Overview of the solar and stellar coronal heating problem

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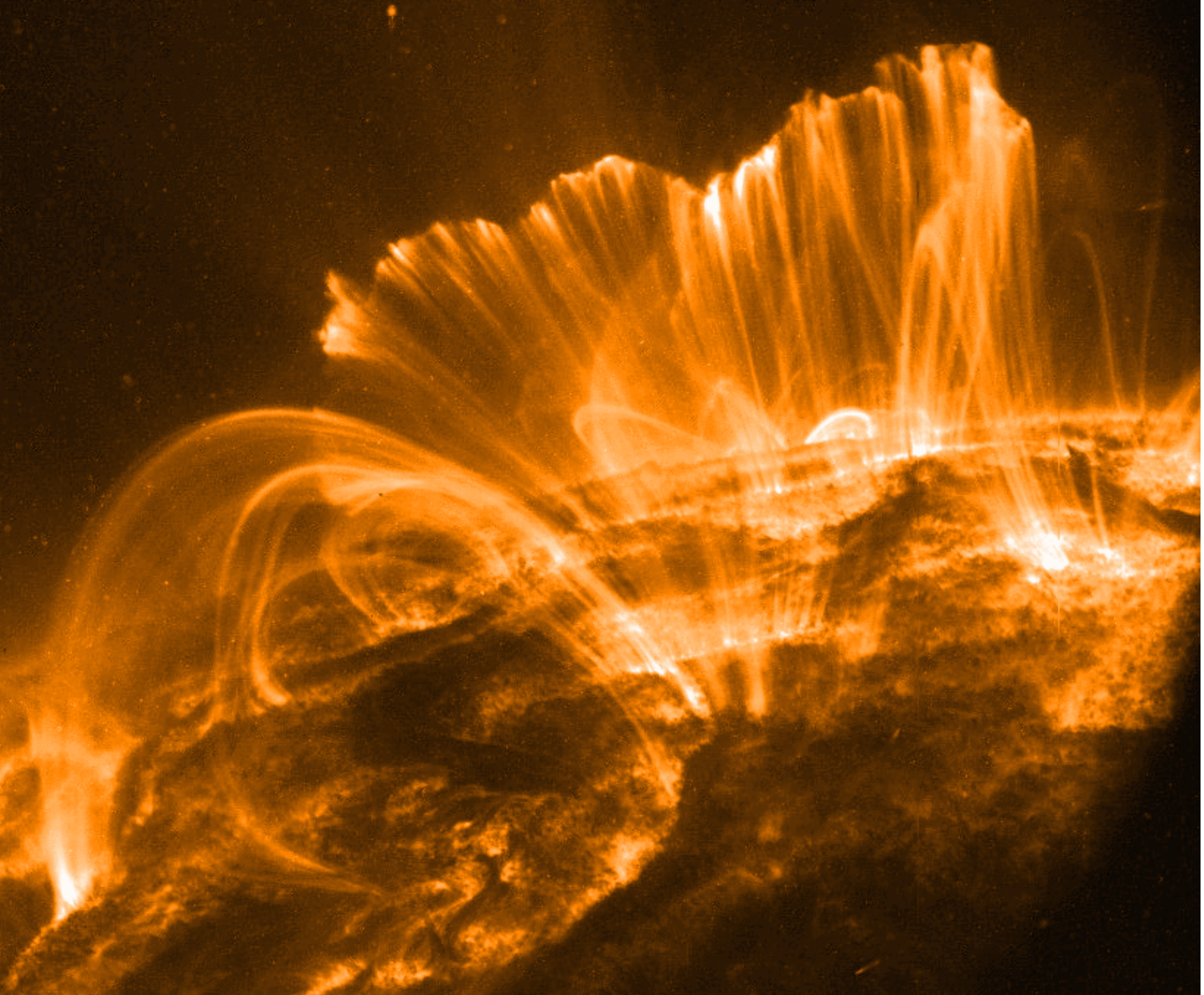
Introduction to solar coronal Heating

- The solar corona is the outermost layer of the Sun's atmosphere, extending millions of kilometers into space.
- Initially it could be observed during solar eclipses and it was thought to be part of the lunar atmosphere
- It is characterized by high temperatures (1-2 million K) and low densities.
- The corona's structure is highly dynamic and it can directly affect the space weather and the Earth



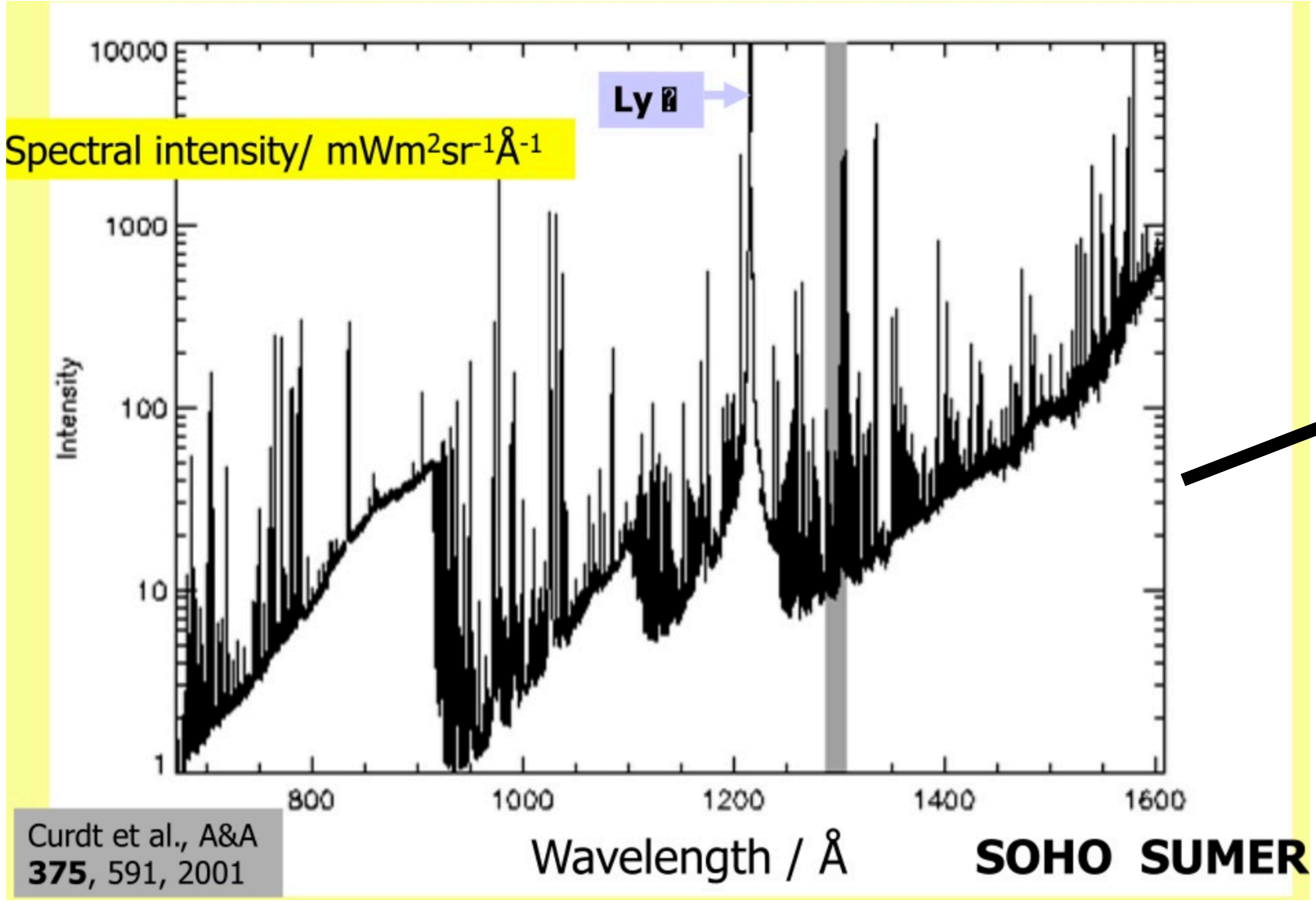
Why study the corona?

- ➢ astrophysical interest in general
  - heating of the corona is is one of the 10 most interesting questions in astronomy!

- ➢ solar-terrestrial relations:
  - strongest variability in UV: <160 nm from corona/TR!
  - coronal mass ejections (CME):
    - satellite disruptions
    - safety of astronauts and air travel
  - geomagnetic disturbances
    - GPS
    - radio transmission
    - Oil pipelines
    - power supply

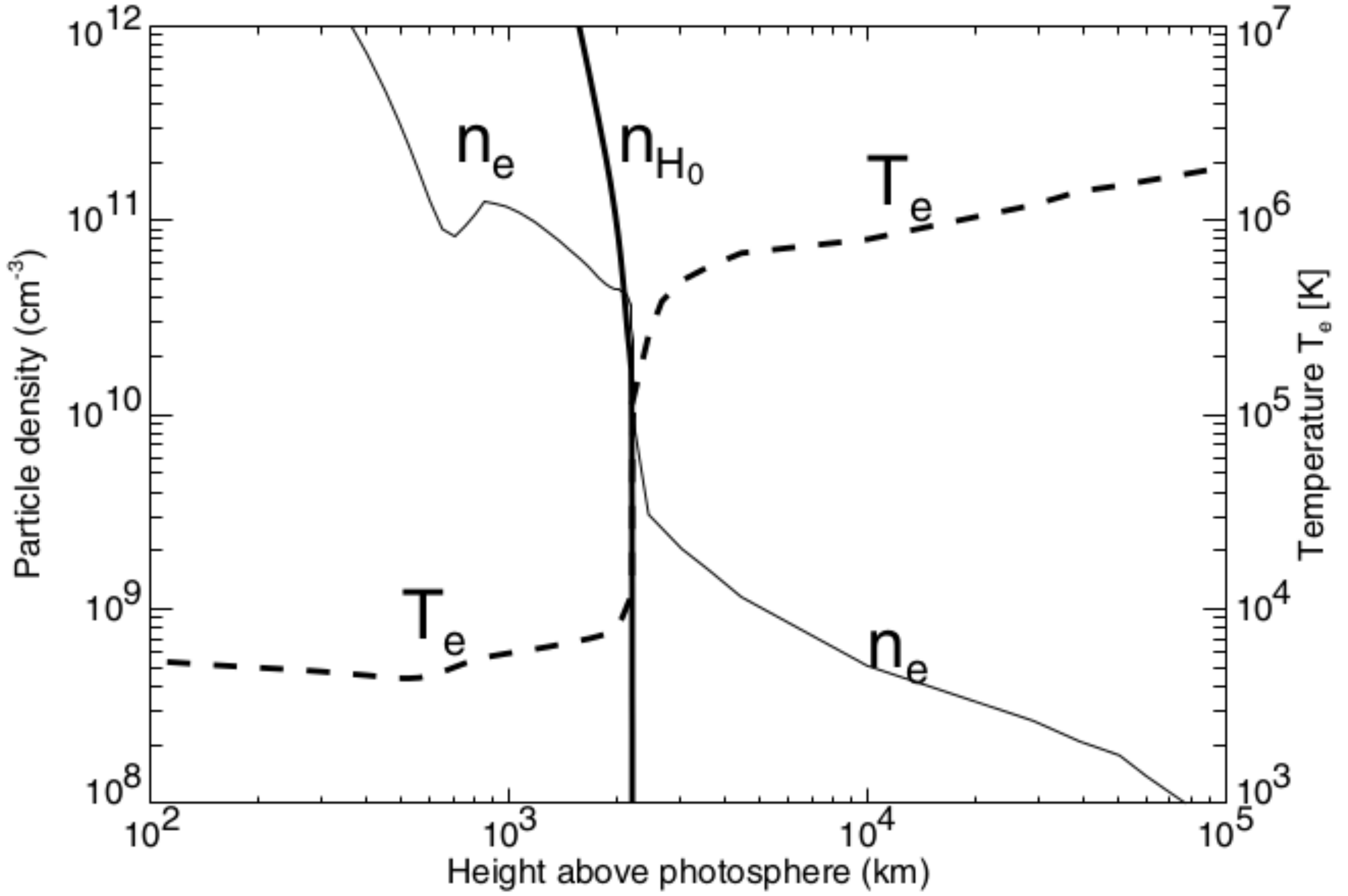
- ➢ other astrophysical objects
  - accretion disks of young stars: stellar and planetary evolution
  - …

Introduction to solar coronal Heating



- Solar photosphere emits as a blackbody with a T=5800 K
- Corona is optically thin with small opacity
- EUV spectrum lines revealed highly ionised elements in the solar corona
- This led to the coronal heating problem: why the corona is much hotter than the photosphere (~6000 K)

- Temperature steeply increases from a few thousand K to a million K
- At the same time density steeply decreases at the corona from n_e~10^{12} cm^{-3} to n_e~10^8 cm^{-3}



Aschwanden, M. J., 2005, Physics of the solar corona (2nd edition)

Introduction to solar coronal Heating

Space-Based Solar Observatories

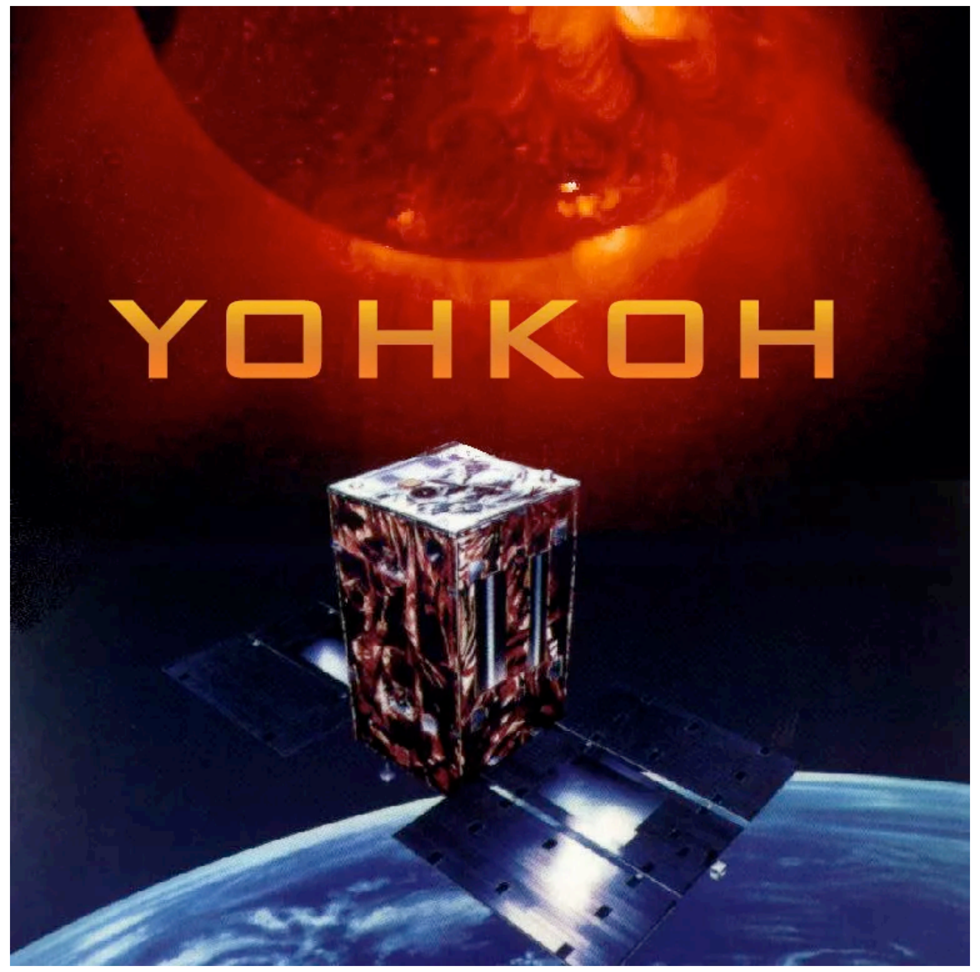
- **Yohkoh**: Launched in 1991, focused on X-ray observations of the solar corona.
- **SOHO**: Launched in 1995, provided continuous observations with multiple instruments.
- **TRACE**: Launched in 1998, offered high-resolution imaging of the solar atmosphere.

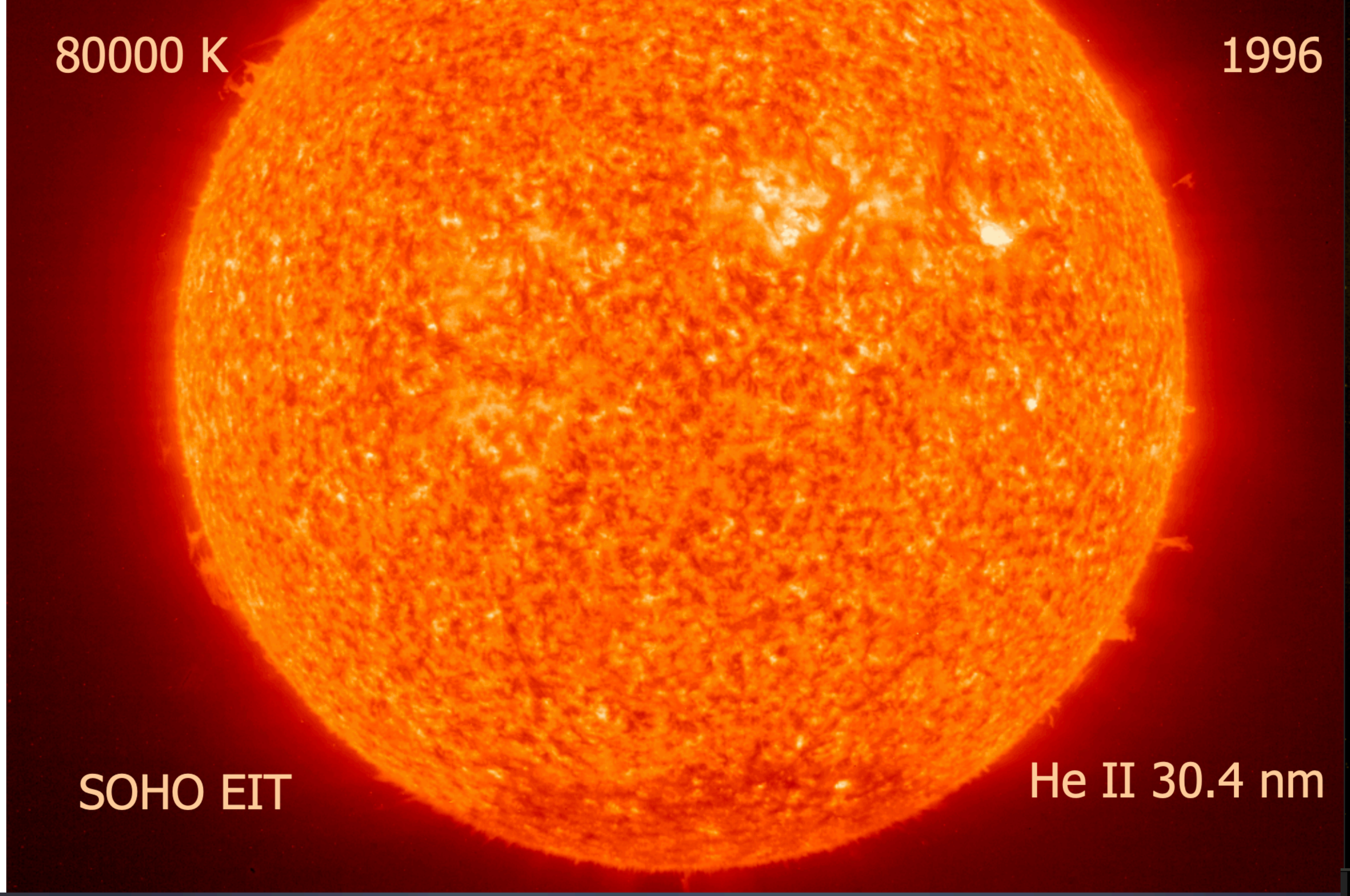
Key Instruments and Their Contributions

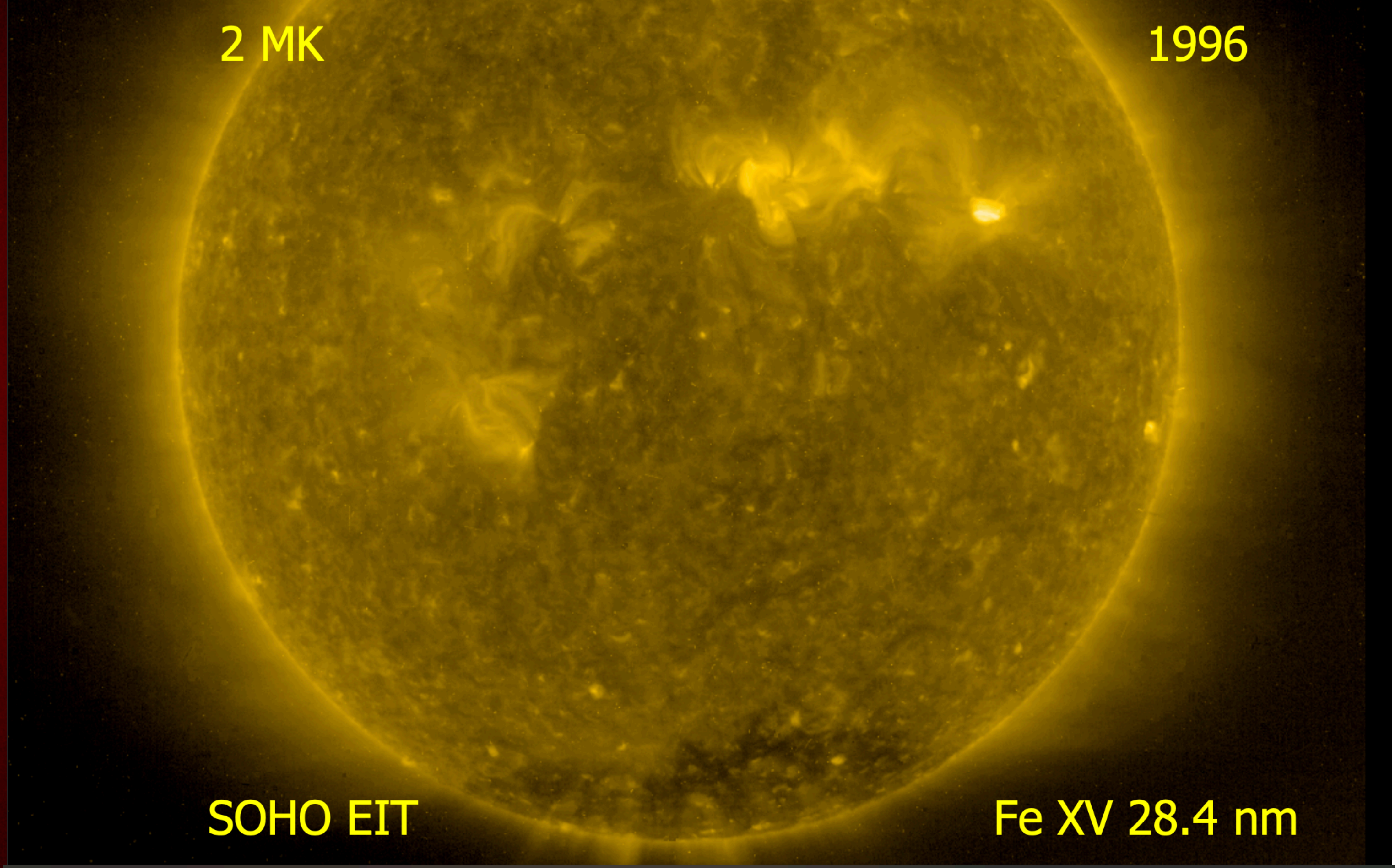
- **EIT (Extreme Ultraviolet Imaging Telescope) on SOHO**: Provided images of the corona in various UV wavelengths.
- **SUMER (Solar Ultraviolet Measurements of Emitted Radiation) on SOHO**: Spectroscopic measurements of the solar atmosphere.
- **CDS (Coronal Diagnostic Spectrometer) on SOHO**: Diagnosed temperature, density, and flows in the corona.

