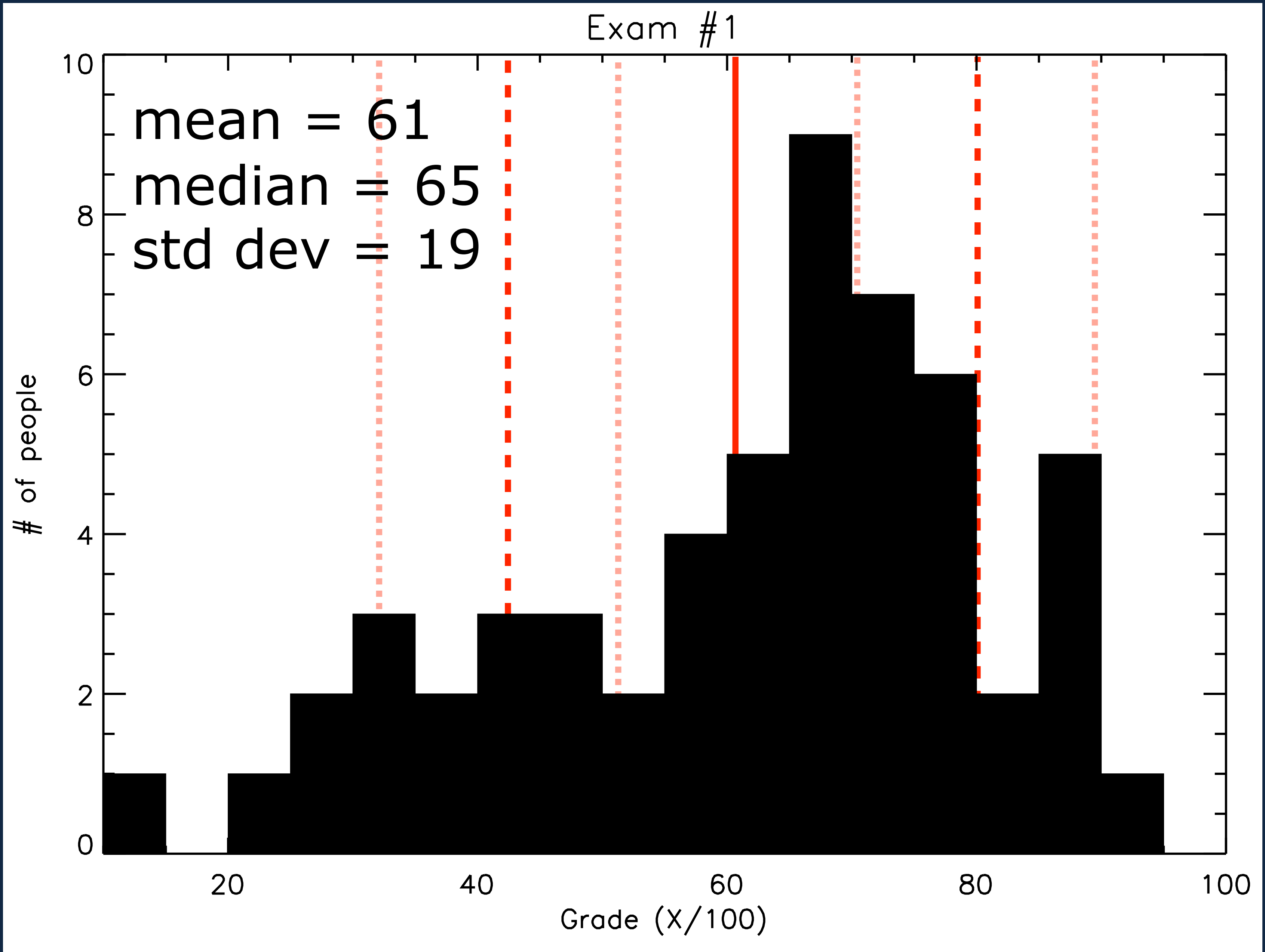
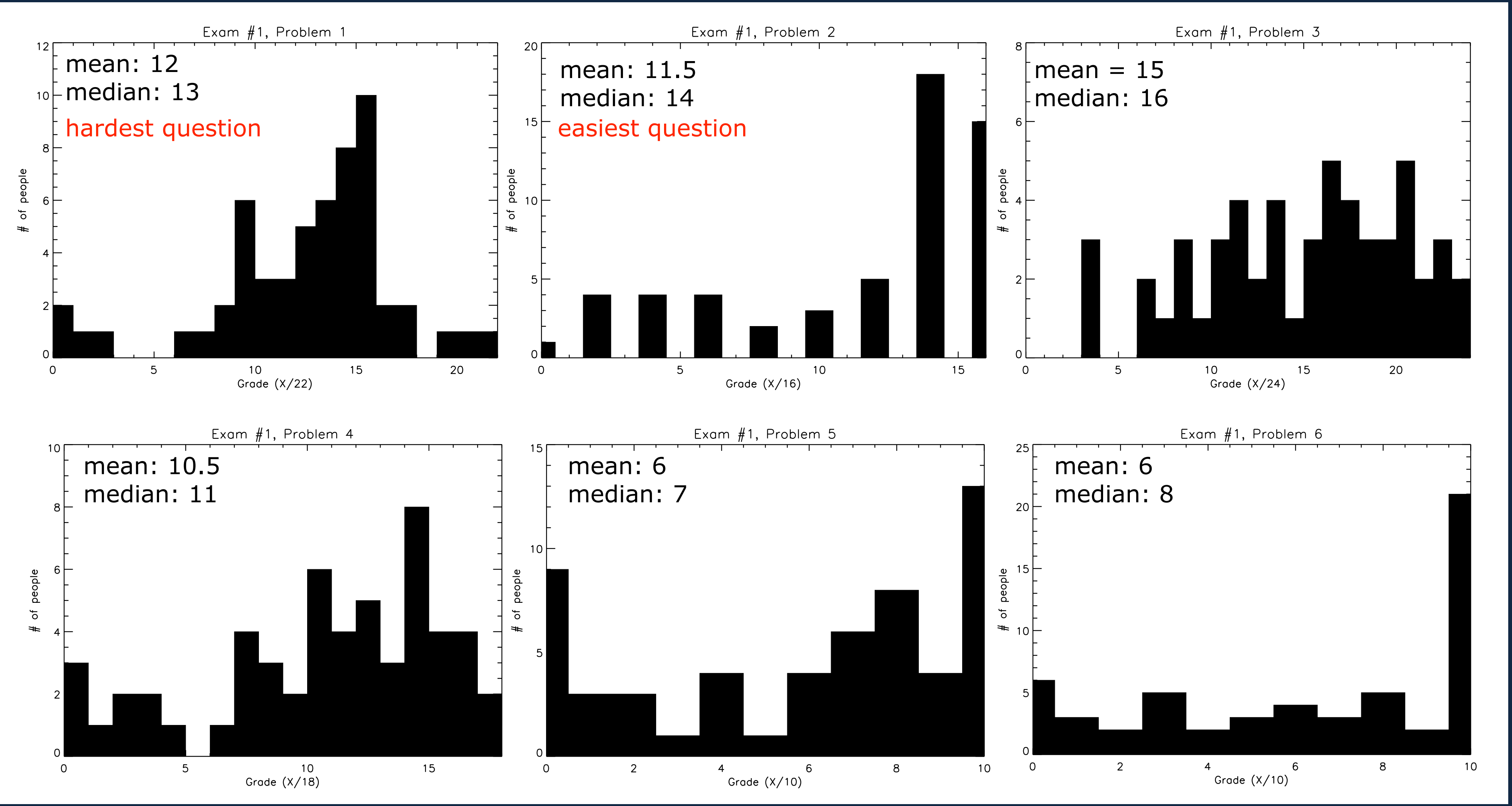
Exam #1


Exam #1
mean = 61
median = 65
std dev = 19
10
8
6
4
2
0
20
40
60
80
100
Grade (X/100)
# of people

Exam #1



Exam #1, Problem 1
mean: 12
median: 13
hardest question
# of people
Grade (X/22)
Exam #1, Problem 2
mean: 11.5
median: 14
easiest question
# of people
Grade (X/16)
Exam #1, Problem 3
mean = 15
median: 16
# of people
Grade (X/24)
Exam #1, Problem 4
mean: 10.5
median: 11
# of people
Grade (X/18)
Exam #1, Problem 5
mean: 6
median: 7
# of people
Grade (X/10)
Exam #1, Problem 6
mean: 6
median: 8
# of people
Grade (X/10)

Short Project due November 21 **by 11:00AM**

Reminders

—sign up for a topic **by the end of today**

—add contact info to the sign-up sheet

—come talk to me! (office hours or appointment)

Star Formation

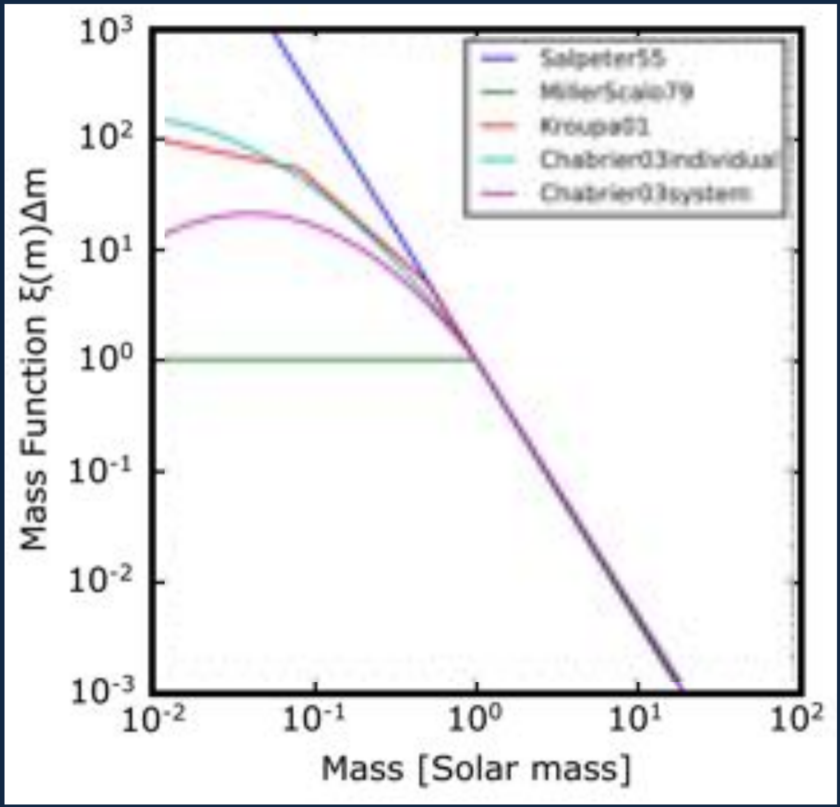
Unfortunately, no good quantitative theory to predict star formation rate or stellar mass distribution!

IMF = Initial Mass Function

$N(m)dm$ = # stars in mass range m to m+dm

$N(m)dm \propto (m/M_{sun})^{-\alpha}$

$\alpha = 2.35$ (Salpeter IMF)



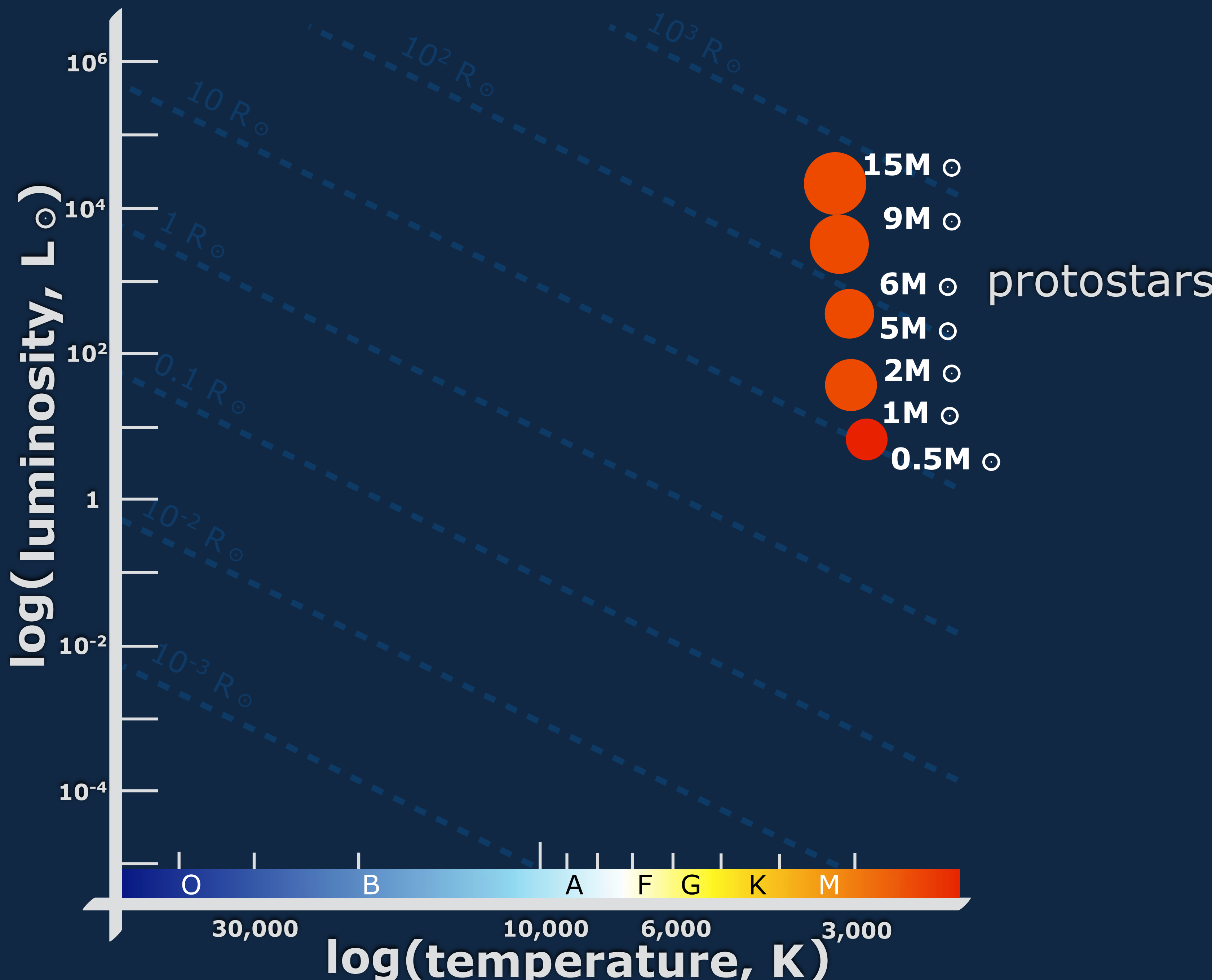
Is it universal?

Star Formation

Birth Sequence

- trigger kicks off process in an interstellar gas cloud
- cloud fragments and collapses [M_J and R_J…]
- early collapse is isothermal; E radiated away
- interior becomes adiabatic; E trapped so T rises
- protostellar core forms (~5AU) w/ free-falling gas above
- dust vaporizes as T increases

Star Formation



Star Formation

Discussion Question

Which stellar structure equation has just been satisfied by these protostars?

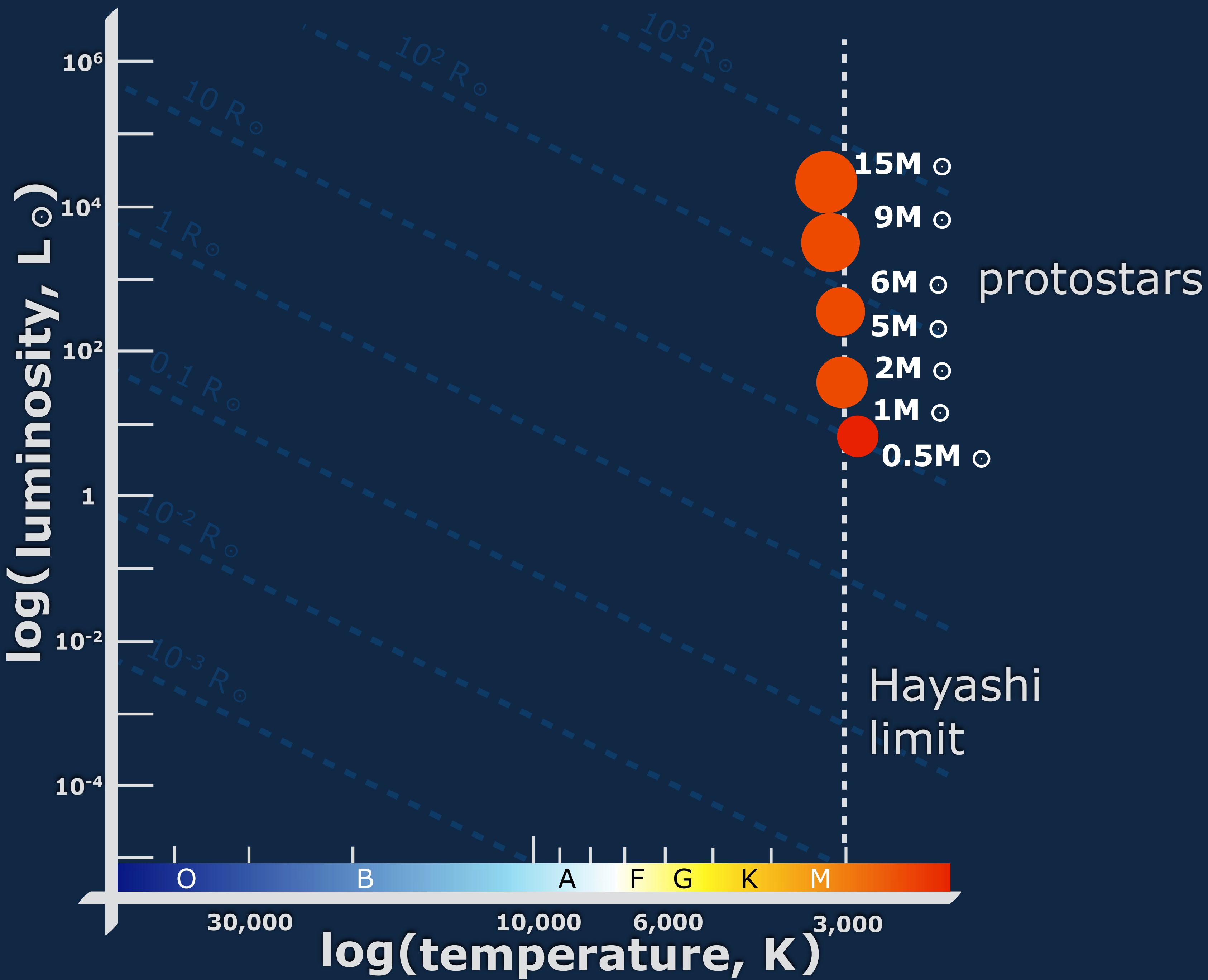
A) equation of state

B) hydrostatic equilibrium

C) mass continuity

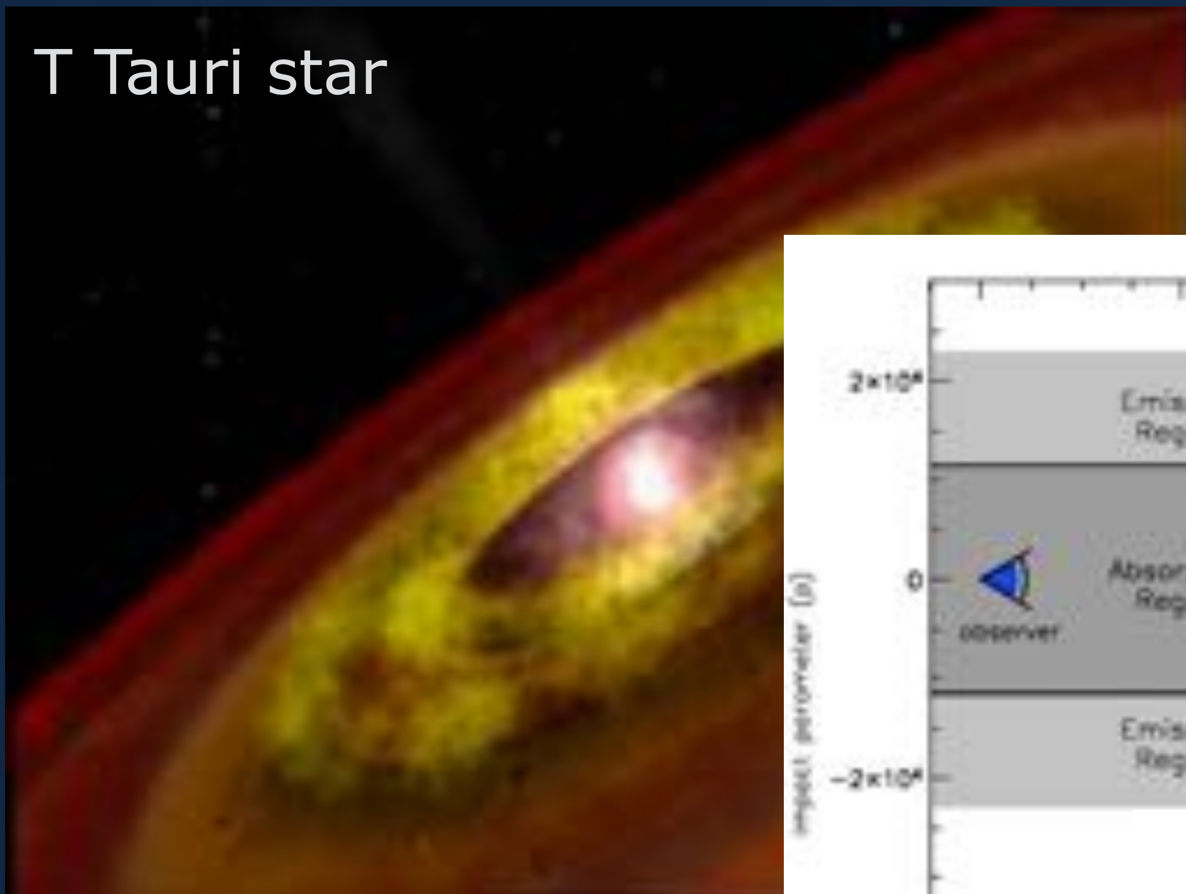
D) temp gradient

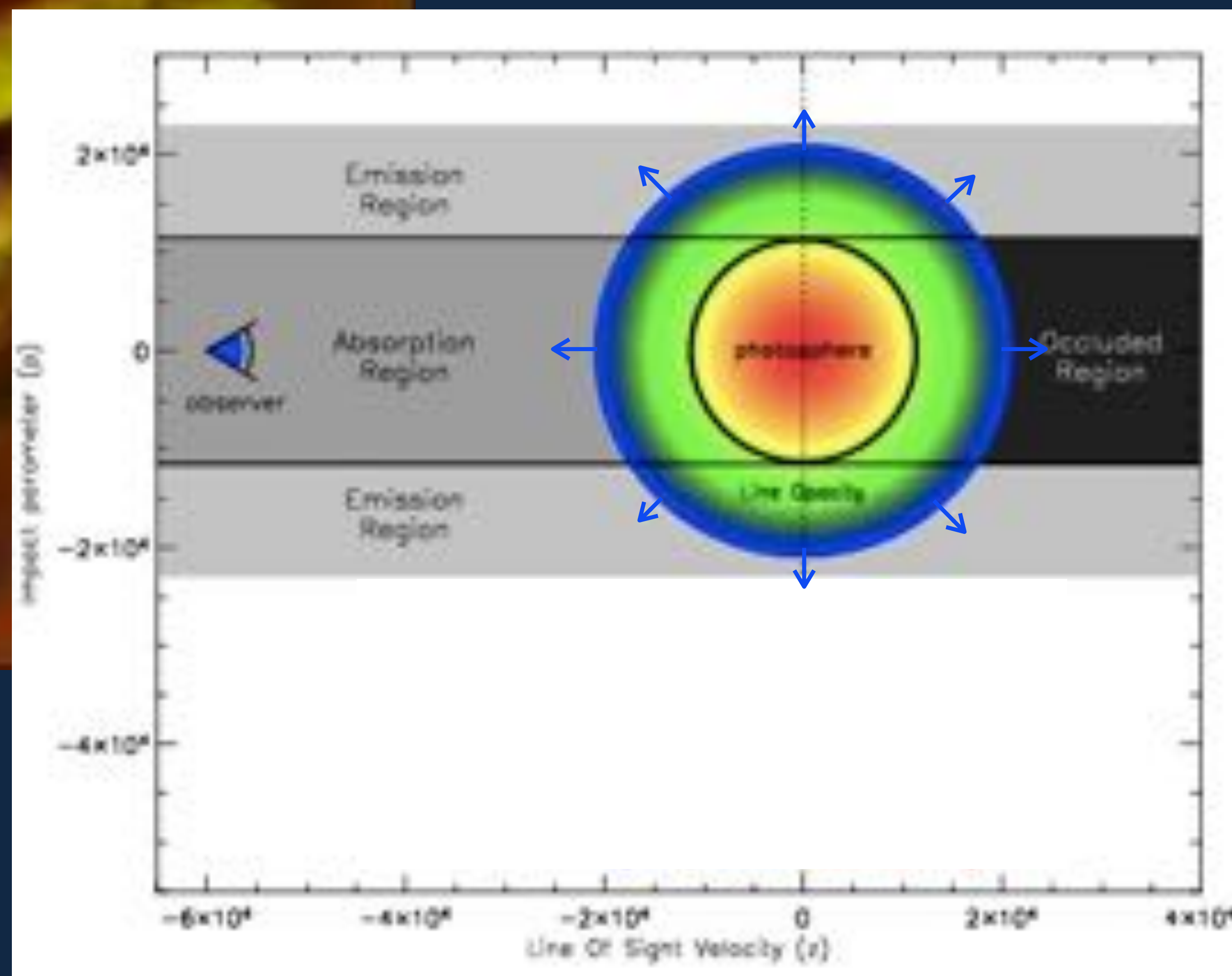
Star Formation



Star Formation

Protostars



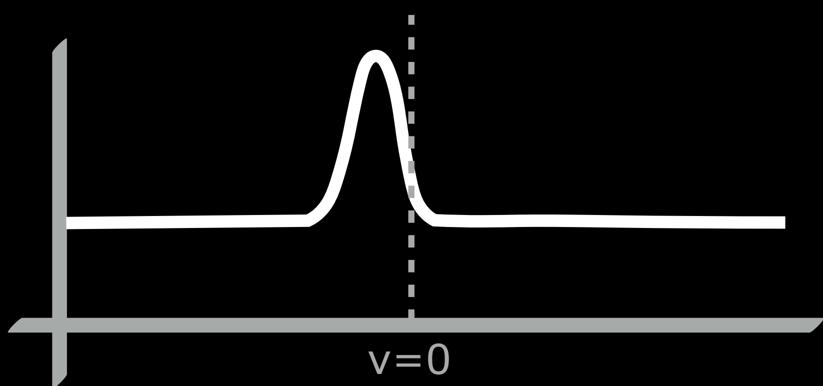


Star Formation

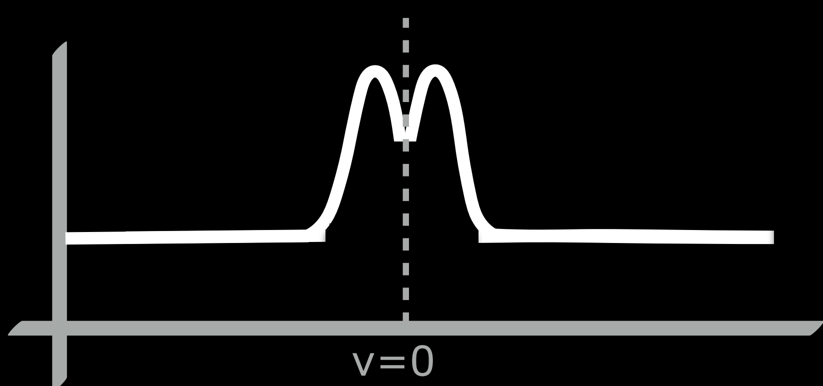
Discussion Question

What will a spectral line <u>emitted</u> by the T Tauri star look like?

