What is driving the Solar atmosphere? Magnetic reconnection, RHMD and kinetic simulation results

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MPI for Solar

System Reserach

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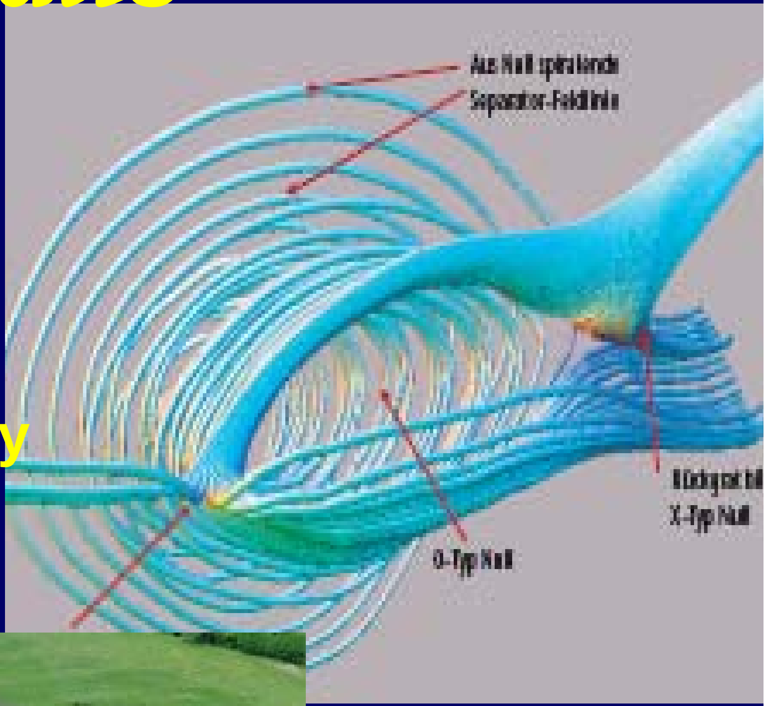
in Germany

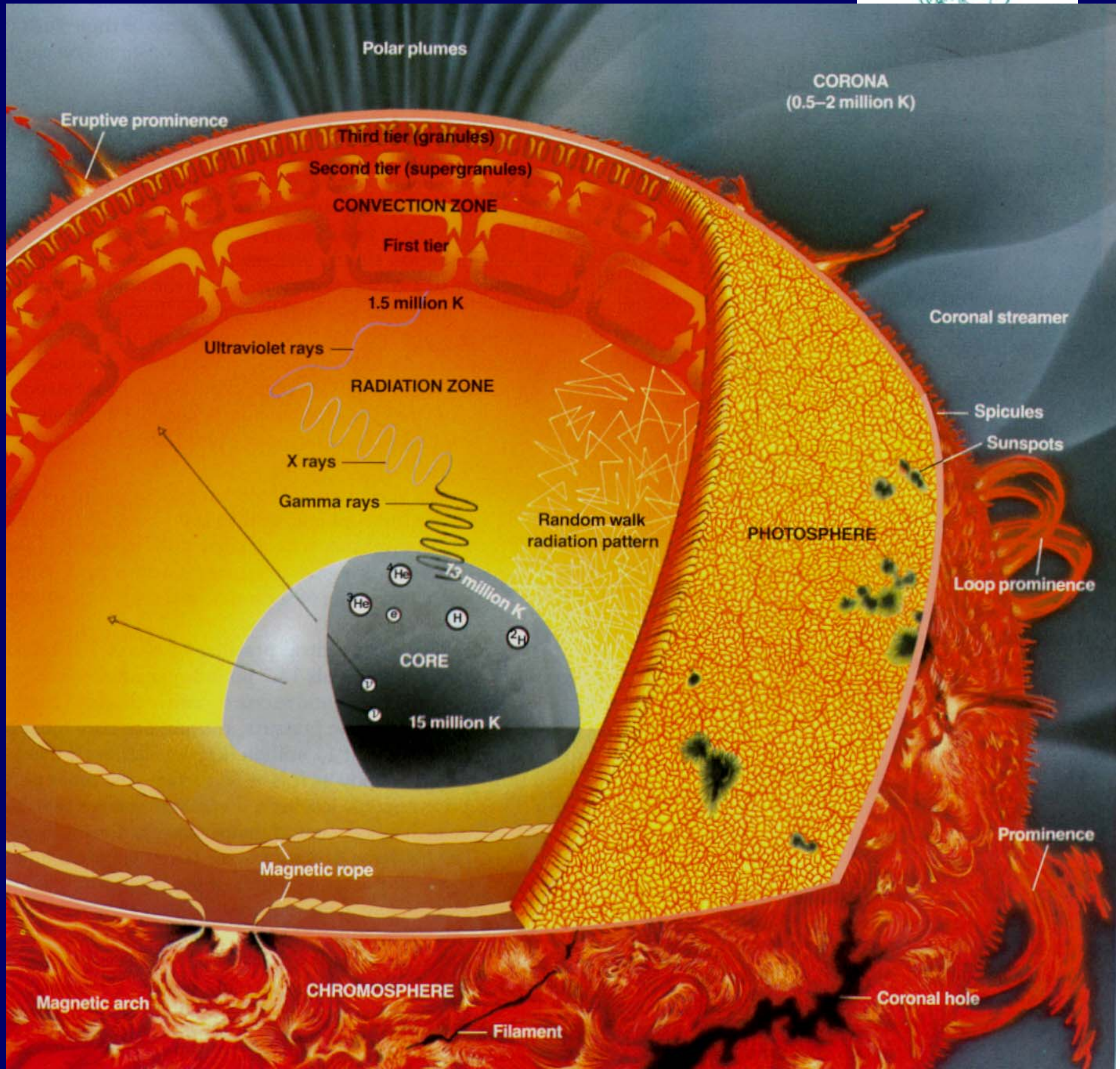


The Sun as a star

Parent galaxy	Milky Way	
Type	fixed star	
Spectral class	G2	
Magnitude	+ 4.8	
Distance to Earth	149 598 000 km	i.e., 1 AU
Radius R_s	696,000 km	i.e., 109 R_E
Total mass M_s	1.989×10^{30} kg	i.e., 333 000 M_E
Density (average)	1.409 g cm^{-3}	
Surface temperature	5800 K	
Rotation duration	25 days at equator.	
	35 days at poles.	
Age	4.60 billion years	
Number of planets	8 by definition	
Next neighbor star	Alpha-Centauri, at 4.37 light years	
Next neighbor galaxy	Magellan's Clouds, at 165.000 light years	
Earth's distance variation	+/- 1.69 % (+ in July, - in January)	
Apparent diameter	31' 59.3" = 1913.3 "	i.e. 0.5 degree
Apparent radius	959.65"	i.e. 1000 arcsec
1 arcsec on sun, from Earth	725 km	
Energy output	3.82×10^{33} Watt	
Energy input into Earth	1.370 Watt/m^{-2}	
total	173 Mio Gigawatt	

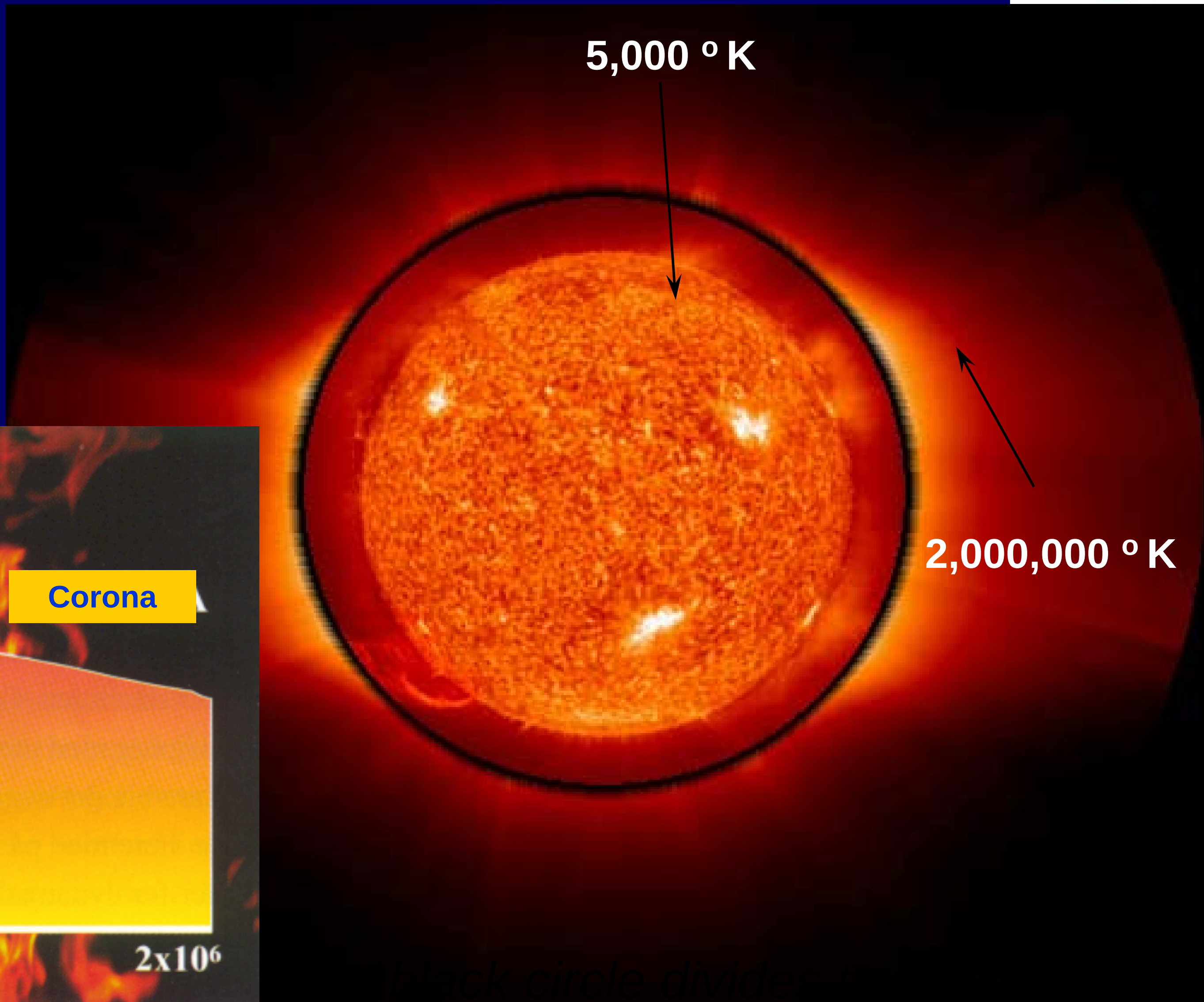
The Sun as an onion

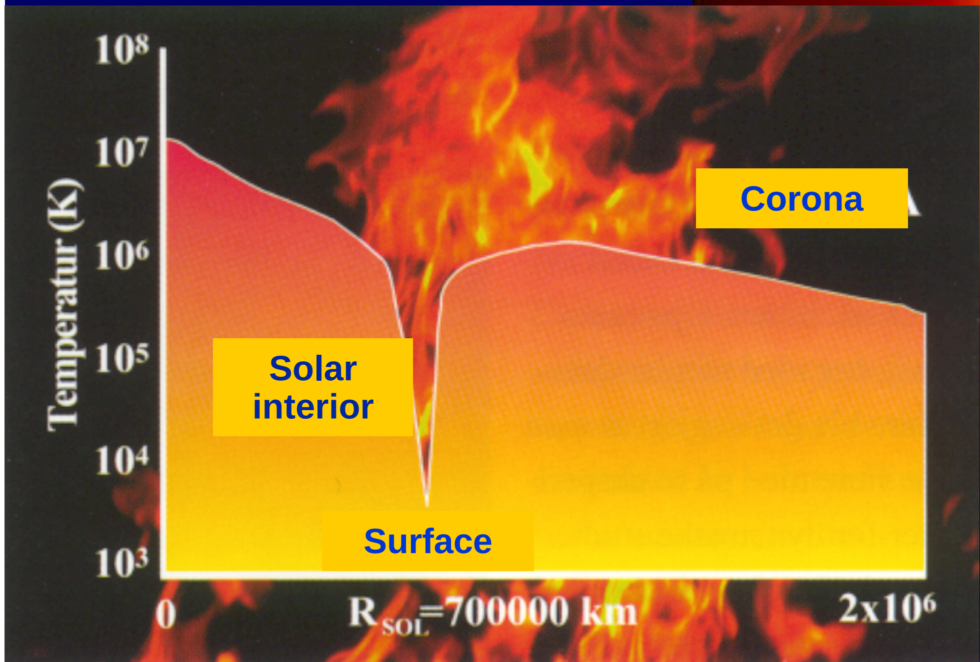
- Source in the **Core:** 700 Million tons of He burned per second
- **Radiation zone:** Photon transport over Millions of years
- **Convection zone:** Cellular convective transport
- **Photosphere:** Plasma cools down to 6000 K
- **Atmosphere: Chromosphere & Corona:**
  - **Temperature rises to millions of K**
  - **Solar WInd ejected**



The atmosphere of the Sun

Above the photosphere the temperature rises from 6000 K to millions of K and the hot plasma is accelerated into the solar wind





Dynamics:150 years of flare observations

MONTHLY NOTICES

OF THE

ROYAL ASTRONOMICAL SOCIETY.

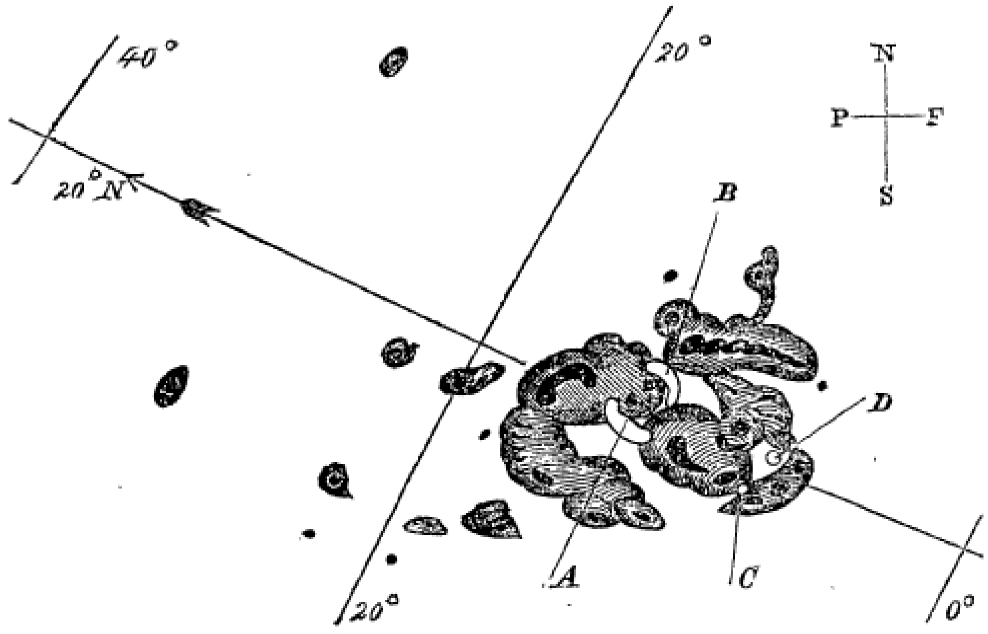
VOL. XX. *Nov.* 11, 1859. No. 1.

It has been very gratifying to me to learn that our friend Mr. Hodgson chanced to be observing the sun at his house at Highgate on the same day, and to hear that he was a witness of what he also considered a very remarkable phenomenon. I have carefully avoided exchanging any information with that gentleman, that any value which the accounts may possess may be increased by their entire independence.

(Mr. Carrington exhibited at the November Meeting of the Society a complete diagram of the disk of the sun at the time, and copies of the photographic records of the variations of the three magnetic elements, as obtained at Kew, and pointed out that a moderate but very marked disturbance took place at about 11^{h} 20^{m} A.M., Sept. 1st, of short duration; and that towards four hours after midnight there commenced a great magnetic storm, which subsequent accounts established to have been as considerable in the southern as in the northern hemisphere. While the contemporary occurrence may deserve noting, he would not have it supposed that he even leans towards hastily connecting them. "One swallow does not make a summer.")

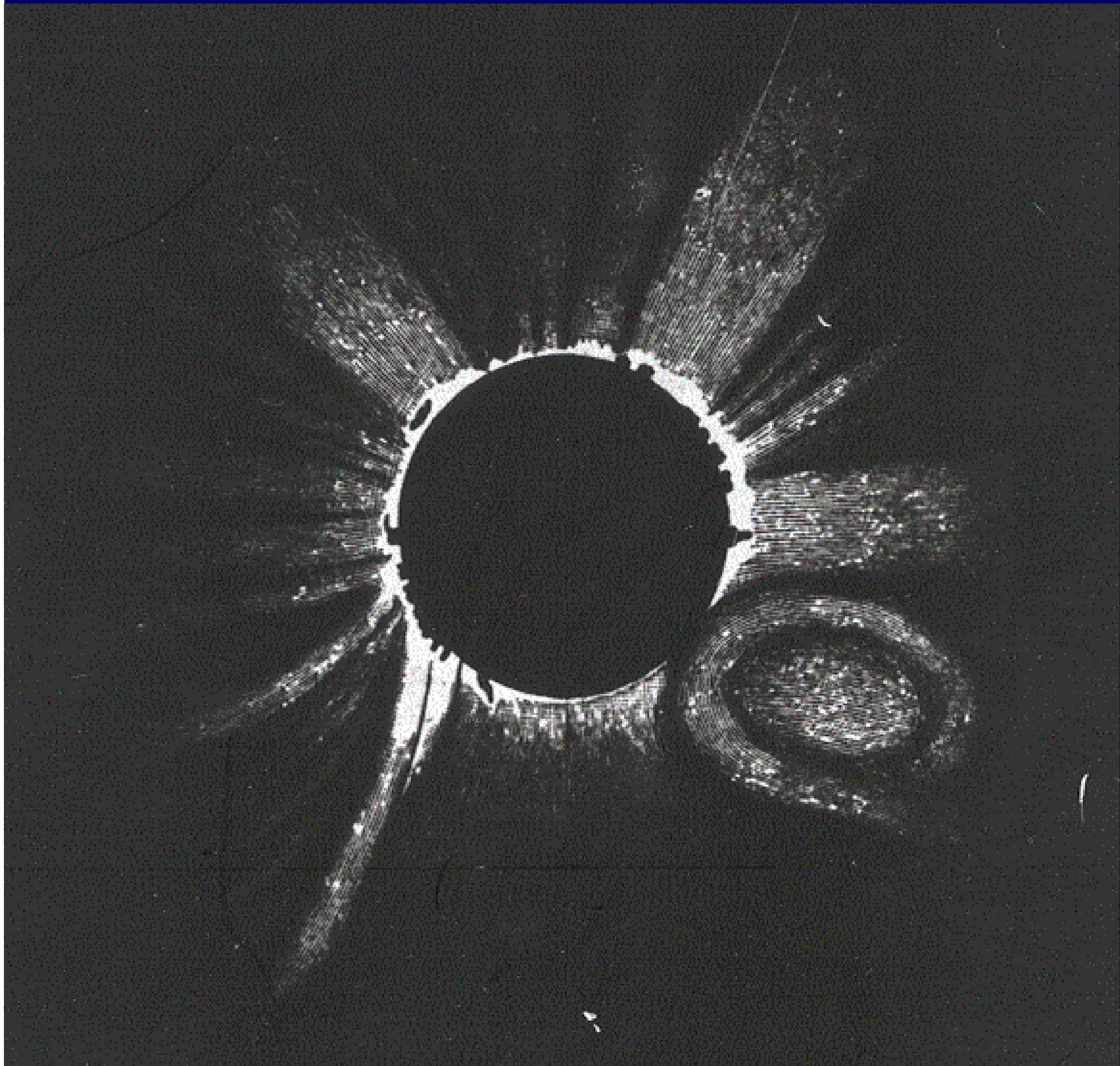
Description of a Singular Appearance seen in the Sun on September 1, 1859. By R. C. Carrington, Esq.

