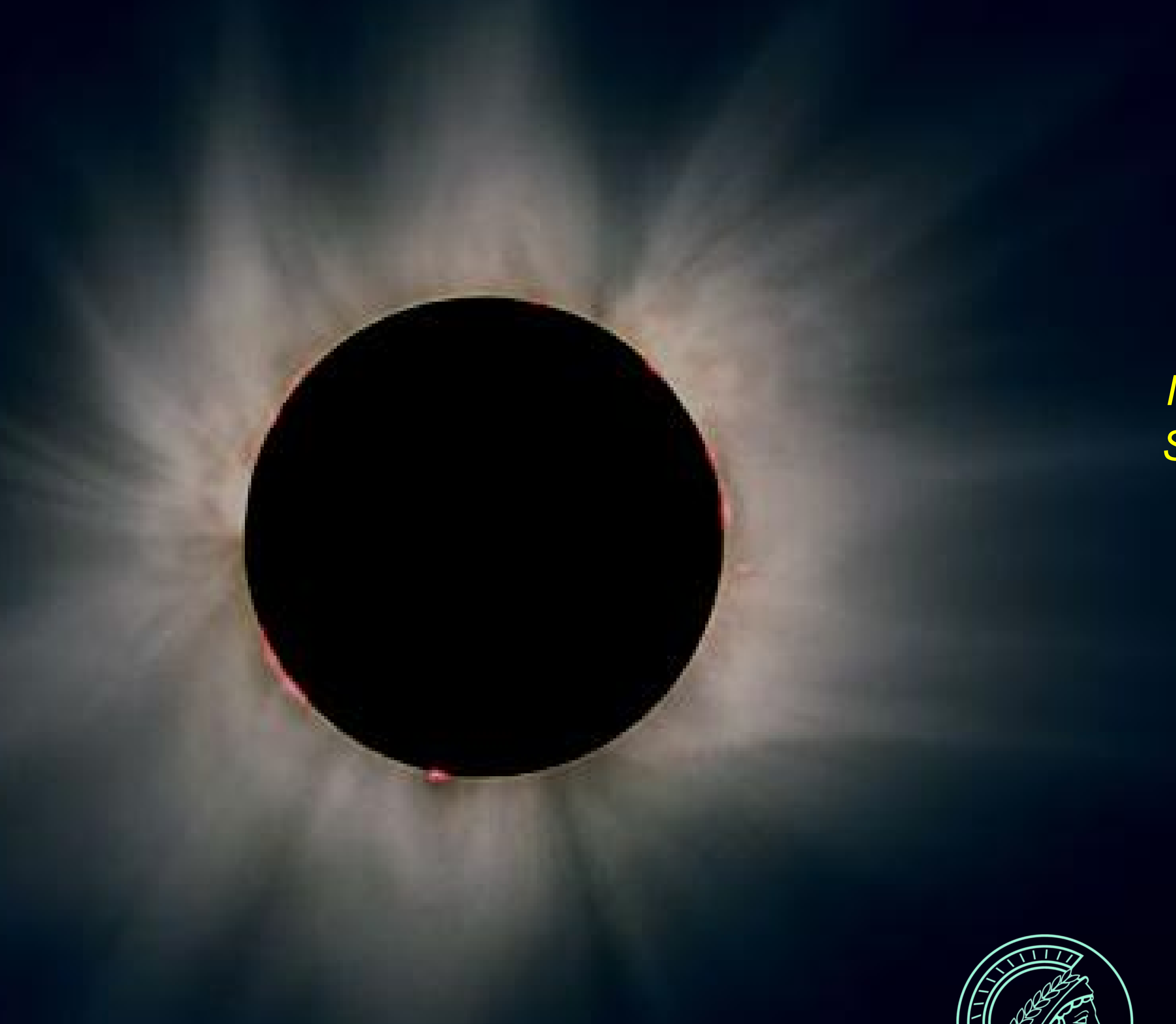
Understanding coronal structures on the Sun



solar eclipse, **11.8.1999**, Wendy Carlos and John Kern

Hardi Peter

Max Planck Institute for Solar System Research Göttingen

peter@mps.mpg.de

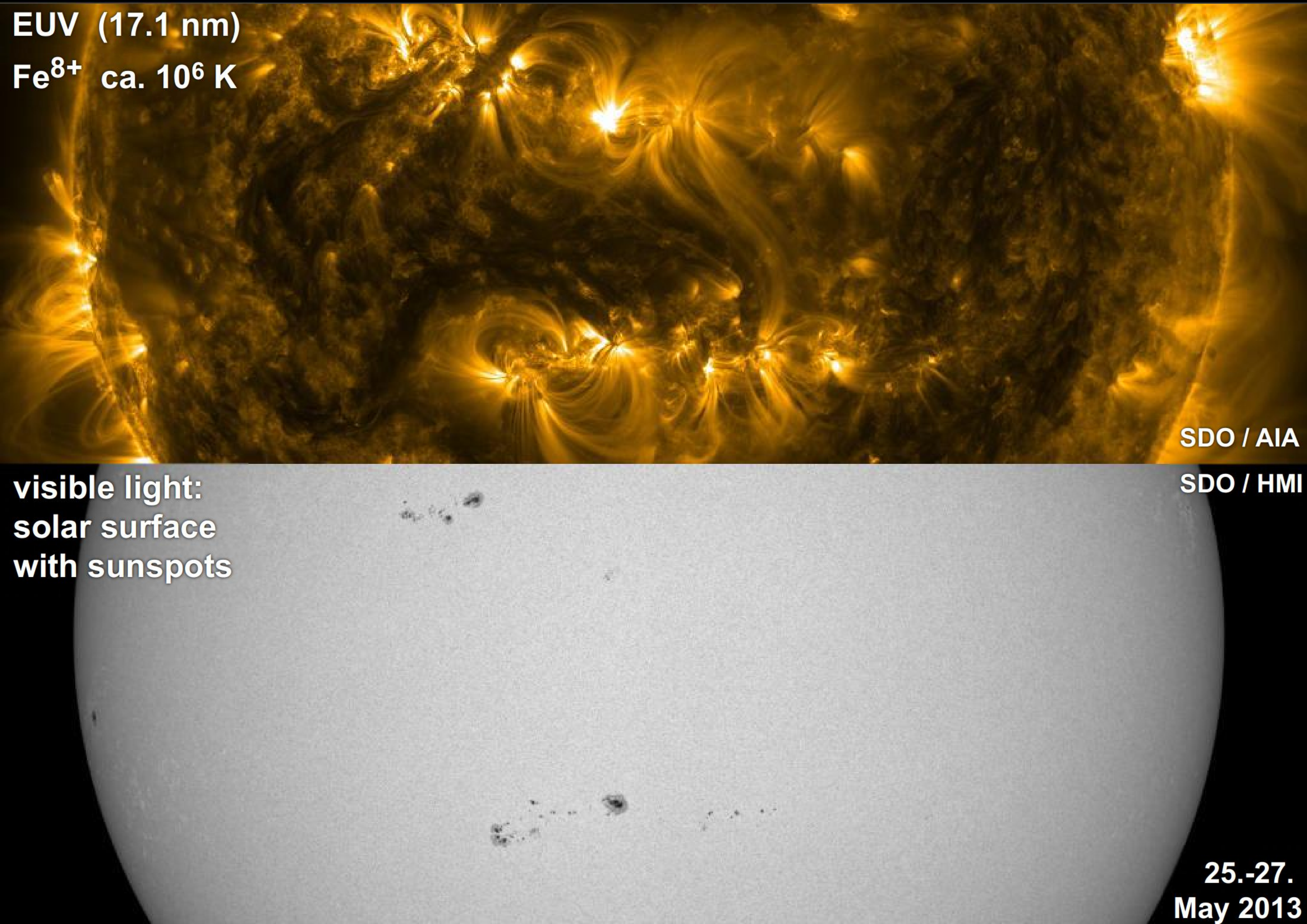
MAX-PLANCK-GESELLSCHAFT

MPS

Abstract

Since decades coronal heating is a buzzword that is used as a motivation on coronal research. Depending on the level of detail one is interested in, one could define this question anything ranging from answered to not understood at all. 3D MHD models can now produce a corona in a numerical experiment that comes close to the real Sun in complexity. And the fact alone that in these models a three-dimensional loop-dominated time-variable corona is produced could be used as an argument that the problem of coronal heating is solved. However, careful inspection of these model results shows that despite their success they leave many fundamental questions unanswered. In this talk I will address some of these aspects, including the mass and energy exchange between chromosphere and corona, the apparent width of coronal loops, the energy source of hot active region core loops, or the internal structure of loops. In this sense this talk will pose more questions that it provide answers.

Observations: the Sun over two days



Magnetohydrodynamics (MHD)

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

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

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

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

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

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

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

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

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

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

Magnetohydrodynamics (MHD)

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→

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

induction eq.

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

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

the energy balance is essential to get right temperature & density

→ prerequisite to determine coronal emission (EUV + X-rays)

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

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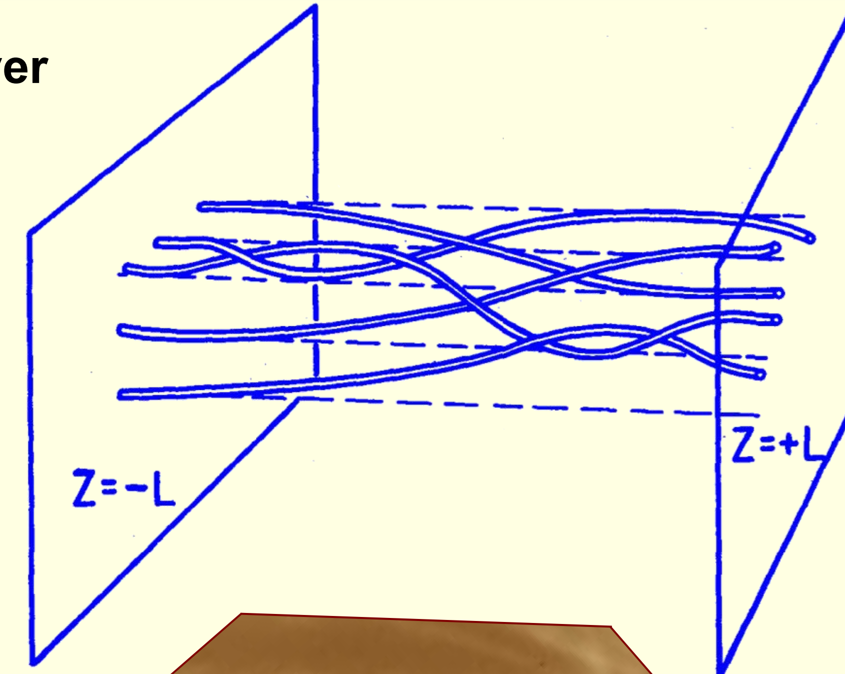
internal energy: $e = n\frac{3}{2}k_{\mathrm{B}}T$

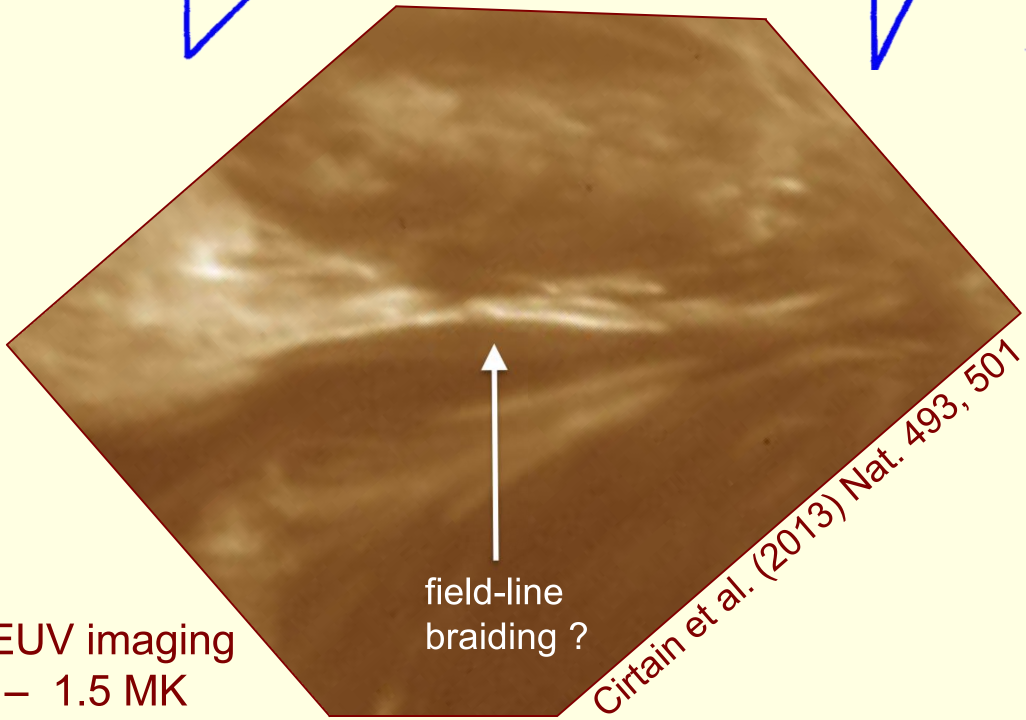
Concept for coronal heating

- ► horizontal motions in photosphere as driver
  - → **field-line braiding**
    (Parker 1972, ApJ 174, 499) →
  - → **flux-tube tectonics**
    (Priest et al 2002, ApJ 576, 533)



- ► is there direct observational evidence for field-line braiding ?

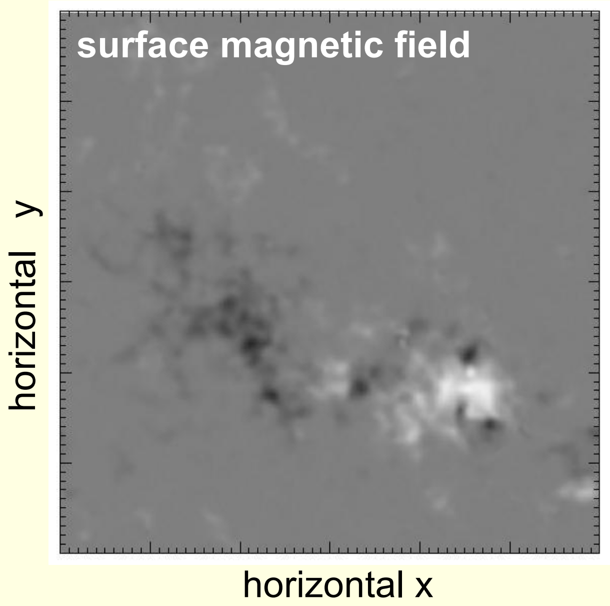
?



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

How to construct a corona in the box…

- take observed magnetogram:
  → surface magnetic field $B_{Z,0}$



How to construct a corona in the box…

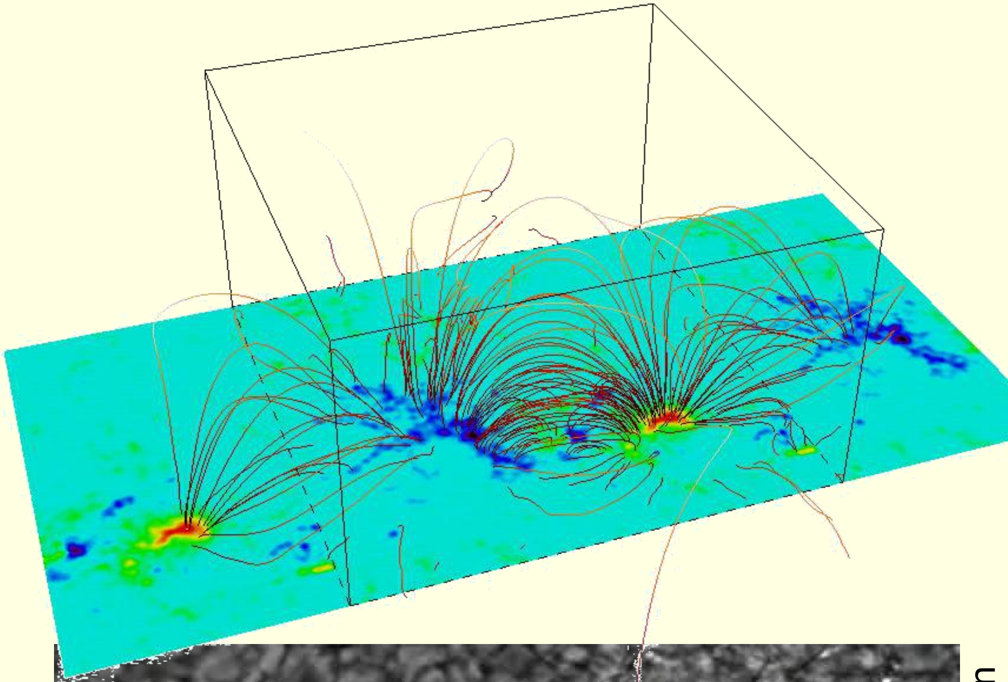
- take observed magnetogram:
  → surface magnetic field B_0

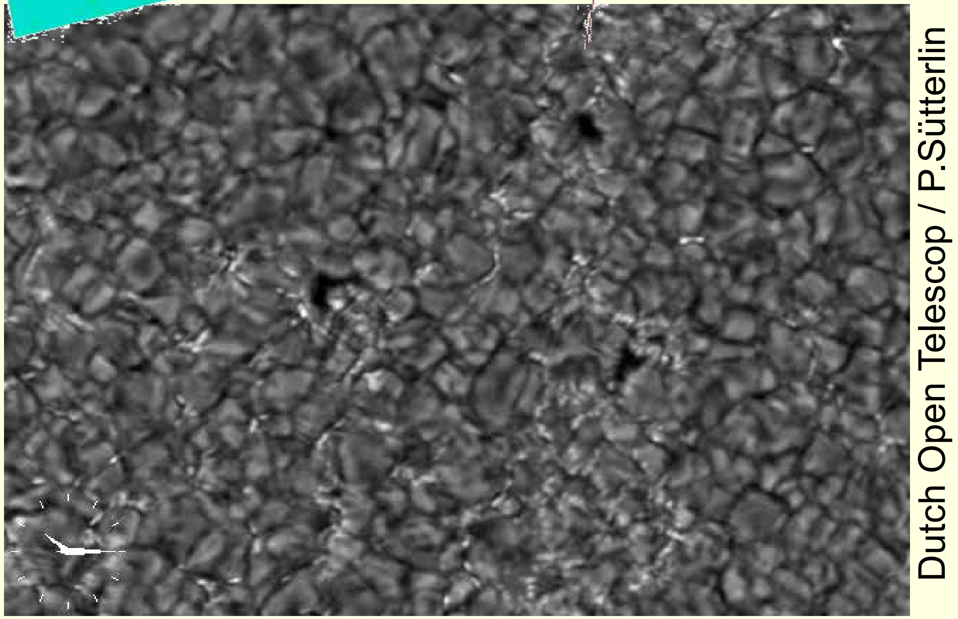
- extrapolate B_0 to fill box
  assume “1D” atmosphere

- surface convection:
  granulation drives magnetic field

- “fieldline braiding”:
  currents induced in corona

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





surface convective flow / granulation

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

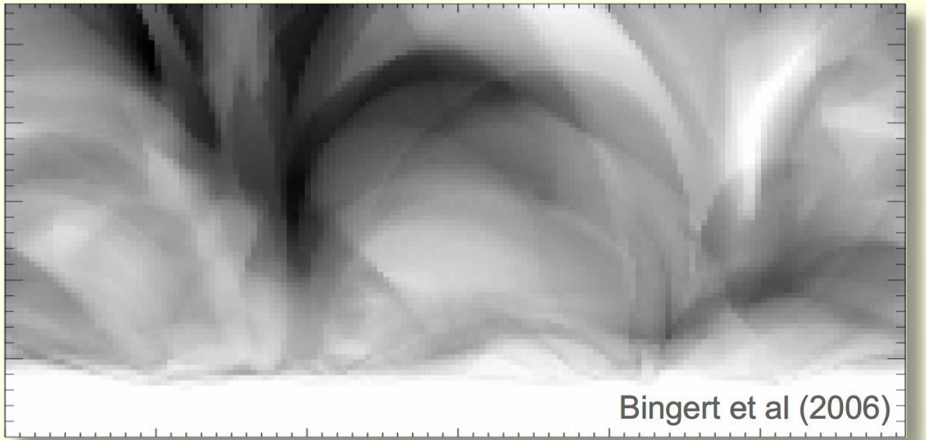
- ► "fieldline braiding":
  currents induced in corona

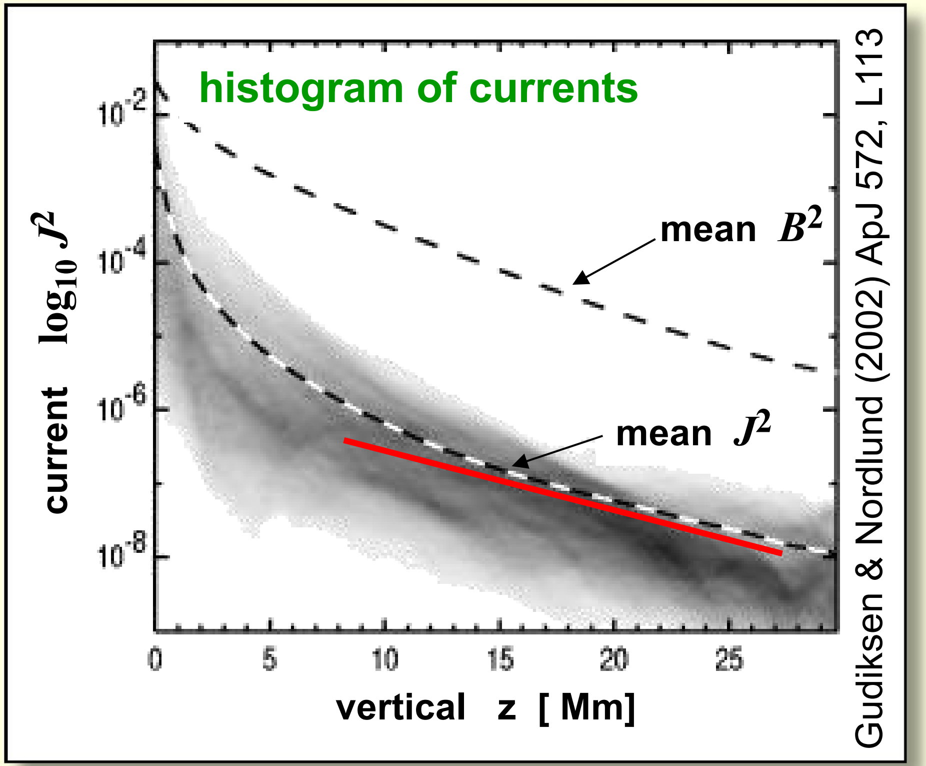
  $$\boldsymbol{j} = (\nabla \times \boldsymbol{B}) \,/\, h$$

- ► heating through Ohmic dissipation:

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

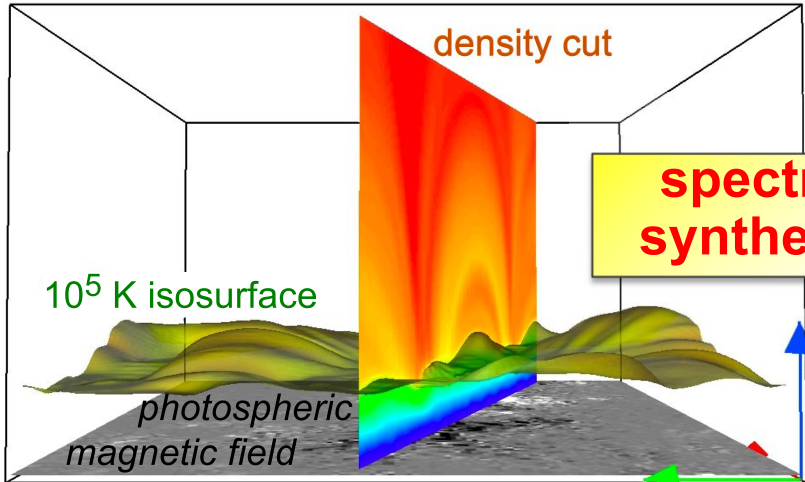
- ► loop-structured 10^6 K corona





3D MHD coronal model including spectral synthesis

3D MHD model: T, ρ, v, B



→ full energy equation
(heat conduction, radiative losses)

- ► horizontally periodic, open top
- ► non-uniform mesh

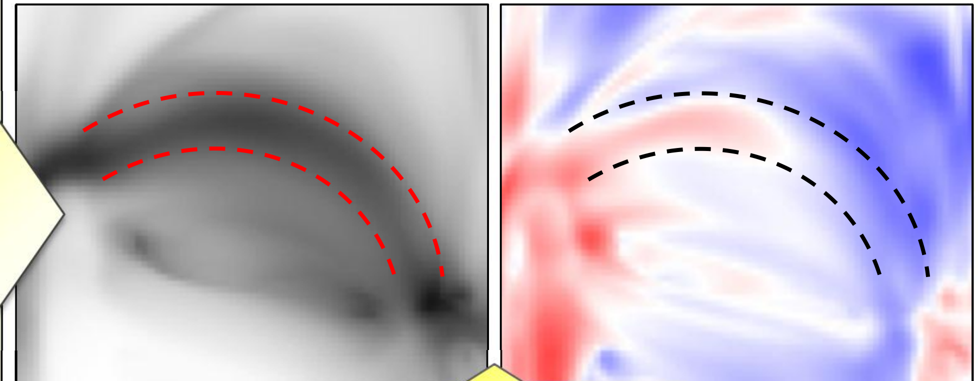
Pencil Code

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

► efficient parallelization (MPI)

spectral synthesis

synthesized coronal emission Mg X 625 Å

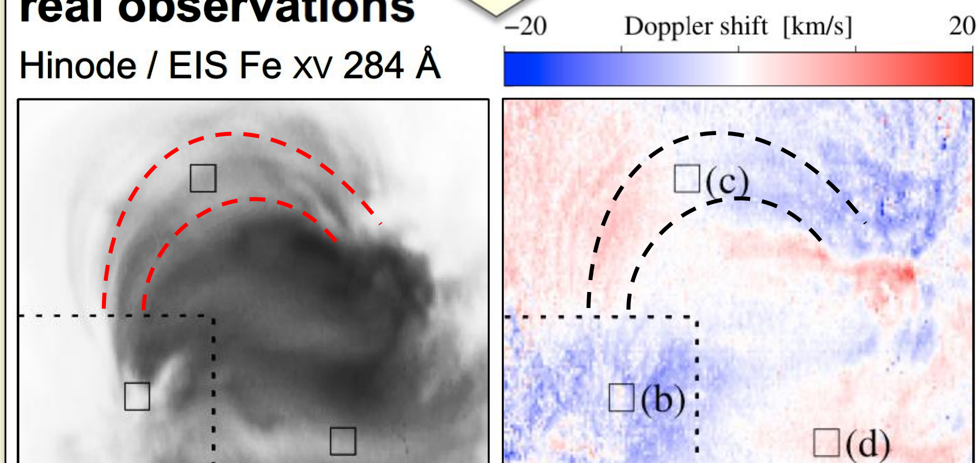


intensity map (inv.) Doppler map

compare

real observations

Hinode / EIS Fe XV 284 Å



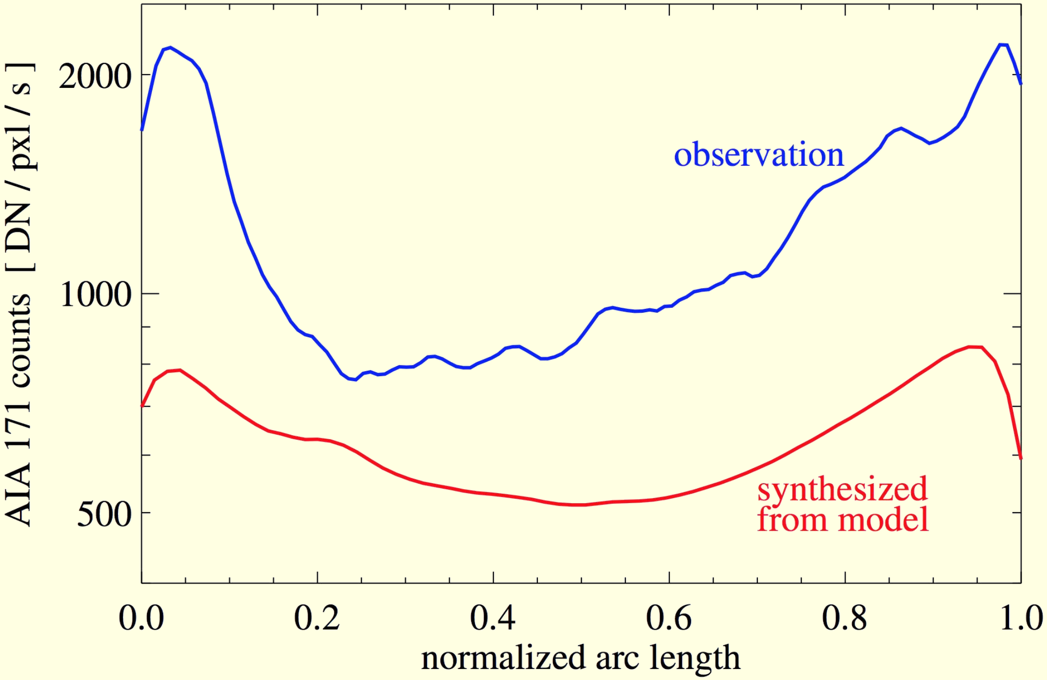
160"x125"

Bingert & hp (2011) A&A 530, A112
hp (2010) A&A 521, A51

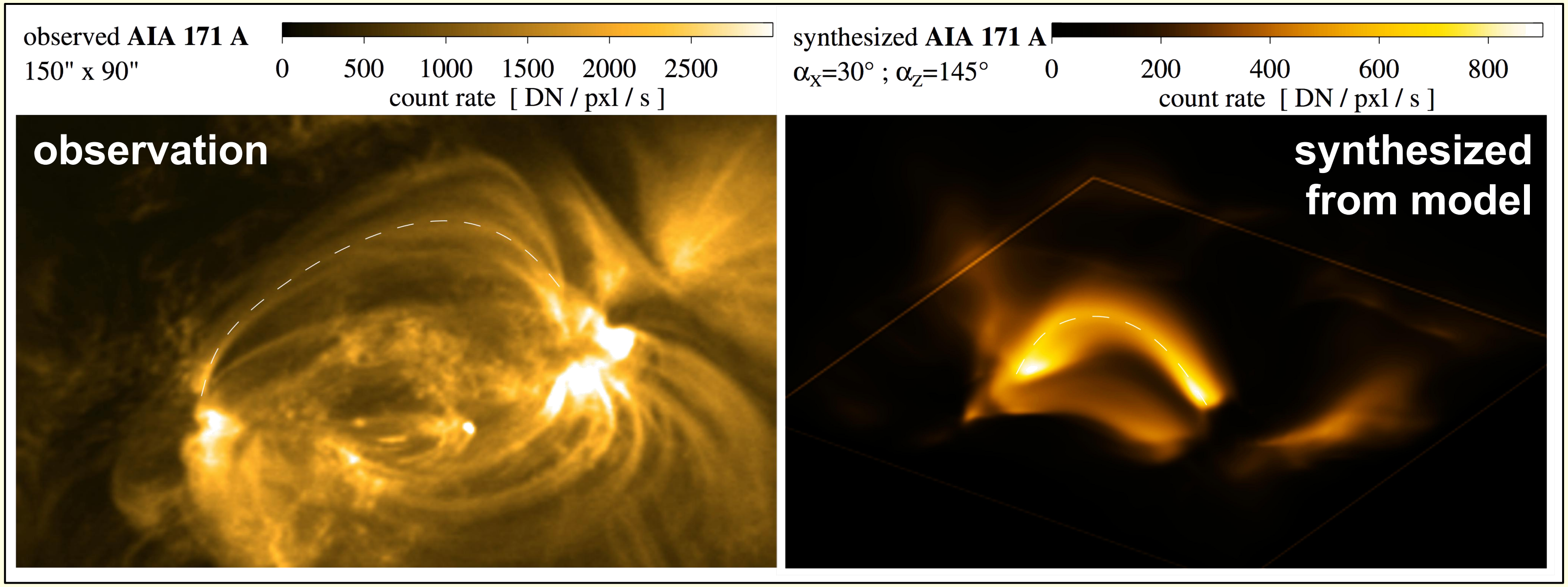
Intensity along an individual loop

- reasonable match to observations

- the real Sun is more complex (than this old model)



hp & Bingert (2012) A&A 548, A1



Coronal emission from 3D MHD model

synthesized AIA 211 Å; ≈2 MK

Chen & hp (2015) A&A 581, A137

Coronal emission from 3D MHD model

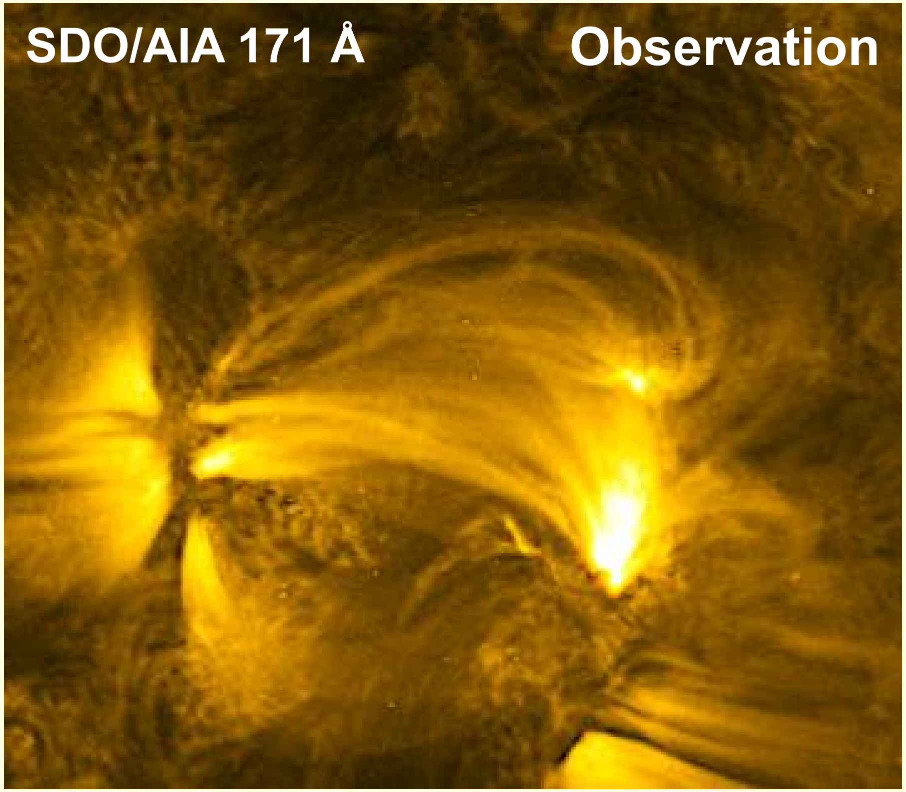
t = 0.00 min

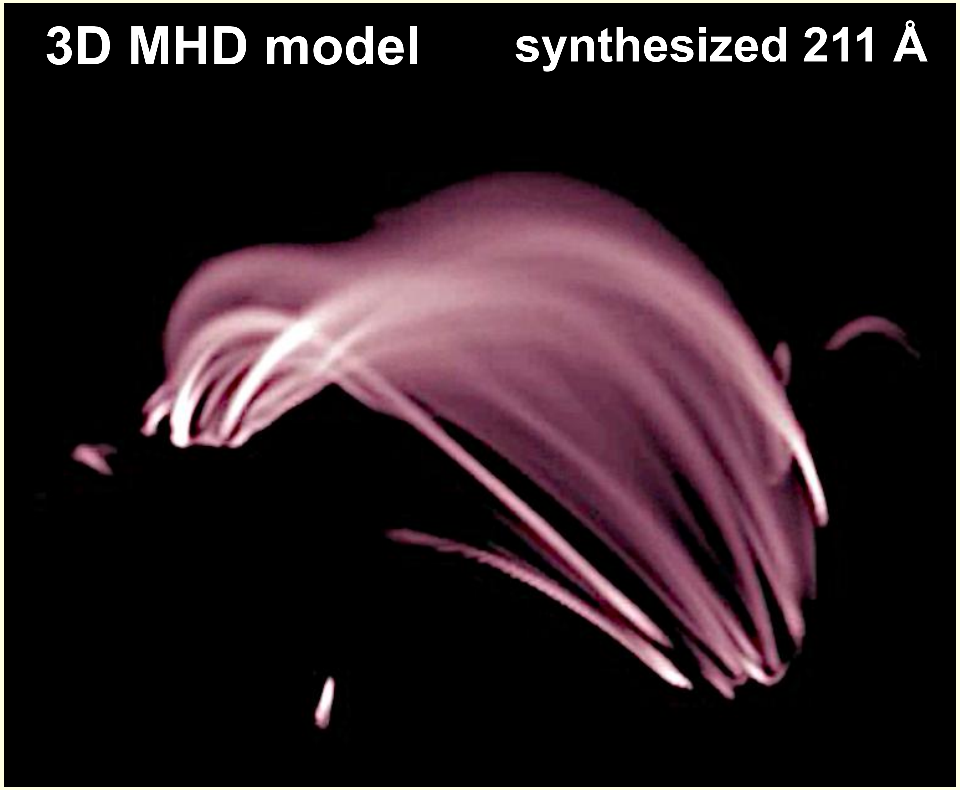
synthesized AIA 211 Å; ≈2 MK

Chen & hp (2015) A&A 581, A137

Coronal loops in active regions

showing plasma at ≈ 1…2 MK

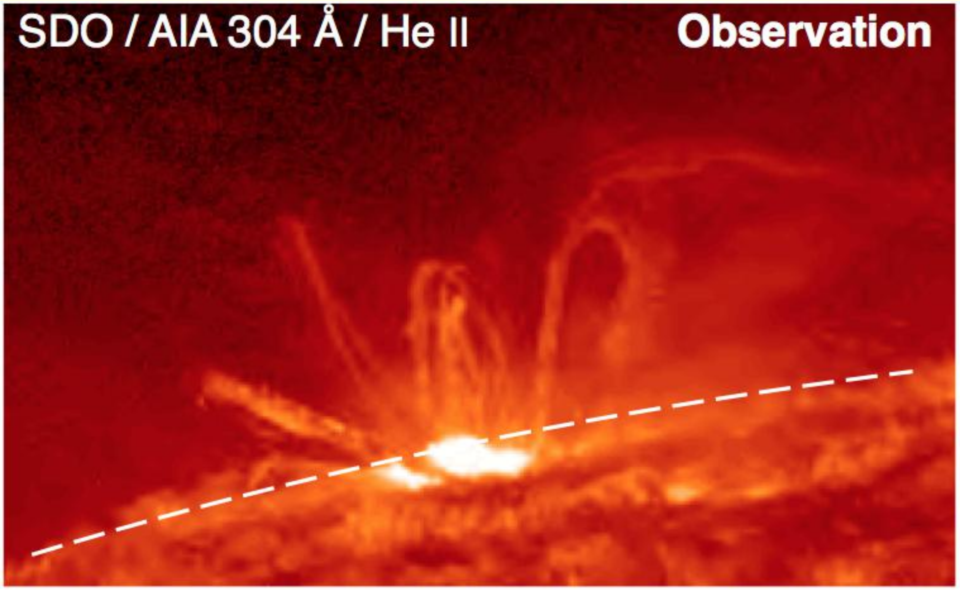


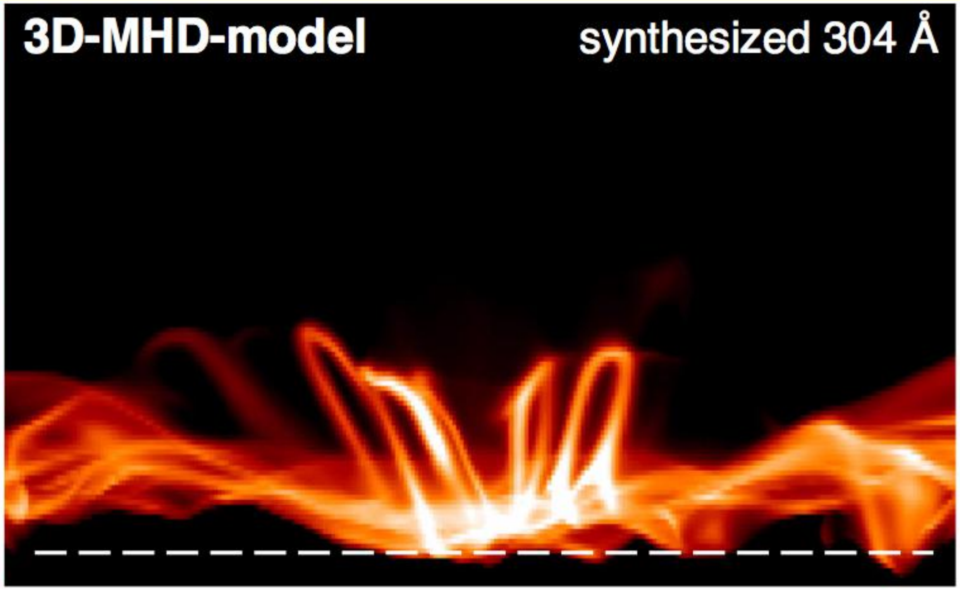


Chen & hp (2015) A&A 581, A137

Cool loops near the solar limb

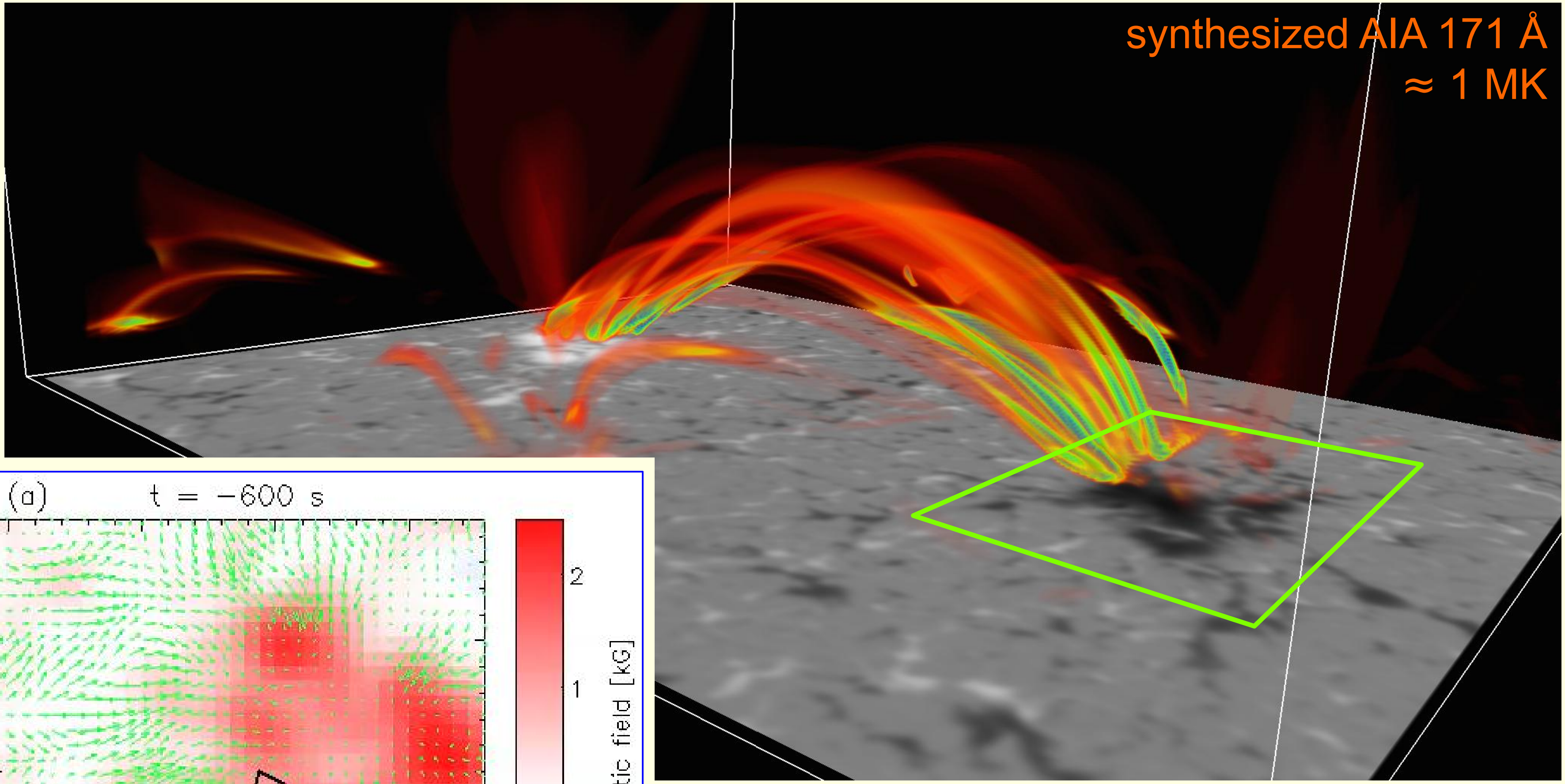
showing plasma at ≈ 100.000 K

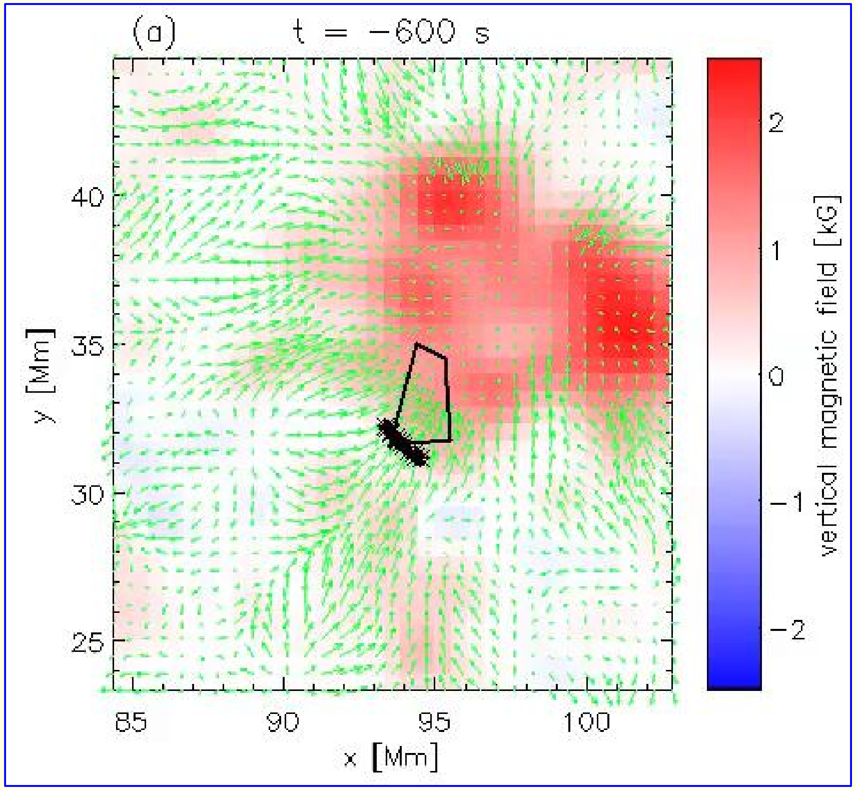




Chen, hp, Bingert, Cheung (2015) Nature Phys. 11, 492

What happens at the footpoints ?





