CORONAL HEATING

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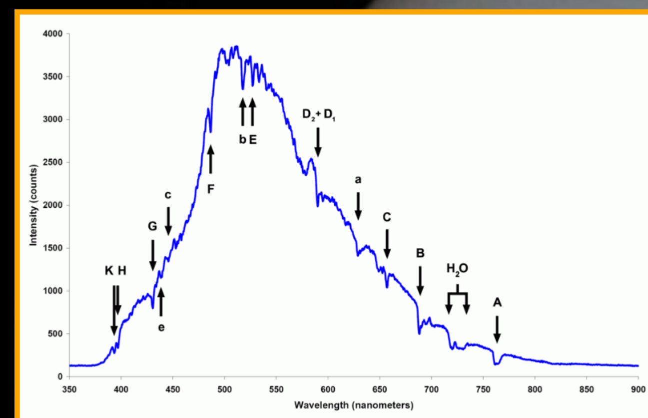
A SHORT HISTORY OF THE CORONAL HEATING PROBLEM

SOLAR SURFACE TEMPERATURE

1890s Solar surface temperature was derived to be around 6600 K, using the newly-discovered Stefan-Boltzmann law. Researchers generally assumed that the sun is made of gas.

SOLAR SURFACE TEMPERATURE

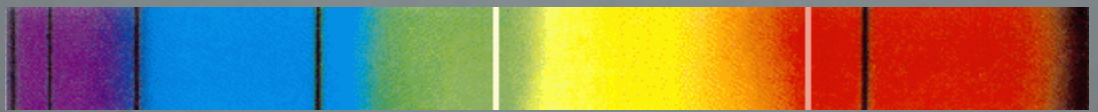
The solar photosphere radiates like a blackbody; its spectrum gives T, and dark “Fraunhofer lines” reveal its chemical composition.



Total eclipses revealed a complex outer solar corona

1870s: spectrographs pointed at corona:

Fraunhofer lines
unknown bright lines



CORONIUM

The eclipse of 1869 revealed an emission line in the green part of the coronal spectrum.

This was named Coronium.

Further reading: https://sunearthday.nasa.gov/2006/locations/coronium.php

courtesy of Sykora 1981

CORONIUM IS FE XIV

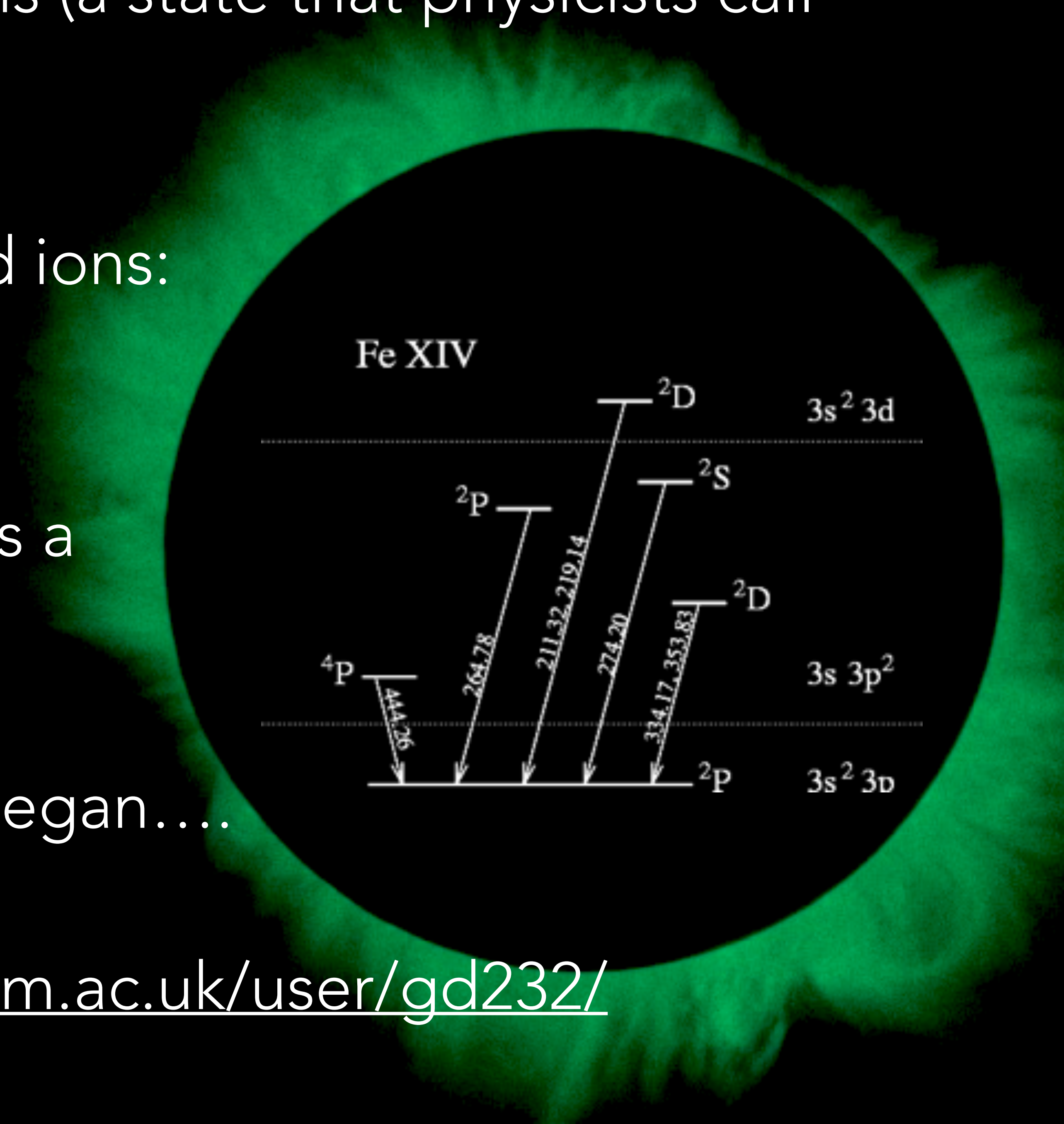
Grotrian in 1939 showed that this emission line to be due to Fe XIV (at 5303Å)

The atom had lost 13 of its 26 electrons (a state that physicists call 'Iron-14').

Other lines identified as highly ionized ions:
CaXII , FeIX to FeXIII

This demonstrated that the corona has a temperature > 1MK,

and so the coronal heating problem began….



Further reading: http://www.damtp.cam.ac.uk/user/gd232/research/cds_guides/slide18-0.html

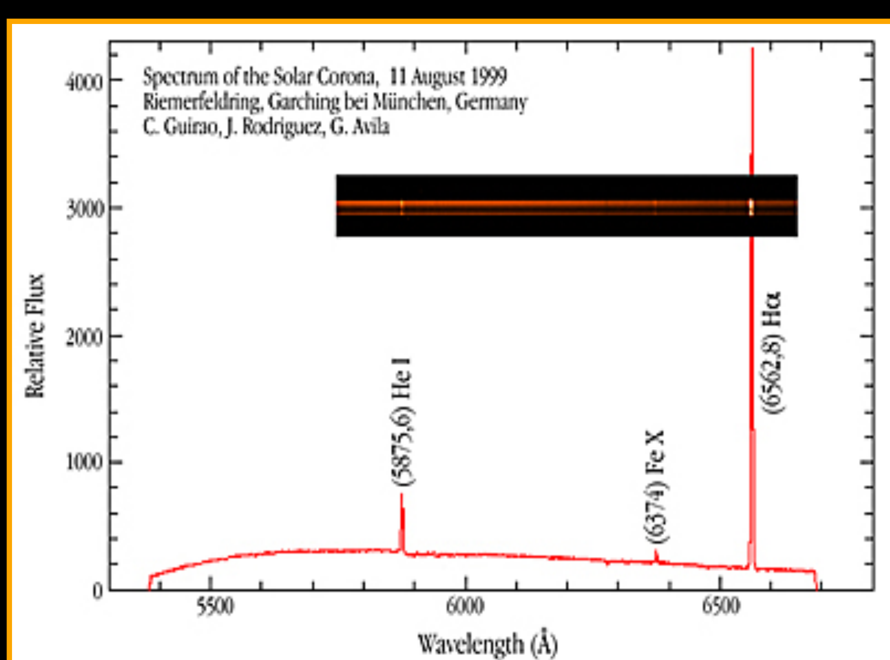
SOLAR RADIO EMISSION

In 1946 the intensity of the steady component of the solar radio emission was explained by:

- 10,000 degree solar chromosphere (emitting at short wavelengths)
- a million-degree solar corona (emitting at long wavelengths).

It was predicted that the extremely hot solar corona would also emit in X-rays.

1949 Solar X-ray emission was observed during a rocket flight.



Soft X-ray Telescope (SXT) - Hinode

WHAT IS THE SOLAR CORONA?

- The Sun is surrounded by an atmosphere of gasses. The Corona is the outer most layer.
- The Corona has a temperature 3-4 orders of magnitude greater than the visible surface.
- Due to the relative brightness of the Sun's surface it is only visible from Earth during total solar eclipses.

Image Courtesy of K. Gazeas

HISTORY OF CORONAL OBSERVATIONS

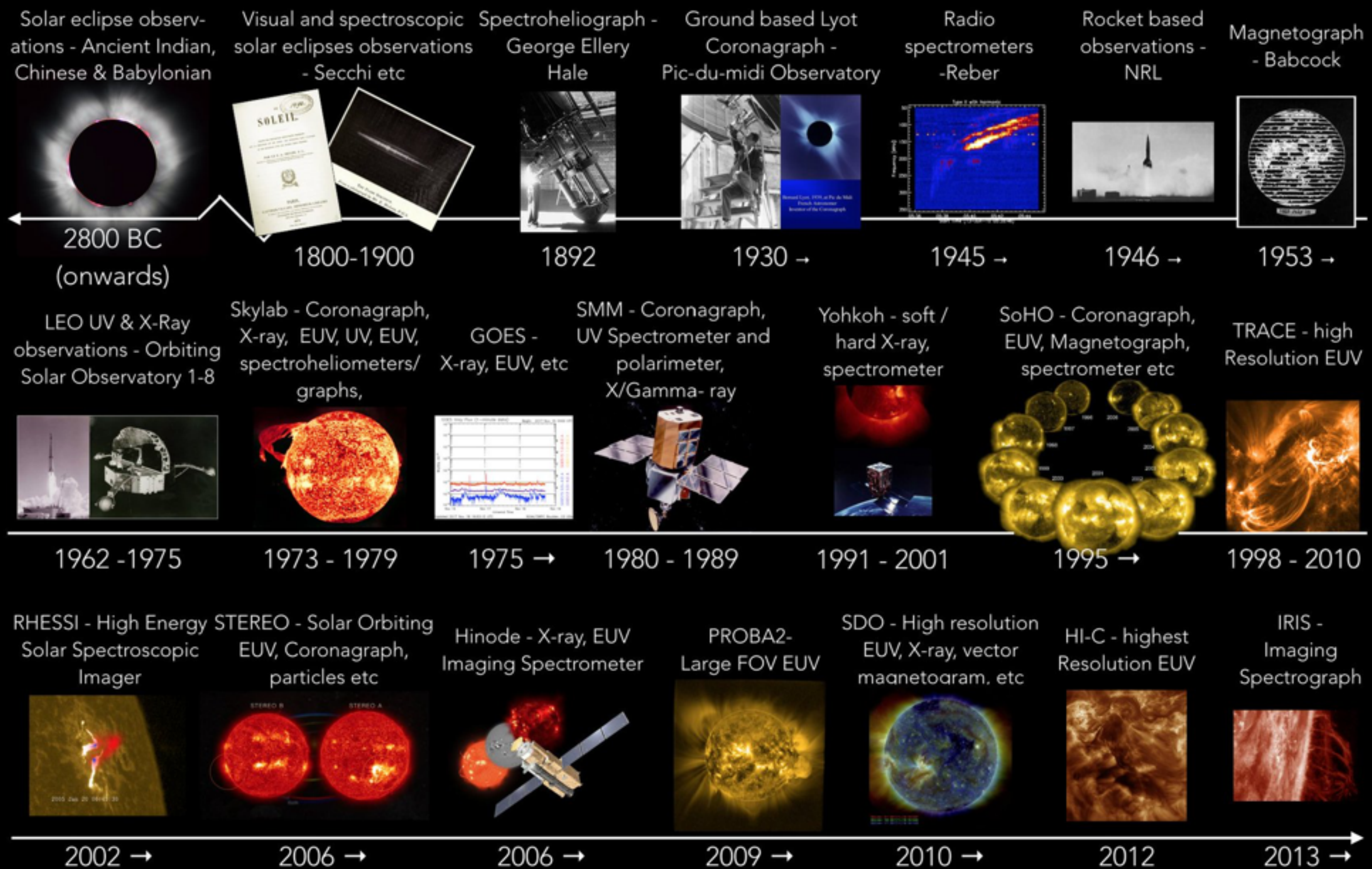
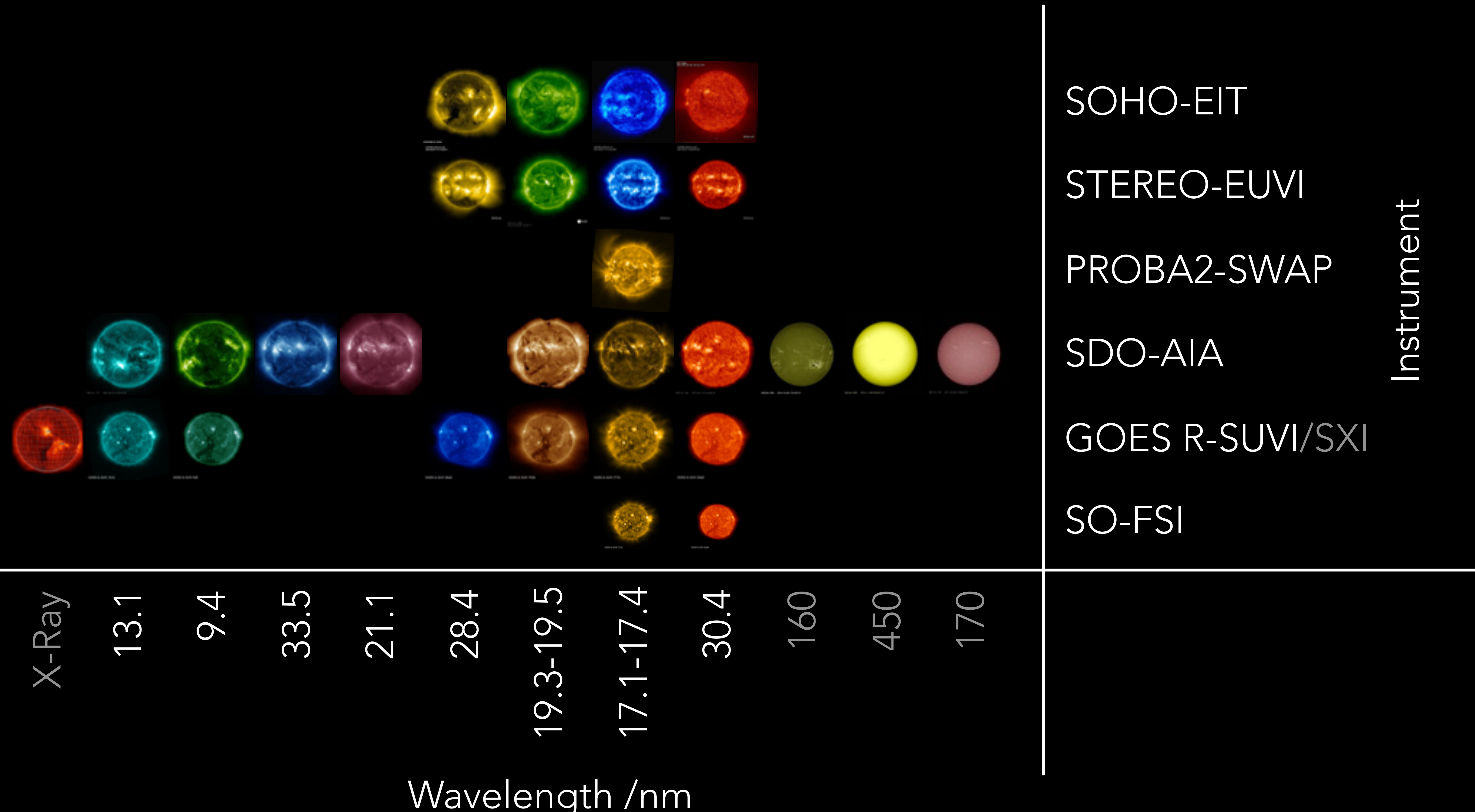


