Small-scale structure of the lower solar atmosphere

Nazaret Bello González, *Institut für Sonnenphysik (KIS, Freiburg)*

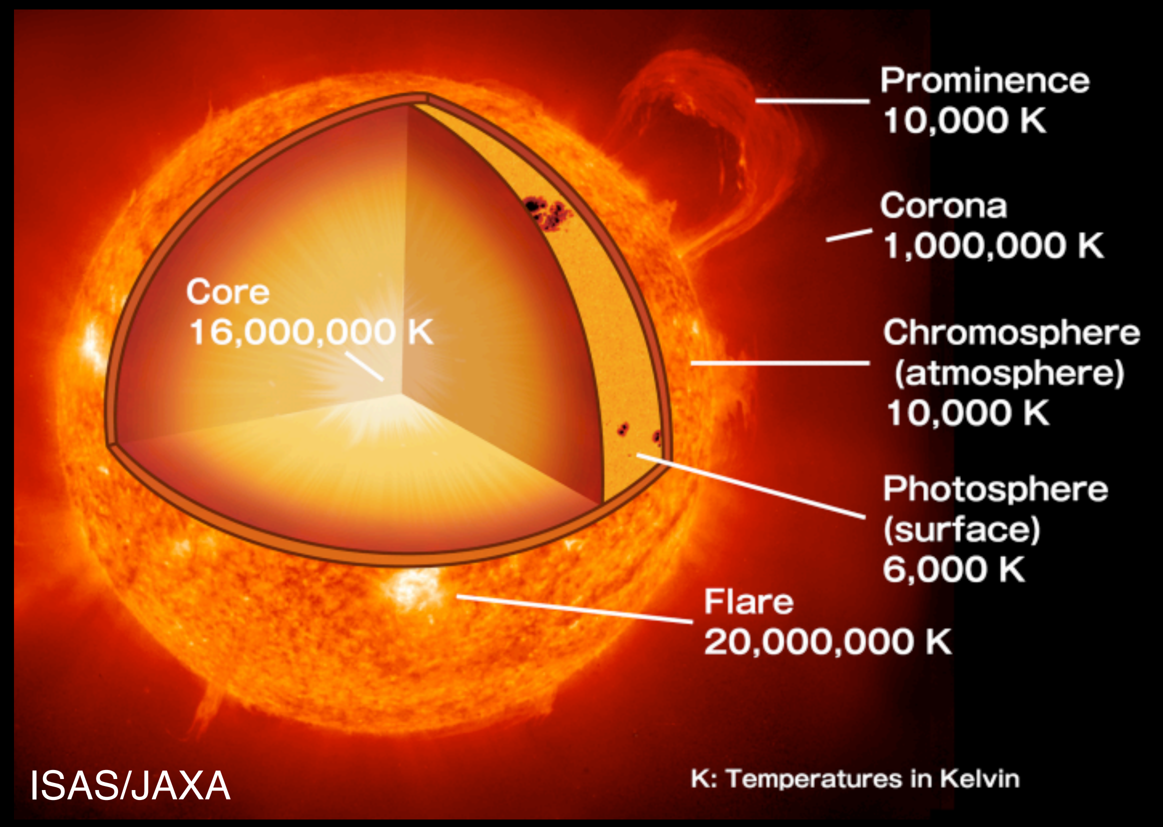
Institut für Sonnenphysik (KIS)

Outline

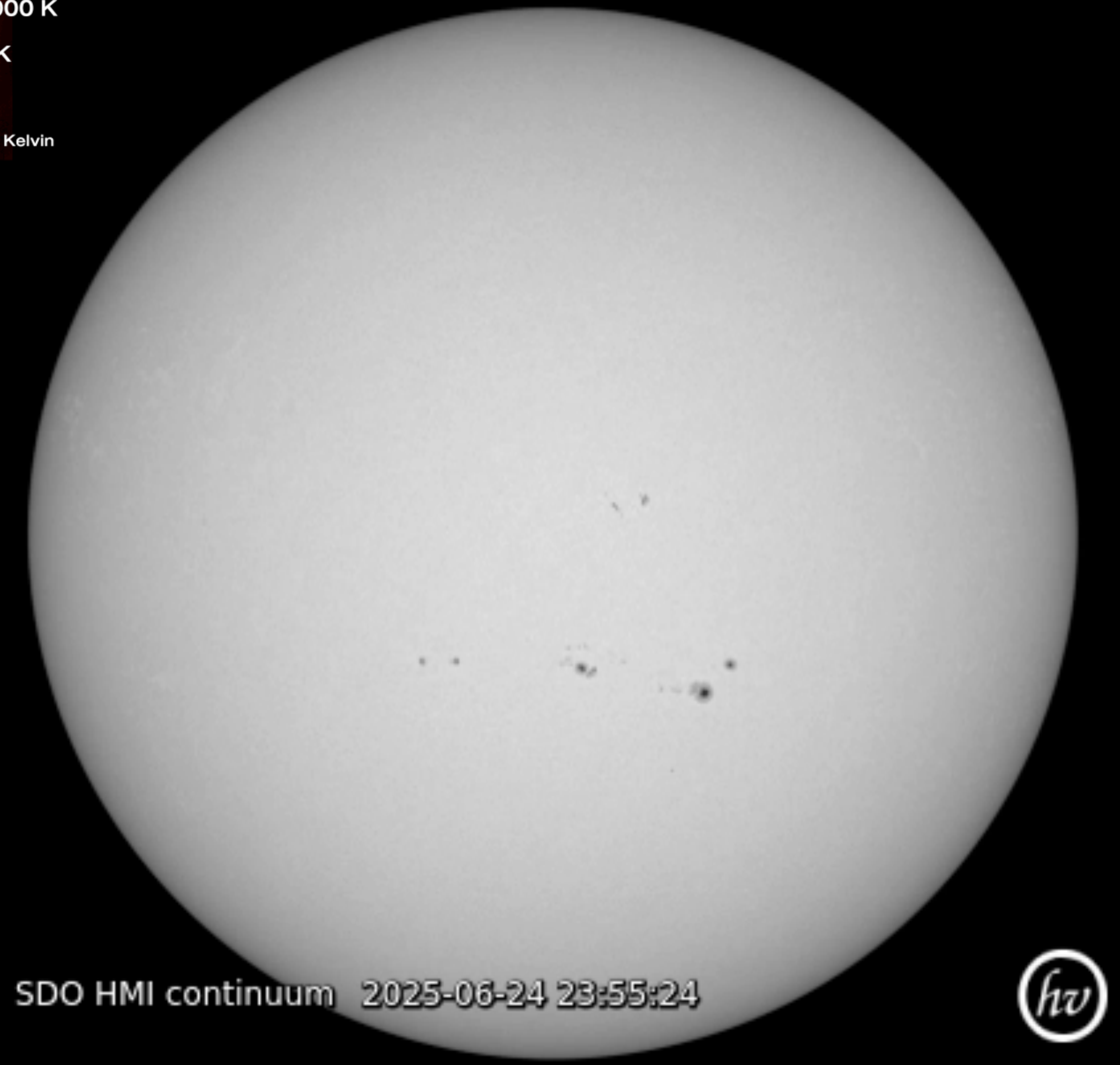
- Intro
  - Lower layers of the Sun: Photosphere & Chromosphere
  - What means ‘small-scales’ in the Sun?
- Solar fine structure — Selected solar features
  - Magnetic bright points, faculae & plages
  - Spicules & fibrils
  - Ellerman bombs and photospheric hot spots
  - Sunspots
  - Oscillatory phenomena — quiet Sun acoustic ans sunspot waves
- Conclusion

What do I mean by the lower solar atmosphere?

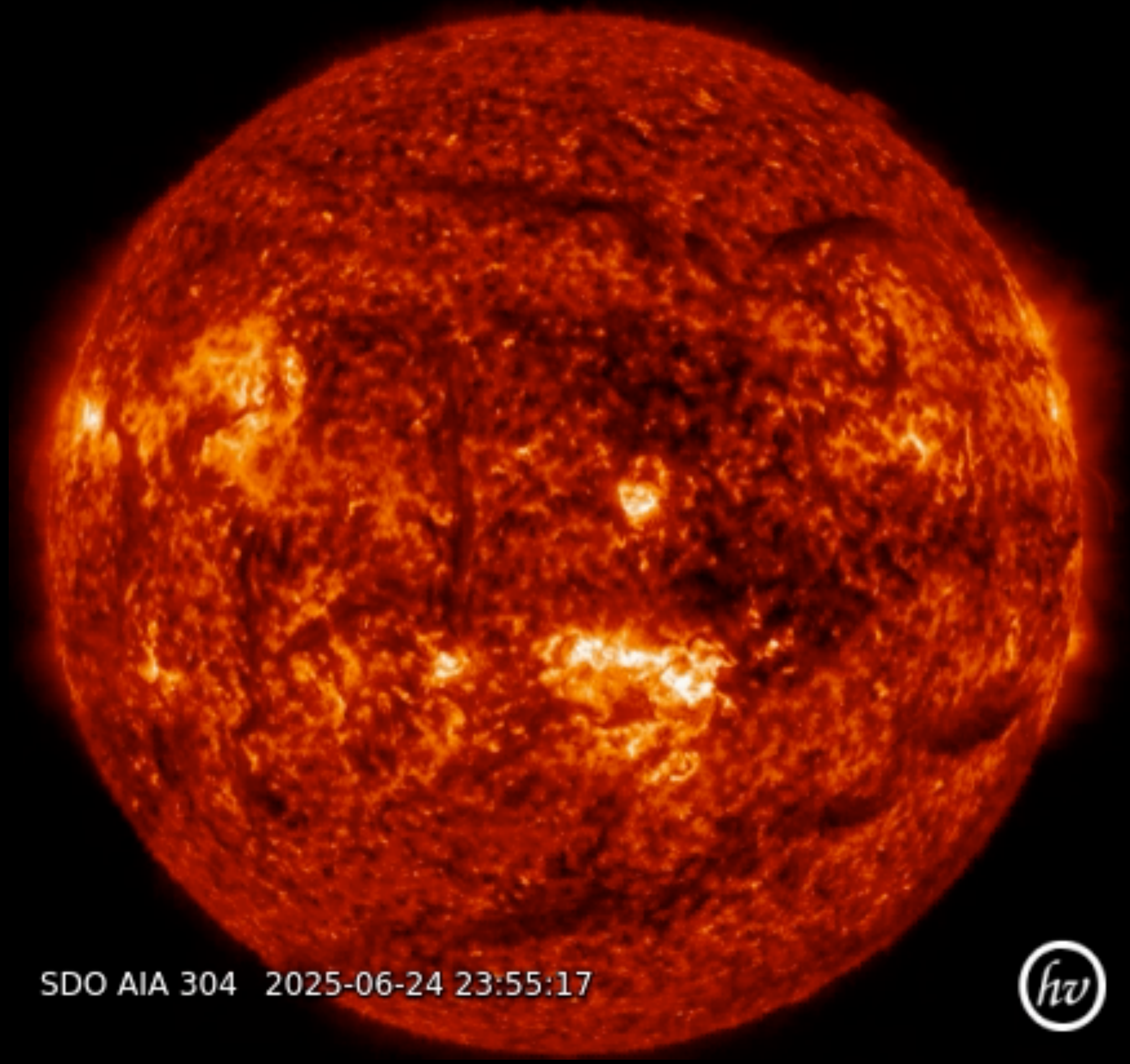
Photosphere and chromosphere



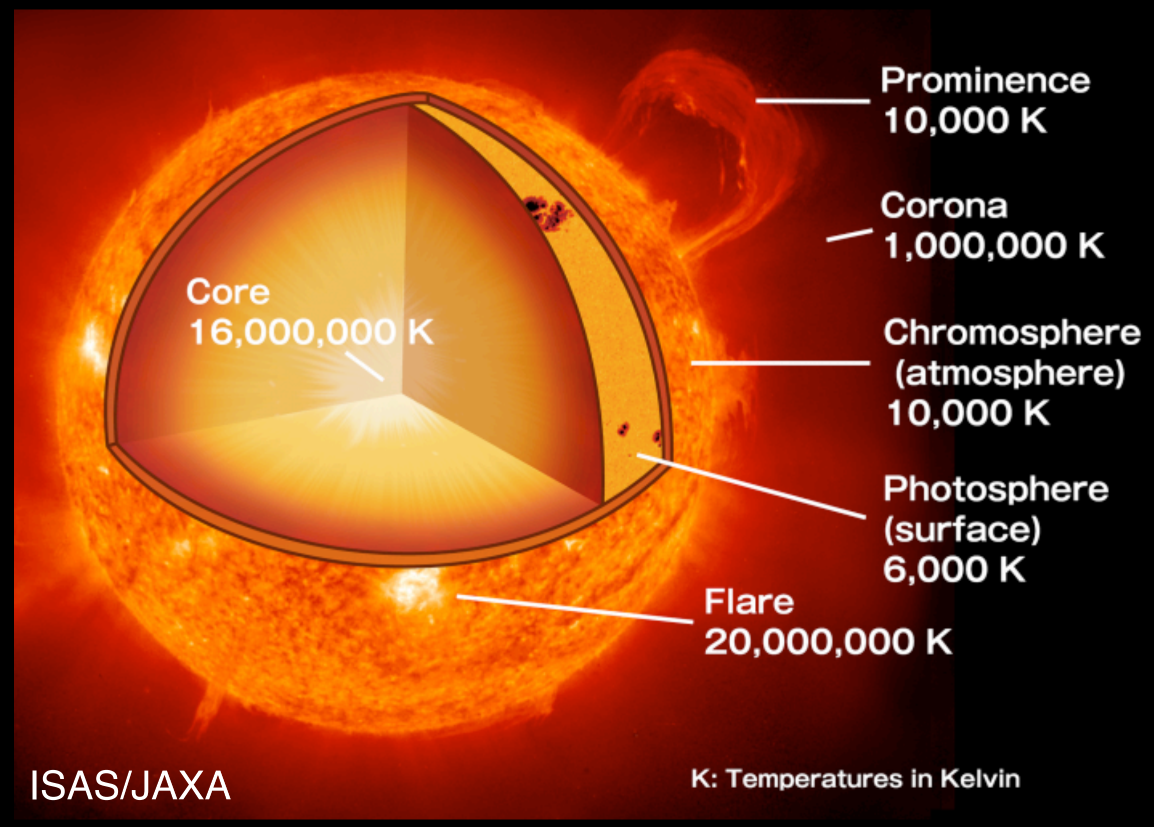
PHOTOSPHERE



CHROMOSPHERE



The Sun's atmosphere gets progressively warmer with height, from the photosphere at 6000K, to the chromosphere at 10000K, to the corona at 1 million kelvin



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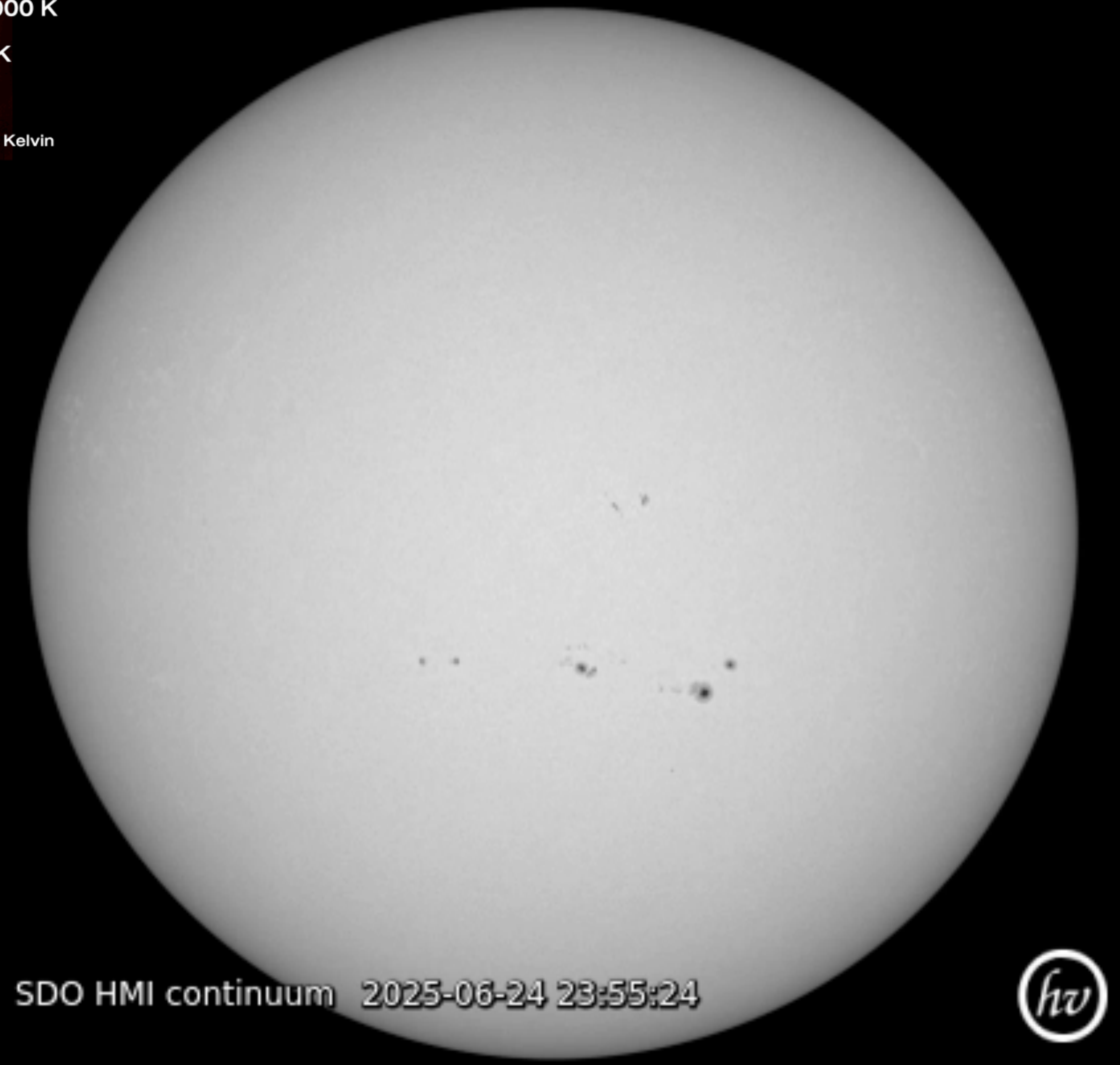

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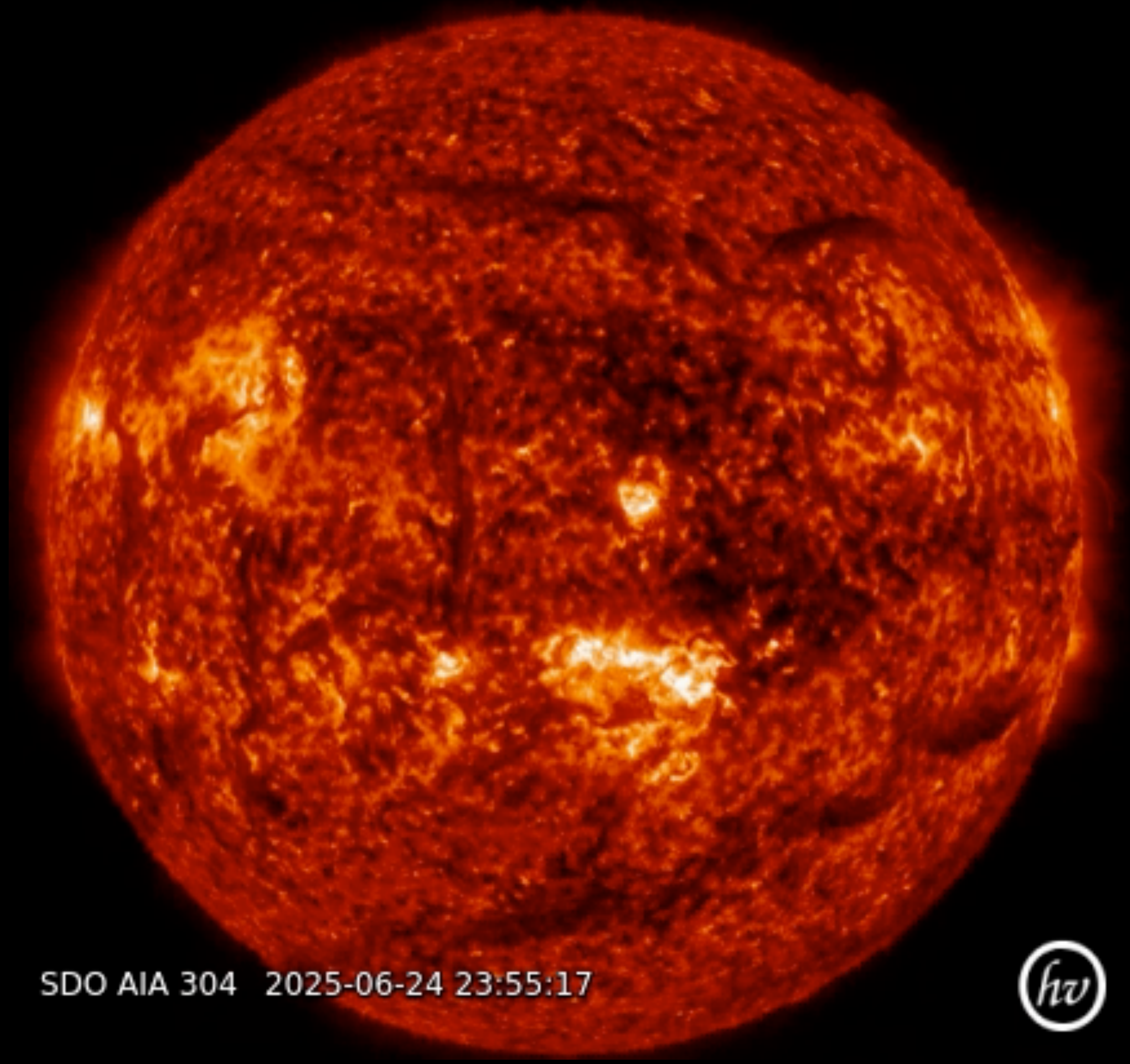

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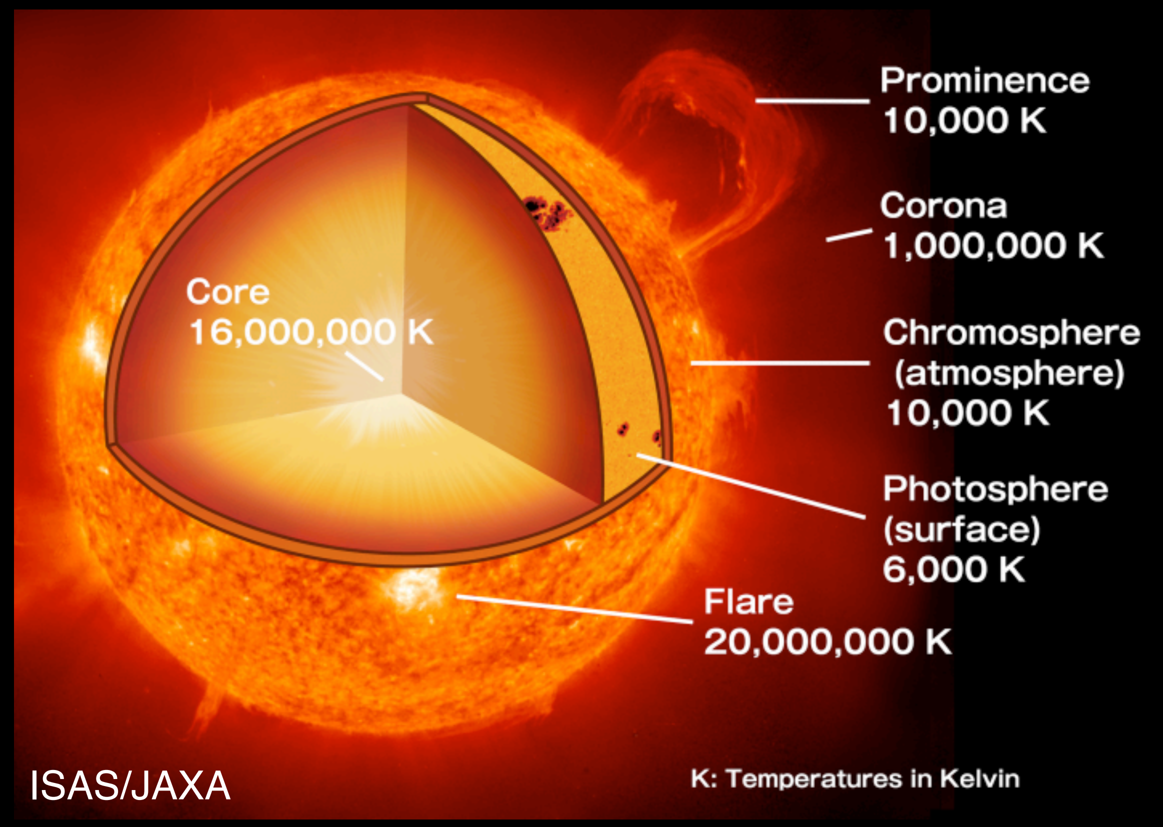

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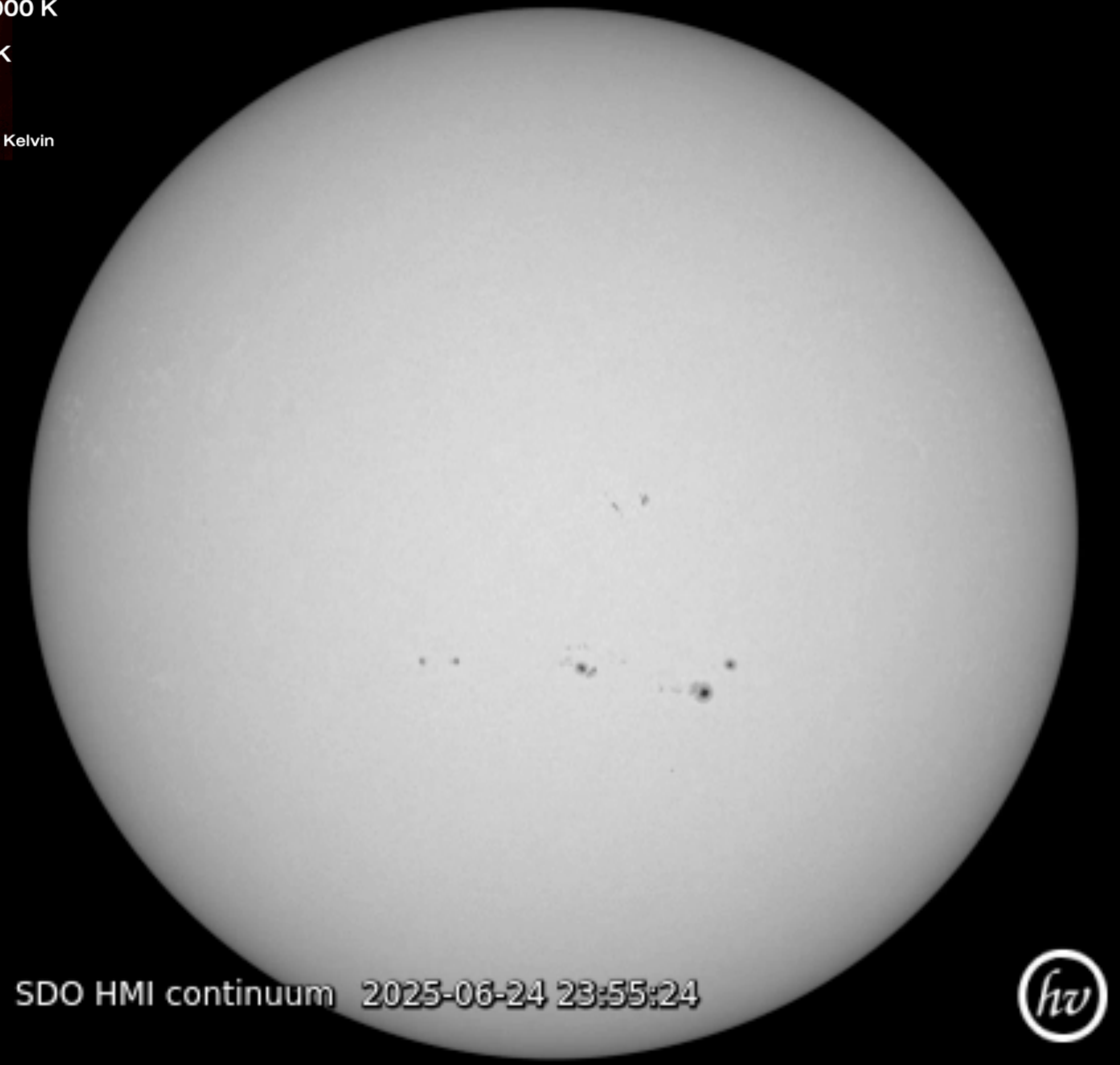

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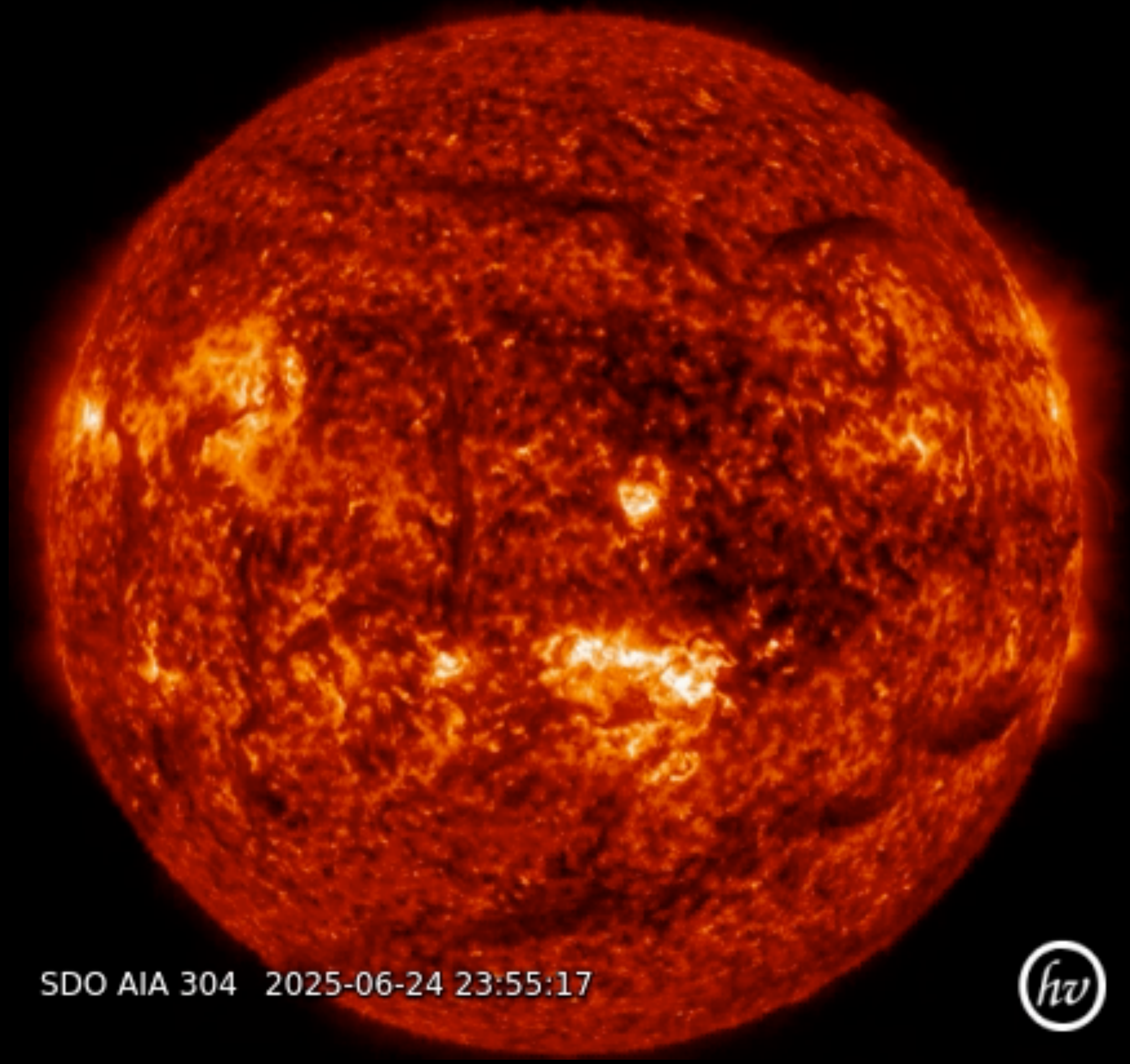

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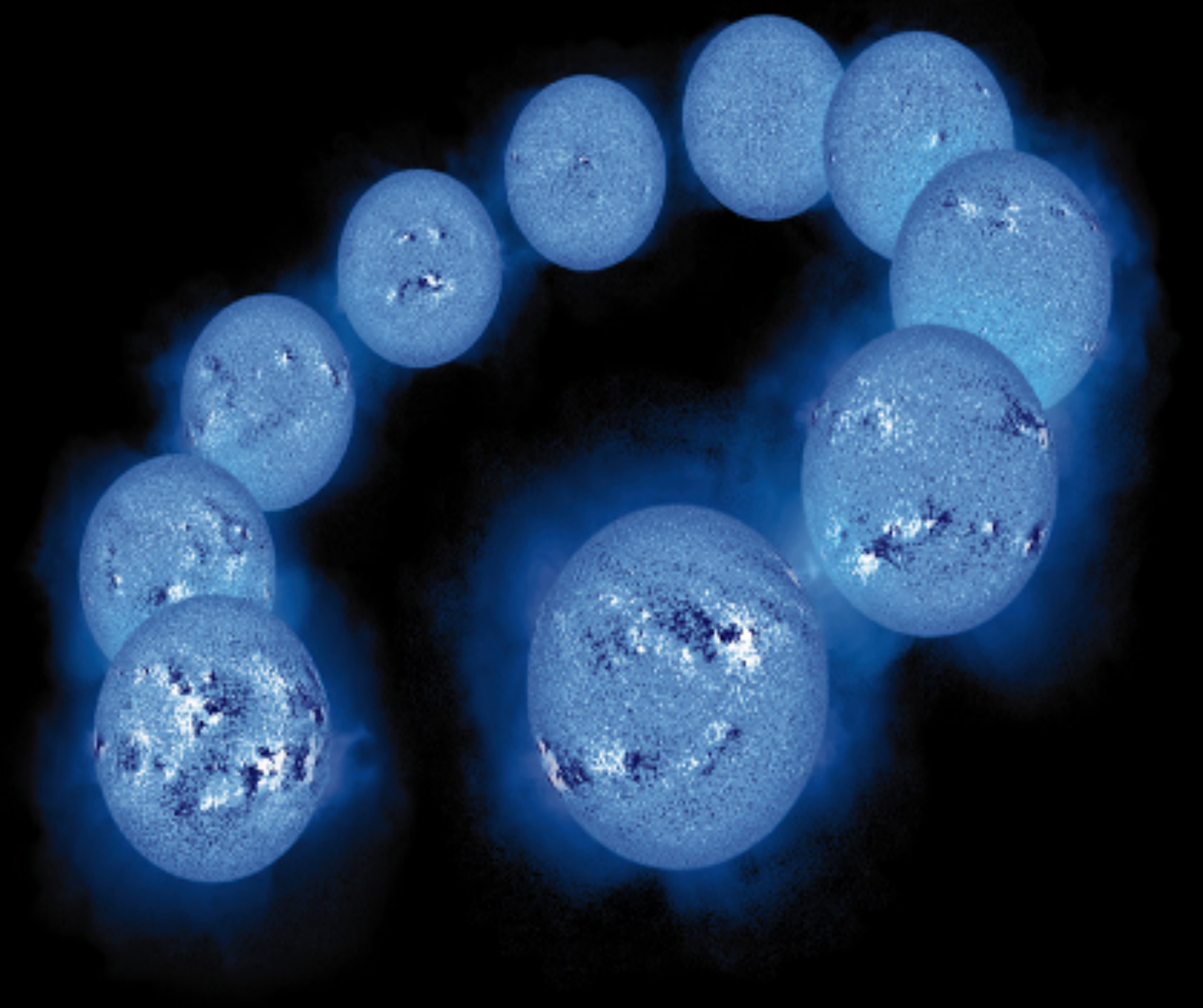
What do we mean by small-scales in the Sun?

The many scales of the Sun

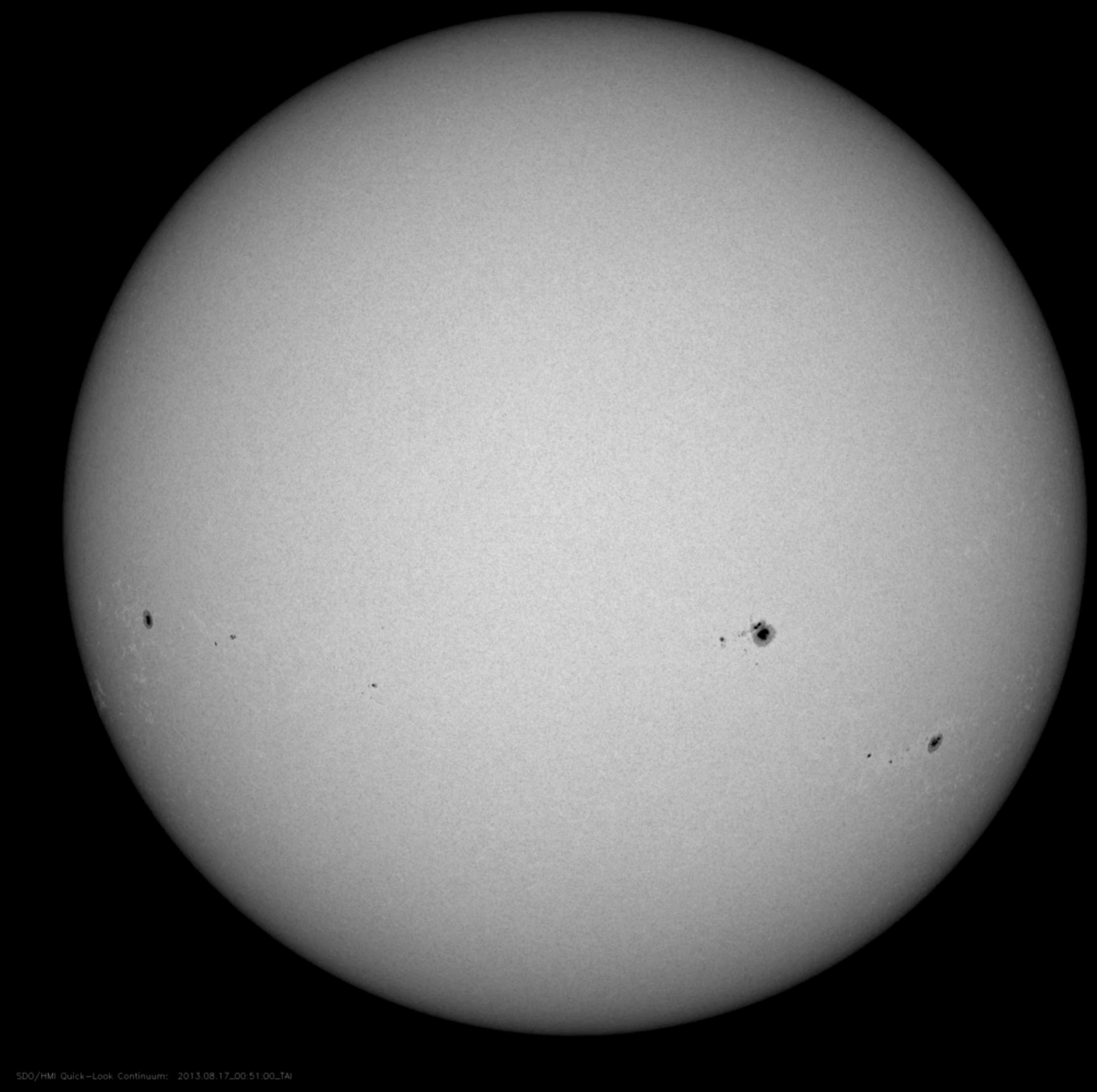
The many scales of the [magnetic] Sun

Solar cycle
Time scale: 22 years
Spatial scale: Global Sun



Kareel Schrijver | NSO | NOAO | NSF | NASA | SoHO/MDI

Active Regions
Time scale: weeks to months
Spatial scale: ~ 200 arcsec



Löhner-Bötcher (KIS) | SDO/HMI & ROSA/DST

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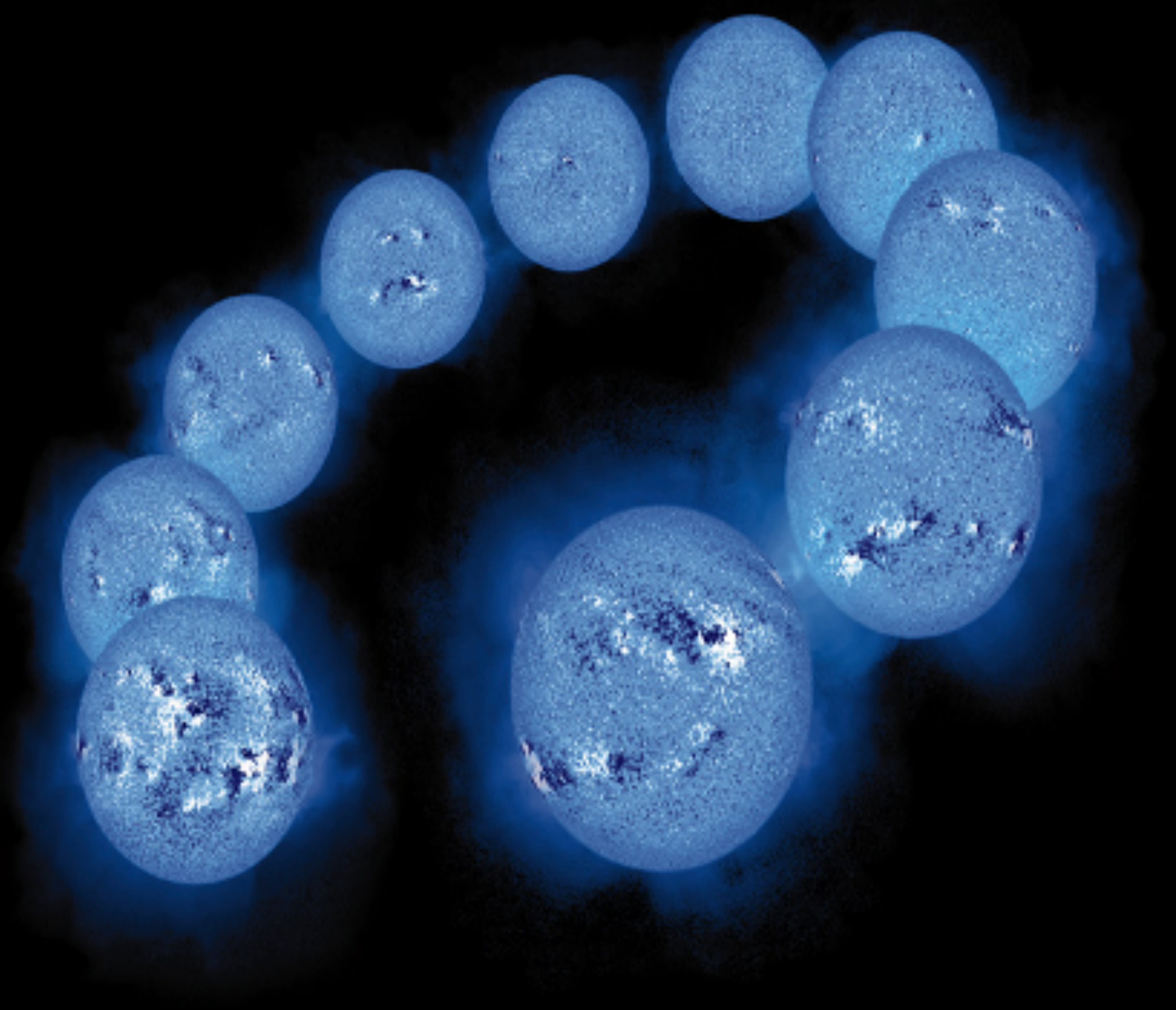

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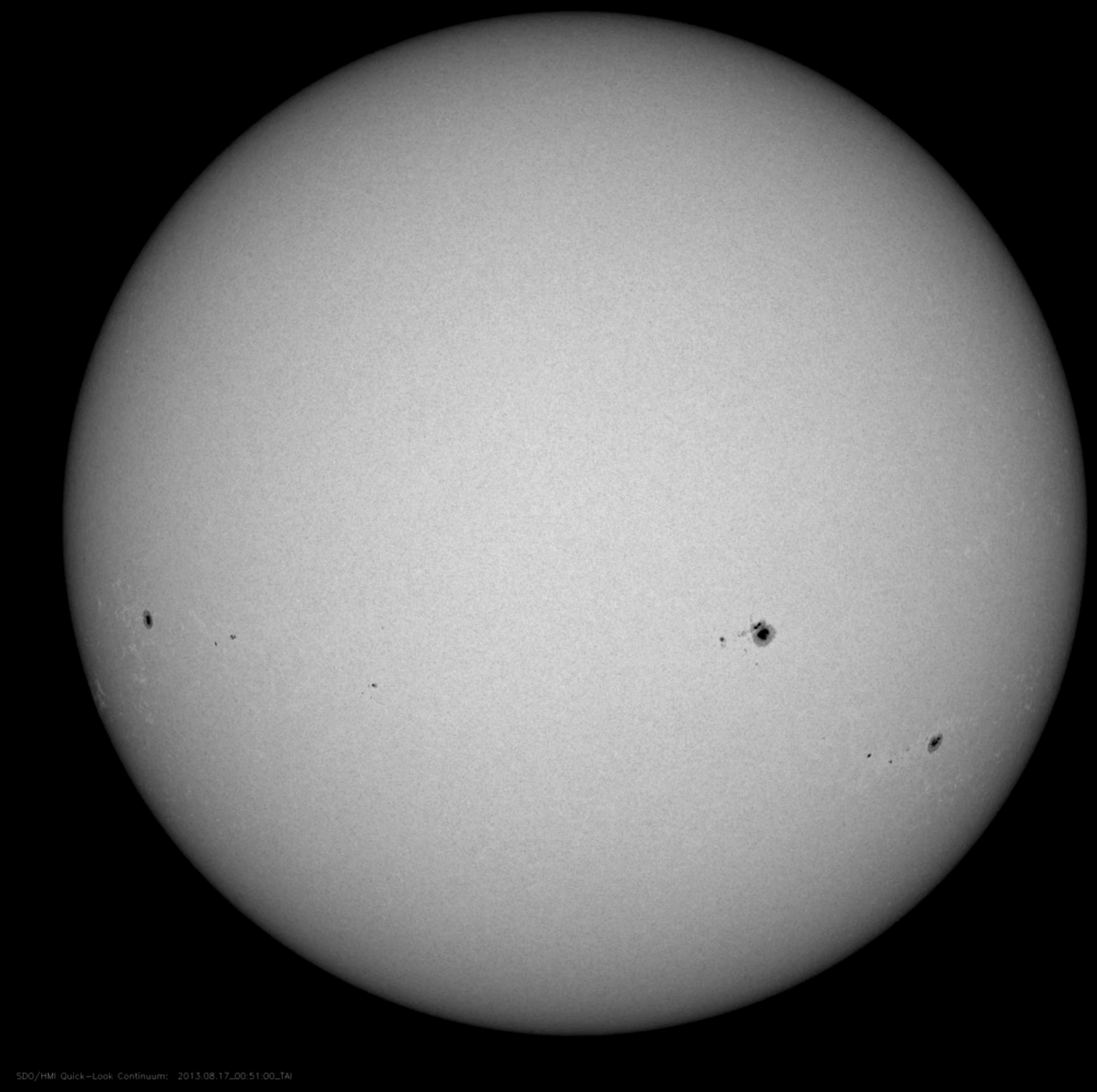

