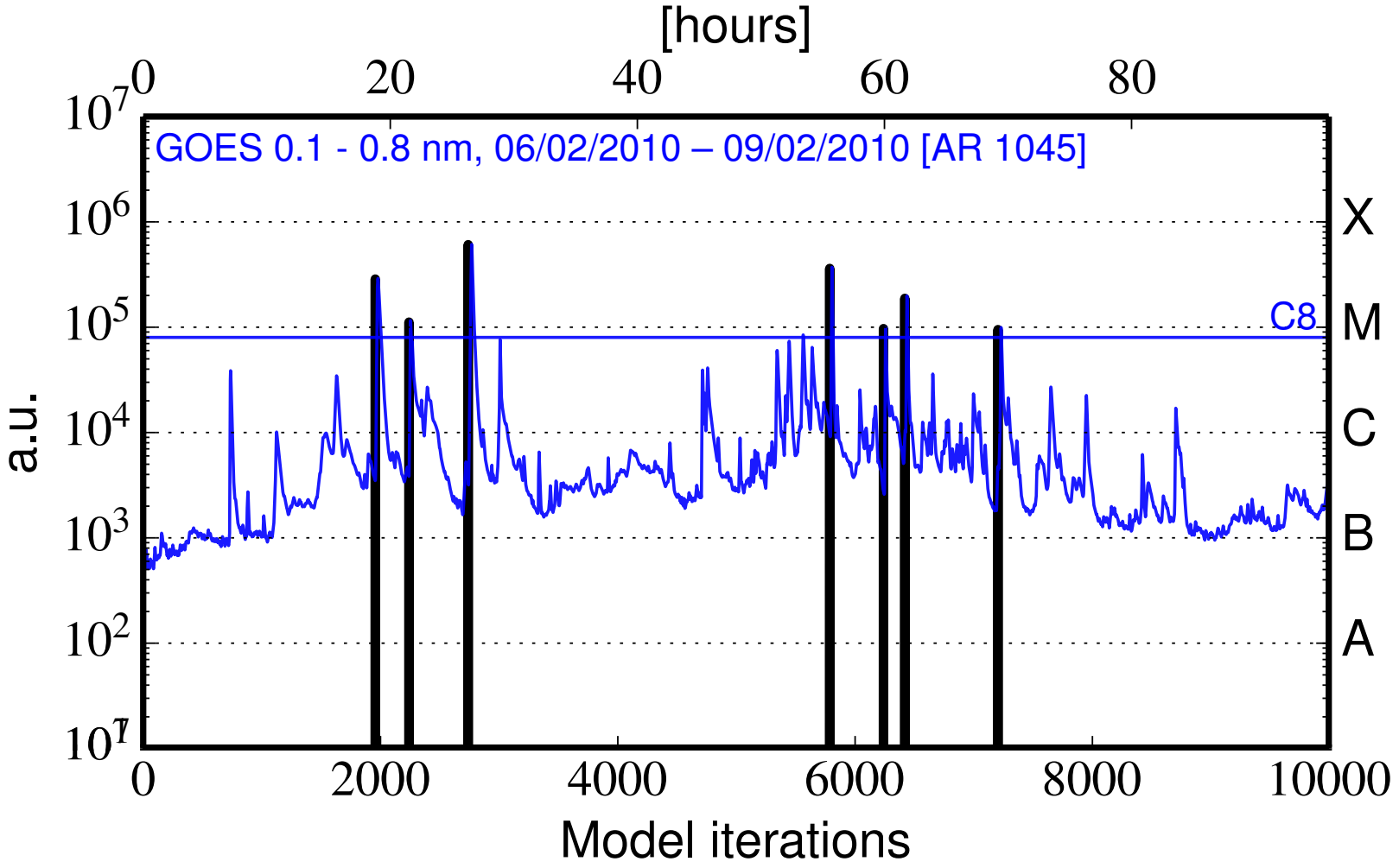
'Hindcasting' on past records first



The different blocks are included in a general framework called **FlarePredict** (under development)

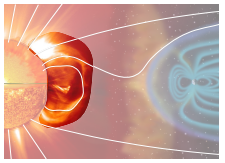
A) Comparing observational data with our model (I)





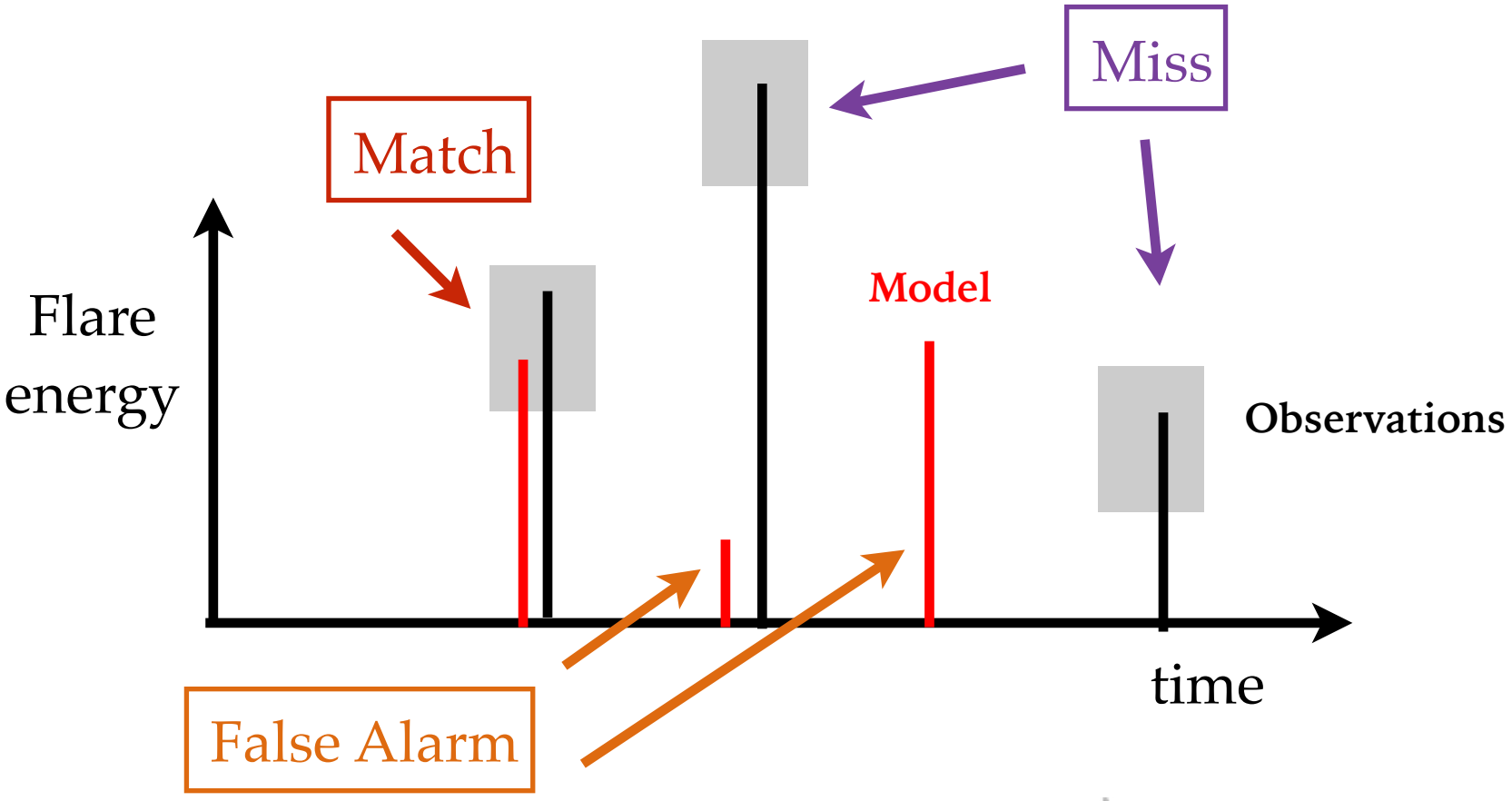
[Aschwanden & Freeland 2012]

A) Comparing observational data with our model (II)

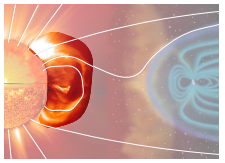


Least squares not efficient because of the discrete character of the events

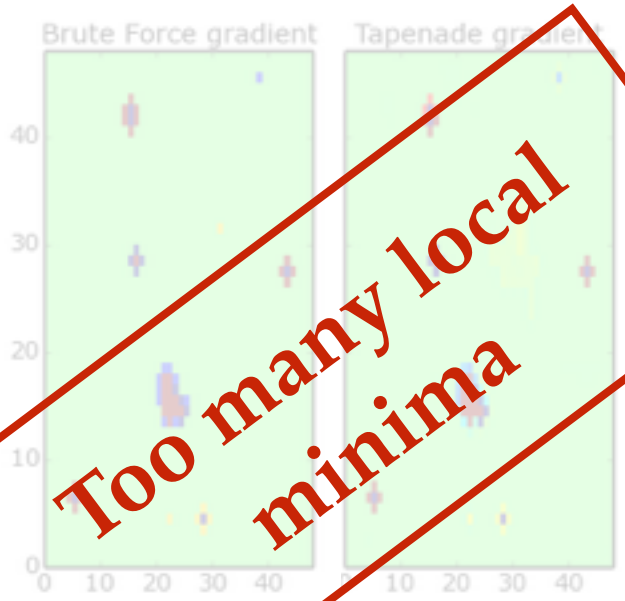
Defining a versatile cost estimate:



B) Finding a new initial condition reproducing the data (I)



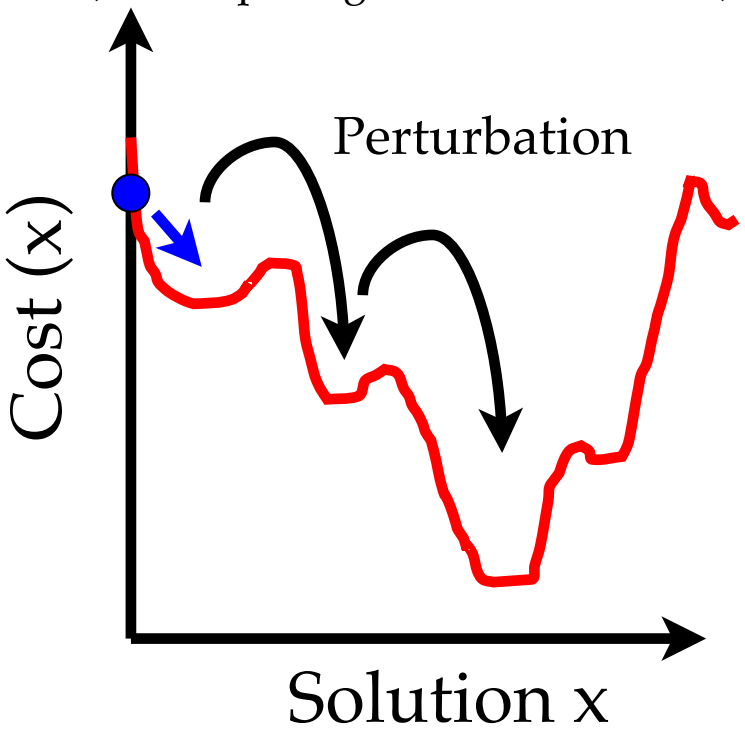
Using the gradient of the cost function



Too many local minima

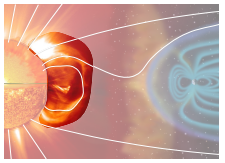
Adjoint method

Using more robust but more expensive methods
(w/o explicit gradient calculation)