While engaged in the forenoon of Thursday, Sept. 1, in taking my customary observation of the forms and positions of the solar spots, an appearance was witnessed which I believe to be exceedingly rare. The image of the sun's disk was, as usual with me, projected on to a plate of glass coated with distemper of a pale straw colour, and at a distance and under a power which presented a picture of about 11 inches diameter. I had secured diagrams of all the groups and detached spots, and was engaged at the time in counting from a chronometer and recording the contacts of the spots with the cross-wires used in the observation, when within the area of the great north group (the size of which had previously excited general remark), two patches of intensely bright and white light broke out, in the positions indicated in the appended diagram by the letters A and B, and of the forms of the spaces left white. My



first impression was that by some chance a ray of light had penetrated a hole in the screen attached to the object-glass, by

… and plasma detachments



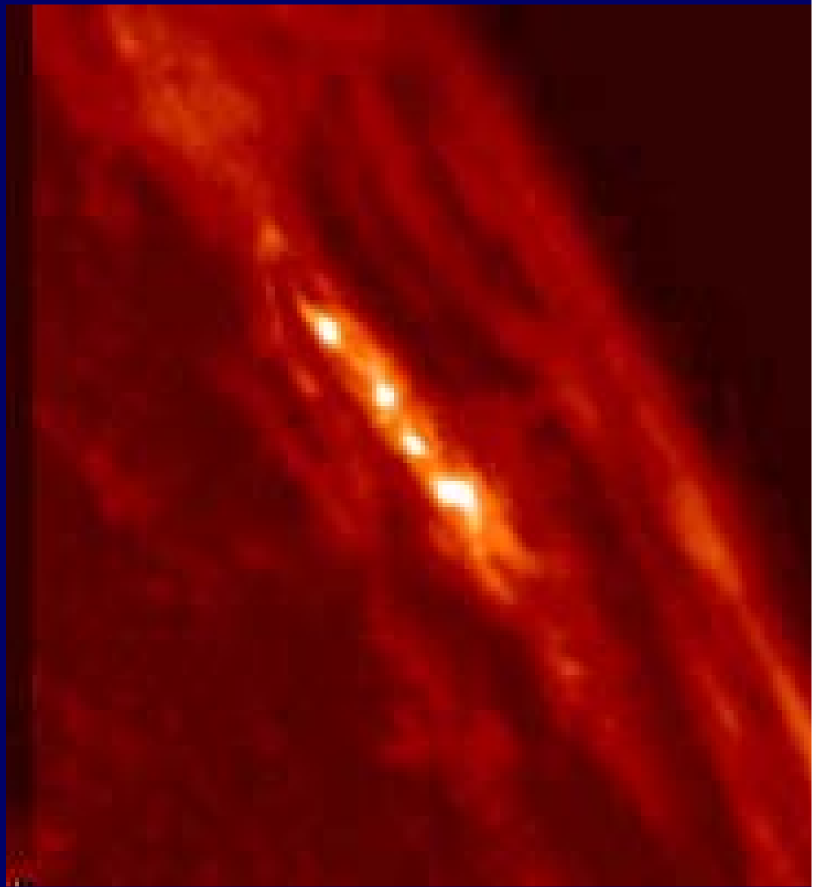
Maybe, the oldest drawing of a plasma detachment from the Sun (or what is now called „CME“, a Coronal Mass Ejection) seen 1860 in Tempel, Spain [Ranyard, 1879]

Flares -> Quakes

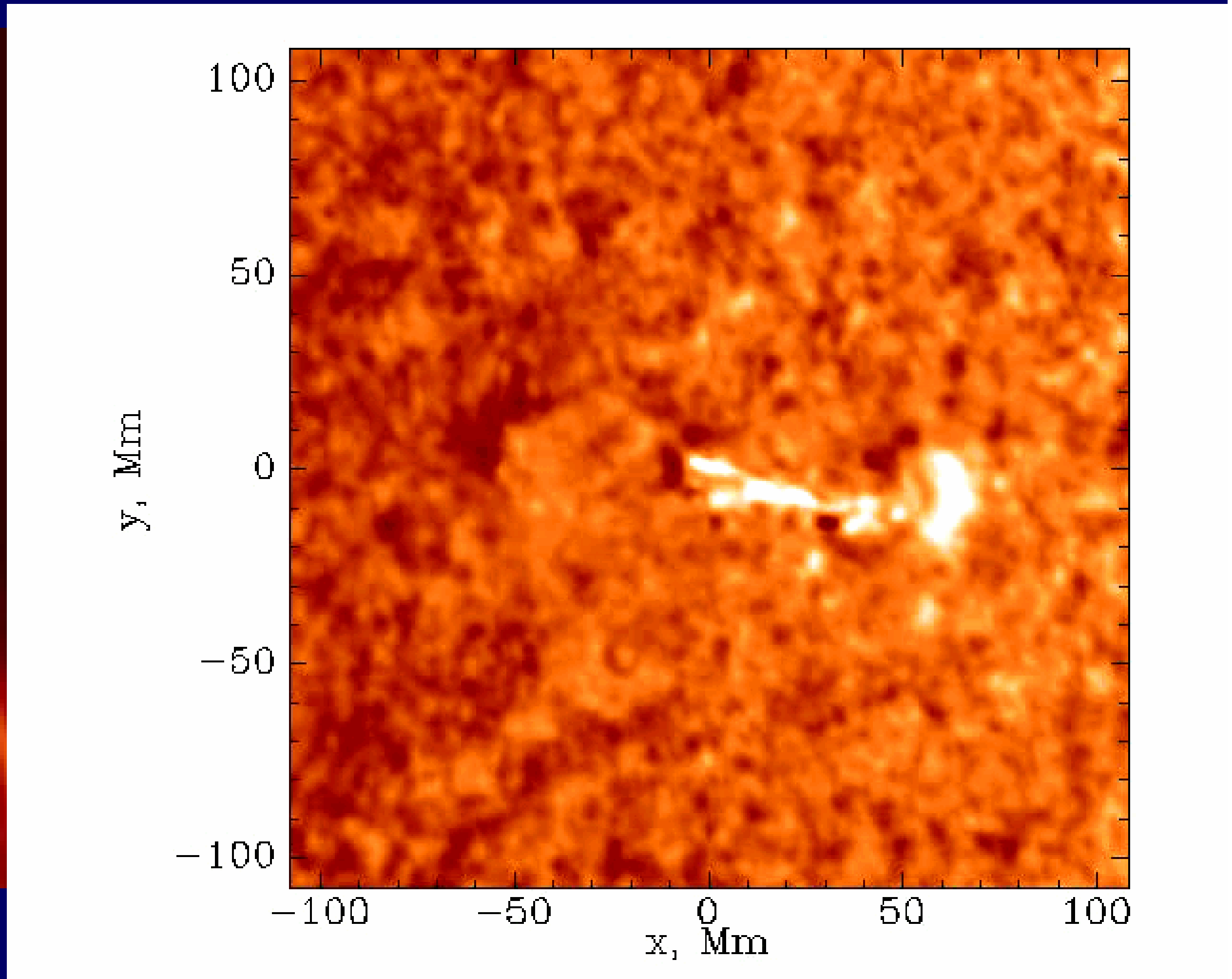
Nowadays: direct observations Flares as sudden eruptions of radiation, especially from so called „active regions“ (sunspots)

Flares -> Quakes

TRACE s/c



SOHO-MDI

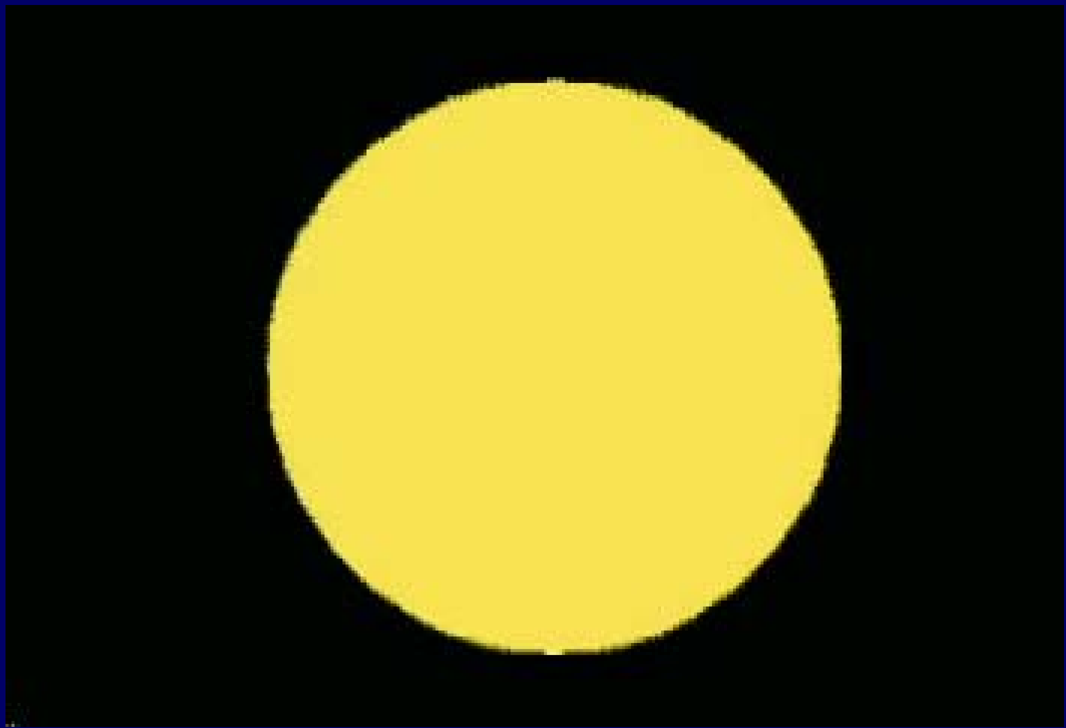


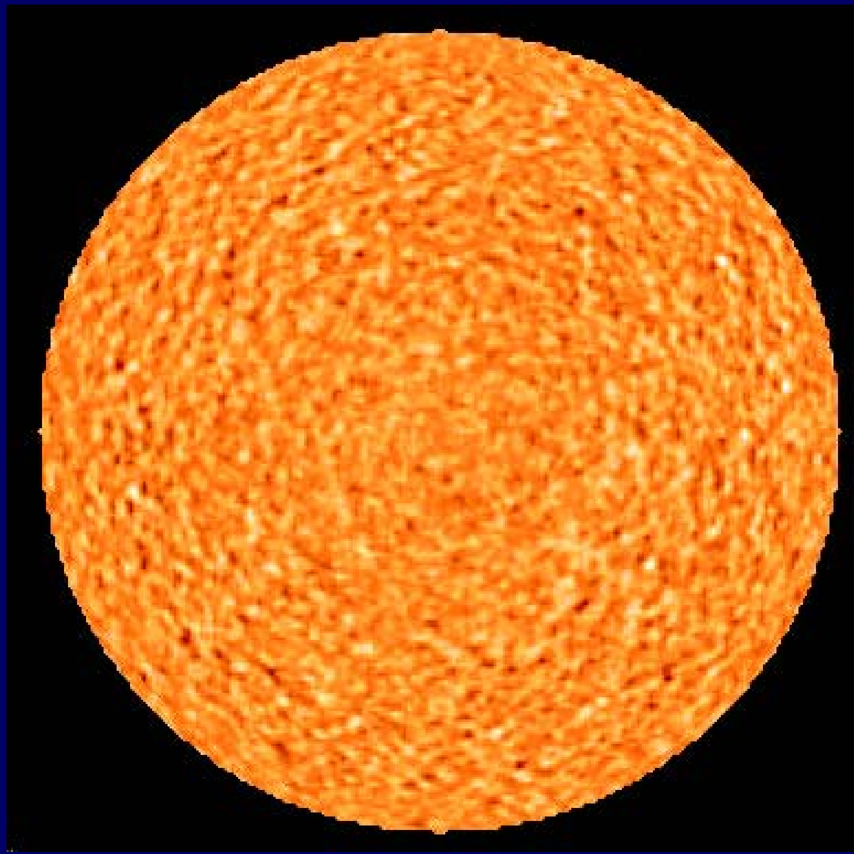
Helioseismology of the interiour

- Quakes and vibrations of the sun are used for diagnostics:
- The internal wave reflections tell us more about the interiour of the sun
  -> helioseismology:

Acoustic signal:

(42 000 times accelerated)

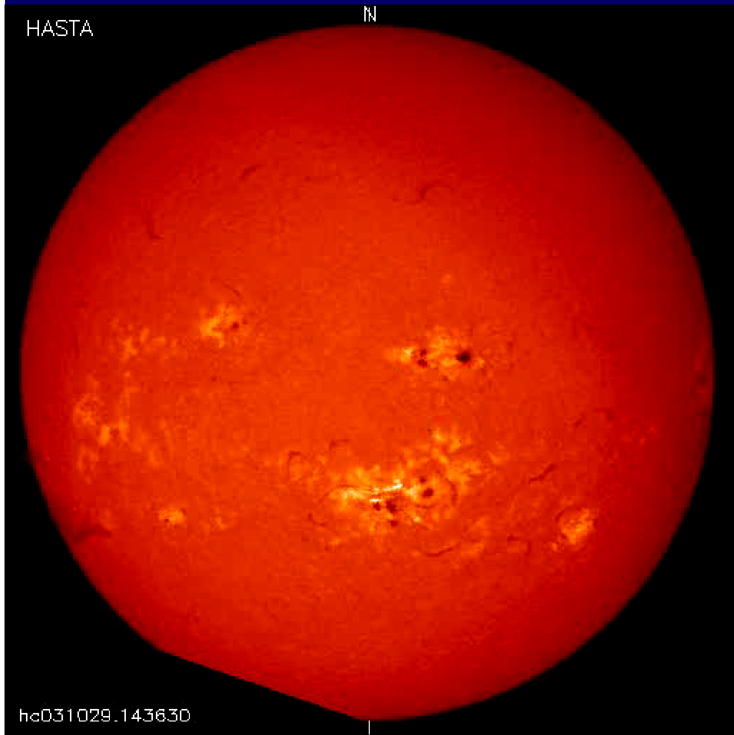


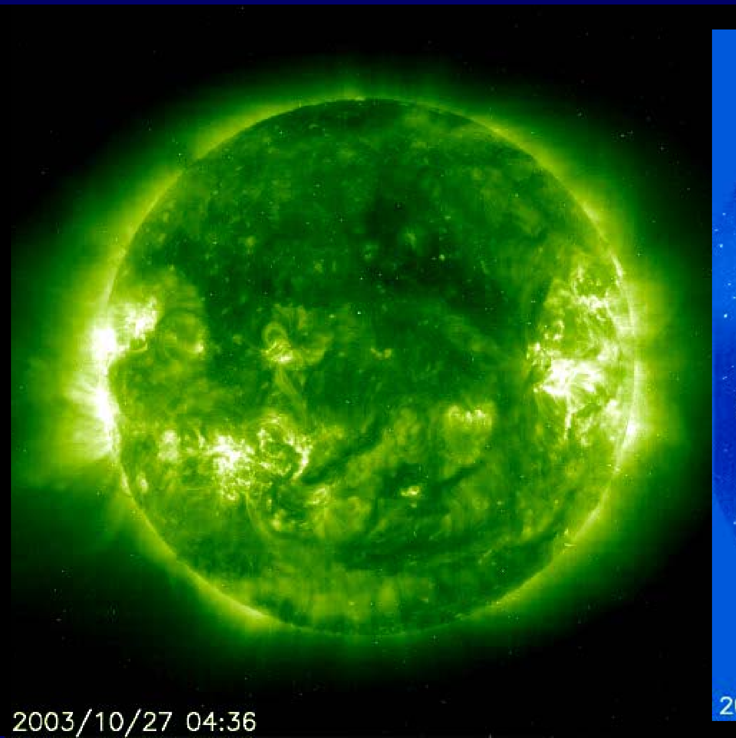


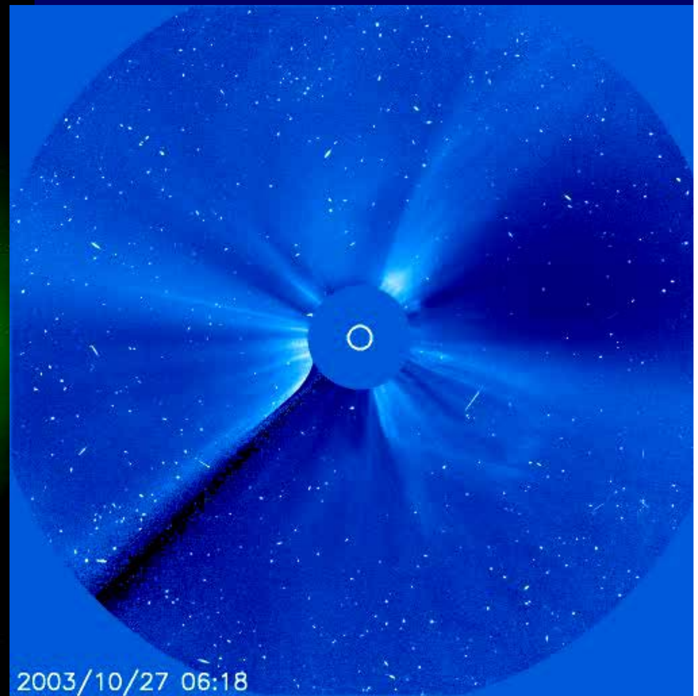
Observations of the atmosphere

**Obervation of two strong Flares:
28.10.2003 (X17.2) and
29.10.2003 (X10.0)**

(„snow storm“: due to energetic particles that disturb the camera CCD)





