The Lives of Stars

Dr. Bill Wolf

Assistant Professor
Planetarium Director
Department of Physics & Astronomy
University of Wisconsin – Eau Claire

Upward Bound High Performance Computing Academy

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The Rundown

Stars in a Nutshell *(30 min)* → **Finding the Main Sequence** *(30 min)* → **Stellar Lifetimes** *(15 min)*

Key

- Lecture
- Working on BGSC2

Slides with a Blue background: computing challenge

`Fixed-width` text with this background indicates commands you should run in the terminal.

```
$ sbatch submit.sh
```

This logo will also remind you that you have work to do.

Slides with a **Gold** background: hints, solutions, or explanations.

They'll also have this logo as a reminder that we're working on a challenge.

Part 1: Stars in a Nutshell

"You'd look pretty simple from 10 parsecs away, too."

– Fred Hoyle


Periodic Table of the Elements
Created in the Big Bang
Created by stars (and their explosive deaths)
Created by the pride of humanity
1 H Hydrogen 1.008
2 He Helium 4.003
3 Li Lithium 6.941
4 Be Beryllium 9.012
5 B Boron 10.811
6 C Carbon 12.011
7 N Nitrogen 14.007
8 O Oxygen 15.999
9 F Fluorine 18.998
10 Ne Neon 20.180
11 Na Sodium 22.990
12 Mg Magnesium 24.305
13 Al Aluminum 26.982
14 Si Silicon 28.086
15 P Phosphorus 30.974
16 S Sulfur 32.066
17 Cl Chlorine 35.453
18 Ar Argon 39.948
19 K Potassium 39.098
20 Ca Calcium 40.078
21 Sc Scandium 44.956
22 Ti Titanium 47.88
23 V Vanadium 50.942
24 Cr Chromium 51.996
25 Mn Manganese 54.938
26 Fe Iron 55.933
27 Co Cobalt 58.933
28 Ni Nickel 58.693
29 Cu Copper 63.546
30 Zn Zinc 65.39
31 Ga Gallium 69.732
32 Ge Germanium 72.61
33 As Arsenic 74.922
34 Se Selenium 78.972
35 Br Bromine 79.904
36 Kr Krypton 84.80
37 Rb Rubidium 84.468
38 Sr Strontium 87.62
39 Y Yttrium 88.906
40 Zr Zirconium 91.224
41 Nb Niobium 92.906
42 Mo Molybdenum 95.95
43 Tc Technetium 98.907
44 Ru Ruthenium 101.07
45 Rh Rhodium 102.906
46 Pd Palladium 106.42
47 Ag Silver 107.868
48 Cd Cadmium 112.411
49 In Indium 114.818
50 Sn Tin 118.71
51 Sb Antimony 121.760
52 Te Tellurium 127.6
53 I Iodine 126.904
54 Xe Xenon 131.29
55 Cs Cesium 132.905
56 Ba Barium 137.327
57-71
72 Hf Hafnium 178.49
73 Ta Tantalum 180.948
74 W Tungsten 183.85
75 Re Rhenium 186.207
76 Os Osmium 190.23
77 Ir Iridium 192.22
78 Pt Platinum 195.08
79 Au Gold 196.967
80 Hg Mercury 200.59
81 Tl Thallium 204.383
82 Pb Lead 207.2
83 Bi Bismuth 208.980
84 Po Polonium [208.982]
85 At Astatine 209.987
86 Rn Radon 222.018
87 Fr Francium 223.020
88 Ra Radium 226.025
89-103
104 Rf Rutherfordium [261]
105 Db Dubnium [262]
106 Sg Seaborgium [266]
107 Bh Bohrium [264]
108 Hs Hassium [269]
109 Mt Meitnerium [268]
110 Ds Darmstadtium [269]
111 Rg Roentgenium [272]
112 Cn Copernicium [277]
113 Uut Ununtrium unknown
114 Fl Flerovium [289]
115 Uup Ununpentium unknown
116 Lv Livermorium [298]
117 Uus Ununseptium unknown
118 Uuo Ununoctium unknown
Configurations denoted with a * are unknown and the listed values are predicted.
57 La Lanthanum 138.906
58 Ce Cerium 140.115
59 Pr Praseodymium 140.908
60 Nd Neodymium 144.24
61 Pm Promethium 144.913
62 Sm Samarium 150.36
63 Eu Europium 151.966
64 Gd Gadolinium 157.25
65 Tb Terbium 158.925
66 Dy Dysprosium 162.50
67 Ho Holmium 164.930
68 Er Erbium 167.26
69 Tm Thulium 168.934
70 Yb Ytterbium 173.04
71 Lu Lutetium 174.967
89 Ac Actinium 227.028
90 Th Thorium 232.038
91 Pa Protactinium 231.036
92 U Uranium 238.029
93 Np Neptunium 237.048
94 Pu Plutonium 244.064
95 Am Americium 243.061
96 Cm Curium 247.070
97 Bk Berkelium 247.070
98 Cf Californium 251.080
99 Es Einsteinium [254]
100 Fm Fermium 257.095
101 Md Mendelevium 258.1
102 No Nobelium 259.101
103 Lr Lawrencium [262]
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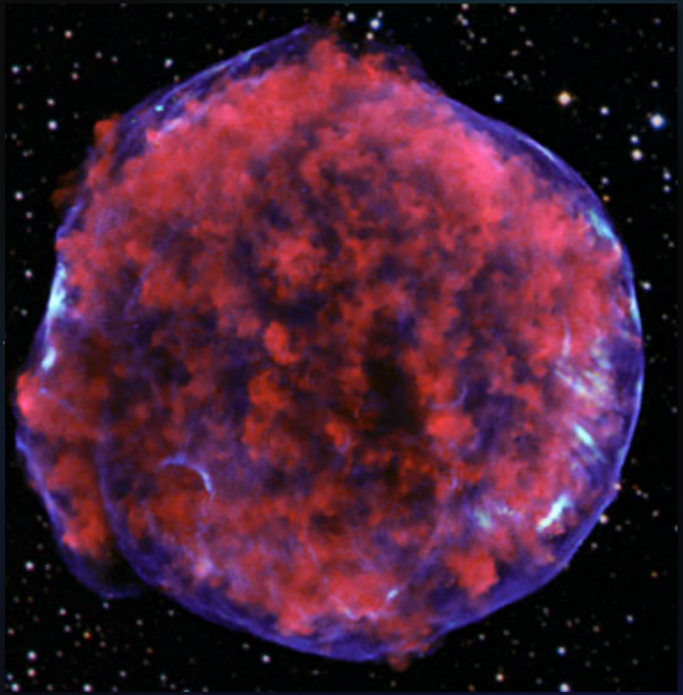
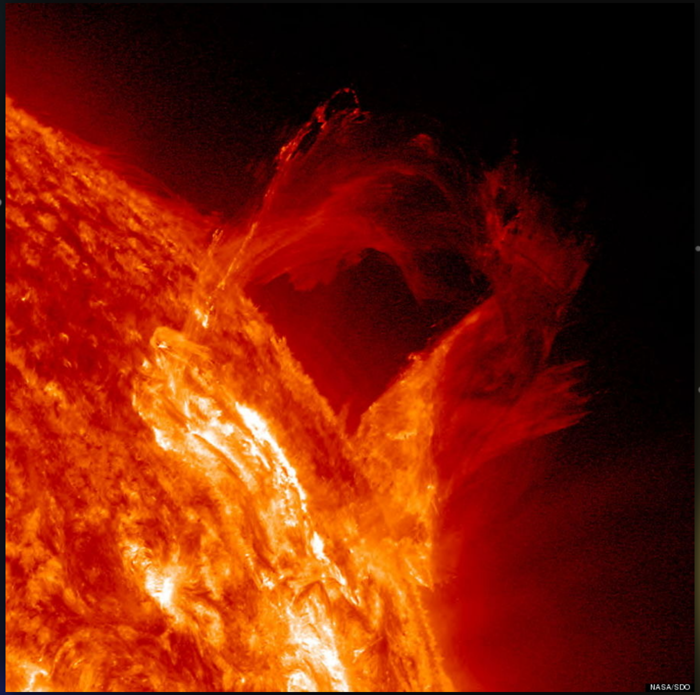
sciencenotes.org