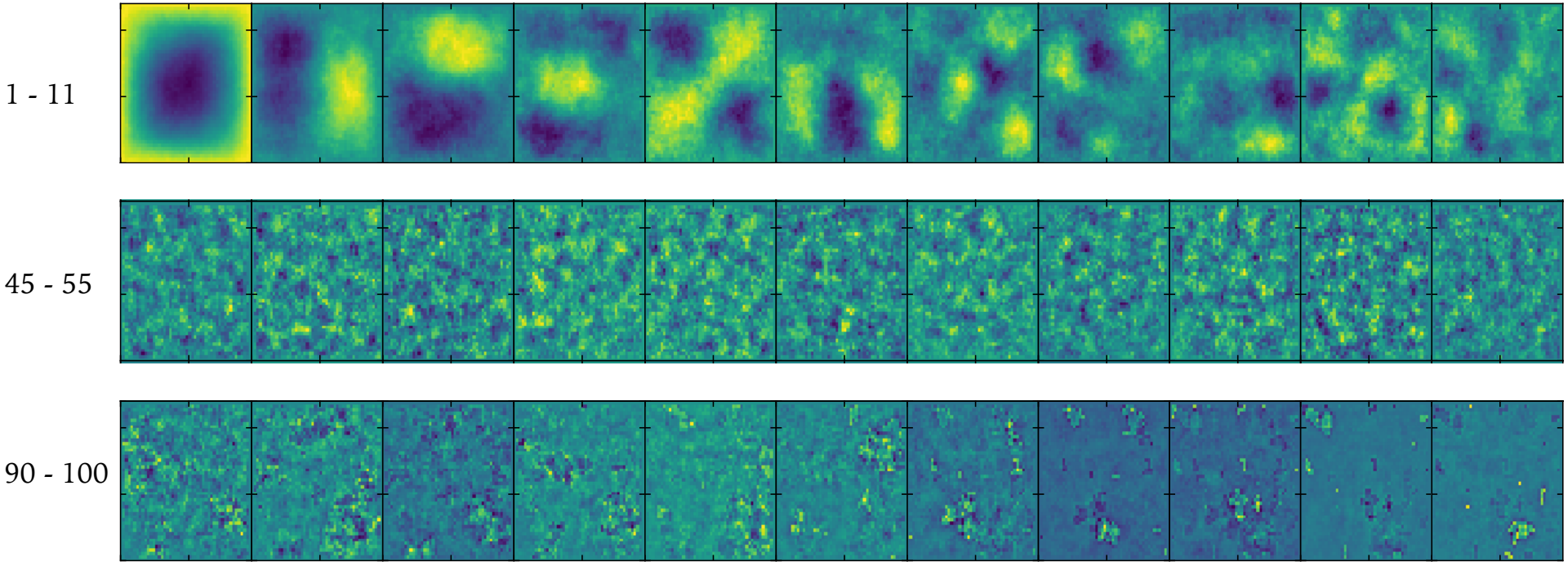
Simulated annealing

B) Finding a new initial condition reproducing the data (II)



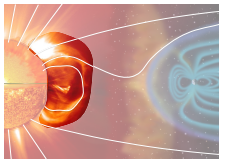
Simulated annealing is not very efficient: N^2 realizations of the model are used to minimize the cost function

Work in progress: reduce this number by projecting the sandpile model on its **eigenvectors**

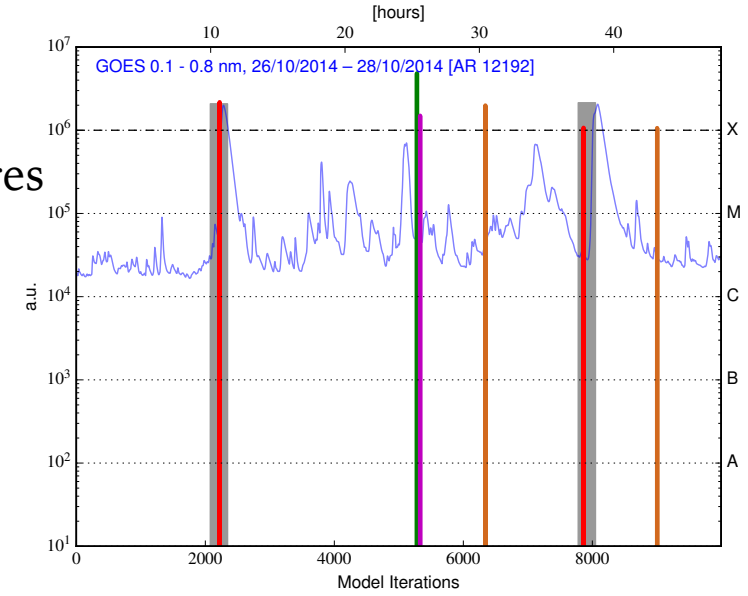


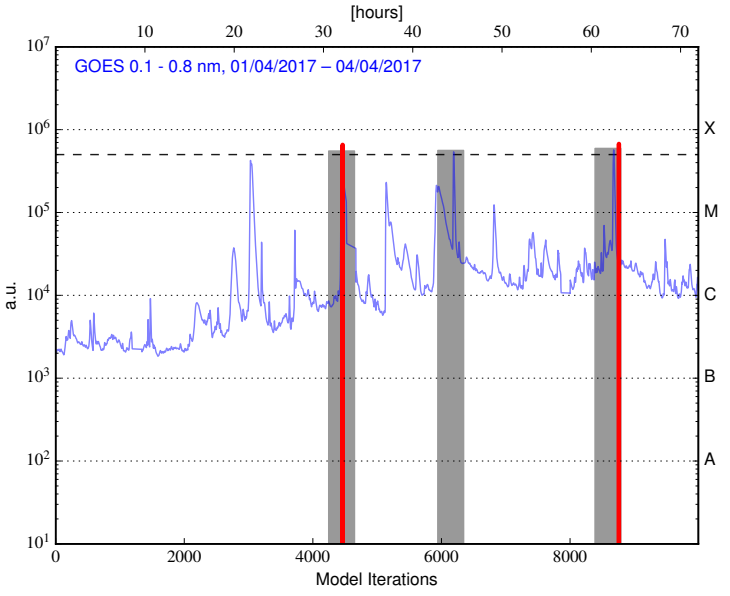
In this case, **N^2 = 2304 eigenvectors** (N degrees of freedom)