Image: https://twitter.com/SolarPhysicist/status/936922310837198848

CONTEMPORARY EUV PASSBANDS USED FOR OBSERVING THE SUN (WITH SOME COMPARATIVE PASSBANDS)



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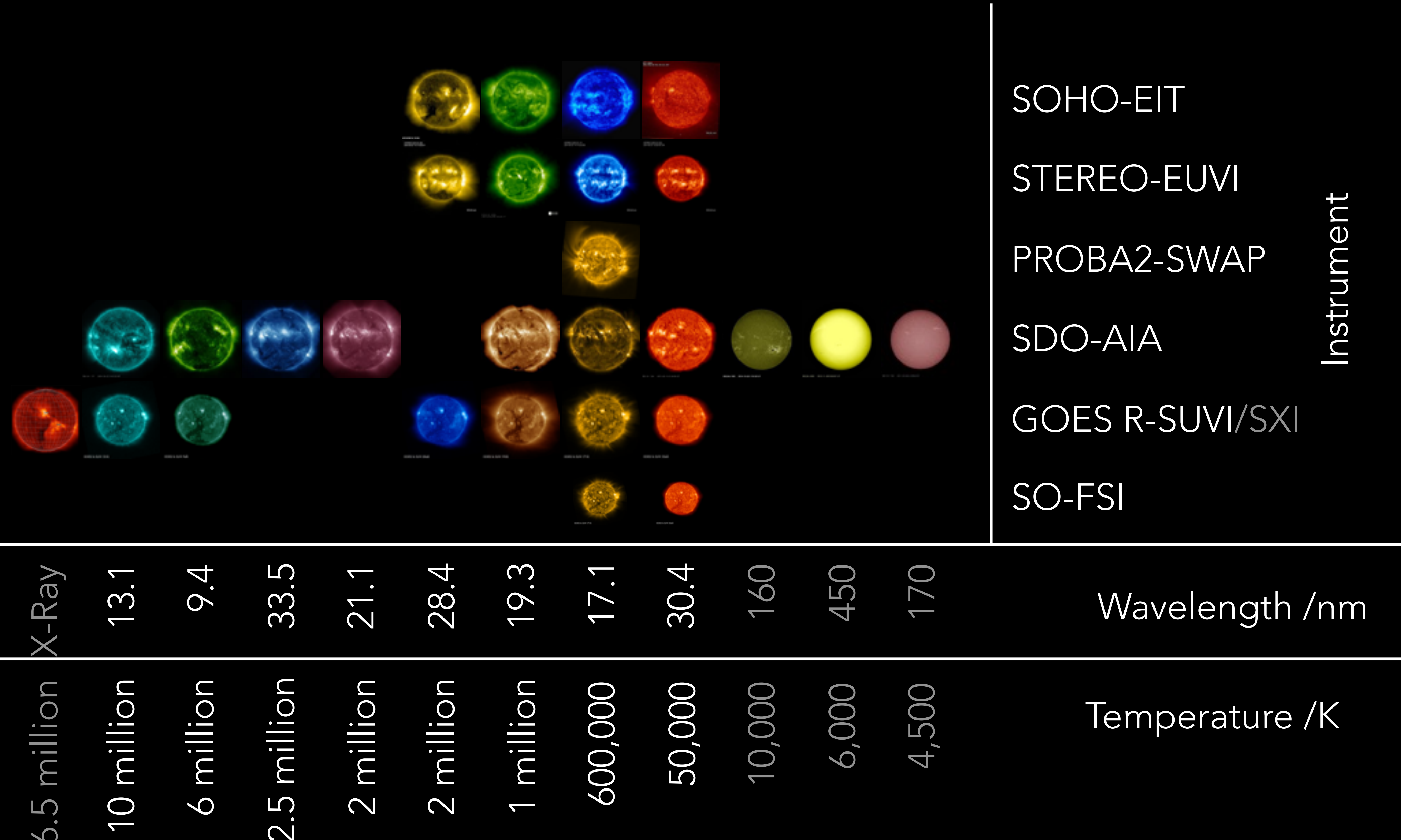
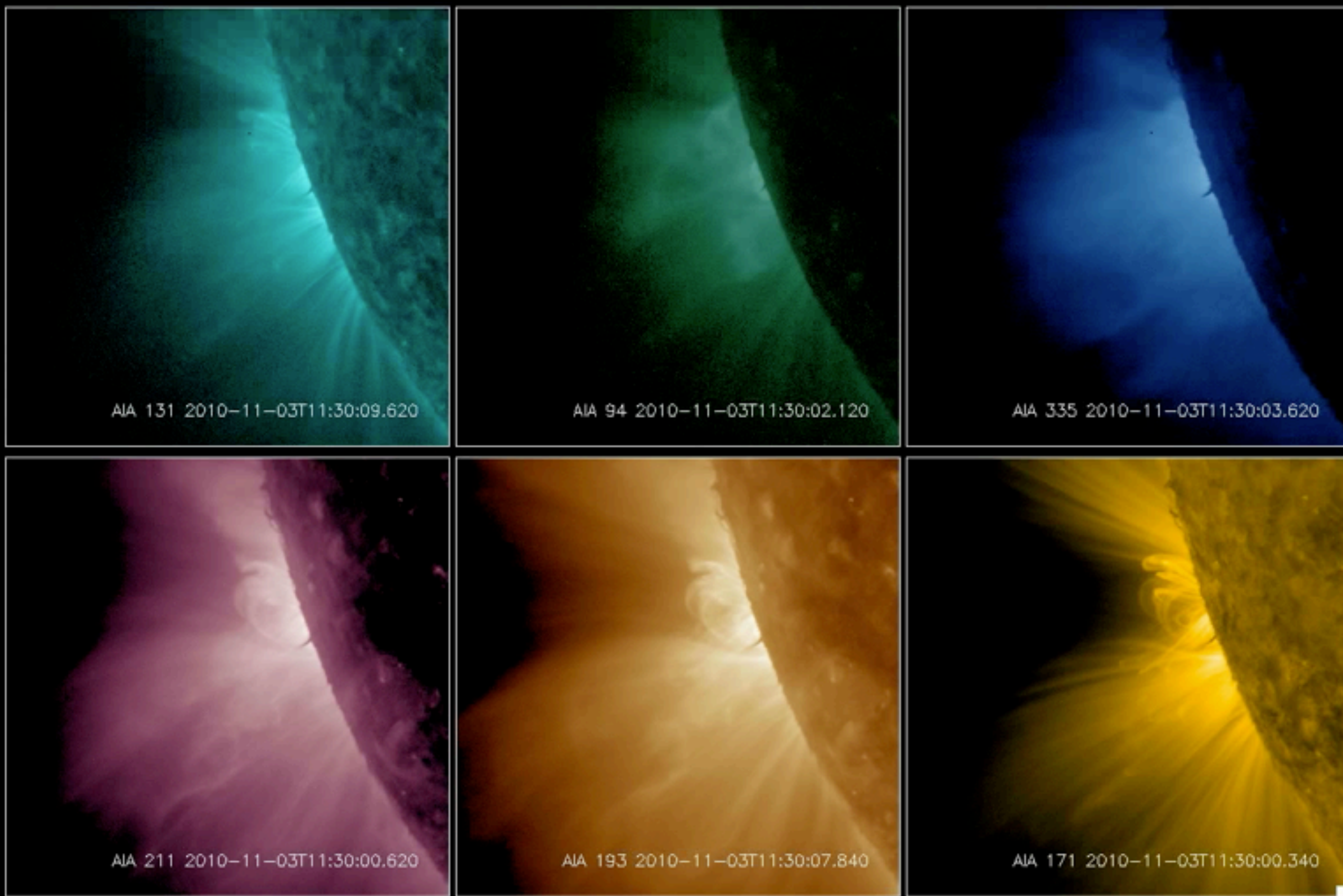
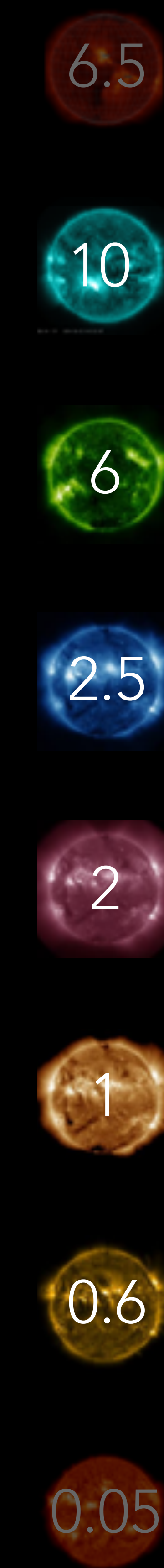


