Modern observational techniques for coronal studies

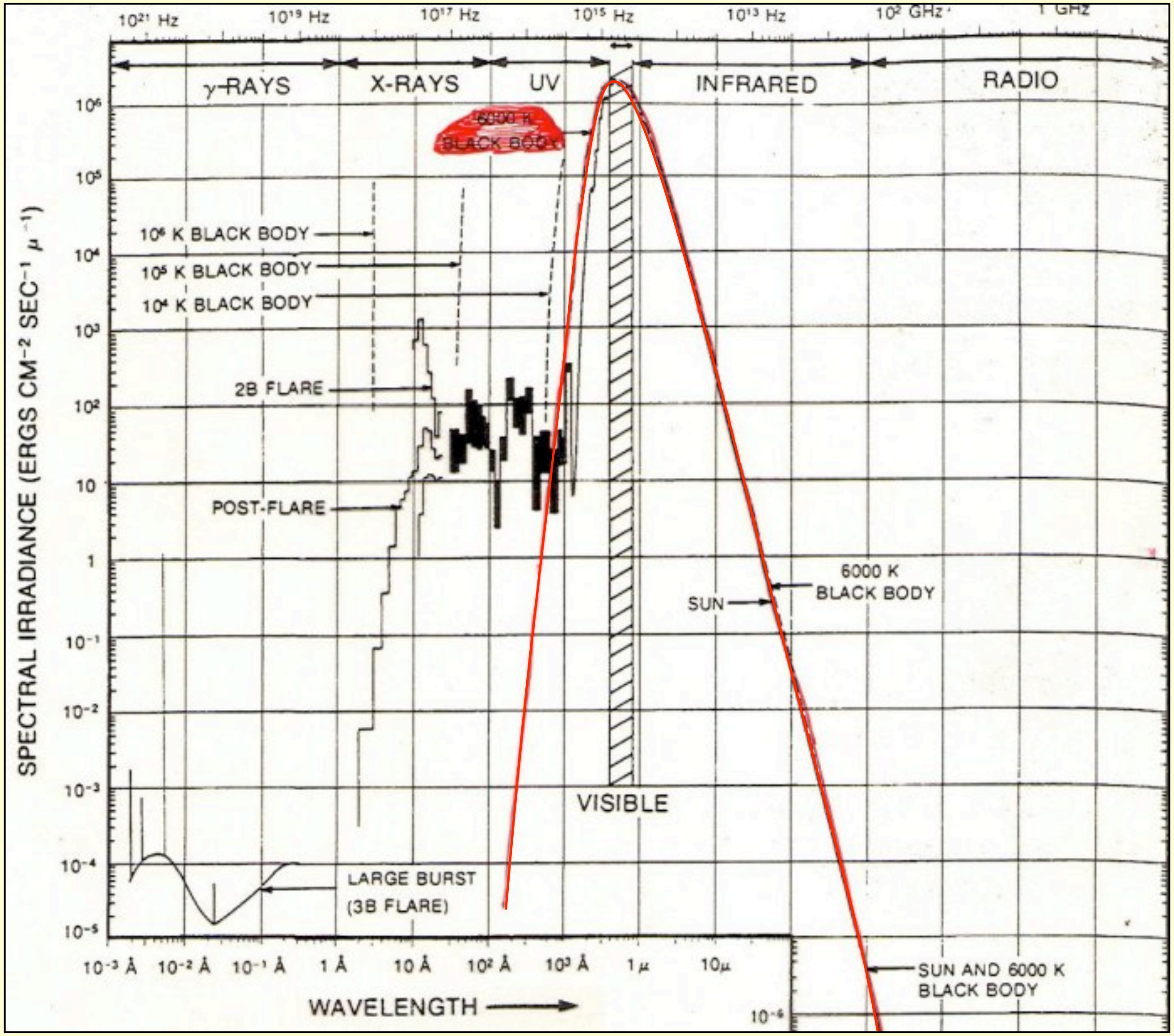
solar eclipse, **11.8.1999**, Wendy Carlos and John Kern

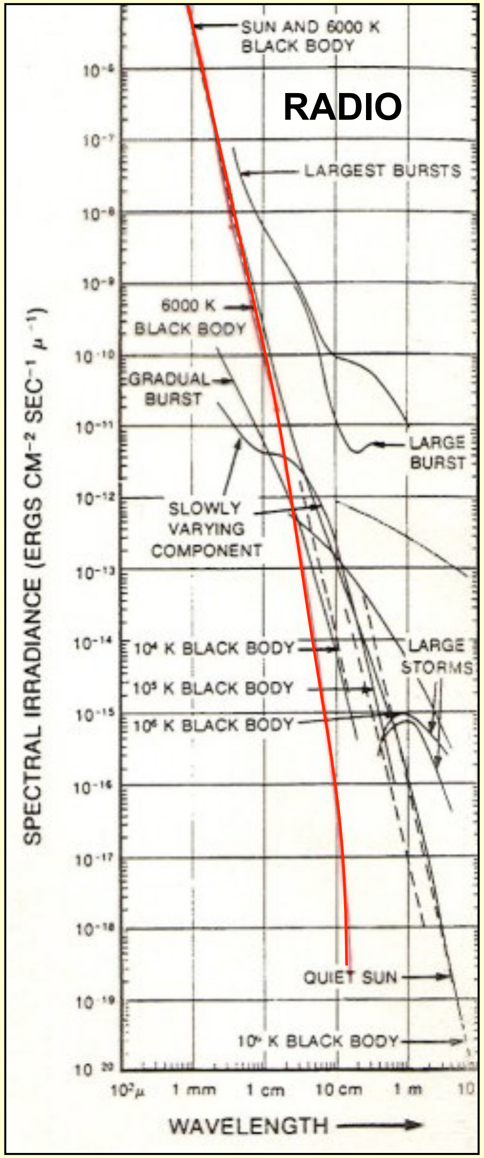
Hardi Peter

MAX-PLANCK-GESELLSCHAFT

MPS

The spectrum of the Sun

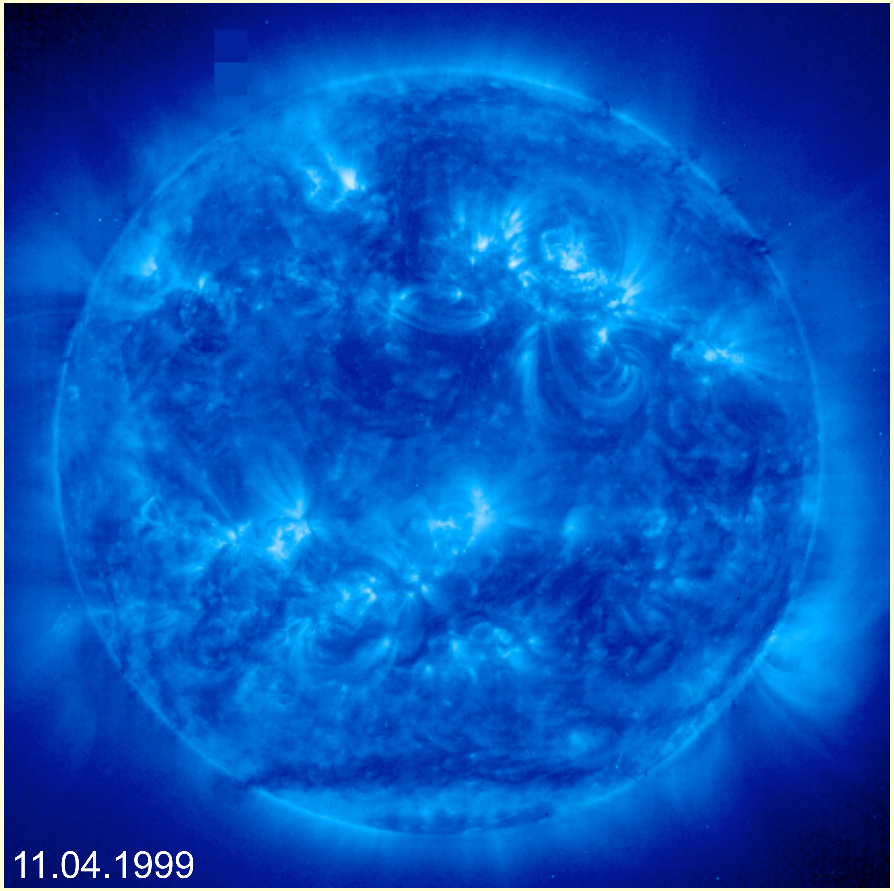




observing in radio or EUV & X-rays / 1500 Å: ➡ the corona seen in front of dark disk!

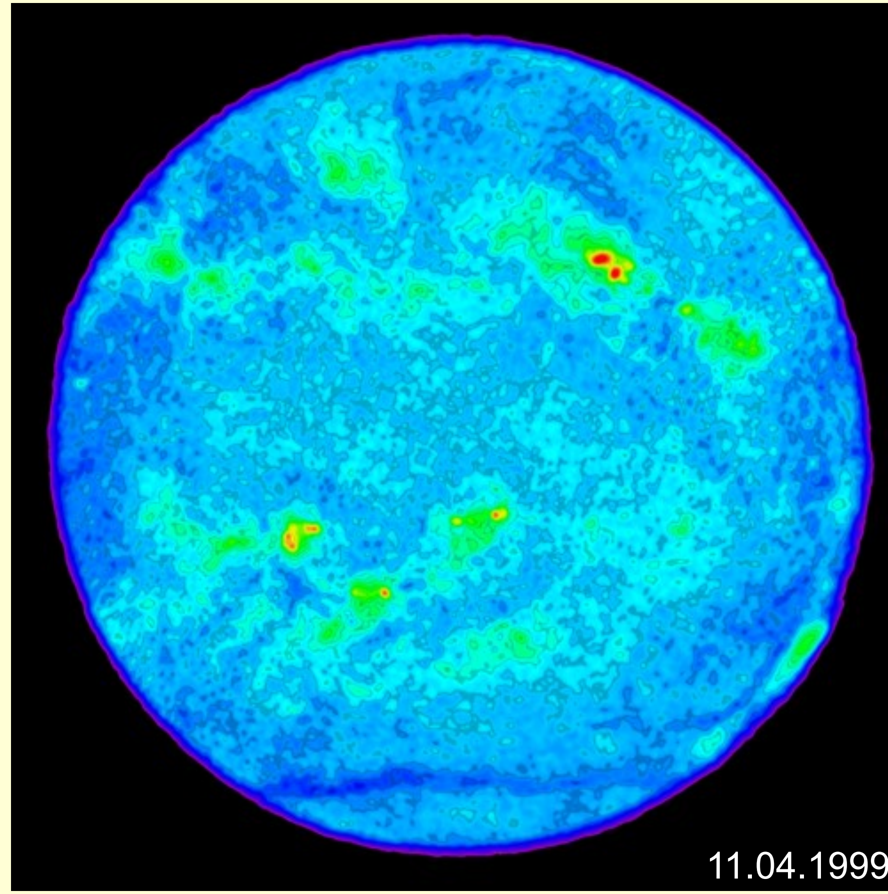
➡ "better" than eclipses!

The Sun in EUV and radio



EUV corona, Fe IX/X 171 Å
EIT / SOHO
spatial resolution ~5"

emission measure / density at ~10^6 K



radio corona @ 5.0 GHz (6 cm)
Stephen White, Very Large Array (VLA)
spatial resolution ~12" (8400 km on the Sun)

red: hot ~10^6 K / presence of strong B
green: less hot but denser
blue: cool < 30 000 K material

Image courtesy of NRAO/AUI and
Image courtesy of Stephen White, University of Maryland, and of NRAO/AUI.

Major coronal facilities (space based)

- **Yohkoh**
  - – hard X-rays (HXT) and soft soft X-rays (SXT): > several MK

- **SoHO @ L1**
  - – EIT: imaging in wavelength bands (100-300 Å): 1 – 2 MK
  - – SUMER: EUV spectrometer (700-1600 Å): 6000 K – 2 MK
  - – CDS: EUV spectrometer (100-700 Å): 0.1 – 5 MK
  - – LASCO: 3 coronagraphs, white light + green line: 1.1 – 32 R_{Sun}

- **TRACE polar orbit**
  - – similar to EIT but higher spatial resolution, smaller FOV, higher cadence

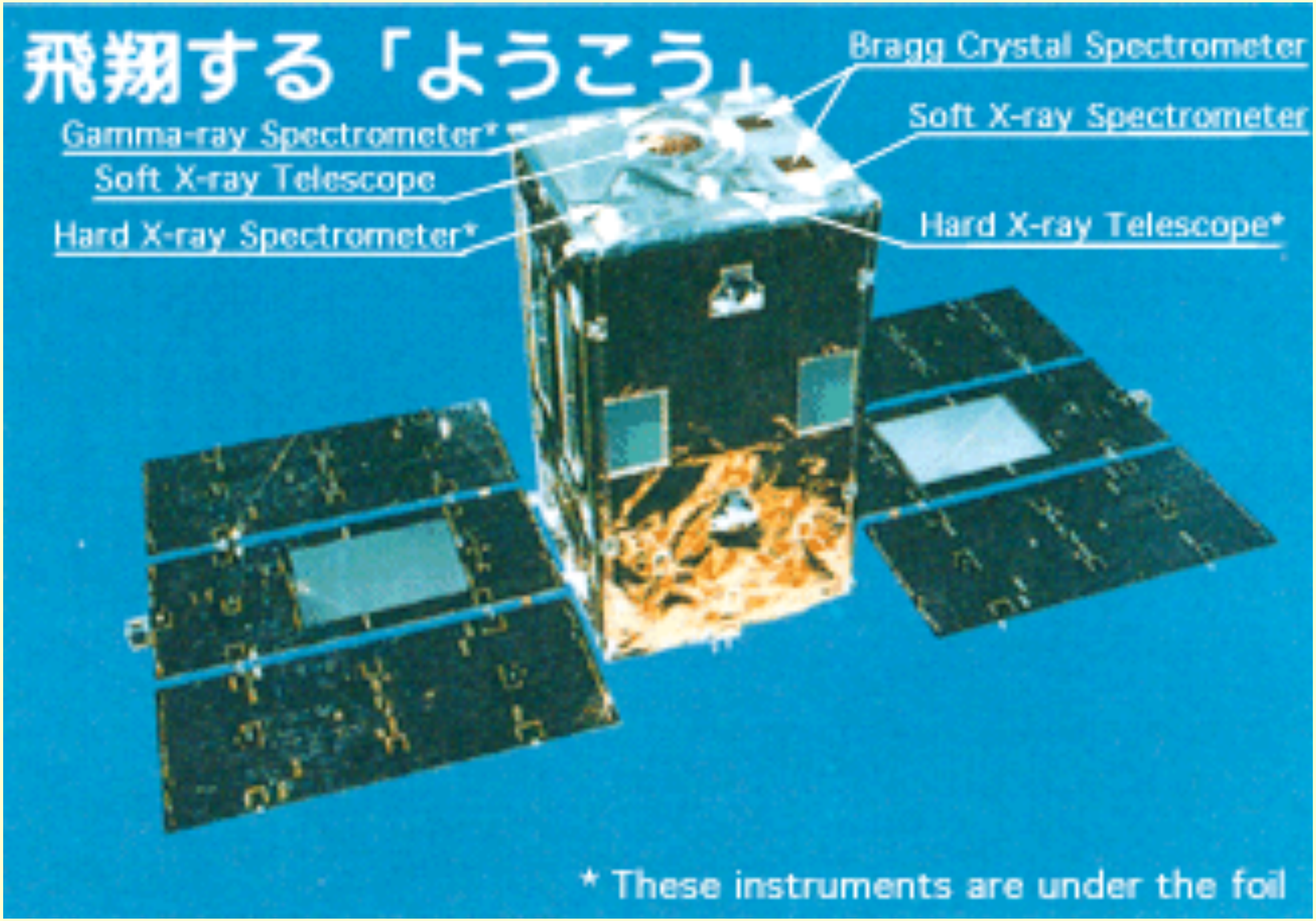
- **STEREO** (Secchi imaging suite) stereoscopic view
  - – EUVI: similar to EIT
  - – Cor1/Cor2: similar to Lasco up to 15 R_{Sun}
  - – HI: heliospheric imager up to 70° FOV off-pointed from Sun (54°)

- **Hinode**
  - – XRT: similar to Yohkoh with higher resolution 1 – 10 MK
  - – EIS: EUV fast scanning spectrometer (170–290 Å) 0.7 – 5 MK

- **SDO**
  - – AIA: “Super”-EIT: 4k x 4k detektor for full disk, 2 sec cadence

Solar A: Yohkoh

study hot parts of solar corona:
- observations from X-rays to gamma-rays
- detect very energetic radiation during flares



Yohkoh SXT design

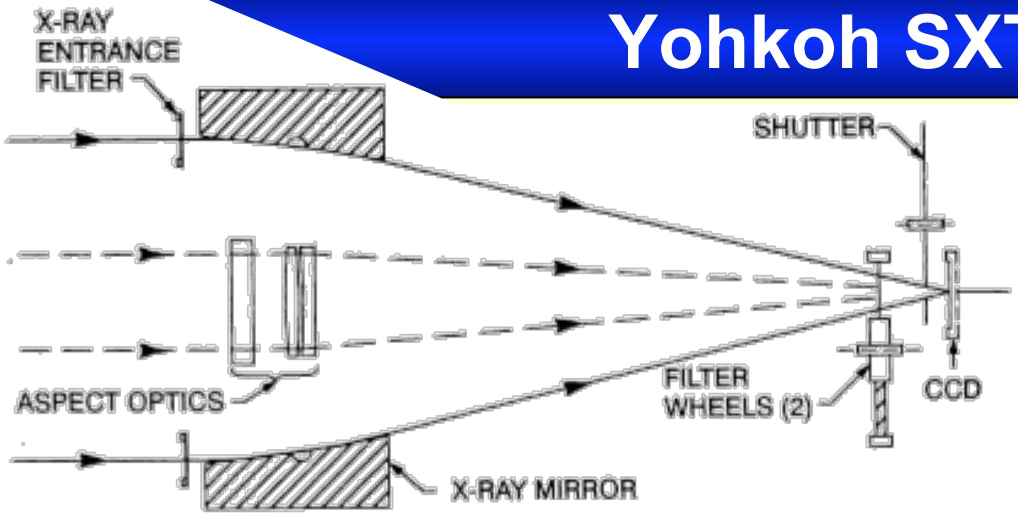


Fig. 1a. Schematic illustration of the optical concept and key elements of the SXT.

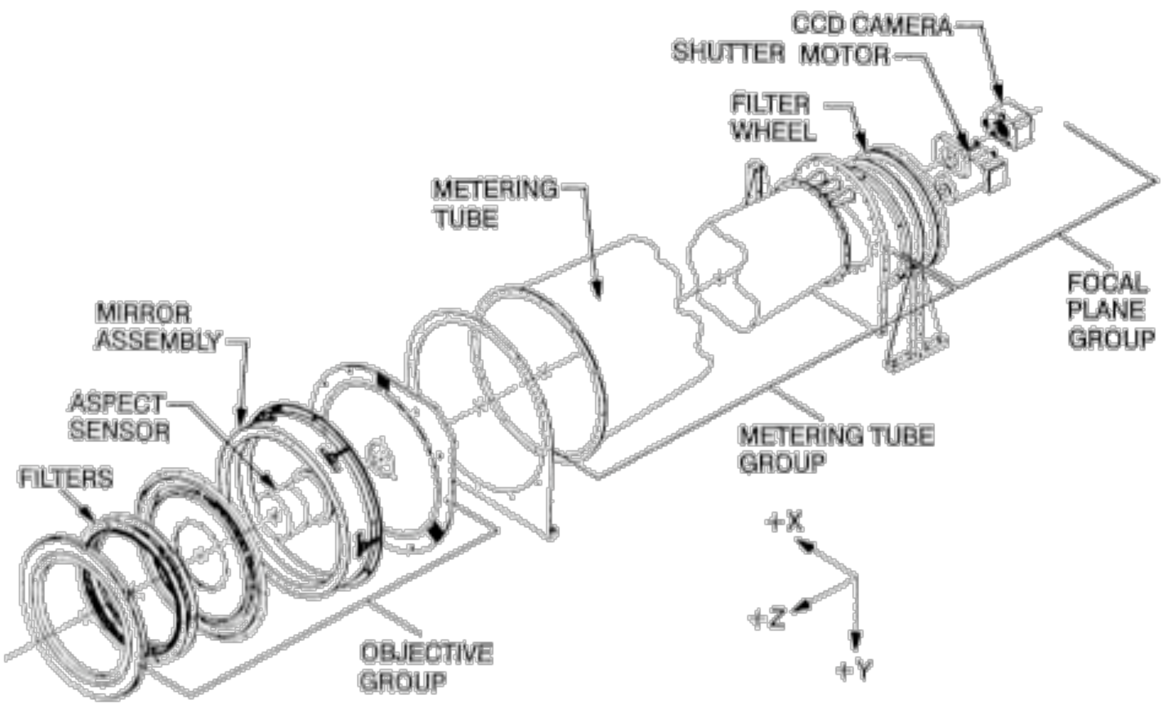


Fig. 1b. Exploded diagram of the SXT. Sub-assemblies mentioned in the text are identified.