C) Towards a predictive tool…



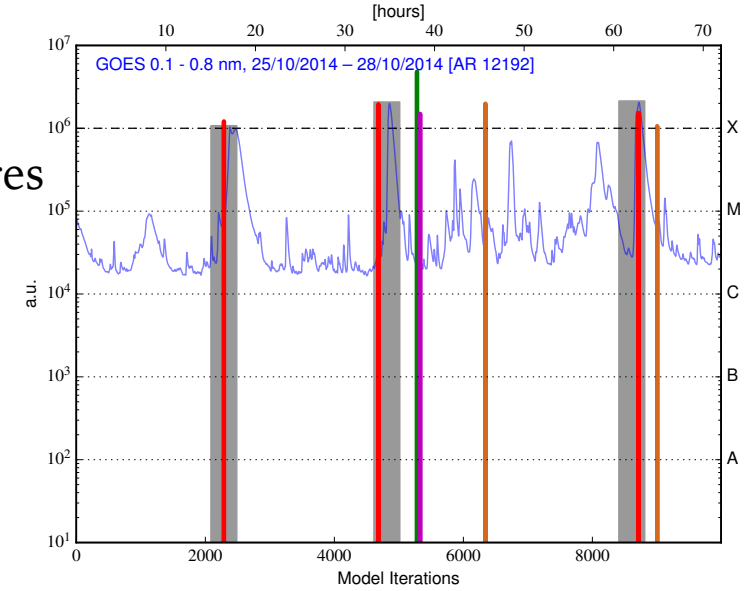
2 X-flares

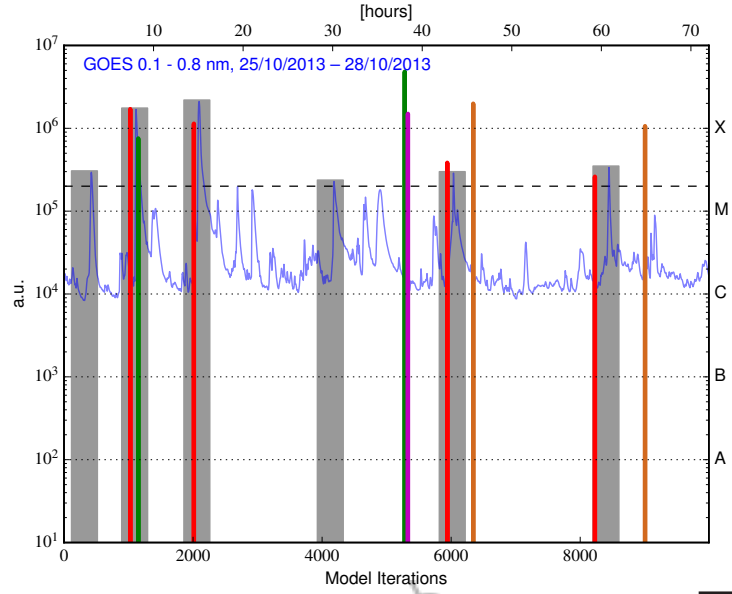




3 M-flares

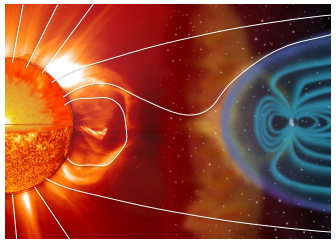
3 X-flares





2 X-flares
+
4 M-flares

Outline



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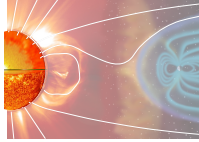
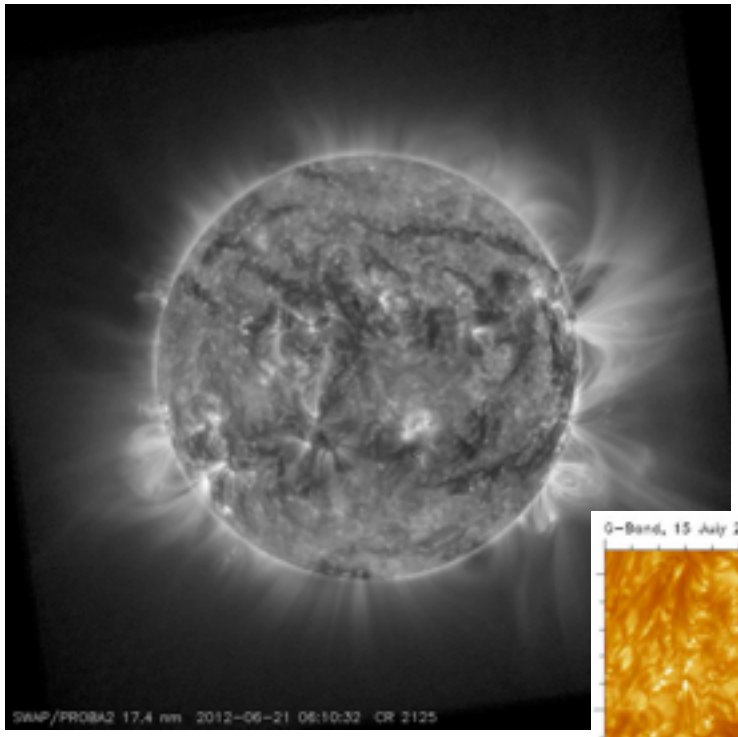
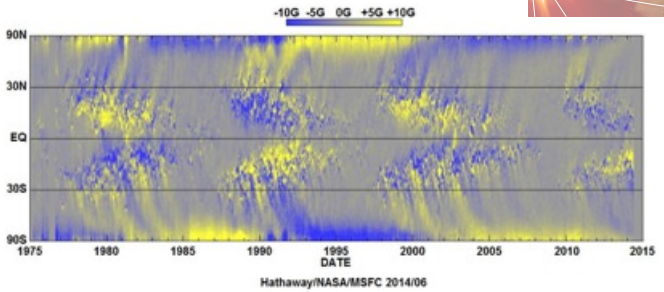
The many scales of solar magnetism

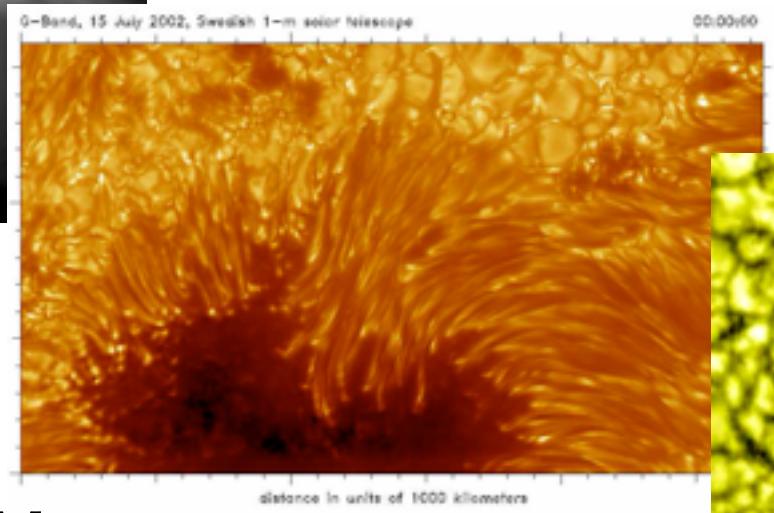


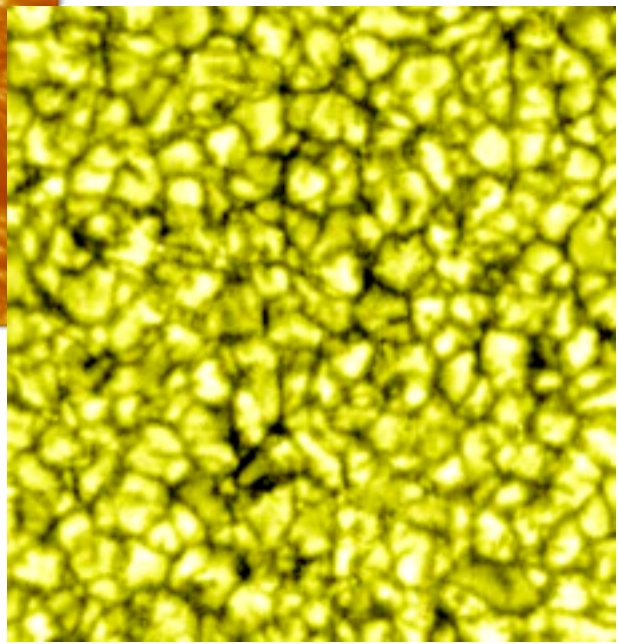


Sun
Size ~ 700 Mm
Rotation ~ month
Cycle ~ 11 years



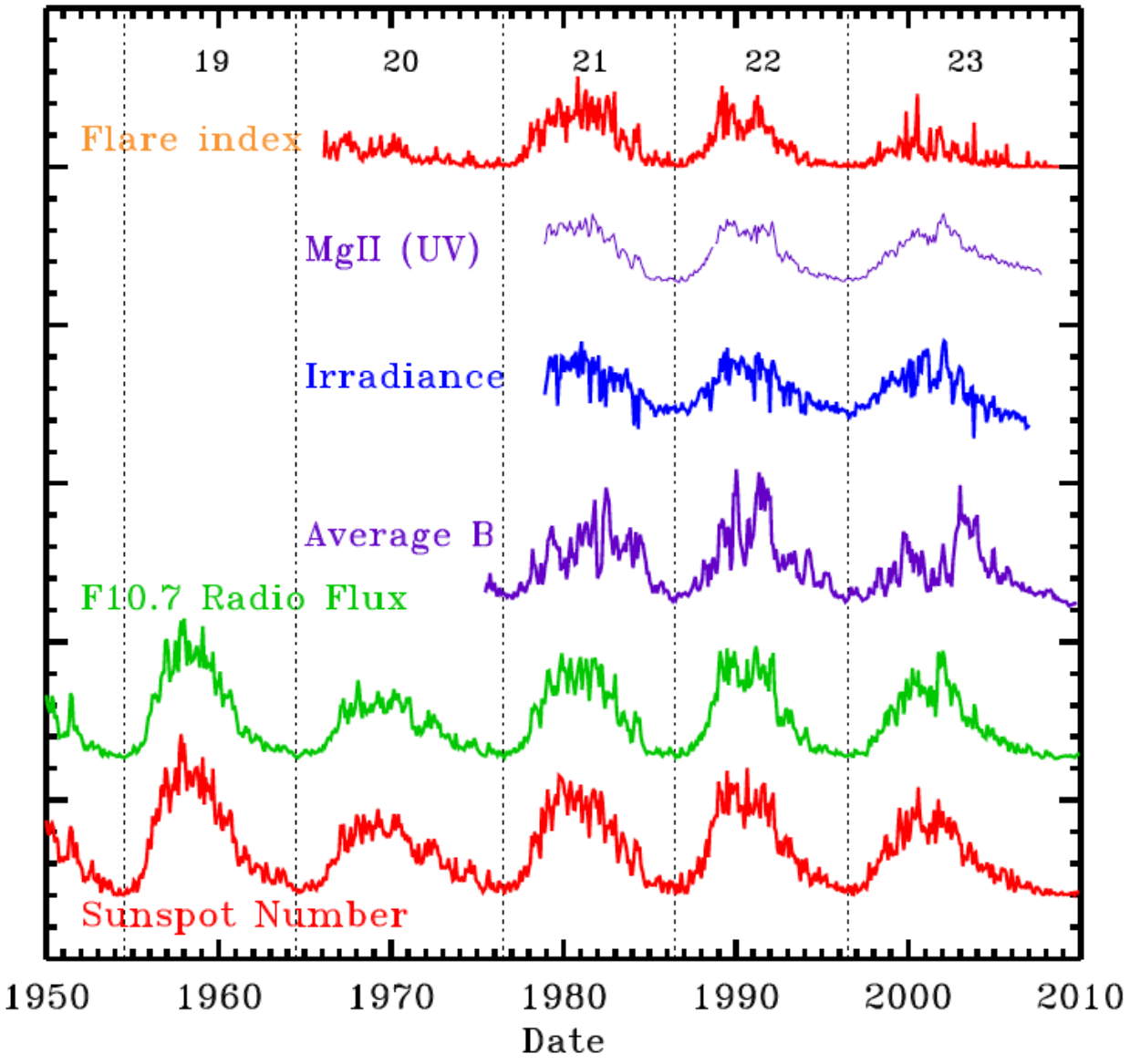
Granules
Size ~ 1 Mm
Life ~ 10 minutes



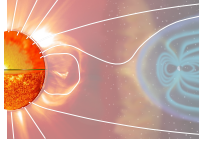


Spots
Size ~ 10 Mm
Life ~ days

One cycle to rule them all

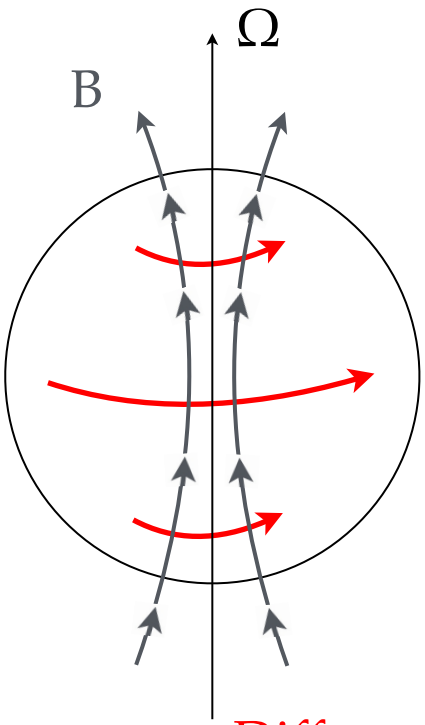


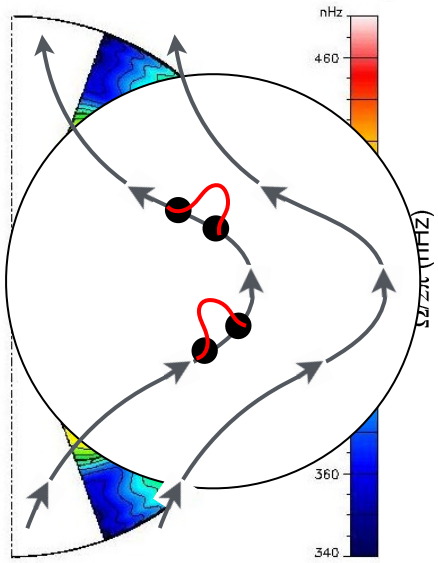
Classical dynamo picture



☛ *Cowling's theorem: 3D axisymmetric flows cannot sustain a dynamo action*

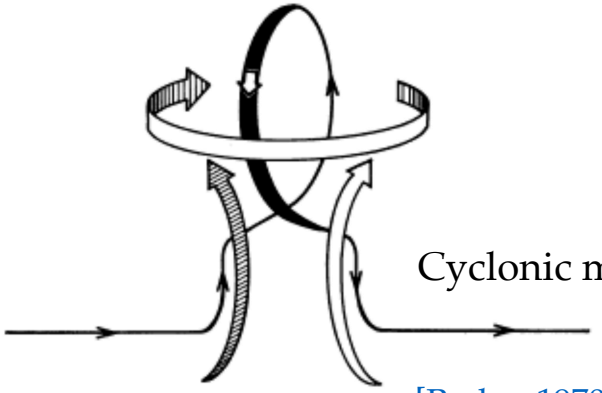
« Omega » effet: differential axisymmetric rotation easily convert poloidal field to toroidal field





