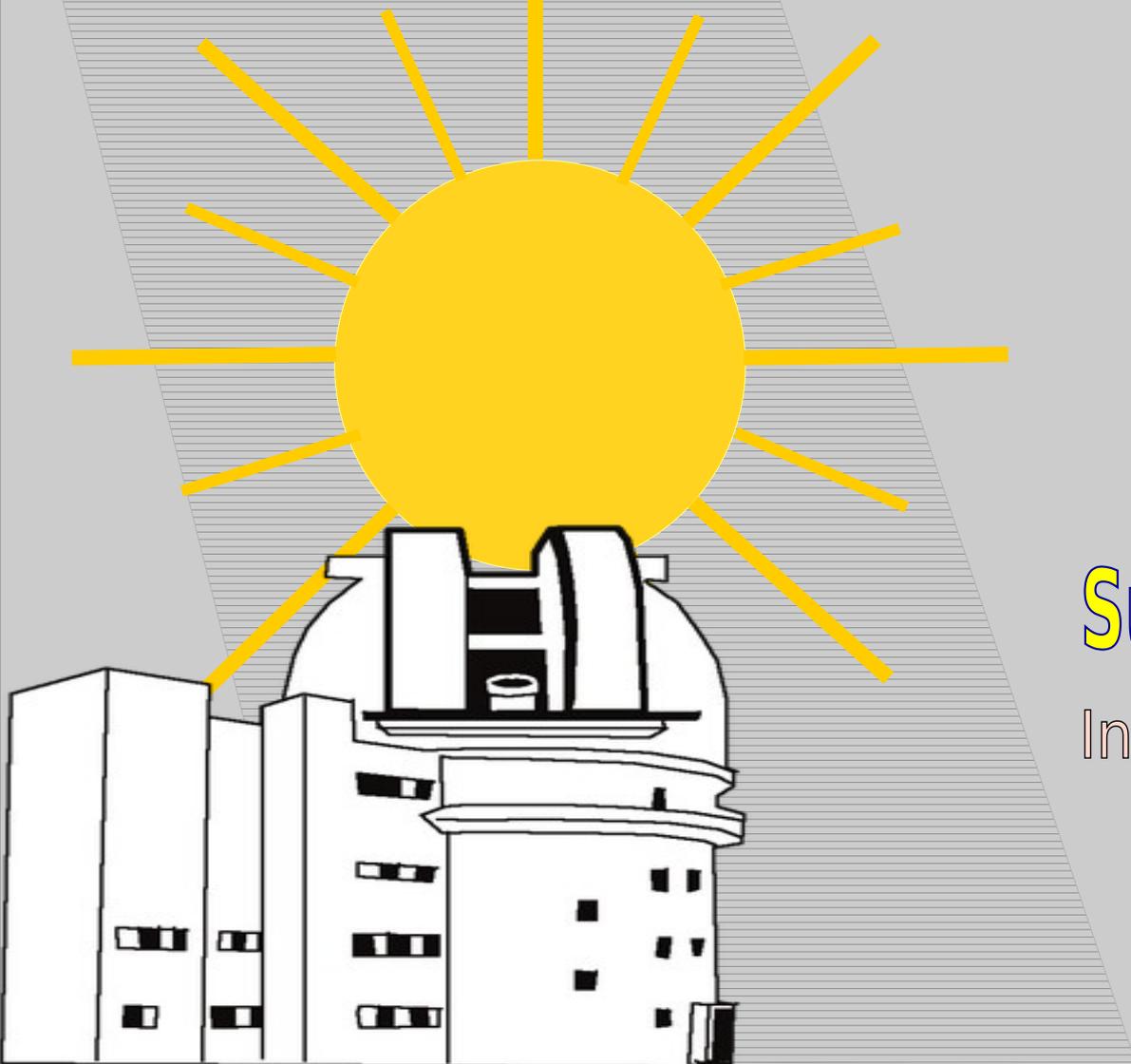


Electro-magnetic wave emission

from the Sun

Part - I



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Talk PLAN

1 **Overview of the Sun (Chronological)**
(Observational View point, No theory, & a few equations)

2 **Sun's layers and the EM wave emission**
(Photosphere, Chromosphere, & Corona)
(White Light, H α , EUV, & X-ray; Radio in Part-II)

3 **Brief about the Standard Solar Model**
(Simplified Picture of the Sun)

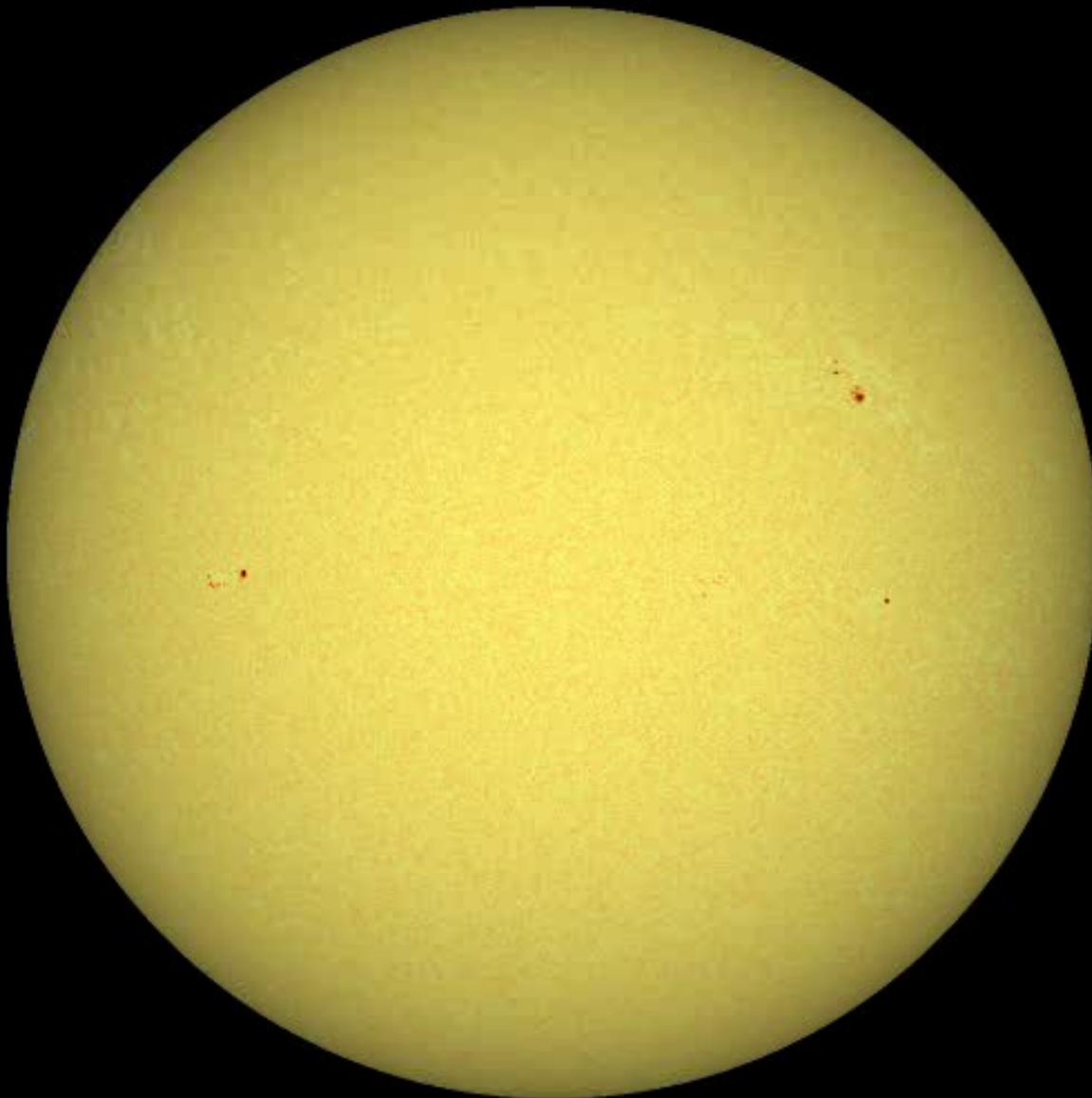
Note: Not all aspects are covered!!

