Solar corona:open questions and how the "Solar Orbiter" mission will help us to solve them

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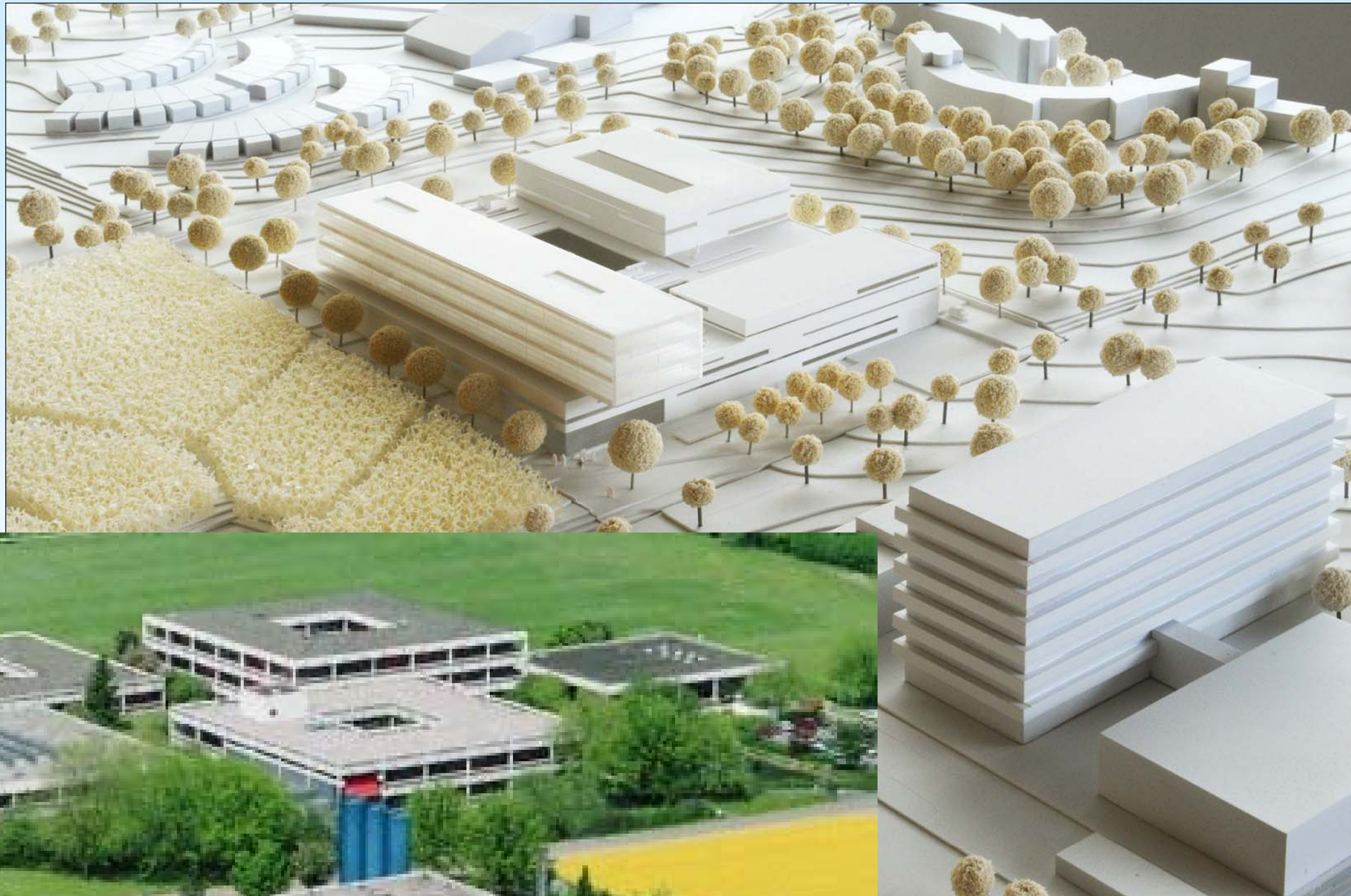
MPS moves 2014 to Göttingen

2014: New MPS building in Göttingen -->

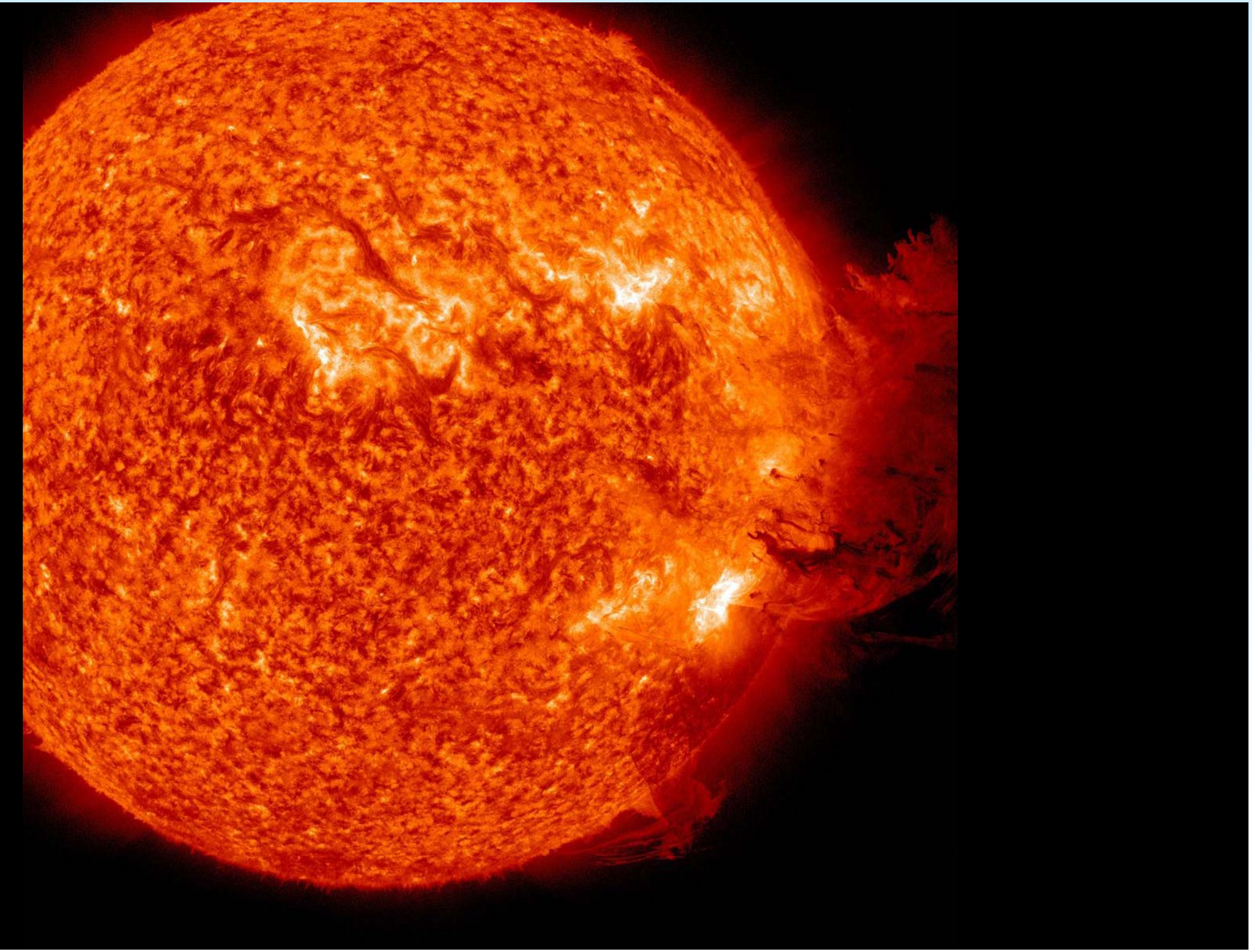
(since 1973 MPAe with Ian Axord as director/ since 2003 MPS,below)



January 2014: MPS in Göttingen

Starting 2014: MPS in Göttingen

Solar storm , Tuesday 7.7.2011:



38:30 h of NASA-SDO (AIA) s/c observations (from June 5 20:30 UT – June 7 11:00 UT)

-> M-2 (medium-sized) flare

-> S1-class (minor) radiation storm

-> coronal mass ejection (CME)

launched on June 7, ~ 7:00 UT from ARs (sunspot complex) 1226 – 1227 at the west limb.

SDO three wavelengh composite movie and X-rays

Top graph - the X-ray flux observed at the geostationary orbit by GOES-15

Main movie: an SDO zoom-in composite of observations at 211 Å, 193 Å and 171 Å wavelengths (21.1, 19.3, 17.1 nm) Between

June 7 6:10 UT and

June 7 7:13 UT

(Blast: 6:20 – 6:41)

Stereo coronographs

Stereo ahead

Stereo behind

Schematics

- **But: it is not known yet, what the physical processes behind are!**

Solar corona – open questions

- **Coronal heating to million K and: what causes**
  - **the solar wind,**
  - **coronal mass ejections,**
  - **particle acceleration,**

  influencing the "Space Weather“ near the Earth, the planets and the interplanetary space?
- **Needed:**
  - **multiwavelengths (visible, EUV, X-rays) and *in situ* observations of waves and particles as close as possible to the Sun**
  - **Modelling, numerical simulation**

Challenging conditions

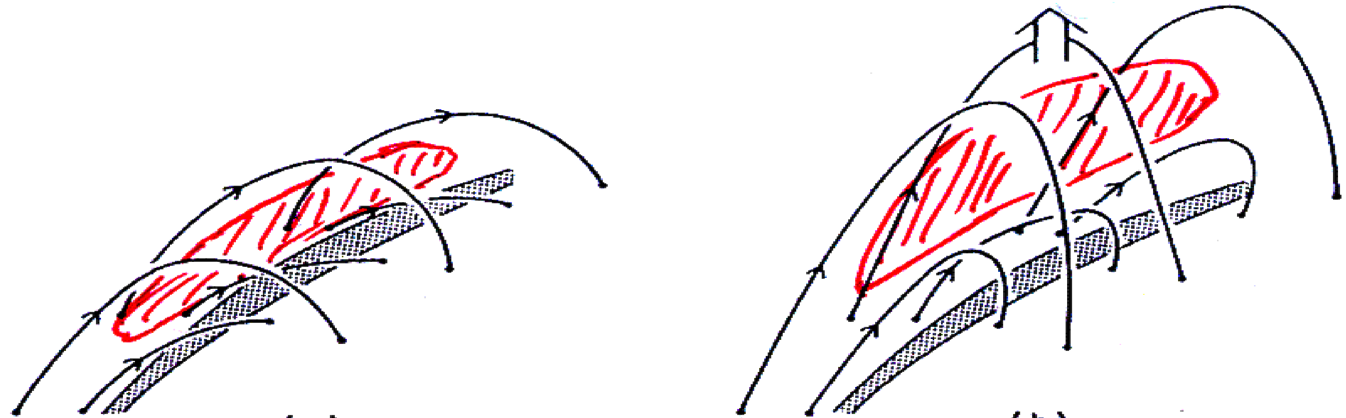
- **Main energy input from below the atmosphere – could be observed indirectly by local helioseismology**

- **The complicated, often complex coronal magnetic field (B) builts current sheets, whose size is below the spatial (pixel) resolution**

- **Large scale B-field energy releases via reconnection, often explosively but also quasi-stationarily**

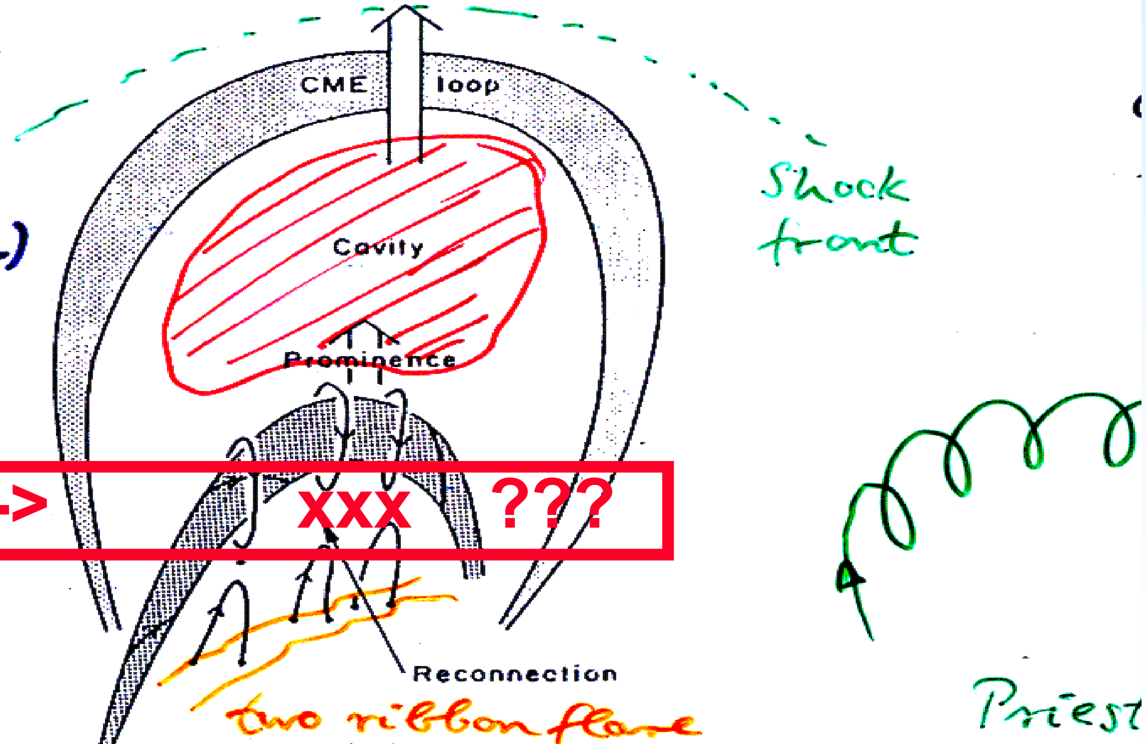
- **Considerably inhomogeneous plasma, structured by gravity, B fields, heat conduction and radiative losses**

