ASTR 421

Stellar Observations and Theory

Lecture 16
Stellar Evolution: II

Prof. James Davenport (UW)

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Today

- Post-Main Sequence Evolution

- BOB, Ch 13.2+

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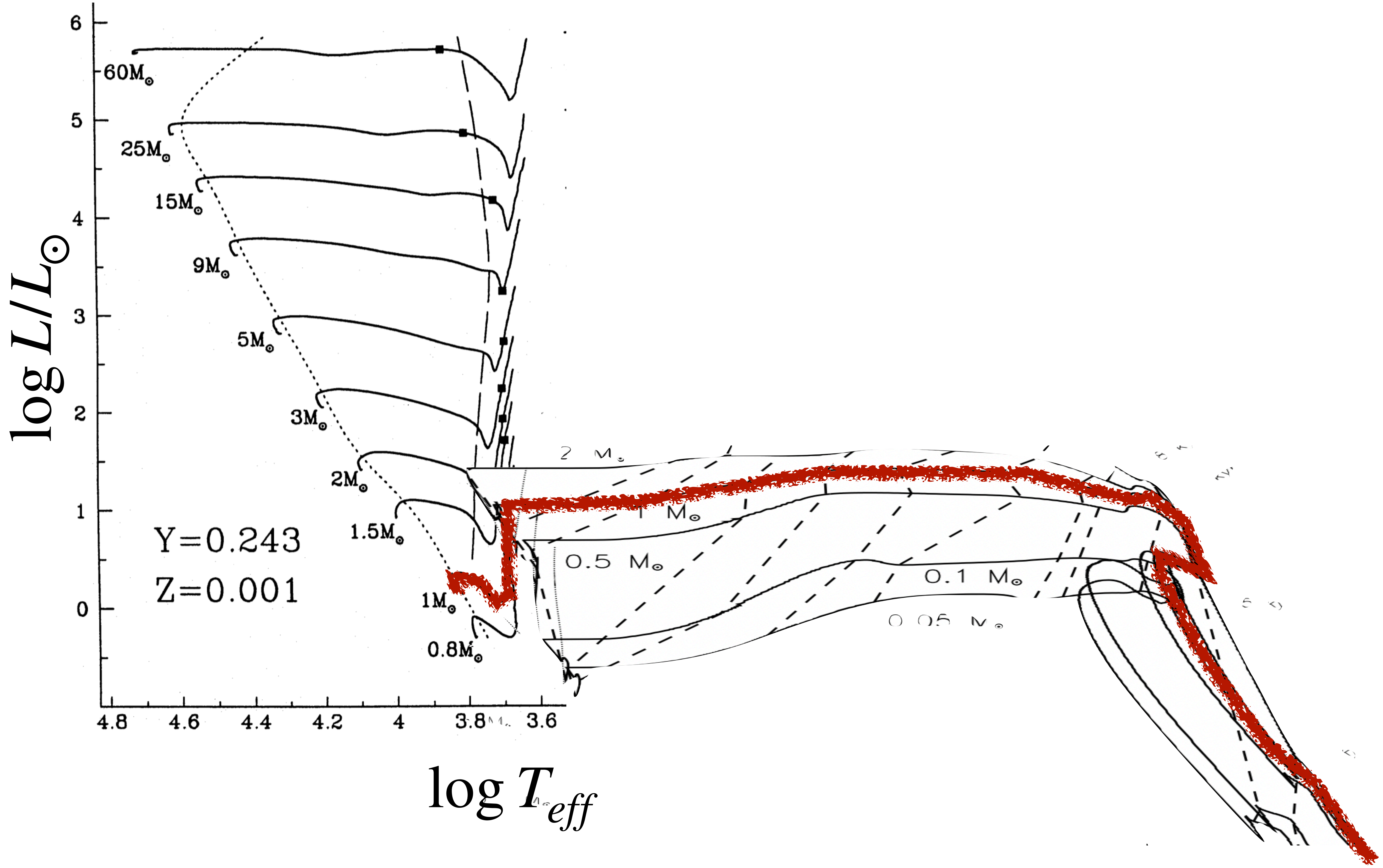
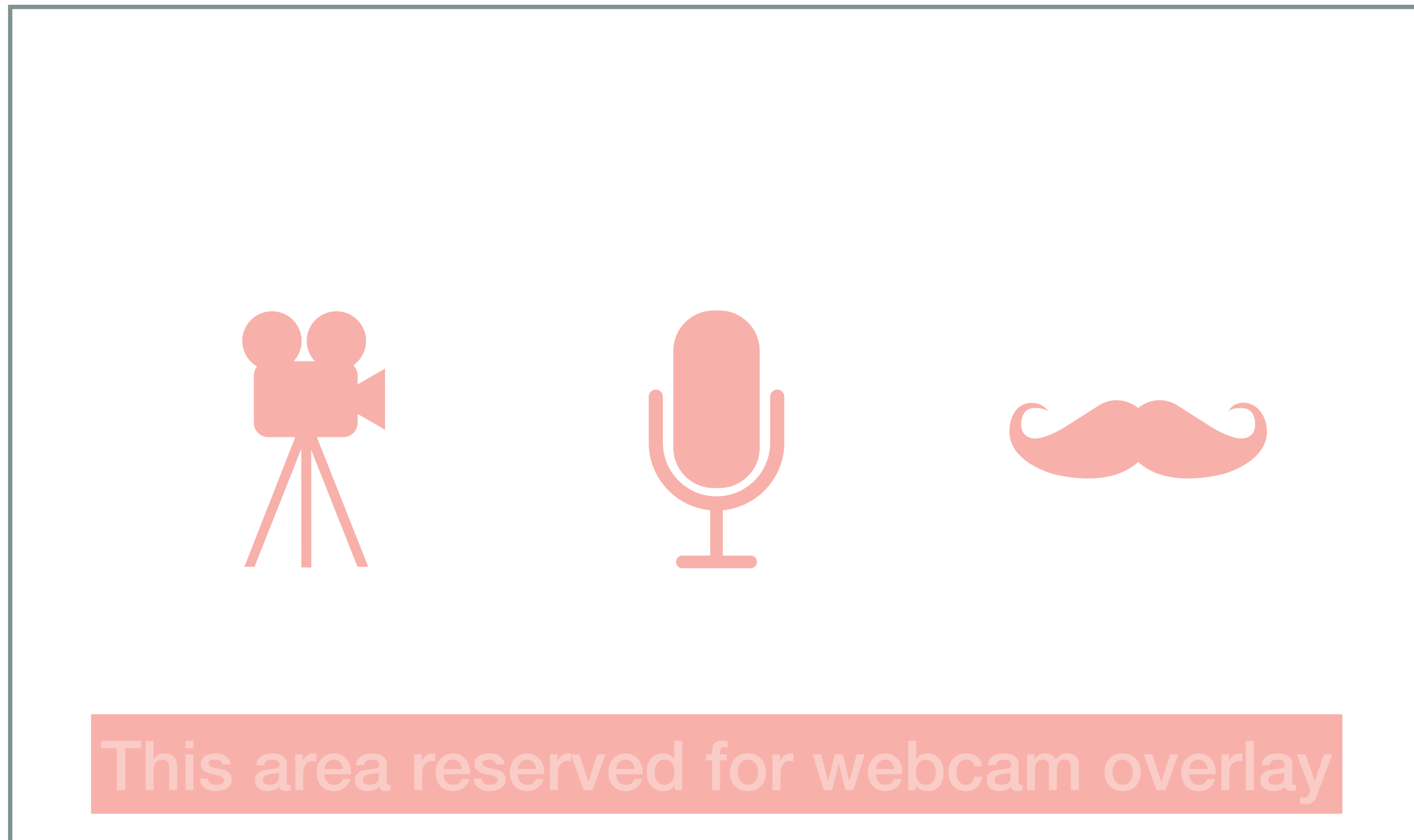
Previously…



log $L/L_\odot$
6
5
4
3
2
1
0
60M⊙
25M⊙
15M⊙
9M⊙
5M⊙
3M⊙
2M⊙
1.5M⊙
1M⊙
0.8M⊙
Y=0.243
Z=0.001
4.8
4.6
4.4
4.2
4
3.8
3.6
log T_{eff}
2 M⊙
1 M⊙
0.5 M⊙
0.1 M⊙
0.05 M⊙



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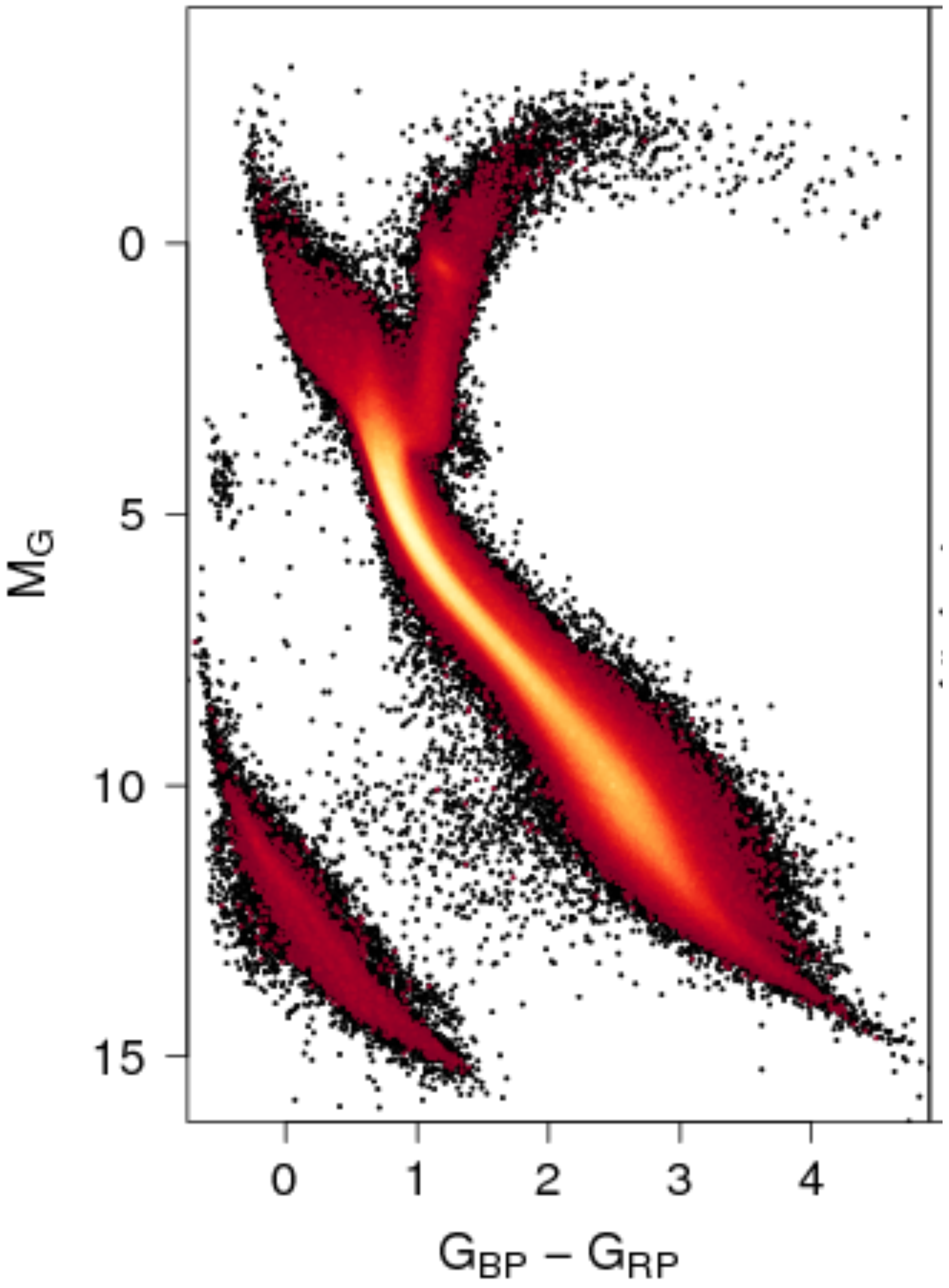
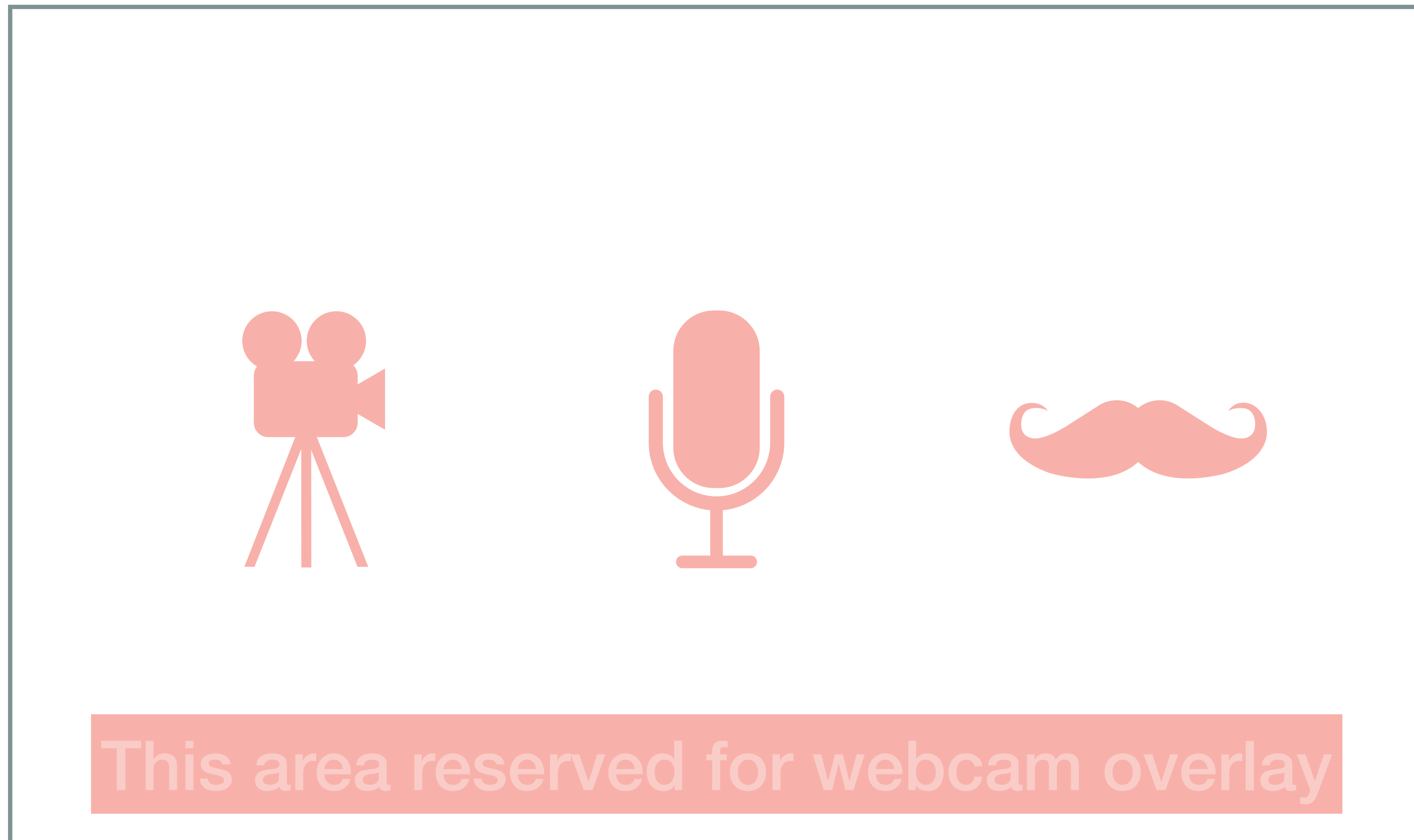
Today

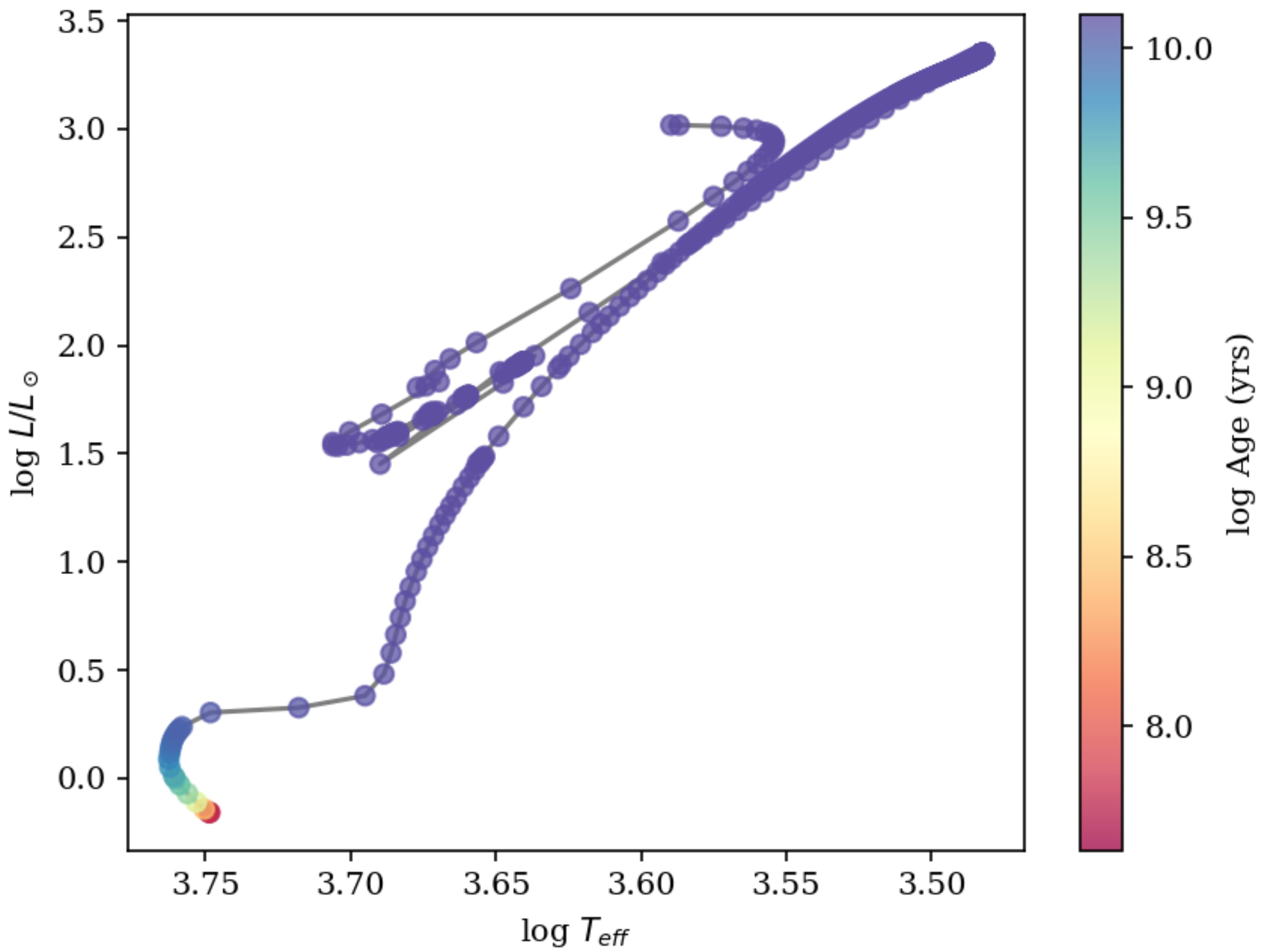


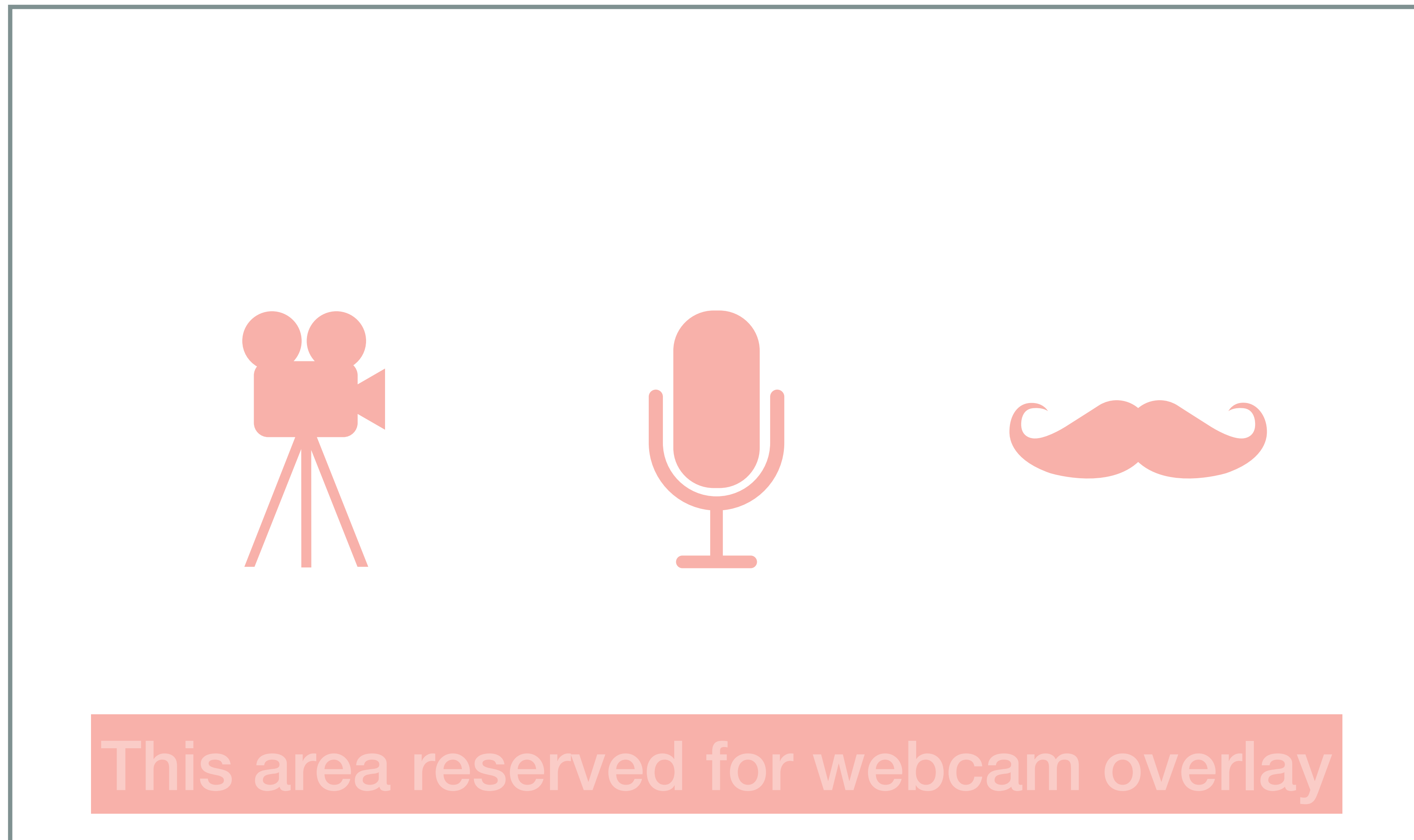
- Today we're focusing on everything else that happens here
- Let's once again recall: gravity wins if there's no support, HSE always fighting back
- Many of the same limits/timescales we've discussed already



Post-MS Evolution

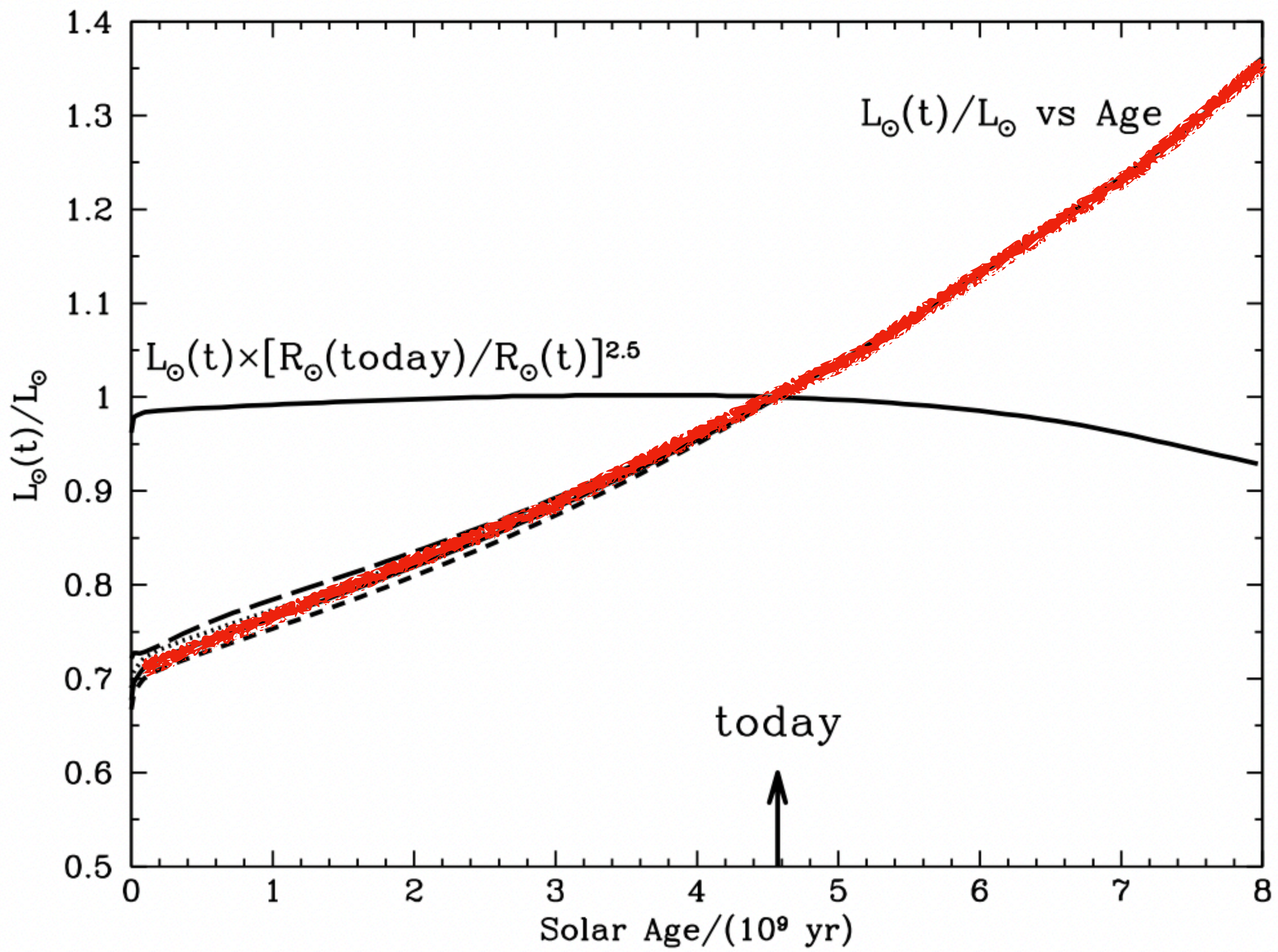
- There is SO MUCH here… we can't do it justice in 1 lecture.
- So let's walk through *broadly* what happens, mostly focused on the Sun
- Fair Warning:
  I'm going to skip stuff you care about…