Sun Photosphere



**Photosphere
Snapshot
- Dark Patches**

Optical Sun

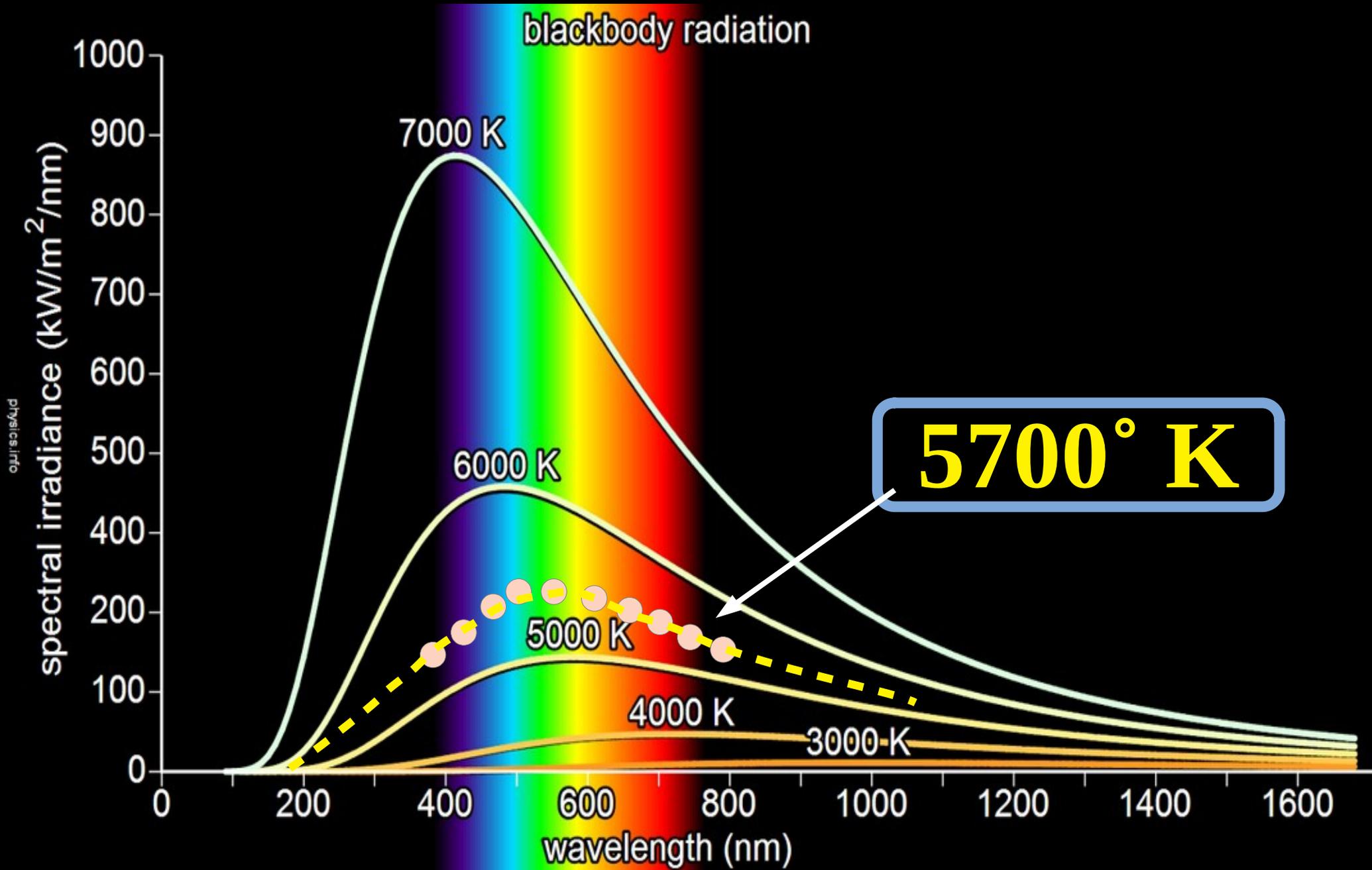


Photosphere

Sun Photosphere

Photosphere :

- 1. Photosphere is the layer from where the visible part of the electromagnetic radiation emanates.**
- 2. It subtends an angle of ~ 0.5 degree from the Earth when viewed using an optical telescope.**
- 3. If we convert the above angular extent into linear scale, its diameter will measure about 15×10^5 km.**



**What are these
dark patches
on the Sun ??**

Sun Photosphere

Sunspots :

1. Dark patches that are seen on the solar photosphere.
2. Appear as a single entity or in groups.
3. Last for several days to months.
4. When the number of spots is higher, it is the solar maximum and lower (or no spot), it is the minimum.

