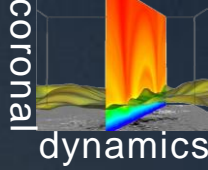# *Structure and evolution of an active region on the Sun*

**Hardi Peter**

*Sven Bingert*
*Philippe Bourdin*
*Feng Chen*

Max-Planck-Institut für
Sonnensystemforschung
Katlenburg-Lindau
Germany

http://www.mps.mpg.de/de/projekte/coronal-dynamics/
peter@mps.mpg.de

coronal
dynamics

MAX-PLANCK-GESELLSCHAFT

MPS

Duckmüller / Aniol, solar eclipse 2006

# The corona of the Sun

> 1 000 000 K
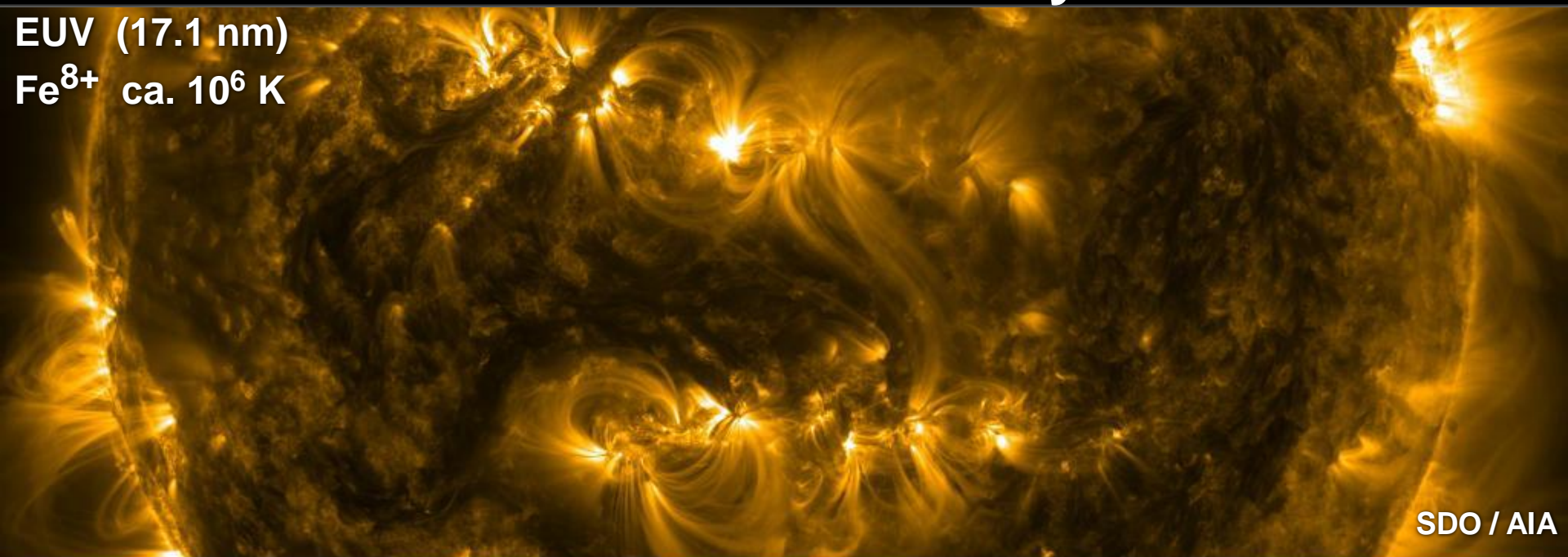
visible surface: 5800 K

EUV / X-rays: plasma at > $10^6$ K

**How can a cool body heat its hot surroundings ?!**

solar eclipse 13.11.2012

# The Sun over two days

EUV  (17.1 nm)
$Fe^{8+}$  ca. $10^6$ K
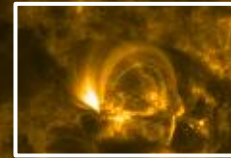
SDO / AIA

SDO / HMI

visible light:
solar surface
with sunspots

25.-27.
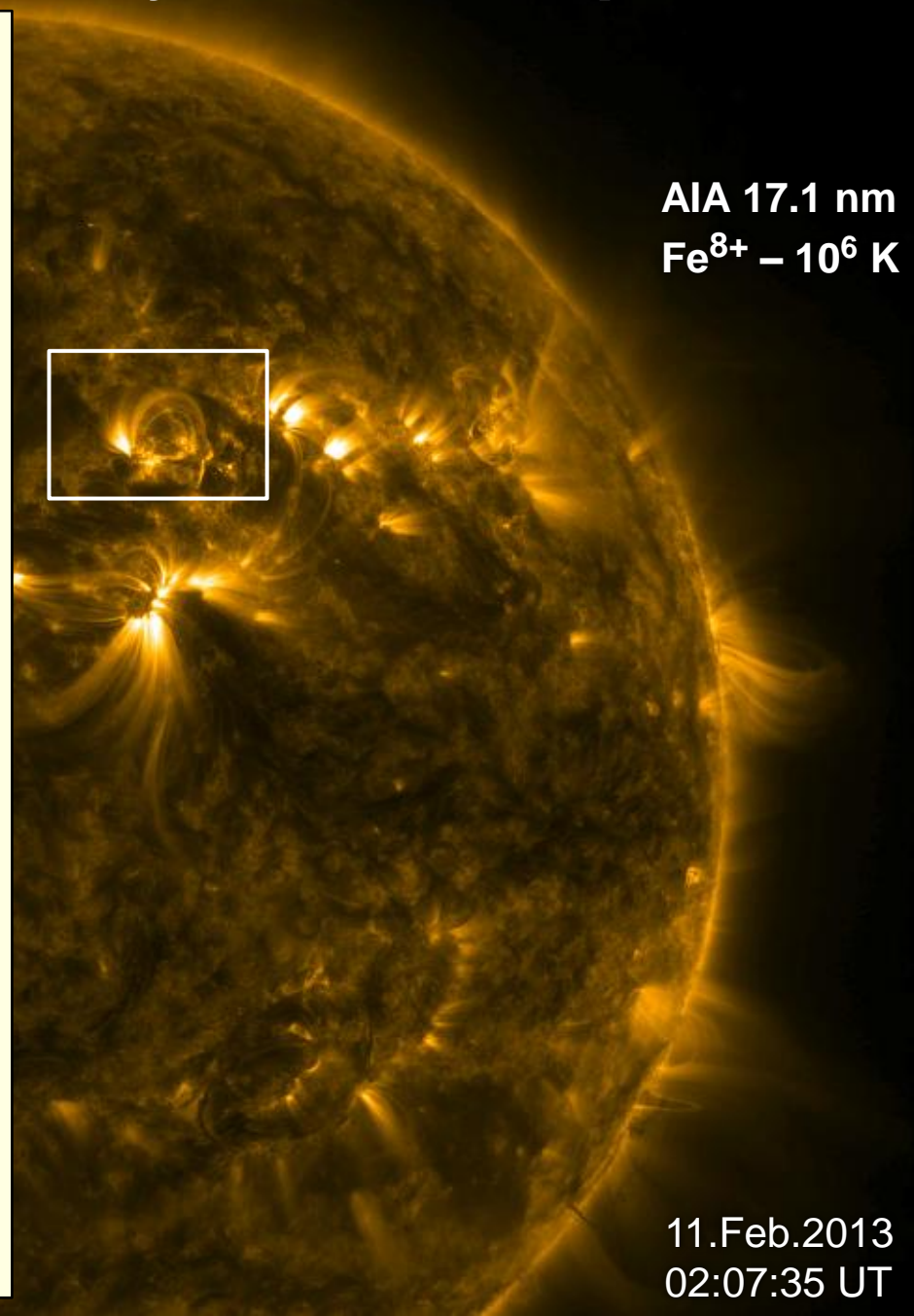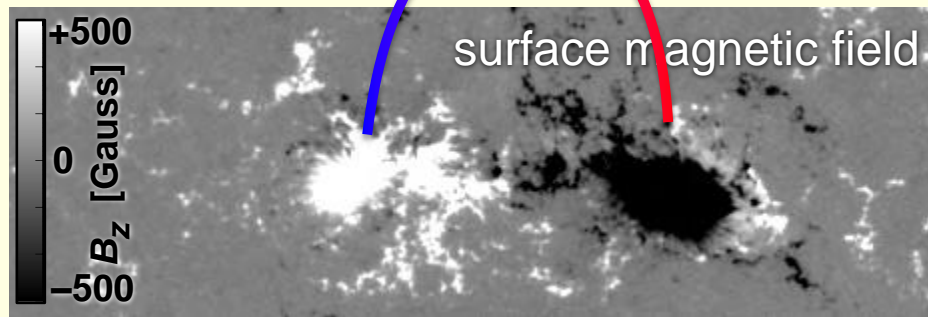May 2013

# Coronal structure: mostly *coronal loops*

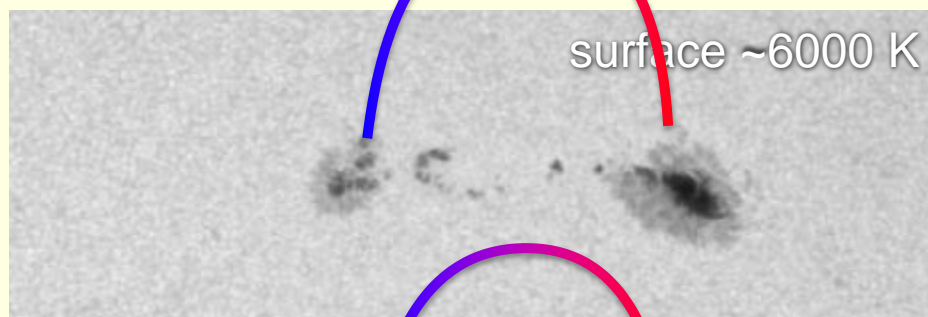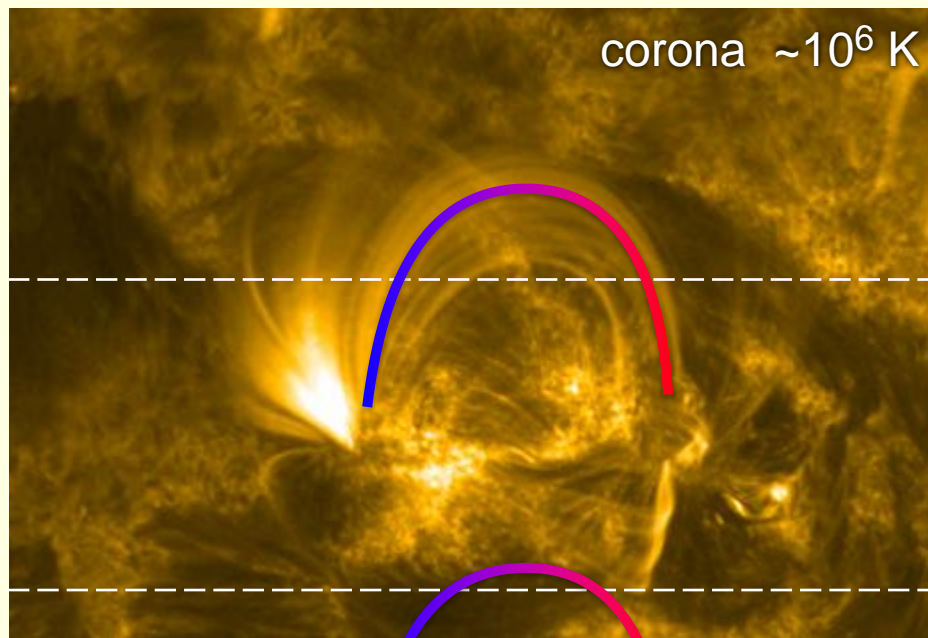AIA 17.1 nm
$Fe^{8+} - 10^6$ K