Scenarios



Three-part structure:

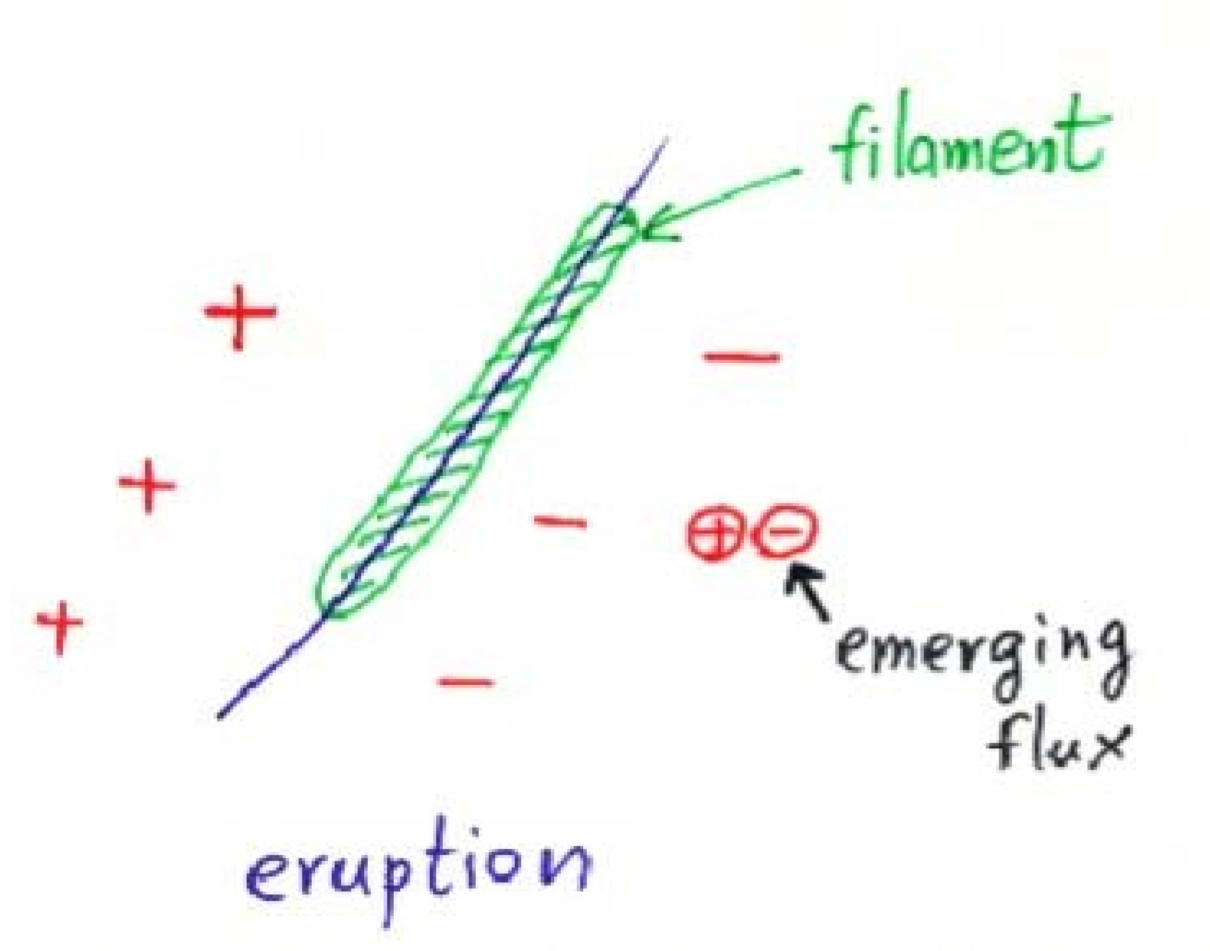
1. CME loop (coronal plasma)
2. Prominence cavity
3. Cold prominence mat.



Reconnection-> xxx ???

Observations before eruptions

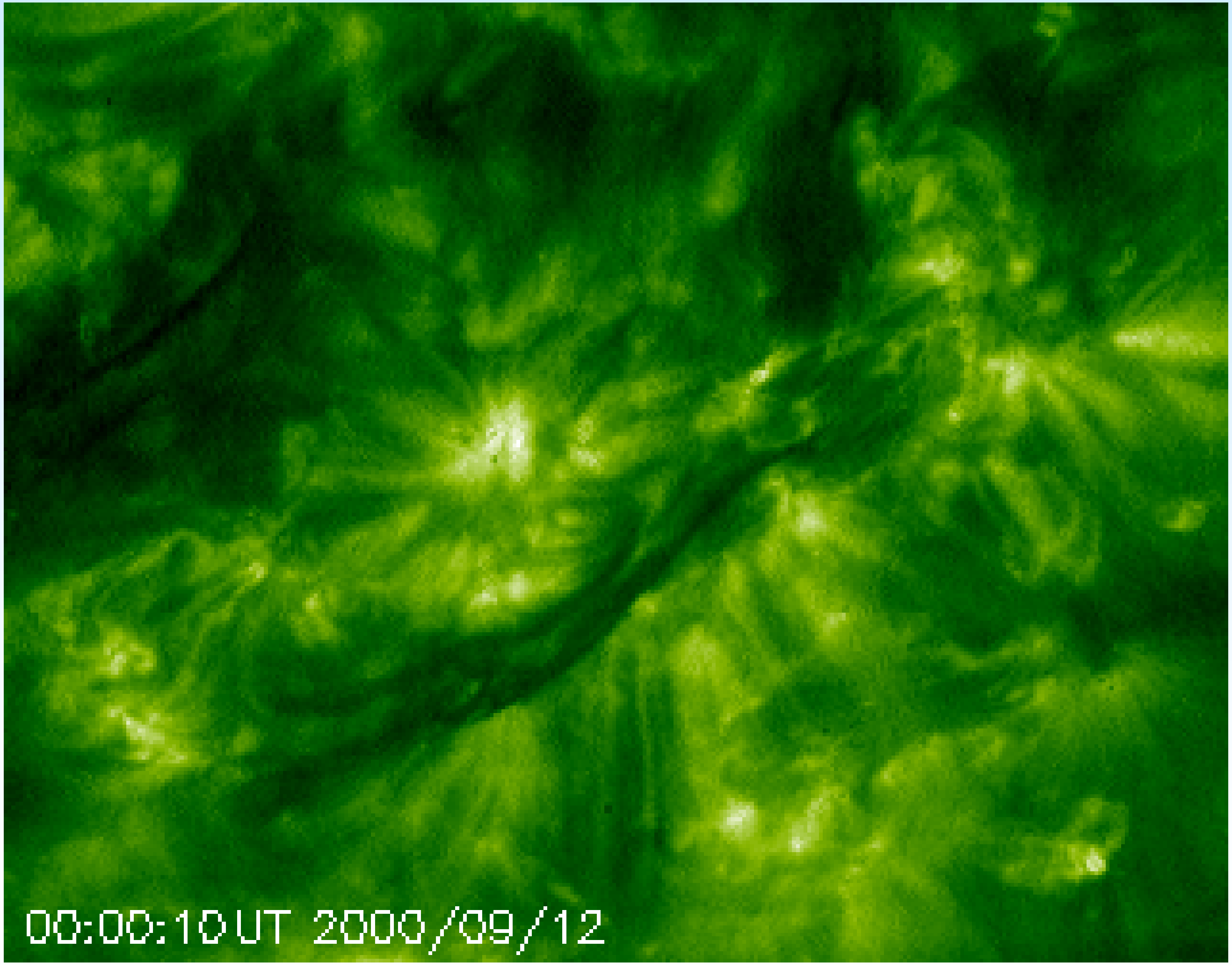
Date of CME	Flux Scenario
23-October 1997	Flux Cancellation
24-Jun-1999	Flux Cancellation
05-Mar-2000	Changes Near-By
04-Sep-2000	Flux Emergence
12-Sep-2000	Flux Emergence
29-Apr-2000	Flux Emergence



- **[Bothmer & Tripathi, 2005]**

- **-> Eruptions, when newly emerging**
- **flux is oppositely directed**

Example: eruption of AR 8210



GIF-Bild

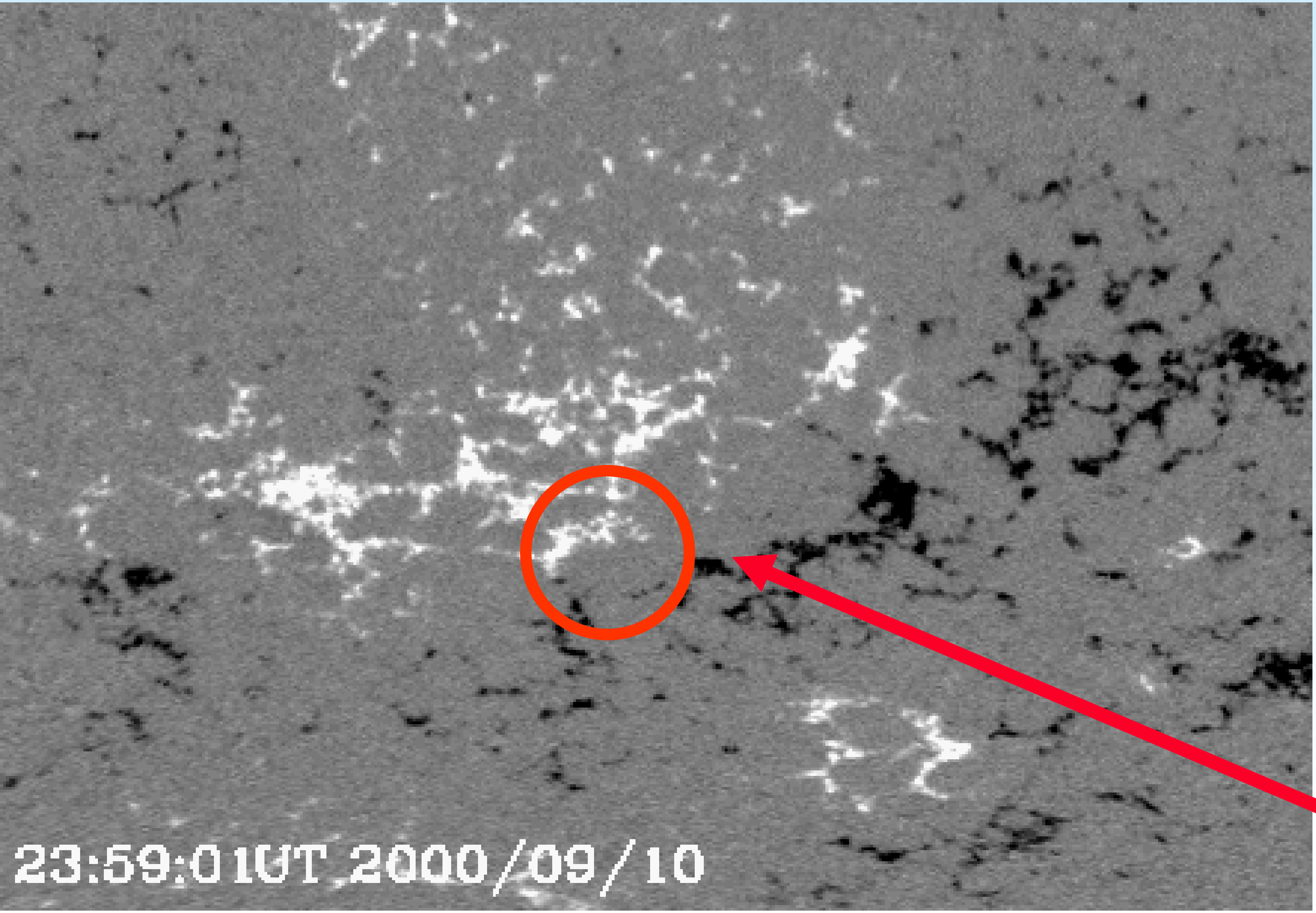
AR 8210
195 Å (EUV)
observation
SOHO/EIT

12.09.2000

After long accumulation of magnetic shear:

Flare eruption at 11:48 UT

Magnetic flux emergence

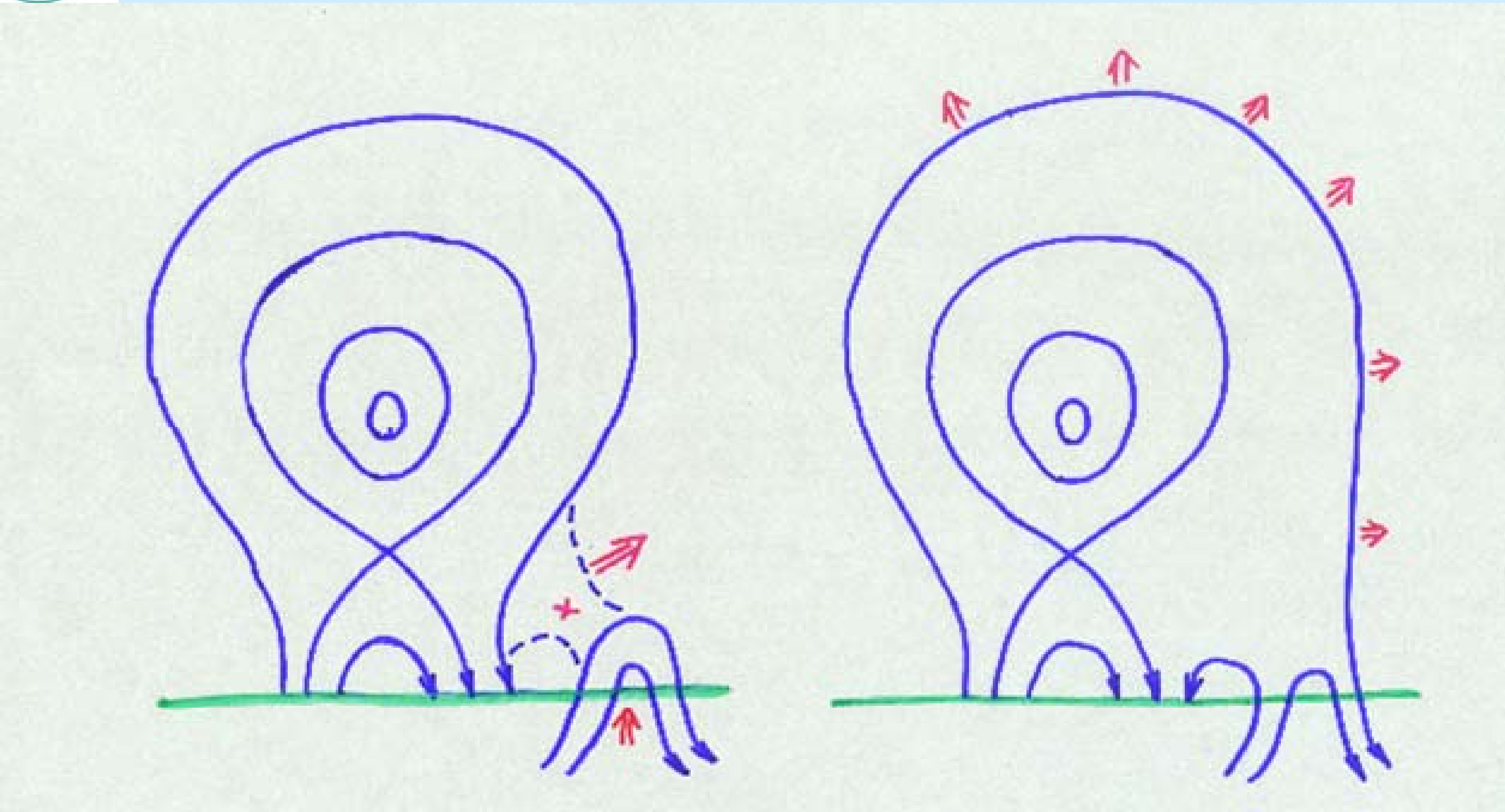


Magnetic Field Movie.gif

SoHO/MDI B-field 10.-13.09.2000, Flare burst on 12.9.00 at 11:48 UT

Site of the emergence of new magnetic flux

Two-dimensional cartoons



Model including coupling to the chromosphere, heat …

Set of MHD equations:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \boldsymbol{u}$$

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

(the index „0“ indicates chromosph. neutrals coupled to the plasma)

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

$$\boldsymbol{E} = -\boldsymbol{u} \times \boldsymbol{B} + \eta \boldsymbol{j}\,,\ \nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{j}\,,\ p = 2n\kappa_B T$$

+ closing energy equation

Energy equation –heat transfer

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

ohmic dissipation

where

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

heat conduction along magnetic field

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

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

radiative cooling

What controls the B–field?

In RMHD induction eq. controls the B-field evolution

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) \overset{\Leftrightarrow}{+} \nabla \times (\eta \nabla \times \mathbf{B}) = 0$$

Typical for the solar corona are huge magnetic Reynolds numbers $R_m \sim 10^{10}$ - i.e. currents cannot simply by dissipated (in contrast to the chromospheric Jpar currents!)

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

The only solution is:

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

R*m* has to become ~1

Since v ~ 10 km/s two ways to decrease R*m*:

1.) Decrease *l* by thinning η he current sheets

2.) Enlarge the resistivity - e.g. by plasma turbulence due to micro-instabilities

How? – Micro-turbulence

The resistivity, parametrized via an effective „collision frequency“, is dominated

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

In the (lower) chromosphere:
by binary particle collision rate
[Spitzer-Härm–Braginski Theory 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]
– for higher beta plasma -> 1D: IA double layers
– for lower beta plasma –> 2D: LH turbulence

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

$$\nu_c \approx \omega_{LH}$$

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

Resistivity models

Resistivity models used:

Current carrier velocity dependend anomalous resitivity (eta$_{eff}$ =10^9 times the Spitzer resistivity)

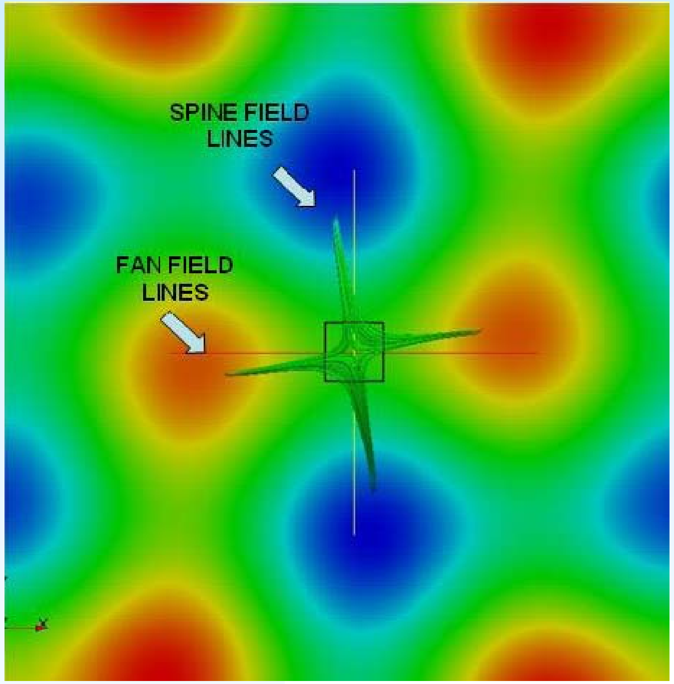
$$\eta = \eta_0 + \begin{cases} 0, & \text{if } |u_{ccv}| < u_{crit} \\ \eta_{eff}\left(\frac{|u_{ccv}|}{u_{crit}} - 1\right), & \text{if } |u_{ccv}| \geq u_{crit} \end{cases}$$

$$\eta_{eff} = \frac{\nu_{eff}}{\epsilon_0\ \omega_{pe}^2} = \frac{\omega_{pi}}{\epsilon_0\ \omega_{pe}^2}$$

Current density dependend resistivity

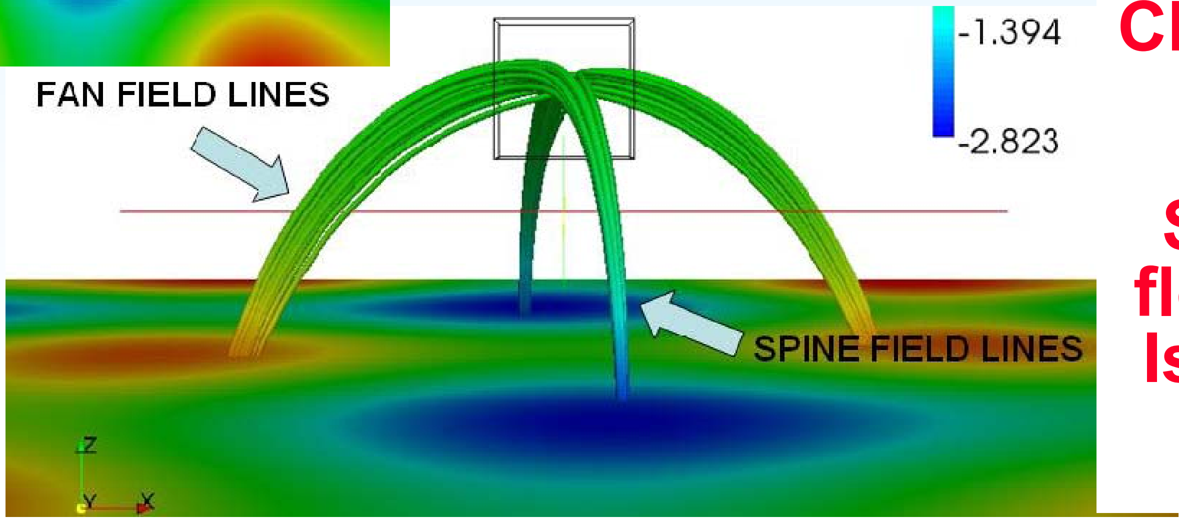
$$\eta = \eta_0 + \begin{cases} 0, & if |j| < j_{crit} \\ \eta_0(\frac{|j|}{j_{crit}} - 1)^2 & if |j| \geq j_{crit} \end{cases}$$

Coronal magnetic Null

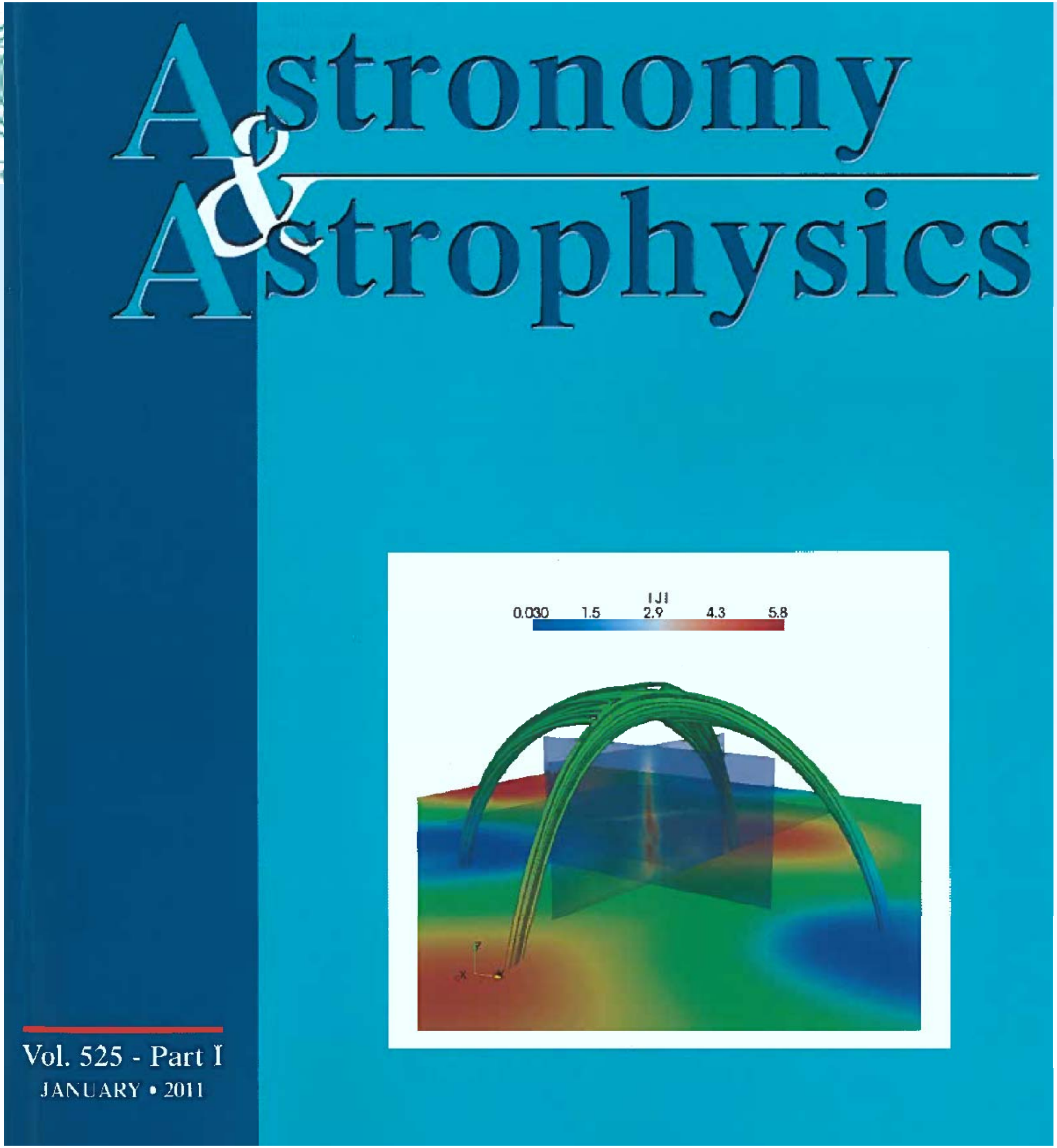


This 3D coronal null results from a quadrupolar photospheric B-field via its fan and spine field lines it is connected to the B-maxima

Eigenvalues of the Jacobian of B around the null: {+2; -1.7; -0.3} {Spine, Fan; Fan}.