the footpoints of the loops get pushed into the sunspot

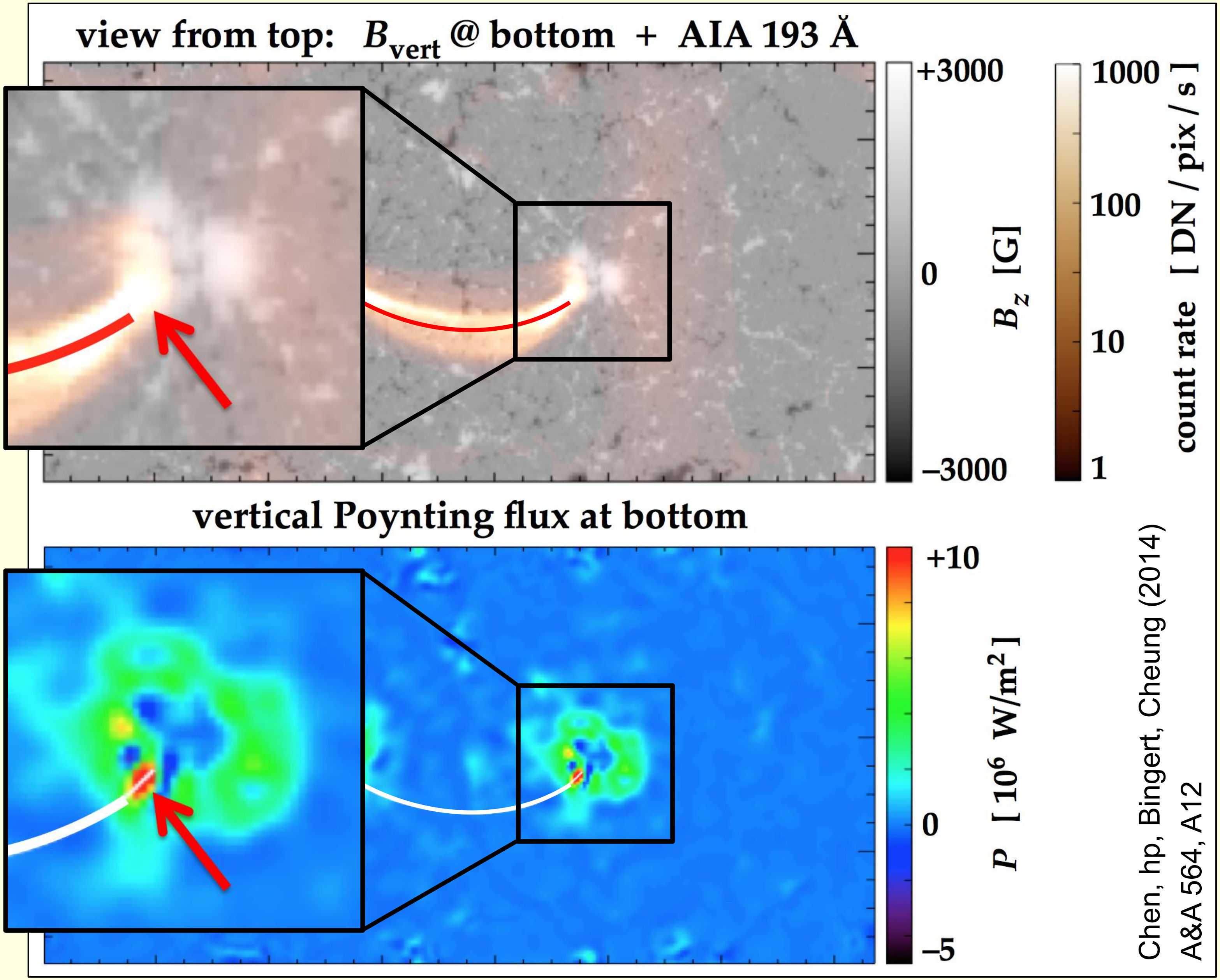
→ **upward Poynting flux**

(like in flux-tube tectonics; Priest et al. 2002, ApJ 576, 533)

Chen, hp, Bingert, Cheung (2015) Nature Phys. 11, 492

Energy input at the bottom (@ $b\approx1$): Poynting flux

coronal loops form where there is Poynting flux through the bottom (@ $b\approx1$)



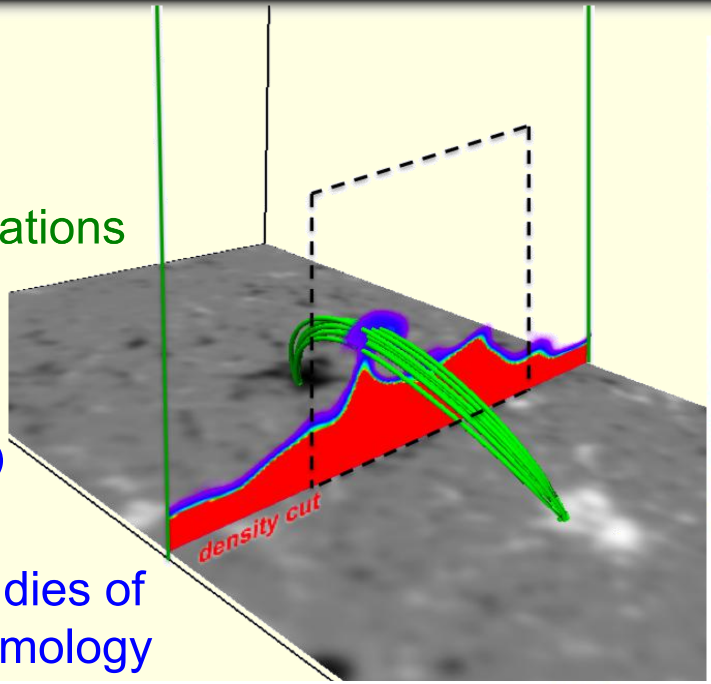
the heating is then concentrated very much towards the footpoints

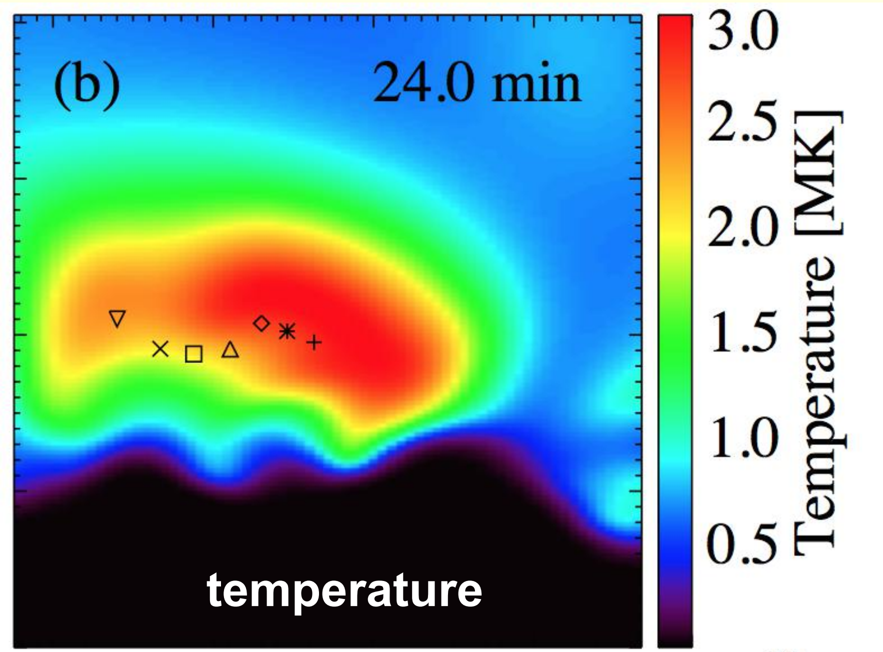
Chen, hp, Bingert, Cheung (2014)
A&A 564, A12

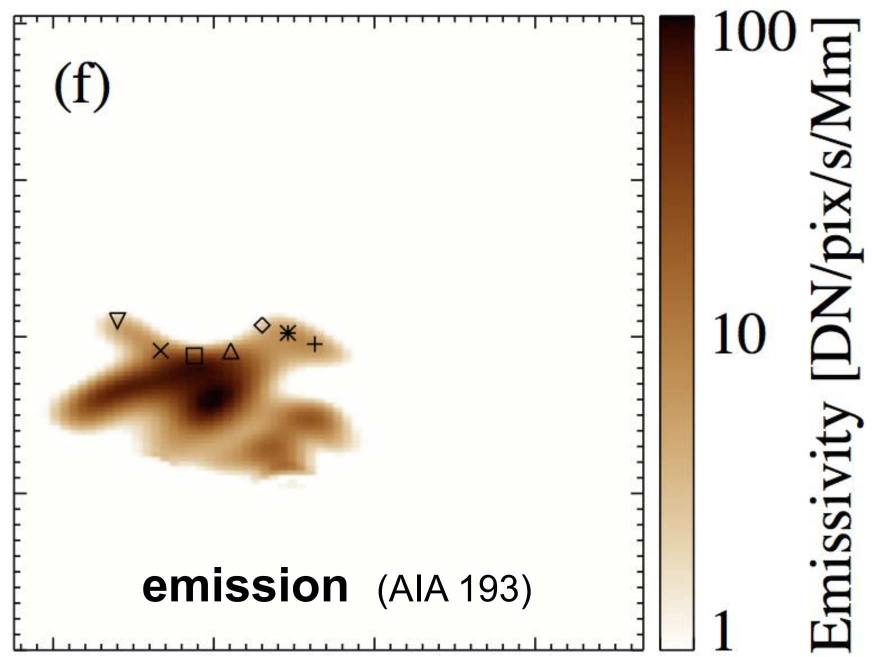
Temperature, density and emission

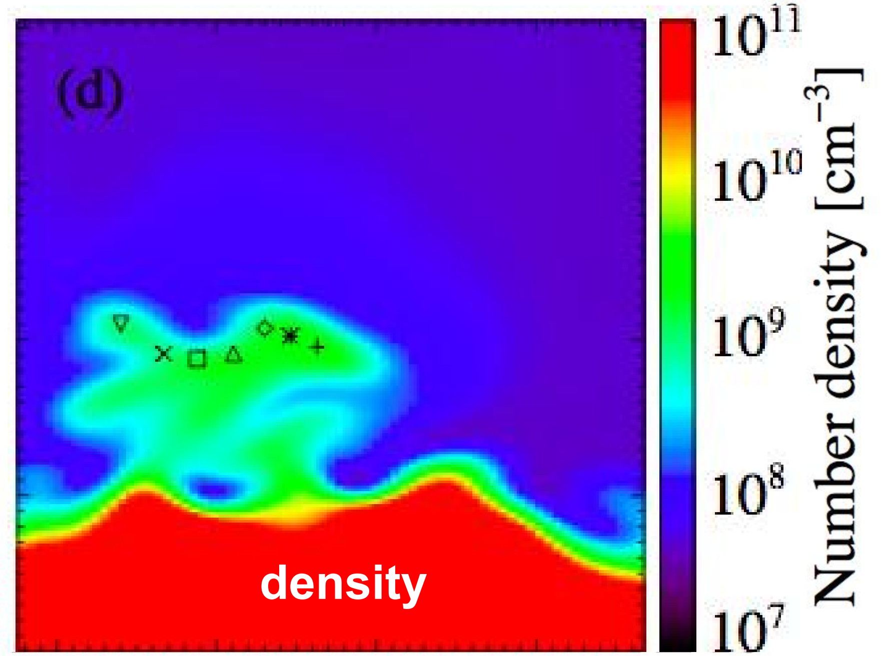
- density: log n ≈ 9.5 consistent with observations
- density contrast (inside/outside) ≈ 10%

supports studies of coronal seismology









Chen, hp, Bingert, Cheung (2014) A&A 564, A12

A closer look at the heating rate

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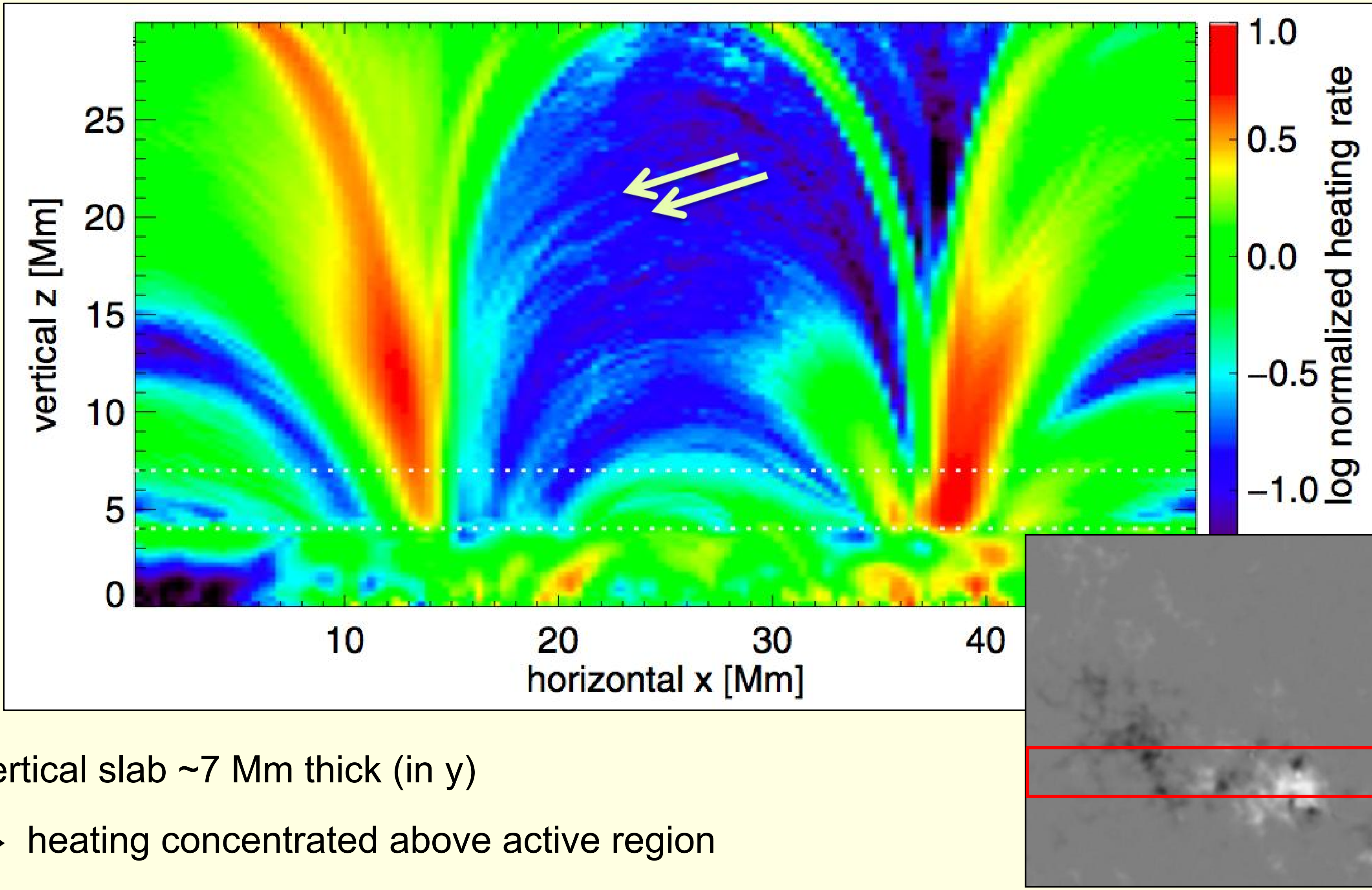
internal energy: $e = n \frac{3}{2} k_{\rm B} T$

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

Heating in vertical slab: field-aligned currents



Bingert & hp (2011 A&A 530, A112

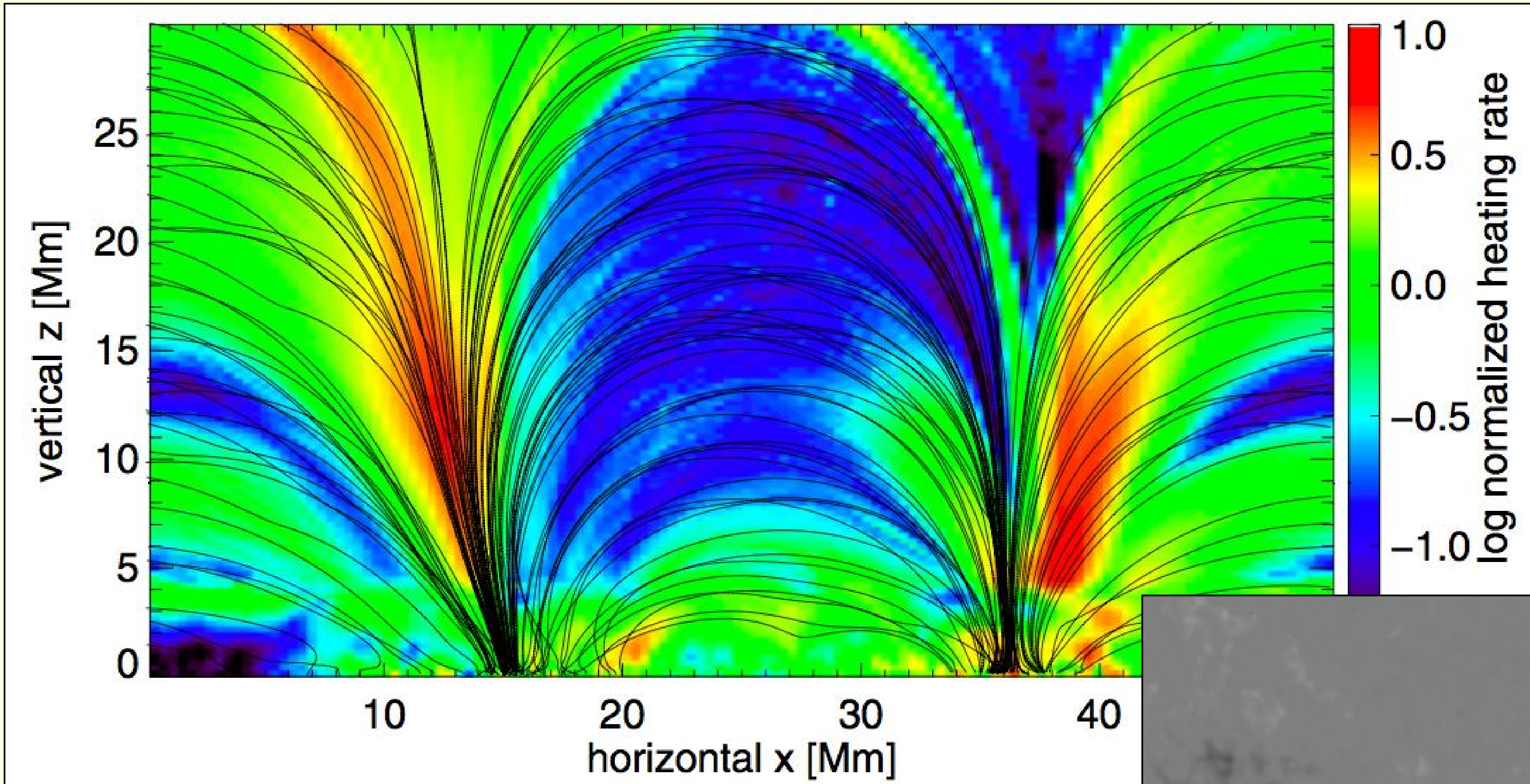
vertical slab ~7 Mm thick (in y)

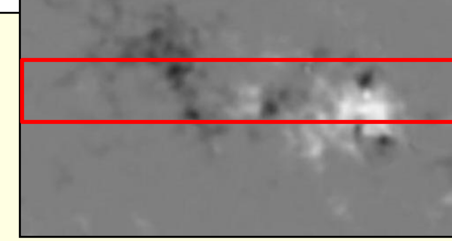
→ heating concentrated above active region

→ heating concentrated in “threads” aligned with *B*: intermittent in space and time!

→ heating concentrated in low corona / transition region (here normalized: H / r)

Heating in vertical slab: field-aligned currents





Bingert & hp (2011) A&A 530, A112

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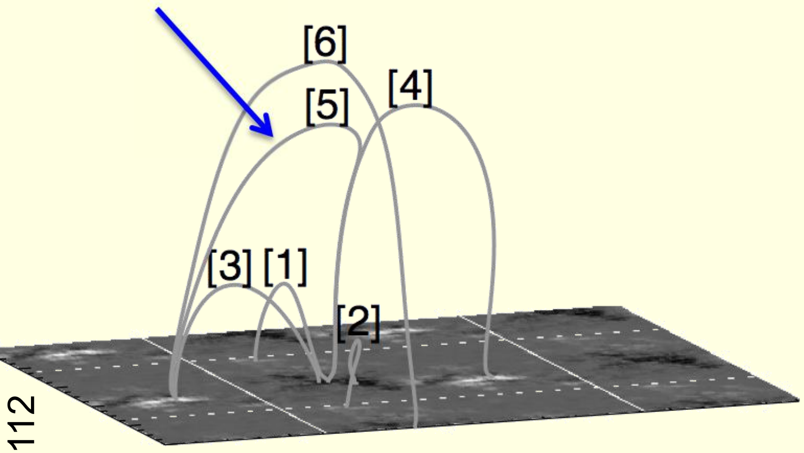
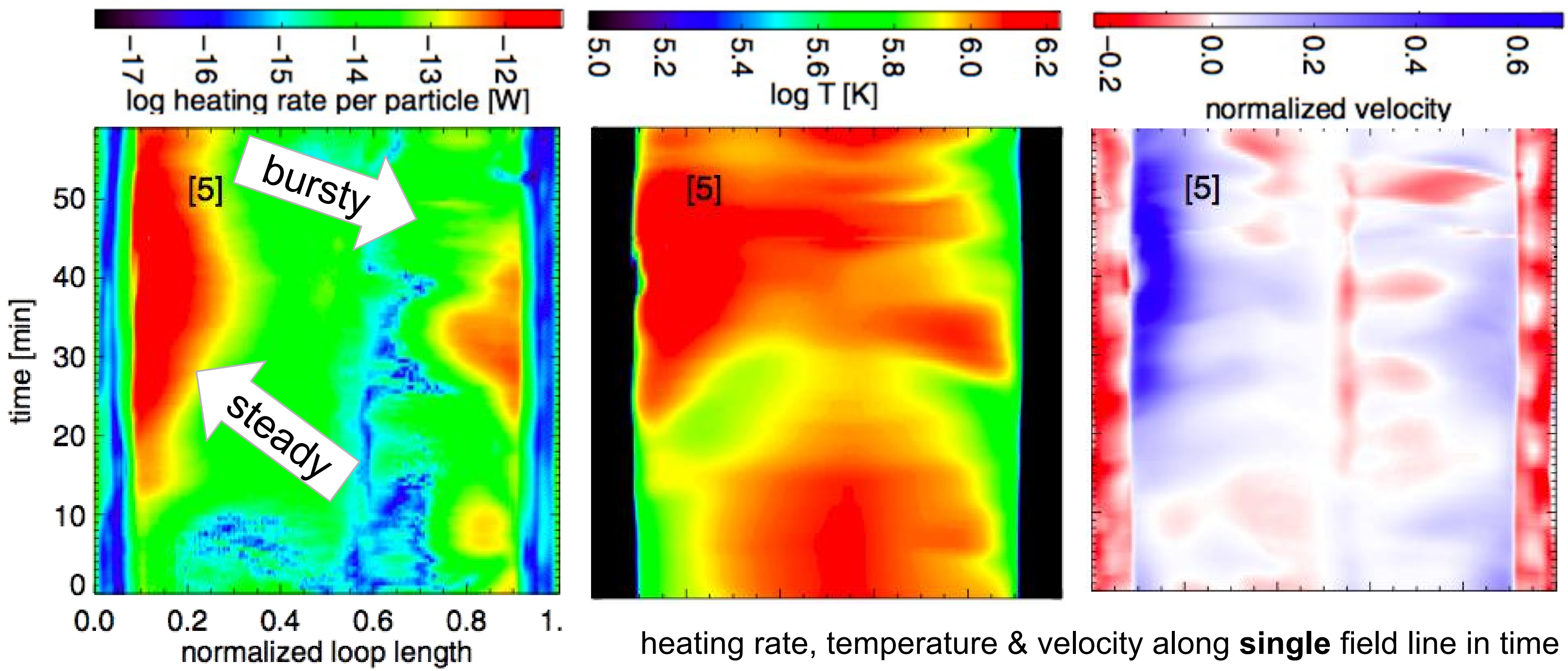
Heating on fieldlines: spatio-temporal variation



- ► "steady" heating: $t_{\mathrm{heat}} > t_{\mathrm{cool}}$
- ► "intermittent" / bursty: $t_{\mathrm{heat}} < t_{\mathrm{cool}}$

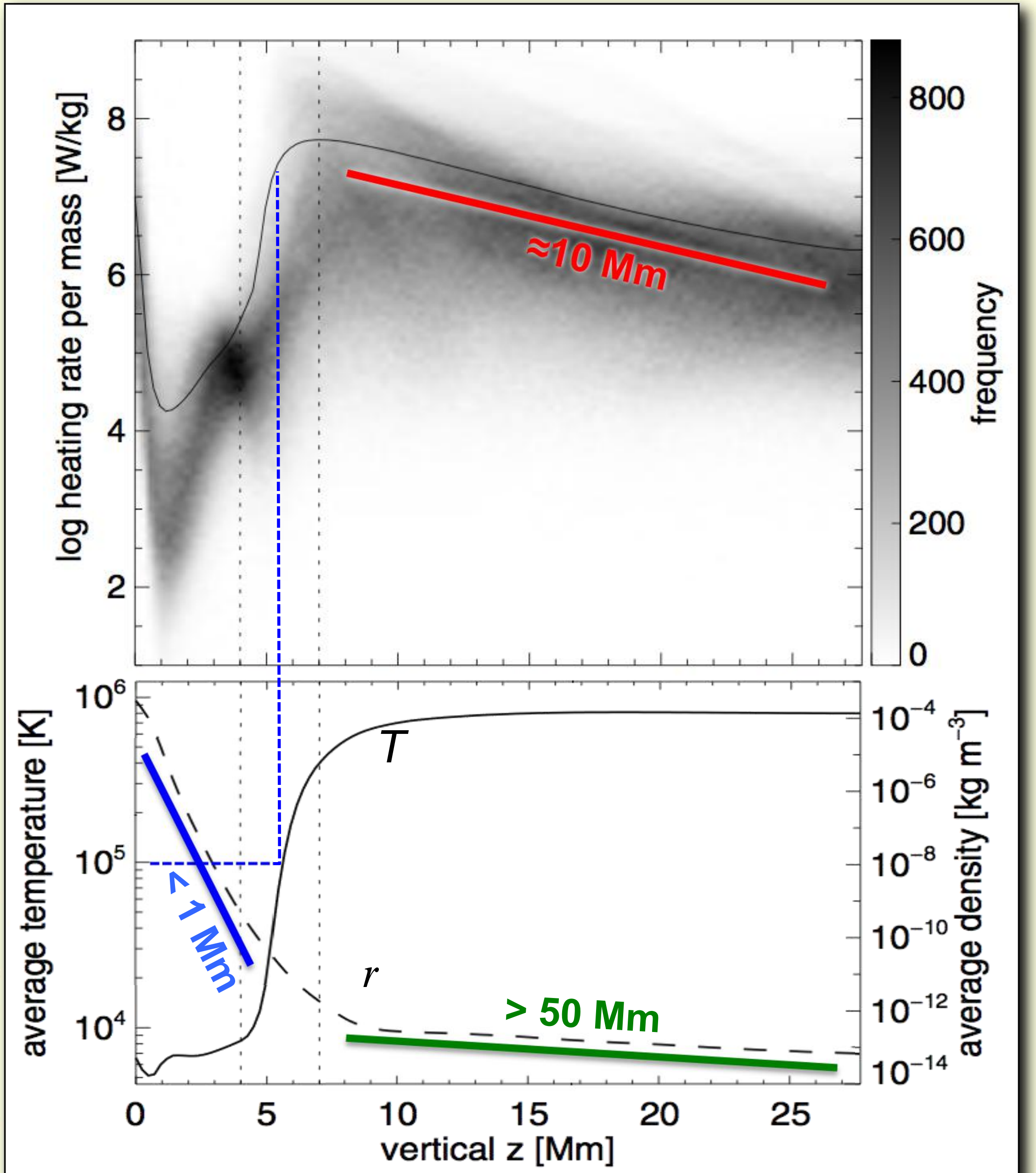
→ "steady" and "intermittent" heating coexist even on same fieldline / in same loop !!

Bingert & hp (2011) A&A 530, A112



heating rate, temperature & velocity along **single** field line in time

Horizontally averaged heating rate (per particle)



Bingert & hp (2011) A&A 530, A112

- ▶ heating concentrated in low atmosphere
- ▶ maximum heating/particle in transition region
- ▶ but there is still heating needed in corona !

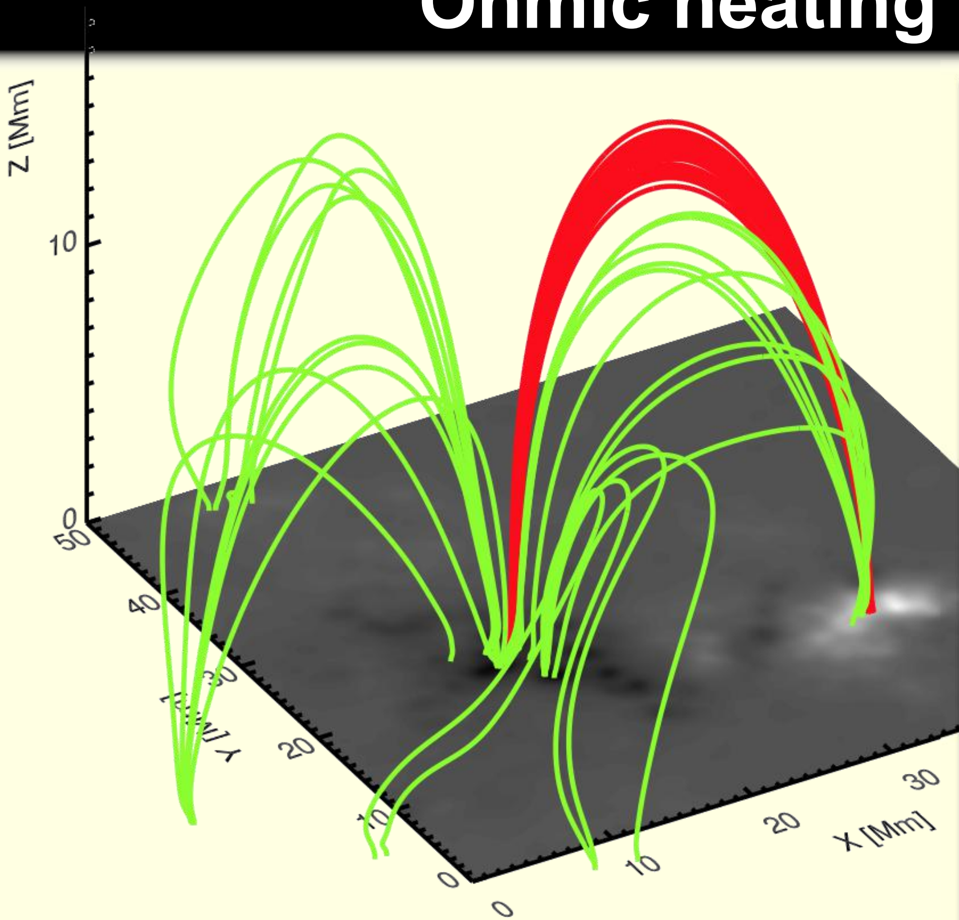
→ is because of scale heights:

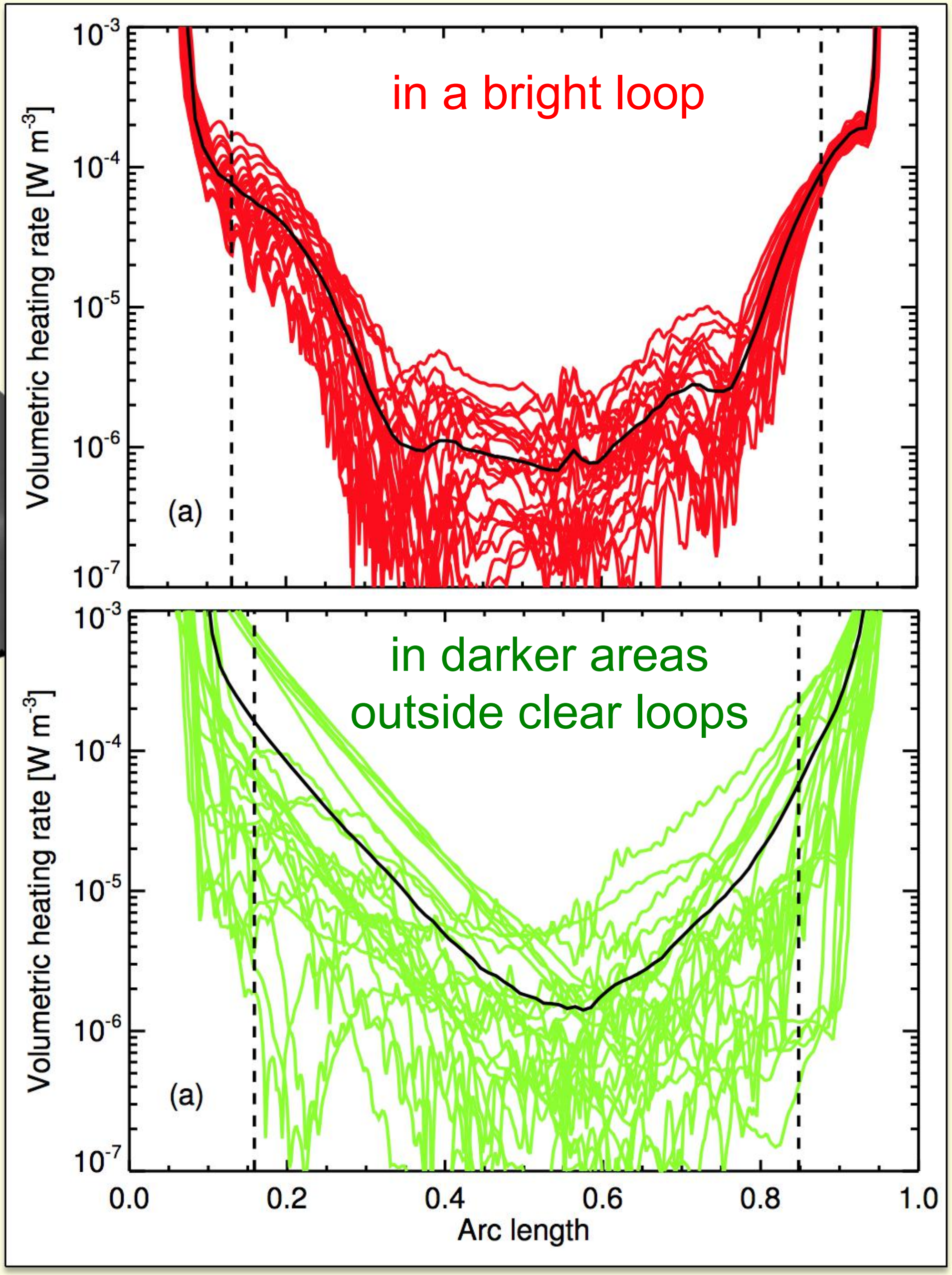
- – *p* chromosphere: < 1 Mm
- – Ohmic heating: ≈ 10 Mm
- – *p* corona: > 50 Mm

similar results by all 3D MHD models with Ohmic heating, e.g.
Gudiksen et al. (2002) ApJ 572, L113
Hansteen et al. (2010) ApJ 718, 1070

already hinted at by
Galsgaard & Nordlund (1996)

