Gravitational-wave progenitors

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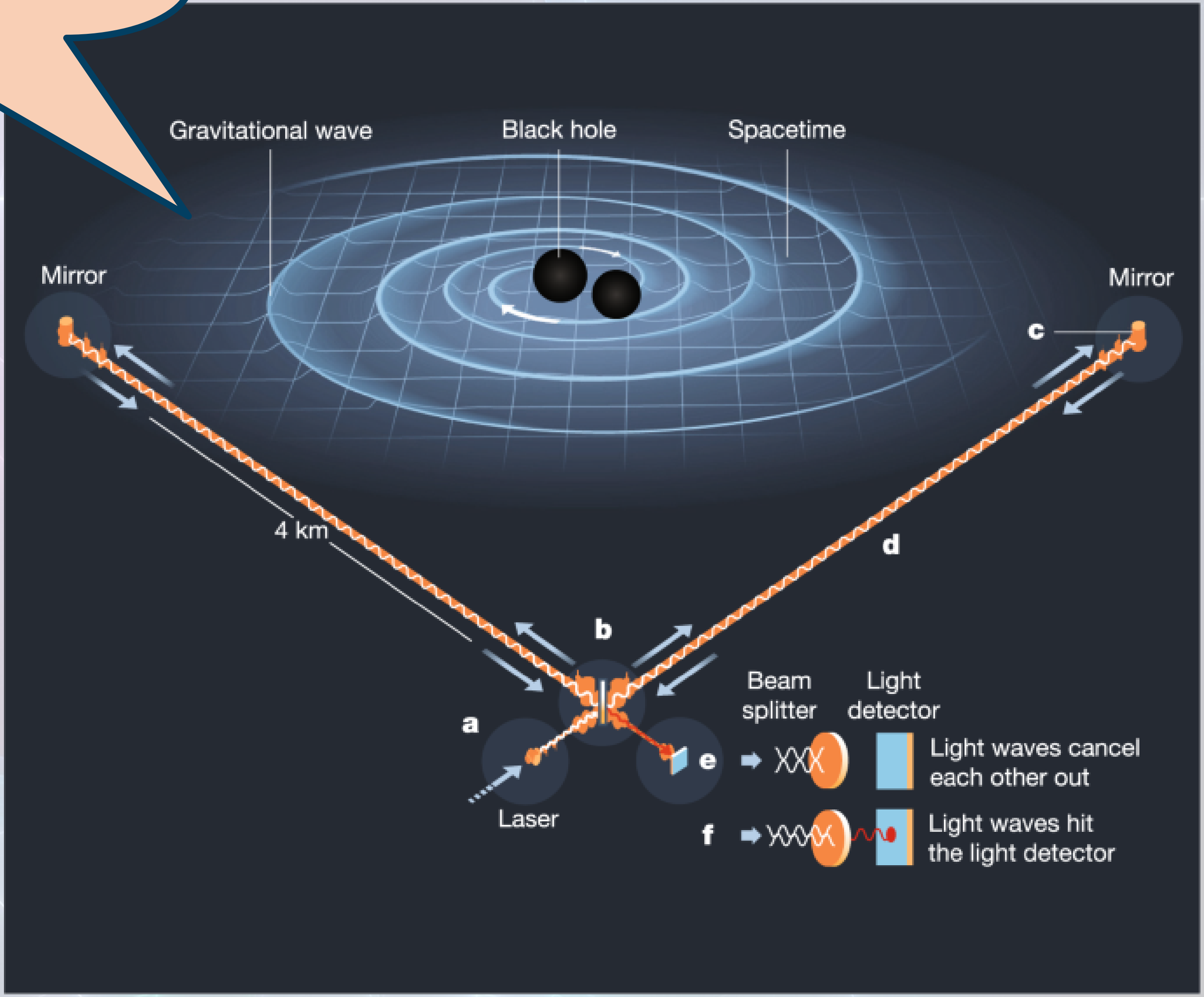
Lecture #4

NCU, Summer Semester 2022

Previously on GW-progenitors…

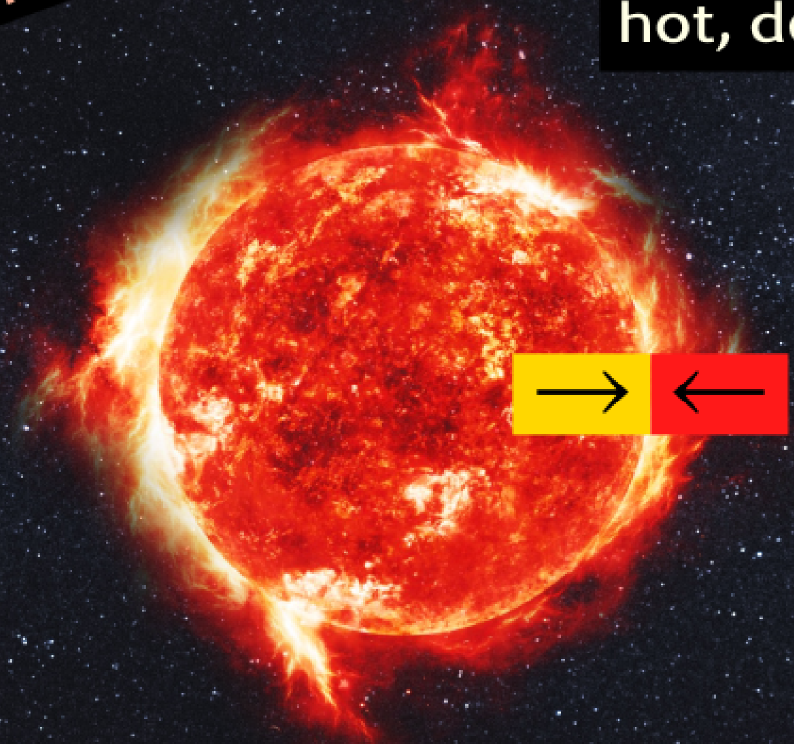
massive star → compact object
(we need two… later)



What is a star?

surface?
→ photons escape
"photosphere"

hot, dense plazma



equilibrium:

pressure gradient

gravity

Theoretical modelling of the stellar structure

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho} \qquad (1)$$

ec **mass conservation**

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4} \qquad (2)$$

momentum conservation

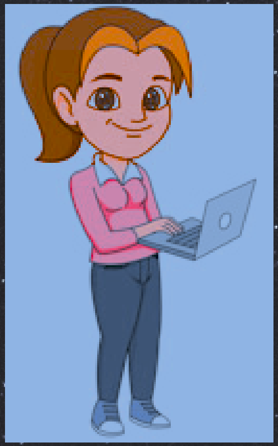
$$\frac{\partial L_r}{\partial m_r} = \epsilon_{\rm pl} - T\frac{\partial S}{\partial t} \qquad (3)$$

energy conservation

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla \qquad (4)$$

transport of energy

Guilera+ 11

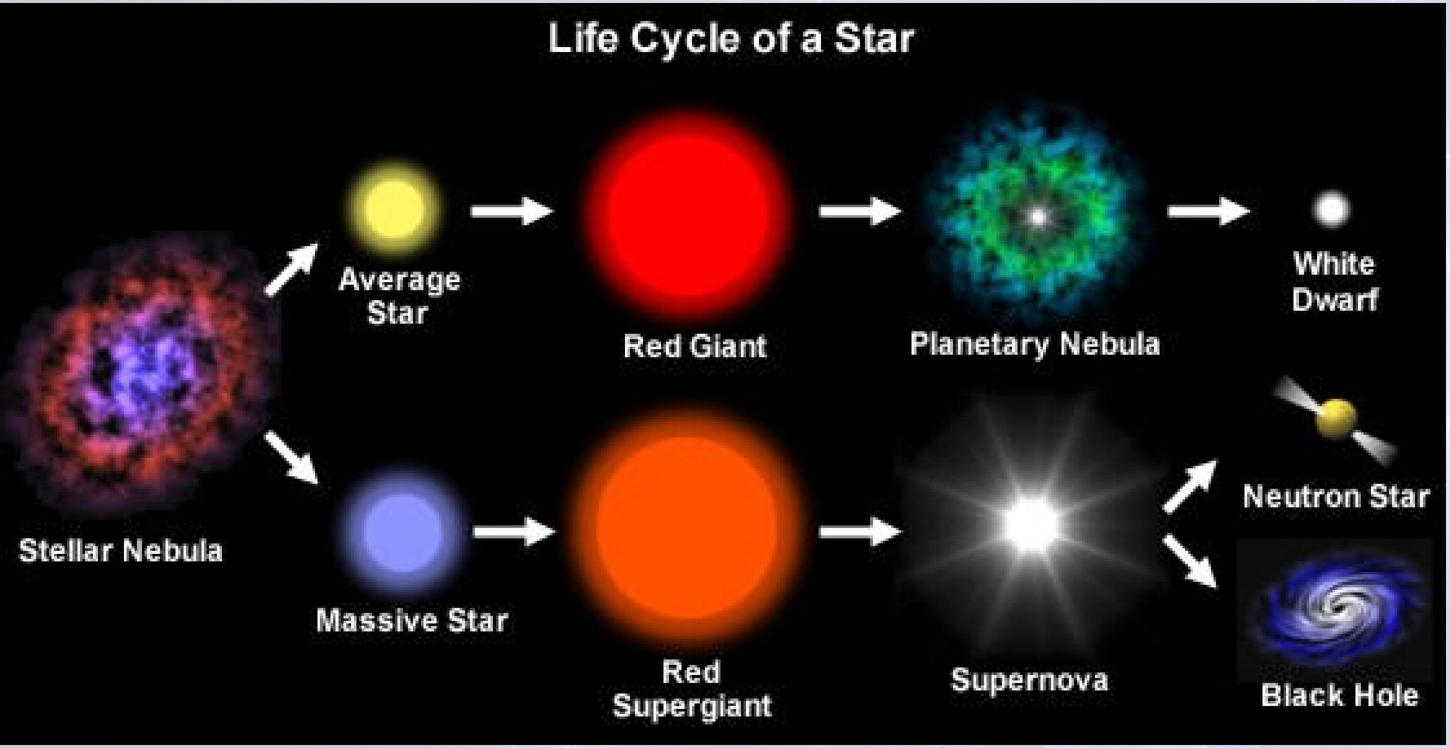


composition change due to nuclear burning:

$$\frac{\partial X_i}{\partial t} = \frac{A_i m_u}{\rho}\left(-\Sigma_{j,k} r_{i,j,k} + \Sigma_{k,l} r_{k,l,i}\right) \qquad (5)$$

Reason: stars evolve

→ stellar evolution

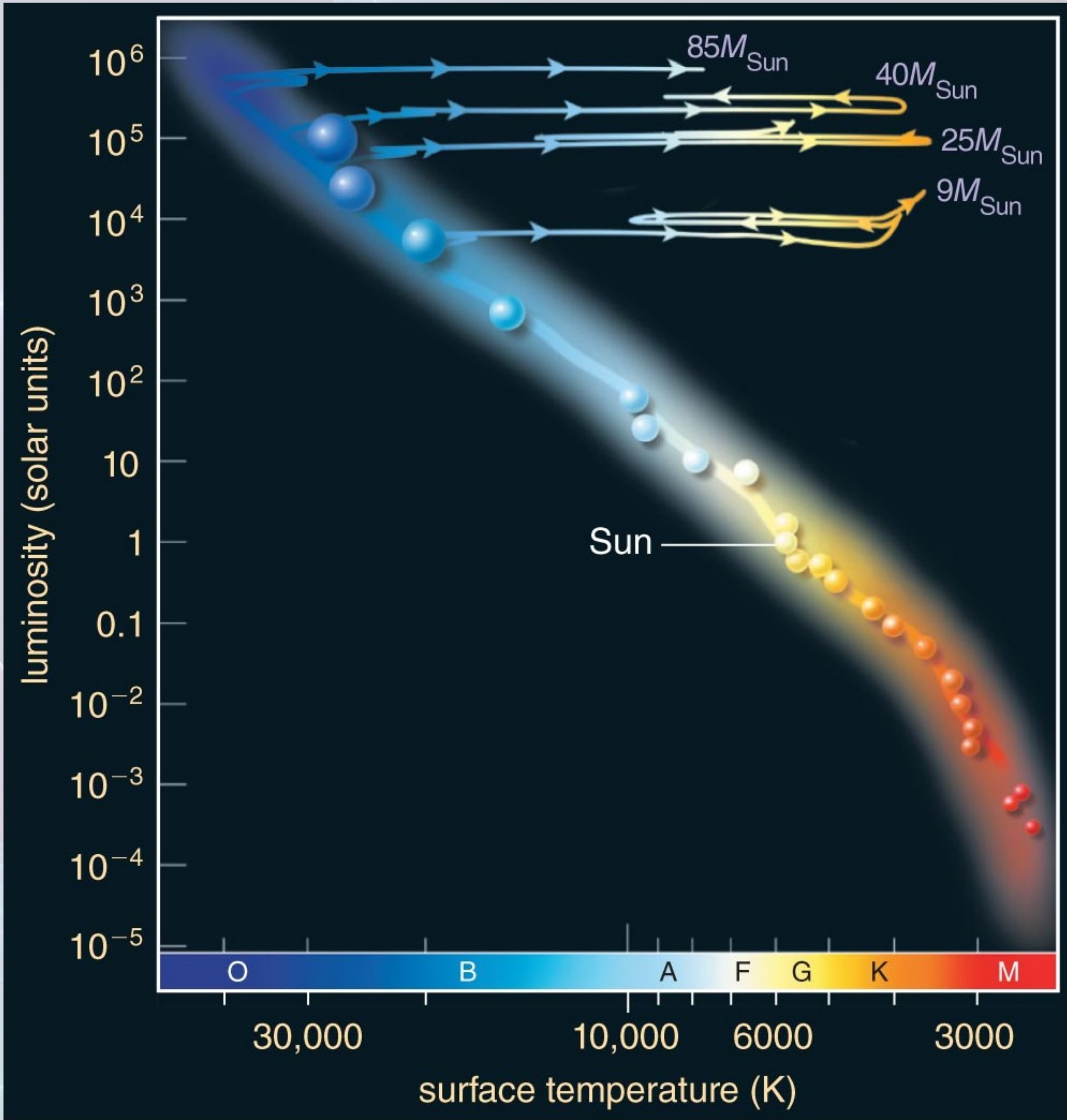


low-mass: $< 8\ M_\odot$

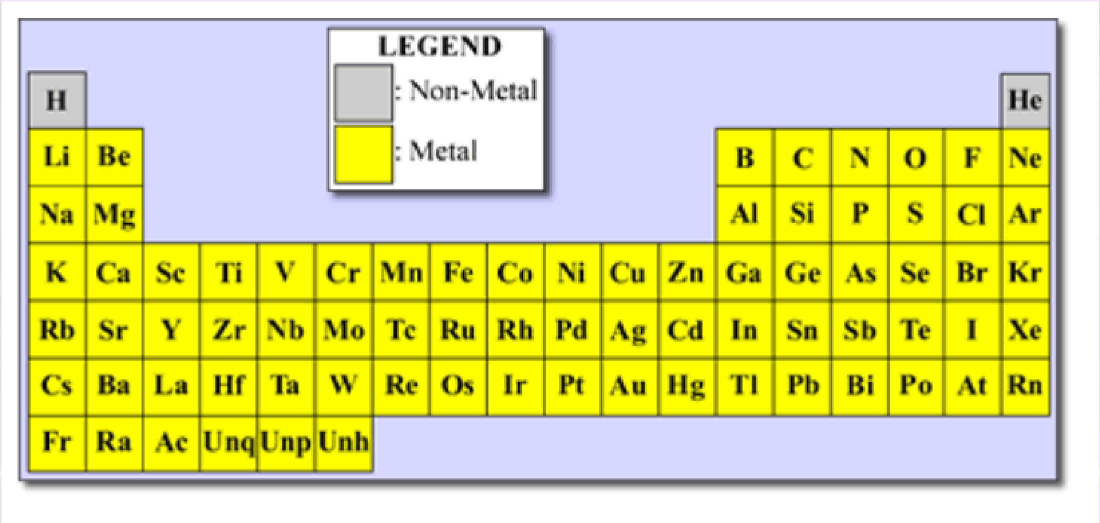
massive: $> 8\ M_\odot$

Further advantages of the HRD

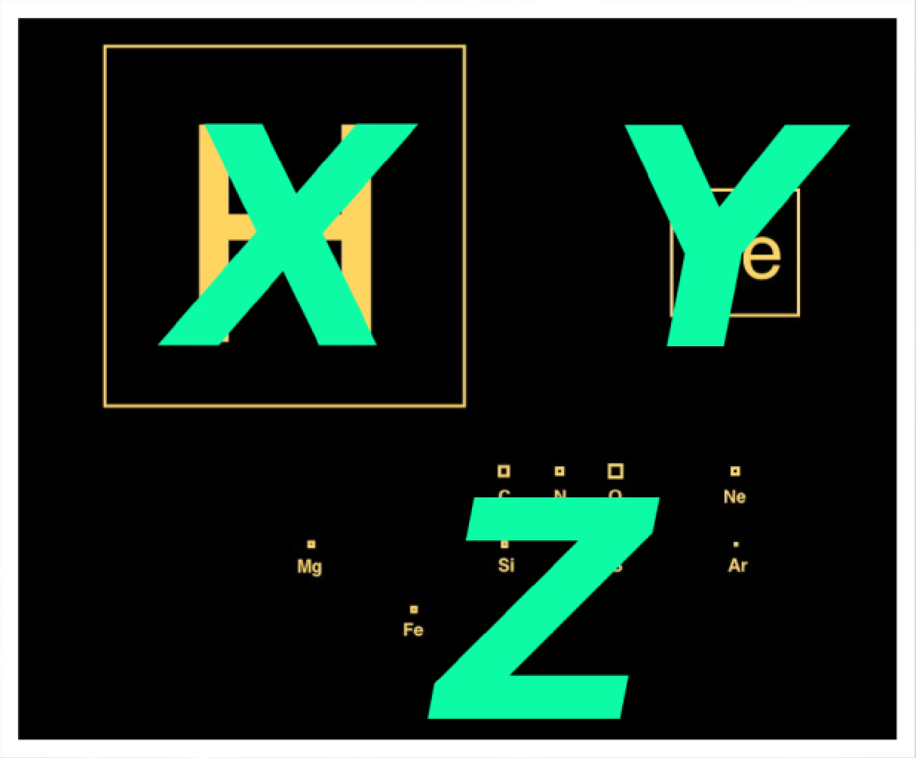
- allows comparison of an observed ***star*** and its corresponding ***stellar evolutionary model***
- allows comparison of low-mass stars vs. massive stars