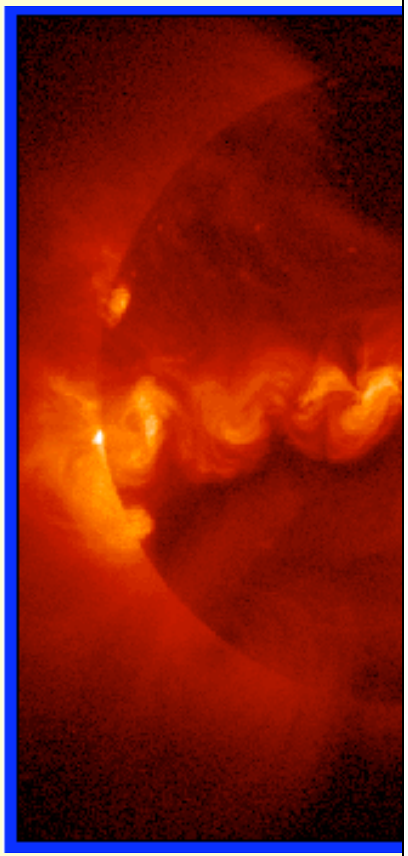
Soft X-ray telescope (SXT):

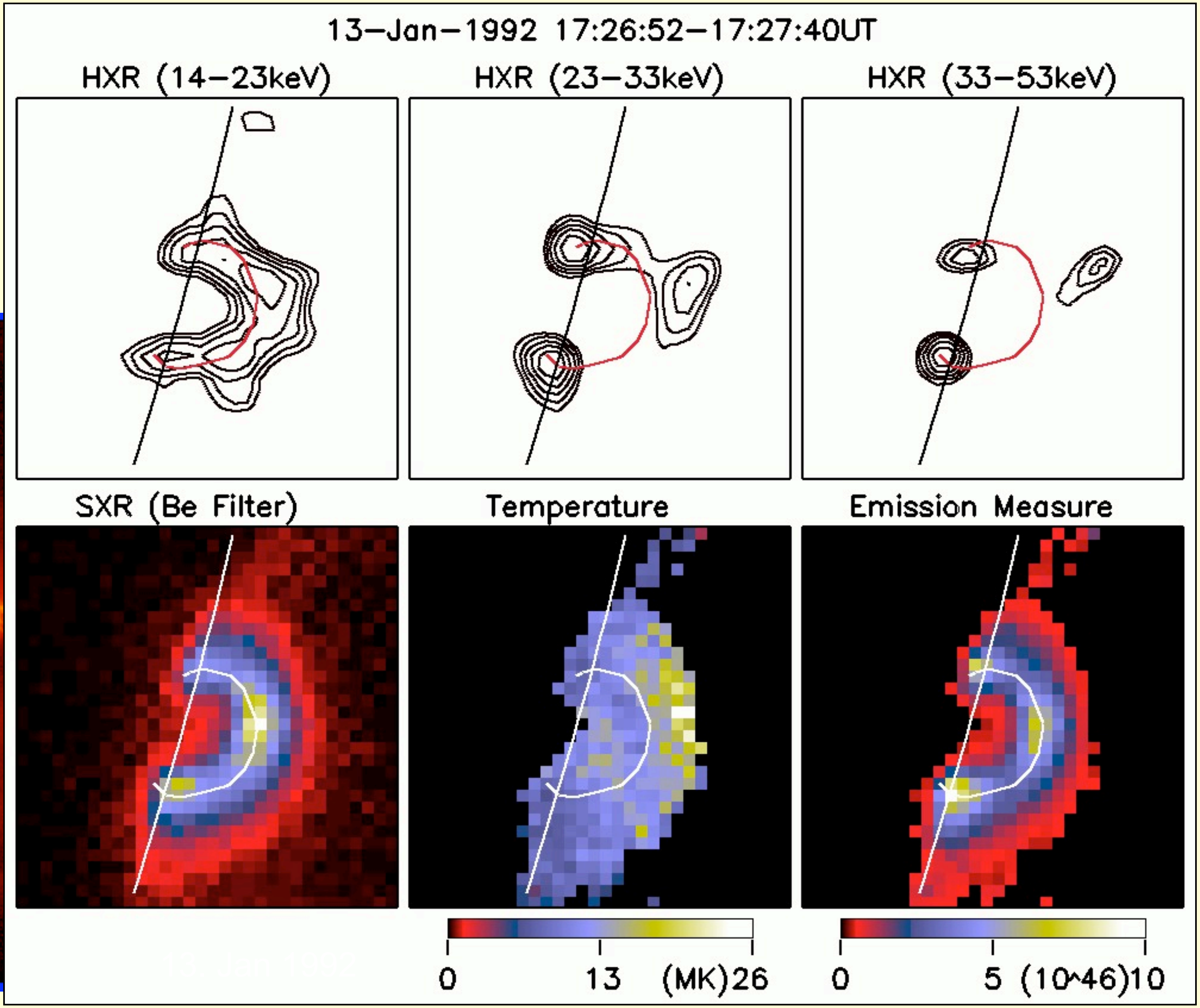
- Wolter-type design
- full-disk images:
  - 1024^2 pixels
  - every 2 min
- partial readout down to 2 sec
- temperatures >2…3 MK
- diagnosics
  - T & ρ structure
  - dynamics of X-ray
  - 3D morphology

Hot, hotter, the hottest: Yohkoh flares

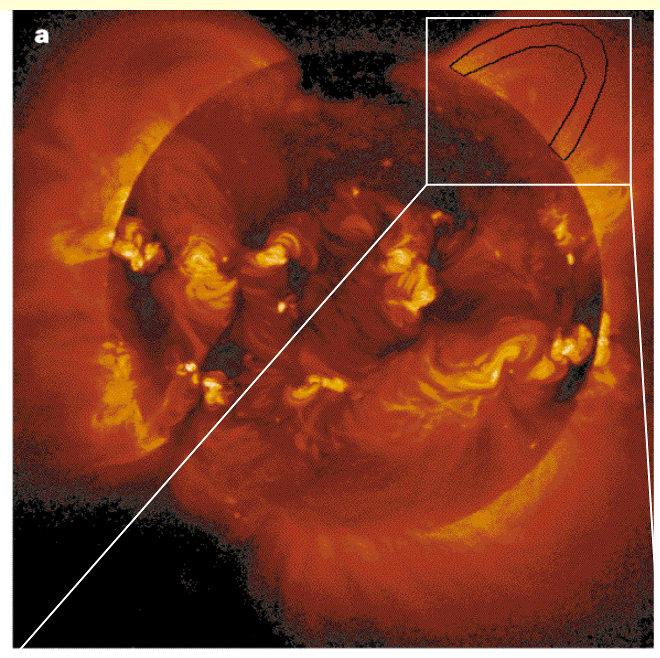
flares are (also) heated at the top! (reconnektion)

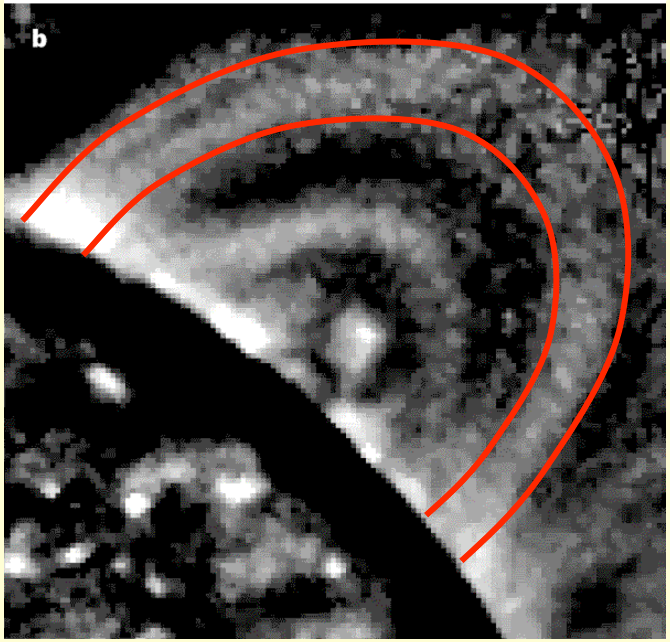
energetic particals go down and heat footpoints





Temperature structure in large hot loops





different filters (foils) for soft X-rays:

different transmission as function of temperature

➡ derive temperature from filter ratios

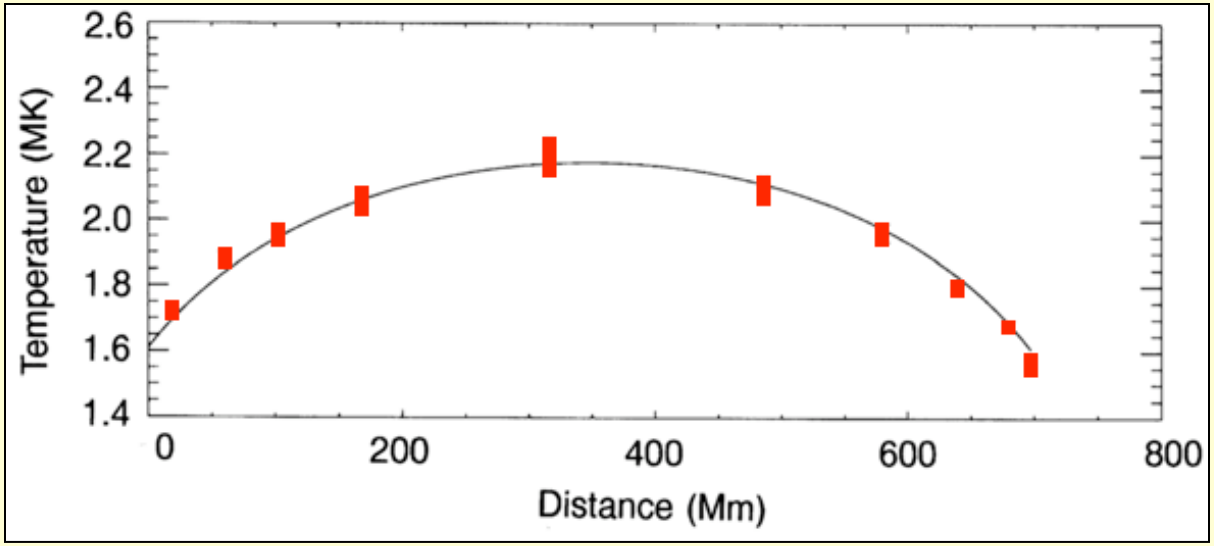
Problem: many implicit assumptions

– static loop

– ionization equilibrium

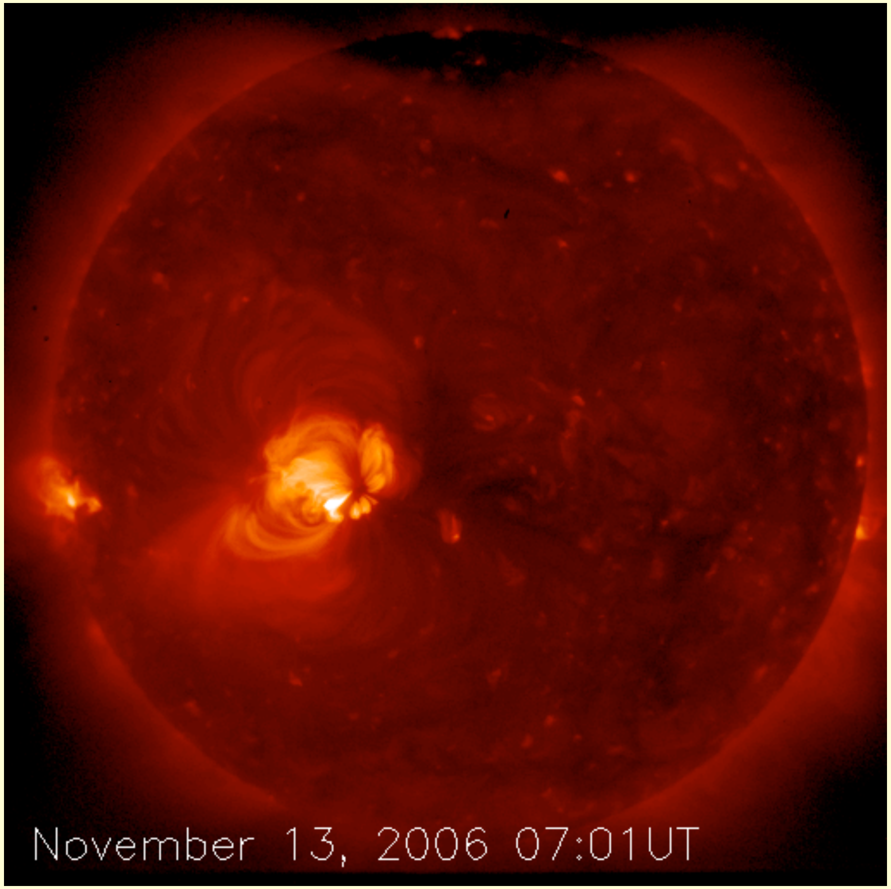
– emission from same structures

➡ is this inversion unique ?

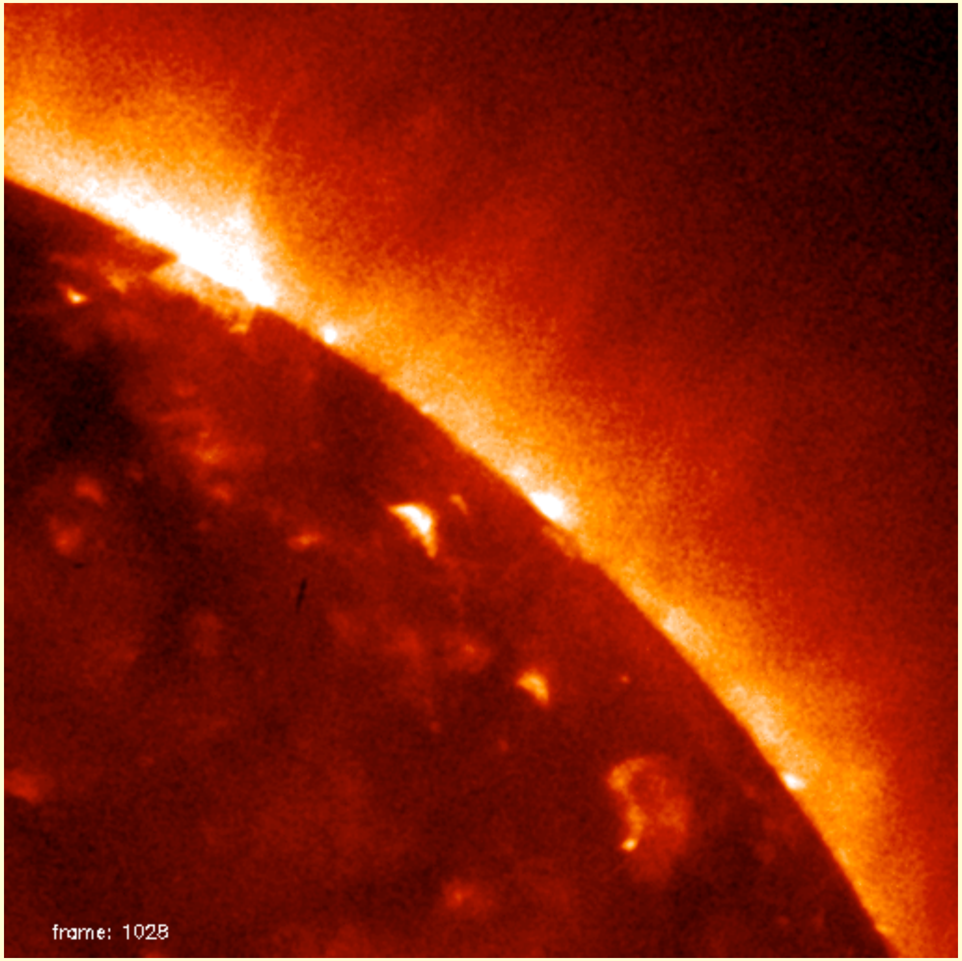


Priest et al. (1998), Nat., 393, 545

Hinode/XRT: micro-flaring hot corona

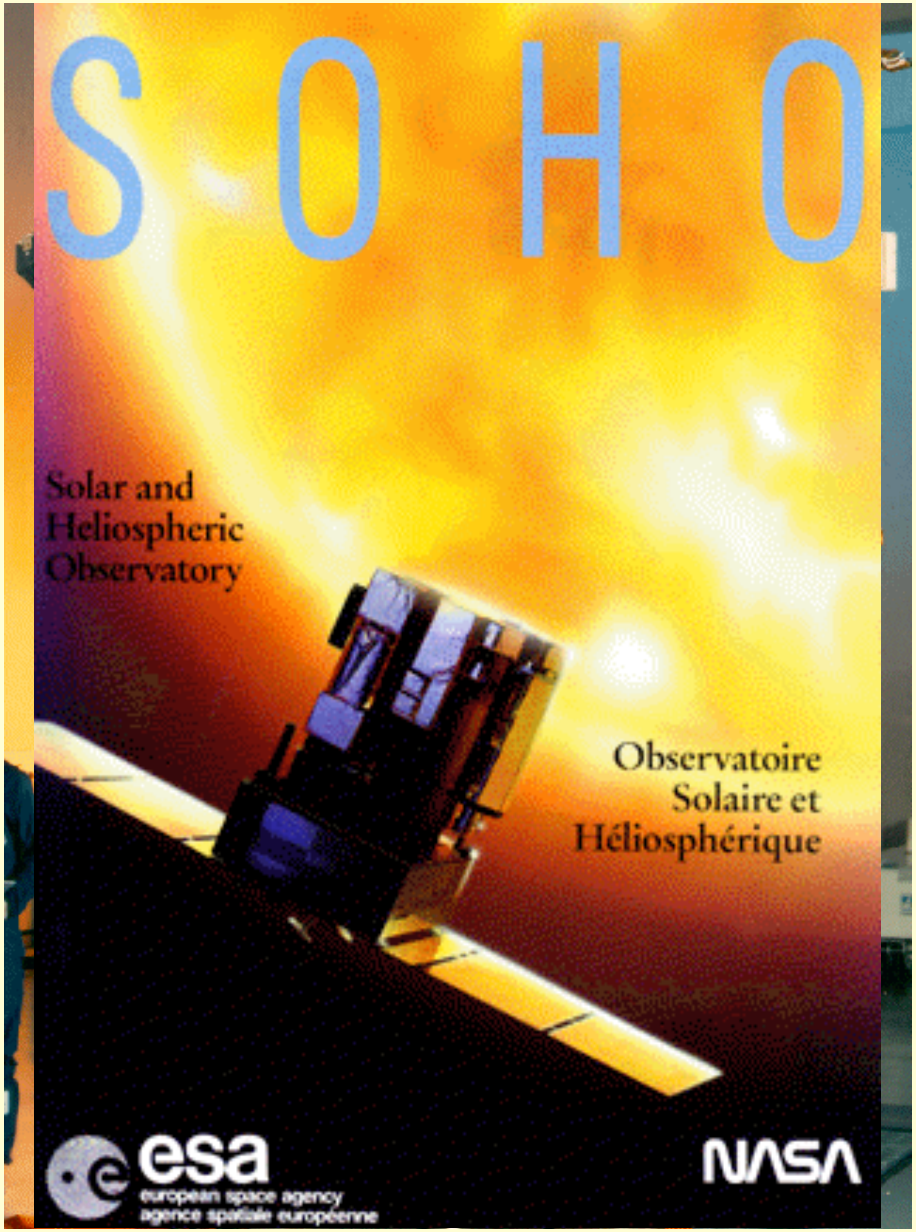


- ► higher spatial resolution than Yohkoh
- ► ubiquitous small-scale reconnection ecents at coronal base
- ► example: reconnection → jet → loop



24.4.2007

Solar and Heliospheric Observatory – SOHO



full solar observatory: 24/7 continuous observations

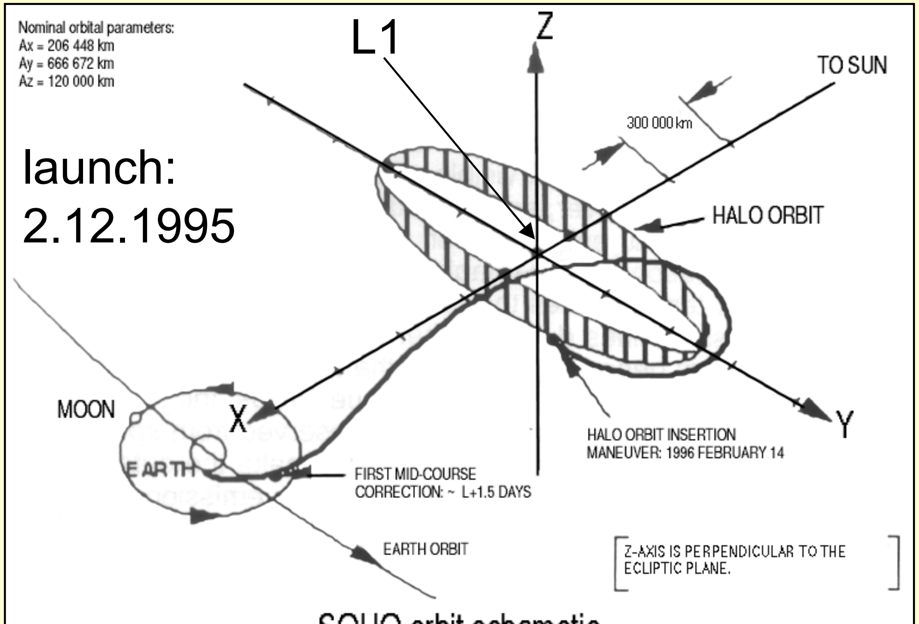
remote sensing:

photospheric *I, v, B*
EUV imaging of corona
EUV spectroscopy (chromosph., TR, corona)

in-situ observations:

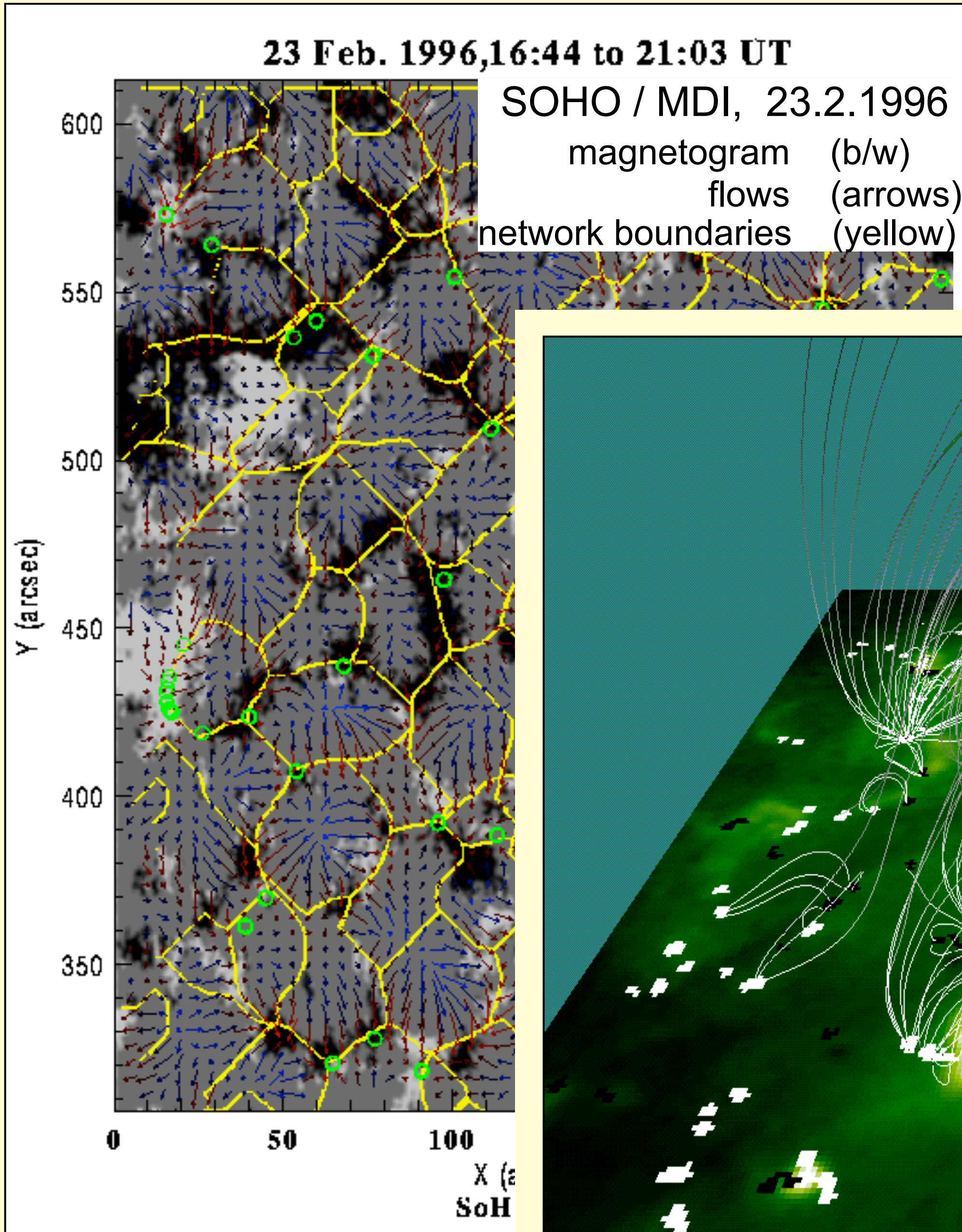
particle fluxes and desities
abundances
magnetic fields