– **what determines the structure and dynamics ?**

– **how is the corona heated ?**

→ **close link between models and observations**
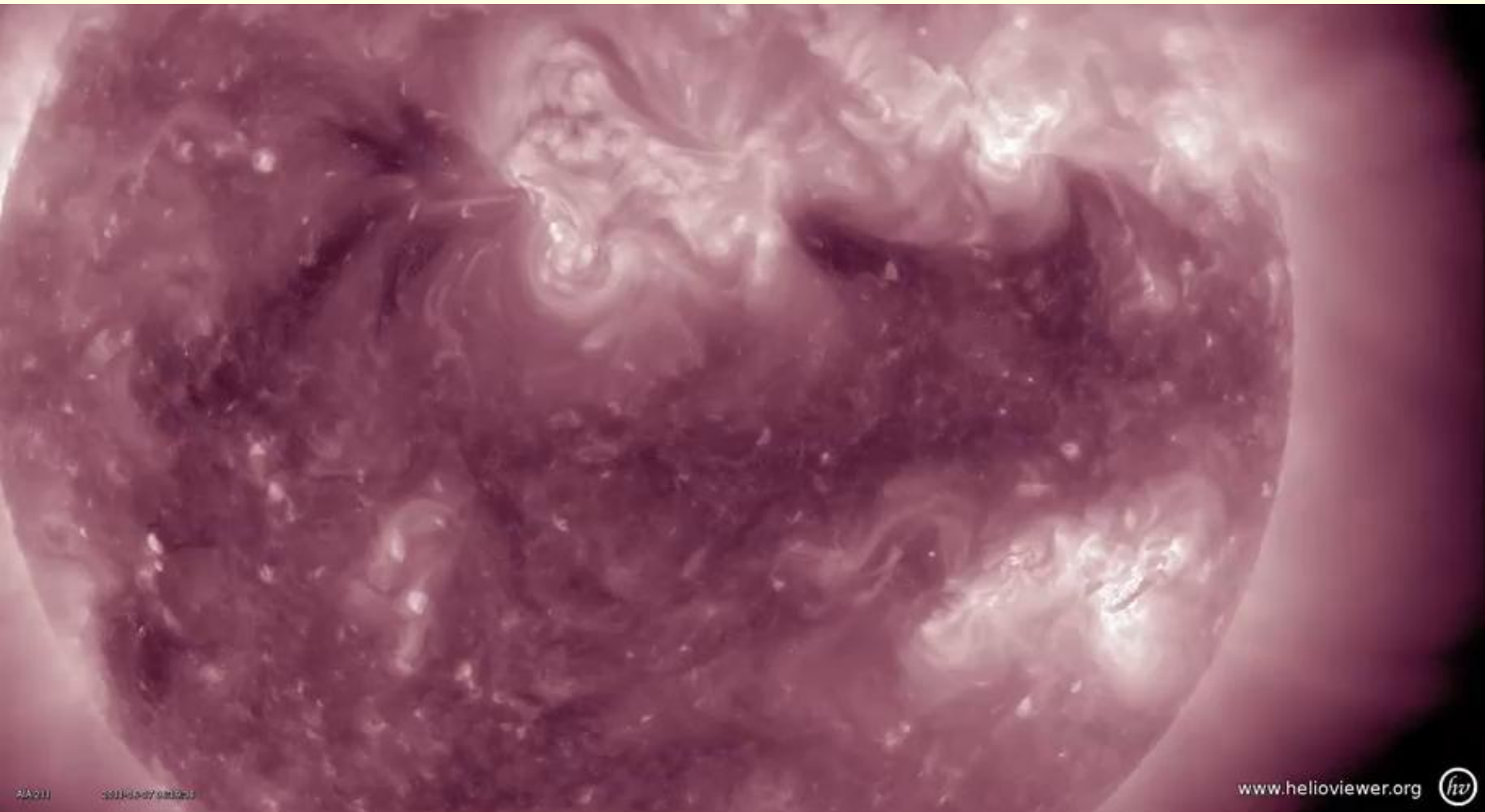
11.Feb.2013
02:07:35 UT

# Coronal structure: mostly *coronal loops*



corona  ~$10^6$ K

surface ~6000 K

surface magnetic field

$B_z$ [Gauss]
+500
0
−500

AIA 17.1 nm
$Fe^{8+}$ − $10^6$ K

11.Feb.2013
02:07:35 UT

3 hours – SDO / AIA 21.1 nm – 2 MK

www.helioviewer.org

# "Normal" variability of the corona
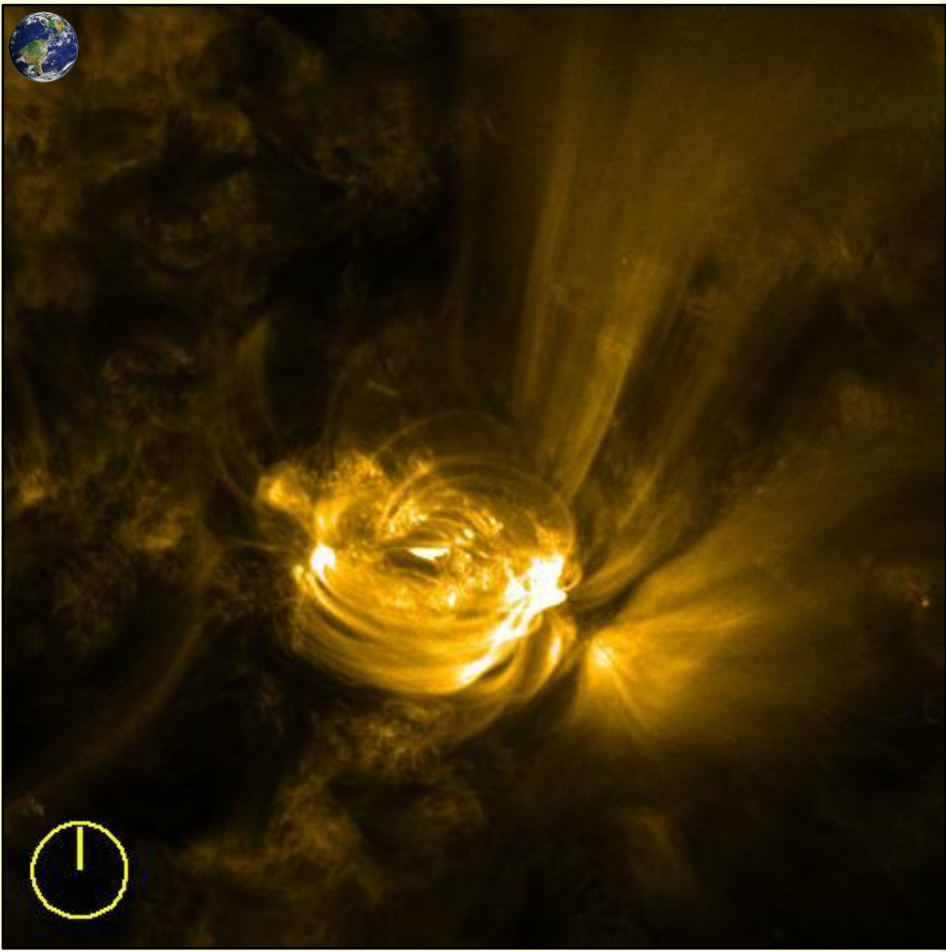
2 hours

SDO / AIA 17.1 nm   –   1 MK
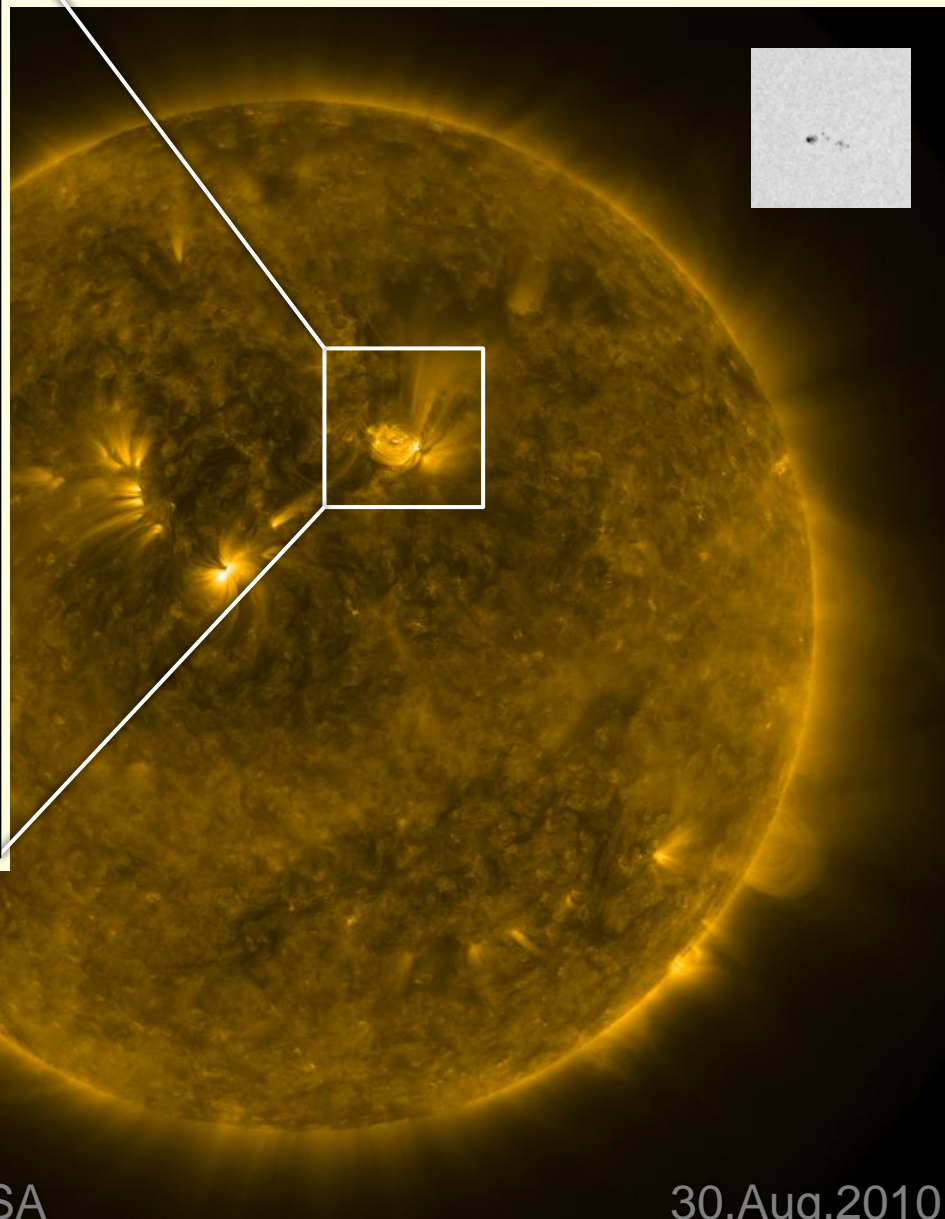
SDO / AIA / NASA                                30.Aug.2010

~1 hour

loops in a
stable active region

Luc Rouppe van der Voort,
Swedish 1-m Solar Telescope (SST), La Palma
2 Jul. 2010, 396.8 nm

Earth to scale

45 x 35 Mm$^2$
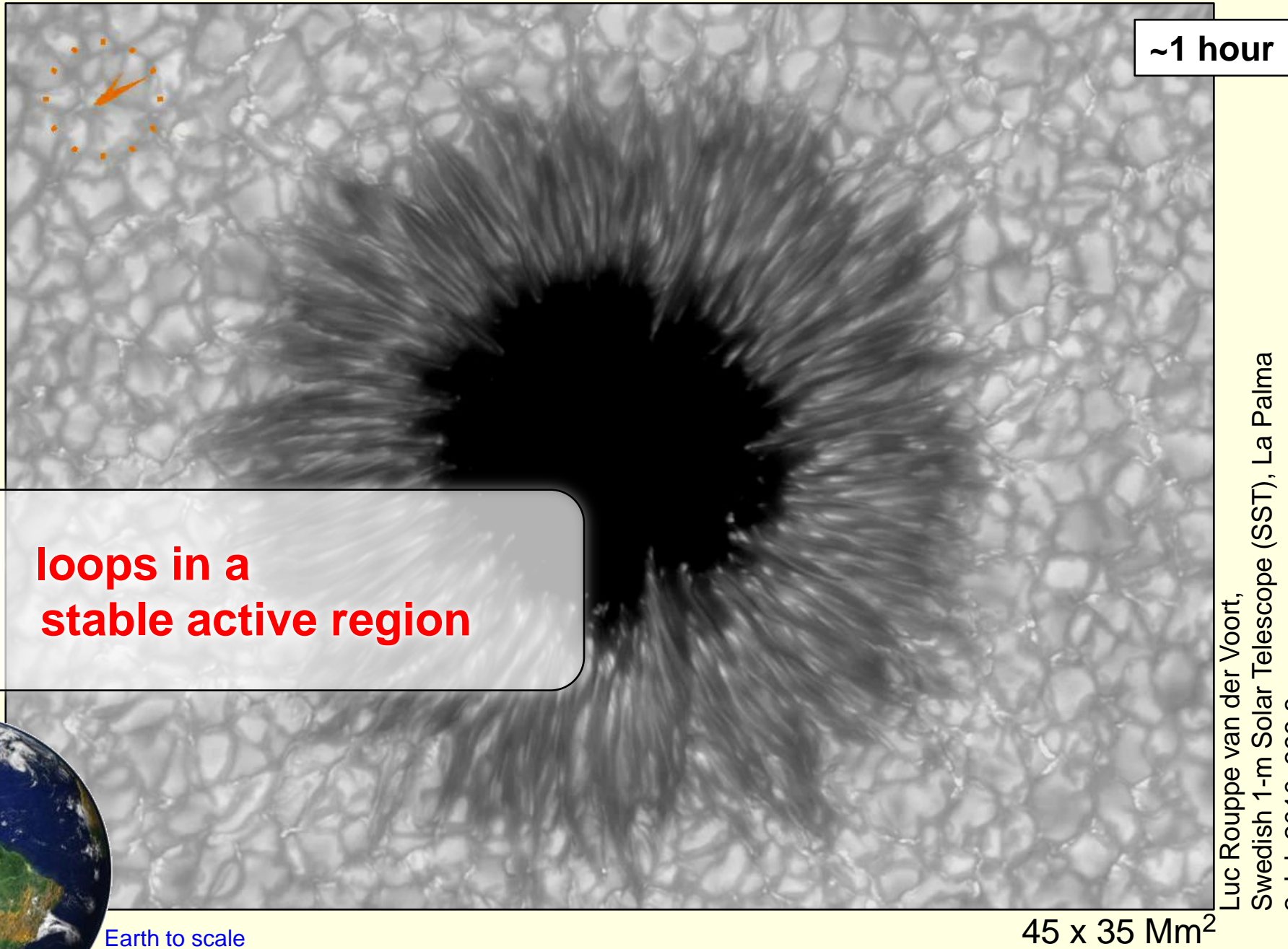
magnetogram



~4 days

Cheung & DeRosa (2012)
ApJ 757, 147

**loop formation in an emerging active region**

$+1000$

$B_z$ [Gauss]