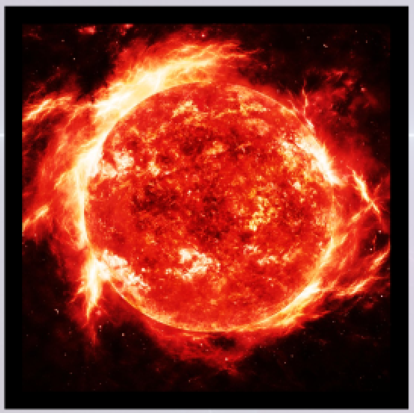
Astronomers and metal

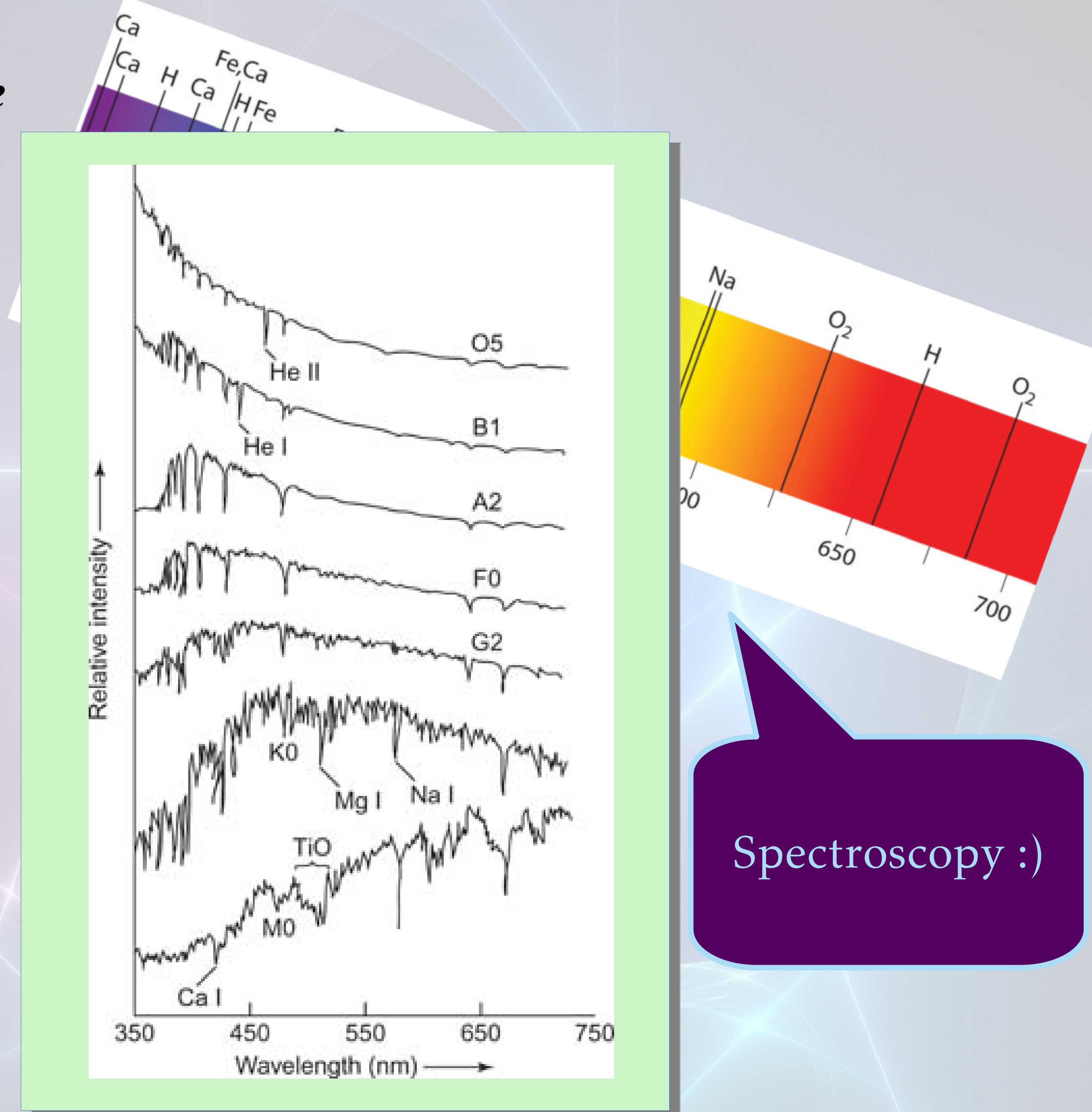


"Z: metallicity"



How to measure composition?





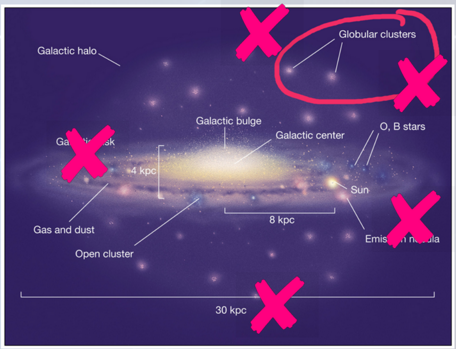
Spectroscopy :)

Where can we find stars*

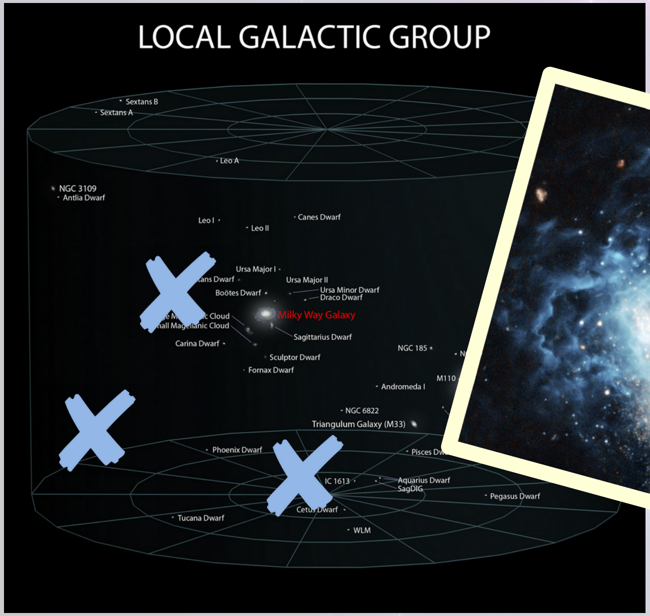
*gas/galaxies/anything: "*environments*"

with sub-Solar Z?

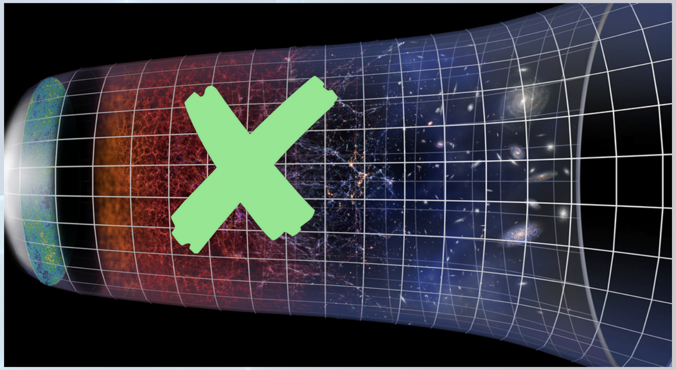
Globular clusters



Dwarf galaxies



Early Universe



The winds of *massive* stars are… strong.

Wolf-Rayet star WR 124 with its surrounding nebula known as M1-67.
The nebula came ***from the star***!

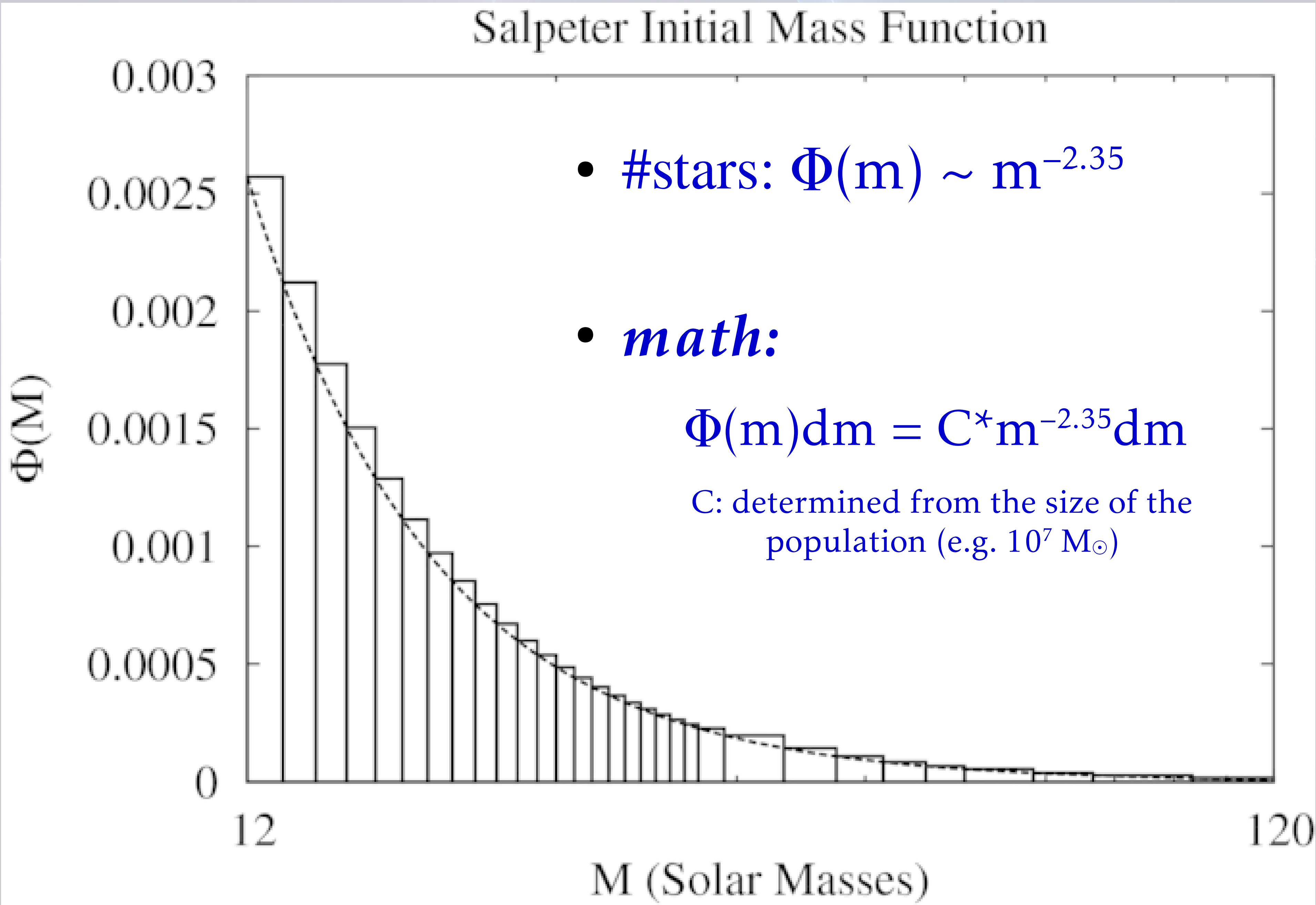
$10^{-7} - 10^{-3}\ M_\odot/yr$

→

loss of 10-70% of material over lifetime…

(Sun: $\sim 10^{-14}\ M_\odot/yr$)

The Initial Mass Function (IMF)

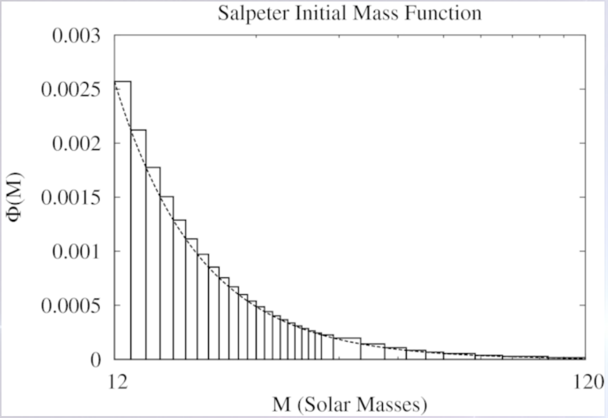


- #stars: $\Phi(m) \sim m^{-2.35}$
- ***math:***

$$\Phi(m)dm = C^* m^{-2.35} dm$$

C: determined from the size of the population (e.g. $10^7\ M_\odot$)

Homework



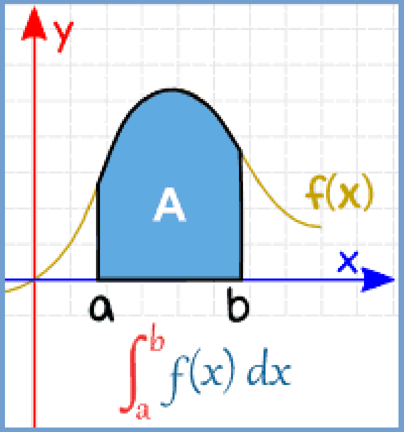
$$\Phi(m) \sim m^{-2.35}$$

math:

$$\Phi(m)dm = C^{*}m^{-2.35}dm$$

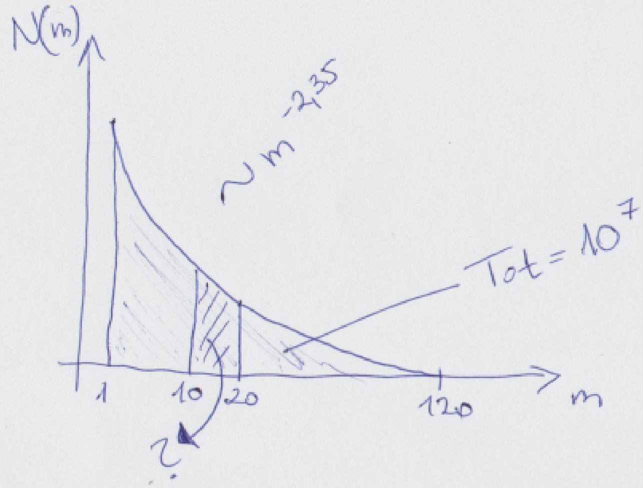
C: determined from the size of the population (e.g. 10^7 $M_\odot$)

definite integral:
how many stars are between e.g. 10-20 $M_\odot$



Compute the number (and mass) of stars between 10-20 $M_\odot$ in a stellar population of 10^7 $M_\odot$ total mass!