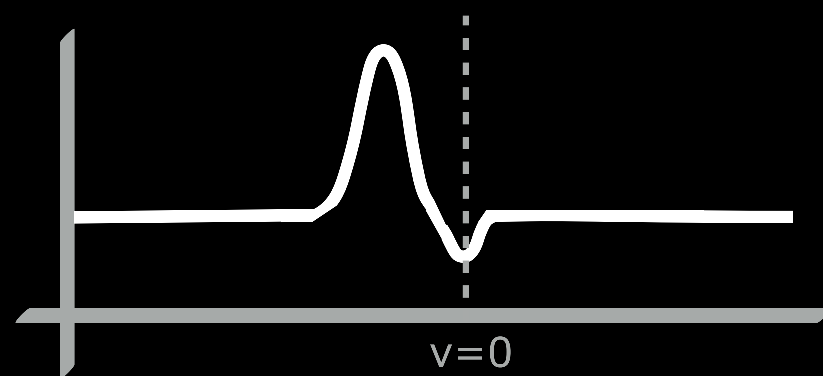
A)



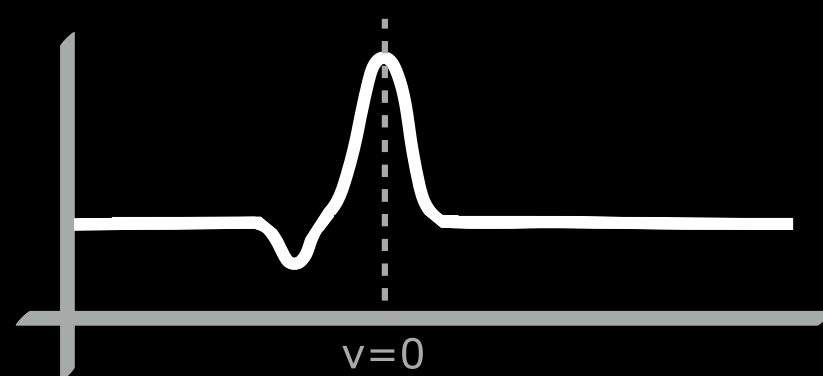
B)



C)

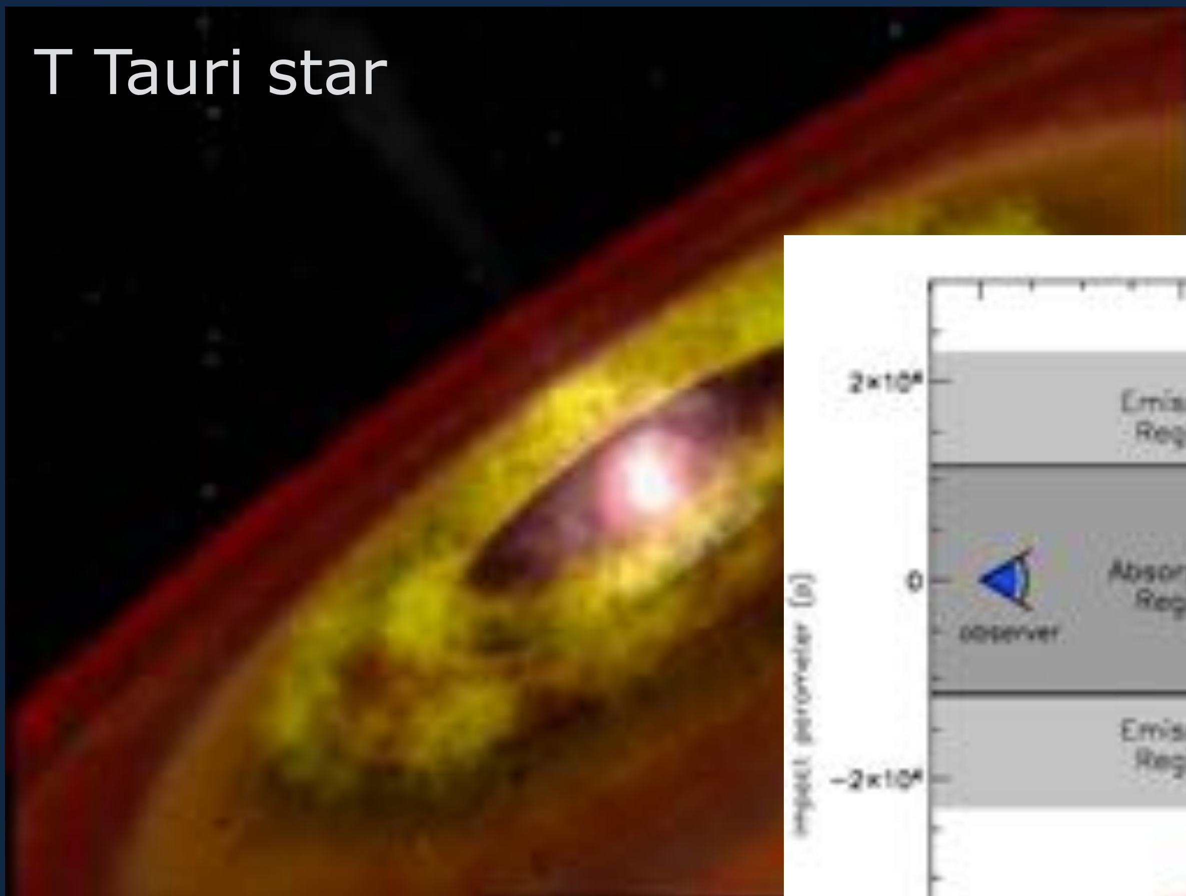


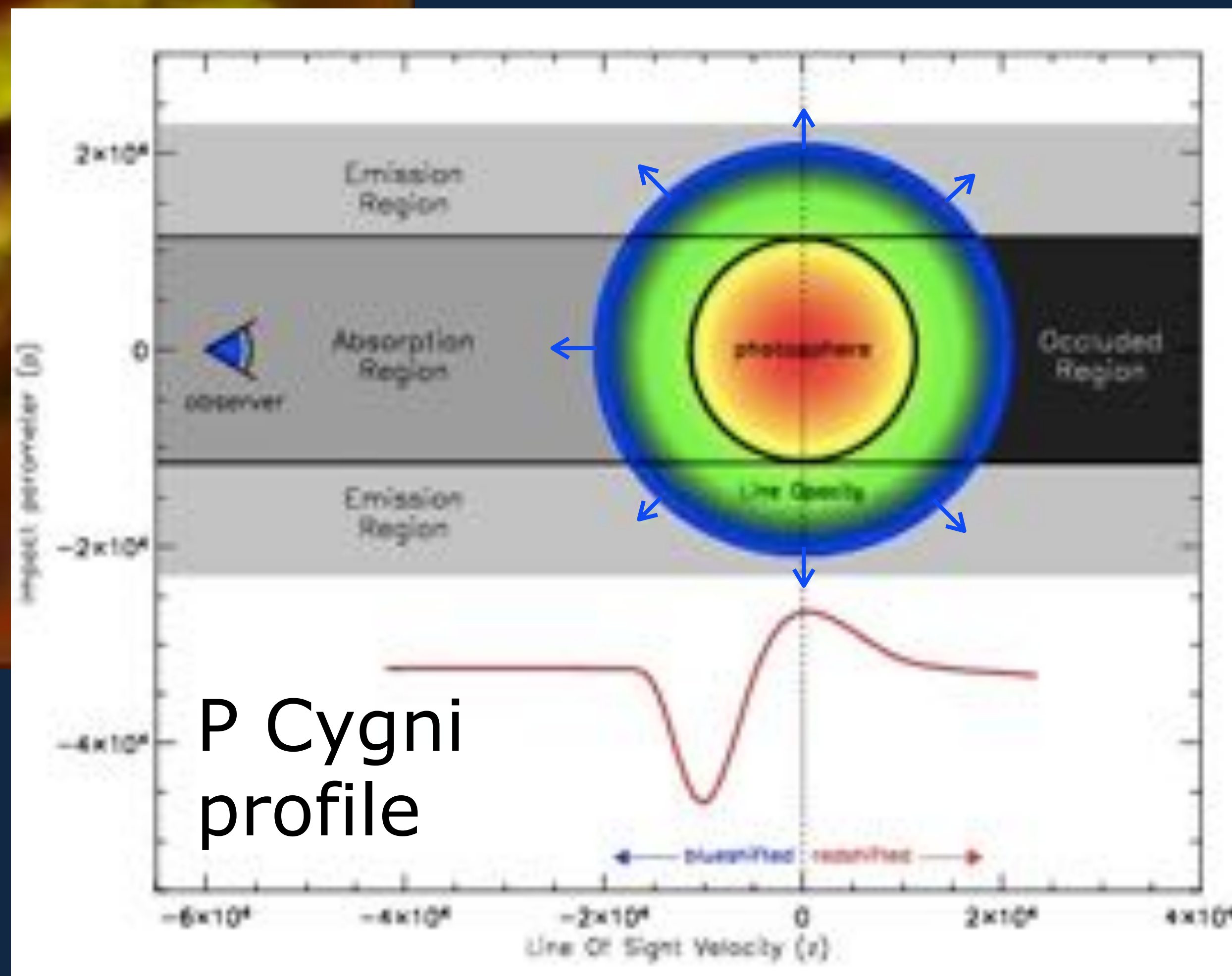
D)



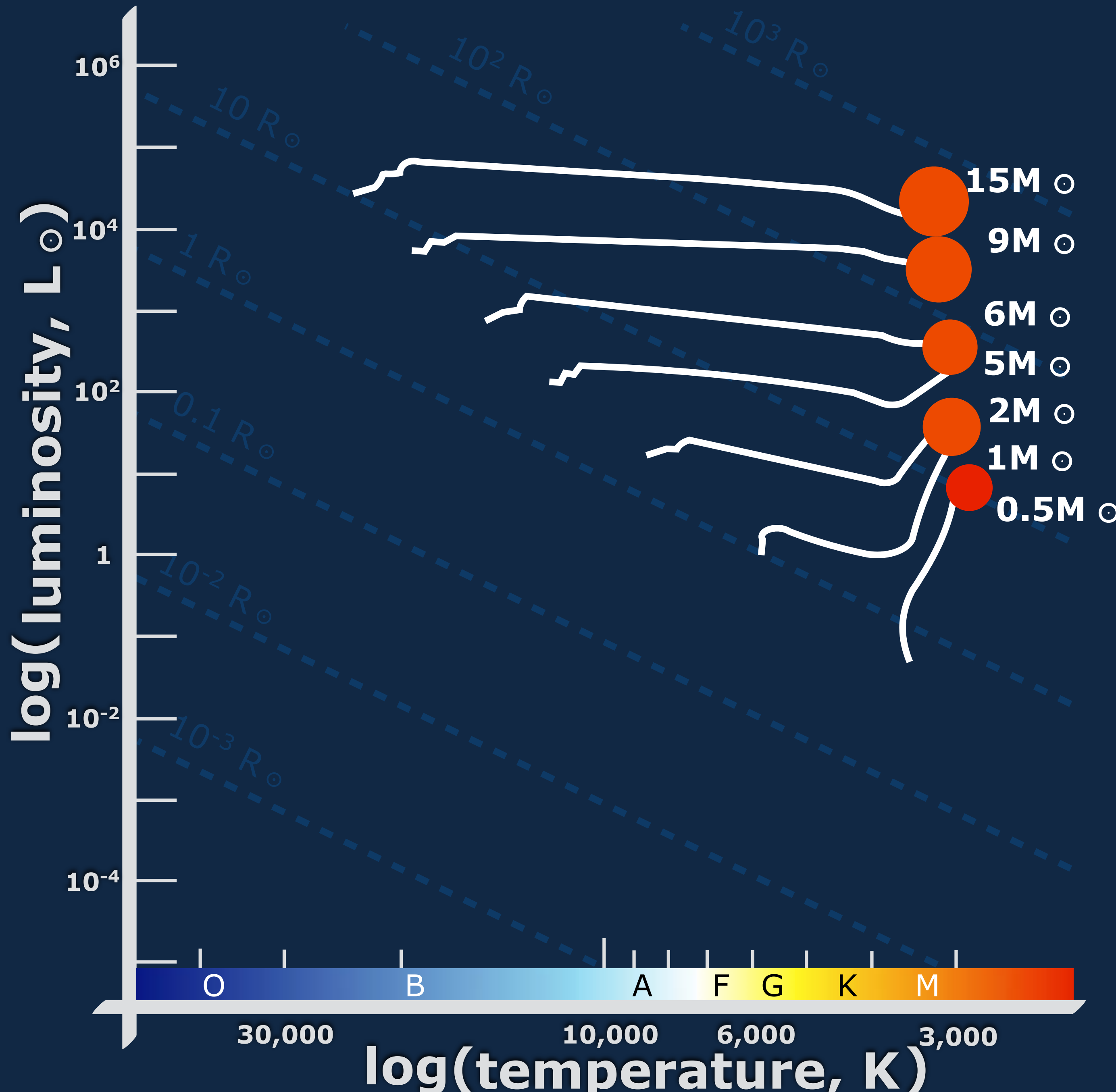
Star Formation

Protostars

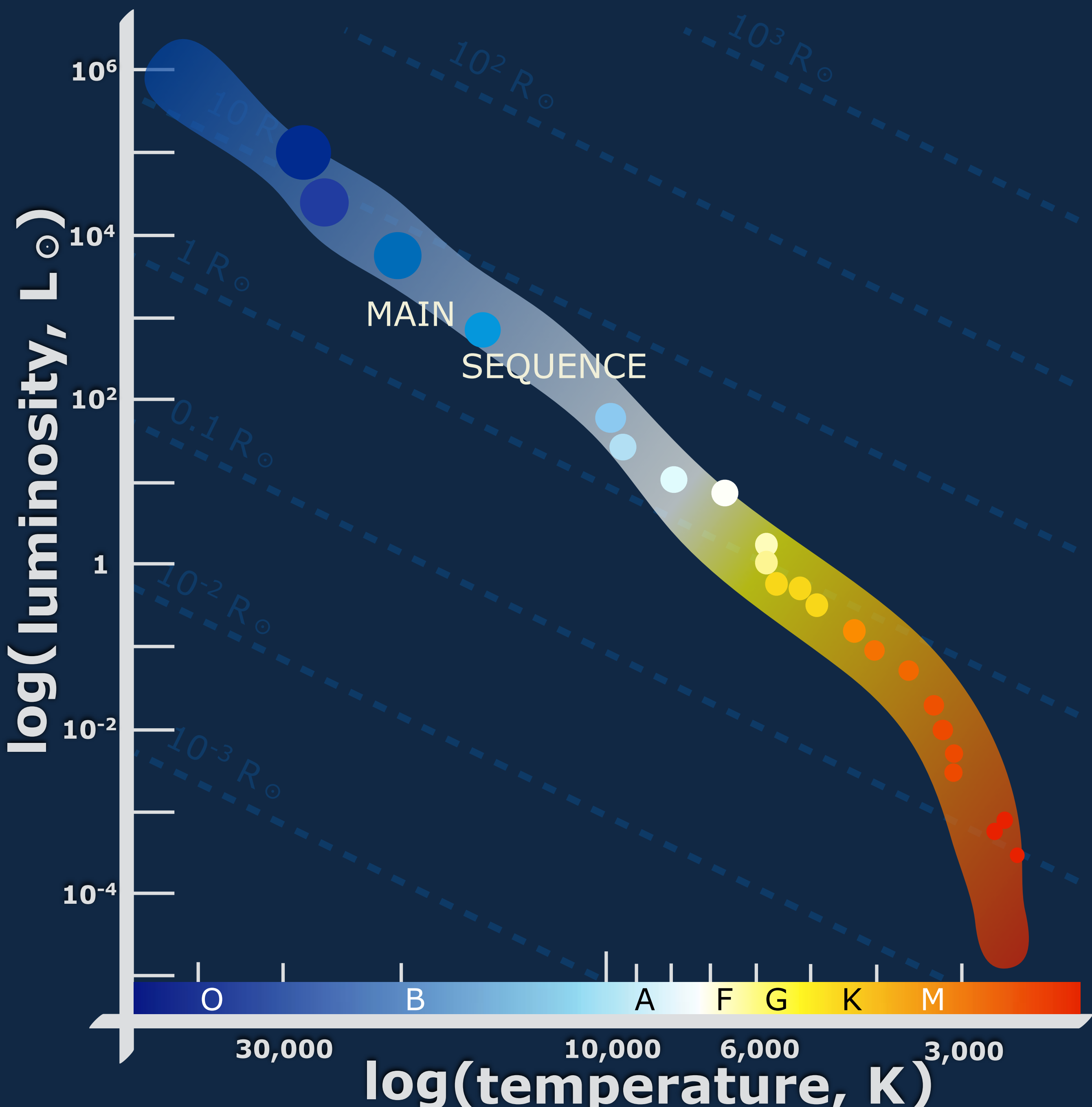




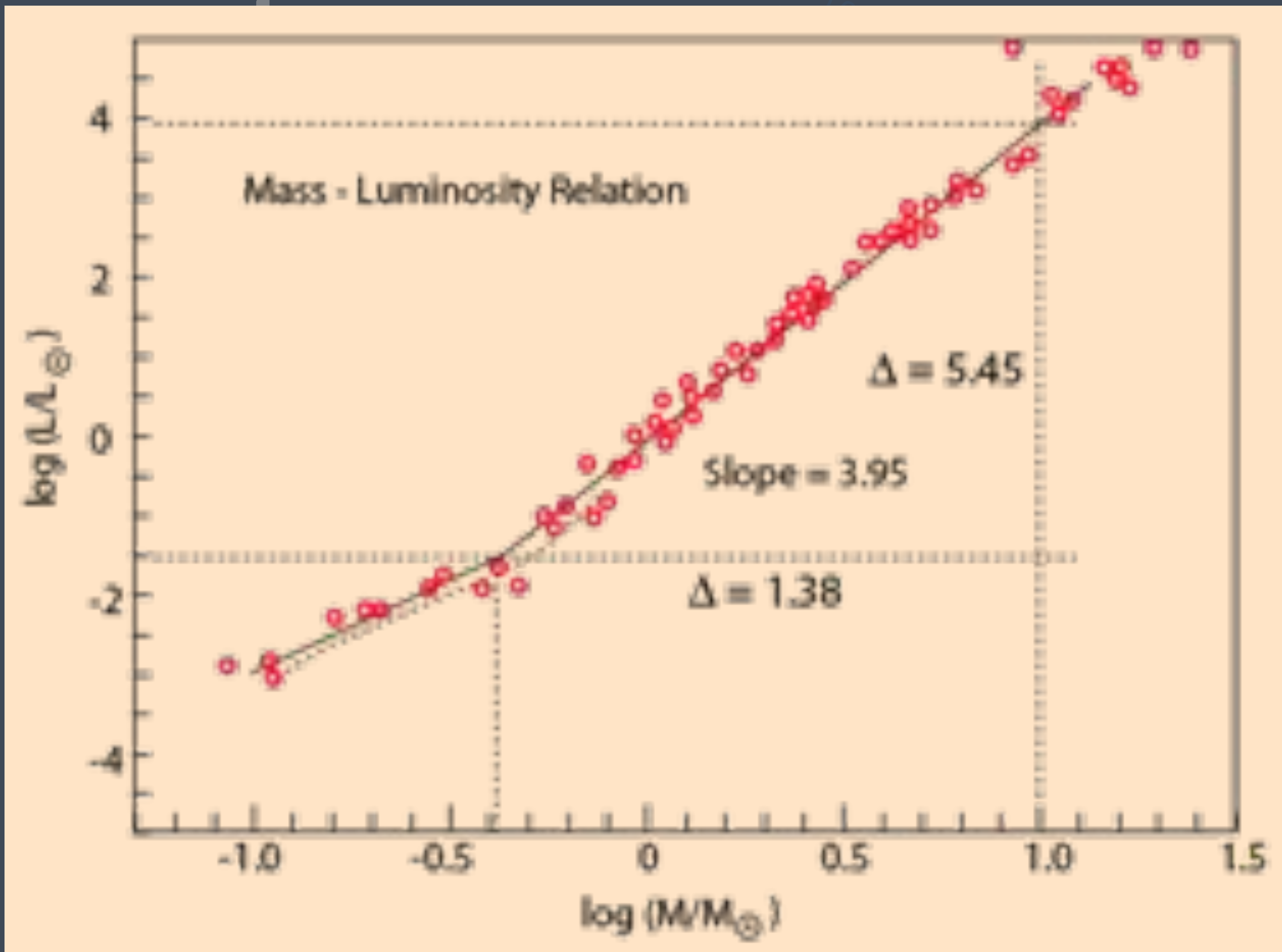
Star Formation



The Main Sequence

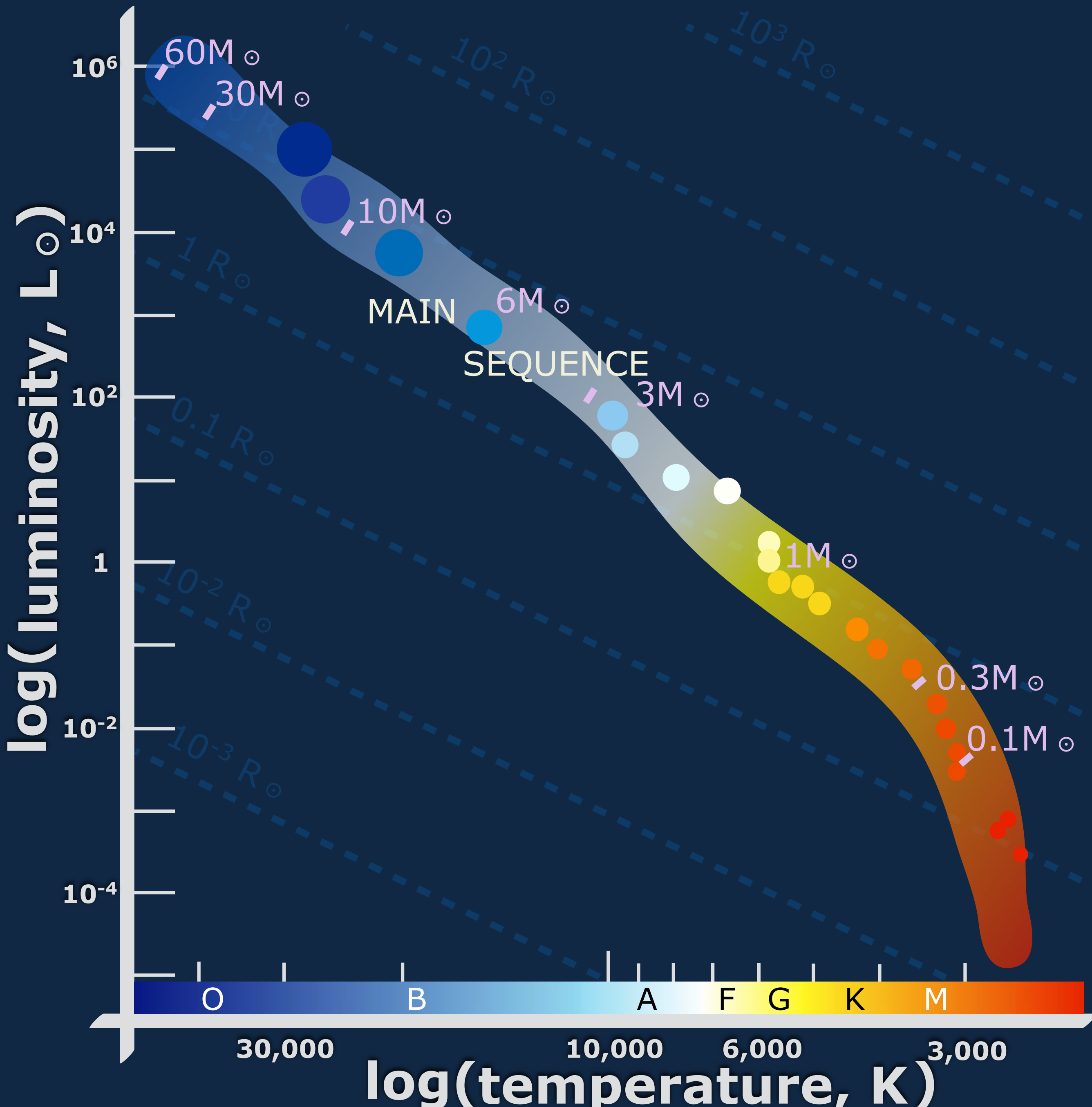


The Main Sequence

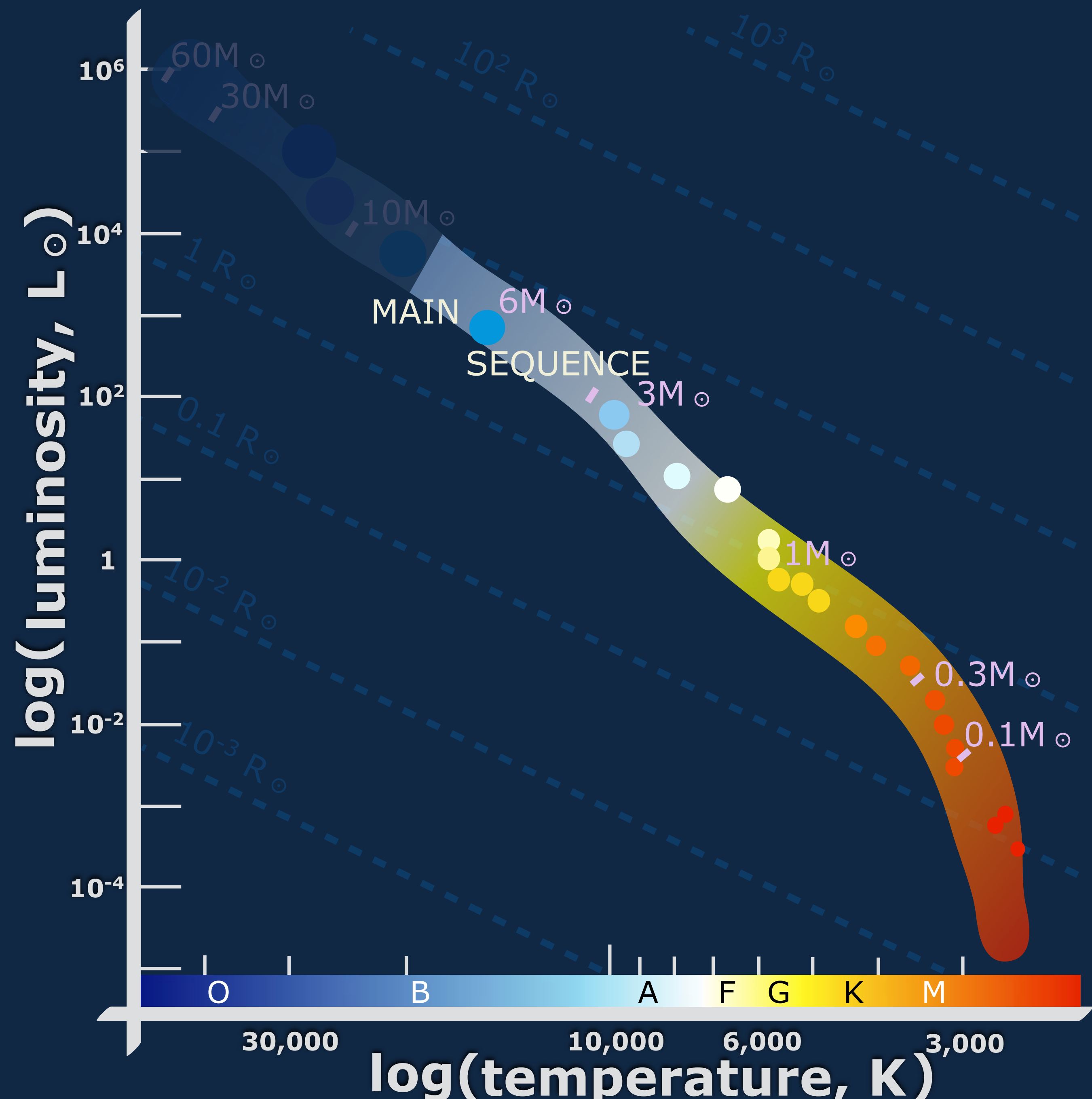


log(temperature, K)

The Main Sequence



Low-Mass Stars - Main Sequence



Low-Mass Stars - Main Sequence

<u>Main Sequence Phase</u>

— Young to middle-age in a star's lifetime

— Gravity balances pressure

$\boxed{\text{Lifetime on Main Sequence} \sim 10^{10}\ M/L}$

Low-Mass Stars - Main Sequence

Main Sequence Phase

$\boxed{\text{Lifetime on Main Sequence} \sim 10^{10}\ M/L}$

$L_\odot = 4 \times 10^{33}$ ergs/s solar constant

$Age_\odot = 4.6$ billion yrs (1.4×10^{17} secs)

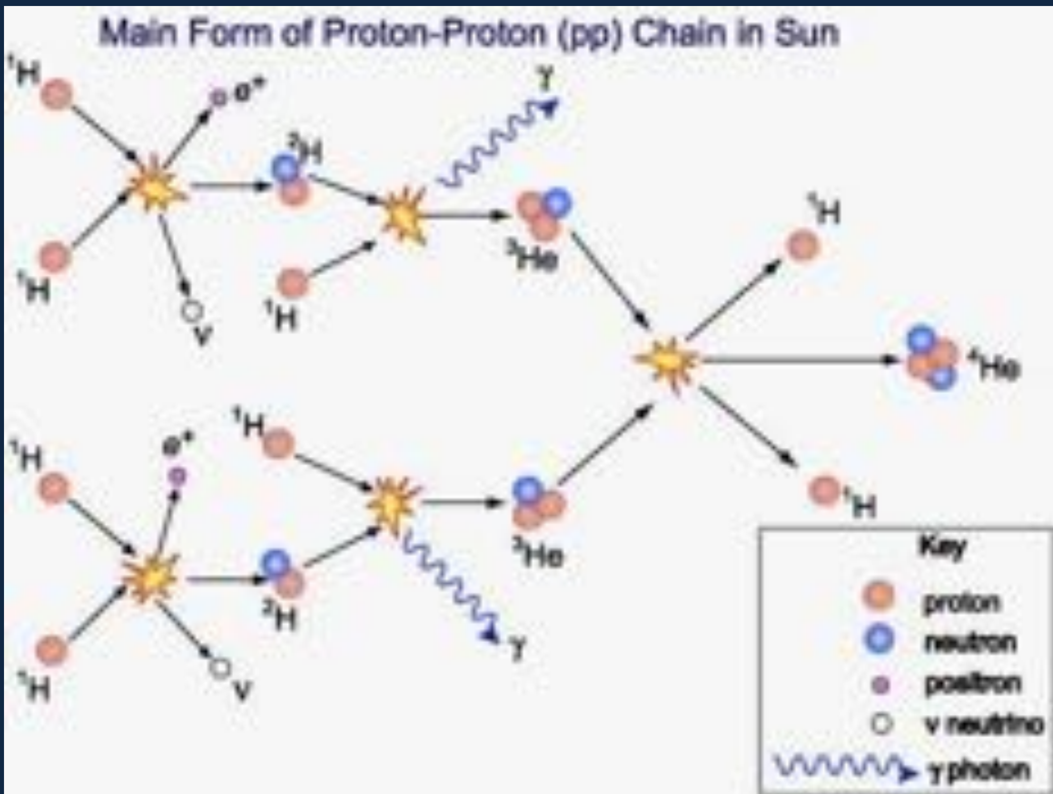
Total $E = 6 \times 10^{50}$ ergs

(fusion is only source capable of this energy)

How much E has the sun *produced*?

