Gravitational-wave progenitors

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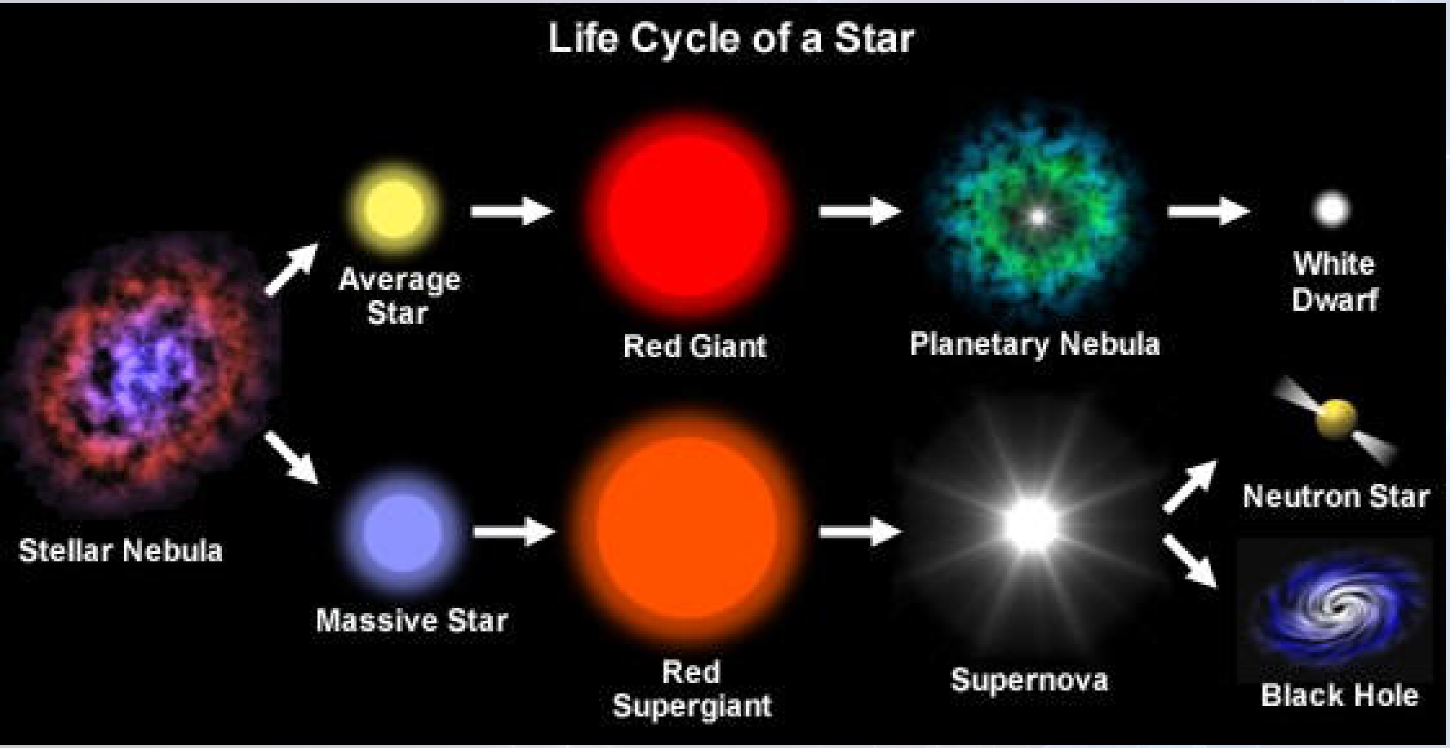
Lecture #14

NCU, Summer Semester 2022

Previously

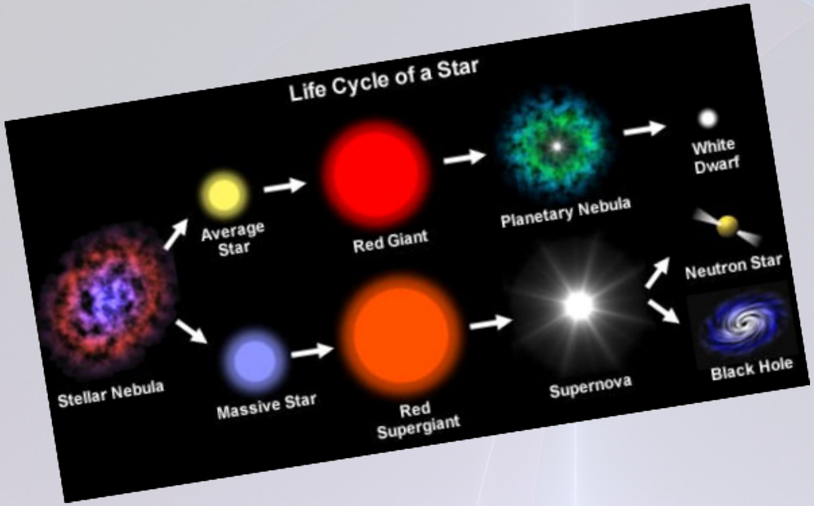
on GW-progenitors...

Stars evolve
→ stellar evolution



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

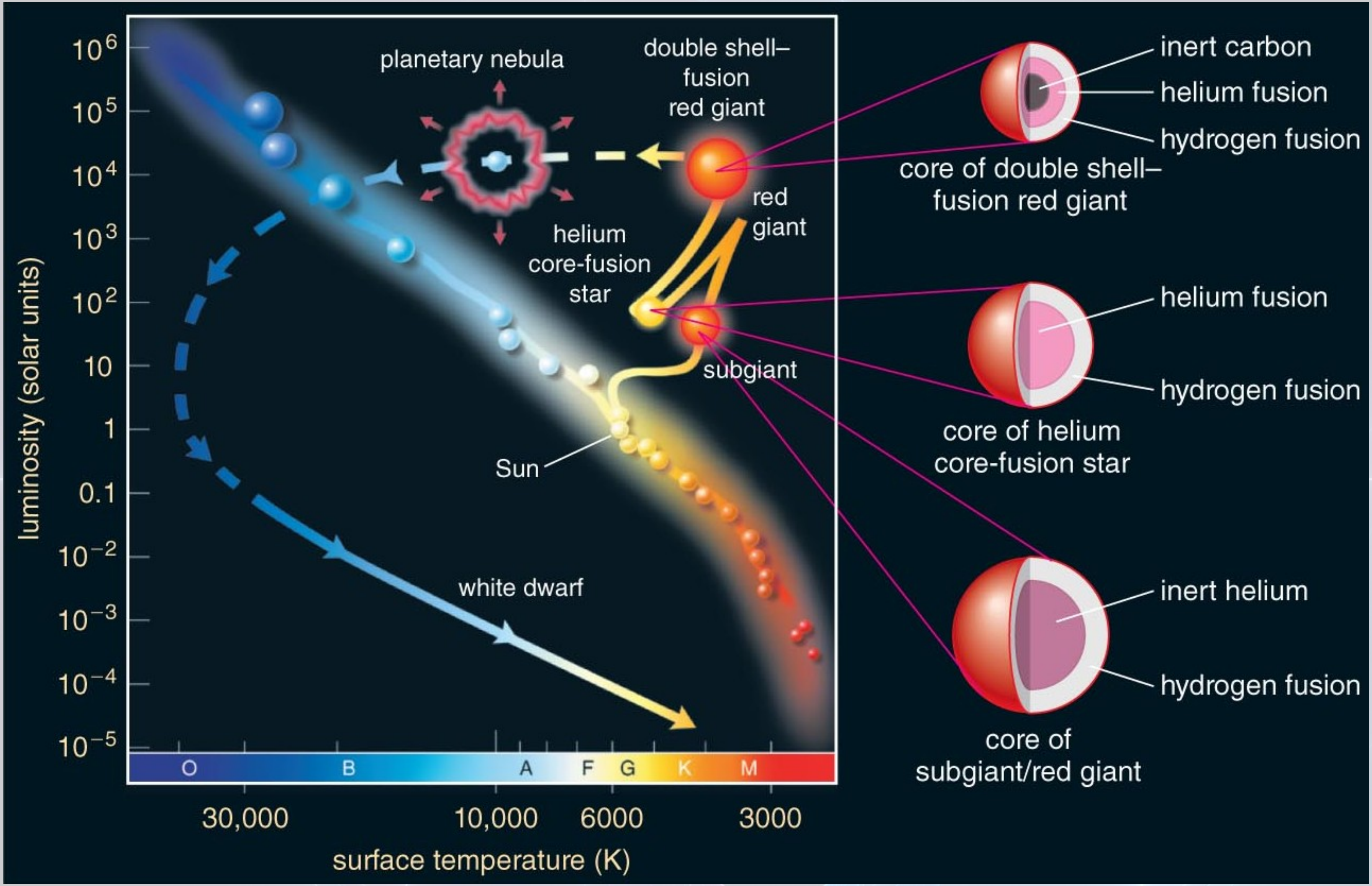
massive: $> 8\ M_\odot$



How to do it more scientifically?

The HRD

Hertzsprung–Russell diagram



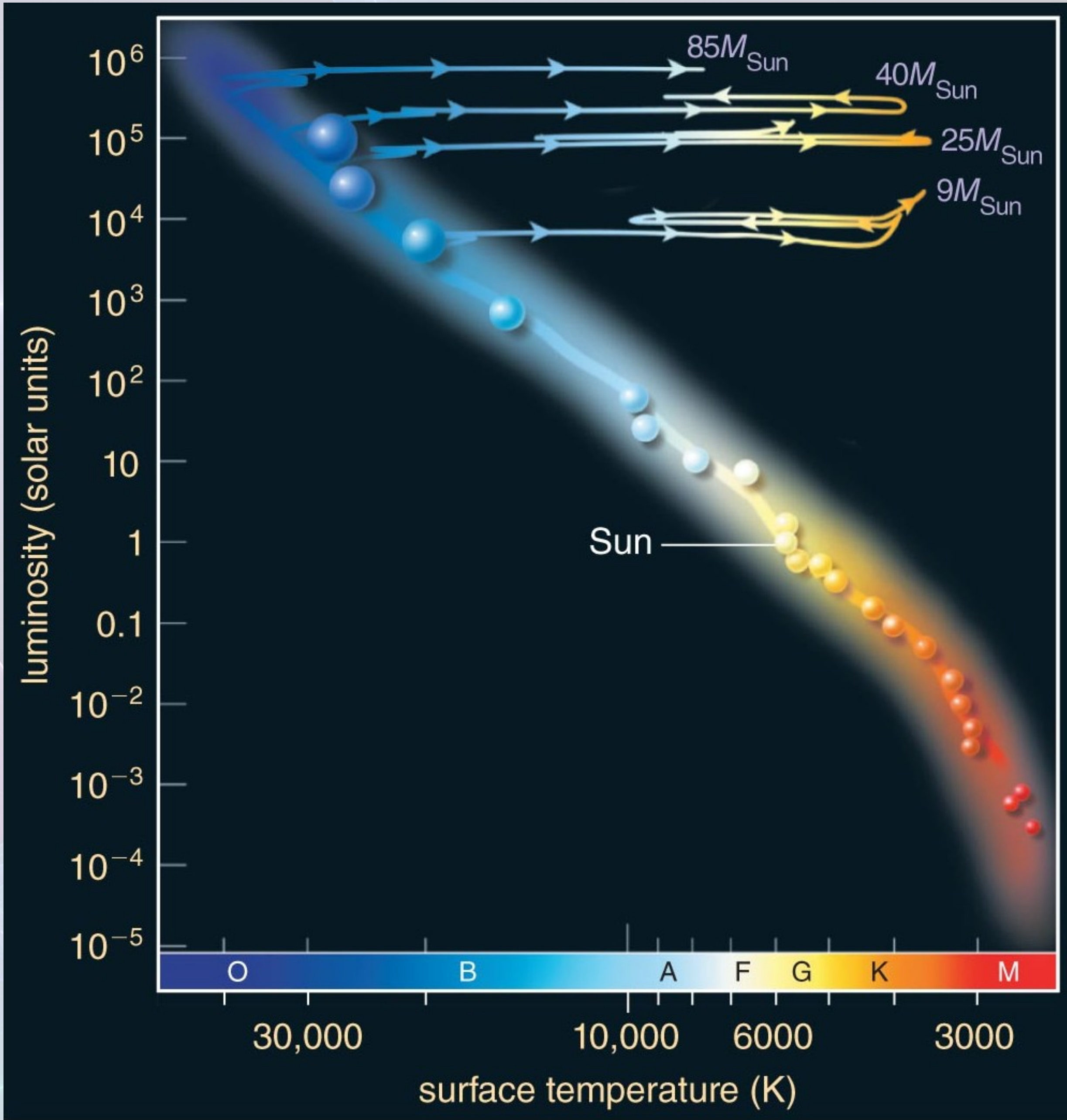
Credit: https://jila.colorado.edu/~ajsh/courses/astr1200_18/starevol.html