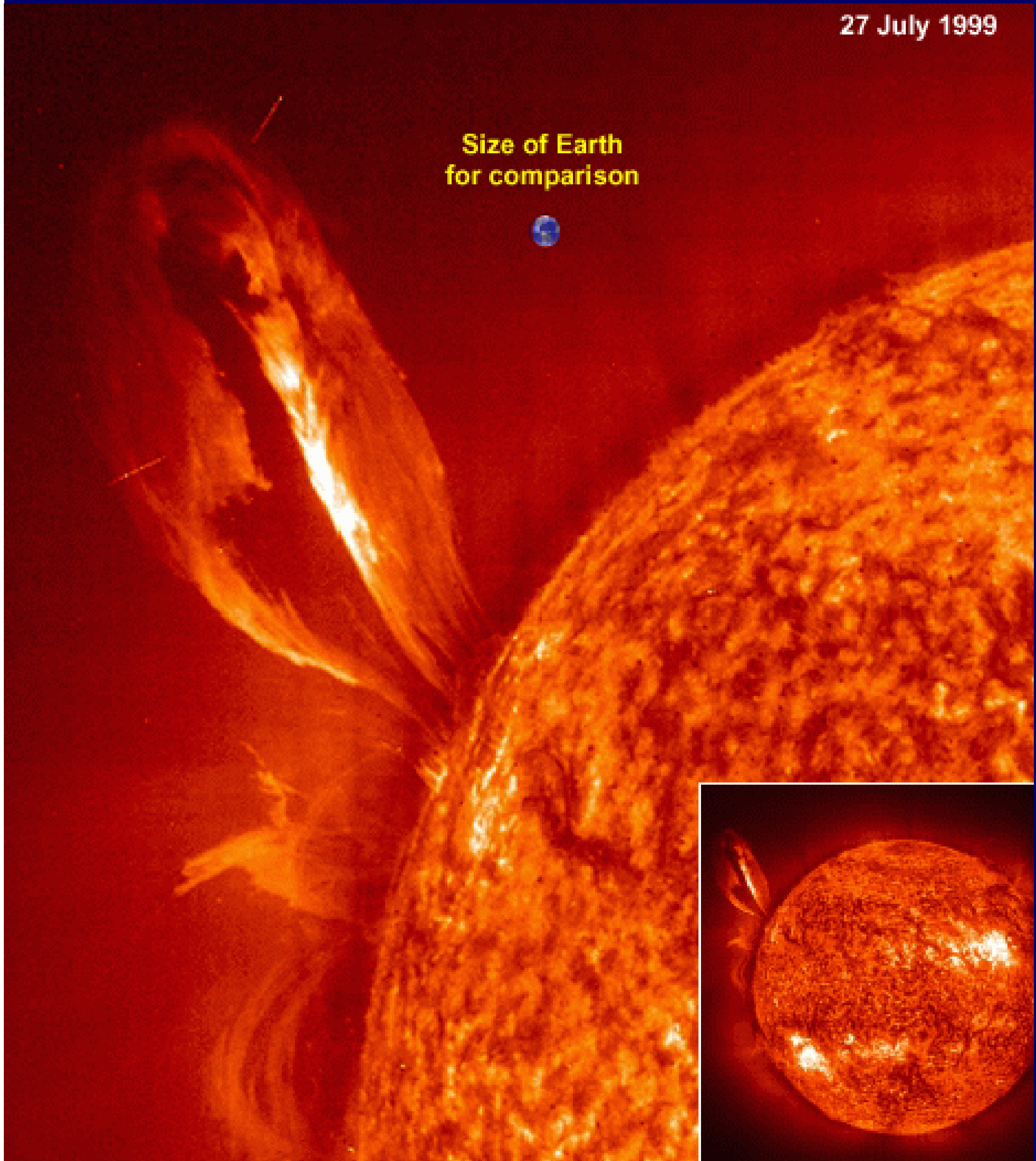


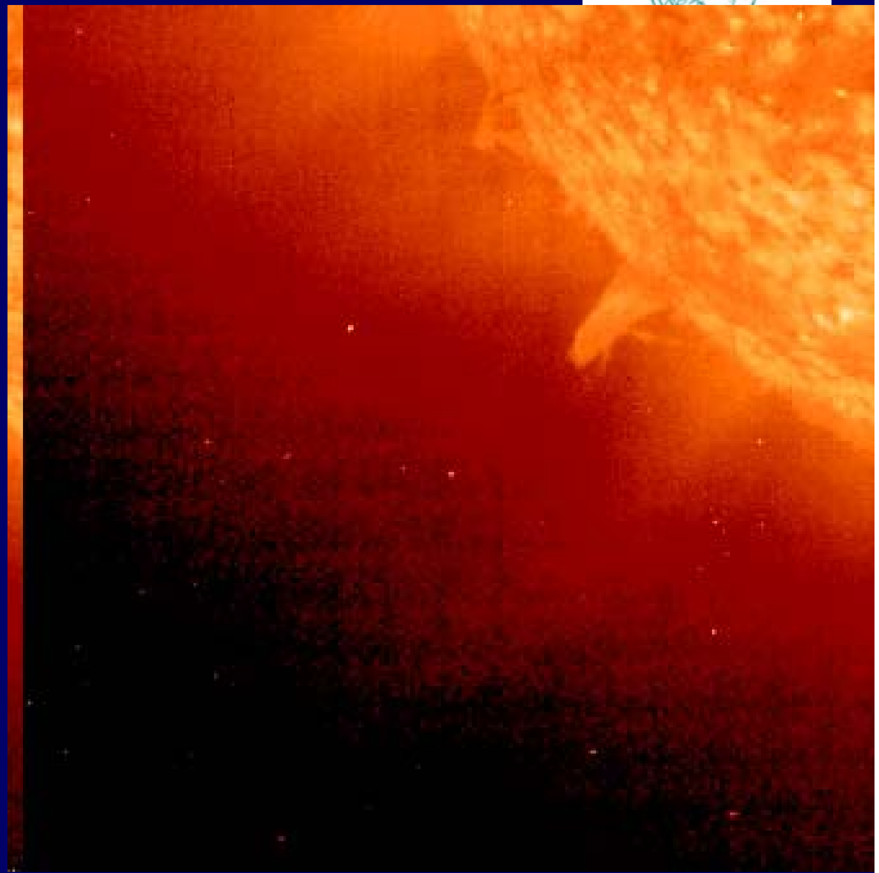
B-field (HASTA, El Leoncito)

EUV Image (EIT on SOHO)

Coronography (LASCO-C3, SOHO)

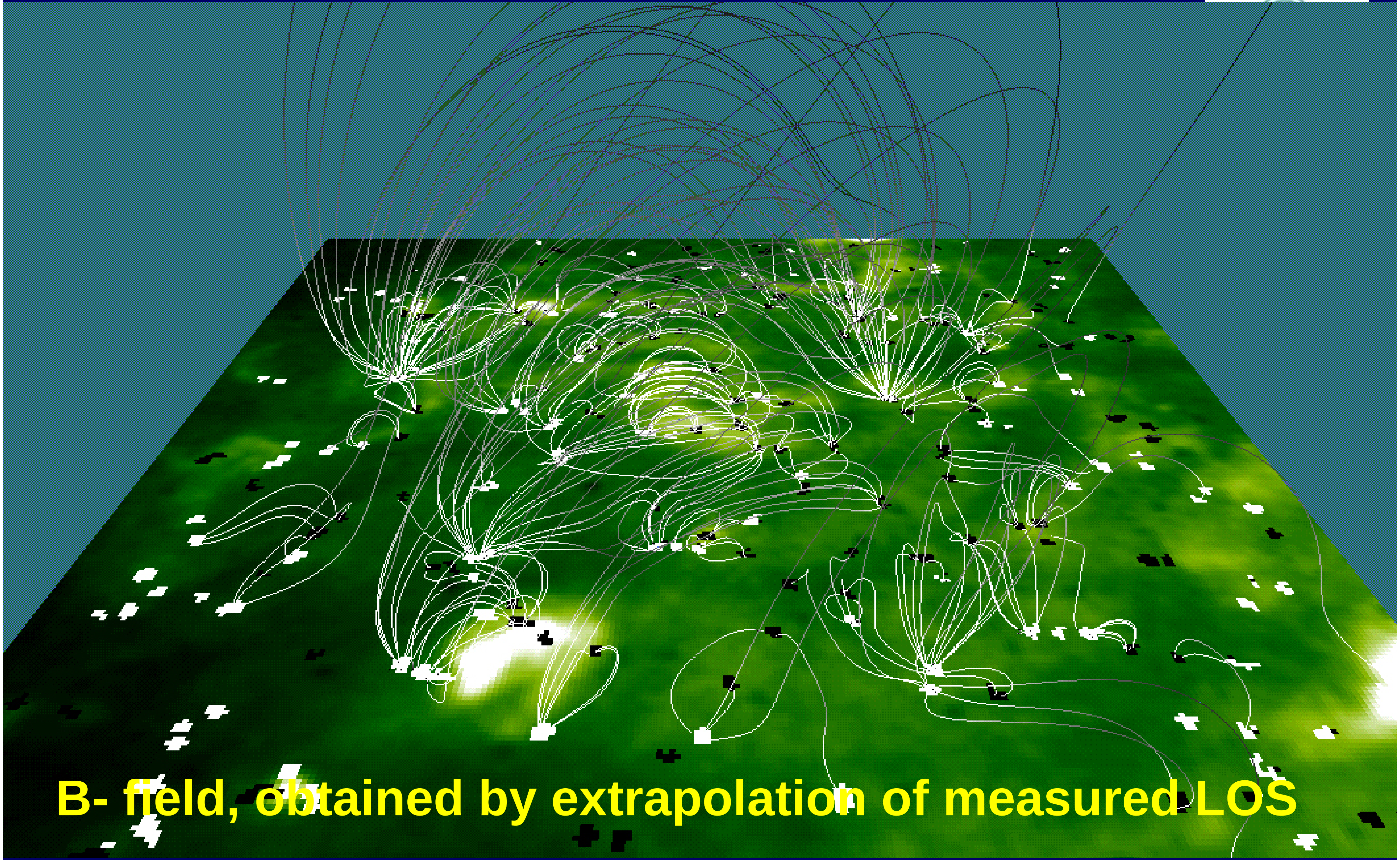
Prominence eruptions



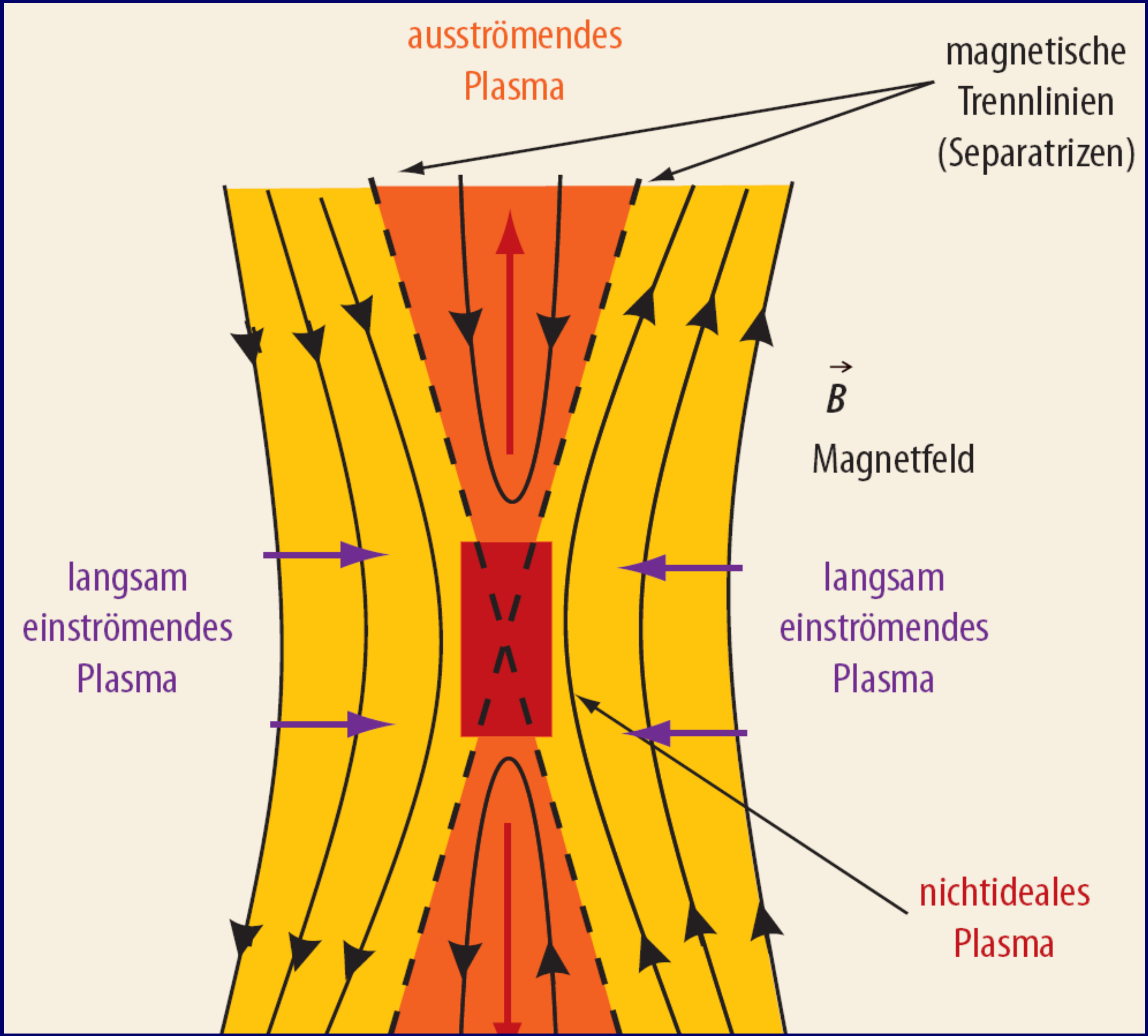


Prominence eruptions -> CMEs

Extrapolation: magnetic carpet

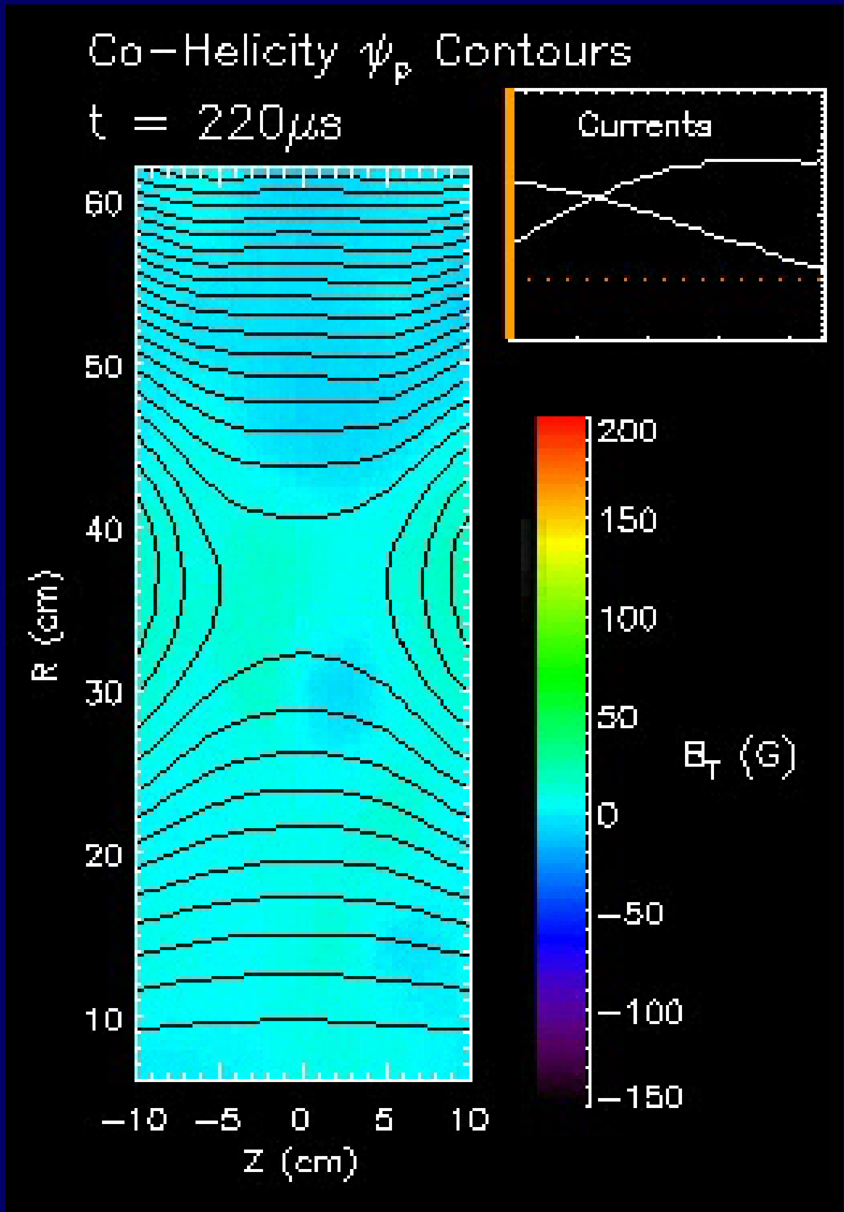


Energy release by reconnection

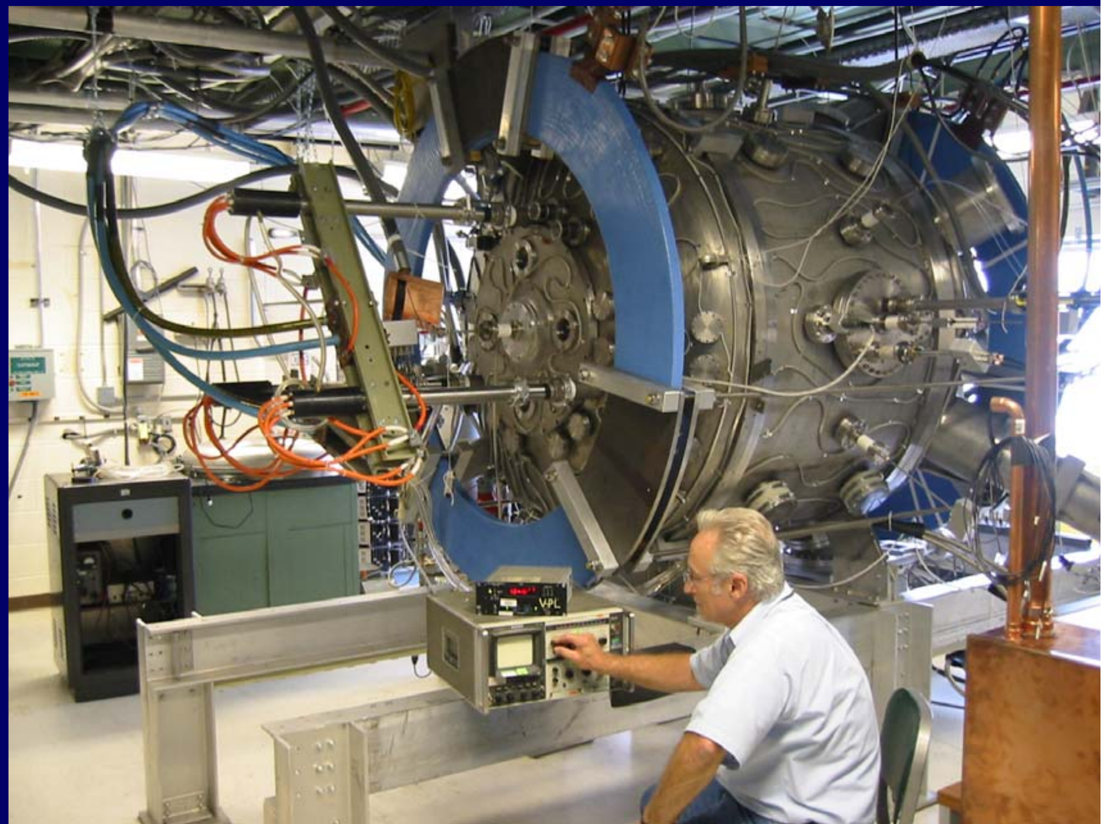


Demonstration of the principle action of reconnection in two dimensions

Reconnection in the laboratory



Laboratory-experiment by Yamada et al.: MRX in the PPP Lab Princeton



Elements to be considered in modelling the solar atmosphere:

- **Energy input and B-fields from the photosphere**
- **Magnetic energy release in the solar atmosphere**
- **Plasma and neutral gas stratificaion in the solar atmosphere by gravity**
- **In the chromosphere: coupling to neutral gas**
- **What is causing energy dissipation in the atmosphere?**
- **Important: heat conduction, radiative losses**

-> Appropriate model - description and applications

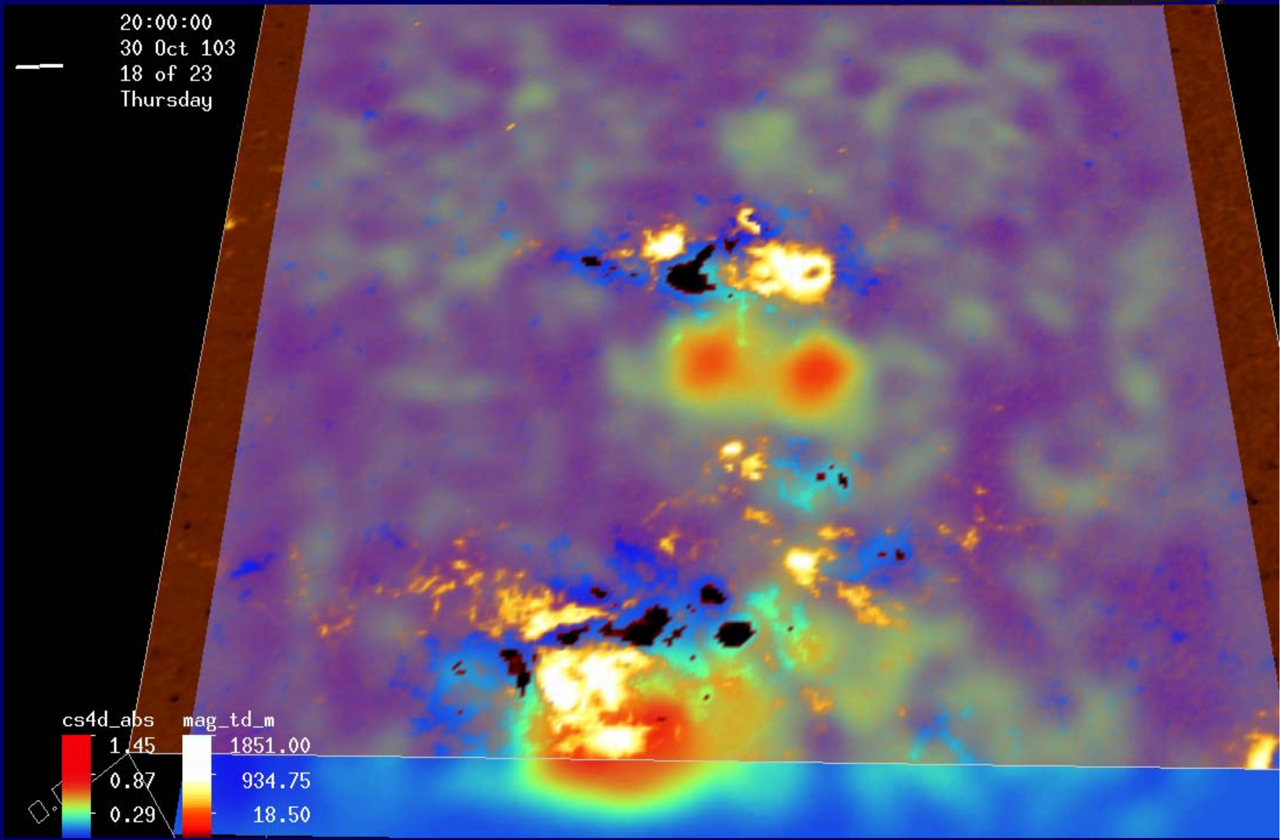
  - **Solar wind acceleration**
  - **Heating of Bright Points**