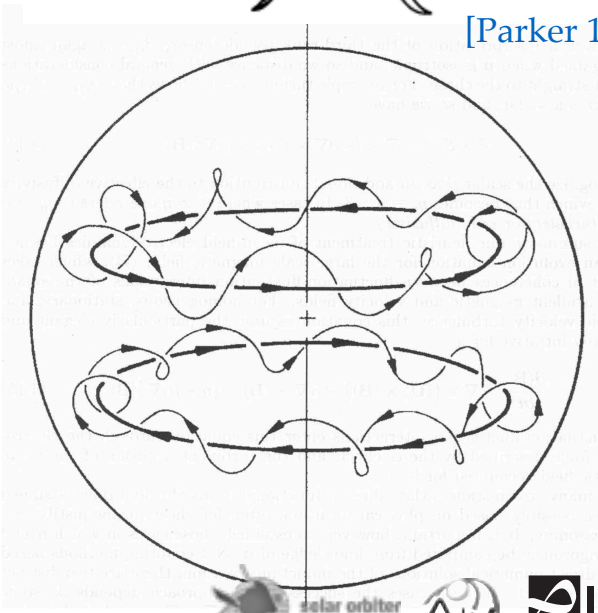
Differential Rotation

Toroidal to poloidal conversion

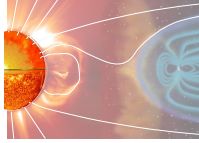


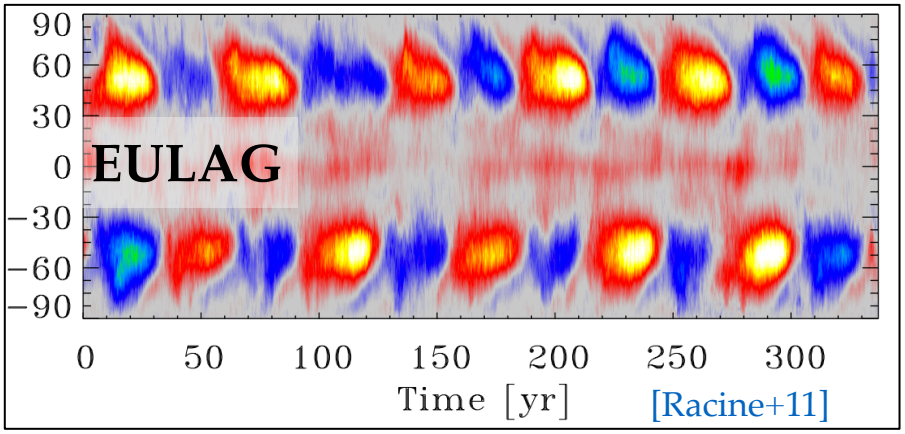
Cyclonic motion

[Parker 1970, 1979]



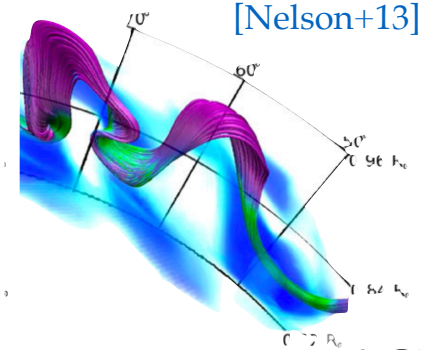
The zoo of 3D numerical simulations



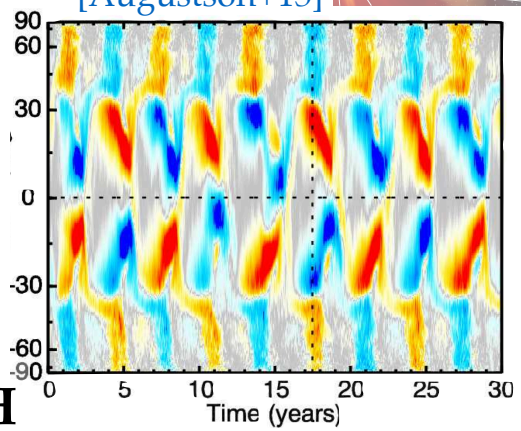


[Racine+11]

[Nelson+13]

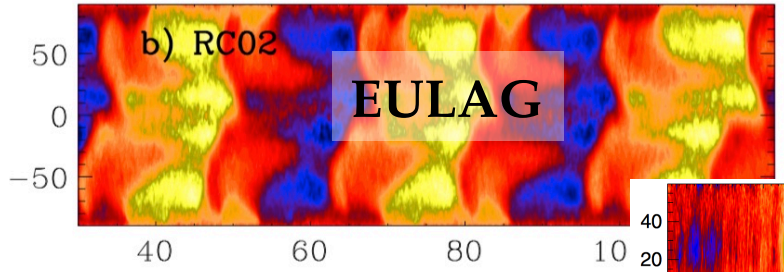


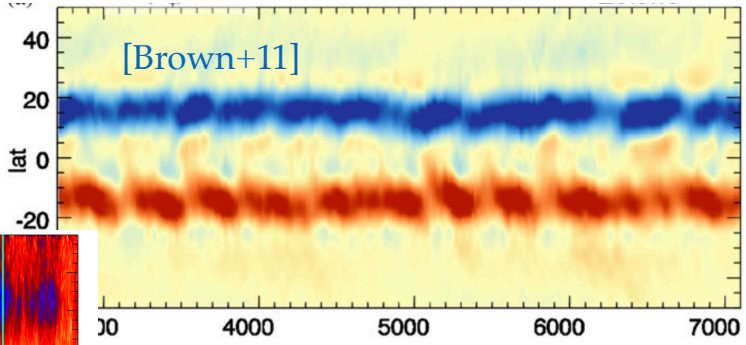
[Augustson+15]

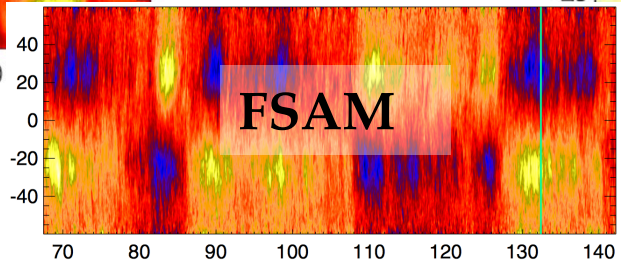


ASH

[Guerrero+16]

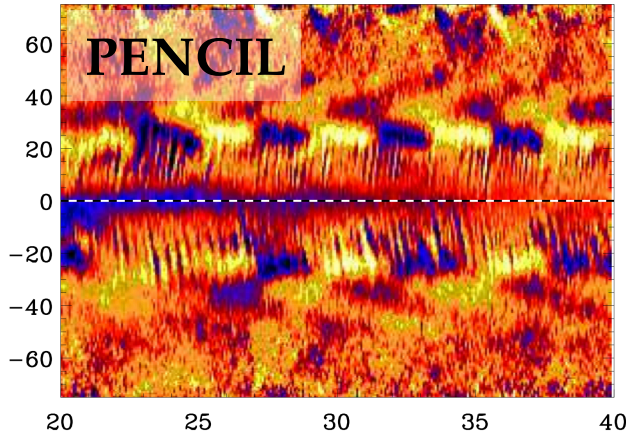


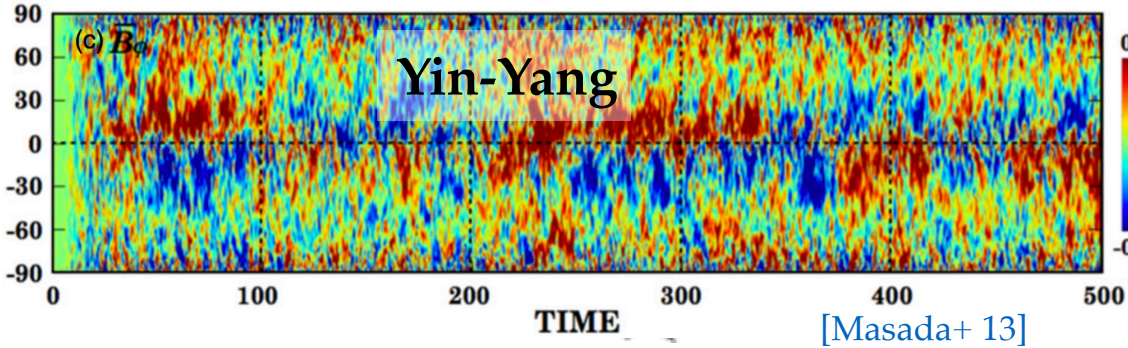




[Fan+14]

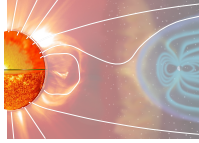
[Kapyla+12,Warnecke+14]