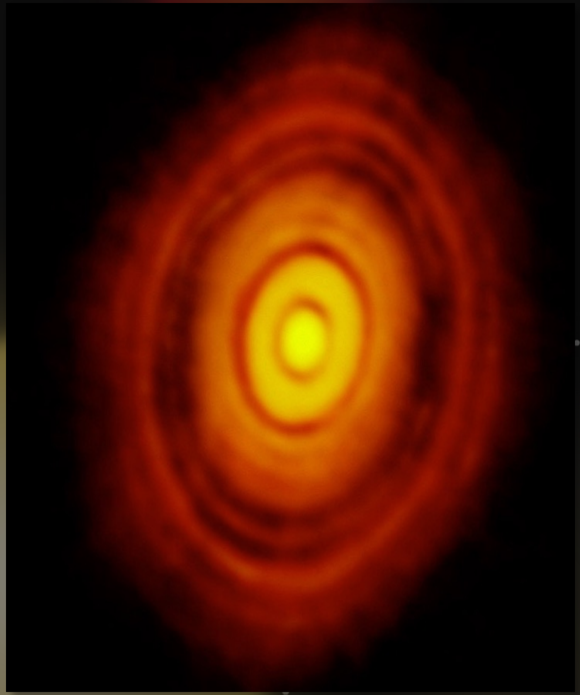
There are many reasons to study stars.



Spectacular Explosions!

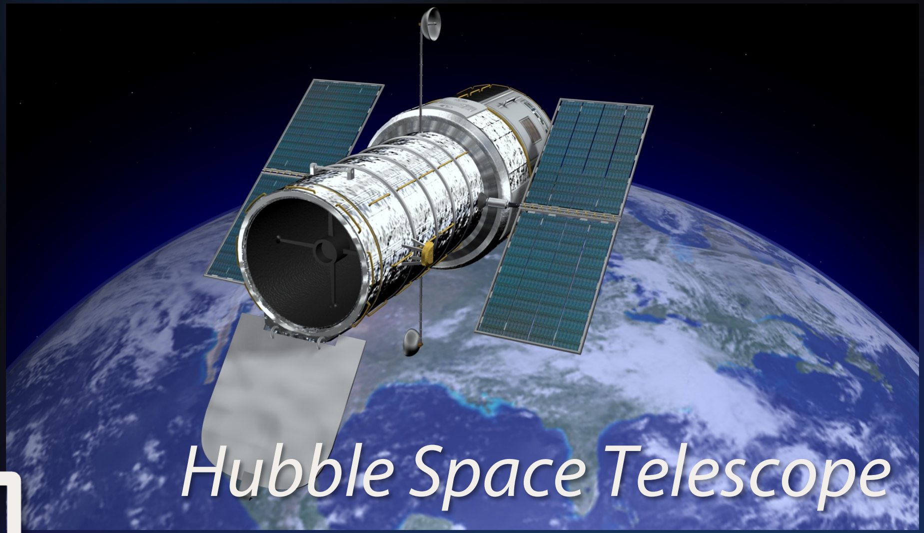


Space Weather



Exoplanets

We can't visit stars (yet), so we can only study the light they emit or models of them.



MESA

***M**odules for **E**xperiments in **S**tellar **A**strophysics*

How do observers tell stars apart?

How do observers tell stars apart?

Brightness

"Luminosity"
(and distance)

Color

"Effective Temperature"

Location

Brightness is how bright a star *appears* to be.
Luminosity is how much energy it emits per unit time in *all* wavelengths.

This bulb has a luminosity of 5 Watts, but its brightness depends on how close you are to it.

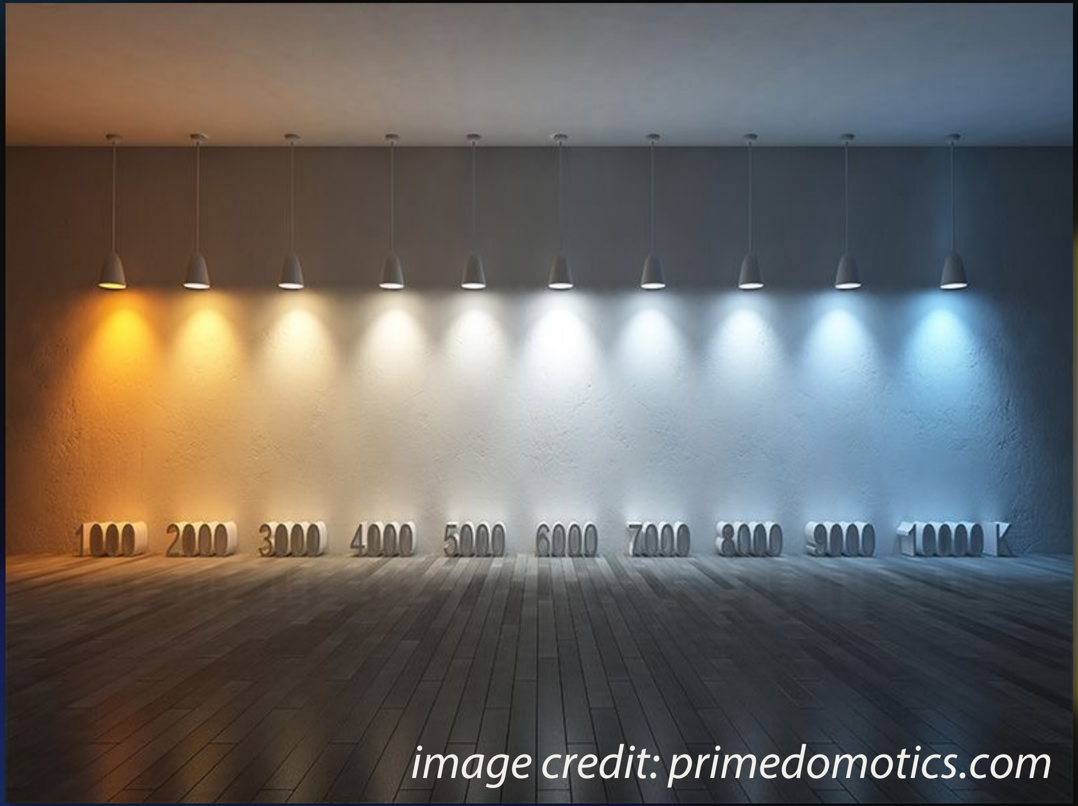
For the sun,

$$L_\odot = 3.83 \times 10^{26} \text{ Watts}$$

We'll call this unit a **solar luminosity**.

The **effective temperature** of a hot object determines its **color**.

