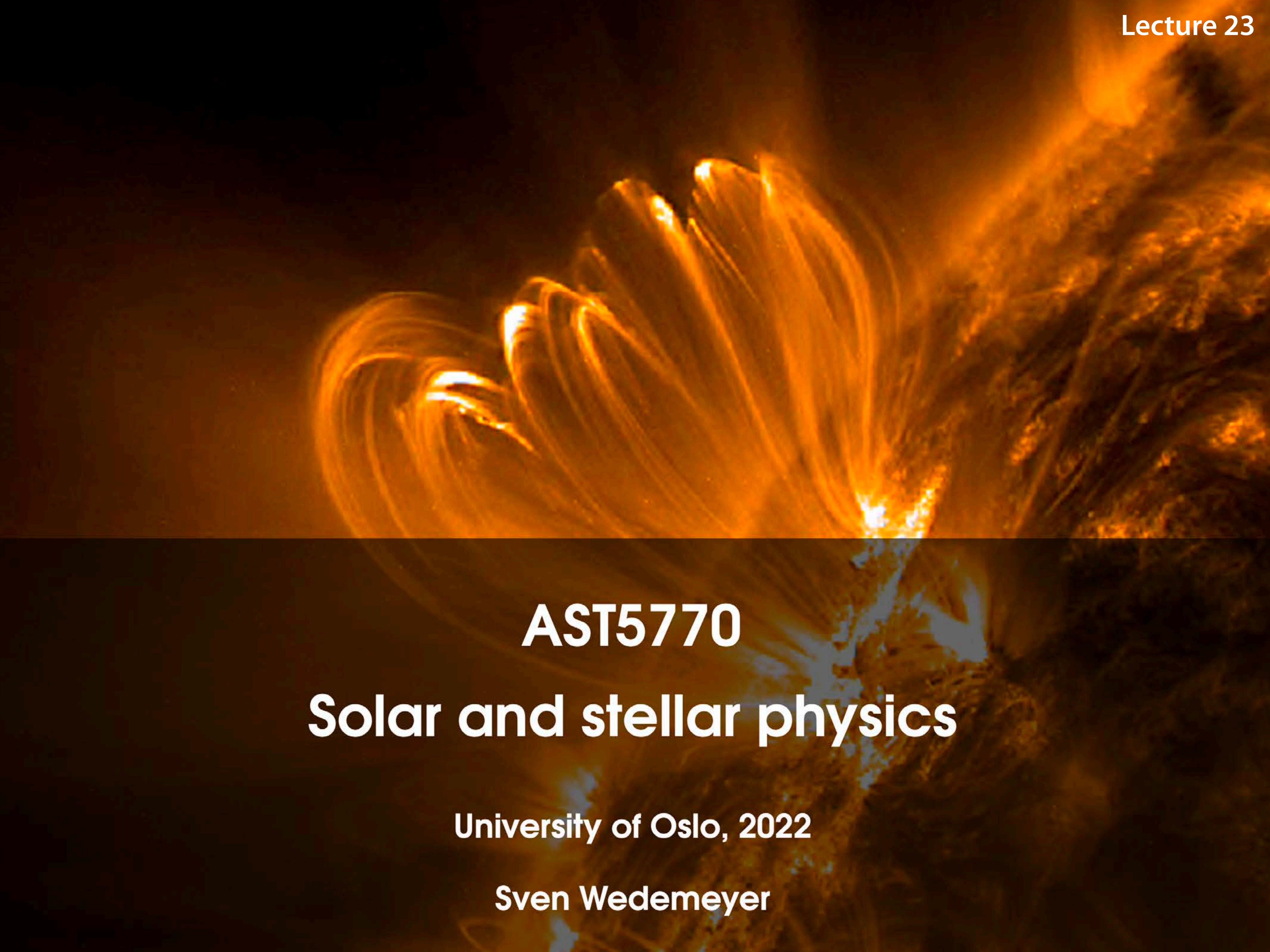


AST5770

Solar and stellar physics

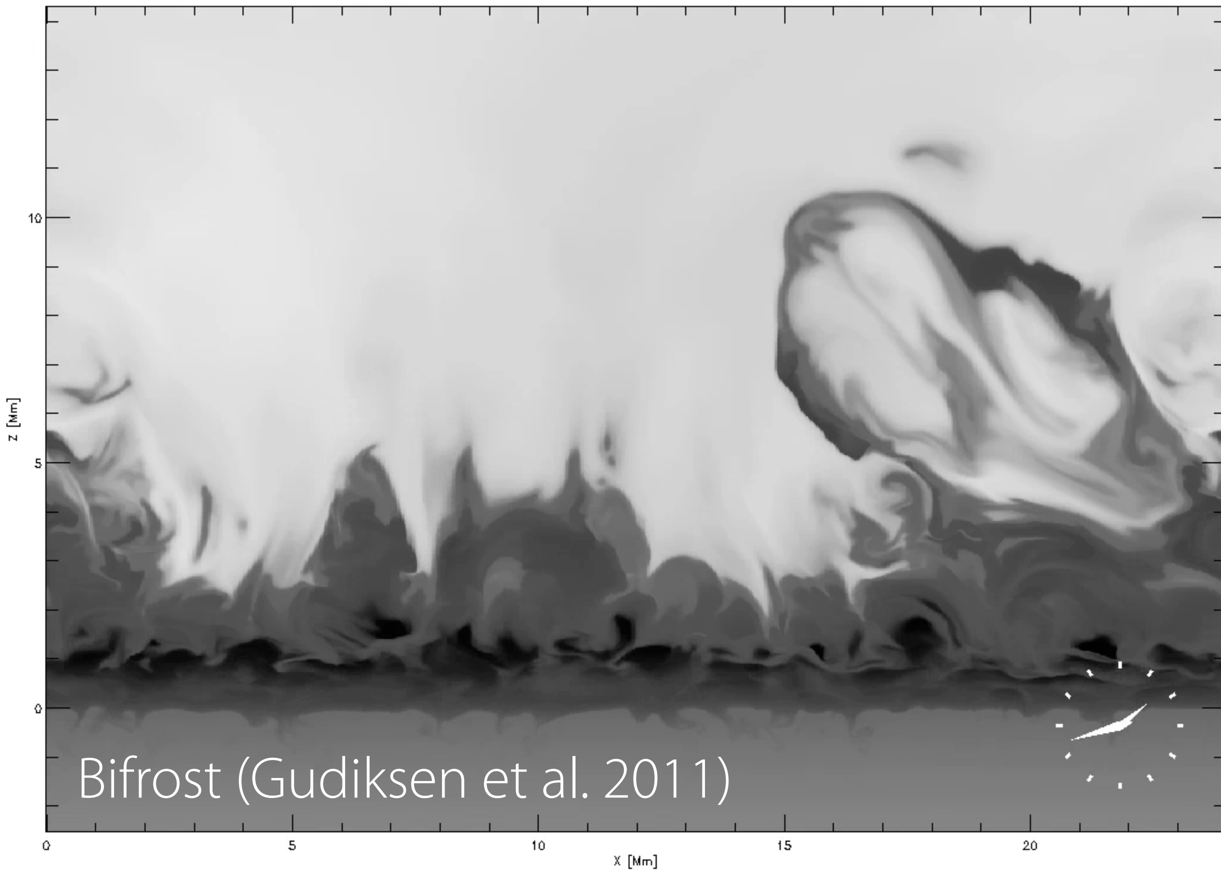
University of Oslo, 2022

Sven Wedemeyer

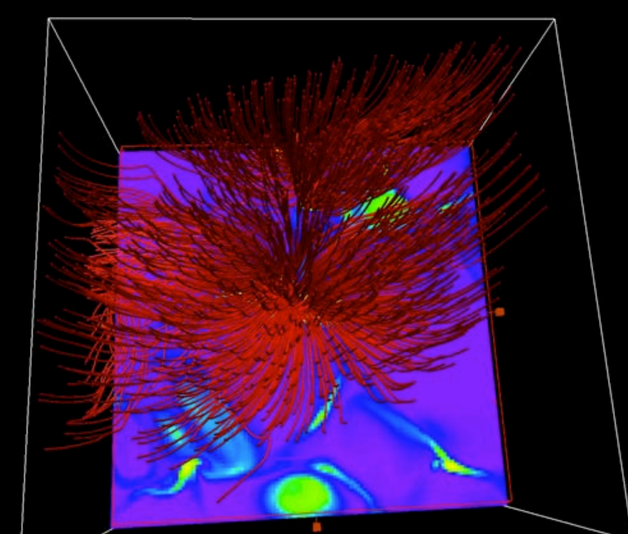
The solar atmosphere

The solar atmosphere

Highly complex and dynamic structure



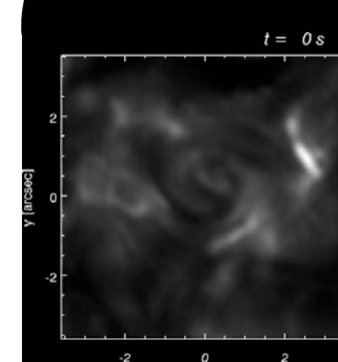
Bifrost (Gudiksen et al. 2011)

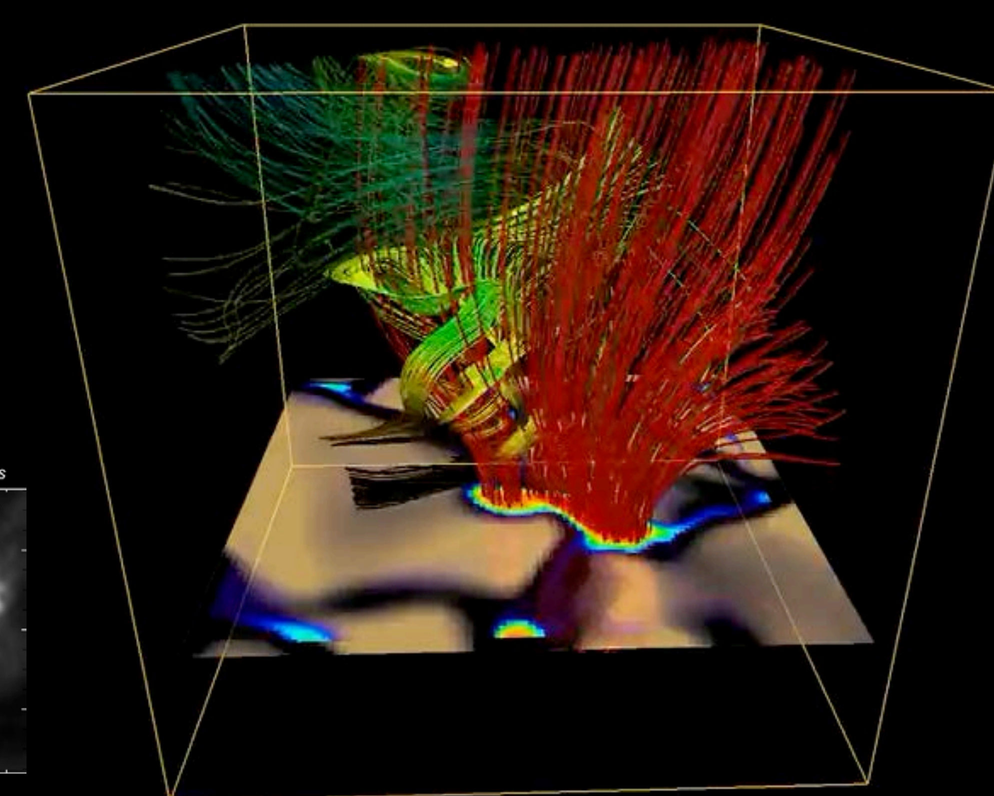


CO5BOLD (close-up, Freytag et al 2012)

- 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)





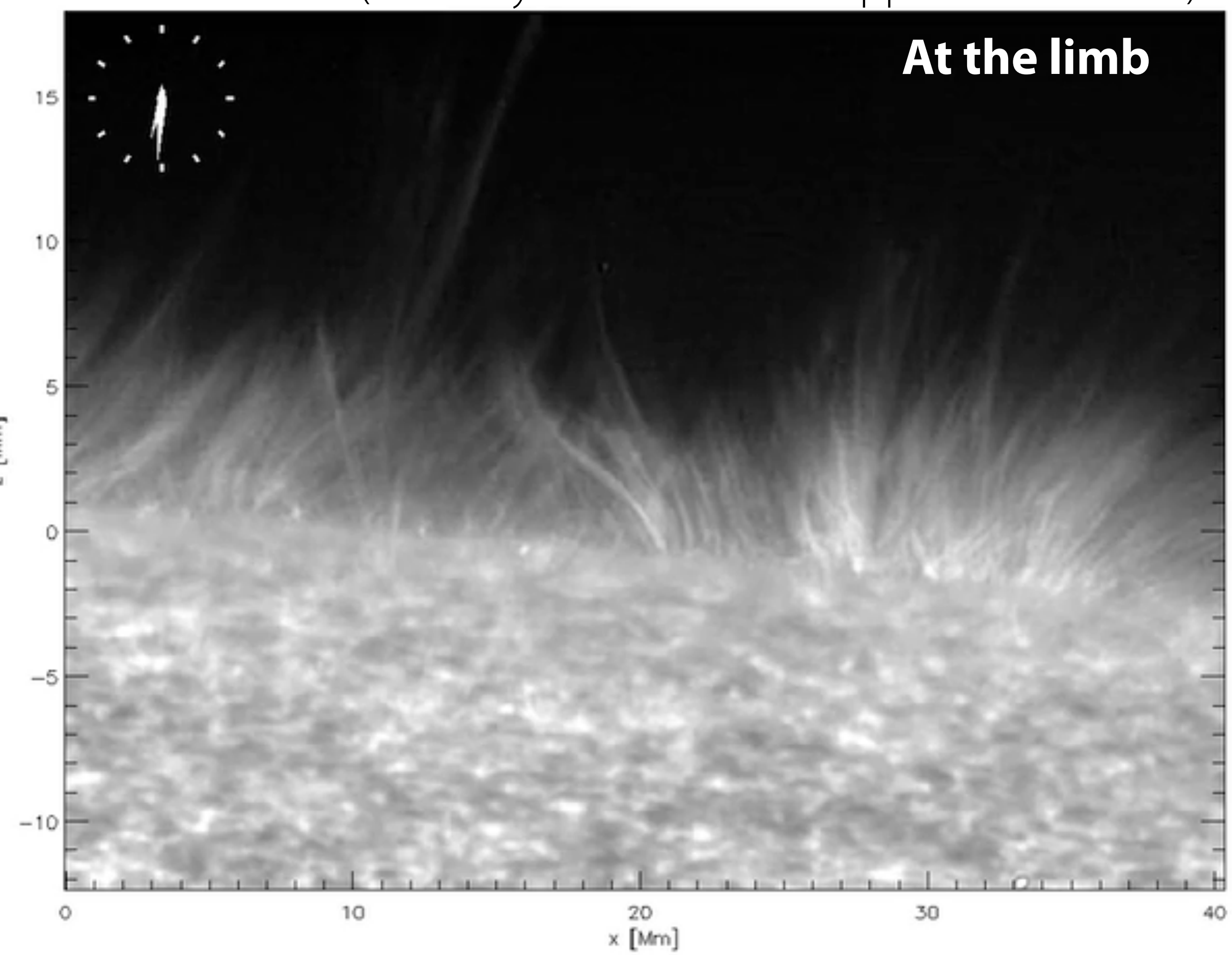
Wedemeyer et al (2012)

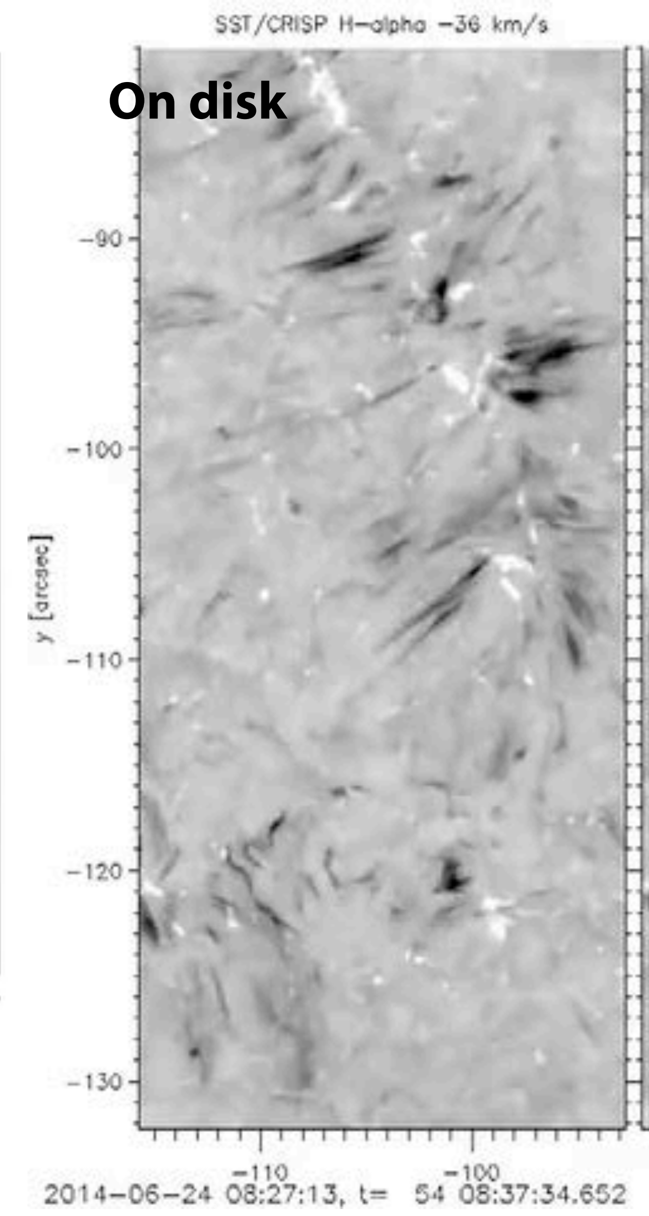
The solar atmosphere

Spicules

- Ubiquitous needle-like phenomenon on the Sun, visible at the limb (filaments when observed on-disk)
- Dynamic + short-lived but ubiquitous
- Jets of plasma shooting up at high speeds along magnetic field

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



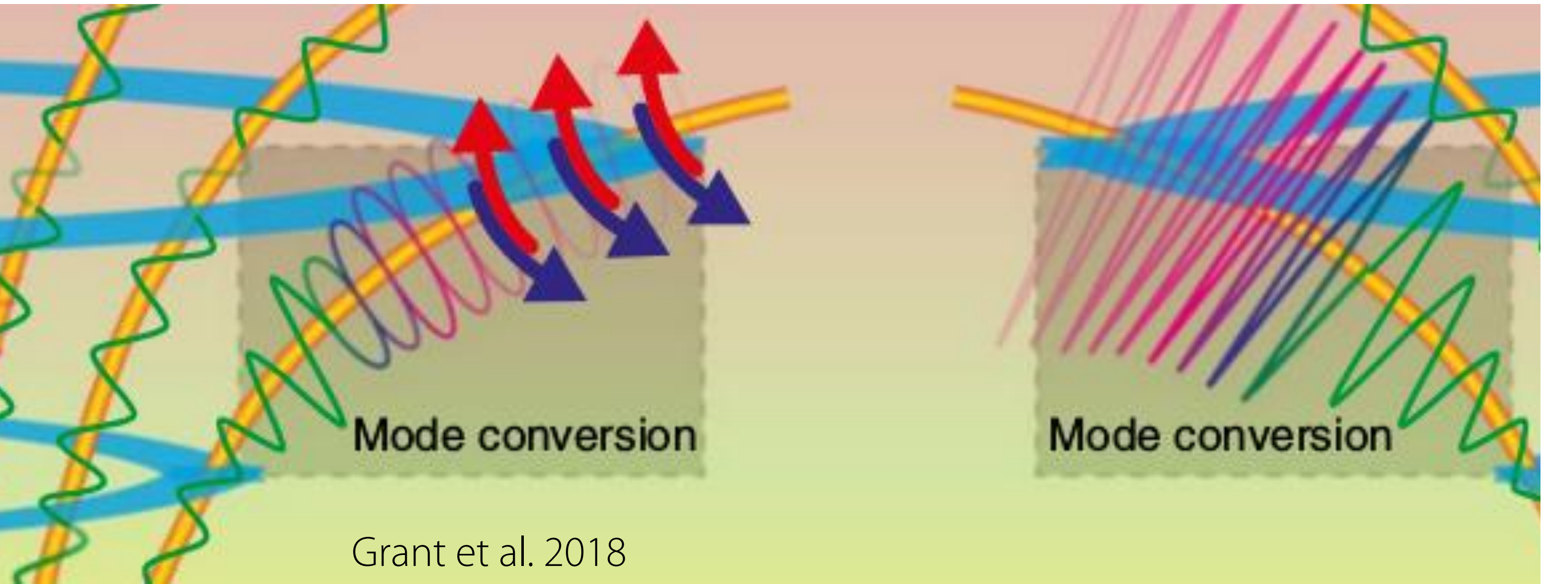


- May serve as magnetic tunnels through which the coronal plasma is "refuelled"
- Act as waveguides for Alfvén waves
- Carry, in principle, enough energy to play an important role for heating of the quiet Sun corona and for acceleration of the solar wind

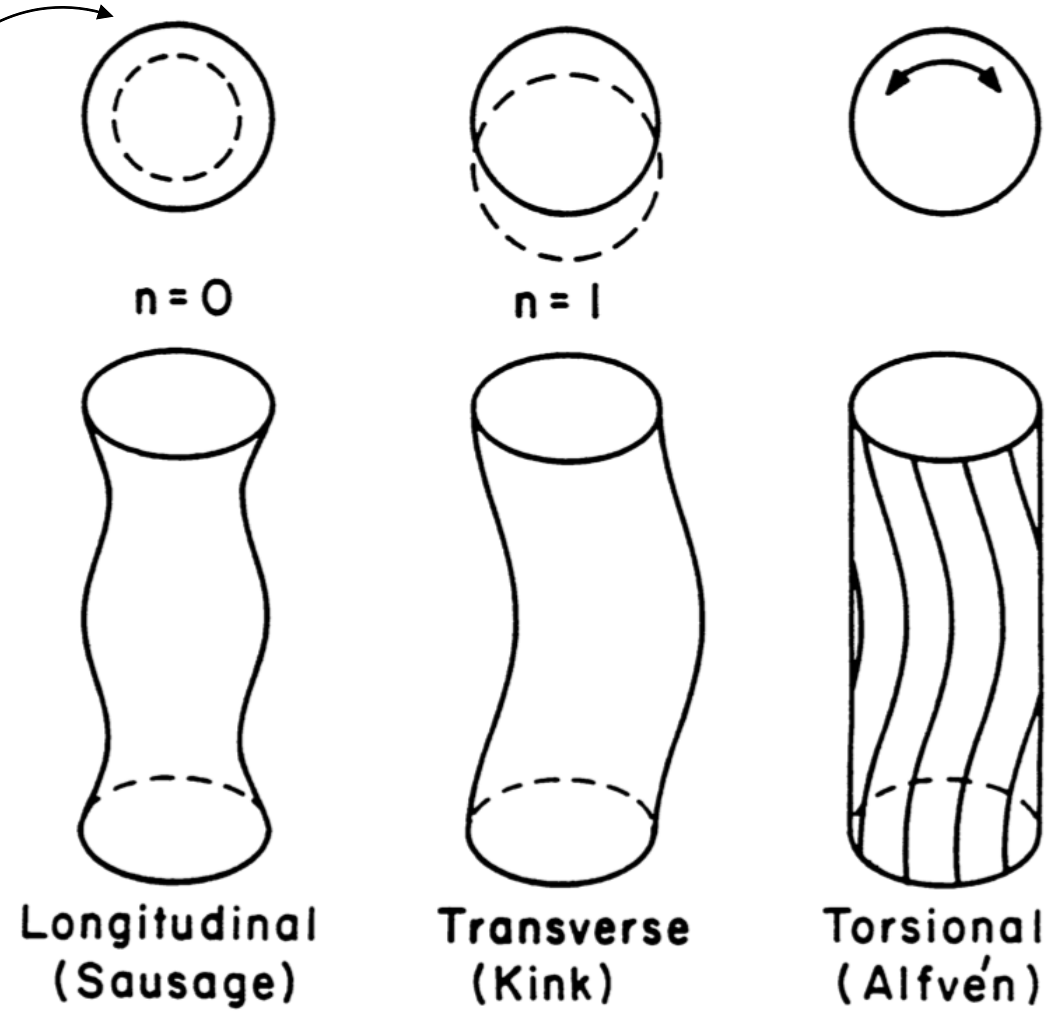
The solar atmosphere

Waves in the solar atmosphere

- **Different wave modes**, incl.
  - **Acoustic** waves
  - **Fast** and **slow magnetoacoustic** waves (acoustic, modified by magnetic field)
  - **Alfvén** waves (propagating along magnetic field — only in the presence of magnetic field)
- Magnetic field structures as **wave guides**
- Magnetic "flux tubes" show different waves modes
- Waves do interact & interfere, can change
  ➡ Wave mode conversion!