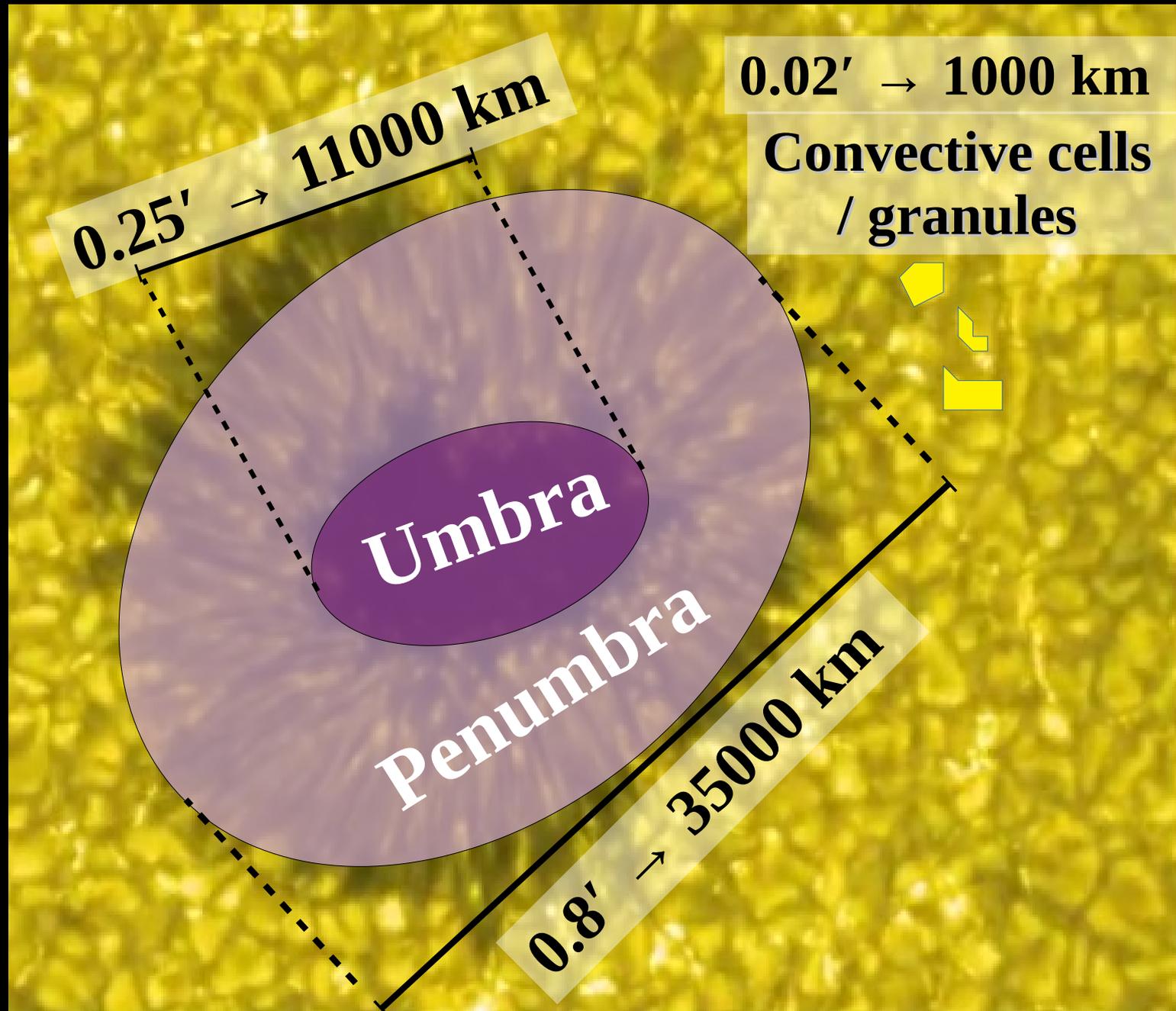
- Dark Patches

Sunspot Snapshot



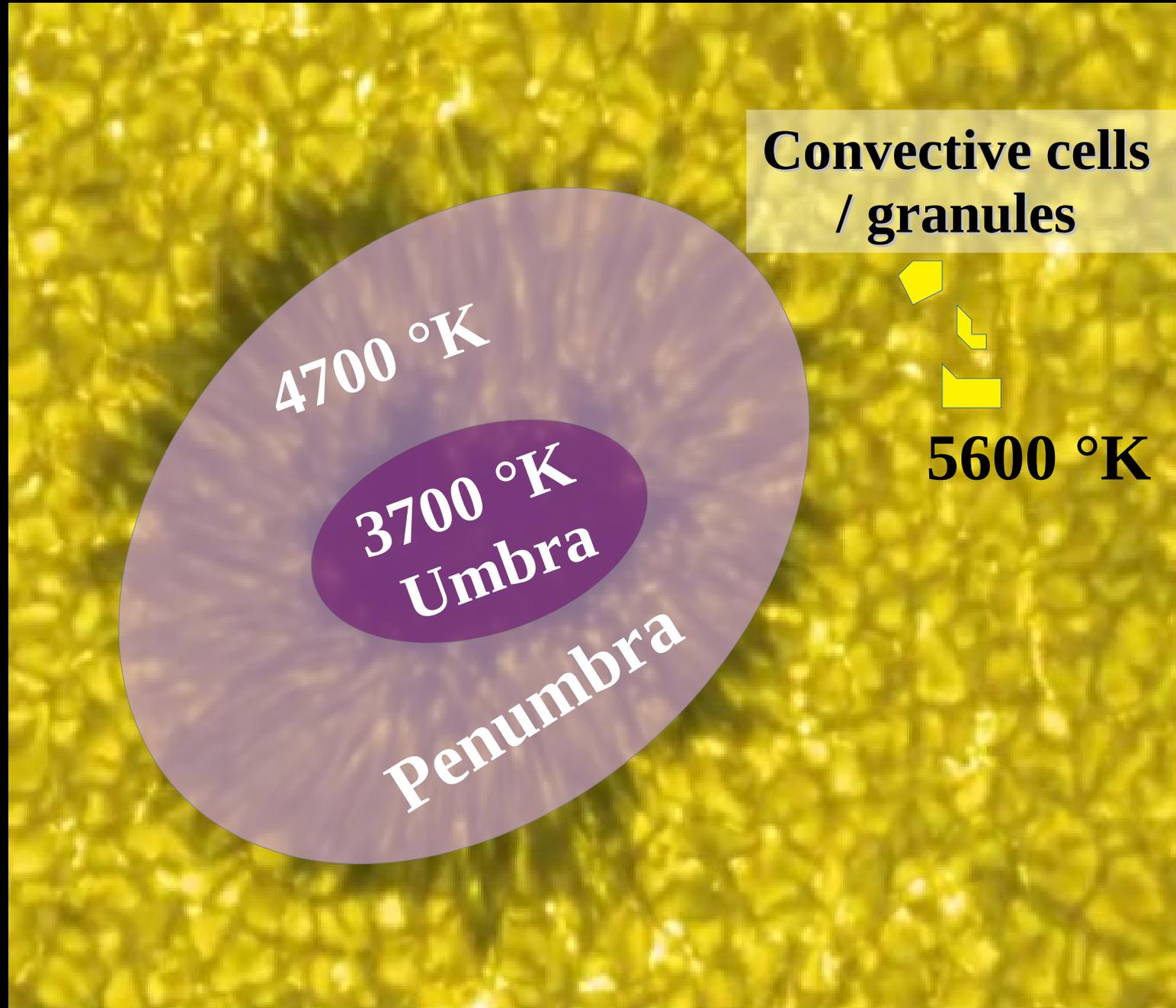
Morphology

Sunspot Snapshot



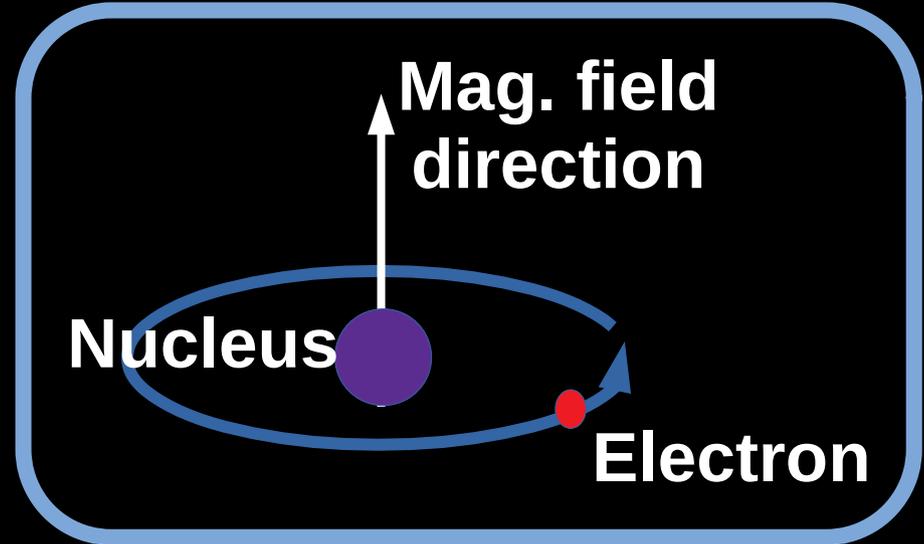
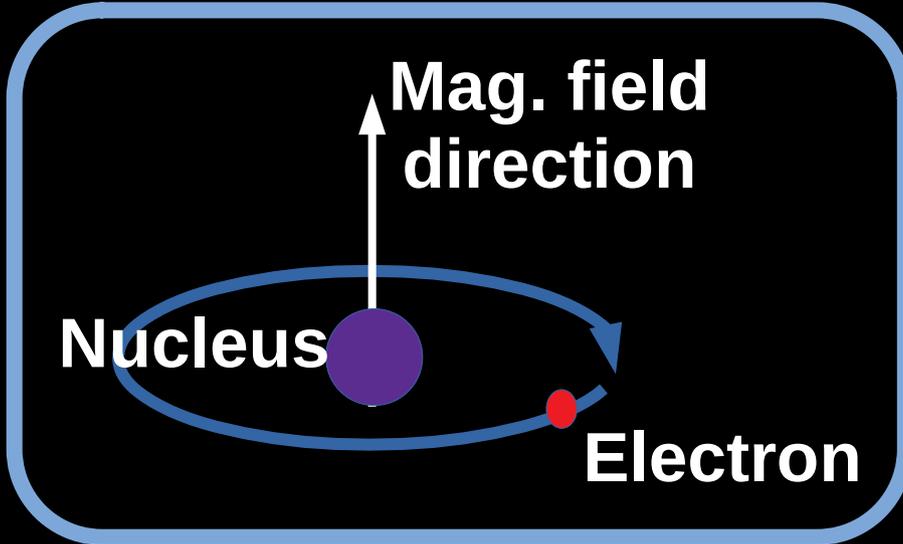
Dimensions

Sunspot Snapshot

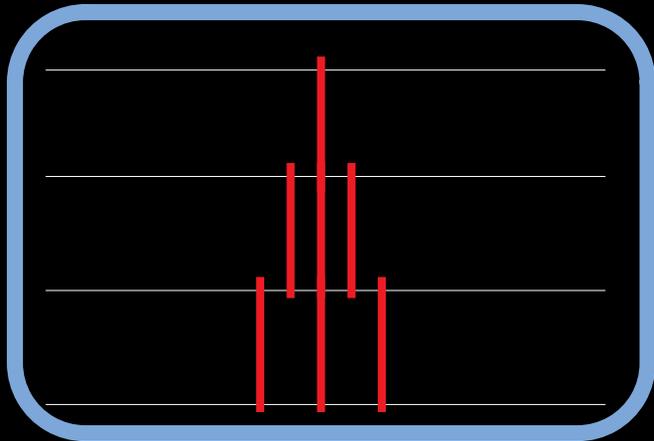


Temperature

Zeeman Effect



$$\Delta E \propto e B / m_e$$

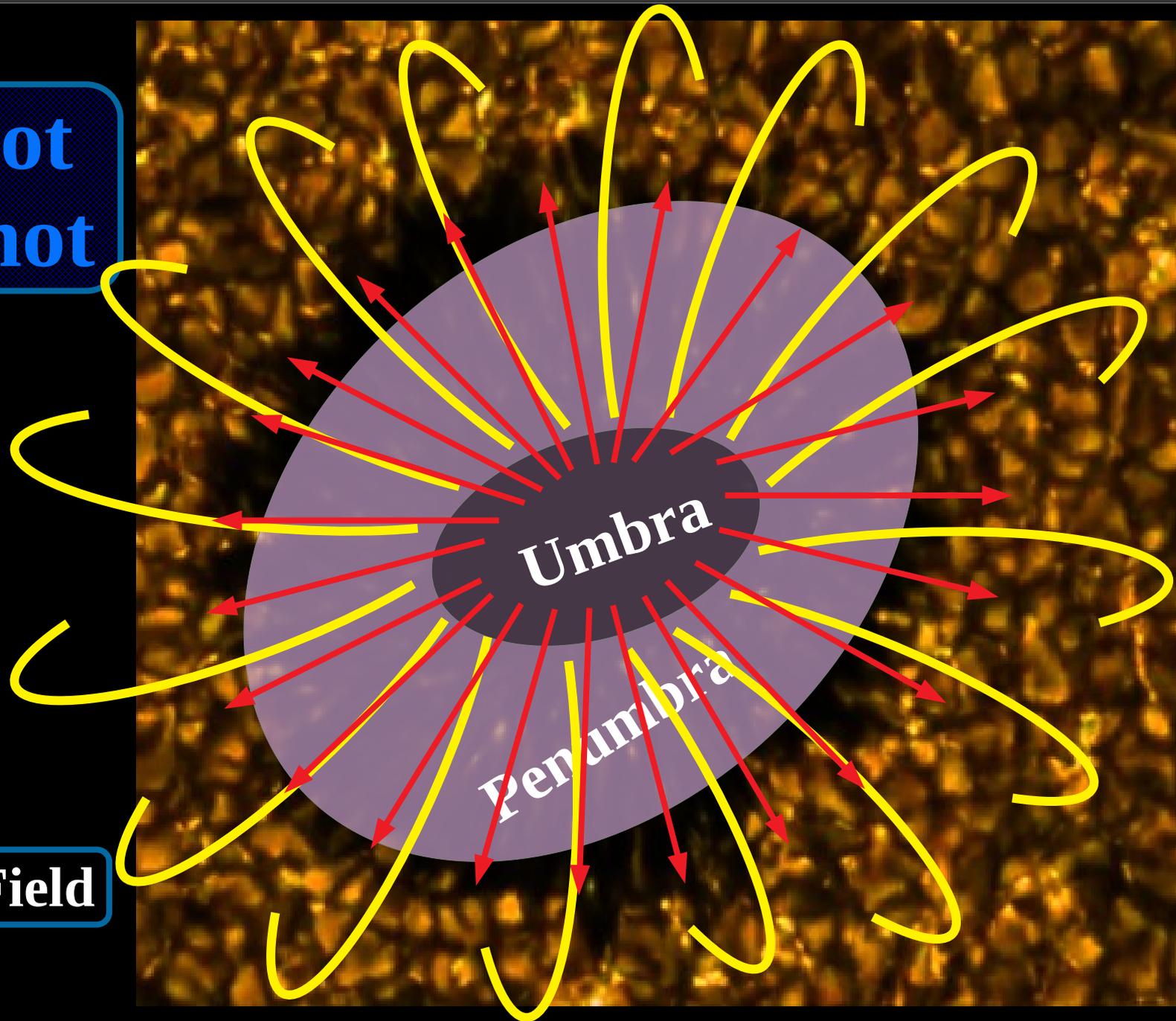


Normal spectrum $B = 0$

Zeeman spectrum $B = \text{low intensity}$

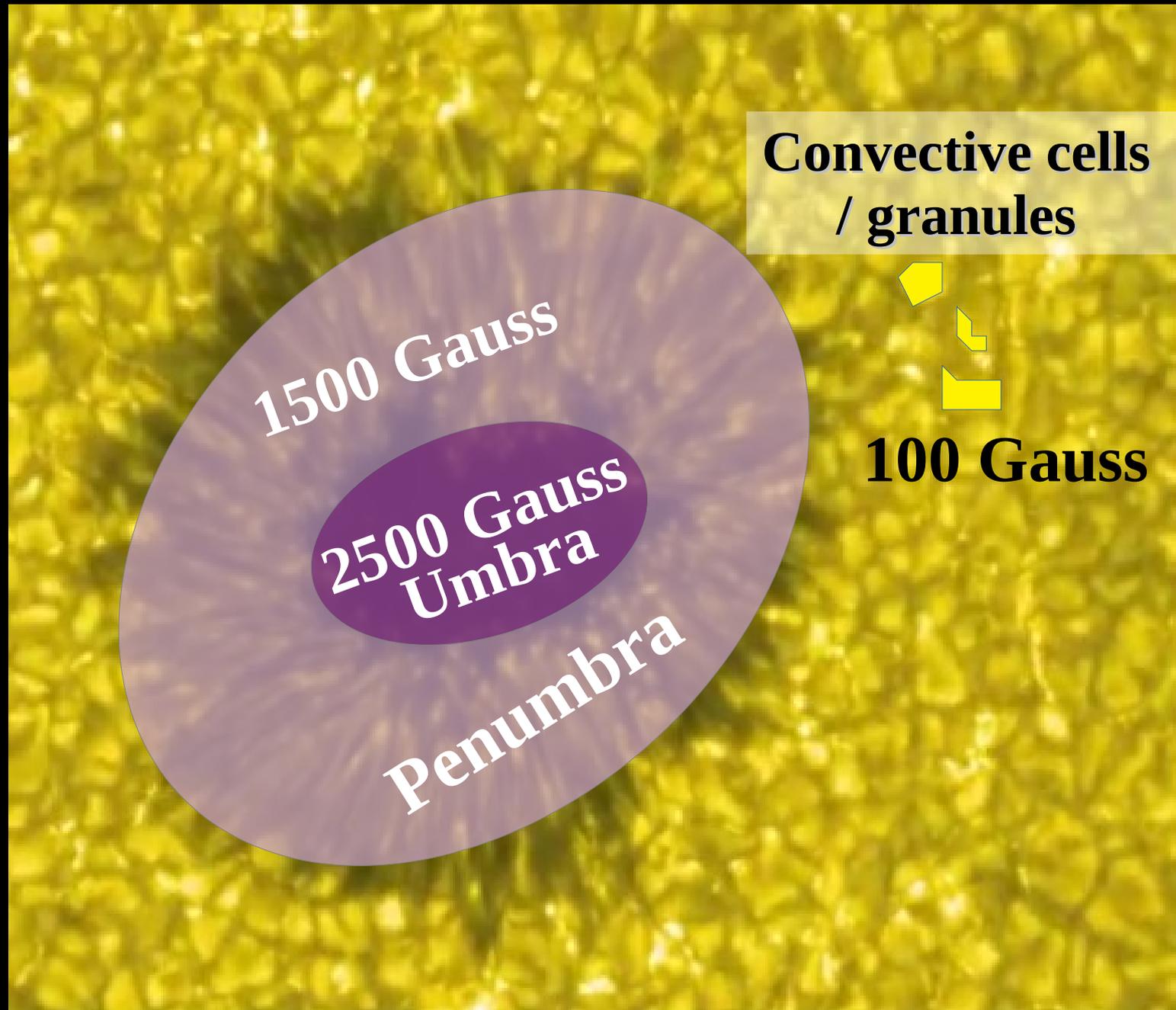
Zeeman spectrum $B = \text{high intensity}$

