Lecture 23

AST5770

Solar and stellar physics

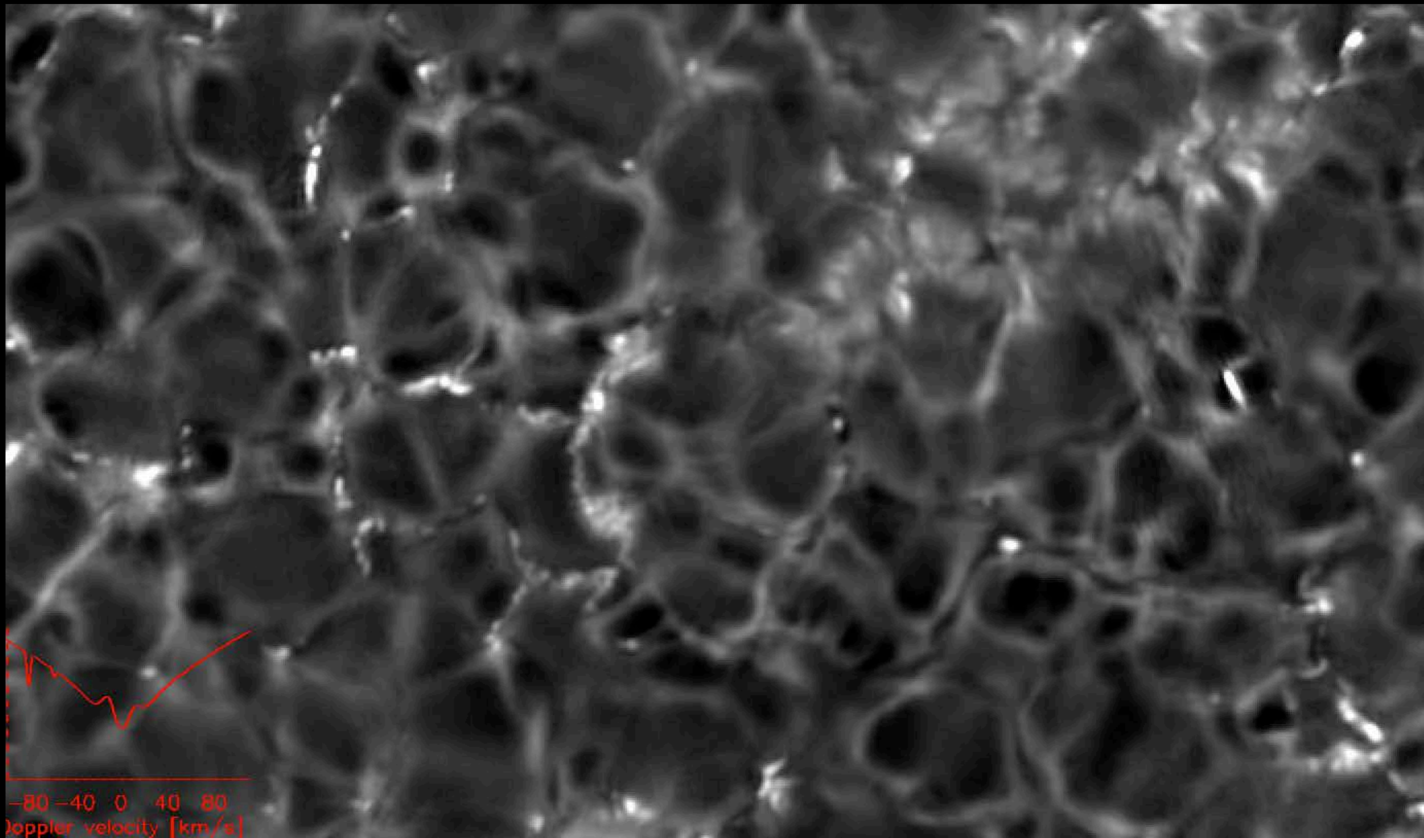
Sven Wedemeyer, University of Oslo, 2023

The solar atmosphere

The solar atmosphere

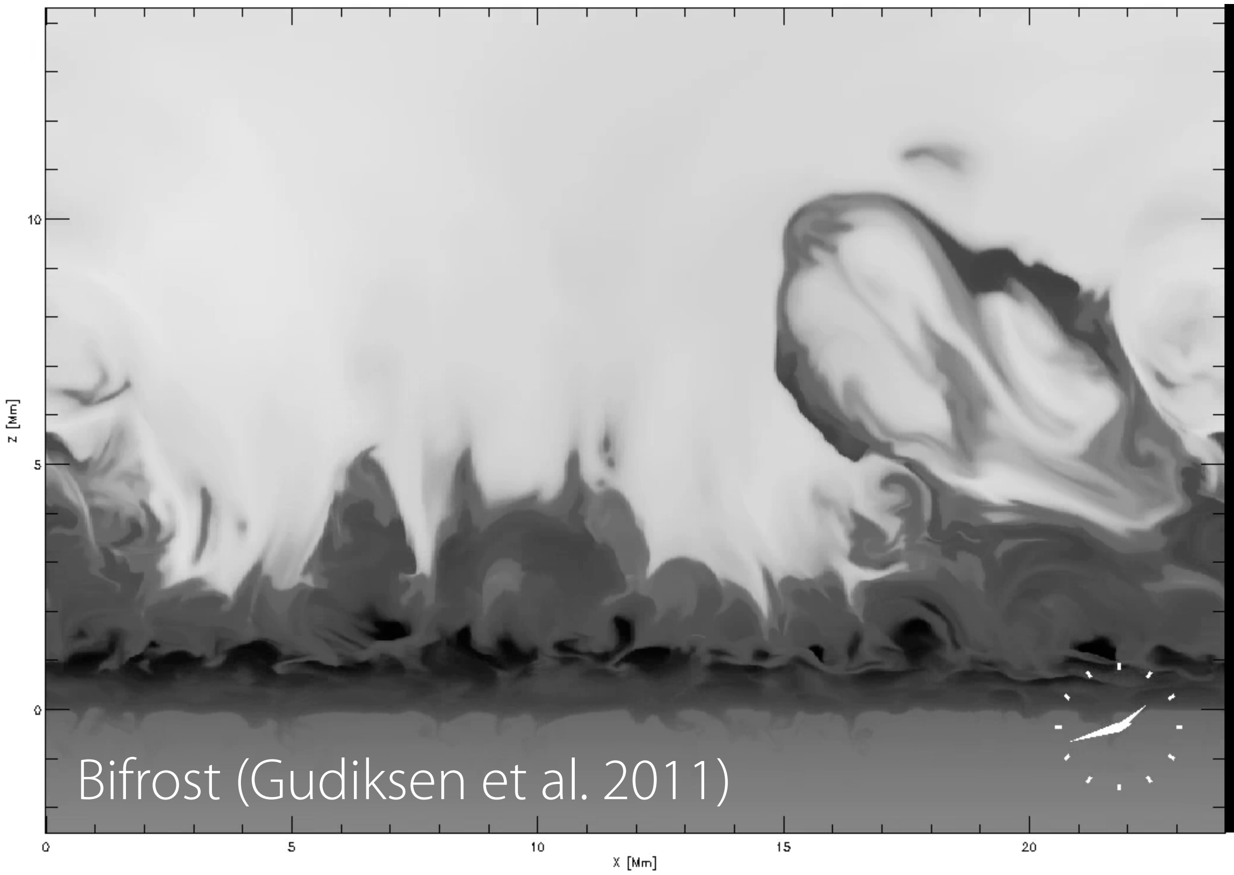
Recap

1. By how many orders of magnitude does the gas density drop throughout the chromosphere?
2. Why is the assumption of local thermodynamic equilibrium (LTE) not valid for many spectral features being formed in solar atmosphere?
3. Spectral lines of carbon monoxide are observed on the Sun. What does that imply?
4. The CO observations seemed to be contradicting observations with UV diagnostics. Why? And how can this apparent contradiction be settled and explained?
5. Free electrons are important in the context of opacity in the solar atmosphere. Which physical process(es) are essential with respect to the density of free electrons?
6. In which layer / height range is the hydrogen ionisation degree lowest?
7. How do chromospheric shock waves affect the hydrogen ionisation degree?
8. Which fundamental physical process makes magnetic tornadoes rotate?

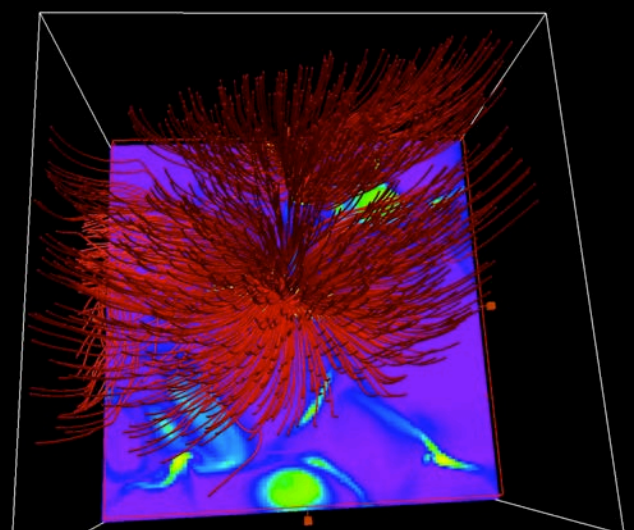


The solar atmosphere

Highly complex and dynamic structure



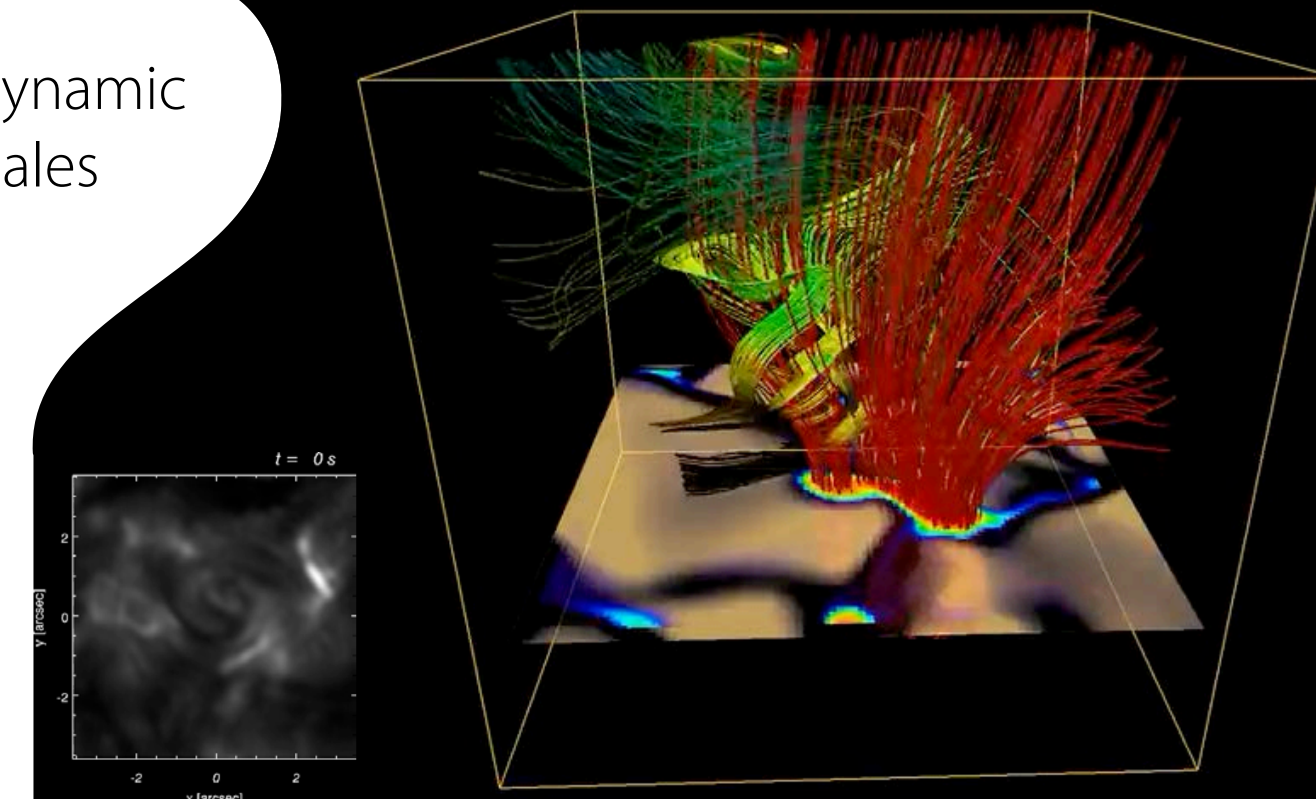
Bifrost (Gudiksen et al. 2011)



CO^{5}BOLD (close-up, Freytag et al 2012)

- Conservation of angular momentum creates photospheric **vortex flows**
- Rotation can be mediated into chromosphere via magnetic fields (magnetic tornadoes), then observed as chromospheric swirls

- Even "Quiet" Sun regions show very complex dynamic structure (large ranges of spatial + temporal scales
- "Layers" dynamically coupled!
- Magnetic field: On average weaker but complicated field structure (incl. rotation and/or swaying)
  - More complicated than individual "flux tubes" (= useful but theoretical concept)



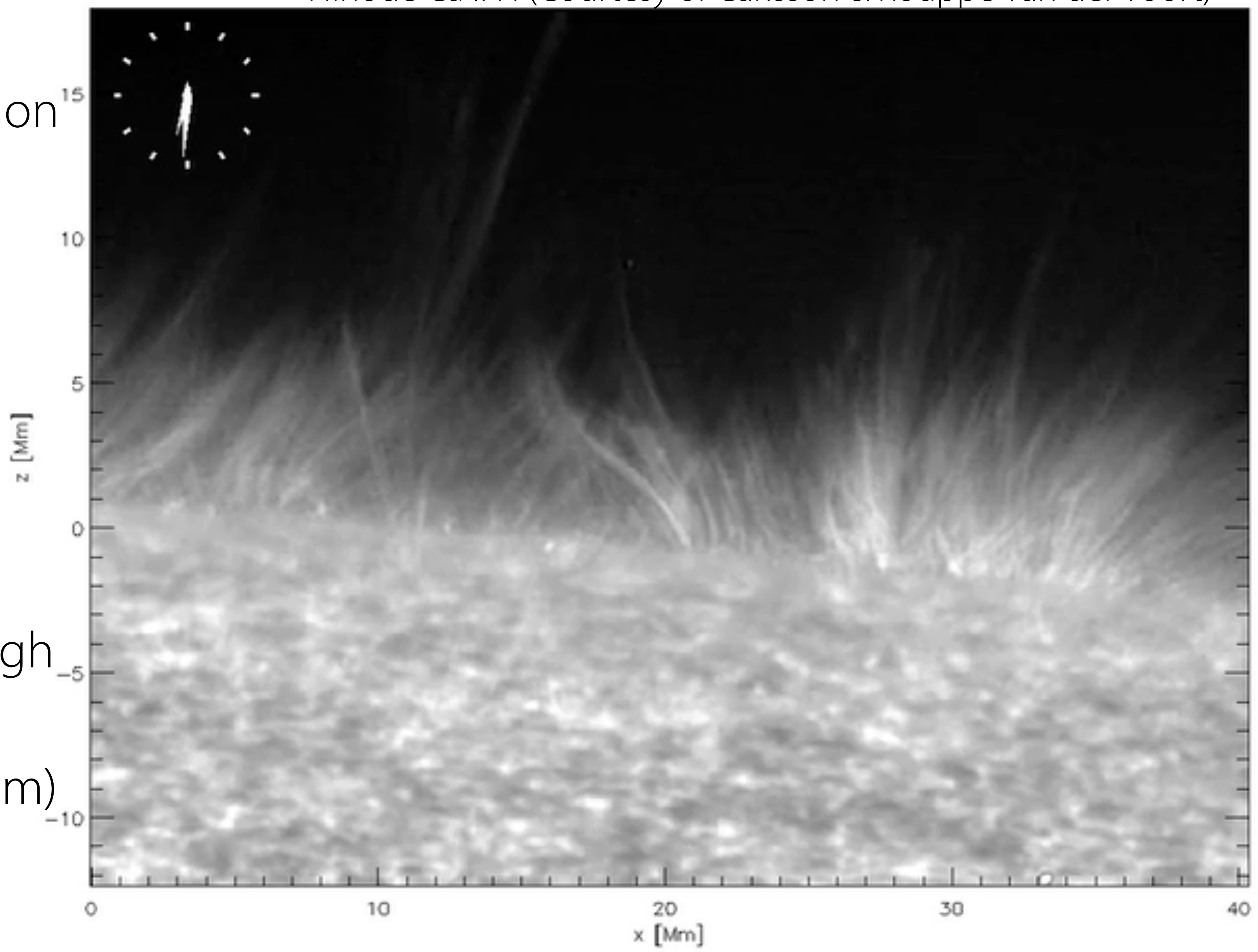
Wedemeyer et al (2012)

The solar atmosphere

Spicules

- Ubiquitous needle-like phenomenon on the Sun, visible at the limb (already seen by Secchi 1887)
- Now disk counterparts observed (also referred to as fibrils or mottles)
- At any time ~4 × 10^5 spicules
- Dynamic and short lived features (lifetimes typically 5–10 min)
- Jets with plasma shooting up at high speeds along magnetic field
- Reach heights of a few Mm (~10Mm)
- Triggered by p-modes at the footprints of the magnetic field structure
  - May serve as magnetic tunnels through which the coronal plasma is "refuelled" (Athay 2000).

Hinode Ca II H (Courtesy of Carlsson & Rouppe van der Voort)



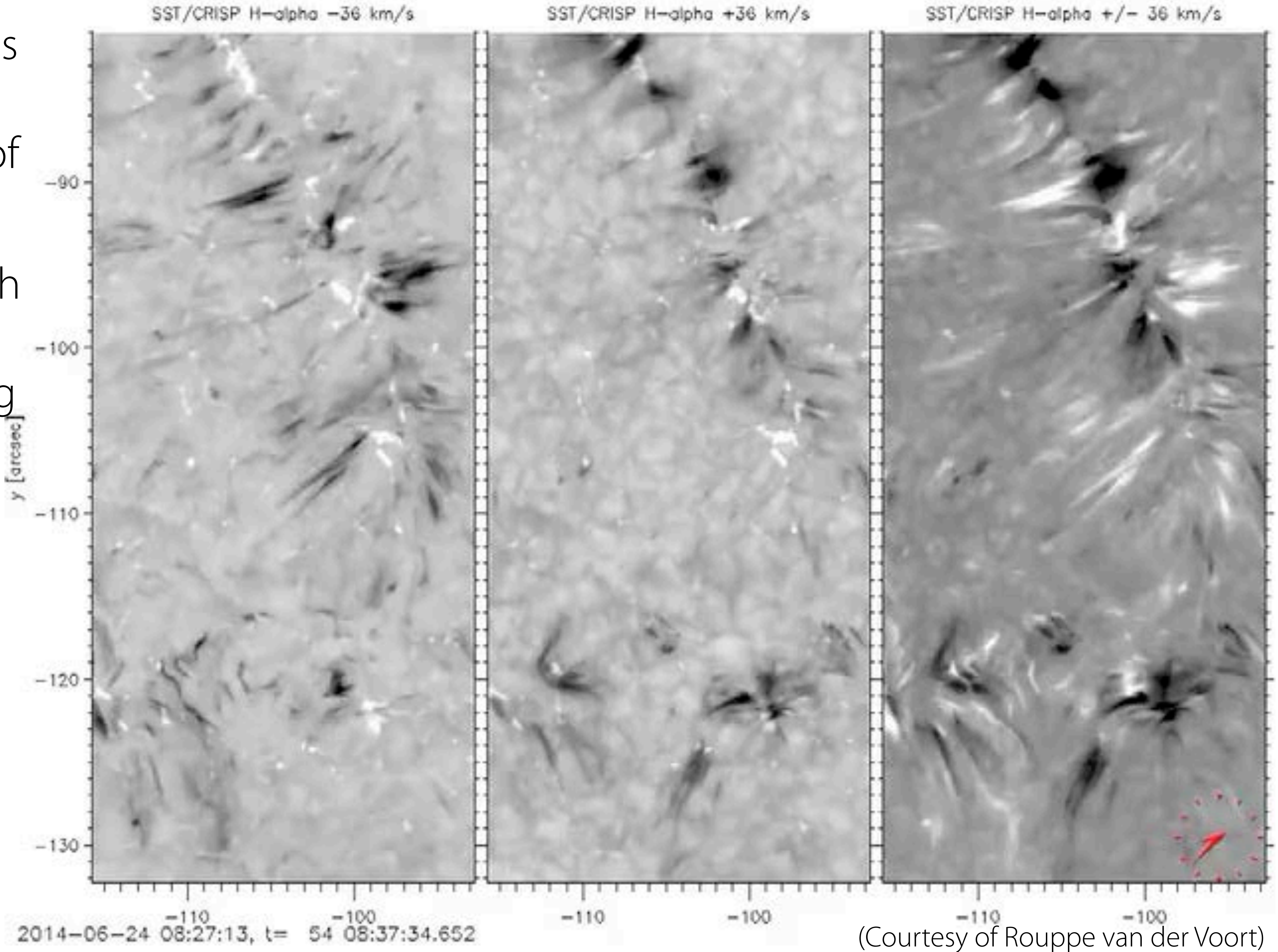
The solar atmosphere

Spicules

- Type II spicules (De Pontieu et al. 2007a) with shorter lifetimes (10–150 s), smaller diameters (< 200 km compared to < 500 km for type I spicules), and shorter rise times.

On disk

- Act as tracers/waveguides for Alfvén waves with amplitudes of the order of 10-25 km s^{-1}
- Carry, in principle, enough energy to play an important role for heating of the quiet Sun corona and for acceleration of the solar wind

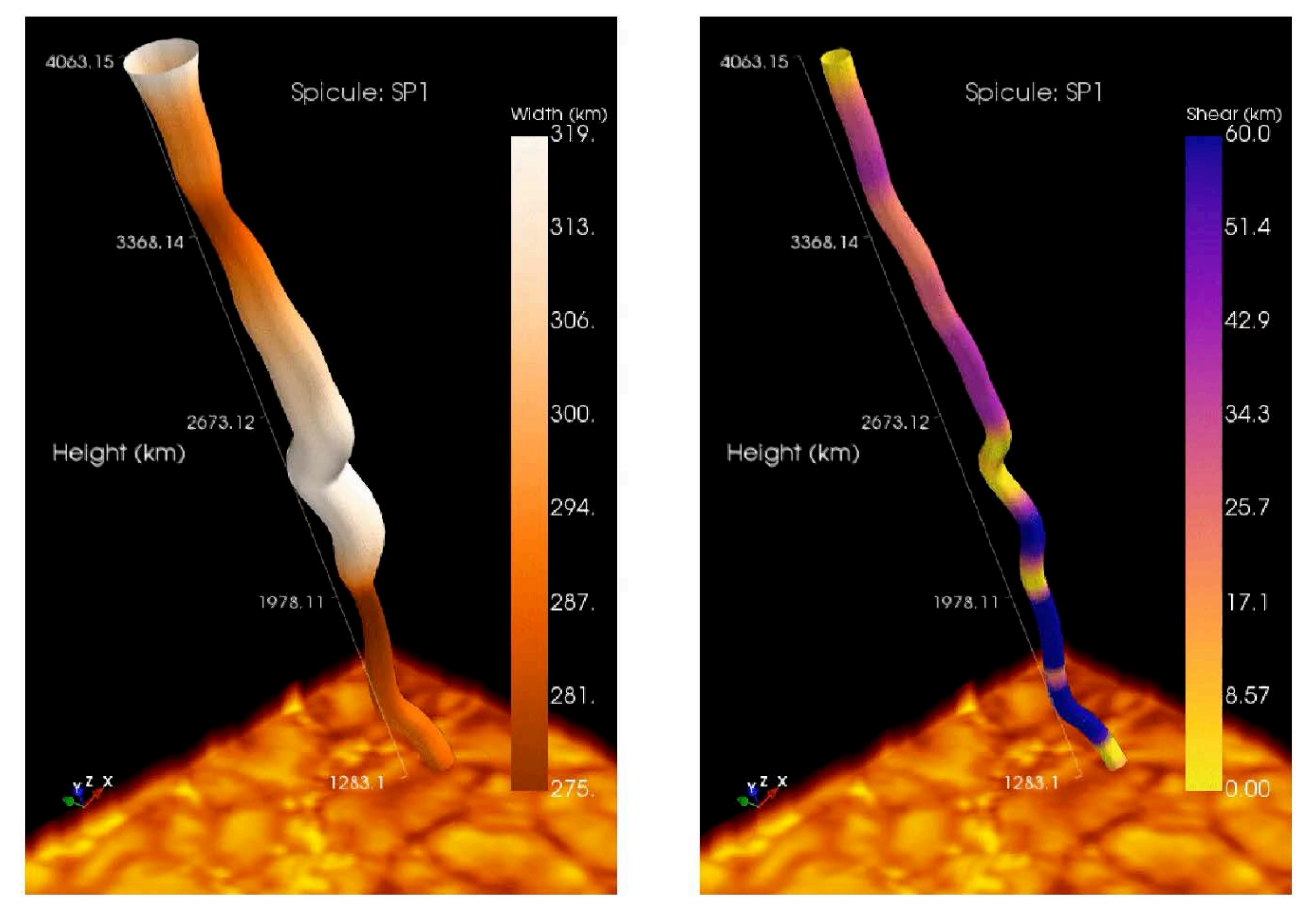


(Courtesy of Rouppe van der Voort)