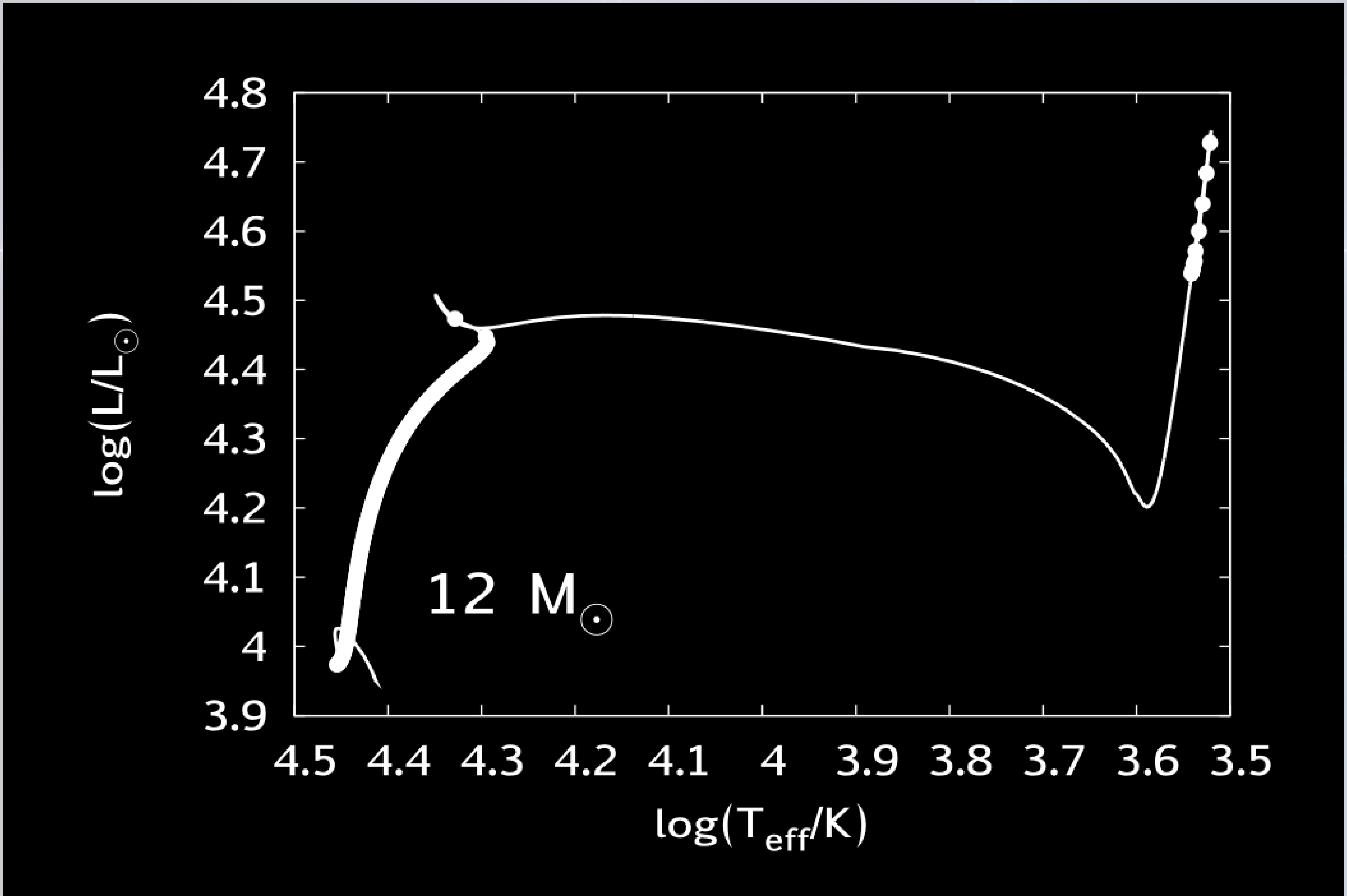
The HRD

Hertzsprung–Russell diagram

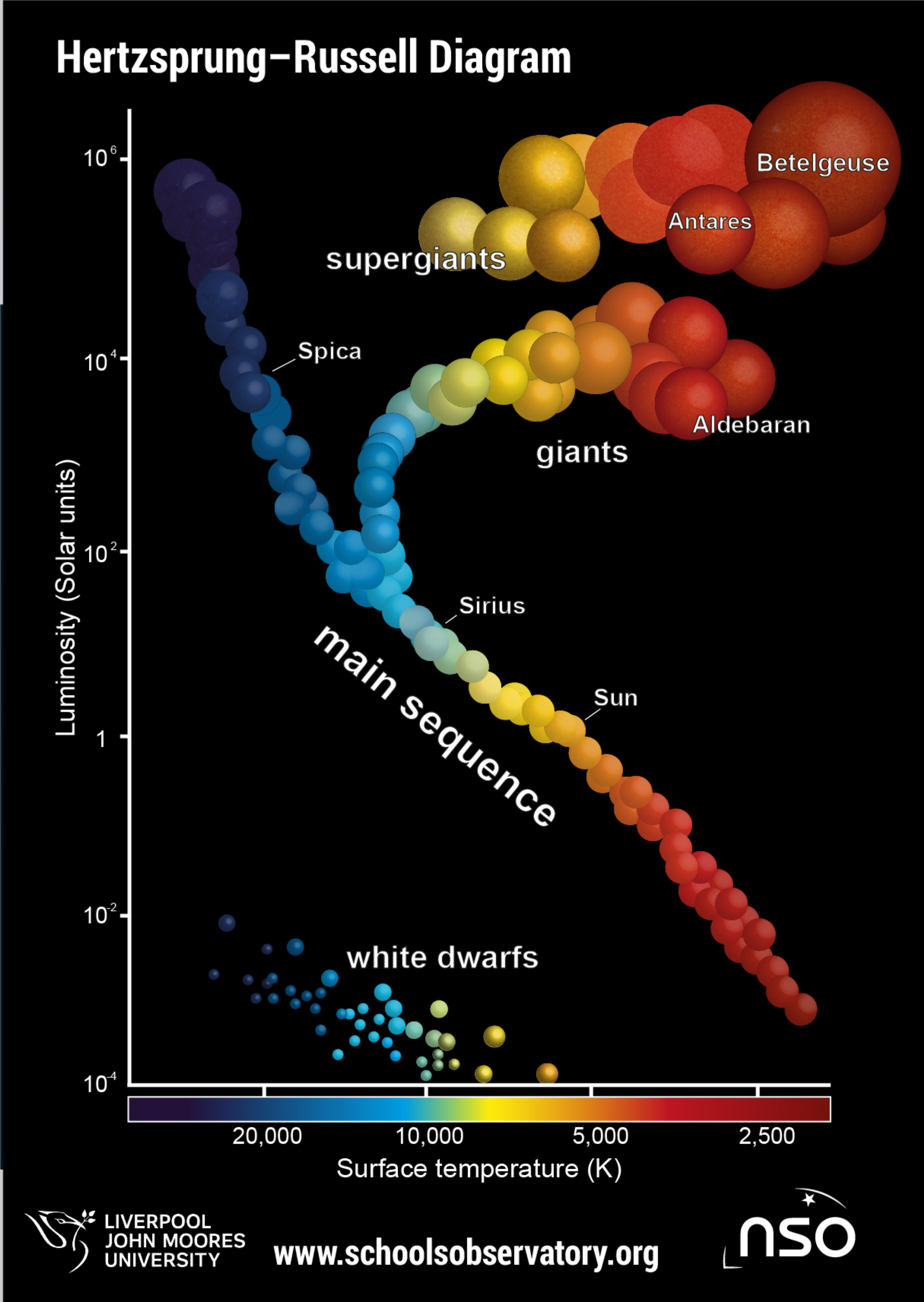
Further advantages of the HRD

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





4.8
4.7
4.6
4.5
4.4
4.3
4.2
4.1
4
3.9
log(L/L⊙)
12 M⊙
4.5
4.4
4.3
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
log(Teff/K)



of the HRD

- radius can be easily read out
  - equiradial lines due to Stephan-Bolzmann law
- color of the star can be easily read out (~surface temp.)
- brightness: ~luminosity

What is a star?

surface?

→ photons escape

"photosphere"

hot, dense plazma

What is inside?

→ ←

theoretical modelling of the stellar structure

equilibrium: pressure gradient gravity

Theoretical modelling of the stellar structure

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

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

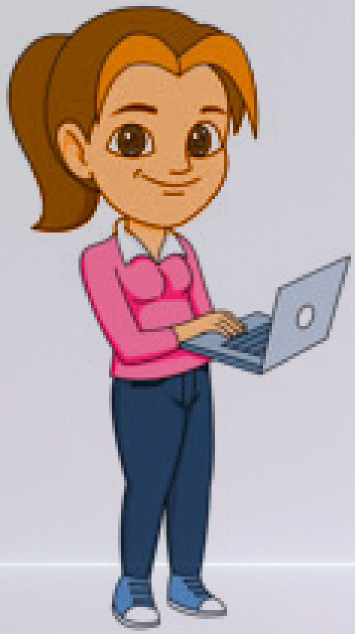
$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla \qquad (4)$$

transport of energy

Guilera+ 11

composition change due to nuclear burning:

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



Where to start:

https://docs.mesastar.org/en/latest/index.html

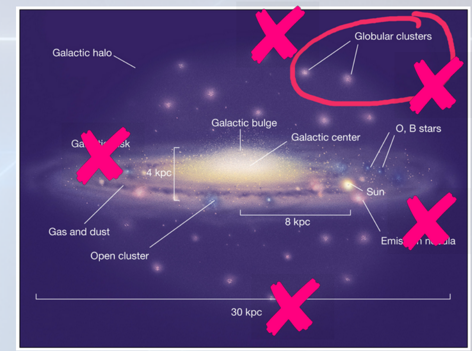
https://cococubed.com/mesa_market/education.html

Where can we find stars*

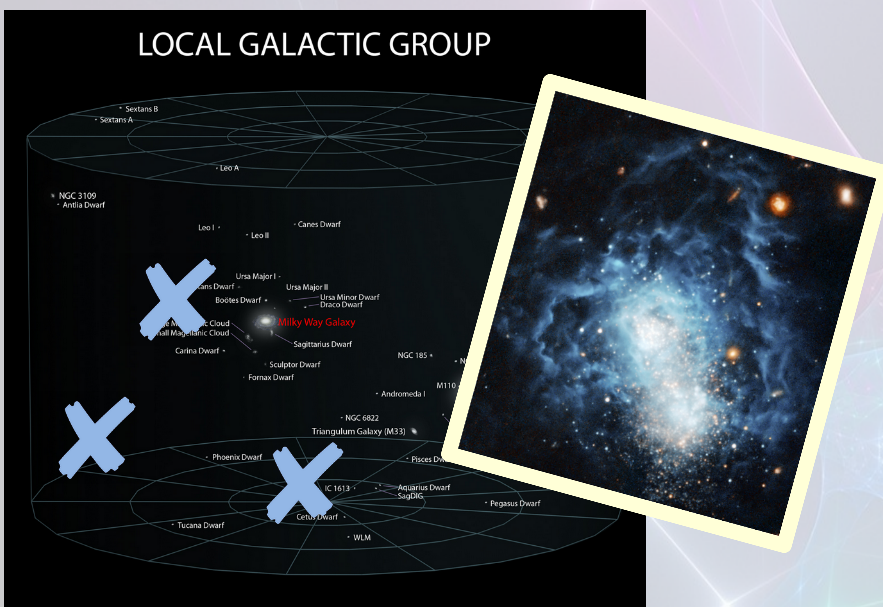
*gas/galaxies/anything: "*environments*"

with sub-Solar Z?

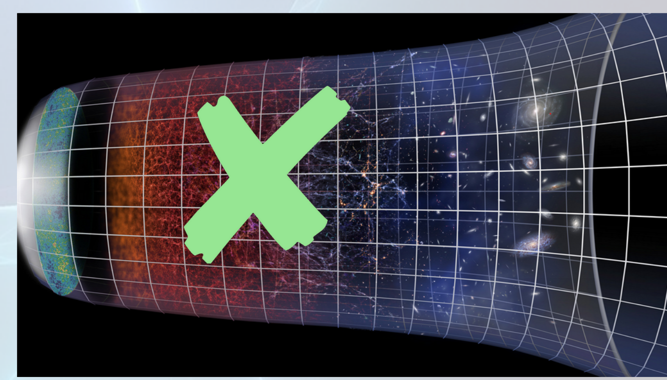
Globular clusters



Dwarf galaxies



Early Universe



The winds of *massive* stars are… strong.

$10^{-7} – 10^{-3}\ M_{\odot}/yr$

→

loss of 10-70% of material over lifetime…

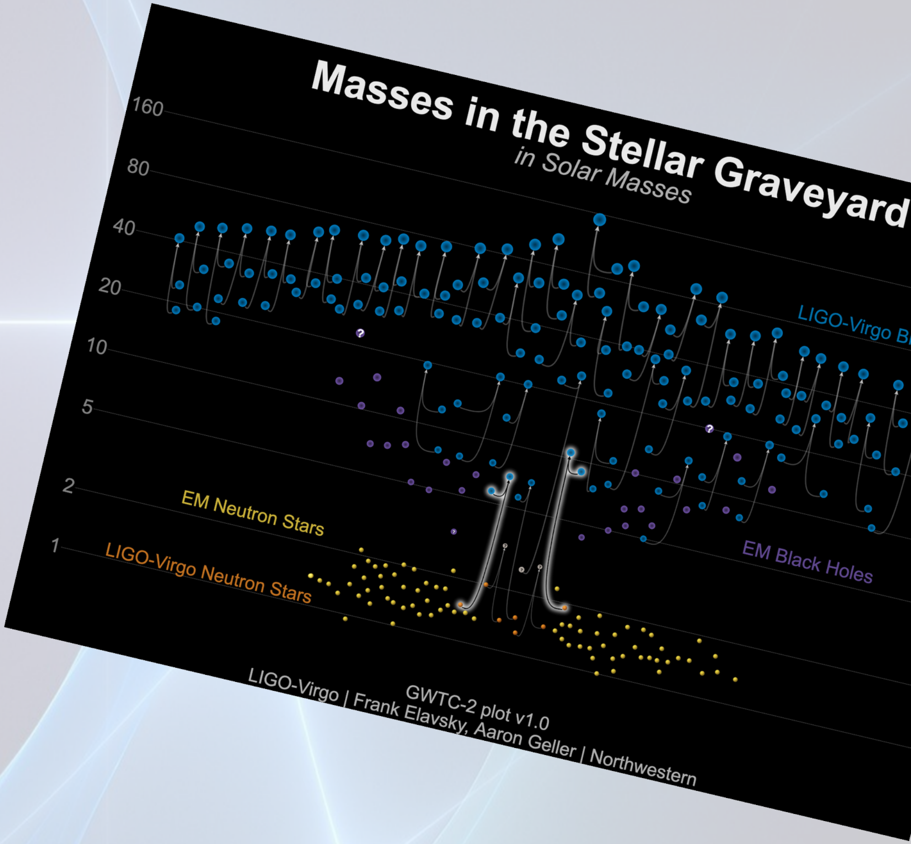
(Sun: $\sim 10^{-14}\ M_{\odot}/yr$)

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

To form a 60 $M_\odot$ black hole…

- start with a very-very massive star*

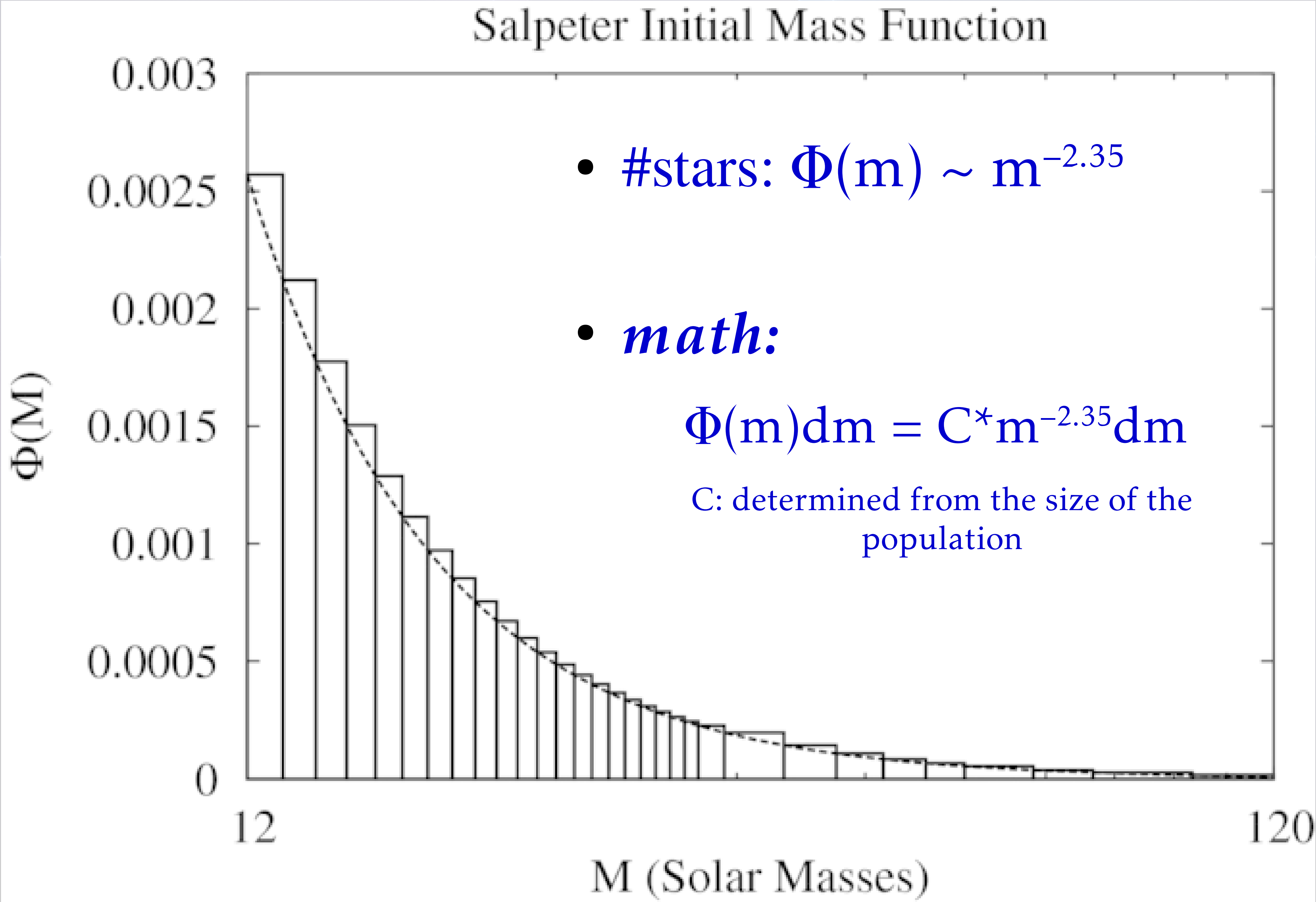
*later
(IMF, mass limits…)



or

- decrease the strength of the wind somehow?

