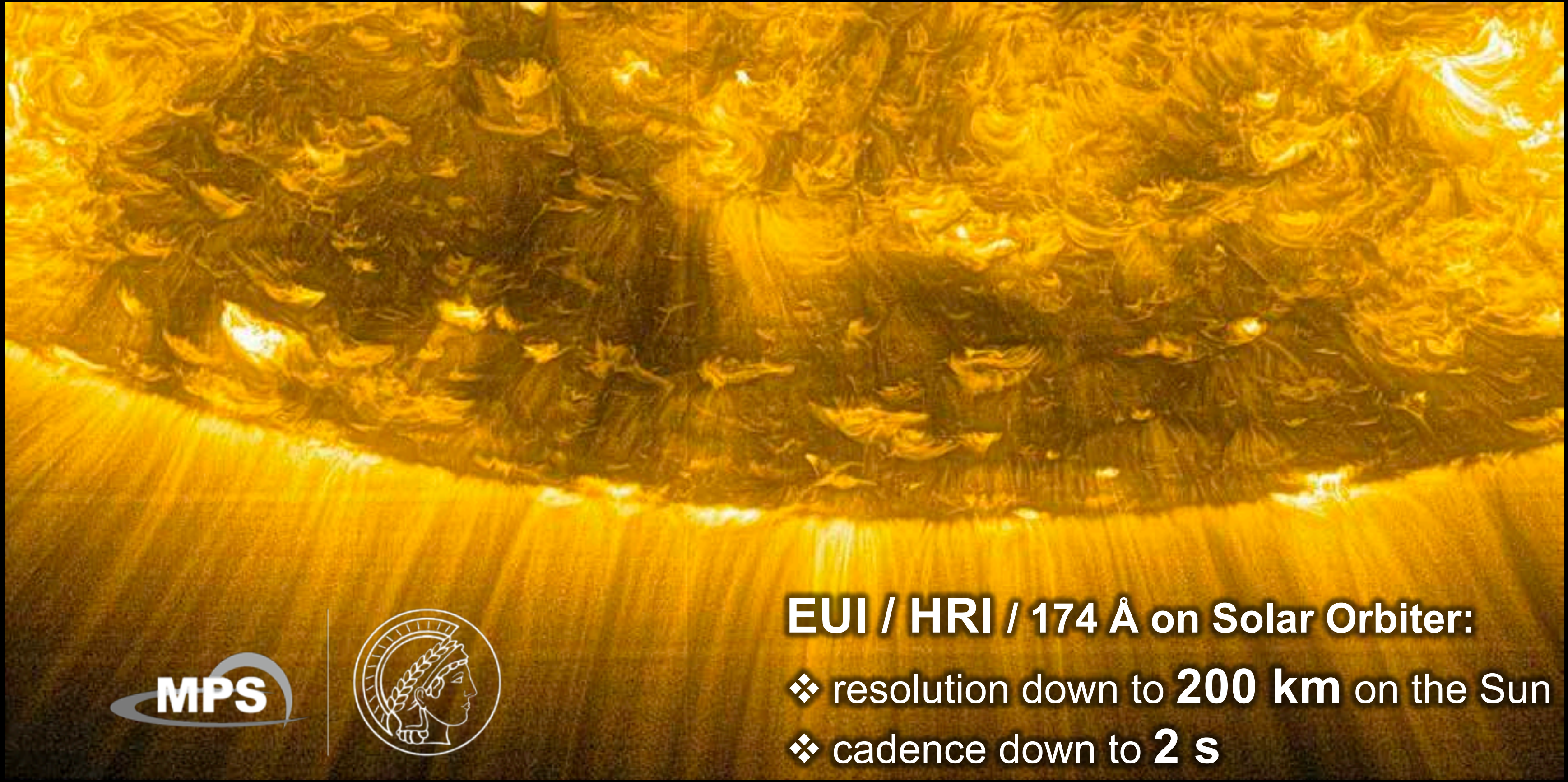
Interplay between modelling and observations of the upper solar atmosphere



processing: L.P. Chitta

Hardi Peter

Max Planck Institute for Solar System Research Göttingen

peter@mps.mpg.de

RoCS/MUSE/IRIS workshop
Feb 28 2023

MAX PLANCK INSTITUTE
FOR SOLAR SYSTEM RESEARCH

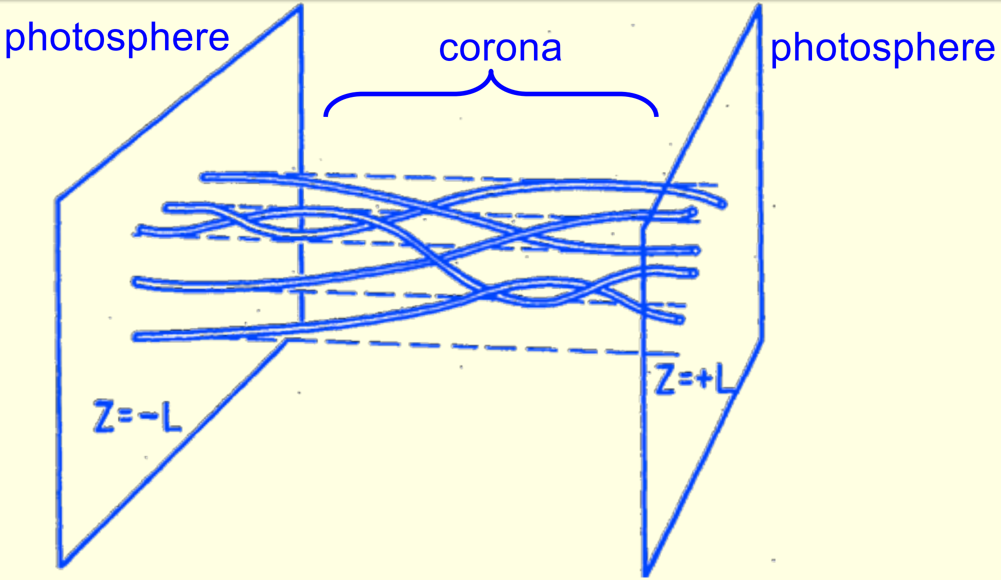
3D models of the TR and corona based on braiding

Field-line braiding / tectonics

► **slow shearing of the magnetic field by horizontal motions in photosphere**
(slower than Alfvén crossing time)

→ **field-line braiding**
(Parker 1972, ApJ 174, 499)

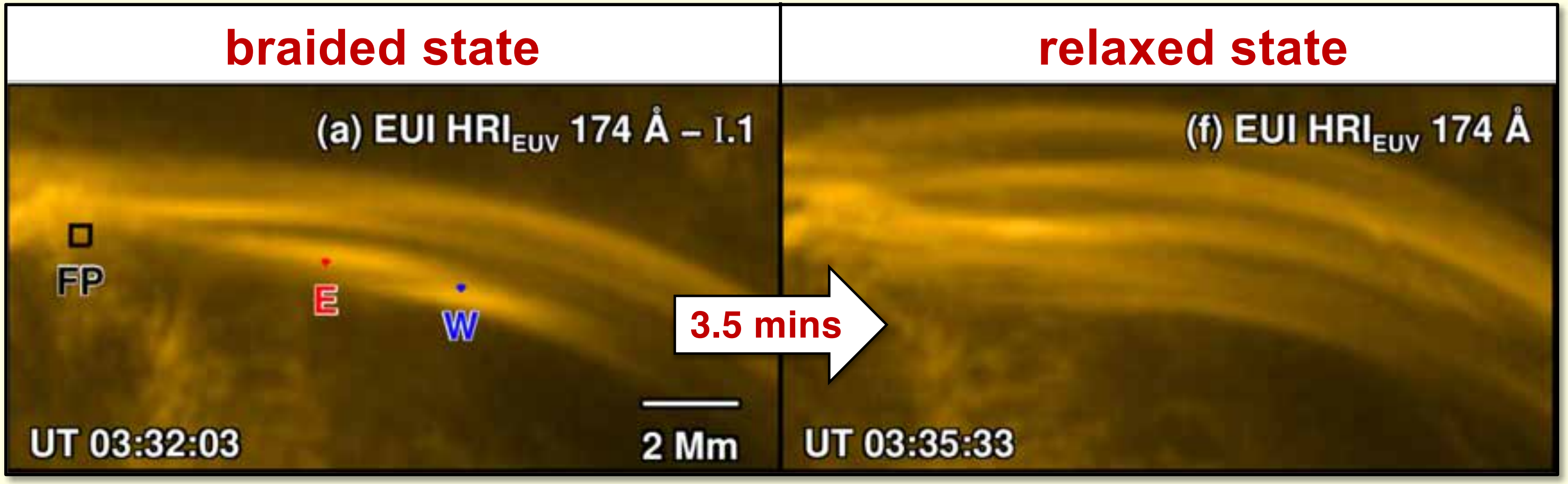
→ **flux-tube tectonics**
(Priest et al. 2002, ApJ 576, 533)



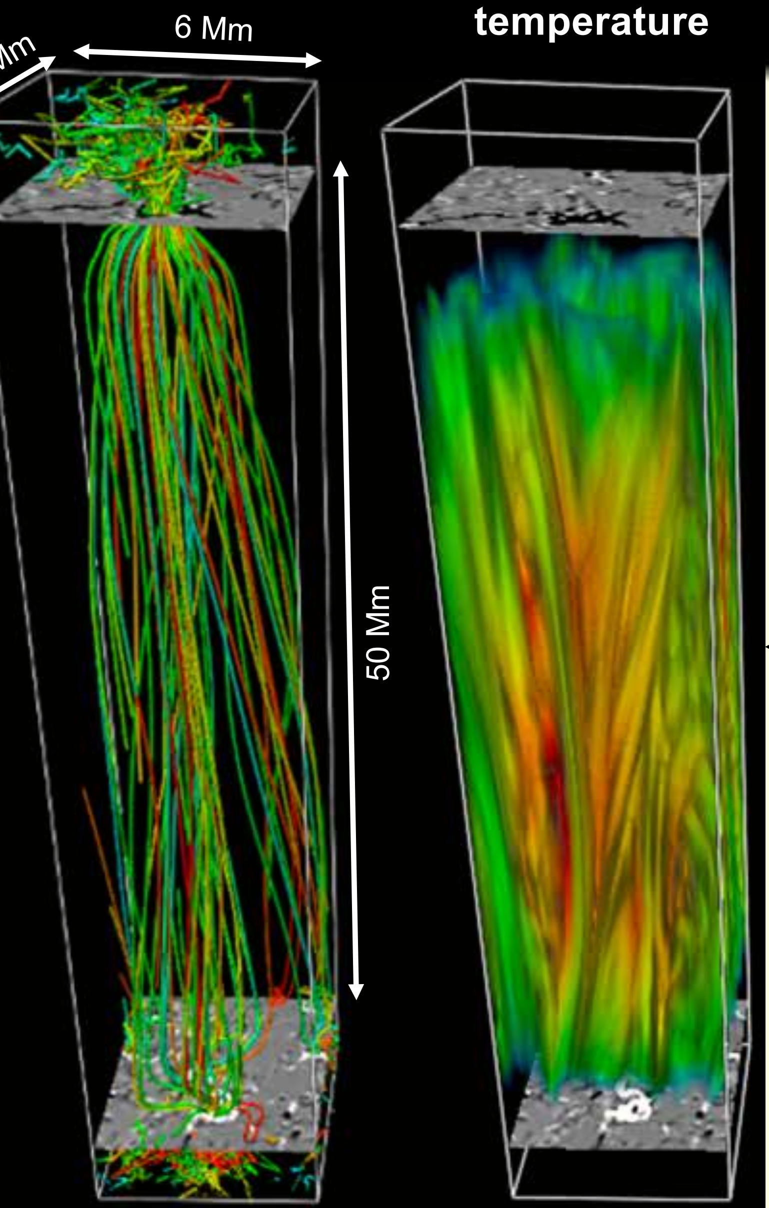
► **direct evidence for braiding is sparse but existent**

e.g. Hi-C 1st flight
(Cirtain et al. 2013; Nat. 493, 501)

or now with EUI →
(Chitta et al. 2022 A&A 667, A166)

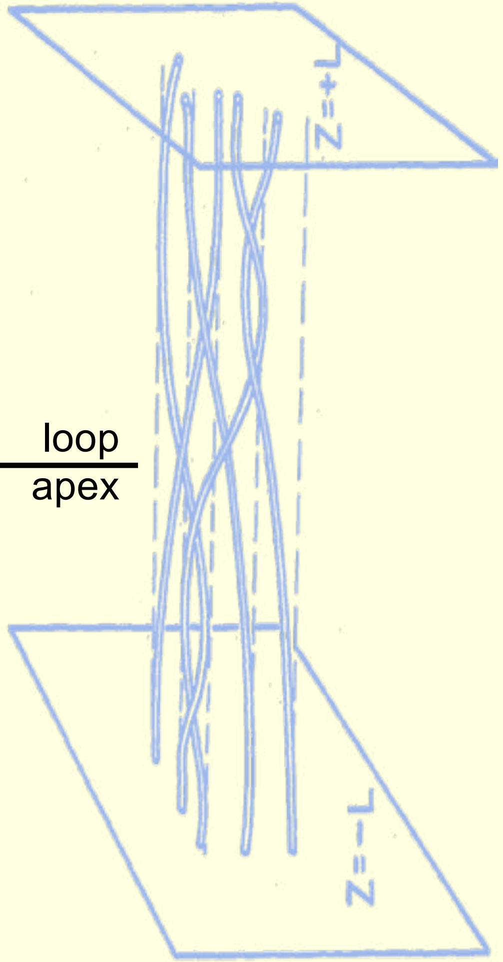


Classical braiding models: Loop in a box



Breu, Peter, Cameron et al. (2022) A&A 658, A45

← photosphere / proper convection zone



← loop apex

← photosphere / proper convection zone

look at a single loop

- straighten out the curved structure so that loop fits in rectangular box with "solar surface at top and bottom"