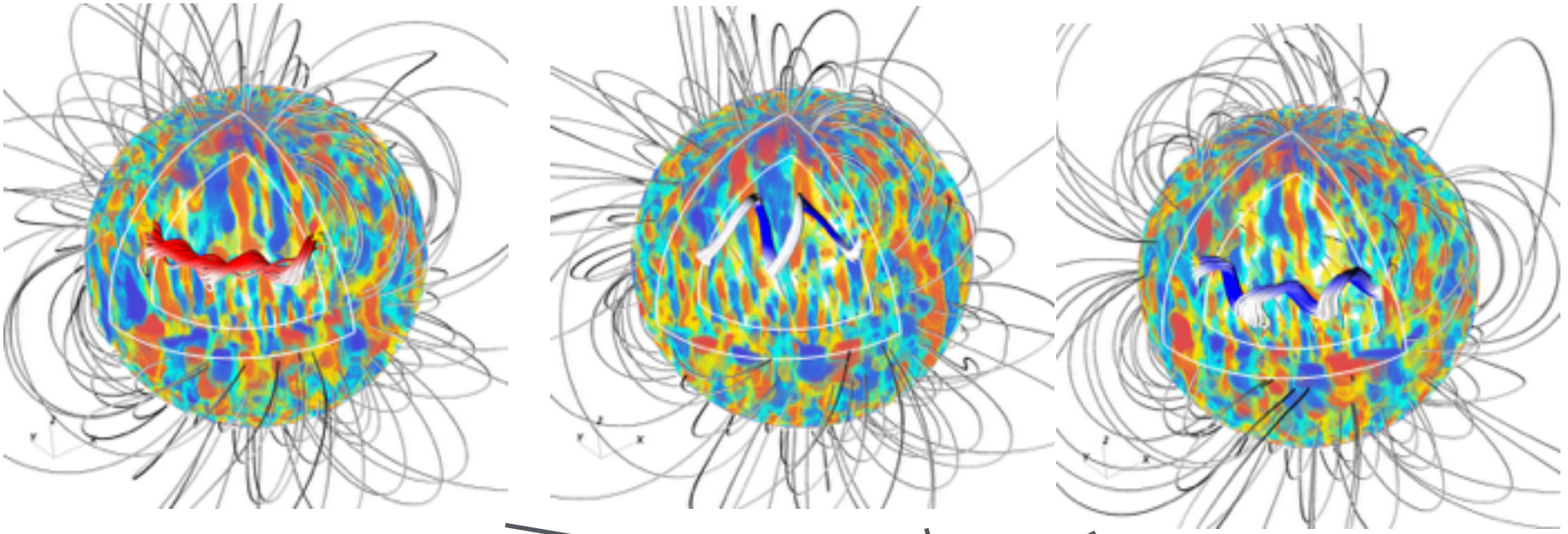


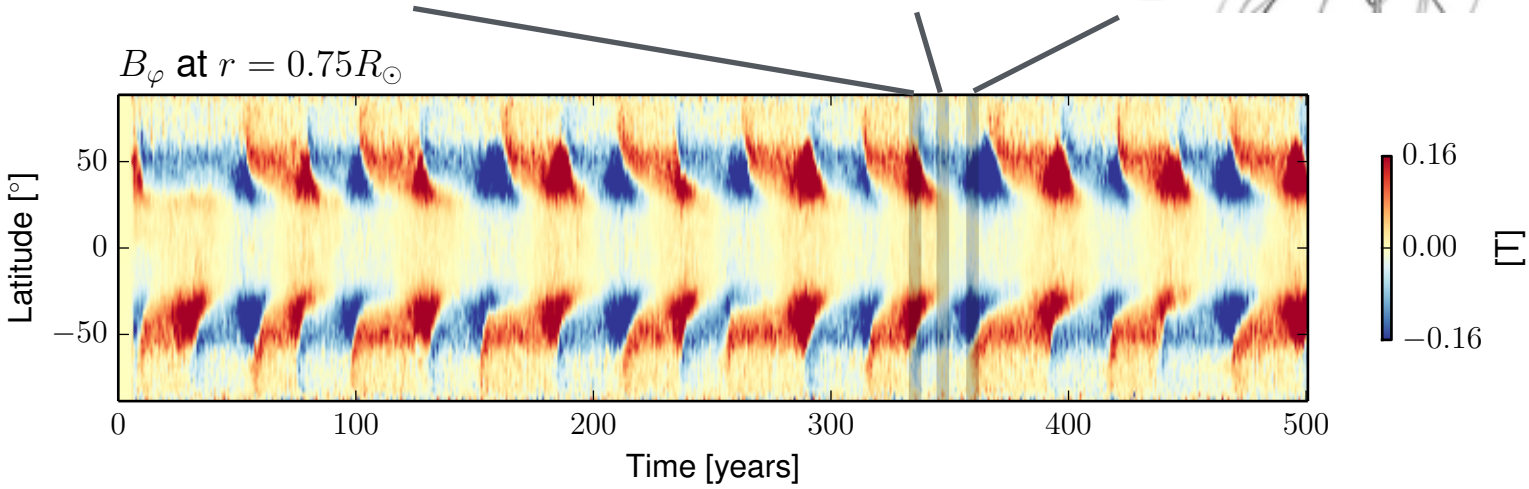


[Masada+ 13]

Prototype cyclic dynamo in a convective enveloppe (I)



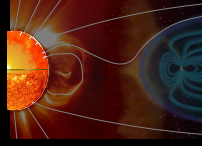


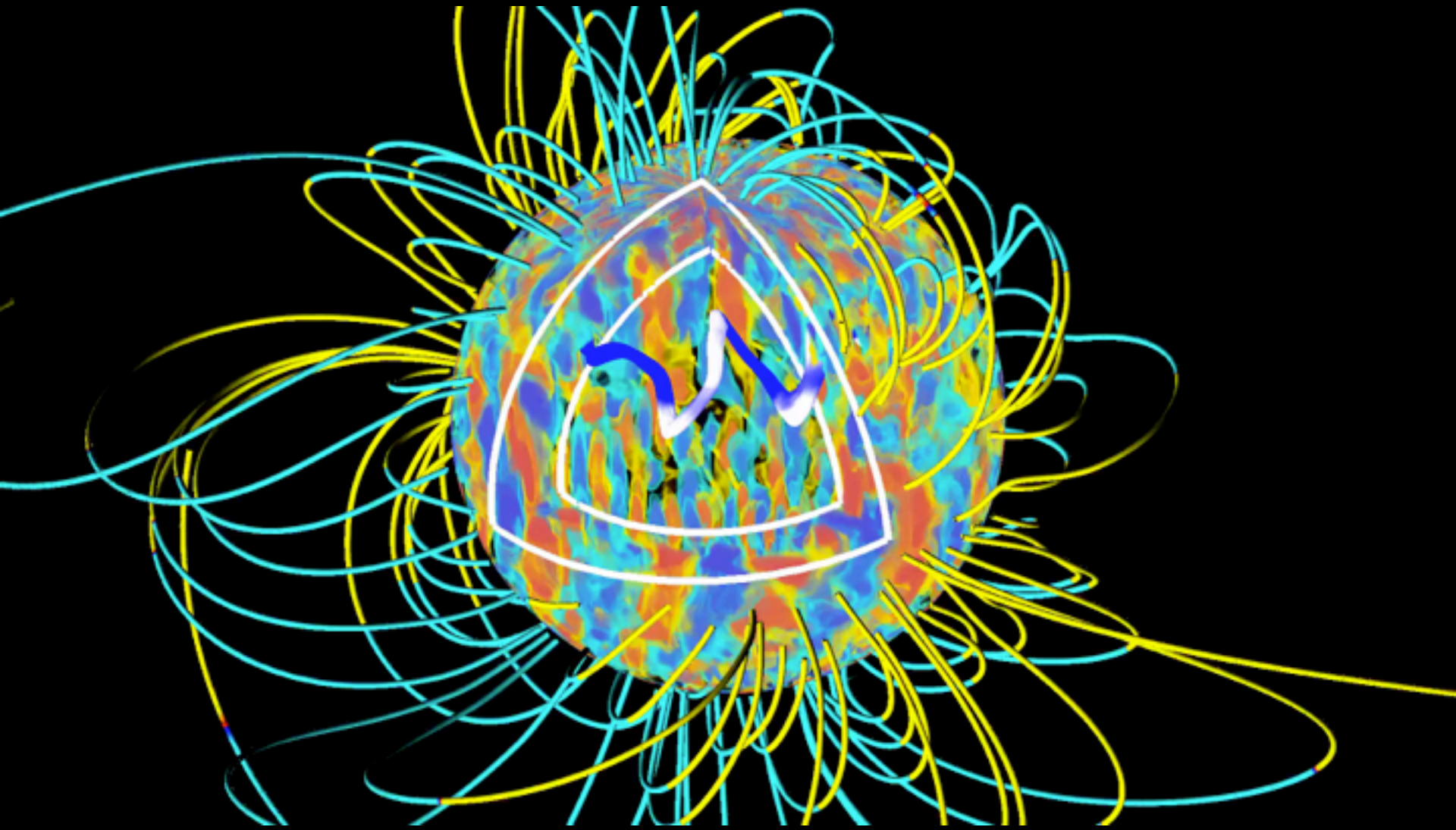


$R_o \sim 0.34$
$N_\rho = 3.2$
$\Delta S = 10^4$ erg/K/g

No stable radiative zone

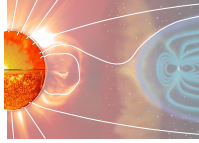
Prototype cyclic dynamo in a convective enveloppe (II)



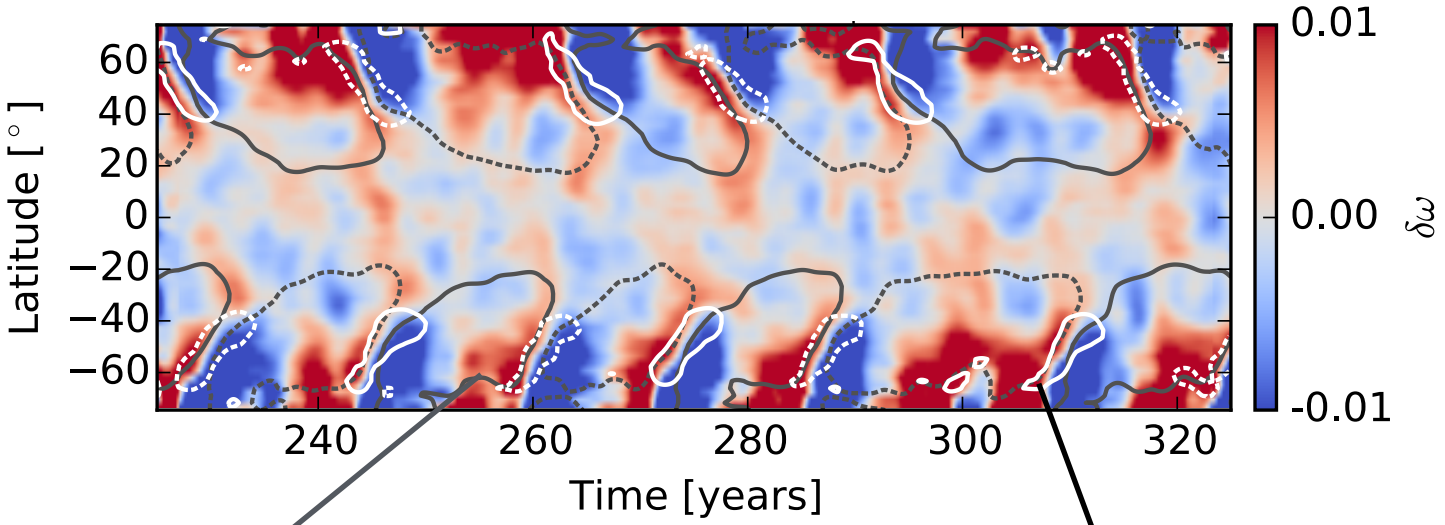


See the new 3D movie ***L'univers numérique*** by B. Thooris

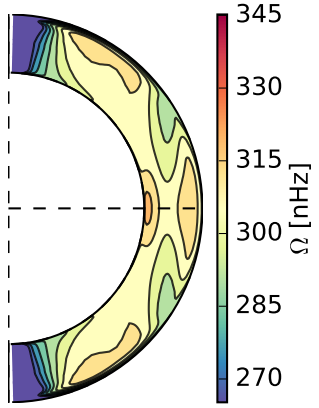
Non-linear cyclic perturbations of the mean diff. rot.