$0$

$-1000$

$350 \times 200$ arcsec$^2$ $= 250 \times 150$ Mm$^2$

Earth to scale

# model introduction

**loops in
a stable active region**

**loop formation in
emerging active region**
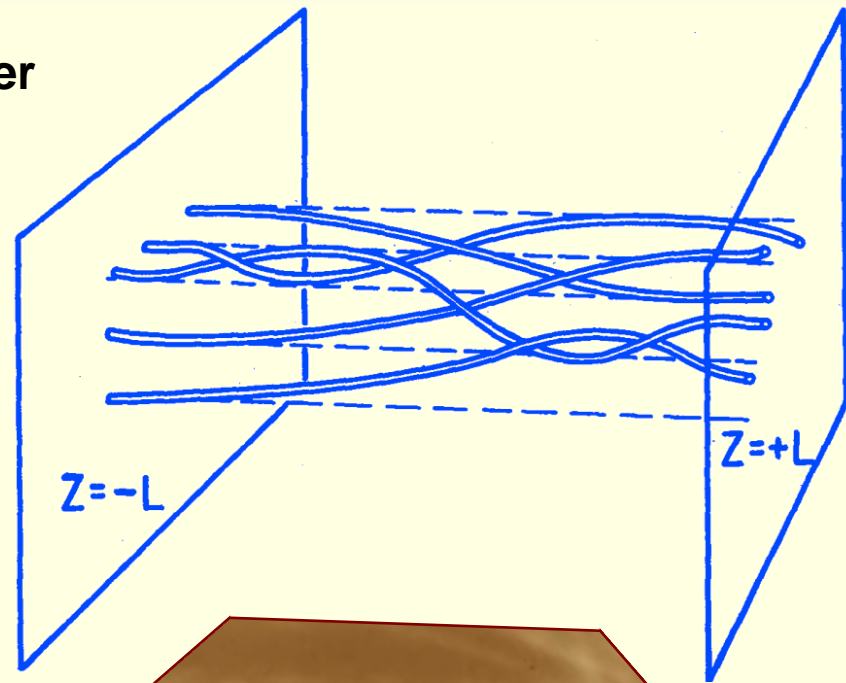
# Concept for coronal heating

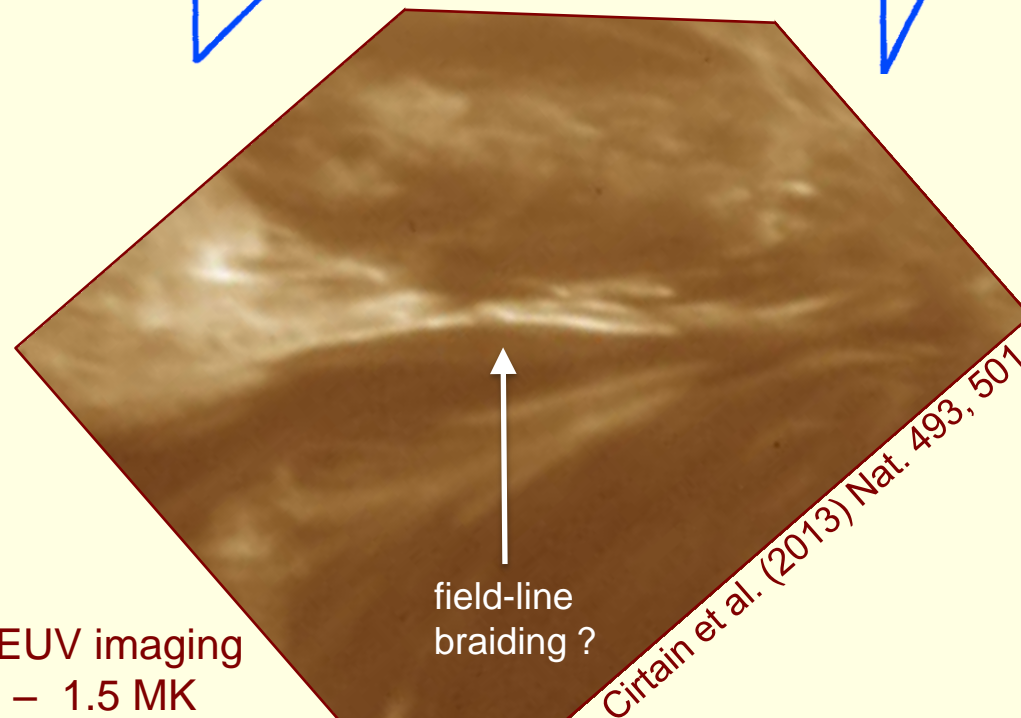► **horizontal motions in photosphere as driver**

→ **field-line braiding**

(Parker 1972, ApJ 174, 499)

→ **flux-tube tectonics**

(Priest et al 2002, ApJ 576, 533)

Z=−L

Z=+L

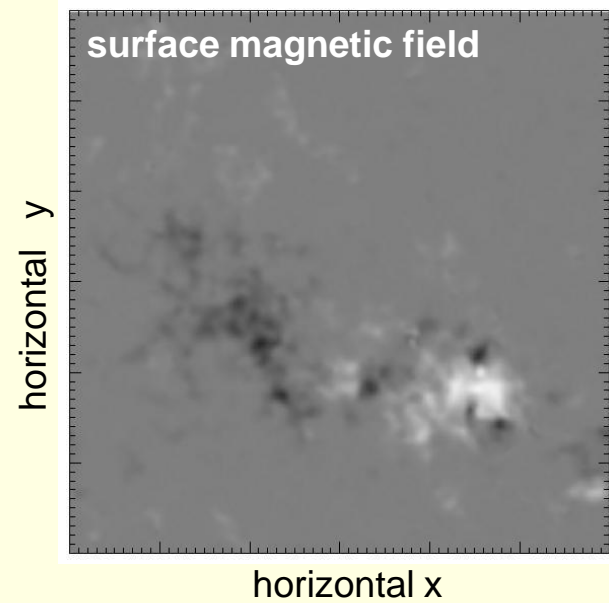► there is some observational evidence
for field-line braiding

field-line
braiding ?

Cirtain et al. (2013) Nat. 493, 501

**Hi-C rocket**
high-resolution EUV imaging
193 Å  –  Fe XII  –  1.5 MK

► take observed magnetogram:
   → surface magnetic field $B_0$



surface magnetic field

horizontal y
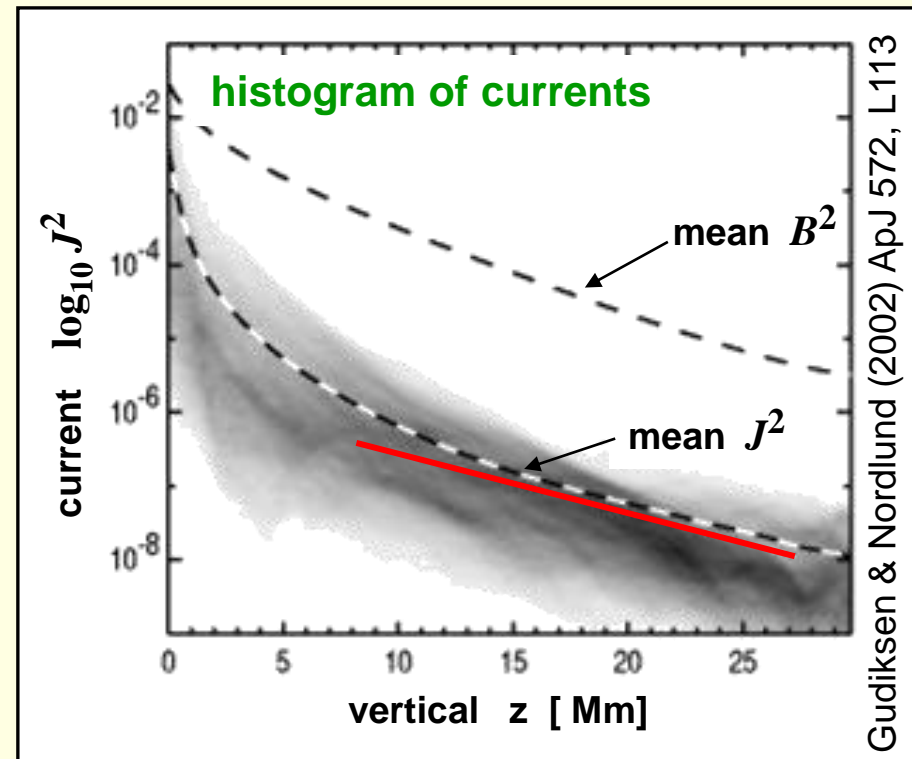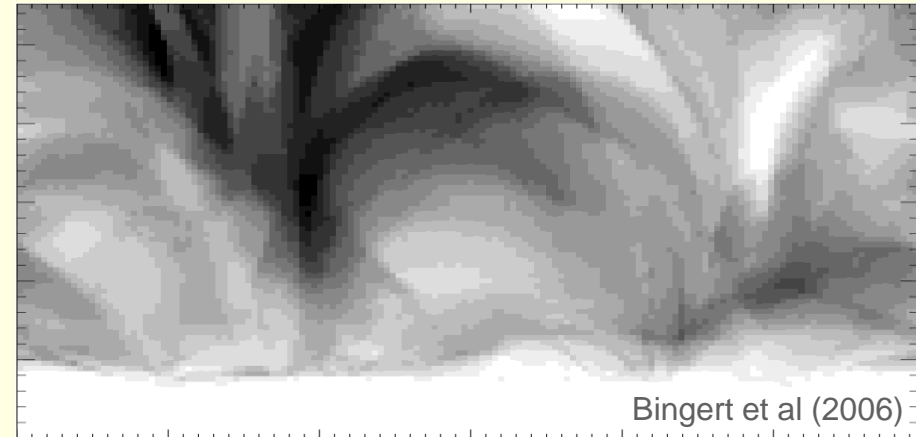
horizontal x