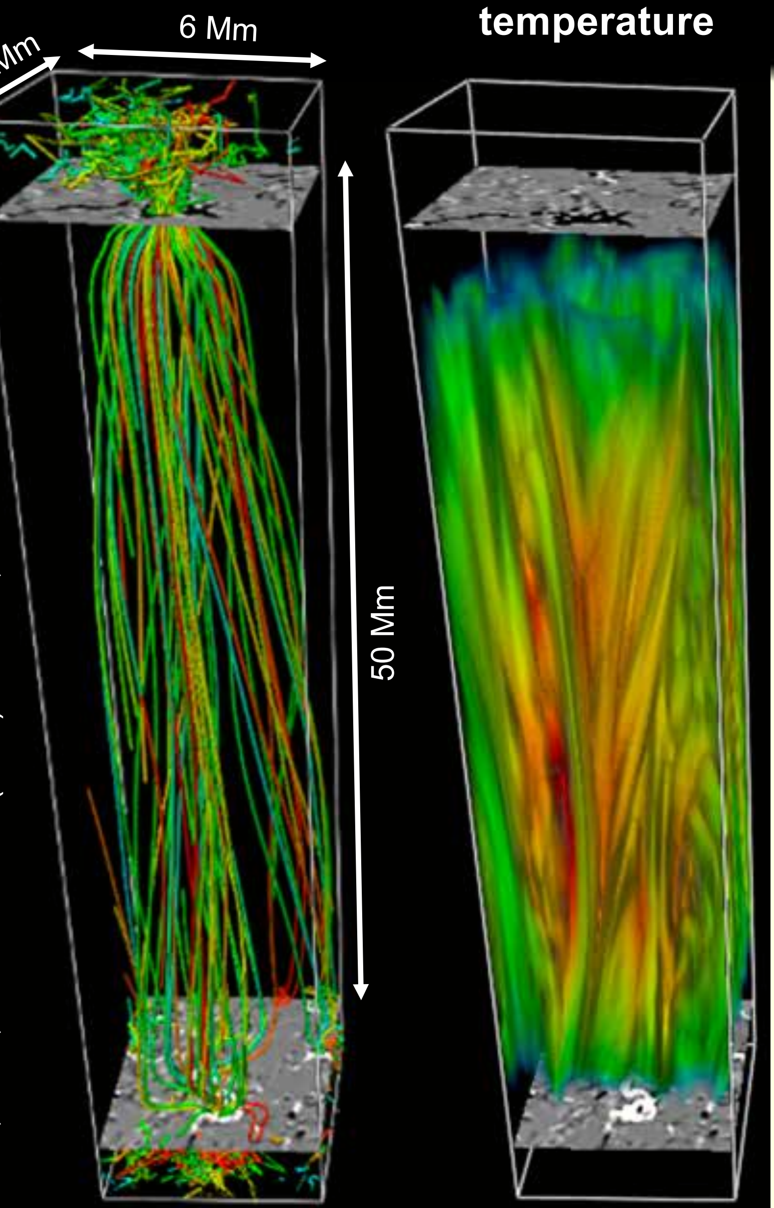
  goes back at least to
  Galsgaard & Nordlund (1996) JGR 101 (A6), 13445

- possible to have self-consistent treatment of photospheric driving

- pro:
  high resolution in loop

- con:
  no interaction of loops

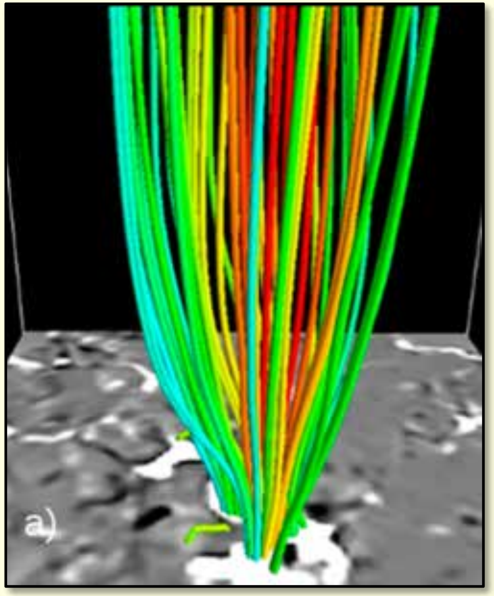
The is nothing like “pure braiding”



Breu, Peter, Cameron et al. (2022) A&A 658, A45

- ❖ any loop is rooted in magnetic concentrations in the photosphere
- ❖ **it is impossible to braid a loop without inducing waves**

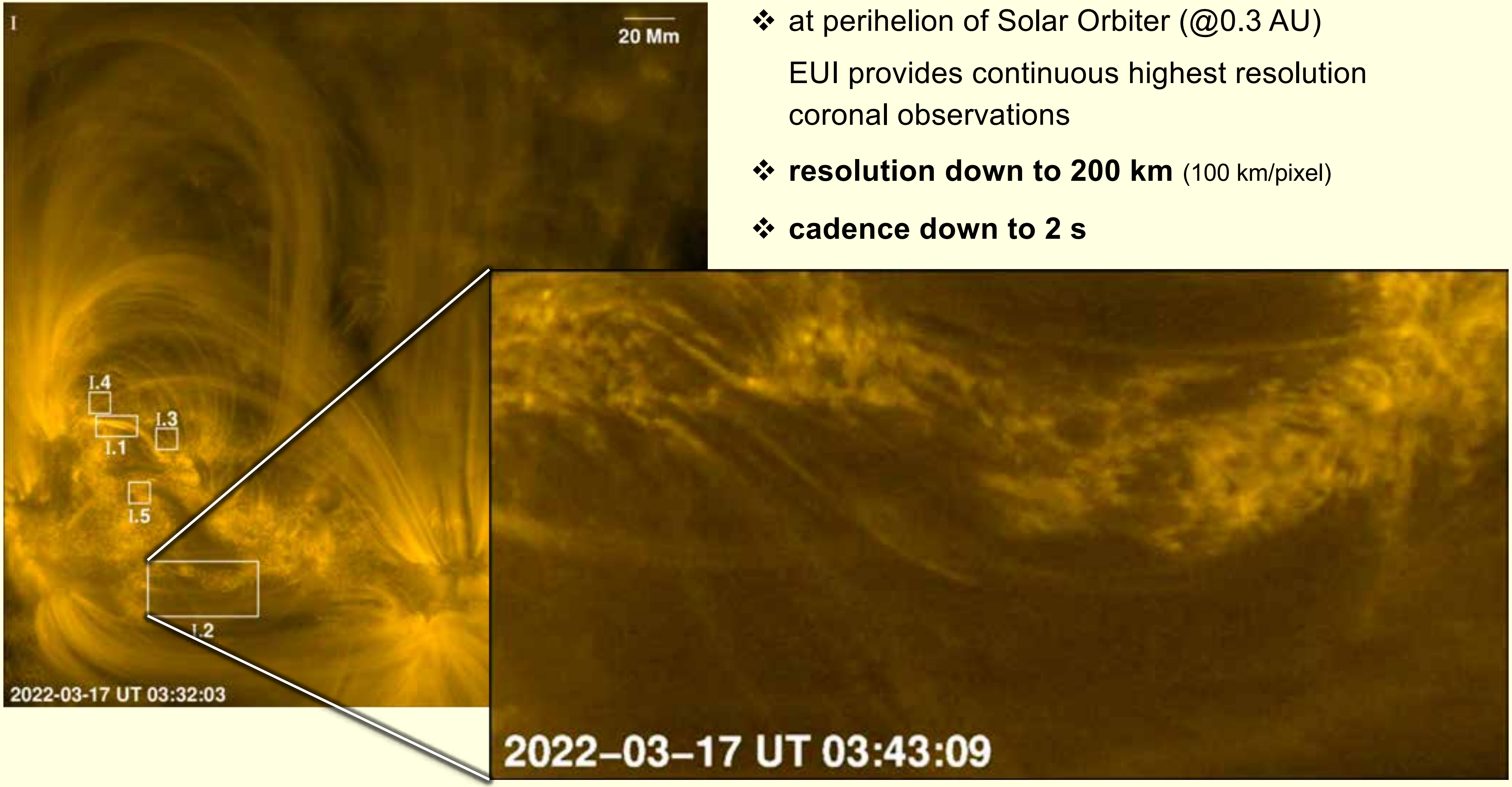
  → question is what is more important…



see talk of **Cosima Breu** later today on non-thermal broadening

Loop (sub) structure and turbulence

Observations of loops substructure



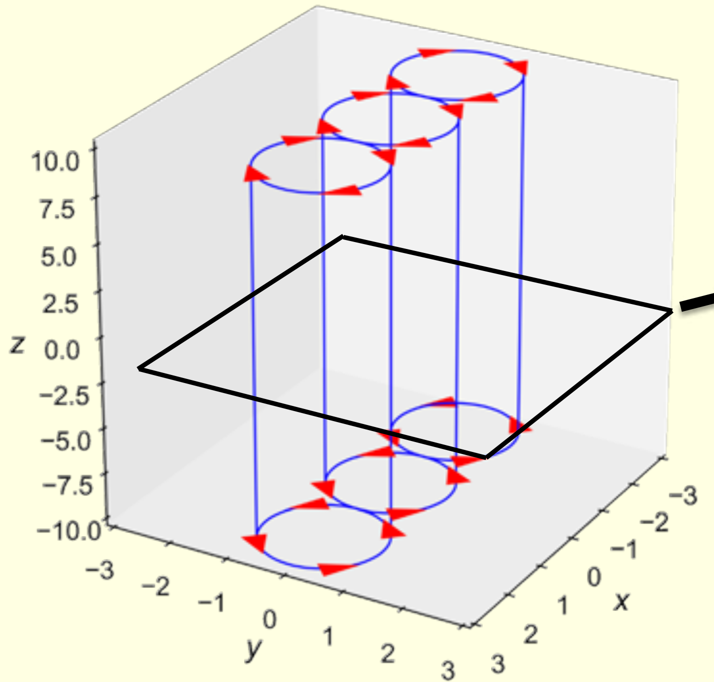
- at perihelion of Solar Orbiter (@0.3 AU)

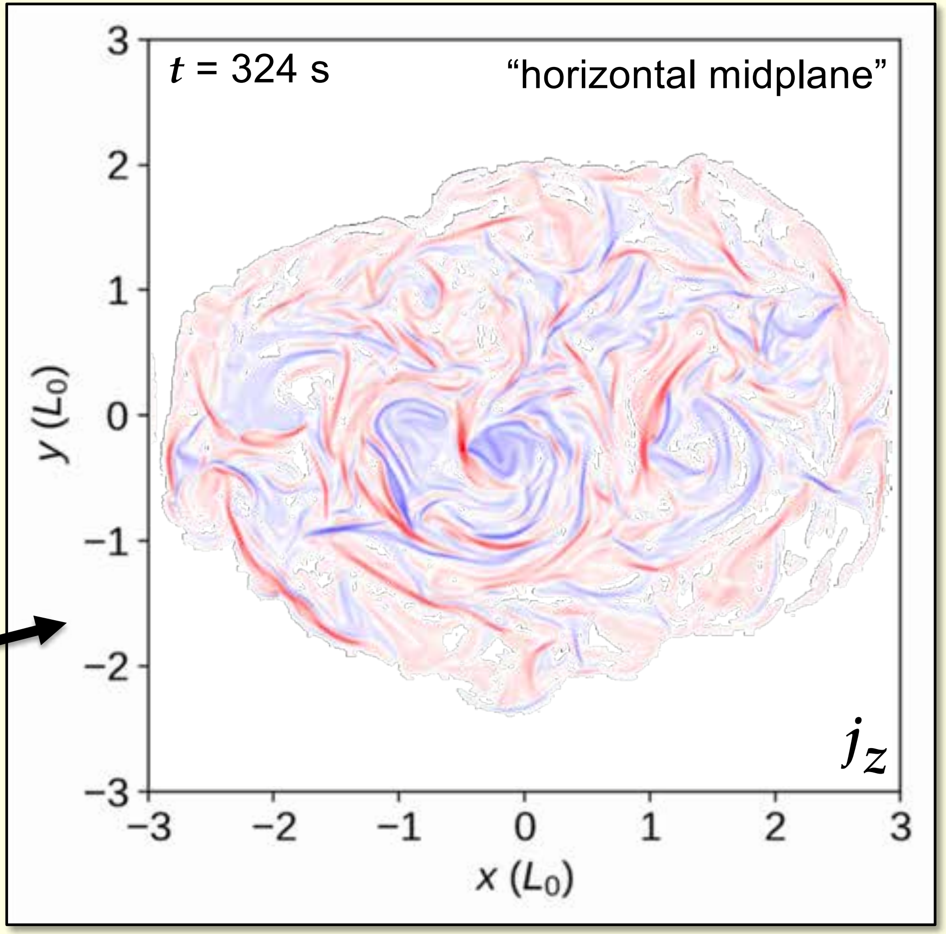
  EUI provides continuous highest resolution coronal observations
- **resolution down to 200 km** (100 km/pixel)
- **cadence down to 2 s**

Chitta. Peter, Parenti, et al. (2022) A&A 667, A166

Driven turbulence in 3D coronal loop models

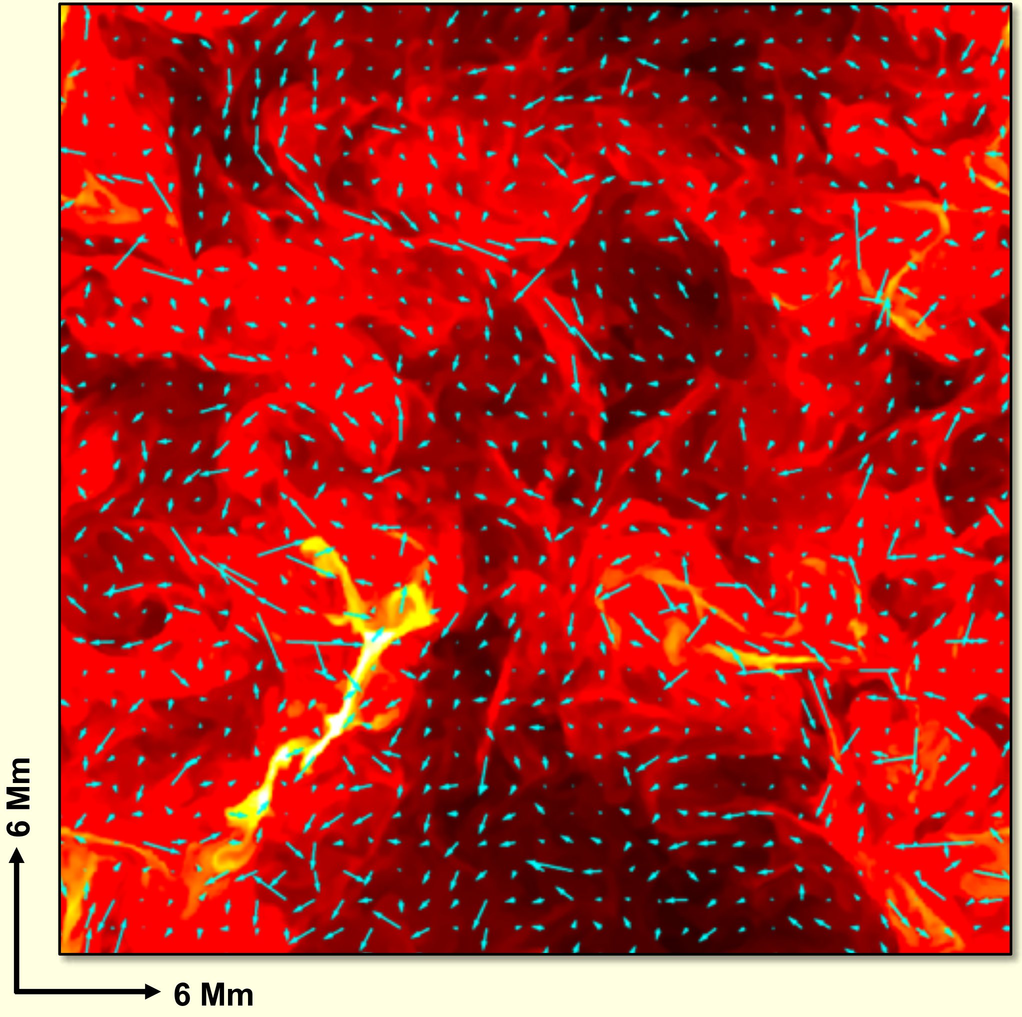
- drive “stretched loops” by rotating footpoints
  (prescribed in three circles)
- model contains no photosphere, just corona
- quickly the whole structure becomes turbulent
  (only few Alfvén crossing times along the loop)
- small current sheets fill whole box