Note that the passbands are broad and the temperatures indicative

EUV WAVELENGTHS

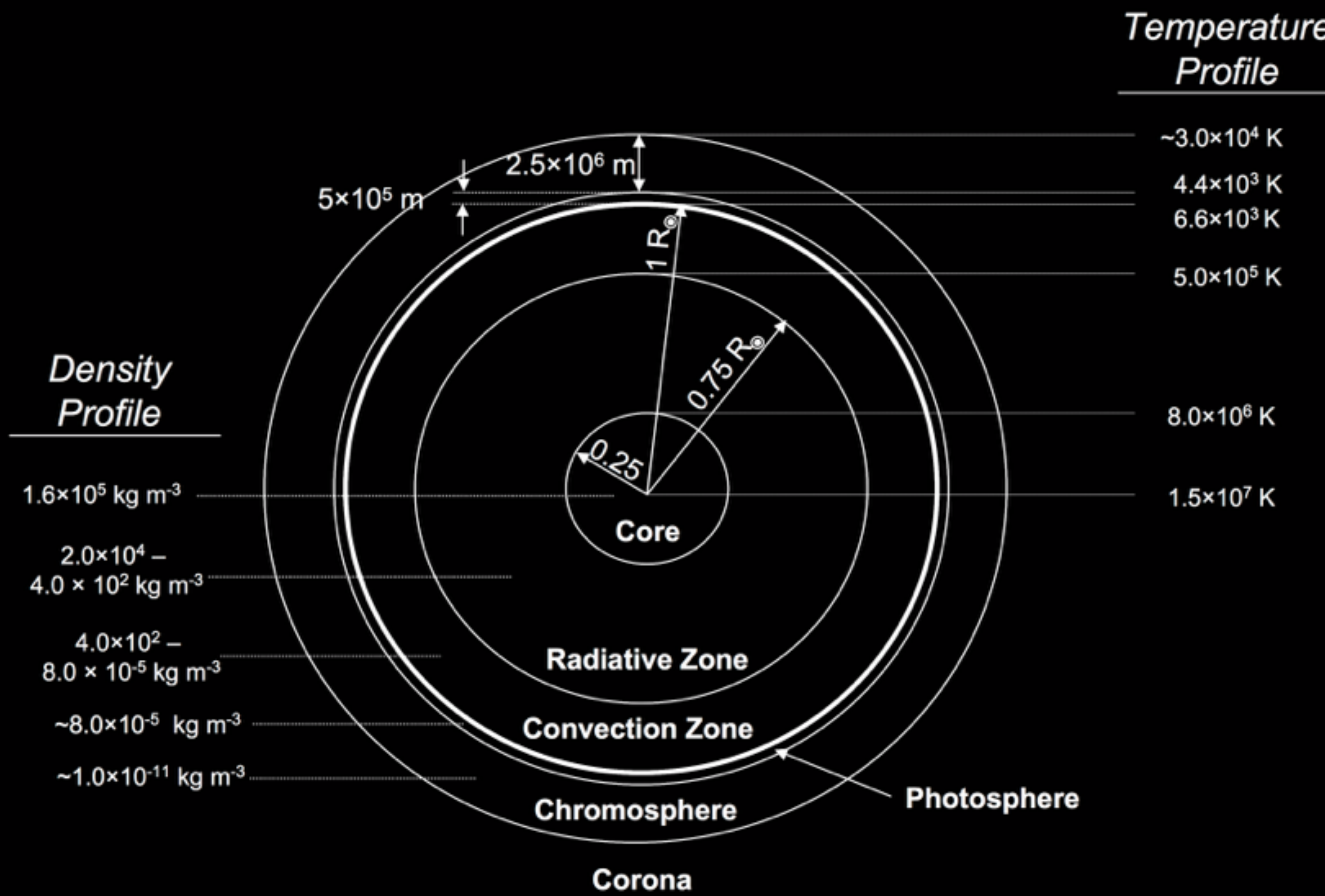


T / MK

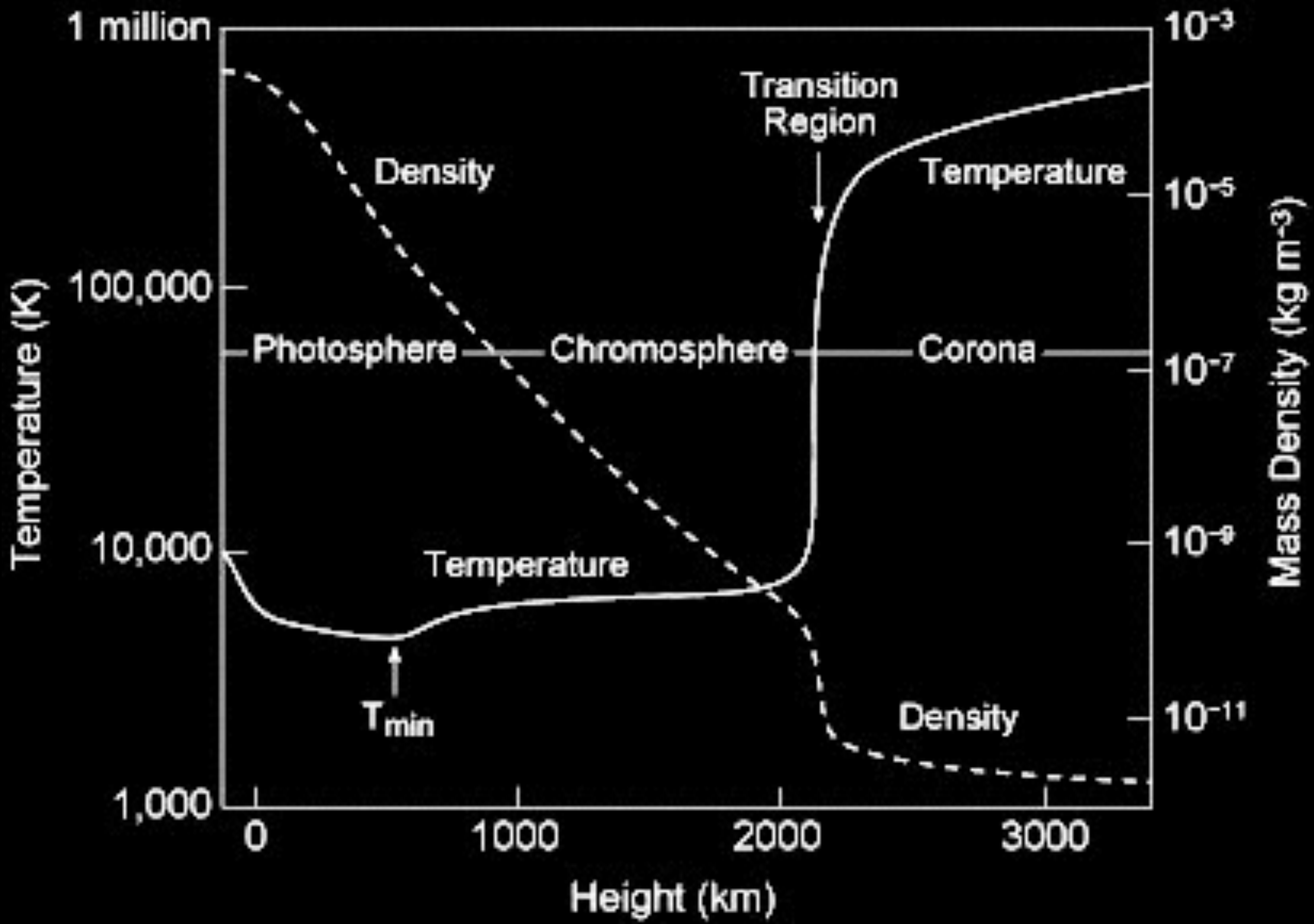


HOW DO WE DEFINE THE CORONA

THE SUN'S TEMPERATURE AND DENSITY STRUCTURE

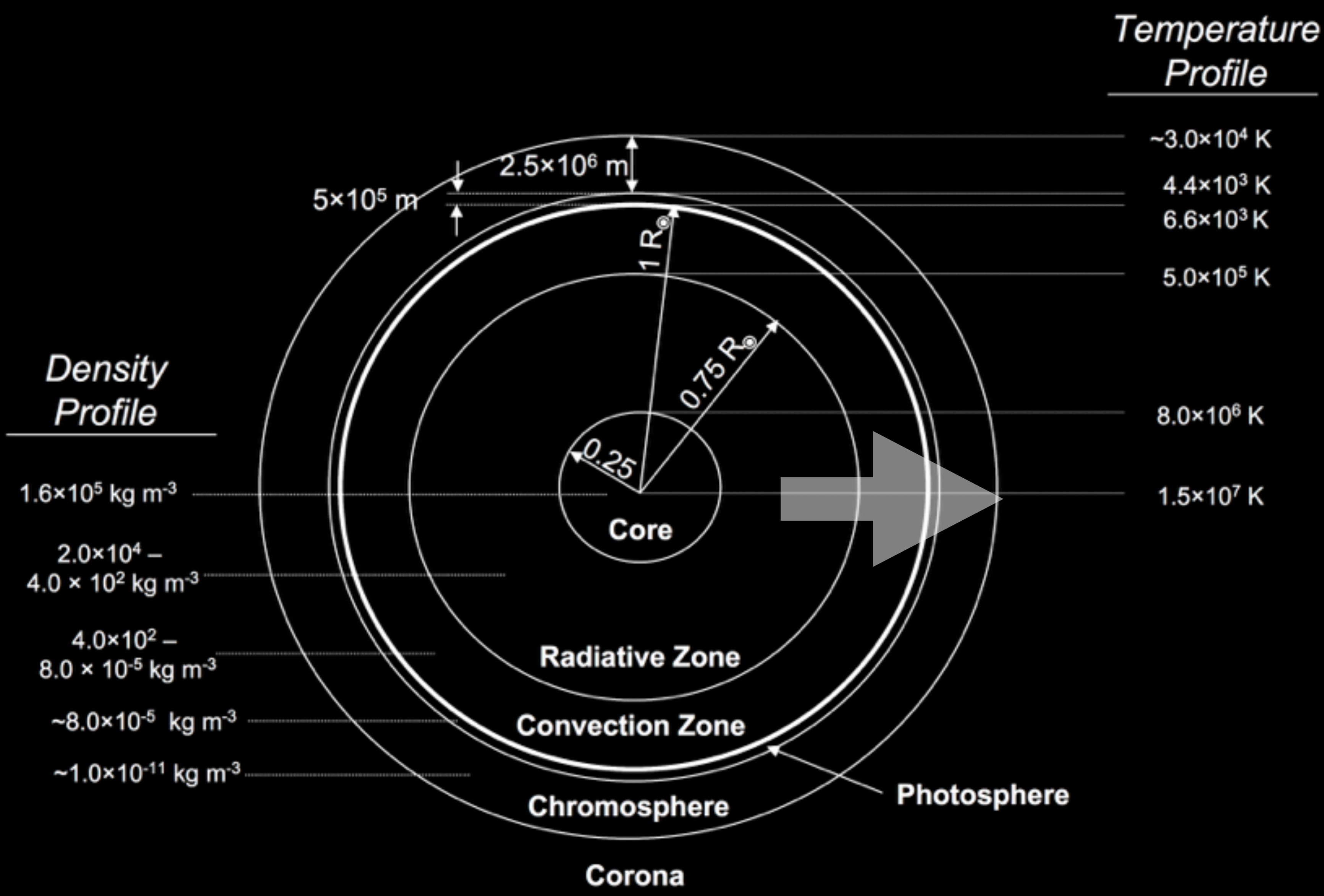


TEMPERATURE AND DENSITY STRUCTURE



Kenneth R. Lang, Tufts University

THE SUN'S TEMPERATURE AND DENSITY STRUCTURE



Problem: very high temperature of the upper atmosphere

Question: what heating mechanism(s) do operate?

THE CORONAL HEATING PROBLEM

"For decades the problem has been known as the coronal heating problem, but it is now clear that `coronal heating' cannot be treated or explained in isolation and that the whole solar atmosphere must be studied as a highly coupled system. The magnetic field of the star is known to play a key role….

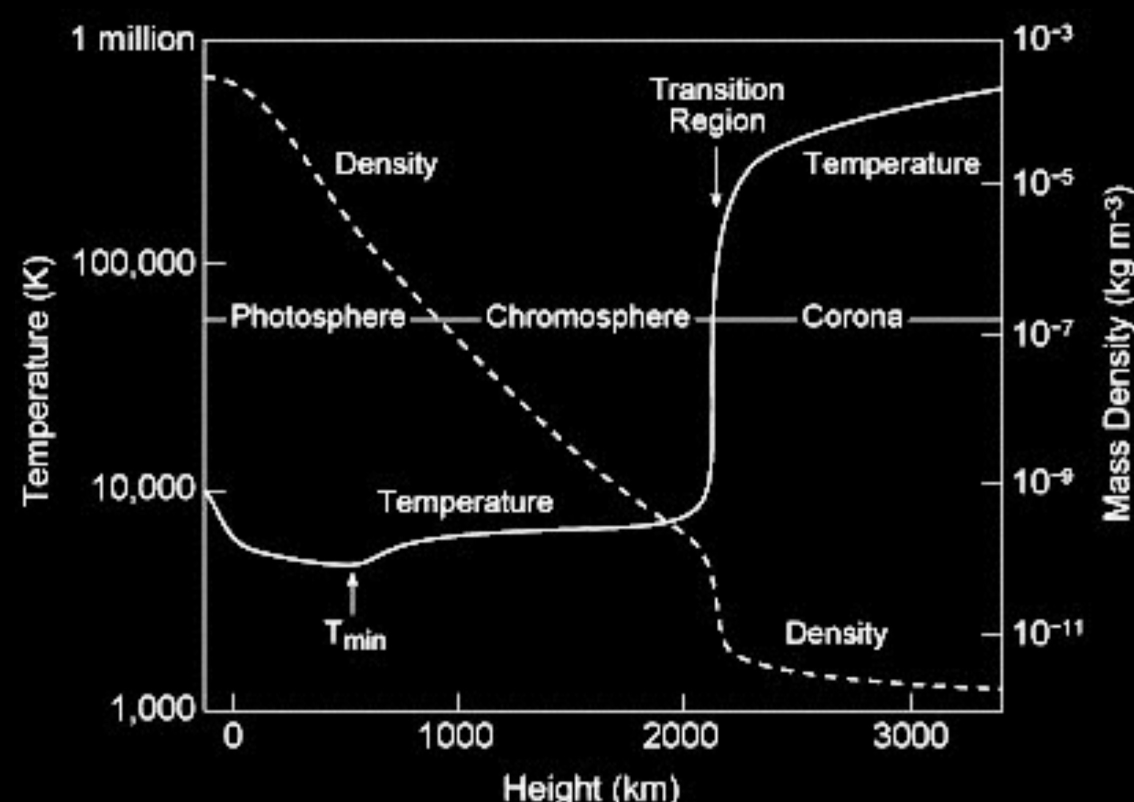
…..the question of which mechanism or mechanisms are the dominant supplier of energy to the chromosphere and corona is still open. "

(Parnell & De Moortel, 2012)

THE CORONAL HEATING PROBLEM

"The chromosphere has very different plasma properties to the corona and so explaining the heating of the solar atmosphere is now recognised to be considerably more complicated than had been appreciated during much of the twentieth century. "

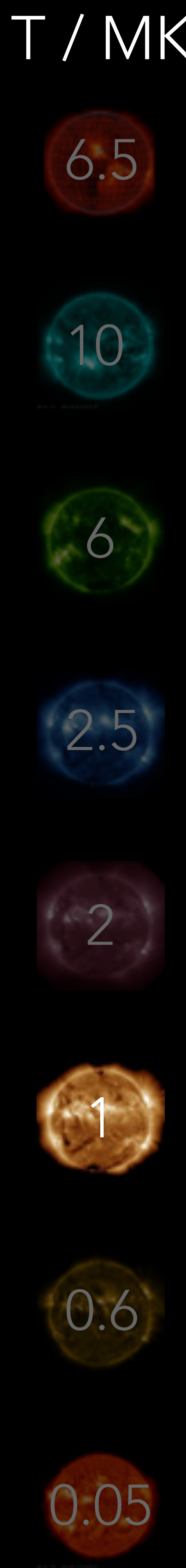
(Parnell & De Moortel, 2012)