launch:
2.12.1995



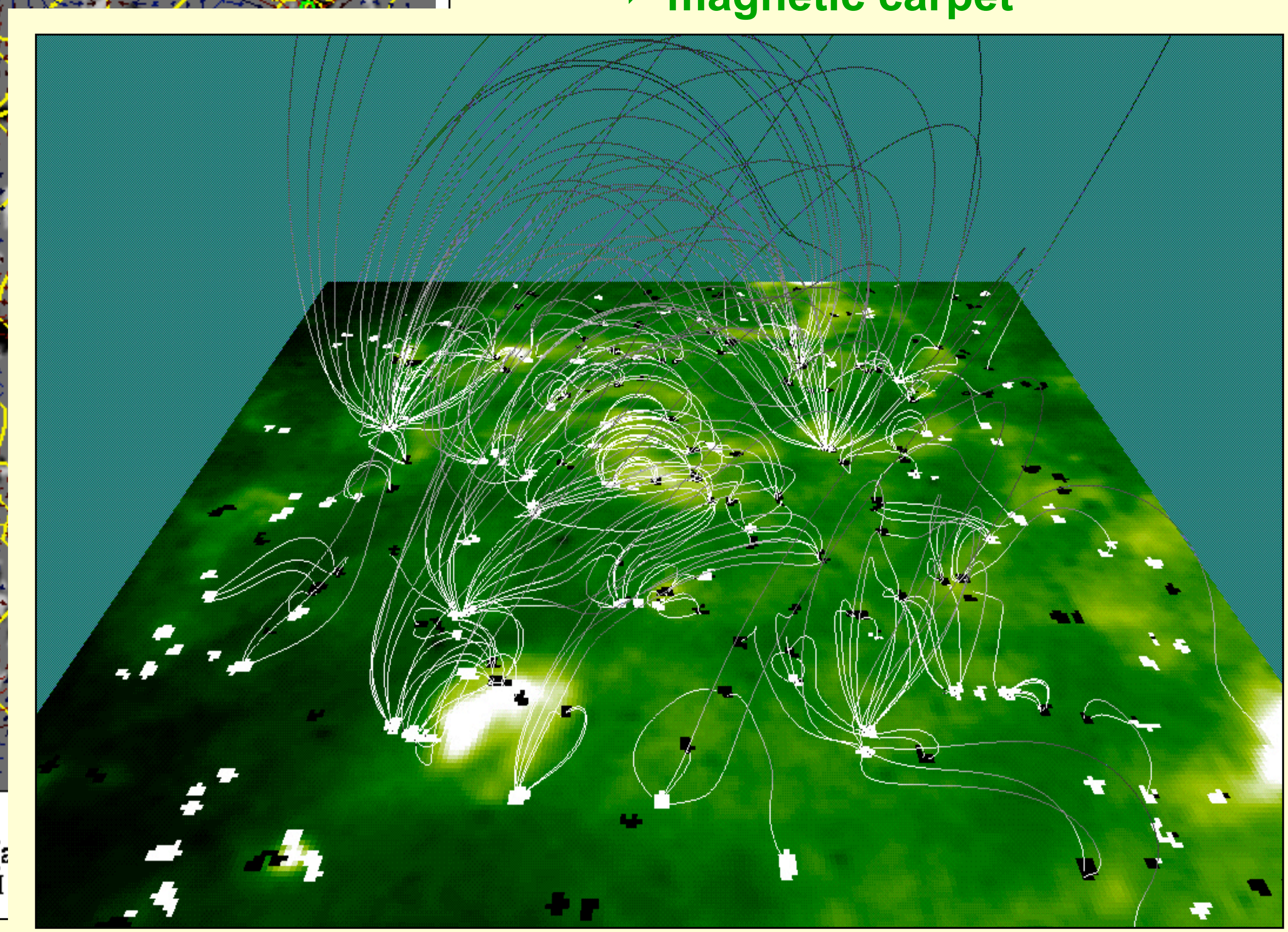
SOHO orbit schematic

Magnetic field, super-granulation and the corona

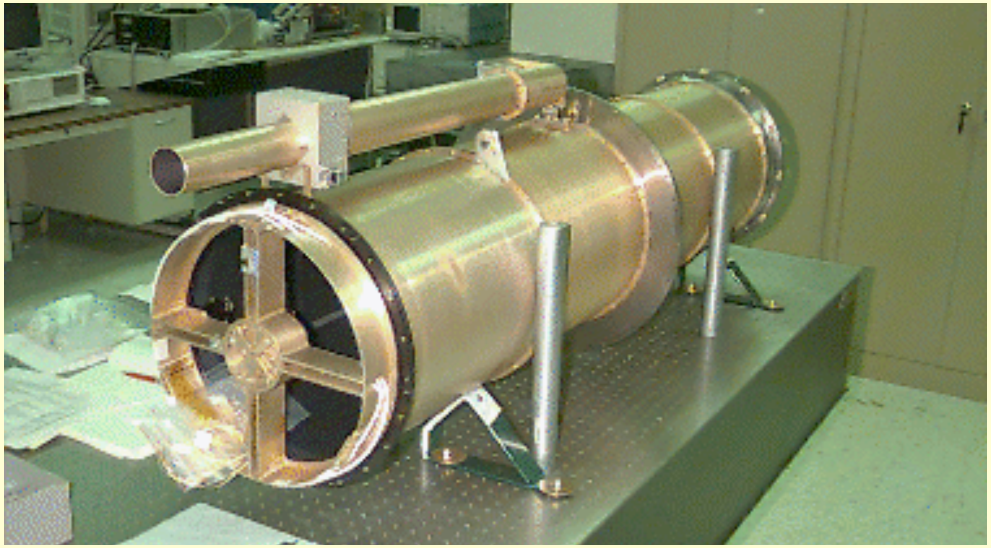


supergranulation

- flow defines supergranulation
- magnetic field is transported to the boundaries
  ➡ **magnetic carpet**

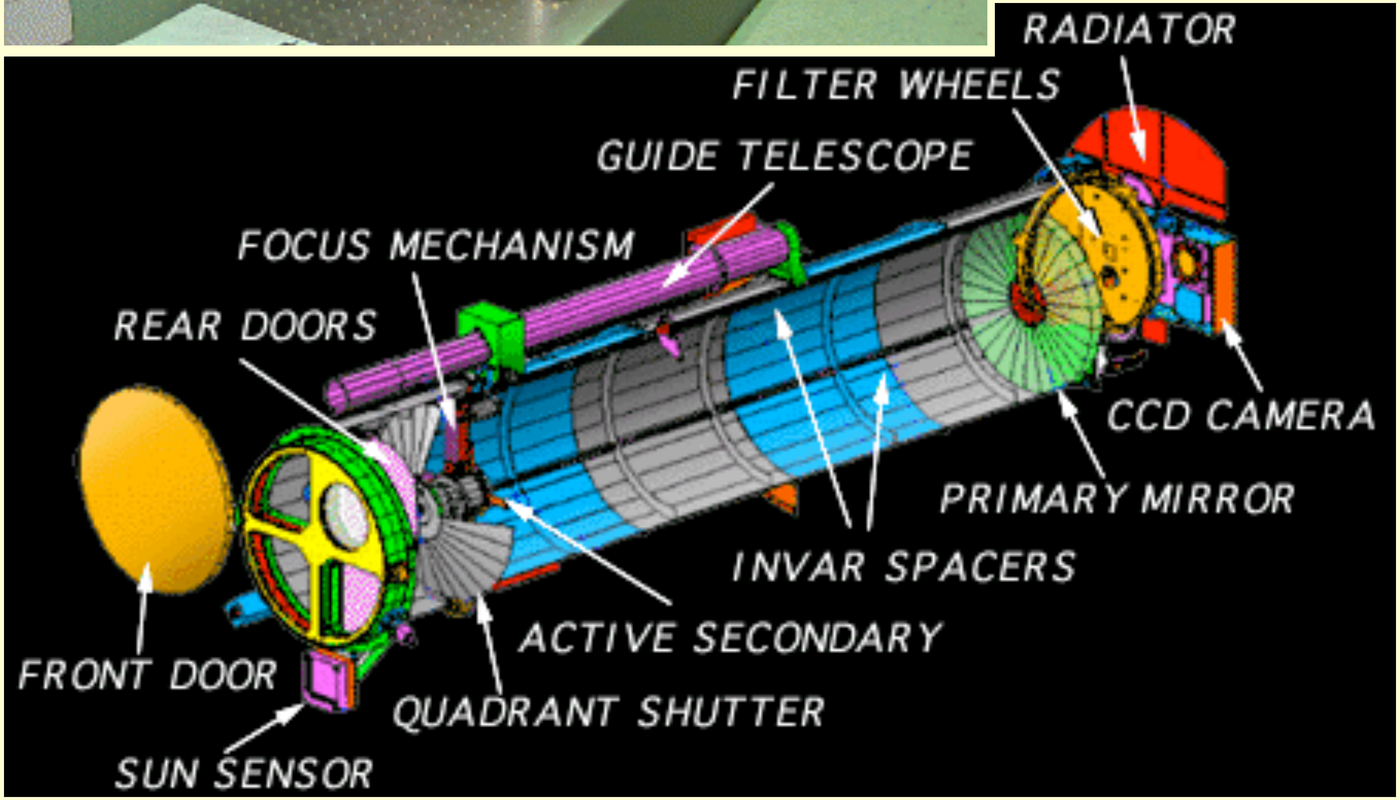


Transition Region And Coronal Explorer – TRACE



30 cm normal incidence telescope

- 4 quadrants of mirror with diferent multi-layer coatings
- additional "narrow band" filters
- 0.5" pixels ➡ resolution: 725 km on Sun
- down to 10 s cadence
- 1024x1024 detector (10% of full Sun)



EUV-channels: **corona**

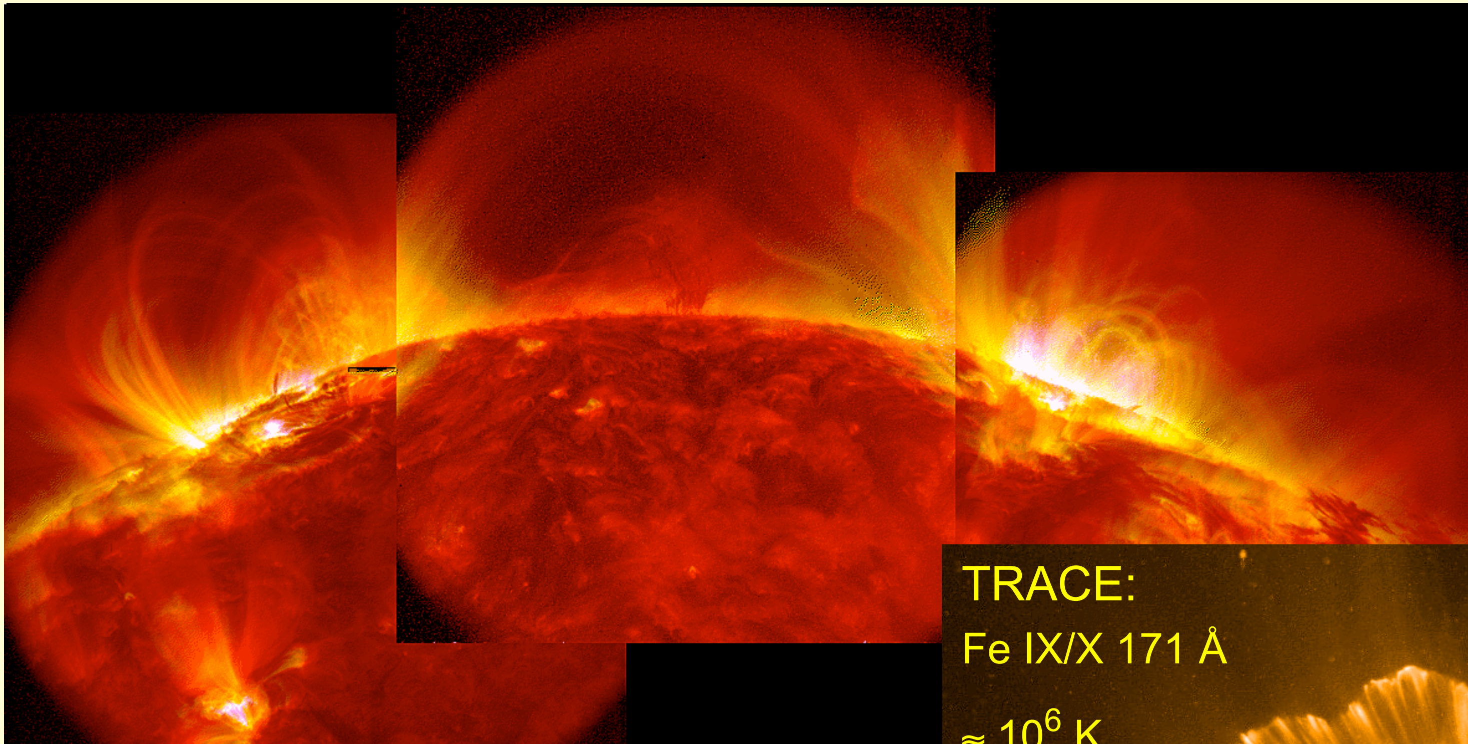
171 Å: Fe IX/X ~1.0 MK
195 Å: Fe XII ~ 1.3 MK
284 Å: Fe XV ~ 2.0 MK

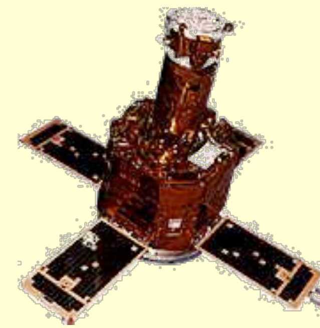
UV channels

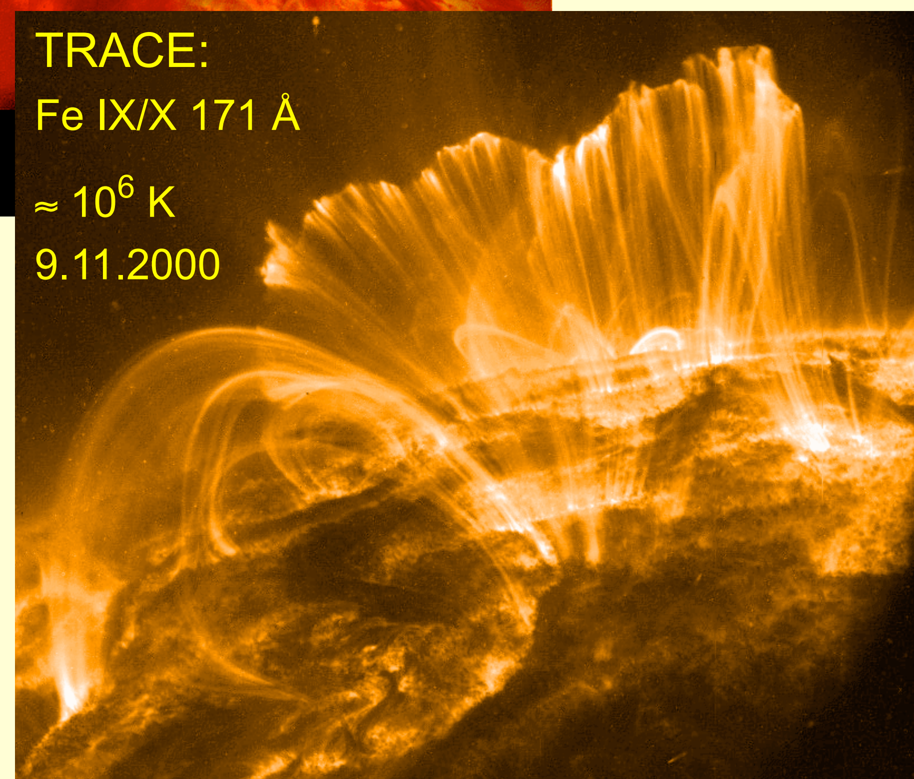
1550 Å: } **TR** / C IV 0.1 MK
1600 Å:
1700 Å: } **chromo/**T-min
Ly-a: chromosph. / TR

launch April 1998

Amazing details…







TRACE does not see the full Sun, but
it shows amazing details in space and time

However: diagnostic value?

- inversion of coronal T ?
  - ➡ to few coronal bands
- plasma flows ?
  - ➡ no line shifts

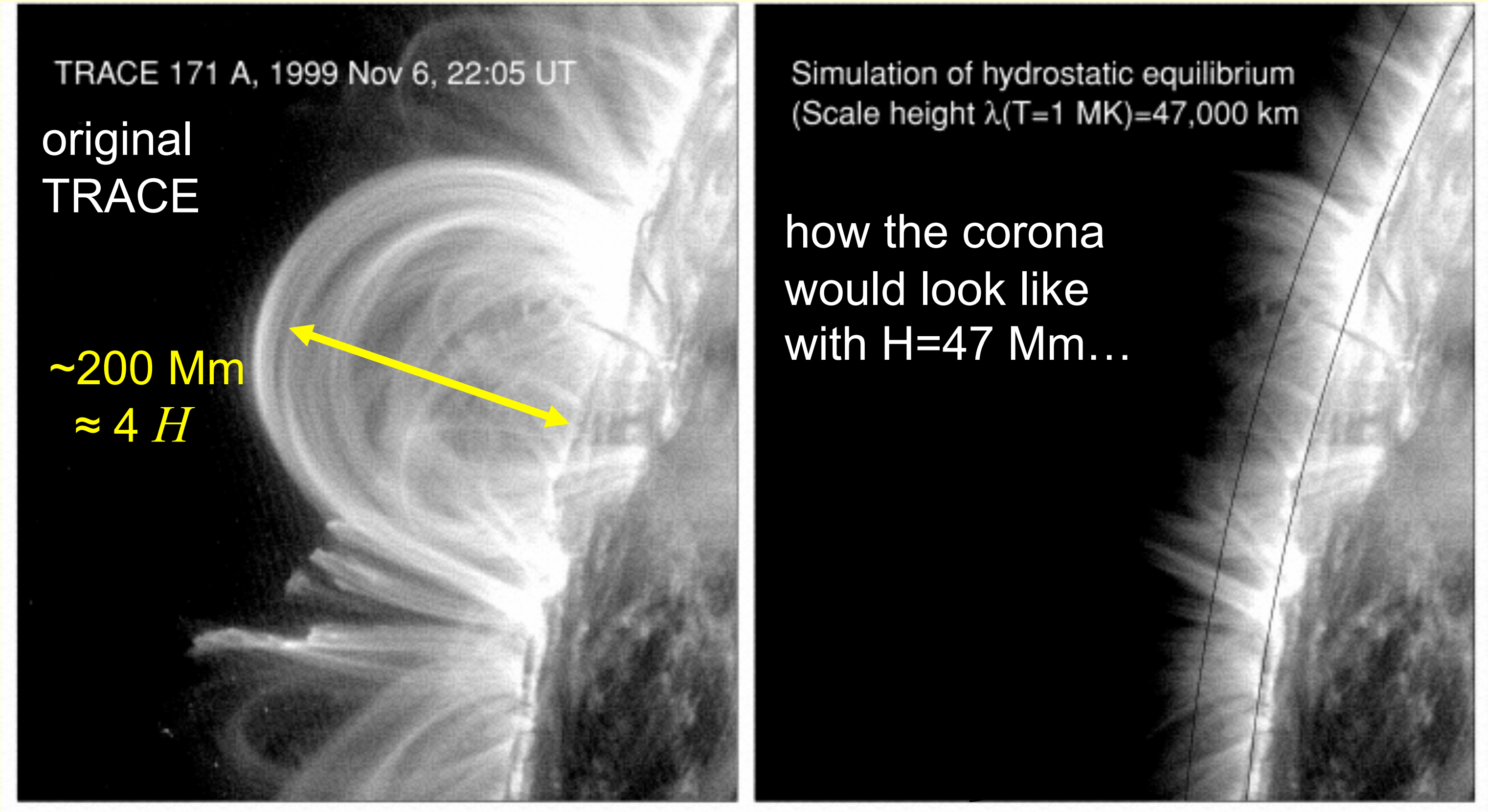
Scale height of the corona

hydrostatic pressure scale height:

$$H = \frac{k_B T}{m g}$$

@ 10^6 K:

$H = 47$ Mm

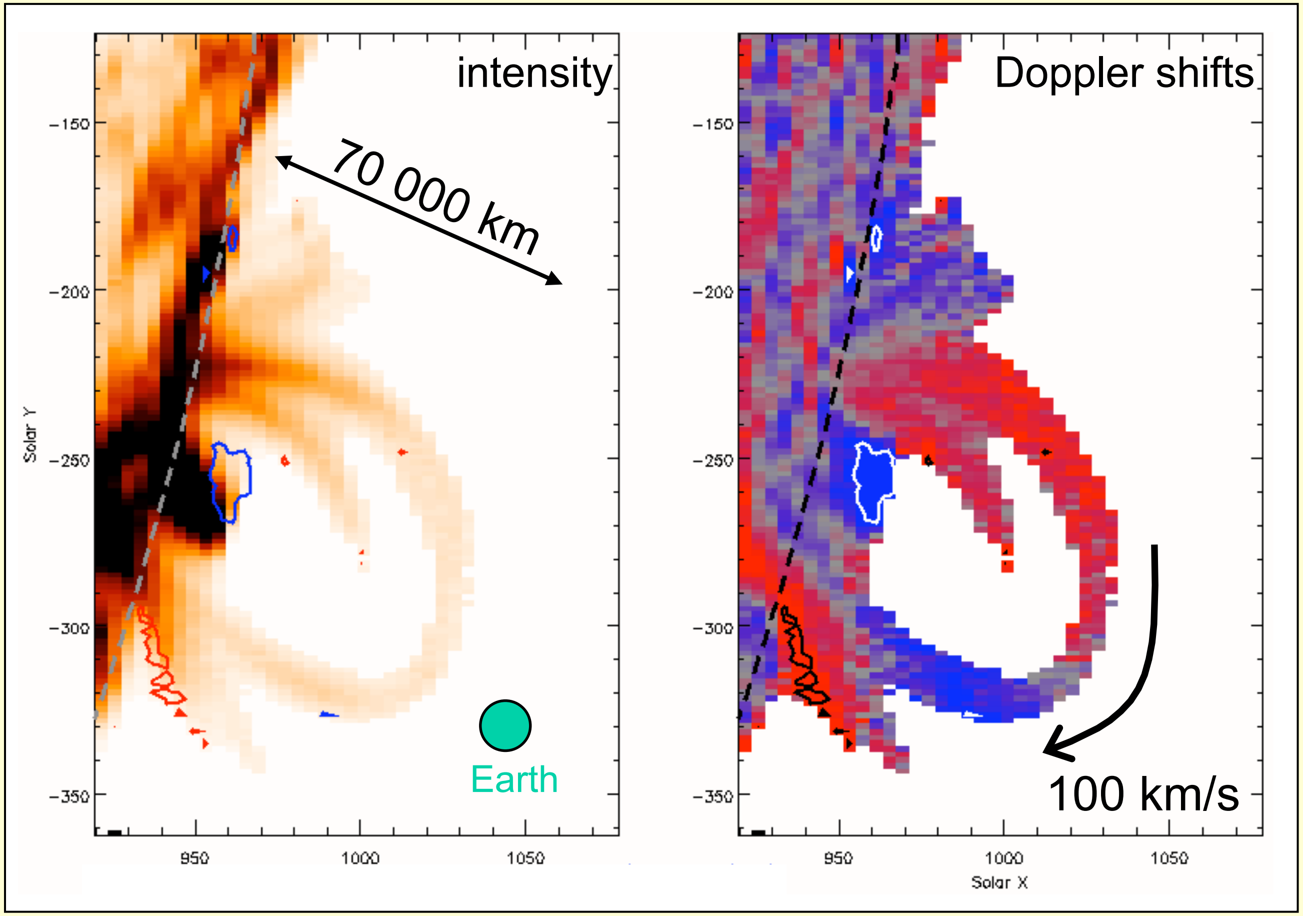


Why do loops seem to have a rather constant intensity ??