Reid, Hood, Parnell et al. (2018; A&A 615, A84)

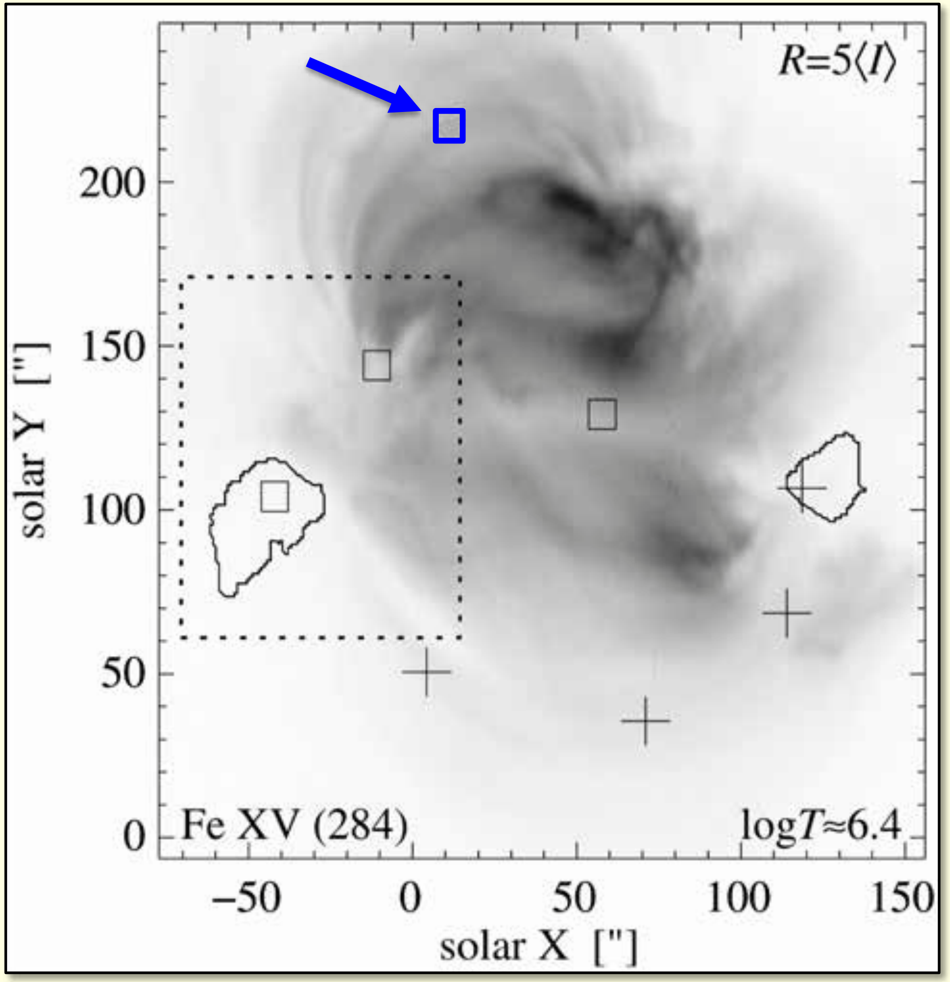
The cross section of a loop will be highly structured



- ❖ **cross-sectional cut of a loop @ apex as XRT would see this cut**
- ❖ based on loop-in-box-model with realistic photospheric driving

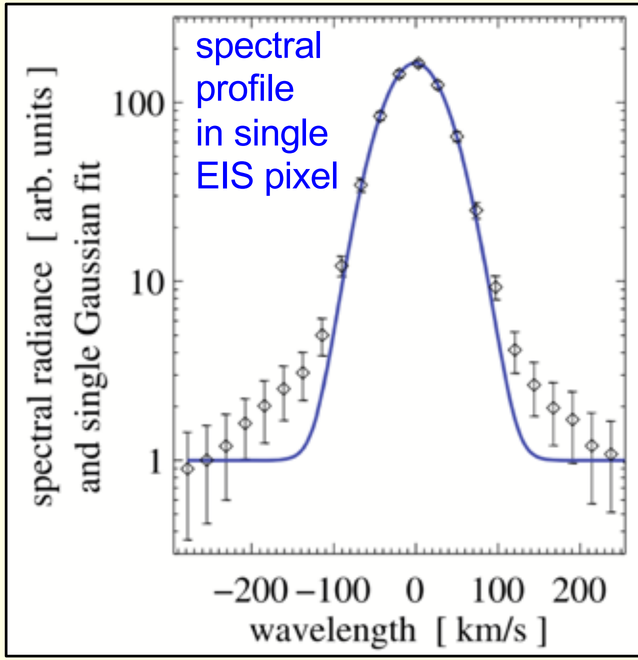
Breu et al. (2023), A&A submitted

A smoking gun? – excess emission in line wings



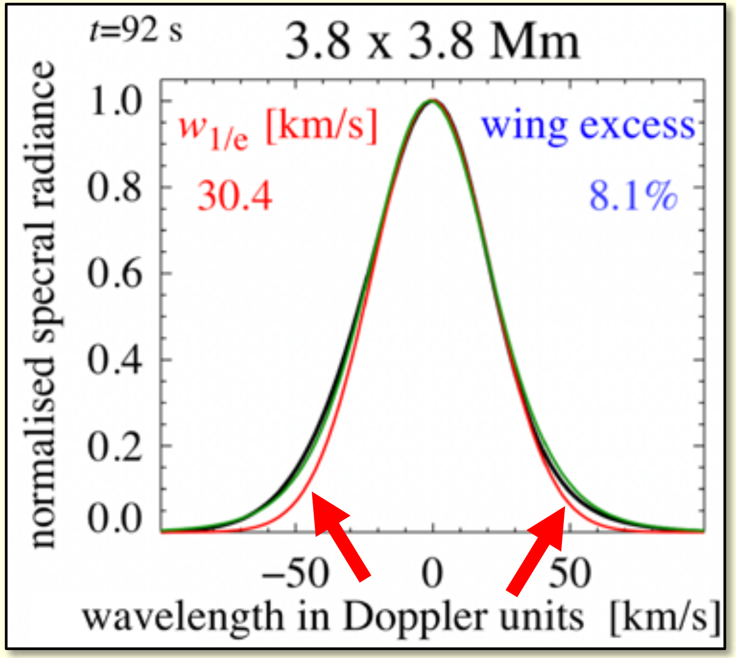
Peter (2010) A&A 521, A51

- if l.o.s. is roughly perpendicular to coronal loop:
  → **symmetric enhancement in both wings**
- seen in active region coronal loops (1−3 MK)
- also in cool (0.1 MK) loops in active regions (Li+Peter 2019; A&A 626, A98)



Velocity distribution and spectral line profiles

3D loop model for the relaxation of braided field: side view in Fe XII



Pontin, Peter, Chitta (2020; A&A 639, A21)

- MHD turbulent motions in direction perpendicular to guide field
- velocity distribution shows deviations from a Maxwellian (often closer to κ-distribution)
- **this results in excess emission in the line wings**

synthesized **spectral line profile** with l.o.s. ⊥ loop

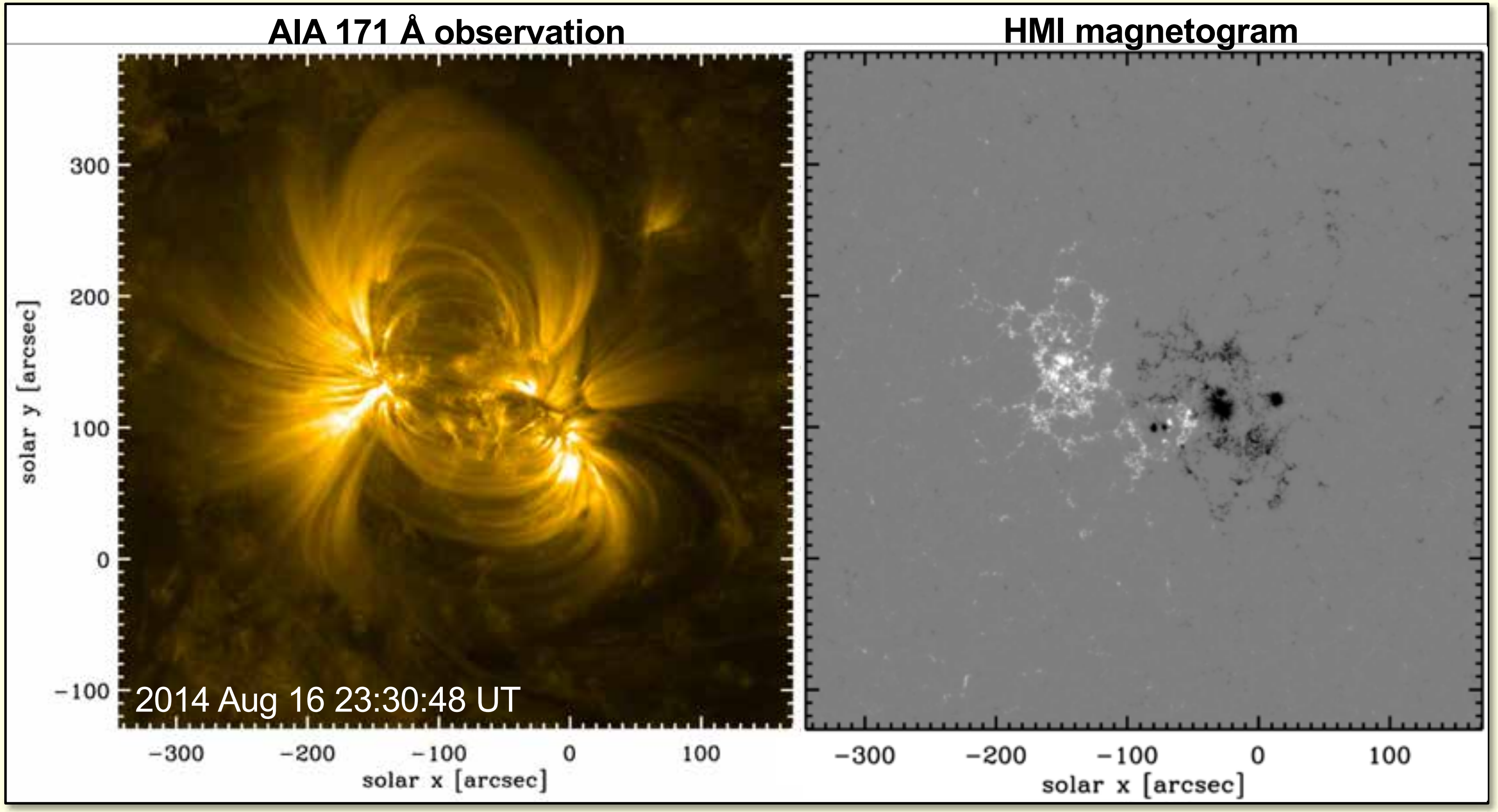
line profile / velocity distribution
kappa fit
single Gaussian fit

Large active region loops

Reproducing an observed active region

- use an observed active region magnetogram and its temporal evolution
- feed this into a 3D MHD model as a time-dependent boundary condition
- let the corona above it evolve

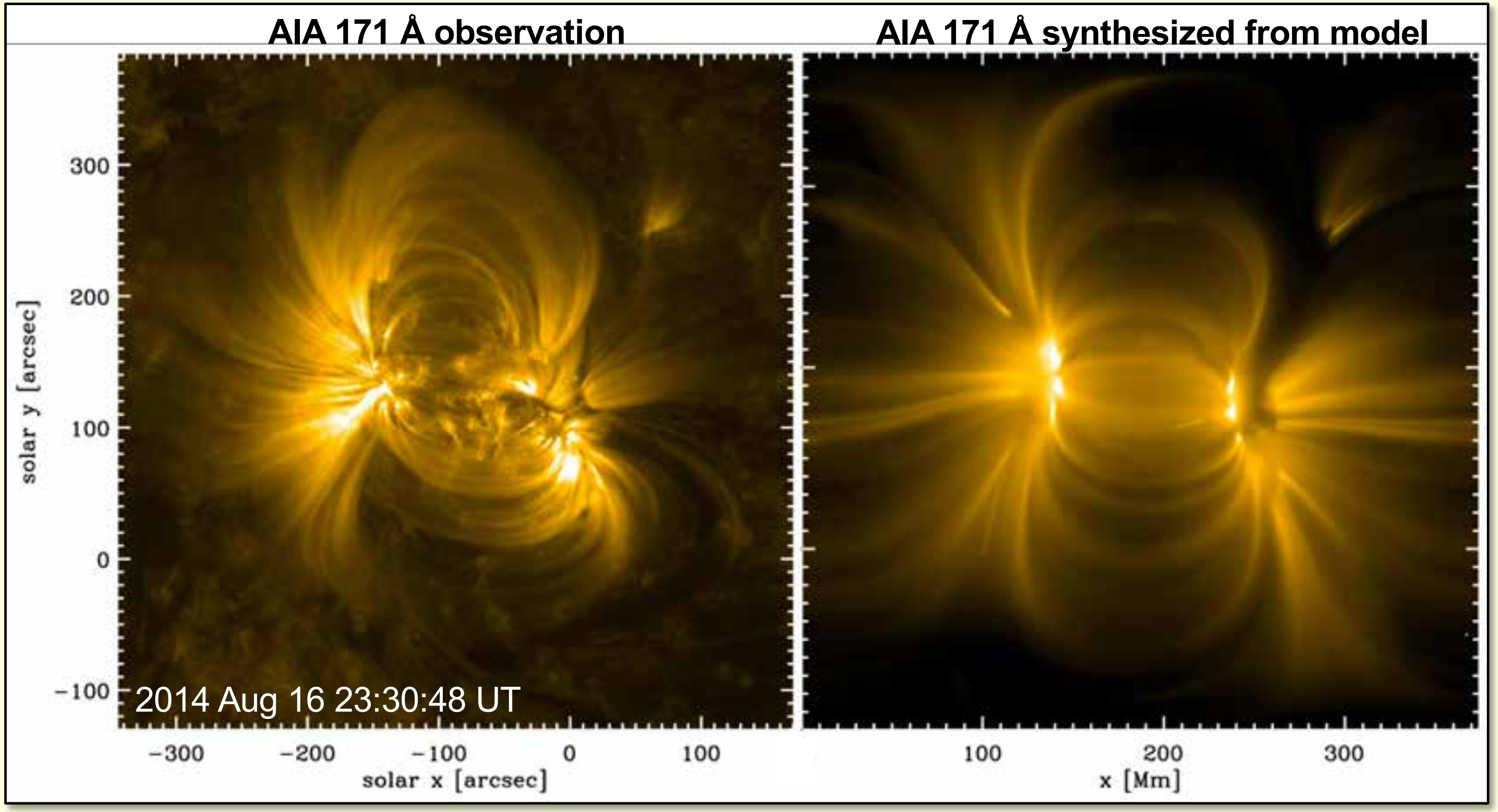
similar to
Gudiksen & Nordlund (2002)
ApJ 572, L113



