Solar spectral irradiance and wind over time scales up to a decade

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Heliophysics Summer School 2013

Topics

- Solar Spectral Irradiance:
  - Atmospheric structure
    - Static atmosphere
    - Waves
    - Magnetic field
      - Photosphere
      - Corona
      - Chromosphere
  - Gradual changes: solar cycle
  - Impulsive changes: flares/eruptions
  - Integration: solar spectral irradiance
- Solar Wind:
  - Background wind:
    - Basics of the solar wind
    - Multi-fluid effects
    - Magnetic field, and angular momentum loss
  - Impulsive/eruptive events and the solar wind
  - Integration: solar wind

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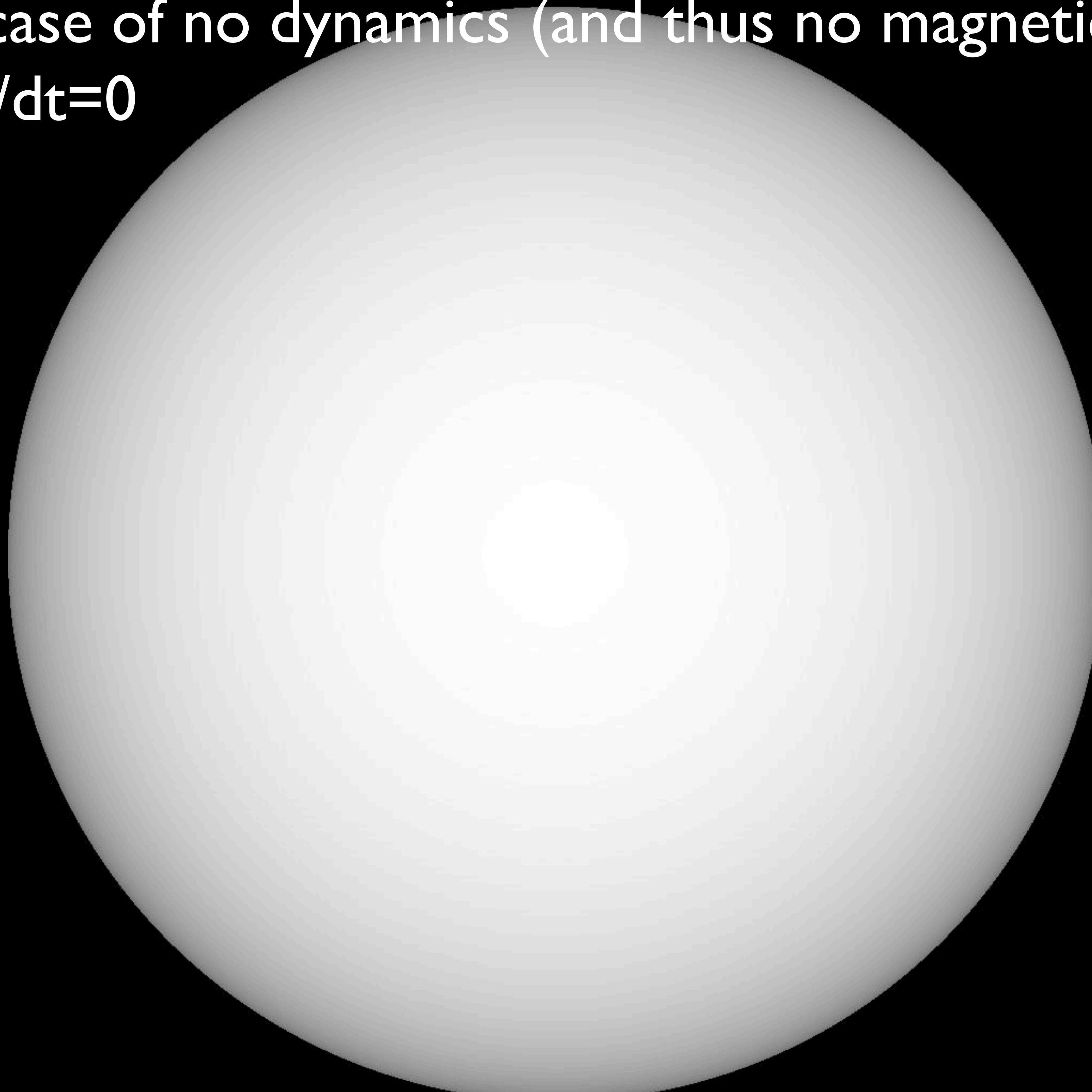
A hypothetical static “Sun”

- In case of no dynamics (and thus no magnetic field)
- dX/dt=0



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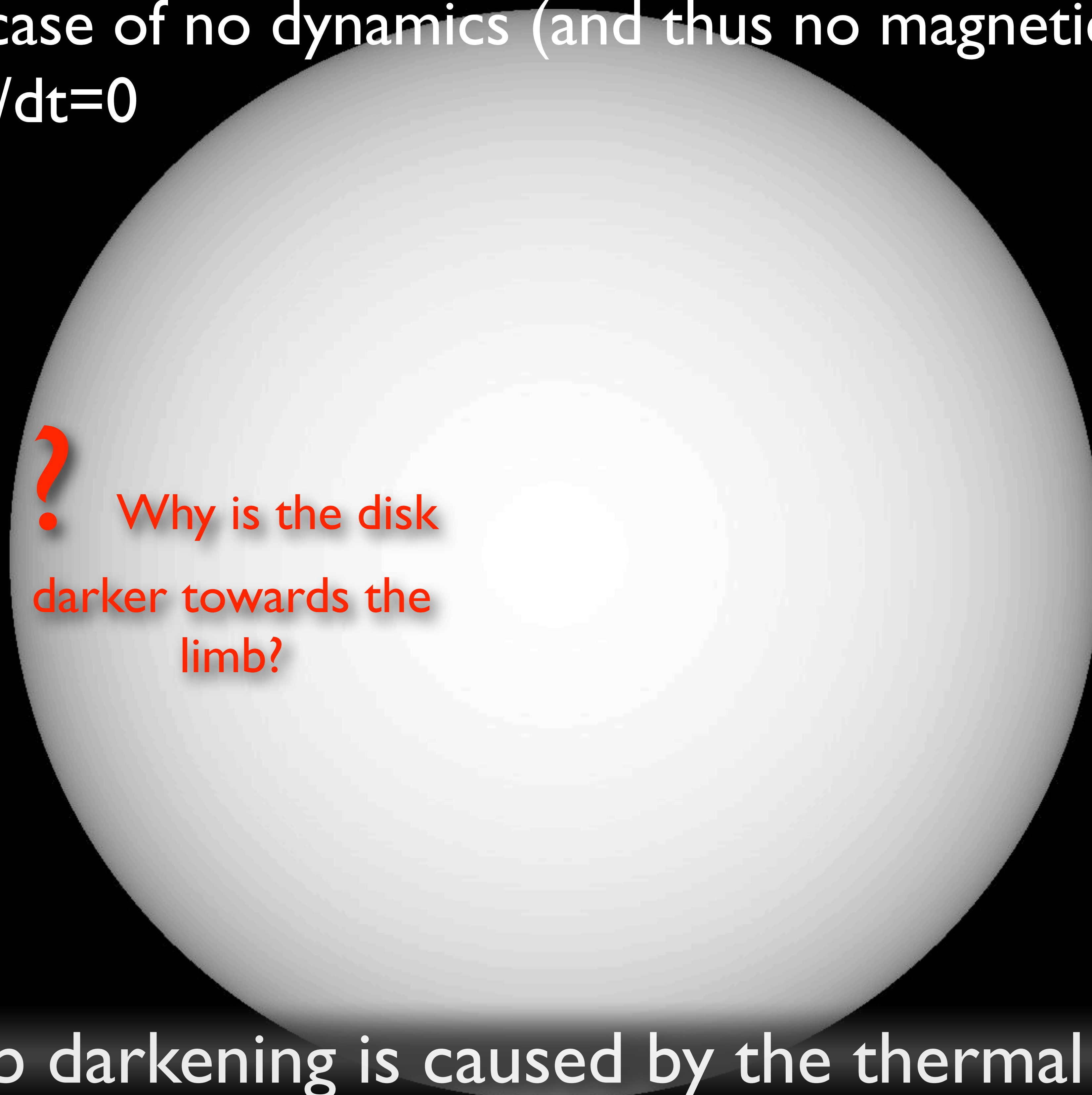

- Limb darkening is caused by the thermal gradient

A dynamic “Sun”

- Opacity unavoidably leads to (noisy) convection

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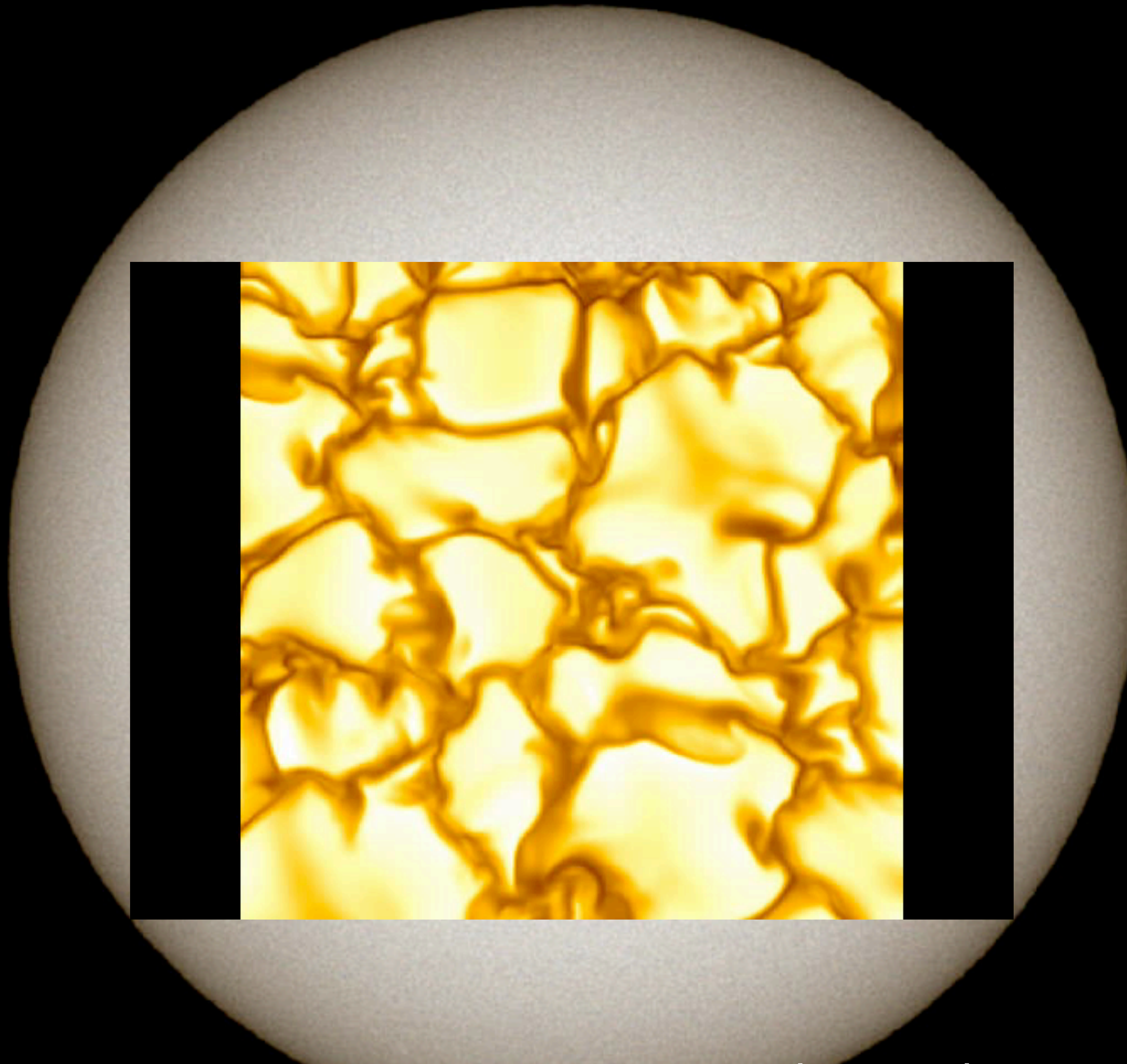

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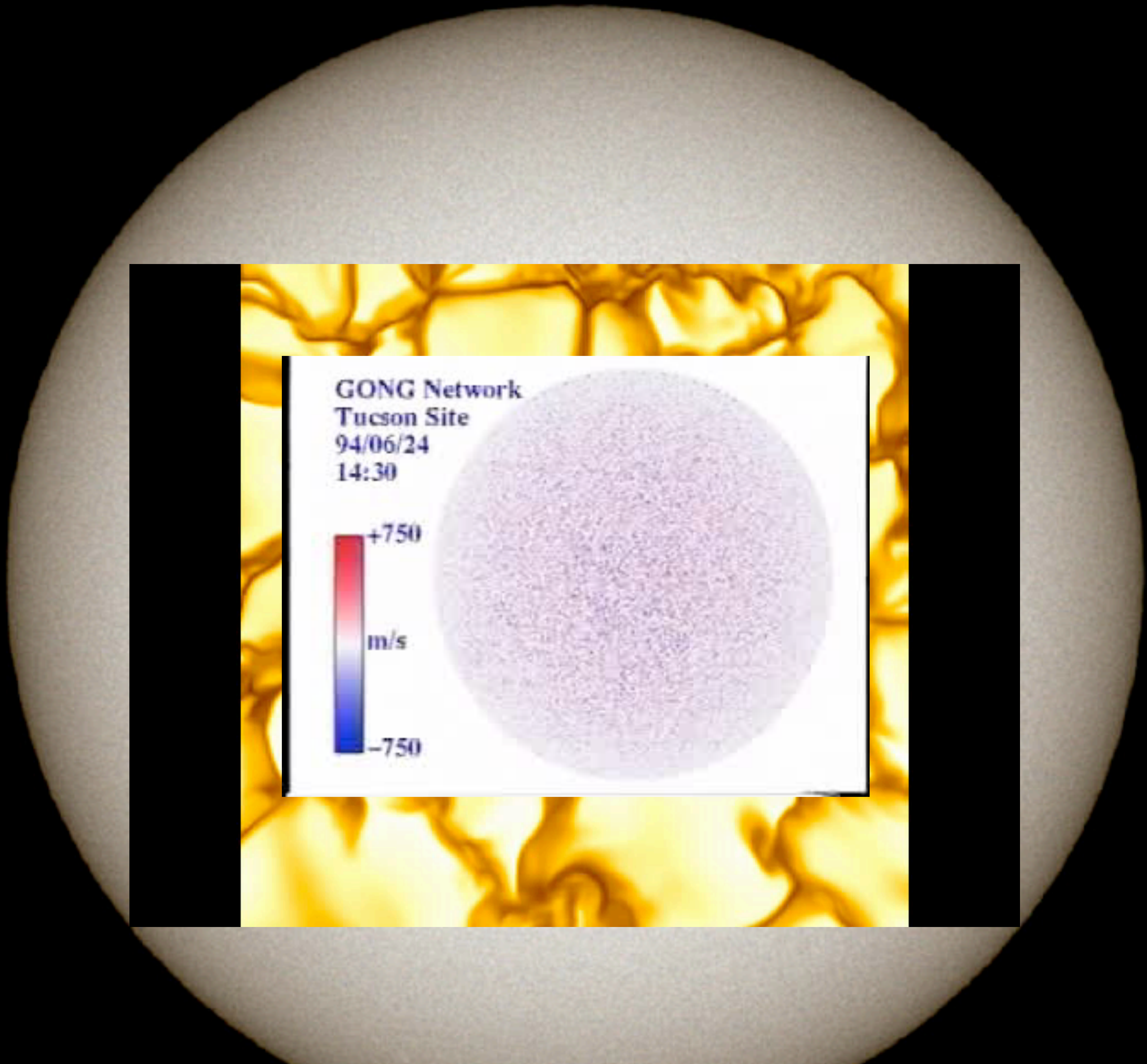

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Solar oscillations in TSI

total solar irradiance

- Full-disk signal:

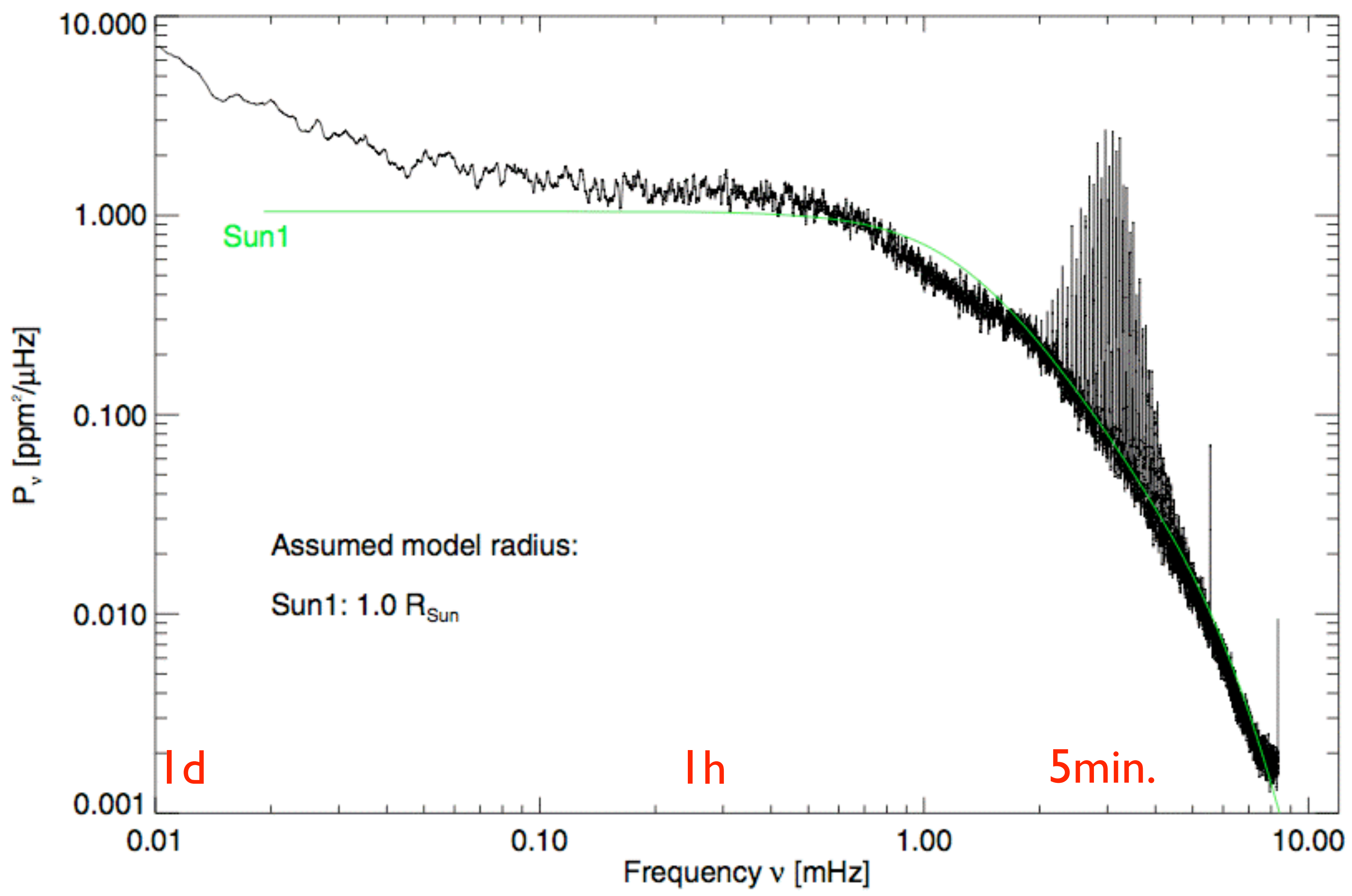

Fig. 2. Power spectra of disk-integrated photometric fluctuations for the Sun: the predicted background signal of model Sun1 (green/grey solid line) and observational data from SOHO/VIRGO (black solid line). Note the steep decline in power towards high frequencies.

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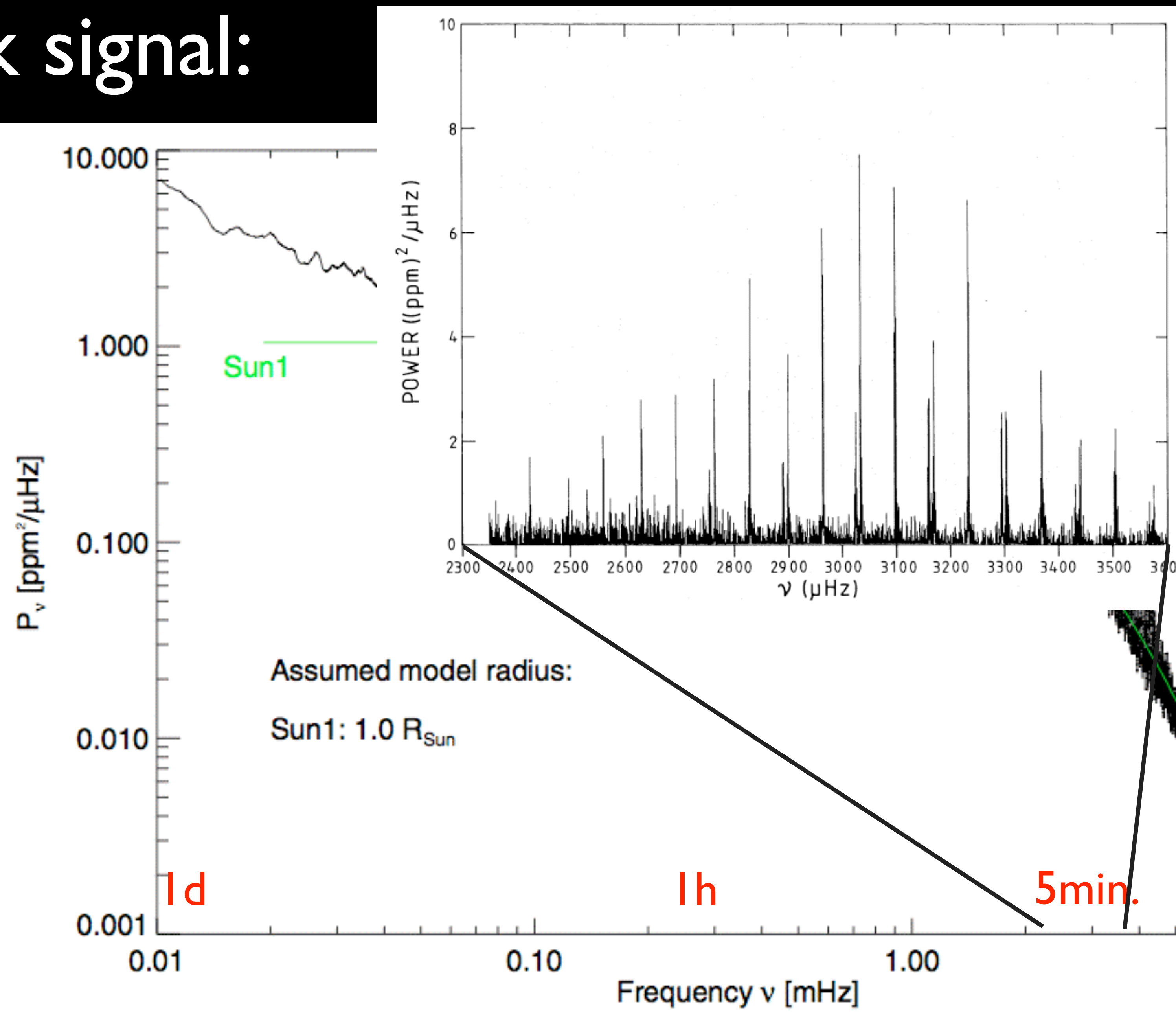

Fig. 2. Power spectrum (in ppm^2/μHz) of the IPHIR data for the entire 155-day interval. Shown is the average result for the red and green channels (weighting the red channel by a factor of 1.25 relative to the green – see Sect. 4.1). The FFT algorithm used 2^{19} points, oversampling by a factor of 1.7. The spectrum was smoothed over 4 points, and the average noise level was subtracted

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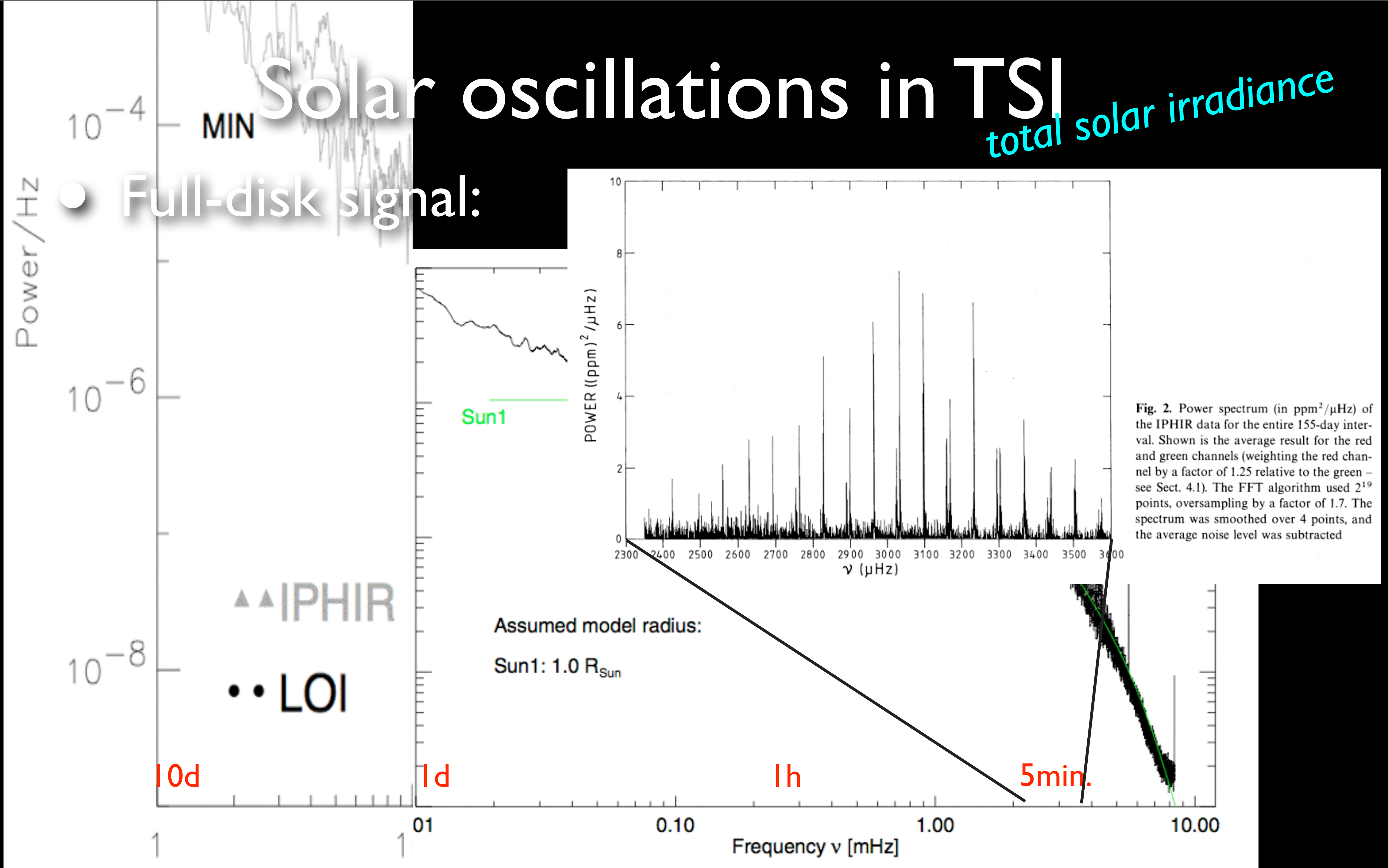

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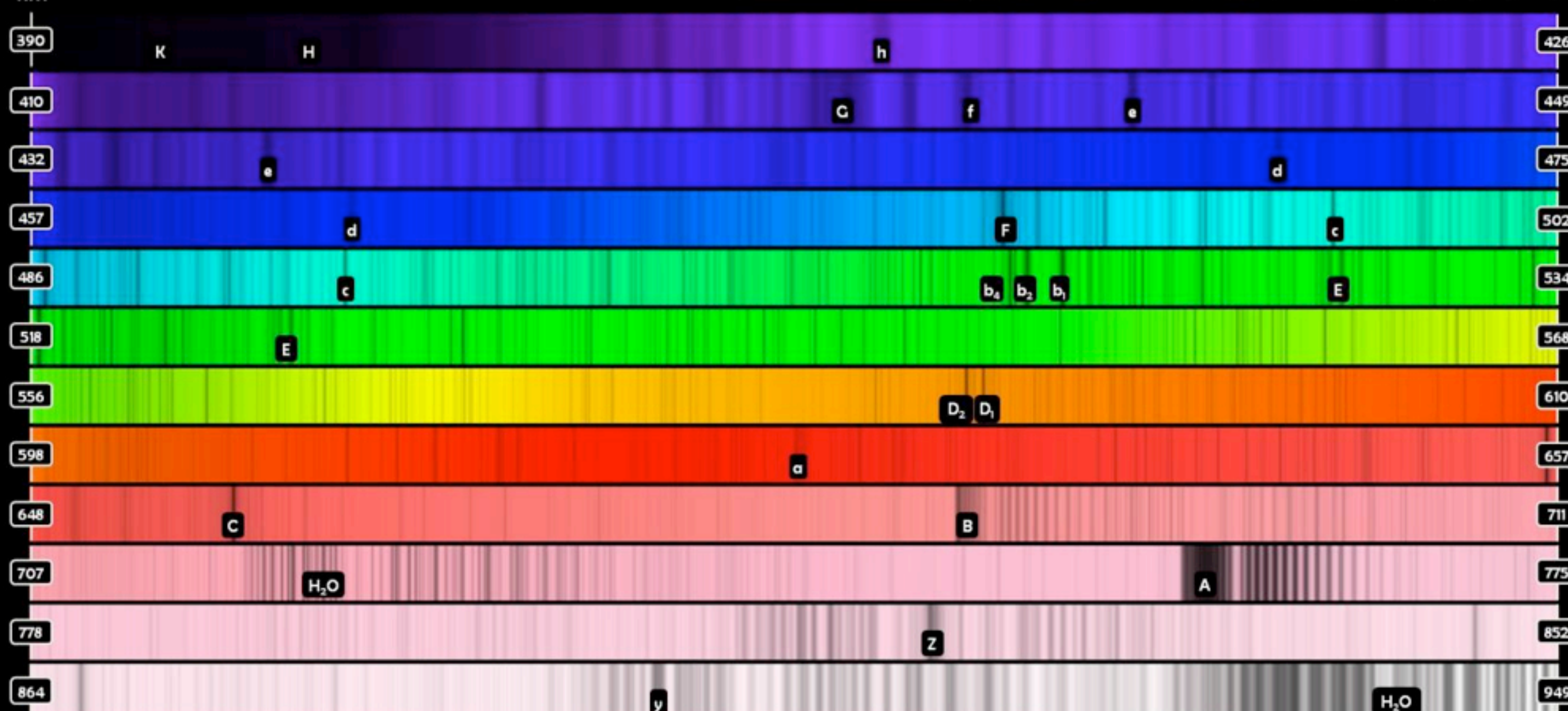
Visible/near-IR solar spectrum (SSI)

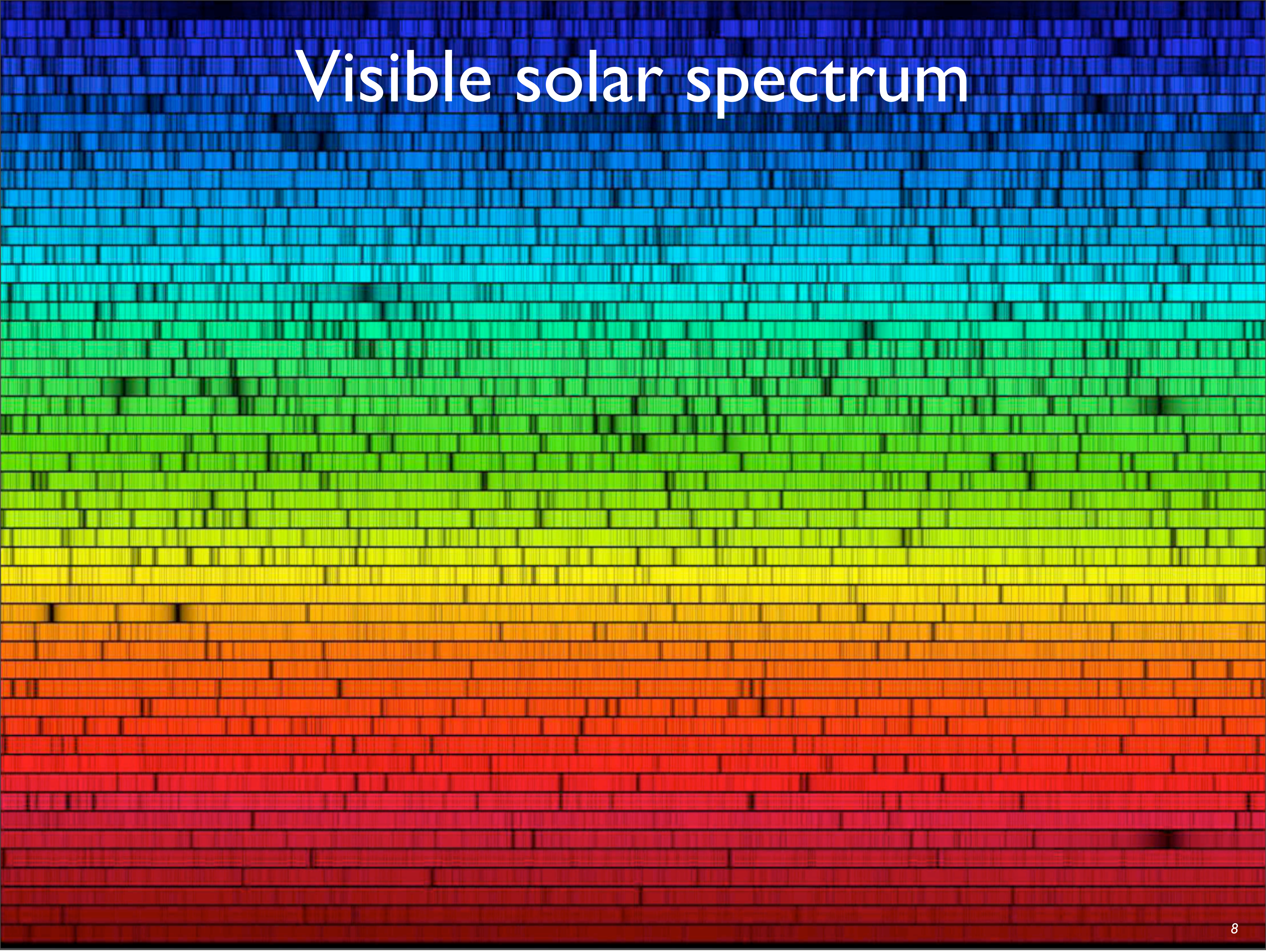
solar spectral irradiance

- To model irradiance of a non-magnetic Sun: include all dynamics, & radiative transfer
- To validate irradiance modeling: remove Earth-atmospheric effects.

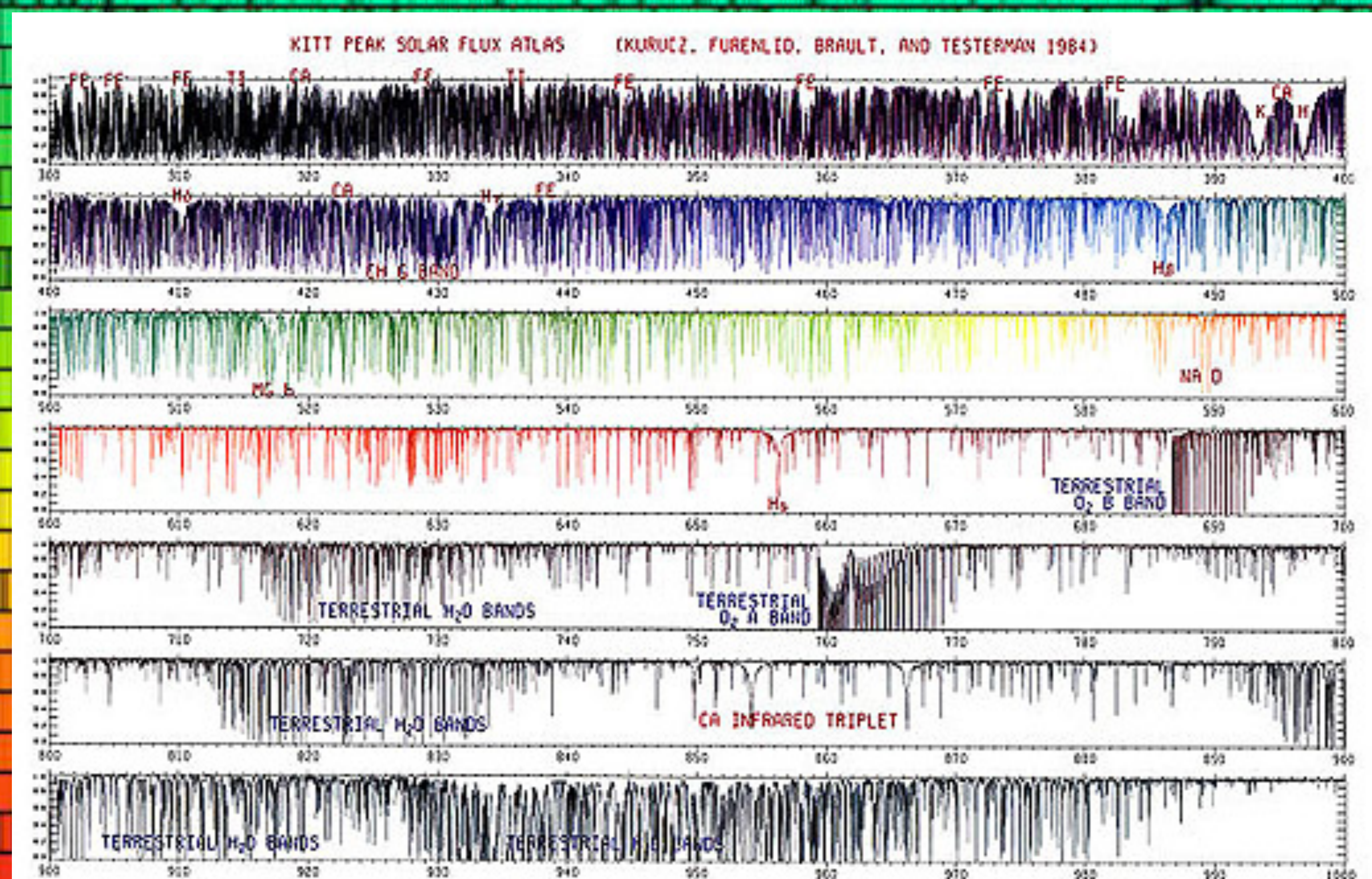


K	H	h	G	G	f	e	d	F	c	b_4	b_4	b_2	b_1	E	D_2	D_1	a	C	B		A	Z	y	
Ca+	Ca+	Hδ	Ca	Fe	H	Fe	Fe	Hβ	Fe	Mg	Fe	Mg	Mg	Fe	Na	Na	O_2	Hα	O_2	H_2O	O_2	O_2	O_2	H_2O
393.368	396.847	410.175	430.774	430.790	434.0	438.355	466.814	486.134	495.761	516.733	516.891	517.270	518.362	527.0	588.995	589.592	627.661	656.281	686.719	720.0	759.370	822.696	898.765	940.0