Low-Mass Stars - Main Sequence

H as Stellar Fuel: **proton-proton chain**



1) ${}^1_1H + {}^1_1H \rightarrow {}^2_1H + e^+ + \nu$
2) ${}^2_1H + {}^1_1H \rightarrow {}^3_2He + \gamma$
3) ${}^3_2He + {}^3_2He \rightarrow {}^4_2He + 2\,{}^1_1H$

$4H \rightarrow 1He + E$
$4.0312 \rightarrow 4.0026$
($\Delta m = 0.05 \times 10^{-24}$ g)

$m_H = 1.67 \times 10^{-24}$ g, so

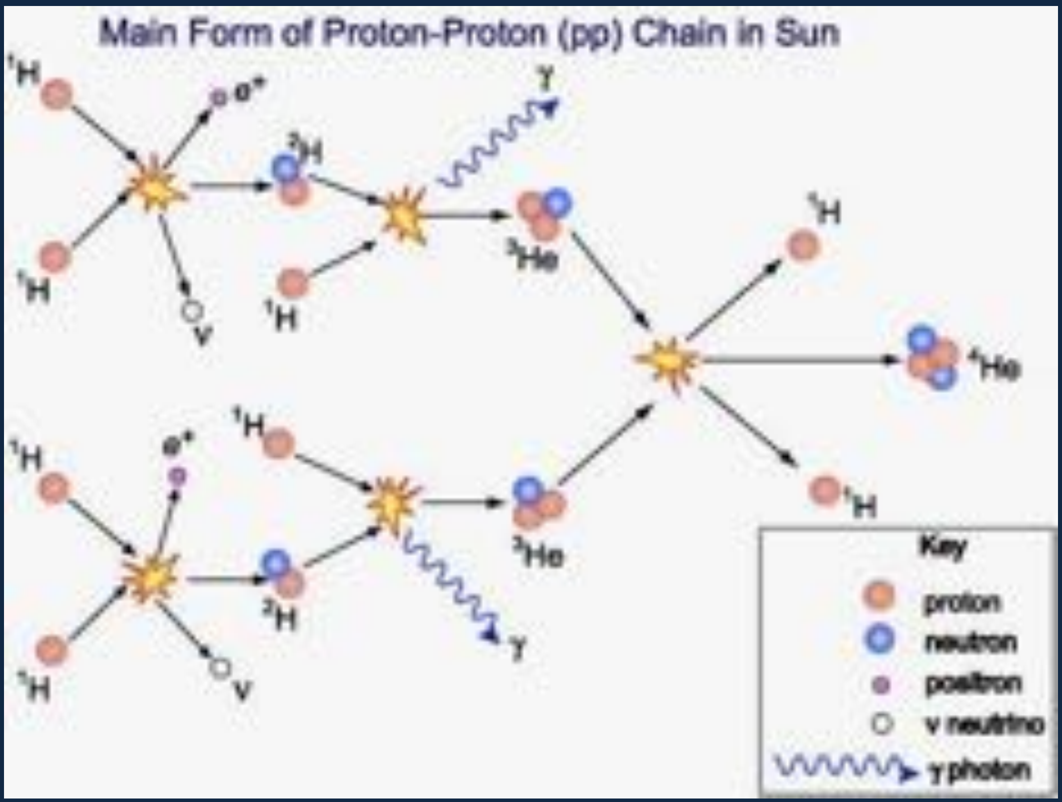
$\Delta m / 4m_H \sim 0.007$

$E = mc^2 = [0.05 \times 10^{-24}\text{ g}] \times [3 \times 10^{10}\text{ cm/s}]^2$
$= 4 \times 10^{-5}$ ergs

For sun: $E = [0.007 \times 0.1\,(2\times10^{33}\text{g})] \times [3 \times 10^{10}\text{ cm/s}]^2$
$= 1.3\times10^{51}$ ergs

Low-Mass Stars - Main Sequence

H as Stellar Fuel: **proton-proton chain**



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$= 1.3 \times 10^{51}$ ergs

core H mass (from stellar structure eq'ns)

Low-Mass Stars - Main Sequence

Main Sequence Phase

$\boxed{\text{Lifetime on Main Sequence} \sim 10^{10}\ M/L}$

$L_\odot = 4 \times 10^{33}$ ergs/s solar constant

$Age_\odot = 4.6$ billion yrs (1.4×10^{17} secs)

Total $E = 6 \times 10^{50}$ ergs

(fusion is only source capable of this energy)

mass with $T > 10$ million K → $E = 1.3 \times 10^{51}$ ergs

$$\text{lifetime} = \frac{\text{E available}}{\text{E loss rate}} = \frac{1.3 \times 10^{51} \text{ ergs}}{4 \times 10^{33} \text{ ergs/s}} \sim 3 \times 10^{17}\text{s} \sim 10^{10} \text{ yrs}$$

Low-Mass Stars - Turn-off

He as Stellar Fuel:

He-C fusion: **triple alpha process**

$$ {}^{4}_{2}He + {}^{4}_{2}He \rightleftarrows {}^{8}_{4}Be + \gamma \longleftarrow $$

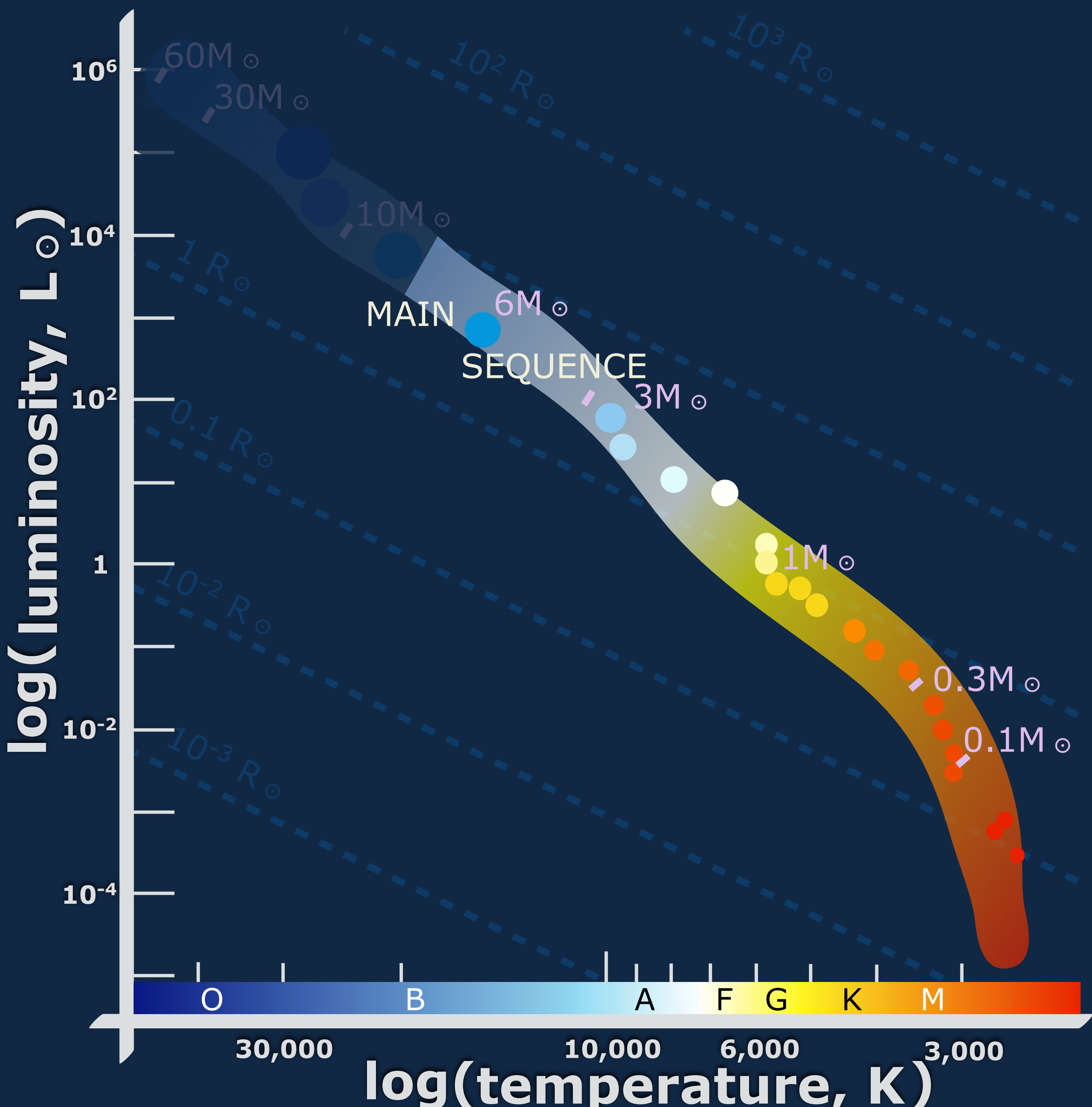
equilibrium reaction;
^{8}Be lifetime $\sim 3 \times 10^{-16}$ s!

$$ {}^{8}_{4}Be + {}^{4}_{2}He \rightarrow {}^{12}_{6}C + \gamma $$

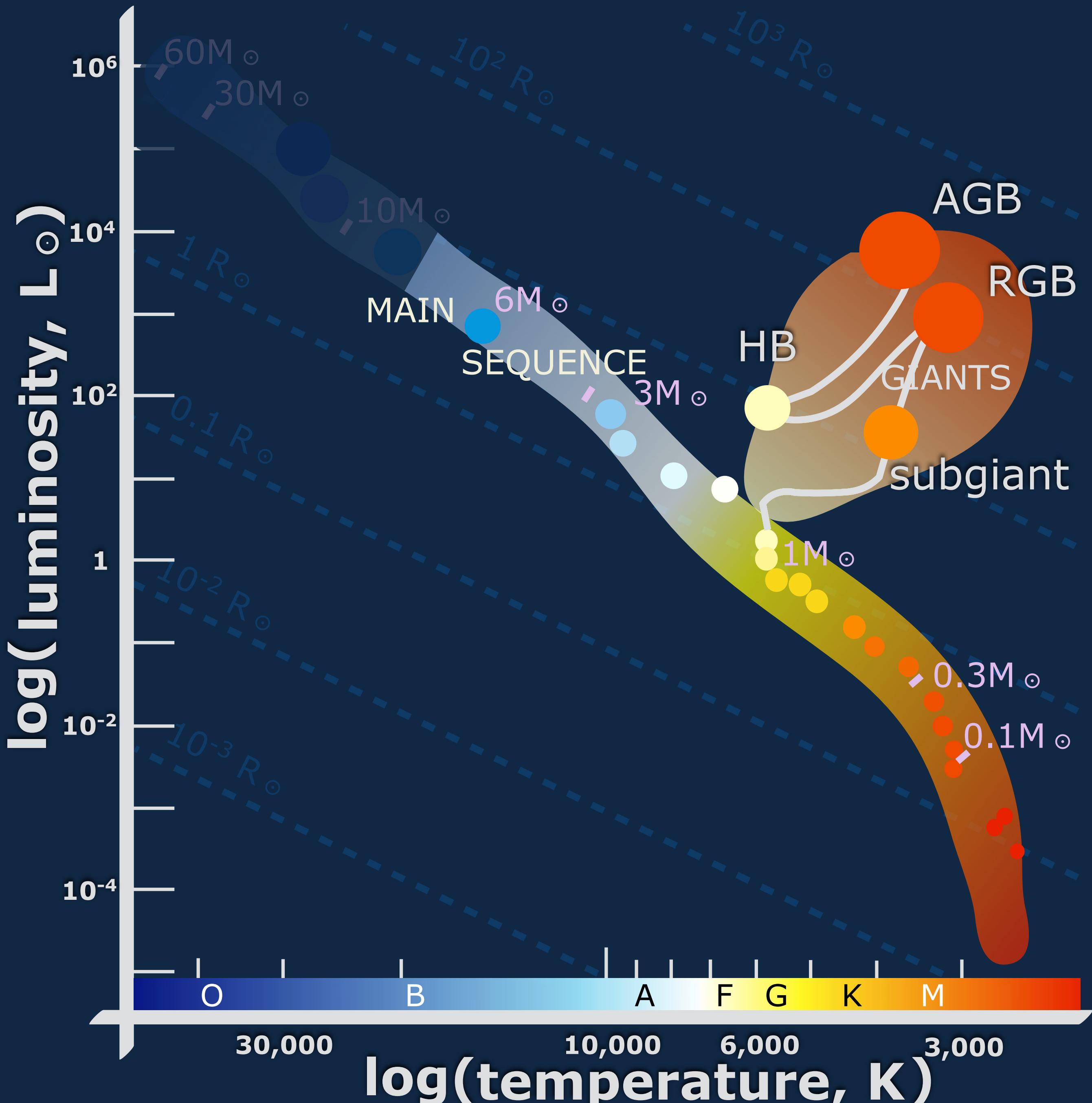
3He → 1C

$E = 1.17 \times 10^{-5}$ ergs

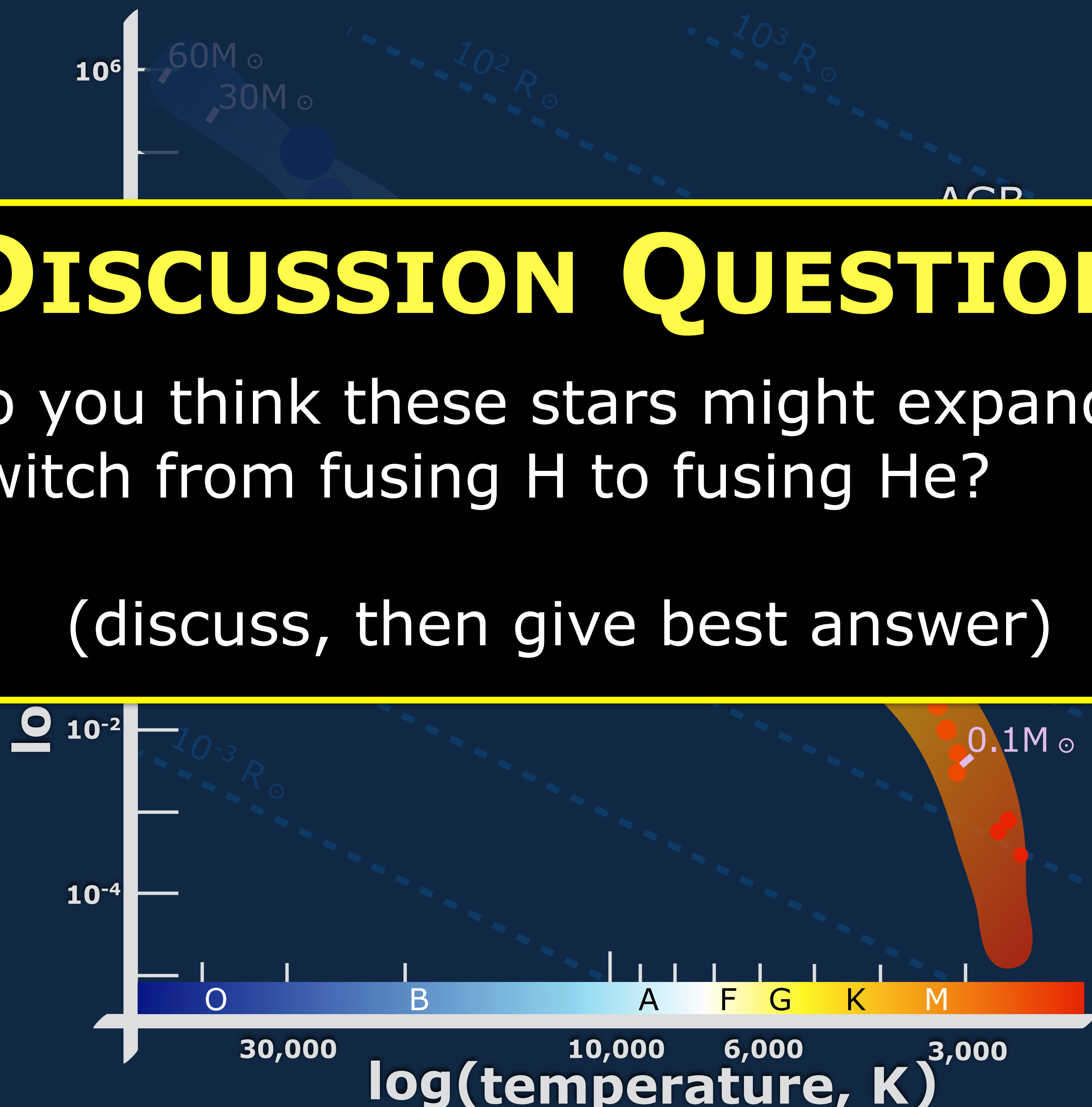
Low-Mass Stars - Turn-off



Low-Mass Stars - Turn-off



Low-Mass Stars - Turn-off



Discussion Question

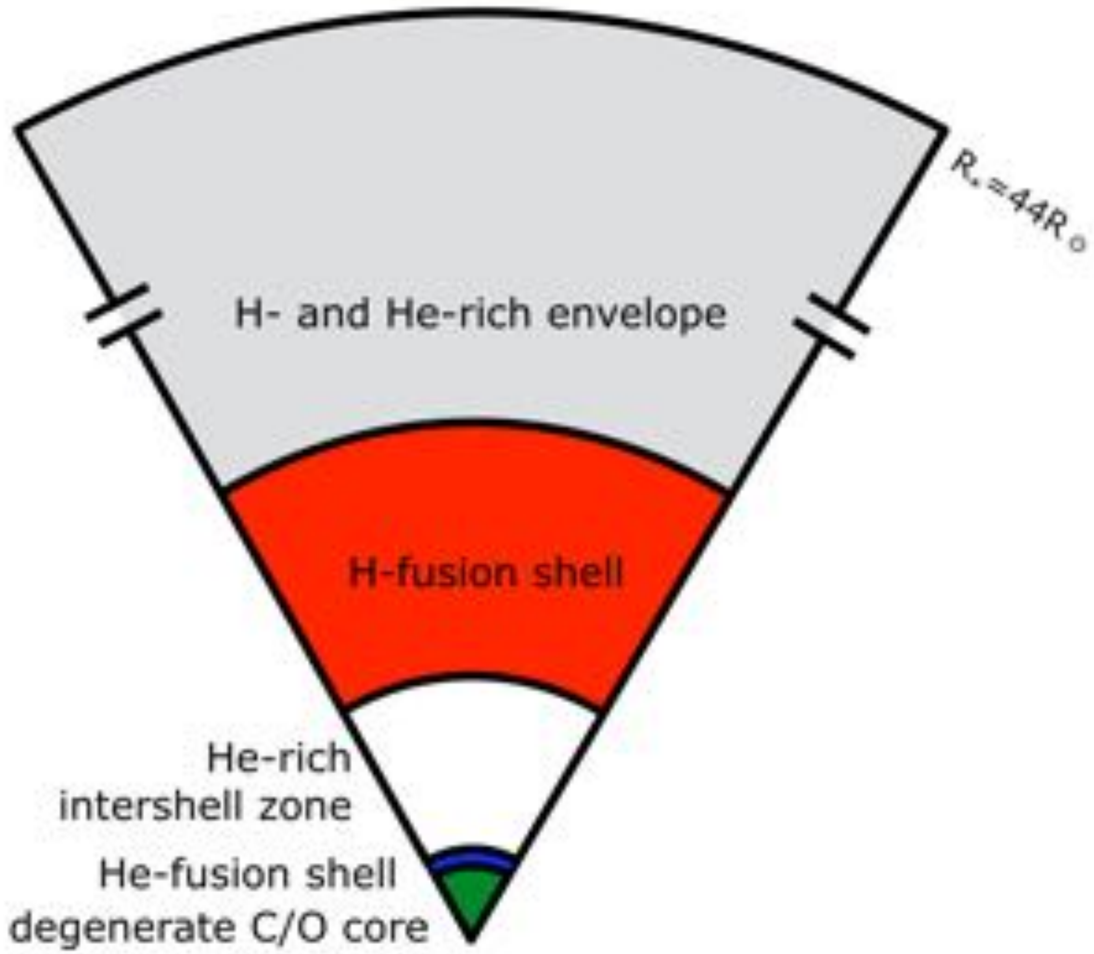
Why do you think these stars might expand when they switch from fusing H to fusing He?

(discuss, then give best answer)

Low-Mass Stars - Turn-off

The "mirror effect"...

Whenever a star has a shell burning source, it appears to act like a mirror.



log(temperature/ K)

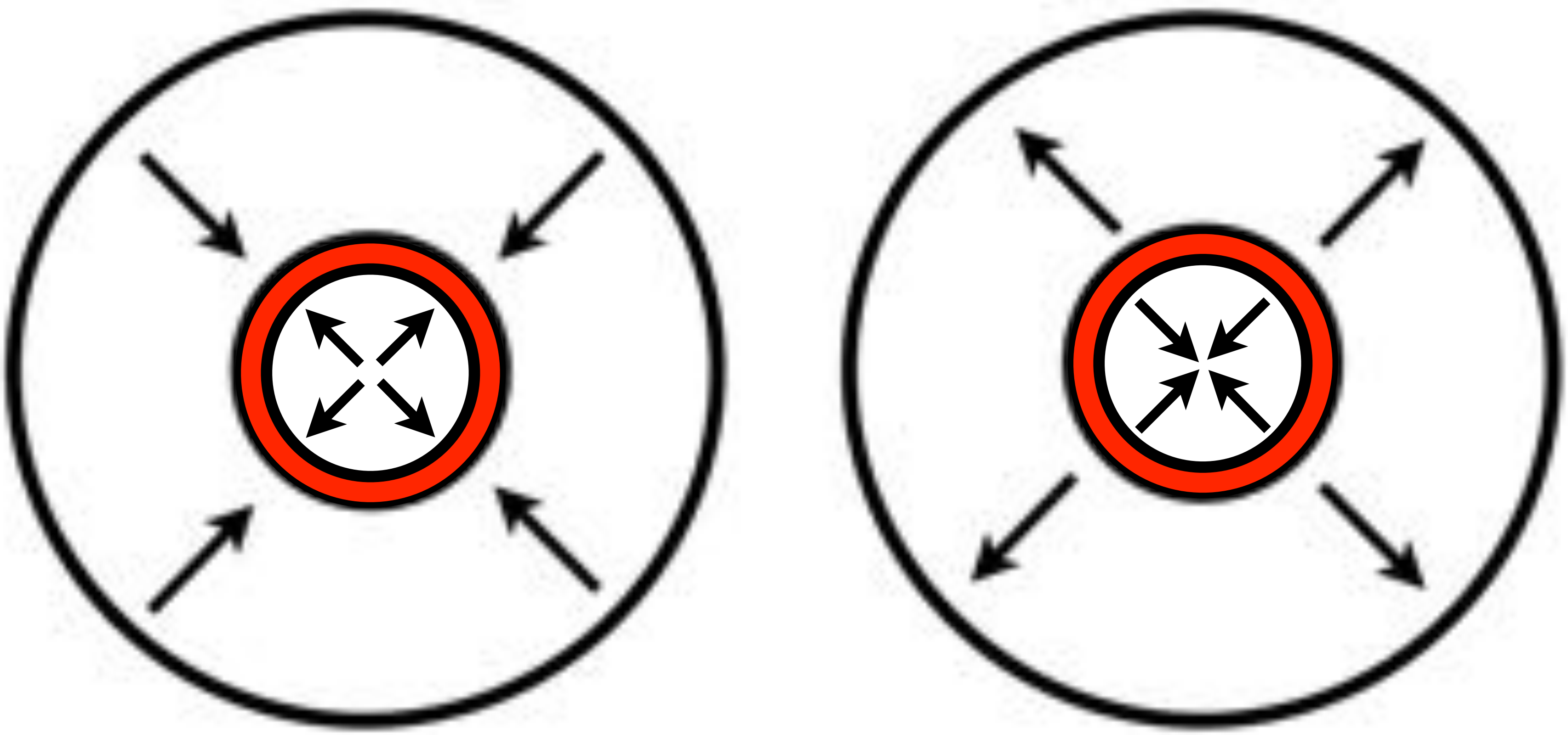
Low-Mass Stars - Turn-off

The "mirror effect"...