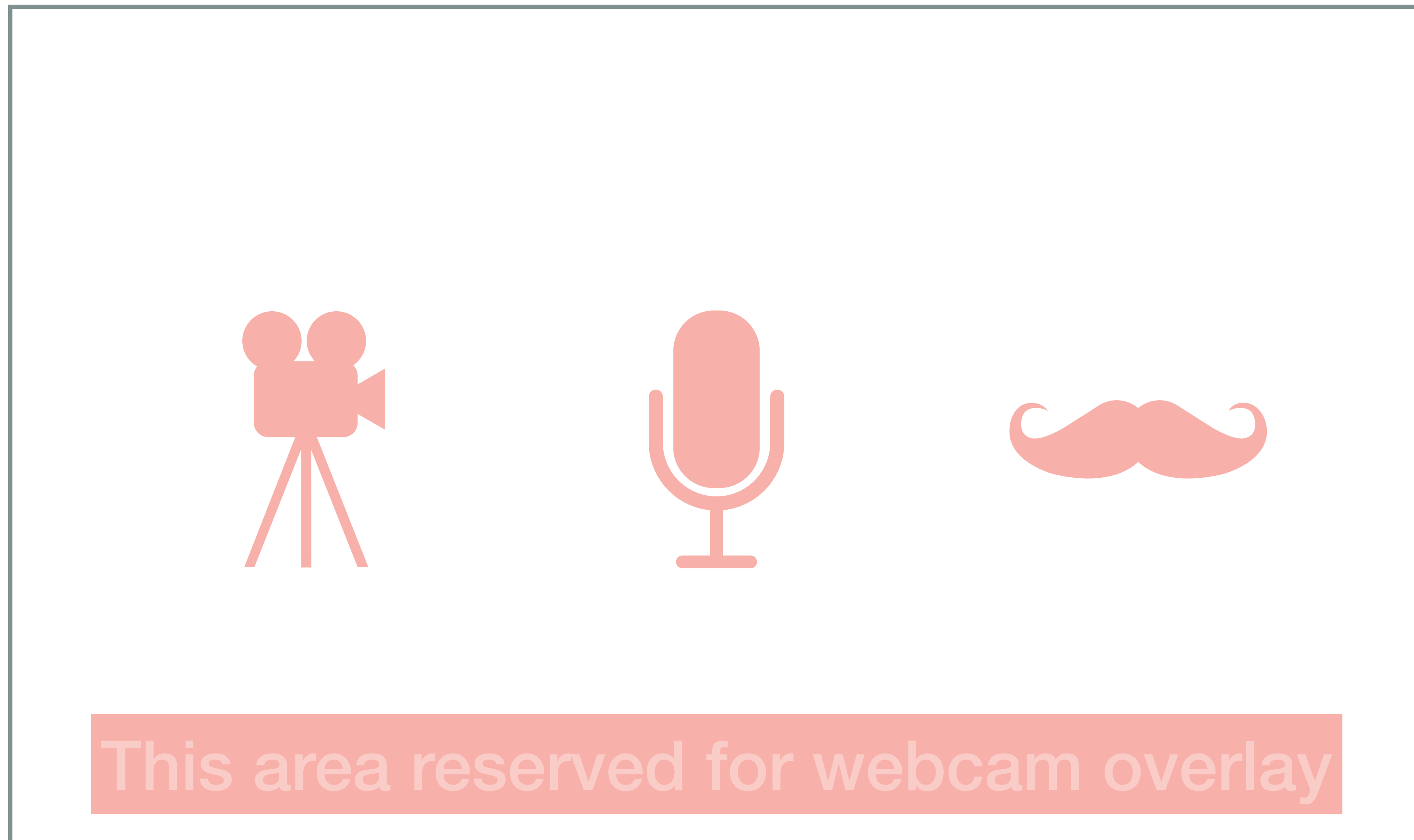




1. The Main Sequence

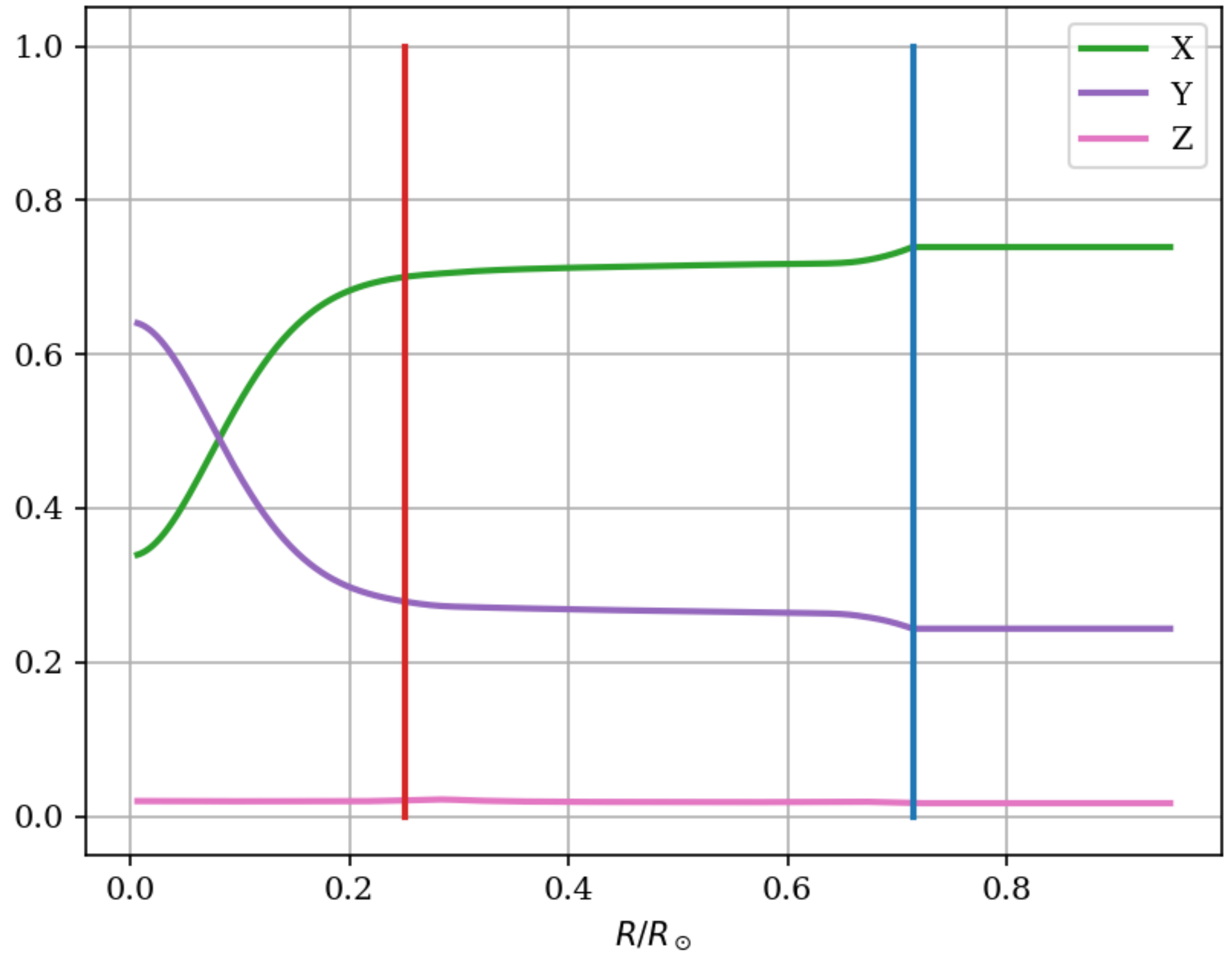
- What happens here sets the stage for what comes after (of course)
- We've already seen the Sun changes over the MS, as star burns H -> He

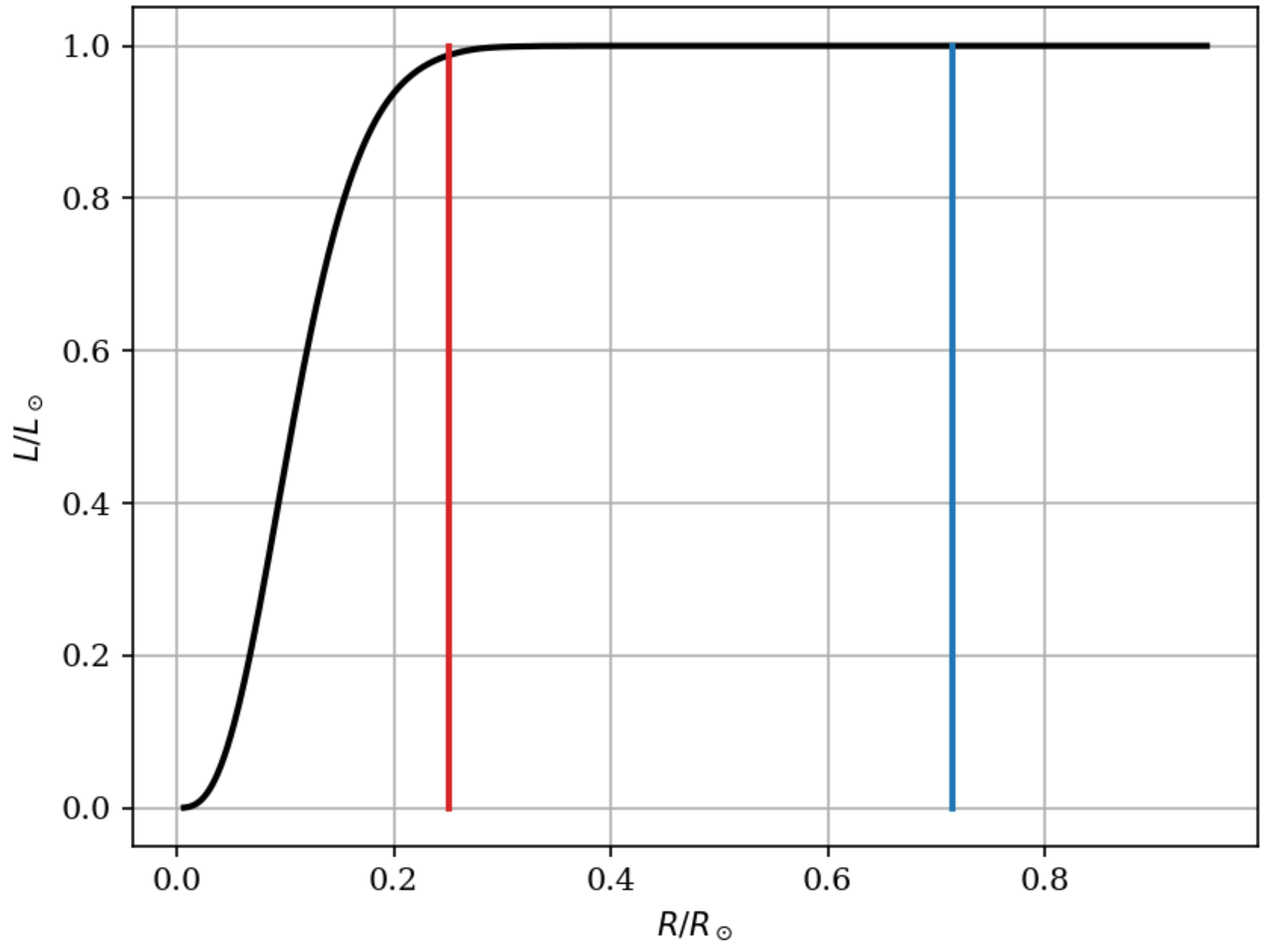


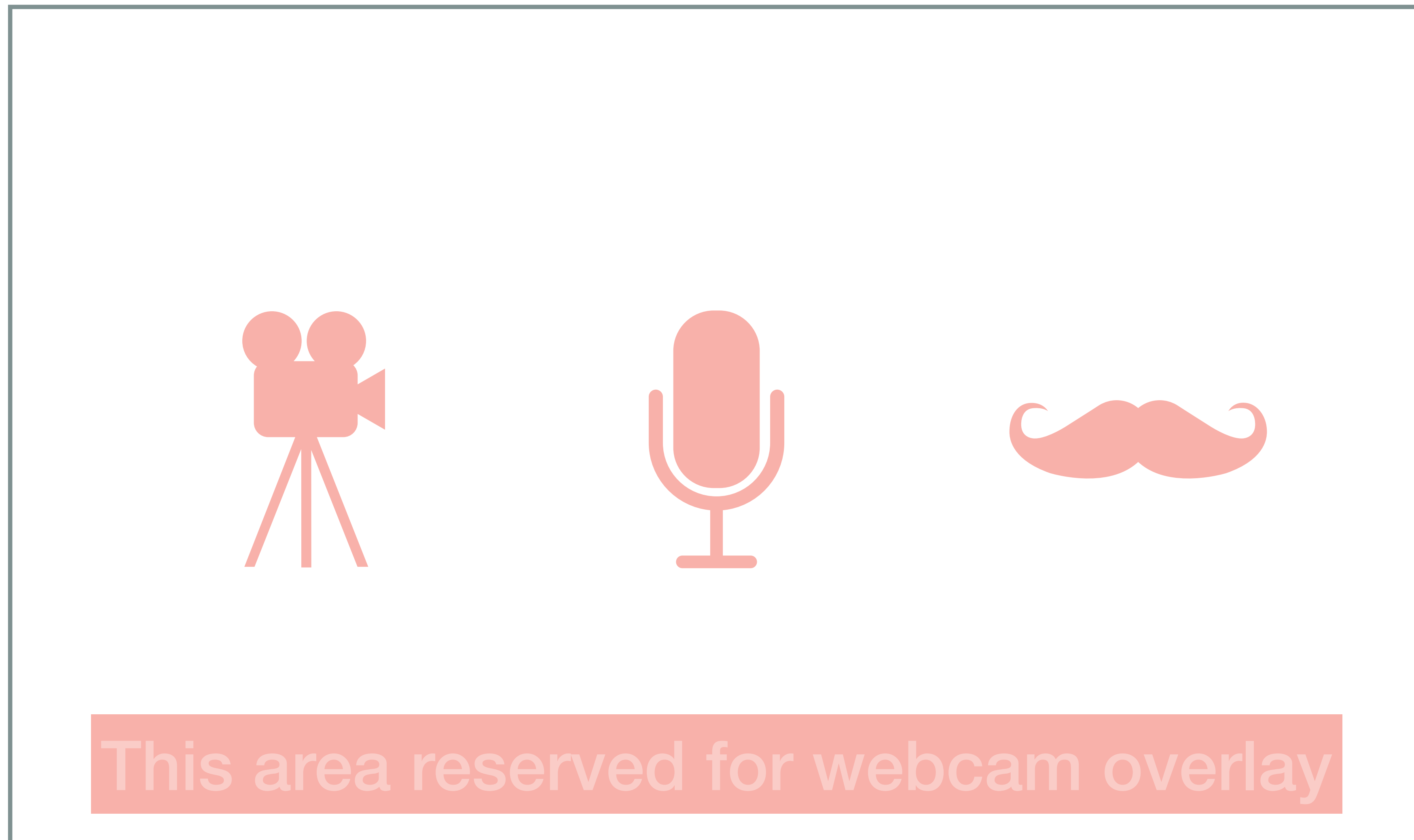


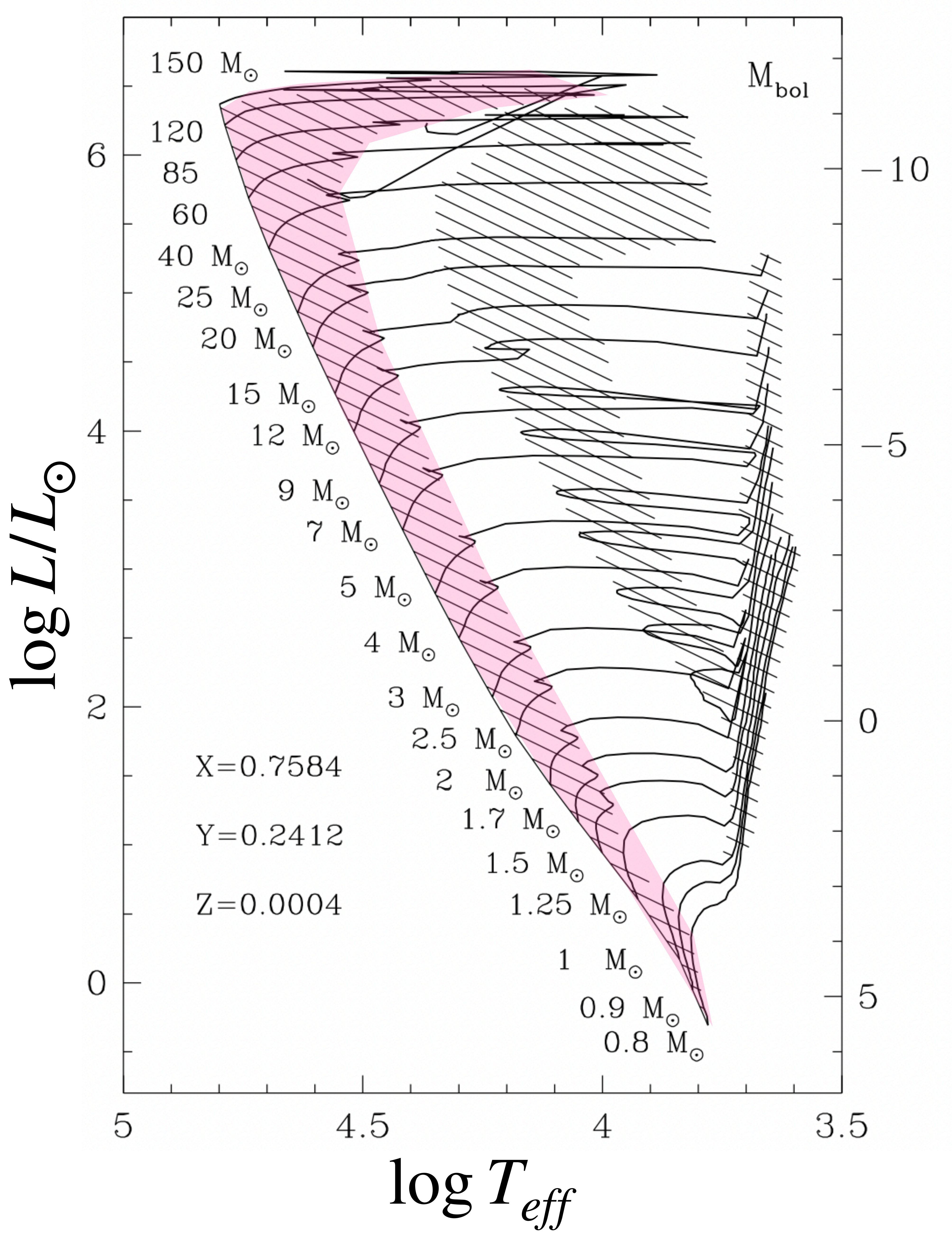
1. The Main Sequence

- Already fusion isn't happening just in the CENTER of the core any more
- Over the MS, star is changing it's **mean composition**, its creating a He-rich core. This drives what happens once H fusion no longer possible (end of MS)





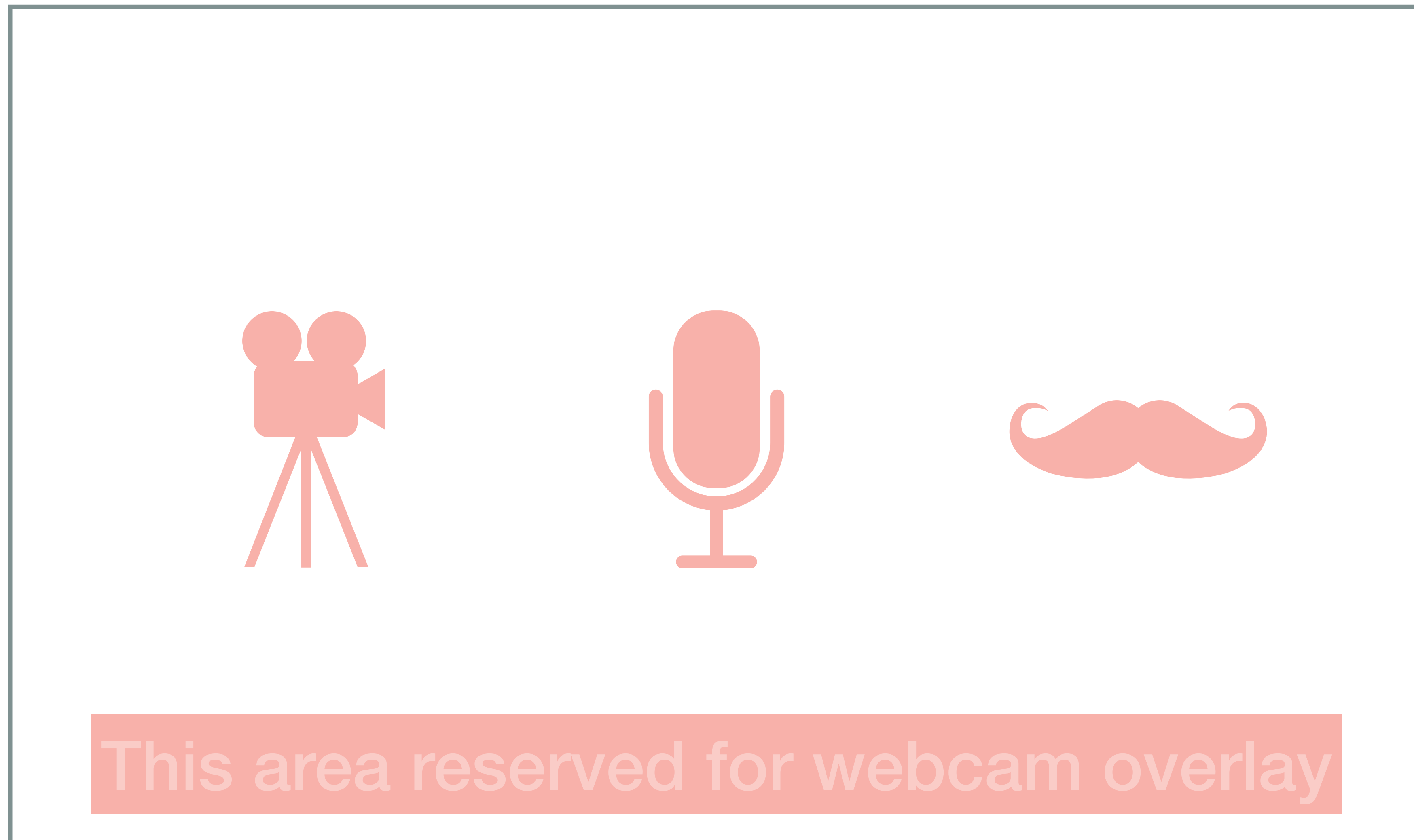




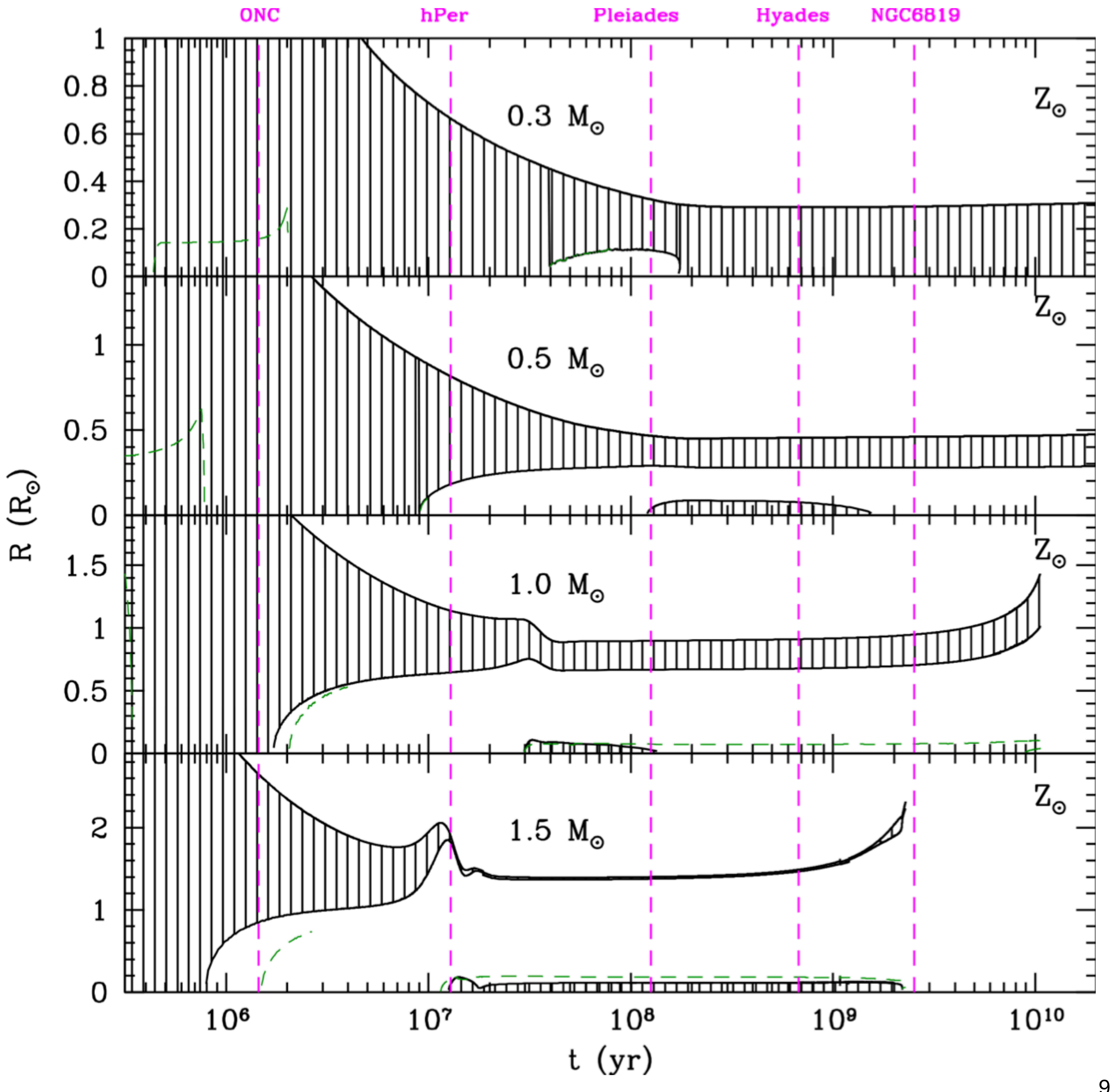
Geneva stellar evolution models

1. The Main Sequence

- This evolution during MS is seen for **all stars**
- Gradually getting brighter and cooler as they burn fuel, core contracts



Amard+2019



Kippenhan Diagrams

- Hashes here are convective regions
- Best way to see the time-evolution of the interior structure of the star
- Here we can compare (early) evolution for stars of different masses