Energy source for the corona:

Plasma convection below the photosphere (to the right: helioseismology of AR10488, 30.10.03, lower panel: 16 Mm deep) [Gizon &, Kosovichev]

-> Dynamo -> B fields

-> upward Poynting flux estimated for:



$$E = -v \times B; v = 0.1\, km \cdot s^{-1}; B = 100\, G$$

$$\frac{\mathbf{E}\times\mathbf{B}}{\mu} \approx \frac{vB^2}{\mu} \approx 10^4 W \cdot m^2$$

Vs. observed fluxes:

Quiet regions	300 W m^{-2}
Active regions	(0.5 -1) 10^4 W m^{-2}
Coronal holes	800 W m^{-2}

Large scale modelling: RHMD

$$\frac{\partial \rho}{\partial t} = -\vec{\nabla}\cdot\rho\vec{u} - \quad - \rho_0)$$

$$\frac{\partial \rho\vec{u}}{\partial t} = -\vec{\nabla}\cdot\rho\vec{u}\vec{u} - \vec{\nabla}p + \vec{j}\times\vec{B} - \nu\rho(\vec{u}-\vec{u}_0)$$

$$= -\vec{\nabla}\cdot\left[\rho\vec{u}\vec{u} + \left(p + \frac{B^2}{2\mu_0}\right)1 - \frac{\vec{B}\vec{B}}{\mu_0}\right] - \nu\rho(\vec{u}$$

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla}\times(\vec{u}\times\vec{B} - \eta\vec{j})$$

$$\frac{\partial p}{\partial t} =$$

Closing energy equation

The index _0 indicates density, temperature and velocity of the neutral gas component, which in chromosphere and photosphere is strongly coupled to the plasma!

$$p = 2n\kappa_B T$$

$$\vec{E} = -\vec{u}\times\vec{B} + \eta\vec{j}$$

$$\vec{\nabla}\times\vec{B} = \mu_0\vec{j}$$

$$\hat{\eta}^* = \begin{cases} \eta^*_{\mathrm{a}}\left(\frac{|v_{\mathrm{dr}}|}{v_{\mathrm{thr}}} - 1\right); & |v_{\mathrm{dr}}| \geq v_{\mathrm{thr}}, \\ 0; & |v_{\mathrm{dr}}| < v_{\mathrm{thr}}. \end{cases}$$

Energy equation

$$\frac{\partial p}{\partial t} = -\nabla \cdot p\boldsymbol{u} - (\gamma - 1)p\nabla \cdot \boldsymbol{u} + (\gamma - 1)S$$

ohmic dissipation

where

$$S = \eta j^2 - \nabla . \boldsymbol{q} - L_r$$

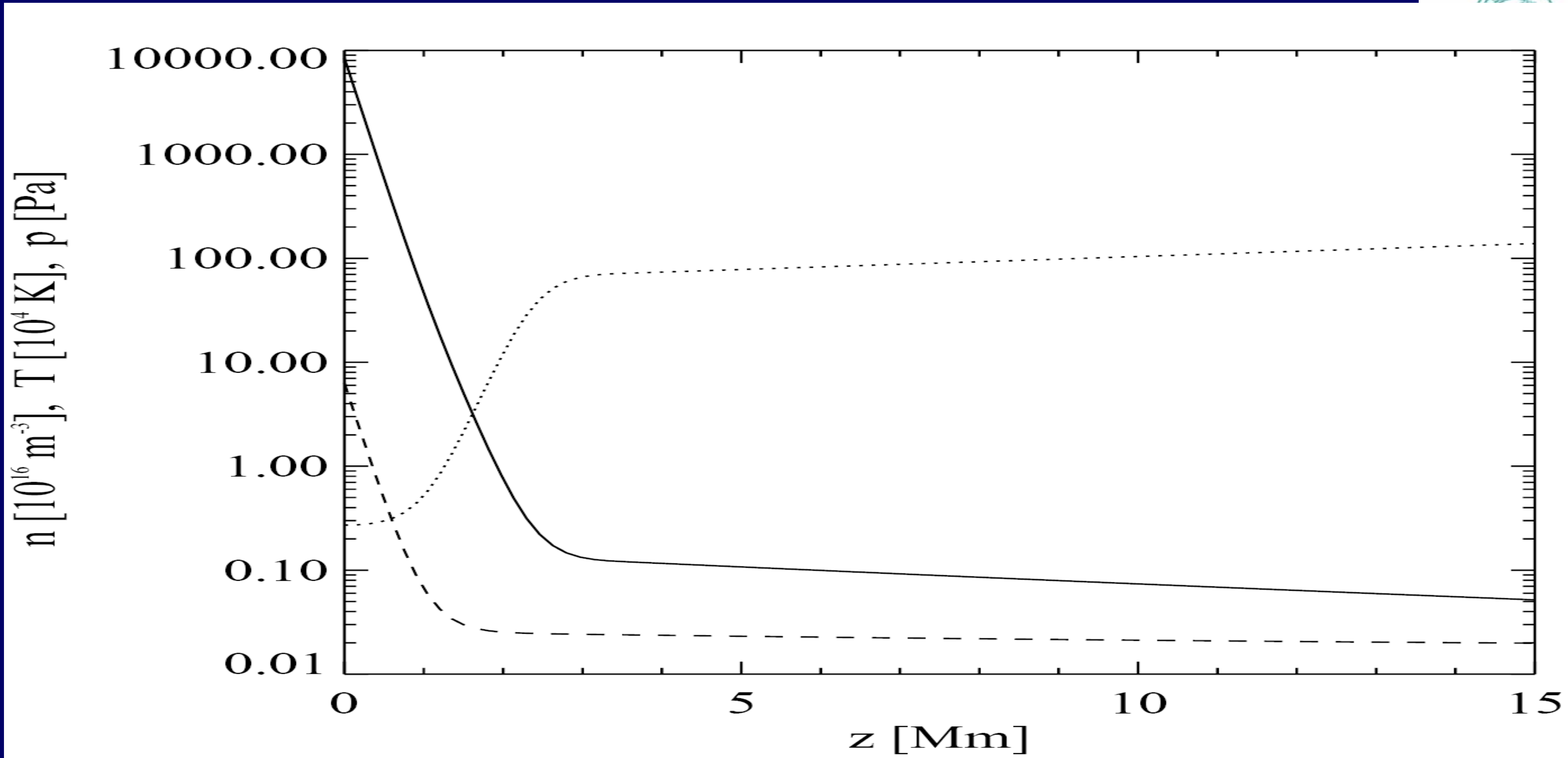
heat conduction along magnetic field

$$\nabla . q = \nabla_{\|} . (\kappa_{\|} \nabla_{\|} T), \quad \textit{where } \kappa_{\|} \sim 10^{-11} T^{5/2}$$

$$L_r = n\, n_n\, \chi T^{\alpha} \; W/m^3$$

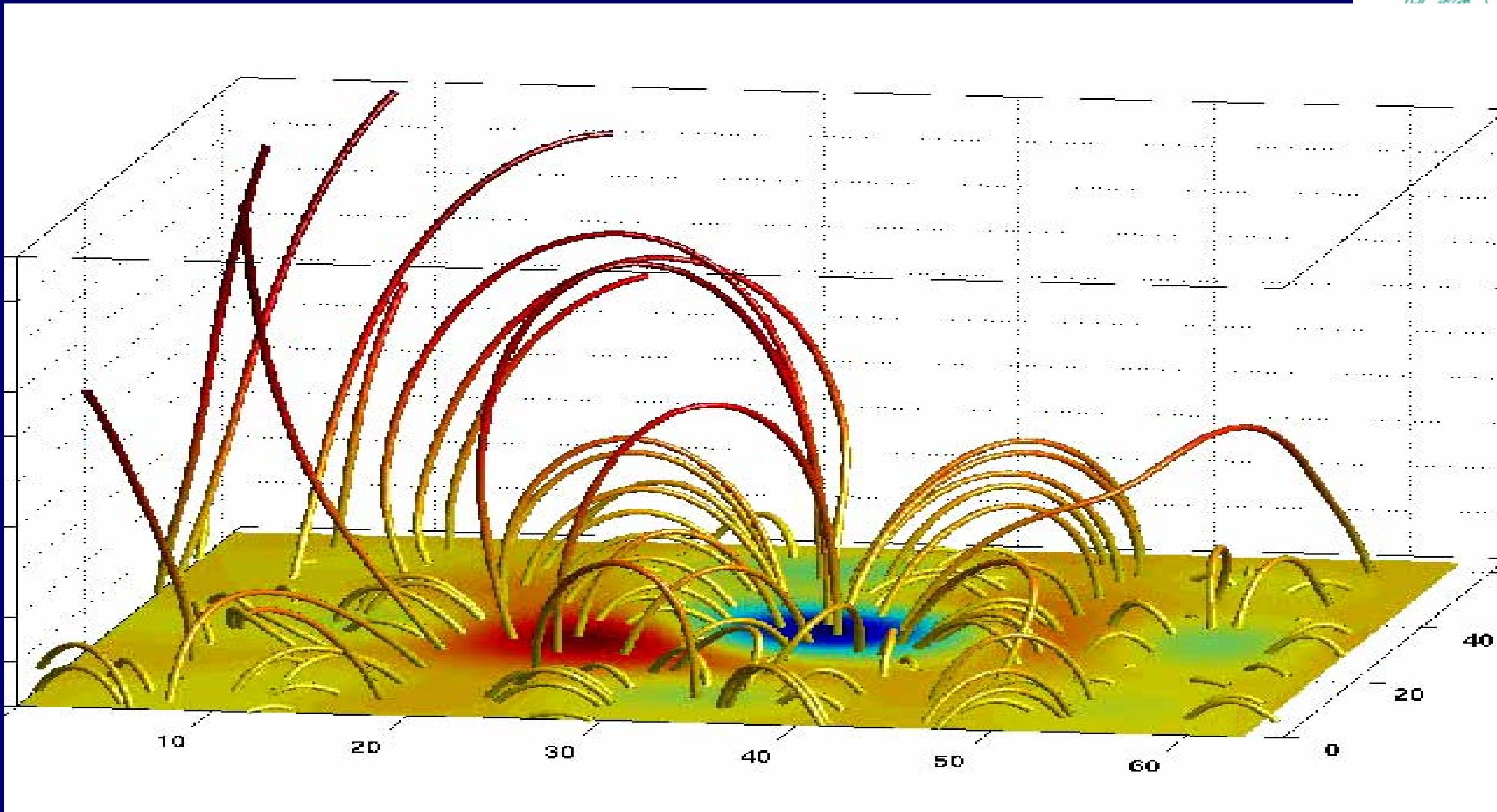
radiative cooling

Initial inhomogeneity



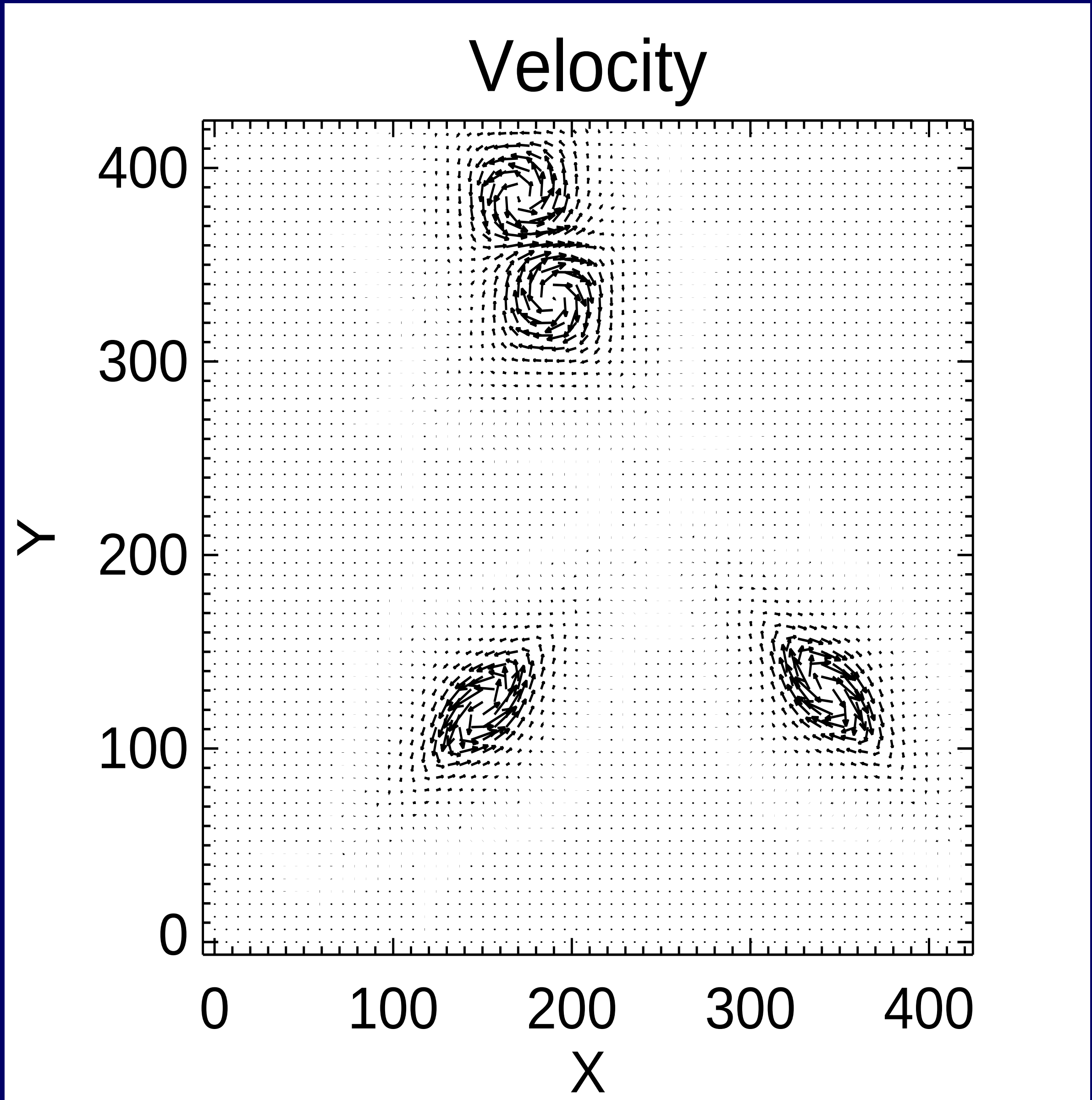
Plasma density, temperature and pressure are radially stratified according to the solar gravitation

Extrapolated initial B-field



The initial magnetic field is extrapolated from the observed photospheric magnetic field

Observed plasma motion as a boundary condition



By correlating the line-of sight B-field patterns one can derive the approximate motion picture as shown and use it as a boundary condition for the simulation.

The motion creates currents in the corona

-> current dissipation?

-> magnetic reconnection?

Dissipation in resistive MHD

Induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

... reveals scales -> magnetic Reynolds number

$$R_m = \frac{\mu_0 \; l \; v}{\eta}$$

Rm must be small, hence,
in the solar atmosphere

1.) l ~ 1 km

2.) η ~ 10^8 times that of collisions

How can these scales / dissipation be reached?

Dissipation in multi-fluids

A two-fluid-description reveals the „generalized Ohm`s law“ of m magnetohydrodynamics (MHD):

$$\frac{4\pi}{\omega_{pe}^2}\frac{d\vec{J}}{dt} = \boxed{\vec{E} + \vec{v}_i \times \vec{B}} - \frac{1}{ne}\vec{J}\times\vec{B} + \frac{1}{ne}\nabla p_e - \eta\vec{J}$$

c/ω_{pe} <- spatial -> <- scales -> ρ_i c/ω_{pi} ^

electron inertia	elektrons - ions decoppled, „Hall“ term“	off-diagonal elements of the pressure tensor	dissipation due to turbulence

Microscale (kinetic) dissipation

Ensemble averaging:

$$\langle \delta f_j \rangle = \left\langle \delta \vec{E} \right\rangle = \left\langle \delta \vec{B} \right\rangle = 0.$$

$$f_j = f_{0j} + \delta f_j \quad E_{\parallel} = \left\langle E_{\parallel} \right\rangle + \delta E_{\parallel}$$

-> Modified Vlasov equation, after velocity averaging -> momentum exchange rate

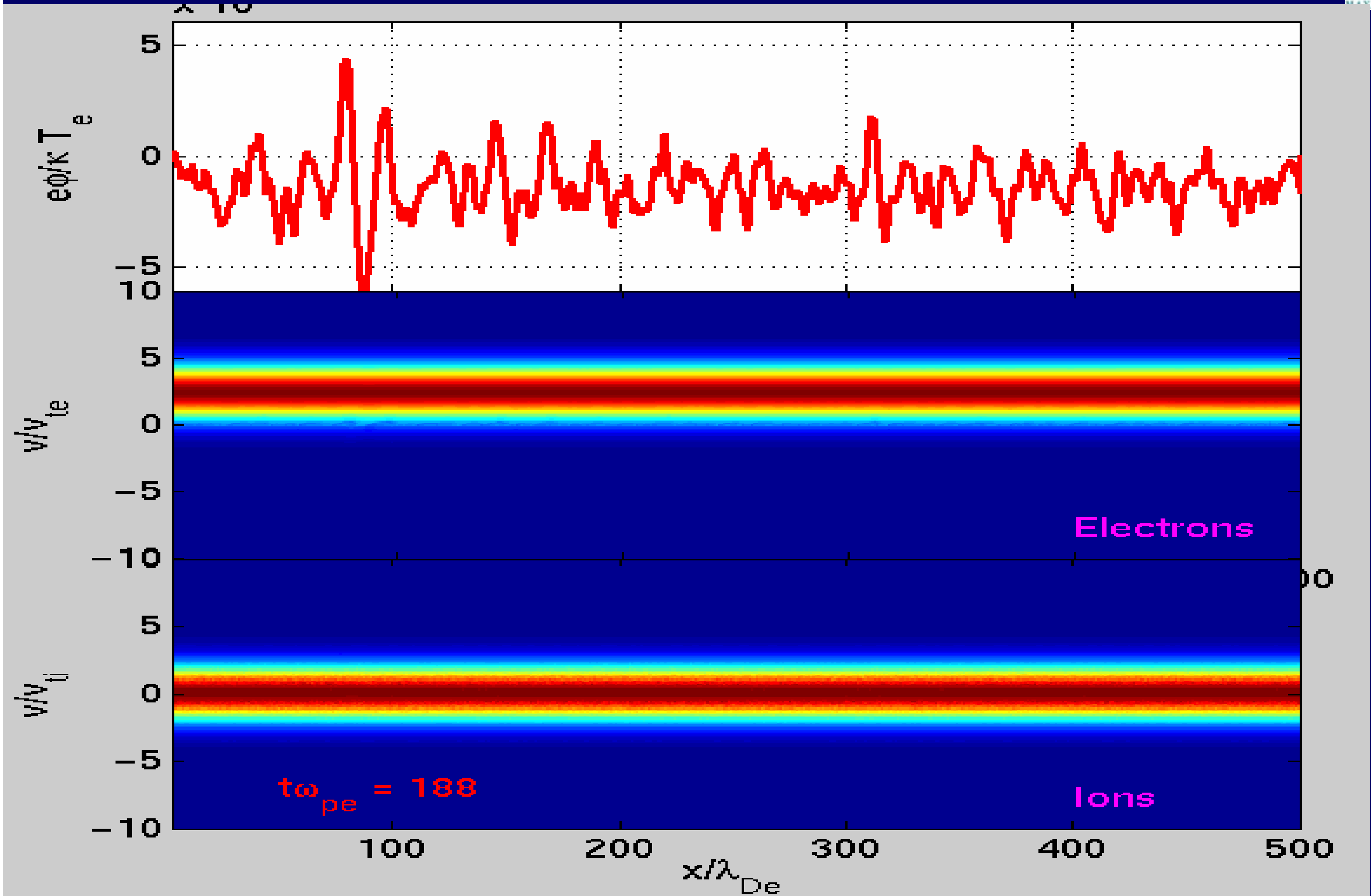
$$\frac{\partial f_{0e}}{\partial t} + \vec{v} \cdot \frac{\partial f_{0e}}{\partial \vec{r}} + \frac{e}{m_e} \vec{E} \cdot \frac{\partial f_{0e}}{\partial \vec{v}} = -\frac{e}{m_e} \left\langle \left(\delta \vec{E} + \vec{v} \times \delta \vec{B} \right) \cdot \frac{\partial \delta f_e}{\partial \vec{v}} \right\rangle$$