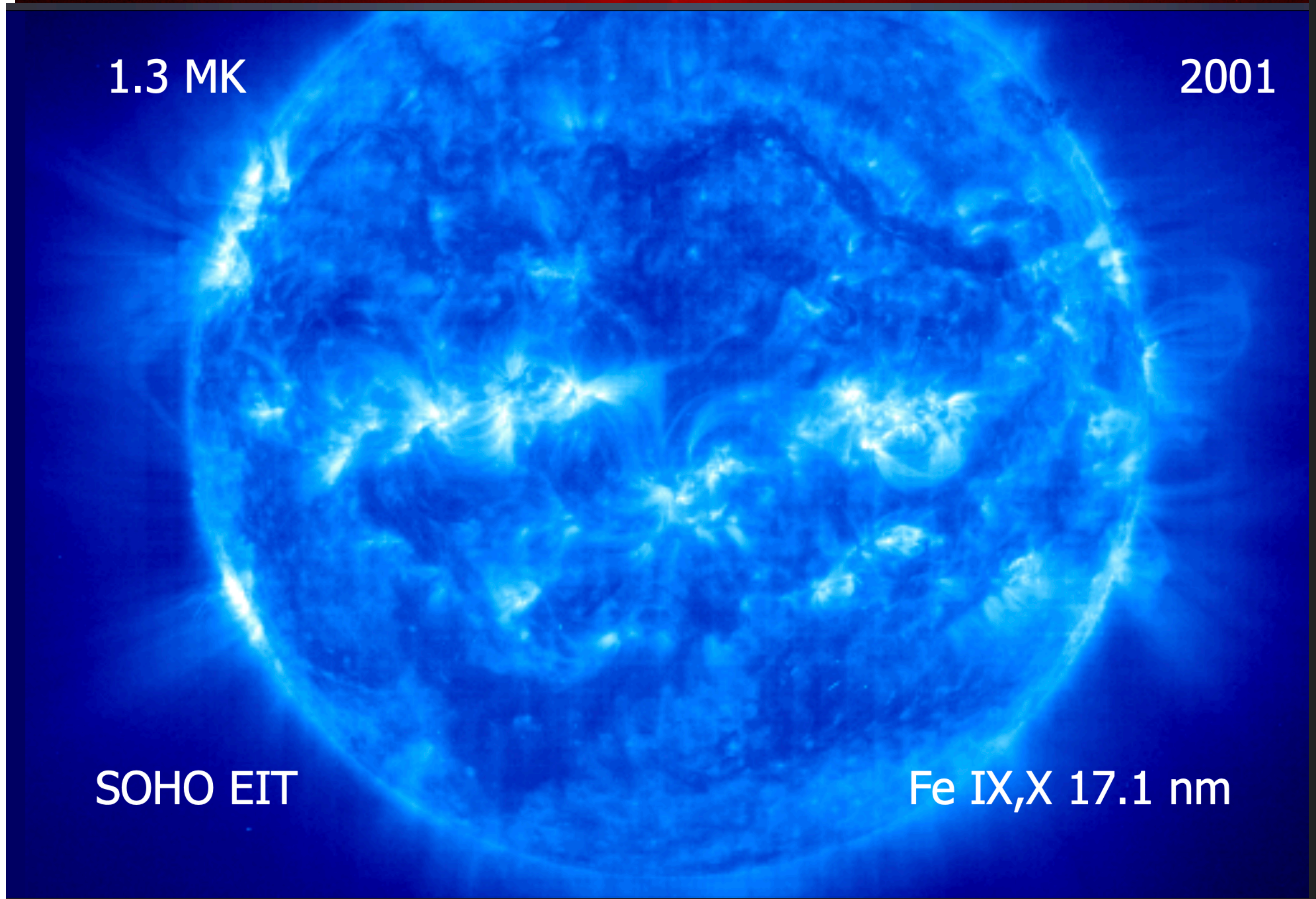
Recent Advancements and Findings

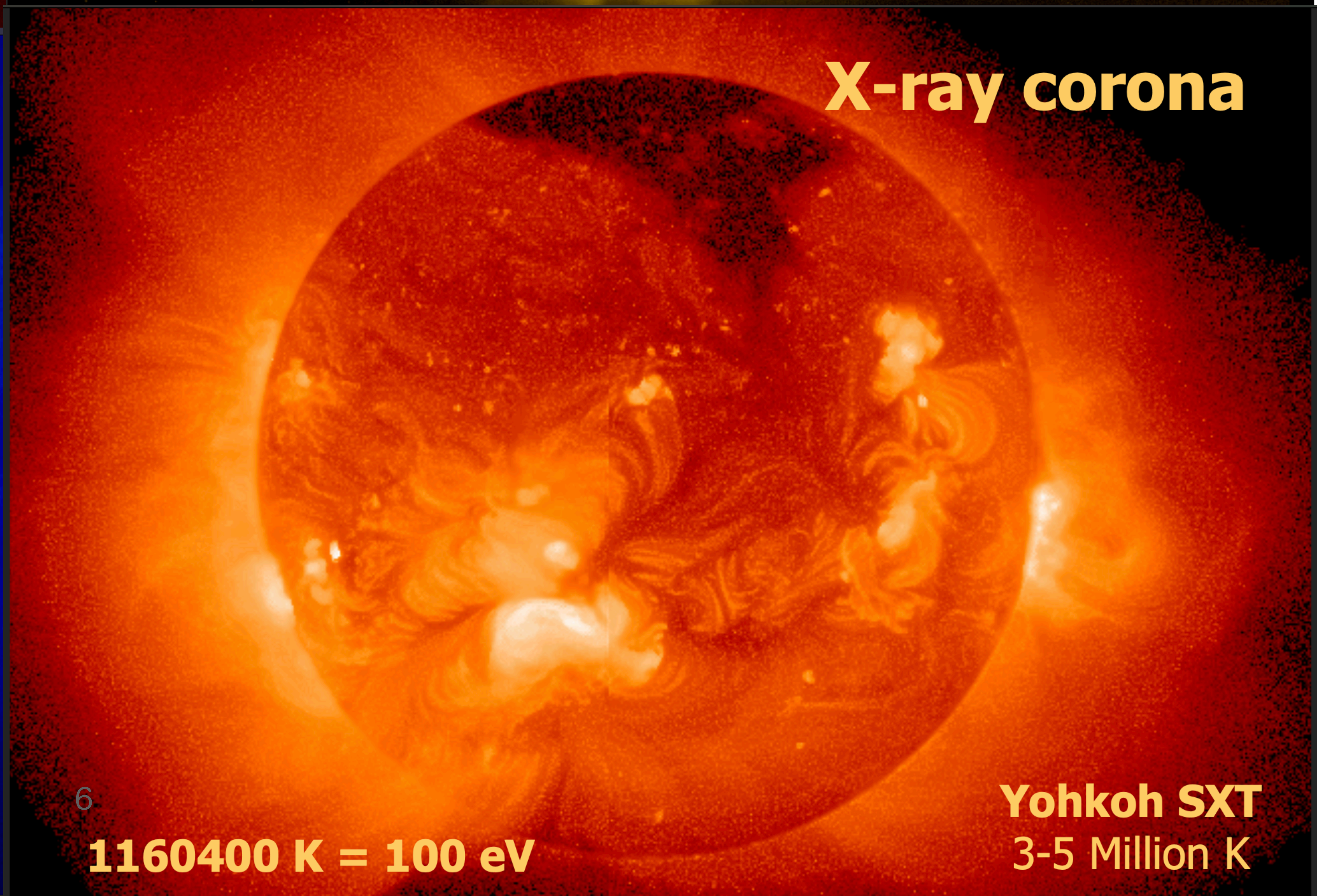
- **High-Resolution Imaging and Spectroscopy**: Unprecedented details of the coronal structure and dynamics.
- **Dynamic Features and Magnetic Interactions**: Observations of flares, loops, and other transient phenomena.



