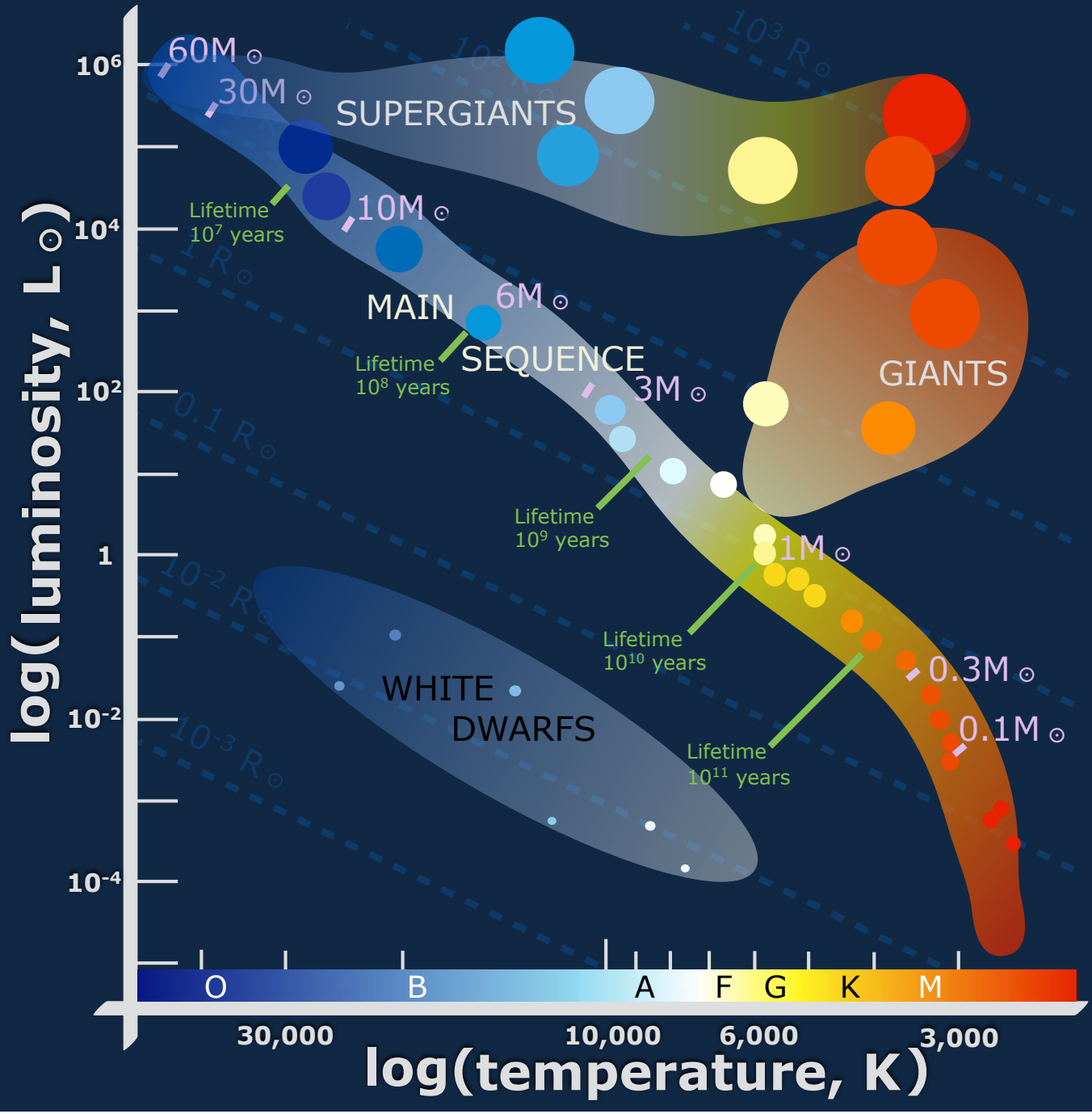
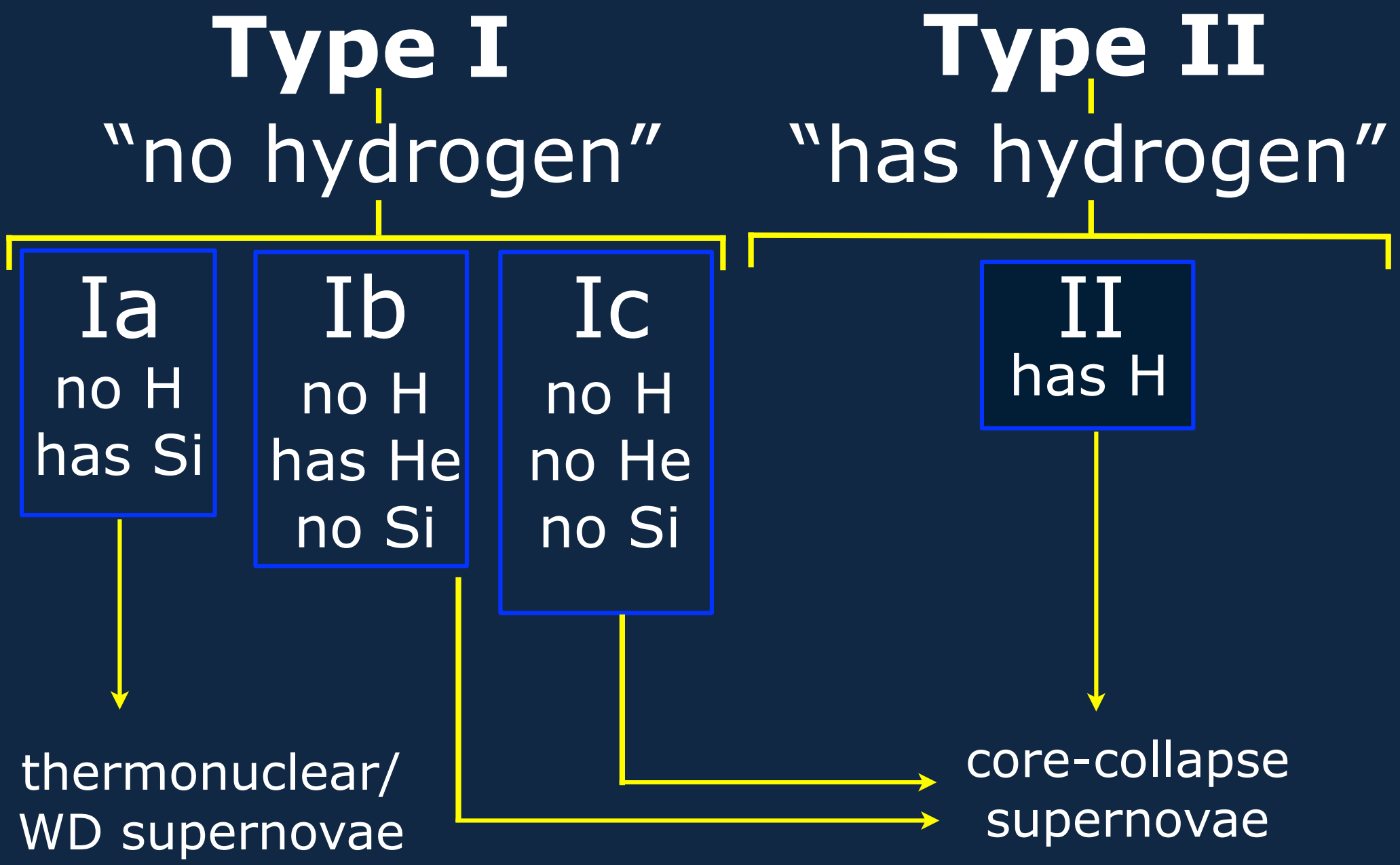
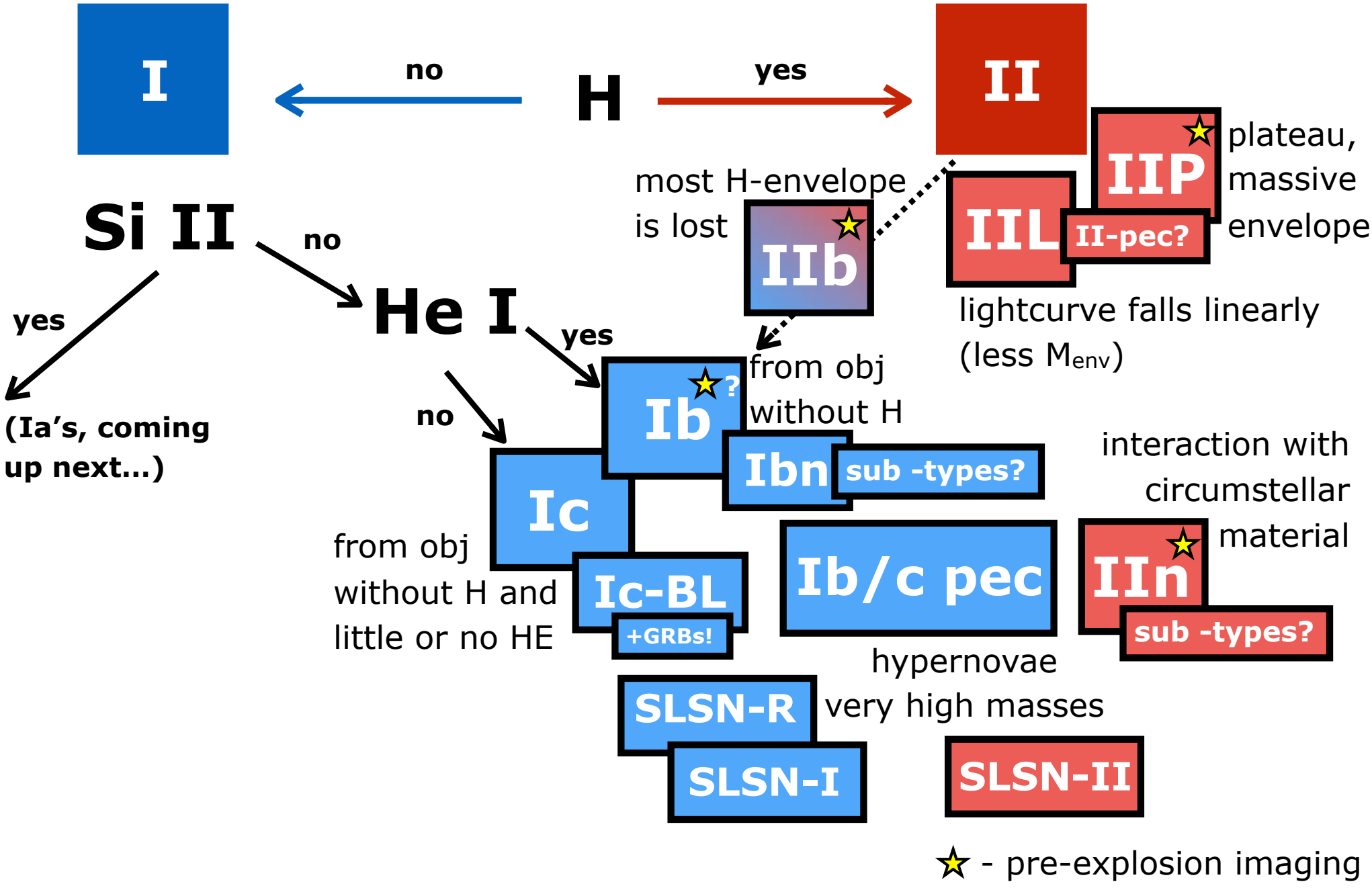
The Hertzsprung-Russell Diagram



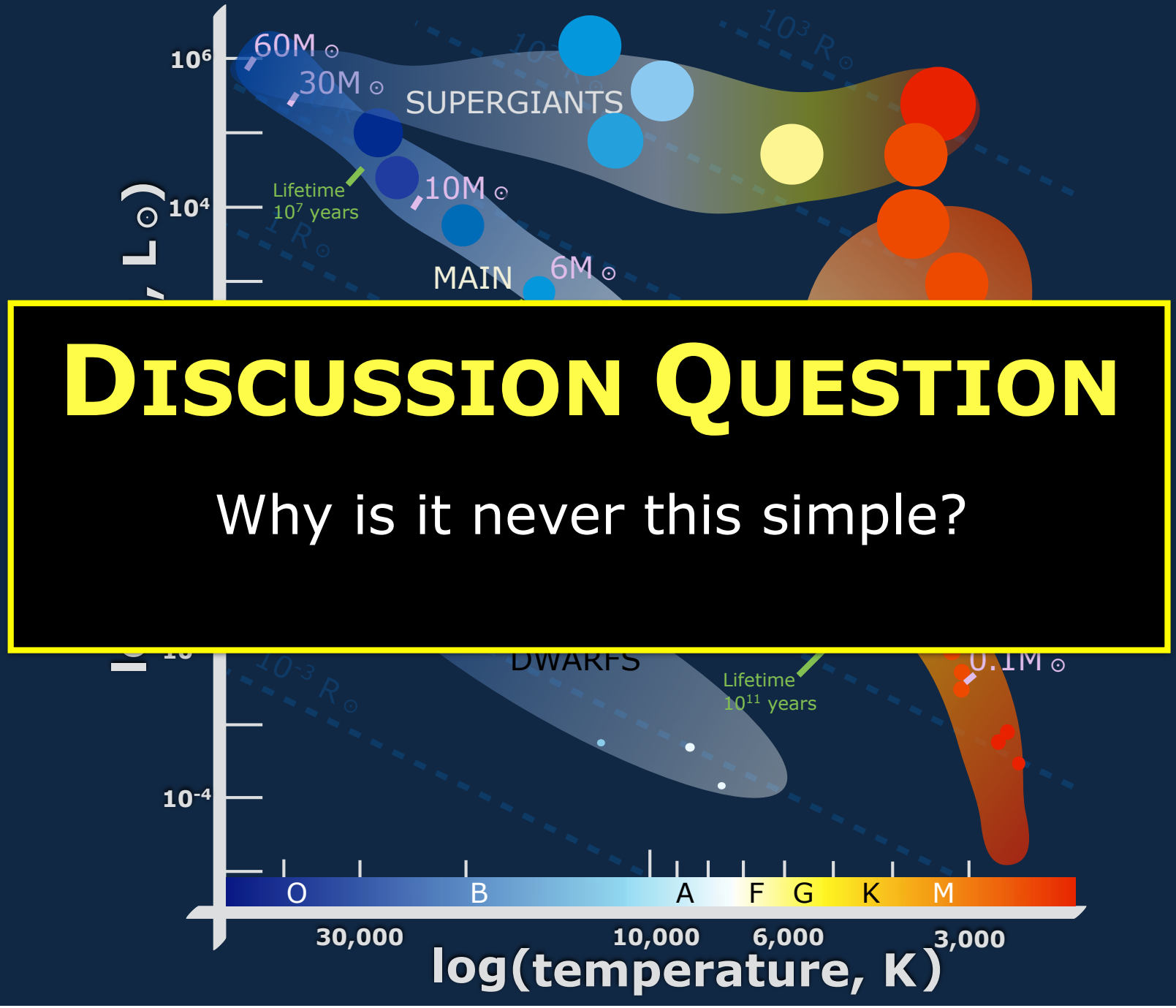
Supernovae


Type I
"no hydrogen"
Type II
"has hydrogen"
Ia
no H
has Si
Ib
no H
has He
no Si
Ic
no H
no He
no Si
II
has H
thermonuclear/
WD supernovae
core-collapse
supernovae

Supernovae


I
no
H
yes
II
Si II
no
He I
yes
(Ia's, coming up next...)
yes
no
most H-envelope is lost
IIb
IIP
plateau, massive envelope
IIL
II-pec?
lightcurve falls linearly (less M_{env})
Ib?
from obj without H
Ibn
sub -types?
Ic
from obj without H and little or no HE
Ic-BL
+GRBs!
Ib/c pec
hypernovae
very high masses
IIn
sub -types?
interaction with circumstellar material
SLSN-R
SLSN-I
SLSN-II
- pre-explosion imaging

The Hertzsprung-Russell Diagram



Discussion Question

Why is it never this simple?

Weird Stars: Low Mass

flare stars

pulsating stars

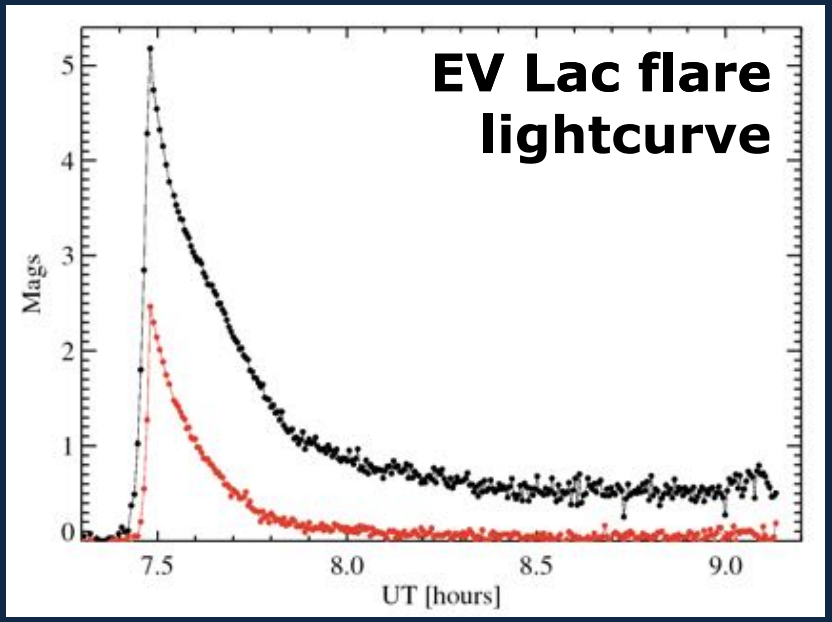
cataclysmic variables

Type Ia supernovae

low mass X-ray binaries

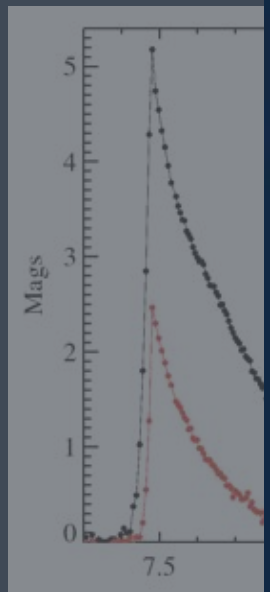
Flare Stars

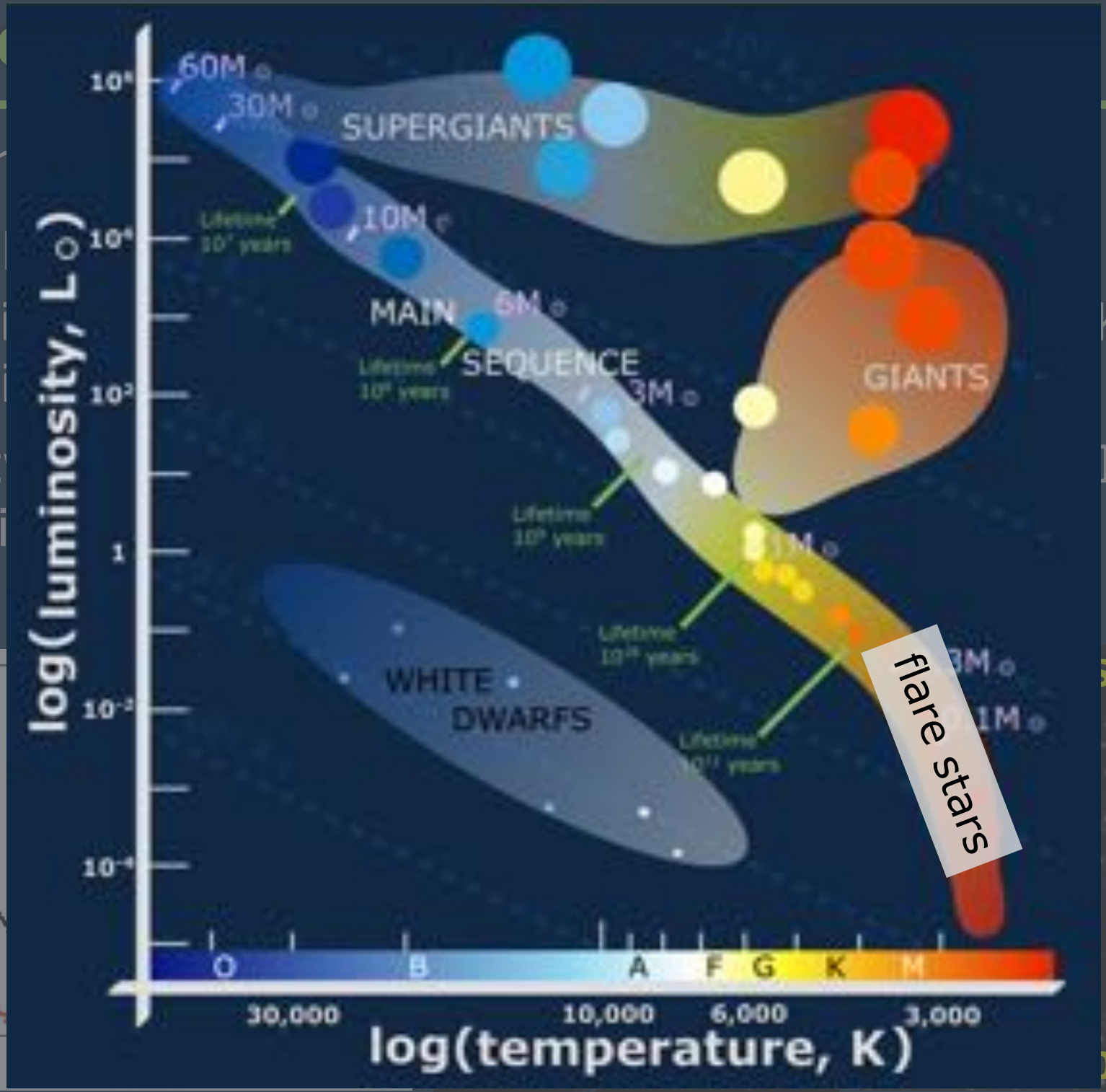
- Flare <15s to 1 hr, repeats hrs - days
- Amplitude up to 4 magnitudes
- optical is thermal bremsstrahlung at T ~ 107K, radio is non-thermal
- Between flares, spectrum is K-M star with Ca II, H emission



Flare

- Flar
- Am
- opti
- Bet





Star

07 - 2015

Flare Stars

Topic on Nov 21!