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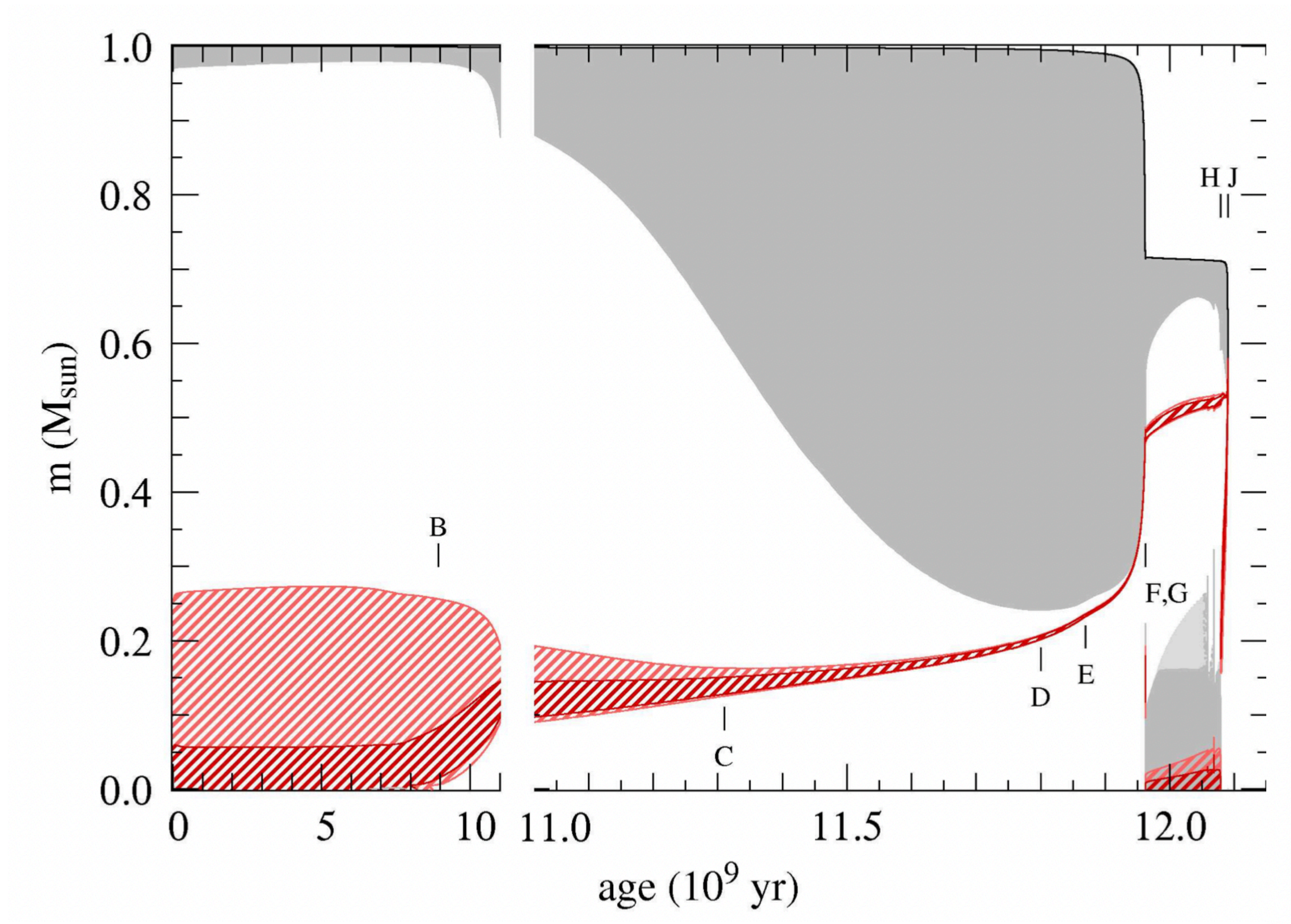
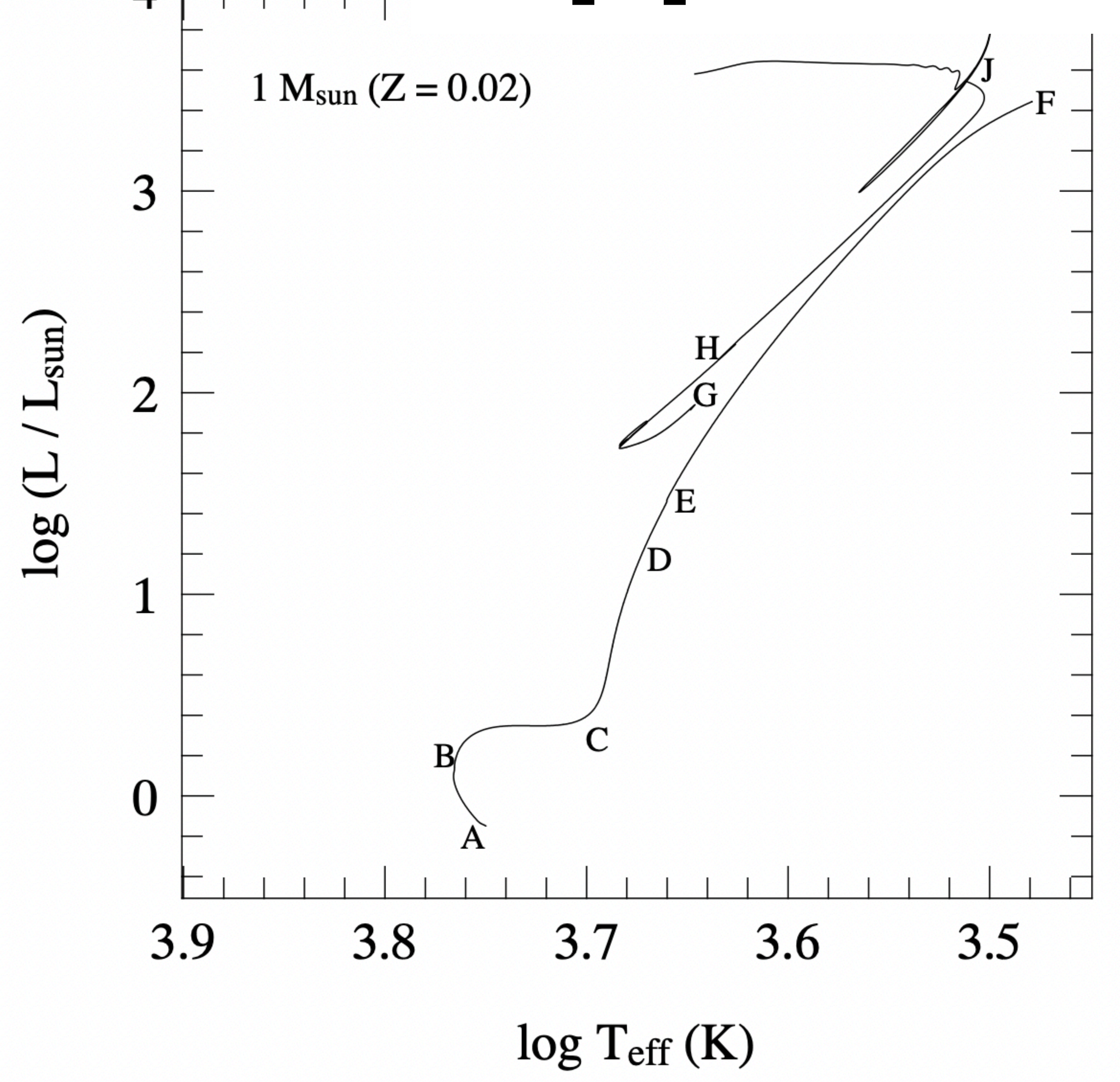
Kippenhan Diagrams





- If you like stars, Pols (2011) grad notes on Stellar Evolution are *awesome*…

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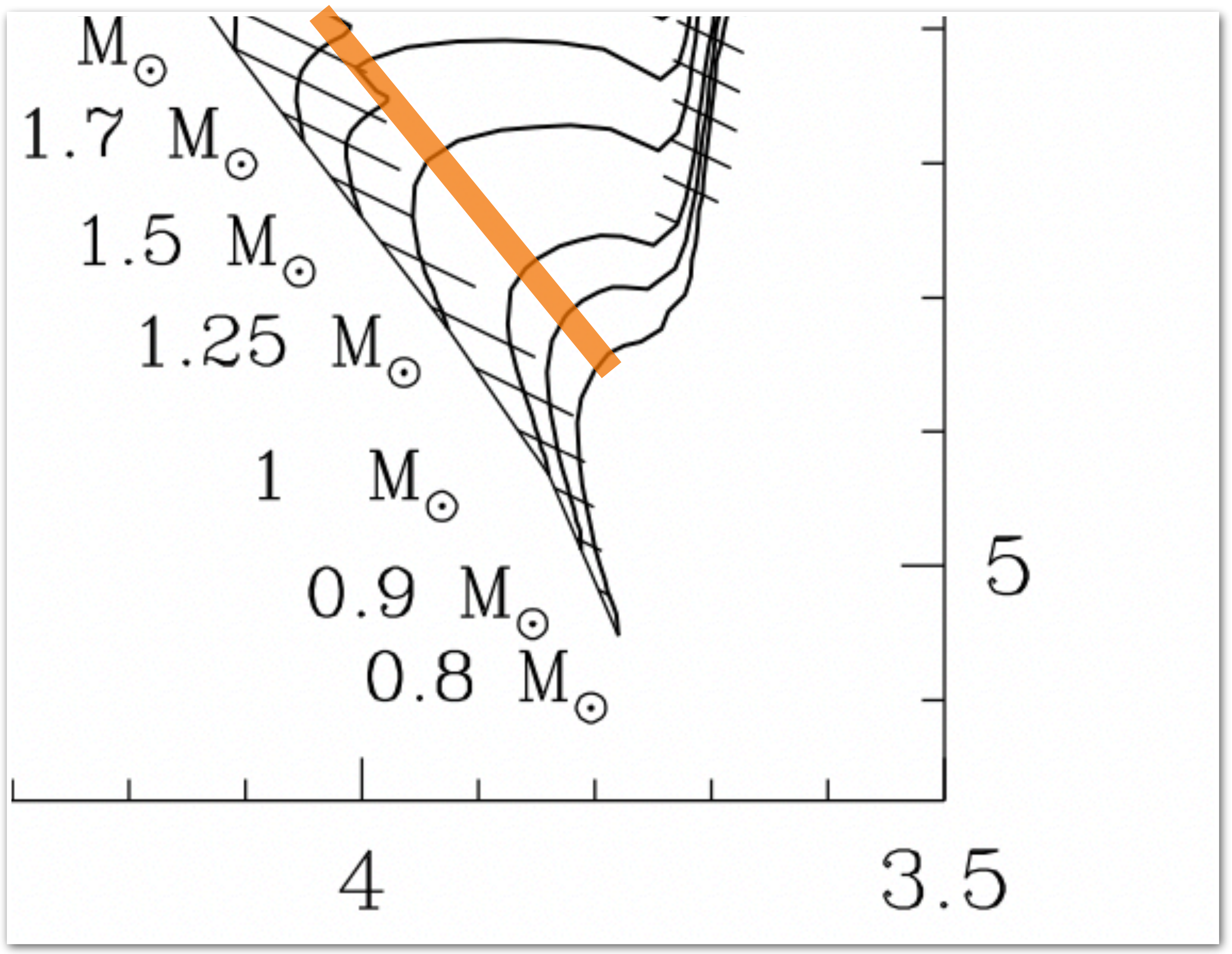
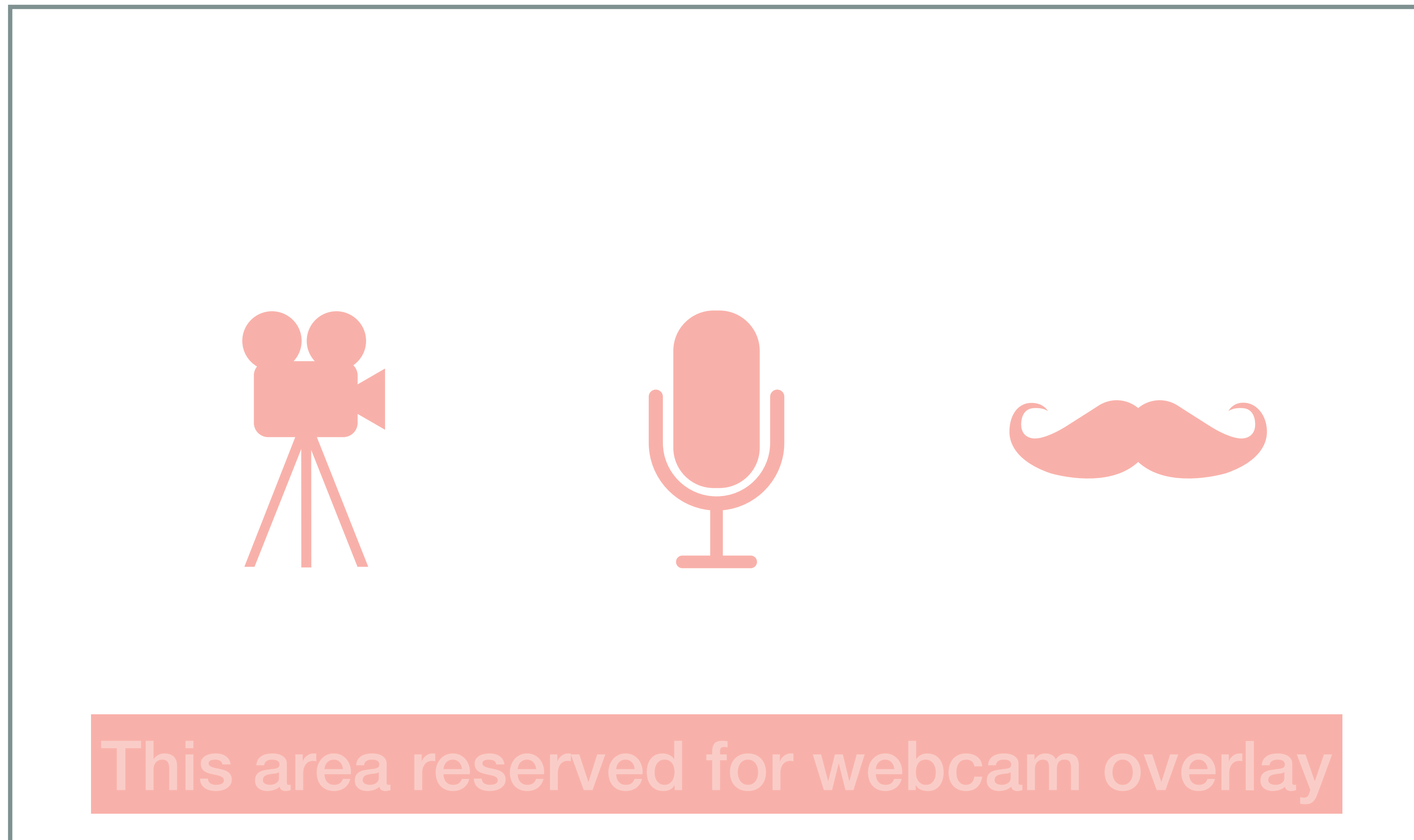
2. End of the H-burning MS

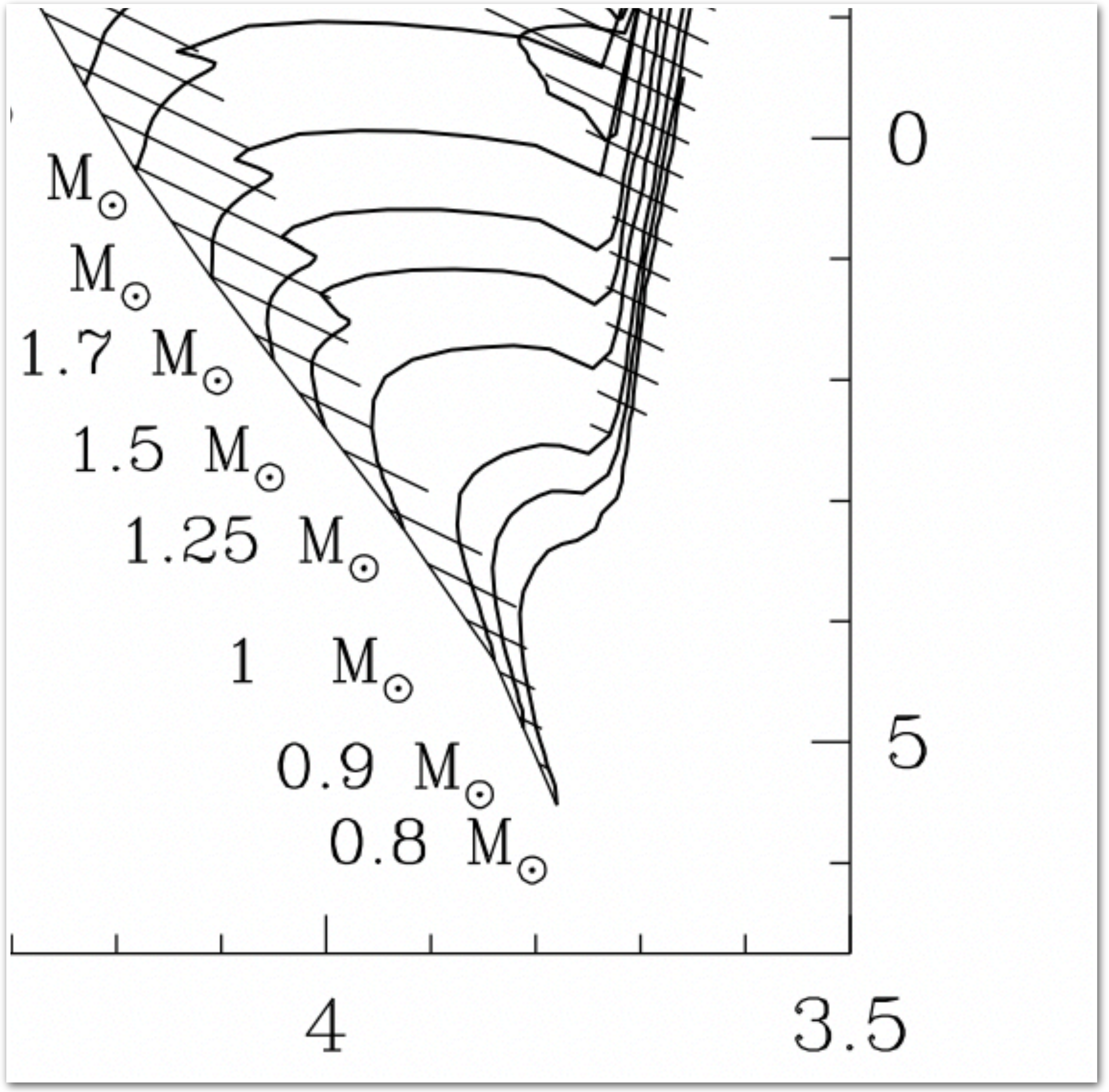
- Run out of fuel, we approach this gradually, core contracting and changing over MS as we've said
- Eventually fall out of the sweet spot for H fusion.
- X too low. Contracting core (increase density) & increasing temp can't get enough H to fuse, support in core declines … gravity wins, core contracts!
  - The MS **turn-off**





2. End of the H-burning MS

- Interesting feature at the turn-off: a fast "jog" for higher mass stars ($M > 1.2M_\odot$)
- These are stars that had convection in the core, lots of mixing. Entire core runs out of H, entire core rapidly contracts when fusion shuts off!
- For lower mass stars, core contraction is gradual.



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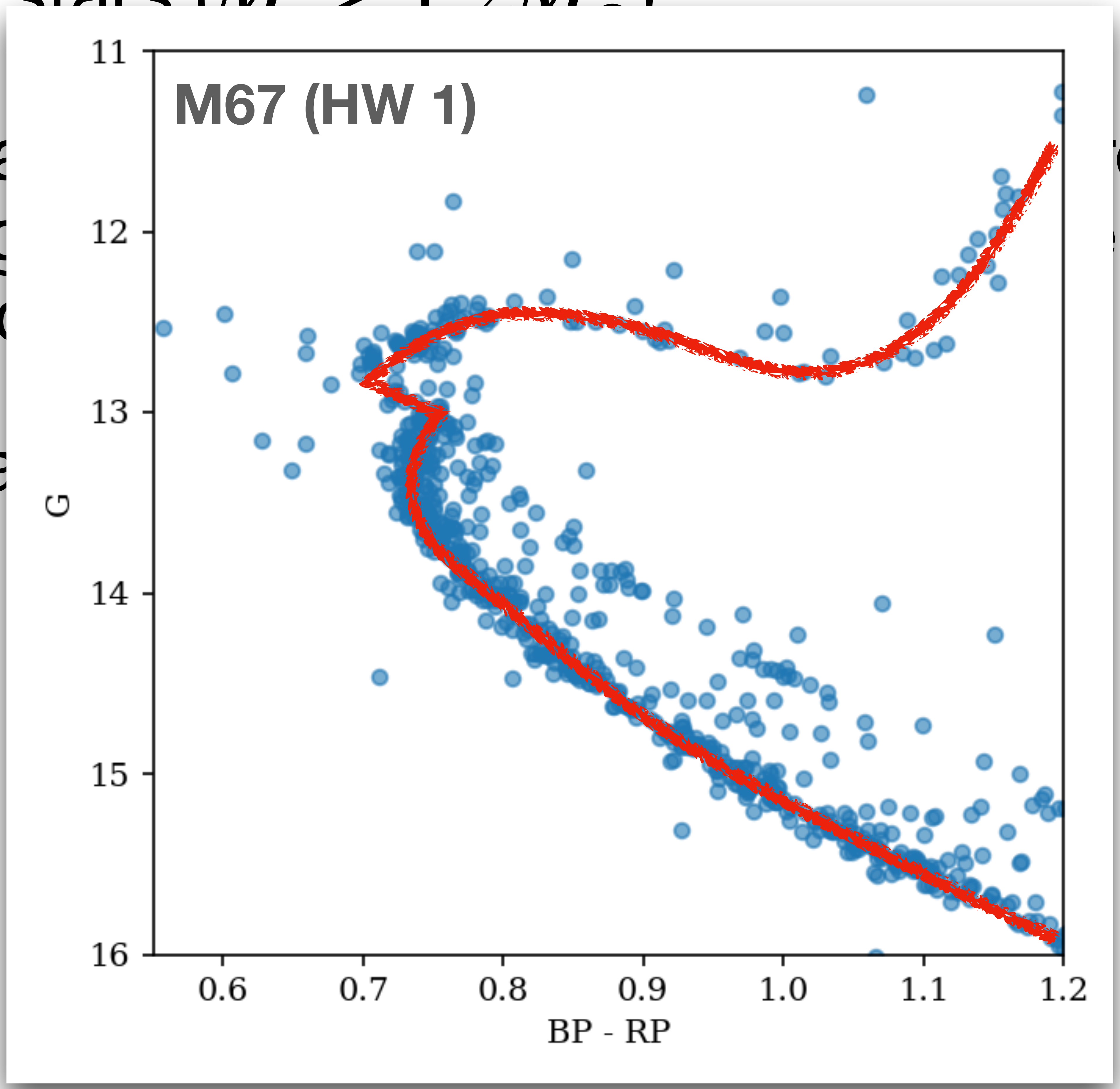
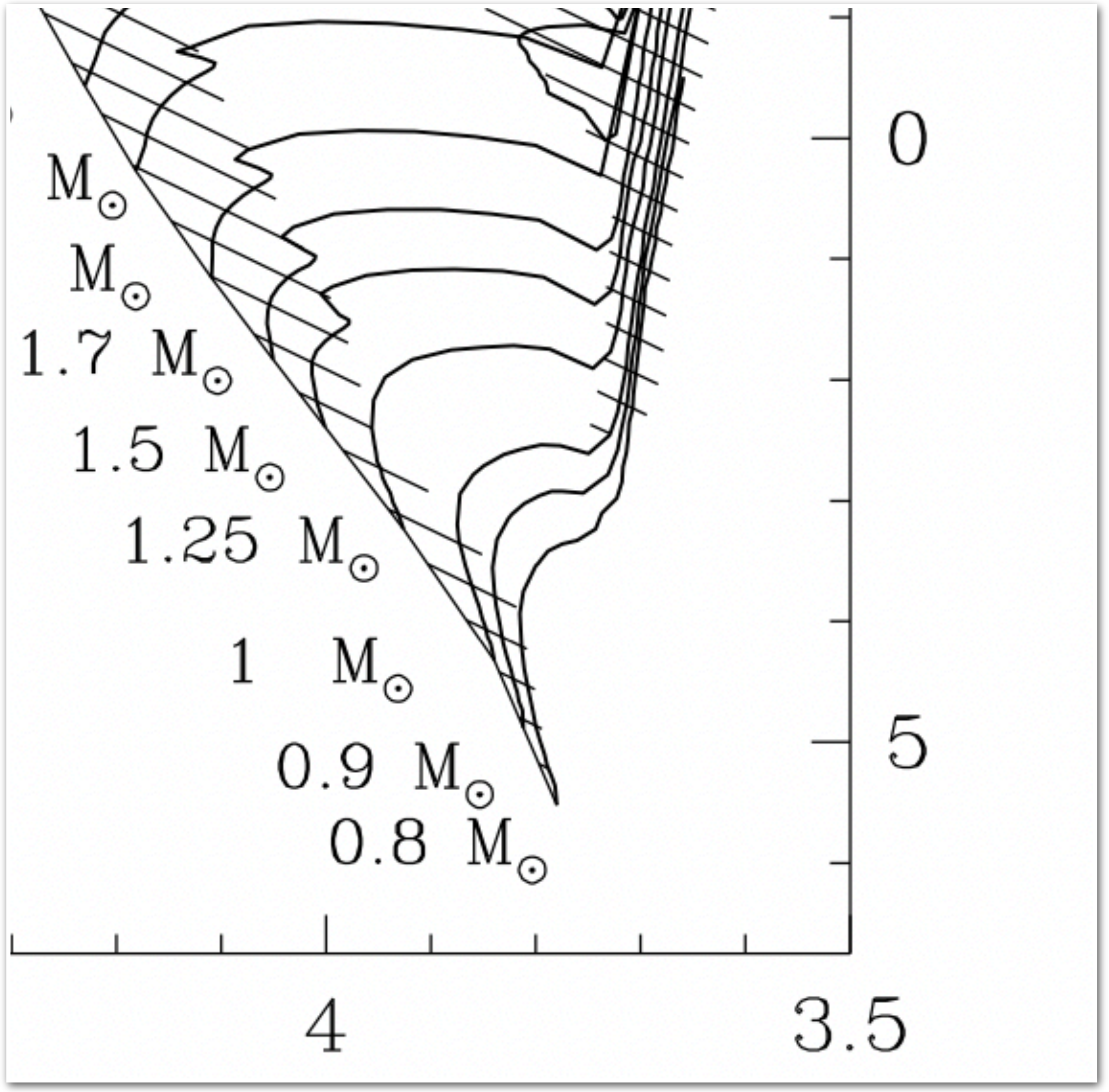
2. End of the H-burning MS

- Interesting feature at the turn-off: a fast “jog” for higher mass stars $(M > 1.2M_\odot)$
- These are sta… …e, lots of mixing … core rapidly …
- For lower ma… …ual.