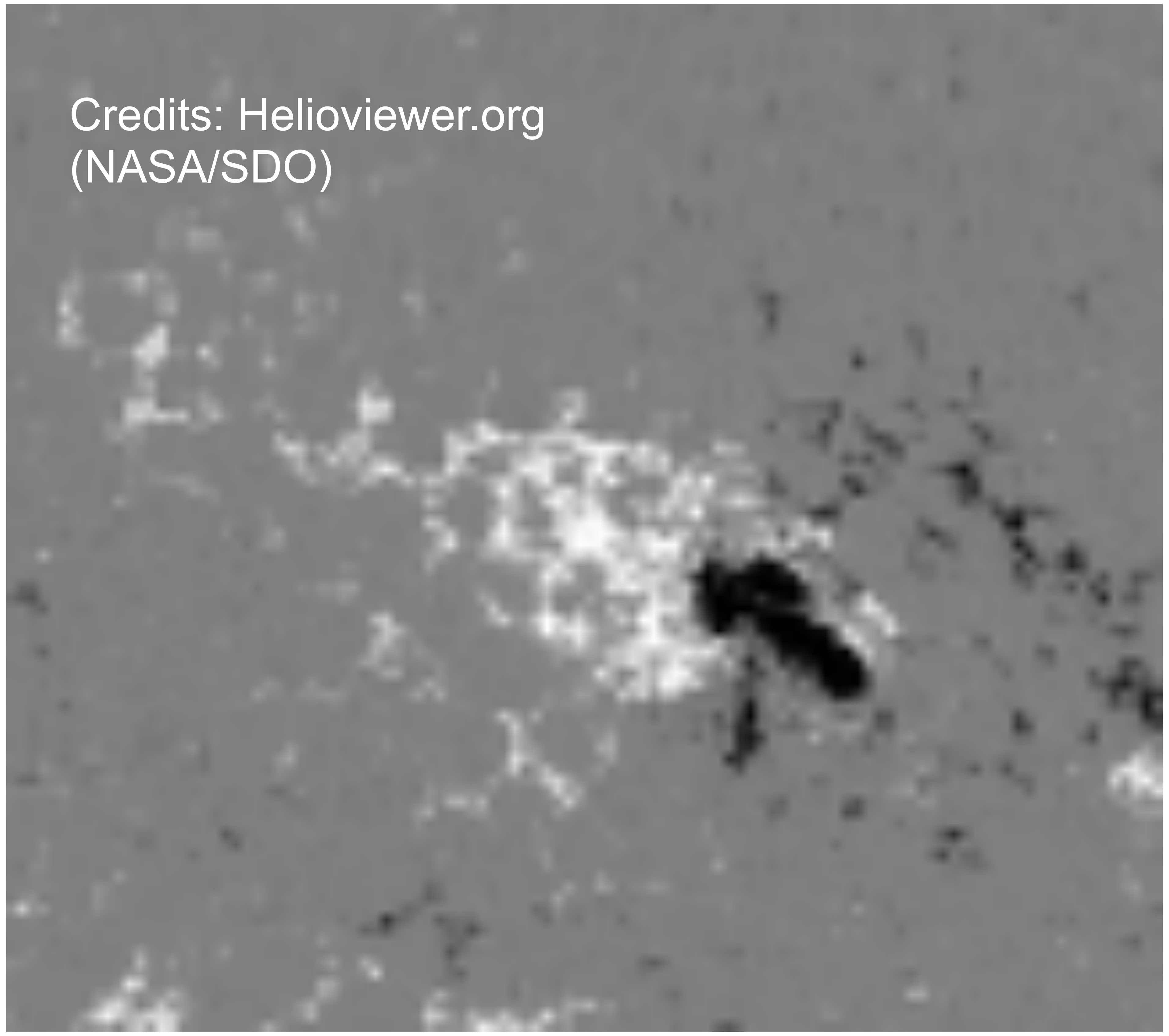

80000 K
1996
SOHO EIT
He II 30.4 nm


2 MK
1996
SOHO EIT
Fe XV 28.4 nm

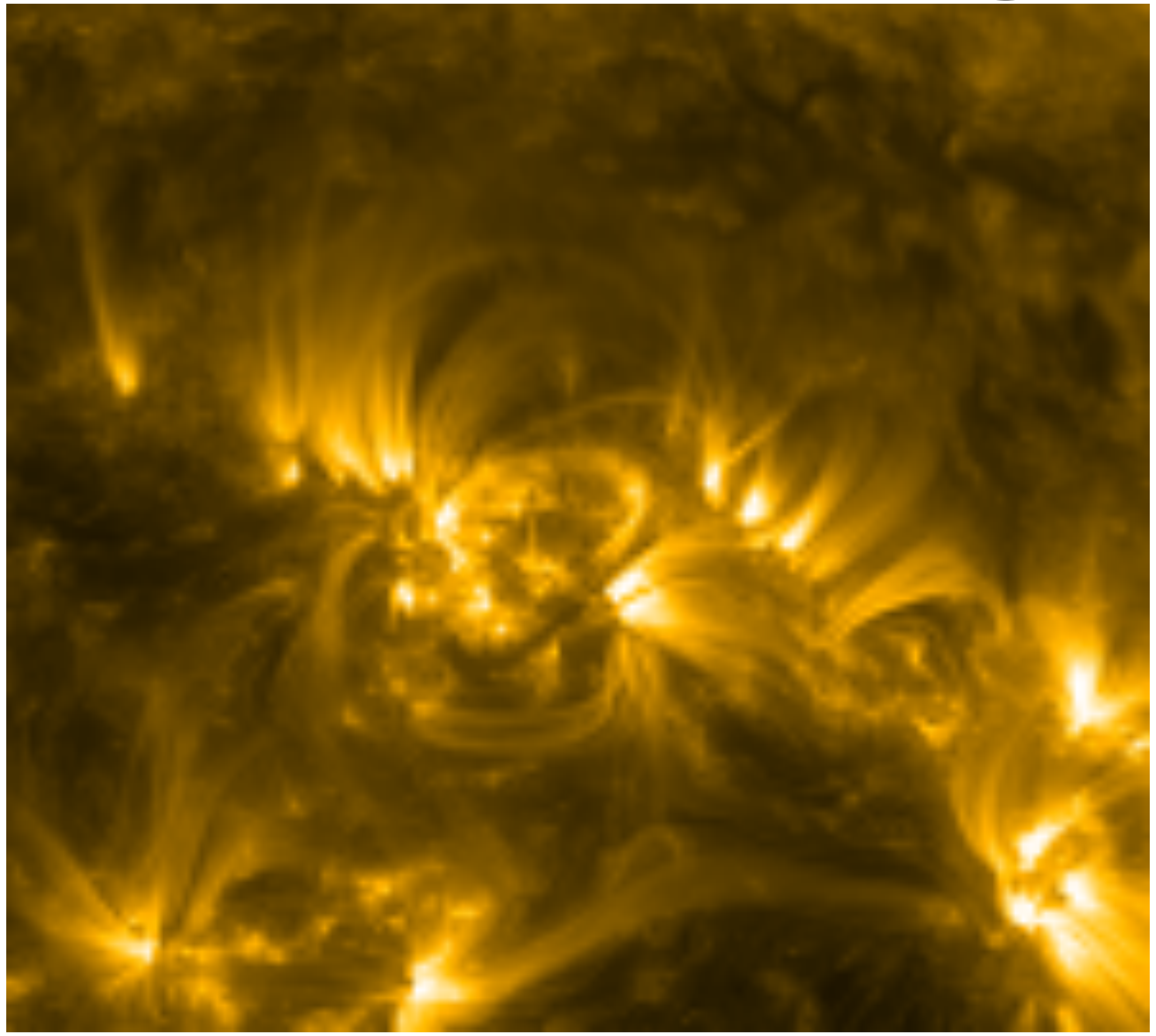

1.3 MK
2001
SOHO EIT
Fe IX,X 17.1 nm


X-ray corona
Yohkoh SXT
3-5 Million K
1160400 K = 100 eV

Introduction to solar coronal Heating



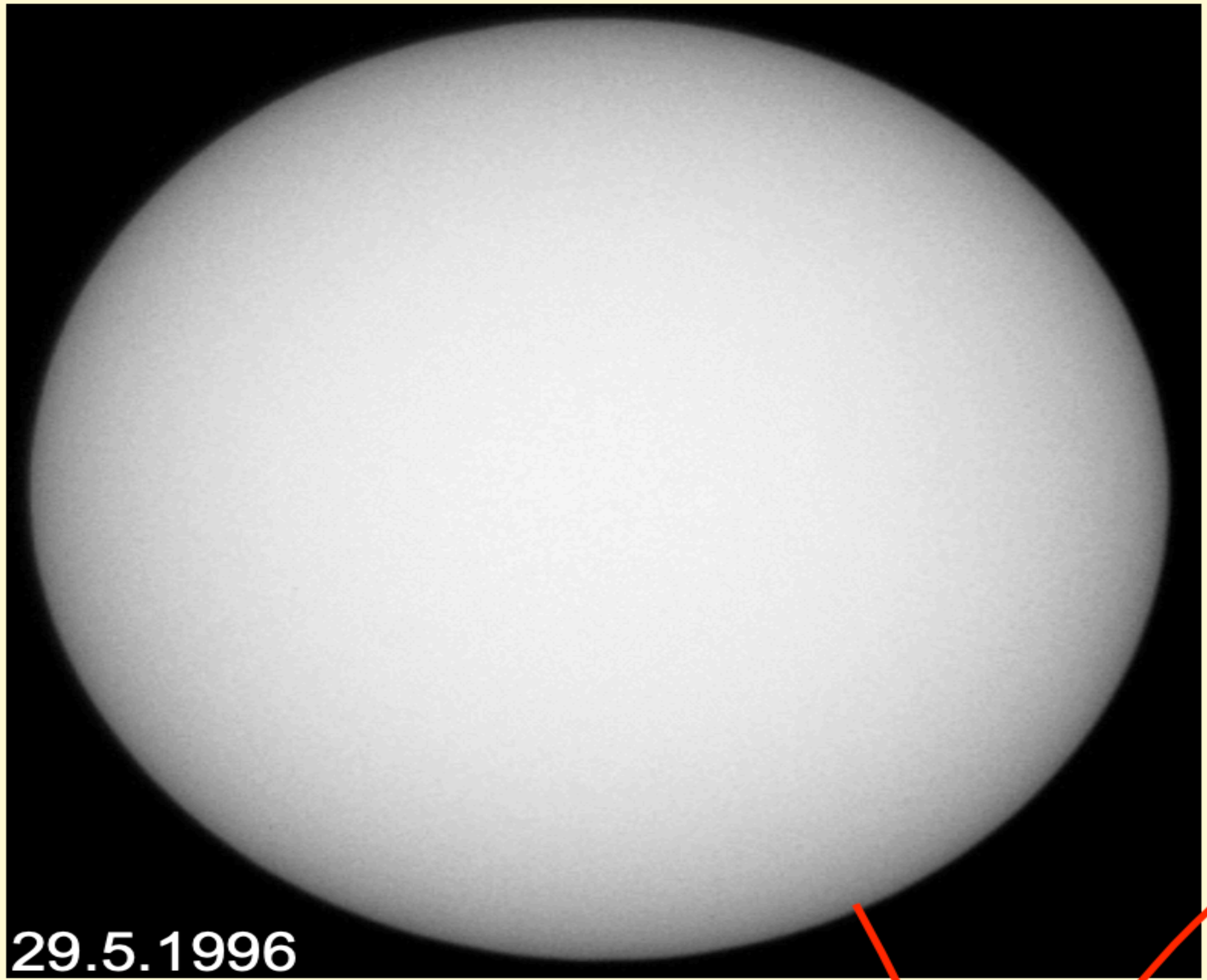
Line of sight surface magnetic field

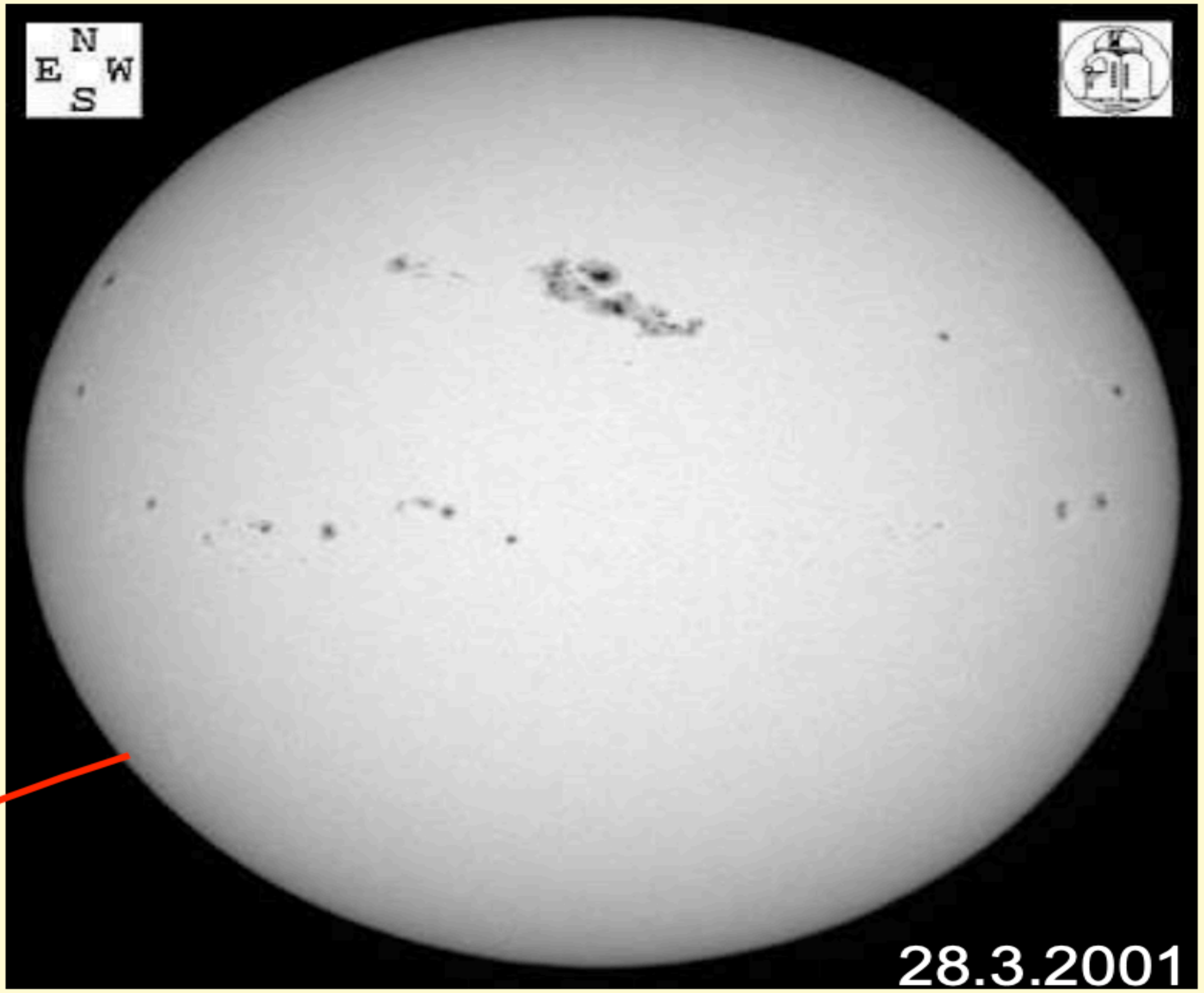


AIA 17.1 nm : *Fe IX* T ~ 1 MK

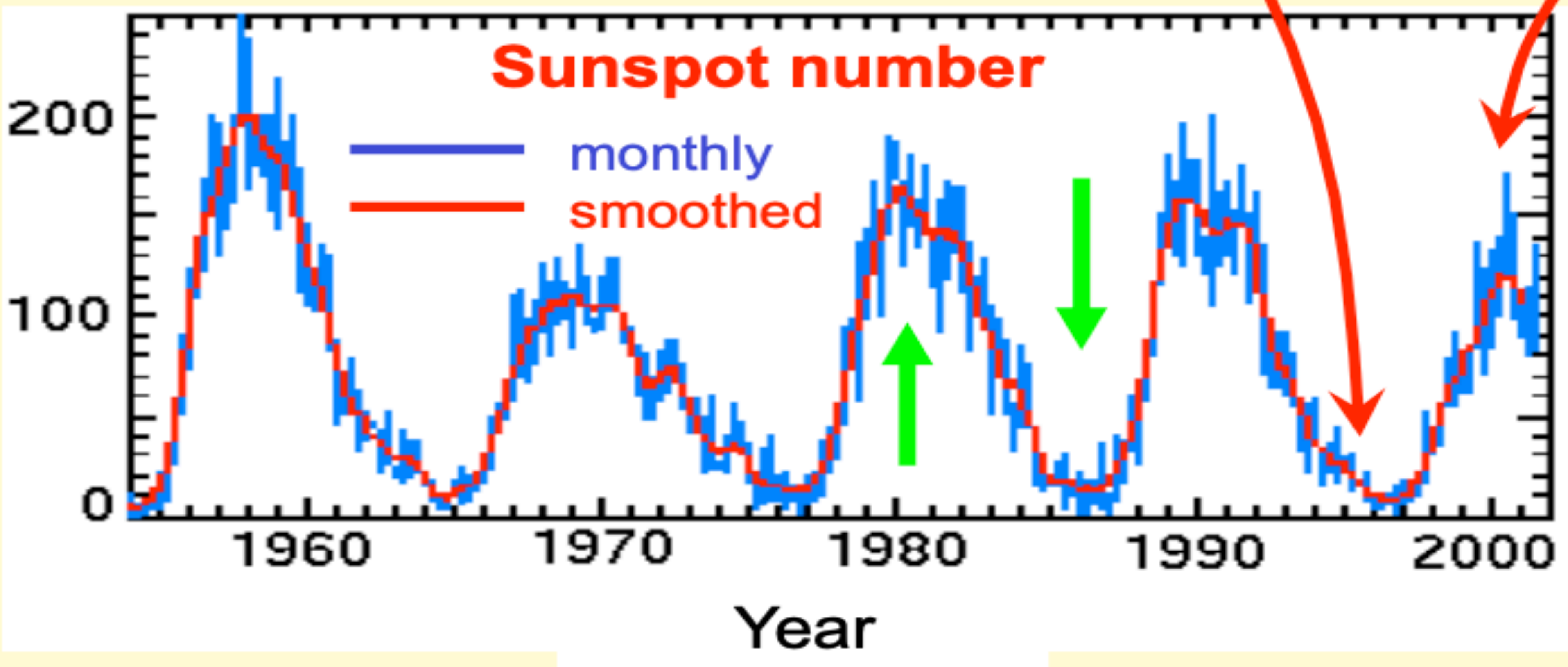
- Strong surface magnetic field concentration is linked to highly dynamic and energetic phenomena that can heat the corona
- Plasma motions and magnetic field interact with each other acting as a magnetized fluid described by the magnetohydrodynamic equations (MHD)
- These phenomena are usually studied in observations but also numerical experiments (MHD simulations)

minimum | the Sun in white light | **maximum**





Big Bear Solar Observatory



H. Peter
lecture

11 year cycle of the Sun:

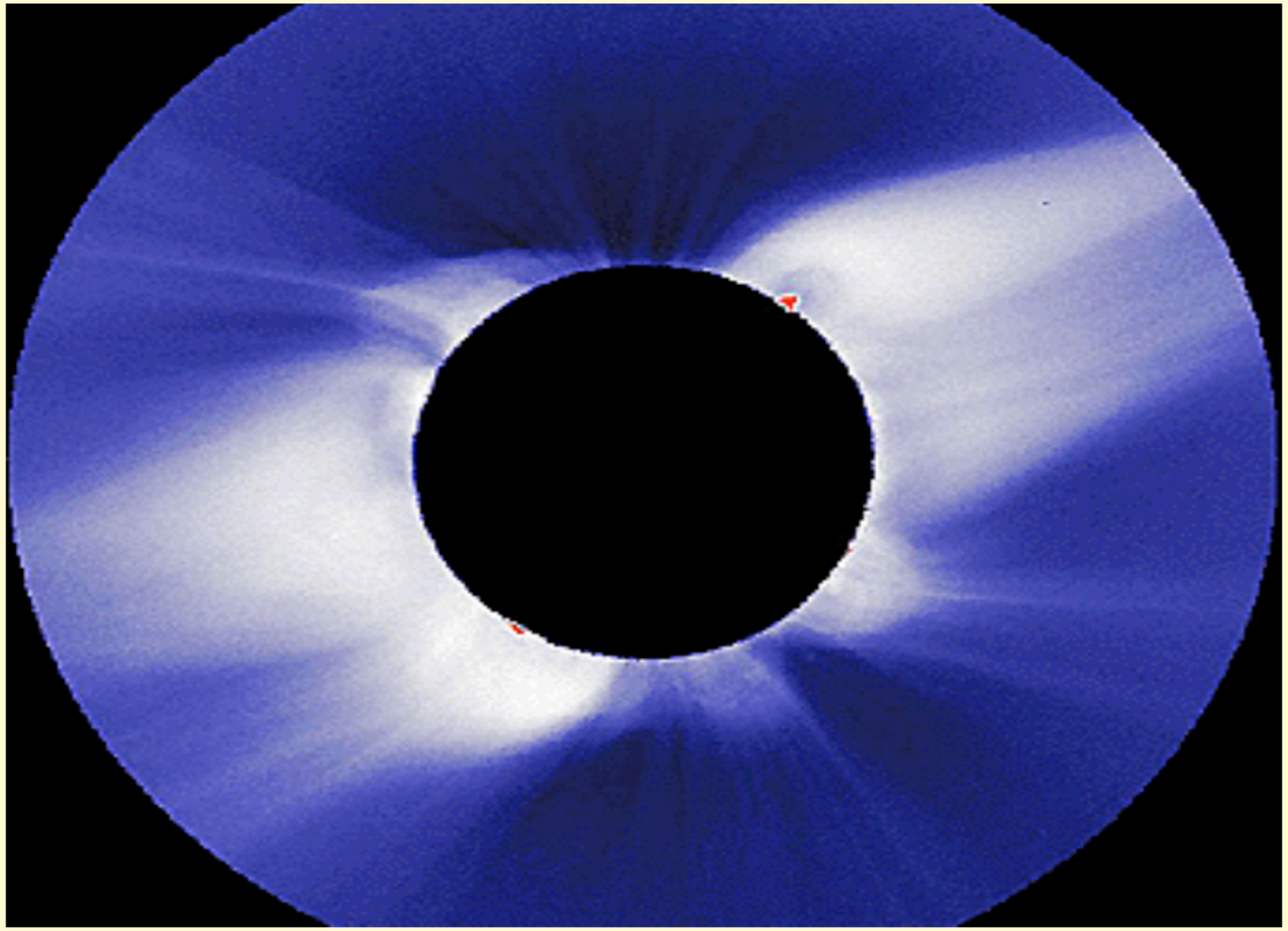
- ➢ sunspot number (since 1843)
- ➢ magnetic polarity (since 1908)
- ➢ magnetic activity

basic mechanism:

⇨ dynamo generating magnetic field

Minimum

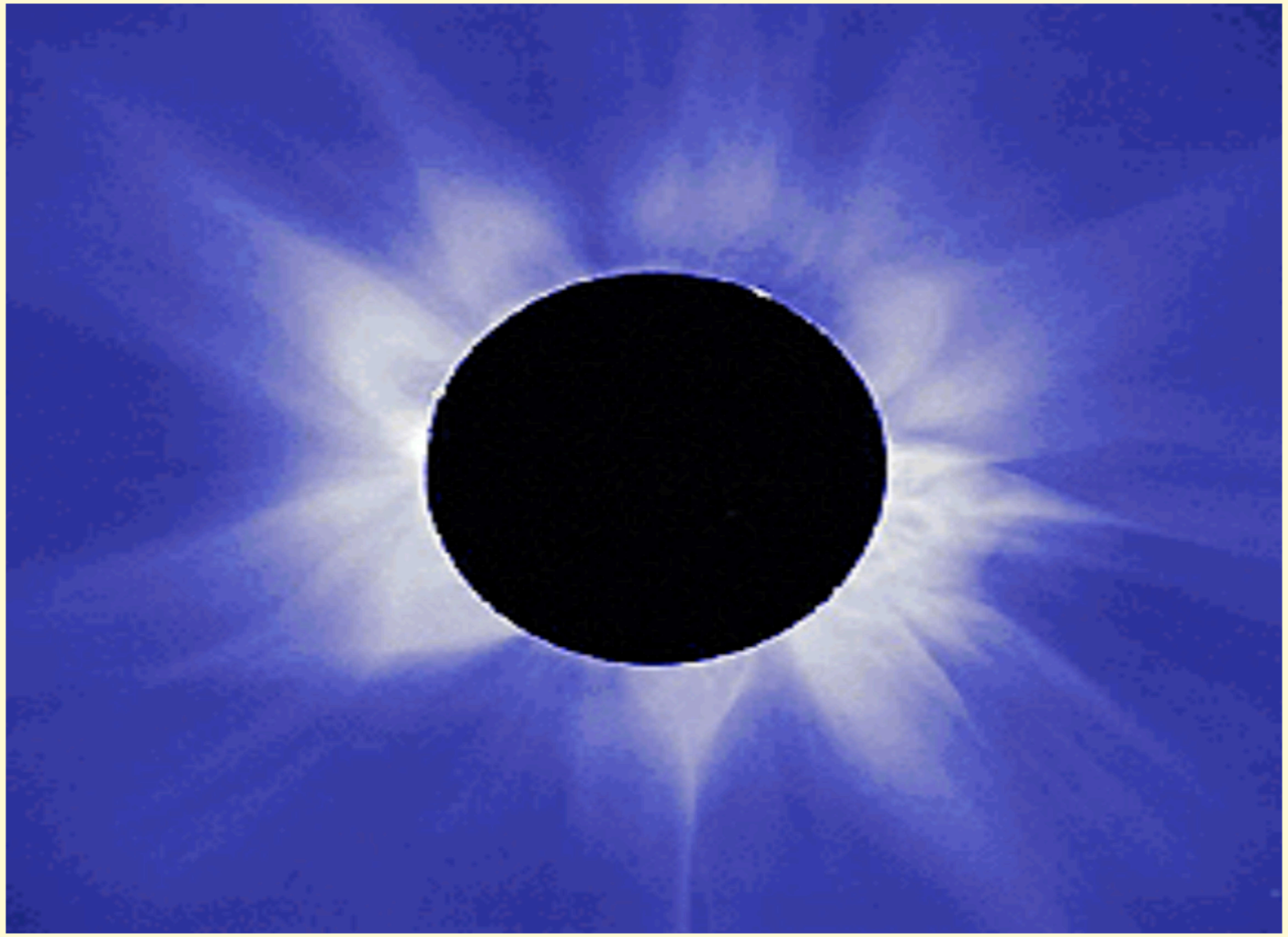
- "simple" dipolar structure
- few active regions (sunspots)
- prominent coronal holes
- "helmet streamer" only at equator



18. 3. 1988, Philippines

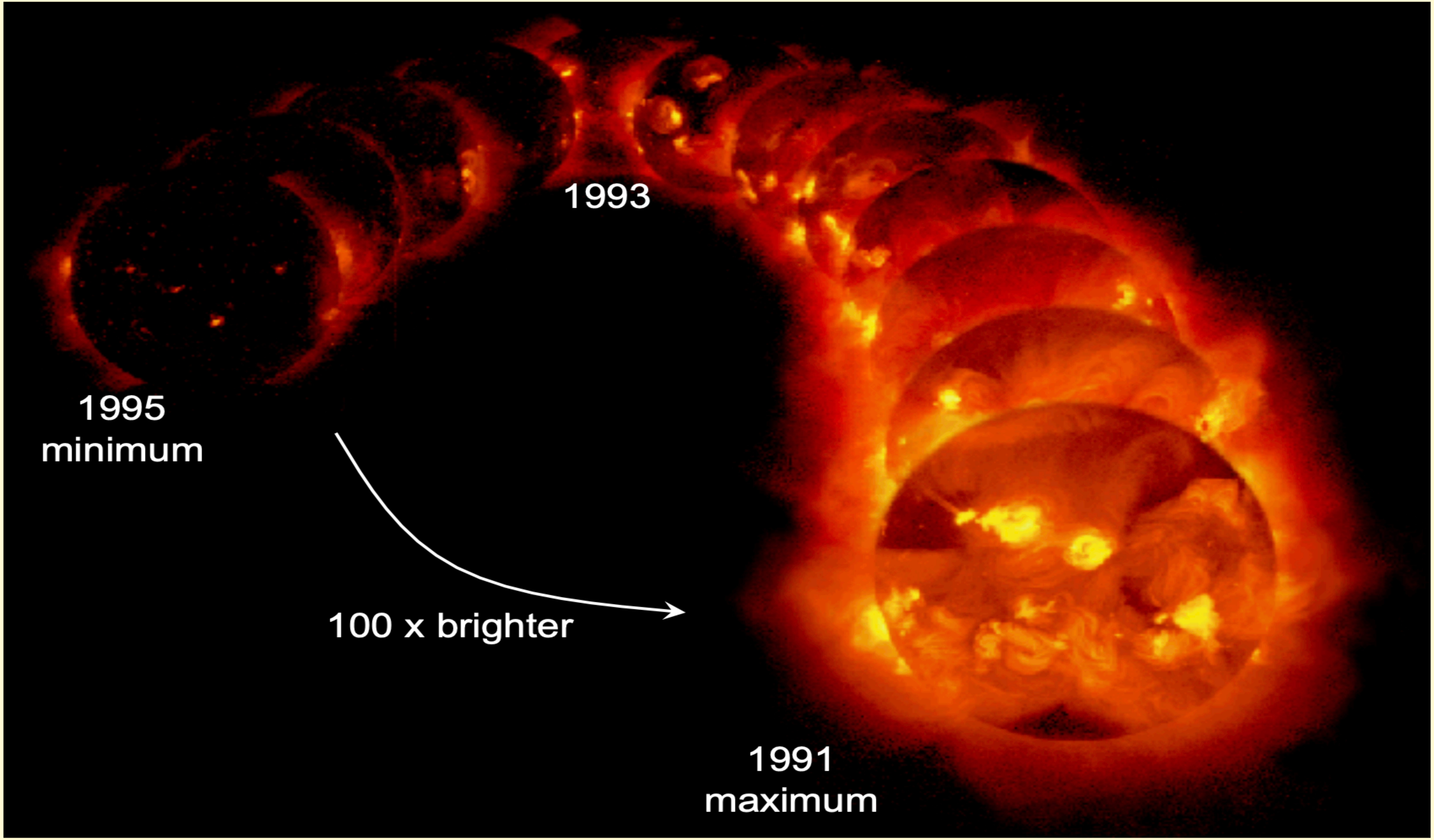
Maximum

- complex magnetic structure
- many active regions
- almost no coronal holes
- "helmet streamer" at all latitudes



16. 2. 1980, India

High Altitude Observatory - NCAR



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lecture

Yohkoh Soft X-ray Telescope (SXT), X-ray emission at about 1 nm

First Summary of the solar corona observations

- 1850: first systematic "modern" eclipse observations
- 1870: introduction of spectroscopy into coronal physics
- 1930: invention of coronagraph
- 1940: coronal lines are from highly ionized species ← the corona ~10^6 K
- 1970: first advanced X-ray observations

1) the corona is magnetically structured
2) the appearance of the corona changes with solar activity cycle
3) Appearance the solar atmosphere changes dramatically with temperature

2nd Part

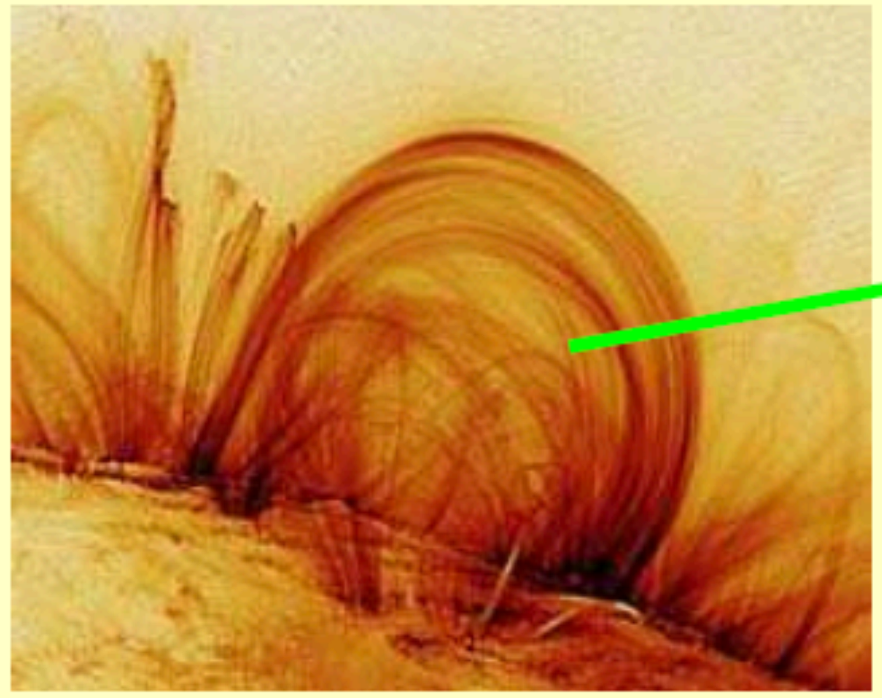
Heating Mechanisms

Coronal heating - an unsolved problem

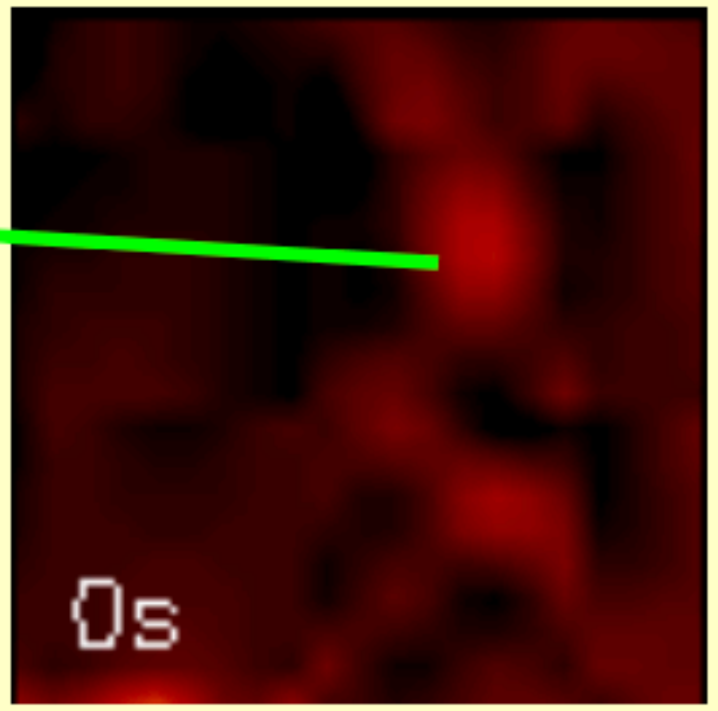
Why?