- >70 % of loops cannot be in hydrostatic equilibrium !!
  ➡ e.g. cooling loops
- of the 30 % that might be in equilibrium:
  most have to be heated at the foot points!

Aschwanden (2001)

Why do we see coronal loops at TR-T ?



Brekke et al. (1999)

O V (62.9 nm)

≈ 200 000 K

Coronal Diagnostic Spectrometer (CDS)

SOHO

27. Oktober 1999

scale height @ 200 000: $H = \frac{k_B T}{m g} \approx$ 6000 km

loop height: 70 000 km $\approx 11\, H$

$$\Rightarrow \quad \frac{I_{\text{top}}}{I_{\text{bottom}}} \approx \left(\frac{\rho_{\text{top}}}{\rho_{\text{bottom}}} \right)^2 \approx \left(\exp[-11] \right)^2 \approx 10^{-10}$$

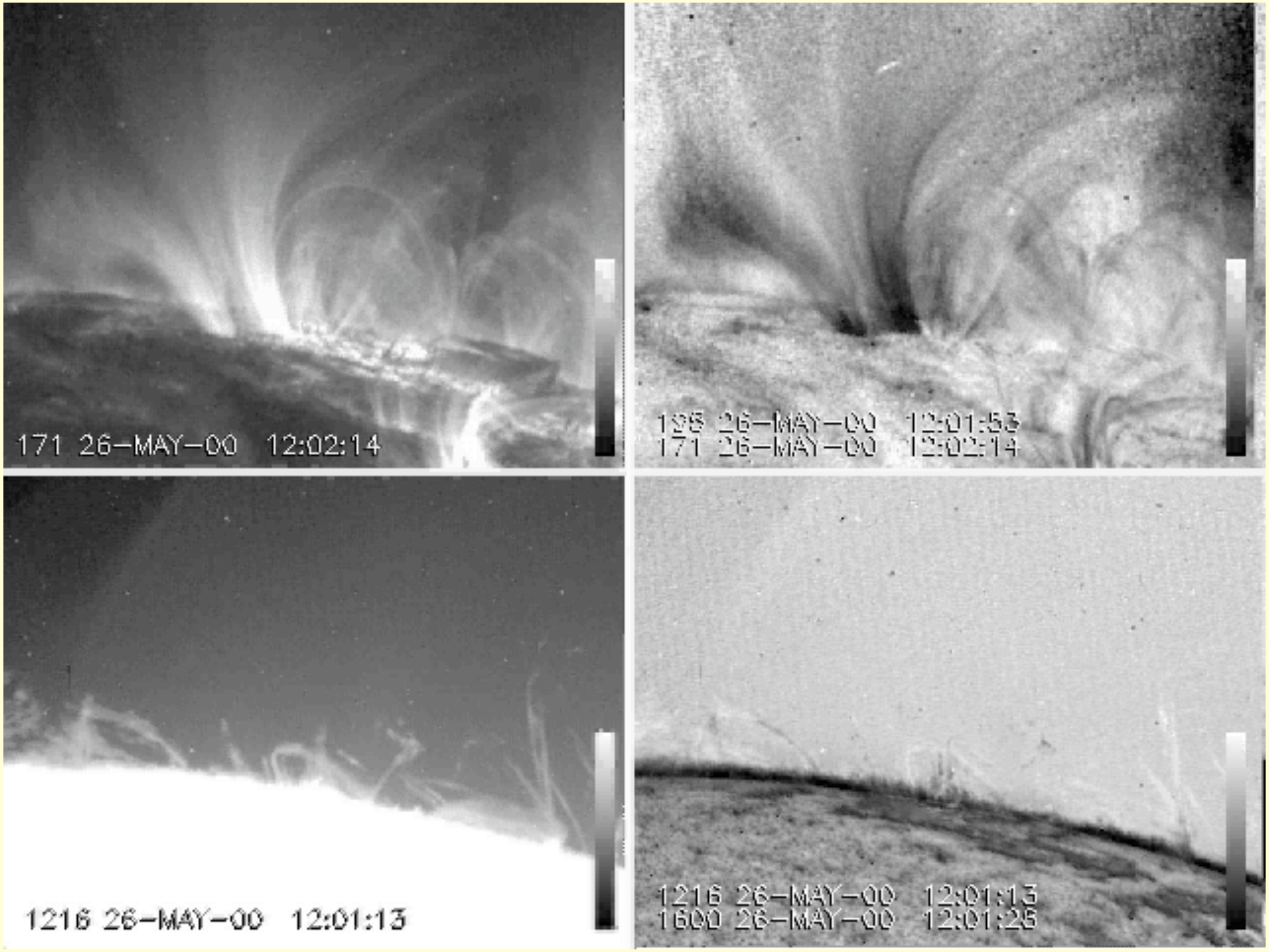
These cool loops cannot be in hydrostatic equilibrium !!

➡ cooling

➡ dynamics

The dynamic ever-changing corona

10^6 K – low corona   hot corona – 1.3×10^6 K / 10^6 K



10^4 K – “chromospheric” plasma   and gradients removed – 10^4 K

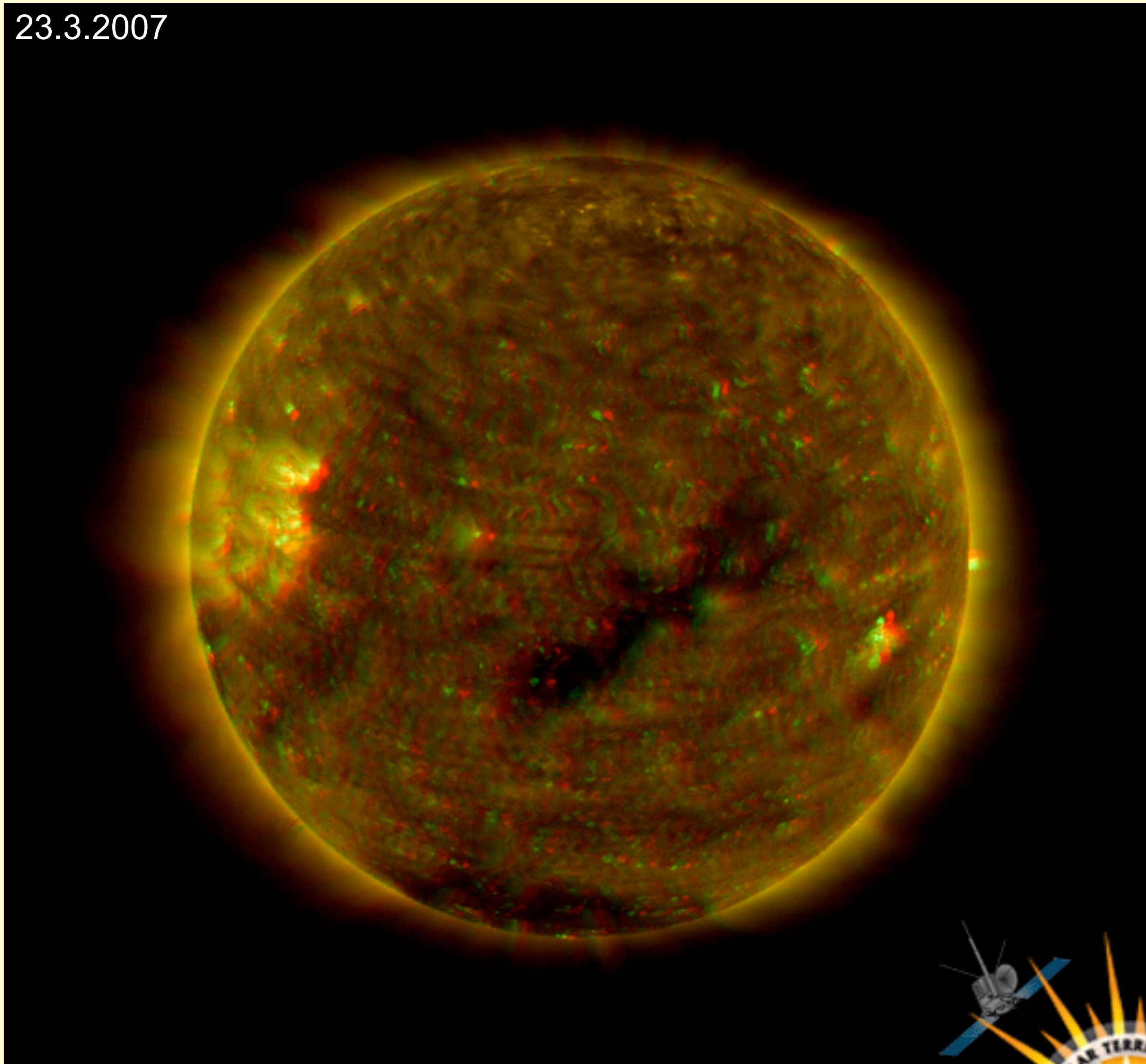
Schrijver (2001) Sol. Phys. 198, 325

dynamic
processes
on **all** scales:

from solar radius
to resolution
of current
instrumentation

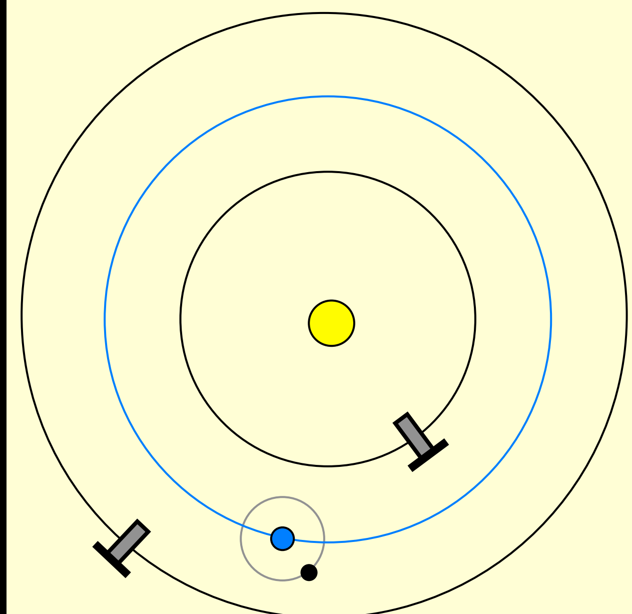
~5 hours

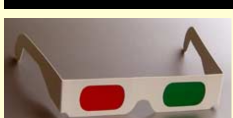
STEREO: 3D imaging



Solar TErrestrial RElations Observatory

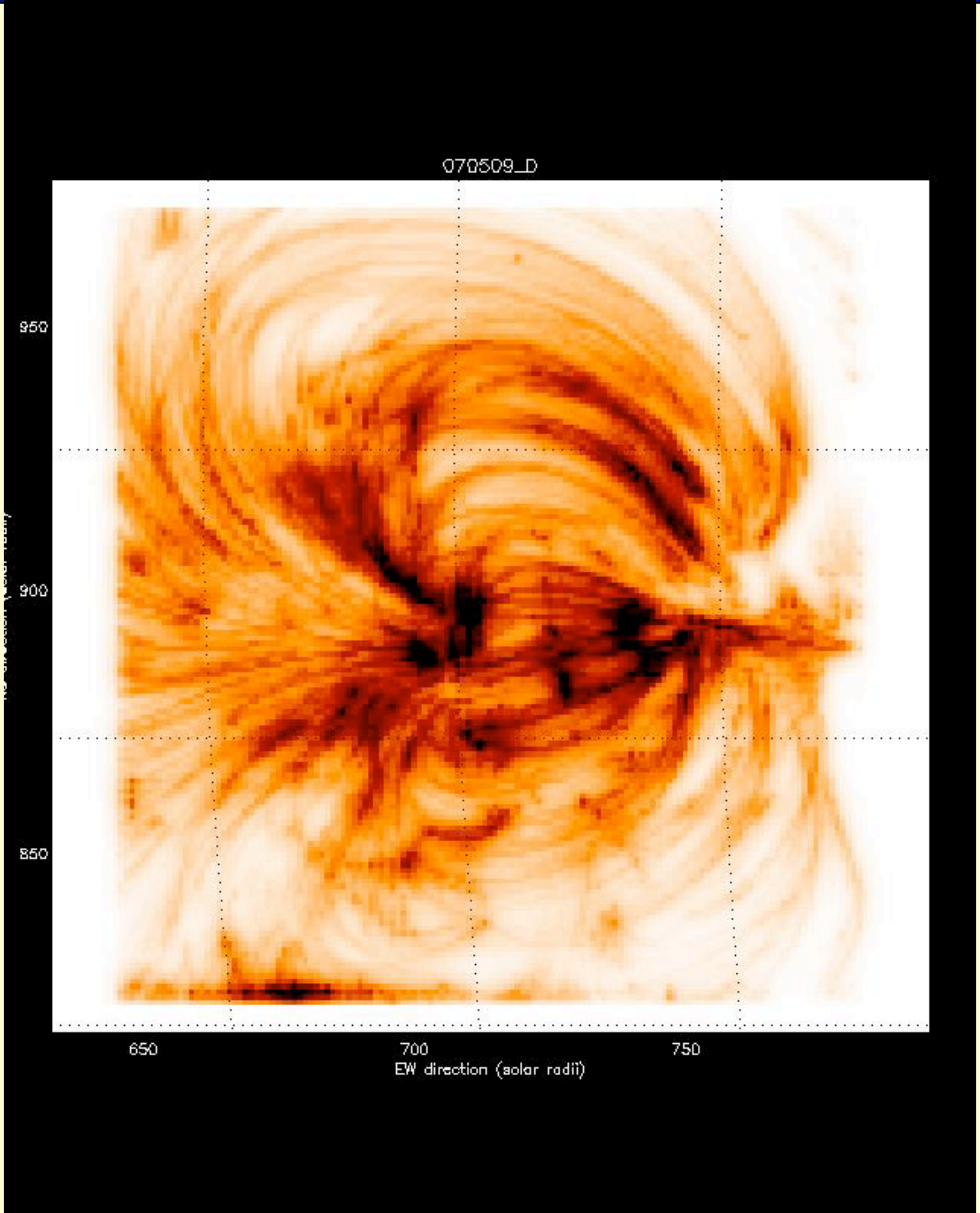
Start: 25.10.2006
two spacecraft:





3D stereo images

Hierarchy of loops in active region



3D reconstruction of active region loop system using stereoscopic techniques

1. identify loops from both viewing angles
   → 3D trajectories

2. simple 1D model for emission along loops

3. optimize to reconstruct observed emission

4. investigate spatial distribution of
   e.g. loop temperatures
   → hottest loops at
   heart of active region

Aschwanden (2008)

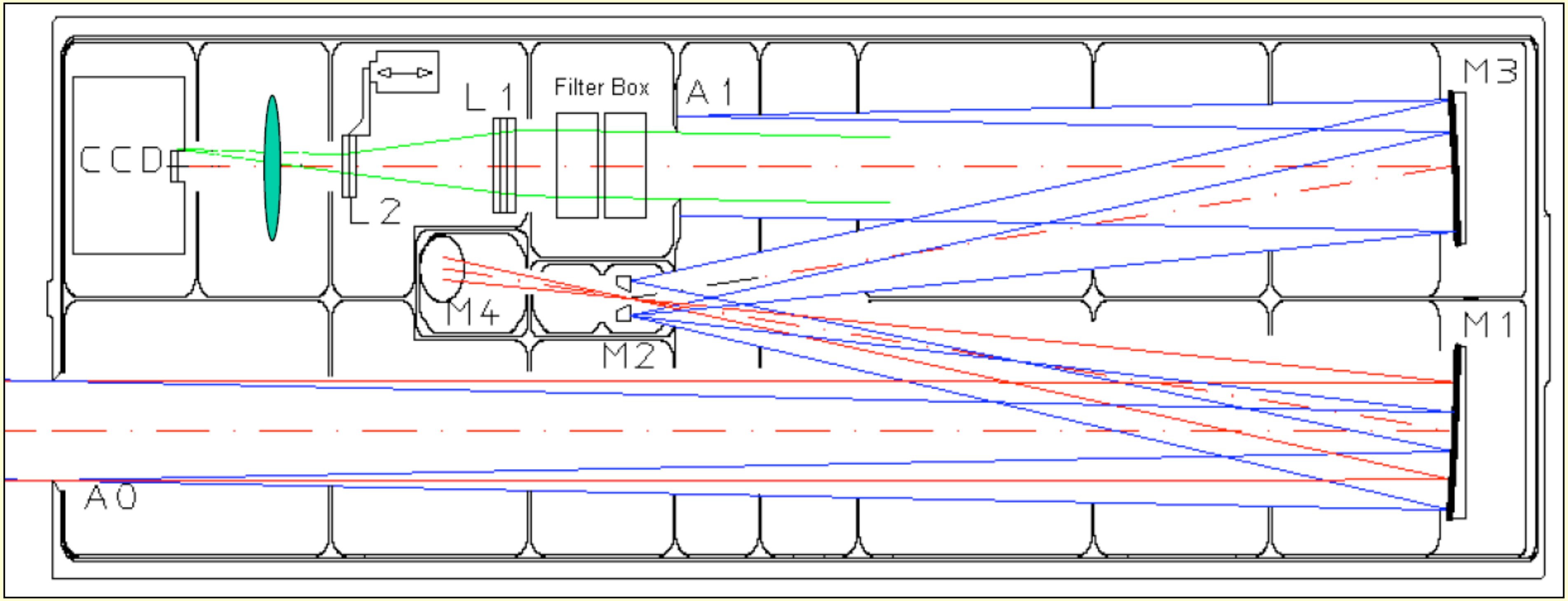
Coronagraph: SOHO / Lasco C1

traditionally: coronagraph has a single lens objective ➡ low straylight

C1 is first operating mirror coronagraph

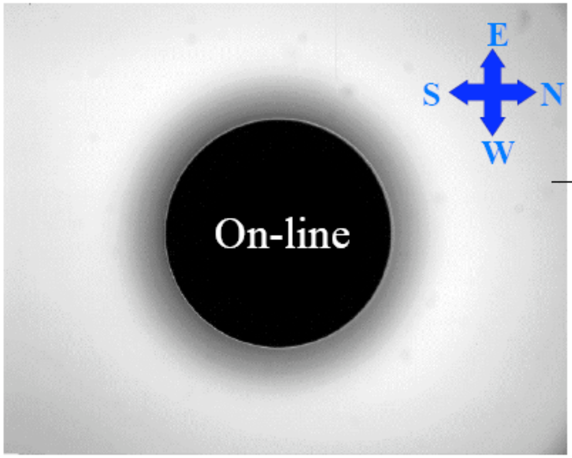
problem: roughness of the mirror ➡ can be handled theses days…

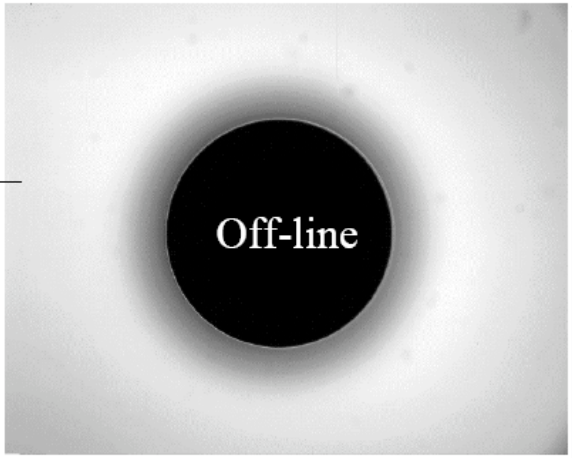
advantage: – no occulter: but hole in a mirror ➡ easy to get rid of solar disk light
– one can even use the solar disk light ➡ simultaneous corona & disk!
(not used with Lasco C1)

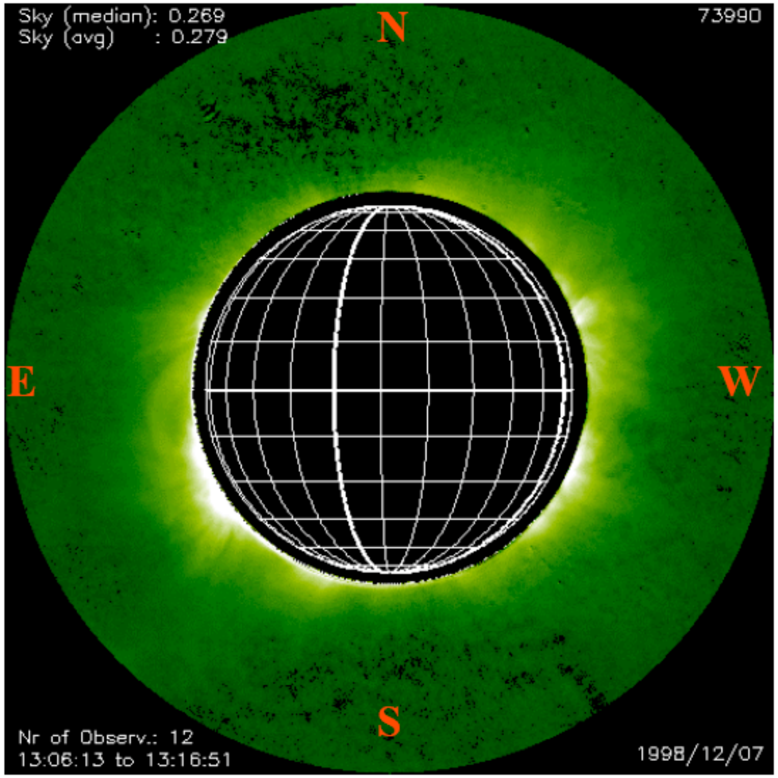


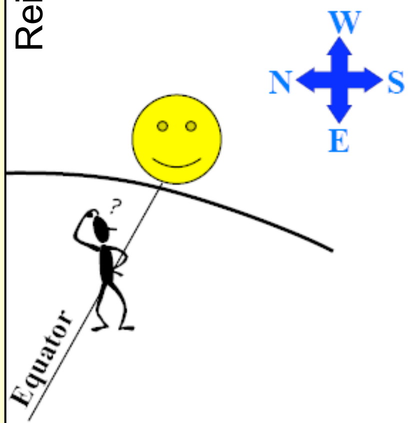
MICA – Mirror coronagraph for Argentina / flight spare of Lasco C1