Grant et al. 2018



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

Modelling the chromosphere — A numerical challenge

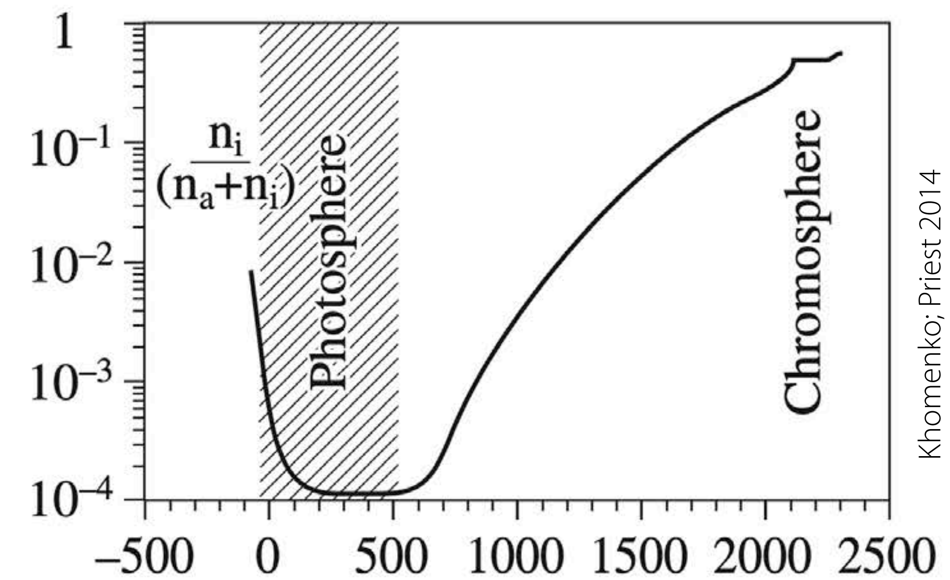
Hydrogen ionisation

- Remember: Change in temperature leads changes in (hydrogen) ionisation degree and thus the number of free electrons!
  - Fully ionised in solar interior
  - Ionisation degree drops to 10^{-4} in photosphere
  - Increases to high values in the chromosphere
- Strong temperature fluctuations in chromosphere!
- Instantaneous equilibrium: Ionisation degree is a function of local temperature, follows changes.
- BUT: Ionisation and especially recombination (of H^+ and e^-) occur on finite time scales!
- Hot shock fronts ionise quickly but recombination in shock wake takes time

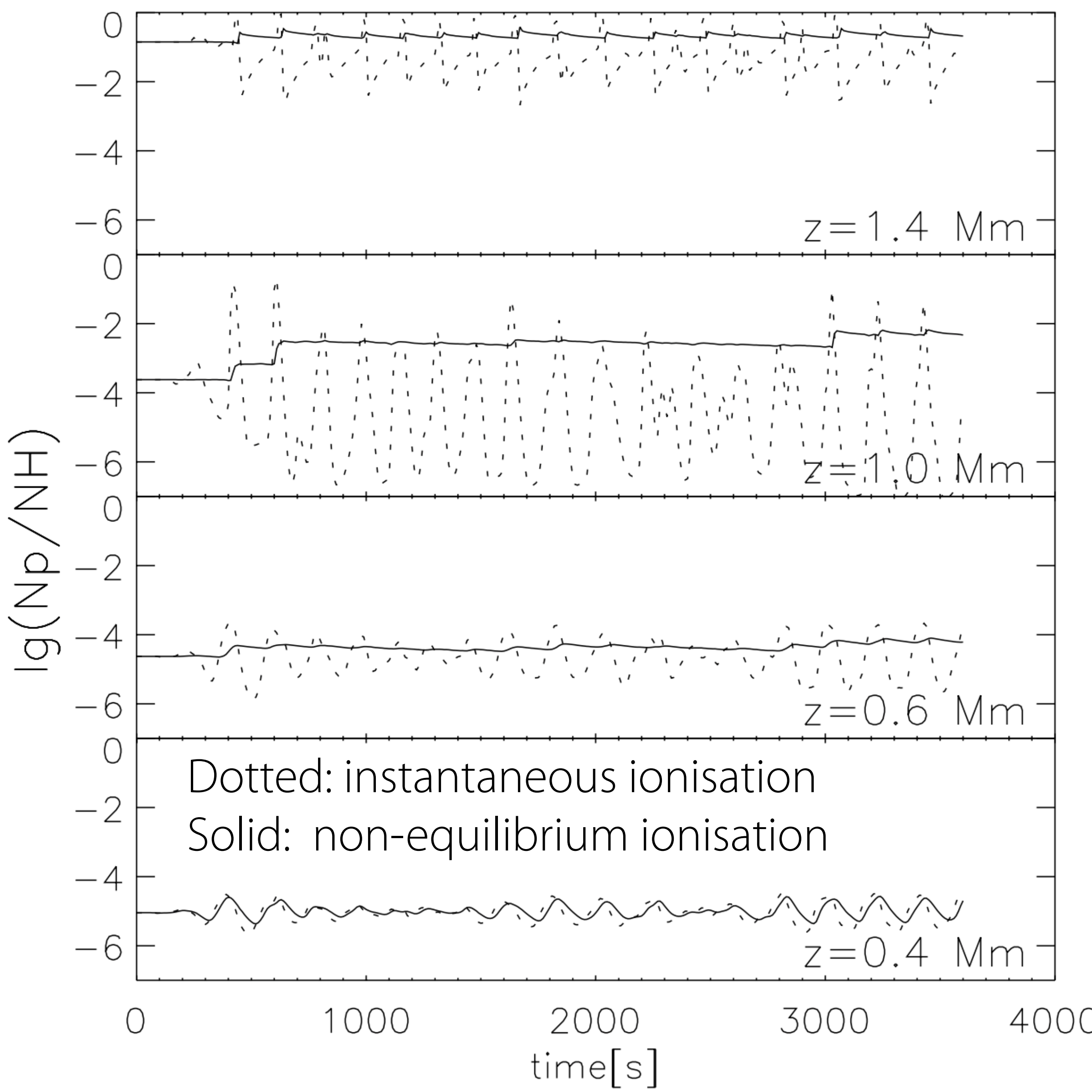
➡ Ionisation degree lacks behind

➡ Time-dependence of ionisation needs be taken into account for realistic electron densities in chromosphere!

- First shown in by 1D by Carlsson & Stein (2002)



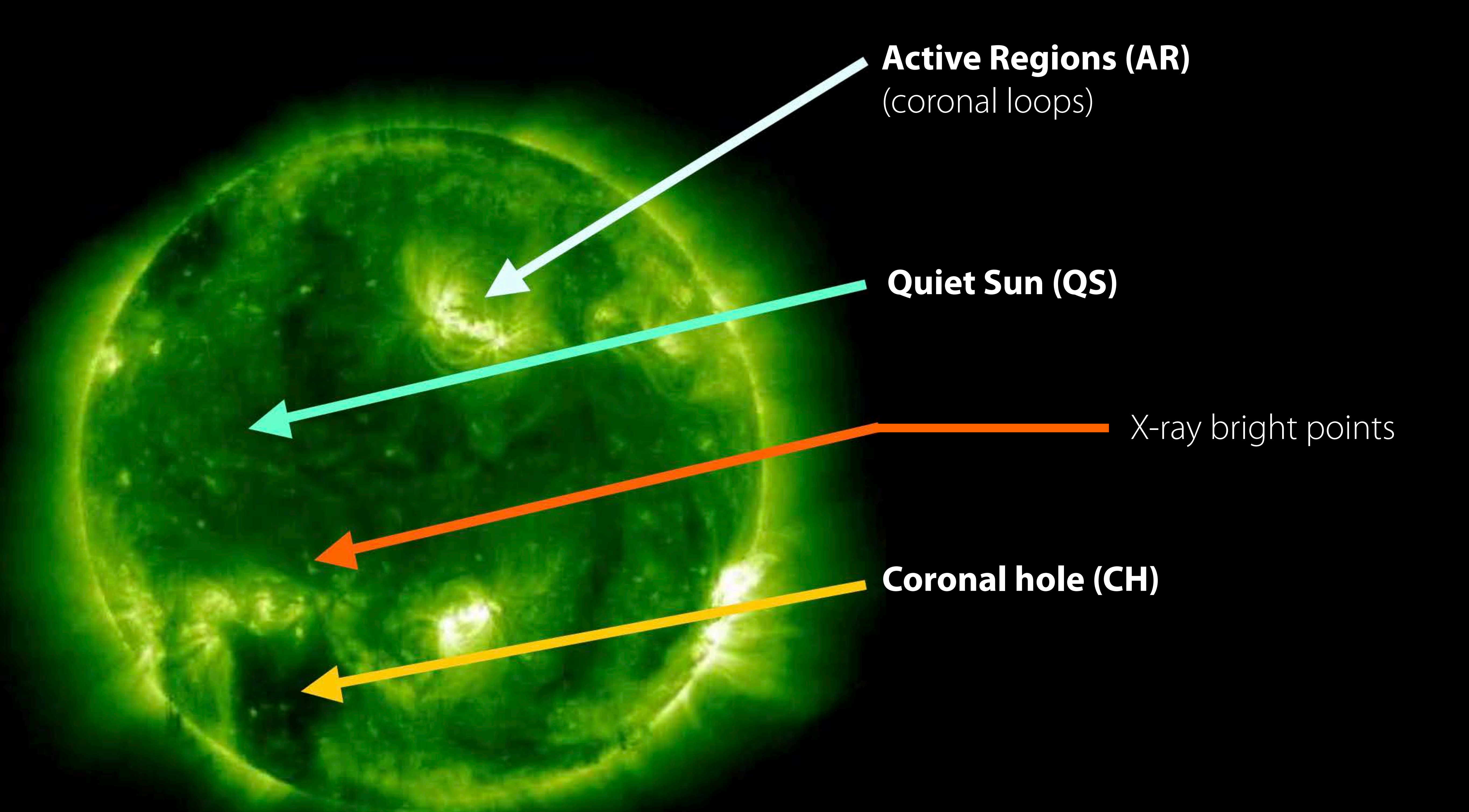
Khomenko; Priest 2014



Corona

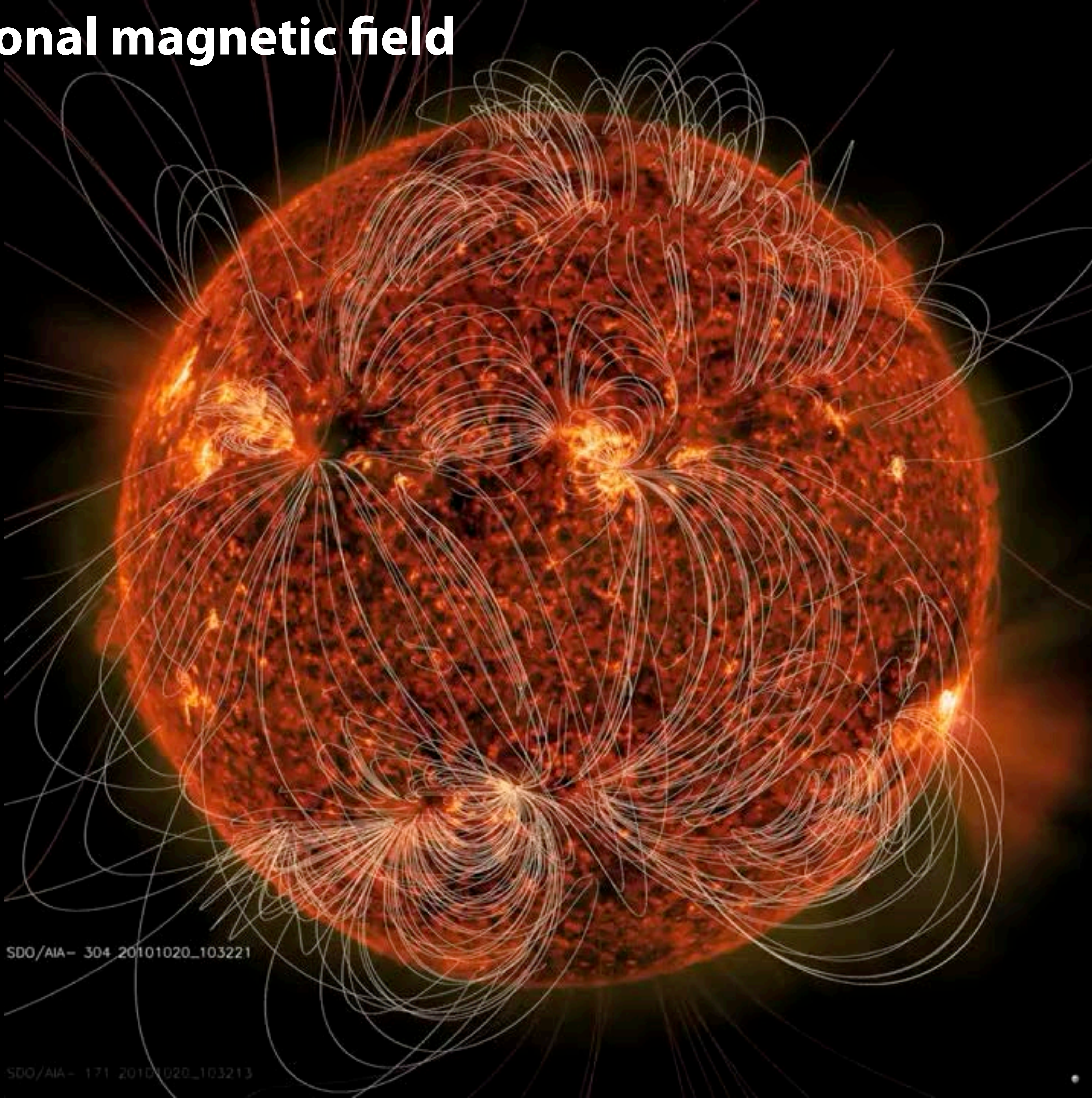
Corona

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



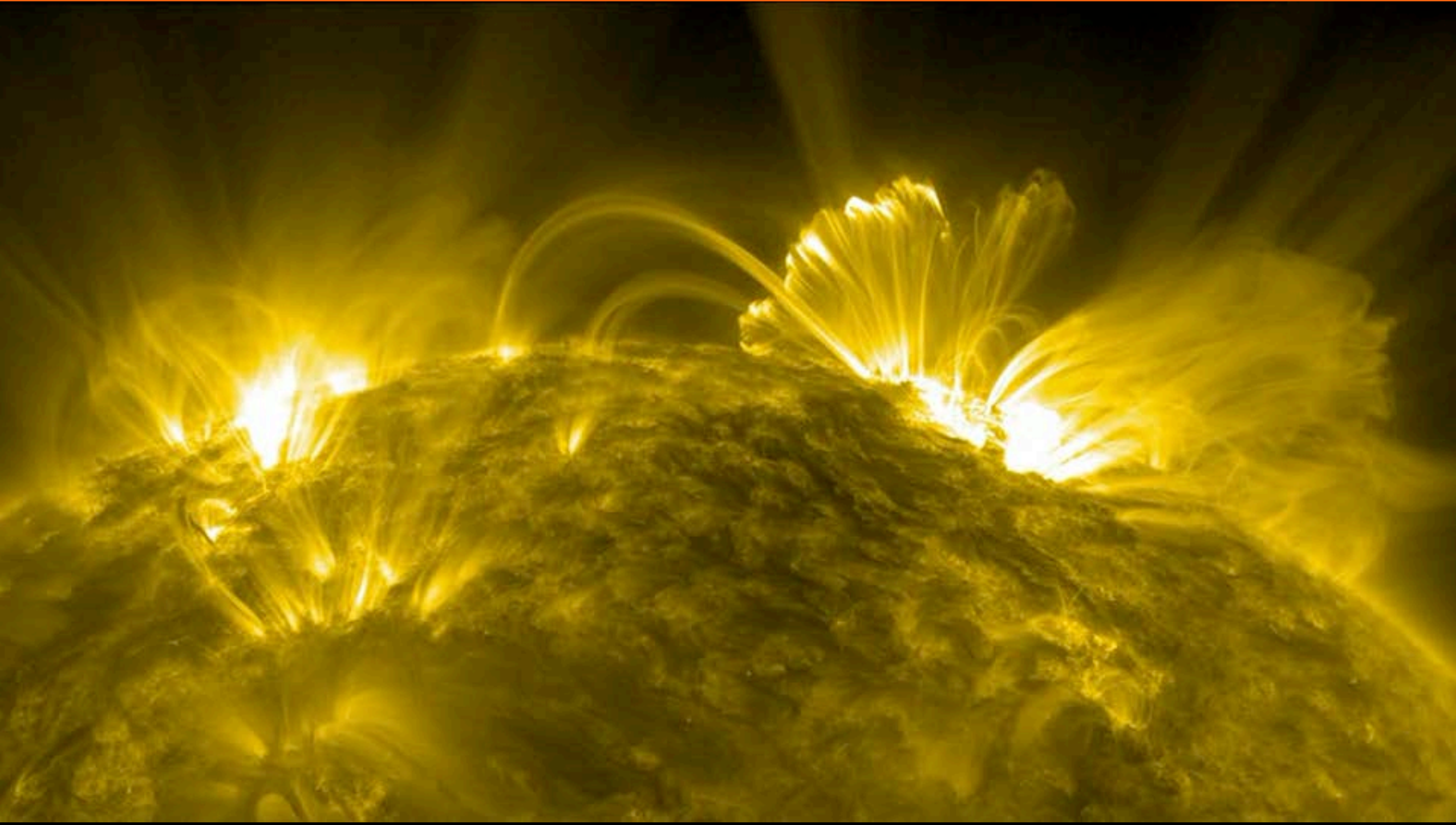
Fe XII 19.5nm (1.5 MK)