- Solar corona is non-uniform and highly structured
- Corona varies in time (magnetic activity cycle)
- Temporal and spatial changes occur on all scales
- Corona is far from thermal (collisional) equilibrium
- Coronal processes are dynamic and often nonlinear

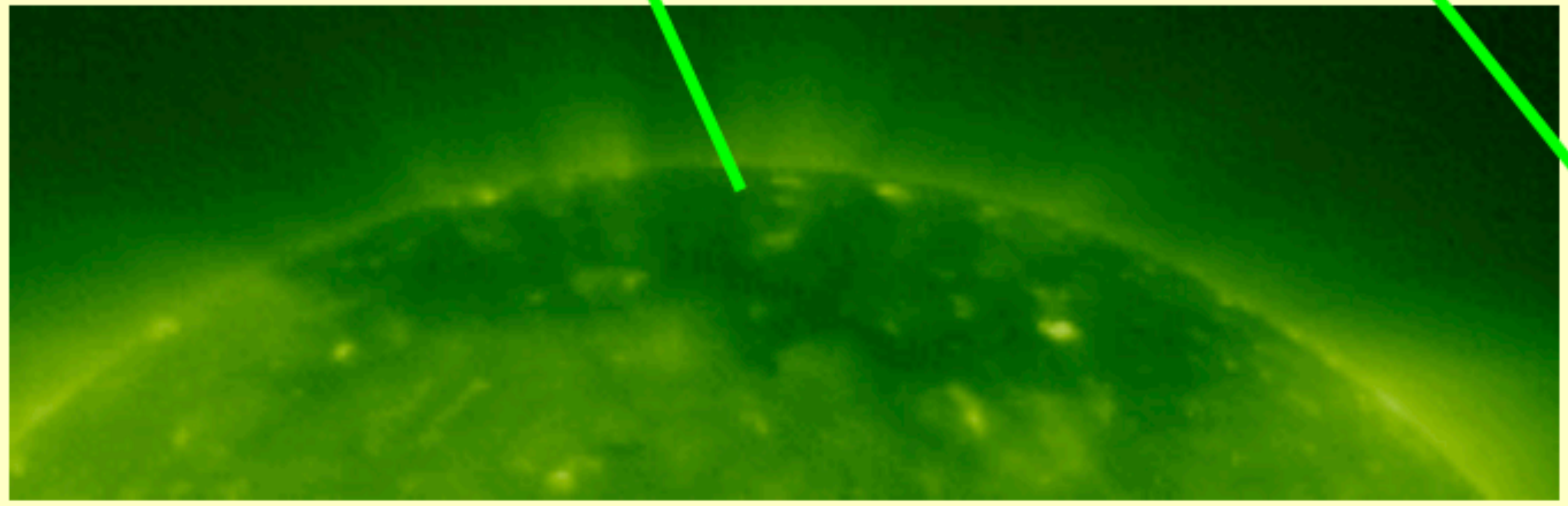
Coronal heating?



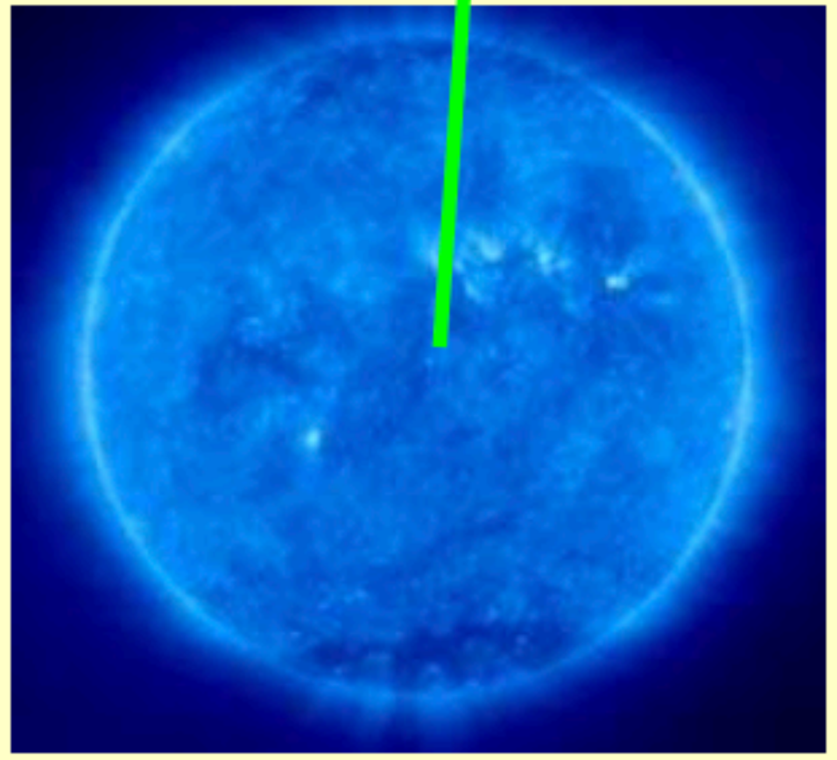
closed magnetic loops are observed at a wide range of temperatures



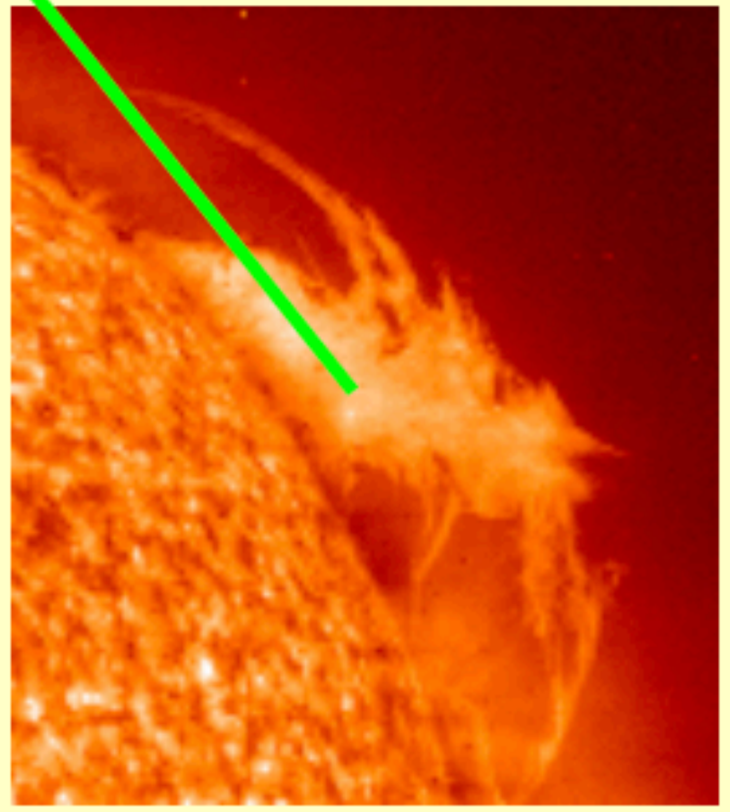
Small brightenings at a range of wavelenths



polar plumes are observed at “coronal” temperatures in open magnetic structure, the coronal holes



“diffuse” corona radiating at 2 MK is not confined to “bright” loops



special energy requirements in cool (10^4 K) prominence

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Time and space dependent

Stages involved in coronal heating

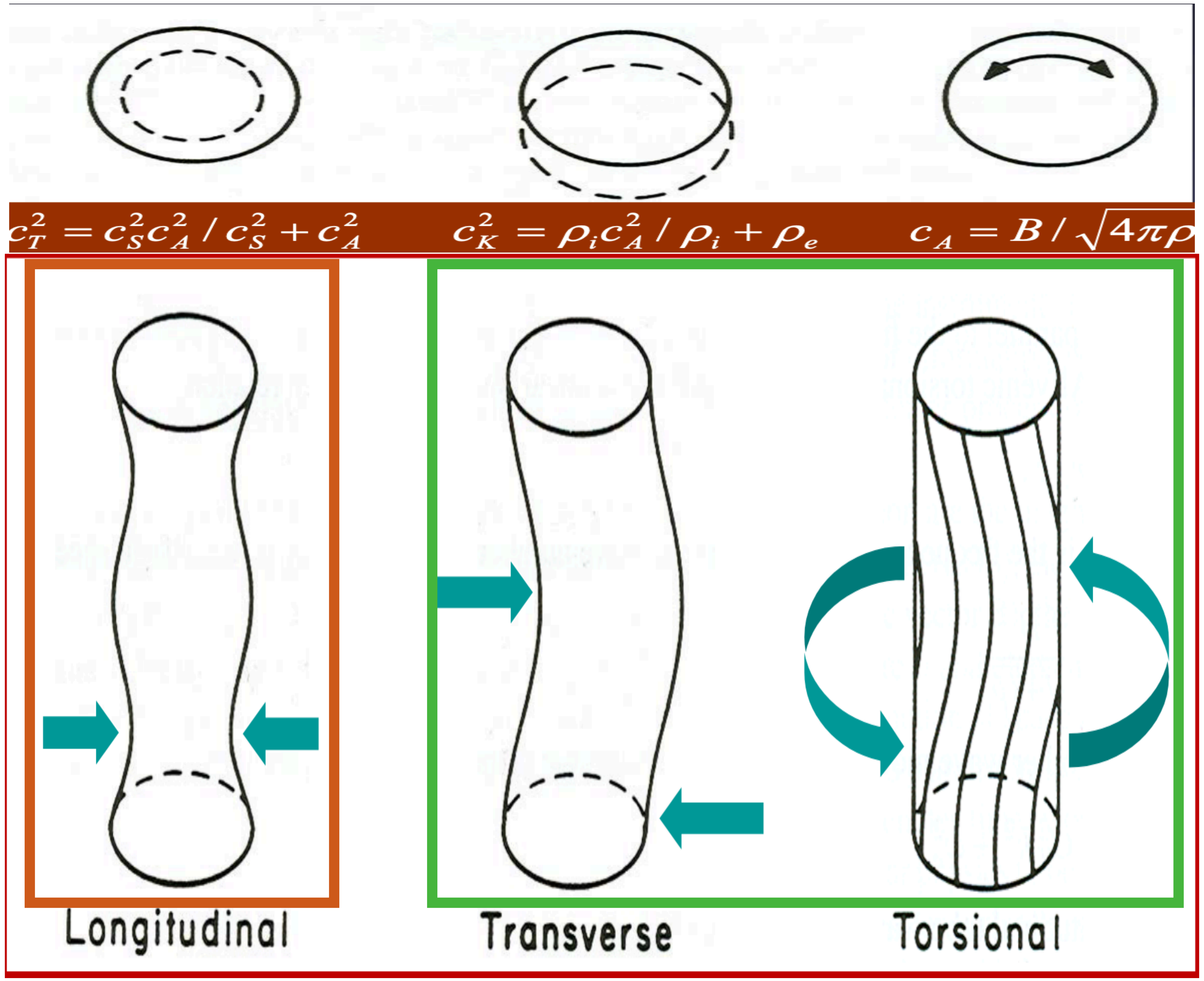
- Generation or storage of mechanical and magnetic energy: photosphere (magneto convection, surface motions)
- Transport of mechanical and magnetic energy: from photosphere via chromosphere and transition region to corona (MHD waves, shocks, currents)
- Release of mechanical and magnetic energy: corona (dissipation of waves and currents, magnetic reconnection)
- Reaction of corona to heating: Redistribution of heating (Heat conduction) and Radiative losses

Coronal Heating Mechanisms

- AC mechanisms: wave heating (energy transported by waves, dissipated in shocks or by ohmic heating)
- DC mechanisms: ohmic dissipation at current sheets due to finite resistivity
- Impulsive heating or nano flare heating: heating by magnetic reconnection: acceleration of particles to supersonic speeds. Heating at shocks, etc
- Other Mechanisms: Turbulent heating, Chromospheric spicules etc.

AC Mechanism

Com-
pressible
Restoring
force:
Magnetic
and
thermal
pressure
(magneto-
acoustic)



Compression

Shear

Vortex flows

(Mainly)
Incom-
pressible
Restoring
force:
Magnetic
curvature
force
(tension)

AC Mechanism II

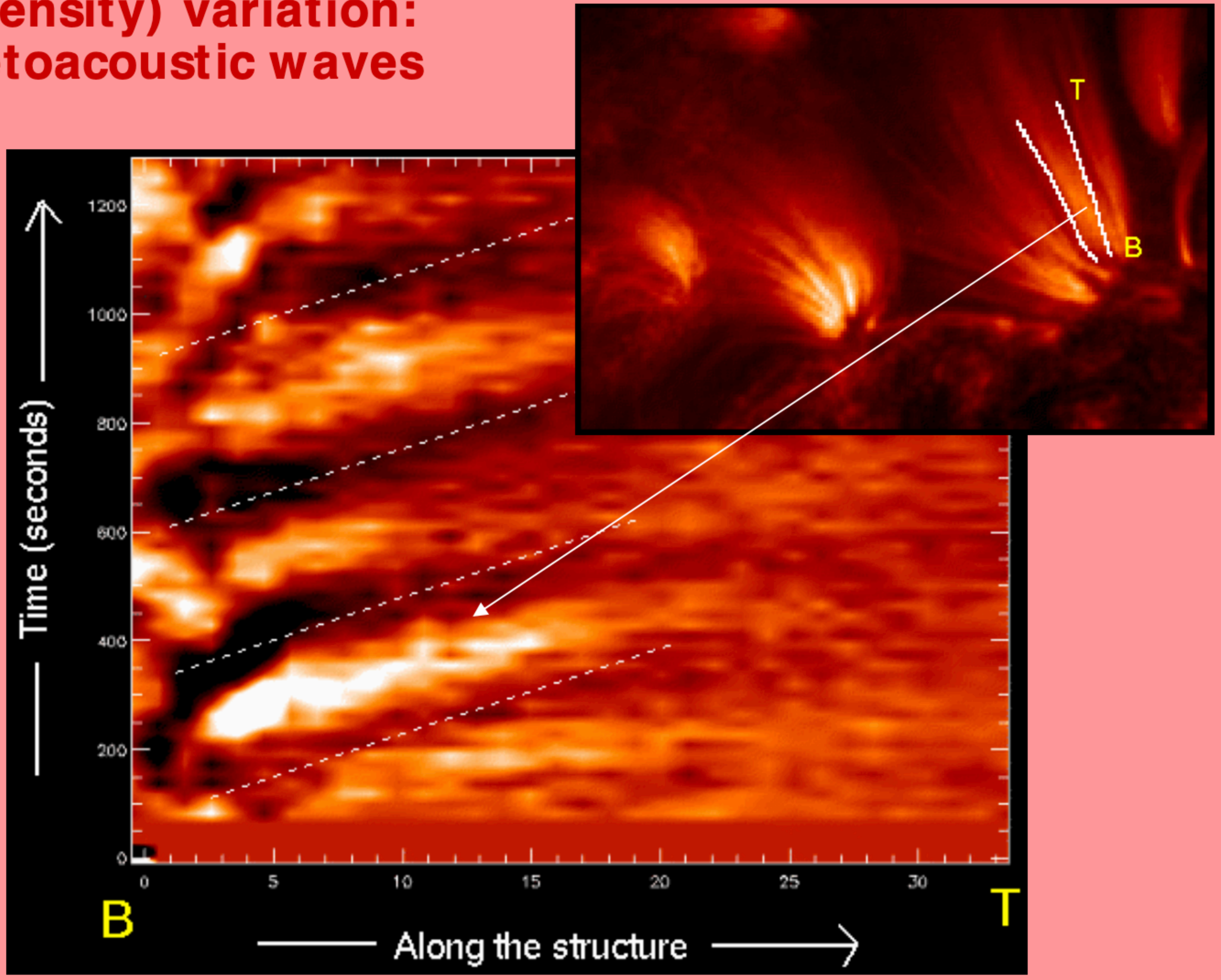
- The turbulent convection that stresses the coronal magnetic field generates a large flux of upwardly propagating waves (acoustic, Alfvén, slow and fast magnetosonic)
- Only a small fraction of the flux is able to pass through the very steep density and temperature gradients in the chromosphere and transition region.
- Acoustic and slow waves steepen into shock waves and are strongly damped, while fast waves are strongly refracted and reflected, only Alfvén waves are able to penetrate into the corona.
- Recent high resolution observations show evidence for waves in the corona, Prominences, Plumes and Corona (EIT/SoHO, TRACE).