- Flare <15s to 1 hr, repeats hrs - days
- Amplitude up to 4 magnitudes
- optical is thermal bremsstrahlung at T ~ 107K, radio is non-thermal
- Between flares, spectrum is K-M star with CaII, H emission

Science from Flare stars

- flare physics and planet habitability
- rate depends on flare energy, spectral type, stellar age, line of sight
- can test models predicting flares
- new observations measure frequency, distribution

Pulsating Stars

Radial pulsators

RR Lyrae: A giants, M_V = 0.5, P<1 day

Cepheids: F-G giants & supergiants, P ~ 2-60 days

Long period: M, S, M_V= 1 to -2, P~100-700 days

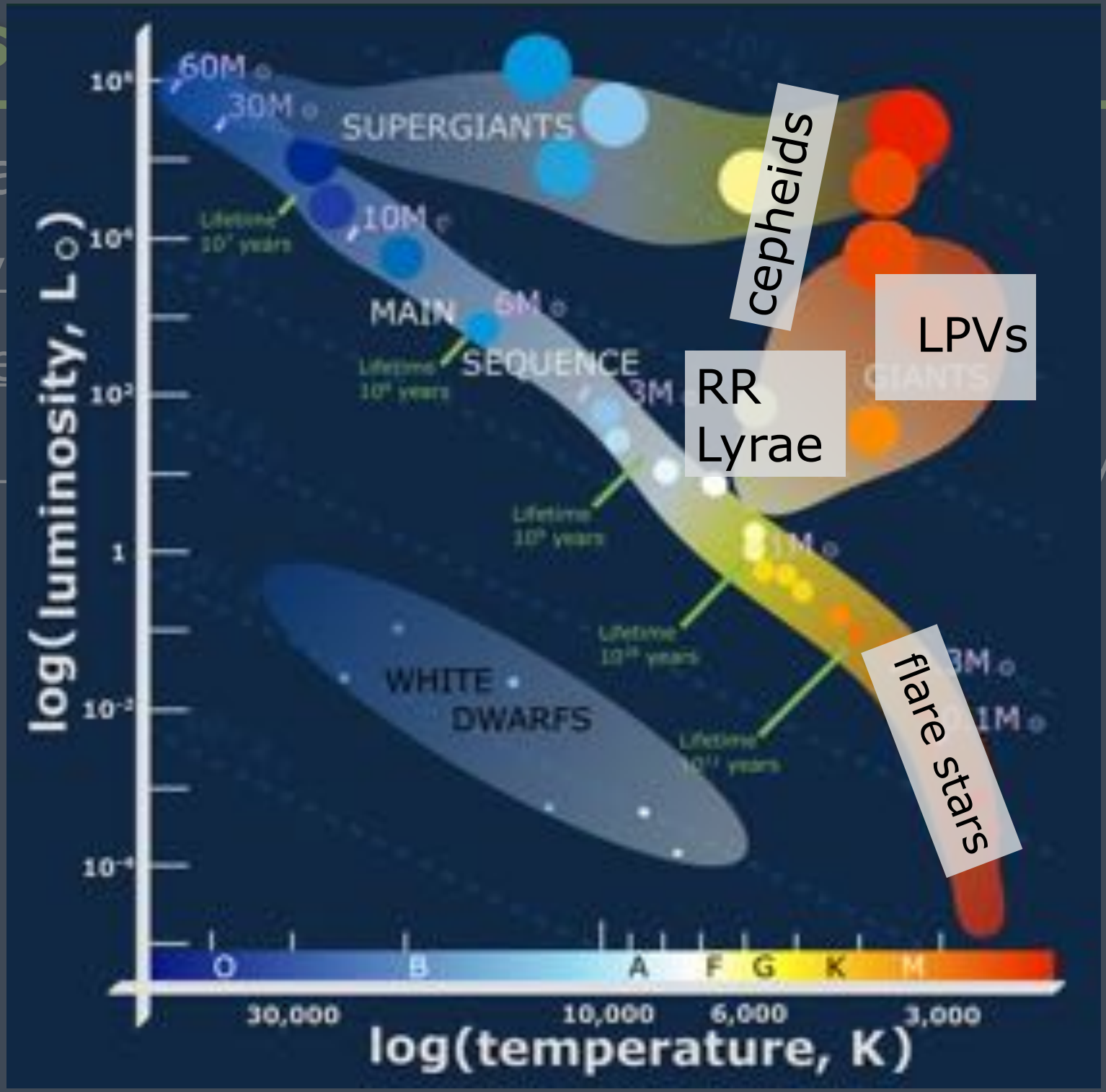
Puls

Radia

RR Ly

Cephe ays

Long ys



Pulsating Stars

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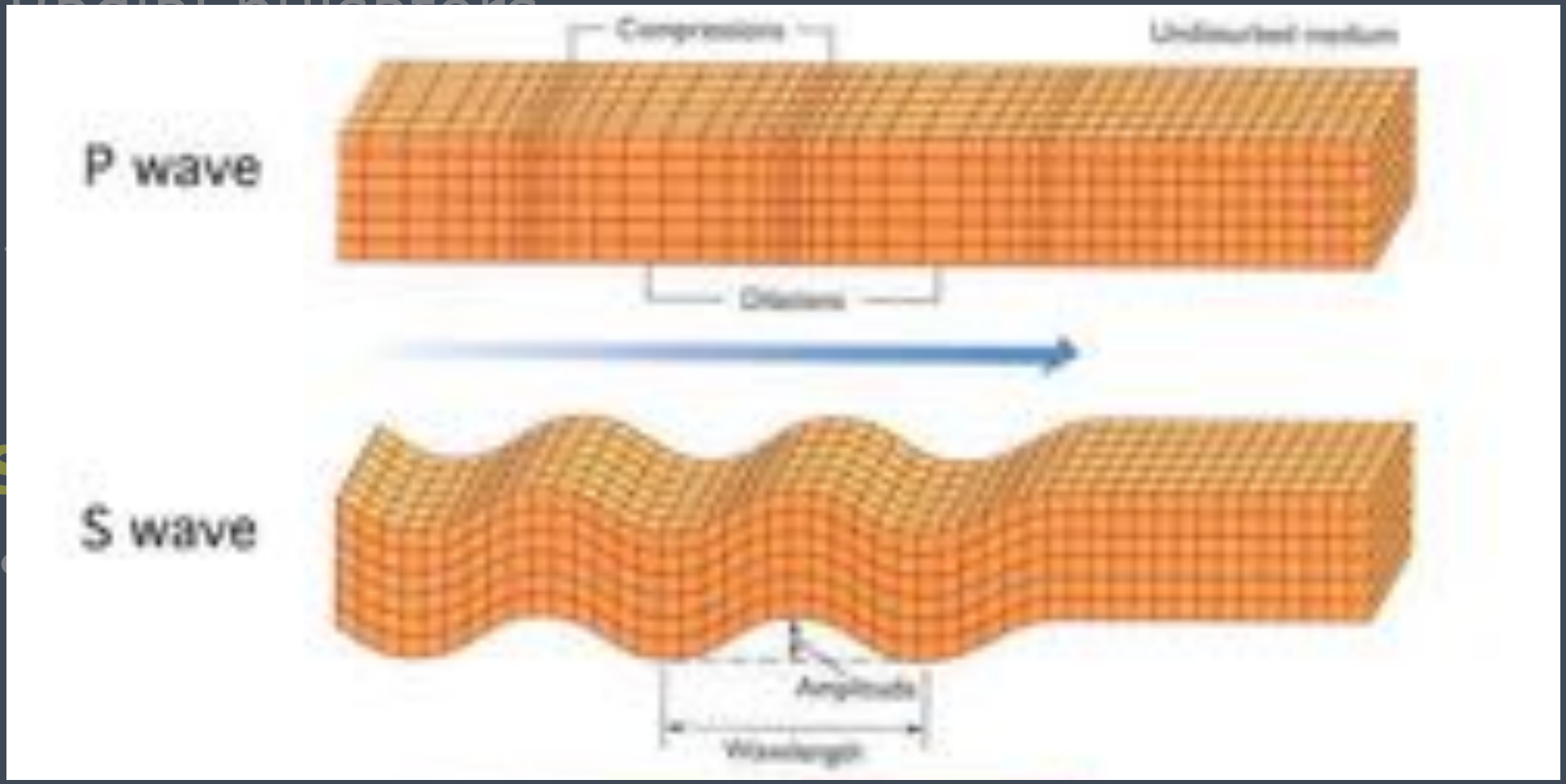
Science from pulsating stars

- only systematic way to study stellar interiors; **asteroseismology**

Pulsating Stars

- Radial pulsators



stellar equivalent of seismology on Earth; wave propagation can tell us about internal structure

Pulsating Stars

Radial pulsators

RR Lyrae: A giants, M_V = 0.5, P<1 day

Cepheids: F-G giants & supergiants, P ~ 2-60 days

Long period: M, M_V= 1 to -2, P~100-700 days

Science from pulsating stars

- only systematic way to study stellar interiors; **asteroseismology**
- small pulsations are observable all over the HRD
- the stars listed above can also be used as standard candles

Pulsating Stars

Topic on Nov 21!

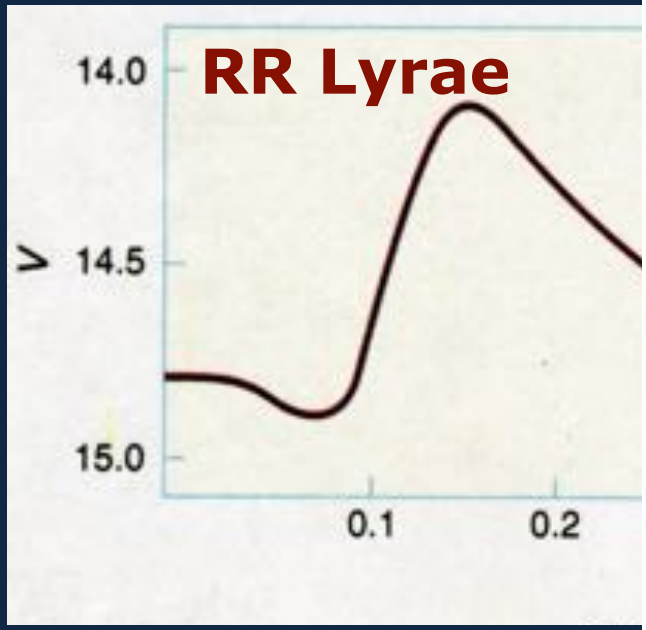
Radial pulsators

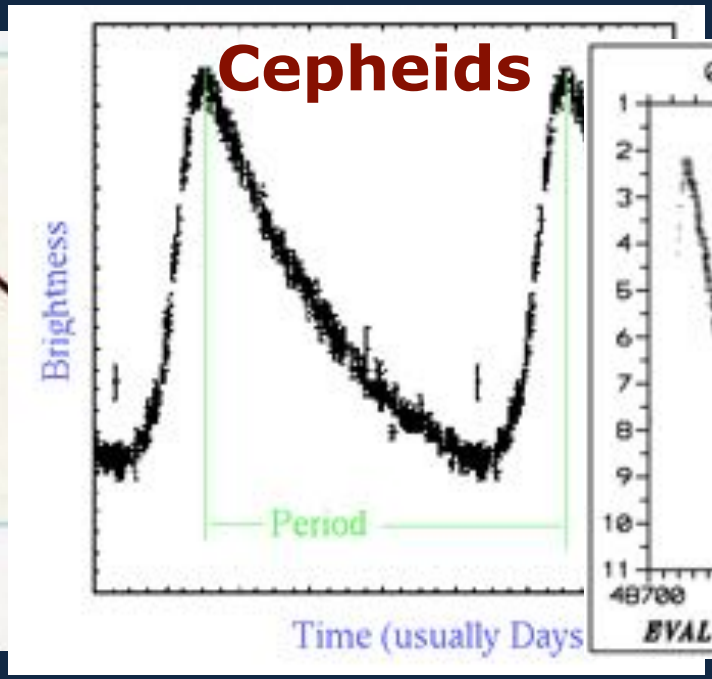
RR Lyrae: A giants, M_V = 0.5, P<1 day

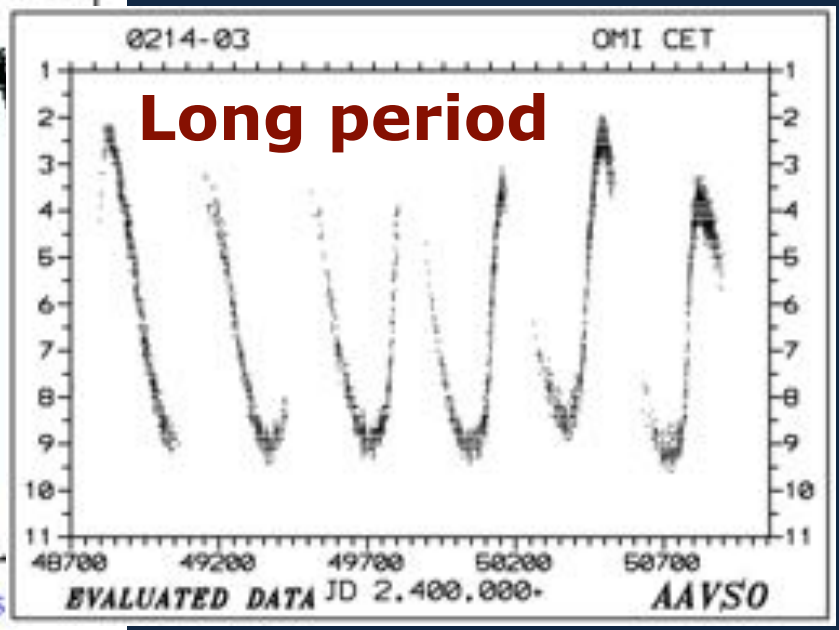
Cepheids: F-G giants & supergiants, P ~ 2-60 days

Long period: M, M_V= 1 to -2, P~100-700 days

Science from pulsating stars - lightcurves





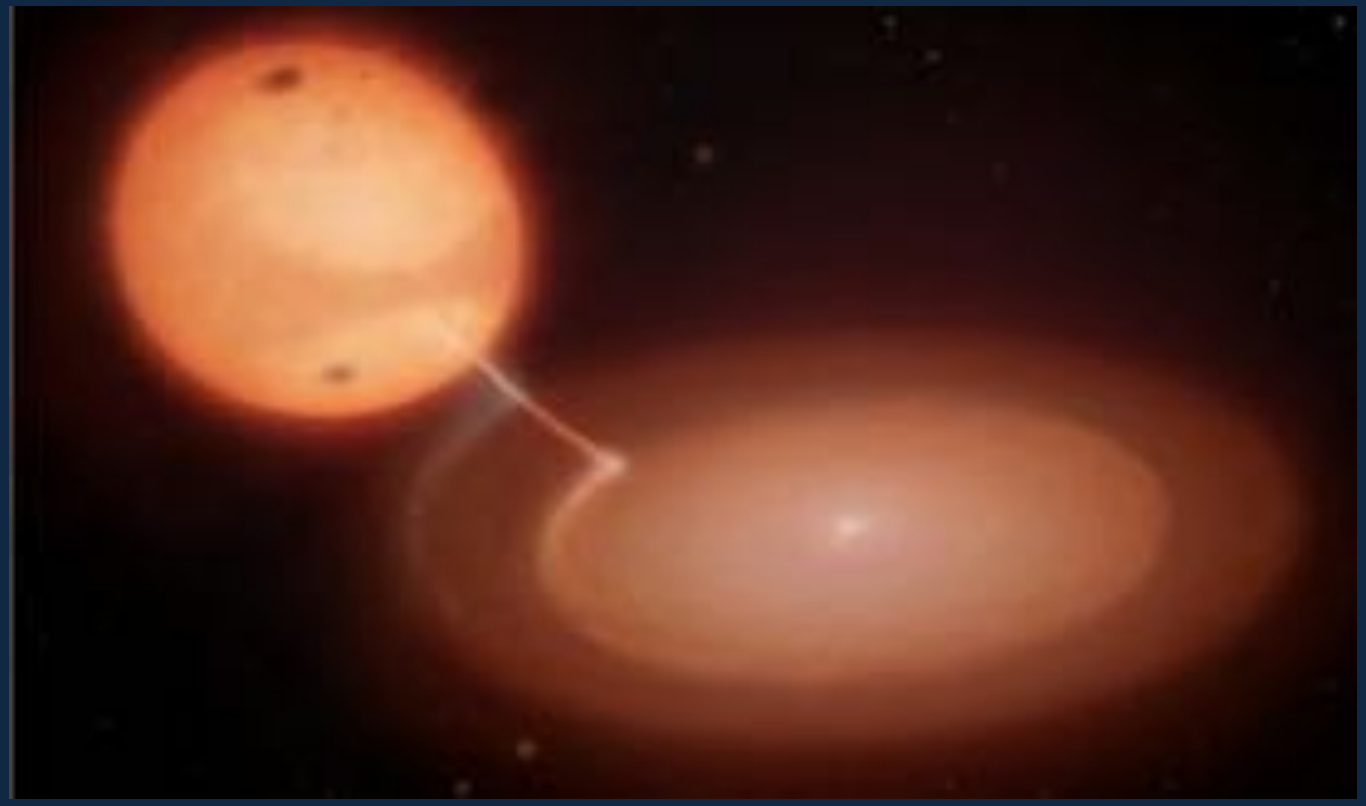


Cataclysmic Variables

White dwarf primaries with a low mass (G-M) secondary, orbital periods of hours-days.

Nova: high mass WD, outbursts 8-15 mag every few thousand yrs, ~28/yr in MW

Dwarf nova: disk instability, outbursts 2-7 mag every week-30 yr

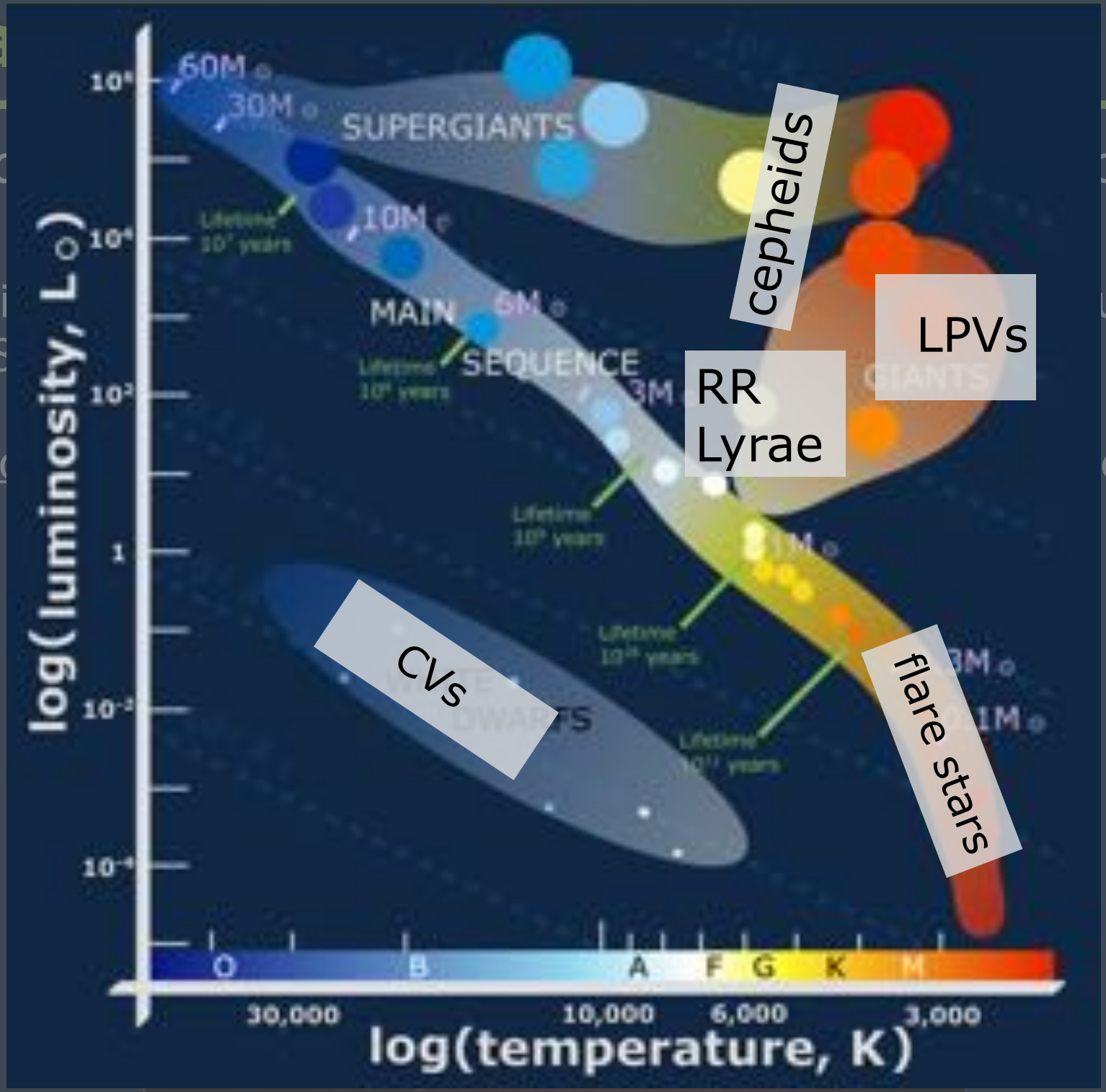


Cata

White d … condary, orbital

Nova: hi … usand yrs, ~28

Dwarf no … ek-30 yr



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Nova: high mass WD, outbursts 8-15 mag every few thousand yrs, ~28/yr in MW

Dwarf nova: disk instability, outbursts 2-7 mag every week-30 yr

Science from CVs

- observable in and beyond Milky Way
- lightcurve shapes and decline give info on WD properties
- correct rates are needed to understand Galactic chemical evolution and star formation history
- past surveys have limited cadence; we may be underestimating the number of recurrent novae by a factor of ~100

Type Ia Supernovae

From last week…

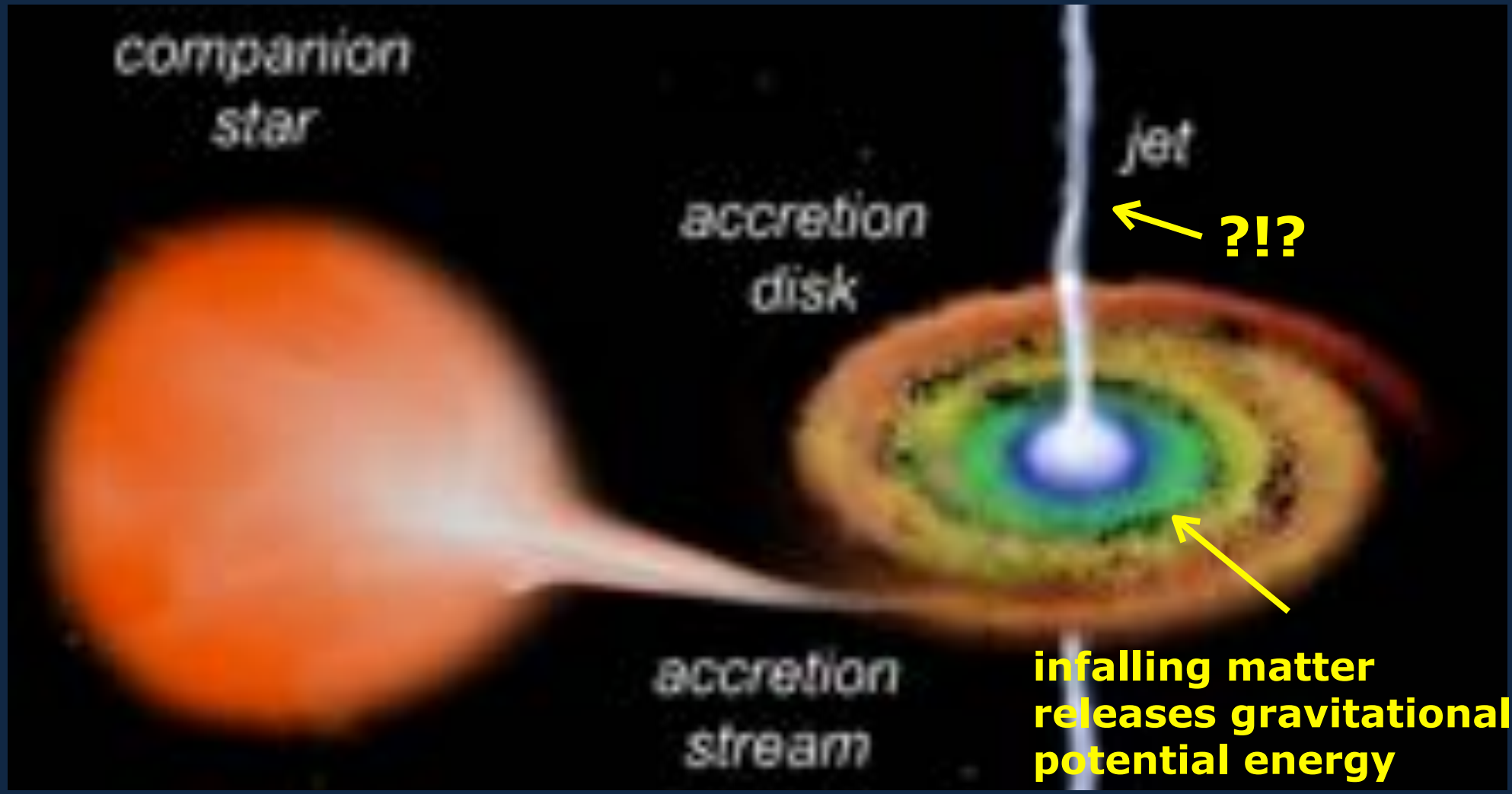
"Thermonuclear supernovae": result of a WD exceeding the **Chandrasekhar mass**

Chandrasekhar mass: maximum mass of a star that can be supported by e^- degeneracy pressure

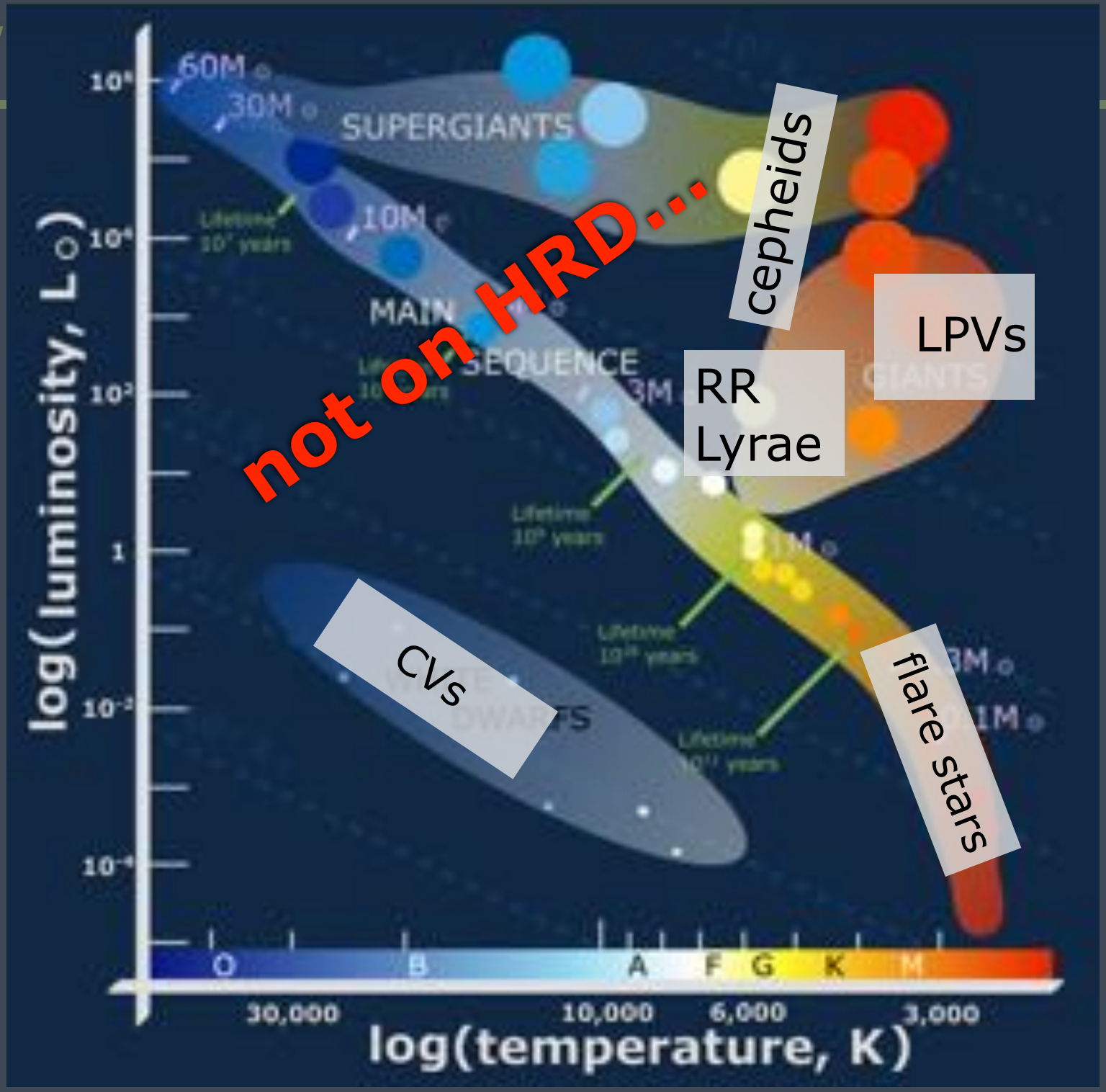
$\sim 1.4 M_\odot$

Low-Mass X-ray Binaries

Binary consisting of a compact object (NS, BH) and a low-mass star close enough to transfer mass.