Ohmic heating along fieldlines

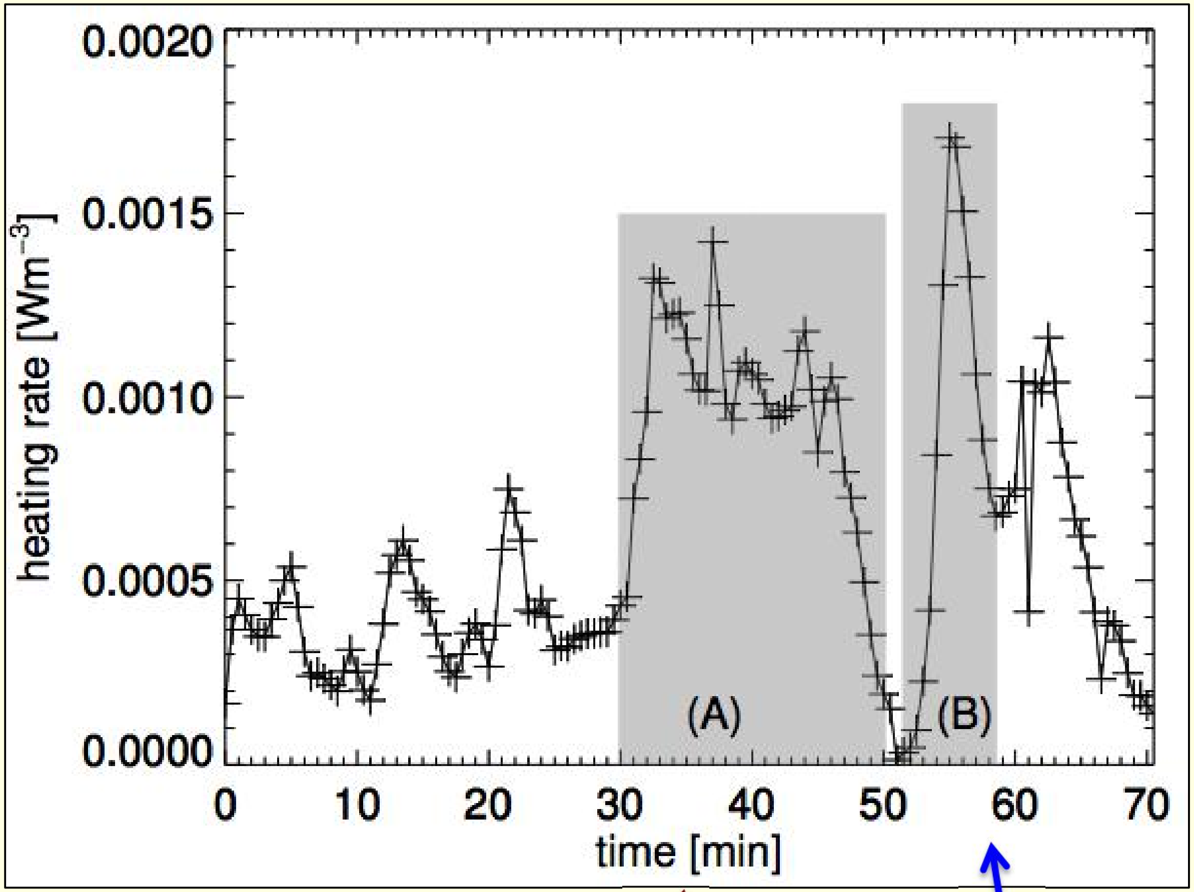




→ **Ohmic heating drops exponentially**
not only on average,
but also along individual field lines

van Wettum, Bingert, hp (2013) A&A 554, A39

Nanoflares and nanoflare storms



Bingert & hp (2013) A&A 550, A30

- ► some of the "heating events" are comparable to a **single nanoflare**

  (Parker: ~10^{24} erg = 10^{17} J)

- ► sometimes nanoflares seem to cluster:

  nanoflare storms

- ► this is only a single event → look for statistics…

- ► but note:

  energy deposition is concentrated towards loop feet

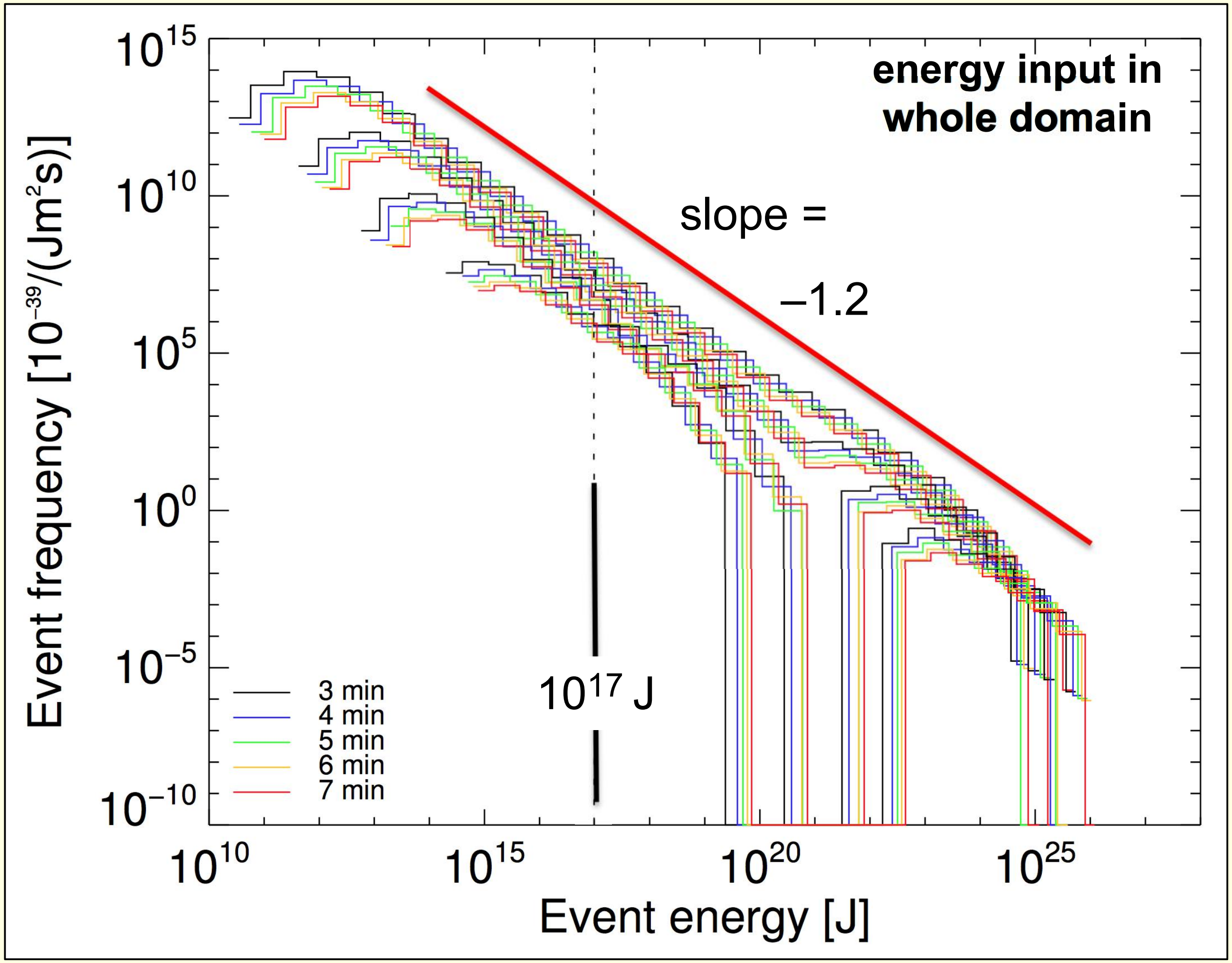
in volume with diameter of ~0.5 Mm →

nanoflare storm ~10^{18} J

single nanoflare ~10^{17} J

Power law distribution of energy deposition

- ► distribution of energies is ≈ power law over > 10 decades!
- ► self-similar process
- ► why does this work so nicely also at this “low” resolution?



Bingert & hp (2013) A&A 550, A30

→ divide computational domain in sub-volumes

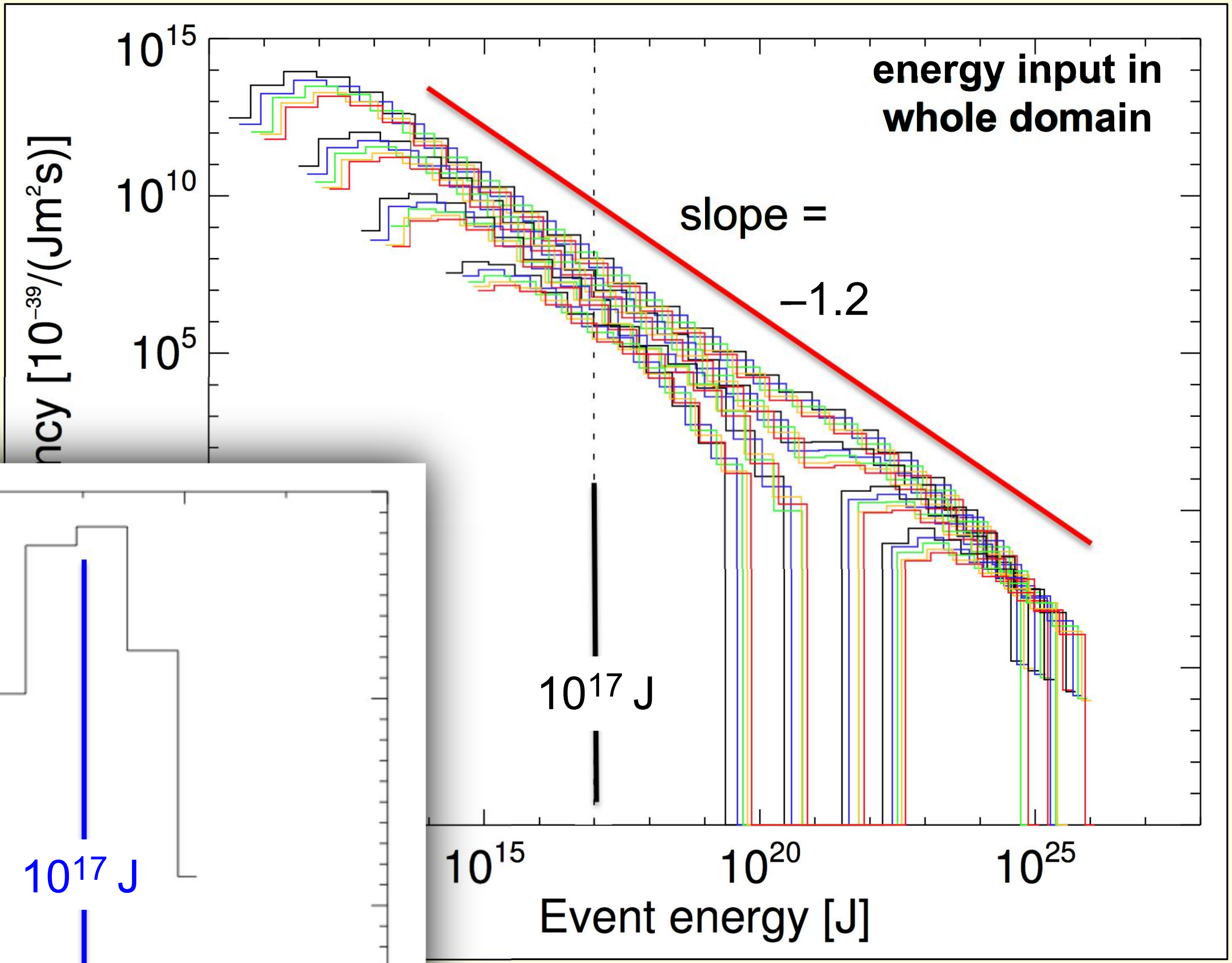
→ divide time series in short intervals

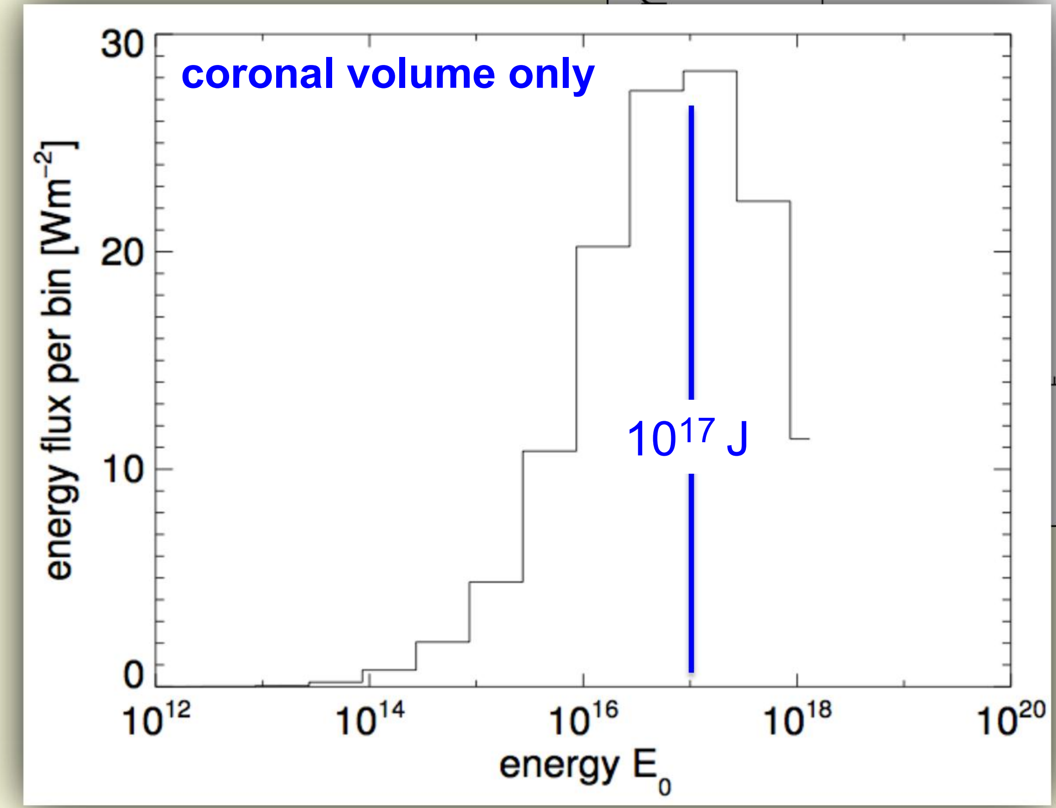
→ do statistics of deposited energy in these intervals

similar results found by
Hansteen et al (2015) ApJ 811, id.106

Power law distribution of energy deposition

- energy is *not* distributed in a *single* power law
- most energy deposition is at ~ 10^{17} J (=10^{24} erg)
  → **nicely fits Parker's nanoflares**





Bingert & hp (2013) A&A 550, A30

similar results found by
Hansteen et al (2015) ApJ 811, id.106

Energy injection at loop feet

From the photosphere into the corona

simple flux conservation:

$F = B\,d^2 = \text{const.}$

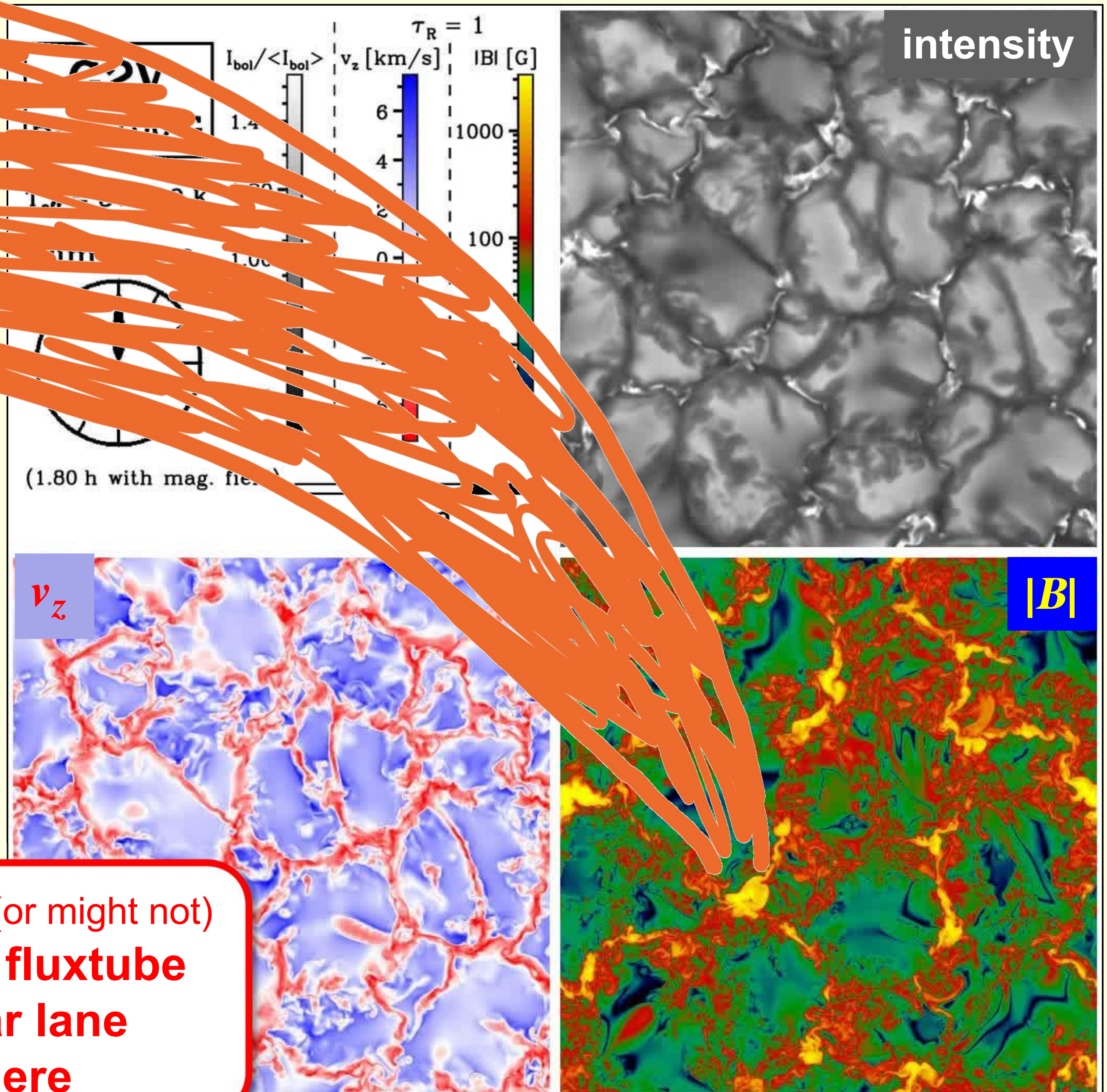
corona / loop apex:

▶ B ≃ 10 G d ≃ 1000 km

photosphere / fluxtube

▶ B ≃ 1000 G d ≃ 100 km

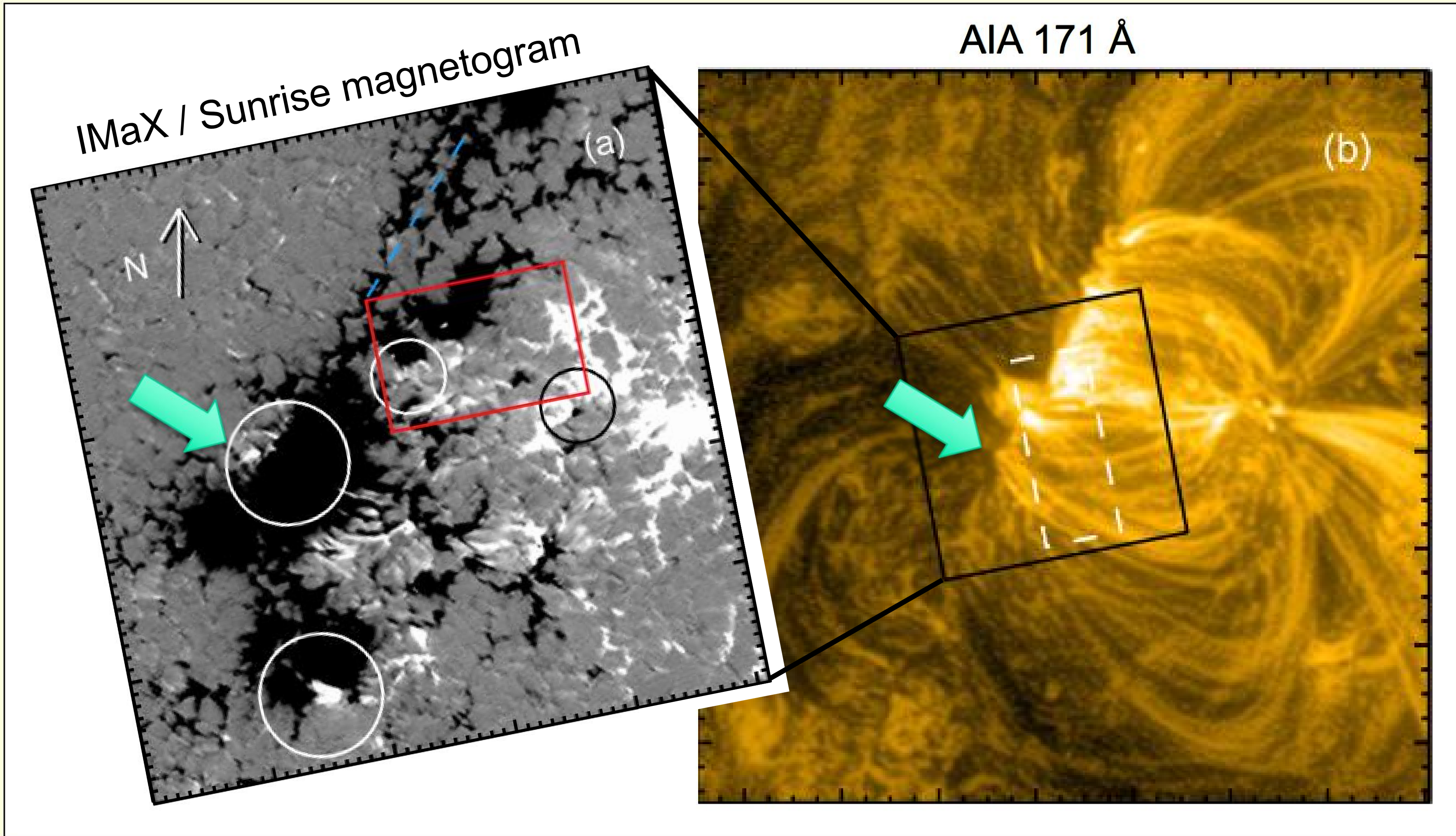
A coronal loop might (or might not) **be rooted in a single fluxtube in an inter-granular lane in the photosphere**



radiation MHD model, courtesy M. Schüssler

Footpoints of loops at high resolution

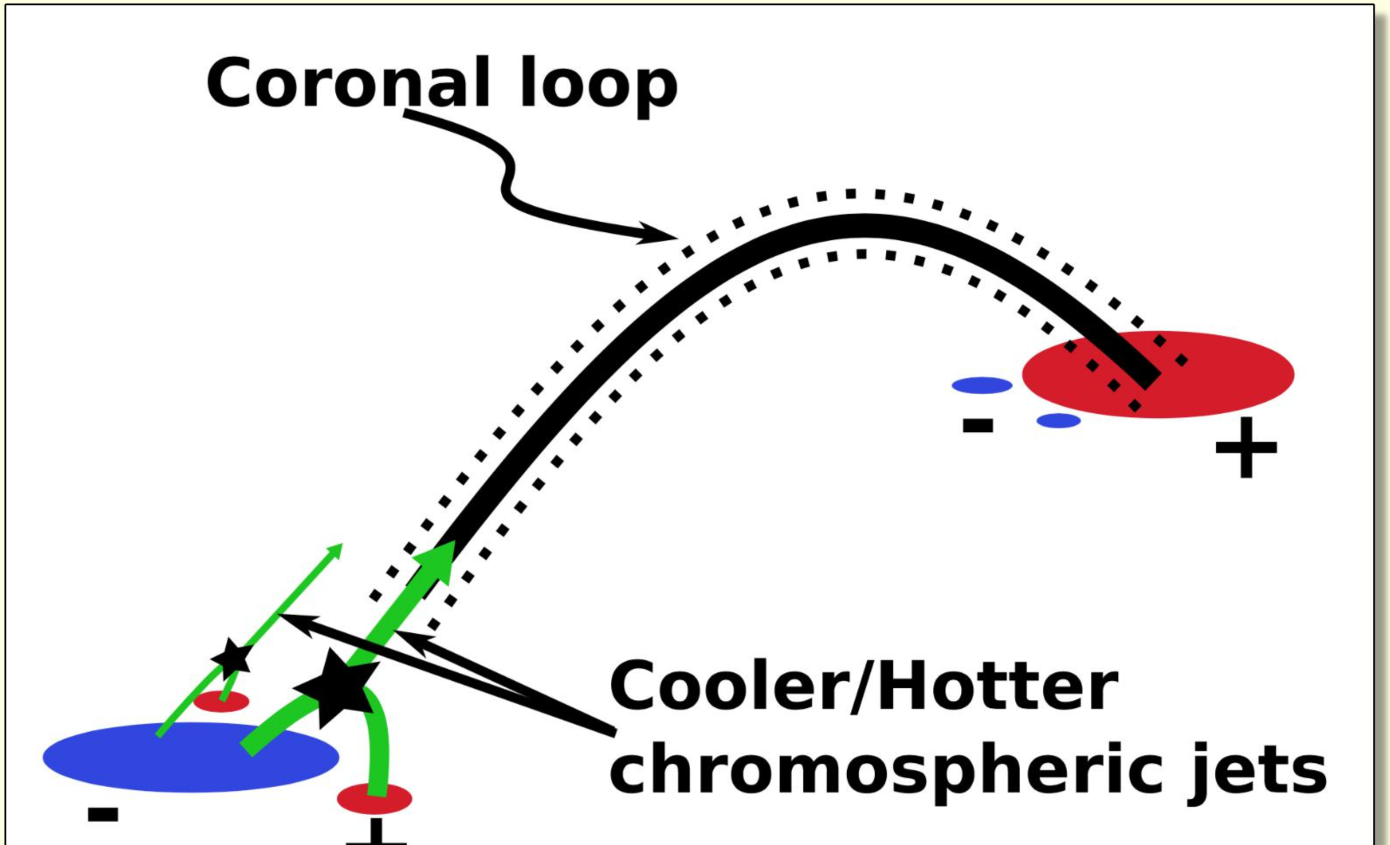
- high-resolution observations with the Sunrise balloon telescope:
  → loops rooted where small-scale parasitic (opposite) polarities are present
- flux-cancellation indicates reconnection at footpoints



Chitta, hp, Solanki, et al. (2017, ApJS 229, id.4)

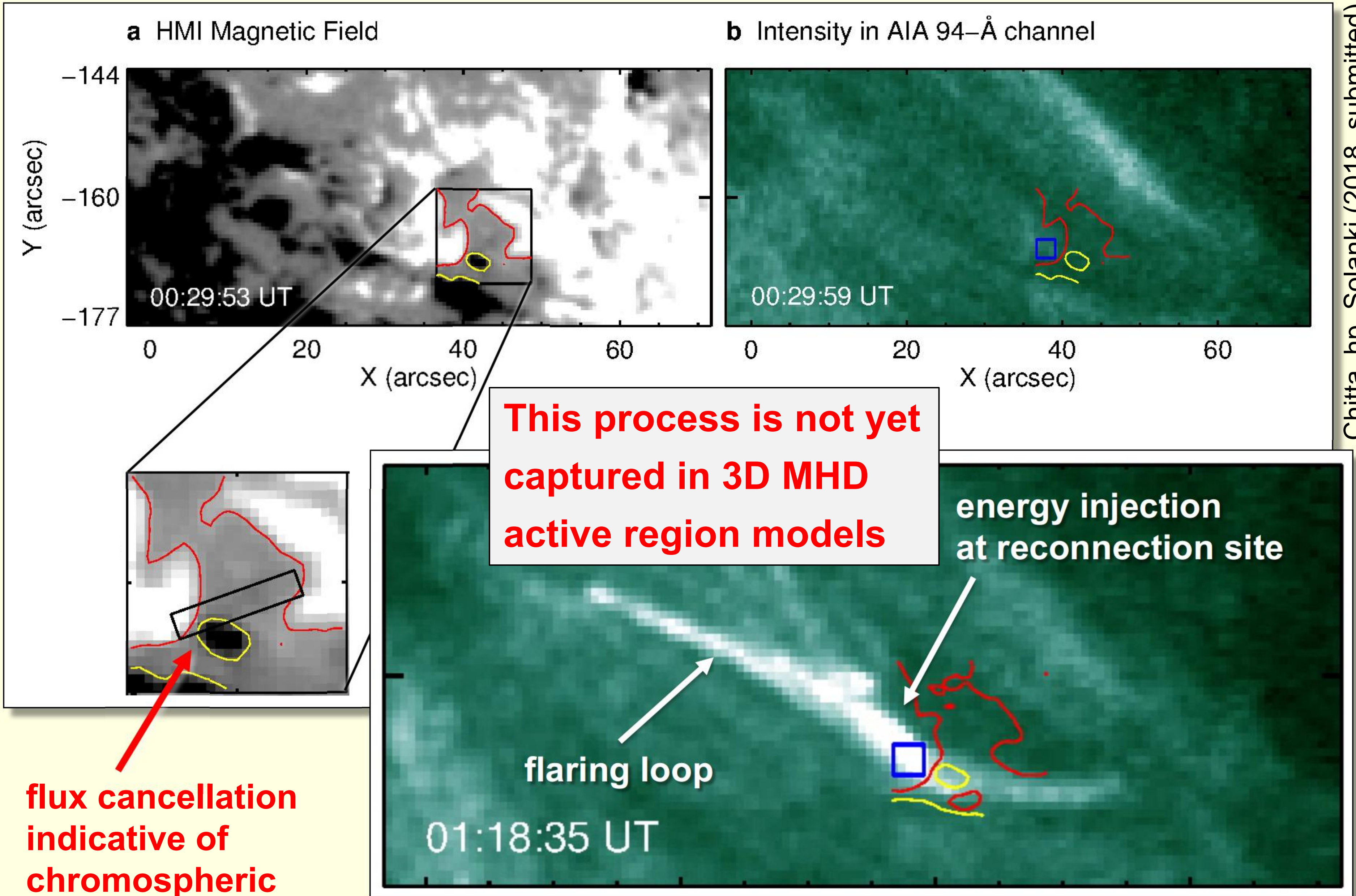
Magnetic reconnection feeding and heating loop

- is reconnection at loop footpoints
  as important as or even more important than AC/DC heating ?
- braiding / waves will be there all the time
  but reconnection will be episodic → could explain why
  (hot) loops are not everywhere



Chitta, hp, Solanki, et al. (2017, ApJS 229, id.4)

Formation of a hot core loop: footpoint reconnection



This process is not yet captured in 3D MHD active region models

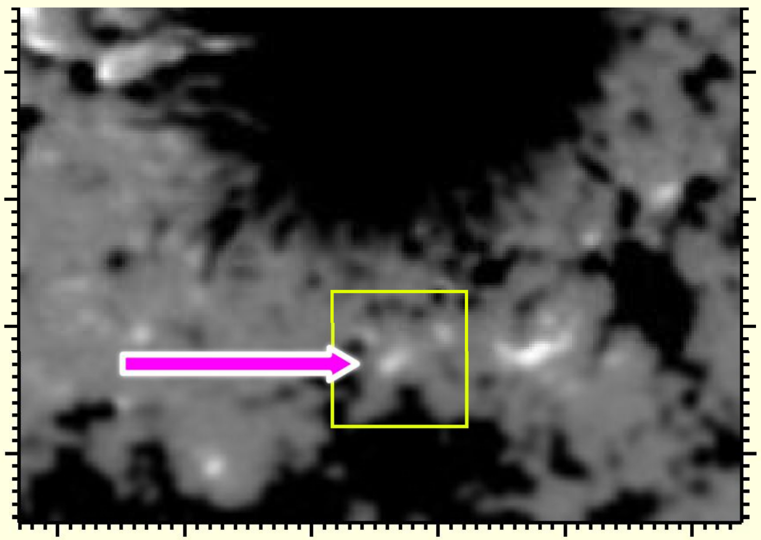
flux cancellation indicative of chromospheric reconnection

Chitta, hp, Solanki (2018, submitted)

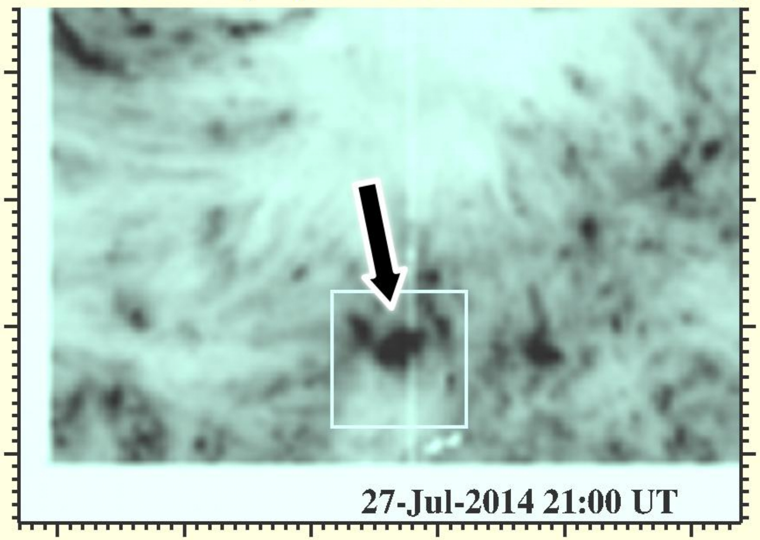
reconnection driven by surface motions

Motivation through magnetic topology of EUV burst

magnetogram (HMI)

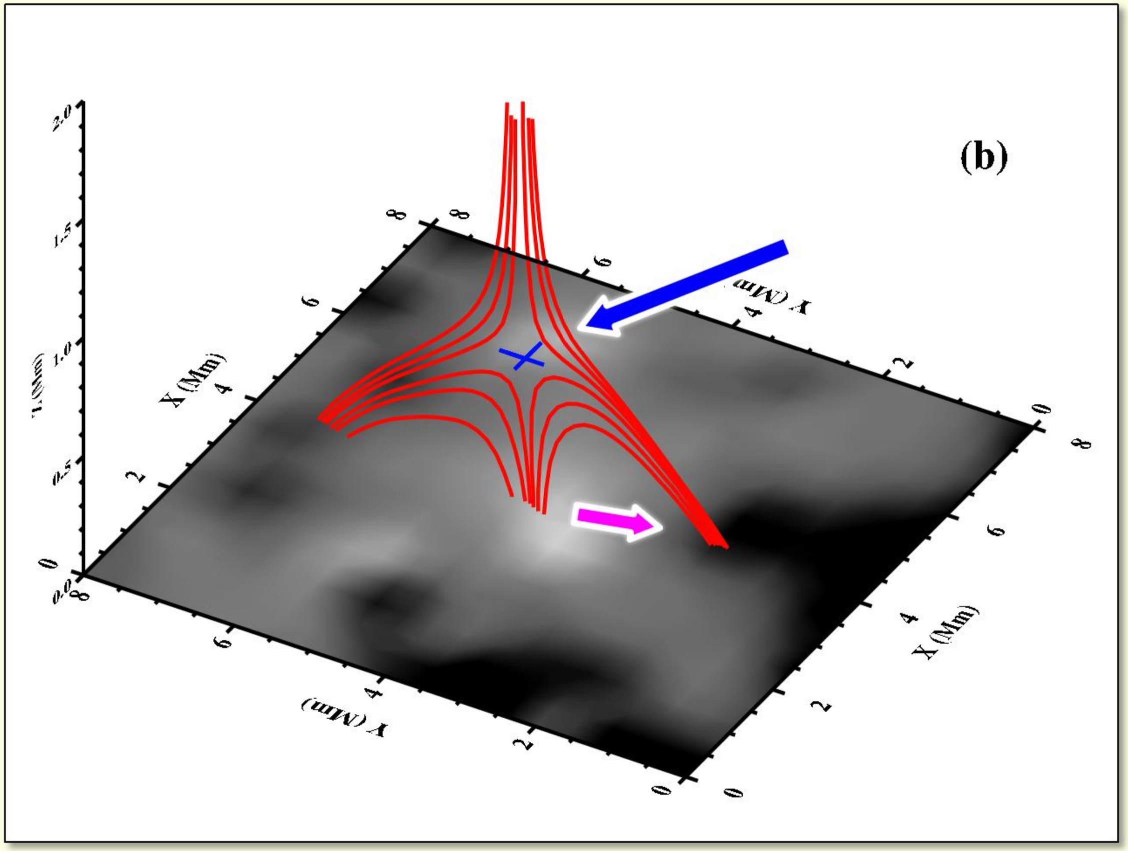


TR intensity (inverse scale, IRIS 1400Å)



≈ 60 x 40 arcsec^2

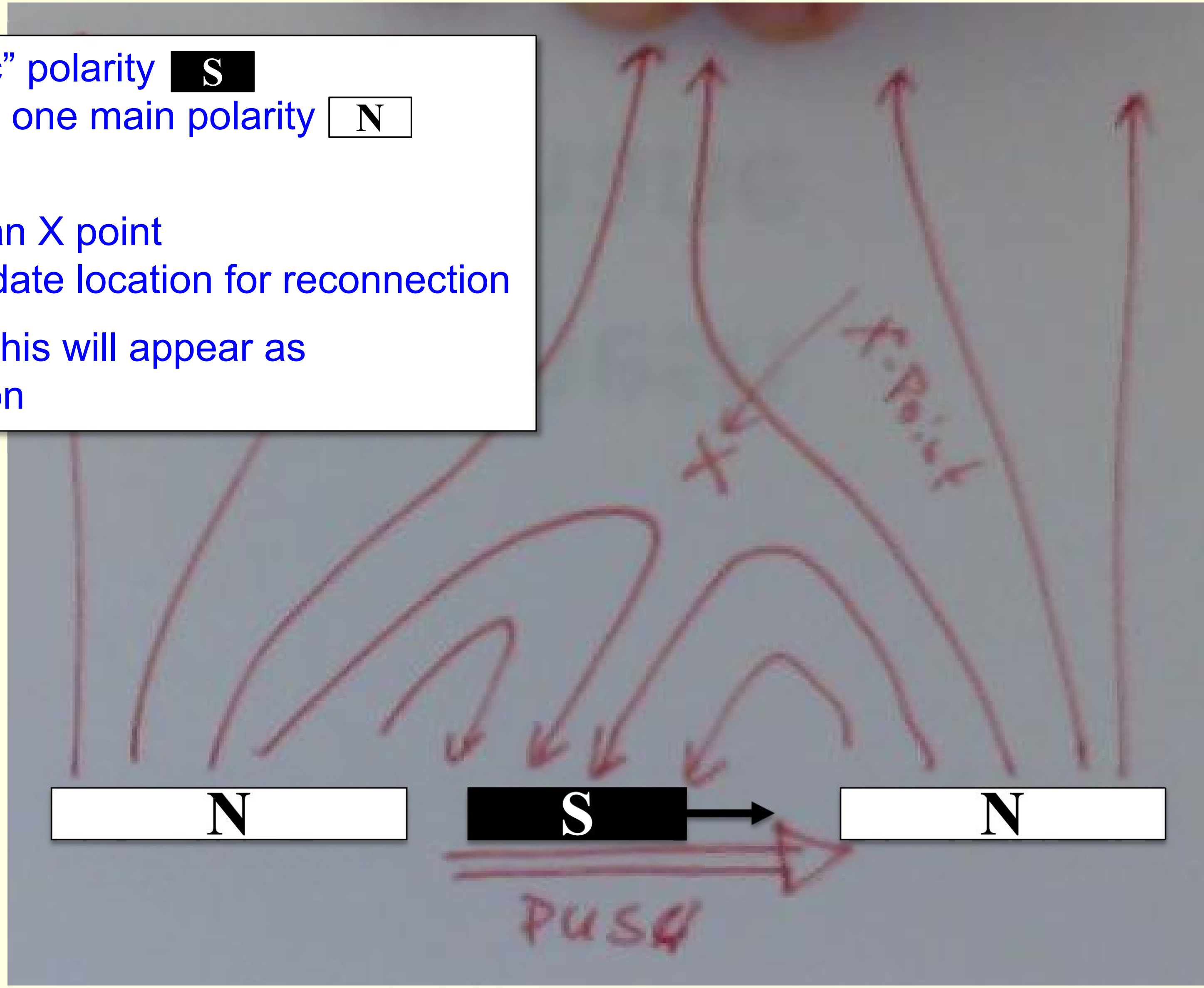
- small ("parasitic") polarity runs into major polarity (pore)
- magnetic field forms X point above
  → reconnection site at low height (chromosphere)
- TR emission (EUV burst) trails location of X point