Suppose that in this star-cluster the lower mass limit is 1 $M_\odot$ and the upper mass limit is 120 $M_\odot$.
Bonus: compute the mass in these stars supposing that all stars in the mass range 10-20 $M_\odot$ have 15 $M_\odot$.



$$N(m) = C \cdot m^{-2,35}$$

$$Tot = \int_1^{120} C \cdot m^{-2,35}\, dm$$

$$10^7 = \left[\frac{1}{-1,35} C x^{-1,35} \right]_1^{120} =$$

$$10^7 = \frac{C}{-1,35} \left(120^{-1,35} - 1^{-1,35} \right)$$

$$C = 1,3521 \cdot 10^7$$

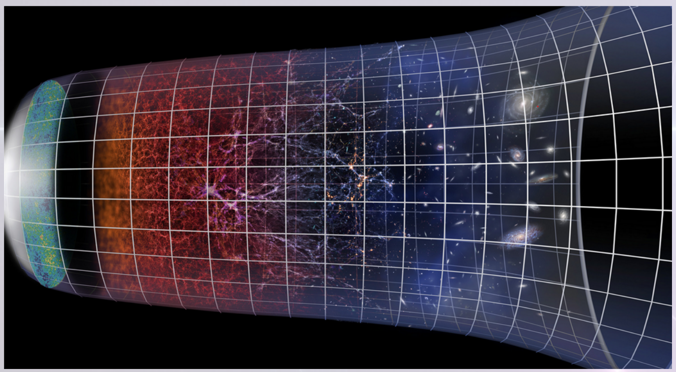
$$? = \int_{10}^{20} N(m)\, dm = \left[\frac{1,3521 \cdot 10^7}{-1,35} x^{-1,35} \right]_{10}^{20} = \frac{1,3521 \cdot 10^7}{-1,35} \left(20^{-1,35} - 10^{-1,35} \right) =$$

$$= \underline{\underline{271.877}}$$

Number of stars between

10-20 $M_\odot$ in a $10^7 M_\odot$ starcluster

with a Salpeter IMF :)



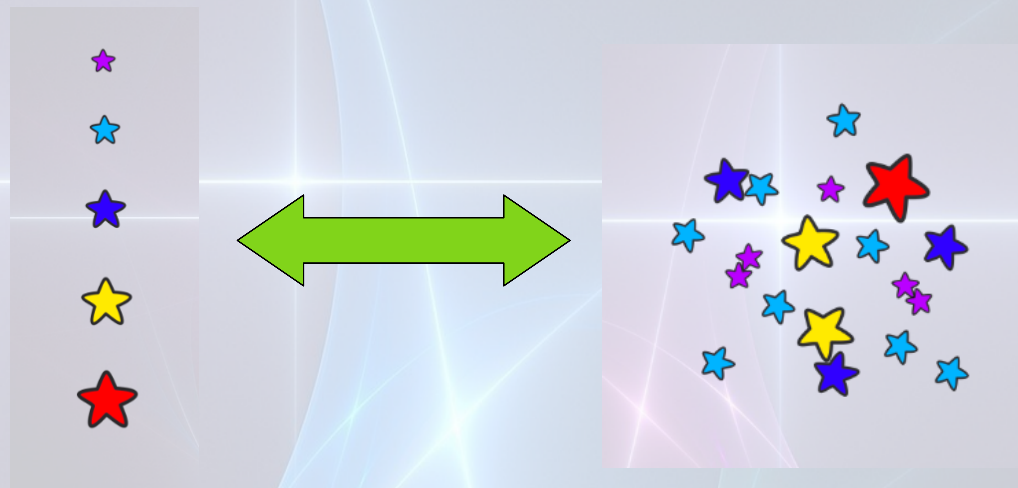
How many
GW events
happen
IN THE UNIVERSE
(per year)?

a star-cluster or galaxy: one star-formation event of size (e.g.) 10^7 $M_\odot$

aLIGO/Virgo detectors observe GWs from the whole Universe…

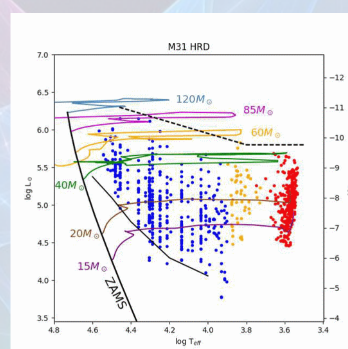
Population synthesis

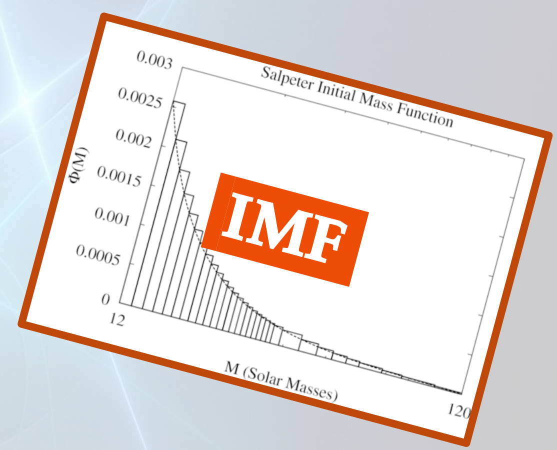
- Synthetic population:
  - time-dependence
  - IMF
  - star-formation history…



stars / stellar models

stellar population



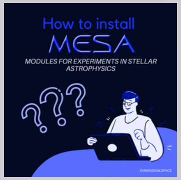


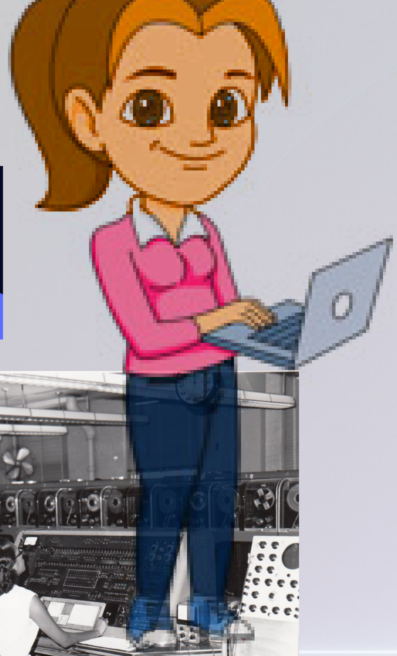
Must-know exam question:

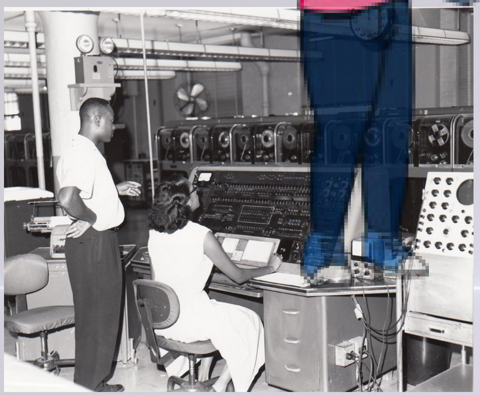
- What is the difference between stellar evolution and population synthesis?

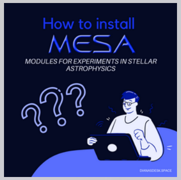
Today...

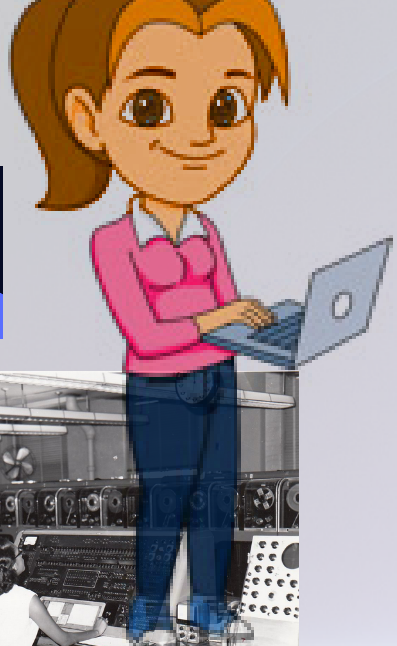
Massive Star Evolution
and the
Kippenhahn diagram

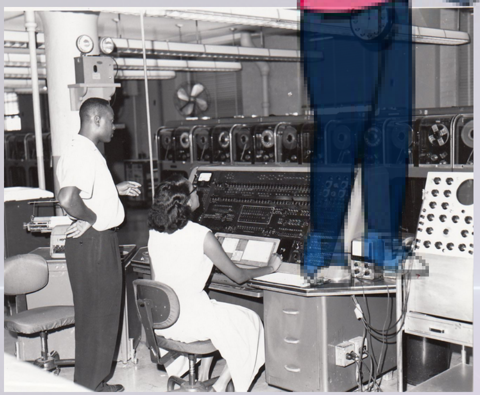

How to install
MESA
MODULES FOR EXPERIMENTS IN STELLAR ASTROPHYSICS











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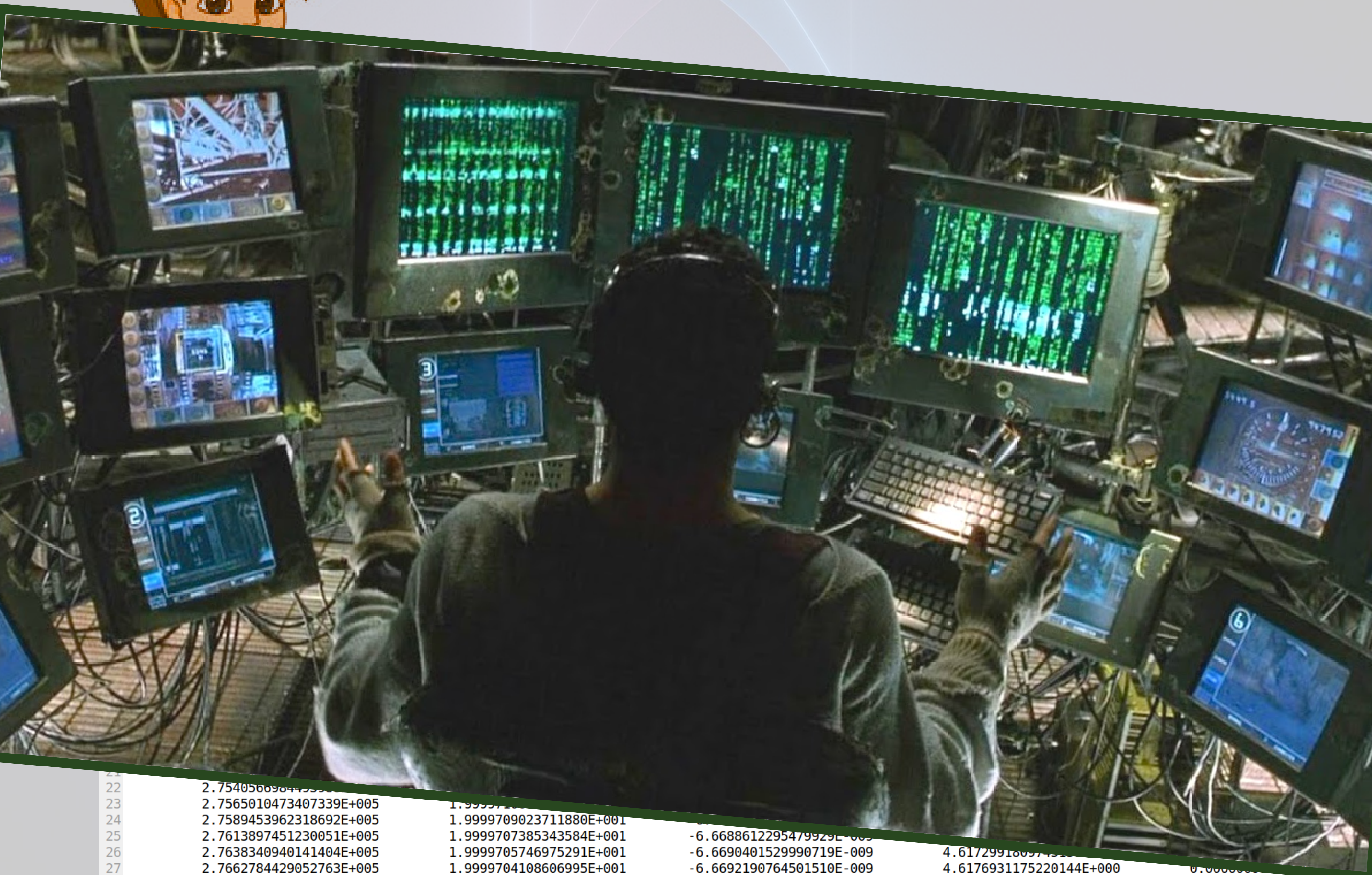

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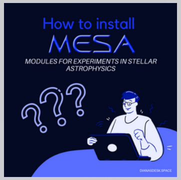

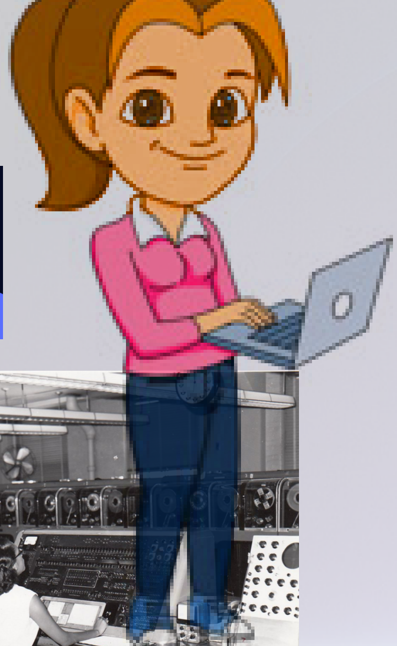

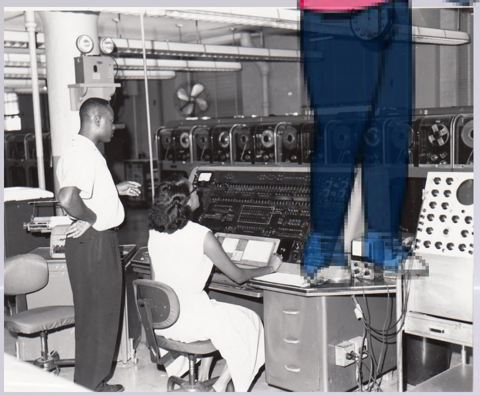

Visualization

& understanding what you see

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# 1.9999727046E+01     808        8       73      YES   high-mass
# EEPs:         1     202      353      454      605      631      707      808
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   2.7369462562116480E+005    1.9999723769026541E+001   -6.6670719950372001E-009    4.6129658789520063E+000    0.0000000000000000E+000
   2.7393906051027833E+005    1.9999722130658245E+001   -6.6672509184882791E-009    4.6133598154995070E+000    0.0000000000000000E+000
   2.7418349539939192E+005    1.9999720492289949E+001   -6.6674298419393581E-009    4.6137537520470087E+000    0.0000000000000000E+000
   2.7442793028850551E+005    1.9999718853921653E+001   -6.6676087653904380E-009    4.6141476885945094E+000    0.0000000000000000E+000
   2.7467236517761904E+005    1.9999717215553360E+001   -6.6677876888415162E-009    4.6145416251420093E+000    0.0000000000000000E+000
   2.7491680006673269E+005    1.9999715577185061E+001   -6.6679666122925961E-009    4.6149355616895100E+000    0.0000000000000000E+000
   2.7516123495584622E+005    1.9999713938816765E+001   -6.6681455357436759E-009    4.6153294982370108E+000    0.0000000000000000E+000
   2.7540566984495980E+005    1.9999712300448472E+001   -6.6683244591947550E-009    4.6157234347845106E+000    0.0000000000000000E+000
   2.7565010473407339E+005    1.9999710662080176E+001   -6.6685033826458340E-009    4.6161173713320123E+000    0.0000000000000000E+000
   2.7589453962318692E+005    1.9999709023711880E+001   -6.6686823060969130E-009    4.6165113078795130E+000    0.0000000000000000E+000
   2.7613897451230051E+005    1.9999707385343584E+001   -6.6688612295479929E-009    4.6169052444270129E+000    0.0000000000000000E+000
   2.7638340940141404E+005    1.9999705746975291E+001   -6.6690401529990719E-009    4.6172991809745136E+000    0.0000000000000000E+000
   2.7662784429052763E+005    1.9999704108606995E+001   -6.6692190764501510E-009    4.6176931175220144E+000    0.0000000000000000E+000
   2.7687227917964122E+005    1.9999702470238695E+001   -6.6693979999012308E-009    4.6180870540695151E+000    0.0000000000000000E+000
   2.7711671406875481E+005    1.9999700831870403E+001   [illegible]695769233523099E-009    4.6184809906170159E+000    0.0000000000000000E+000
   2.7736114895786840E+005    1.9999699193502106E+00[illegible]   [illegible]558468033889E-009    4.6188749271645166E+000    0.0000000000000000E+000
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   2.7785001873609552E+005    1.9999695916765514E+001   [illegible]37055478E-009    4.6196628002595173E+000    0.0000000000000000E+000
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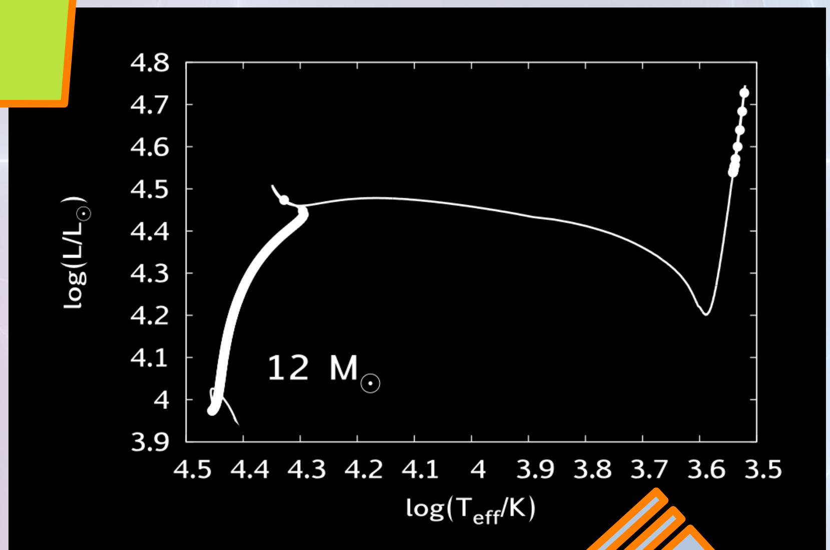
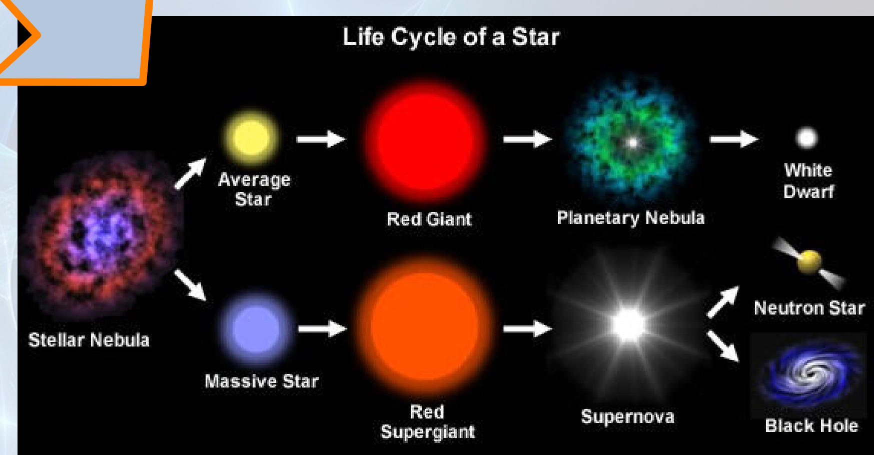
Visualization