The Initial Mass Function (IMF)



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

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

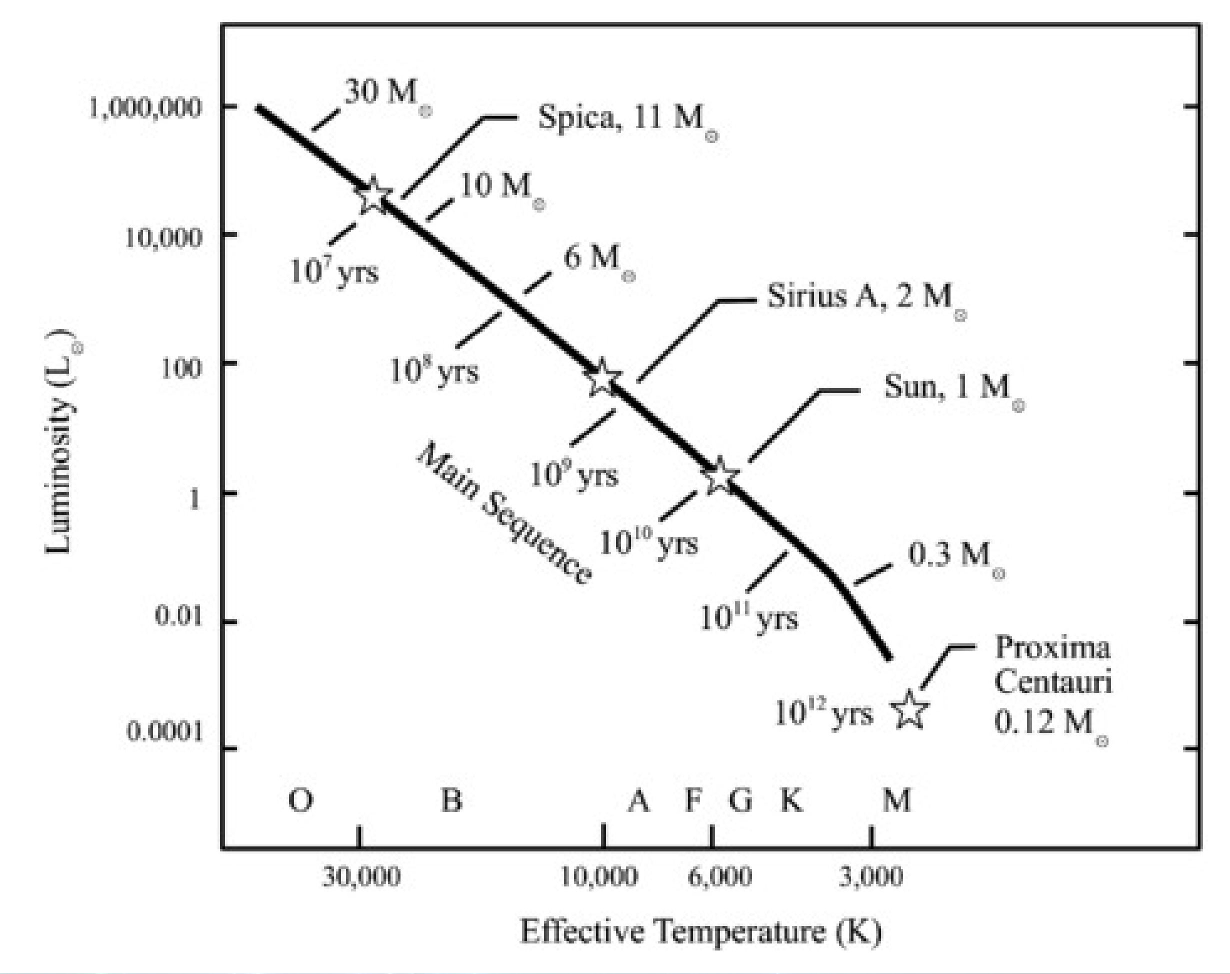
C: determined from the size of the population

Lifetime of stars

- $\tau(m) \sim m^{-2.5}$
  - Sun's lifetime: $\sim 10*10^9$ yrs
  - an 8 $M_\odot$ star's lifetime: $\sim 5*10^7$ yrs
  - a 100 $M_\odot$ star's lifetime: $\sim 2*10^6$ yrs

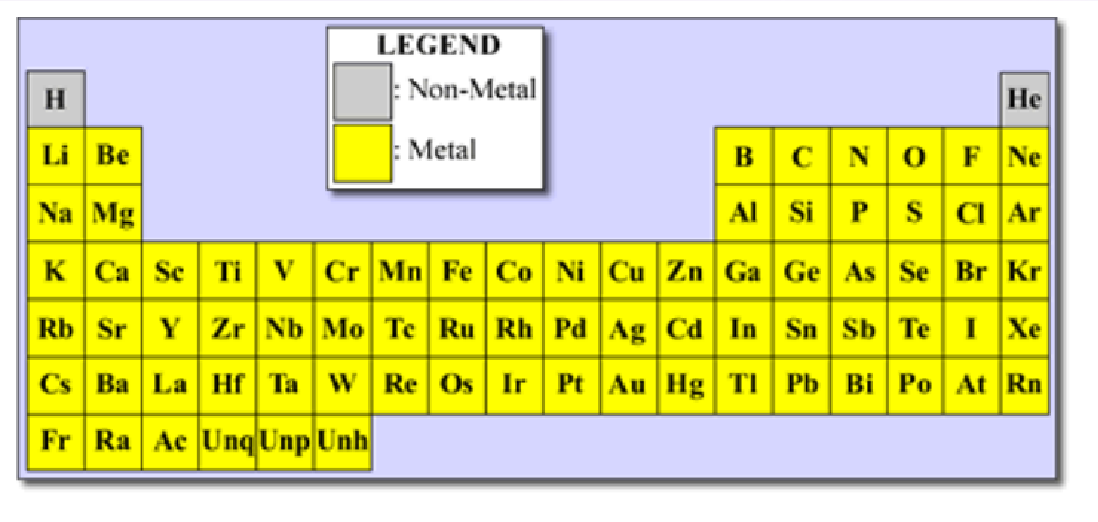
Stars of higher mass are more luminous. They burn their fuel at a faster rate.