THE ENERGY REQUIREMENT

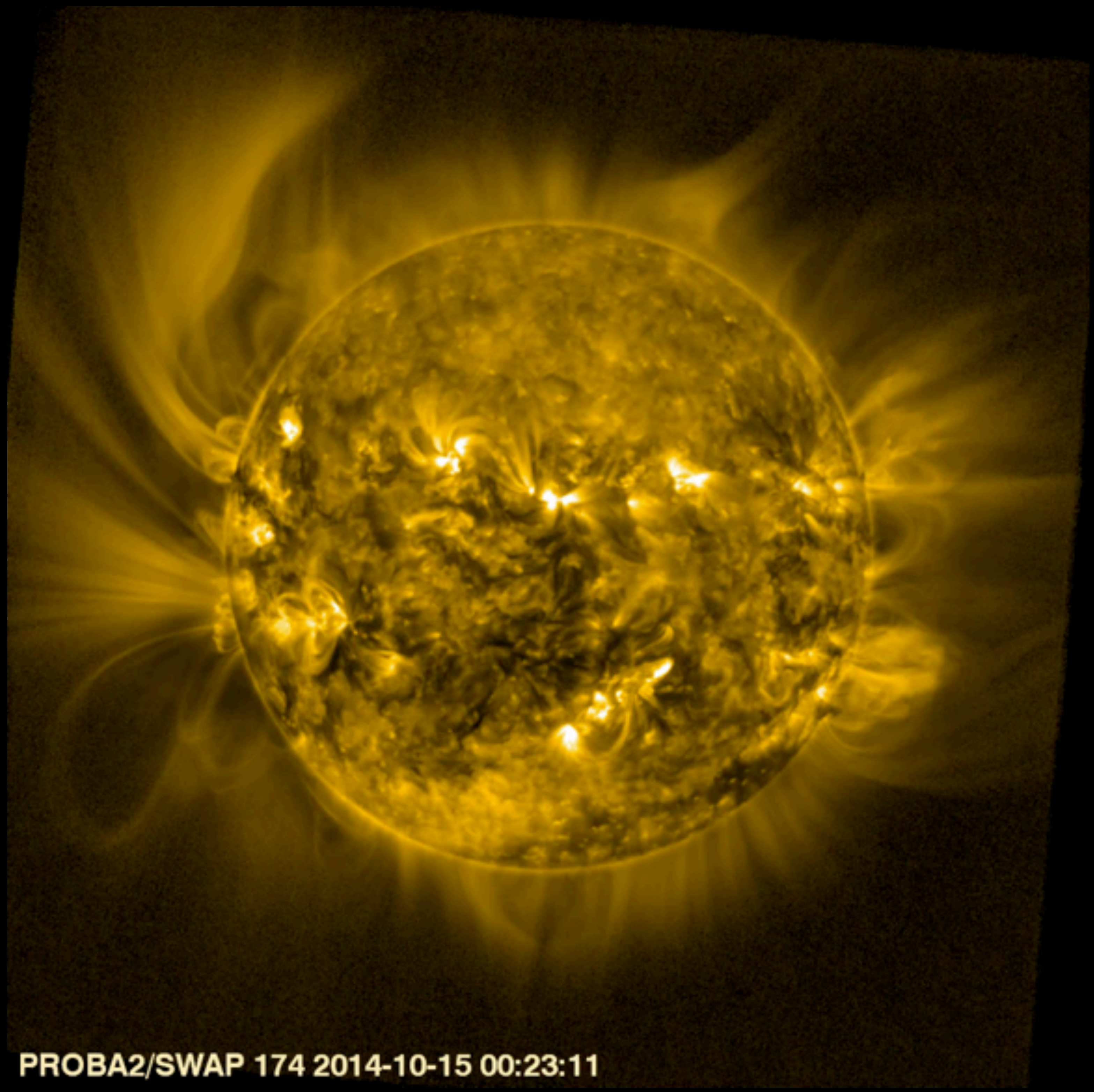
PARAMETER (ERG CM^{-2} S^{-1})	CORONAL HOLE (OPEN)	ACTIVE REGION (CLOSED)
Chromosphere	4×10^6	2×10^7
Corona	3×10^5	10^7
Solar Wind	$(5\text{-}10)\times10^5$	$(<10^5)$

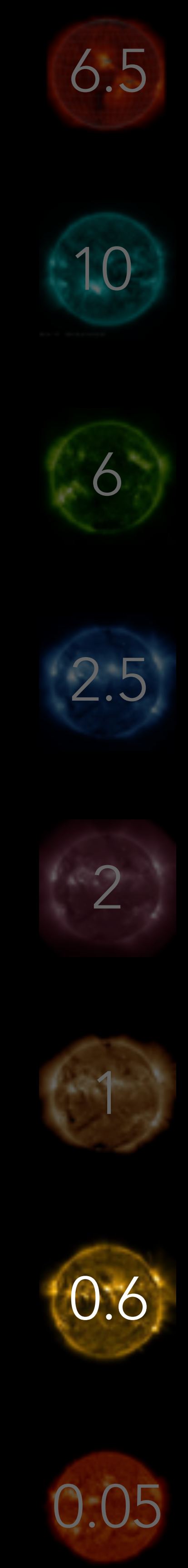
(Withbroe & Noyes, 1977)



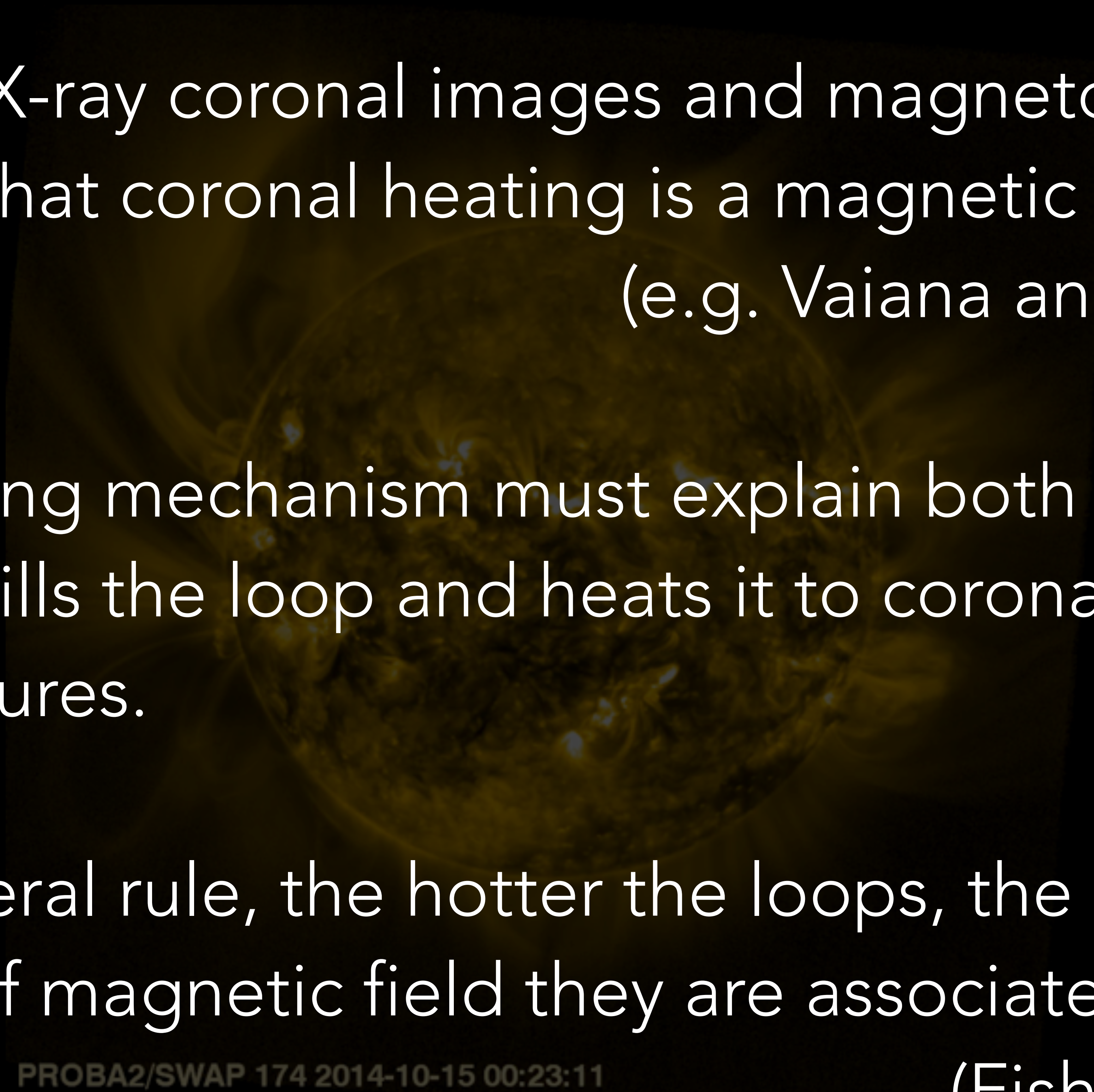
1 erg = 1×10^{-7} Joule

MAGNETIC LOOPS ON THE SUN





MAGNETIC LOOPS ON THE SUN



EUV, UV, X-ray coronal images and magnetograms indicate that coronal heating is a magnetic phenomenon.
(e.g. Vaiana and Rosner 1978)

The heating mechanism must explain both how the material fills the loop and heats it to coronal temperatures.

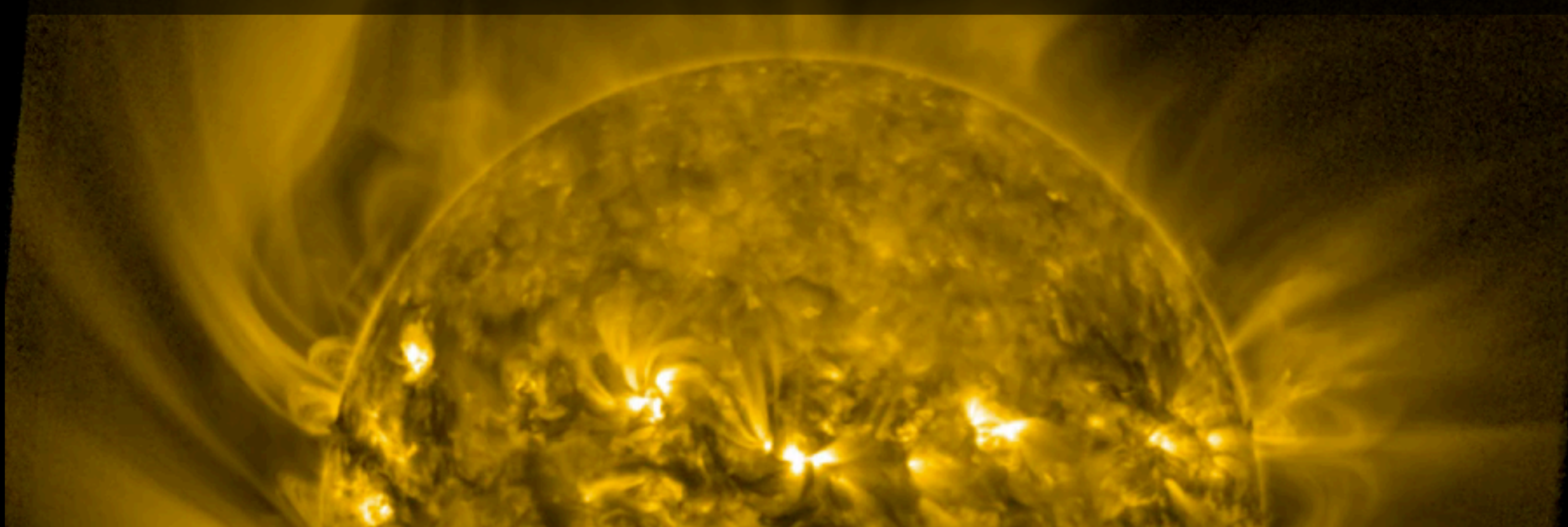
As a general rule, the hotter the loops, the stronger the regions of magnetic field they are associated with
(Fisher et al., 1998).

MAGNETIC LOOPS ON THE SUN

T / MK

The photospheric driving and the complex geometry/topology of the magnetic field are determined globally.

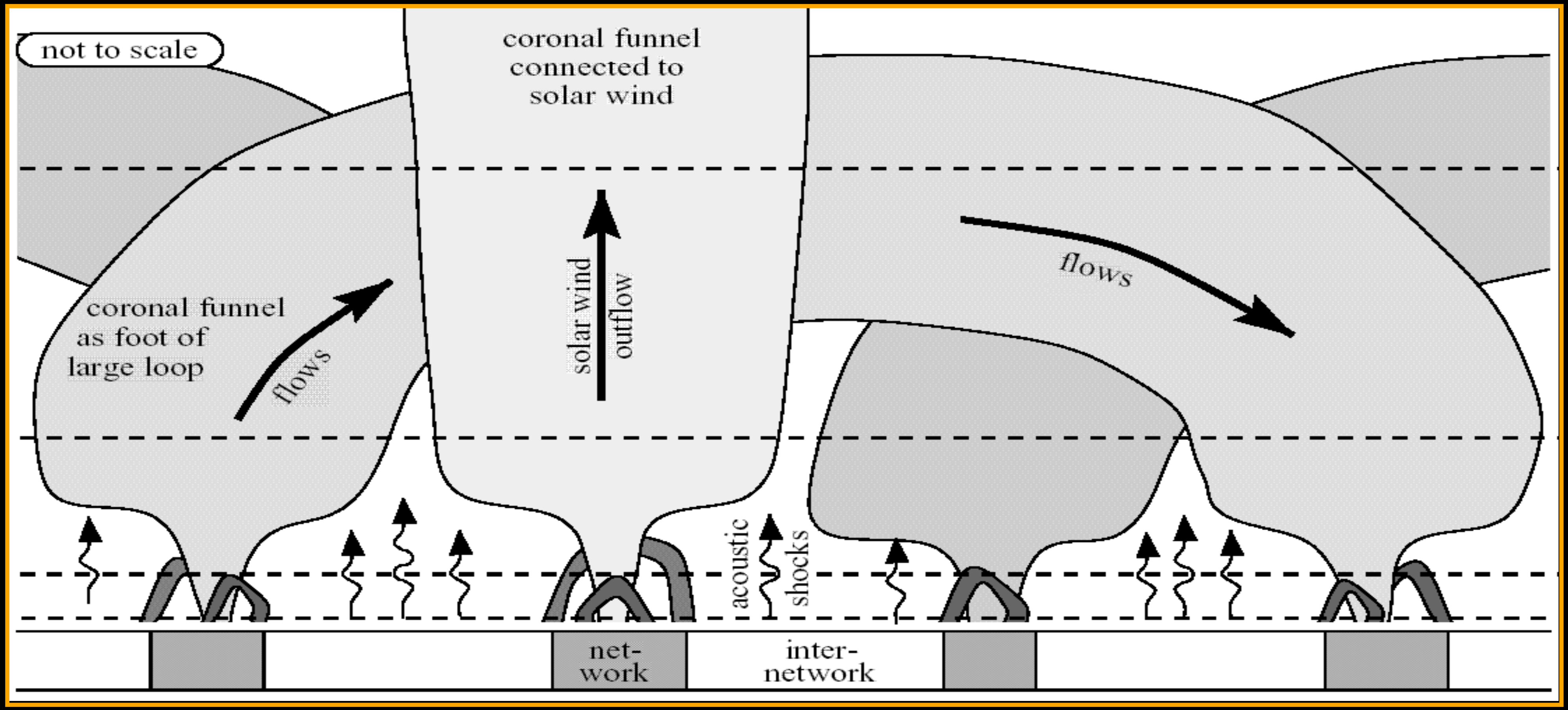
The massive range of scales which need to be addressed by coronal heating models poses a problem for both theorists and observers.