Cooler = Redder



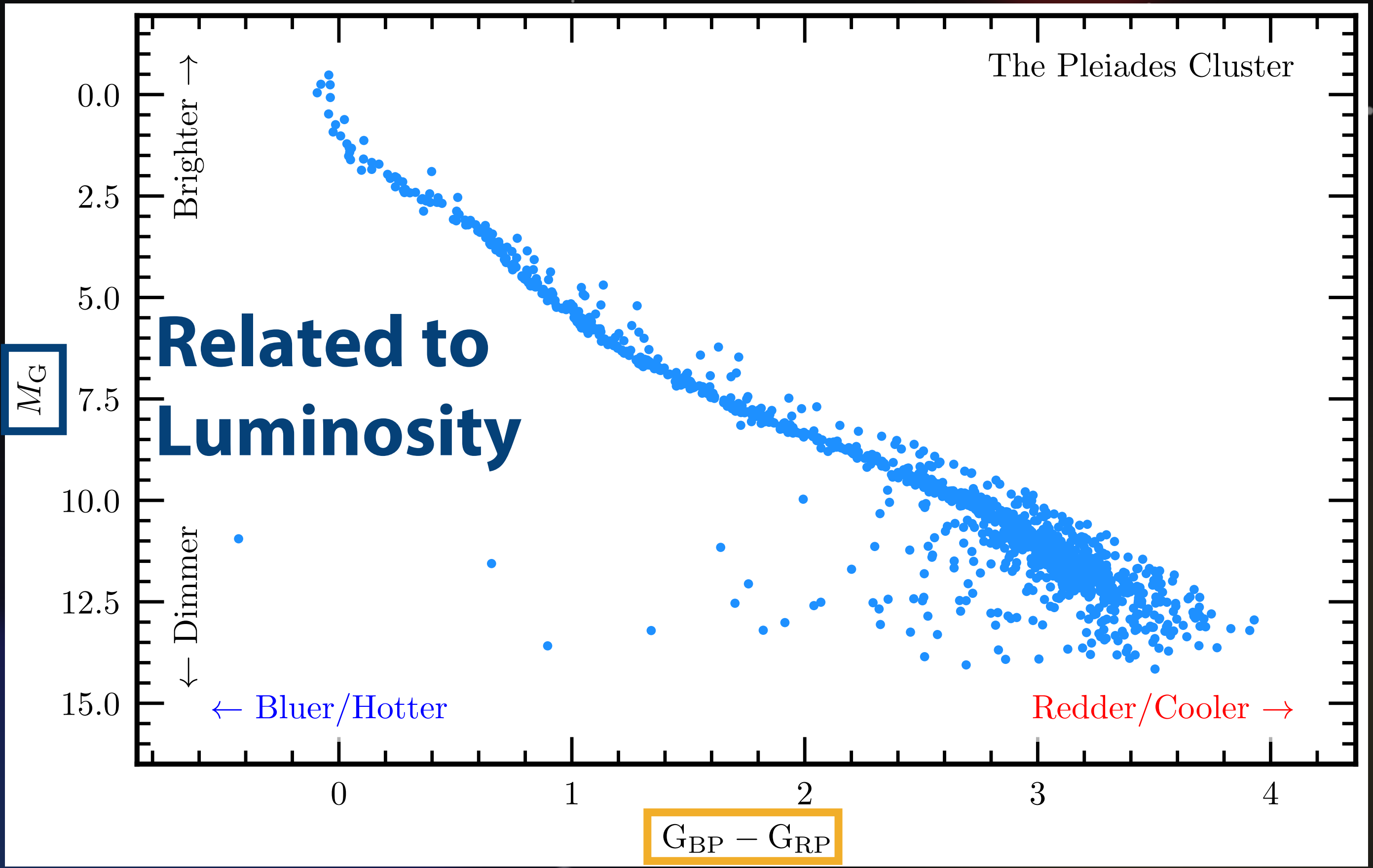
Hotter = Bluer

Stars in **clusters** have the same age and distance, but different luminosities and colors.

The Pleiades star cluster

Image credit: Raul Villaverde Fraile

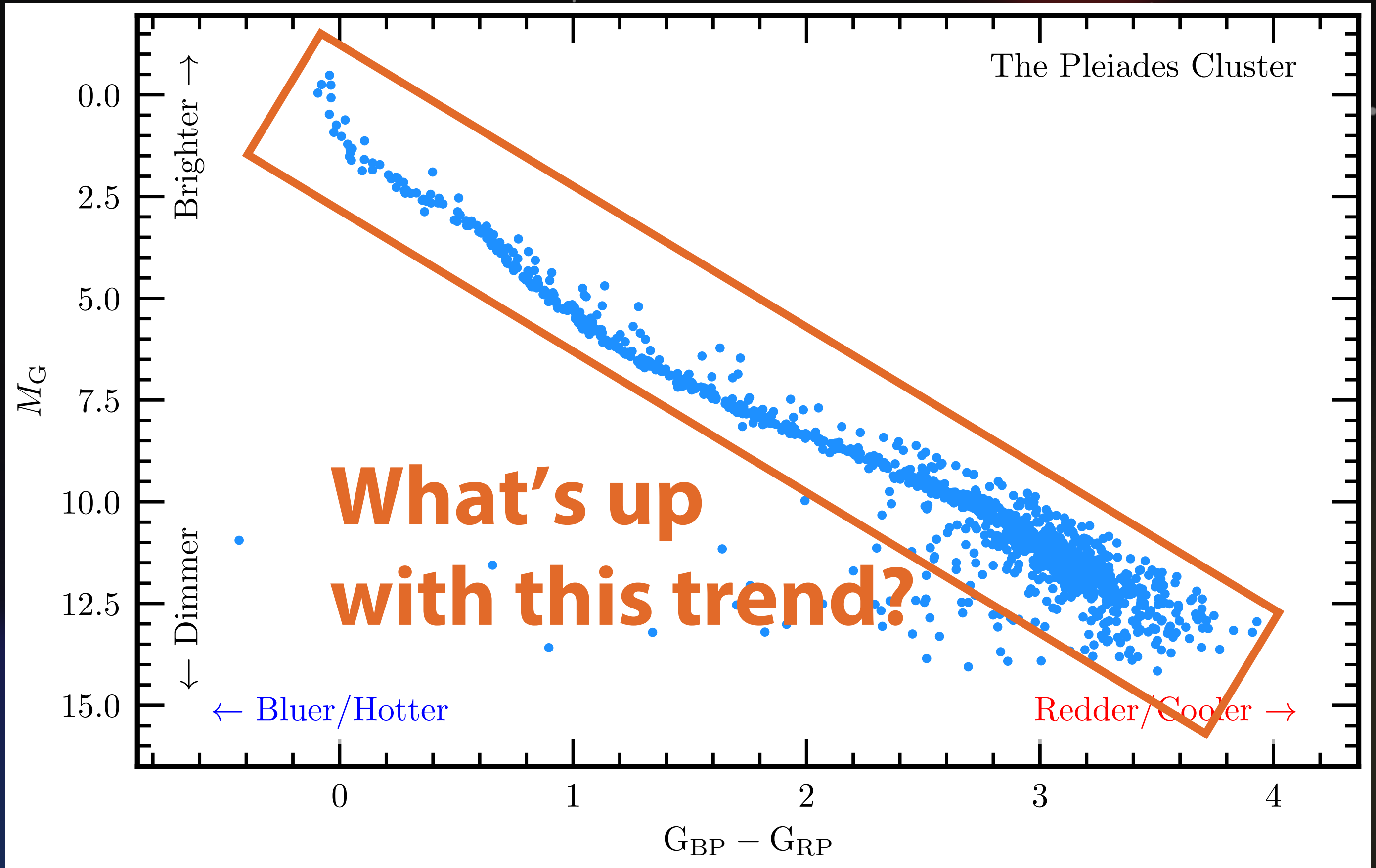
We show the luminosity/color of a stars on a **Hertzsprung-Russell (HR)** diagram.