-> correlation of e/m fluktuations and plasma density /current fluctuations

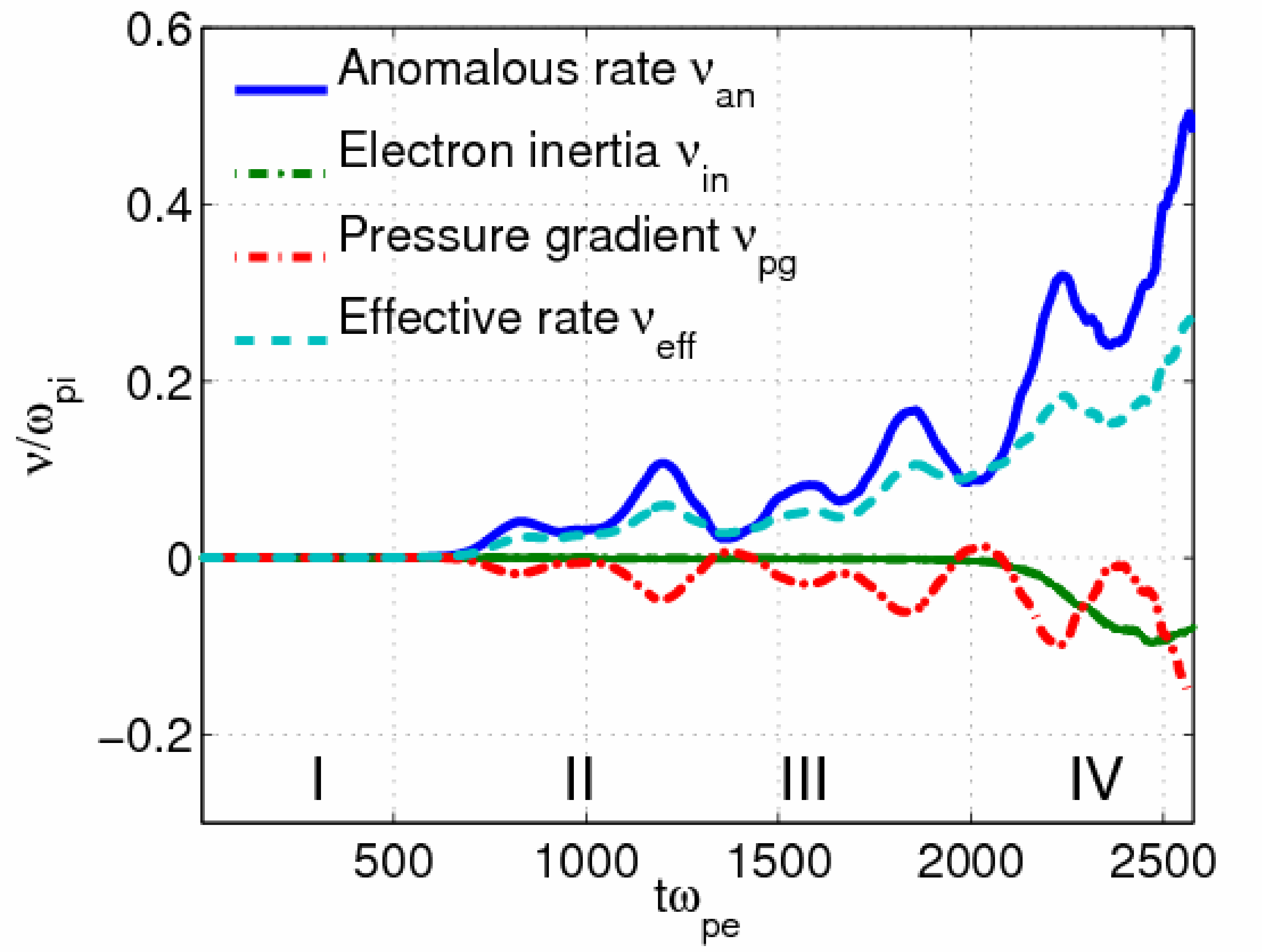
$$\left(\frac{d}{dt} n m_e v_{y,e} \right)_{eff} = \langle \delta E_y \delta \rho_e + \delta j_{z,e} \delta B_x - \delta j_{x,e} \delta B_z \rangle$$

-> These correlations can be taken either from theory, from observations or from numerical simulations !

Vlasov code kinetic simulation: evolution of potential, Fe and Fi



Effective „collision rates“



Dissipation in the solar atmosphere

Current dissipation, characterized as resistivity via an effective „collision frequency“ ->

$$\eta = \frac{\nu}{\epsilon_0 \omega_{pe}^2}$$

is dominated

In the (lower) chromosphere:

by binary particle collision rate

[Spitzer, Härm & Braginski 1958-63]

$$\nu_{coll} \cong \frac{\omega_{pe}}{n\lambda_D^3}$$

In the corona:

by plasma turbulence as obtained by Vlasov code simulations for coronal conditions, Te~Ti etc:

[Büchner & Elkina 2006/2007]

$$\nu_c \approx \omega_{pi}/2\pi$$

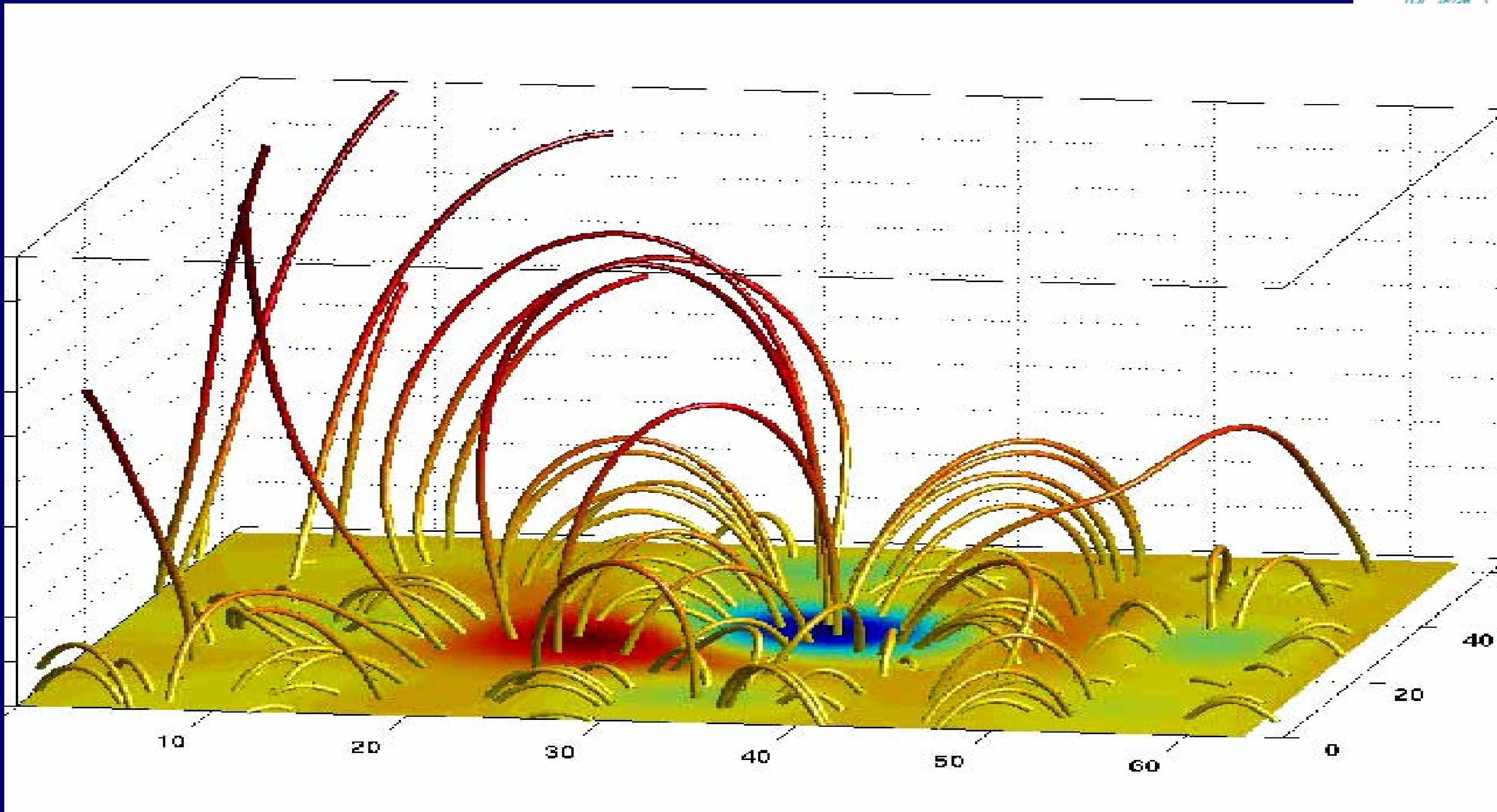
– for higher beta plasma -> 1D: IA double layers

– for lower beta plasma –> 2D: LH turbulence

$$\nu_c \approx \omega_{pi}$$

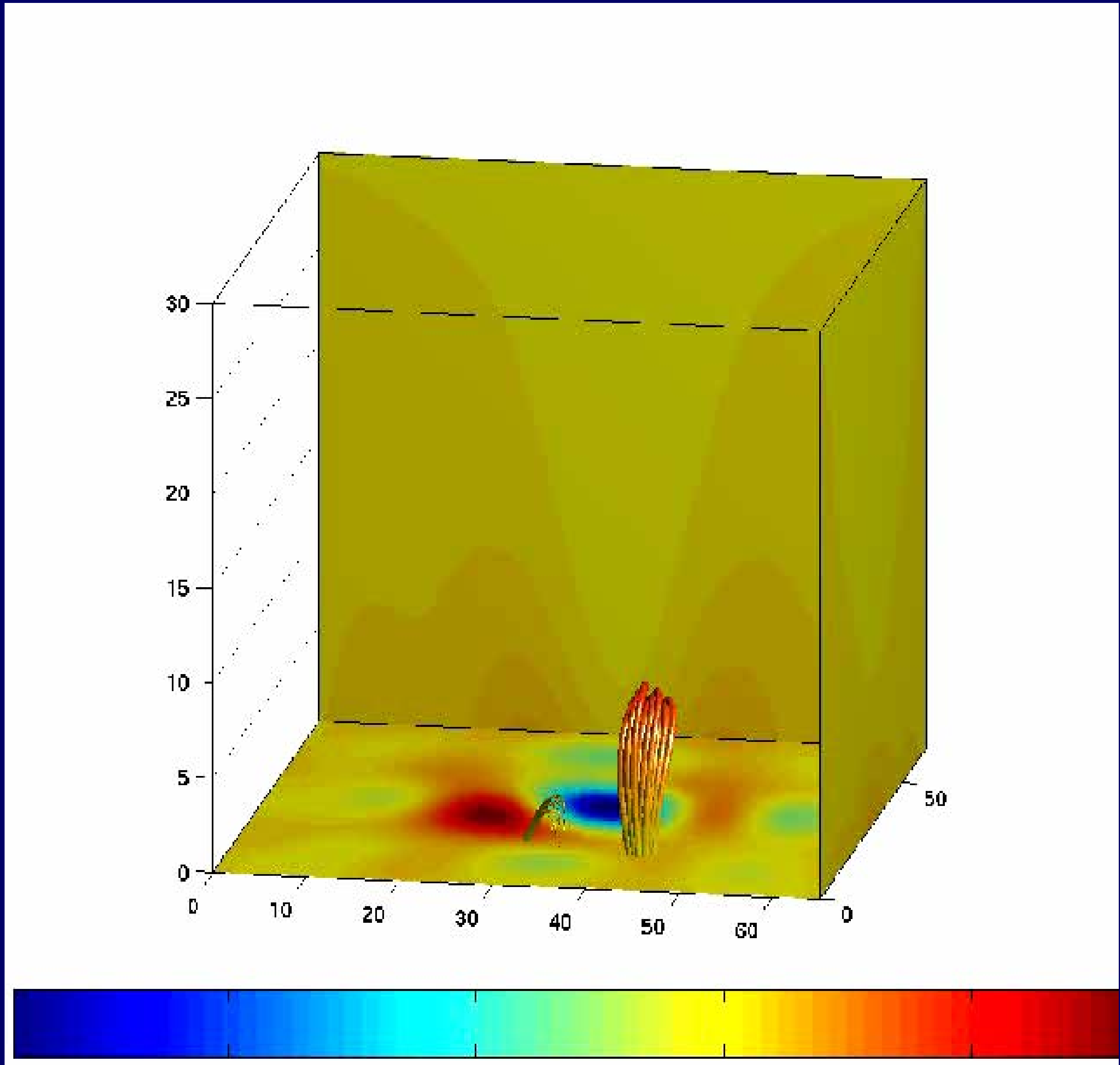
But: as threshold: a large current carrier drift velocity *j/ne* > v_te (-> thin sheets!)

Resulting magnetic reconnection



When currents caused by the photospheric plasma motion are dissipated -> reconnection

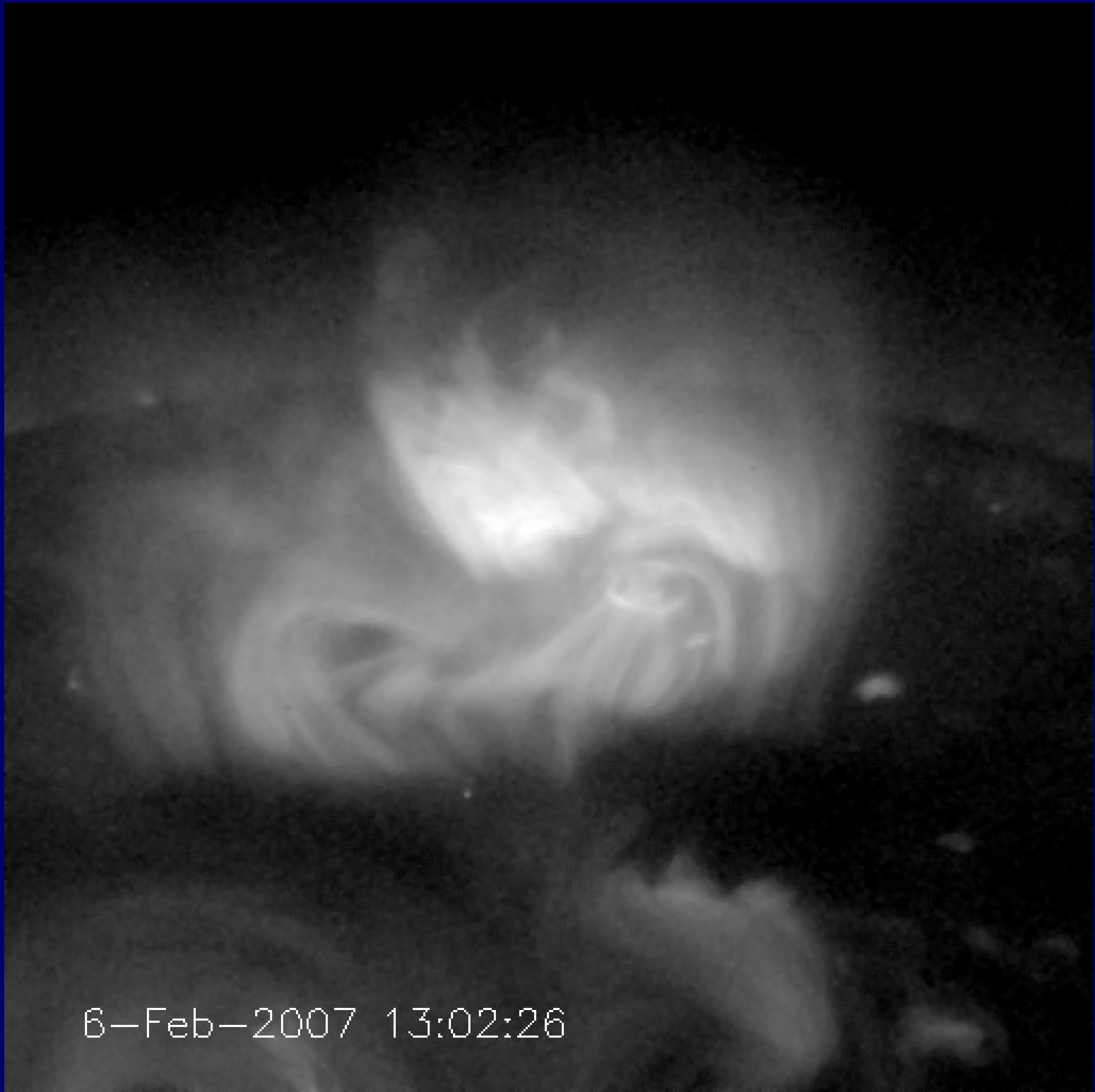
3D magnetic reconnection



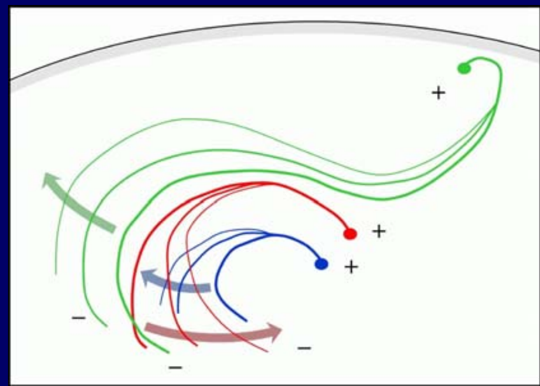
3D magnetic reconnection dynamics

[Büchner 2008]