Detection of longitudinal waves

Intensity (density) variation:
Slow magnetoacoustic waves

TRACE

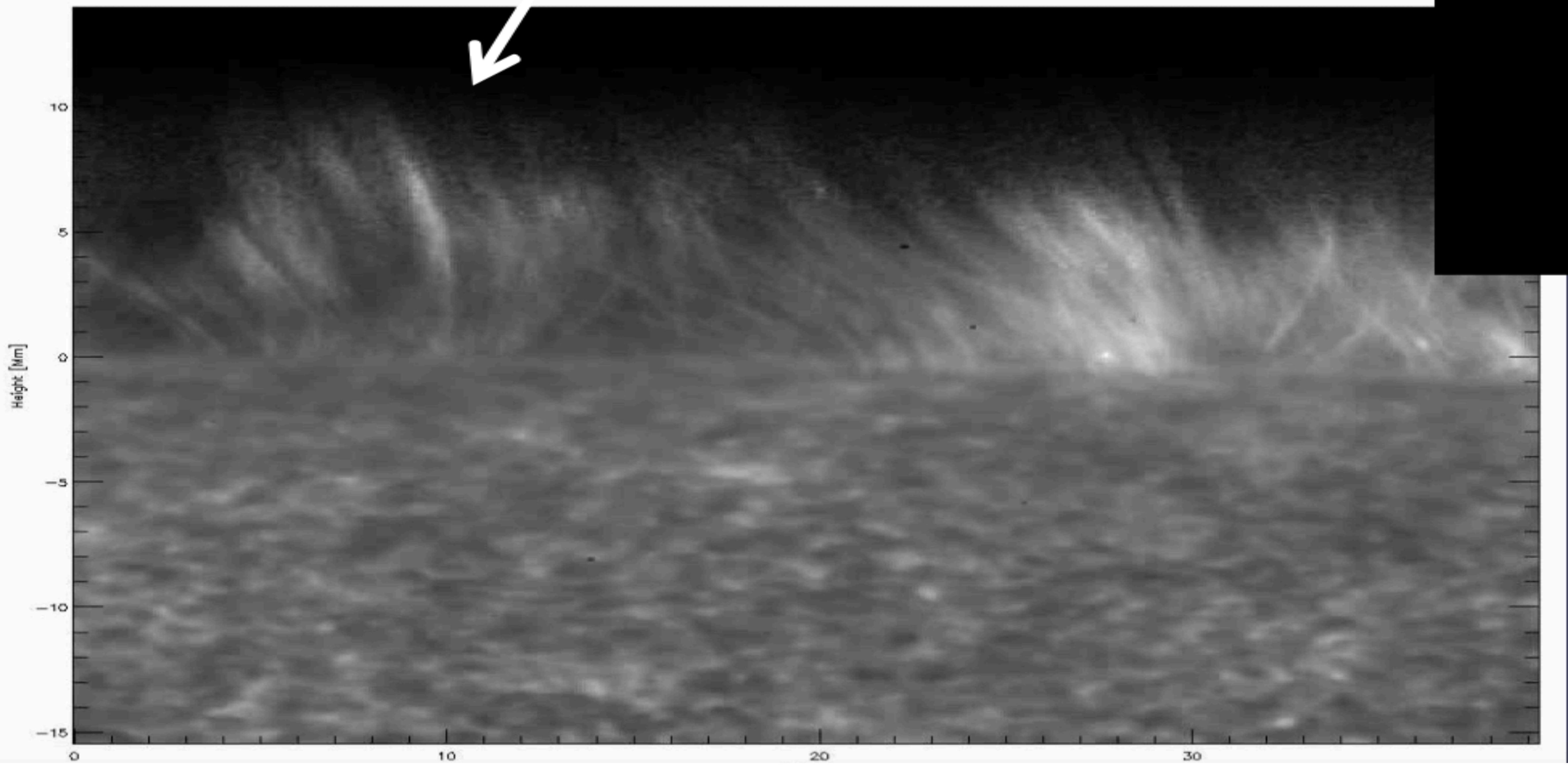
Loop images in Fe 171 Å at 15 s cadence

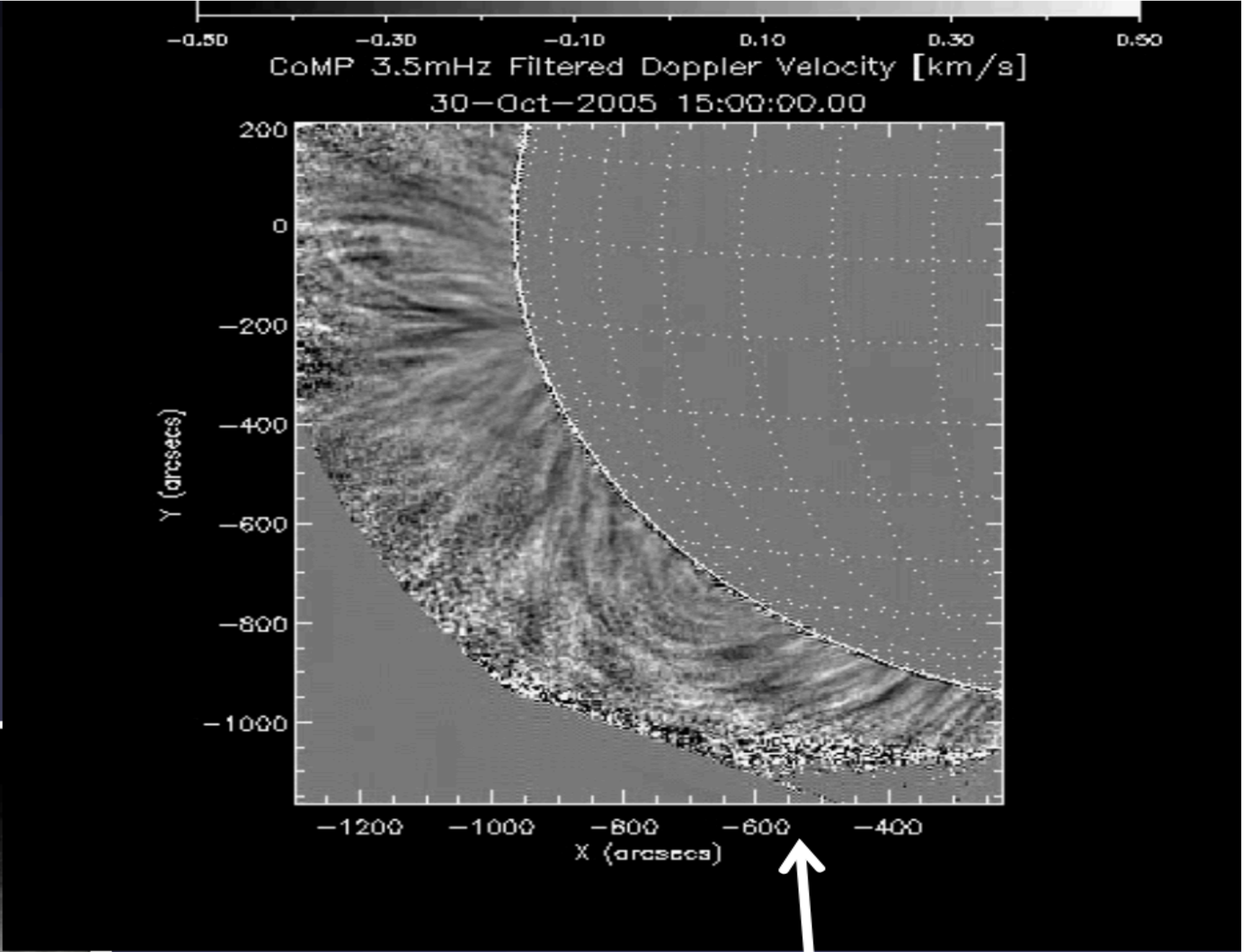


De Moortel et al., 2000

Evidence of waves in solar atmosphere

Kink-mode wave in spicules





Propagating Alfven (or possibly kink) waves in Corona

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How Is Wave Energy Converted To Heat ?

- waves must be generated in (or below) the solar surface layers

1) Solar convection generates a mixture of upward propagating waves with an energy flux of several times 10^7 erg cm−2 s−1 (Narain & Ulmschneider, 1996), which would be more than adequate to heat the solar corona (and accelerate the solar wind)

- sufficient energy flux has to be transported as only a fraction of the wave energy will be transmitted into the corona

2) most of the (magneto)acoustic waves do not propagate into the corona due to strong reflection and refraction off the rapid density and temperature change in the Transition Region

3) Wentzel (1974, 1976) pointed out that Alfvén waves could heat the corona, their weak damping makes them problematic as a coronal heating mechanism. This led to the development of a variety of mechanisms which are likely to enhance the dissipation of Alfvén waves such as resonant absorption and phase mixing.

- In general Alfven wave amplitude is smaller and not easily detectable making it challenging to observe and confirm their ability to heat the corona sufficiently

Detectability of coronal MHD waves

- **Spatial** (pixel size) and **temporal** (exposure/cadence) **resolution** be less than **wavelengths** and **periods**

- **Spectral resolution** to be sufficient to resolve Doppler shifts and broadenings (best, SUMER, 1-15 km/s)

Spacecraft/Instrument	Spatial Resolution, Minimum pixel size/ arcsec	Temporal resolution, Maximal cadence/ s	Spectral bands
SOHO/EIT	2.6	30	EUV
SOHO/CDS	2	30	EUV
SOHO/UVCS	12	seconds - hours	EUV/FUV/WL
SOHO/SUMER	1	10	EUV/FUV
SOHO/LASCO C1	5.6	60	WL
Yohkoh/SXT	4	a few	SX
Yohkoh/HXT	60	0.2	HX
TRACE	0.5	10	EUV/FUV/WL

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Nakariakov, 2003

AC Mechanism- Summary

- Dissipation -> The ordered motions of waves are converted into disordered motions of particles (heat). It occurs at small scales -> Difficult to observe!

- Longitudinal (magnetoacoustic): Dissipation in shocks (very high densities, very large gradients) -> Not able to reach and dissipate in corona (possible for chromosphere heating

- Alfvenic (incompressible) waves: Dissipation in presence of magnetic field gradient. Leads to current sheets -> ohmic dissipation-> Probably sufficient to heat the corona

DC Mechanism

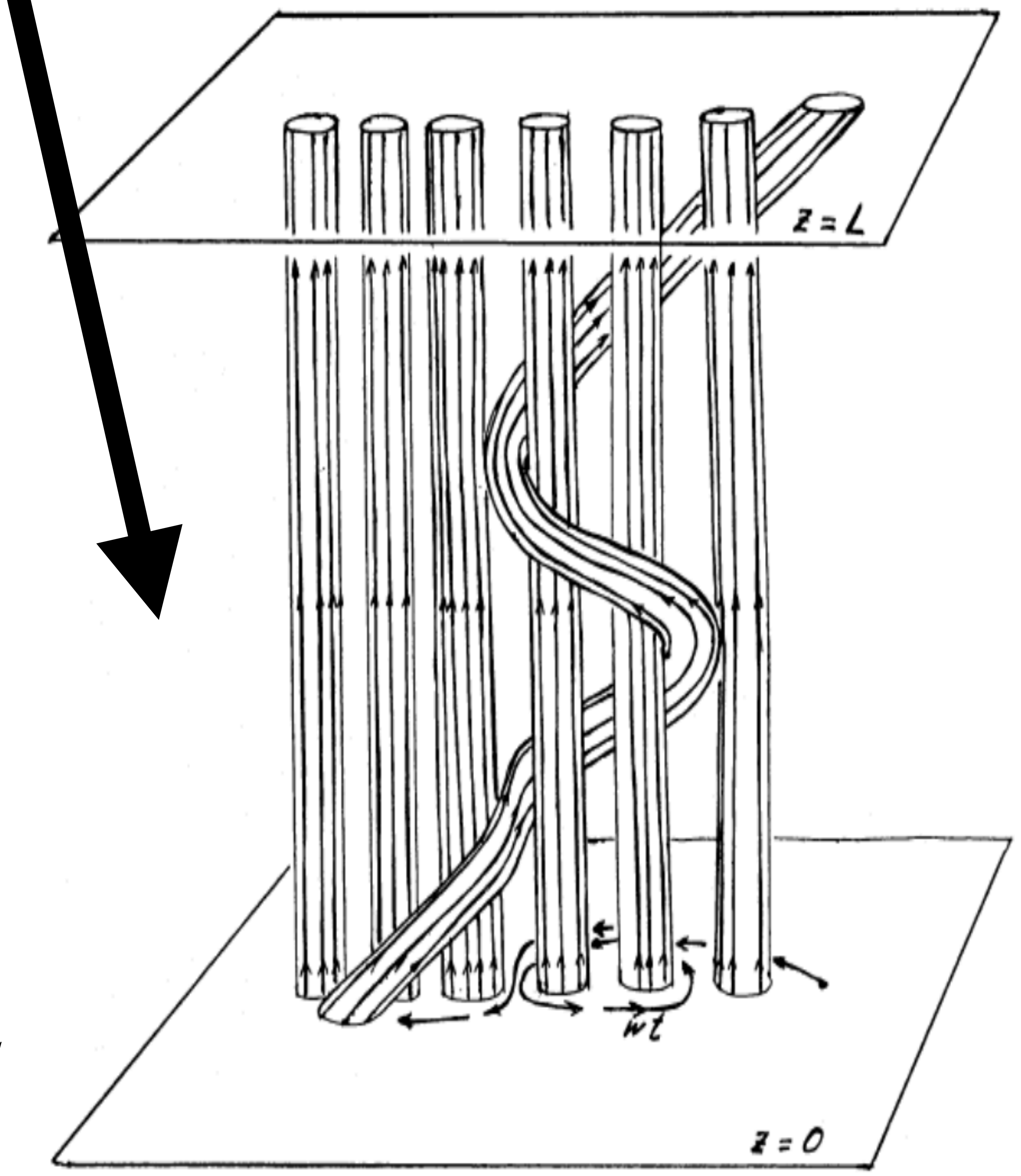
- Slow build up of magnetic energy and its non-catastrophic release
- Energy release (dissipation) possible at current sheets = tangential discontinuities of magnetic field = sharp boundaries between magnetic field lines pointing in different directions
- Ohmic dissipation: gradual energy release; efficient at very small scales

Ohmic Heating

- Ohmic dissipation of magnetic energy acts where resistivity is finite and electric current is large
- Heating rate: $H = \eta j^2$
- $\eta = \sigma^{-1}$= resistivity (magnetic diffusivity)
- $j = (c/4\pi)\nabla \times B$= electric current density
- Heating is large where currents are large, i.e. where the field changes on small length scales, so-called tangential discontinuities, or electric current sheets
- Ohmic heating: important for AC & DC mechanisms

Field Line Braiding / Nanoflare Heating I

- Parker (1972): Flows in photosphere move footpoints of coronal field lines around
- Random flows -> small-scale braiding of field
- The braided fields carry large currents: $j = \nabla \times B$
- Ohmic dissipation is effective at locations of large j: $H \propto j^2$



Parker 1972

Field Line Braiding/ Nanoflare Heating II

- Build-up of magnetic energy through
  1) footpoint motions (random or ordered, e.g. shearing)
  2) emergence of fresh magnetic flux

- Catastrophic release of excess magnetic energy through magnetic reconnection

- Energy release is visible as brightening: flare or microflare

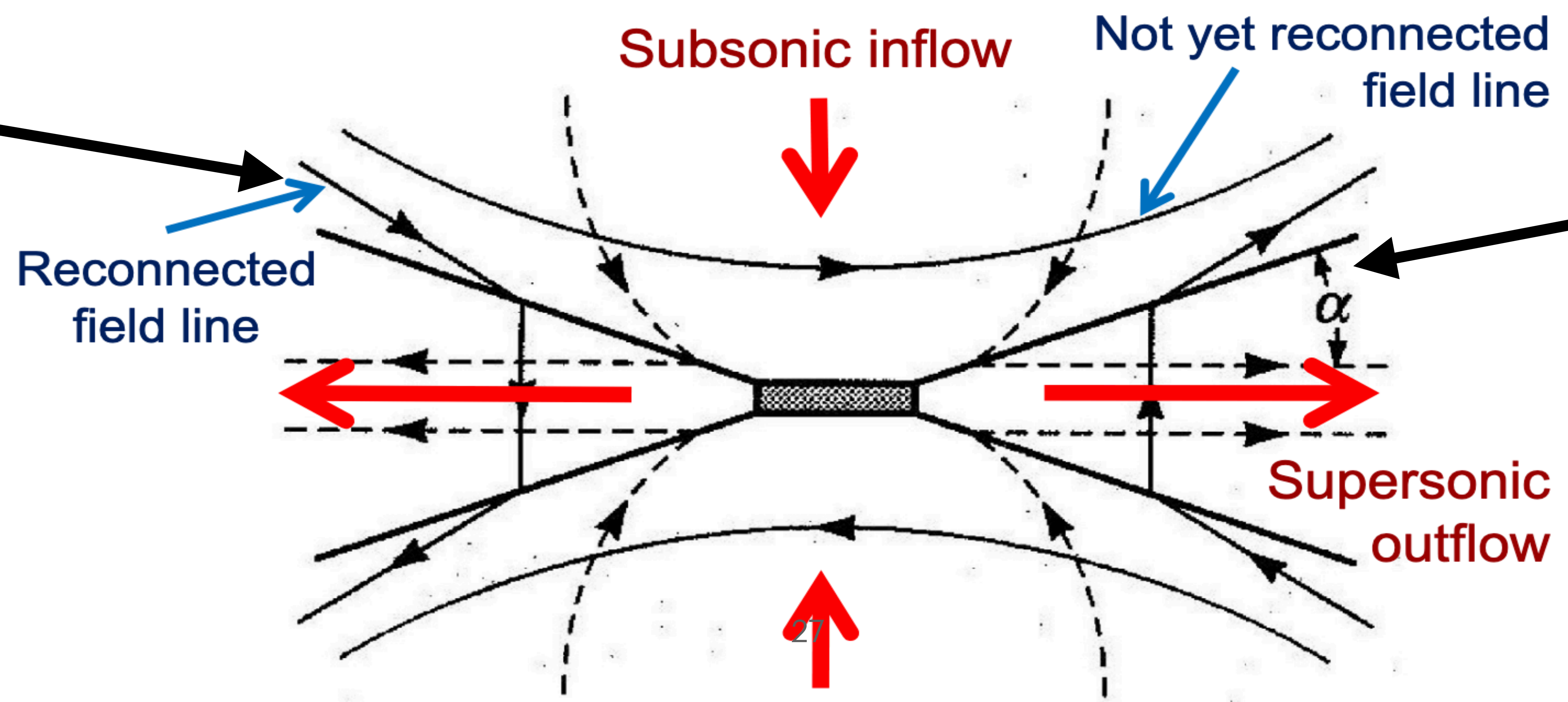
- Energy is released in multiple locations leading to a avalanche of nano flare (nano flare storm) (Campfires detected by Solar Orbiter Chitta et al. 2022)

Magnetic Recconection - 2D Case

- Magnetic tangential discontinuities (e.g. X-type configuration)
- Opposite polarity field lines are pushed towards each other
- Energy released from the dissipation of current sheets
- Tension forces act to straighten the field lines accelerating particles in the form of plasma jets.
- Magnetic energy converted to thermal, Kinetic energy and fast particles
- Source of heating and of many dynamic processes (flares, CME's, Solar Jets etc.)

Sweet Parker model (1958)

Slow reconnection rate

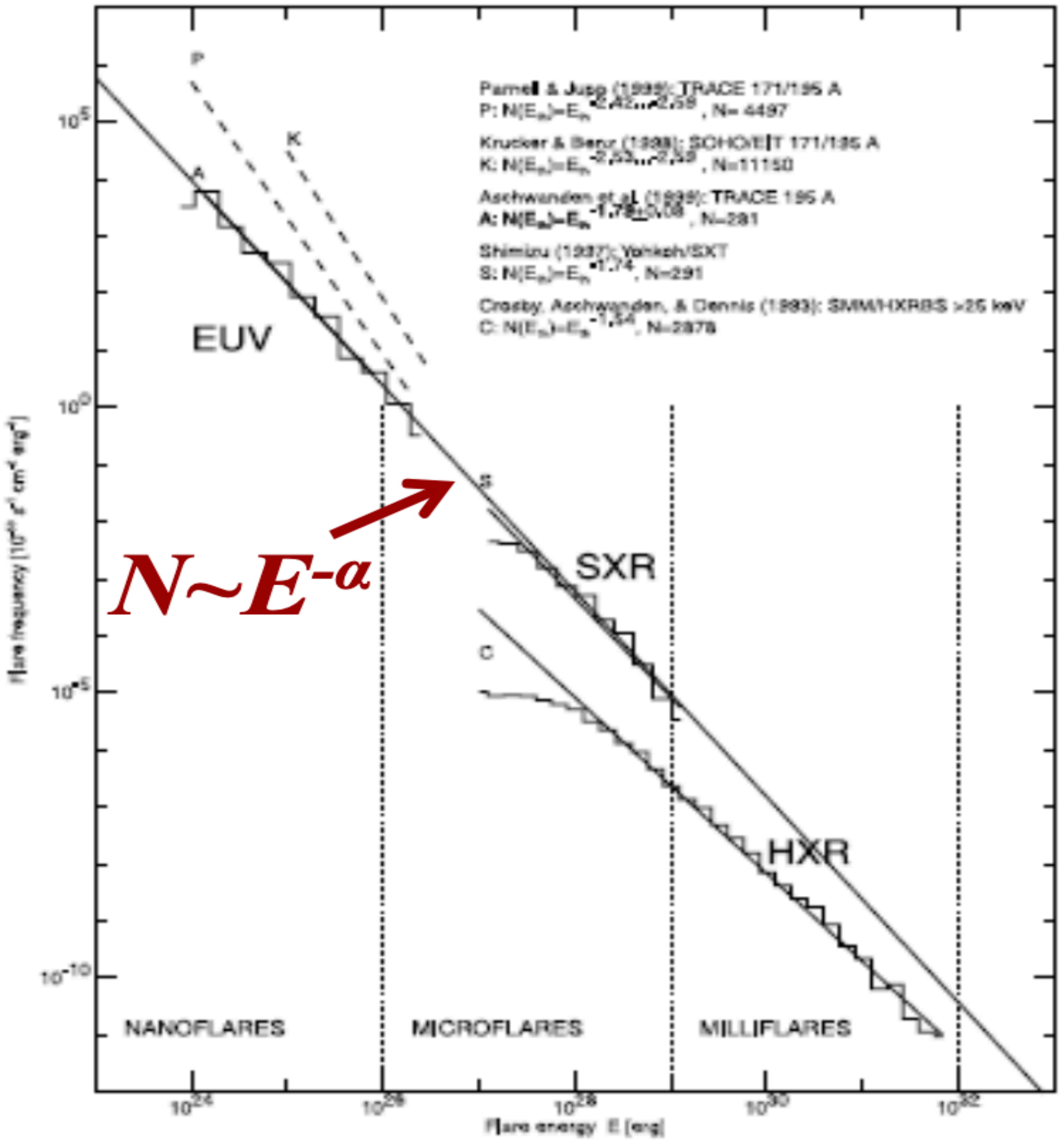


Petschek model (1964)

Fast reconnection rate

The Missing Energy Problem

- Reconnection is believed to occur on all size scales.
- Observations indicate a greater number of flares on smaller scales.
- There is an insufficient number of flares or even microflares to heat the corona.
- Frequency of energy release at different energy scales following a power-law: $\frac{dN}{dE} = kE^{-a}$
- Sufficient energy to heat if power law exponent a>2
- Most observations give a<2
- Hypothetical nanoflares needed in large numbers (Possible first observations of Nanoflares in campfires with EUI/Solar Orbiter Chitta et al. 2022)



Ascwanden 2000

DC Mechanism- Summary

- Dissipation: Random surface motion lead to small scale braiding of magnetic fieldlines -> Braided field lines carry large currents which dissipate due to reconnection releasing the energy in small fractions in multiple locations (nano-flare storm)

- Missing energy problem: A larger amount of micro-flares or nano flares is needed to have suffiecient energy to heat the corona-> Other mechanisms might contribute-> Observations of nano flares are required-> Possible with Solar Orbiter

- DC mechanism: The best candidate to explain the coronal heating problem !

3rd Part

3D MHD Models

Why Use MHD models

1. Why Use Magnetohydrodynamics (MHD)?

- MHD is crucial for studying how magnetic fields and plasma interact in the solar corona, where magnetic forces dominate.
- It helps us understand phenomena like solar flares, coronal mass ejections, and the overall heating of the corona.

2. The Need for MHD Simulations

- The Solar corona is a complex environment with structures and dynamics that span across multiple scales
- MHD simulations allow us to model the full 3D structure and dynamics of the corona, helping us explore how energy is stored, transported, and released

3. 3D Numerical Models

- To capture the various characteristics of the corona we use 3D MHD models
- These simulations give us the tools to explore the key processes, like magnetic reconnection that are responsible for coronal heating.
- Multiple Codes exist in the literature, STAGGER (Nordlund 1996),PENCiL CODE (Brandenburg 200), MURAM (Vogler 2005), BIFROST (Gudiksen 2011) etc,

MHD equations

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

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

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

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

induction eq.