The solar atmosphere

Spicules

- Combination of different MHD wave mode observed (incl. torsion)
- Oscillations coupled transverse and width with intensity
- transverse and azimuthal shear components



Sharma et al. 2018

Waves and oscillations in the solar atmosphere

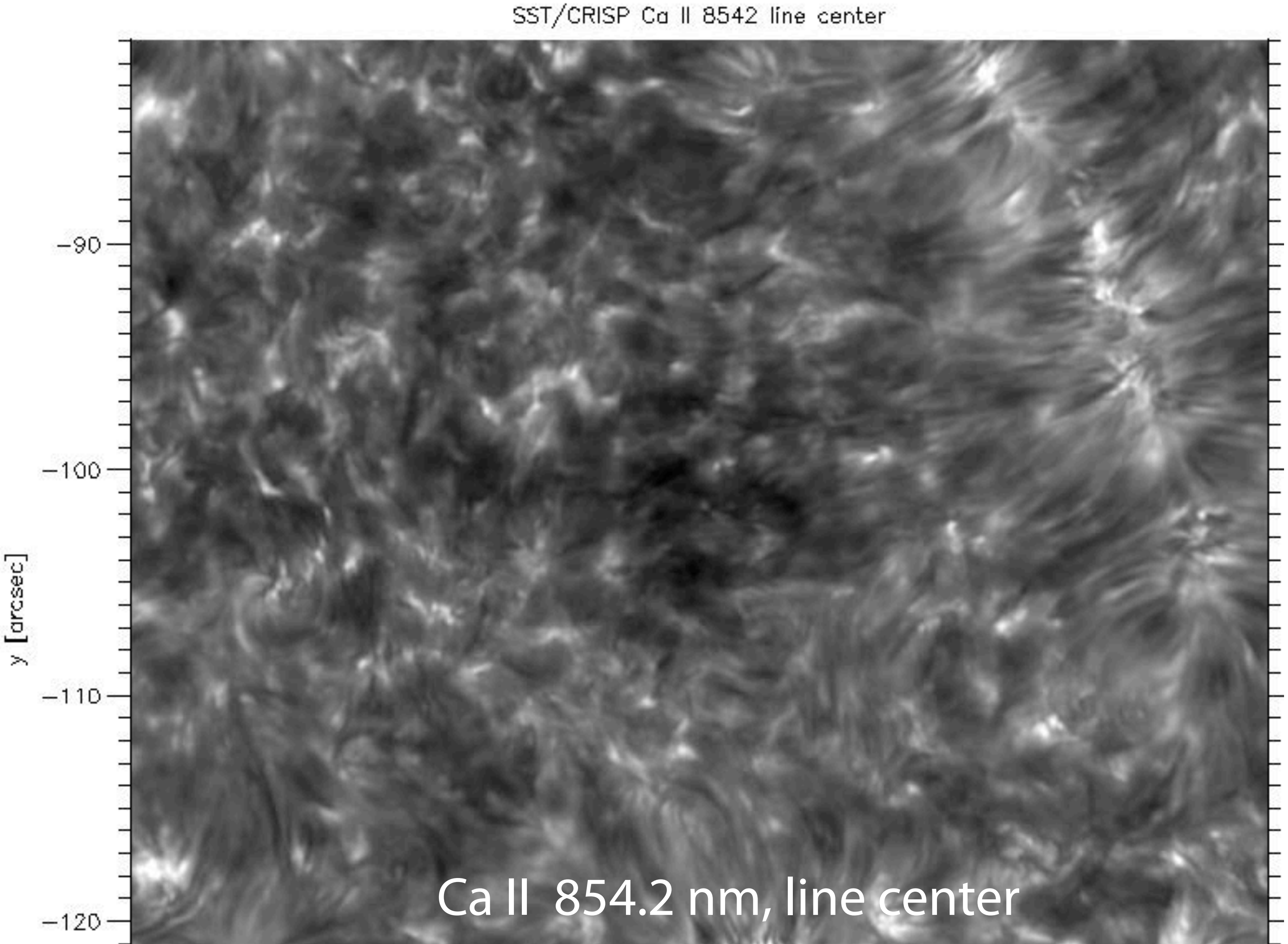
Waves in the solar atmosphere

Acoustic waves and shocks

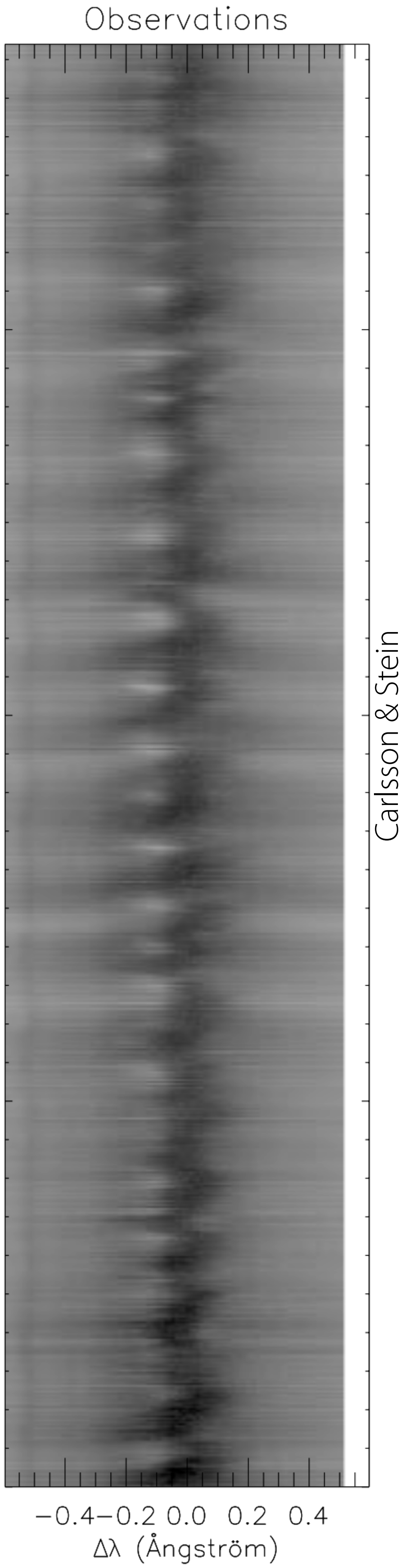
- Observations in spectral lines with cores formed in the chromosphere show periodic changes

  ➡ Bright grains with Dopplers shifts of several km/s

Ca II H



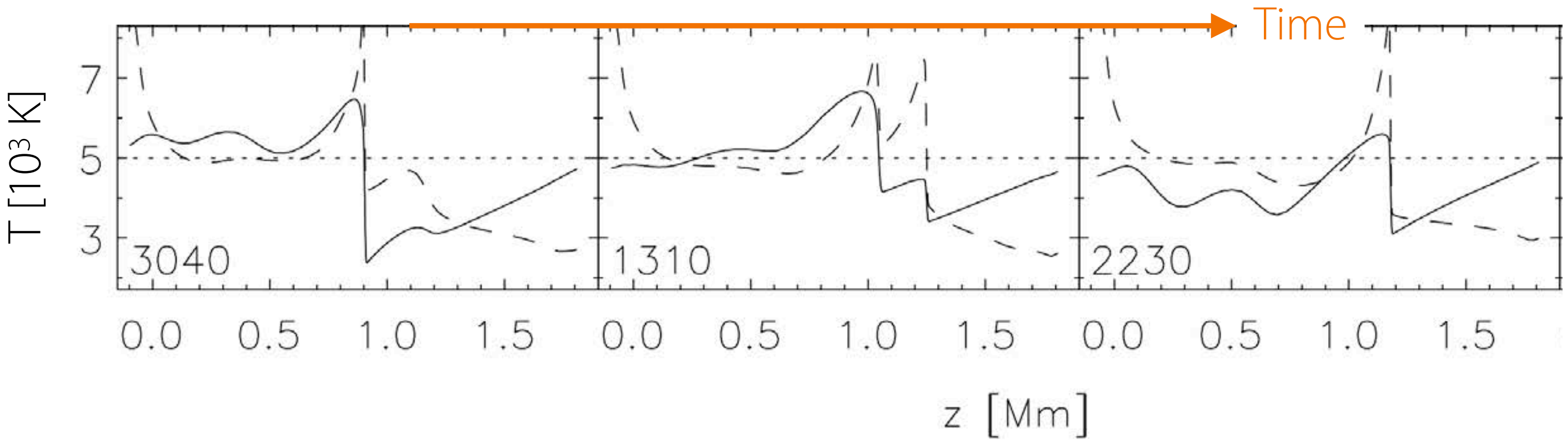
Ca II 854.2 nm, line center

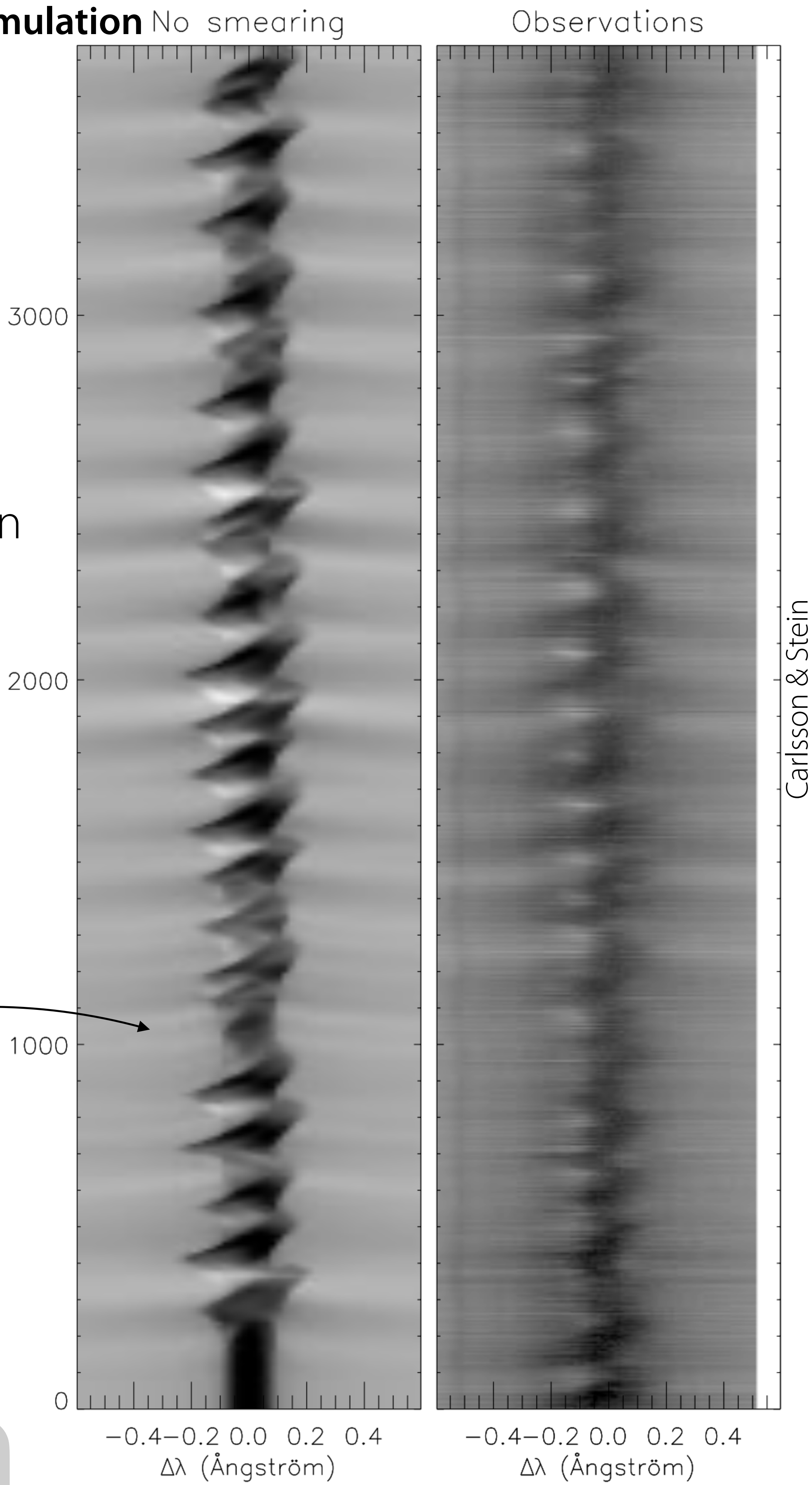


Waves in the solar atmosphere

Acoustic waves and shocks

- Observations in spectral lines with cores formed in the chromosphere show periodic changes
  ➡ Bright grains with Dopplers shifts of several km/s
  ➡ Caused by upwards propagating waves that steepen into shock waves in the chromosphere!
- Successfully explained by 1D simulations (Carlsson & Stein 1992-1997, RADYN code)
  - Time-dependent hydrodynamics, driven by empirical piston at the bottom, detailed treatment of physics (e.g., non-LTE, ionisation)
  - Radiative transfer calculations, produces observables that can be tested





- Before that: static theoretical models (Ulmschneider 1971, etc)

Waves in the solar atmosphere

Acoustic waves and shocks

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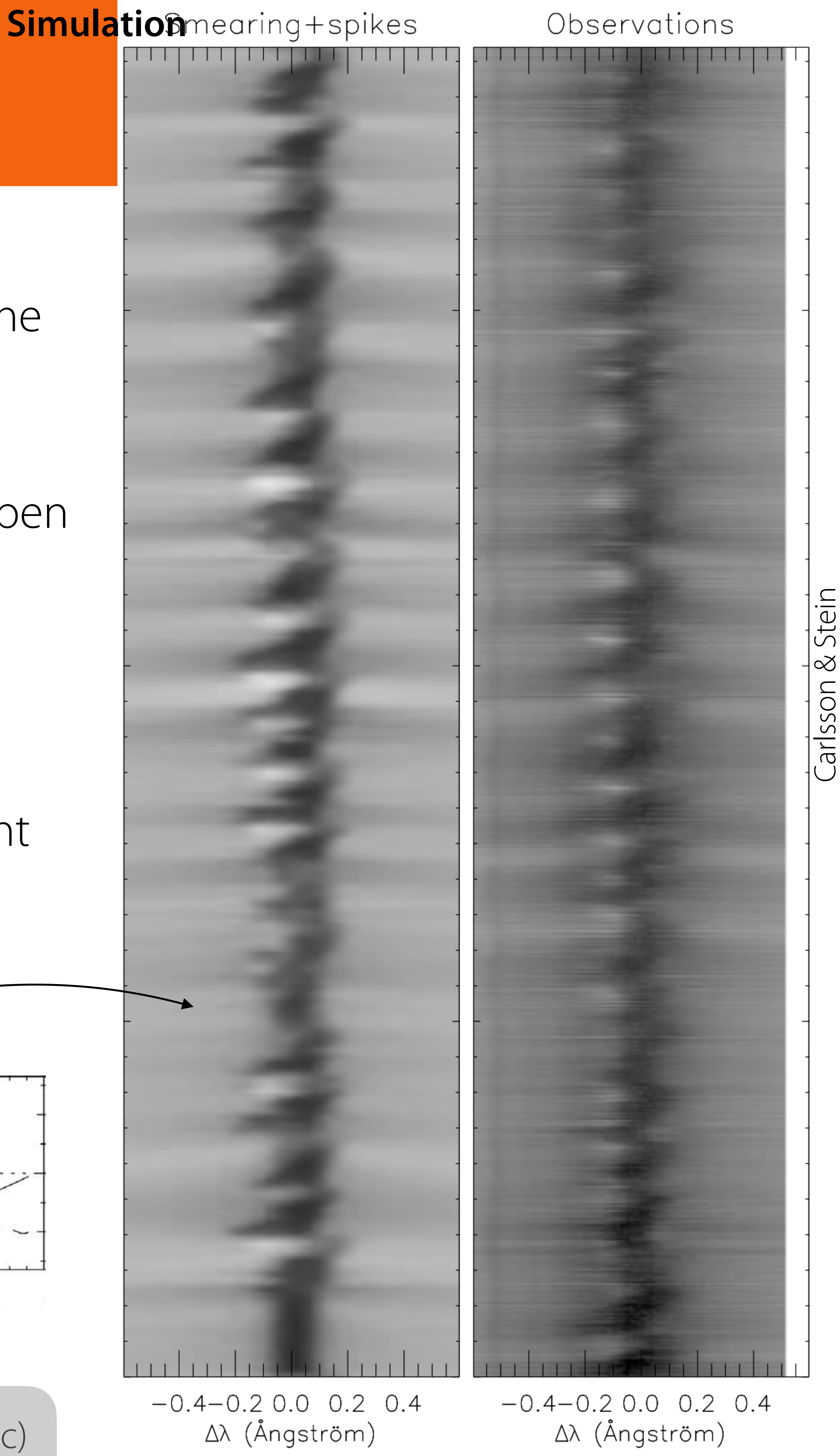

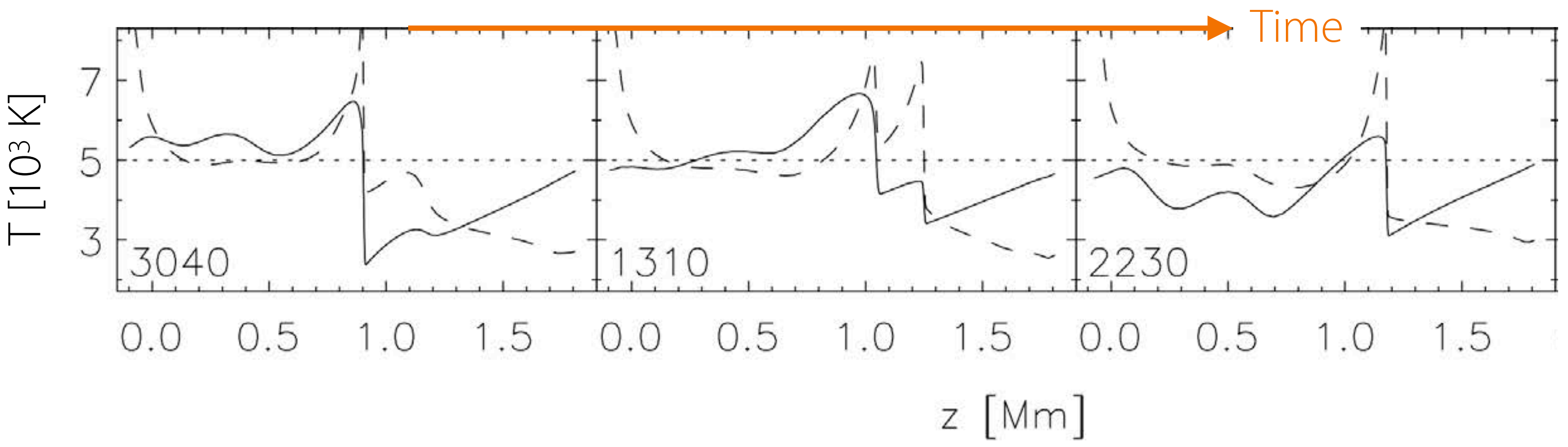

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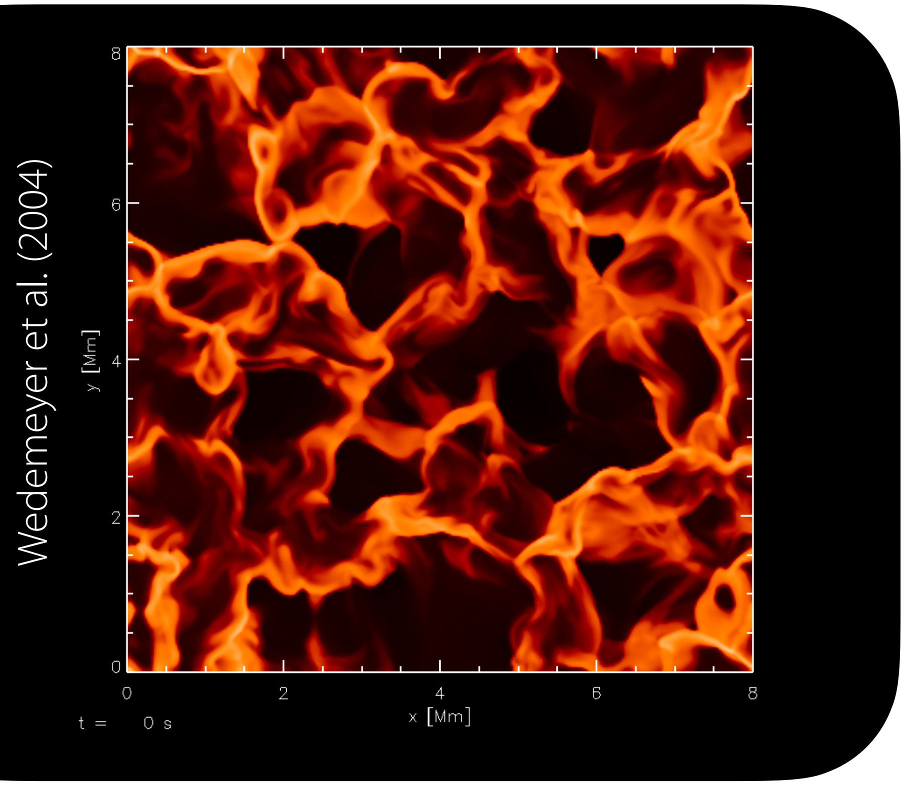
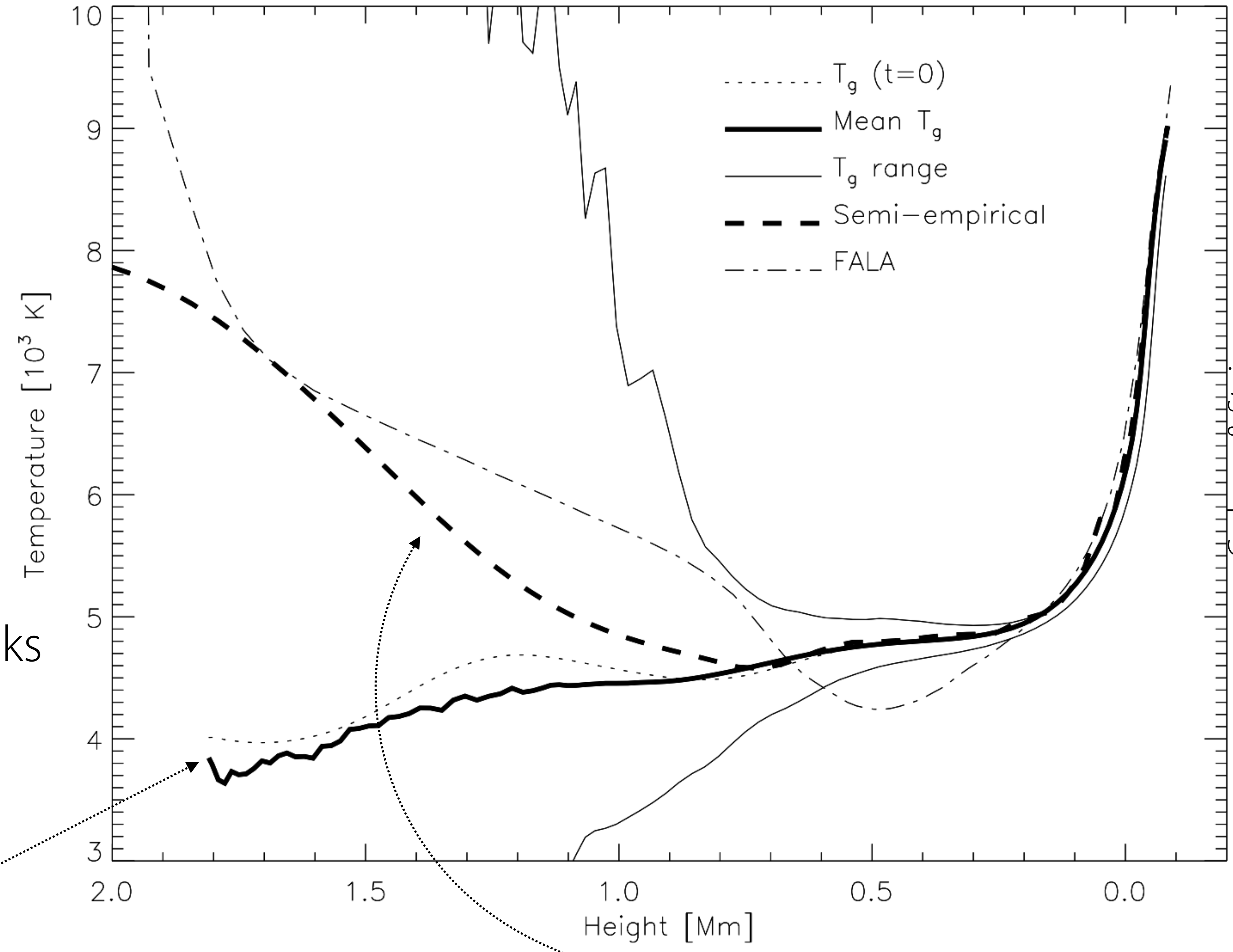
Waves in the solar atmosphere

Acoustic waves and shocks



Wedemeyer et al. (2004)



Carlsson & Stein

- Shock waves: high temperature peaks
- Post-shock regions (wake): low temperatures but fill more space than the shock fronts

➡ Arithmetic average shows no chromospheric temperature increase

➡ Reconstructing temperature stratification from UV emission averaged over these components (as for semi-empirical models) does show an increase!