Classification, e.g. by [Priest & Pontin 2009]: Torsional Spine / Fan / Shear flow reconnection -> Is decided by flows!

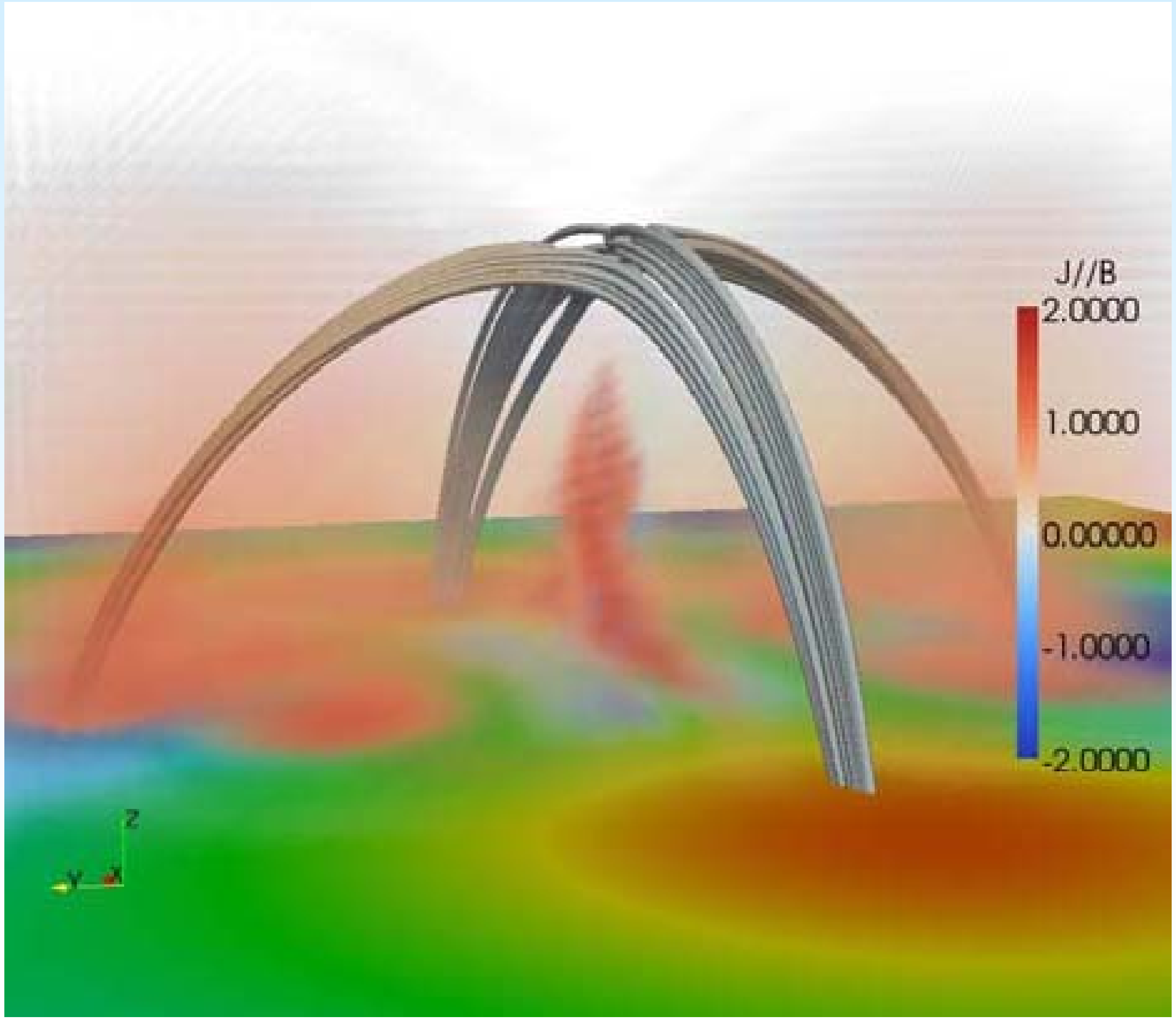


If the the plasma at the footpoints of the fan field lines is moved clockwise -> strong central shear

-> Formation of a current channel below the Null

[Santos,Büchner,Otto,11]
(from the title page of Astronomy& Astrophys., January 2011)

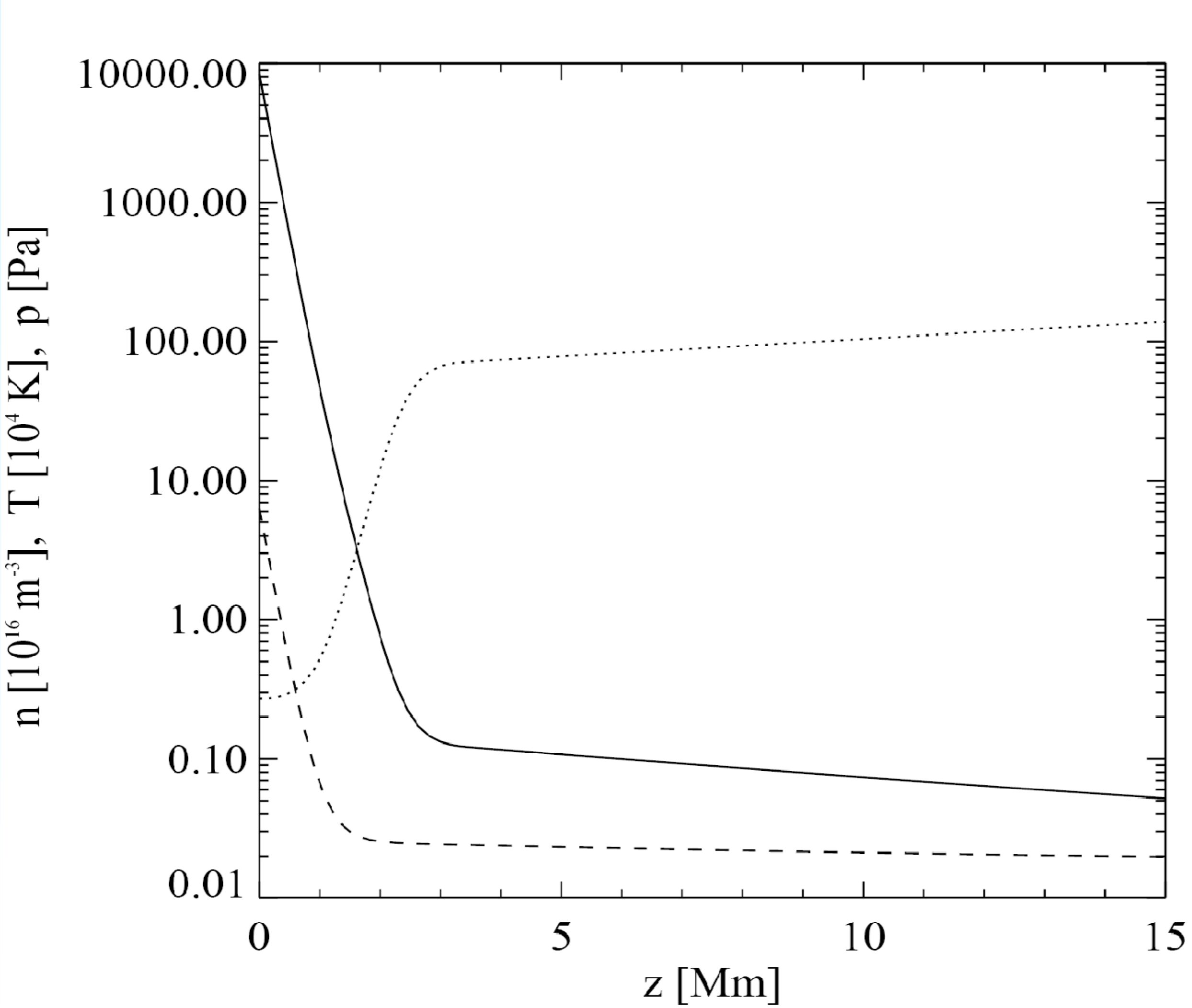
Corresponding Epar distribution



Result for the case where the plasma at both footpoints of the spine field lines are moved clockwise:

Eta j electric fields are maximum below the Null

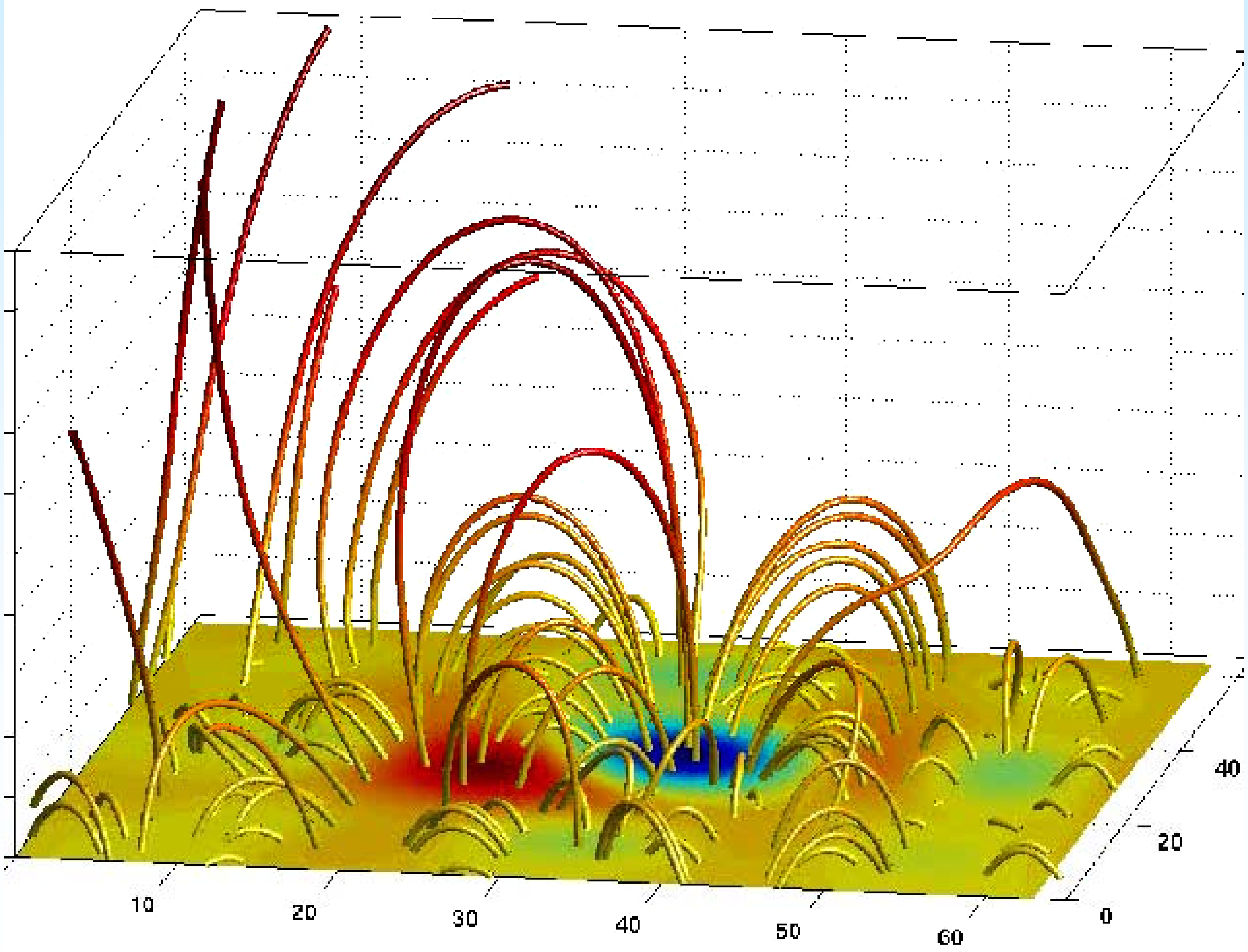
Initial stratified equilibrium



Plasma density [height] temperature and pressure in the solar gravitation

- On average: height-stratified equilibrium
- add B-fields extrapolated from observed LOS
- Energy input: Plasma motion in the photosphere
- Important: Rescaling of current densities to the plasma scales, not yet resolvable by MHD