Low


60M
30M
SUPERGIANTS
10M
MAIN SEQUENCE
3M
1M
not on HRD...
cepheids
LPVs
RR Lyrae
CVs
flare stars
log(luminosity, L⊙)
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
log(temperature, K)

Weird Stars: High Mass

luminous blue variables

neutron stars

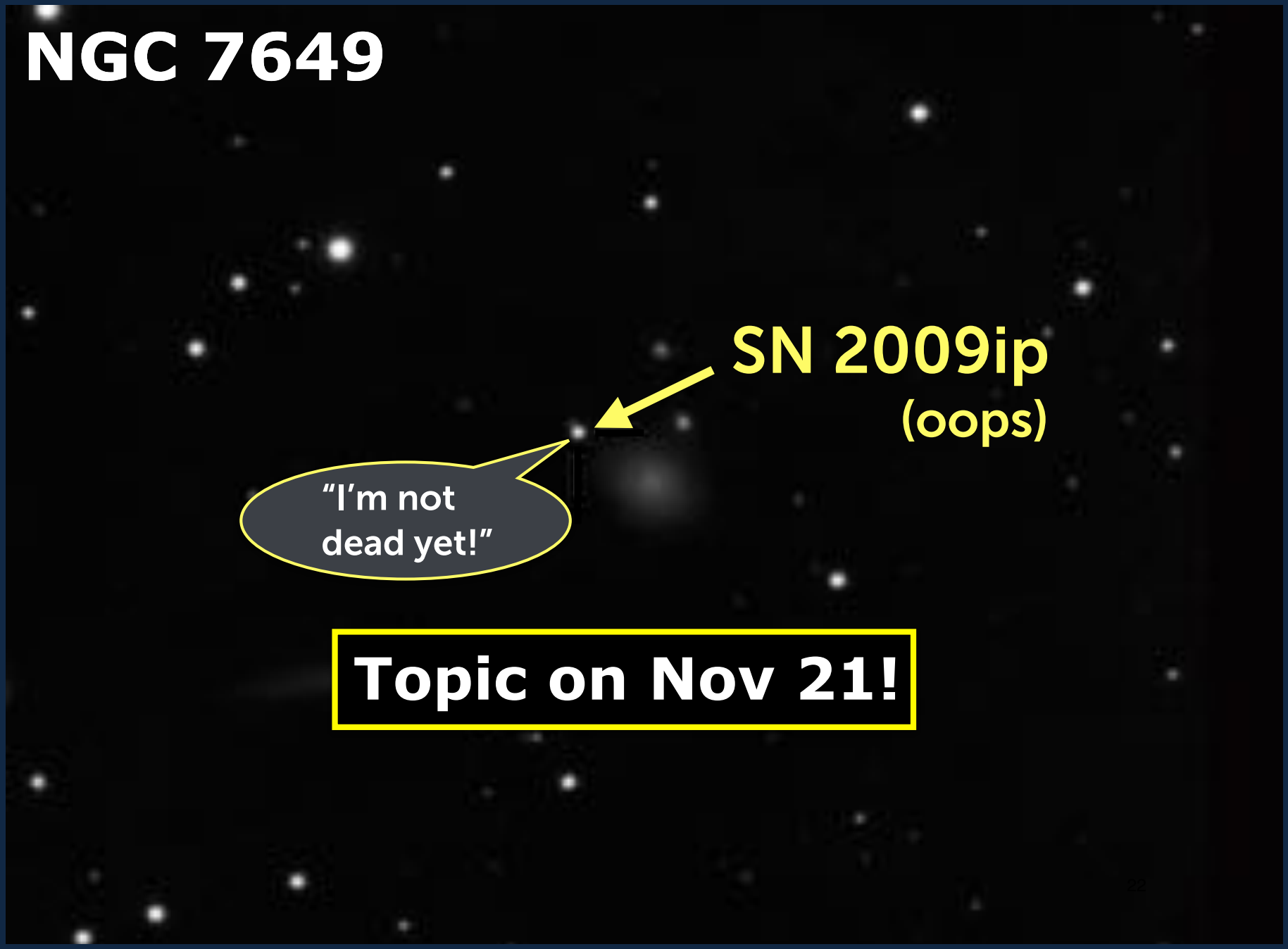
black holes

high mass X-ray binaries

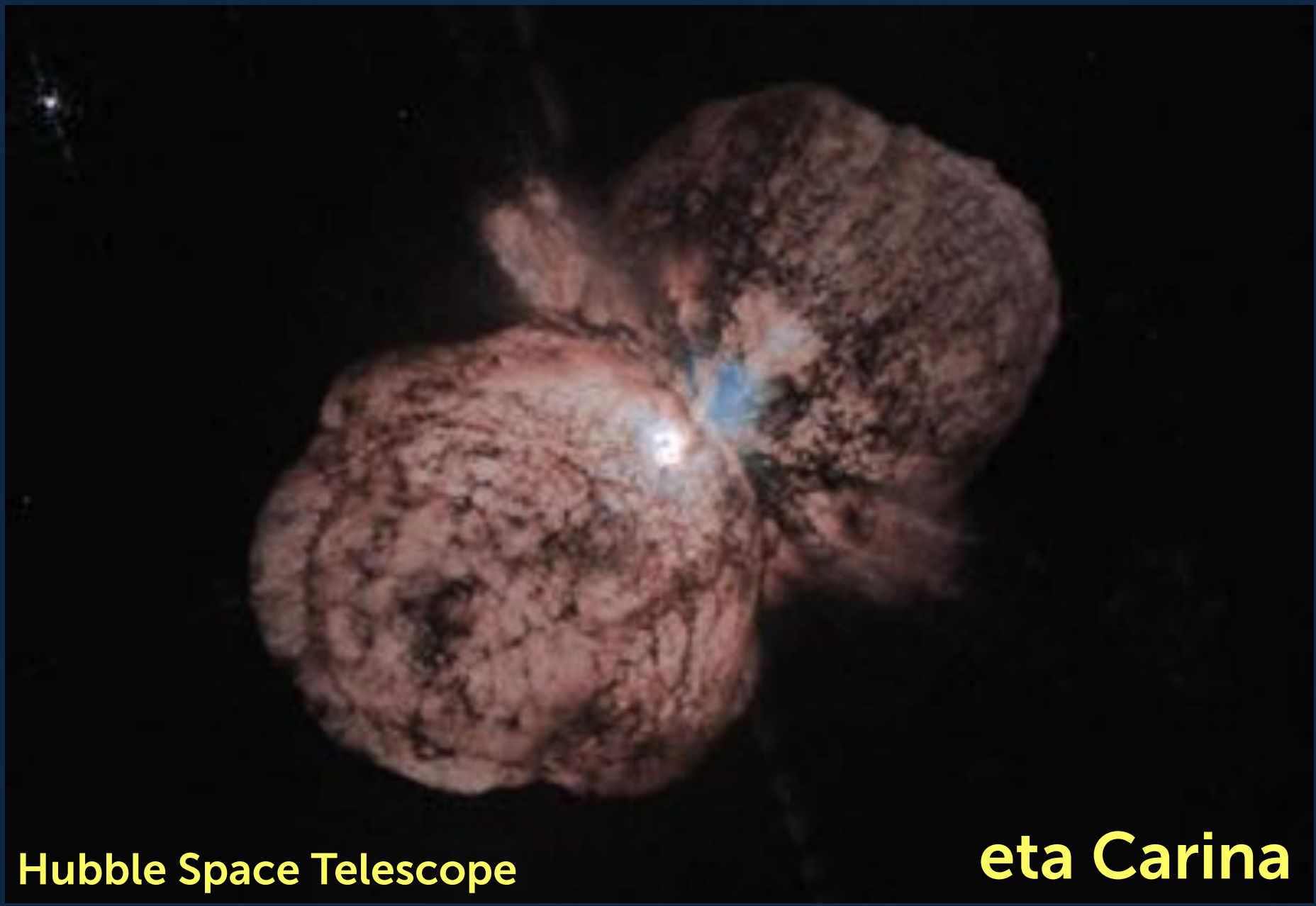
gamma-ray bursts

Thorne-Żytkow objects

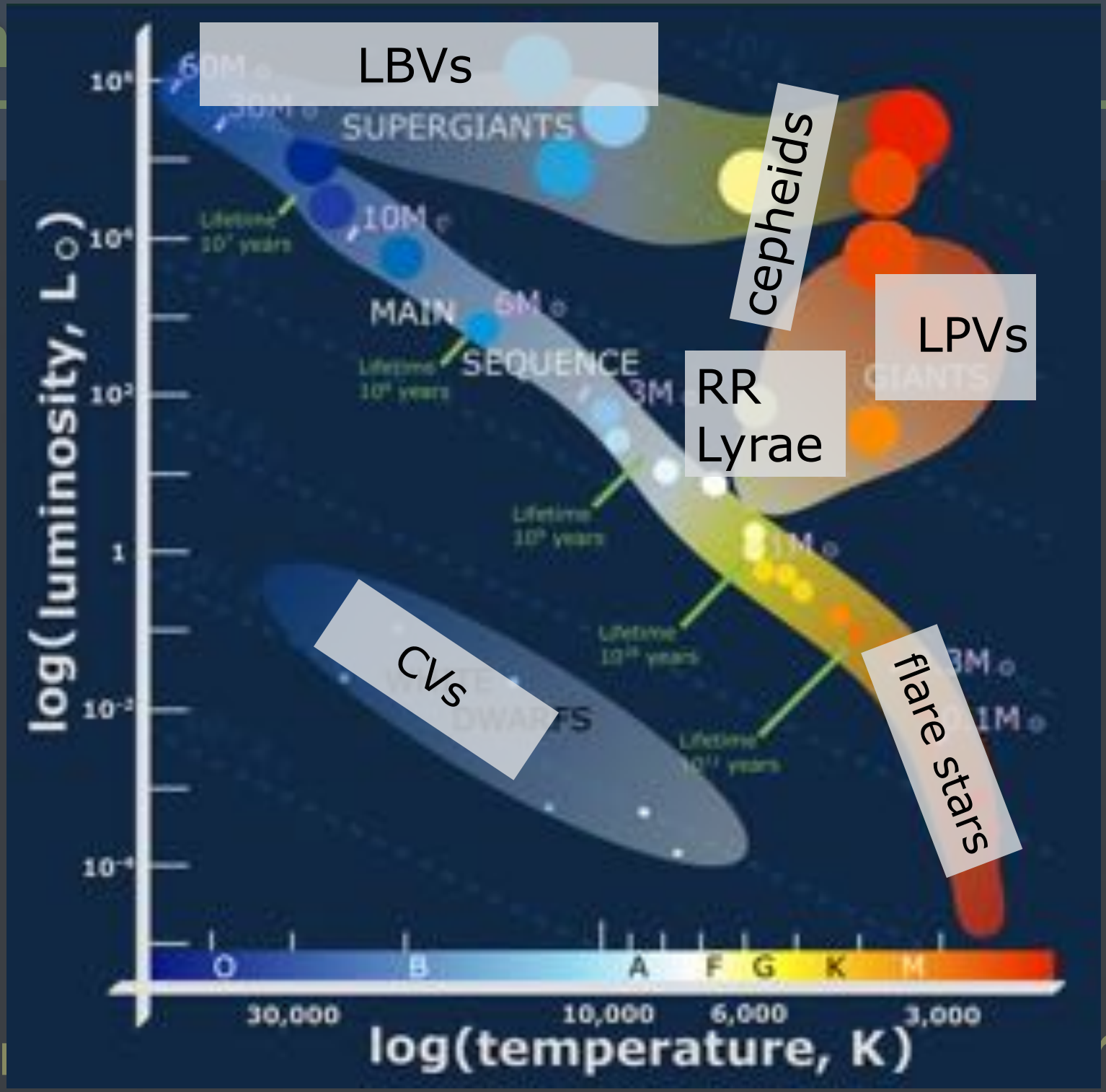
Luminous Blue Variables



Luminous Blue Variables



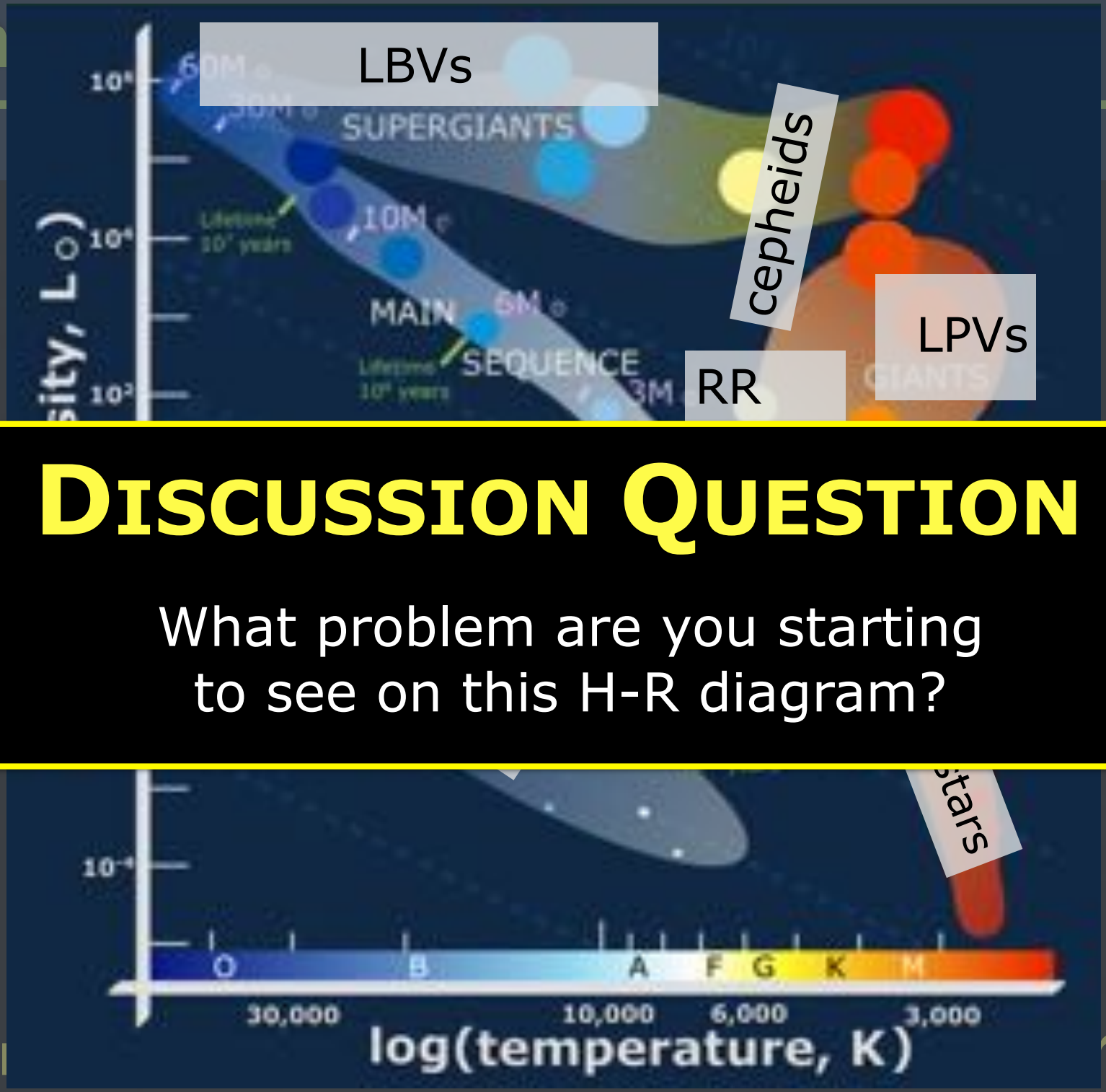
Lum



Hubl

rina

Lum

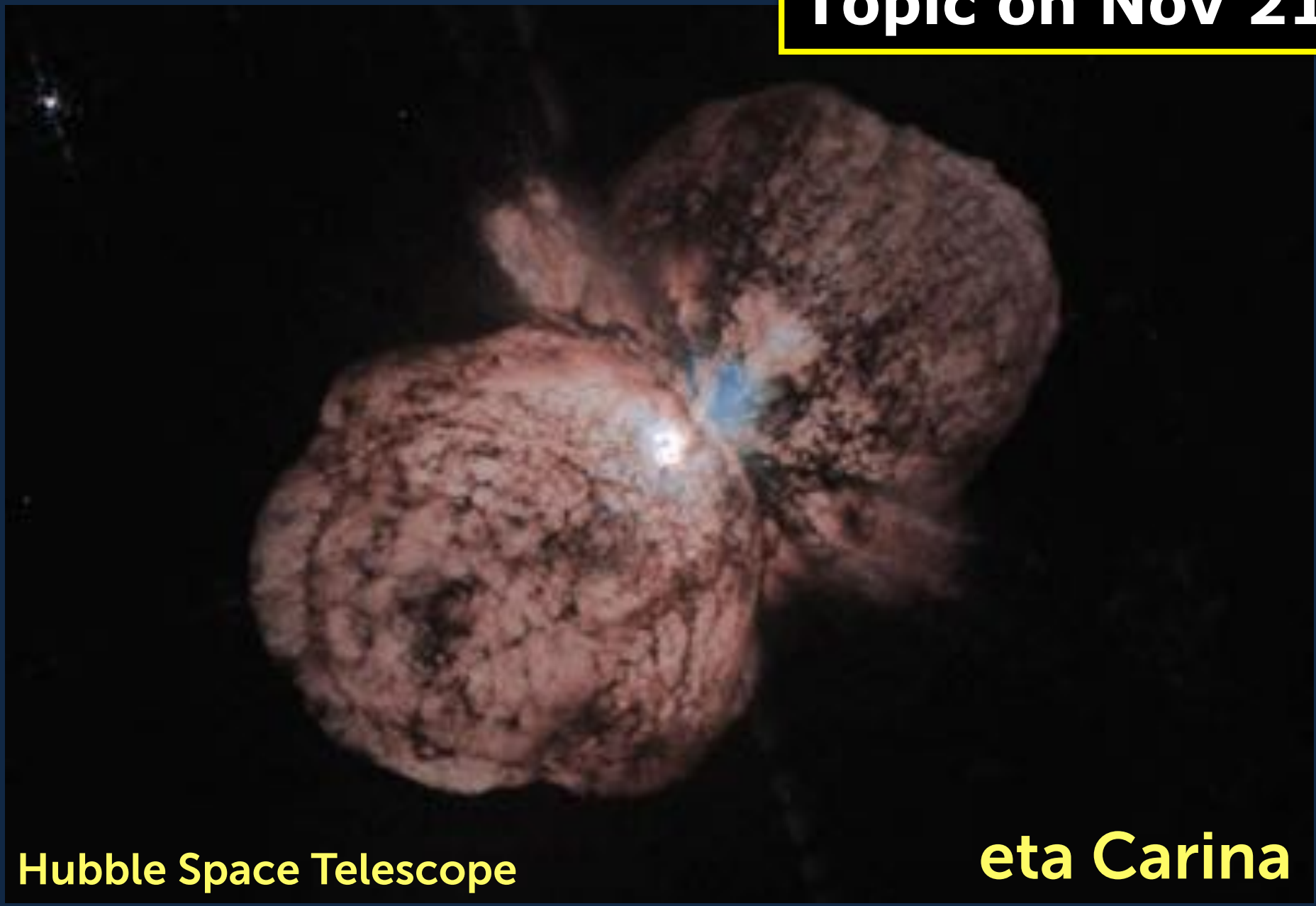


Discussion Question

What problem are you starting to see on this H-R diagram?

Luminous Blue Variables

Topic on Nov 21!



Neutron Stars/Pulsars

Product of core-collapse supernovae…

Size: ~15 km

Density: 10^{14} g/cm^3

B-Field (G): 10^{12} G

Rotation: ≲ sec

Fastest: 1/700 sec

Slowest: ~8 sec

Pressure: n degeneracy

Topic on Nov 21!

Black Holes

Topic on Nov 21!

Product of core-collapse supernovae…

Size: ??

Density: infinite

B-Field (G): ??

Rotation: <<sec??

Pressure: none?

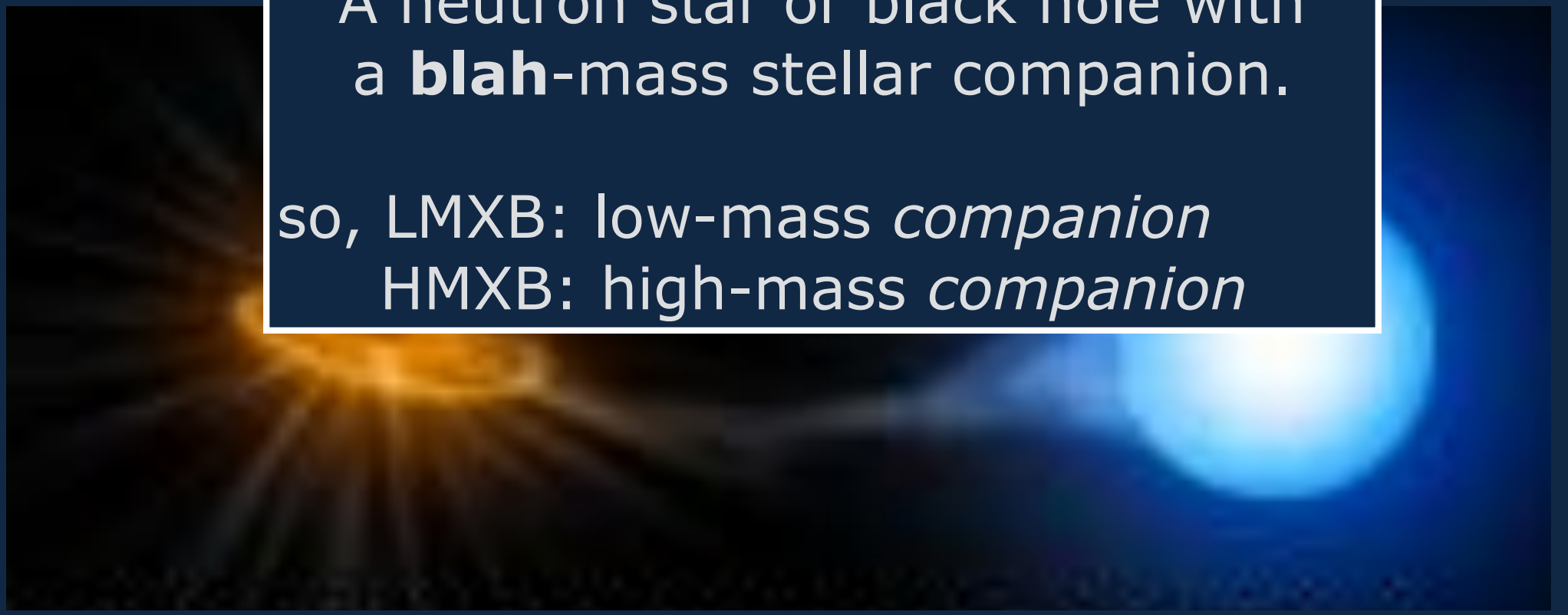
High Mass X-ray Binaries

Binary consisting of a compact object (NS, BH) and a *massive* star close enough to transfer mass.

A **Blah Mass** X-ray Binary

A neutron star or black hole with a **blah**-mass stellar companion.

so, LMXB: low-mass *companion*
HMXB: high-mass *companion*



High Mass X-ray Binaries

Binary consisting of a compact object (NS, BH) and a *massive* star close enough to transfer mass.

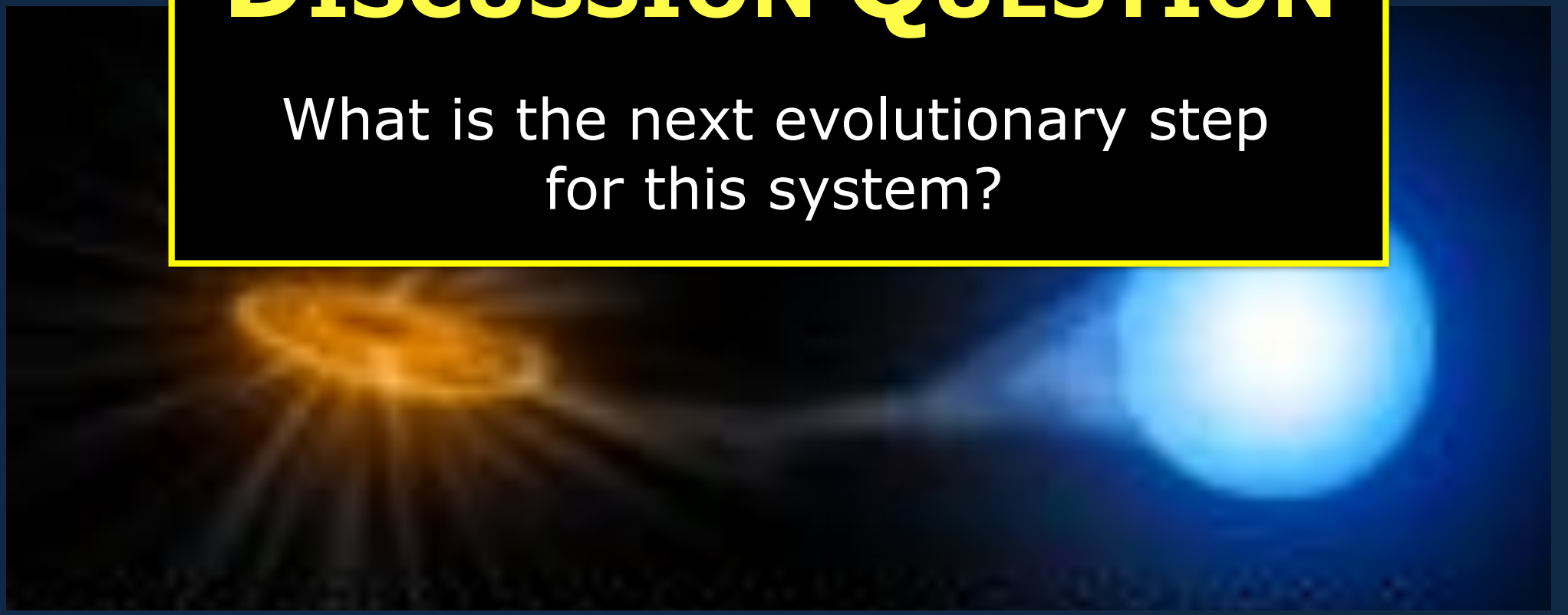
Topic on Nov 21!

High Mass X-ray Binaries

Binary consisting of a compact object (NS, BH) and a *massive* star close enough to transfer mass.

Discussion Question

What is the next evolutionary step for this system?