Sunspot Snapshot



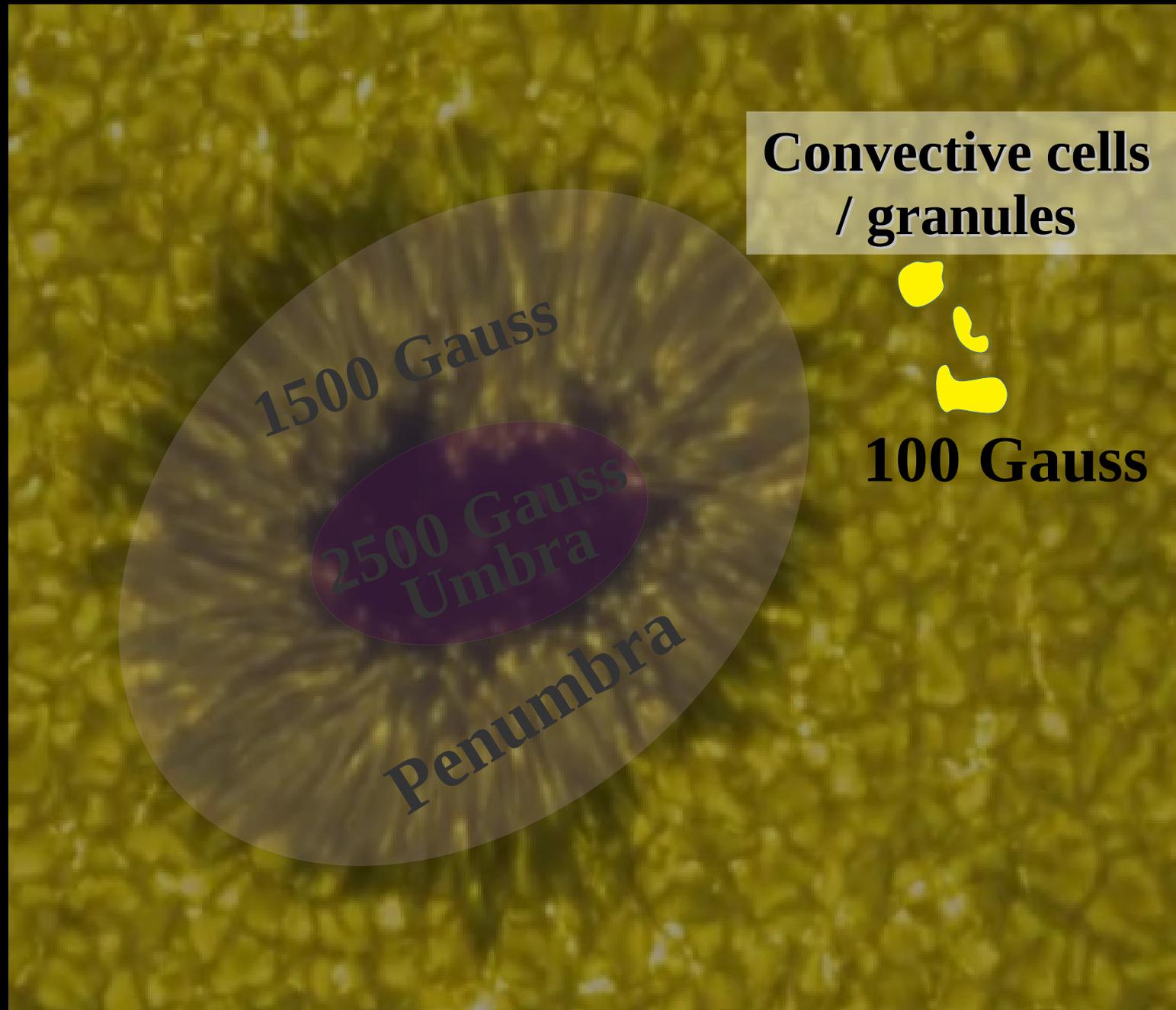
Magnetic Field

Sunspot Snapshot



Magnetic Field

Sunspot Snapshot



Granules

Sunspot Snapshot

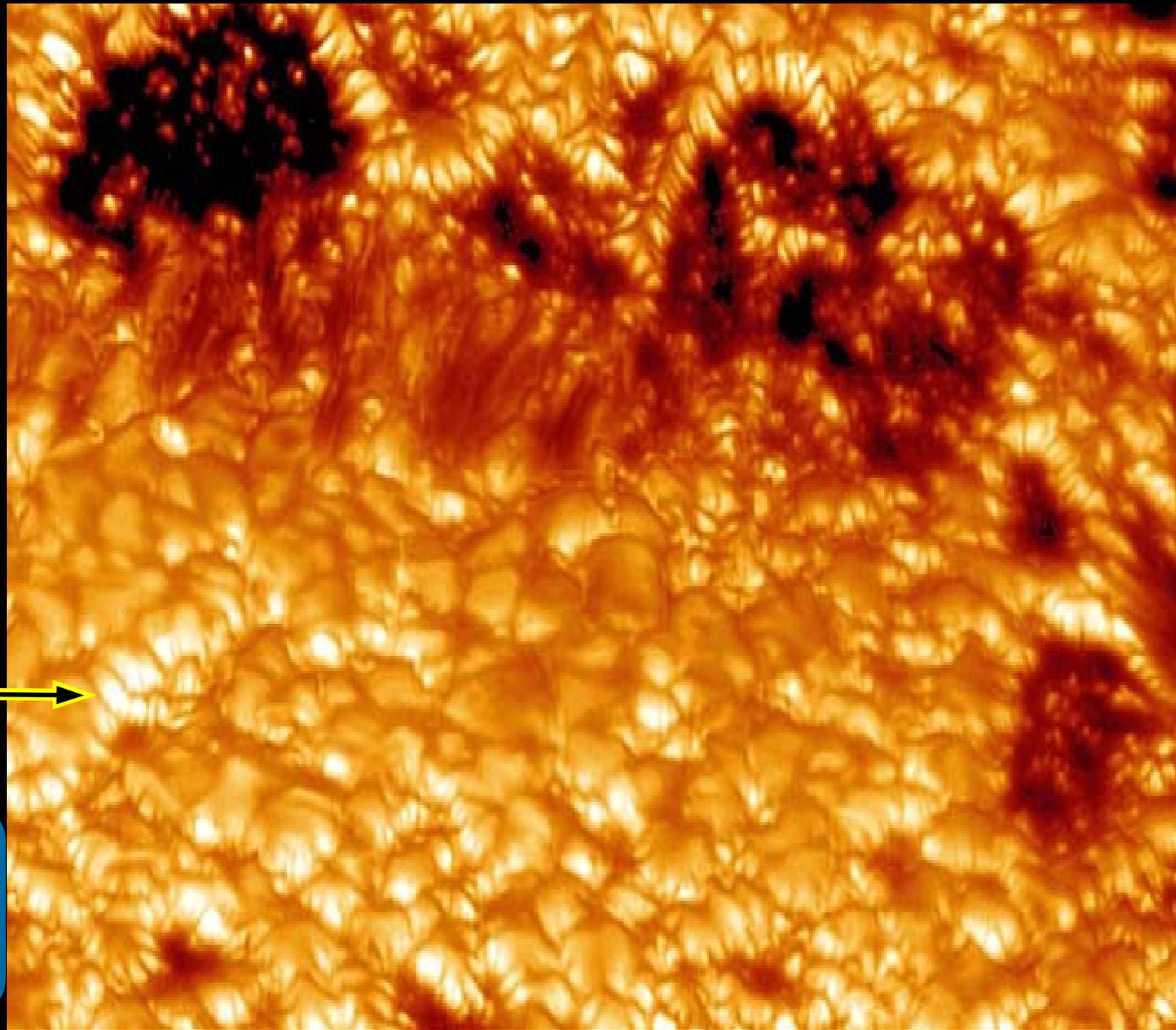
Convective cells
/ granules

Granules :

1. Ascending stream cells due to turbulent convection.
2. Hot gases move upward, appear brighter whereas the cool gases move downward, appear darker.
3. Excess temperature $\sim 100^\circ$ (wrt ambient).
4. Size $\sim 1''$; Lifetime $\sim 3-8$ sec; Velocity ~ 0.5 km/s.