+ initial magnetic field =>

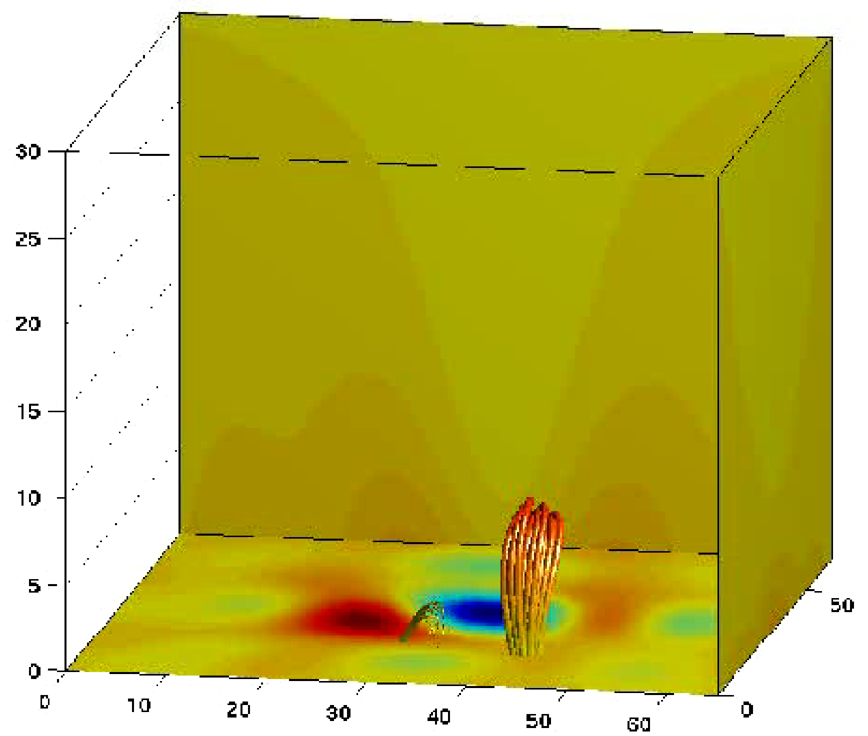


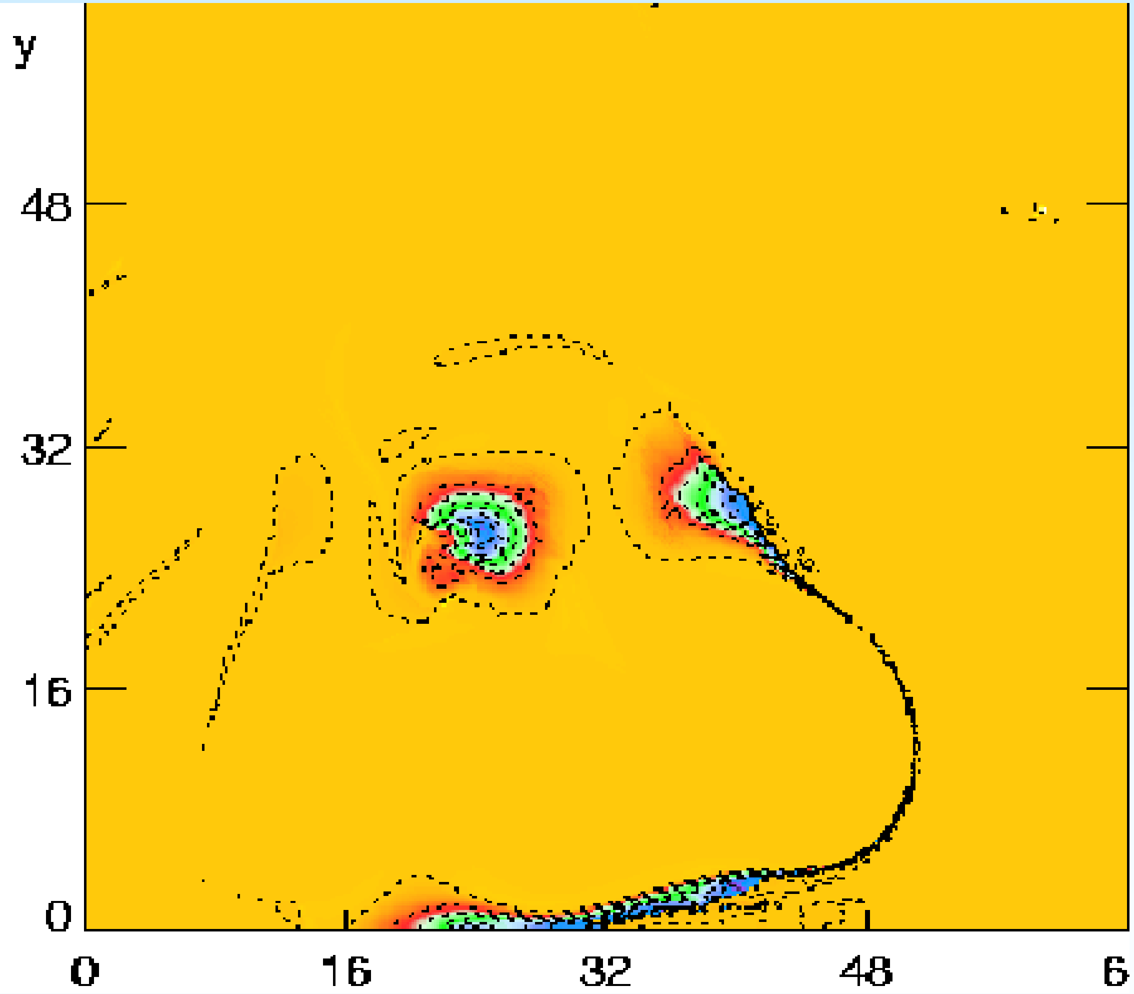
The solar magnetic is complex.

It evolves due to the photospheric plasma motion away from the lowest energy state.

This causes currents including non-force-free ones - and, finally, reconnection.

3D reconnection through QSLs

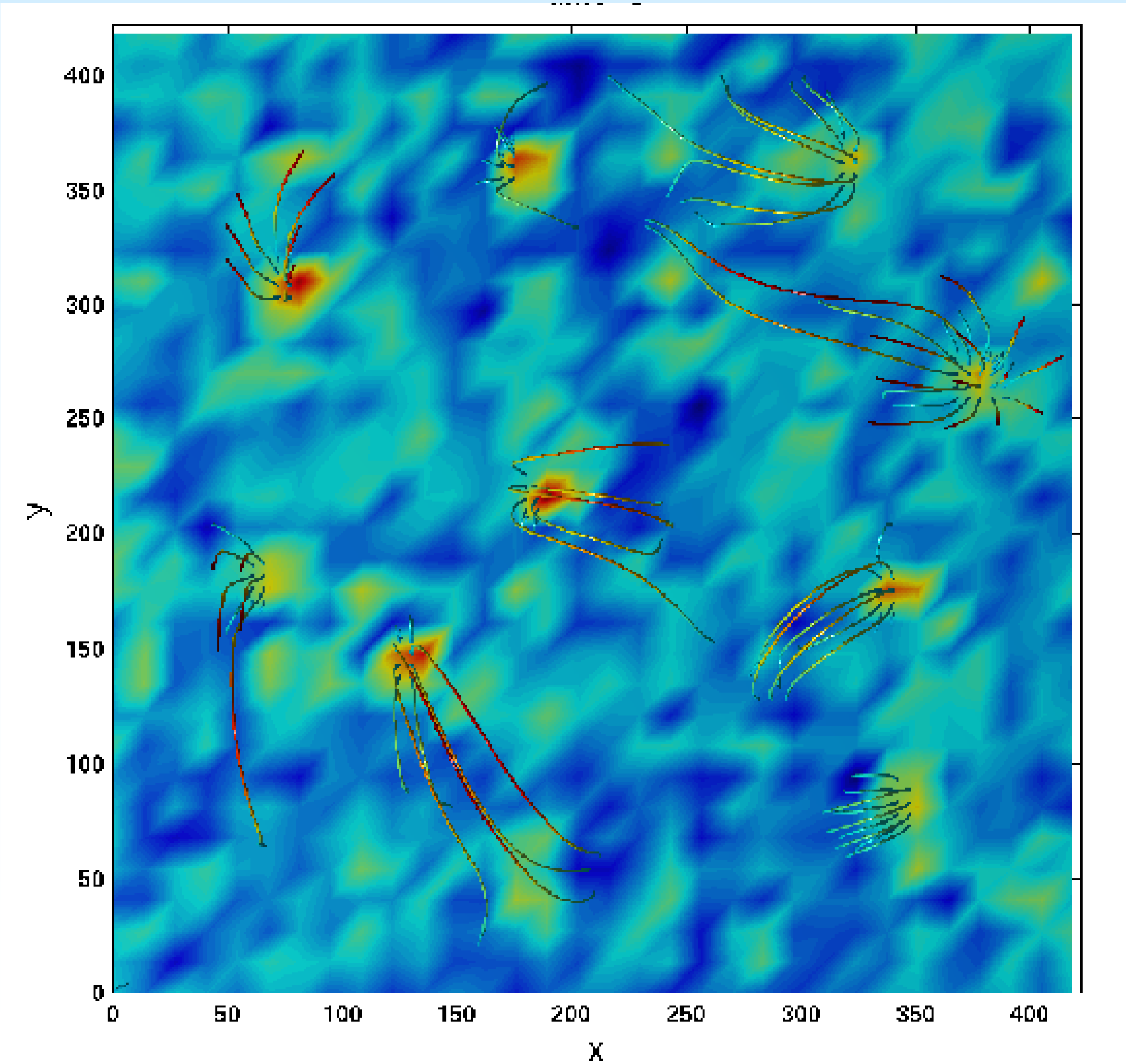




Finite-B 3D reconnection due to plasma motion through a QSL (quasi-separatrix-layer = topological boundary)

3D reconnection is characterized by strong Epar-here: field-line integrated

Coronal hole observations

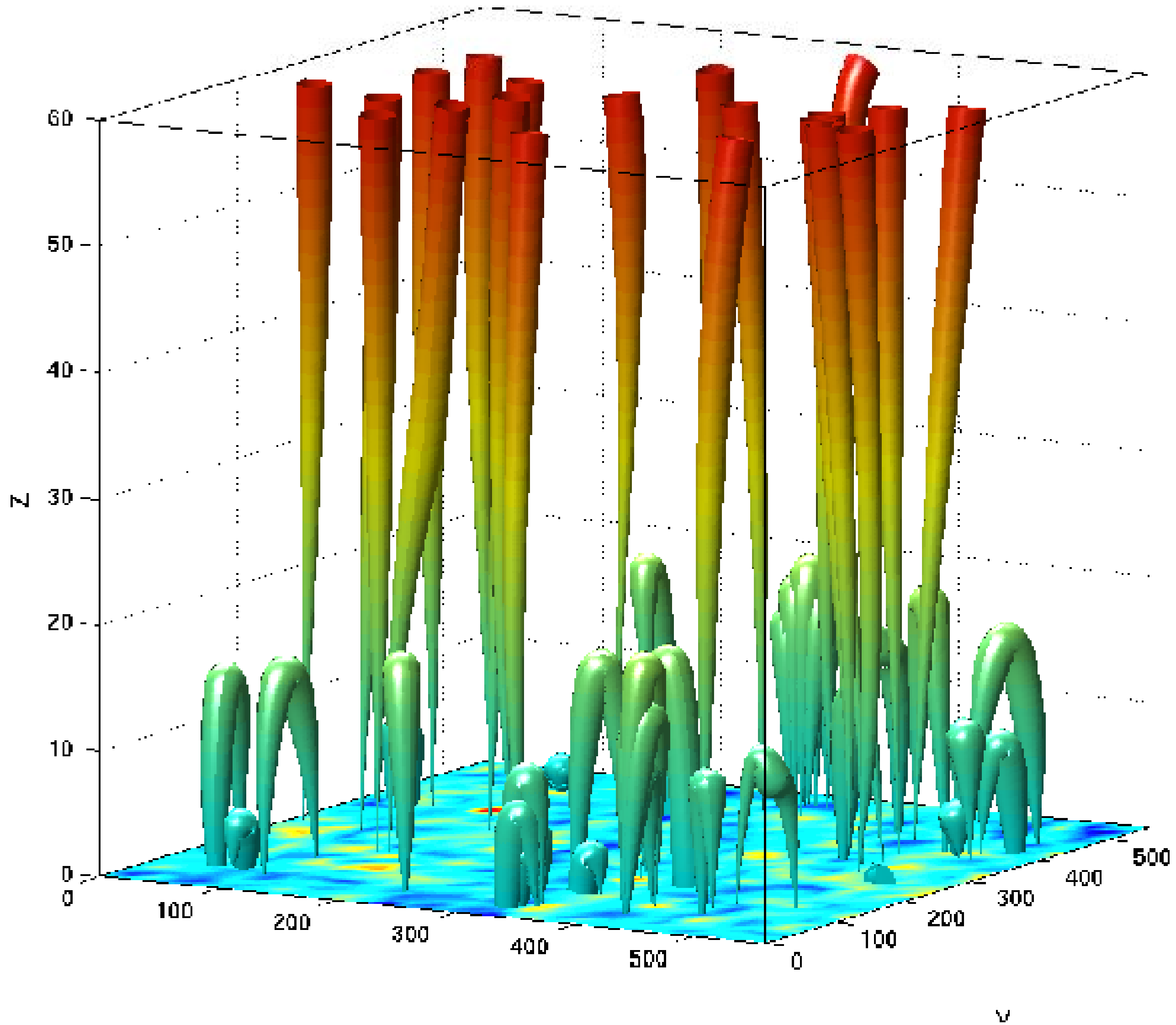


Magnetic field at 1:36 UTC for an area of about 180 Mm x 180 Mm between -41.6`` and 211,8`` longitude and 536.7`` and 790.1`` latitude on June 26, 1996 located inside a coronal hole around at 55‘ latitude.

Shown are also projections of the extrapolated potential fields.