High Mass X-ray Binaries

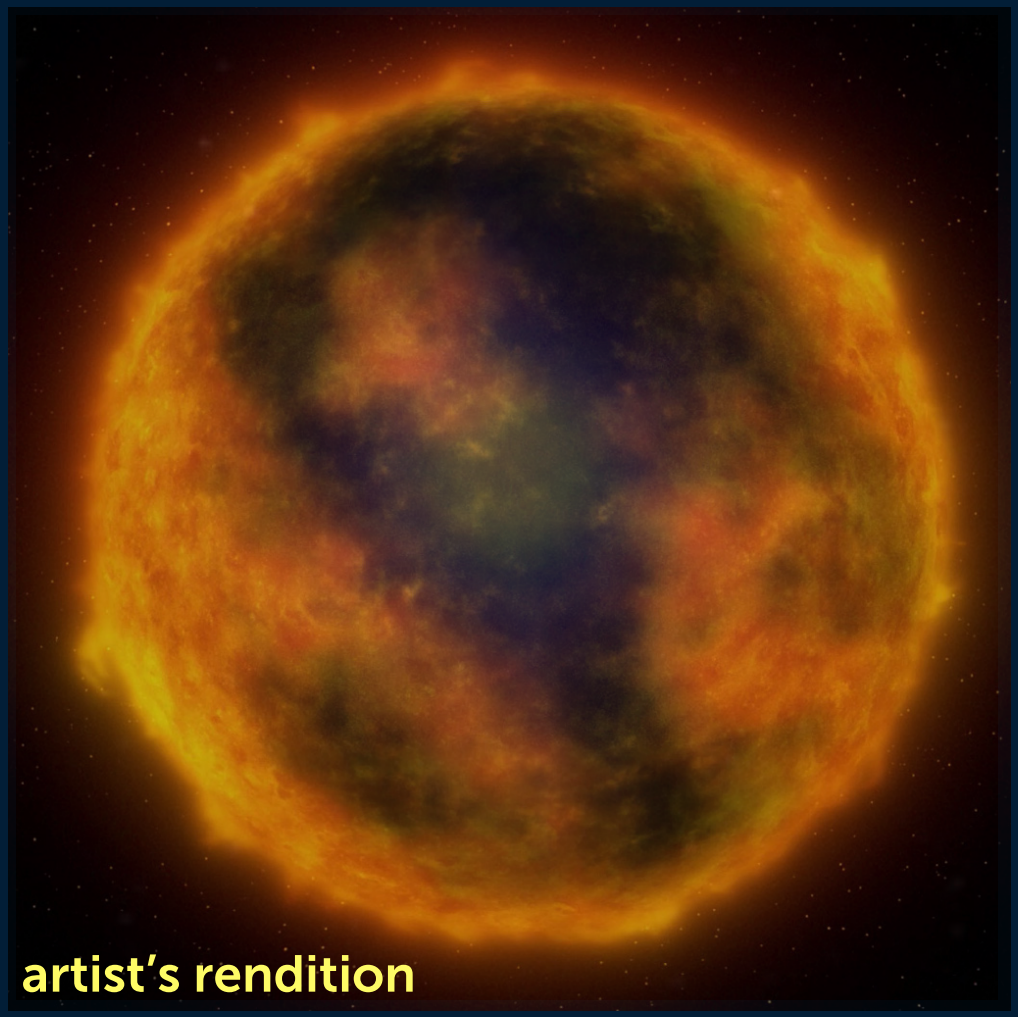
Binary consisting of a compact object (NS, BH) and a *massive* star close enough to transfer mass.

Progenitors of dual compact object systems (NS-NS, NS-BH, BH-BH) ⟶ **gravitational waves!**

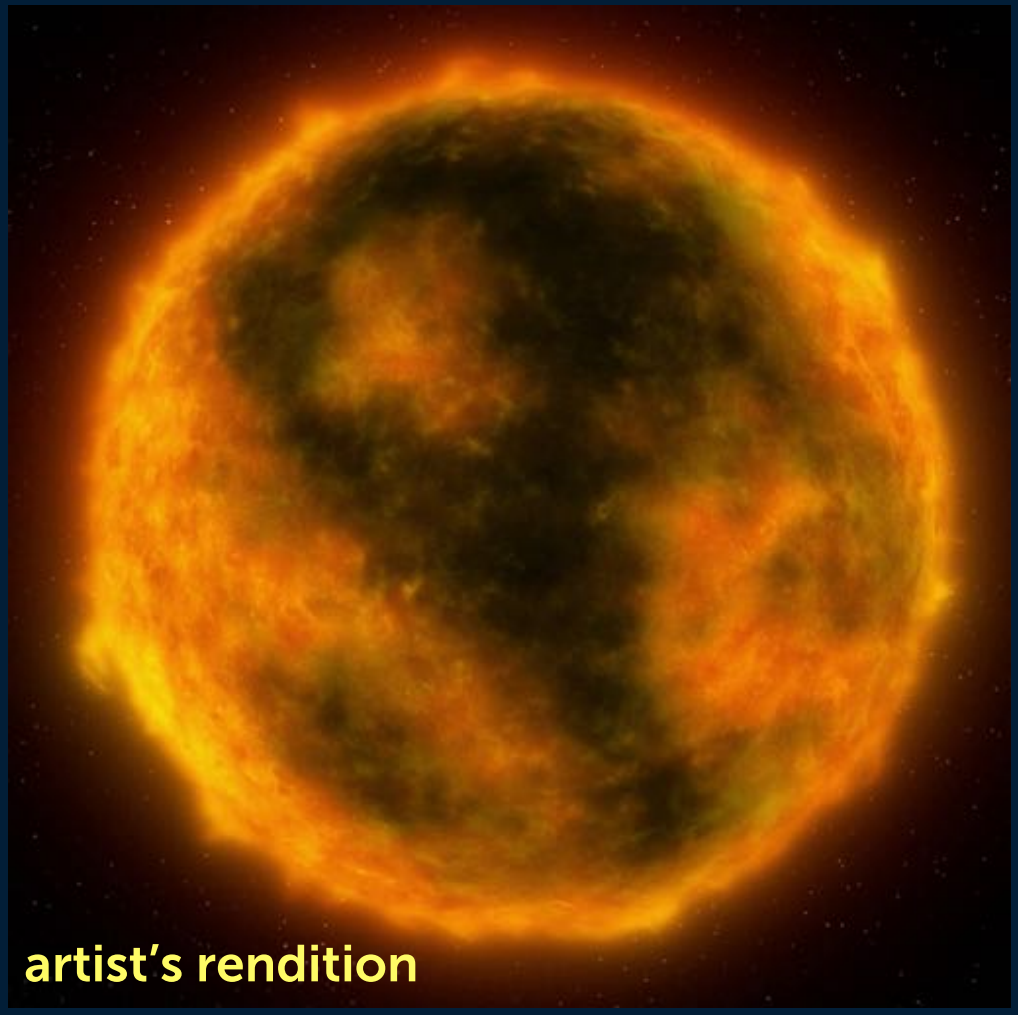
Gamma-Ray Bursts

Thorne-Żytkow Objects

Thorne-Żytkow Objects (TŻOs) are a theoretical class of star: a neutron star "core" surrounded by a large cold puffy envelope.



Thorne-Żytkow Objects



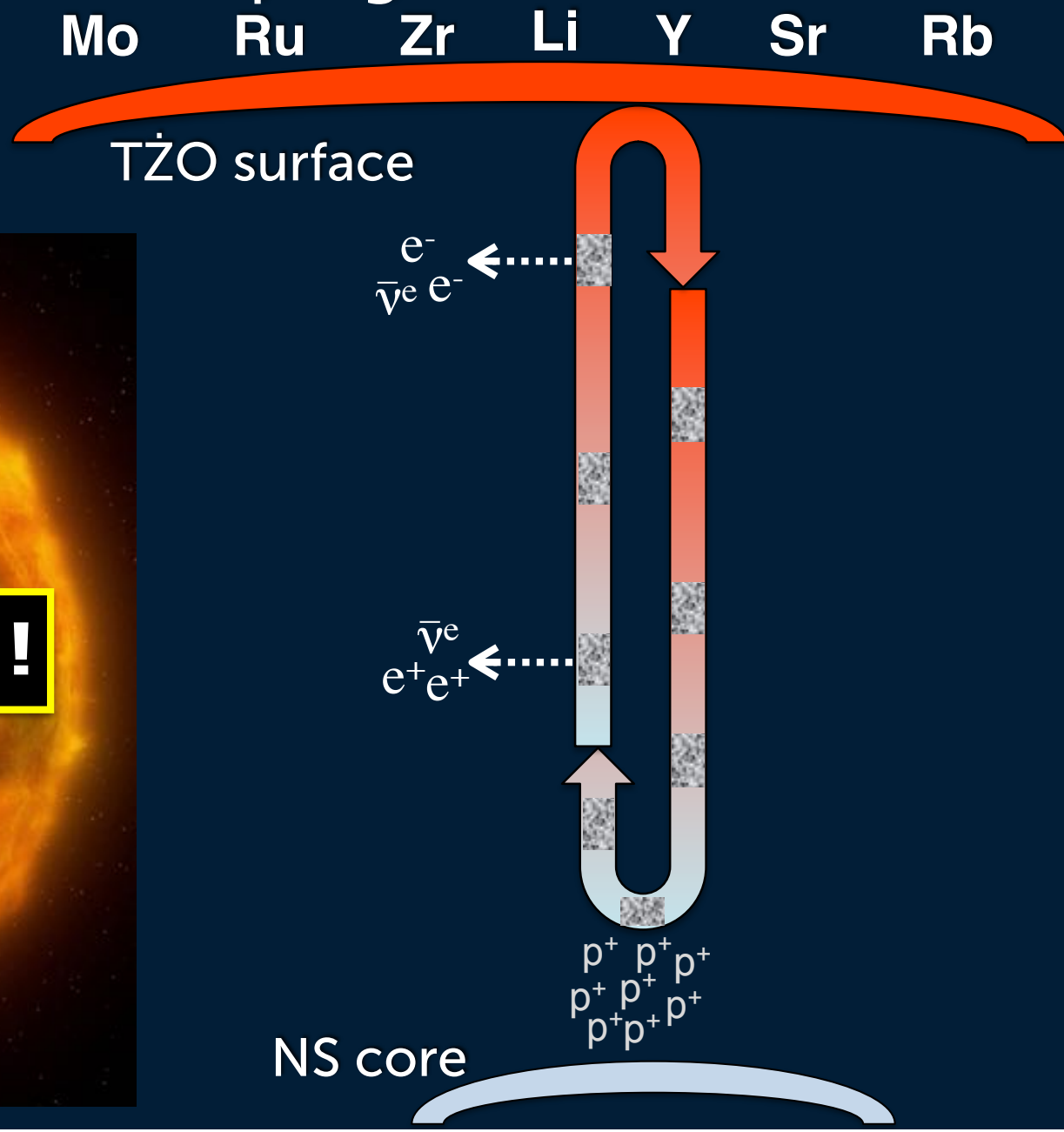
size of Jupiter's orbit

size of city of Seattle

Thorne-Żytkow Objects

TŻOs look exactly like red supergiants...

almost!



Coming up next...

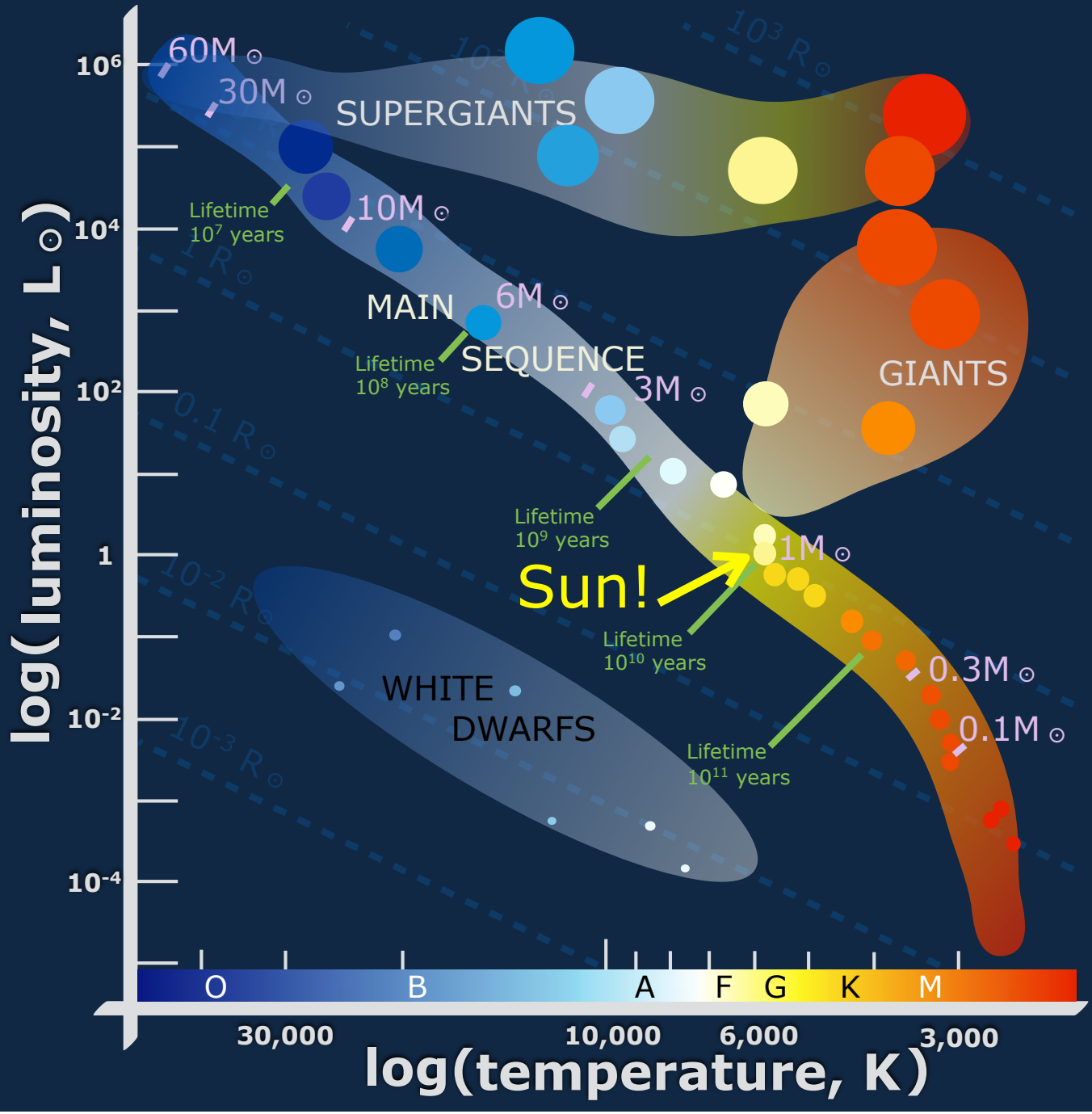
Thu Nov 16: The Sun

Tue Nov 21: project presentations!

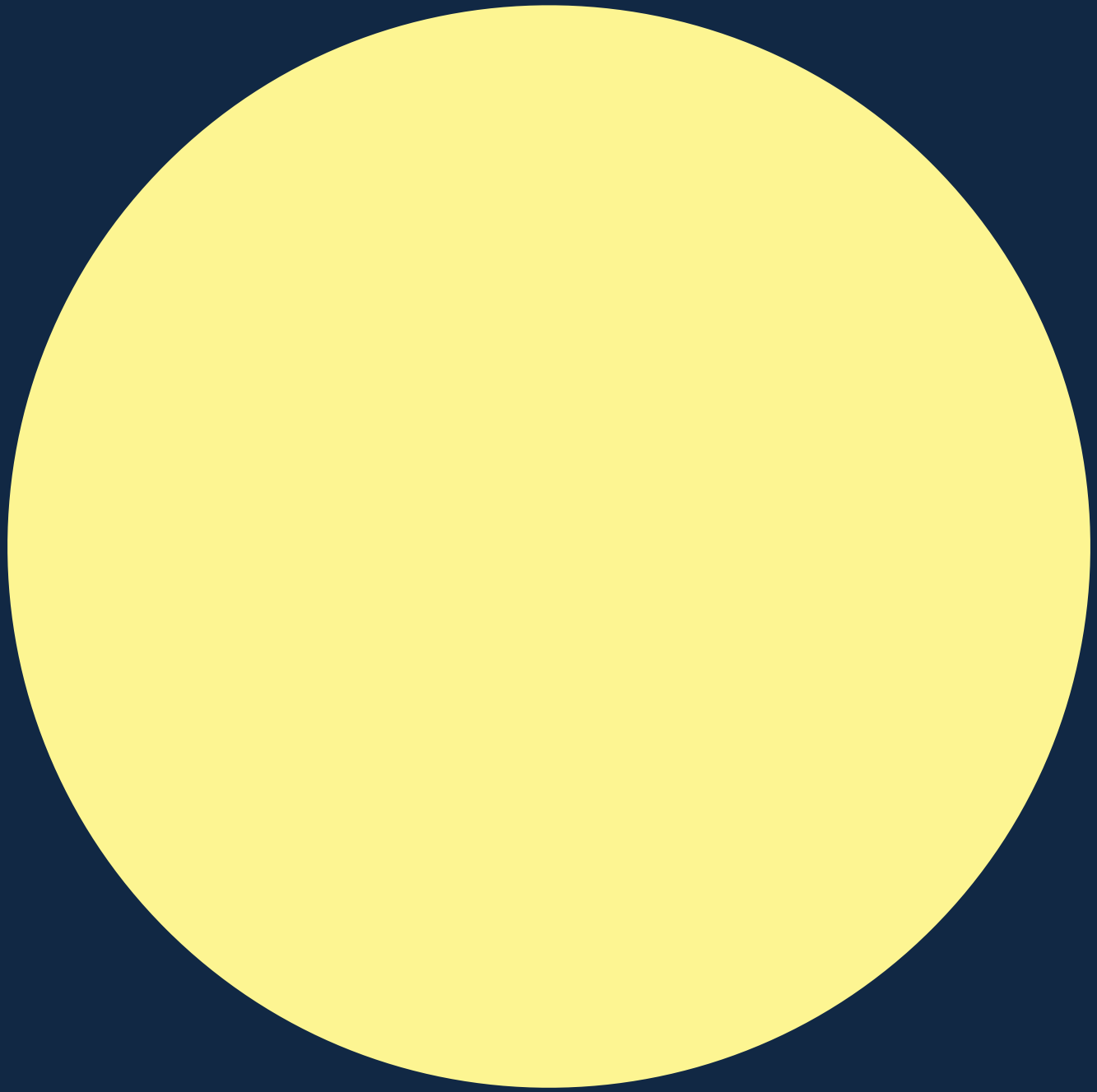
T Tauri stars
red giants
planetary nebulae
Wolf-Rayet stars
core-collapse SNe
flare stars
runaway stars

Cepheids
cataclysmic variables
luminous blue variables
high mass x-ray binaries
pulsars
black holes
Thorne-Żytkow objects

The Sun


60M ⊙
30M ⊙
SUPERGIANTS
10M ⊙
Lifetime
10^7 years
MAIN
SEQUENCE
6M ⊙
Lifetime
10^8 years
3M ⊙
GIANTS
Lifetime
10^9 years
1M ⊙
Sun!
Lifetime
10^10 years
0.3M ⊙
0.1M ⊙
Lifetime
10^11 years
WHITE
DWARFS
10^3 R ⊙
10^2 R ⊙
1 R ⊙
0.1 R ⊙
10^-2 R ⊙
10^-3 R ⊙
10^6
10^4
10^2
1
10^-2
10^-4
log(luminosity, L⊙)
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
log(temperature, K)

The Sun

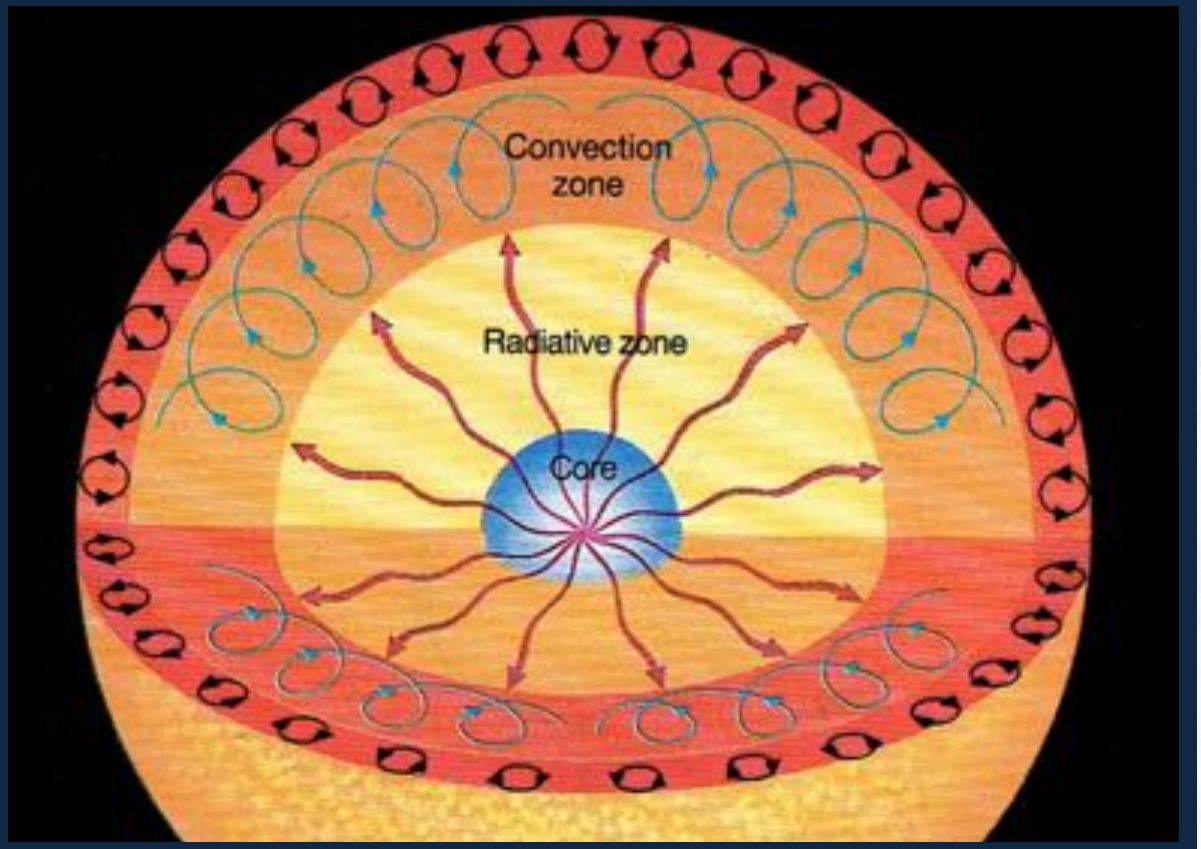


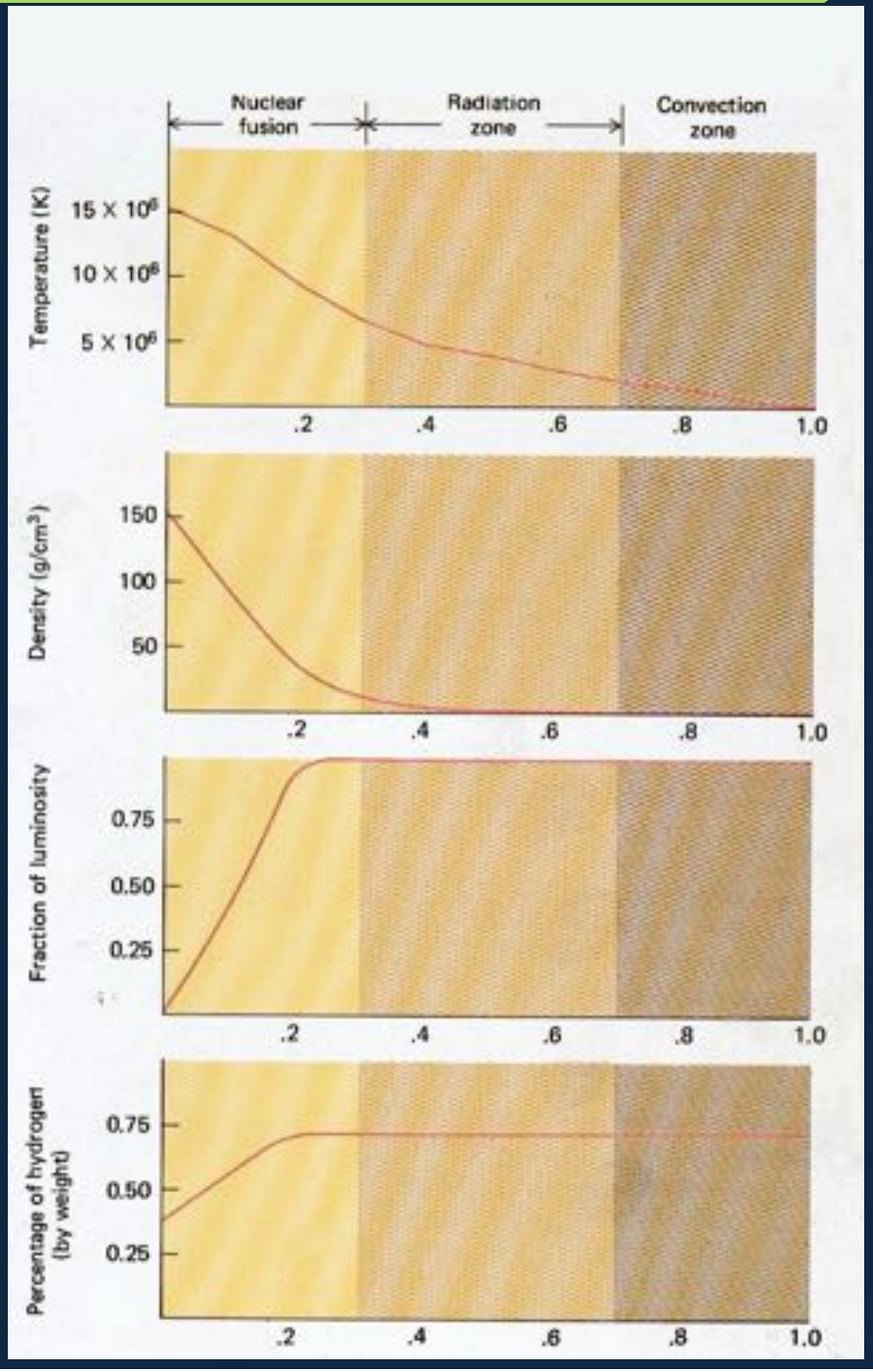
The Sun

Basic Properties

Distance	1 AU
Radius	6.96 x 10^8 m (100x Earth)
Mass	1.99x10^{30} kg (300,000x Earth)
Density	1.4 g cm^{-3}
Gravity	30 x Earth (at surface)
Surface comp	~ 73.46% H, 24.85% He, 0.77% O…
Temperature	5777 K (surface), 1.5 x 10^7 K (core)