Interpretation

"understanding what you see"

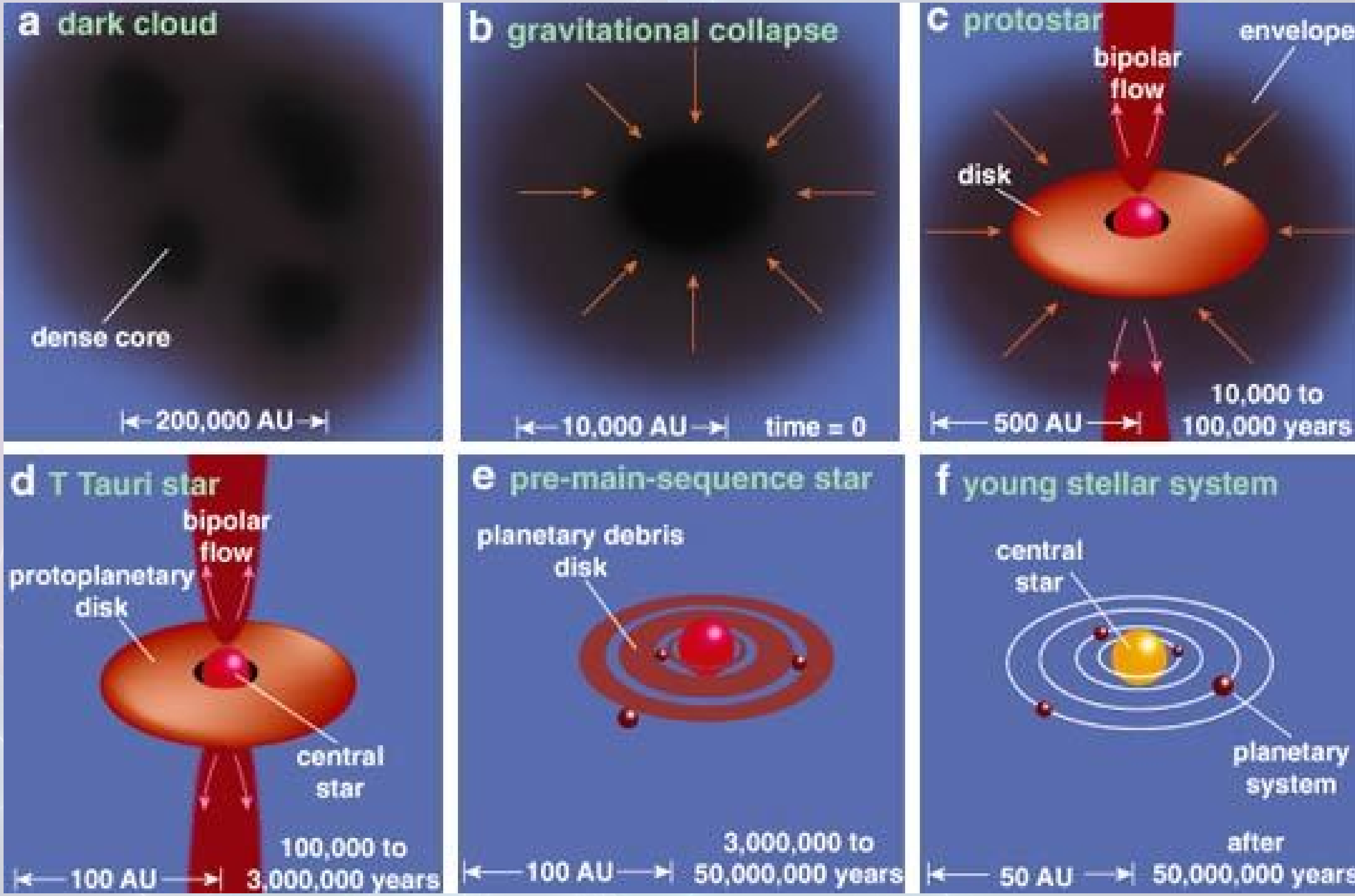


Star-formation (of massive stars)

- under active research

Star-formation (of massive stars)

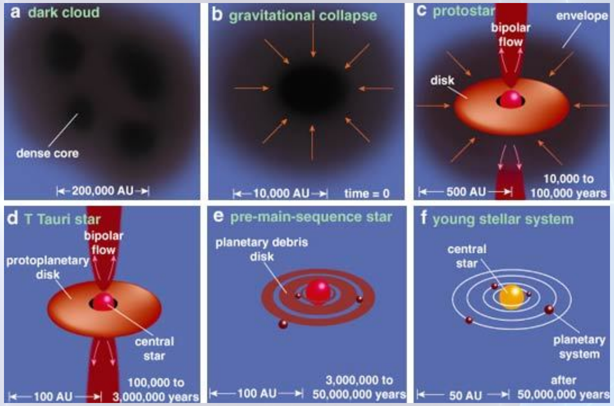
- under active research
- low-mass stars:



Credit: S. K. Sahoo (2016)

Star-formation (of massive stars)

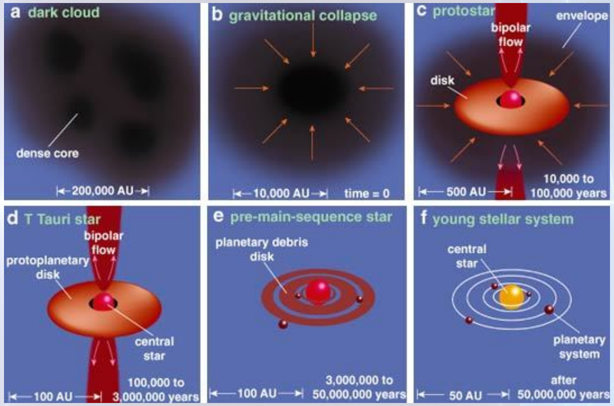
- under active research
- low-mass stars:



- massive stars?
  - strong radiation may blow away the material

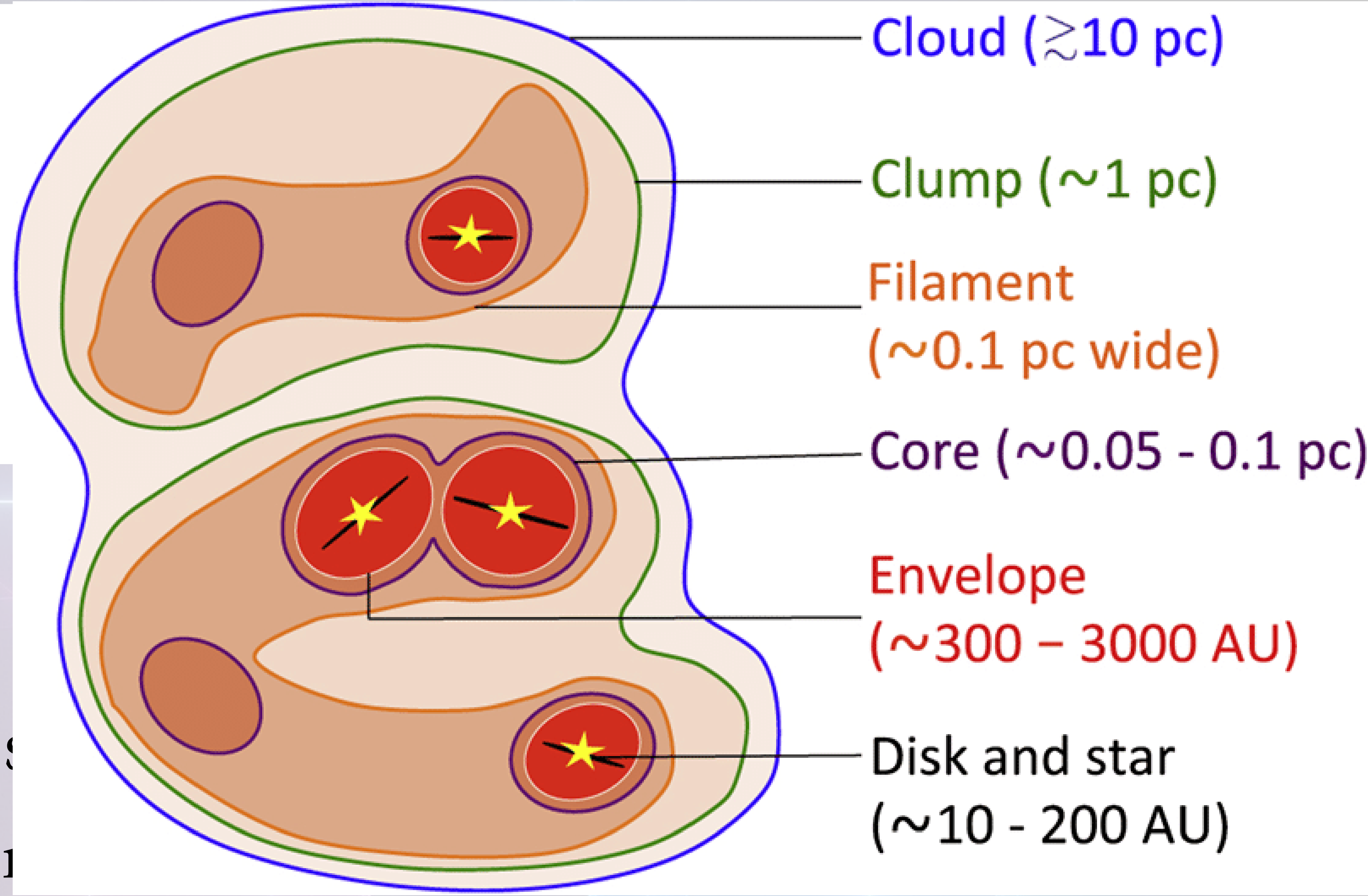
Star-formation (of massive stars)

- under active research
- low-mass stars:



- massive stars?
  - strong radiation may blow away the material
  - hierarchical star formation?

Structure of a molecular cloud (where stars are born)

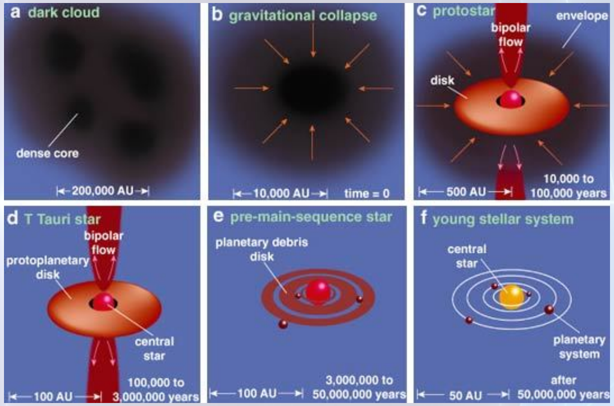


- massive s
  - strong r
  - hierarchical star formation?

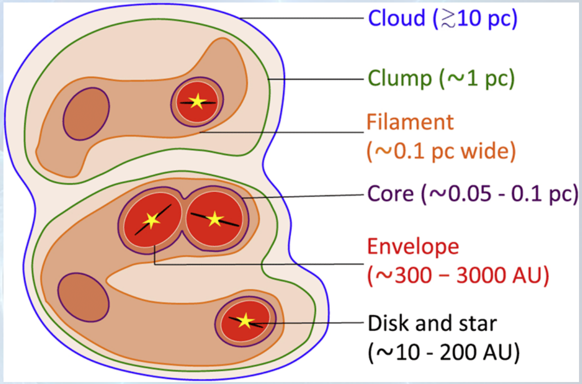
Credit: A. L. Rosen et al. (2020)

Star-formation (of massive stars)

- under active research
- low-mass stars:

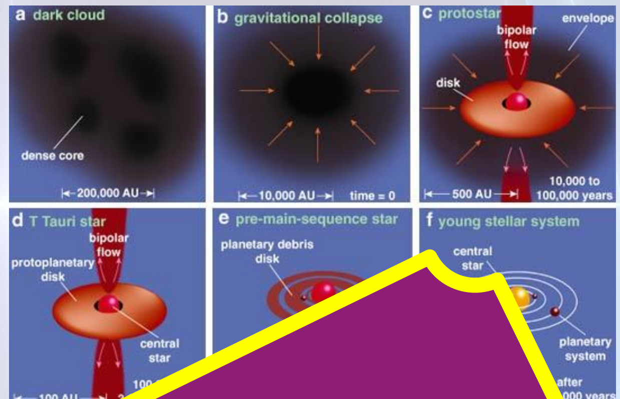


- massive stars?
  - strong radiation may blow away the material
  - hierarchical star formation?



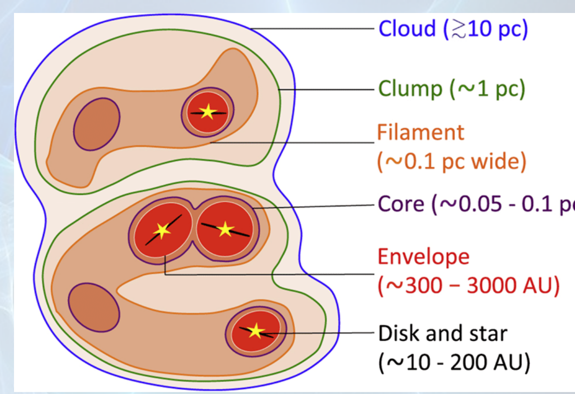
Star-formation (of massive stars)

- under active research
- low-mass stars:



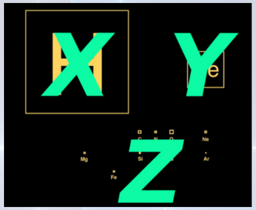
- massive stars?
  - strong ... away the material
  - ... ination?