- Reason: Non-linear dependence of UV intensity on temperature!!

Waves in the solar atmosphere

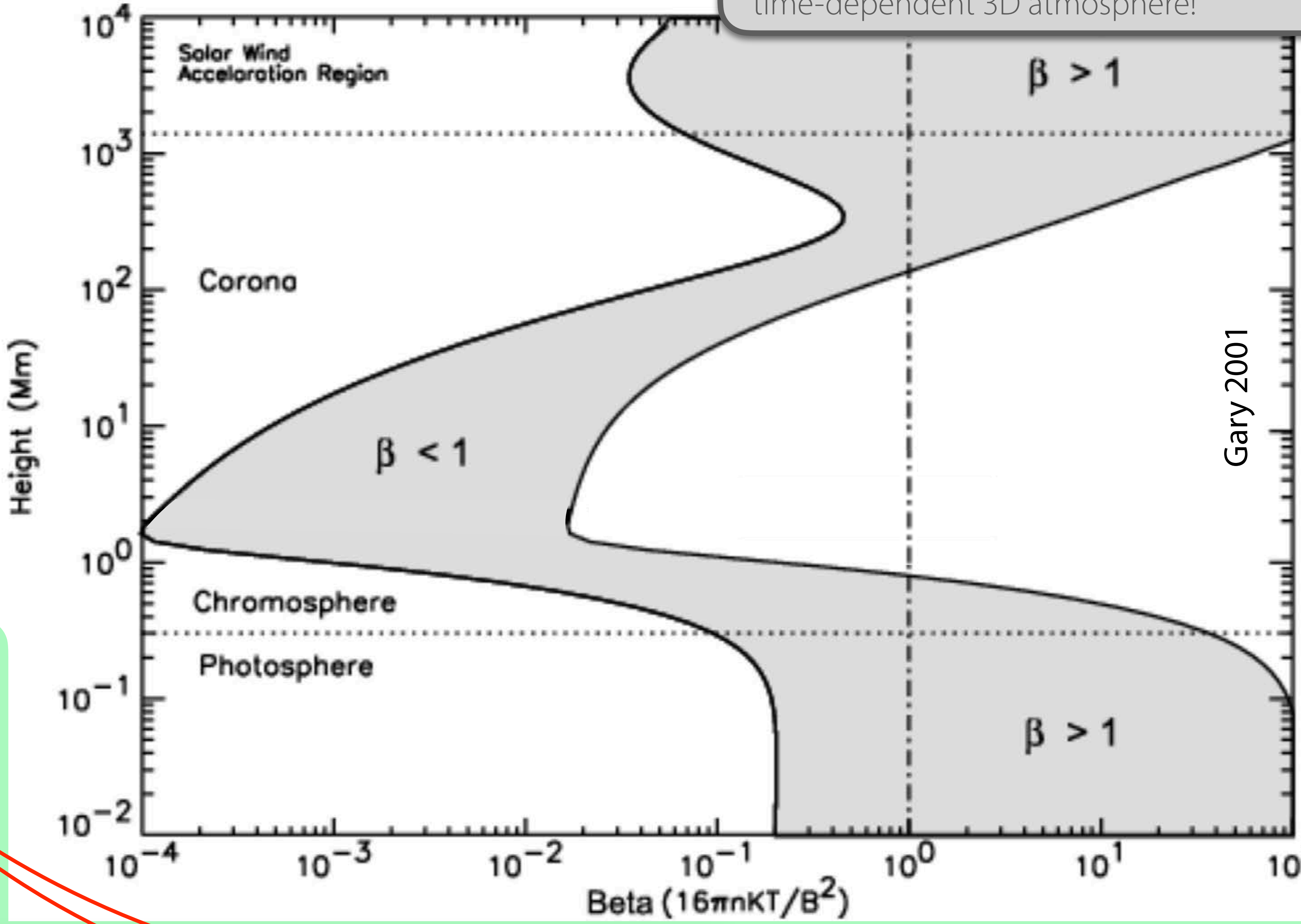
Waves in a magnetic environment

Careful: Based on average stratification; more variations to be expected for a time-dependent 3D atmosphere!

- **Plasma-β!**
- **Chromospheric plasma typically β<1**

➡ MHD wave modes to be considered

➡ Magnetic flux structures can serve as wave guides



Gary 2001

- Remember: Magnetic tension as restoring force

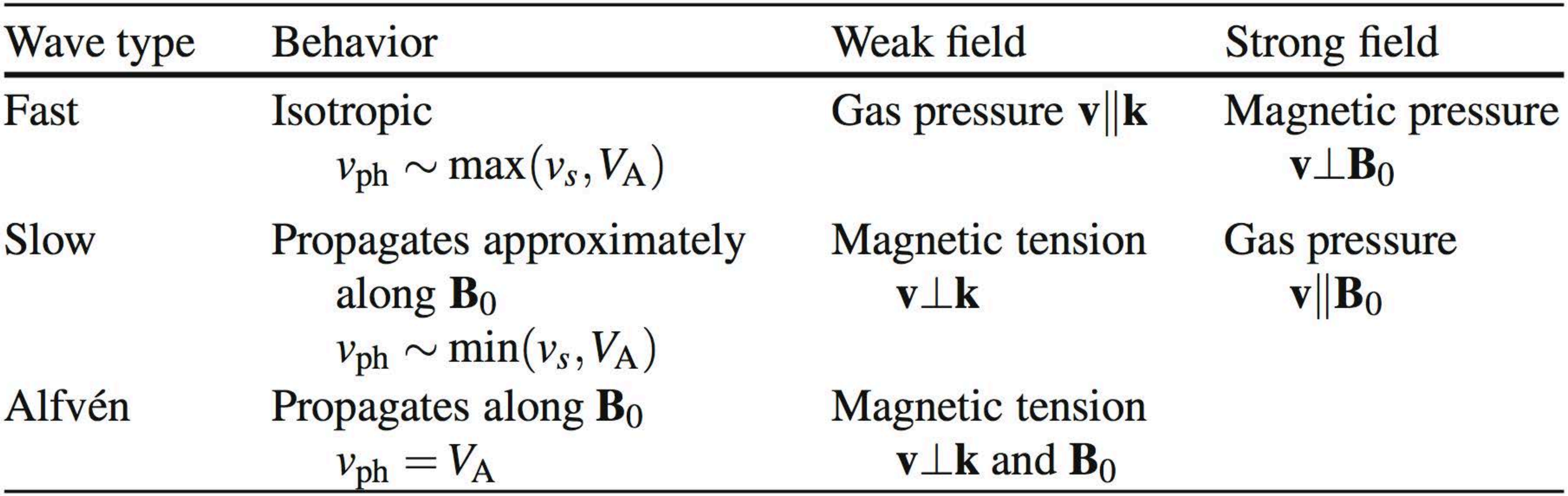
➡ Waves

Lorentz Force

$$\mathbf{J}\times\mathbf{B} = (\nabla\times\mathbf{B})\times\mathbf{B}/\mu = \boxed{(\mathbf{B}.\nabla)\frac{\mathbf{B}}{\mu}} - \nabla\left(\frac{B^2}{2\,\mu}\right)$$

Waves in the solar atmosphere

- Remember: Dispersion relations, evanescence, cutoff frequencies etc.
- Here now expanded to magnetohydrodynamic waves
- **Different wave modes**, incl.
  - **Acoustic** waves: Gas pressure fluctuations. Restoring force: pressure gradient.
  - **Fast** and **slow magnetoacoustic** waves: Acoustic character, modified by the magnetic field, coupling between magnetic field and pressure fluctuations.
  - **Alfvén** waves: Waves propagating along magnetic field, magnetic tension as restoring force; Only in the presence of a magnetic field, absent otherwise.



Wave type	Behavior	Weak field	Strong field
Fast	Isotropic $v_{\mathrm{ph}} \sim \max(v_s, V_{\mathrm{A}})$	Gas pressure $\mathbf{v} \| \mathbf{k}$	Magnetic pressure $\mathbf{v} \perp \mathbf{B}_0$
Slow	Propagates approximately along $\mathbf{B}_0$ $v_{\mathrm{ph}} \sim \min(v_s, V_{\mathrm{A}})$	Magnetic tension $\mathbf{v} \perp \mathbf{k}$	Gas pressure $\mathbf{v} \| \mathbf{B}_0$
Alfvén	Propagates along $\mathbf{B}_0$ $v_{\mathrm{ph}} = V_{\mathrm{A}}$	Magnetic tension $\mathbf{v} \perp \mathbf{k}$ and $\mathbf{B}_0$	

Narayanan, A. S., 2013

Waves in the solar atmosphere

- **Different wave modes** (incl. acoustic waves, magneto acoustic waves, Alfvén waves, …)
- Fast and slow magnetoacoustic mode due to two possible solutions in the dispersion relation
- Phase speed of Alfvén waves in between phase speed of slow and fast modes.
  ➡ Also referred to as "intermediate mode"

Sound speed $$C_S = \sqrt{\frac{\gamma\, p_0}{\rho_0}}$$

Kink speed $$C_K = C_A \sqrt{\frac{\rho_0}{\rho_0 + \rho_e}} = \frac{B_0}{\sqrt{4\pi\,(\rho_0 + \rho_e)}}$$

Alfvén speed $$C_A = \frac{B_0}{\sqrt{\mu\, \rho_0}} \simeq \frac{B_0}{\sqrt{4\pi\, \rho_0}}$$

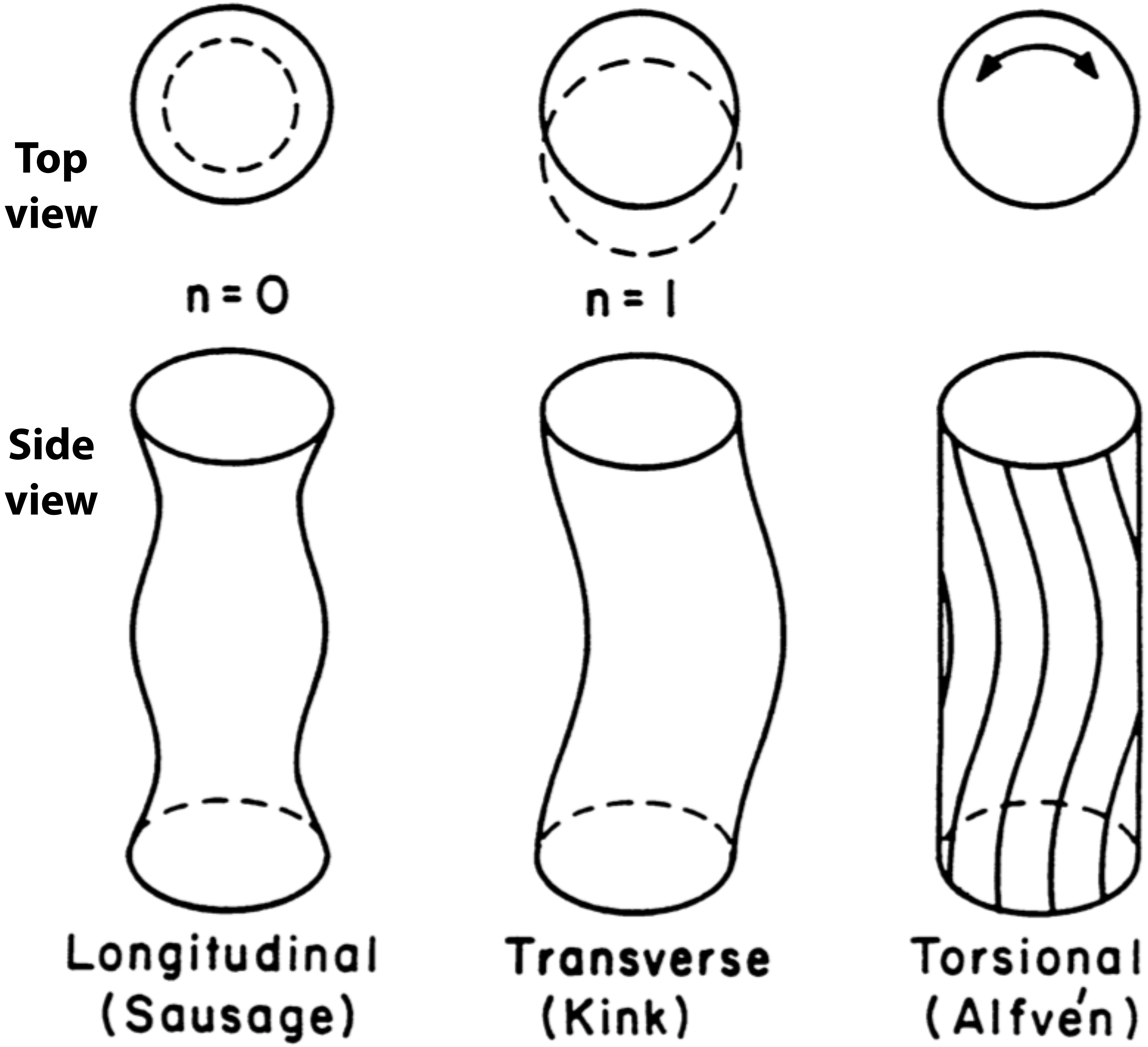
Tube speed $$C_T = \frac{C_S\, C_A}{\sqrt{C_S^2 + C_A^2}}$$

Fast wave's speed $$V_{Fast} = \sqrt{C_S^2 + C_A^2}$$

Waves in the solar atmosphere

MHD waves

- Magnetic flux "tubes" act as wave guide but also offer other possibilities for oscillation and waves, e.g. by periodic deformation, displacement, and/or twisting of the flux tube



Periodic squeezing and rarefying of the flux tube

Periodic displacement of central tube axis (Bulk motion)

Periodic twisting of tube (Torsional oscillations)

Solanki, S. K., 1993, Space Science Reviews 63: 1-188

Waves in the solar atmosphere

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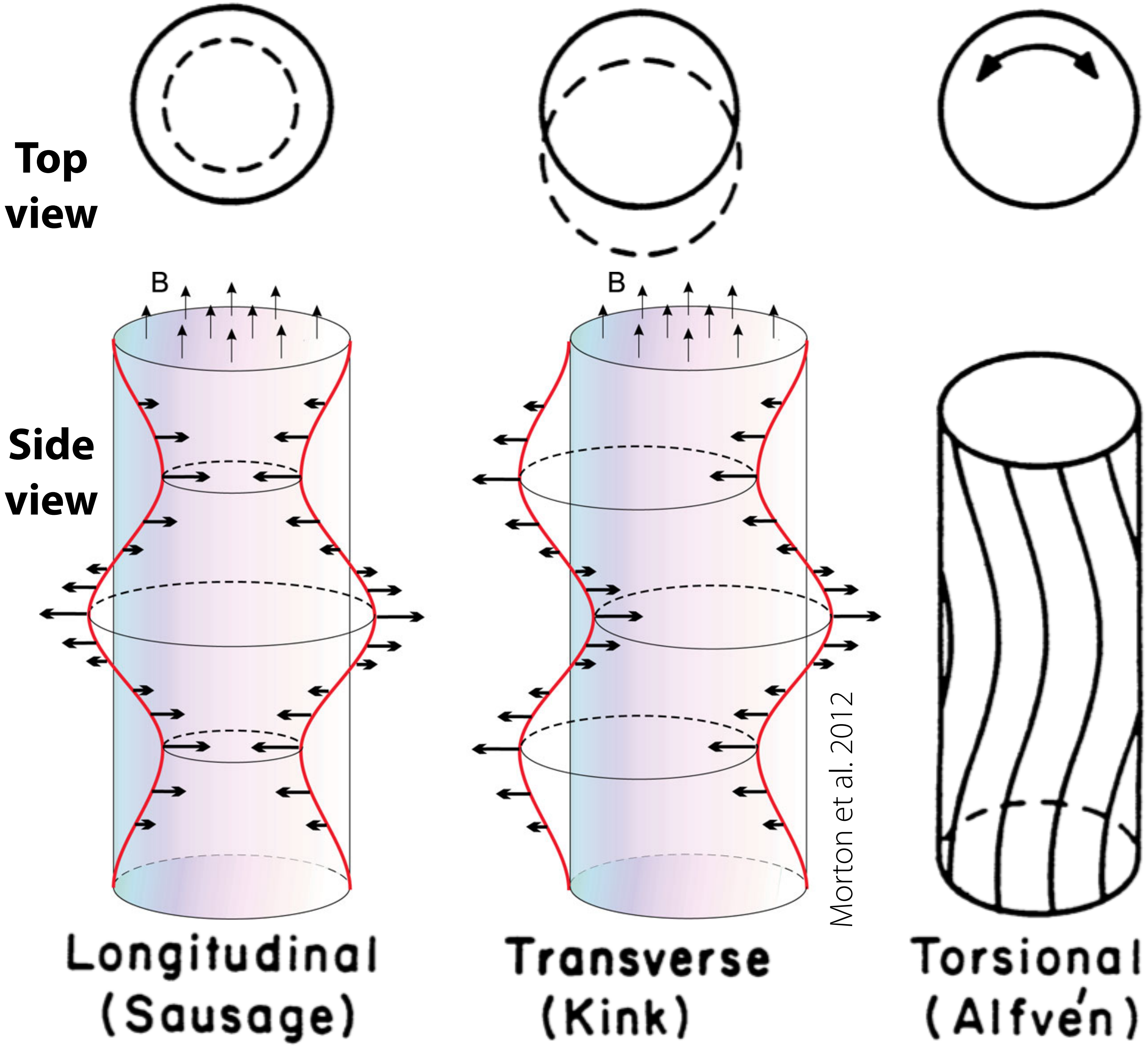

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Morton et al. 2012

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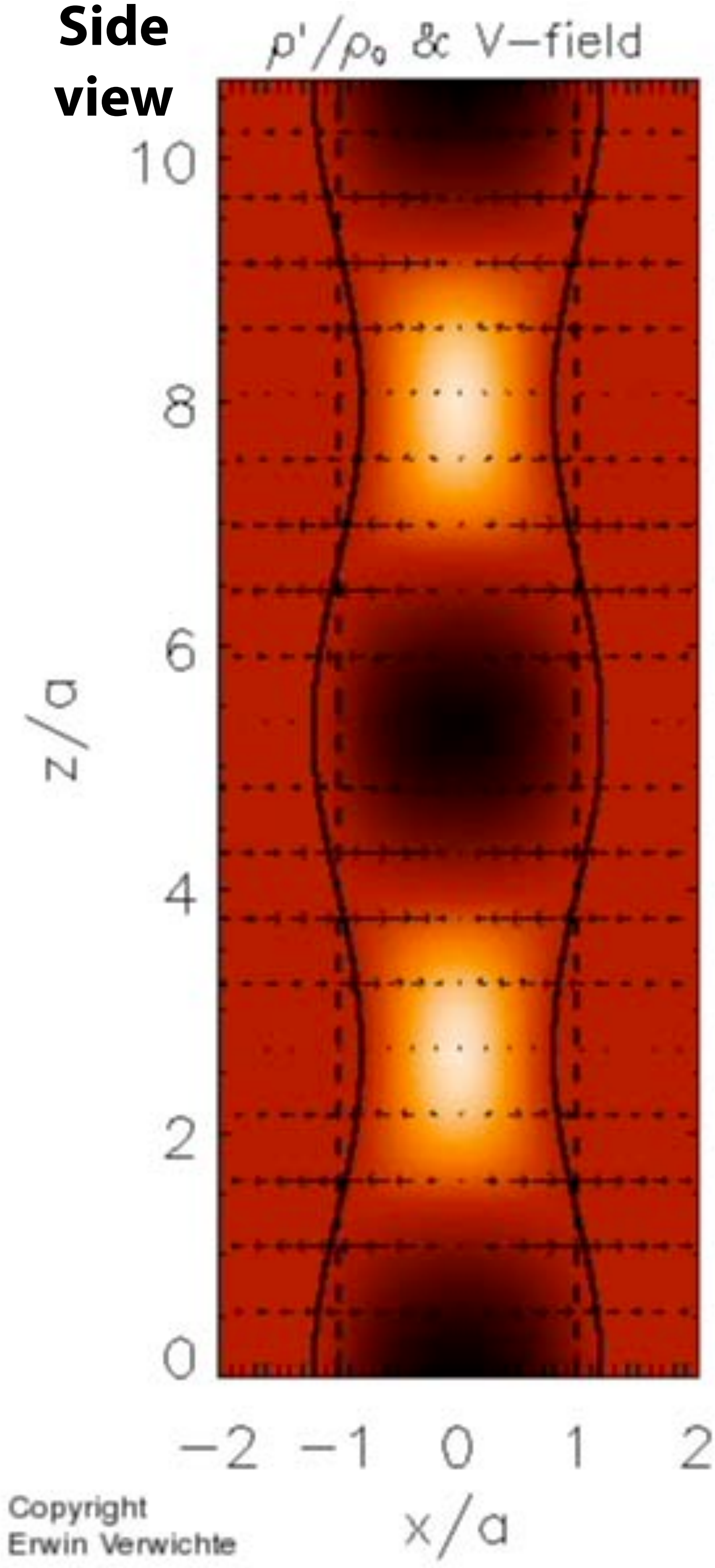
Waves in the solar atmosphere

MHD waves — Sausage mode

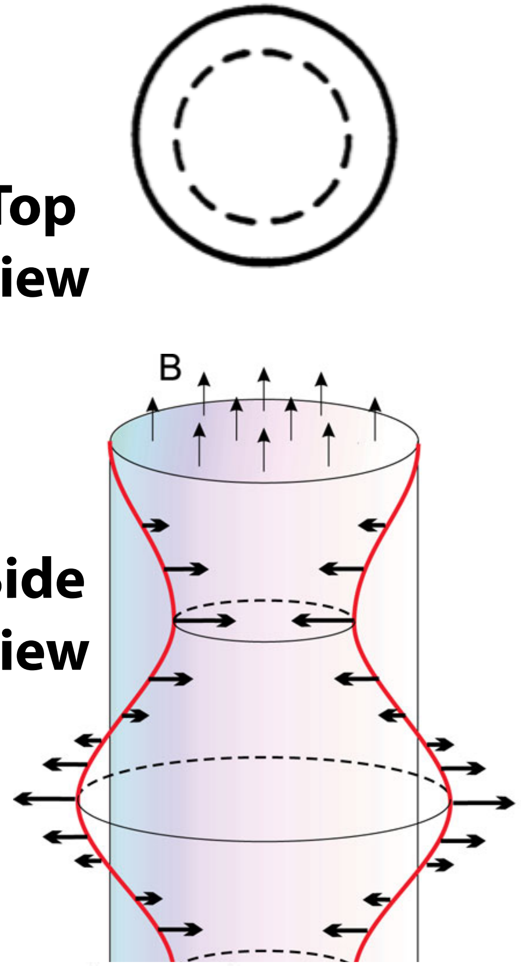
Side view

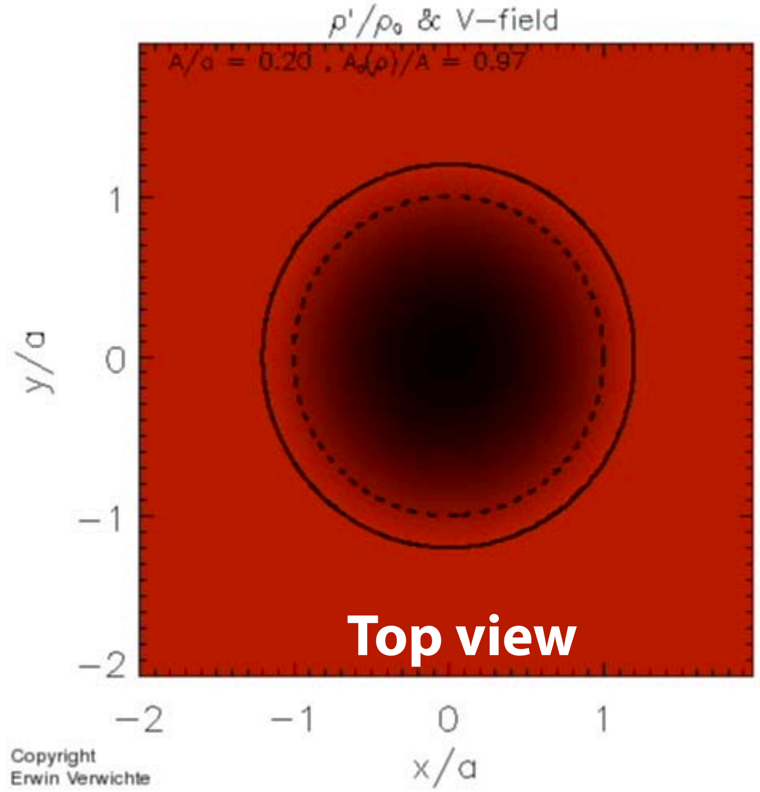


Nakariakov, V. M., Verwichte, E., 2005, Living Rev. Solar Phys., 2

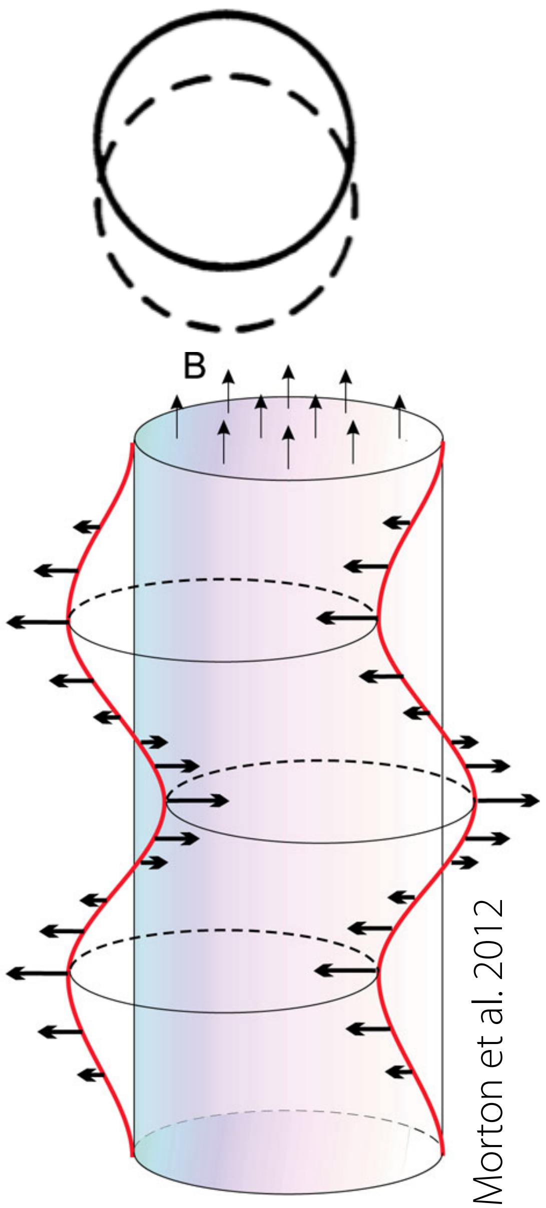
Top view

Side view





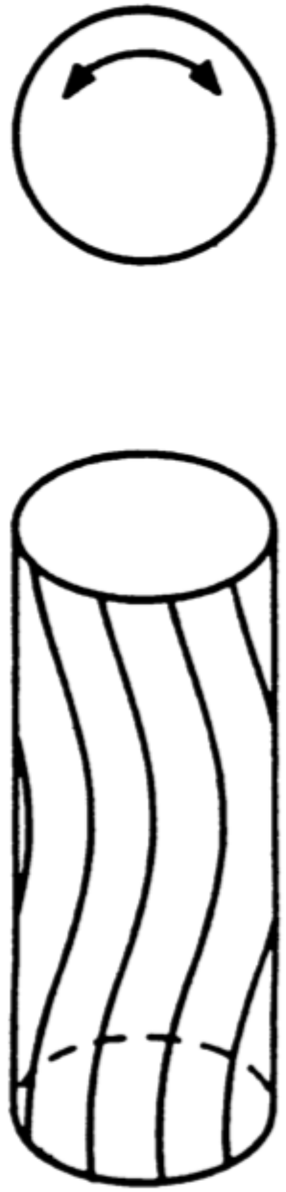
Top view



Transverse (Kink)