Observation: Hinode 2007

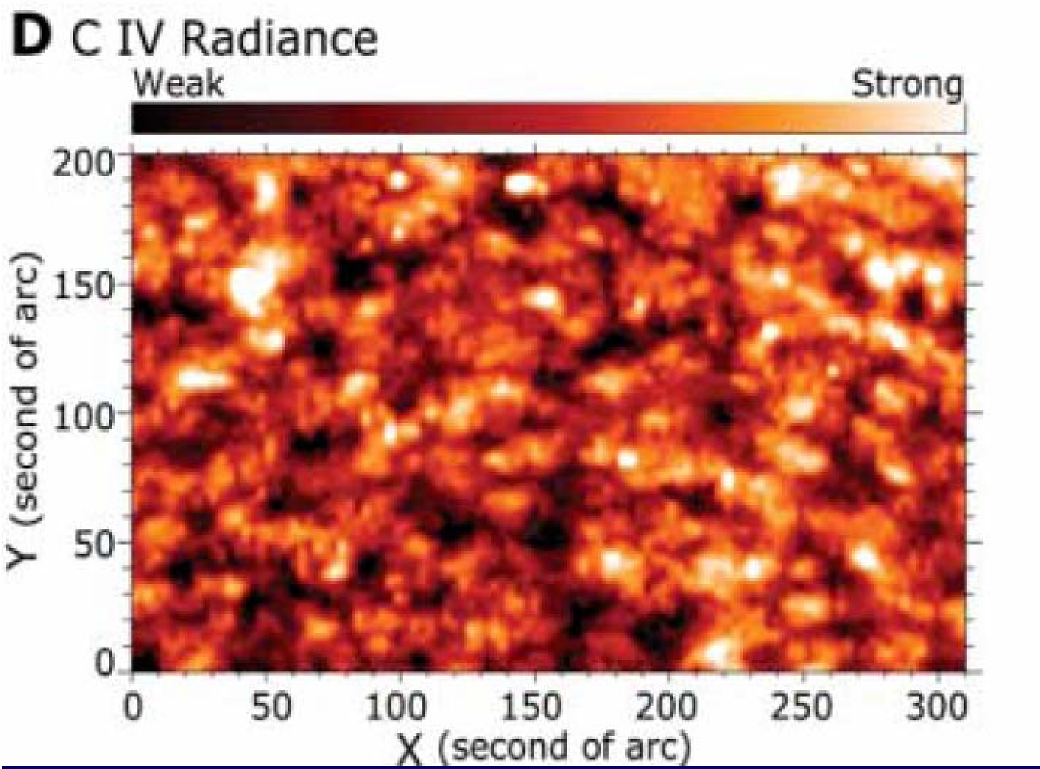


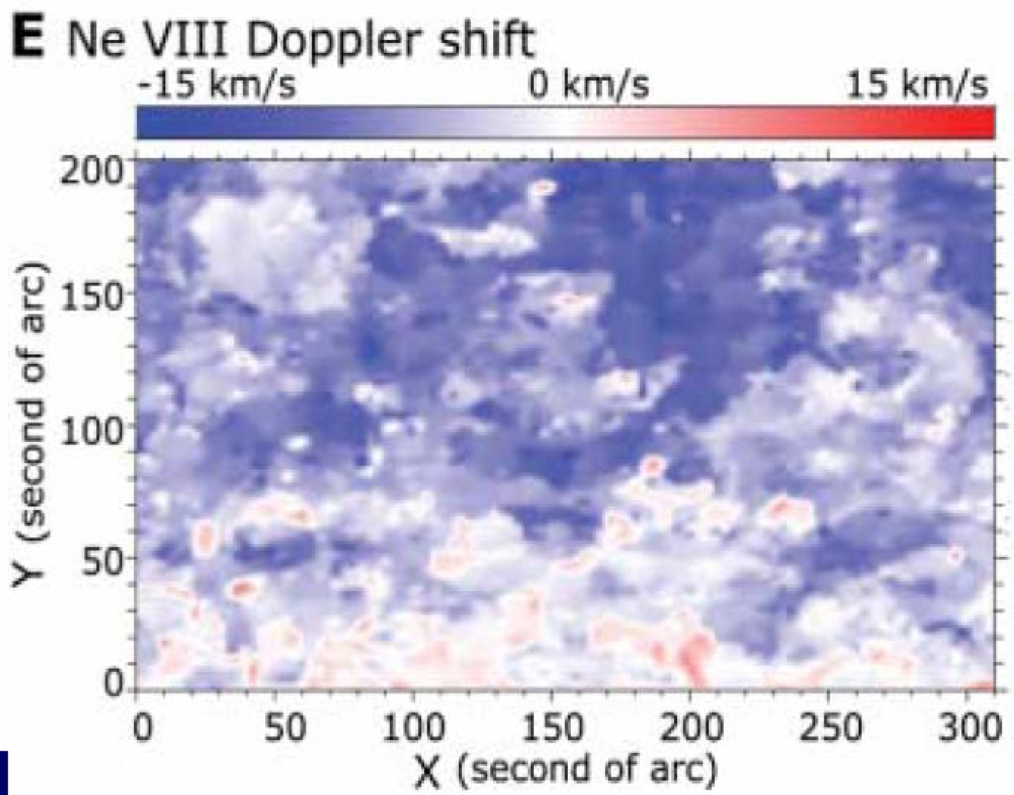
Japanese Space Solar Telescope mission (launch: 2006) -> Observation of the imging X-ray telescope XRT



Sketch

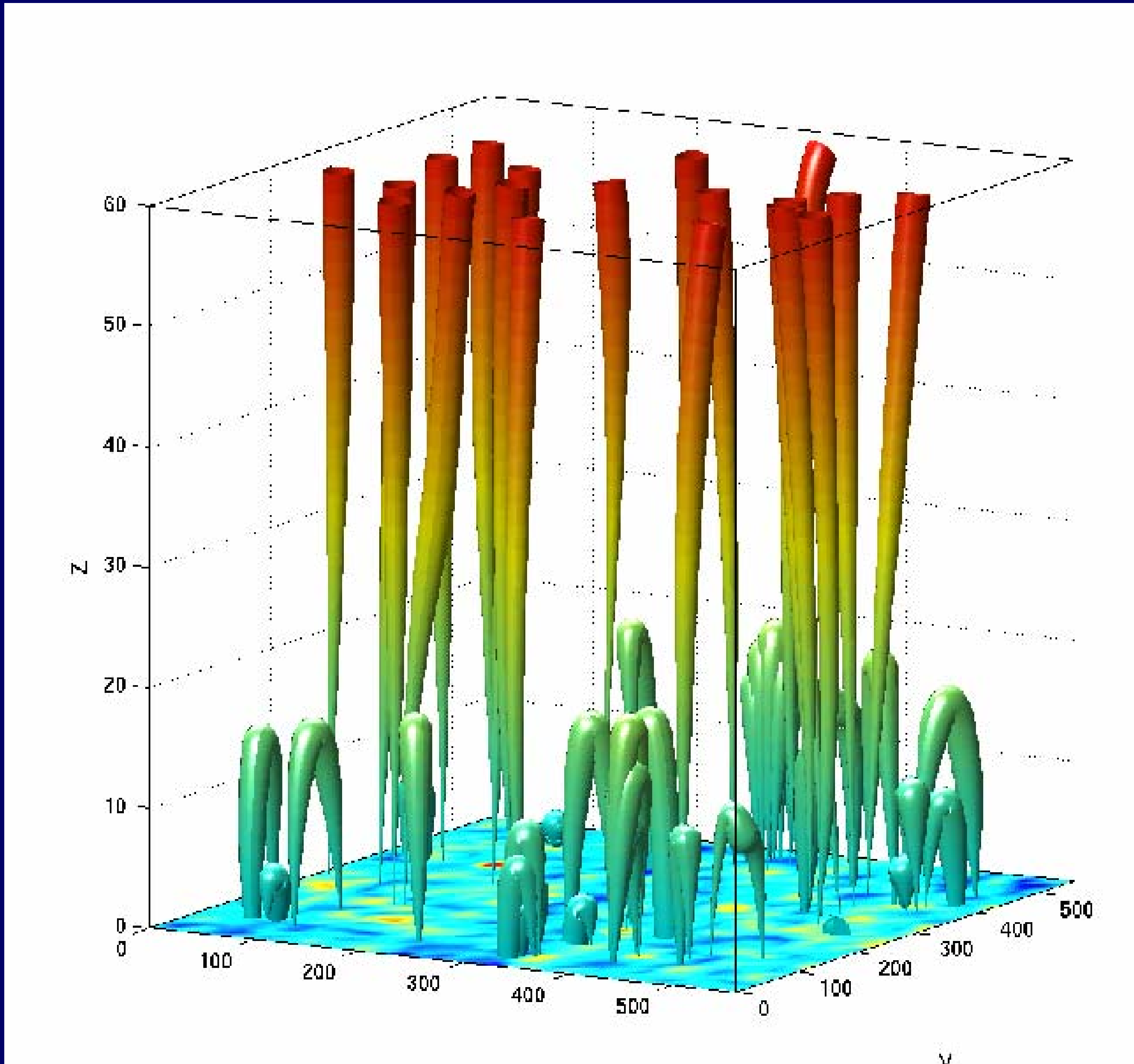
1.) Solar wind from coronal holes





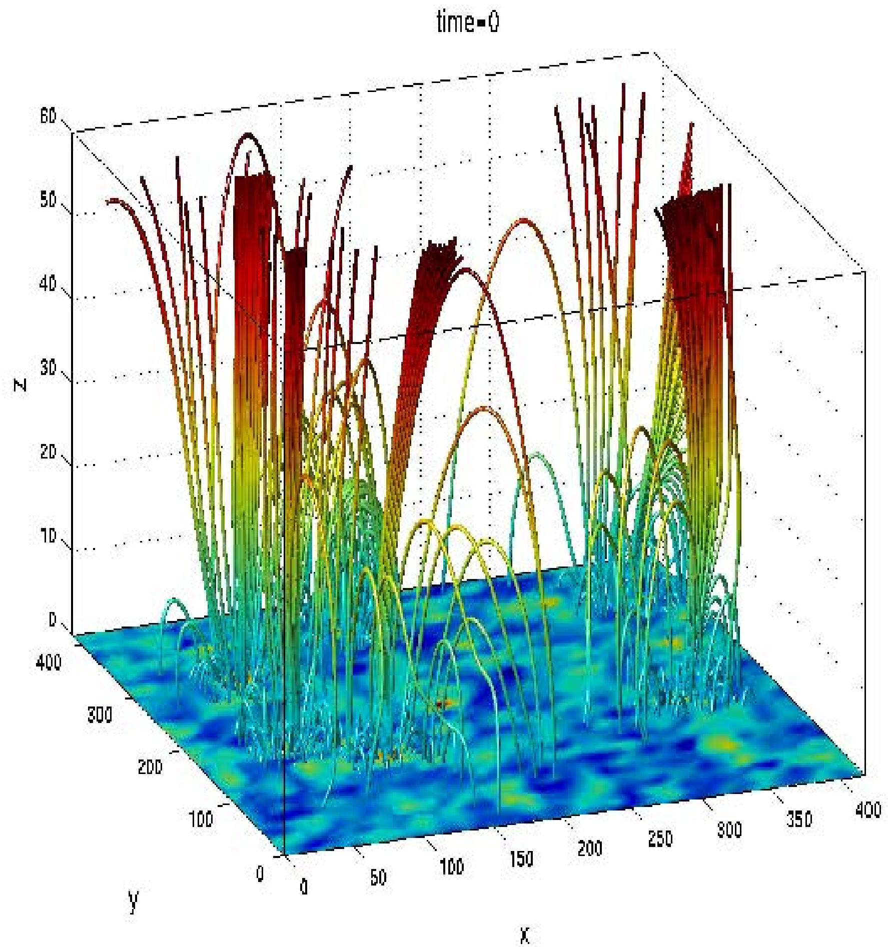
-> Observed radiance and velocities [Tu et al., 2005])

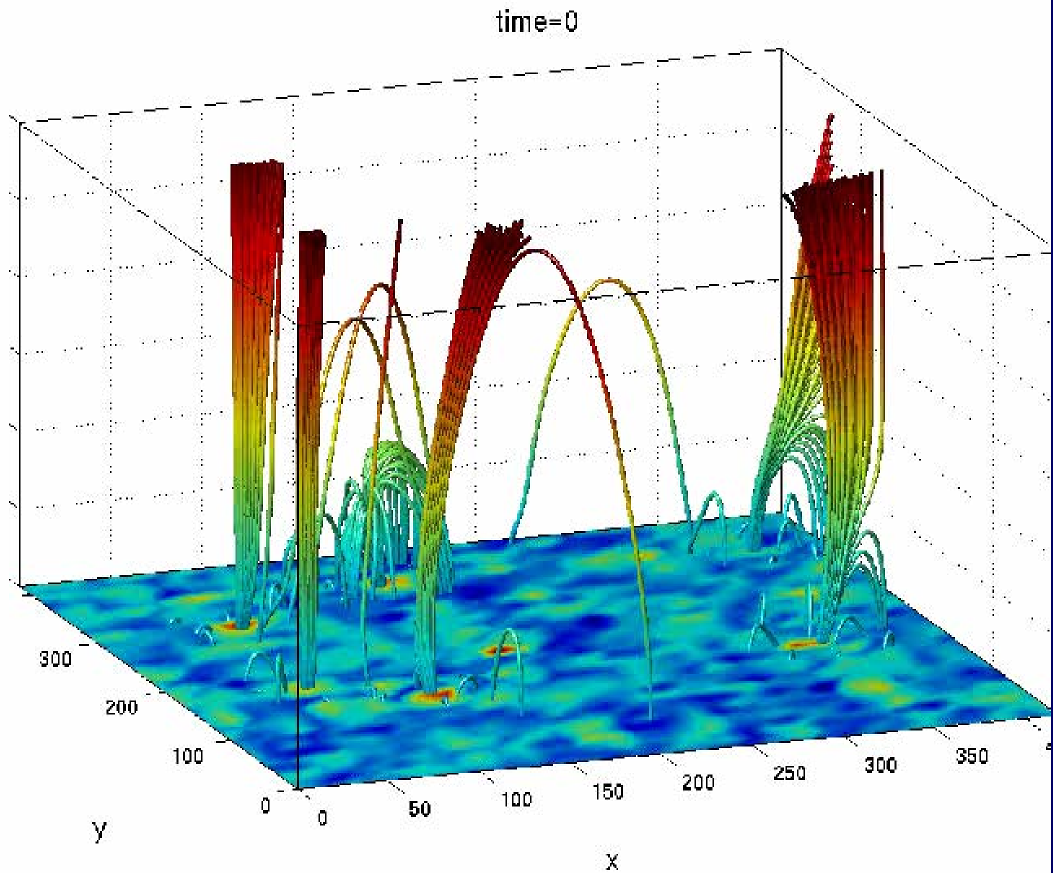
3D initial force free magnetic fields



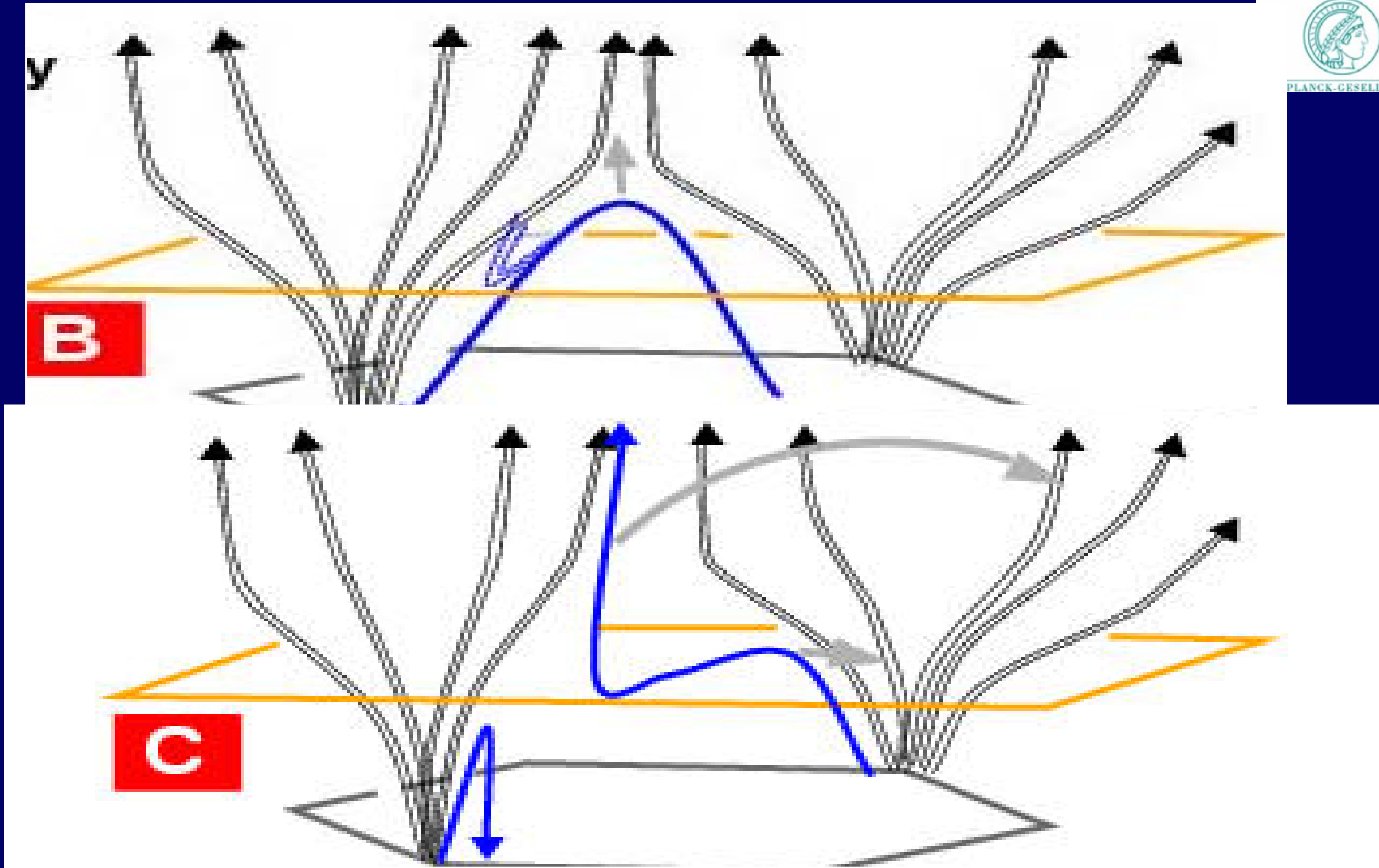
The magnetic field consists of funnels – open magnetic flux along the boundaries of the coronal hole and low rising loops inside and outside the hole [Büchner, 2010]