Chitta, hp, Young, Huang (2017) A&A 605, A49

Magnetic setup

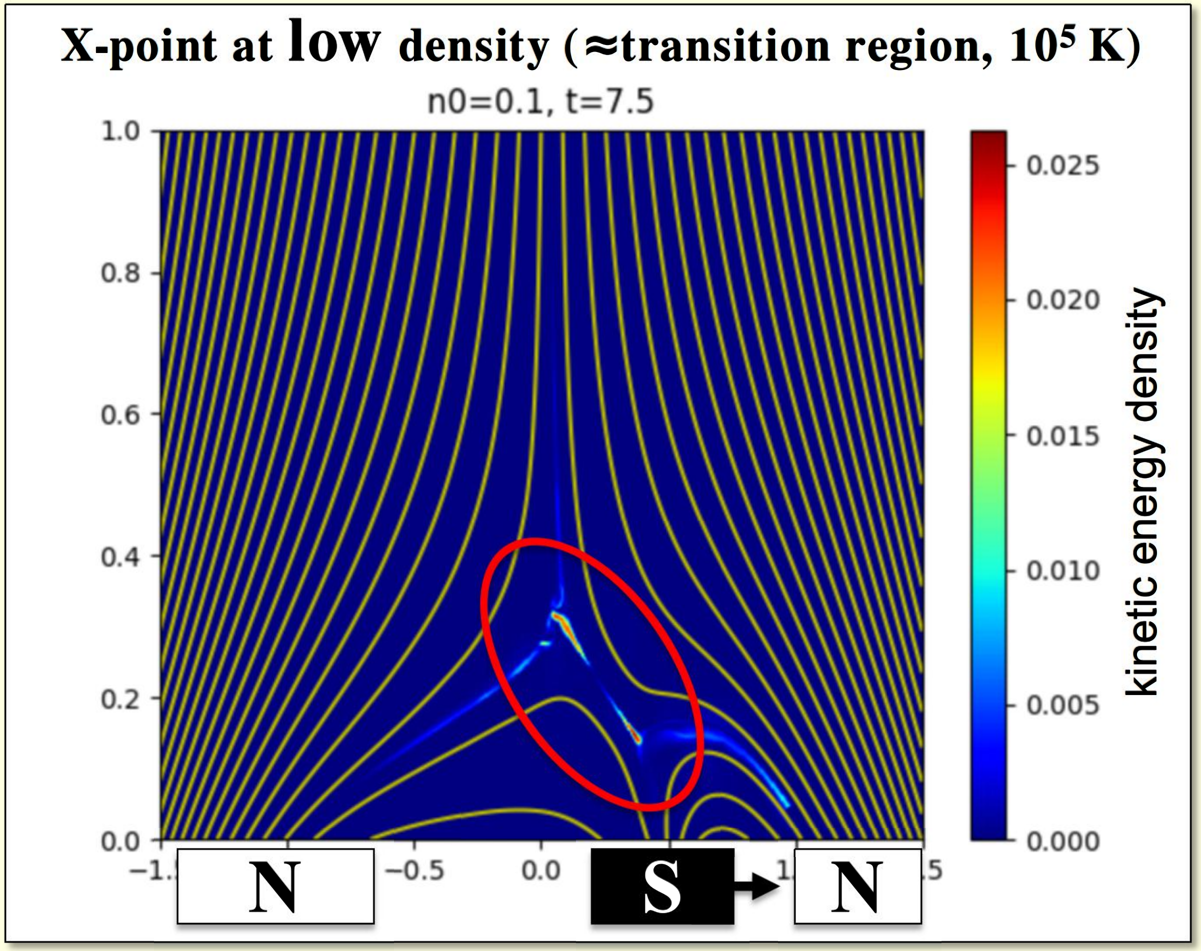
- small “parasitic” polarity **S** is moving from one main polarity **N** to the other
- this stretches an X point that is a candidate location for reconnection
- at the surface this will appear as flux cancellation



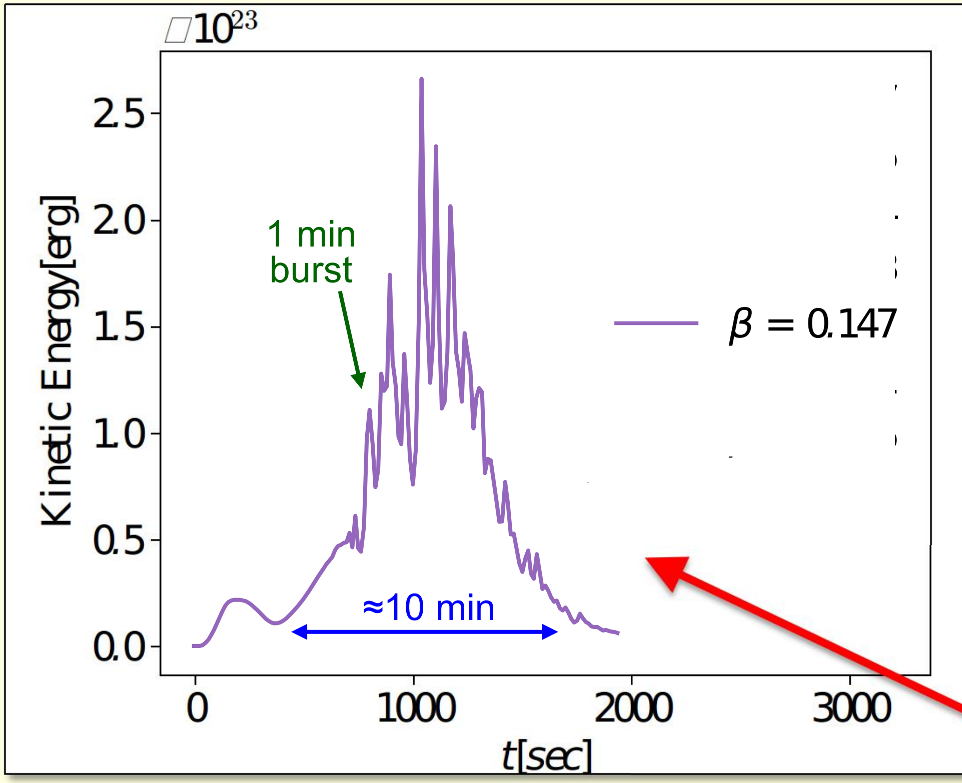
Driving from the solar surface

- X-point trails photospheric flux concentration
- after some photospheric driving
  reconnection sets in and drives a bi-directional jet
  → this is the first model that produces an explosive event by surface driving

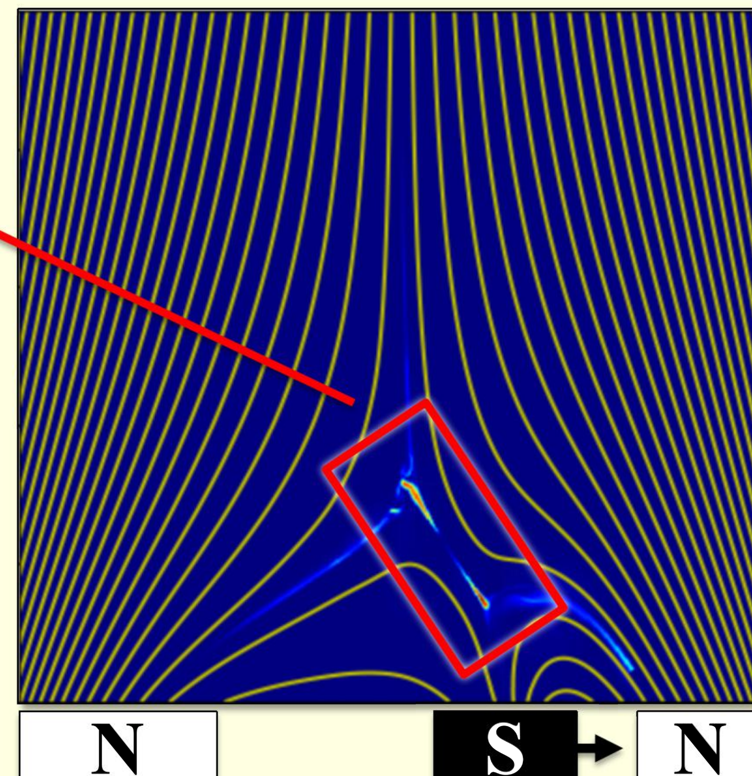
(1)



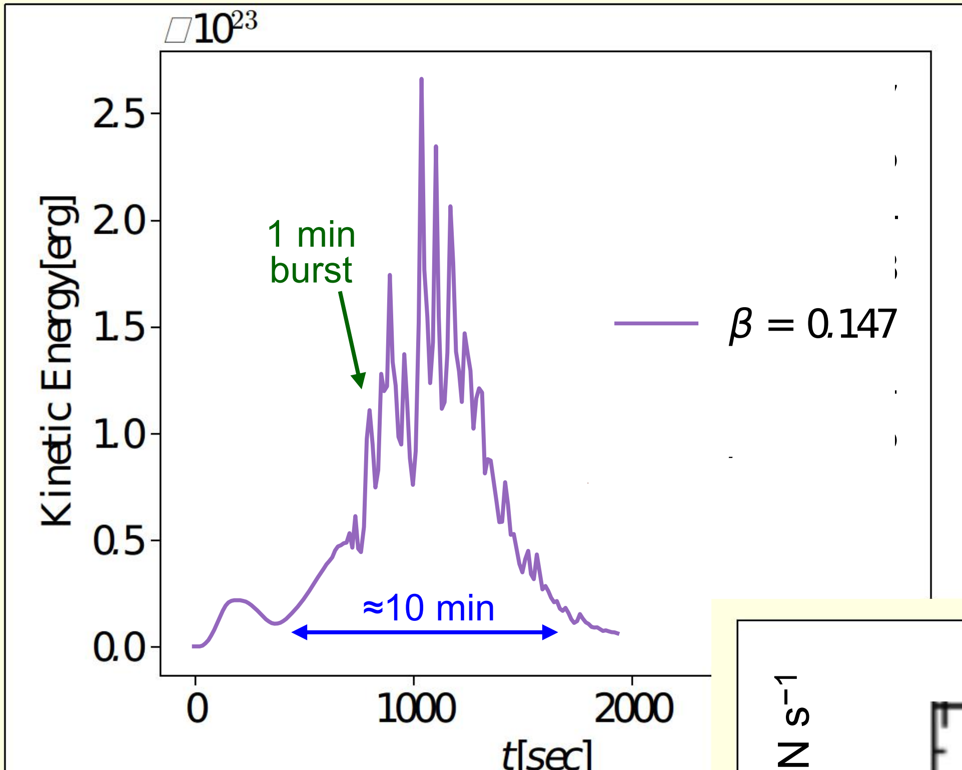
Energy release in TR explosive event



- for case with reasonable plasma-*b*: release of energy in bursts
- overall length is ≈10-20 min
  set by how long we drive, but we can drive only so long before hitting other polarity
- individual bursts of 1-2 min length due to the formation of individual (larger) plasmoids

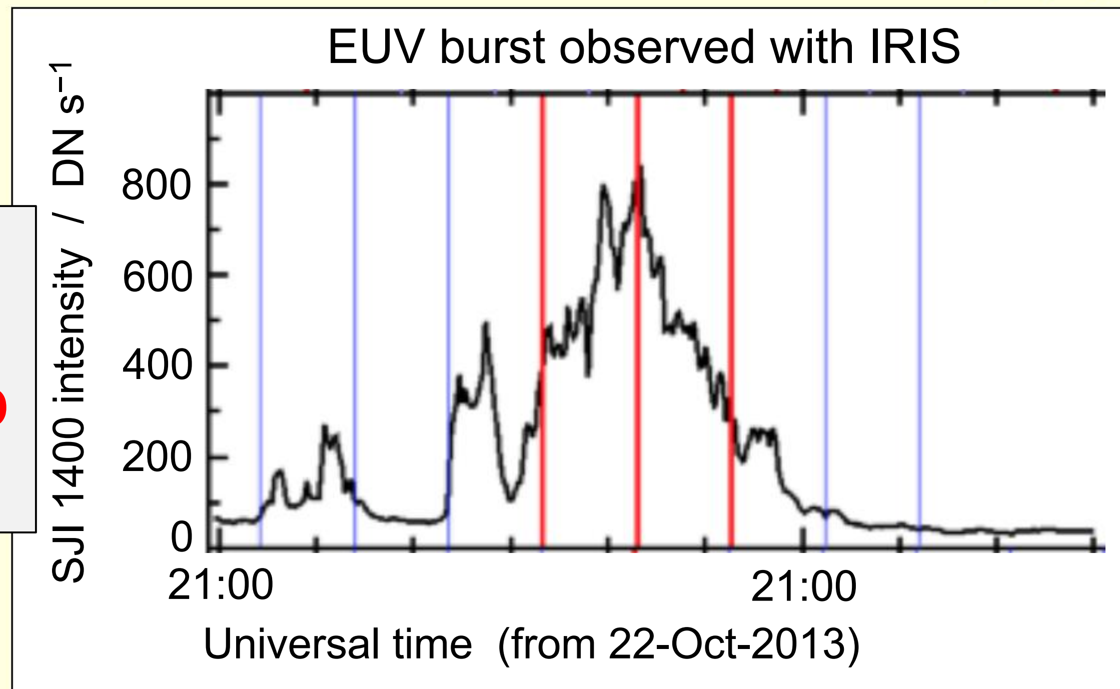


Energy release in TR explosive event

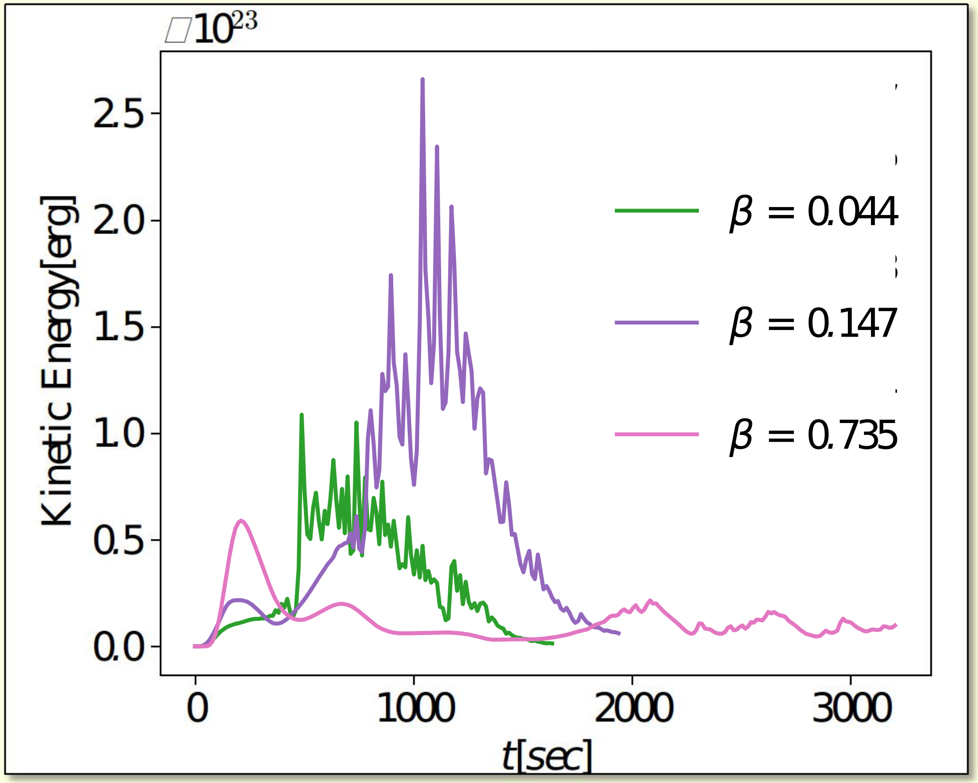


- for case with reasonable plasma-b: release of energy in bursts
- overall length is ≈10-20 min
  set by how long we drive, but we can drive only so long before hitting other polarity
- individual bursts of 1-2 min length due to the formation of individual (larger) plasmoids
- evolution fits to observations ✓ (2)

These, maybe crucial, details of energy injection not yet captured in 3D MHD active region models



Energy release and location of reconnection



- **small plasma-*b*:**

  (reconnection "higher up in the atmosphere")

  – energy conversion starts earlier

  – converted energy is smaller

  no sufficient energy build-up early on

  → **still: more energy/particle**

  → **higher temperature**

- **for higher plasma-*b*:**

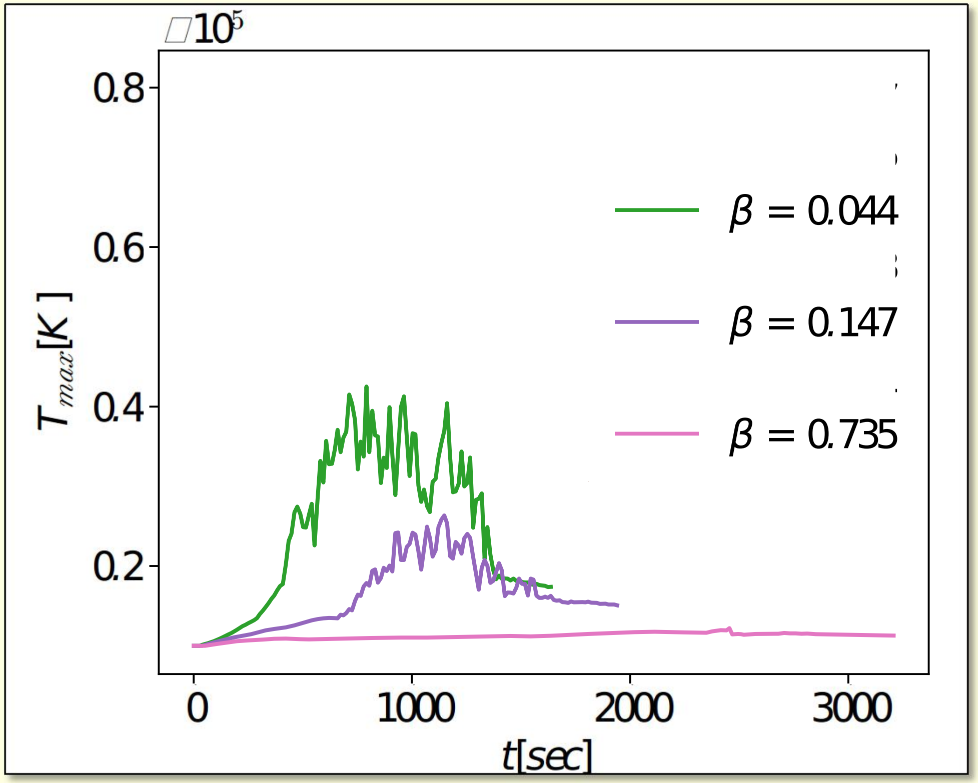
  (reconnection "lower down", in chromosphere)

  – energy conversion starts later (more driving needed)

  – much lower energy conversion

  → **almost no increase in temperature**

Peak temperature and location of reconnection



► **small plasma-*b*:**

(reconnection "higher up in the atmosphere")

− energy conversion starts earlier

− converted energy is smaller

higher up → lower B → less energy available

→ **still: more energy/particle**

→ **higher temperature**

► **for higher plasma-*b*:**

(reconnection "lower down", in chromosphere)

− energy conversion starts later
(more driving needed)

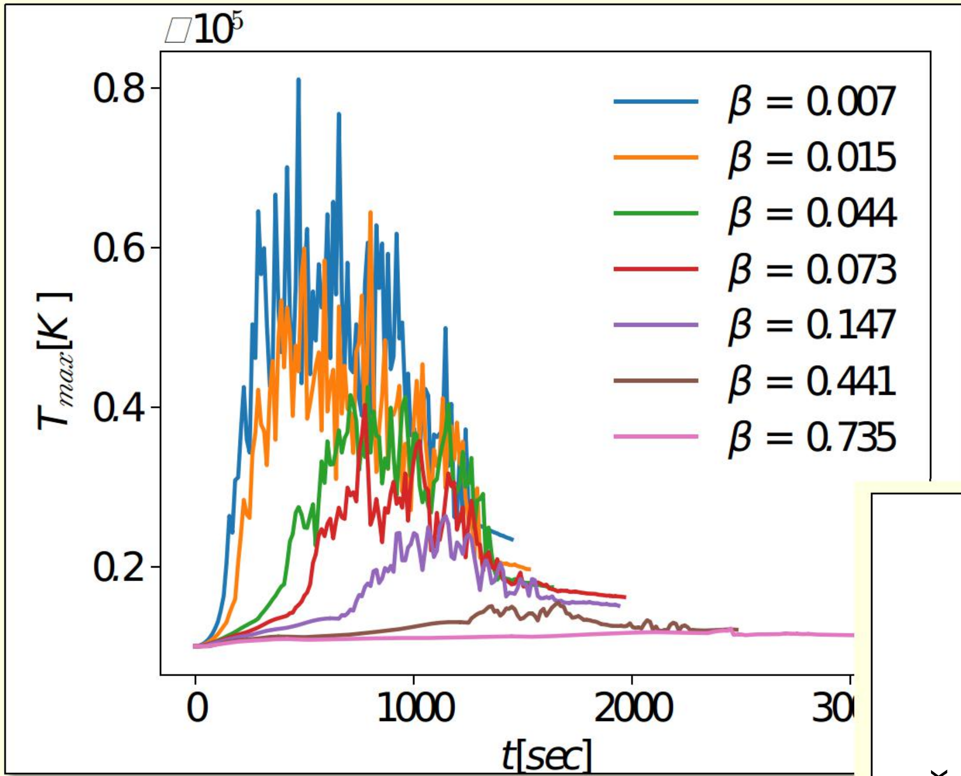
− much lower energy conversion

→ **almost no increase in temperature**

→ this driving cannot produce events in the photosphere and chromosphere (e.g. Ellerman bombs)

(3)

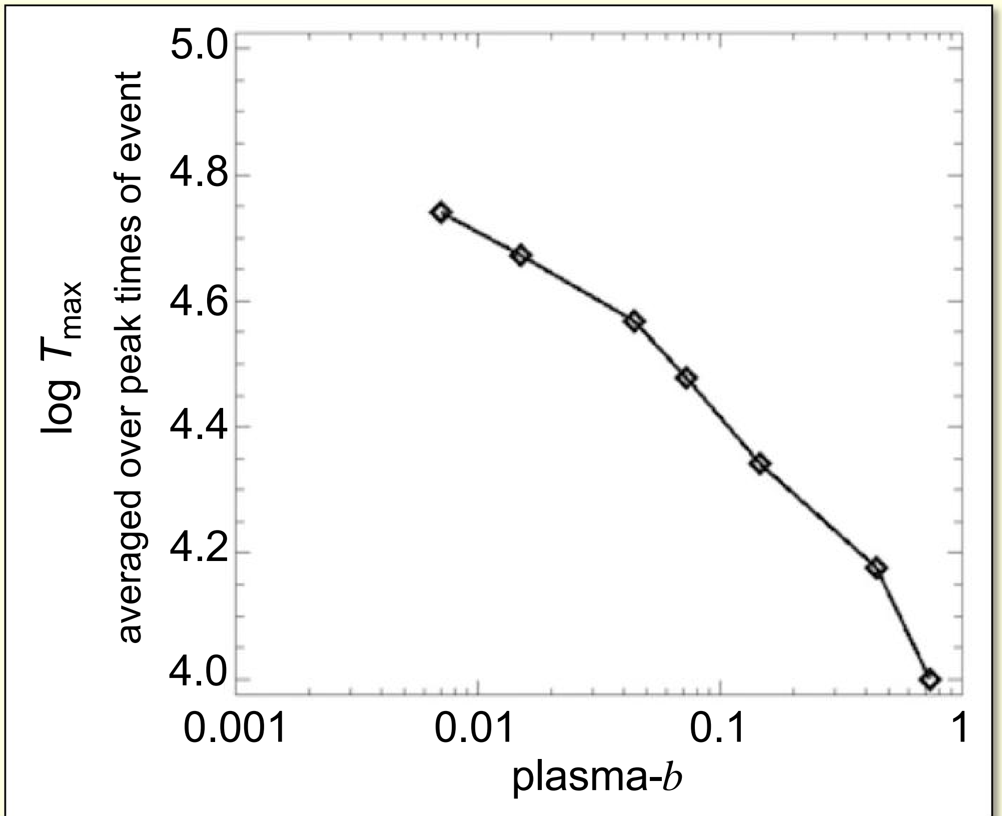
Peak temperature and plasma-*b*



► for reasonable plasma-*b* (>10^{-3}) the temperature will stay below 10^5 K

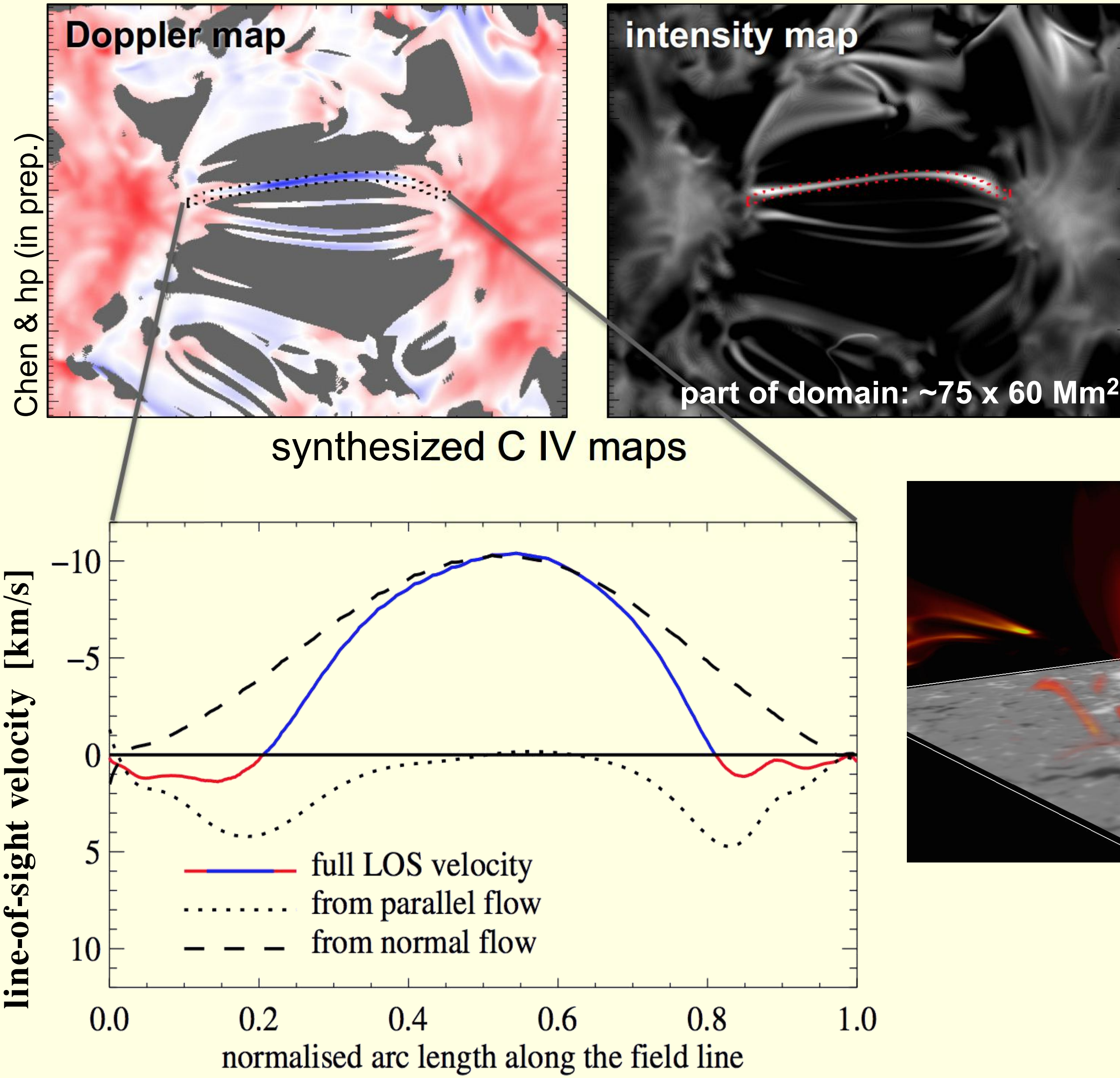
► this could explain why we do not see explosive events and EUV bursts at coronal temperatures

(4)



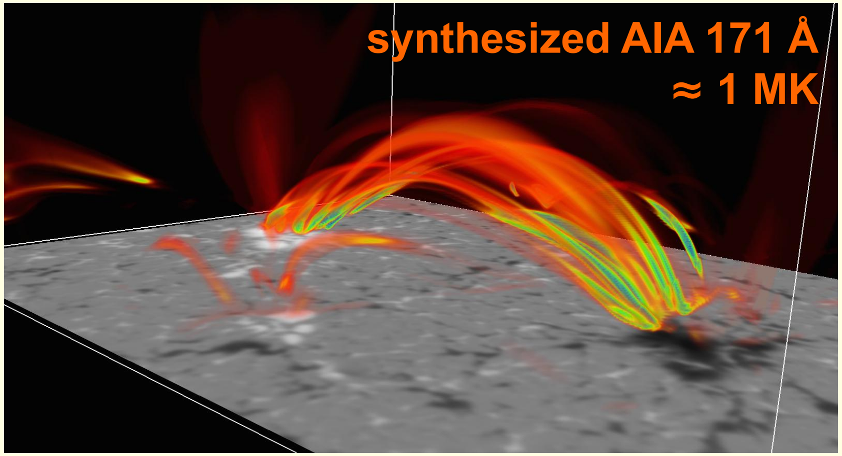
Mass cycle

Rising magnetic field and draining loop

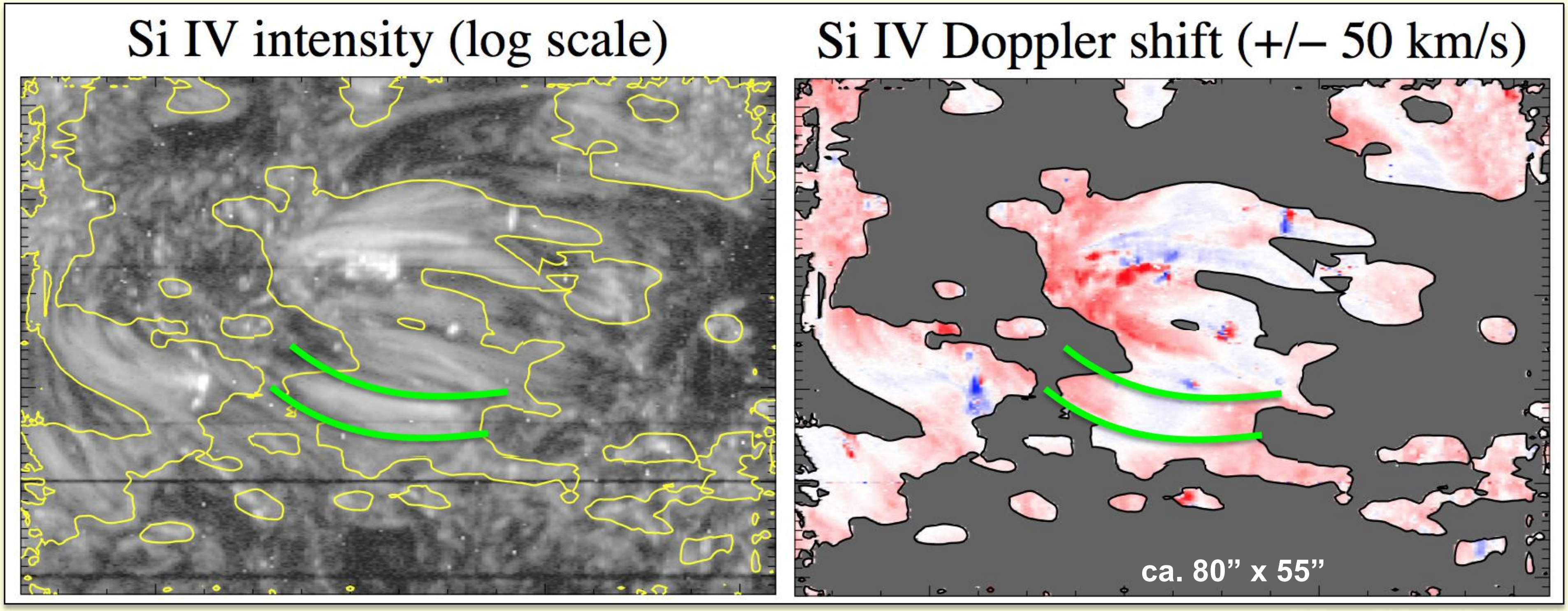


model prediction for Doppler patterns:

- ► middle of loop blue:
  → rising magnetic field
- ► loop footpoints red:
  → draining of plasma



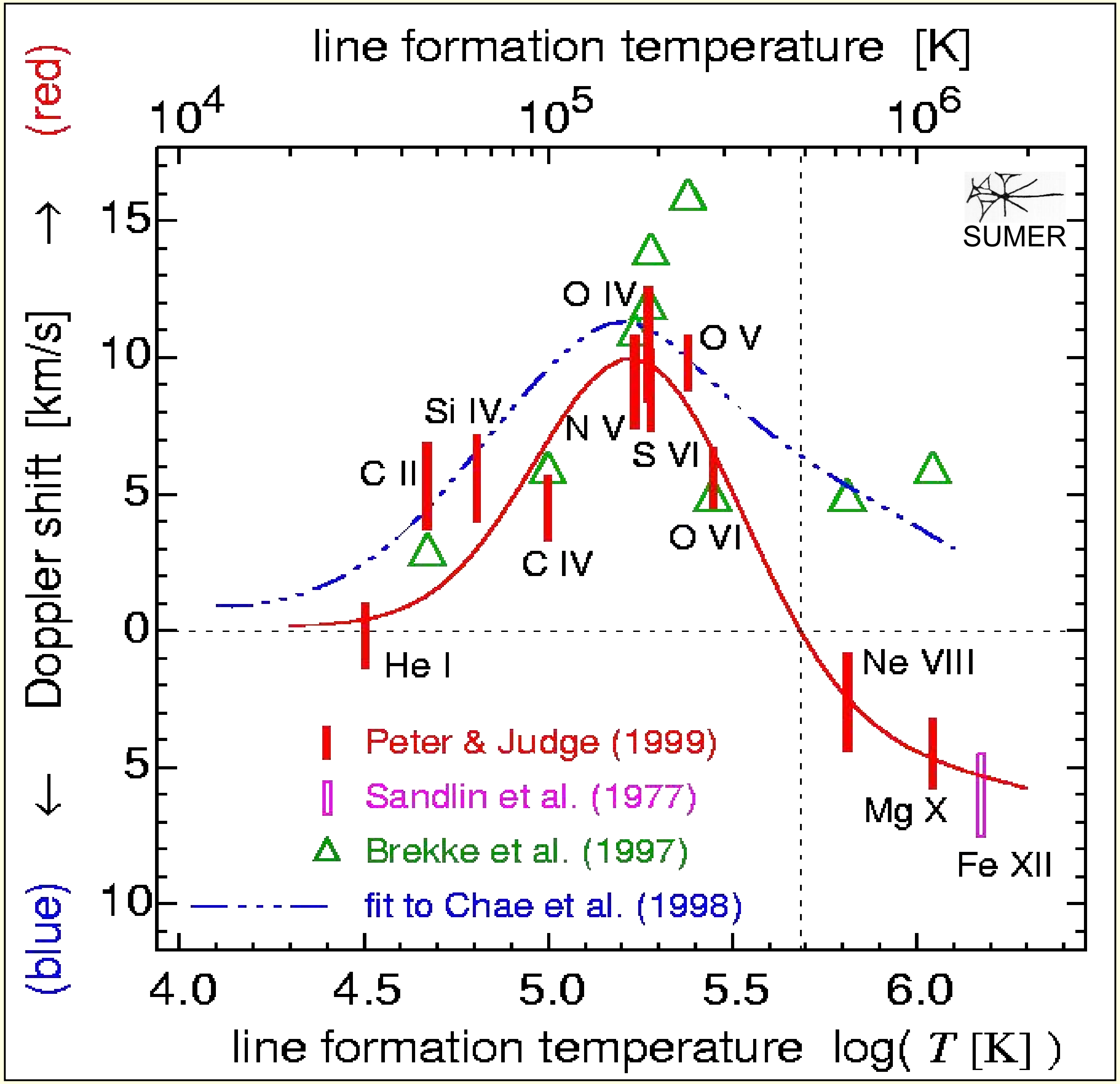
Emerging loops seen with IRIS



Chen & hp (in prep.)

pattern of
blue loop center and
red footpoints
is also found in observations !

Mass cycle (in the quiet Sun)



hp & Judge (1999) ApJ 522, 1148

observations:

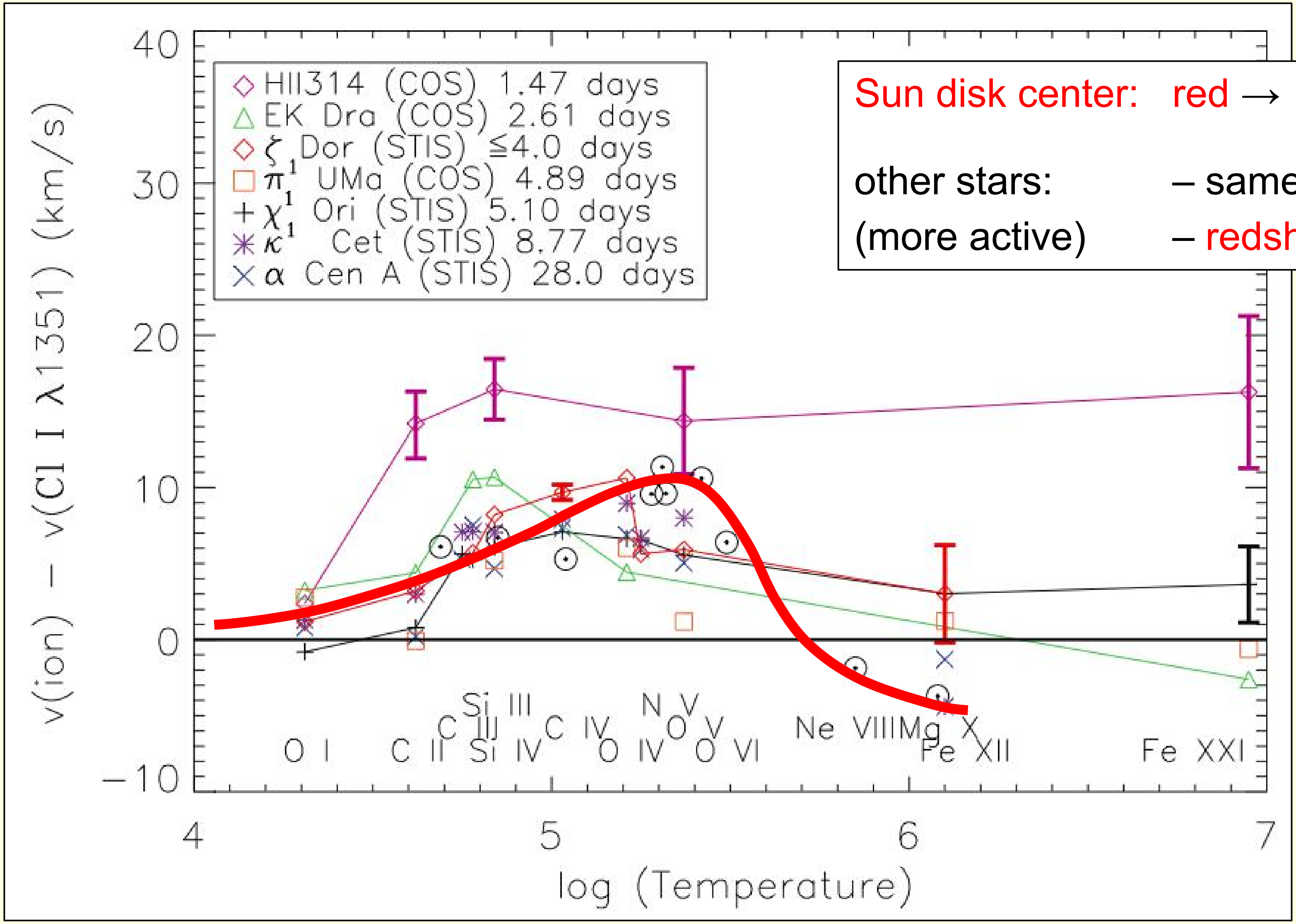
mean quiet Sun Doppler shifts at disk center

→ what causes the redshifts ?

→ what causes the blueshifts ?

→ where does the mass come from ?