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

$$R_\mathrm{m} = \frac{U\,L}{\eta} = \frac{L^2}{\tau\,\eta}$$

mag. diffusivity $\eta = \dfrac{1}{\mu\,\sigma}$

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

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

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

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

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

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

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

H. Peter lecture

Numerical Simulations

Study of corona in 1D or 3D models

- Solving 1D time-dependent hydrodynamic equations (e.g. Hansteen 1993; Antiochos et al. 1999; Bradshaw and Cargill 2006) -> Magnetic field is not important -> Heating function mush be prescribed ad hoc
- A more realistic approach -> 3D MHD numerical simulations

1) STAGGER CODE-> Field line braiding mechanism using a realistic heat conduction and radiative losses (Gudiksen & Nordlund 2002)-> No magneto convection

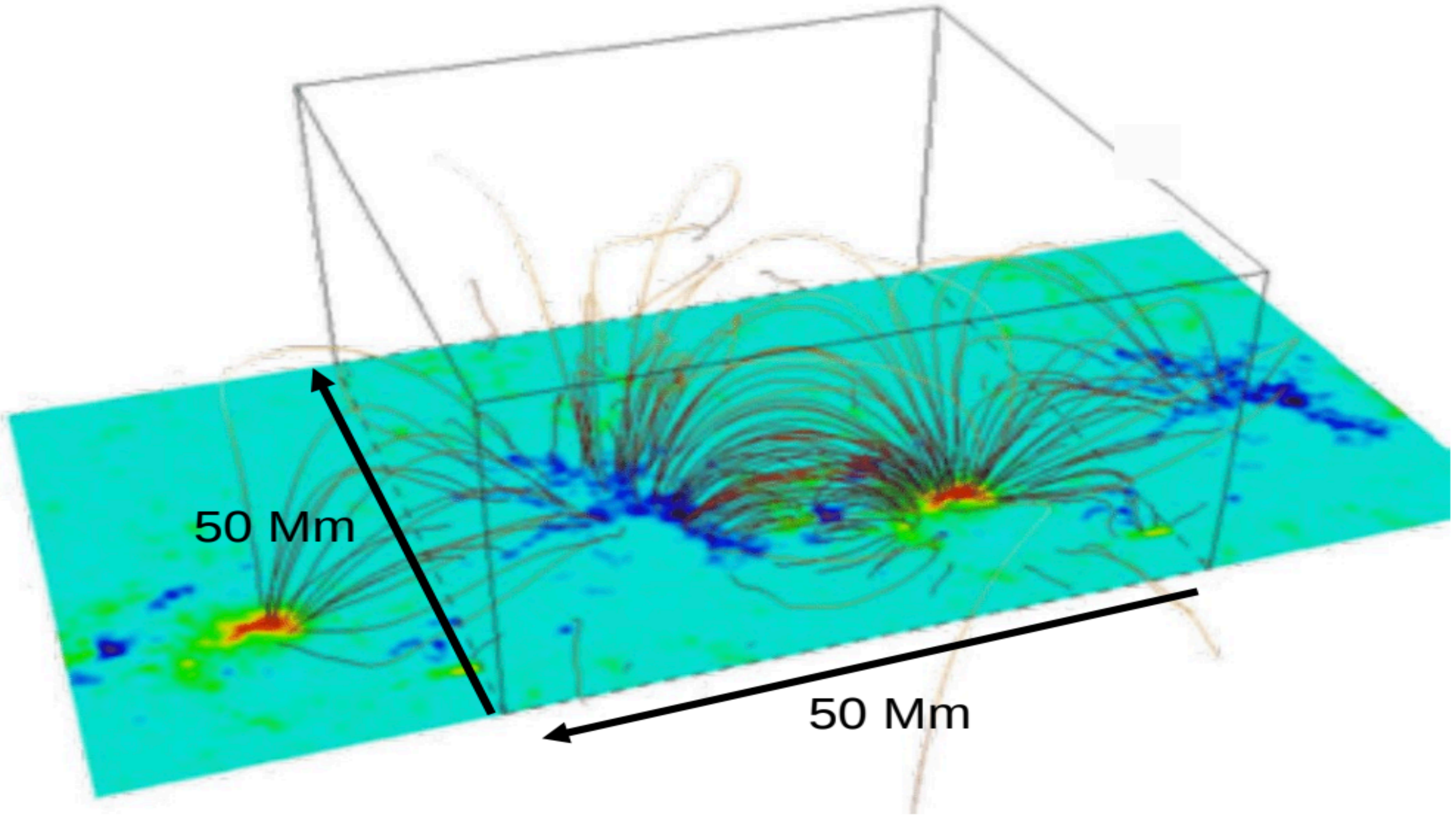
2) BIFROST -> Gudiksen and Nordlund 2011 -> including convection

3) MURAM CODE -> Vogler et al. 2005, Rempel et al. 2017—> Including convection zone and creating the granular motion self consistently

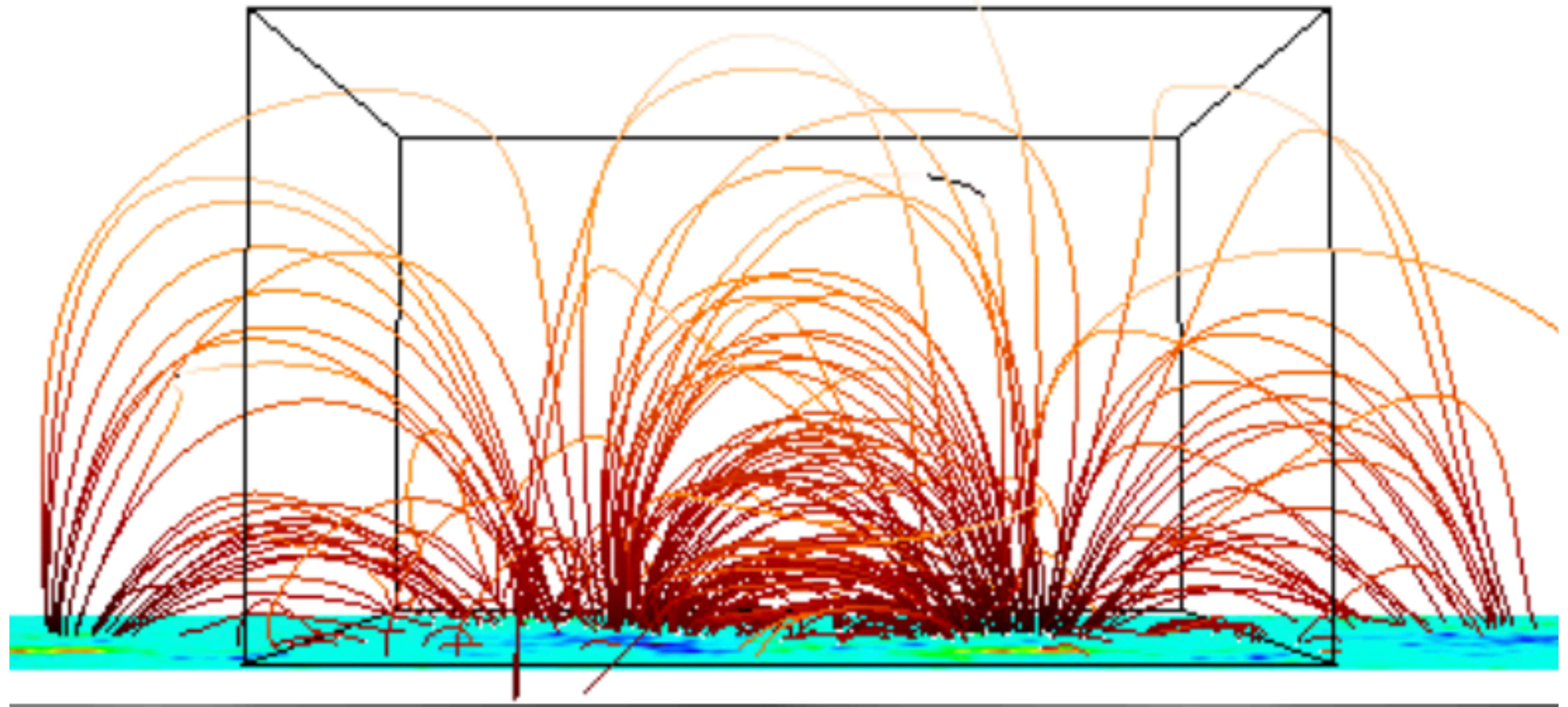
4) PENCIL CODE -> Bingert et al. 2017, Warnecke et al. 2019, Zhuleku et al, 2021 etc-> No convection zone -> Good match with observations of SDO/AIA and TRACE

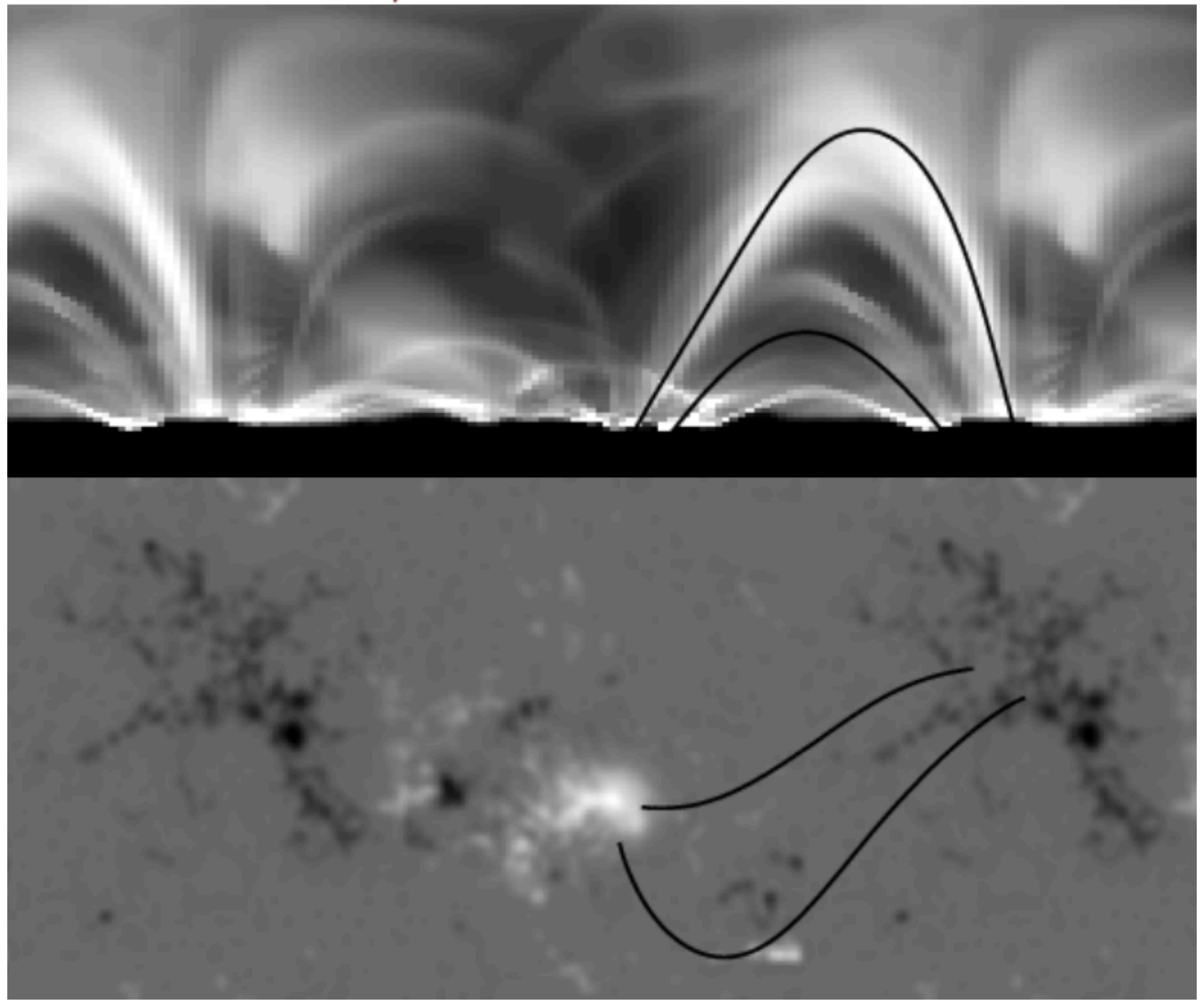
5) A limited number of codes using Alfven wave heating of corona such as AWSOM (van der Holst et al. (2014))

Fieldline Braiding Model



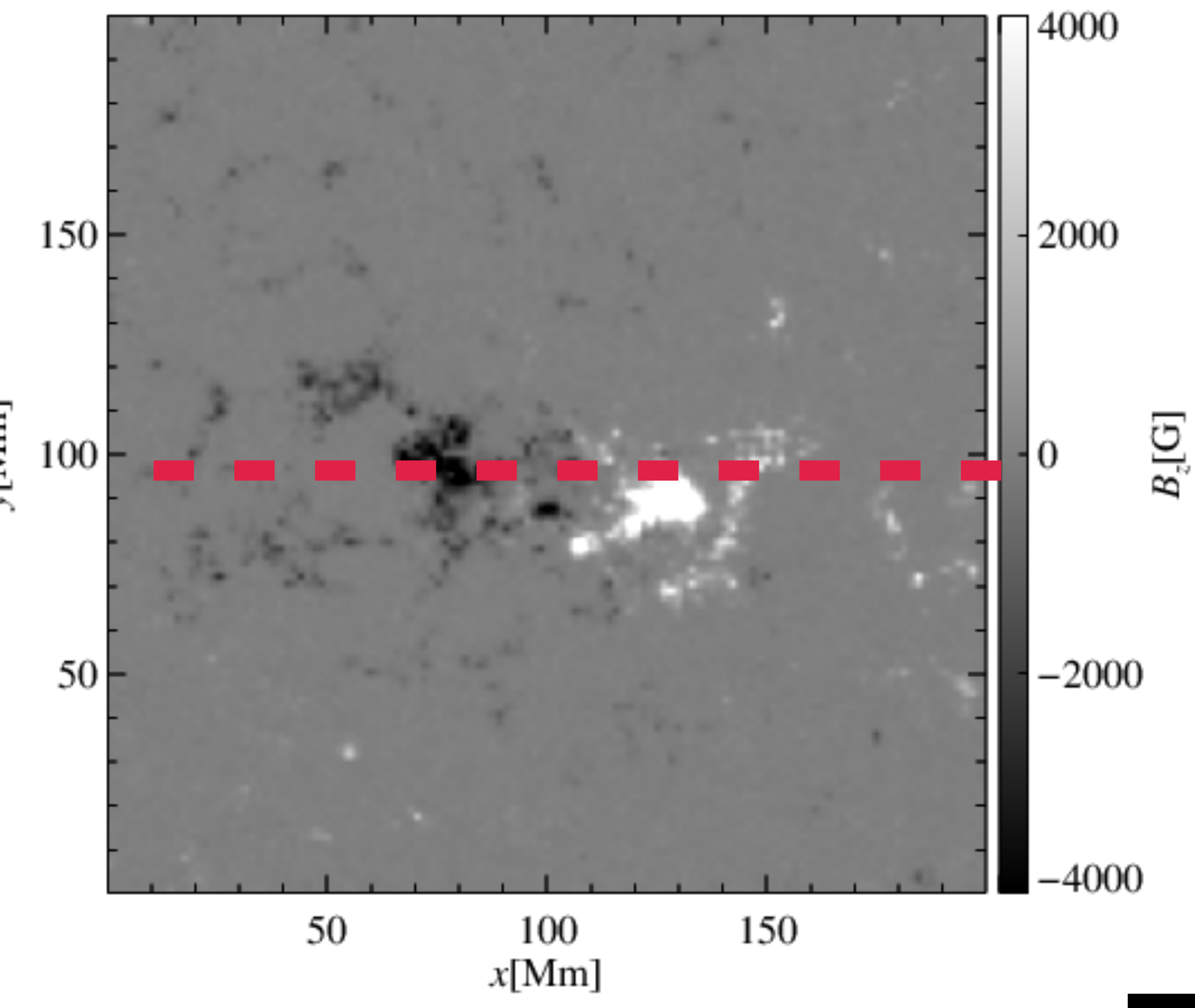
- 3D MHD model for the corona in a cartesian box 50x50x30 Mm
- Full 3D MHD equations + heat conduction + radiative losses
- A MDI magnetogram used as initial condition
- Heating: DC current dissipation (Parker 1972) -> Self-consistently
- Coronal temperatures of > 10^6 K
- Good match with AIA/SDO and TRACE (Peter et al. 2004)





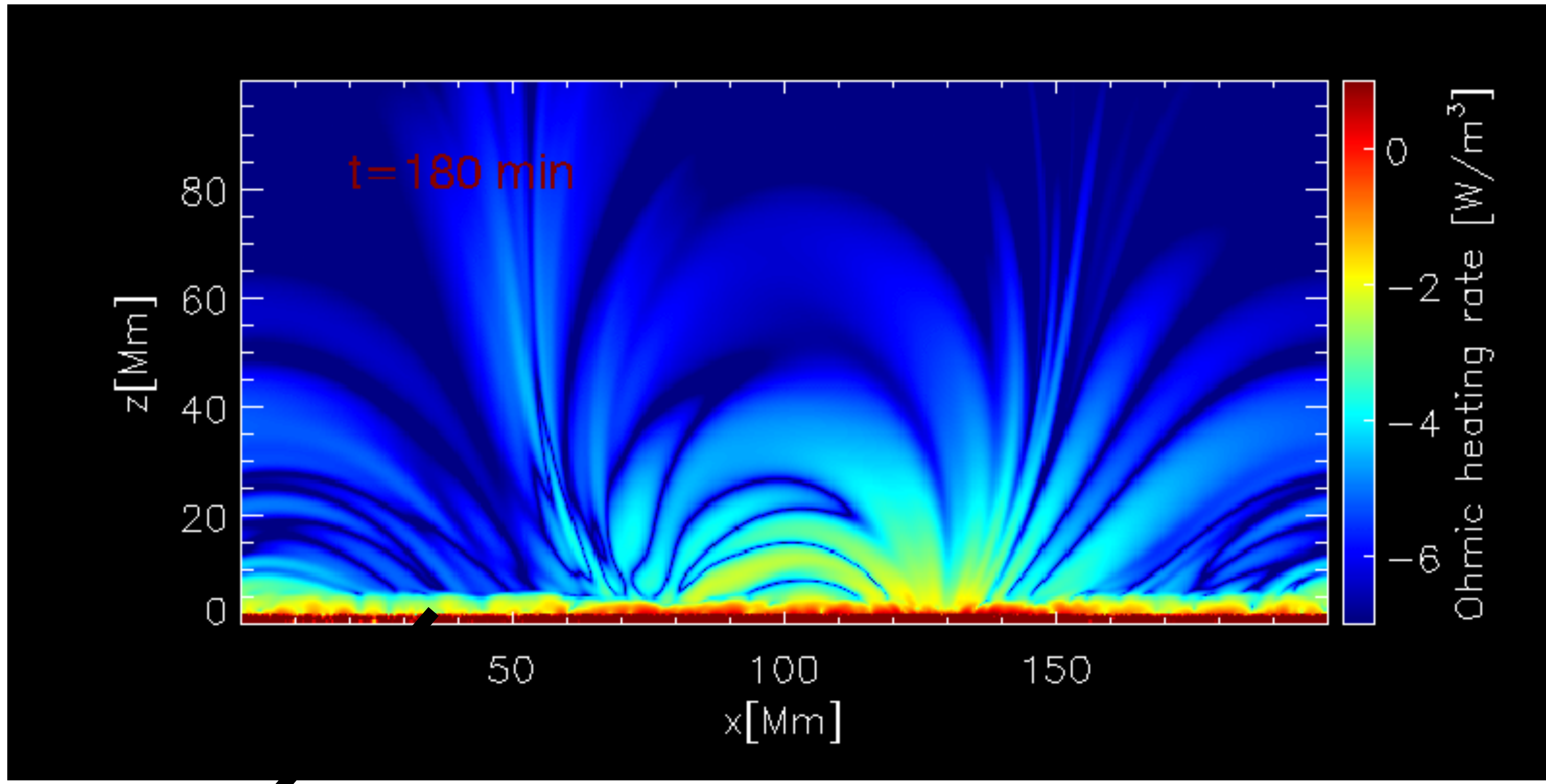
Gudiksen and Nordlund 2002

PENCIL CODE

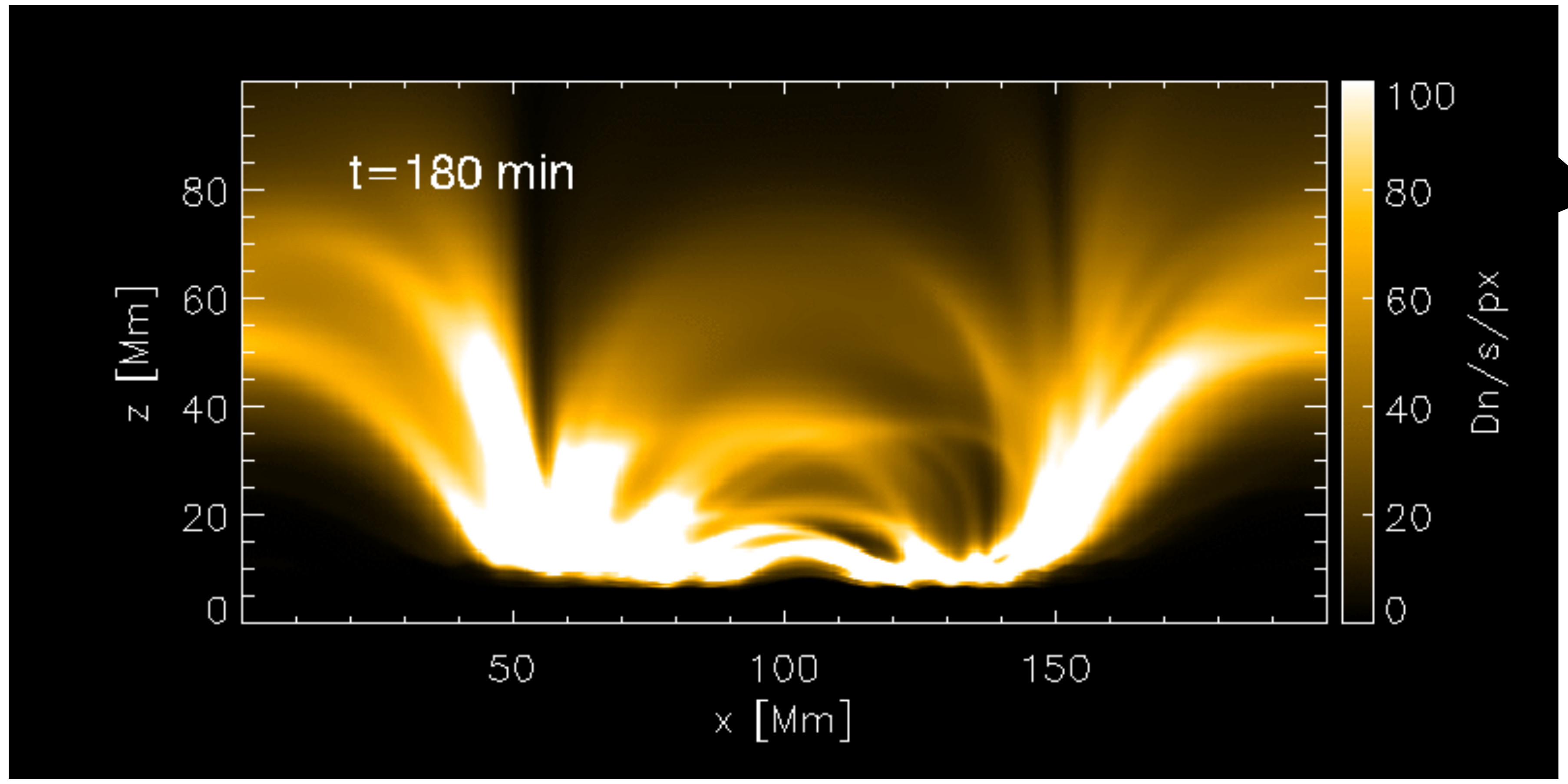


Surface Velocities

Currents →Ohmic heating
(vertical cut in the middle of the box)