Warnecke & Peter (2019; A&A 624, L12)

Reproducing an observed active region

- use an observed active region magnetogram and its temporal evolution
- feed this into a 3D MHD model as a time-dependent boundary condition
- let the corona above it evolve → compare to real corona observed at the same time

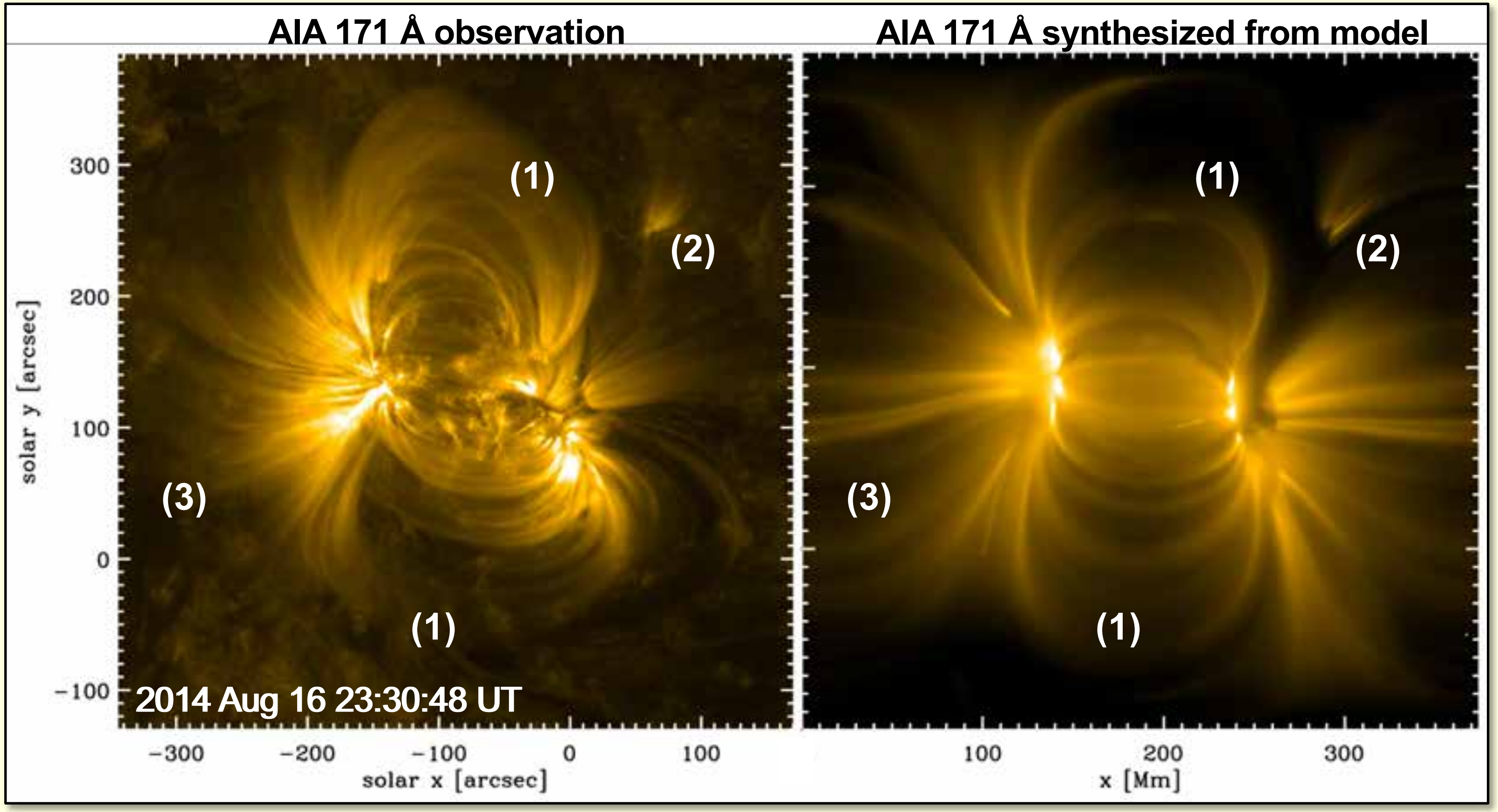


grid spacing in model matches plate scale in obs. (0.5” ≈ 365 km)

Warnecke & Peter (2019; A&A 624, L12)

Reproducing an observed active region

common features:
(1) large loops connecting the main polarities
(2) fan(s) at edges of the AR
(3) background (i.e. low contrast loops)

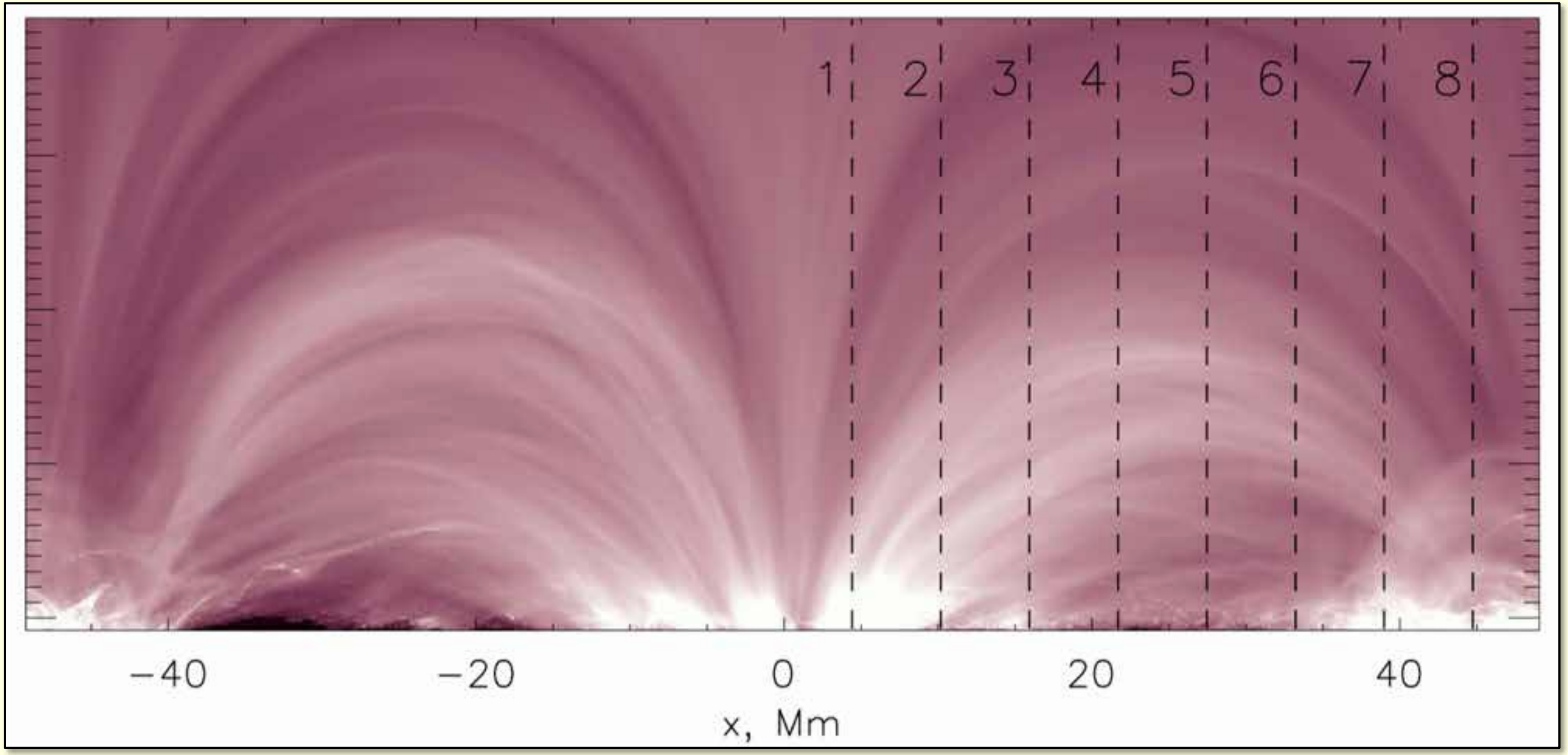


grid spacing in model matches plate scale in obs. (0.5” ≈ 365 km)

Warnecke & Peter (2019; A&A 624, L12)

Higher resolution → more structure: a coronal veil

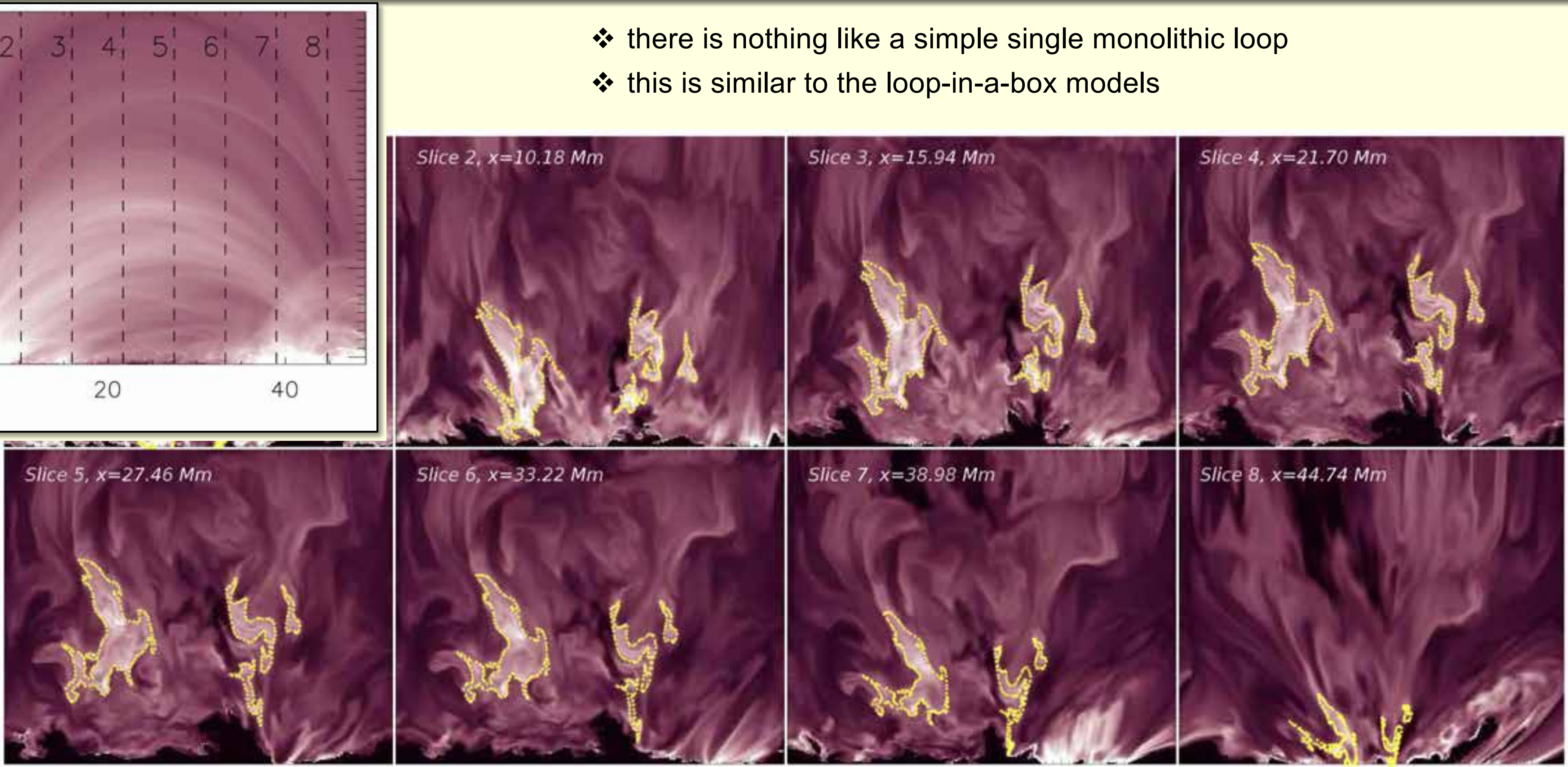
- side view of a more recent 3D MHD model
- much higher resolution → much more sub-structure