# How to construct a corona in the box…

▶ take observed magnetogram:
→ surface magnetic field $B_0$

▶ extrapolate $B_0$ to fill box
assume "1D" atmosphere

▶ surface convection:
granulation drives magnetic field

▶ "fieldline braiding":
currents induced in corona

$$j = (\nabla \times B) / \eta$$

Dutch Open Telescop / P.Sütterlin
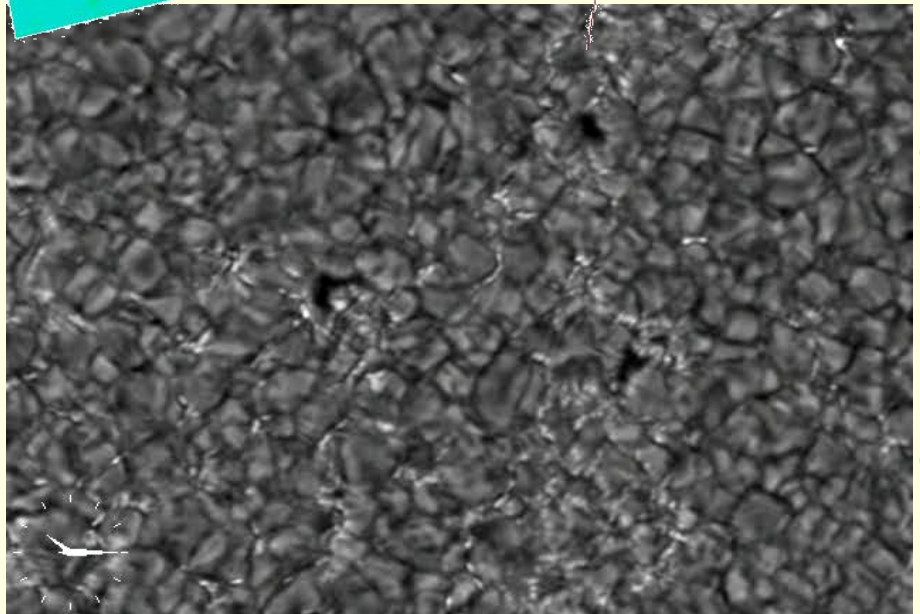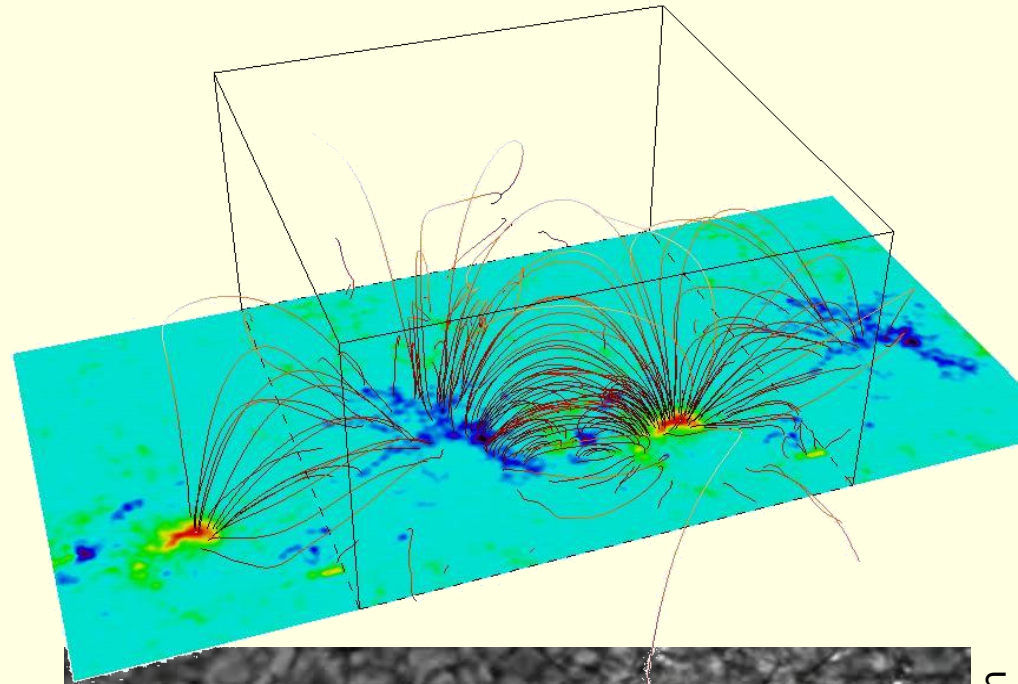
surface convective flow / granulation

▶ take observed magnetogram:
→ surface magnetic field $B_0$

▶ extrapolate $B_0$ to fill box
assume "1D" atmosphere



Bingert et al (2006)

▶ surface convection:
granulation drives magnetic field

▶ "fieldline braiding":
currents induced in corona

$$j = (\nabla \times \boldsymbol{B}) / \eta$$

heating through Ohmic dissipation:

$$\eta j^2 \sim \exp(- z/H)$$

loop-structured $10^6$ K corona



histogram of currents

mean $B^2$

mean $J^2$

current   $\log_{10} J^2$

vertical   z   [ Mm]

Gudiksen & Nordlund (2002) ApJ 572, L113

# Magnetohydrodynamics (MHD)

$$\nabla \times \boldsymbol{B} = \mu \boldsymbol{j} \qquad \boxed{\nabla \cdot \boldsymbol{B} = 0}$$

$$\nabla \times \boldsymbol{E} = -\partial_t \boldsymbol{B} \qquad \nabla \cdot \boldsymbol{E} = \frac{1}{\varepsilon} \rho_e$$

$$\boldsymbol{j} = \sigma (\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

$$\boldsymbol{j} \times \boldsymbol{B} = \frac{1}{\mu} (\nabla \times \boldsymbol{B}) \times \boldsymbol{B}$$

**induction eq.**

$$\partial_t \boldsymbol{B} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \nabla \times (\eta \nabla \times \boldsymbol{B})$$

mag. diffusivity

$$\eta = \frac{1}{\mu \sigma}$$

**continuity eq.** $\qquad \partial_t \rho + \nabla \cdot (\rho \boldsymbol{u}) = 0$

**momentum eq.** $\qquad \rho \partial_t \boldsymbol{u} + \rho (\boldsymbol{u} \cdot \nabla) \boldsymbol{u} = -\nabla p + \rho \boldsymbol{g} + \boldsymbol{j} \times \boldsymbol{B} + \nabla \cdot \boldsymbol{\tau}$

viscous stess tensor $\boldsymbol{\tau}$:

$$\nabla \cdot \boldsymbol{\tau} = \rho \nu \left( \Delta \boldsymbol{u} + \frac{1}{3} \nabla (\nabla \cdot \boldsymbol{u}) \right)$$

**energy eq.** $\qquad (\partial_t + \boldsymbol{u} \cdot \nabla) e + \frac{5}{2} p \nabla \cdot \boldsymbol{u} = -\nabla \cdot \boldsymbol{q} - L_{\mathrm{rad}} + \eta \boldsymbol{j}^2 + Q_{\mathrm{visc}}$

internal energy: $e = n \frac{3}{2} k_{\mathrm{B}} T$

➡ for coronal diagnostics it is essential to get energy equation right

# Pencil code   http://pencil-code.googlecode.com/

Brandenburg & Dobler (2002)
Comp. Phys. Comm., 147, 471

designed for
 compressible turbulent MHD flows

wide range of applications

high-order explicit finite difference

high-order Runge-Kutta time stepping

non-equidistant grids

highly modular

extensions to standard MHD

– Spitzer heat conduction
– radiative losses / radiative transfer
– particles
– eight moment approximation
– …
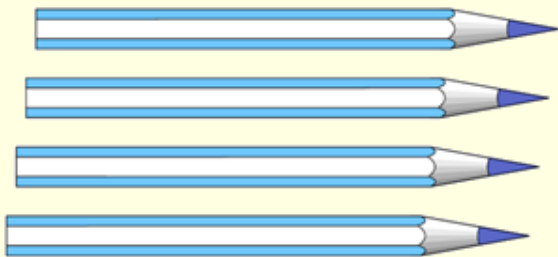
*Pencil*

freely available

over 100 contributors world wide

tested on many platforms

large set of samples included

Tools for visualization
 and data analysis

MPI parallelized
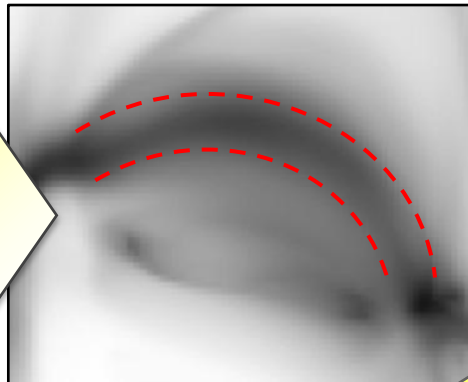
scales well
 up to more than 80.000 cores



scaling for coronal models
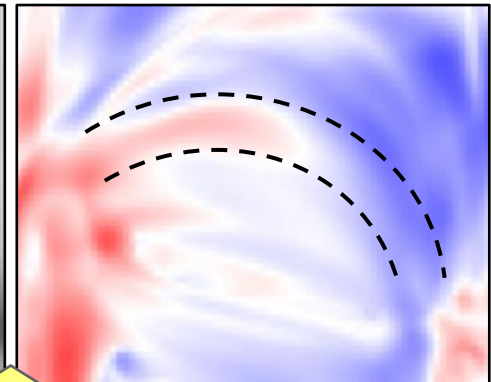
CPU time / core / timestep / meshpoint [1e-6 s]

| ideal scaling |
| CPU time (cubic subdomains) |
| CPU time (penciled subdomains) |

Number of cores

# Model and observations

**3D MHD model:** *T*, $\rho$, *v*, *B*

density cut

$10^5$ K isosurface

*photospheric*
*magnetic field*
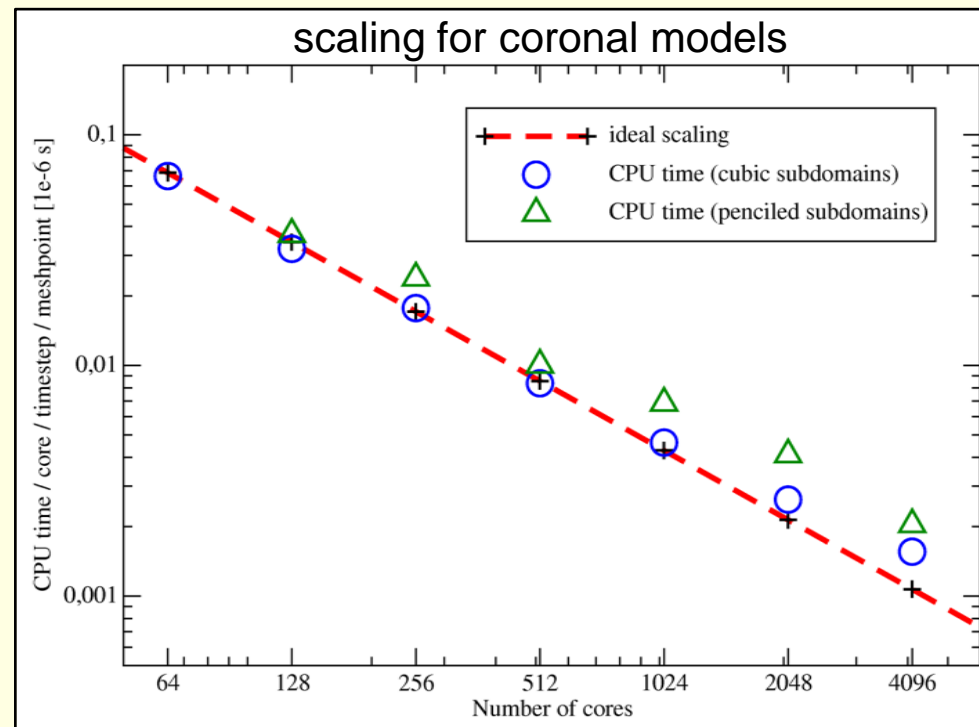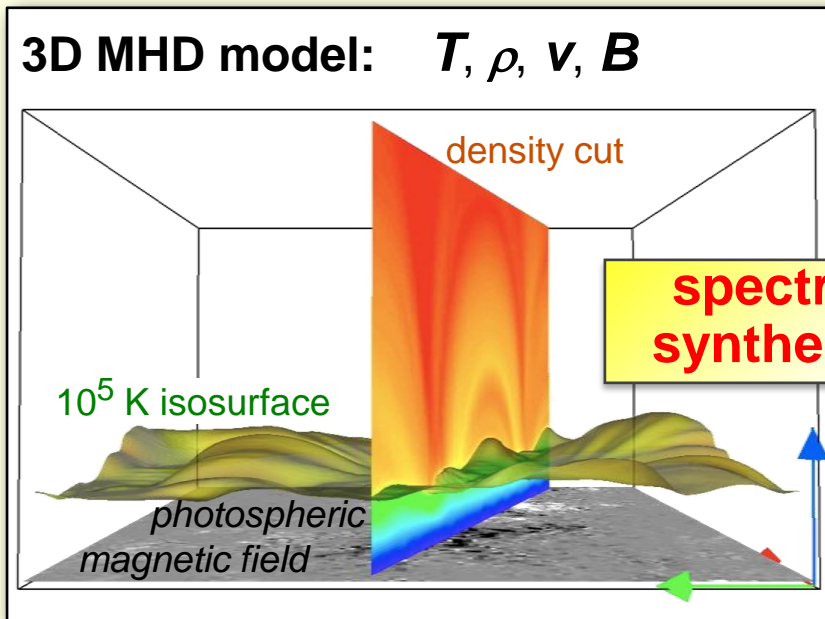
Bingert & hp (2011) A&A 530, A112
hp (2010) A&A 521, A51

**spectral synthesis**

**synthesized coronal emission**  Mg x 625 Å

intensity map (inv.)