Fluctuation of the mean differential rotation



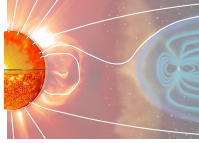
Mean differential rotation



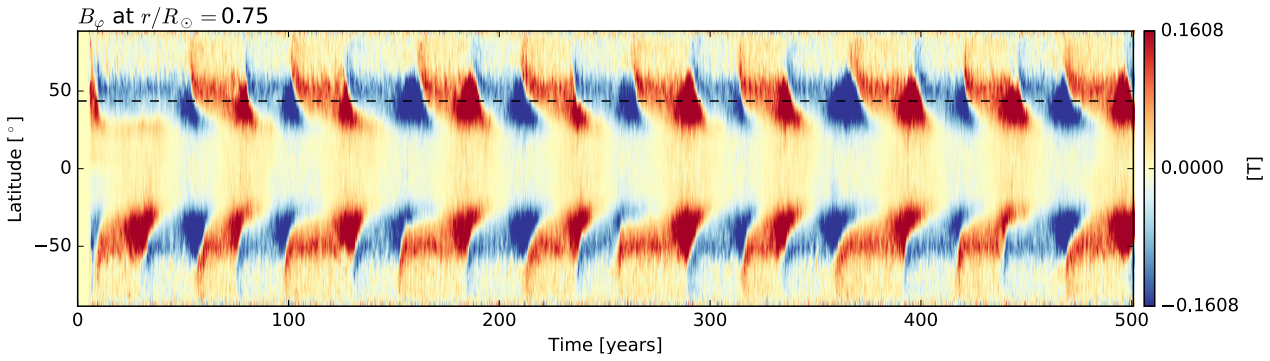
$\langle B_\varphi \rangle$

$$\partial_t \langle B_\varphi \rangle = \nabla \times (\langle \mathbf{U}_\varphi \rangle \times \langle \mathbf{B}_{\mathrm{pol}} \rangle)|_\varphi$$

Systematic modulation of the cycle period

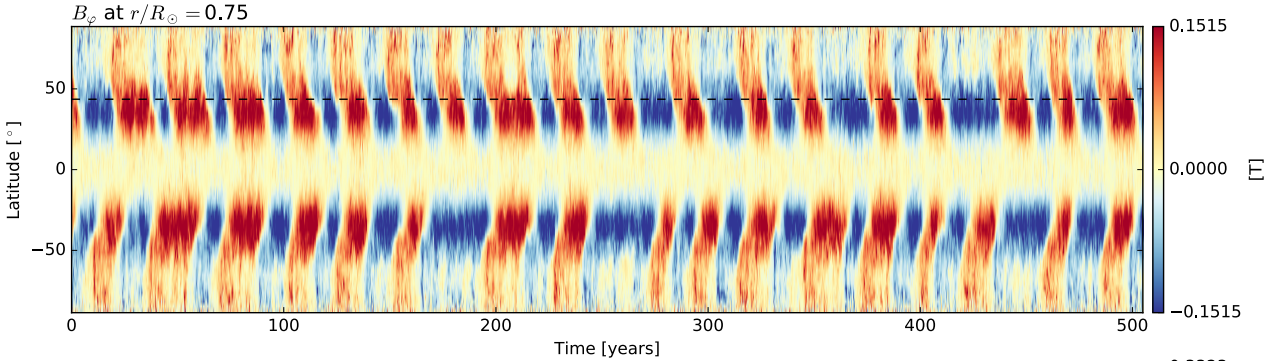


Ref.



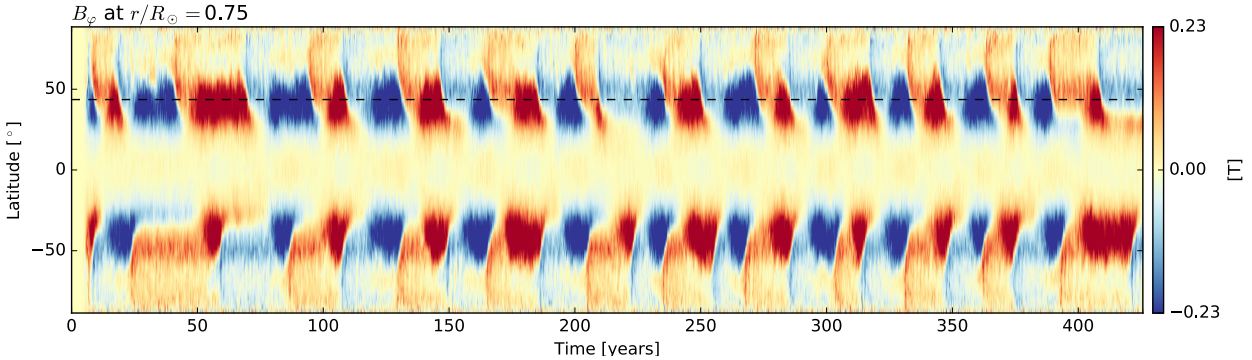
$P_{\rm cyc} = 28$ yrs

$\Omega/2$



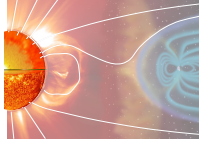
$P_{\rm cyc} = 13$ yrs

Lum. x 2



$P_{\rm cyc} = 17$ yrs

Cycle period is inversely prop. to the Rossby number



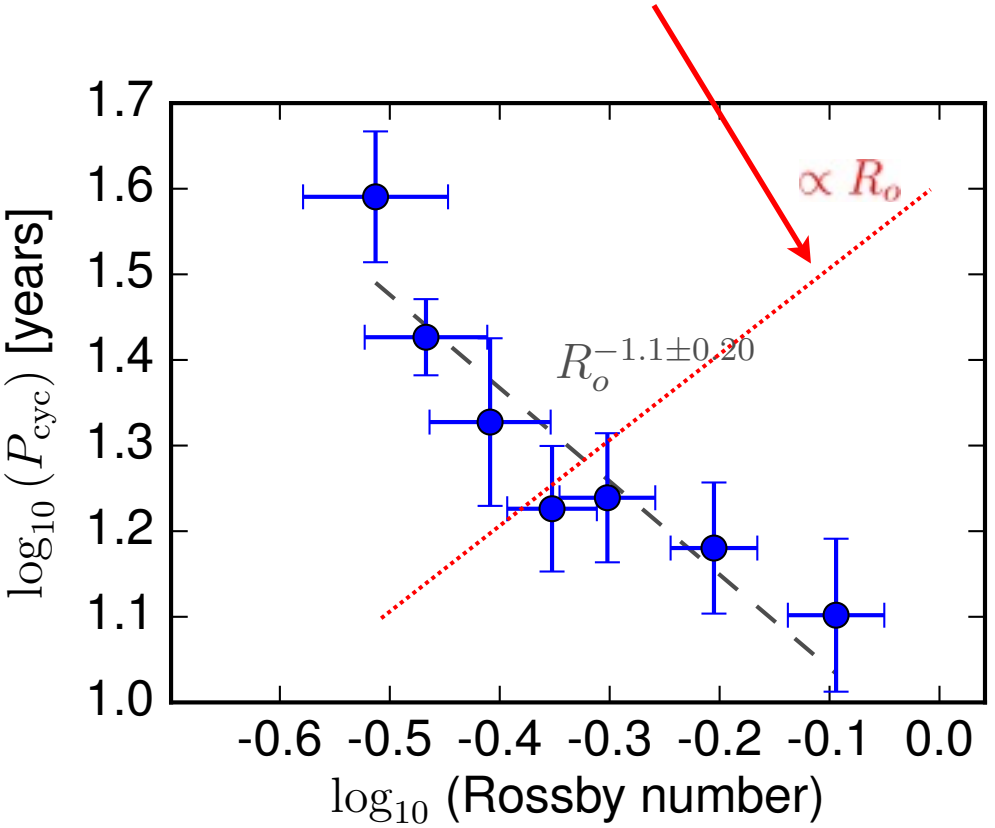
Basic linear $\alpha\Omega$ kinematic dynamo theory

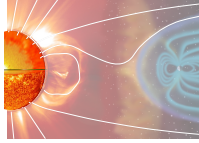
Basic ingredients of stellar dynamos

- Differential rotation
- Cyclonic turbulence

'Go to' parameter is the **Rossby number**

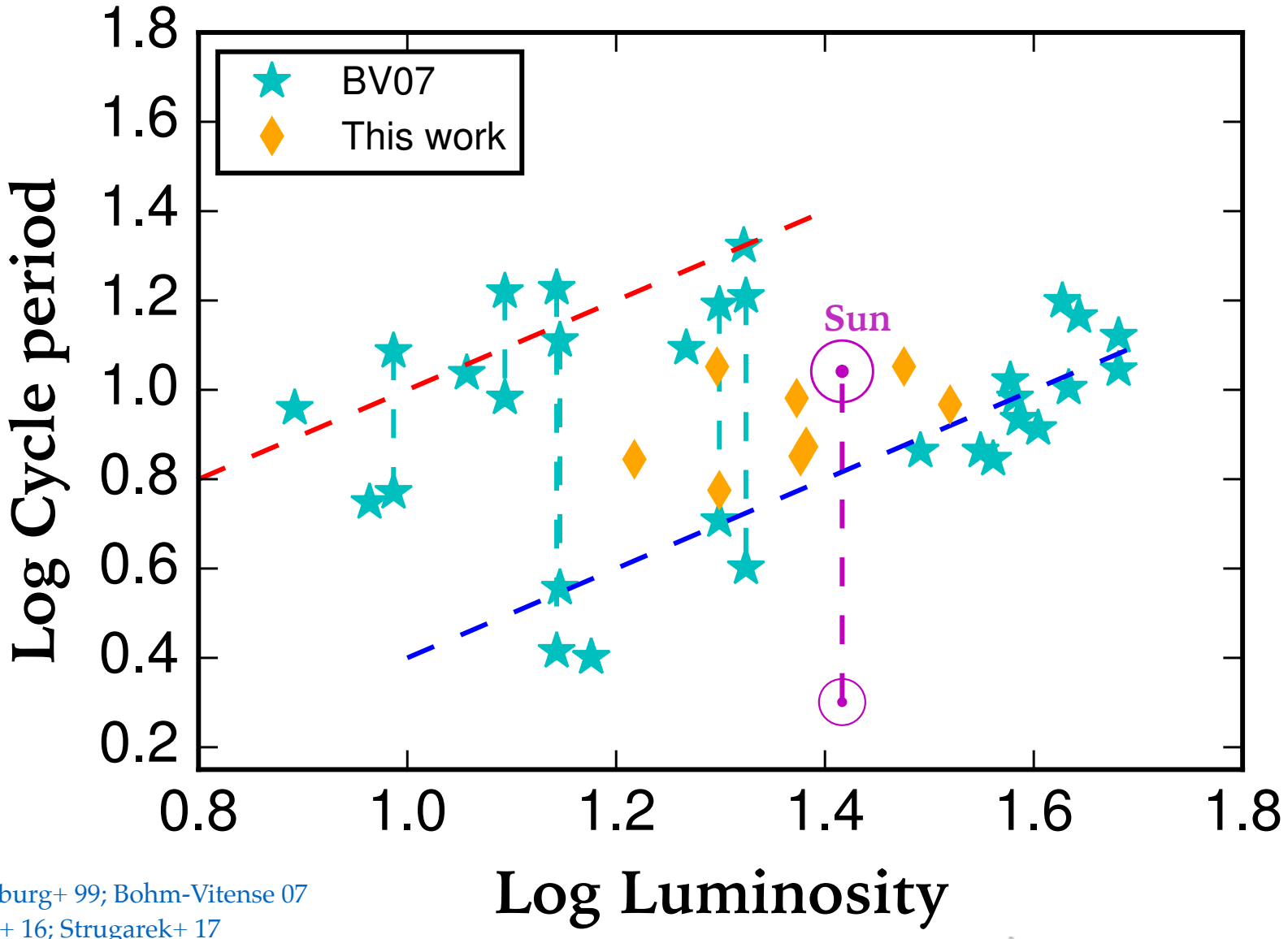
$$R_o = \frac{\text{NL Advection}}{\text{Coriolis}} \sim \frac{|\nabla \times \mathbf{U}|}{2\Omega_\star}$$