Coronal magnetic field



NASA/SDO - HMI

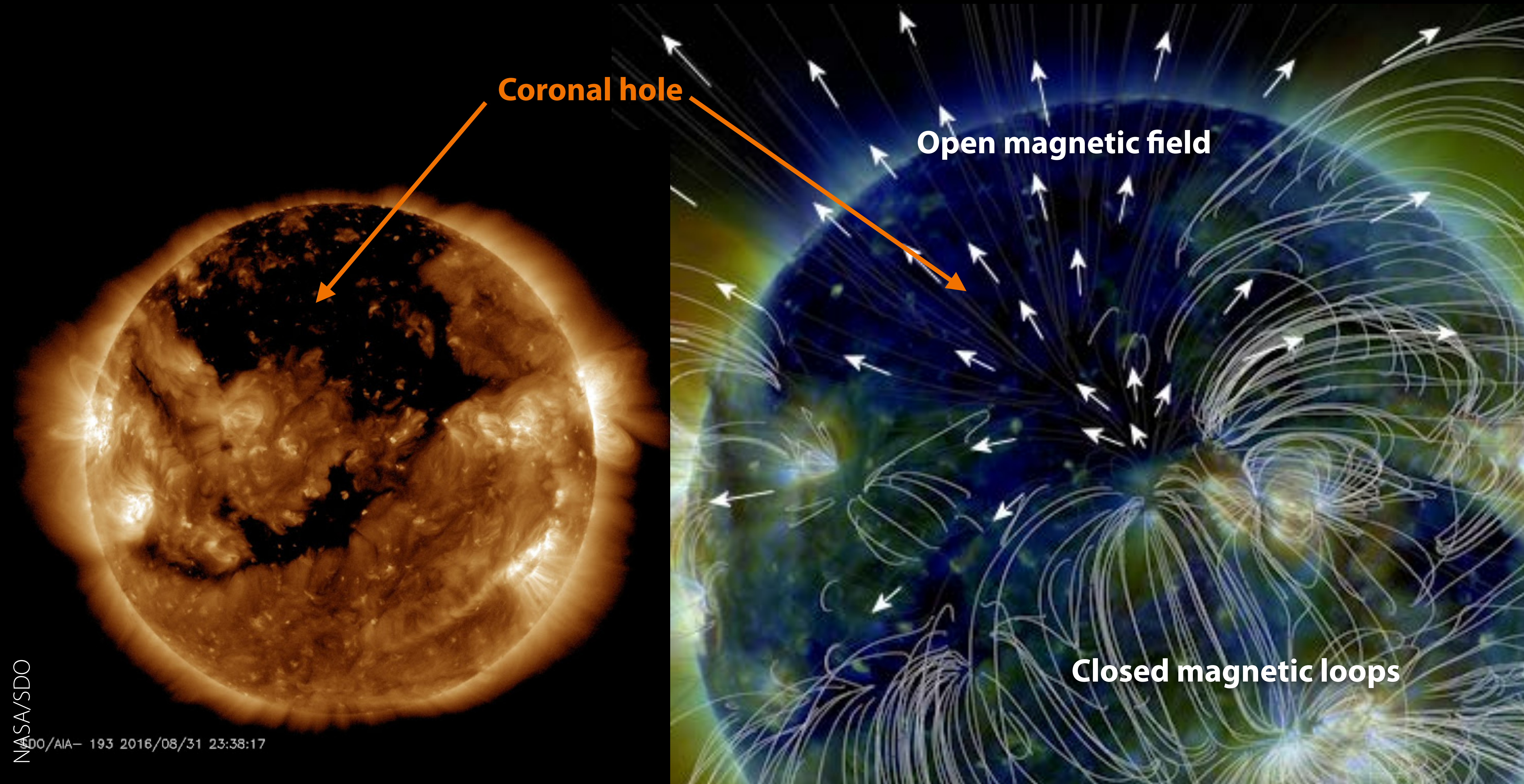
Corona



Corona

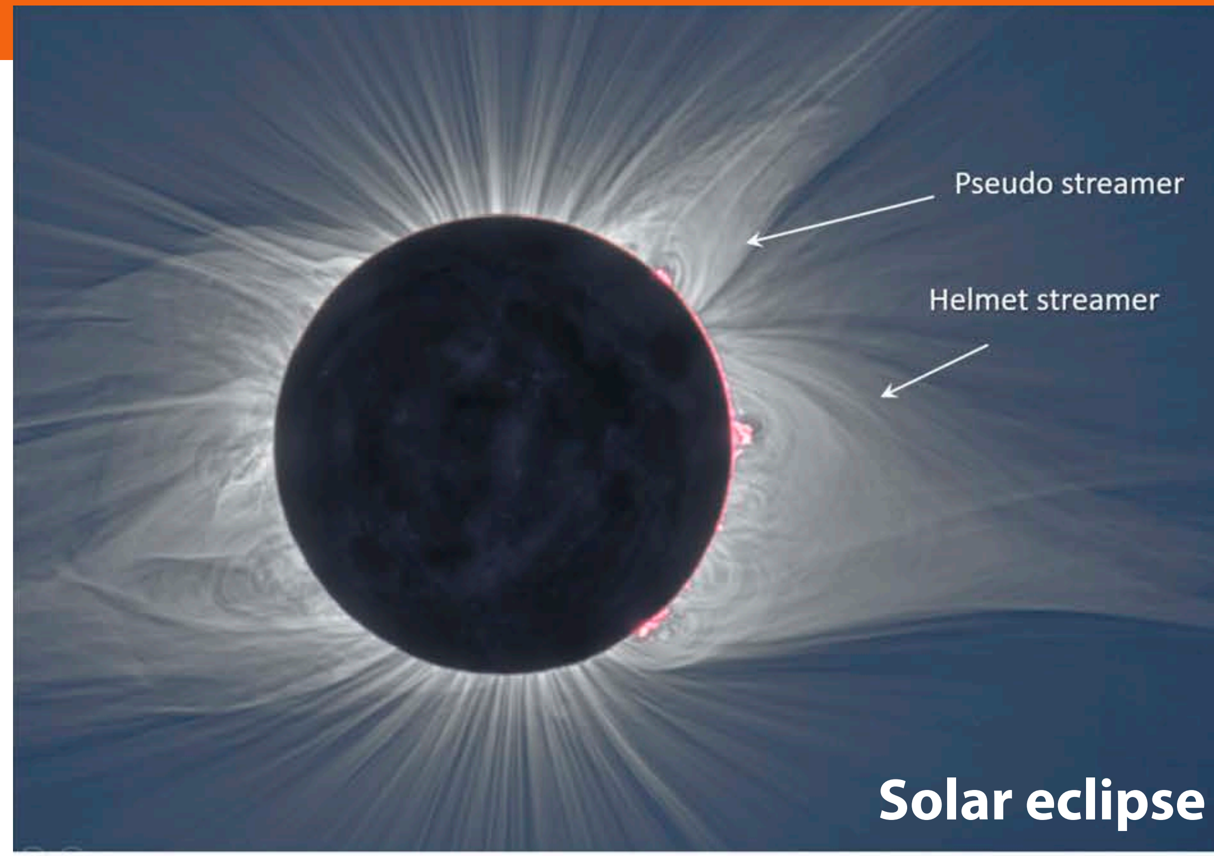
Coronal magnetic field

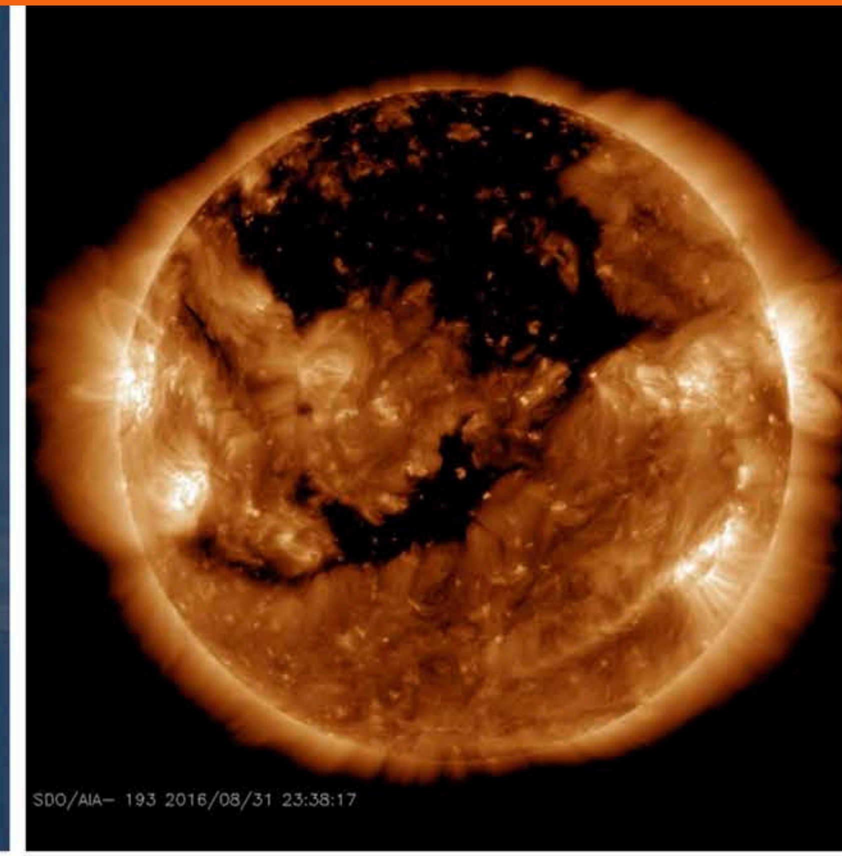
- **Open field lines in coronal holes!**
- Coronal holes can appear all over the Sun, incl. at the poles