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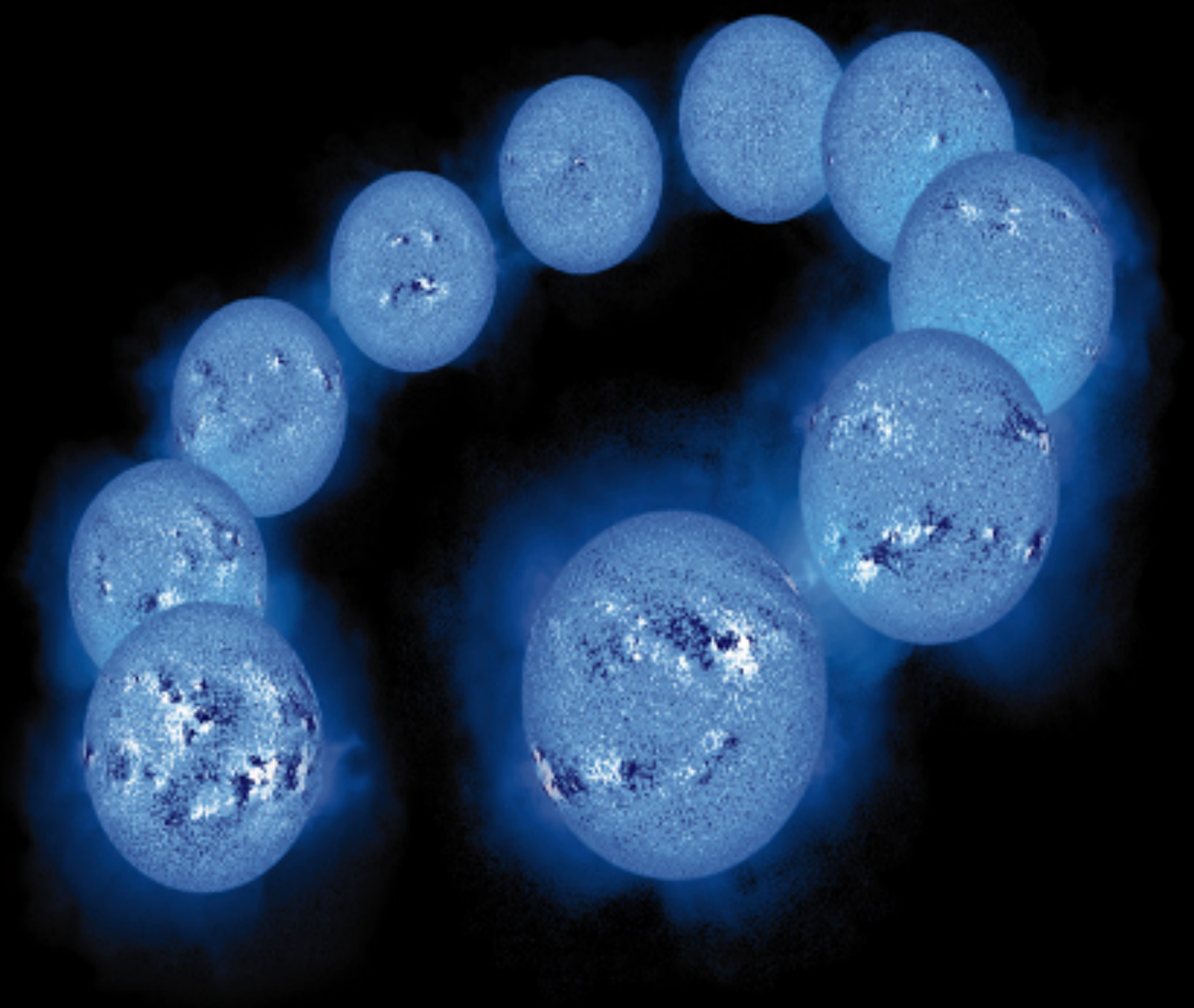
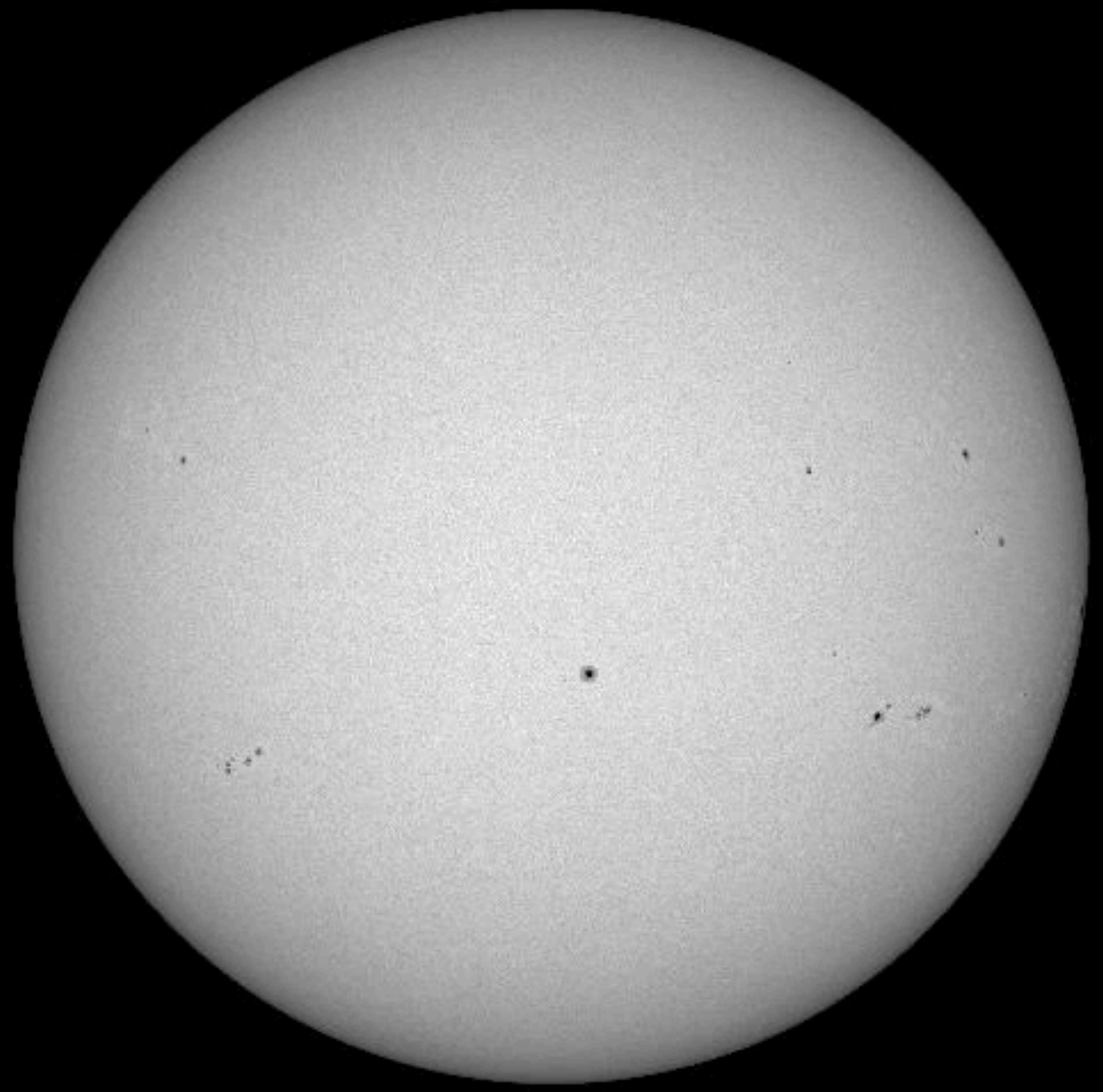
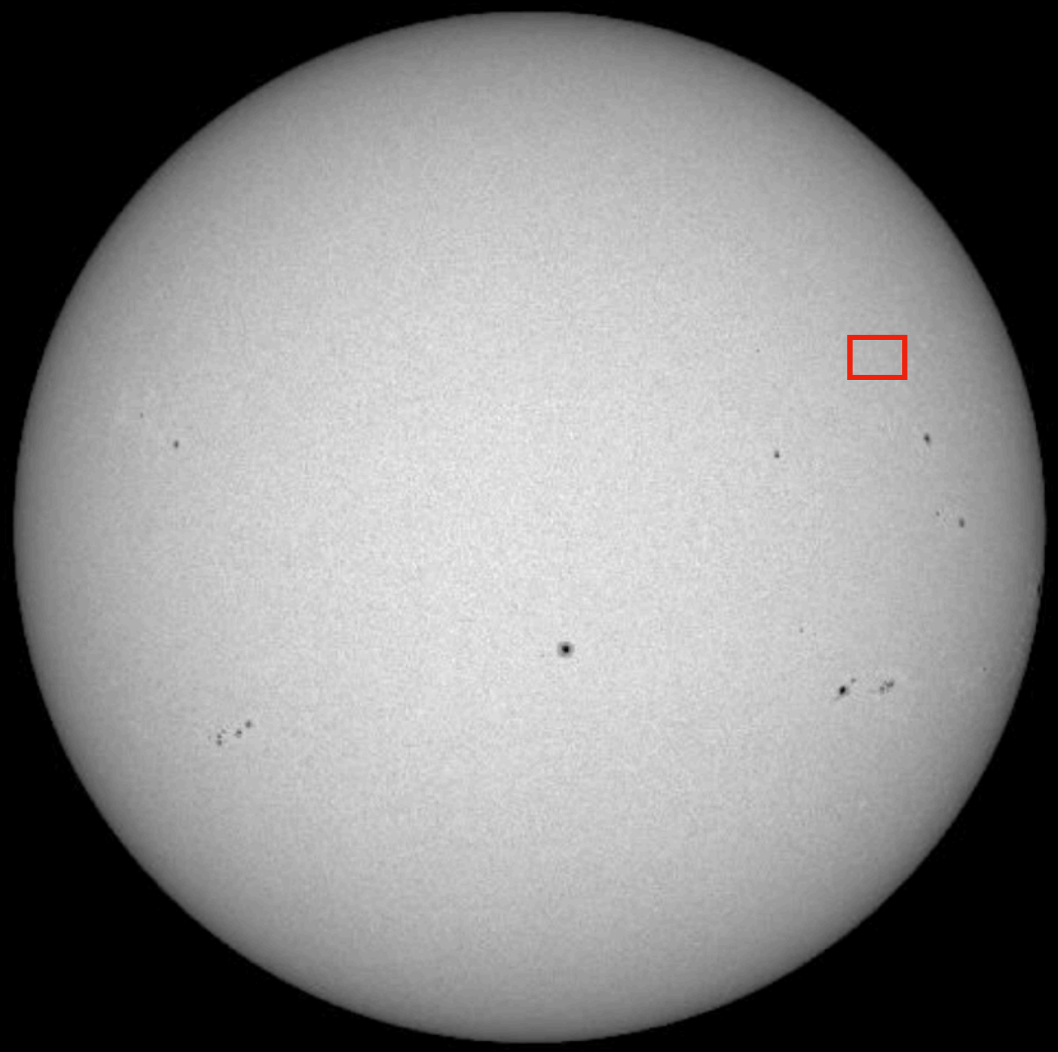


Kareel Schrijver | NSO | NOAO | NSF | NASA | SoHO/MDI

Fine structure
Time scale: seconds - minutes
Spatial scale: < 1 arcsec



Löhner-Bötcher (KIS) | SDO/HMI & ROSA/DST

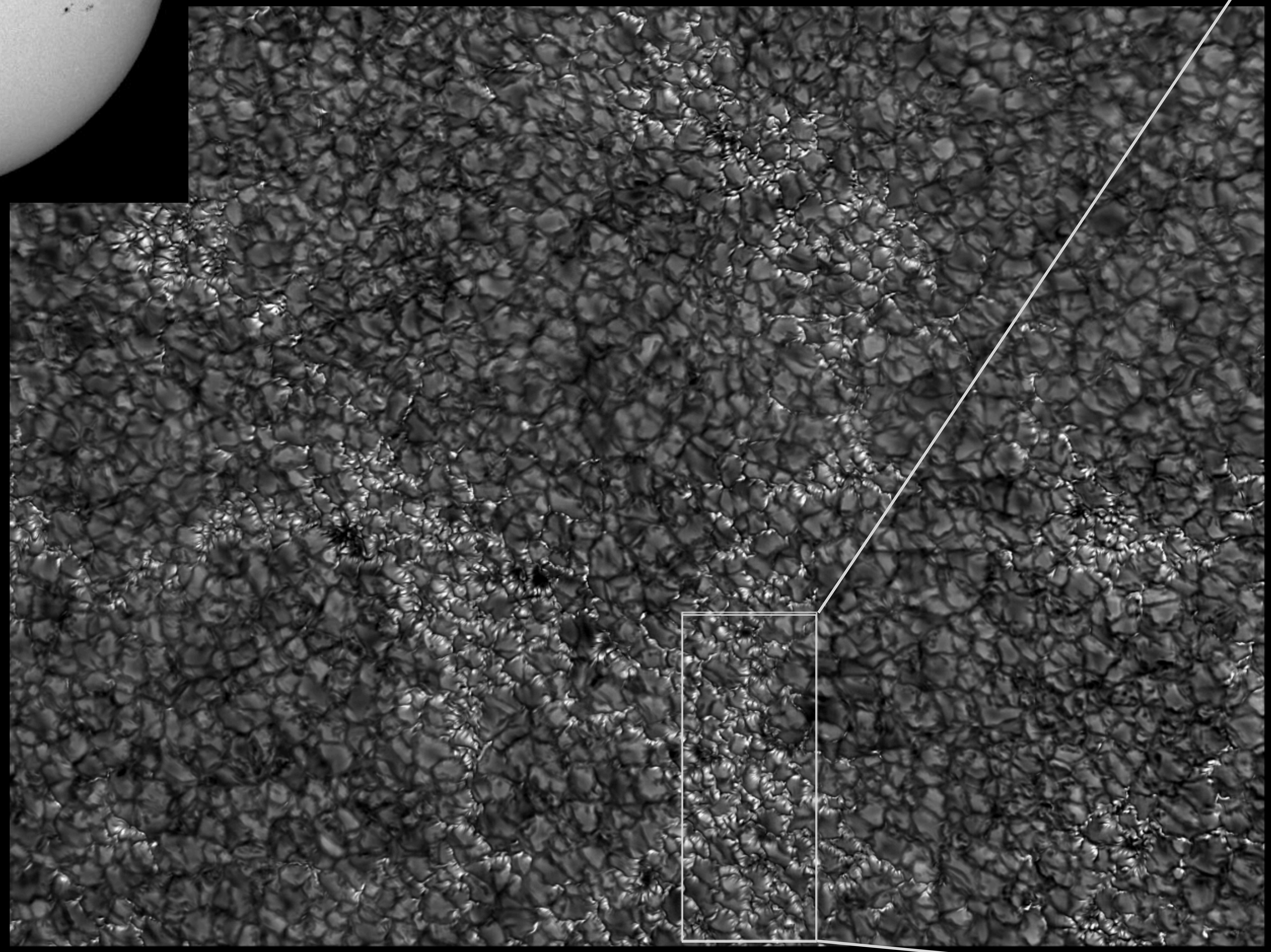


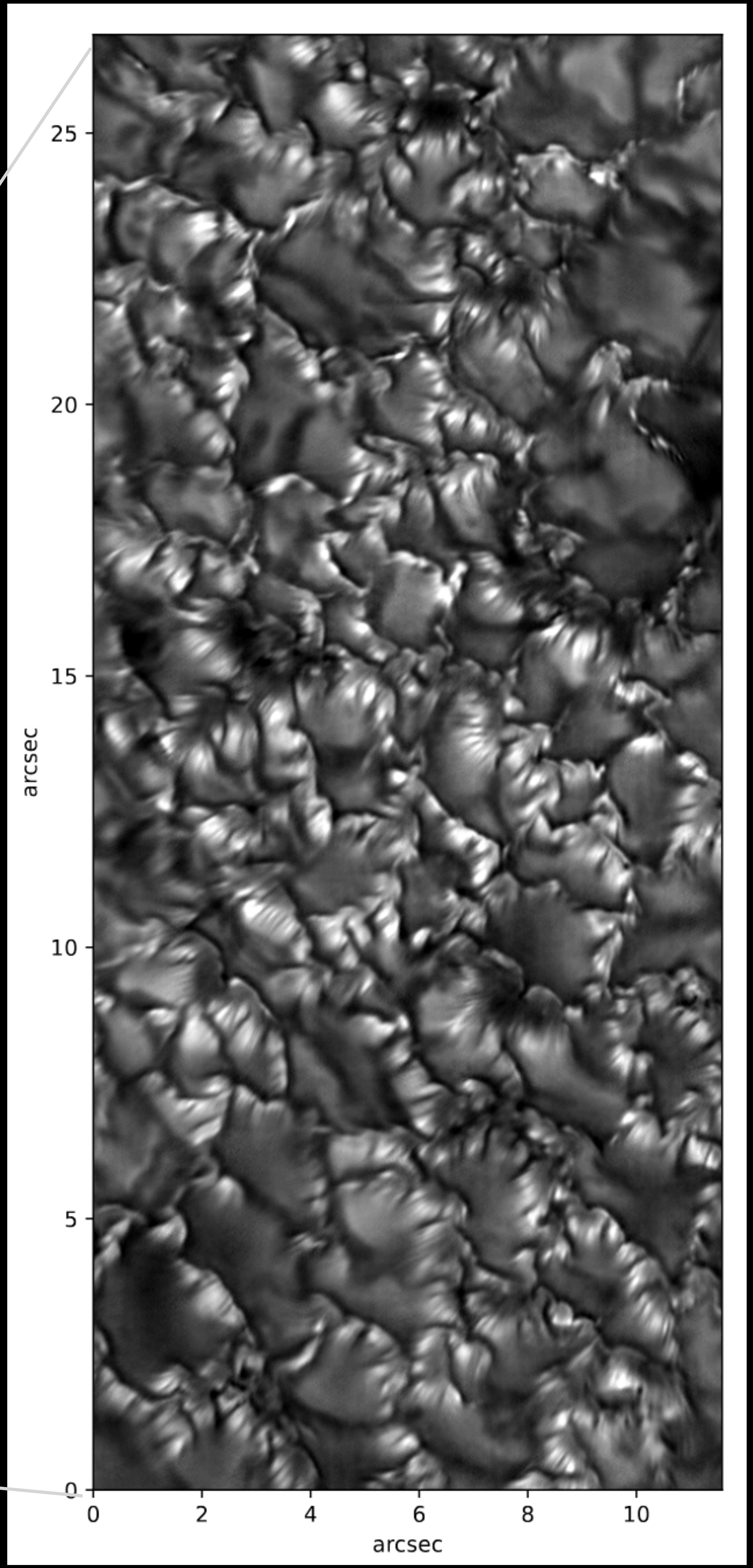
Ultra fine-structure

Time scale: seconds

Spatial scale: < 0.05 arcsec (40 km)

75”





Kuridze et al. (2025) | DKIST/VBI data

DANIEL K. INOUYE SOLAR TELESCOPE

Observing the solar fine-structure from the ground

Telescopes & Instrumentation

European ground-based solar telescopes

Adapted from
M. Collados (IAC) &
EST Office

El Roque de Los Muchachos Observatory | La Palma

SST 1m
Sweden (2002)

DOT 45cm
Netherlands (1997)

EST 4m
European
Consortium
(upcoming)

El Teide Observatory
Tenerife

VTT 70cm
Germany (1989)

Themis 90cm
France (1996)

Gregor 1.5m
Germany
(2012)

European ground-based solar telescopes

Adapted from
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EST Office

El Roque de Los Muchachos

Lecture on
European Solar Telescope
by

Héctor Socas Navarro
Wed 9:00h

EST 4m
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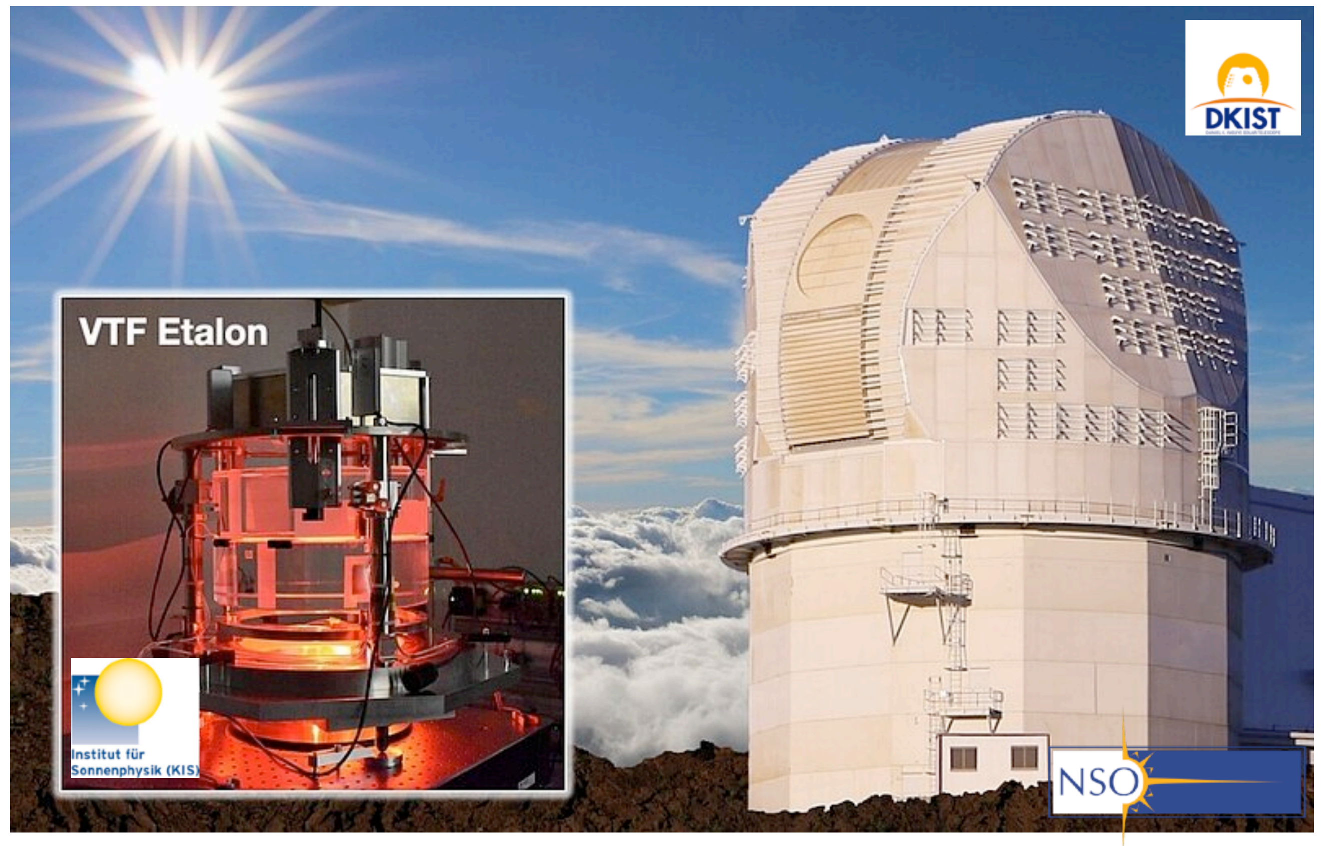
Other ground-based facilities and space missions

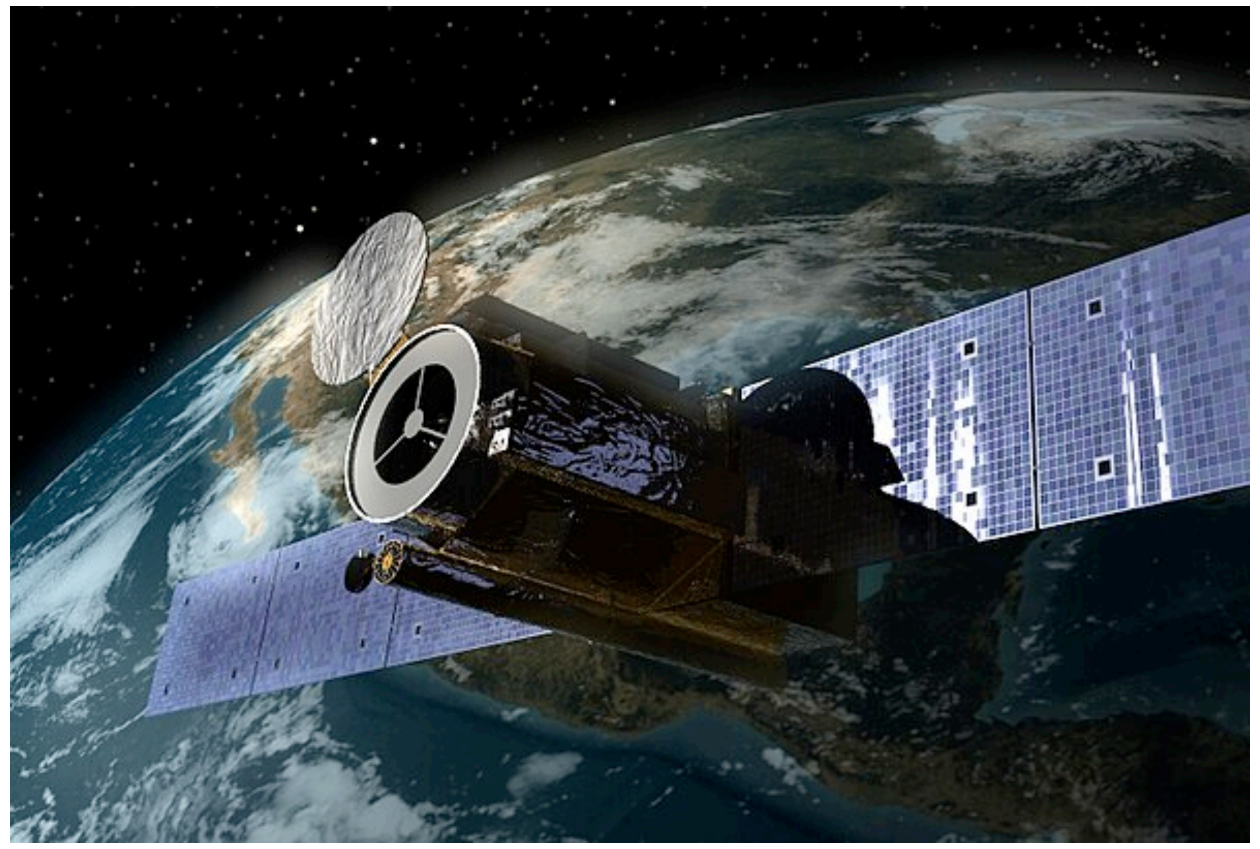
Daniel K. Inouye Telescope 4m
NSO/NSF, Hawaii, Haleakala Observatory



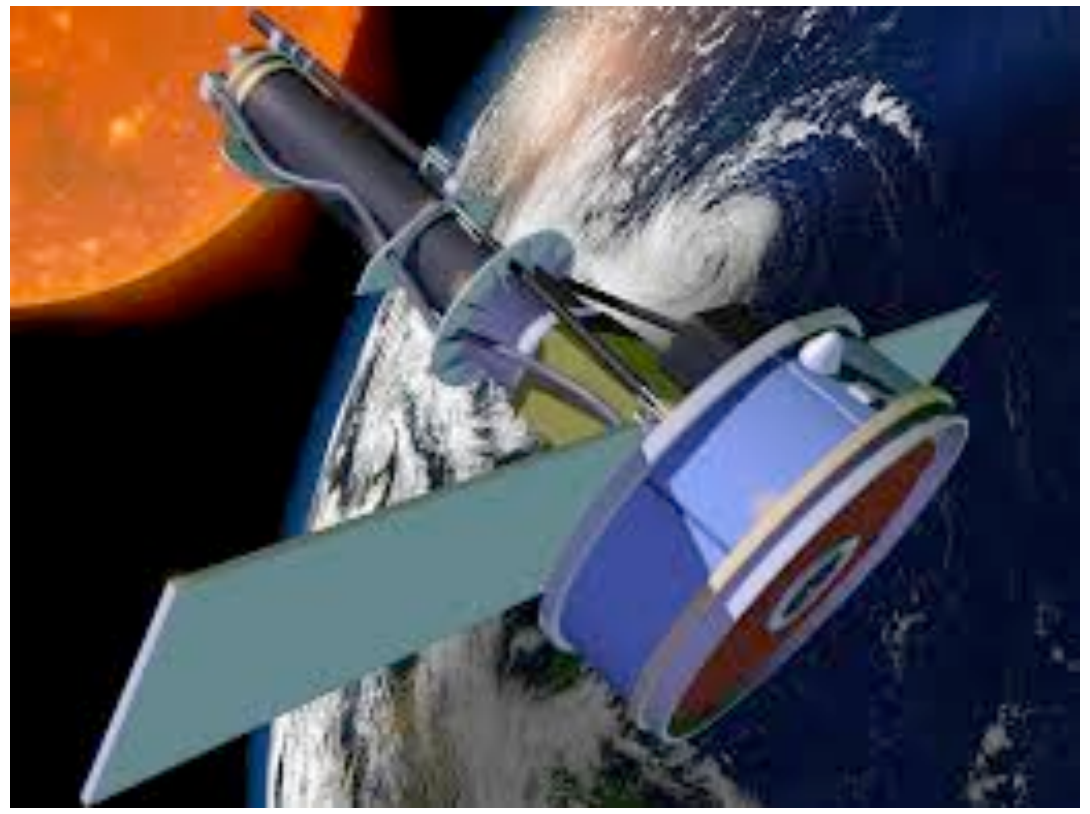
Goode Solar Telescope 1.6m
NJIT | Big Bear Observatory

Sunrise
Balloon-borne solar observatory
MPS

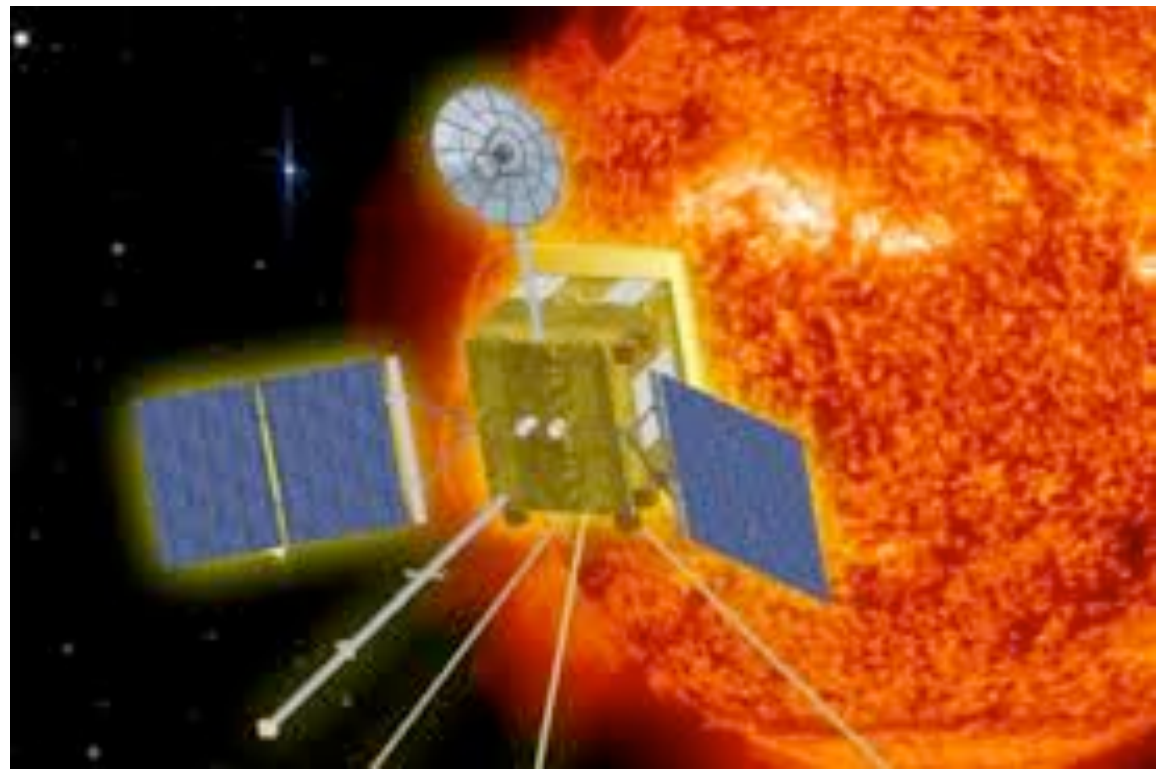
Hinode
Space mission
JAXA/ NASA / PPARC



IRIS
Space Sun Observatory
NASA

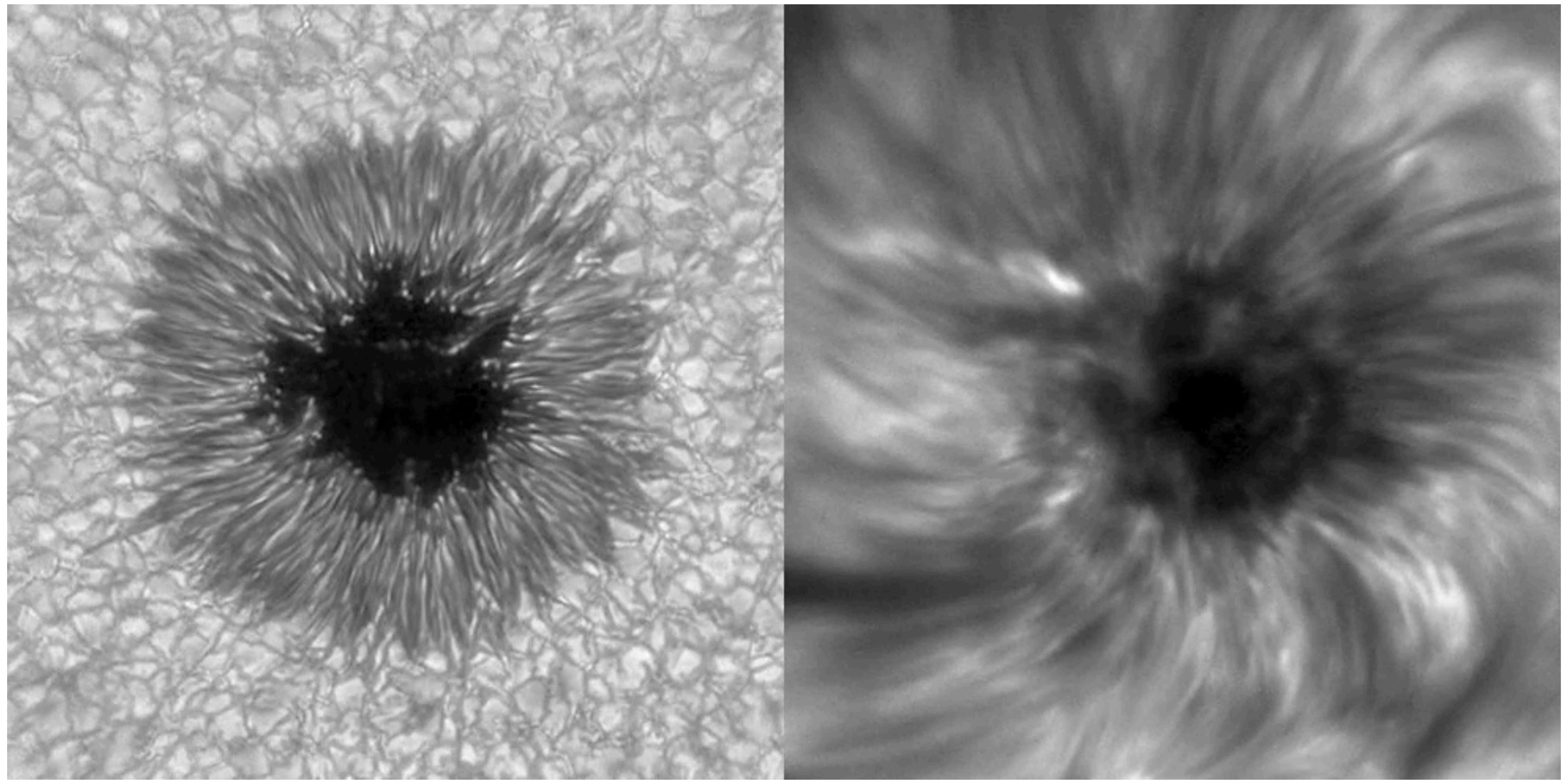


Solar Orbiter
Space mission
ESA/NASA

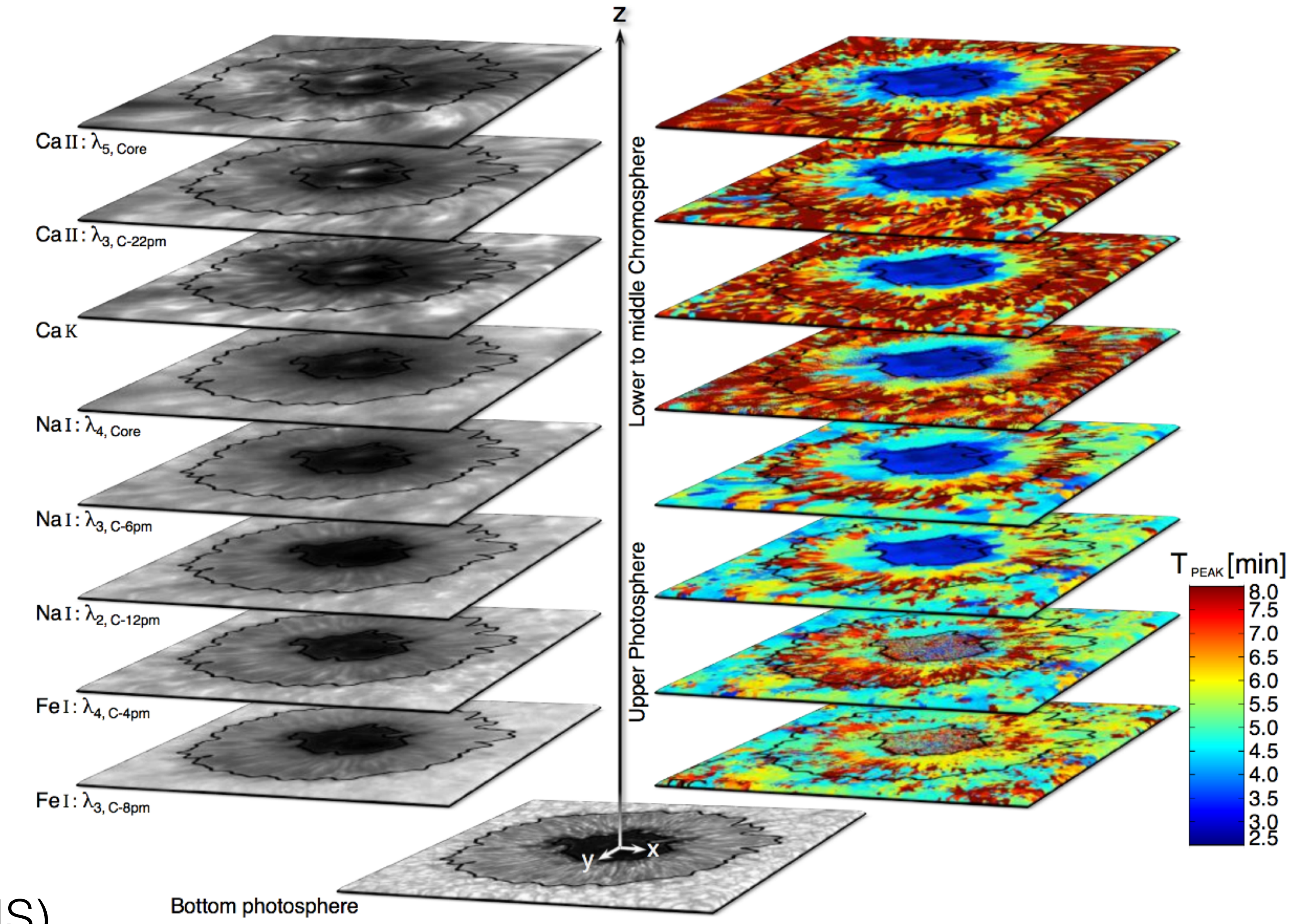


High-res solar instrumentation

GOAL: Multi-wavelength/multi-layer imaging and spectro-**polarimetric** data with **high-res**



IBIS/DST & ROSA/DST data (J. Löhner-Bötcher, KIS)



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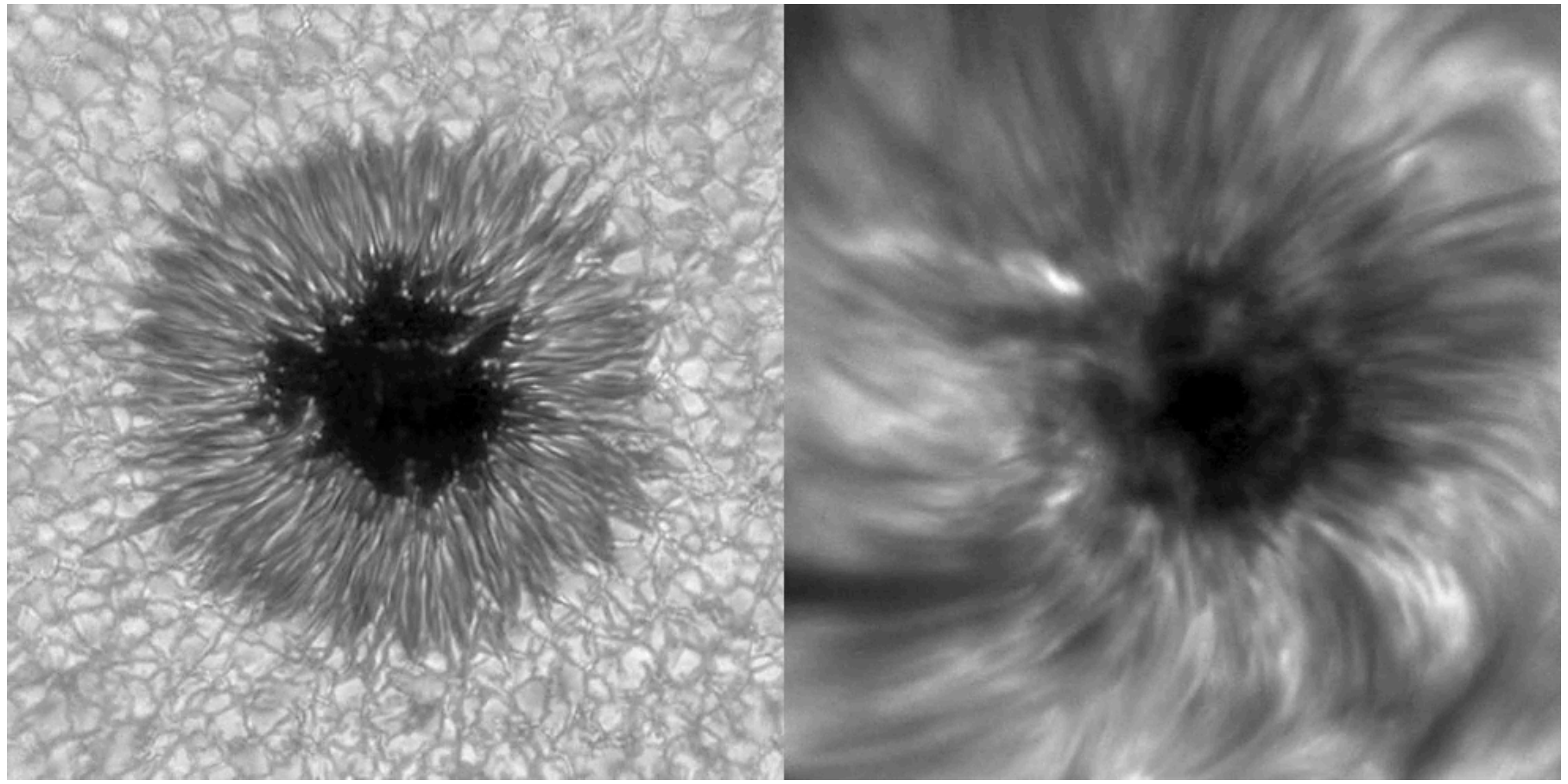

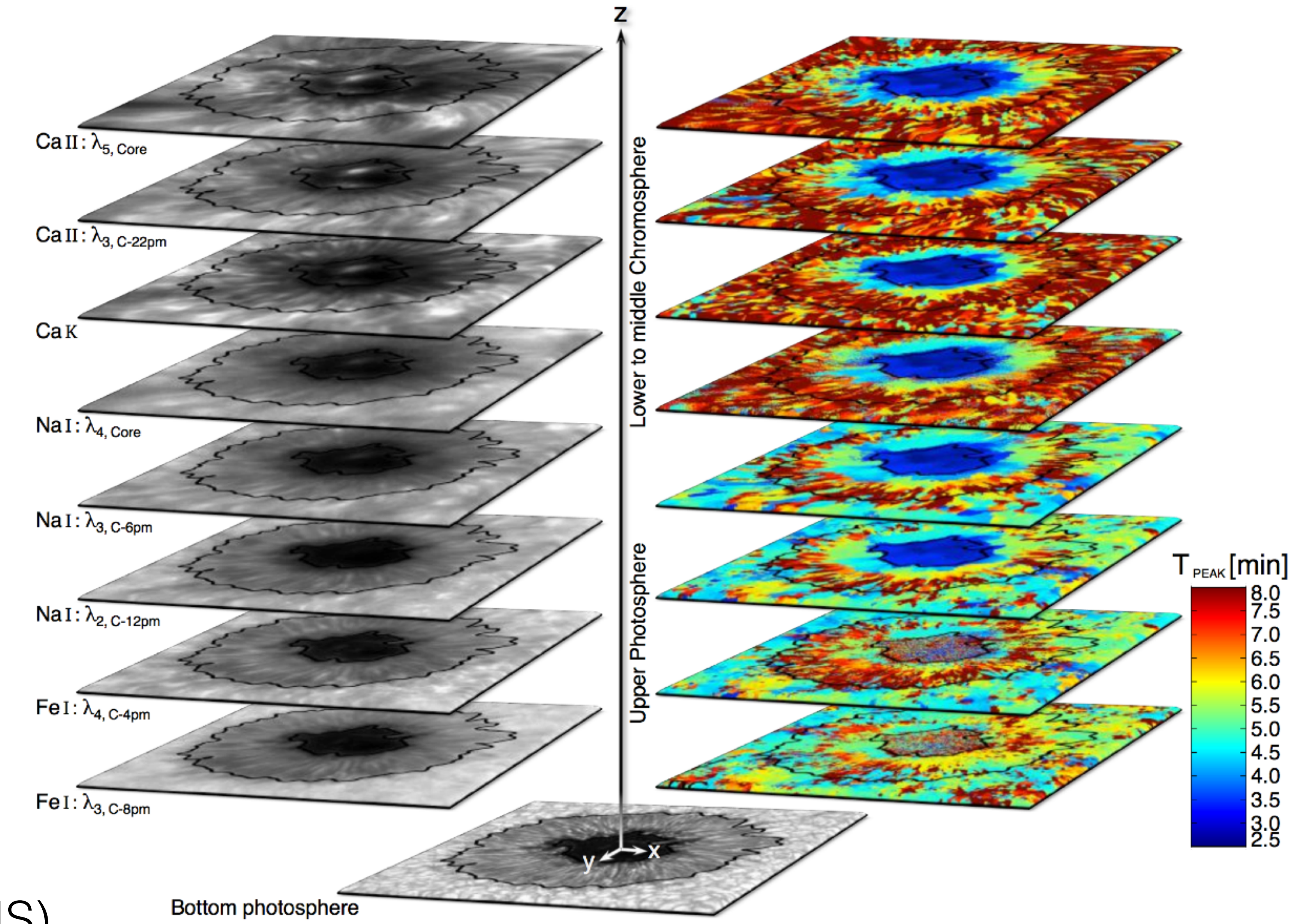

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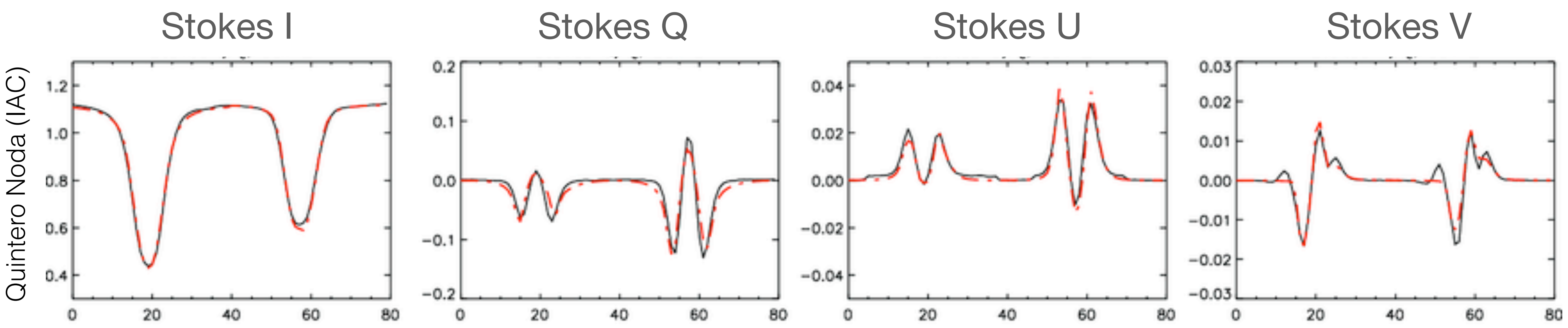
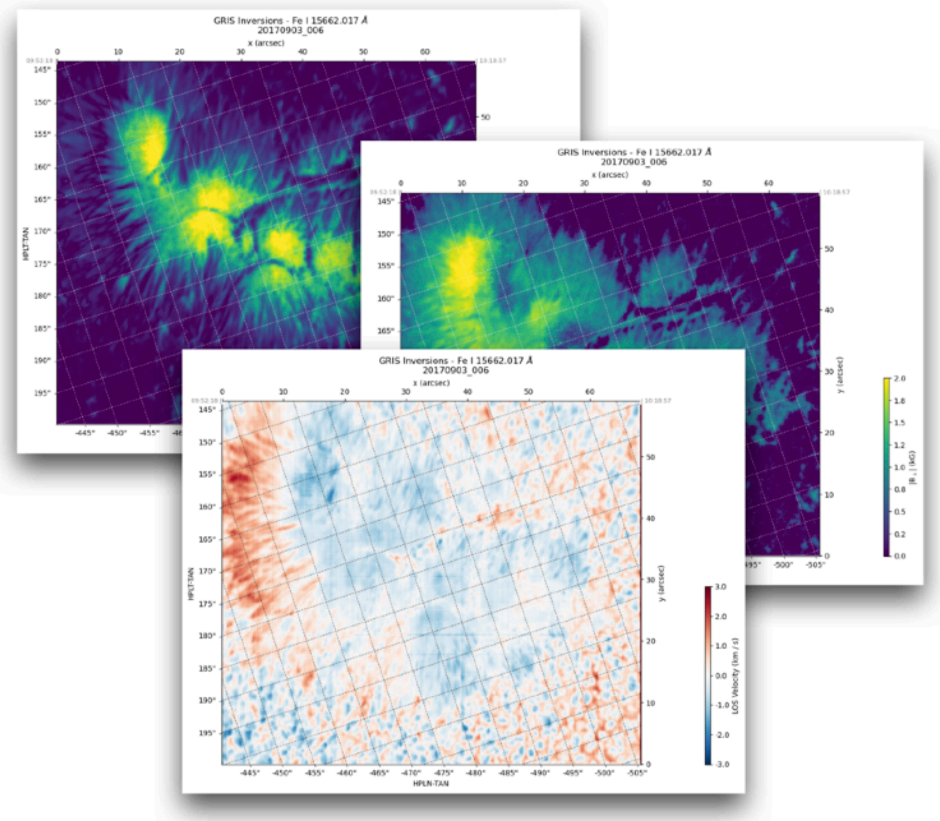
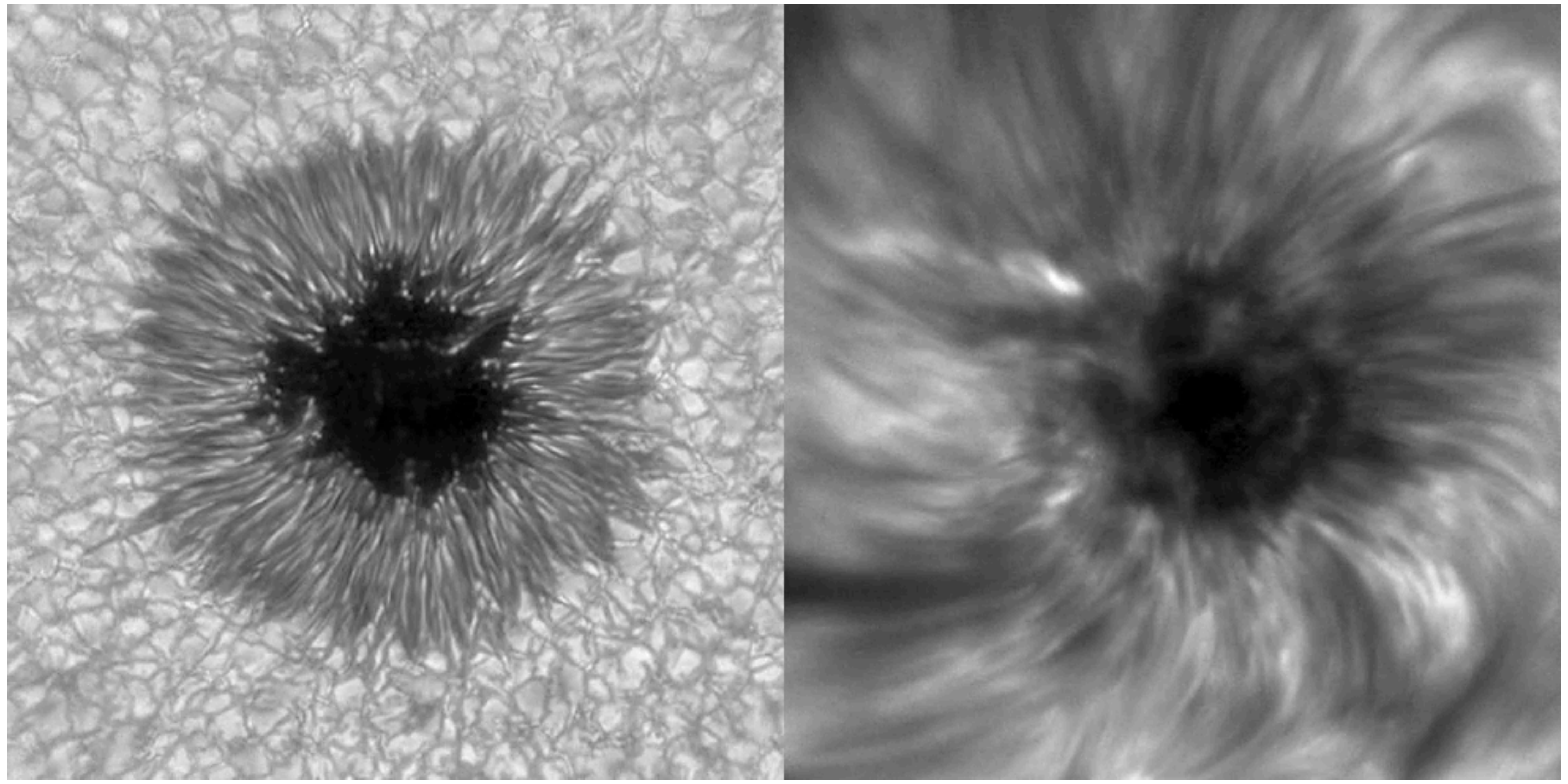