→ shorter lifetimes

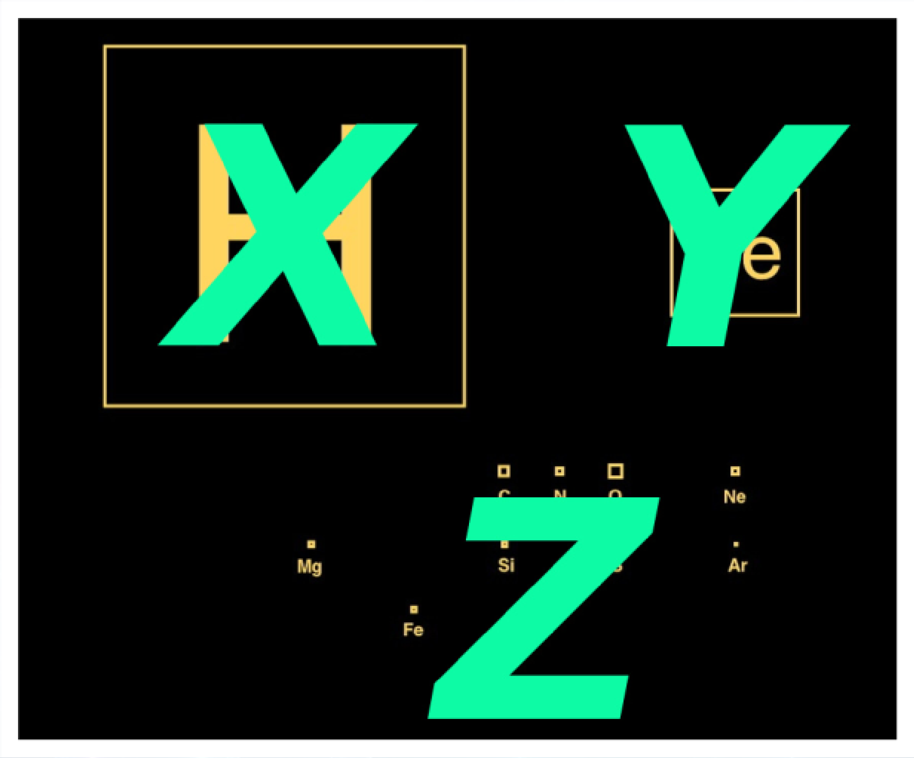


Credit: ase.tufts.edu/cosmos

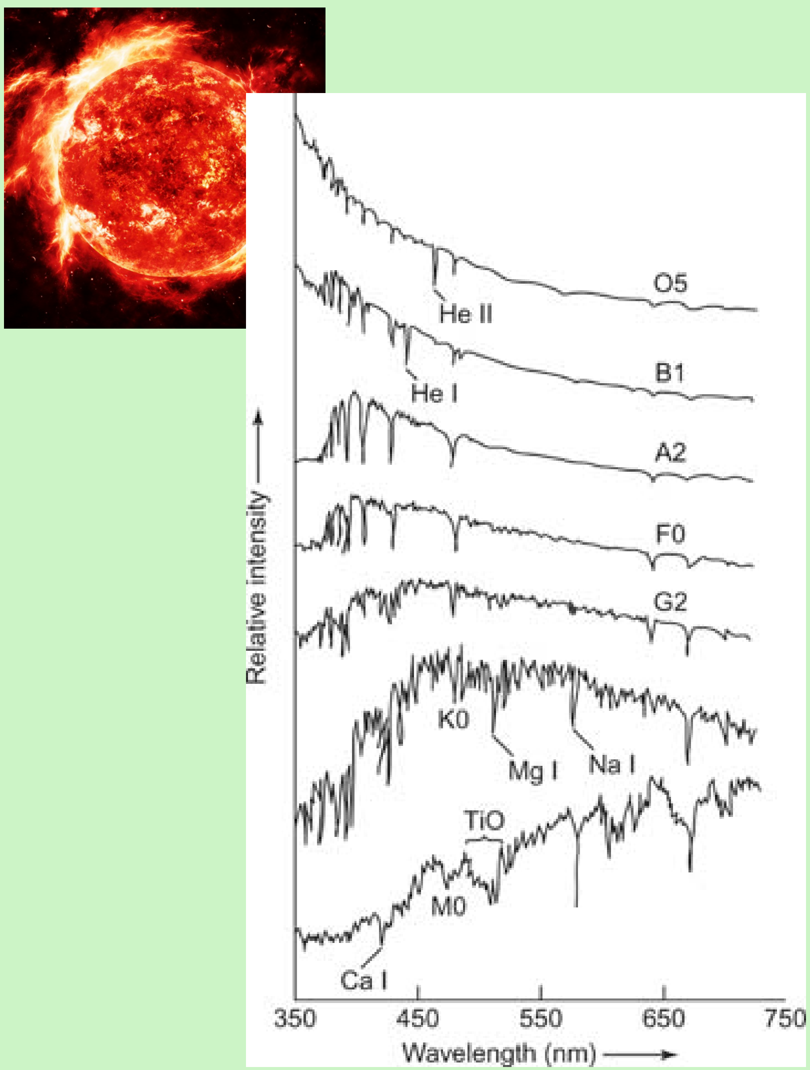
Astronomers and metal

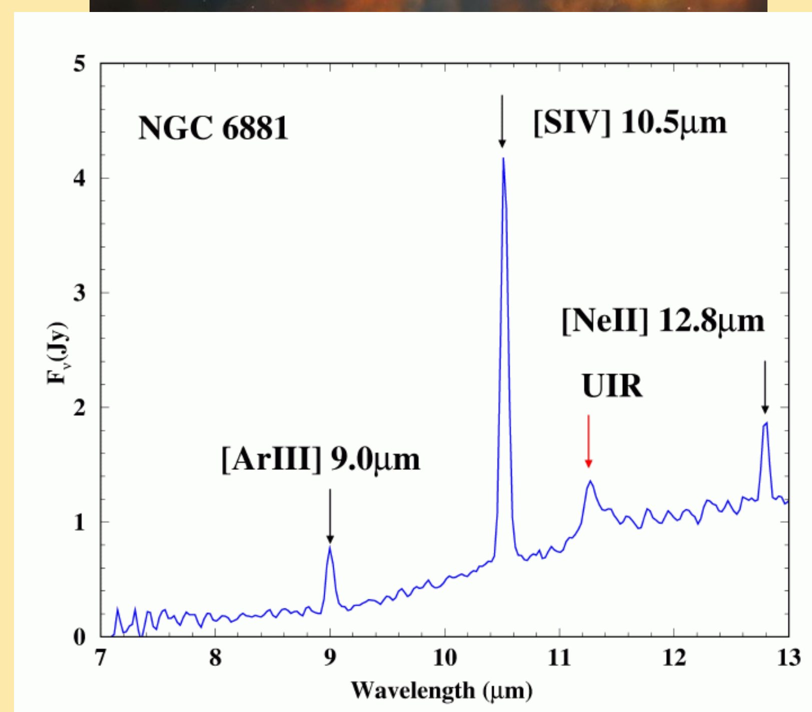


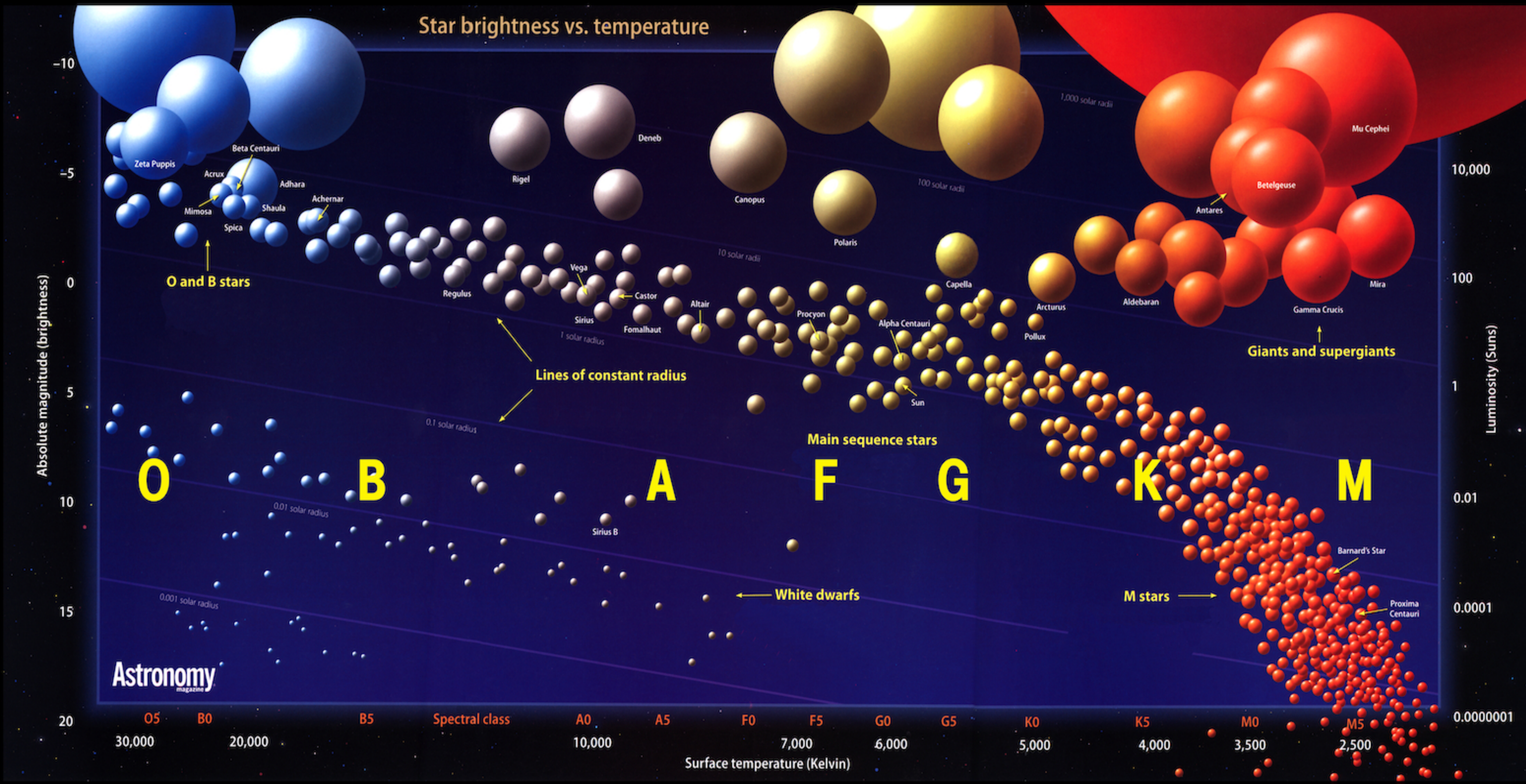
"Z: metallicity"



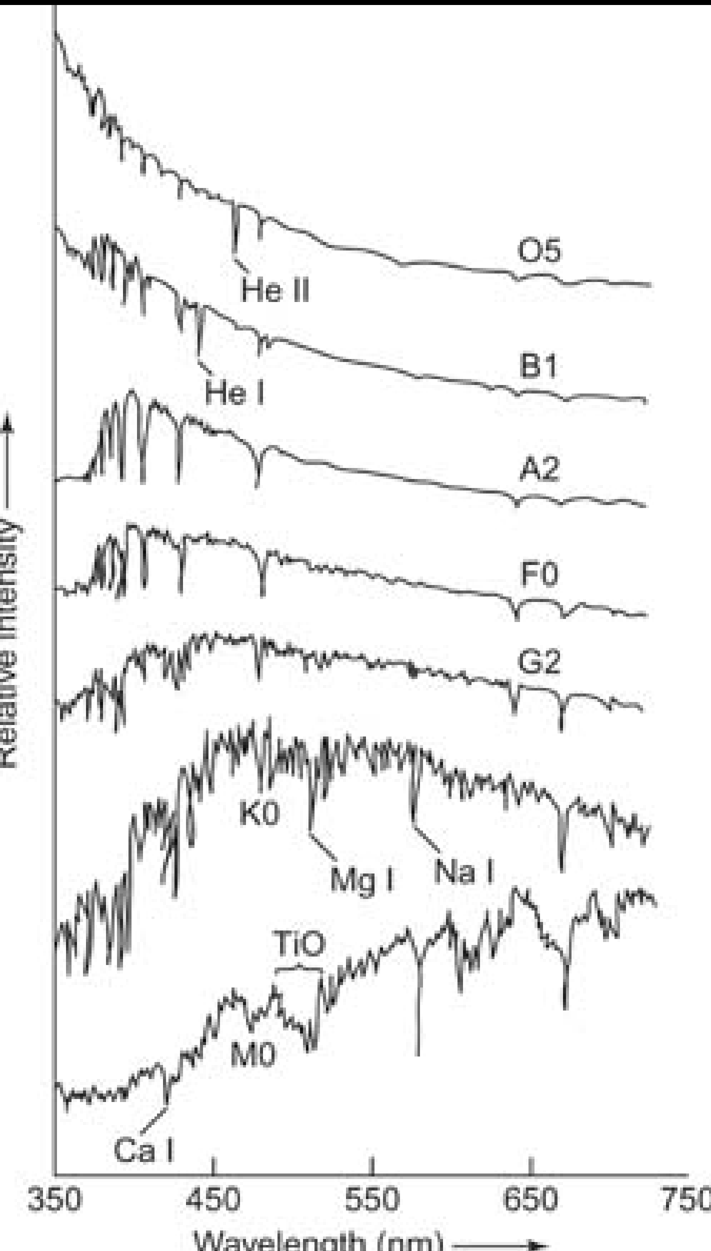
- Stellar spectra
  - absorption lines (mostly)
- Nebular spectra
  - emission lines (a light source needed for the excitation)



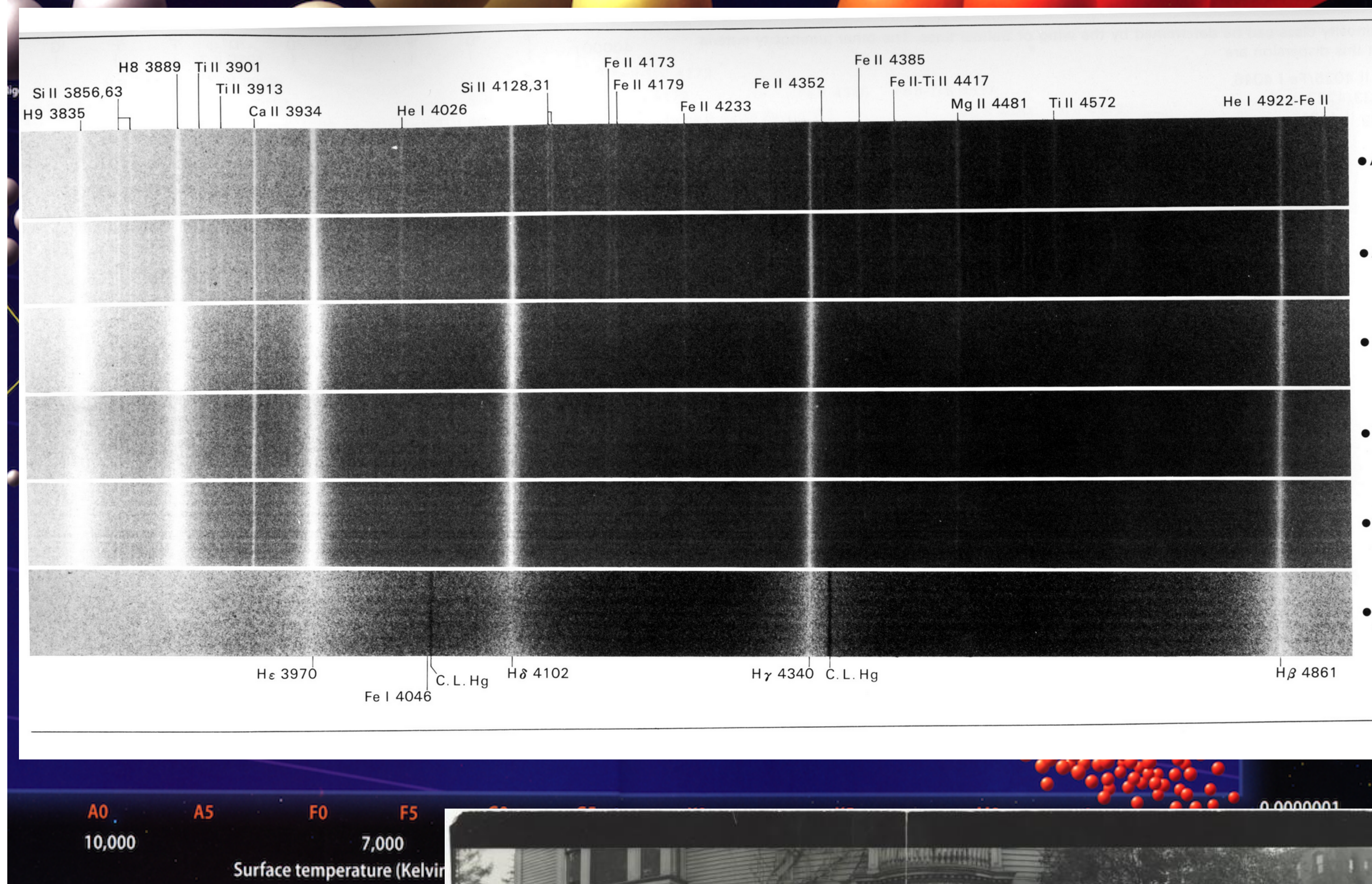




Star brightness vs. temperature
Absolute magnitude (brightness)
–10
–5
0
5
10
15
20
Luminosity (Suns)
10,000
100
1
0.01
0.0001
0.0000001
Zeta Puppis
Beta Centauri
Acrux
Adhara
Mimosa
Shaula
Spica
Achernar
O and B stars
Rigel
Deneb
Canopus
Polaris
Regulus
Vega
Castor
Sirius
Fomalhaut
Altair
Procyon
Alpha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


Relative Intensity
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)


ness vs. temperature


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
10,000
7,000
Surface temperature (Kelvin

Planck law

$$B(\nu, T_{eff}) = \frac{2h}{c^2} \frac{\nu^3}{e^{\frac{h\nu}{k_B T_{eff}}} - 1} \qquad (3)$$

here: as a function of frequency
(works with wavelength as well)

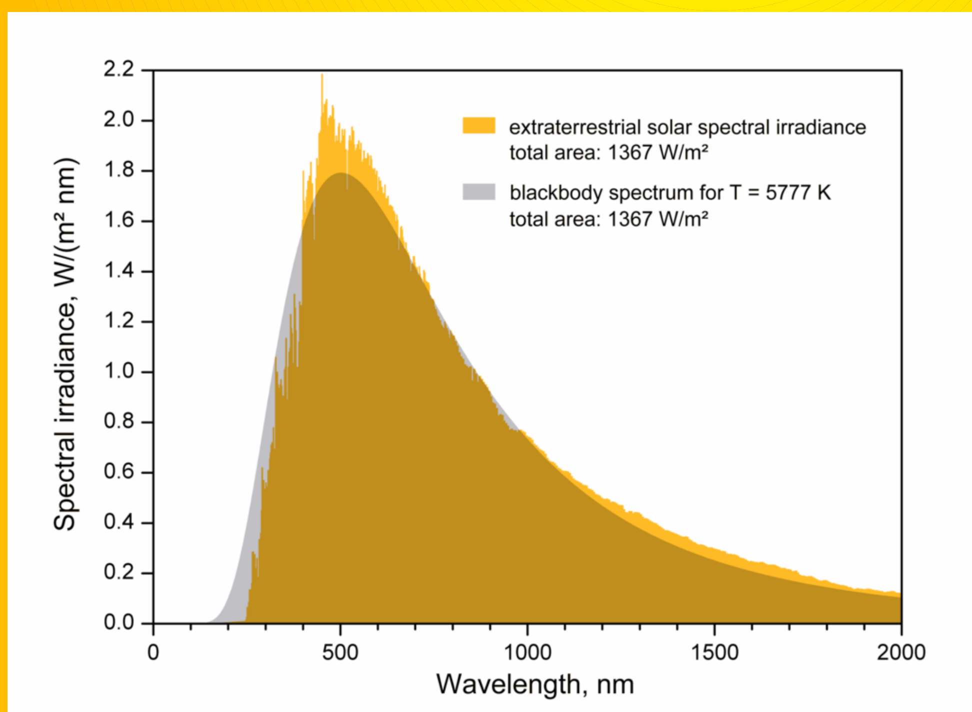
Note: there is a T value in it!

Moral of the story:

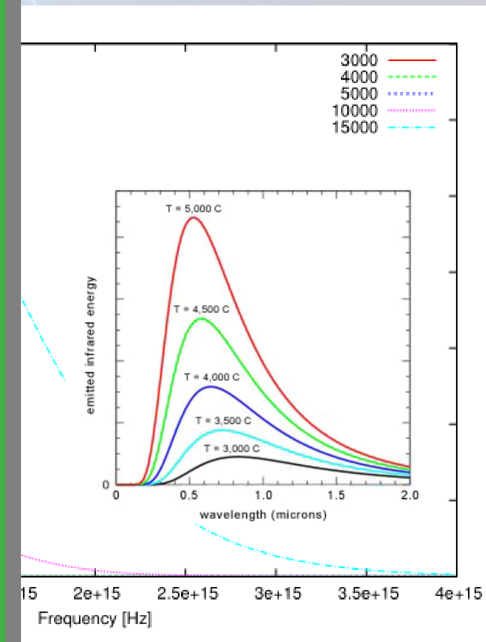
Stars are perfect Black Bodies.