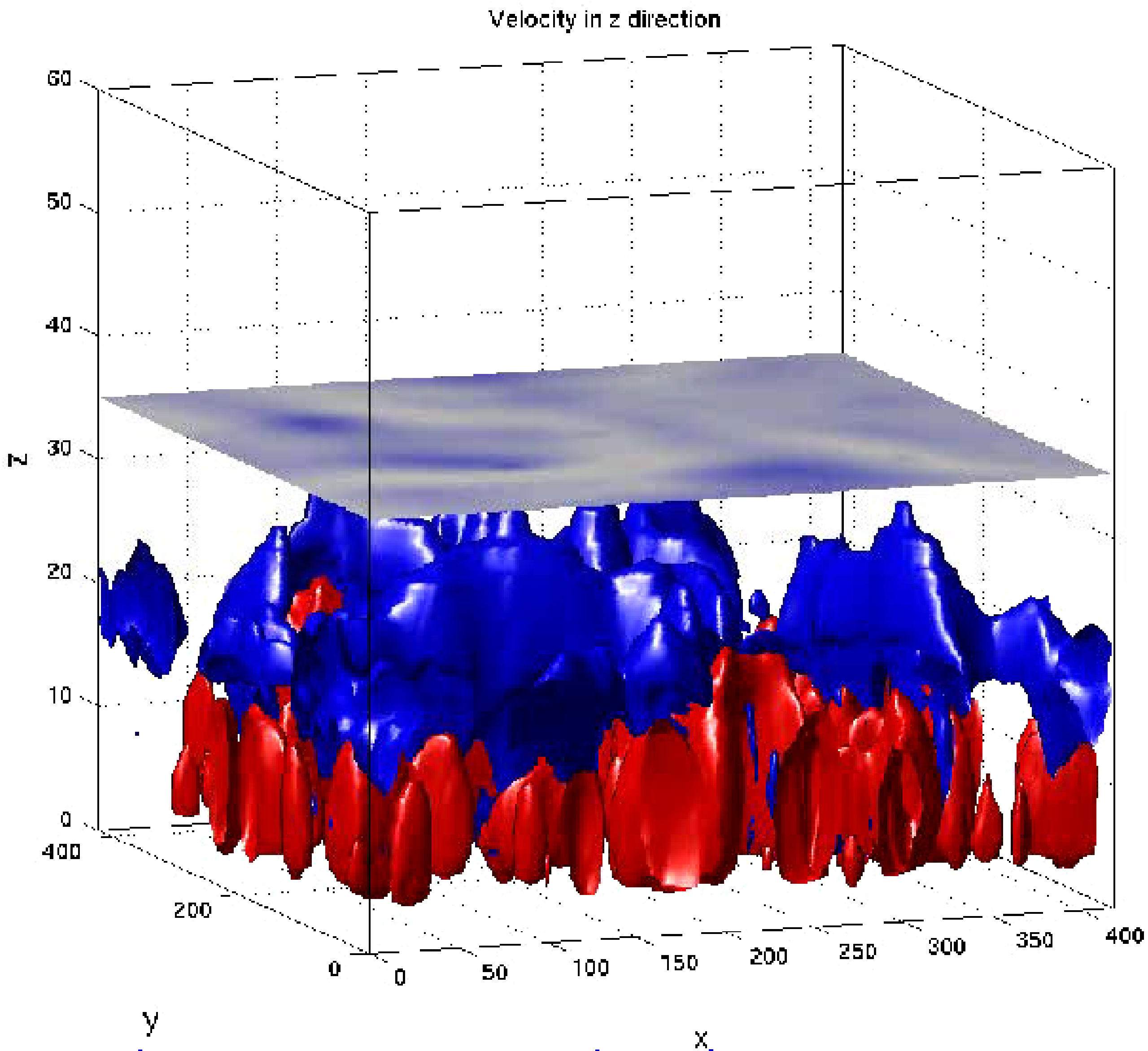
(Polar coronal hole)

3D magnetic field structure



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

Epar -> Plasma acceleration

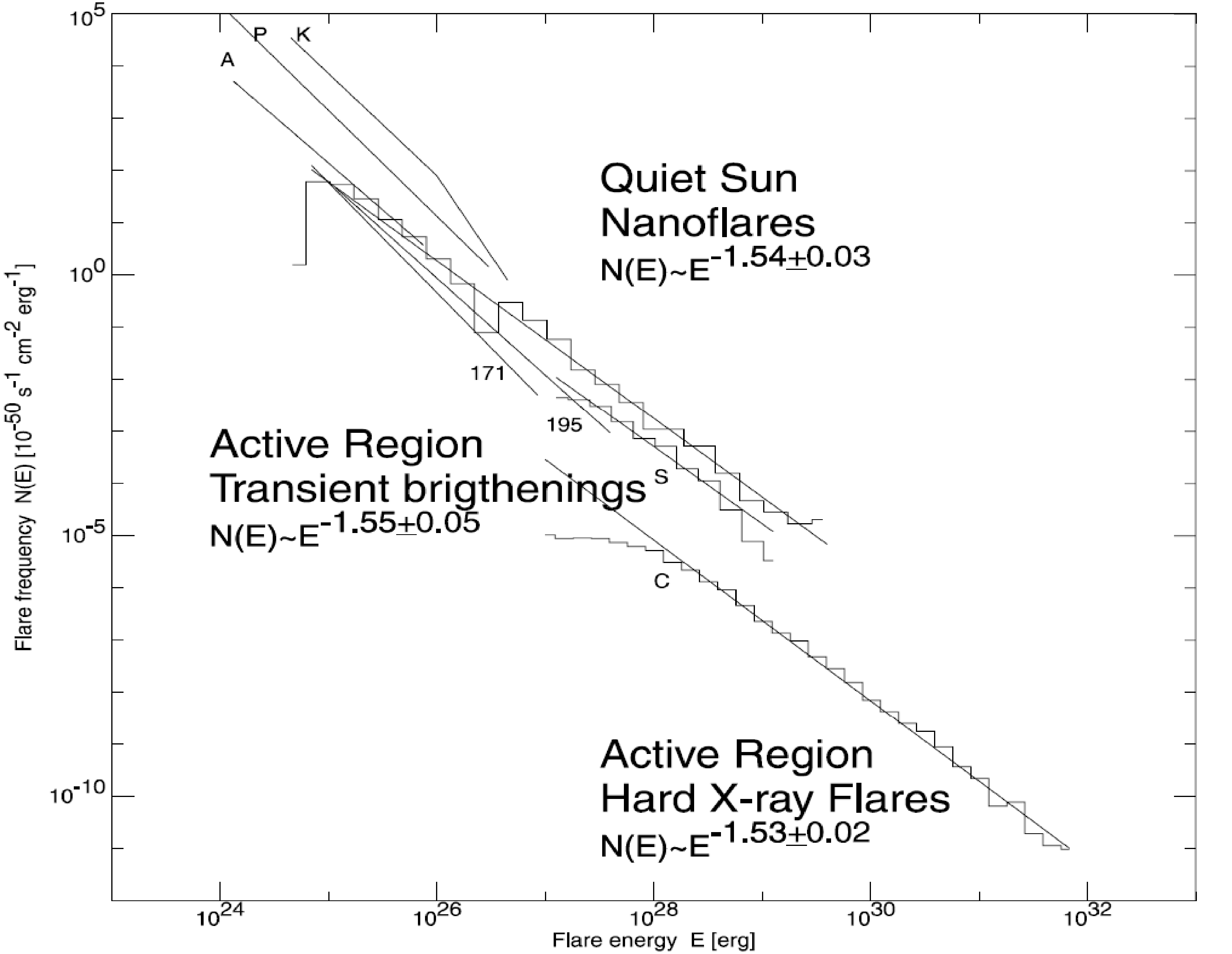


The isosurfaces
Vz=10 km/s
- **blue: upward**
- **red: downward**

demonstrate:

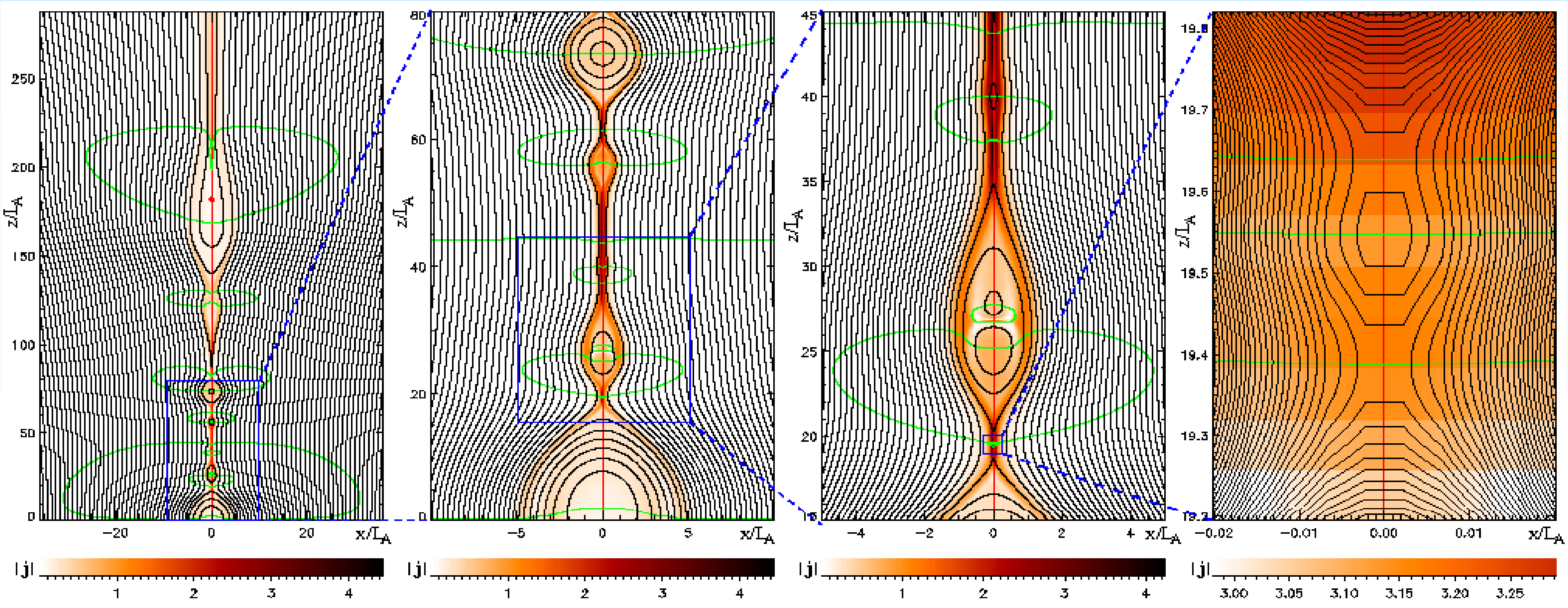
3D reconnection electric fields accelerate plasma both upward and downward

3. Scales of energy release



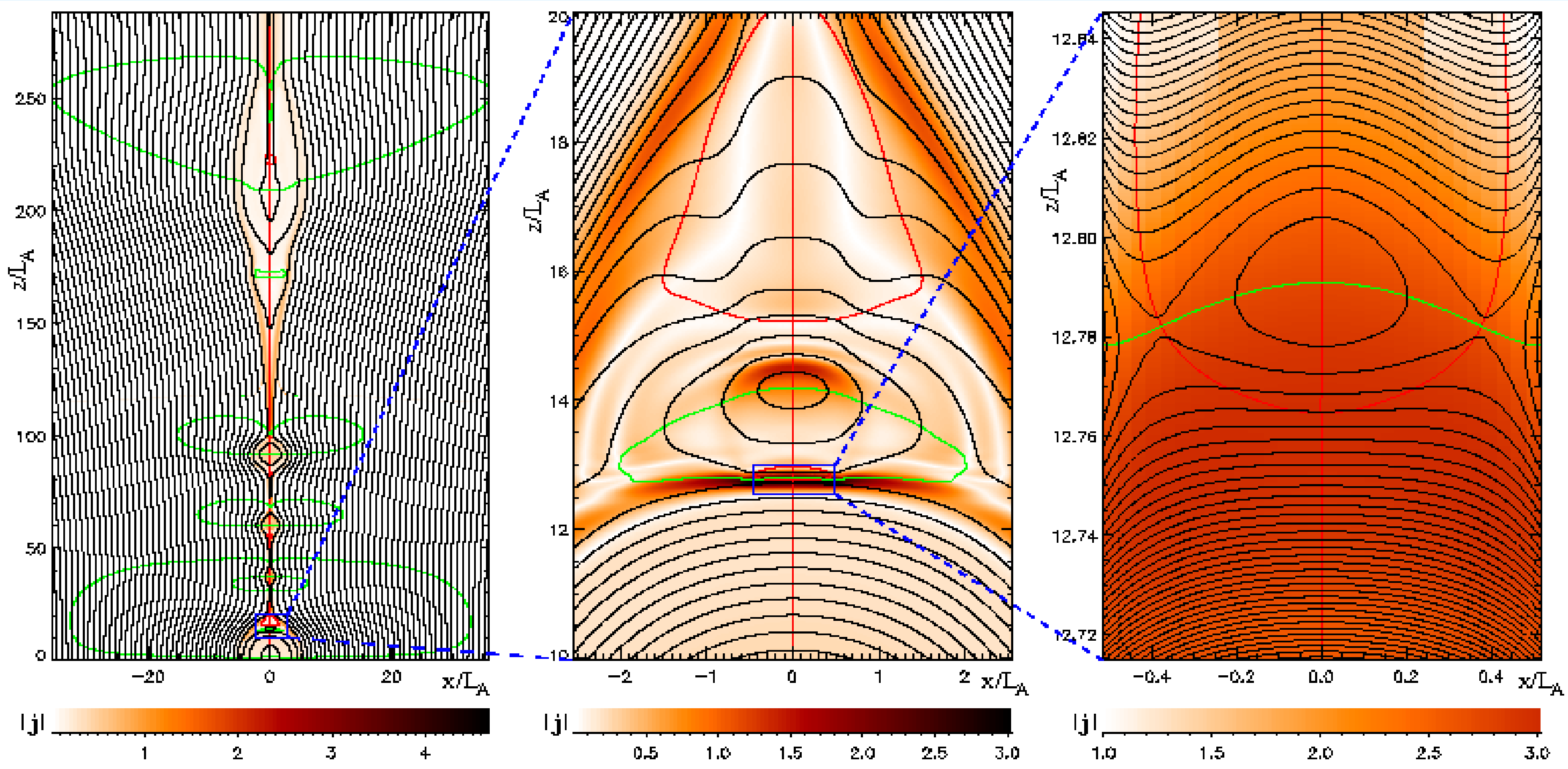
- N(E) is the probability of an
- energy ouburst event within dE dA dt
- (The total energy release is the integral over N(E) dE dA dt)
- [Aschwanden and Parnell 2008]

AMR simulation of cascading reconnection – 1. Multiple Tearing



2.5 D high-resolution adaptice-mesh refinement MHD, tearing mode instability lets islands grow see [Bárta, Büchner, Karlicky and Kotrc, ArXive 2010, ApJ, 2011, paper 1, in press]

AMR simulation of cascading reconnection – 2. Coalescence



Coalescence also contributes to the direct cascade !