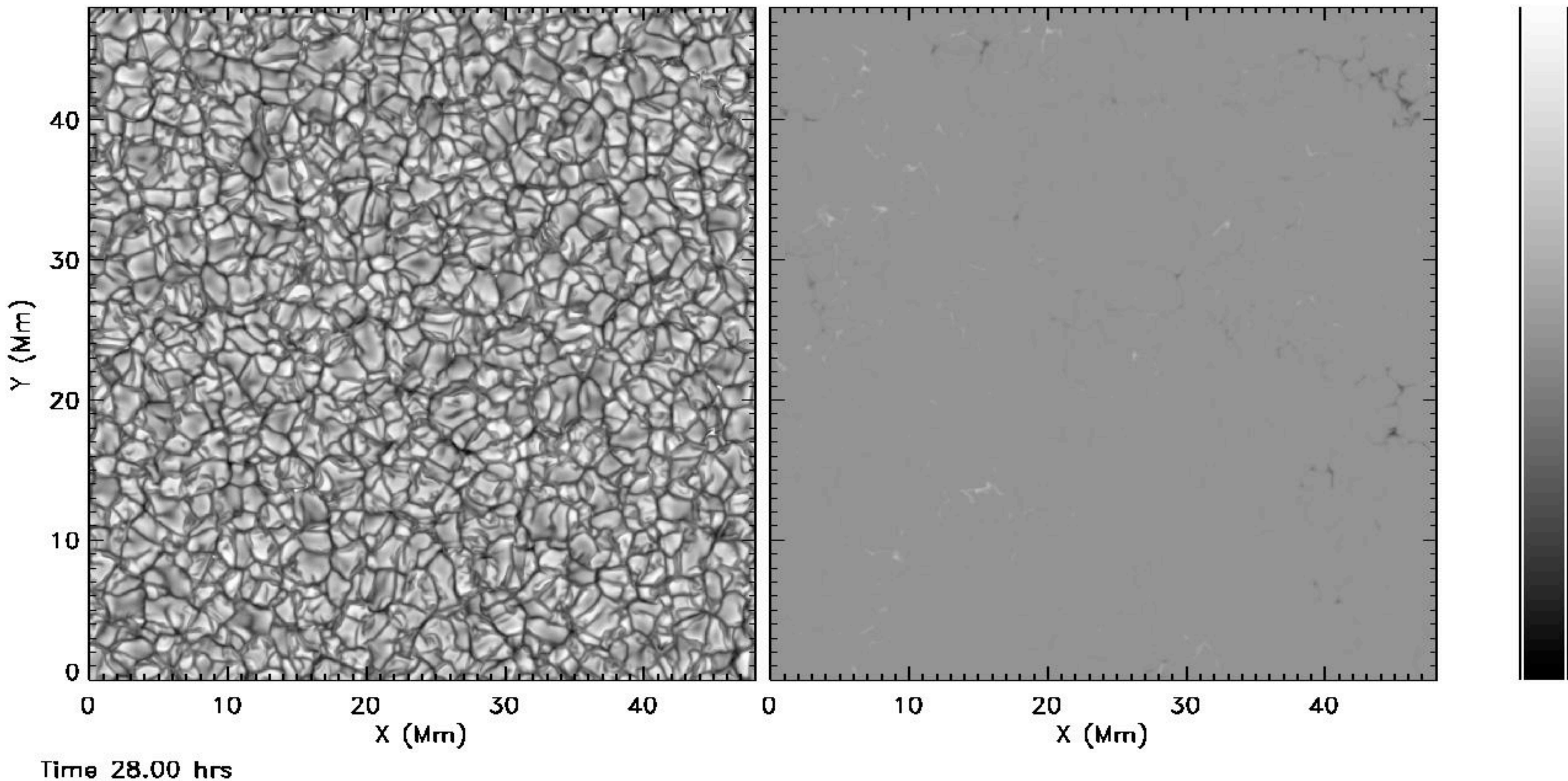
Visible solar spectrum



Visible solar spectrum



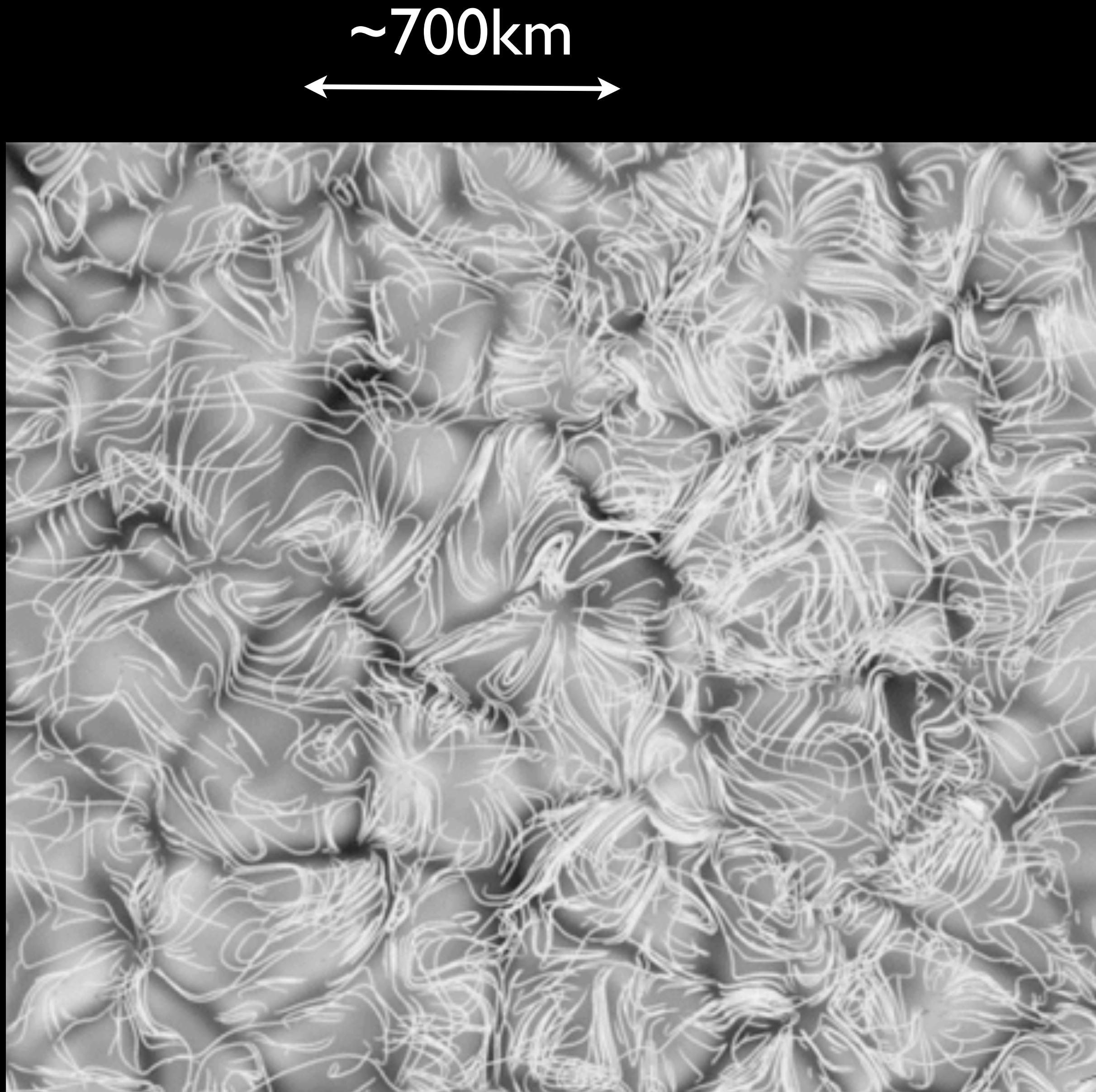
Simulated magnetoconvection

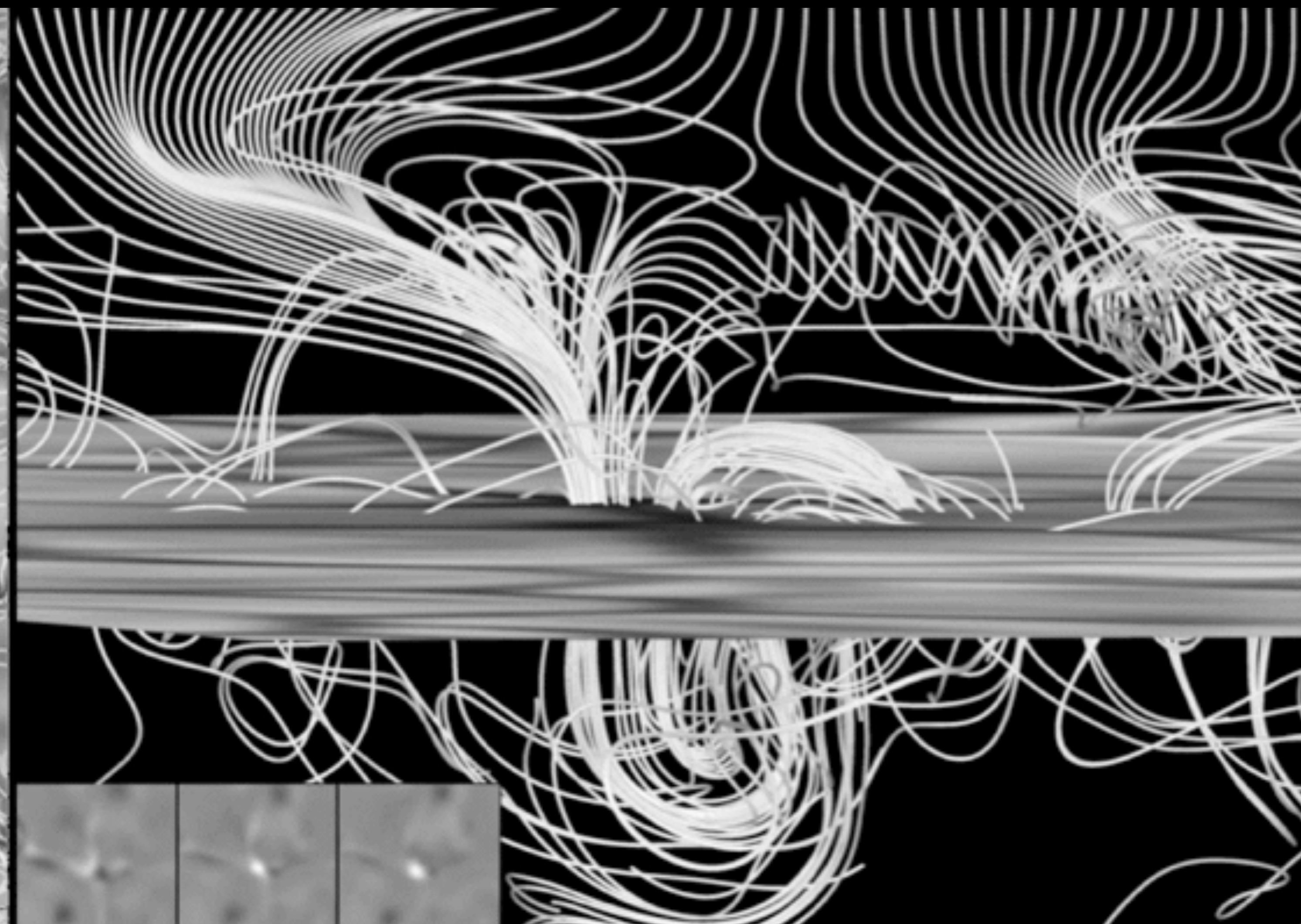


Movie: Emergent continuum intensity (left) and vertical magnetic field at (right) from simulation with initial/boundary condition of convective inflows advecting 1 kG uniform, untwisted, horizontal field into the computational domain at 20 Mm depth. The intensity range is and the magnetic field range is ± 3.5 kG. The pores may form spontaneously in vertical flux tubes from magnetic loops that have reached the surface and opened out through top boundary. Compare this with Figure 14 for the rise of a coherent twisted flux tube. (Movie shows the initial "pepper and salt" emergence, the horizontal advection of the field, its concentration into unipolar regions with cancellation where opposite polarities meet and merging of like polarities to form pores. Resolution was increased from 48 km to 24 km horizontally at time 51.7 hrs.)

From http://solarphysics.livingreviews.org/Articles/lrsp-2012-4/

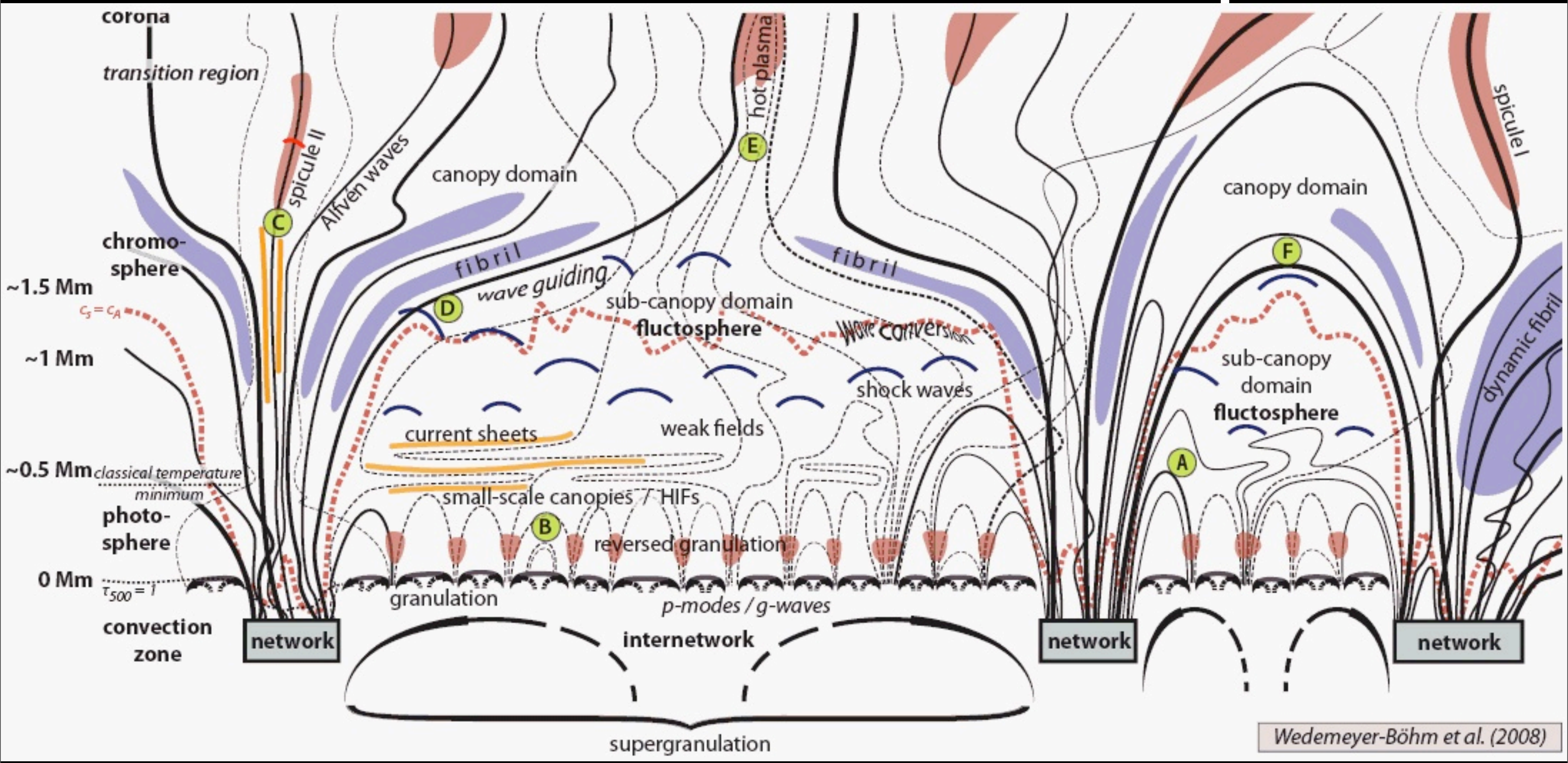
Pervasive magnetic field



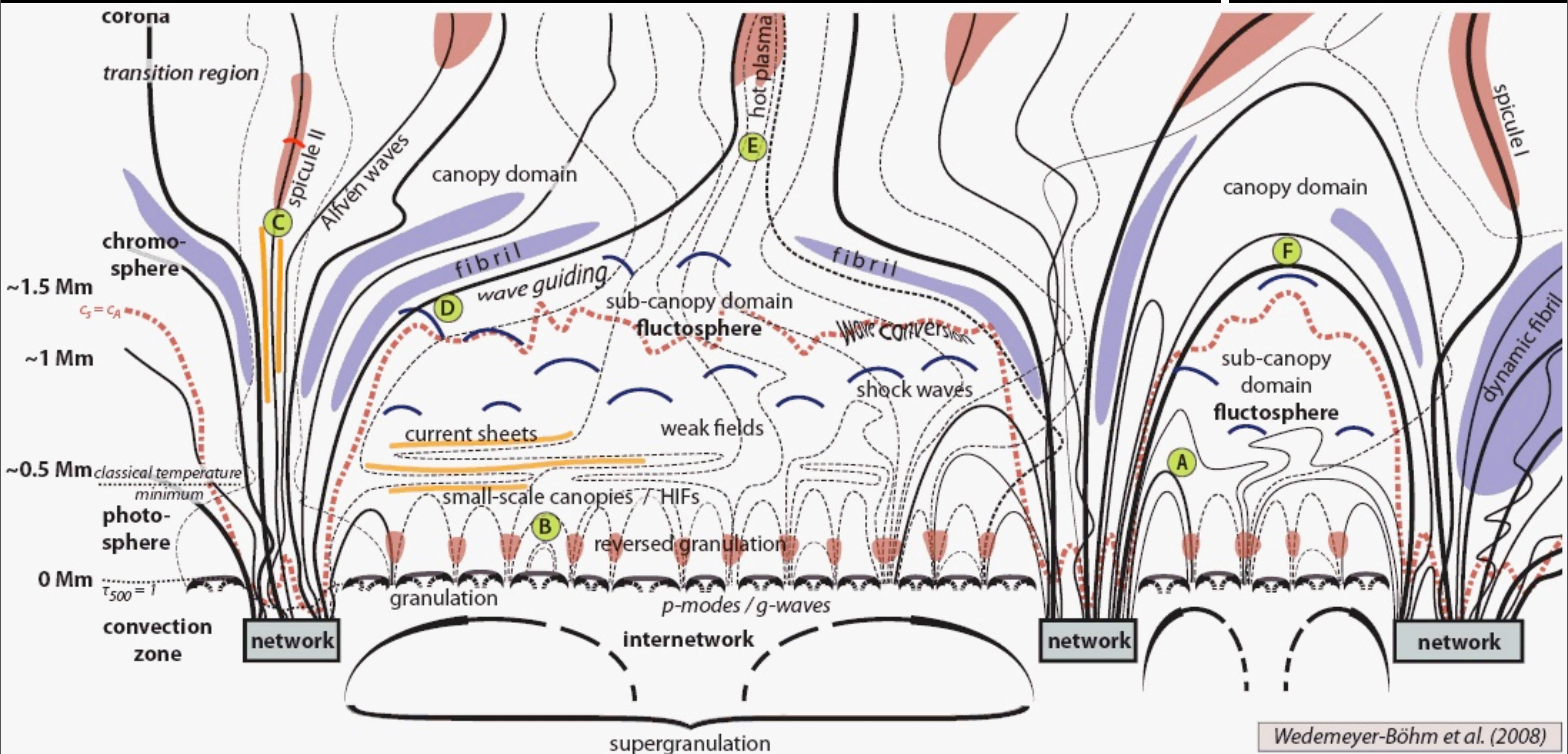


- Dynamic, hierarchy of scales, electrical currents, reconnection, non-thermal/non-radiative energy

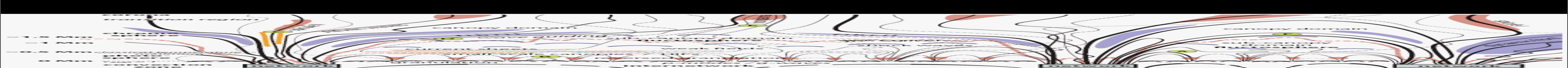
Processes in the solar atmosphere



Processes in the solar atmosphere



- Actual aspect ratio:



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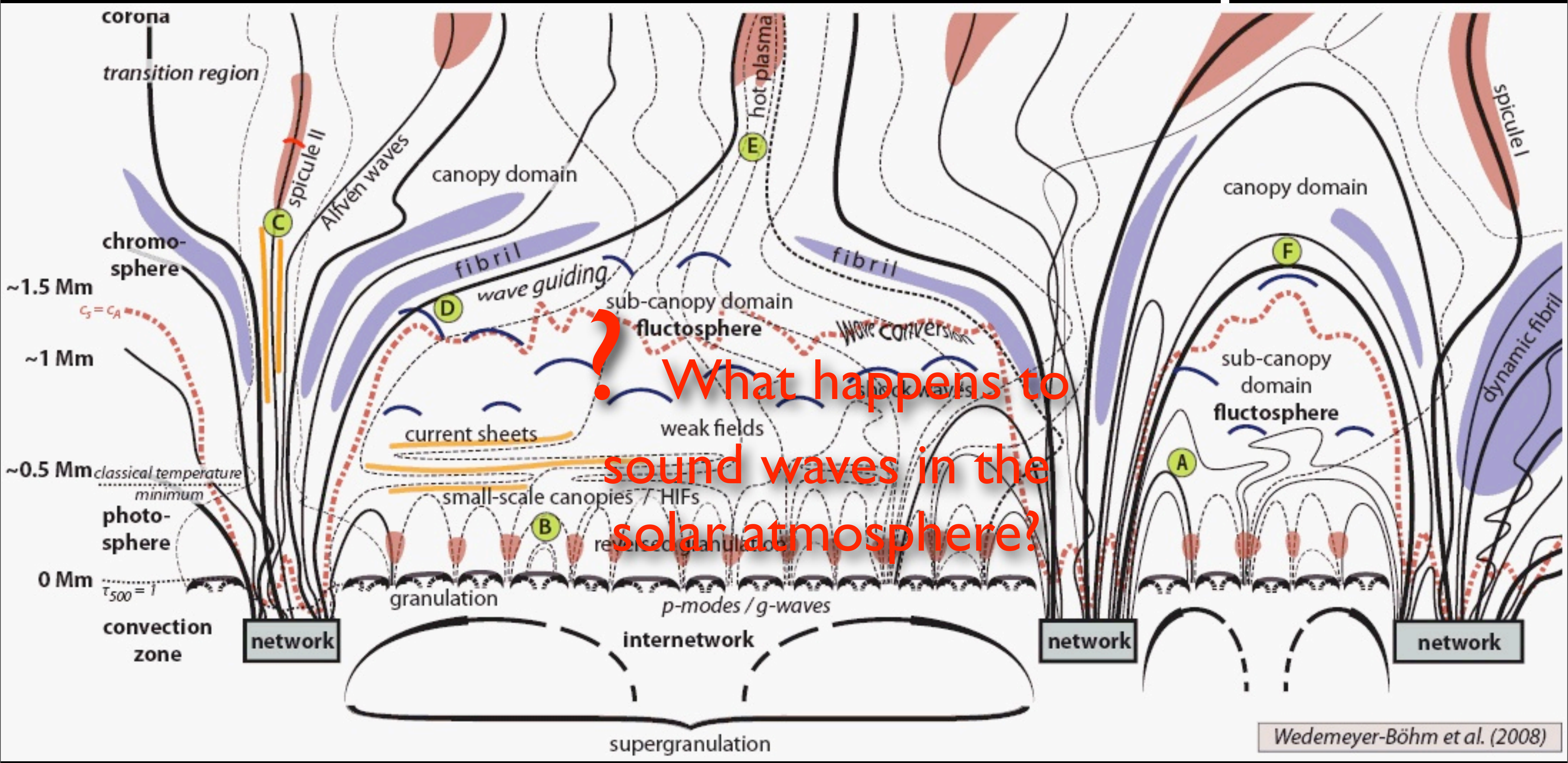

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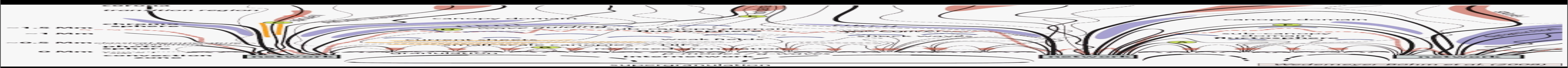
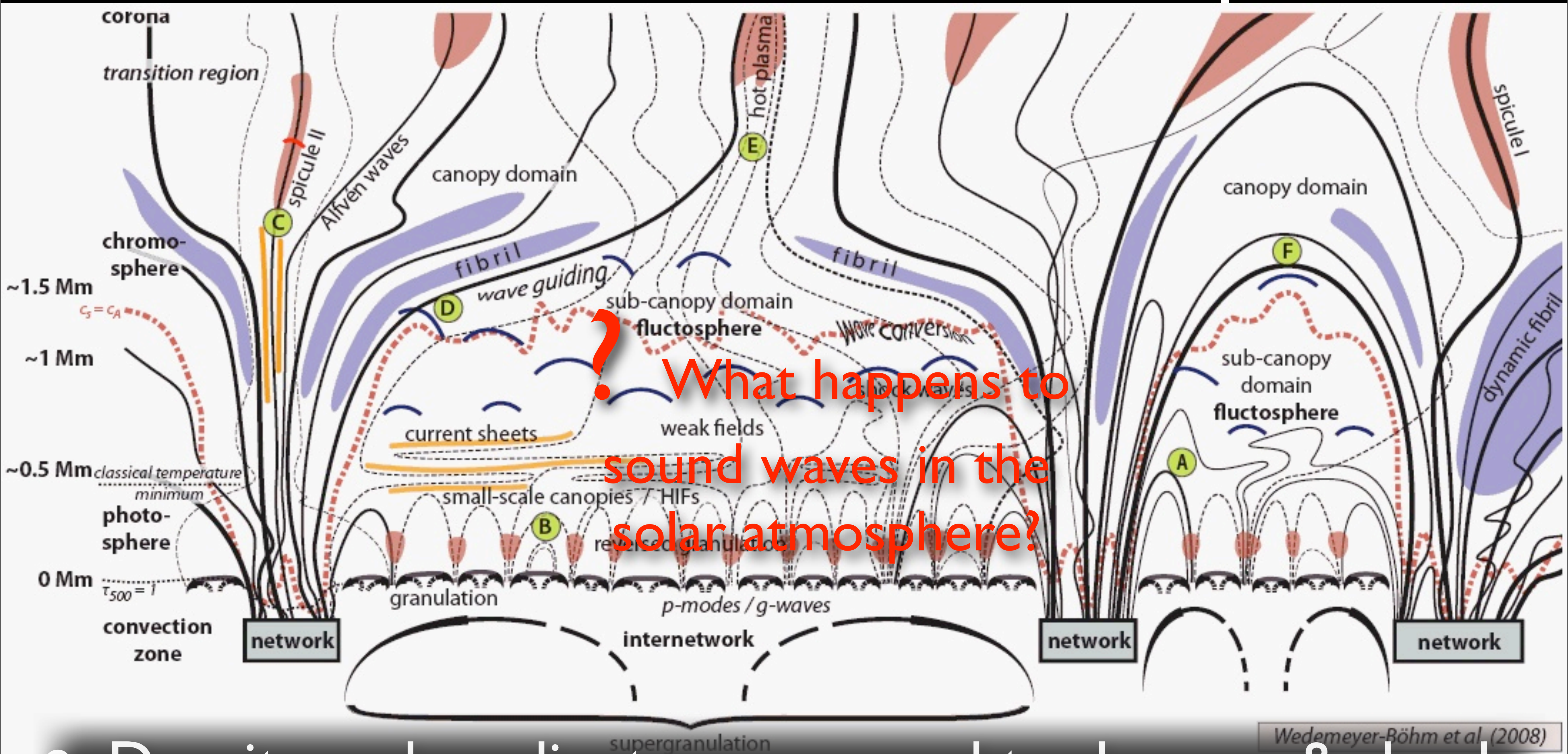
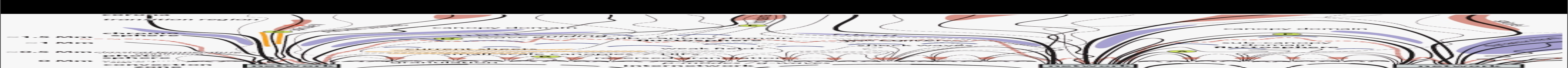


Processes in the solar atmosphere



- Density and gradient cause sound to dampen & shock
  - Actual aspect ratio:



Terminology/definitions

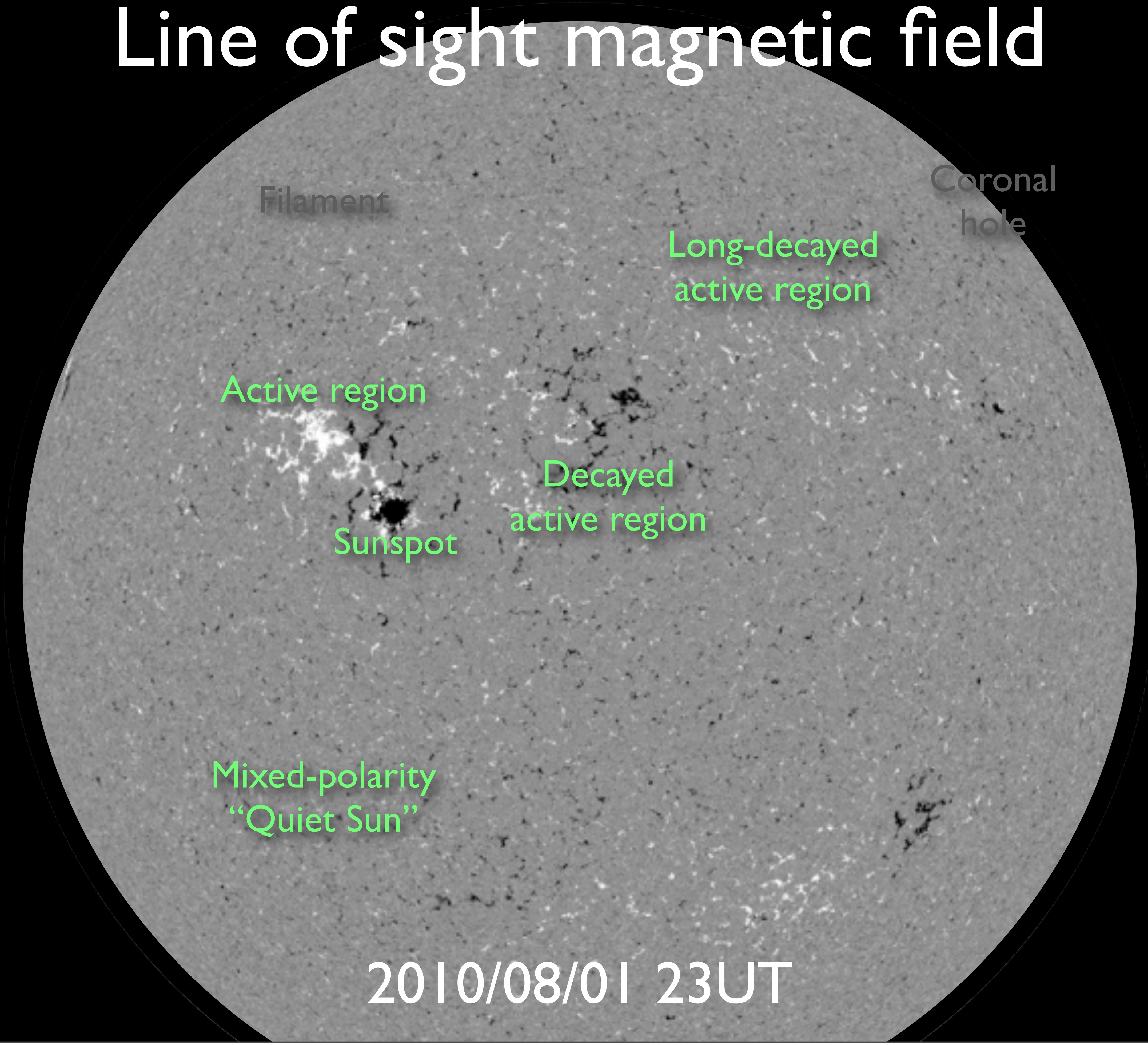
- Solar (and stellar) atmospheric domains

Table 8.1. *Basic parameters for domains in the solar atmosphere, and their definitions. Note that all regions of the solar atmosphere are very inhomogeneous and that these values are only meant to give a rough idea of their magnitudes.*

Region	n [m^{-3}]	n_e/n_H	T [K]	B [Gauss]	β
Photosphere[1]	10^{23}	10^{-4}	$6\,10^3$	$1-1500$	>10
Chromosphere[2]	10^{19}	10^{-3}	$2\,10^4-10^4$	$10-100$	$10-0.1$
Transition region[3]	10^{15}	1	10^4-10^6	$1-10$	10^{-2}
Corona[4]	10^{14}	1	10^6	$1-10$	$10^{-2}-1$

Definitions: [1] the *photosphere* is the layer from which the bulk of the electromagnetic radiation leaves the Sun, This layer has an optical thickness $\tau_\nu \lesssim 1$ in the near-UV, visible, and near-IR spectral continua, but it is optically thick in all but the weakest spectral lines; [2] the *chromosphere* is optically thin in the near-UV, visible, and near-IR continue, but optically thick in strong spectral lines - it is often associated with temperatures around $10,000-20,000\,\mathrm{K}$; [3] the *transition region* is a thermal domain between chromosphere and corona in which thermal conduction leads to a steep temperature gradient; [4] the *corona* is optically very thin over the entire EM spectrum except for the radio waves a a few spectral lines - it is often used to describe the solar outer atmosphere out to a few solar radii with temperatures exceeding $\sim 1\,\mathrm{MK}$.

Line of sight magnetic field



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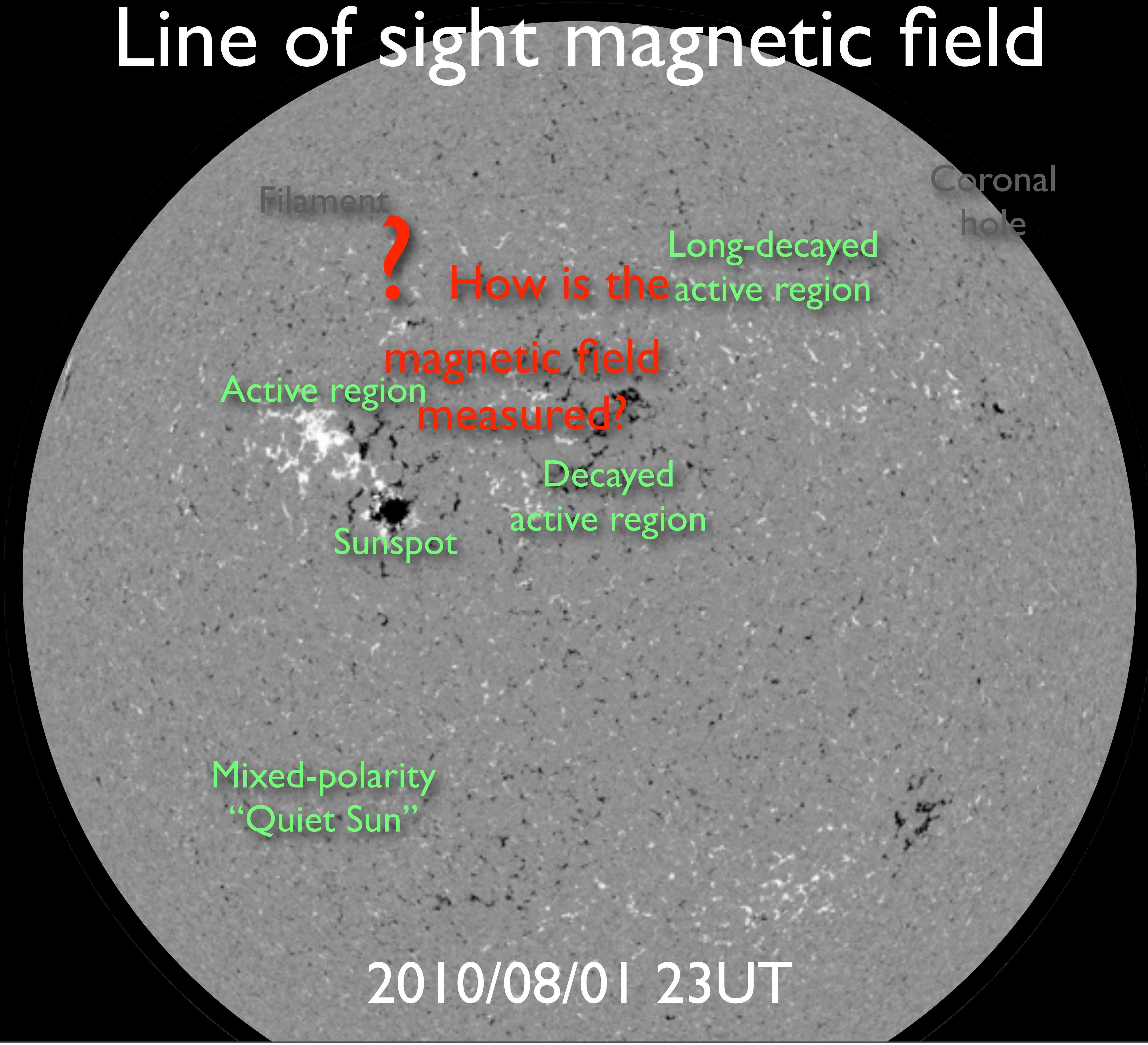

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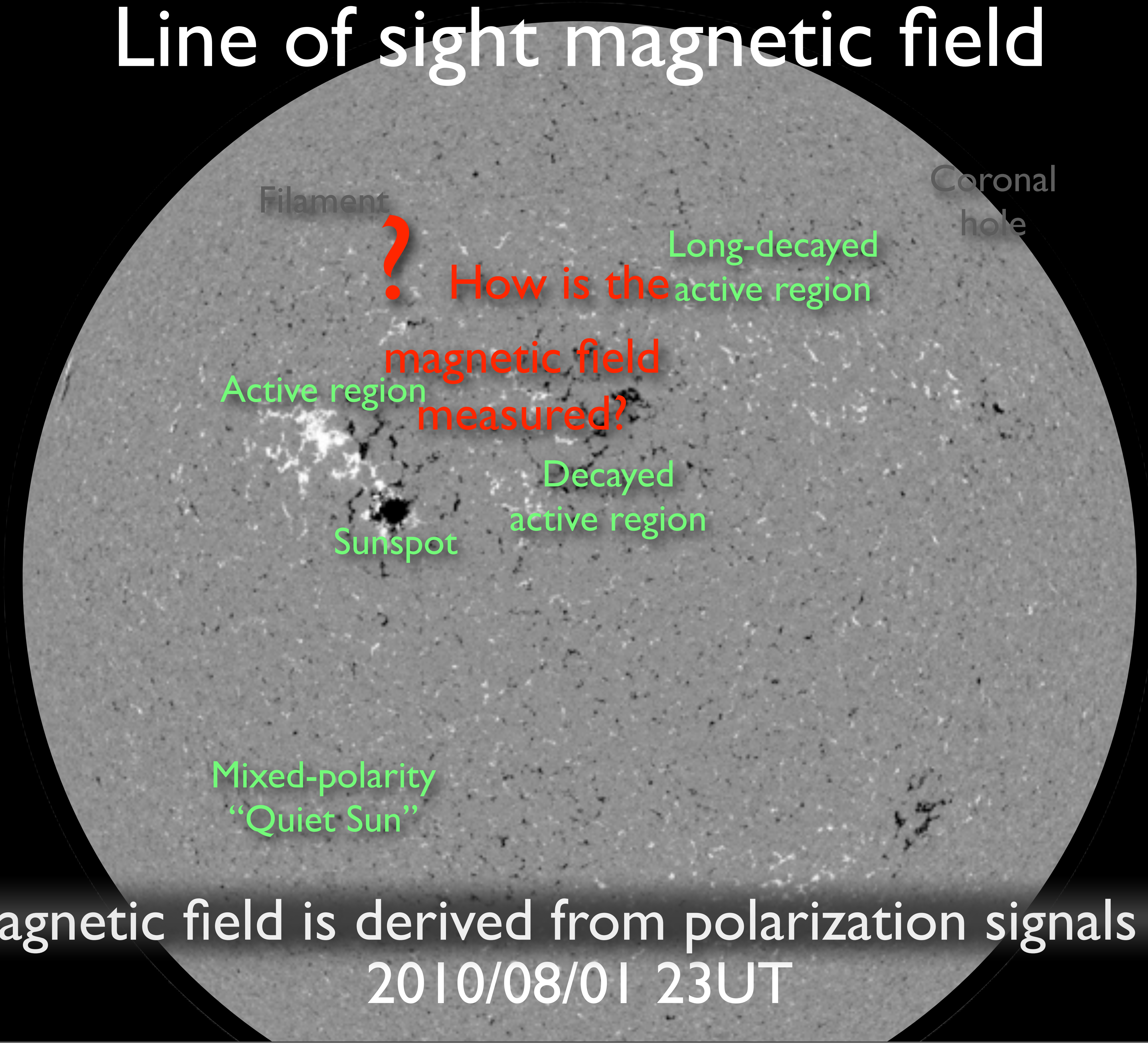

- Magnetic field is derived from polarization signals

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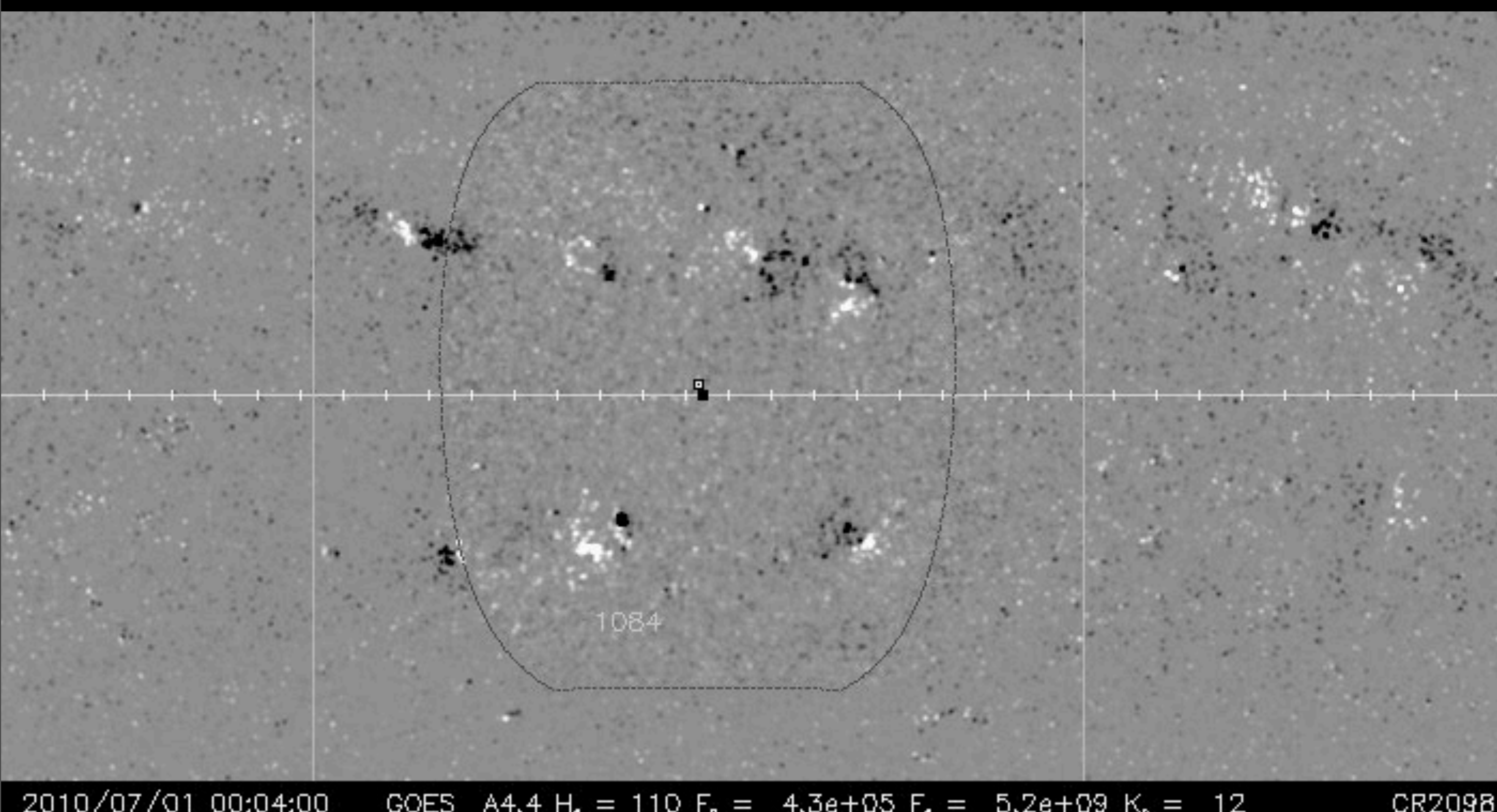
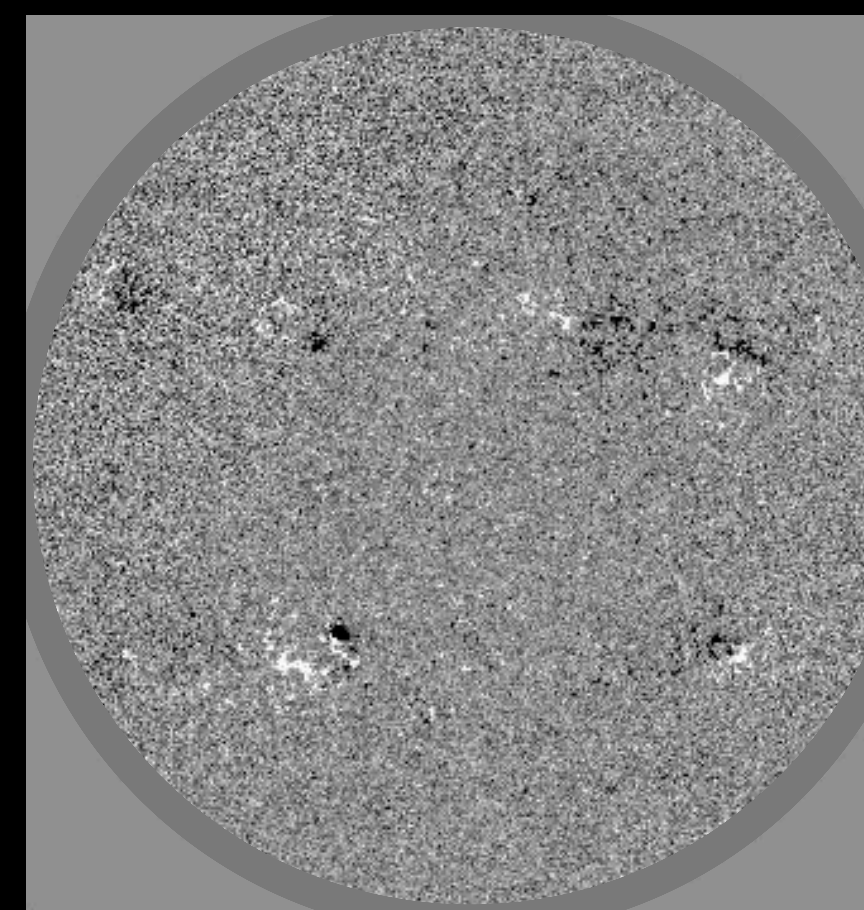
The dynamic magnetic field

“Carrington map”