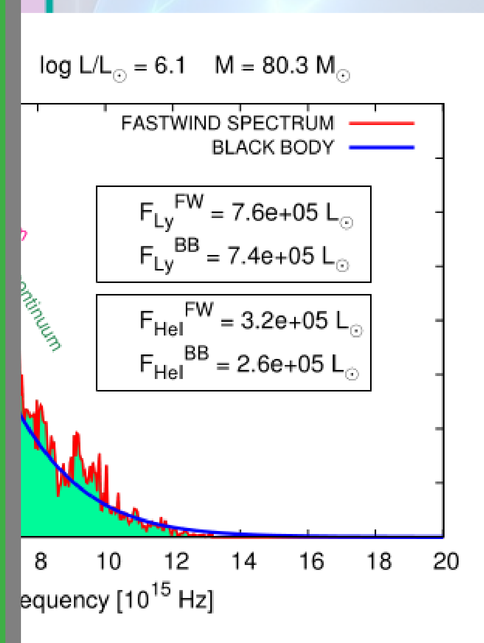
(Most of the time, more or less; but basically they are.)

Their T_{eff} in the HRD is the T_{eff} from the Planck law.

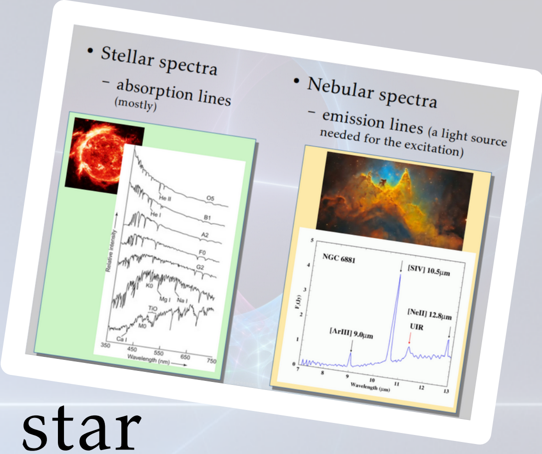


T_{eff}

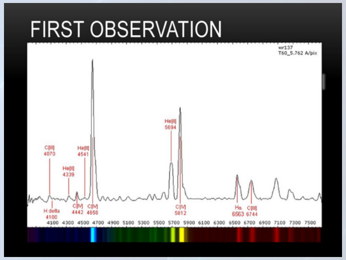




Side-notes on Wolf-Rayet stars



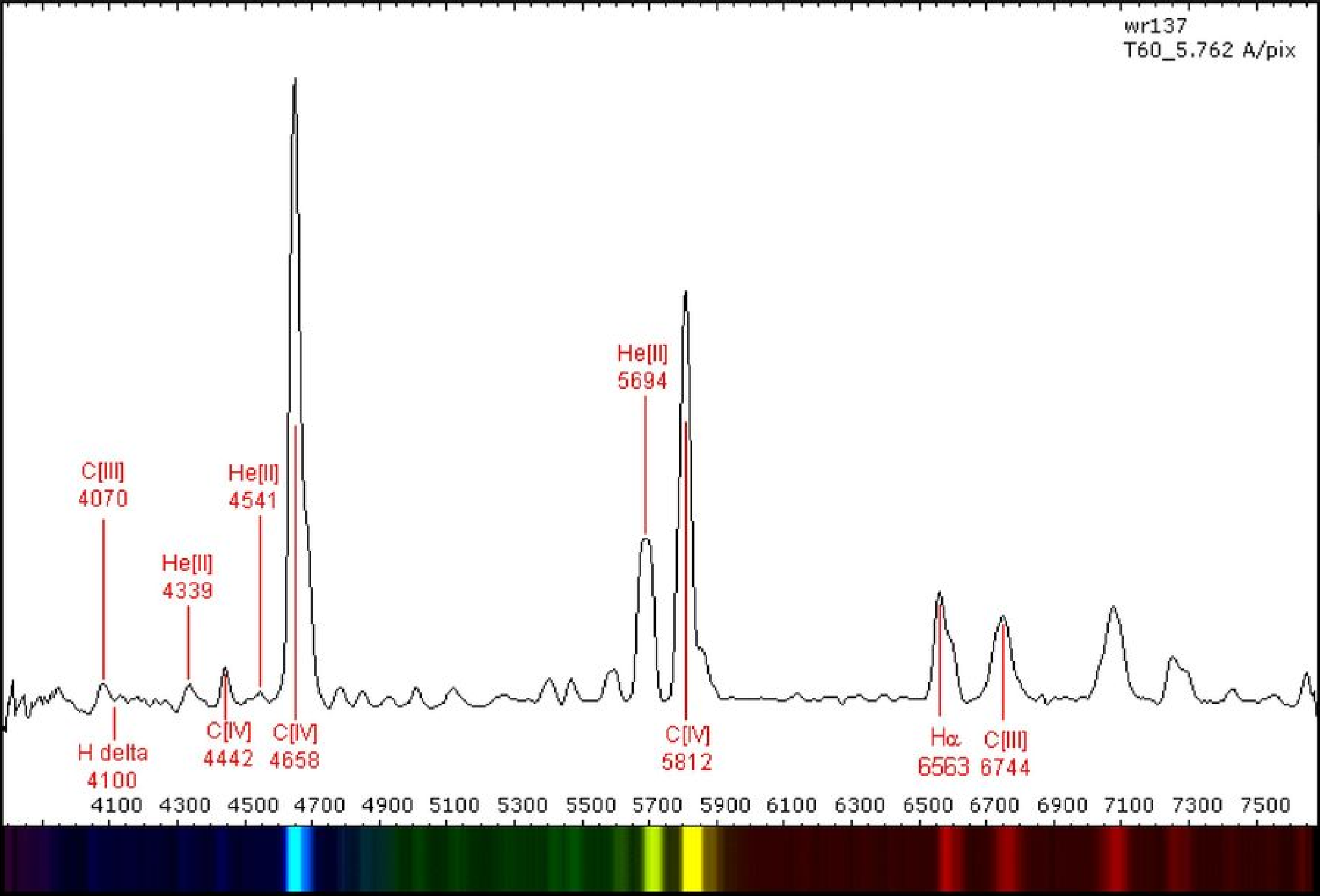
- Observationally:
  - broad emission lines in the spectrum
  - meaning there is a nebula around the star
  - composition: (usually) H-free

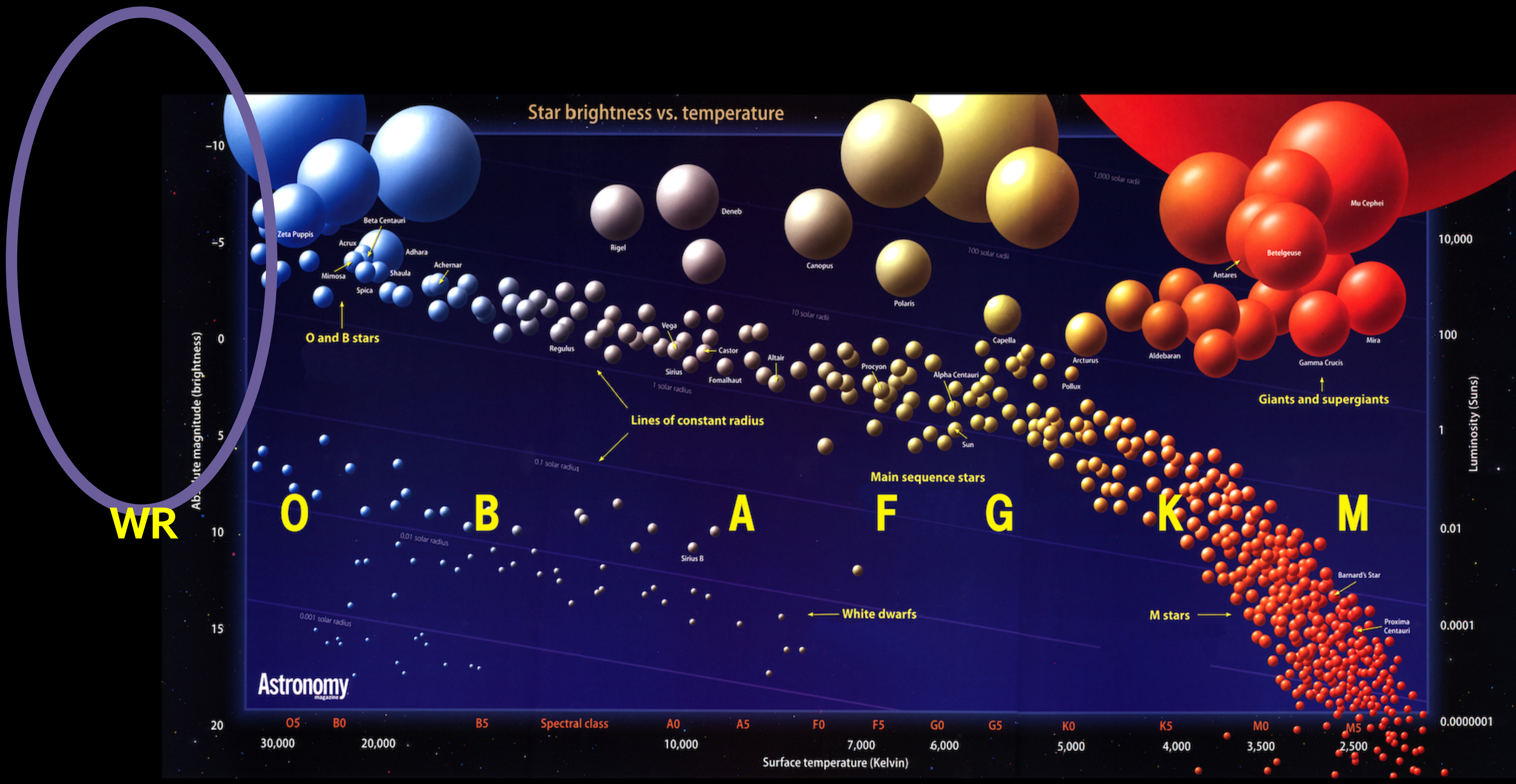


- Theoretically:
  - a H-free star with a nebula around it can be produced by:
    - strong wind (single & binary stars) when the mass is very high (> 40 $M_\odot$, but highly Z-dependent!)
    - binary interaction (needs a close-enough companion & a so-called non-conservative mass transfer, etc.)