Resulting B field evolution

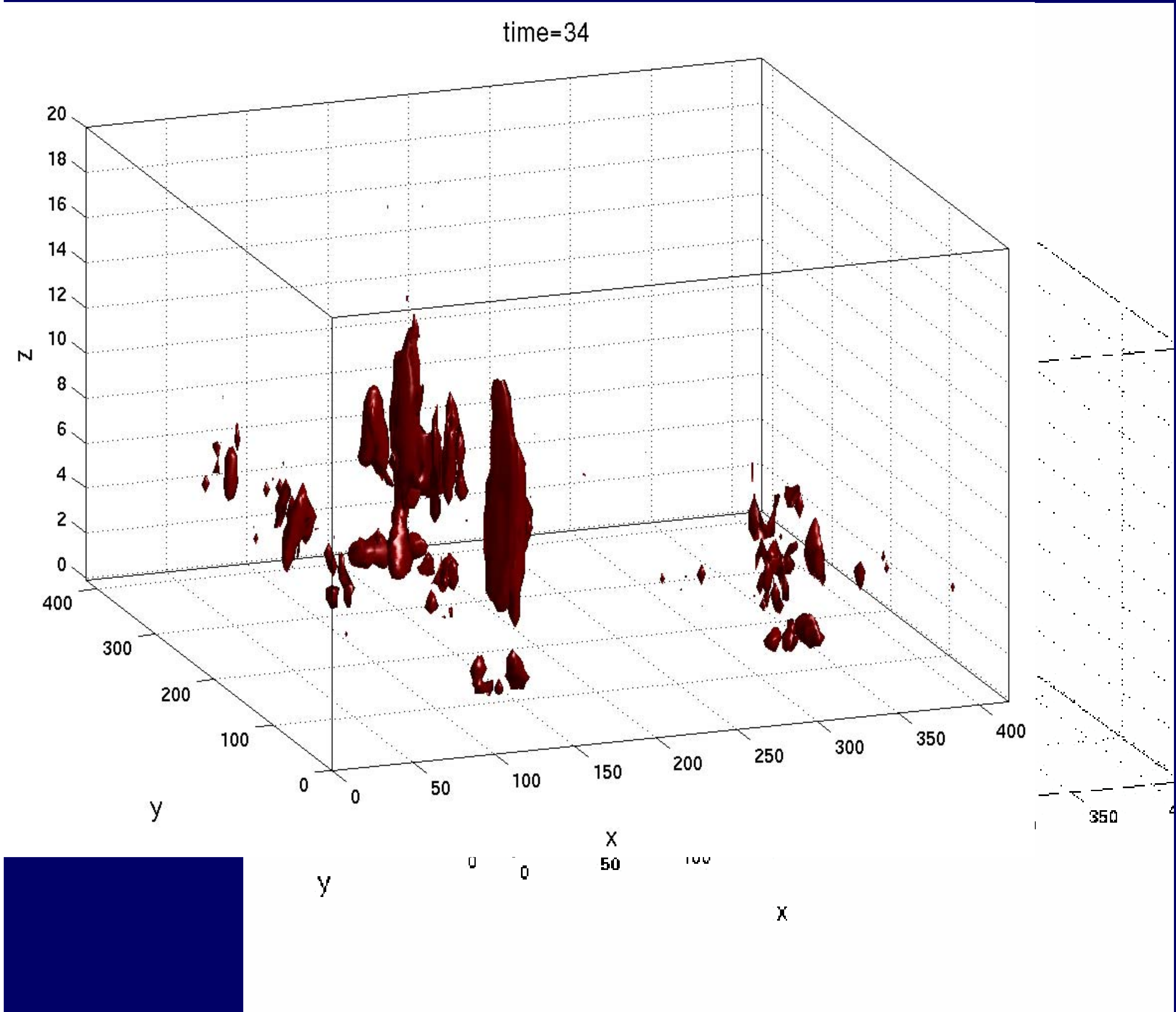




Reconnection - cartoon



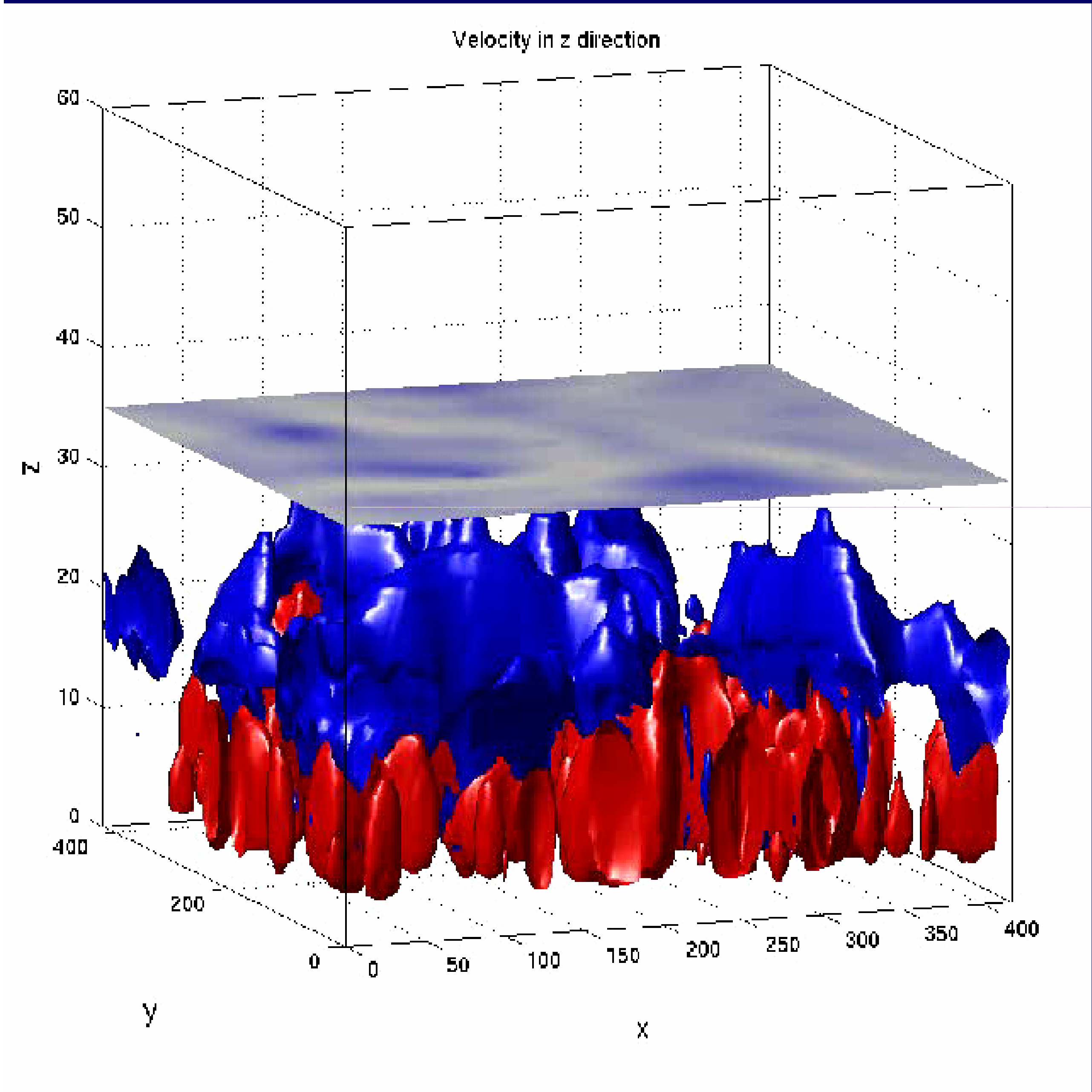
Reconnection: Epar field



3D reconnection is characterized best by the parallel electric field, shown to the left

-> Epar and, therefore, the 3D reconnection rate is highest between 5 and 10 Mm above the photosphere

Epar -> Plasma acceleration

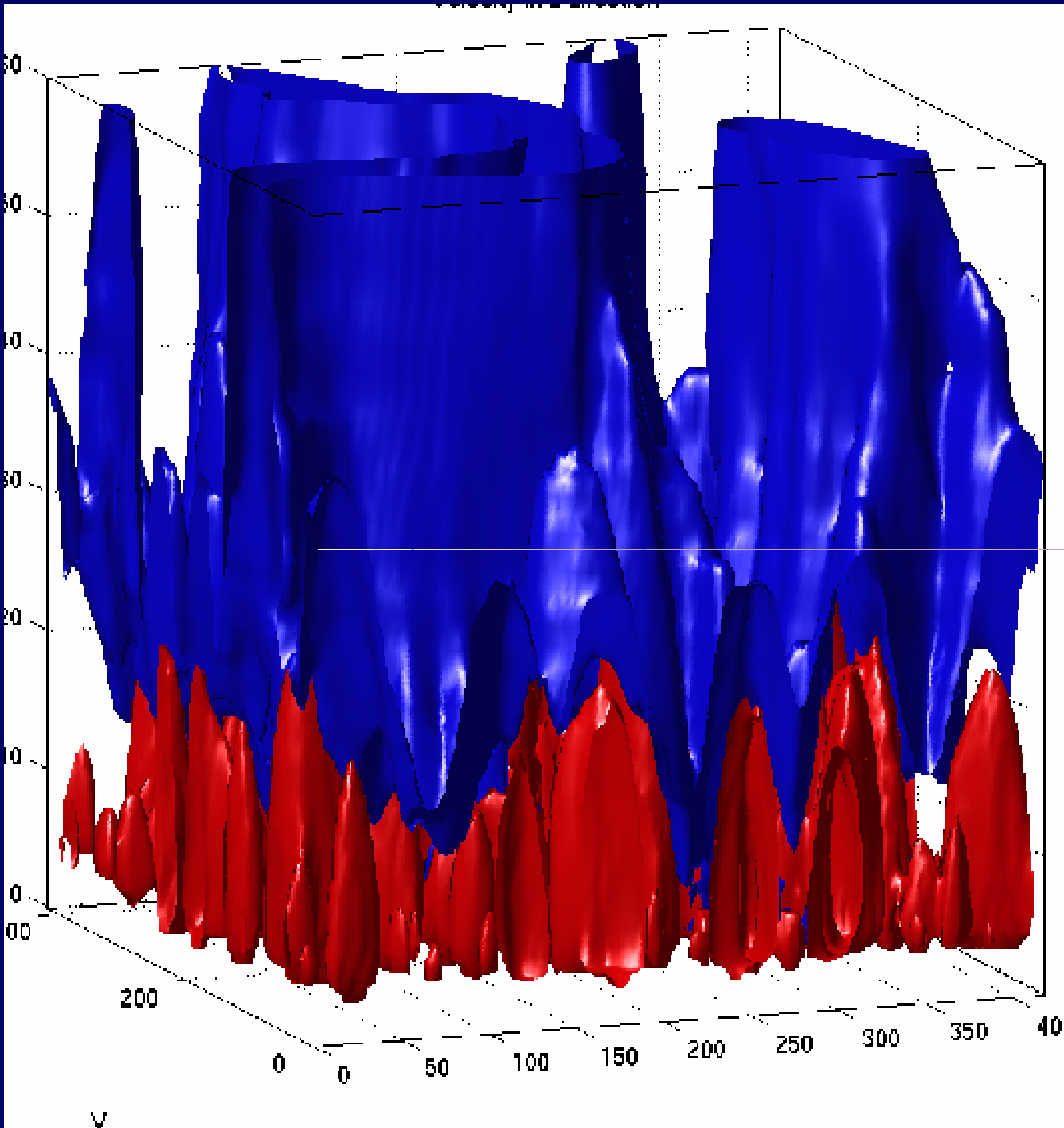


The isosurfaces
Vz=10 km/s
- **blue: upward**
- **red: downward**

demonstrate:

3D reconnection electri
fields accelerate plasm
both upward and
downward

Accelerated solar wind plasma



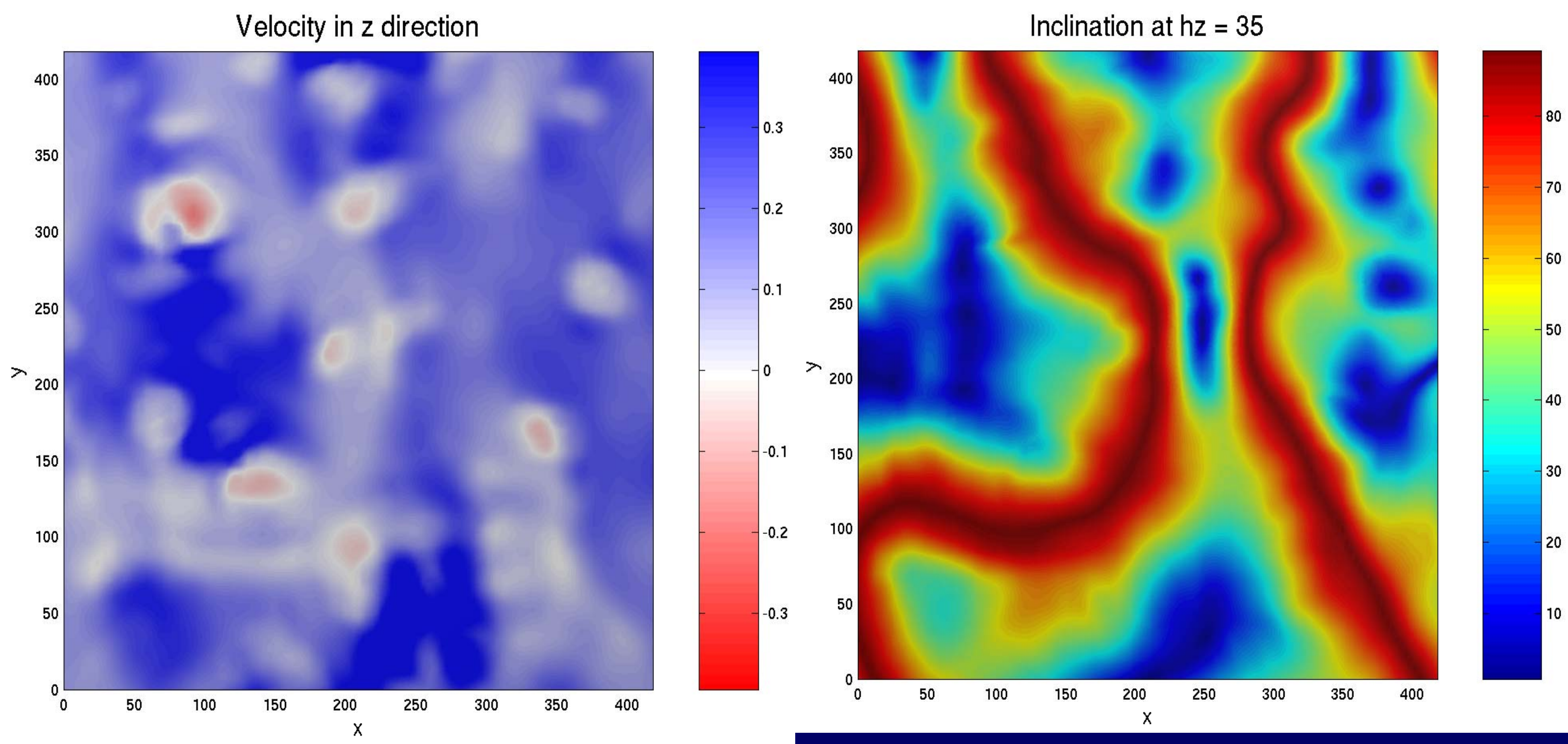
These stationary upward (blue) and downward (red) accelerated plasma flows –velocity isosurfaces 10 km/s show:

- the upward directed acceleration takes place

mainly above 5 Mm and

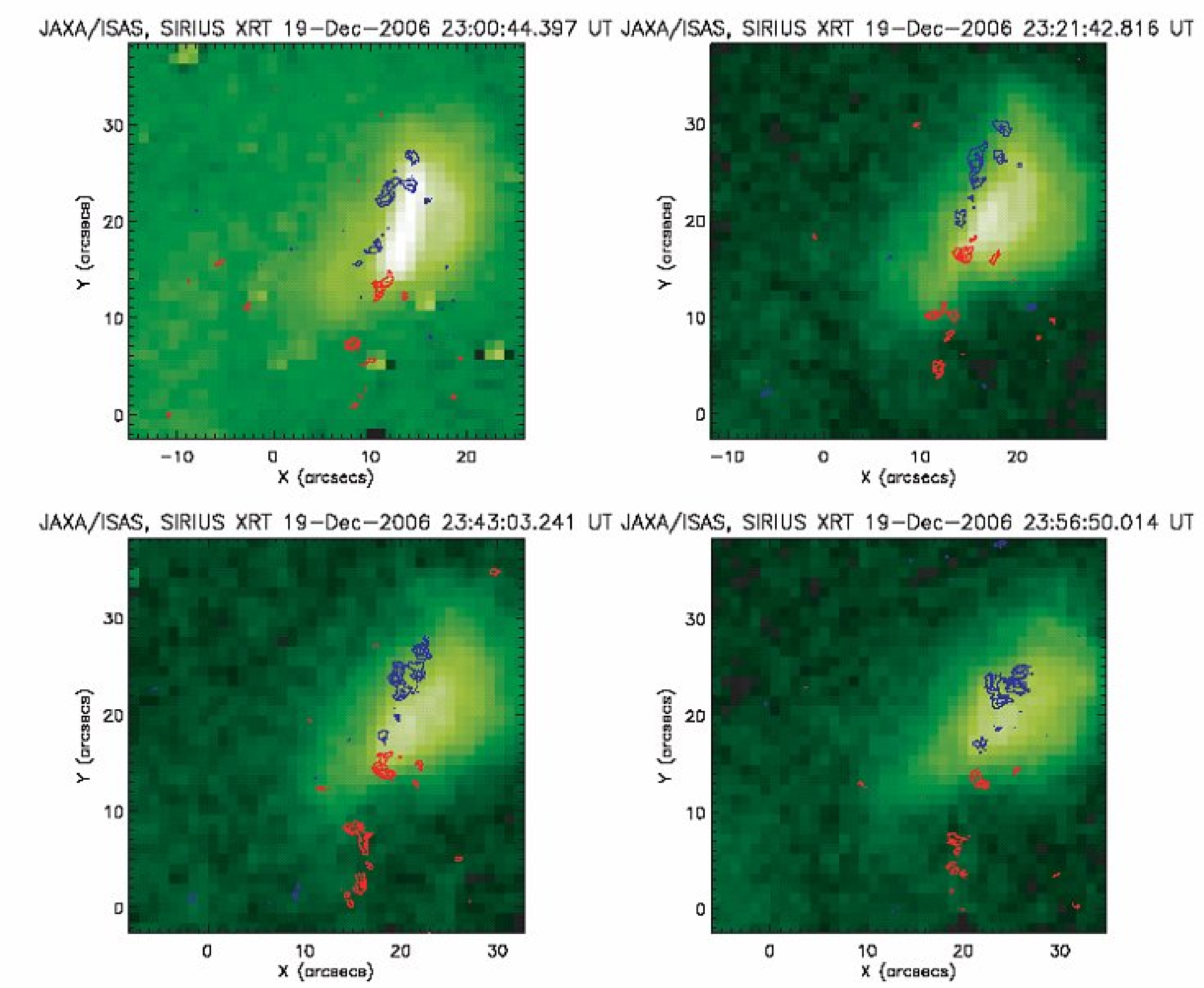
- higher up the accelerated flows fill almost the whole coronal hole area

Simulated Vz and B-inclination



Comparison Vz (left) and B-inclination (right) at H=20 Mm -> clear correlation: downward and stagnant flows on closed field lines (sm inclination) and upward flows on open field lines (large inclination)

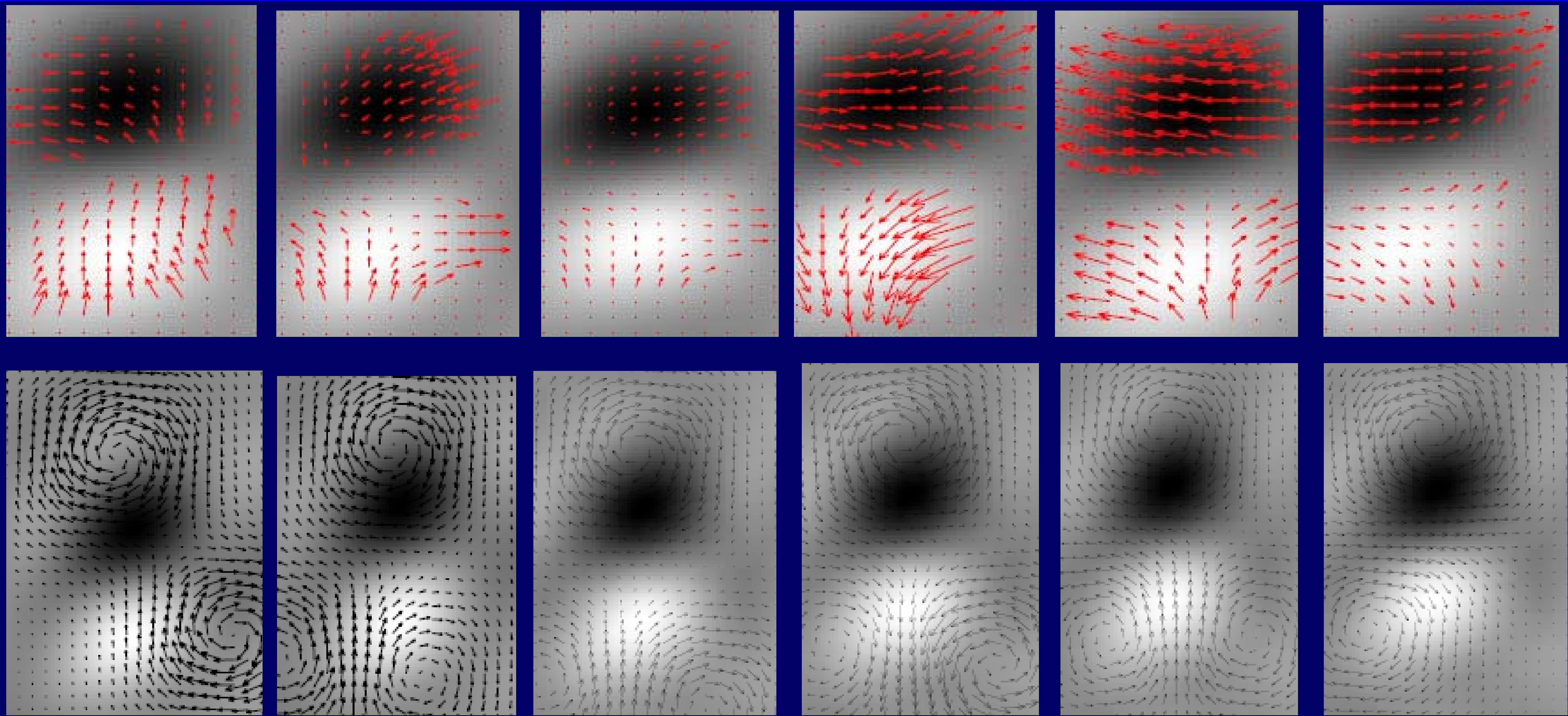
2.) X-ray Bright Point (Hinode)