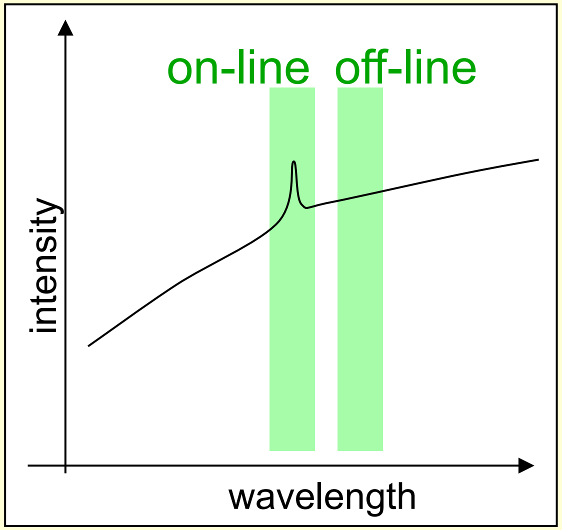
Extracting the emission line corona





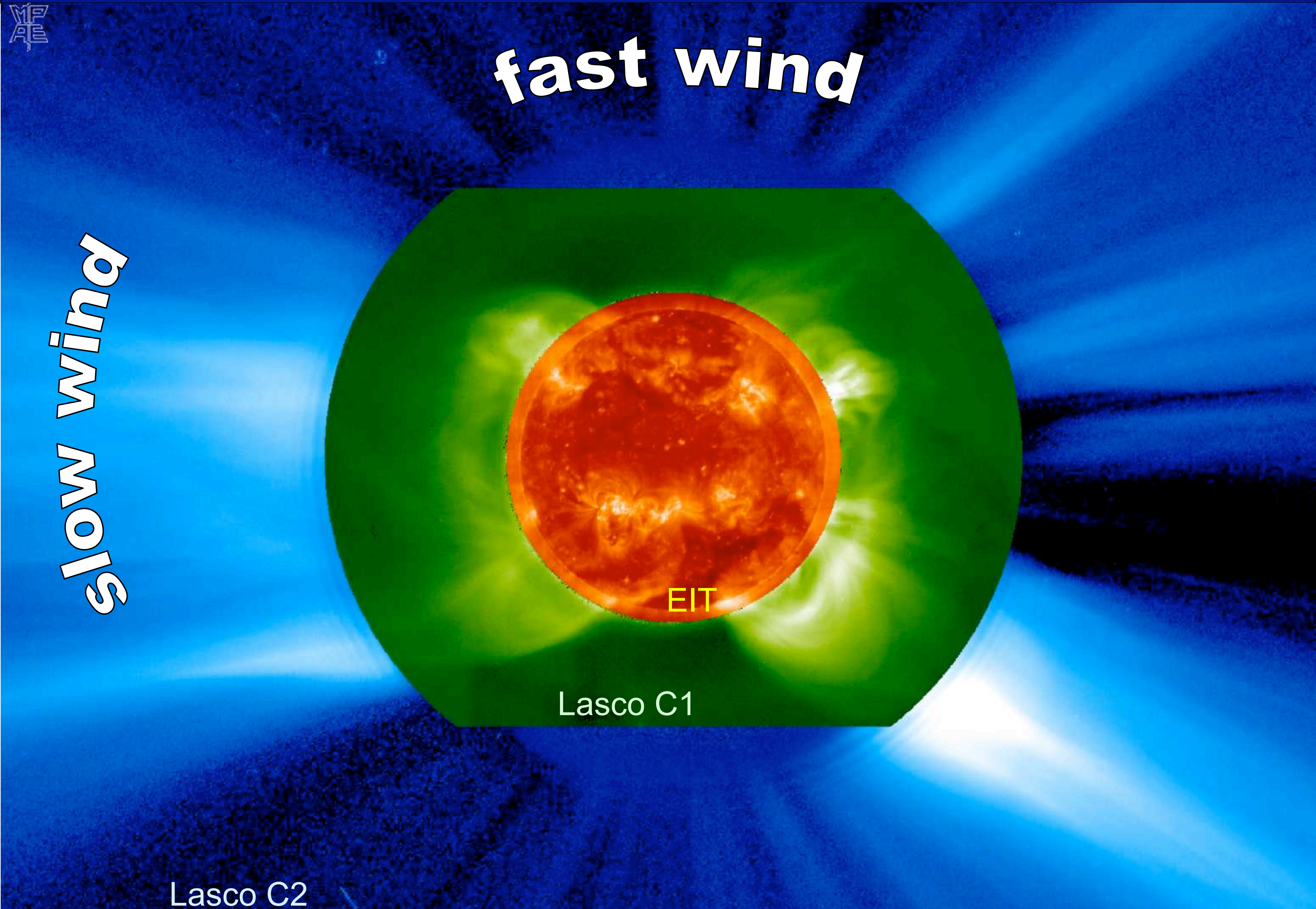






Reiner Schwenn

The corona – on disk and above limb

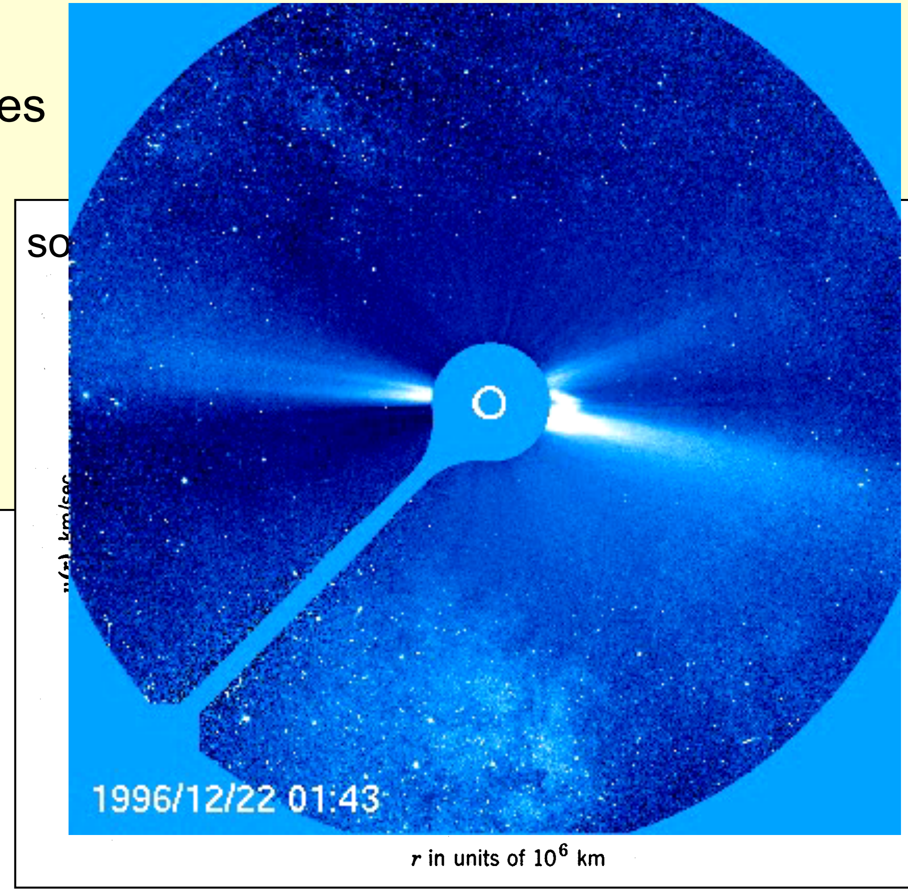


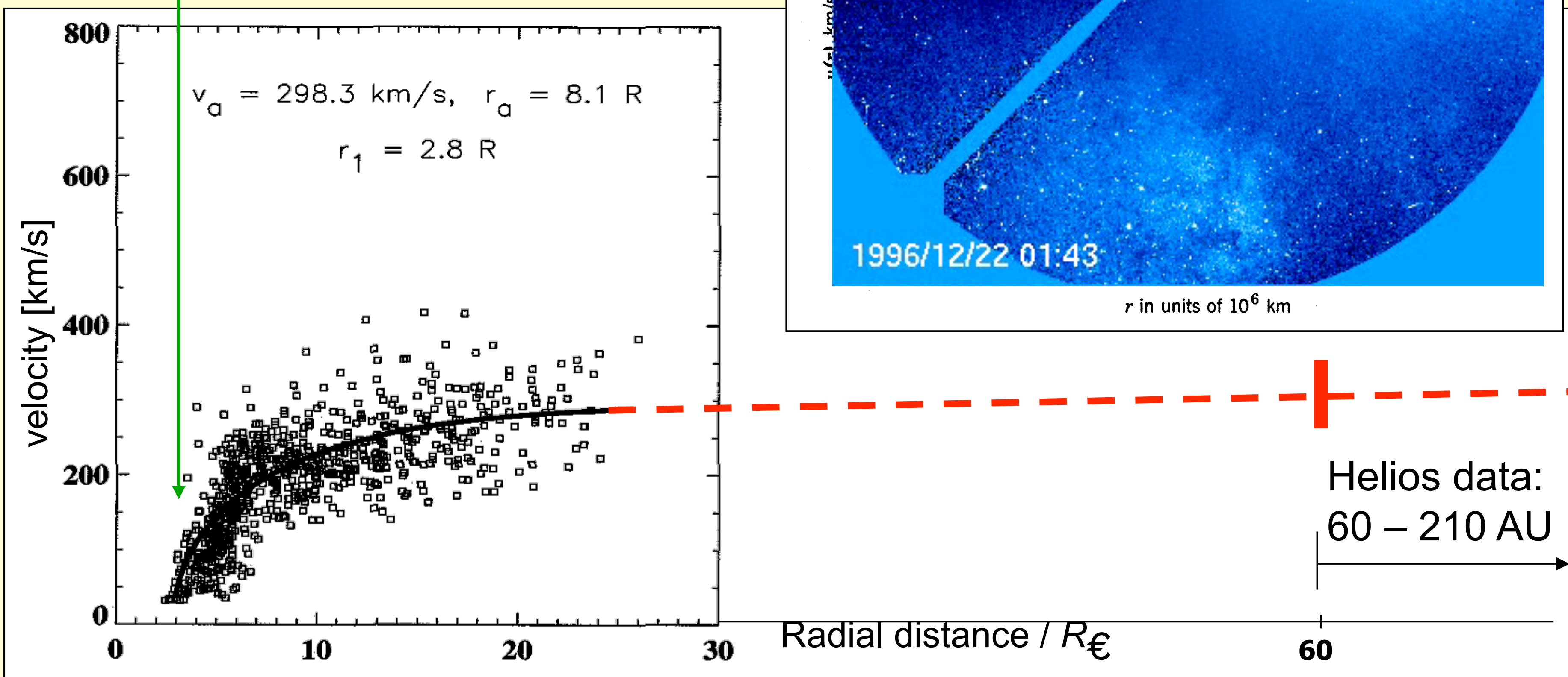
Acceleration of the slow solar wind

analyze time series of coronagraph images

➡ acceleration of slow solar wind
from magnetically closed corona

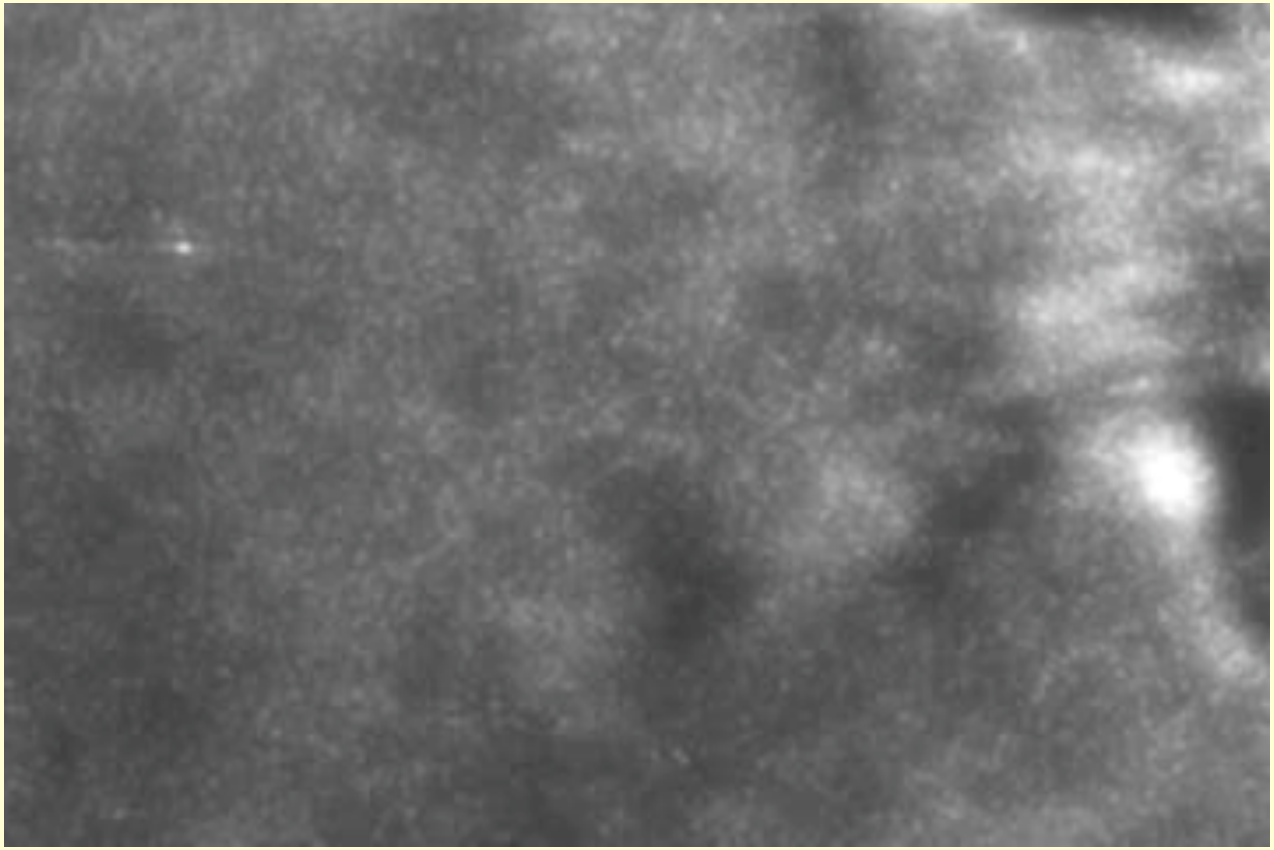
➡ starts at ≈ 3 R_{Sun}





Sheeley et al. (1998) ApJ 484, 472

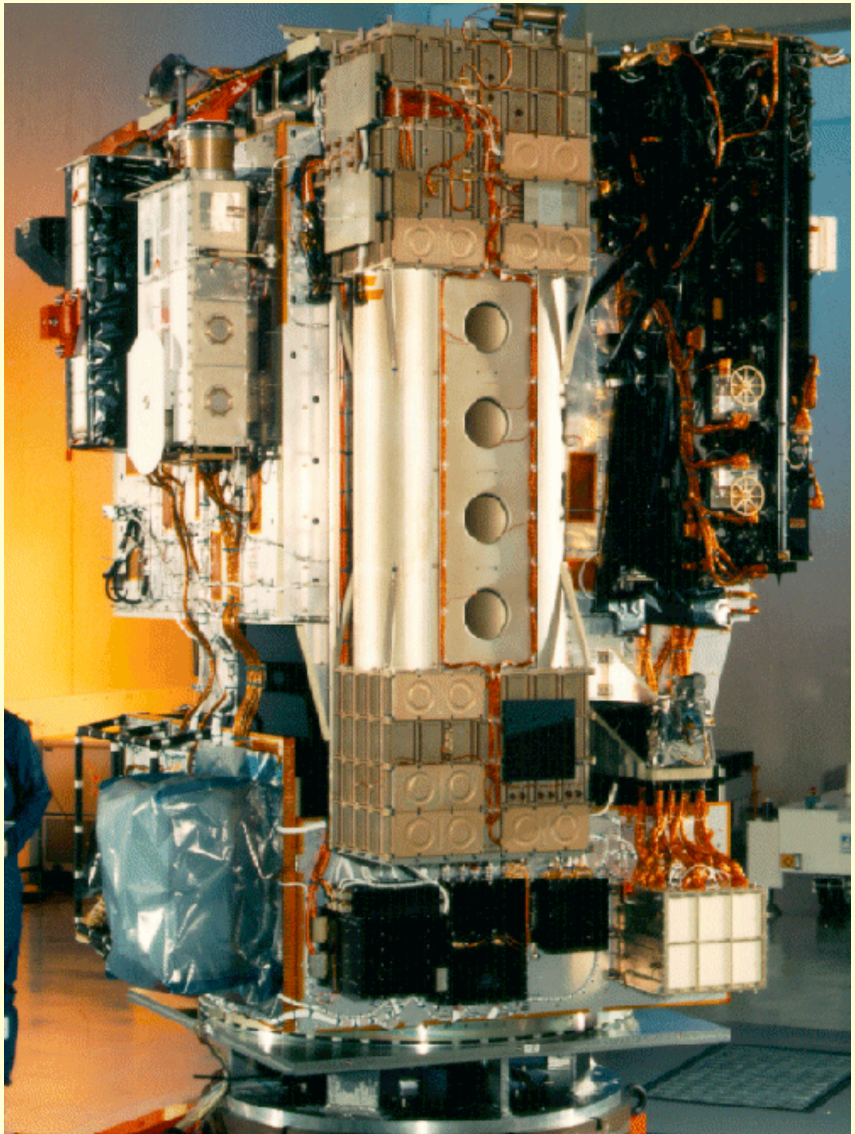
STEREO / HI coronagraph



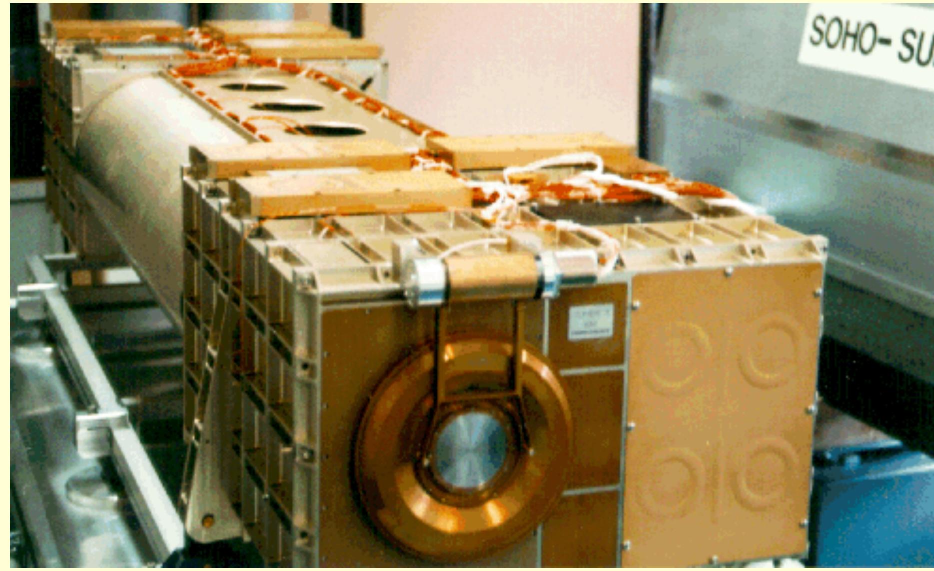
Comet Encke
within Mercury orbit
looses its tail
during CME eruption

Maddock et al (2007)

EUV Spectroscopy: SOHO / SUMER



SUMER on the SOHO spacecraft



EUV-Spectrograph **SUMER**

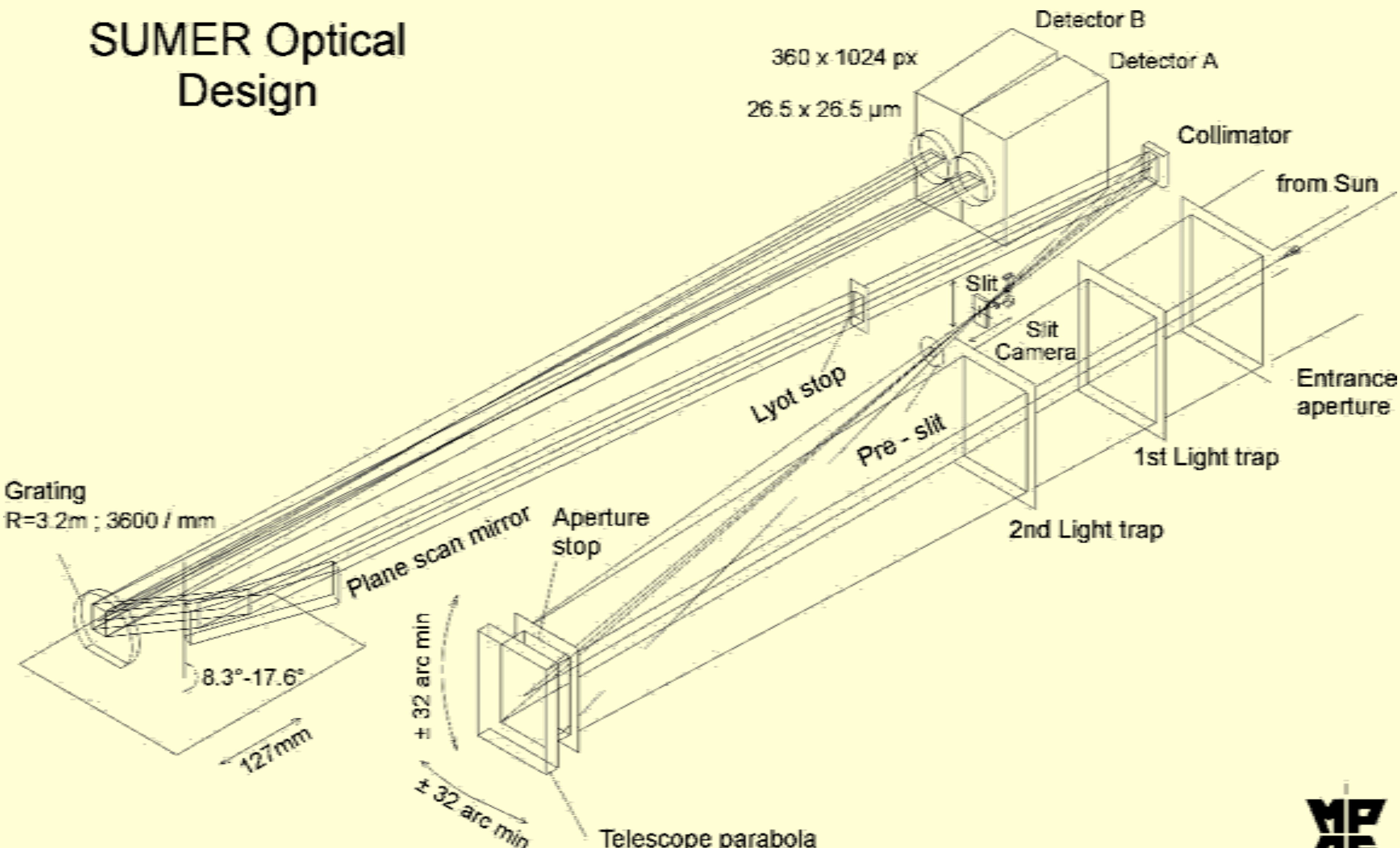
Solar Ultraviolet Measurements of Emitted Radiation

spatial resolution: 2” (1” pixel) (1500 km)
spectral resolution: $\lambda/\Delta\lambda \approx$ 30 000
wavelength range: 50 – 155 nm