2.5 D high-resolution MHD, see [Bárta, Büchner, Karlicky and Kotrc, ApJ, 2011, paper 1, in press]

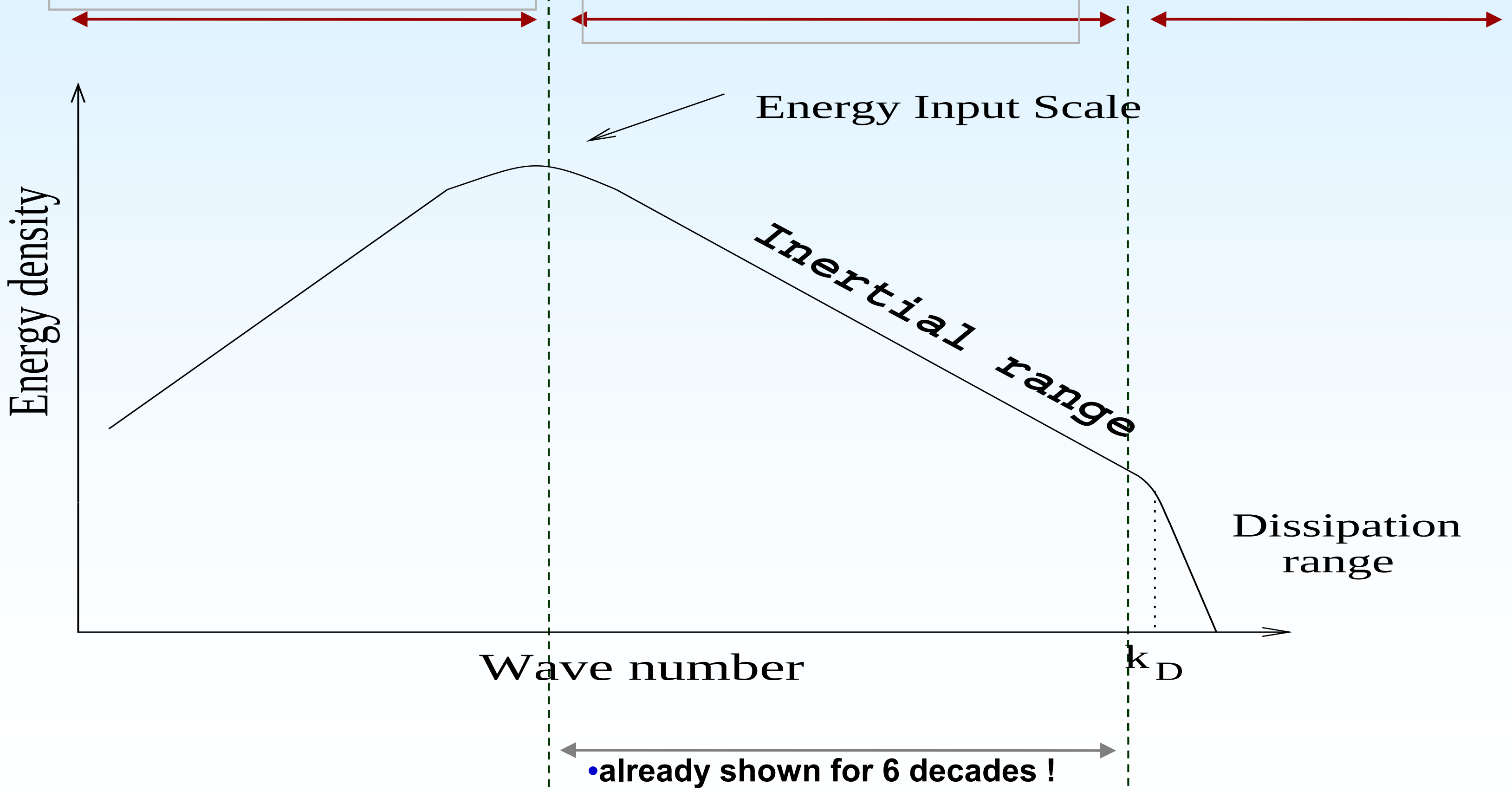
-> Wide spectrum of energy release by cascading reconnection

- Energy accumulation
- Ideal evolution, e.g. interaction with pre-existing B-fields field → current-layer formation

Energy distribution:

by cascading reconnection

- Energy dissipation
- By plasma micro-instabilities
- (e.g. Büchner, Elkina, 2006-2008)
- …



Solar Orbiter – The Mission

Launch: January 2017, but ongoing: definition phase of 1. Solar Orbiter, 2. Euclid, 3. Plato; ESA decision of 2 M-class launches (470 MEURO) 2017 & 18 in October 2011

Solar Orbiter

- **Main question: How does the Solar System work?**
- **Specific goals:**
  - **produce images of the Sun at high resolution**
  - **perform closest ever in-situ measurements**
- **Target:**
  - **The Sun in visible light, extreme ultra violet, X-rays**
- **Orbit:**
  - **Elliptical orbit around the Sun, perihelion 0.28 AU**
  - **inclination increasing up to more than 30° with respect to the solar equator.**
- **Lifetime: 9-10 years, i.e. more than the 6 years for a nominal Type M-class mission!**

Remote sensing instruments

Polarimetric and Helioseismic Imager (PHI)	29.1	25.0	31.0	25.0	Optical unit: 79.5 x 40 x 29 cm Electronics: 20 x 40 x 29 cm	20	HRT: 16.8 x 16.8 arcmin FDT: 2.6° cone	SUNRISE/IMaX
EUV Imager (EUI)	18.1	20.0	24	25.0	Optical bench: 83 x 54.5 x 22.8 cm Electronics: 120x300x250 mm	20	FSI: 5.2 x 5.2 arcdeg HRI: 1000 x 1000 arcsec	SOHO, STEREO, TRACE, PROBA2
Spectral Imaging of Coronal Environment (SPICE)	18.4	18.0	28.8	25.0	Optical bench: 91.1 x 34.9 x 17.7 cm Electronics: 20 x 18.6 x 12.4 cm	17	1 arcsec x 17 arcmin slit	SOHO, SUMER, CDS, HINODE
X-ray Spectrometer Telescope (STIX)	4.4	10.0	4.4	10.0	Imager Module: 55 x dia. 18 cm Spectrometer: 18 x 20 x 22 cm Electronics: 16 x 20 x 22 cm	0.2	2.5° for spectroscopy 1.5° for imaging	RHESSI
Coronagraph (METIS/COR)	20.6	25.0	26.0	25.0	Optical Bench: 90 x 44 x 25 cm Electronics: 22 x 25 x 10 cm	10	1.3°-3° annular, off-limb corona	SCORE/ HERSCHEL
Heliospheric Imager (SolOHI)	11.2	20.0	10.0	10.0	Optical unit: 425x140x180 mm Electronics: 100x100x50 mm	20	40° x 40°, offset 5° from Sun centre	STEREO

PHI: Magnetograph-Polarimeter (S. Solanki, PI instrument of the MPS Lindau)

EUI(P.Rochus, Liege, Belgium; MPS Germany: hydrogen Lyman-α line 121.6nm)

STIX:X-ray Spectrometer(A. Benz,Switzerland+UniKiel/ AIP Potsdam, Germany)

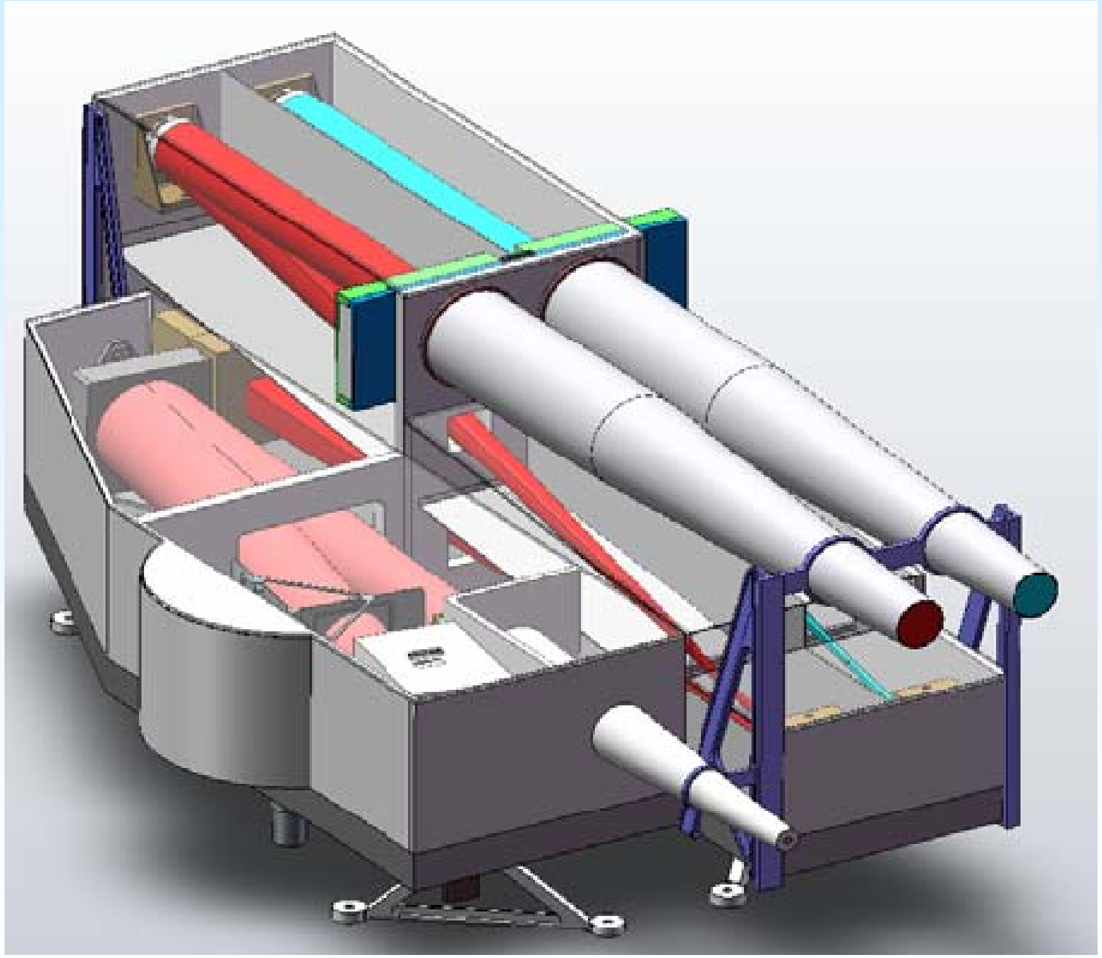
METIS: Coronal imager and spectrograph (E. Antonucci, Italy + MPS Germany)

SPICE: the extreme ultraviolet imaging spectrograph (Don Hassler, SWRI San Antonio) - is not funded by NASA at the moment!