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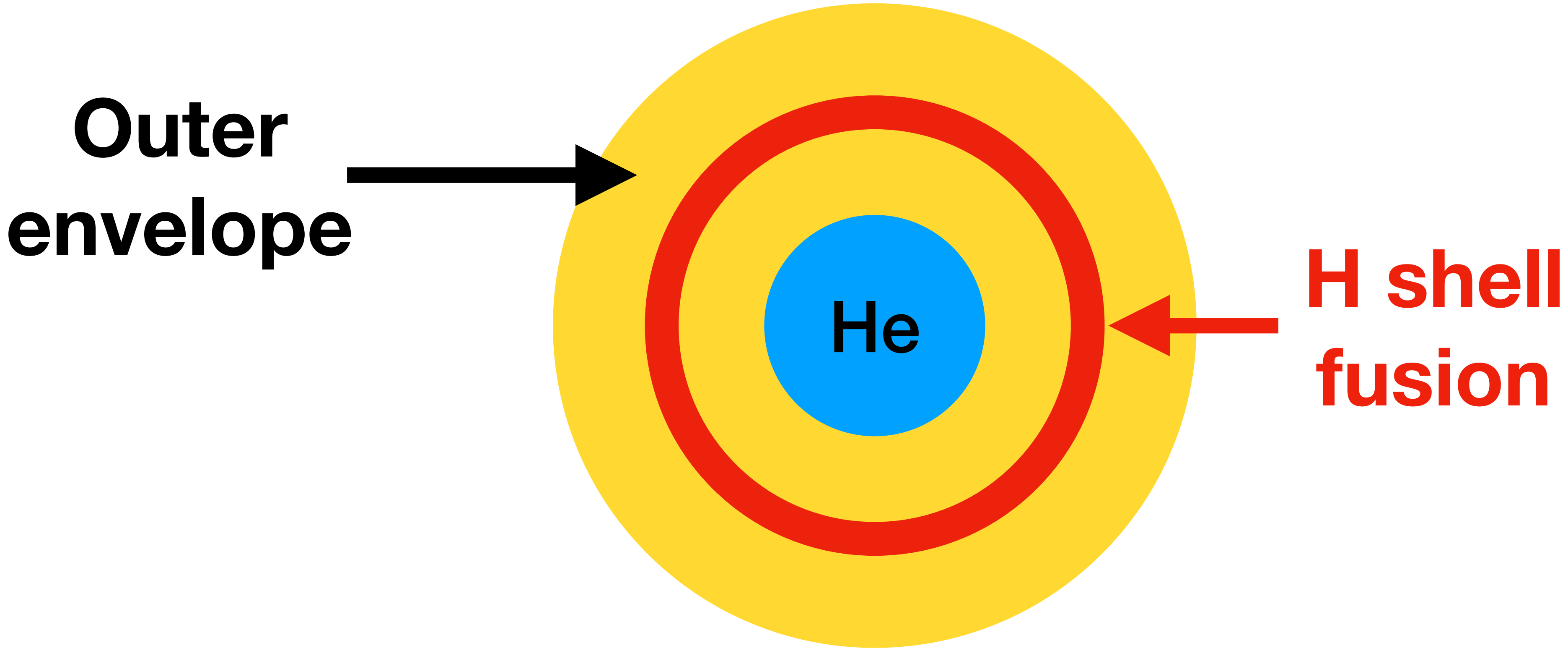
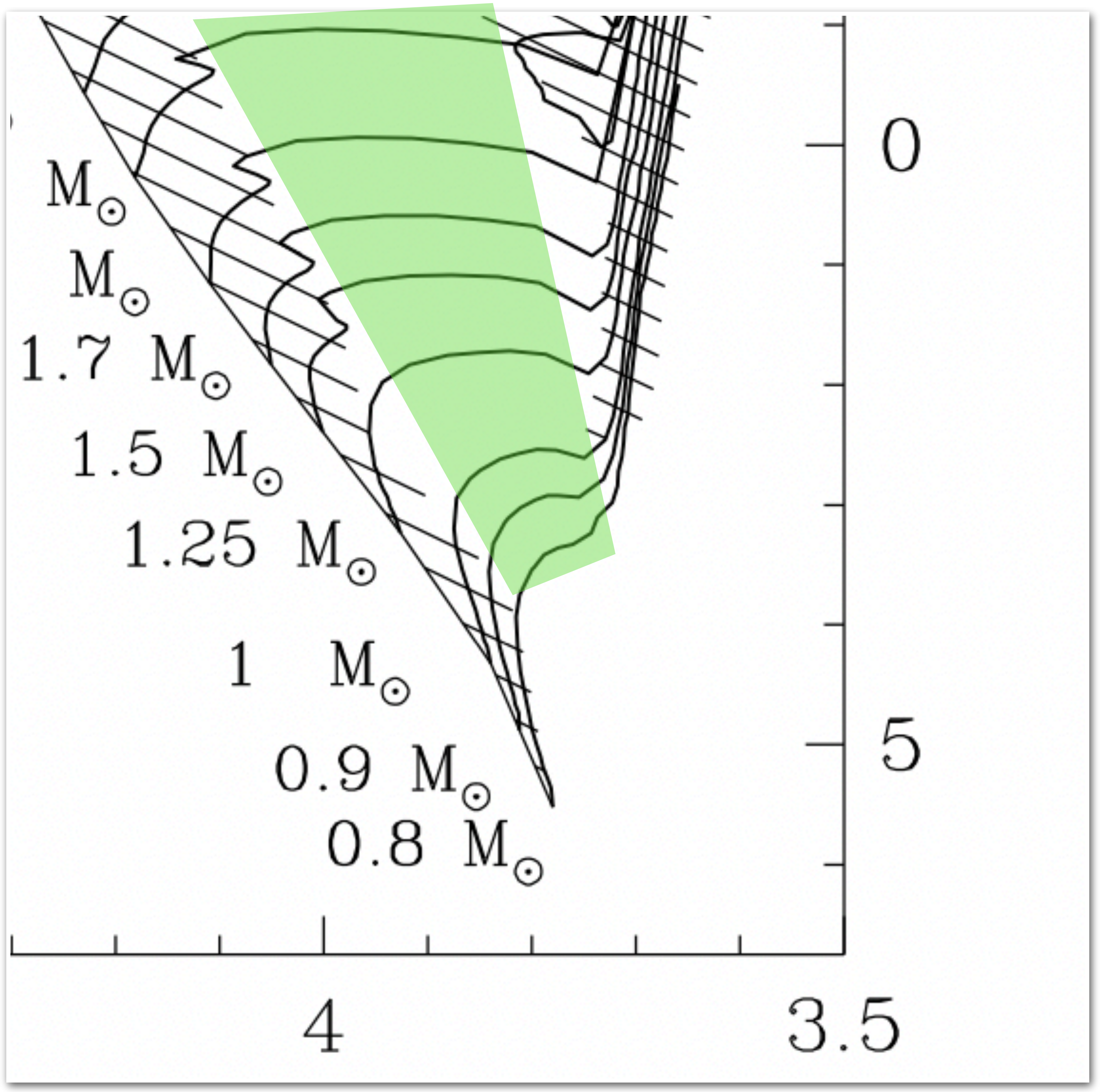
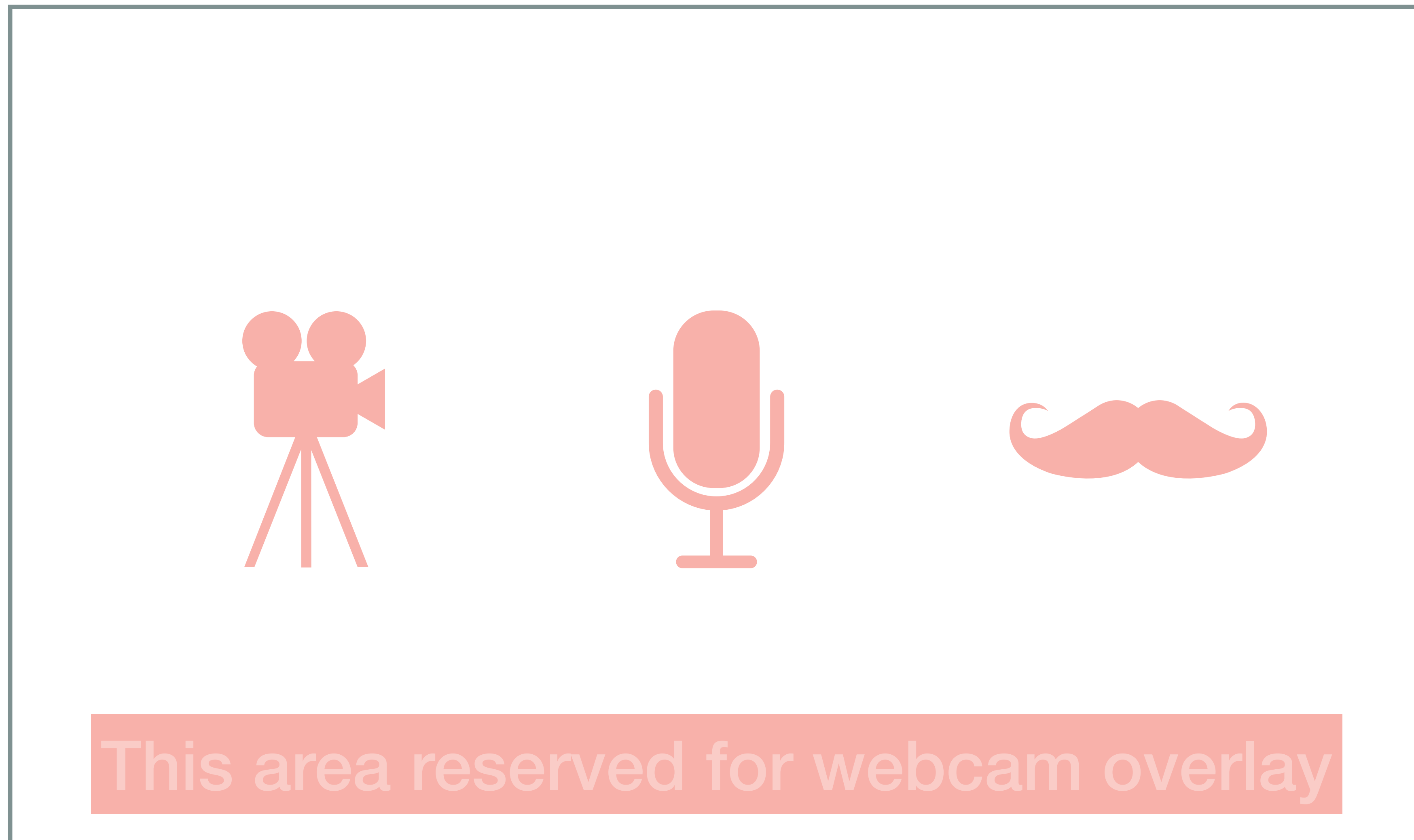
3. Sub-Giant Phase

- Core out of support, contracts (on K-H timescale)
- Core temp steadily increasing
- H fusion in a *shell* begins around core



- Shell fusion acts like a “MIRROR"… why?!
(core contracts, envelope expands)





The “mirror principle” for shell burning

(One way to interpret this effect)

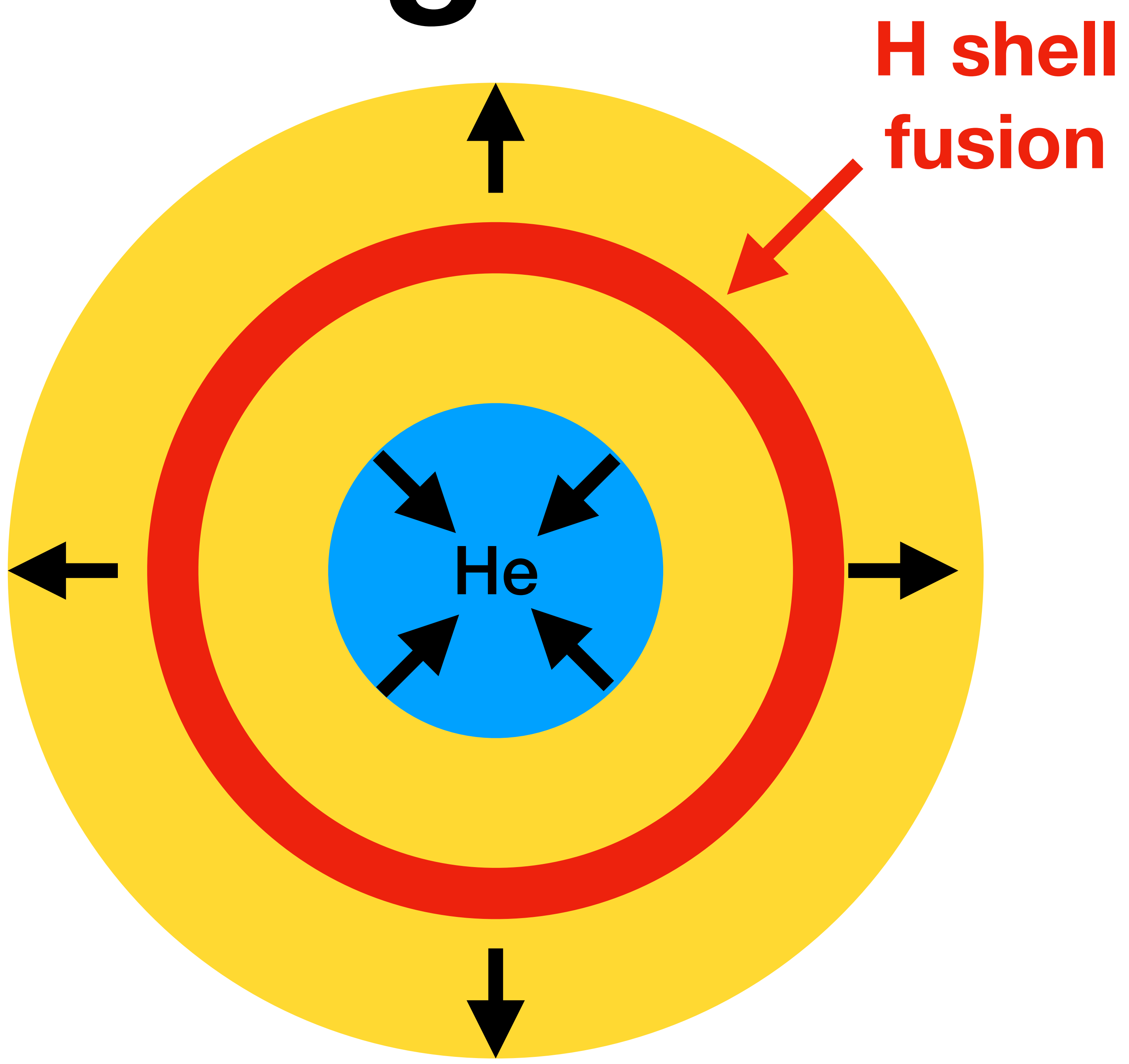
- As core contracts, heats up… this would increase temp of H shell, but recall fusion efficiency *very* sensitive to temperature! So shell can’t contract as much

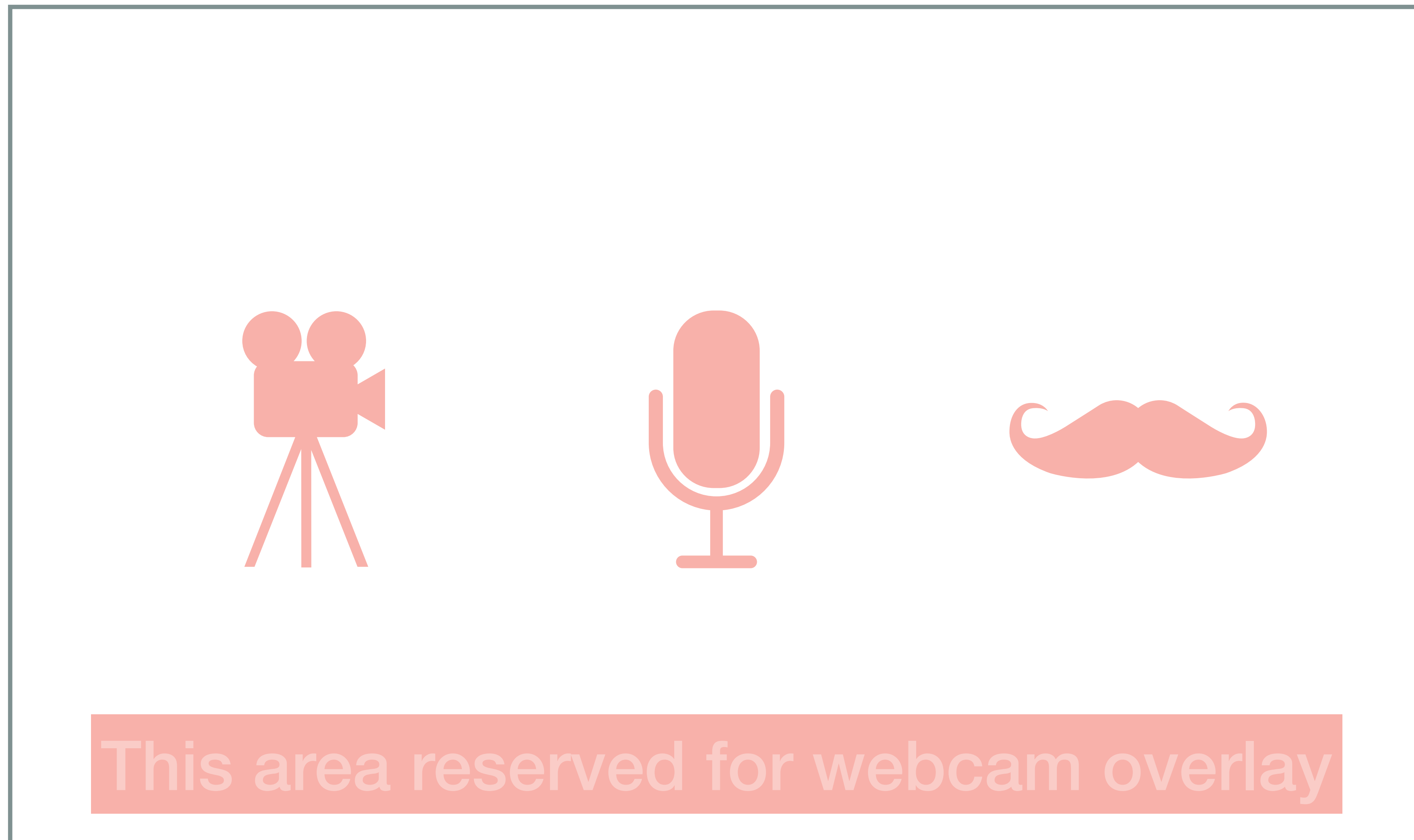
- So the shell basically stays put, meaning the envelope has to expand to preserve gravitational potential energy

- This principle is why we see a “giant” star phase

  - Causes envelope to expand greatly

  - Big T gradient -> convection!

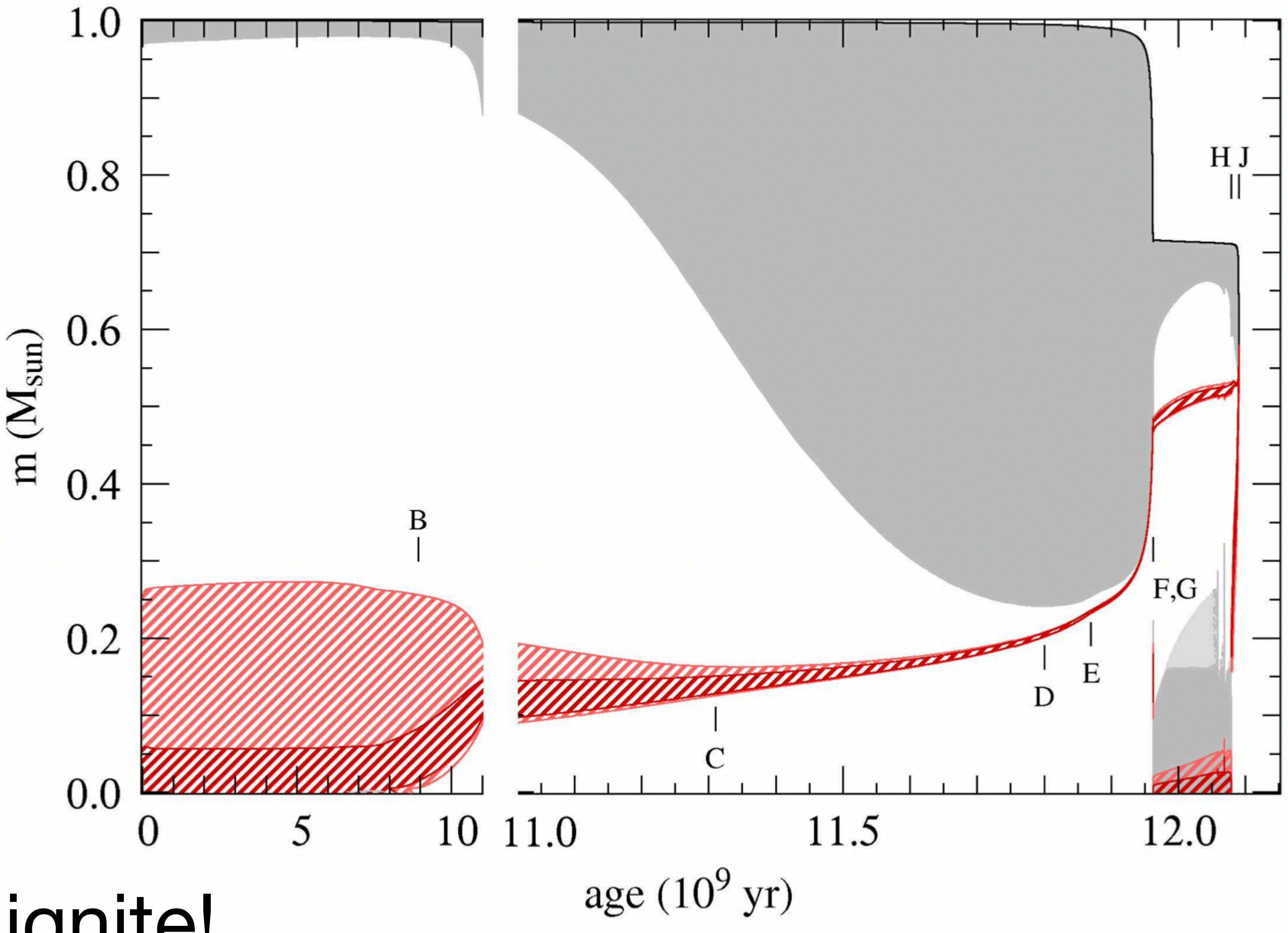


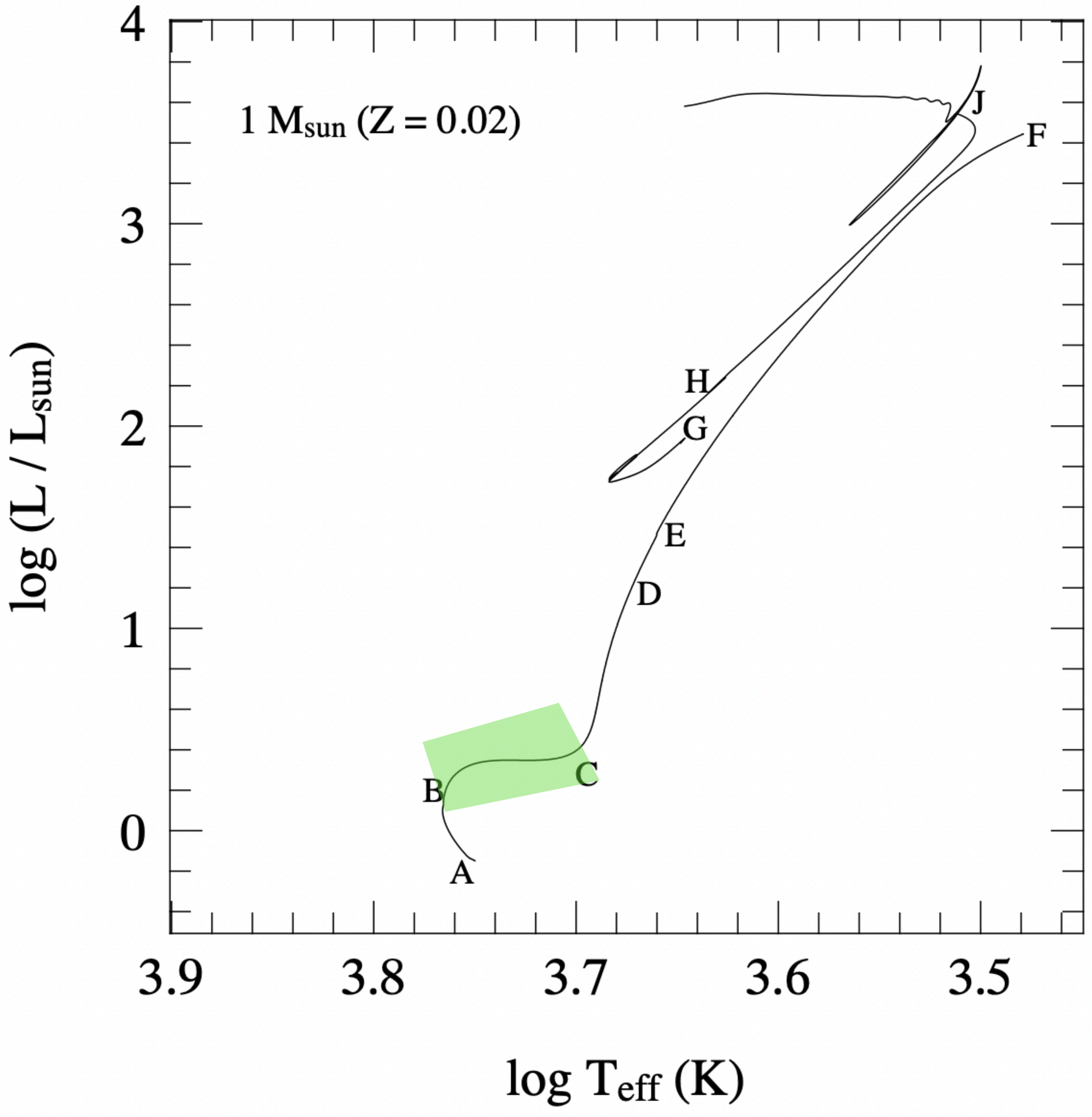


Sub-Giant

- Shell fusion causes envelope to grow slowly

- Core contracts, is “degenerate”, lots of He, & hot… but not enough to ignite!





- Hits the Hayashi limit (point C), ~half of outer envelope is convective. As core continues to contract, envelope must expand rapidly. Luminosity increases!