Doppler map

**compare**

**real observations**

Hinode / EIS Fe xv 284 Å

−20  Doppler shift [km/s]  20

(c)

(b)

(d)
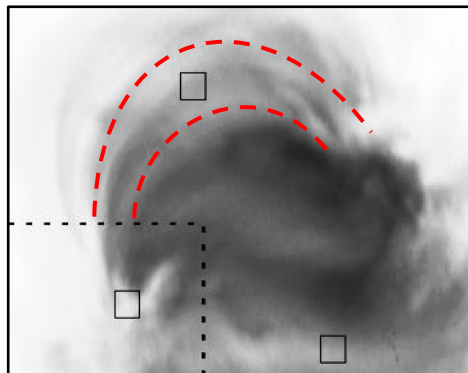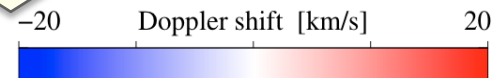
160"x125"

model introduction

**loops in
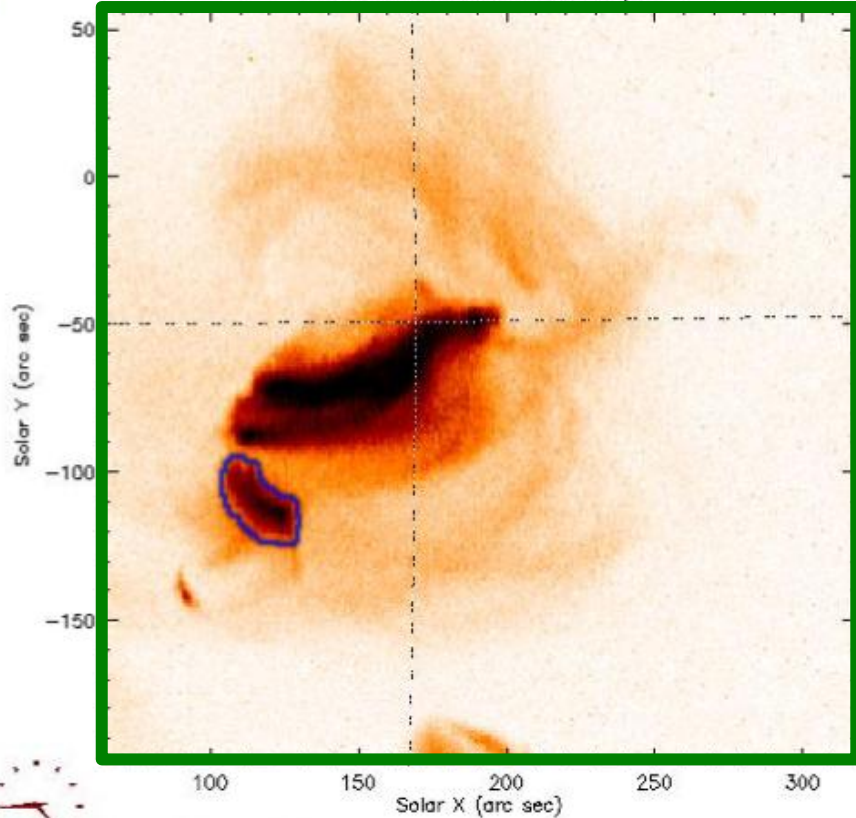a stable active region**

loop formation in
emerging active region

**Hinode/SOT magnetogram**

– 14.Nov.2007, 12:15-18:00 UT
– time-series: 90 s cadence
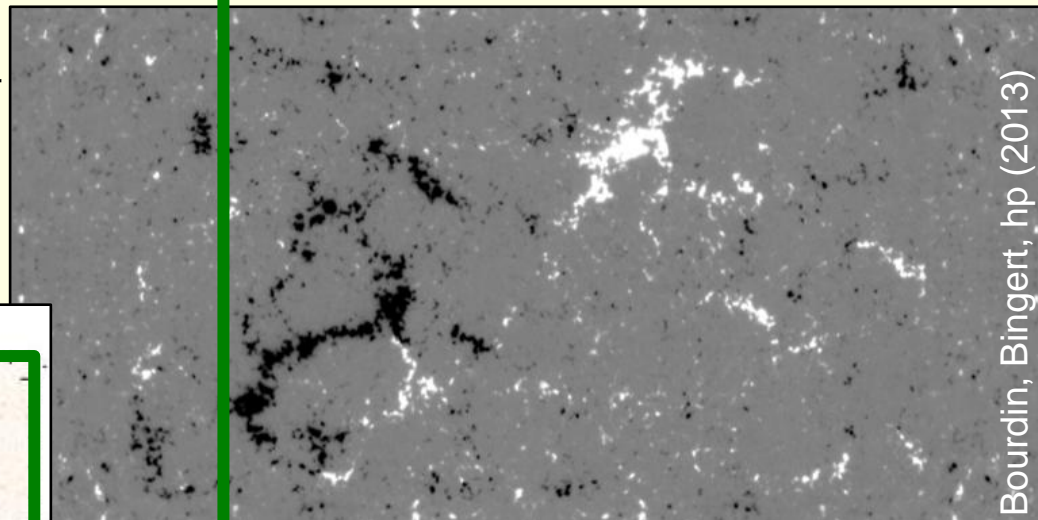


Bourdin, Bingert, hp (2013)



Fe XV 284.16 Å, 256x256 pix

2007-11-14 16:44:32

**EIS / Hinode raster scan**

– covering similar FOV
– acquired during same time frame
– full spectral profile of many lines
  e.g.  Fe XV (284 Å)

# A one-to-one model of an "old" active region
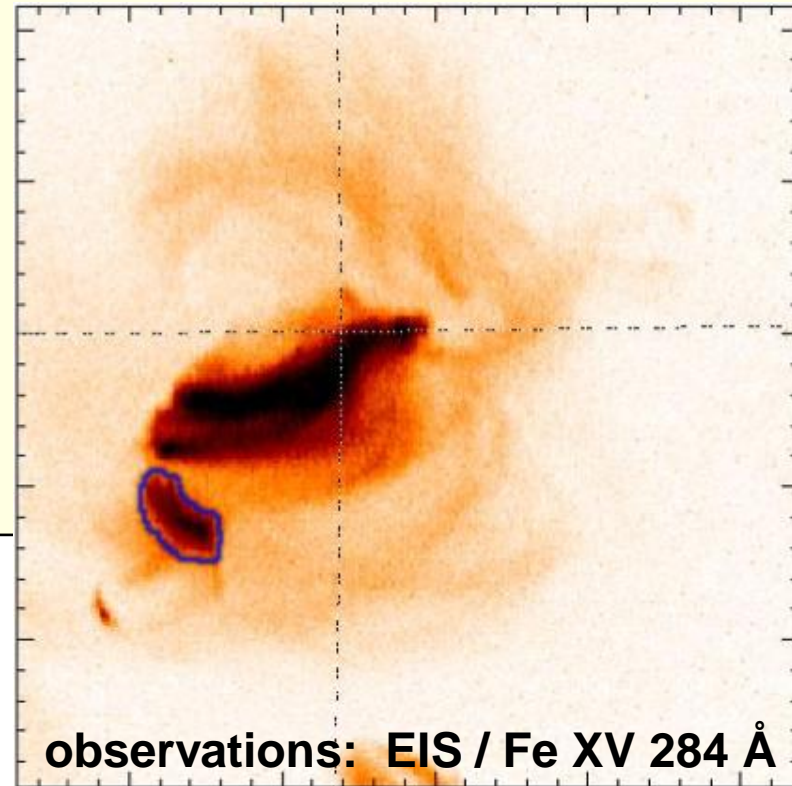
**3D MHD numerical model**

– 235 x 235 x 156 $Mm^3$ → full active region

– 1024 x 1024 x 256 grid points

– driven by *observed* velocities
  and observed photospheric magnetogram

– ran on Curie on typically 4000 cores

– ca. 8 M core hrs

**post processing:**

– synthesize emission
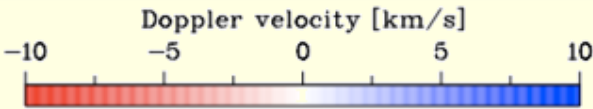
– spectral line synthesis
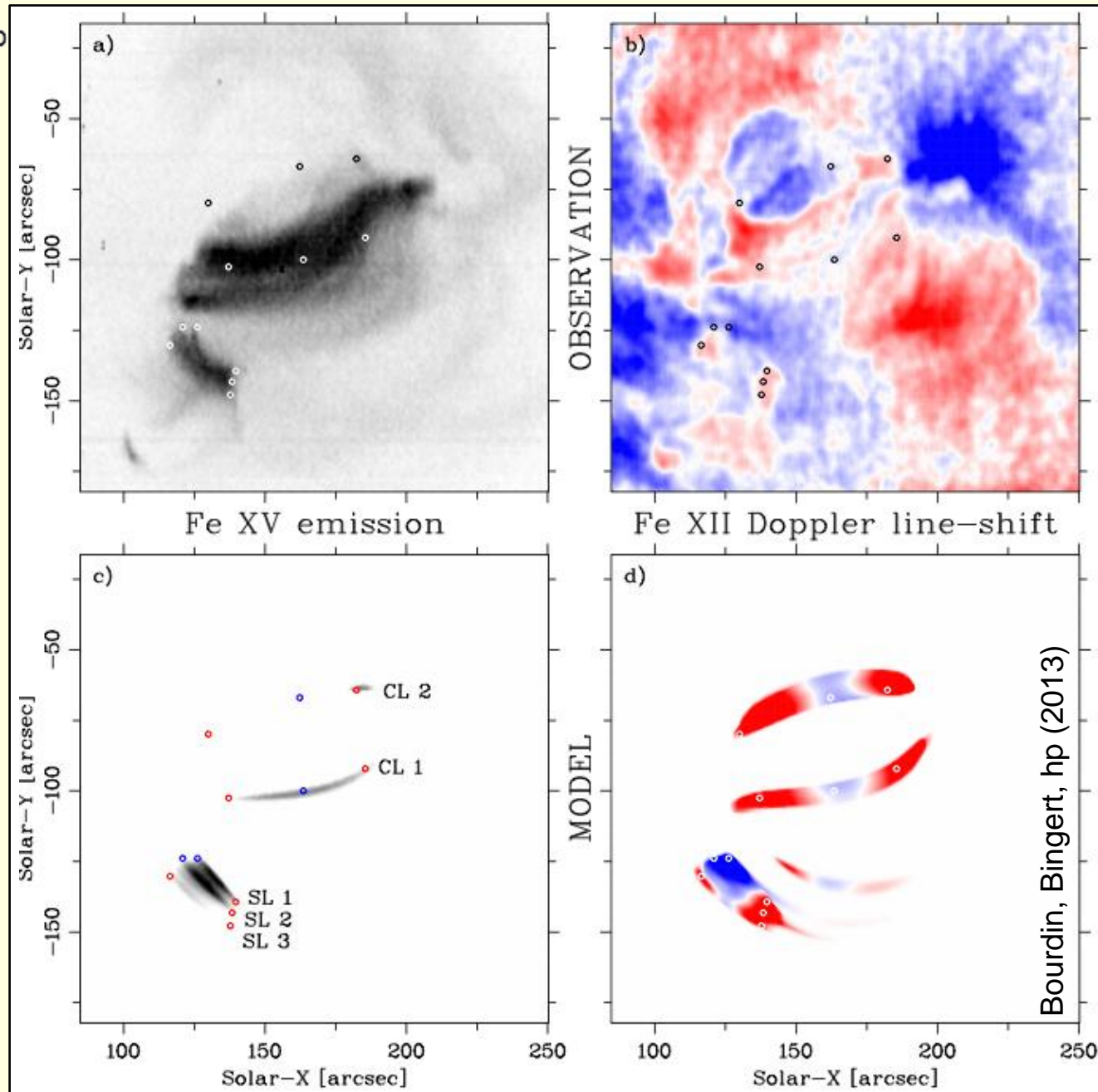– field-line evolution

*Pencil*

**observations:  EIS / Fe XV 284 Å**

**model: synthesized  Fe XV 284 Å**
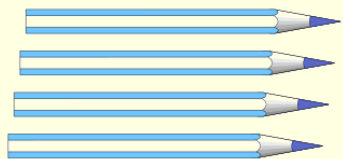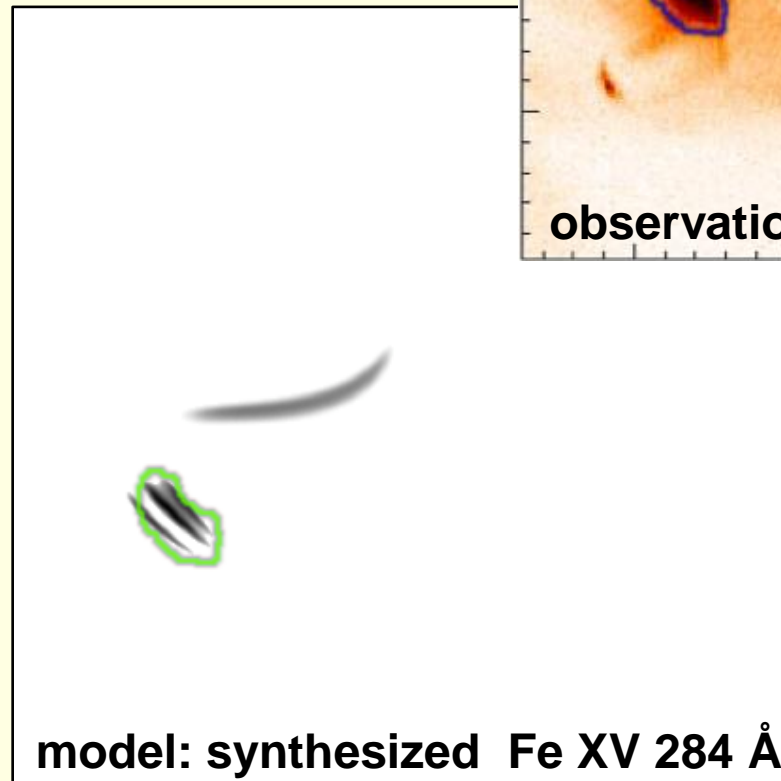
Bourdin, Bingert, hp (2013)