Faculae

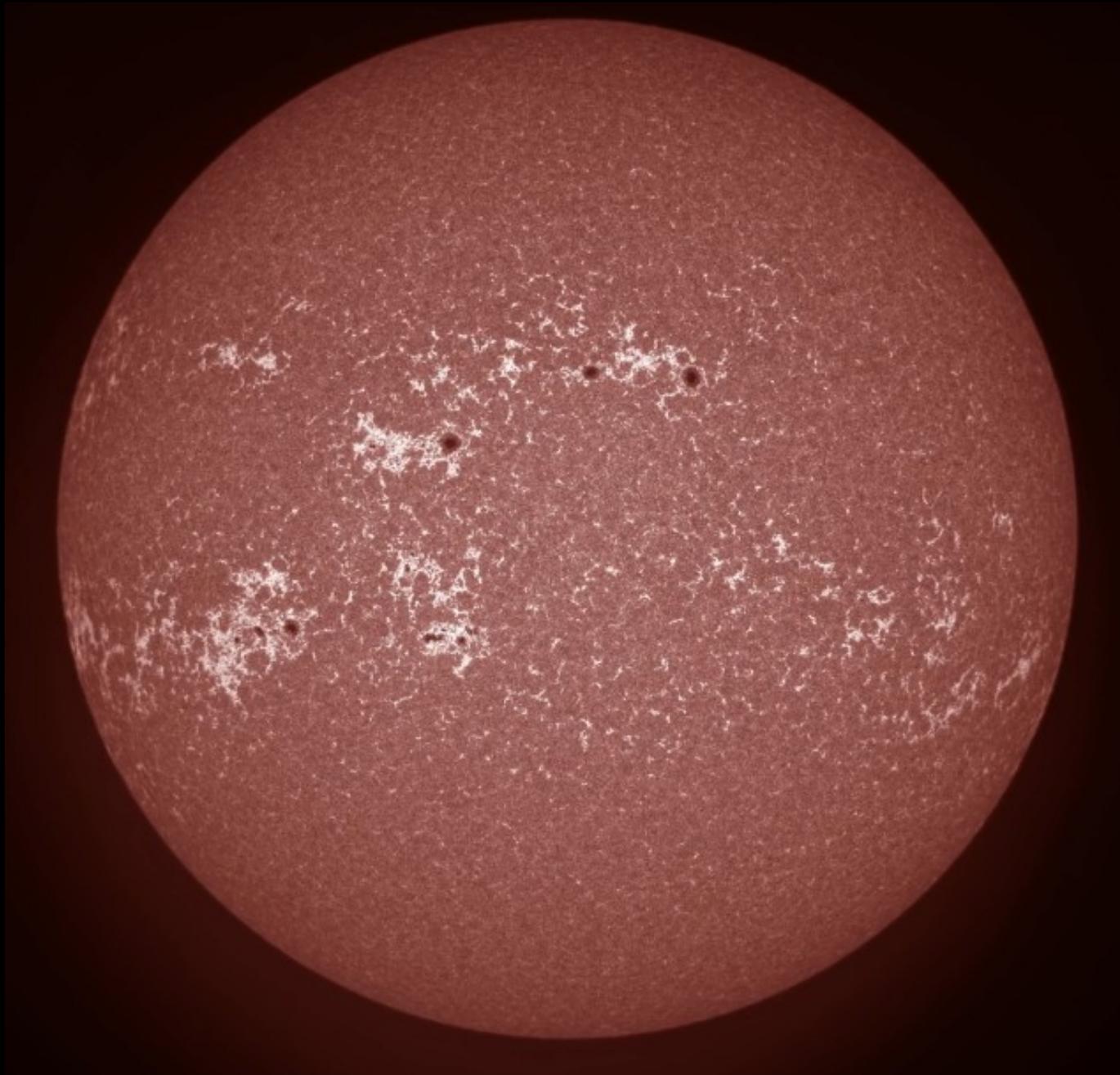
Little Torches



Bright patches
or spots seen
around sunspots

Faculae

**1700 Å
AIA image**



Faculae

Faculae:

1. Extended bright speckled regions tend to form around the sunspots, but, live longer than Sunspots.
2. Hotter than the background.
3. Discernible in 1700 \AA images.
4. Form due to concentration of magnetic field lines around sunspots or on the quiet background.

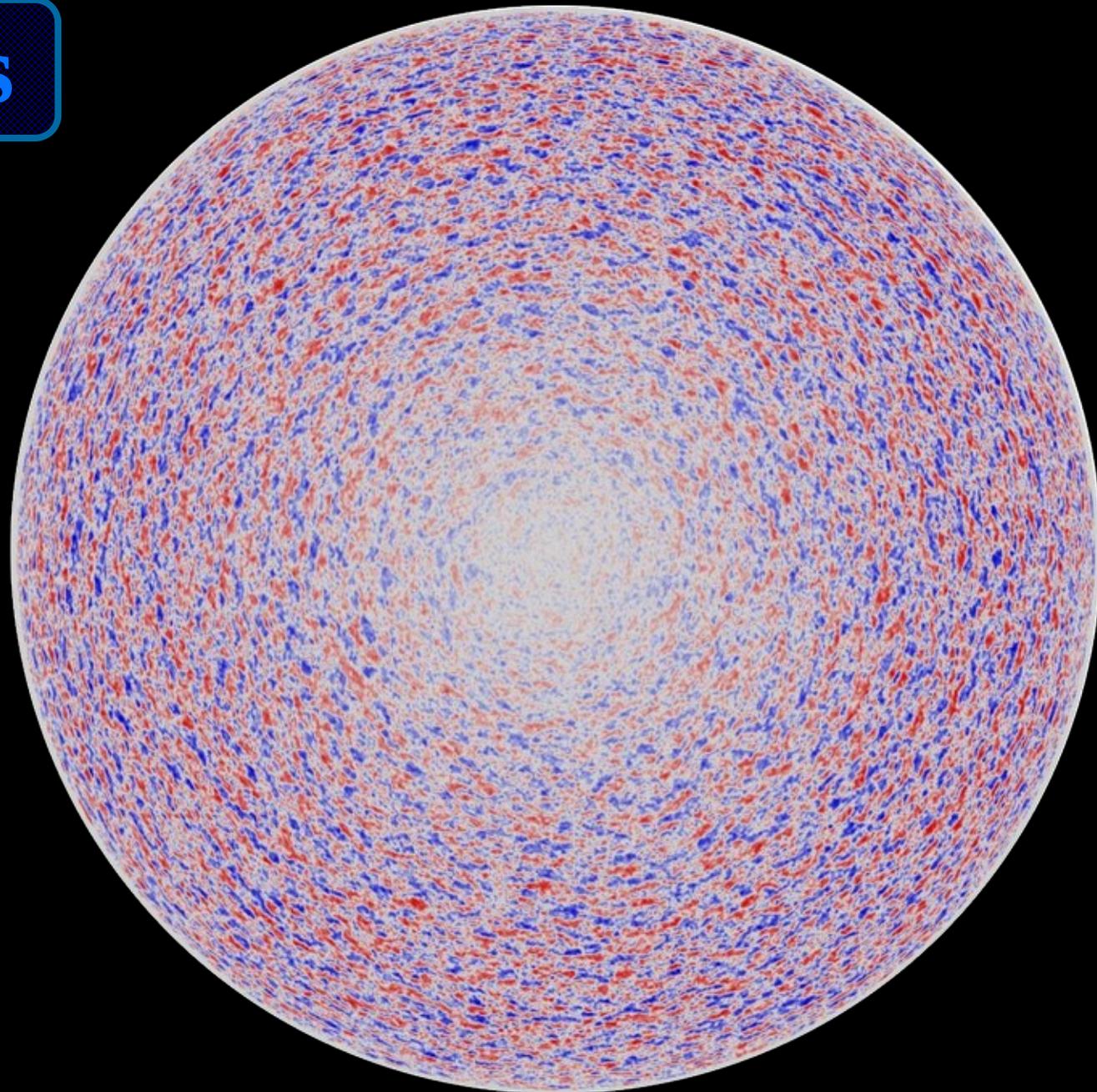
or spots seen

around sunspots

Supergranules

Blue – Toward observer
Red – Away Observer

Dopplergram
(MDI / SOHO)
Bubble size 30 Mm



Supergranules

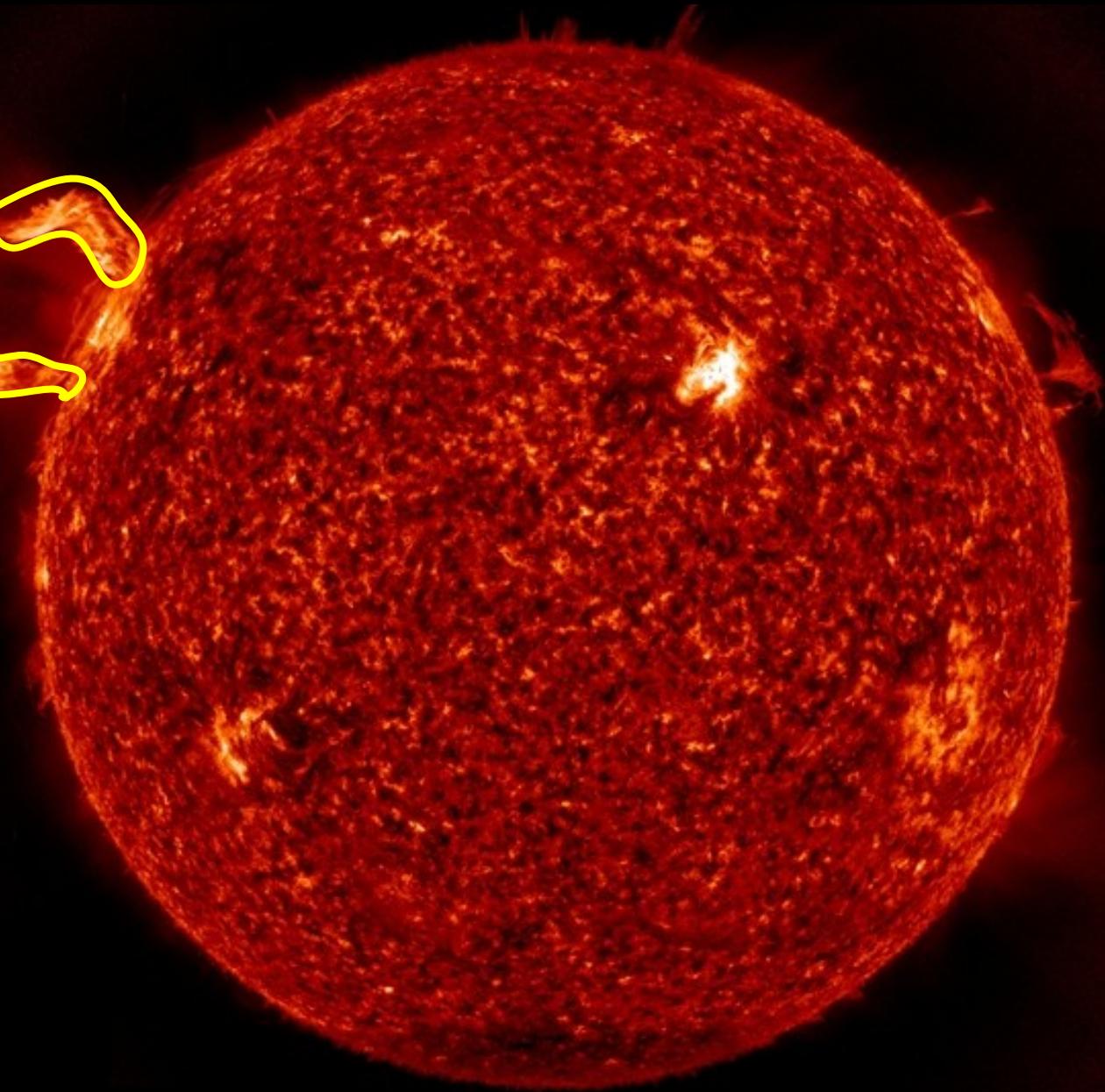
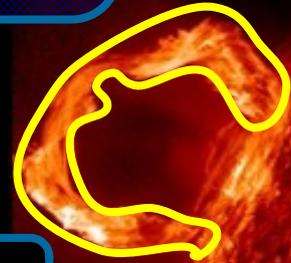
Supergranulation :

1. Signatures of large-scale non-linear thermal convection; horizontal spatial scale size $\sim 30\text{-}35$ Mm.
2. Evolution time scale $\sim 24\text{-}48$ hours.
3. Horizontal flow speed $\sim 300\text{-}500$ m/s; Vertical flow speed $\sim 20\text{-}30$ m/s.
4. At higher atmospheric heights, supergranules are believed to be fragmented to mesogranules and regular granules.