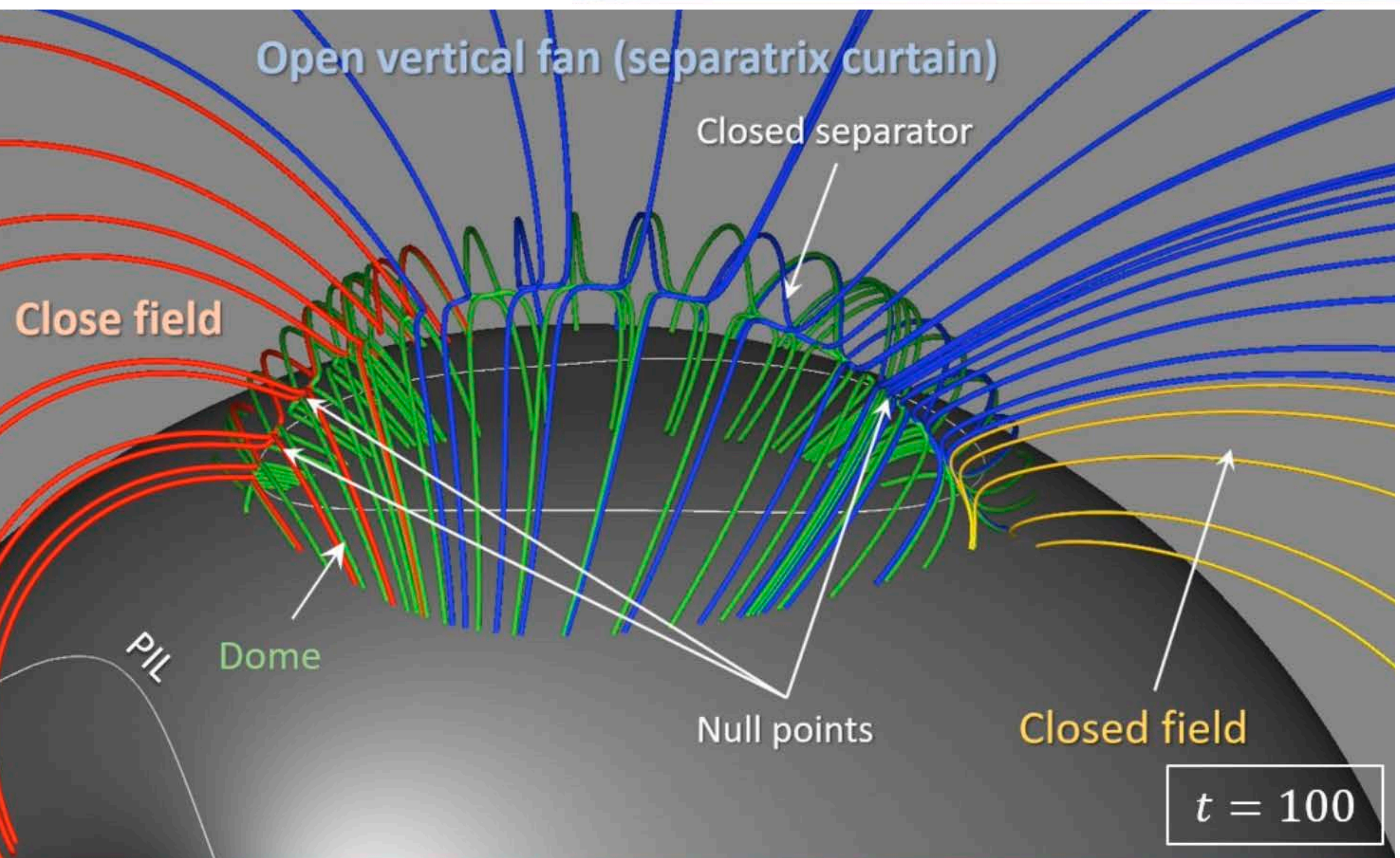


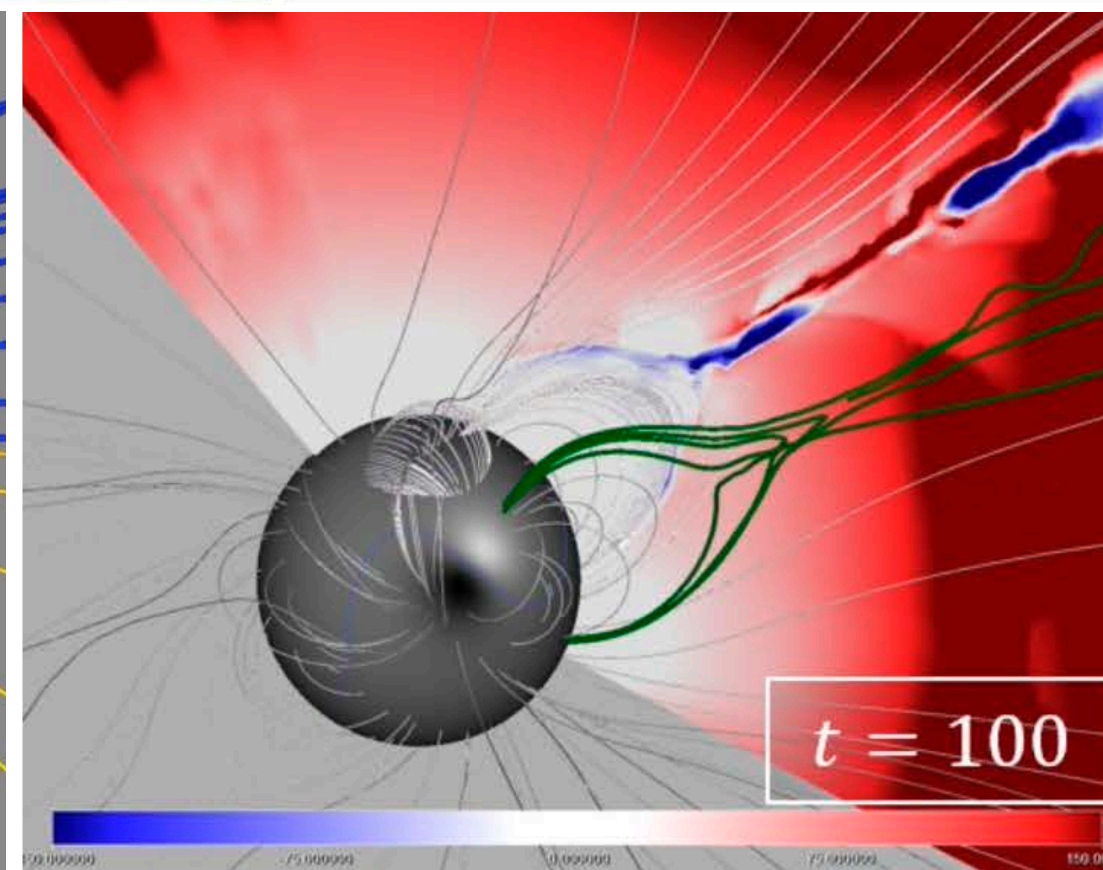
Corona

Streamers





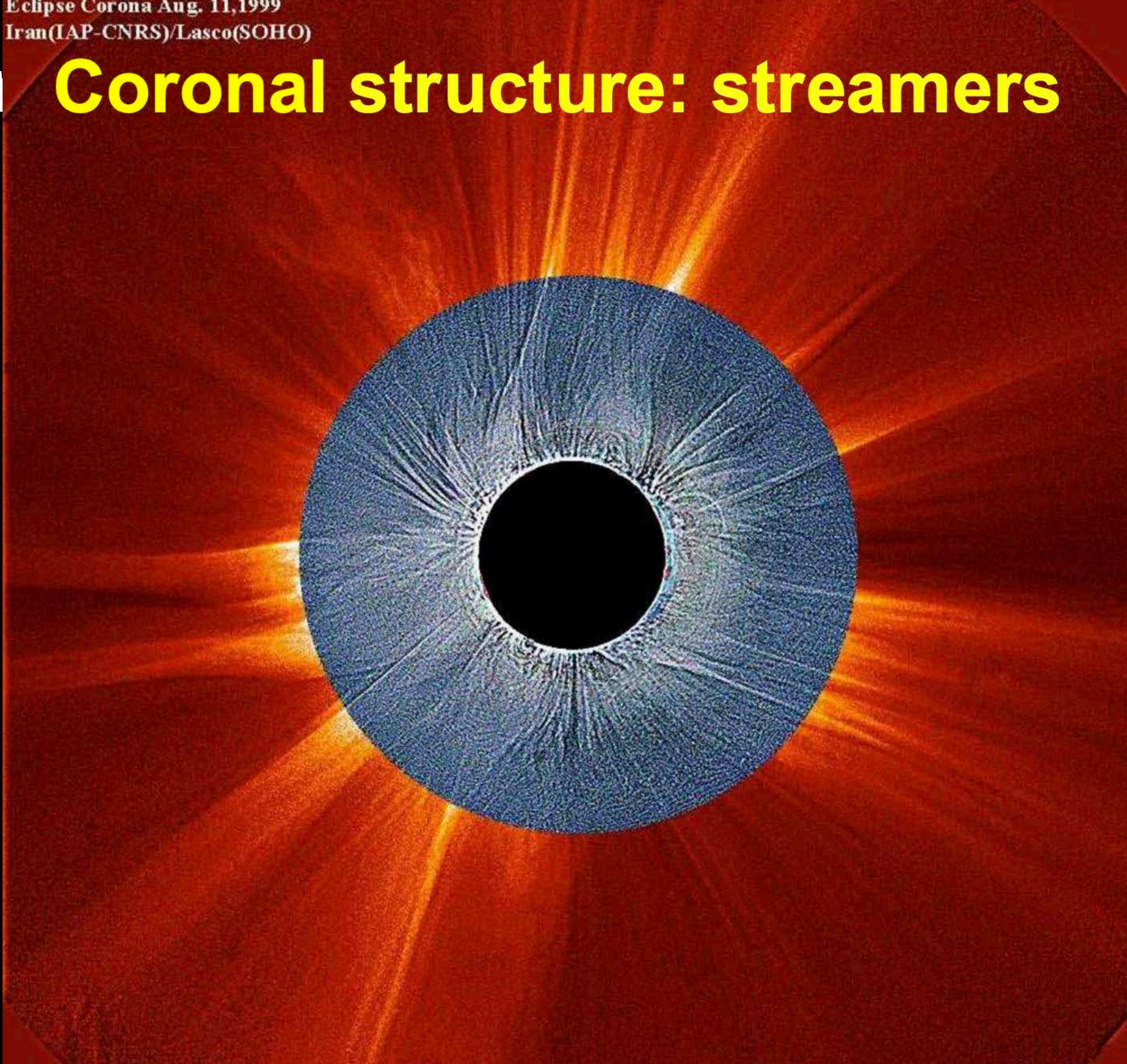




Pellegrin, Masson & Pariat

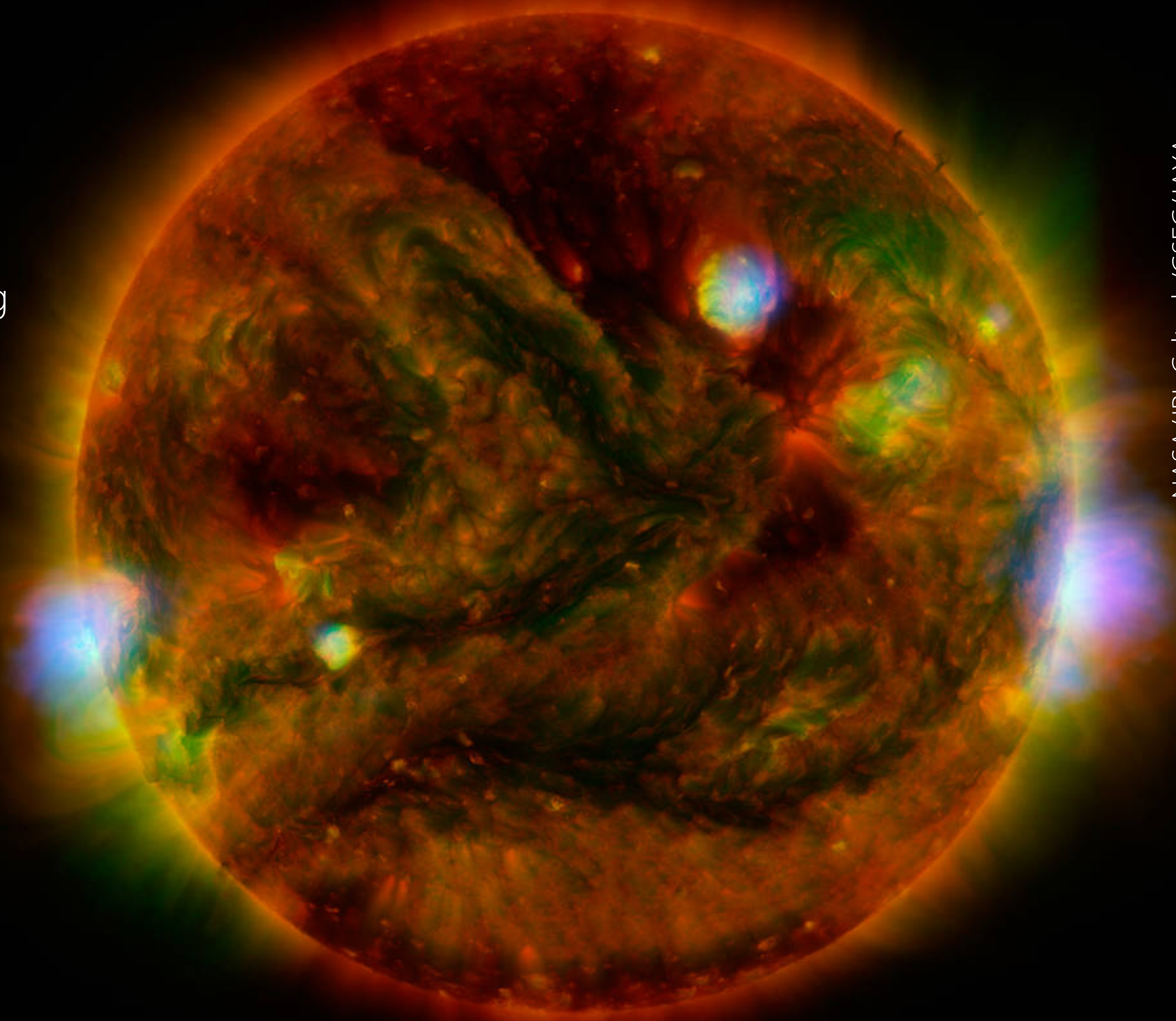
Cor

Coronal structure: streamers



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

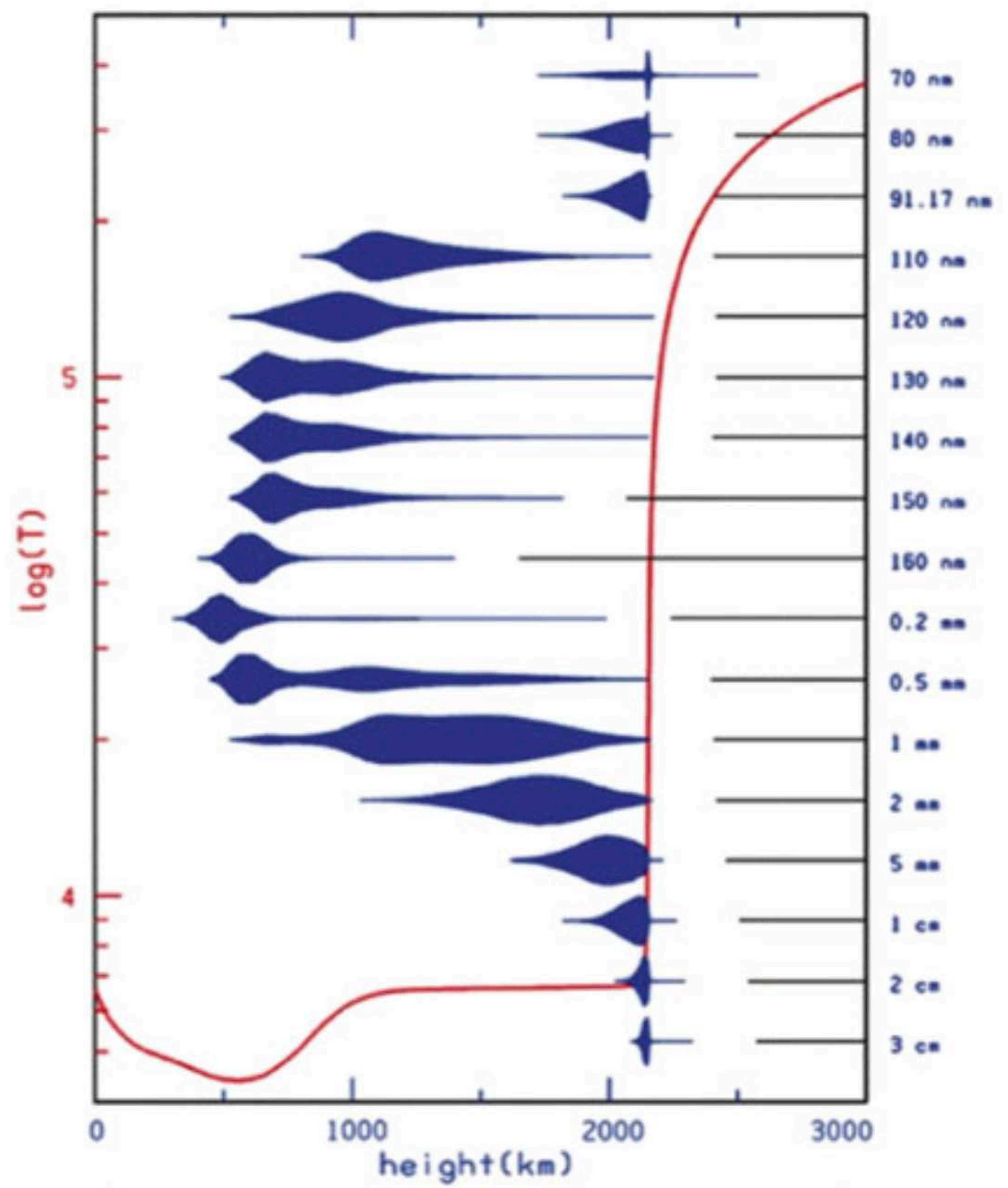
Corona

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

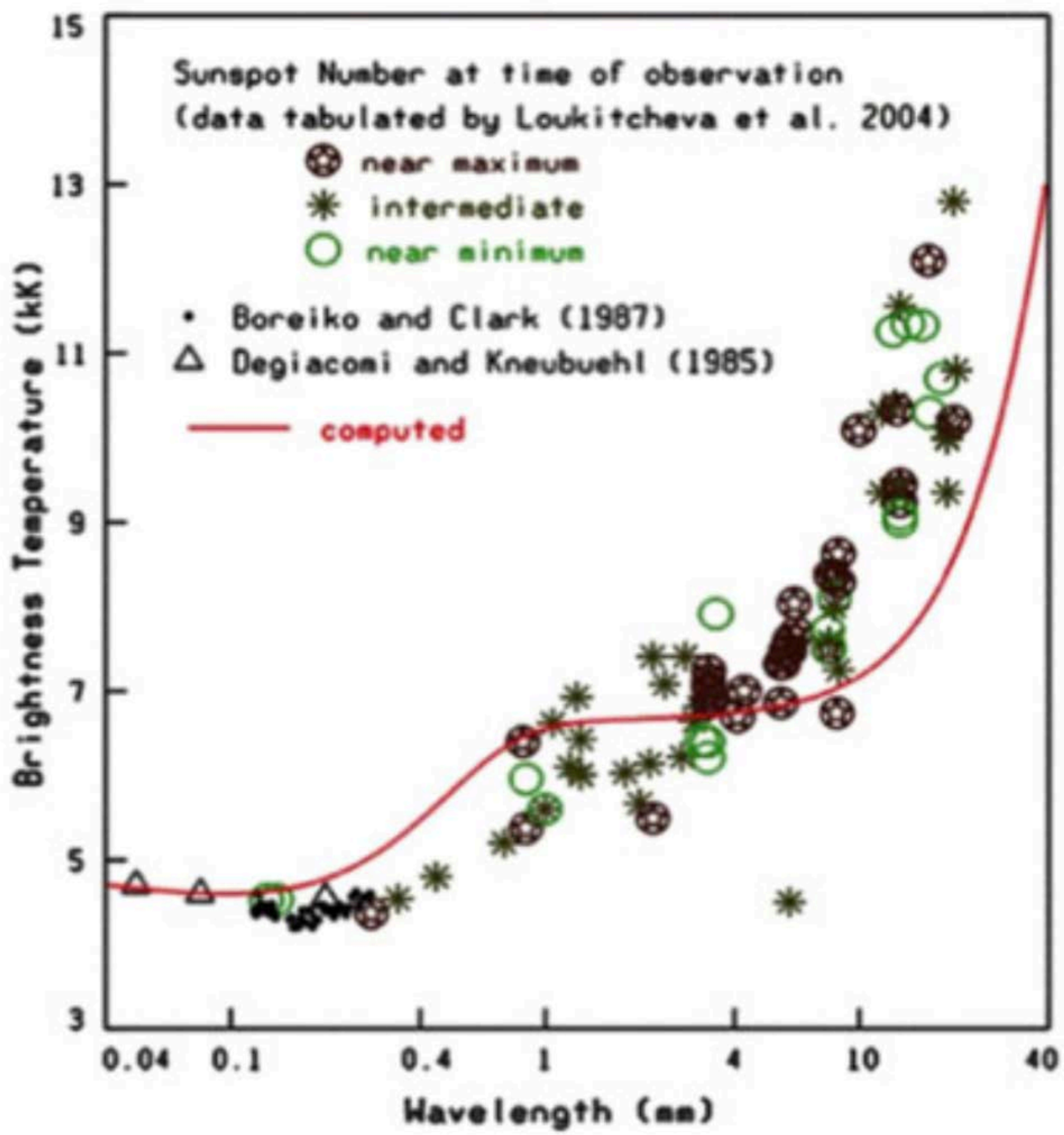
Emission

- **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

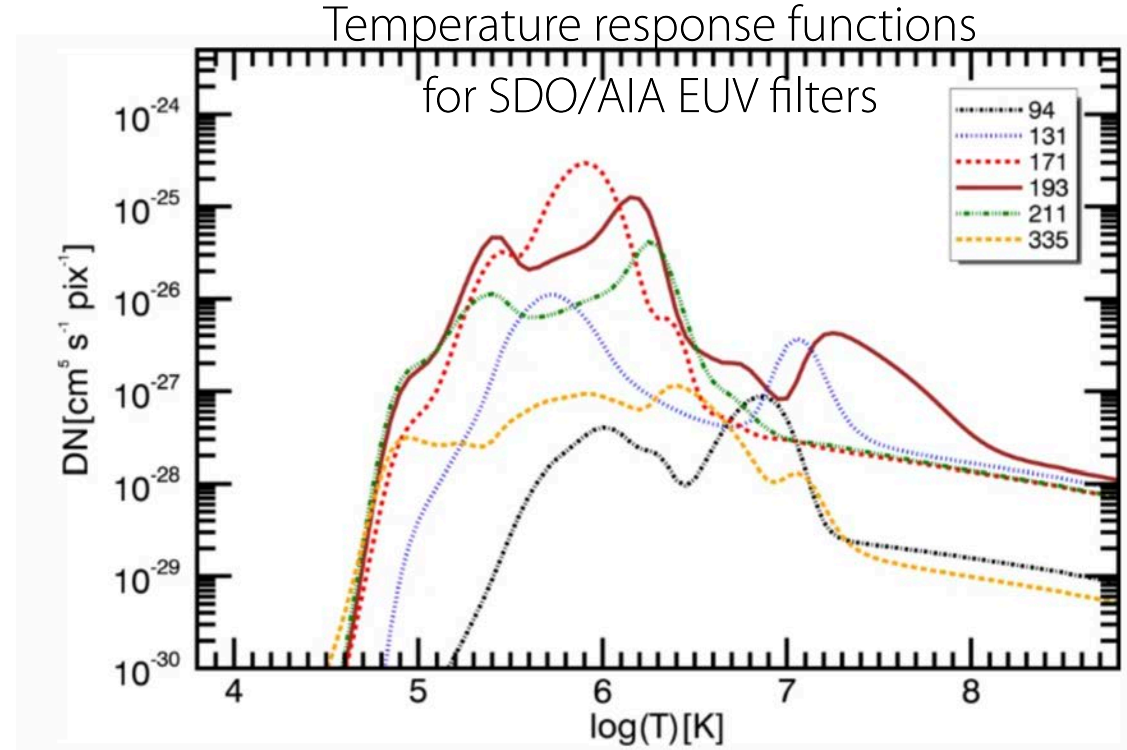
➡ Shows temperature increase in the atmosphere as continuum formation increases with wavelength



Corona

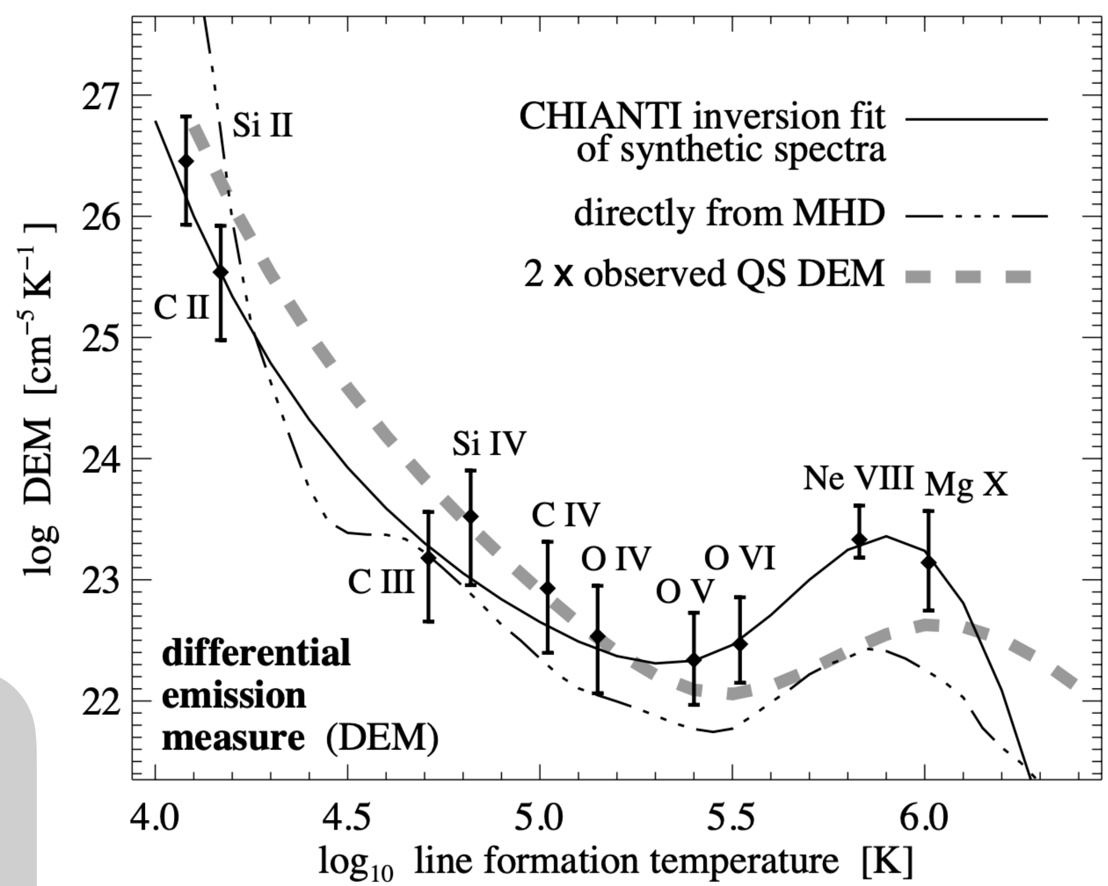
Coronal diagnostics

- 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)



Sagri et al. (2020)

- **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



Peter et al. (2005)

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

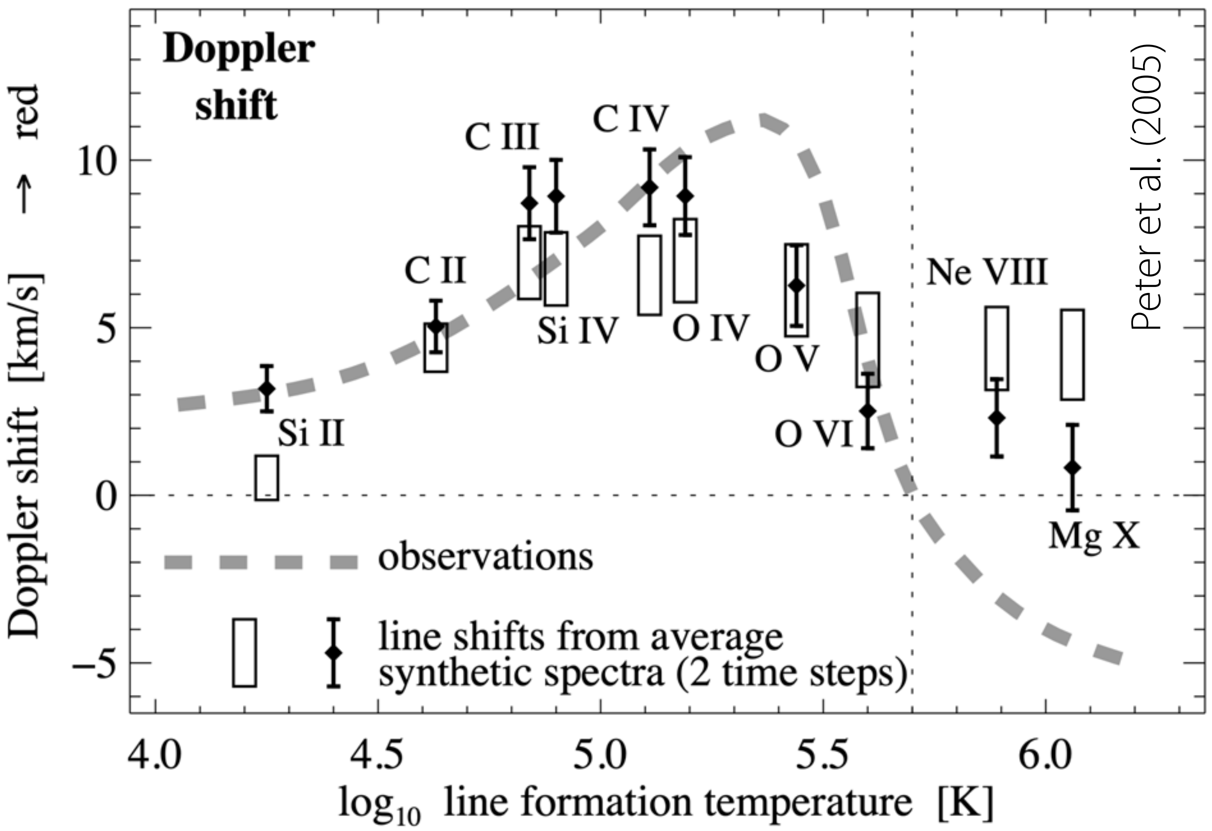
h: coordinate along line of sight
T: temperature
n: (electron) density

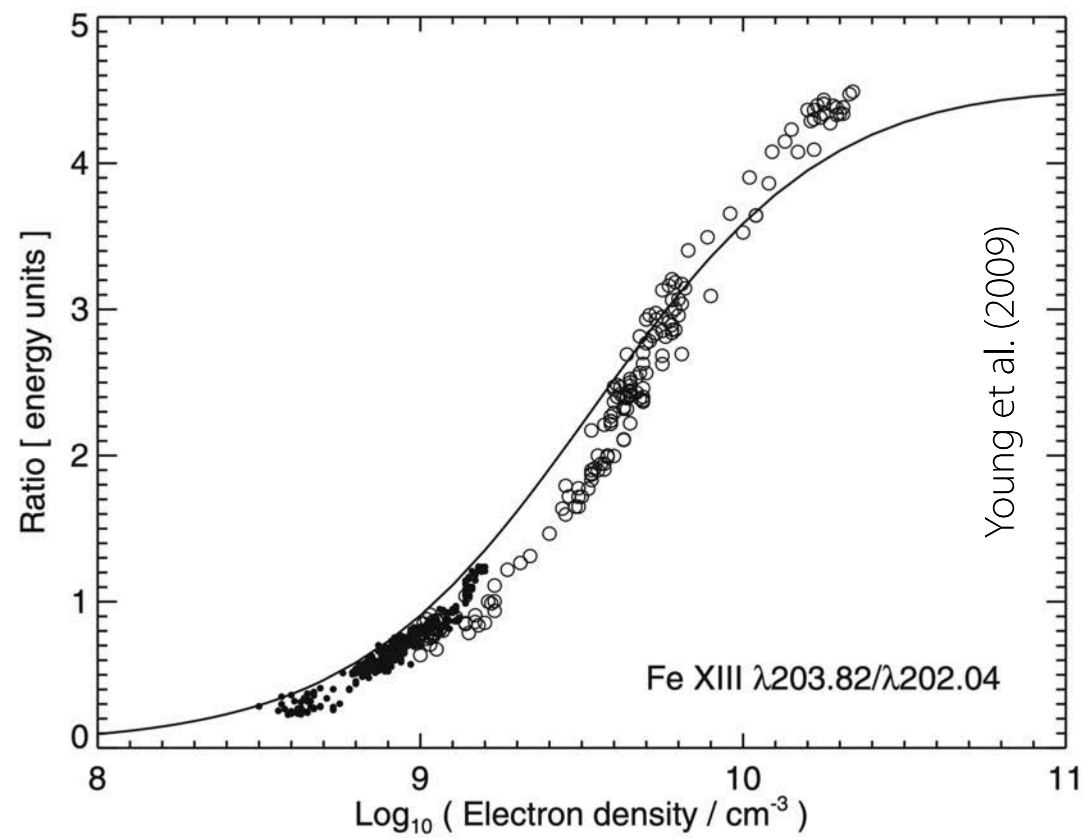
Corona

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

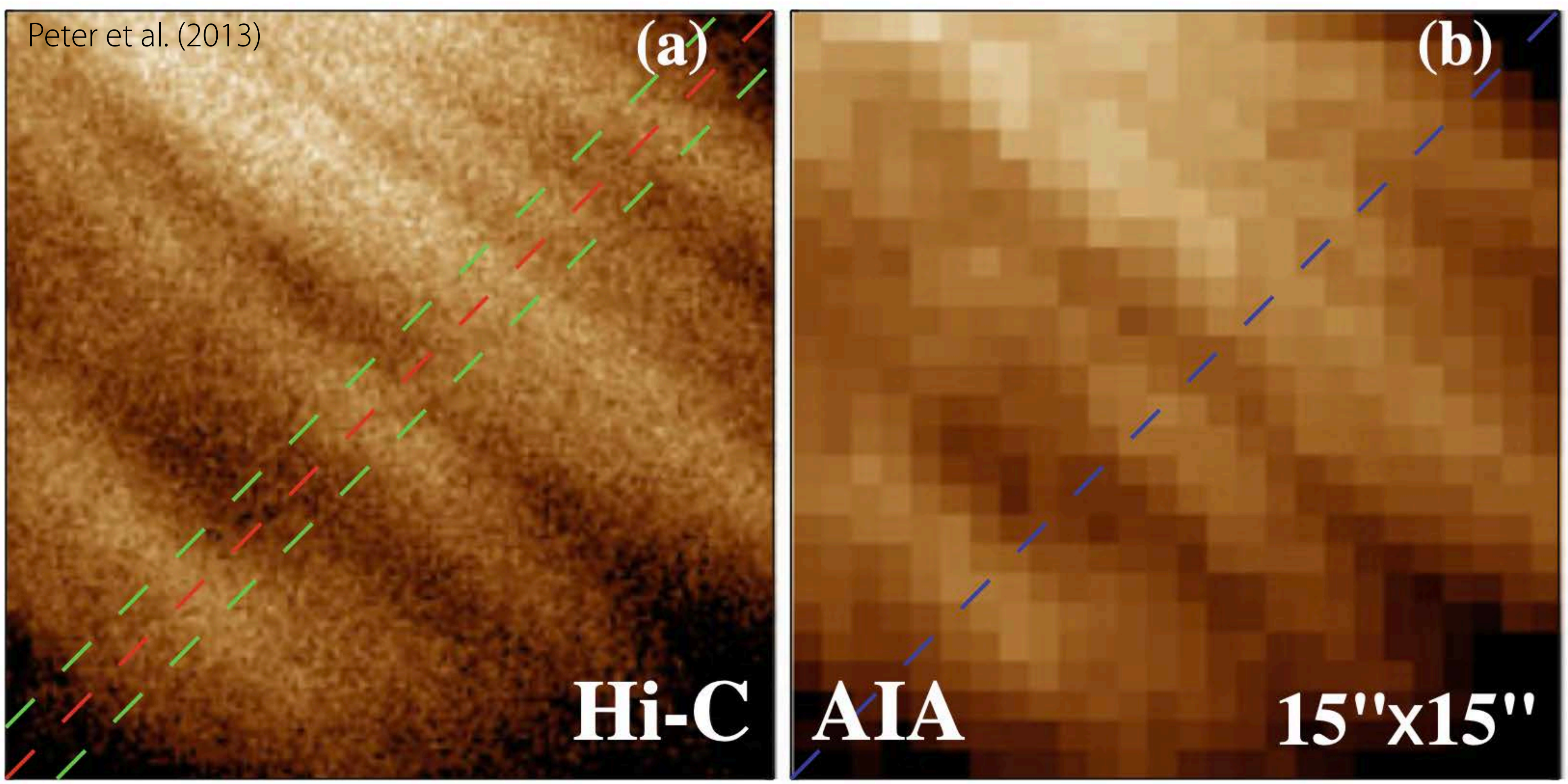




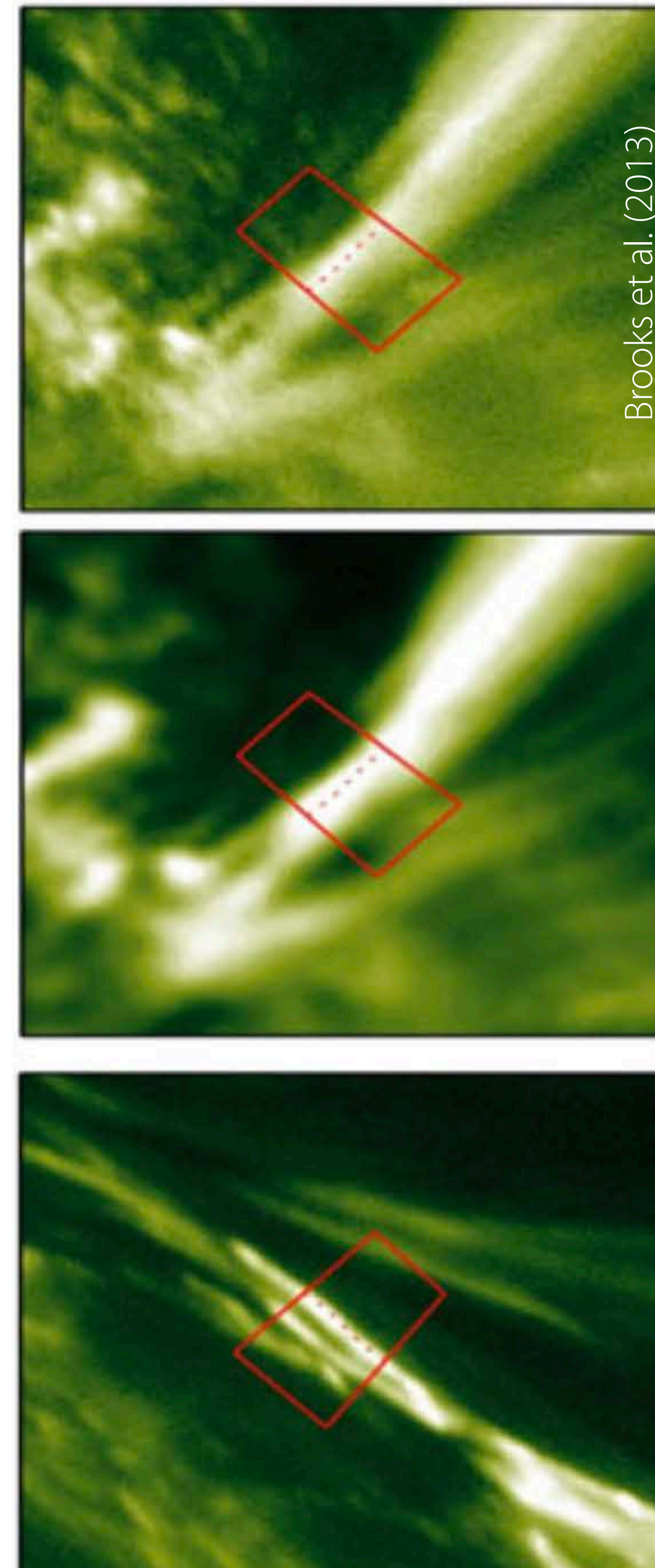
Corona

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)