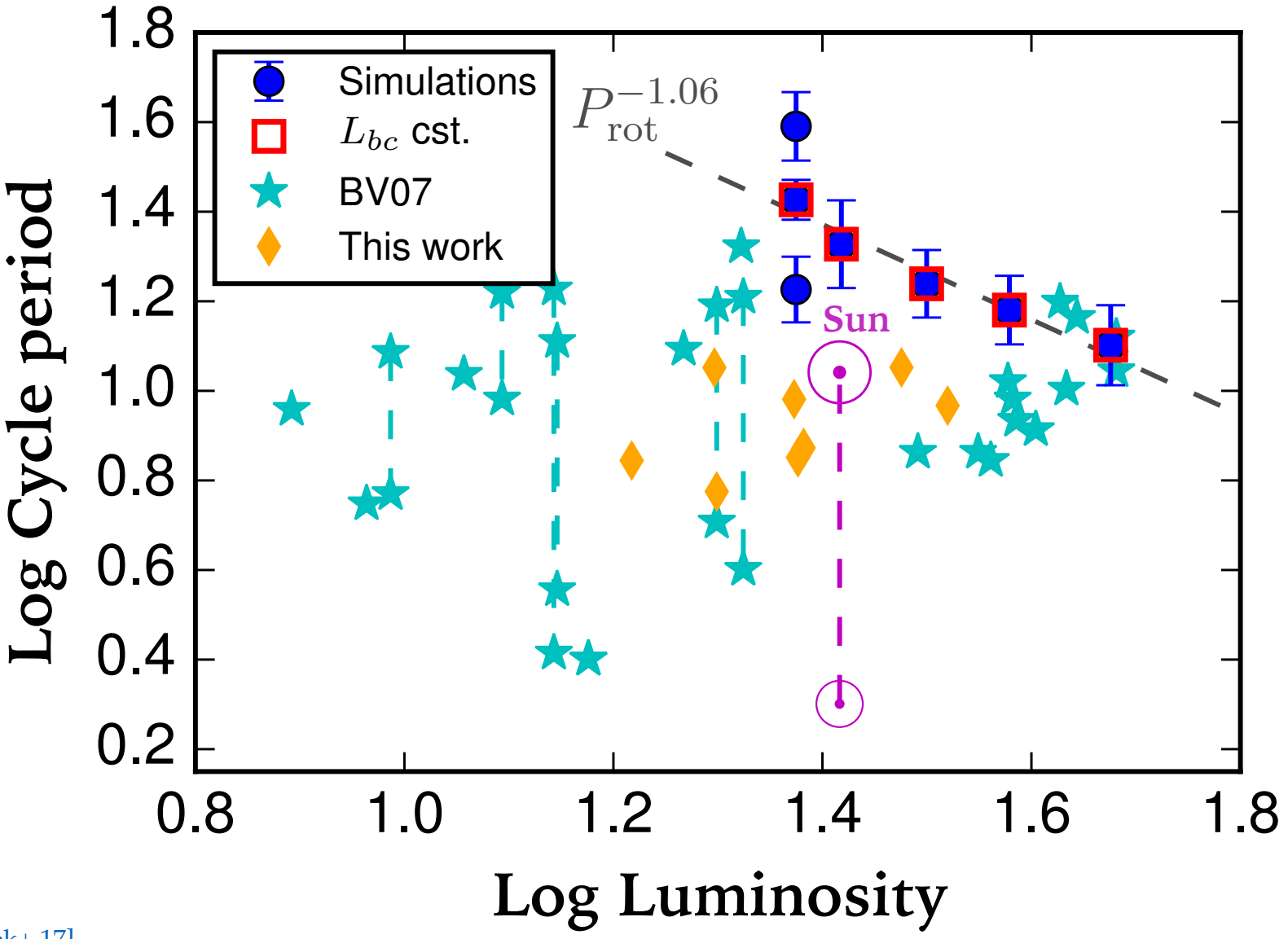
Could this be realistic?

Magnetic cycles in a stellar context



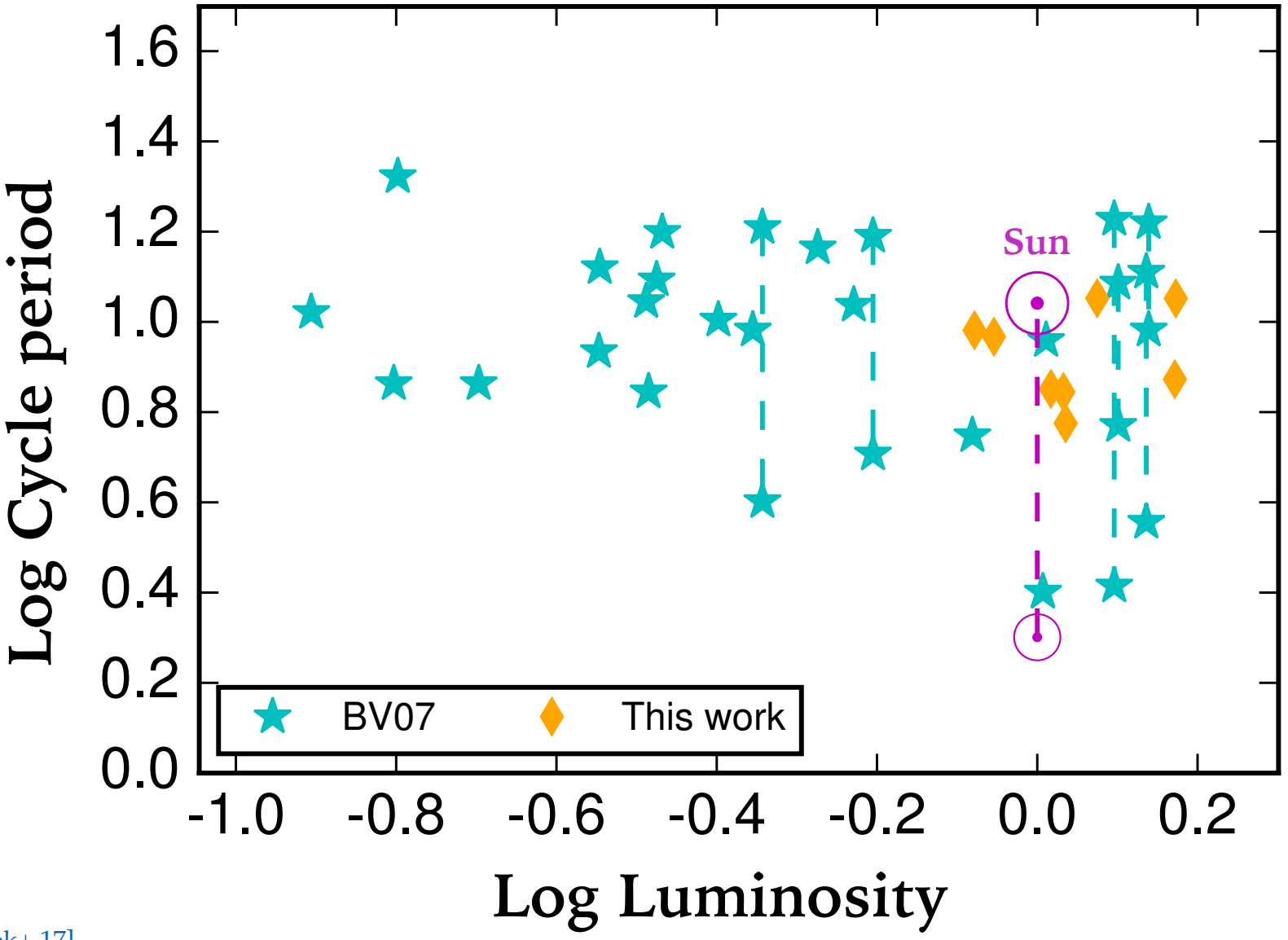
Brandenburg+ 99; Bohm-Vitense 07
Metcalfe+ 16; Strugarek+ 17