Inversion Techniques



Atmospheric parameters

Magnetic field vector, doppler velocities, Temperature,…



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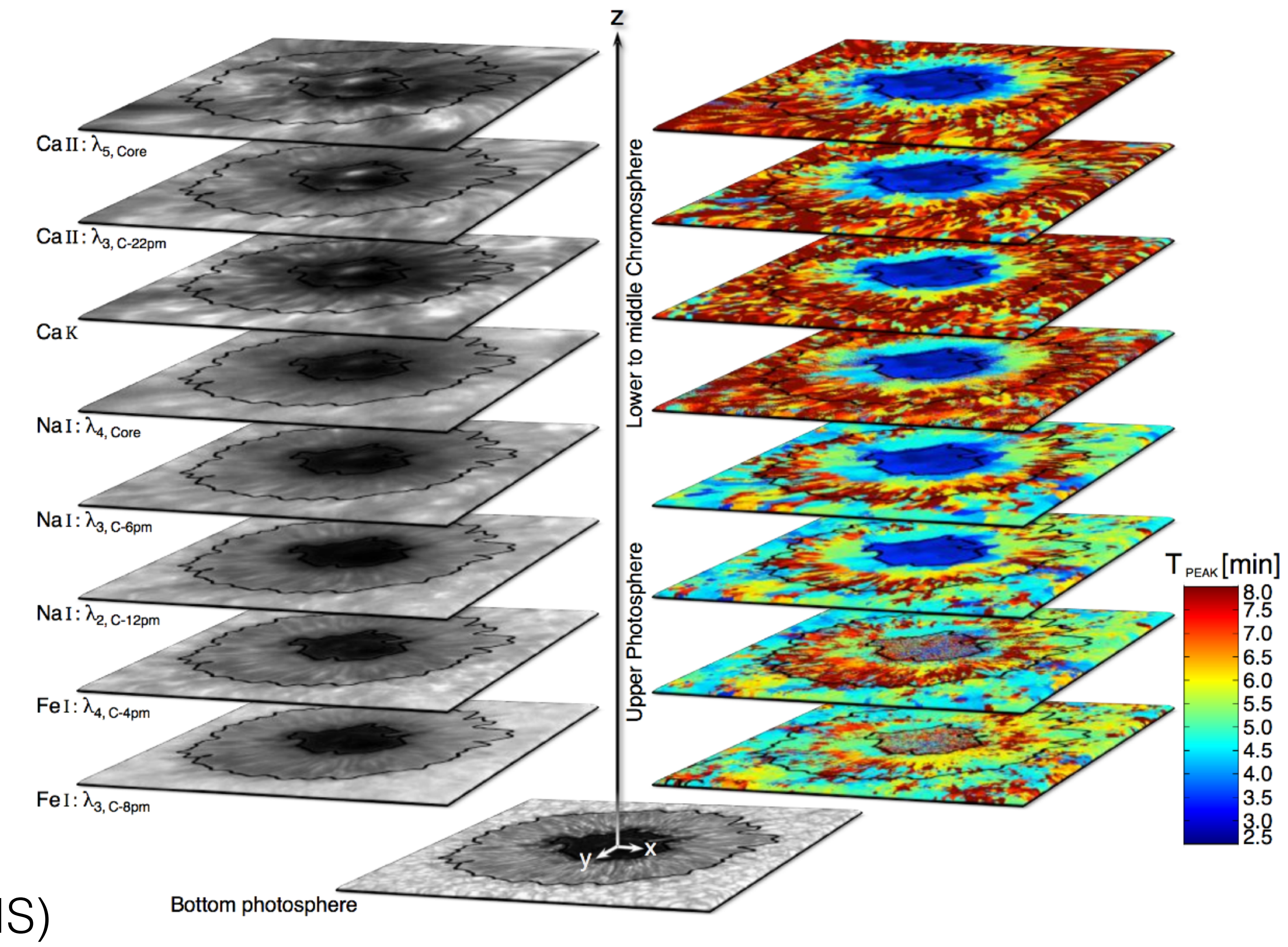

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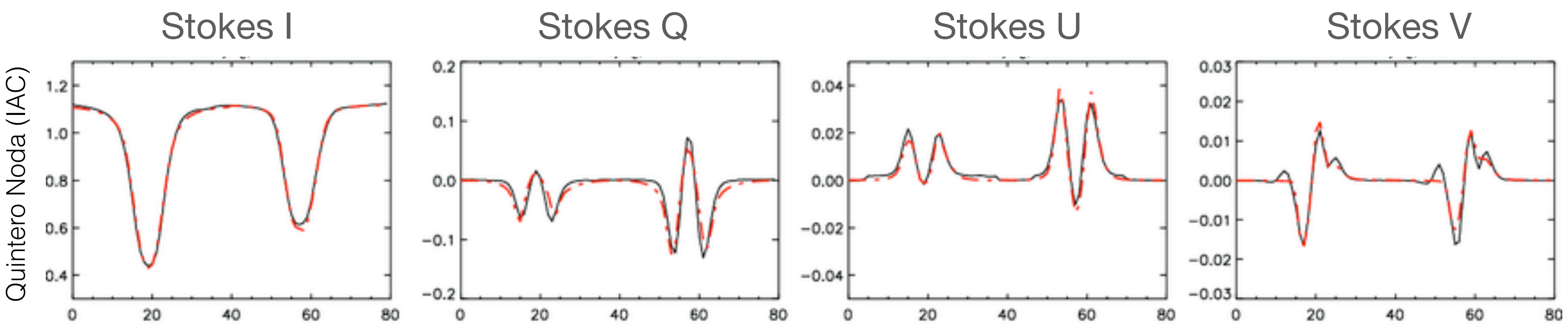

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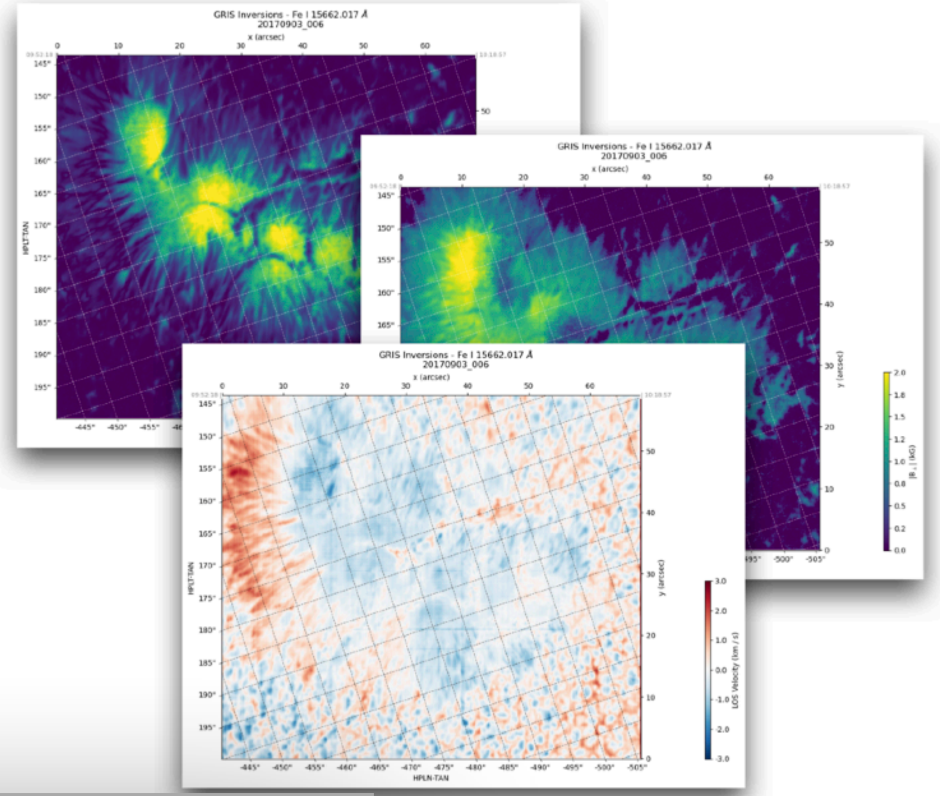

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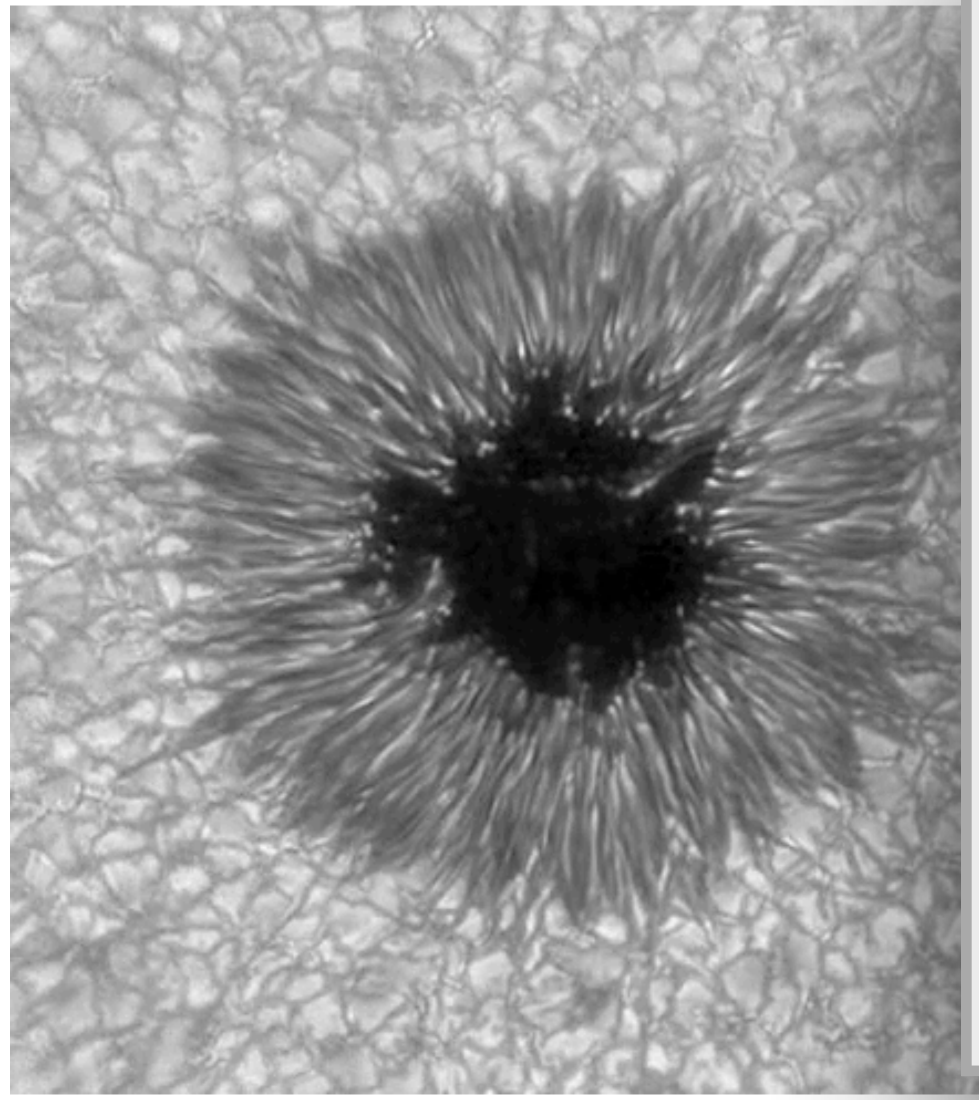
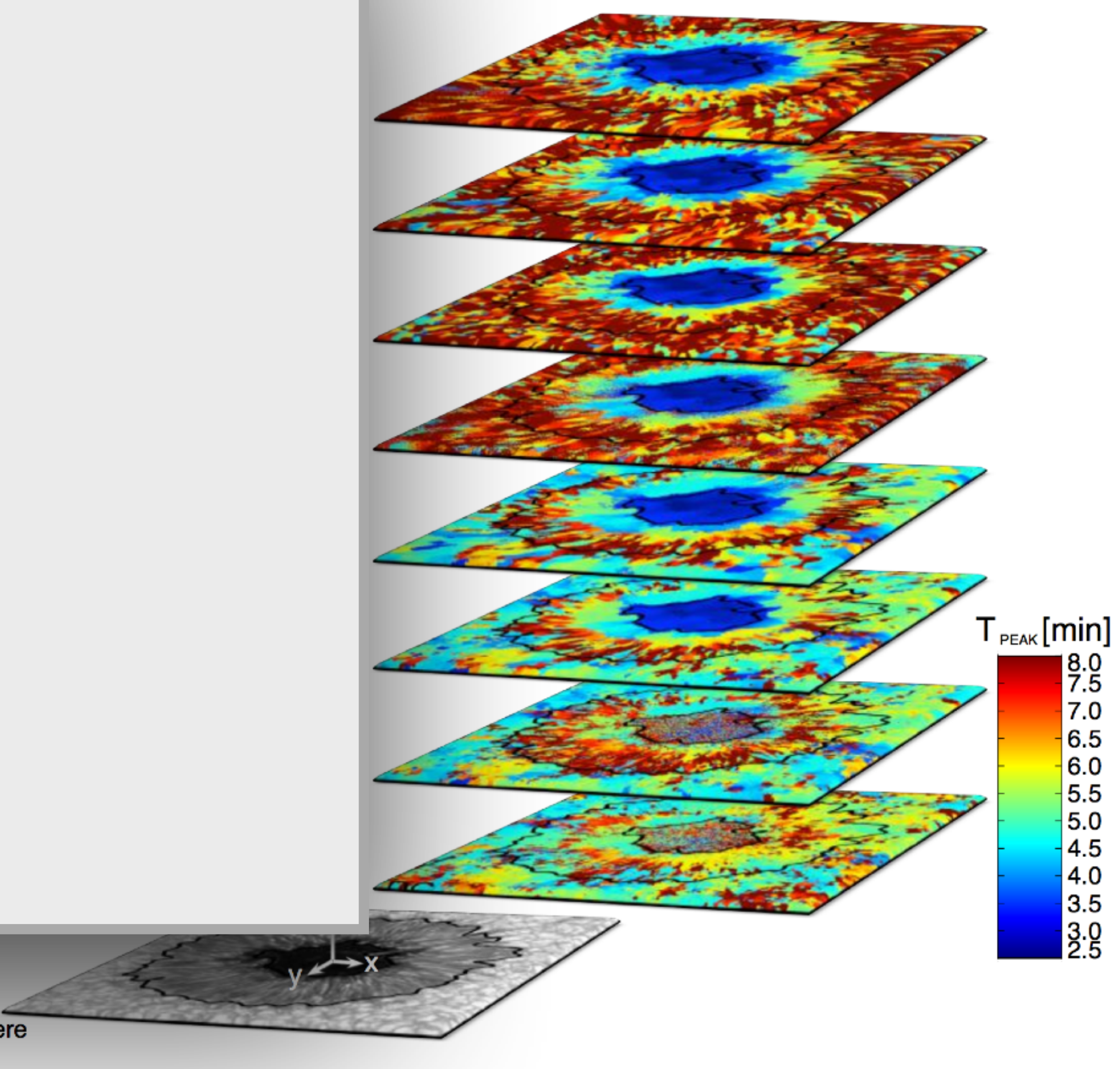
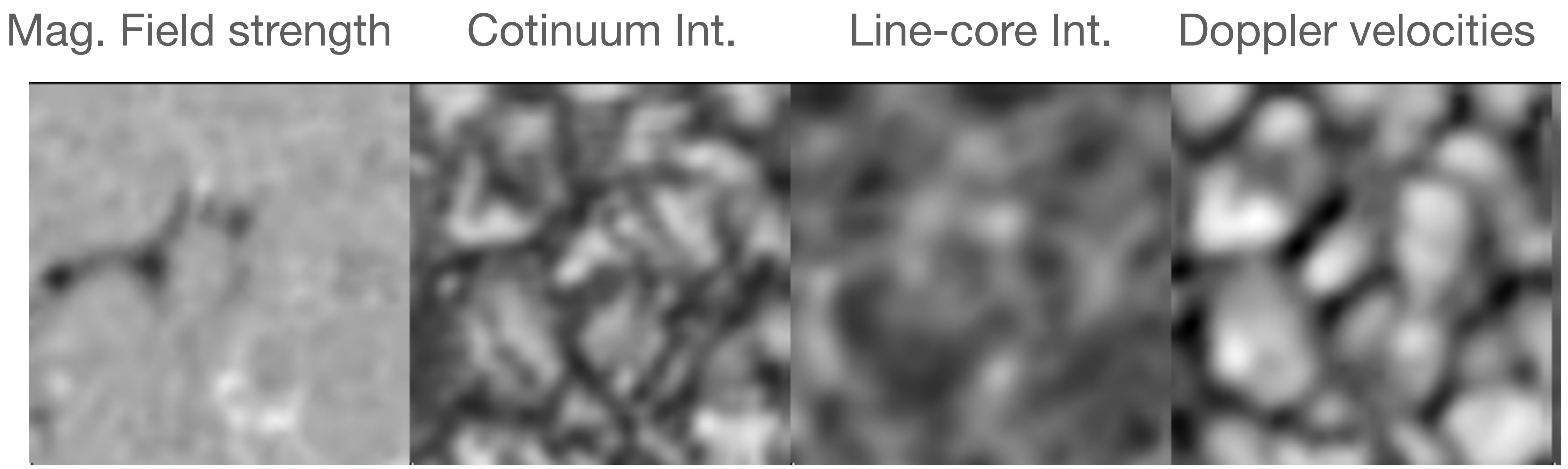


Lecture on
Solar Spectropolarimetry
by
Juanma Borrero
Tue, 16:50h

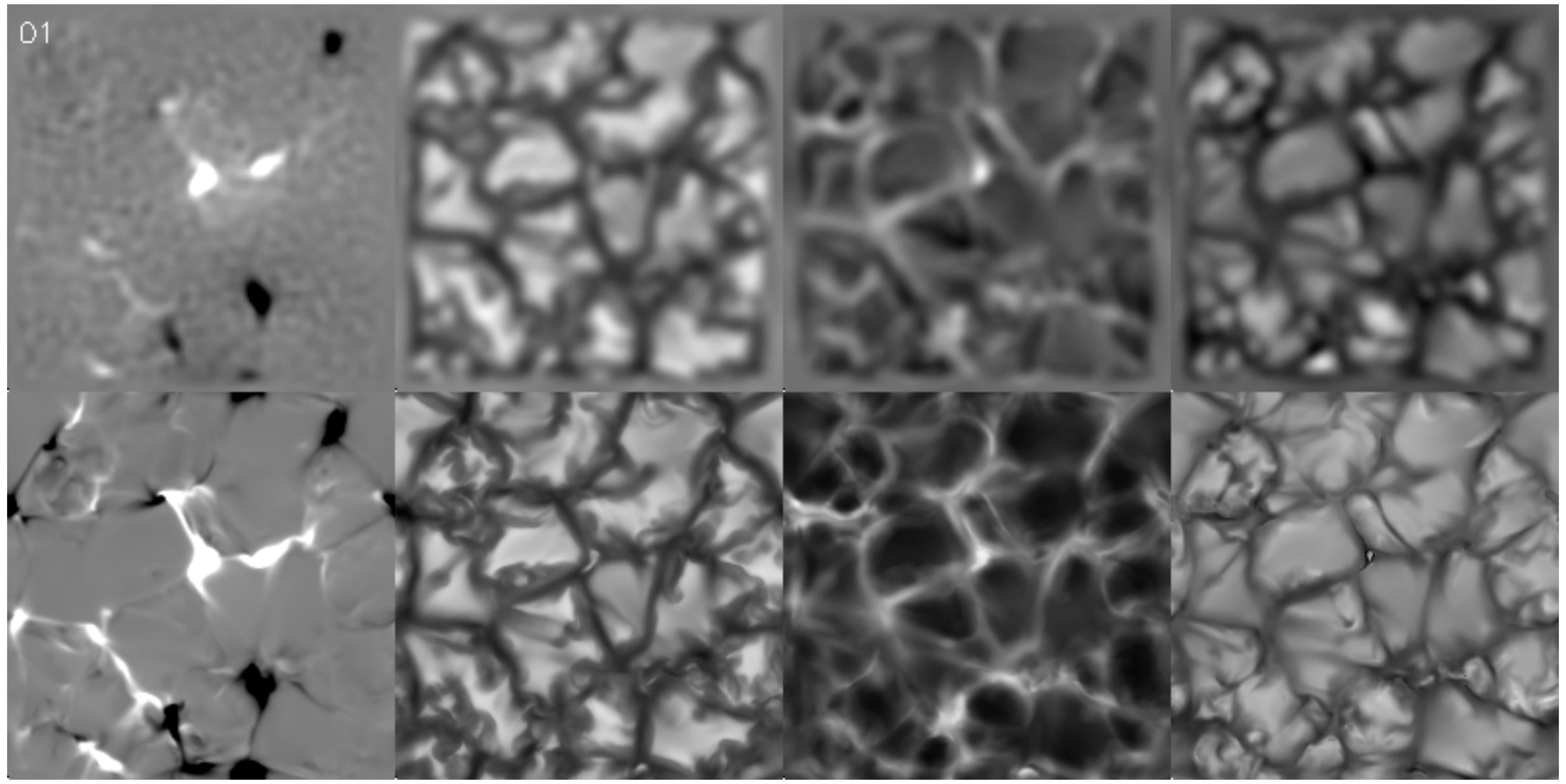


IBIS/DST & ROSA/DST data (J. Löhner-Bötcher, KIS)

Observations and simulations



OBSERVATIONS
VTT, quiet Sun

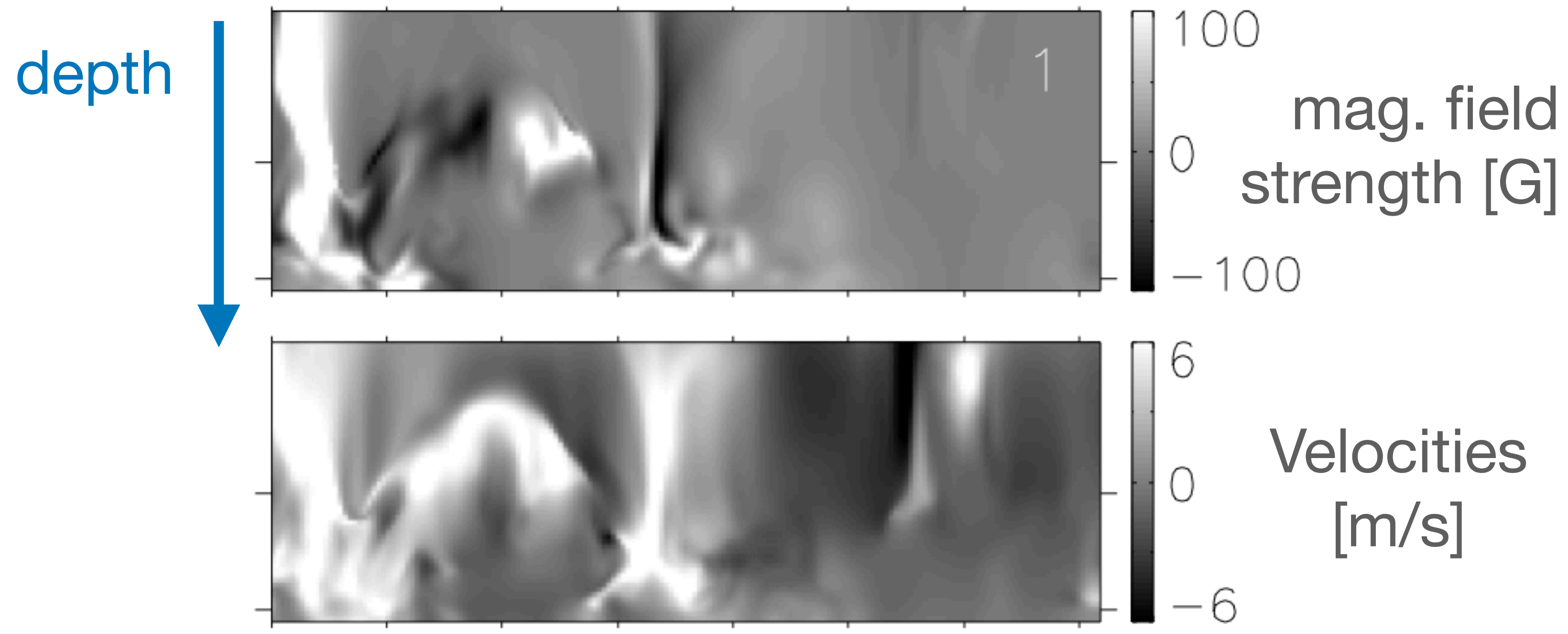


SIMULATIONS | MURaM, ‘quiet Sun’

Spatially degraded to VTT resolution
MURaM + Radiative Transfer (STOPRO) +
VTT Point Spread Function

Full resolution
MURaM +
Radiative Transfer (STOPRO)

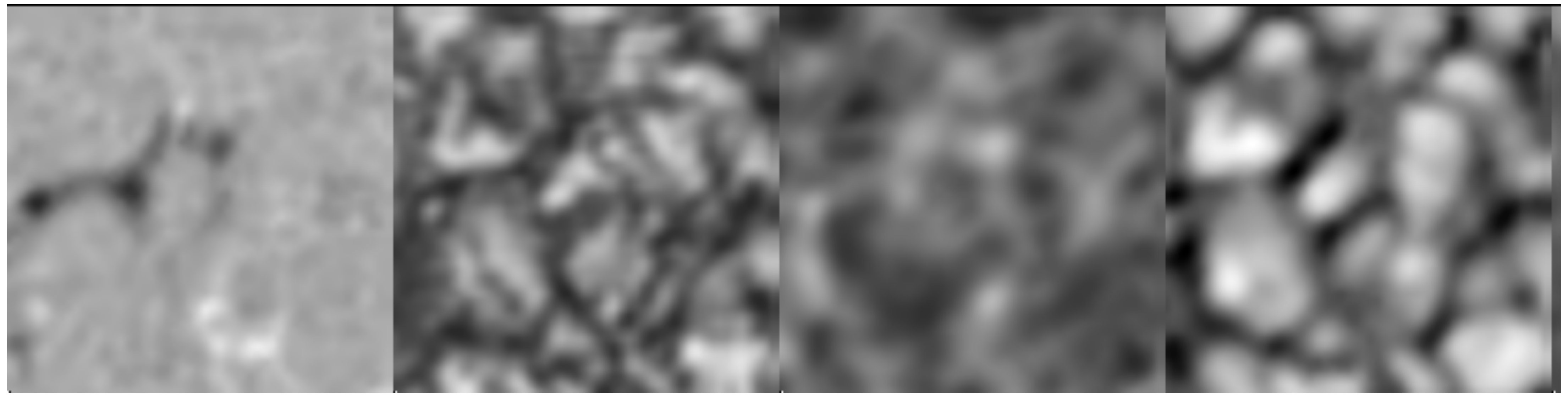
Vertical cuts



Bello González et al. (2008)

Observations and simulations

Mag. Field strength Cotinuum Int. Line-core Int. Doppler velocities



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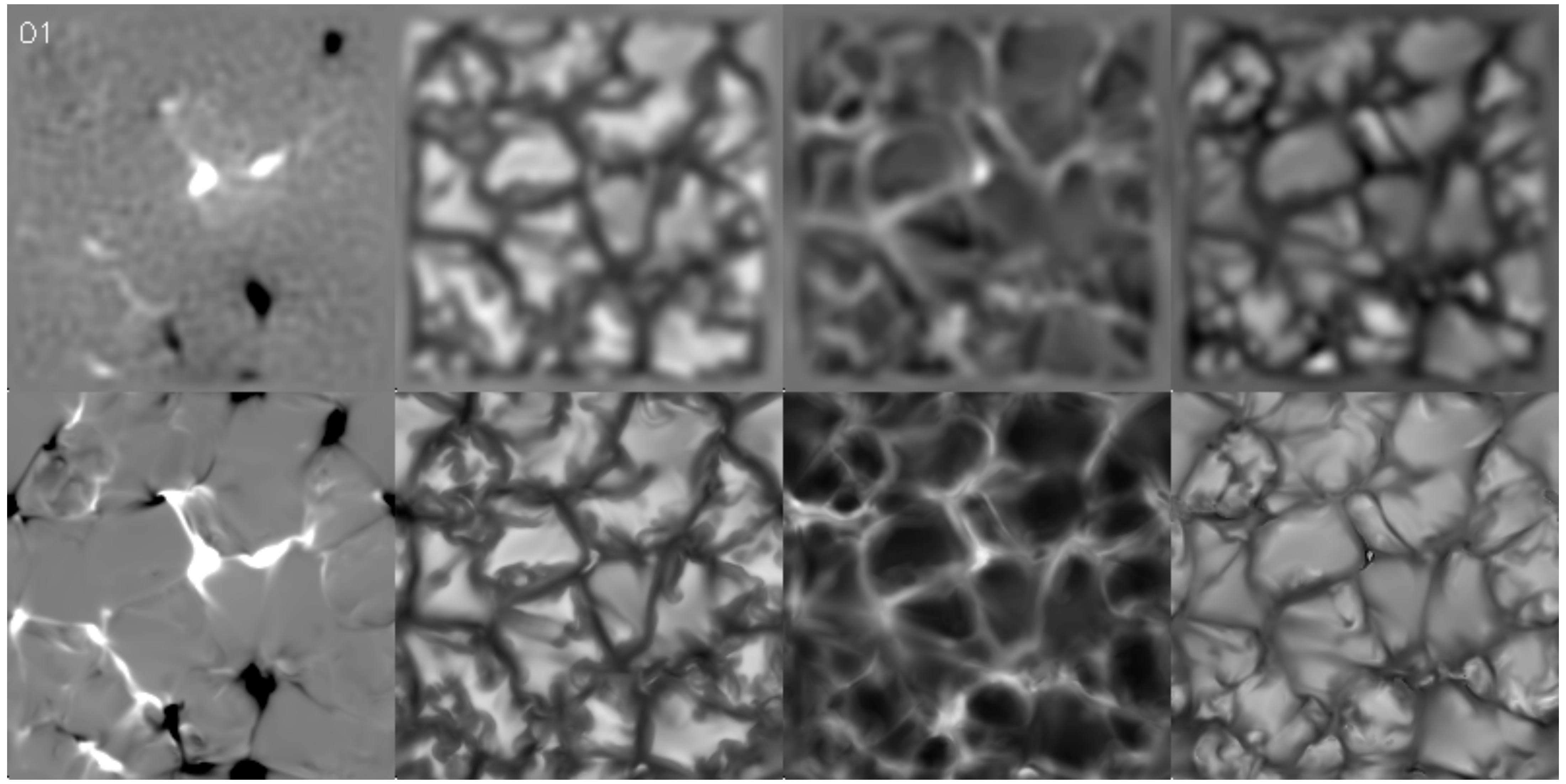

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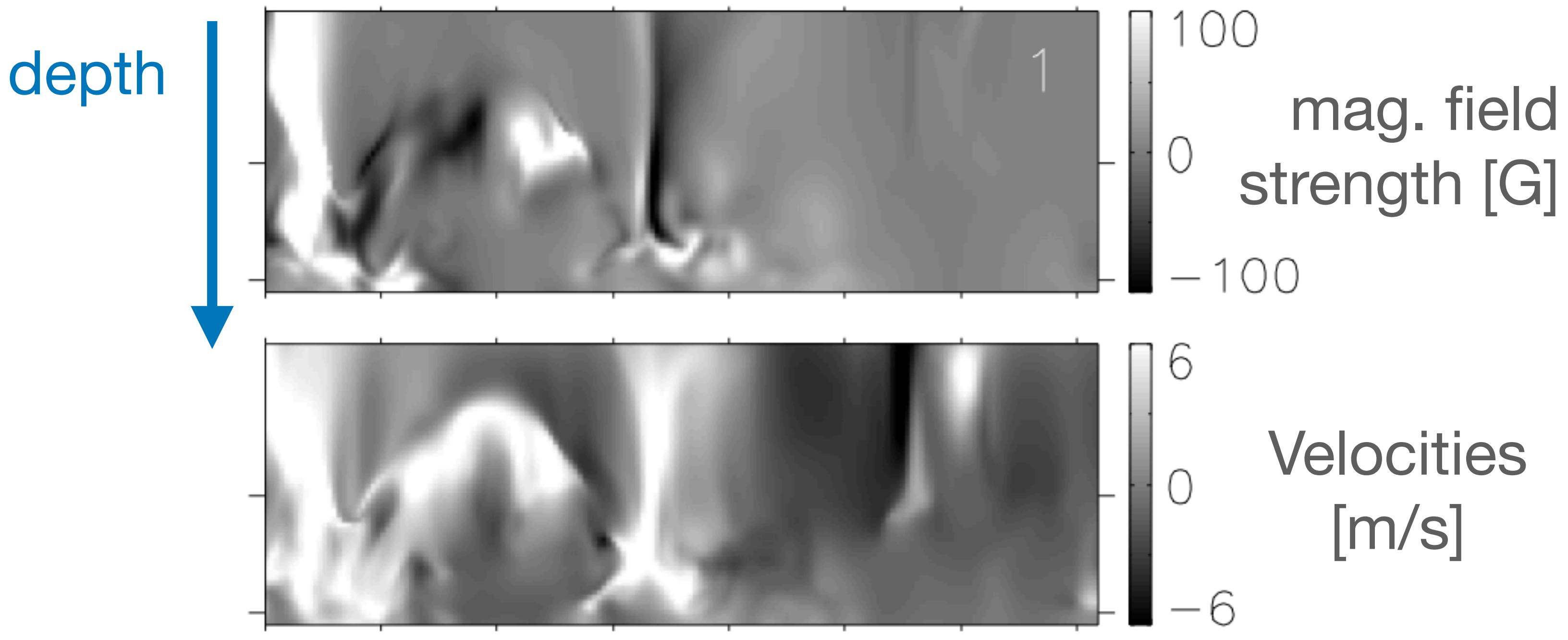

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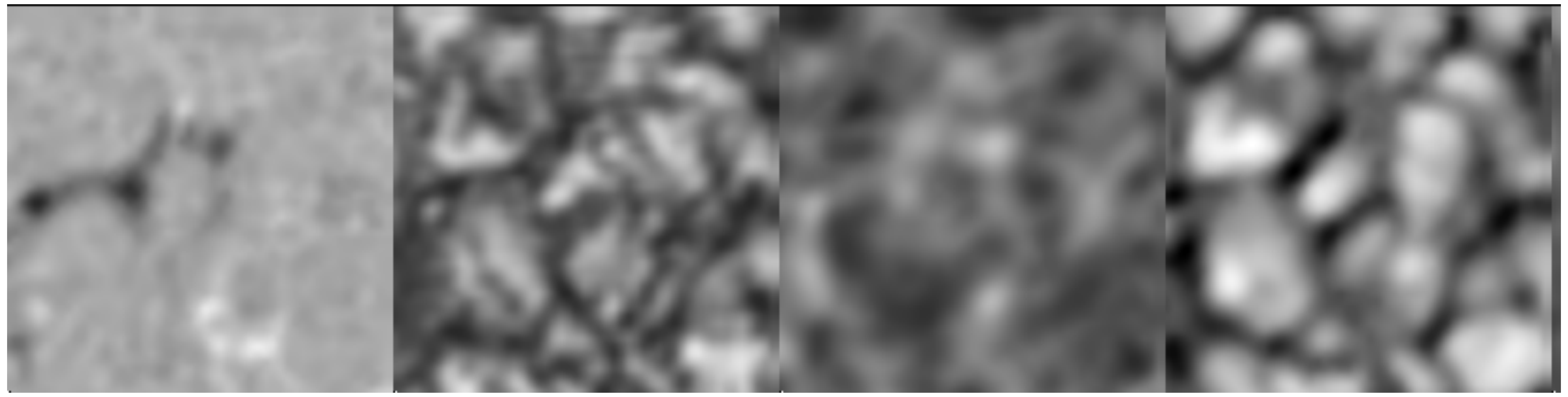

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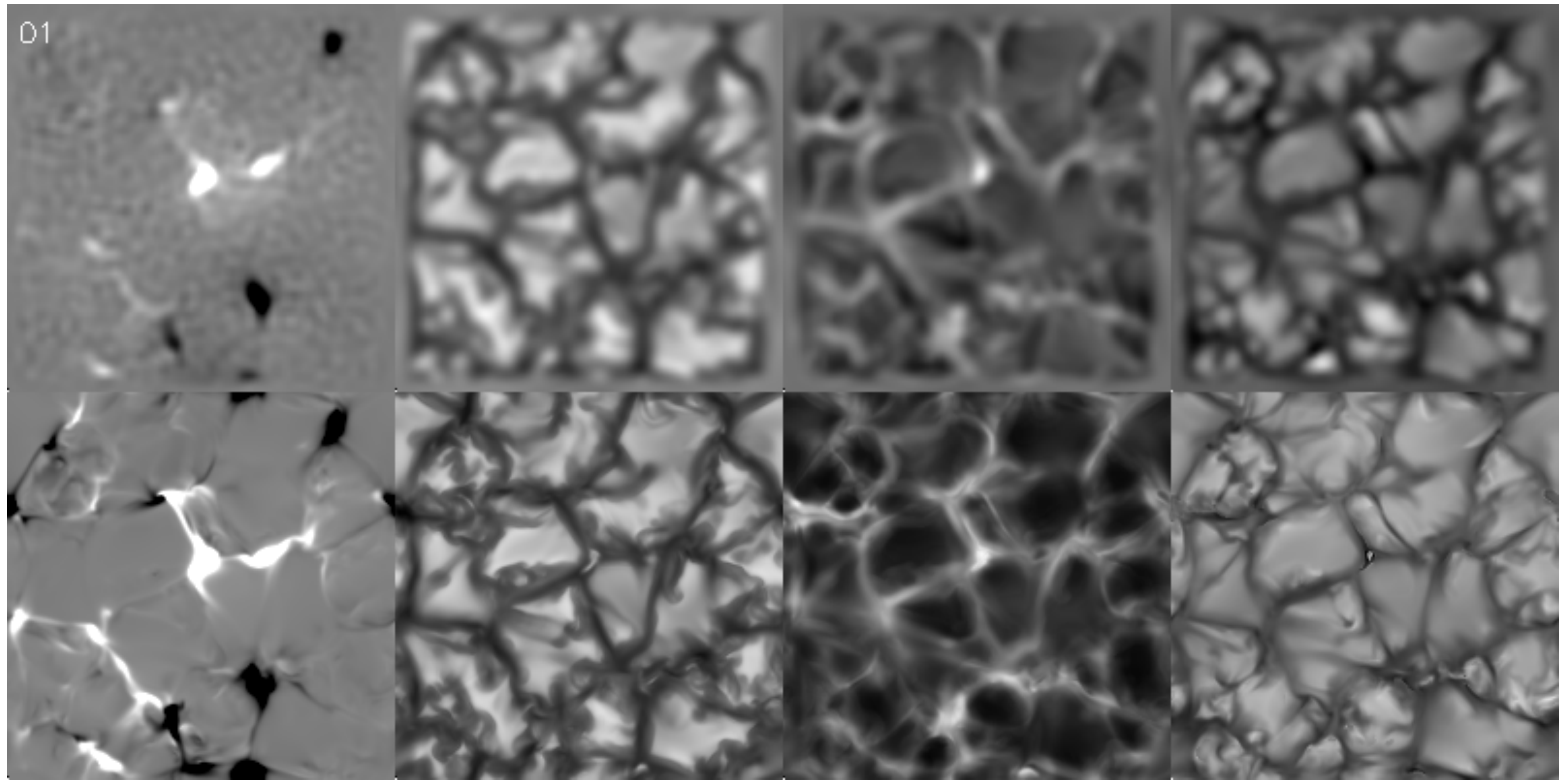

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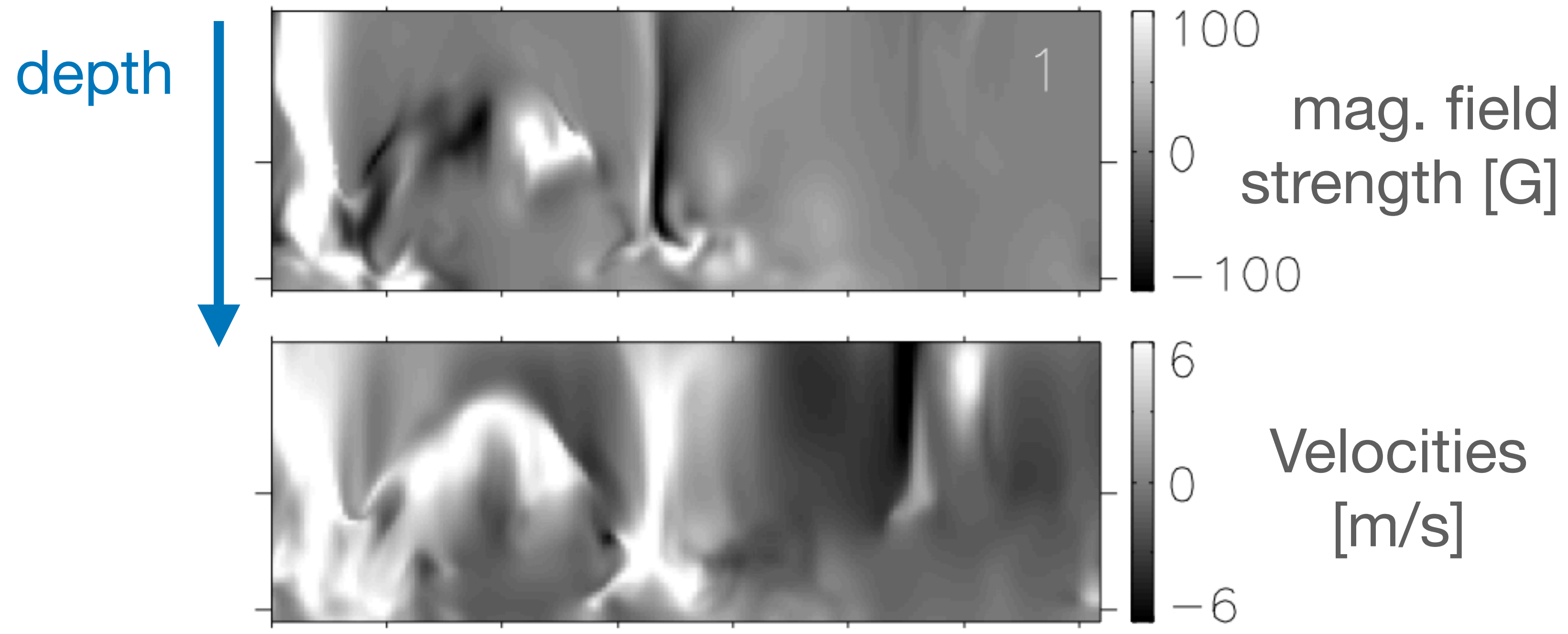
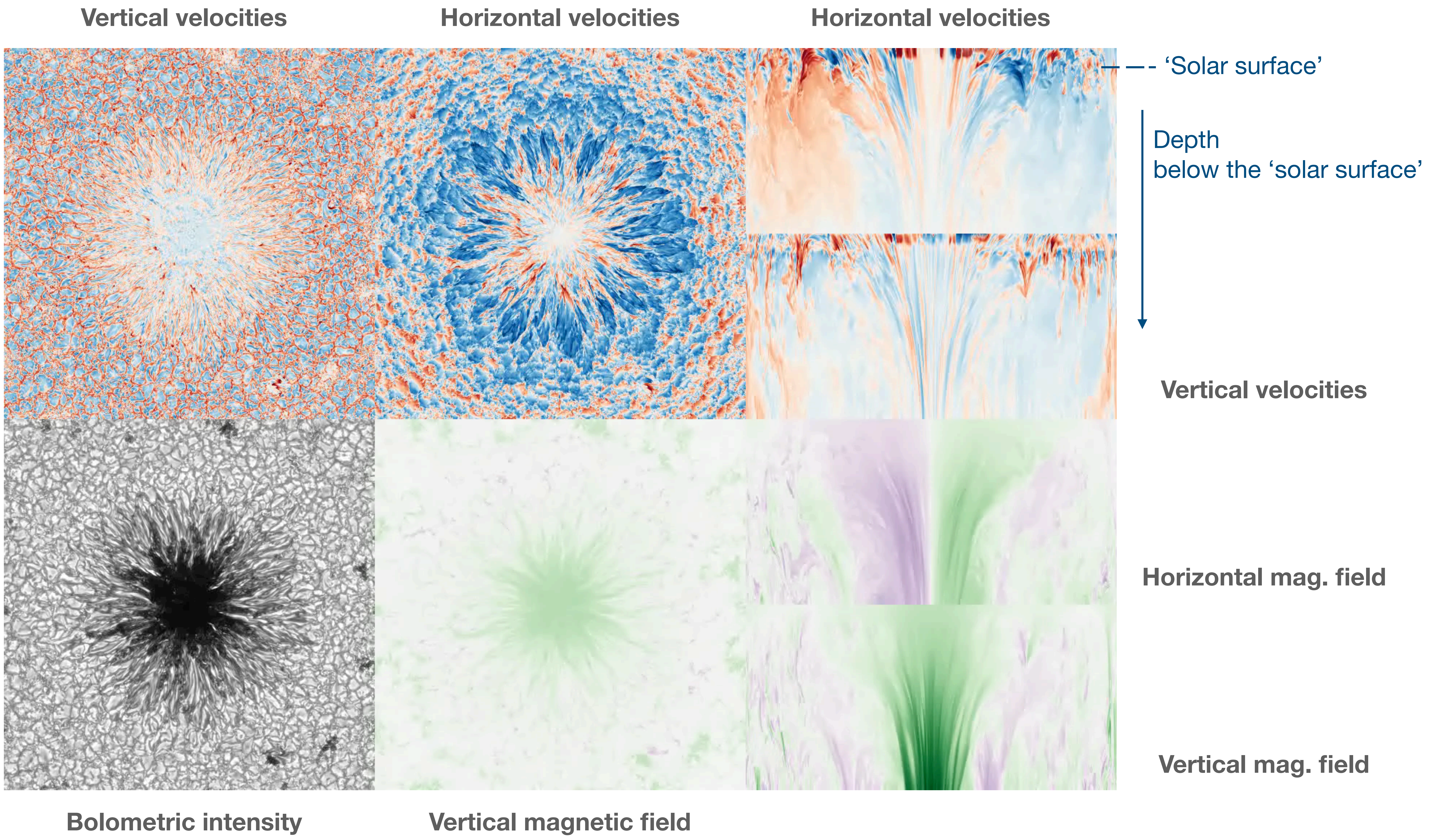


Bello González et al. (2008)