The Sun - Interior





The Sun - Interior

The solar neutrino problem…

Should be capable of detecting neutrinos from p-p chain reactions in Sun's core…

The Sun - Interior

Th

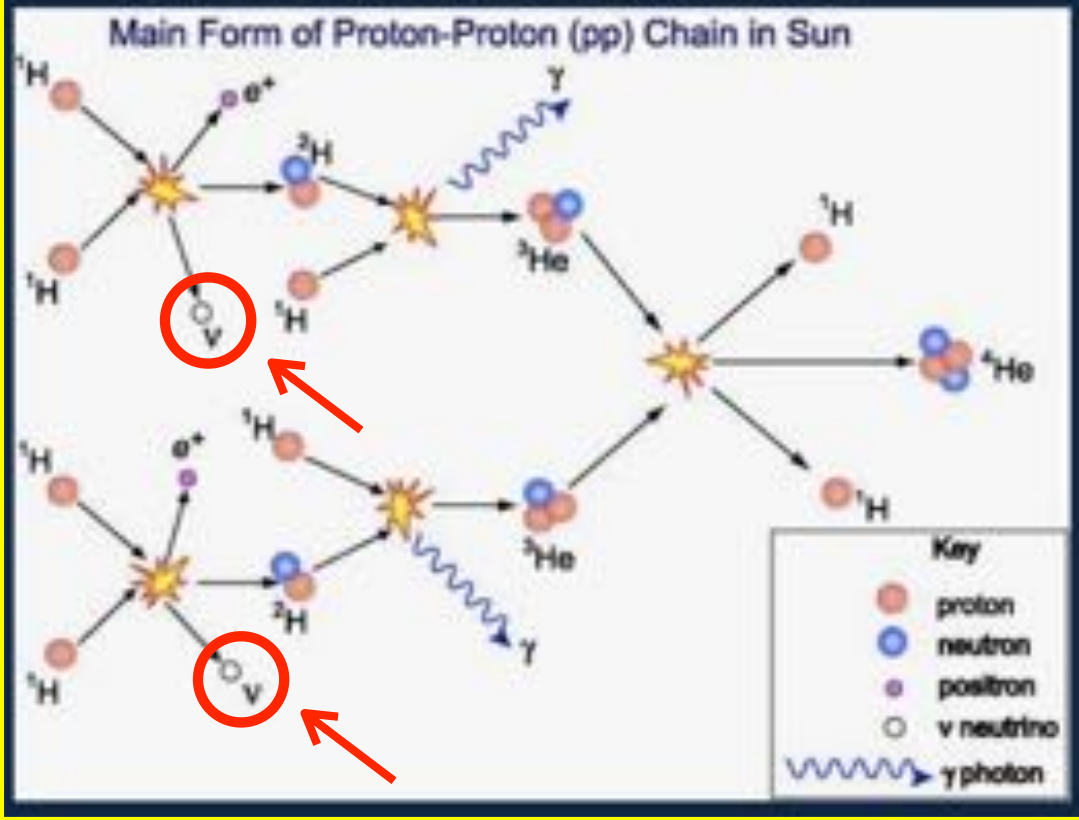
Sh chain
rea

Low-Mass Stars - Main Sequence

H as Stellar Fuel:

proton-proton chain

1) ${}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + e^{+} + \nu$
2) ${}^{2}_{1}H + {}^{1}_{1}H \rightarrow {}^{3}_{2}He + \gamma$
3) ${}^{3}_{2}He + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + 2{}^{1}_{1}H$



The Sun - Interior

The solar neutrino problem…

Should be capable of detecting neutrinos from p-p chain reactions in Sun's core…

1970: Raymond Davis's neutrino detector

—100,000 gallons of C_2Cl_4

$$^{37}_{17}Cl + \nu_e \rightleftarrows {}^{37}_{18}Ar + e^-$$

Predicted:

$\gtrsim 1\ {}^{37}_{18}Ar$ atom per day

Observed:

$\sim 0.5\ {}^{37}_{18}Ar$ atom per day!

The Sun - Interior

The solar neutrino problem…

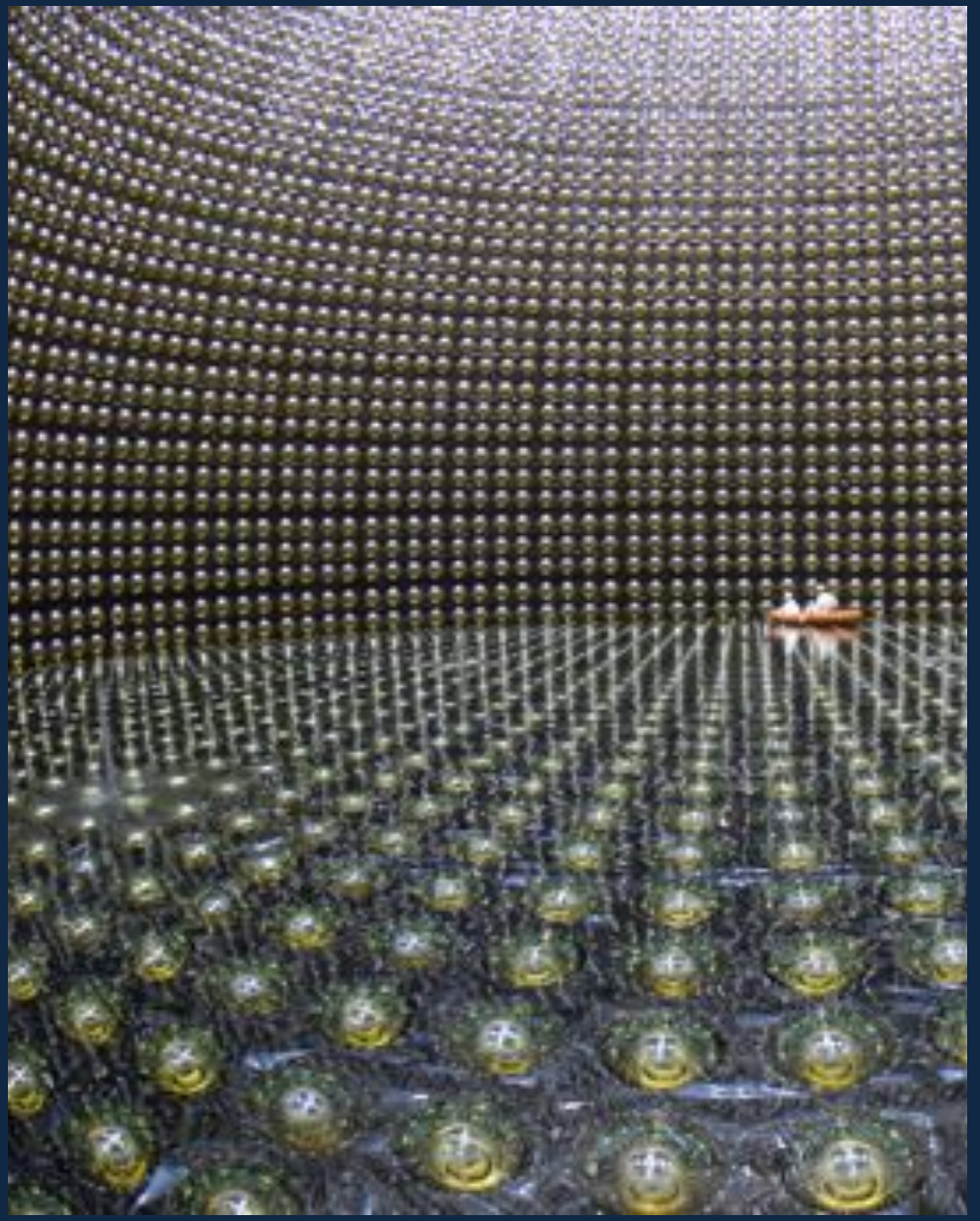
1996: Super-Kamiokande observatory

—confirmed ν_e deficit

What's wrong?

— ~~solar model wrong?~~

— something happening to the neutrinos?



The Sun - Interior

The solar neutrino problem…

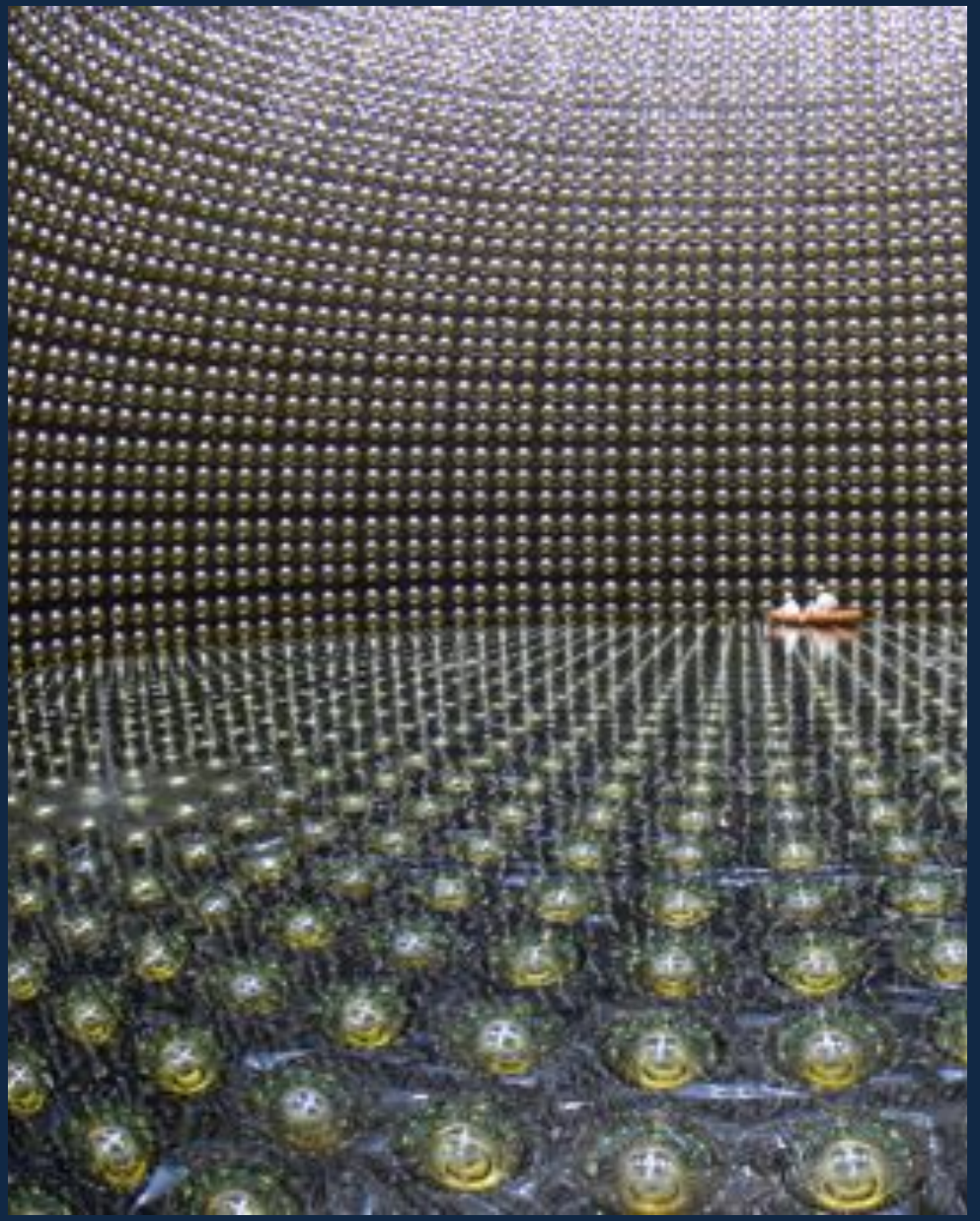
What's wrong?

— something happening to the neutrinos?

Neutrinos come in *flavors:*

ν_e, ν_μ , ν_τ

If flavors can oscillate, would explain "missing" ν_e!



The Sun - Interior

The solar neutrino problem…

Neutrinos come in *flavors:*

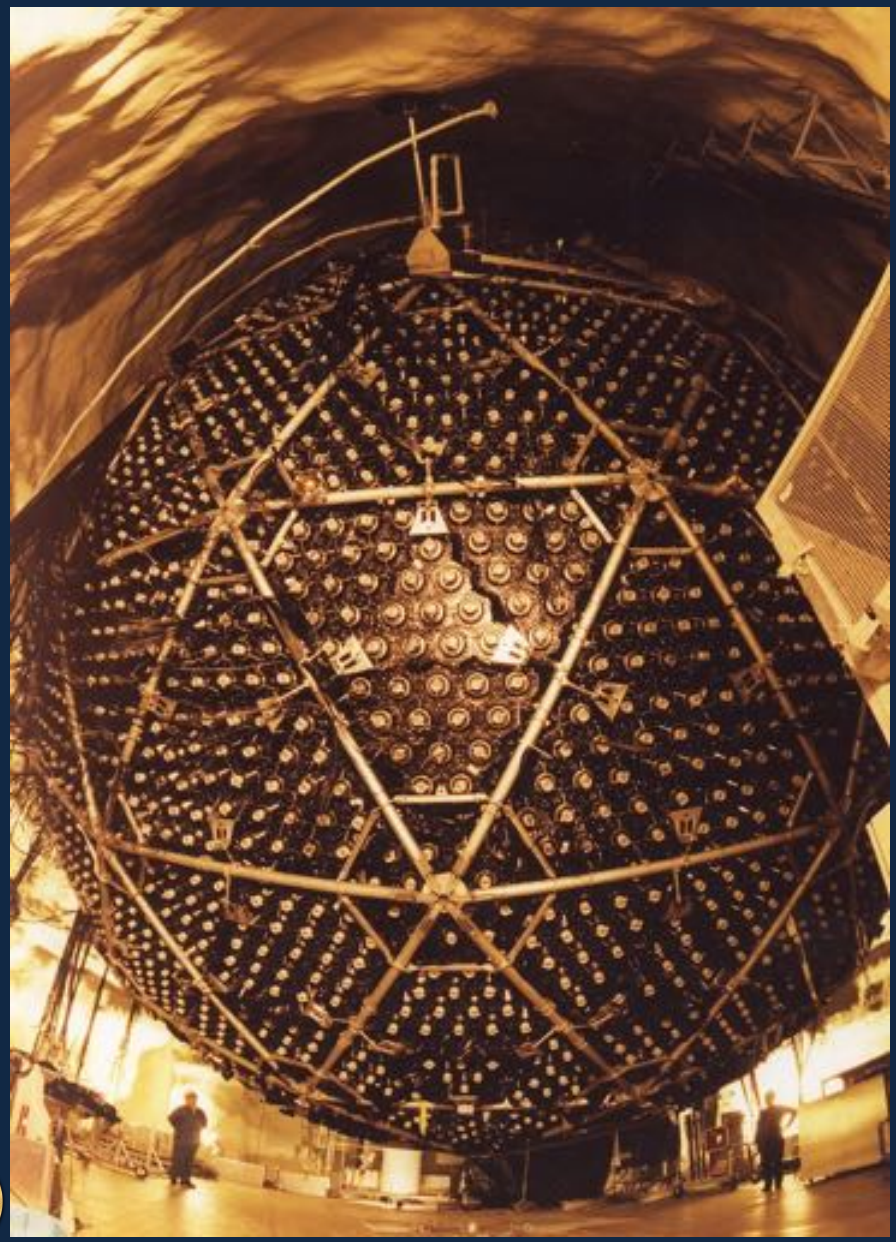
ν_e, ν_μ , ν_τ

If flavors can oscillate, would explain "missing" ν_e!

Implied in 1998 by Super-K observations of atmospheric neutrinos.

Confirmed in 2001 for solar neutrinos & all flavors by Sudbury Neutrino Observatory

"Neutrinos have mass"= 



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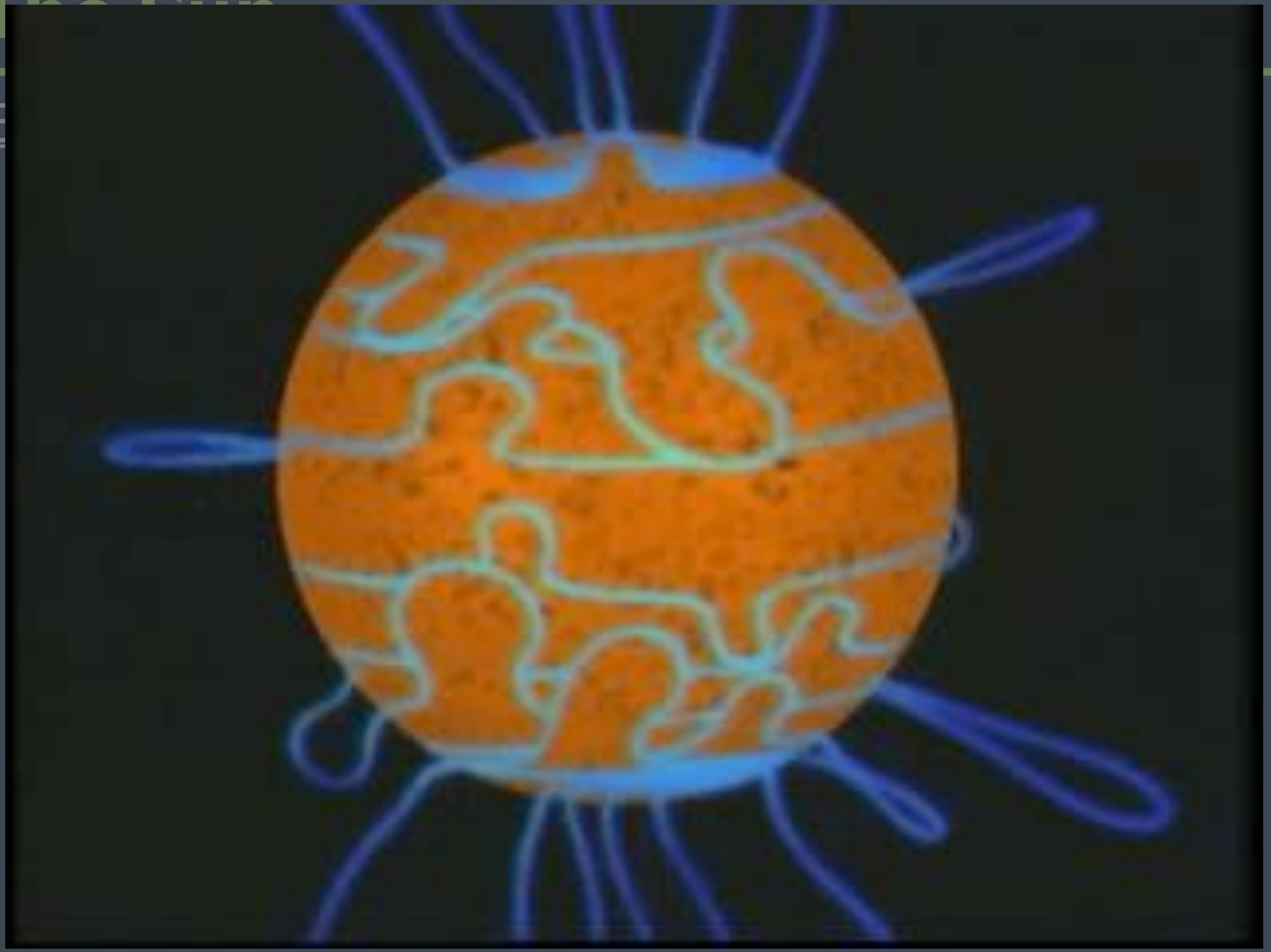
Gravity	30 x Earth (at surface)
Surface comp	~ 73.46% H, 24.85% He, 0.77% O…
Temperature	5777 K (surface), 1.5 x 10^7 K (core)
Rotation	25 days (eqtr), 28 days (poles) !
B-Field	2 Gauss (all), 2000G (spots)

The Sun



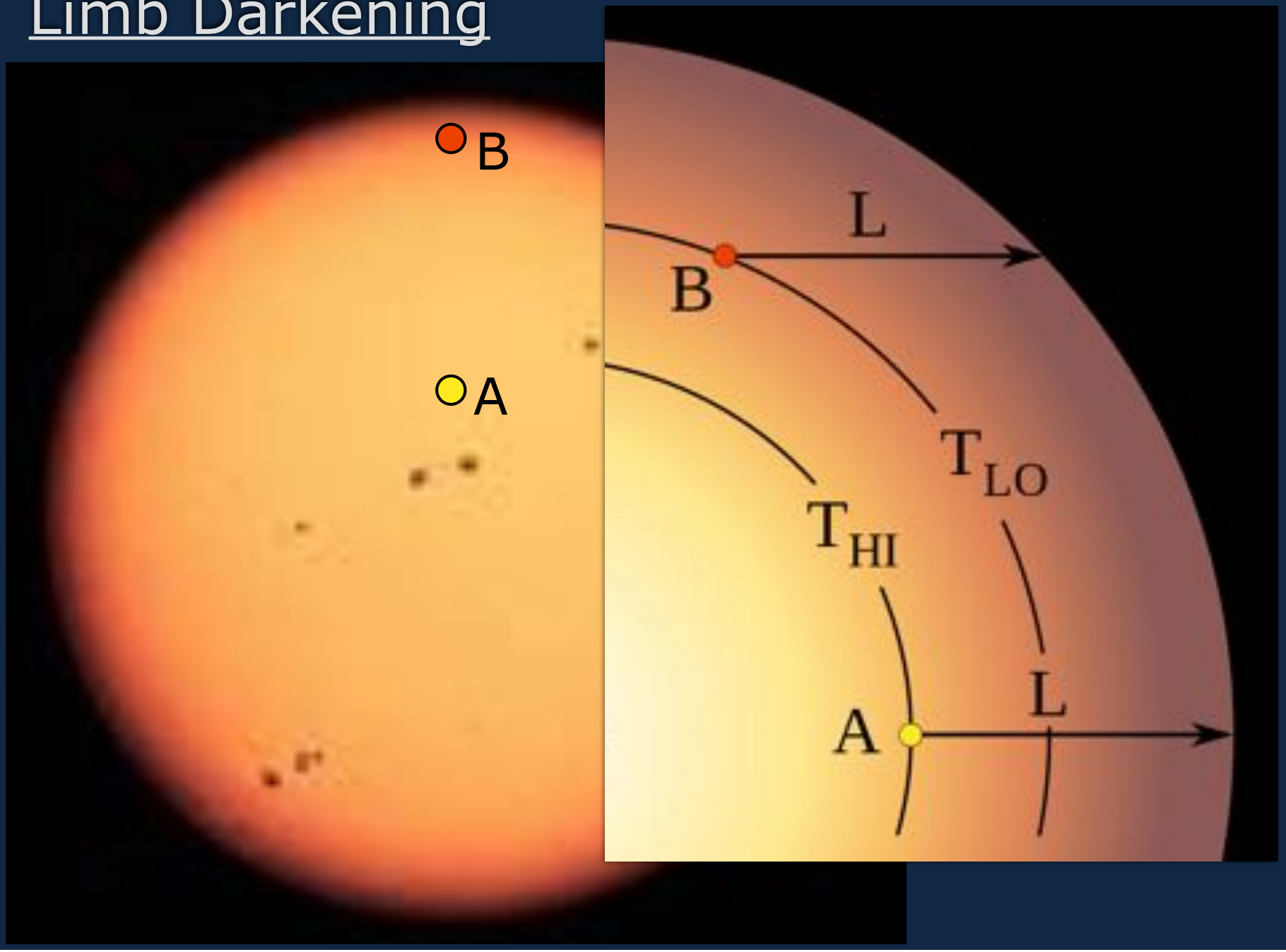
The Sun - Photosphere

Discussion Question

What is unexpected about this image?