Obs. magnetogram



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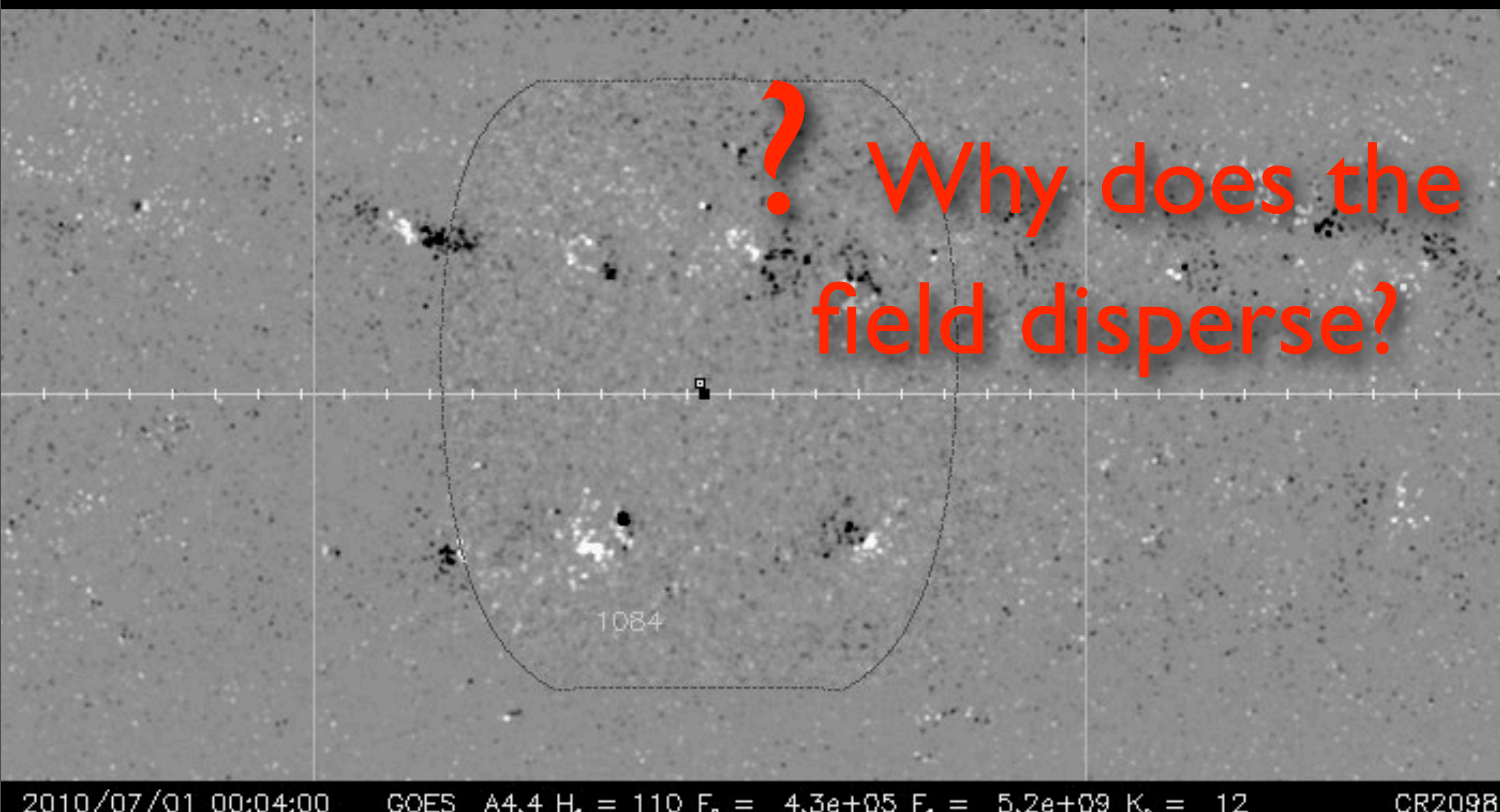

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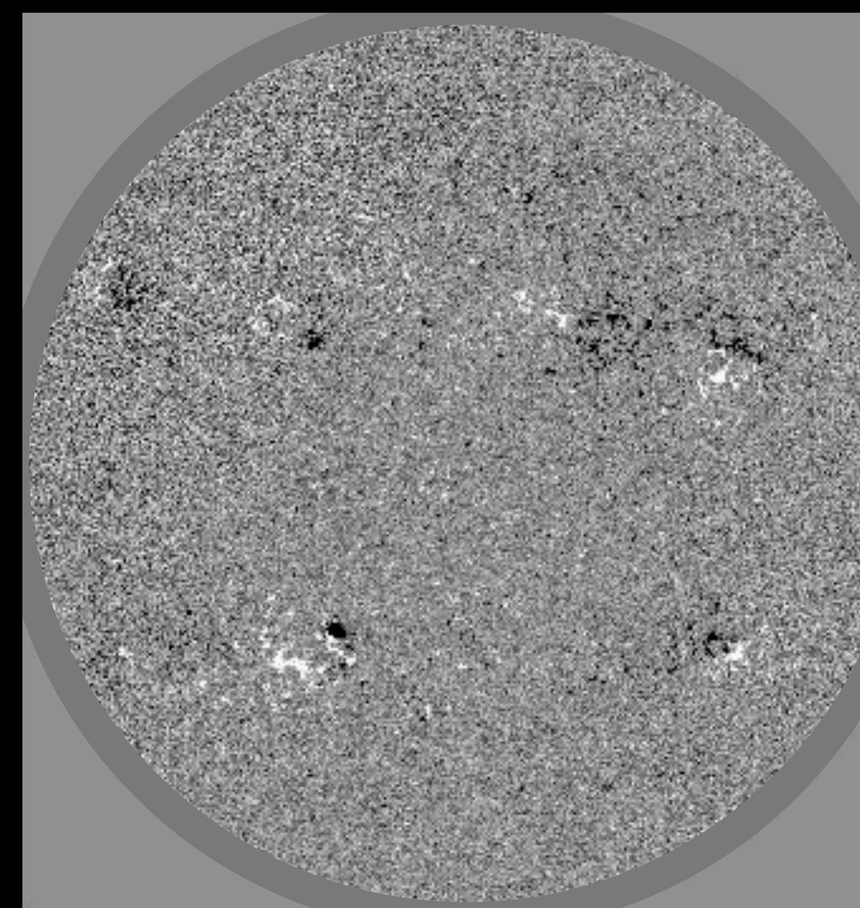

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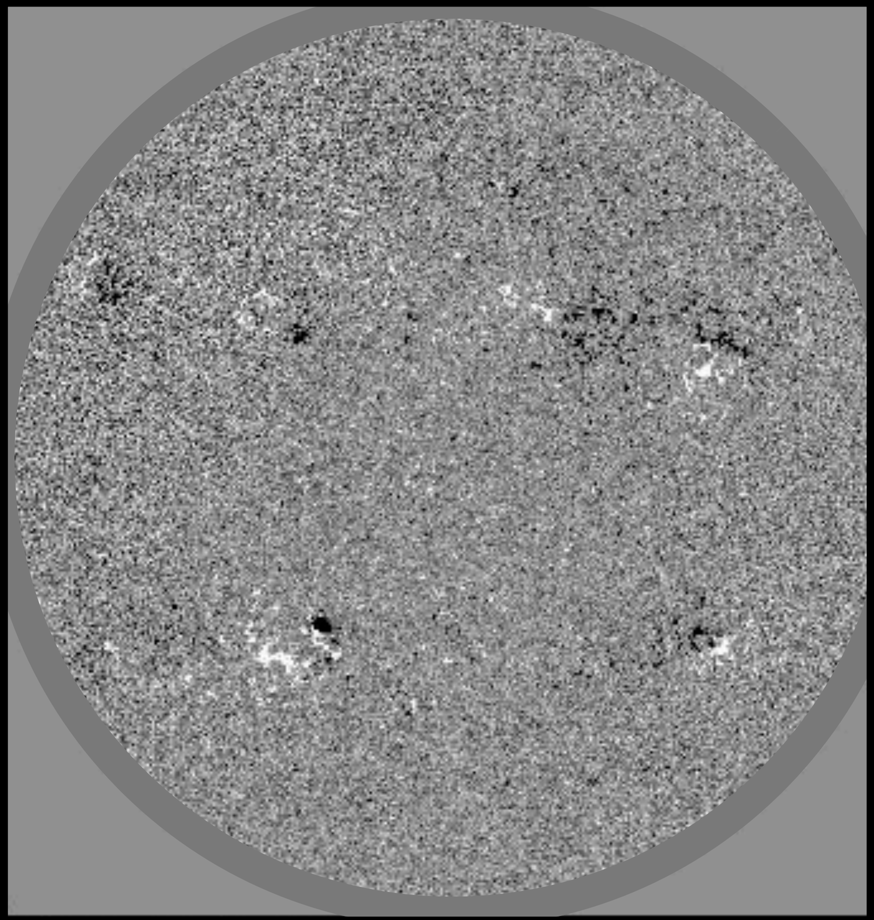
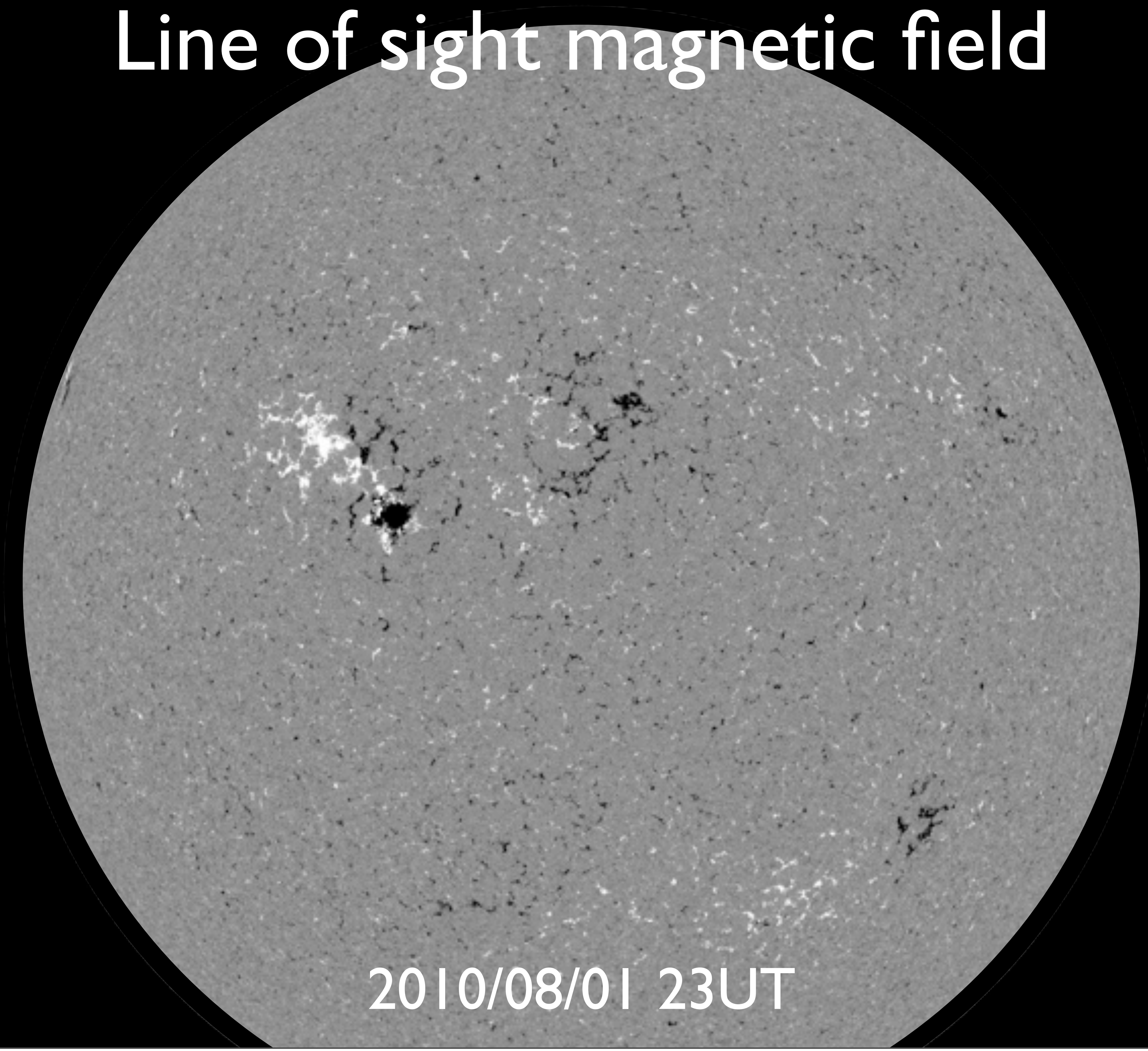
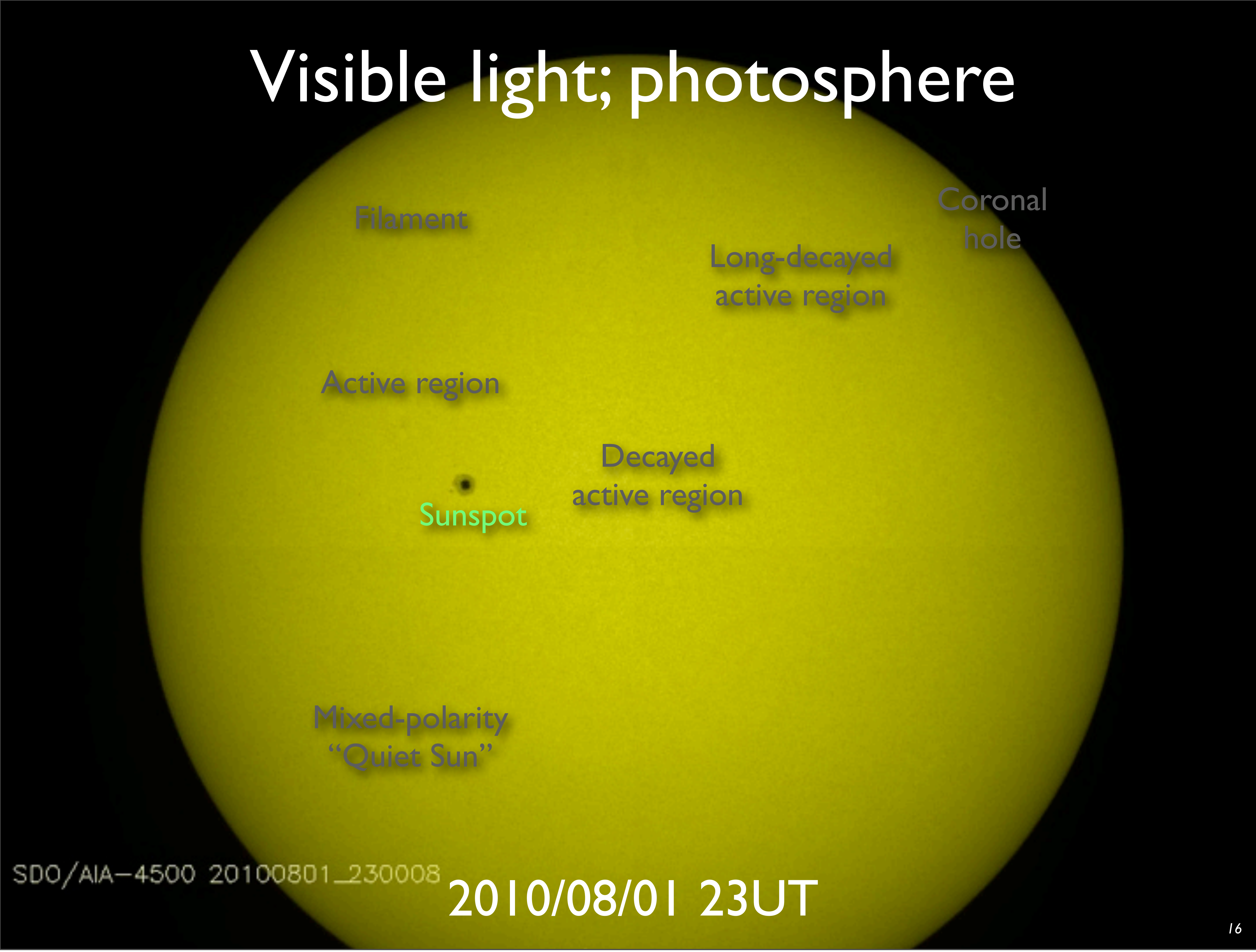


- Random walk >> resistive diffusion: scales!

Line of sight magnetic field



Visible light; photosphere



Visible light; photosphere

Visible light; photosphere

- B-field invisible in intensity, unless it changes the atmosphere

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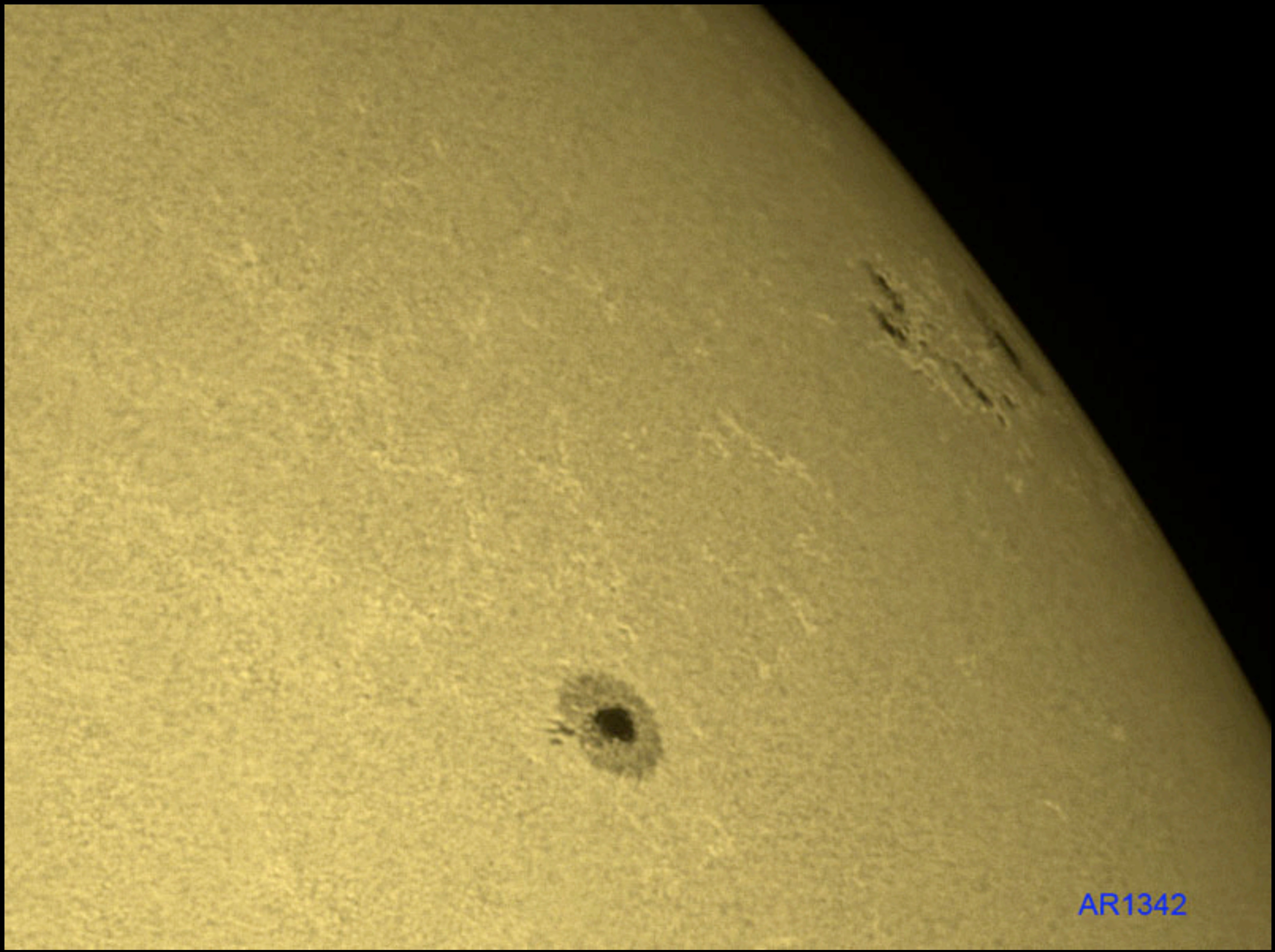
Dark-bright: function of size



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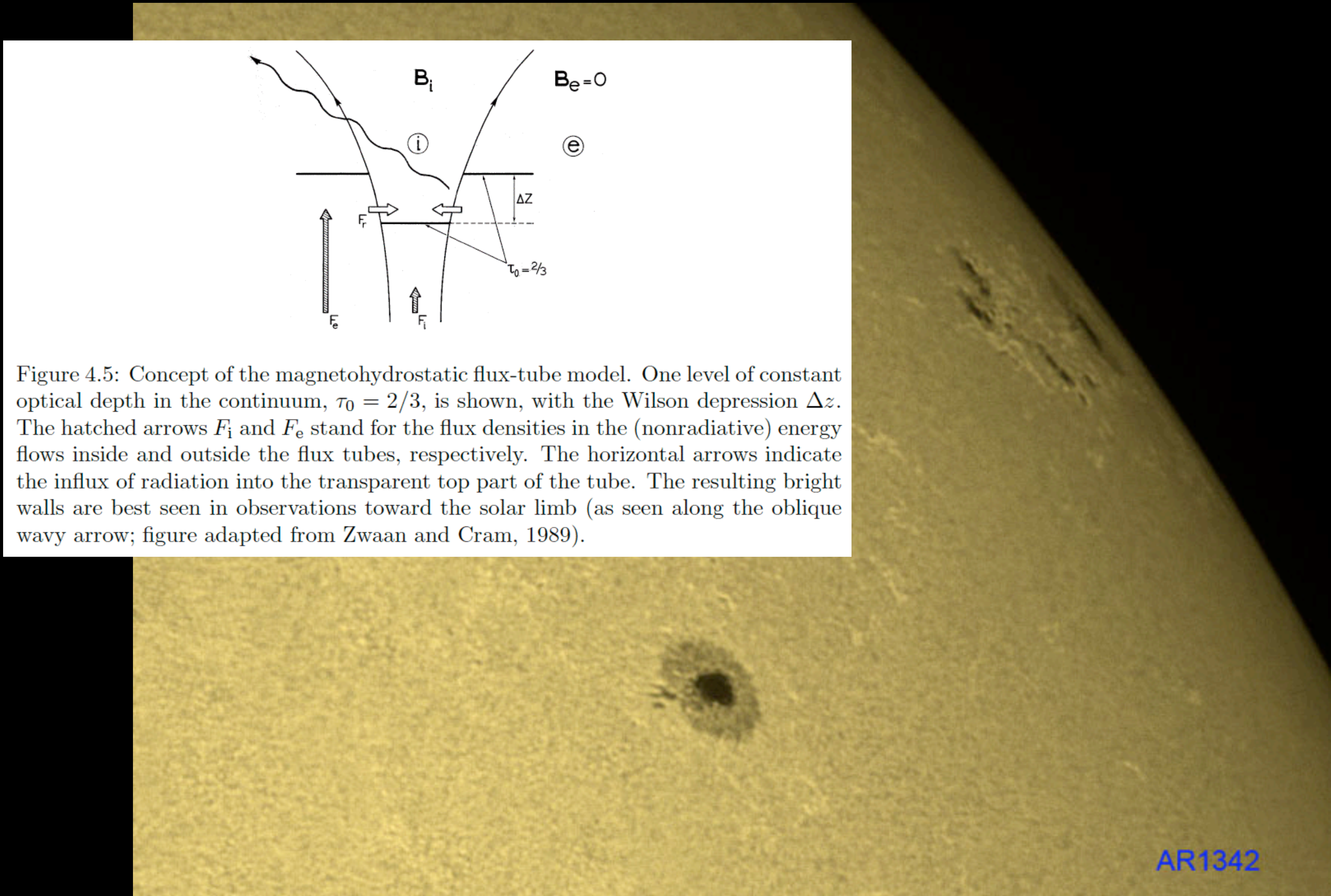
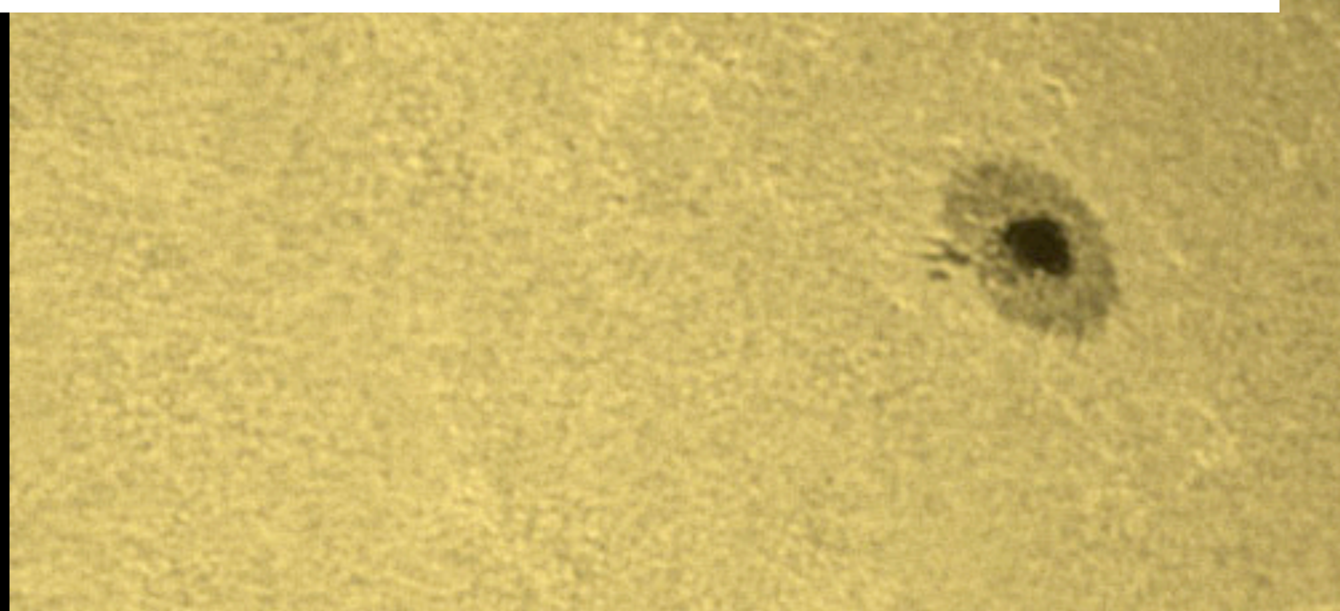
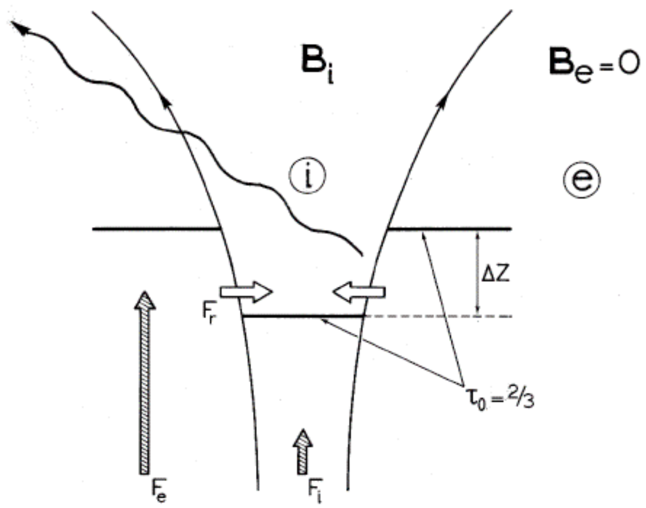


Figure 4.5: Concept of the magnetohydrostatic flux-tube model. One level of constant optical depth in the continuum, $\tau_0 = 2/3$, is shown, with the Wilson depression Δz. The hatched arrows $F_{\rm i}$ and $F_{\rm e}$ stand for the flux densities in the (nonradiative) energy flows inside and outside the flux tubes, respectively. The horizontal arrows indicate the influx of radiation into the transparent top part of the tube. The resulting bright walls are best seen in observations toward the solar limb (as seen along the oblique wavy arrow; figure adapted from Zwaan and Cram, 1989).

Dark-bright: function of size





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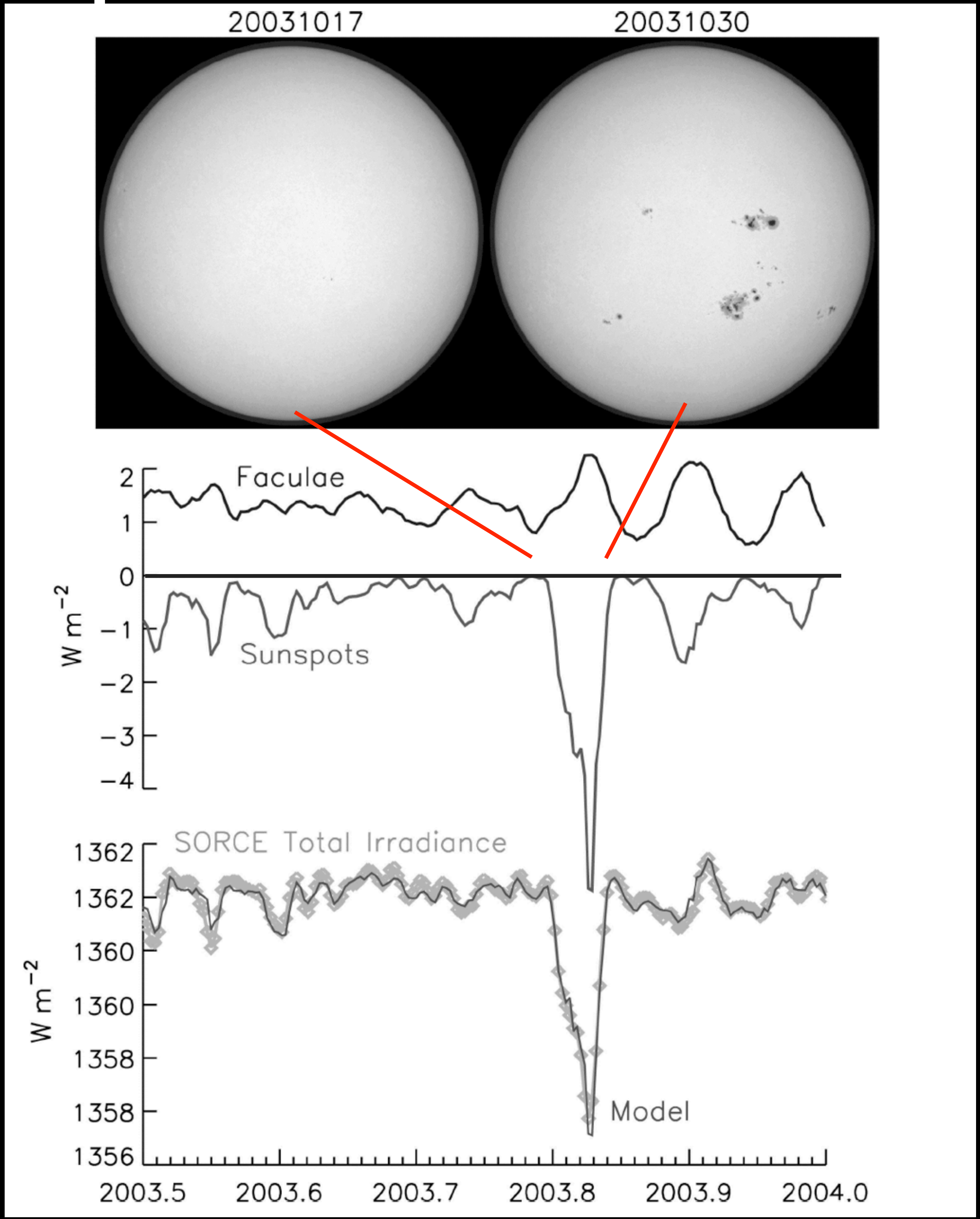
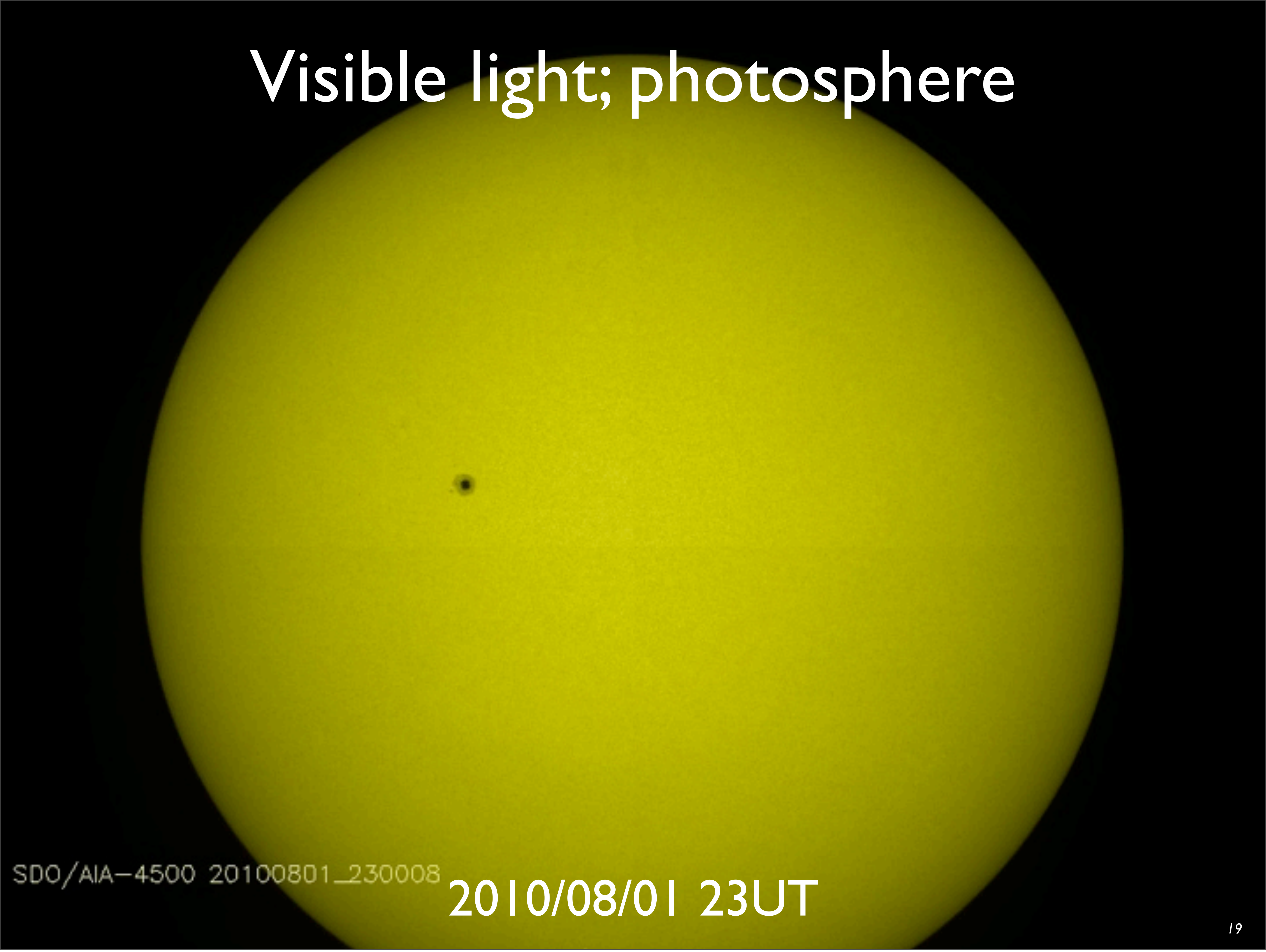
Wilson depression

Spots, pores, faculea, ... and TSI



Visible light; photosphere



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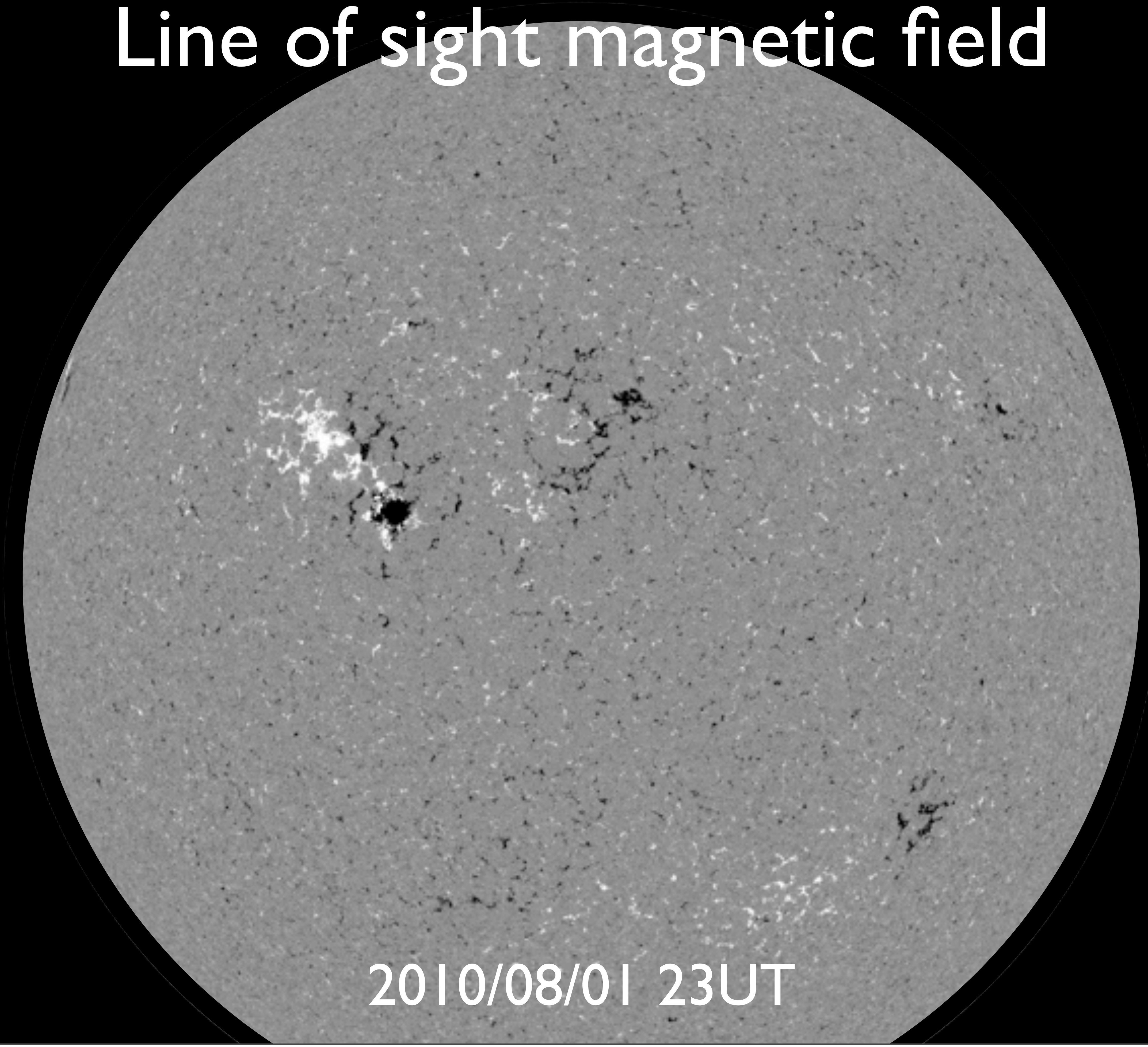
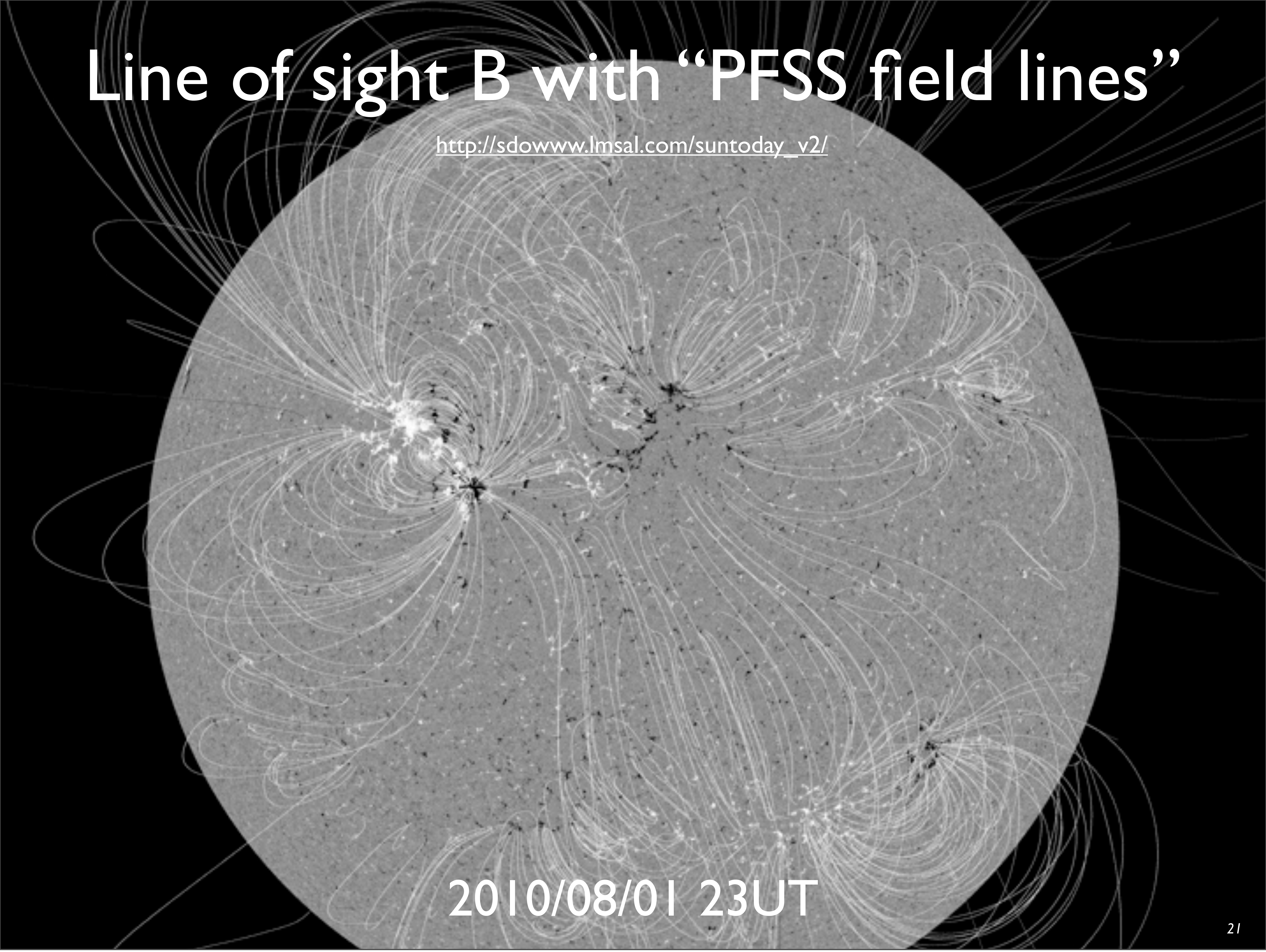
Line of sight magnetic field

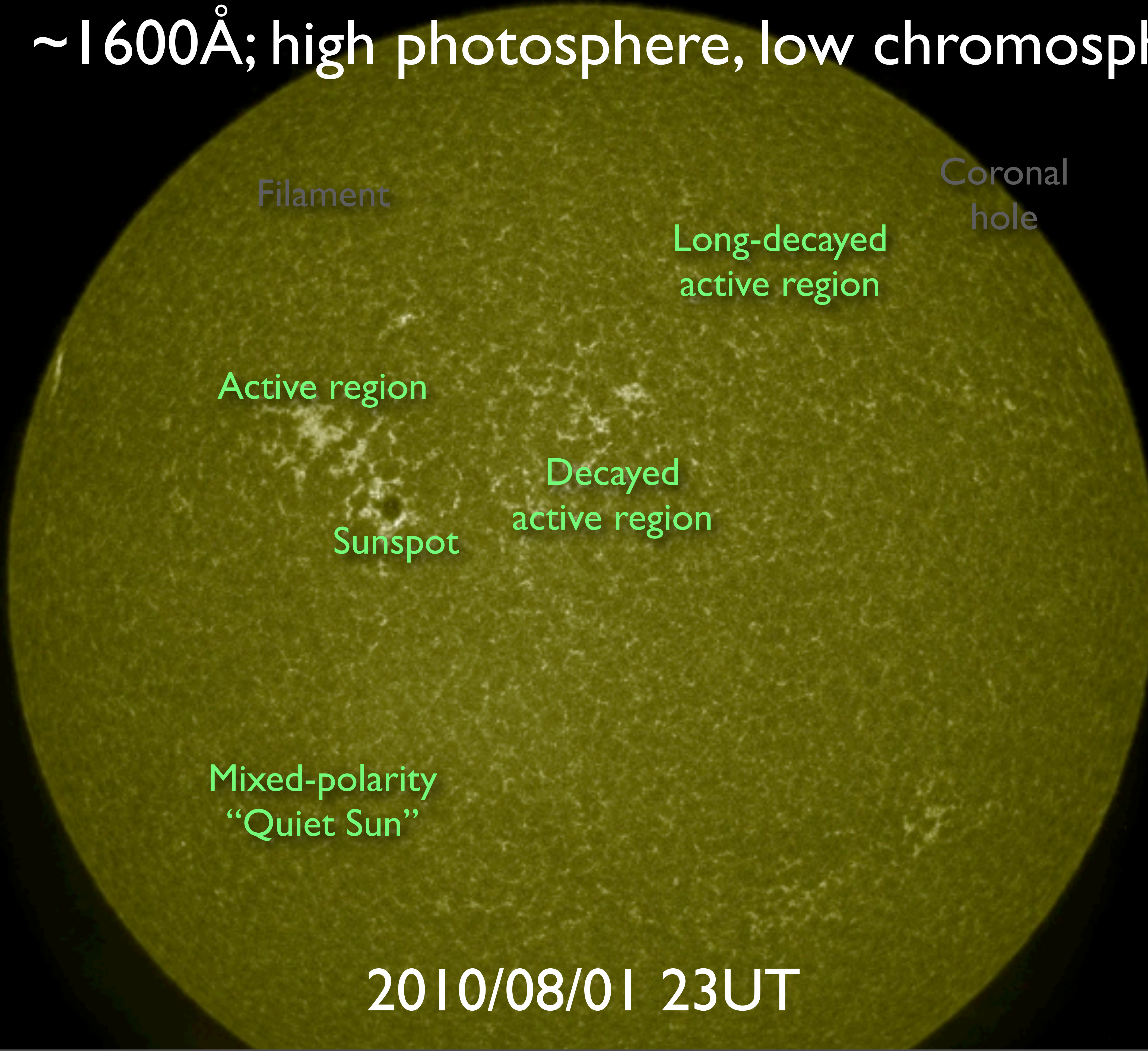


Line of sight B with "PFSS field lines"