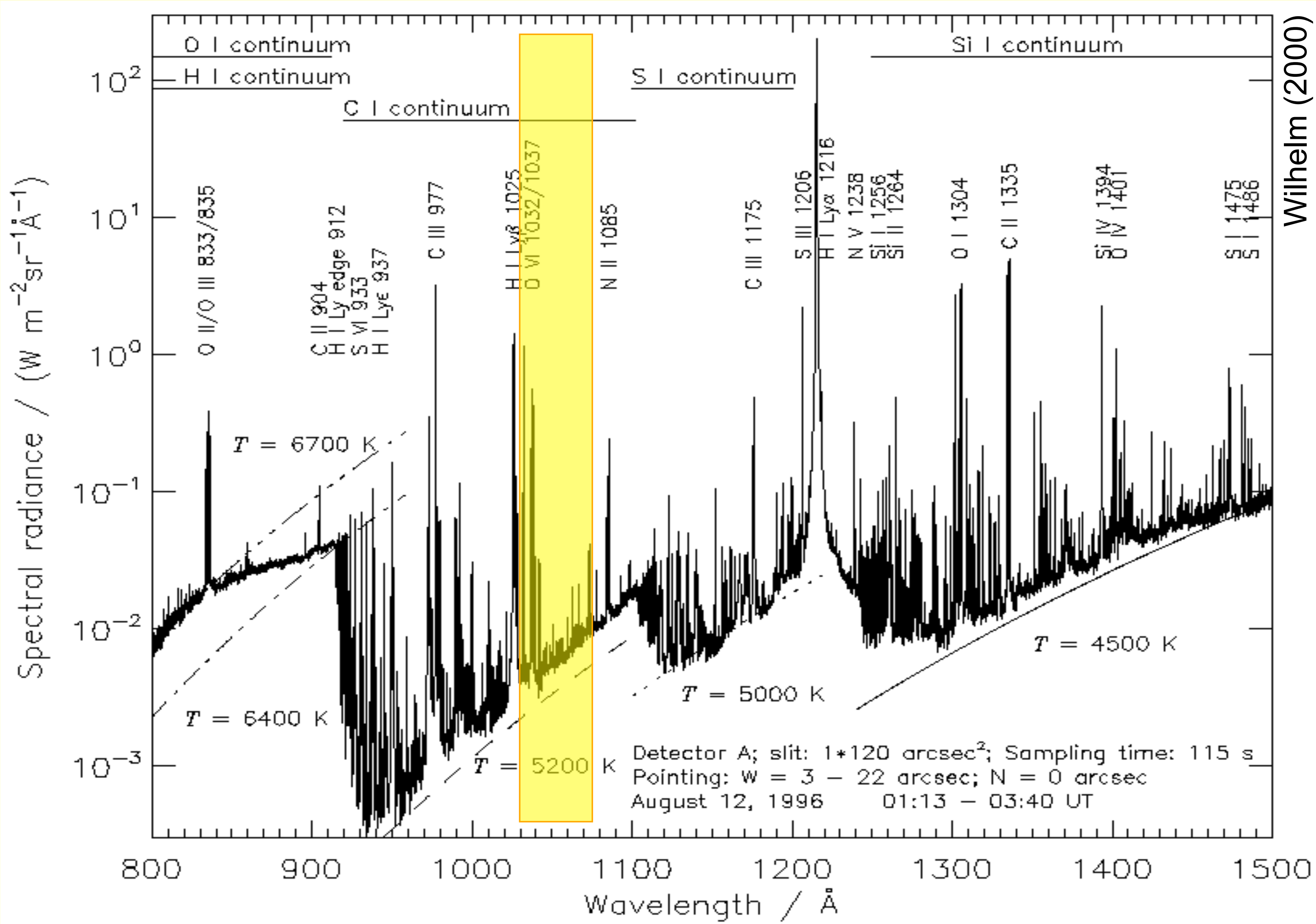
covering temperatures on the Sun: 5000 – 10^7 K

- dynamics and structure of the transition region from the chromosphere to the corona
- **accuracy for Doppler shifts: ~ 2 km/s**

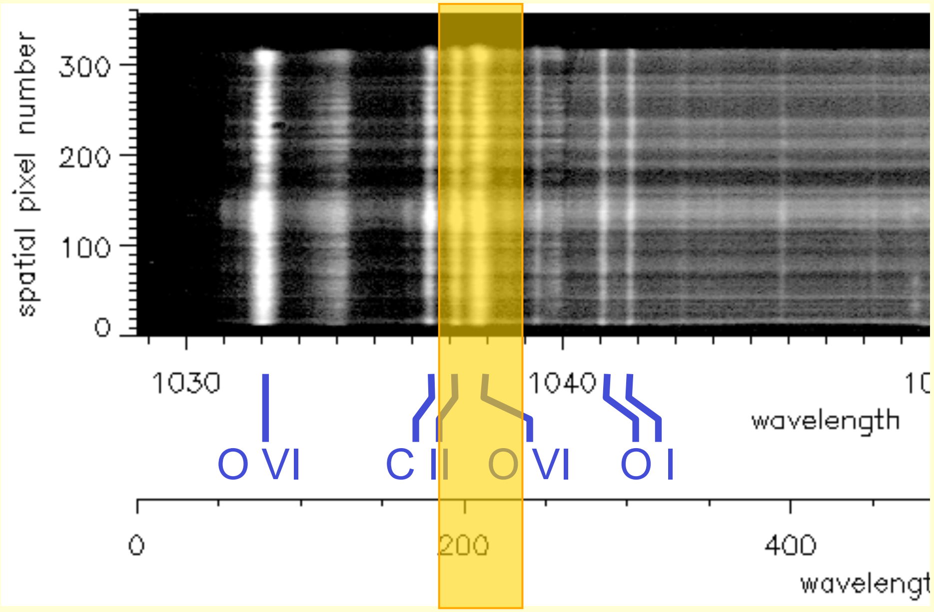
SUMER optical design

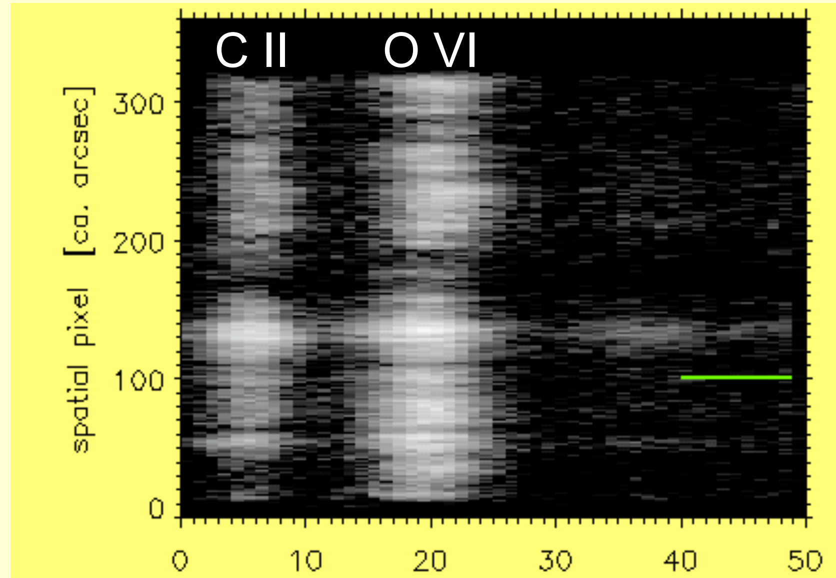


SUMER: spectral range (1st order)



Full spectral frame and spectral windows





full frame:
1024 spectral pixels ≈ 44 Å (1st order)

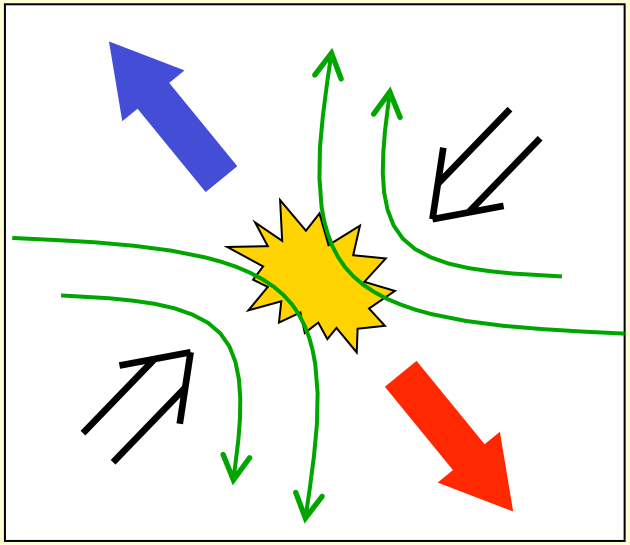
spectral window:
often 50 spectr. pxl ≈ 2 Å (1st order)
(or 25, 512, …)

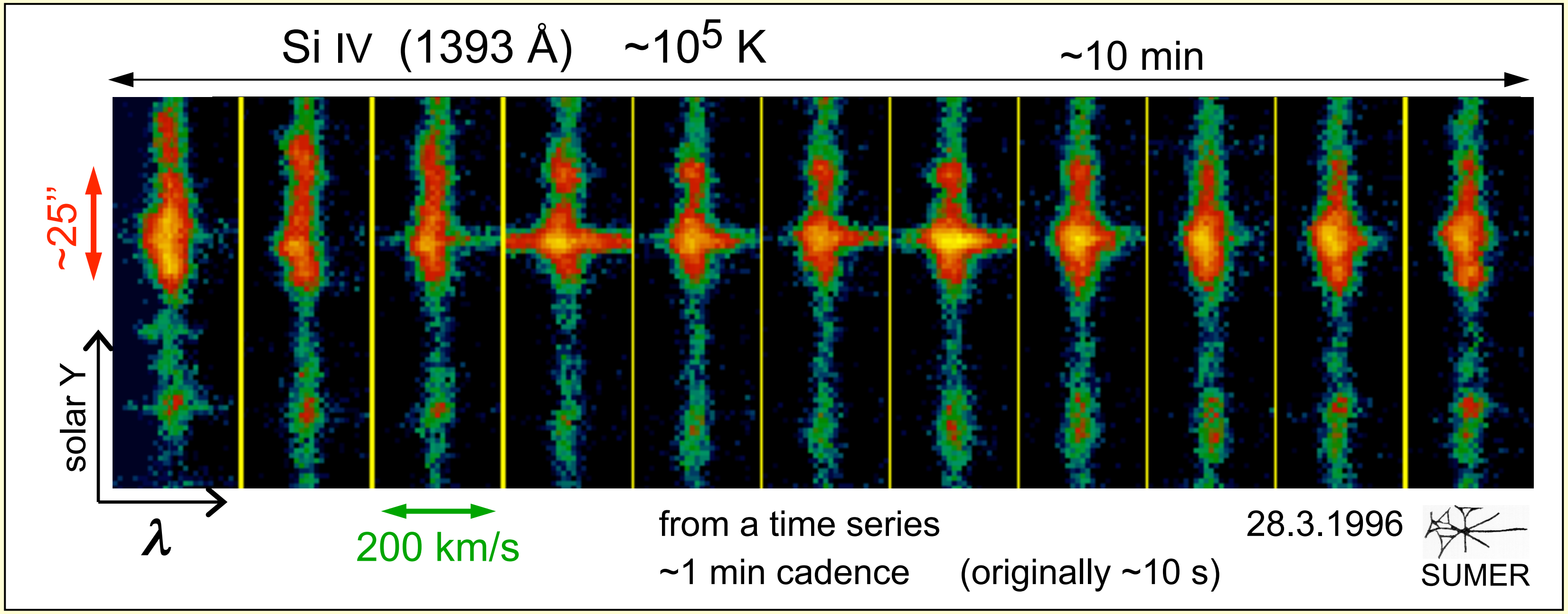
Problem:
sometimes windows not wide enough
(telemetry…)

→ ***Images by raster procedure***

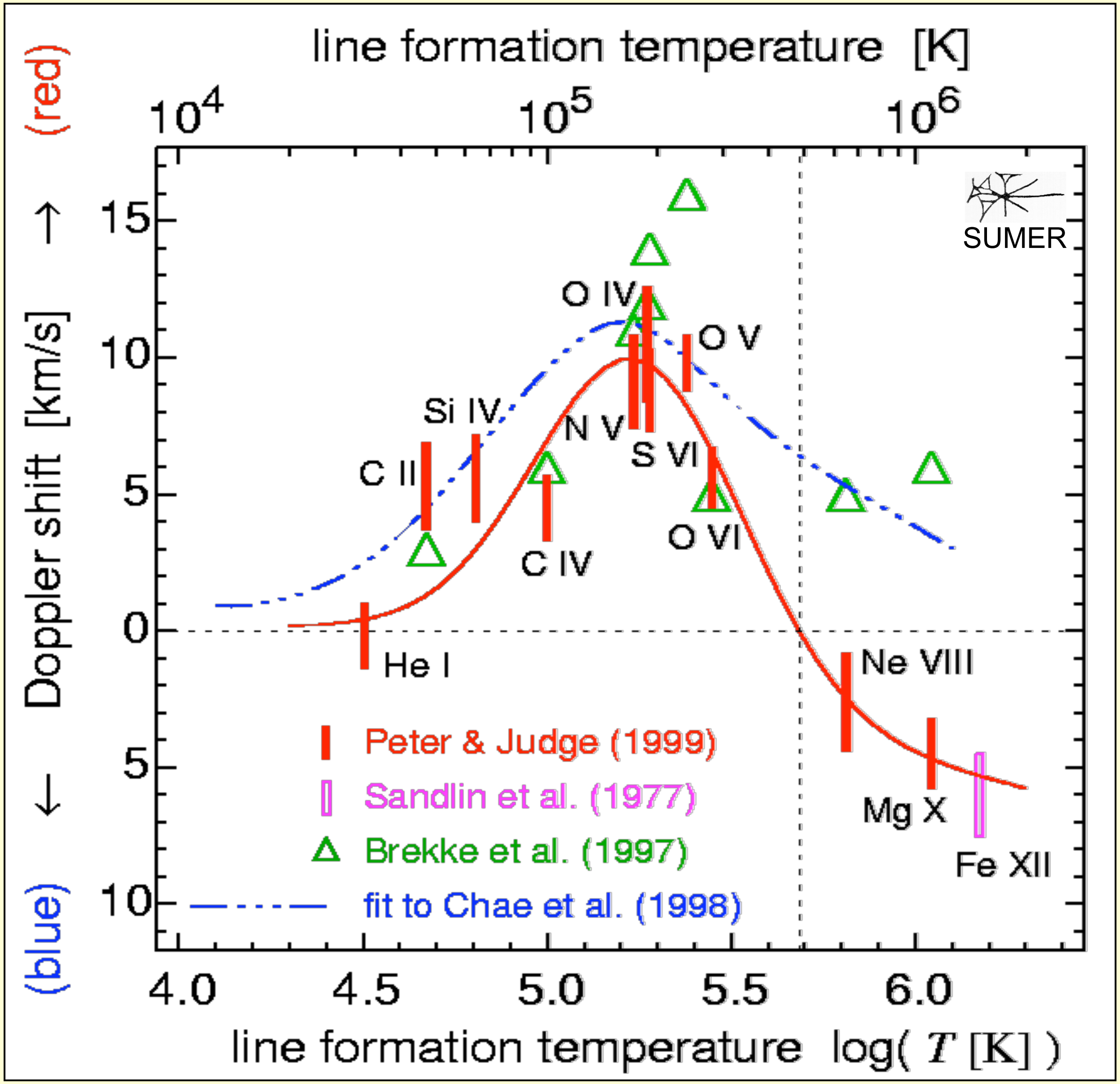
Coronal heating and TR explosive events

- transient broadening of TR emission lines
  sometimes distinct emission peaks visible
  (e.g. Dere et al.,1989, Sol. Phys. 123, 41)
- interpreted as bi-directional jets after reconnection
  (e.g. Innes et al., 1997, Nat. 386, 811)
- explosive events are restricted to TR temperatures
- are they related to the dissipation of energy in the 3D MHD flux-braiding coronal models?





Doppler shifts in the low corona & TR

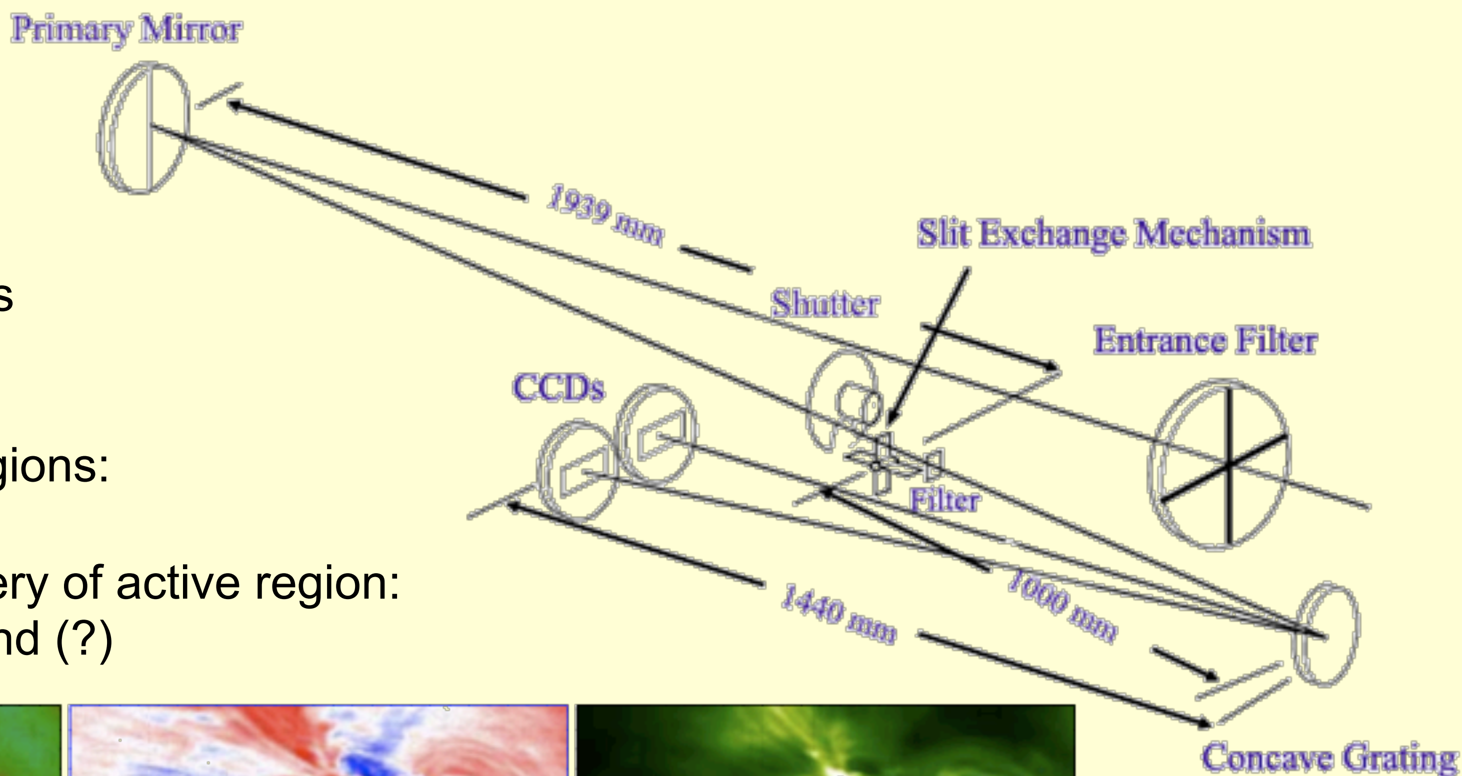


Peter & Judge (1999) ApJ 522, 1148

mean quiet Sun Doppler shifts at disk center

- net redshift in transition region
- net blueshift in corona
- in active region similar but with higher amplitude
- also found with solar-like stars

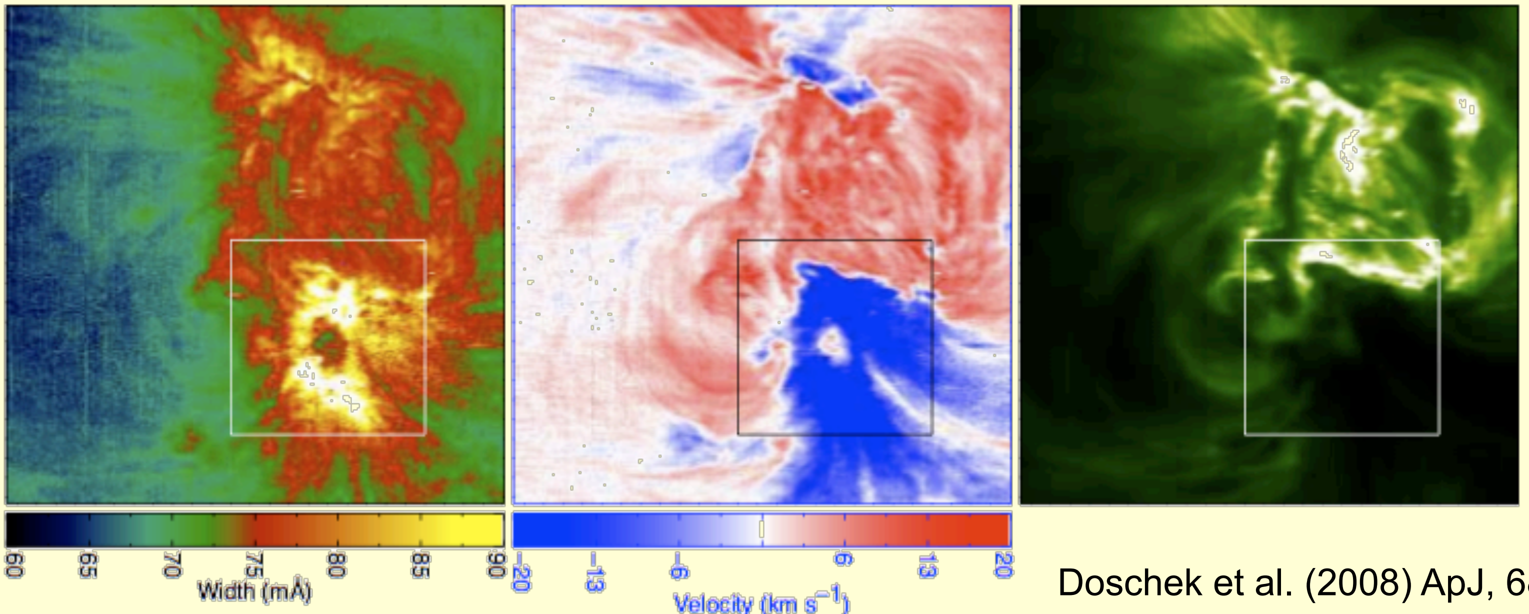
Hinode/EIS: coronal spectroscopy



Better diagnostics
at high temperatures

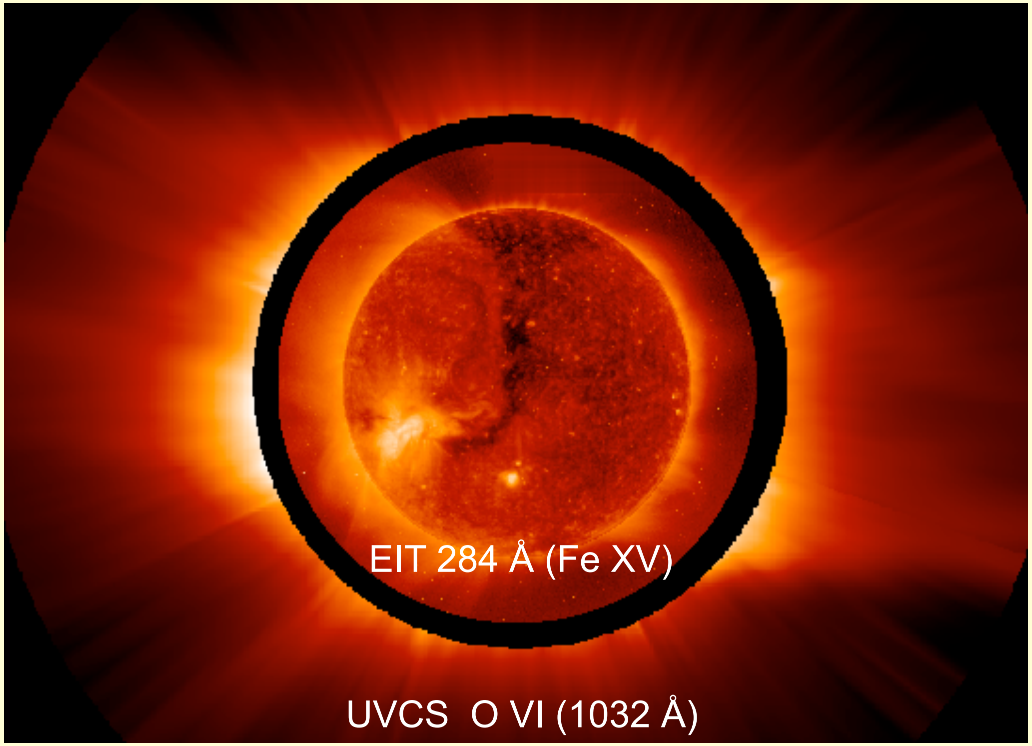
investigations
of flows in active regions:

outflow from periphery of active region:
feeding the solar wind (?)