Stellar evolution *technically* starts where star-formation ends
(IRL: ?? ...*under active research*)



Onset of stellar evolution: ZAMS

- Zero-Age Main Sequence
  - (core) composition:
    same as the molecular cloud

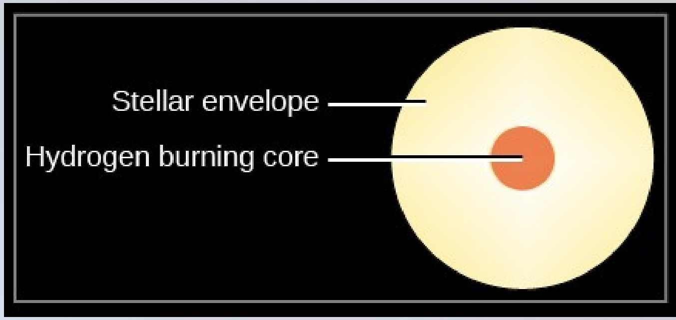


$Z_{\odot} \sim 0.014$ (<2%)
$Z_{LMC} \sim 0.004$
$Z_{SMC} \sim 0.002$
$Z_{GCs} \sim <0.005$
$Z_{PopIII} = 0$

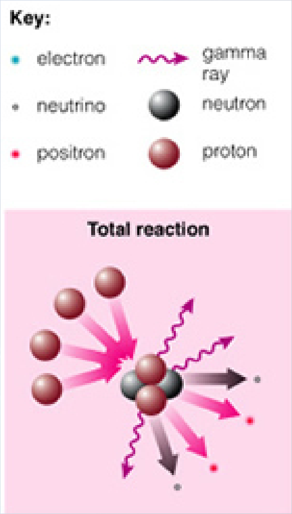
- hydrogen burning starts (in the core)
- hydrostatic & thermodynamic equilibrium
  - no bipolar outflows etc.
  - stellar structure equations hold*

*"pre-MS": last phases of star-formation modelled using the structure equations

Longest phase of stellar evolution: MS

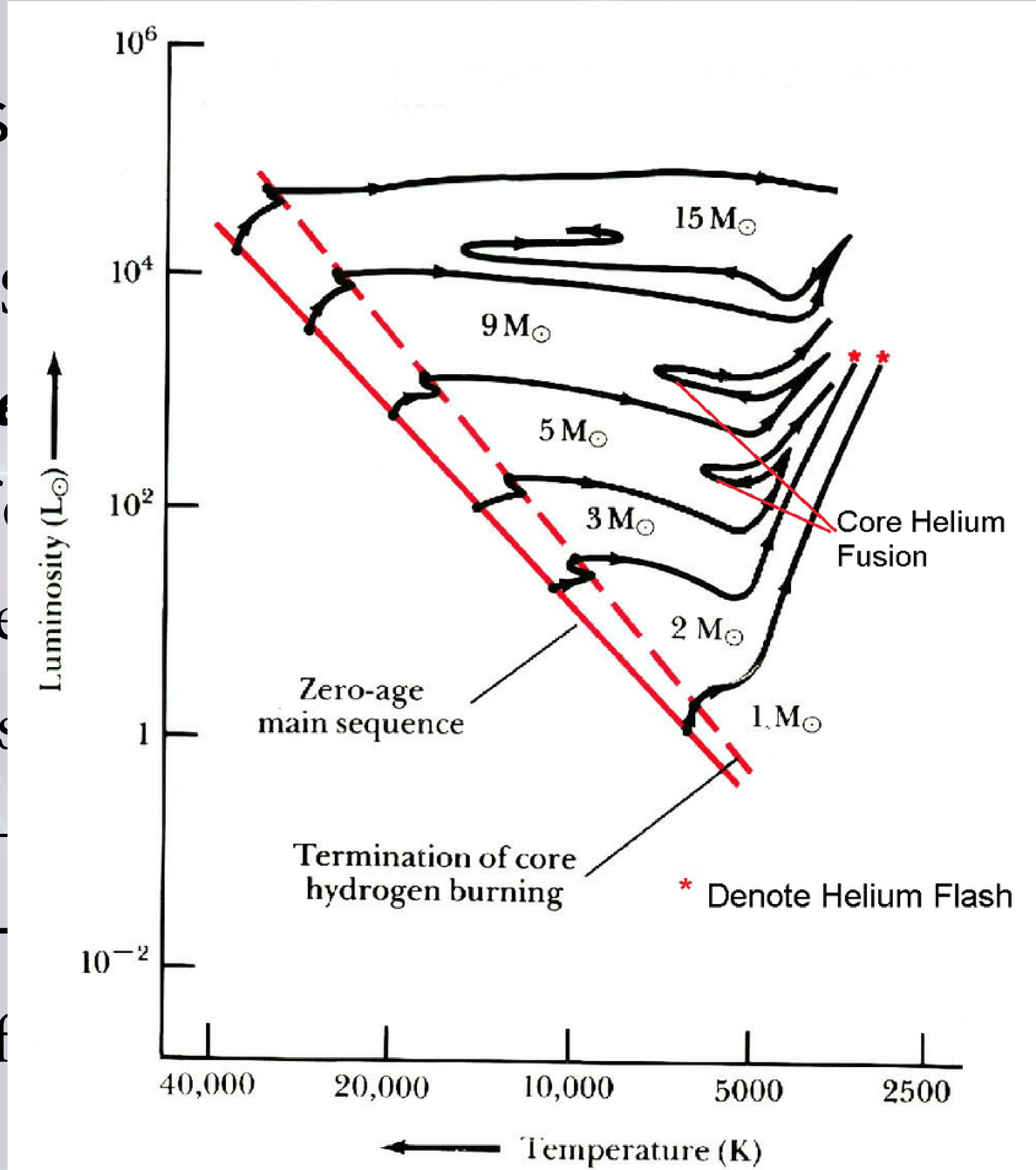


- Main Sequence
  - ***core***-hydrogen-burning phase
- lasts for ~90% of the lifetime (longest of them all)
- core temperatures: ~40M K
- in massive stars: CNO cycle
  - low-mass stars like the Sun: pp-chain
- $4\ ^{1}H \rightarrow\ ^{4}He + \gamma$
- end of MS: Terminal-Age Main Sequence (TAMS)



Longes… on: MS

- Main S…
  - ***core…***
- lasts f… n all)
- core te…
- in mas…
  - low-…
- 4 ¹H –…
- end of… (TAMS)

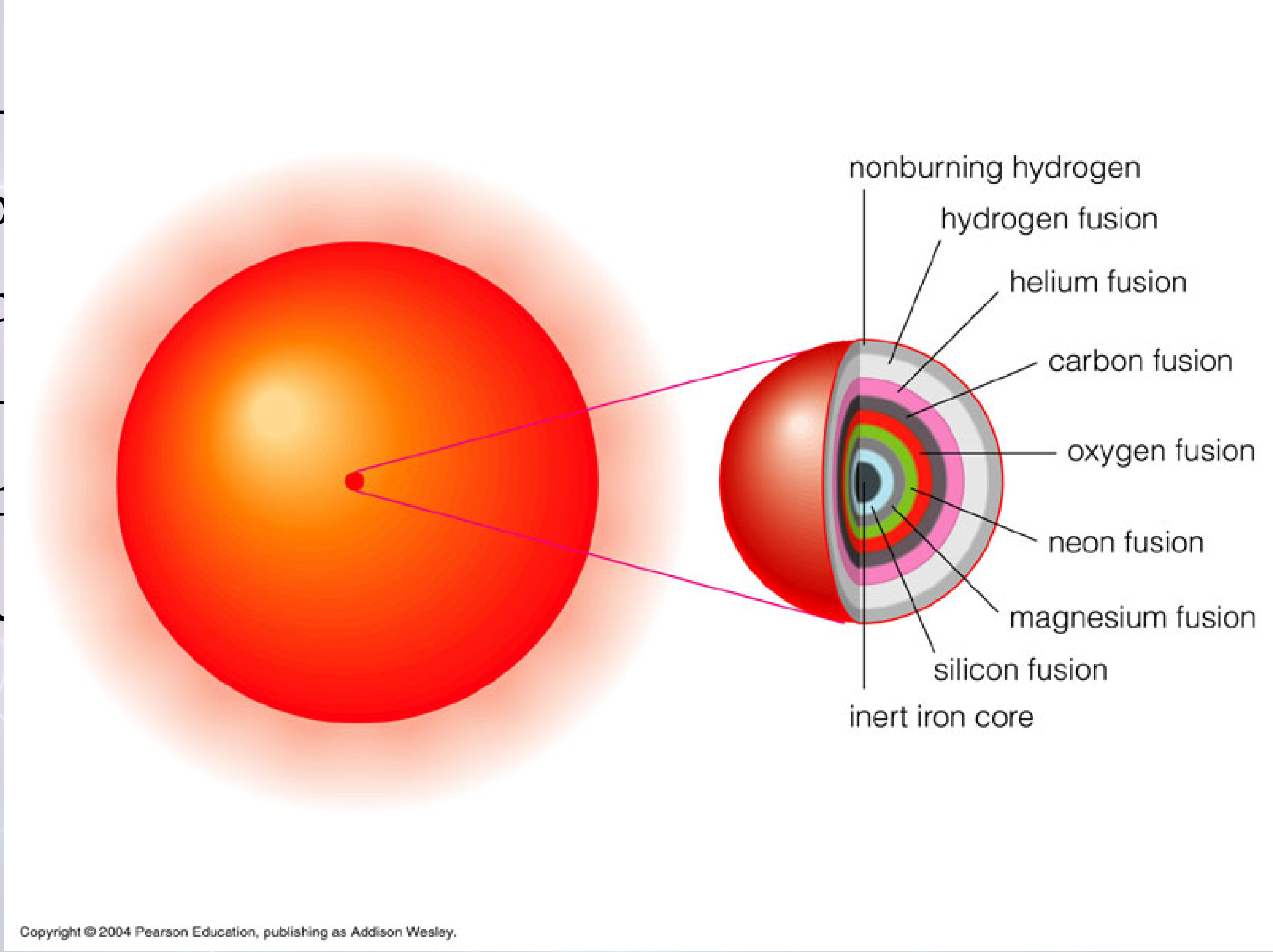


Post-MS

- Includes:
  - core-He-burning (& shell-H-burning)
  - core-C-burning (& shell-He & shell-H-burning)
  - core-O-burning (& shell-C, shell-He, shell-H…
  - core-Ne-burning (& shell…
  - core-Si-burning (& shell...
- onion-structure of massive stars

Post-MS

- Includes:
  - core-He-
  - core-C-b
  - core-O-b
  - core-Ne-
  - core-Si-b
- onion-stru

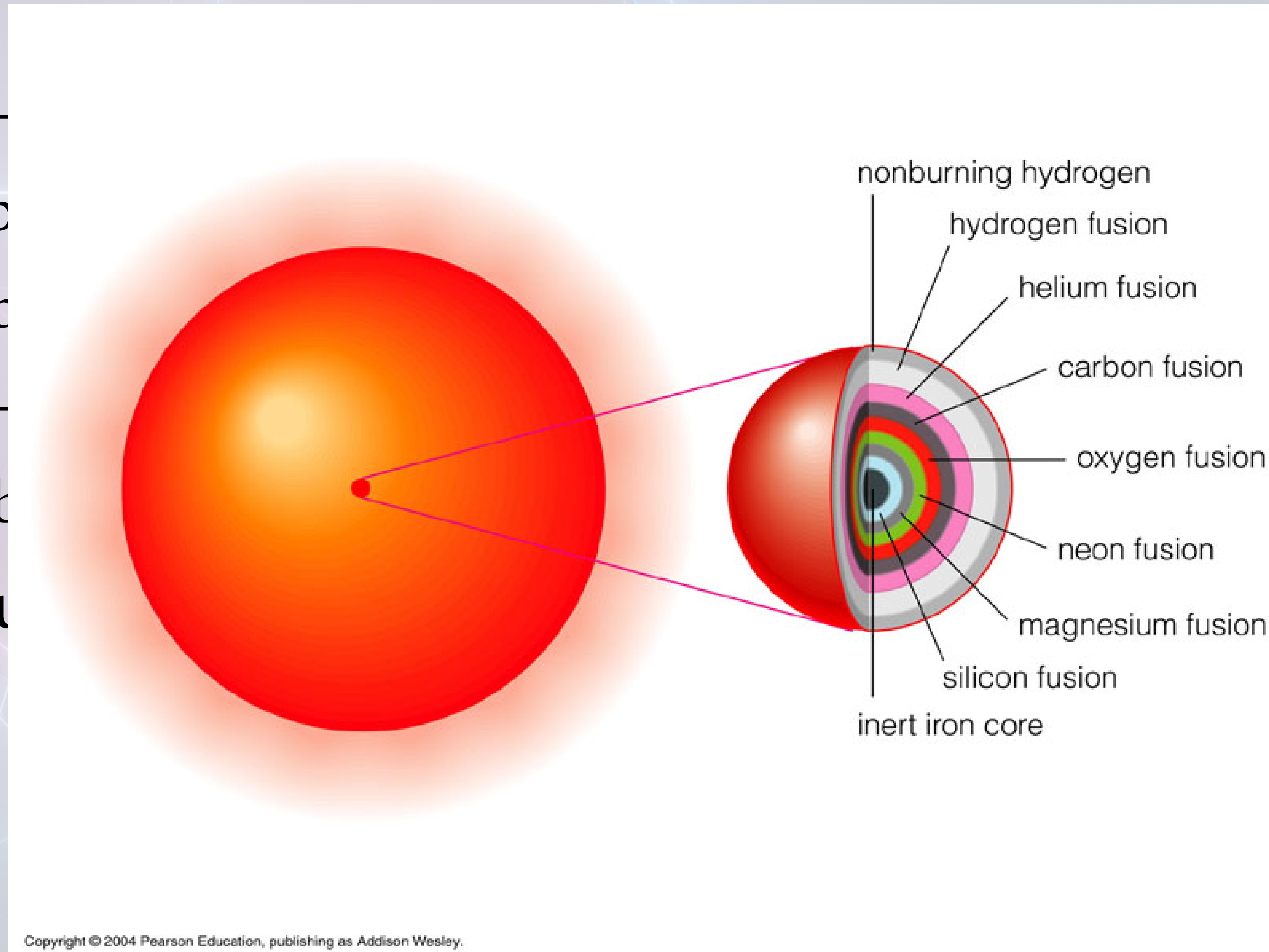


Post-MS

- Includes:
  - core-He-
  - core-C-b
  - core-O-b
  - core-Ne-
  - core-Si-b

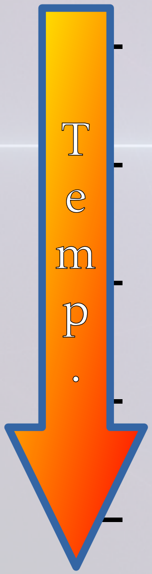
Temp.

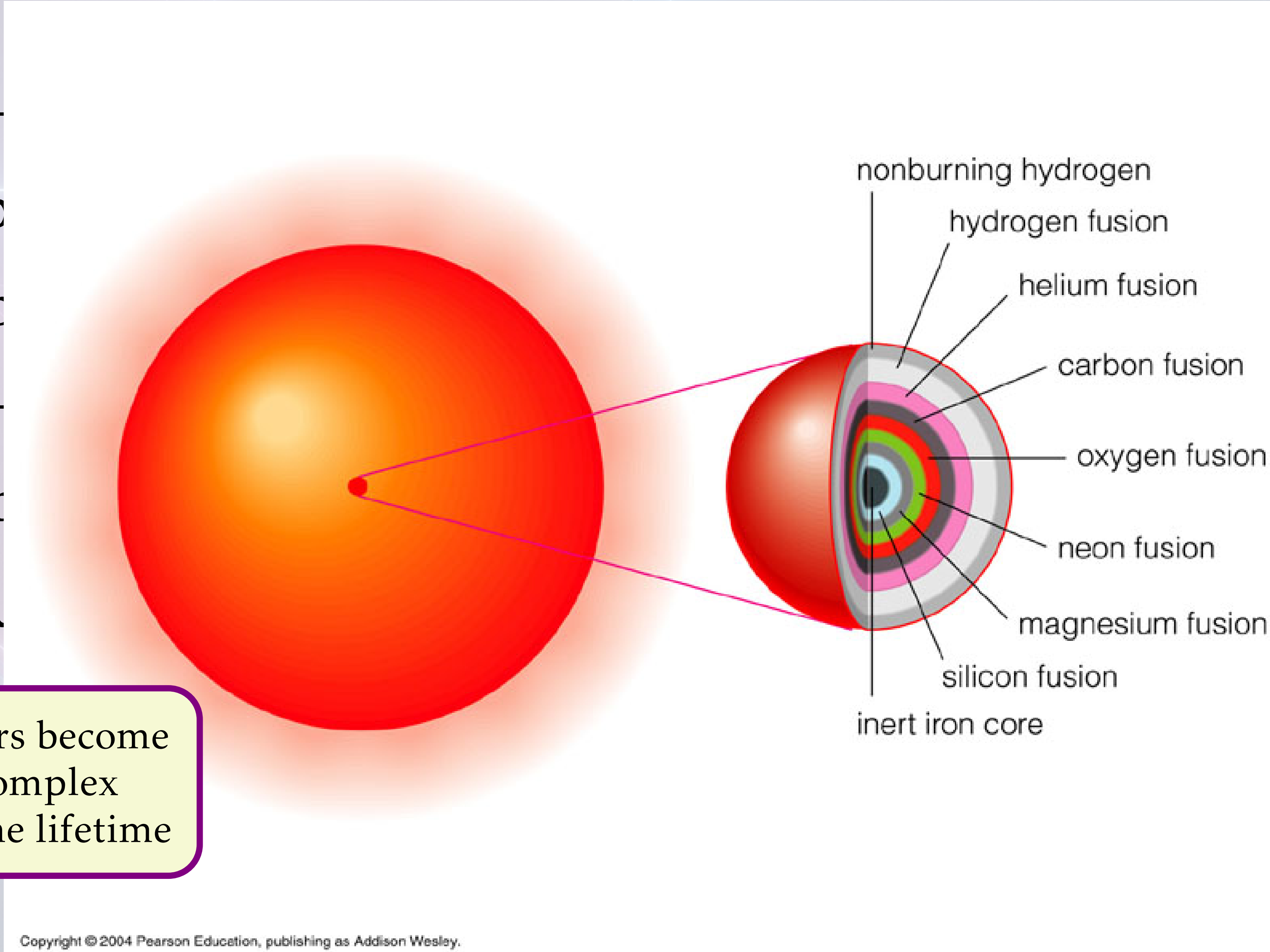
- onion-stru



Post-MS

- Includes:
  - core-He-
  - core-C-b
  - core-O-b
  - core-Ne-
  - core-Si-b
- onion-stru