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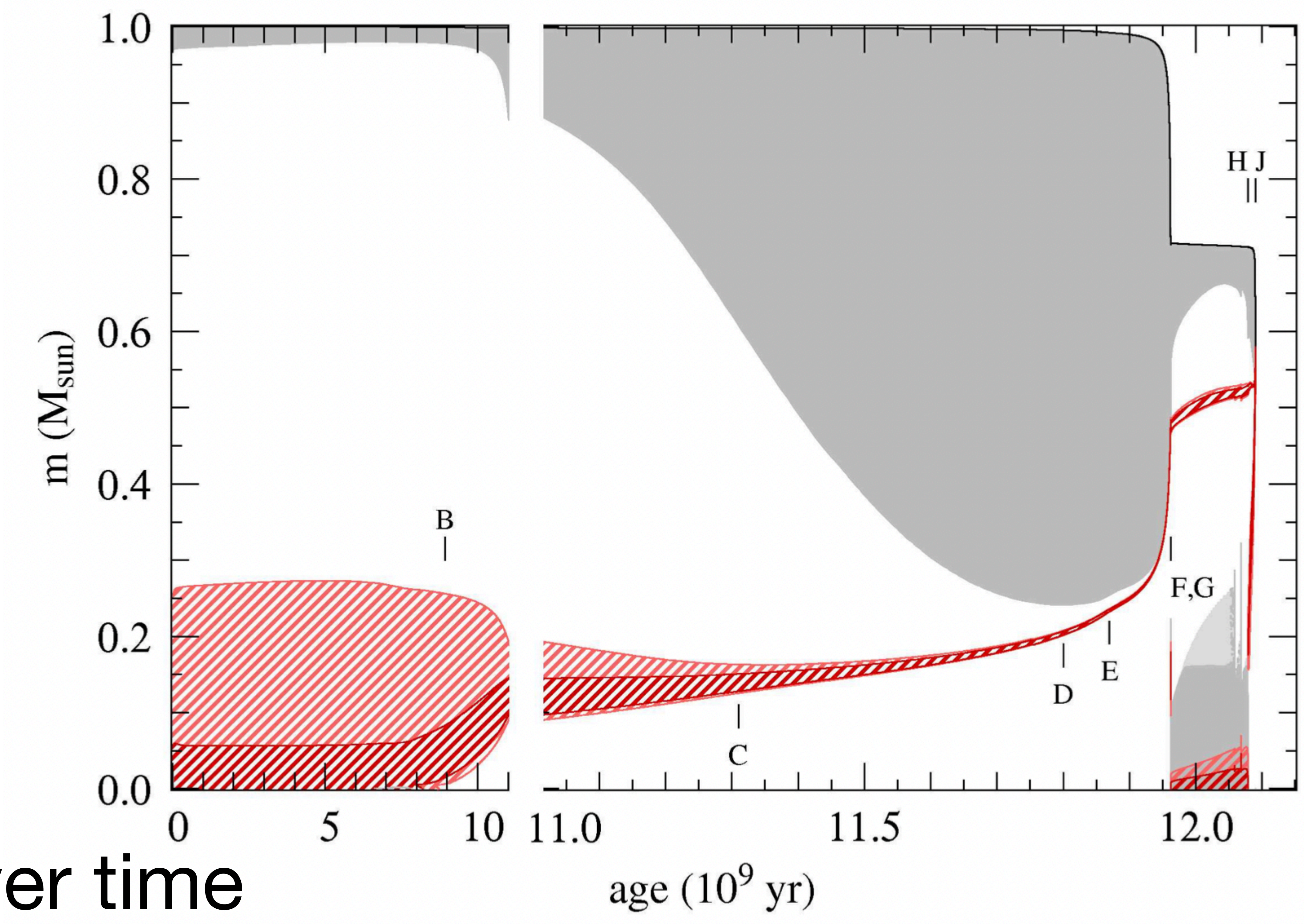
RGB

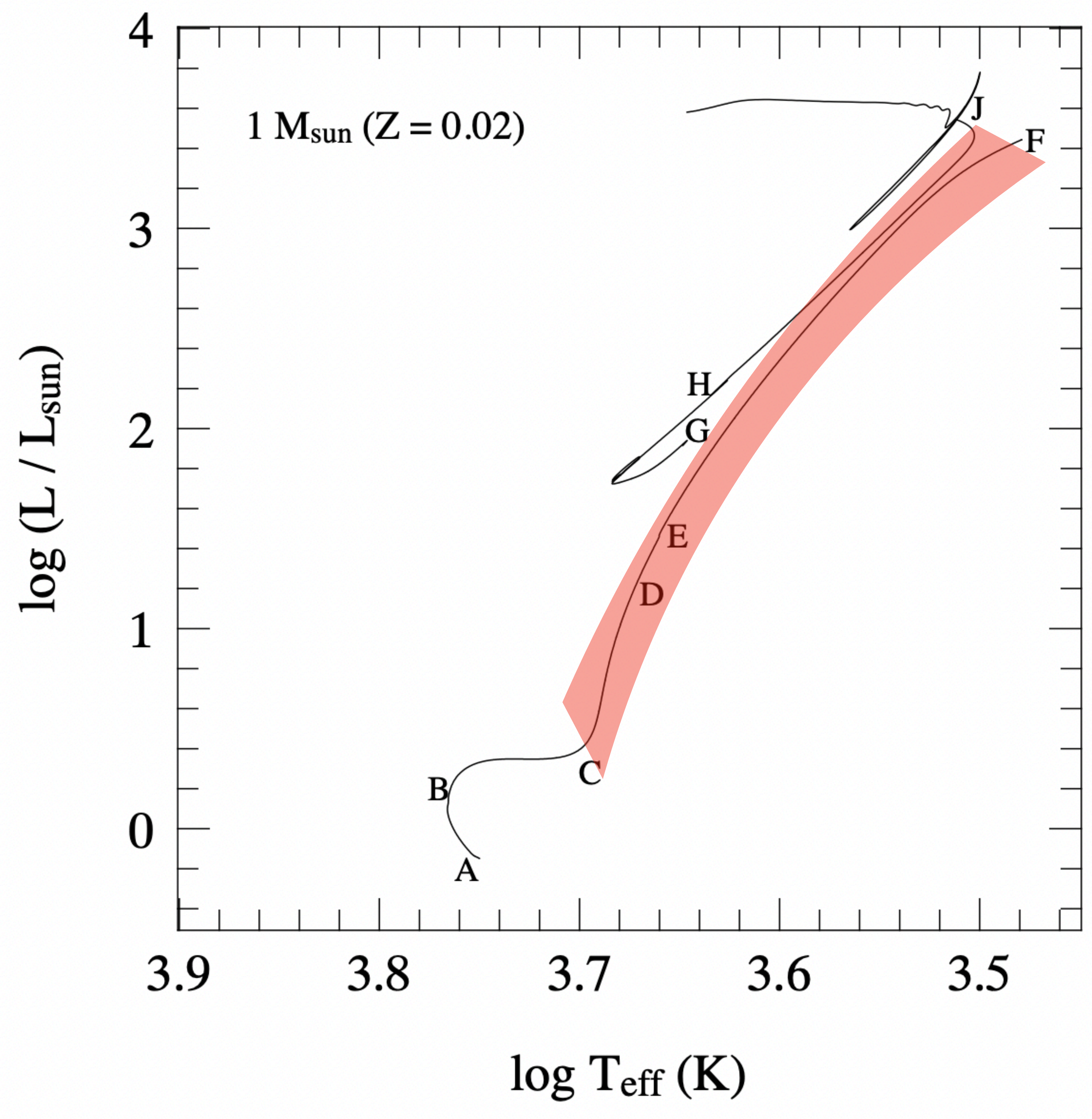
- Red Giant Branch phase goes "up" the Hayashi line

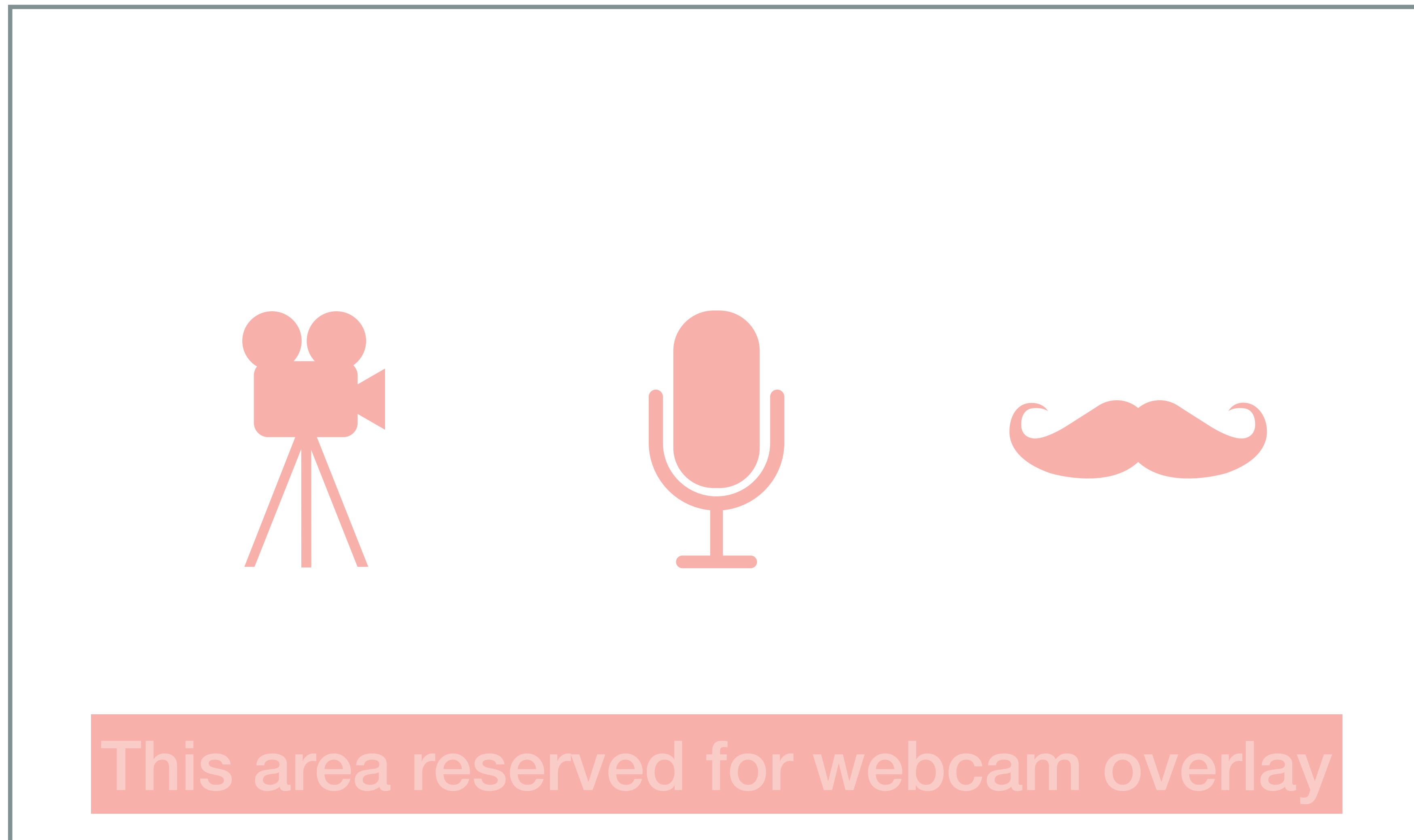
- He core continues to contract

- Shell moves *out* over time

- D: "first dredge up"
  Convective zone reaches place where MS core used to be, brings lots of He and N to surface

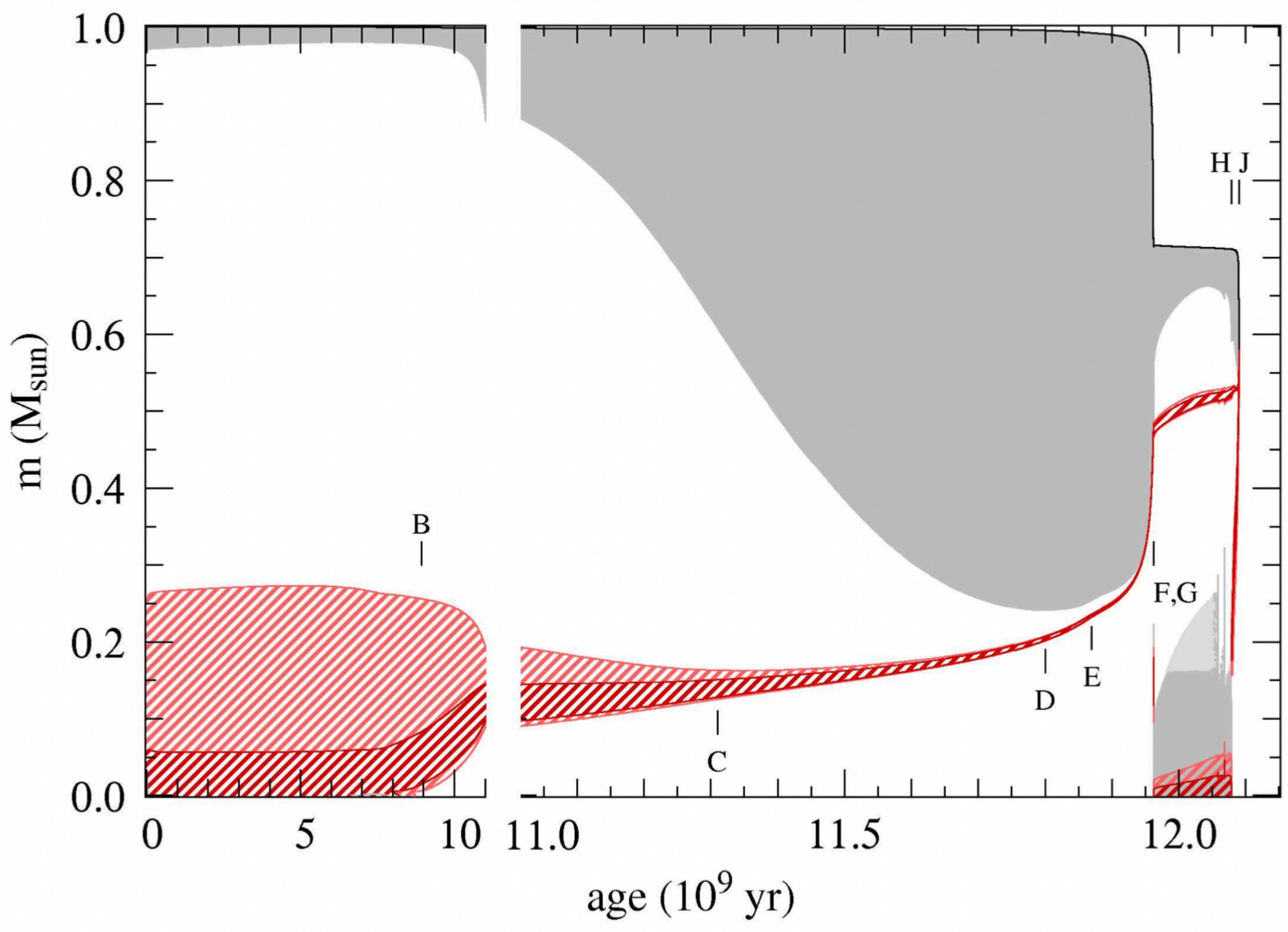


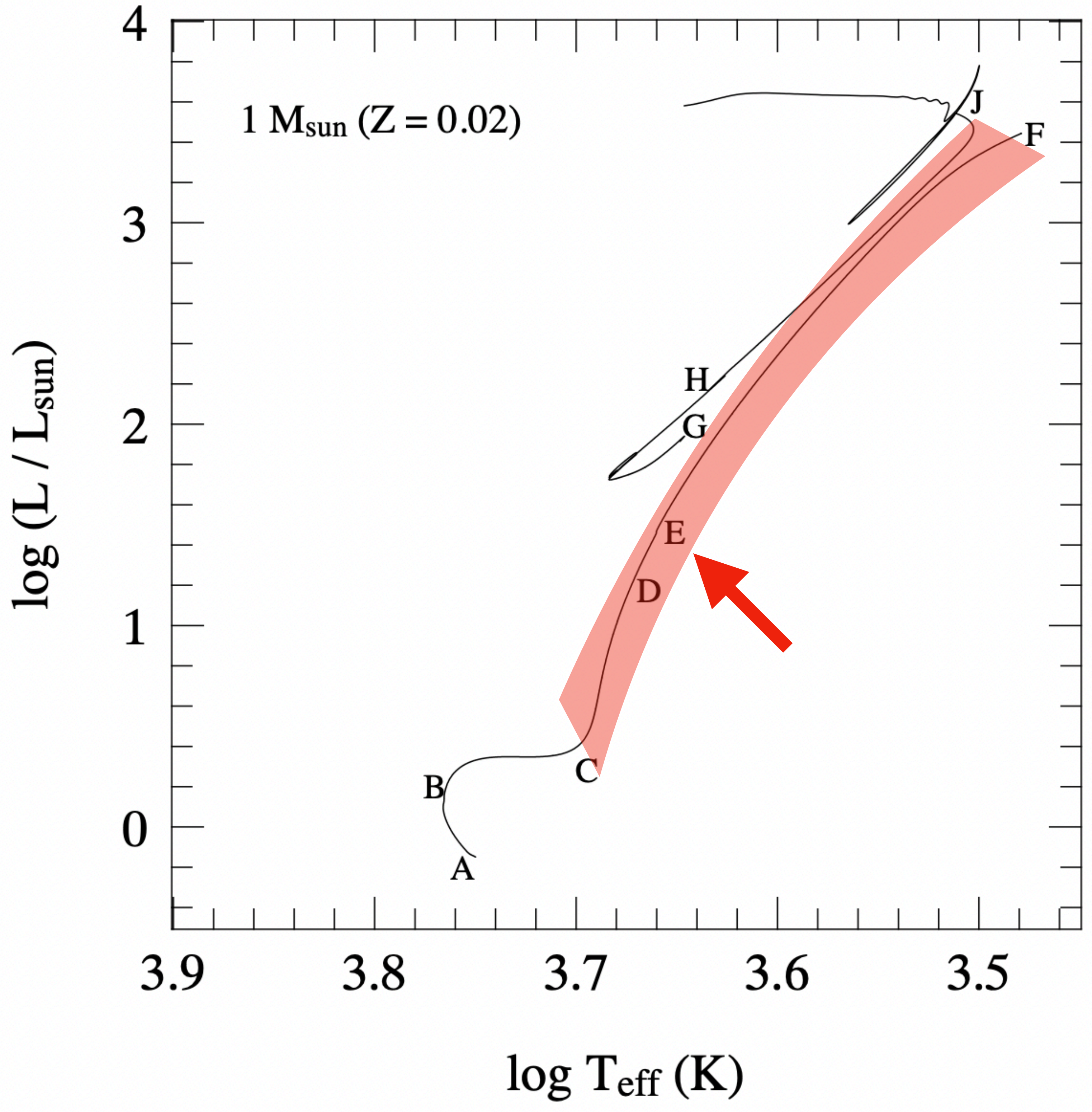




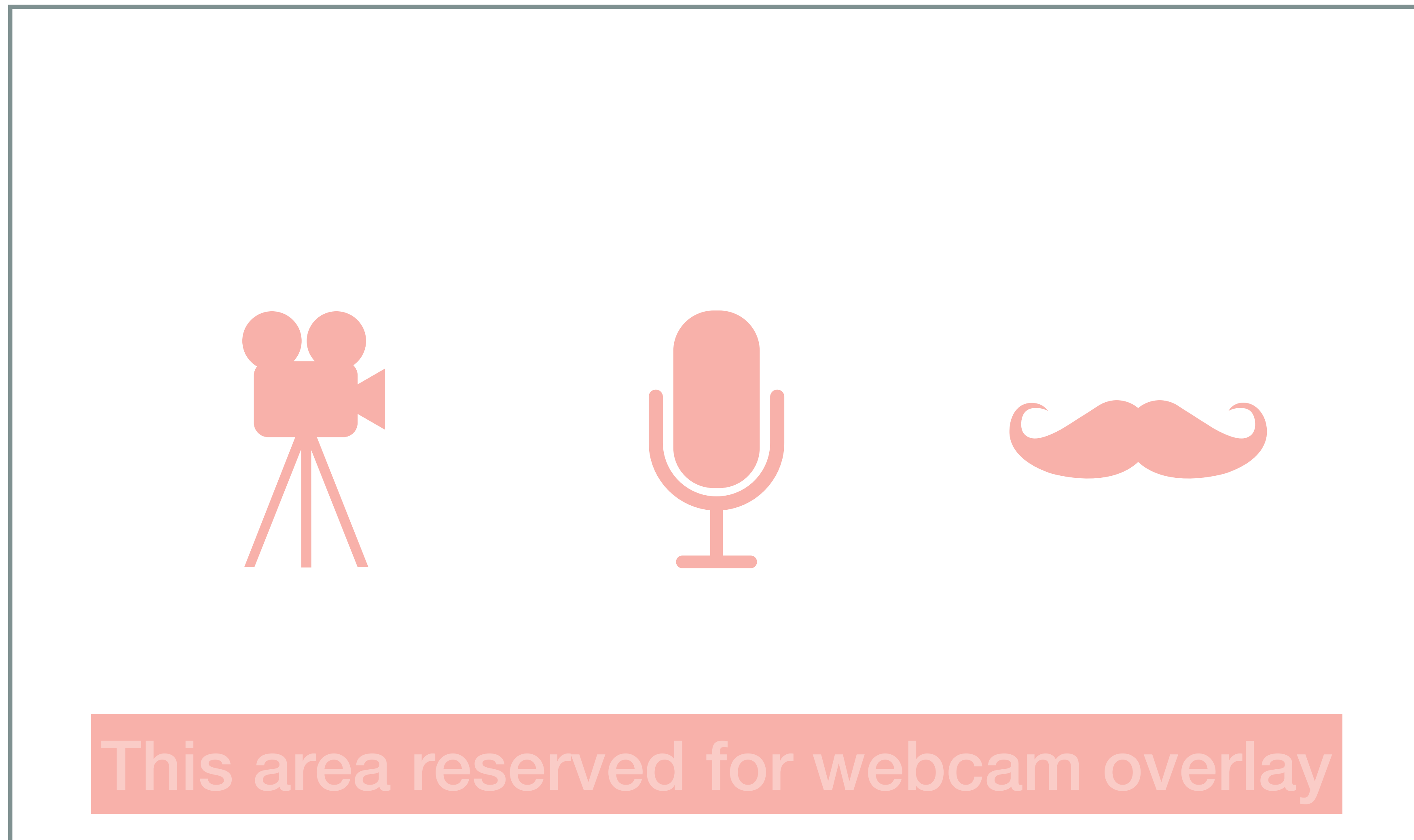
RGB

- E: hits a snag… The shell fusion reaches place where convective zone was



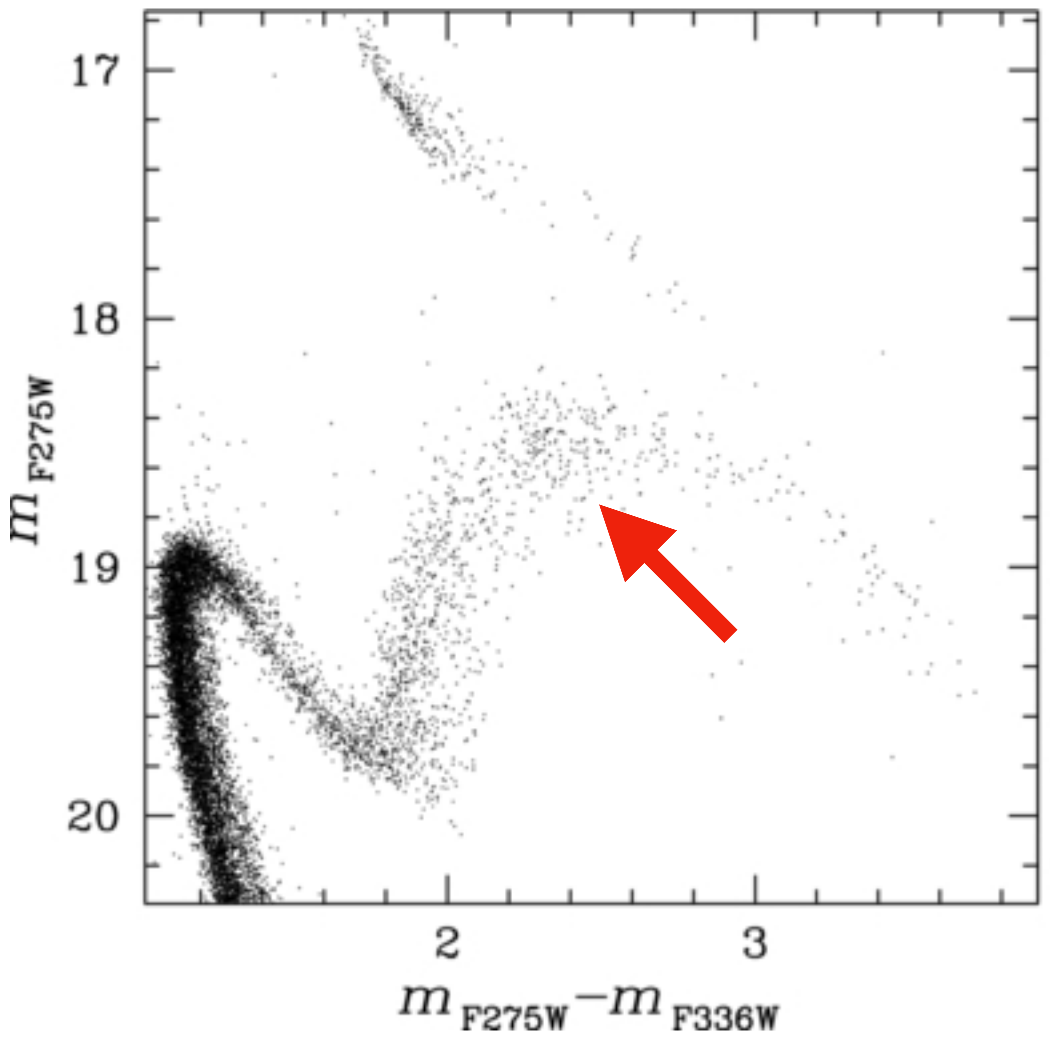


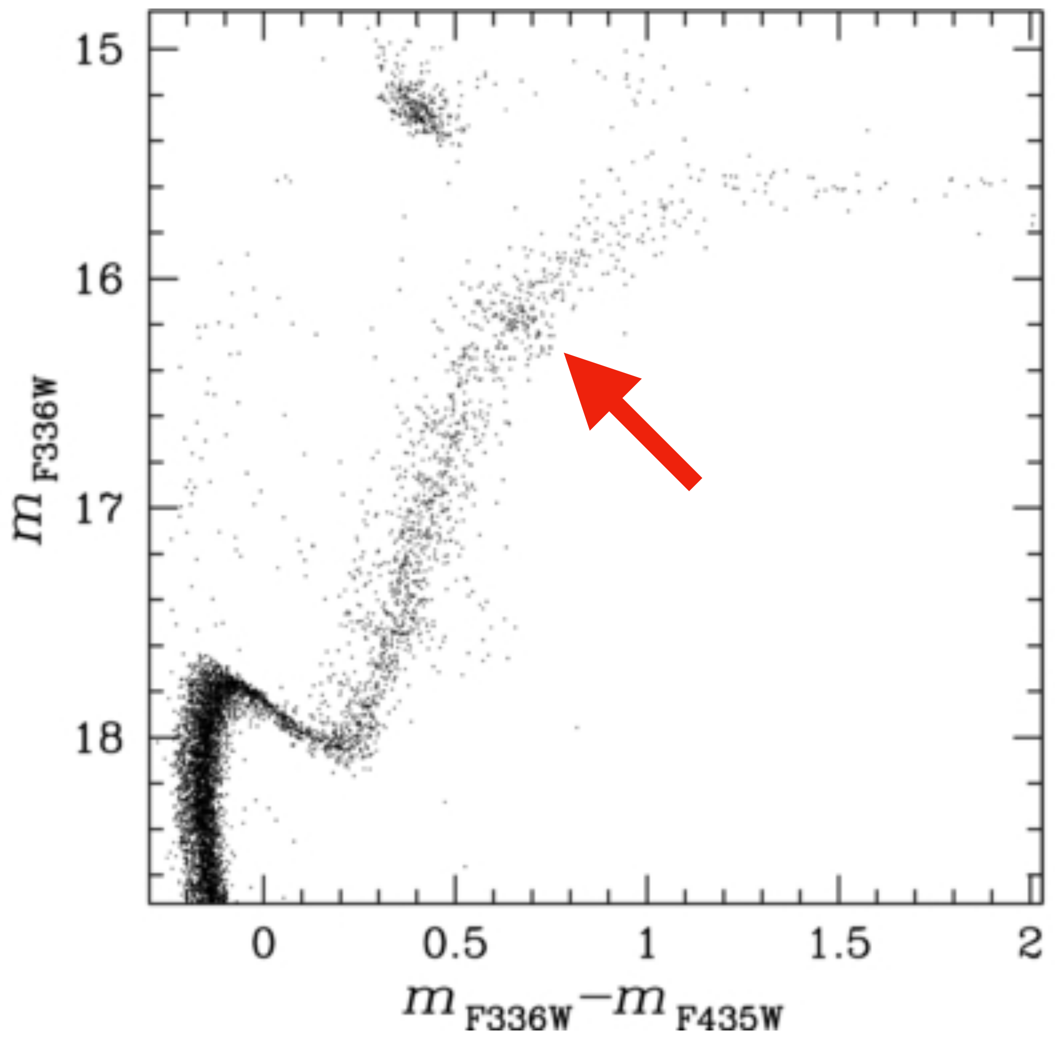
- This called the "**Red Giant Branch Bump**" (RGBB)… not to be confused with the "Red Clump"