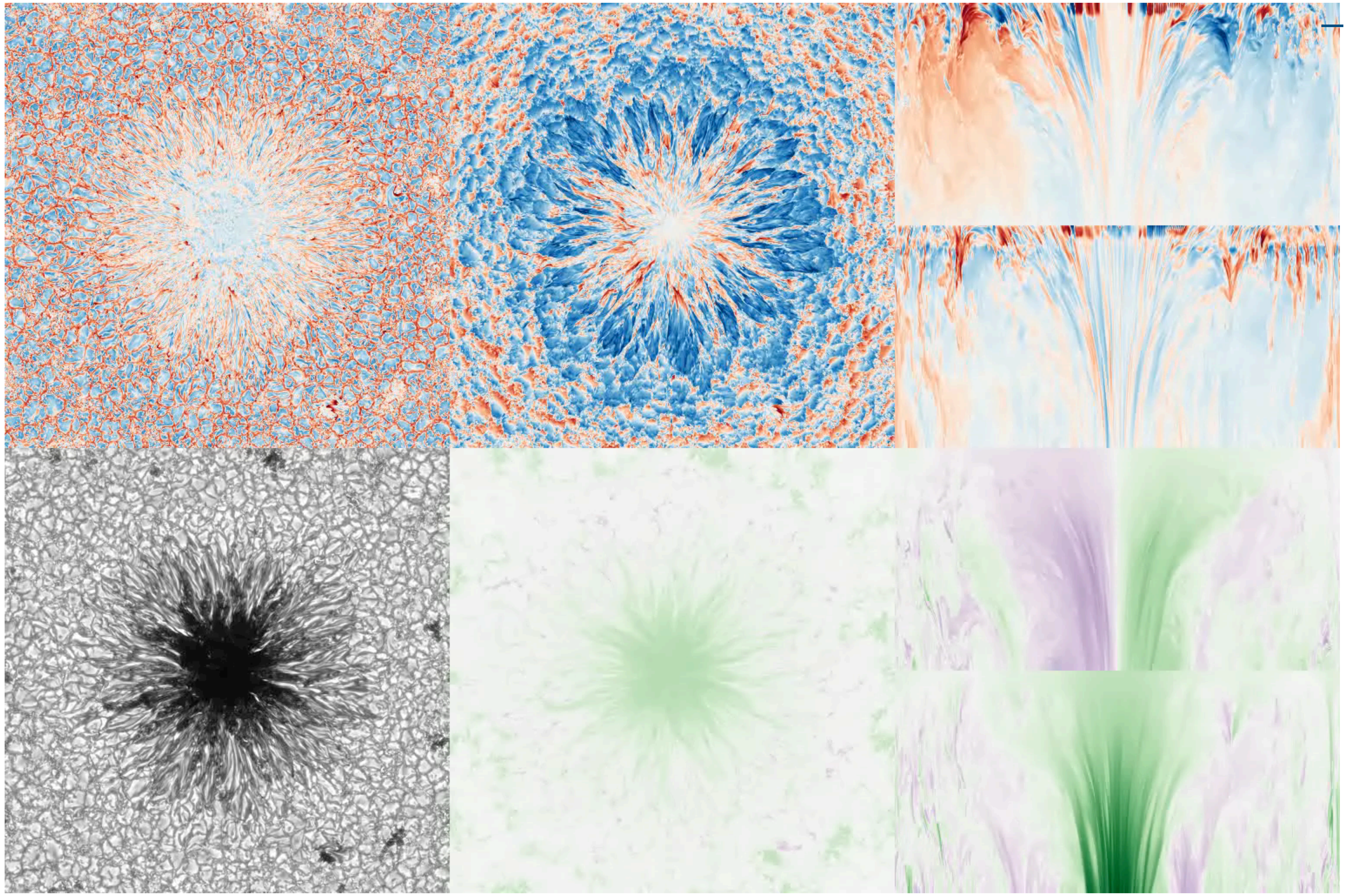
Realistic MHD sunspot simulations



Schmassmann (KIS) | MURaM simulations

Realistic MHD sunspot simulations

Vertical velocities | Horizontal velocities | Horizontal velocities



‘Solar surface’

Depth
below the ‘solar surface’

Vertical velocities

Horizontal mag. field

Vertical mag. field

Bolometric intensity | Vertical magnetic field

Solar fine-structure

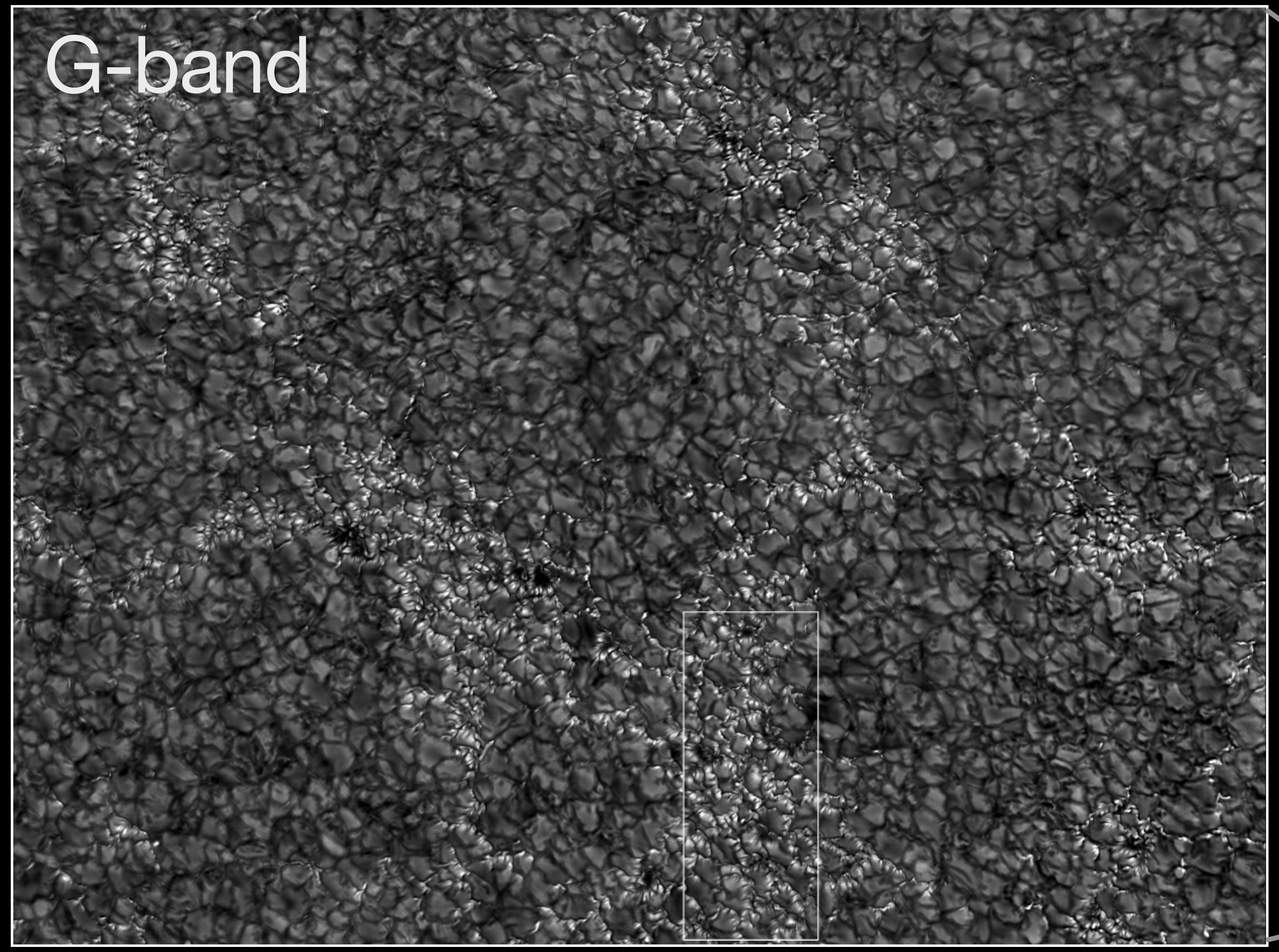
Selected cases

light-bridges
umbral-dots network solar-tornados
penumbral-filaments
striations sunspots
umbra
faculae fibrils
ellerman-bombs waves convection plage
penumbra
intergranular-lanes granules flux-emergence
pores spicules
supergranulation filaments prominences
filigree

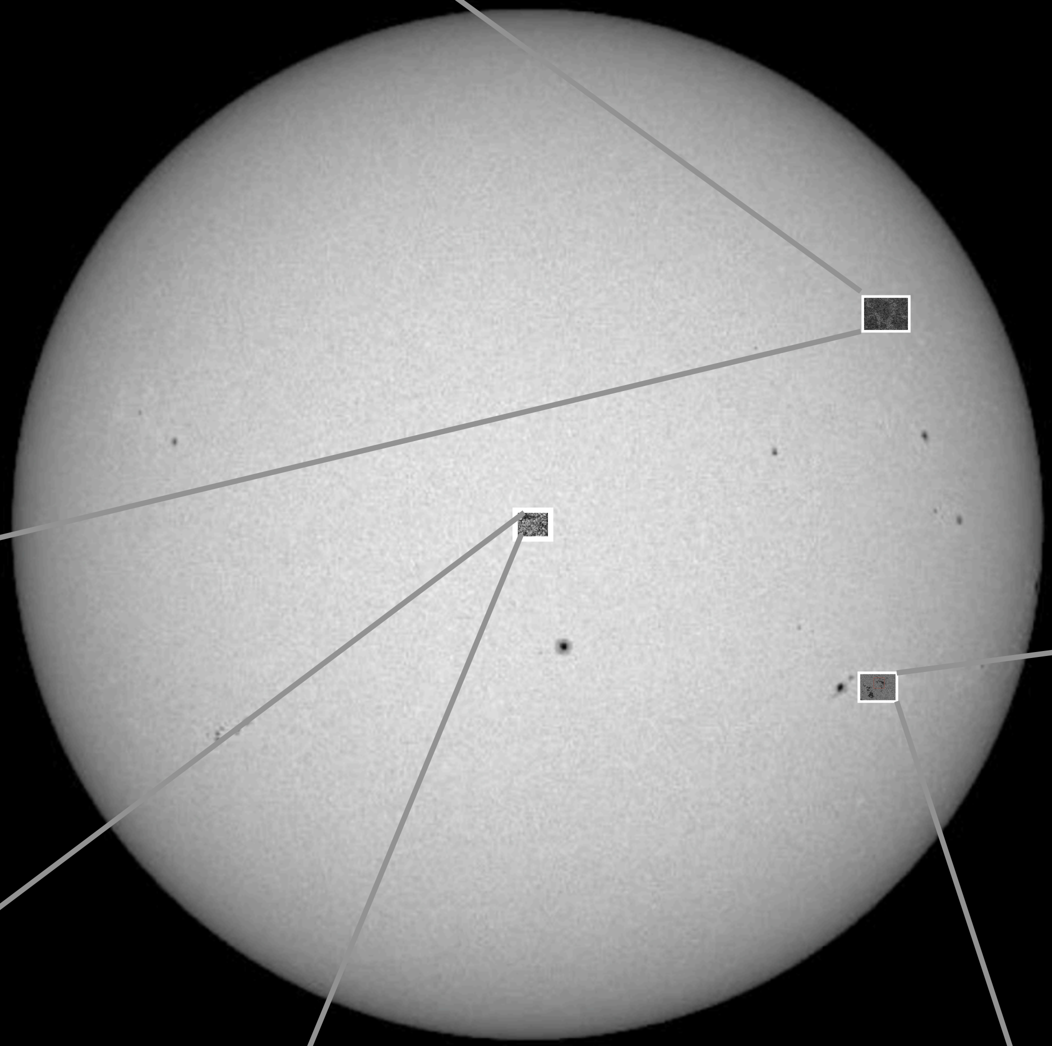
Magnetic bright points, faculae, and plages

Faculae, Plages & Magnetic Bright Points

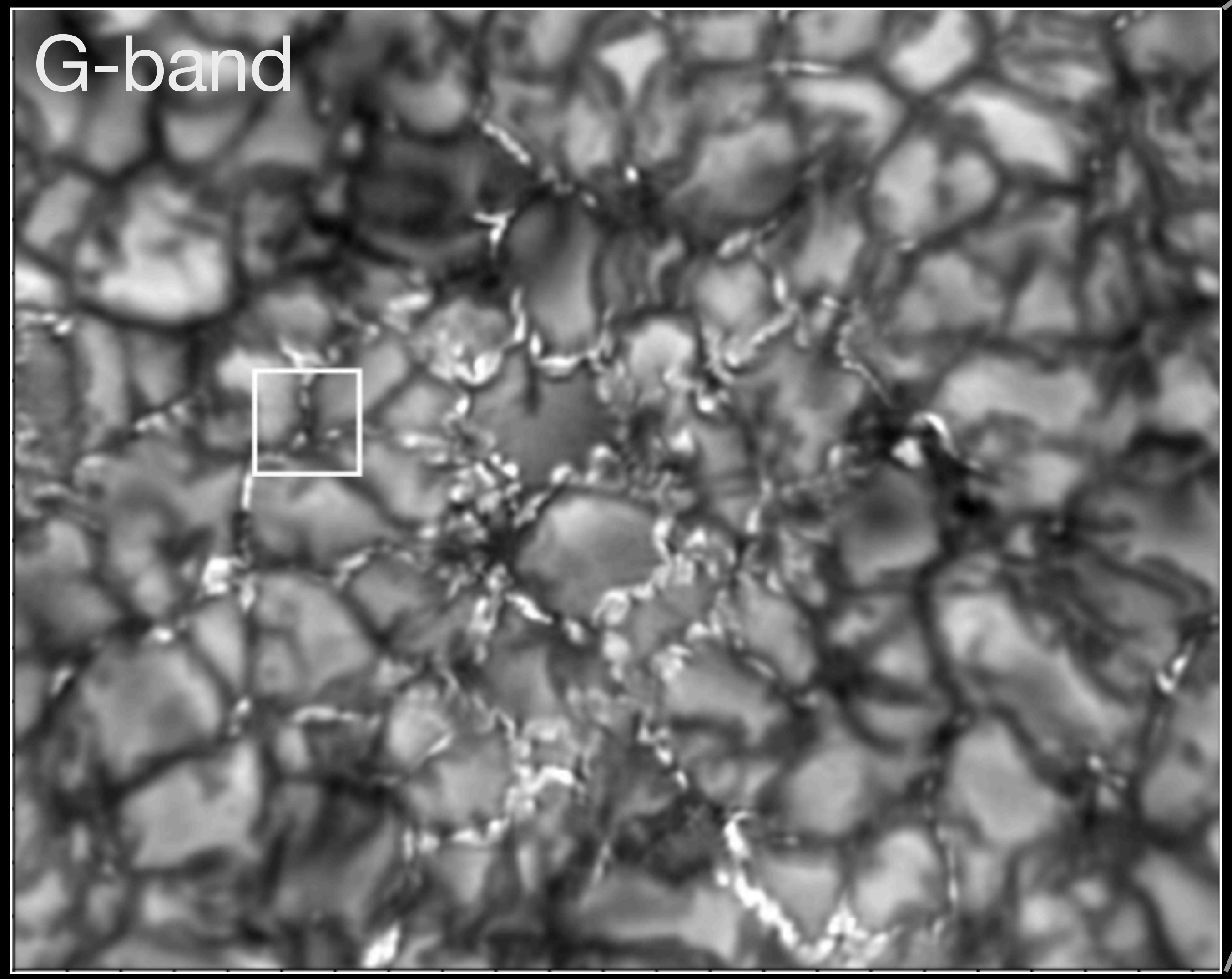
Faculae
Magnetic Network in
quiet Sun close to the solar limb



Kuridze et al. (2025) | DKIST/VBI

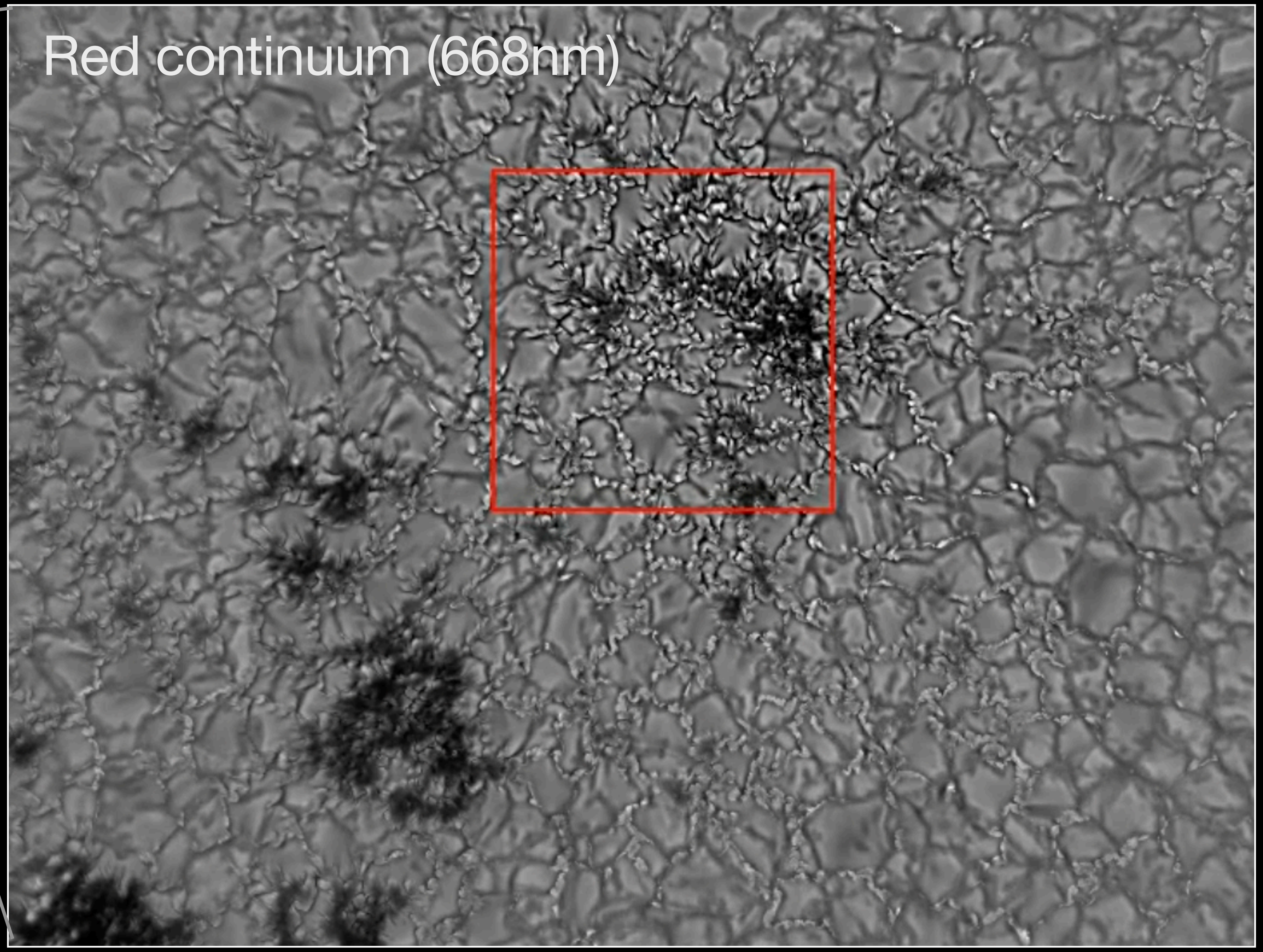


MBPs
Magnetic Network in
quiet Sun close to disc centre



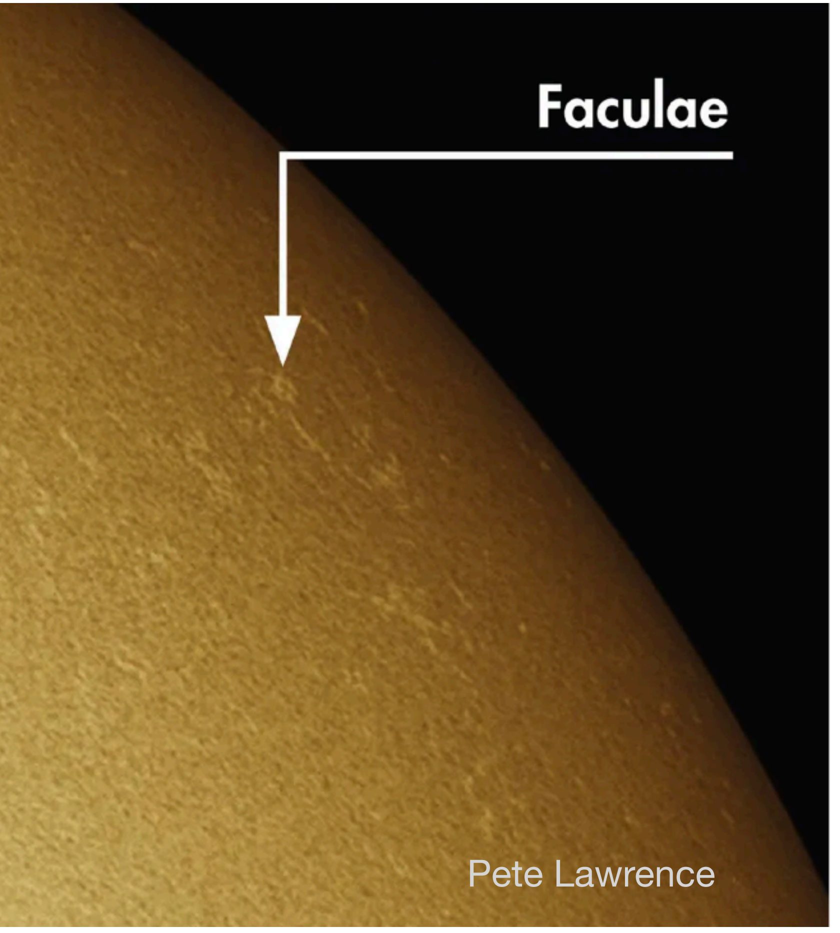
Schlichenmaier et al. (2023) | GREGOR/HiFI

Plages
Magnetic Network in Active Regions
at disc centre and close to the limb

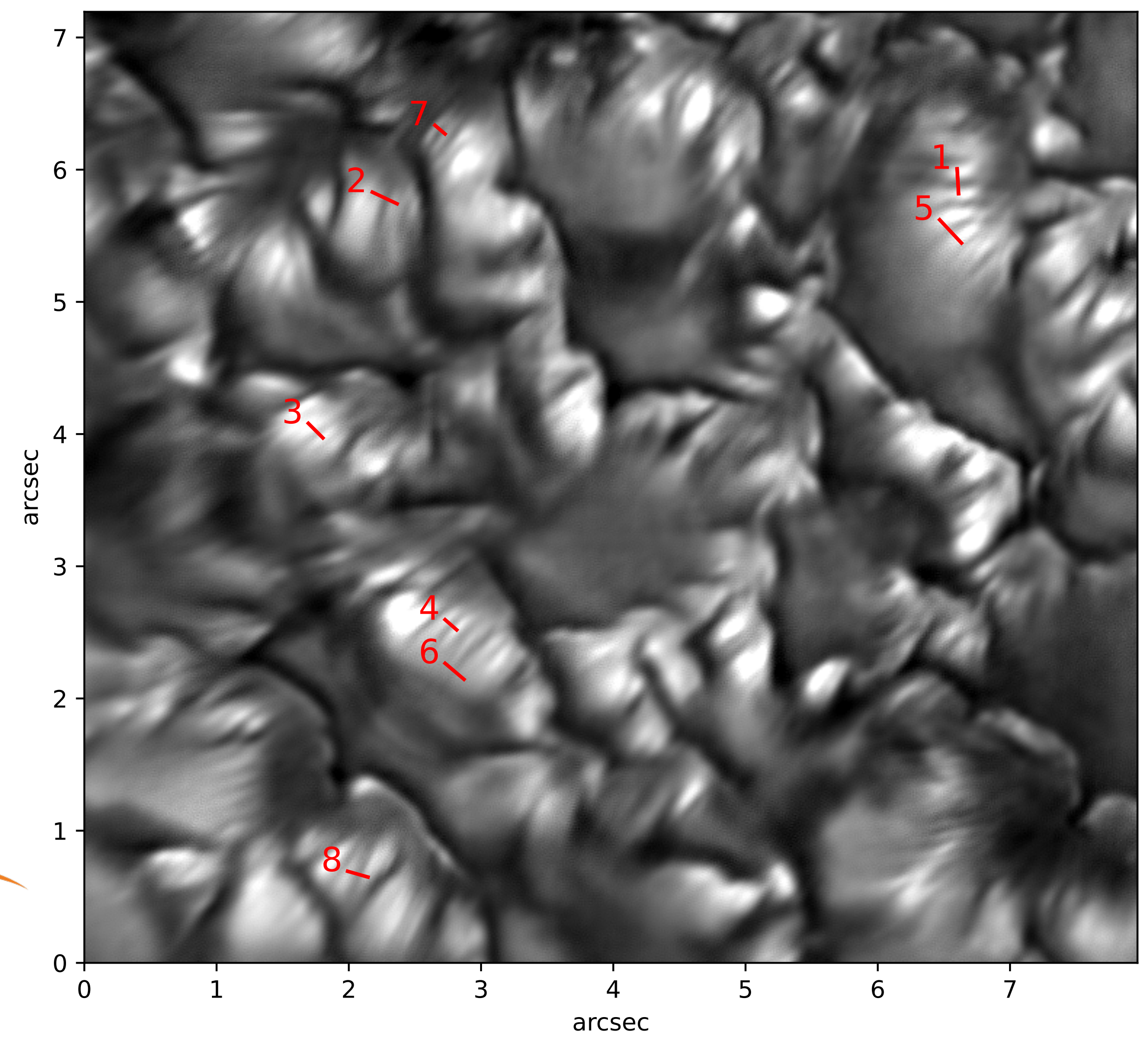


Van Noort & Wöger | DKIST Fast Cam (2025)

Faculae

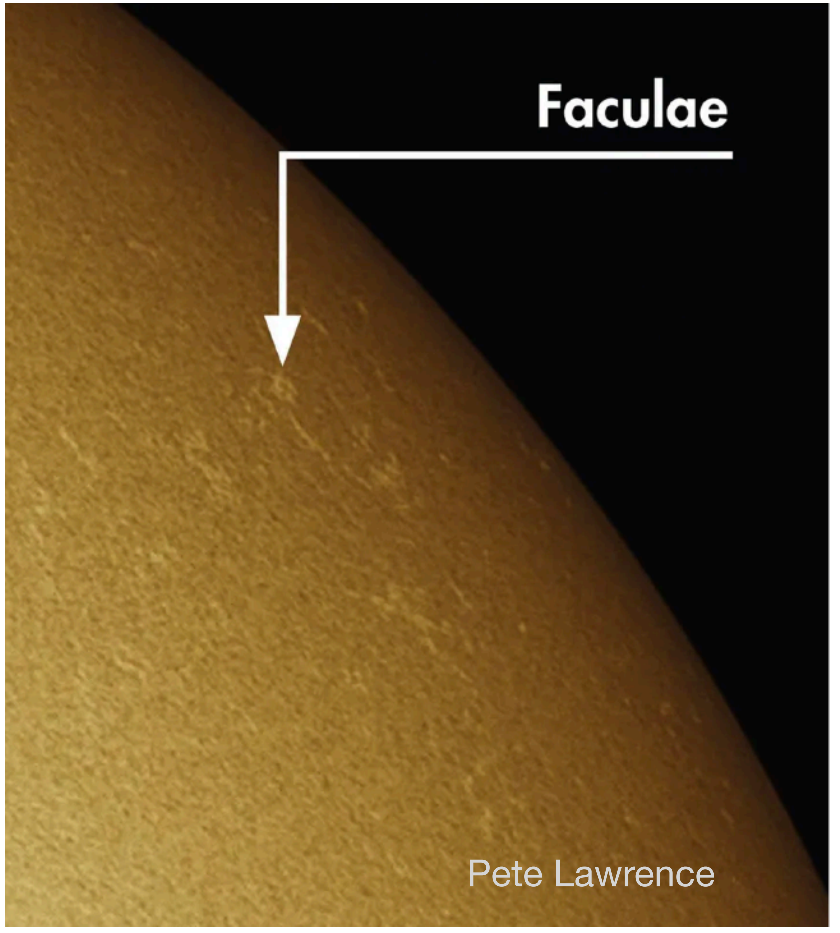


DKIST/VBI observations



Kuridze et al. (2025) | DKIST/VBI data

- **Structures of enhanced brightness** visible on the solar surface best seen near the solar limb
- **Disc-centre counterpart:** Magnetic Bright Points of smaller size (due to projection effects)
- **Magnetic origin:** Formed by bundles of strong, concentrated magnetic fields
- **Hot-wall effect:** The intense magnetic field induces an evacuation of plasma, allowing observers to see slightly deeper, hotter layers of the solar photosphere. This "hot wall" effect is enhanced at the limb due to viewing angle
- **Contribution to solar irradiance:** Contribute to variations in the Sun's total irradiance, making the Sun slightly brighter during peak magetic activity



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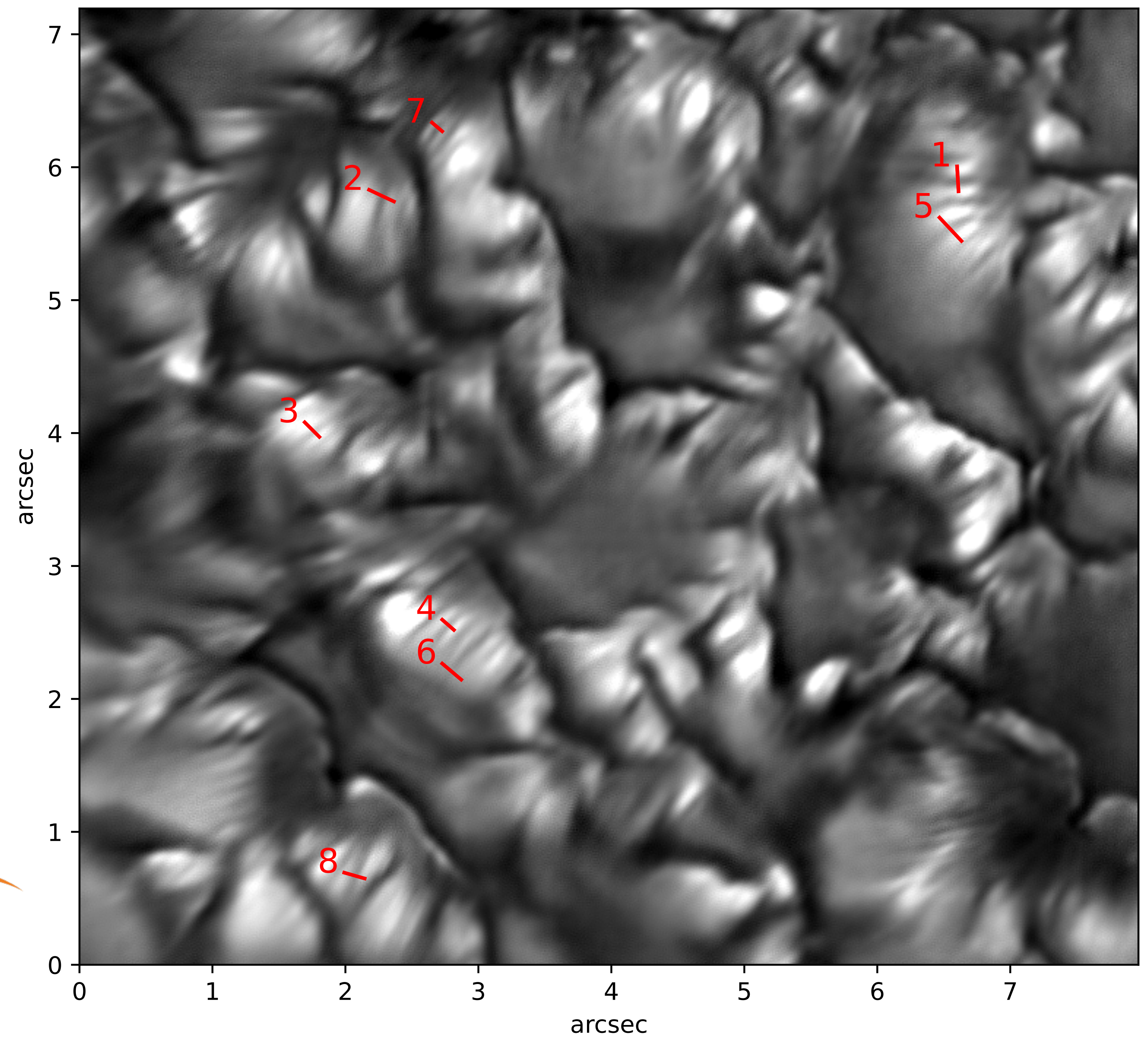
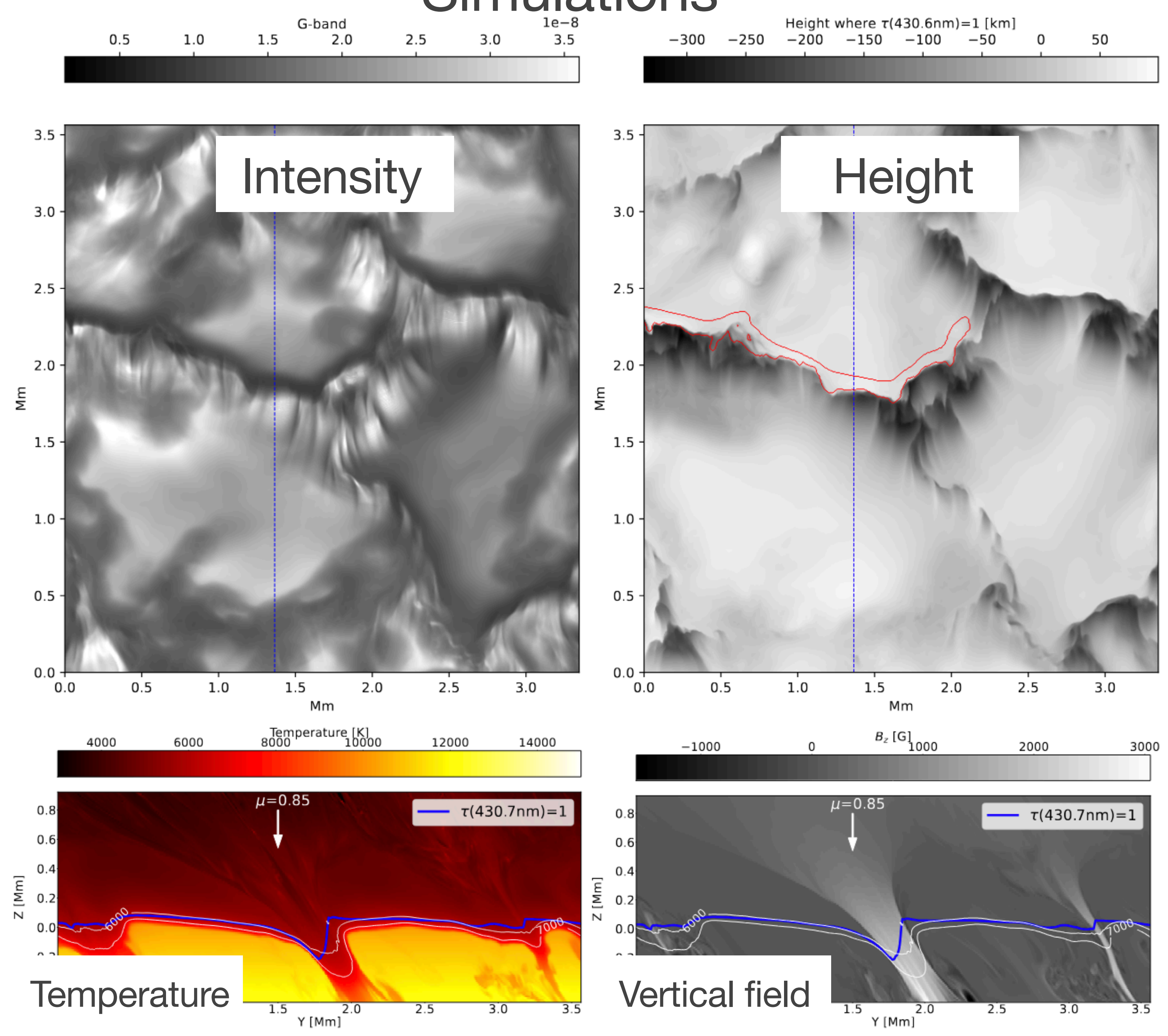


Simulations



Kuridze et al. (2025) | DKIST/VBI data

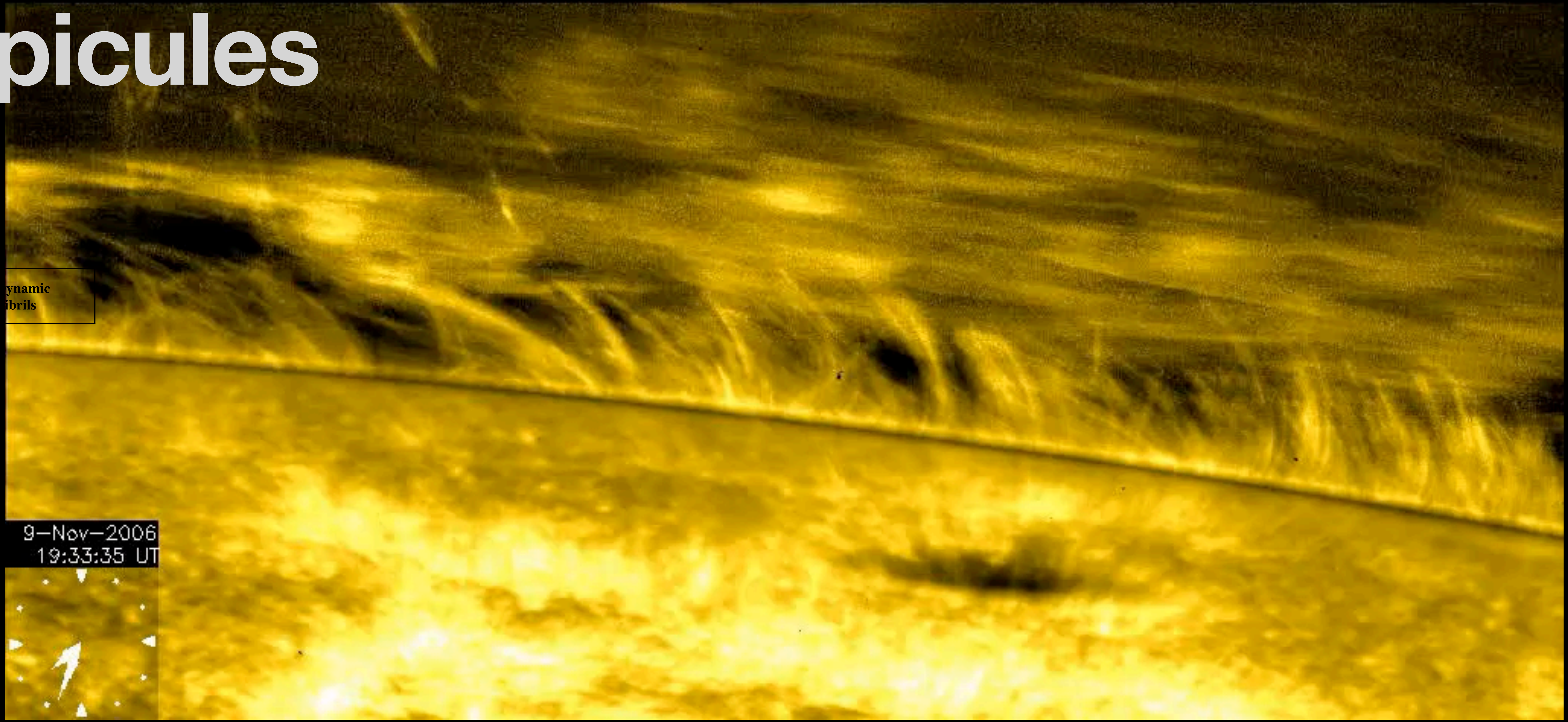
Striations

- Corrugation at the borders of granules seen as **dark, thin stripes** along the bright facular regions
- Dark stripes are more elevated than bright ones
- **Widths:** Ranging from **17 to 46 km (~0.03 arcsec)**
- **Magnetic origin:** Coincide with variations in vertical magnetic field strength (Bz) of 100 to 250 G.

  Bz is weaker in the dark striations than in the adjacent bright ones
- **Also seen:** in peumbral filaments

Spicules

Spicules



Hinode/SOT

Feature	Type I Spicules	Type II Spicules
Lifespan	Long: 3–10 minutes	Short: 10–150 seconds
Motion	Up-and-down (ballistic/parabolic)	Primarily upward, then fade/disappear
Velocity (upward)	15–40 km/s	50–150 km/s
Trajectory	Rise and fall — returning material	Rapid rise — no fall

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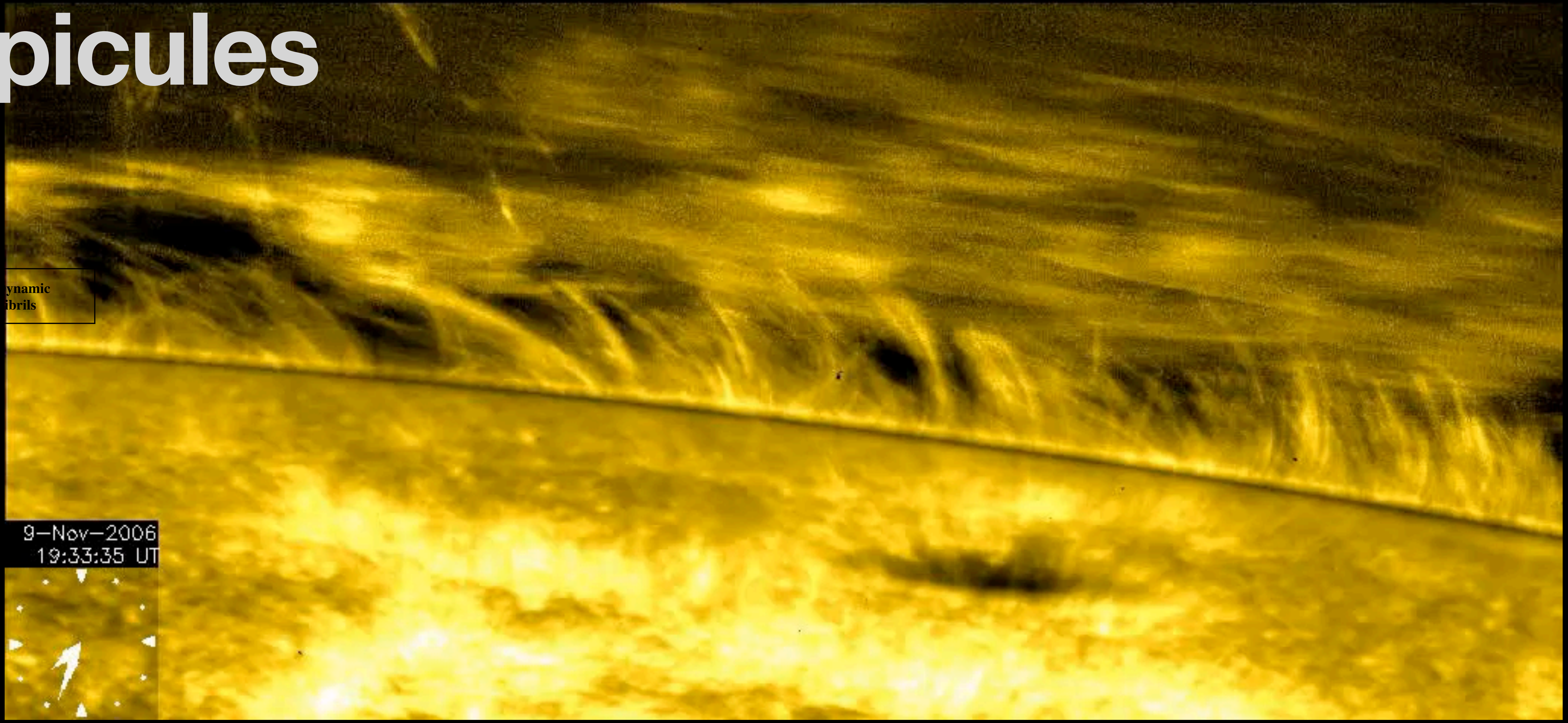

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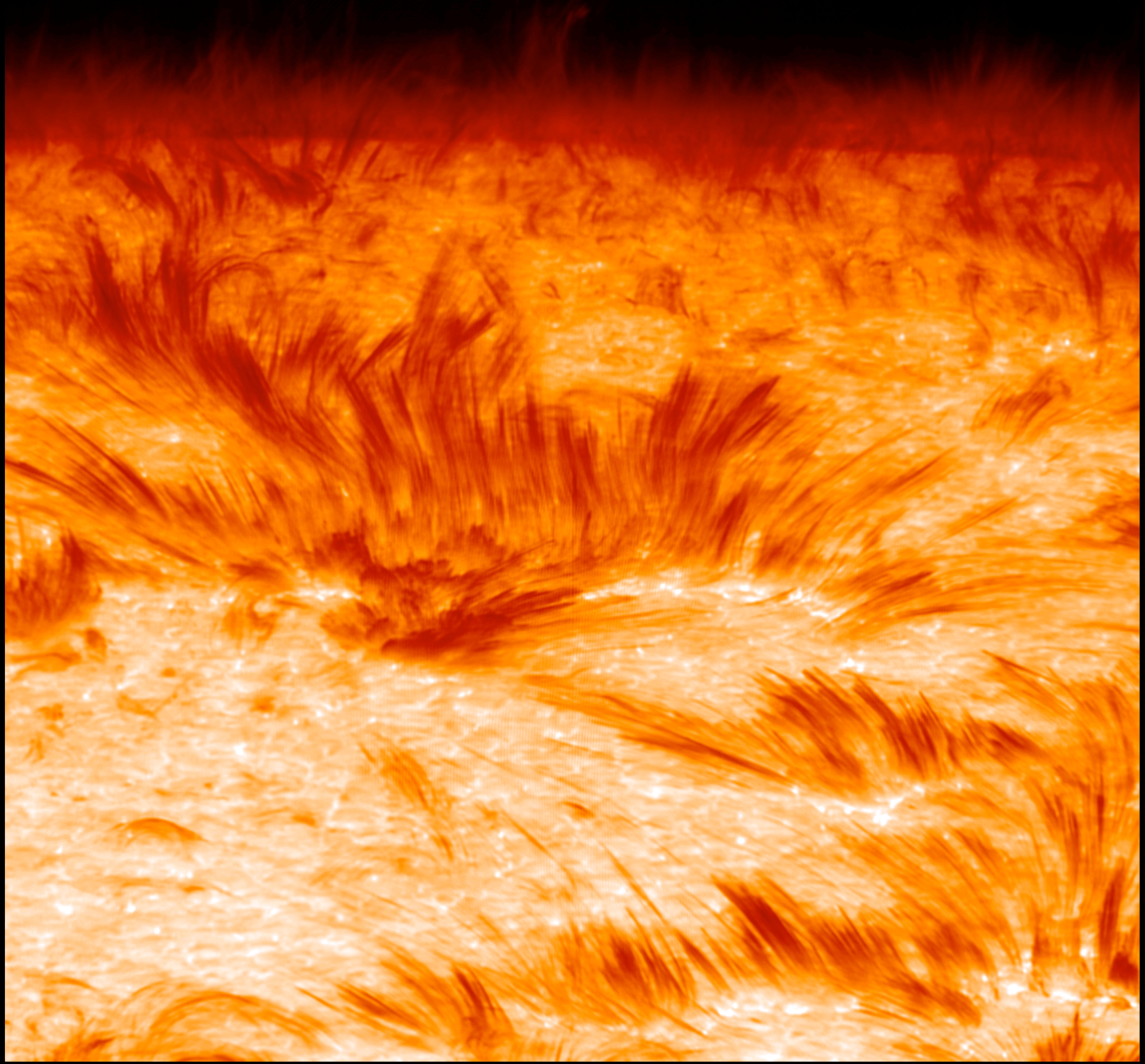
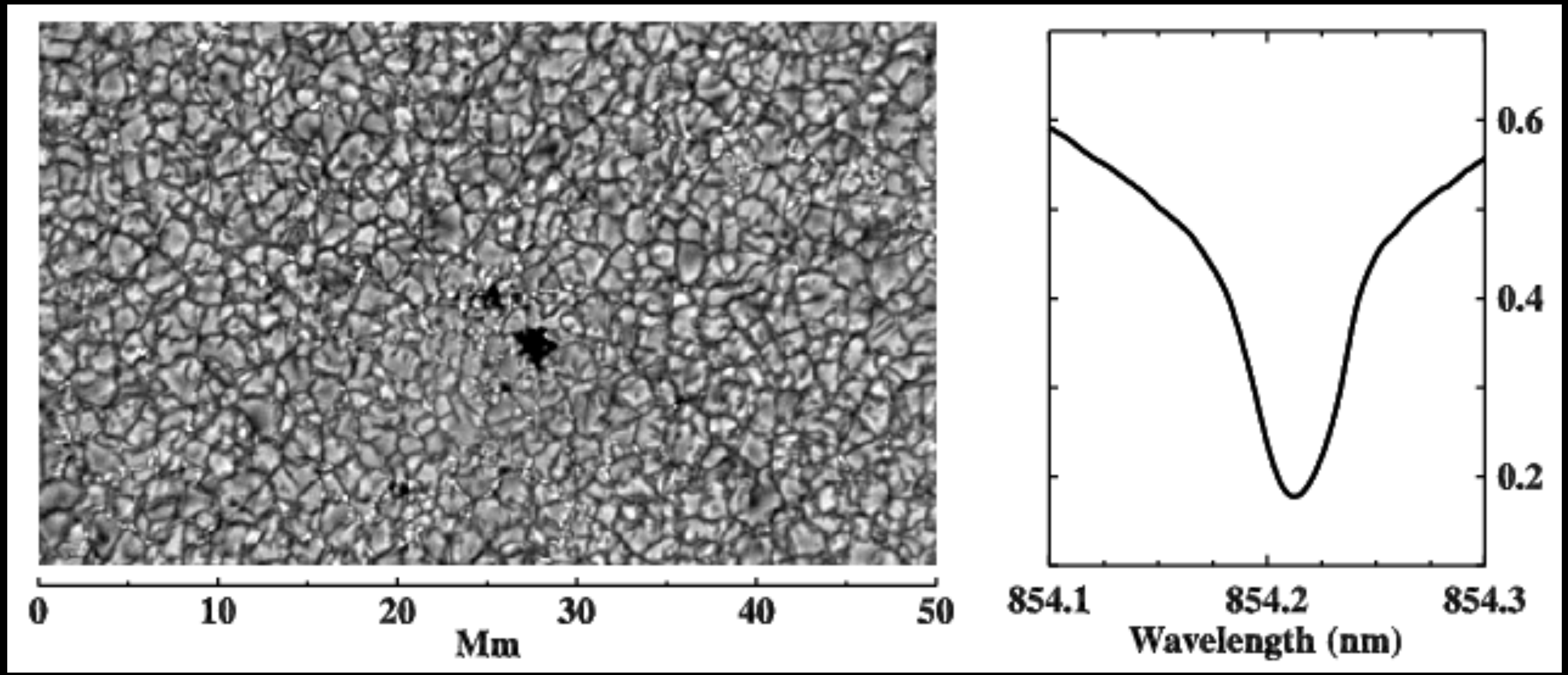
- Chromospheric fine multi-threaded structures visible close to the solar limb
- Best visible in H-alpha and Ca line wings