► coronal loops
form above
well developed
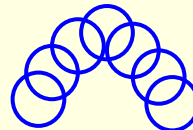active region

▶ **reproduces hot core**

▶ **active region loops are in right places**

▶ less clear agreement in Doppler shifts

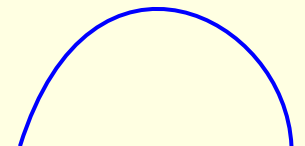▶ large loop does not show in full (more time would be needed)
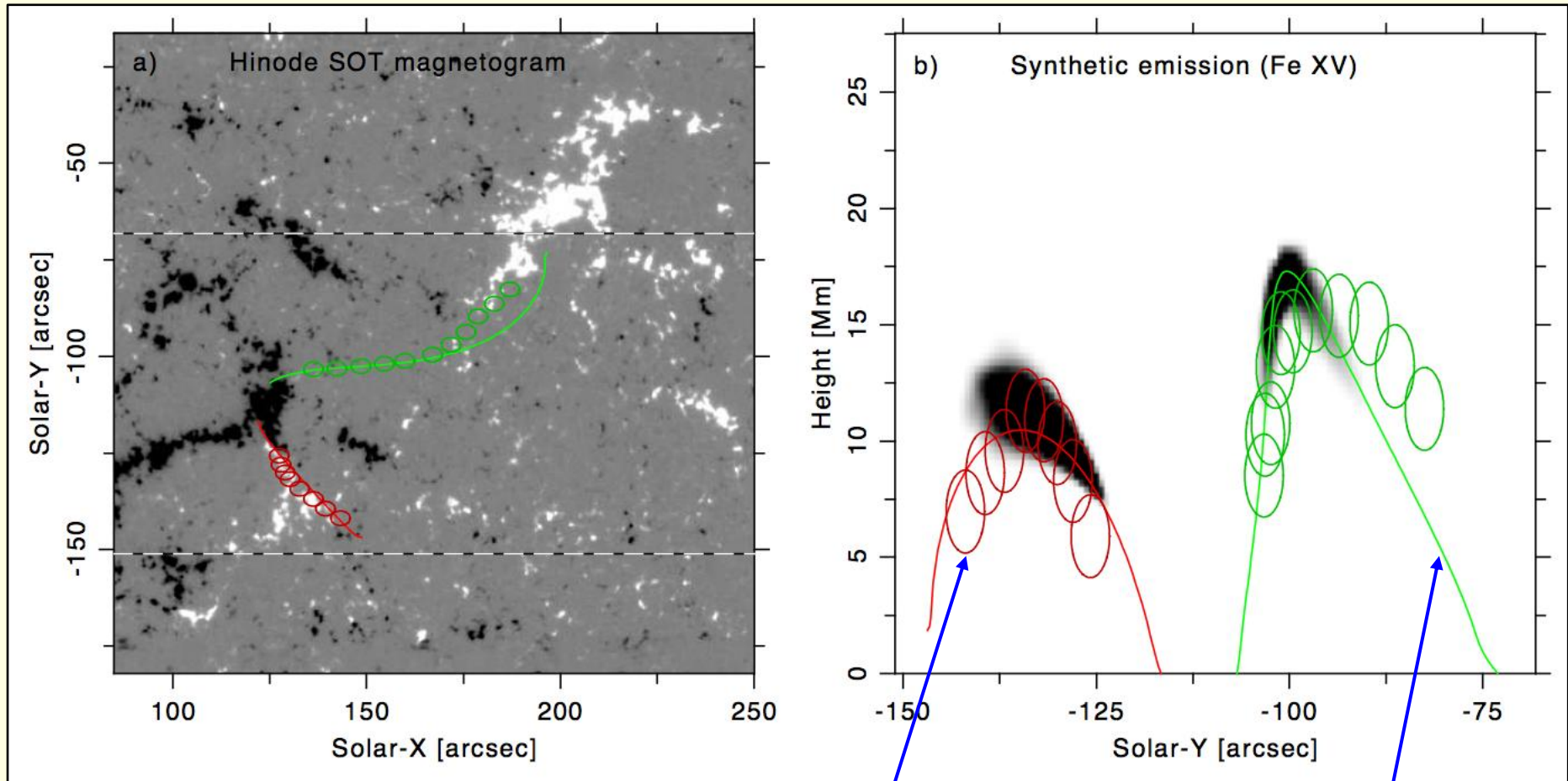
position of *observed* loops determined by stereoscopic reconstruction

match central field line of loops in model !

**model introduction**
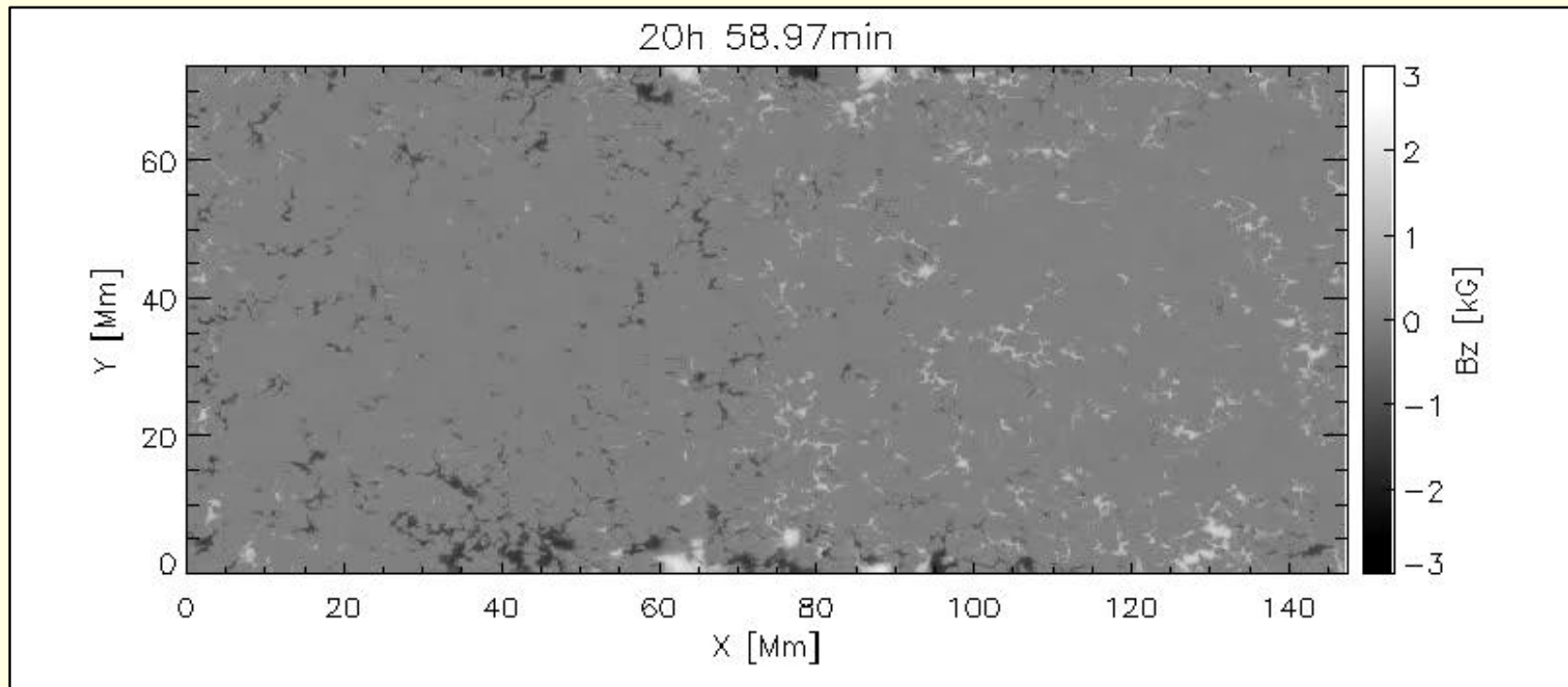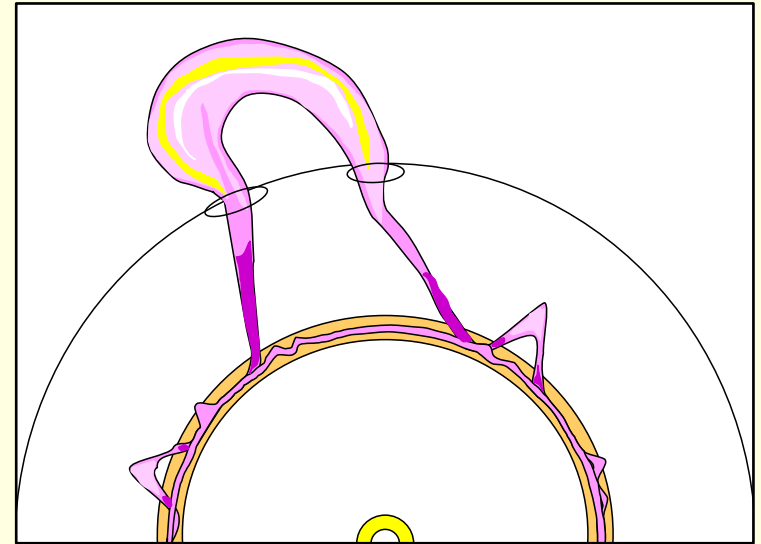
**loops in
a stable active region**

**loop formation in
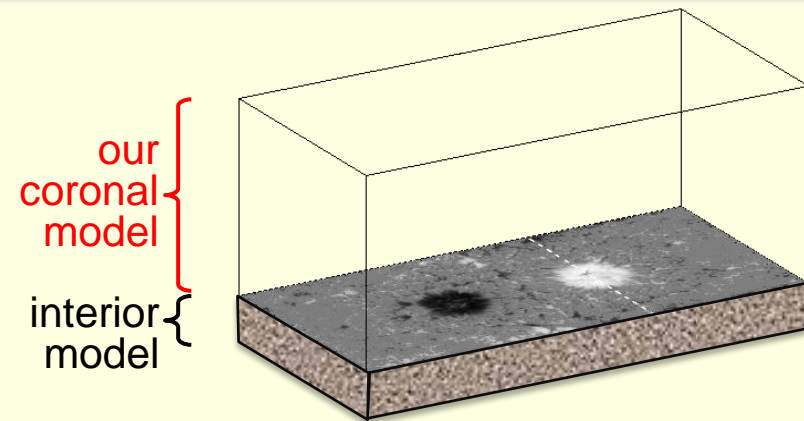emerging active region**

**flux-emergence simulation**

(Cheung et al. 2010, ApJ 720, 233)

– magnetic flux rope rises from bottom and breaks through surface

→ **formation of sunspot pair**

→ limited to interior and surface
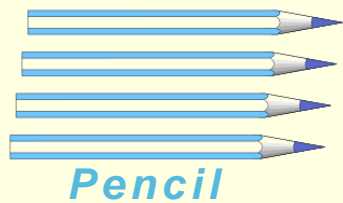
# Coronal model driven by emerging flux simulation