THE MAGNETIC FIELD

The Magnetic field is concentrated in small flux tubes (~kG) which expand out in the chromosphere and transition region.

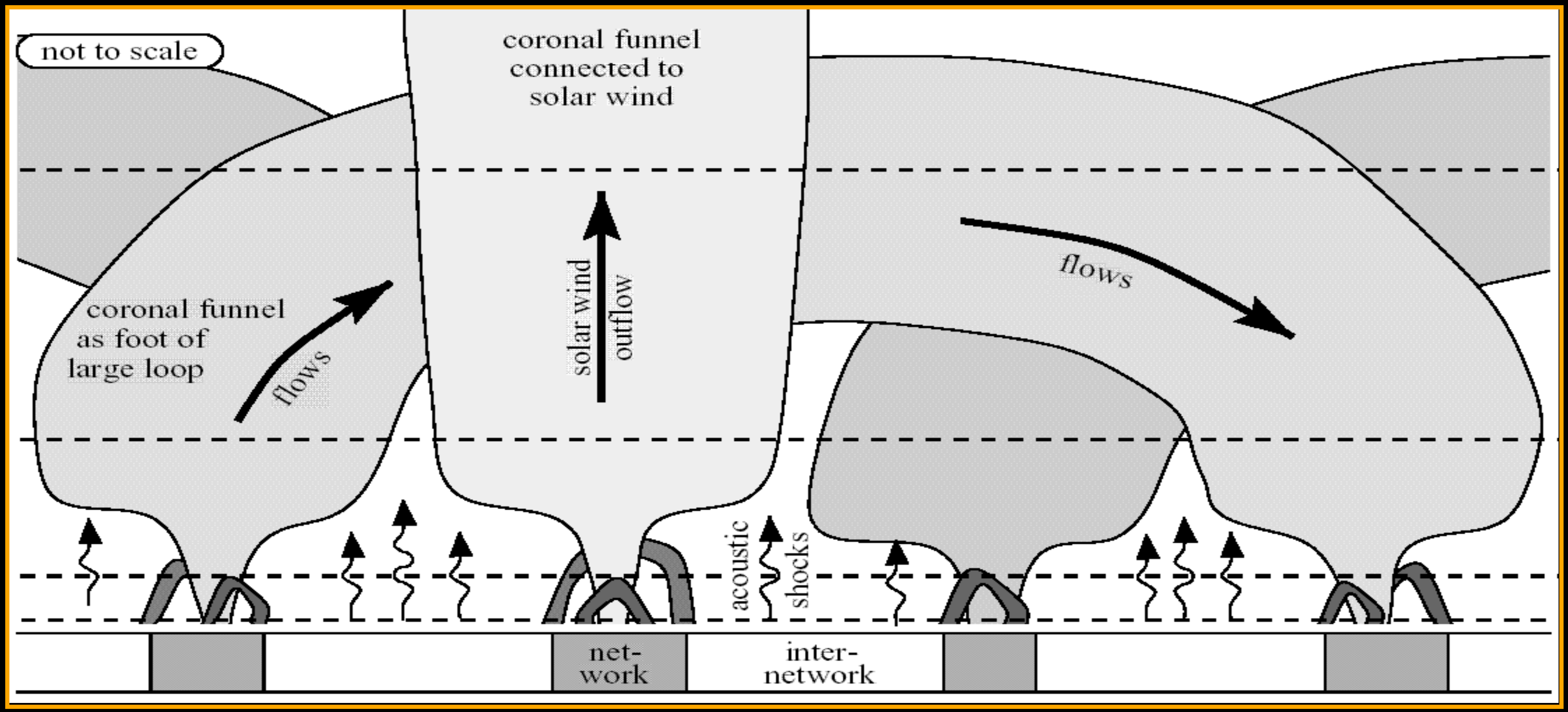
Small loops form a low-laying "magnetic carpet" and they do not penetrate far into the corona,



Courtesy Peter (2001)

THE MAGNETIC FIELD

Part of the inter-network flux extends above the carpet and spreads out in the corona the magnetic field in the quiet Sun is a mixture of network field and surviving inter-network field.



Courtesy Peter (2001)

POYNTING FLUX

The energy transported into or out of the solar atmosphere is provided by a Poynting flux through the surface of the Sun

$$S = \frac{1}{\mu_0} \int \int_{S_\circ} \mathbf{E} \times \mathbf{B} \cdot \mathbf{dS}$$

Quiet-Sun (with a mean field strength of 10 G), then the Poynting flux per unit area is about:

$$>2.5 \times 10^7 \text{ erg cm}^{-2} \text{ s}^{-1}$$

Active Region Poynting flux per unit area:

$$>1.0 \times 10^9 \text{ erg cm}^{-2} \text{ s}^{-1}$$

(See Parnell & De Moortel, 2012)

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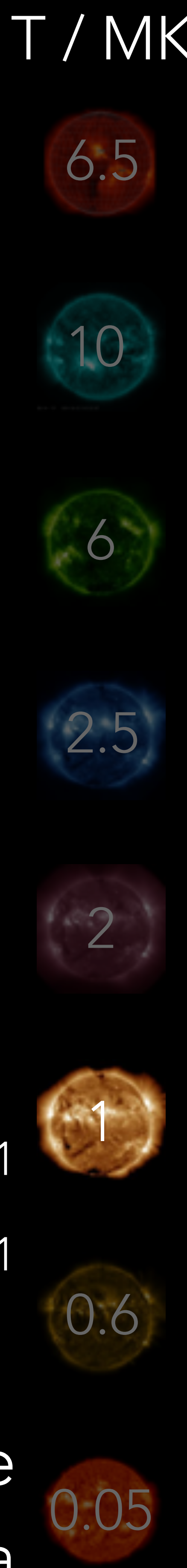
(Withbroe & Noyes, 1977)

Quiet-Sun: $>2.5 \times 10^7$ erg cm^{-2} s^{-1}

Active Region: $>1.0 \times 10^9$ erg cm^{-2} s^{-1}

the energy injected by moving the footpoints seems to give more than enough energy to heat both the chromosphere and corona



REVIEWS

A huge number of heating mechanisms have been suggested. Here I focus on a couple of the most favoured.

Good reviews include:

Klimchuk (2006; Heating of the Mag- netically Closed Corona. In Soho-17. 10 years of soho and beyond, vol. 617 of ESA Special Publication),

Aschwanden et al. (2007; doi:10.1086/513070) ,

Goossens et al. (2011; doi:10.1007/BF00151914),

Reale (2010; Coronal Loops: Observations and Modeling of Confined Plasma. Living Reviews in Solar Physics, 7).

Parnell & De Moortell (2012; doi: 10.1098/rsta.2012.0113)

TWO MOST POPULAR MECHANISMS

THE ENERGY REQUIREMENT

The energy that heats the solar atmosphere comes from the convection zone and this energy manifests itself both as:

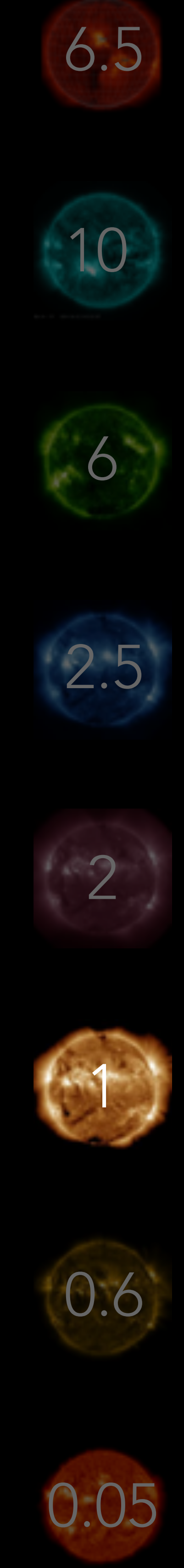
waves

and, through the slow stressing, current sheets leading to

reconnection.

Which of these is most important for chromospheric and coronal heating is still very much an open question.

T / MK



MAGNETIC LOOPS ON THE SUN

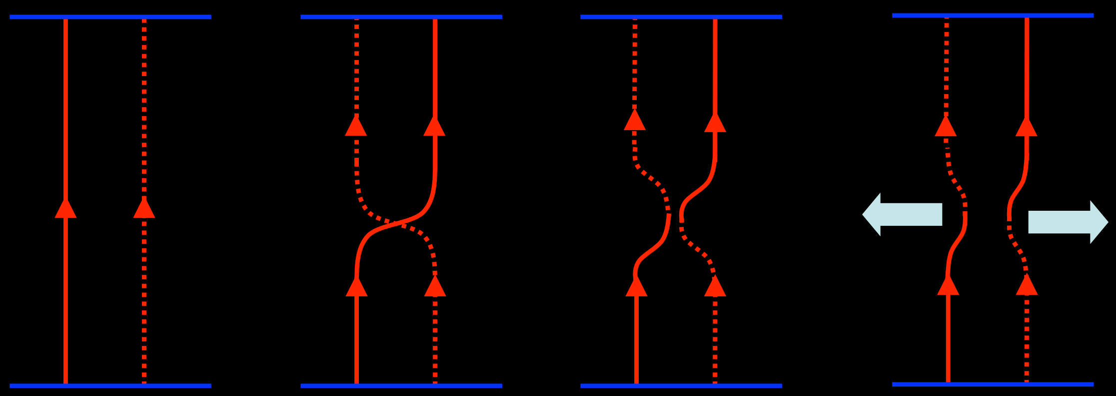
Widely accepted: mechanical motions in and below the photosphere lead to a heating mechanism.

Slow (long timescale) motions result in a quasi-static stressing of the field.

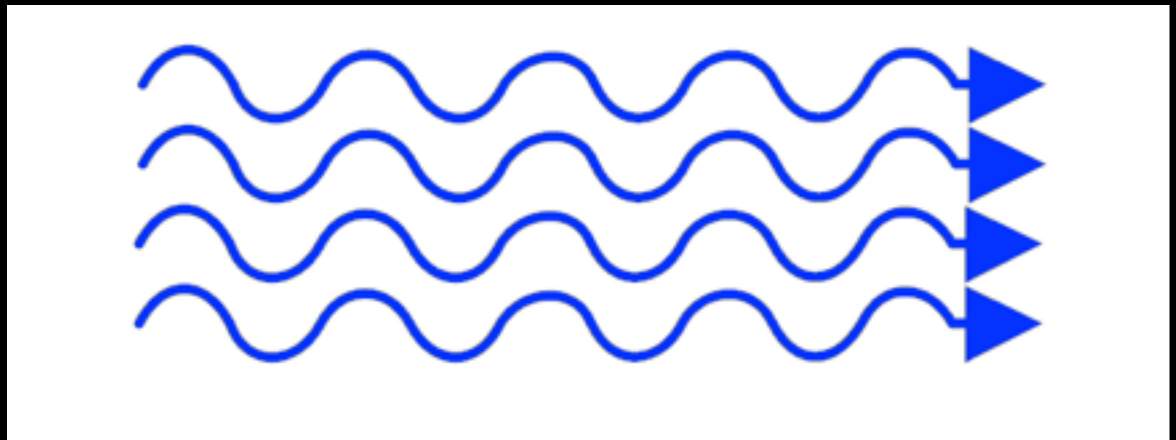
Fast (short timescale) motions generate waves.

MAGNETIC LOOPS ON THE SUN

The dissipation of magnetic stresses (typically manifest as current sheets) leads to magnetic reconnection and is known as DC heating,



The dissipation of waves is referred to as AC heating.