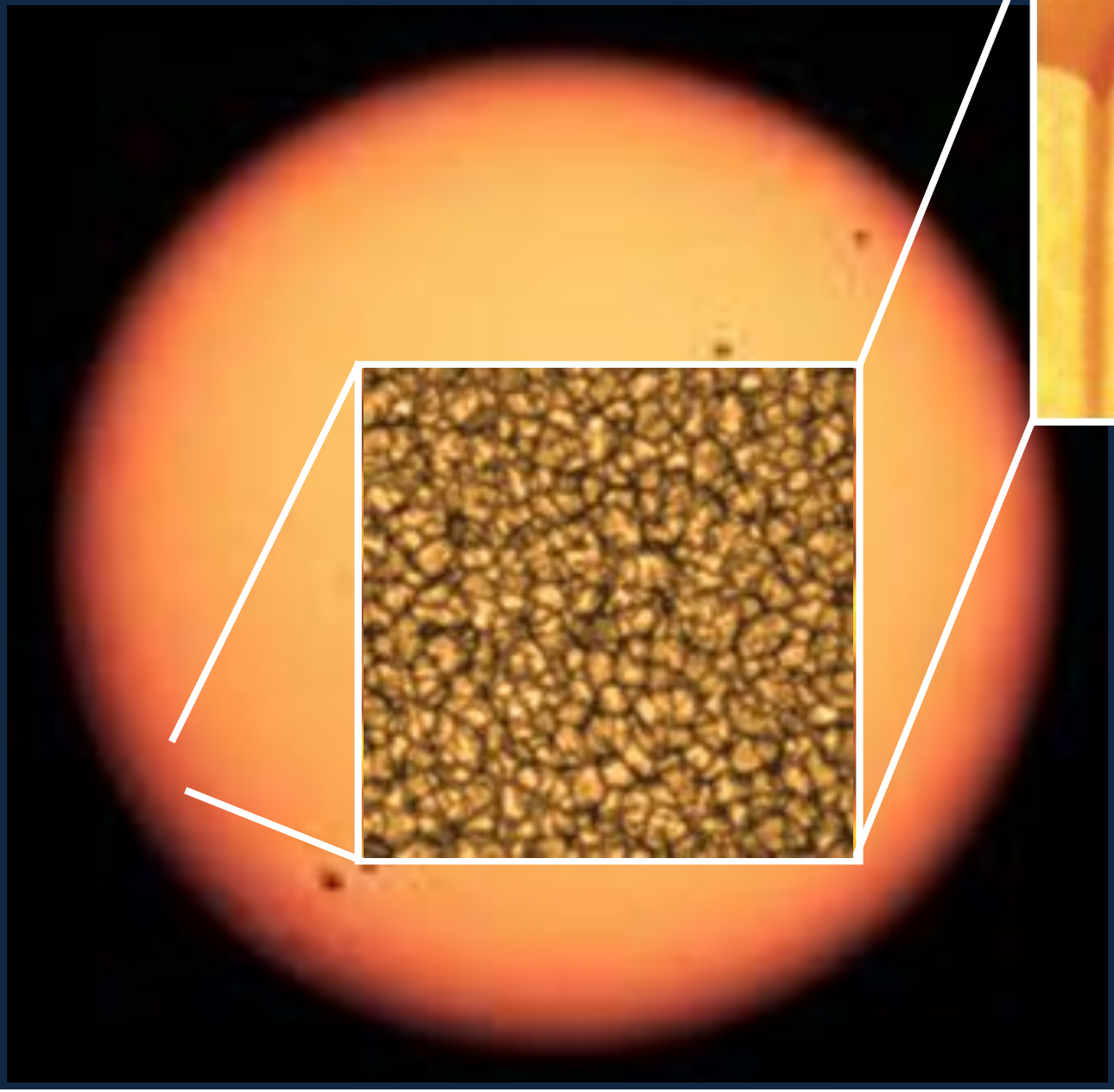
The Sun - Photosphere

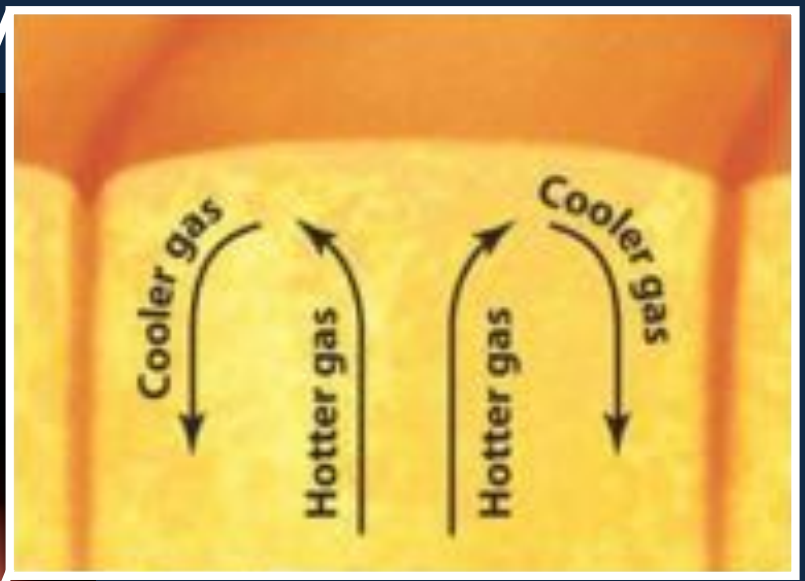
Limb Darkening



The Sun - Photosphere

Granulation





—top of convection zone protruding into base of stellar photosphere

—bright centers are blueshifted; dark edges redshifted

The Sun - Photosphere & beyond

corona: up to 1 million K **?!?!?**

plasma extending millions of km into space

chromosphere: ~6000 - 35000 K; $\rho = 10^{-4}$ x phot

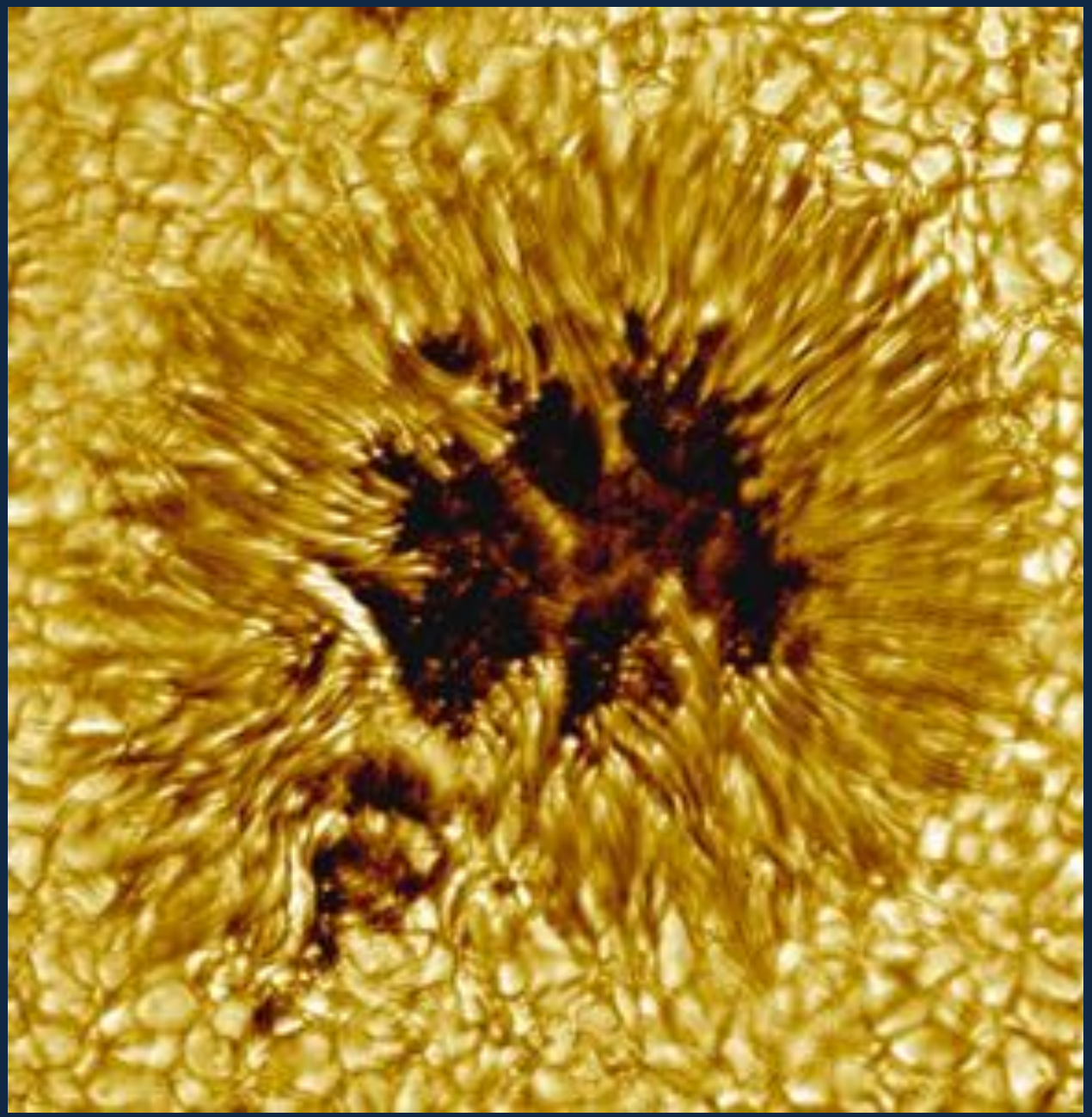
?!?!?

photosphere: ~4500-6000K (T_{eff} = 5777 K)

"the surface of the sun"

The Sun - Sunspots

—cooler patches appearing on Sun's surface…



The Sun - Sunspots

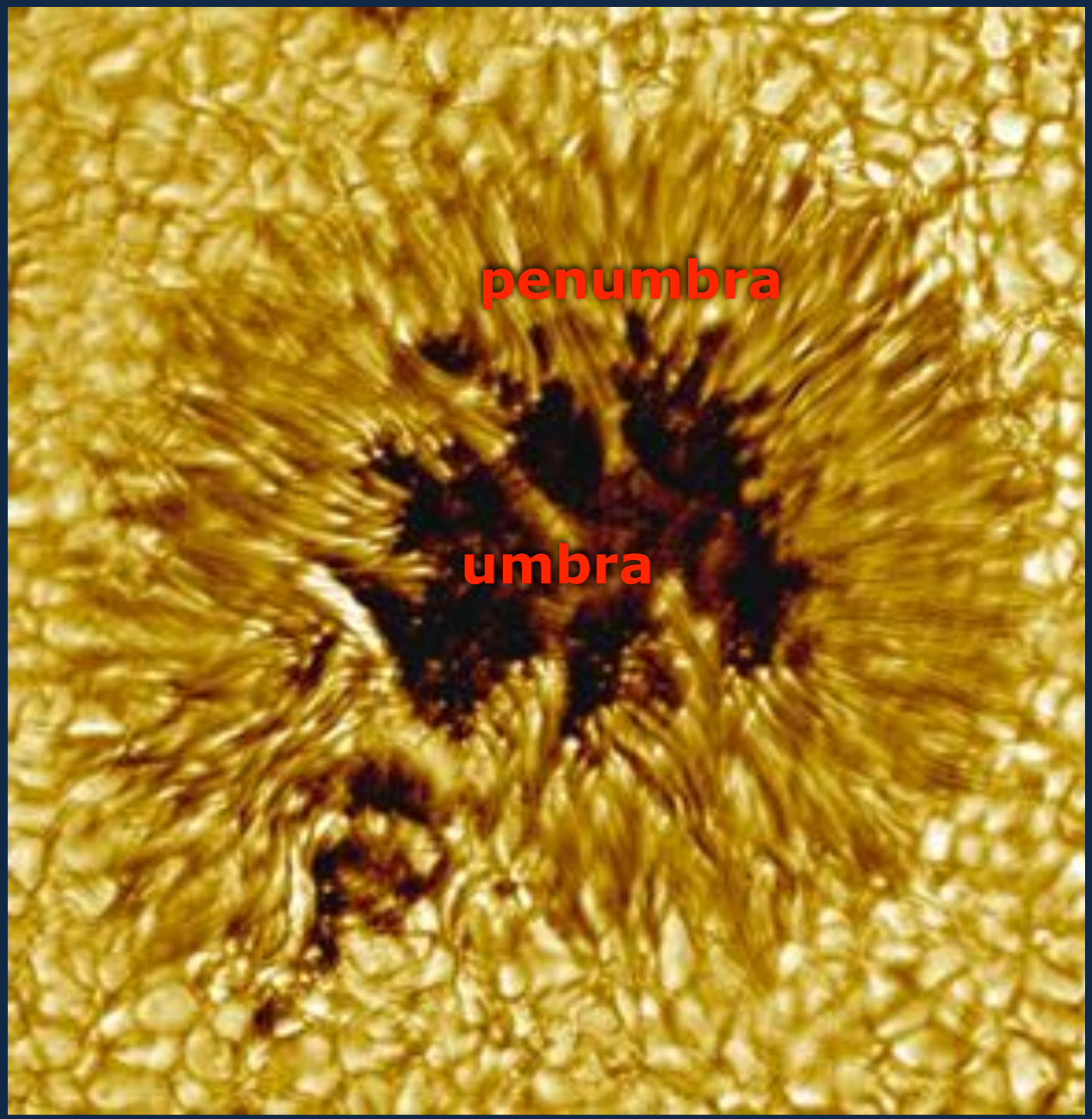
The Sun - Sunspots

—cooler patches appearing on Sun's surface…

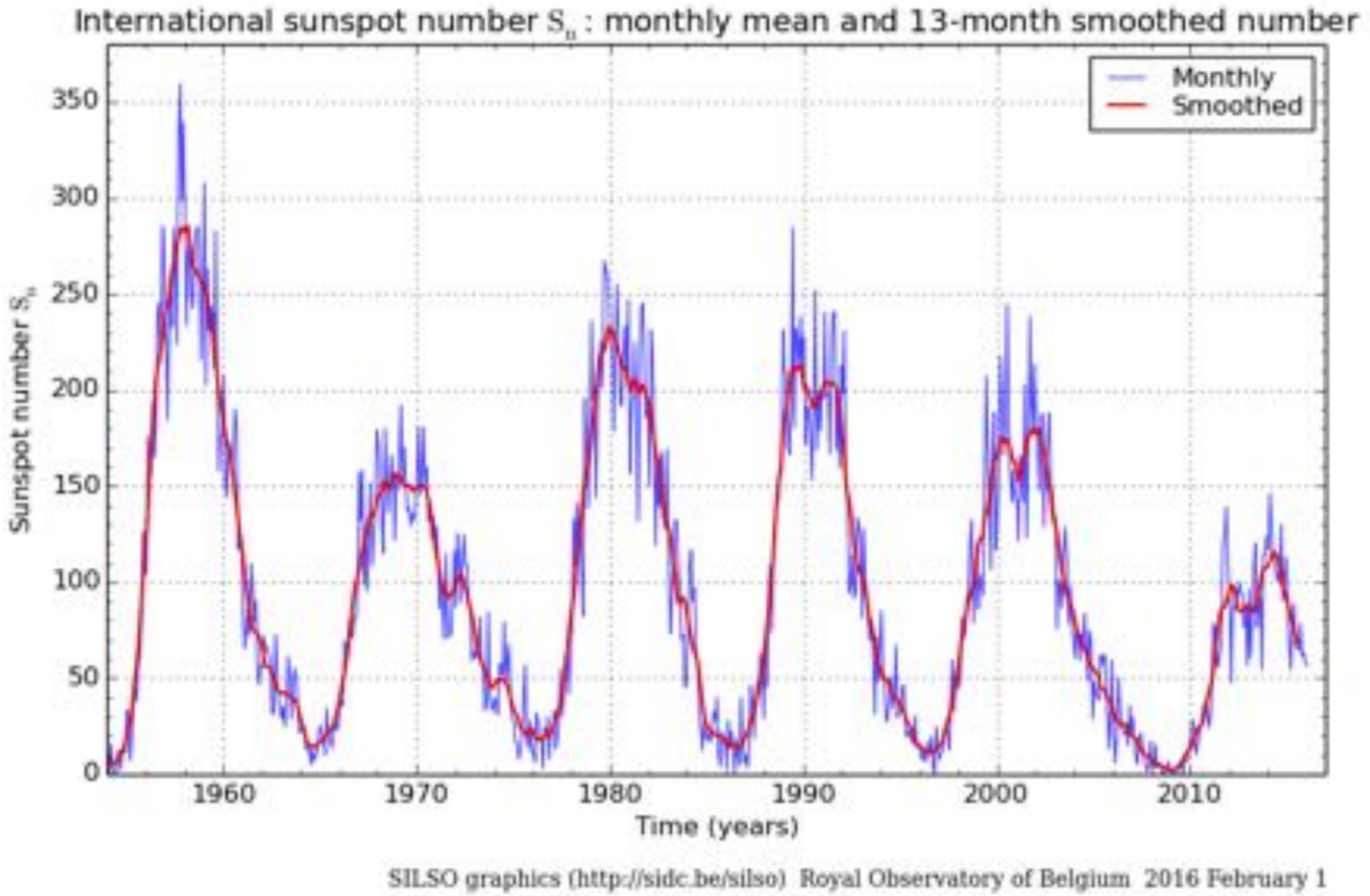
—dark central umbra, surrounding penumbra

—number of sunspots is periodic; follows 11-year cycle, then reverses polarity

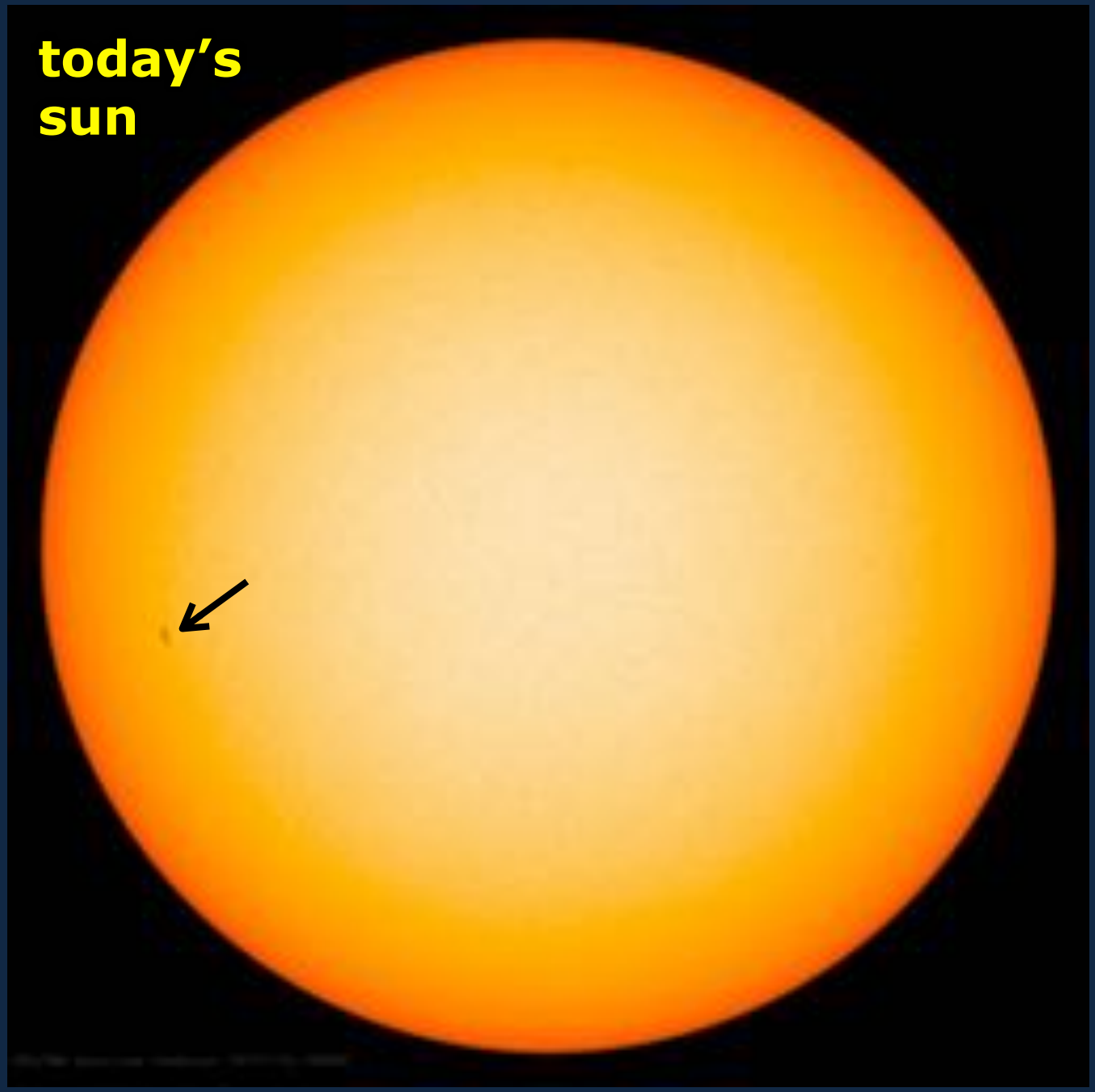
(22y solar cycle)