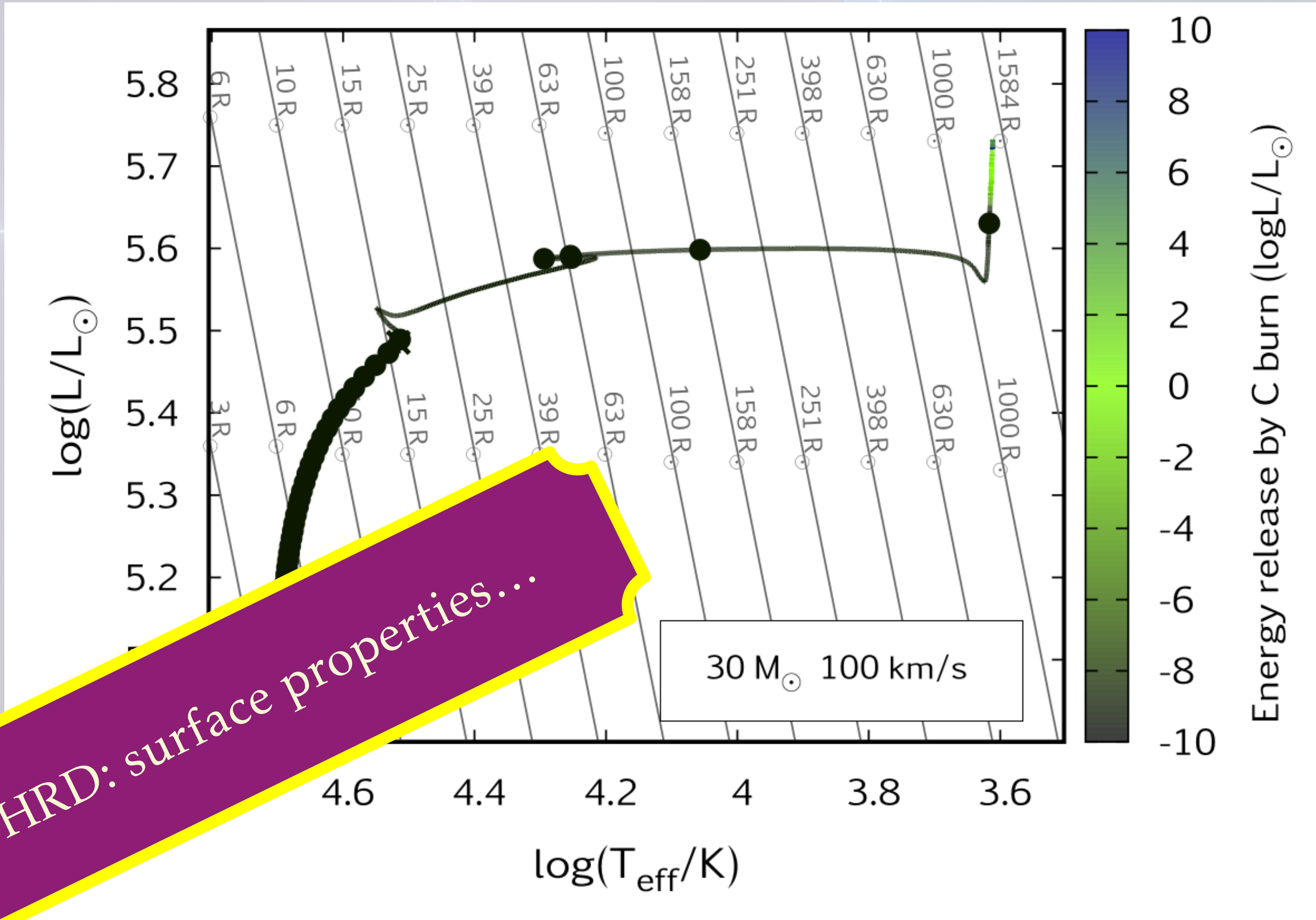




Note: the onion layers become more and more complex nearing the end of the lifetime

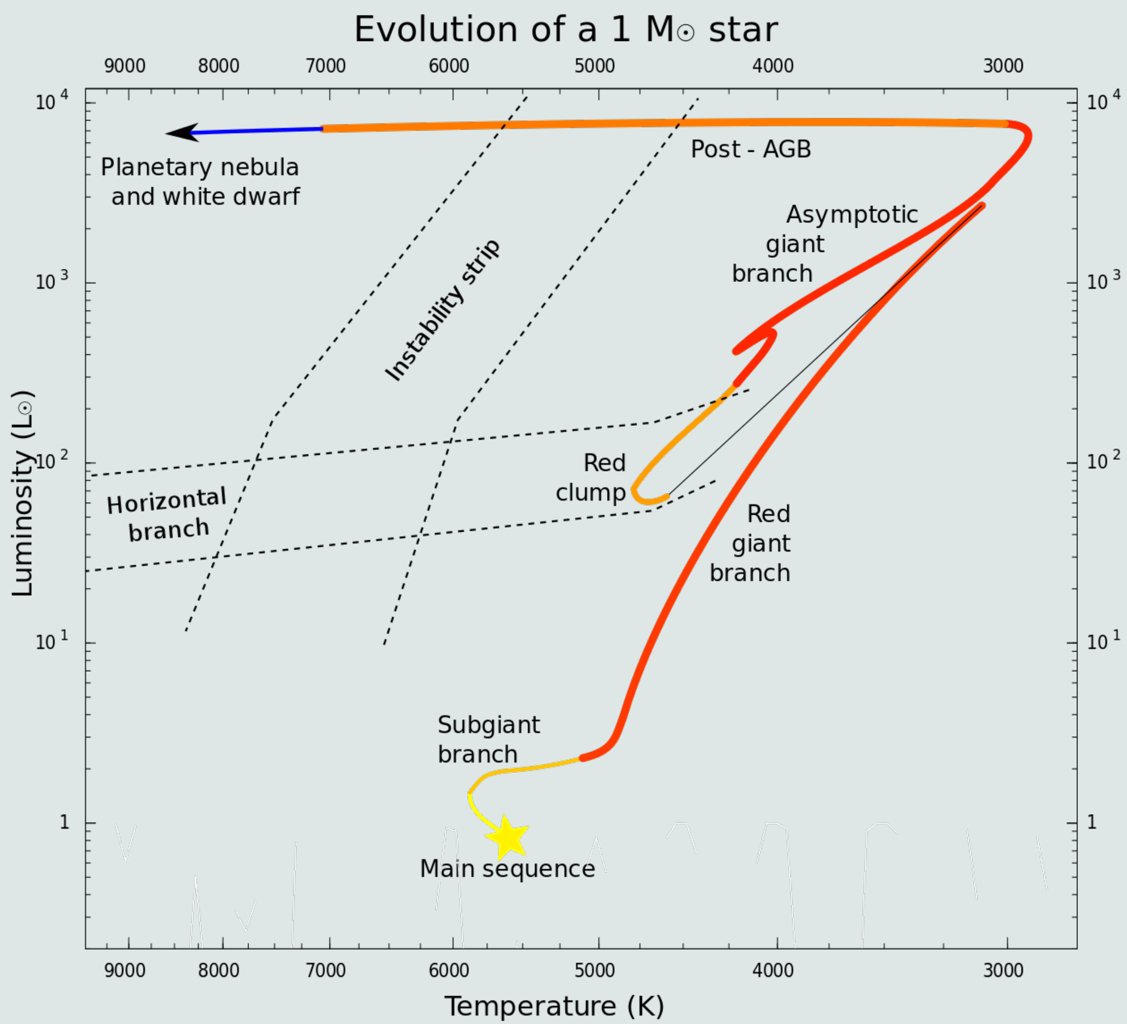
How much do we see from this in the HRD?

How much do we see from this in the HRD?



HRD: surface properties…

Sidenote:
low-mass stars' HRD is more informative for their post-MS evolutionary features



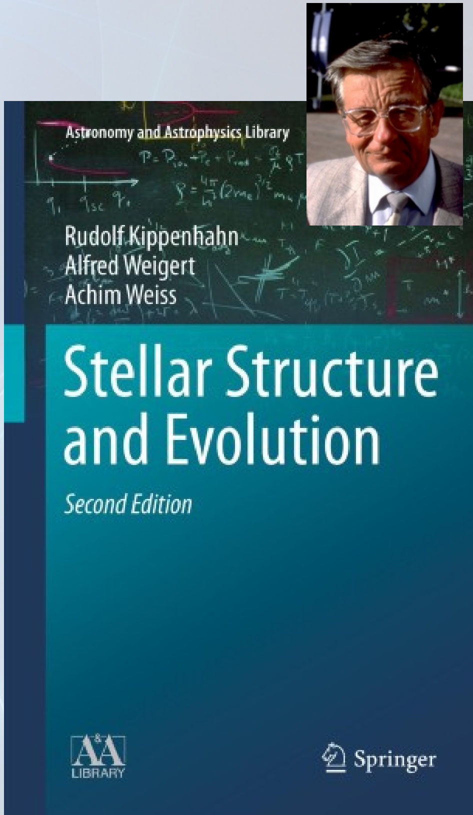
Energy release by C burn (logL/L☉)

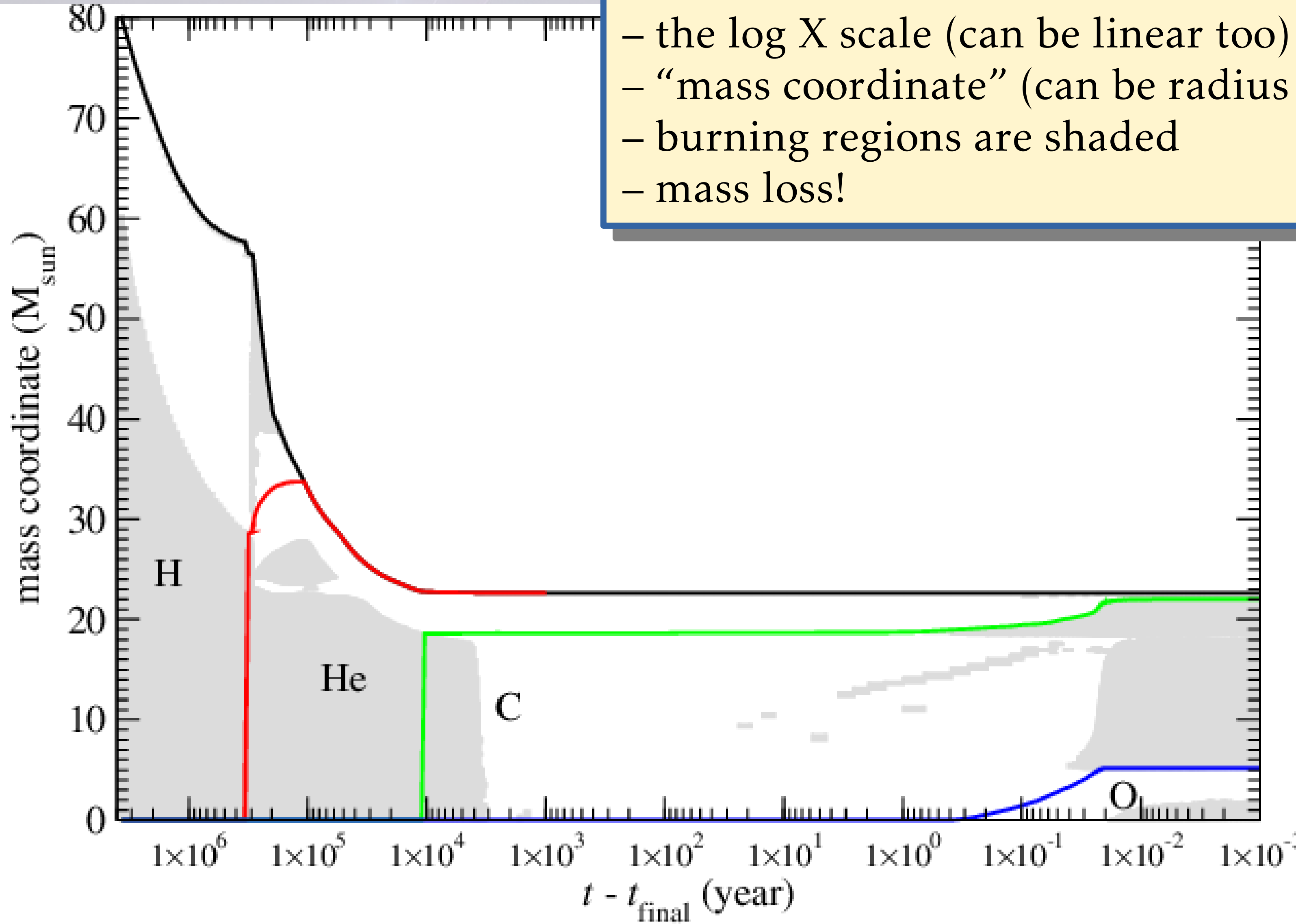
log(L/L☉)

HRD

Kippenhahn diagram

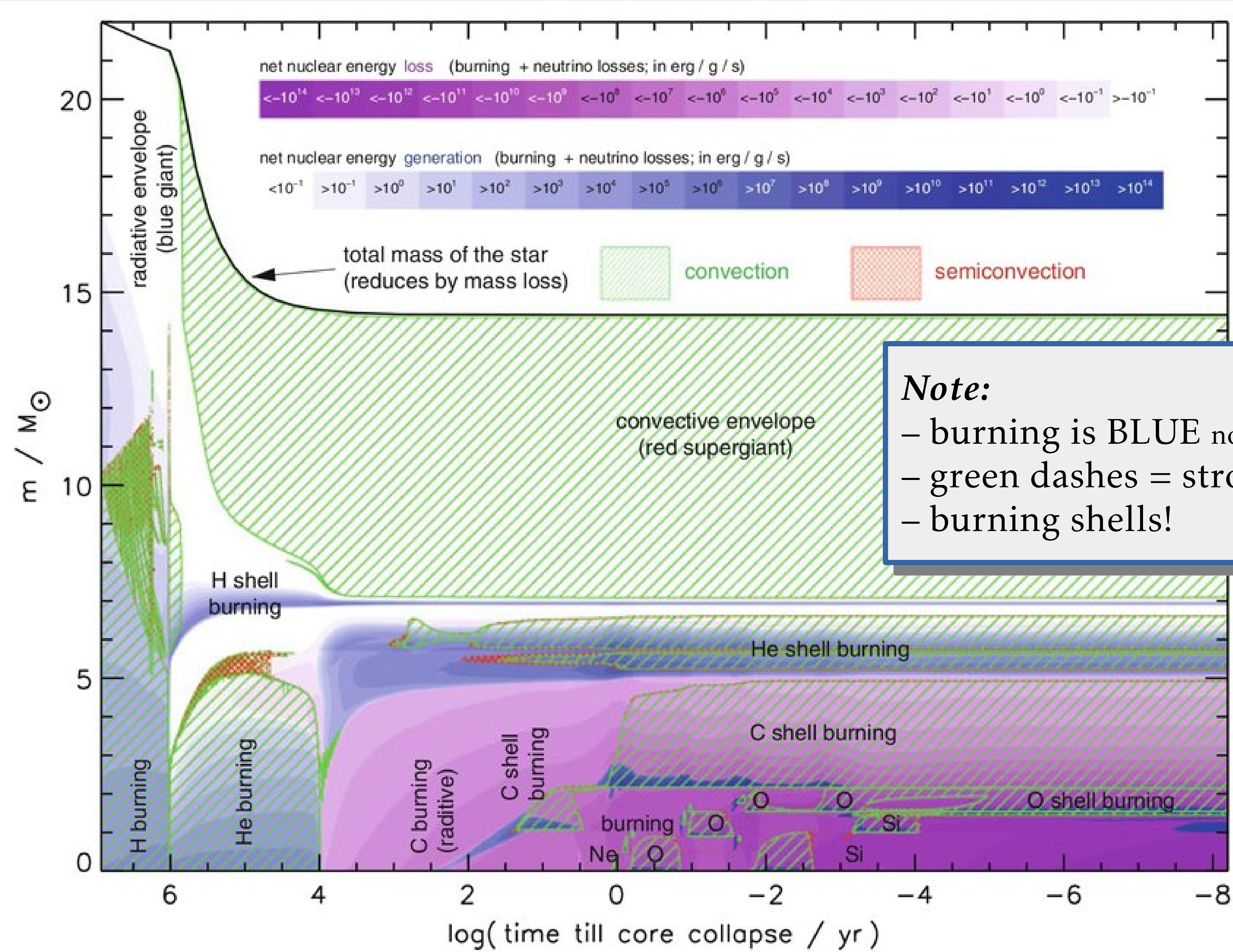
Kippenhahn diagram





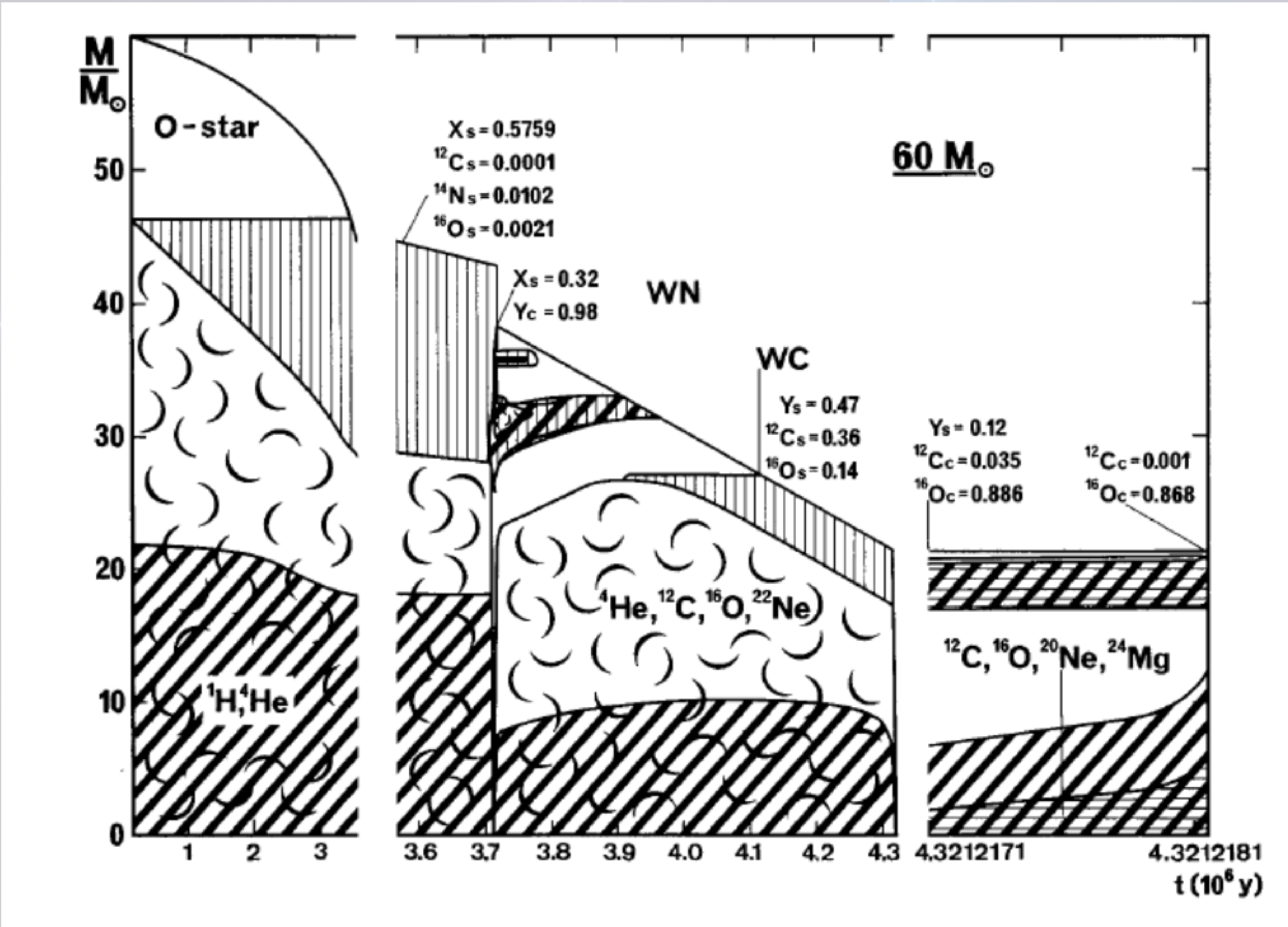
Note:
- the log X scale (can be linear too)
- "mass coordinate" (can be radius too)
- burning regions are shaded
- mass loss!