Whenever a star has a shell burning source, it appears to act like a mirror.

expanding core = contracting envelope

contracting core = expanding envelope

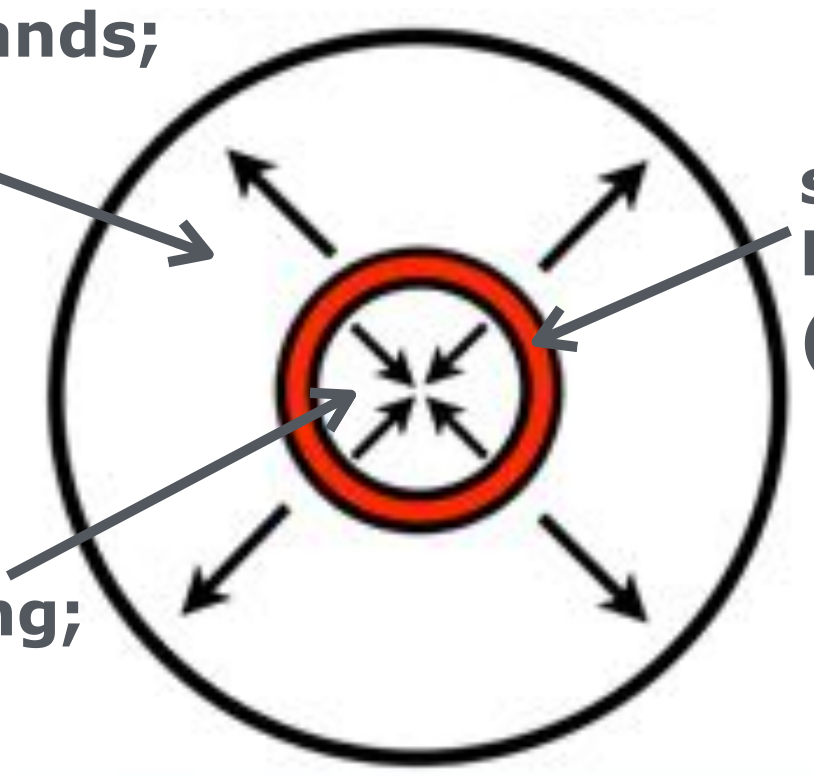


Low-Mass Stars - Turn-off

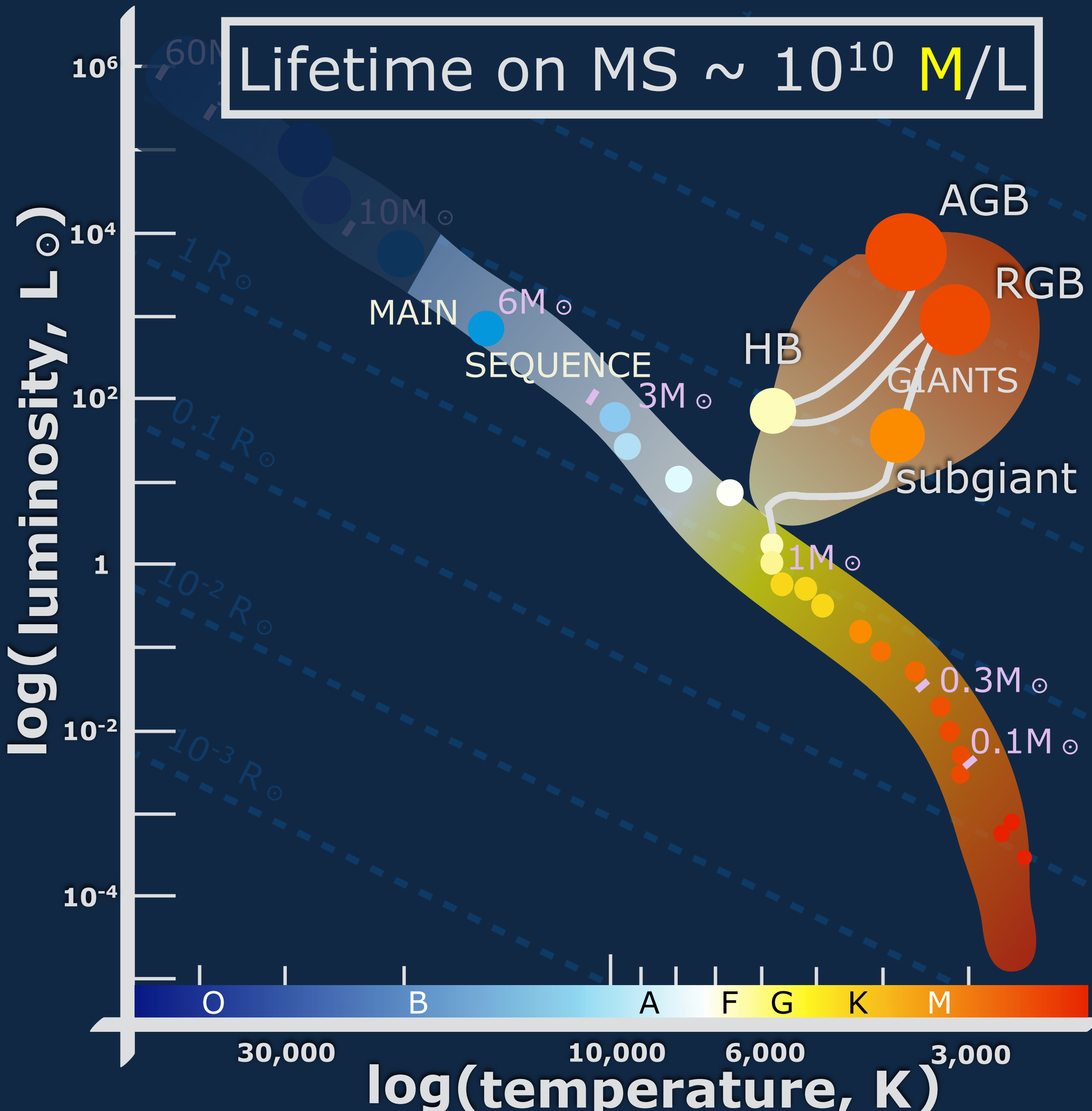
The "mirror effect"...

Whenever a star has a shell burning source, it appears to act like a mirror.

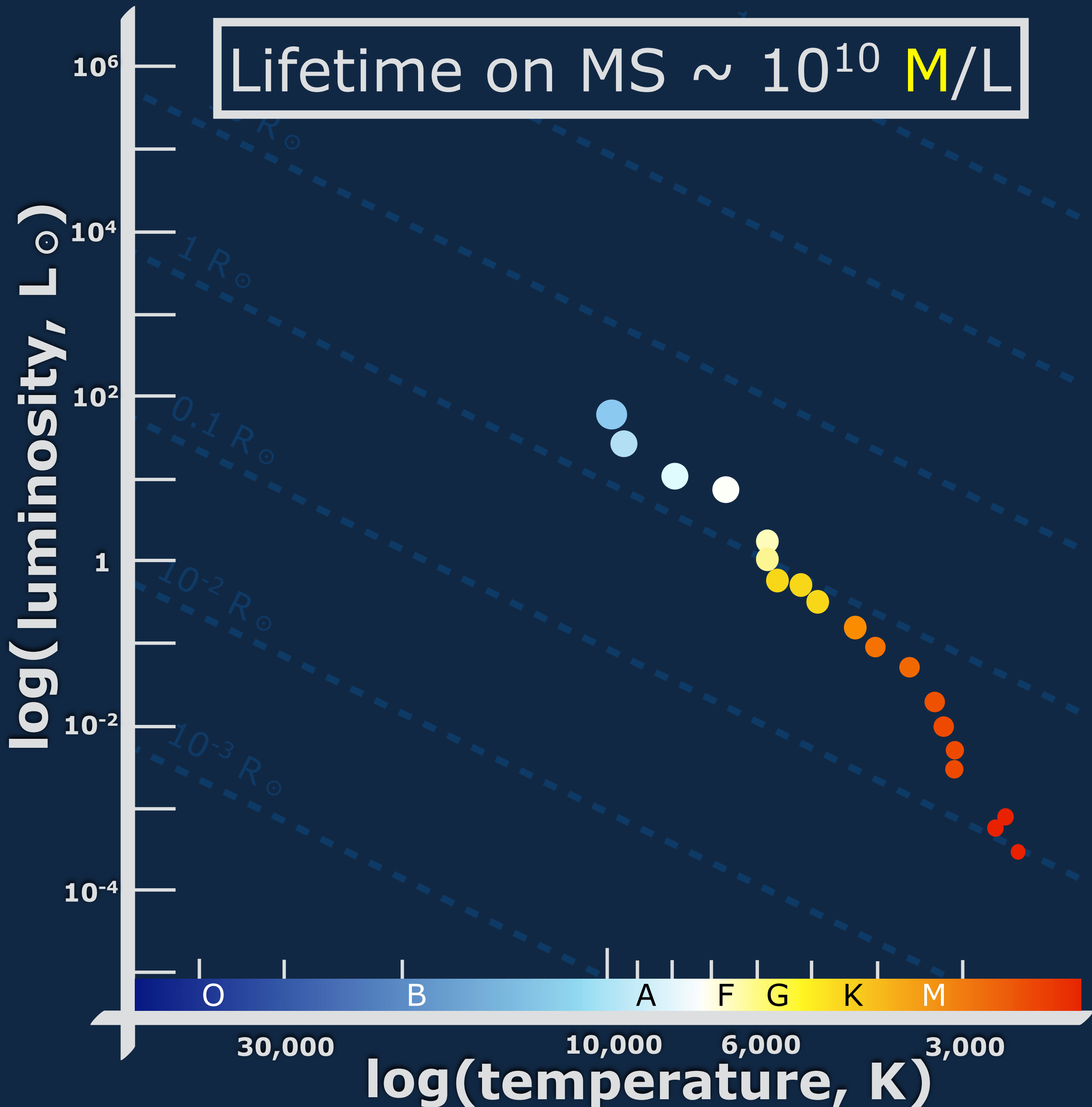
Best current explanation: the virial theorem! $\mathrm{E_{kin}} = -\frac{1}{2}\mathrm{E_{pot}}$



Low-Mass Stars - Turn-off



Low-Mass Stars - Turn-off

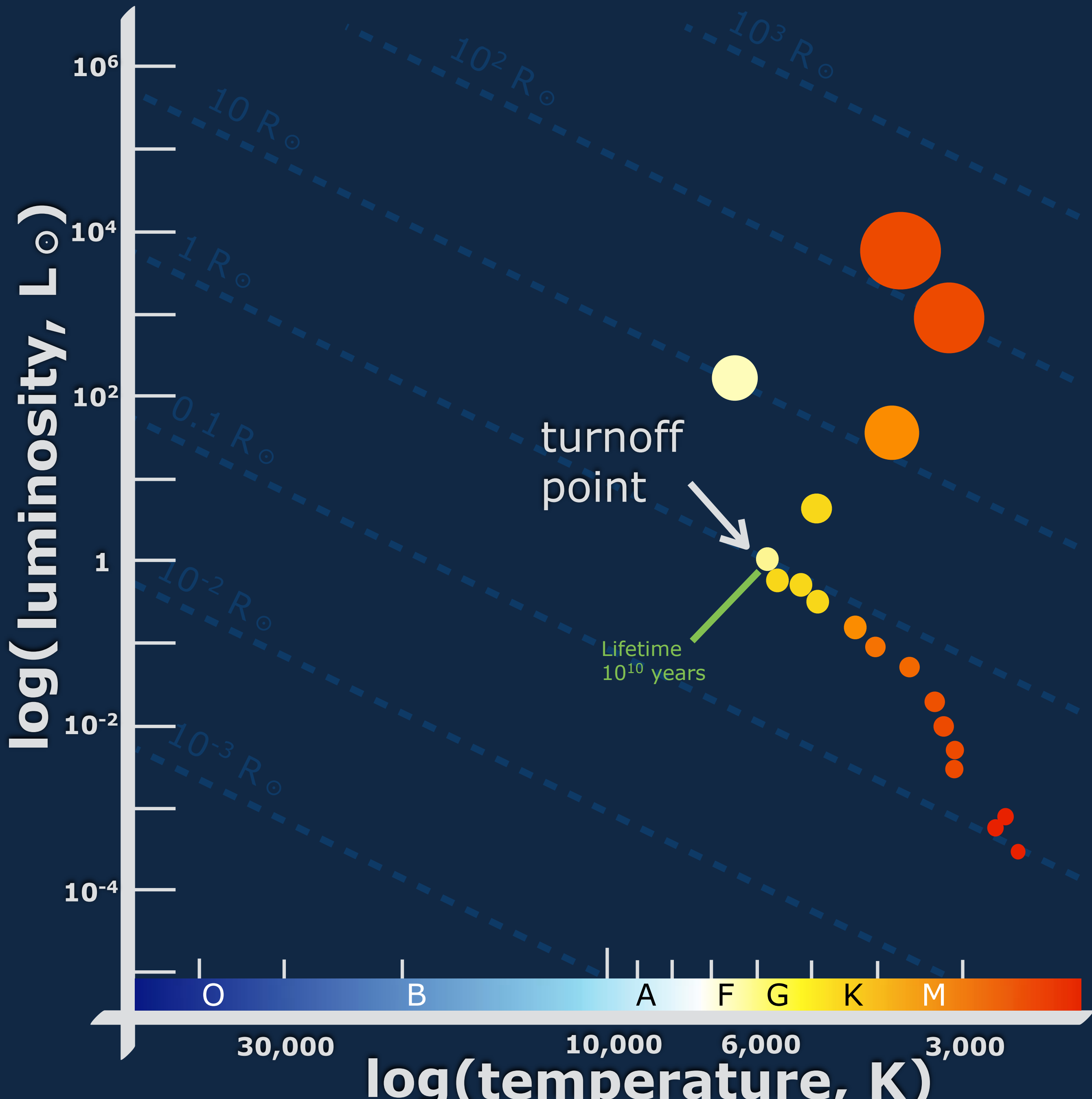


Open Clusters

<1000 stars

< 10 pc diameter

Low-Mass Stars - Turn-off



Open Clusters

<1000 stars

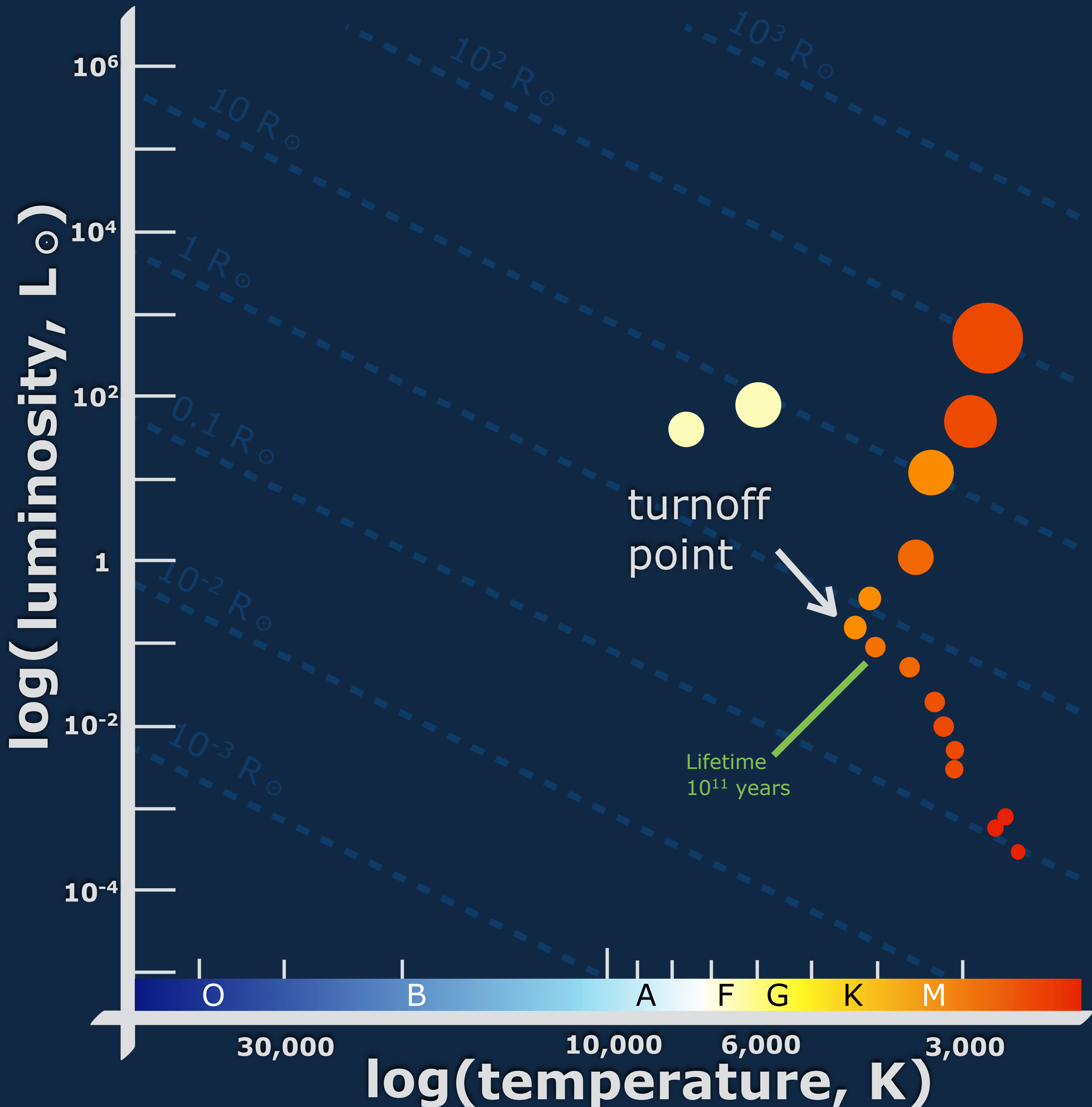
< 10 pc diameter

Globular Clusters

~10^4-10^6 stars

~20-100 pc

Low-Mass Stars - Turn-off



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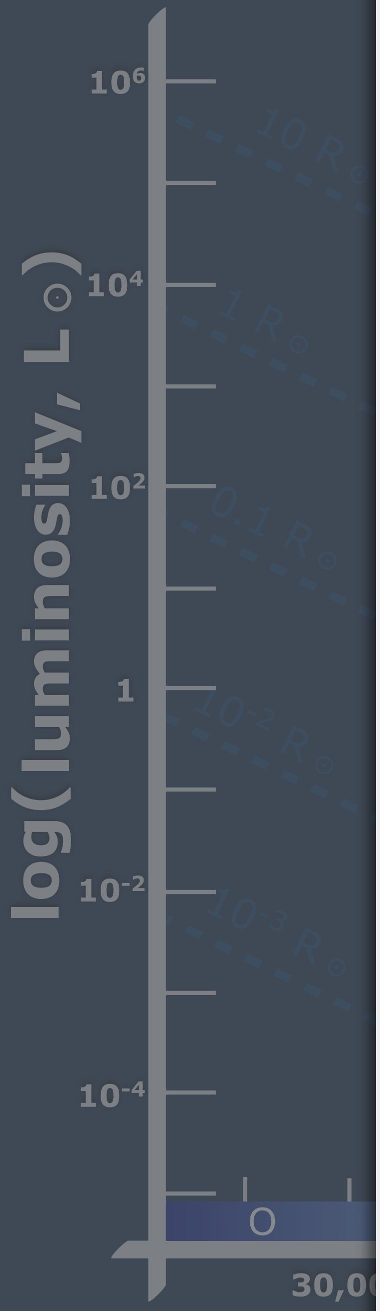
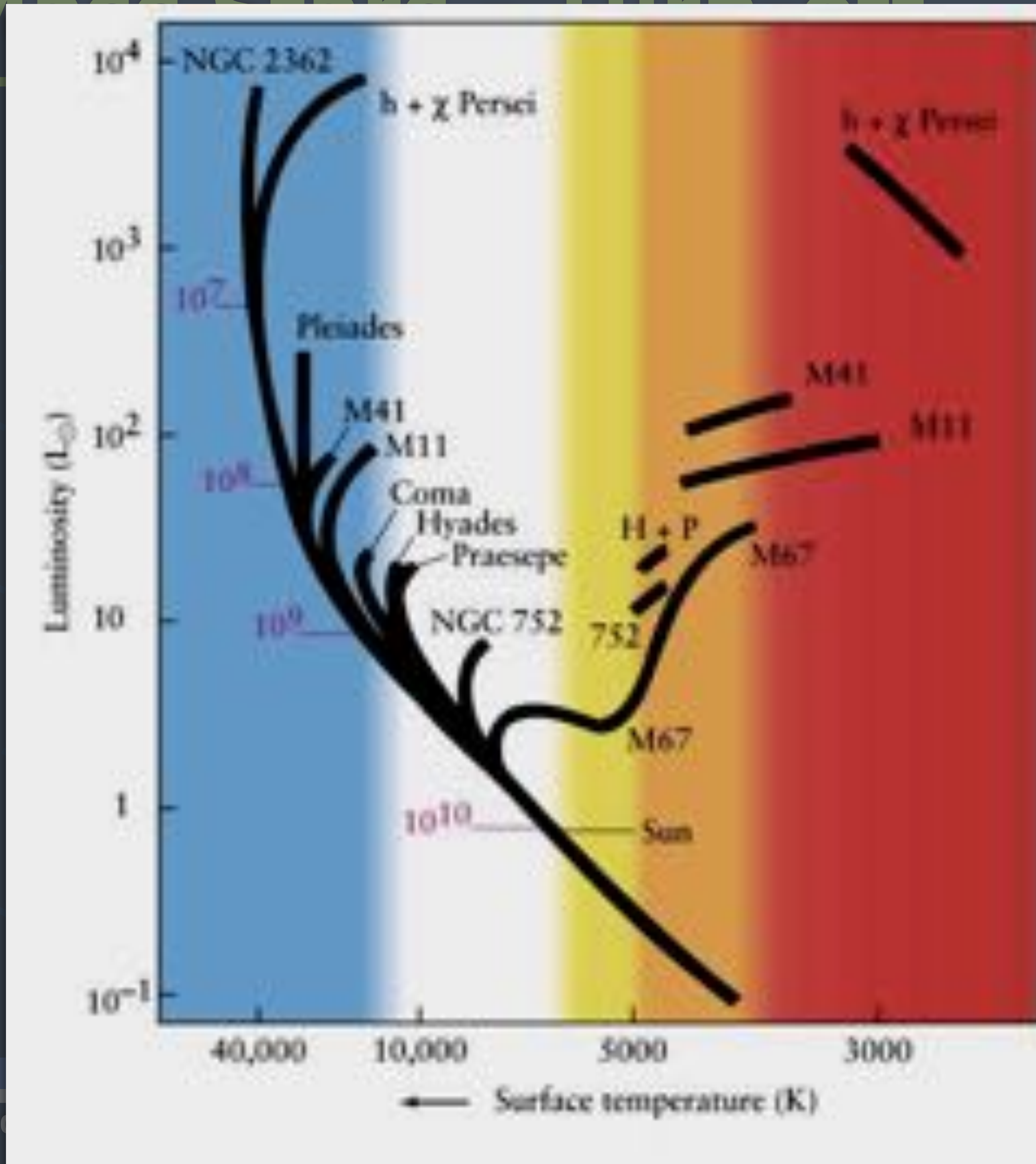
Low-M… Stars – Turn-off





Clusters

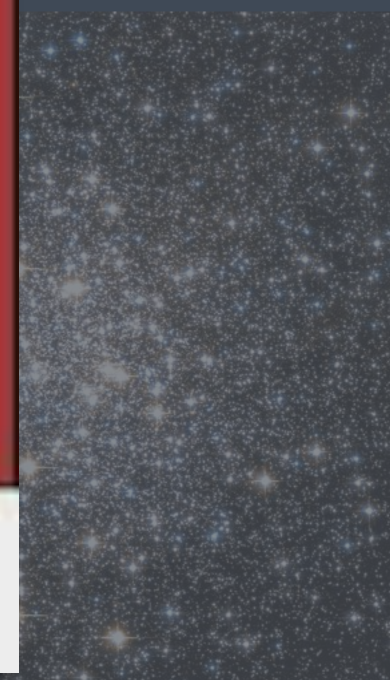
stars

diameter

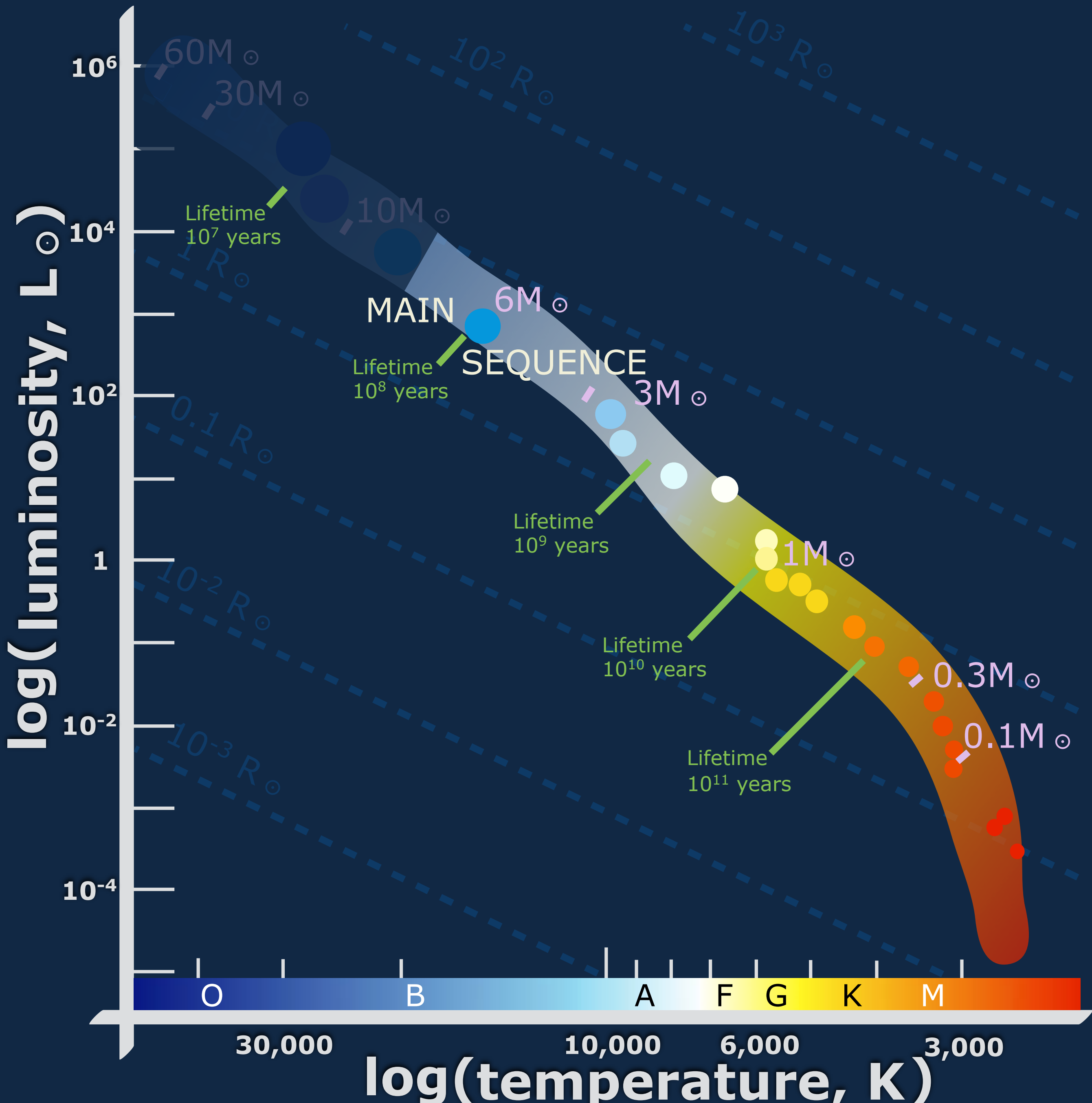
r Clusters

6 stars

pc



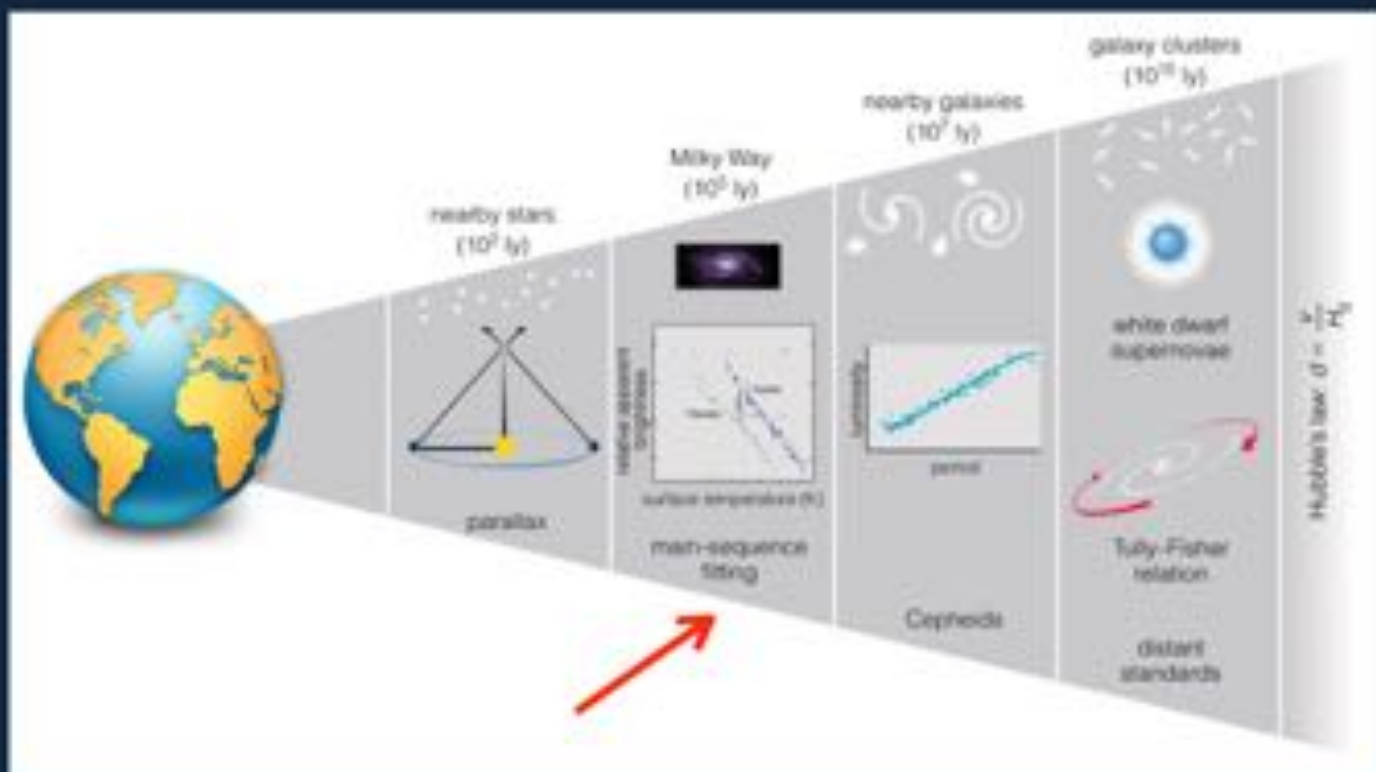
Low-Mass Stars - Turn-off



From a couple weeks ago…

Properties of Stars - Distance

"Main sequence fitting" will be discussed in a few weeks…



log(temperature, K)