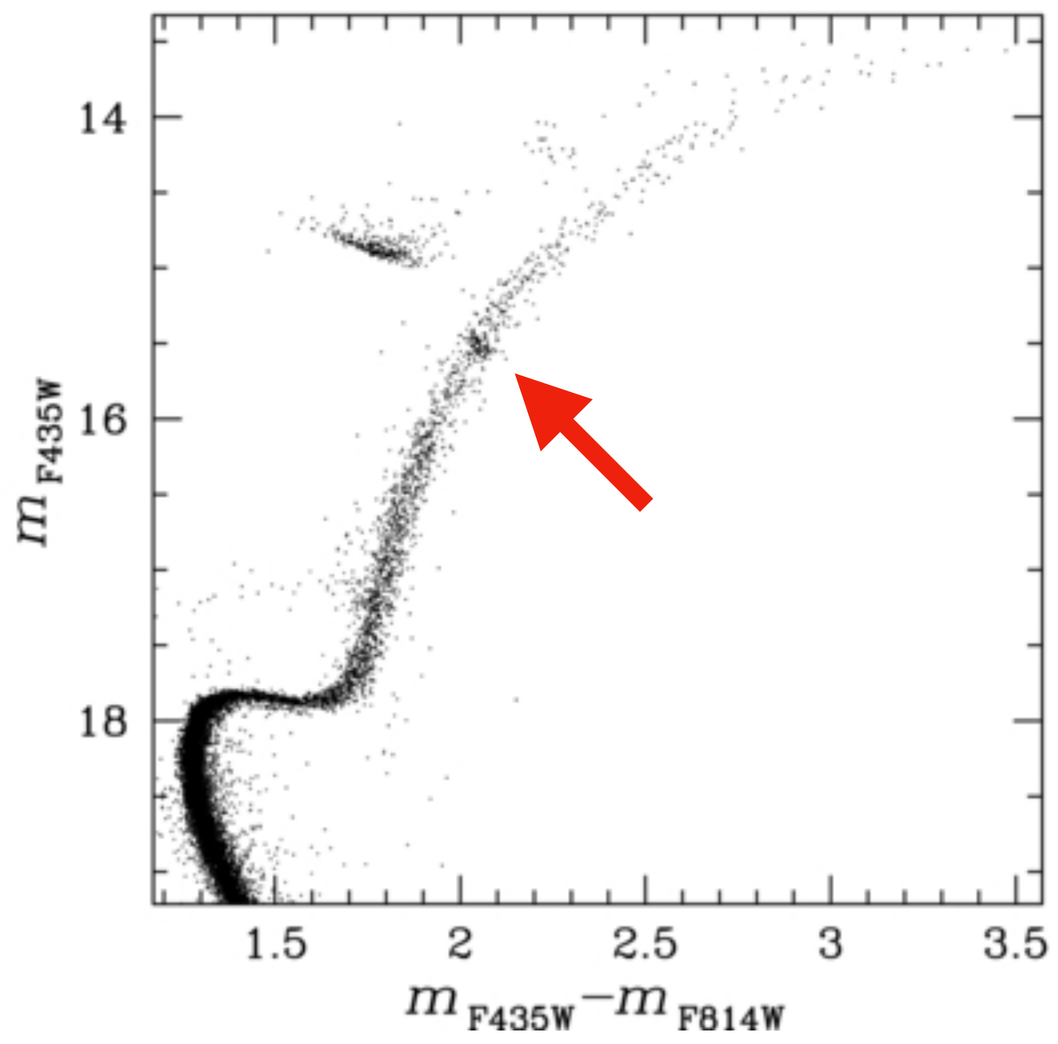


Milone+2012 (47 Tuc)

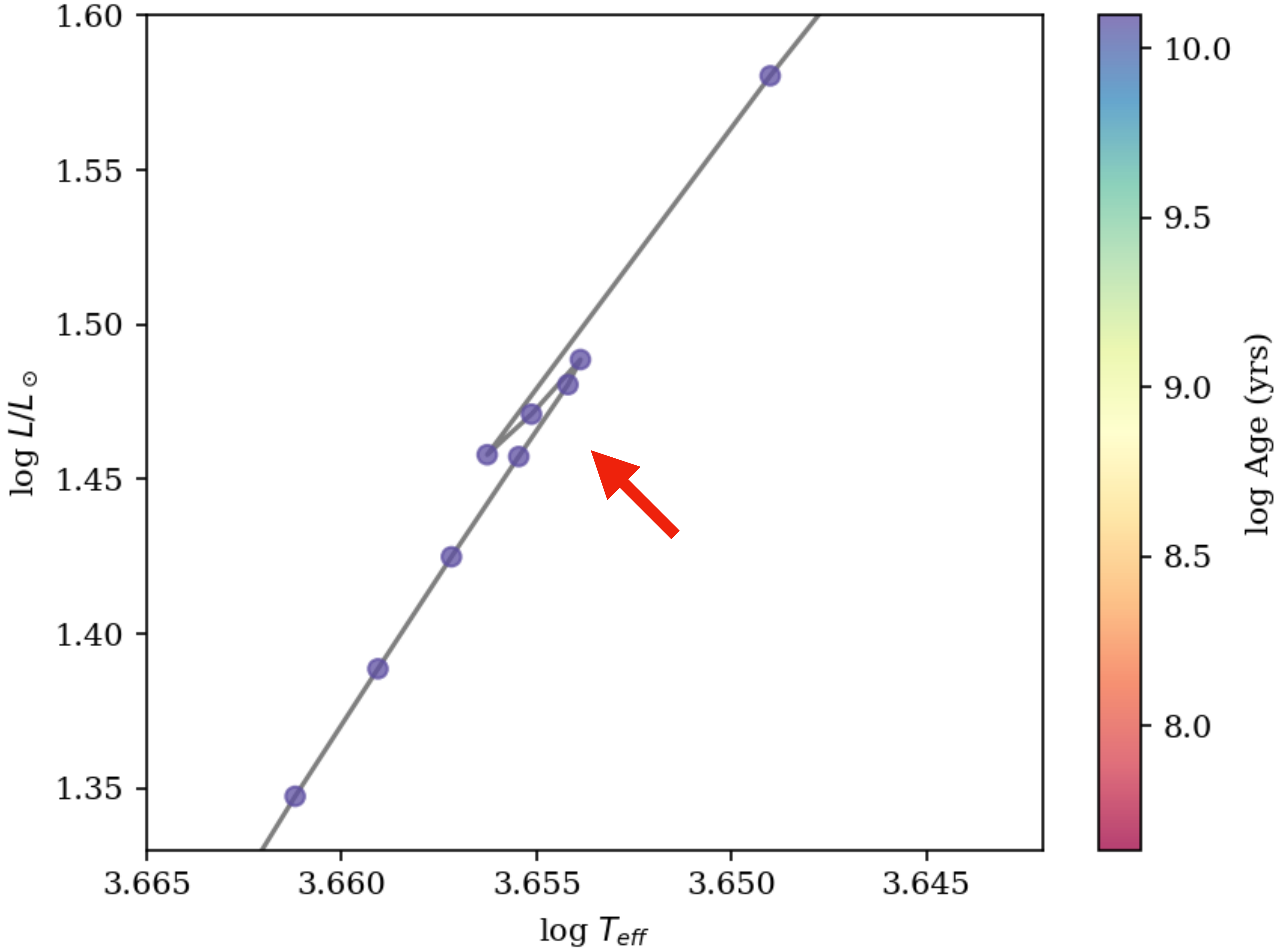
RGBB

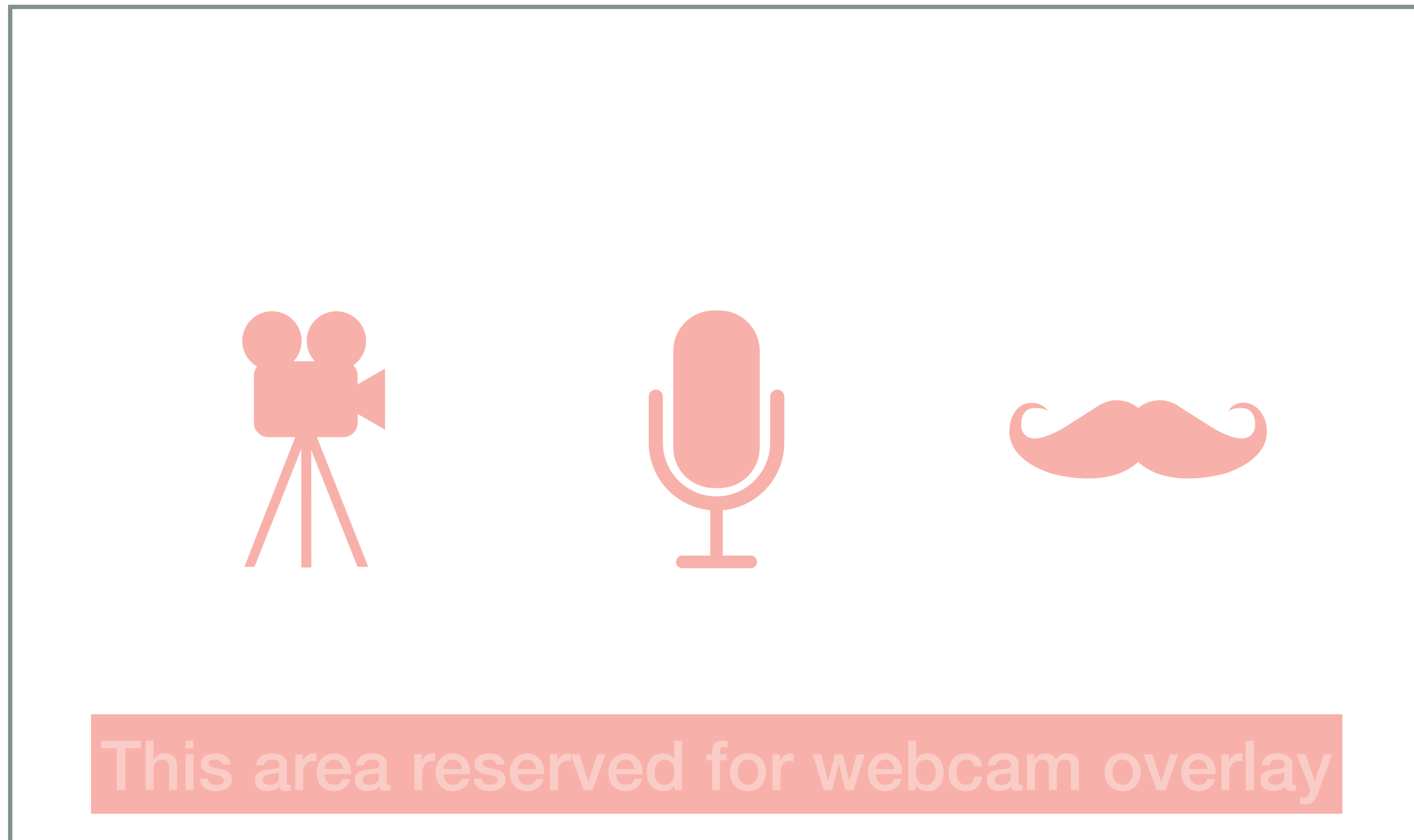






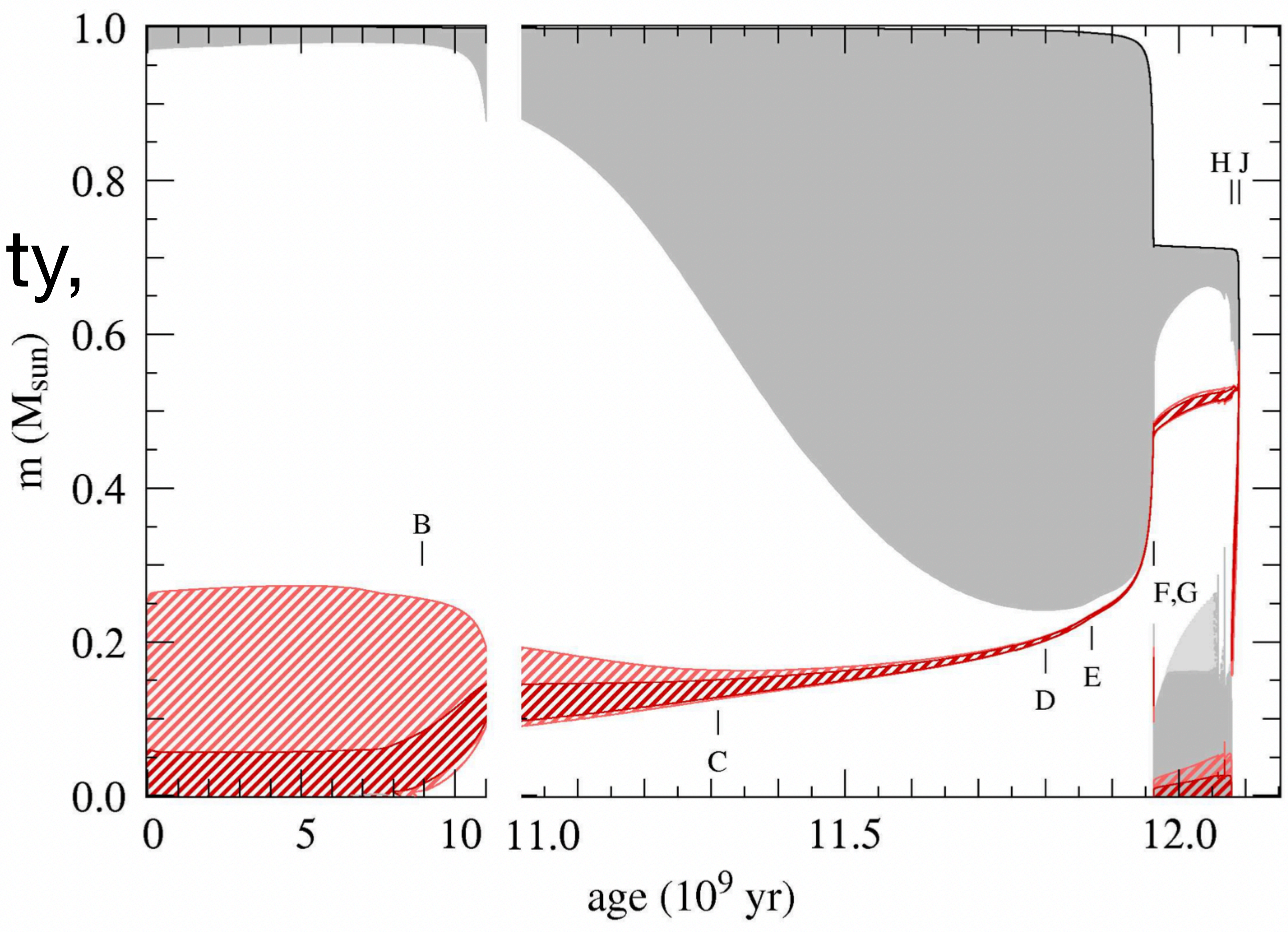
From HW 6

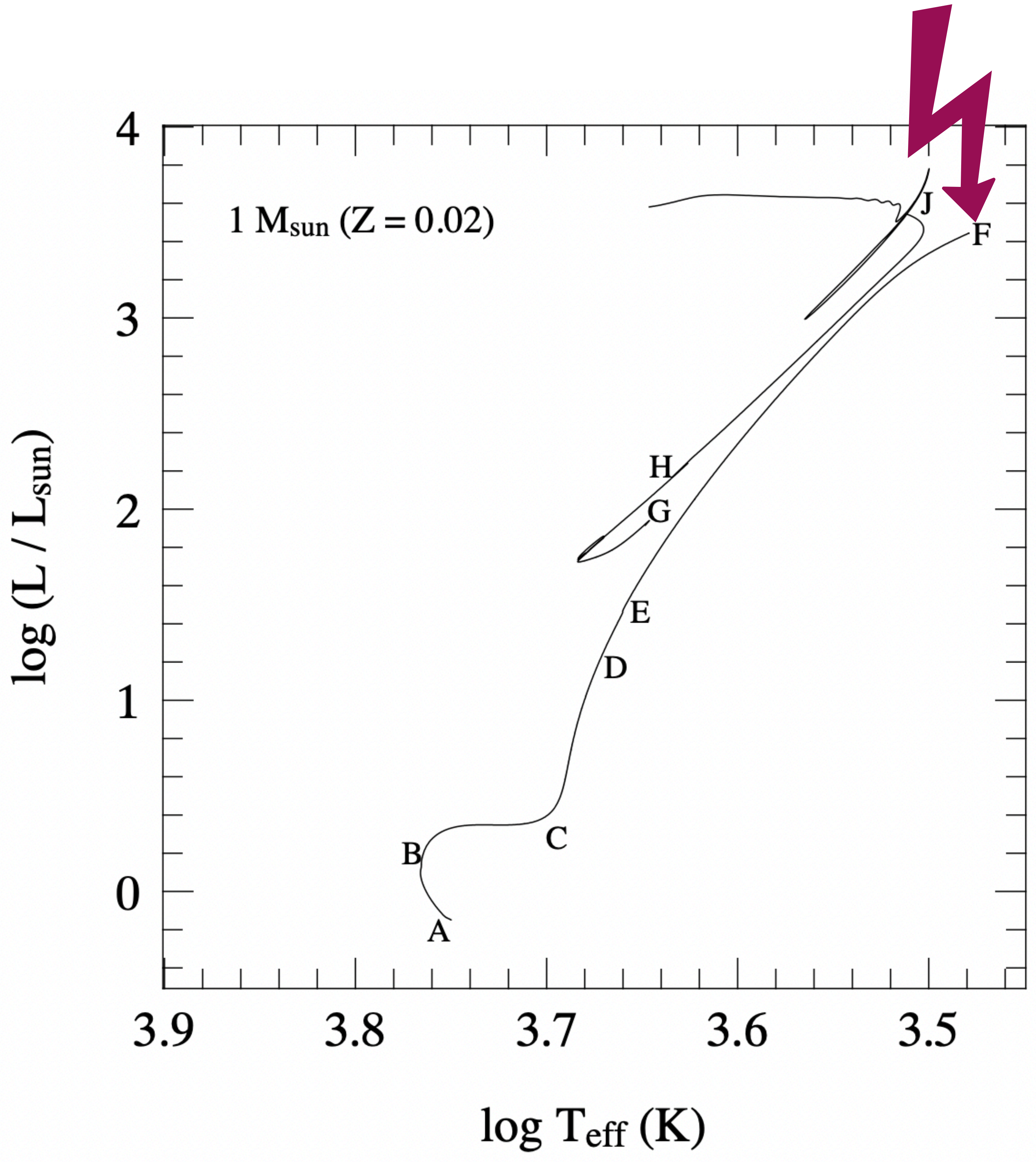




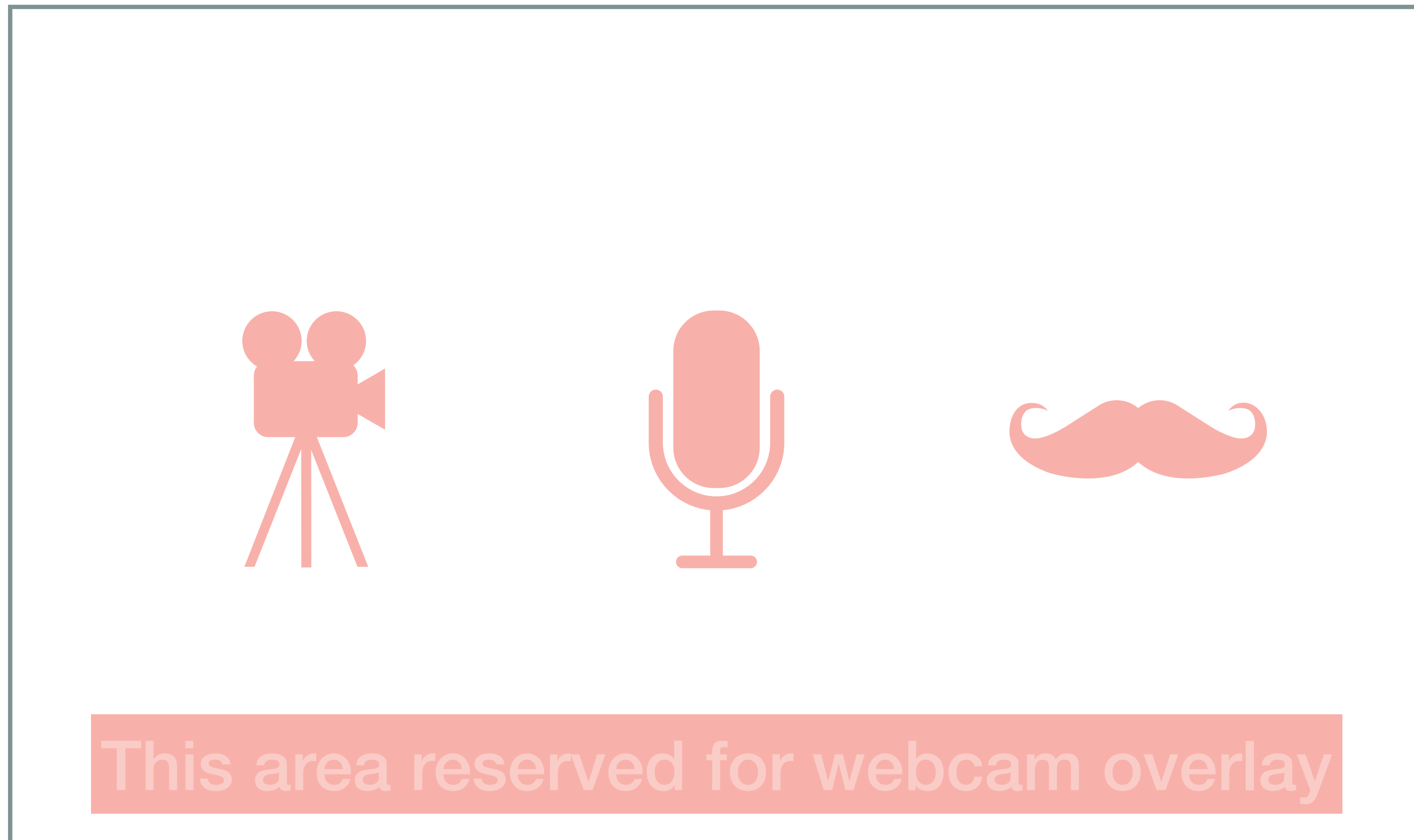
TRGB

- Reach a max luminosity, "tip" of the RGB
- He core finally ignites
  - "The Helium Flash"
- Happens super fast, (minutes) tends to break stellar models…



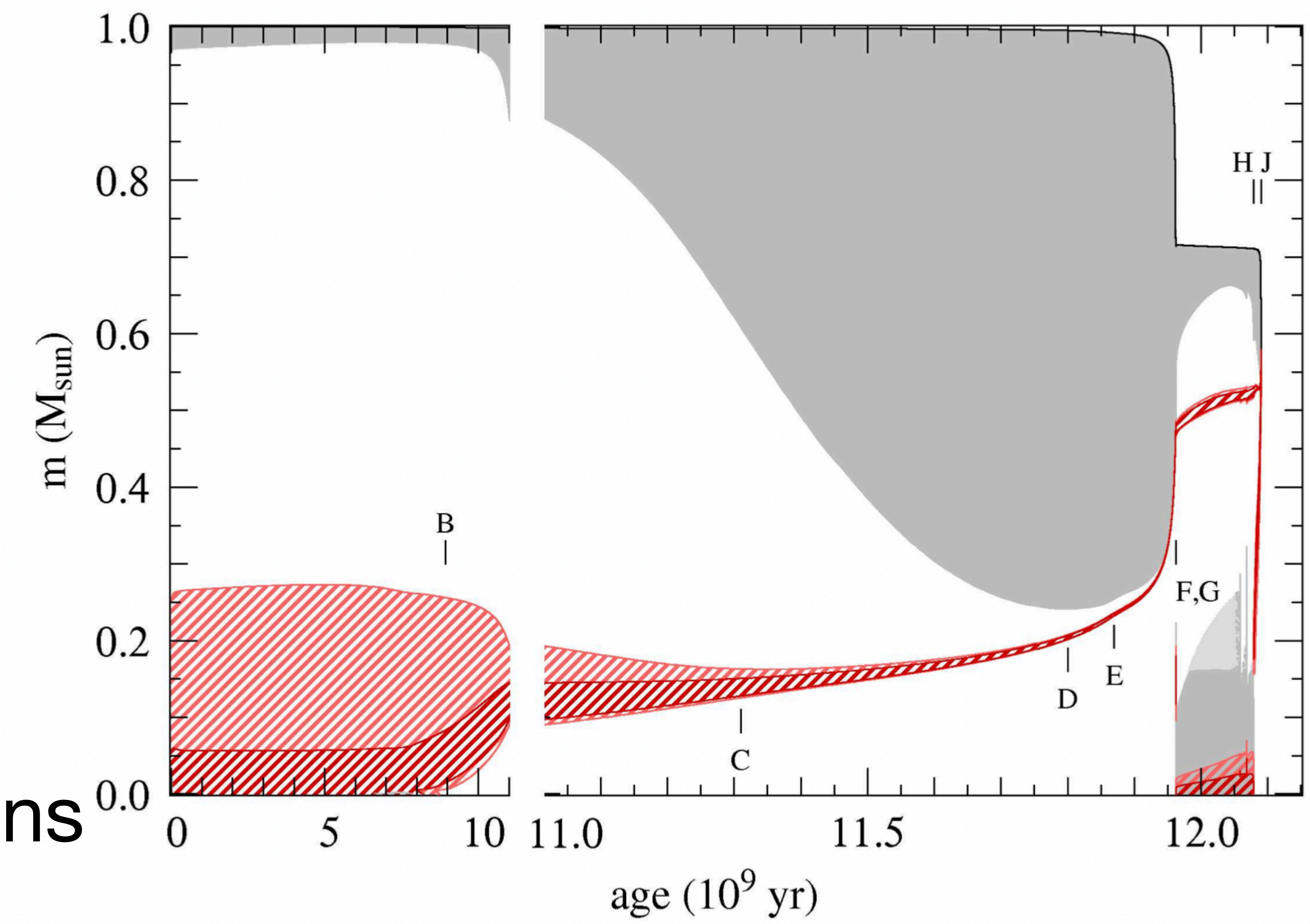


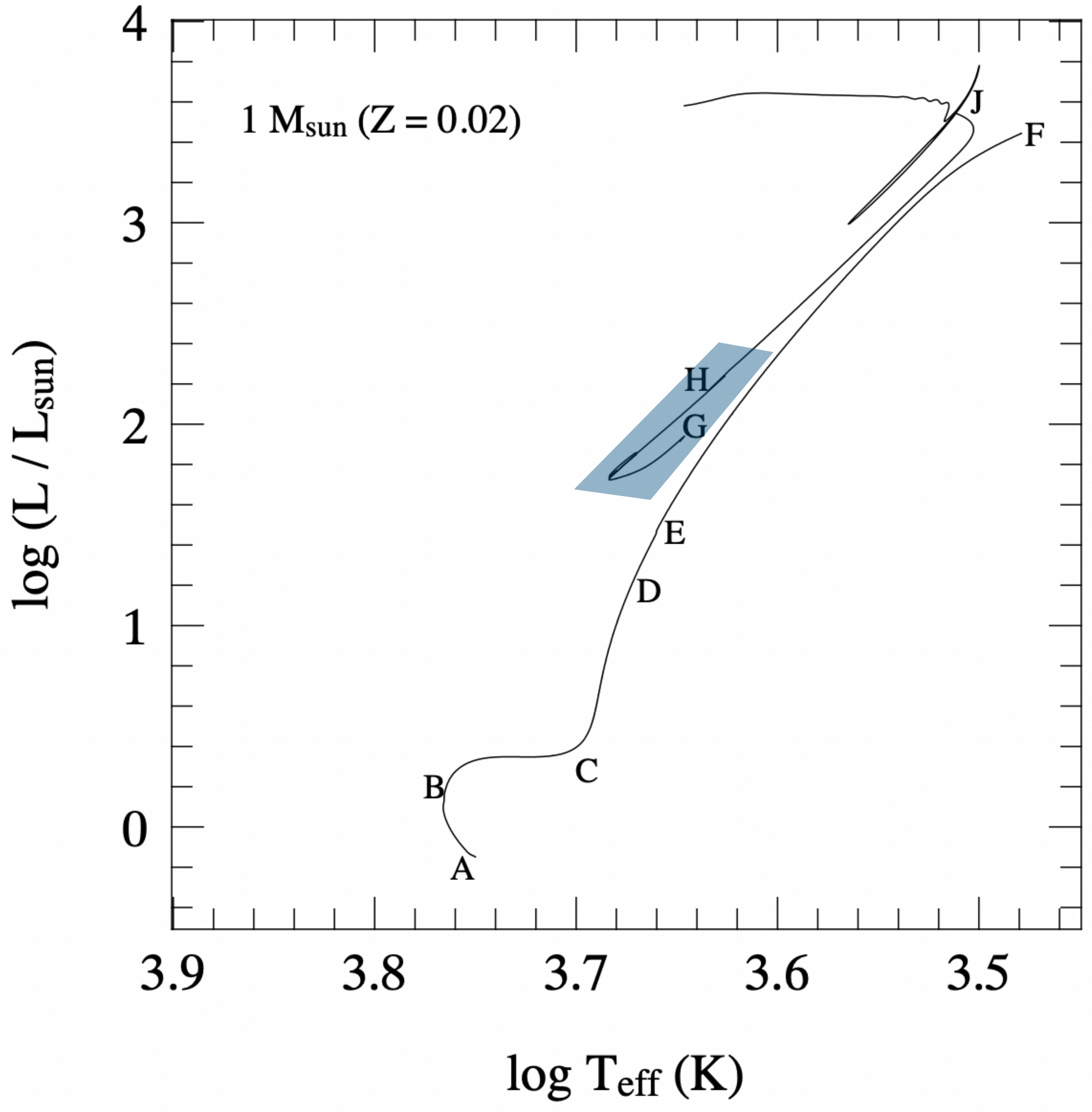
- But we don't see stars "jump" from the TRGB to the horizontal branch, though its been proposed, should be quick (years?)
- TRGB used as a "standard candle"



Horizontal Branch

- He core fusion "main sequence" (points G-H)
- Still have H fusion in a shell, so the mirror effect happens





- Mass loss from the He Flash (top of Kippenhan diagram)
- Not long-lived: 120Myr for sun, ~20Myr for $5M_\odot$
- This where RR Lyr live!