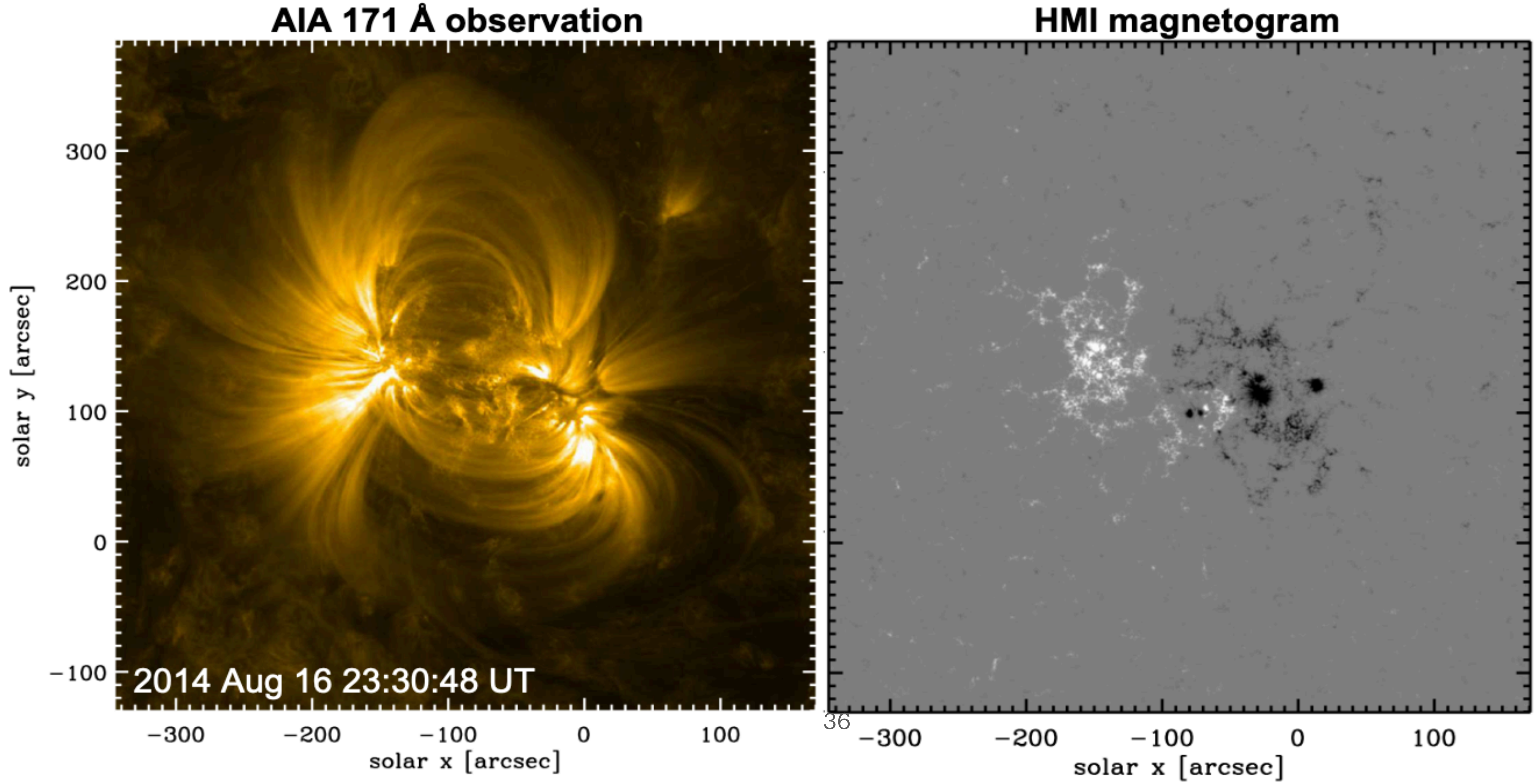


EUV synthetic emission, AIA 171



High Resolution Simulations

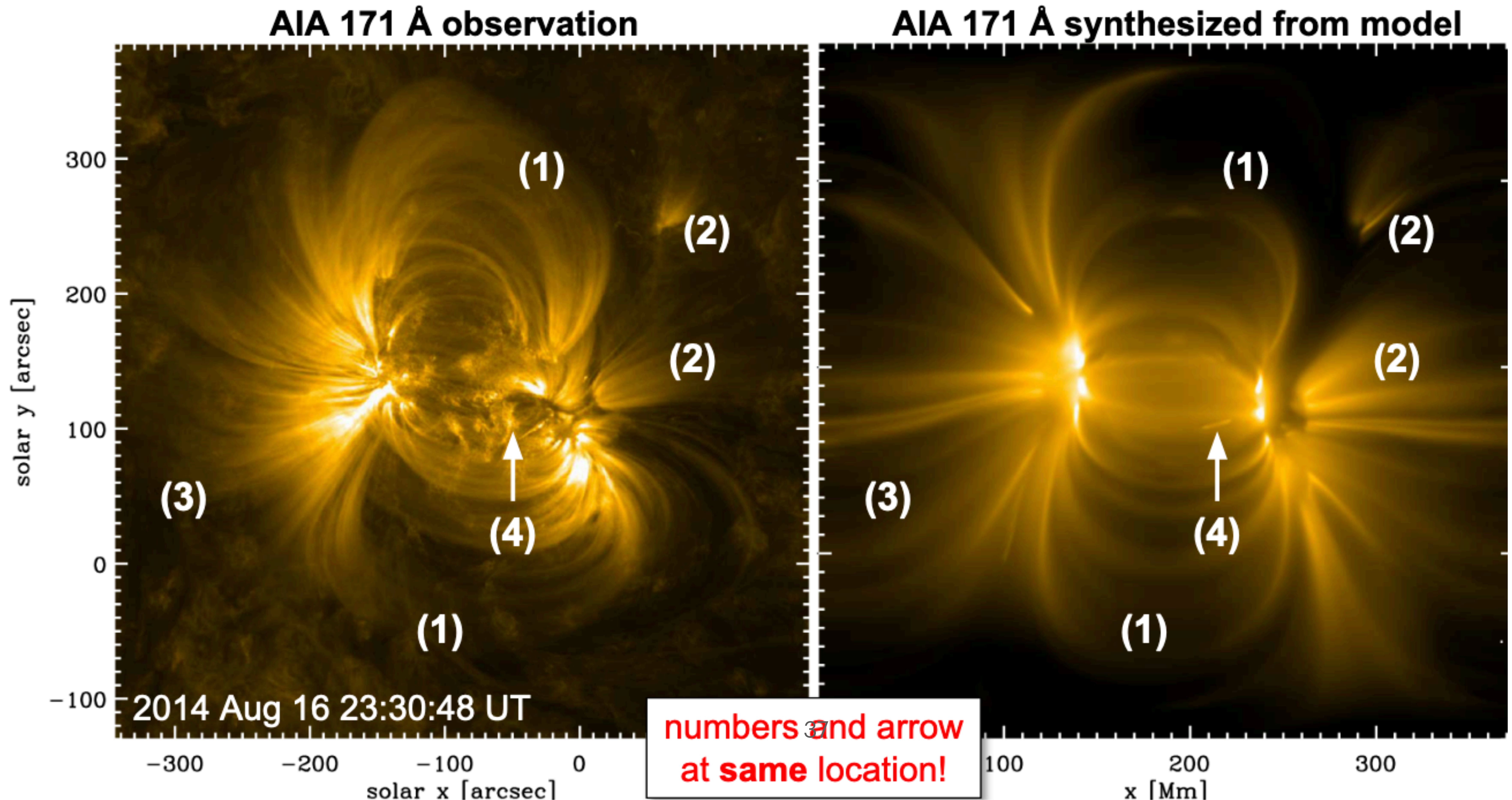
- use an observed active region magnetogram and its temporal evolution
- Feed this into a 3D MHD model as a time-dependent boundary condition
- let the corona above it evolve
- compare to real corona observed at the same time



Warnecke & Peter 2019

High Resolution Simulations

common features: (1) large loops connecting the main polarities
(2) fan(s) at edges of the AR
(3) background (i.e. low contrast loops)
(4) small-scale brightenings in the core (small loops in model)



numbers and arrow at **same** location!

Warnecke & Peter 2019

3D MHD Models- Summary

- 3D MHD simulations are crucial for modeling the complex dynamics of the solar corona, capturing the interactions between magnetic fields and plasma that drive coronal heating.

- Simulation codes like STAGGER, BIFROST, and PENCIL CODE provide realistic models of coronal heating, closely matching solar observations.

- 3D MHD models show that magnetic reconnection and DC current dissipation are key mechanisms in achieving the high temperatures observed in the solar corona.

4th Part

Stellar Coronae

Characteristics of Stellar Coronae

1. **Temperature and Density**

- Coronae of stars often reach temperatures from 1 to 10 million K, with some extremes in highly active stars.
- Density is generally lower than in the star's surface layers, leading to emission in X-rays and UV.
- Instruments like Chandra, XMM-Newton, and Hubble have provided valuable data on stellar coronae.

2. **Magnetic Activity**

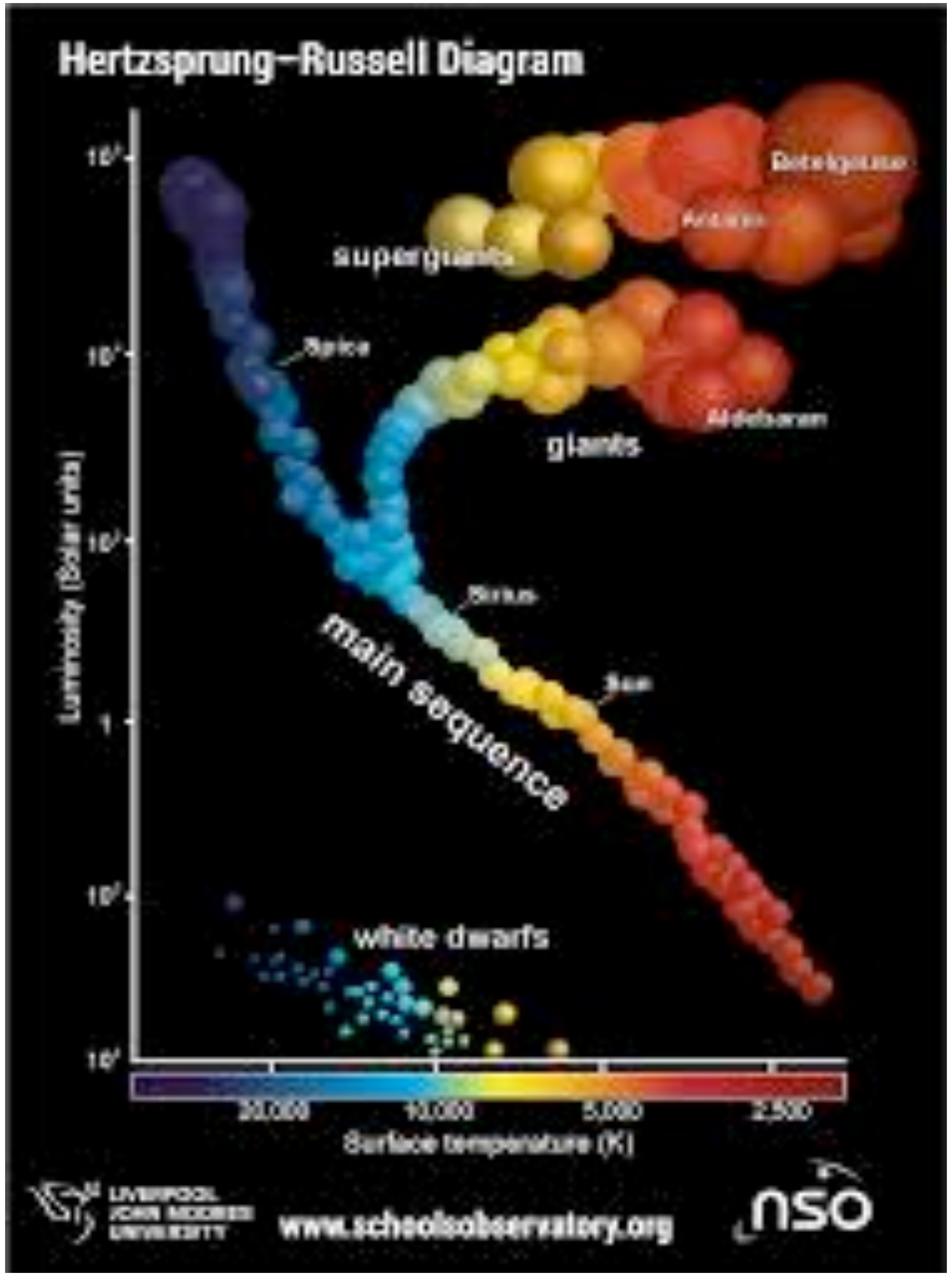
- Stellar coronae are strongly linked to magnetic fields; more active stars have stronger, more dynamic coronae.
- Magnetic reconnection and wave heating play roles similar to those in the Sun's corona.

3. **Coronal Heating Mechanisms**

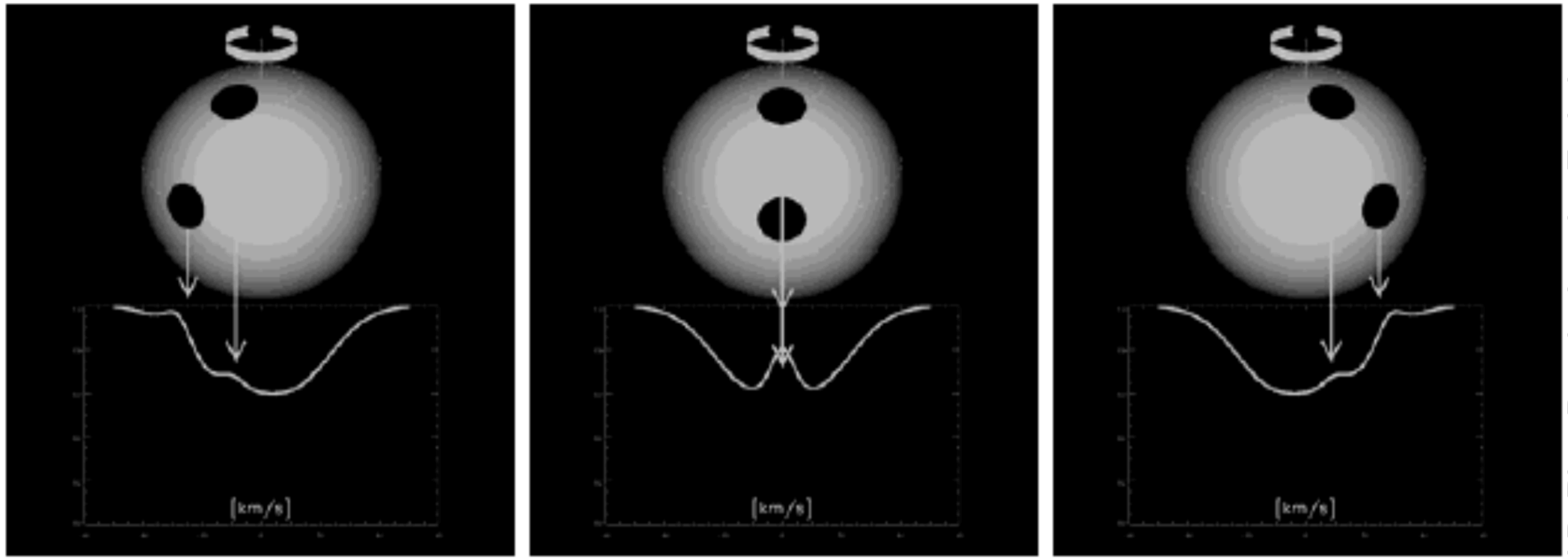
- Just like in the Sun, the exact mechanisms behind coronal heating in other stars remain a topic of research.
- Evidence suggests a combination of wave heating, magnetic reconnection, and possibly other, less understood processes.

Stellar Coronae in HRD

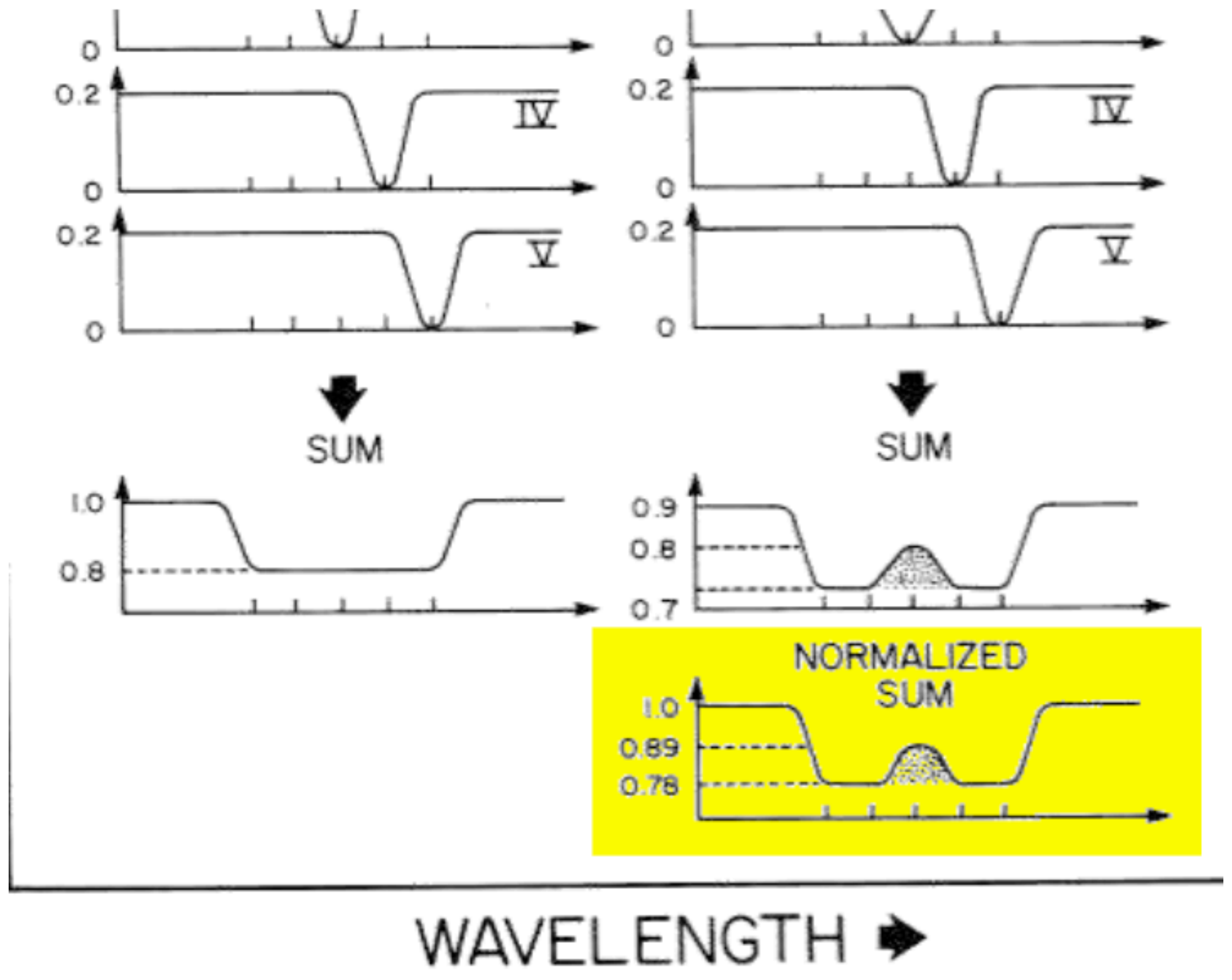
- Almost all cool stars (main sequence) have a hot coronae
- Young stars are very X-ray active (e.g. T-Tauri stars)
- Giants and Super Giants do not have a coronae (Linsky & Haisch (1979) ApJ 229, L27)