Luc Rouppe van der Voort (ITA, University of Oslo) | SST/SOUP | H-alpha wing



Cauzzi et al. (2008) | DST/IBIS | Ca II 854.2nmn

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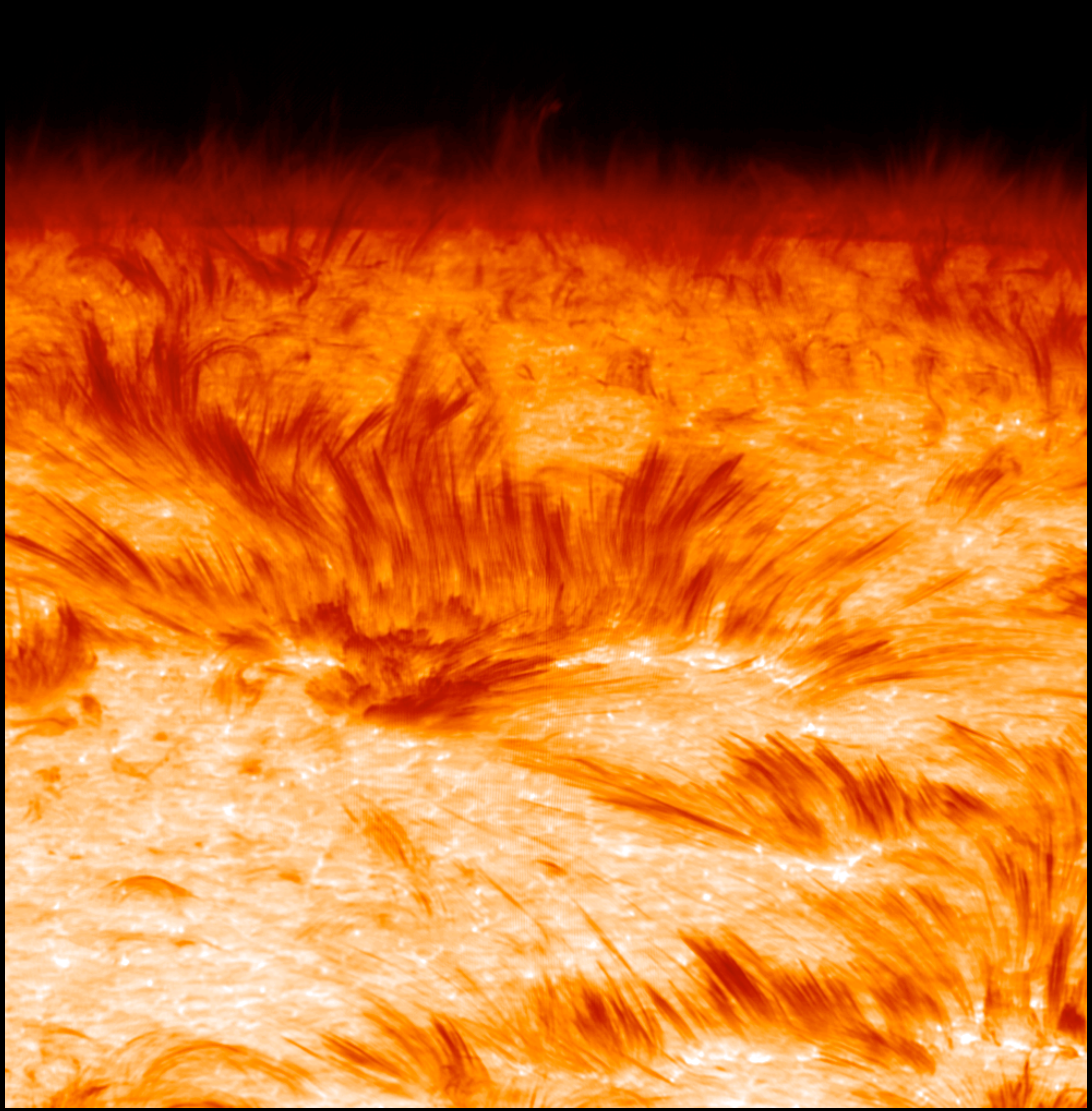

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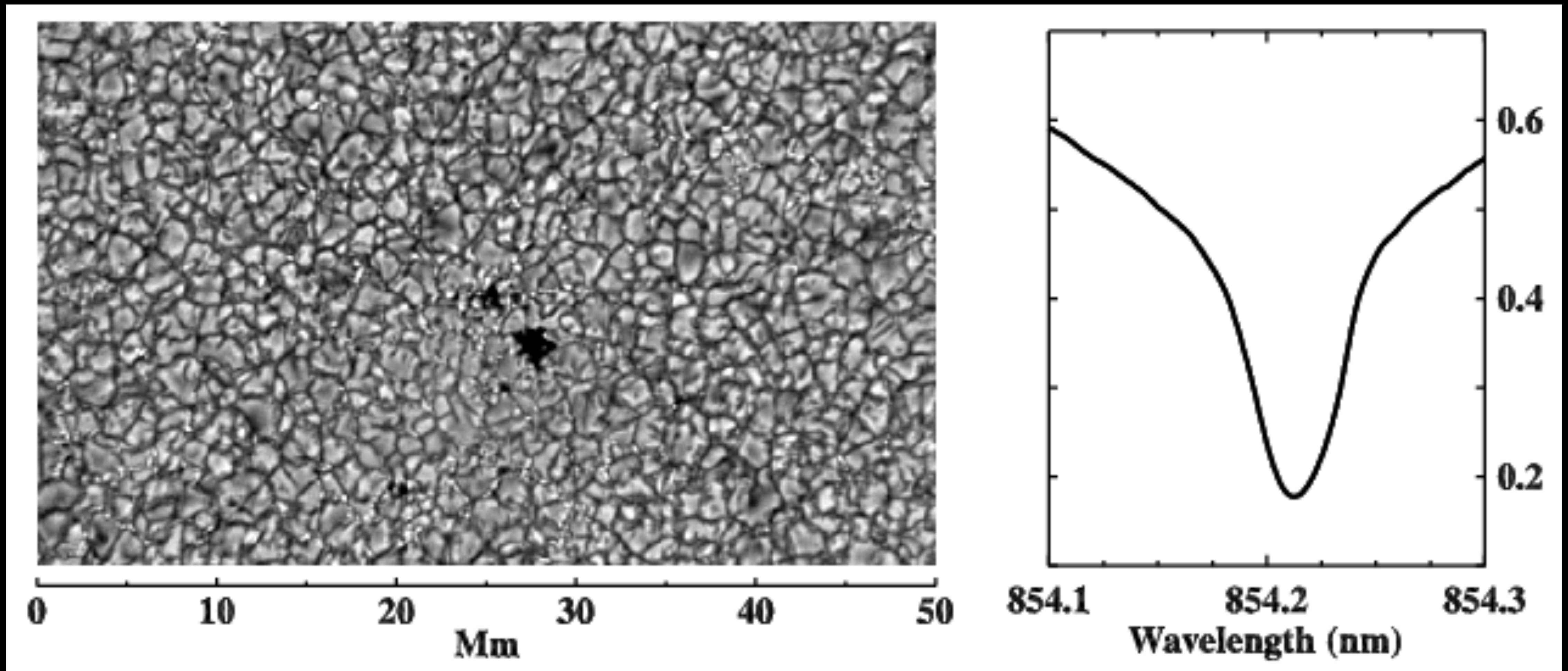

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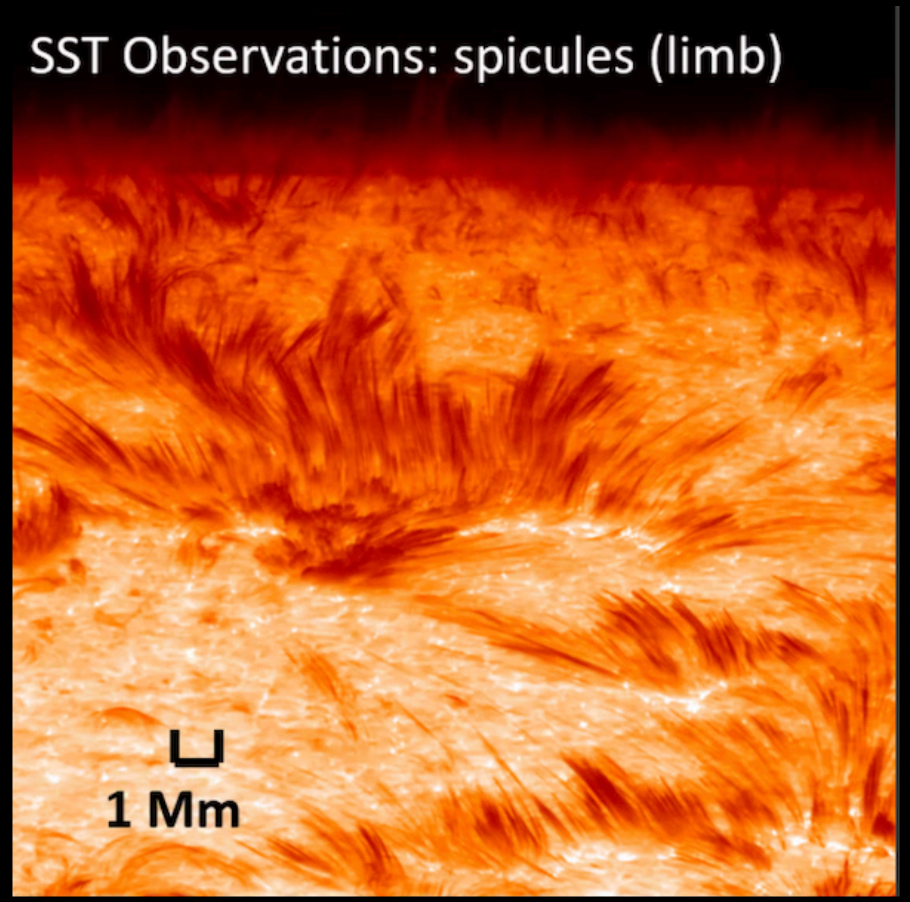


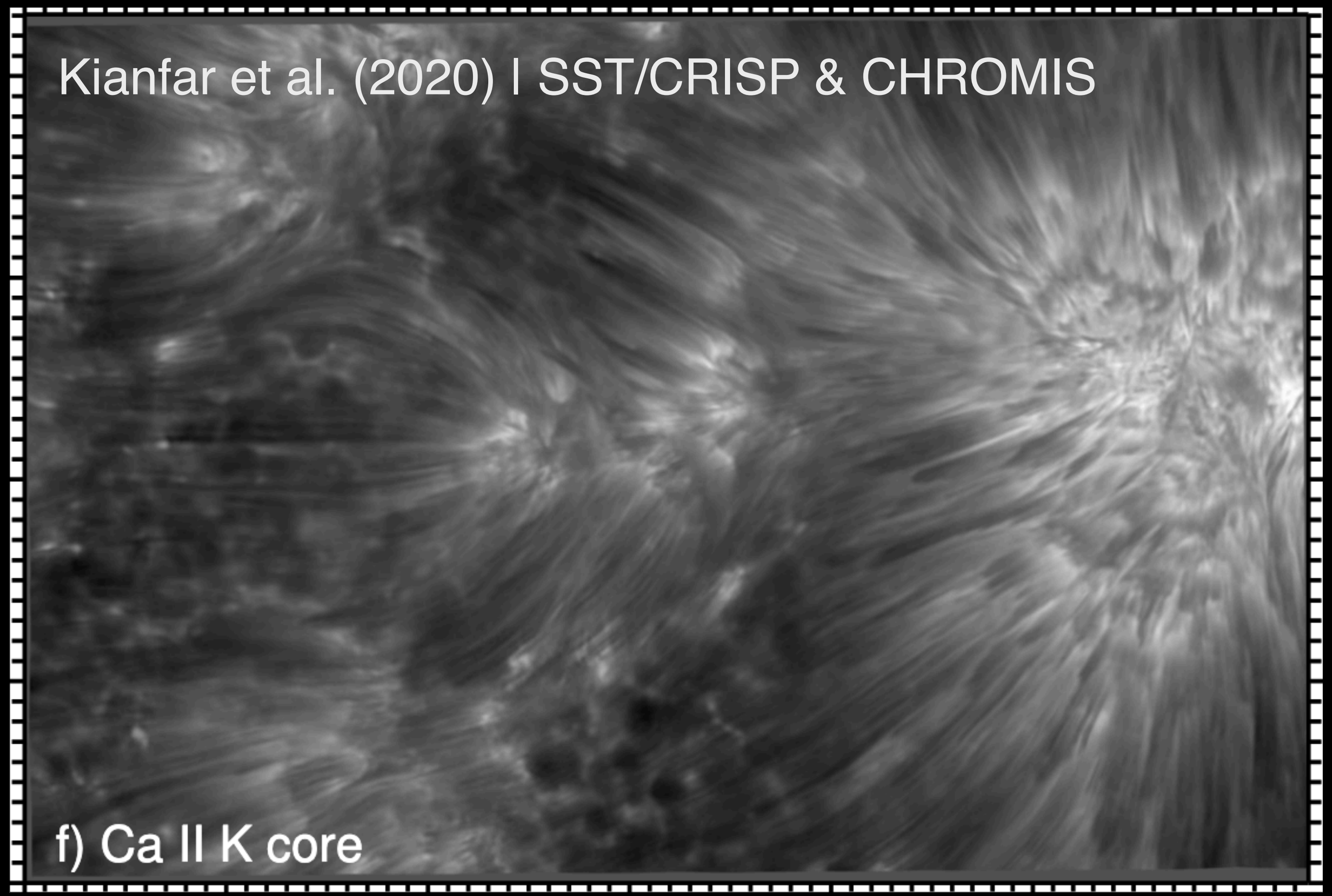
Spicules — On-disc counterparts

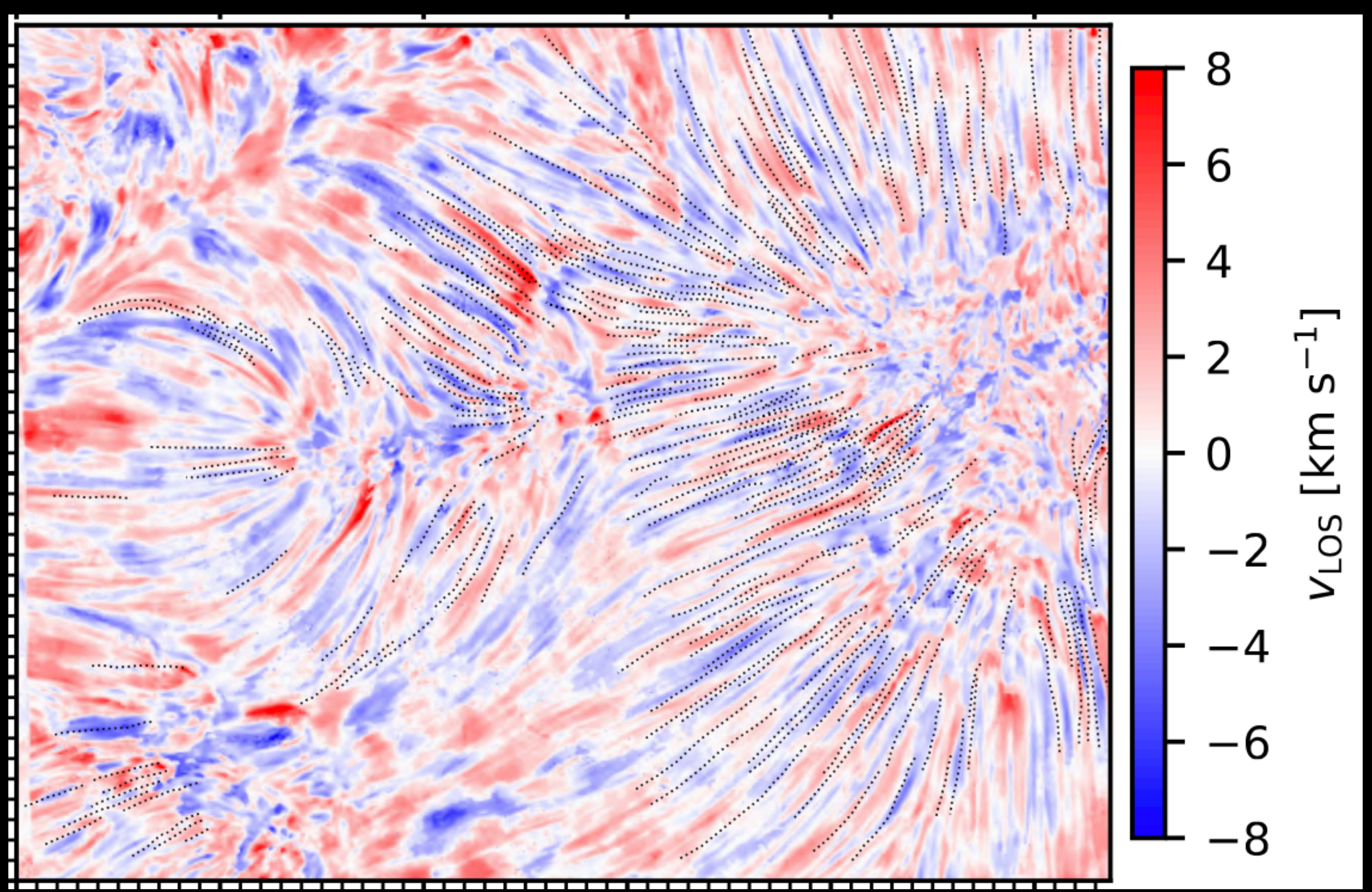
TYPE I: Dynamic bright fibrils

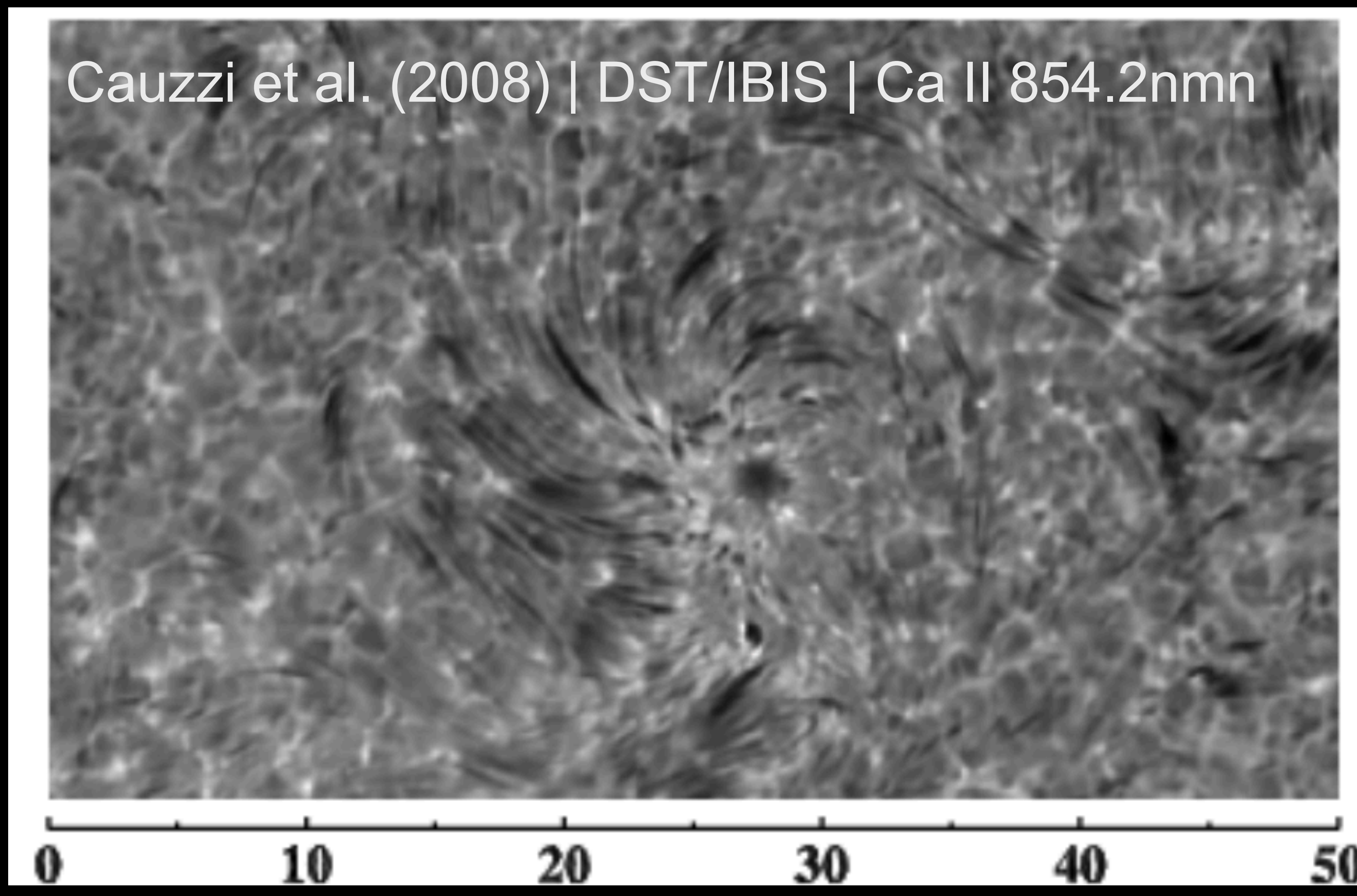
- Mostly involved in chromospheric mass cycling
- Limited direct energy contribution to the corona as plasma largely falls back

Type II: Rapid Blue/Red Excursions

- More impulsive energy transfer with potential for directly injecting heated plasma or significant wave energy into the lower corona though their total impact is still debated



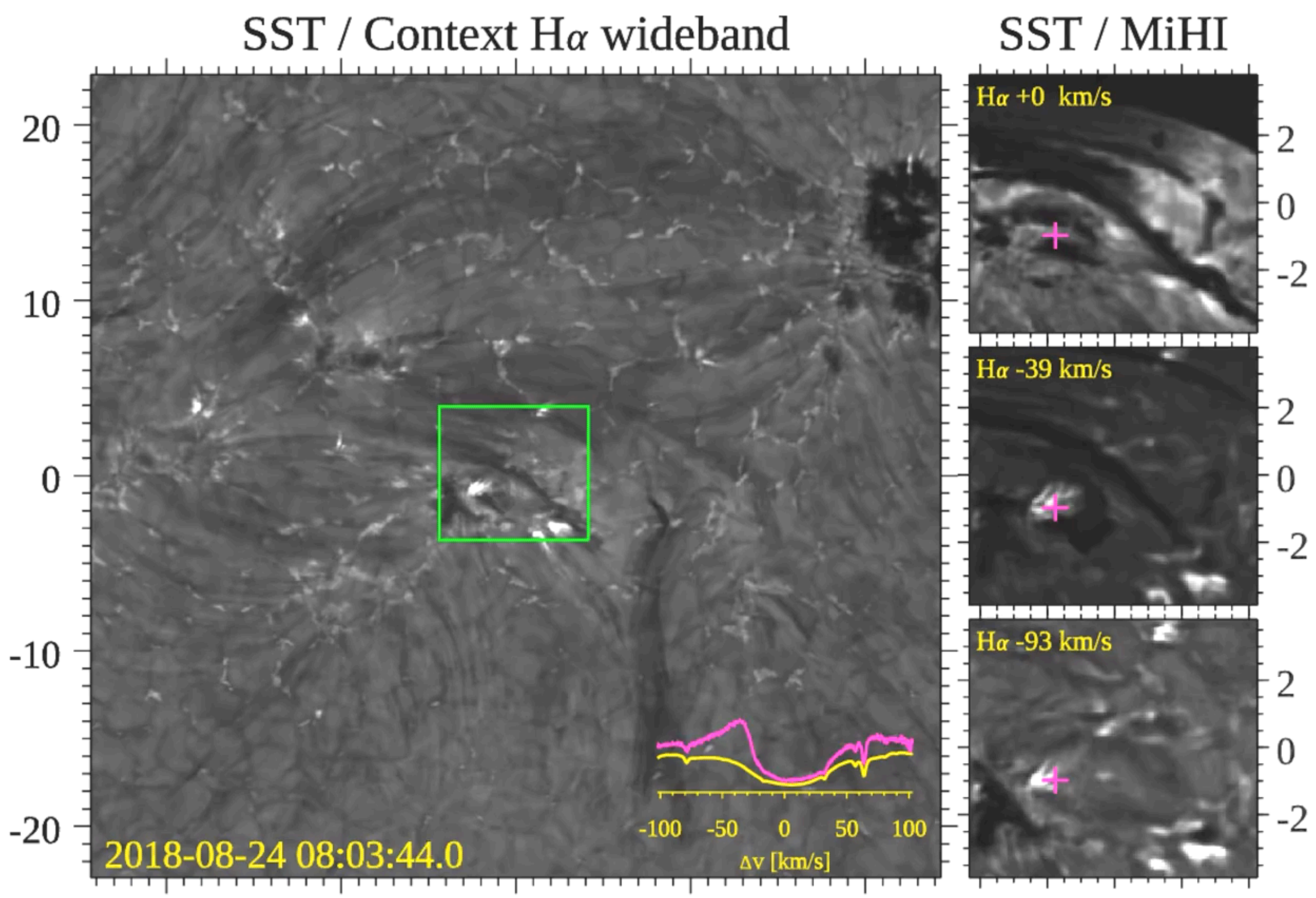




Ellermann bombs & hot spots

Ellerman bombs

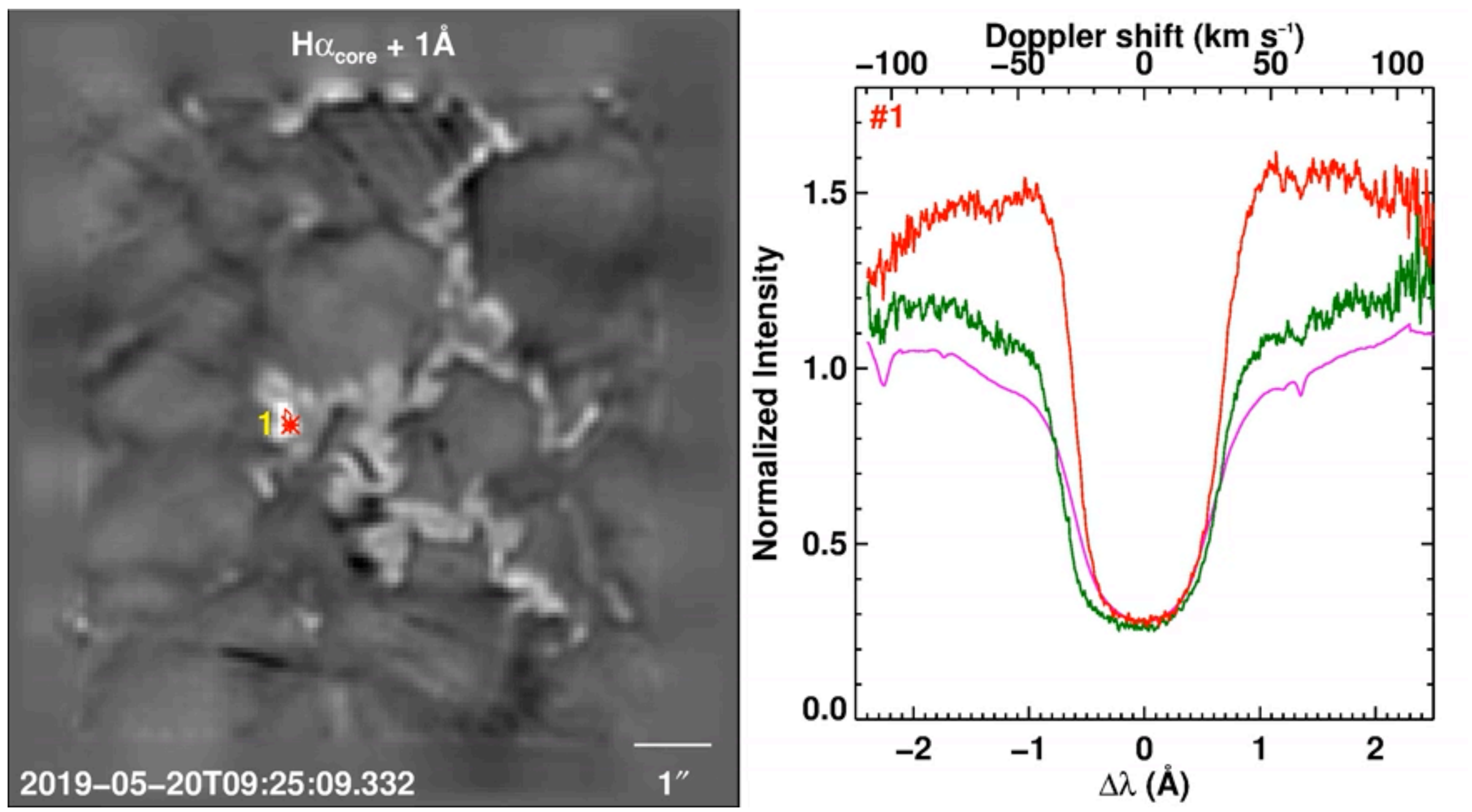
- Enhancement of the **H-alpha blue wing**
- **Ellerman Bombs** are typically interpreted as products of **magnetic reconnection on** the high photosphere
- Mostly in **Active Regions**, where newly emerging flux reconnects with overlying pre-existinng field



Rouppe van der Voort et al. (2023) | SST/MiHI, van Noort (MPS)

Photospheric hot spots

- Enhancement of the H-alpha red wing
- Photospheric ***hot spots*** are observed in quiet-Sun areas
- **Interpretation:** proxies of locations where convection-driven **magnetic field intensification** in the photosphere can lead to **energy transfer into higher layers**
- Chitta et al. suggest that such hot spots at **coronal loop footpoints** may be indicative of the specific locations and onset of **energy flux injection into the upper atmosphere**



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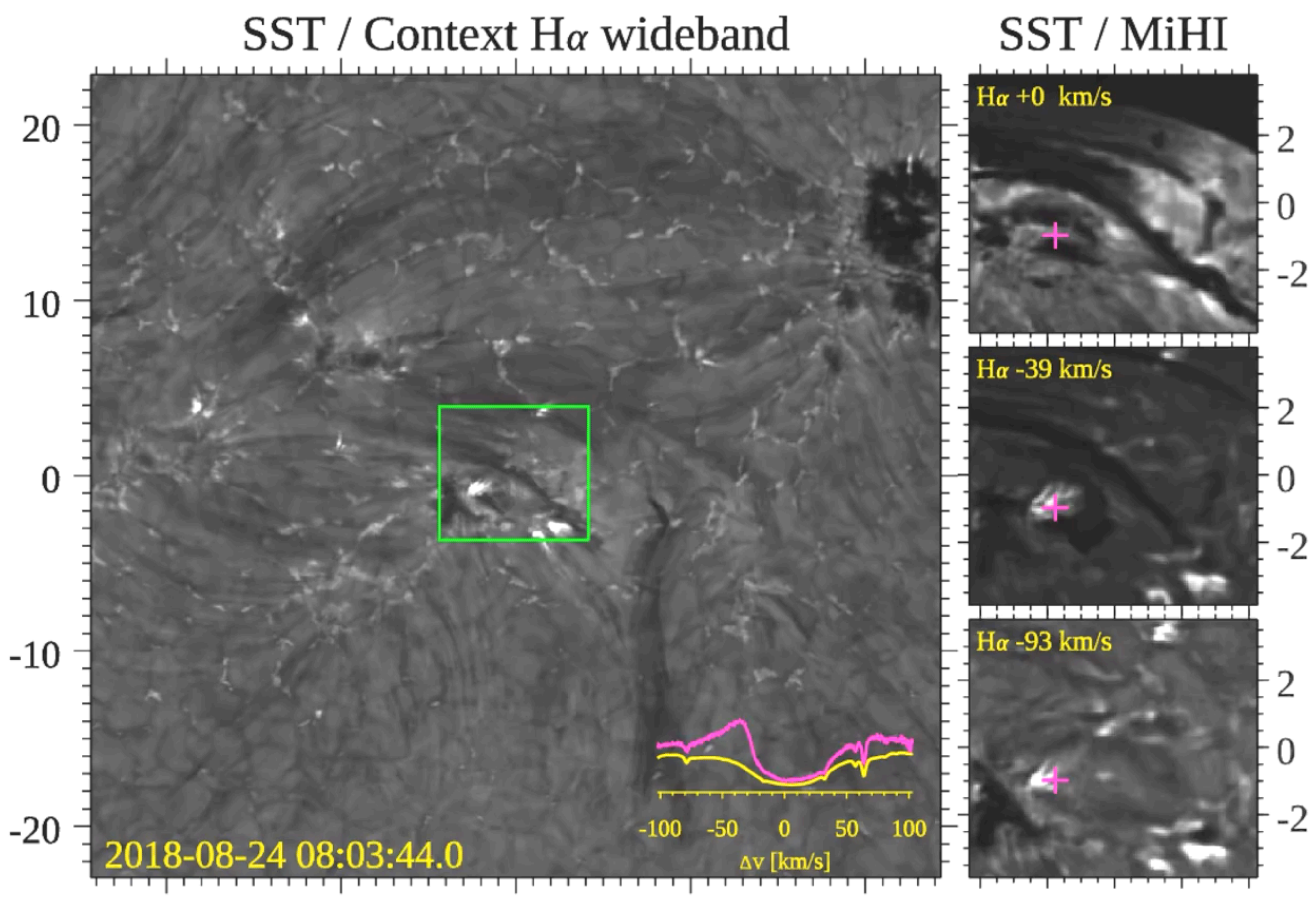

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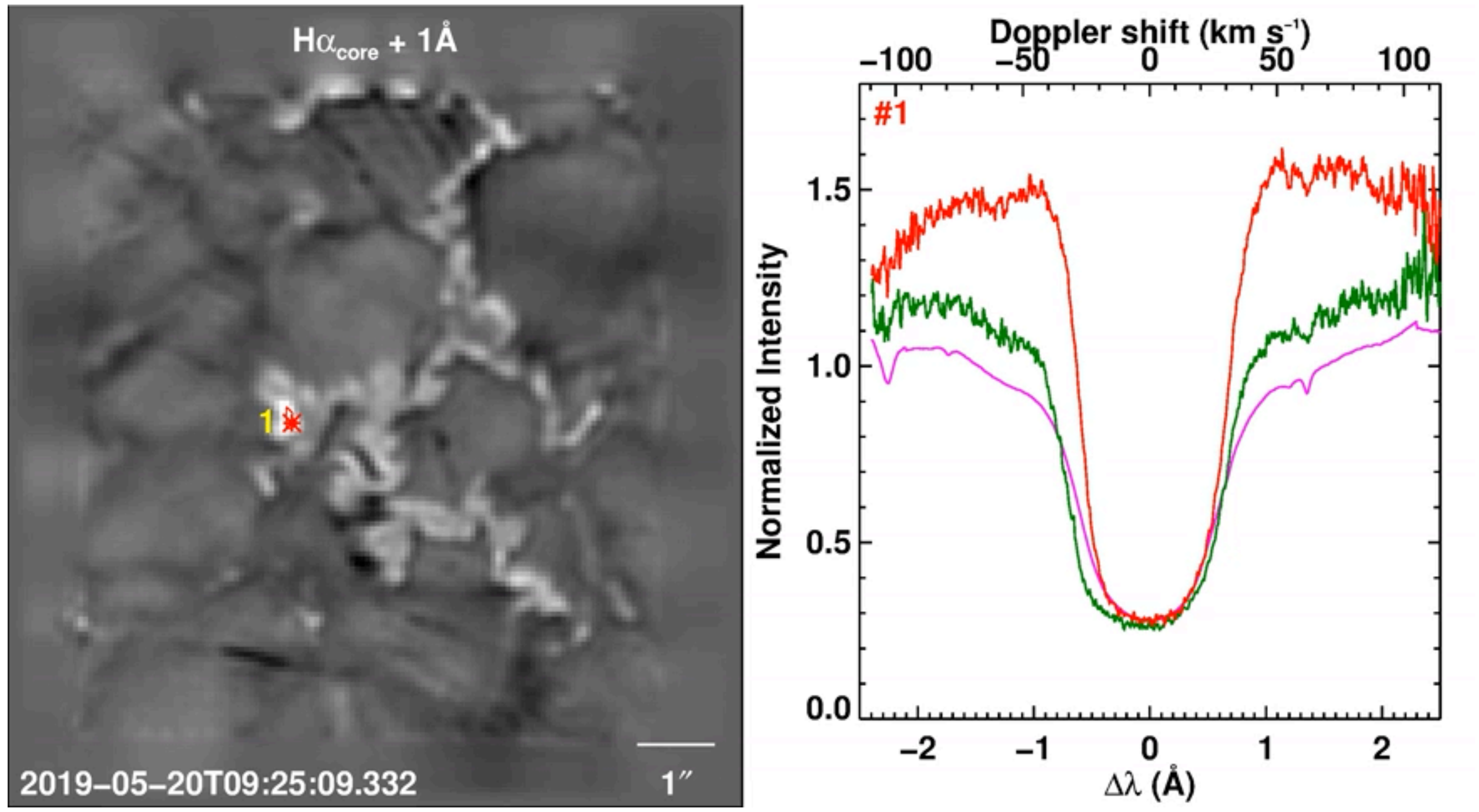

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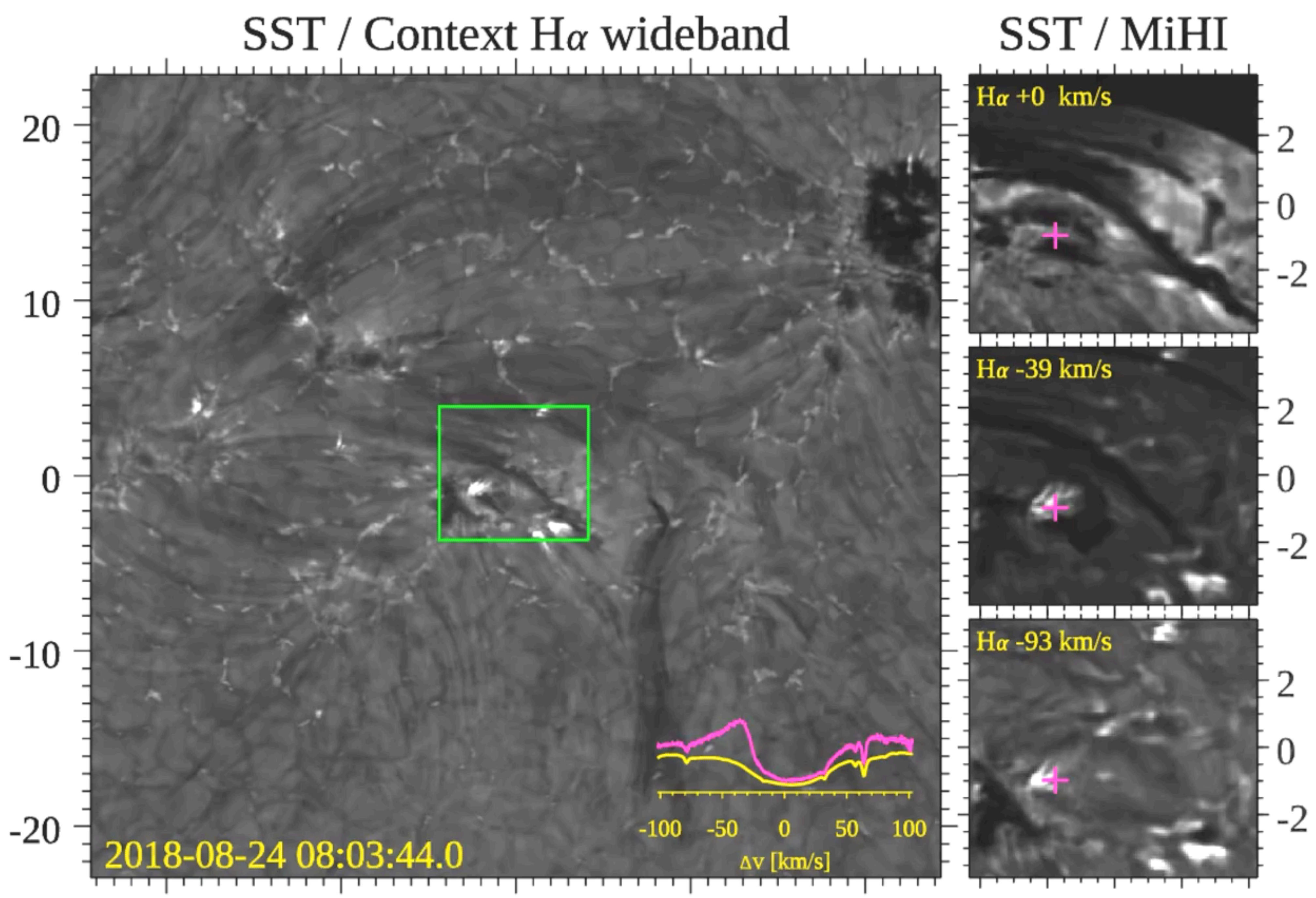

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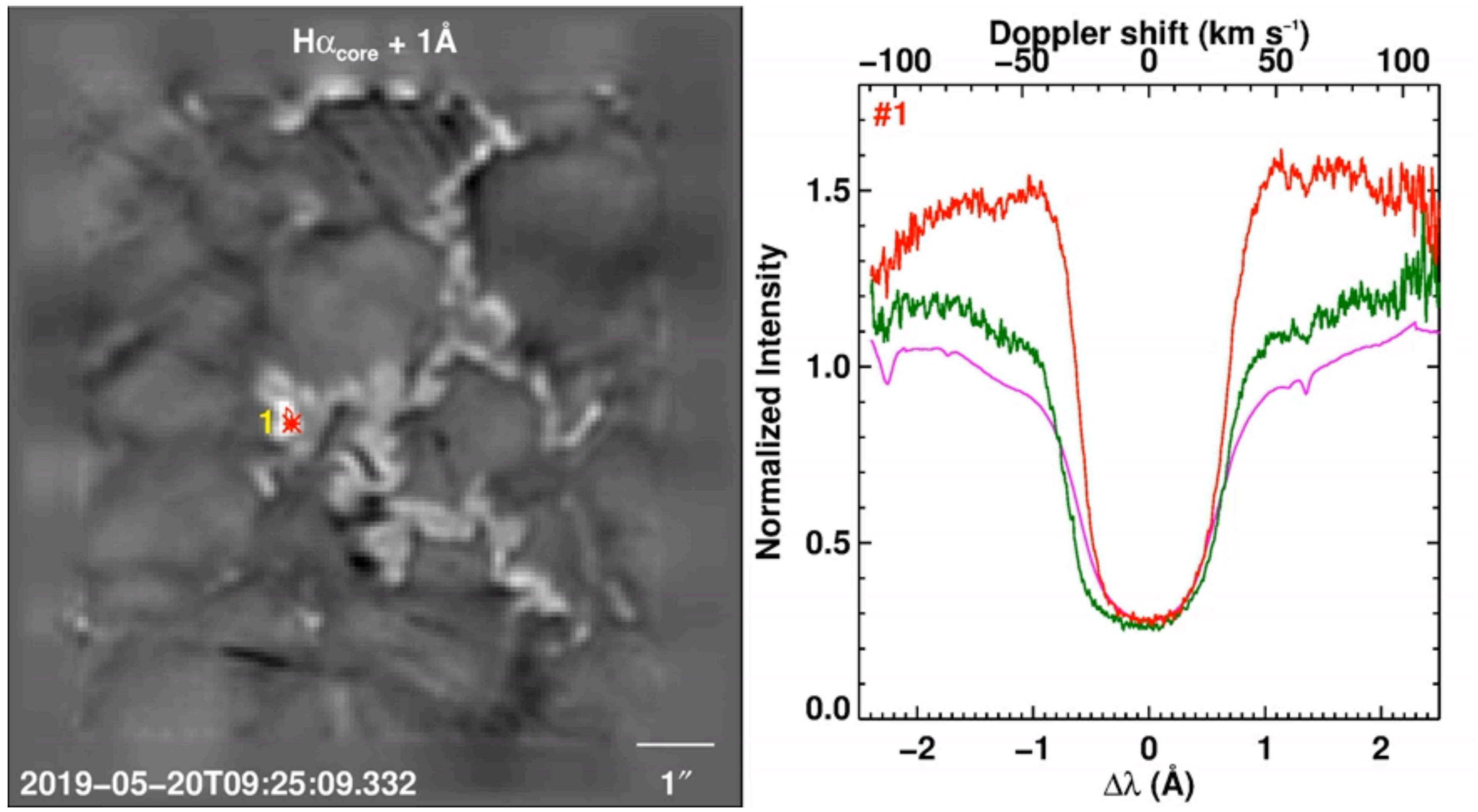

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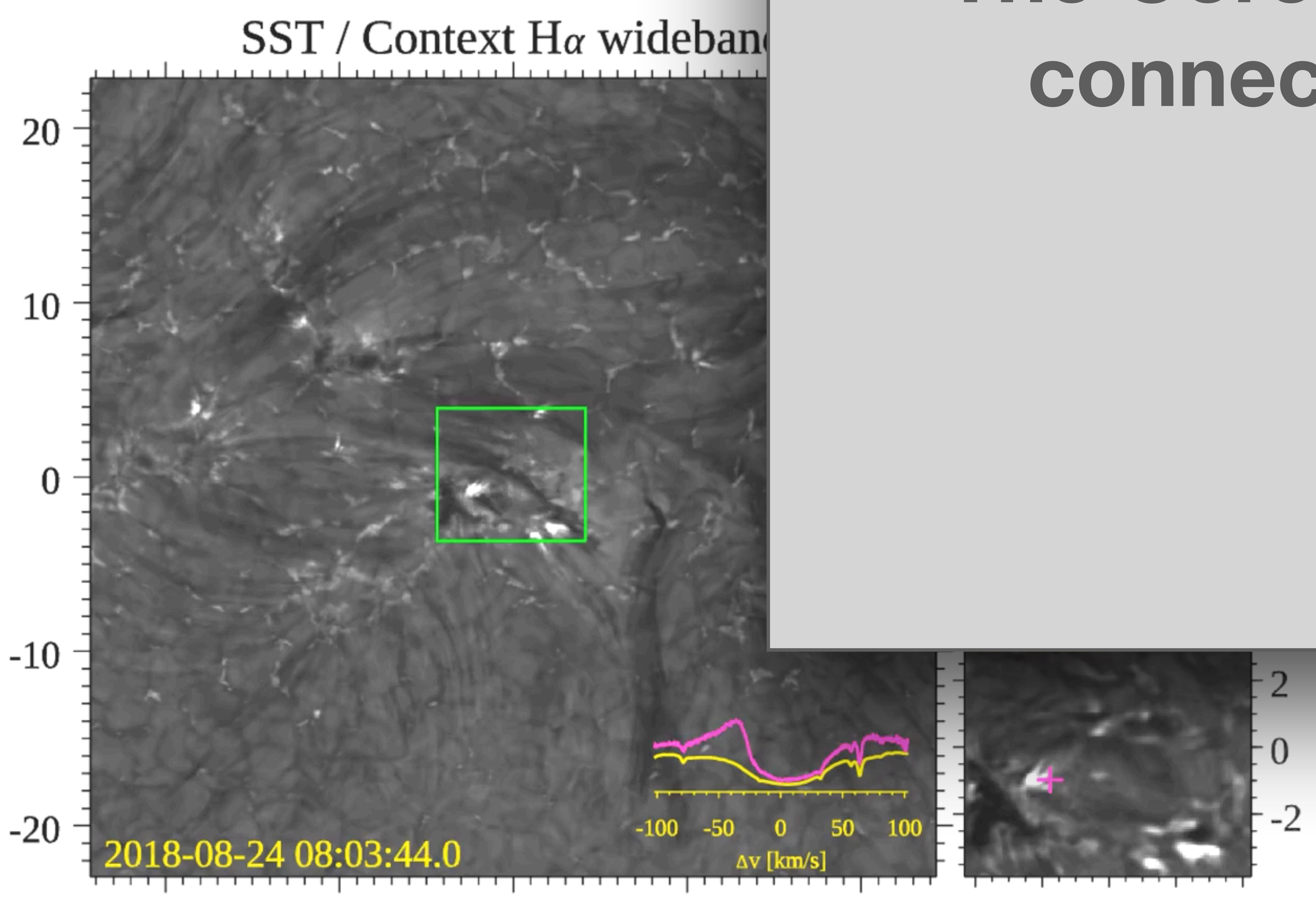

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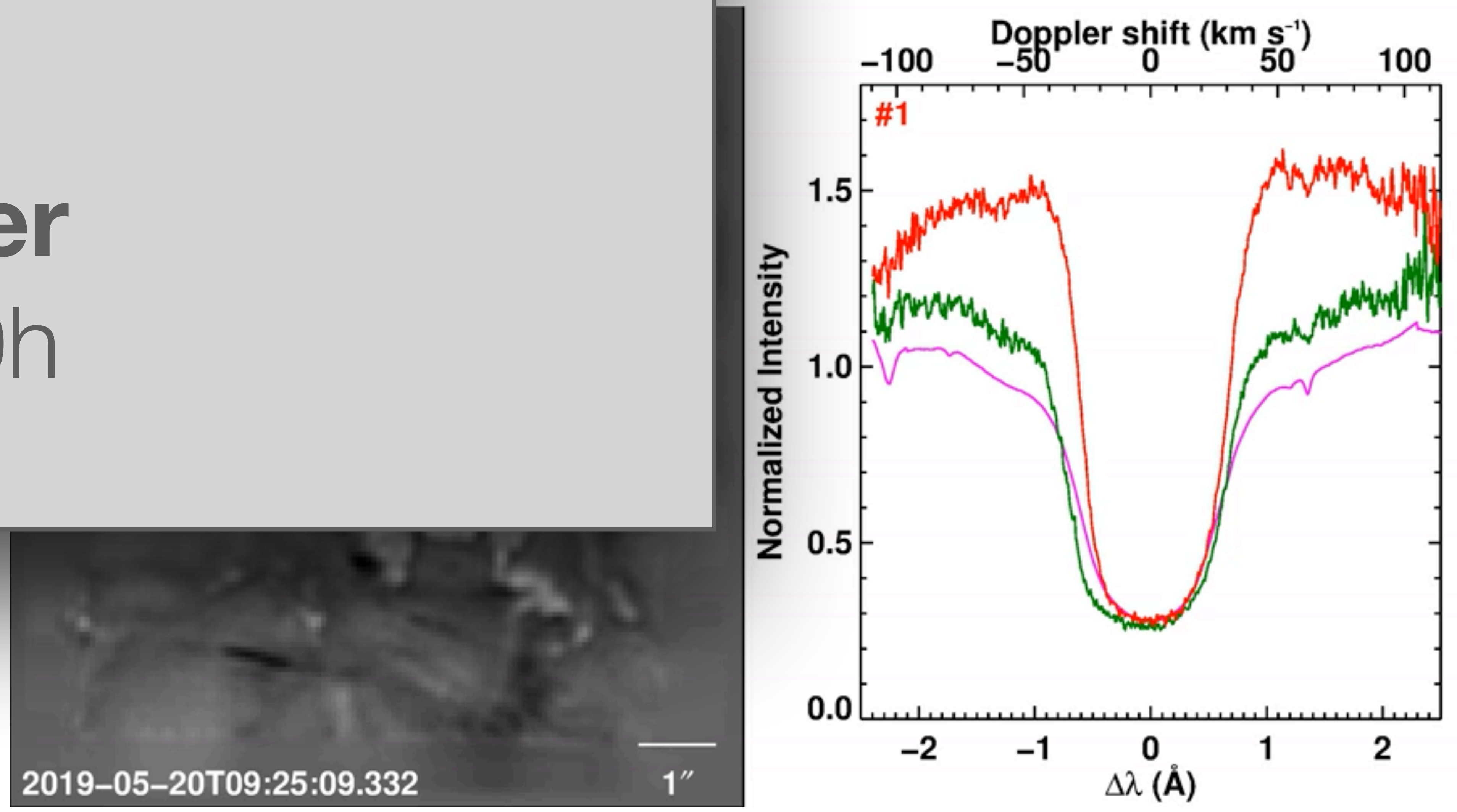