Luminosity increases along *y*-axis
Effective Temperature *decreases* along *x*-axis

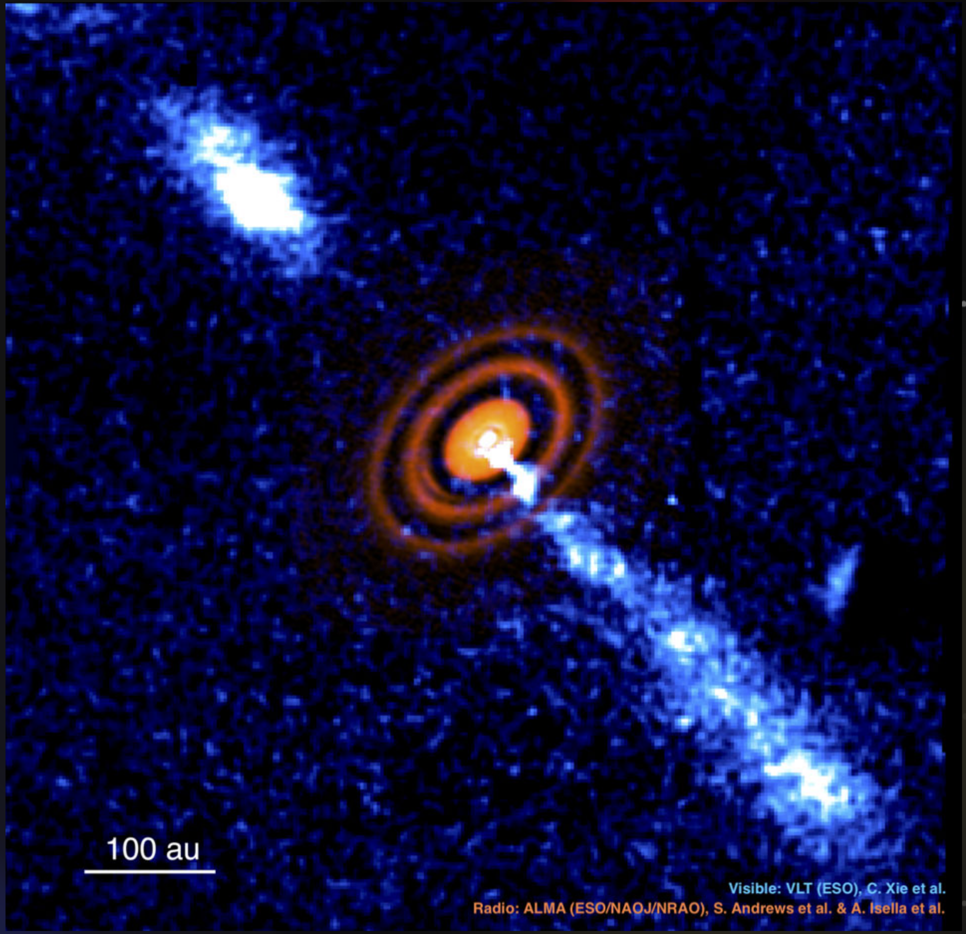
Related to Effective Temperature

We show the luminosity/color of a stars on a **Hertzsprung-Russell (HR)** diagram.



Luminosity increases along *y*-axis
Effective Temperature *decreases* along *x*-axis

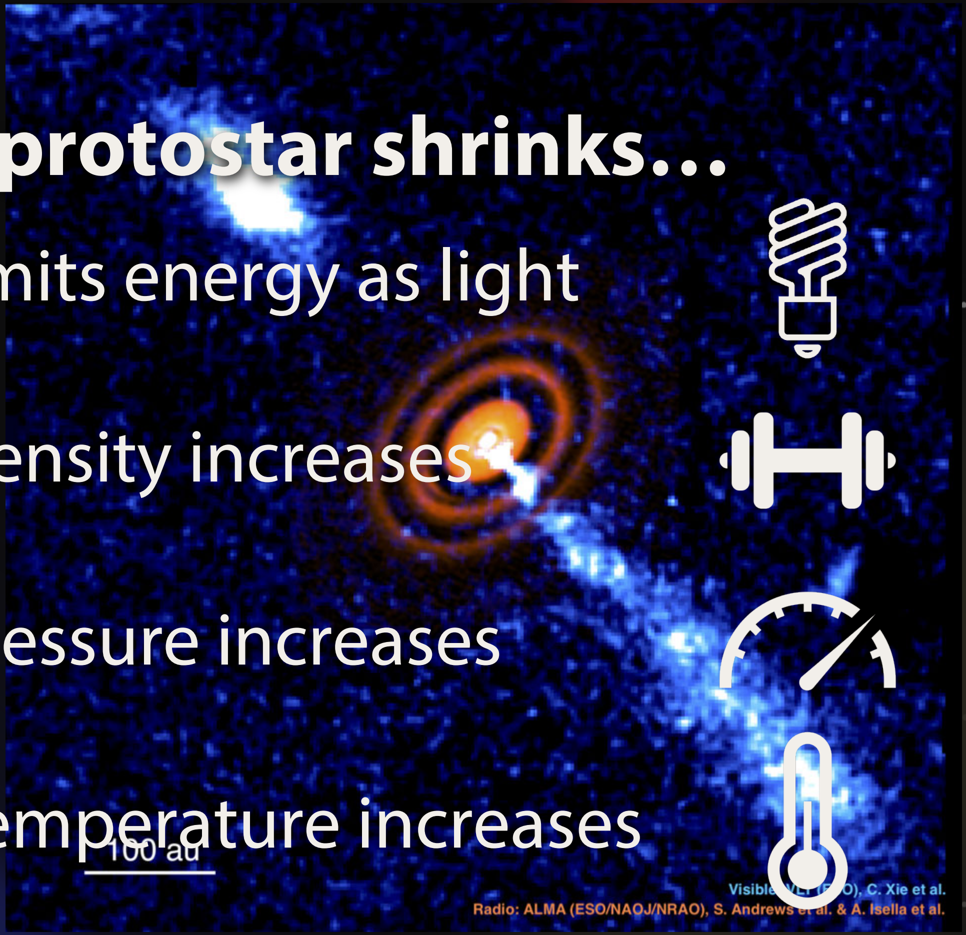
Stars form when a cloud of mostly hydrogen gas and dust is compressed by its own gravity.



Stars form when a cloud of mostly hydrogen gas and dust is compressed by its own gravity.

As a protostar shrinks…

- Emits energy as light
- Density increases
- Pressure increases
- Temperature increases



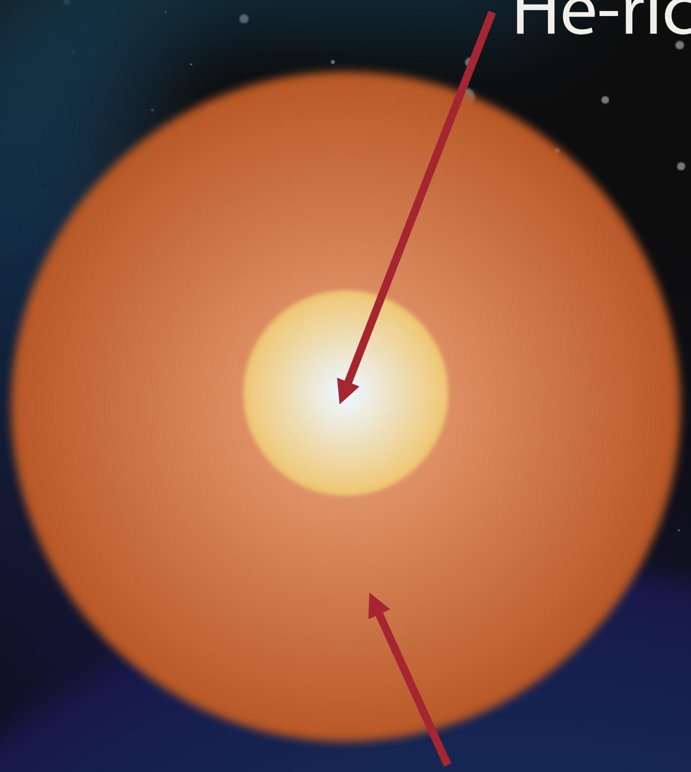
Stars form when a cloud of mostly hydrogen gas and dust is compressed by its own gravity.