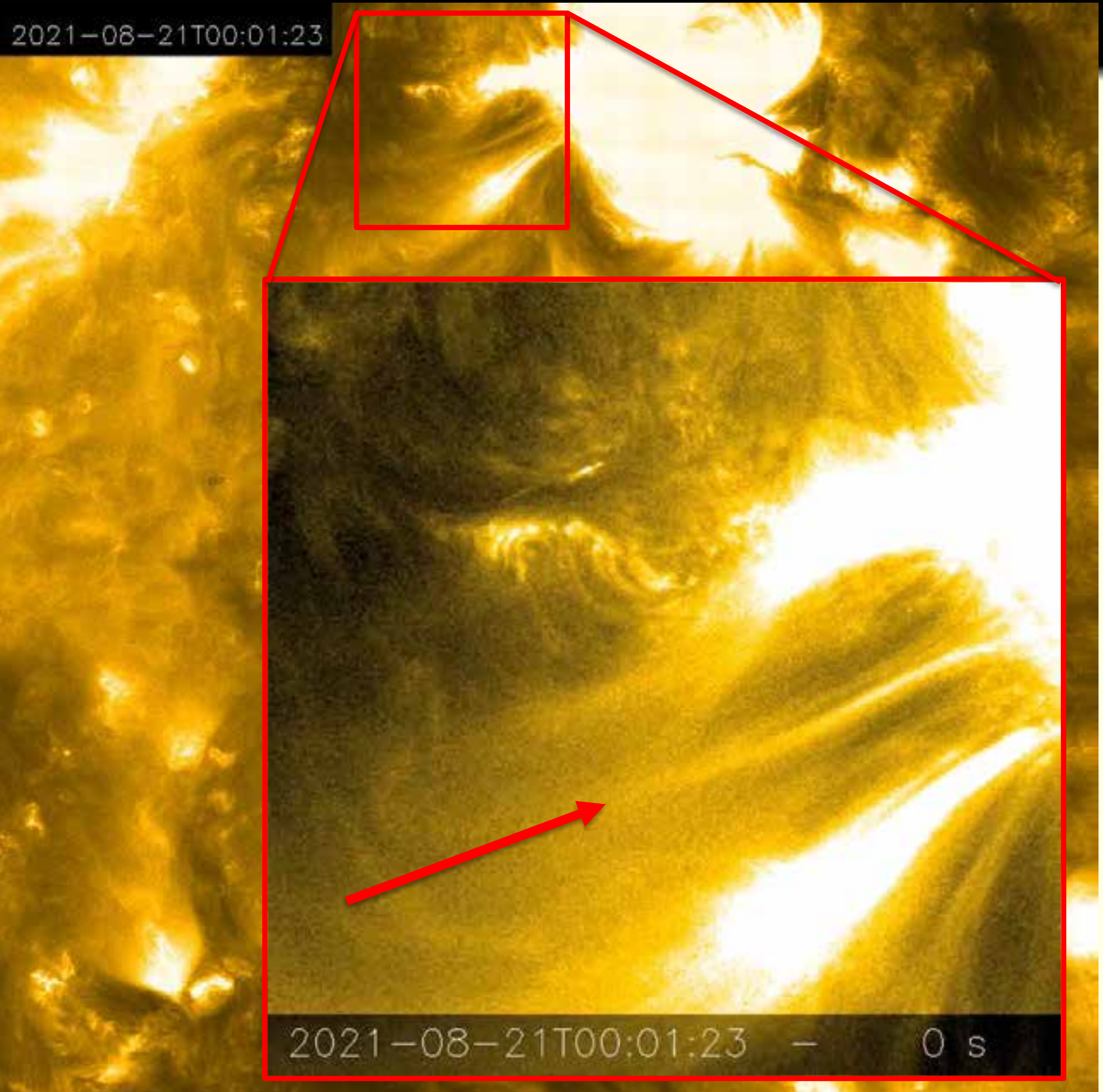
Malanushenko, Cheung, de Forest, et al. (2022) ApJ 927, 1

Coronal Veil

- there is nothing like a simple single monolithic loop
- this is similar to the loop-in-a-box models



Malanushenko, Cheung, de Forest, et al. (2022) ApJ 927, 1



Stable thick AR loop

- AR observation in August 2021
  with Solar Orbiter / EUI / HRT EUV 174 Å
- distance: 0.65 AU → ca. 240 km / pixel
- 5 s cadence
- 1 MK loops in periphery of AR

- ca. 50 Mm long loop
  evolving only gradually
  over more than one hour
- seems to be a smooth thick loop:

  FWHM ≈ 7 pixel (>1.5 Mm)
- **somehow the Sun has to find ways to avoid being messy**

hp et al., in prep

small-scale transient brightenings

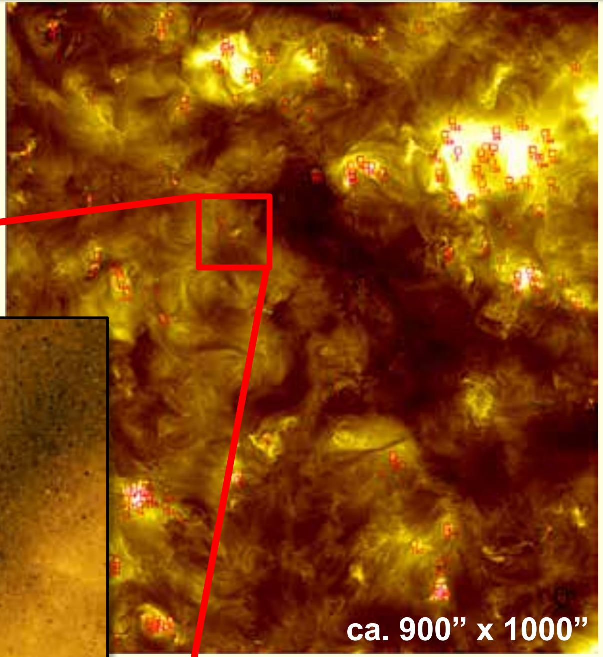
Extreme-UV quiet Sun brightenings (aka campfires)

- ubiquitous EUV brightenings in the quiet Sun
- **short lifetime** (< minutes)
- **small size** (Mm and smaller)
- low in the atmosphere (triangulation)

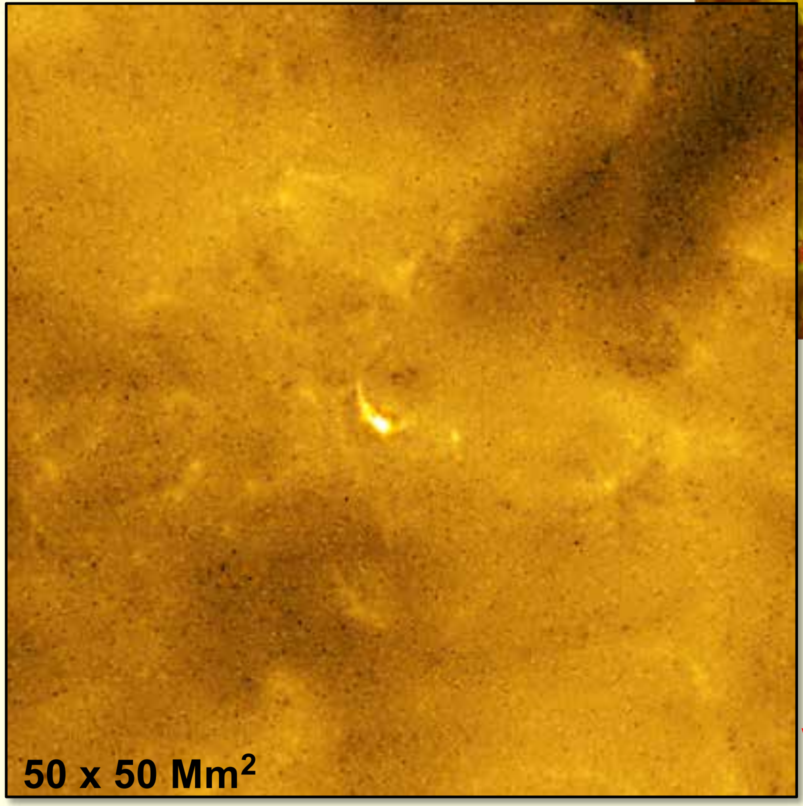
  (Berghmans et al. (2021) A&A 656, L4)

- often but not always related to flux cancellation
  - Panesar et al. (2021) ApJL 921, L20
  - Kahil et al. (2022) A&A 660, A143

Berghmans et al. (2021) A&A 656, L4



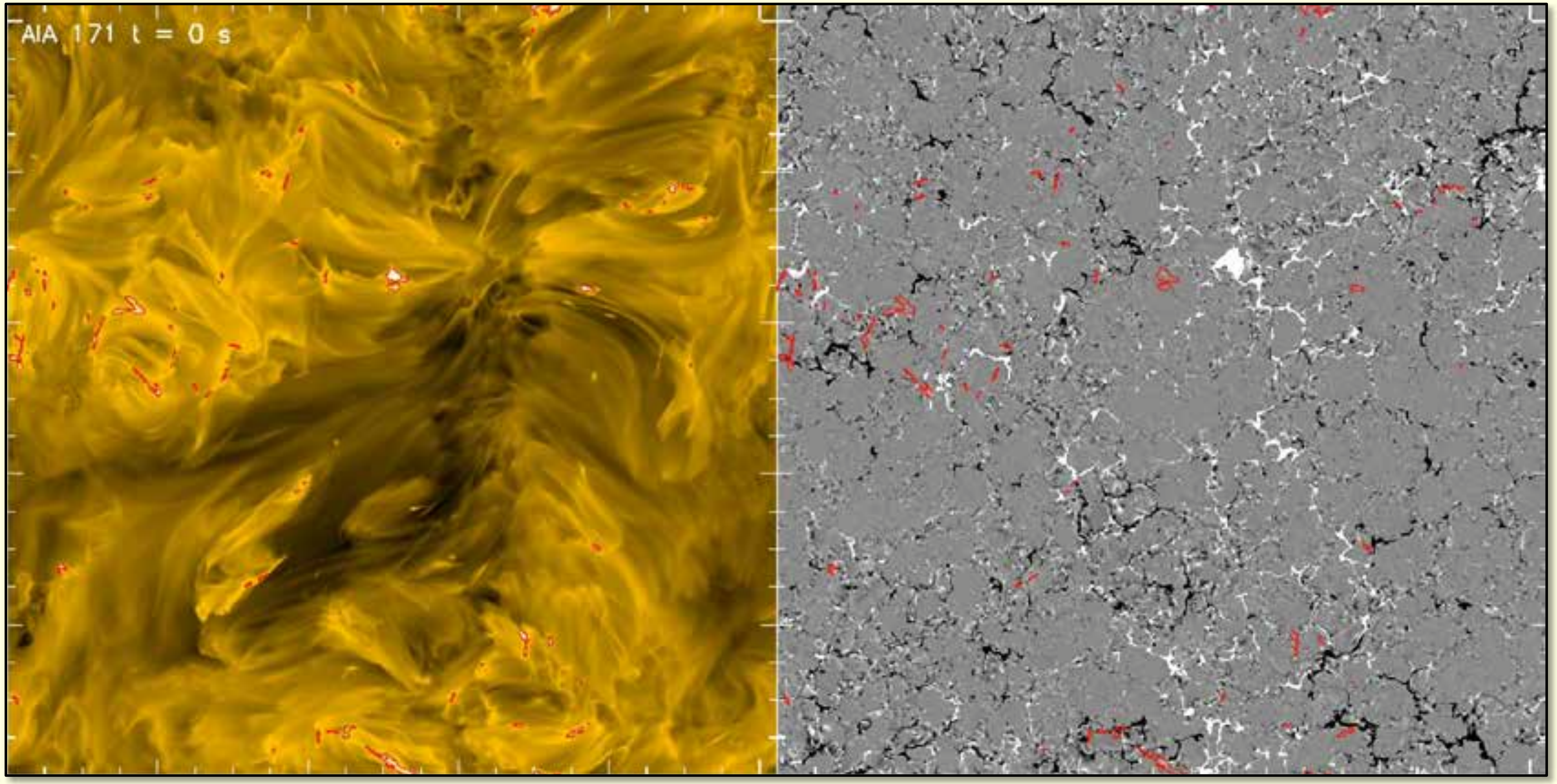
EUI / HRI / 174 Å



Transient quiet Sun EUV brightenings in a 3D MHD model

- quiet Sun model
- magnetic field based solely on small-scale dynamo

Chen, Przybylski, Peter, et al. (2021) A&A 656, L7



50 x 50 Mm^2

synthesized coronal emission
(seen from straight above)

vertical magnetic field at surface
(average τ=1)

Transient quiet Sun EUV brightenings in a 3D MHD model

Chen, Przybylski, Peter, et al. (2021) A&A 656, L7

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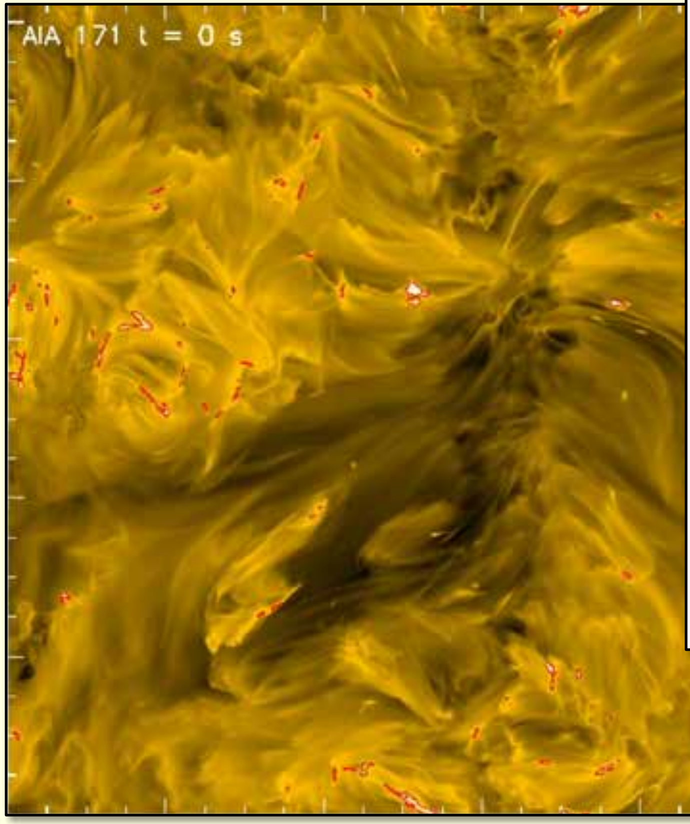
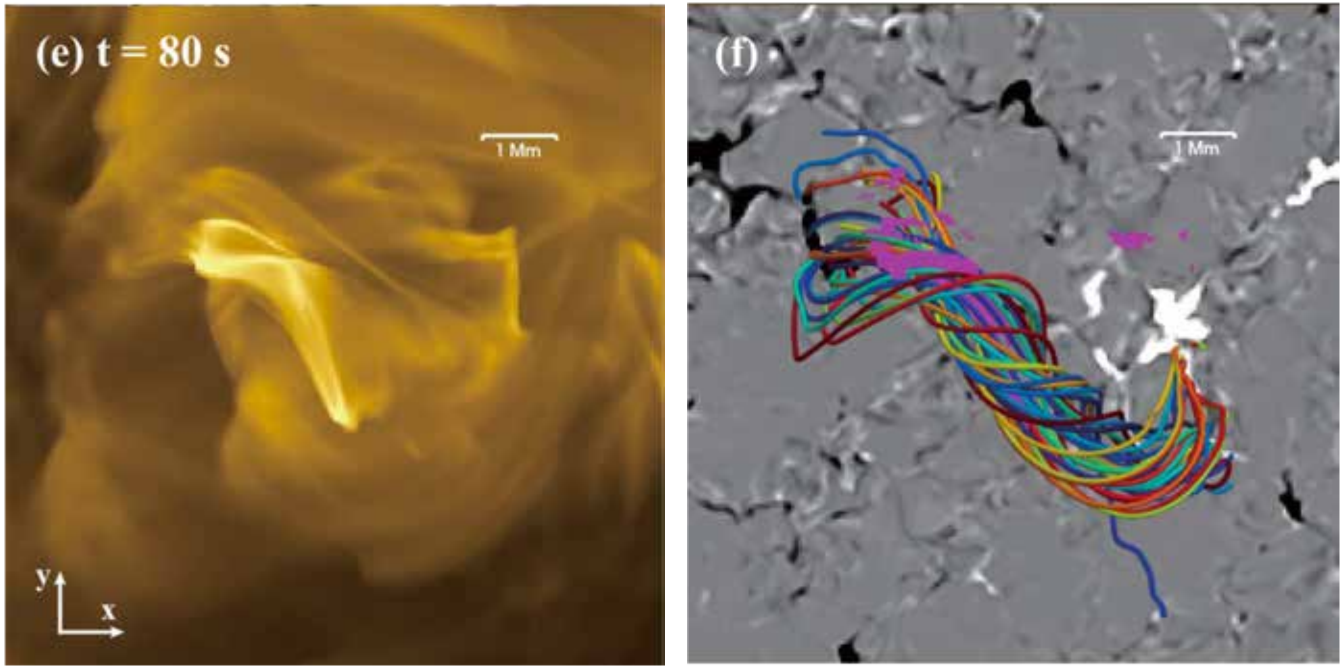
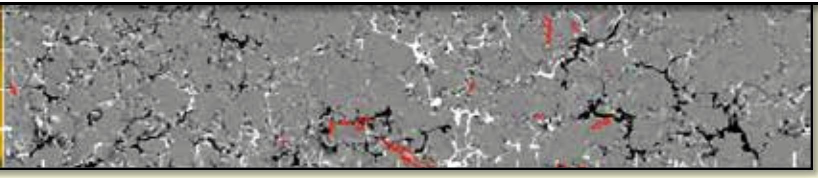