Doppler shifts in solar-like stars



Sun disk center: red → blue

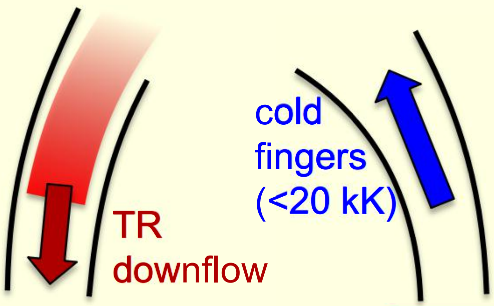
other stars: – same in TR

(more active) – redshifts at high *T*

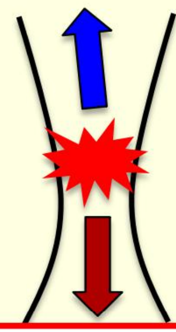
Linsky et al (2012) ApJ 754, 69

Average mass cycle understood (?) by 3D models

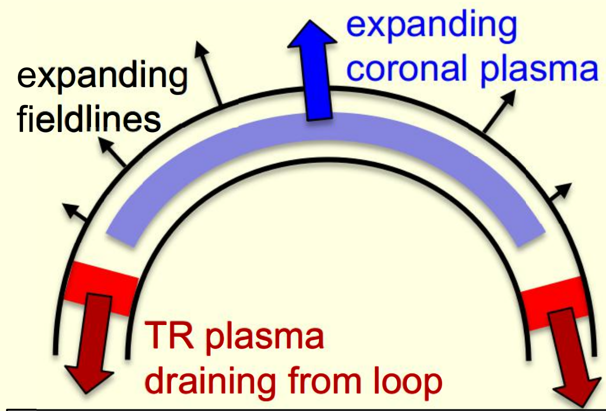
- ► cold fingers reaching into corona



- ► heating in TR: local pressure increase

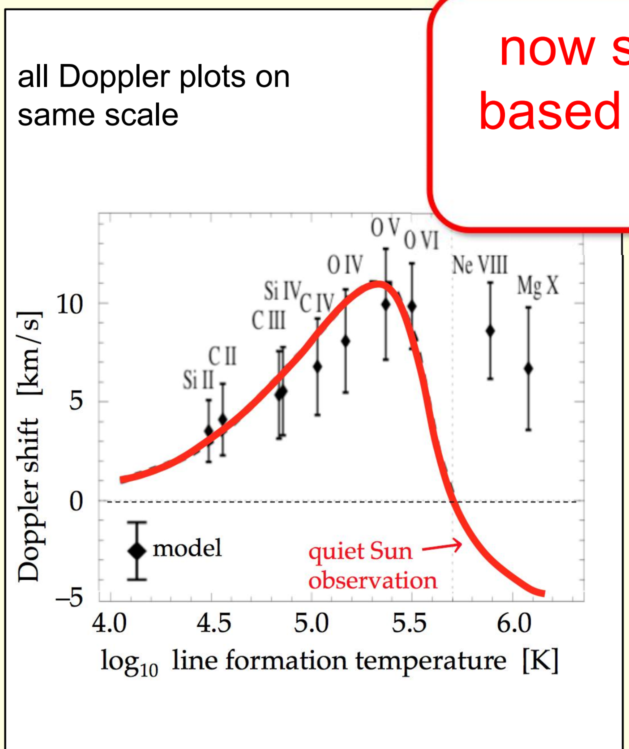


- ► emerging magnetic field:

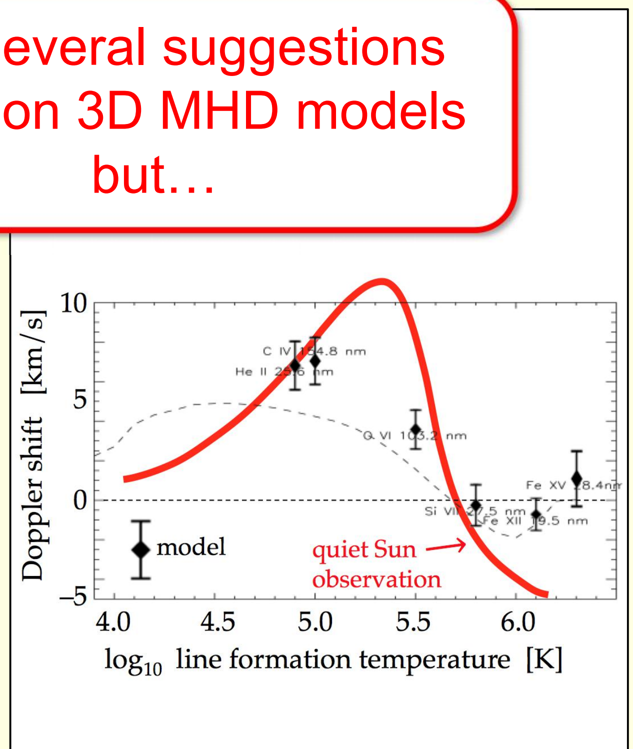


all Doppler plots on same scale

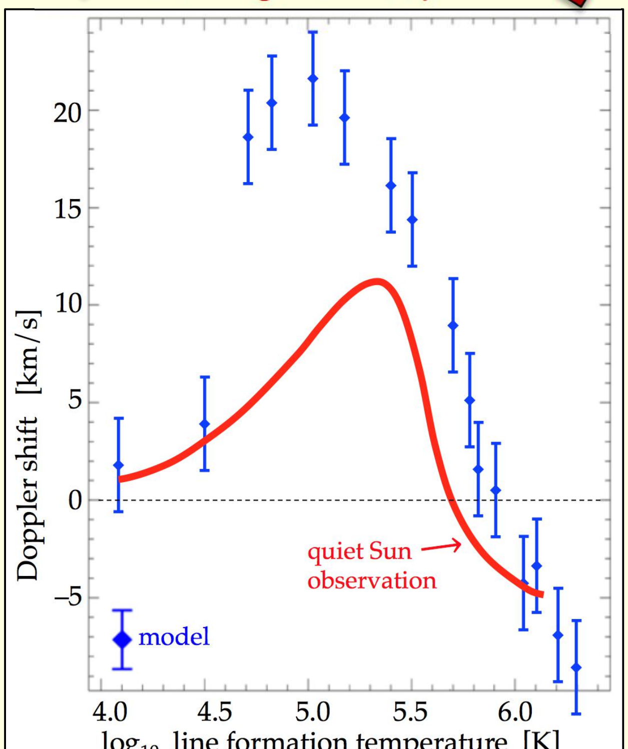
now several suggestions based on 3D MHD models but…



Zacharias, Bingert, hp (2011) A&A 531, A97
hp, Gudiksen, Nordlund (2006) ApJ 617, L85

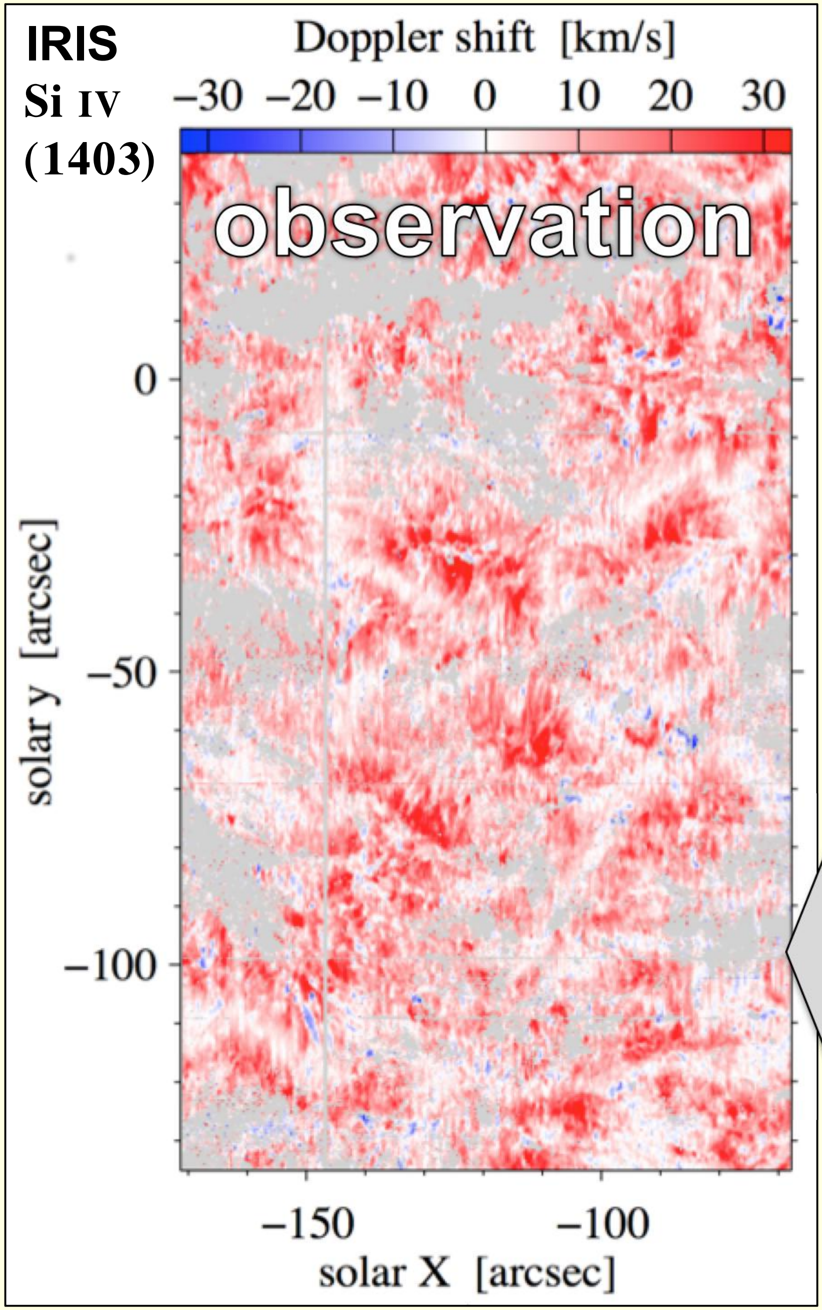


Hansteen et al. (2010) ApJ 718, 1070



Bourdin, Bingert, hp (n prep.)
Chen, Bingert, hp (in prep)

Spatial distribution of Doppler shifts: Obs. & model

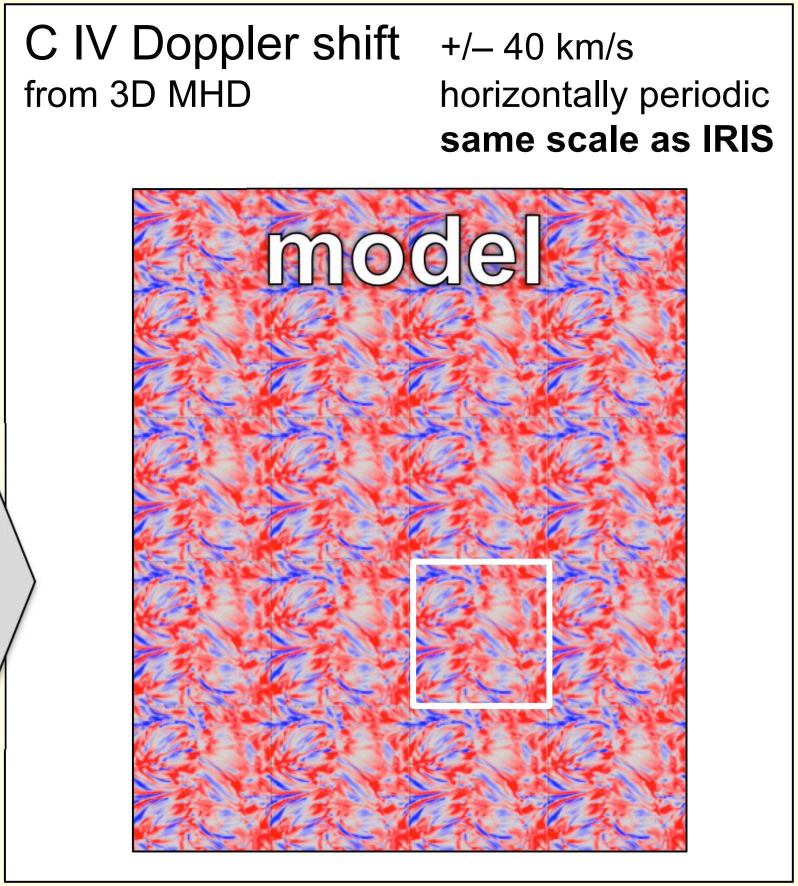


hp et al (2014) in prep

…but: spatial structure of Doppler shifts does not really match observations…

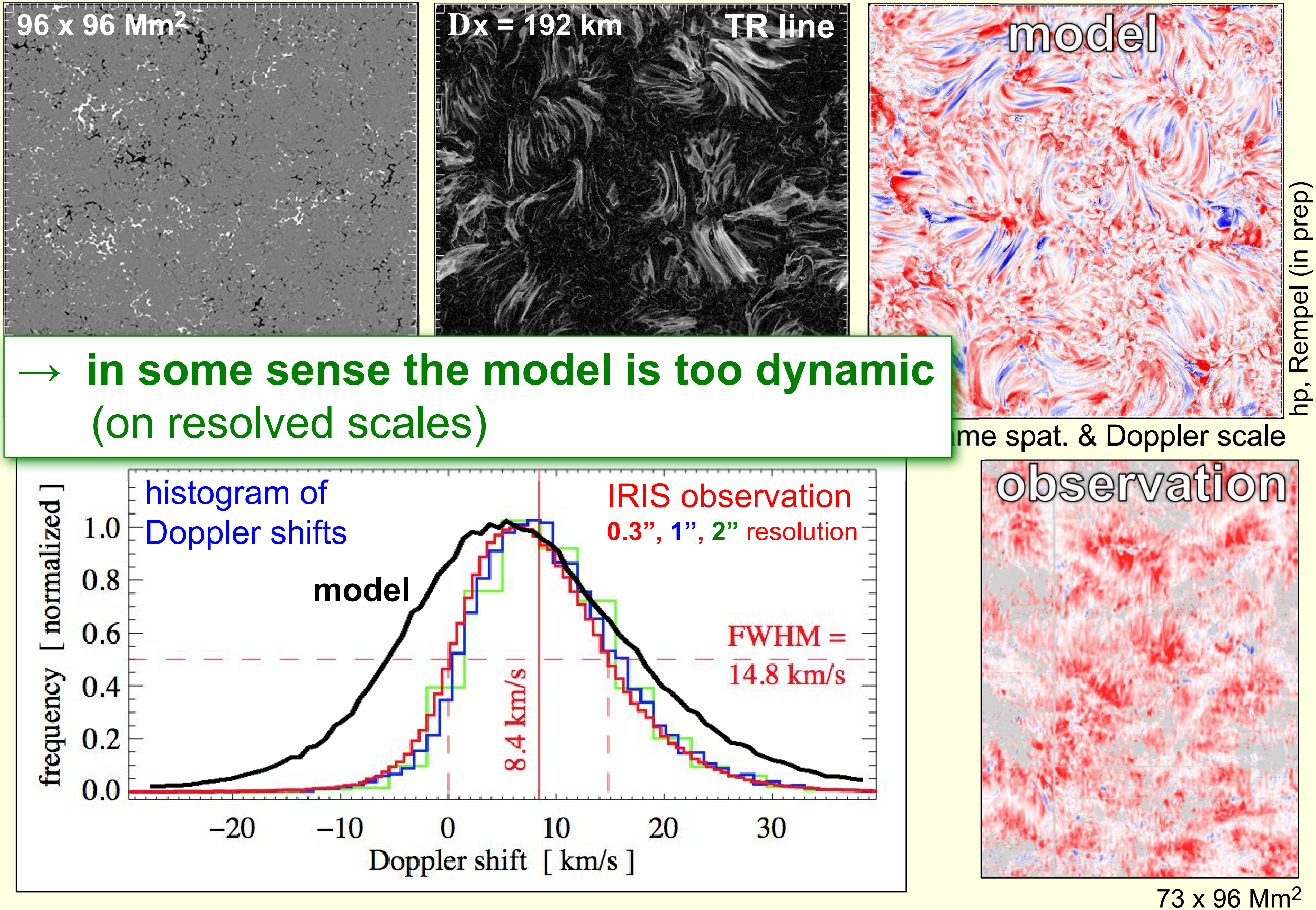
→ because large-scale (supergranular) structure is missing ?

same spatial scale



Hansteen et al (2010) ApJ 718, 1070

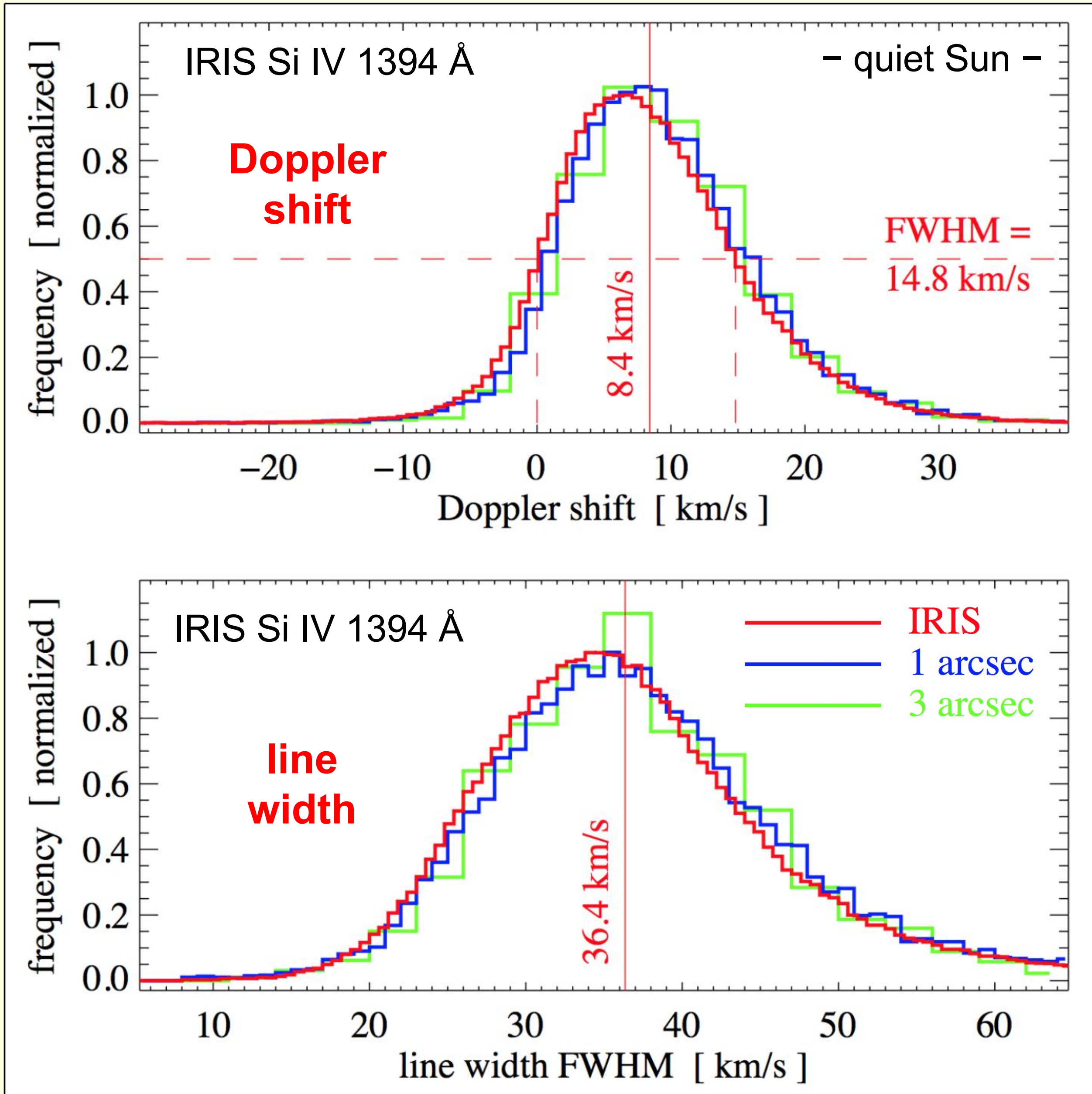
Model including super-granulation



→ **in some sense the model is too dynamic**
(on resolved scales)

line width

Resolved and non-resolved velocities in the QS



- resolved motions: in TR mostly

  $v_D \simeq$ **0 ... 15 km/s**

  (almost no redshifts!)

(independent of spatial resolution at currently observable scales)

- non-resolved motions: broad distribution

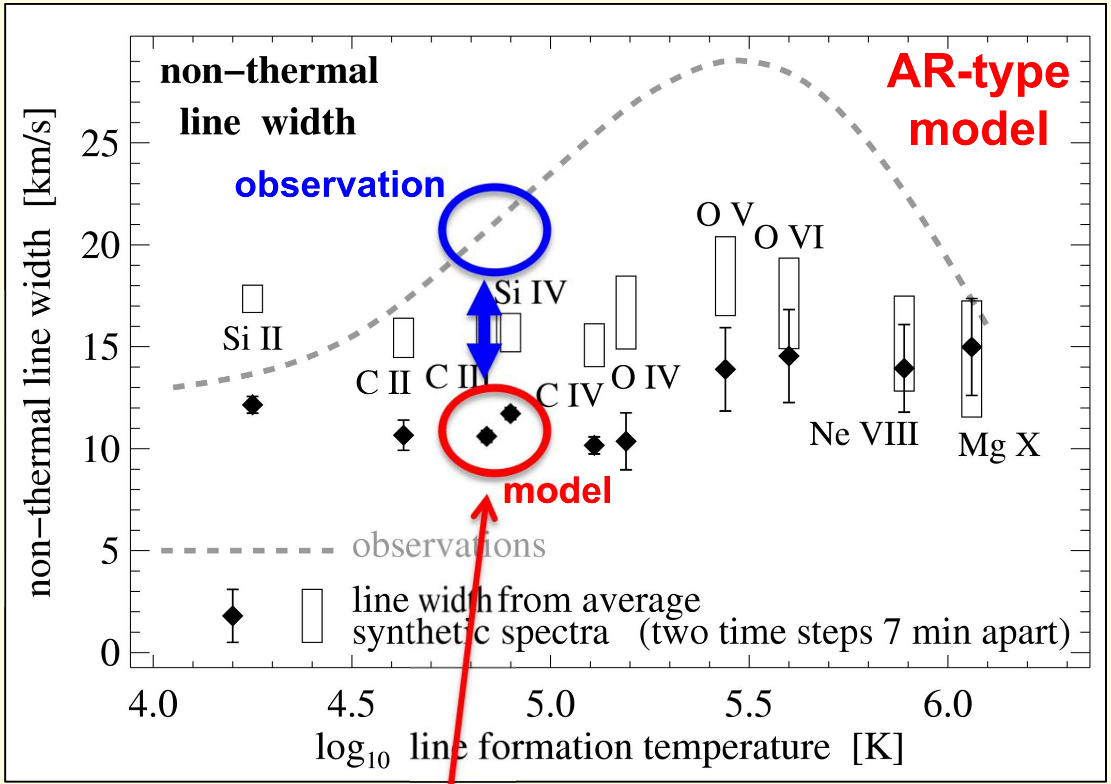
  $v_{nt} \approx$ **20 ... 40 km/s**

remember:
sound speed @10^5 K / Si IV:
$\simeq$ 50 km/s

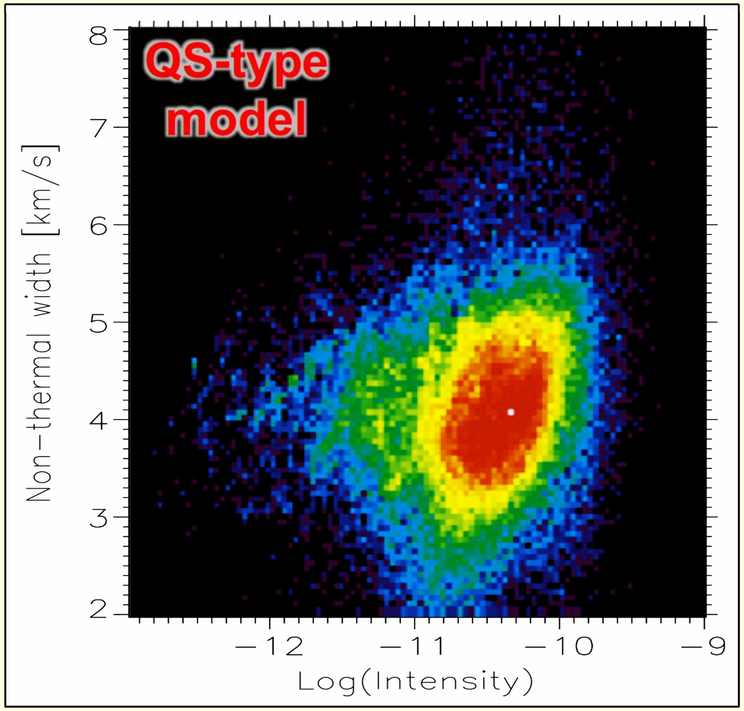
Average line width

- line widths of current models are significantly underestimating the non-thermal width of TR lines

→ in some sense the model not dynamic enough



hp, Gudiksen & Nordlund (2006)
ApJ 638, 1166



at ≈10^5 K:
observation: w_{nt} ≈ 20 km/s
models: ≈ 5… 10 km/s

De Pontieu, McIntosh, Martinez-Sykora, hp, Pereira (2015)
ApJ 799, L12

Loop widths

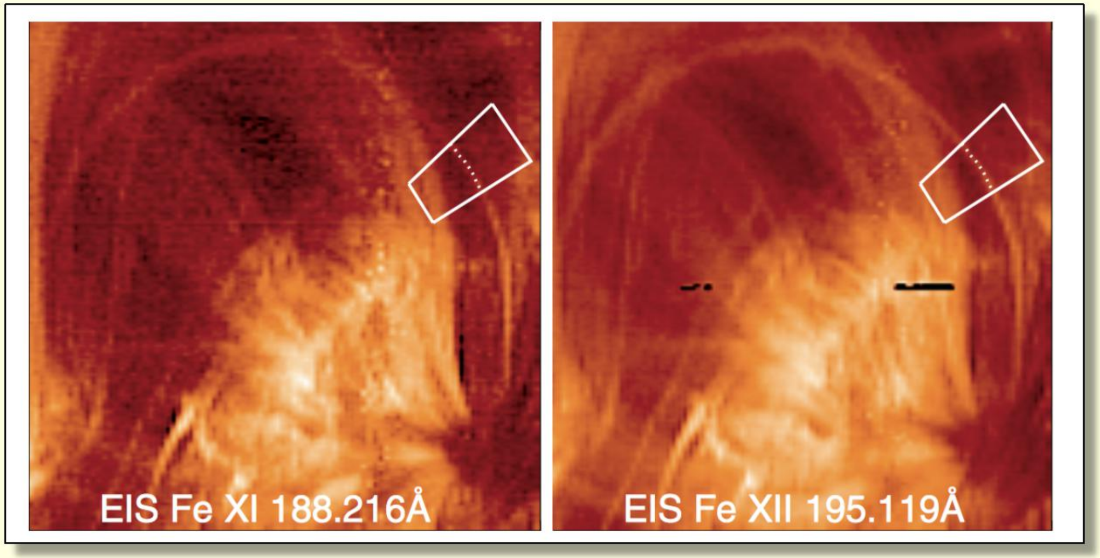
Thin strands in coronal loops seen by AIA & EIS

20 isolated active region loops
with EIS/Hinode and AIA/SDO:
(Brooks et al. (2012) ApJ 755, L33)

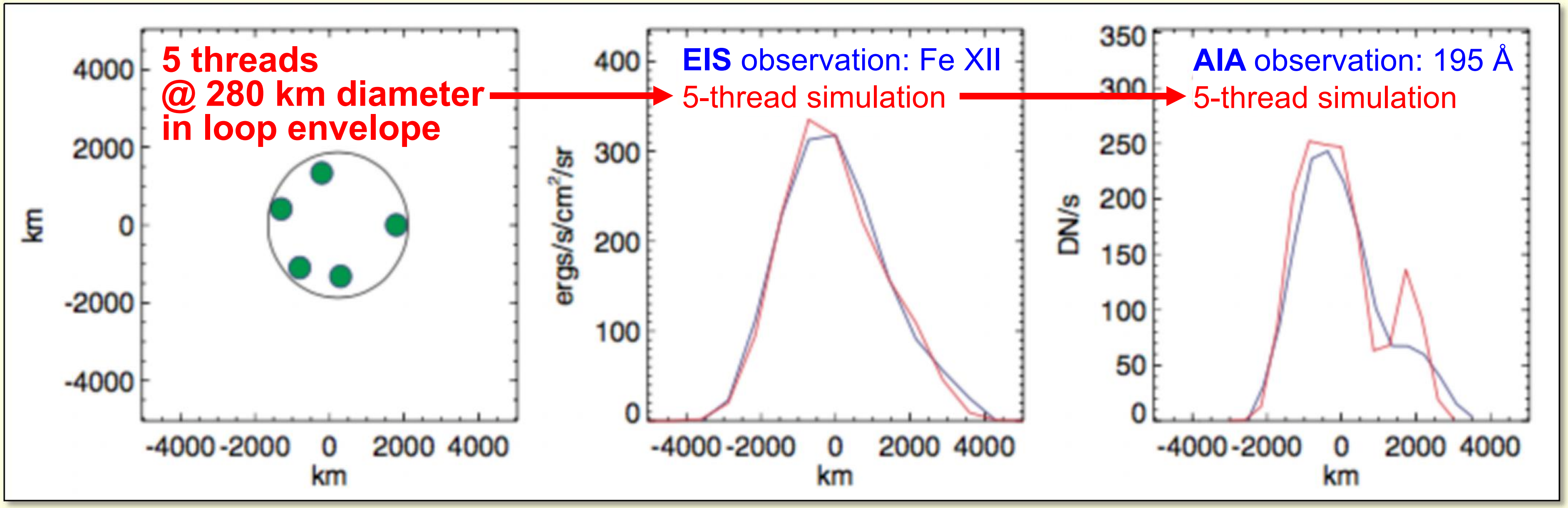
► a few (3) loops consist of single monolithic stand: > 300 km

► most (17) loops made up by several (3–5) strands each with diameters from ≈ **300 km to 500 km**

→ **close to resolved!**

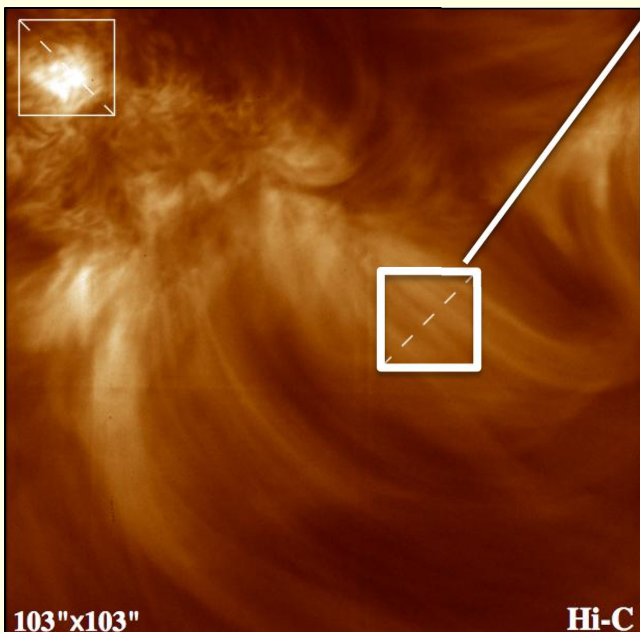


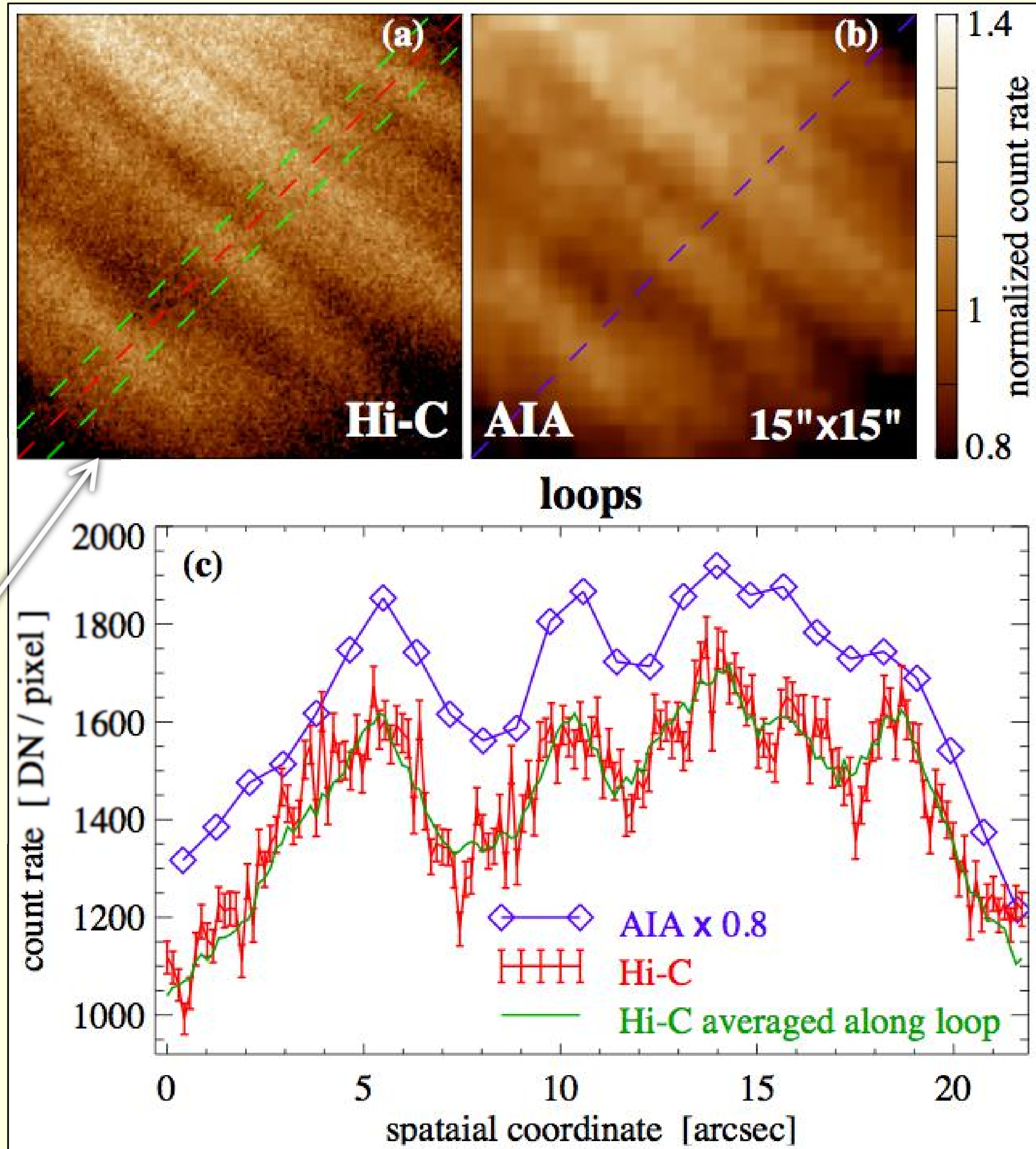
Brooks et al. (2012) ApJ 755, L33



Thick coronal loops seen by Hi-C

- ► Hi-C sees thin structures: (450 Mm; Brooks et al. 2013, ApJ 772, L19)
- ► **Hi-C sees also thick loops showing no substructure**
  → width > 2 Mm FWHM
  (hp et al. 2013, A&A 56, A104)
- ► clearly, there is a broad distribution of structure widths

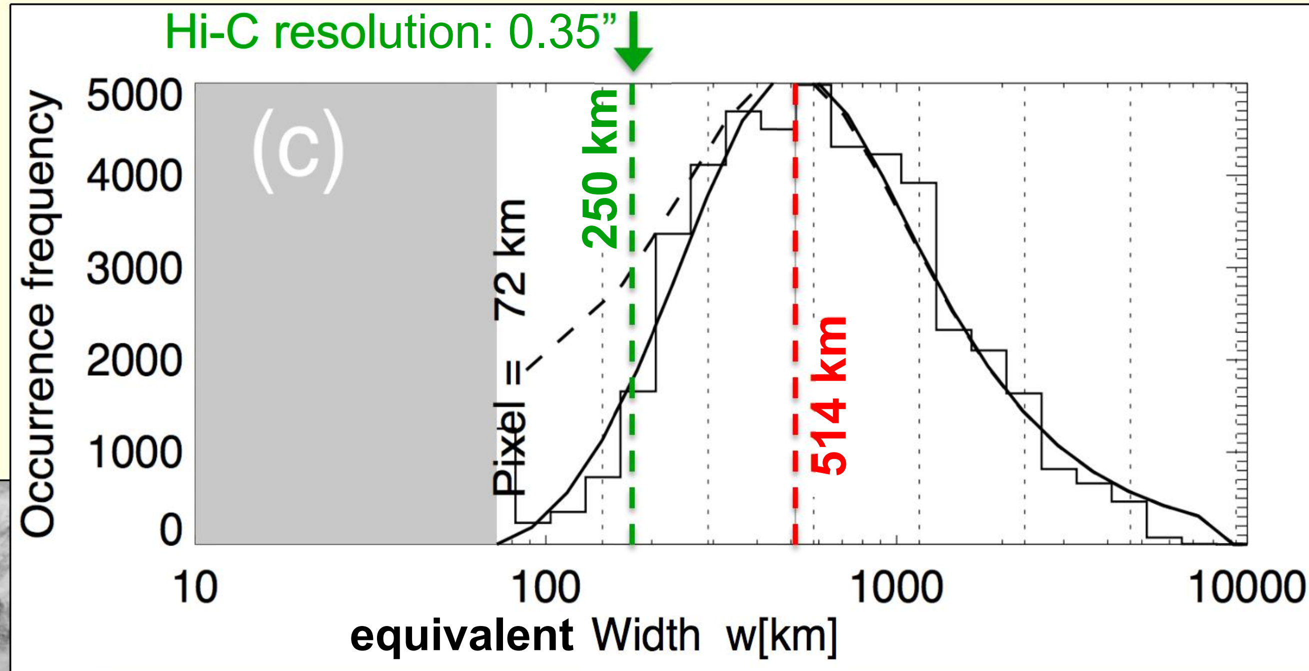




hp, Bingert, Klimchuk et al. 2013, A&A 56, A104

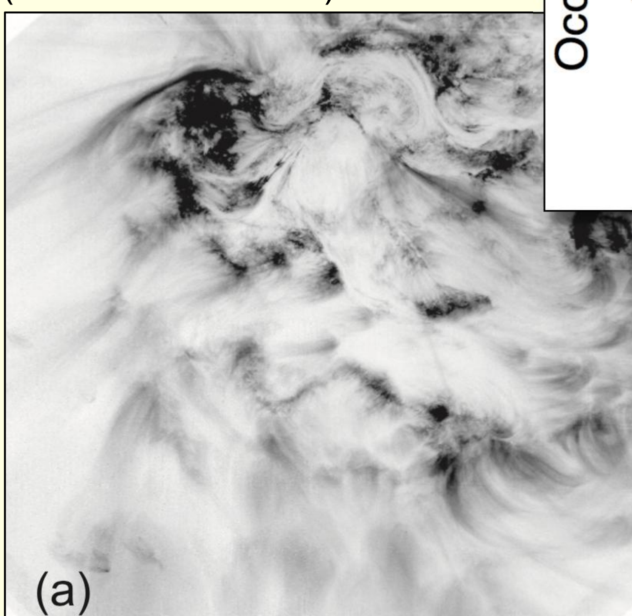
Loop widths seen by Hi-C

- [there might be a minimum width of cornal loops]
- **there is a tail of thick coronal loops (up to ≈ 2 Mm** ; above probably complex structures)

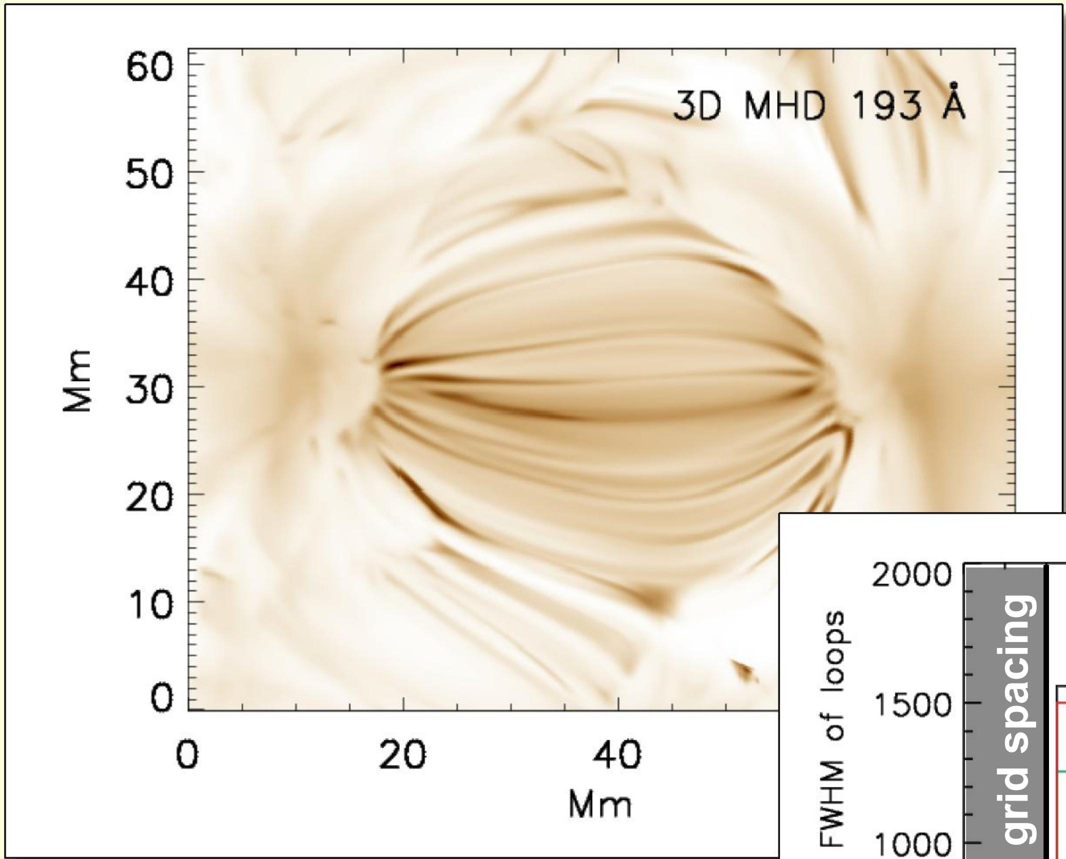


Aschwanden, hp (2017) ApJ 840, id.4

Hi-C 193 Å
(inverse color scale)



Width of coronal loops in 3D MHD AR model



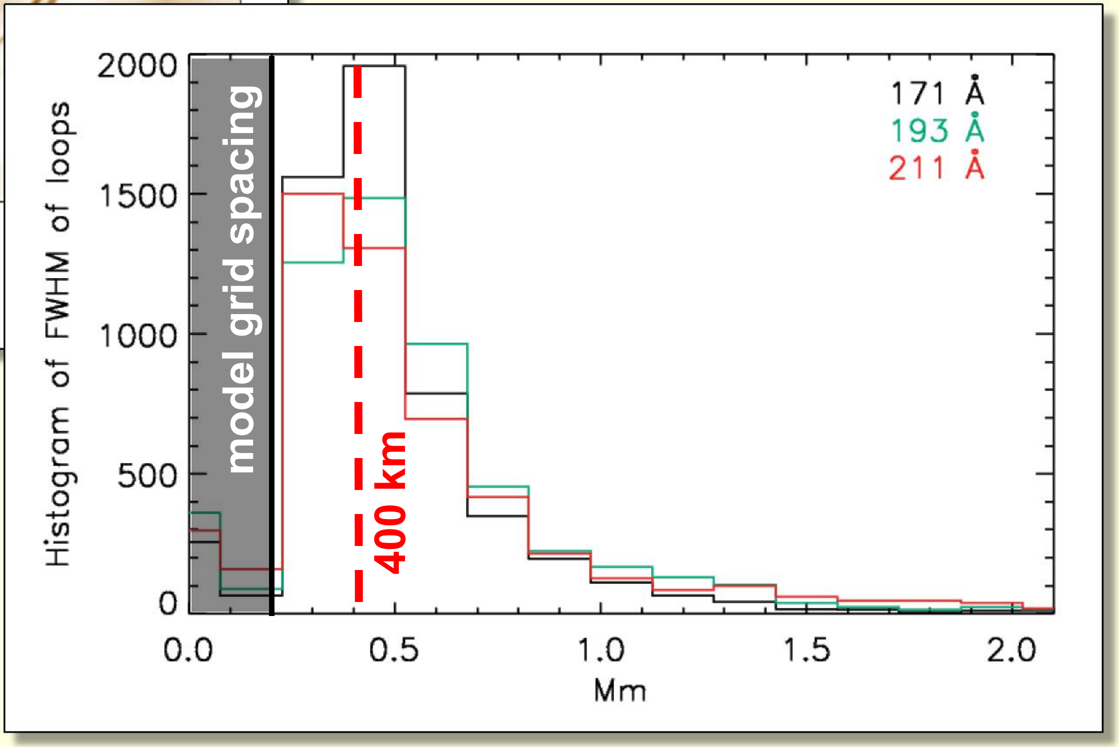
data from Chen, hp (2015) A&A 581, A137

- ► loops mostly as fine as simulation allows

  (also a feature in other 3D models)

- ► mostly, high-res. simulations do *not* show “thick” loops

  (with exceptions, e.g. Bingert, hp, 2012, A&A 548, A1)



are models not dissipative enough?