**coronal simulation:**

– use photospheric layer ($T, \rho, v, B$)

   as time-dependent lower boundary

   → magnetic field expands

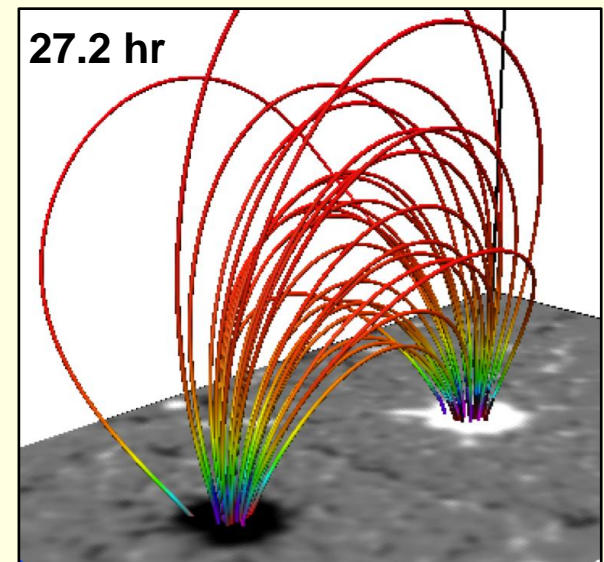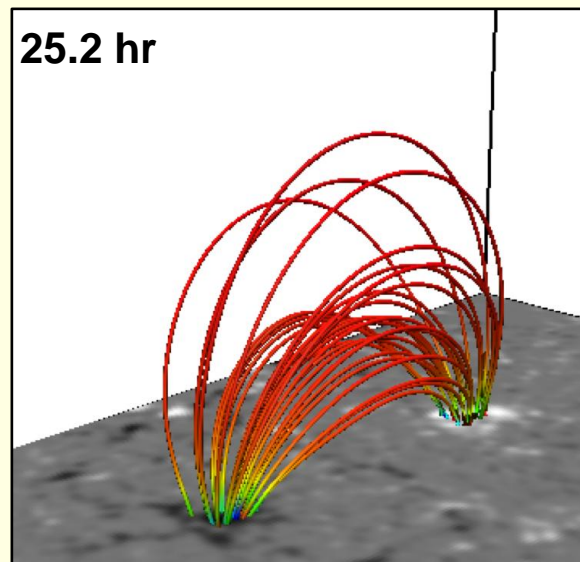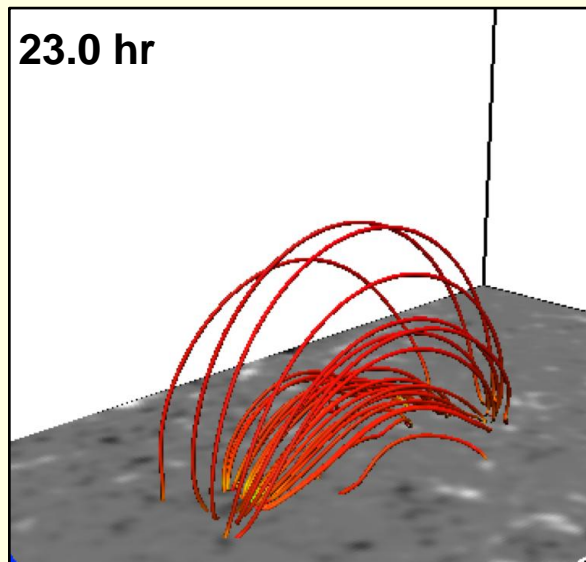   → coronal loops form

our coronal model

interior model

**3D MHD numerical model**

– 1024 x 512 x 512 grid points

– temporal evolution over 10 hours

– runs on SuperMUC ~ 7 M core hrs

– using 4000 cores

*Pencil*

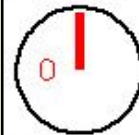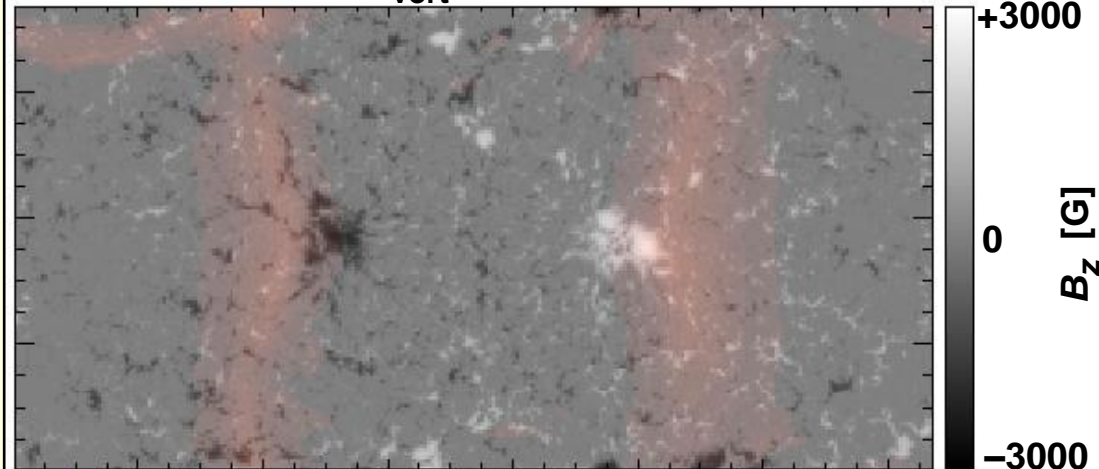**post processing:**

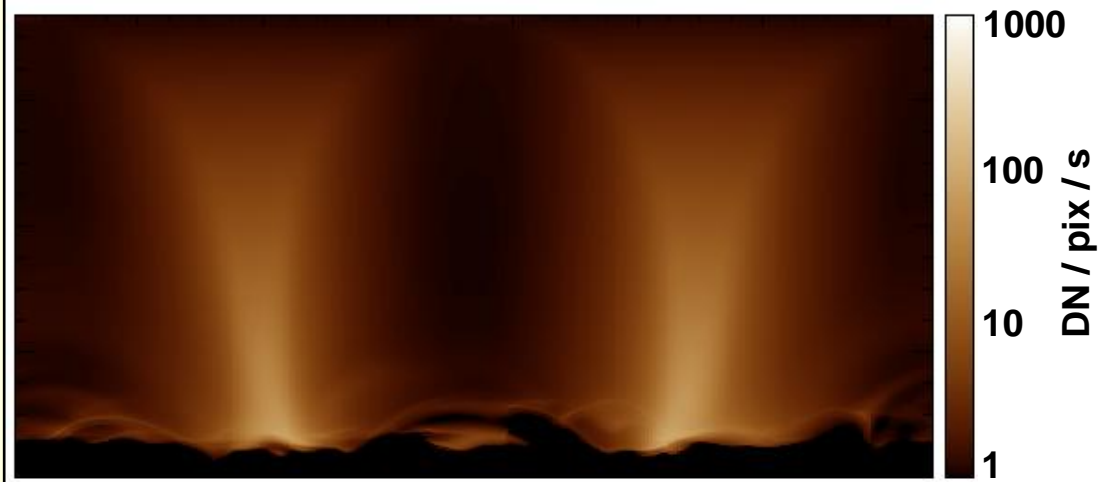– synthetic coronal emission

– field-line tracing



23.0 hr

25.2 hr

27.2 hr

Chen, Bingert, hp, Schüssler Cameron, Cheung (2013)

# Coronal model driven by emerging flux simulation

synthesized coronal emission  (1.5 $10^6$ K )

► loops form at different places
   at different times

► loop footpoints are in
   sunspot periphery  (penumbra)

► loop fragments

**view from top:**  $B_{vert}$ @ bottom  +  AIA 193 Å

+3000

0

$B_z$ [G]

−3000

146 x 73 Mm$^2$

**view from side:**  AIA 193 Å

1000

100

10

DN / pix / s

1

34 min
out of 10 hrs

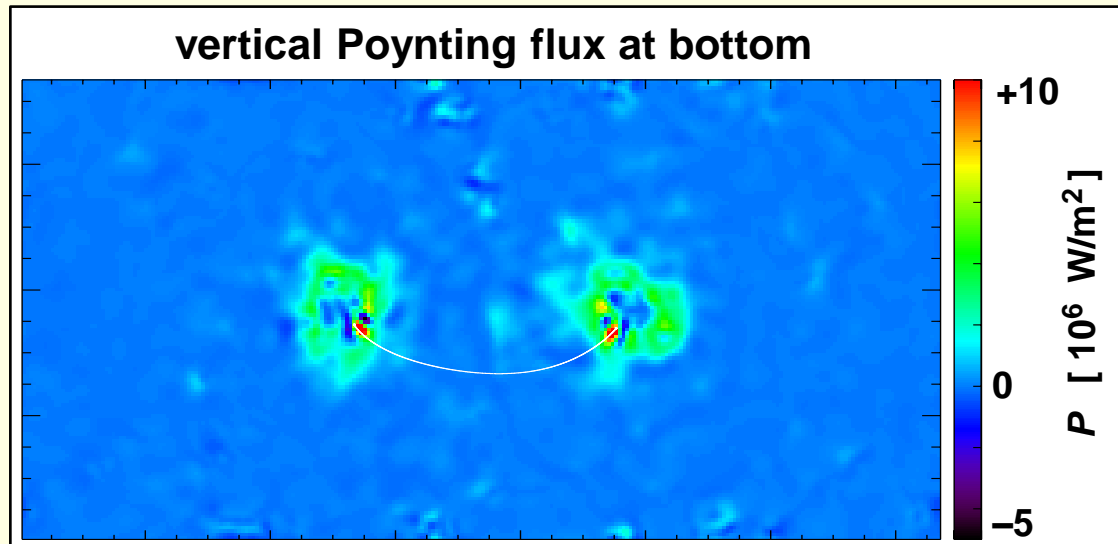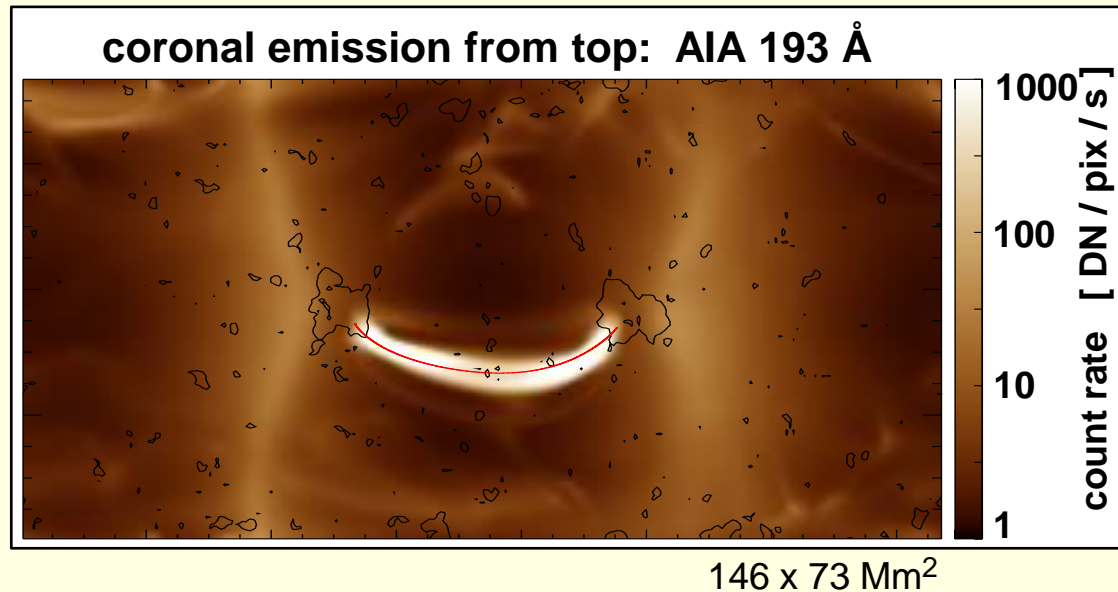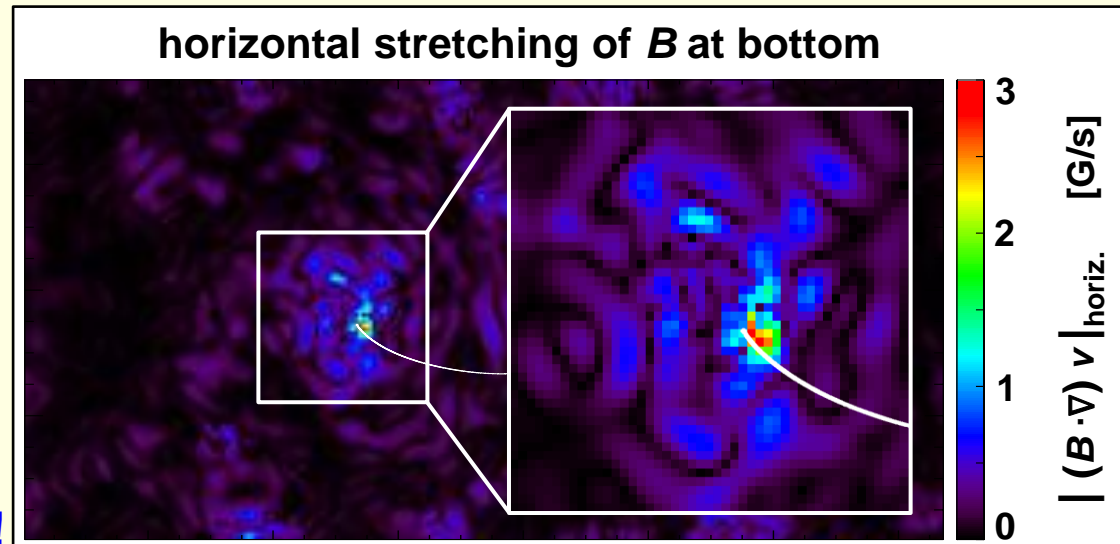Chen, Bingert, hp, Schüssler, Cameron, Cheung (2013)