one case: relaxing helical flux-rope structure



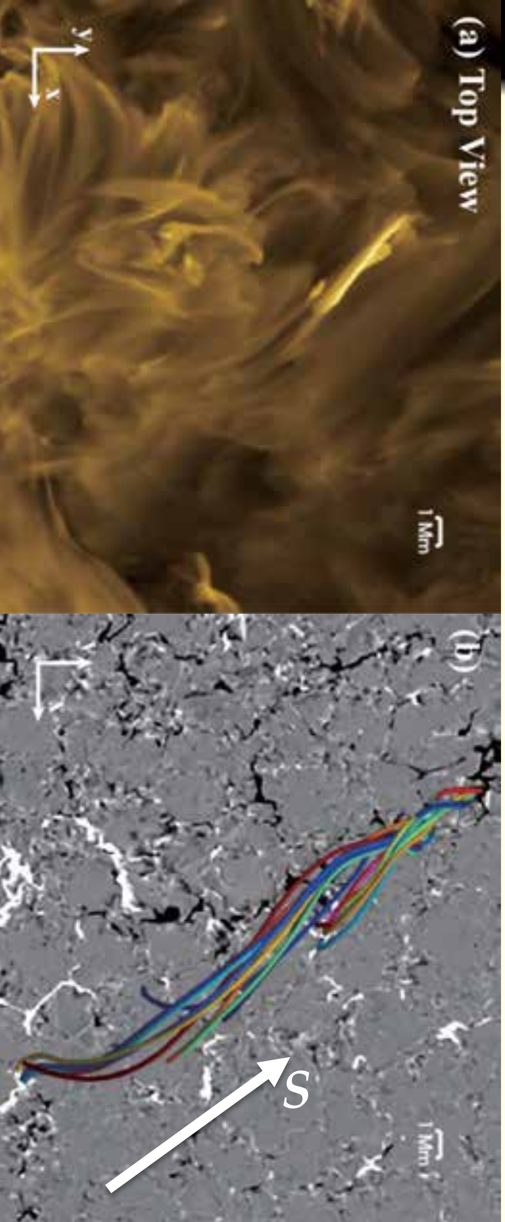


50 x 50 Mm^2

synthesized coronal emission
(seen from straight above)

vertical magnetic field at surface
(average $\tau=1$)

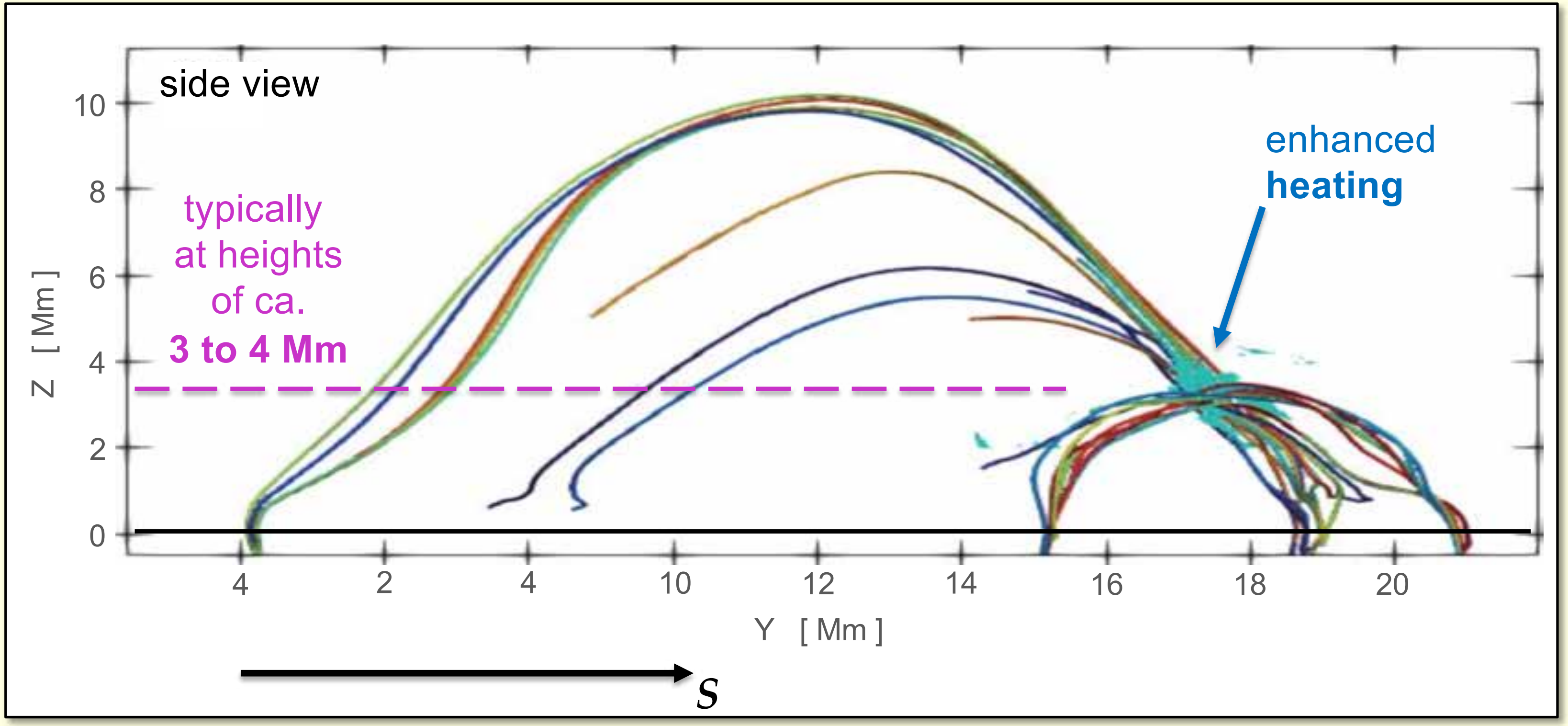
Transient QS EUV brightenings in a 3D MHD model



more typical cases:

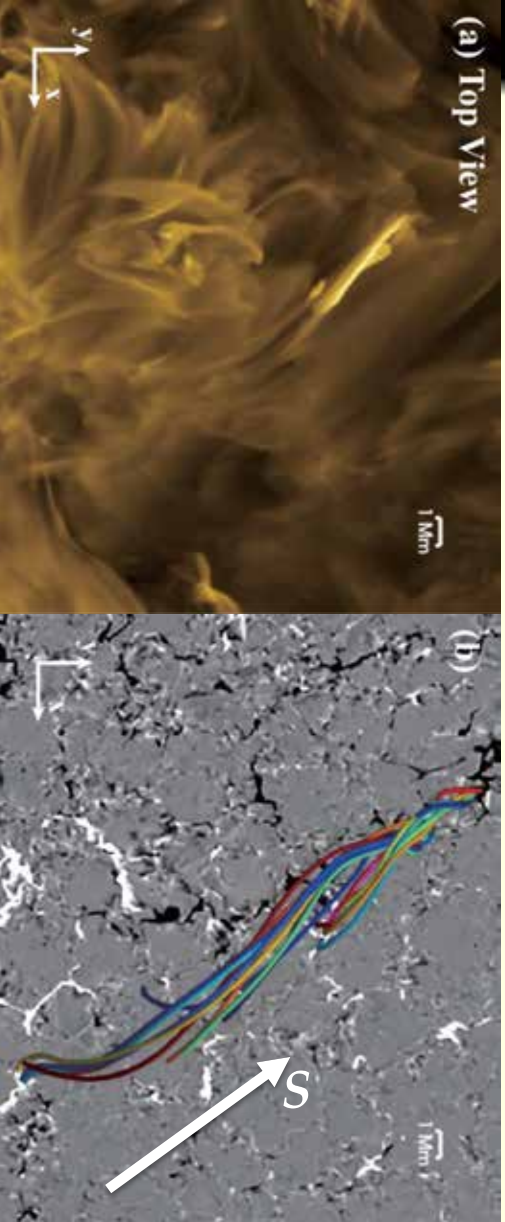
Chen, Przybylski, Peter, et al. (2021) A&A 656, L7

❖ reconnection where field-line bundles interact → **increase of T → brightening**



similar process found also for higher magnetic activity in microflares (Li et al. 2022; ApJL 930, L7)

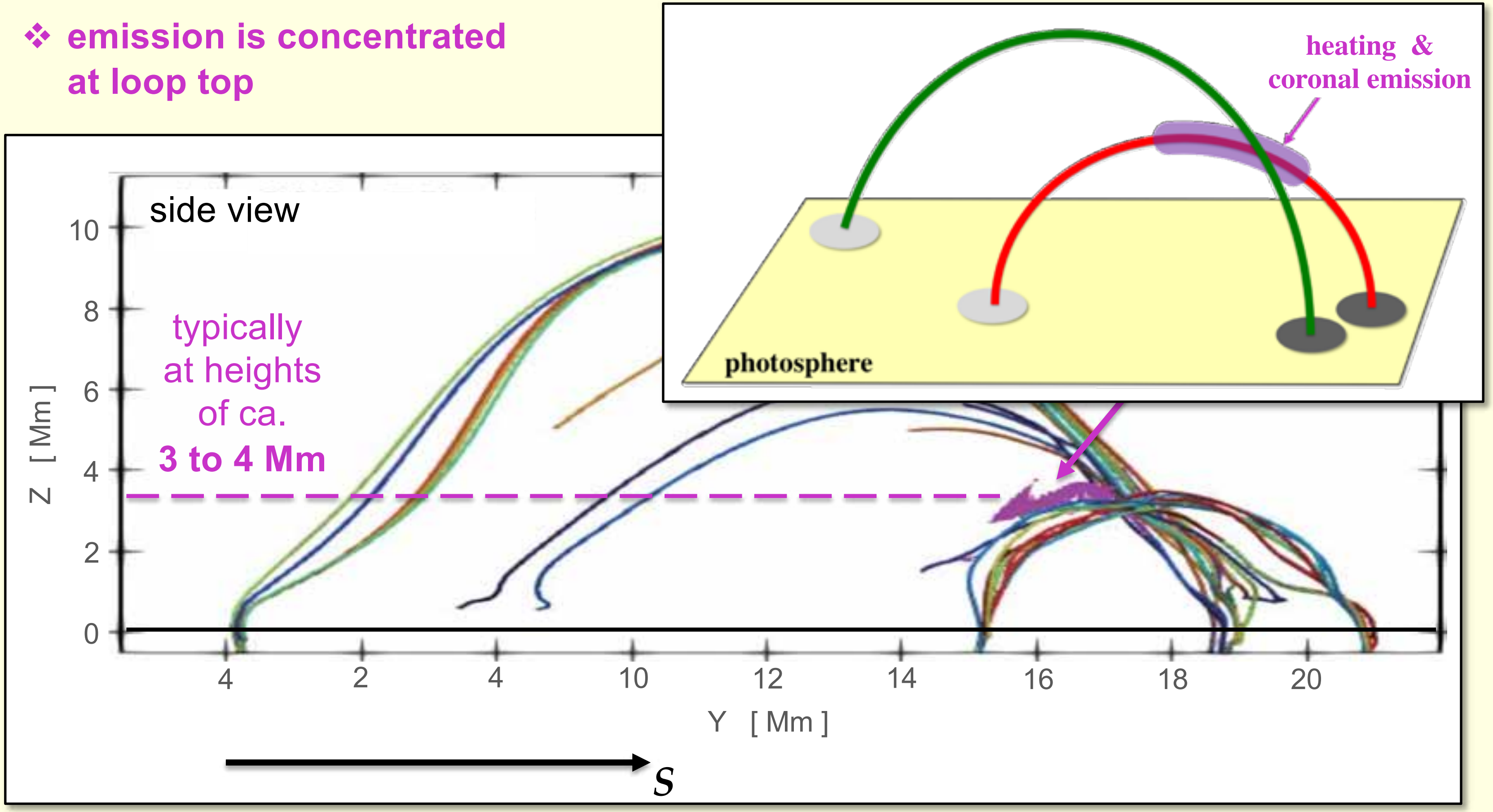
Transient QS EUV brightenings in a 3D MHD model



more typical cases:

Chen, Przybylski, Peter, et al. (2021) A&A 656, L7

- reconnection where field-line bundles interact → **increase of T → brightening**
- **emission is concentrated at loop top**