If protostar is ***massive and gets hot enough…***

It begins ***fusing hydrogen to helium*** *in its core and stops contracting*

A star is born!

While stars fuse hydrogen to helium, we say they are **main sequence** stars.



ZAMS: Zero **A**ge **M**ain **Sequence**
Newborn stars at the beginning of their main sequence lifetime

TAMS: Terminal **A**ge **M**ain **S**equence
Stars that have *just* run out of hydrogen to fuse in their cores

The sun is roughly halfway between ZAMS and TAMS

The main difference between stars in a cluster is their initial mass.

The main difference between stars in a cluster is their **initial mass**.

Part 2: Finding the Main Sequence

"To err is human, but to really foul things up requires a computer."

Goal: Use MESA to create stars of a **variety of masses** to reproduce the main sequence.

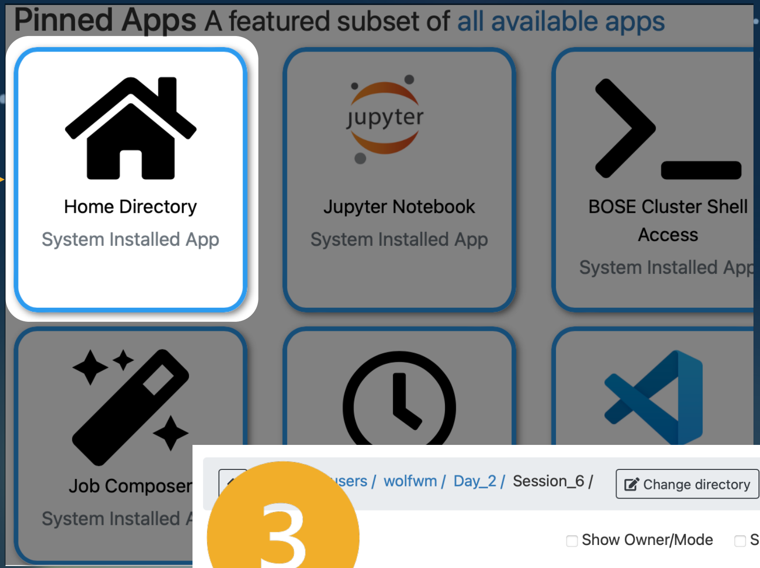
MESA

Modules for
Experiments in
Stellar
Astrophysics

Task 1: Get set up

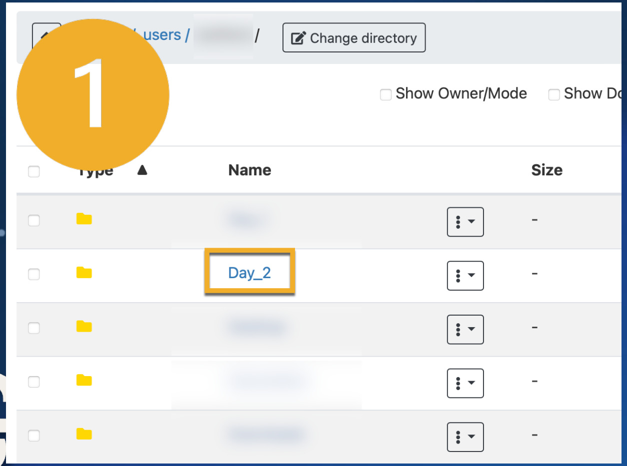
A. **Launch/Login to Open OnDemand (ondemand.hpc.uwec.edu)**

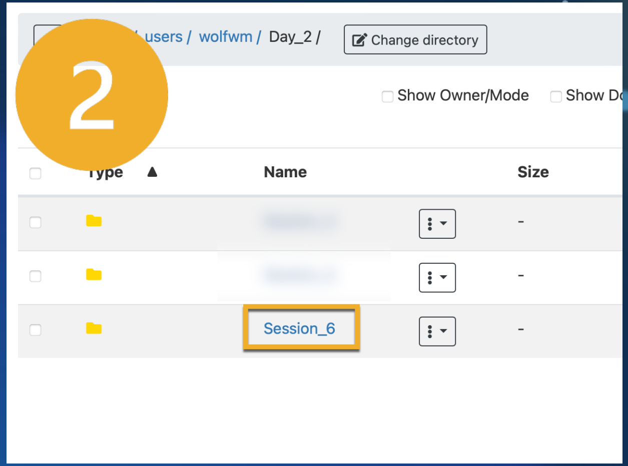
B. **Launch "Home Directory" App**

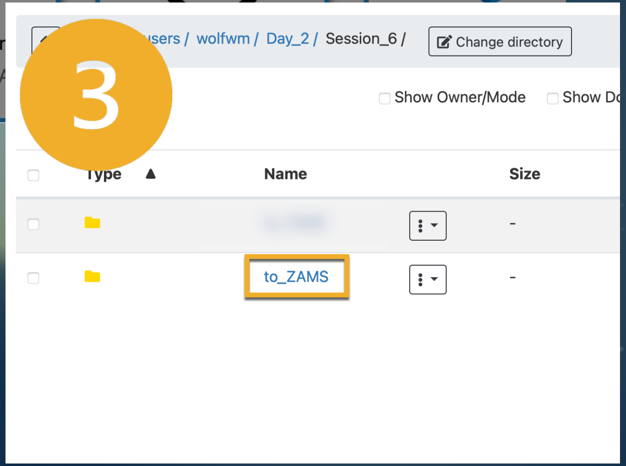


C. **Navigate to directory:**

Day_2 → Session_6 → to_ZAMS







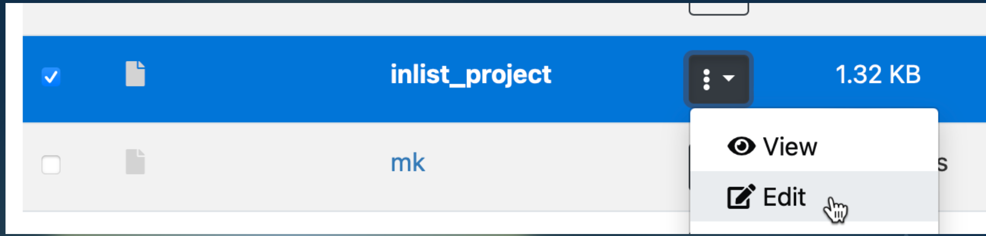
Task 2: Set the mass of your star

A. Select your mass

- Visit this page: **bit.ly/hpc-stars-2024**
- Follow instructions to pick a “random” mass

B. Set mass for simulation

- **Edit** `inlist_project` in OnDemand
- Fill in the mass on the right side of the equal sign of the line that sets `initial_mass`, and click on the " Save" button in upper left. You can then close that tab.