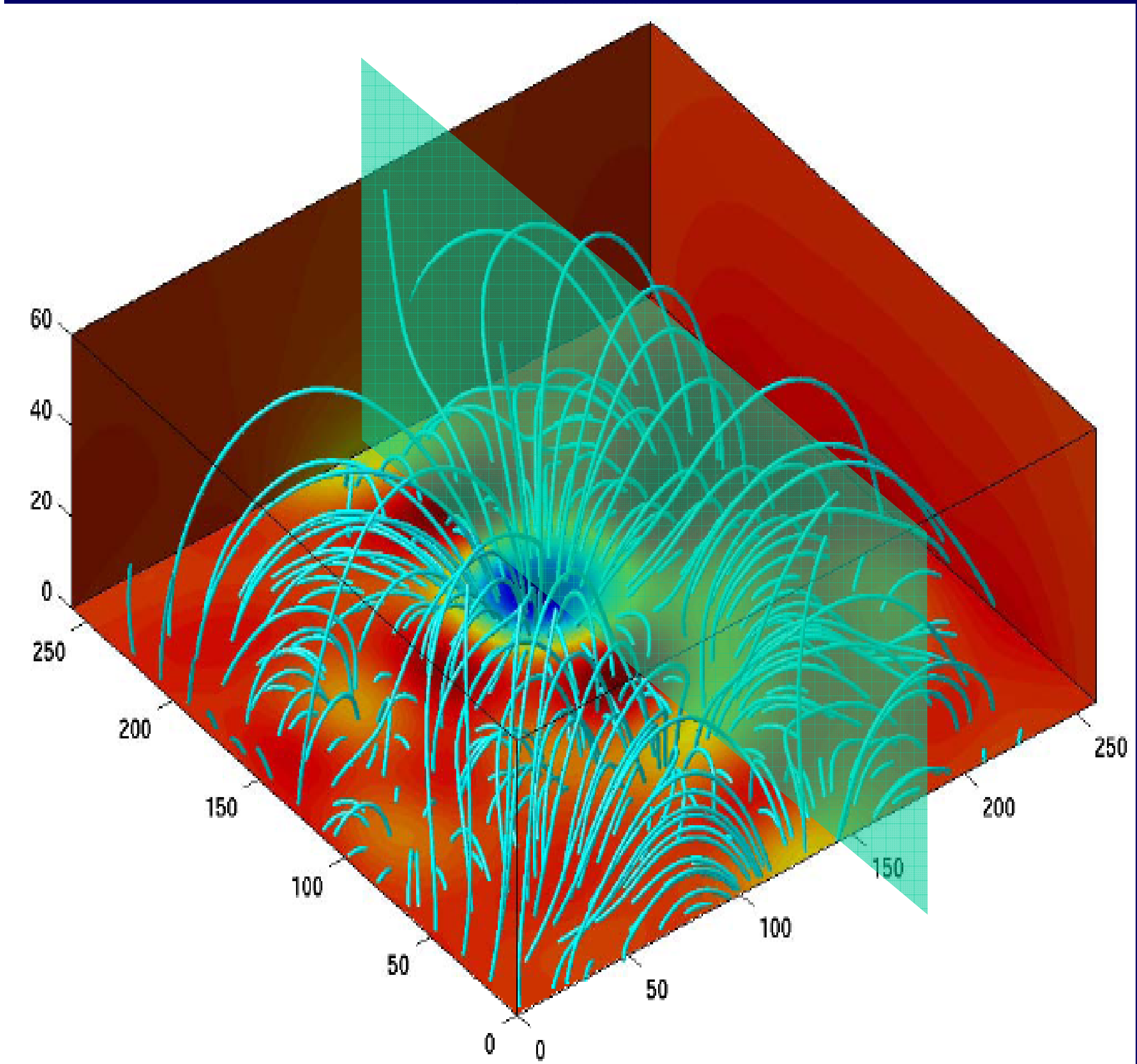
These four X-ray images were observed by Hinode XRT between 23:00 UT and 24:00 UT on December 12, 2006

Energy input by various types of photospheric plasma motion

23:02 – 23:07UT	23:07 – 23:12UT	23:12 – 23:17UT	23:17 – 23:22UT	23:22 – 23:27UT	23:27 – 23:32UT



Simulation results

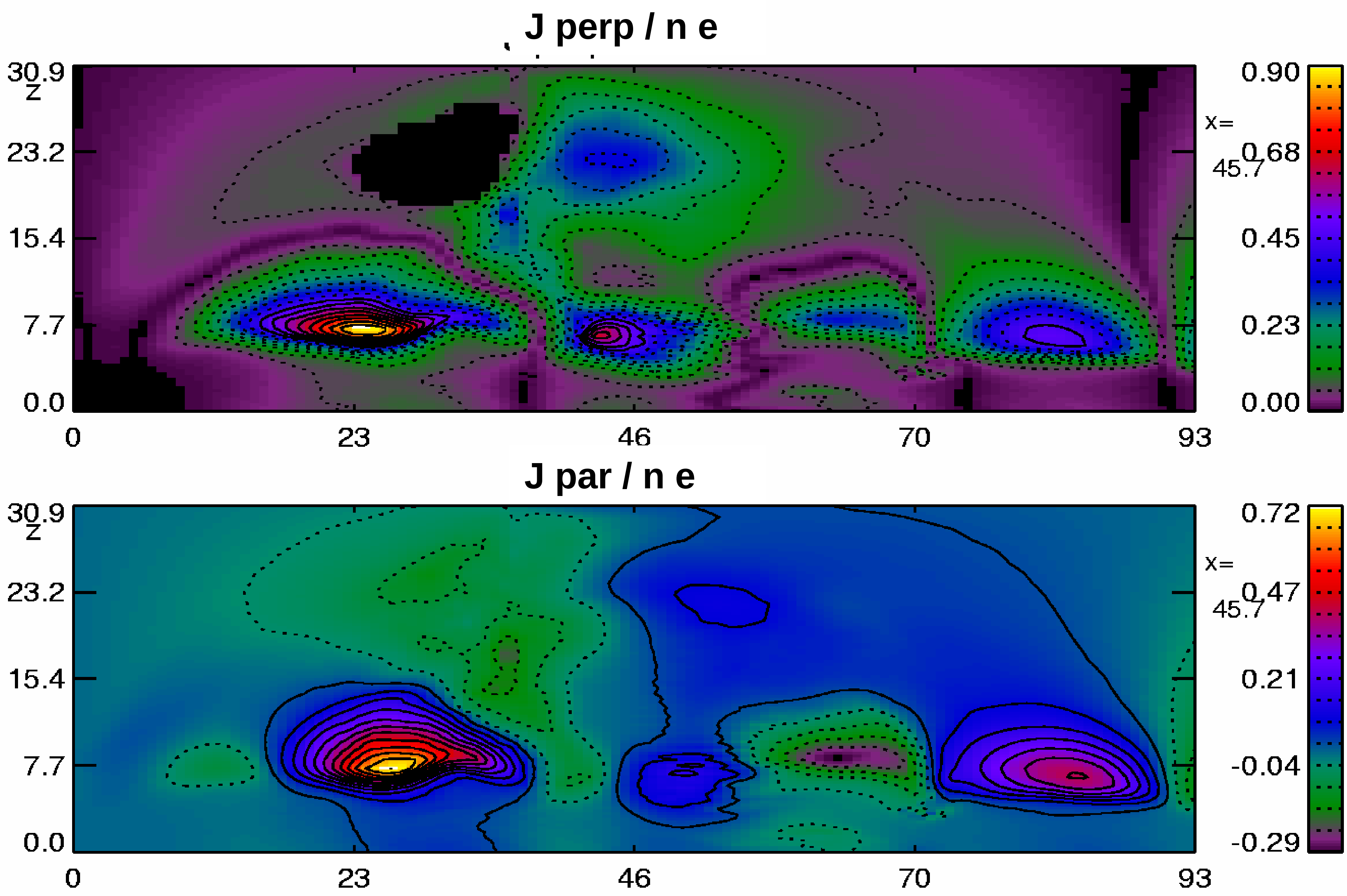


-> not any more force-free, i.e. Jperp

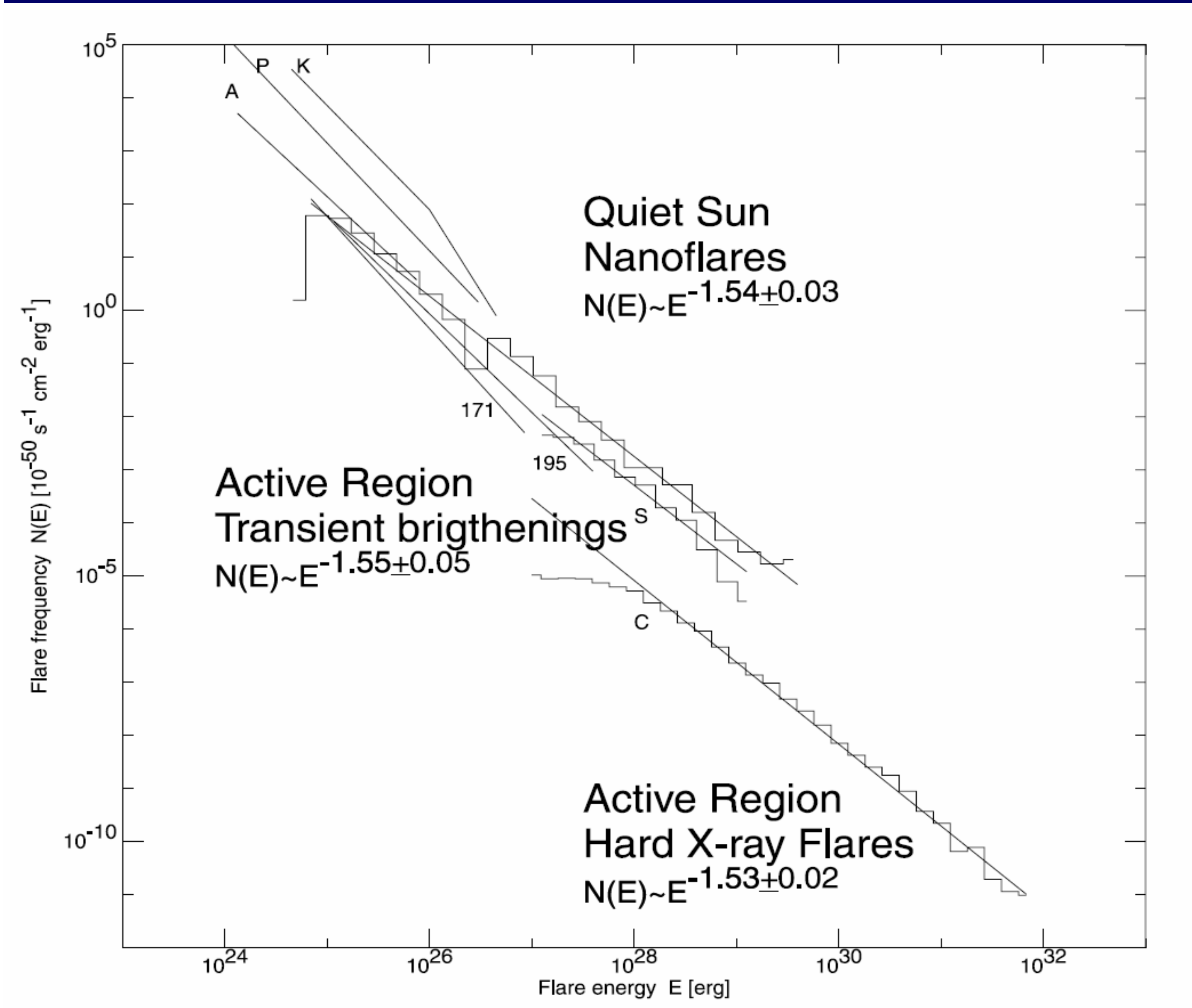
-> The basic features are robust, do not depend on the details of the photospheric plasma motion.

Vertical cut: plane of diagnostics (through the main polarities)

Generation of Jpar and Jperp



Energy release at many scales

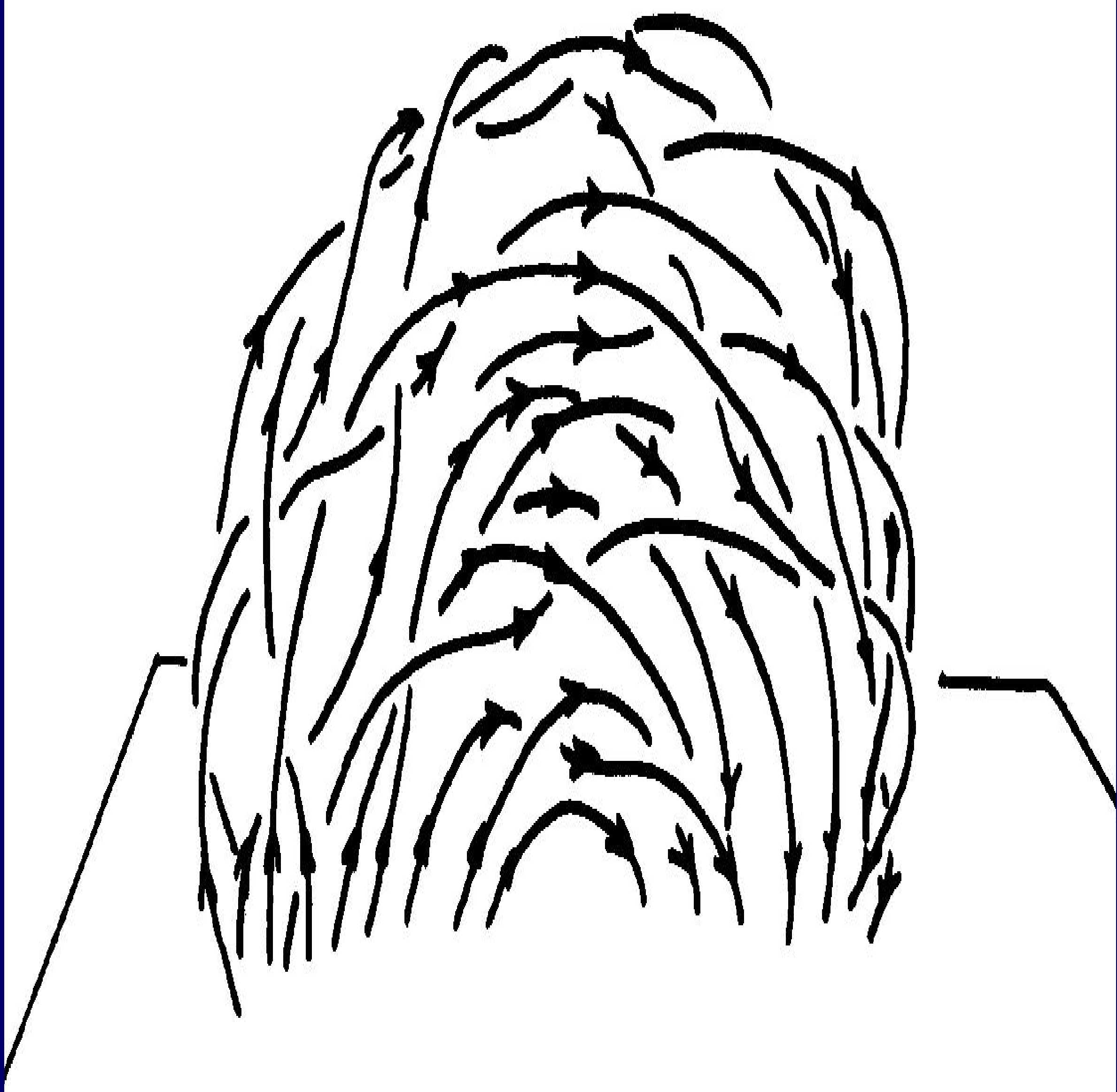


[Aschwanden and Parnell 2008]

N(E) is the probability of an event in dependence on its energy dE dA dt

The total number of events is The integral over N(E) dE dA dt.

Heating by nanoflares

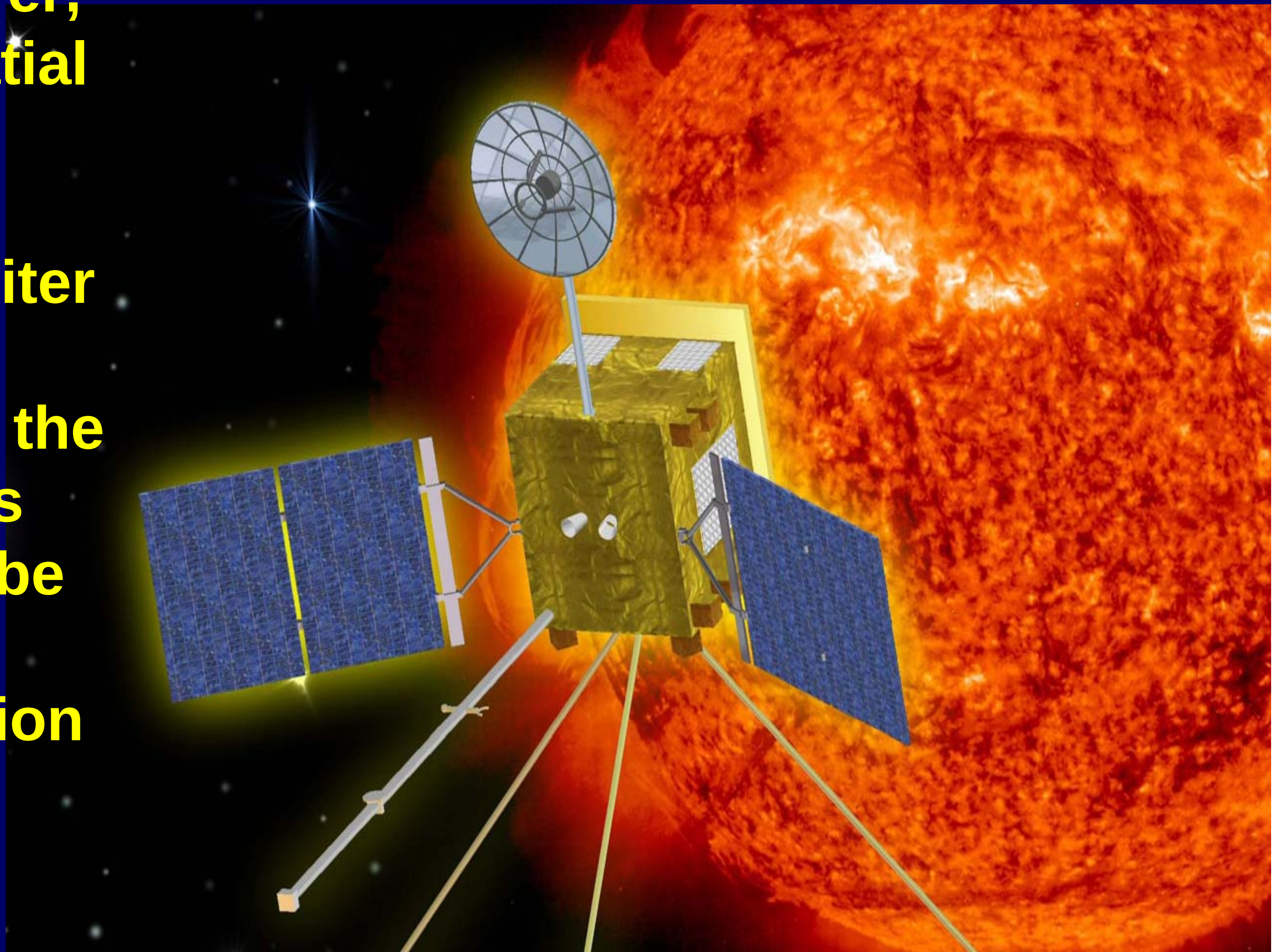


Footpoint motion in the photosphere
-> tangential discontinuities
-> small scale reconnection
-> '*Nano-Flares*'
***E* ~10^{24} ergs, t ~1s**
[Parker, 1988]

But: Not observable at Sun in principle !!

Next steps:

- 2010 „SDO“ (Solar Dynamics Explorer, NASA): High spatial and temporal resolution
- 2017: Solar Orbiter (ESA): Investigation of the Solar poles
- 2018: Solar Probe Plus: *In situ* investigation of the solar atmosphere



Summary

- The heating and dynamics of the solar atmosphere is mainly due to its magnetic coupling to the photosphere
- The energy is initially transfered by the interacting plasma and neutral gas in the chromosphere
- Complex solar B field + photo-/chromospheric plasma motion -> Large scale 3D current systems
- Currents reach small (plasma) scales -> their dissipation is microscopic, to be described kinetically
- Combining RMHD and kinetic physics one can model
  - solar wind acceleration
  - coronal heating (bright points!)
  - heating by nanoflares