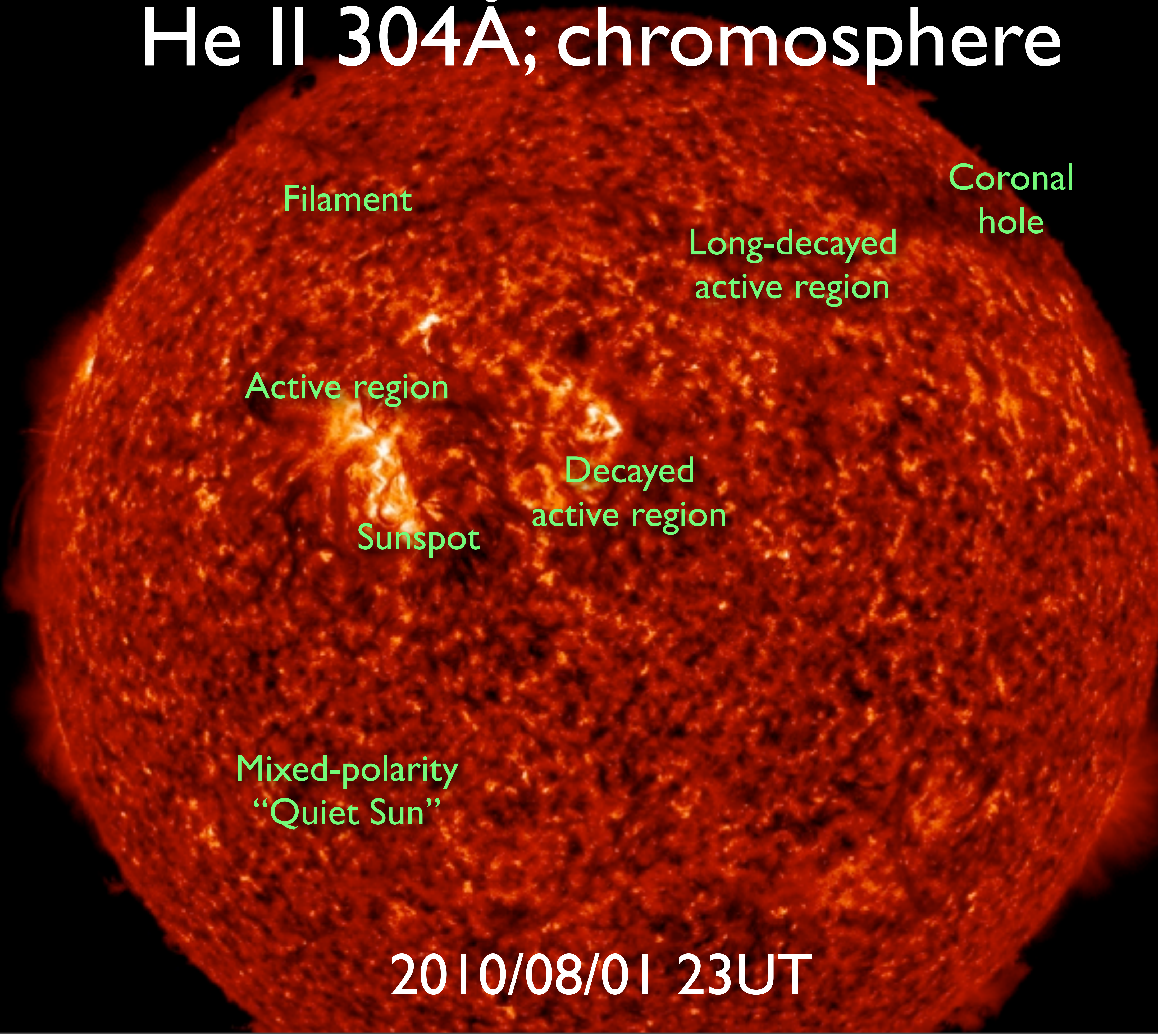
http://sdowww.lmsal.com/suntoday_v2/



UV ~1600Å; high photosphere, low chromosphere



He II 304Å; chromosphere



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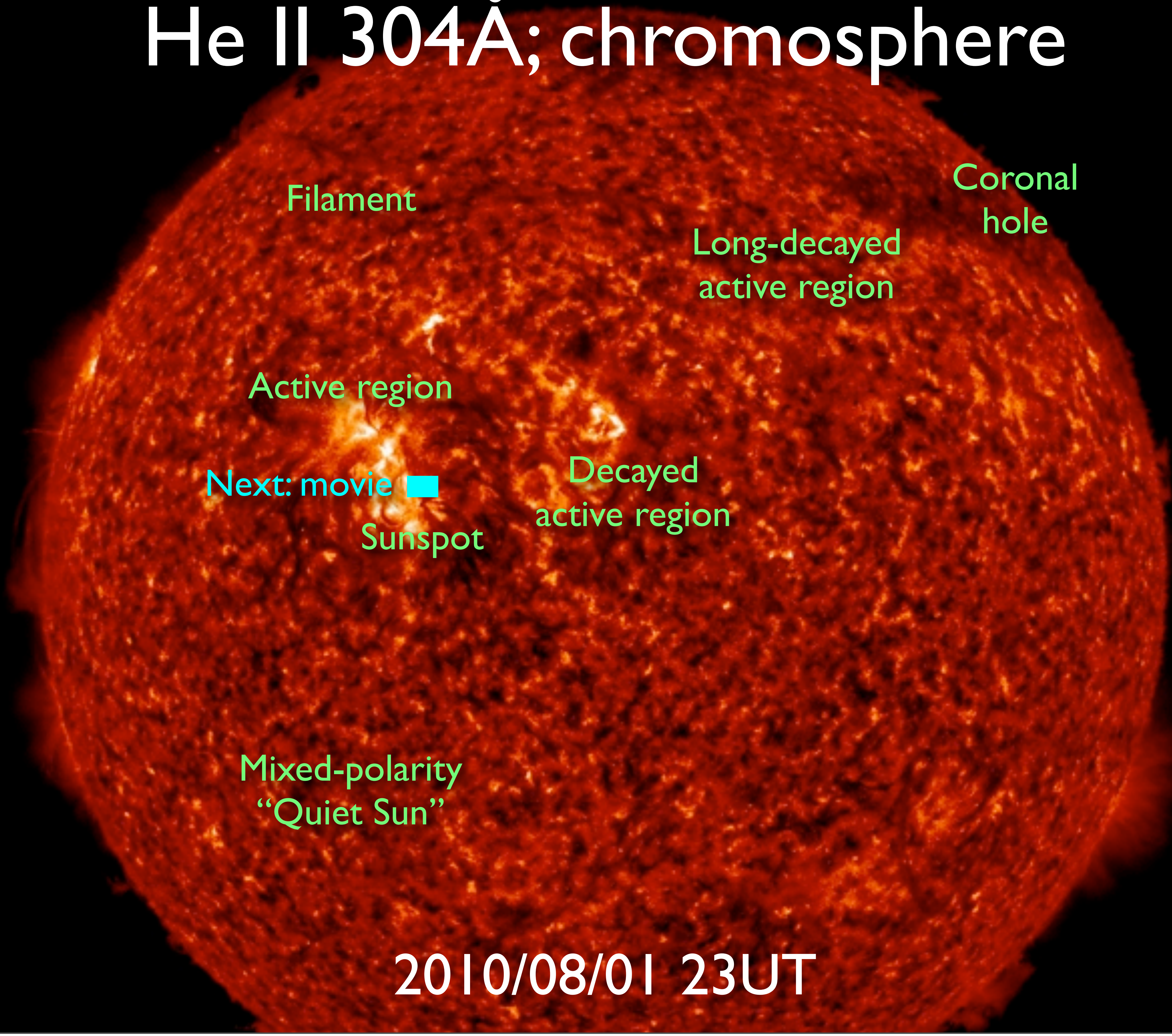
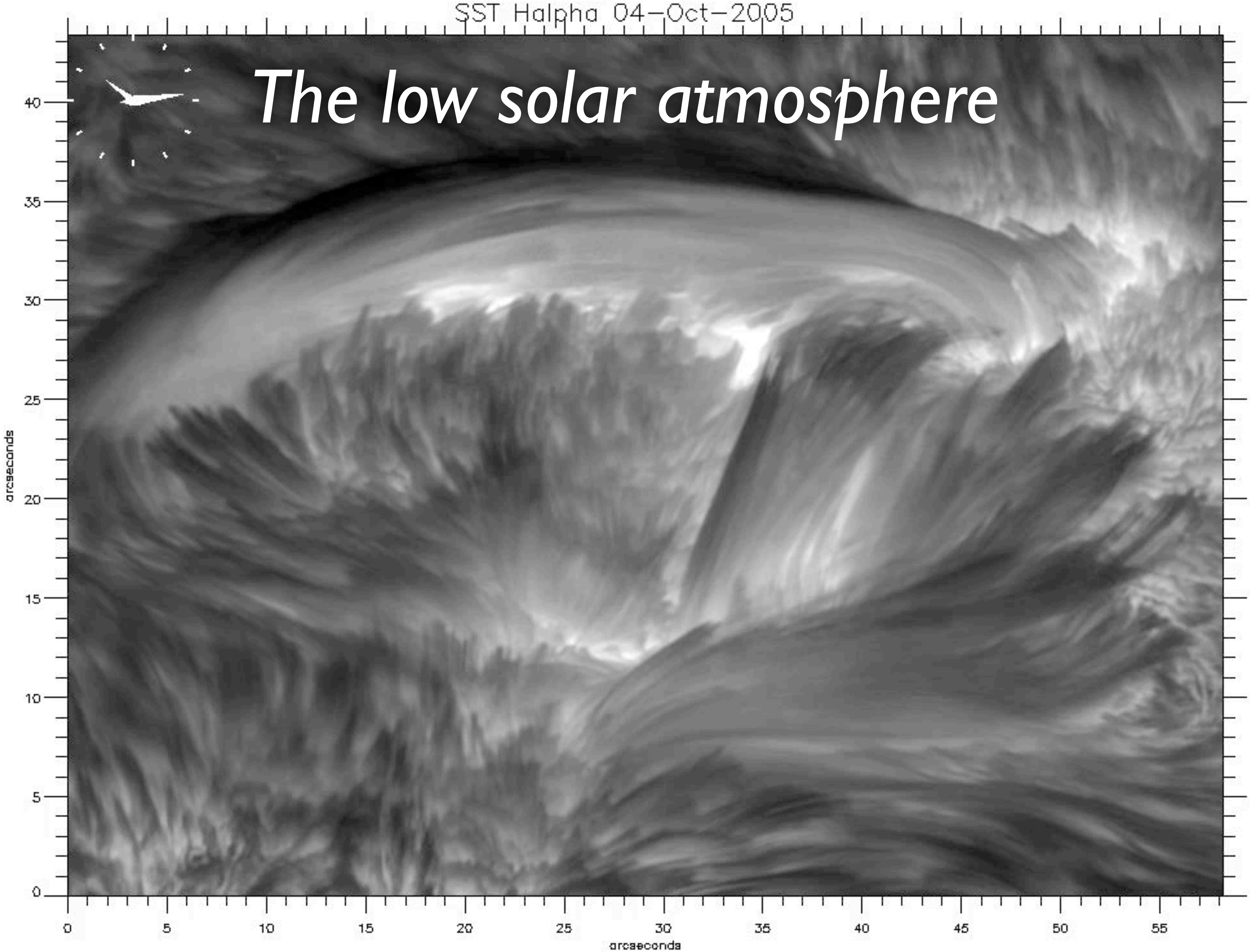
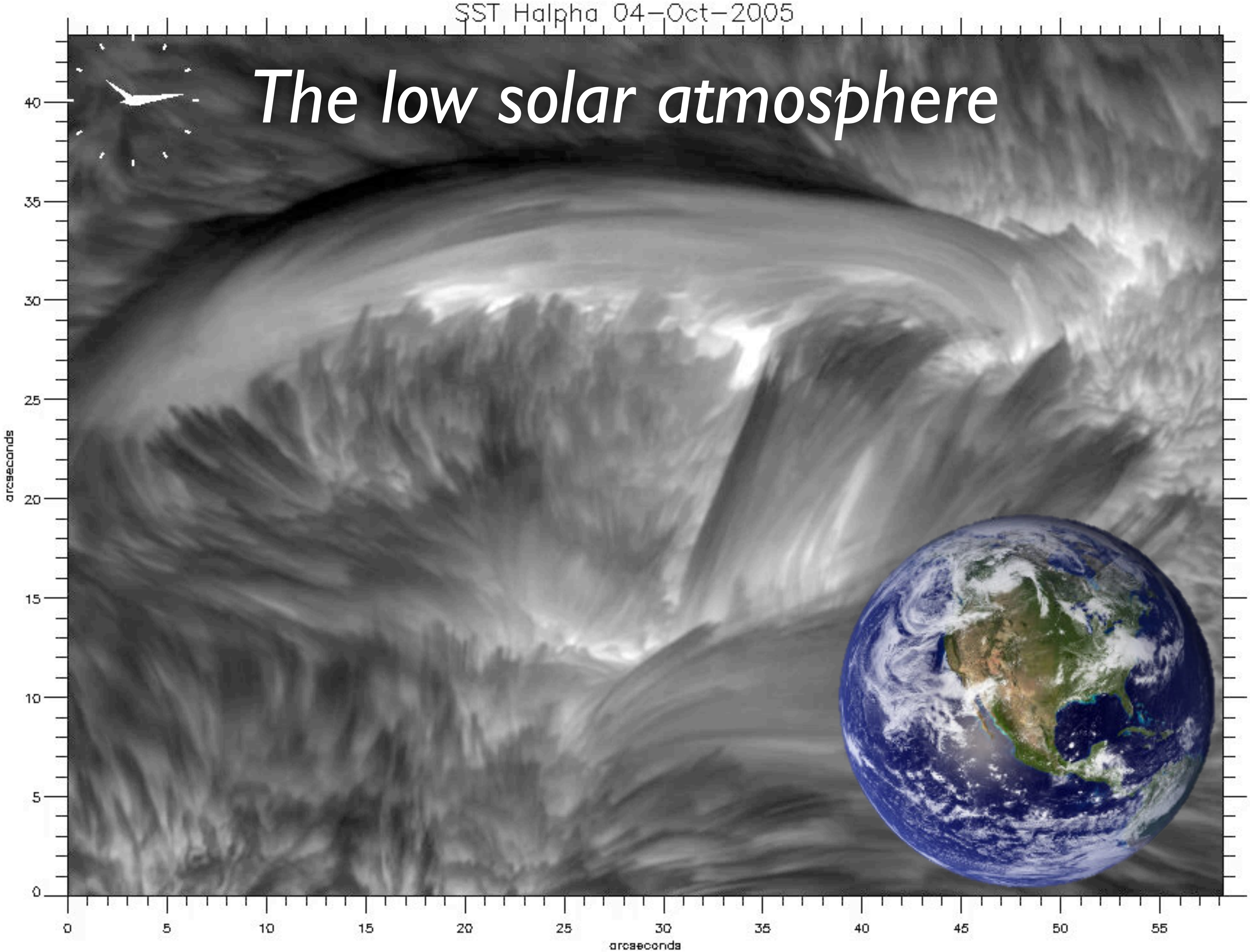
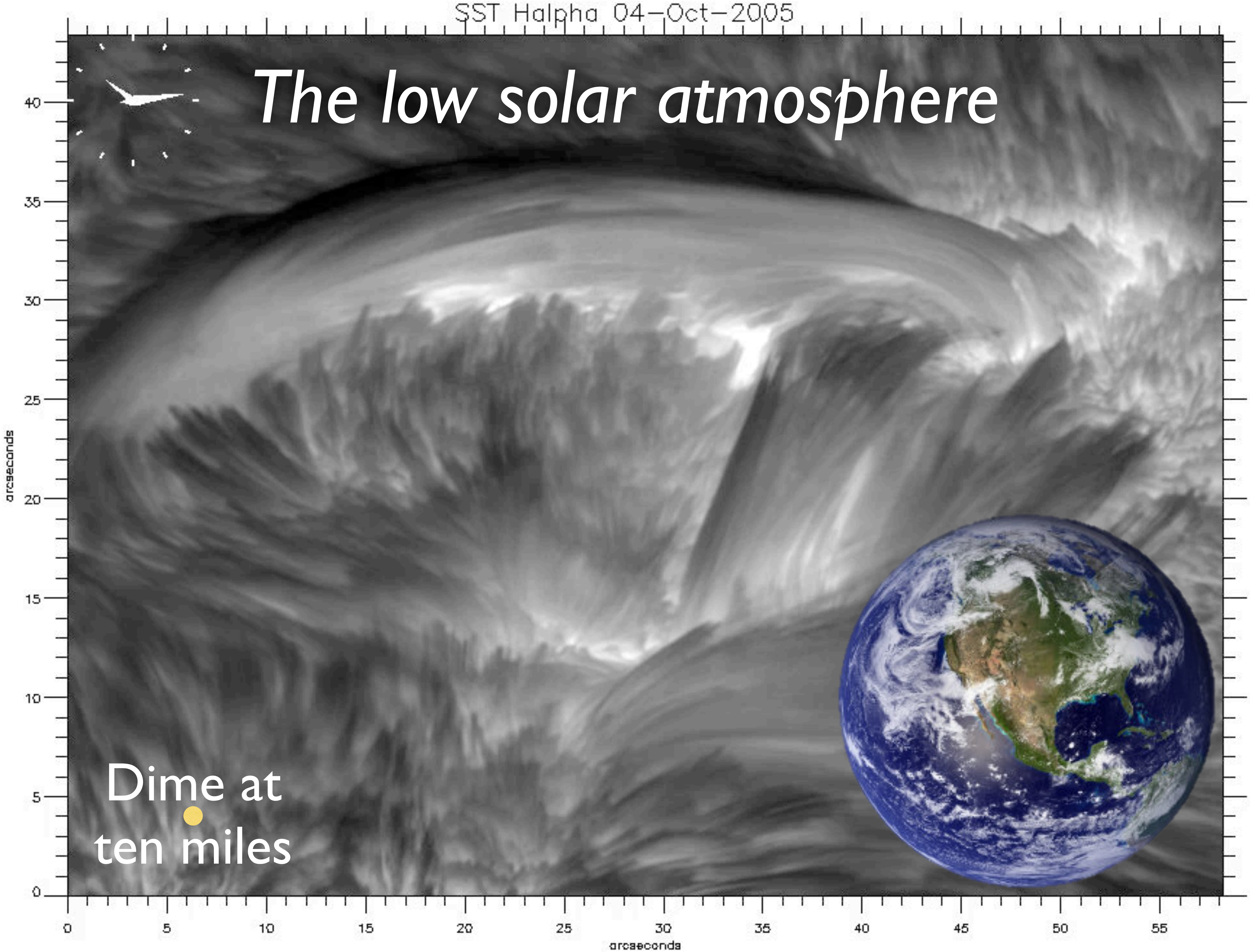


The low solar atmosphere




The low solar atmosphere
SST Halpha 04-Oct-2005
arcseconds
arcseconds
0 5 10 15 20 25 30 35 40 45 50 55
0 5 10 15 20 25 30 35 40


SST Halpha 04-Oct-2005
The low solar atmosphere
Dime at
ten miles
arcseconds
arcseconds
0
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10
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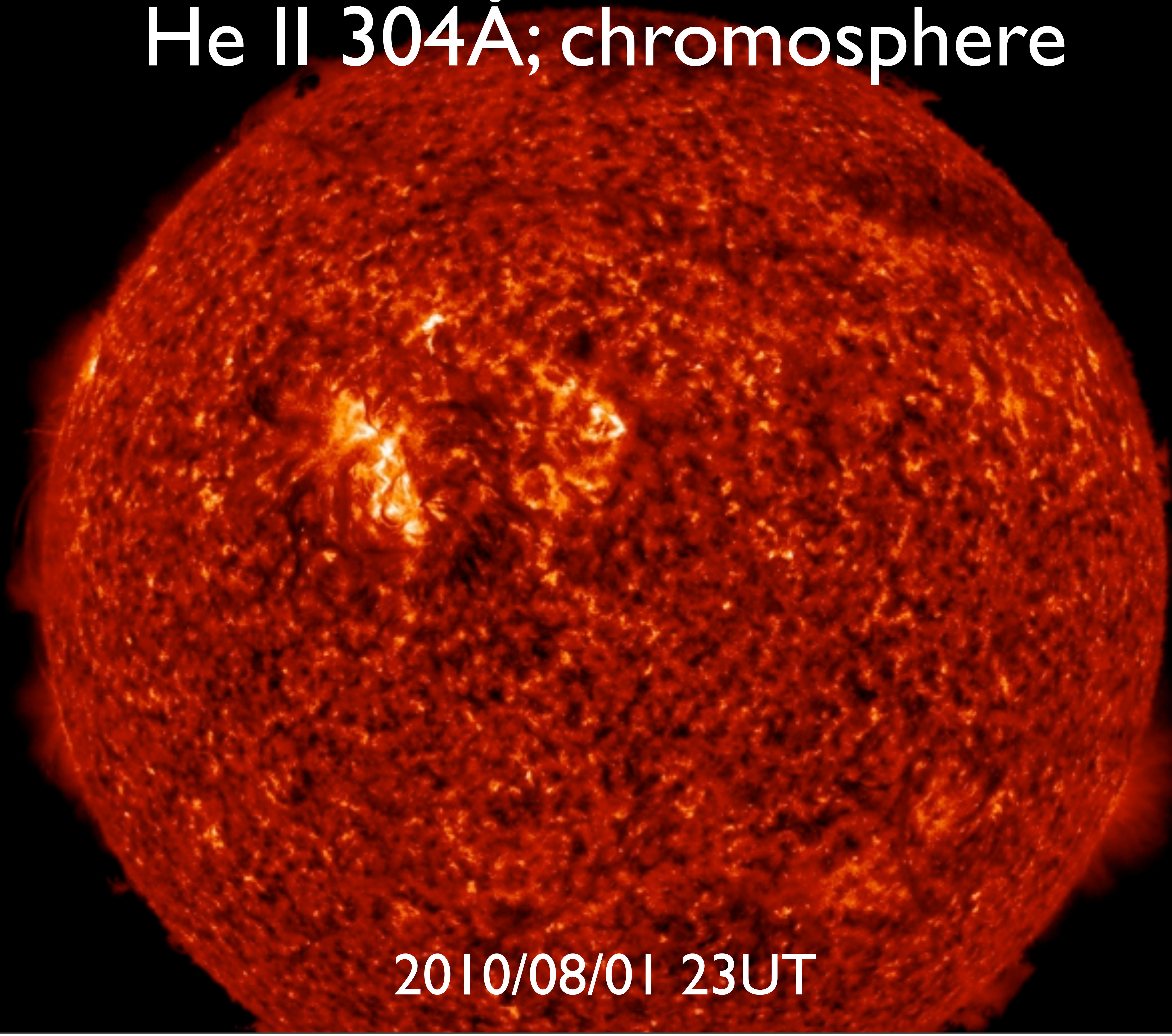
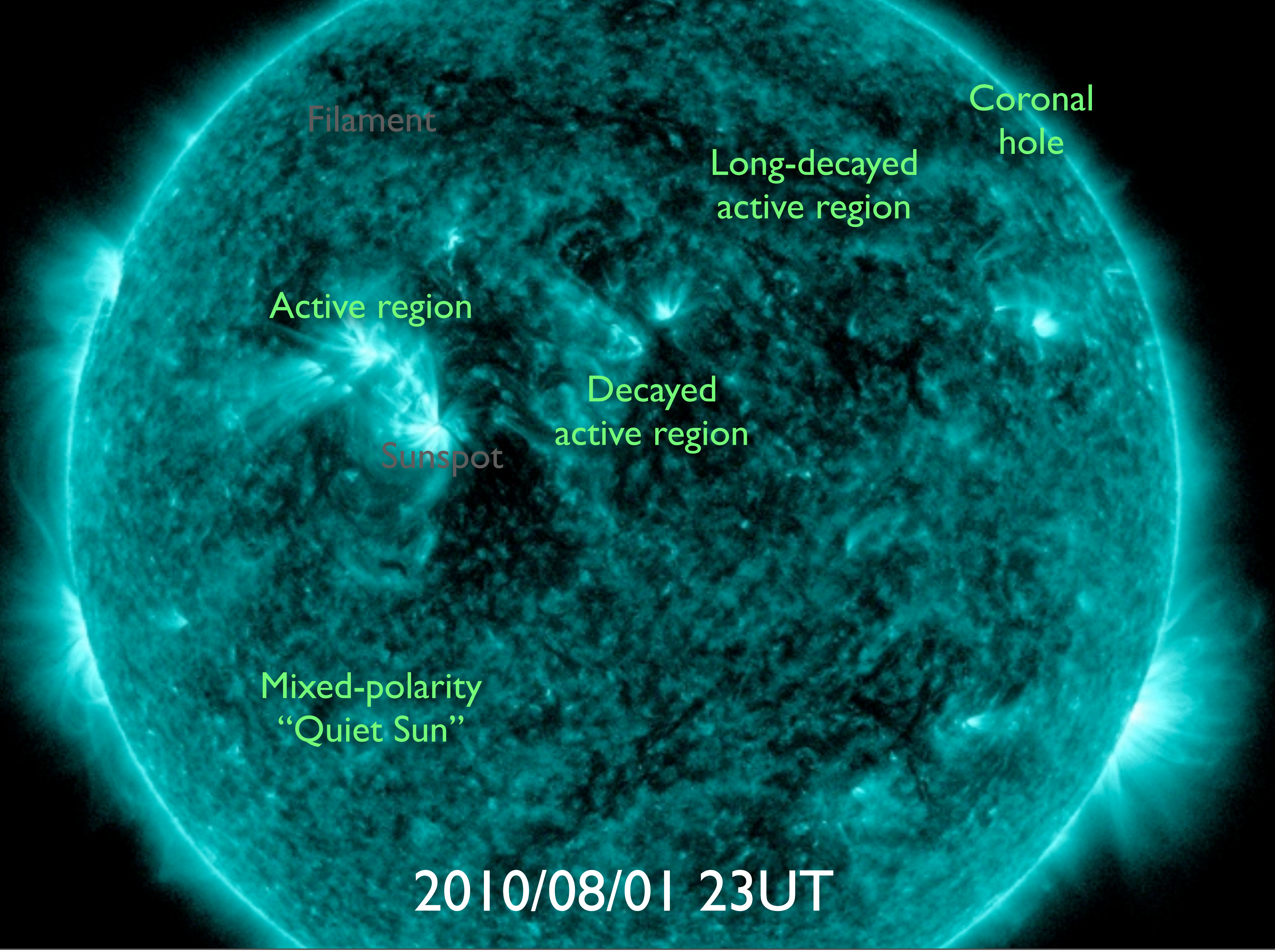
50
55

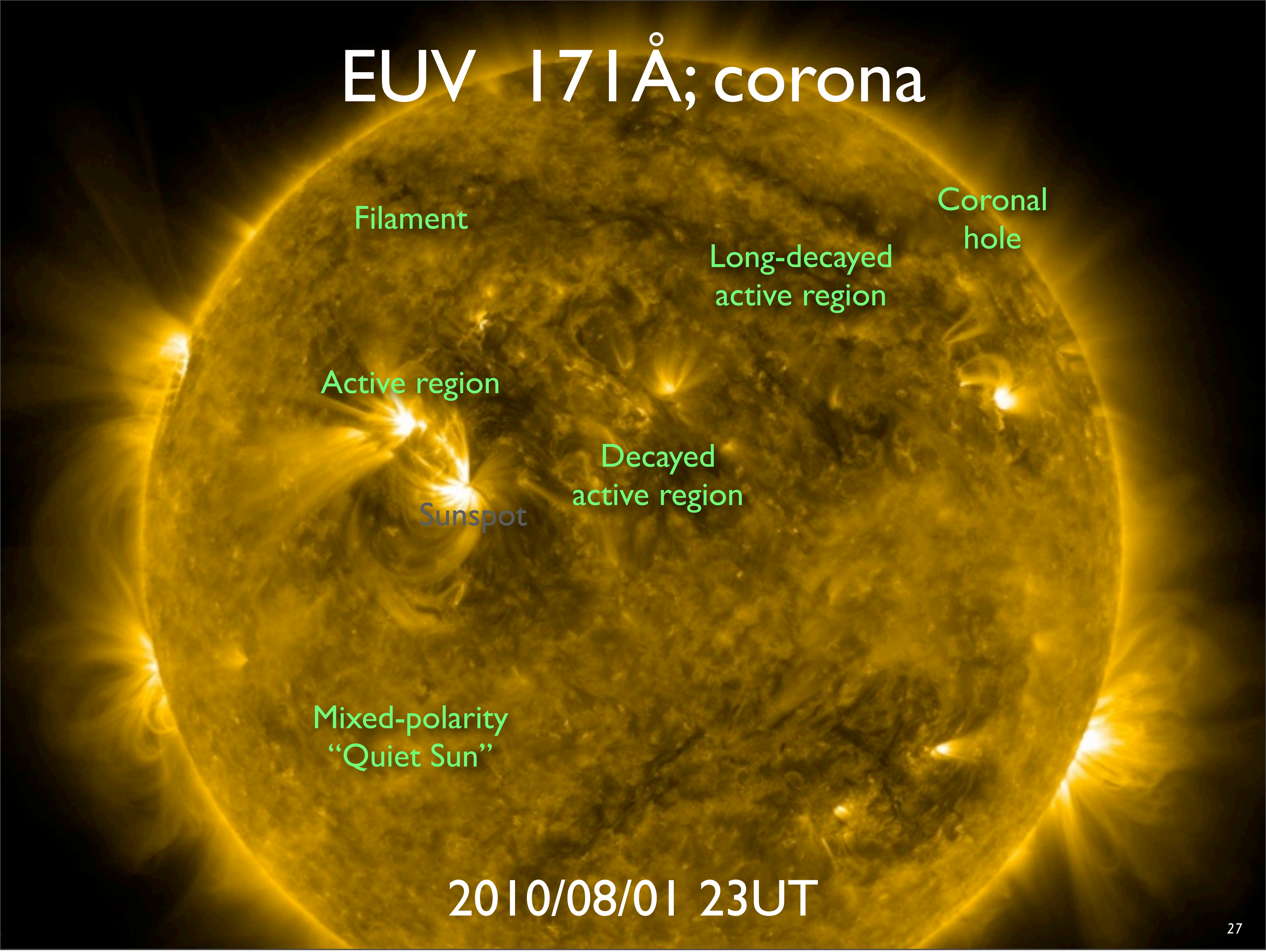
He II 304Å; chromosphere



EUV 131Å; corona



EUV 171Å; corona



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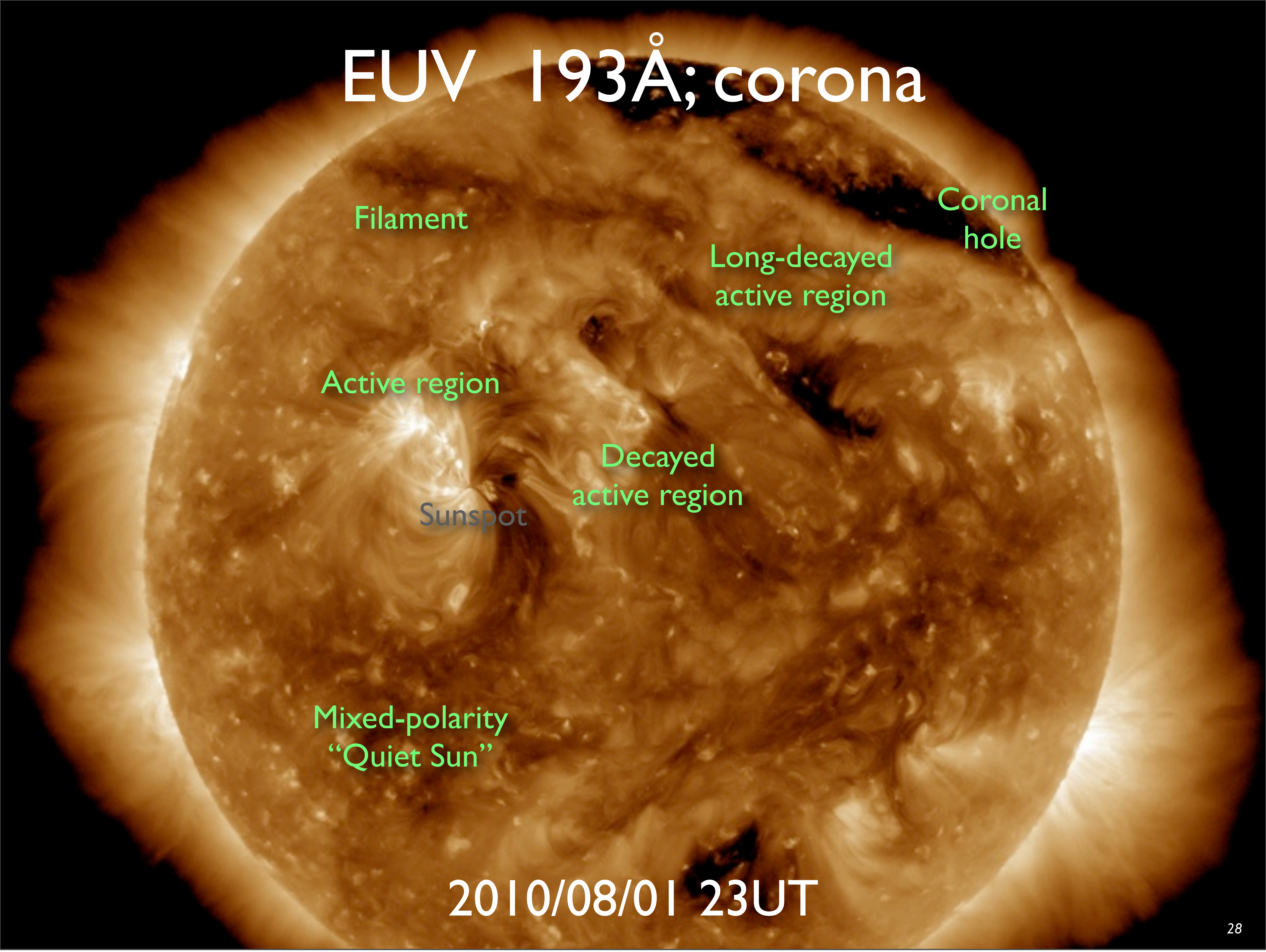
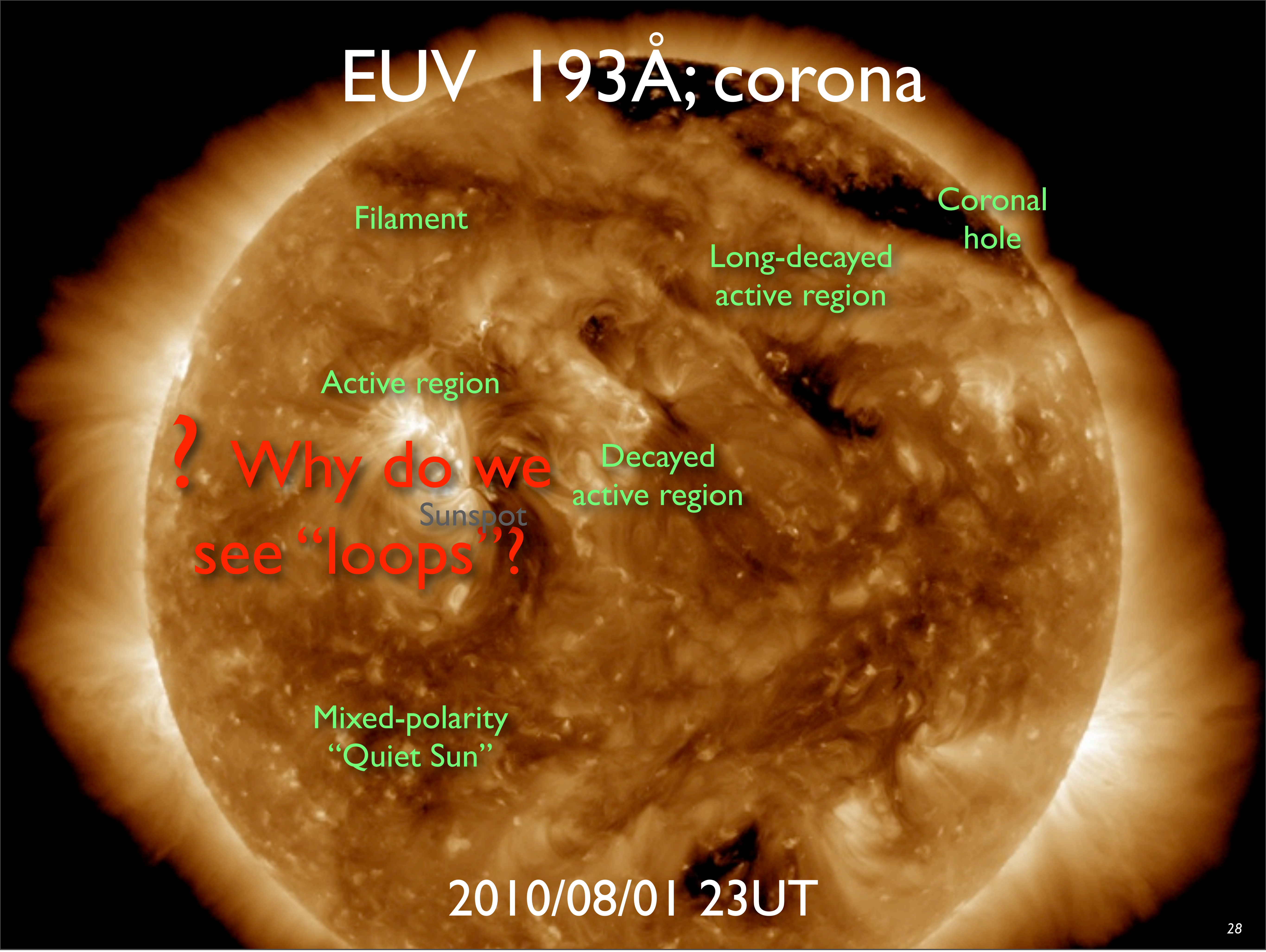
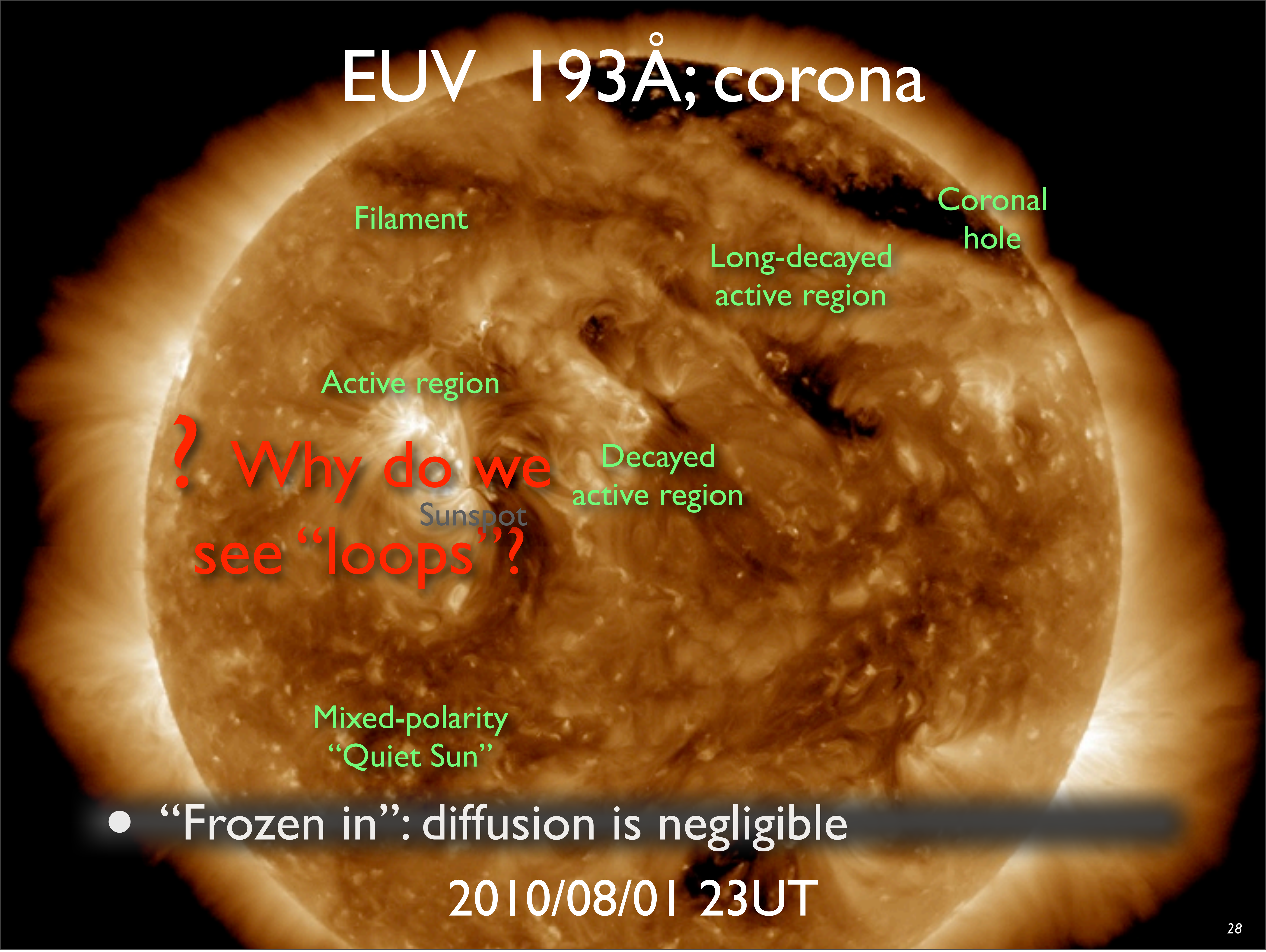

EUV 193Å; corona
Filament
Coronal
hole
Long-decayed
active region
Active region
Decayed
active region
Sunspot
Mixed-polarity
“Quiet Sun”
2010/08/01 23UT
28

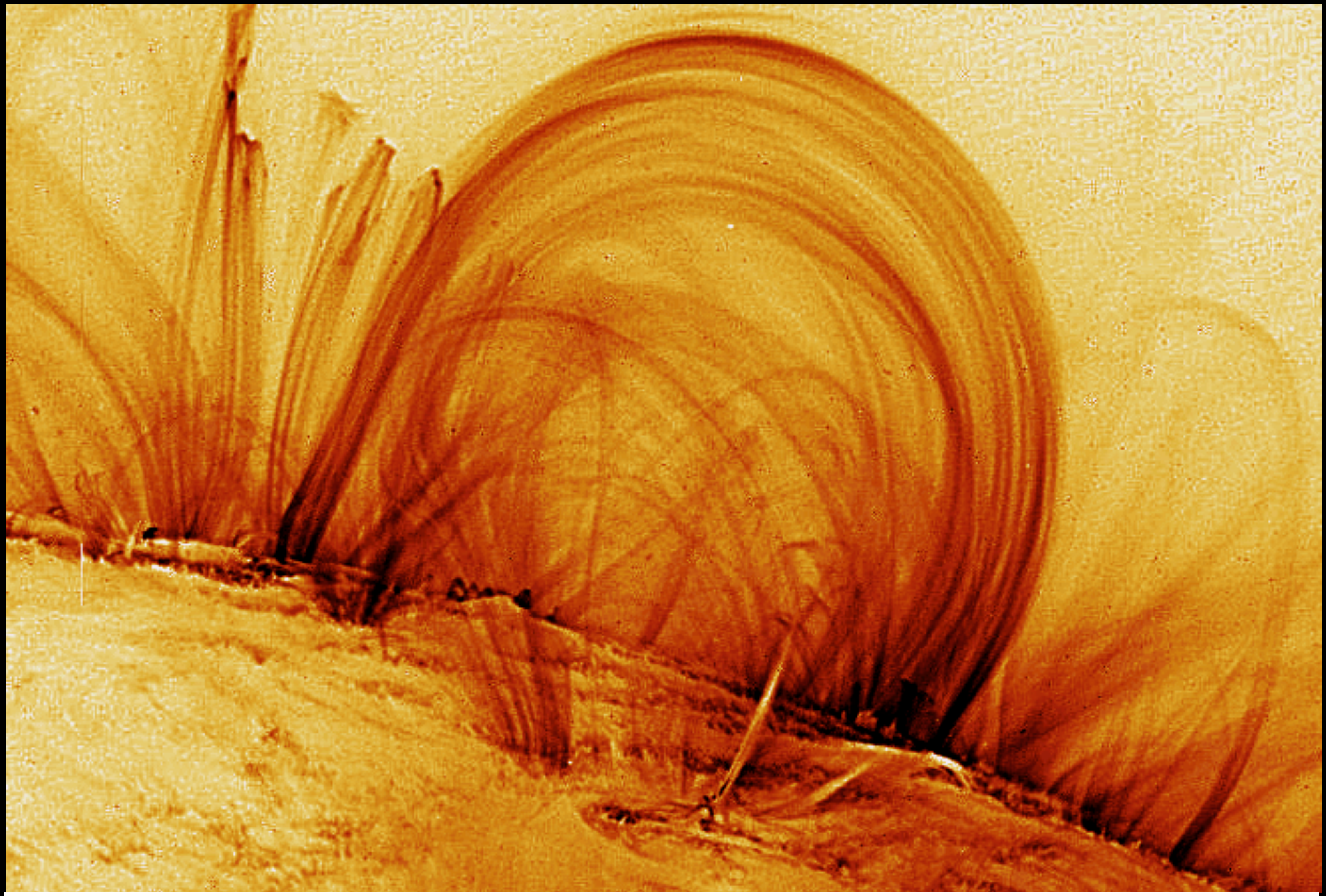

EUV 193Å; corona
Filament
Coronal
hole
Long-decayed
active region
Active region
? Why do we
see "loops"?
Sunspot
Decayed
active region
Mixed-polarity
"Quiet Sun"
2010/08/01 23UT