Replace “CHANGE ME” with your mass

```
! starting specifications
  initial_mass = CHANGE ME ! in Msun units
  initial_z = 0.02 ! 2% of star by mass is elements
```

Task 3: Run the Simulation

A. Submit the job

- In File viewer, click on ">_ Open in Terminal" button
- Execute `$ sbatch job.sh`

B. Wait for job to complete (typically around 2 minutes)

- You can check how it is doing by looking at the end of the `mesa.out` file `$ tail -n 20 mesa.out`
- Simulation is done when you see something like

```
***********************************************
* Final Luminosity           : 1.22E+05 L_sun *
* Final Effective Temperature:  39977.8 K     *
***********************************************
```

Task 4: Report Final Luminosity and Effective Temperature

A. After run is over, locate final luminosity and effective temperature from `mesa.out`

```
$ tail -n 20 mesa.out
```

B. Report data to google form (same as earlier)

bit.ly/hpc-stars-2024

- *Note*: `6.02E23` is shorthand for 6.02×10^{23} (scientific notation). Google forms understands this notation, so you can use it.

C. Check out the neat video of your simulation!

- Refresh OnDemand file browser tab and download `to_ZAMS.mp4` (three dot menu → select "Download")

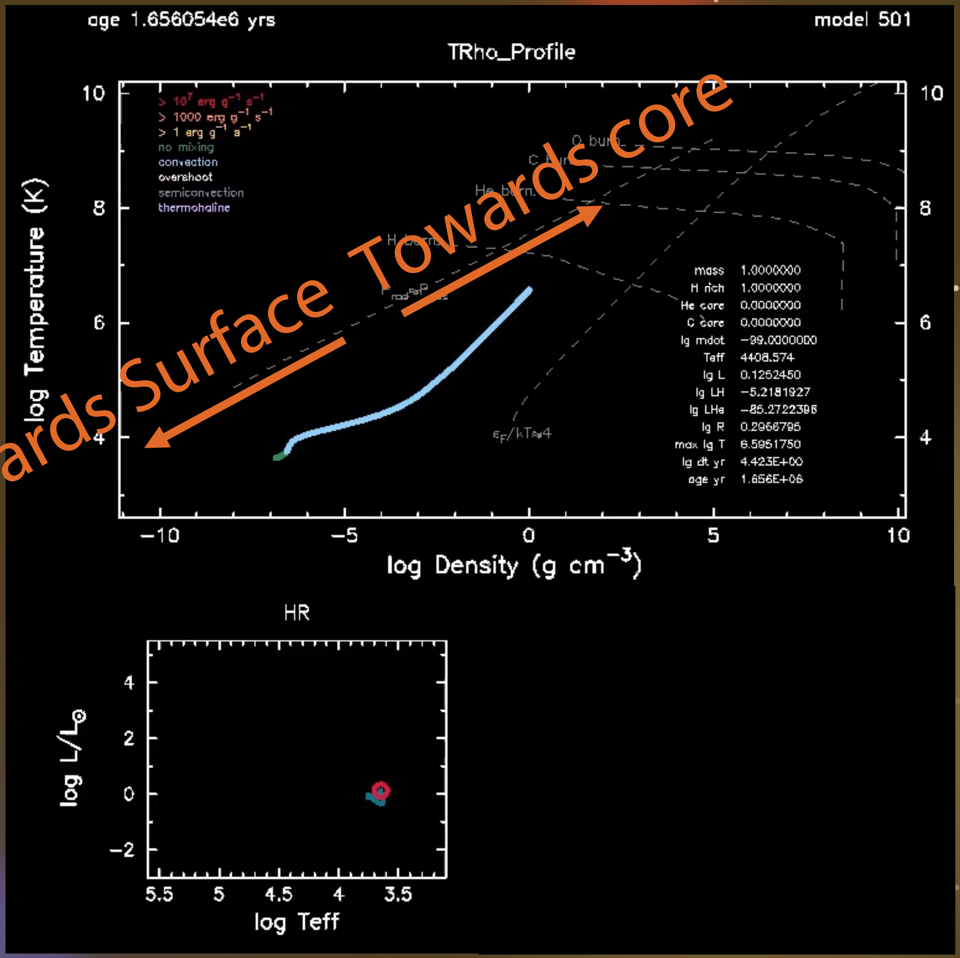
Your simulation *should* produce a video with plots showing how your stellar model is evolved.

- **Top:** Temperature vs. Density **in the stellar model**

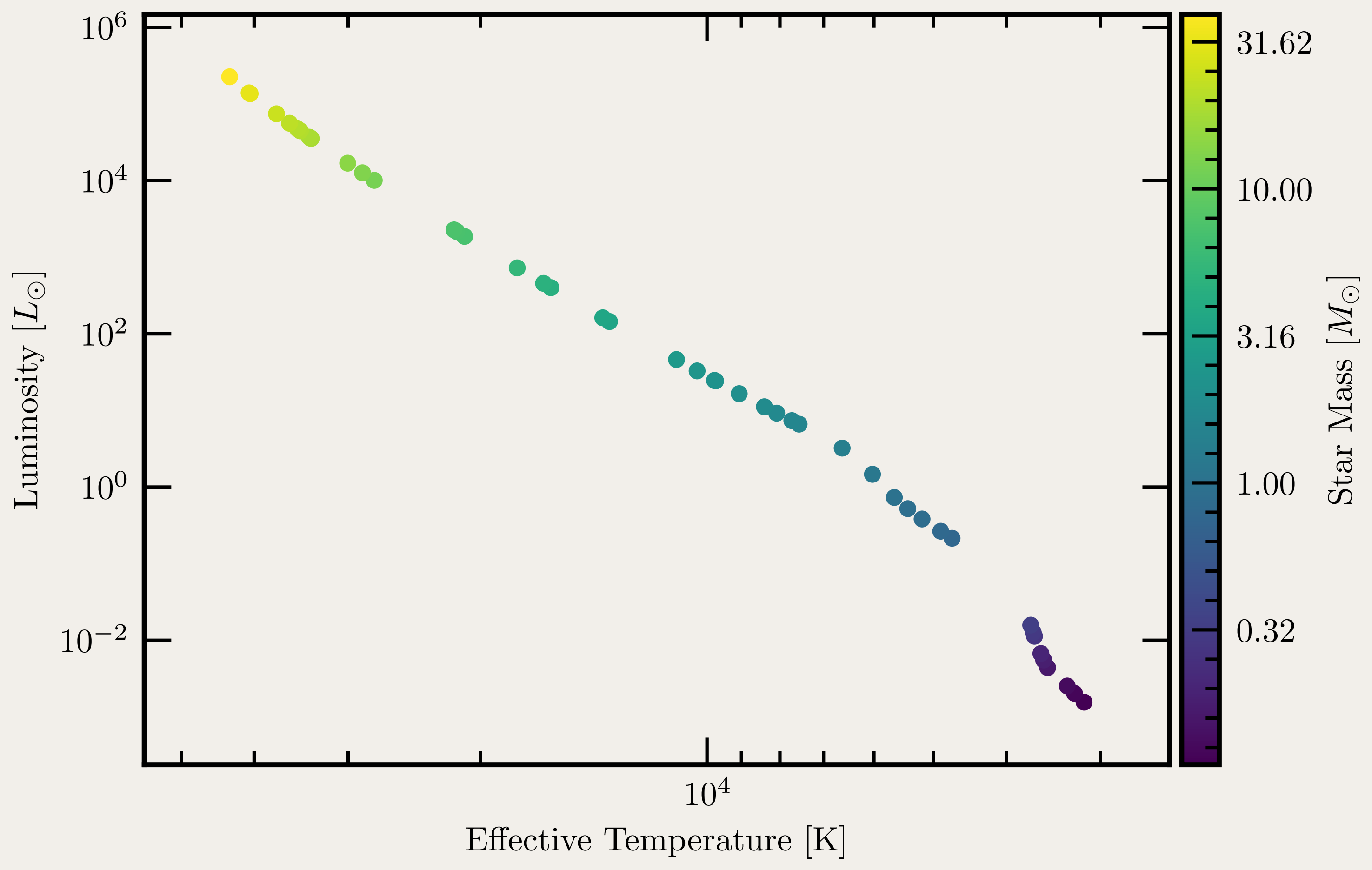
Lightning introduction to logarithms

$$100 = 10^2 \quad \Leftrightarrow \quad \log_{10}(100) = 2$$

- **Lower left:** Path of star through HR diagram. Vertical: logarithm of luminosity; horizontal: logarithm of effective temperature



Yes! The variety of masses helps explain where on the main sequence a star falls.