QS transition region structure

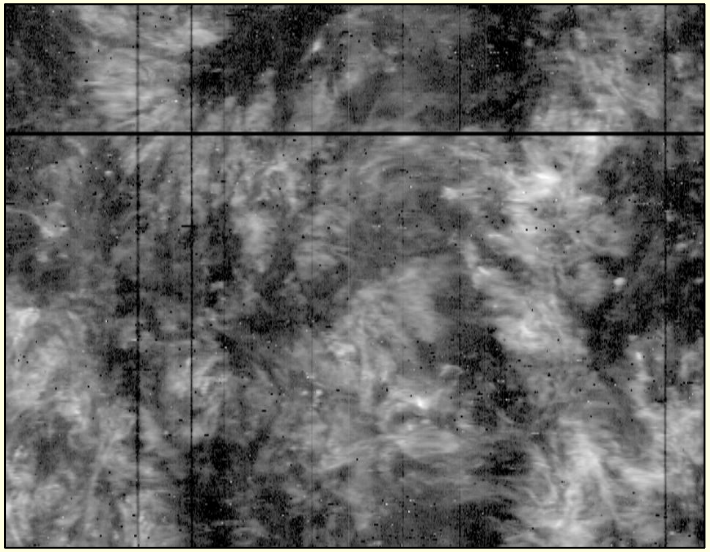
observation (IRIS Si IV)

(spat.scale: 250 km x 125 km)

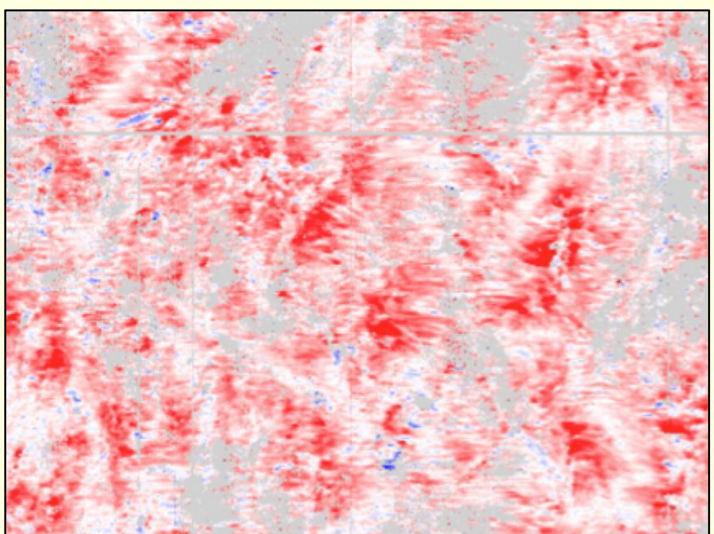
model (TR line)

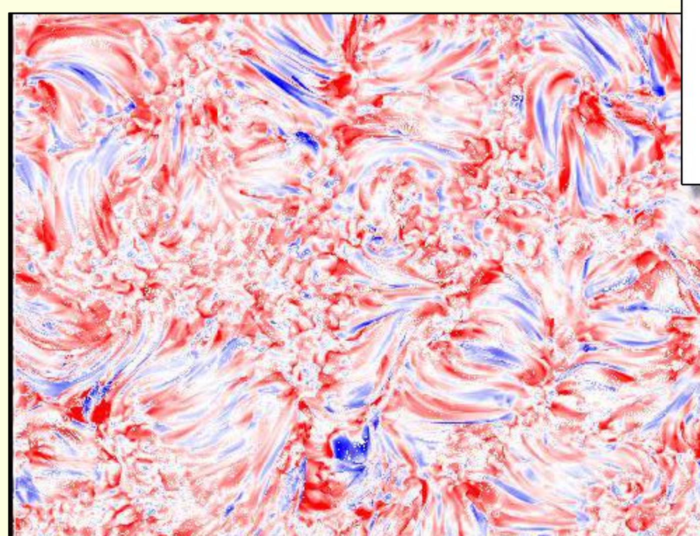
(horiz. grid spacing: 192 km x 192 km)

line intensity



Doppler shift





the real Sun

− is more fuzzy
(spicules?)

− shows only redshift in QS

the model

− has thin loops ("1 pxl wide")

same spatial scale

same Doppler range (±30 km/s)

hp, Rempel (in prep)

field of view: 73 x 96 Mm^2

Posing the problem

- models fail to get resolved motions right
  - → too dynamic on scales $\gtrsim$1 Mm
- models fail to reproduce observed non-thermal line widths
  - → not dynamic enough on scales $\lesssim$1 Mm
- models do not predict correct (finite) cross-sectional width of loops
  - → what could cause cross-field structures?
- models predict structures to be (much) finer than in observations
  - → models are not dissipative enough

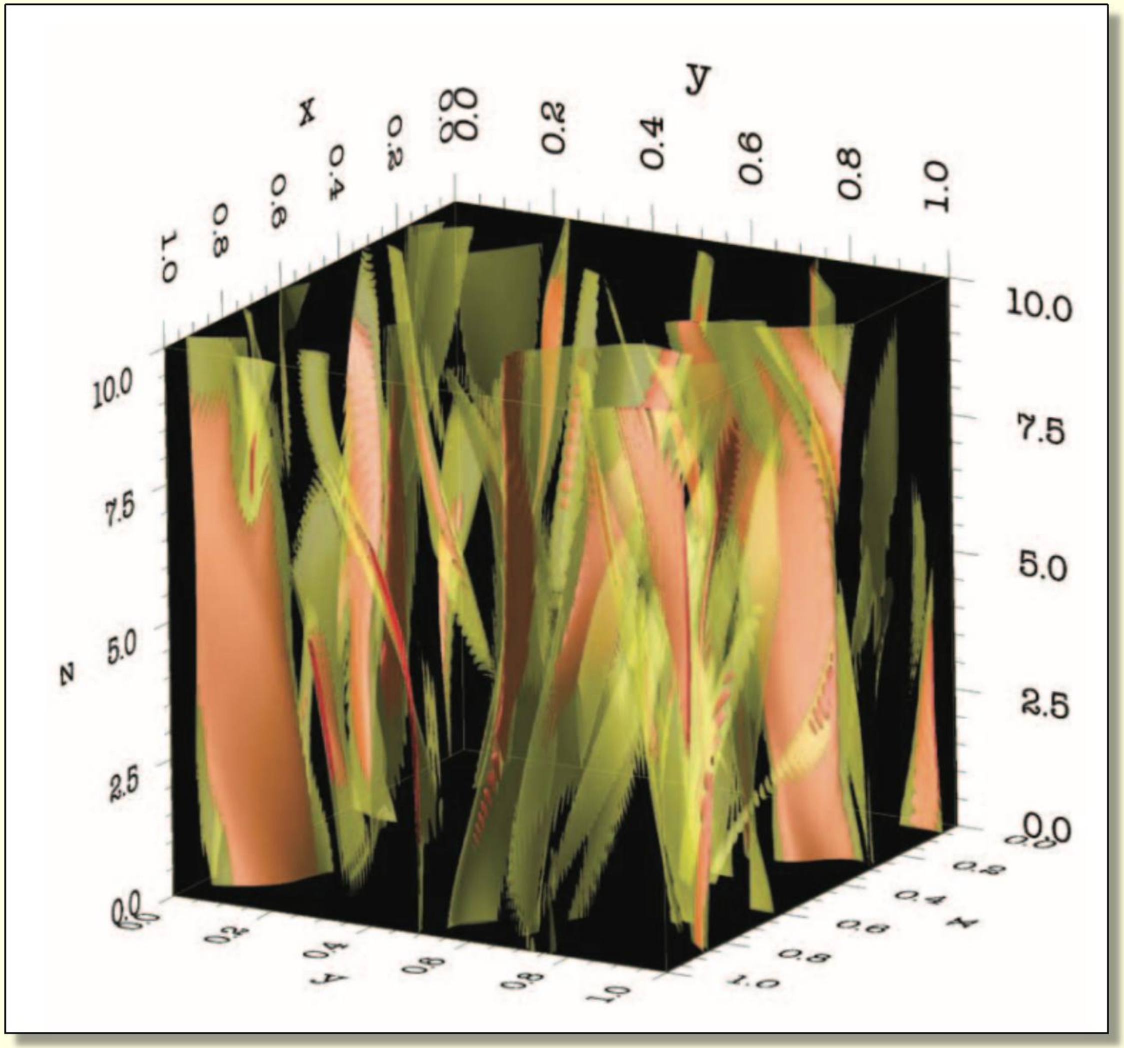
→ **could these problems be related ?**

→ **could MHD turbulence be an answer to both**

remember: current 3D MHD models of ARs or quiet Sun/plage do not have a resolution sufficient to resolve internal loop dynamics / turbulence)

MHD turbulence in loops

MHD turbulence in a Parker-type braiding scenario



current sheets in a 3D reduced MHD simulation of fieldline braiding
Rappazzo et al. (2008) ApJ 677, 1348

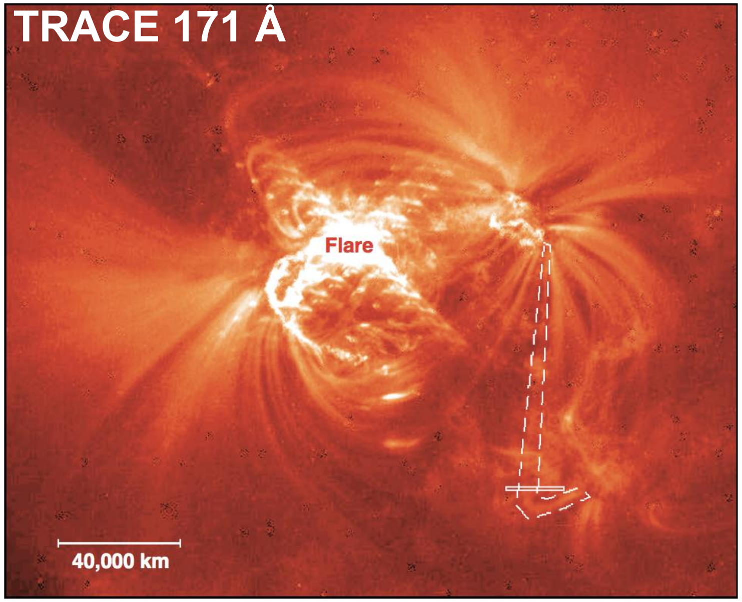
- driving from the photosphere
- current sheets aligned with magnetic field
- no obvious cross-field scale in these experiments
- typical other cross-field scales:
  - individual current sheets
  - gyration radius
  - etc

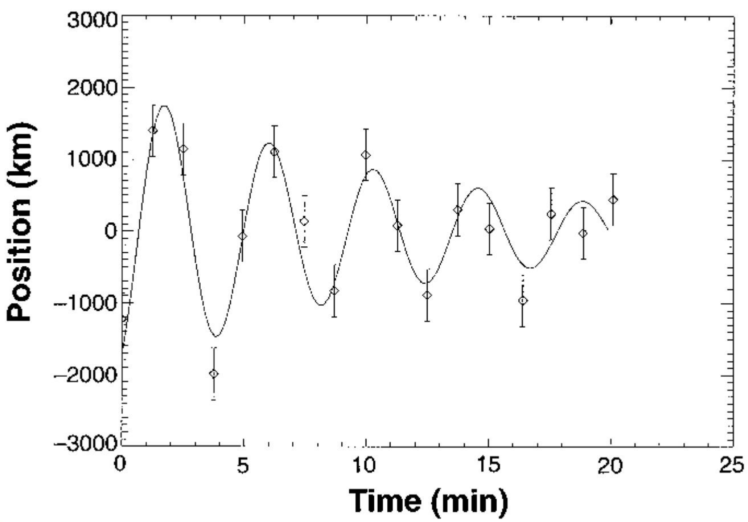
  are much too small (< m range)

Effective resistivity in the corona

first report of oscillation after flare

Nakariakov et al. (1999) Science 285, 862





from coronal loop oscillations:

- period → magnetic field
- damping time → magnetic resistivity

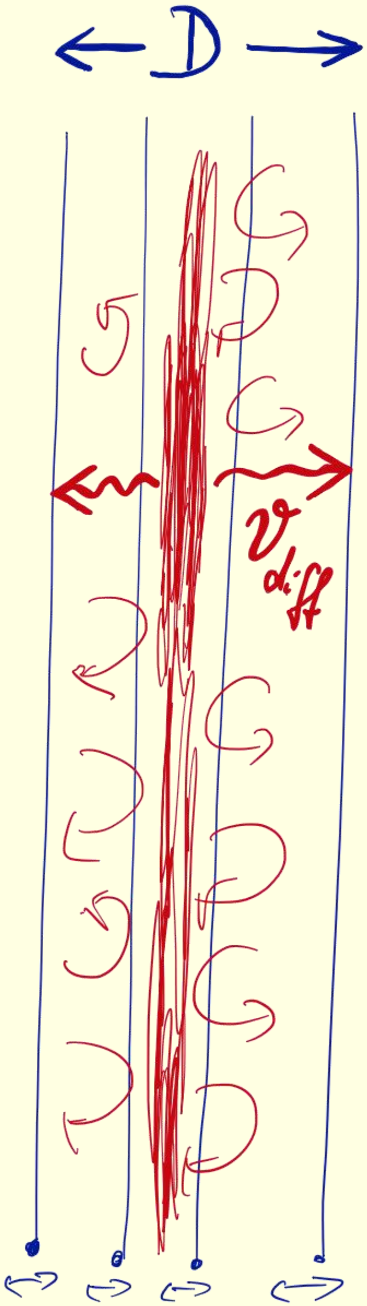
Nakariakov et al. (1999):

(effective)
Lundquist number: $S := \frac{L\, v_A}{\eta} \approx 10^{5.0\ldots5.8}$

→ (effective) resistivity: $\eta_{\mathrm{eff}} \approx 10^{8\ldots9}\ \mathrm{m}^2/\mathrm{s}$

(L = 100 Mm; n=10^9 cm^{-3}, B=10 G → v_A = 1000 km/s)

Diffusion across fieldlines



- assume:
  - heating occurs along "single" thin thread i.e. current sheet along a fieldline
  - creates a thin loop
  - non-thermal motions represent the turbulent motions within the loop

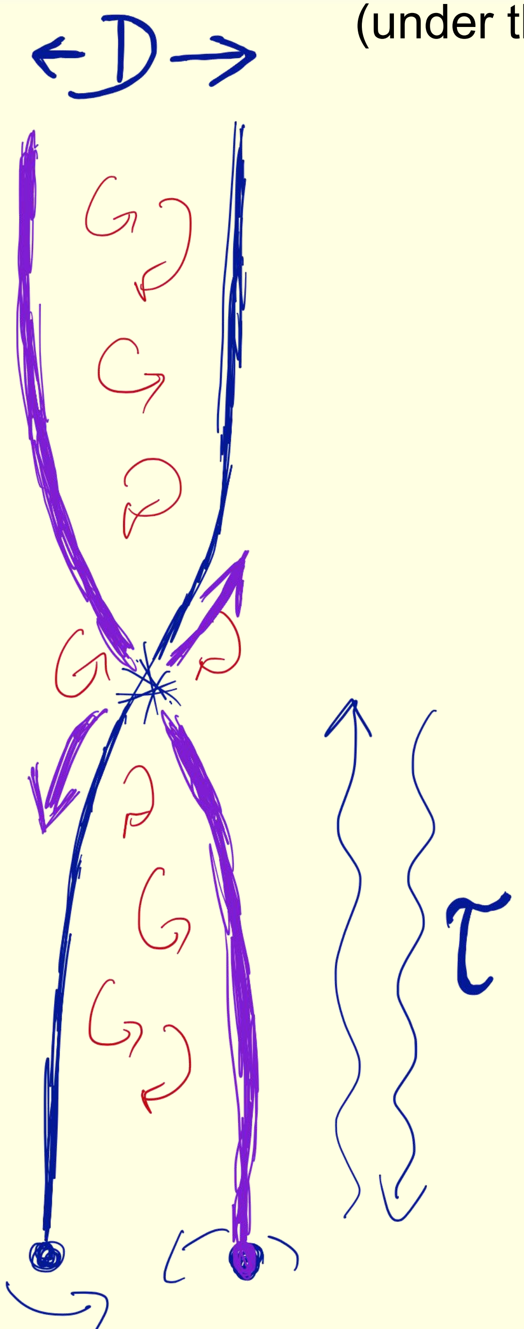
- hot dense core of a loop would diffuse with speed (consistent with non-thermal broadening)

$$v_{\rm diff} \;\approx\; v_{\rm nt} \approx 10\,{\rm km/s}$$

$$D \;\approx\; \frac{\eta_{\rm eff}}{v_{\rm nt}} = 10 \ldots 100 \text{ km}$$

How long do fieldlines keep their identity?

(under the presence of turbulence induced reconnection / diffusion)



- long fieldlines will interchange
- once this happens:
  there is time t to communicate this change
  - Alfven crossing time along (part of) loop $t_A \approx 100$ s
  - heat conduction time scale $t_{cond} \approx 1...10$ s
- resulting cross-field scale:

$$D \approx (\eta_{eff})^{1/2}\, \tau = 10 \ldots 100 \text{ km}$$

Of course, these cartoons are over-simplifying.
Proper models will have to show what role small-scale MHD turbulence plays within coronal loops

Conclusions

Conclusions

3D MHD models of active regions explain lots of observations despite of all their shortcomings

they fail to get resolved motions right

→ too dynamic on scales $\gtrsim$1 Mm

they fail to reproduce observed non-thermal line widths

→ not dynamic enough on scales $\lesssim$1 Mm

they fail to predict correct cross-sectional width of loops

→ what could cause cross-field structures?

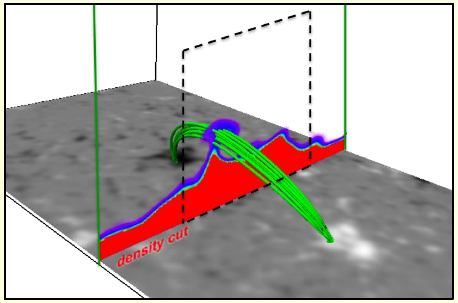
modeled structures are (much) finer than in observations

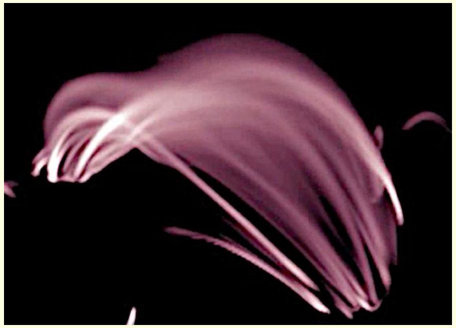
→ models are not dissipative enough

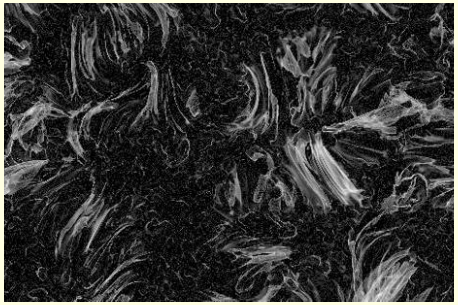
what 3D models of active regions miss (because of resolution) is the internal dynamics and turbulence within the loop

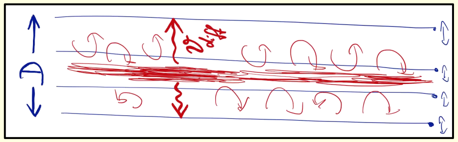
→ this might be a key to understand active region loops

what about the actual heating/dissipation mechanism?









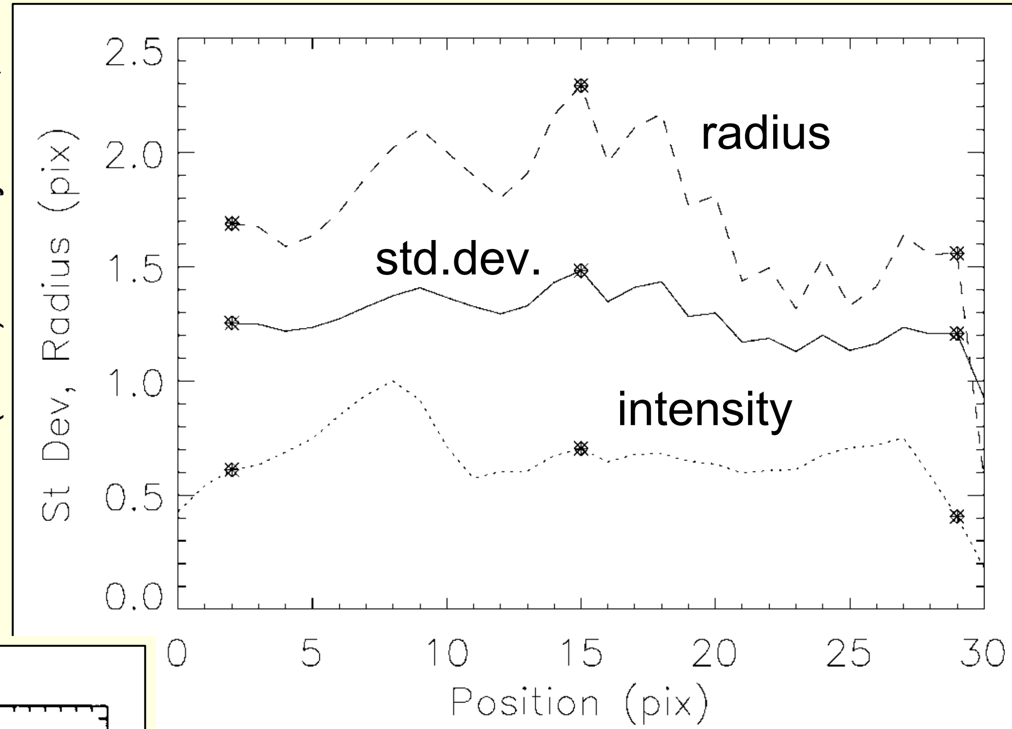
thanks…

Loops at constant cross-section

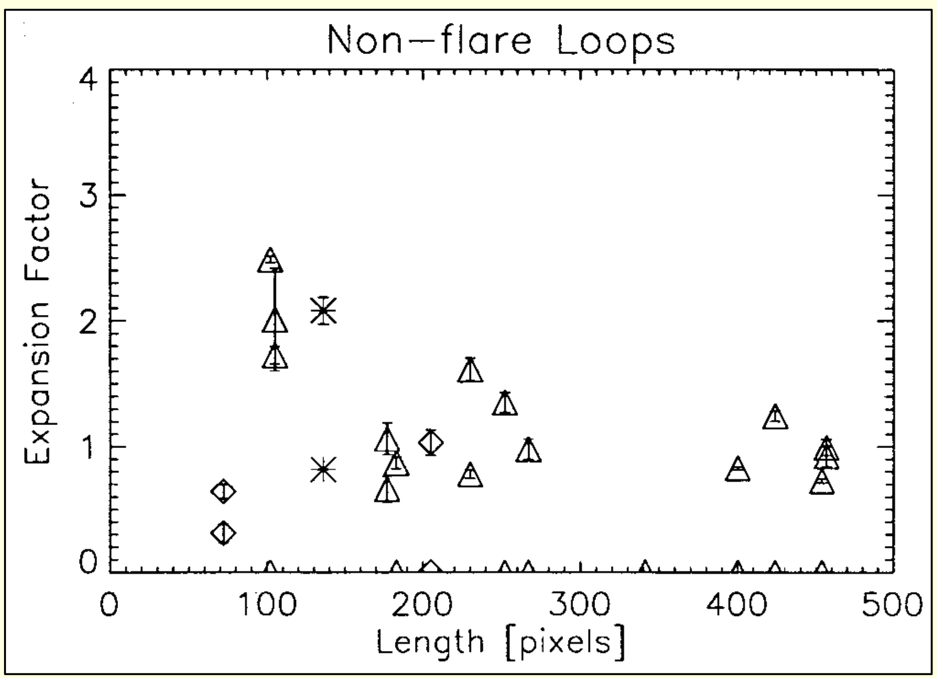
Constant cross section of loops: $T > 10^6$ K

Yohkoh SXT, 11.Aug.1992, 145"x140"

Klimchuk (2000) Sol.Phys. 193, 53

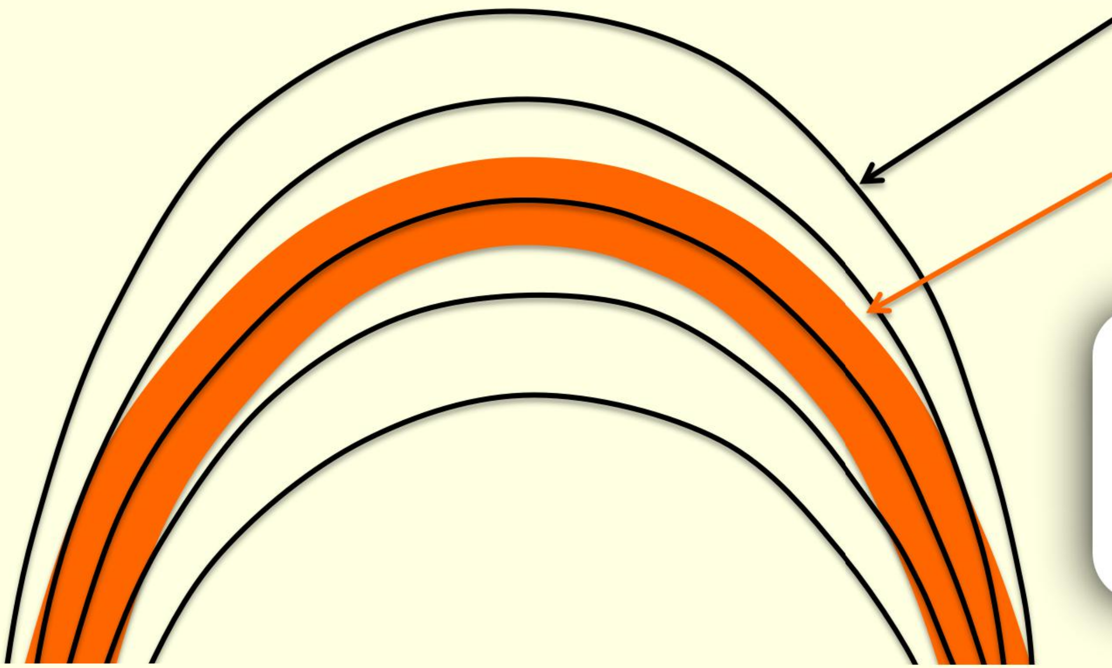


Watko & Klimchuk (2000) Sol.Phys. 193, 77



► many X-ray and most EUV loops have constant cross section! (not only post-flare loops)

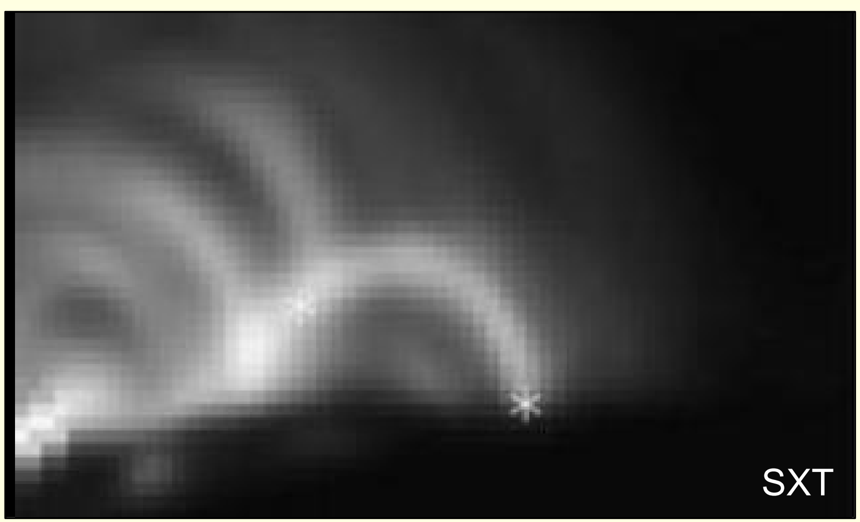
Constant cross section: the problem

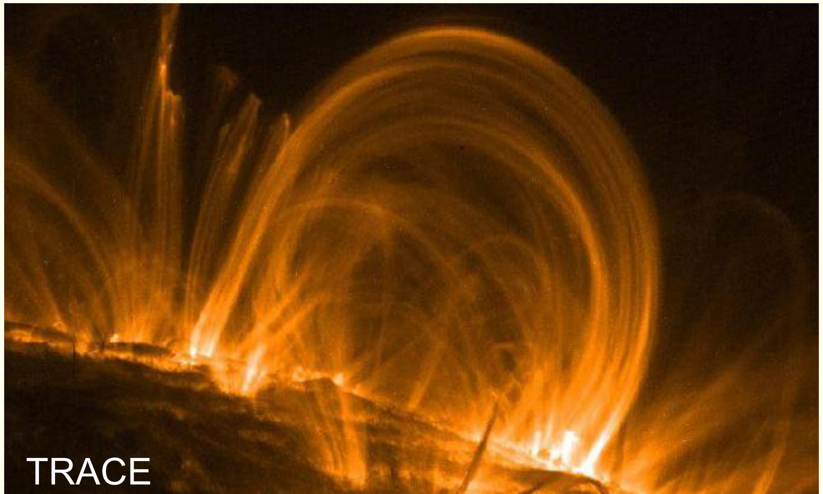


a potential-like magnetic field which expands with height.

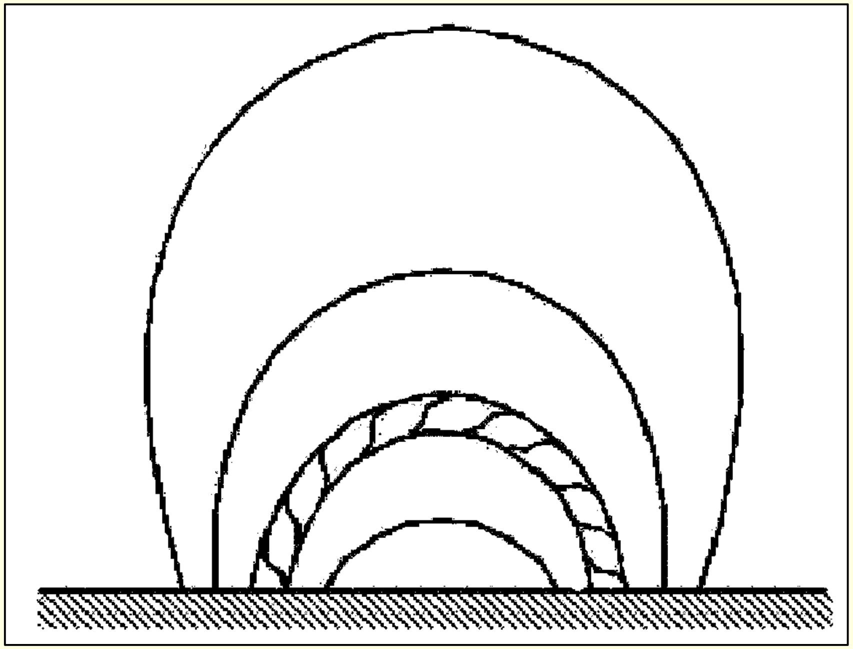
loop seen in coronal emission with constant cross section

- if the plasma is confined within magnetic flux tubes, how can this be ?!

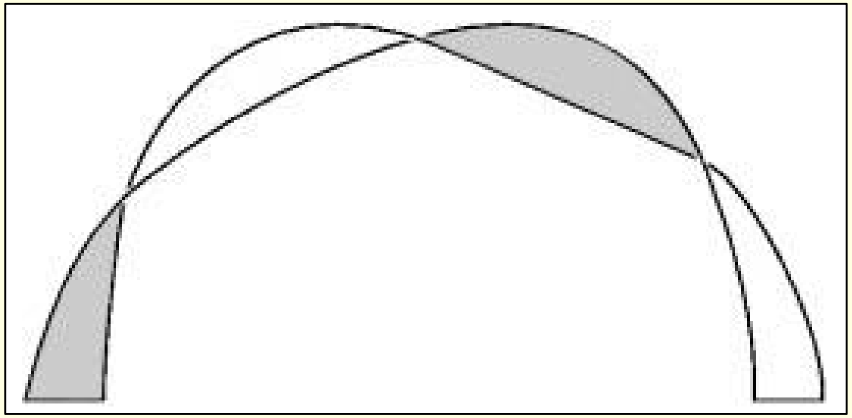




Constant cross section: suggestions



from Klimchuk (2000) Sol.Phys. 193, 53



twisted flux tube surrounded
by untwisted expanding field

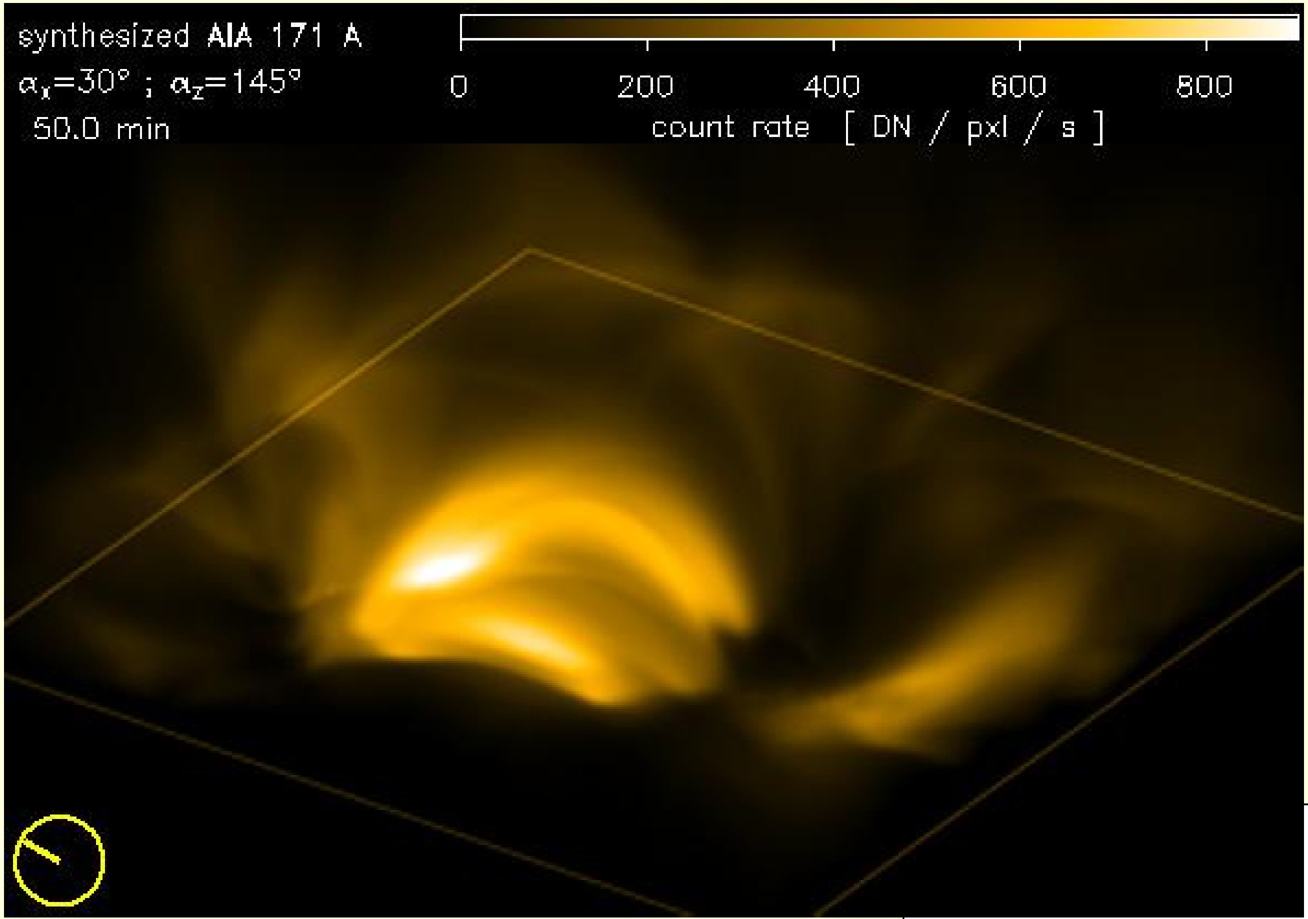
hypothetical ribbon-like loop
that is twisted

evidence for twisted flux tubes
in "quiet corona" is missing

evidence for "knots"
is missing

these and other suggestions fail…

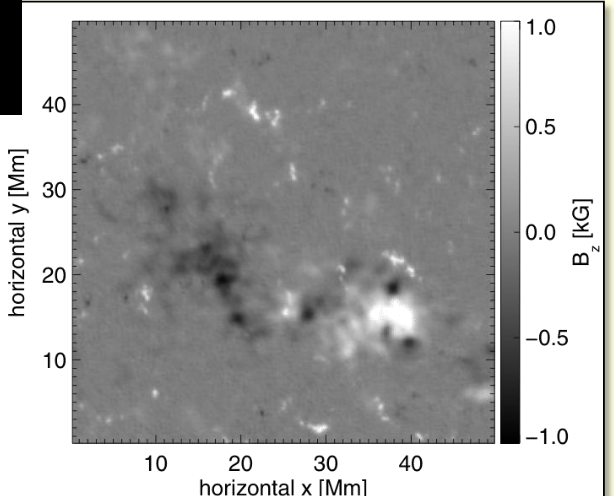
Temporal evolution of loops – 3D model



50 x 50 x 30 Mm^3

Bingert & hp (2011) A&A 530, A112

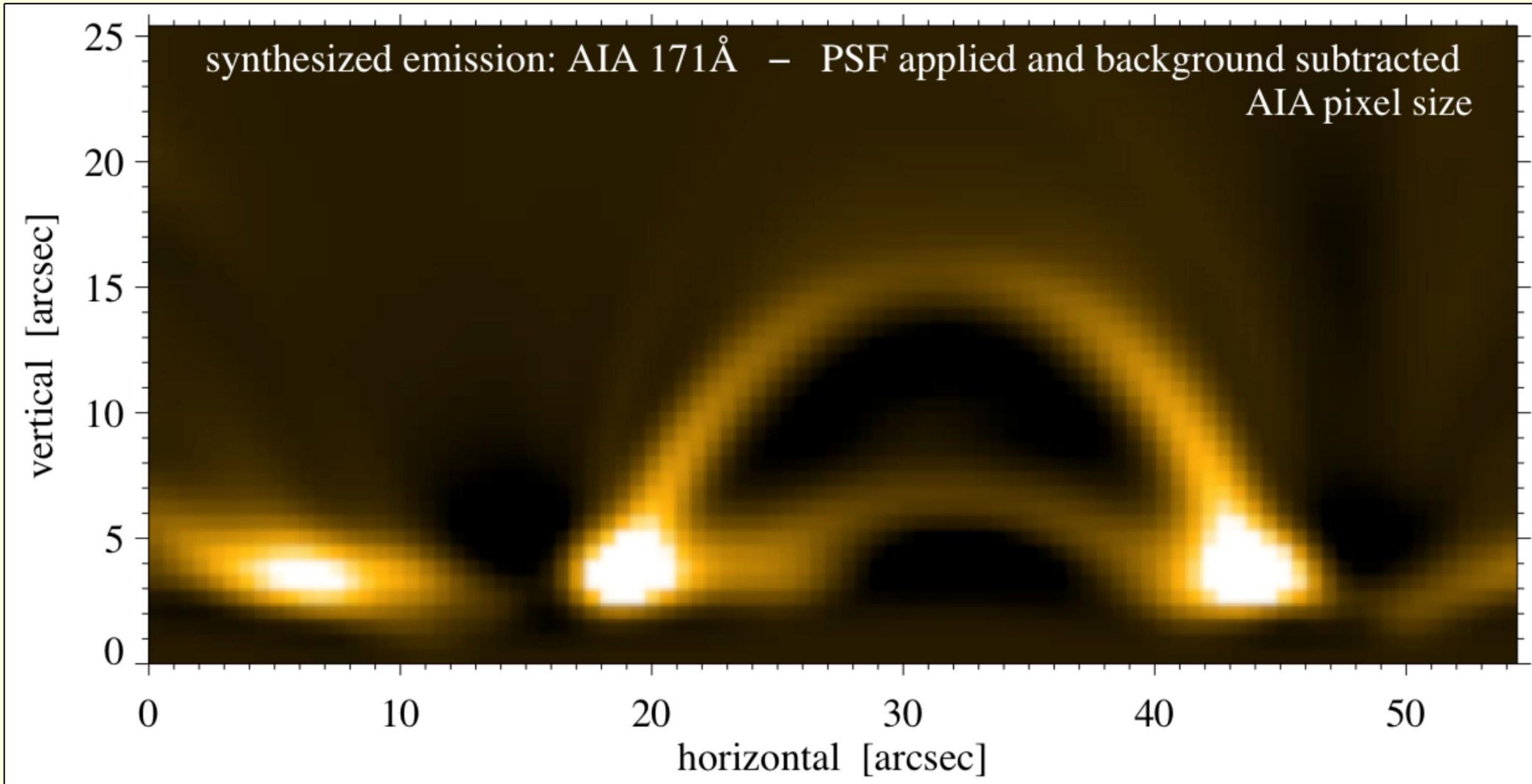
magnetic field
at lower boundary
driven by
horizontal motions



Coronal loop in 3D MHD model

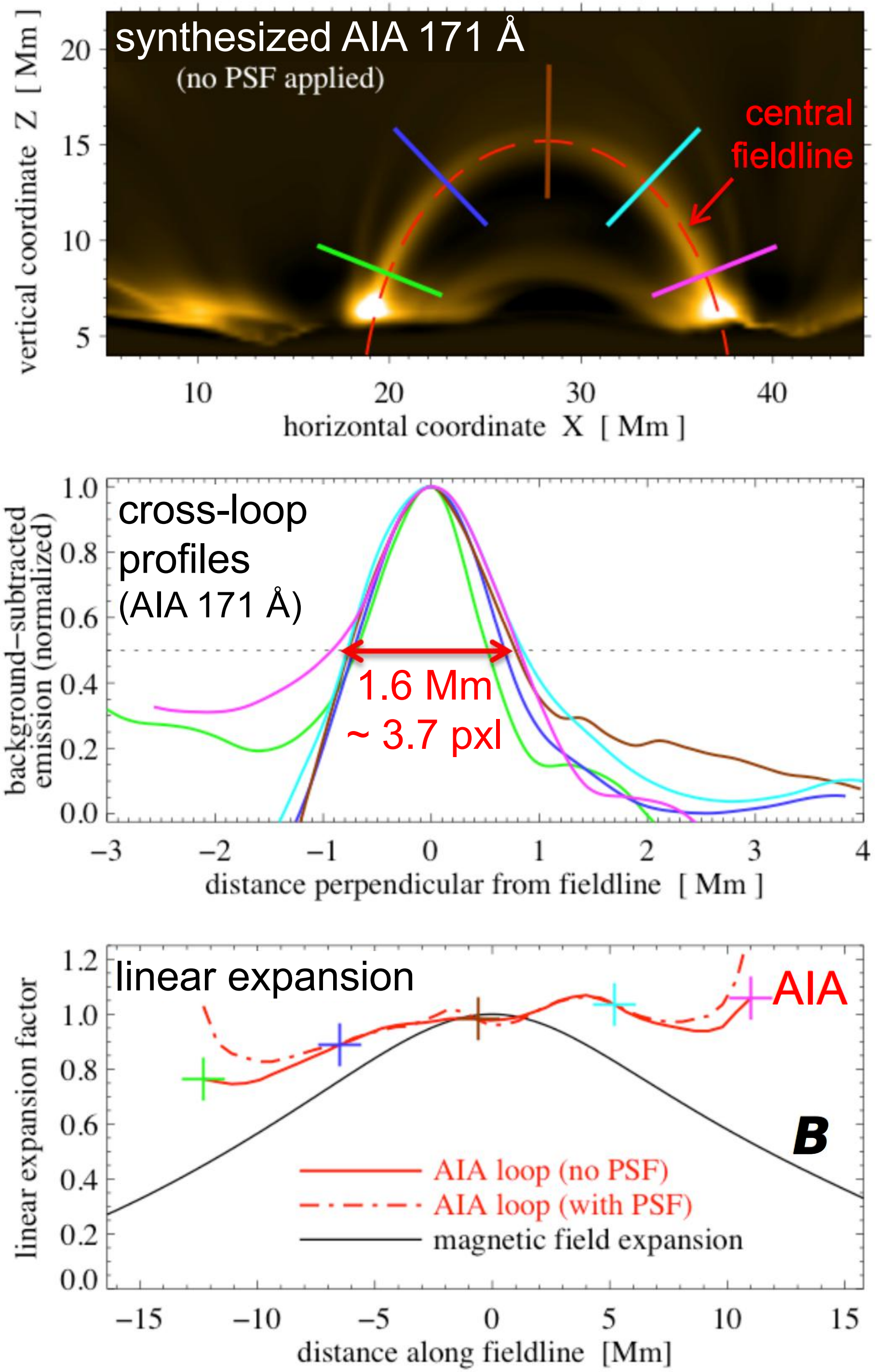
synthetic AIA 171 Å (10^6 K)

loop has cross section of ~2x AIA PSF width (PSF ≈1.3" ≈ 2.5 pxl)



hp & Bingert (2012) A&A 548, A1

horizontally integrated
through computational box



Quantitative analysis

- **cross section:**
  visible EUV loop almost constant width:
  FWHM ≈ 1.6 Mm = 2.2” = **3.7 AIA pxl**

  (consistent with
  Aschwanden & Boerner 2011, ApJ 732, 81).