DC-HEATING

THE ENERGY SOURCE – DC HEATING

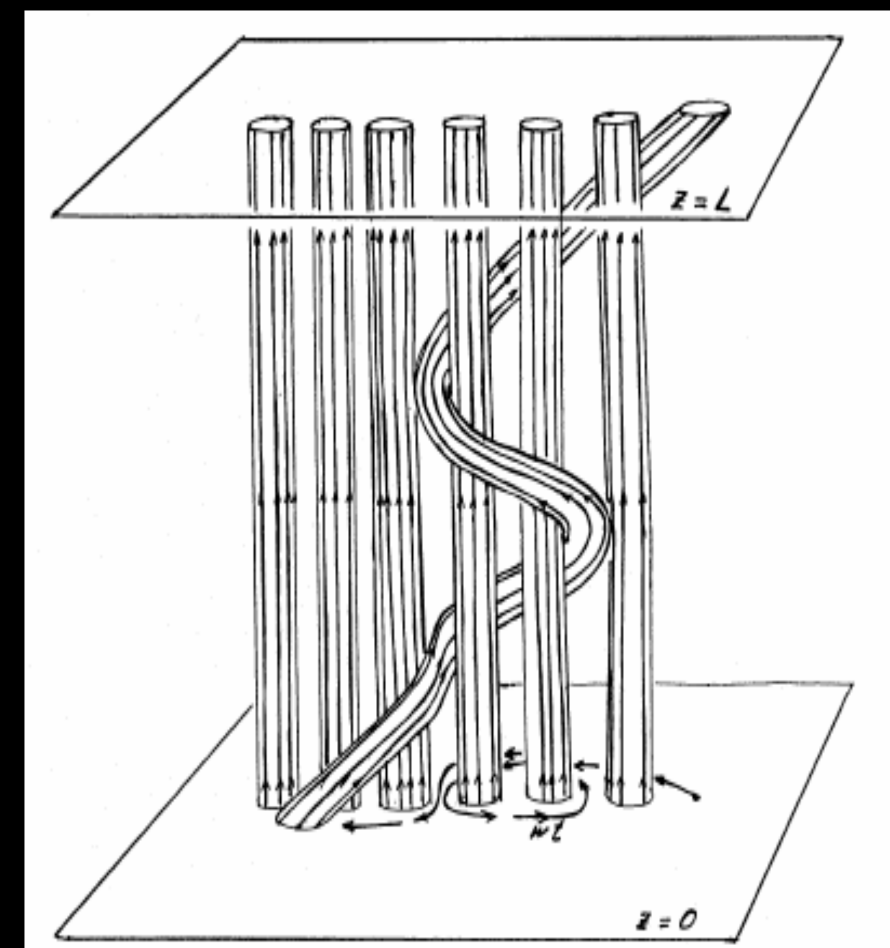
One consequence of new flux (10^{19} Mx) emerging into the photosphere is the formation of new coronal loops connecting the new flux features to pre-existing ones.

The only way these new loops could have formed is through magnetic reconnection allowing a global restructuring of the magnetic field.

(see Priest & Forbes (2000) for more details)

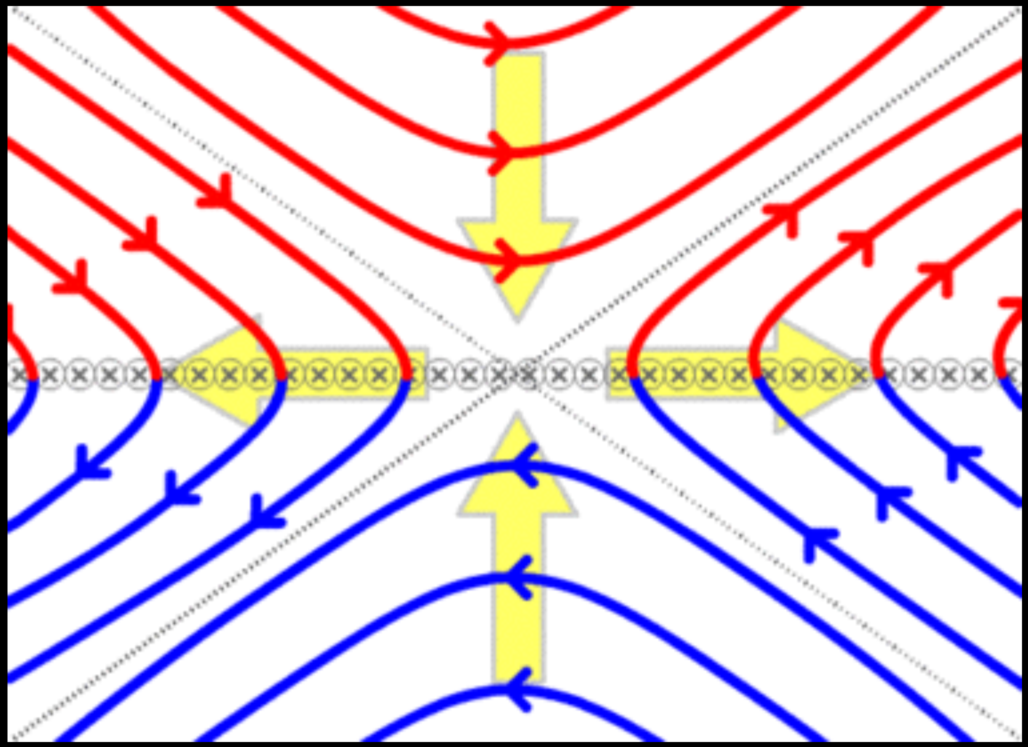
Footpoint motions perform work on the coronal magnetic field and increase its free energy at a rate given by the Poynting flux through the base.

2D RECONNECTION THEORIES



Photospheric motions randomly twist up the coronal magnetic field, creating small localised current sheets

2D RECONNECTION THEORIES



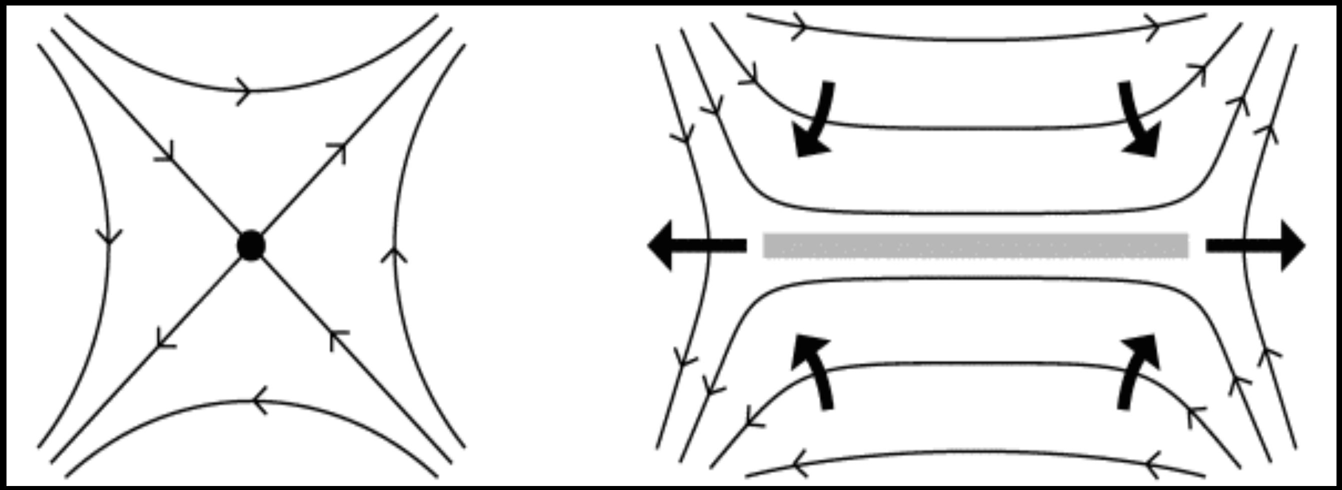
Field lines of opposite polarity are forced together.

Energy released from the dissipation of current sheets.

Tension forces act to straighten the field lines accelerating particles in the form of plasma jets.

2D RECONNECTION THEORIES

2D reconnection: X-point collapses to a singular sheet



Magnetic energy converted to thermal, Kinetic energy and fast particles

Source of heating and of many dynamic processes (flares, Bright pots etc.)

2D RECONNECTION THEORIES

In 2D well-developed:

Slow Sweet-Parker reconnection (1958)

Fast Petschek reconnection (1964)

Many other fast regimes:

Almost uniform (Priest &Forbes, 1986)

Non-uniform (Priest & Lee, 1992)

(See Priest and Forbes Magnetic reconnection, CUP, 2000)

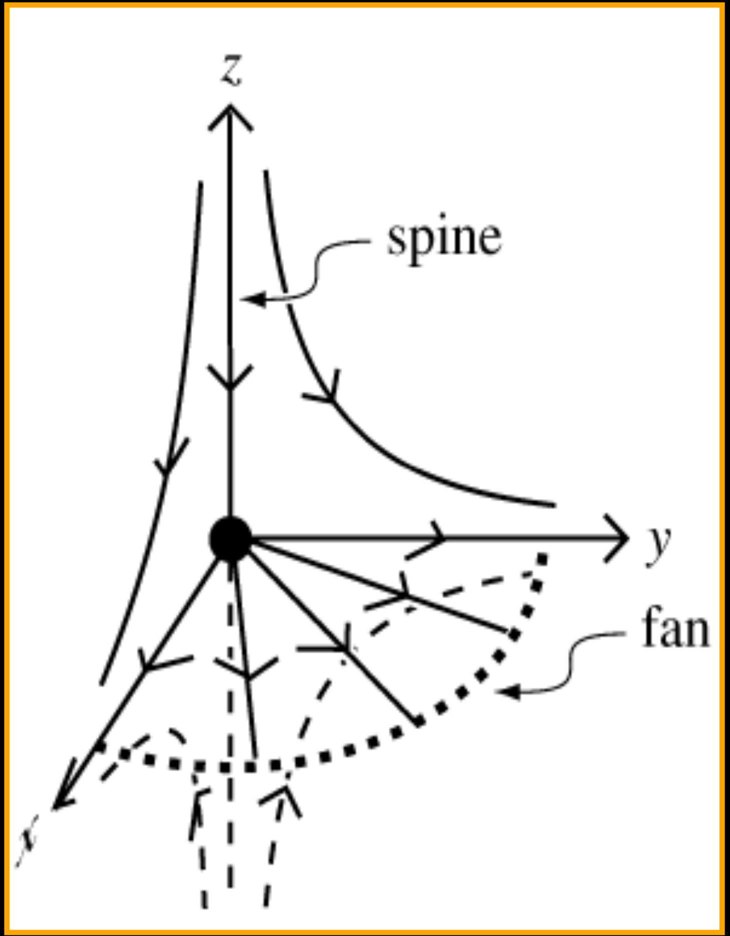
3D RECONNECTION THEORIES

3D reconnection is dependent on the structure of the null-point

Simplest: B=(x , y, -2z)

Two families of field lines pass through the null-point:

Spine field lines
Fan surface



Courtesy of Pontin et al.: Kinematic Reconnection at a Magnetic Null Point: Spine Reconnection

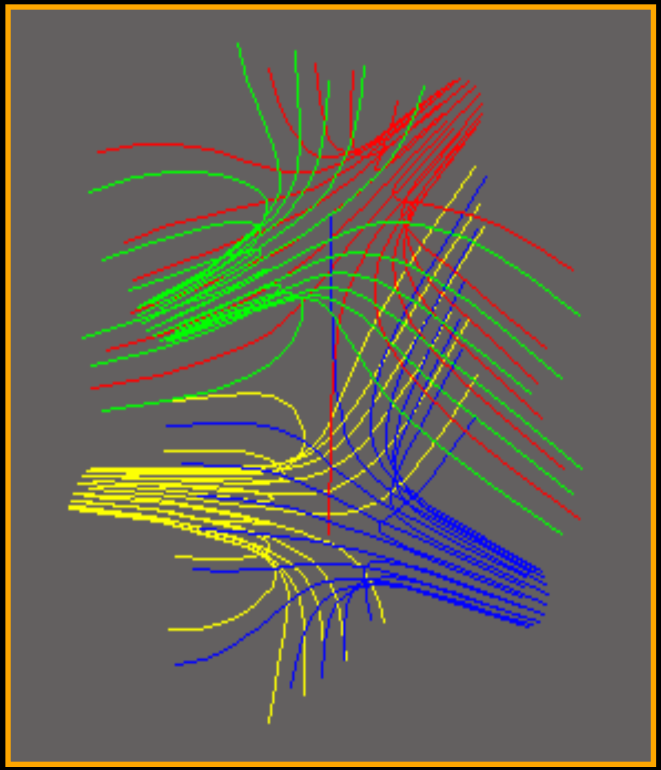
3D RECONNECTION THEORIES

Three types of reconnection at Null

Spine reconnection

Fan reconnection

Separator reconnection



Double 3D null-point topology
(courtesy of K. Garlsgaard)

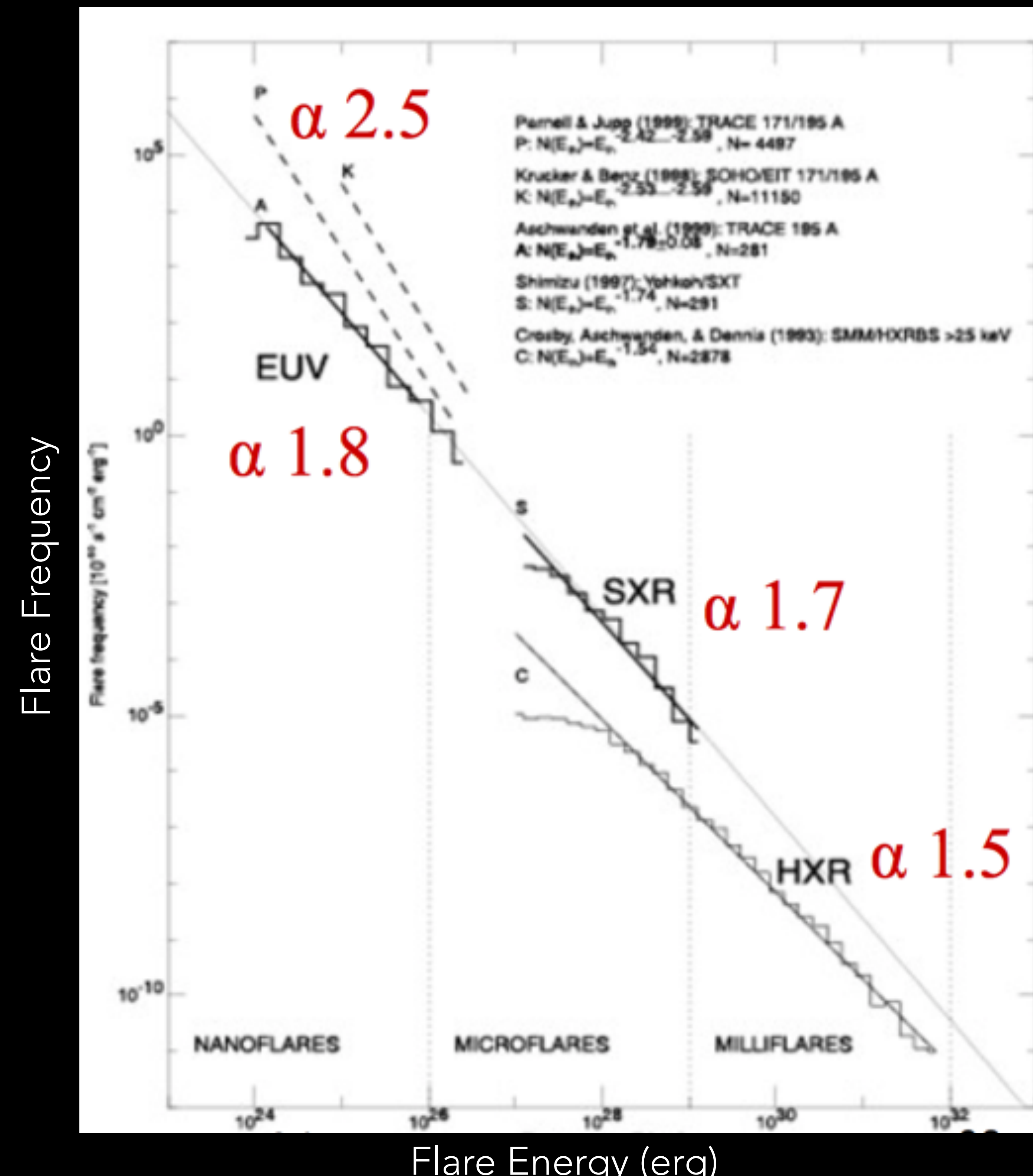
CAN RECONNECTION HEAT THE CORONA?-OBSERVATIONAL EVIDENCE

Reconnection is believed to occur on all size scales.