Periodic displacement of central tube axis (Bulk motion)

Morton et al. 2012



Torsional (Alfvén)

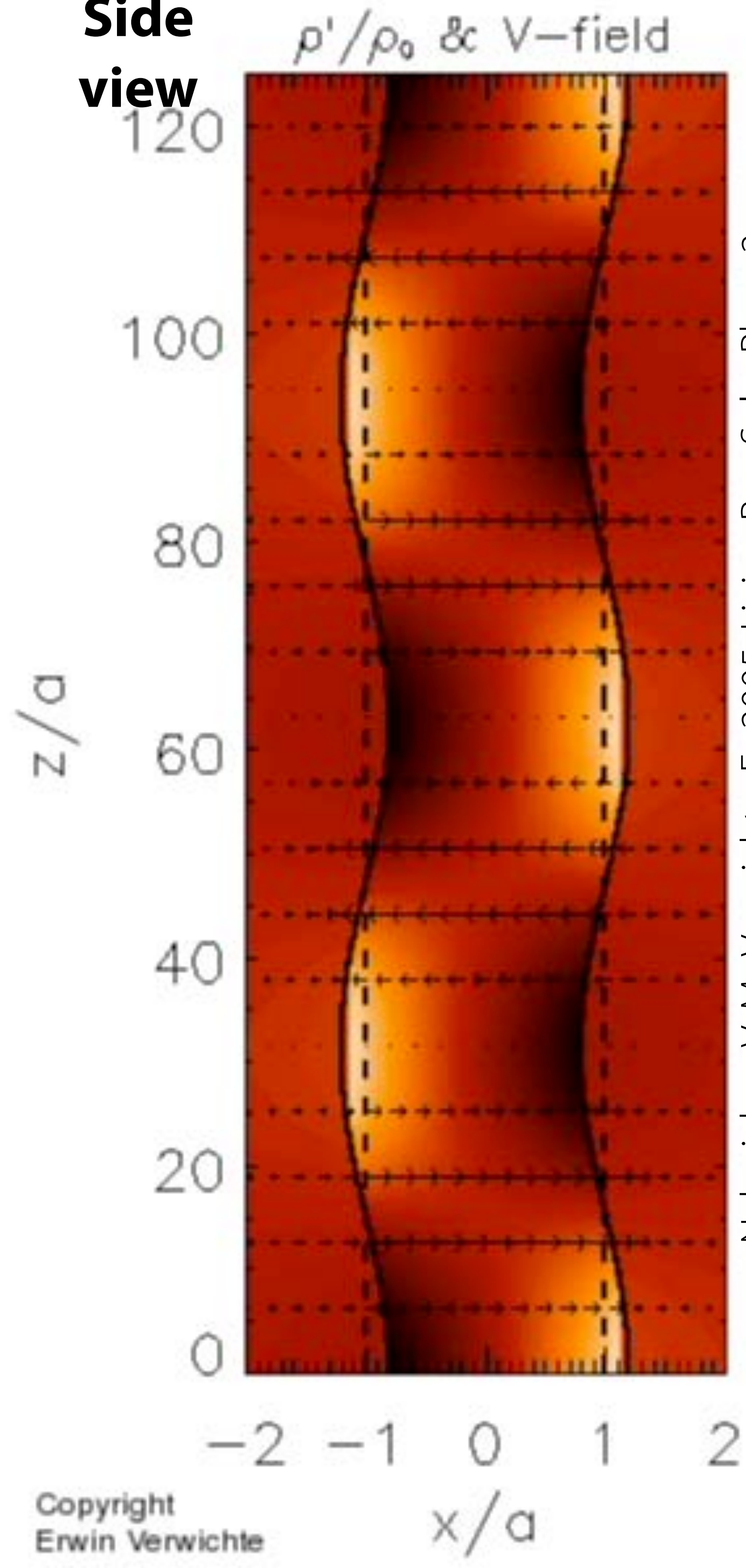
Periodic twisting of tube (Torsional oscillations)

Solanki, S. K., 1993, Space Science Reviews 63: 1-188

Waves in the solar atmosphere

MHD waves — Kink mode

Side view



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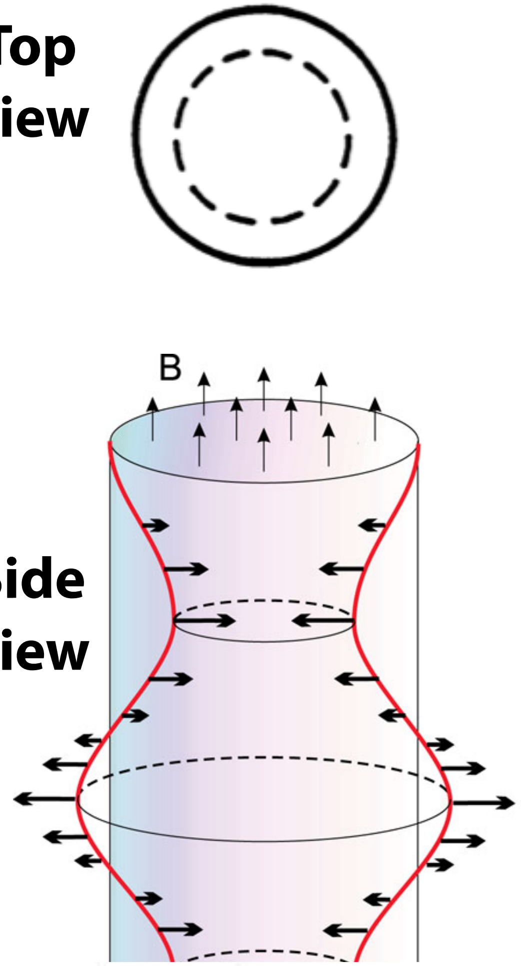
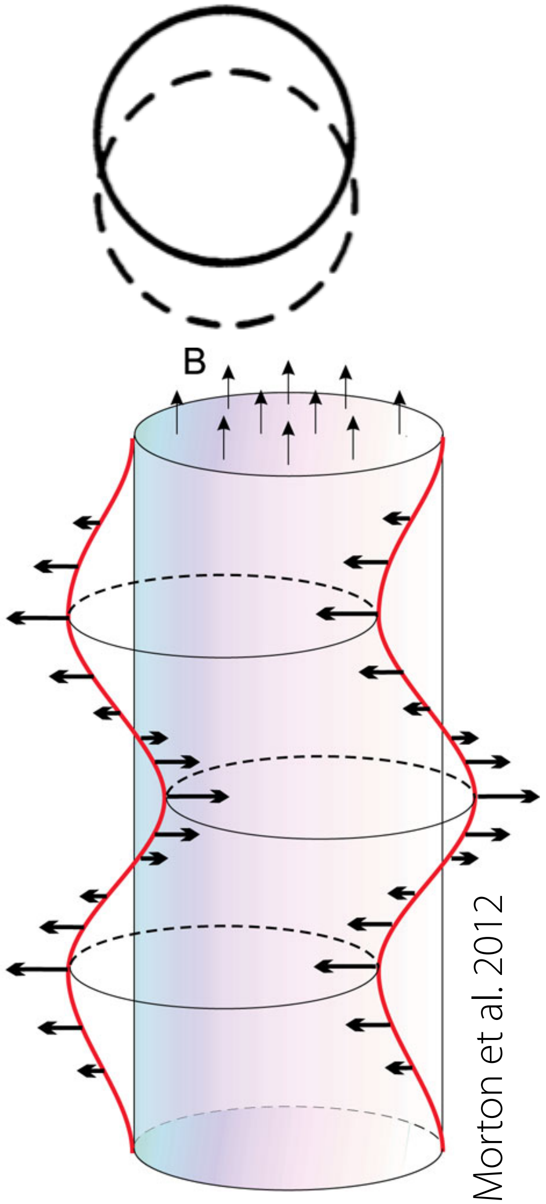
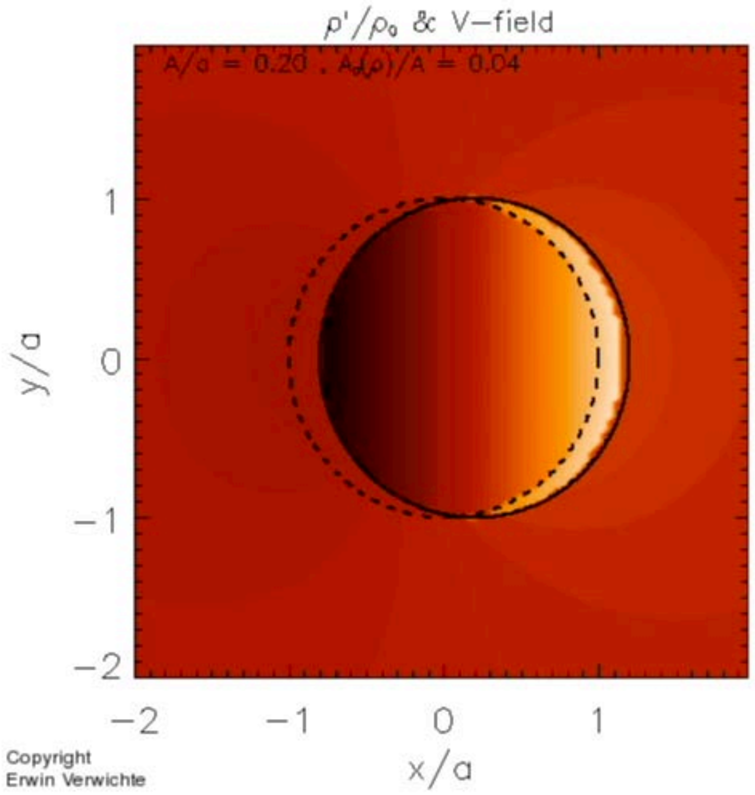
Top view

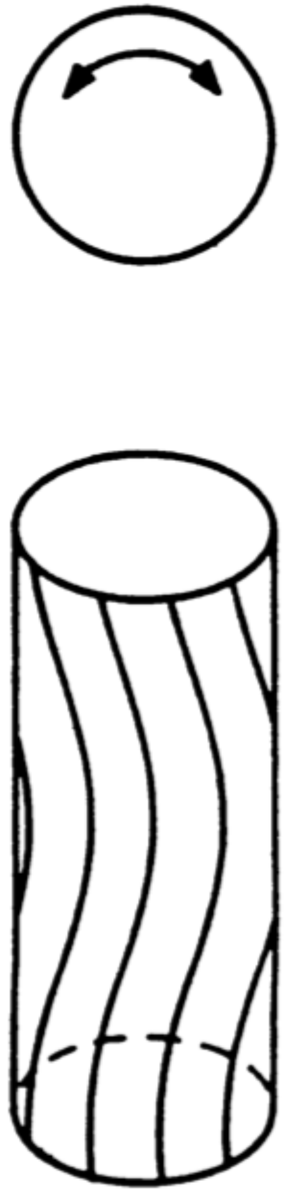
Side view







Morton et al. 2012



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Transverse (Kink)

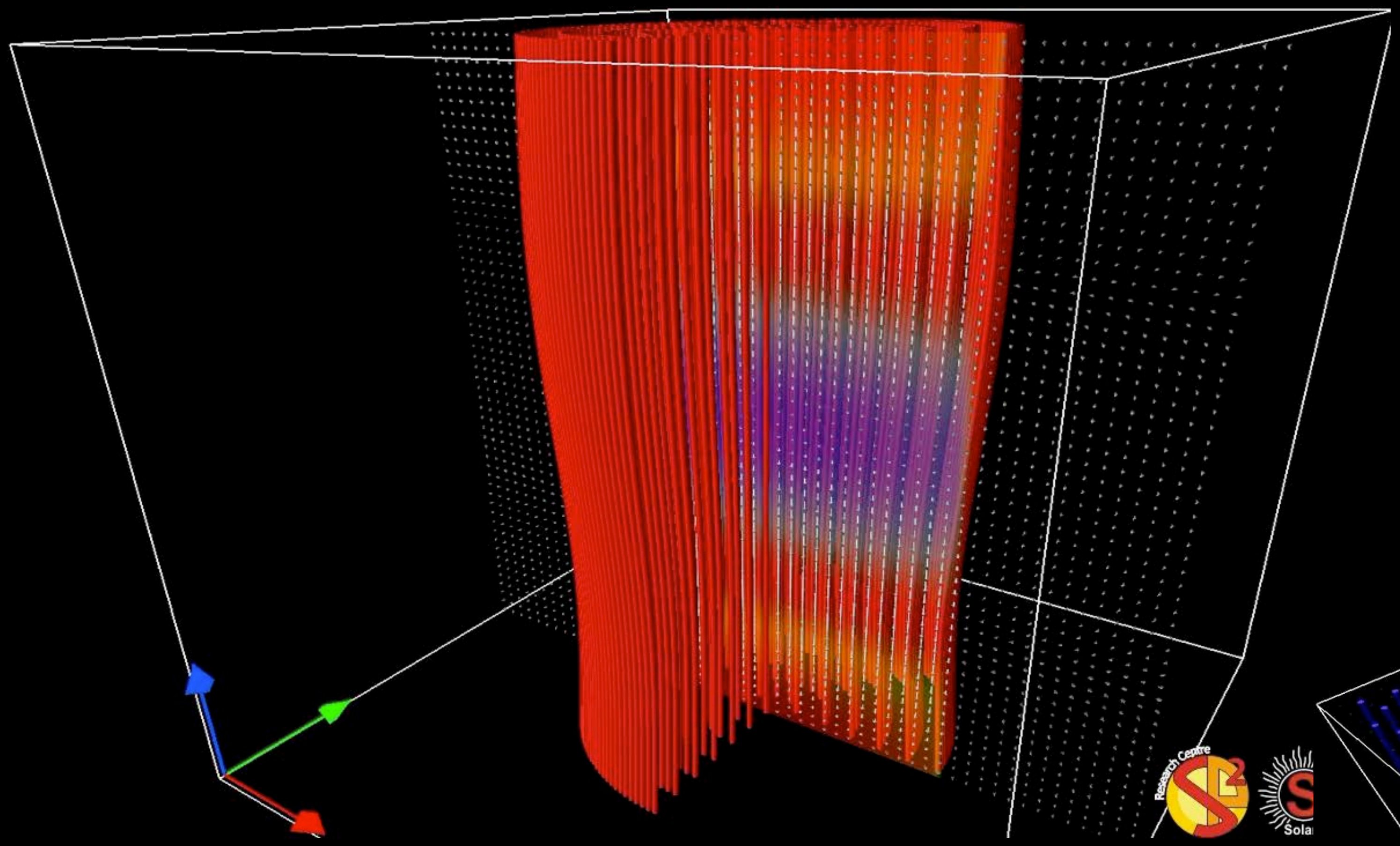
Periodic displacement of central tube axis (Bulk motion)

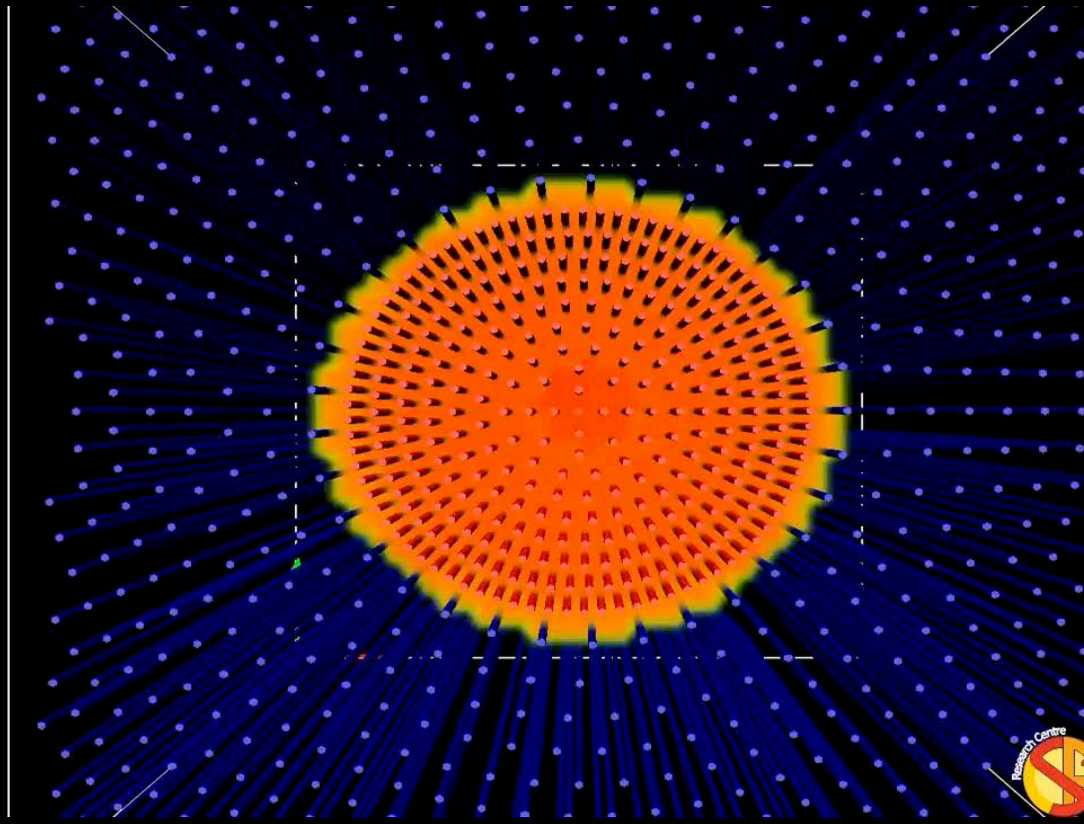
Torsional (Alfvén)

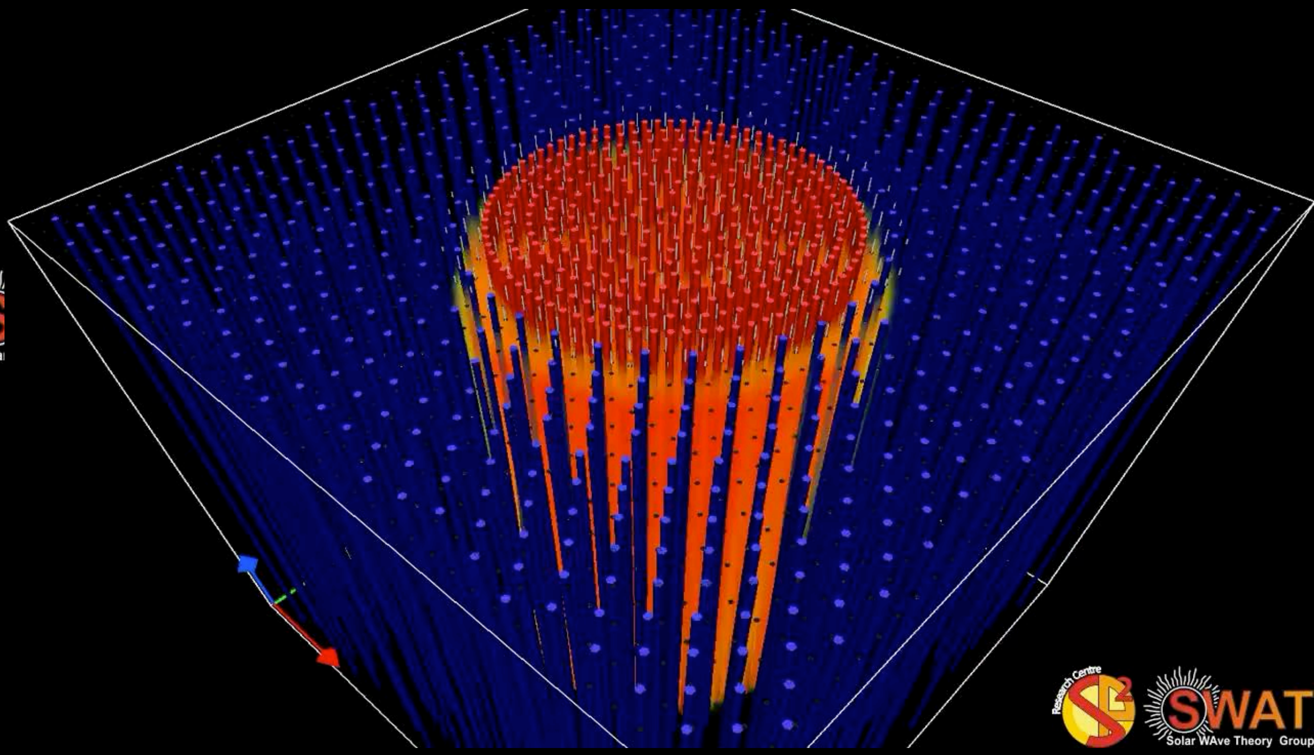
Periodic twisting of tube (Torsional oscillations)