EUV 193Å; corona



- "Frozen in": diffusion is negligible

Coronal loop atmospheres

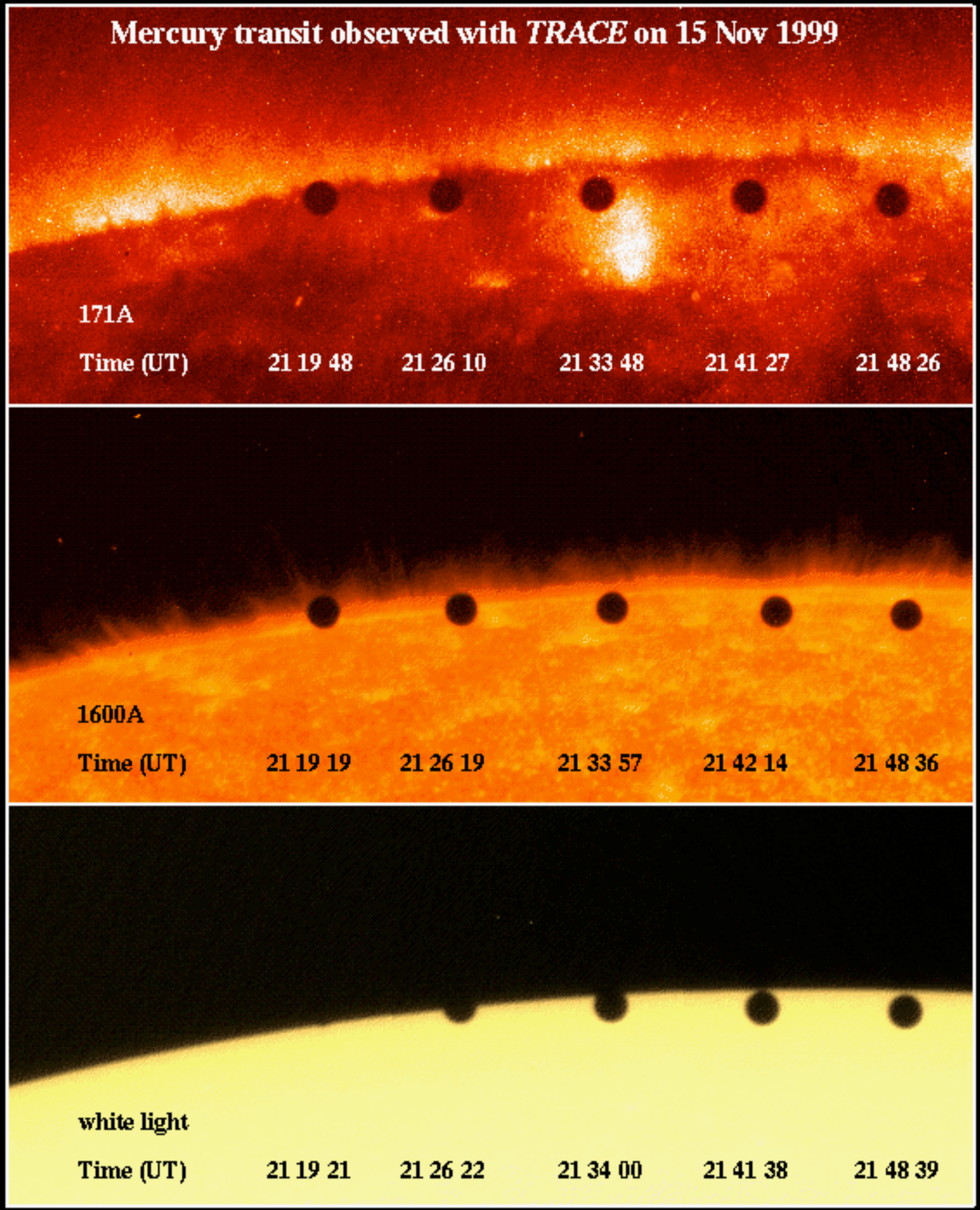


In quasi-static models, only three terms are involved in the energy balance at any point at a distance s above the base, measured along the loop: the local volume energy deposition, $\epsilon_{\rm heat}$, the conductive flux density, $F_{\rm c}$, along the loop, and the radiative losses per unit volume $\epsilon_{\rm rad} = n_{\rm e} n_{\rm H} \mathcal{P}(T, \ldots)$ for radiative losses from an optically thin plasma [Eq. (2.59)]. Then:

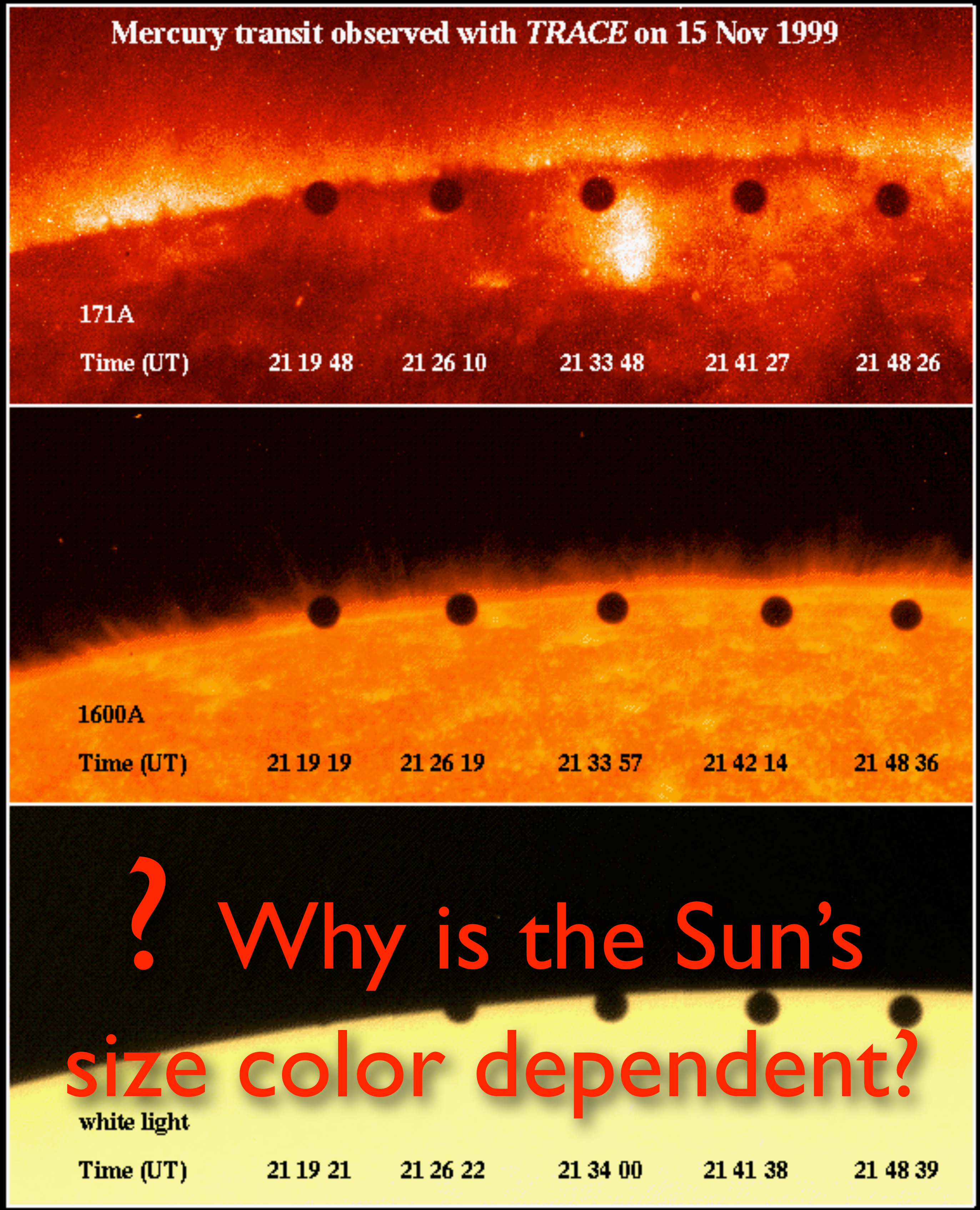
$$\epsilon_{\rm heat}(T, n_{\rm e}, s, \ldots) = \frac{1}{A(s)} \frac{d}{ds} \left[A(s) \kappa_{\rm c} \frac{dT(s)}{ds} \right] + n_{\rm e} n_{\rm H} \mathcal{P}(T, n_{\rm e}, A_{\rm i}, \ldots). \qquad (8.20)$$

In general, the loop cross section $A(s)$ is expected to change along the loop. The classical heat conductivity $\kappa_{\rm c}$ equals 8×10^{-7} erg cm^{-1} s^{-1} K$^{-7/2}$ (Spitzer, 1962).

Solar atmosphere > size

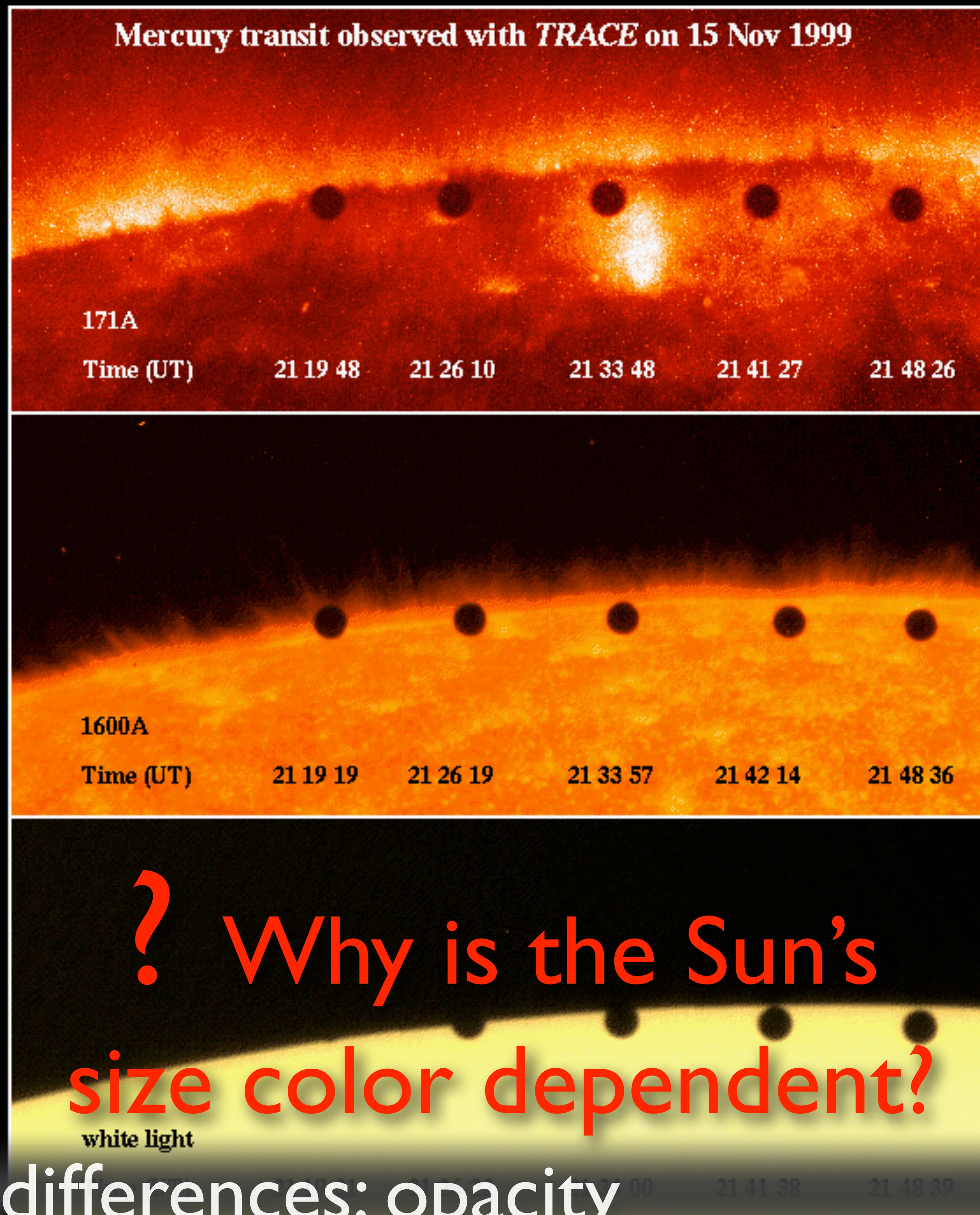


Solar atmosphere > size



Saturday, July 13, 2013

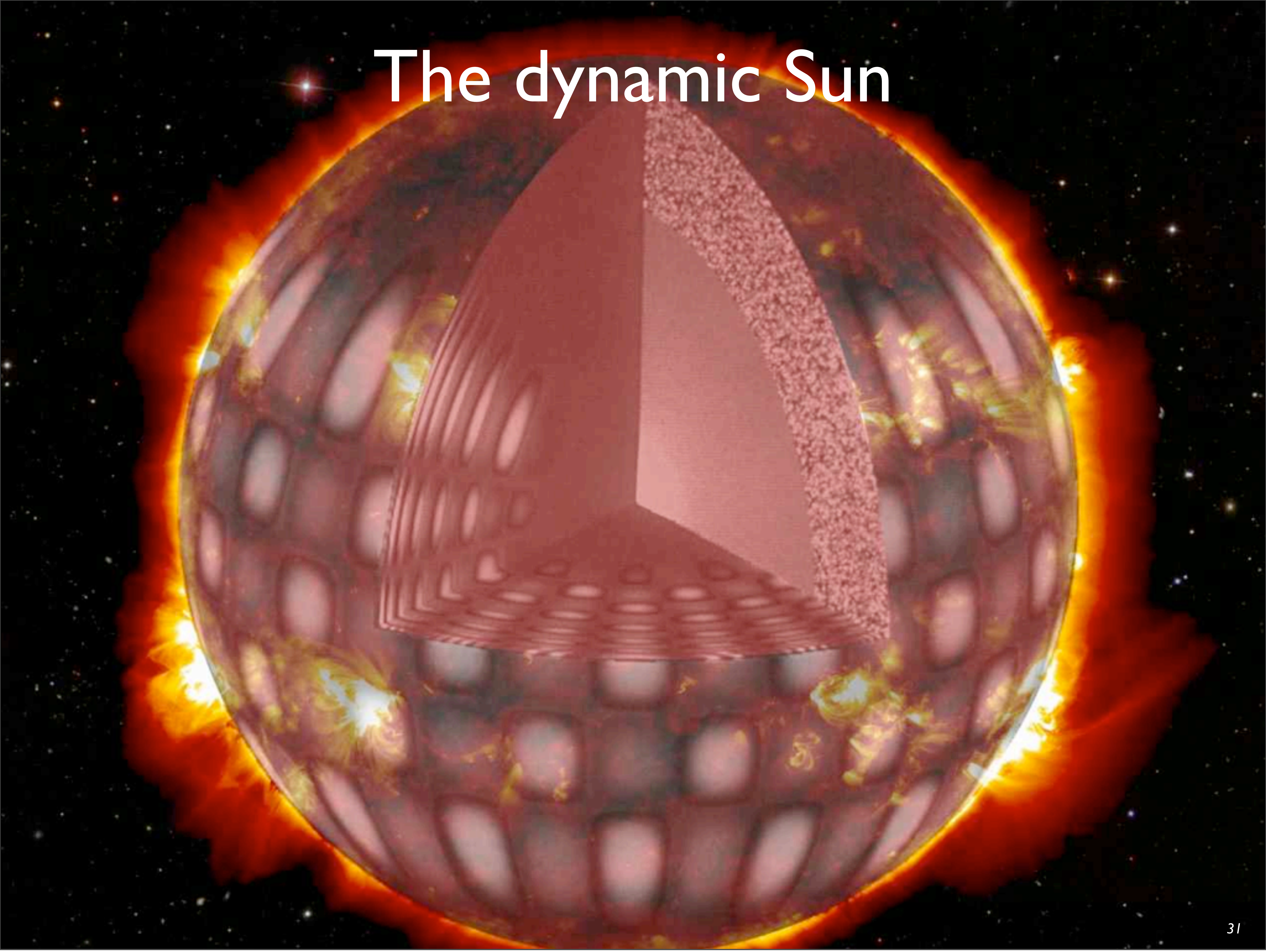
Solar atmosphere > size



? Why is the Sun's size color dependent?

- Radius differences: opacity

The dynamic Sun



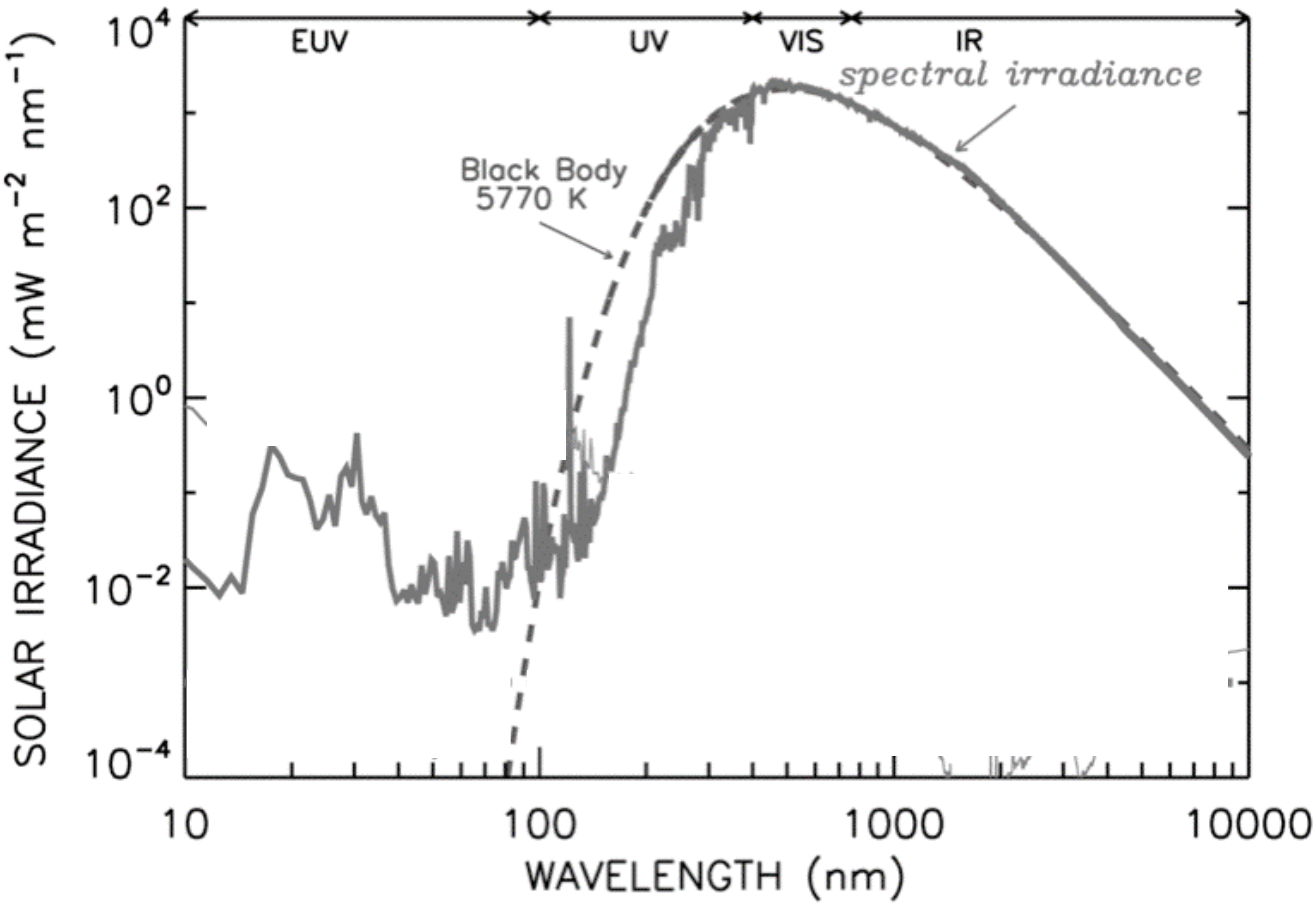


Fig. 10.1. Comparison of the solar spectrum and the black body spectrum for radiation at 5770 K (the approximate temperature of the Sun's visible surface).

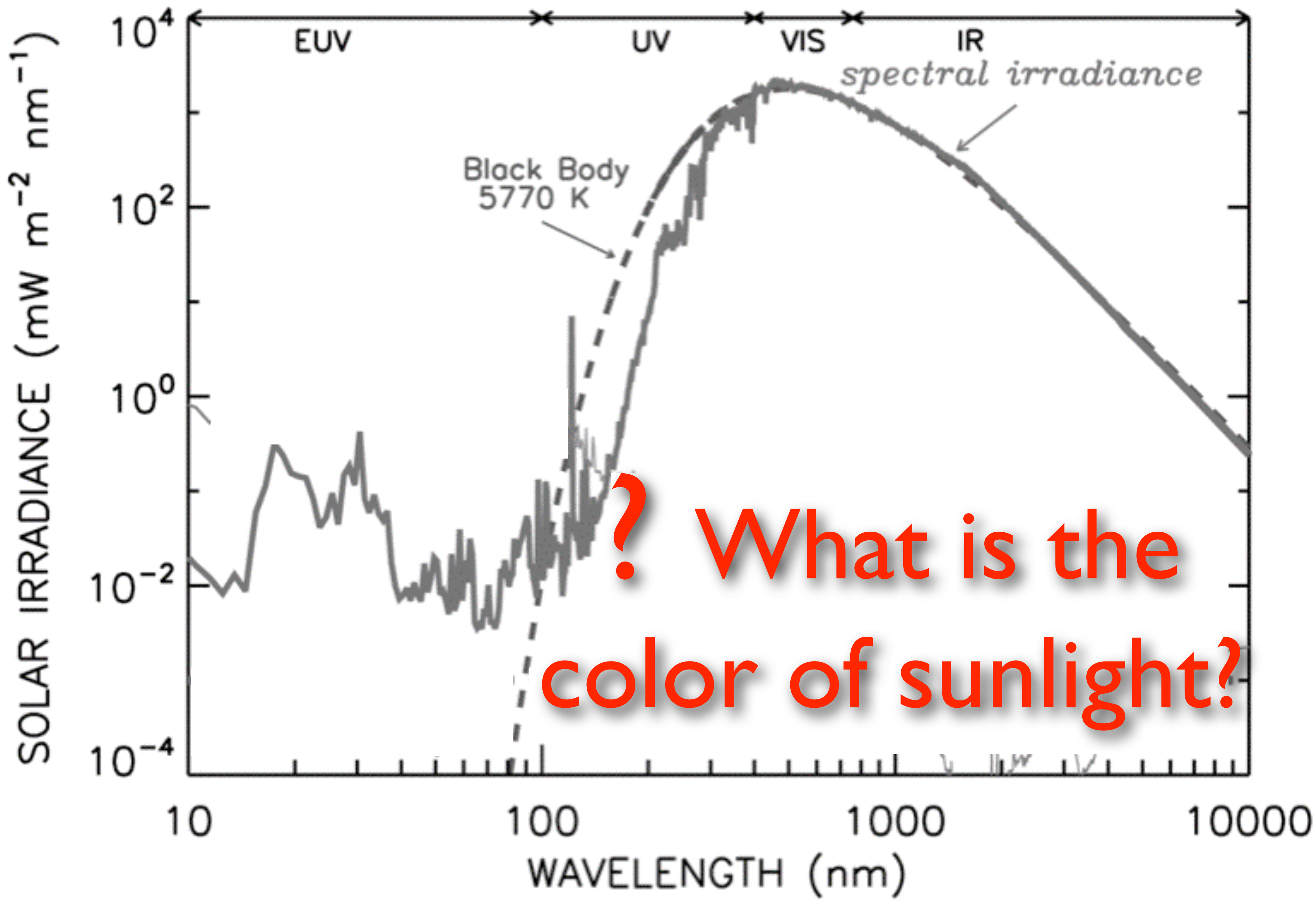


Fig. 10.1. Comparison of the solar spectrum and the black body spectrum for radiation at 5770 K (the approximate temperature of the Sun's visible surface).

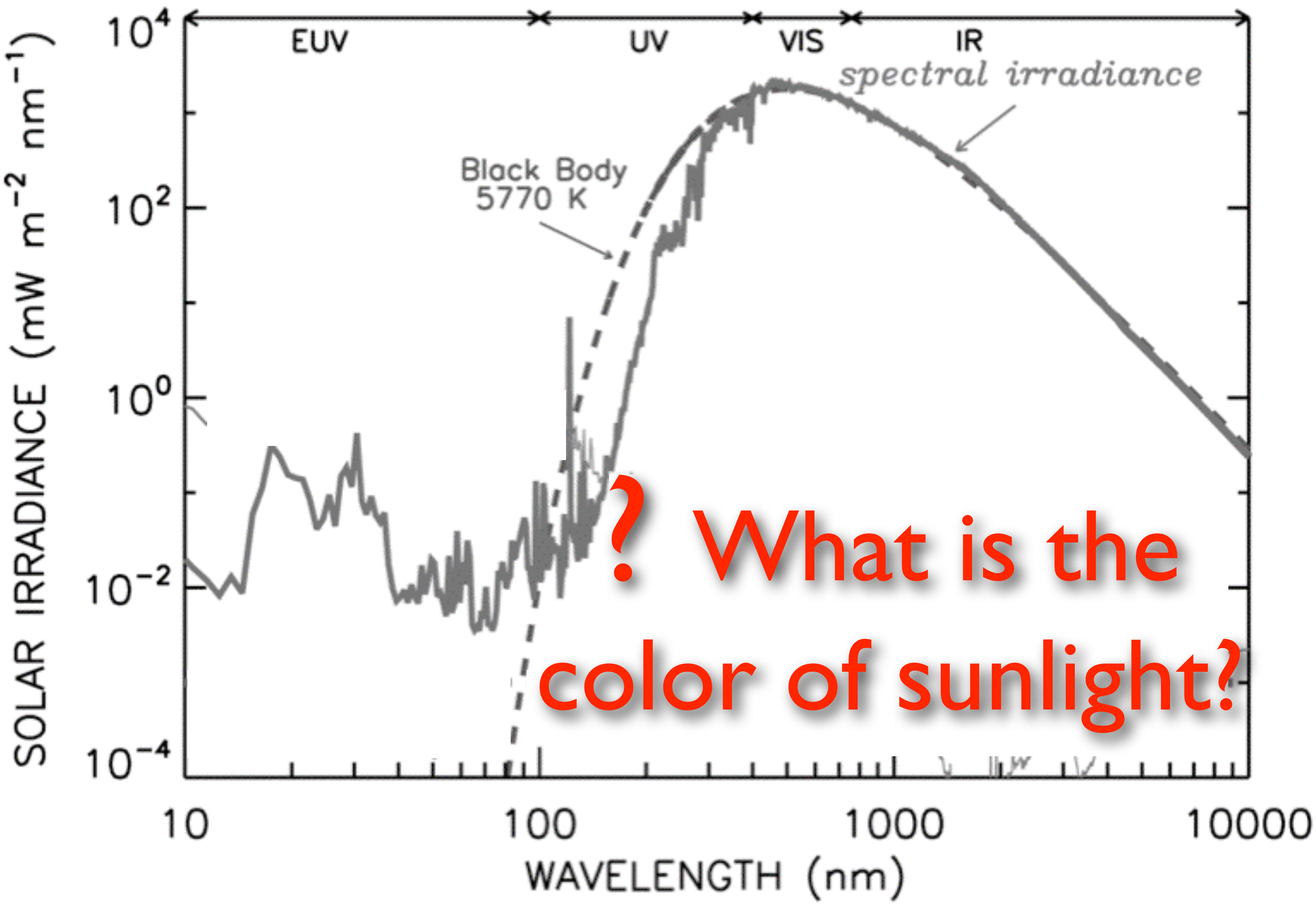


Fig. 10.1. Comparison of the solar spectrum and the black body spectrum for radiation at 5770 K (the approximate temperature of the Sun's visible surface).

- Color of sunlight: white

Topics

- Solar Spectral Irradiance:
  - Atmospheric structure
    - Static atmosphere
    - Waves
    - Magnetic field
      - Photosphere
      - Corona
      - Chromosphere
  - Gradual changes: solar cycle
  - Impulsive changes: flares/eruptions
  - Integration: solar spectral irradiance
- Solar Wind:
  - Background wind:
    - Basics of the solar wind
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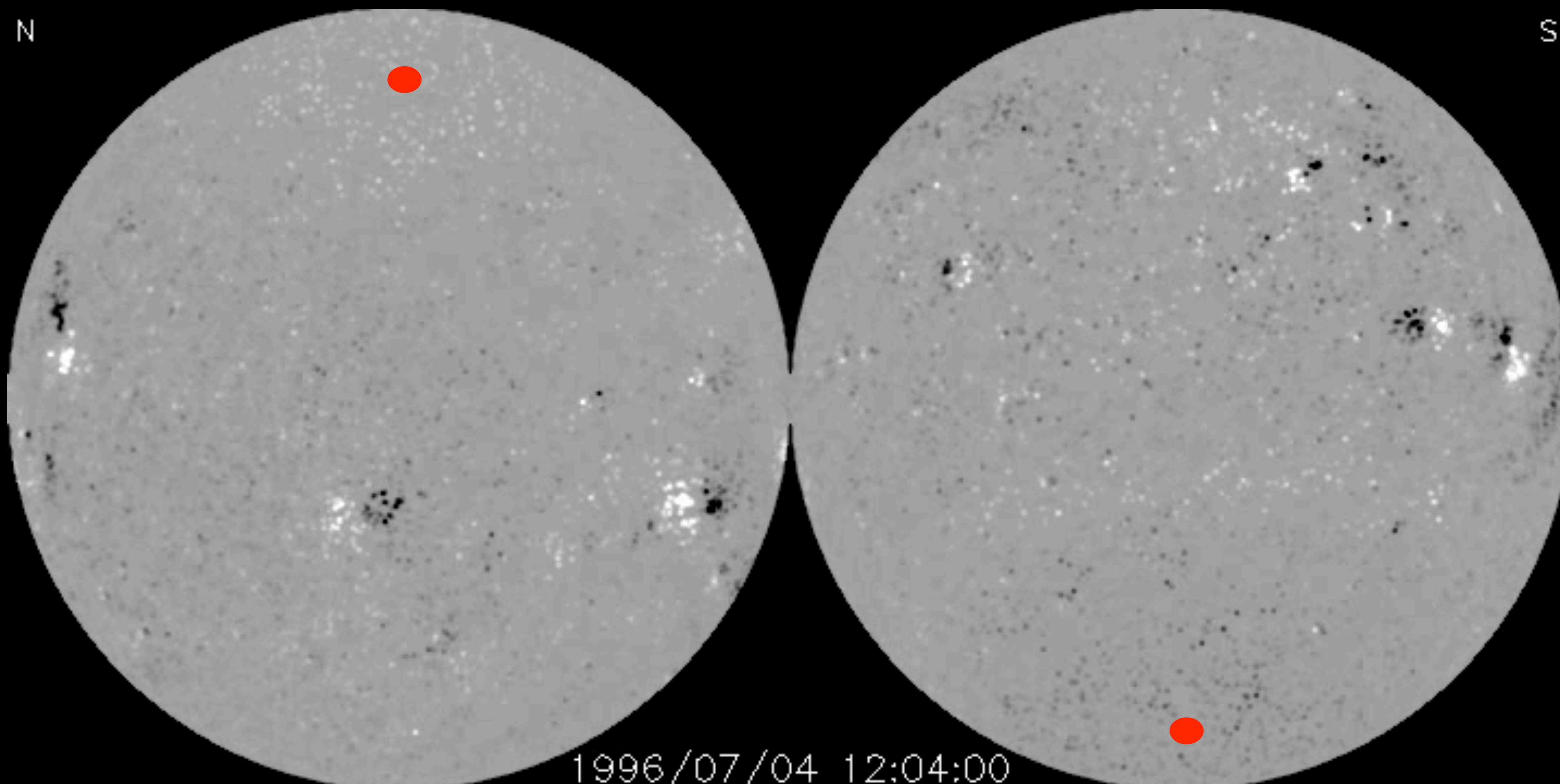
    - Magnetic field, and angular momentum loss
  - Impulsive/eruptive events and the solar wind
  - Integration: solar wind

16-y of magnetogram assimilation,

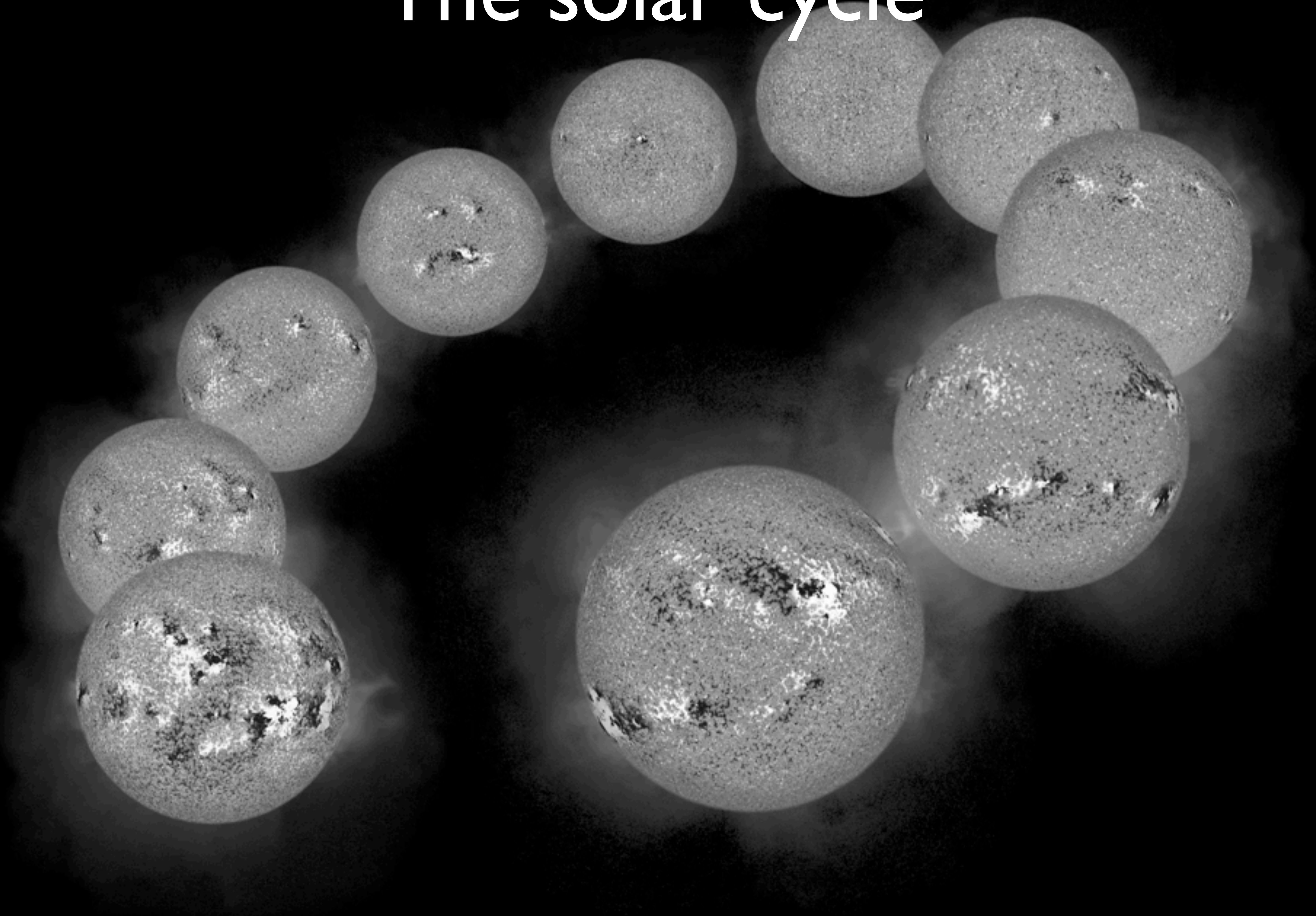
viewed as Solar Orbiter may see it

Lat. +30°; Car.r long. 0° *Lat. -30°; Carr. long. 180°*

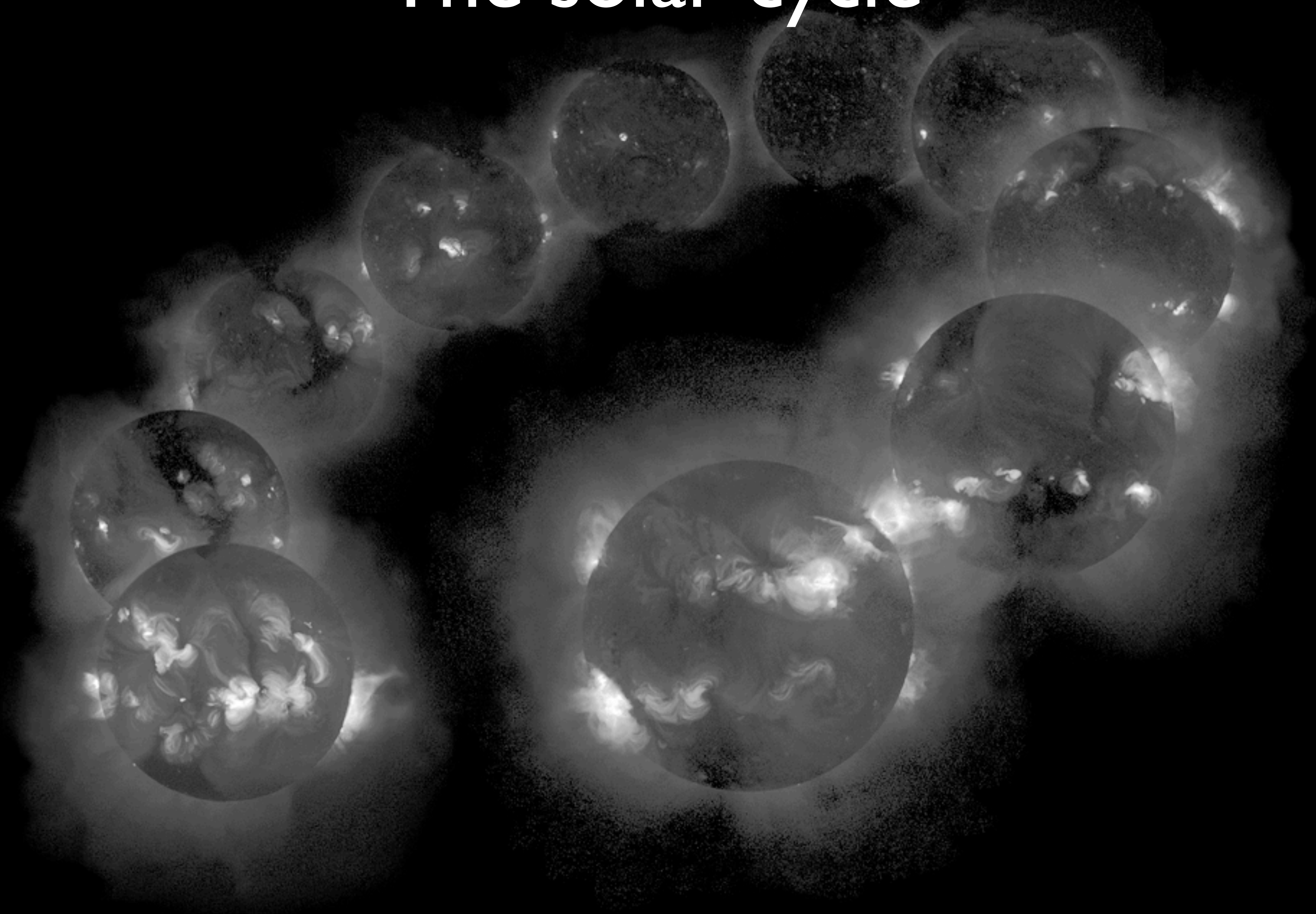


Lat. -60° – +60° assimilated; high-latitude field advected by transport code

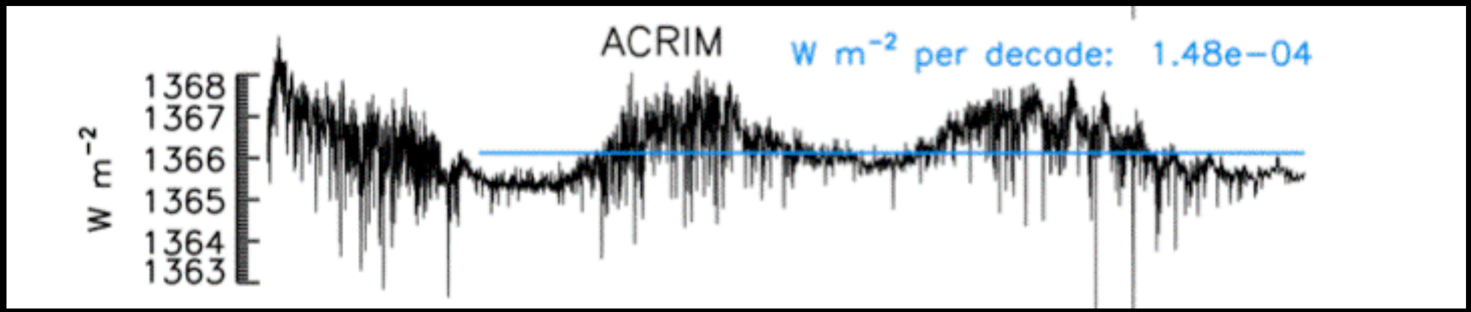
The solar cycle



The solar cycle

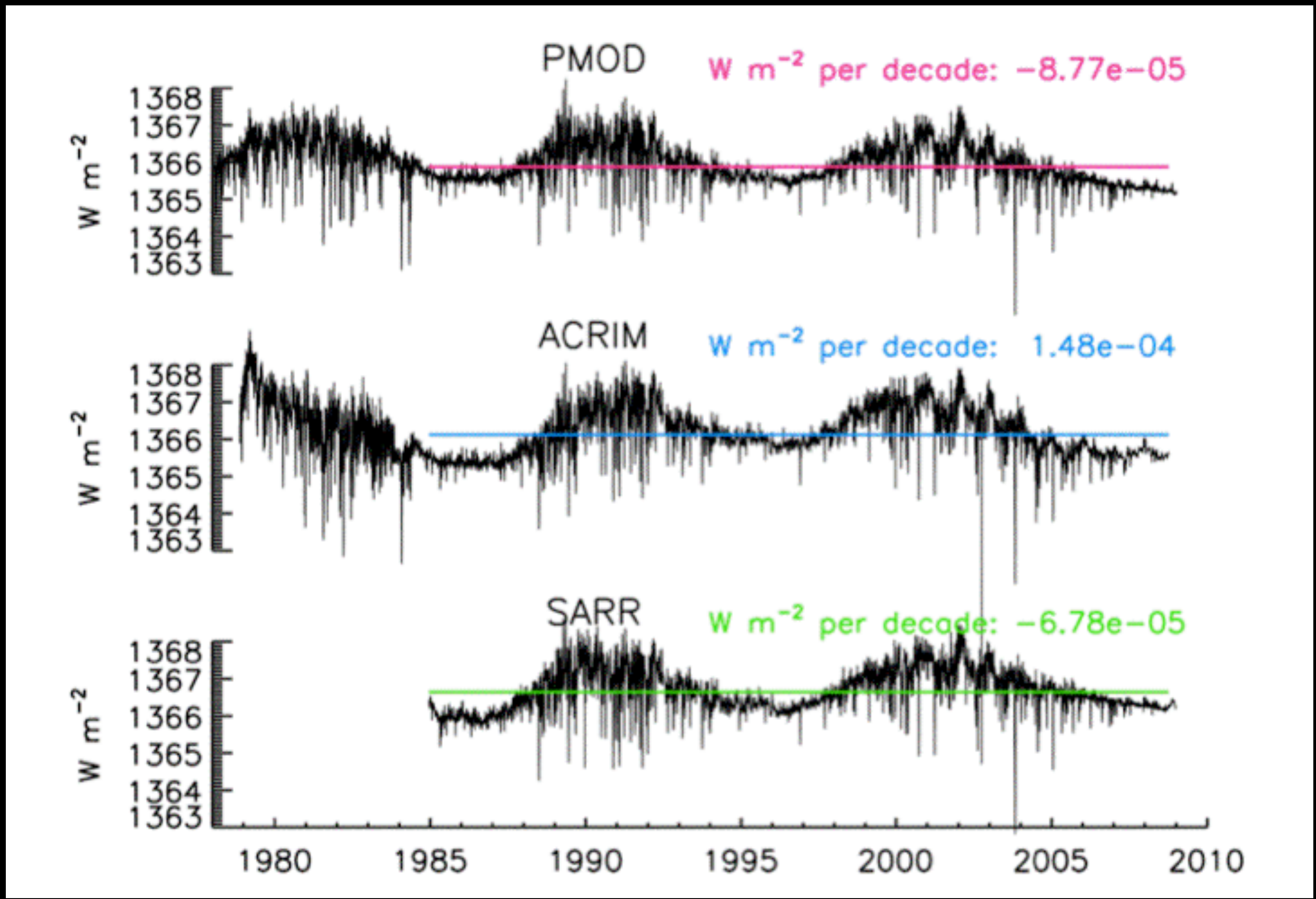


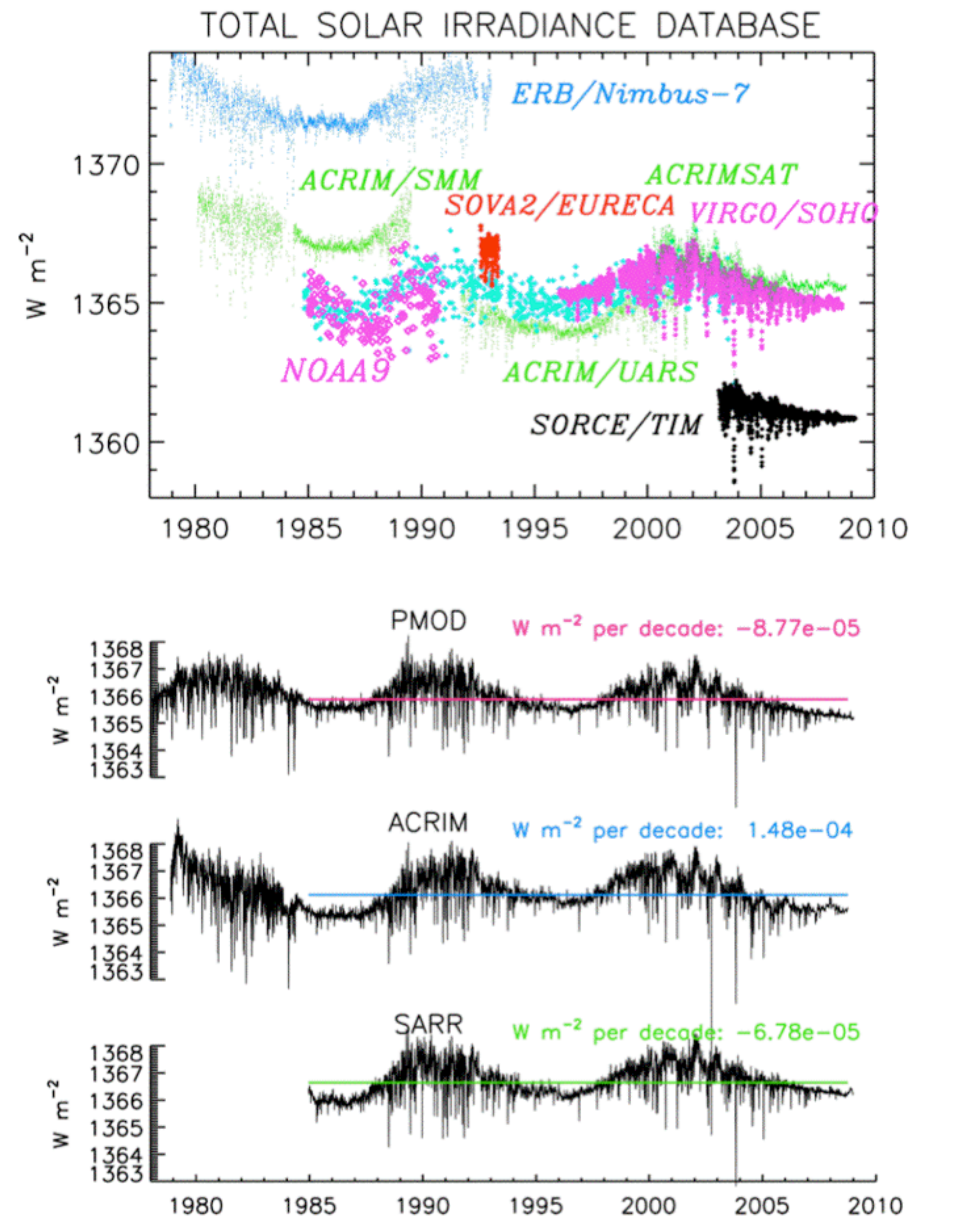
TSI(t)