The Sun - Sunspots

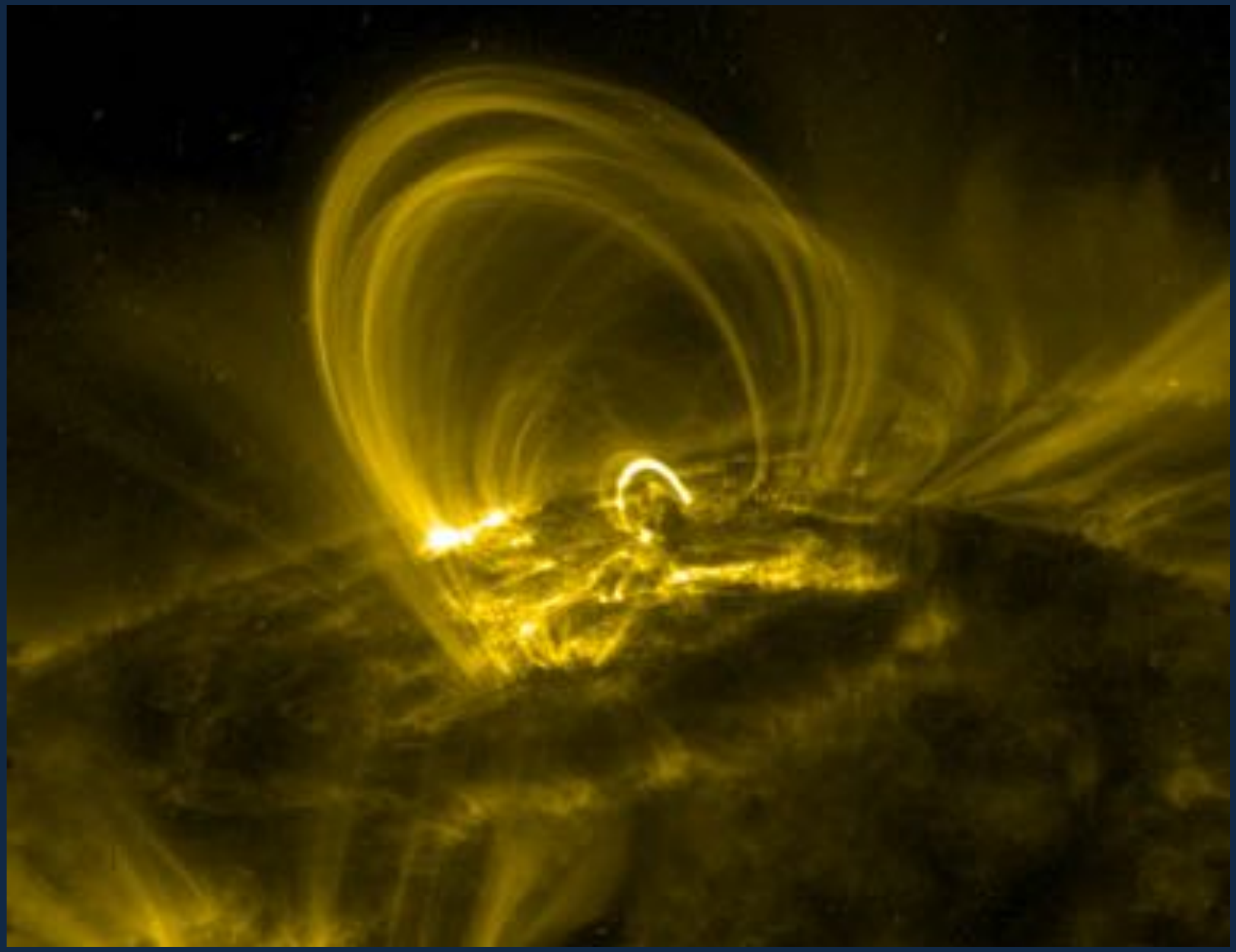


The Sun - Sunspots



The Sun - Coronal Loops

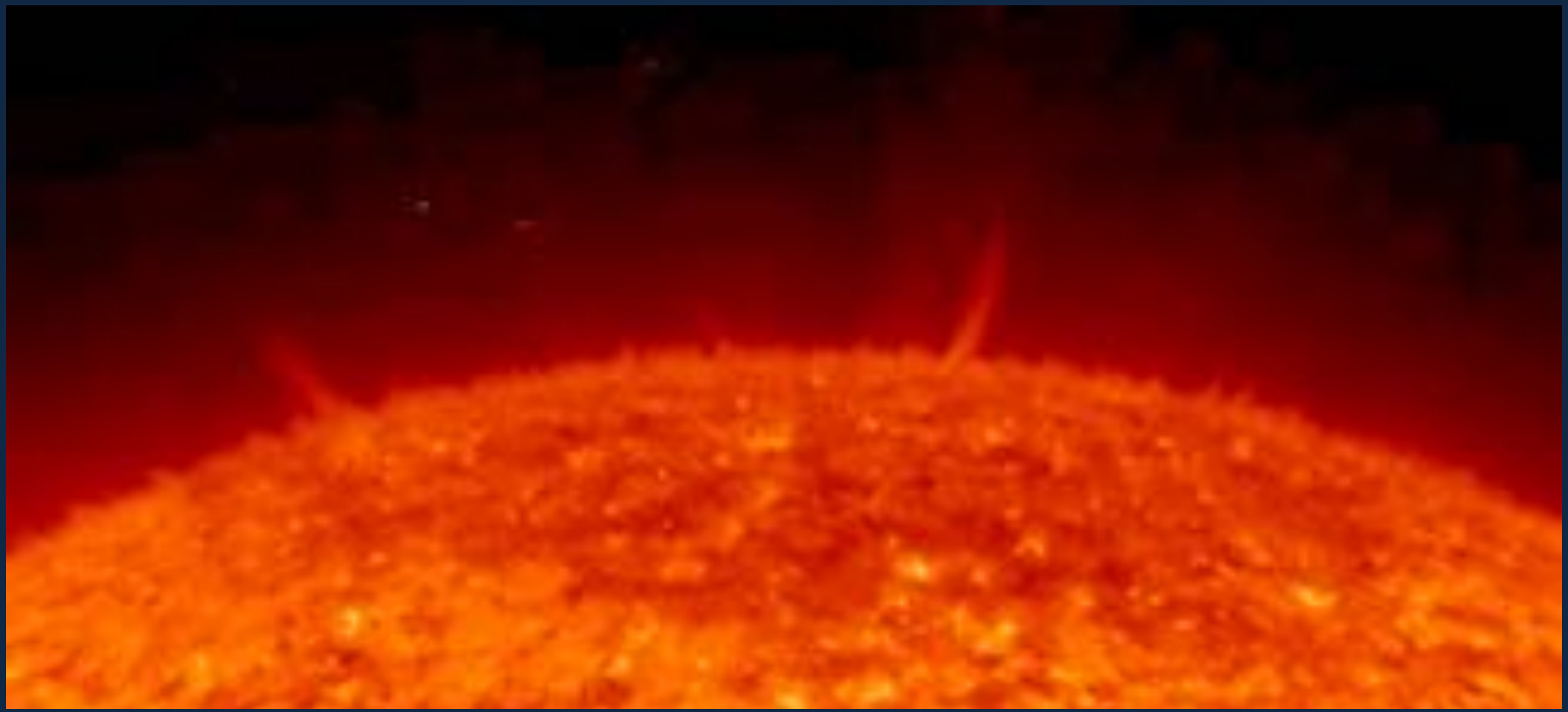
The Sun - Coronal Loops



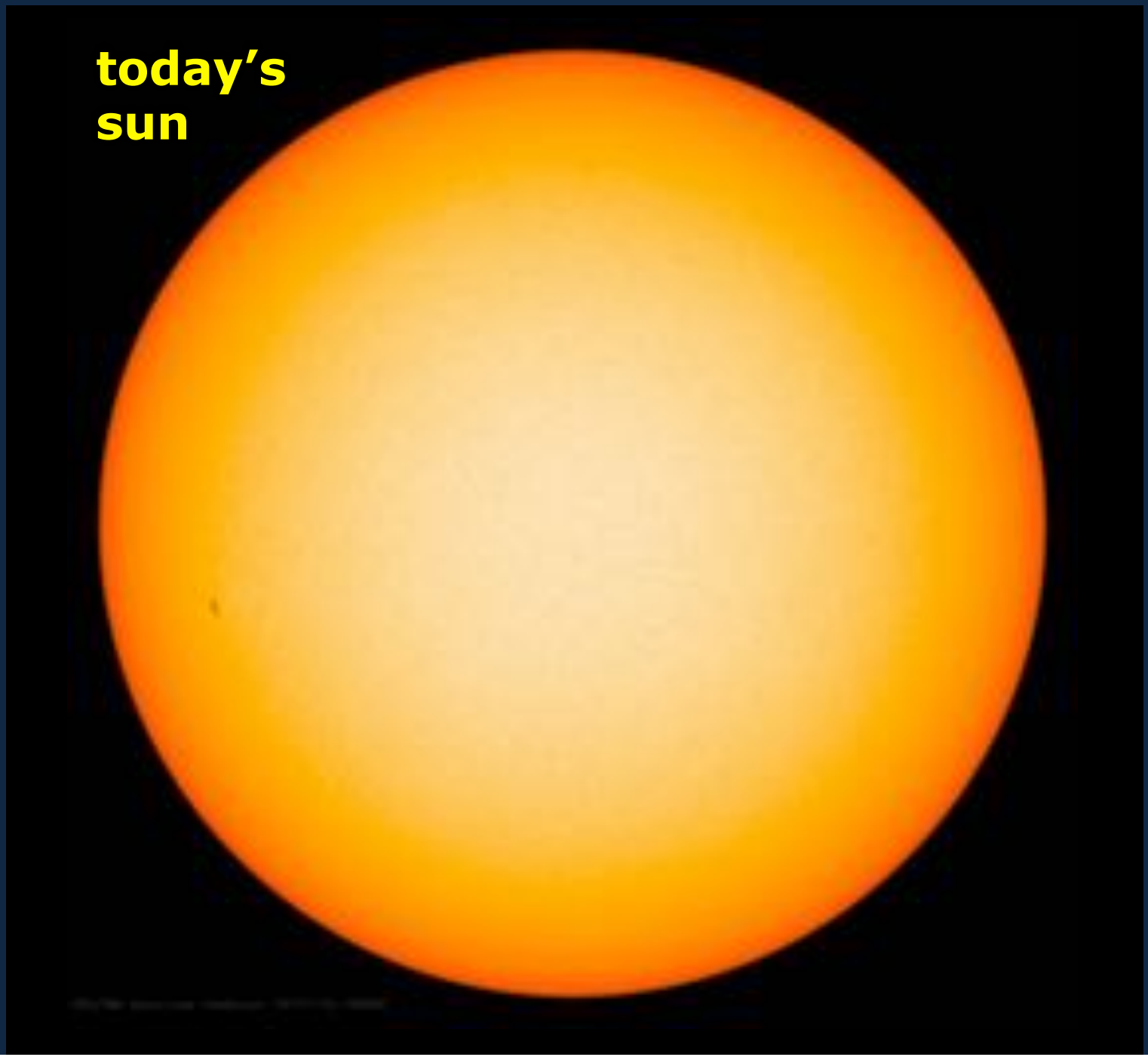
The Sun - Spicules

- Dynamic jets in chromosphere of the Sun; t~15min

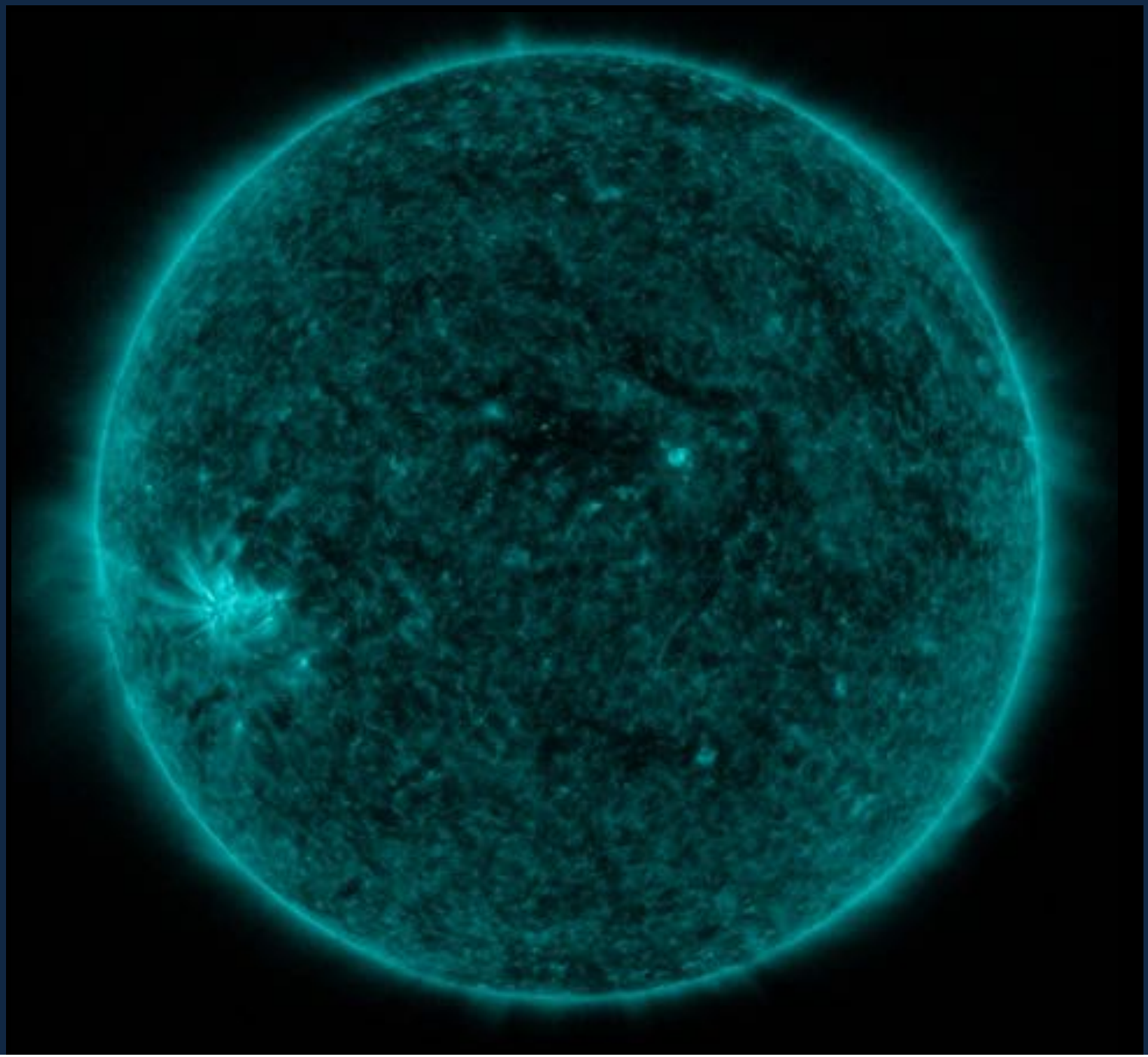
- may form as a result of magnetic flux tubes directing material rising and falling on Sun's surface as a result of p-mode oscillations



The Sun



The Sun



The Sun - Solar Flares

Solar flares are eruptive **electromagnetic** events.

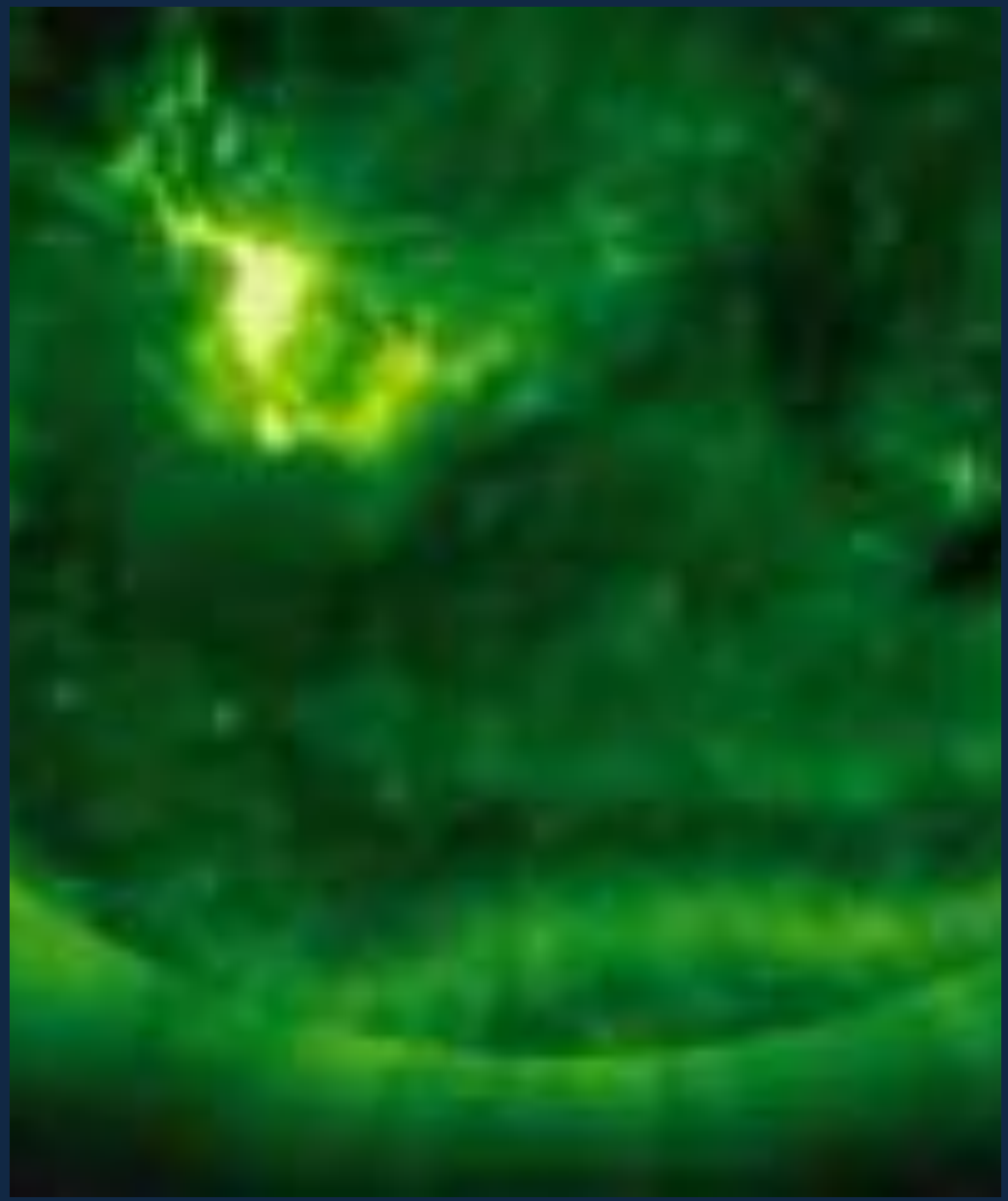
- occur in active regions around sunspots

- energy released from disturbed B field (?)

- emit 10^{17}-10^{25} J on millisec to hour timescales

- bright across spectrum

- also release charged particles; in largest flares these reach Earth in ~30 minutes



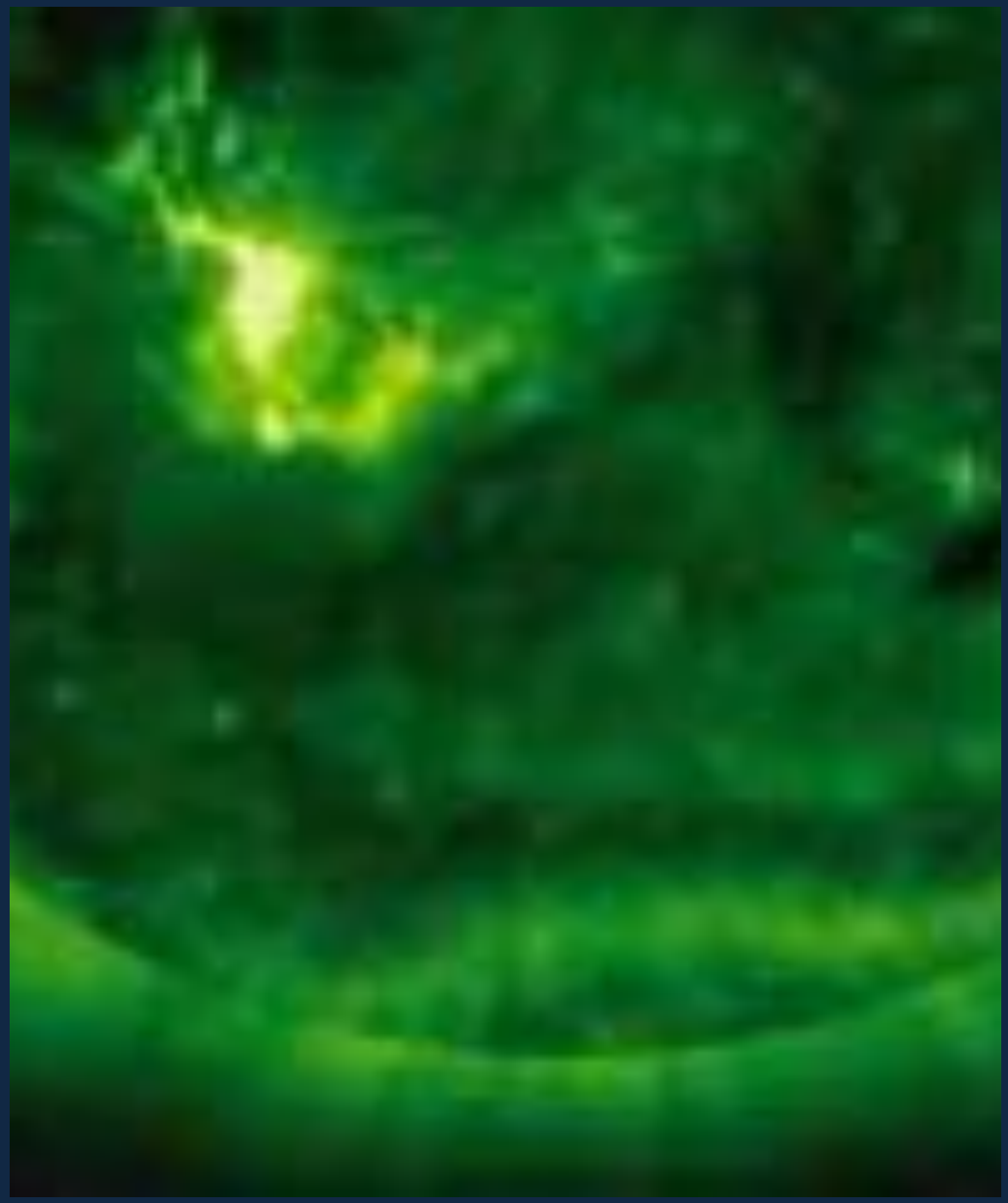
The Sun - Solar Flares

Solar flares are eruptive **electromagnetic** events.

Classified based on their peak flux in the X-ray regime:

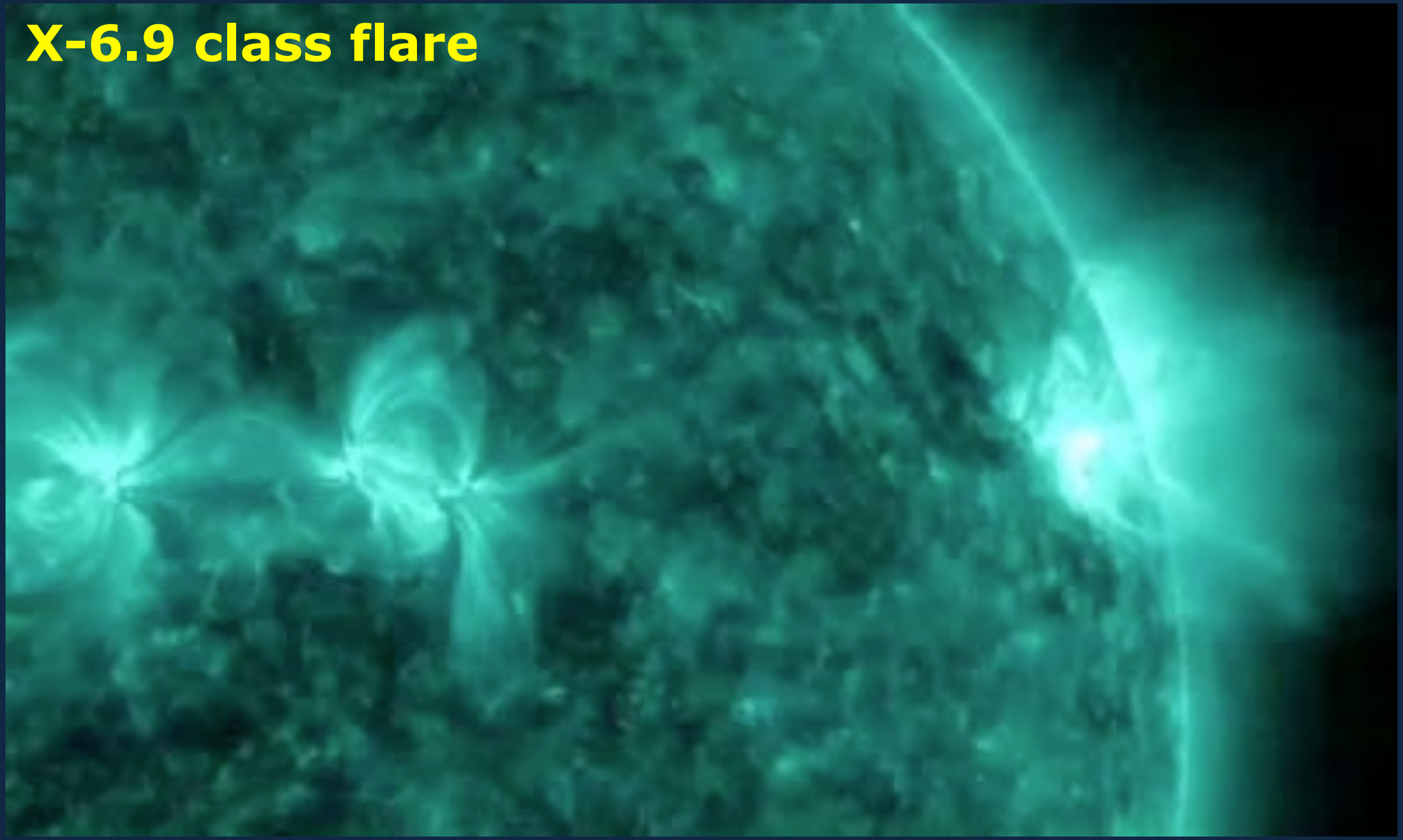
Class	Peak flux
A	$<10^{-7}$
B	10^{-7}-10^{-6}
C	10^{-6}-10^{-5}
M	10^{-5}-10^{-4}
X	$>10^{-4}$

(X-ray, W m^{-2})



The Sun - Solar Flares

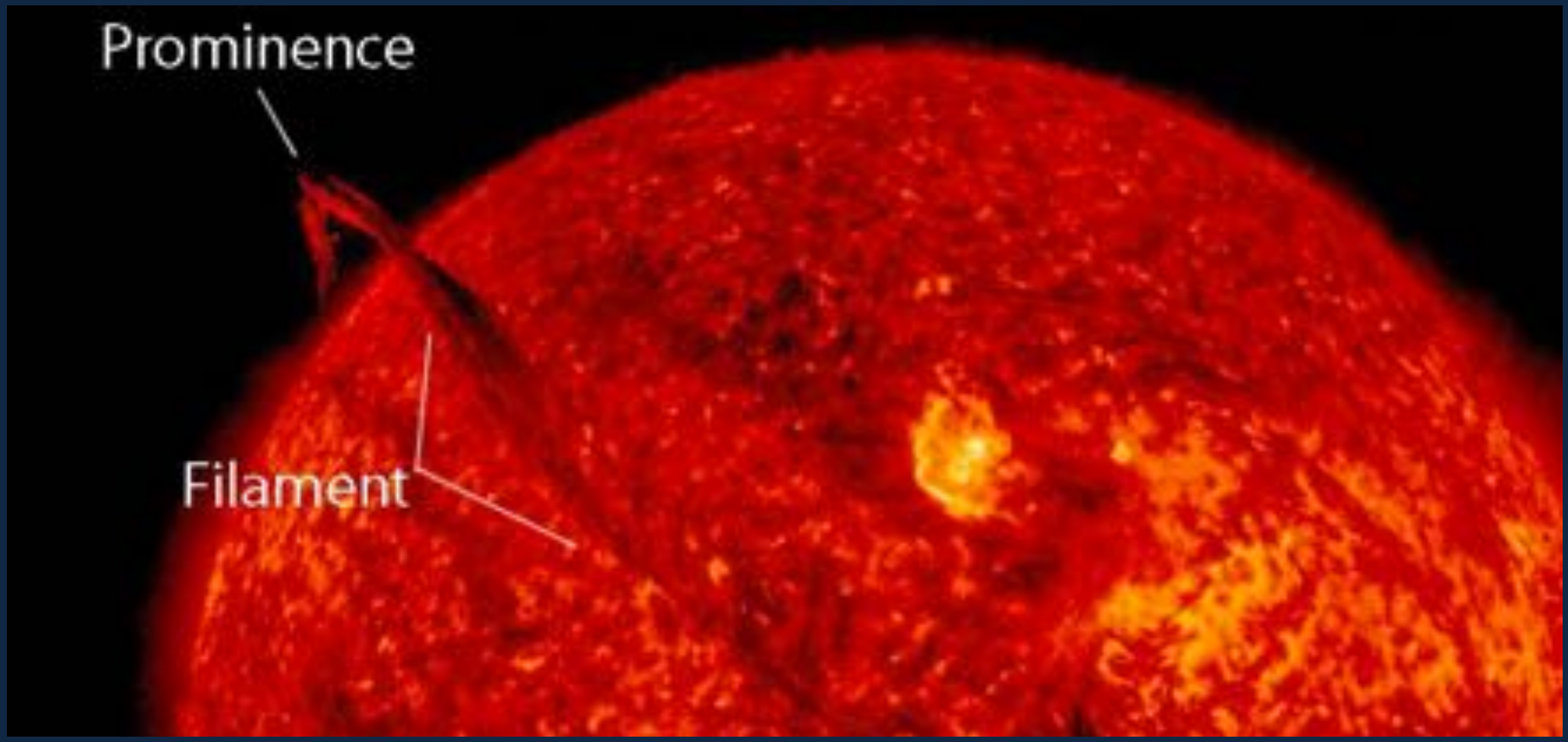
The Sun - Solar Flares



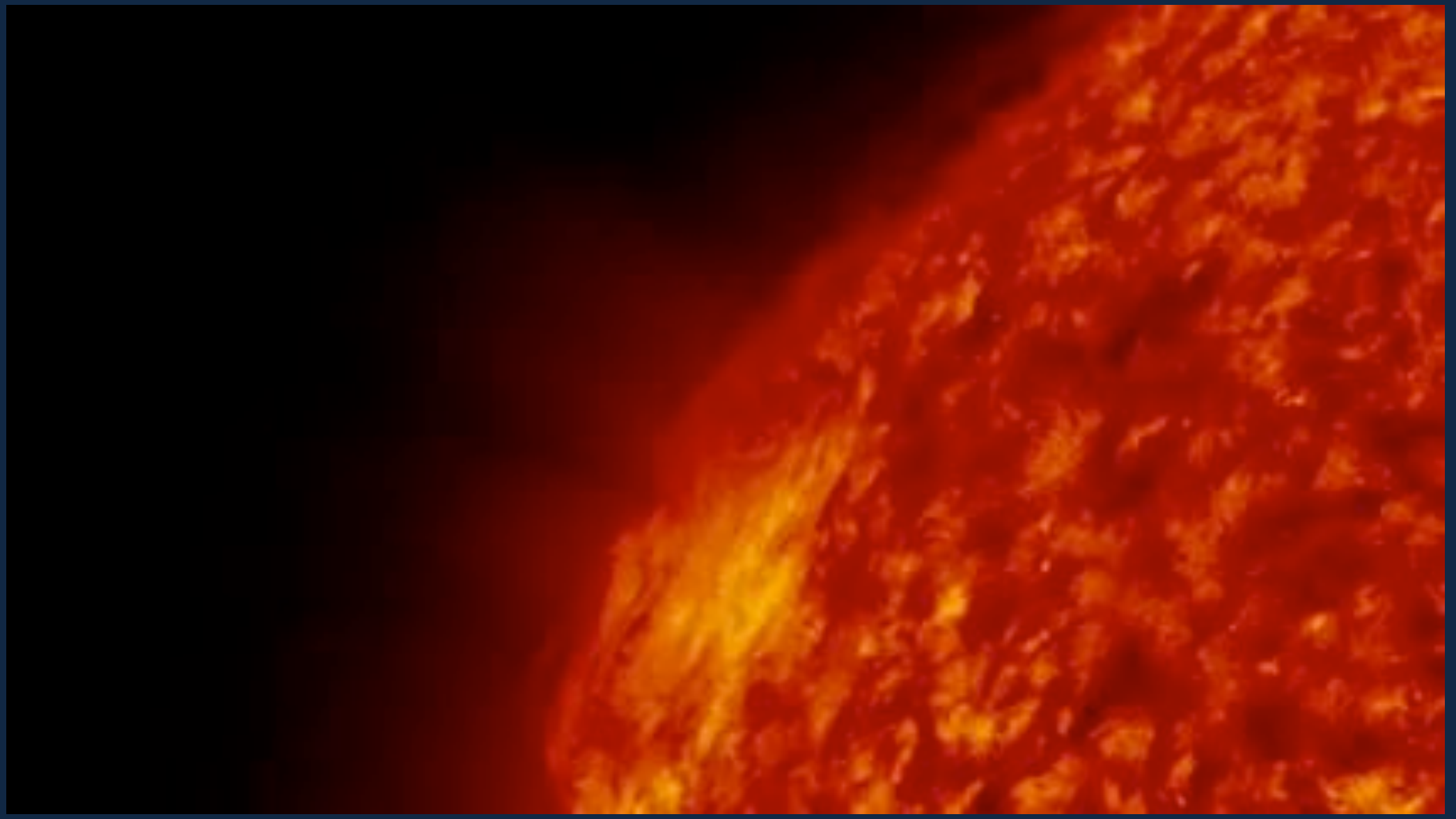
The Sun - Prominences/Filaments

Prominence: loop of cool dense plasma extending outward into Sun's corona; collects along B field lines of an active region. Viewed at limb.