Waves in the solar atmosphere

Sausage mode



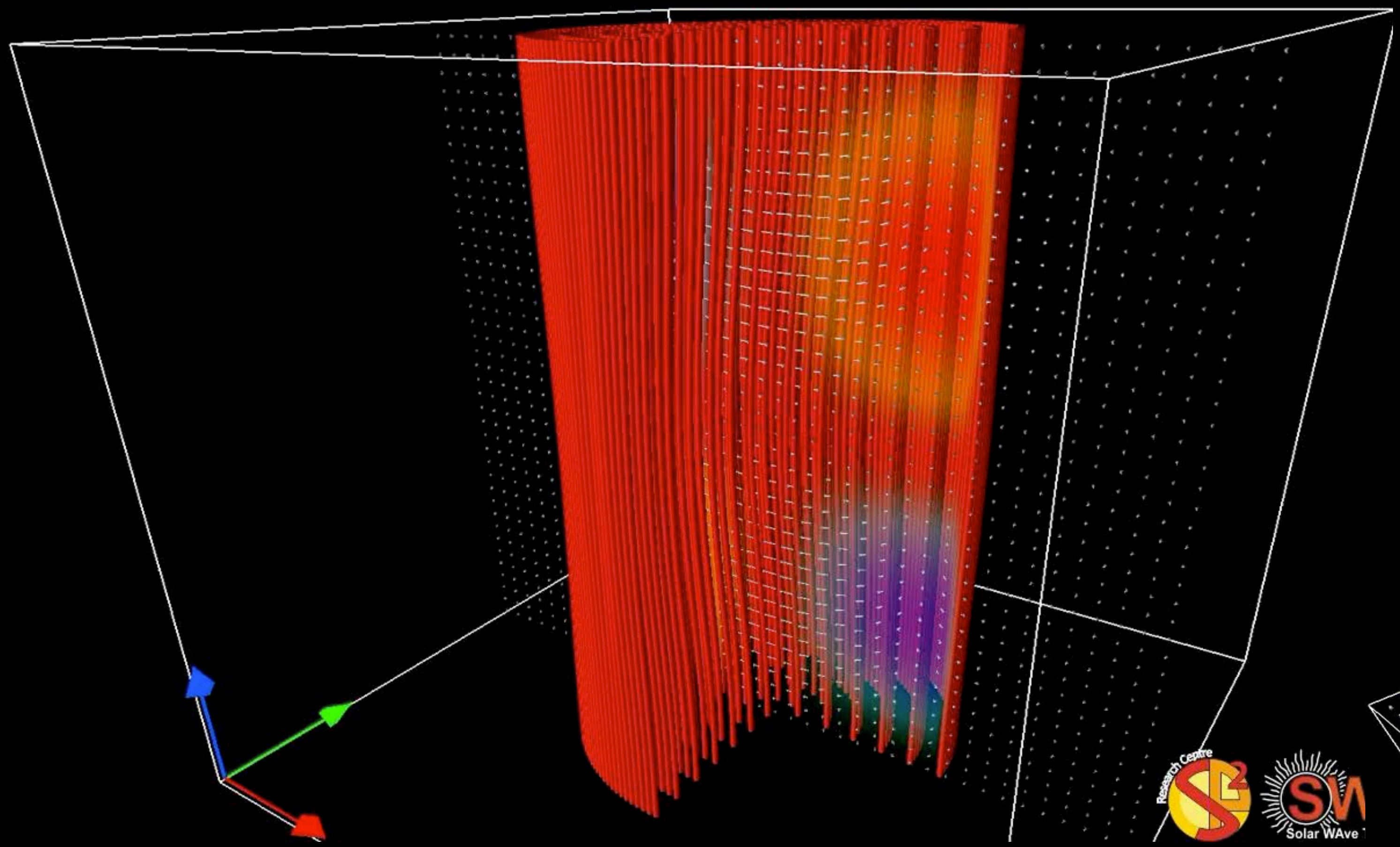


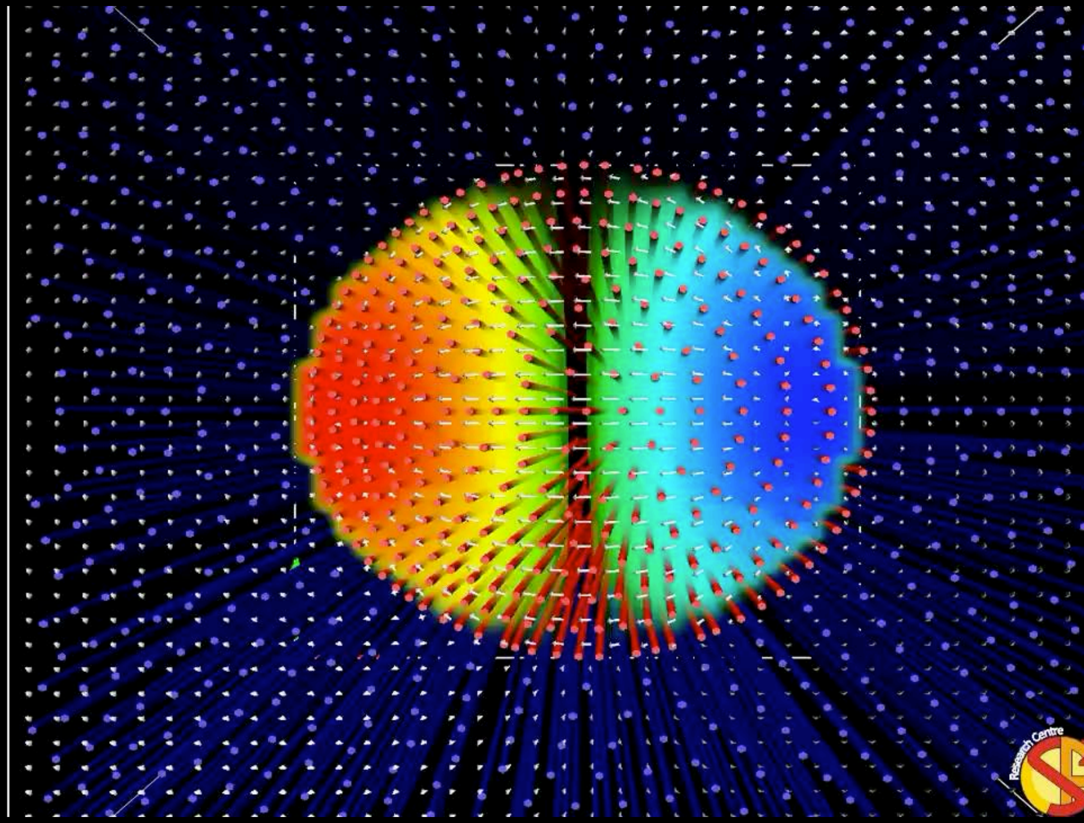


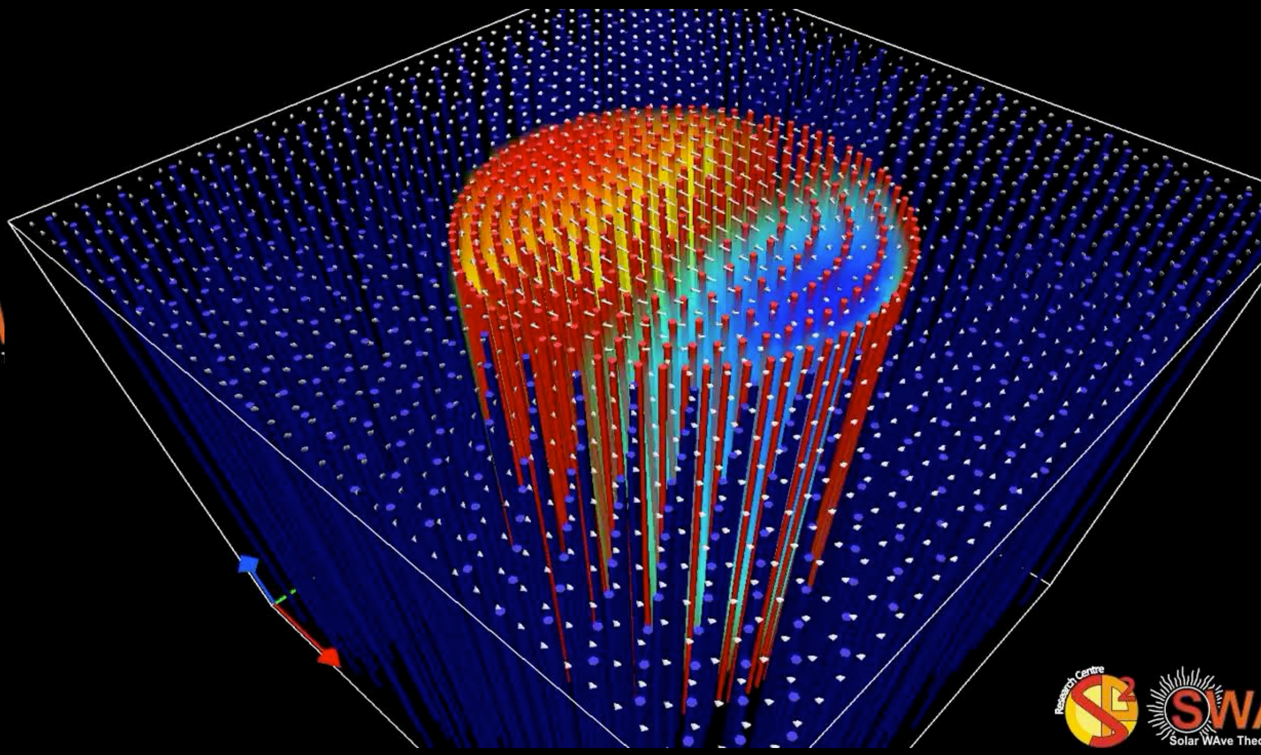
Courtesy of: The University of Sheffield — Edwin and Roberts (1983)

Waves in the solar atmosphere

Kink mode







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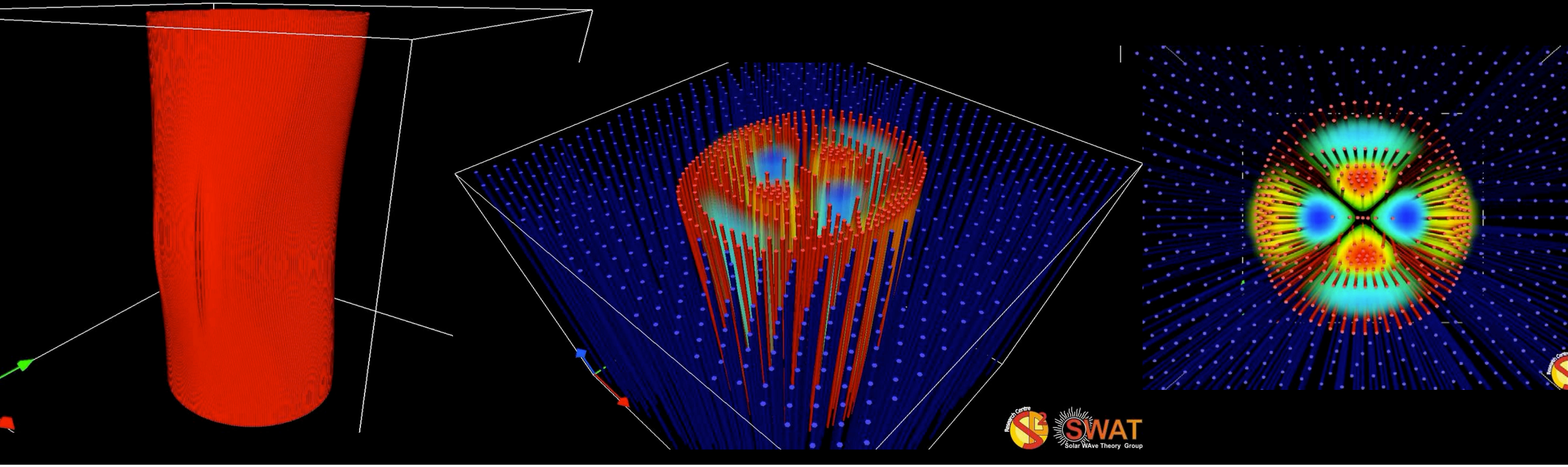
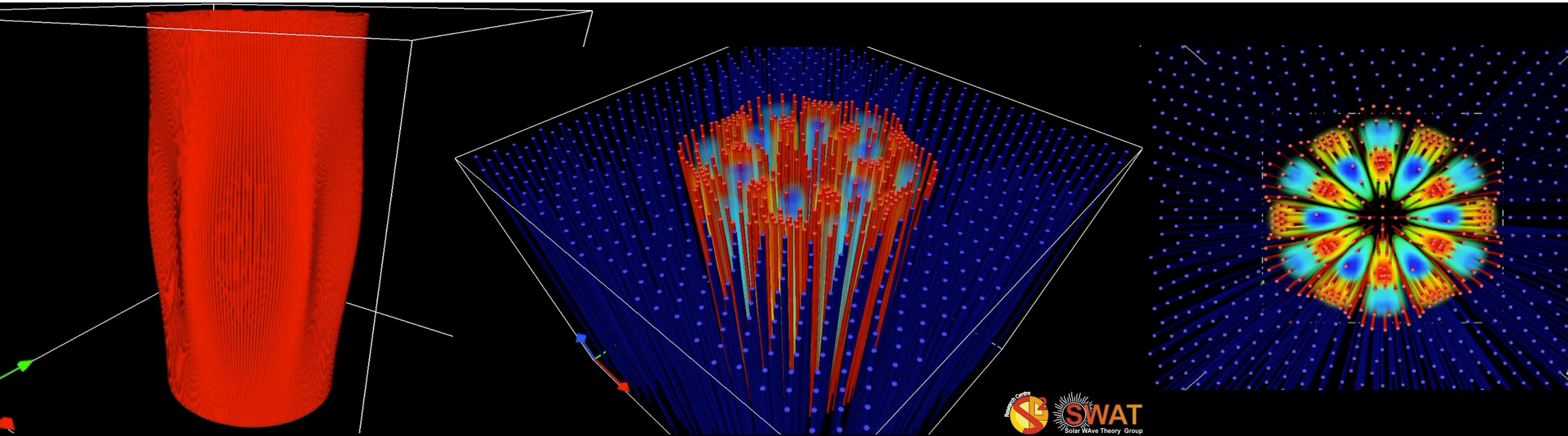
Waves in the solar atmosphere

Fluting modes

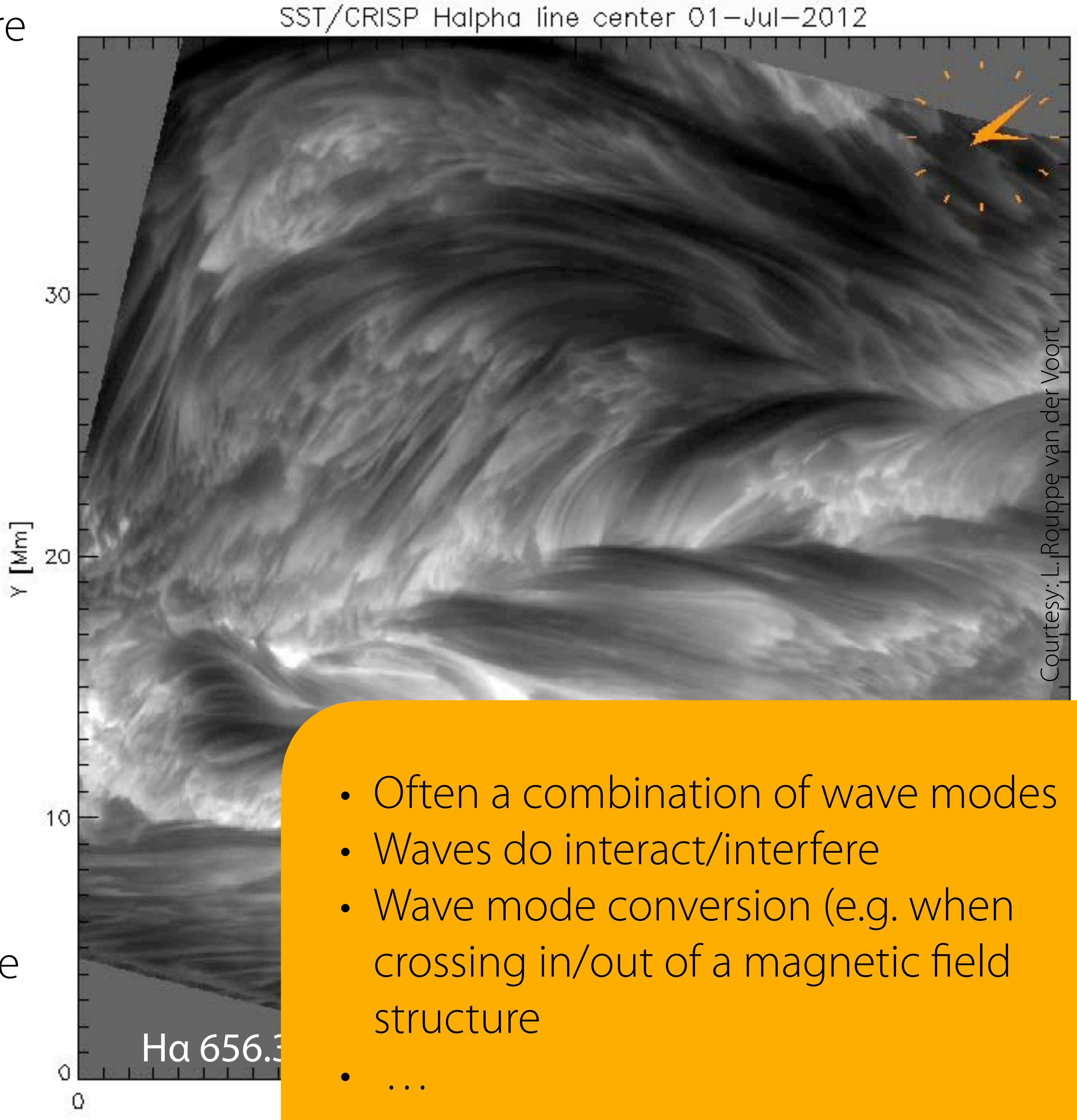
Periodic deformations of tube cross-section,
deviating from circular shape





Waves in the solar atmosphere

- Oscillations and waves occur in many different places in the solar atmosphere
  - Sunspots
  - Pores
  - Large-scale magnetic structures (e.g. filaments, coronal loops)
  - Chromospheric fibrils
  - Small-scale magnetic elements
  - …
- Observable forms/affected properties
  - Intensity oscillations — Thermodynamic quantities
  - Velocity oscillations — Doppler Shifts
  - Magnetic oscillations — Magnetic field strength and inclinations
  - Note: Different wave modes leave different imprints, which in principle helps to identify different wave modes (not always easy!)



Courtesy: L. Rouppe van der Voort

- Often a combination of wave modes
- Waves do interact/interfere
- Wave mode conversion (e.g. when crossing in/out of a magnetic field structure
- …

Modelling the chromosphere

A numerical challenge

Modelling the chromosphere — A numerical challenge

- Many physical processes need to be taken into account
    - Radiative transfer
    - (Magneto-)hydrodynamics
    - Thermodynamics (equation of state)
    - Gravity
    - Ionisation
    - Conduction
    - Ion-neutral effects
    - (Chemistry)
    - …
- Deviations from equilibrium conditions:
    - Ionisation degree
    - Atomic level populations (non-LTE)
    - Molecules … (within limits for the Sun)

- Chromosphere (weakly) ionized

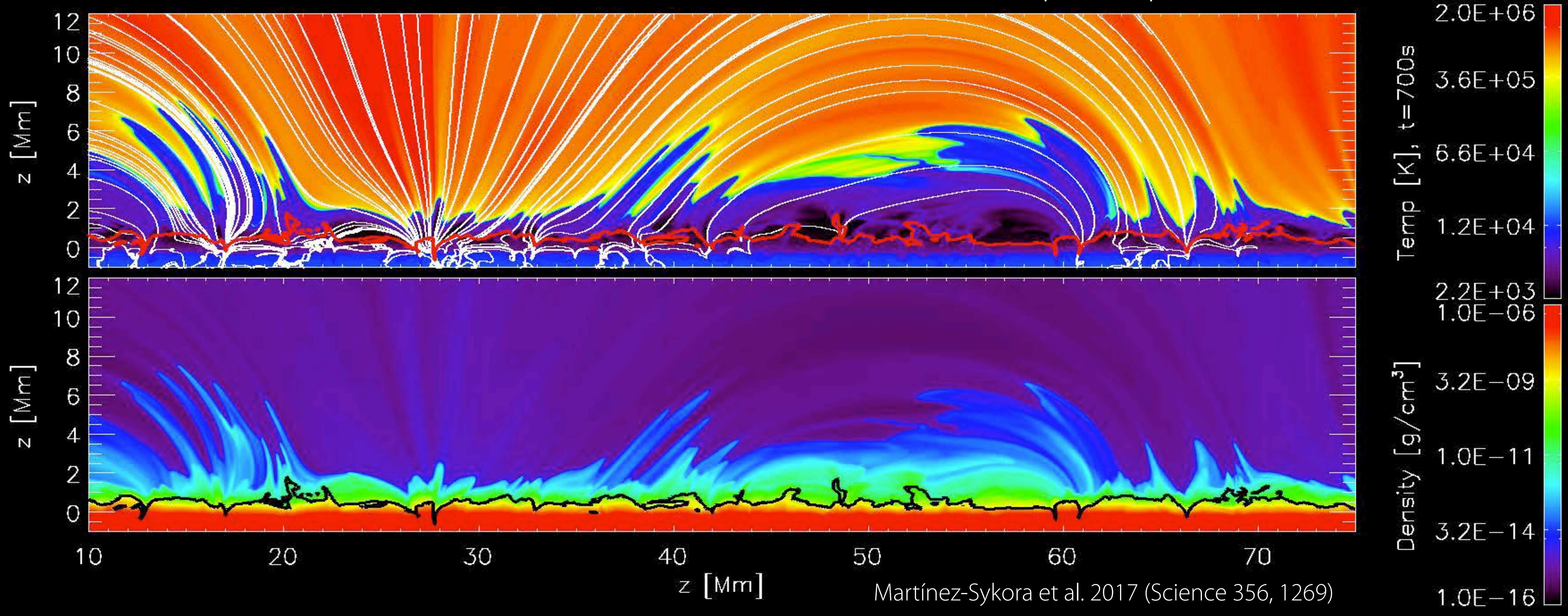
  ➡ Thermodynamics affected by interaction between ionized and neutral particles
- Next step: multi-fluid / multi-species 3D radiative MHD code (species, e.g.: ions, neutrals, free electrons, …)
- Hall and ambipolar diffusion in the electric field

Modelling the chromosphere — A numerical challenge

Generalized Ohm's Law

- So far ideal MHD but chromosphere partially ionized
- Next step: Single fluid MHD + Good approximation as long as collision times are short

Bifrost simulation (90 Mm x 43 Mm at 16 km resolution, 190 G in photosphere)

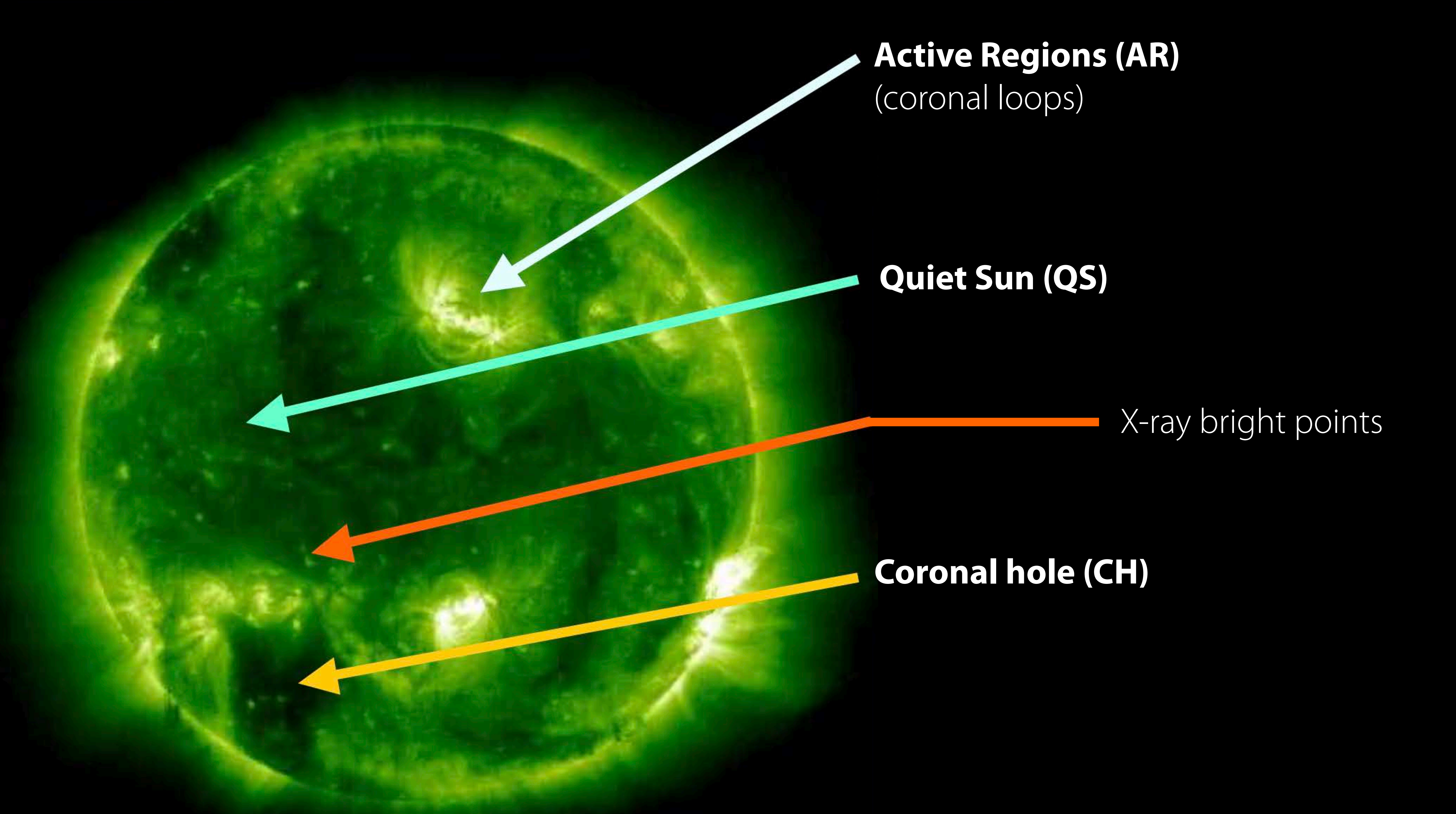


Martínez-Sykora et al. 2017 (Science 356, 1269)

Corona

Corona

- Notable: Different regions with large difference in EUV brightness (and implied temperature)



Active Regions (AR)
(coronal loops)