Magnetic cycles in a stellar context



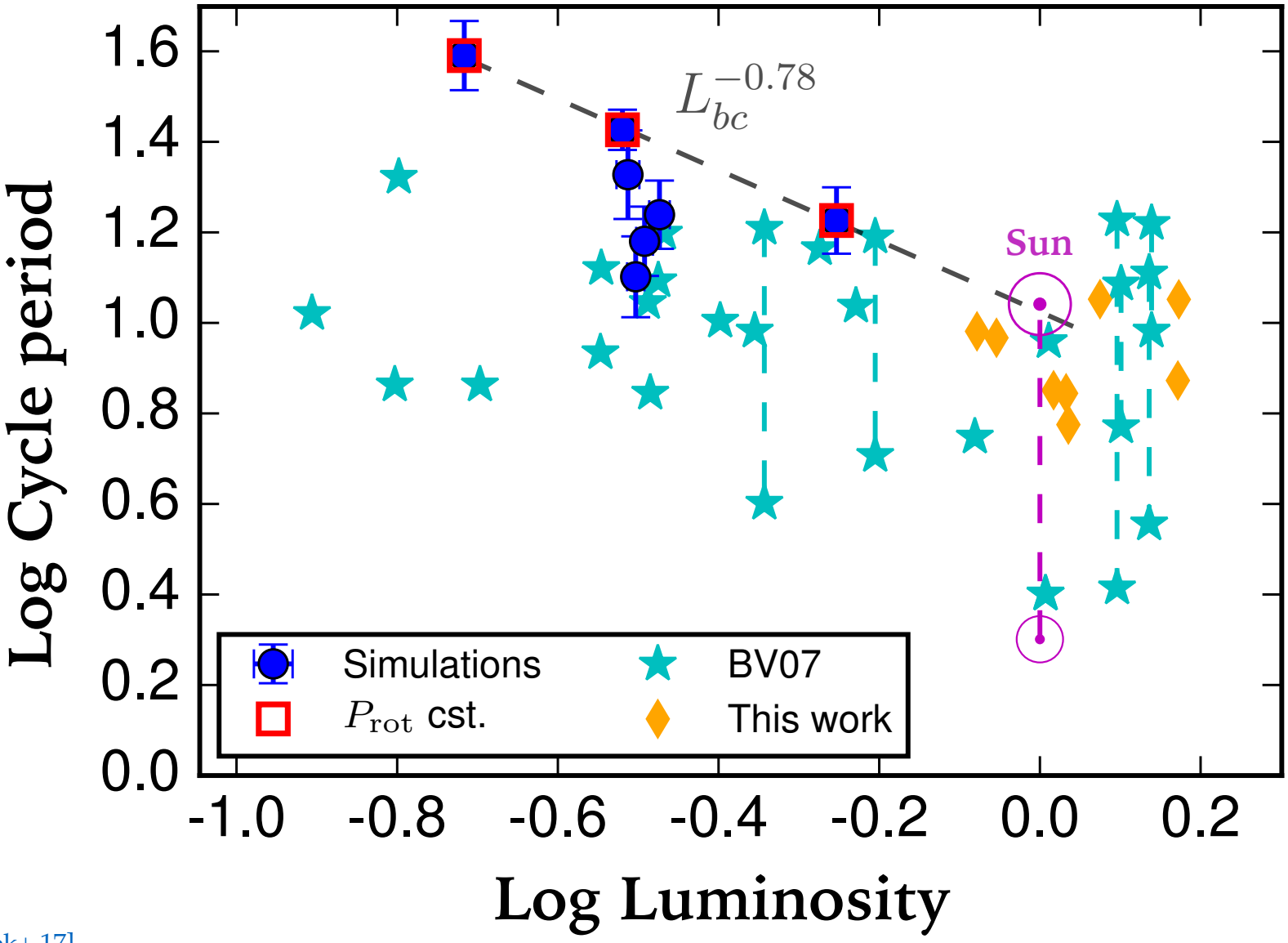
[Strugarek+ 17]

Magnetic cycles in a stellar context



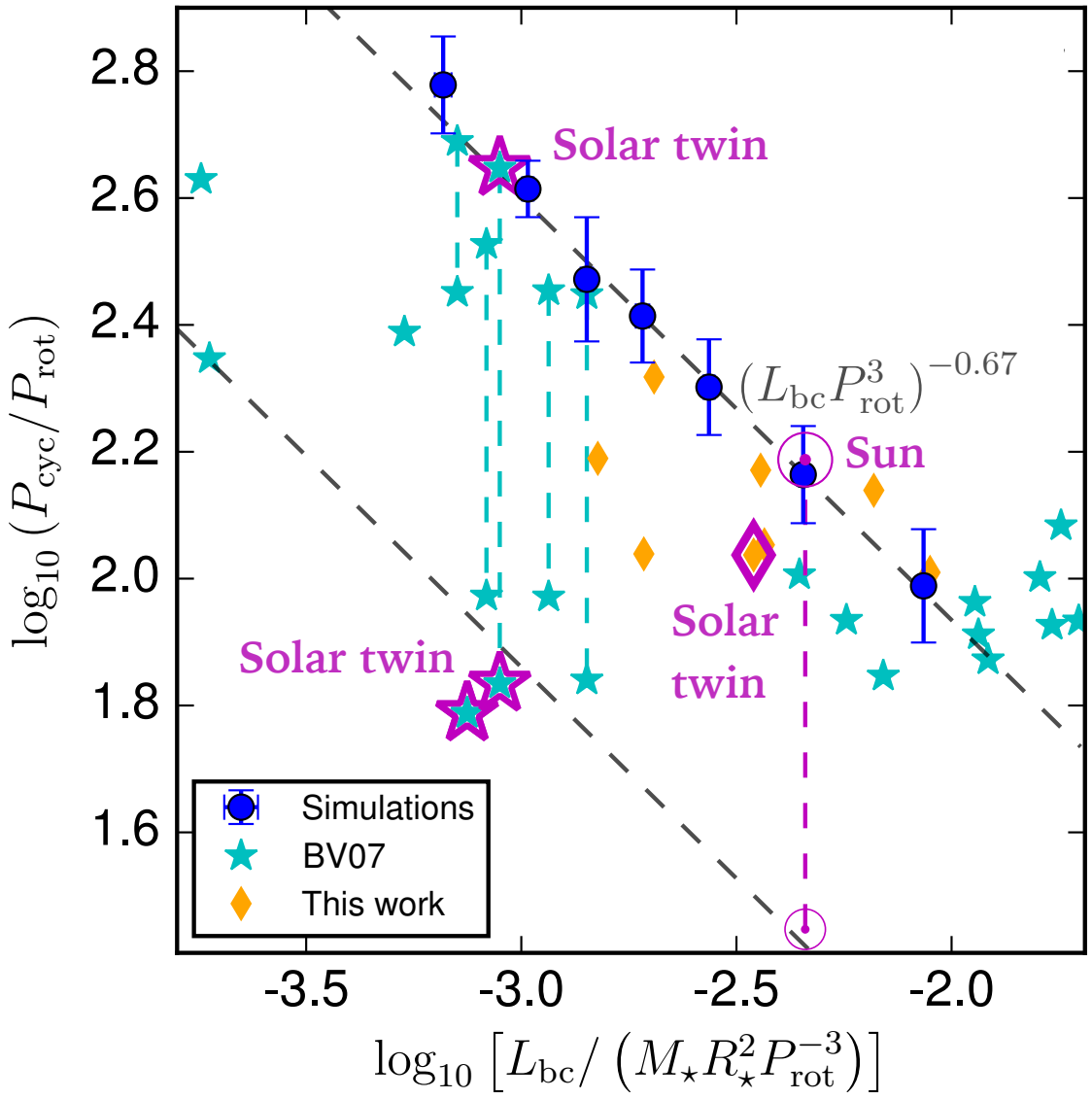
[Strugarek+ 17]

Magnetic cycles in a stellar context



[Strugarek+ 17]

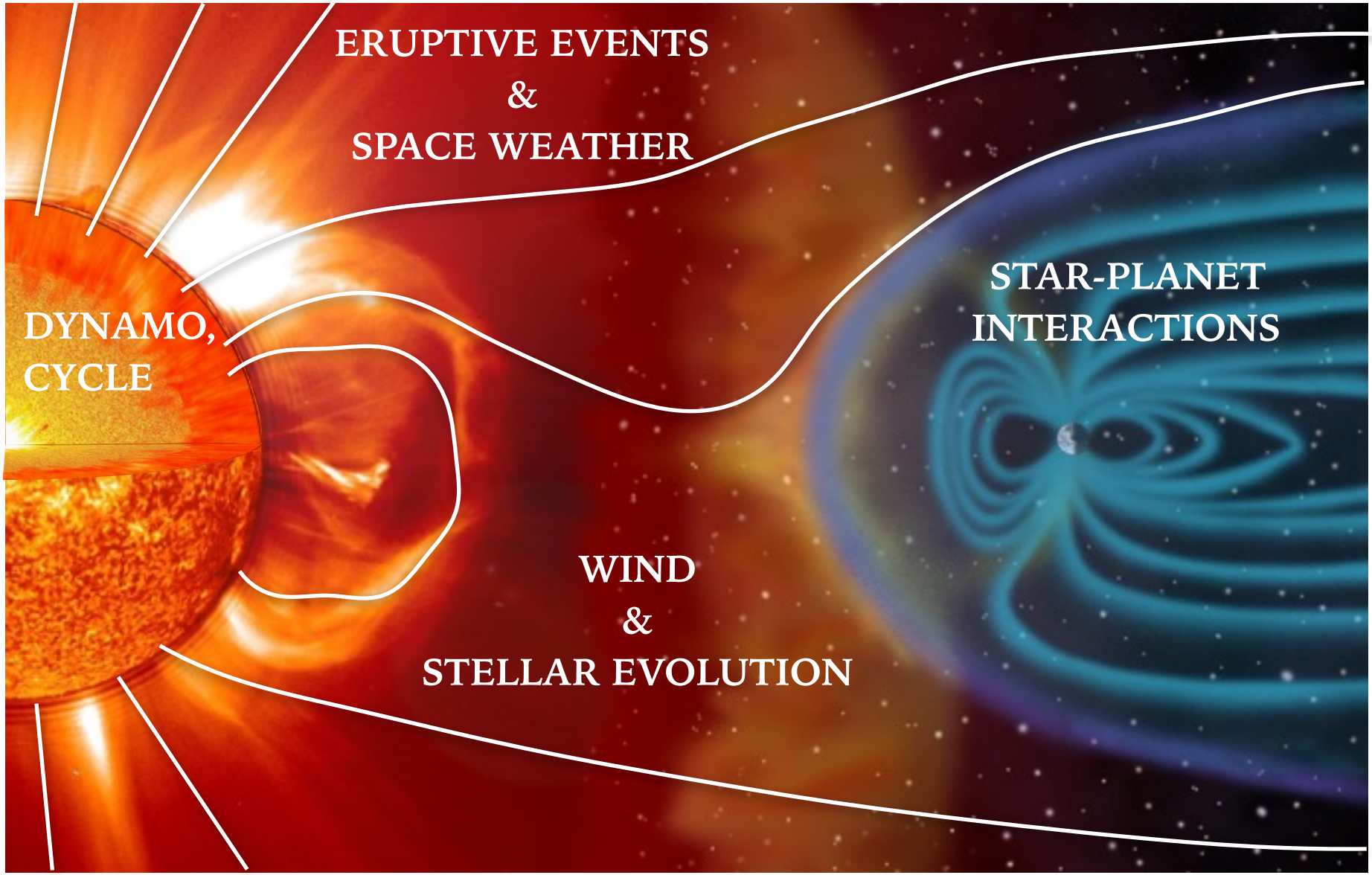
Magnetic cycles in a stellar context

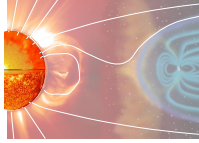


A **non-linear dynamo mechanism** relying on the temporal **fluctuation** of the **large-scale differential rotation**, **reconciling solar and stellar magnetic cycle periods**

[Strugarek+ 17]

Solar & Stellar magnetism: from dynamo to space weather





Thank you for your attention