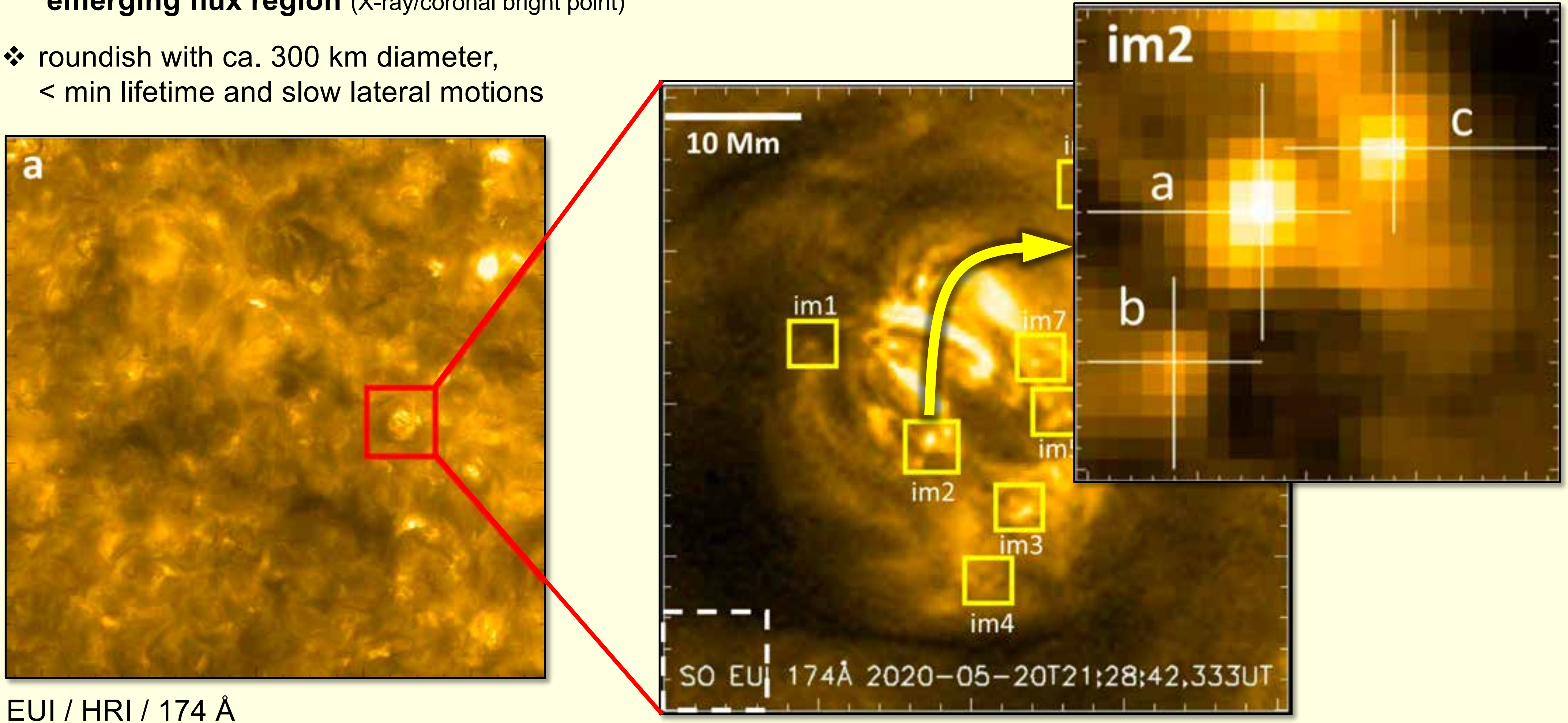


similar process found also for higher magnetic activity in microflares (Li et al. 2022; ApJL 930, L7)

Fine-scale Bright Dots in an Emerging Flux Region

Tiwari et al. (2022) ApJ 929, id.103

- **tiny bright dots in and around emerging flux region** (X-ray/coronal bright point)
- roundish with ca. 300 km diameter, < min lifetime and slow lateral motions



EUI / HRI / 174 Å

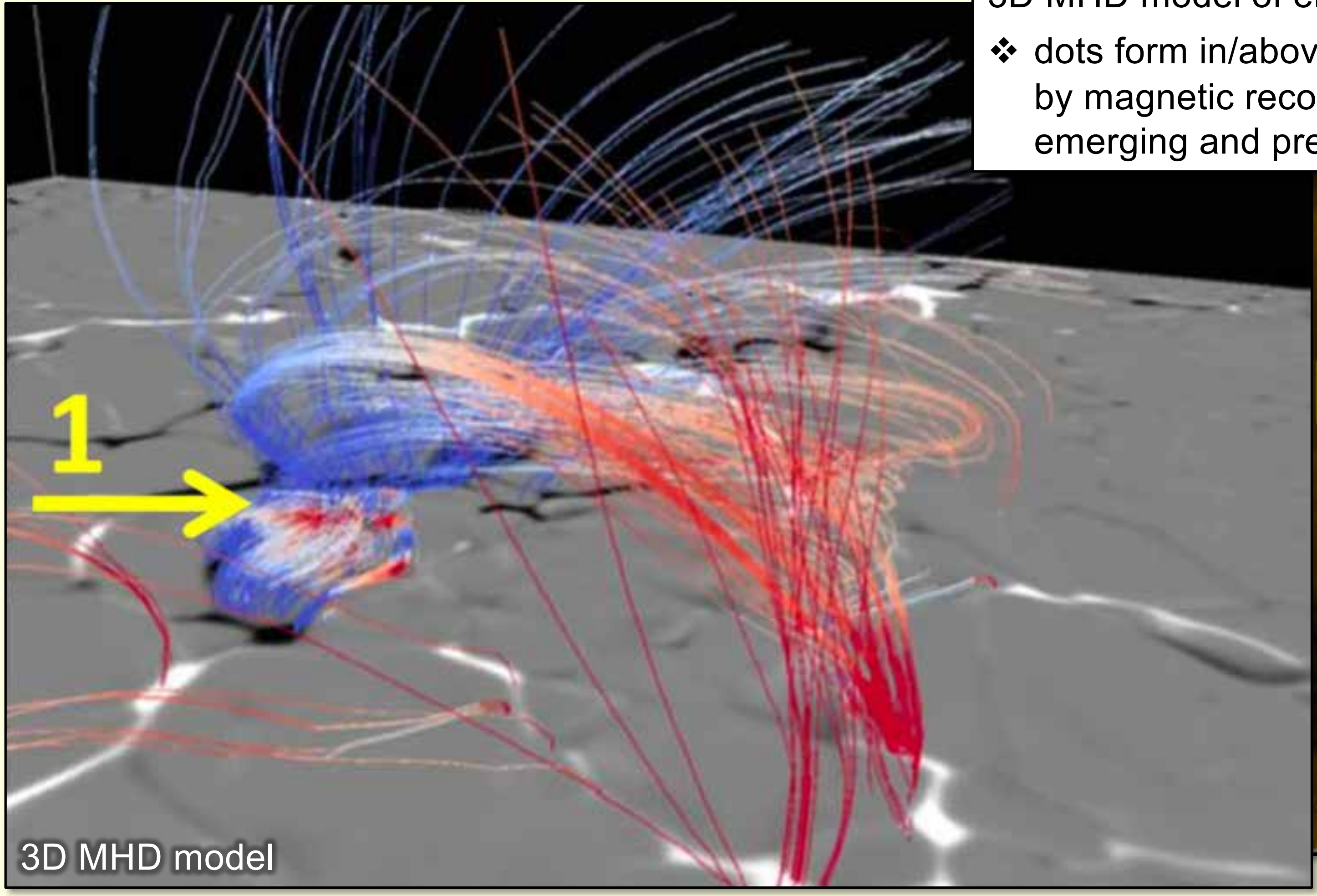
Fine-scale Bright Dots in an Emerging Flux Region

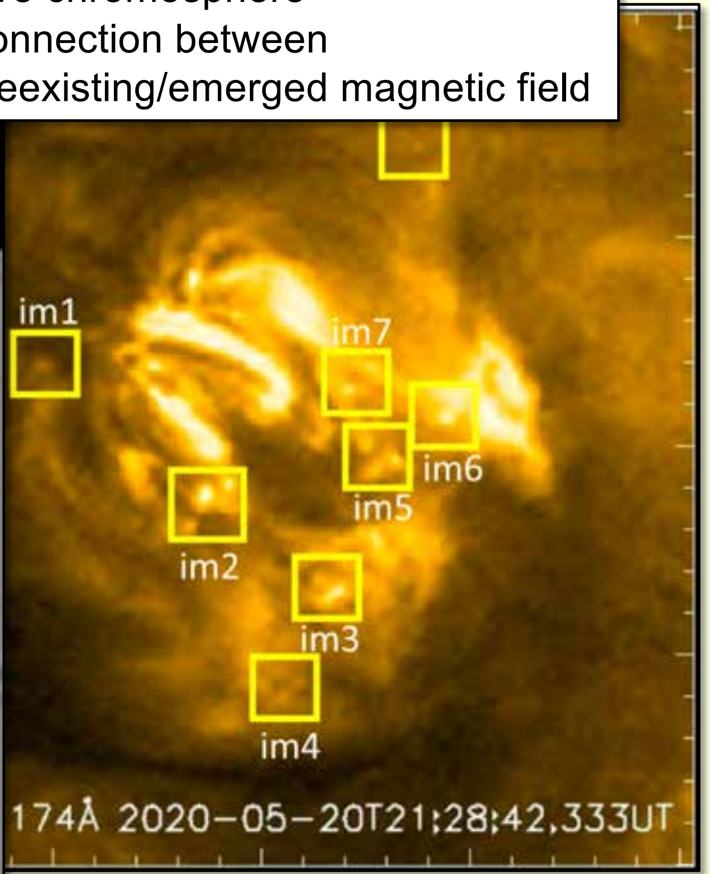
- ❖ **tiny bright dots in and around emerging flux region** (X-ray/coronal bright point)

Tiwari et al. (2022) ApJ 929, id.103

3D MHD model of emerging active region:

- ❖ dots form in/above chromosphere by magnetic reconnection between emerging and preexisting/emerged magnetic field



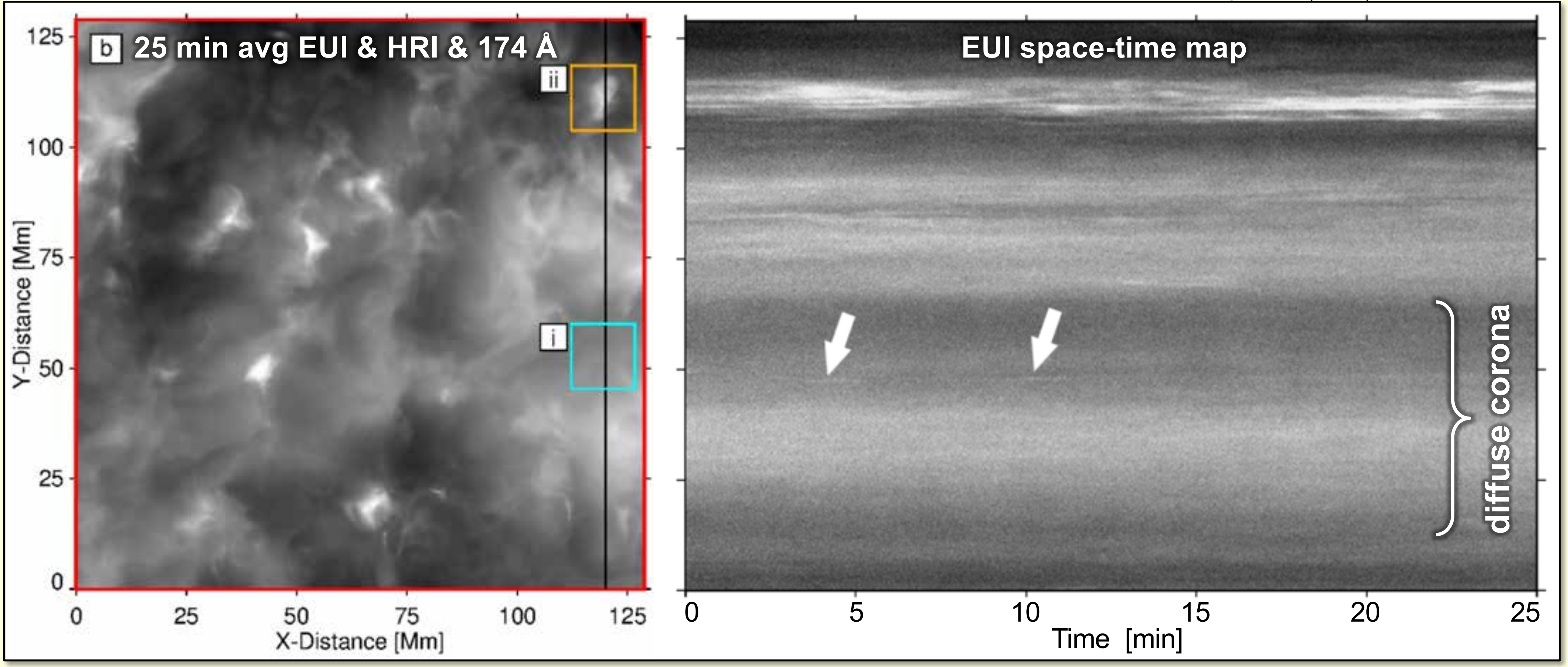


the opposite
of
small-scale
features

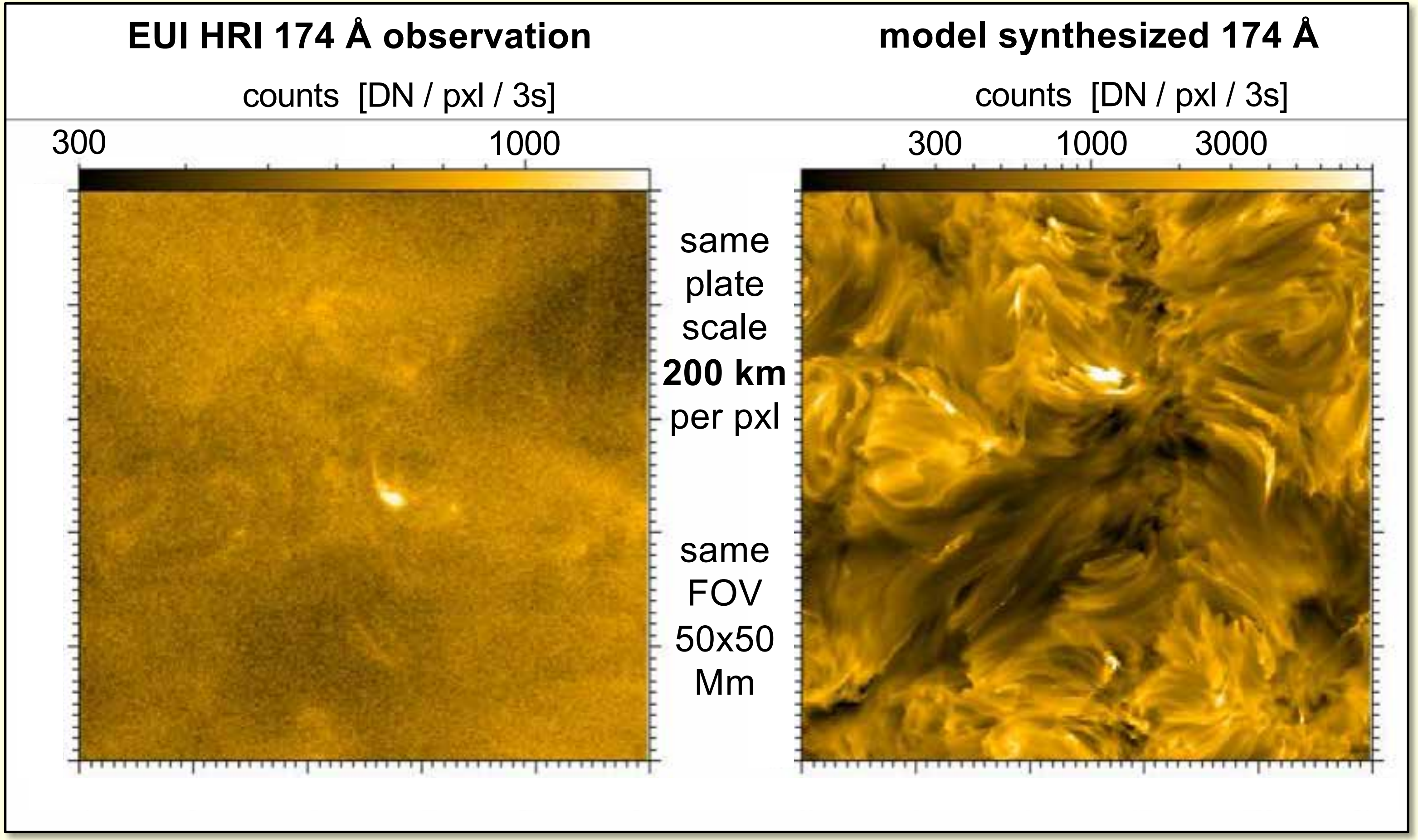
The diffuse quiet Sun corona

- **large patches of the QS are featureless or diffuse**
- How does the Sun produce this diffuse emission?
- Can it be composed of small scale events?