Credit: Leung, Nomoto & Blinnikov (2019)



Note:
- burning is BLUE not green/purple
- green dashes = strong mixing
- burning shells!

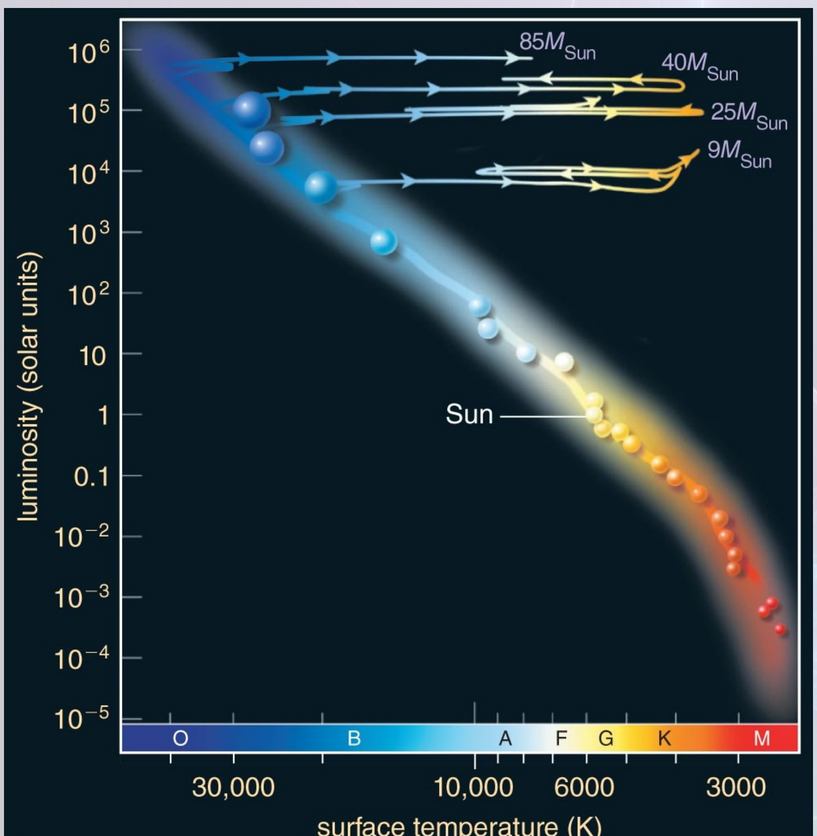
Credit: Braithwaite & Spruit (2015)

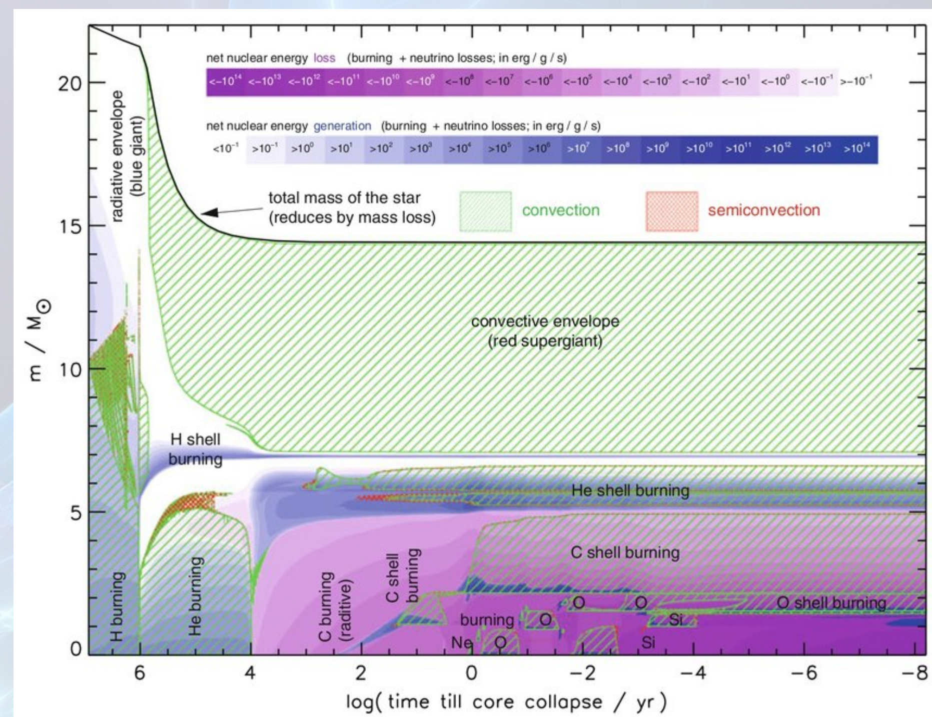


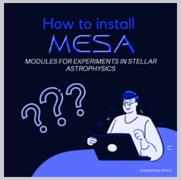
Credit: Maeder & Meynet (1987)

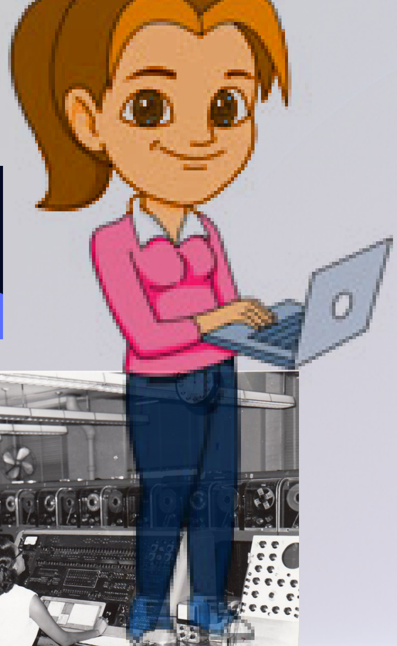
HRD vs. Kippenhahn

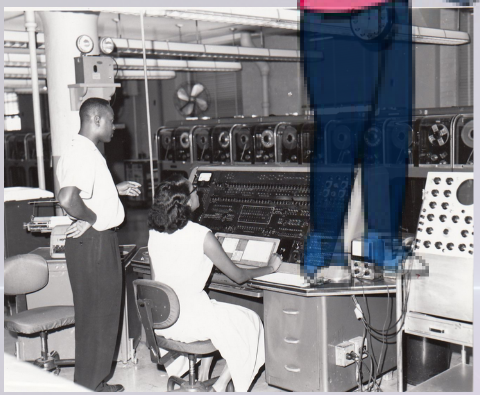
- surface T, L
  - helps observational comparison
- interior structure
  - e.g. pre-supernova structure, mixing…

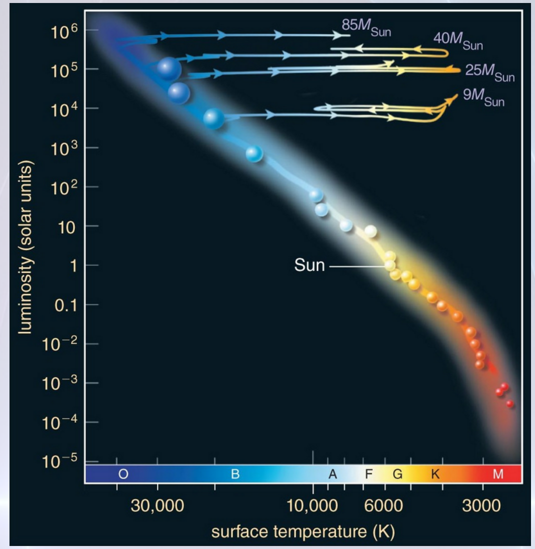


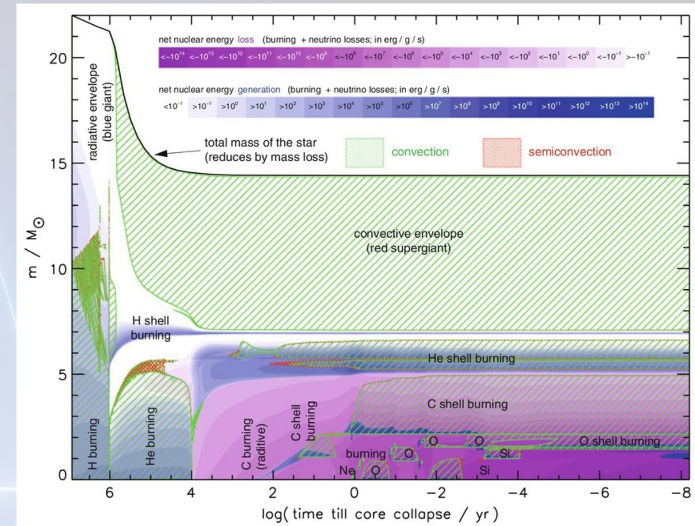













```
# MIST version number  = 10.1
# MESA revision number =    11701
# --------------------------------------------------------------------------------------
#  Yinit        Zinit   [Fe/H]   [a/Fe]  v/vcrit
# 0.2511  1.42857E-03    -1.00     0.00     0.00
# --------------------------------------------------------------------------------------
#     initial_mass   N_pts   N_EEP   N_col    phase        type
# 1.9999727046E+01     808       8      73      YES   high-mass
# EEPs:          1     202     353     454      605     631      707      808
# --------------------------------------------------------------------------------------------
#                             1                             2                             3                             4                             5
#                      star_age                     star_mass                     star_mdot                        log_dt                  he_core_mass
         2.7320575584293762E+005       1.9999727045763130E+001      -6.6667141481350412E-009       4.6121780058570057E+000       0.0000000000000000E+000
         2.7345019073205121E+005       1.9999725407394834E+001      -6.6668930715861210E-009       4.6125719424045064E+000       0.0000000000000000E+000
         2.7369462562116480E+005       1.9999723769026541E+001      -6.6670719950372001E-009       4.6129658789520063E+000       0.0000000000000000E+000
         2.7393906051027833E+005       1.9999722130658245E+001      -6.6672509184882791E-009       4.6133598154995070E+000       0.0000000000000000E+000
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         2.7540566984495980E+005       1.9999712300448472E+001      -6.6683244591947550E-009       4.6157234347845106E+000       0.0000000000000000E+000
         2.7565010473407339E+005       1.9999710662080176E+001      -6.6685033826458340E-009       4.6161173713320123E+000       0.0000000000000000E+000
         2.7589453962318692E+005       1.9999709023711880E+001      -6.6686823060969130E-009       4.6165113078795130E+000       0.0000000000000000E+000
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         2.7638340940141404E+005       1.9999705746975291E+001      -6.6690401529990719E-009       4.6172991809745136E+000       0.0000000000000000E+000
         2.7662784429052763E+005       1.9999704108606995E+001      -6.6692190764501510E-009       4.6176931175220144E+000       0.0000000000000000E+000
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         2.7785001873609552E+005       1.9999695916765514E+001      -6.6701136937055478E-009       4.6196628002595173E+000       0.0000000000000000E+000
```
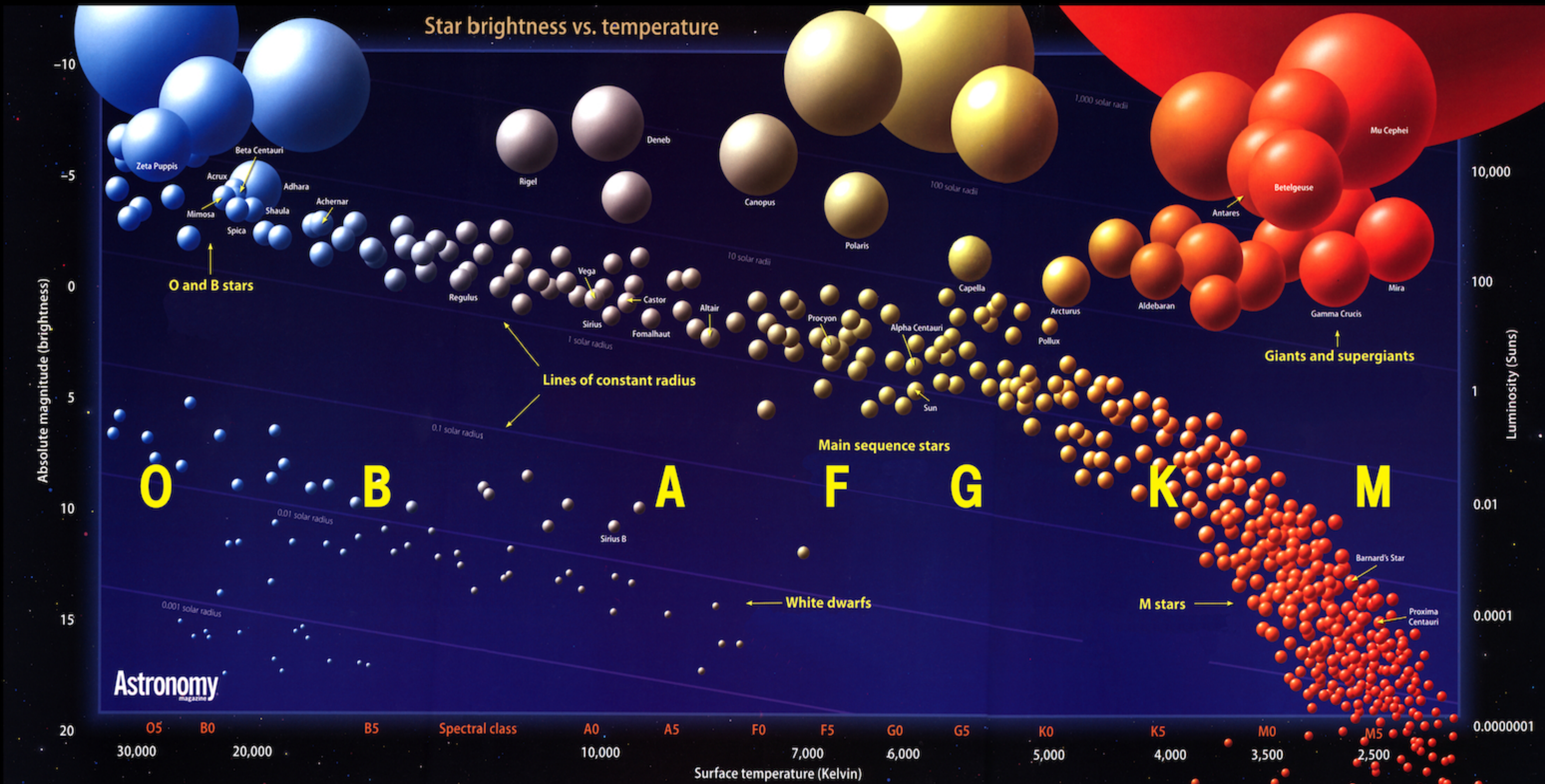
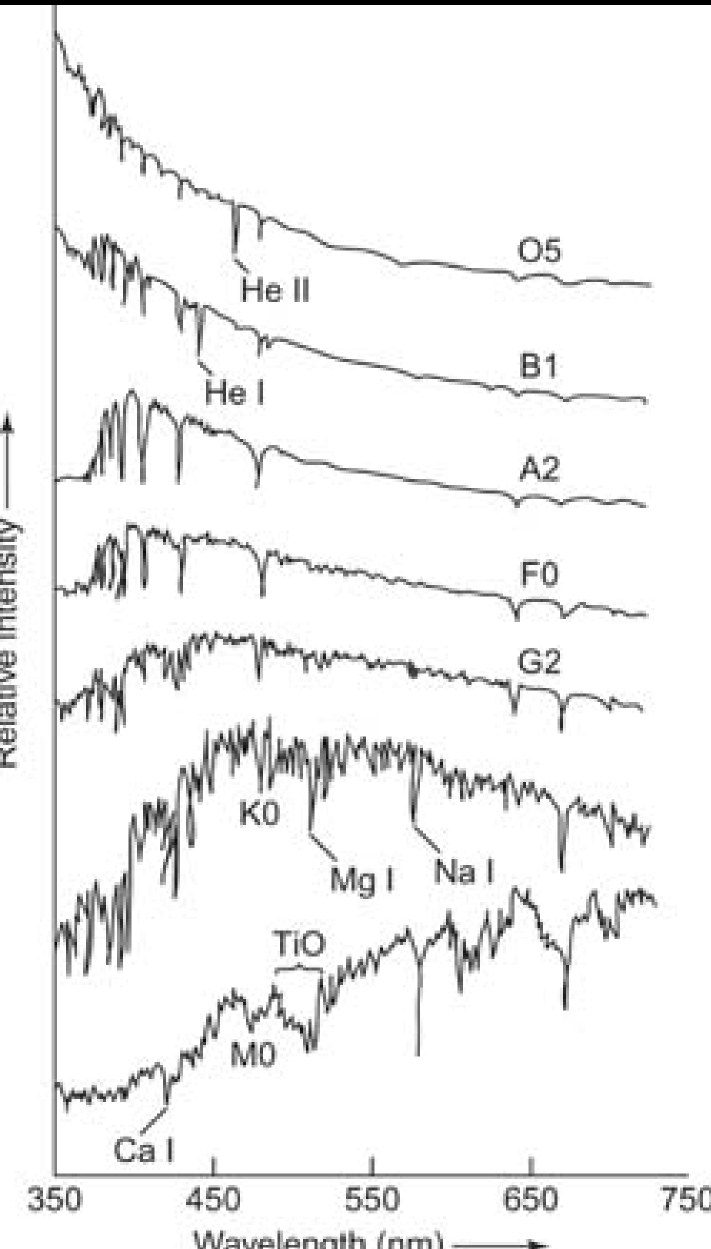