Doschek et al. (2008) ApJ, 686, 1362

Coronagraphic spectroscopy: SOHO / UVCS



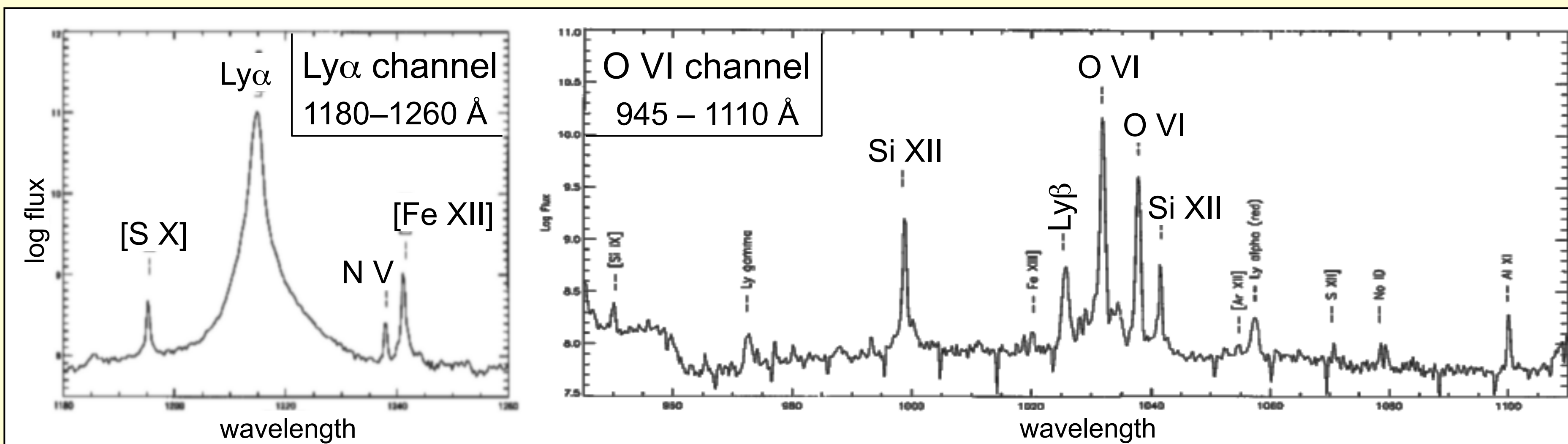
(Ultra-Violet Coronagraphic Spectrograph)

UVCS combines:

- coronagraph and an
- EUV spectrograph

➡ spectroscopic analysis:

- line widths / temperatures
- outflow through Doppler dimming
- hints on abundances



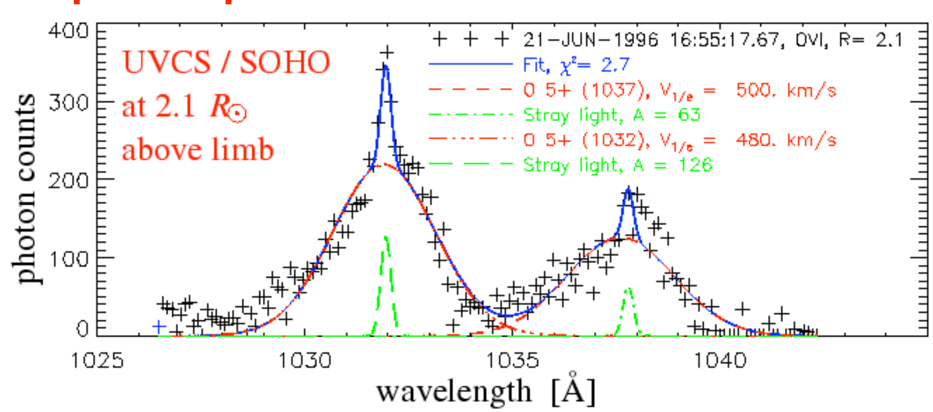
Ion-cyclotron heating in the outer corona

UVCS / SOHO

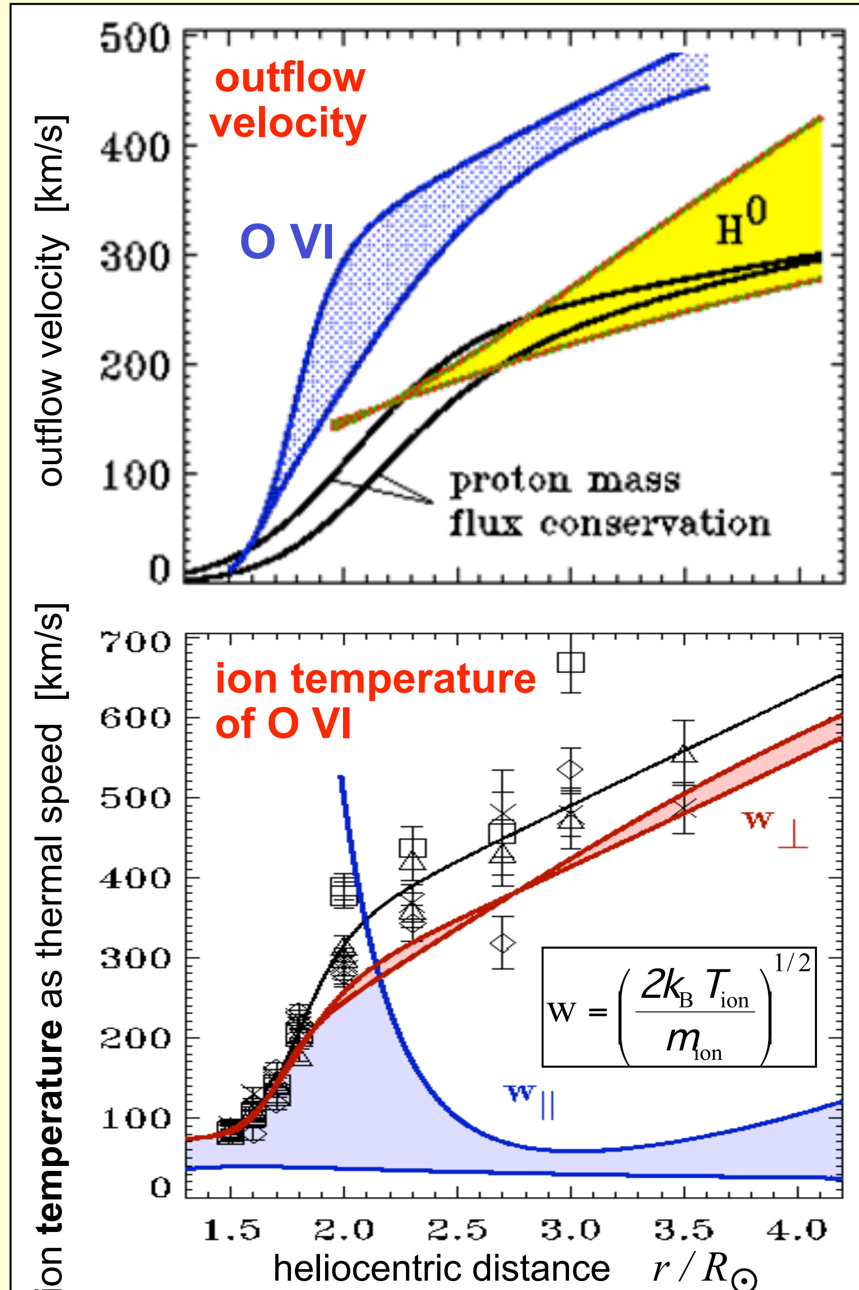
- very broad line profiles in outer corona
  e.g. 500 km/s = 500·10^6 K in O VI !!
- Doppler-dimming analysis:
  — rapid acceleration
  — high ion perpendicular temperatures
  $T_\perp >> T_\parallel$

➡ *consistent with ion-cyclotron heating*

spectral profile of O VI at 1032 and 1037 Å



Kohl et al (1998) ApJ 501, L127



Cranmer et al. (1998) ApJ 511,481

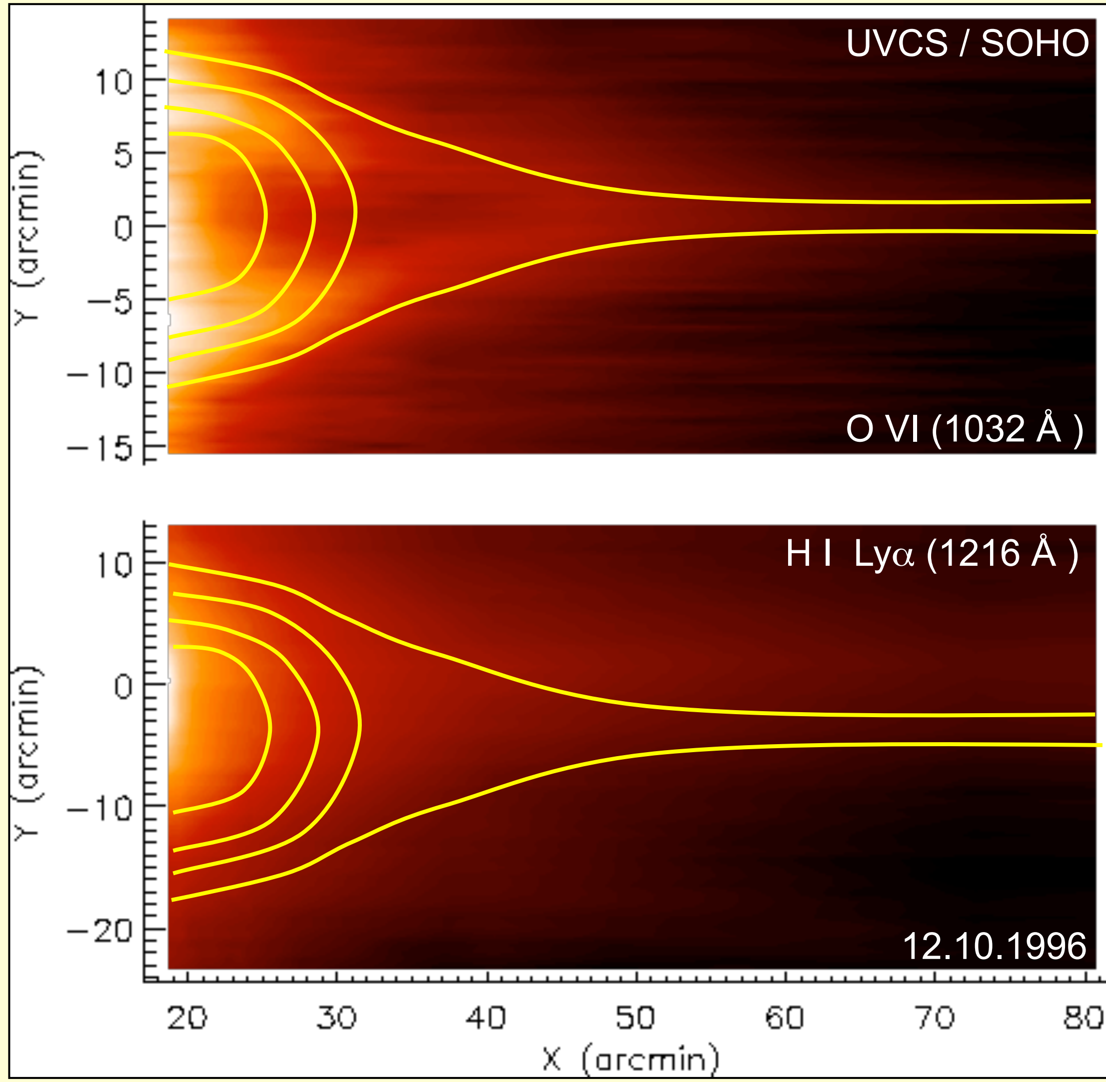
Abundances and solar wind origin

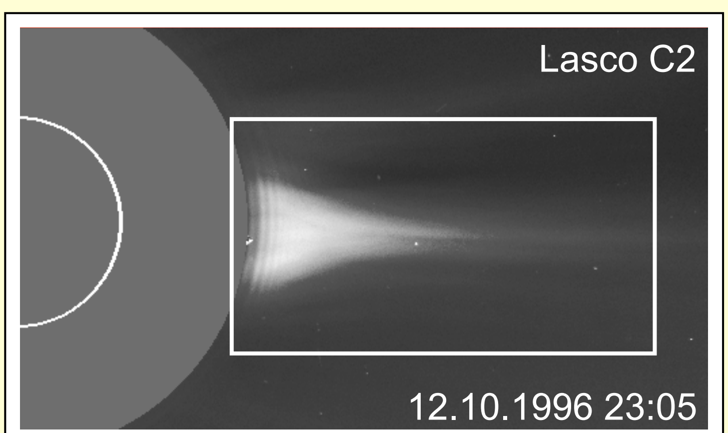
helmet streamer

- dark cavity in O VI :
  - ➡ gravitational settling of oxygen / heavy elements ?
- steamer legs show abundances of slow solar wind [SUMER] (FIP-effect)

scenario:

- wind is leaving through legs
- inner part is static





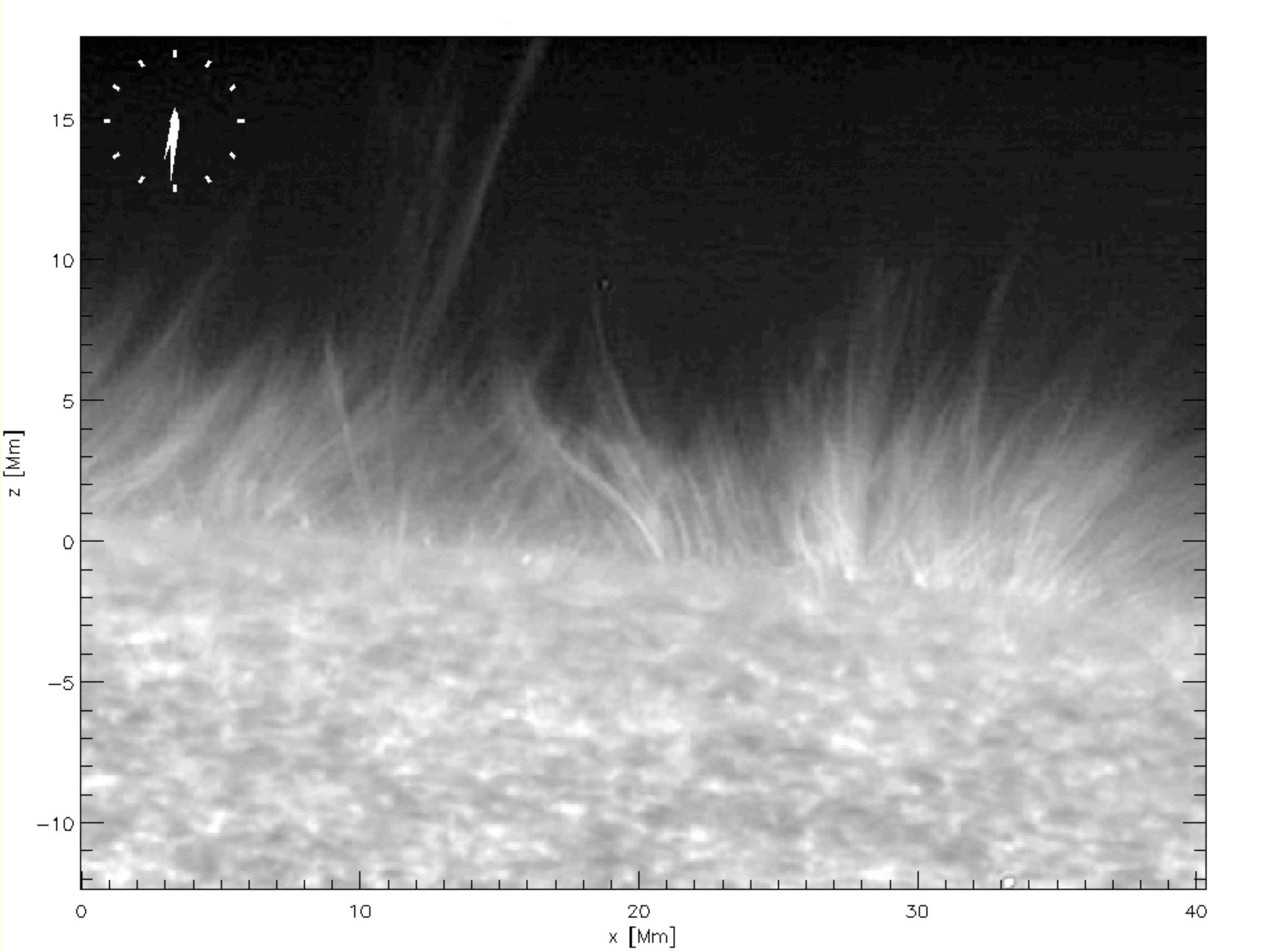
white light corona (K corona)

emission lines in the corona

Raymond et al. (1997) Solar Phys. 175, 645

Hinode/SOT: cool material feeding (?) corona

Ca II K



M. Carlsson (2007)

Solar Dynamics Observatory (SDO)

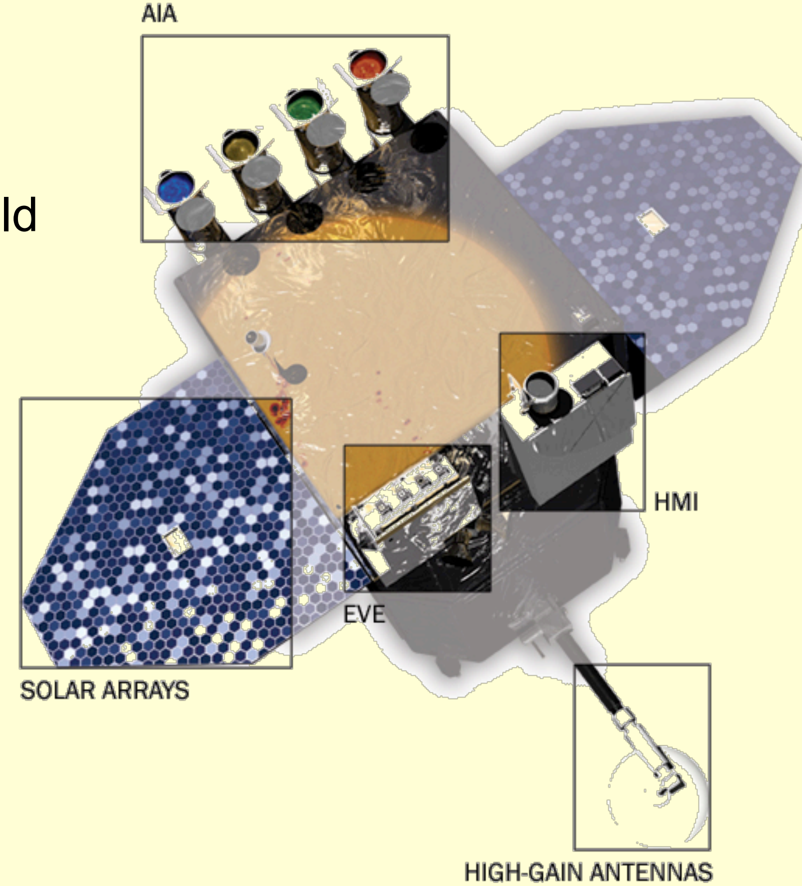
full disk imagers (4k x 4k detektors) for
with high cadence (up to 2 sec) over full solar cycle

► **HMI**: visible light: intensity & vector magnetic field

► **AIA**: EUV in 8 bands covering 10 000 K – 3 MK

spectral radiance observation:

► **EVE**: from EUV to IR



Main scientific goals for the SDO mission:

► Driving of solar magnetic activity cycle

► Evolution of magnetic flux on surface

► role of reconnection for large-scale fields, coronal heting and wind acceleration