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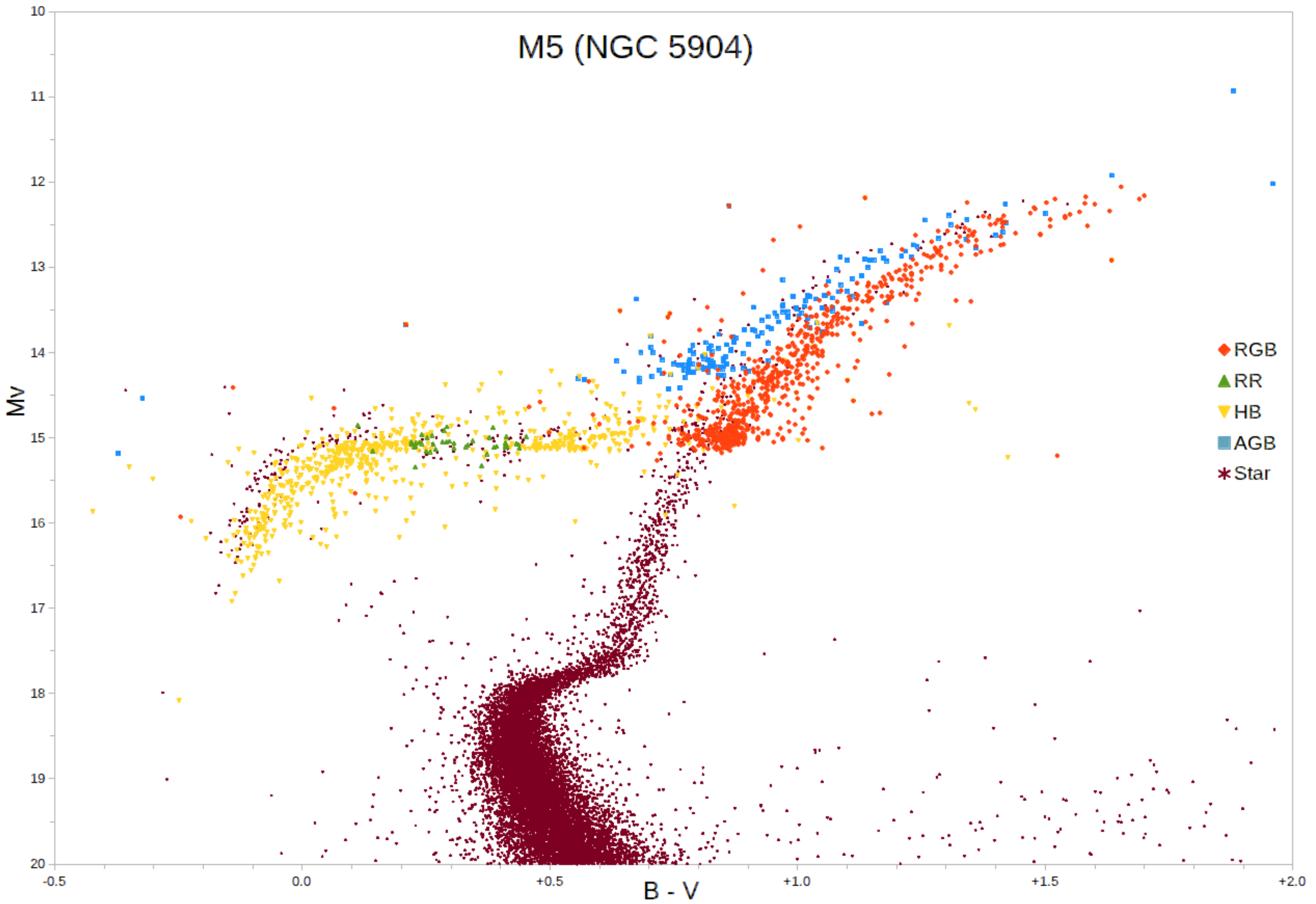
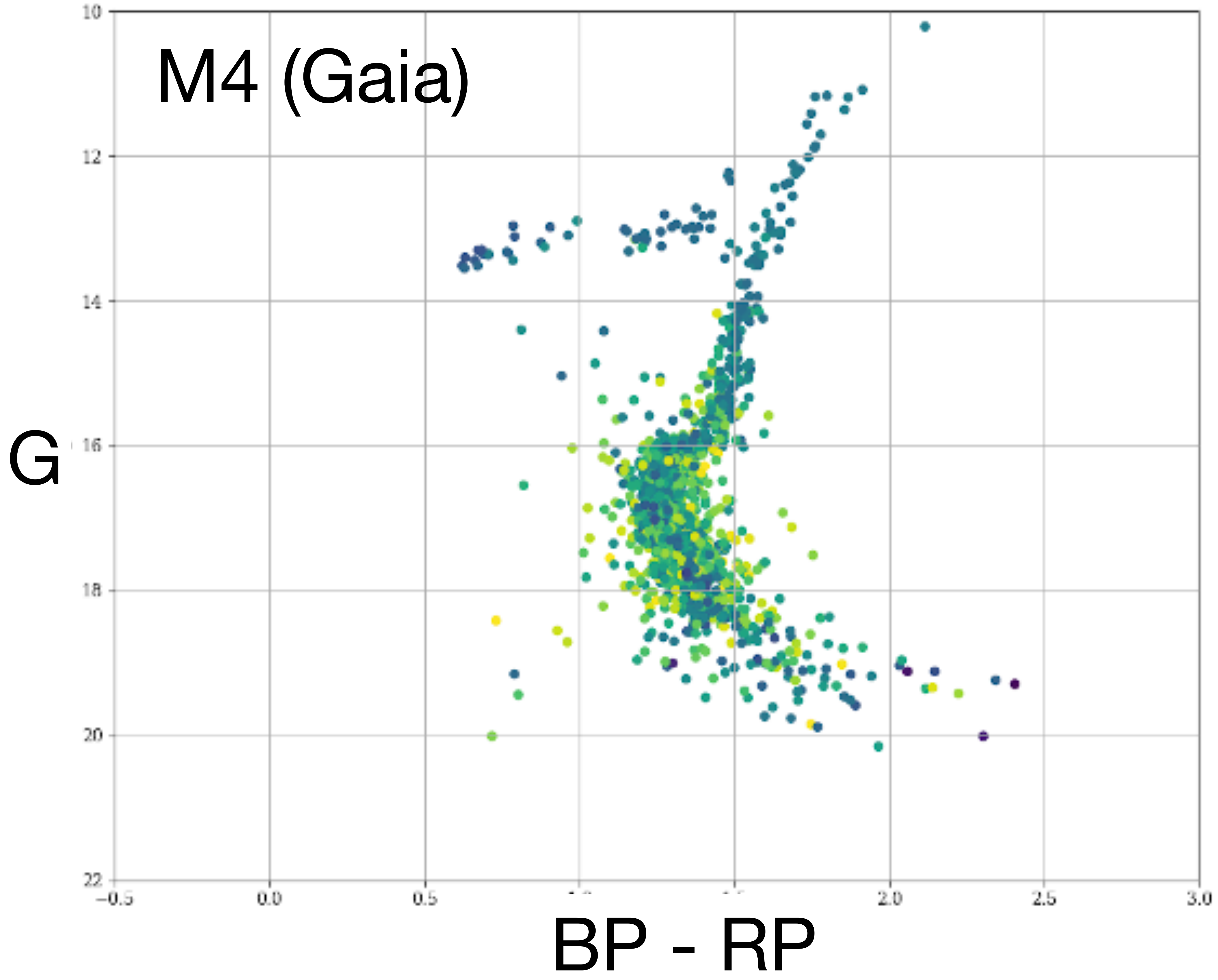
Horizontal Branch

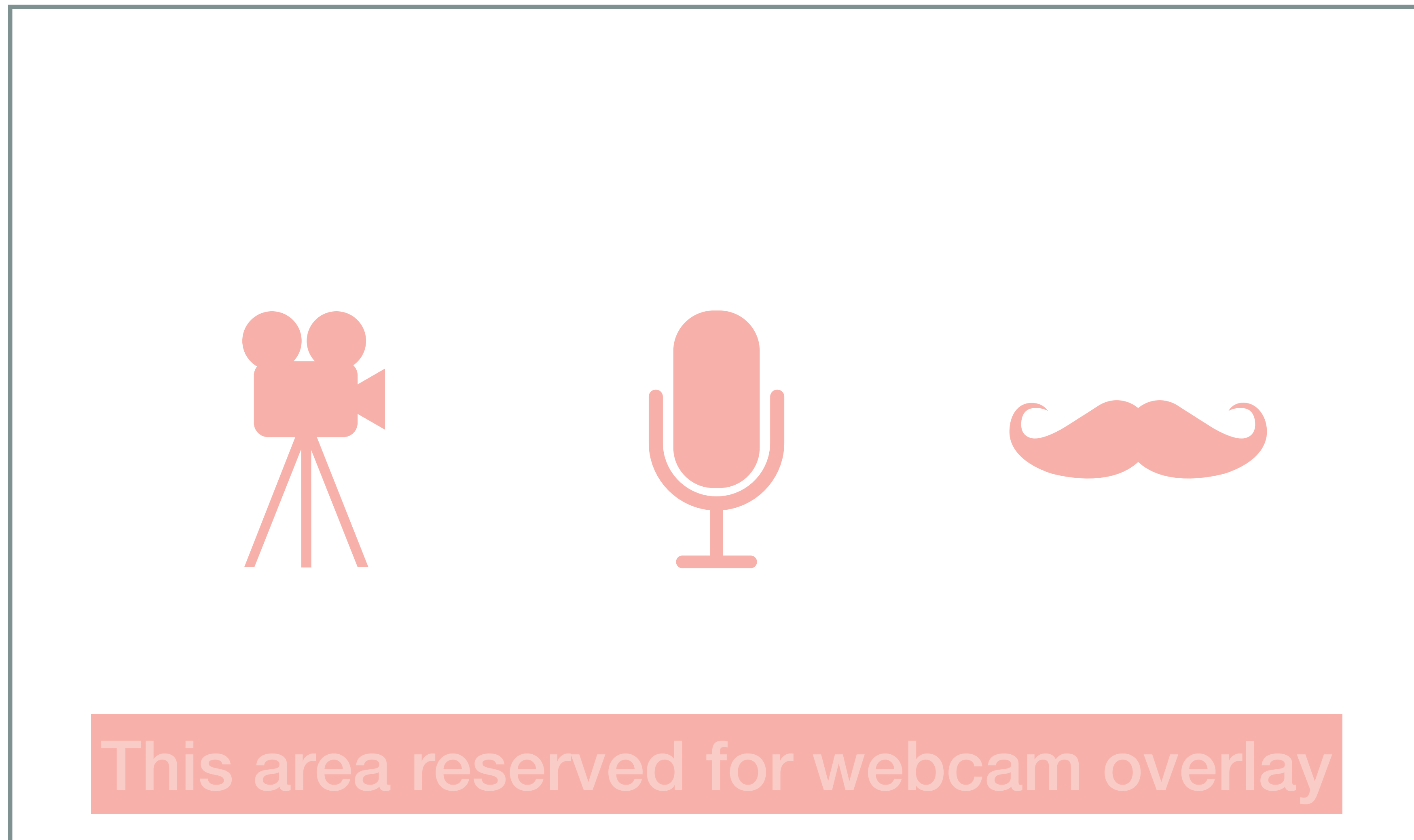
- Gets its name from studies of globular clusters, can be spread out a lot

- You can see a “gap” in the HB this is due to the **RR Lyr**!



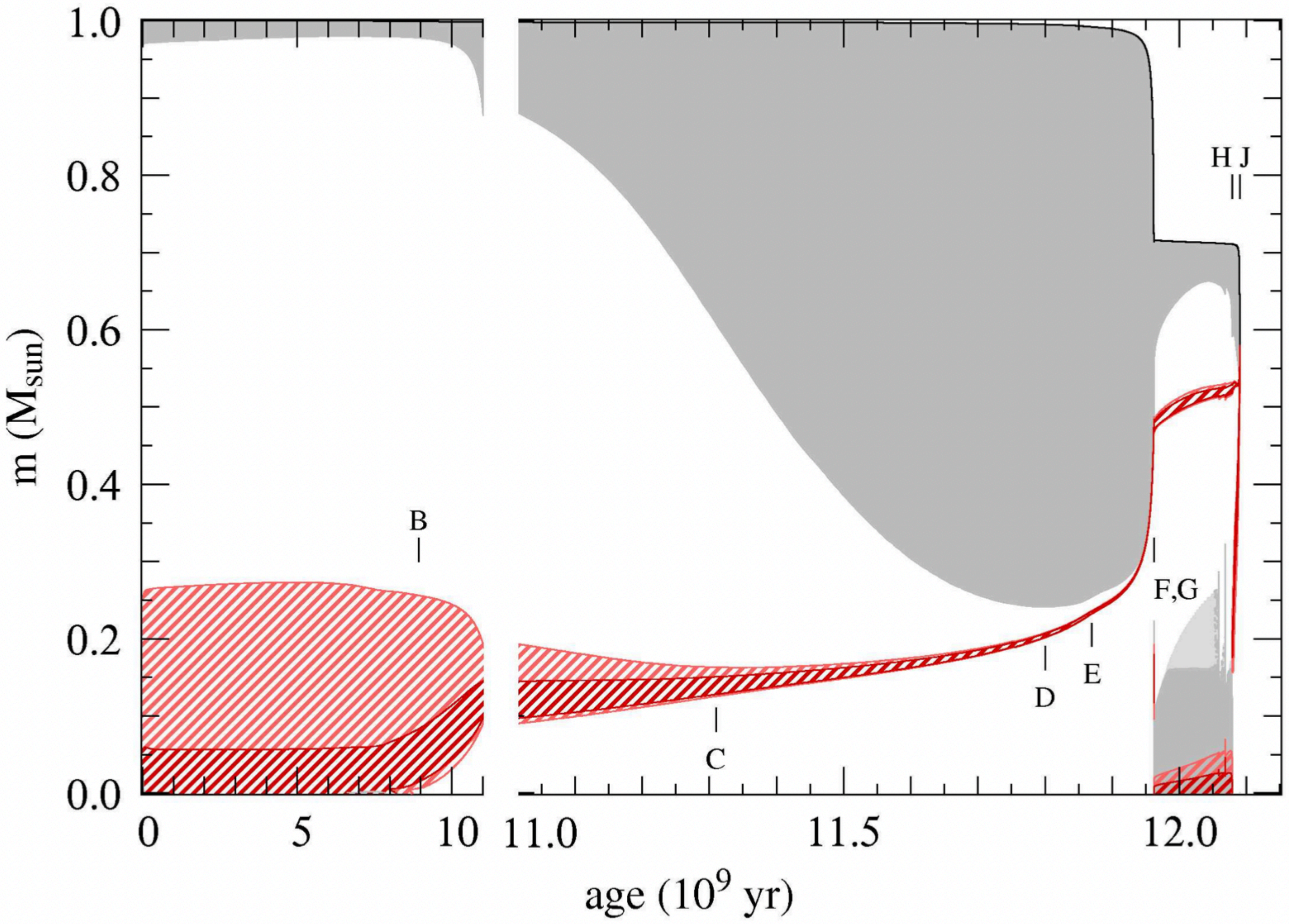
https://commons.wikimedia.org/wiki/File:M5_colour_magnitude_diagram.png

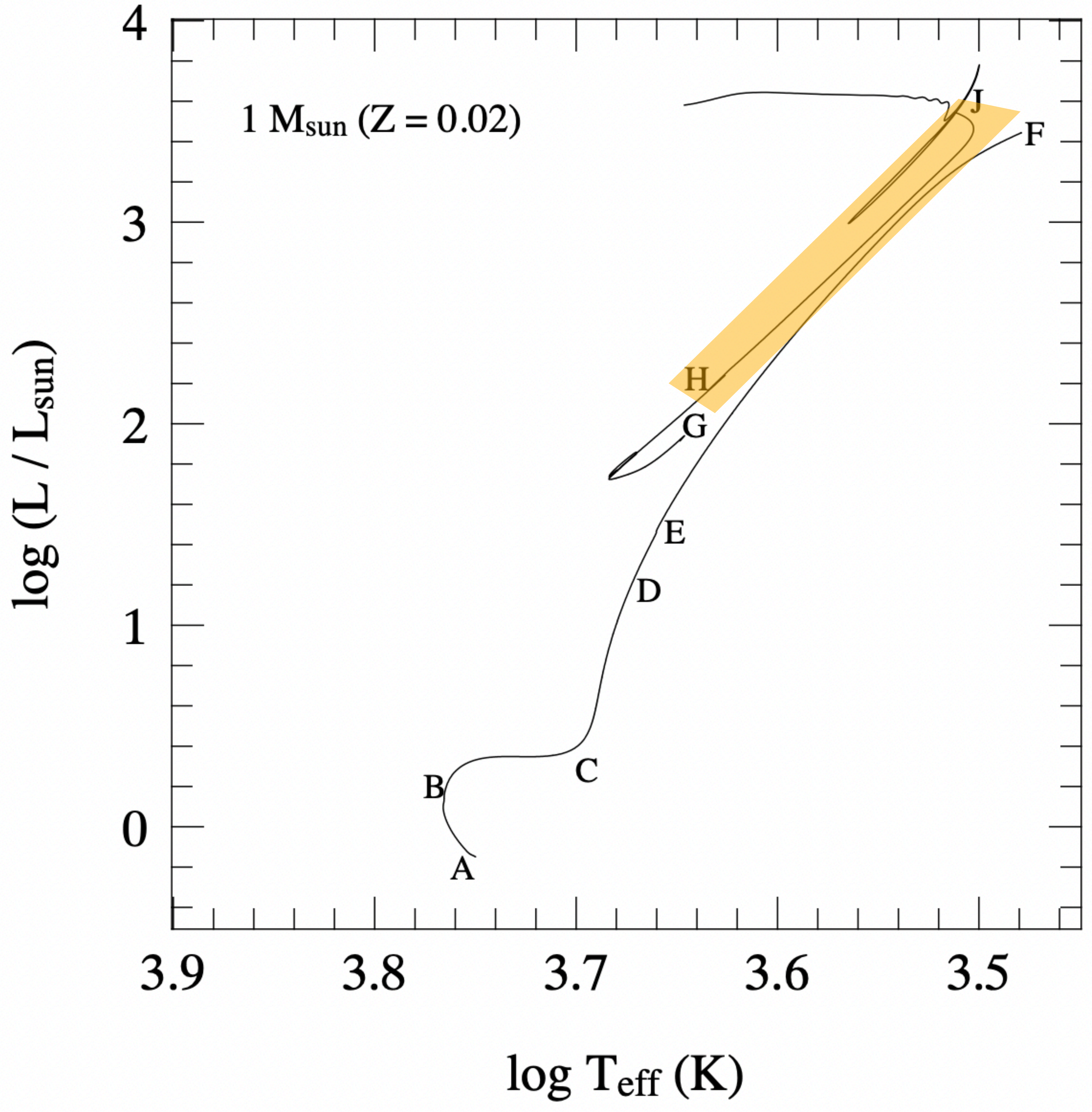




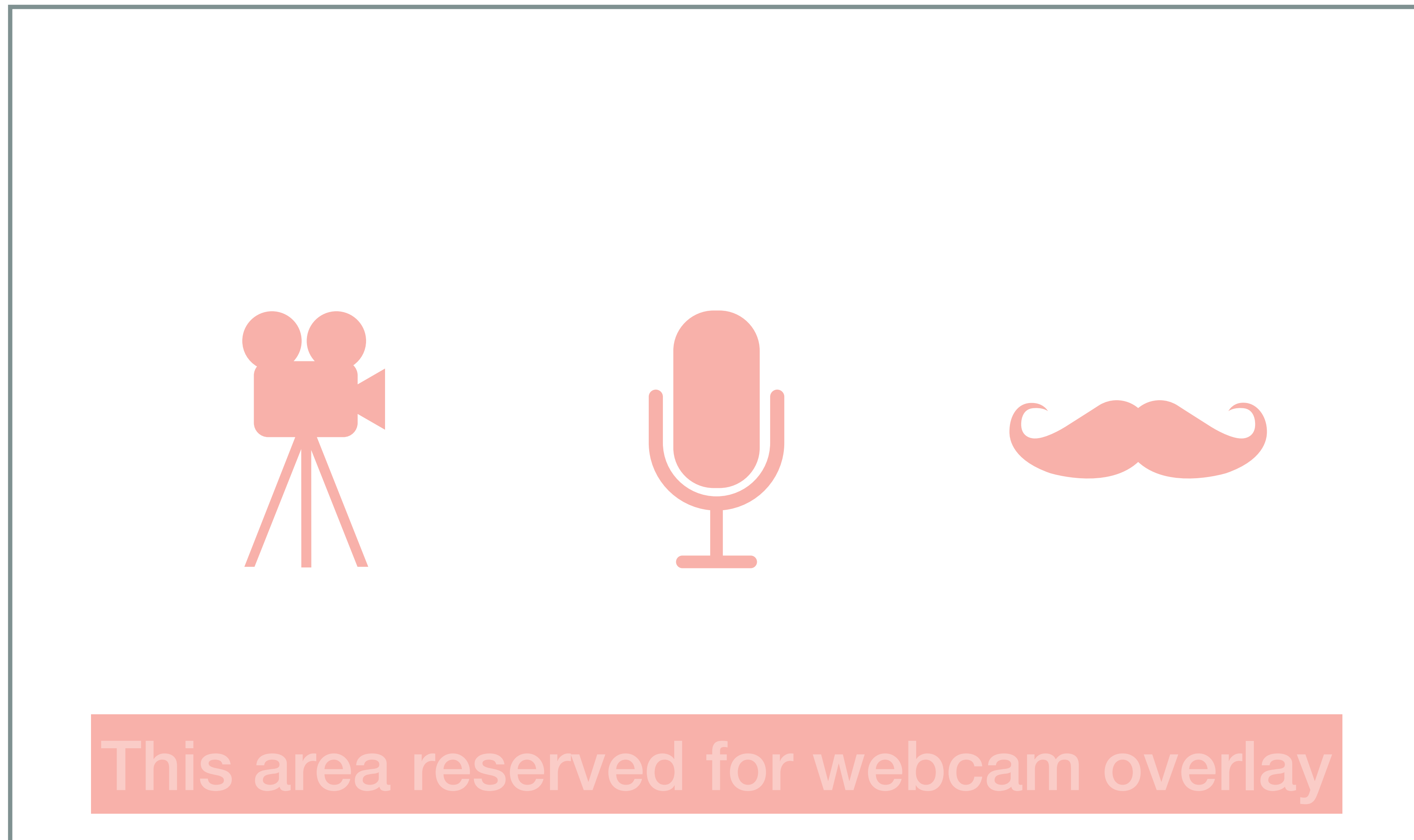
AGB

- Up it goes *again* (2 phases of AGB)
- Now with H and He shell fusion!
- Up against almost the same Hayashi line, slightly hotter



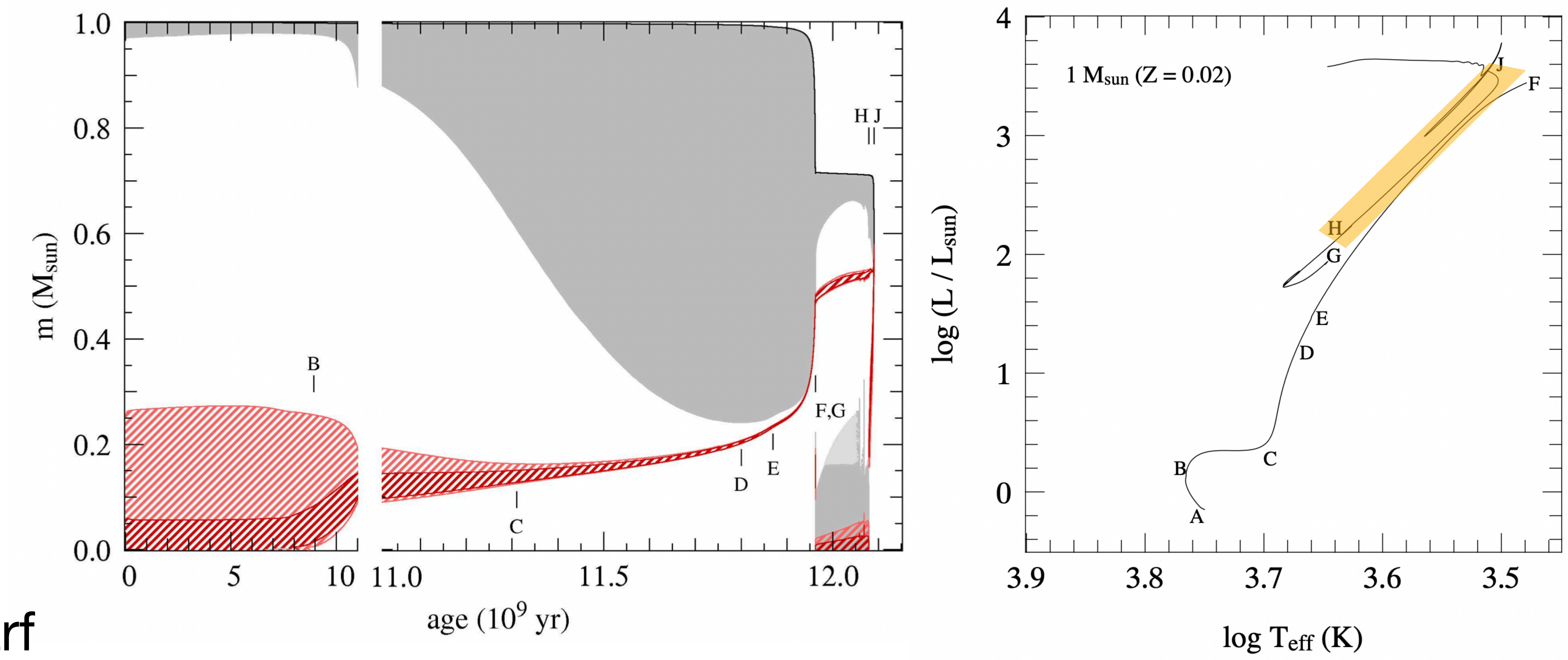


- Forming a degenerate C/O core
- He shell runs out of fuel, but H shell can cause it to reignite (He shell flashes), causes thermal pulses
- Tons of mixing w/ each pulse, drives mass loss!