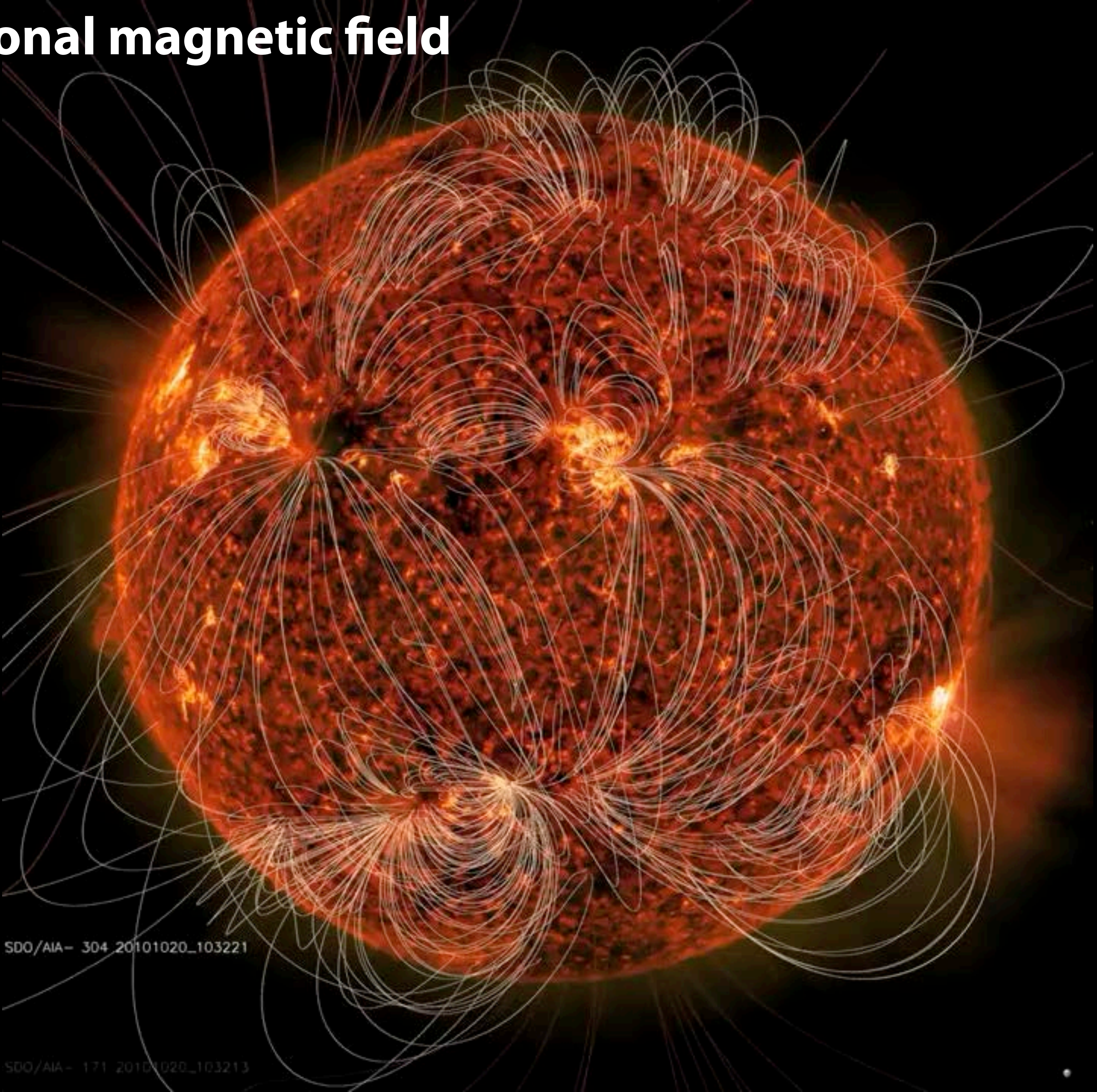
Quiet Sun (QS)

X-ray bright points

Coronal hole (CH)

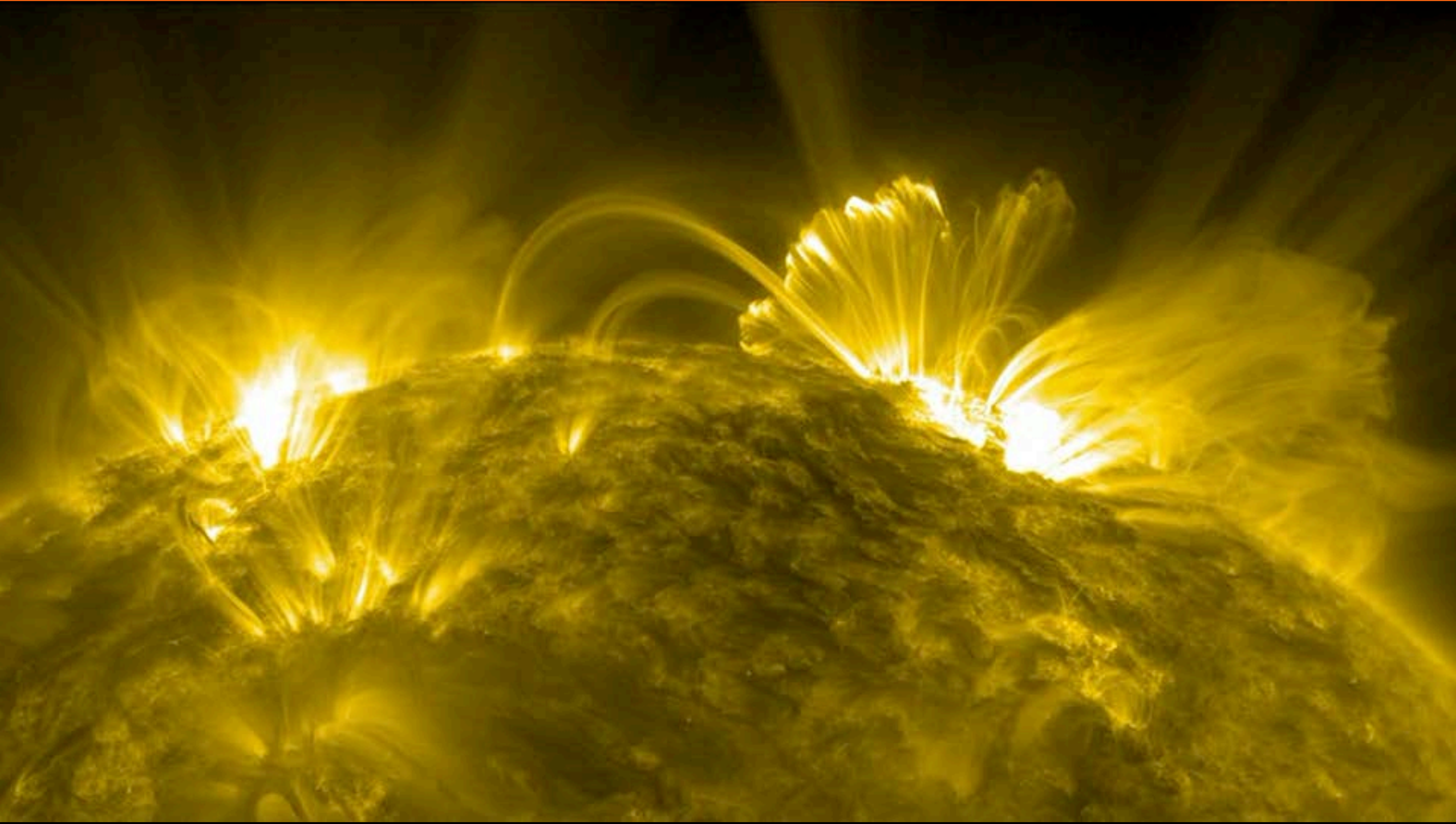
Fe XII 19.5nm (1.5 MK)

Coronal magnetic field



NASA/SDO - HMI

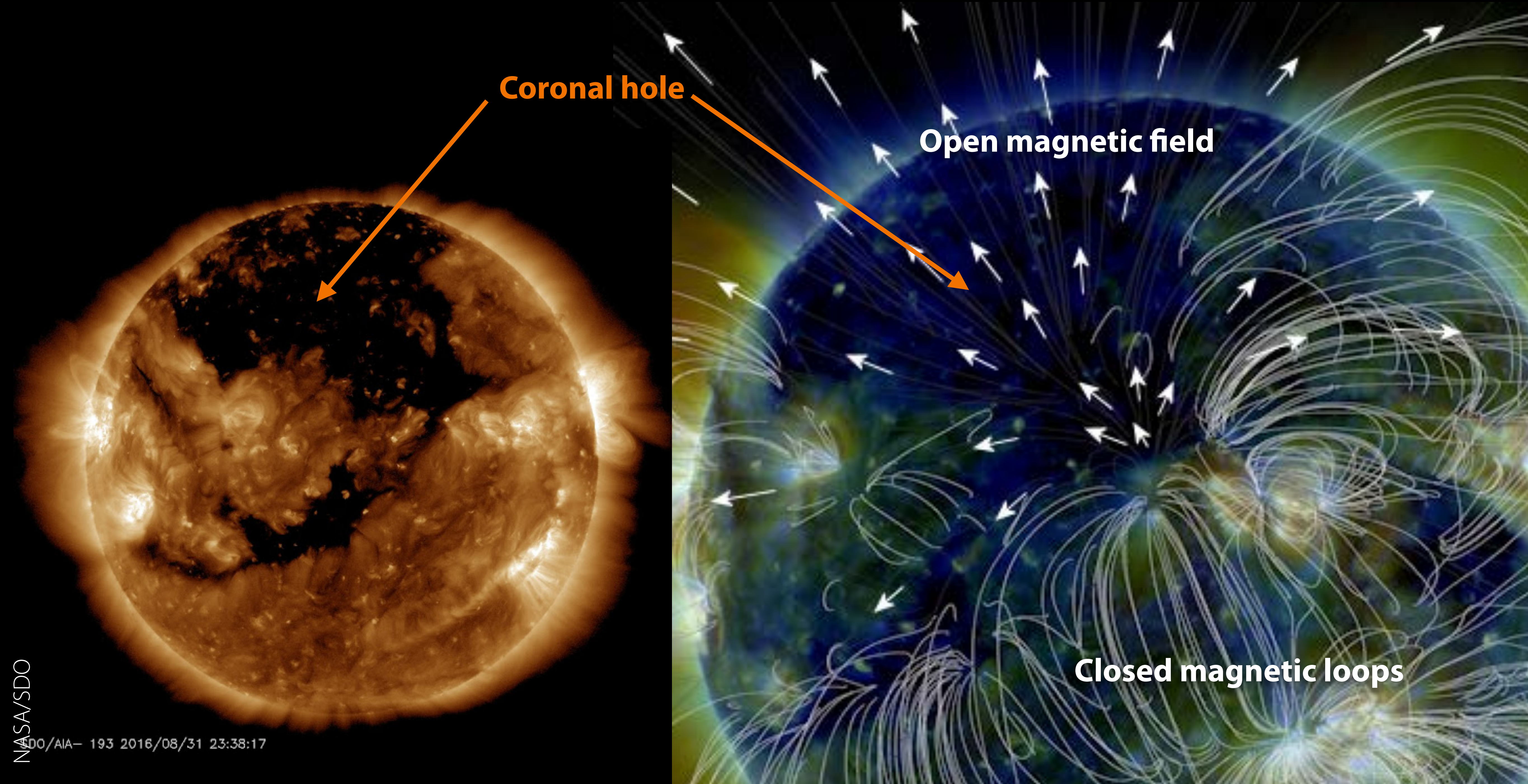
Corona



Corona

Coronal magnetic field

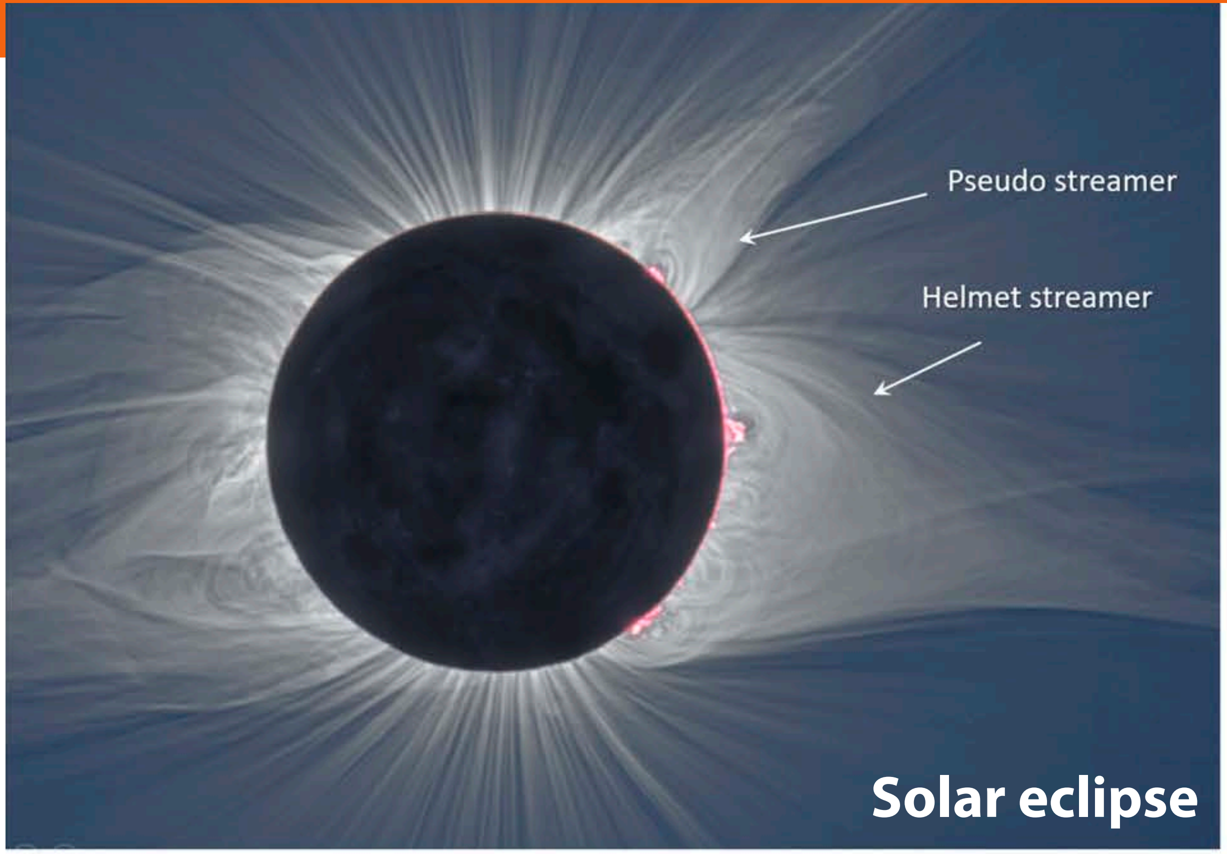
- **Open field lines in coronal holes!**
- Coronal holes can appear all over the Sun, incl. at the poles