What are the Structures seen on the Chromosphere ??

Sun Chromosphere

Prominence



$H\alpha$ / 6563 Å

Sun

Chromosphere

Prominence :

Prominence

1. Denser and cooler chromospheric plasma confined to large scale magnetic loop / arch / arcade.
2. Temperature $\sim 8200 \text{ }^\circ\text{K}$; Height $\sim 0.2 - 1.0 R_\odot$
3. Called as prominence above the limb; Appear brighter against the faint background (corona).
4. $B \sim 2-20 \text{ G}$ (Quiet) & $\sim 100 \text{ G}$ (Active Region)

Prominences

BBSO, H-ALPHA 0.00

Sun Chromosphere

Bright patches

Dark Lanes

2014JUL02 18:20:17

BBSO, H-ALPHA 0.00

Sun Chromosphere

Plages :

1. Plage (Beach / seashore) – Elevated structures around the sunspots (or superpenumbra)
2. Regions of higher intensity in $H\alpha$ & Ca-II (H&K) lines.
3. Magnetic field (B) - Higher than the photospheric background and lower than the sunspot B; ~ 250 G.
4. Temperature ~ 8000 °K.

2014JUL02 18:20:17

BBSO, H-ALPHA 0.00

Sun Chromosphere

Bright patches

Filaments:

1. Prominence above the disk is called a filament.
2. Width ~ 10 Mm.
3. Appears dark due to absorption of background radiation.
4. $B \sim 2-20$ G (Quiet) & ~ 100 G (Active Region).

2014JUL02 18:20:17

Sun Chromosphere

Spicules



Sun Chromosphere

Spicules:

1. Hair / forest like structures seen above the limb.
2. Dynamic plasma jets with diameter ~ 0.1 Mm.
3. Lifetime ~ 10 minutes; Represent transverse oscillations – signatures of traveling MHD waves.
4. Rise speed ~ 20 km/s & mass flux $\sim 10^{10}$ cm⁻²s⁻¹
5. B ~ 10 G (Quiet) & ~ 50 G (Active Region).

The CORONA



**The effect of blocking the photospheric light
Happens naturally in an Eclipse**

The CORONA

X-ray
EUV
White-light
Radio

EUV 171 Å
SWAP / PROBA2
Total Solar Eclipse

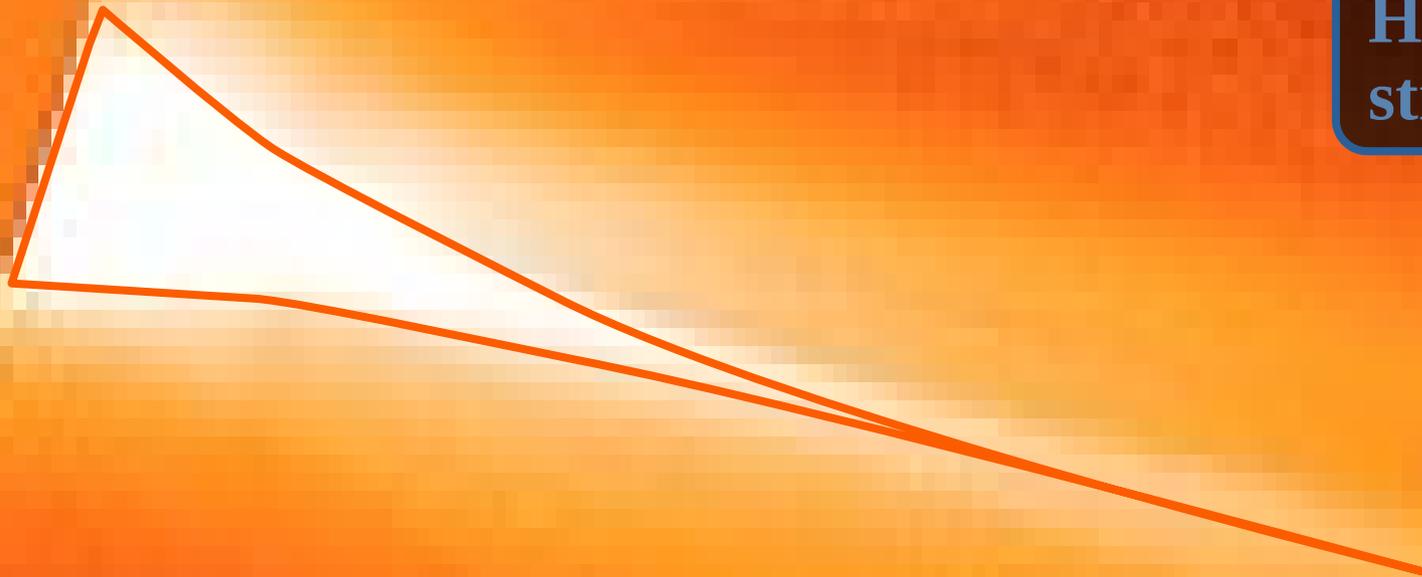
Transition Region ↔ 1 AU

S. R. Cranmer et al. *ARAA*, 2019, 57, 157

What are the Structures in the Corona ??

Coronal Structure

Helmet streamer



WL 5300 - 6400 Å

Coronal Structure

Coronal Helmet Streamer :

1. White conspicuous helmet like structure seen in WL coronagraph image.
2. These form above Active Regions.
3. Signature of plasma streaming out along magnetic field lines.
4. Source of slow solar wind (100 – 200 km/s).