AGB

- Tons of mass loss
- Whole phase is fairly short (few Myr)
- What is left in the core IS a white dwarf



- The envelope finally gets fully stripped away from thermal pulses (and dust condensation, etc)

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Planetary Nebulae (PNe)

- Post AGB, the core contracts & gets HOT
- The core is now a WD (~0.6Msun)
- This hot star ionizes the material kicked out by the AGB phase

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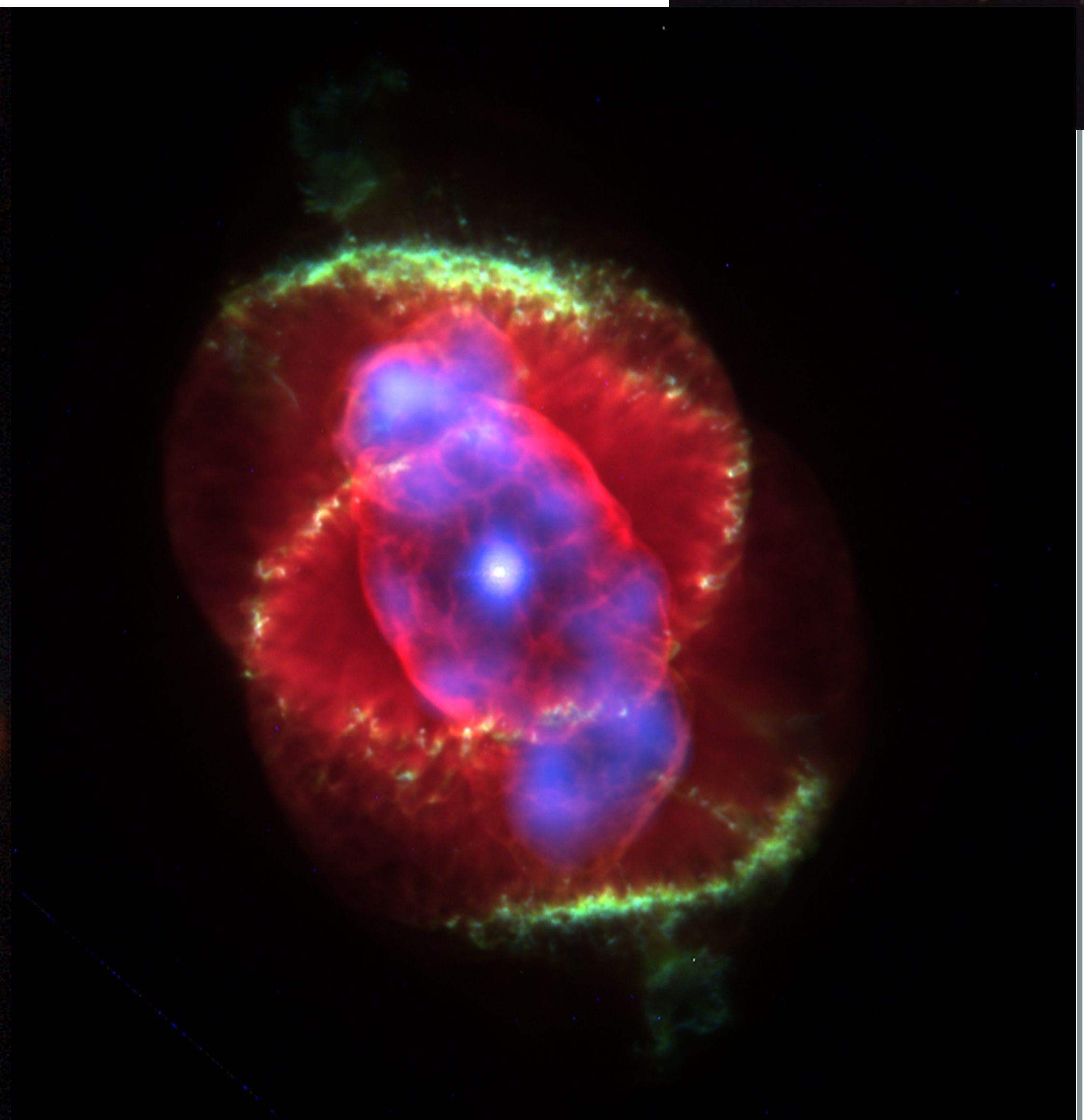
Planetary Nebulae (PNe)

- Lots of shapes/sizes for PNe.
  Due to winds, dust, binaries, **B** fields…
- More than 2000 known in MWY
  (González-Santamaría+2021, w/ Gaia)
- Can even see them in nearby galaxies!



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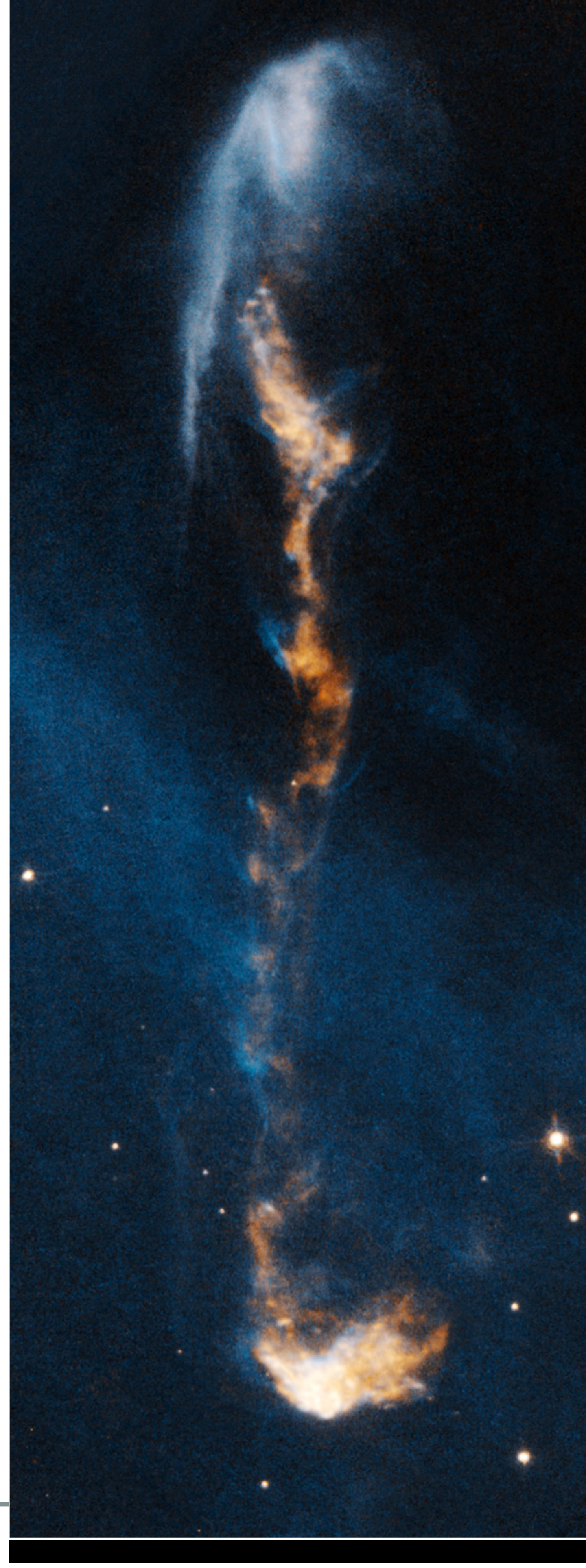
Which is more beautiful?

No wrong answers…



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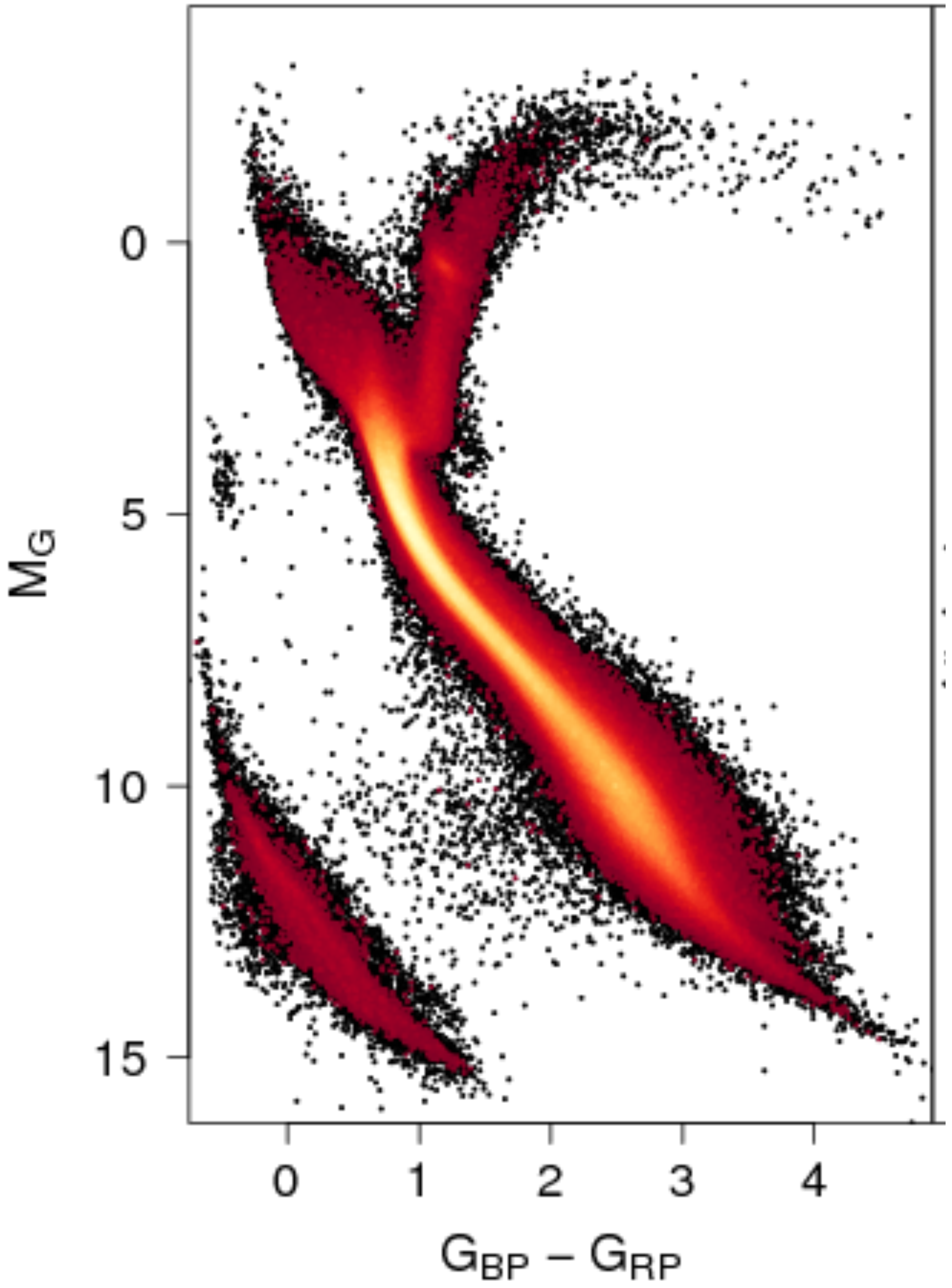
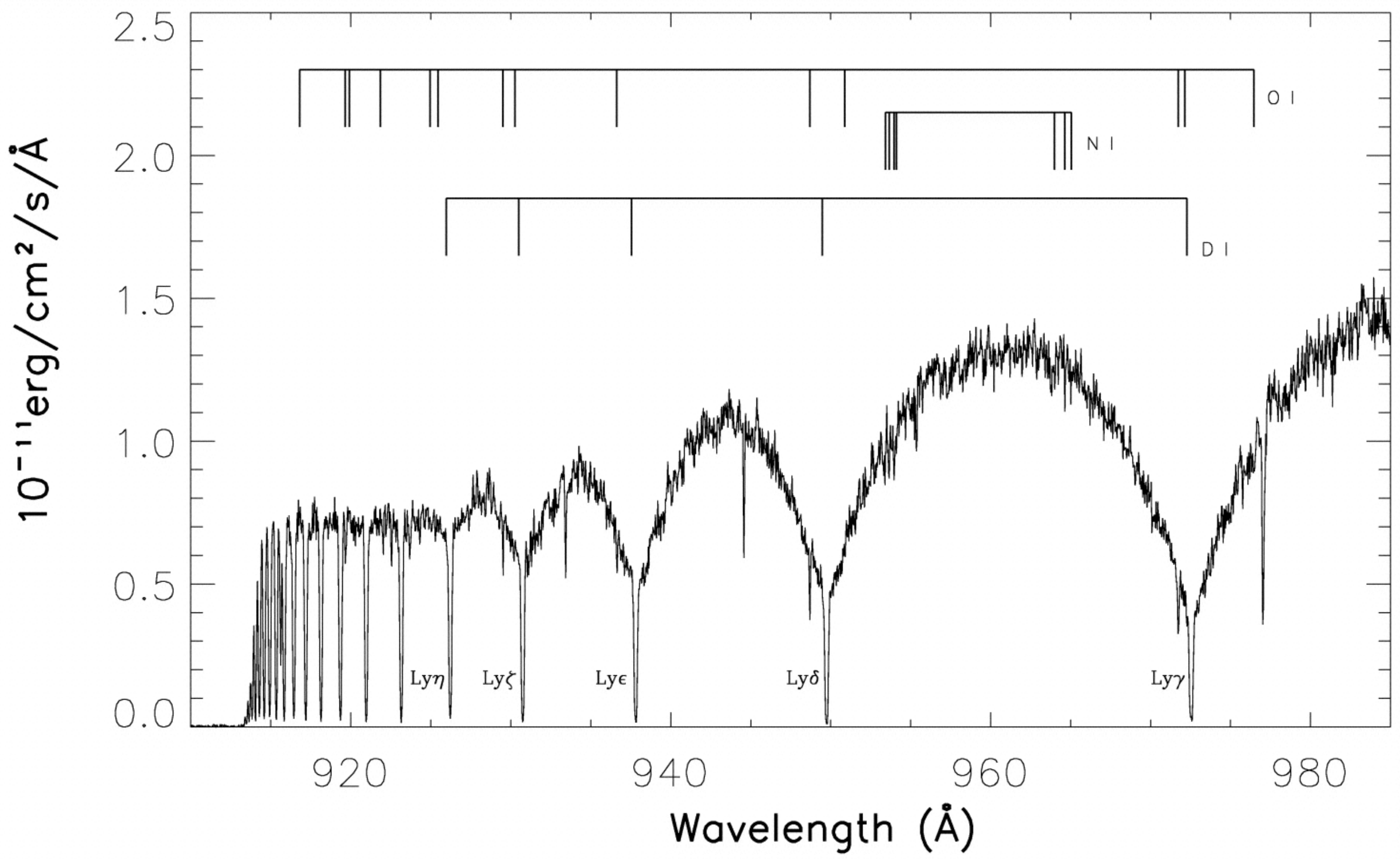
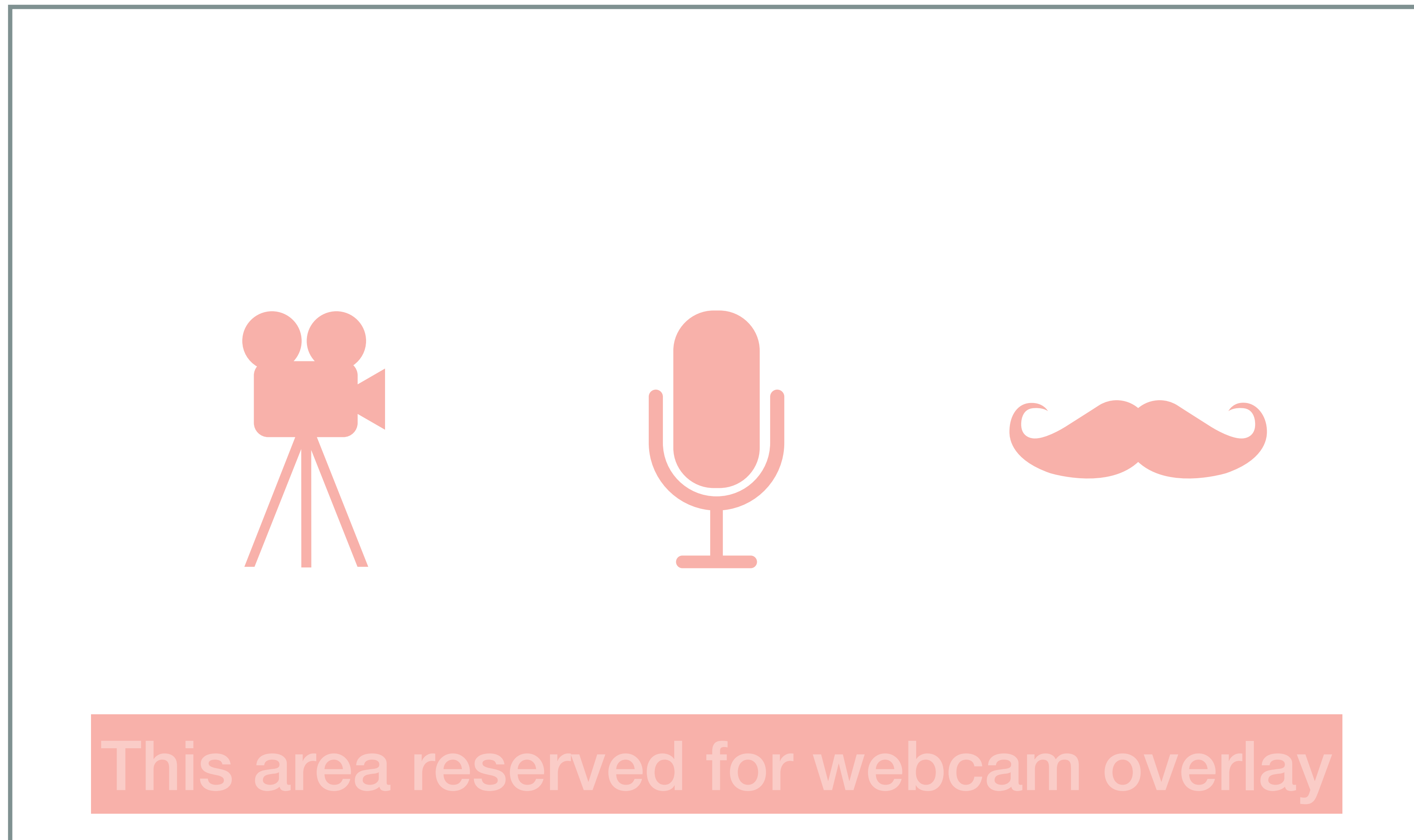
White Dwarf

- The star is held up by e- degeneracy pressure
  - Density structure similar to a polytrope
- Composition of WD determined by initial mass of stellar core, which stages of fusion it gets to
- Small envelope of material still around it, (where these absorption lines comes from!) Composition depends on what happens to envelope

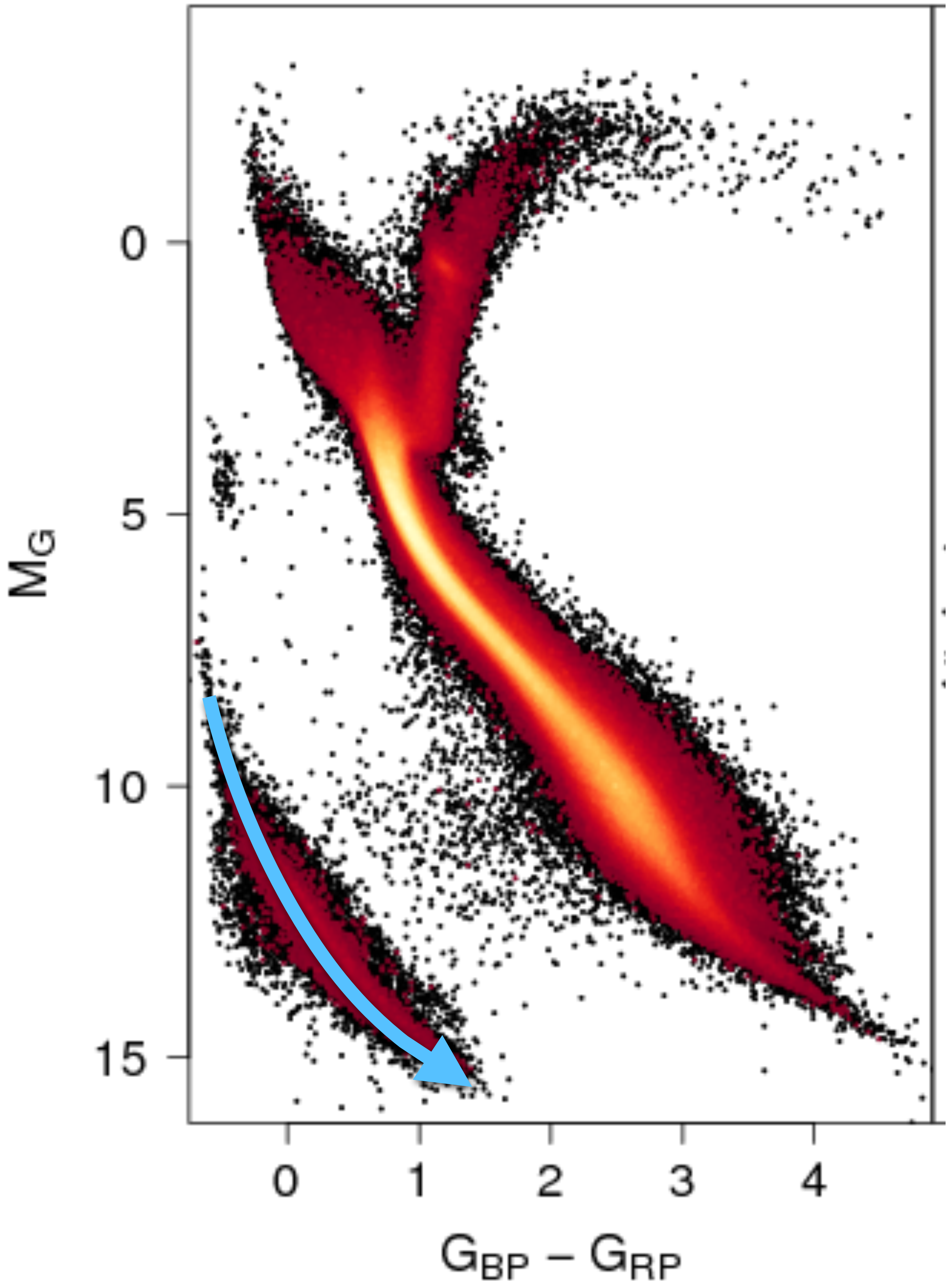


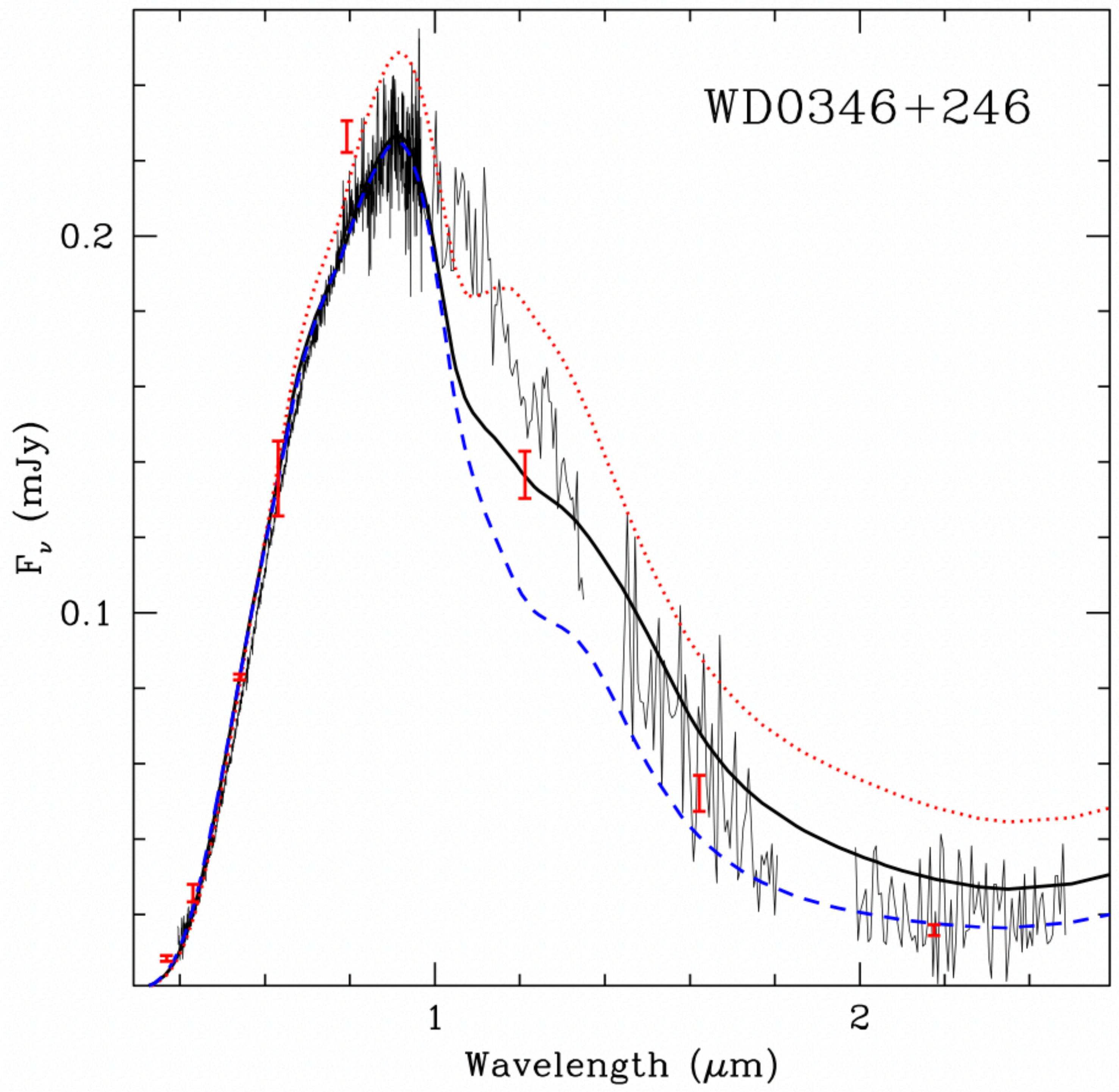




White Dwarf

- Typical mass ~$0.6 M_\odot$, cools over time
- can use to get ages for WD's if you have a good model for the composition & crystallization. **"Cosmochronology"**





Kilic+2012

- The *coolest* WD's: <4000K (!)

This area reserved for webcam overlay

The End

- And this is where our story ends…
  its no longer a star

- Gas has been dramatically returned to the ISM, young WD has lots of ionizing photon to add pressure to things

- If it's higher mass ($M > 8M_{\odot}$) it will explode as a SNe

  - LOTS of pressure added to the ISM!

This area reserved for webcam overlay