# Coronal model driven by emerging flux simulation

▶ loops form at different places at different times

▶ loop footpoints are in sunspot periphery (penumbra)

▶ loop fragments



**coronal emission from top: AIA 193 Å**

146 x 73 Mm$^2$

▶ EUV loops form through increased heating:

higher Poynting flux @ loop feet



**vertical Poynting flux at bottom**

Chen, Bingert, hp, Schüssler, Cameron, Cheung (2013)

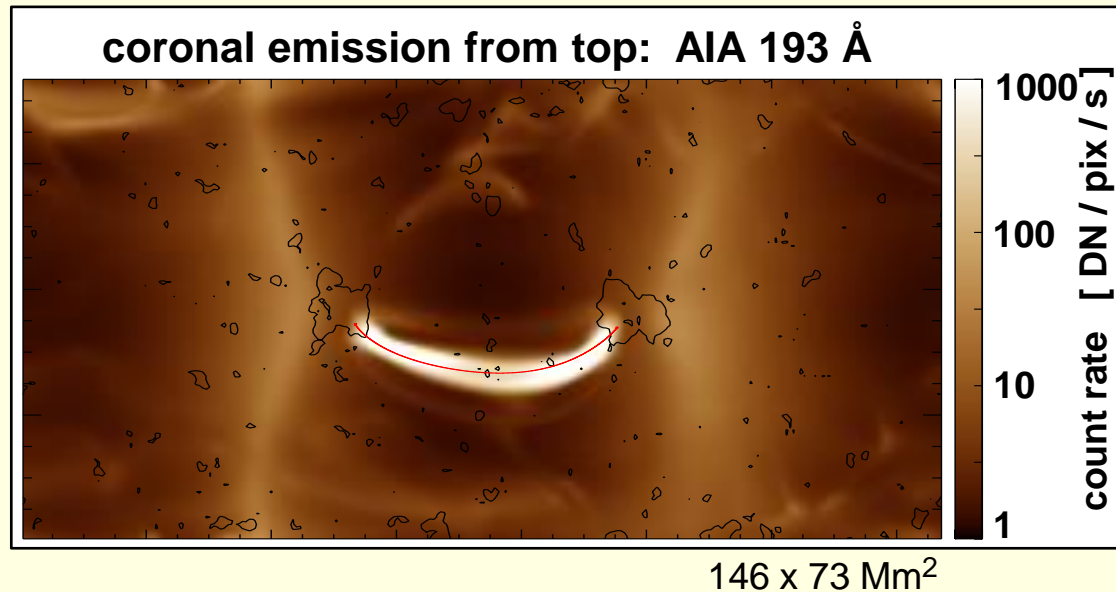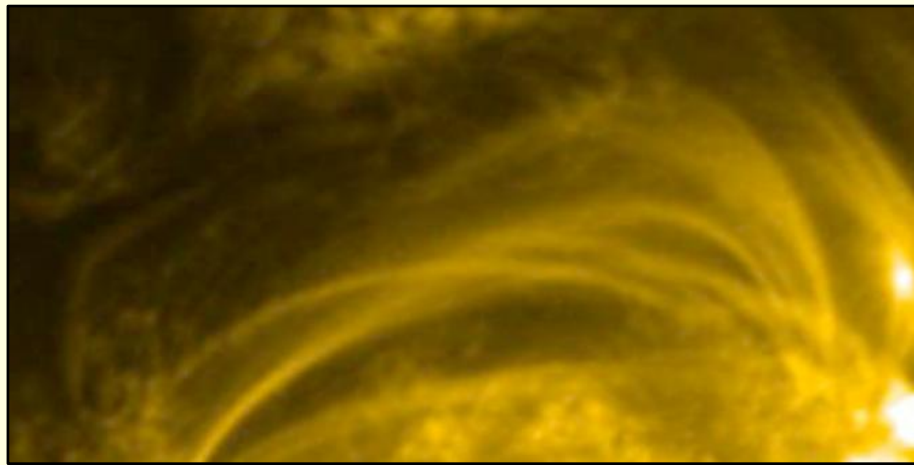# Coronal model driven by emerging flux simulation

▶ loops form at different places
   at different times

▶ loop footpoints are in
   sunspot periphery  (penumbra)

▶ loop fragments

**coronal emission from top:  AIA 193 Å**



146 x 73 Mm$^2$

▶ EUV loops form through
   increased heating:

   higher Poynting flux @ loop feet

▶ loop footpoints where
   strongest stretching of B

→ **field-line braiding**
  **flux-tube tectonics**  } **at work !**

**horizontal stretching of *B* at bottom**


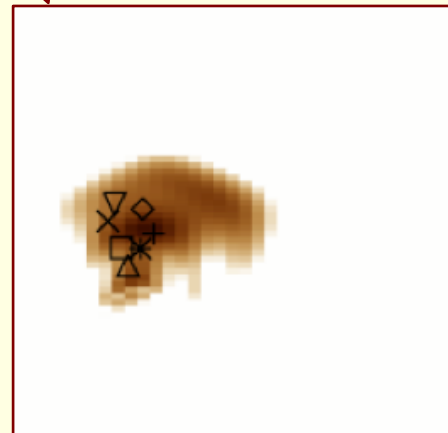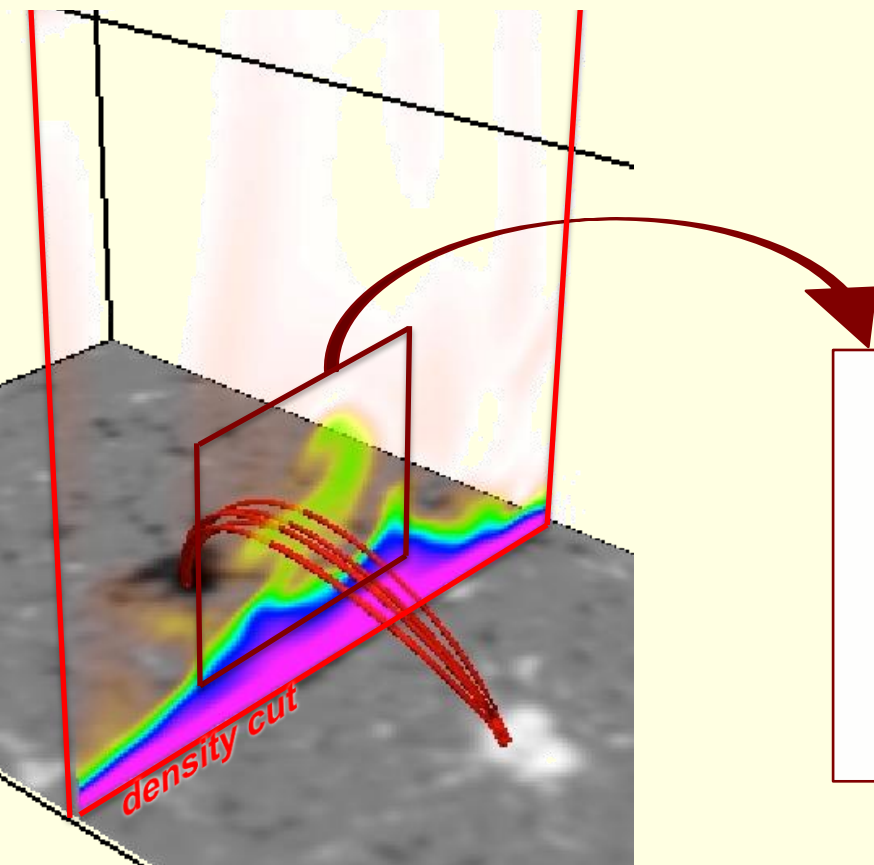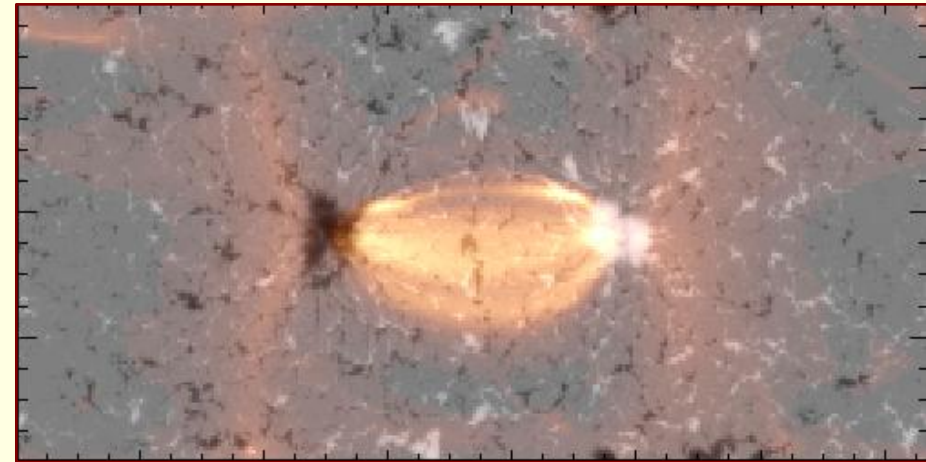
Chen, Bingert, hp, Schüssler, Cameron, Cheung (2013)

# Fragmentation of coronal structures

observation

our model (top view)

density cut

10 min
later
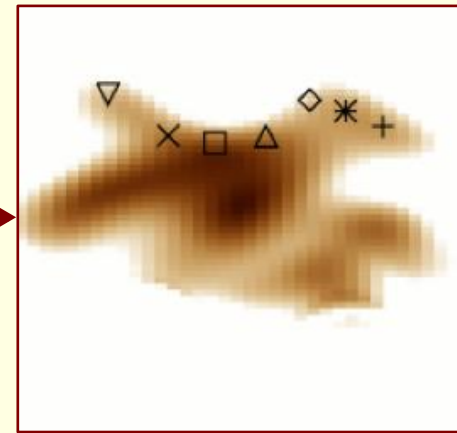
AIA 193 emission

# Conclusions

► **field line braiding provides**
**proper spatial and temporal distribution**
**to heat the corona and drive its dynamics**

→ matching structures in model and observations

→ understanding loop formation

→ and many more... (Doppler shifts, variability, …)

► **HPC is pivotal**
**to capture spatial and temporal complexity**

→ numerical experiments to test model ideas

→ reveals which processes are at work

► **next steps**

→ more realistic match of individual structures

→ investigate parameterization of heat input

→ investigate different levels of activity (→ other stars)

► **new opportunities for comparison to observations**
IRIS / NASA  –  Solar Orbiter / ESA  –  Solar-C / JAXA
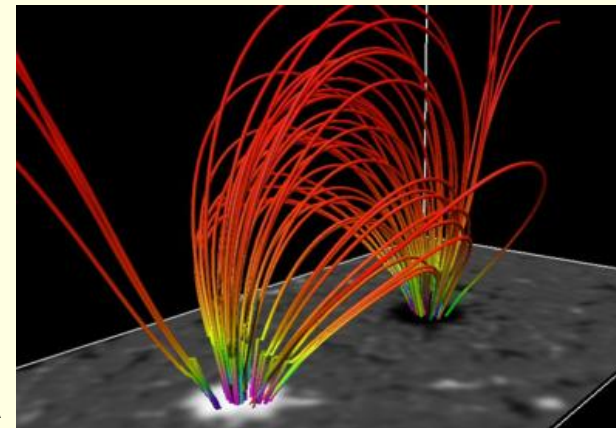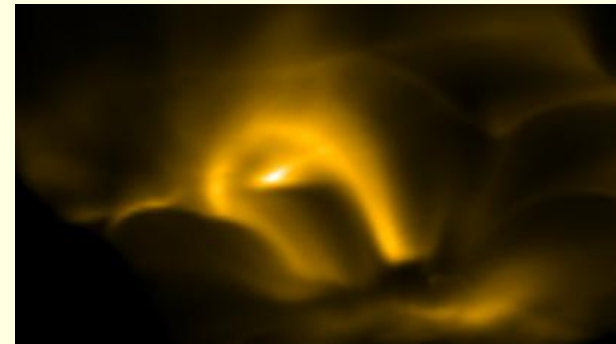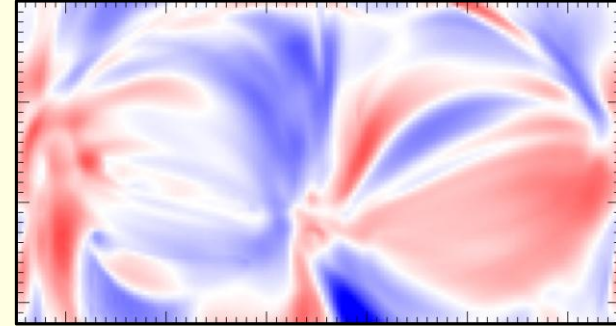
*Structure and evolution*
*of an active region on the Sun*

Beware of the monster !!