Bonus topic…

Stellar classification

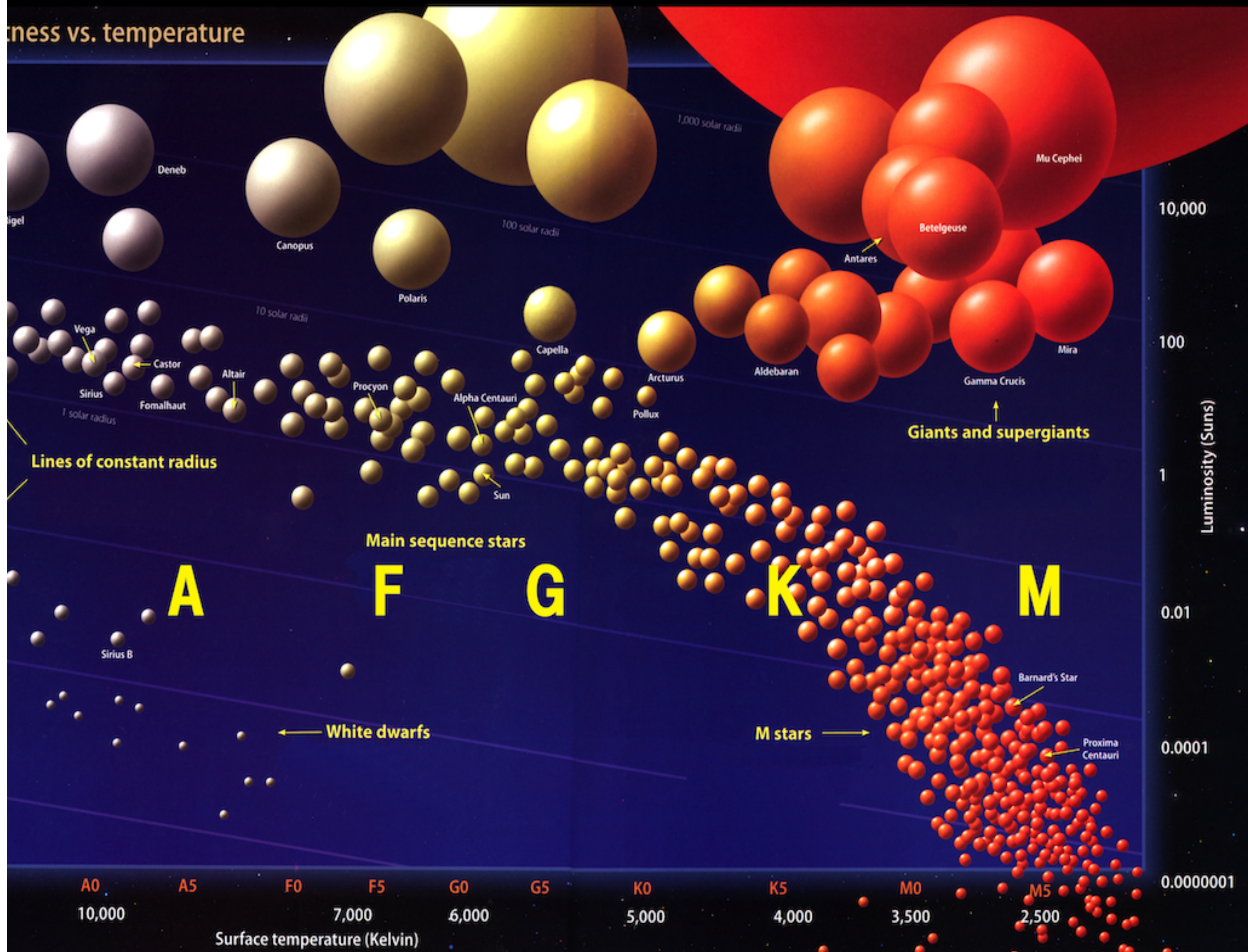
So much history…!



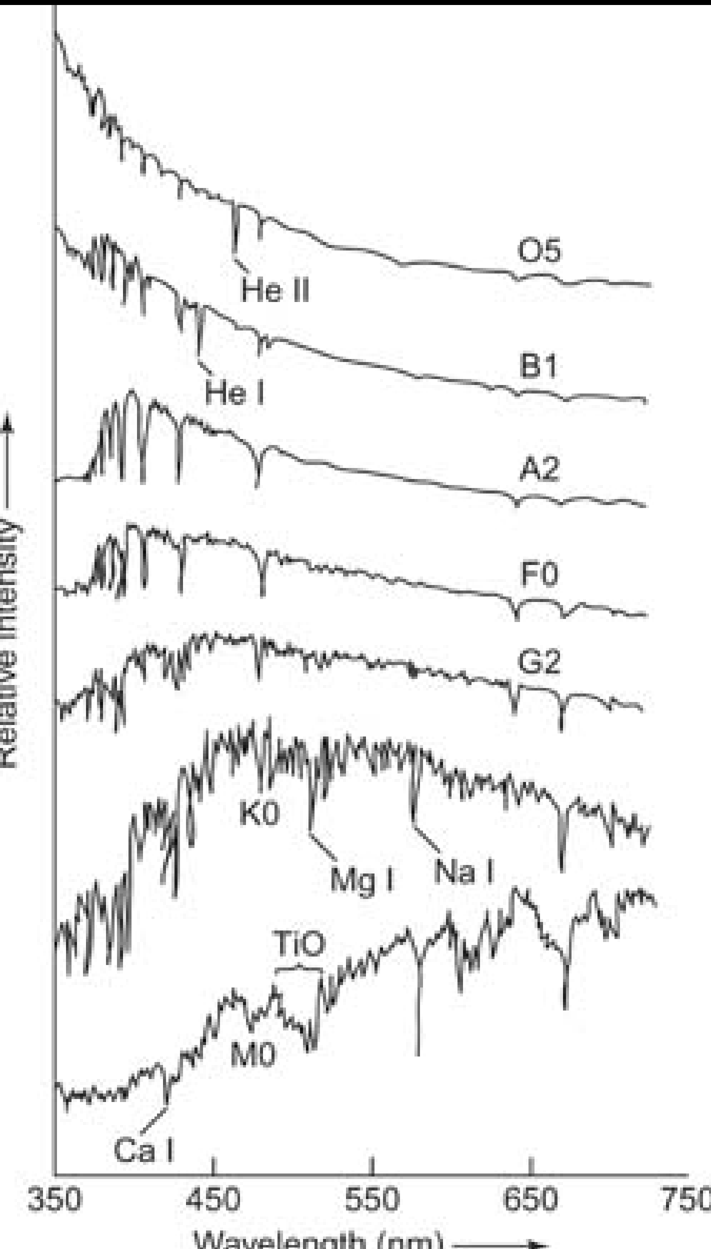
Star brightness vs. temperature
Absolute magnitude (brightness)
-10
-5
0
5
10
15
20
Luminosity (Suns)
10,000
100
1
0.01
0.0001
0.0000001
Zeta Puppis
Beta Centauri
Acrux
Adhara
Mimosa
Shaula
Spica
Achernar
O and B stars
Rigel
Deneb
Canopus
Polaris
Mu Cephei
Betelgeuse
Antares
Capella
Arcturus
Aldebaran
Mira
Gamma Crucis
Pollux
Regulus
Vega
Castor
Sirius
Fomalhaut
Altair
Procyon
Alpha Centauri
Sun
Giants and supergiants
Lines of constant radius
1,000 solar radii
100 solar radii
10 solar radii
1 solar radius
0.1 solar radius
0.01 solar radius
0.001 solar radius
Main sequence stars
O
B
A
F
G
K
M
Sirius B
White dwarfs
Barnard's Star
M stars
Proxima Centauri
Astronomy magazine
O5
B0
B5
Spectral class
A0
A5
F0
F5
G0
G5
K0
K5
M0
M5
30,000
20,000
10,000
7,000
6,000
5,000
4,000
3,500
2,500
Surface temperature (Kelvin)

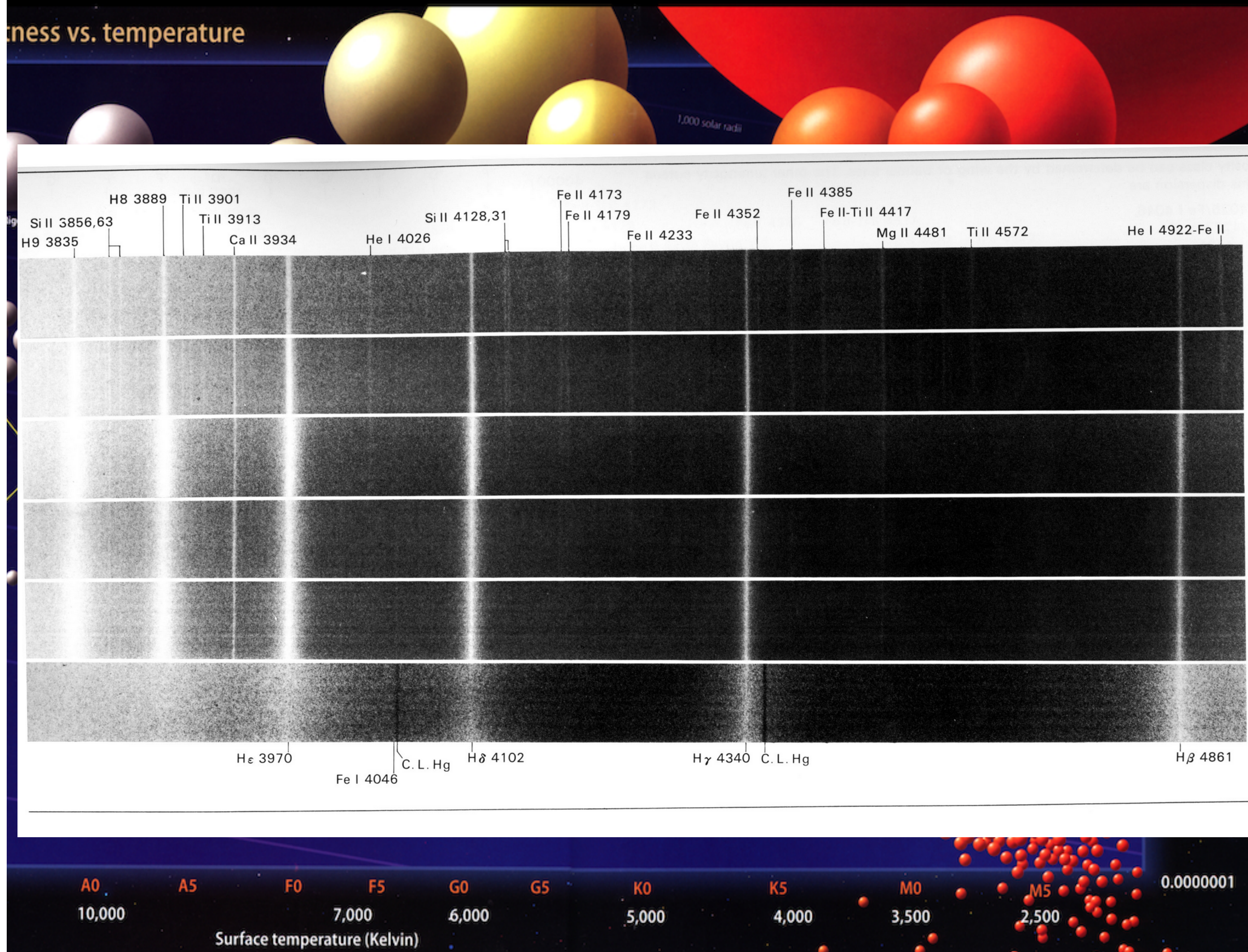


O5
He II
B1
He I
A2
F0
G2
K0
Mg I
Na I
TiO
M0
Ca I
350
450
550
650
750
Wavelength (nm)
Relative intensity



ness vs. temperature
Rigel
Deneb
Canopus
Polaris
Mu Cephei
Betelgeuse
Antares
Capella
Arcturus
Aldebaran
Mira
Gamma Crucis
Pollux
Vega
Castor
Sirius
Fomalhaut
Altair
Procyon
Alpha Centauri
Sun
1,000 solar radii
100 solar radii
10 solar radii
1 solar radius
Lines of constant radius
Giants and supergiants
Main sequence stars
A
F
G
K
M
Sirius B
Barnard's Star
Proxima Centauri
White dwarfs
M stars
10,000
100
1
0.01
0.0001
0.0000001
Luminosity (Suns)
A0
A5
F0
F5
G0
G5
K0
K5
M0
M5
10,000
7,000
6,000
5,000
4,000
3,500
2,500
Surface temperature (Kelvin)


O5
He II
B1
He I
A2
F0
G2
K0
Mg I
Na I
TiO
M0
Ca I
Relative intensity
350
450
550
650
750
Wavelength (nm)


ness vs. temperature
1,000 solar radii
H9 3835
Si II 3856,63
H8 3889
Ti II 3901
Ti II 3913
Ca II 3934
He I 4026
Si II 4128,31
Fe II 4173
Fe II 4179
Fe II 4233
Fe II 4352
Fe II 4385
Fe II-Ti II 4417
Mg II 4481
Ti II 4572
He I 4922-Fe II
Hε 3970
Fe I 4046
C. L. Hg
Hδ 4102
Hγ 4340
C. L. Hg
Hβ 4861
A0
A5
F0
F5
G0
G5
K0
K5
M0
M5
10,000
7,000
6,000
5,000
4,000
3,500
2,500
0.0000001
Surface temperature (Kelvin)


Star brightness vs. temperature
Absolute magnitude (brightness)
-10
-5
0
5
10
15
20
Luminosity (Suns)
10,000
100
1
0.01
0.0001
0.0000001
Zeta Puppis
Beta Centauri
Acrux
Adhara
Mimosa
Shaula
Spica
Achernar
O and B stars
Rigel
Deneb
Canopus
Polaris
Regulus
Vega
Castor
Sirius
Fomalhaut
Altair
Procyon
Alpha Centauri
Sun
Capella
Arcturus
Pollux
Aldebaran
Antares
Betelgeuse
Mu Cephei
Mira
Gamma Crucis
Giants and supergiants
Lines of constant radius
Main sequence stars
1,000 solar radii
100 solar radii
10 solar radii
1 solar radius
0.1 solar radius
0.01 solar radius
O
B
A
F
G
K
M

Make sure to read more!

Suggested article:
"Women Astronomers
at Harvard at the Turn of the Century"
https://www.carleton.edu/goodsell/research/student-research/women/harvard/

...also: come to Torun Observatory ;) :D