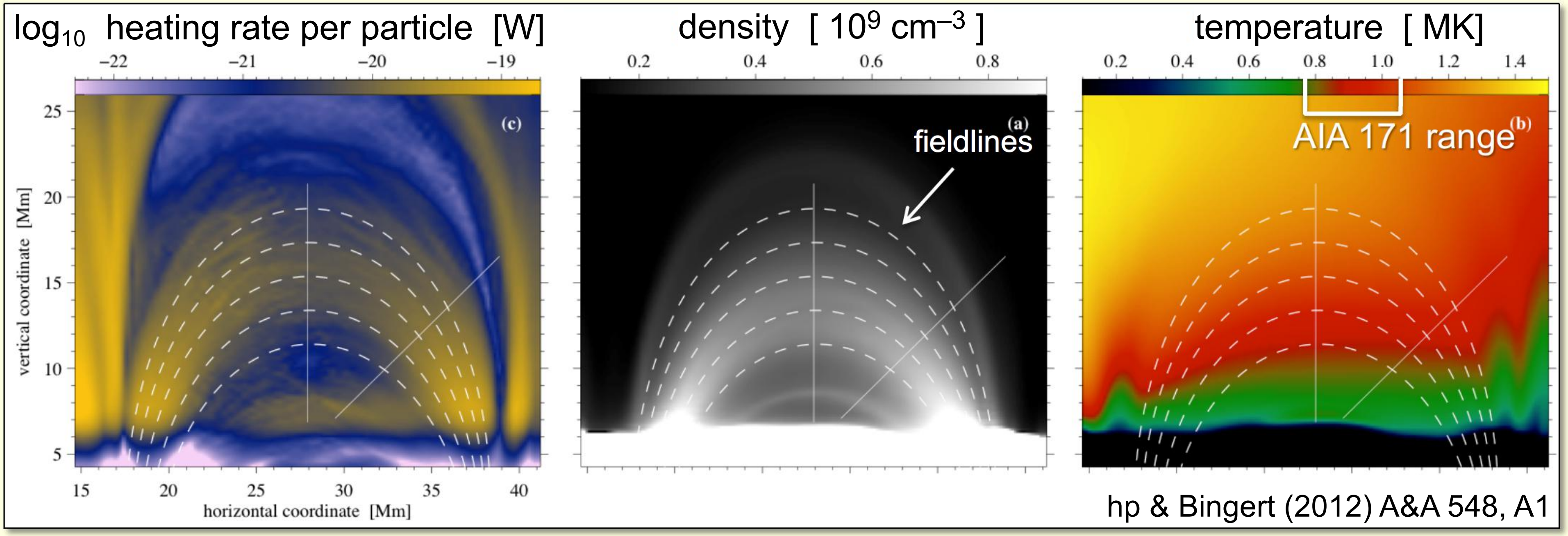
- radius (linear) **expansion:**
  → magnetic field: ≈ factor 3
  → visible loop ≈ factor 1.1 … 1.2

  (consistent with
  Watko & Klimchuk (2000) Sol.Phys. 193, 77).

- while the magnetic field expands
  (close to a potential field)
  the resulting loop seen in EUV does *not* expand !

→ why is this?

Cut in loop plane: heating → n, T



hp & Bingert (2012) A&A 548, A1

► heating rate follows magnetic structure

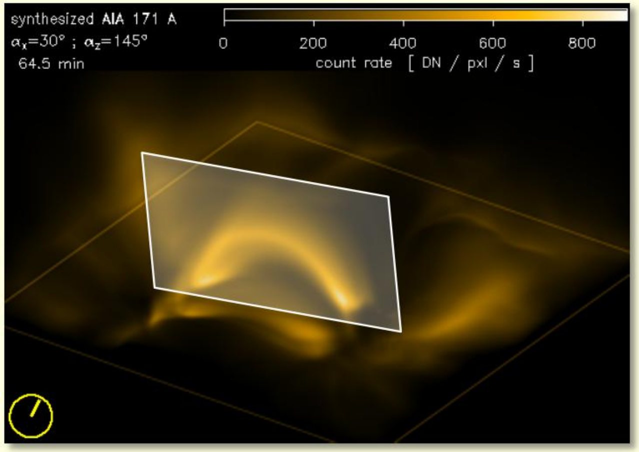
► increased heating rate leads to evaporation

► plasma filled in expanding magnetic structure

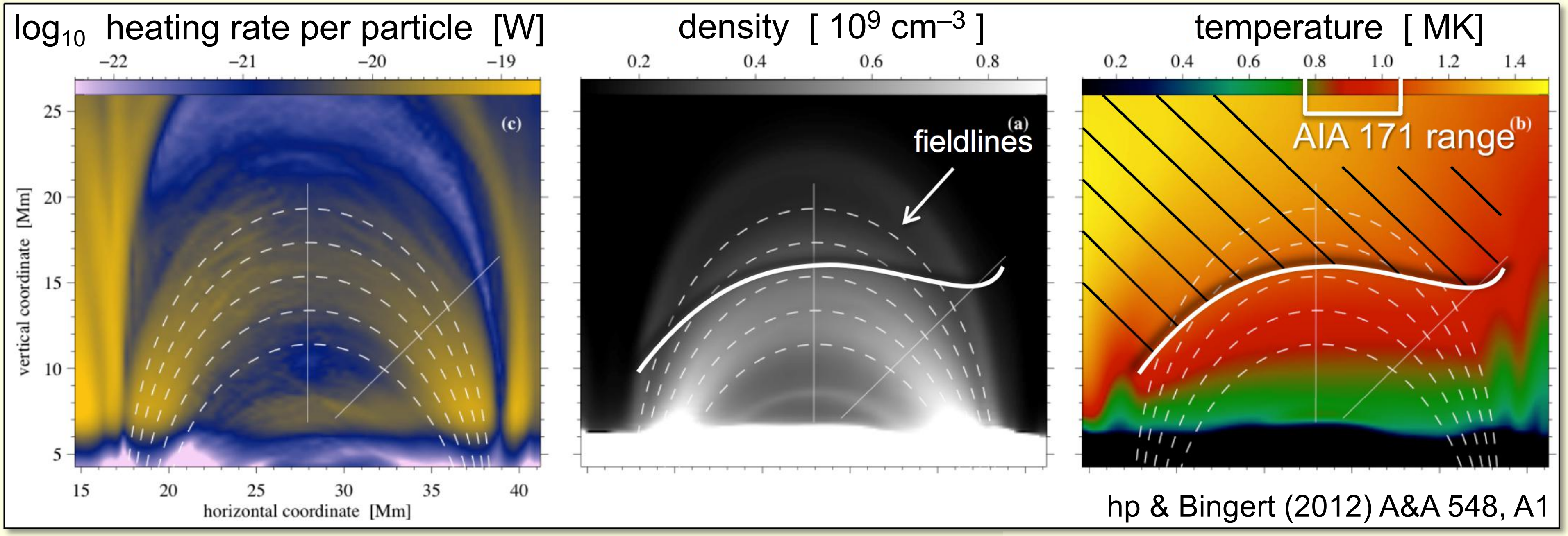
► **“plasma loop” (density) expands with height**

► temperature increases with height

scaling laws: longer loops are hotter (at same hating rate)



Cut in loop plane: heating → n,T



hp & Bingert (2012) A&A 548, A1

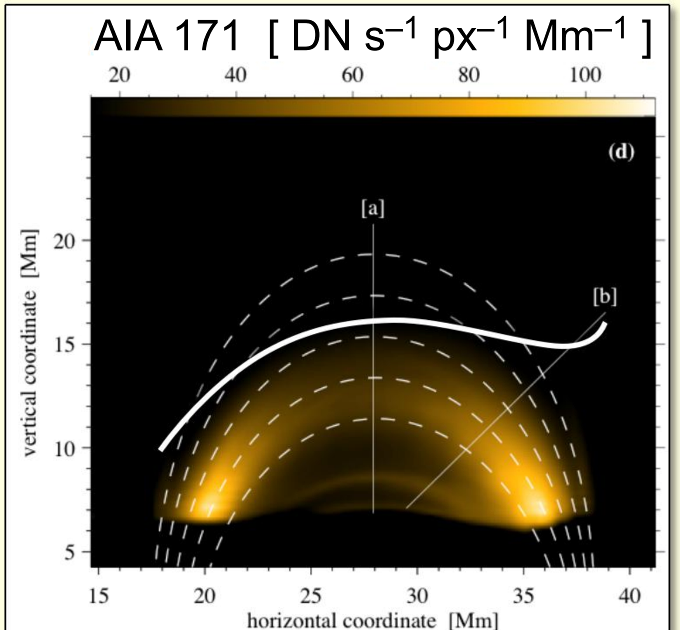
- ► part of plasma loop too hot to contribute to EUV emission in respective band

> ► top part of loop is "cut off"
>
> → **approx. constant cross section**

– other explanations exist ………… … Malanushenko & Schrijver (2013) ApJ 775, id.120

… Lionello et al. (2013) ApJ 773, id.134

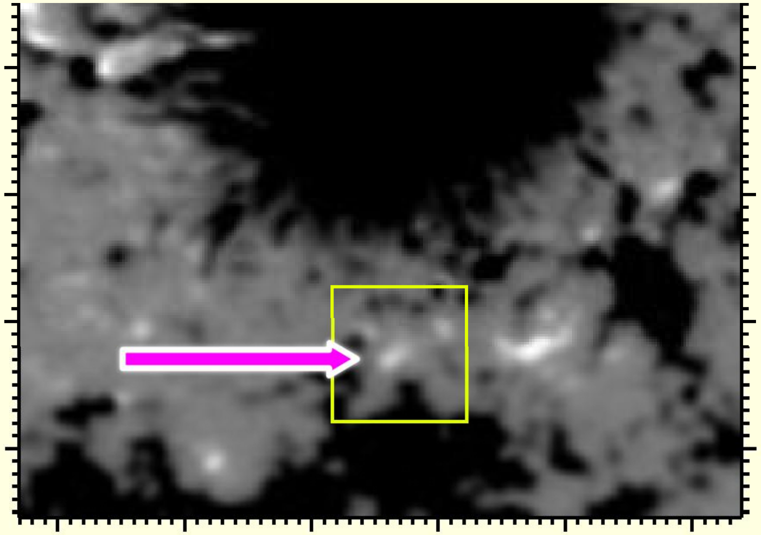
– this is to show importance of relation of magnetic field to temperature & density structure



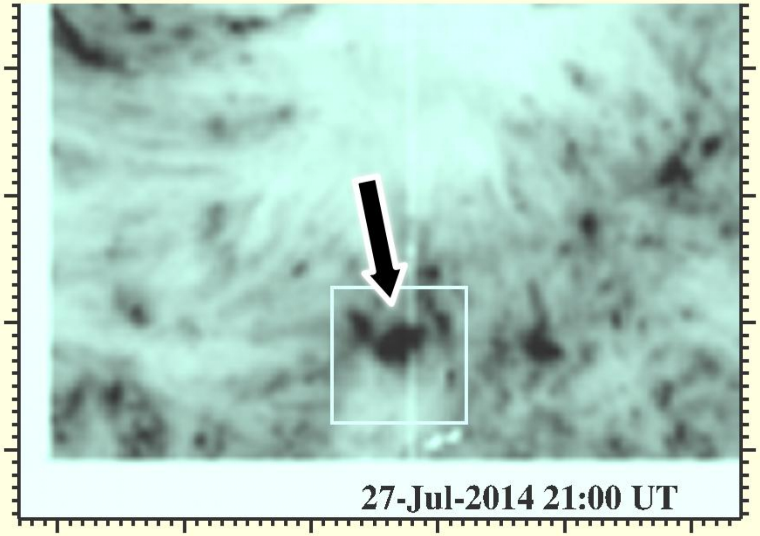
reconnection driven by surface motions

Motivation through magnetic topology of EUV burst

magnetogram (HMI)



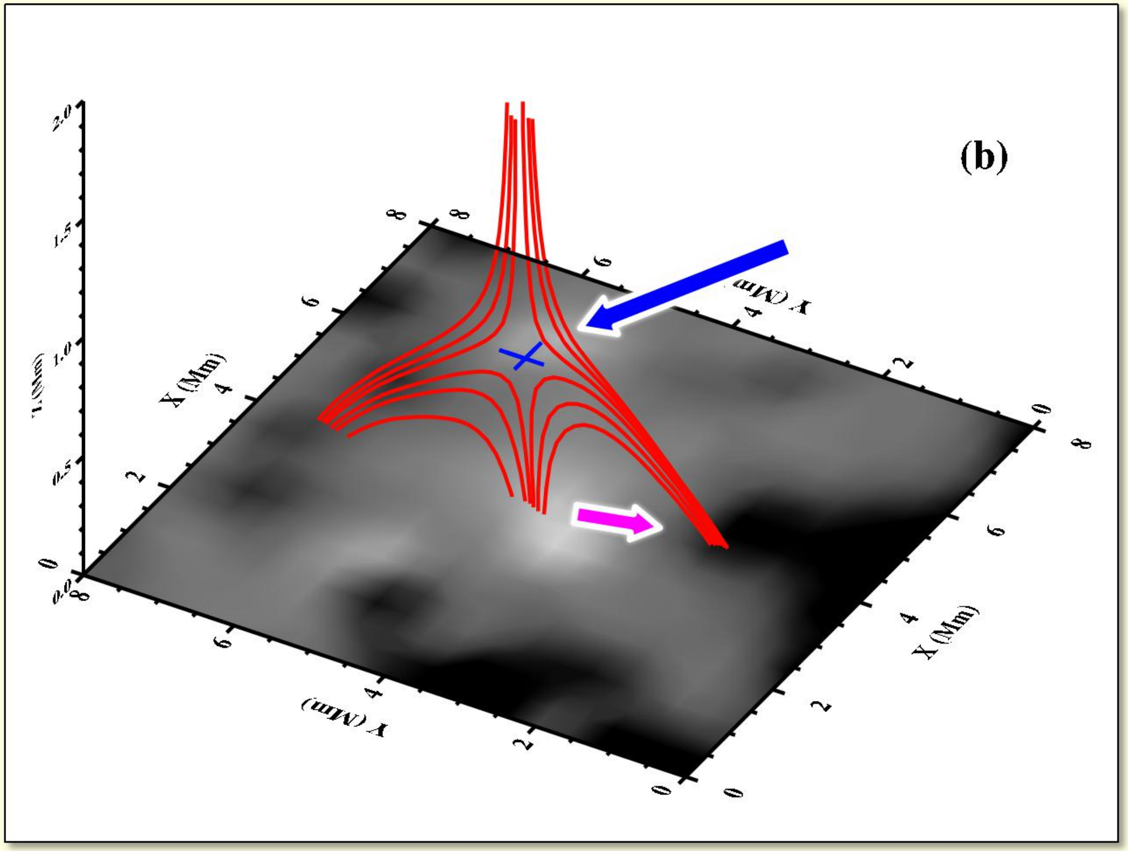
TR intensity (inverse scale, IRIS 1400Å)



≈ 60 x 40 arcsec^2

- ► small ("parasitic") polarity runs into major polarity (pore)
- ► magnetic field forms X point above

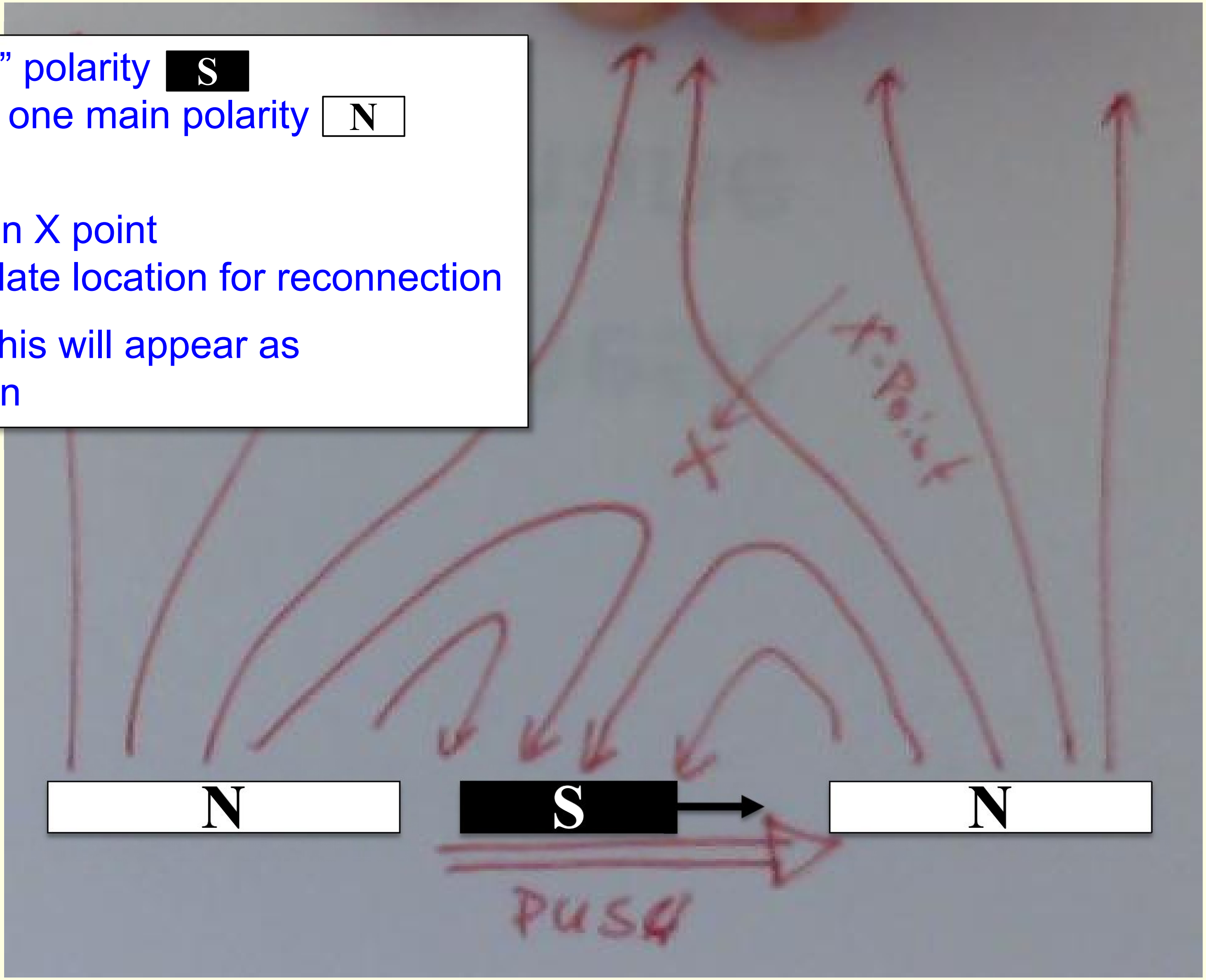
  → reconnection site at low height (chromosphere)
- ► TR emission (EUV burst) trails location of X point



Chitta, hp, Young, Huang (2017) A&A 605, A49

Magnetic setup

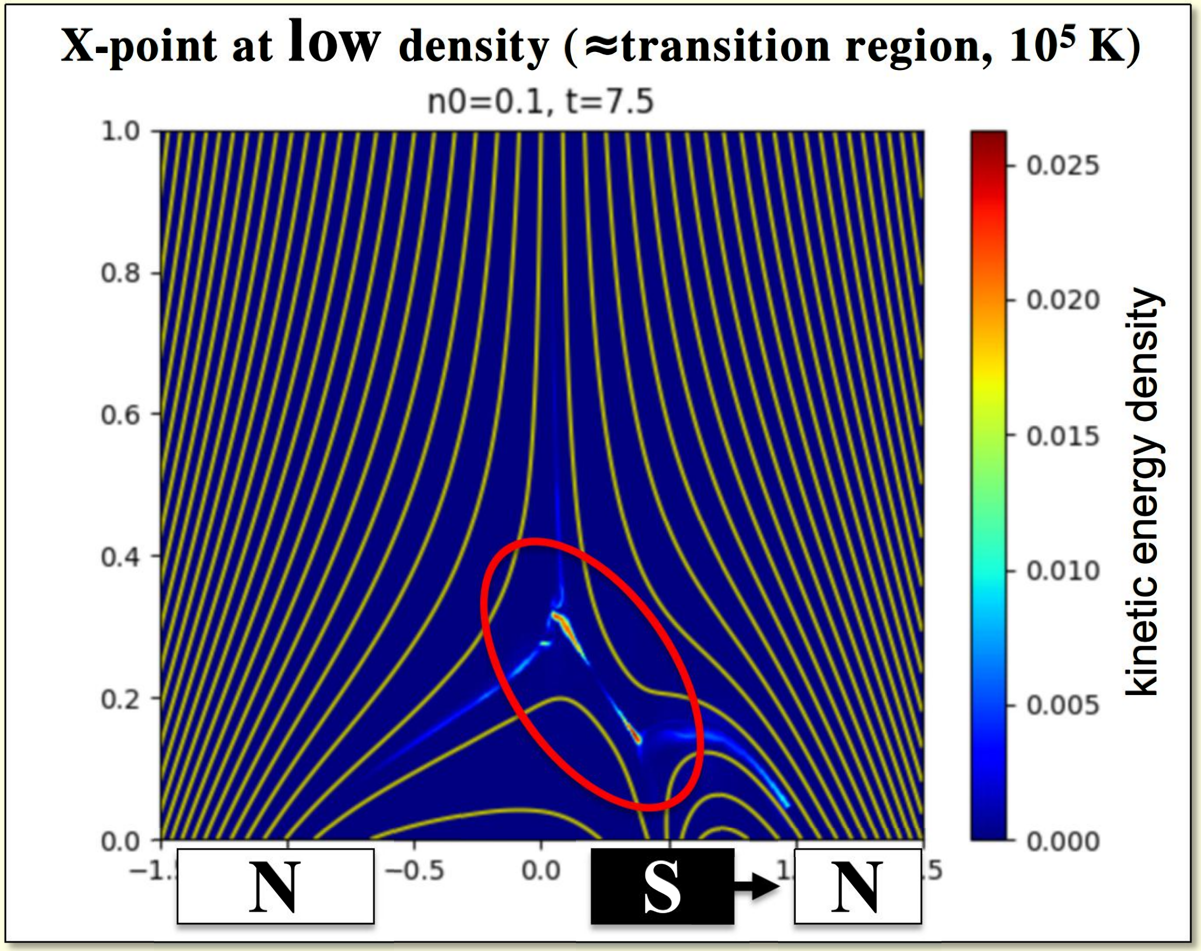
- small “parasitic” polarity **S** is moving from one main polarity **N** to the other
- this stretches an X point that is a candidate location for reconnection
- at the surface this will appear as flux cancellation



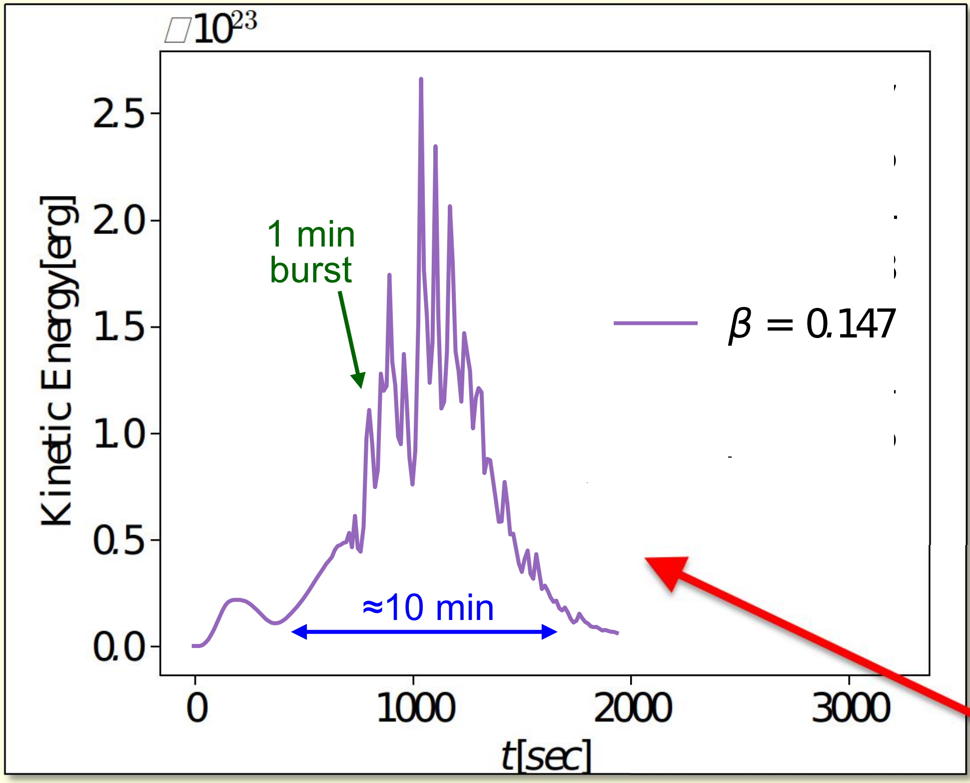
Driving from the solar surface

- X-point trails photospheric flux concentration
- after some photospheric driving
  reconnection sets in and drives a bi-directional jet
  → this is the first model that produces an explosive event by surface driving

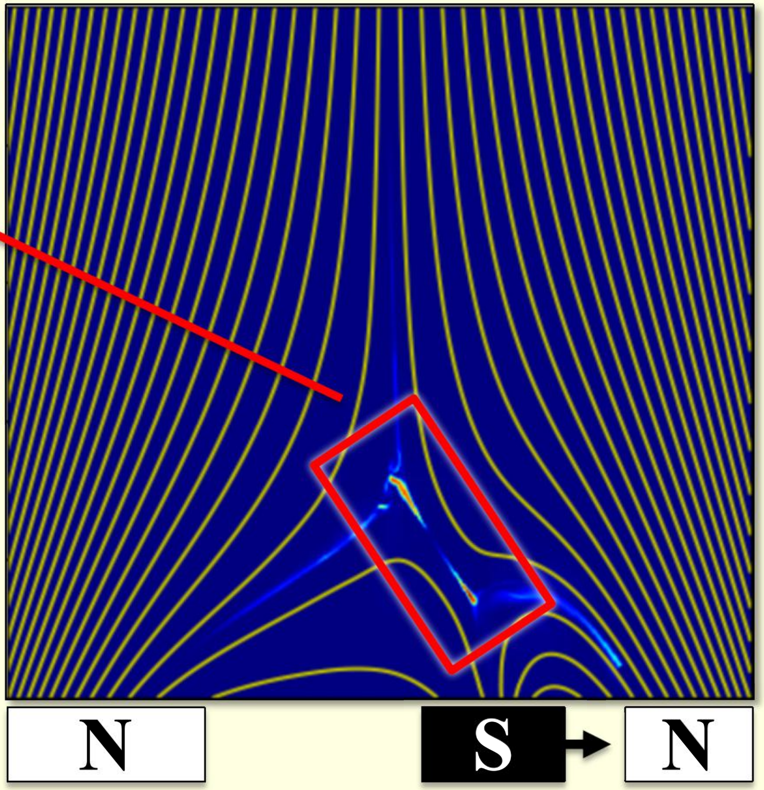
(1)



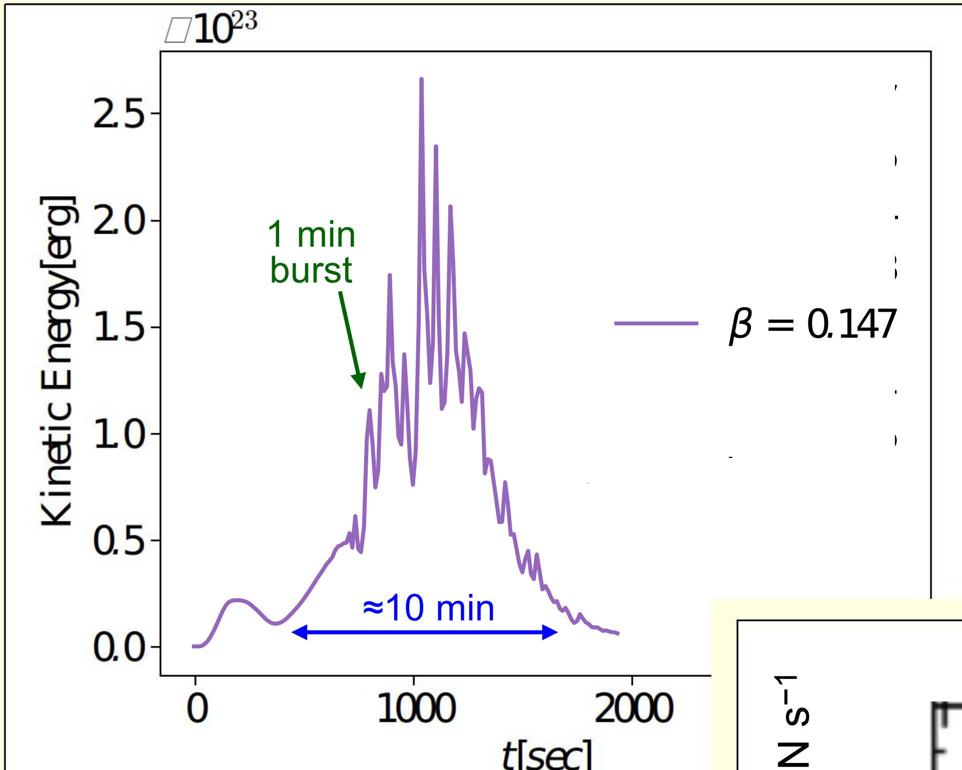
Energy release in TR explosive event



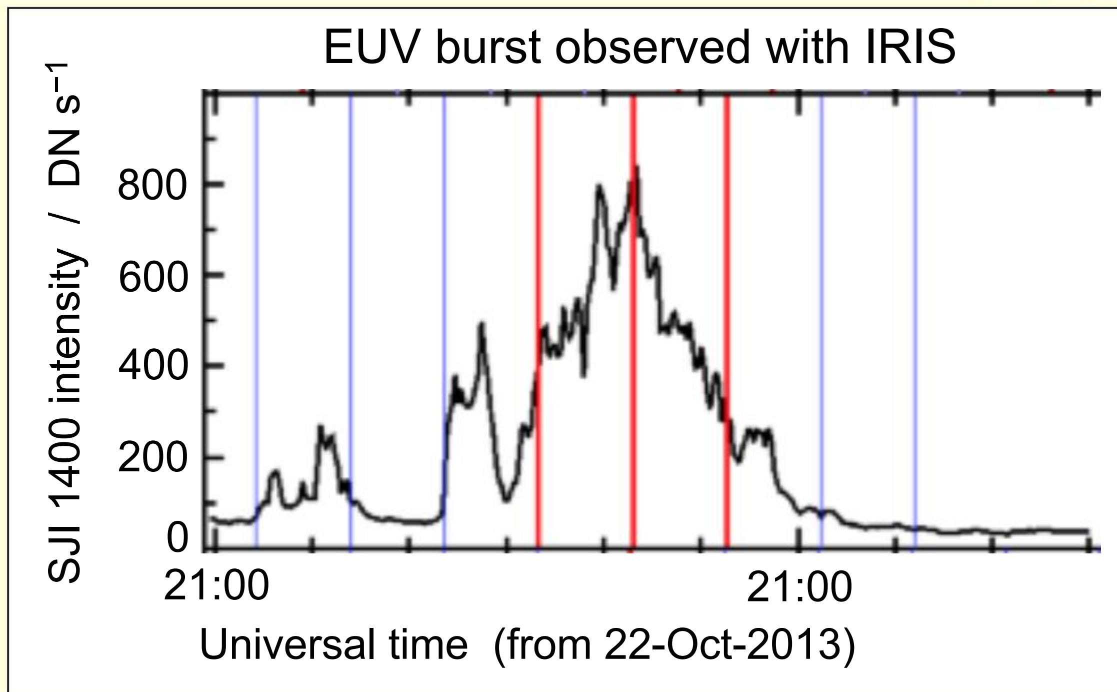
- for case with reasonable plasma-b: release of energy in bursts
- overall length is ≈10-20 min
  set by how long we drive, but we can drive only so long before hitting other polarity
- individual bursts of 1-2 min length due to the formation of individual (larger) plasmoids



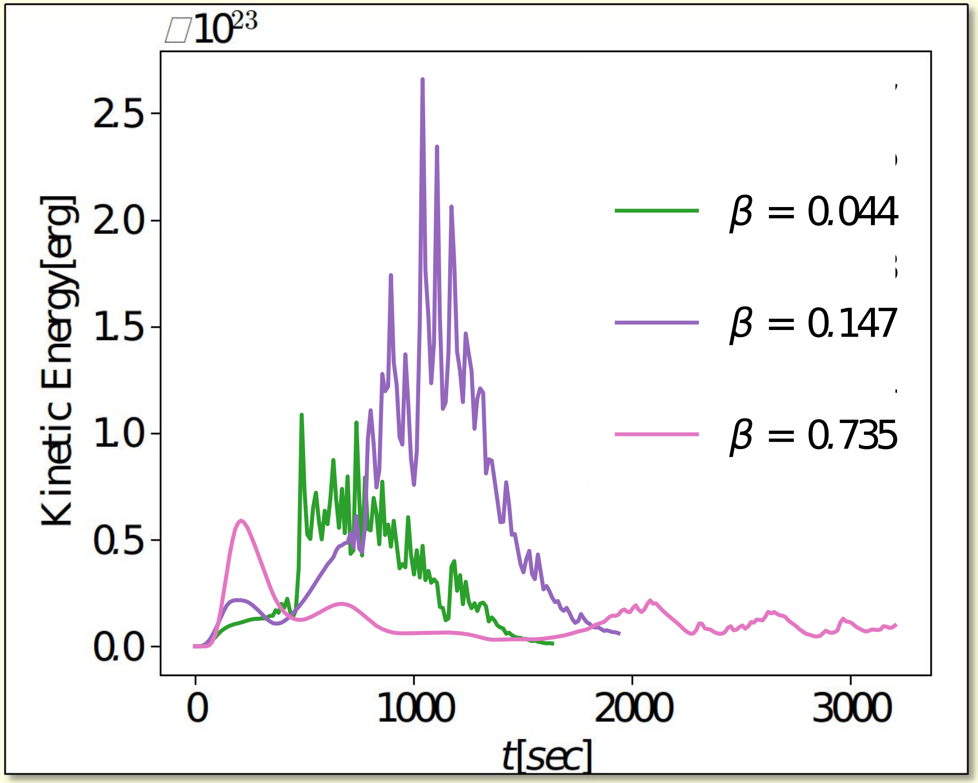
Energy release in TR explosive event



- for case with reasonable plasma-b: release of energy in bursts
- overall length is ≈10-20 min
  set by how long we drive, but we can drive only so long before hitting other polarity
- individual bursts of 1-2 min length due to the formation of individual (larger) plasmoids
- evolution fits to observations ✓ (2)



Energy release and location of reconnection



► **small plasma-*b*:**

(reconnection "higher up in the atmosphere")

– energy conversion starts earlier

– converted energy is smaller

no sufficient energy build-up early on

→ **still: more energy/particle**

→ **higher temperature**

► **for higher plasma-*b*:**

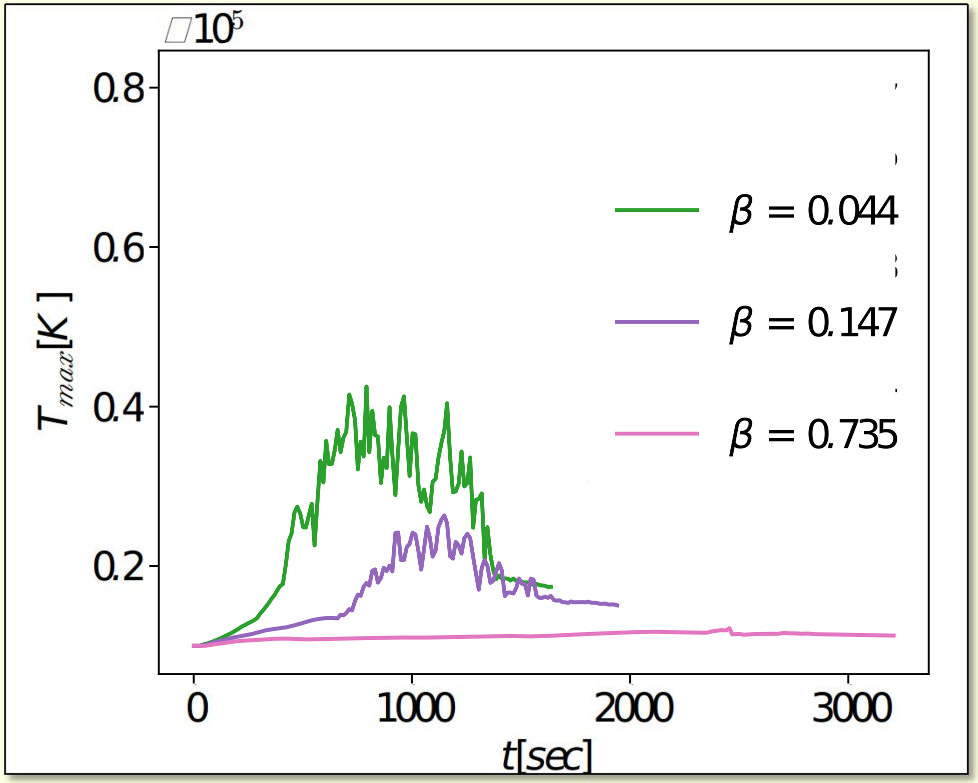
(reconnection "lower down", in chromosphere)

– energy conversion starts later (more driving needed)

– much lower energy conversion

→ almost no increase in temperature

Peak temperature and location of reconnection



- **small plasma-b:**

  (reconnection “higher up in the atmosphere”)

  – energy conversion starts earlier

  – converted energy is smaller

  higher up → lower B → less energy available

  → **still: more energy/particle**

  → **higher temperature**

- **for higher plasma-b:**

  (reconnection “lower down”, in chromosphere)

  – energy conversion starts later (more driving needed)