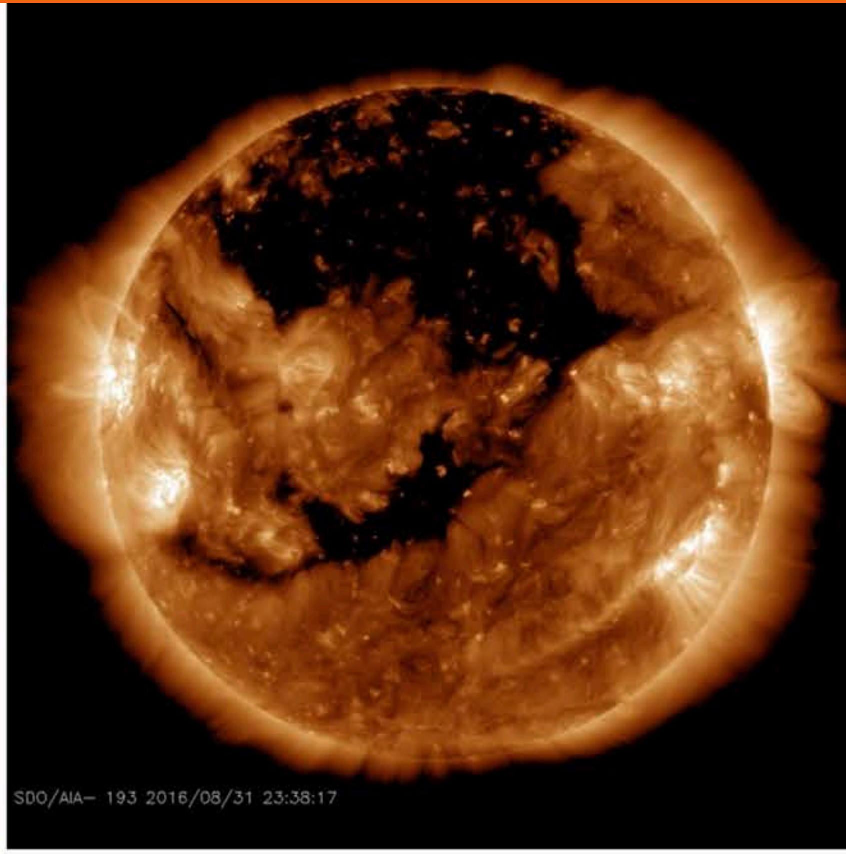
NASA/SDO

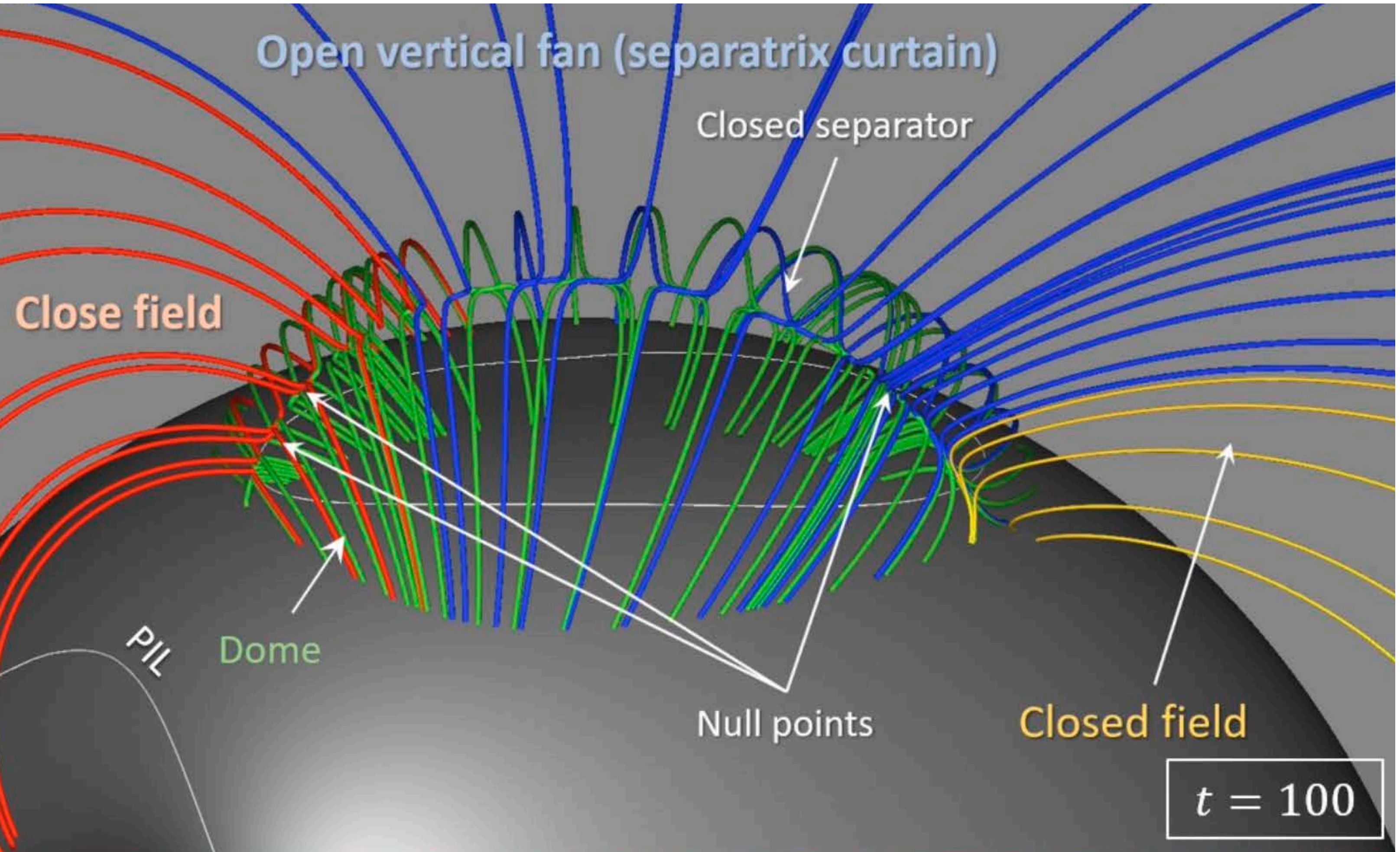
Corona

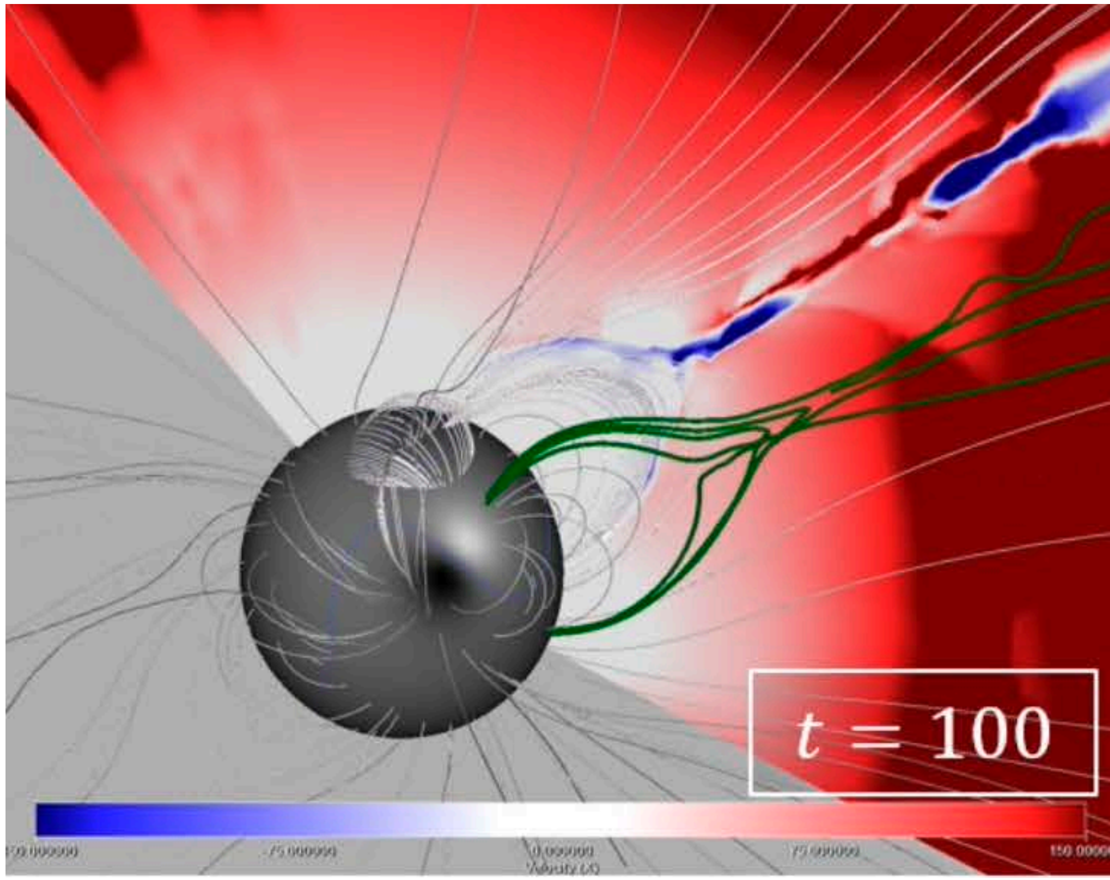
Streamers



Solar eclipse



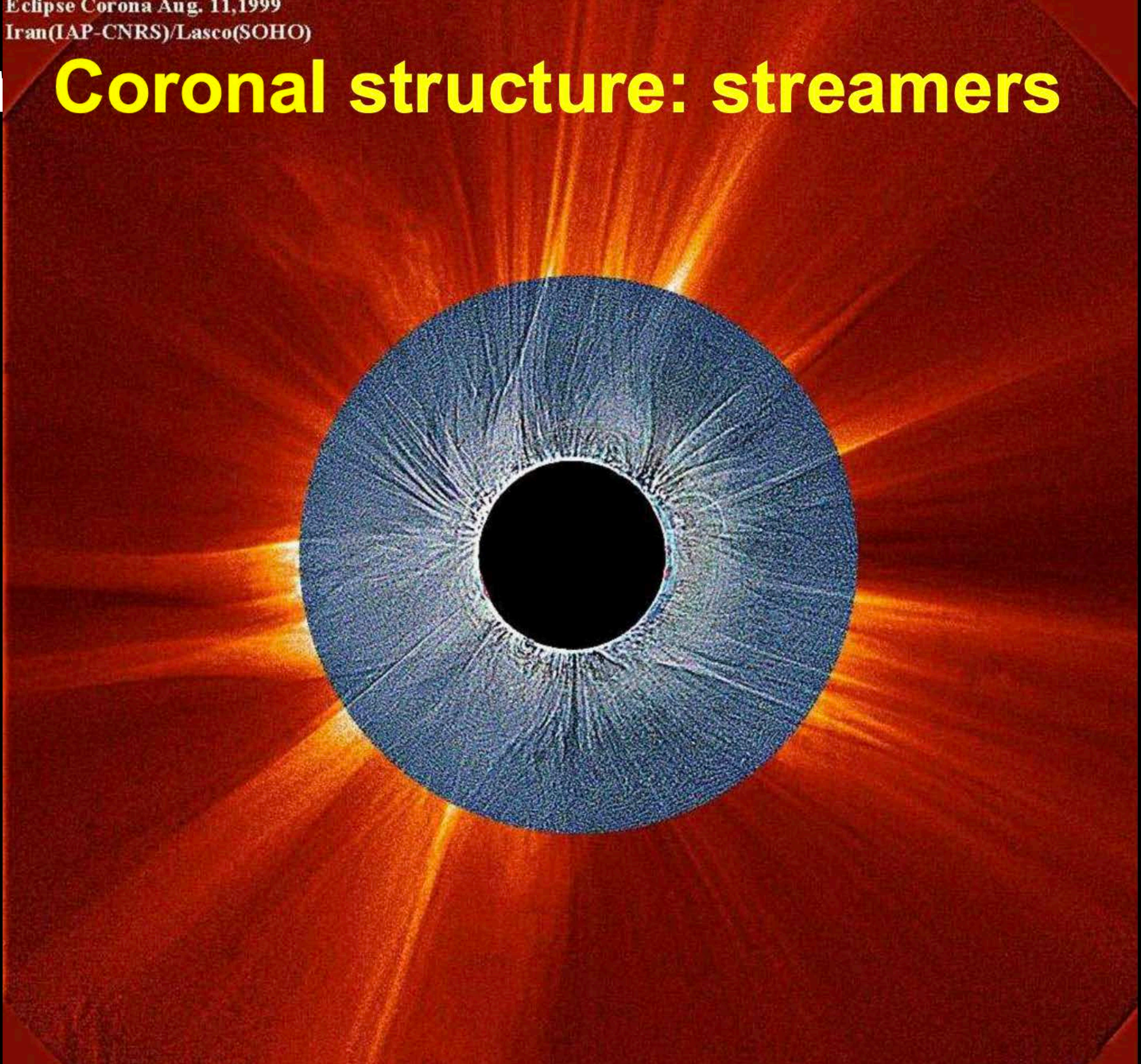




Pellegrin, Masson & Pariat

Cor

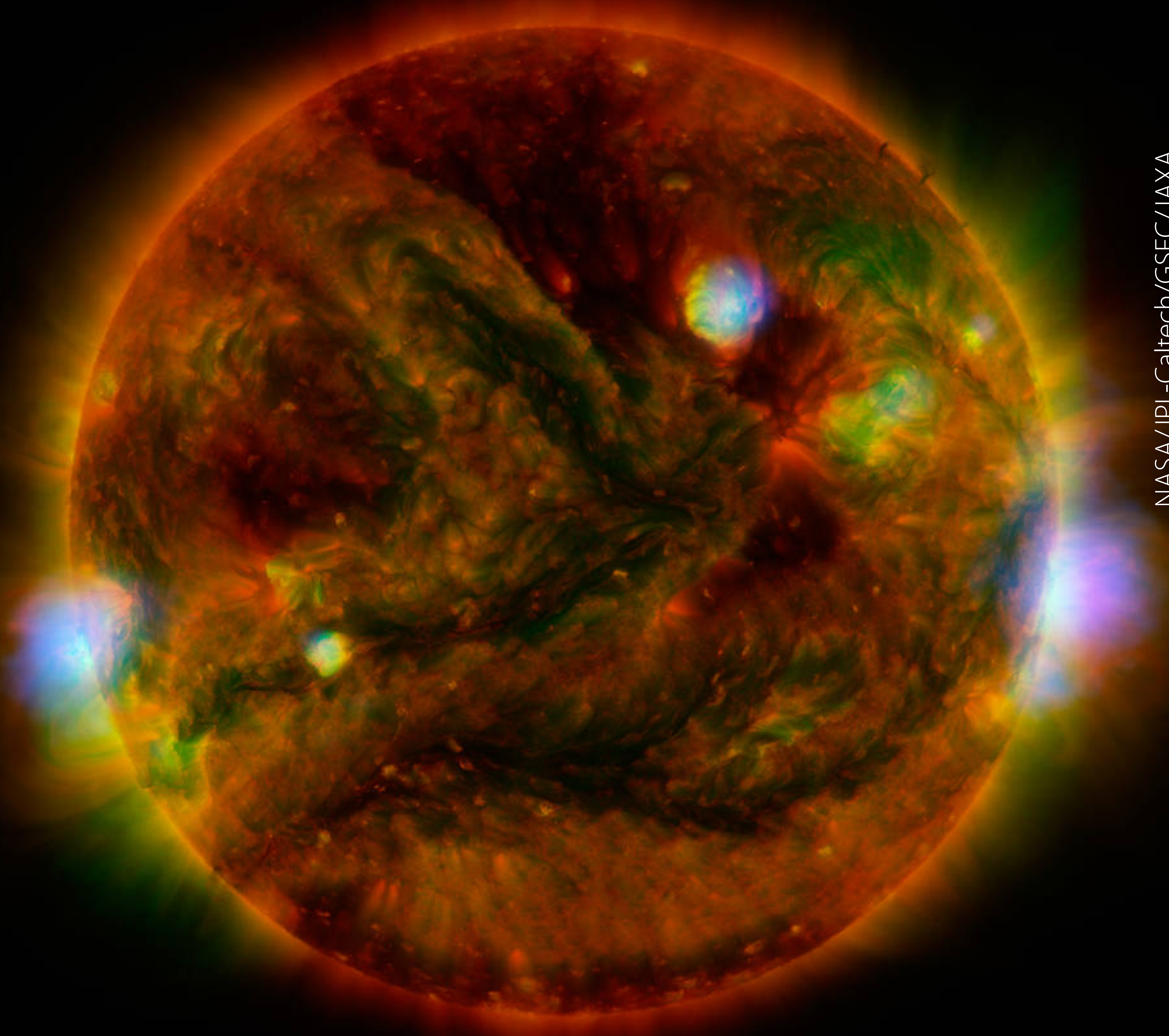
Coronal structure: streamers



Eclipse Corona Aug. 11,1999
Iran(IAP-CNRS)/Lasco(SOHO)

Corona

- Flaring, active regions of our sun are highlighted in this new image combining observations from several telescopes.
- Blue: High-energy X-rays from NASA's Nuclear Spectroscopic Telescope Array (NuSTAR)
- Green: Low-energy X-rays from Hinode spacecraft
- Yellow/red: Extreme ultraviolet light from NASA's Solar Dynamics Observatory (SDO)



NASA/JPL-Caltech/GSFC/JAXA

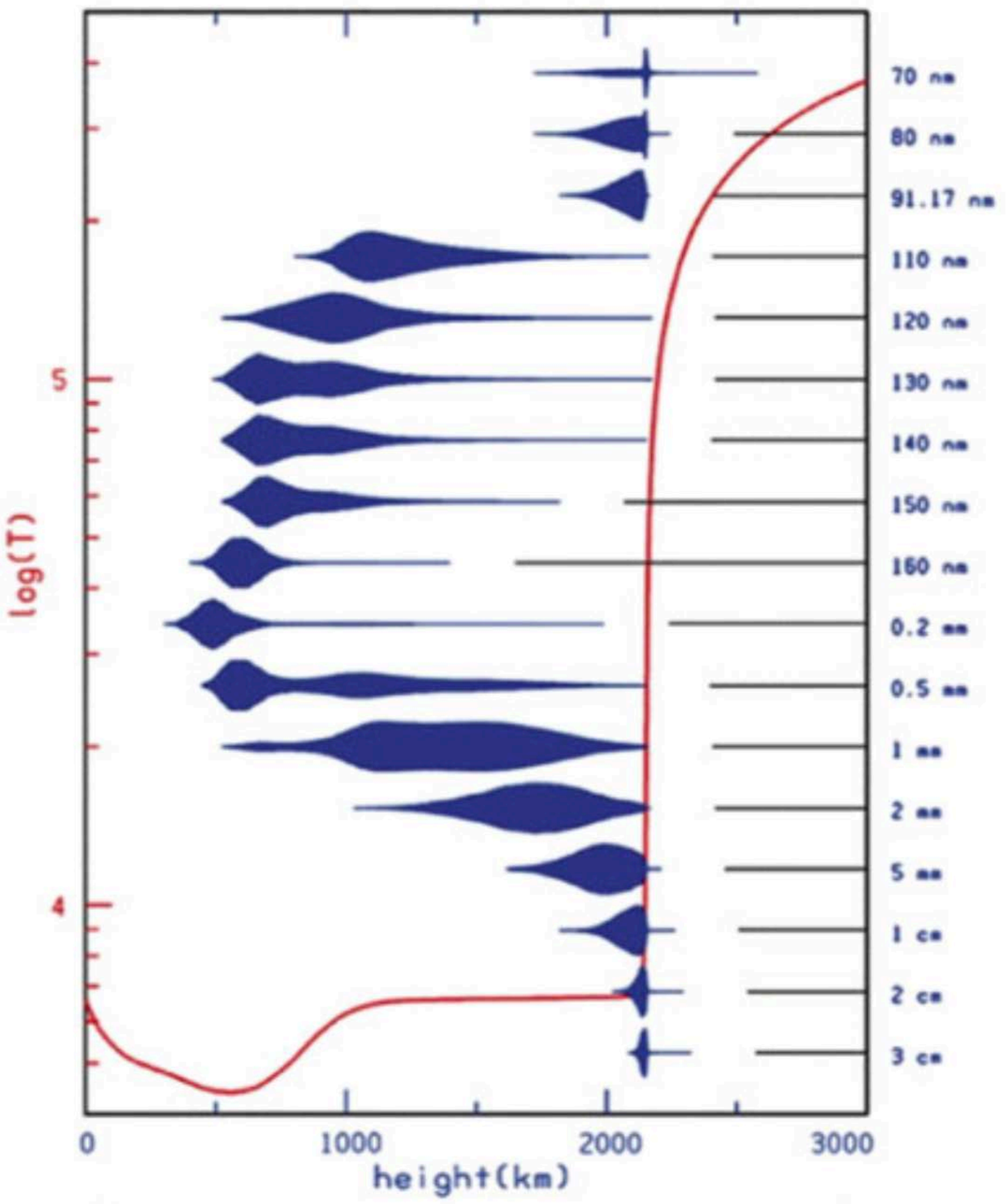
Corona

Emission

- High-energy: gamma, X-rays (especially in Active Regions, during flares)
- EUV
- Radio

- Gamma, X-rays, EUV not observable from ground

➡ Before space age:
  - Observations during eclipses
  - Coronographs (blocking bright disk)
  - Radio observations



Corona

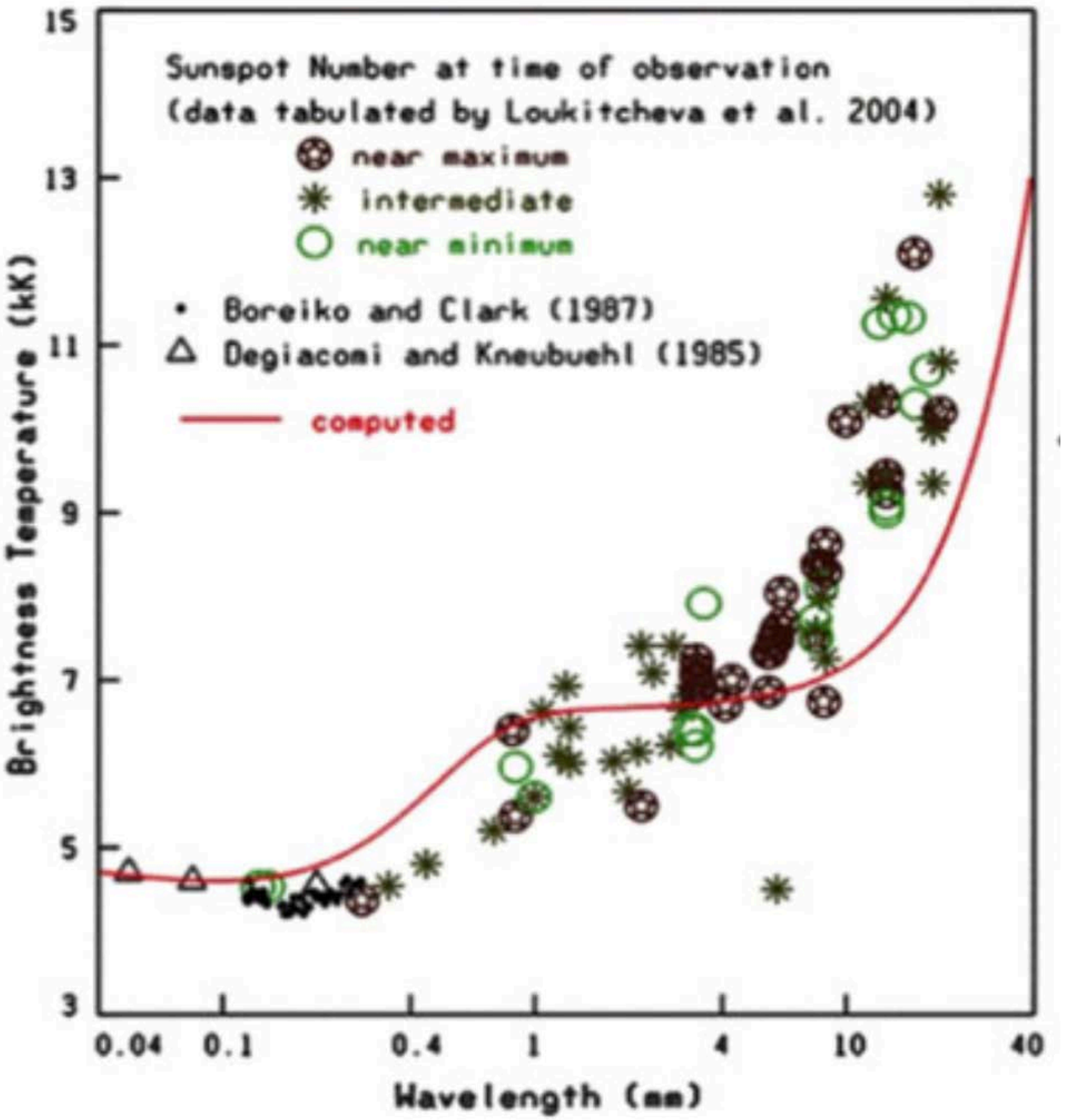
Emission

- **Radio and mm wavelengths:**
- At long wavelengths Planck function in the Rayleigh-Jeans limit
- Radiative flux is closely related to the temperature of the local emitting plasma (more precisely: electron temperature)
- **Brightness temperature** equivalent to flux:

$$T_\mathrm{b} = \frac{c^2}{2k_\mathrm{B}}\nu^{-2}I_\nu = \frac{\lambda^4}{2ck_\mathrm{B}}I_\lambda$$

➡ Proxy for the temperature of the emitting layer/region

➡ Shows temperature increase in the atmosphere as continuum formation increases with wavelength



Corona

Coronal diagnostics

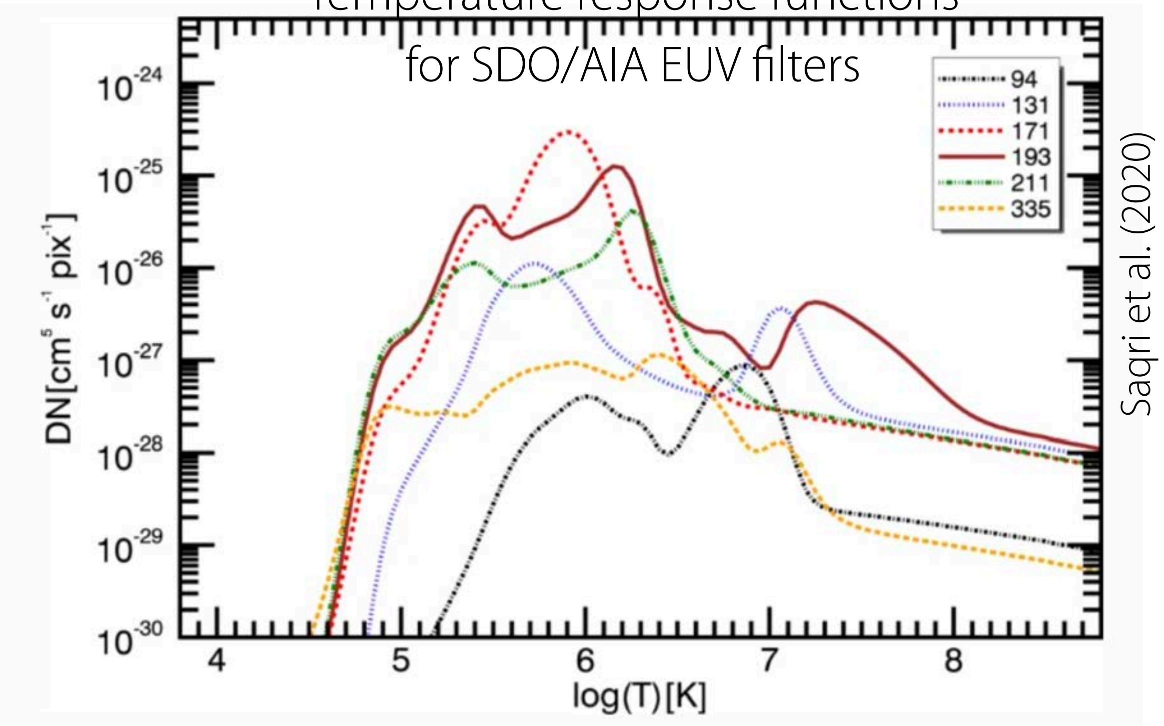
- Low densities! Plasma optically thin!
- Different wavelength (filter) ranges (and included spectral) correspond to different temperatures
- Note: High temperature (>10^5 to several 10^6 K) — high ionisation stages (e.g., even Fe XXIV — SDO/AIA193)

- **Differential emission measure (DEM)** as a temperature diagnostic for coronal plasma:
  - Instrument-independent function characterising electron density and temperature of an optically thin structure that emits (in EUV and soft X-rays)
  - Exploiting combination of different filter to estimate plasma conditions
  - Unresolved multi thermal structure — temperature distribution

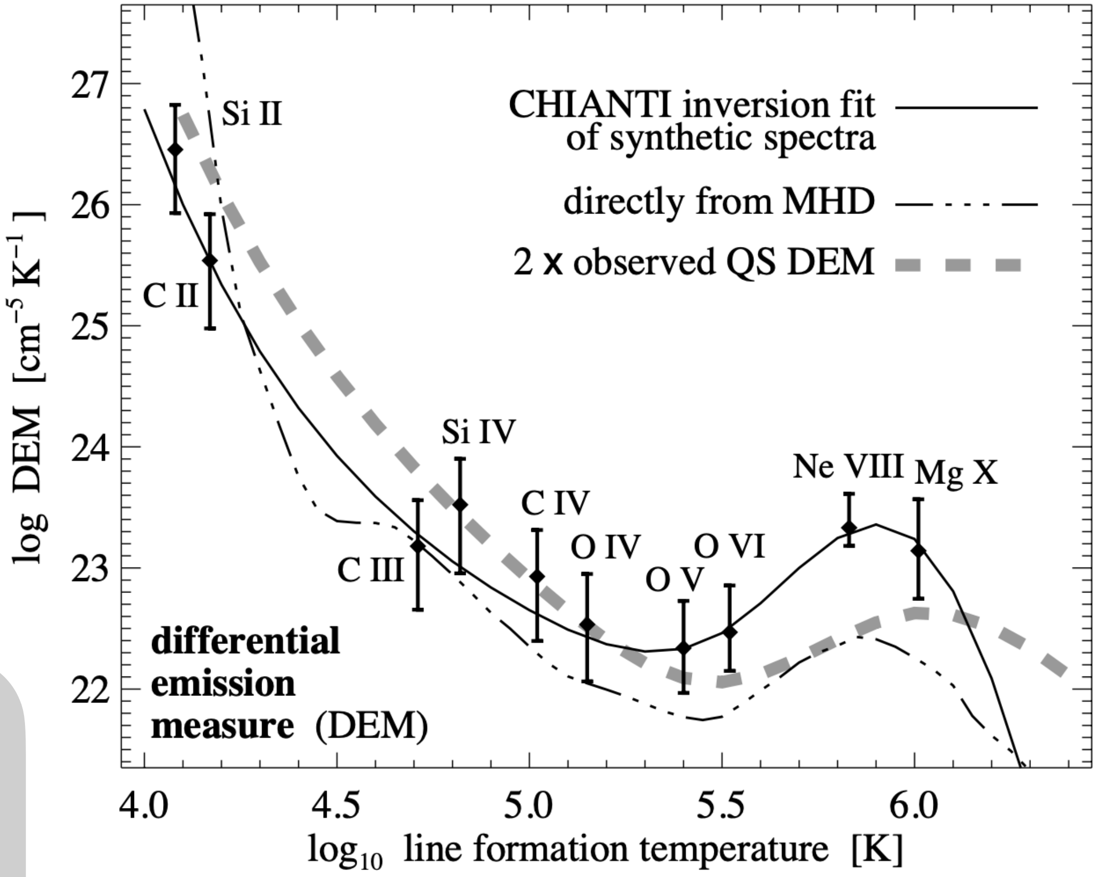
$$\mathrm{DEM}(T) = n(T)^2 \frac{\mathrm{d}h}{\mathrm{d}T}$$

h: coordinate along line of sight
T: temperature
n: (electron) density

Temperature response functions for SDO/AIA EUV filters



Sagri et al. (2020)



Peter et al. (2005)

Corona

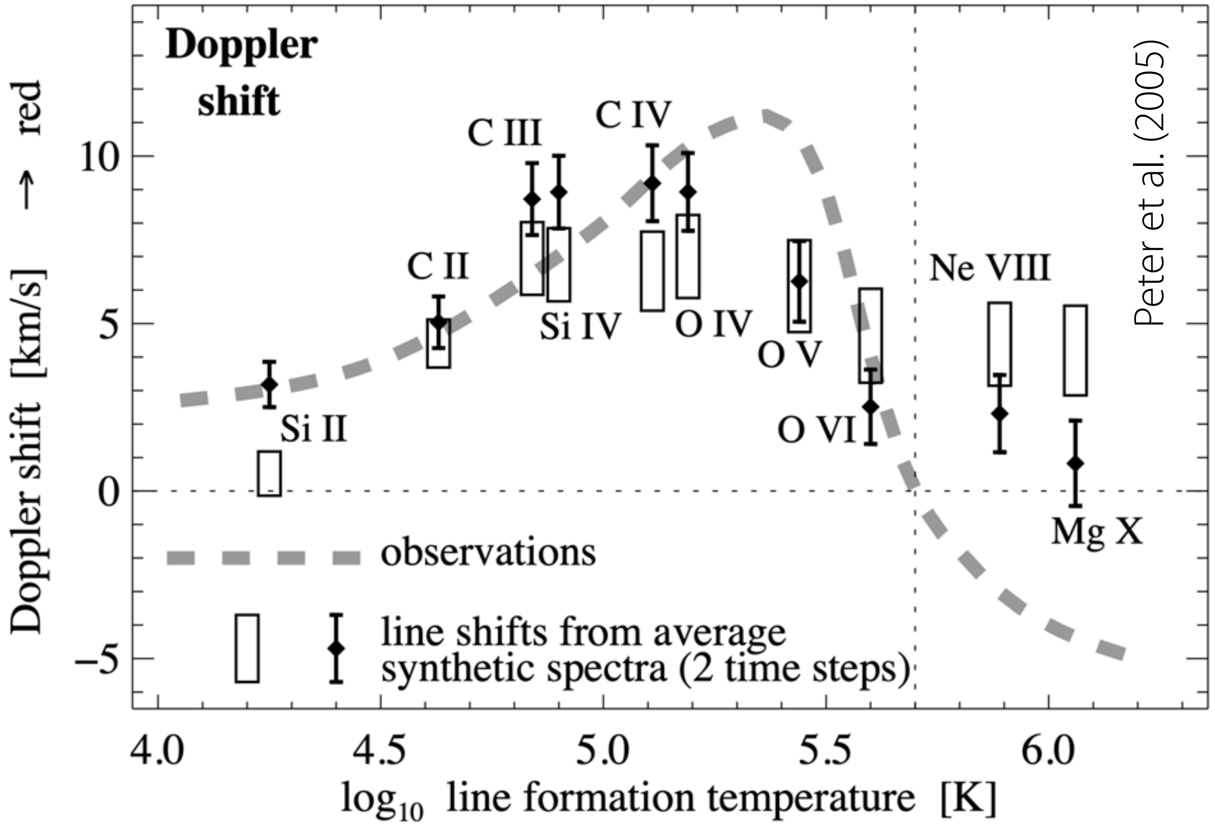
Coronal diagnostics

- **Doppler shifts** for different spectral lines formed for ions

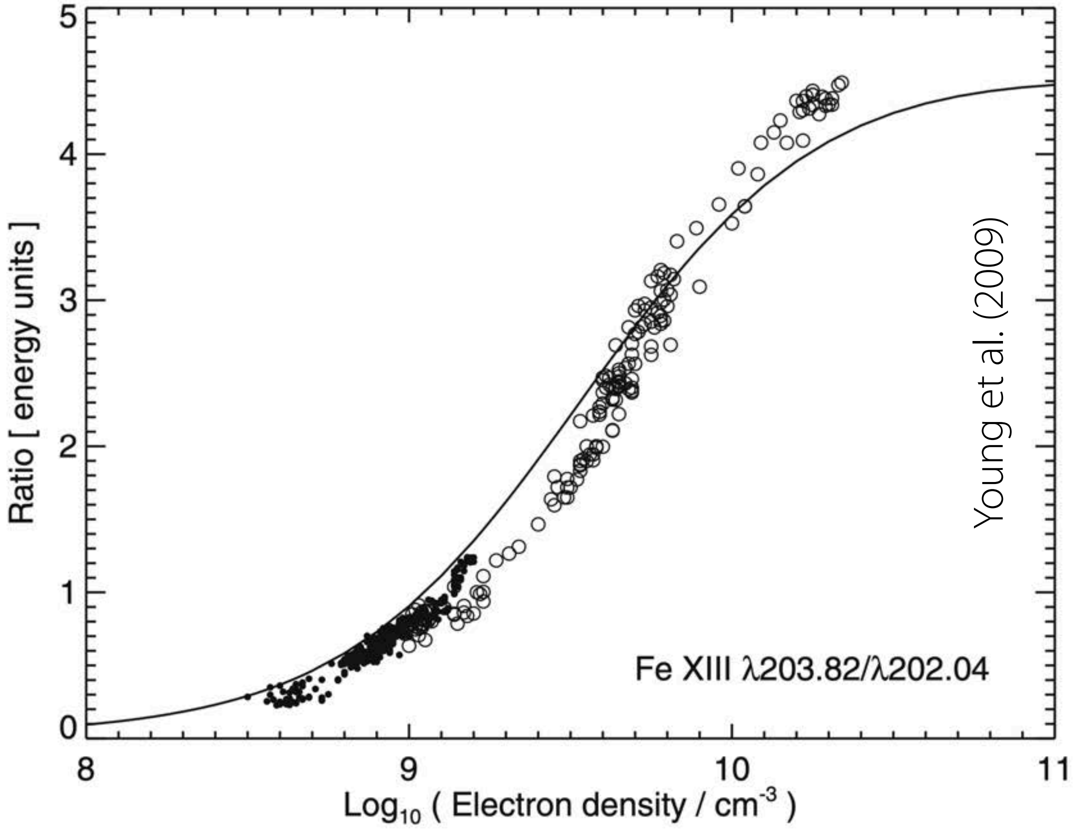
  ➡ Velocity profile as function line formation temperature (and thus temperature in the corona)