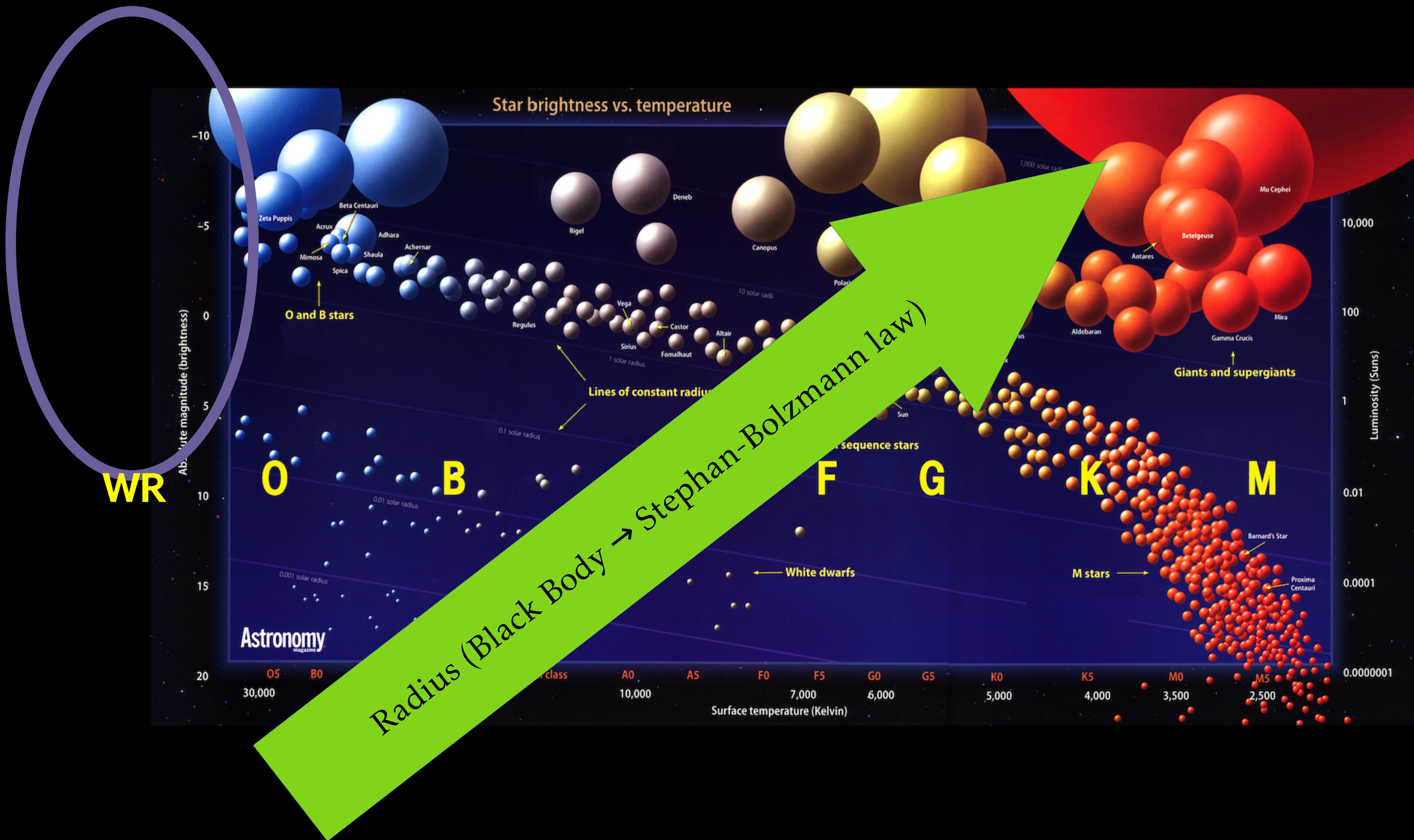
FIRST OBSERVATION

1867: Wolf & Rayet



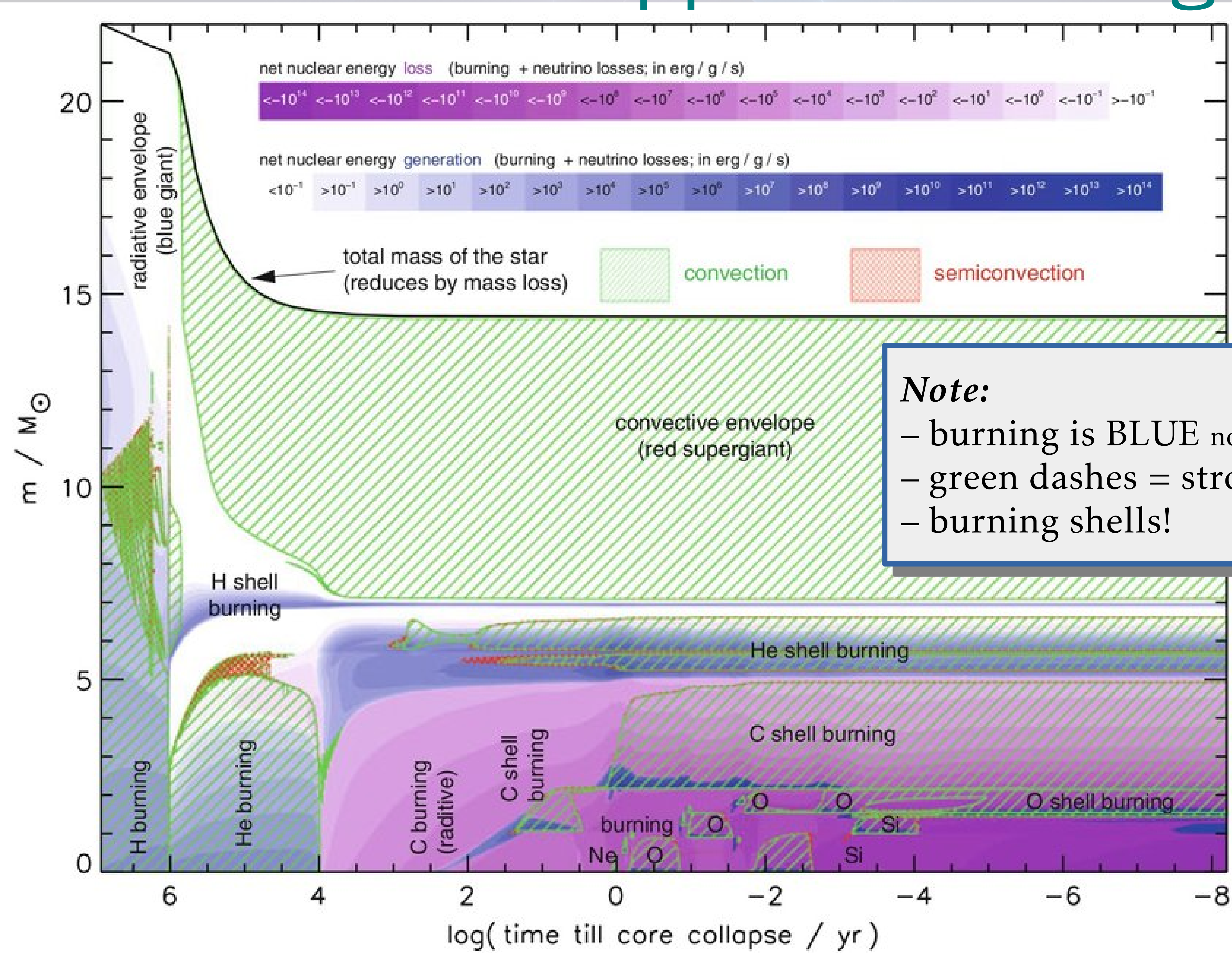


Star brightness vs. temperature
WR
O
B
A
F
G
K
M
O and B stars
Lines of constant radius
Main sequence stars
Giants and supergiants
White dwarfs
M stars
Absolute magnitude (brightness)
Luminosity (Suns)
Spectral class
Surface temperature (Kelvin)
Zeta Puppis
Beta Centauri
Acrux
Adhara
Mimosa
Shaula
Spica
Achernar
Rigel
Deneb
Canopus
Polaris
Regulus
Vega
Sirius
Castor
Fomalhaut
Altair
Procyon
Alpha Centauri
Sun
Capella
Arcturus
Pollux
Aldebaran
Antares
Betelgeuse
Mu Cephei
Gamma Crucis
Mira
Sirius B
Barnard's Star
Proxima Centauri
Astronomy



Star brightness vs. temperature
WR
Radius (Black Body → Stephan-Bolzmann law)
O
B
F
G
K
M
O and B stars
Zeta Puppis
Beta Centauri
Acrux
Adhara
Mimosa
Shaula
Spica
Achernar
Rigel
Deneb
Canopus
Regulus
Vega
Sirius
Castor
Fomalhaut
Altair
Sun
Mu Cephei
Betelgeuse
Antares
Aldebaran
Mira
Gamma Crucis
Giants and supergiants
Lines of constant radiu
sequence stars
White dwarfs
M stars
Barnard's Star
Proxima Centauri
Astronomy
Surface temperature (Kelvin)
Luminosity (Suns)
Absolute magnitude (brightness)
-10
-5
0
5
10
15
20
10,000
100
1
0.01
0.0001
0.0000001
O5
B0
A0
A5
F0
F5
G0
G5
K0
K5
M0
M5
30,000
10,000
7,000
6,000
5,000
4,000
3,500
2,500

Kippenhahn diagram

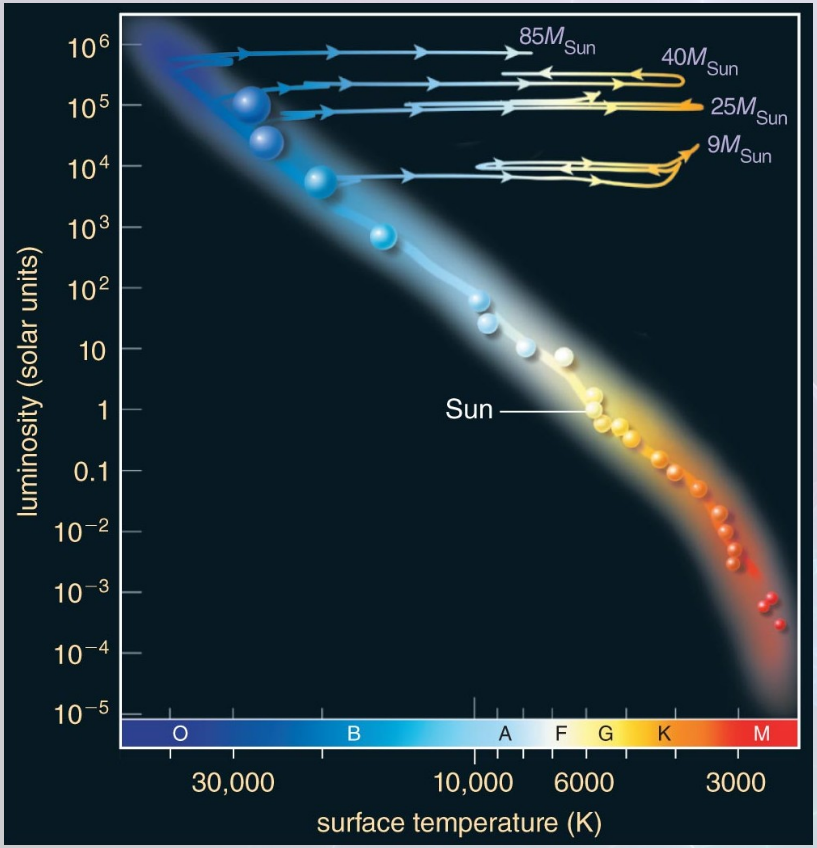


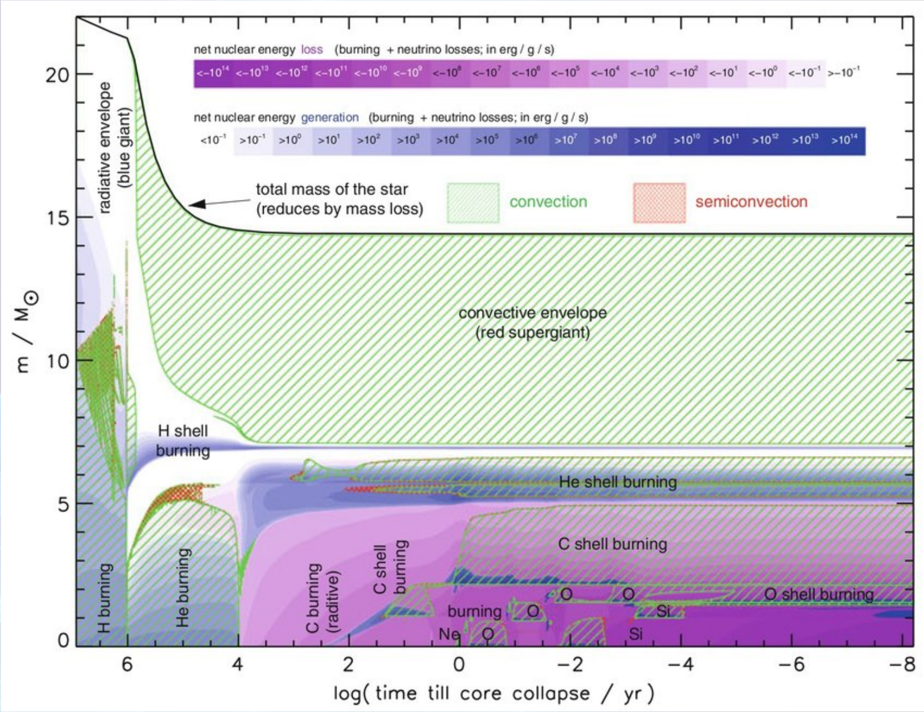
Note:
– burning is BLUE not green/purple
– green dashes = strong mixing
– burning shells!

Credit: Braithwaite & Spruit (2015)

HRD vs. Kippenhahn

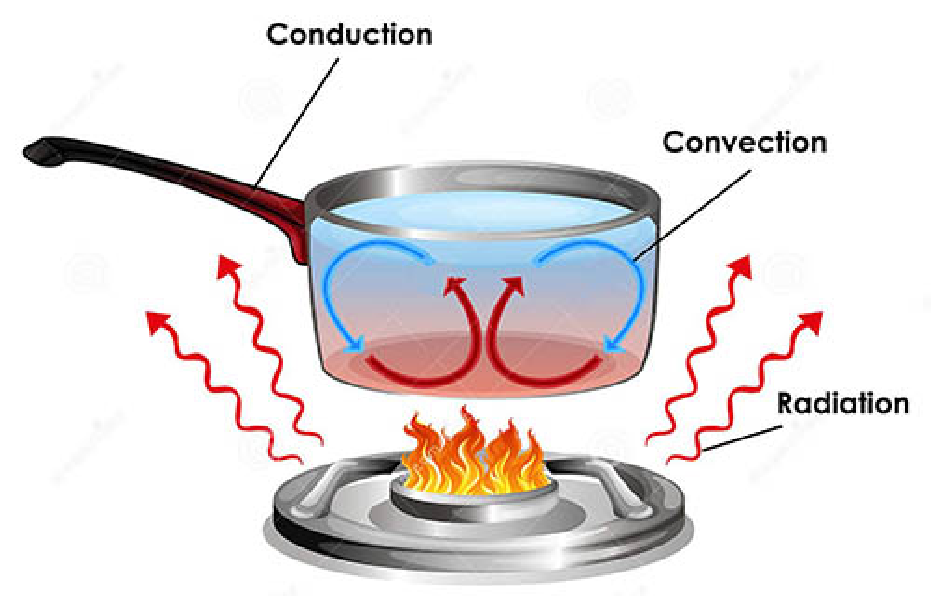
- surface T, L
  - helps observational comparison
- interior structure
  - e.g. pre-supernova structure, mixing…

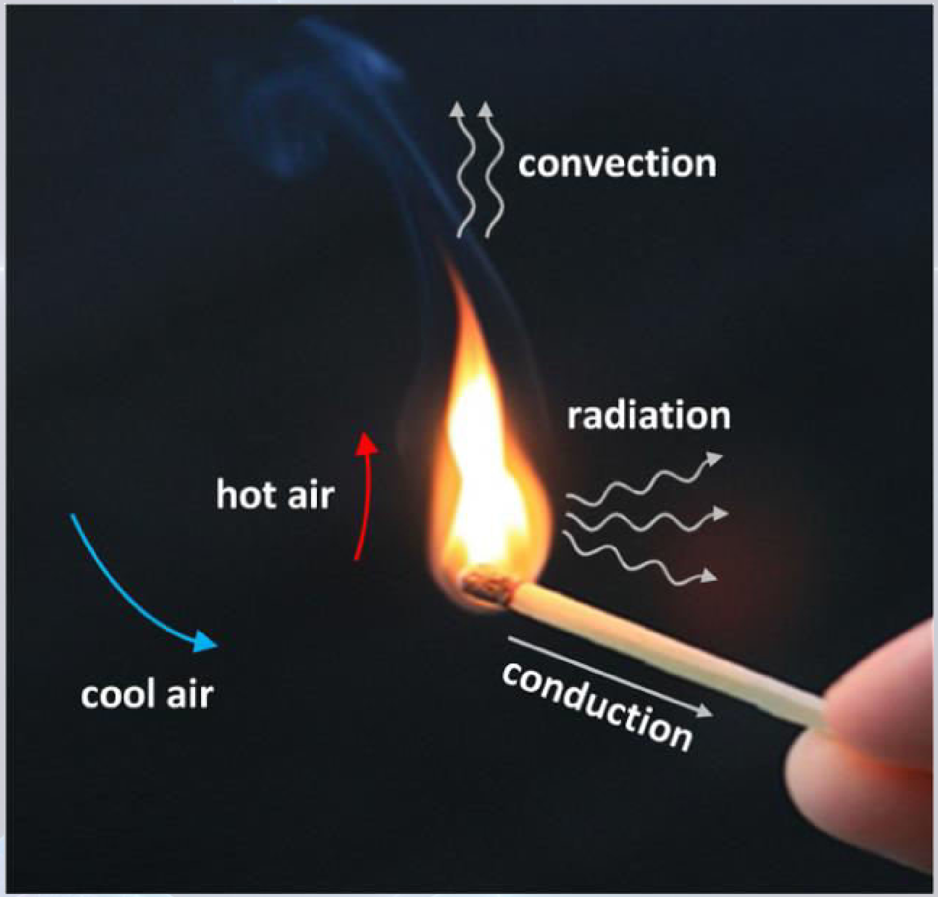




Some words about convection

and about ***heat transfer*** in general





– convection arises wherever heat needs to be transported extra efficiently
e.g. burning core of massive stars, envelope of (super)giants and low-mass stars…
– leads to strong mixing (cf. boiling soup)

Some ection

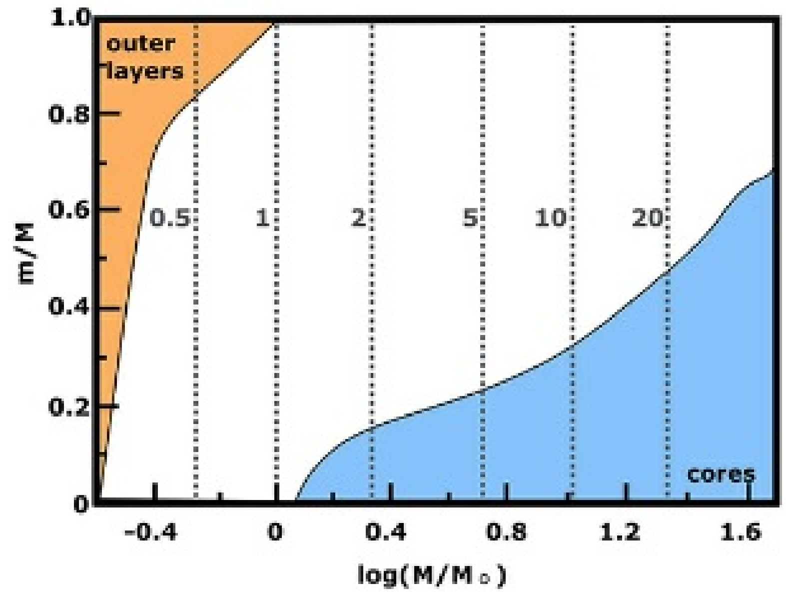
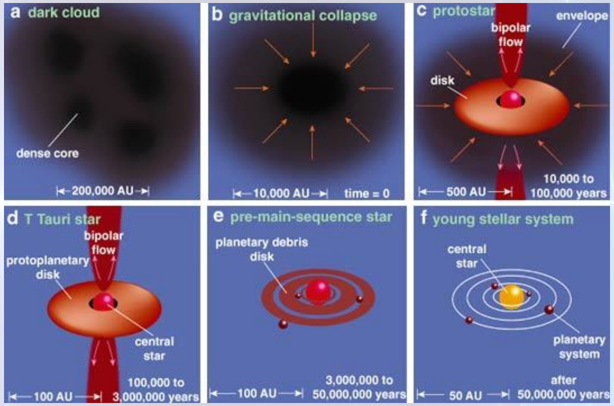