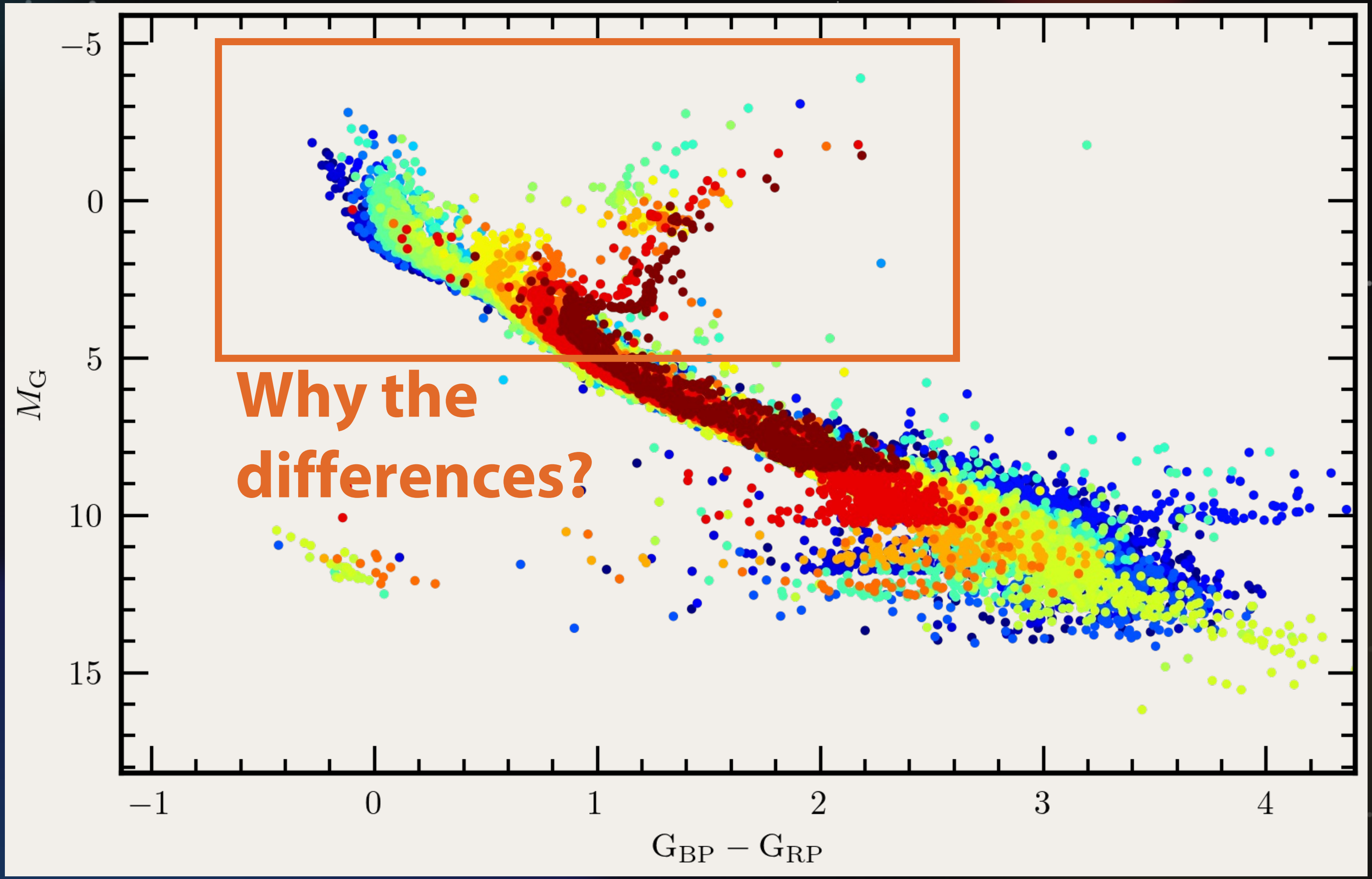


Part 3: Stellar Lifetimes

"The bigger they are, the harder they fall."

Different clusters look slightly different on the HR diagram.

- Different colors = different clusters
- Low-luminosity cutoffs due to telescope sensitivity
- High-luminosity differences… less clear



Perhaps massive stars leave main sequence more rapidly than low-mass stars?

As star runs out of hydrogen

- Core contracts
- Envelope expands

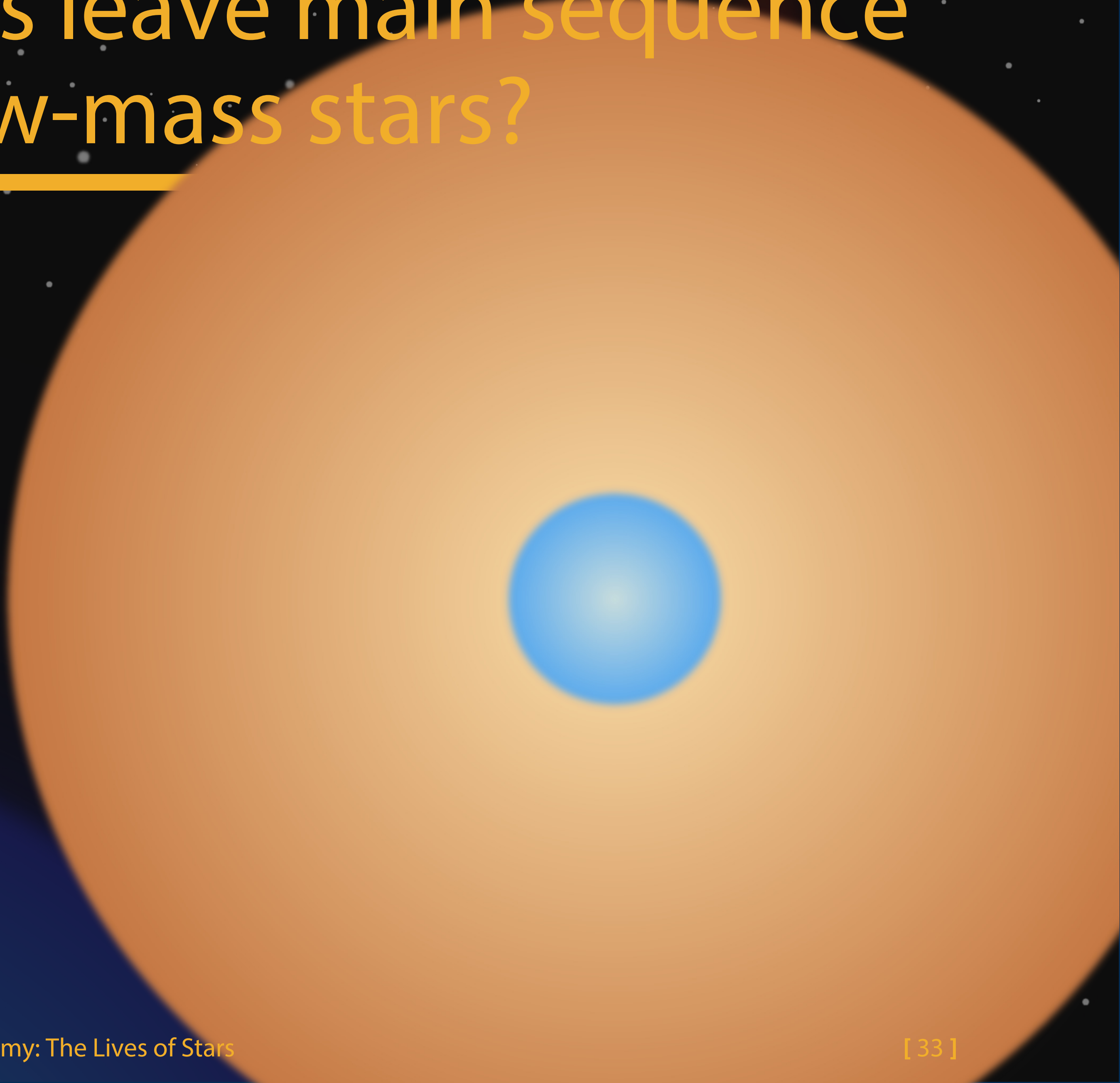
Perhaps massive stars leave main sequence more rapidly than low-mass stars?