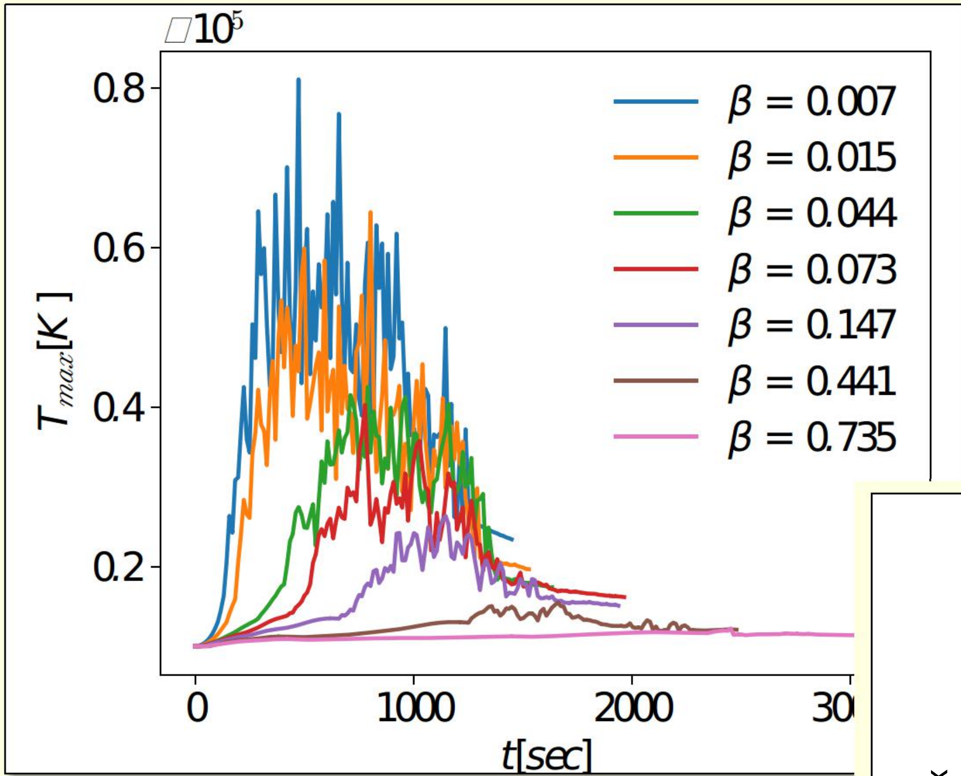
  – much lower energy conversion

  → **almost no increase in temperature**

→ this driving cannot produce events in the photosphere and chromosphere (e.g. Ellerman bombs)

(3)

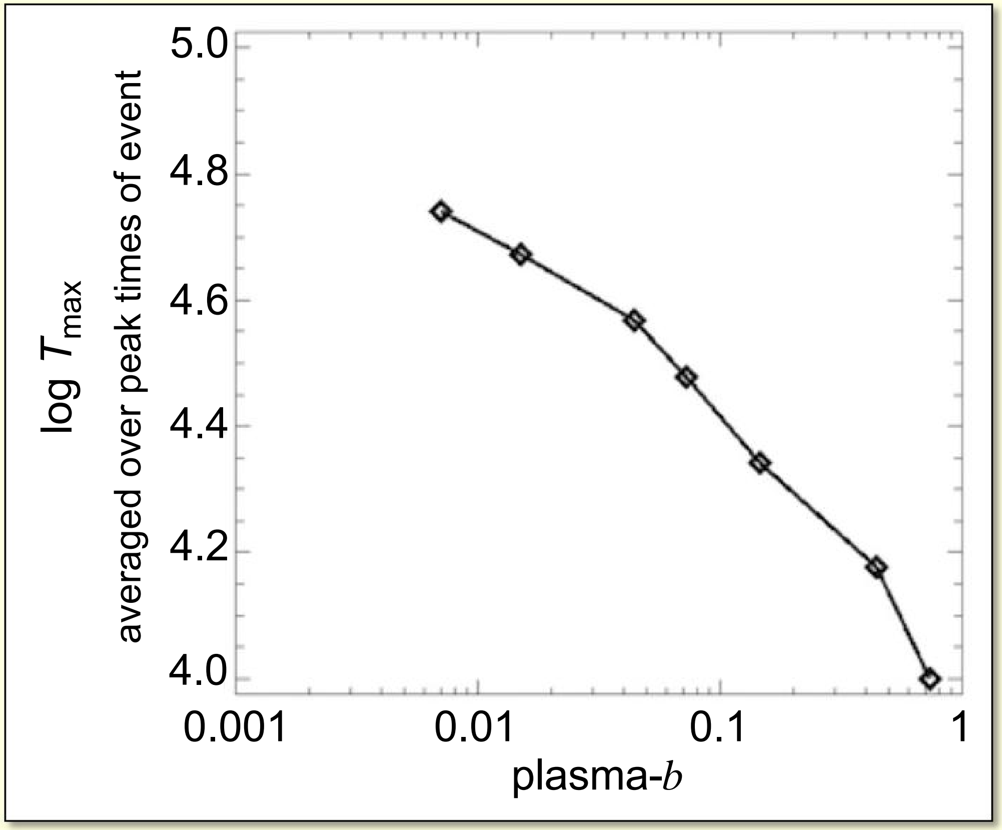
Peak temperature and plasma-b



► for reasonable plasma-b (>10^{-3}) the temperature will stay below 10^5 K

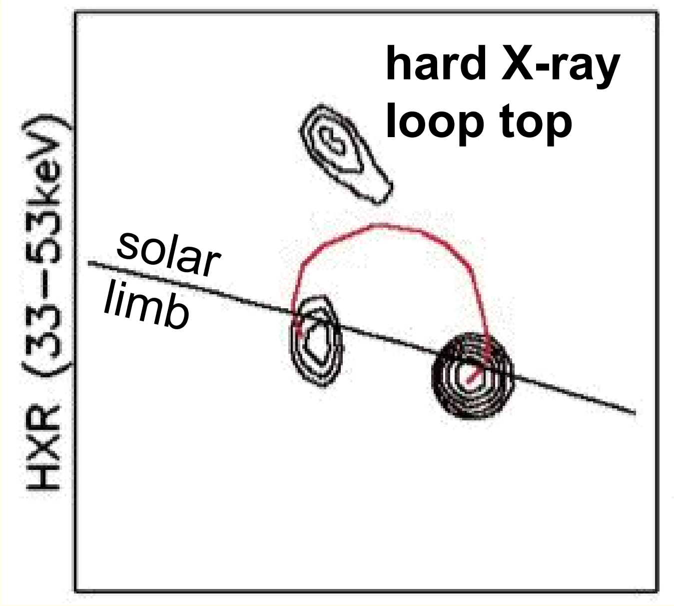
► this could explain why we do not see explosive events and EUV bursts at coronal temperatures

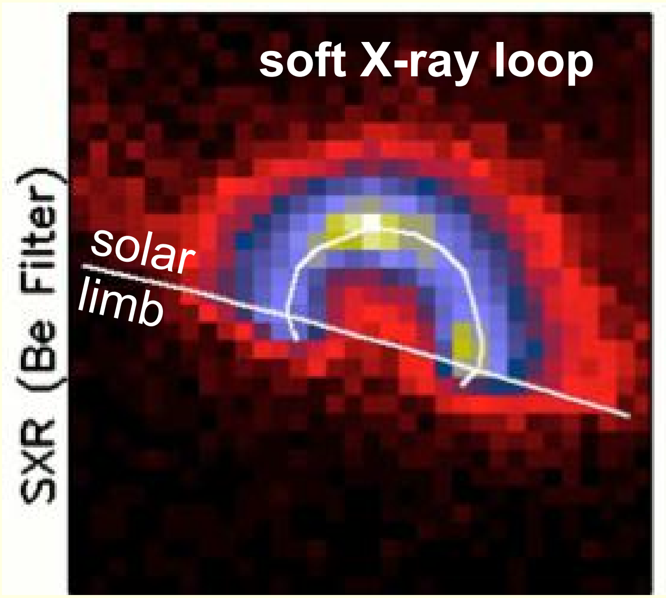
(4)



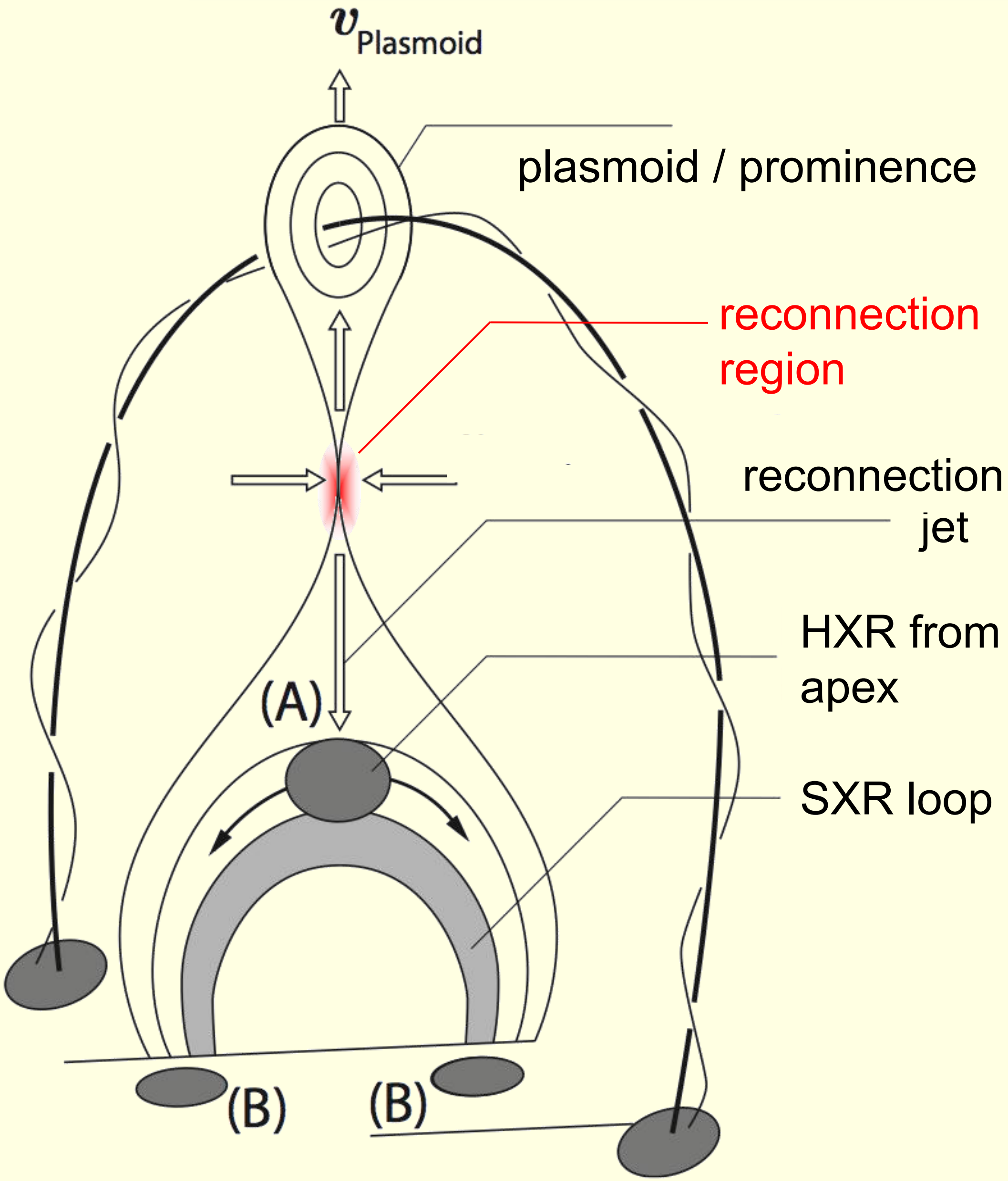
perspective

Classical flare scenario: loop-top source

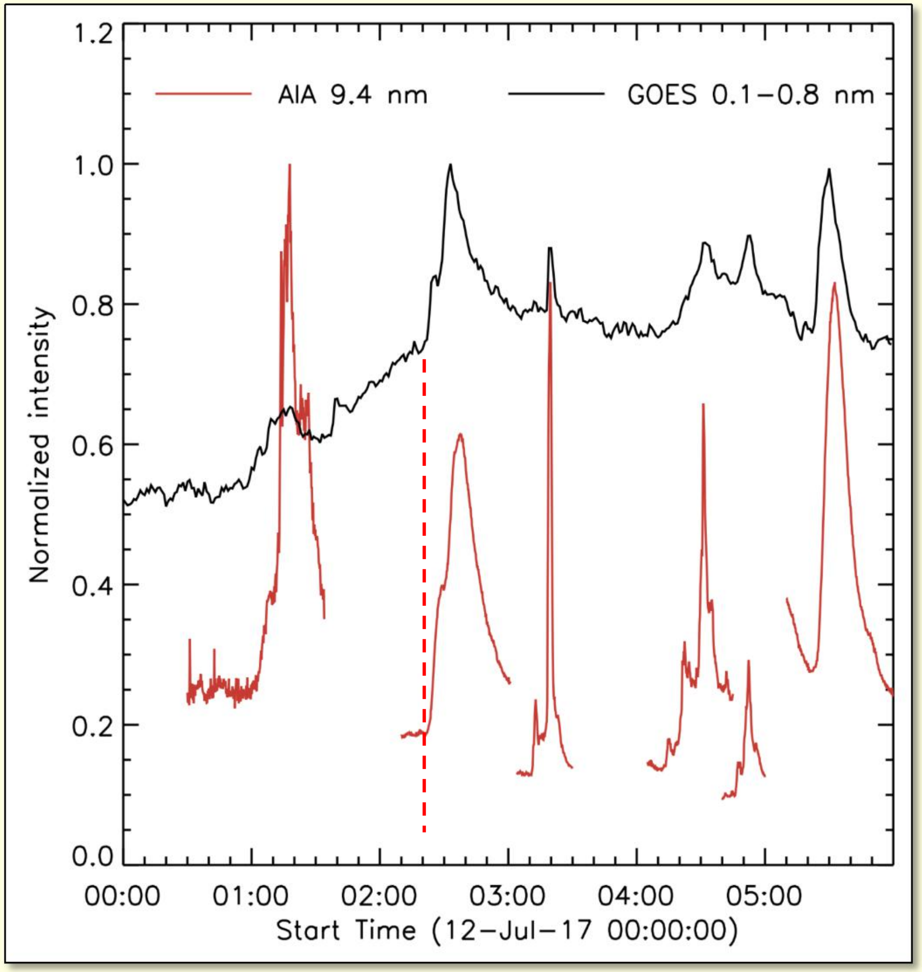


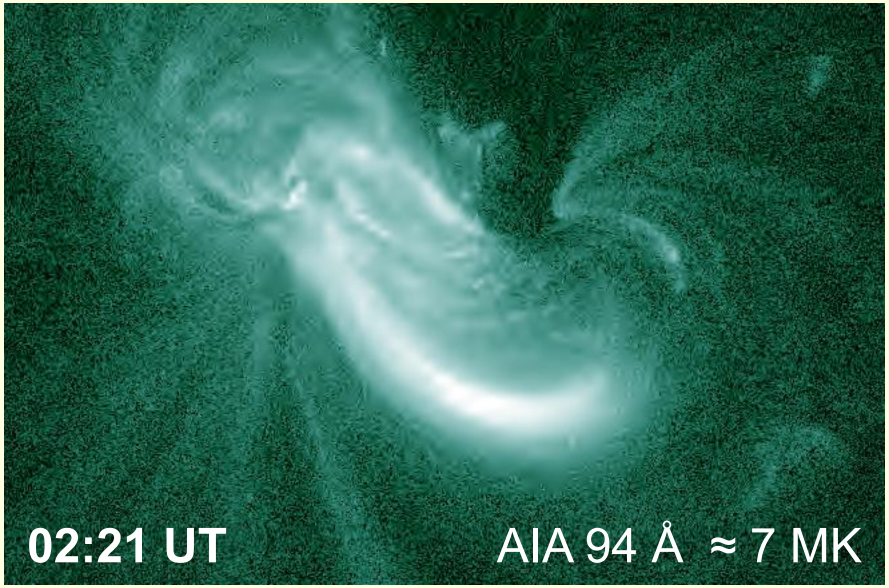


Yohkoh



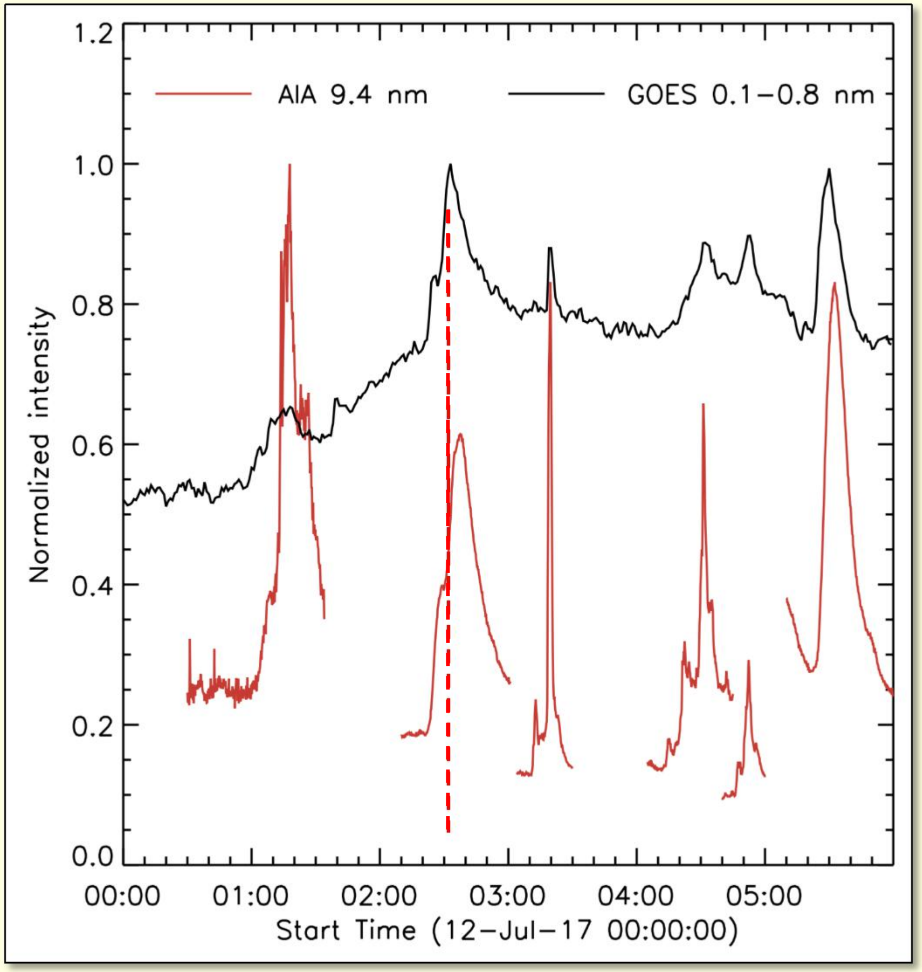
Flare events from compact hot loops

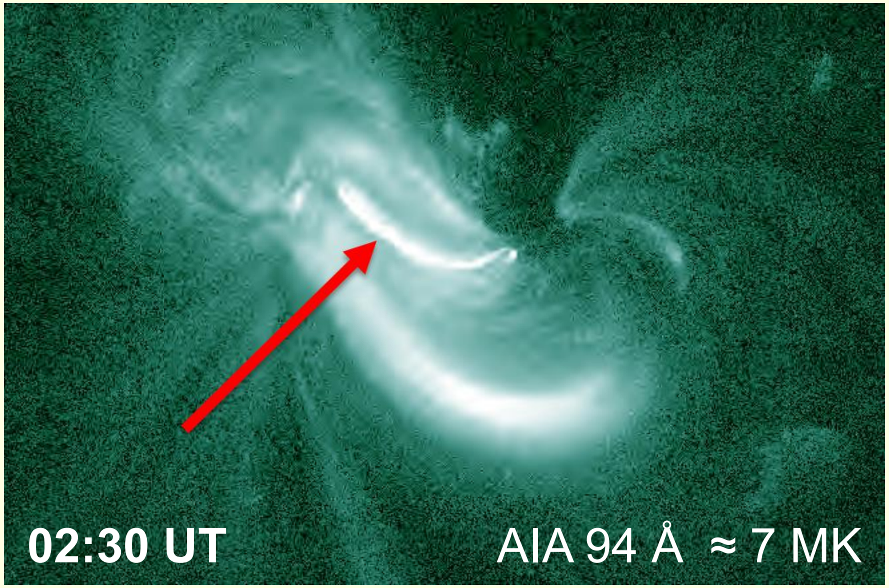




► **with AIA we can spatially locate GOES B3 flare**

Flare events from compact hot loops

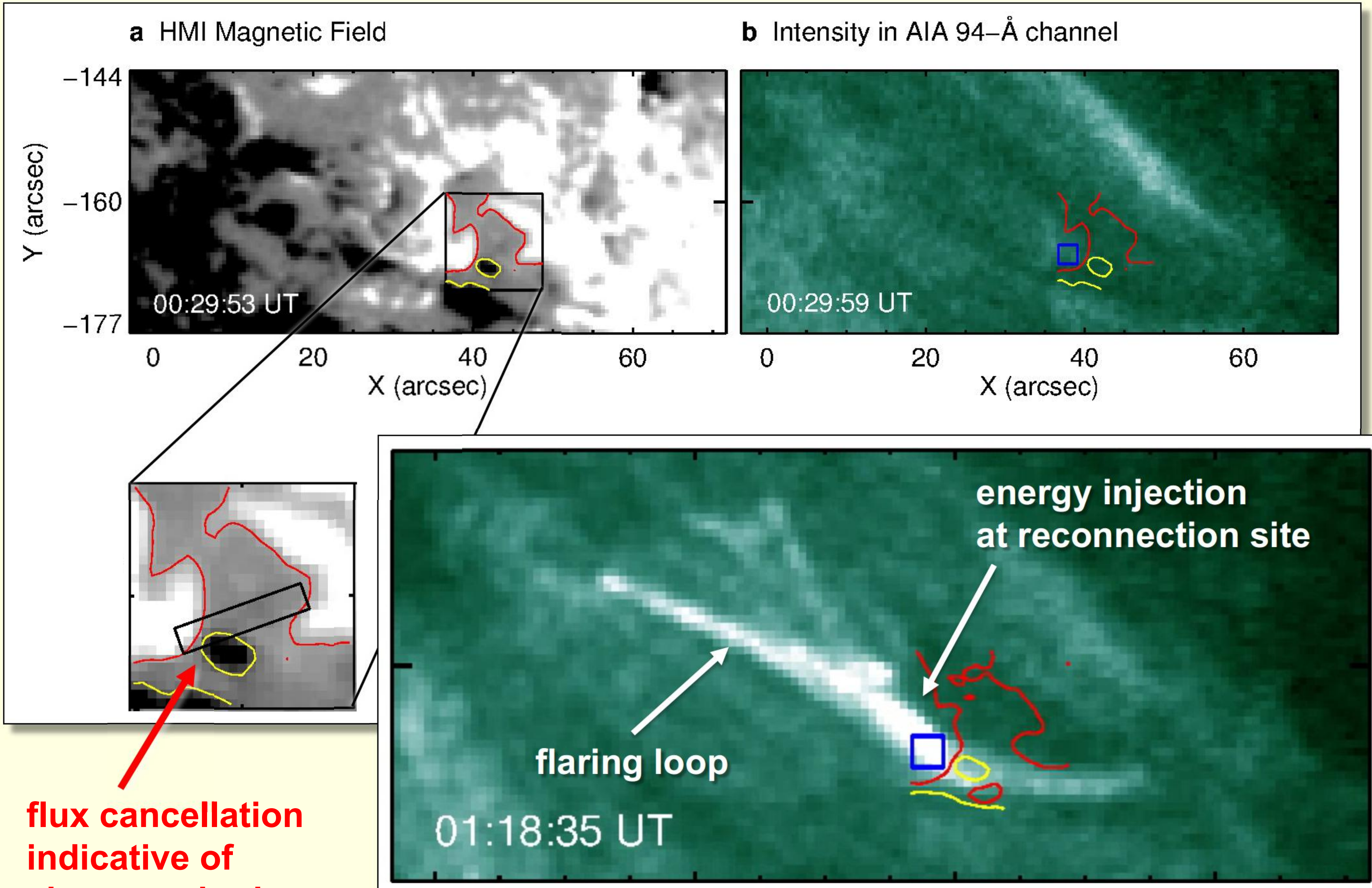




► **with AIA we can spatially locate GOES B3 flare**

→ **compact hot loop in AR**

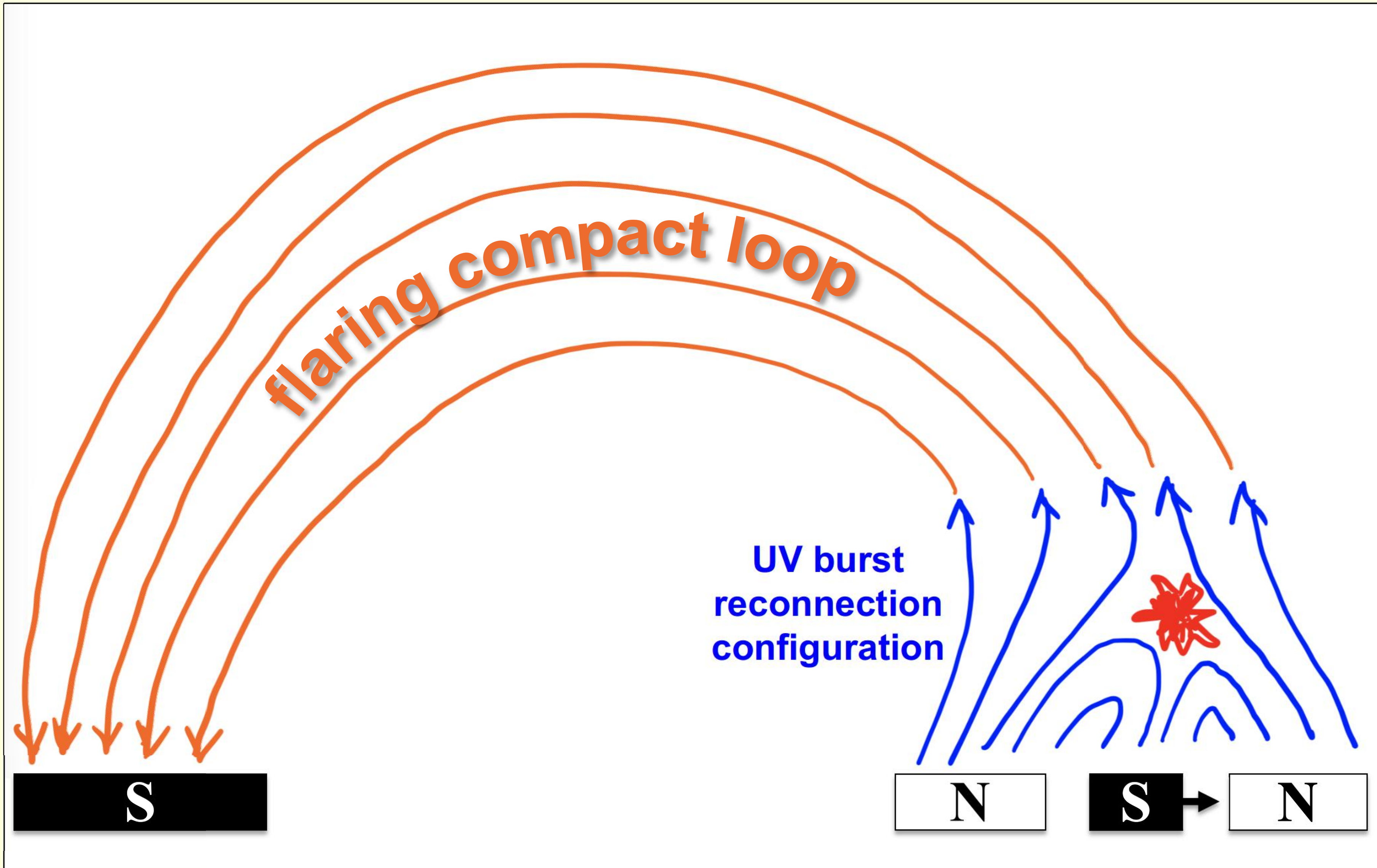
Evidence for footpoint reconnection in hot loops



flux cancellation
indicative of
chromospheric
reconnection

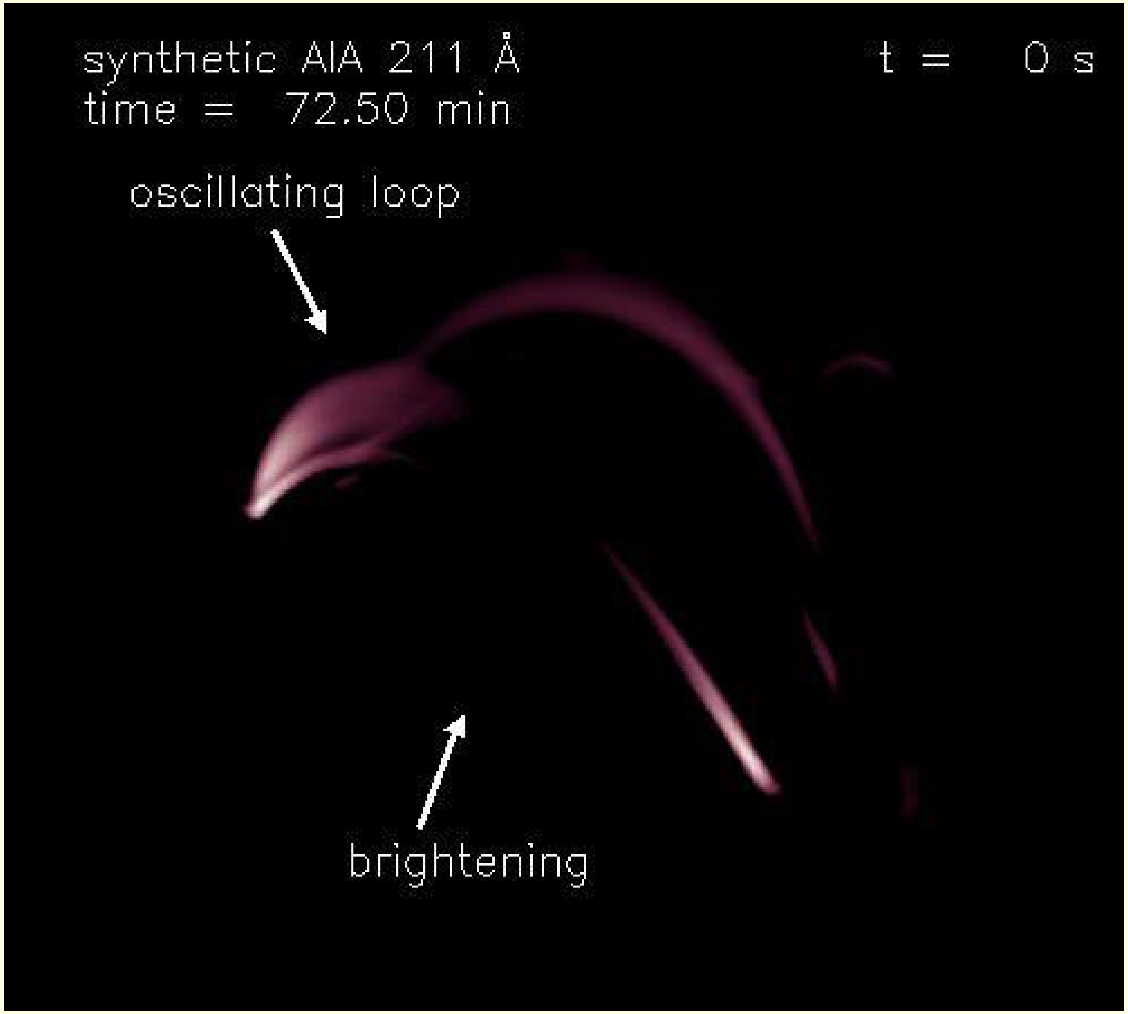
Footpoint heated flaring compact hot loops ?

extension of the reconnection model of UV bursts to heating of compact hot loops



Coronal oscillations

Loop oscillation in the 3D MHD model



Chen & hp (2015) A&A 581, A137

- ► in the model X-point appears
- ► high energy input associated with brightening
- ► this triggers oscillation of nearby loops

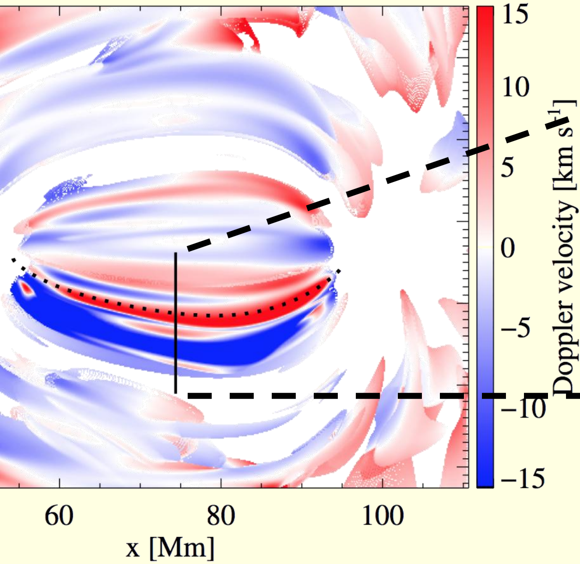
→ how does this compare to observed oscillations?

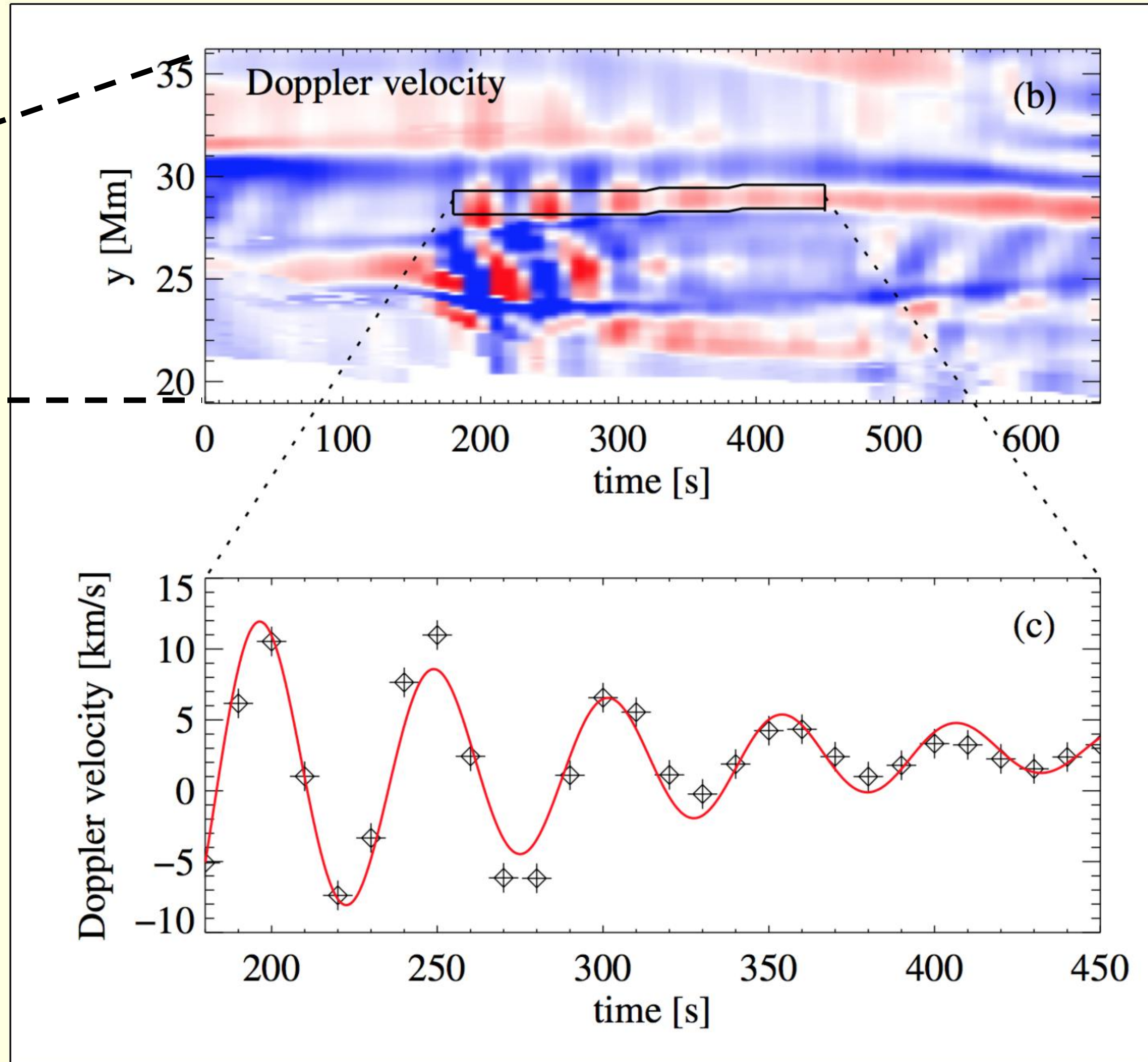
→ what can we learn on magnetic field inferred from coronal seismology?

Oscillation in Doppler shift

(similar for spatial displacement)

top view (“disk center)





oscillation period: ≈ 1 min

damping time: ≈ 2 min

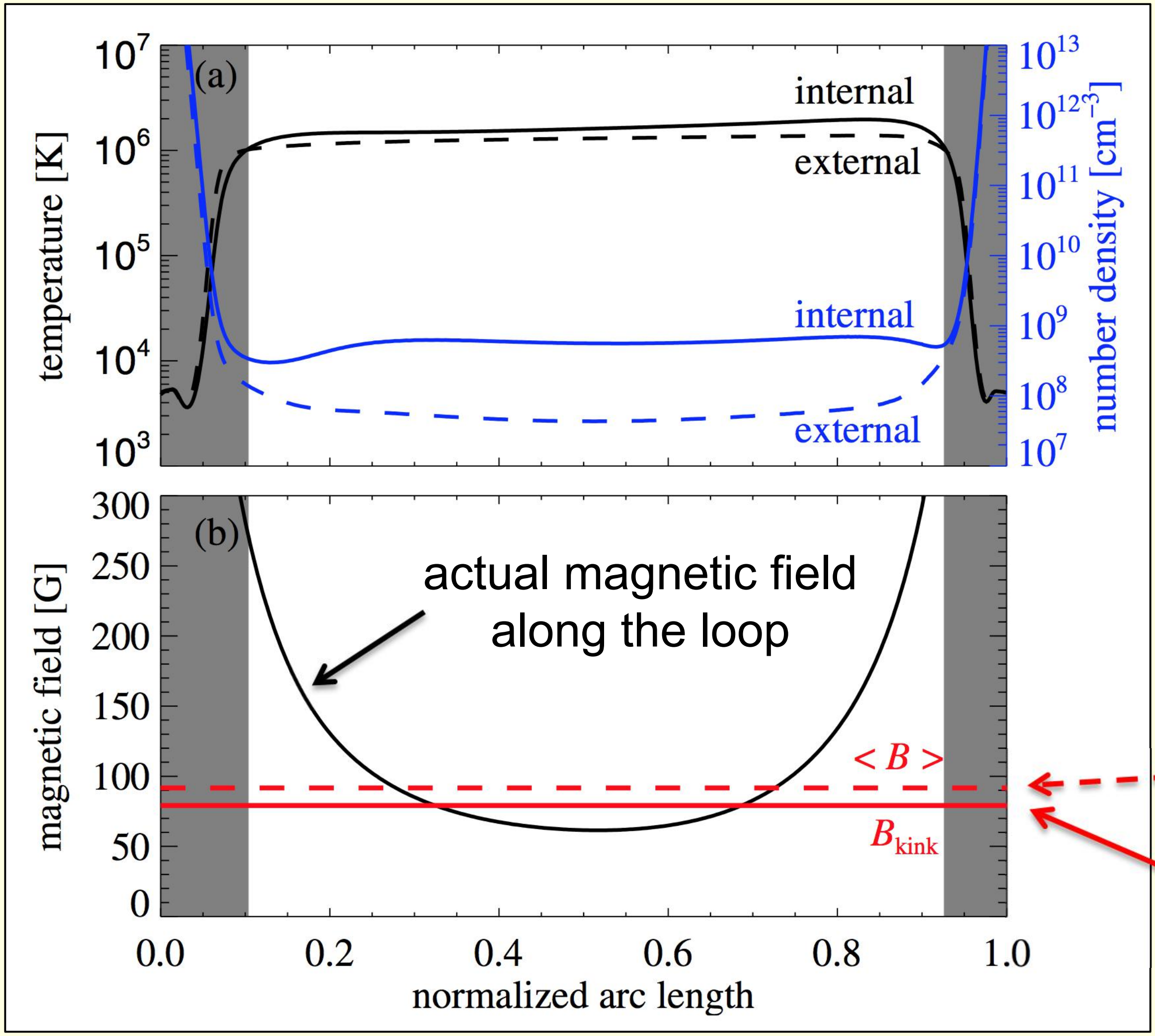
time scales are shorter than observed oscillations

but these loops are much shorter than in obs.:

→ time scales consistent !

Chen & hp (2015) A&A 581, A137

Magnetic field along the loop and average



Chen & hp (2015) A&A 581, A137

magnetic field derived by coronal seismology is consistent with an average

(B of a loop with constant B and same Alfvén crossing time)

→ still, there are only two points where the magnetic field equals the value derived by seismology…

average along loop

$$\langle B \rangle = L \left[\int \frac{ds}{B(s)} \right]^{-1}$$

B_{kink} inferred from seismology

Single-sided heating

1D model **first 5s only !**

- energy input on one side only
- fast T-rise on that side (low density → high energy/particle)
- very fast heat conduction transports energy to other footpoint (in 1s)
- then brightening on other footpoint, too
- in AIA (12 s cadence) brightening at both feet looks co-temporal
- any other fast enough energy transport would do (e.g. energetic particles, but not Alfvén waves)