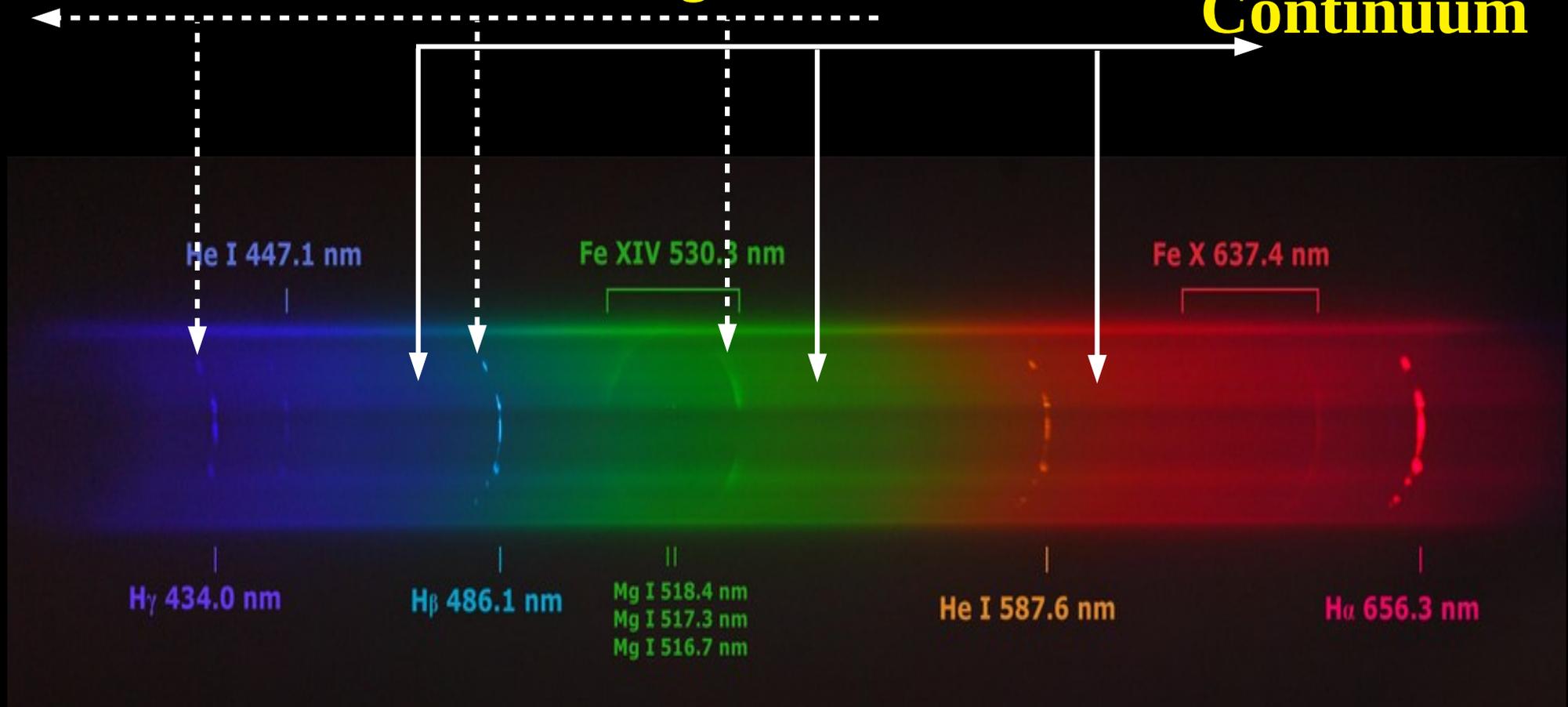
Helmet
streamer

WL 5300 - 6400 Å

Coronal Streamer

Line emission + broadening

Continuum



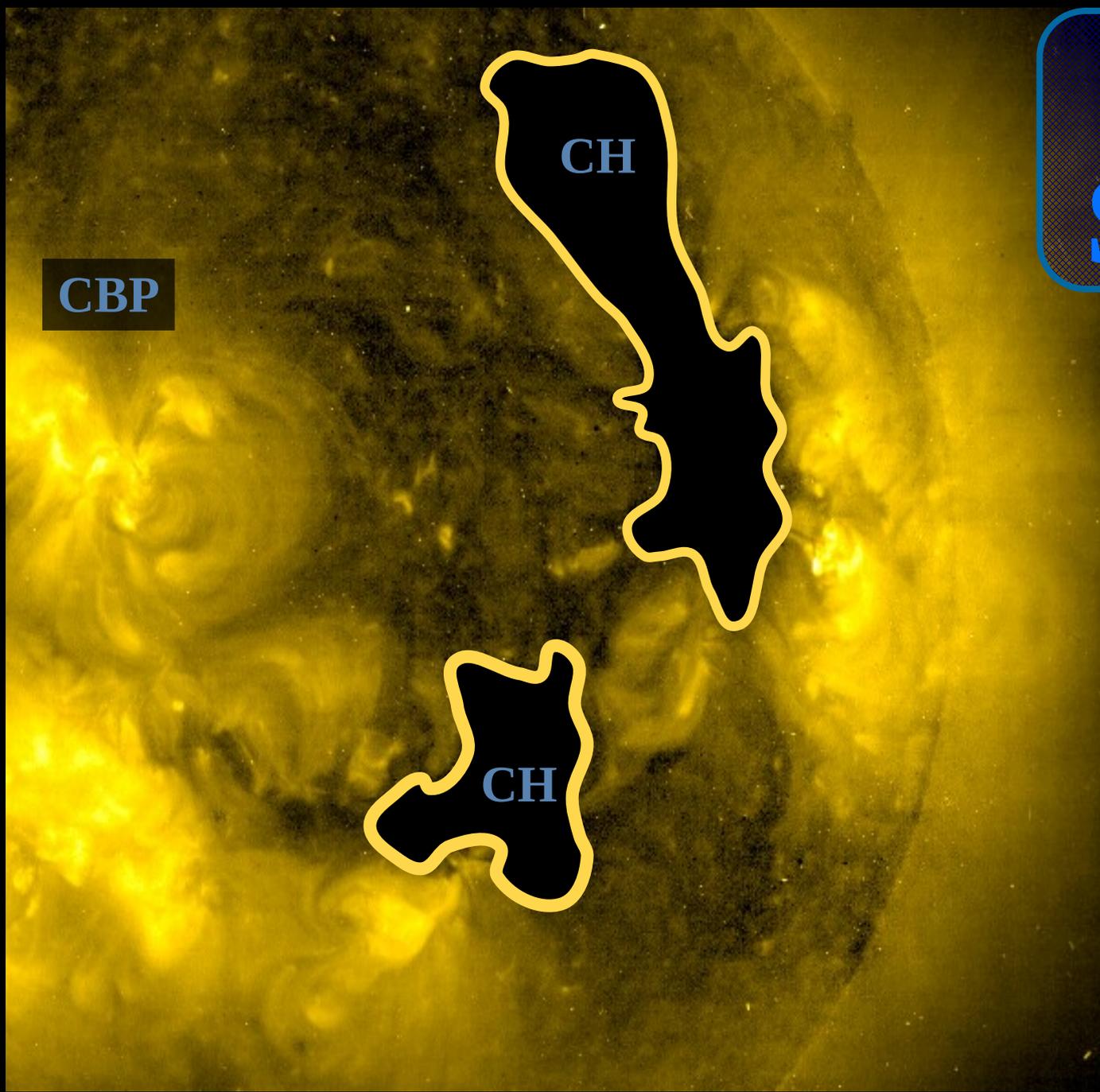
Coronal Streamer

Coronal Streamers:

1. Seen due to scattered photospheric light
2. Ionized Iron → Indicating Million Kelvin plasma
3. Spectral broadening → 200-500 km/s
4. Ion density → 10^{36} particles/sec
5. Ion speed → 200–400 km/s

EUV & X-ray Corona

The Spectral observations carried out by Edlen further indicated the EUV & X-ray emission from the Solar Corona.



Coronal Structure

X-ray Image

(S/Ca/Al/Mn)
Fe-VII - Fe-XIV
2-32 Å (≥ 2 MK)
5 - 40 keV

Coronal Holes (CH)
Coronal X-ray Bright Points (CBP)

Coronal Structure

CBP

CH

X-ray
Image

Coronal Bright Points :

1. Regions that appear brighter in X-ray images.
2. These are associated with Active Region Loops or Interconnecting loops.
3. Due to heating of thermal plasma.

Fe-VII - Fe-XIV
2-32 Å (≥ 2 MK)
5 – 40 keV

Coronal Holes (CH)
Coronal Bright
Points (CBP)

Coronal Structure

CBP

CH

X-ray
Image

Coronal Holes :

1. Regions that appear darker in X-ray images.
2. Are associated with coronal open magnetic field lines.
3. Dark due to lower X-ray emission wrt to Bg.
4. Are sources of fast solar wind (300–700 km/s).

(In)
Fe-VII - Fe-XIV
2-32 Å (≥ 2 MK)
5–40 keV

Coronal Holes (CH)
Coronal Bright
Points (CBP)

Coronal Structure

EUV
Image

Coronal
Loops

Fe-IX
171 Å (≥ 2 MK)



Coronal Structure

Coronal Loops :

Structures that appear brighter due to hot ions trapped in arch like structures anchored to bipolar magnetic field regions.

EUV
Image

Coronal
Loops

Fe-IX
171 Å (≥ 2 MK)

Coronal Structure

Coronal Plumes
(Polar)

Plasma flow speed
10 – 100 km/s
Alfven Velocity
140 – 1000 km/s

O-XI
1030 Å (2 MK)

Thin streamer like structures
- Associated with Open B lines

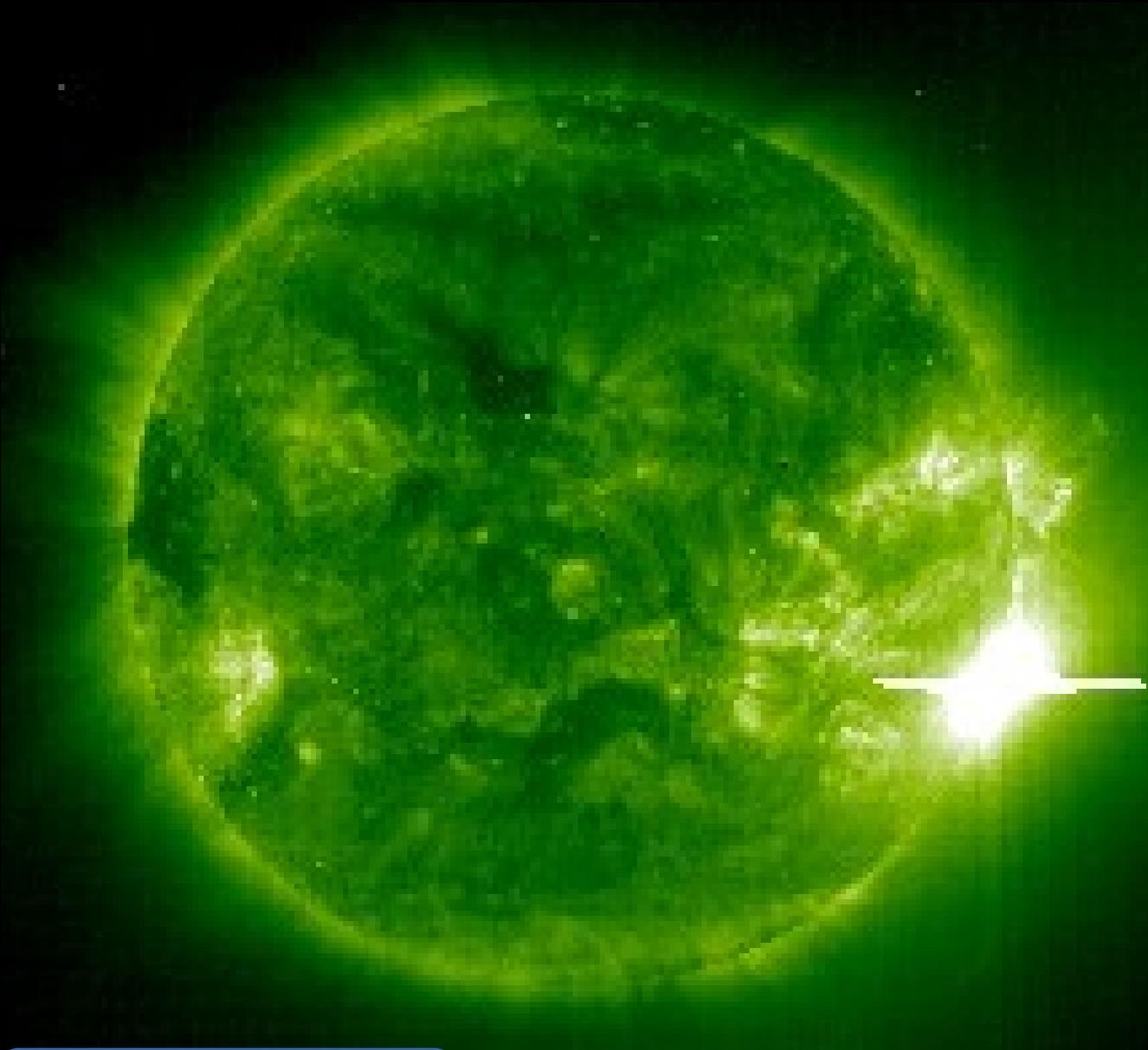
When Sun Is Active ...