As star runs out of hydrogen

- Core contracts
- Envelope expands

Star appears redder!

If massive stars leave main sequence first, should find a turnoff on HR diagram that varies with age



Task 5: Set up for finding **T**erminal **A**ge **M**ain **S**equence (TAMS)

A. Navigate to `Day_2/Session_6/to_TAMS`

- Close the browser tab with the terminal from task 4
- Switch to OnDemand file browser tab
- Use "breadcrumbs" near top to get back to `Session_6`, then open `to_TAMS`

B. Edit `inlist_project` again to set the mass to your value

- Open `inlist_project` in file viewer in **edit** mode
- Fill in the mass on the right side of the equal sign of the line that sets `initial_mass`, and then save and close it

Task 6: Run the Simulation

A. Open a terminal and submit the job `$ sbatch job.sh`

B. Wait for job to complete (typically around 2 minutes)

- You can check how it is doing by looking at the end of the `mesa.out` file `$ tail -n 20 mesa.out`
- This shows the last 20 lines of the file `mesa.out`
- Simulation is done when you see something like this near the bottom (but not at the very bottom) of `mesa.out`.

```
*****************************
* Final Age: 6.04E+06 years *
*****************************
```

Task 7: Report Final Age at TAMS

A. After run is over, locate final age from `mesa.out`

```
$ tail -n 20 mesa.out
```

- Final results should be surrounded by a box of asterisks near the bottom of the file
- *Note*: this will again be in scientific notation

B. Report mass and final age (at TAMS) on the form

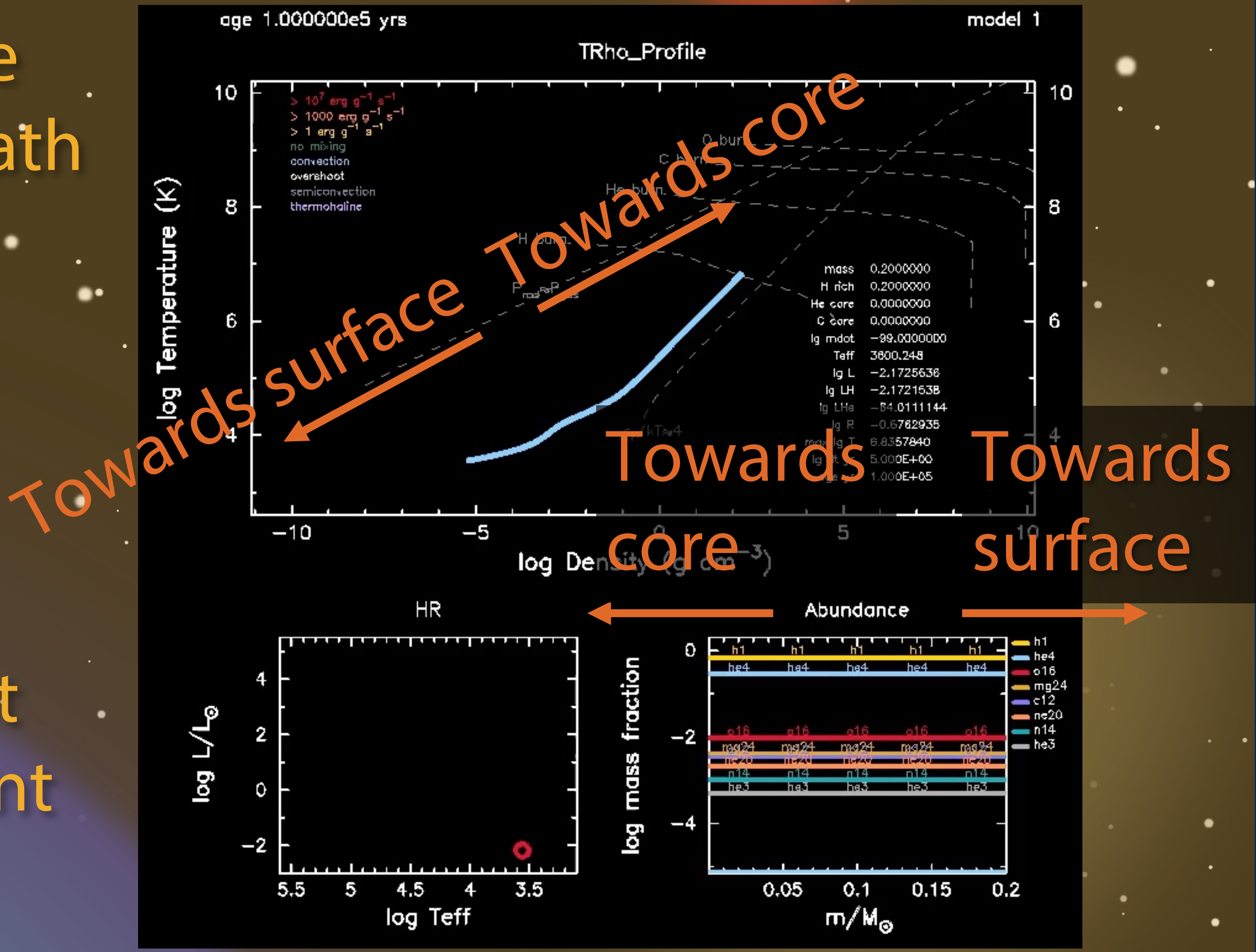
https://bit.ly/hpc-star-ages-2024

- Scientific notation is still valid. For example, $1.2\text{E}9 = 1.2 \times 10^9$

Check out `to_TAMS.mp4` to see how your star evolves!

- **Top and lower left:** Same as before (temperature-density profile and path through HR diagram)

- **Lower right:** Abundance Profile
  - **x-coordinate**: how much mass is enclosed by this position
  - **y-coordinate:** fraction of matter at that location that is a given element



Yes! Massive stars live fast and die hard.

Massive stars are gas guzzlers: big tank and horrible efficiency

Low-mass stars are the fuel-efficient cars with tiny gas tanks.

Astronomers use this **"Main Sequence Turnoff"** to estimate the age of clusters