How do we measure stellar surface magnetic field

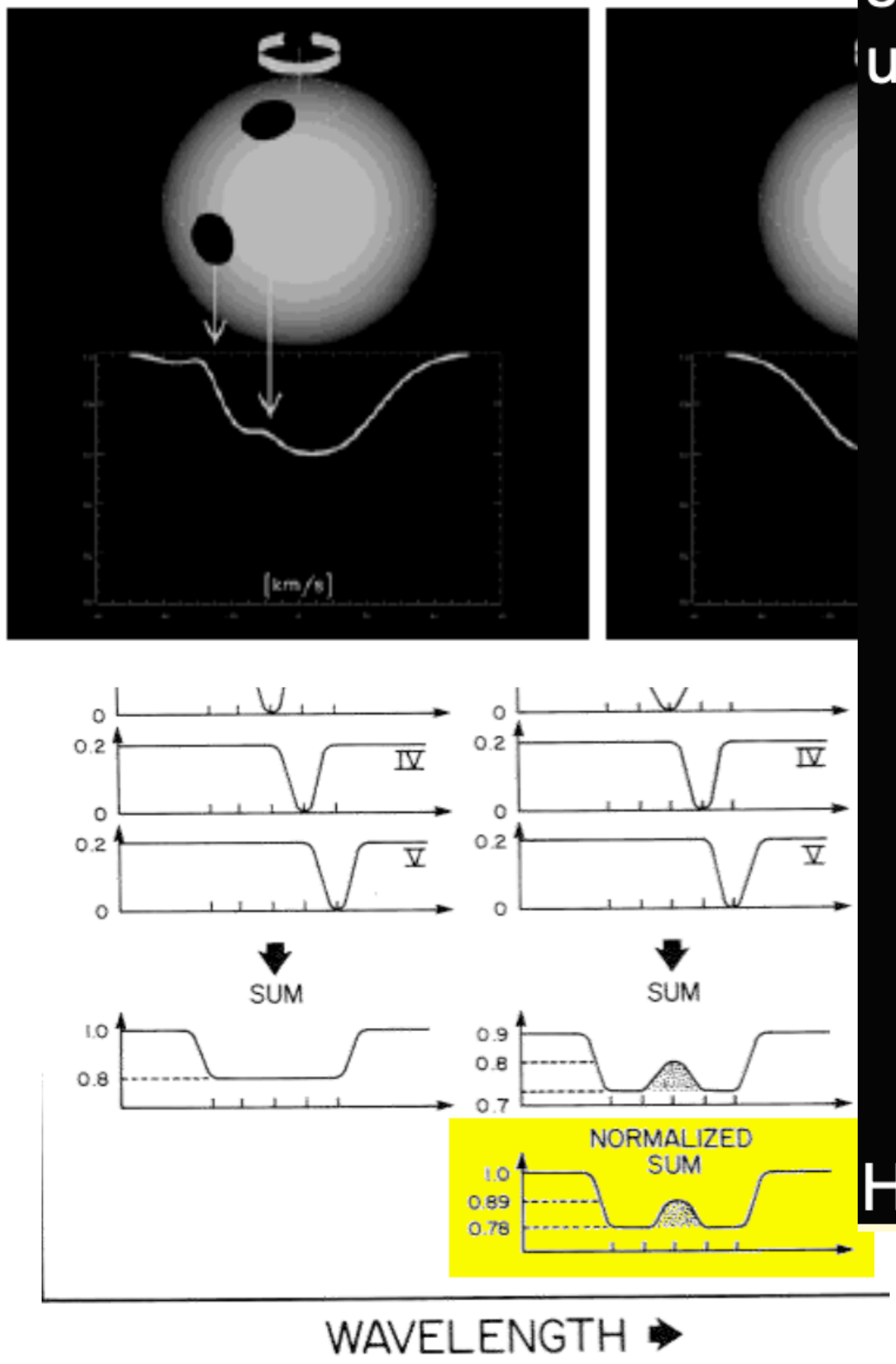


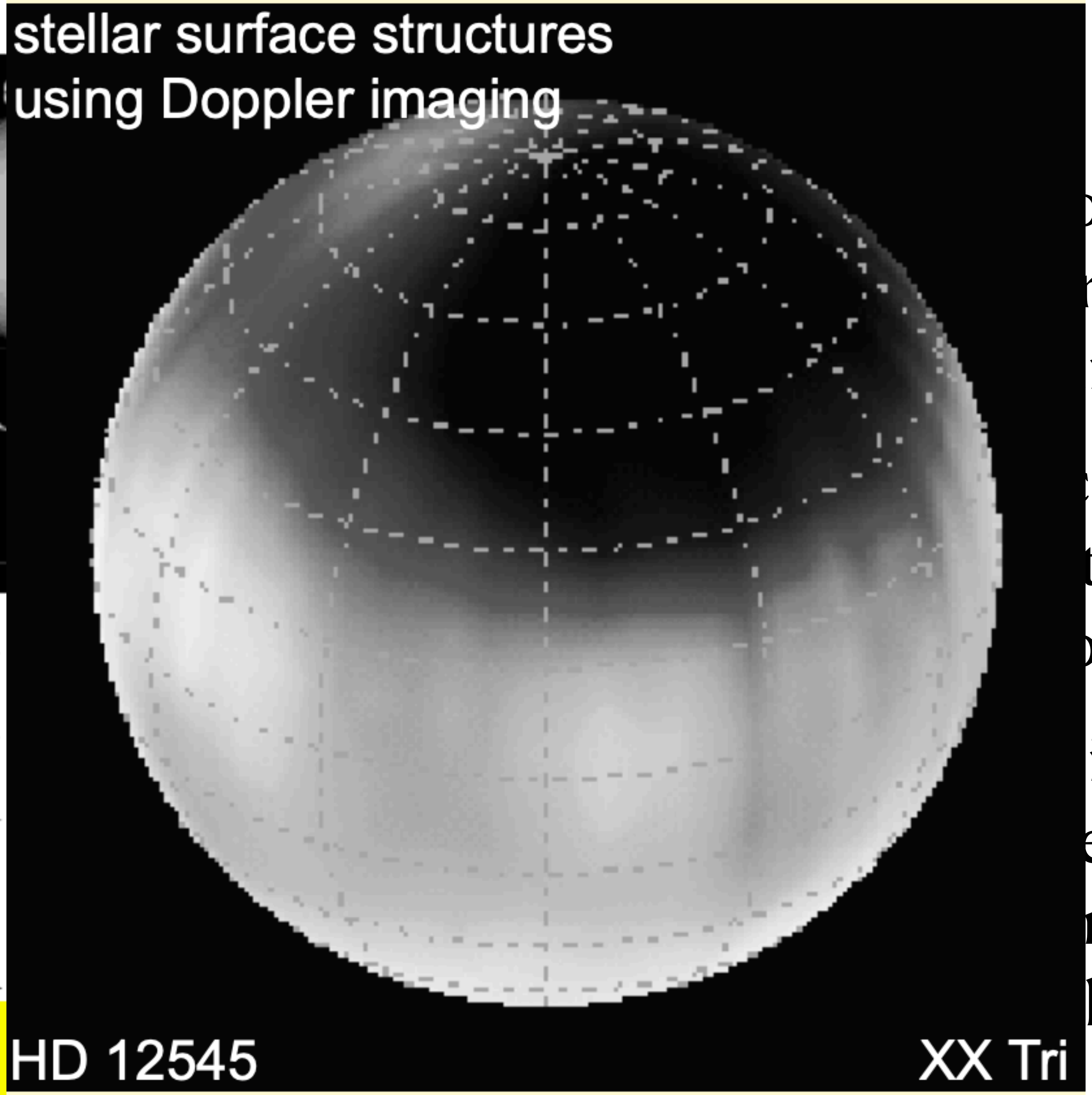
J.B. Rice: Doppler Imaging Techniques



- Doppler-Zeeman-Imaging: Structures on Stellar Surface
- Active regions as they rotate reduce emission from the spectra
- Using Stokes profiles and the spectra of a star you can measure magnetic field at the surface

How do we measure stellar surface magnetic field





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Strassmeier & Rice (2001) A&A 377,264

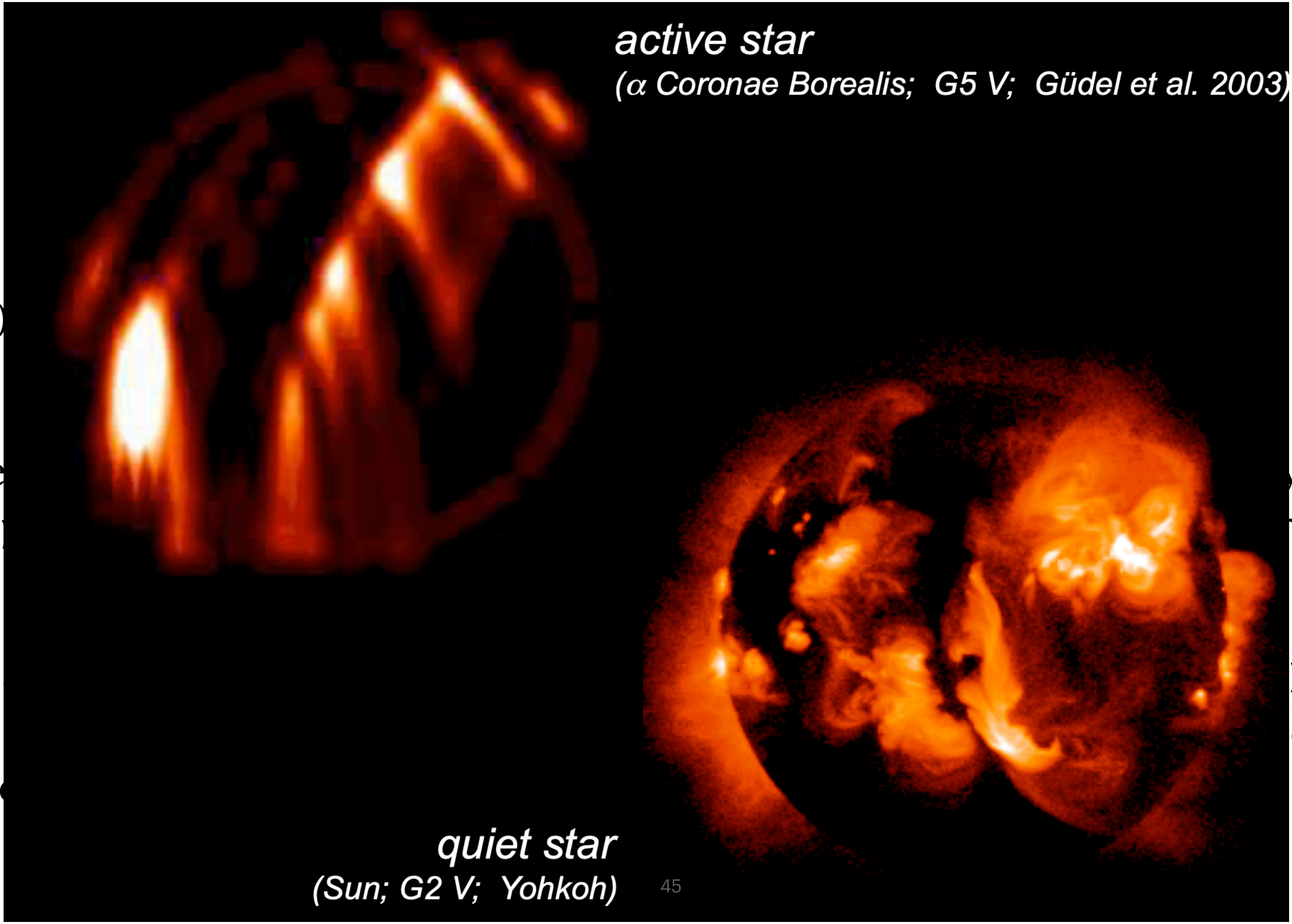
How does Stellar Coronae Looks?

- Stellar coronae is invisible to EUV emission (Absorbed or scattered by dust in the galaxy)

- X-ray emission mainly concentrated above few active regions or dominated by stellar flares (point source as observed by instruments like Chandra or XMM Newton)

- ZDI -> Surface magnetic field measurements -> Potential field extrapolation-> Basic model assumption (temperature and density) lead to a first order reconstruction of a stellar coronae

- Stellar the galaxy)
- X-ray e stellar flares (n)
- ZDI -> Basic model on of a stellar

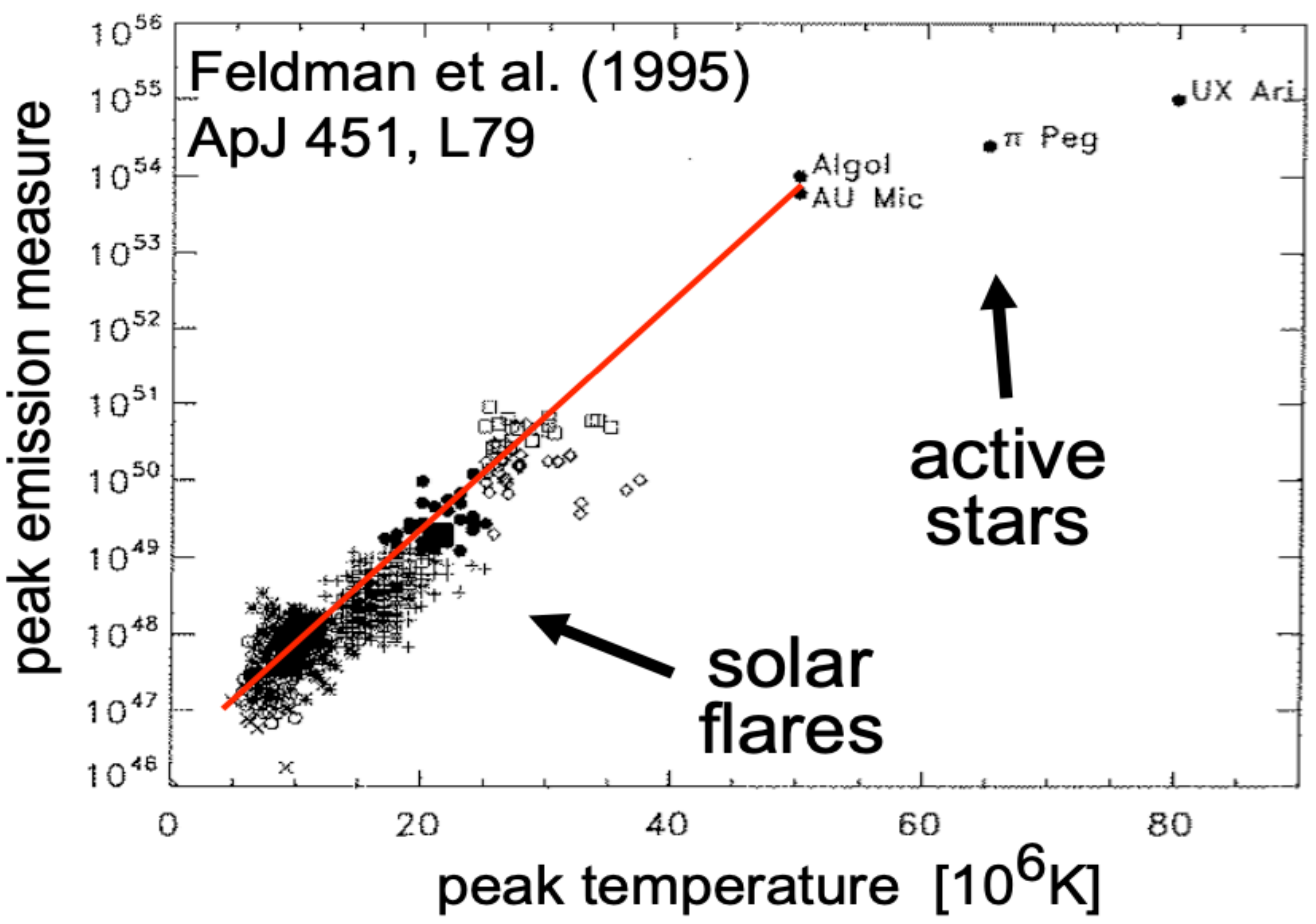


What are the dominant X-ray sources for Stars

- Where does X-ray emission comes from other stars:

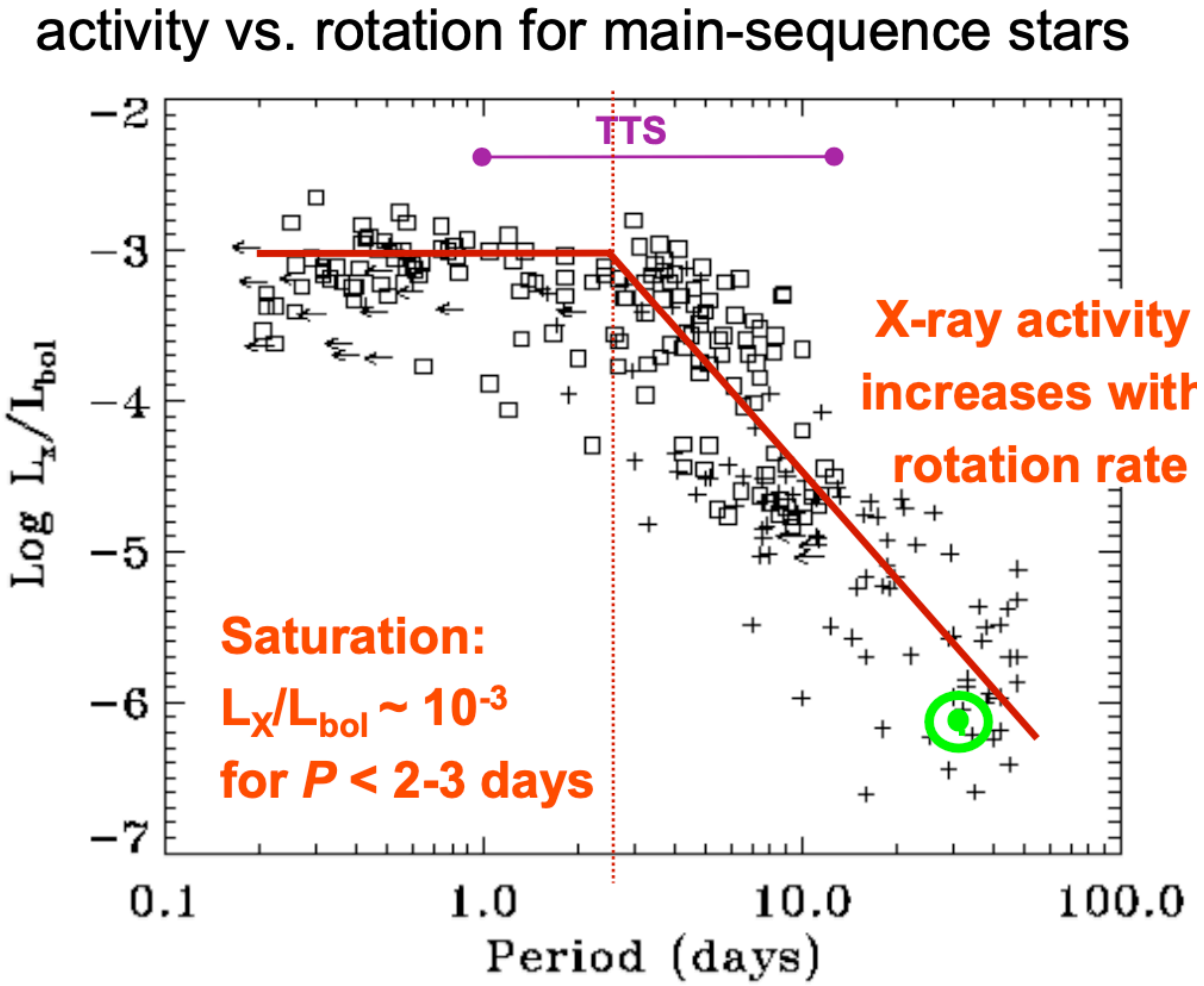
1. Solar X-ray emission has peak temperature around 20 MK-> Stelar X-ray emission reach roughly 60-80 MK
2. Possible higher filling factor for the Sun -> For smaller stars there is not enough space -> Possible active regions with much stronger magnetic field

- Stellar Coronae not only brighter but also denser and hotter than the Sun



X-ray emission Vs Rotation

- Activity increases with rotation(due to stronger dynamo action)
- There is a saturation of X-ray for rapid rotators -> No clear answer yet
- Interpretation of major contribution to X-rays depends on
  energy distribution of flares:
  $dN/dE \propto E^{-\alpha}$, If a>2 -> Flare dominated; If a<2 -> Flares not sufficient (other mechanisms needed)



Pizzolato et al. 2003

Summary of Stellar Coronae

- Almost all main sequence stars have a coronae
- In general Stellar coronae are stronger than our Sun's
- Zeeman-Dopler-Imaging helps us measure the surface magnetic field
- Reconstruction methods show a first look of Stellar coronae
- stellar corona are concentrated in small active regions (-> filling factor?)
- coronal activity related to rotation / age / dynamo action
- Future stellar 3D MHD models can help us interpret stellar structures

Conclusions I

- Solar Coronal Heating

1) The solar corona remains a complex and dynamic region with temperatures reaching over 1-2 million K, much hotter than the photosphere.

2) The coronal heating problem is still unsolved, but significant progress has been made through space-based observations (SOHO, TRACE, Yohkoh).

3) Magnetic fields play a crucial role in the heating mechanisms, with AC (wave heating) and DC (reconnection-driven) models being central to current theories.

- Coronal Heating Mechanisms

1) AC Mechanisms: Wave heating, particularly Alfvén waves, is a plausible contributor but is limited by wave dissipation and reflection challenges.

2) DC Mechanisms: Magnetic reconnection and the formation of current sheets provide a robust framework for explaining coronal heating, especially through nanoflare activity.

3) Which mechanism heats the corona? -> Maybe a combination of AC and DC or even other mechanisms

Conclusions II

- 3D MHD Simulations

1) MHD simulations are critical for capturing the interactions between plasma and magnetic fields in the corona.

2) High-resolution models, like PENCIL CODE and MURAM provide realistic simulations that closely match observations of the solar corona.

3) These simulations offer insights into processes like field line braiding and ohmic heating, supporting the theory of DC heating.

- Stellar Coronae

1) Stellar coronae share many characteristics with the solar corona, including high temperatures and a dependence on magnetic fields.

2) Young, rapidly rotating stars tend to have more intense and active coronae, while older stars show reduced coronal activity due to weaker dynamo action.

3) Zeeman-Doppler Imaging (ZDI) and X-ray observations reveal detailed information about stellar magnetic fields and coronal structures, though much is still to be explored.

Future Prospects

- Continued advancements in 3D MHD simulations and computational power will help refine our understanding of coronal heating mechanisms with the use of more advanced and sophisticated numerical codes.

- New solar and stellar missions, such as Solar Orbiter, will provide higher-resolution observations that may finally solve the coronal heating problem.

- Exploring the relationship between stellar rotation, magnetic activity, and coronal heating in a broader range of stars can help us identify trends.


Thank you for your attention!
Questions?