Observations indicate a greater number of flares on smaller scales.

Various observations indicate different slopes

$$\frac{dN}{dE} = kE^{-\alpha}$$



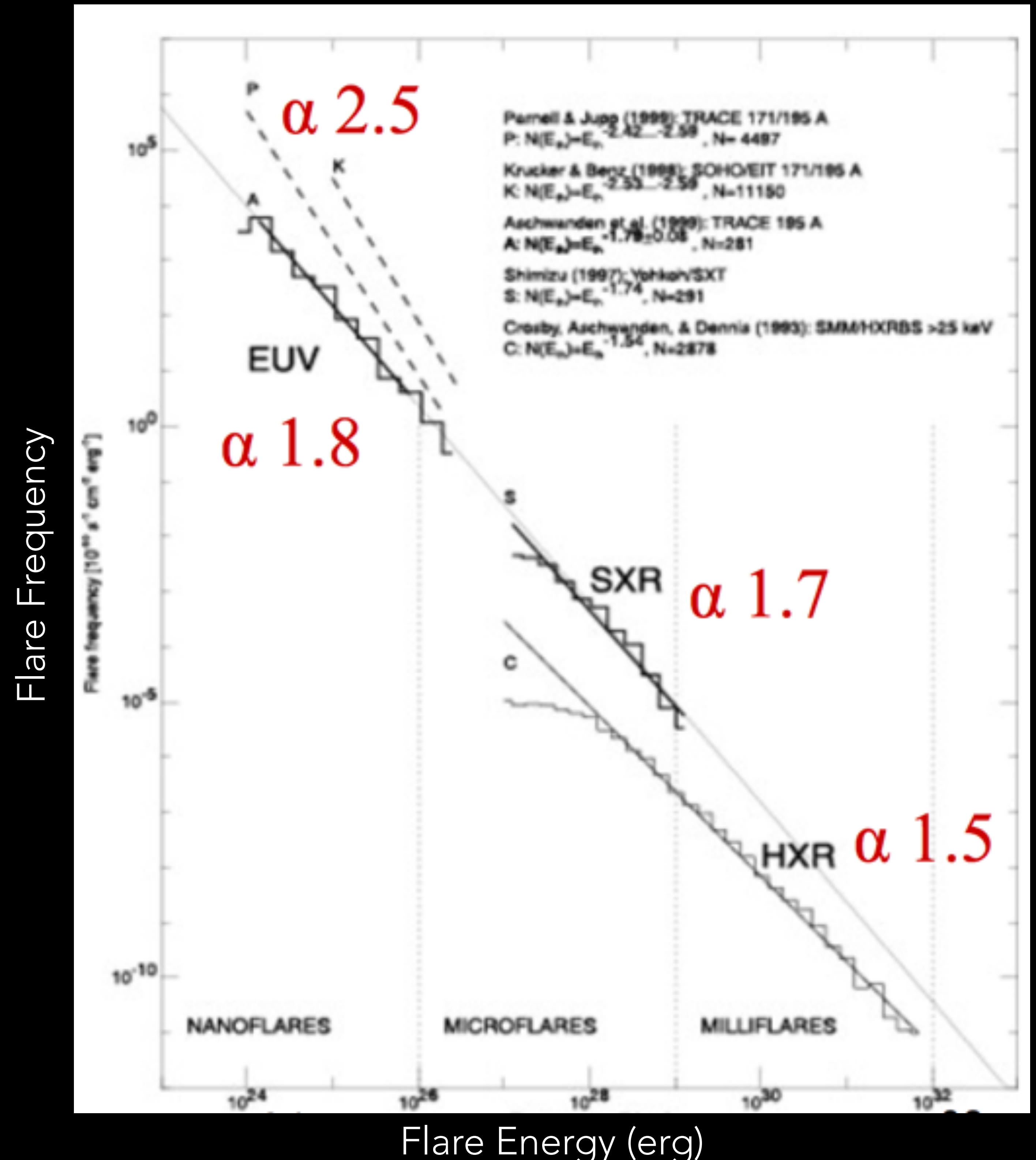
Aschwanden et al. 2000 ApJ, 535

CAN RECONNECTION HEAT THE CORONA?-OBSERVATIONAL EVIDENCE

It's believed to meet the coronal energy budget

$\alpha \approx 2.0$

$$\frac{dN}{dE} = kE^{-\alpha}$$



Aschwanden et al. 2000 ApJ, 535

AC-HEATING

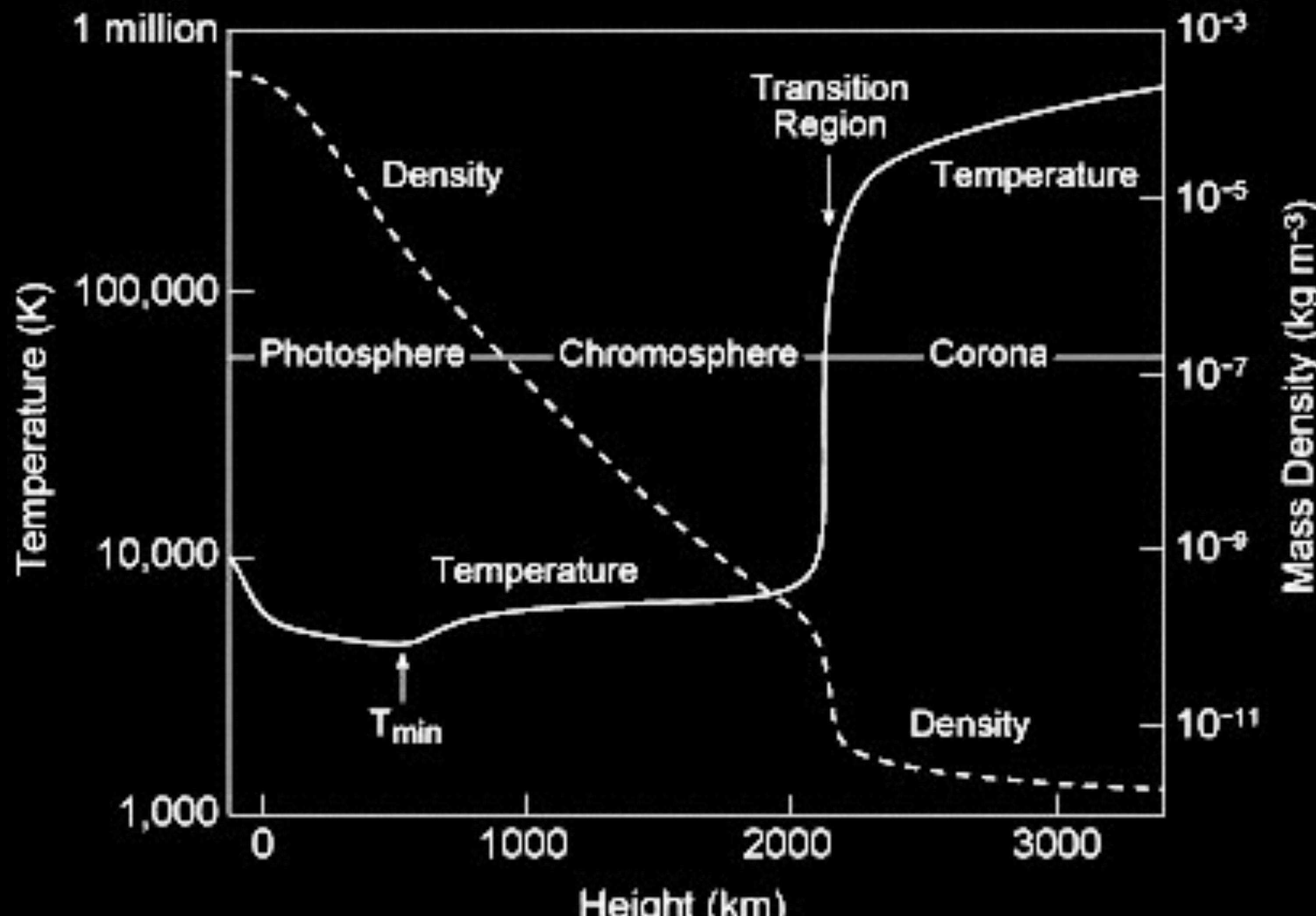
THE ENERGY SOURCE – DC HEATING

The turbulent convection that stresses the coronal magnetic field generates a large flux of upwardly propagating waves (acoustic, Alfvén, slow and fast magnetosonic).

Mode coupling and other processes transfer energy between different types of waves, so the mix of waves changes as a function of height.

THE ENERGY SOURCE – DC HEATING

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

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.

They do not form shocks since they are transversal and their energy is moved along the magnetic field rather than being refracted across it.

ACOUSTIC WAVES

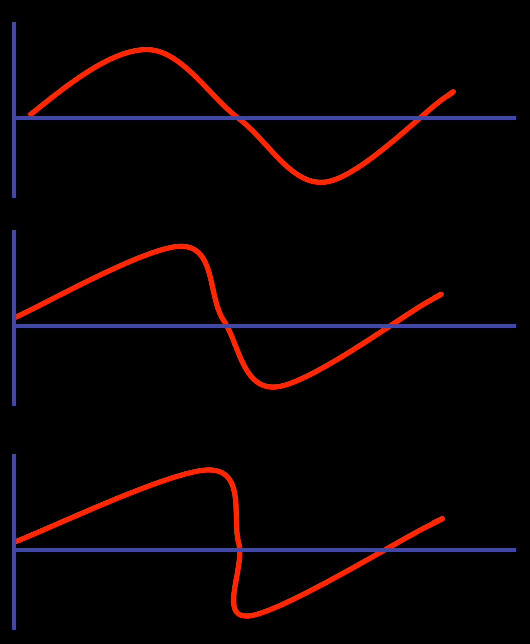
Chromospheric heating by acoustic waves

Convection generates acoustic waves propagating upwards, steepens into shock waves or are reflected by the density gradients in the TR

$F_M = \rho C_S \langle v^2 \rangle$ $\qquad$ $\rho = \rho_0 e^{-h/H}, \quad H \approx 160\,Km$ $\qquad$ $\langle v^2 \rangle \propto A^2$

so $\qquad A \propto e^{h/2H}$

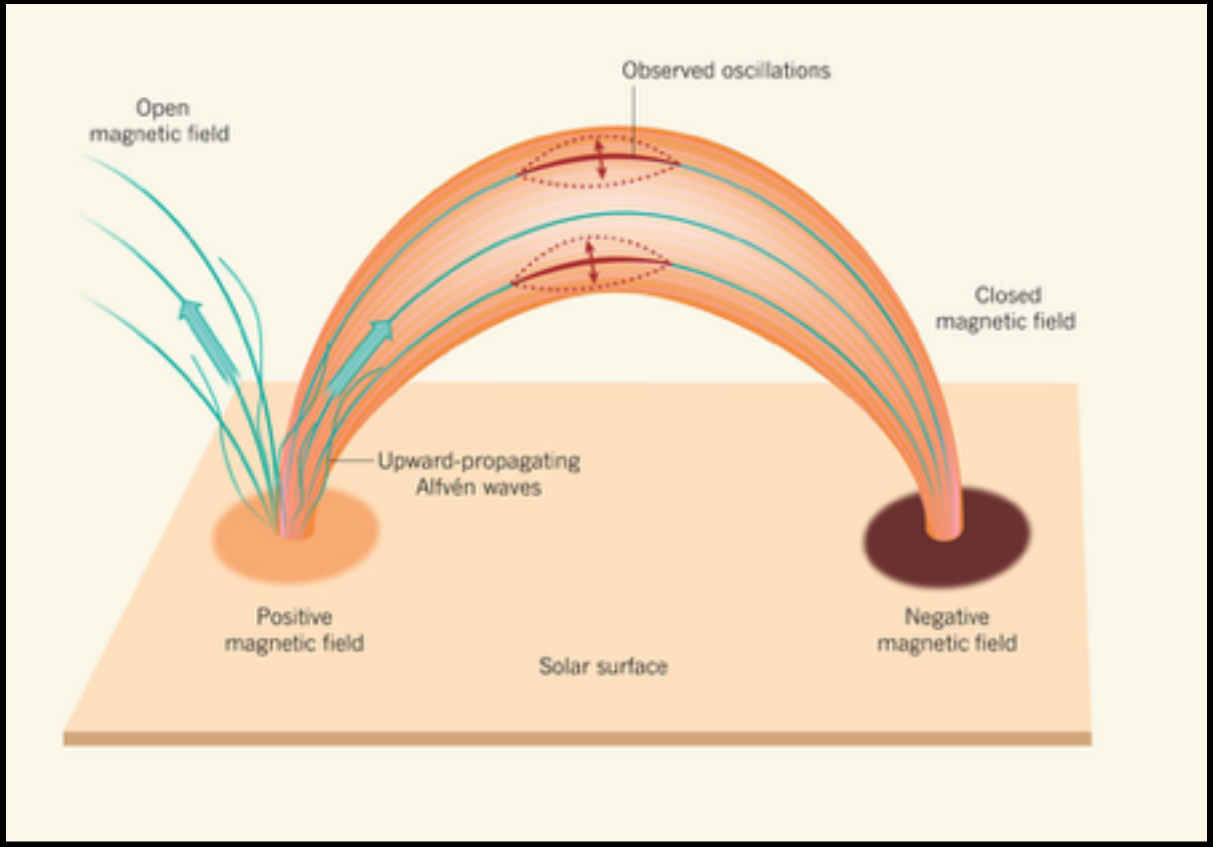
$k_v^2 = \omega^2 / v_A^2 - k_h^2$ $\qquad$ $k_v^2 < 0 \rightarrow$ evanescent waves



ALFVÉN WAVES

Significant transmission of Alfvén waves is possible only within narrow frequency bands centered on discrete values where loop resonance conditions are satisfied (Hollweg, 1981)

Enough flux may pass through the base of long (>100 Mm) active regions loops to provide their heating (Hollweg, 1985); in the case of short loops this does not apply.