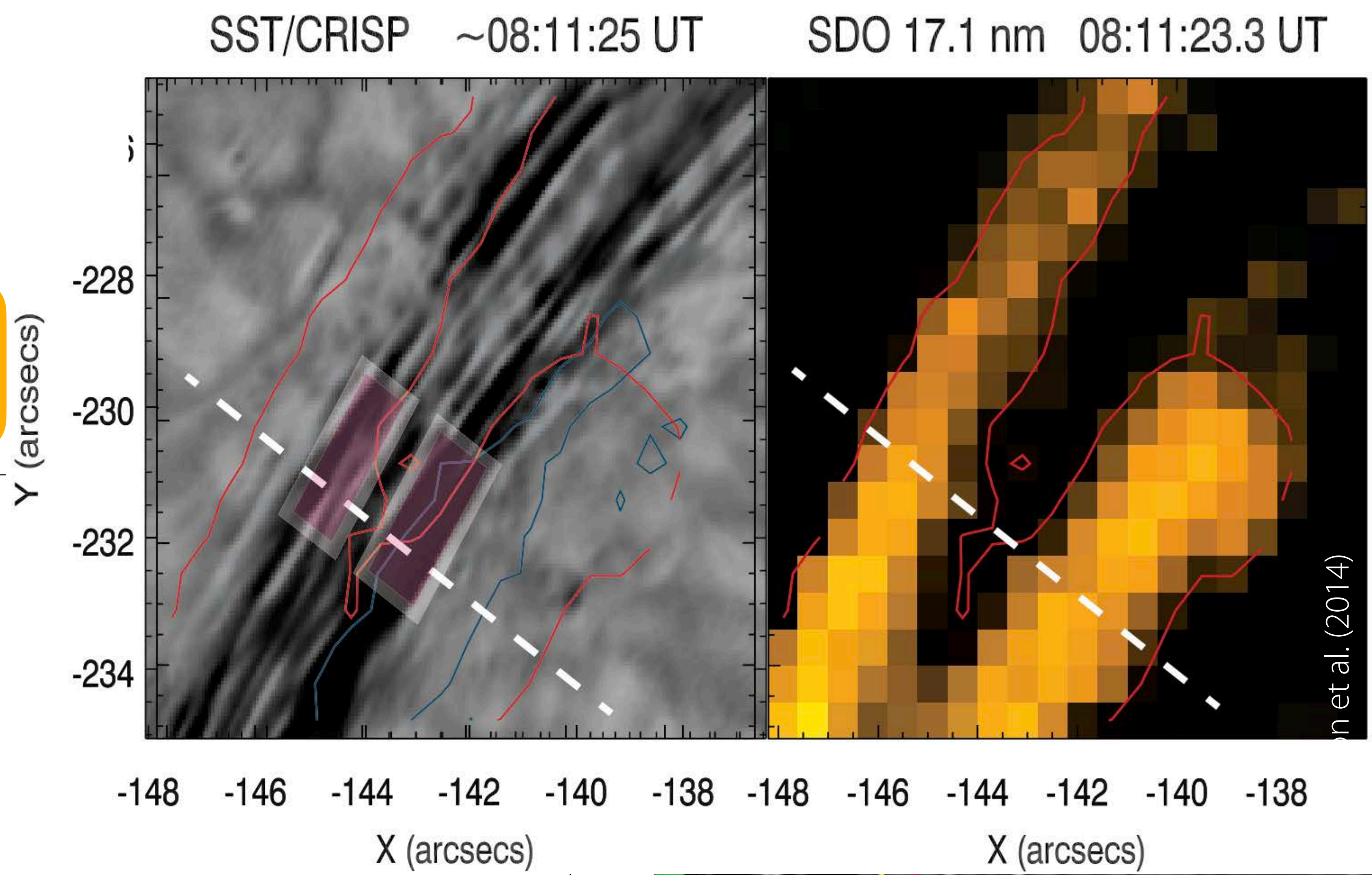


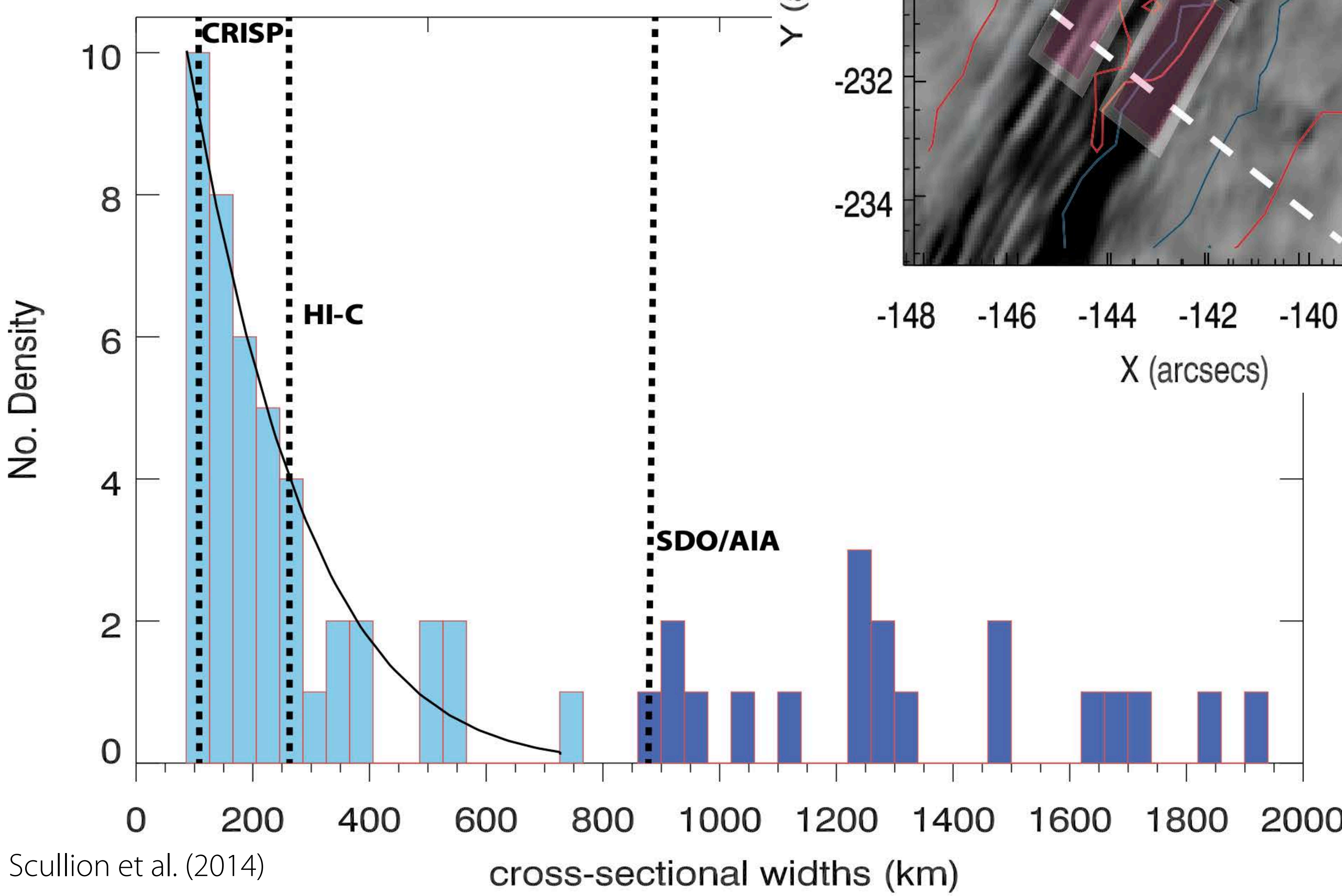
Brooks et al. (2013)

Corona

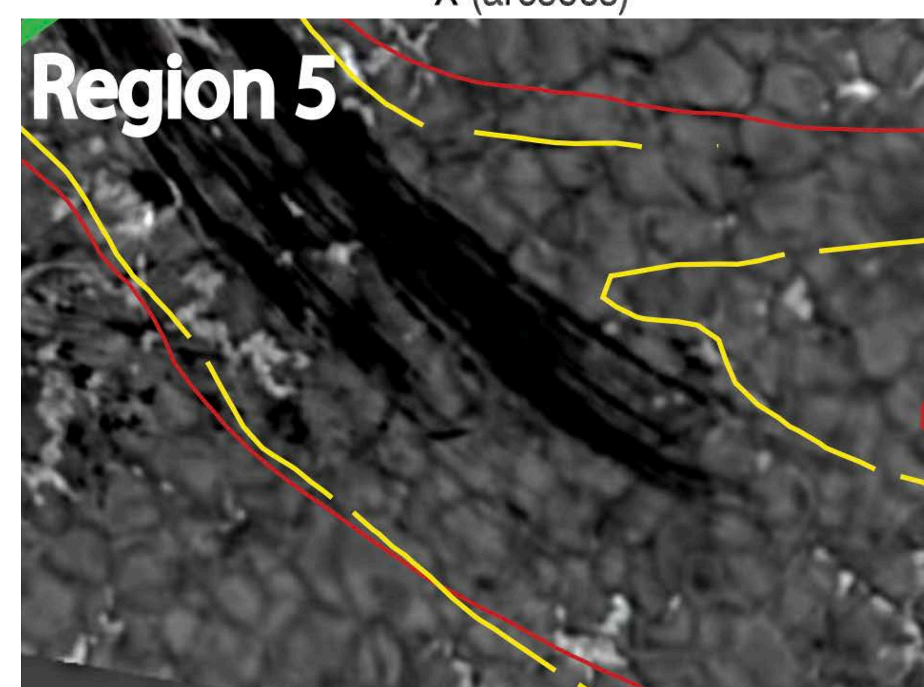
Coronal Loops

- 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

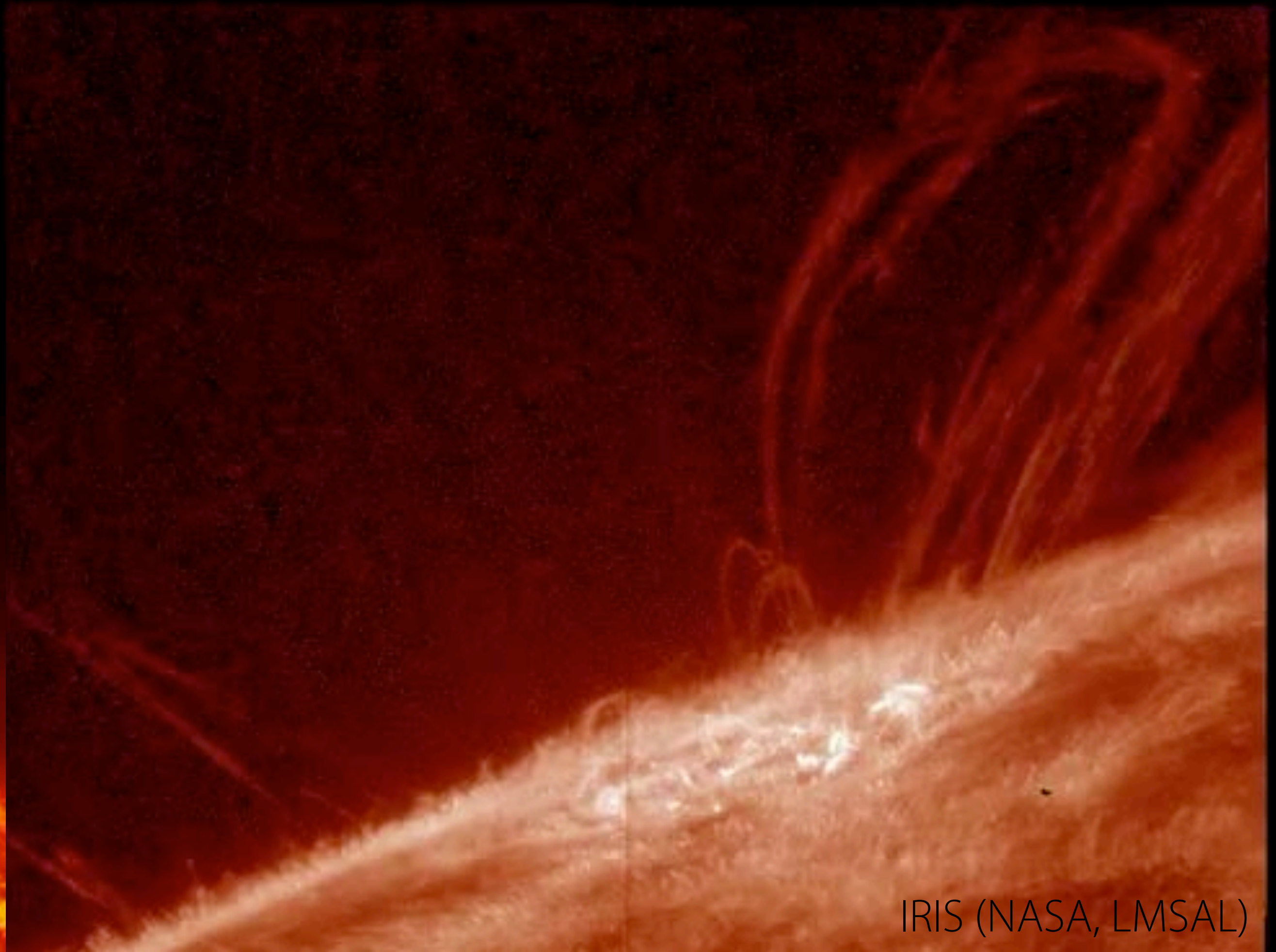
Energy loss and catastropic cooling

- **Thermal conduction** along magnetic field important for energy transport in the corona
- Energy loss/cooling
  - Thermal conduction (dominates for hot coronal loops, T_e >~ 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)

Chromospheric / coronal heating

Chromospheric / coronal heating

- Observations of spectral lines for high ionisation stages (Grotrian 1939, Edlén 1940)

➡ Implies gas temperature T > 1 000 000 K in the outer layers of the Sun.

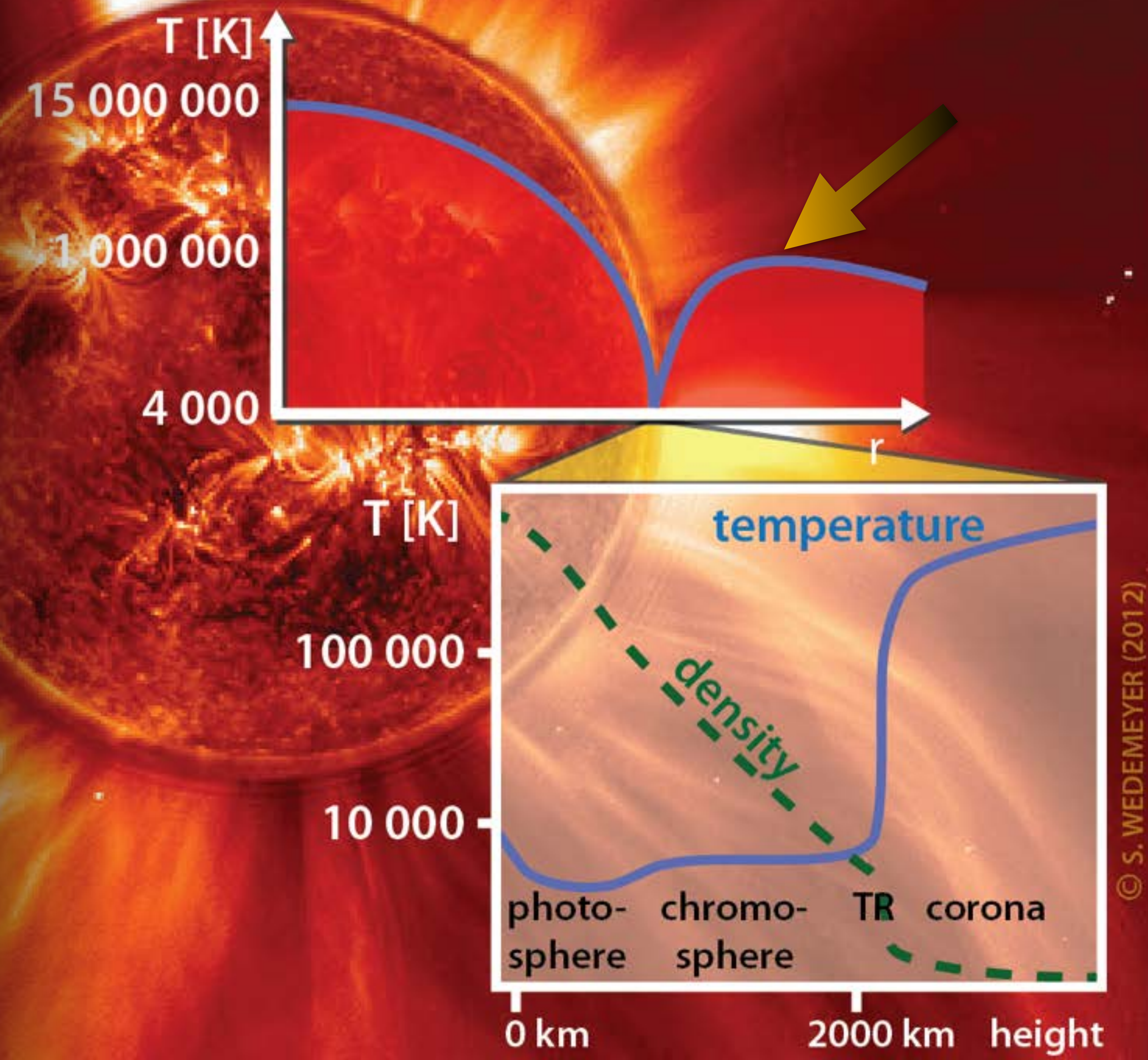
- A long-standing central problem in solar / stellar astrophysics (known and unsolved for > 80 yr)
- Temperatures far above radiative equilibrium values

➡ **Outer layers heated!**

- But how?!

➡ **"Coronal heating problem"**

- Applies to (solar-like) stars in general



Chromospheric / coronal heating

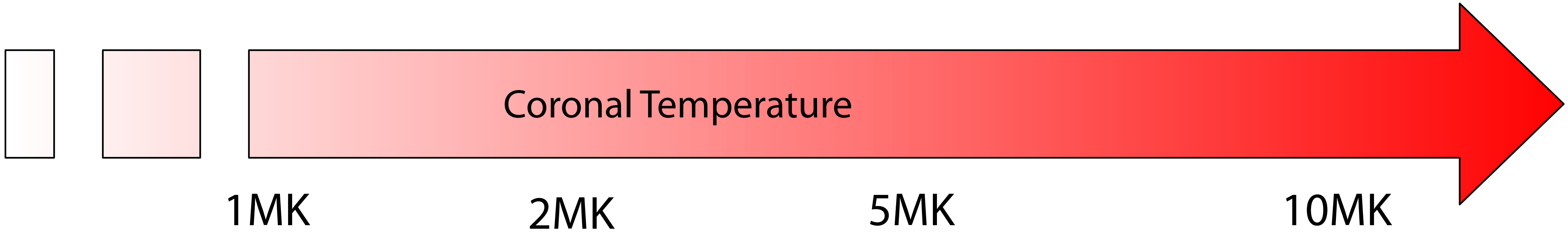
Multi-temperature structure of active regions

- Large difference in temperature between different parts of the corona (Quiet Sun, Active Regions, Coronal Holes — Flares)

➡Required heating input to compensate for radiative losses is one order of magnitude different

  - Hot (T > 2MK) ~10^7 erg cm-2 s-1
  - Cool (T ~ 1MK) ~10^6 erg cm-2 s-1

- "One size won't fit all"? Scalable heating process? Or different processes dominating / contributing differently in different situations/regions (with different temperature)?



"Cool" — Stationary/continuous heating

Hot — Transient heating (localised)

Many candidates

Not understood yet.

Magnetic reconnection
(flares, microflares)
Required due to the large amount of released energy

Chromospheric / coronal heating

Candidates for continuous heating mechanims

- Previously thought: **acoustic heating** accounts for "basal flux" (remember stellar activity!), whereas processes involving magnetic fields would add varying contribution on top.
- Two major categories — AC-DC:
  - **AC — MHD waves**: High frequency slow MHD waves, fast waves, Alfvén(ic) waves; combined with linear mechanisms (e.g., mode conversion, resonant absorption and phase mixing) or nonlinear mechanisms (e.g., dynamic instabilities and turbulence, wave-to-wave interaction, parametric decay)
  - **DC — Small-scale magnetic reconnection**: Frequent nanoflares outside active regions (continuous non-thermal heating contributions); stress-induced, field line braiding
- Other possible contributors:
  - Gravity waves
  - Multi-fluid effects
  - Plasma instabilities
  - …

"Updated coronal heating problem"

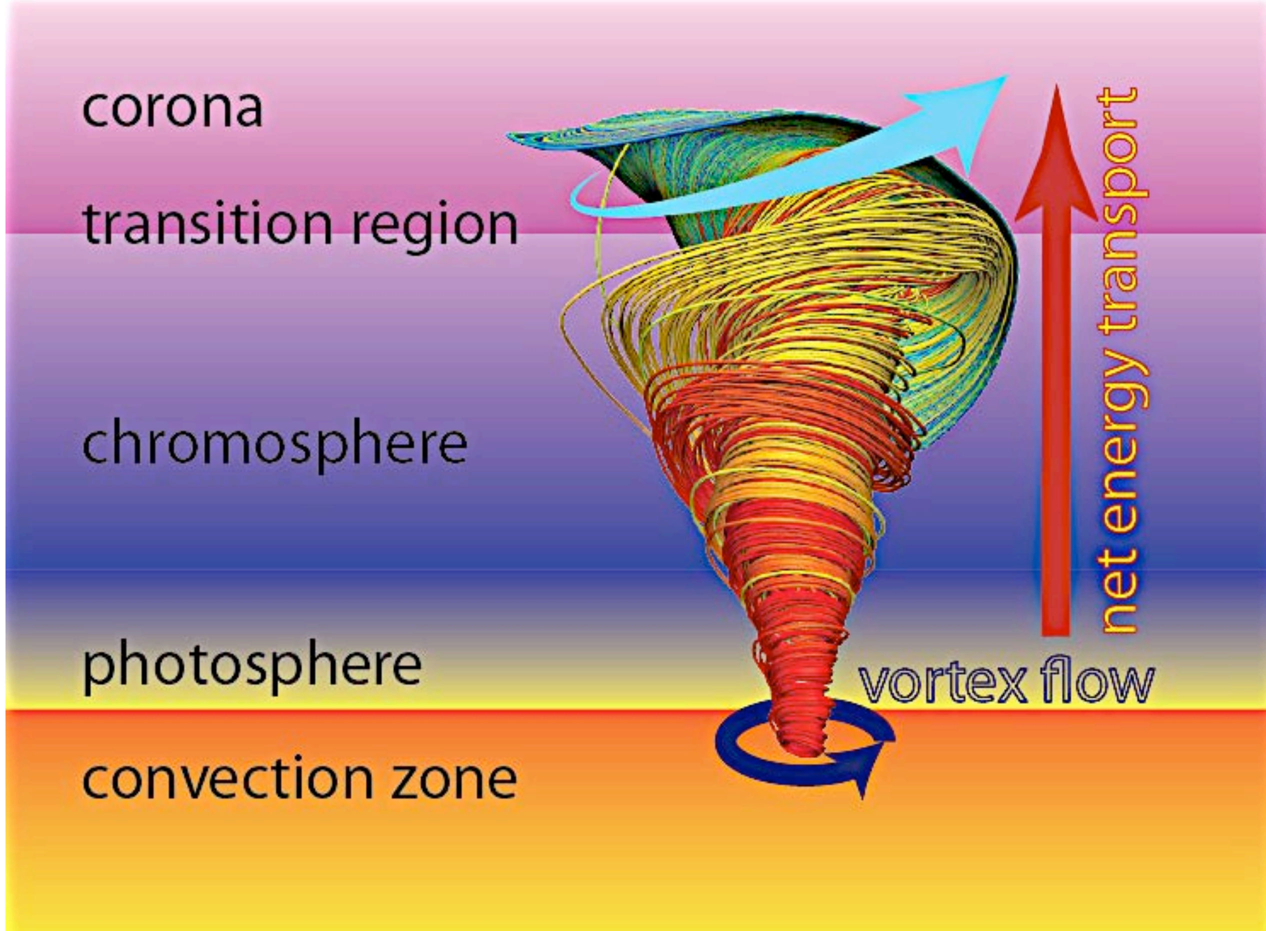
- Many known candidates that can provide more than enough energy in chromosphere/corona (alone or combined)
- Question(s) now:
  - How is the energy **dissipated**?!
  - Which process is contributing how much in different types of region?

Chromospheric / coronal heating

Candidates for continuous heating mechanims

- **Hot candidate: Alfvén waves**
  - Once generated, Alfvén waves propagate easily along the magnetic field structures into upper atmosphere
  - Just dissipation not that easy and not sufficiently understood yet.