Figure 7.6. Occurrence of convection in stars at the beginning of the core H-fusion phase (ZAMS). The mass of convective envelopes (orange) and convective cores (blue) is expressed as a fraction of the stellar mass, from $m/M = 0$ in the core to $m/M = 1$ at the surface. The vertical lines indicate the stel-

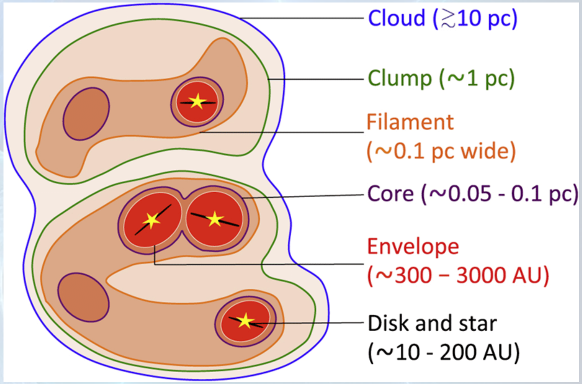
– convection arises wherever heat needs to be transported extra efficiently
e.g. burning core of massive stars, envelope of (super)giants and low-mass stars…
– leads to strong mixing (cf. boiling soup)

Star-formation (of massive stars)

- under active research
- low-mass stars:



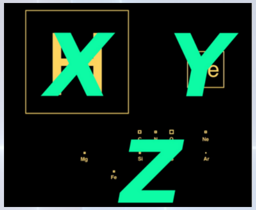
- massive stars?
  - strong radiation may blow away the material
  - hierarchical star formation?



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

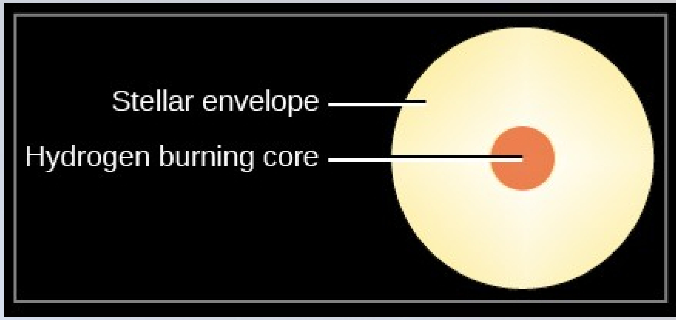


$Z_\odot \sim 0.014$ (<2%)
$Z_{\rm LMC} \sim 0.004$
$Z_{\rm SMC} \sim 0.002$
$Z_{\rm GCs} \sim <0.005$
$Z_{\rm PopIII} = 0$

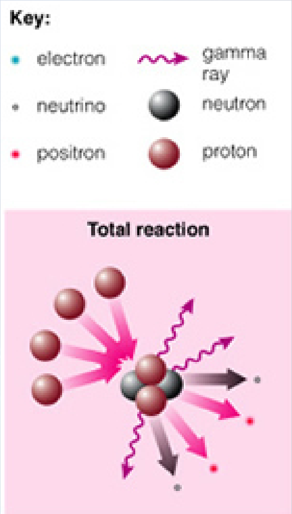
- hydrogen burning starts (in the core)
- hydrostatic & thermodynamic equilibrium
  - no bipolar outflows etc.
  - stellar structure equations hold*

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

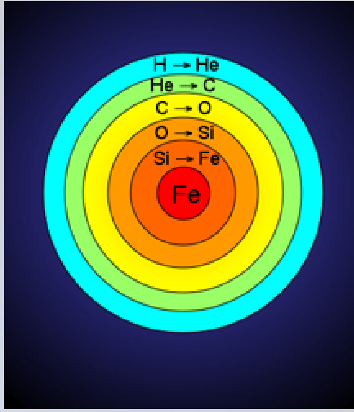
Longest phase of stellar evolution: MS



- 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)



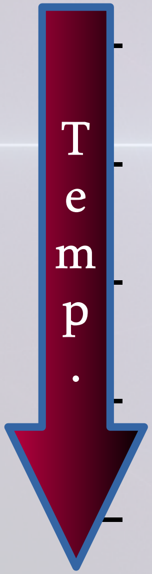
Post-MS
Pre-supernova structure



For a 25 solar mass star:

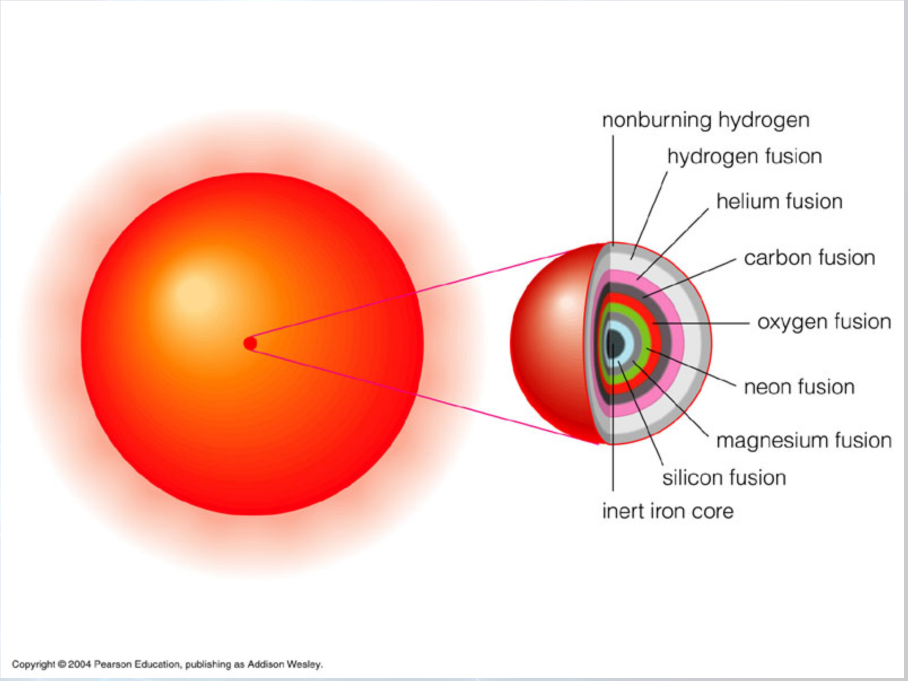
Stage	Duration
H → He	7x10^6 years
He → C	7x10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

- Includes:

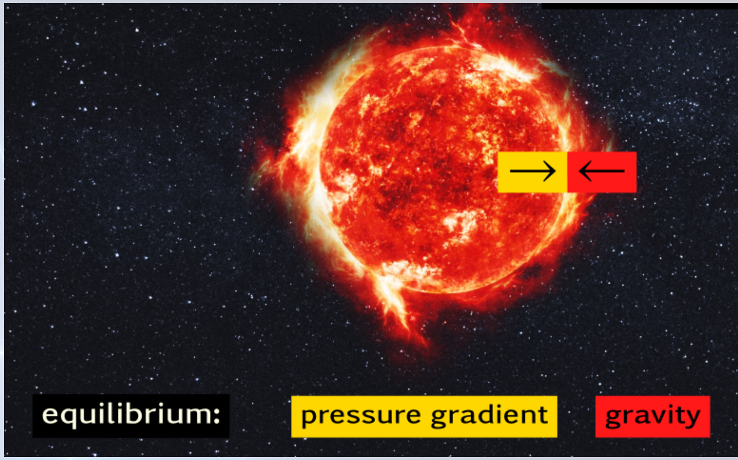


  - core-He-burning (& shell-H-burning)
  - core-C-burning (& shell-He & shell-H-burning)
  - core-O-burning (& shell-C, shell-He, shell-H…
  - core-Ne-burning (& shell…
  - core-Si-burning (& shell...
- onion-structure of massive stars

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

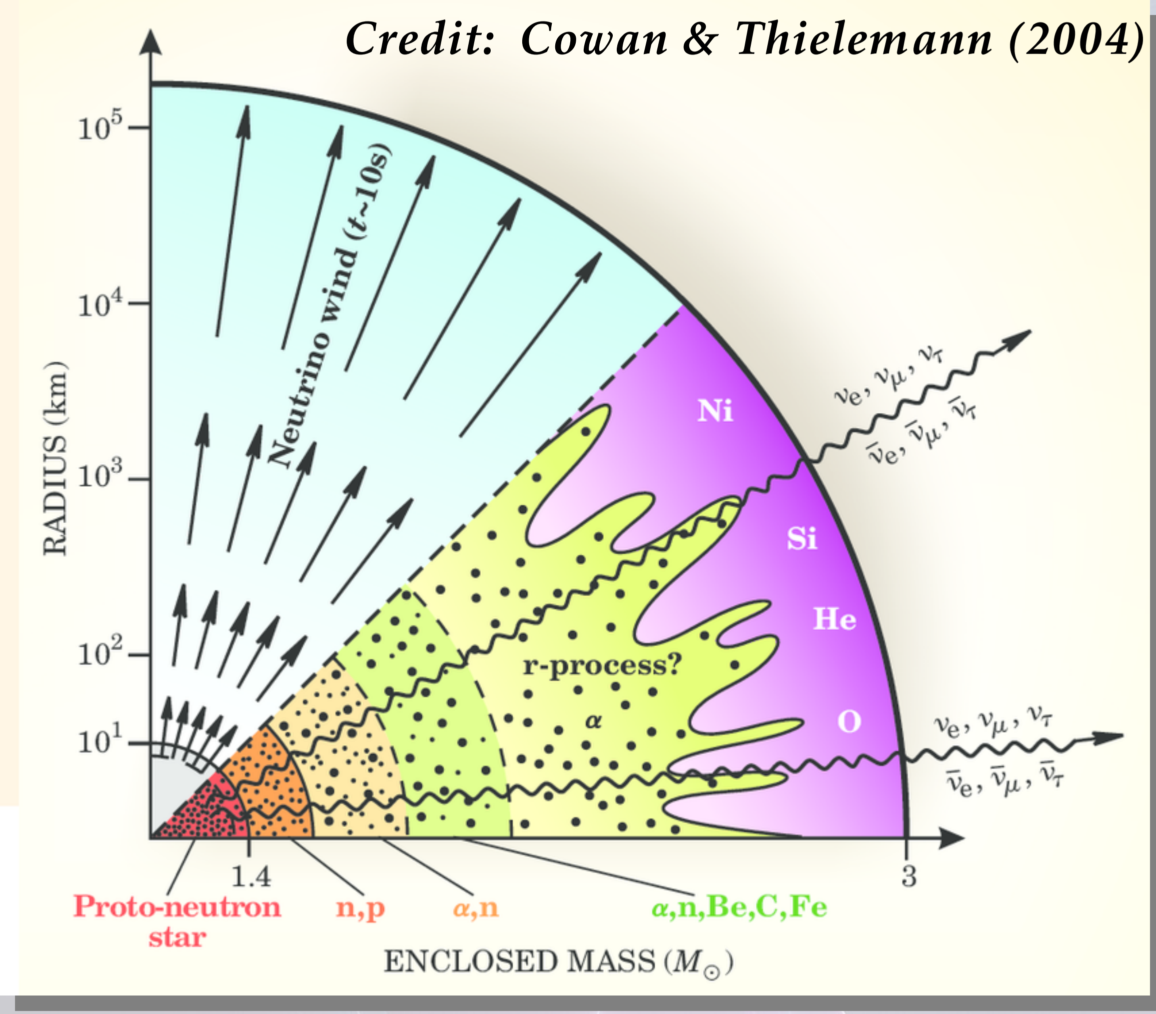


Core collapse



- Gravity takes over
  - end of the long-term equilibrium
  - fall-in: on the free-fall timescale
- …is there something to stop it?
  - Well… it depends.
  - Most of the time ("classical" case): a neutron star forms in the center ("proto-neutron-star")
    - a neutron star is: one giant nucleus. dense. stable.
    - bounce-back, shock waves, emission of neutrinos and light = **SUPERNOVA EXPLOSION**
  - technically: a core-collapse supernova (CCSN)

…apse



Credit: Cowan & Thielemann (2004)

u…

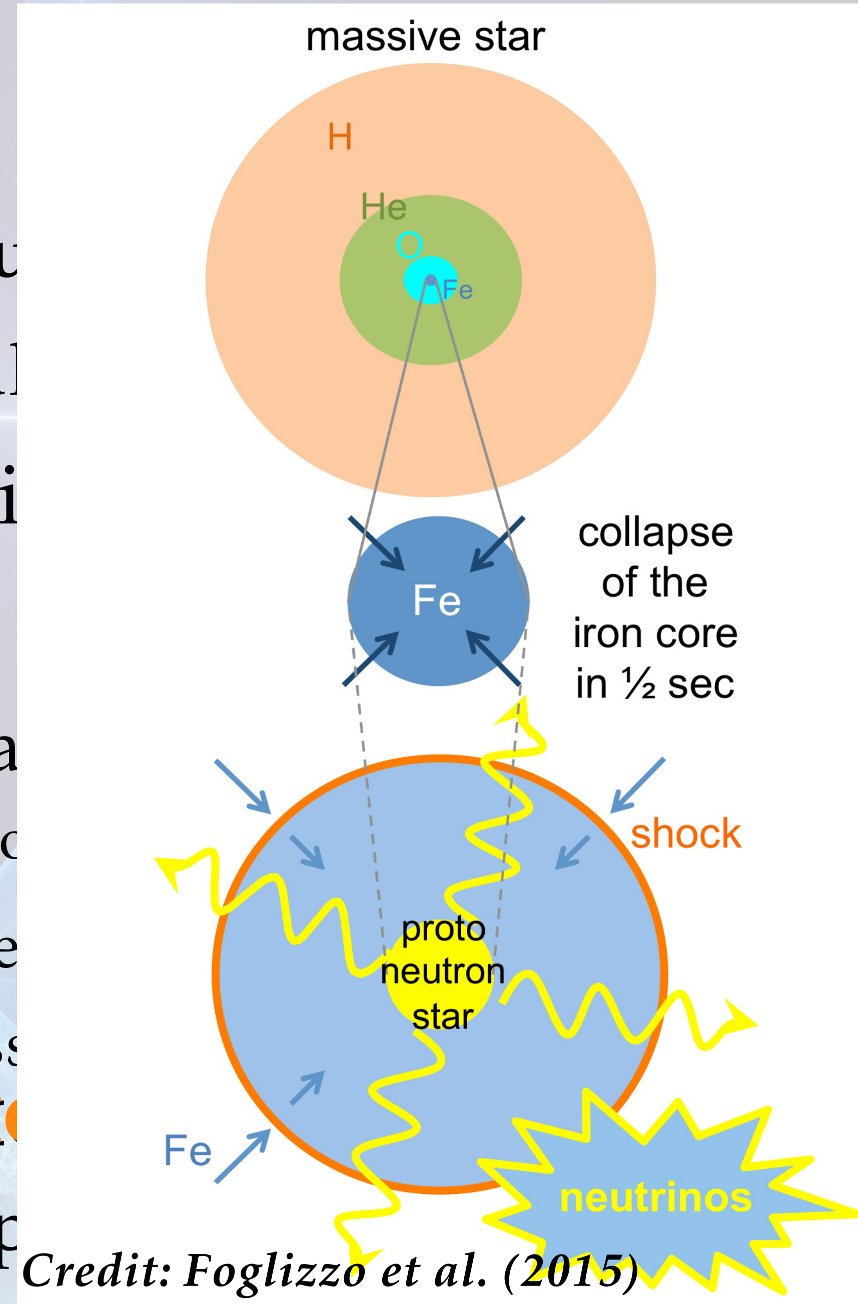
al…

i…

a…
forms in the center ("proto-neutro…

- a neutron star is: one giant nucle…
- bounce-back, shock waves, emiss… light = **SUPERNOVA EXPLOSI…**