Main-sequence fitting for cluster distances

1. Observe B & V images of cluster stars

2. Plot color-mag diagram of B-V vs. V

3. Find main sequence turnoff & lower MS stars

4. For the SAME B-V on lower MS, read m_V from cluster and M_V from H-R diagram

5. Use distance modulus m-M to calculate d

log(temperature, K)

Main-sequence fitting for cluster distances

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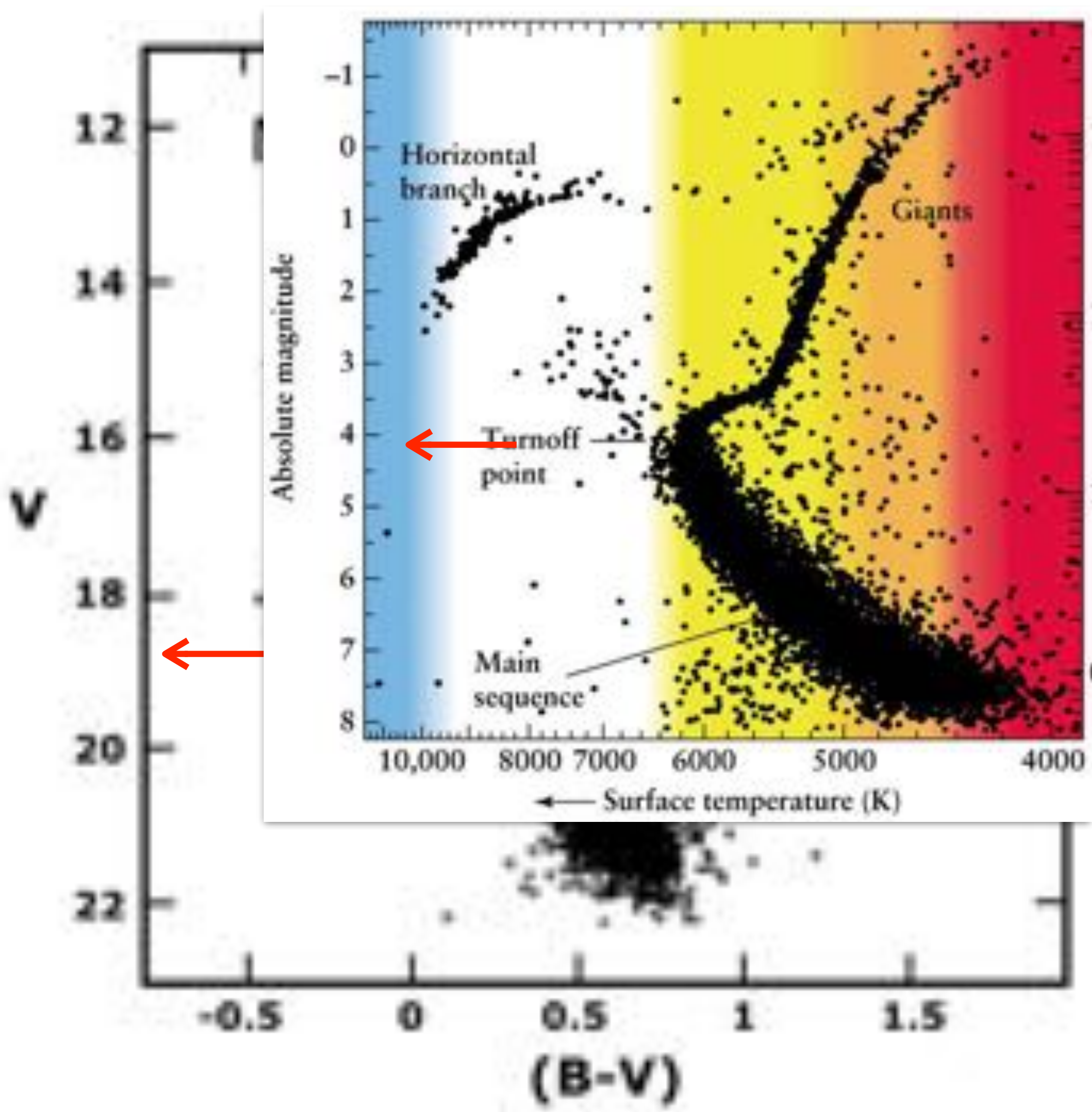
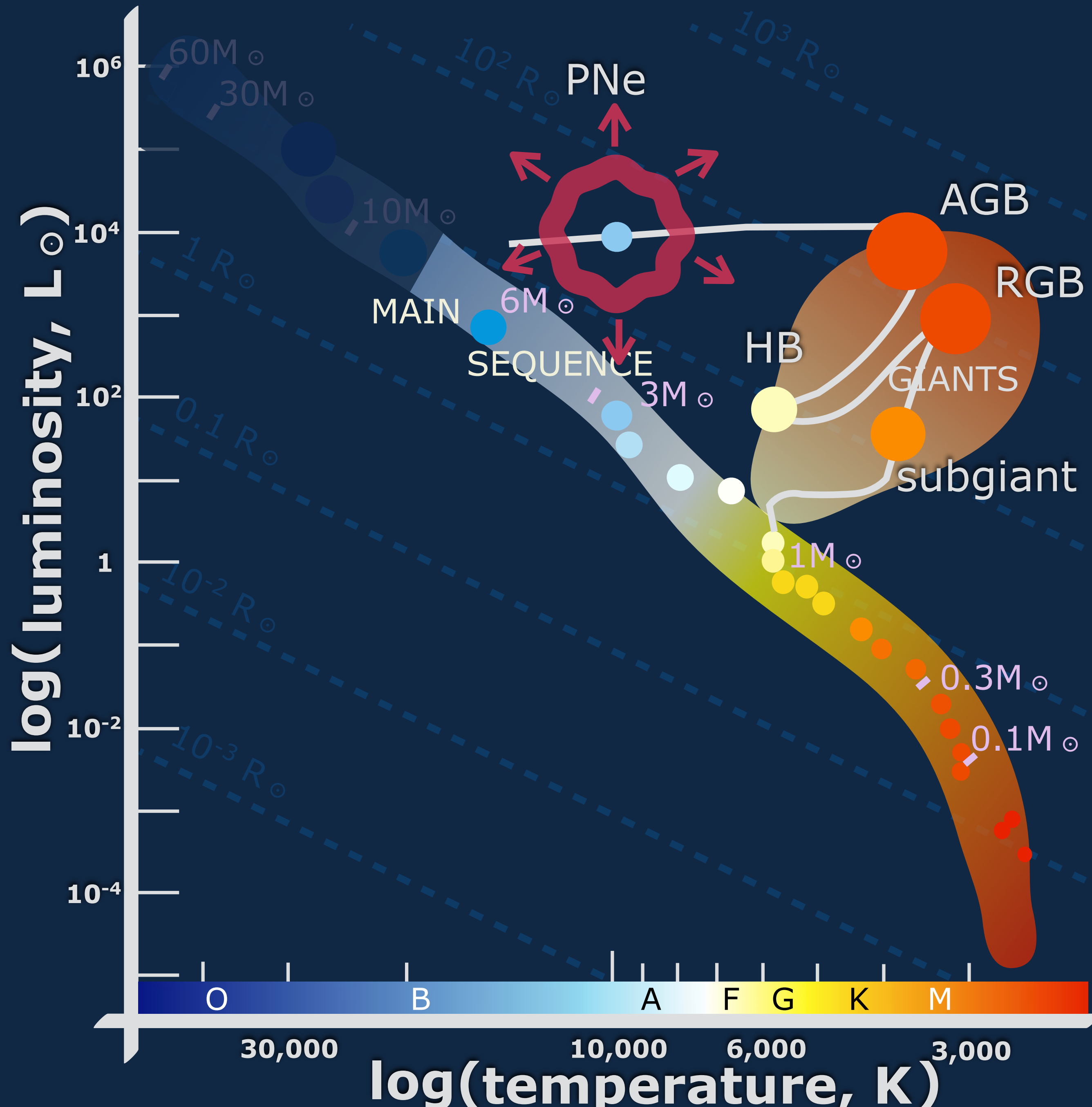
5. Use distance modulus m-M to calculate d

$$m - M = 5(\log(d) - 1)$$



log(temperature, K)

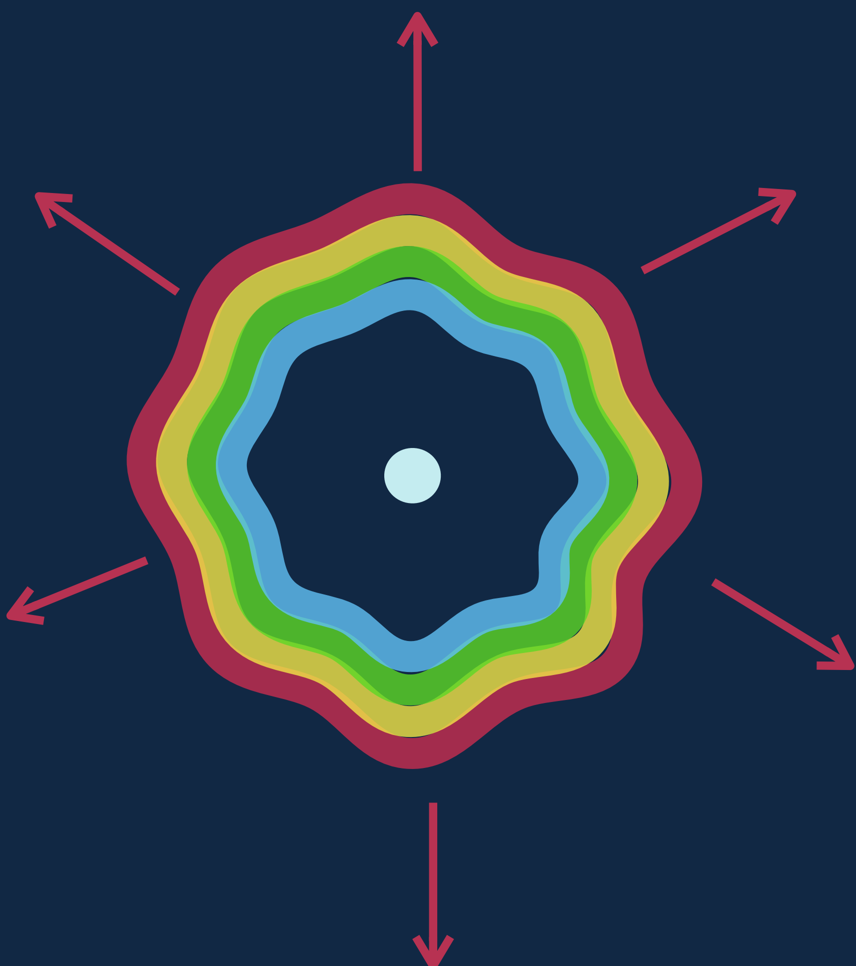
Low-Mass Stars - Deaths



Low-Mass Stars - Deaths

Planetary Nebulae

Expanding glowing shell of ionized gas ejected from a red giant at the end of its life.



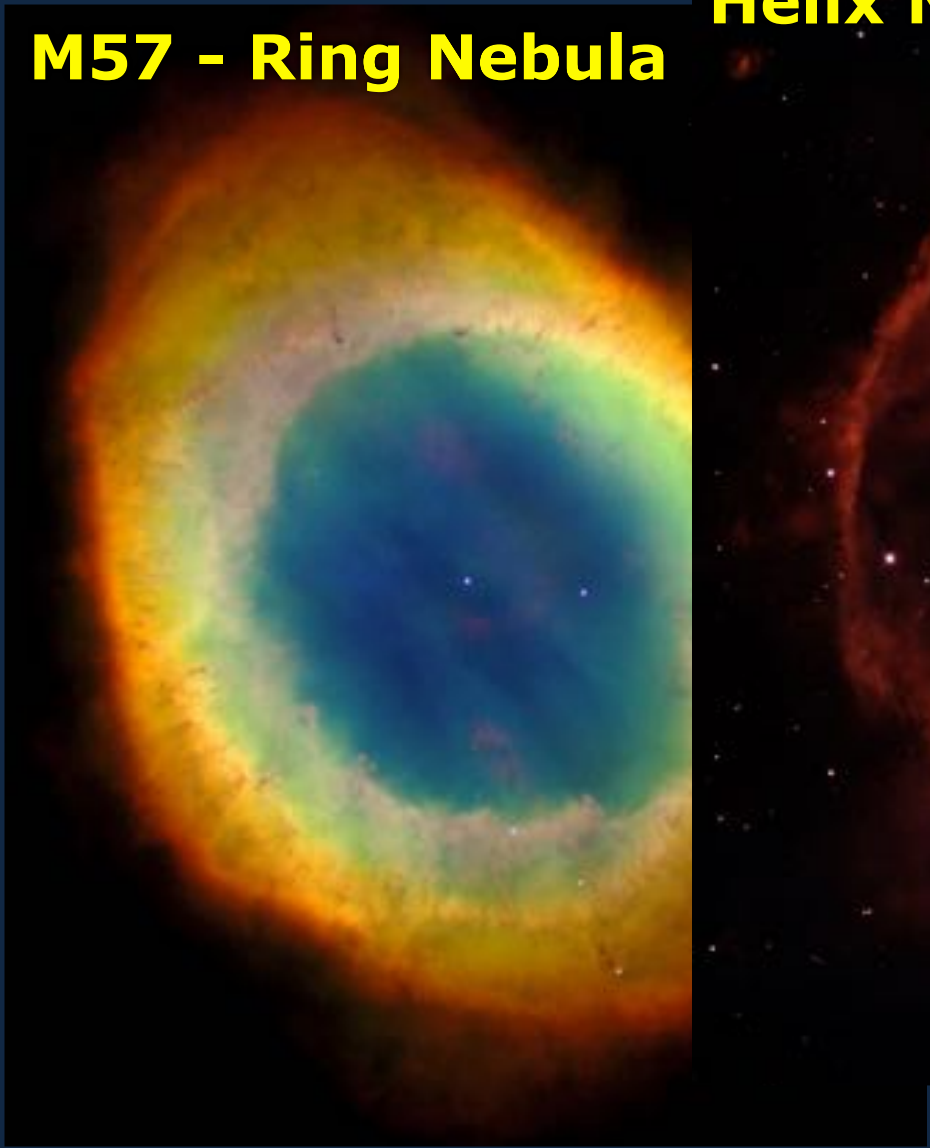
1) Outer layers ejected by strong stellar wind

2) As hot luminous core is exposed it emits UV

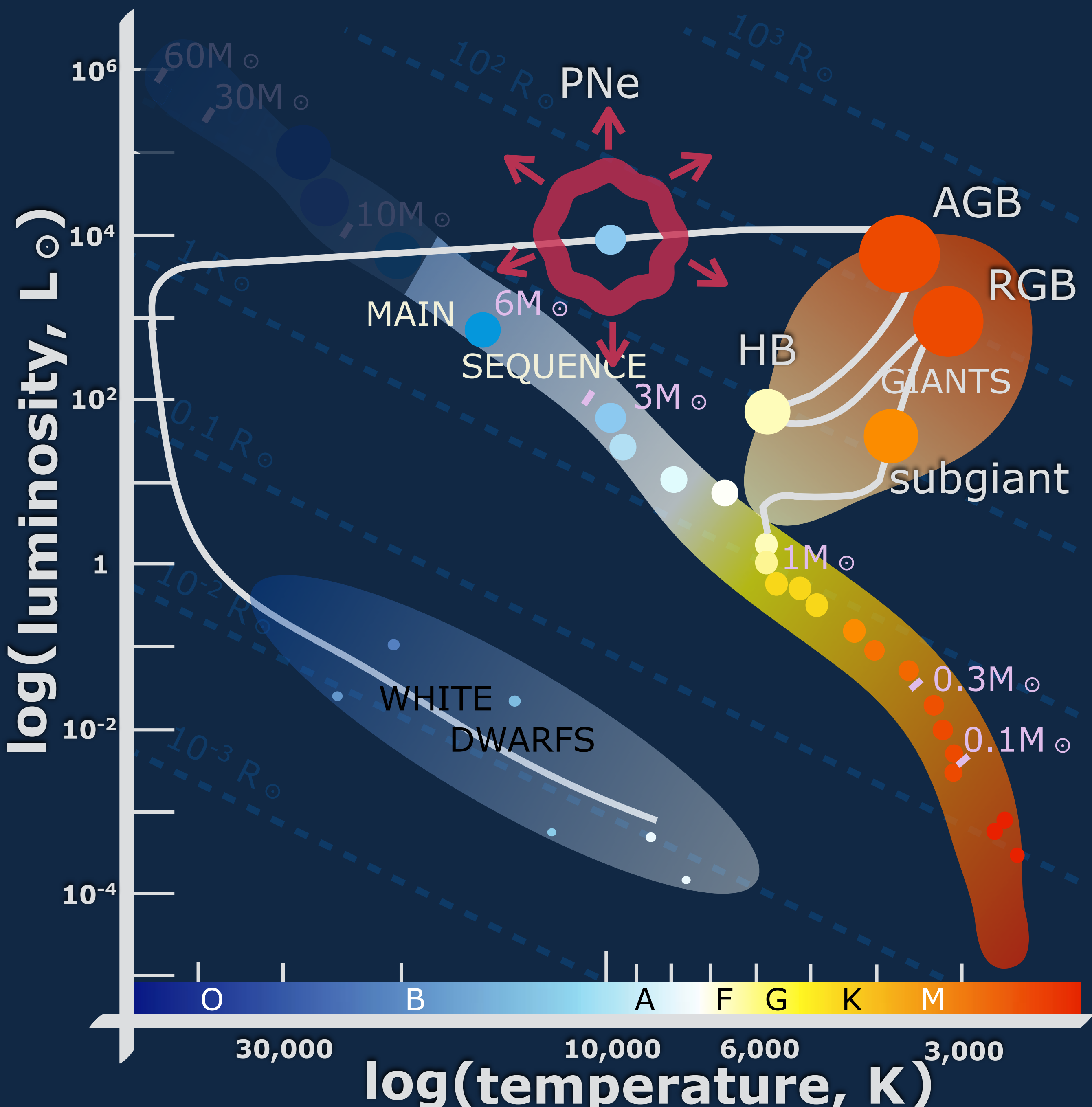
3) UV ionizes the ejected layers

Low-Mass Stars - Deaths

Planetary Nebulae



Low-Mass Stars - Deaths



Low-Mass Stars - Deaths

White Dwarfs

Size: ~Earth

Density: 10^6 g/cm^3

B-Field (G): 10^4-10^8 G

Rotation: minutes

Pressure: e^- degeneracy

Low-Mass Stars - Deaths

White Dwarfs

WDs aren't undergoing core fusion; supported by **electron degeneracy pressure**.

Pauli exclusion principle: no 2 e^- can be in same state (position & momentum)

If all states are full, the gas is degenerate.

(as T increases, more states available, $P \propto T$)

(at high density, collisions restricted $P \propto \rho$)

When He-C fusion starts, core is e^- degenerate; He flash removes degeneracy. Then as the star contracts in the WD phase, ρ increases, whole star becomes e^- degenerate.

Low-Mass Stars - Deaths

White Dwarf M-R Relation

$$P \propto \rho^{5/3}$$

hydrostatic equilibrium

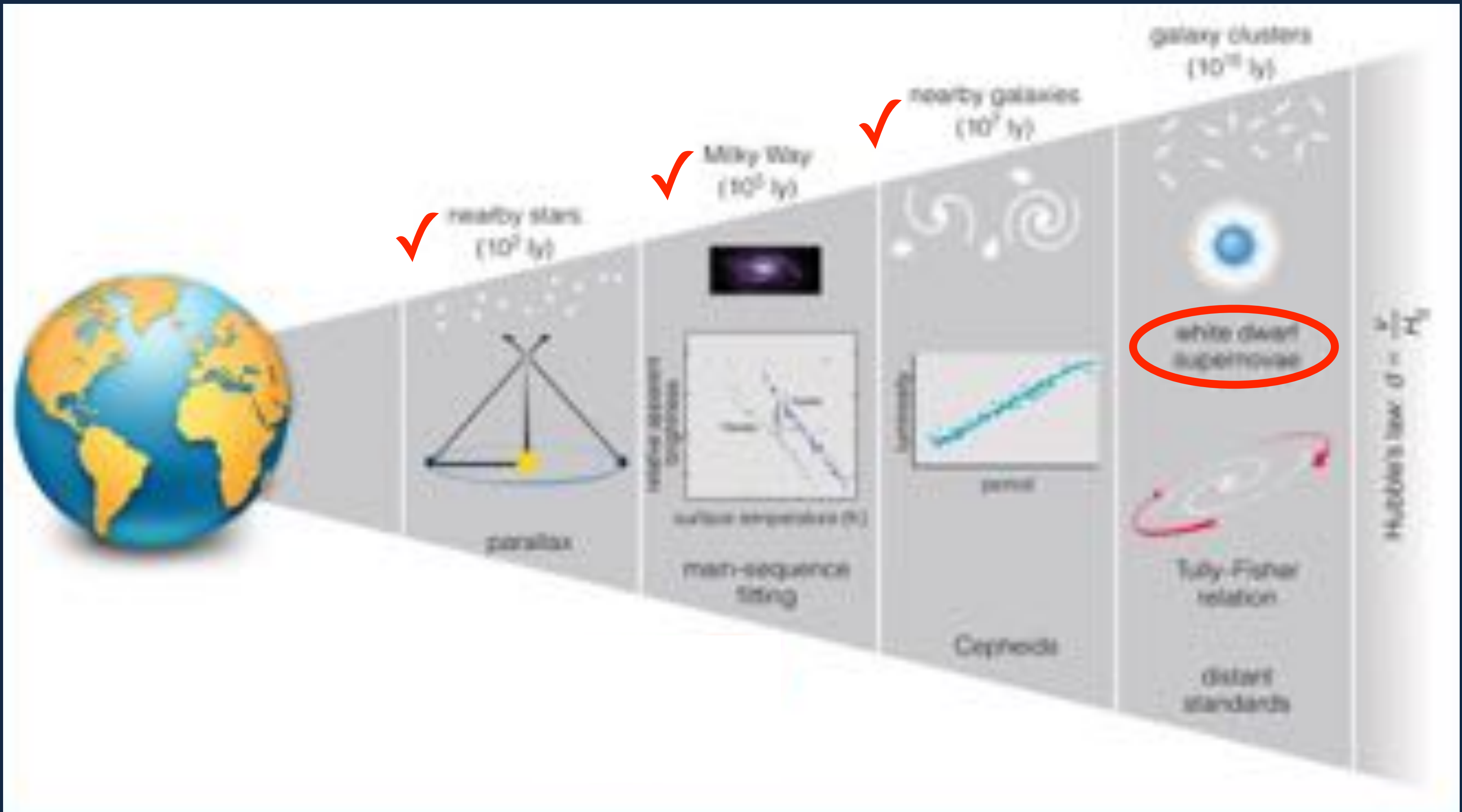
$$P \propto M^2/R^4$$

$$\rho \propto M/R^3$$

$$R \propto 1/M^{1/3}$$

Type Ia Supernovae

The distance ladder…



Type Ia Supernovae

Type I

"no hydrogen"

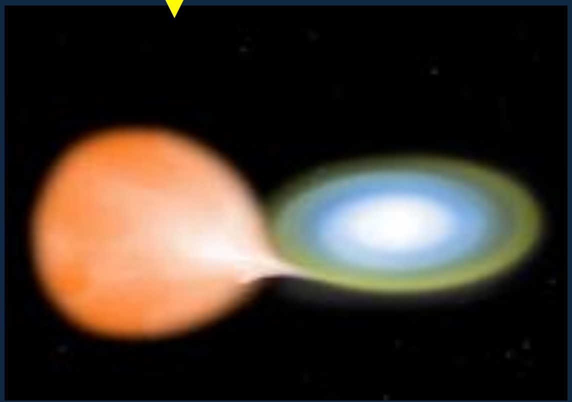
Type II

"has hydrogen"

Ia

no H

has Si



"Thermonuclear supernovae": result of a WD exceeding the Chandrasekhar limit

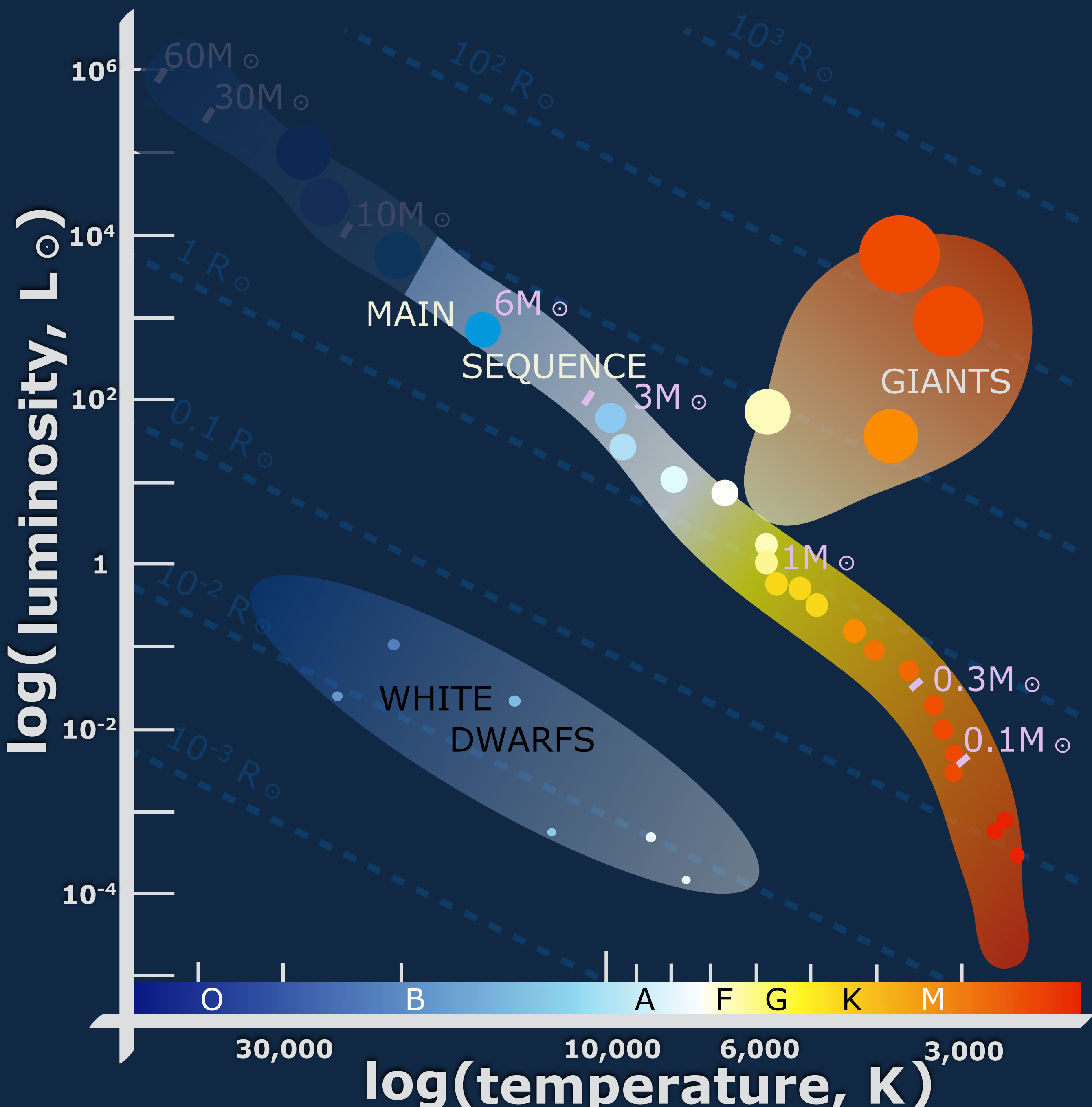
Type Ia Supernovae

"Thermonuclear supernovae": result of a WD exceeding its maximum mass, **Chandrasekhar mass**