  - Wave guides:
    - Loops
    - Spicules
    - Magnetic tornadoes
    - …

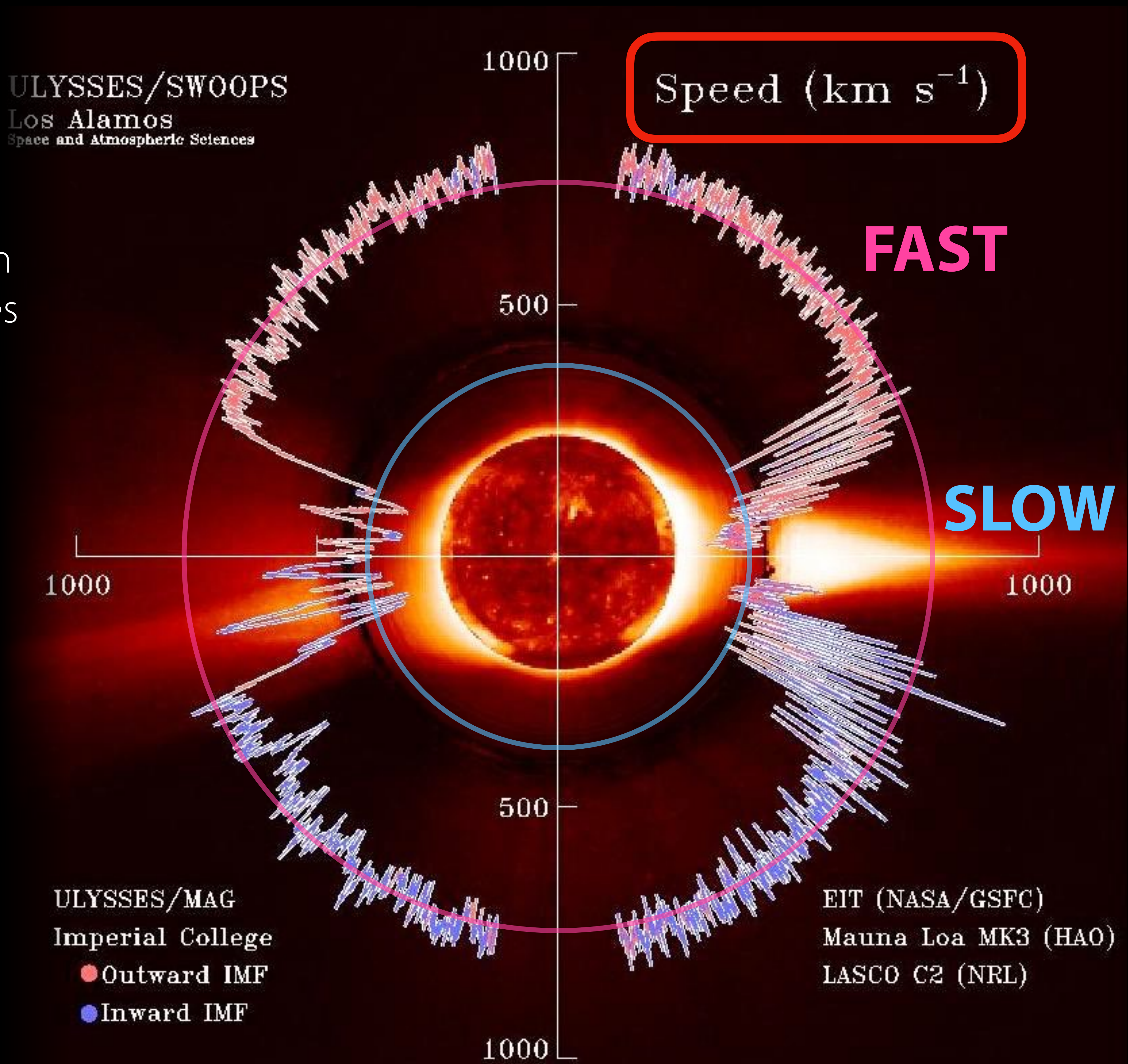


Solar Wind and Heliosphere

Solar Wind and Heliosphere

Components

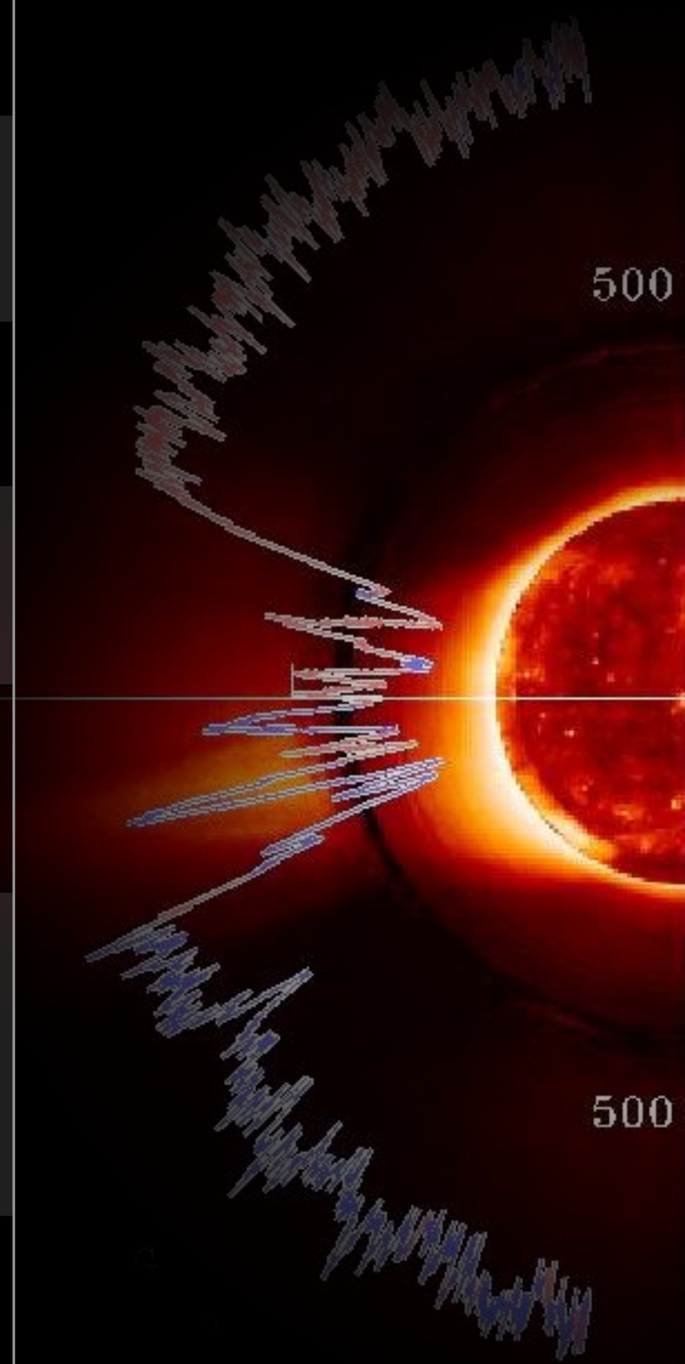
- Ulysses 1990-2009 (ESA/NASA)
- Left the ecliptic to study Sun from other inclination angles
  - Such an orbit challenging (gravity assist at Jupiter)
- Many instruments onboard, incl. SWOOPS (Solar Wind Plasma Experiment)
- 3D measurements of solar wind, ions + electrons
- Measured variation of solar wind as function of latitude
- Different components of solar wind (fast, slow)
- Solar wind varies over solar cycle



Solar Wind and Heliosphere

Properties

	Fast solar wind	Slow solar wind	Transient solar wind
Speed	> 400 km/s	<400 km/s	from < 300 km/s up to >2000 km/s
Proton density	~3 cm^{-3} homogeneous	~ 8 cm^{-3} highly variable	Often very low density
Magnetic field strength	~5 nT = 0.0005G	< 5 nT	Variable, up to 100 nT (0.01G)
Composition	95% H, 4% He	94% H, 5% He	Sometimes up to 30% He
Fluctuations	Alfvenic	Density	Often associated with interplanetary shock waves
Origin	Coronal holes coronal	Connected to coronal streamers	CMEs

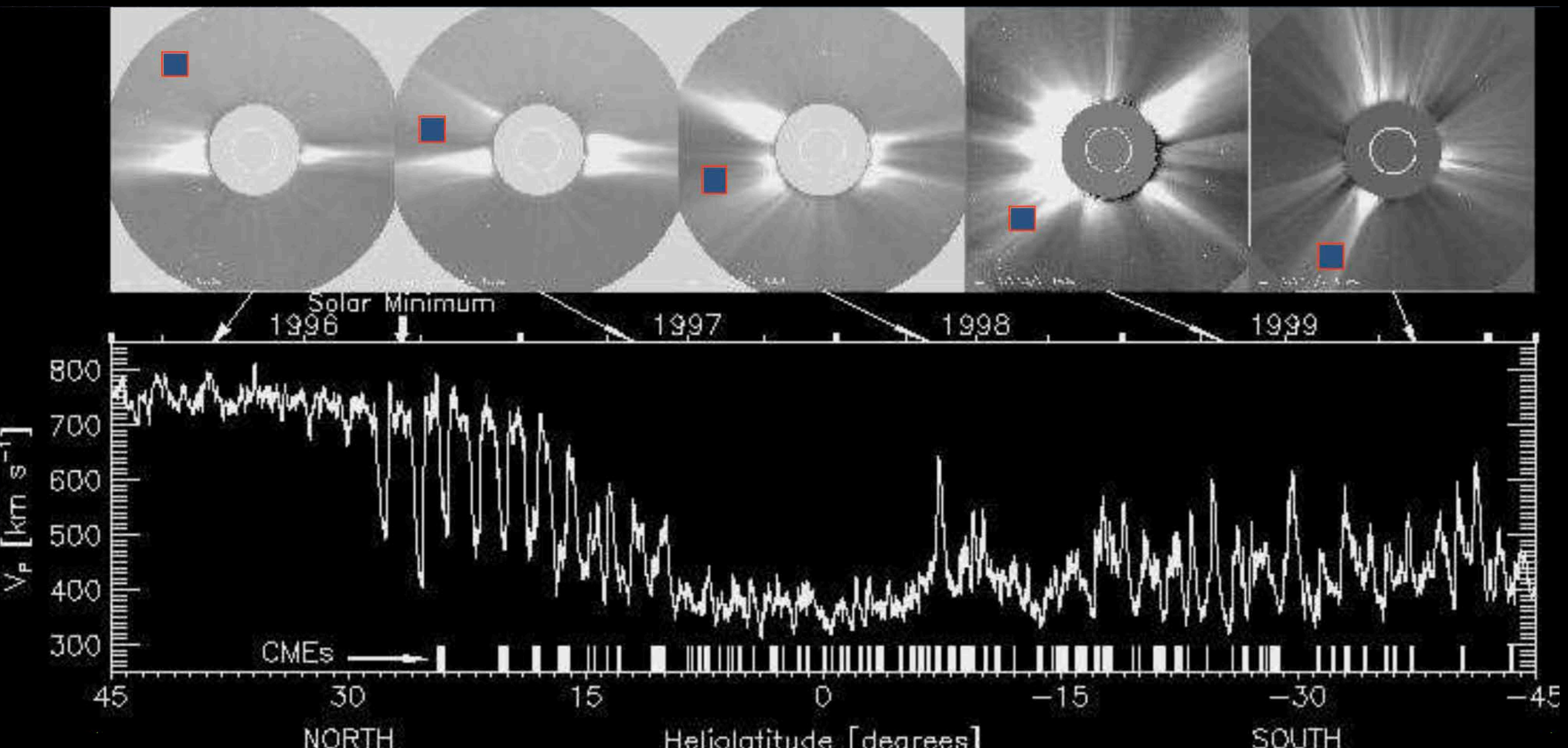


Solar Wind and Heliosphere

Variation with solar cycle

Solar activity minimum (8/1996)

Increasing activity, towards solar maximum



Solar Wind and Heliosphere

Solar Wind generation

- Still many open questions (one of the key objectives of Solar Orbiter!)
- Possible explanation for the solar wind:
  - Plasma confined lower solar atmosphere in closed magnetic field
  - Magnetic reconnection events between open and closed magnetic field

  ➡ Dynamical released into open field

- Fast Wind generation in Coronal Holes:
- Many possible physical processes (yet to be explained):
    - Reconnection events in the low corona
    - MHD turbulence
  - MHD waves
  - Low-frequency Alfvén waves
  - Heavy ion velocity filtration
  - . . .
  - Some include generation of different types of MHD waves, ion cyclotron waves, fast collisionless shocks, cascades …

Solar Wind and Heliosphere

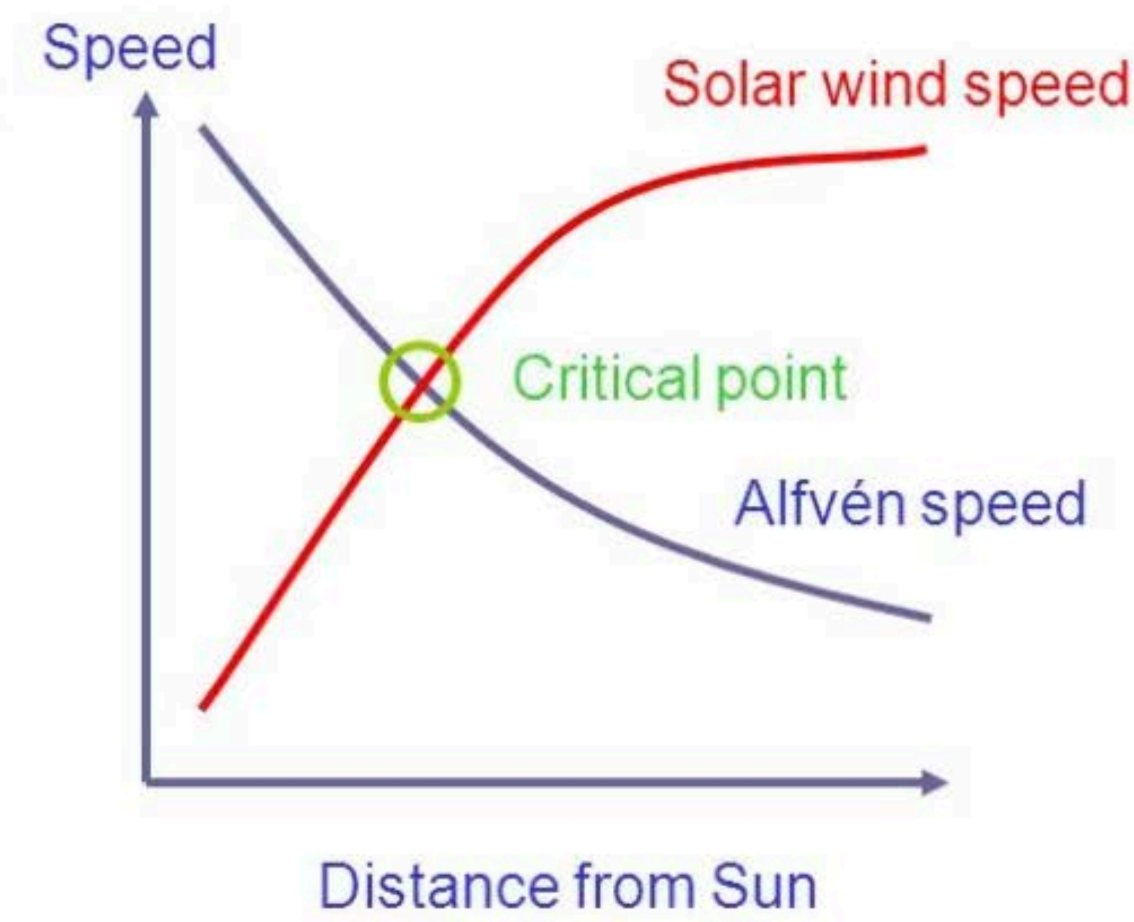
Solar Wind generation

- Solar wind is channeled by magnetic field up to the Alfven radius R_A, i.e. point where wind speed > Alfven speed
  ➡ Critical point

Alfvén speed

$$v_A \equiv \frac{B}{\sqrt{\mu_0 \rho}}$$

- Important:
  - At which height is the energy deposited that is needed for accelerating the solar wind?
  - Where are waves reflected and damped? (radial gradient of Alfvén speed!)
  - Energy deposited below or above the Parker critical point?



Solar Wind and Heliosphere

Parker's theory of the solar wind

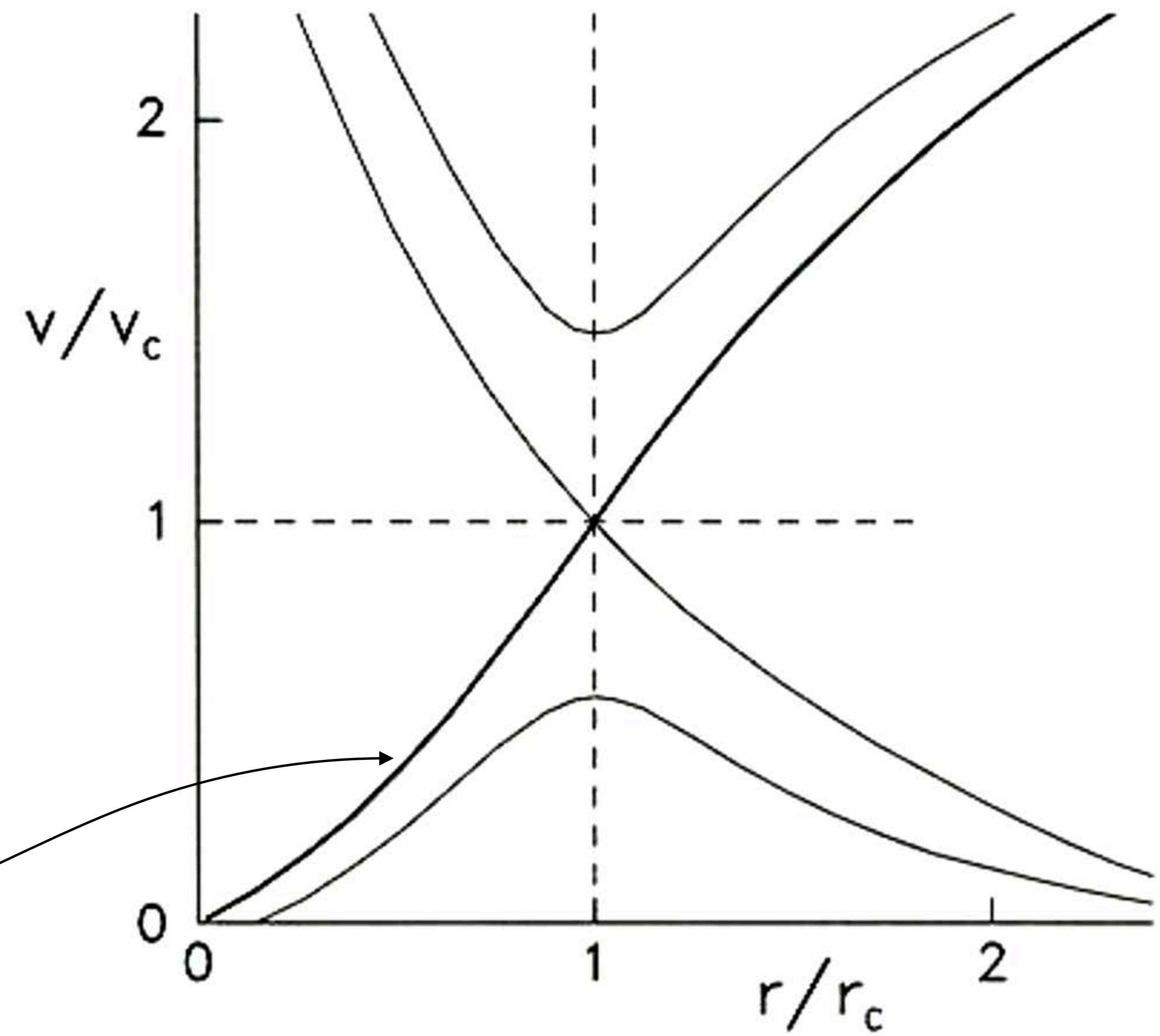
- **Basic idea:** Dynamic equilibrium between hot corona and interstellar medium.
- Mass and momentum balance equations:

$$\frac{d}{dr}(\rho r^2 v) = 0 \qquad v\frac{dv}{dr} = -\frac{1}{\rho}\frac{dP}{dr} - \frac{GM}{r^2}$$

➡ Parker's Equation for solar wind speed (assuming isothermal atmosphere)

$$\frac{1}{v}\frac{dv}{dr}(v^2 - c_S{}^2) = \frac{2c_S{}^2}{r} - \frac{GM}{r^2}$$

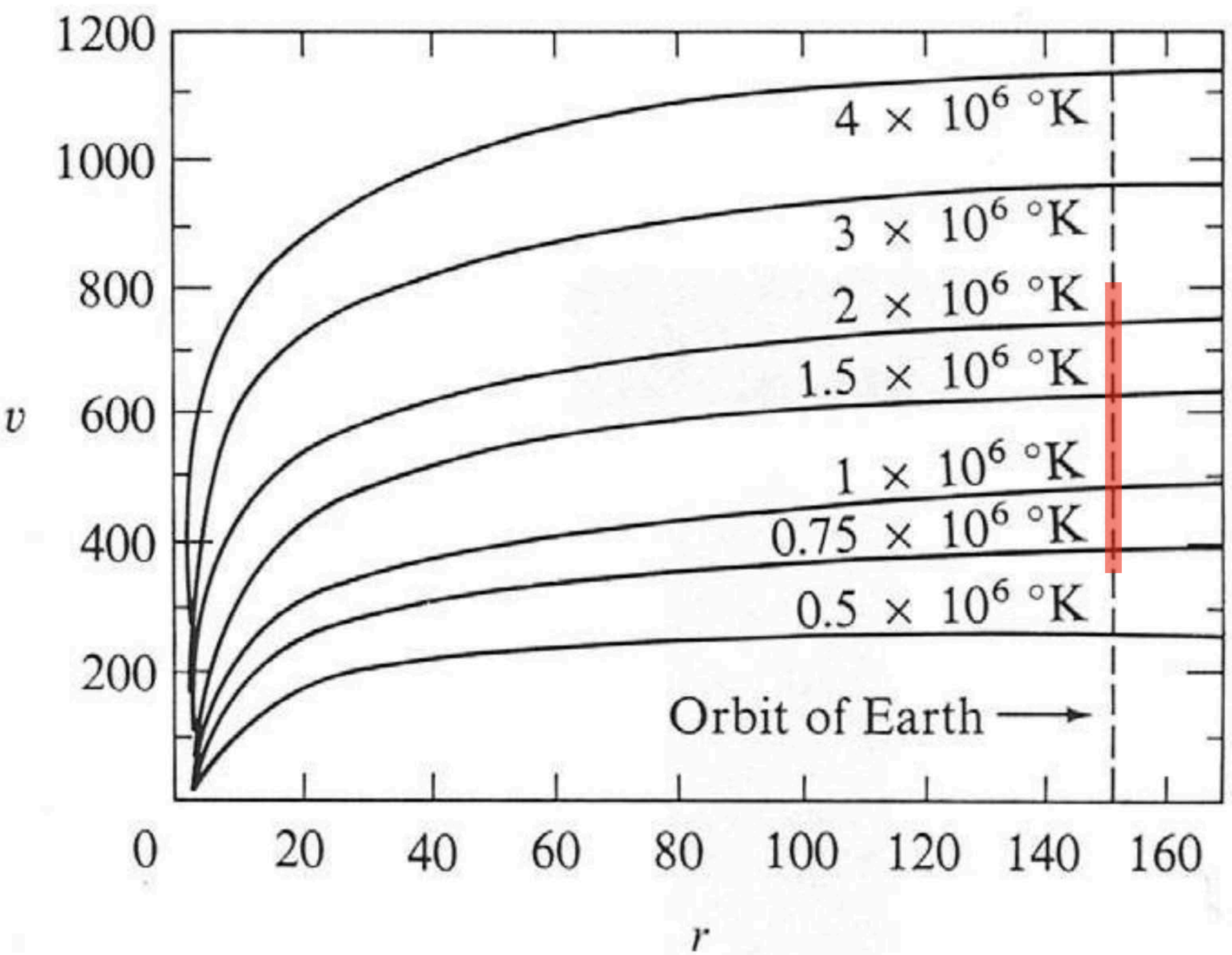
- Different (theoretically) possible solutions but some not valid for various reasons as in contrast to observations (some imply supersonic at solar surface or produce insufficient pressure against interstellar medium)
- One left: Correct solution (?!)