Gorman, Chitta, hp et al. (2023) submitted to A&A



Contrast in coronal EUV emission: observation vs. model



EUI data

3D MHD QS model

(Chen et al. 2021; A&A 656, L7)

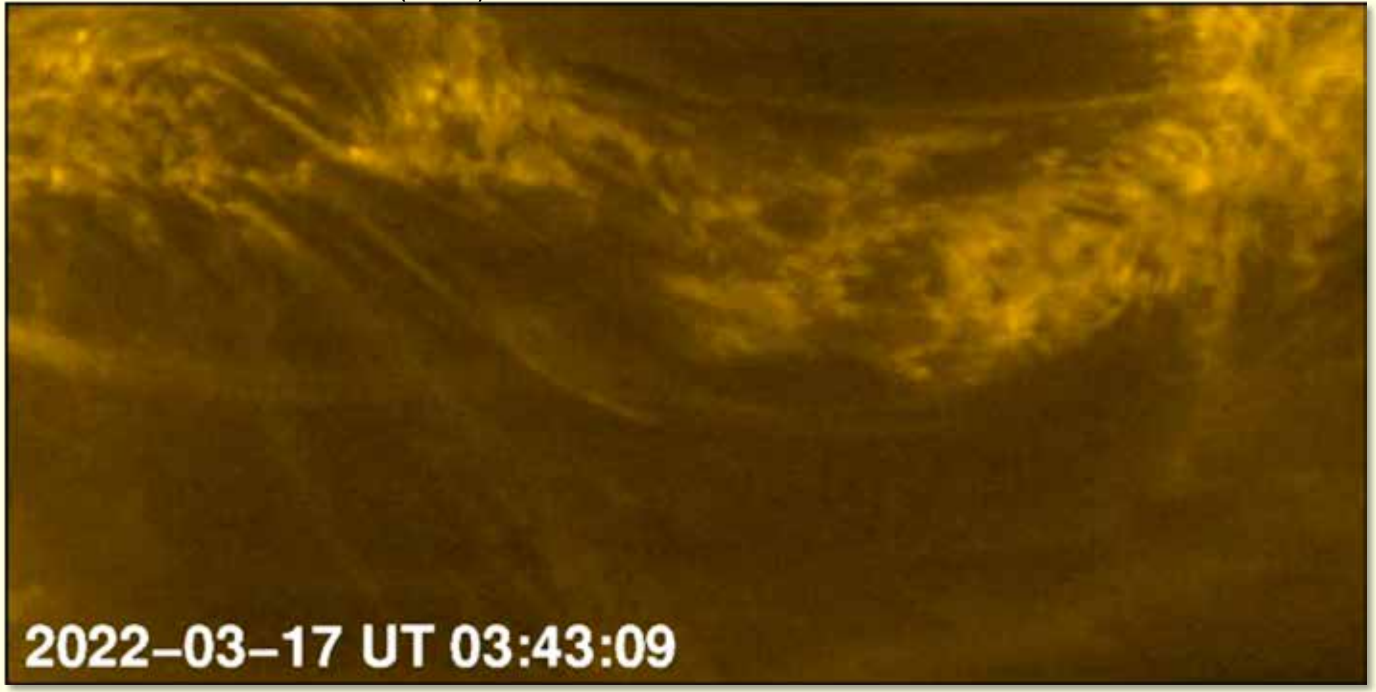
- simulations show much larger contrast than real observations
- How does the Sun avoids to produce the fine structure seen in models? (or fine structure in loops)
- is the (effective) diffusion larger than we think?
- will MHD turbulence in models with much higher resolution smooth out structures?

Why MUSE?

– only a few selected arguments –

Why MUSE? Dynamics / flows

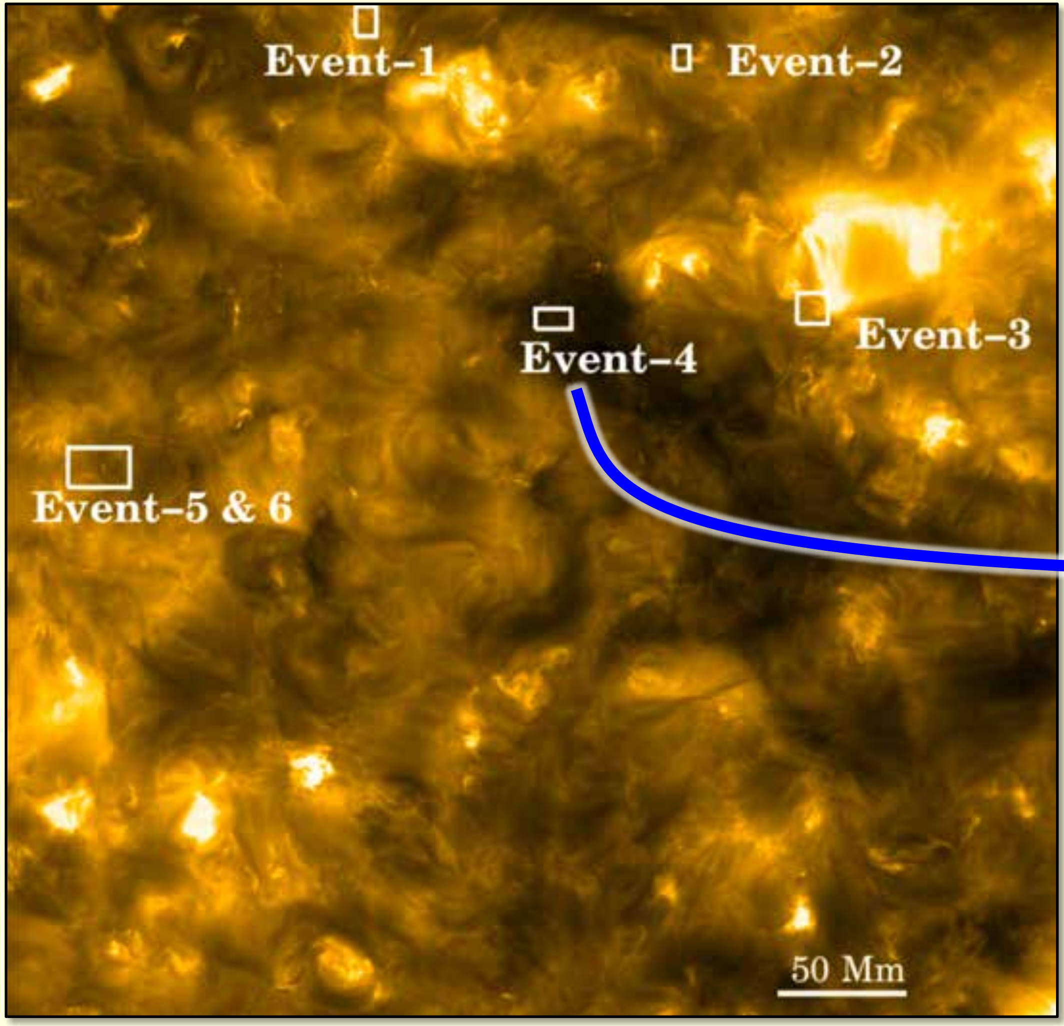
Chitta. Peter, Parenti, et al. (2022) A&A 667, A166



- we need to capture flows and non-thermal broadening in the substructure of coronal loops…

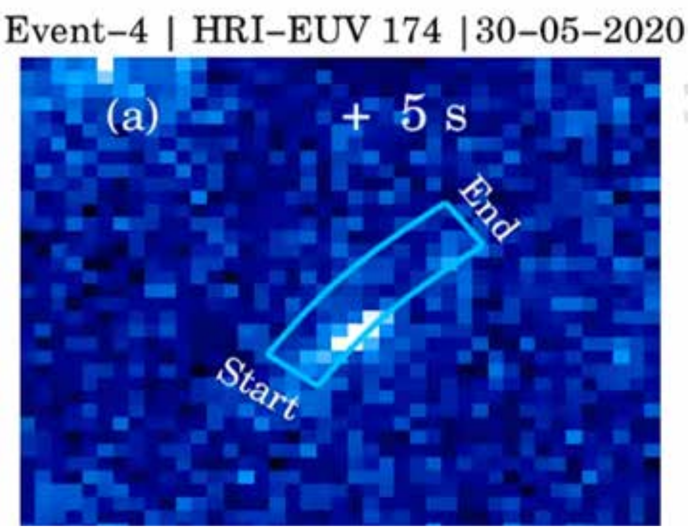
Pontin, Peter, Chitta (2020; A&A 639, A21)

Why MUSE? Temporal evolution



Mandal, Peter, Chitta, et al. (2021) A&A 656, L16

- **… and we need to capture this fast enough in a large enough FOV**



1 pixel ≈ 200 km
5 s cadence

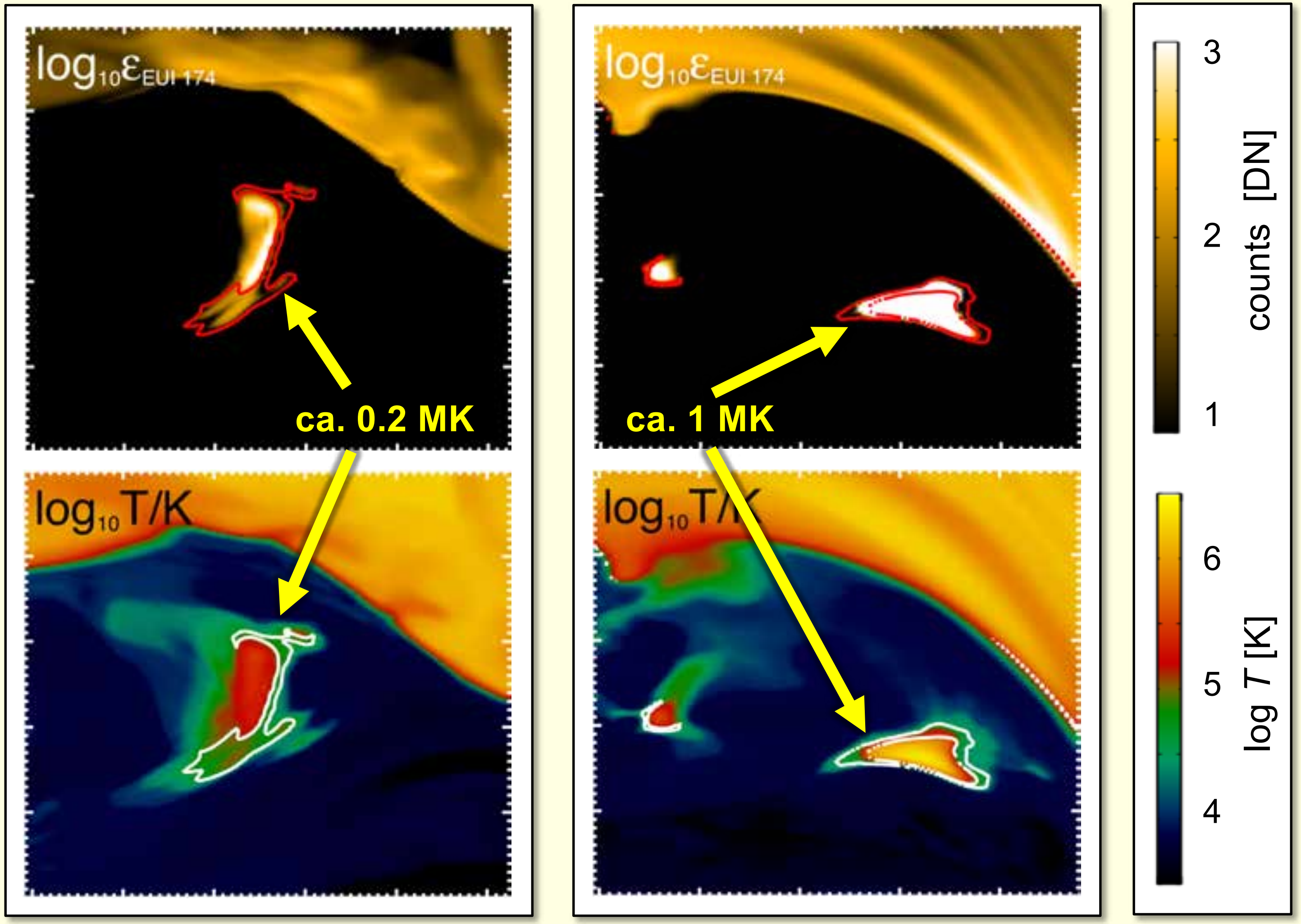
Why MUSE? Spectral purity

comparison of two EUV brightenings in a 3D MHD model

EUV filtergraphs usually have contributions from different temperatures

e.g. AIA 171, 193
or EUI 174
contain also O V / VI

as a spectrograph, MUSE will be spectrally (more) pure



model synthesized **EUI 174 Å** (side view)

temperature in vertical cut through brightening

see poster by **Yajie Chen** "Investigating transition region explosive events in a quiet-Sun model"

conclusions

Conclusions

- **braiding models** including the synthesis of coronal emission
  - might reproduce overall appearance of an active region
  - do show substructure in loops (if resolution is sufficient)
  - can explain (some) properties of spectral line profiles
  - might provide model of small-scale brightenings
  - and are useful for many more things…
- limitations are in particular concerning fast and energetic processes: MHD + optically thin radiation in ionization equilibrium not sufficient then
- EUI/HRT/EUV at 174 Å provides very high resolution coronal data
  - at perihelia **spatial resolution of ca. 200 km** (100 km pixels)
  - equally important is very **fast image cadence down to 2 s**
- **it will be exciting to see MUSE data with comparable performance but including information on the profiles of individual lines!**