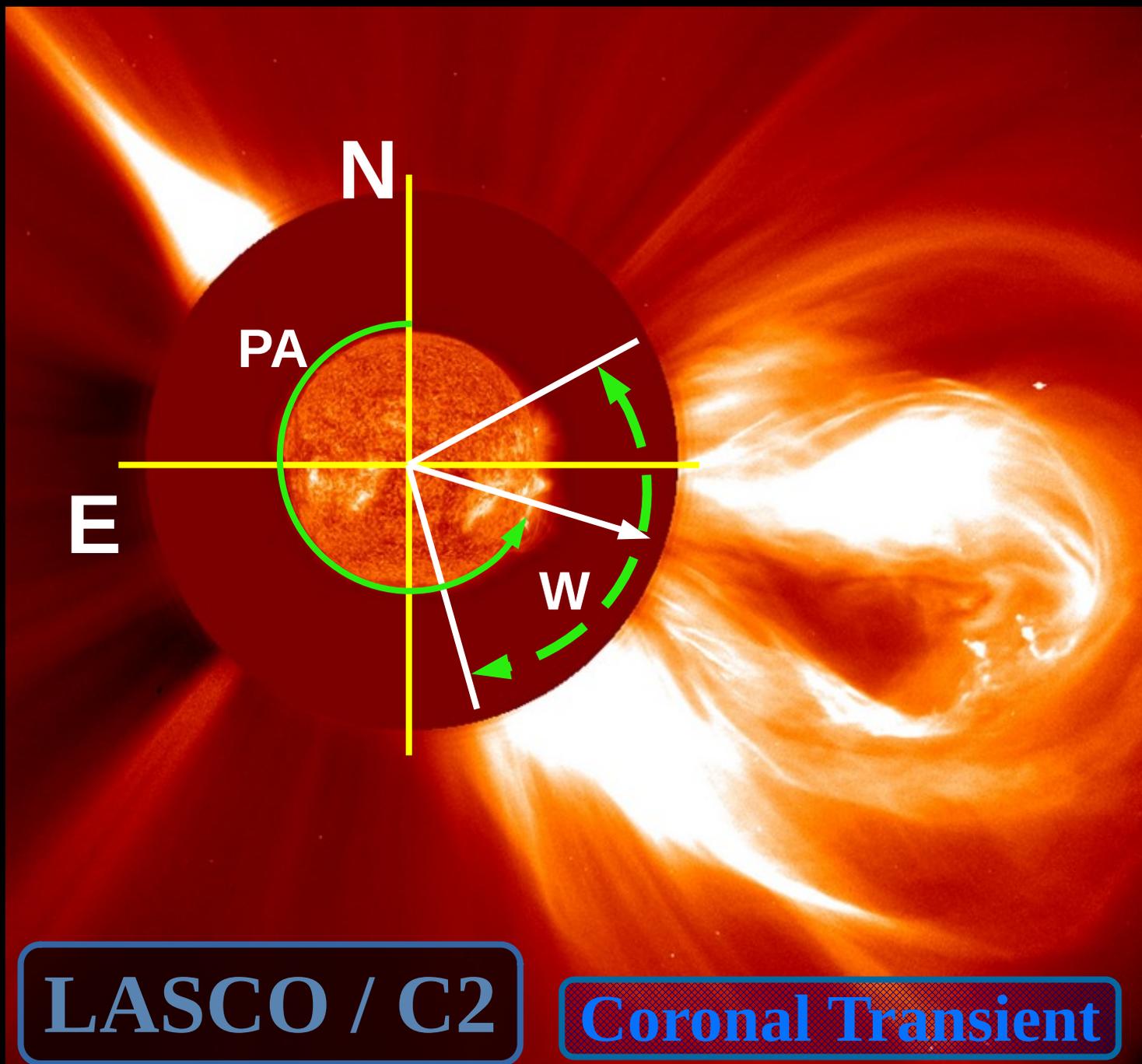
Flares

X-ray
EUV
H α
WL
Radio

EIT / EUV

Coronal Transient





When Sun Is Active ...

CMEs

Mass $\sim 10^{16}$ g
V $\sim 100 - 3000$ km/s
KE $\sim 10^{36}$ joule

LASCO / C2

Coronal Transient

White-Light

Standard Solar Model

SSM:

A reasonable theoretical framework that explains major observable solar phenomena

Assumptions:

- 1. Sun evolves hydrostatically**
- 2. Energy transport – Conduction, Convection, radiation, neutrino losses**
- 3. Thermo-nuclear reaction inside the core is the only source of energy**
- 4. Initially homogeneous, primordial composition of H & He, and convection is predominant.**

Standard Solar Model

SSM:

These 4 assumptions gave 4 basic equations.

Sun evolves hydrostatically: Pressure = Gravity

$$\frac{dP}{dr} = \frac{-Gm\rho}{r^2}$$

$P \rightarrow$ Pressure

$r \rightarrow$ radius

m & $\rho \rightarrow$ mass & density

$$P = \frac{\rho T R}{\mu}$$

$T \rightarrow$ Temperature

$R \rightarrow$ Gas constant

$\mu \rightarrow$ mean molecular weight

Standard Solar Model

SSM:

These 4 assumptions gave 4 basic equations.

Energy Transport: Convection & Radiation dominant
Radiation transport & Conduction transport

$$\frac{dT}{dr} = \frac{-3}{4} \frac{\kappa \rho}{ac} \frac{L}{4\pi r^2}$$

$T \rightarrow$ Temperature

$a \rightarrow$ radiation constant

κ & $\rho \rightarrow$ opacity & density

$L \rightarrow$ Luminosity

$$\frac{dT}{dr} = \left(1 - \frac{1}{\gamma}\right) \left(\frac{T}{P}\right) \left(\frac{dP}{dr}\right)$$

$\gamma \rightarrow$ ratio of specific heats

$$\gamma \rightarrow \frac{C_P}{C_V}$$

Standard Solar Model

SSM:

These 4 assumptions give 4 basic equations.

Thermo-nuclear reaction inside the core is the only source of energy

$$\frac{dL}{dr} = 4\pi r^2 \epsilon$$

$L \rightarrow$ Luminosity

$r \rightarrow$ radius

$\epsilon \rightarrow$ energy generation rate

Nuclear Fusion Reaction
p-p cycle & CNO cycle

Fusion requires high
temperature & density

Standard Solar Model

SSM:

These 4 assumptions give 4 basic equations.

Initially homogeneous, primordial composition of H & He, and convection is predominant.

Initial abundances are estimated from the relative amounts of H & He since they are the indicators of evolution.

**To summarize the
above discussion**

Sun Structure

Chromosphere
 Layer thickness ~ 2500 km

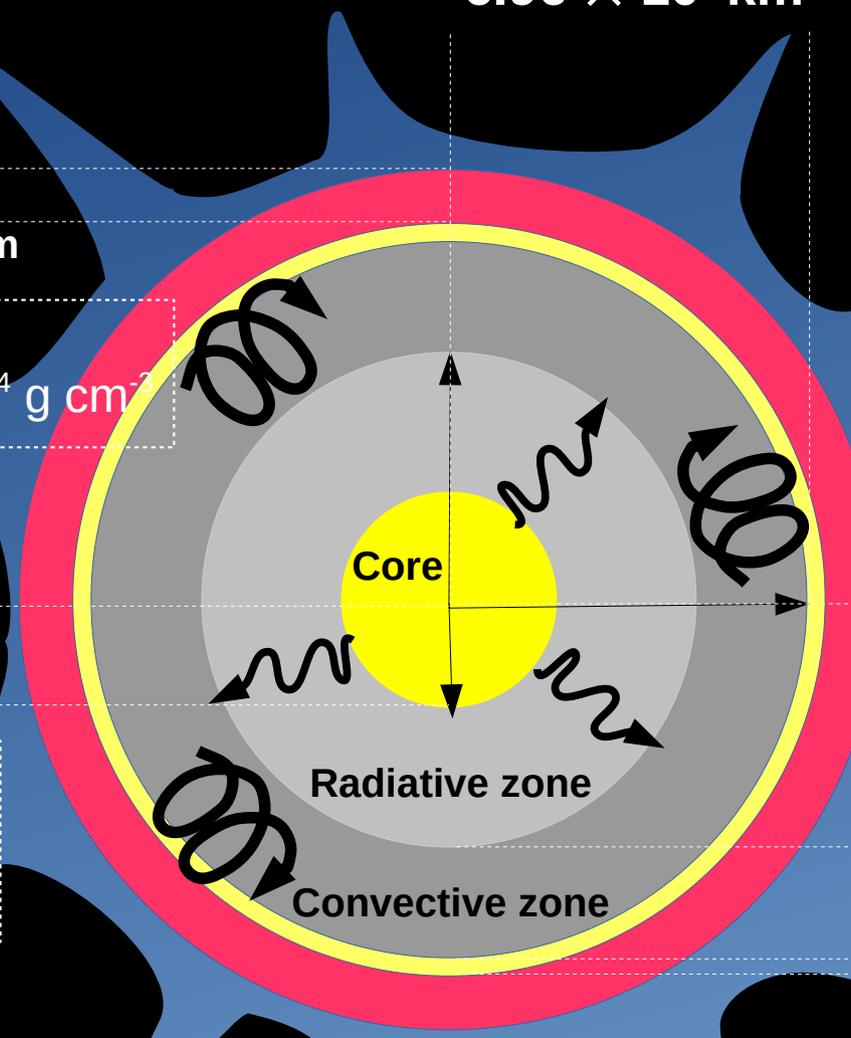
$T = 5600 \leftrightarrow 2 \times 10^4 \text{ K}$
 $D = 2 \times 10^{-7} - 2 \times 10^{-14} \text{ g cm}^{-3}$

$1.7 \times 10^5 \text{ km}$

Nuclear reactions
 $T = 15 \leftrightarrow 7 \times 10^6 \text{ K}$
 $D = 150 \leftrightarrow 20 \text{ g cm}^{-3}$

Corona
 $T = 2 \times 10^4 - 2 \times 10^6 \text{ K}$
 Num. Density = $10^8 \leftrightarrow \text{few } e^- \text{ cm}^{-3}$

$6.96 \times 10^5 \text{ km}$



Convective transport
 $T = 2 \times 10^6 \leftrightarrow 5600 \text{ K}$
 $D = 0.2 \text{ g cm}^{-3} \leftrightarrow 2 \times 10^{-7} \text{ g cm}^{-3}$

Radiative transport
 $T = 7 \leftrightarrow 2 \times 10^6 \text{ K}$
 $D = 20 \leftrightarrow 0.2 \text{ g cm}^{-3}$

$5.2 \times 10^5 \text{ km}$

Photosphere
 Layer thickness = few 100 km

$T = 5600 \text{ K}$
 $D = 2 \times 10^{-7} \text{ g cm}^{-3}$

**So far we saw the overview
of different structures on the Sun
using Optical, H α , EUV, and X-Ray**

**Note : Not ALL structures were discussed
Radio emission?? - Part II**

Thank you ALL

Organizers

(SU-UZB, COSPAR, ISWI, SCOSTEP, e-CALLISTO)

Participants

IIA & GBR observatory staff