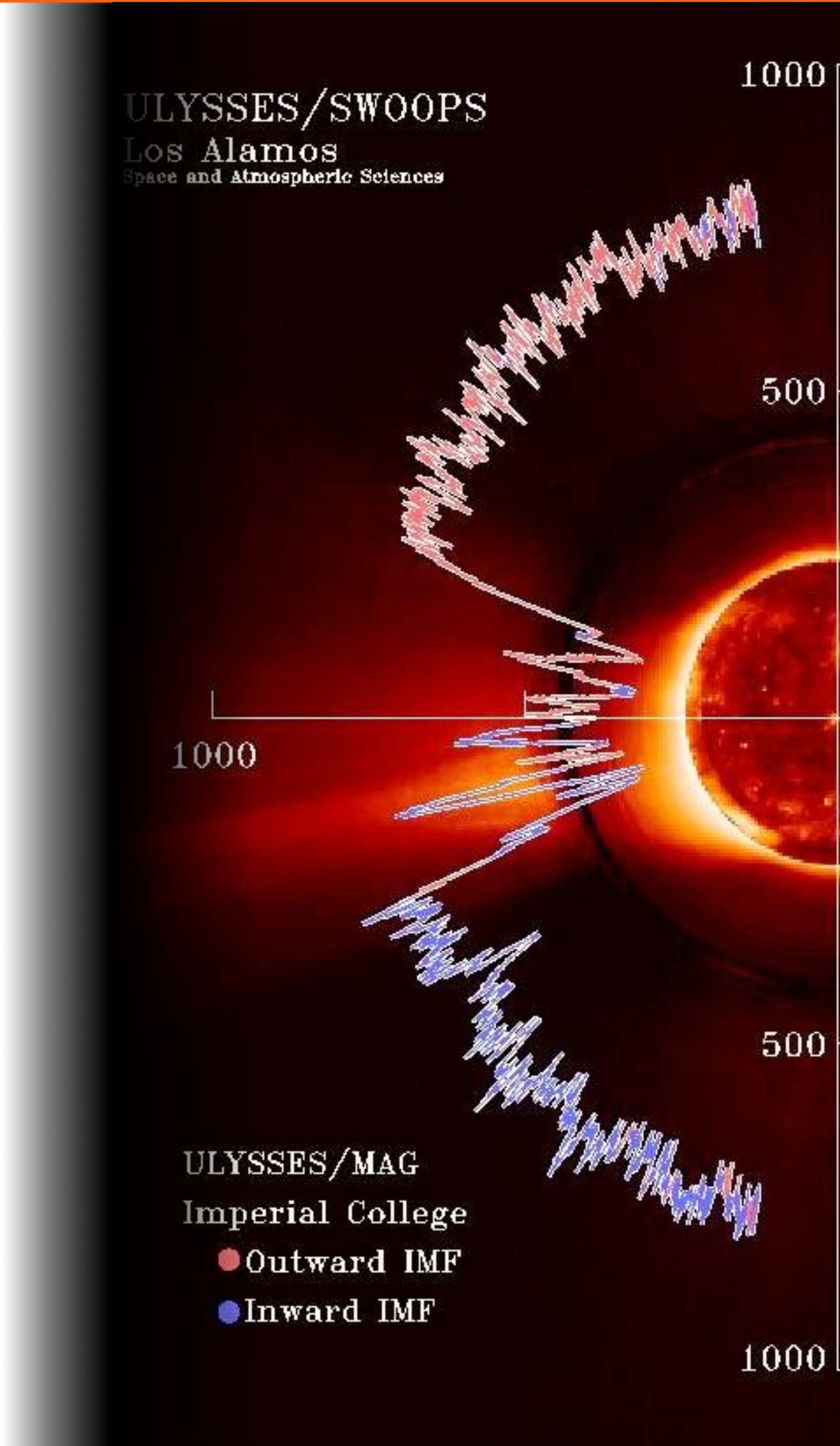


Solar Wind and Heliosphere

Parker's theory of the solar wind

- Speed of solar wind predicted by Parker's model for different coronal temperatures
  (simplified, isothermal case; no magnetic field)
- Consistent with measured velocities and coronal temperatures





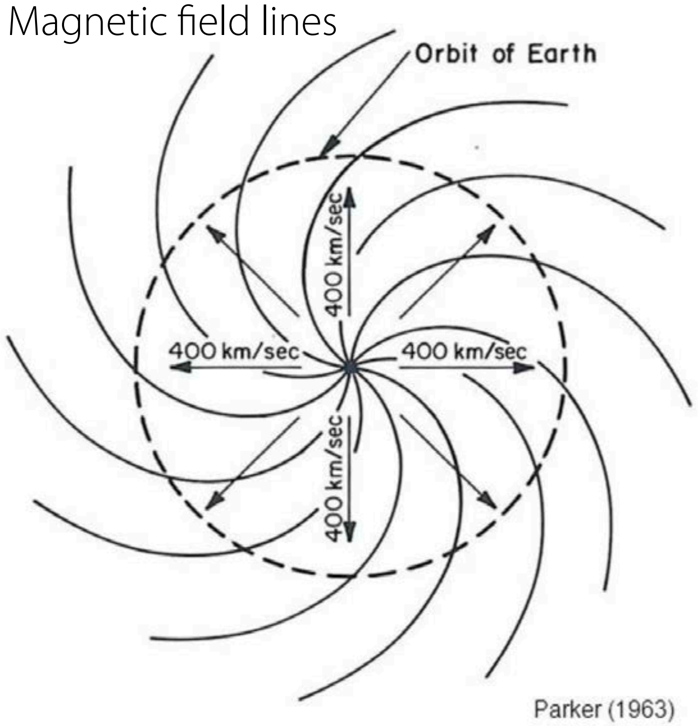
Solar Wind and Heliosphere

Parker spirals

- Magnetic field of the Sun extends into interplanetary space (throughout solar system)
- Field tethered to Sun while Sun rotates, magnetic tension

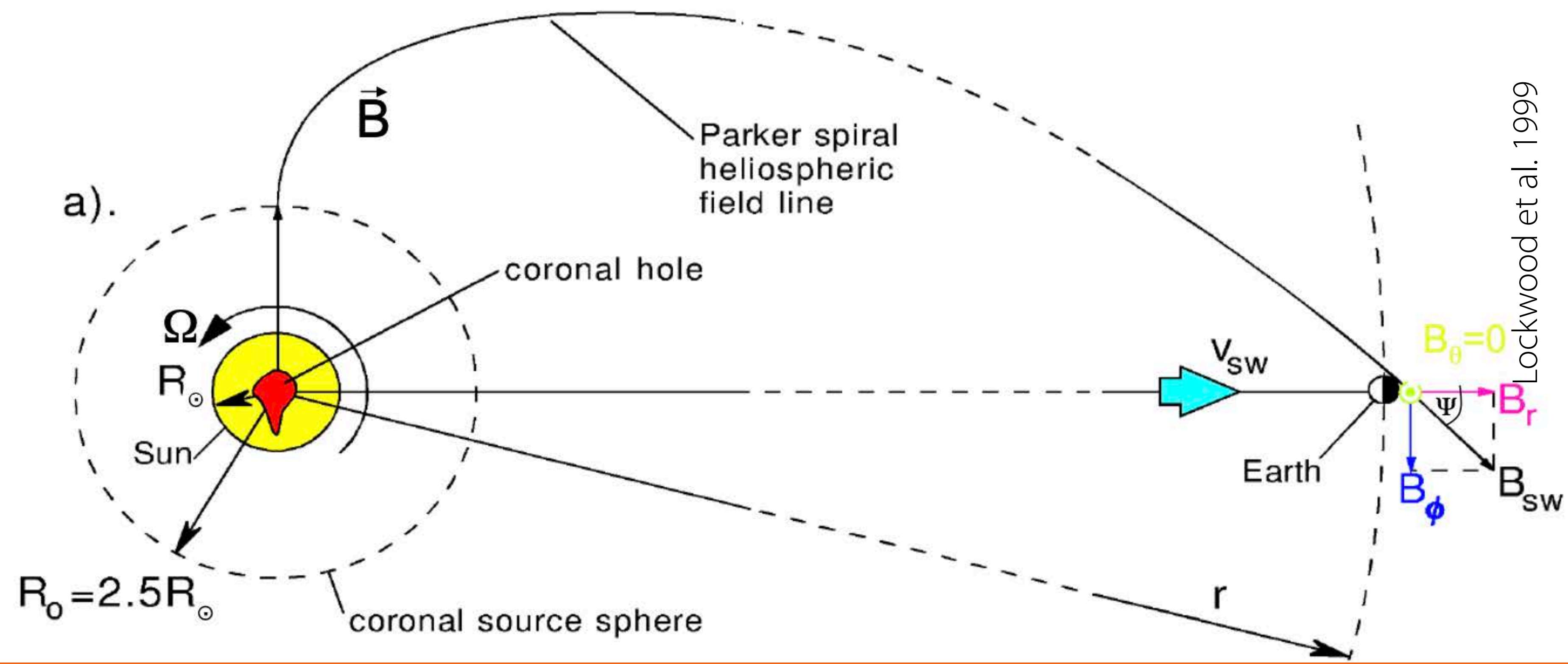
  ➡ **Parker spirals**

Magnetic field lines

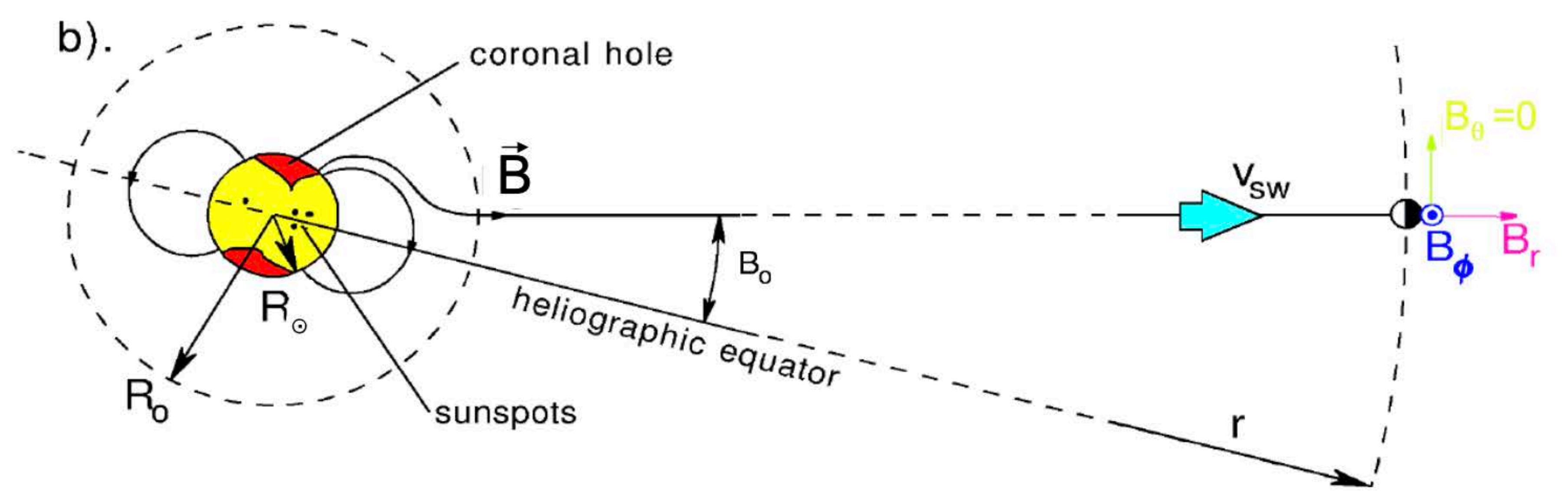


Parker (1963)

Poleward view



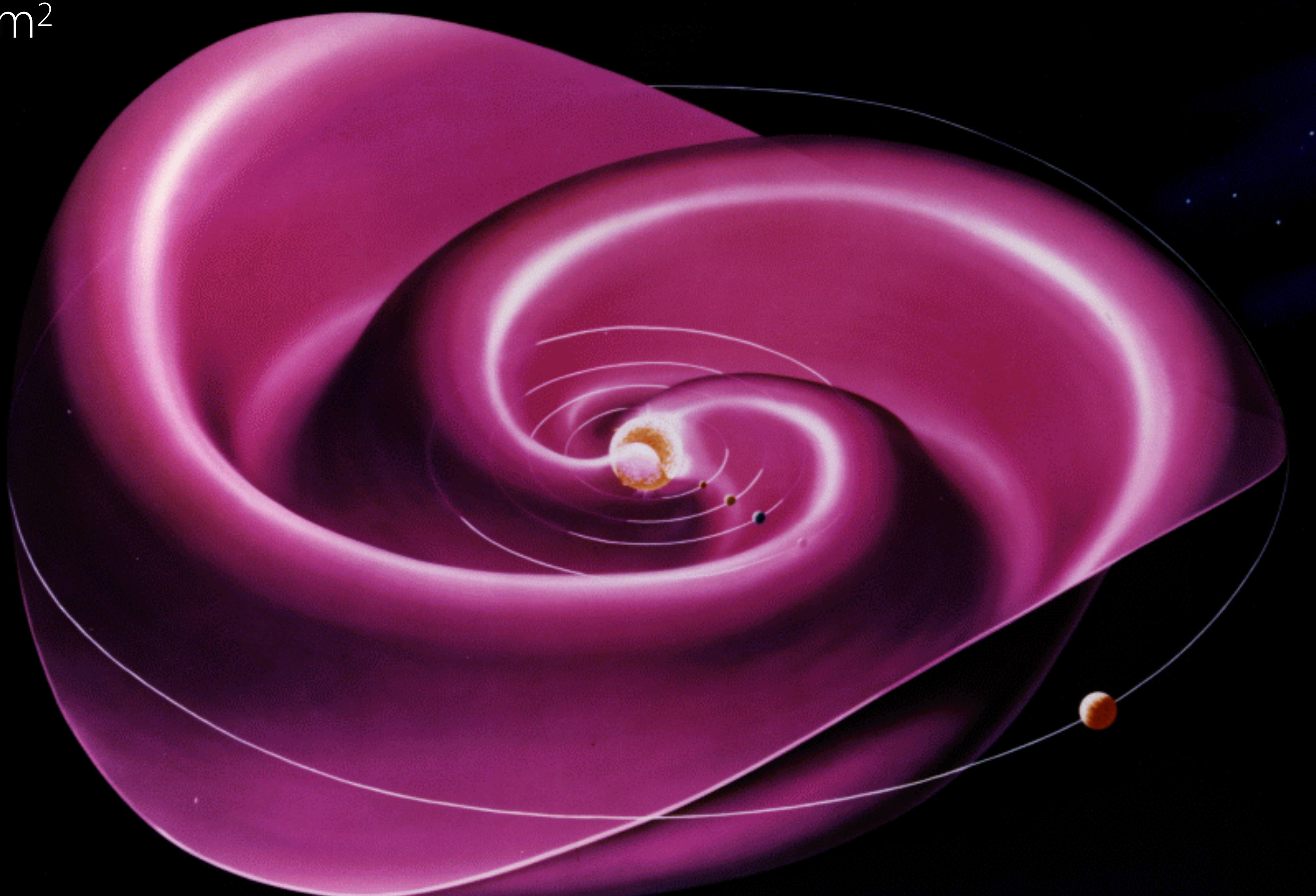
View from ecliptic



Solar Wind and Heliosphere

Heliospheric current sheet

- As a result:
  Heliospheric/interplanetary **current sheet** = surface where polarity of solar magnetic field changes
  - Electric current only ~10^{-10} A/m^2
  - Thickness of current sheet ~10 Mm at 1AU

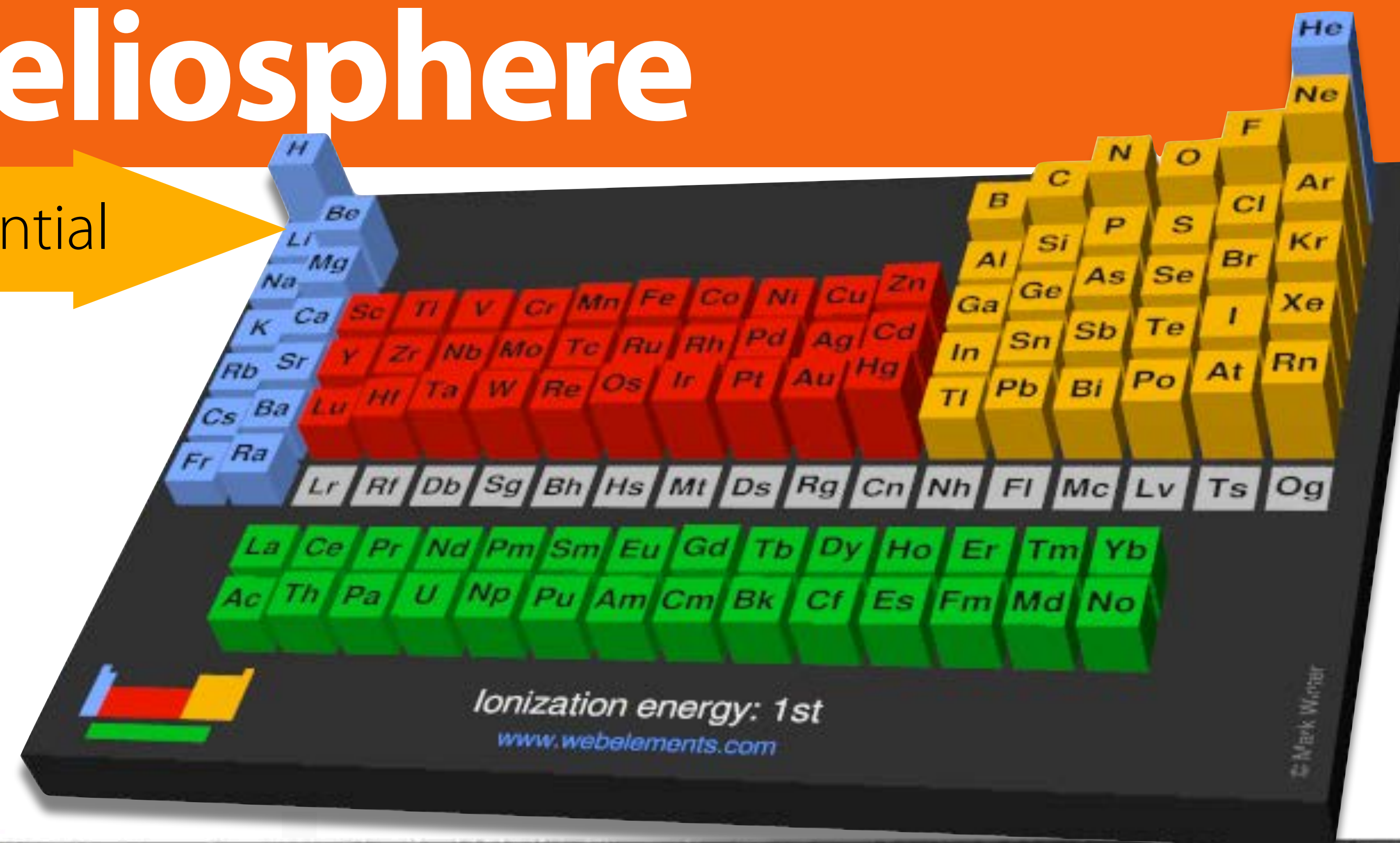


Heil / L. Svalgaard and J.M. Wilcox, Nature 262, p. 766, 1978.
K. Schatten, J.M. Wilcox, and N. Ness, Solar Physics, 6, p. 442, 1969.

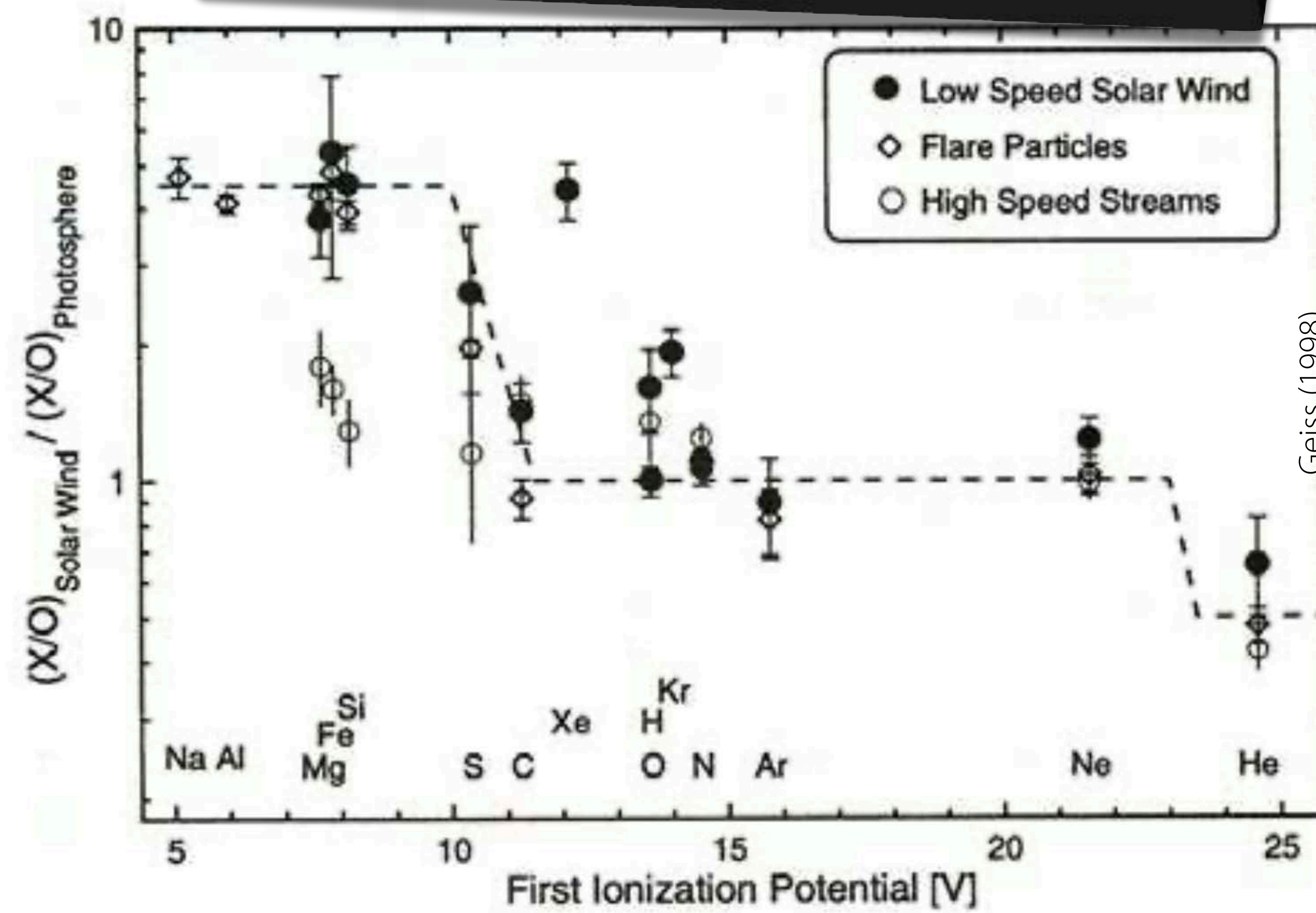
Solar Wind and Heliosphere

FIP effect

FIP = First Ionisation Potential



- Transition region, corona, solar wind: **Element abundances** differ from photospheric values!
- Elements with low FIP (< 10 eV): up to six times more abundant than elements with FIP> 10 eV.
- Fast solar wind: only weak (or absent) FIP effect
- Slow solar wind: FIP effect very pronounced
- Fast CME ejecta: Higher fractionation
- Differences imply dependence on the conditions in the region from where the wind plasma is originating in the first place



Geiss (1998)