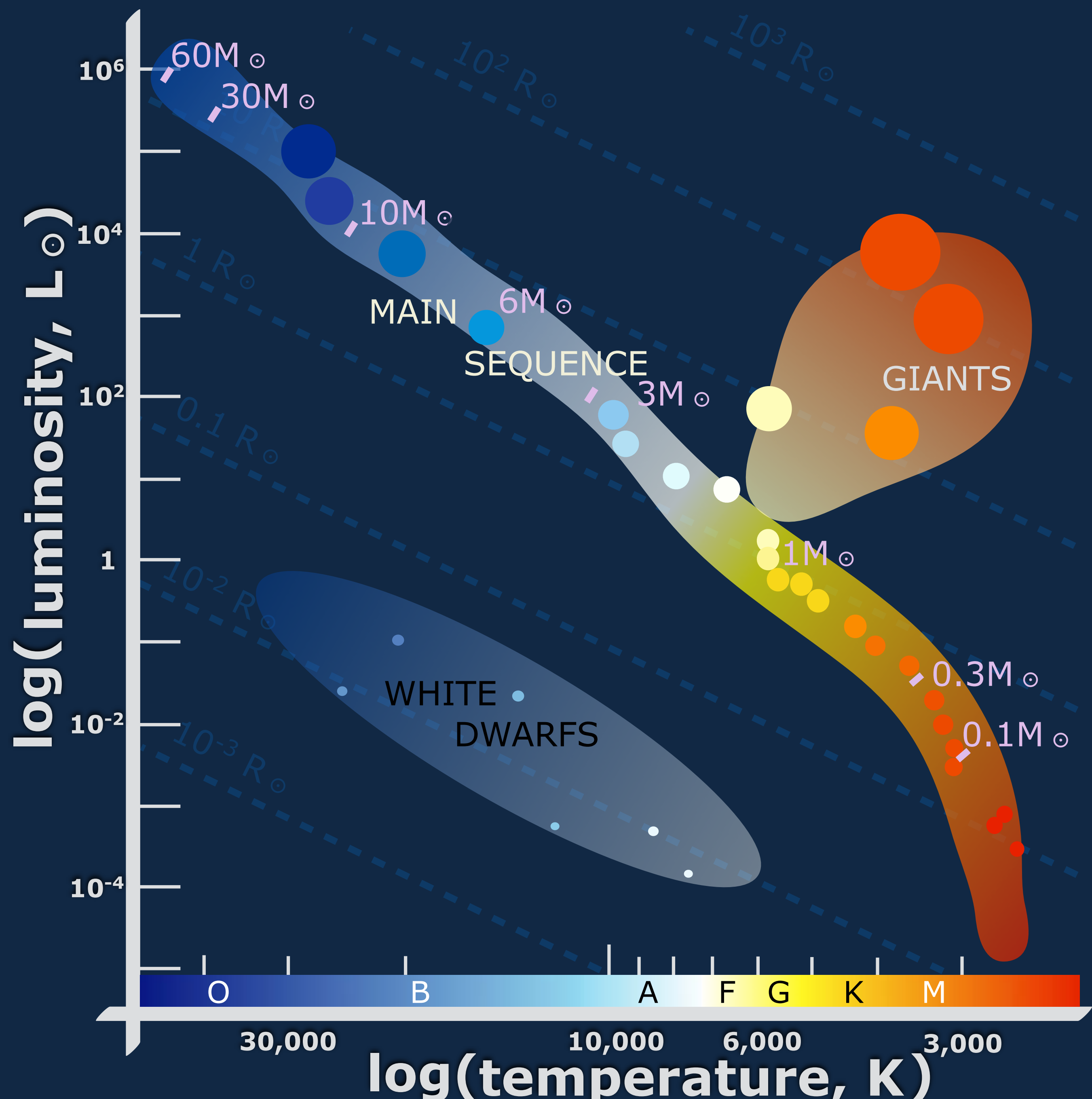
Chandrasekhar mass: maximum mass of a star that can be supported by e^- degeneracy pressure

$\sim 1.4 M_\odot$

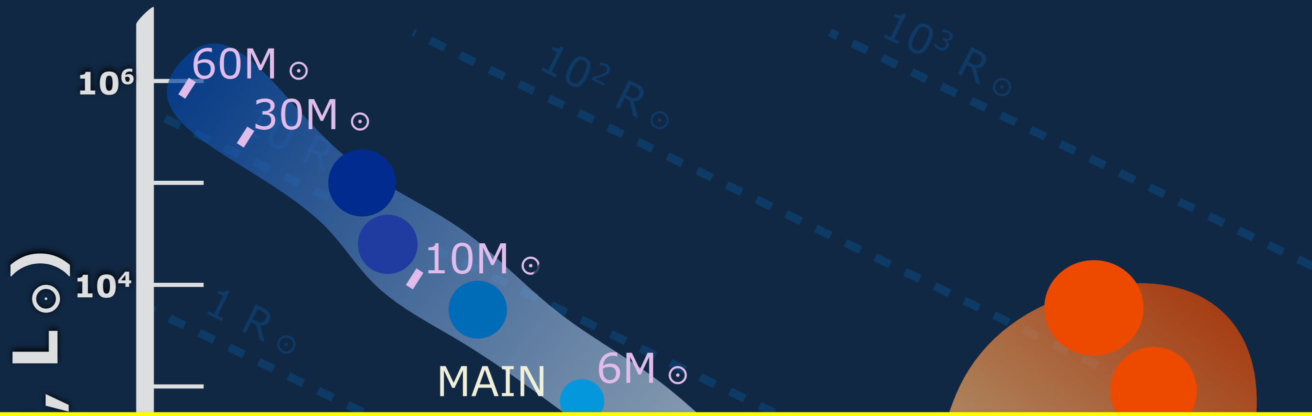
Low-mass Stellar Evolution



Massive Stellar Evolution



Massive Stellar Evolution: MS



Quick Question

Given the data in the H-R diagram and the fact that a star's main sequence lifetime ~ 10^{10} M/L years, how long do massive stars stay on the main sequence?

A) $10^{12\text{-}13}$ years

B) $10^{10\text{-}11}$ years

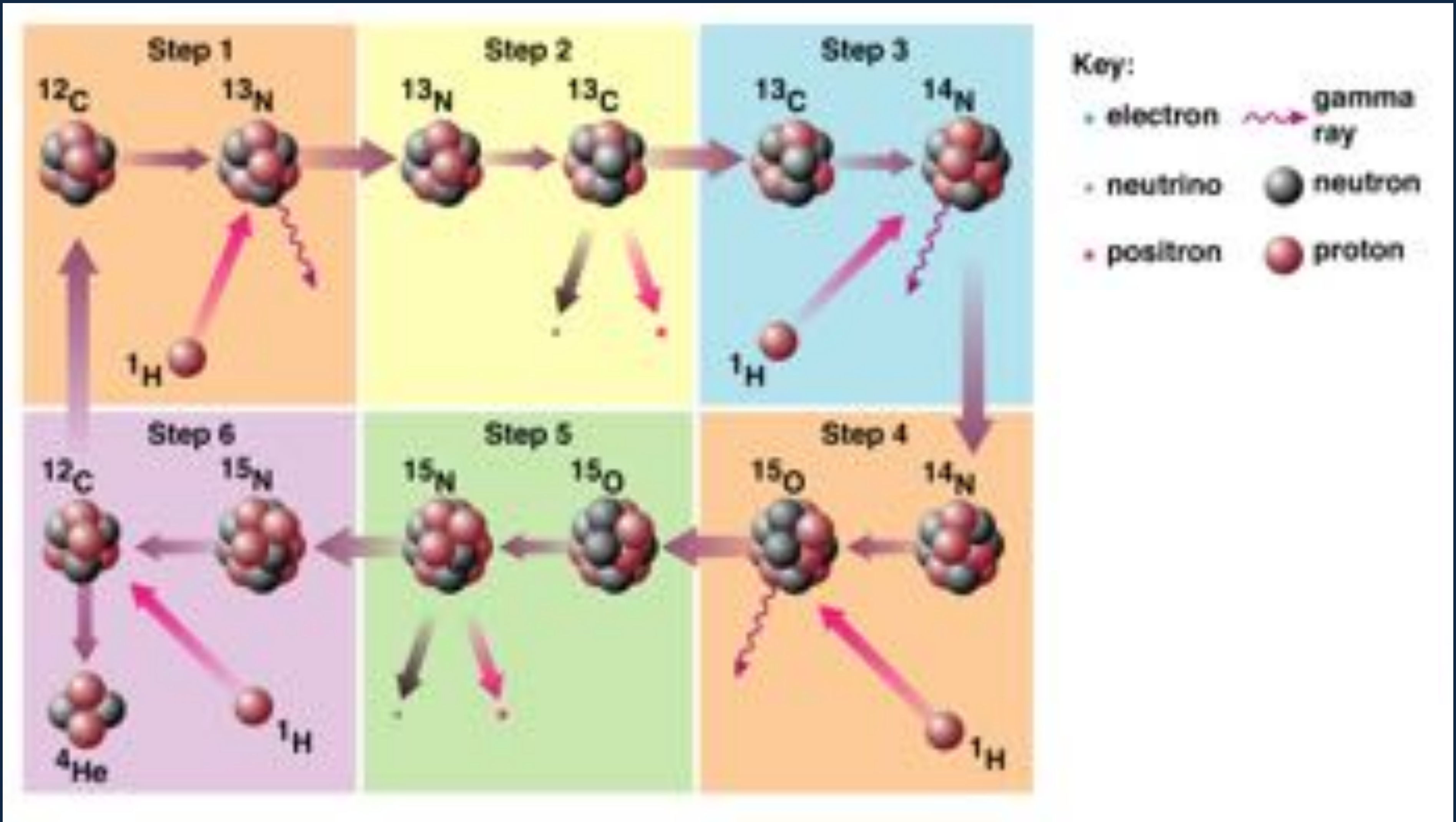
C) $10^{8\text{-}9}$ years

D) $10^{6\text{-}7}$ years

Massive Stellar Evolution: MS

H as Stellar Fuel, v2.0

CNO Cycle



Massive Stellar Evolution: MS

Discussion Question

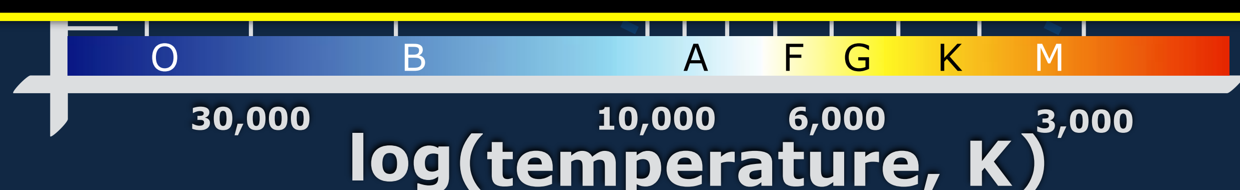
You observe a site with lots of O- and B-type stars in a nearby galaxy. What might you conclude?

A) the site is actively forming stars

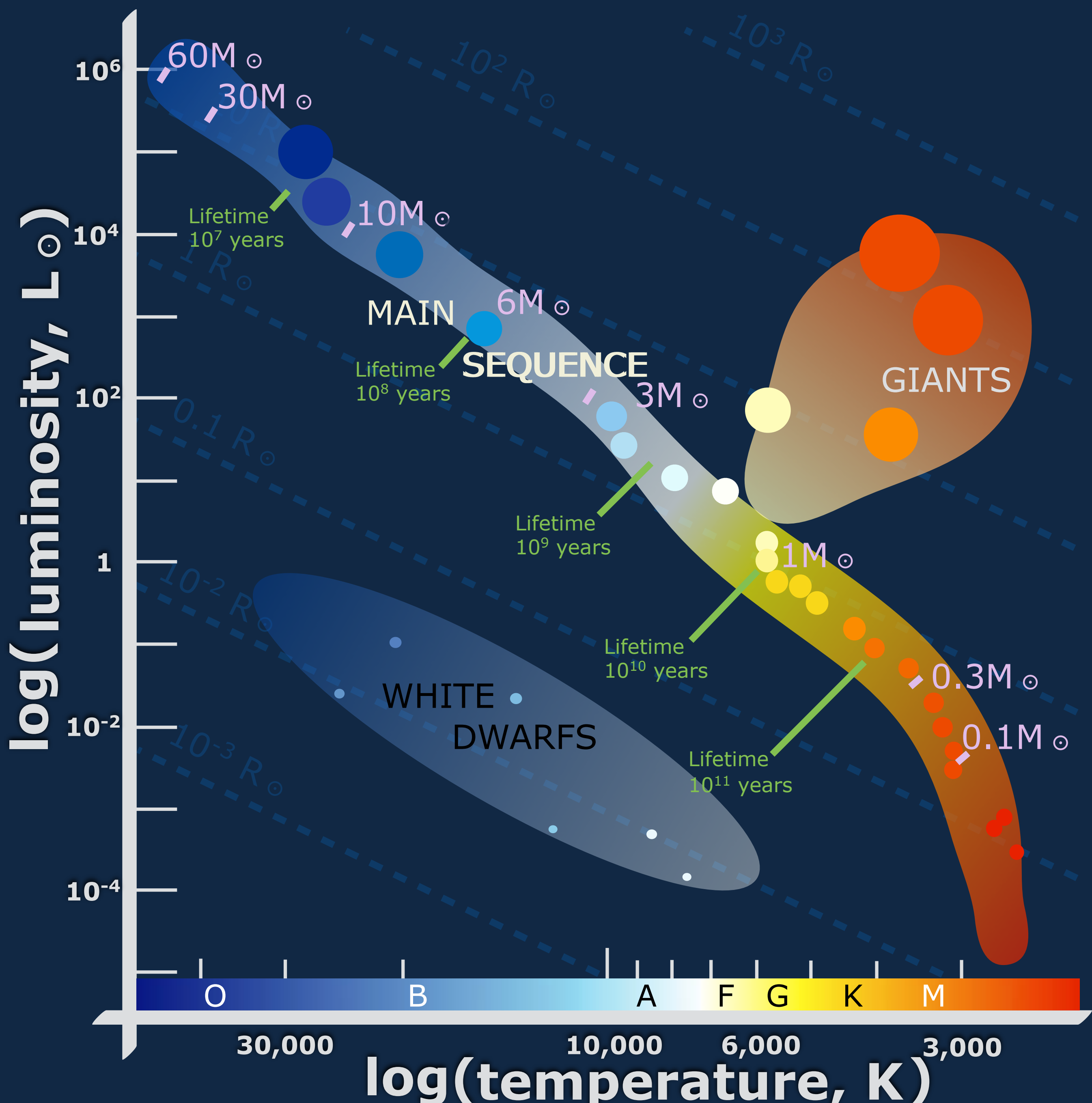
B) the site stopped forming new stars long ago