ACRIM
W m⁻² per decade: 1.48e-04
1368
1367
1366
1365
1364
1363
W m⁻²

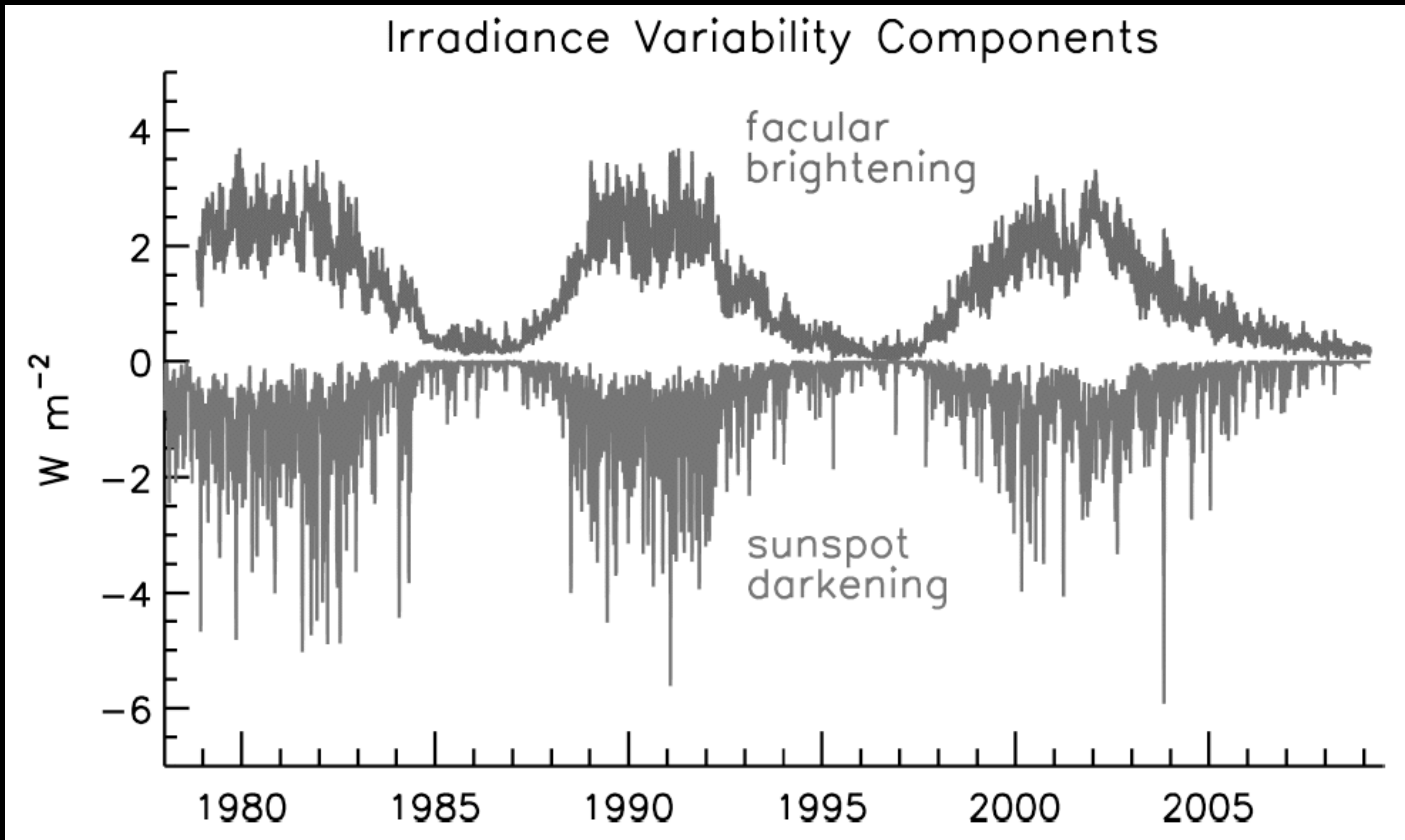
TSI(t)


PMOD
W m⁻² per decade: −8.77e−05
ACRIM
W m⁻² per decade: 1.48e−04
SARR
W m⁻² per decade: −6.78e−05
W m⁻²
1368
1367
1366
1365
1364
1363
1980
1985
1990
1995
2000
2005
2010



TOTAL SOLAR IRRADIANCE DATABASE
ERB/Nimbus-7
ACRIM/SMM
ACRIMSAT
SOVA2/EURECA
VIRGO/SOHO
NOAA9
ACRIM/UARS
SORCE/TIM
W m^-2
1370
1365
1360
1980
1985
1990
1995
2000
2005
2010
PMOD
W m^-2 per decade: -8.77e-05
ACRIM
W m^-2 per decade: 1.48e-04
SARR
W m^-2 per decade: -6.78e-05
1368
1367
1366
1365
1364
1363

Spots, pores, faculae, ... and TSI(t)



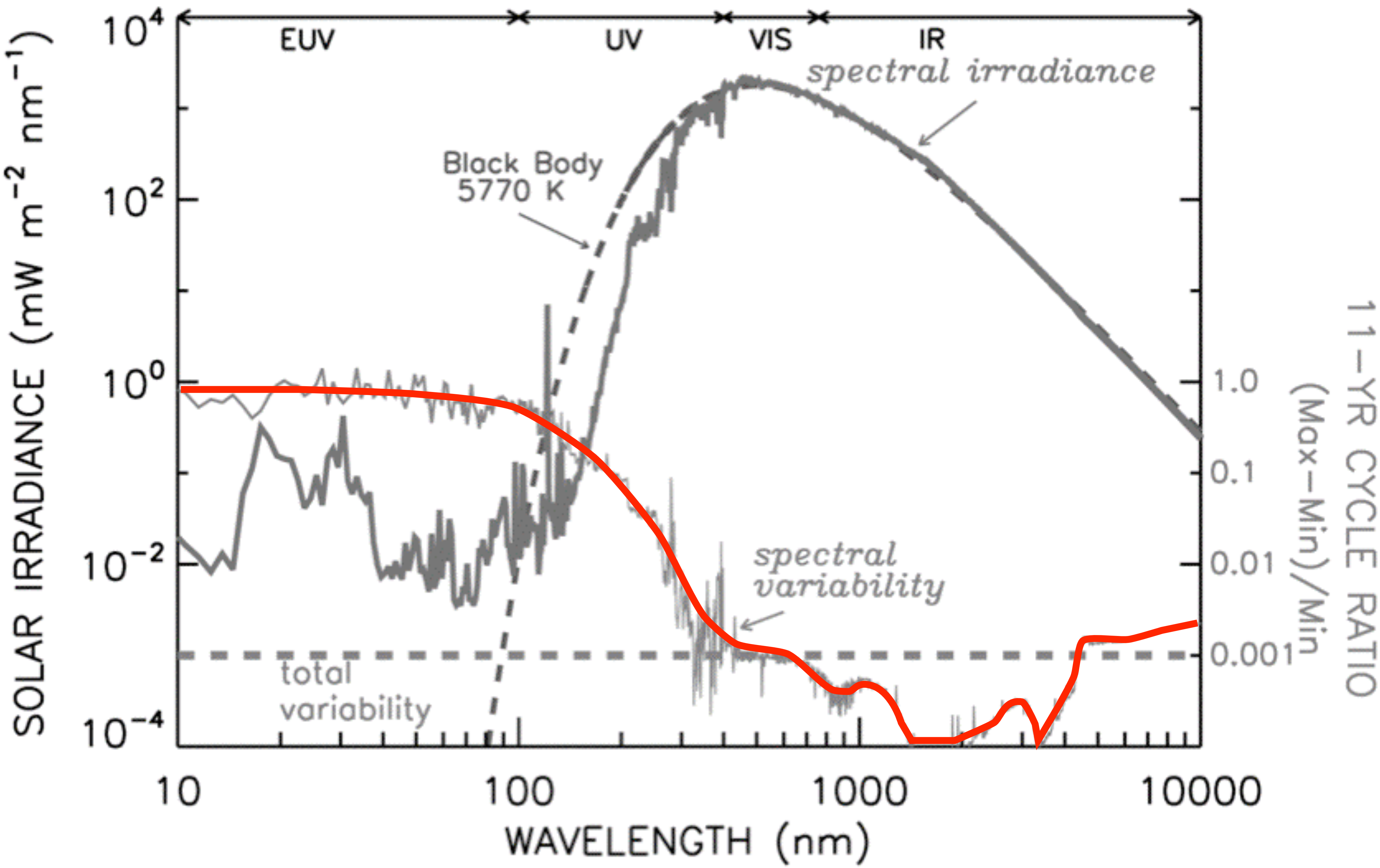


Fig. 10.1. Comparison of the solar spectrum and the black body spectrum for radiation at 5770 K (the approximate temperature of the Sun's visible surface). Also shown is an estimate of the variability of the solar spectrum during the 11-y solar cycle, inferred from measurements (at wavelength below 400 nm) and models (at longer wavelengths) and, for reference (dashed line), the solar cycle 0.1% change in the total solar irradiance.

Topics

- Solar Spectral Irradiance:
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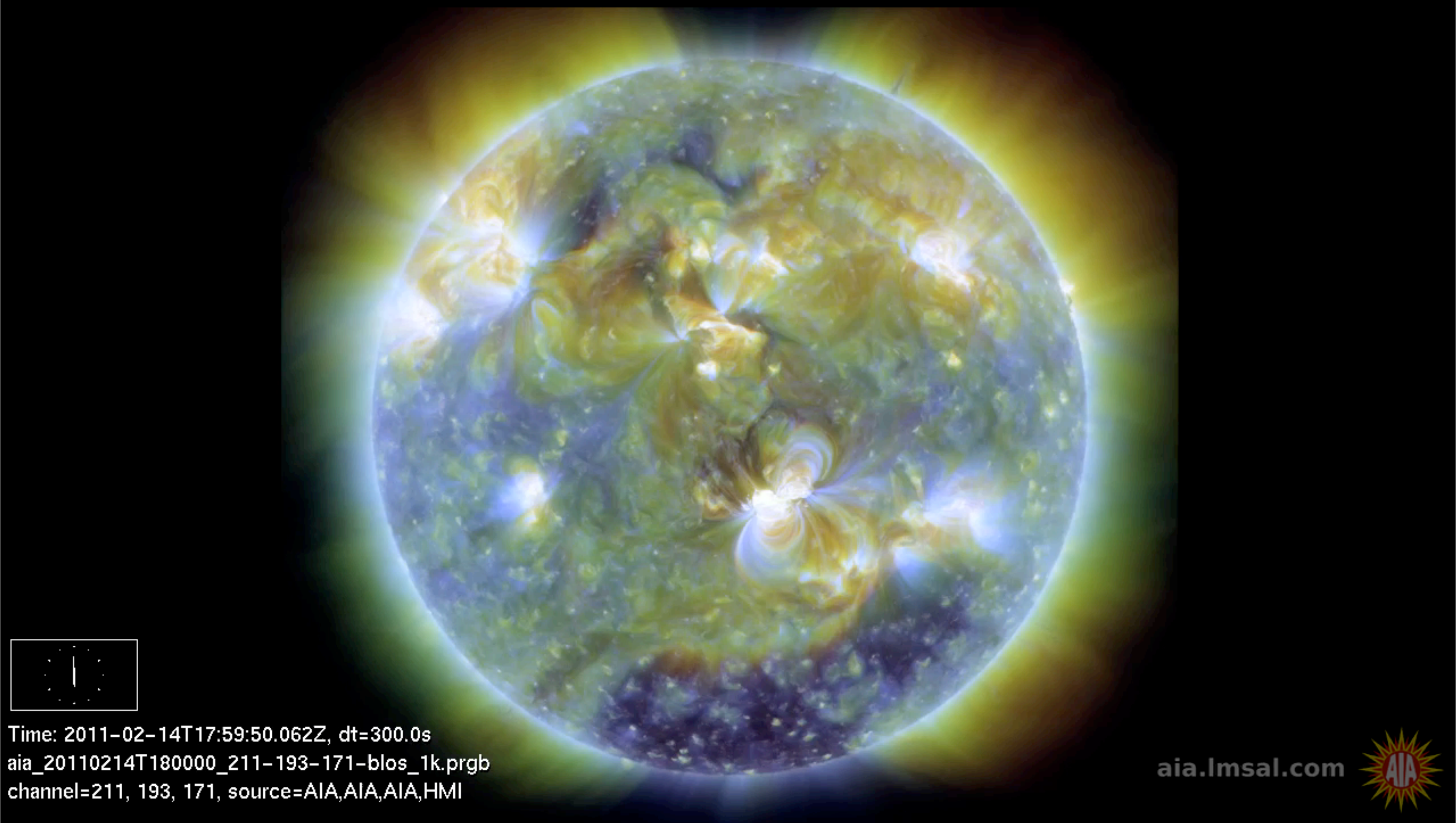
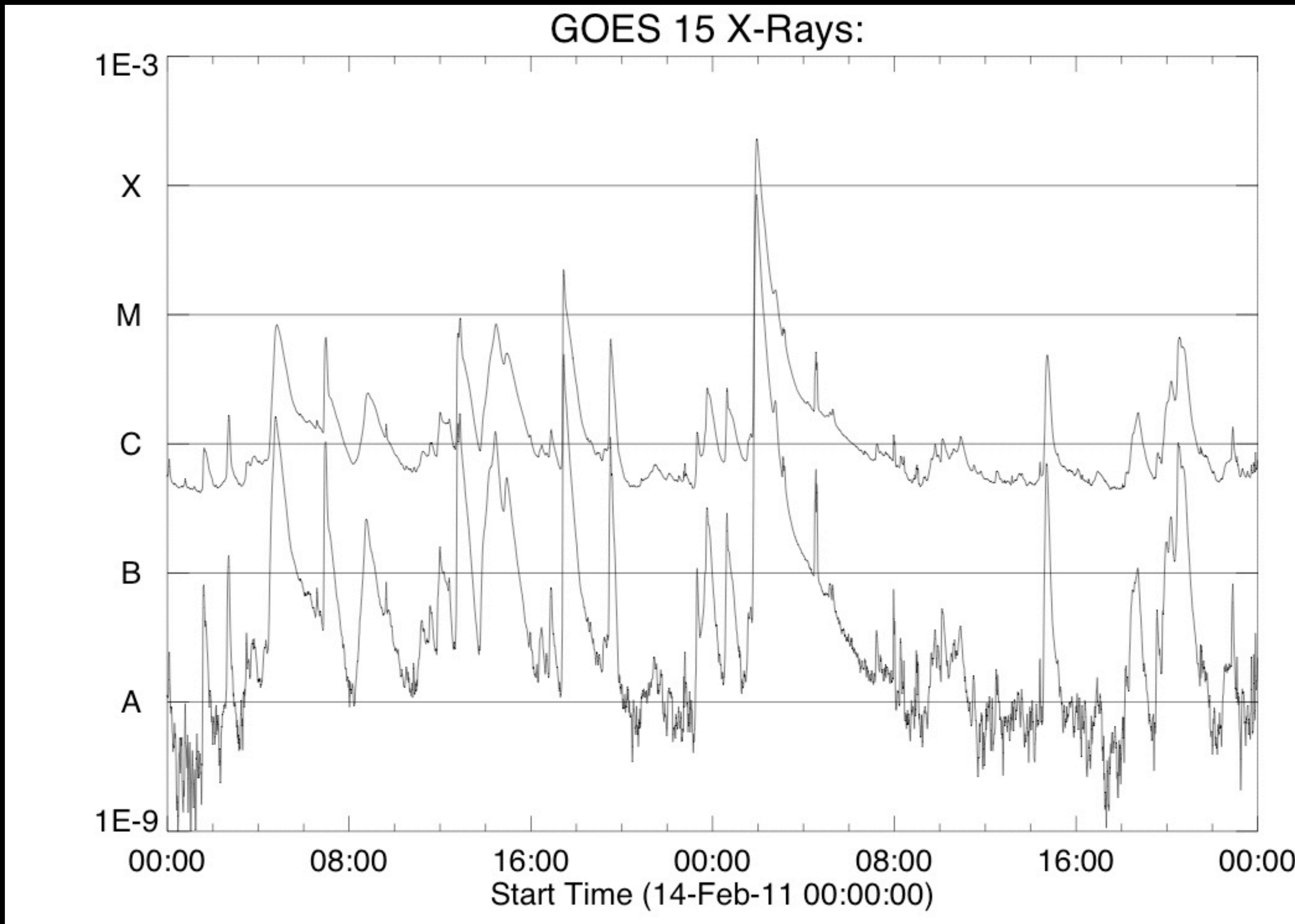
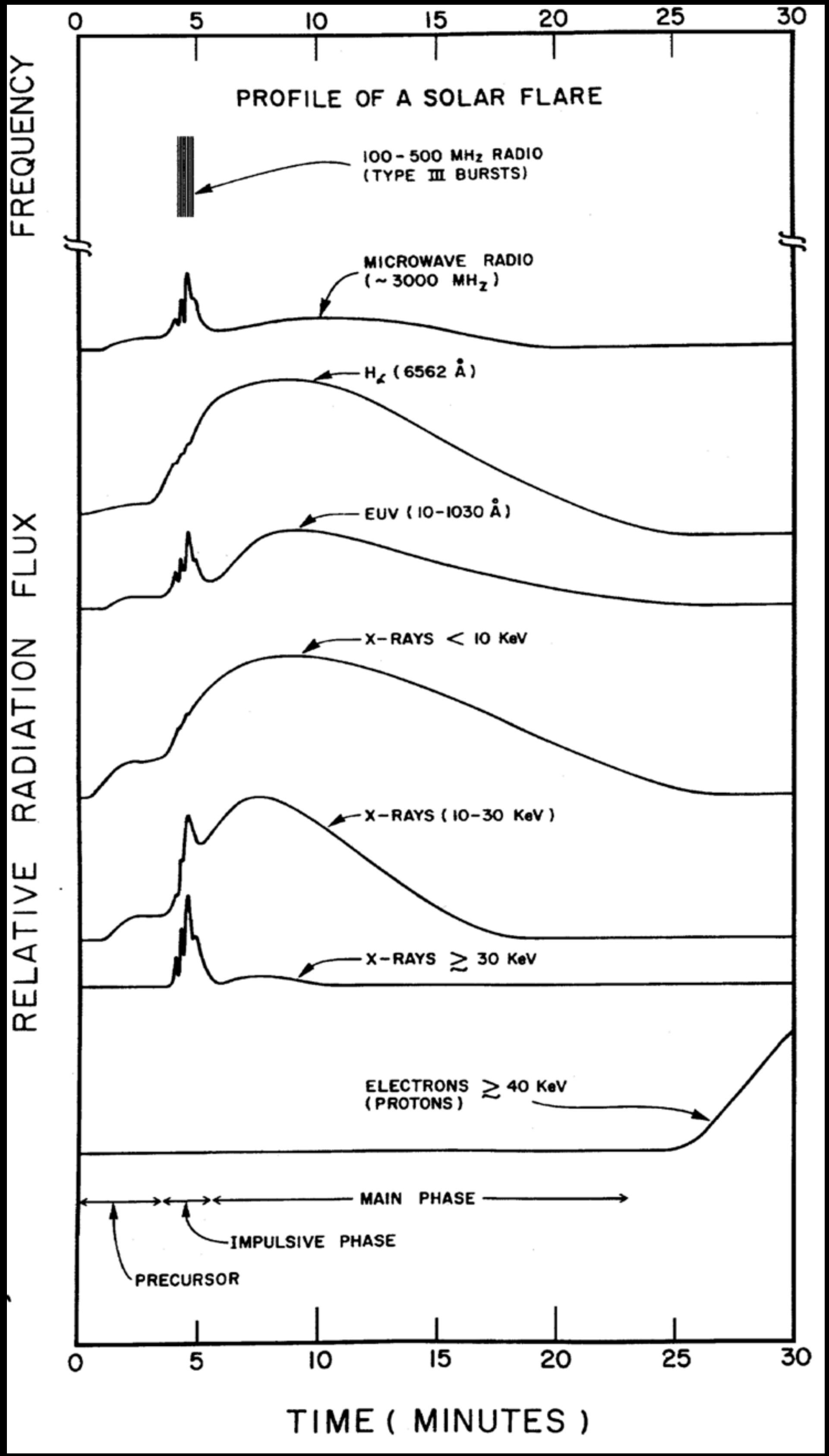
Dynamic atmosphere



X-ray flaring: rapid, high contrast



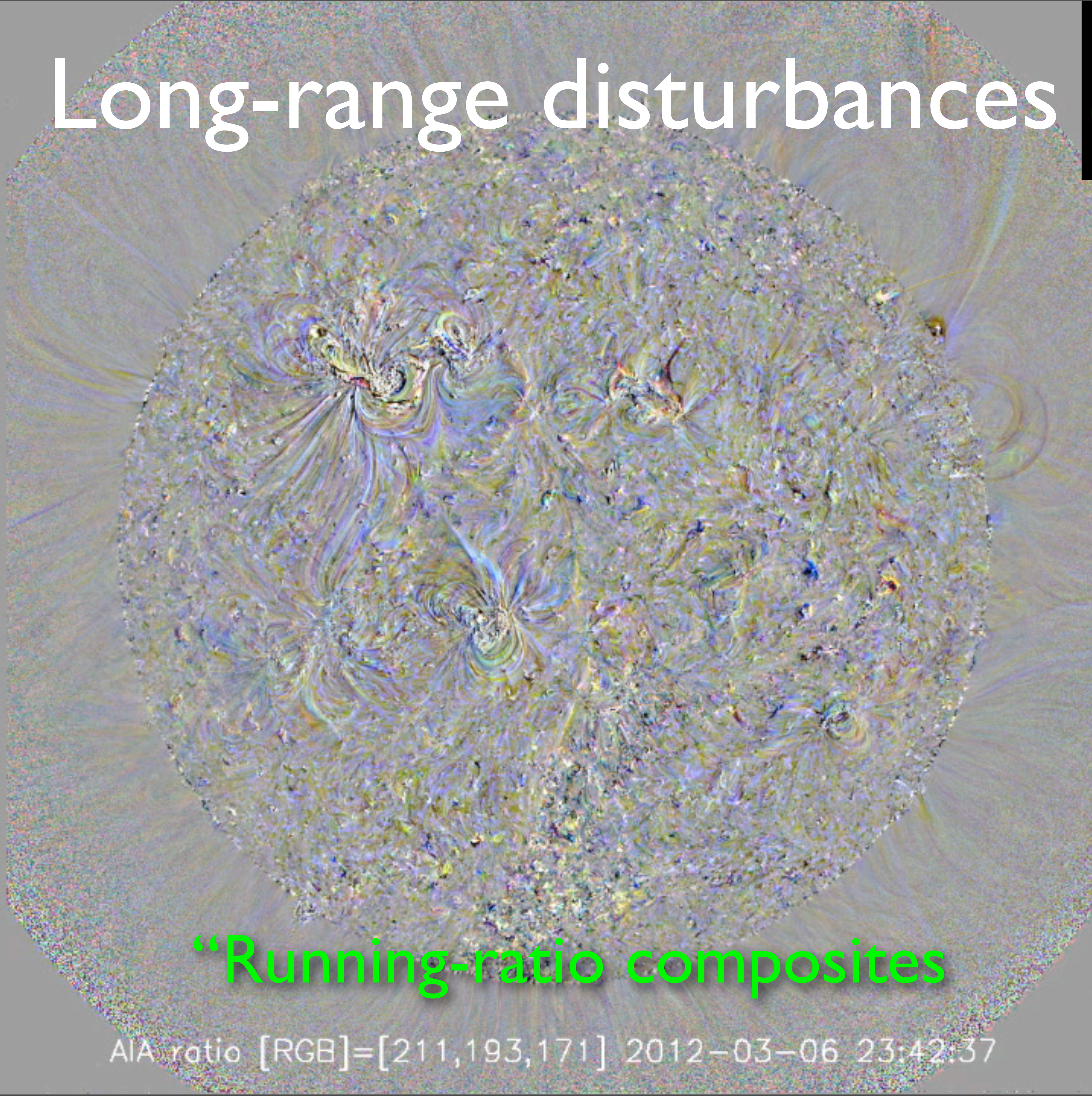
Flare evolution over the spectrum

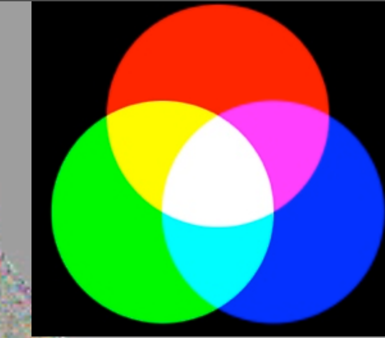


Long-range disturbances

"Running-ratio composites

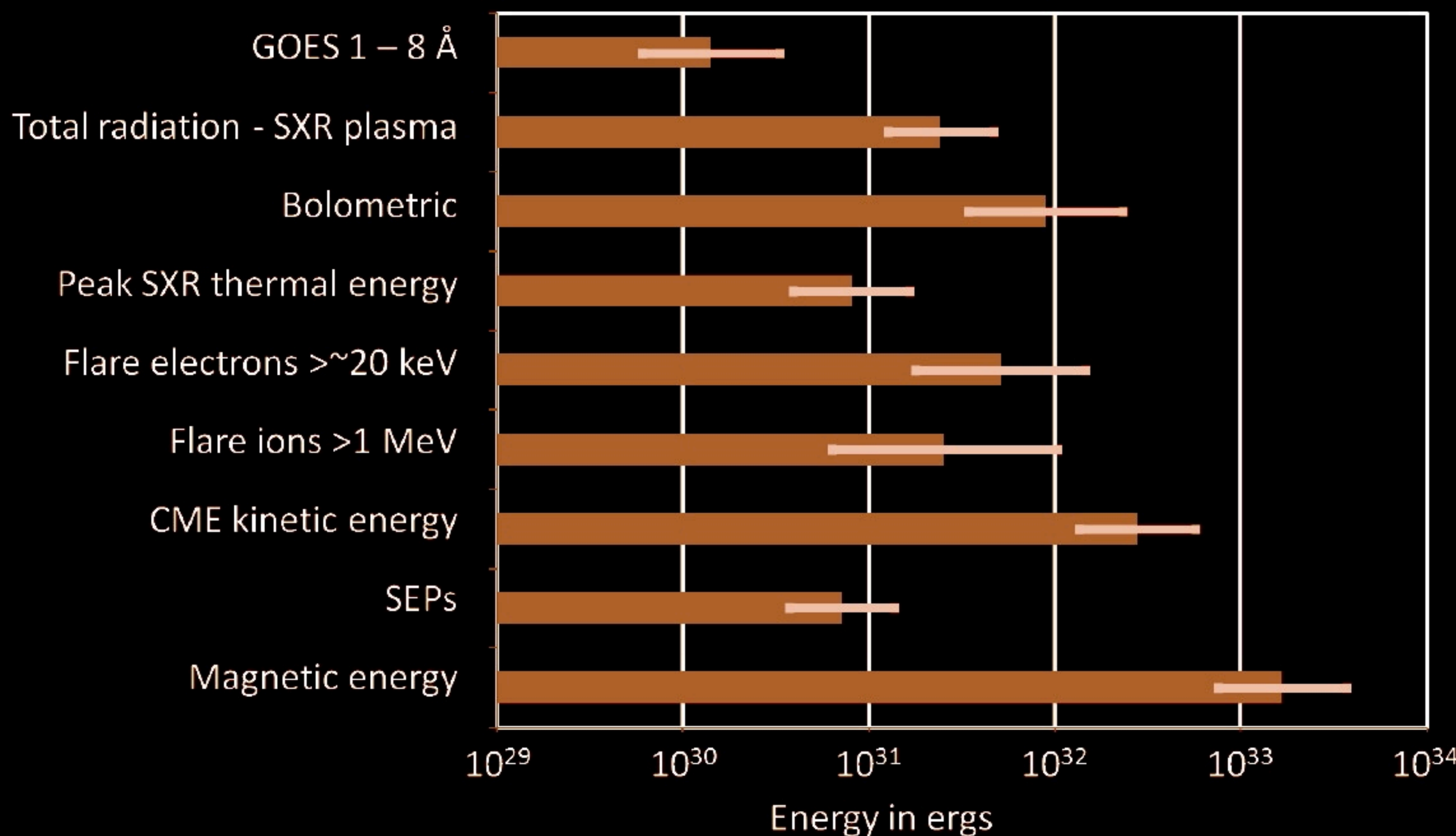
Long-range disturbances





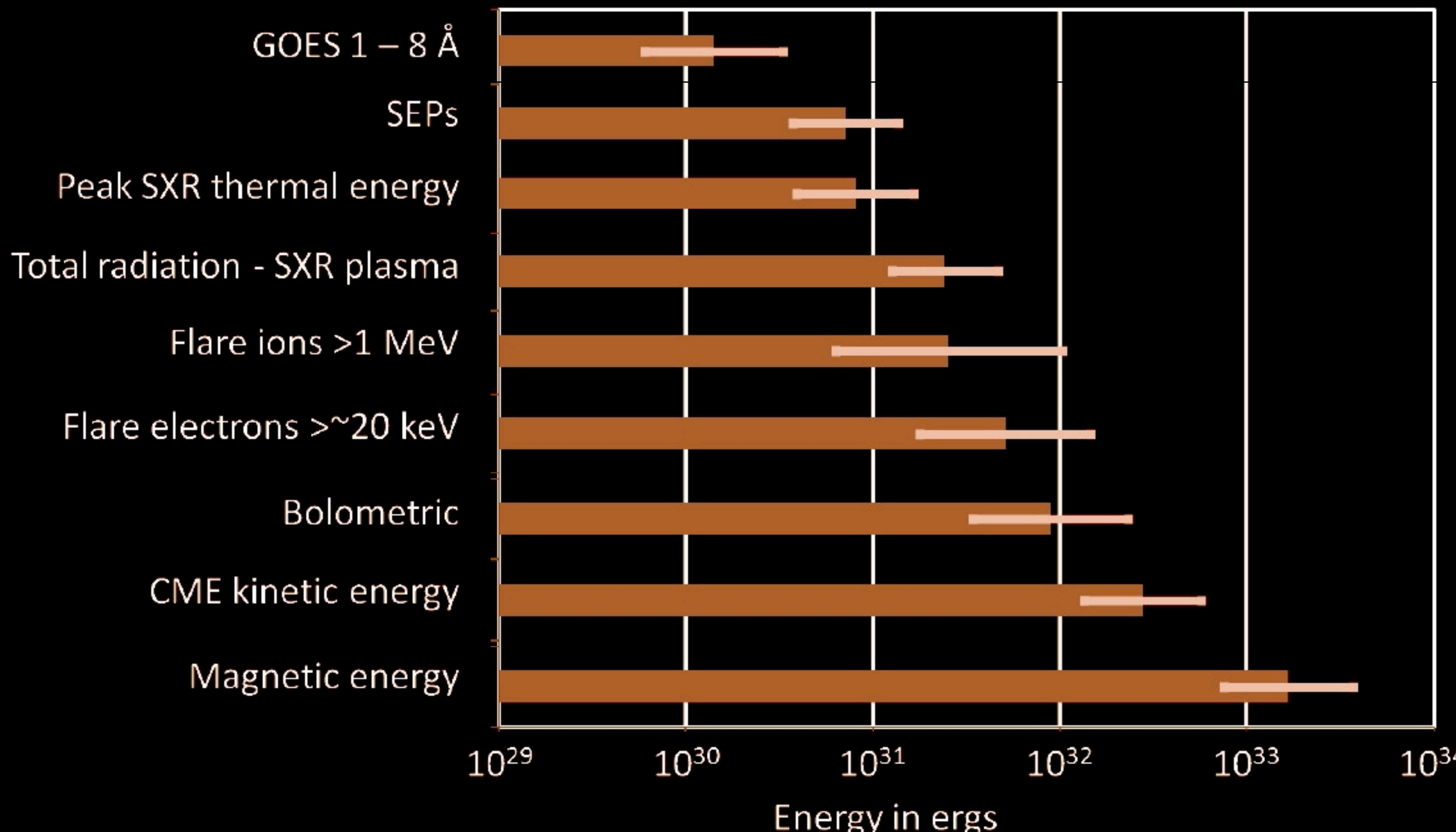
“Running-ratio composites

Flare energy: mostly WL and kinetic



From Emslie et al. (2012): values for X3, X3, X4, X7, X8, X10 flares.

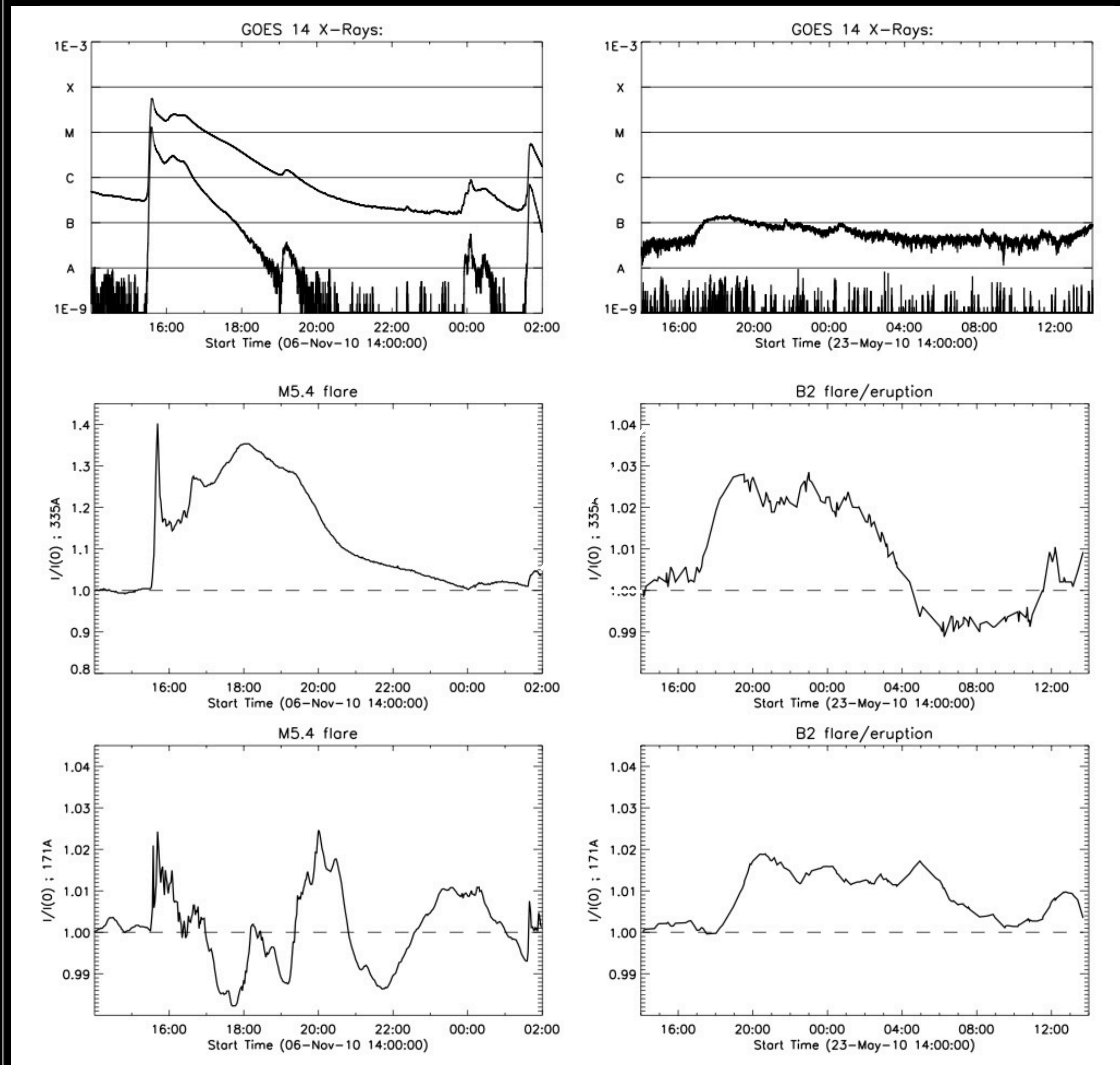
Flare energy: mostly WL and kinetic



From Emslie et al. (2012): values for X3, X3, X4, X7, X8, X10 flares.

Chameleon behavior of solar storms

- GOES class provides a very uncertain measure of the energy in a solar coronal storm event.
- Example: GOES classes for an active-region flare and quiet-Sun filament eruption *differ by factor of ~250 for comparable 'bolometric' energies in the X-ray/(E)UV domain.*



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Solar spectral/total irradiance

- TSI(t) in phase with sunspot cycle: faculae outshine sunspots (on average, not when spots are near disk center).
- TSI(t)/SSI(t) variations attributable to atmospheric magnetic field, with little/no effect of internal changes.
- Long-term trends in TSI(t) and SSI(t) in visible light: to be determined.
- Explosive events: at short wavelengtsh very strong contrasts but small contributions to TSI; most energy emitted in visible light, where that hardly makes a difference.
- (X)(E)UV changes associated with "closed field": reconstructing (T)(S)SI(t) by terrestrial proxies remains uncertain, debated, and to be explored.