Filament: …exact same thing, viewed at solar disk.

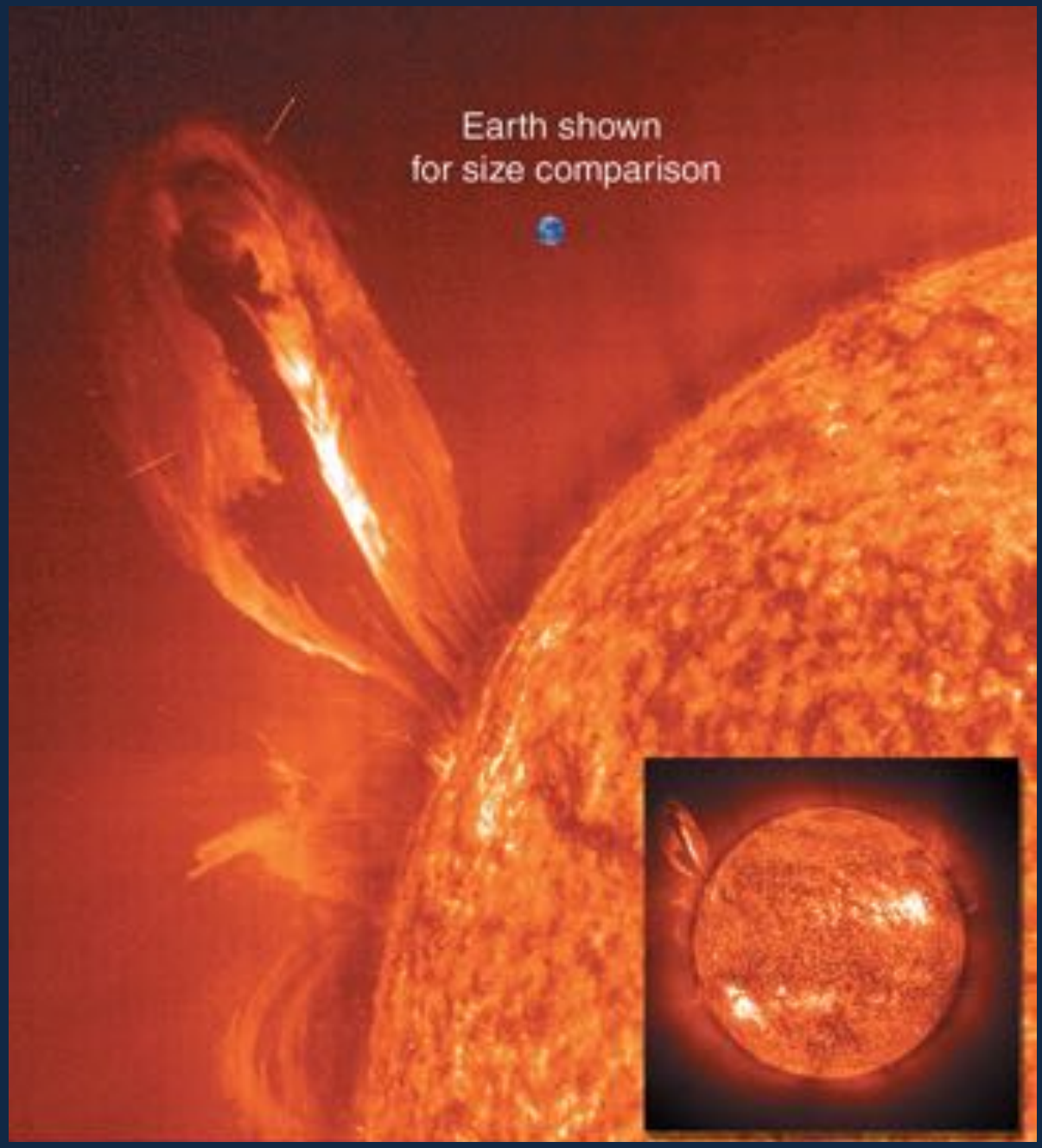


The Sun - Prominences/Filaments

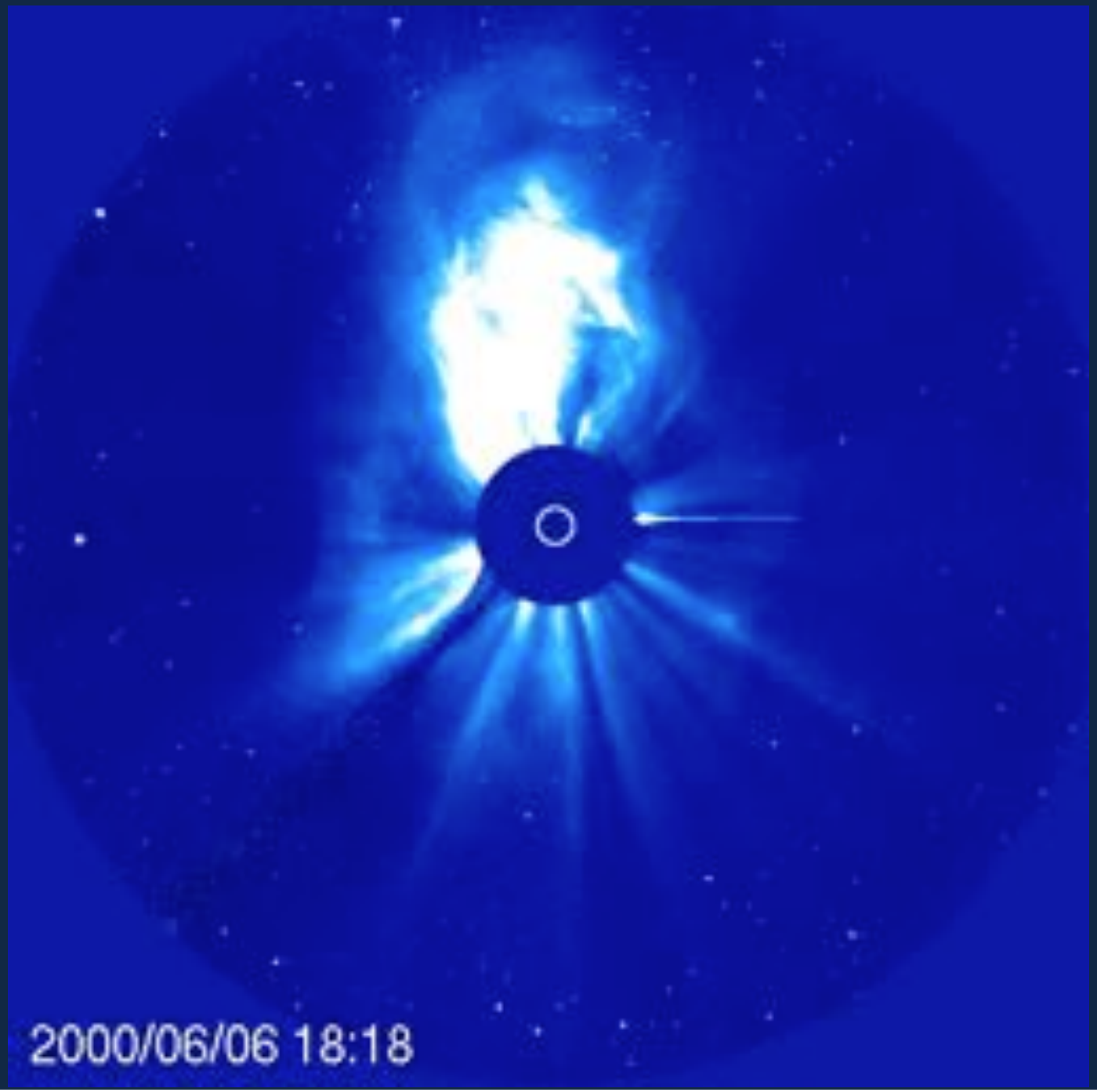


The Sun - Prominences/Filaments

The Sun - Prominences/Filaments



The Sun - Coronal Mass Ejections



The Sun - Coronal Mass Ejections

The Sun - "solar storms"

Solar storm of 1859 (The "Carrington" Event)

Aug 28: lots of sunspots observed

Aug 29: spectacular southern aurora (initial CME?)

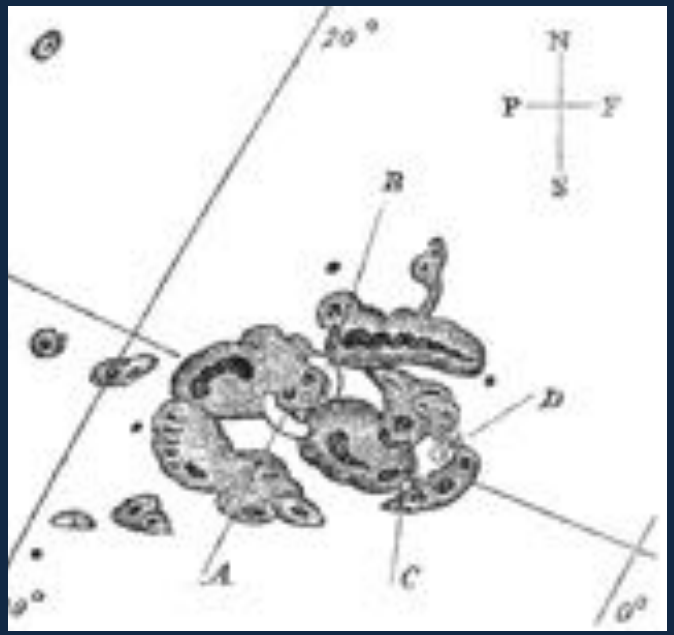
morning, Sep 1: first obs of solar flare

Sep 1-2: enormous geomagnetic storm (large CME)

— aurora observed in Hawaii

— telegraph malfunctions across Europe & North America

Sep 3: more spectacular aurora



Smaller storms in 1921, 1960, 1989.

"Near-miss" in 2012…

The Sun - Solar Observatories

Discussion Question

What are the biggest priorities when designing a solar telescope?

The Sun - Solar Observatories

Discussion Question

What are the biggest priorities when designing a solar telescope?

heat inside - prevented with "heat stops"

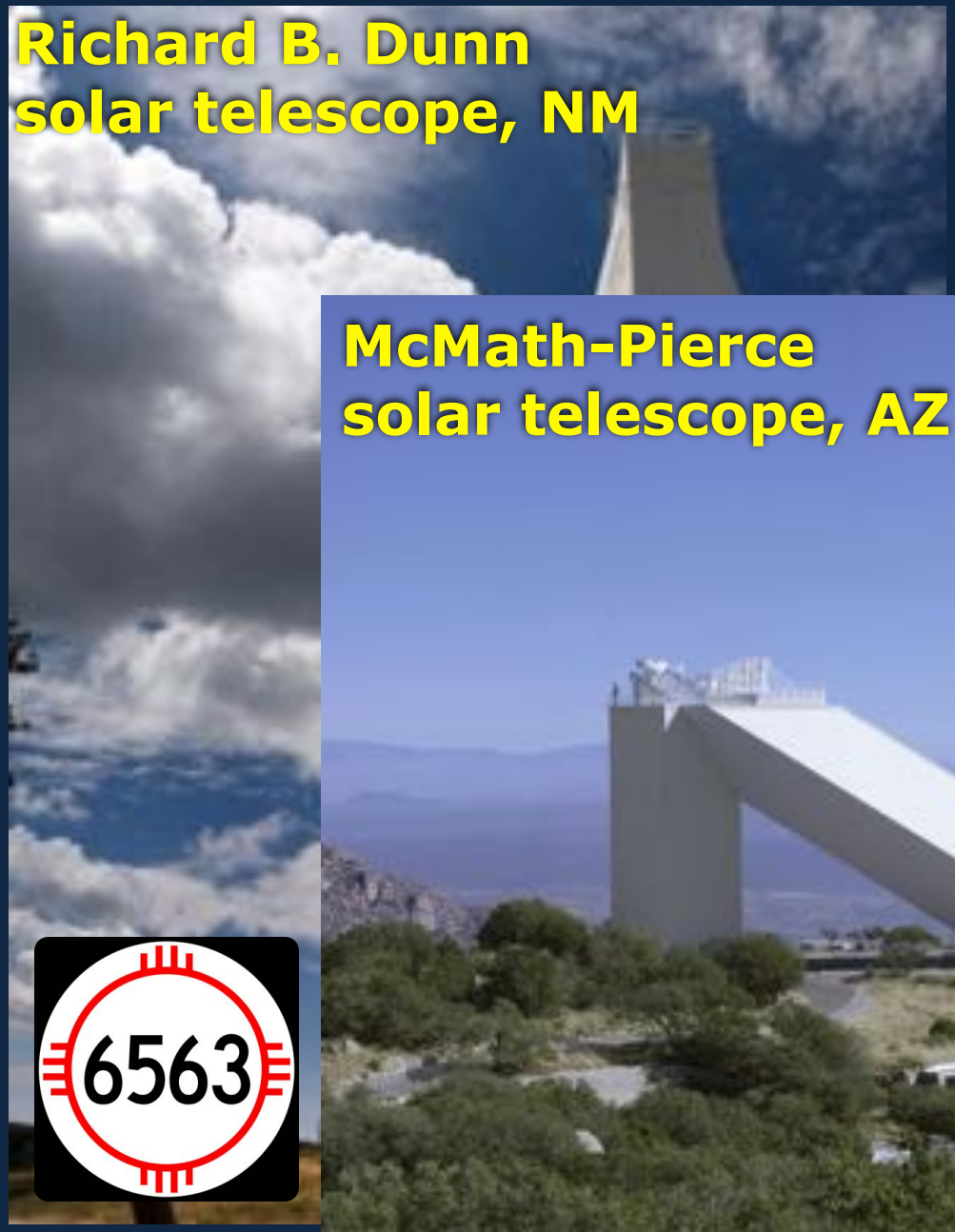
heat outside - prevented with tower designs

heat convection - prevented with vacuum ligltpath or cooled telescope

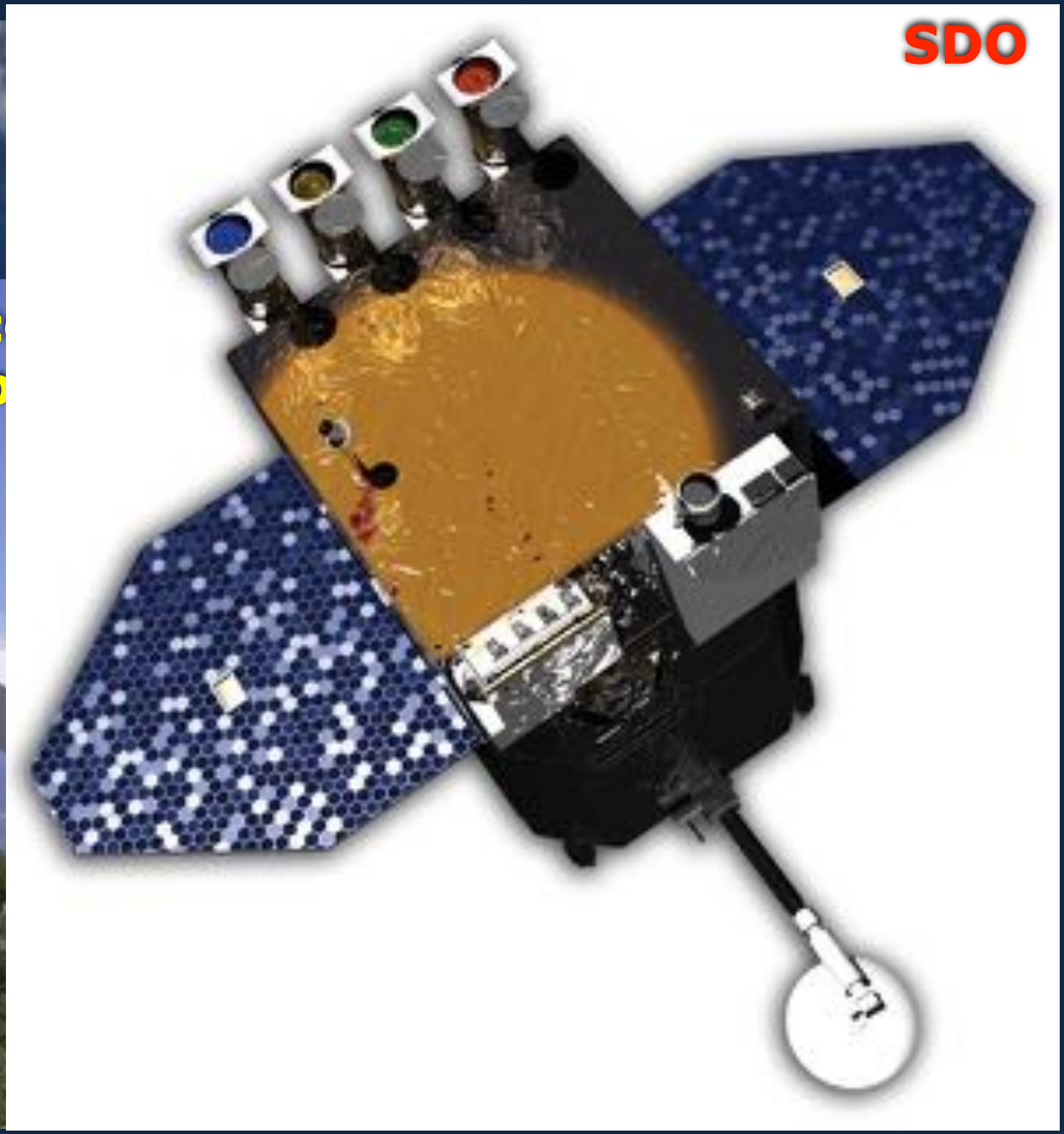
diffraction limit - here a long focal length is better than a large mirror

The Sun - Solar Observatories

The Sun - Solar Observatories



The Sun - Solar Observatories



The Sun - 2017 total eclipse!

The Sun - 2017 total eclipse!

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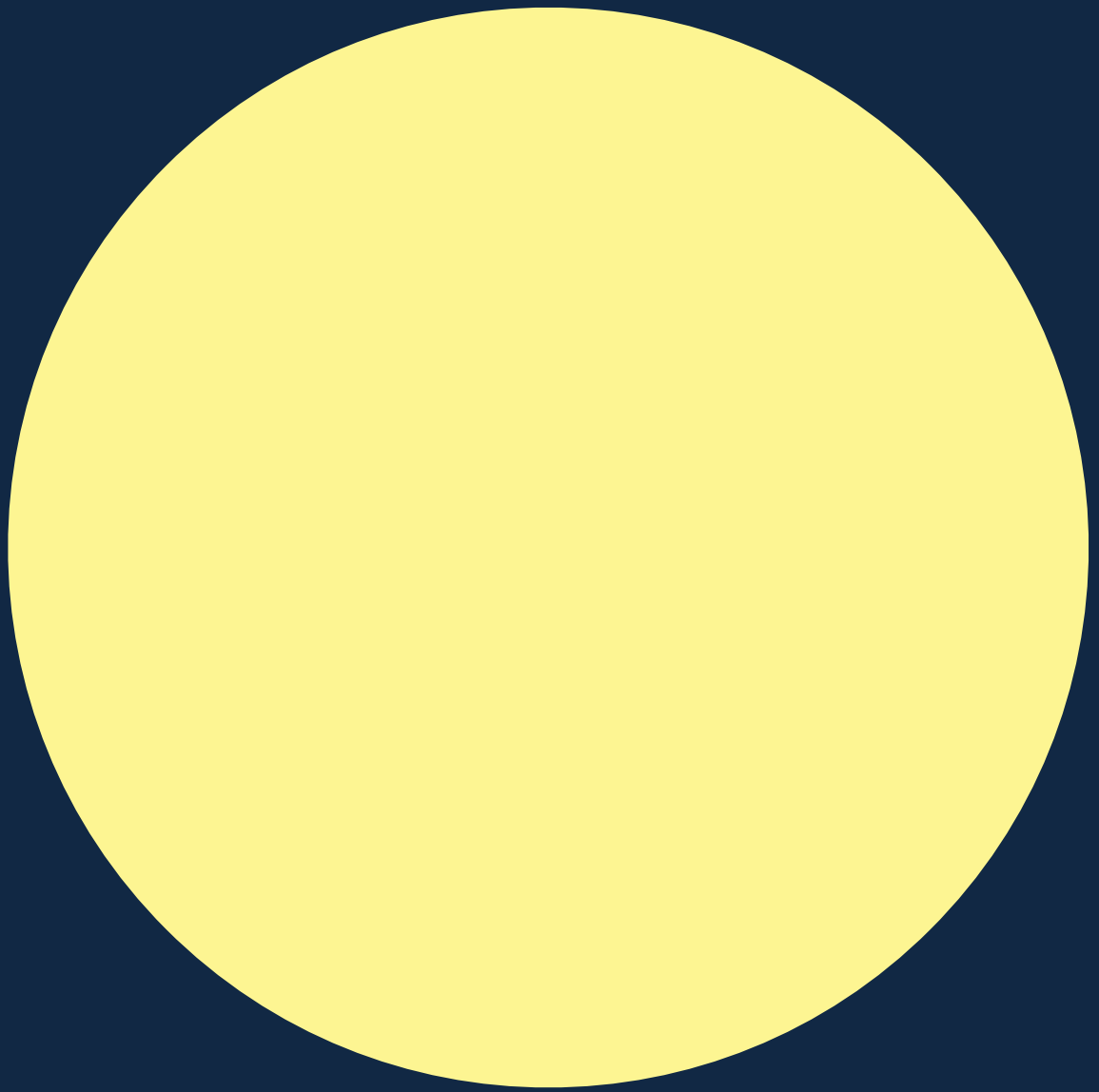
The Sun - 2017 total eclipse!

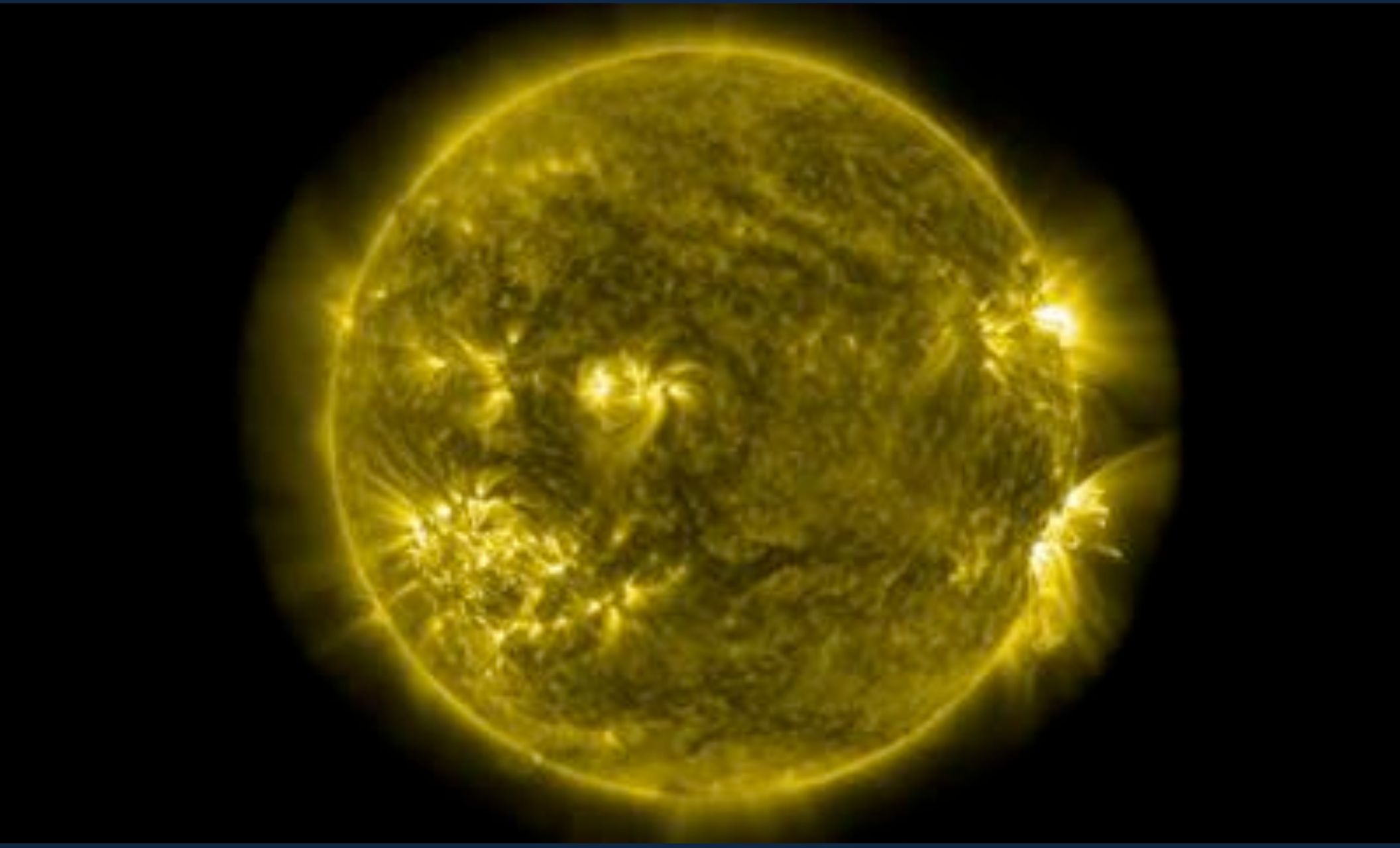
Discussion Question

What do you think causes Baily's Beads during a solar eclipse?

The Sun



The Sun



Tuesday - Project Presentations

- submit materials via email **by 11am**

- order will (mostly) follow topic list; final order will be posted in class & emailed out around noon

- 4min presentations + 1min for questions & changeover (w/ 5min break)

- be on time!