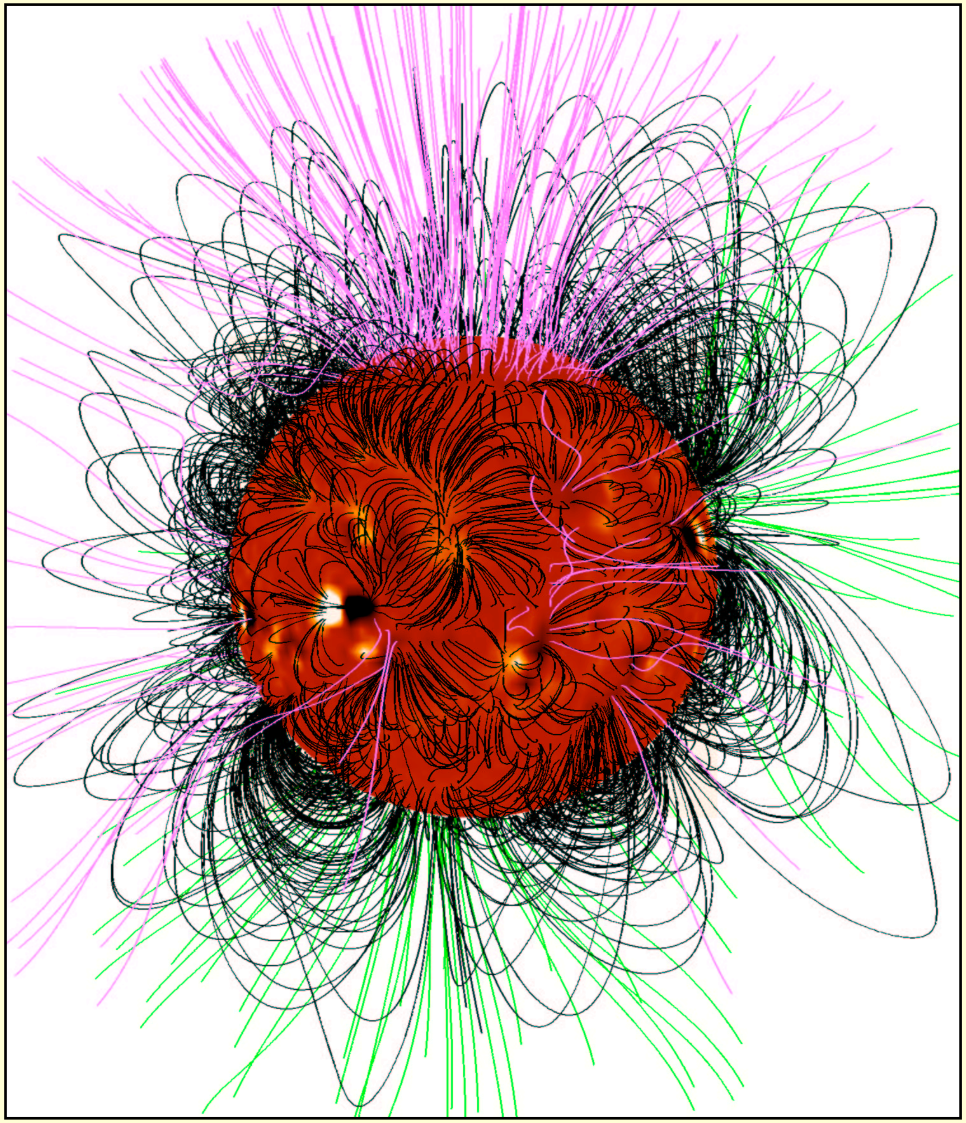
► EUV variability and relation to magnetic cycle

► initiation of CMEs, flares anf filament eruption and their role for energetic particles

► relation of heliospheric magnetic field to solar surface

► forecast of solar activity, space weather and climate

Coronal magnetic fields



Schrijver & DeRosa (2003) Solar Phys. 212, 165

Magnetic field extrapolations do a pretty good job…

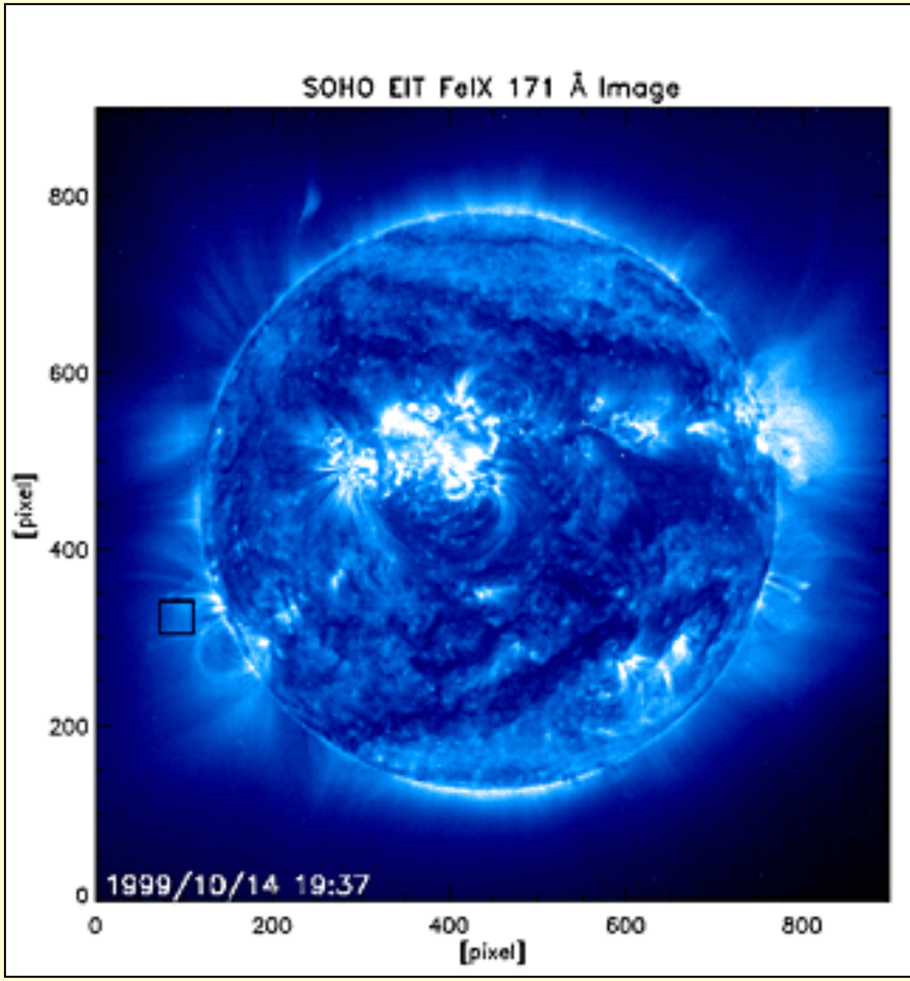
BUT:

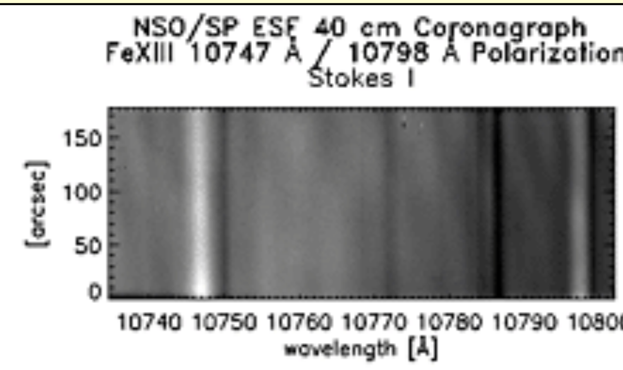
- *B* is not potential or (nonlinear) force free everywhere!
- extrapolations assume a static magnetic field structure
- dynamic evolution of *B* during transient events
- we have to know what *B* really is

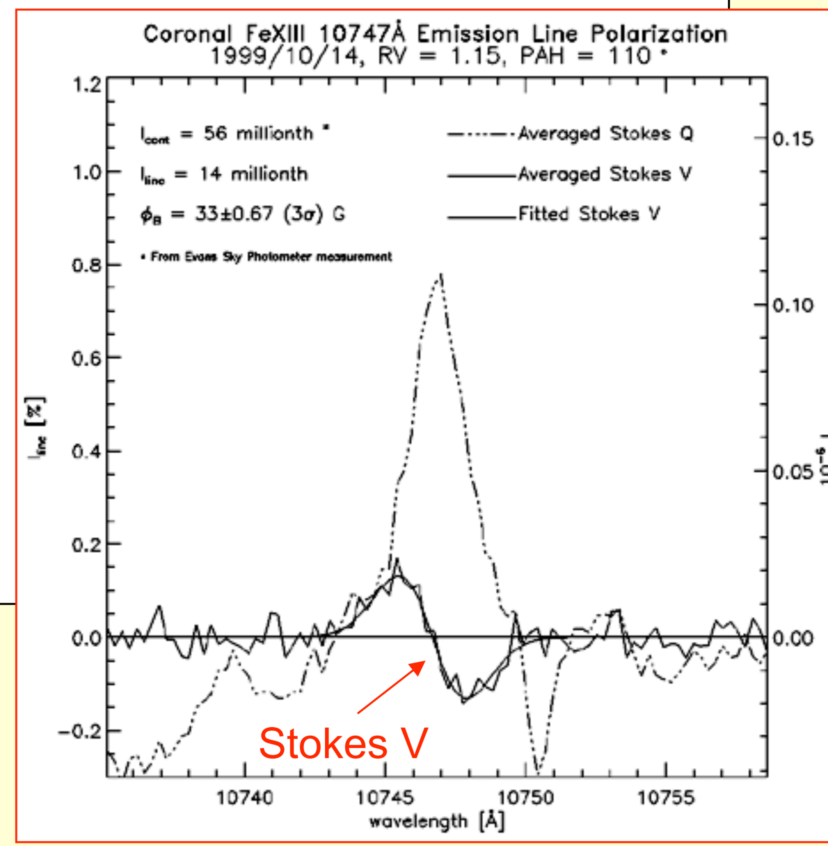
➡ Need for direct measurements of coronal magnetic fields

Direct coronagraphic observations

Haosheng Lin et al. (1999)



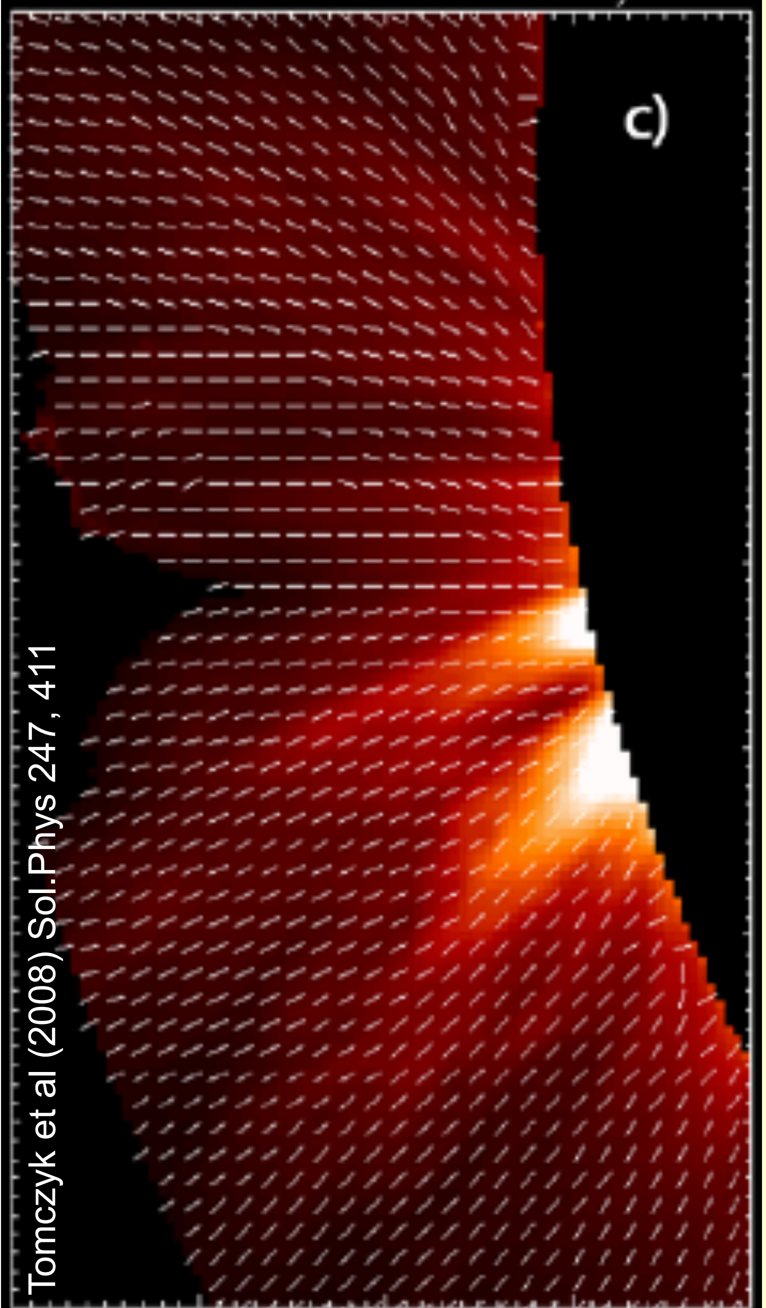




NSO / Sac Peak Evans Solar Facility (ESF)
40 cm coronagraph + IR spectropolarimeter:
first detection of coronal Stokes V signal: 14.10.99

Problem: ➡ B only where bright structures…
➡ 3D structure of coronal field?!

Coronal IR spectropolarimetry



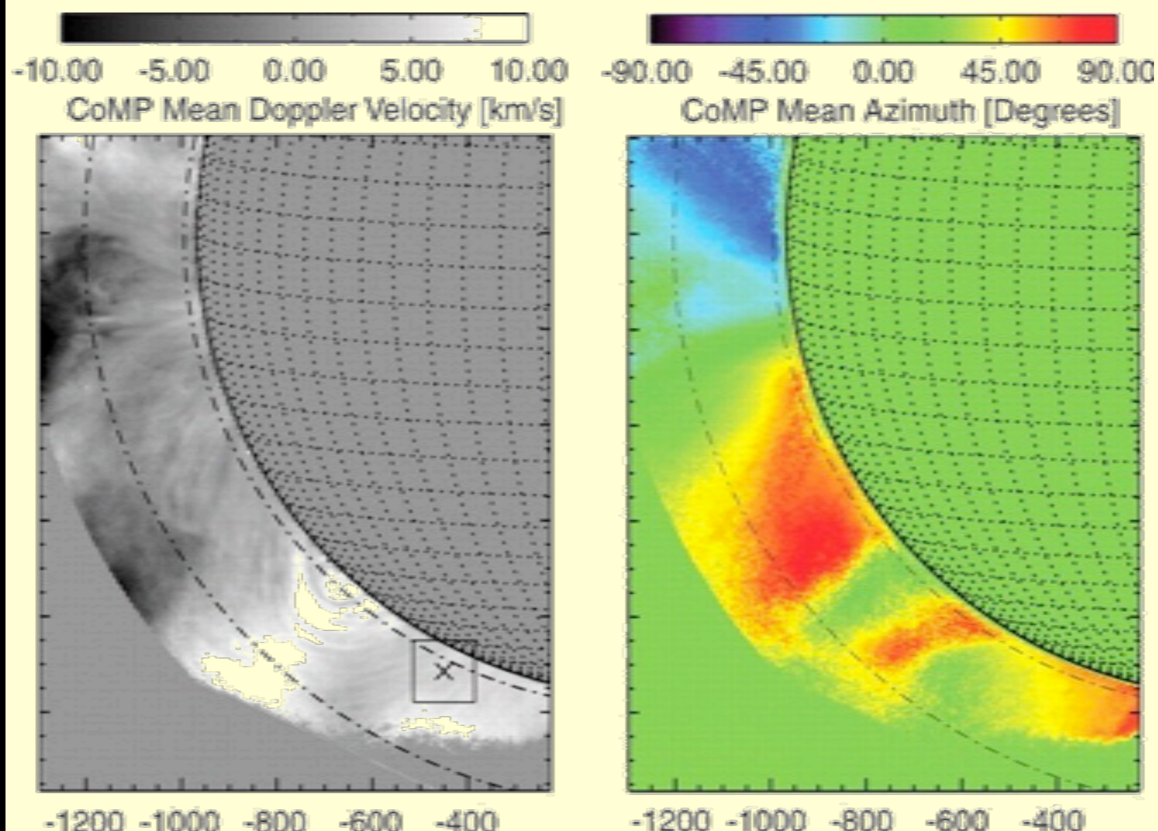
20 cm aperture coronagraph at SacPeak

with Coronal Multichannel Polarimeter, CoMP (HAO)

corona: Fe XIII (10747 Å & 10798 Å)

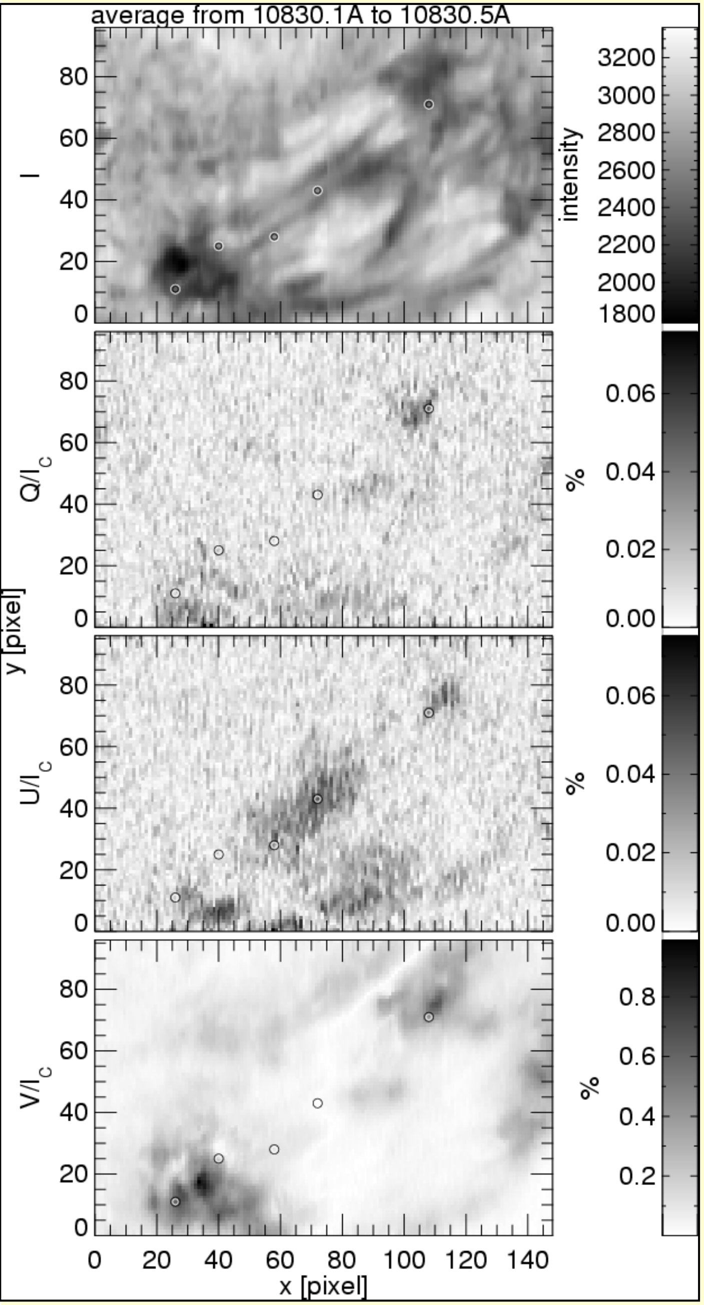
chromosphere: He I (10830 Å)

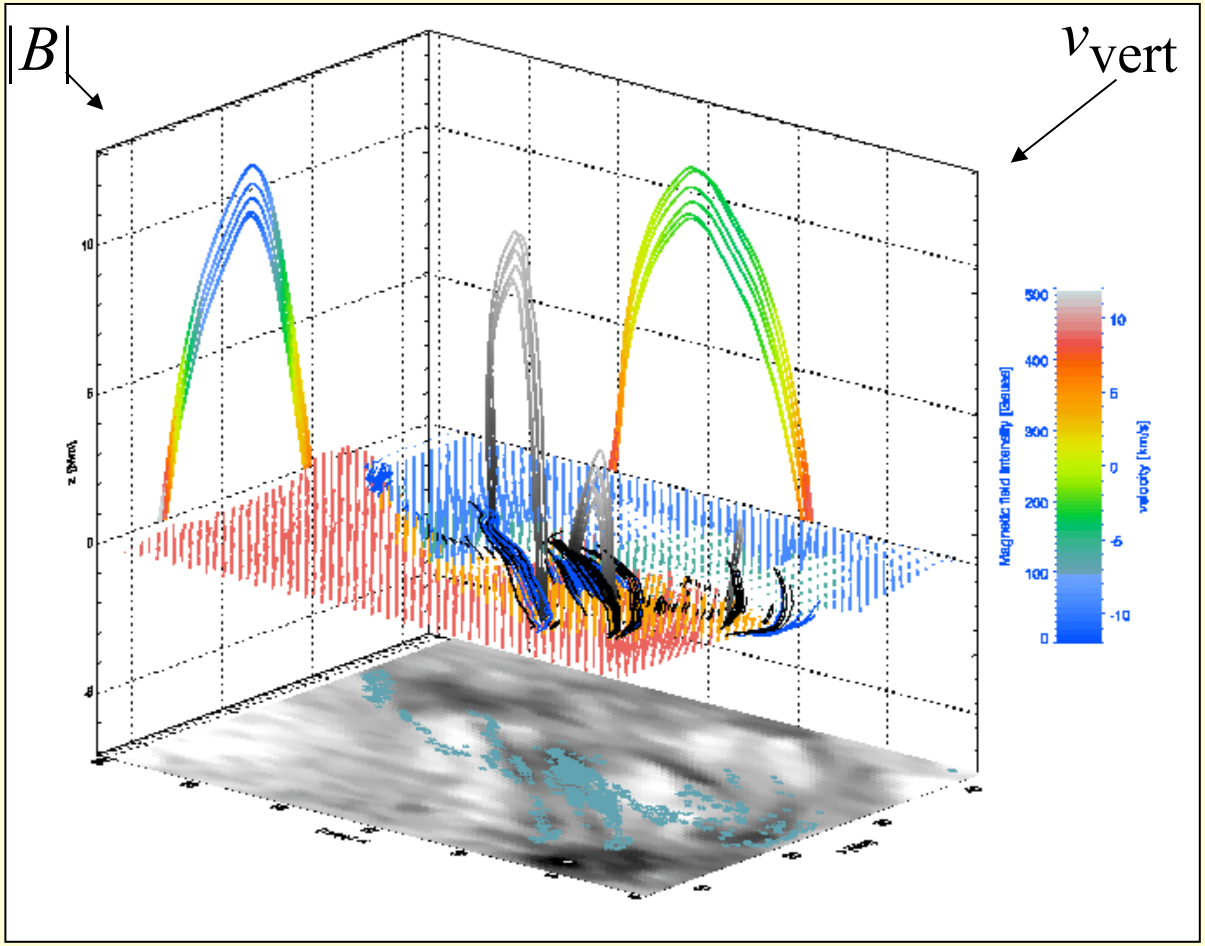
► measures full stokes Vector → reconstruction of *B*



Tomczyk et al (2007) Sci 317,1192

3D magnetic fields of emerging flux





magnetic loop is emerging through photosphere carrying cool material seen in He I (10830 Å)

- polarimetric inversion (data from TIP / VTT / Tenerife)
- 3D B reconstruction assuming cool material is on loop

Lagg et al (2004), A&A 414,1109; Solanki et al. (2003) Nat 425, 692

Summary / lessons learnt

- **the corona dominates the emission in X-rays, EUV and radio**
- soft X-rays (Yohkoh, Hinode/XRT)
  - hot coronal emission > 3 MK
  - flares, quiescent hot coronal loops
- EUV imaging (TRACE, EIT/SOHO, SDO)
  - evolution of 1–2 MK corona
  - corona is very dynamic and fine structured
- coronagraphic imaging (Lasco/SOHO, HAO/Mauna Loa)
  - coronal mass ejections
  - onset of solar wind
- EUV spectroscopy (SUMER, CDS/SOHO, Hinode/EIS)
  - dynamics – from average line shifts to explosive events
  - temperatures, densities, abundances
- coronagraphic spectroscopy (UVCS/SOHO)
  - solar wind acceleration and heating
  - solar wind origin
- coronal magnetic fields (VTT/Tenerife, SacPeak ESF)
  - this is the REAL challenge
  - some information from coronagraphic or IR observations