C) the site has a low Jeans mass

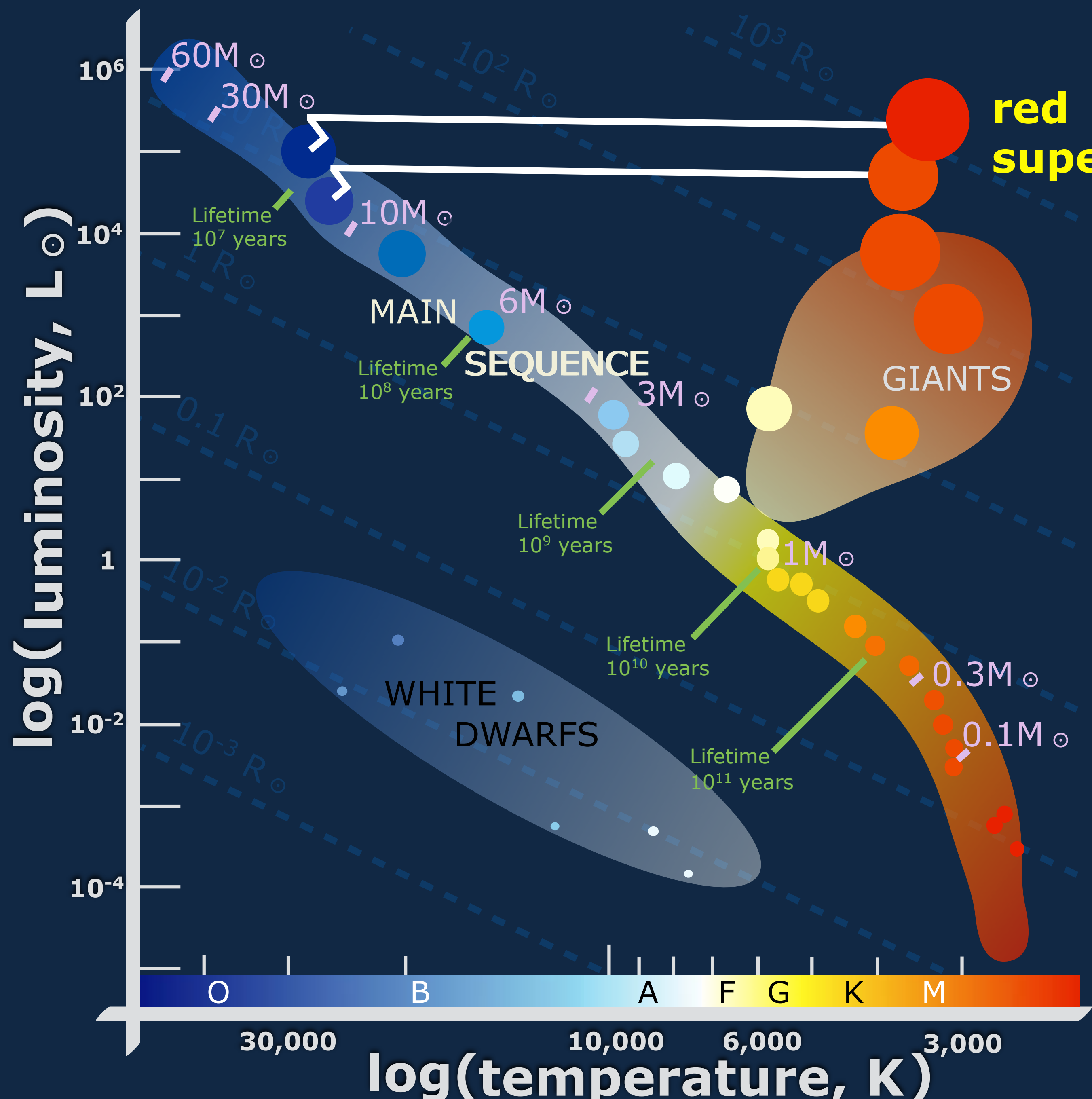
D) the site has a large Jeans radius



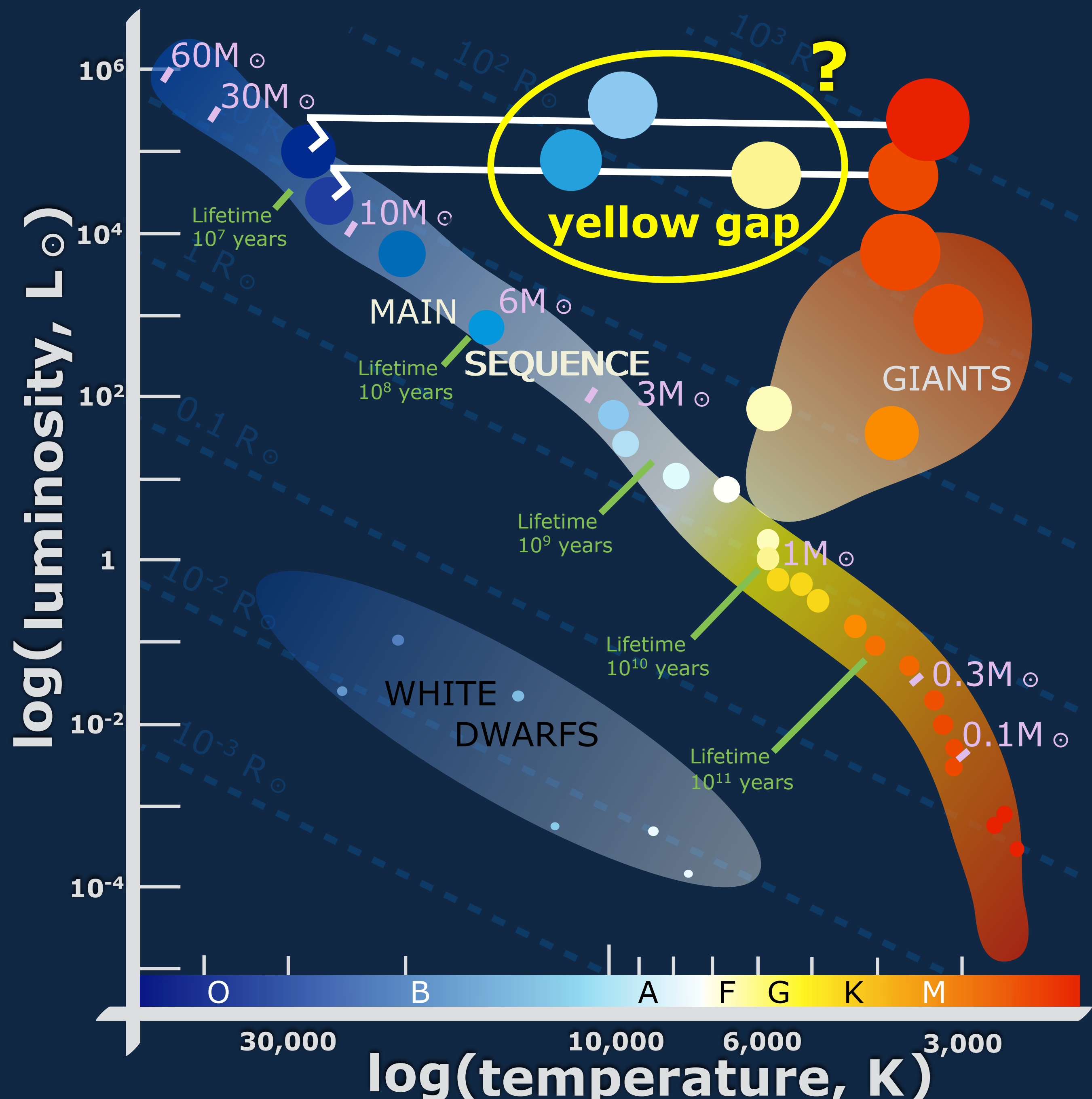
Massive Stellar Evolution: MS



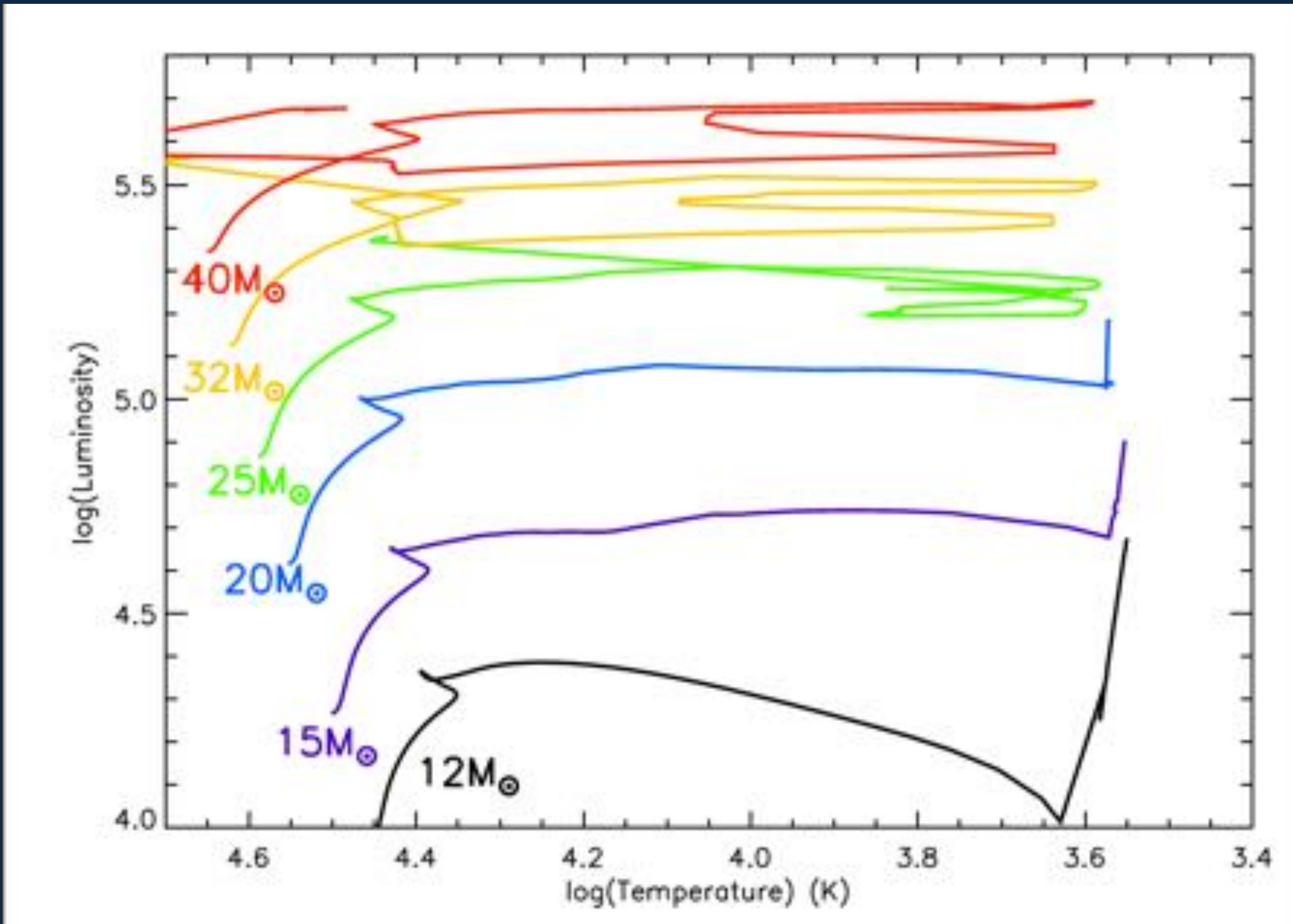
Massive Stellar Evolution: Post-MS



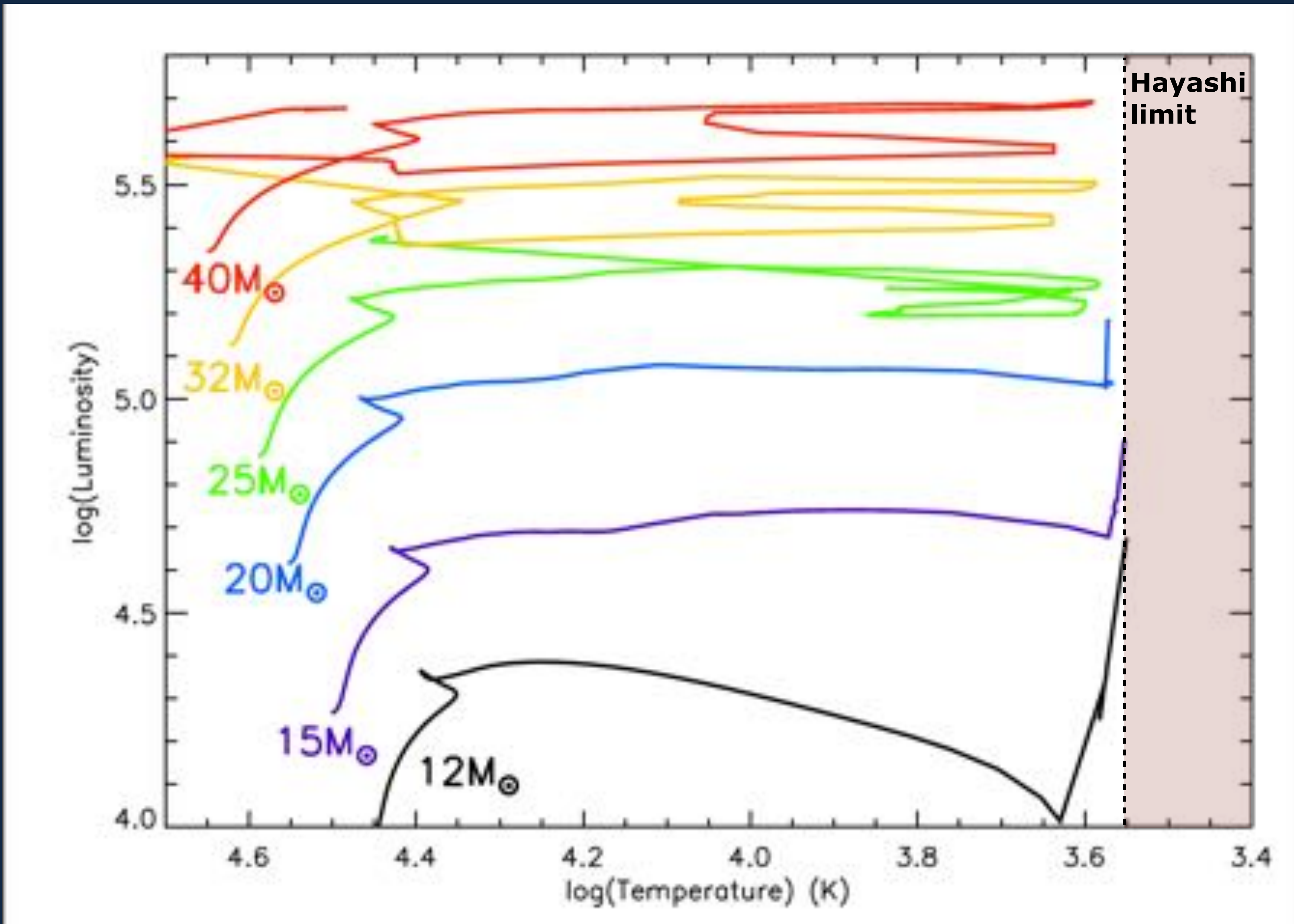
Massive Stellar Evolution: Post-MS



Massive Stellar Evolution: Post-MS

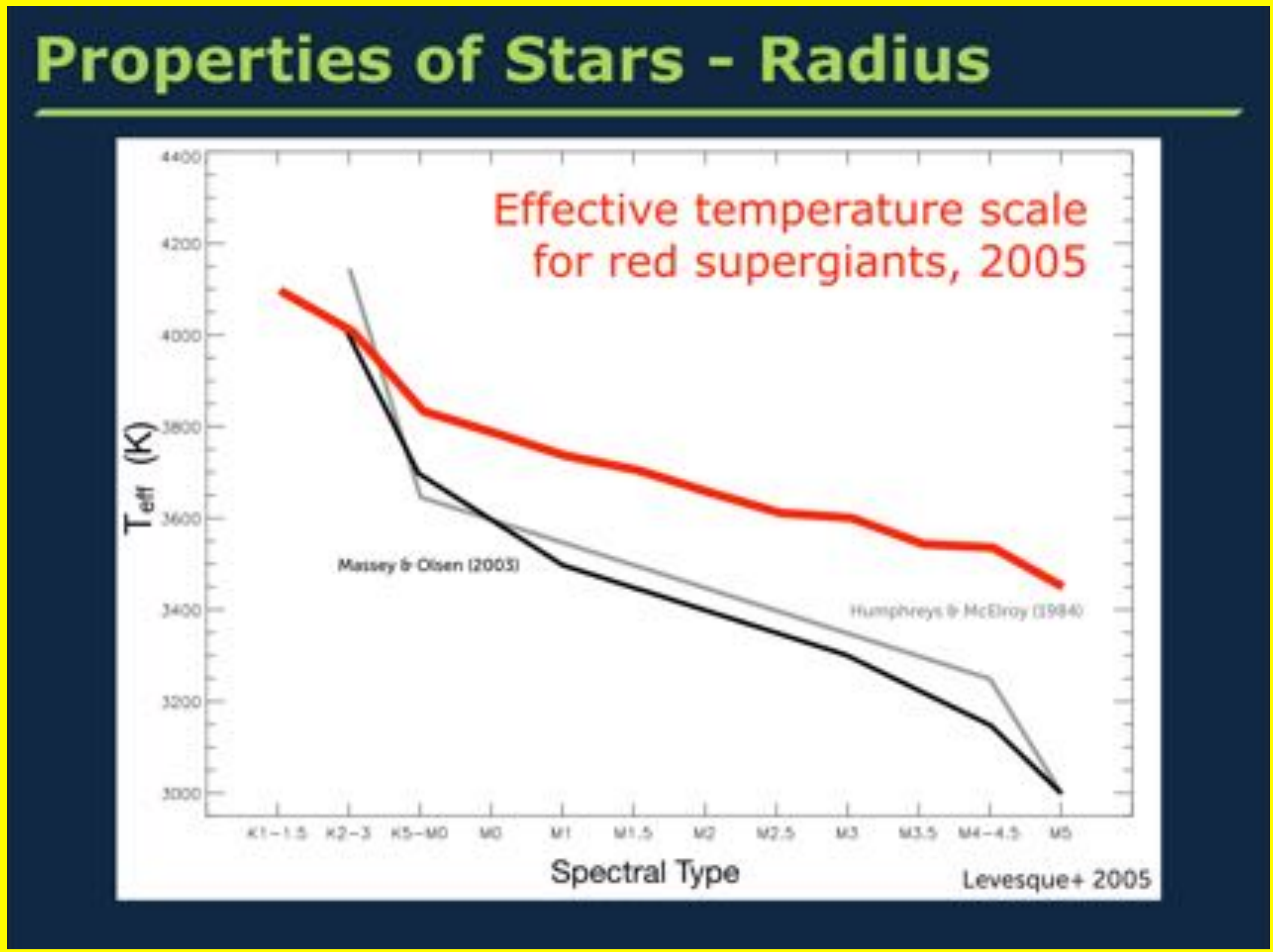


Massive Stellar Evolution: Post-MS

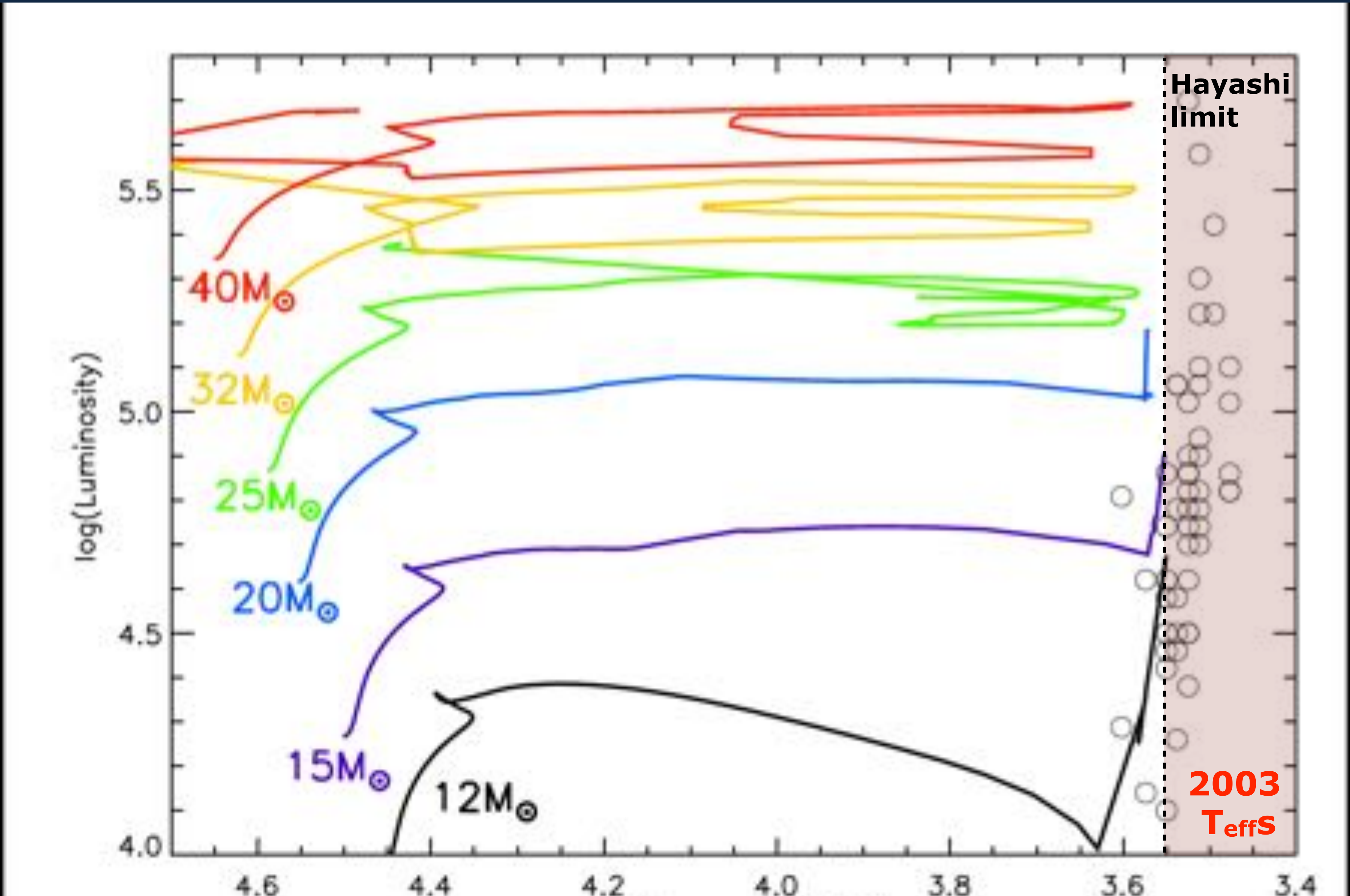


Massive Stellar Evolution: Post-MS

A couple weeks ago…

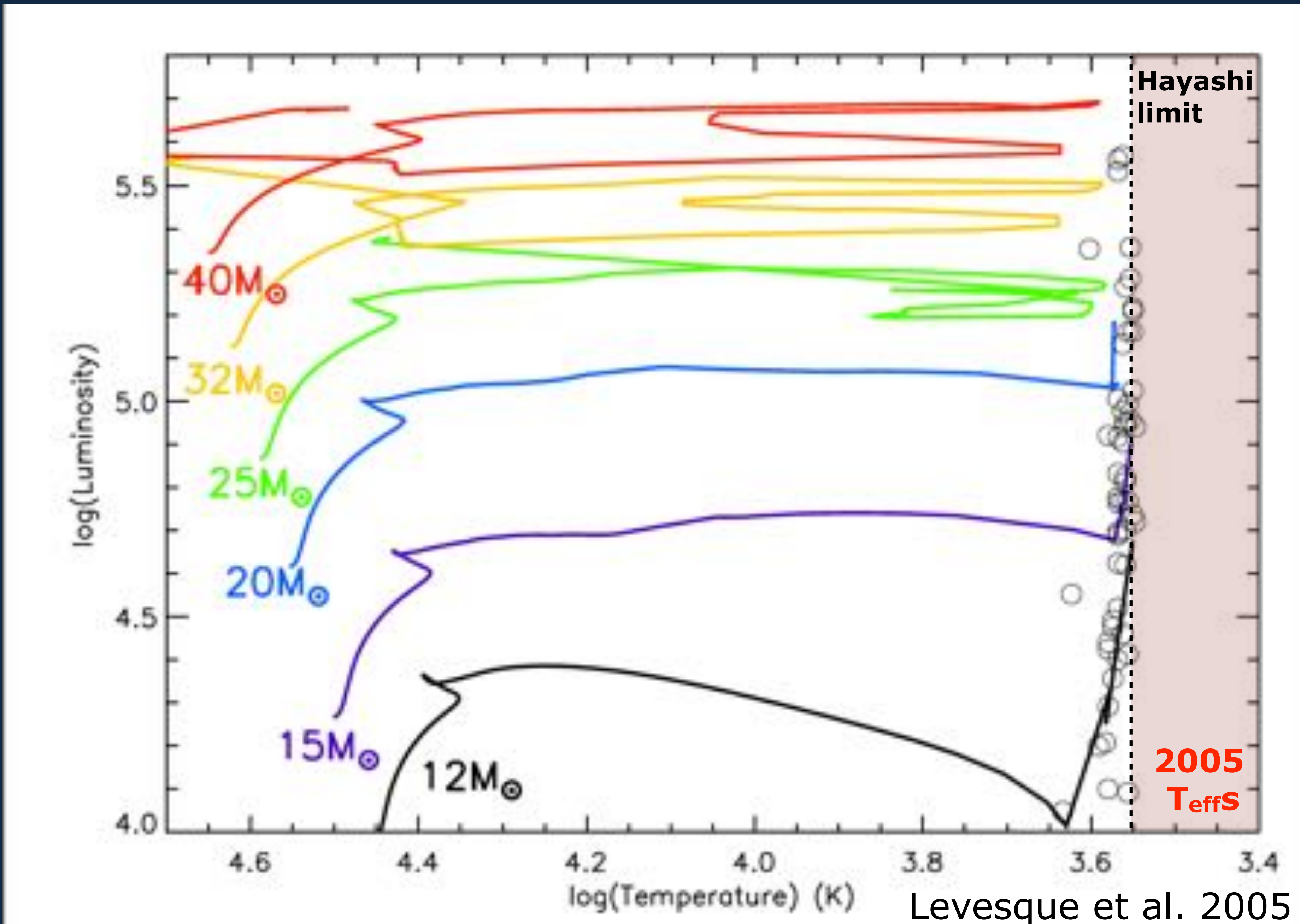


Massive Stellar Evolution: Post-MS



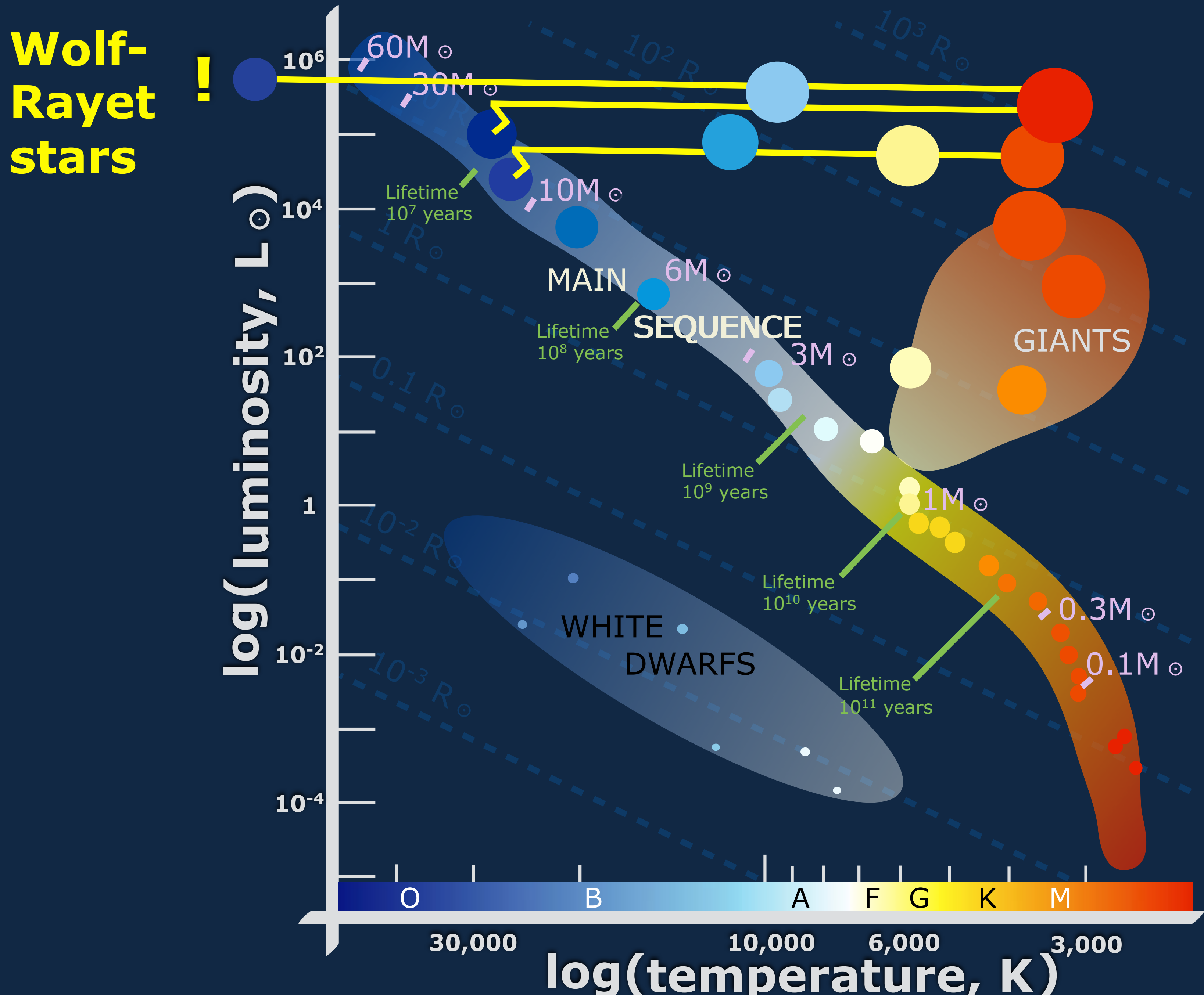
Levesque et al. 2005

Massive Stellar Evolution: Post-MS

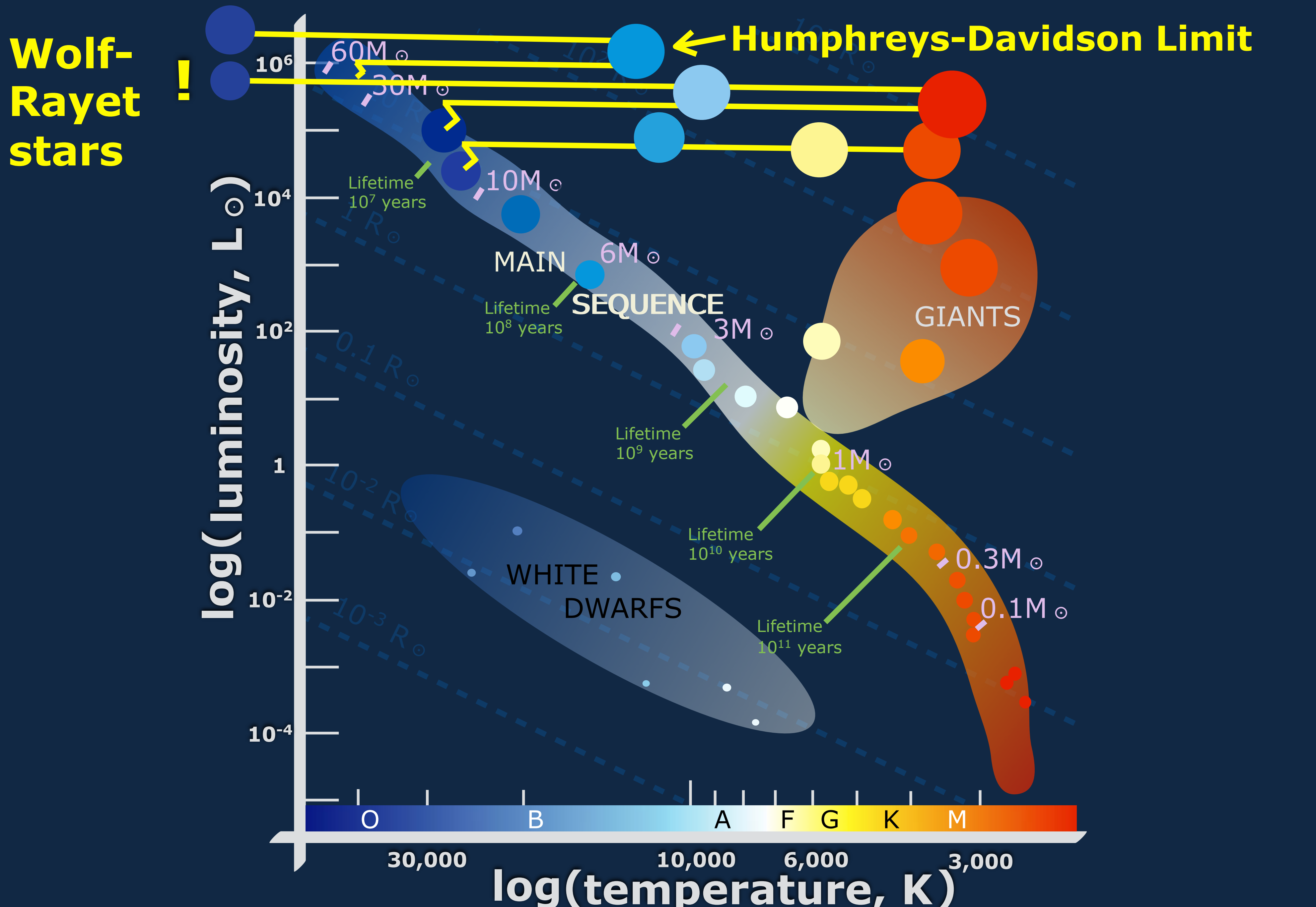


Levesque et al. 2005

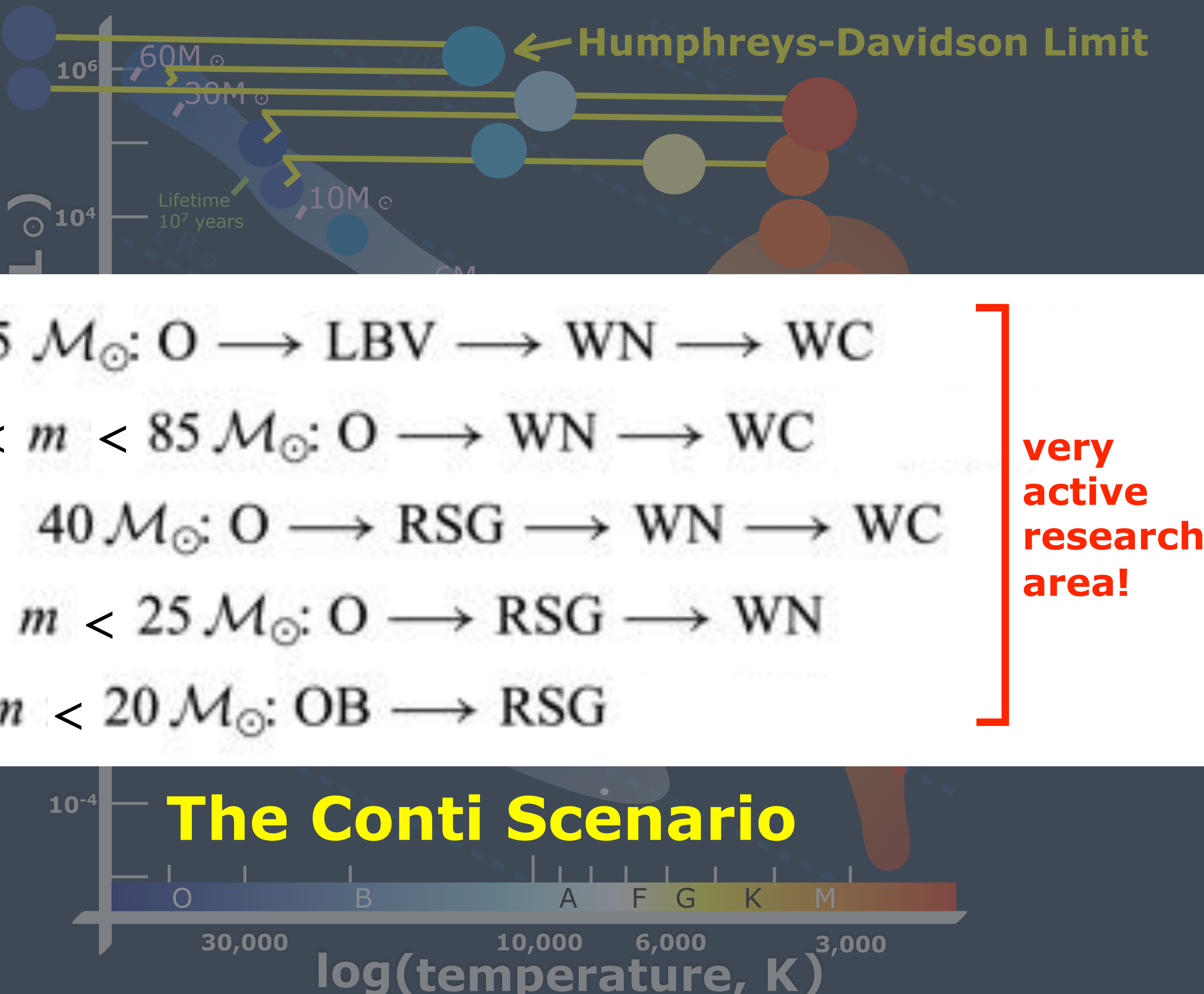
Massive Stellar Evolution: Post-MS



Massive Stellar Evolution: Post-MS



Massive Stellar Evolution: Post-MS



$$m > 85\,\mathcal{M}_\odot\text{: O} \longrightarrow \text{LBV} \longrightarrow \text{WN} \longrightarrow \text{WC}$$

$$40 < m < 85\,\mathcal{M}_\odot\text{: O} \longrightarrow \text{WN} \longrightarrow \text{WC}$$

$$25 < m < 40\,\mathcal{M}_\odot\text{: O} \longrightarrow \text{RSG} \longrightarrow \text{WN} \longrightarrow \text{WC}$$

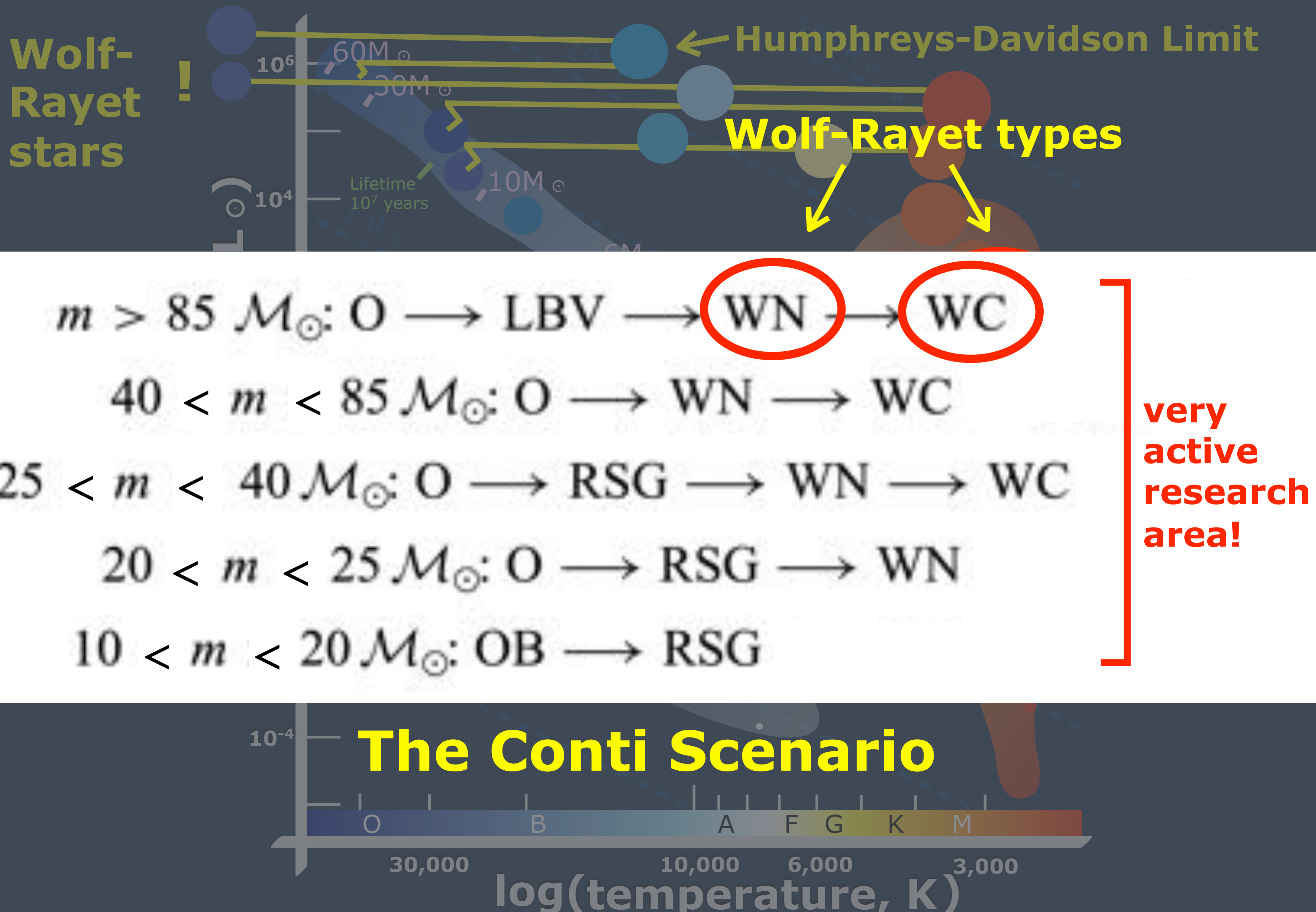
$$20 < m < 25\,\mathcal{M}_\odot\text{: O} \longrightarrow \text{RSG} \longrightarrow \text{WN}$$

$$10 < m < 20\,\mathcal{M}_\odot\text{: OB} \longrightarrow \text{RSG}$$

very active research area!