OBSERVATIONS

Recent high resolution observations show evidence for waves in the corona, Prominences, Plumes and Corona (EIT/SoHO, TRACE).

Flare excited waves in loops-fast kink modes (Aschwanden et al. 1999, Nakariakov and Ofman 1999)

Feet of long loops-slow waves (De Moortel et al. 2002ab, Aschwanden et al. 2002)

CME/flare excited global waves (EIT waves) –fast waves (Thompson et al. 1999, Ballai and Erdélyi 2003a,b, Ballai et al. 2005).

HOW IS WAVE ENERGY CONVERTED TO HEAT?

A heating theory based on waves must overcome several obstacles, namely:

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

(ii) sufficient energy flux has to be transported as only a fraction of the wave energy will be transmitted into the corona and

(iii) the waves have to dissipate (very) efficiently to convert the energy flux into heat in the right place, at the right time.

Parnell & De Moortell (2012)

HOW IS WAVE ENERGY CONVERTED TO HEAT?

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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).

HOW IS WAVE ENERGY CONVERTED TO HEAT?

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Not so easy to satisfy since most of the (magneto)acoustic waves do not propagate into the corona due to strong reflection and refraction off the rapid density and temperature increase in the Transition Region

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Additionally, mode coupling is expected to take place in regions where the sound and Alfvén speed are approximately equal reducing the flux reaching the corona still further.

Alfvén waves, on the other hand, are generally seen as very efficient carriers of energy over large distances

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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.

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(iii) the waves have to dissipate (very) efficiently to convert the energy flux into heat in the right place, at the right time.

Both resonant absorption and phase mixing are based on the property that in an inhomogeneous plasma, individual surfaces can oscillate with their own Alfvén frequency.

HOW IS WAVE ENERGY CONVERTED TO HEAT?

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(iii) the waves have to dissipate (very) efficiently to convert the energy flux into heat in the right place, at the right time.

In resonant absorption, on a specific magnetic surface, an incoming wave motion can be in resonance with local oscillations, allowing the transfer of energy from large-scale motions to small lengthscales where dissipation can become effective.

HOW IS WAVE ENERGY CONVERTED TO HEAT?

A heating theory based on waves must overcome several obstacles, namely:

(iii) the waves have to dissipate (very) efficiently to convert the energy flux into heat in the right place, at the right time.

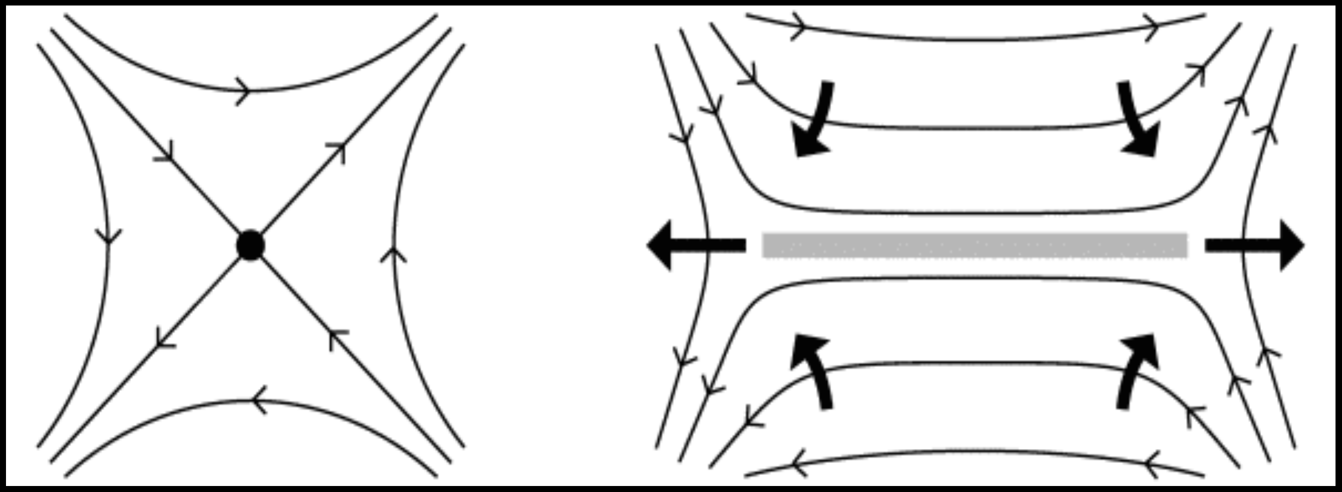
Similarly, phase mixing describes how Alfvén waves on neighbouring field lines gradually become out of phase, again generating increasingly large transverse gradients until dissipative lengthscales are reached.

AC/DC-HEATING

FEEDBACK LOOPS

The Sun is probably not heated by a single mechanism but several or a combination.

E.g. Waves can be generated in the corona itself by, e.g. magnetic reconnection and change of the equilibrium (AC/DC heating mechanism)



OPEN QUESTIONS & CONCLUSIONS

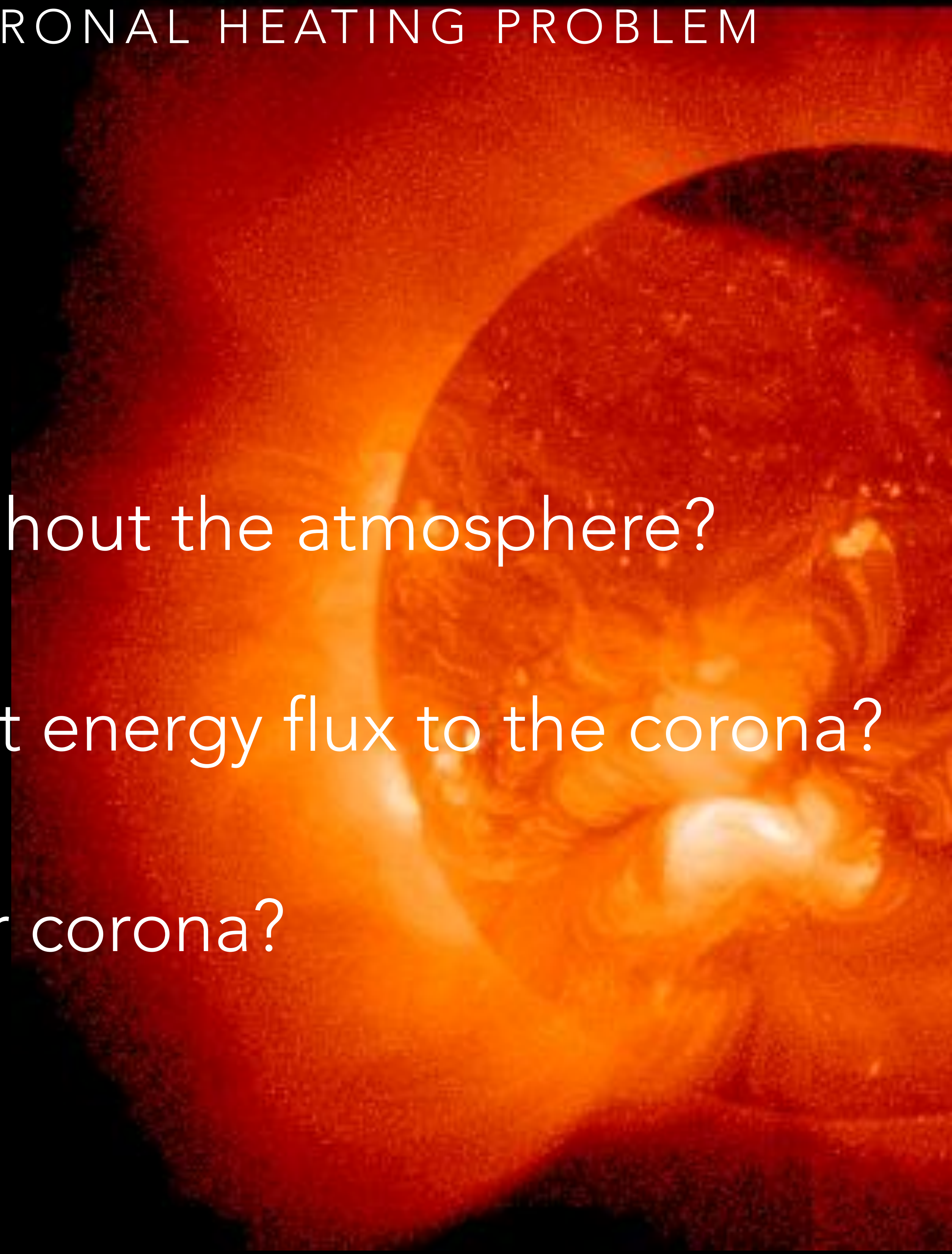
OPEN QUESTIONS IN THE CORONAL HEATING PROBLEM

Are there enough flares?

Are they ubiquitous throughout the atmosphere?

Can waves deliver sufficient energy flux to the corona?

Can waves reach the upper corona?



OPEN QUESTIONS IN THE CORONAL HEATING PROBLEM

Are distinct coronal loops heated differently from the diffuse corona?

Are there different classes of loops that are heated in different ways?

Is quiet Sun heating similar to Active Region heating?

How the AC/DC mechanisms work together?

HEATING MECHANISMS

A surplus of proposed ideas? (Mandrini et al. 2000; Aschwanden et al. 2001)

TABLE 5

SUMMARY OF THE SCALING LAW FOR DIFFERENT MODELS OF CORONAL HEATING

Model Characteristics	N^0	References	Scaling Law	Parameters
Stressing Models (DC)				
Stochastic buildup	1	1	$B^2L^{-2}V^2\tau$	
Critical angle	2	2	$B^2L^{-1}V \tan \theta$	
Critical twist	3	3	$B^2L^{-2}VR\phi$	
Reconnection $\propto v_A$	4	4	$BL^{-2}\rho^{1/2}V^2R$	
Reconnection $\propto v_{A\perp}$	5	5	$B^{3/2}L^{-3/2}\rho^{1/4}V^{3/2}R^{1/2}$	
Current layers	6	6	$B^2L^{-2}V^2\tau \log R_m$	
	7	7	$B^2L^{-2}V^2\tau S^{0.1}$	
	8	8	$B^2L^{-2}V^2\tau$	
Current sheets	9	9	$B^2L^{-1}R^{-1}V_{ph}^2\tau$	
Taylor relaxation	10	10	$B^2L^{-2}V_{ph}^2\tau$	
Turbulence with:				
Constant dissipation coefficients	11	11	$B^{3/2}L^{-3/2}\rho^{1/4}V^{3/2}R^{1/2}$	
Closure	12	12	$B^{5/3}L^{-4/3}\rho^{1/6}V^{4/3}R^{1/3}$	
Closure + spectrum	13	13	$B^{s+1}L^{-1-s}\rho^{(1-s)/2}V^{2-s}R^s$	$s = 0.7$, $m = -1.$
	14			$s = 1.1$, $m = -2.5$
Wave Models (AC)				
Resonance	15	14	$B^{1+m}L^{-3-m}\rho^{-(1+m)/2}$	$m = -1.$
	16			$m = -2.$
Resonant absorption	17	15	$B^{1+m}L^{-1-m}\rho^{-(1+m)/2}$	$m = -1.$
	18			$m = -2.$
	19	16	$B^{1+m}L^{-m}\rho^{-(m-1)/2}$	$m = -1.$
	20			$m = -2.$
Current layers	21	17	$BL^{-1}\rho^{1/2}V^2$	
Turbulence	22	18	$B^{5/3}L^{-4/3}R^{1/3}$	

REFERENCES.—(1) Sturrock & Uchida 1981, Berger 1991; (2) Parker 1988, Berger 1993; (3) Galsgaard & Nordlund 1997; (4) Parker 1983; (5) Parker 1983, modified; (6) van Ballegooijen 1986; (7) Hendrix et al. 1996; (8) Galsgaard & Nordlund 1996; (9) Aly & Amari 1997; (10) Heyvaerts & Priest 1984, Browning & Priest 1986, Vekstein et al. 1993; (11) Einaudi et al. 1996, Dmitruk & Gómez 1997; (12) Heyvaerts & Priest 1992, Inverarity et al. 1995, Inverarity & Priest 1995a; (13) Milano et al. 1997; (14) Hollweg 1985; (15) Ofman et al. 1995, Ruderman et al. 1997; (16) Halberstadt & Goedbloed 1995; (17) Galsgaard & Nordlund 1996; (18) Inverarity & Priest 1995b.

CONCLUSIONS: WHAT DO WE NEED?

High resolution EUV, Magnetograph and Spectrogragh observations. More observations are needed (Solar Orbiter, Lagrange, Hi-C 2) to establish the effects of magnetic carpet, and of zoo of transients!

Data analysis (bigger models - more length scales)

In-situ observations

Direct or indirect evidence for heating, e.g. mean flow for resonant heating

Observe reconnection driven resonant MHD waves