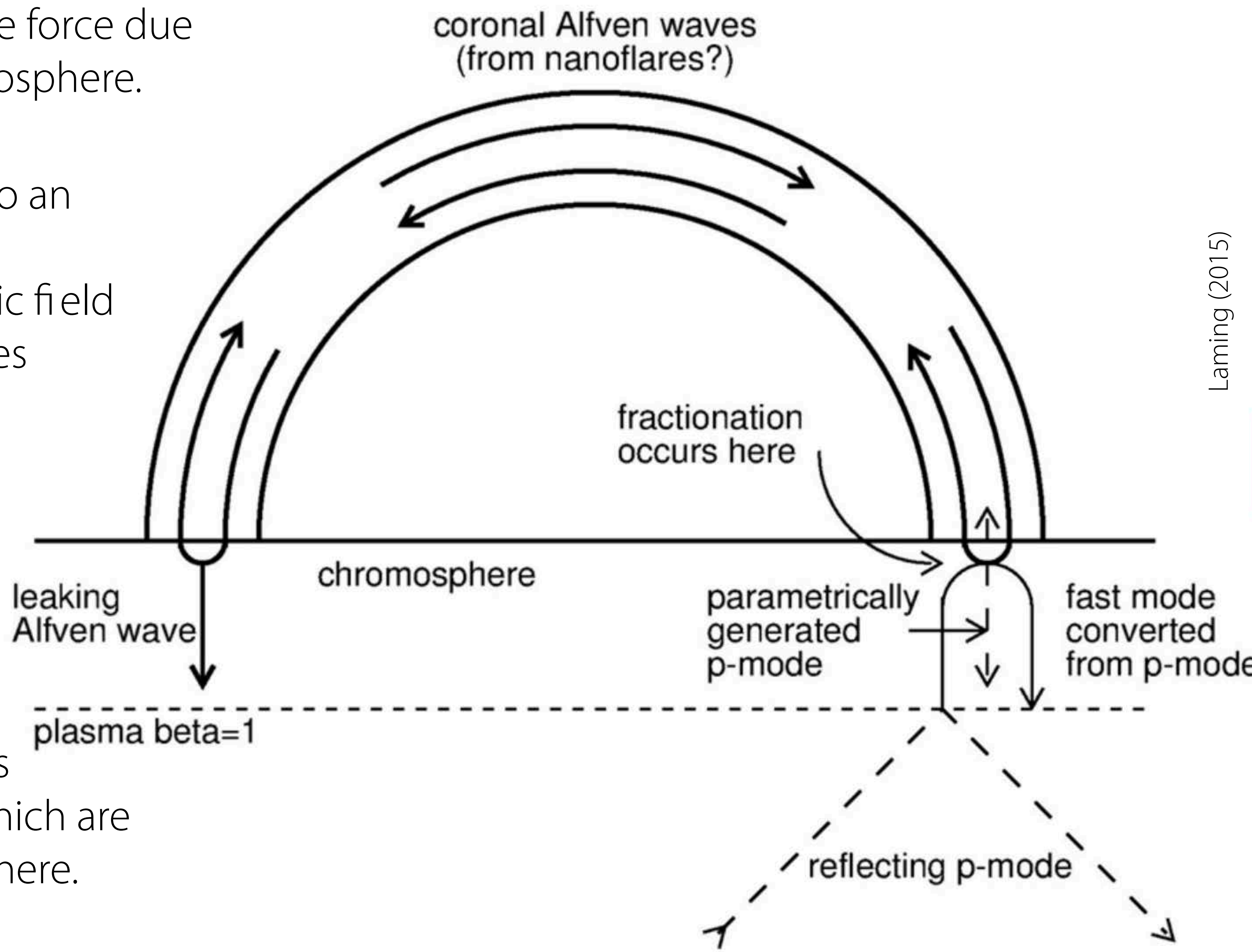
Solar Wind and Heliosphere

FIP effect

- Explanation: Acceleration of particles in chromosphere more efficient for low-FIP elements (ionised in chromosphere, high-FIP elements not ionised)
- Caused by ponderomotive force due to Alfvén waves in chromosphere.
- **Ponderomotive force** = net non-linear force due to an **inhomogeneous** (!) oscillating electromagnetic field acting on charged particles

➡ Charged particle moves towards area of weaker field strength (instead of oscillating around an initial point as in a homogeneous field)

➡ Acts on charged particles and thus on elements which are ionised in the chromosphere.

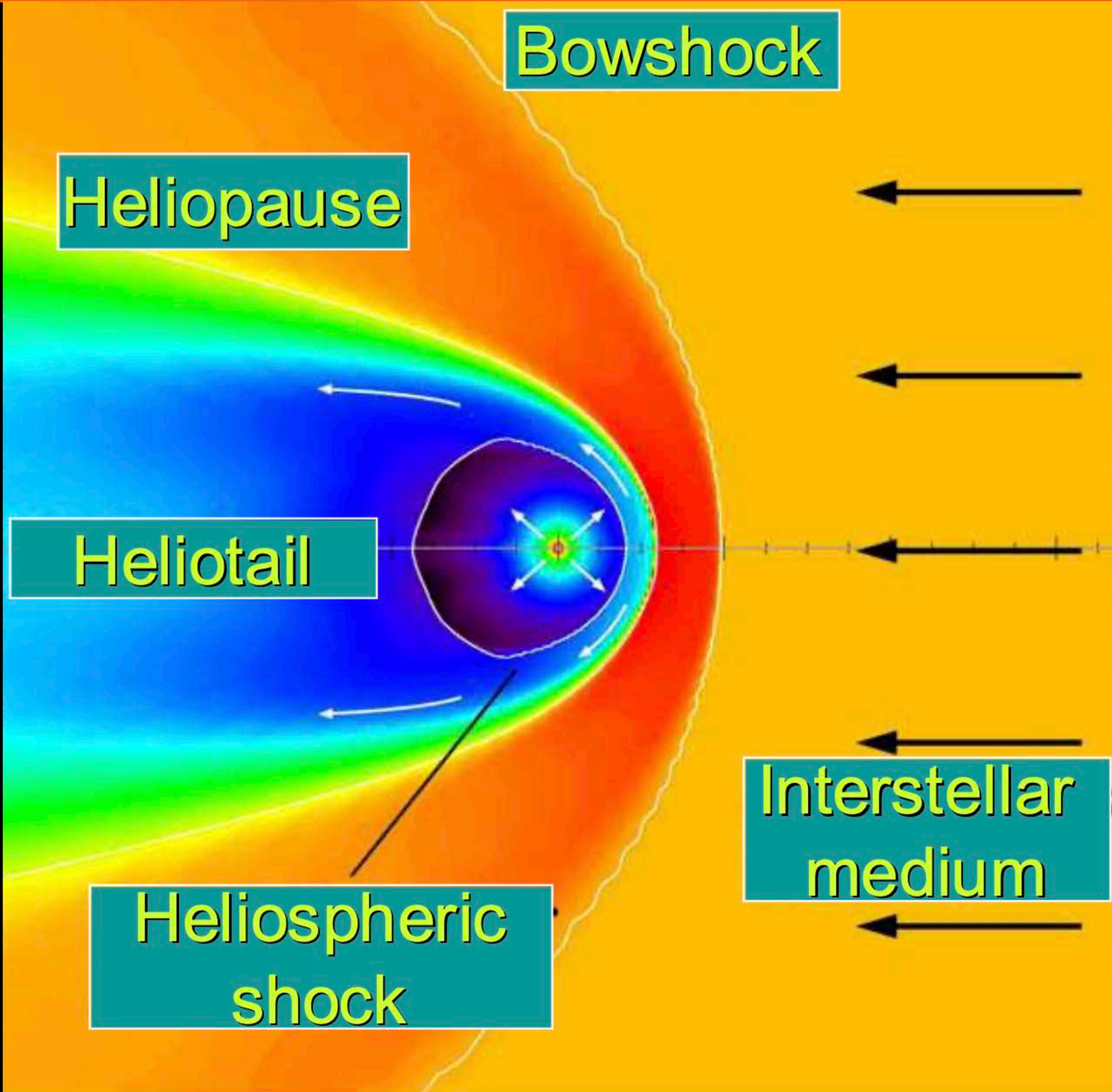


Laming (2015)

Solar Wind and Heliosphere

Heliosphere

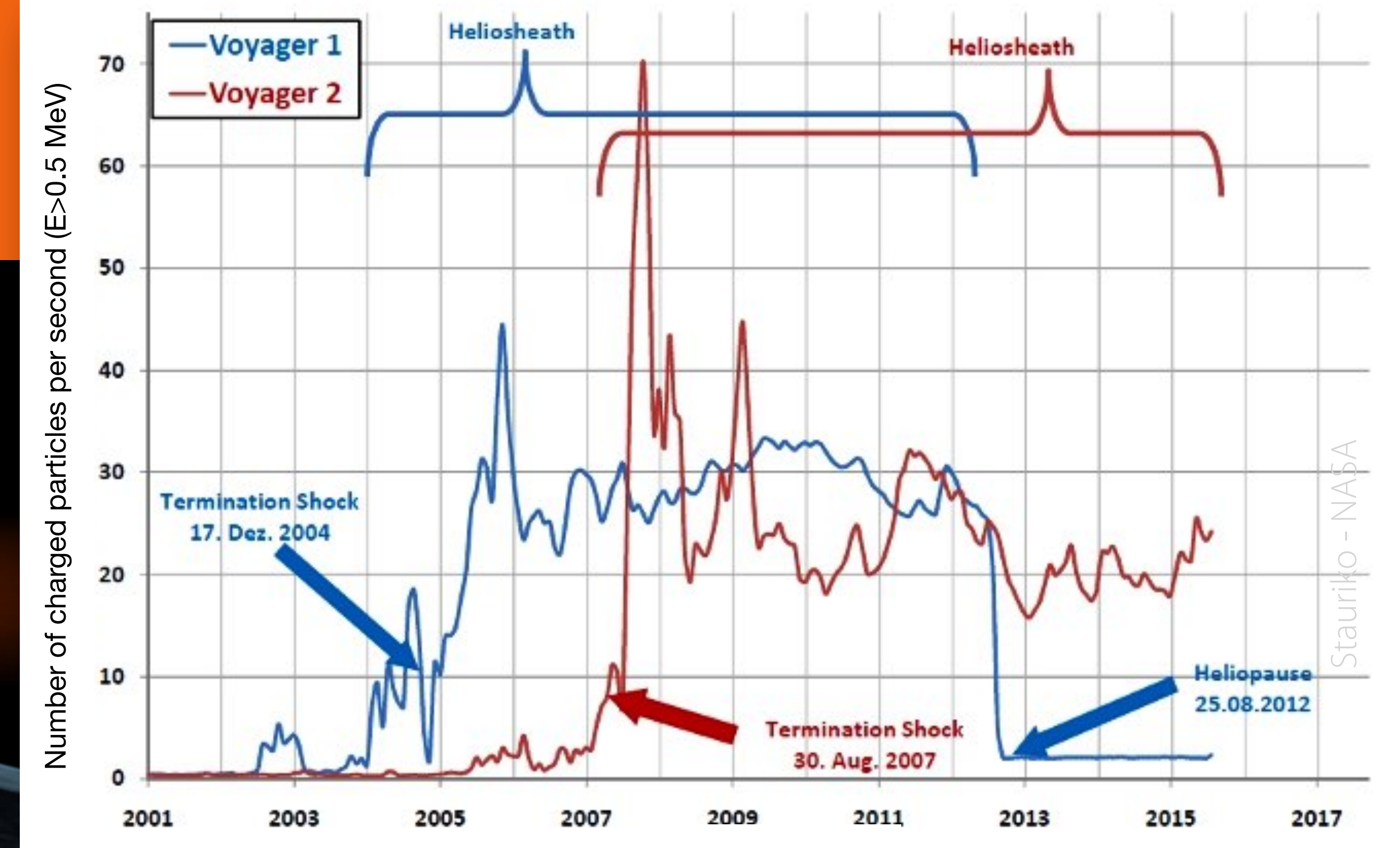
- Definition: Region where solar wind and solar magnetic field dominate over interstellar medium and galactic magnetic field
- "Bubble" embedded in interstellar medium, produced by outflowing solar wind
- **Heliopause:** boundary of the heliosphere
- **Bow shock:** interstellar medium is slowed relative to the Sun.
- **Heliospheric shock:** solar wind is decelerated relative to Sun

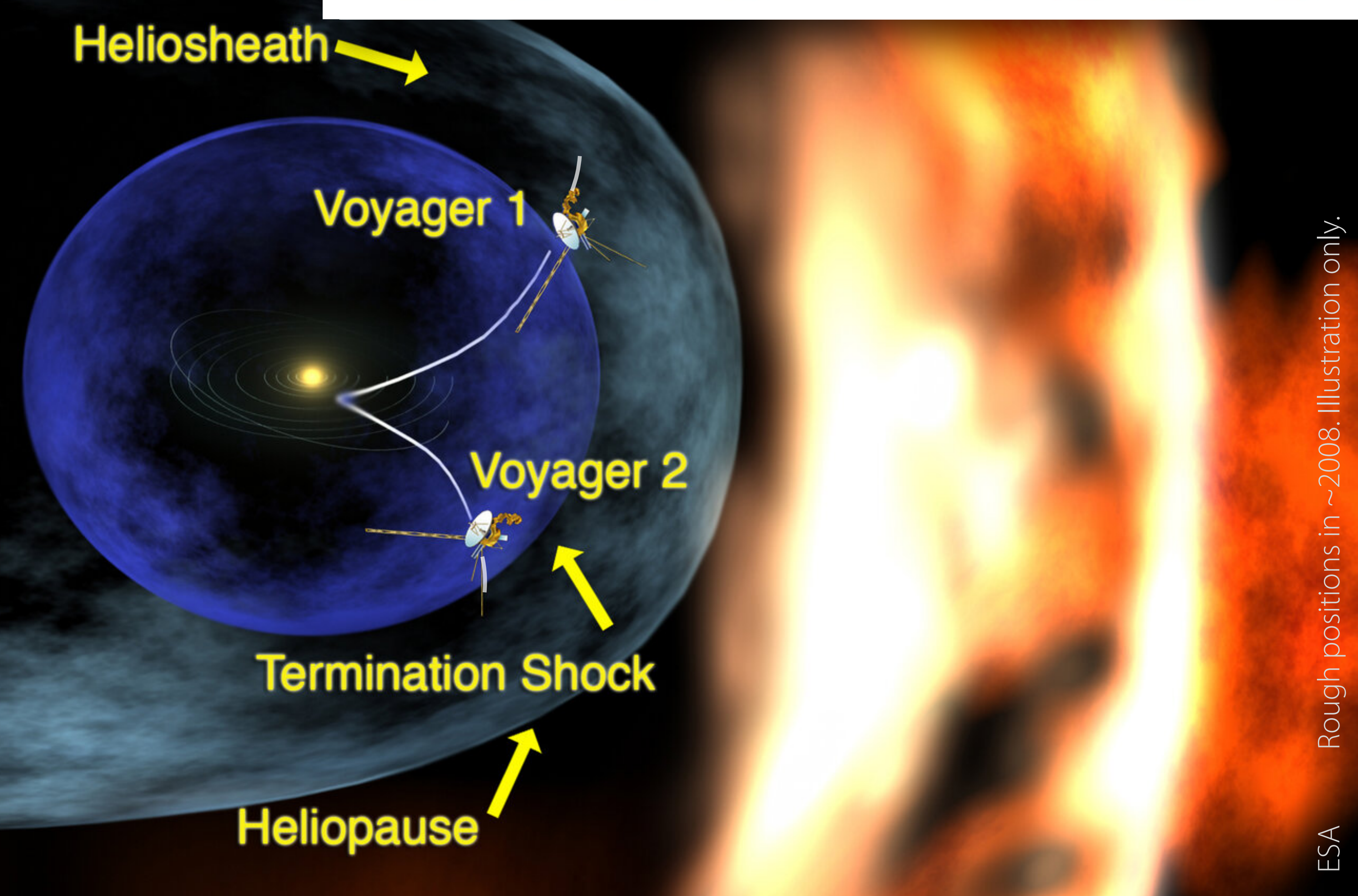


Solar Wind and Heliosphere

Heliosphere

- Voyager 1 and 2 launched in 1977, in different directions
- Reached heliopause:
    - Voyager 1: 2012
    - Voyager 2: 2018
    - Measured changes in number density of charged particles

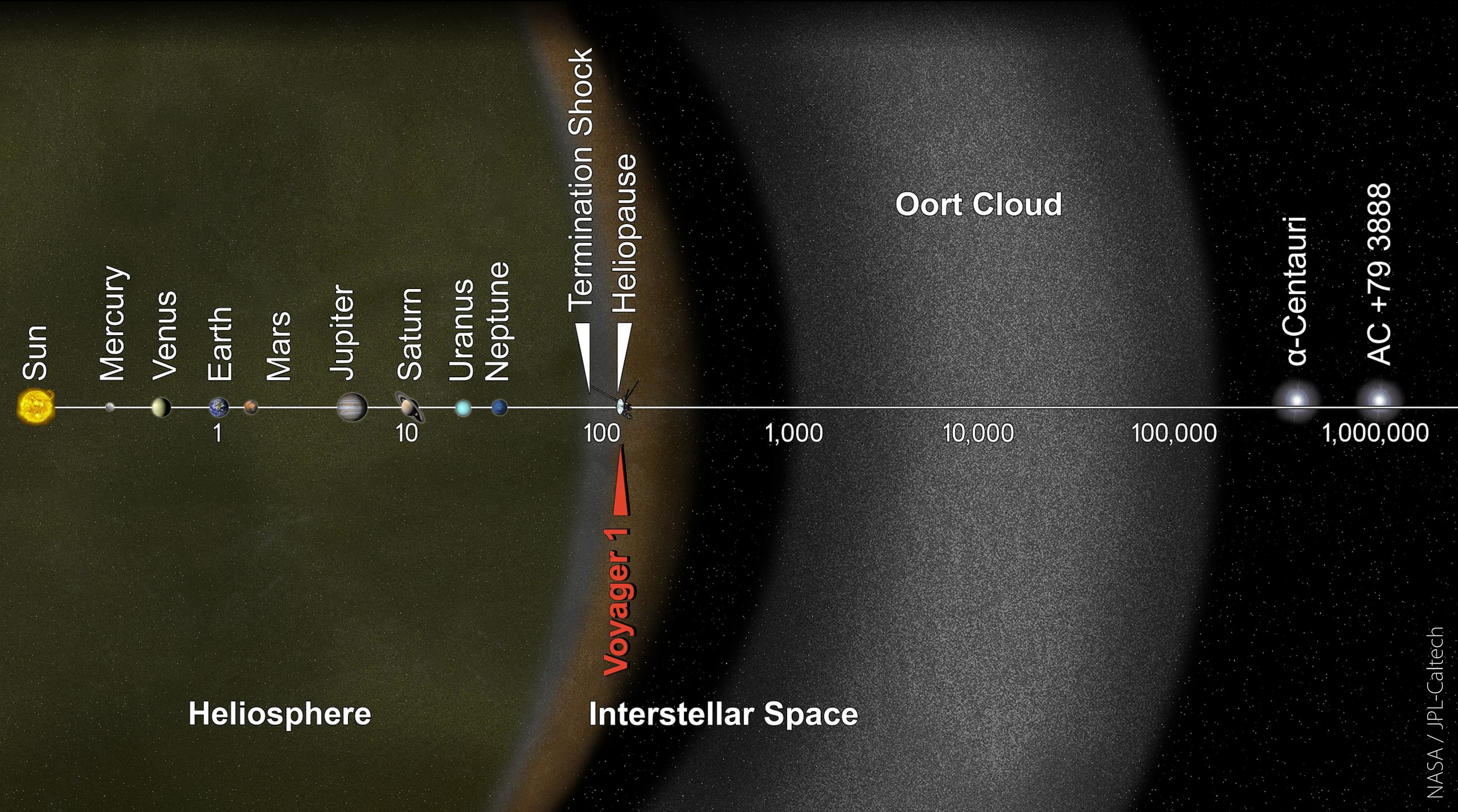




Solar Wind and Heliosphere

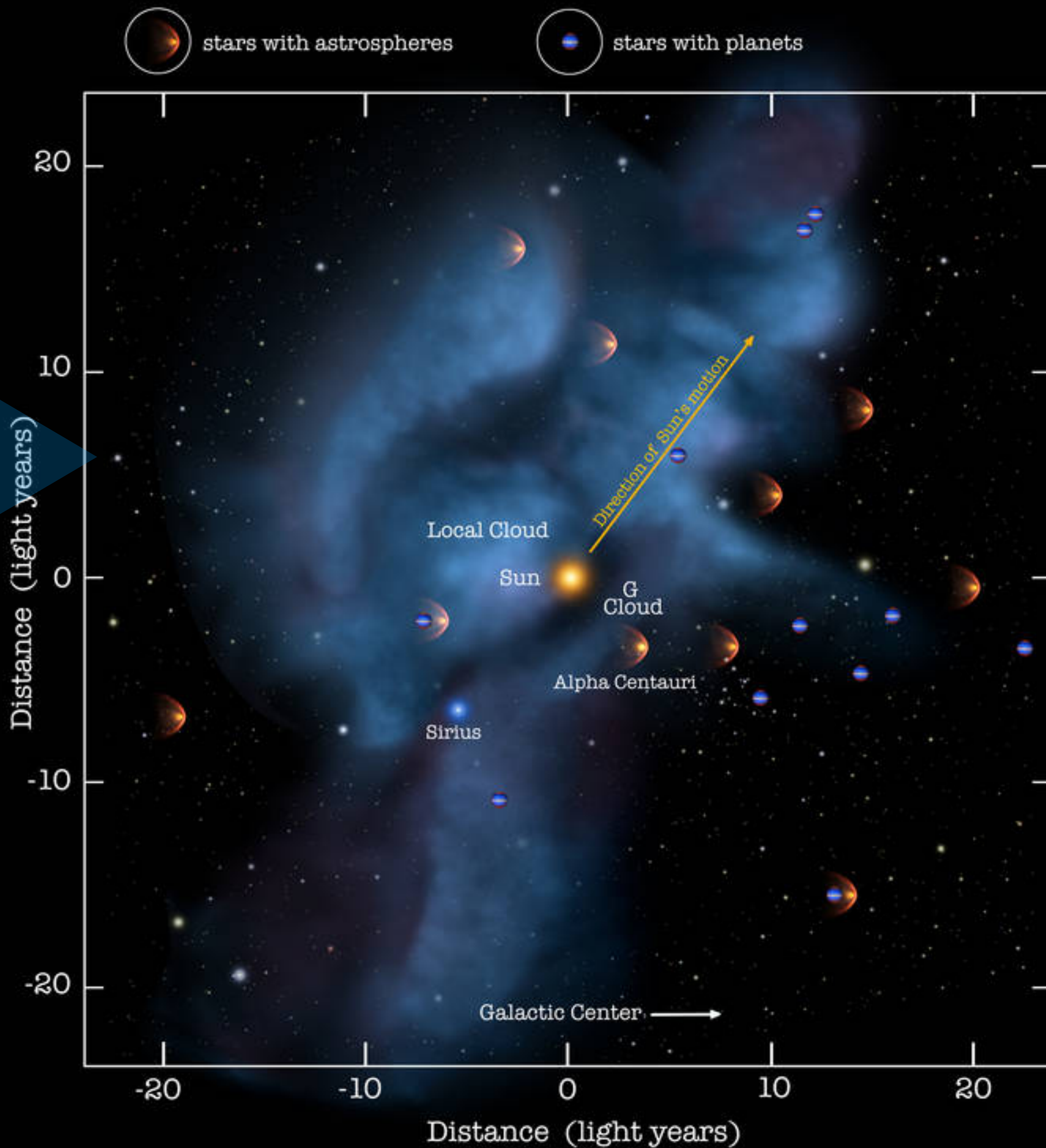
Heliosphere

- **Heliosphere:** protective shielding against Galactic Cosmic Rays (hazardous for life)



Beyond the heliosphere

- Astrosphere = like heliosphere but around other stars
- Detected around some other (nearby) stars
- Astrosphere around α Centauri (nearest star)!
- More candidates
- Many systems likely analogous to our solar system with astrospheres shielding a planetary system.



NASA/Goddard/Adler/U. Chicago/Wesleyan