The Conti Scenario

Massive Stellar Evolution: Post-MS



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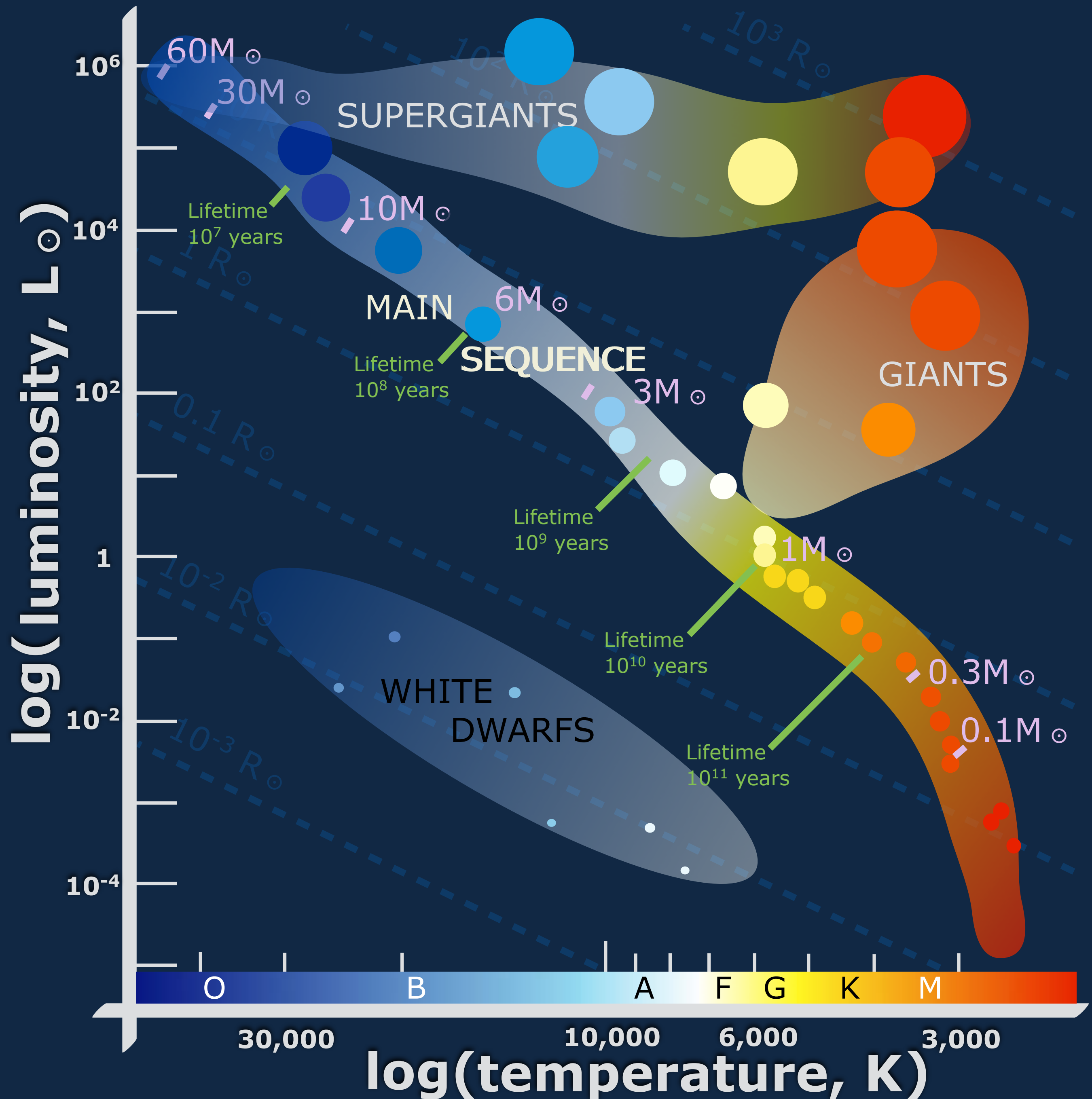


now what?

Massive Stellar Evolution: Post-MS

Post-MS reactions

Fe fusion **requires** rather than **produces** energy…

H fusion: ~10^7 years

He fusion: ~10^6 years

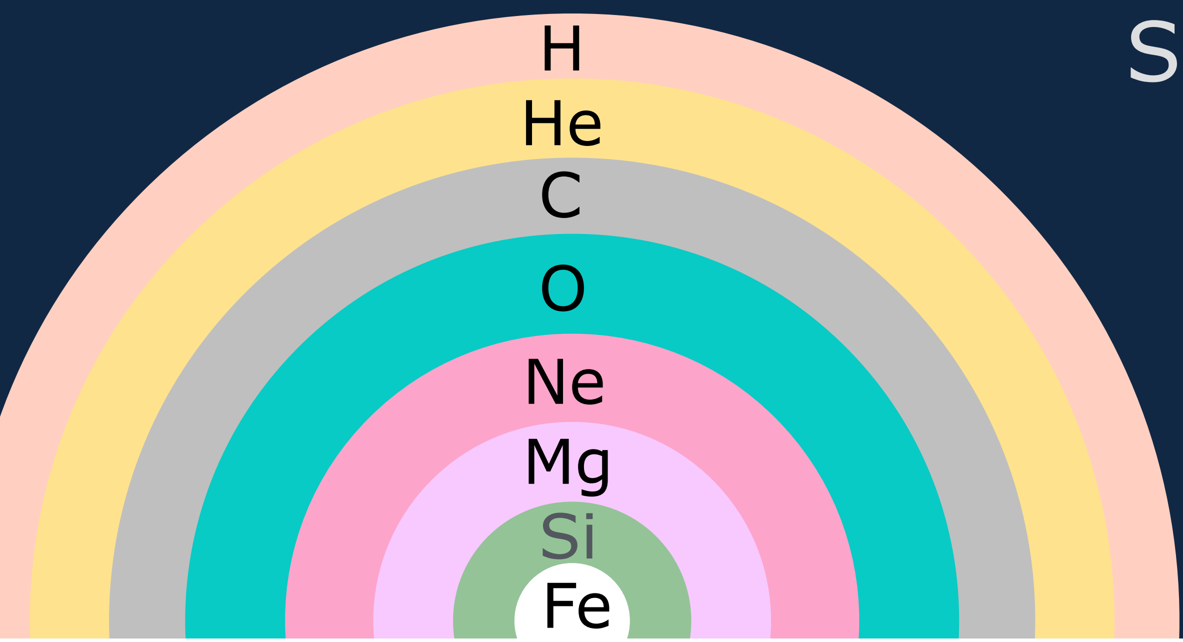
C fusion: ~300 years

O fusion: ~200 days

Ne fusion: ~days

Mg fusion: ~days

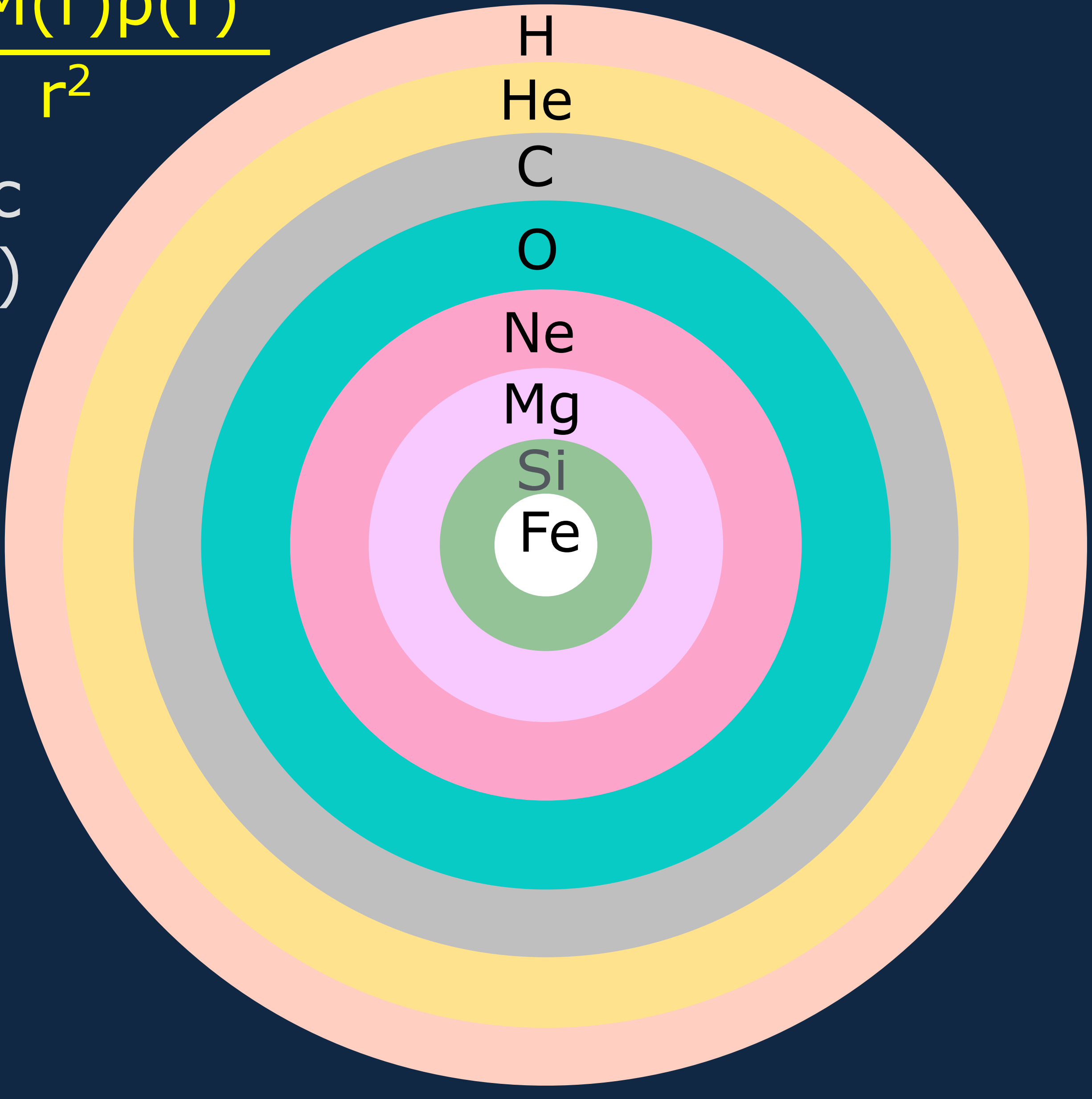
Si fusion: ~days



Massive Stellar Evolution - Deaths

$$\cancel{\frac{\Delta P(r)}{\Delta r}} = \frac{-GM(r)\rho(r)}{r^2}$$

(hydrostatic equilibrium)



Massive Stellar Evolution - Deaths

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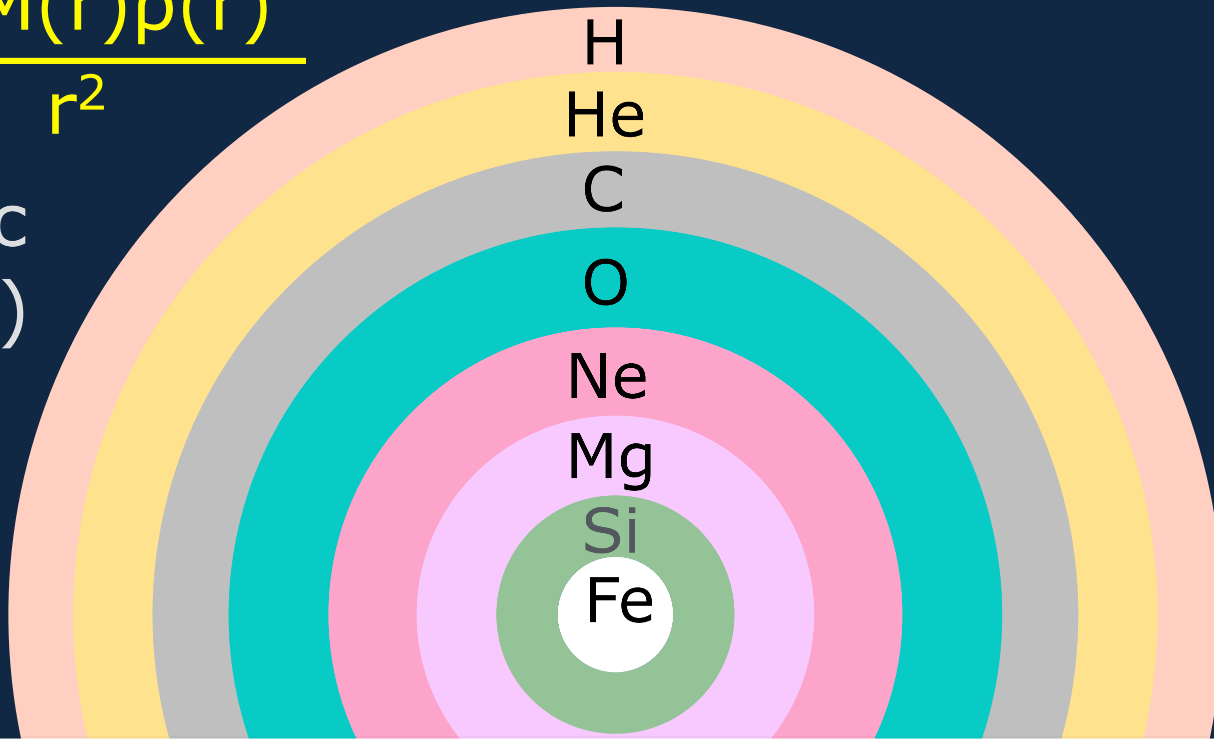


—At very high T, Fe core is destroyed by photodisintegration

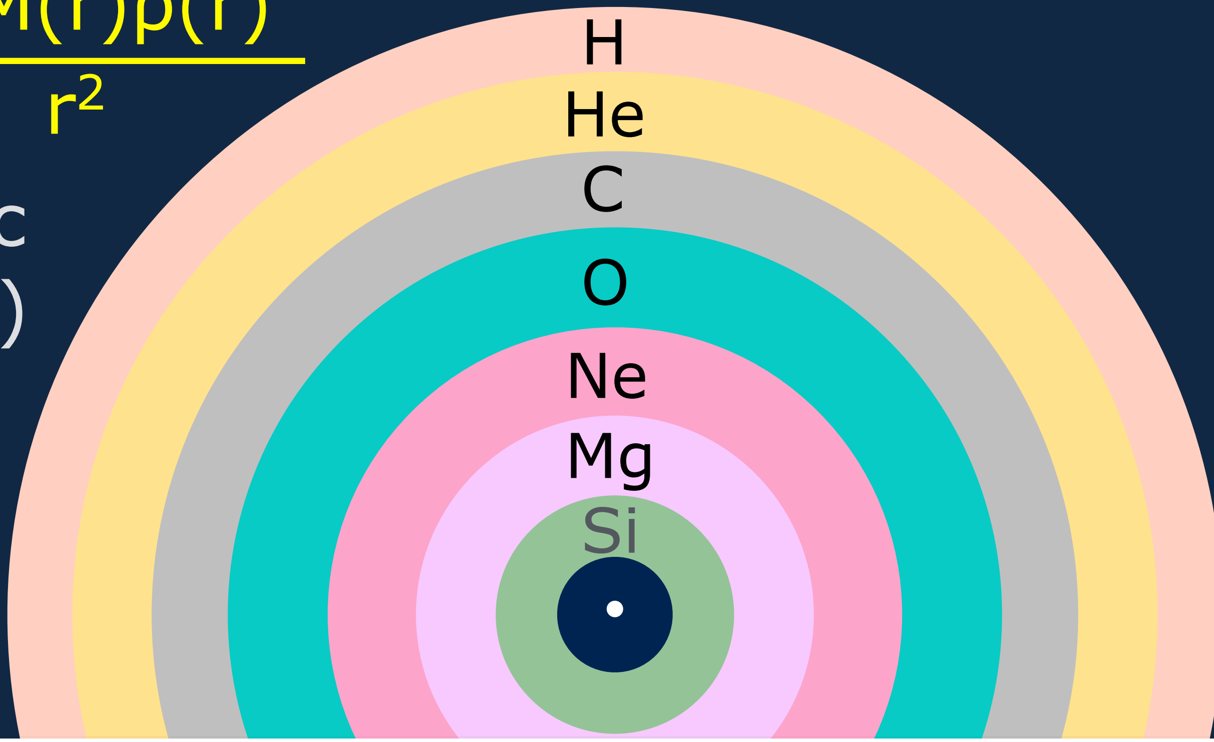
—free e^-'s captured by photodisintegration products; e^- degeneracy pressure can no longer help…

—core collapses in a matter of seconds (supersonic speeds)

Massive Stellar Evolution - Deaths

$$\cancel{\frac{\Delta P(r)}{\Delta r}} = \frac{-GM(r)\rho(r)}{r^2}$$

(hydrostatic equilibrium)



—density of inner core exceeds ~ 8 x 10^{17} kg m^{-3}

—n degeneracy pressure kicks in, repels further collapse

—core rebounds, sends pressure waves that become a shock wave at sonic speed and propagates outward

Massive Stellar Evolution - Deaths

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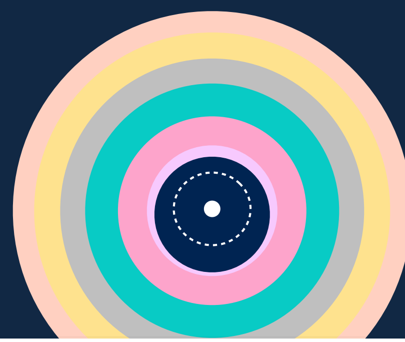

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Massive Stellar Evolution - Deaths

$$\cancel{\frac{\Delta P(r)}{\Delta r}} = \frac{-GM(r)\rho(r)}{r^2}$$

(h

ec

Quick Question

Will the green bouncy ball rebound to a maximum height of:

A) H/4

B) H/2

C) H

D) ≥2*H

—d

—n

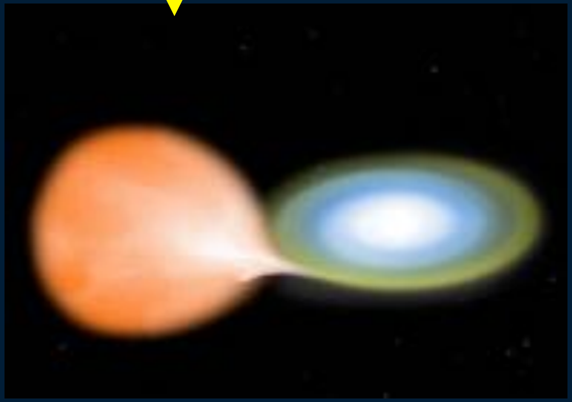
—core rebounds, sends pressure waves that become a shock wave at sonic speed and propagates outward

Massive Stellar Evolution - Deaths

Type I

"no hydrogen"

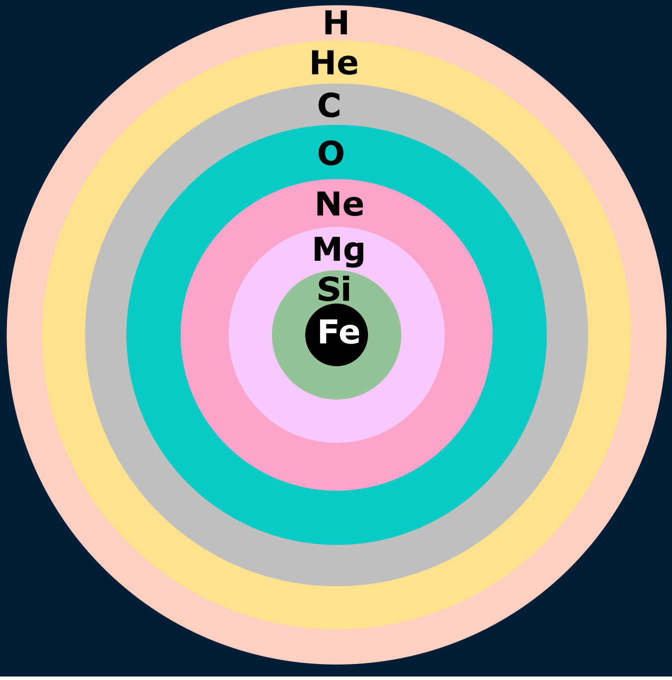
- **Ia**: no H, has Si
- **Ib**
- **Ic**



Type II

"has hydrogen"

- **II**: has H



Massive Stellar Evolution - Deaths

Type I
"no hydrogen"

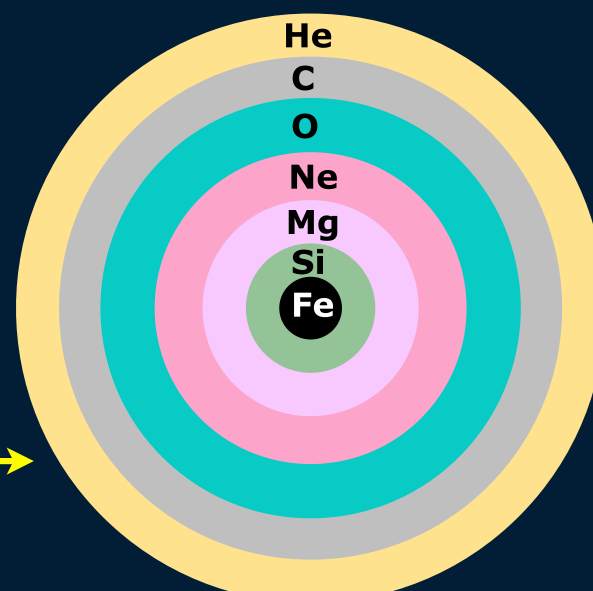
Ia
no H
has Si

Ib
no H
has He
no Si

Ic

Type II
"has hydrogen"

II
has H



Massive Stellar Evolution - Deaths

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"no hydrogen"

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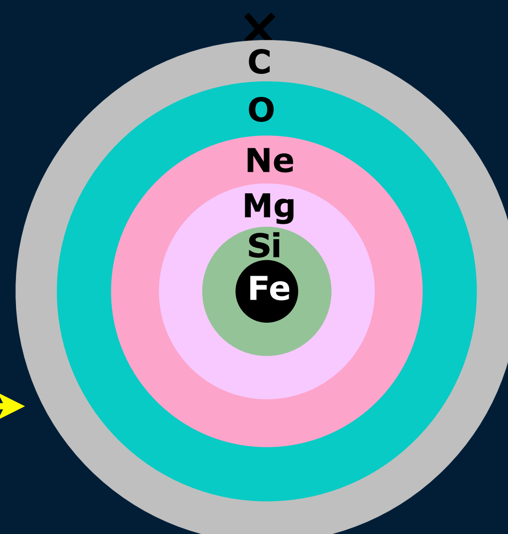
has H



Massive Stellar Evolution - Deaths

Massive Stellar Evolution - Deaths

supernova remnant

SN 1054/
Crab Nebula

Hubble Space Telescope

Massive Stellar Evolution - Deaths

SN 1572
"Tycho's Supernova"

Massive Stellar Evolution - Deaths

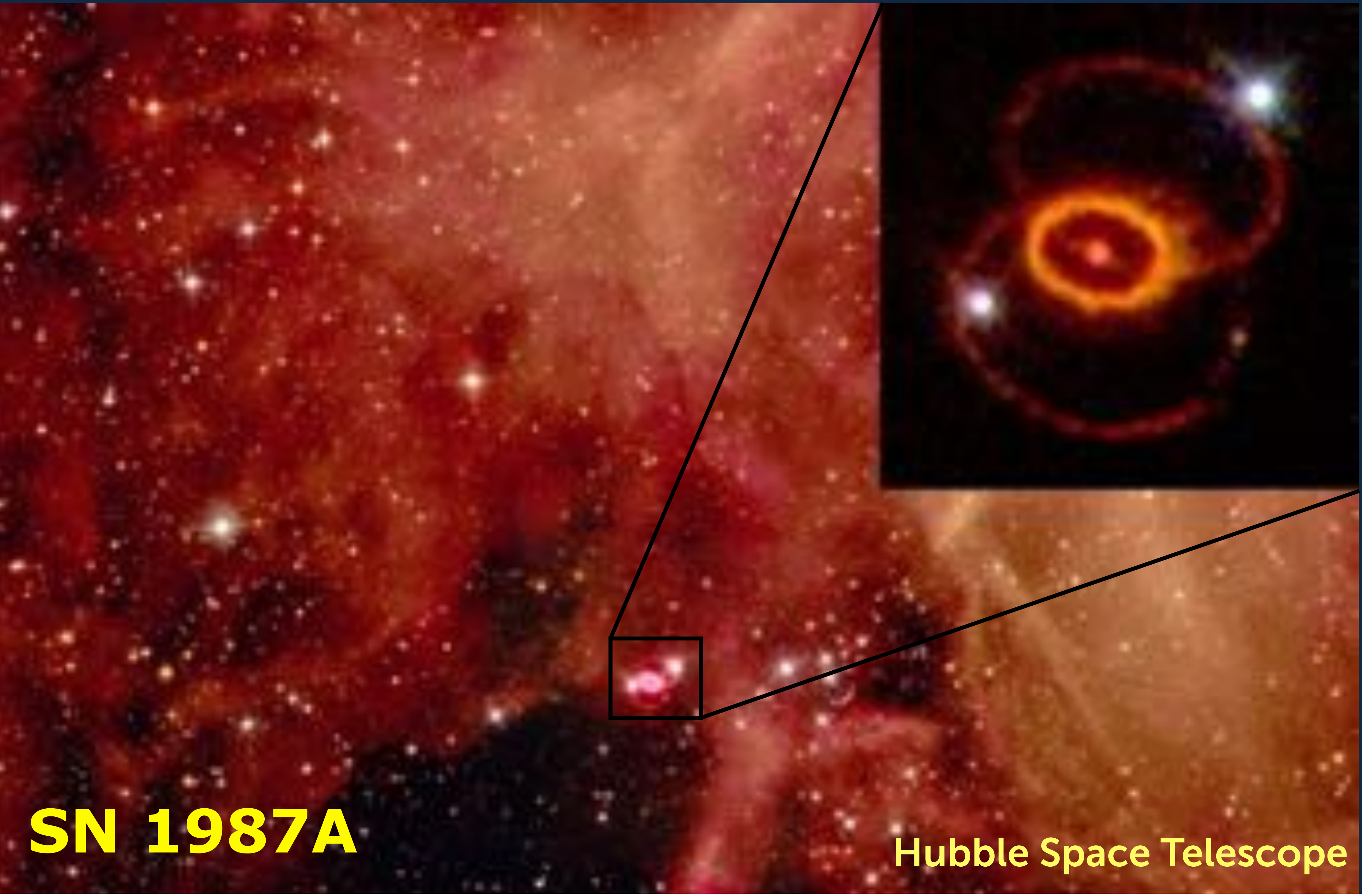
supernova remnant

SN 1572
“Tycho’s Supernova”

Chandra X-ray Observatory

Massive Stellar Evolution - Deaths

Massive Stellar Evolution - Deaths



Massive Stellar Evolution - Deaths

July 2005

Massive Stellar Evolution - Deaths

June 2011

Massive Stellar Evolution - Deaths

Massive Stellar Evolution - Deaths

A few weeks ago…

Next time: weird stars...