EUI – the EUV Imager

The EUI instrument suite:

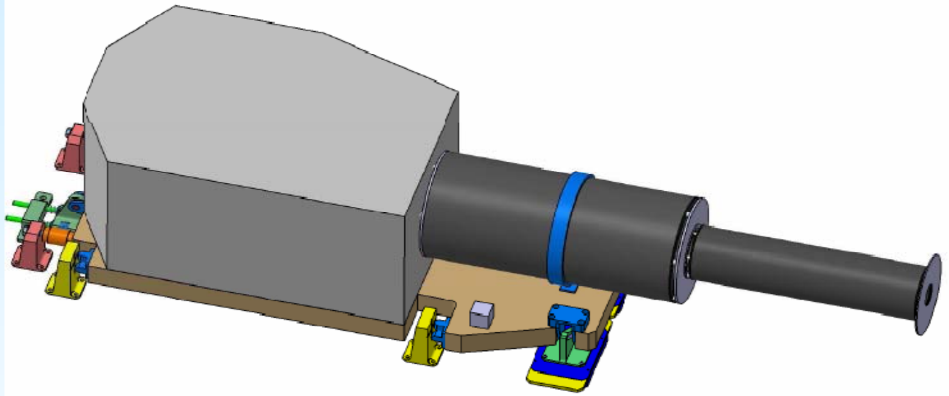
- **Two high resolution imagers (HRI)**
  - **Lyman-α**
  - **EUV (174 Å)**
- **One dual band full-sun imager (FSI)**
  - **174 and 304 Å EUV**



METIS

- the Multi Element Telescope for Imaging and Spectroscopy
- a Coronograph and Spectrometer

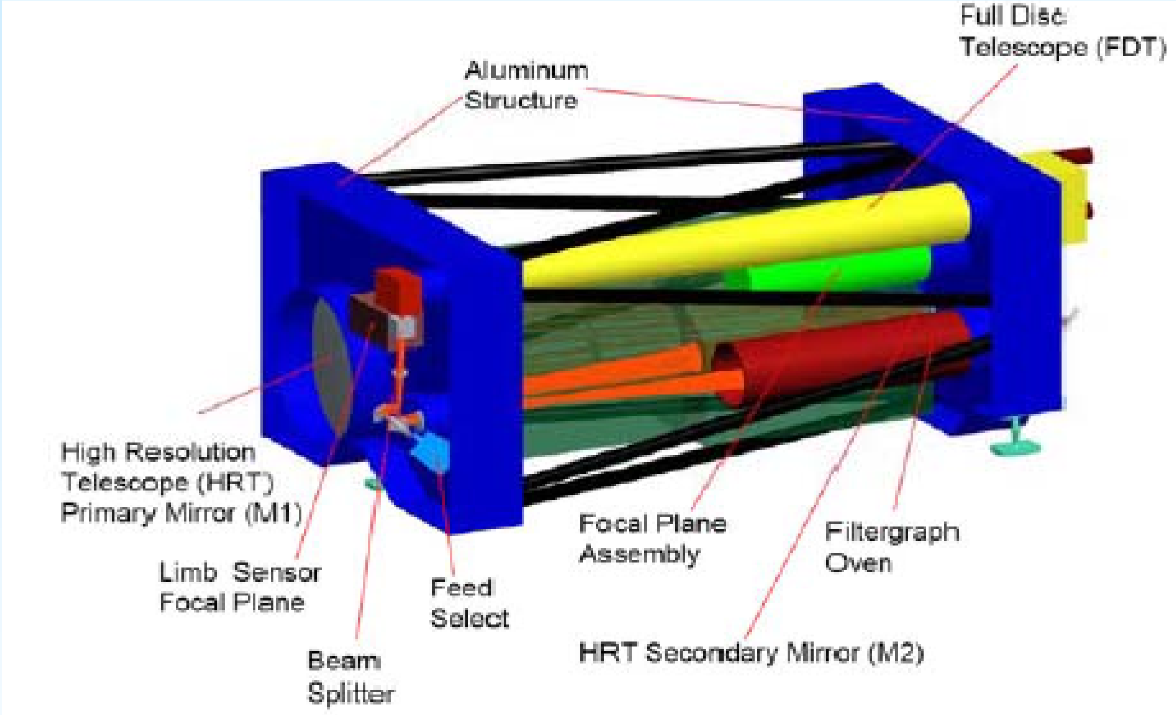
METIS Instrument Performance	
CORONAL IMAGING	
Avg. Instrumental Stray Light (Bcor/Bsun)	VL <10^{-9} UV/EUV <10^{-7}
Wavelength range:	VL: 500-650 nm; UV: 121.6 ± 10 nm EUV: 30.4 ± 2 nm
Spatial Resolution	20 arcsec
Field-of-view	1.5° - 2.9° annular, off-limb corona
CORONAL SPECTROSCOPY	
Wavelength range:	UV: 121.6 ± 0.9 nm EUV: 30.4 ± 0.22 nm
Spectral Resolution	UV: 0.054 nm EUV: 0.013 nm
Spatial Resolution	34 arcsec
Field-of-view	Slit radial positions: 1.5°, 1.8°, 2.1° Slit extension: 0.8°
GENERAL	
Telemetry rate	10 kbit/s
Data volume (compression up to 10)	26 Gb/orbit



PHI

The Polarimetric and Helioseismic Imager

	Requirement
Field of view (HRT)	>15 arcmin on 2kx2k detector
Field of view (FDT)	>150 arcmin on 2kx2k detector
Spatial resolution (HRT)	1 arcsec (0.5 arcsec pixel size)
Spatial resolution (FDT)	few arcsec pixel size
B_{LOS}	± 3.5 kG
B_{TRA}	± 3.5 kG
v_{LOS} (long term)	> 47 km s^{-1}

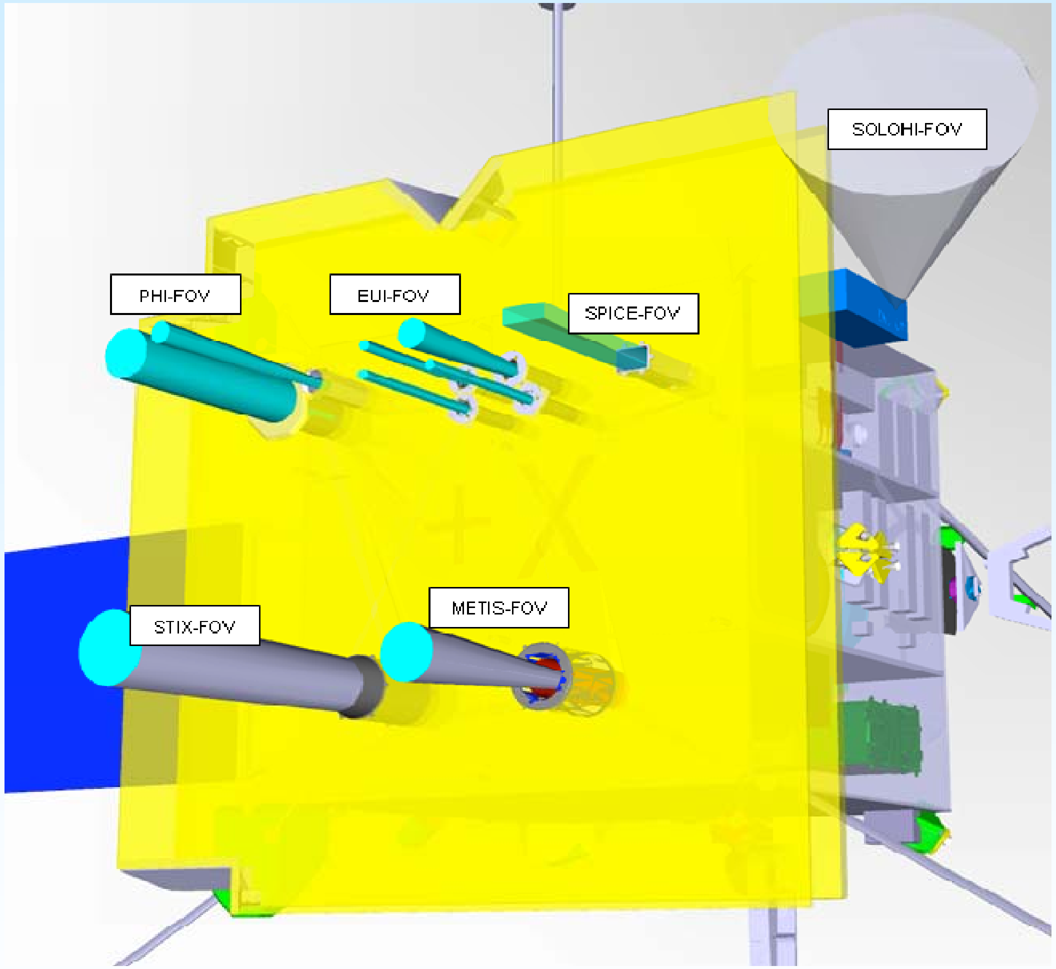


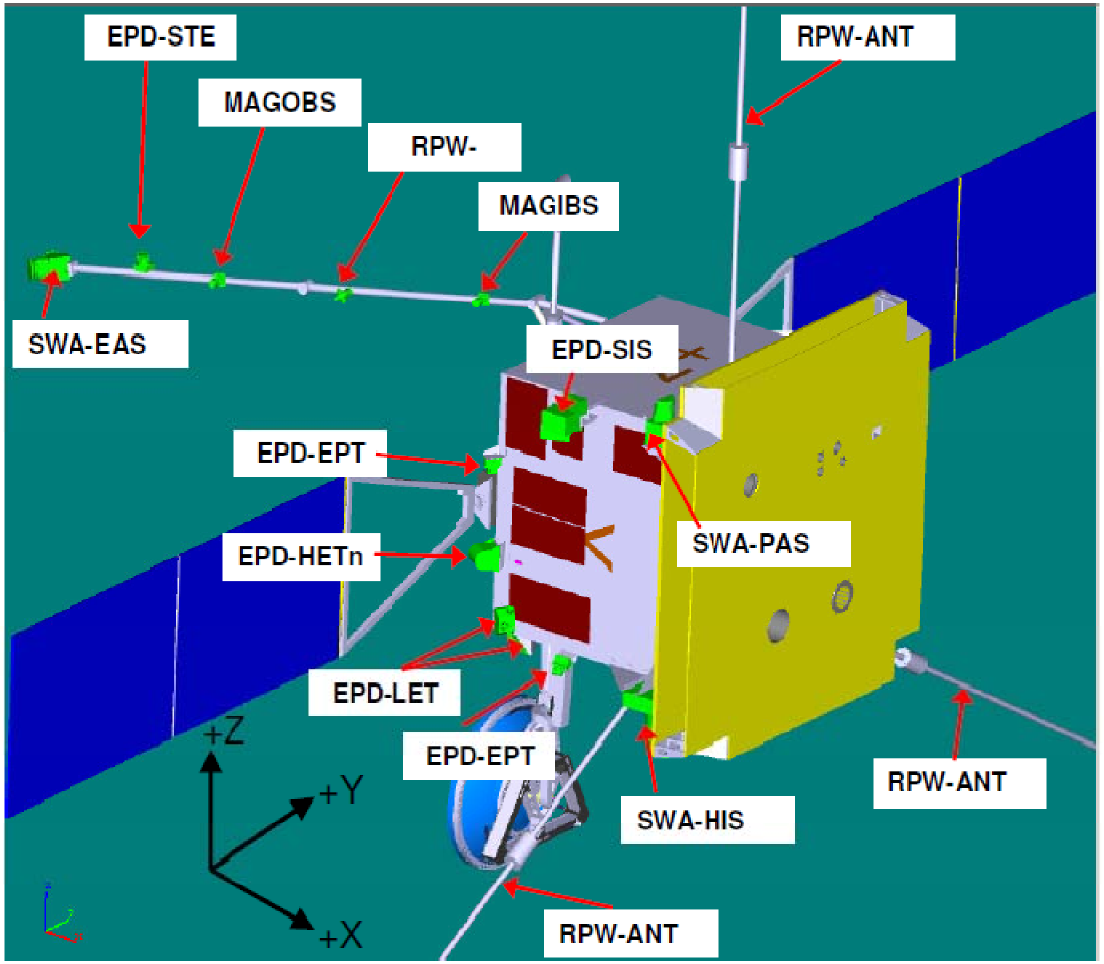
In situ instrument packages

Table 3.7 Solar Orbiter selected payload resource summary.

Investigation	Total Mass (kg)	Margin (%)	Power (W)	Margin (%)	Dimensions	Telemetry (kbps)	FOV	Heritage
Solar Wind Analyzer (SWA)	15.9	15.0	14.2	~15	EAS: 11.6 cm x dia. 13.6 cm PAS: 30 x 20 x 20 cm HIS: 31 x 28 x 25 cm	14	EAS: 360° x ±45° x 2 orthogonal sensors to provide 4-π ster FOV PAS: -17.5° to +47.5° Azimuth-22.5° to +22.5° Elevation HIS: -33° to +63° Azimuth -17° to +17° Elevation	Ulysses, ACE, STEREO
Energetic Particle Detector (EPD)	13.8	15.0	16.1	20.0	EPT1,2: 11 x 7 x 12 cm SIS1,2: 35 x 13 x 11 cm LET1,2: 22 x 15 x 11 cm HET: 13.6 x 17 x 16.2 cm STEIN: 10 x 13 x 13 cm CDPU/LVPS: 15 x 15 x 10 cm	3.1	EPT 1,2: 30° cones SIS: 22° cone (2x) LET1,2: 40° cone (3x) HET: 50° cone (x2) STEIN: 60° x 70° (2x)	STEREO, SOHO, ACE
Magnetometer (MAG)	2.1	10.0	1.9	25.0	Fluxgate sensor (2x): 9.75 x 4.9 x 6.7 cm Electronics: 15.9 x 16.2 x 9.8 cm	0.9 (normal) 6.8 (burst mode)	N/A	VEX, Themis, Rosette Lander, Double Star
Radio & Plasma Waves (RPW)	13.6	15.0	11.5	20.0	Antenna (3x): 650 cm long SCM: 13.6 x dia. 10.4 cm Electronics: 24 x 21 x 15 cm	5	N/A	STEREO

Instruments‘ accomodation





Remote-sensing instruments: locations and fields of view

In-situ instruments

Summary – Mission overview