Solar spectral irradiance and wind over time scales up to a decade

Karel Schrijver
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Heliophysics Summer School 2013

Topics

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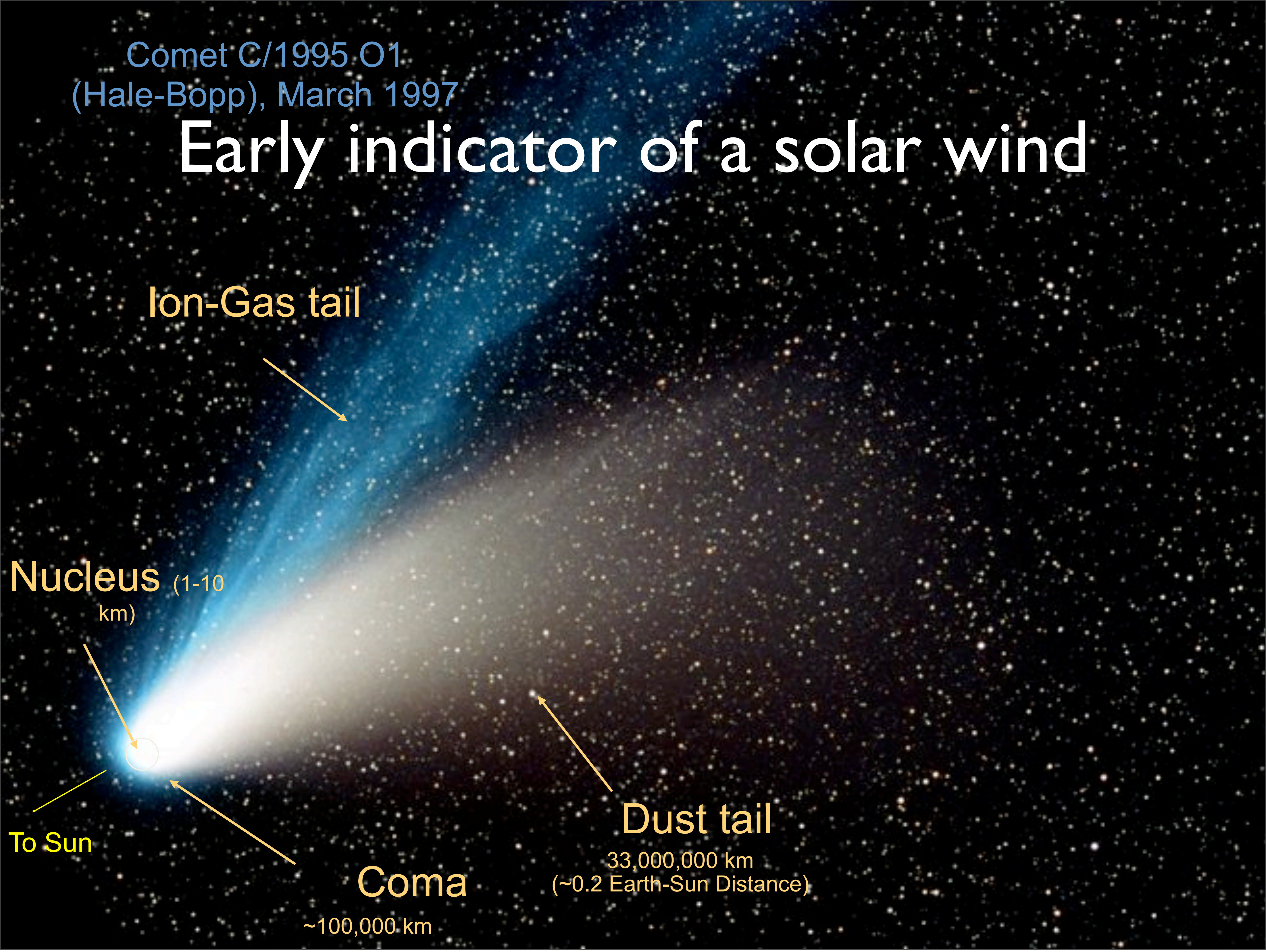
Early indicator of a solar wind



Solar wind parameters

Table 9.1. *Basic parameters of the fast and slow solar wind (based on Holzer (2005) and Feldman* et al. *(1977) and references cited therein). See also Ch. 11.3 and Table 11.1.*

Property (1 AU)	Slow wind	Fast wind
Speed	430 ± 100 km/s	$700 - 900$ km/s
Density	$\simeq 10$ cm^{-3}	$\simeq 3$ cm^{-3}
Flux	$(3.5 \pm 2.5) \times 10^8$ cm^{-2}s^{-1}	$(2 \pm 0.5) \times 10^8$ cm^{-2}s^{-1}
Magnetic field	6 ± 3 nT (~0.06 G)	6 ± 3 nT
Temperatures	$T_p = (4 \pm 2) \times 10^4$ K	$T_p = (2.4 \pm 0.6) \times 10^5$ K
	$T_e = (1.3 \pm 0.5) \times 10^5 \text{ K} > T_p$	$T_e = (1 \pm 0.2) \times 10^5 \text{ K} < T_p$
Anisotropies	T_p isotropic	$T_{p\perp} > T_{p\parallel}$
Structure	filamentary, highly variable	uniform, slow changes
Composition	He/H$\simeq 1 - 30\%$	He/H$\simeq 5\%$
	low-FIP enhanced	near-photospheric
Minor species	n_i/n_p variable	n_i/n_p constant
	$T_i \simeq T_p$	$T_i \simeq (m_i/m_p)T_p$
	$v_i \simeq v_p$	$v_i \simeq v_p + v_A$
Associated with	streamers, transiently open field	coronal holes

Solar wind parameters

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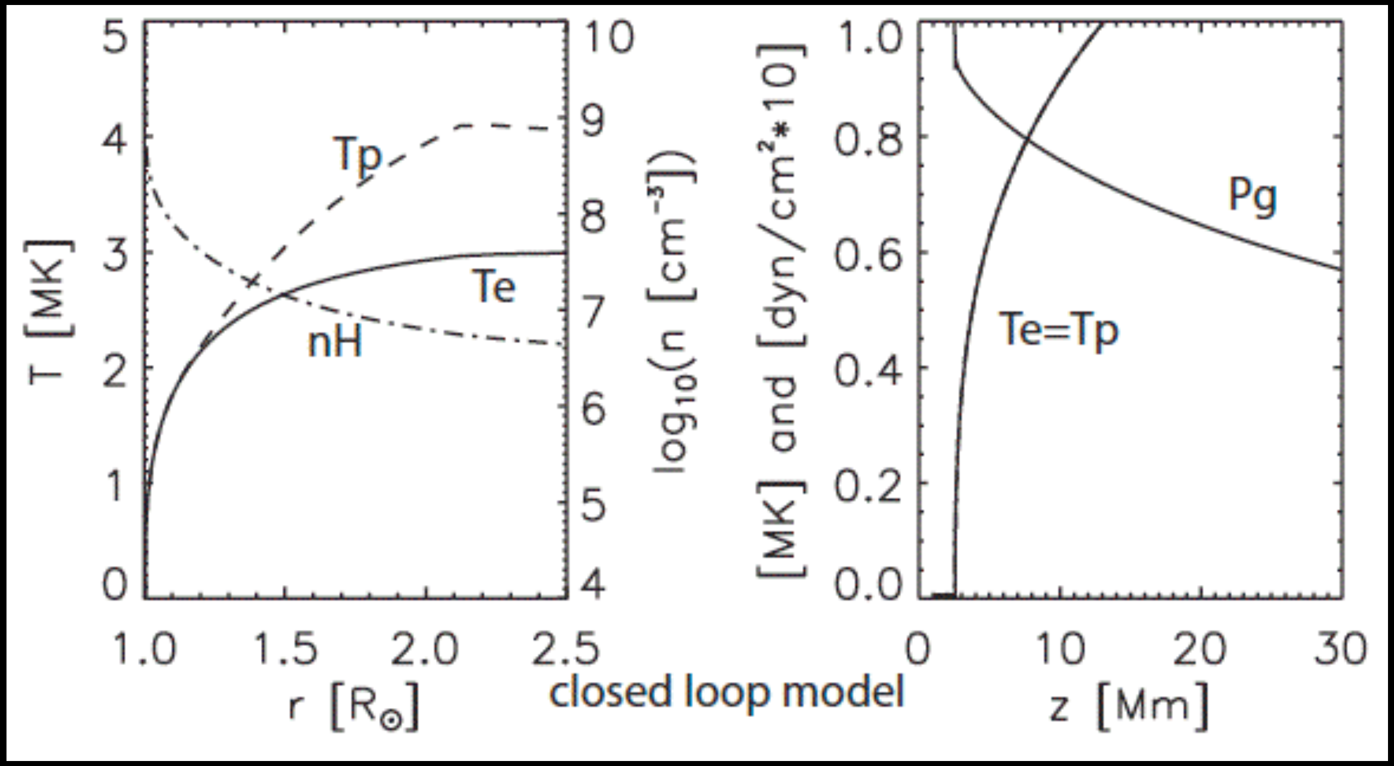
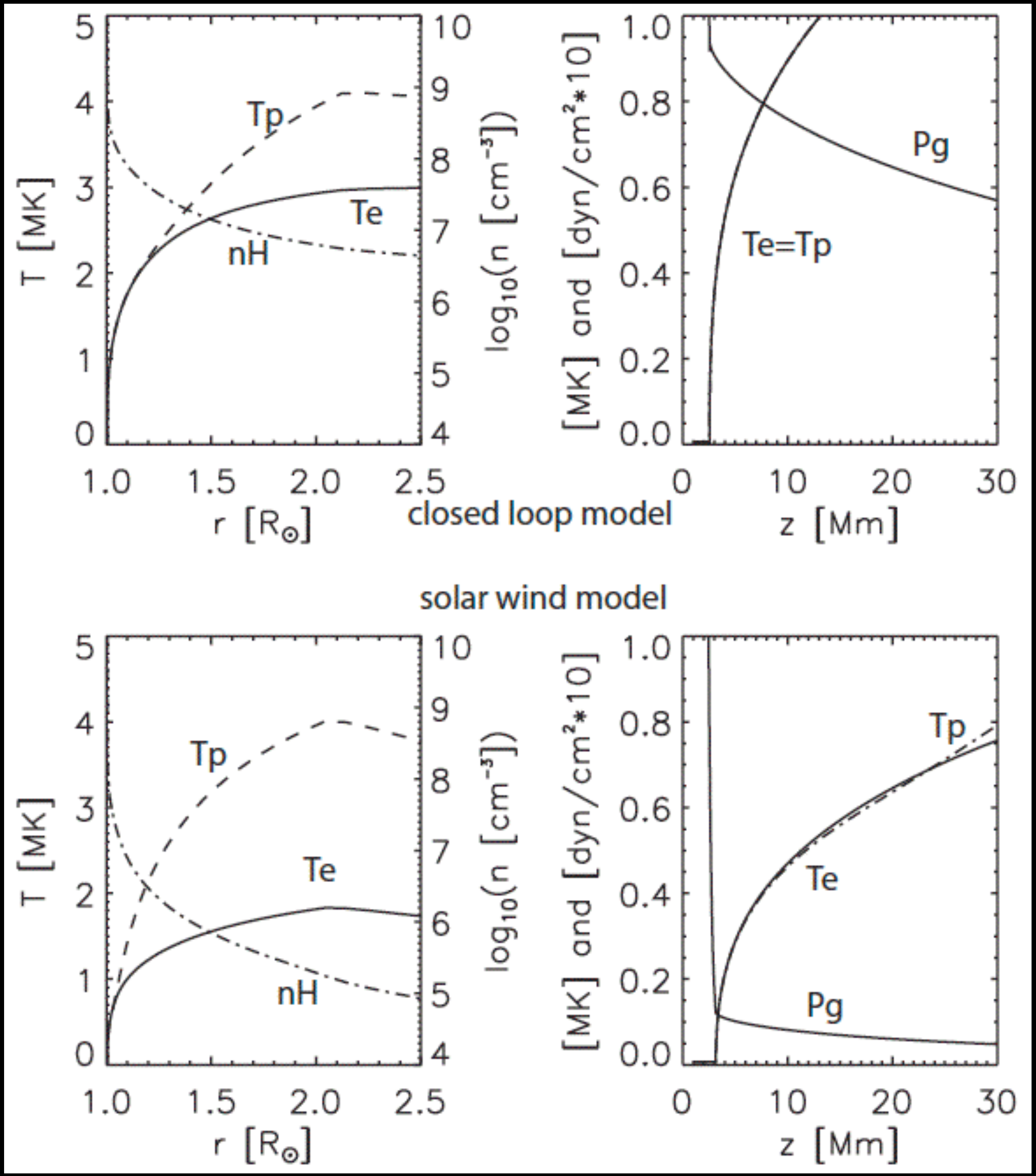
Anisotropies	T_p isotropic		$T_{p\perp} > T_{p\parallel}$
Structure	filamentary, highly variable		uniform, slow changes
Composition	He/H$\simeq 1 - 30\%$ low-FIP enhanced		He/H$\simeq 5\%$ near-photospheric
Minor species	n_i/n_p variable $T_i \simeq T_p$ $v_i \simeq v_p$		n_i/n_p constant $T_i \simeq (m_i/m_p)T_p$ $v_i \simeq v_p + v_A$
Associated with	streamers, transiently open field		coronal holes

Region	n [m^{-3}]	n_e/n_H	T [K]	B [Gauss]	β
Photosphere[1]	10^{23}	10^{-4}	$6\,10^3$	$1 - 1500$	> 10
Chromosphere[2]	10^{19}	10^{-3}	$2\,10^4 - 10^4$	$10 - 100$	$10 - 0.1$
Transition region[3]	10^{15}	1	$10^4 - 10^6$	$1 - 10$	10^{-2}
Corona[4]	10^{14}	1	10^6	$1 - 10$	$10^{-2} - 1$

Closed / open field; 2-fluid

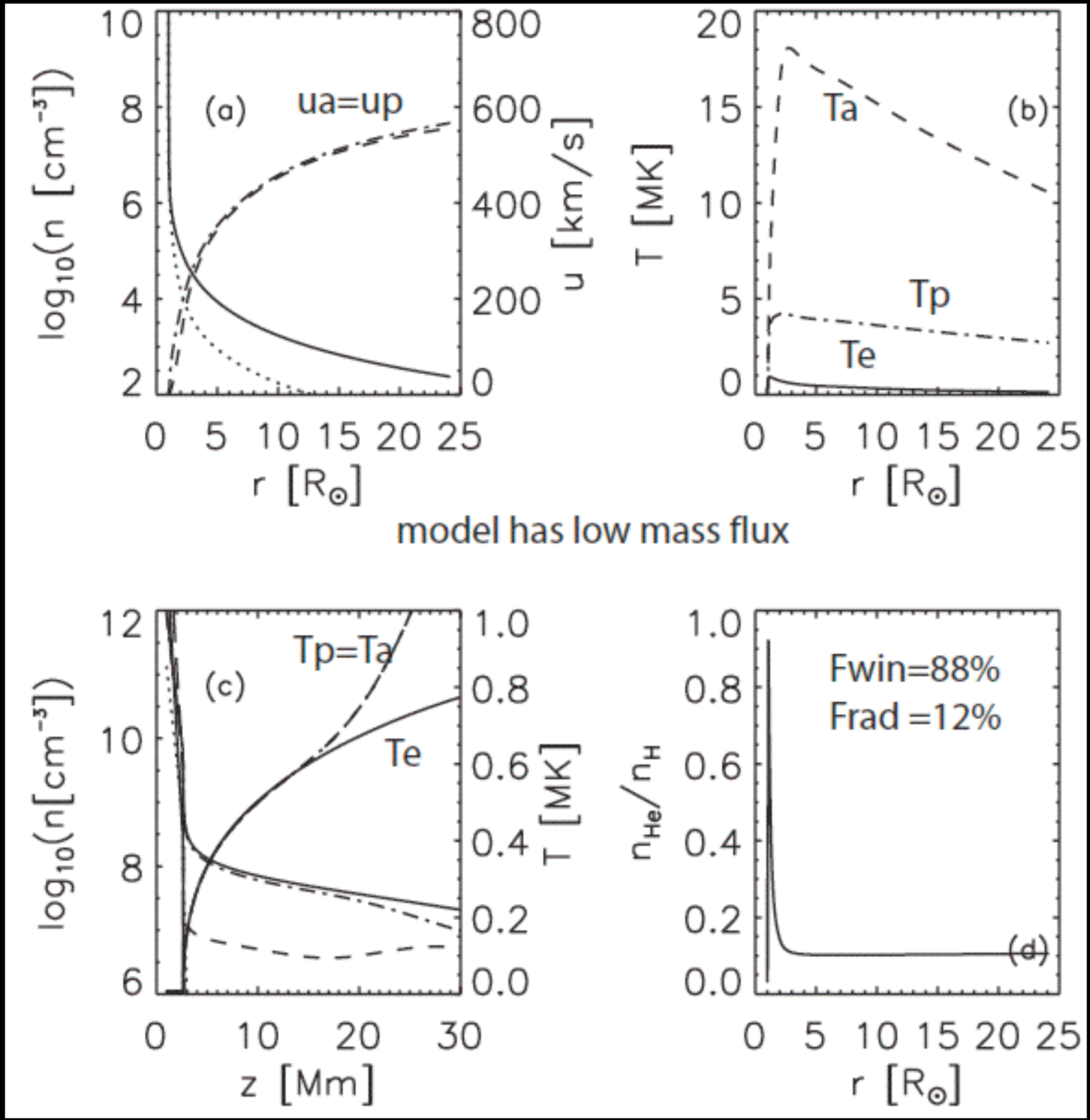


Closed / open field; 2-fluid



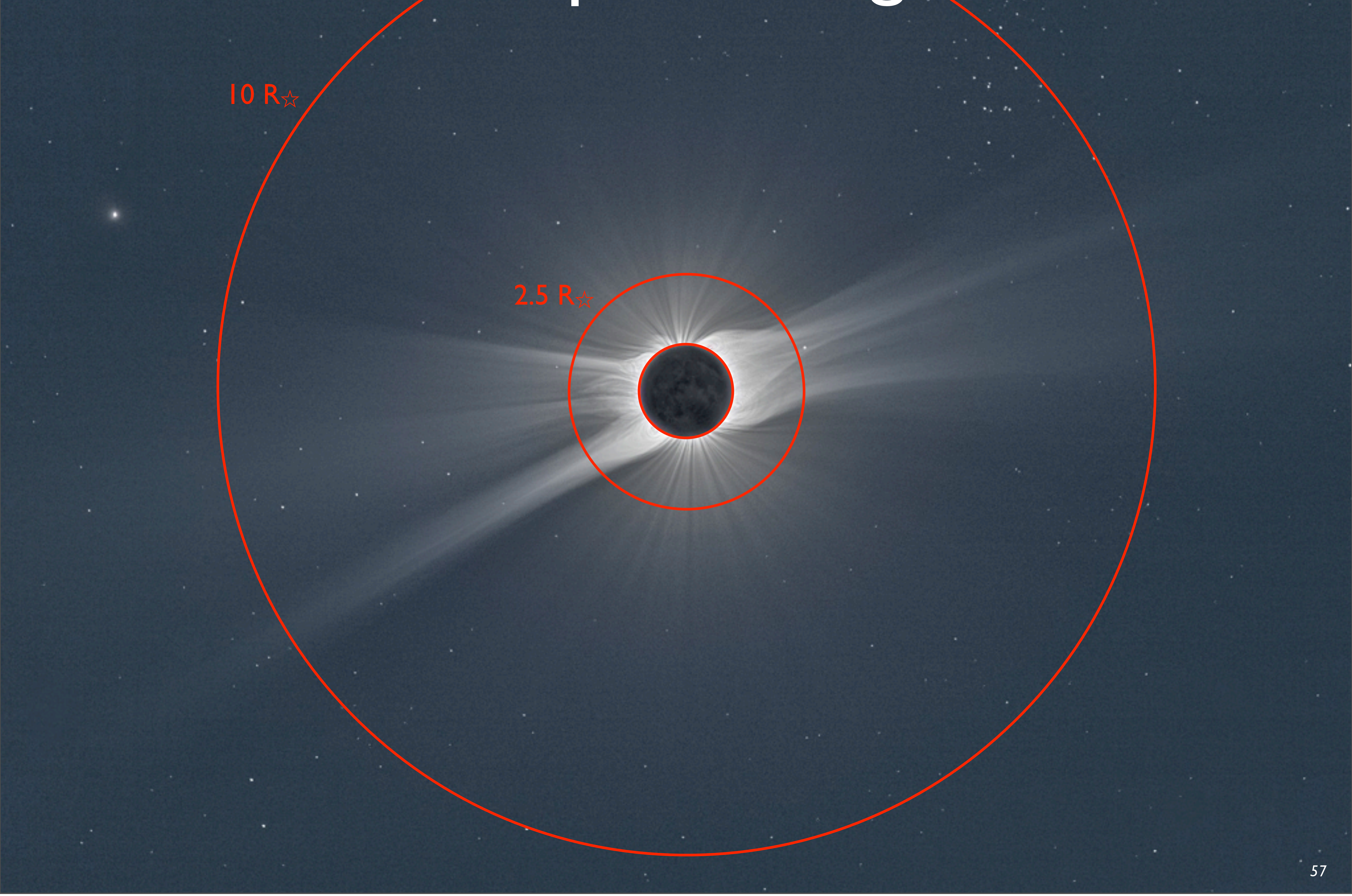
Closed / open field; 3-fluid

- Heat: 60% into H, 40% into He



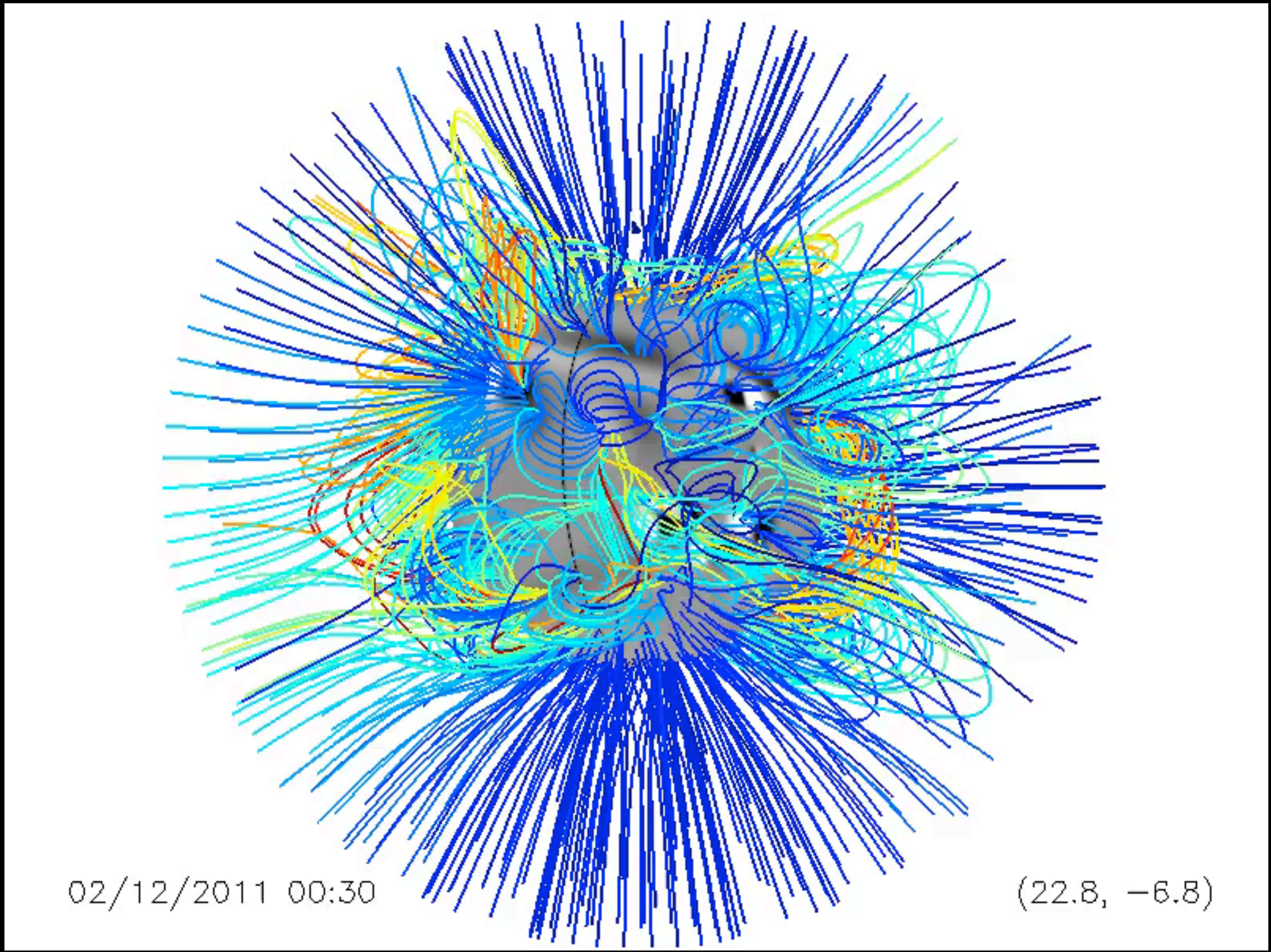
Solar wind "opens" magnetic field

Solar wind "opens" magnetic field



MHD-lite: magnetofrictional model

MHD-lite: magnetofrictional model



Heliospheric field reversals

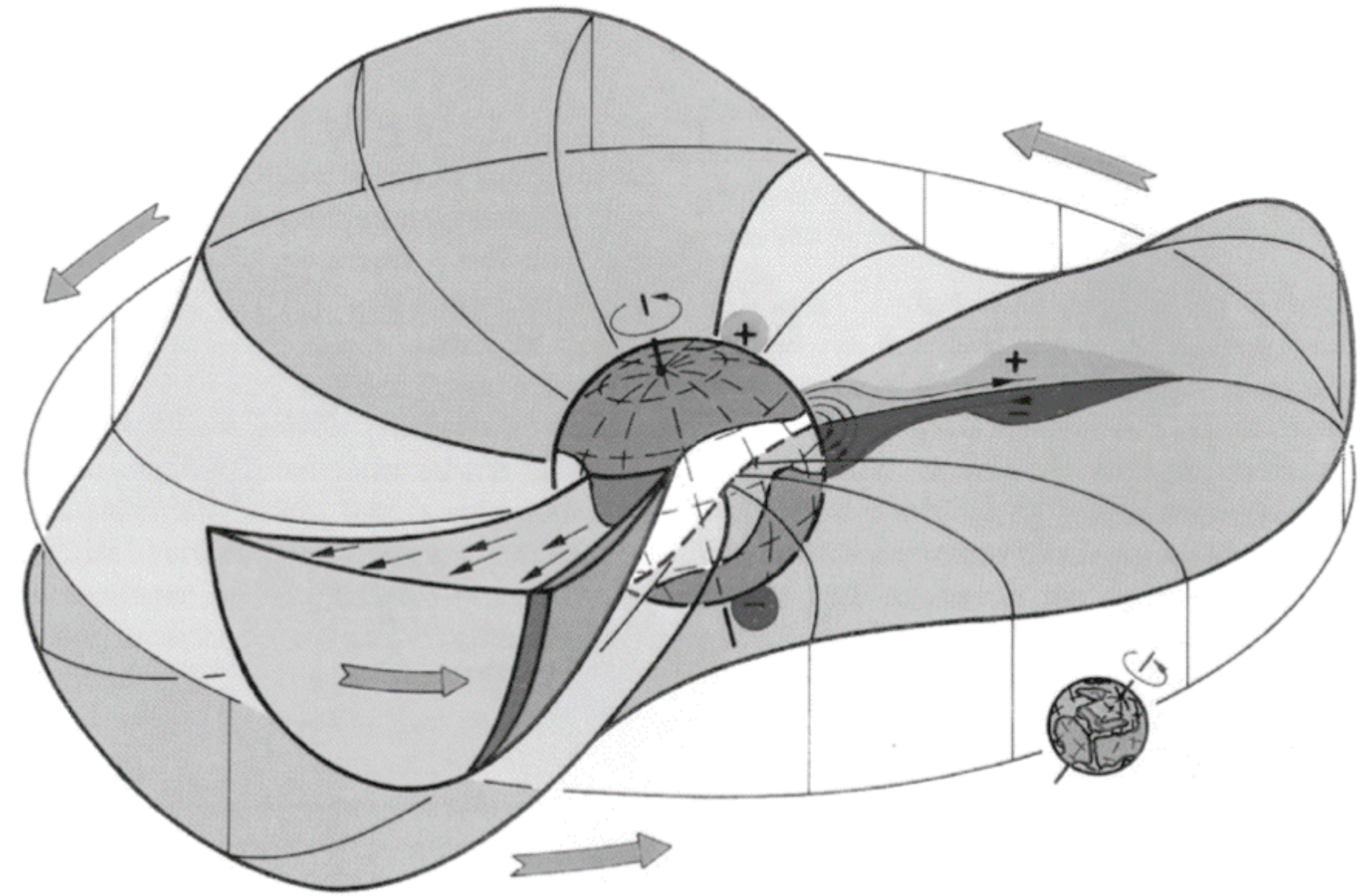
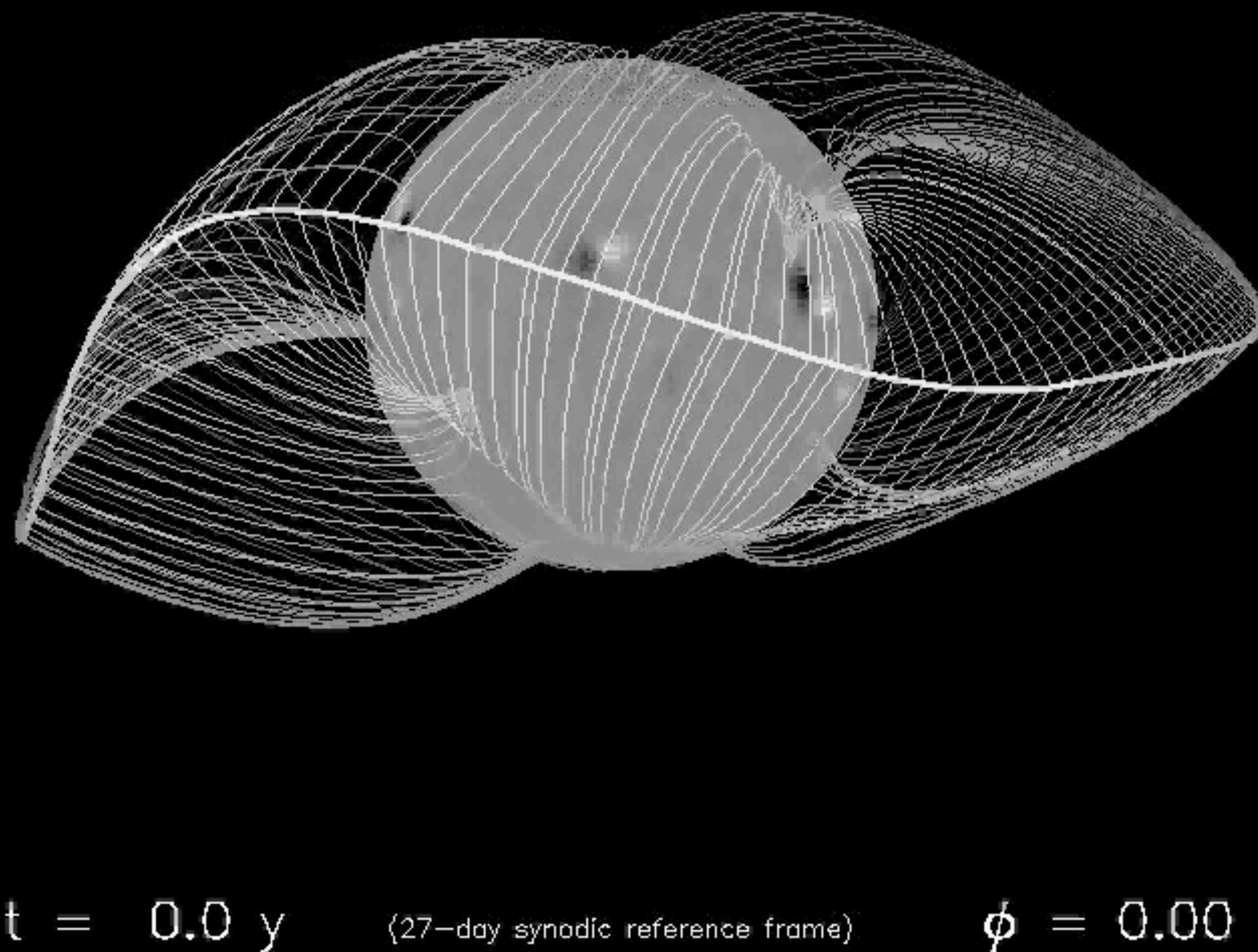


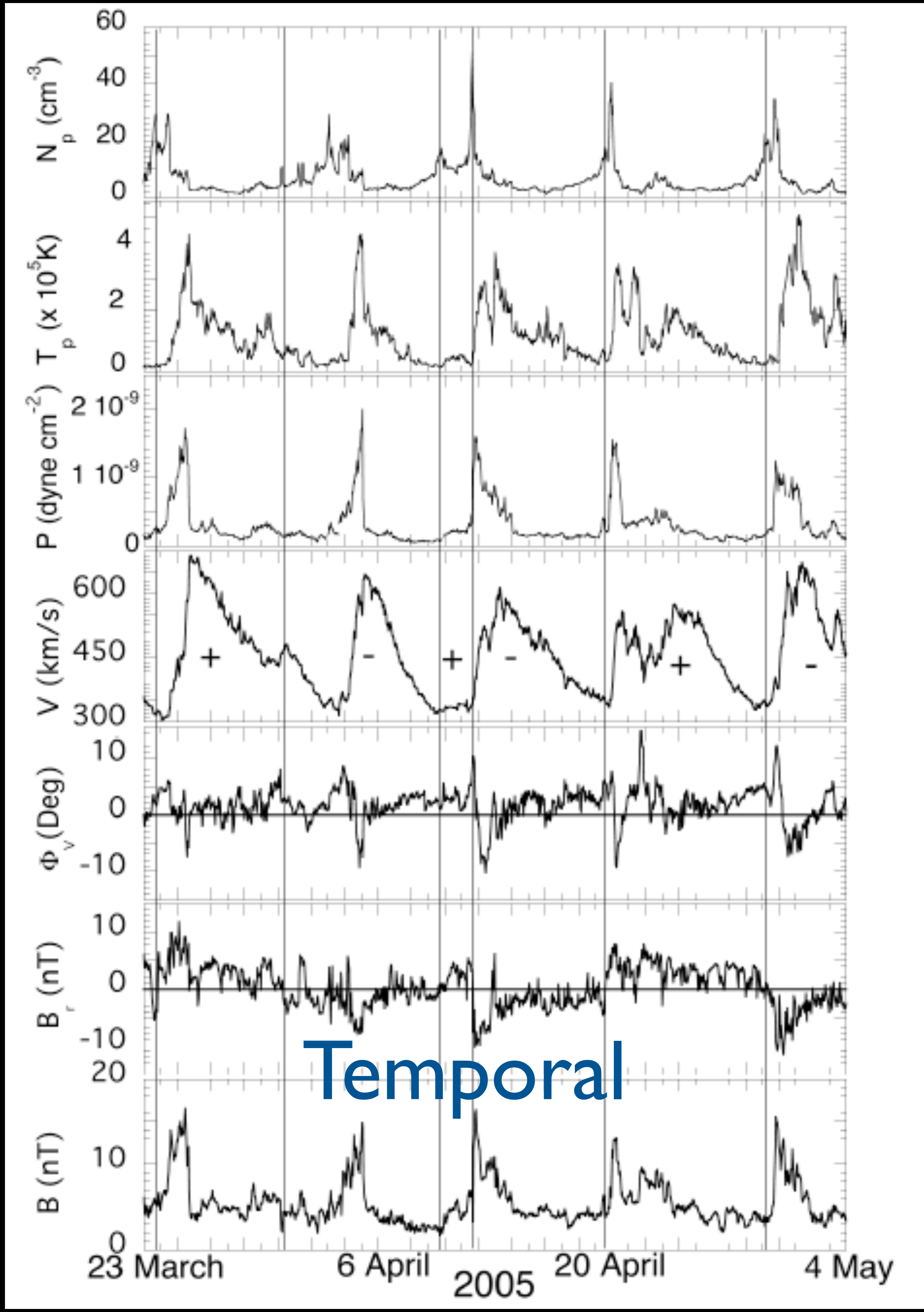
Fig. 9.3. The heliospheric current sheet forms a warped, undulating structure extending from the top ridge of the helmet streamer belt (cf., Figs. 1.3 [top] and 8.1) that sweeps by the Earth as the Sun rotates once per 27 days (synodic period). The magnetic field changes direction across the current sheet. (From Alfvén, 1977)

Potential-field simulation

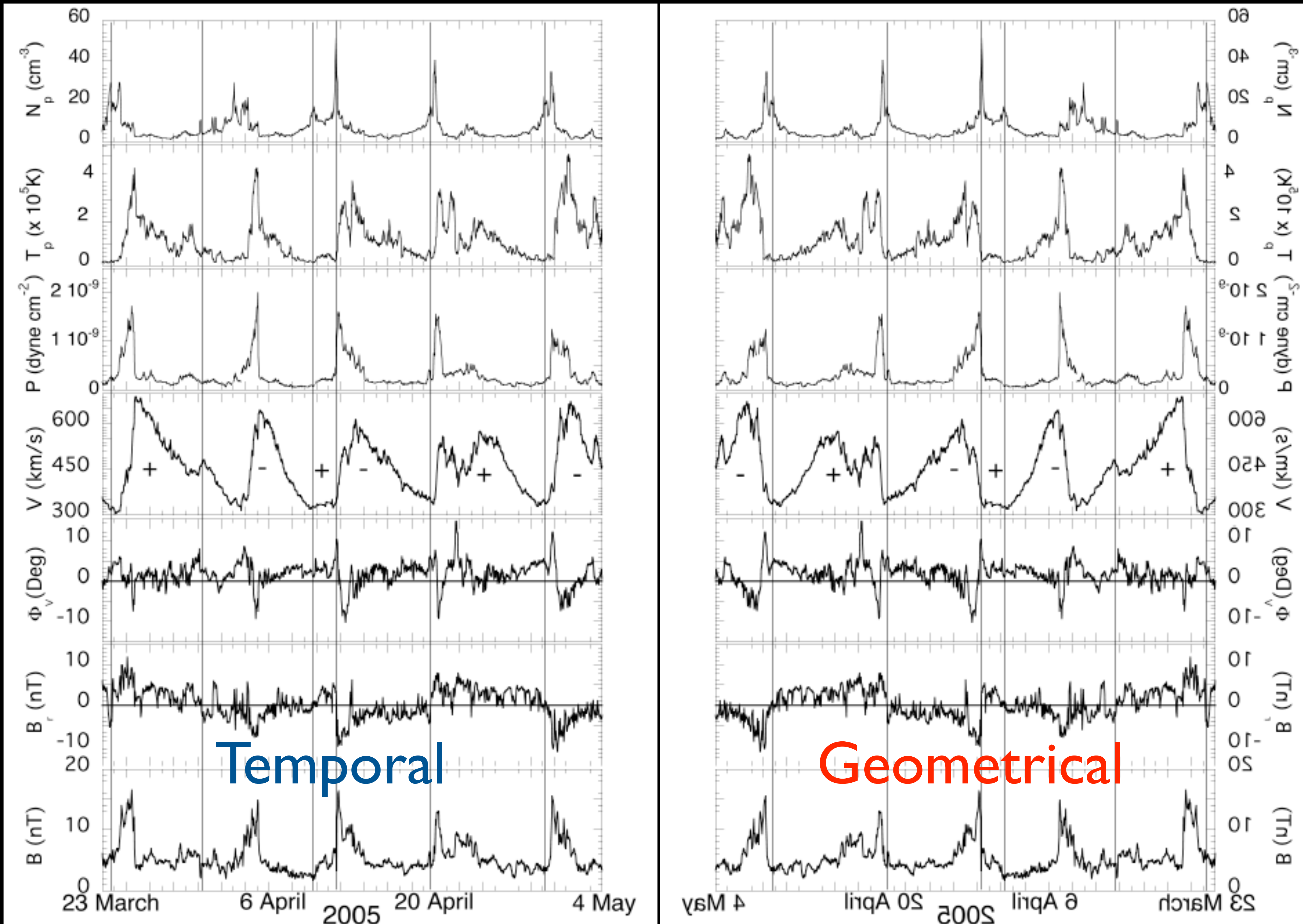
- Heliospheric field base over a full cycle



Elements of the solar wind

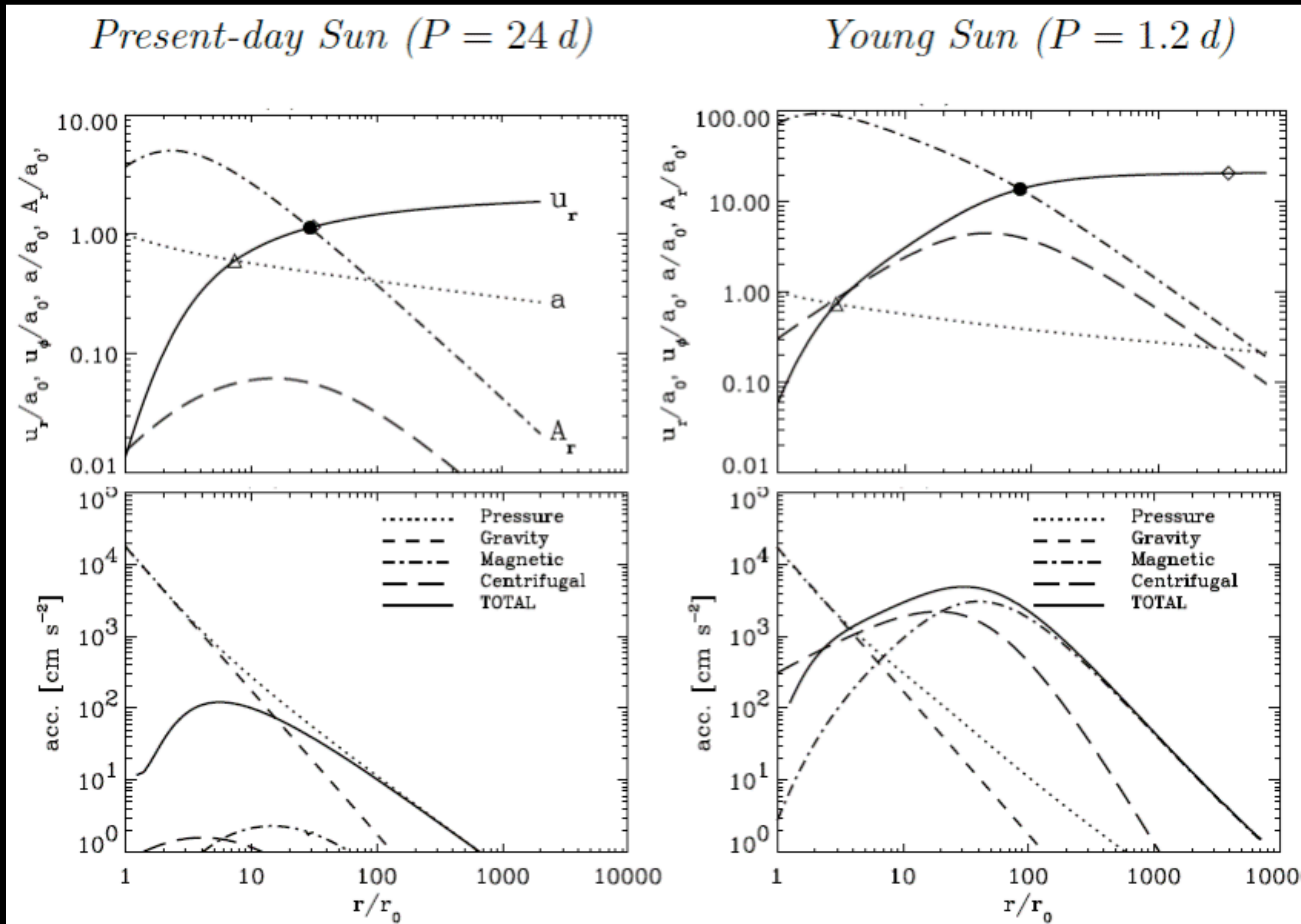


Elements of the solar wind



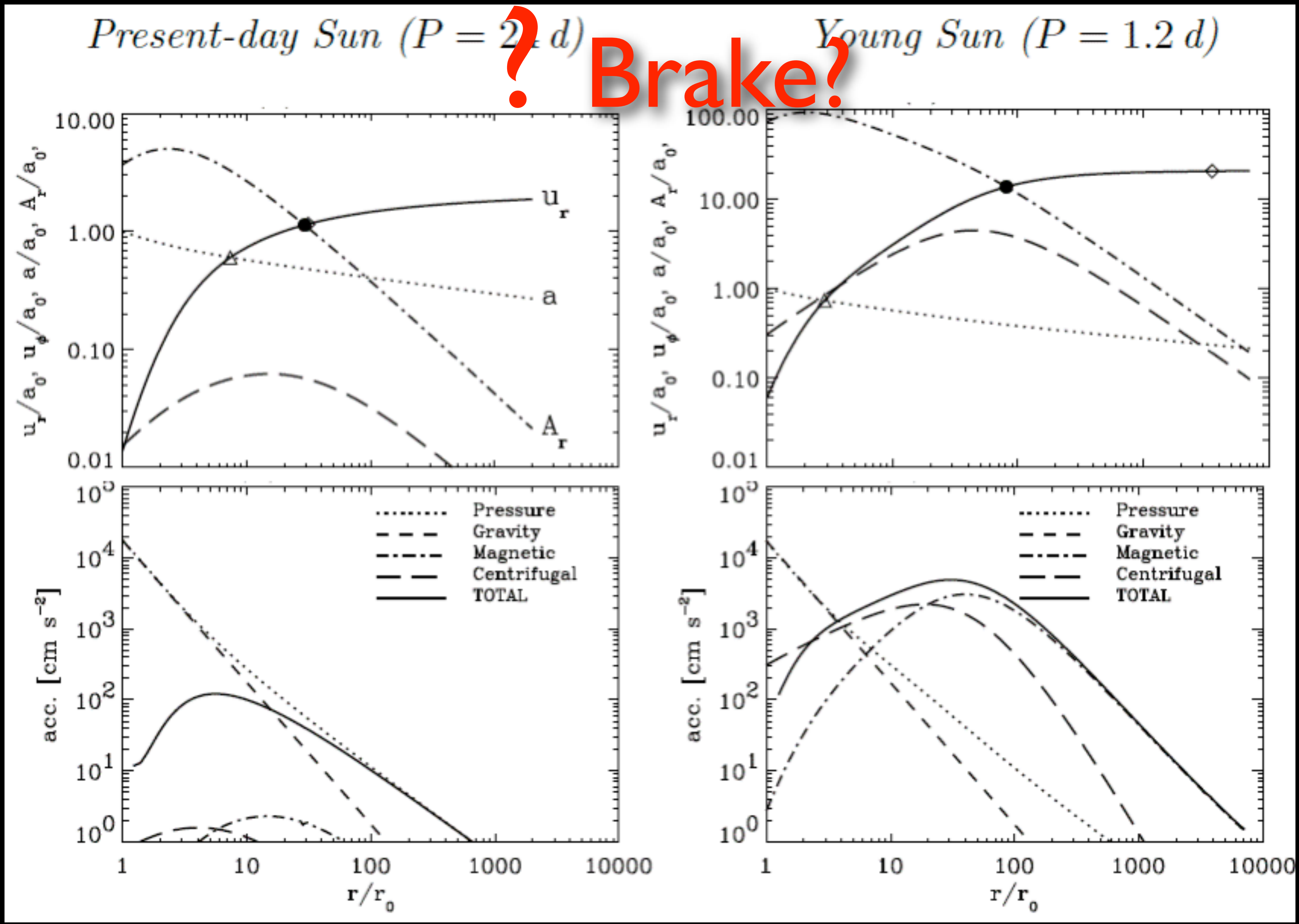
Saturday, July 13, 2013

“Air brake”