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Lecture on

The Corona of the Sun and its connection to the surface

by

Hardi Peter

Thu 16:00h

Solar tornados

Magnetic tornados

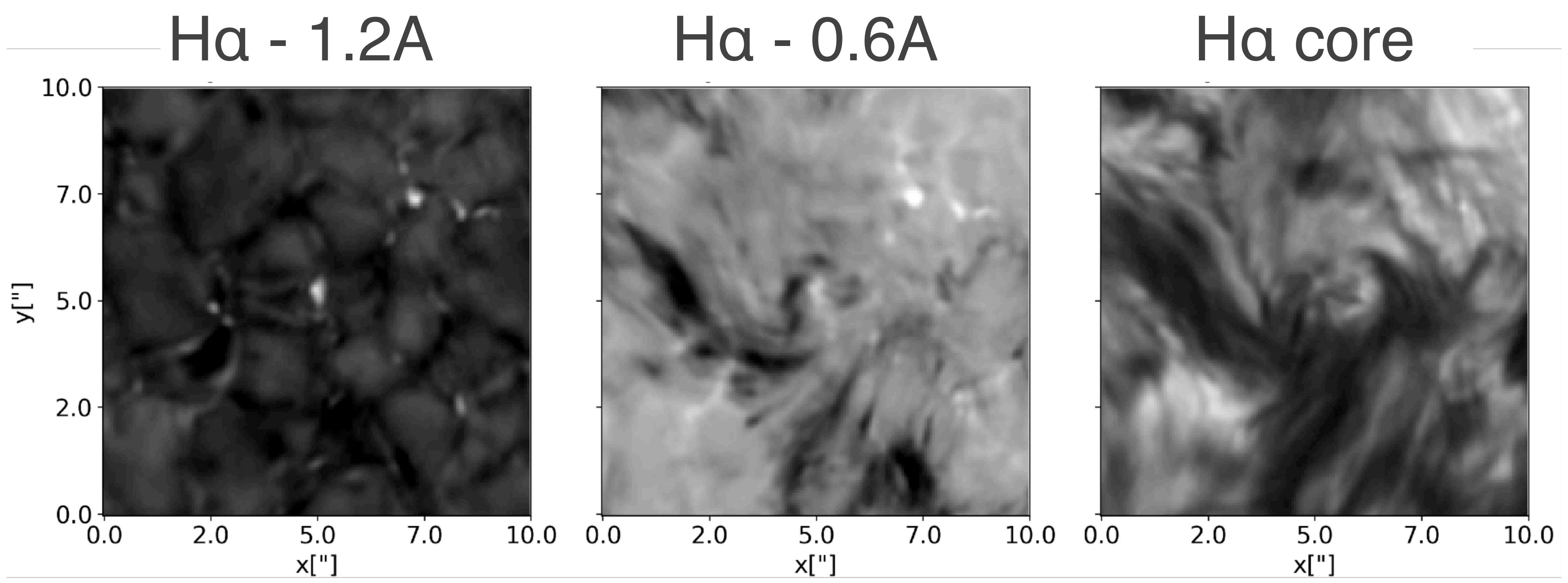
The swirl is caused by an **intergranular vortex flow** generated by:

- **Strong photospheric downflows**, likely due to **angular momentum conservation** (Nordlund, 1985)
- These downflows **drag magnetic field lines** inward, concentrating and twisting them into a **spiral** pattern around a central magnetic bright point
- This results in a **vortex motion** in the photosphere that **amplifies the magnetic field within it**

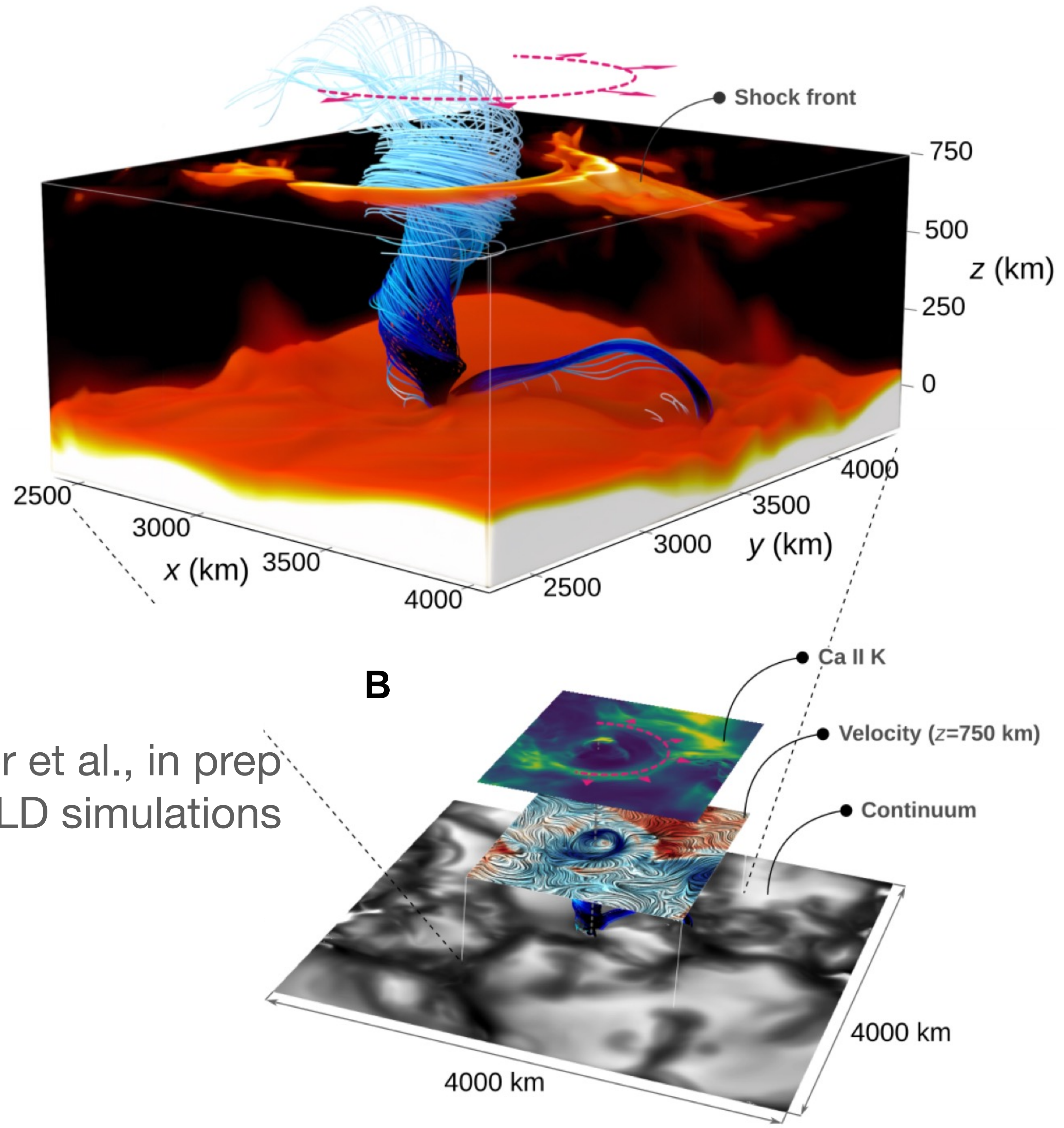
Swirl Connectivity to Upper Atmosphere:

- The swirl **extends into the chromosphere**, forming a **chromospheric swirl** or **magnetic tornado**.
- This structure acts as a **mass and energy conduit** between the photosphere and chromosphere.
- It supports **wave propagation** (acoustic and Alfvénic), and **triggers a chromospheric jet** (similar to spicules)

Díaz-Castillo et al. (2024, from Swedish Solar Telescope data)



SIMULATIONS



Fischer et al., in prep
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Magnetic tornados

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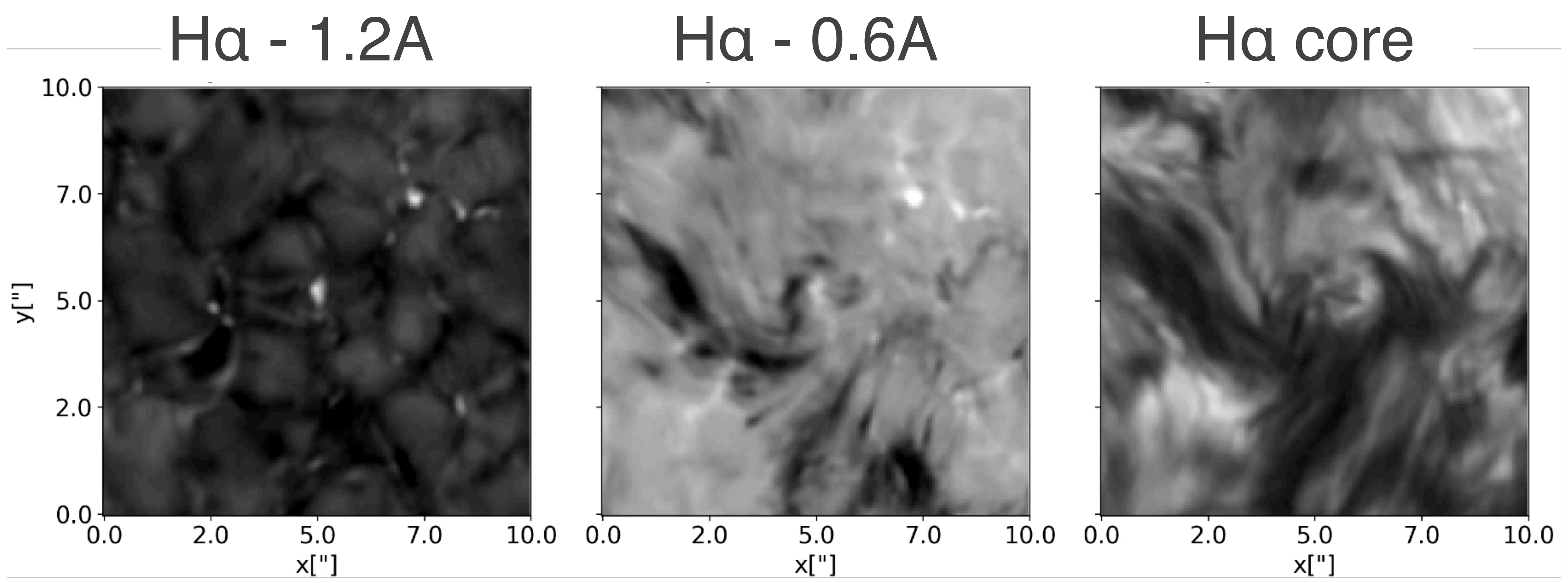

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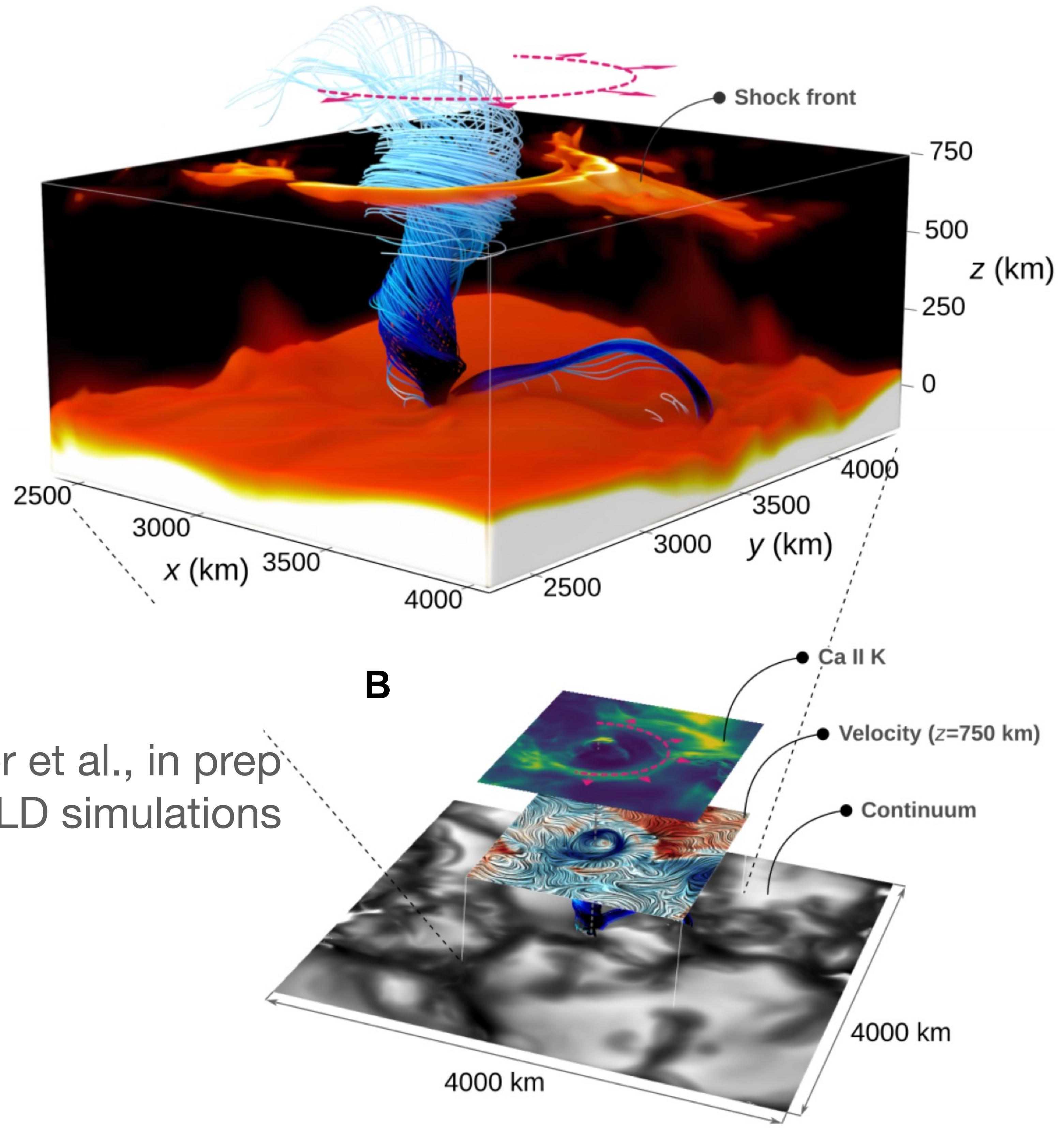

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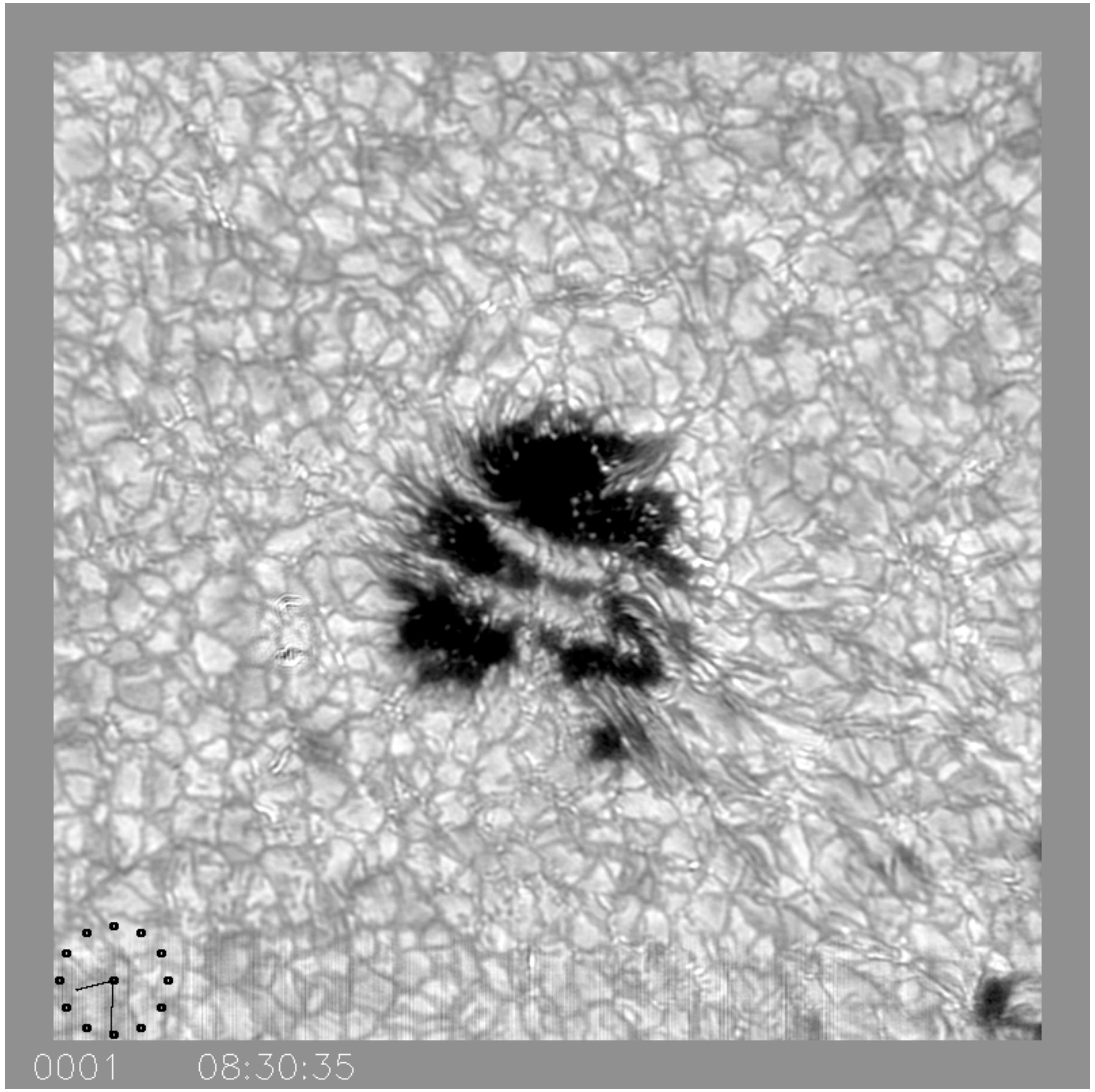
Sunspots

Sunspots

Active regions provide with a wealth of case studies of convective cells moulded by the presence of strong (>1kG) magnetic fields with disparate inclinations

giving rise to various modes of magneto-convection

From a protospot to a fully fledged sunspot



Schlichenmaier+ 2010a

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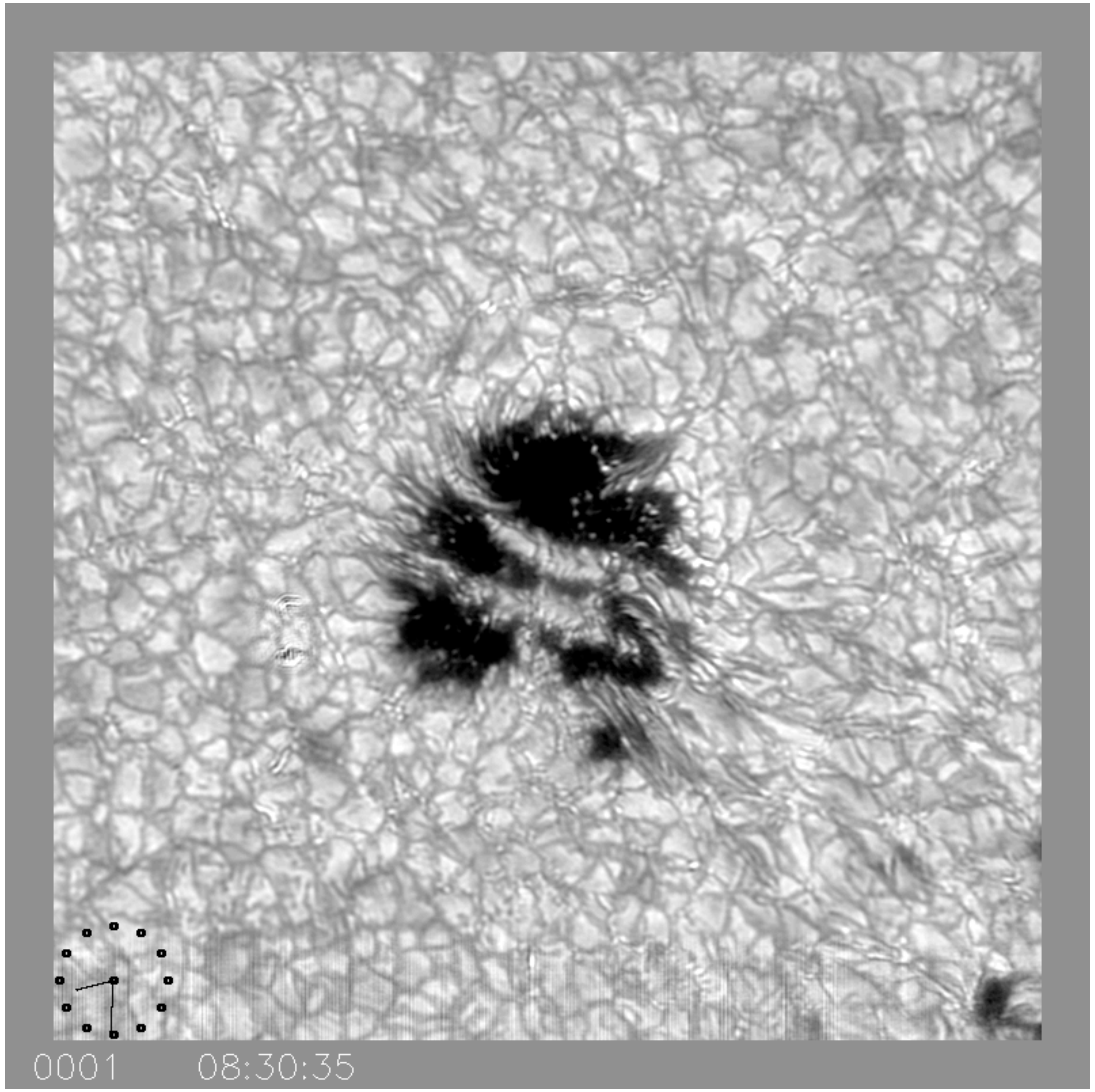

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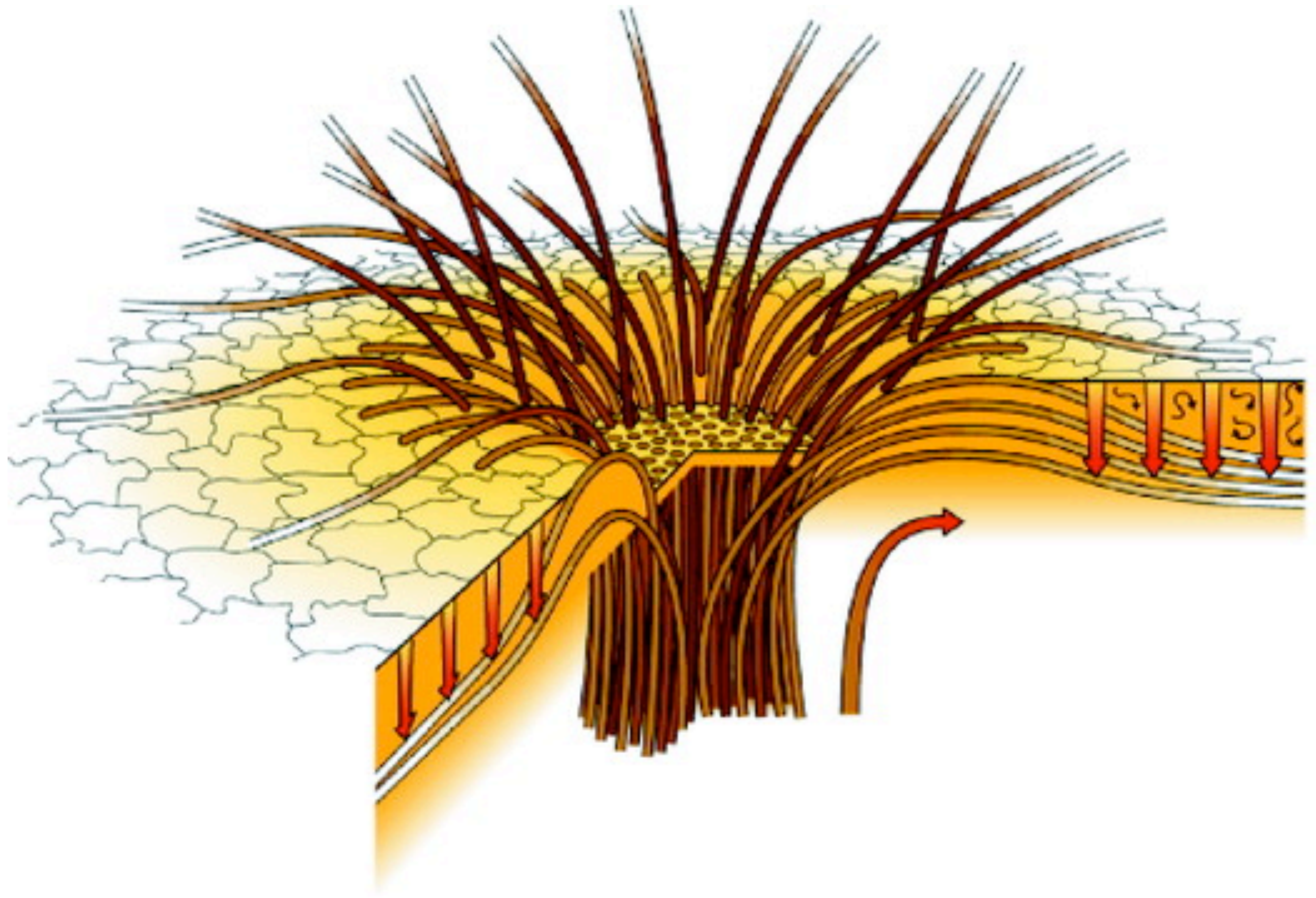
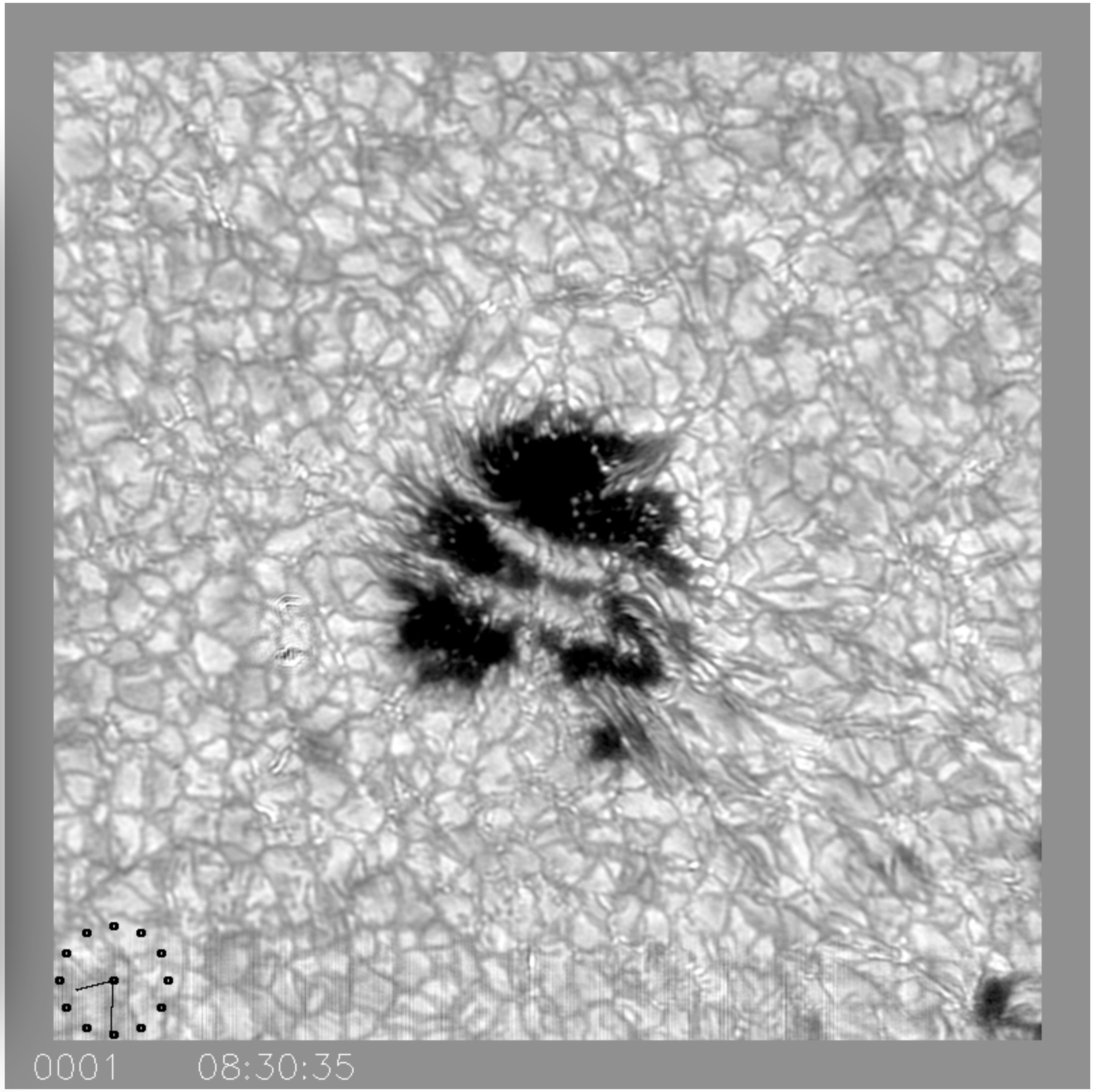
A
c
b
fi

Sunspot magnetic field model

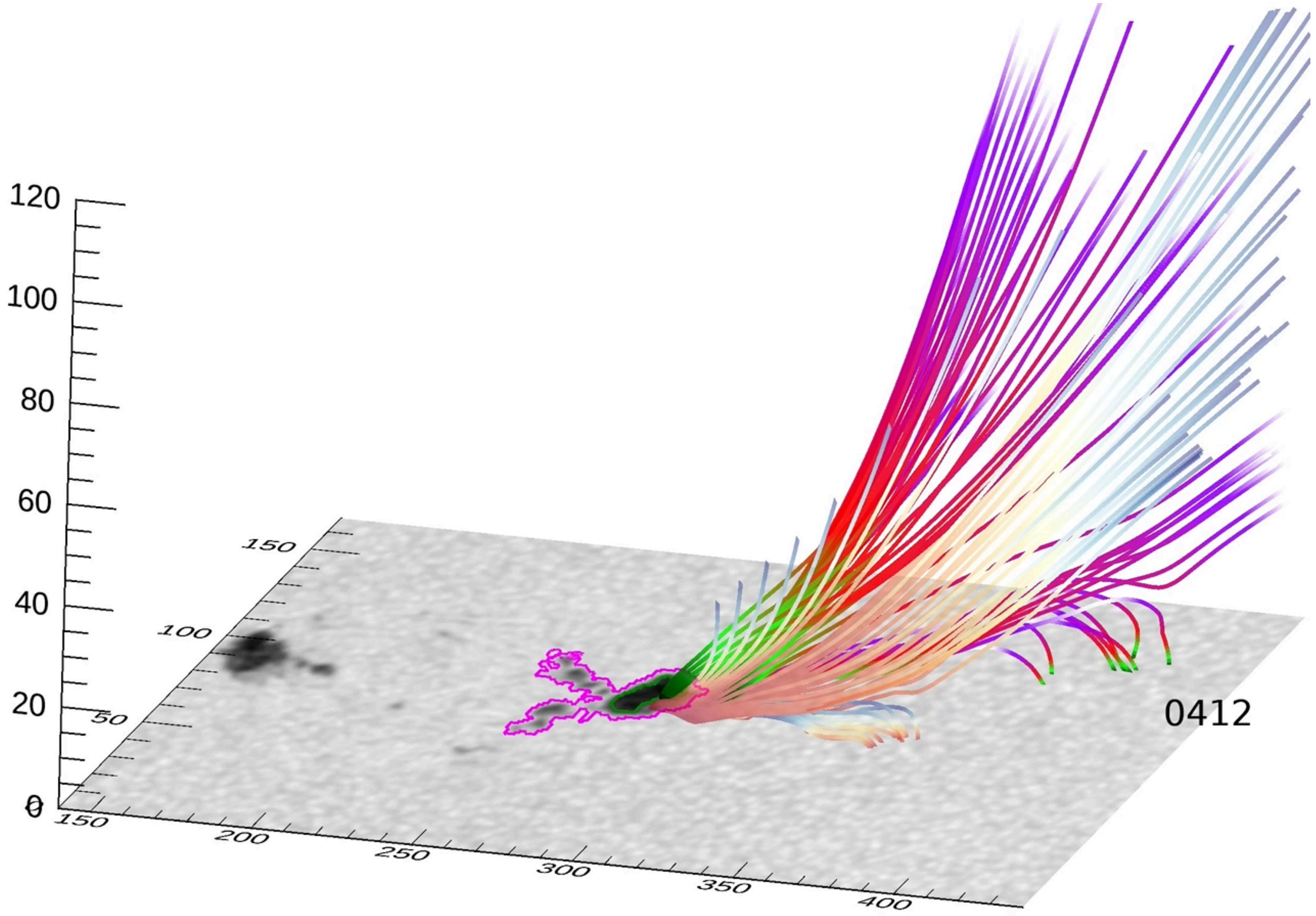


Thomas et al. (2002b)



Schlichenmaier+ 2010a

Sunspot magetic field — Extrapolations



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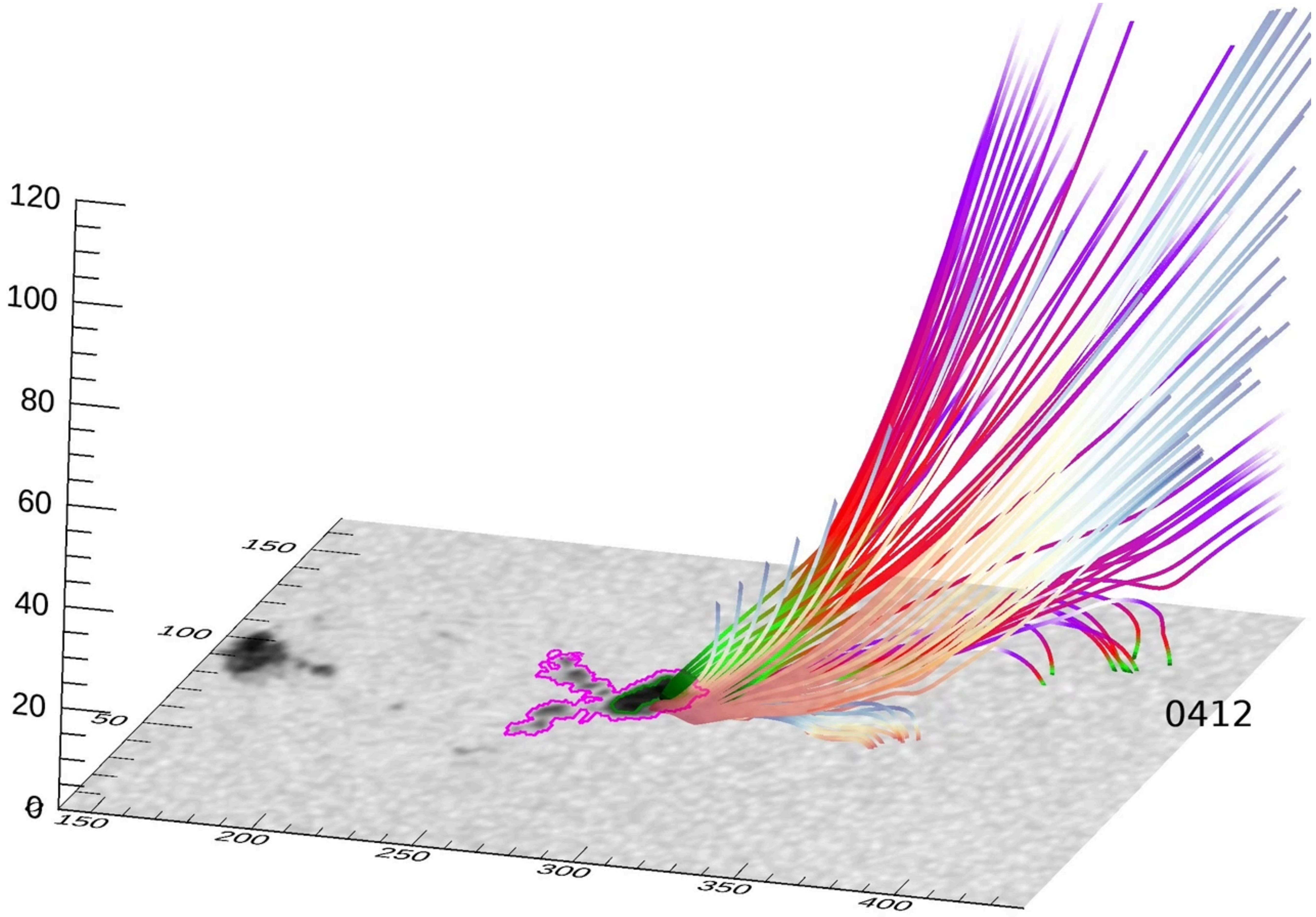

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Sunspots

Penumbra

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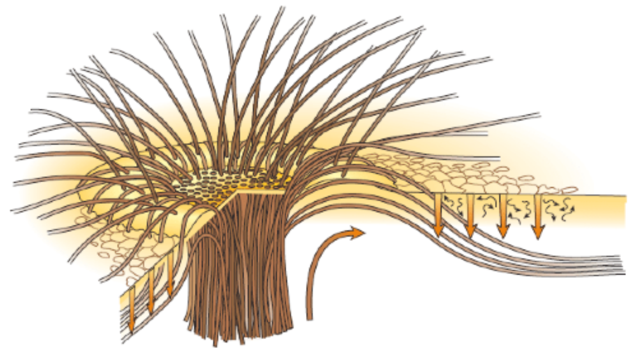
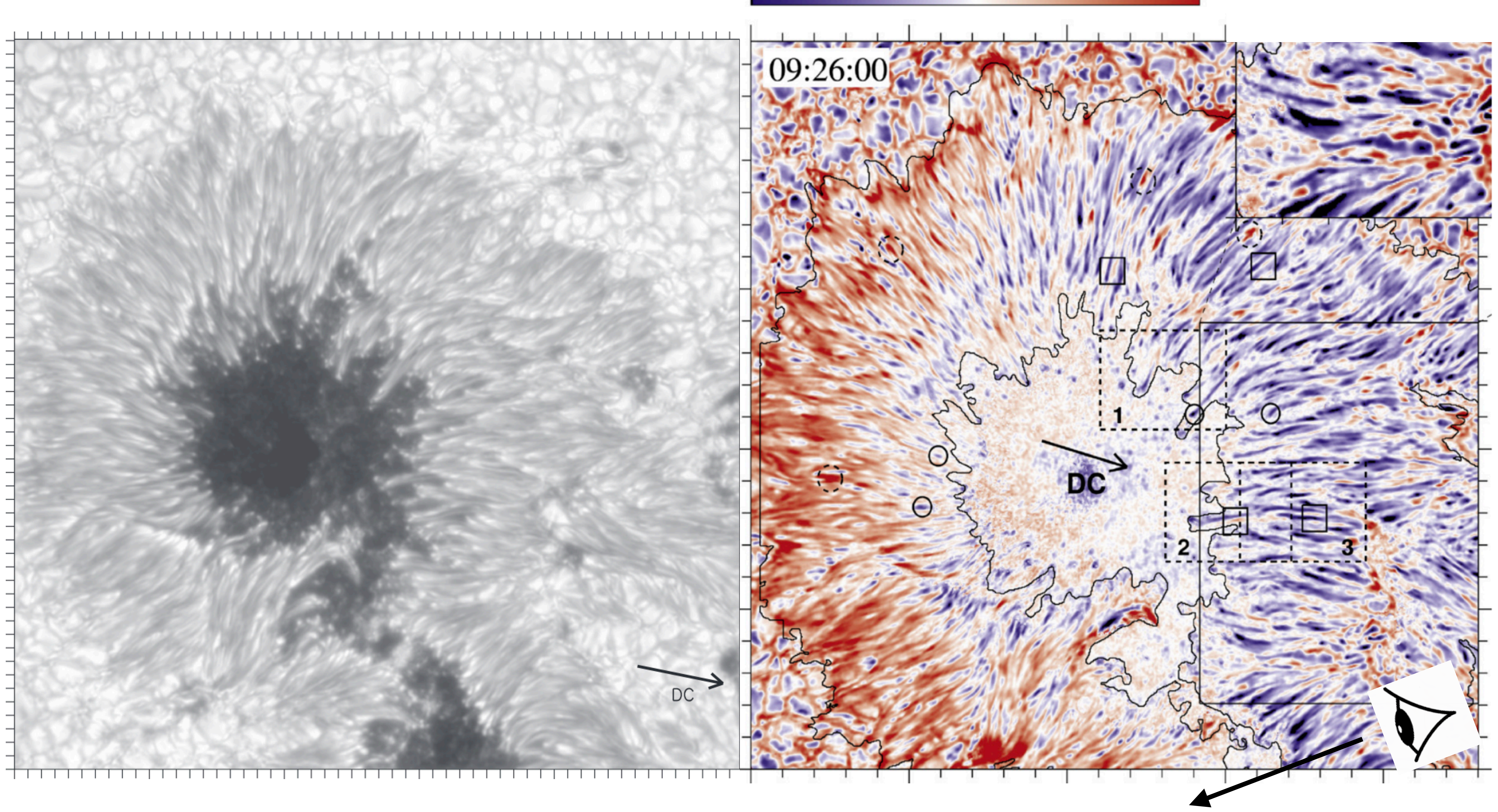


Esteban Pozuelo et al. (2015) | SST/CRISP



Away from the observer ←

Towards the observer →

Penumbrae are mainly characterised by

- A **filamented** structure — Penumbral filaments radially directed from the centre of the umbra
- The filaments host **strong horizontal magnetic fields** interlaced with the spot background — Ucombed structure of the penumbra
- Plasma upflows at the inner heads and downflows at their outer end
- Plasma flows along the penumbral filaments — **Evershed flow**
- Plasma also **downflows** at the **lateral edges of filaments**

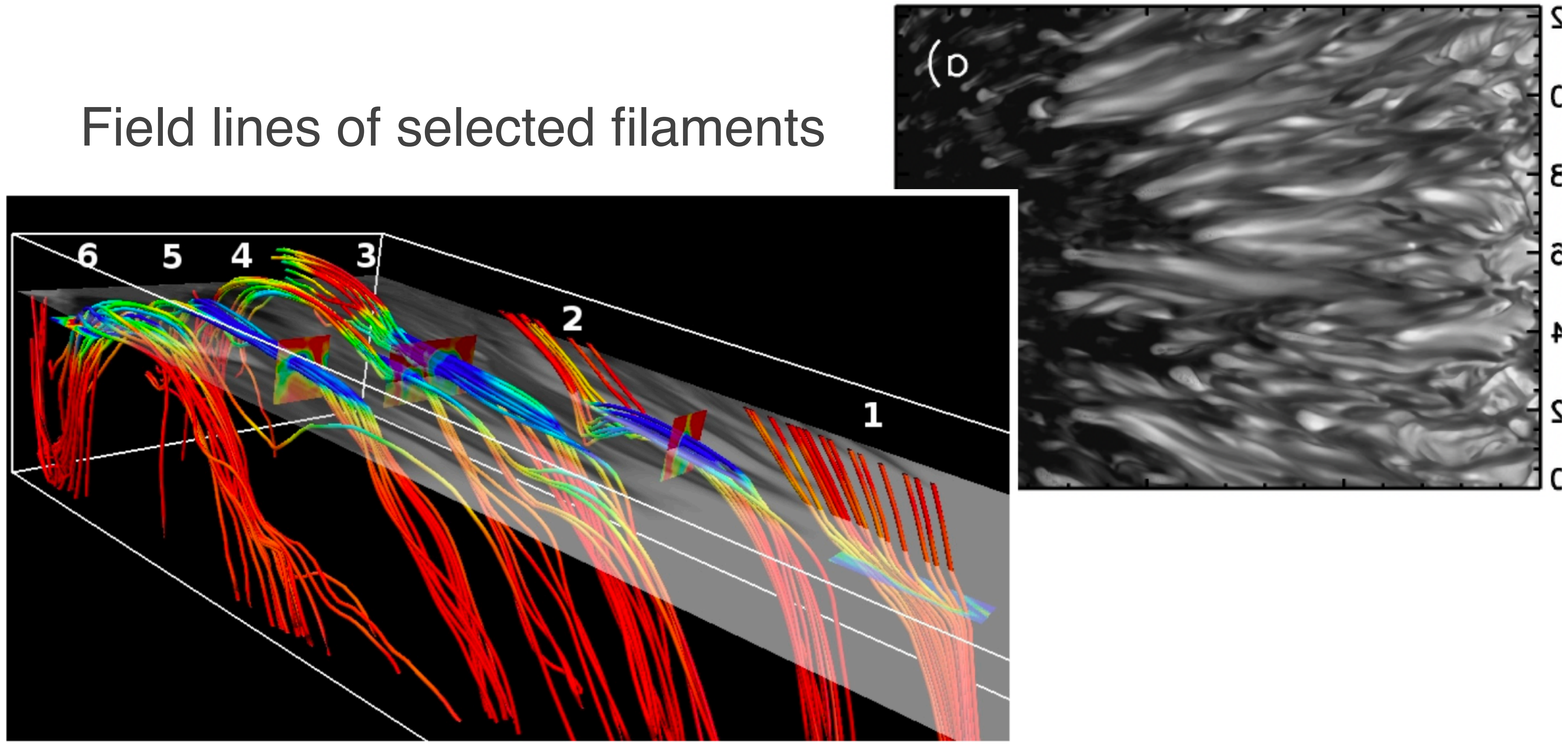
The **extreme elongation of the penumbral magneto-convective** cells is shaped by the **strong** and **highly inclined** fields present in the penumbral areas (Rempel 2011; Rempel 2012; Kitiashvili+2009; Panja+2021) and **reduced vertical field**

Penumbra — Simulations

<u>Magnetic topology of filaments</u>

Field lines **emerge** from **subphotospheric** layers, **extend** (horizontally) **parallel to the solar surface** carrying an Evershed flow, and **dive back** below the surface **carrying the plasma with it**