- **Density-Sensitive Line Ratio Diagnostics**: ratios of density-sensitive atomic lines (by same ion)

  ➡ Electron densities



Peter et al. (2005)

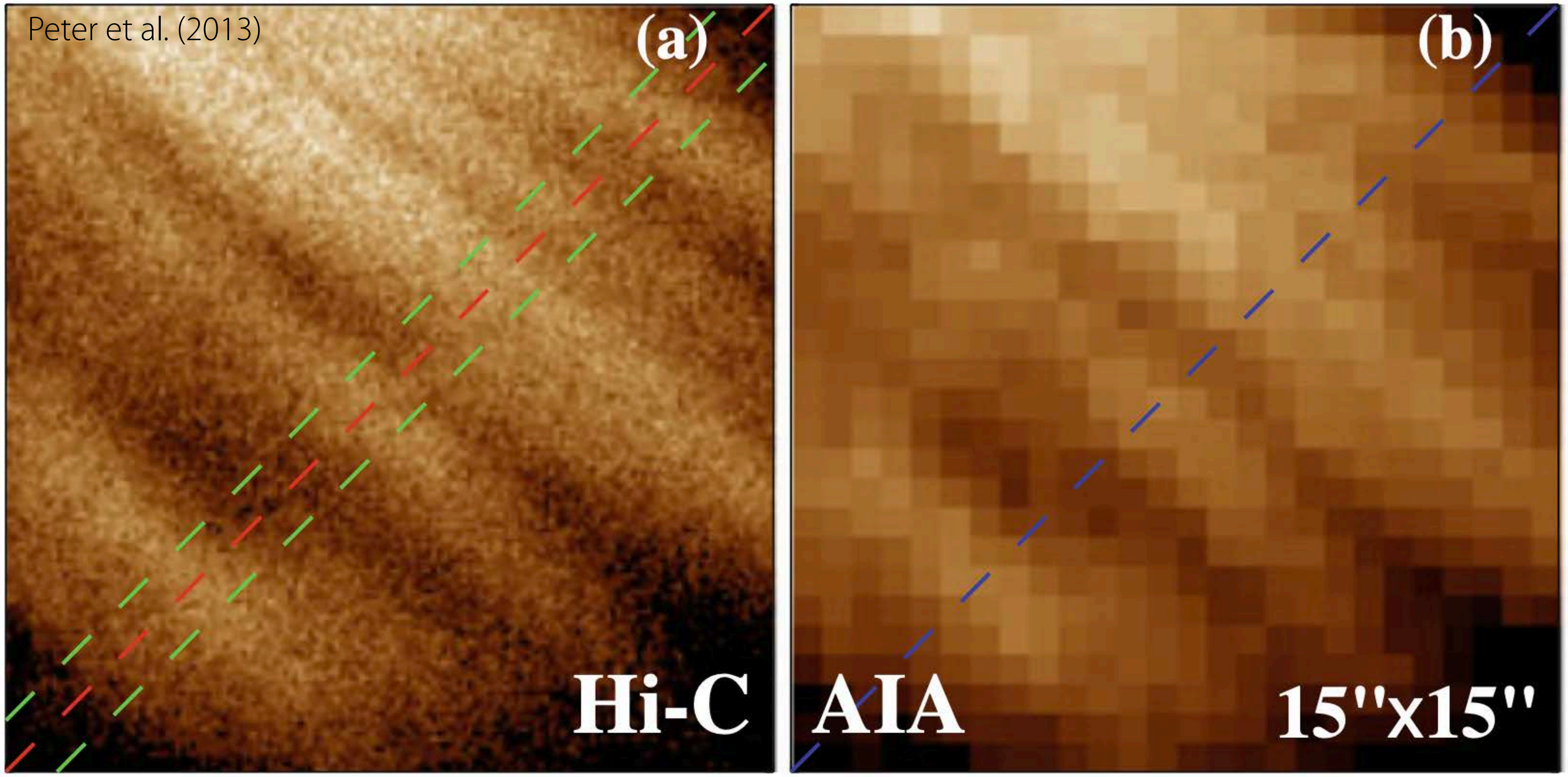


Young et al. (2009)

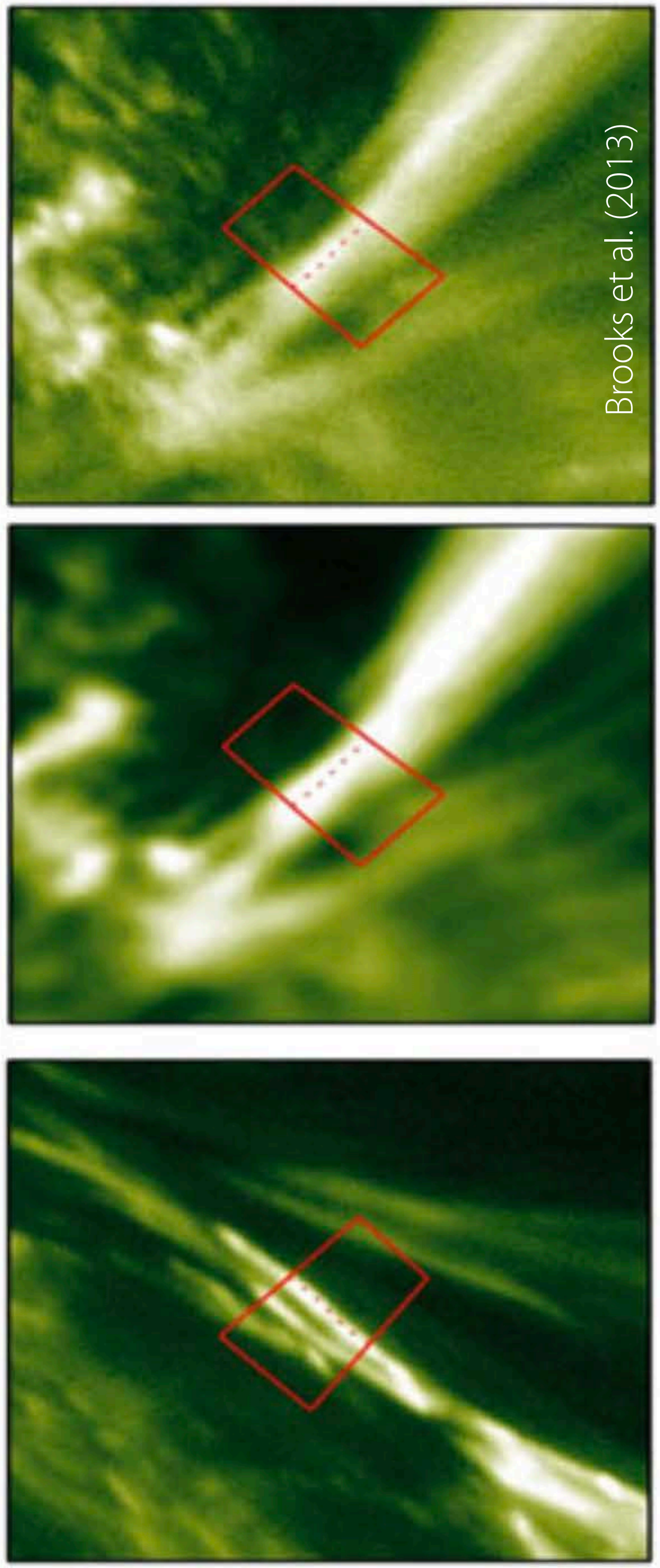
Corona

Coronal Loops

- Observations with higher and higher spatial resolution reveal **multi-stranded fine-structure of coronal loops**
- Width (cross-section) of loop strands important for coronal heating
  1. Very thin loop strands — Parker's nanoflare scenario
  2. Wider loops strands: cross-field diffusion
- Currently, widths around 500 km most frequent, would imply #1 for widths < 500 km energetically less important but …



Peter et al. (2013)

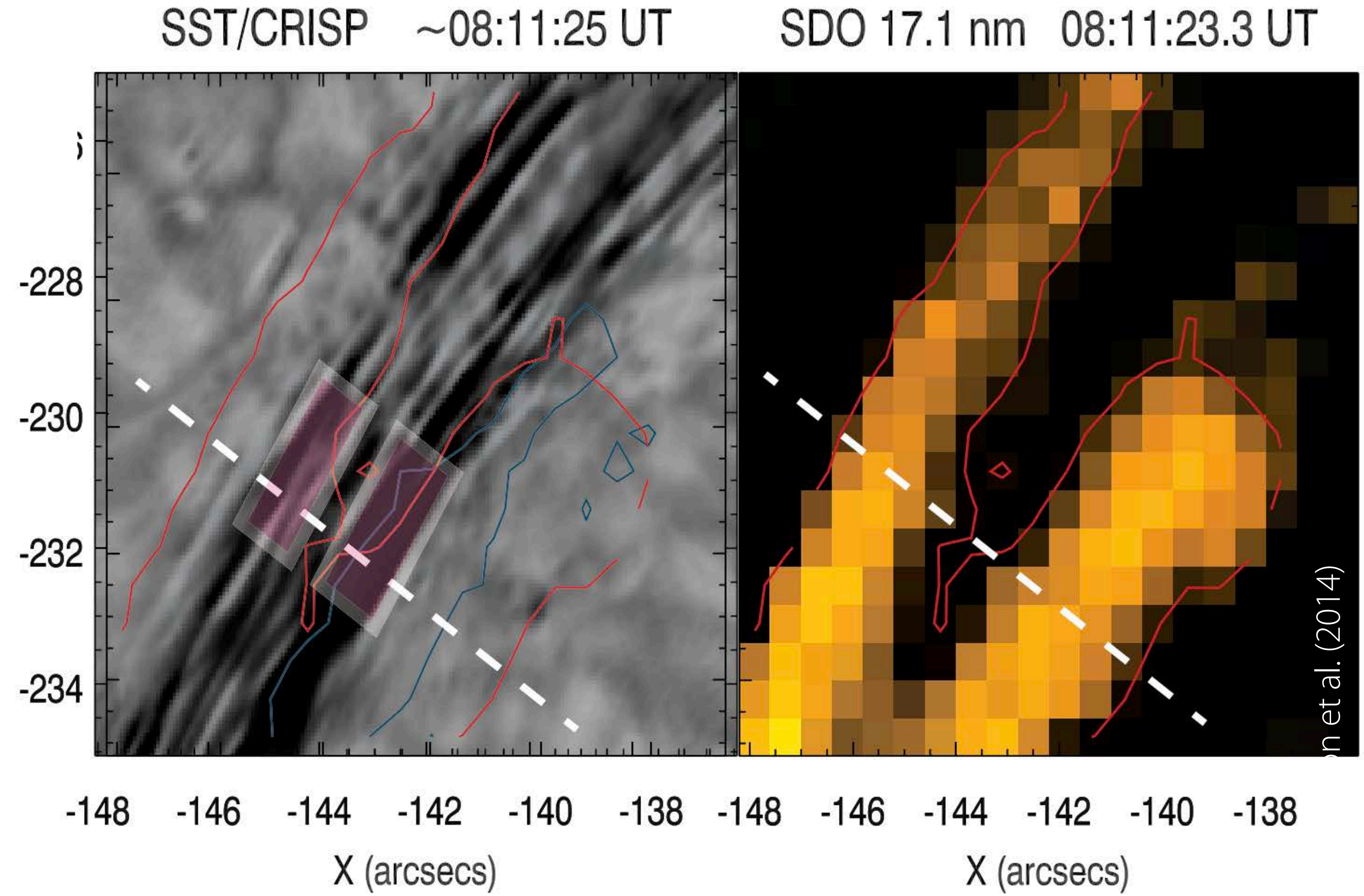


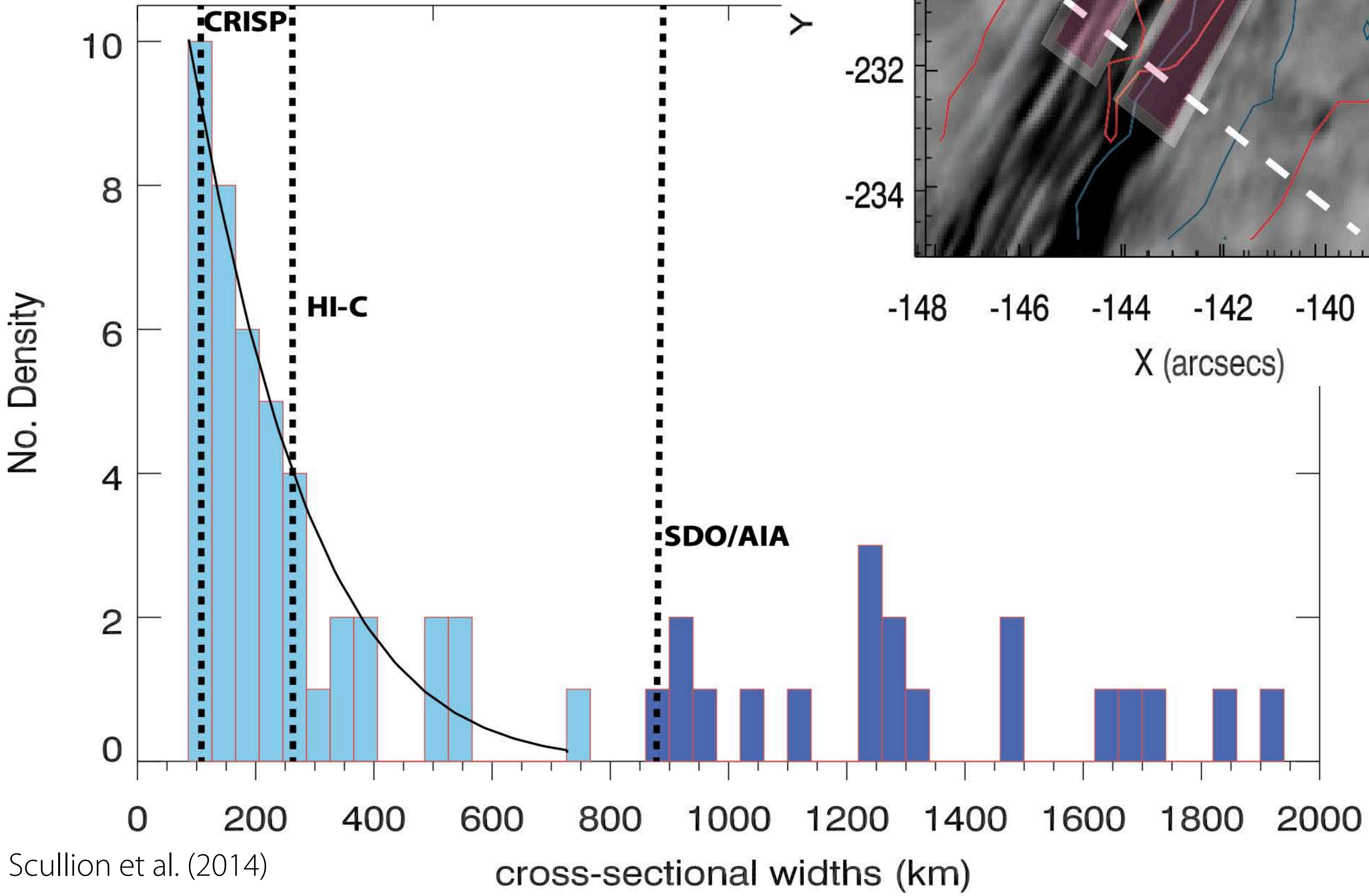
Brooks et al. (2013)

Corona

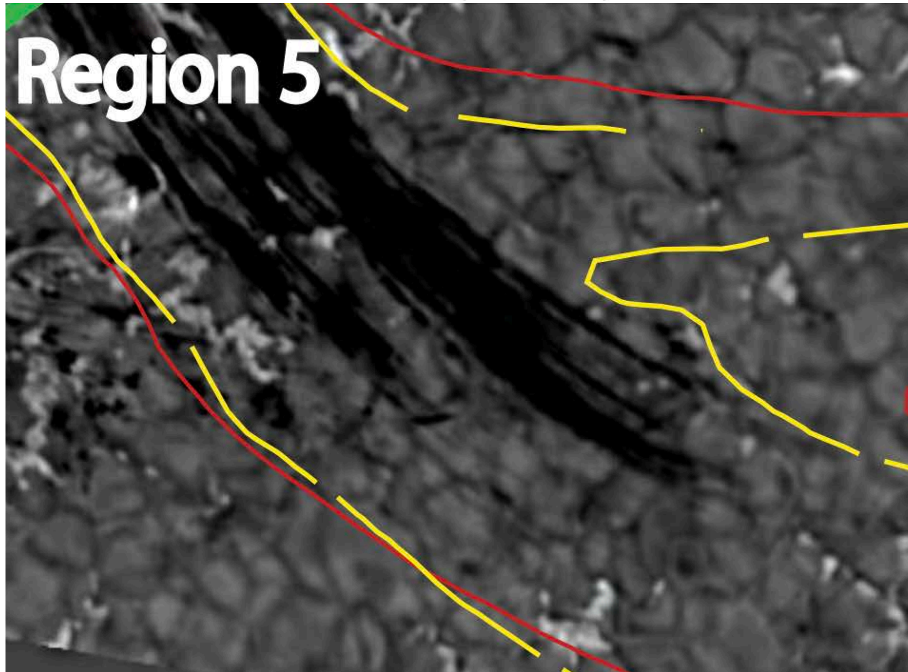
Coronal Loops

- Smallest loop strands down to currently reached resolution limit (~100km)
- How thin can they get?
- What is the true size distribution?





Scullion et al. (2014)



Corona

Thermal structure of coronal loops

- Temperatures of coronal loops **debated**, too, as it depends on the cross-section
  - Monolithic (macroscopic) **isothermal** loops?
  - Or unresolved multi-stranded **multi-thermal** loops?

- Multi-stranded loops:
  - Inhomogeneous in temperature and density
  - Unresolved strands independently heated by microscopic heating sources (e.g. nanoflares)

  ➡ Broad multi-temperature distribution (differential emission measure)

- Loop temperatures
  - Quiescent loops (in active regions) often exhibit narrow (near-isothermal) DEM (if spatially resolved)
  - Flaring loops tend to exhibit broadband (multi-thermal) DEMs

Corona

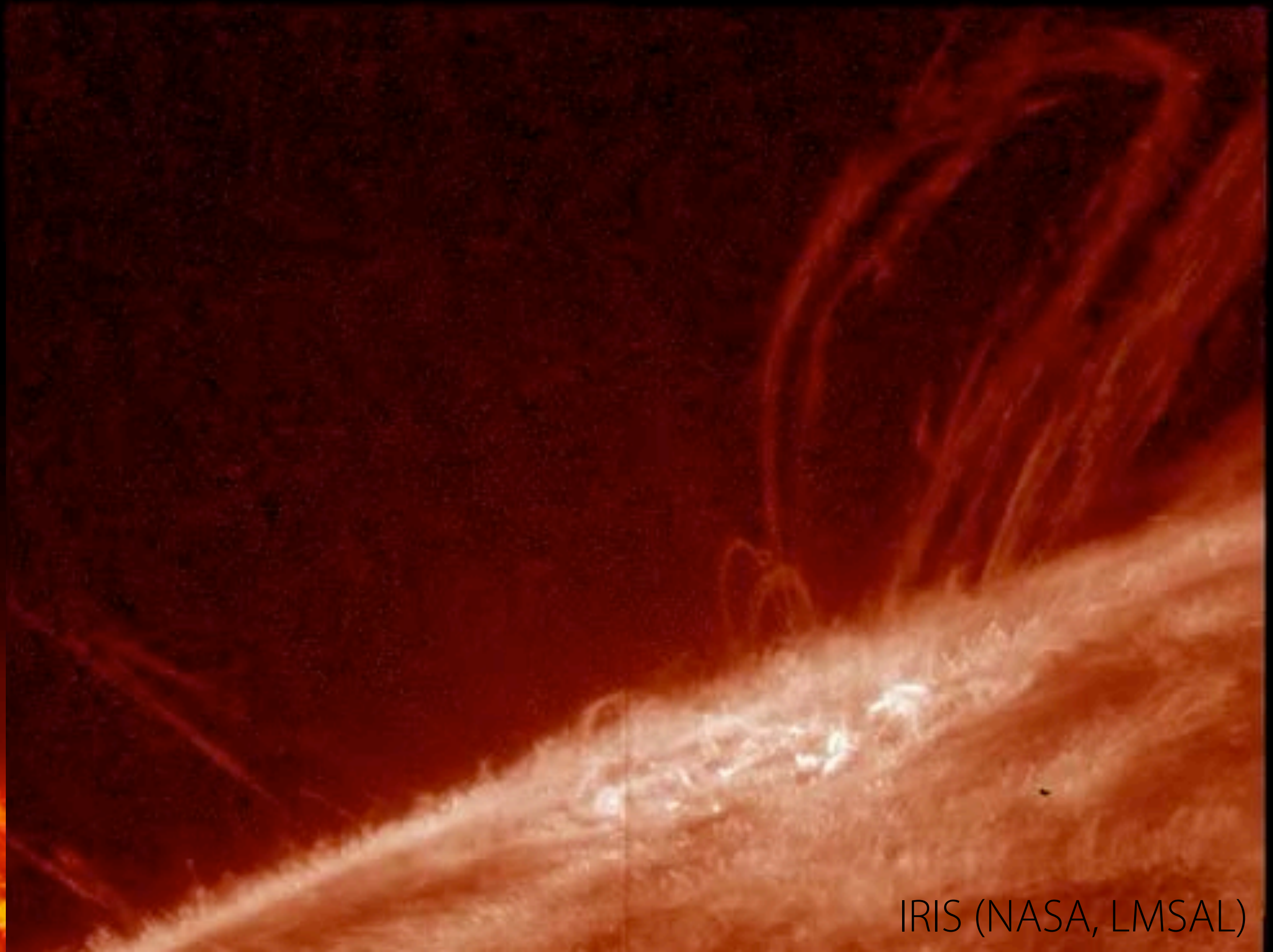
Energy loss and catastropic cooling

- **Thermal conduction** along magnetic field important for energy transport in the corona
- Energy loss/cooling
  - Thermal conduction (dominates for hot coronal loops, $T_e >\sim 3\ 10^6$ K)
  - Radiative energy loss dominates in warm loops ($T_e \approx 1–3$ MK).
- Radiative losses not compensated for (by conduction of local heating) at $T_e < 10^6$ K
- Radiatively-driven thermal instabilities: "**catastrophic cooling**" / "condensation".

➡ **Coronal rain:** "cooled+condensed plasma blobs fall down guided by magnetic fields

- Observed in active regions, post-flare loops, eruptive filaments, and prominences)
- clumpy and stranded

NASA/SDO



IRIS (NASA, LMSAL)