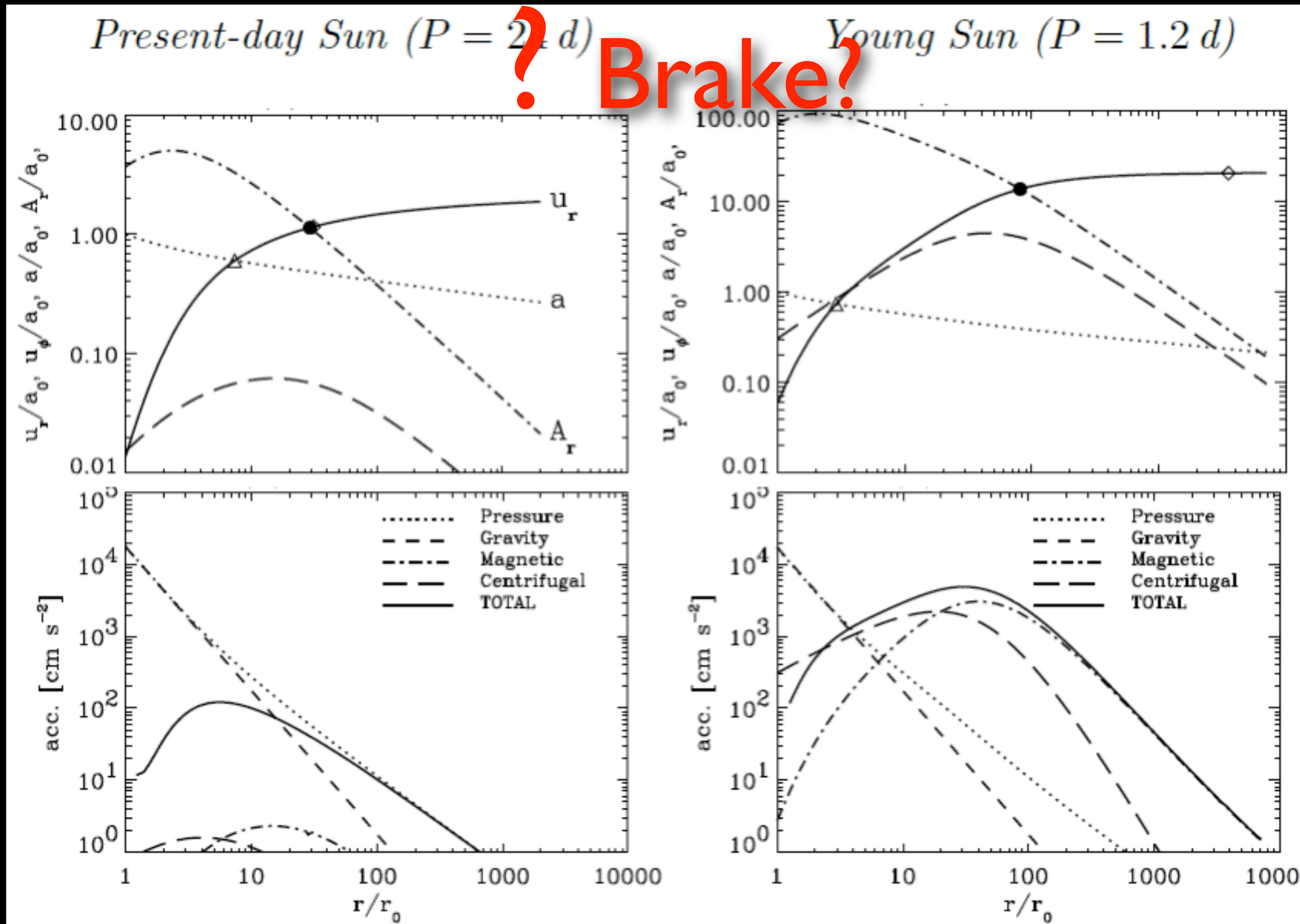
Present-day Sun (P = 24 d)
Young Sun (P = 1.2 d)
u_r
a
A_r
u_r/a_0, u_φ/a_0, a/a_0, A_r/a_0,
Pressure
Gravity
Magnetic
Centrifugal
TOTAL
acc. [cm s^-2]
r/r_0

“Air brake”



Present-day Sun (P = 2? d)
Brake?
Young Sun (P = 1.2 d)
u_r/a_0, u_φ/a_0, a/a_0, A_r/a_0
10.00
1.00
0.10
0.01
u_r
a
A_r
100.00
acc. [cm s^-2]
Pressure
Gravity
Magnetic
Centrifugal
TOTAL
1
10
100
1000
10000
r/r_0

"Air brake"



- Spin down because of magnetic "arm" in the wind

Topics

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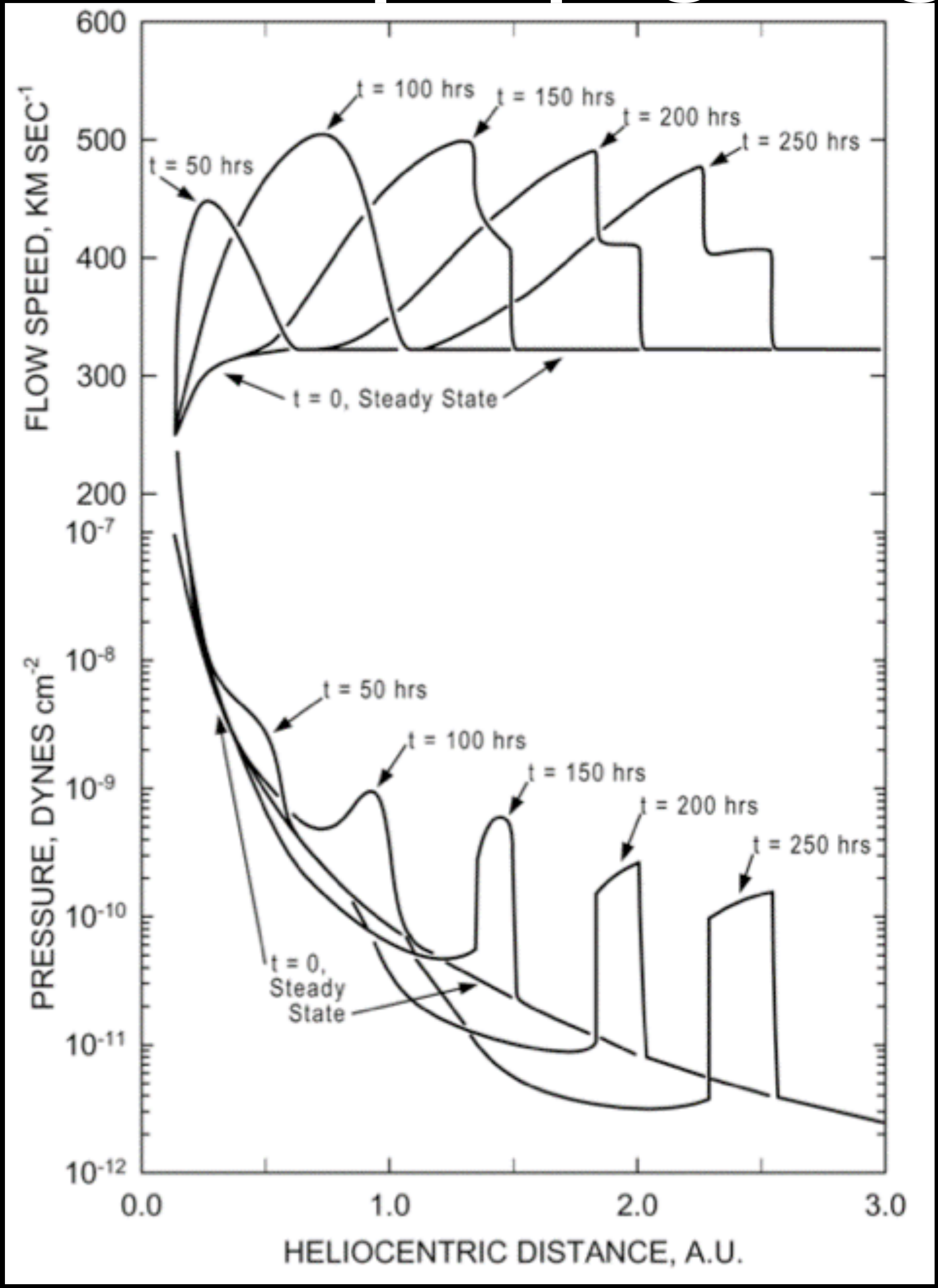
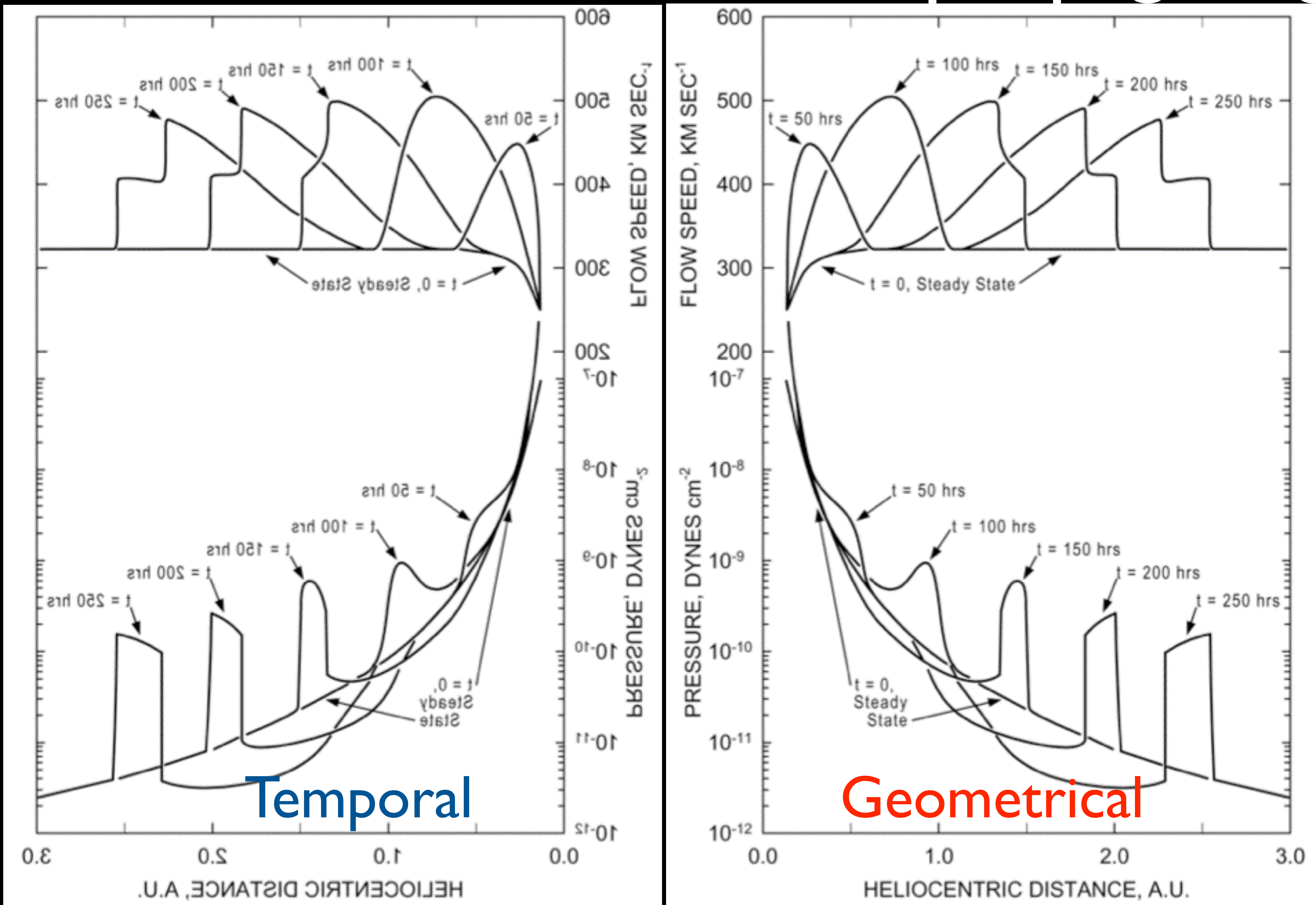
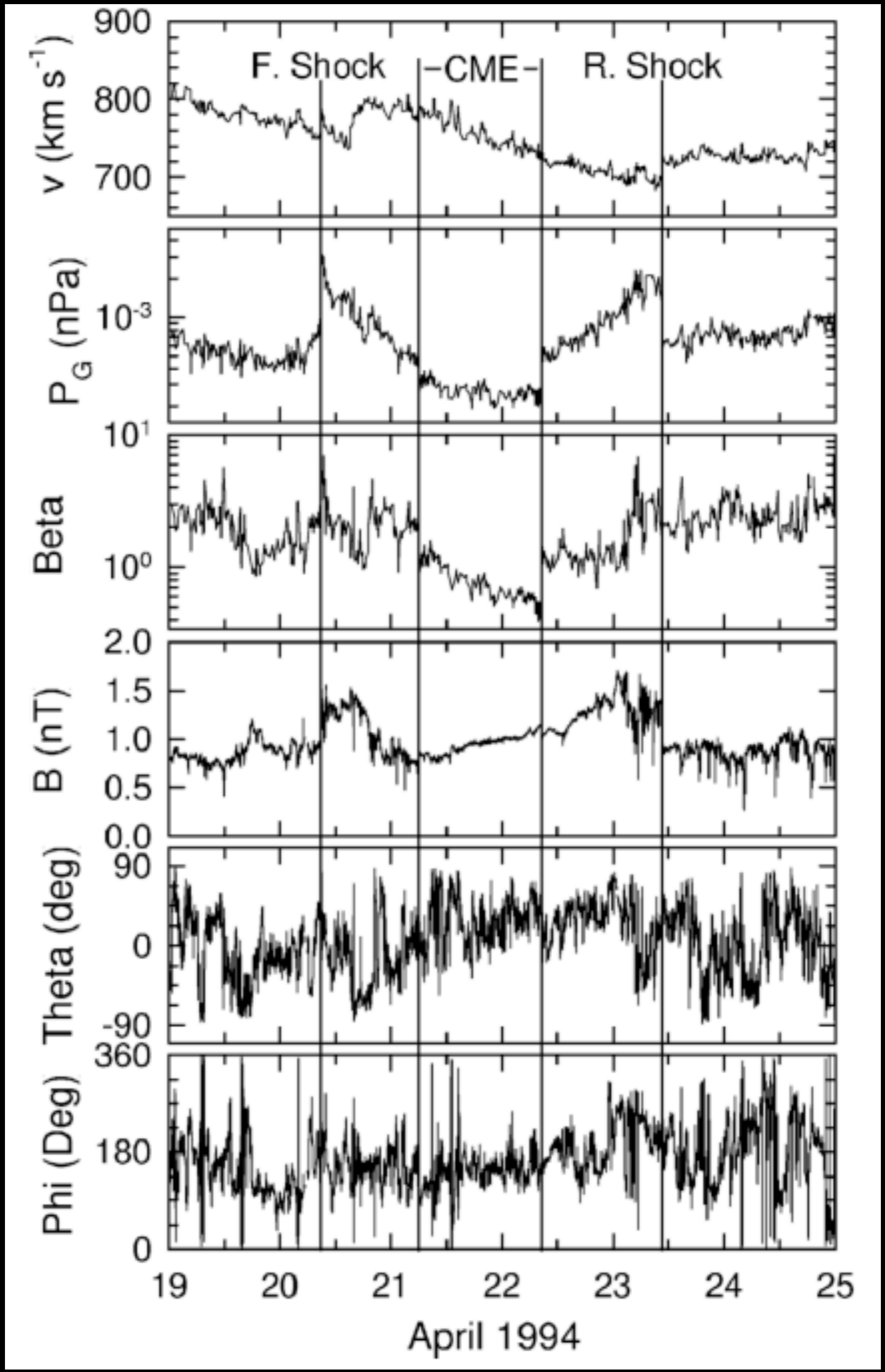
Pulse in the wind: model, propagating



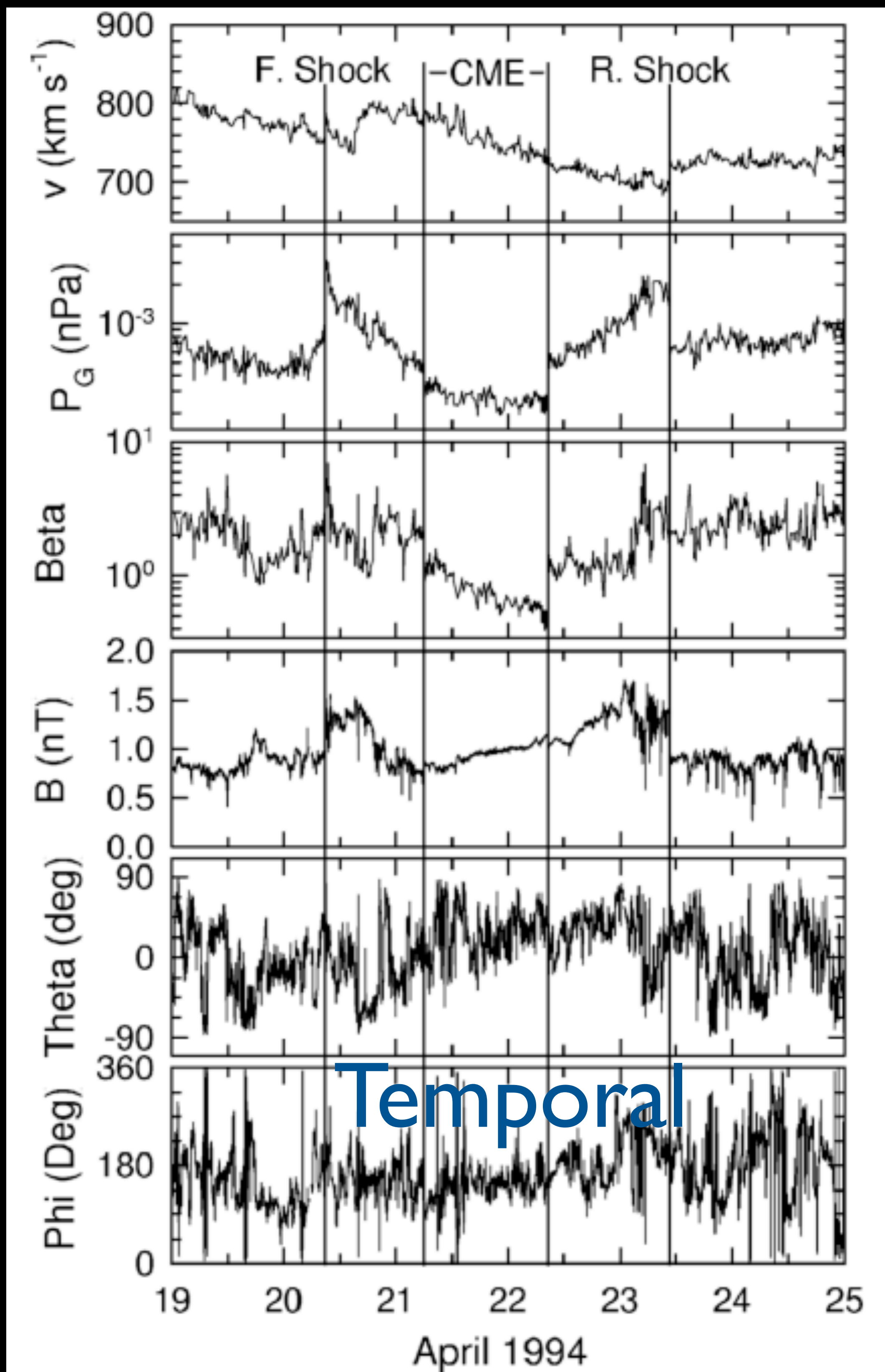
Pulse in the wind: model, propagating

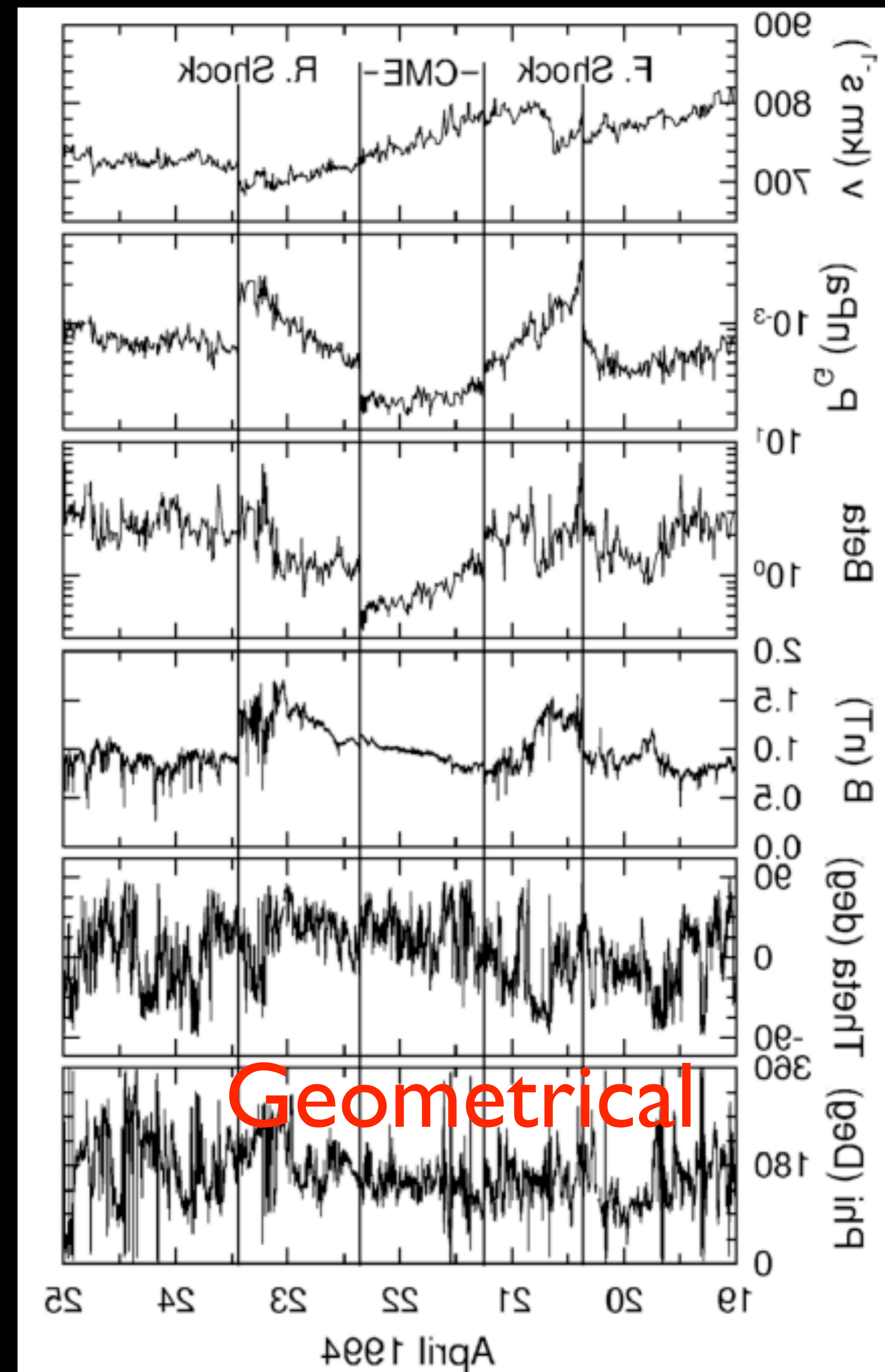


Pulse in the wind: real, at Earth



Pulse in the wind: real, at Earth





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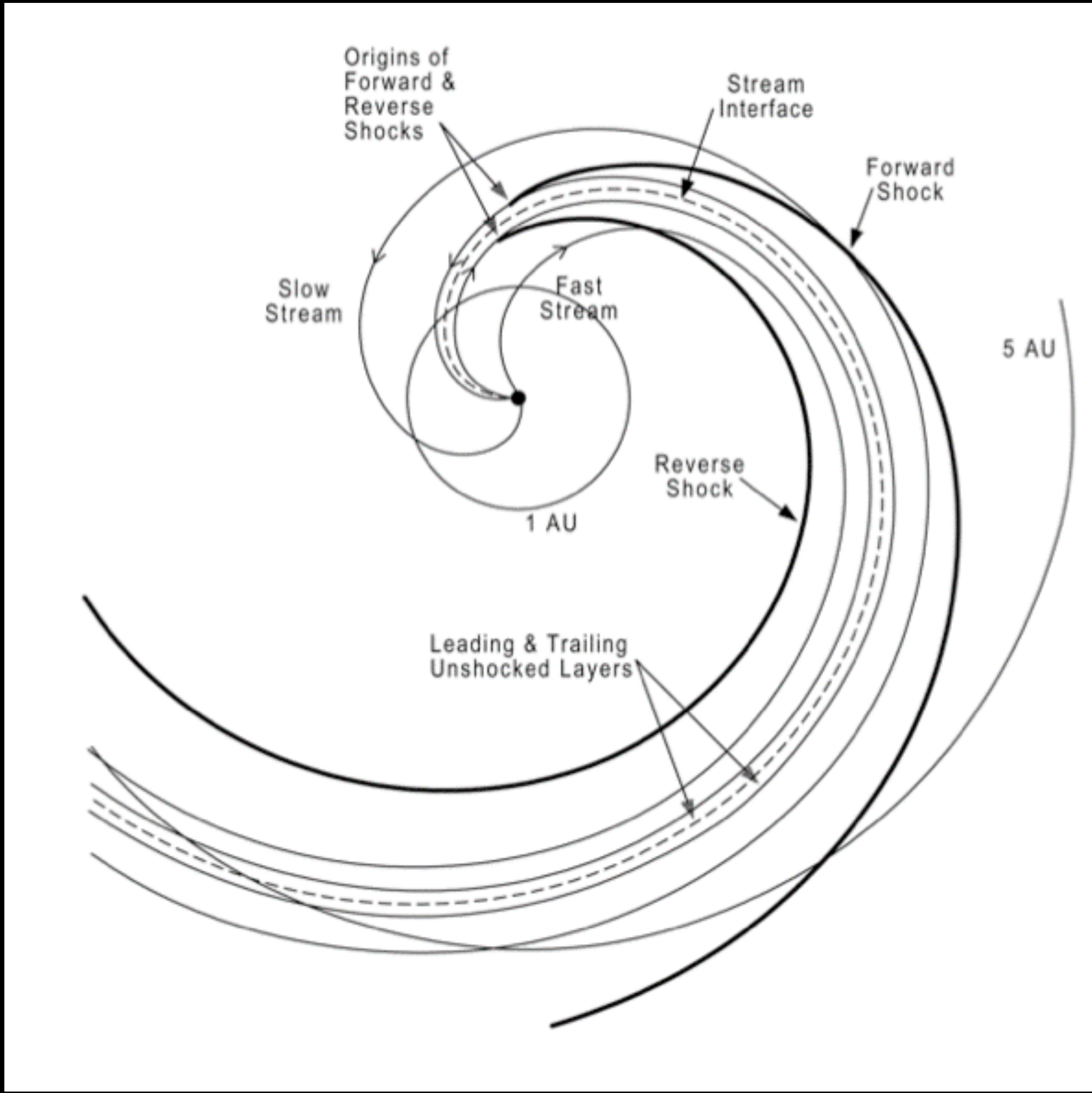
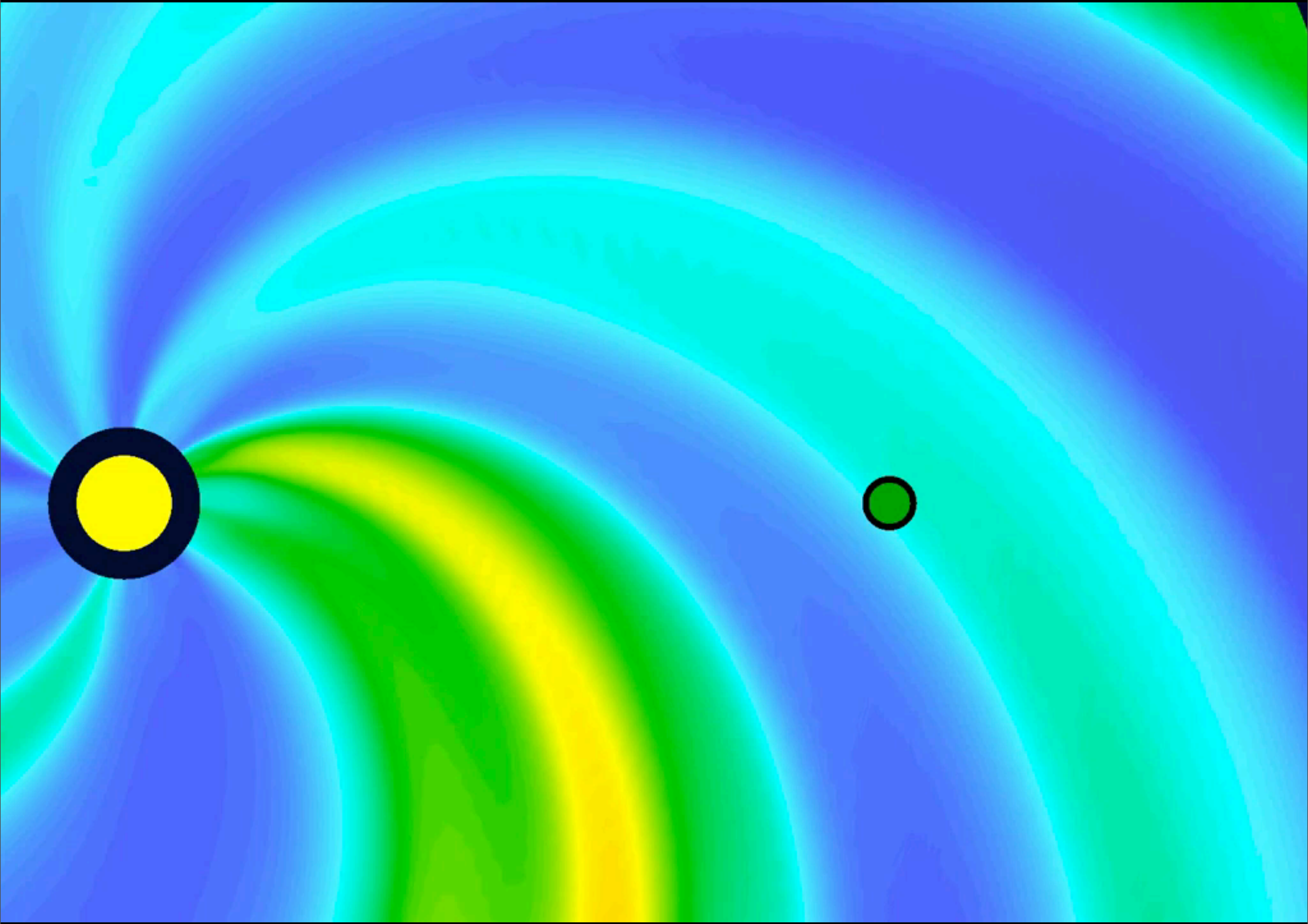
Stream interactions





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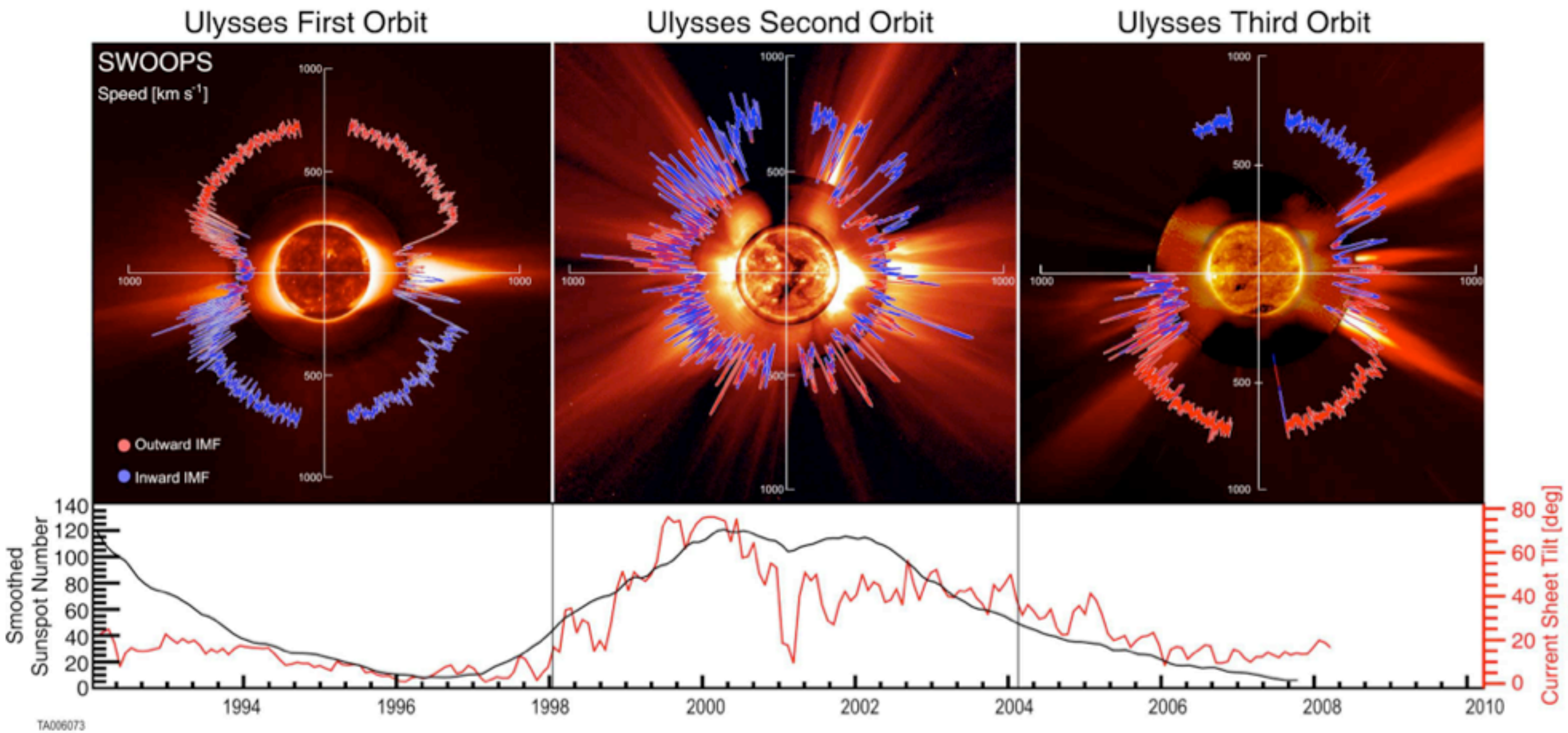
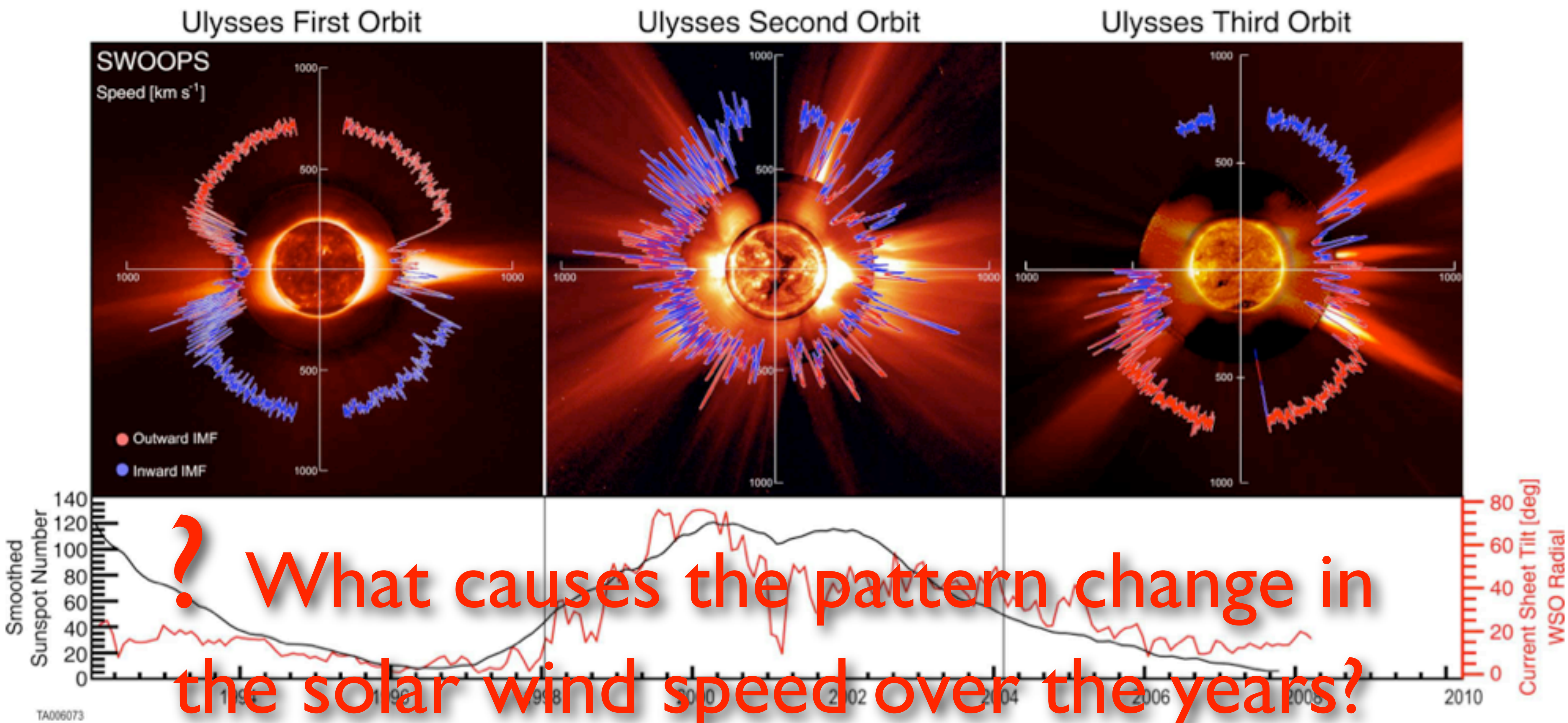
Topics

- Solar Spectral Irradiance:
  - Atmospheric structure
    - Static atmosphere
    - Waves
    - Magnetic field
      - Photosphere
      - Corona
      - Chromosphere
  - Gradual changes: solar cycle
  - Impulsive changes: flares/eruptions
  - Integration: solar spectral irradiance
- Solar Wind:
  - Background wind:
    - Basics of the solar wind
    - Multi-fluid effects
    - Magnetic field, and angular momentum loss
  - Impulsive/eruptive events and the solar wind
  - Integration: solar wind

Solar wind over a sunspot cycle

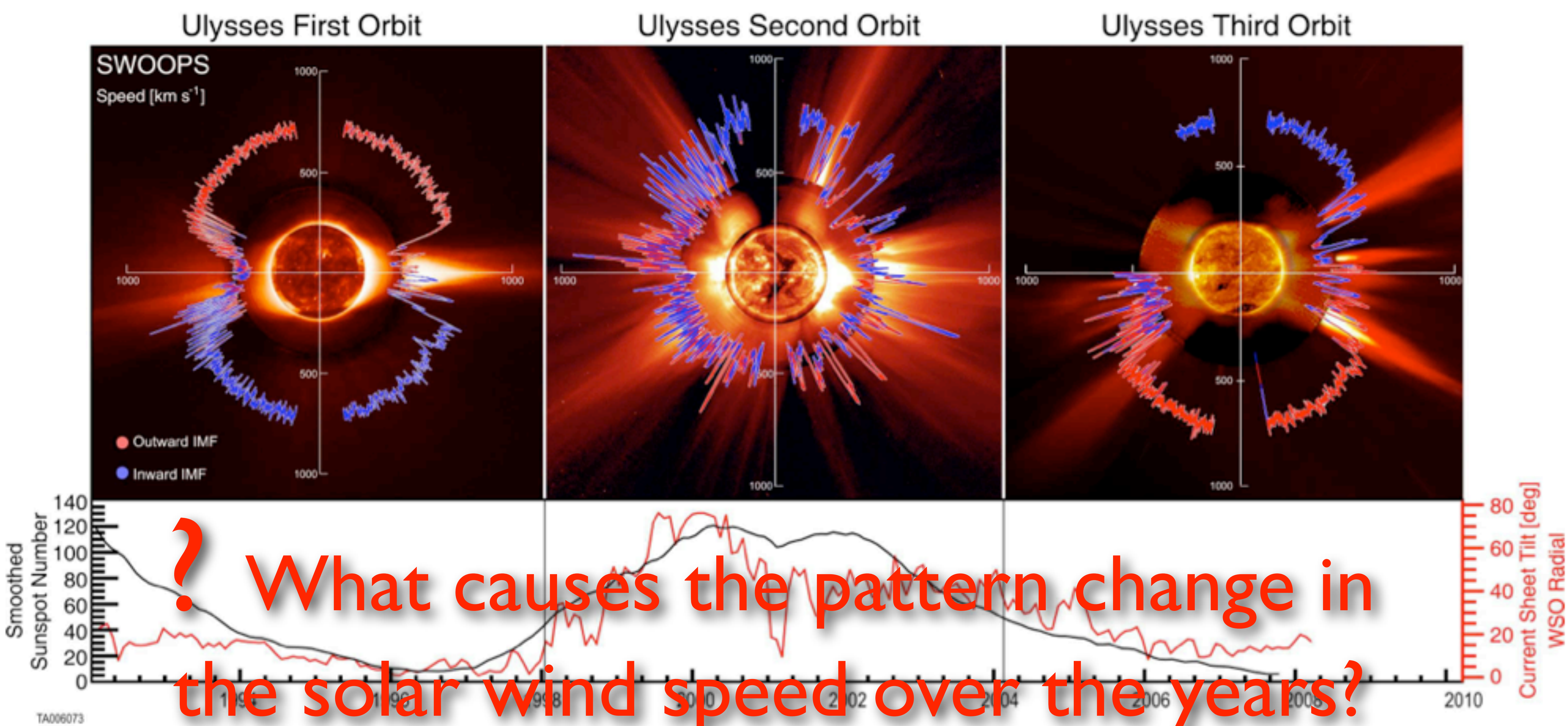


Solar wind over a sunspot cycle



? What causes the pattern change in the solar wind speed over the years?

Solar wind over a sunspot cycle



- Dipole tilt and CMEs involved in wind pattern