Field lines of selected filaments



Rempel 2011

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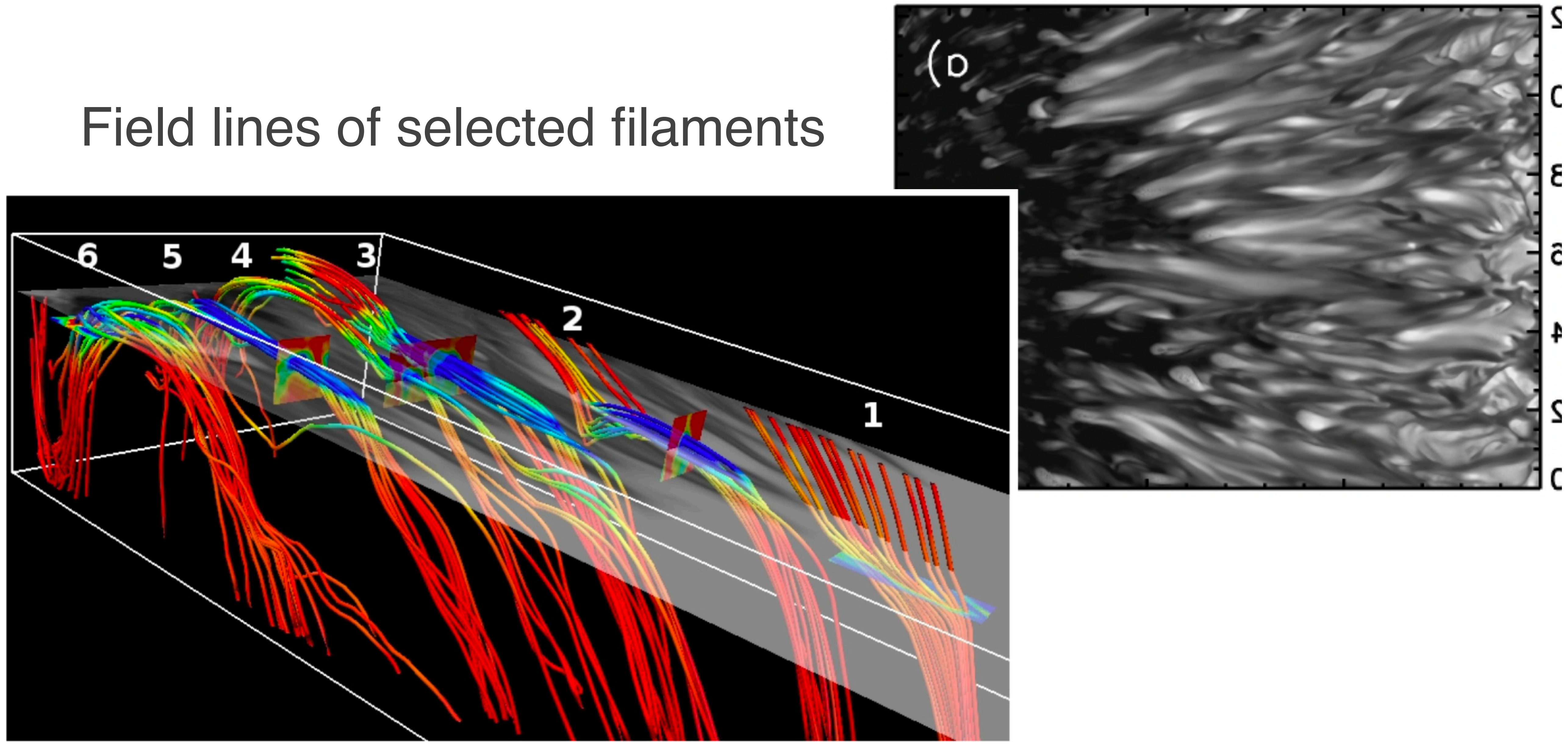
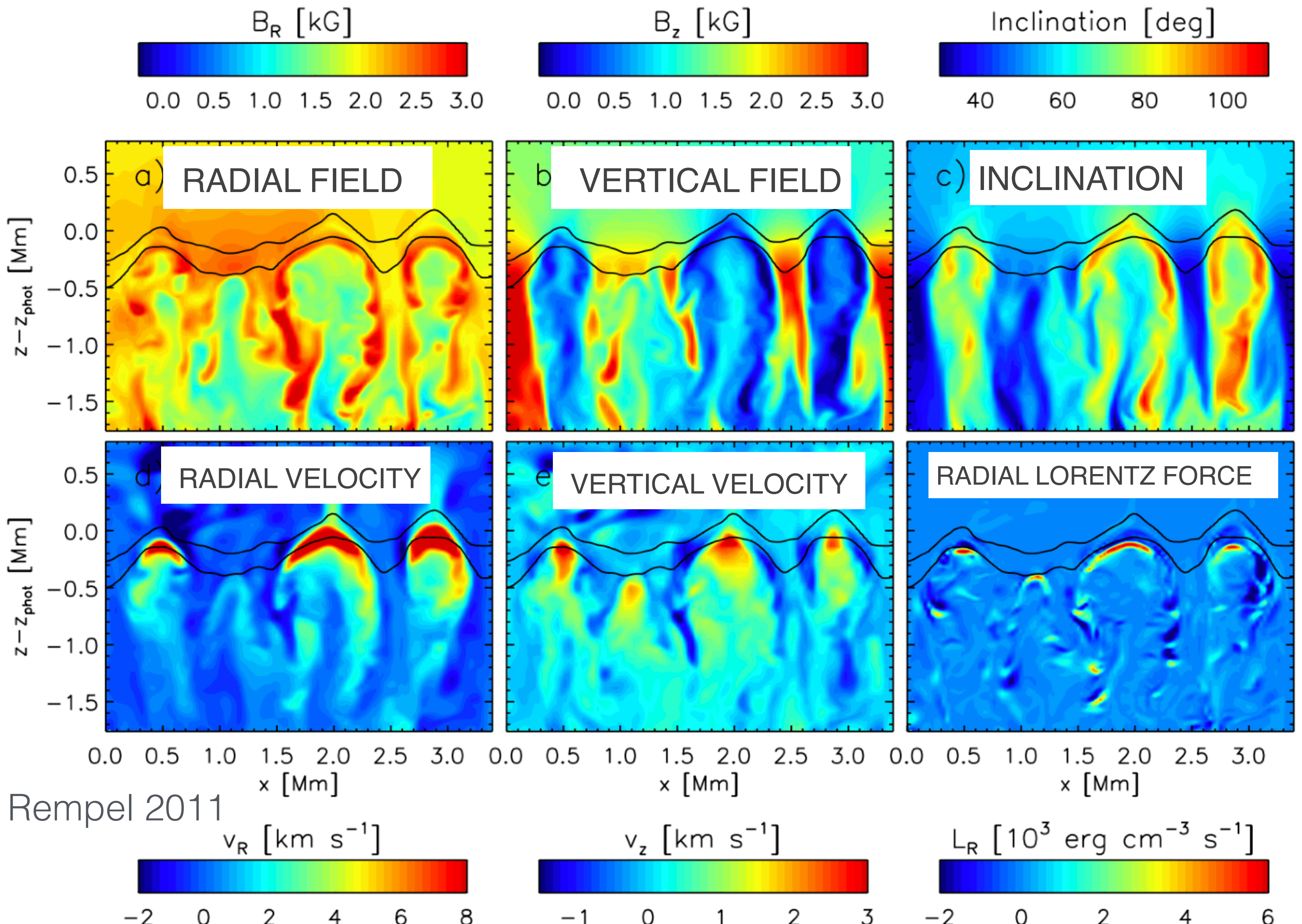


Rempel 2011

VERTICAL CUTS ACROSS A FILAMENT



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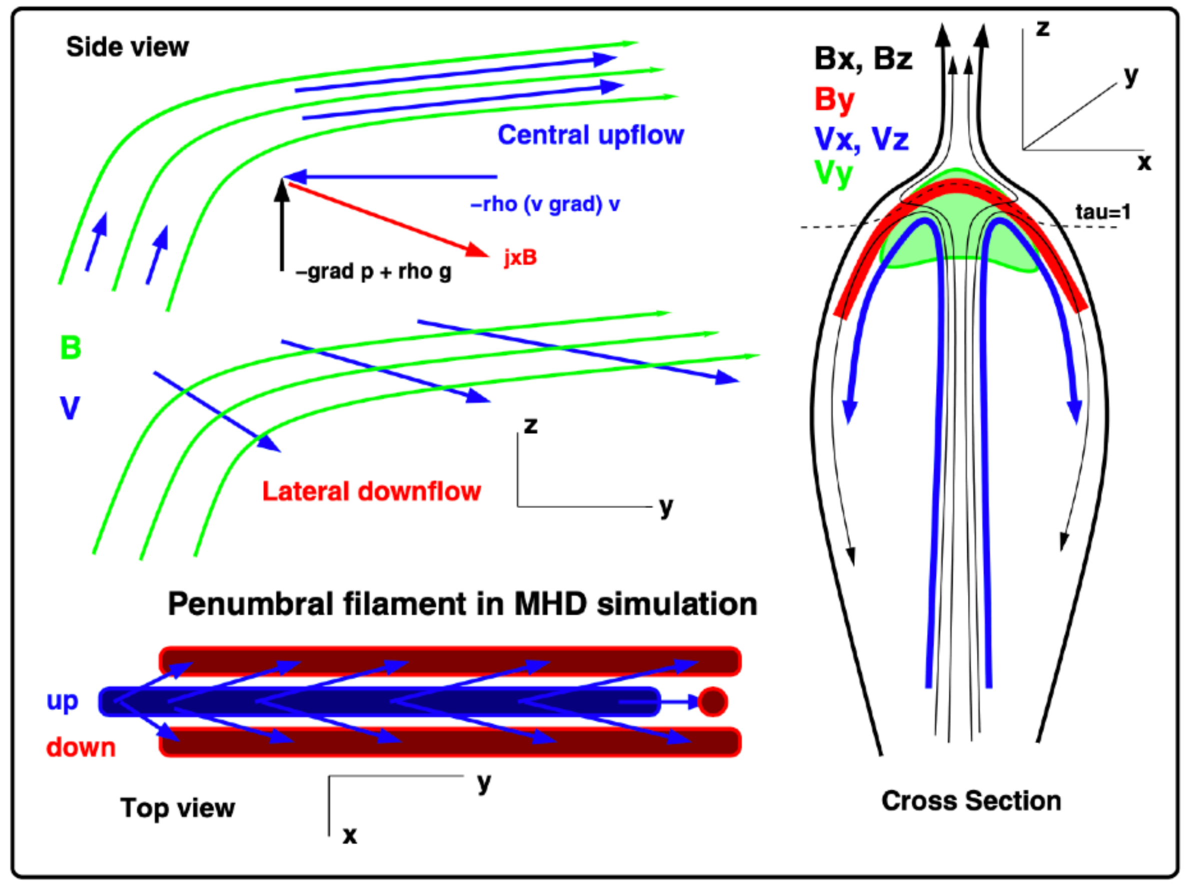


Rempel 2012

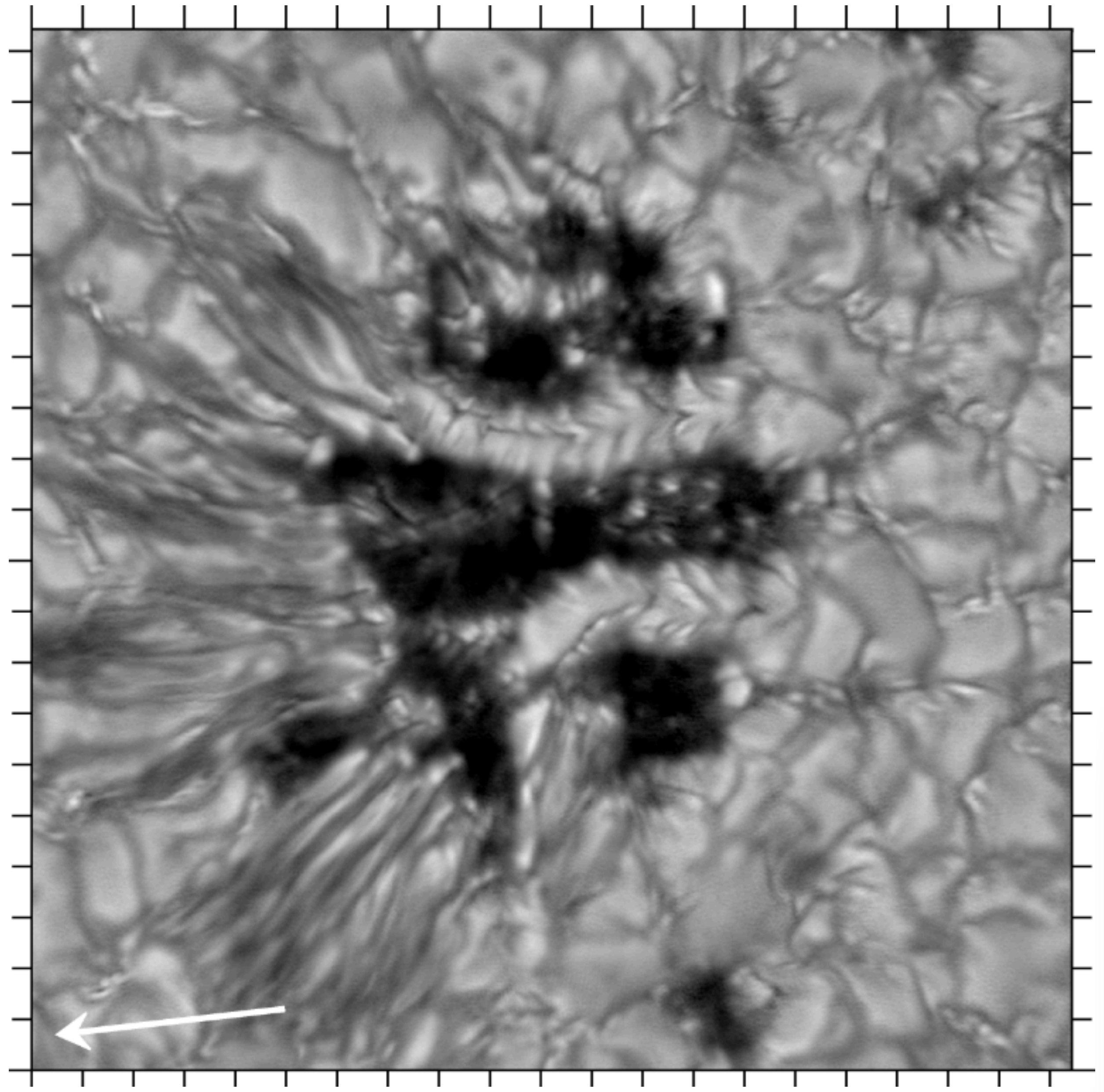
Origin of the Evershed flow

Evershed-flows developed by the (convective) **upflow deflected** by the **strong Lorentz force** at the solar surface

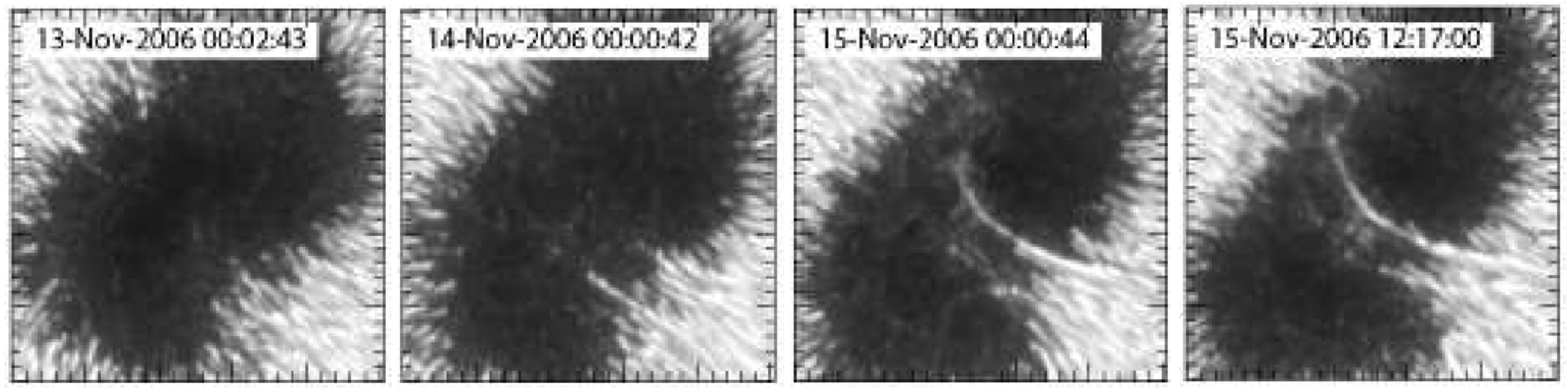
Sunspots
Light bridges

Light bridges

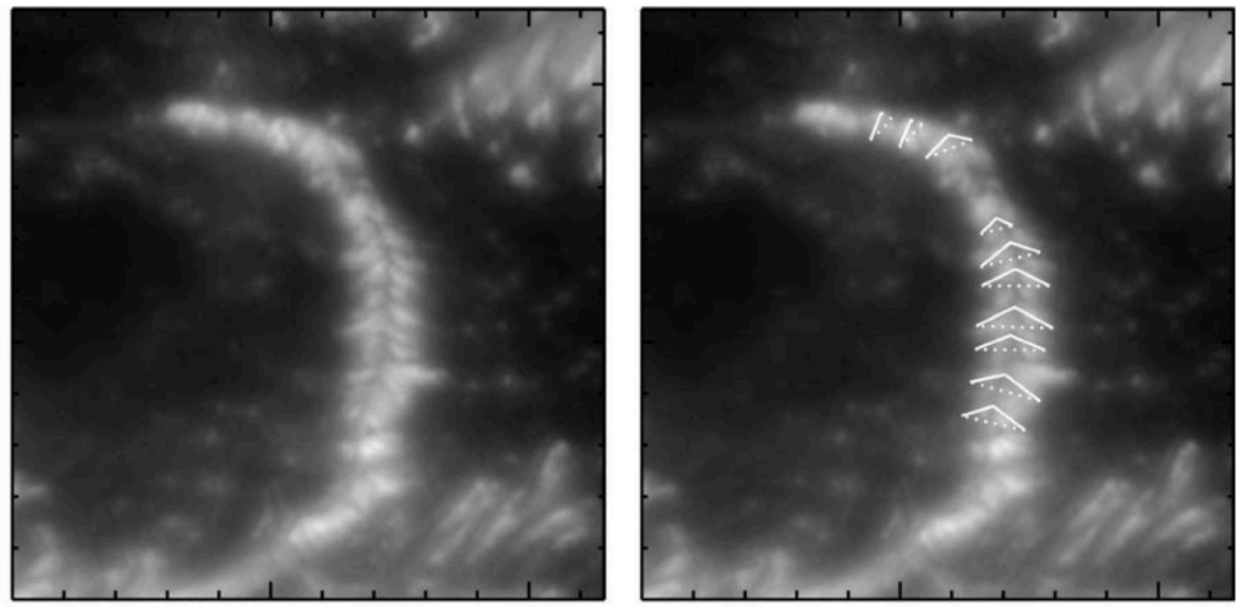
Light bridges show magneto-convective cells ranging from **extended granular cells** with properties comparable to quiet Sun granules (e.g., Lagg+14) to more conspicuous **cells with summits and valleys** (e.g., Lites+2004, Schlichenmaier+2016) or a **filamentary appearance** (Katsukawa+2018)



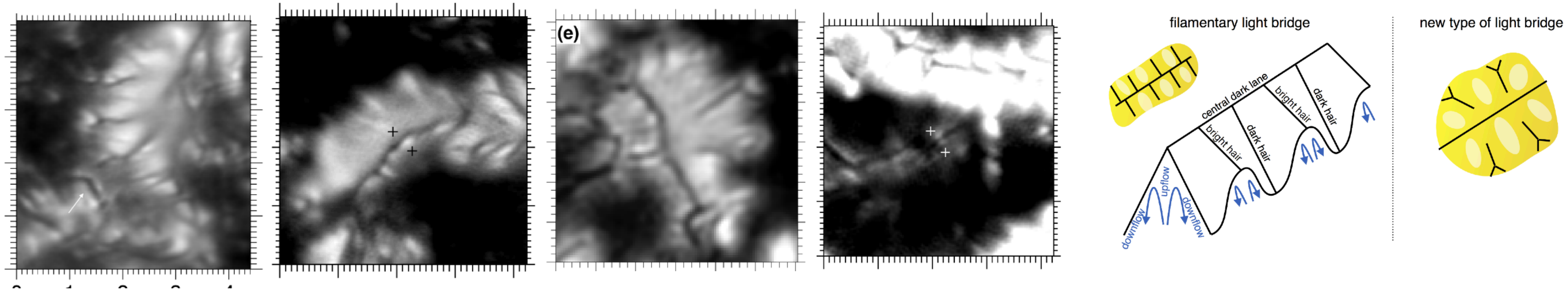
Schlichenmaier 2016 | GREGOR



Katsukawa et al. 2018 | Hinode SOT data



Lites 2004 | from SST data



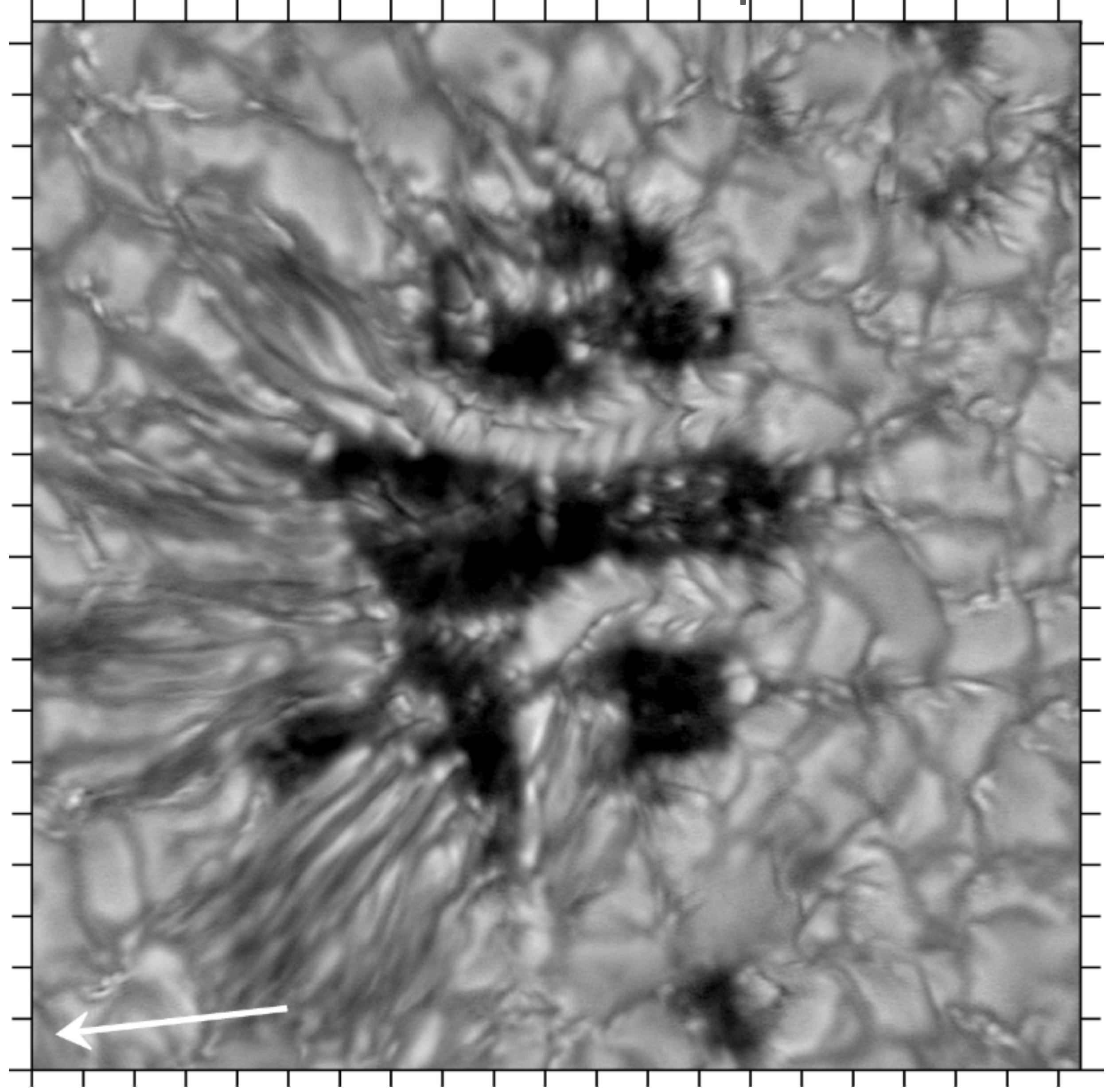
Schlichenmaier 2016 | GREGOR

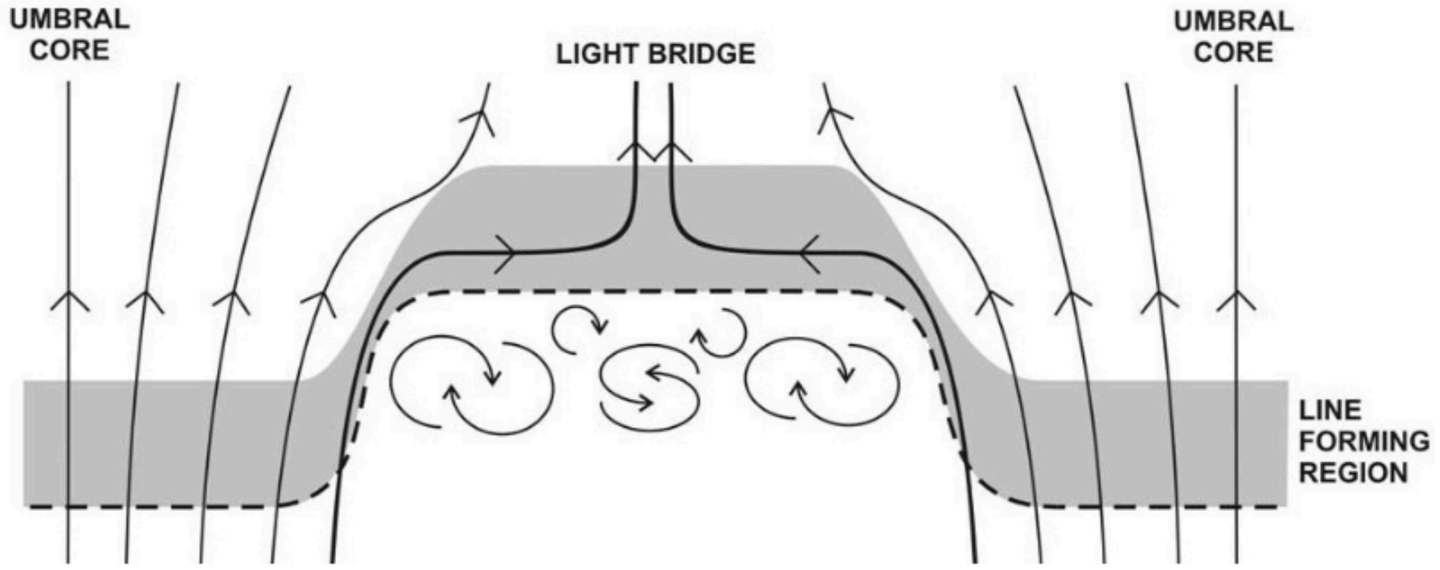
Light bridges

Convective cells in light bridges appear to

- have longer lifetimes than in quiet Sun areas (Hirzberger+2002)
- decreased magnetic field strength and increased inclination (w.r.t. to umbrae)
- a temperature increase with respect to the surrounding umbrae

Schlichenmaier 2016 | GREGOR



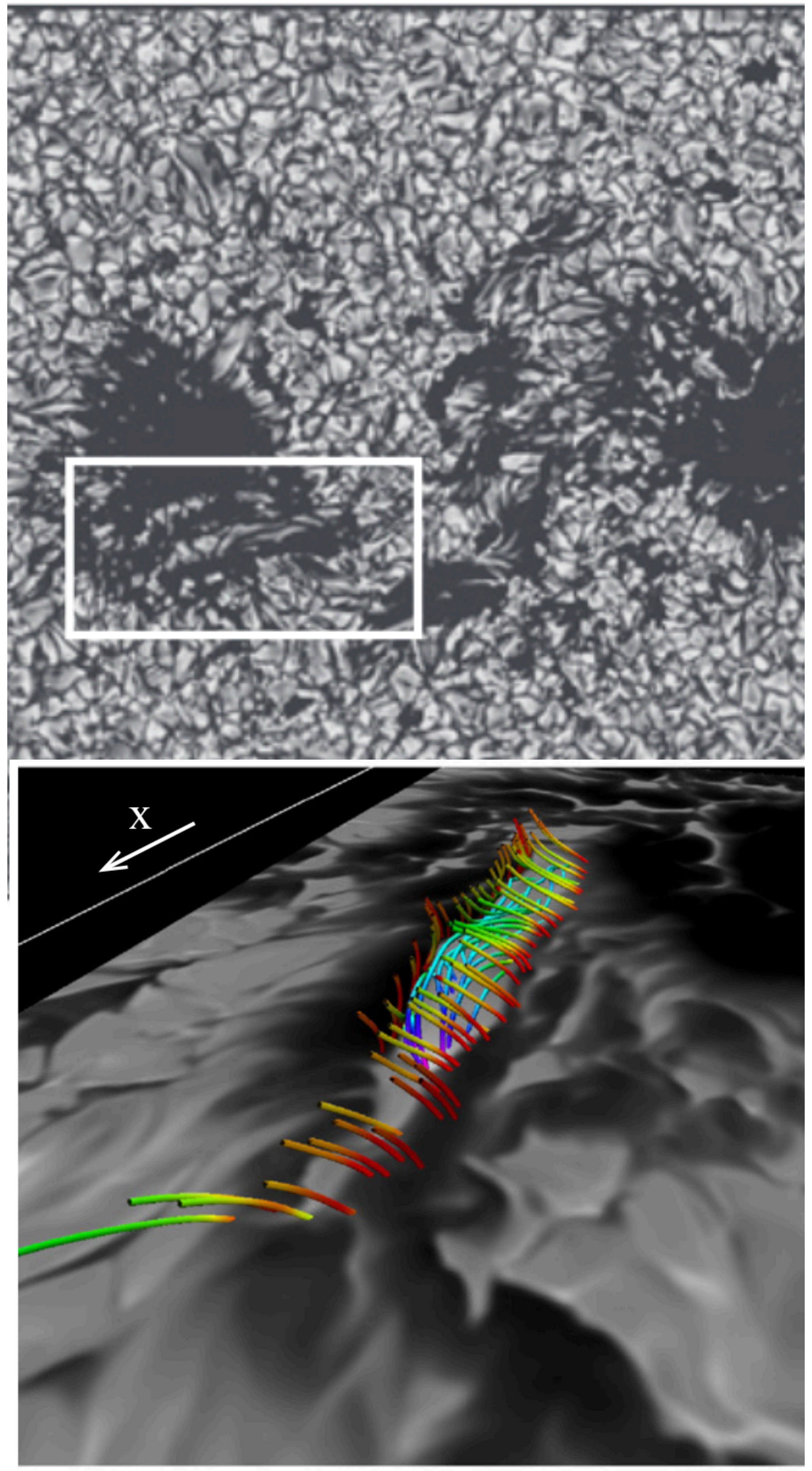


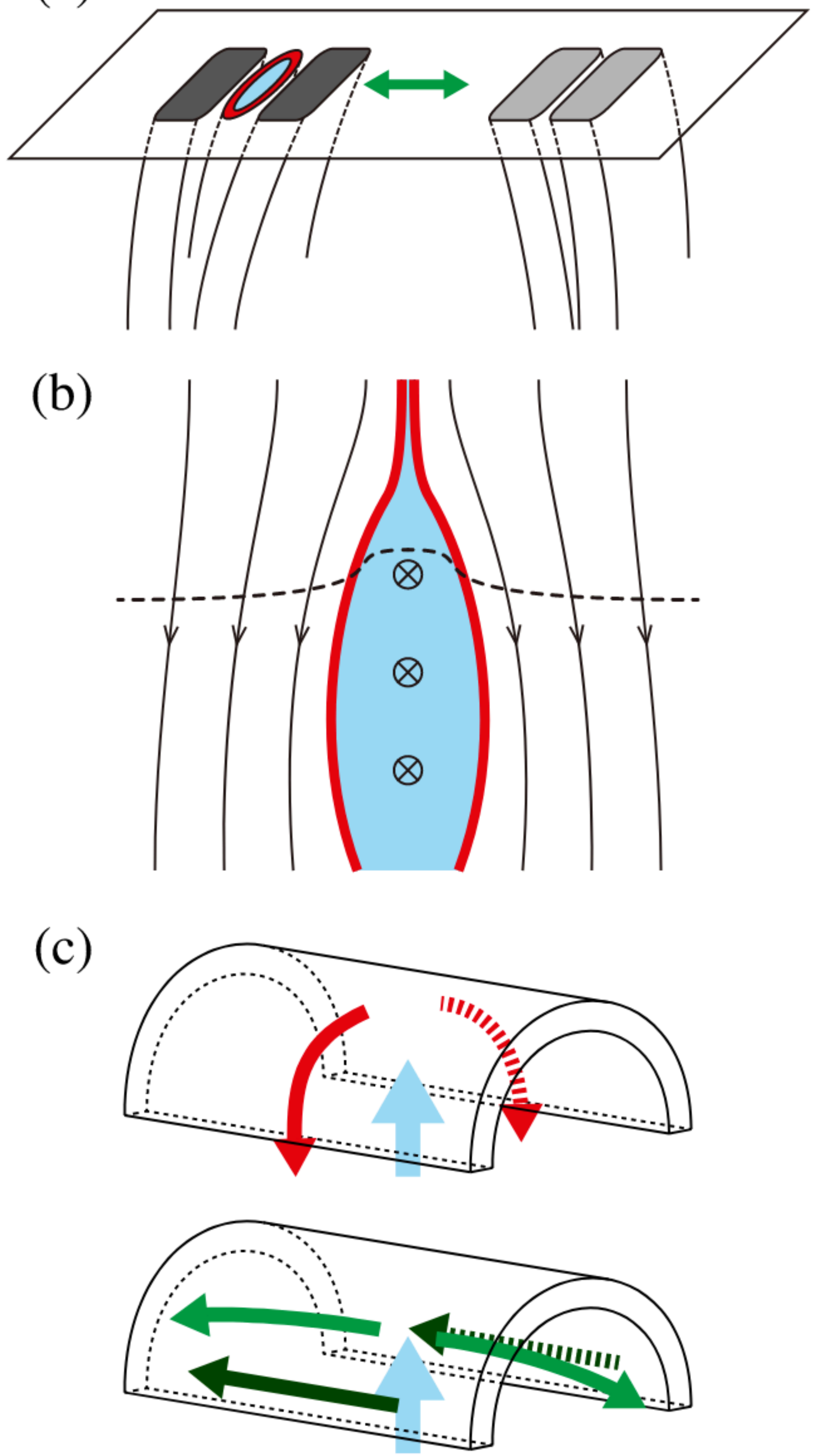
Jurcak+ 2006, from LPSP/SST data

Maps of magnetic field strength and orientation of the magnetic field vector indicate the presence of a **canopy** structure **above the light bridges**

Many such light bridges are originated by the trapping granulation between pores during their coalescence in the formation of sunspot/larger pores in forming active regions (e.g., García de la Rosa+1987, Schlichenmaier+ 2010 from HMI data, Toriumi+2015a from Hinode/SOT data)

Light bridges origin— Simulations





Toriumi et al. (2015) | MURaM simulations

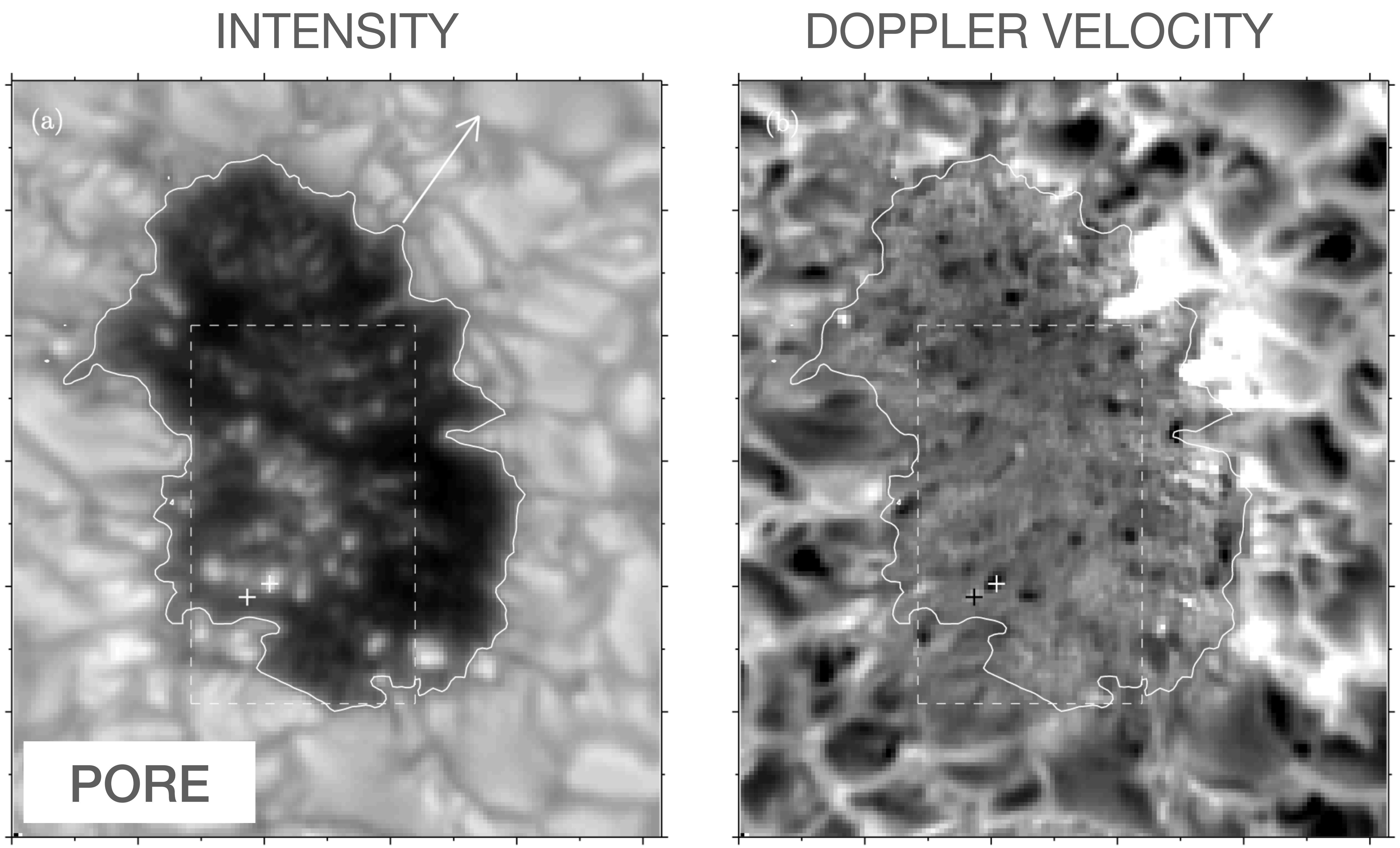
From the MHD simulation of a large-scale flux emergence from the convection zone by Cheung +2010, Toriumi+ 2015 found that

- a **weakly magnetised plasma upflow** in the near-surface layers of the convection zone is **entrained** between the **emerging magnetic bundles** that appear **as pores** at the solar surface
- This convective **upflow** continuously **transports horizontal fields to the surface** layer and **creates** a **light bridge** structure
- Due to the **magnetic shear** between the **horizontal fields of the bridge** and the **vertical fields of the ambient pores**, an elongated cusp-shaped current layer is formed above the bridge, which may be **favorable for magnetic reconnection**

Sunspots
Umbral dots

Umbral dots

Umbrae and **pores** host the strongest vertical magnetic fields giving rise to umbral dots



Ortiz+ 2010, from CRISP/SST data

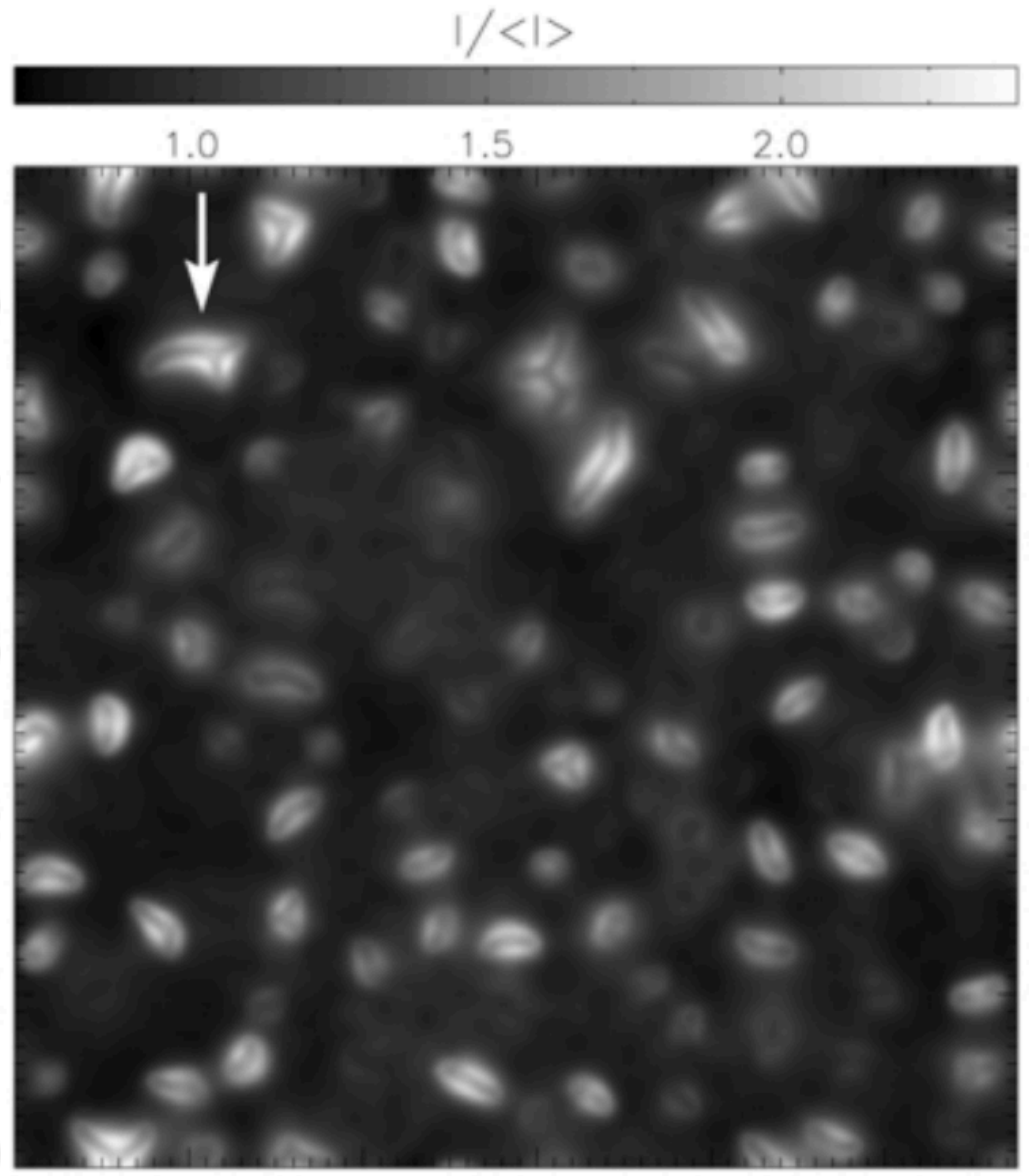
- UDs are associated with **strong upflows** (up to 1.5km/s) in deep photospheric layers
- Some of them also show concentrated patches of downflows (400-1000 m/s) at their **edges**(!) —> signature of their **magneto-convective nature**

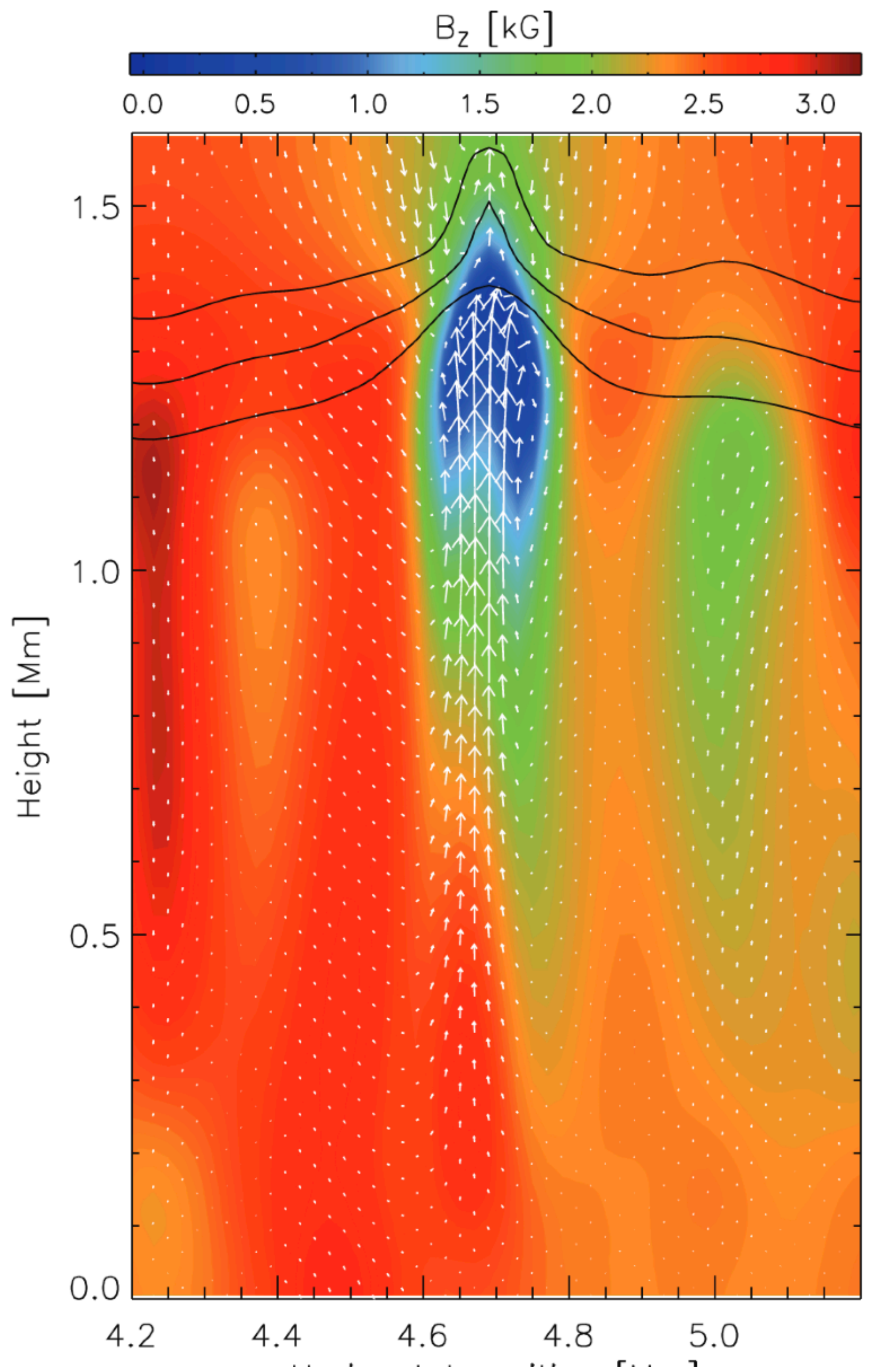
Umbral dots origin — Simulations

UMBRA. The **stabilising effect** of the **strong vertical fields** inhibits the penetration of this perturbations into sub-photospheric layers

- below 3-4 Mm -> central umbral dots characterised by a **shallow** and frail mode of **magneto-convection**
- below 7 Mm -> peripheral (close to the penumbra) umbral dots with a somewhat more vigorous mode of magneto-convection

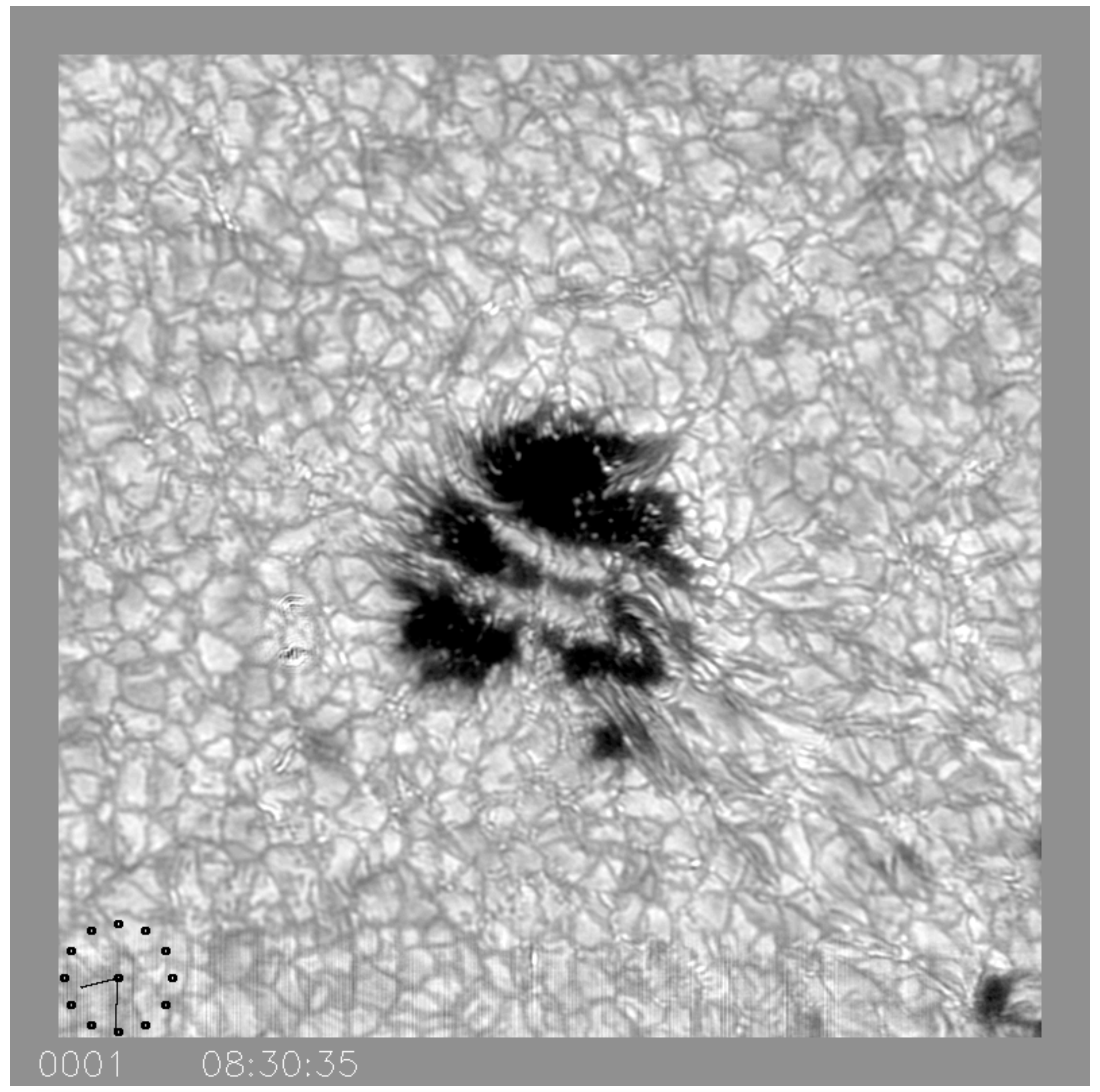
These results are in line with those from simulations by Schüssler & Vögler (2006)

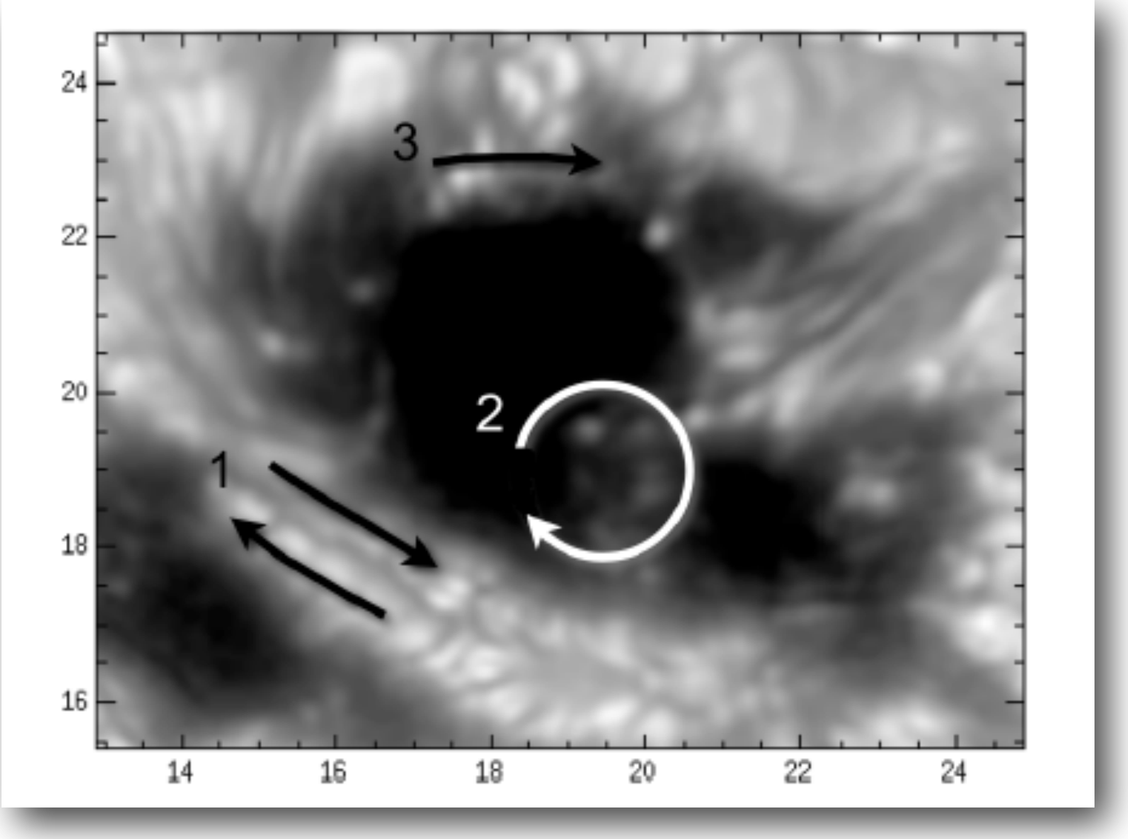


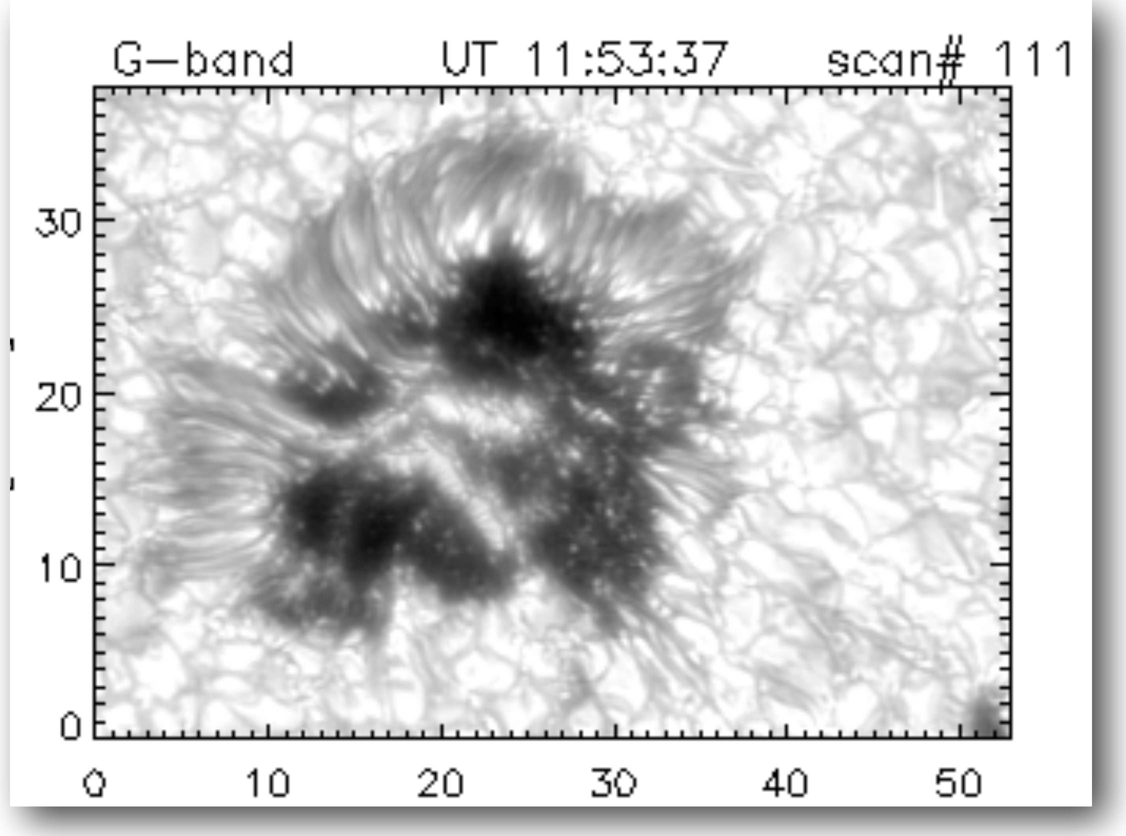


Schüssler & Vögler 2006

Twist relaxation in sunspot magnetic flux ropes

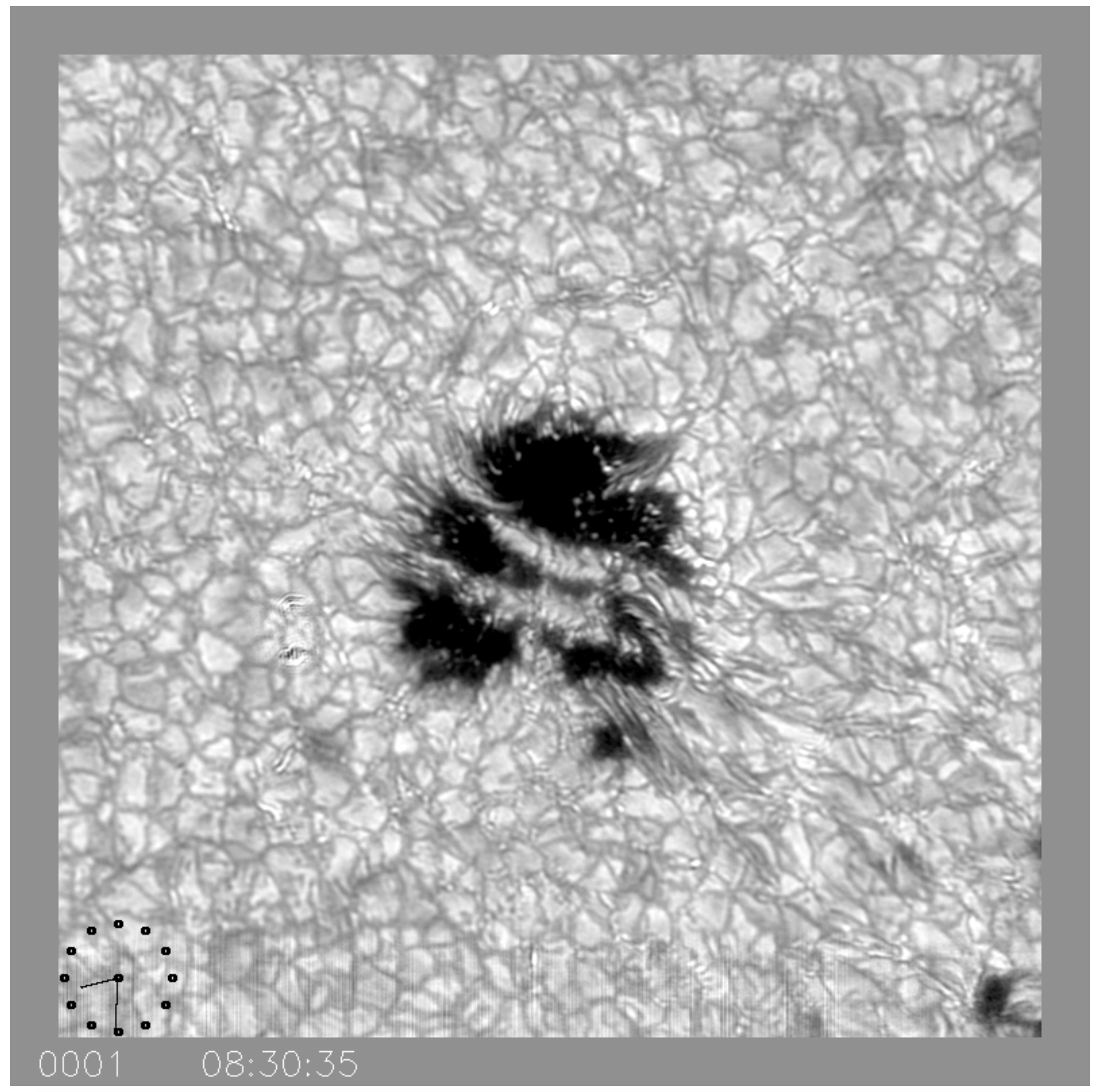


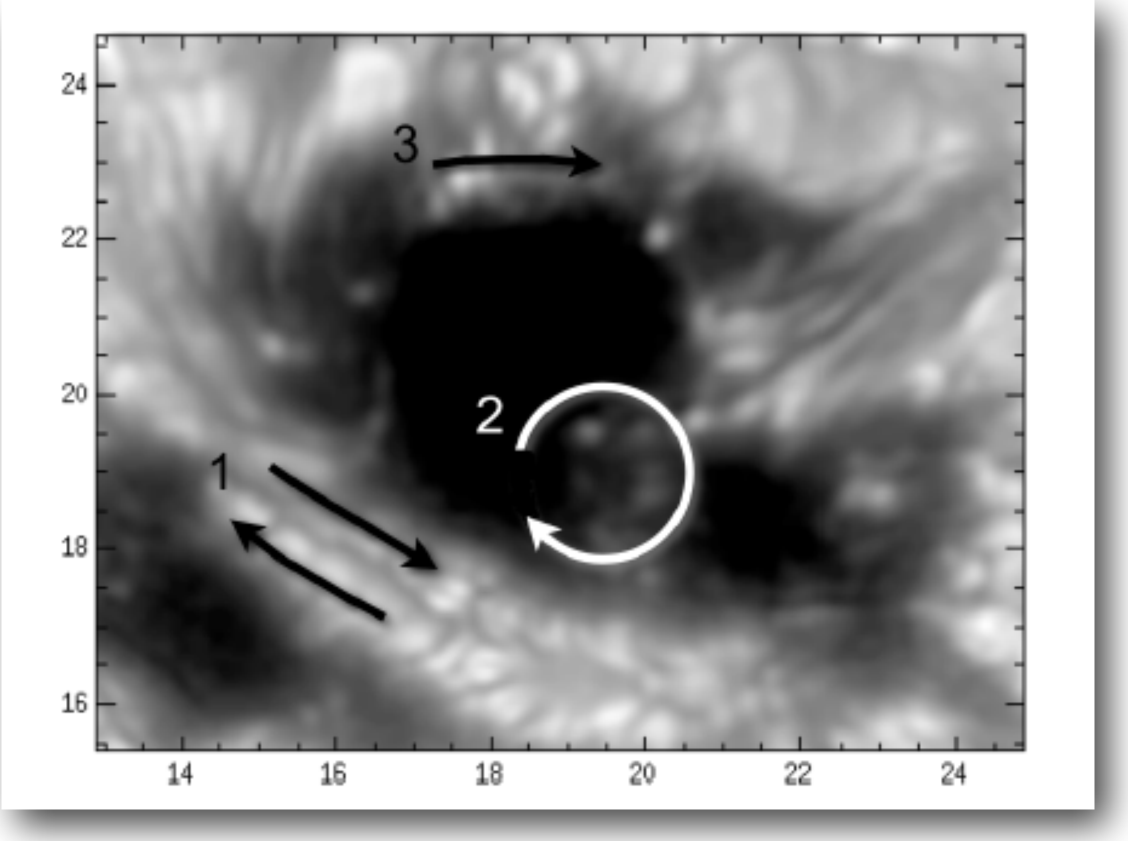


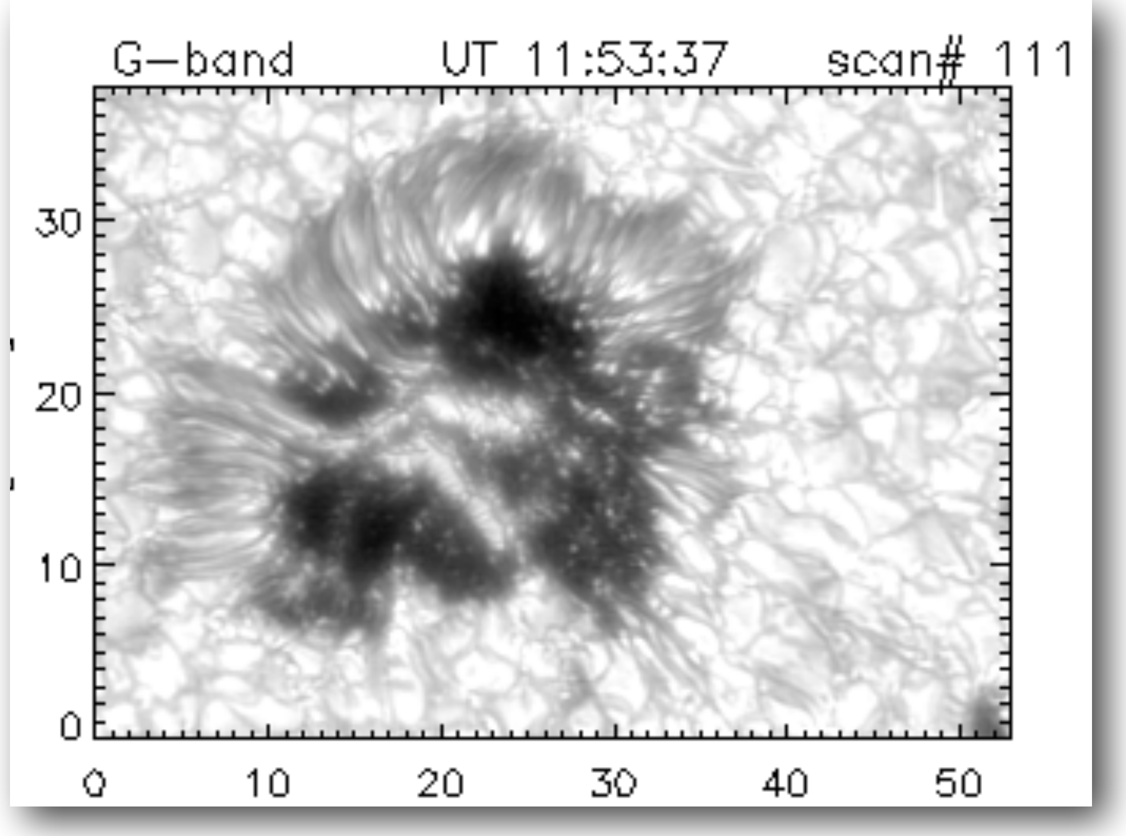


Twist relaxation in sunspot magnetic flux ropes

- The **sunspot** developed out of **two coalescent individual pores** separated by a light bridge
- **No** signature of an **overall rotation** that some sunspots undergo during their evolution
- Instead, **individual rotation** of **one part (upper umbral core)** of the spot
- The **penumbral filaments** formed later around the umbral core show a clear **curvature**, additional indication of a twist in this part of the umbra
- **Several flares** were emitted by this AR during the emergence phase (Valori et al. 2011). Flare energy generation is thought to be favoured by twisting processes in emerging flux ropes (Schrijver et al. 2008; Padinhatteeri & Sankarasubramanian 2010).







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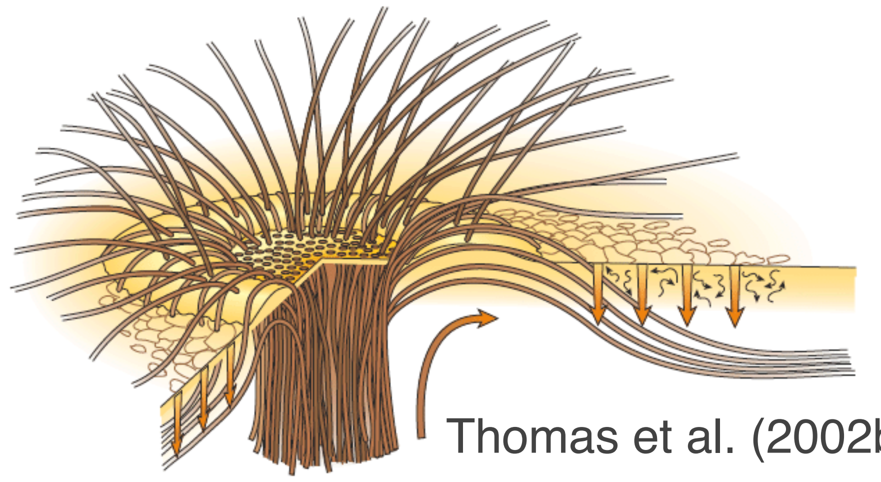
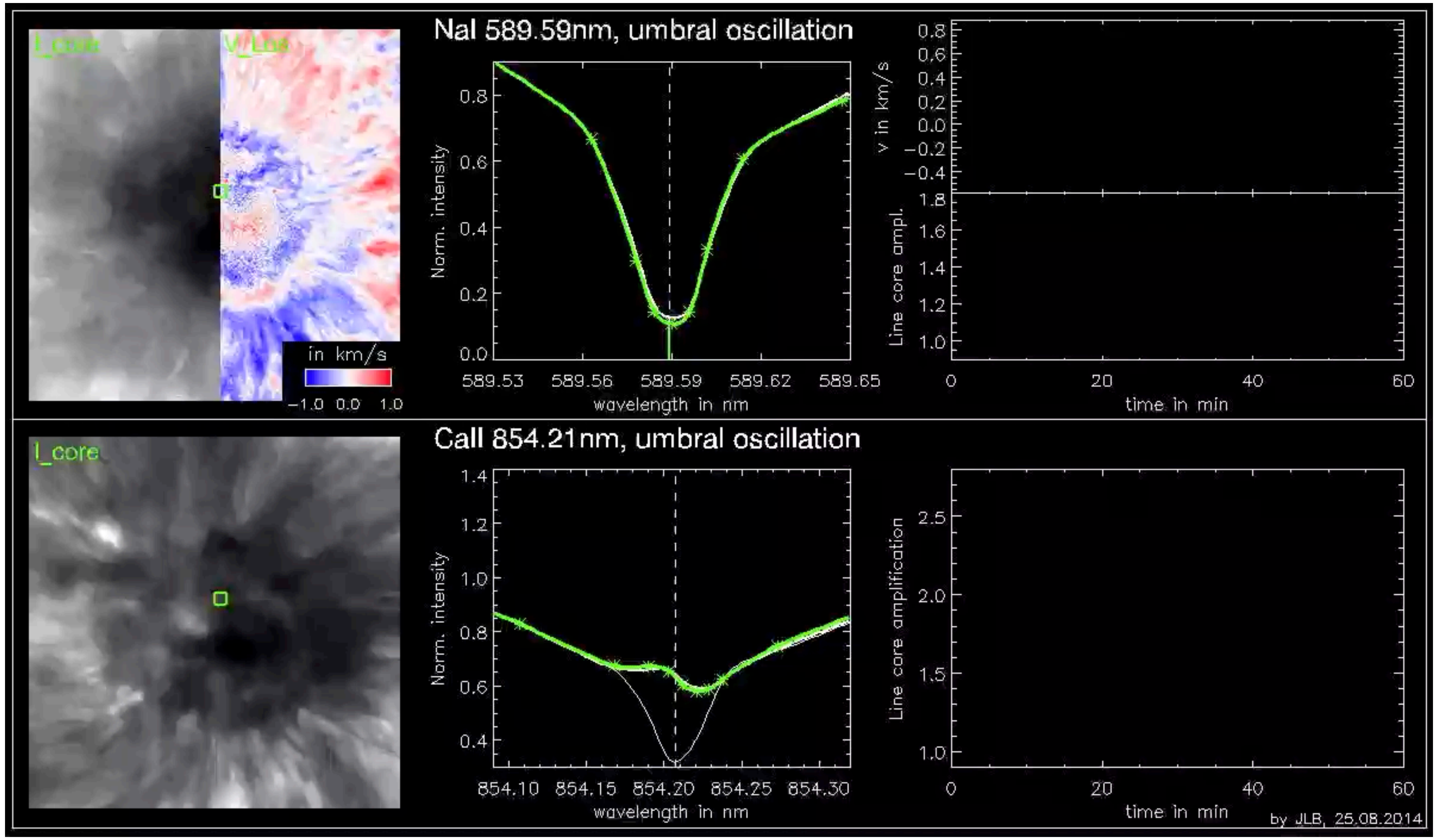
Oscillations in the solar atmosphere

Umbral flashes & penumbral running waves



Löhner-Böttcher (PhD Thesis, 2016)



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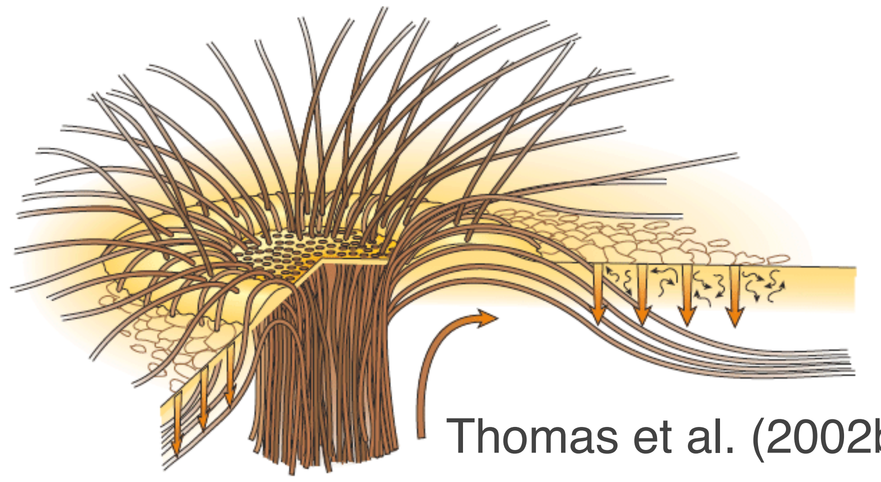

Thomas et al. (2002b)

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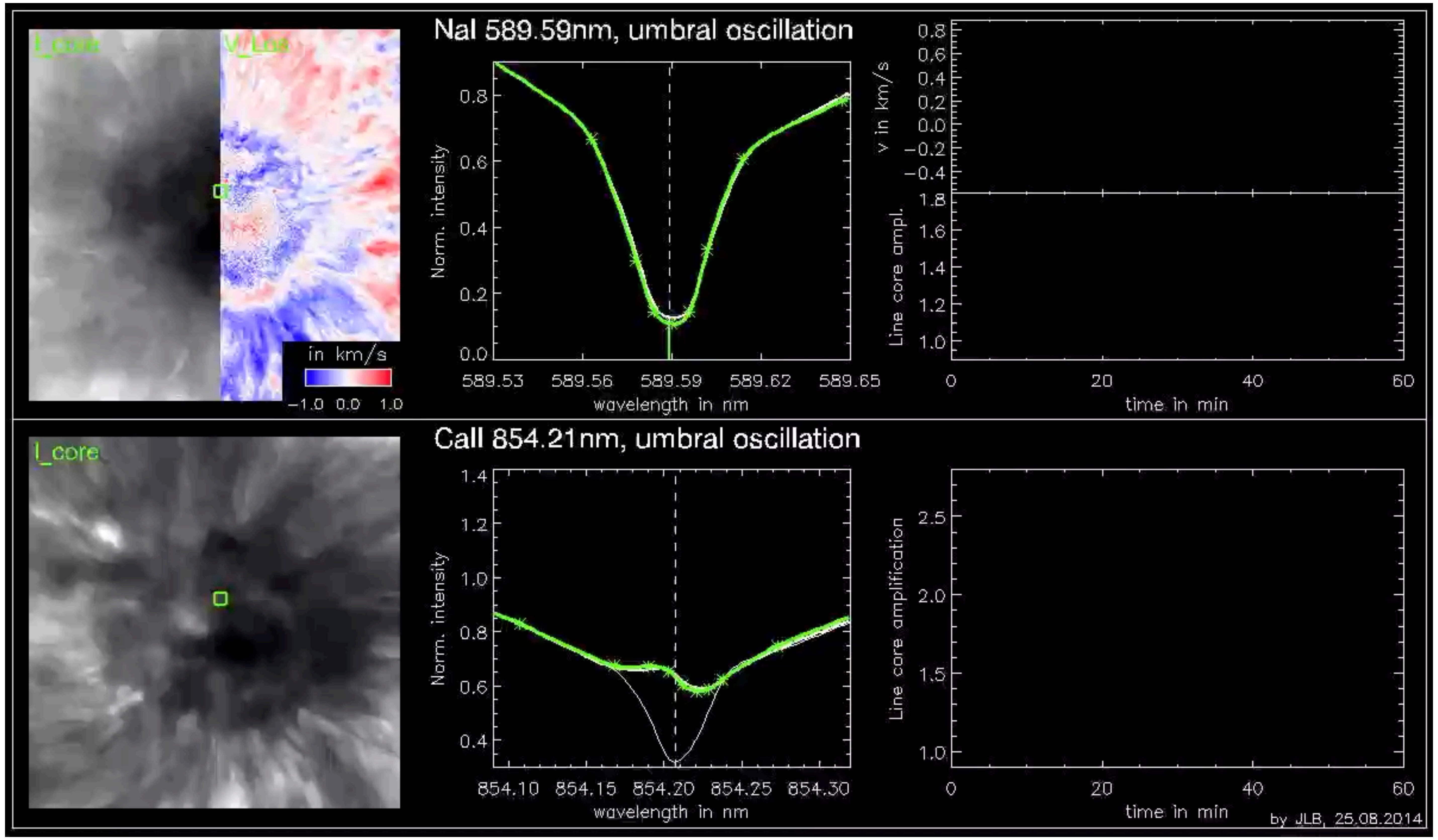
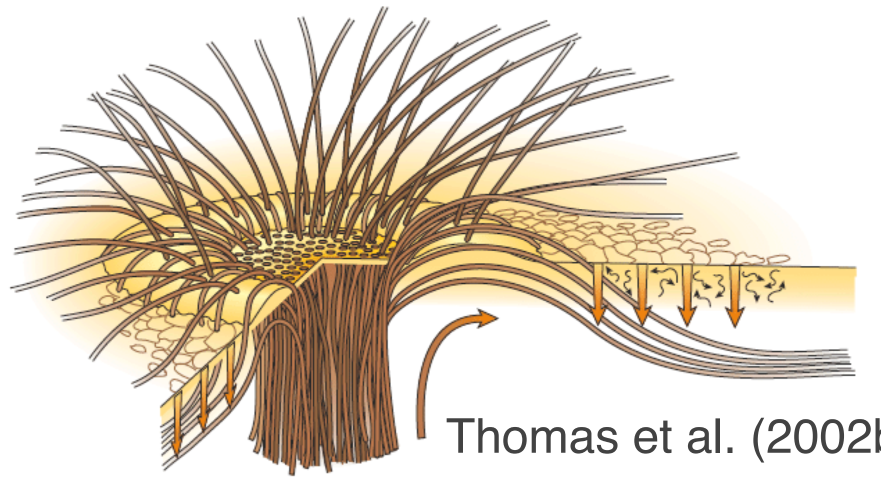


UMBRAL FLASHES (3 min)

Umbral flashes & penumbral running waves

Upward-traveling magneto-acoustic waves that steepen as they move into the less dense chromosphere
=> **Shock waves:**

- A sudden rise in temperature and pressure
- Enhanced emission in chromospheric lines => **bright flash** visible in narrowband imaging or spectral observations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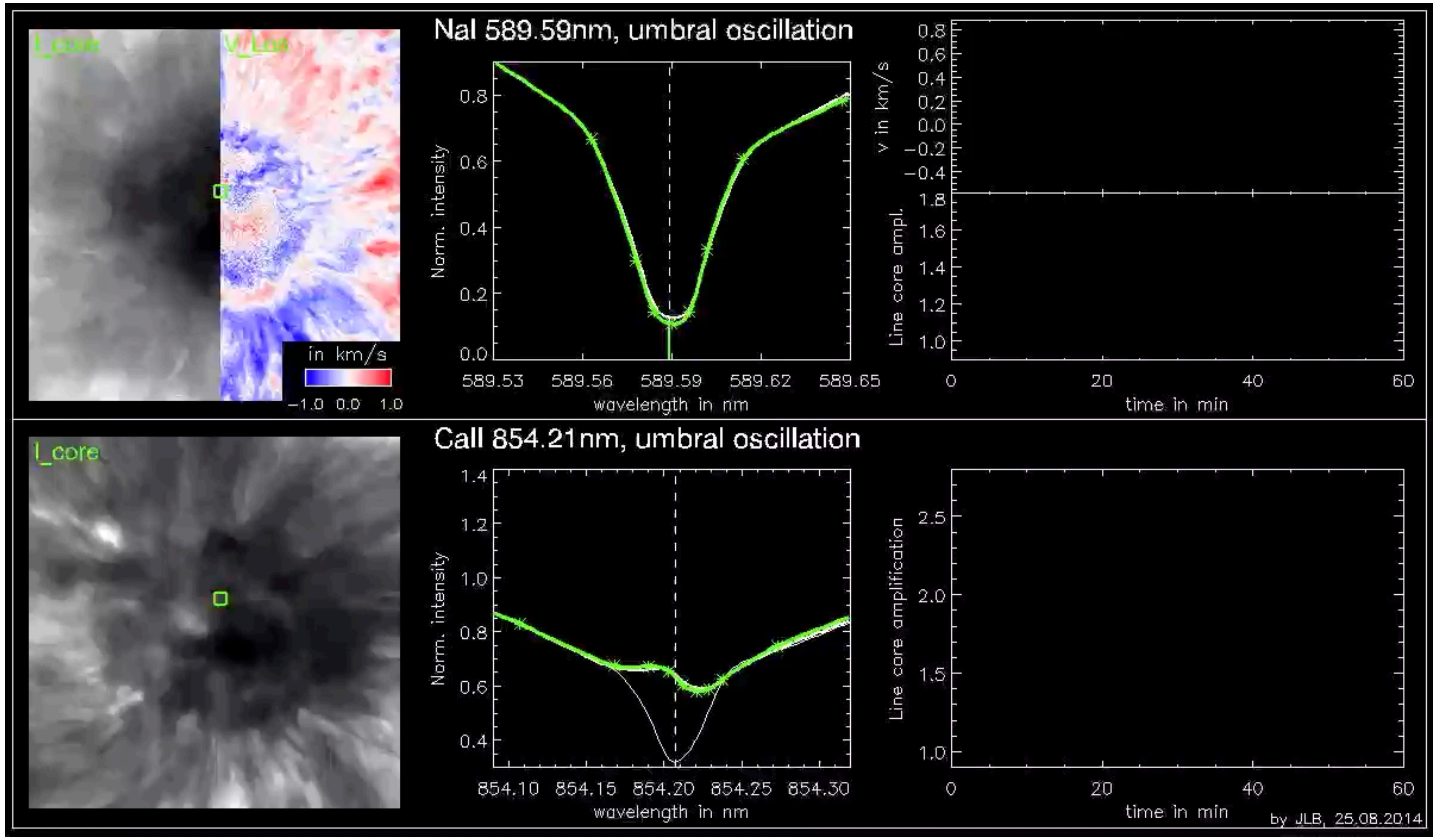

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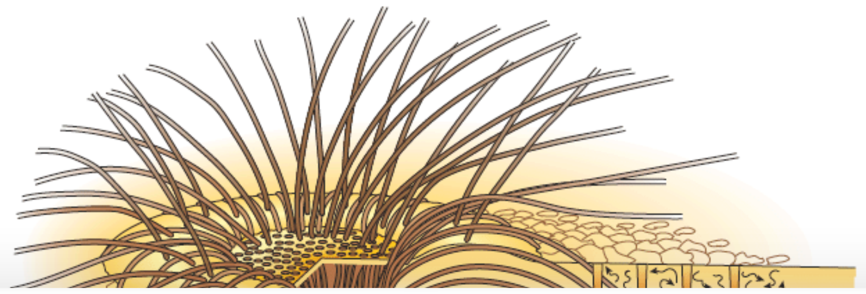
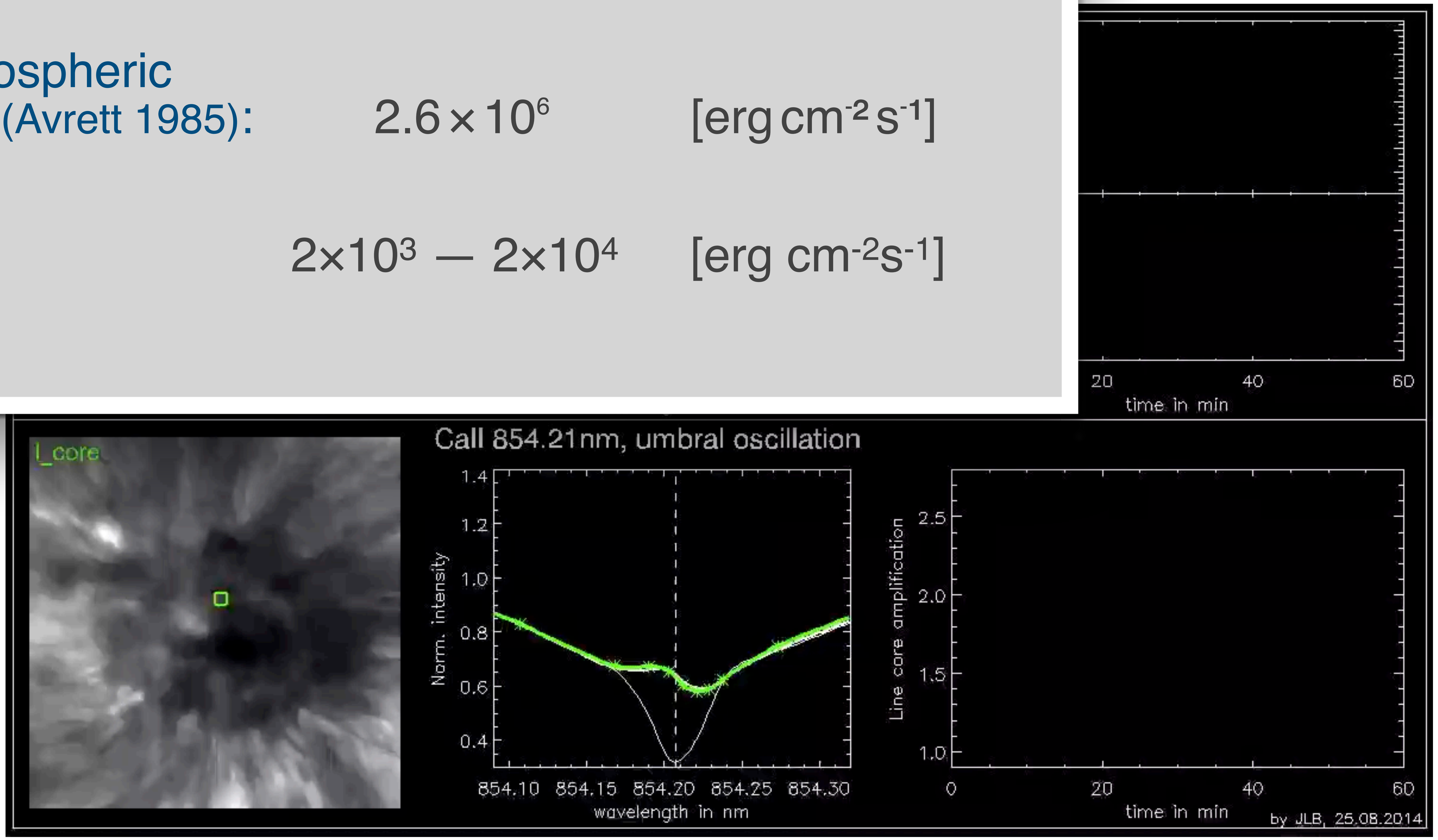


…r (PhD Thesis, 2016)

Required Energy for Chromospheric **Heating** in Sunspot **Umbrae** (Avrett 1985):	2.6×10^{6}	[erg cm^{-2} s^{-1}]
Energy Delivered by **Umbral Flash Shocks** (Anan+ 2019):	2×10^{3} — 2×10^{4}	[erg cm^{-2}s^{-1}]



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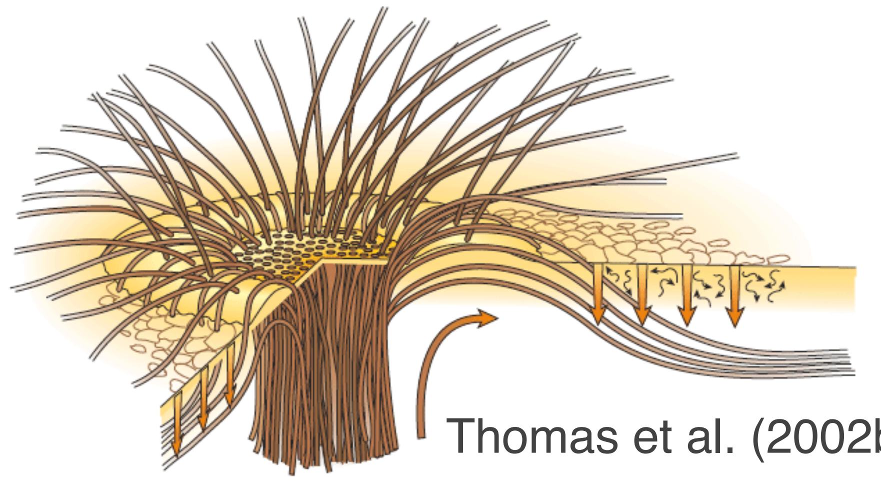
PENUMBRAL RUNNING WAVES

Magneto-acoustic waves originated from **umbral oscillations** and appear to **move outward** along the penumbra guided by the inclined magnetic field lines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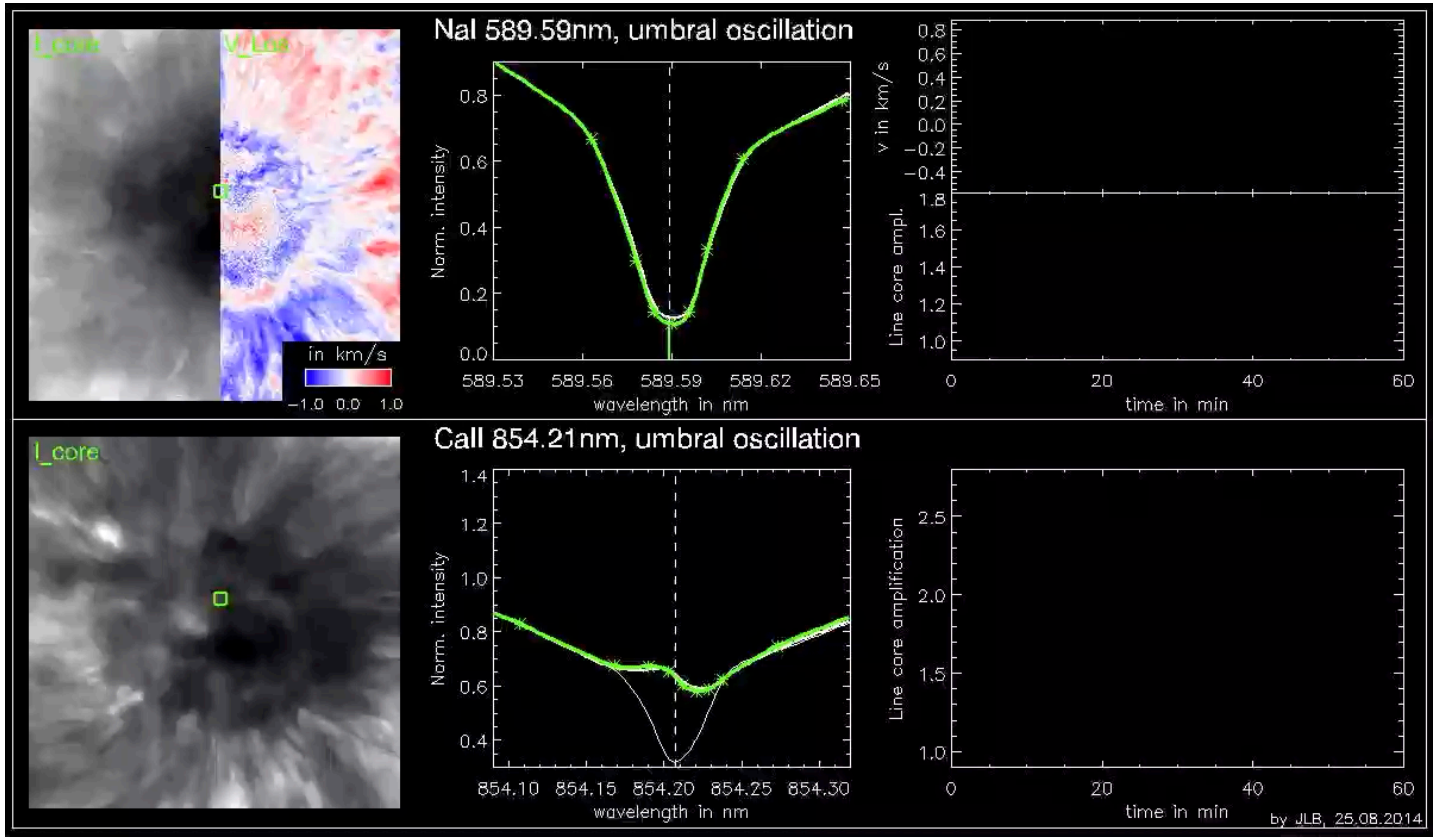
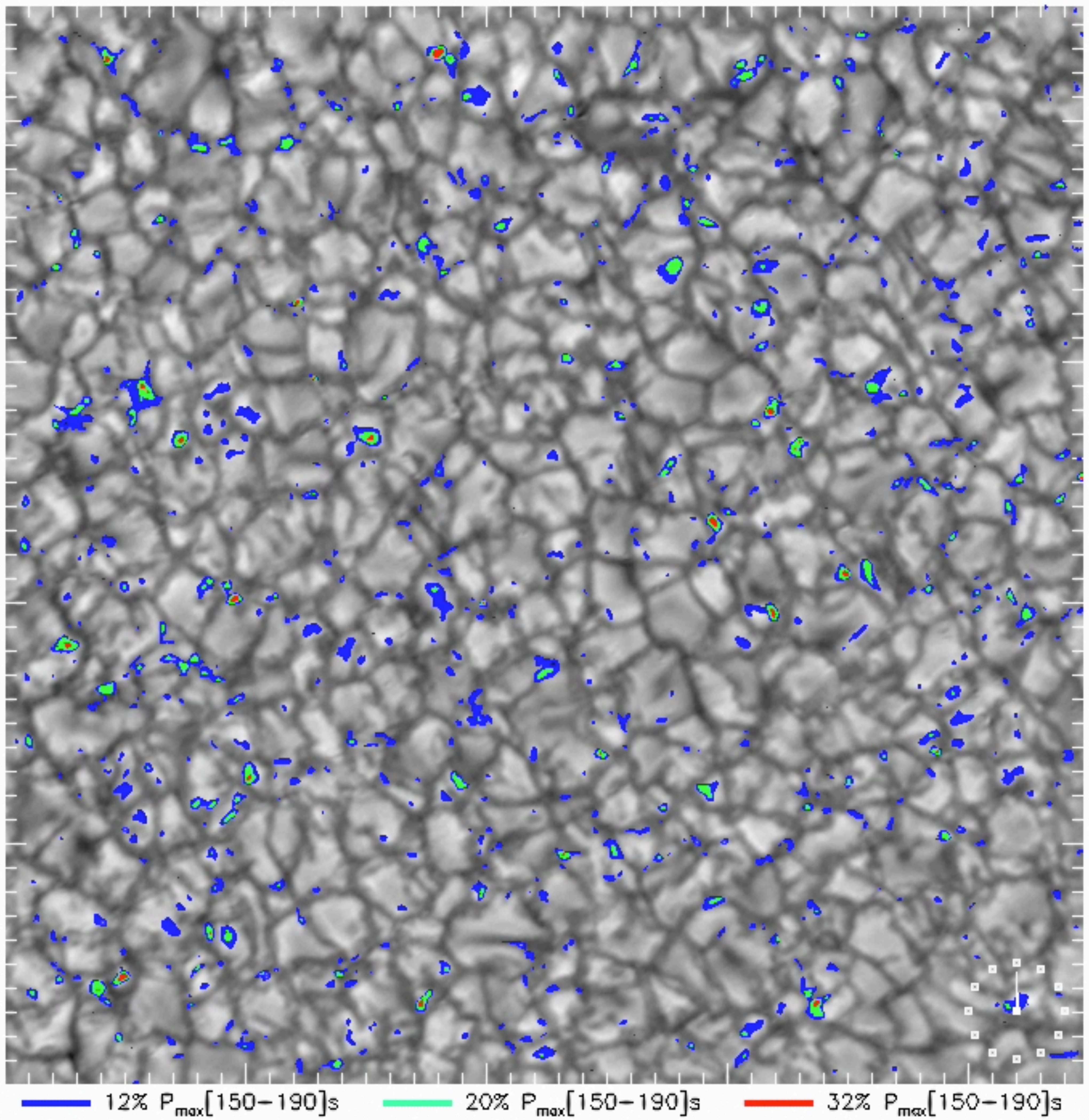


Acoustic power at the smallest scales



Bello González et al. (2010, from Sunrise/IMaX data)

Chromospheric heating by short-period acoustic waves hidden in the smallest spatial scales

- Short-period (10–100 s) acoustic waves from turbulent convection have long been proposed as significant for **energy transport** and **heating**
- **Simulations** indicate that **insufficient spatial resolution** may **underestimate** short-period energy flux by a factor of 10
- **Recent instruments** have **improved** flux detection, though still within half the level needed to offset chromospheric radiative losses

DKIST and **EST unprecedented spatial resolution** will decisively clarify the role of these small-scale acoustic waves in chromospheric heating

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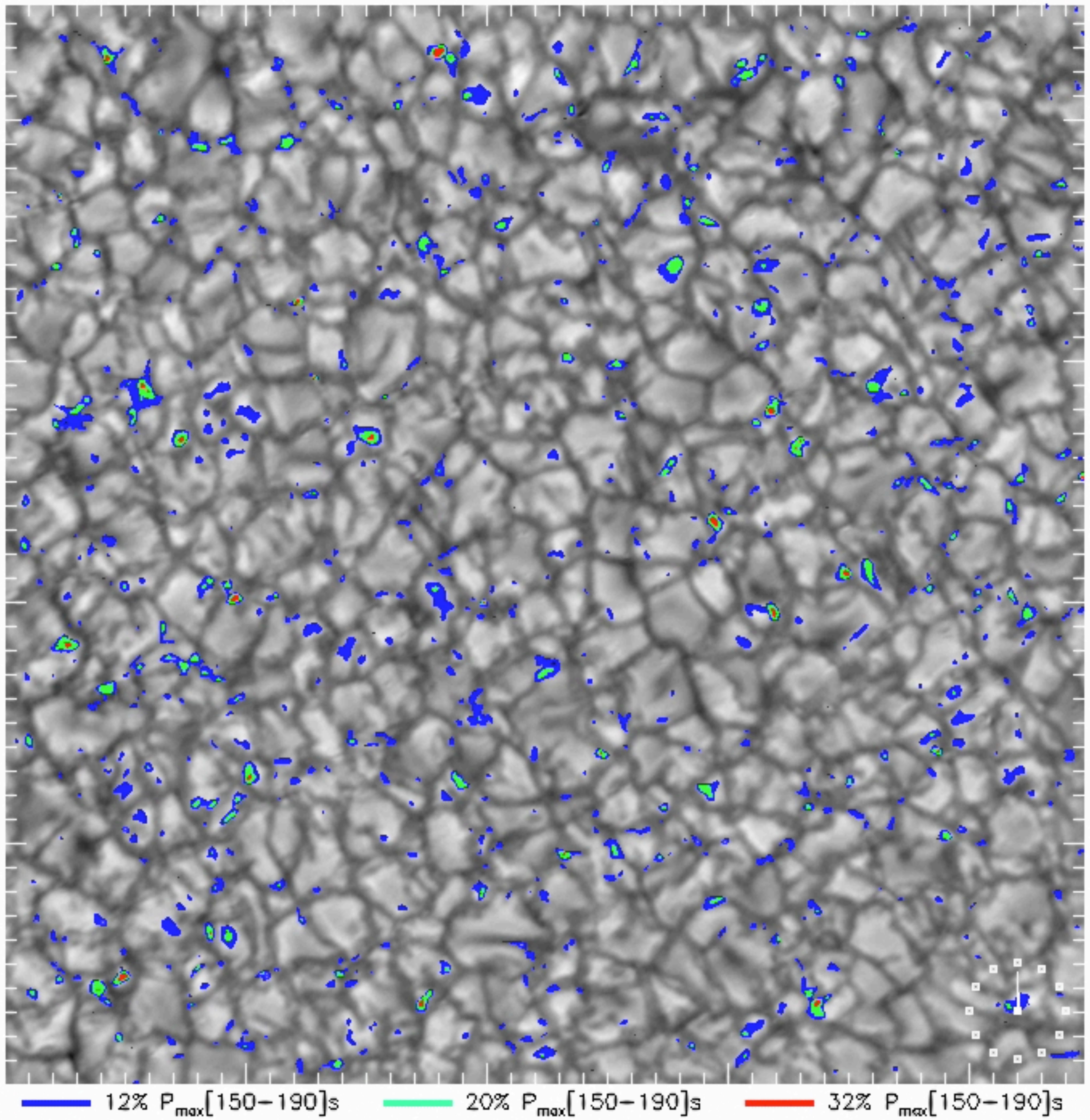

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Conclusion

The Sun displays a remarkable variety of structures across all spatial and temporal scales

Continuous advancements in observational and data analysis techniques are revealing features as small as 30 km on the solar disc, offering deeper insights into the Sun's dynamic atmosphere

With the capabilities of next-generation 4-meter solar telescopes such as DKIST and EST, the exploration of our star enters an exciting new chapter — and the quest continues.