– technically: a core-collapse sup…



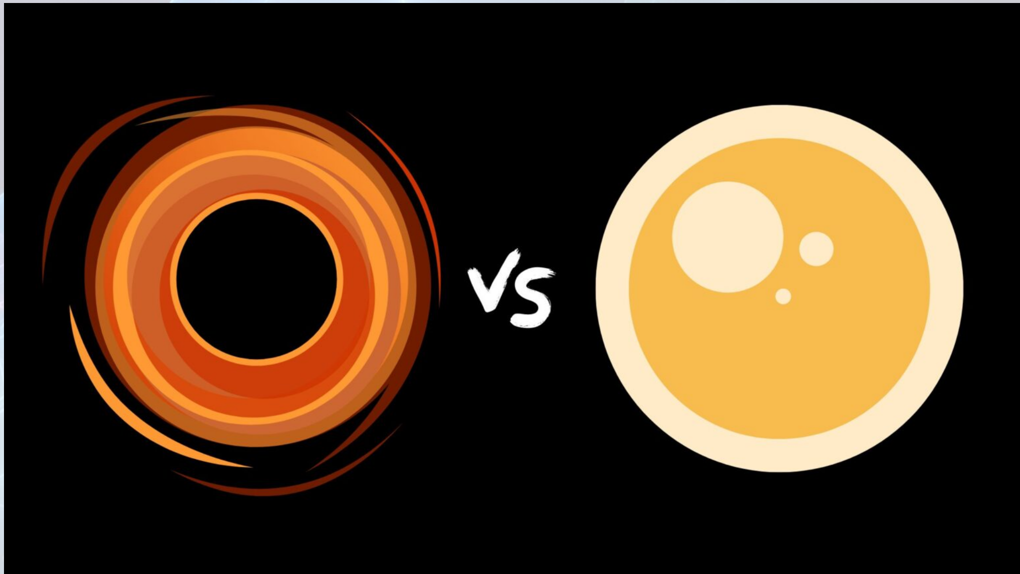
Credit: Foglizzo et al. (2015)

Fate of the proto-NS

- depends on the mass of the object
  - $M_{ini} < \sim 20\ M_\odot$: NS
  - $> \sim 20\ M_\odot$: BH
  - but… explosion physics is complicated (as is stellar evolution…)
- Tolman–Oppenheimer–Volkoff limit: **$2.16\ M_\odot$**
  - maximum observed mass of a neutron star is $2.14\ M_\odot$ for PSR J0740+6620 discovered in 2019

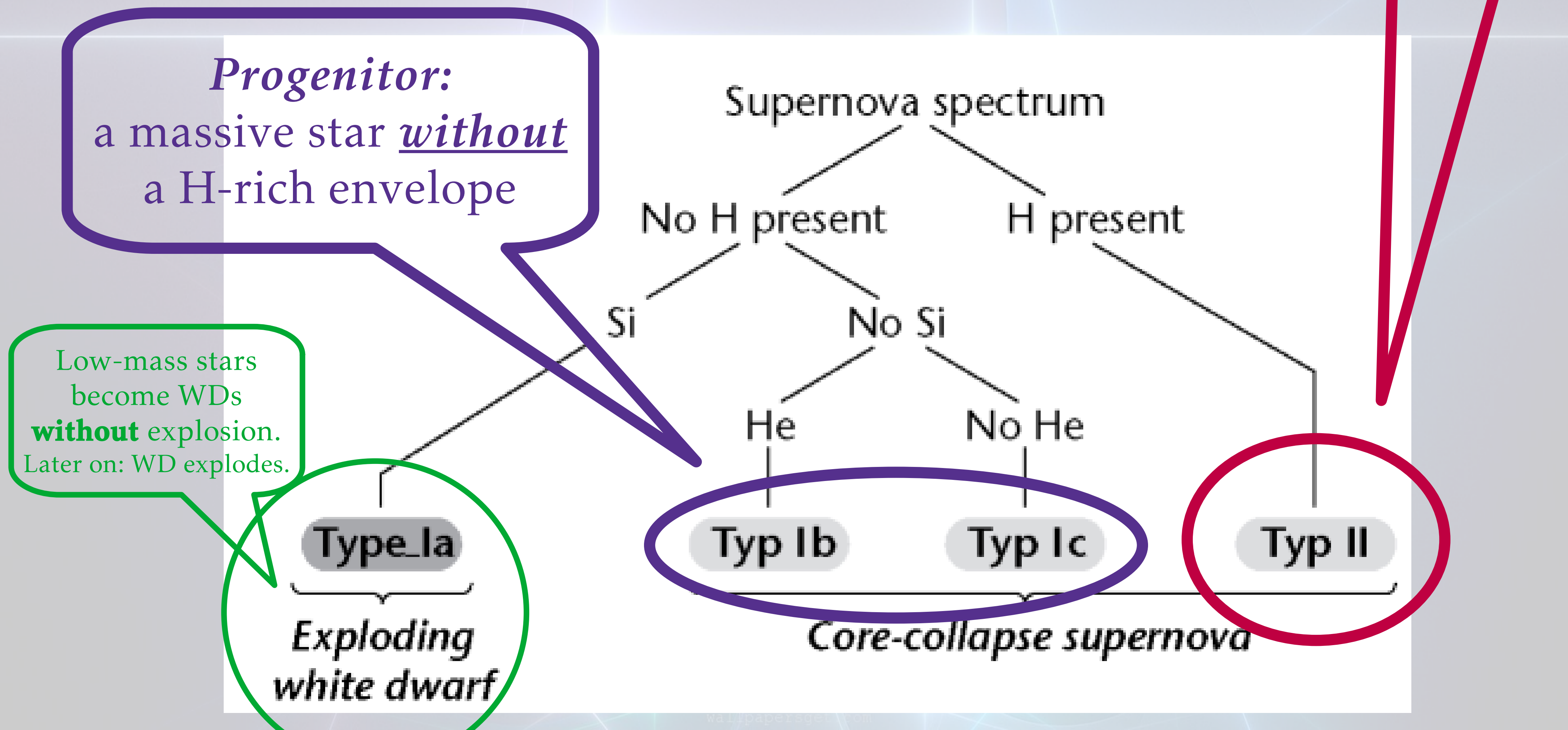
under active research

<u>Not</u> the Chandrasekhar limit! *$\sim 1.4\ M_\odot$*
(= limit between NSs and white dwarfs)



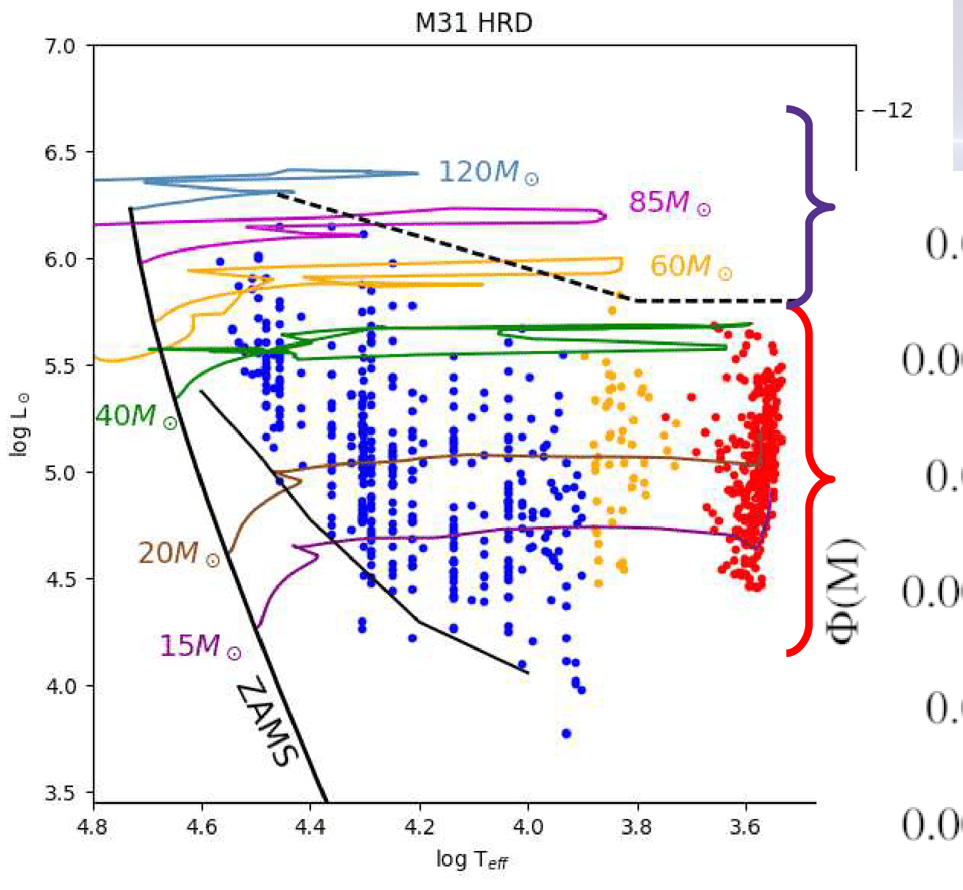
Supernova types

- There are many types…
- Classified by observers (simple picture):



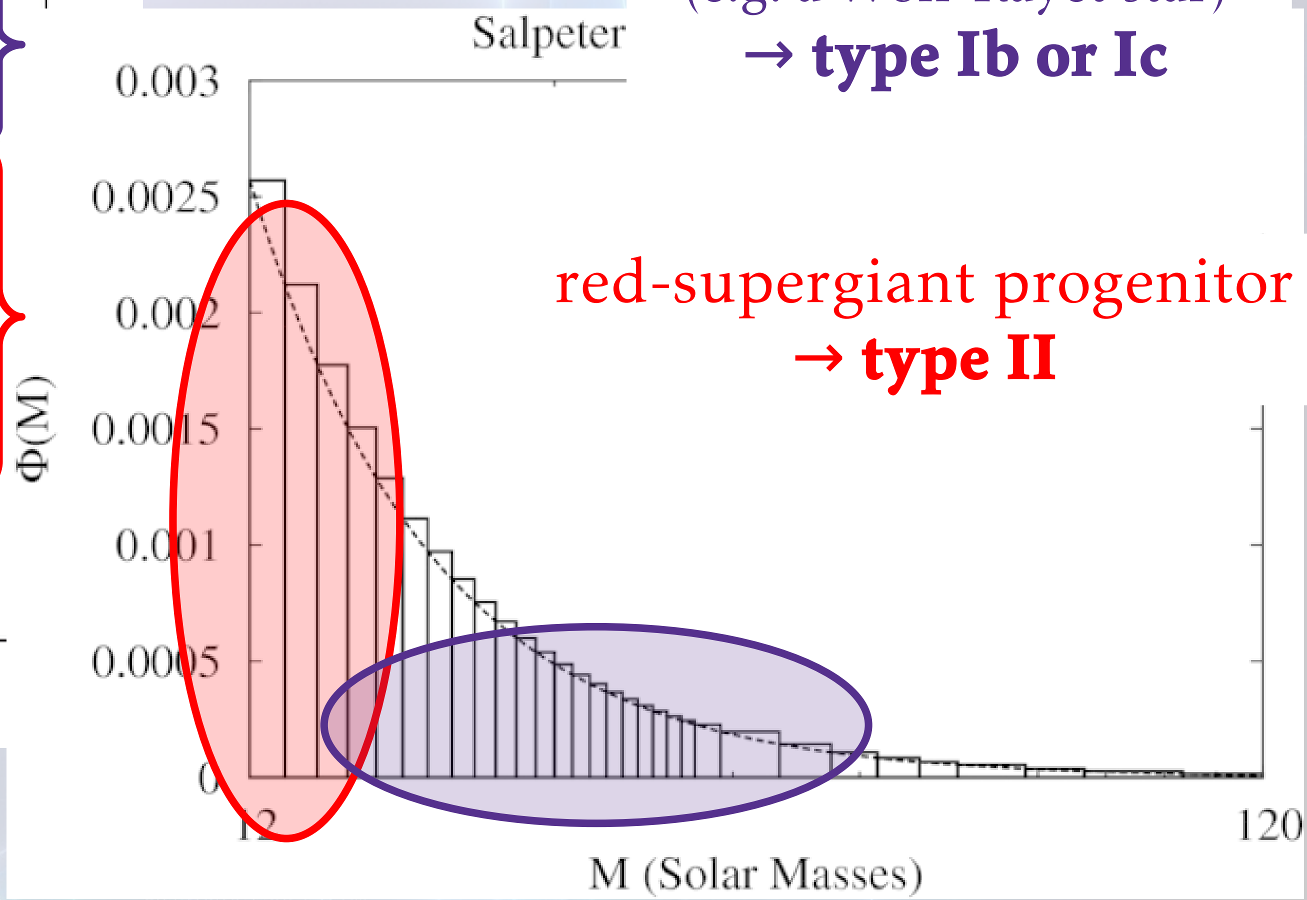
Only true for: single stars
at solar metallicity
no (or slow) rotation

*stripping = loss of H-rich top layers
In the context of ***single*** stars:
'stripping' is due to losing
mass in the strong wind
In the context of ***binary*** stars:
mass transfer



'stripped' progenitor*
(e.g. a Wolf-Rayet star)
→ **type Ib or Ic**

red-supergiant progenitor
→ **type II**



What are compact objects?

stellar 'corpses' **= remnants**

- three main types:
  - white dwarf
  - neutron star
  - black hole

  (white dwarf, neutron star: **degenerate stars**)

other (speculative) degenerate stars:
– quark star
– preon star
– boson star
– … (see e.g. Wikipedia)

- WDs: electron degeneracy
  - nuclei (He/O/C/Ne/Mg) are ***not*** in degenerate state

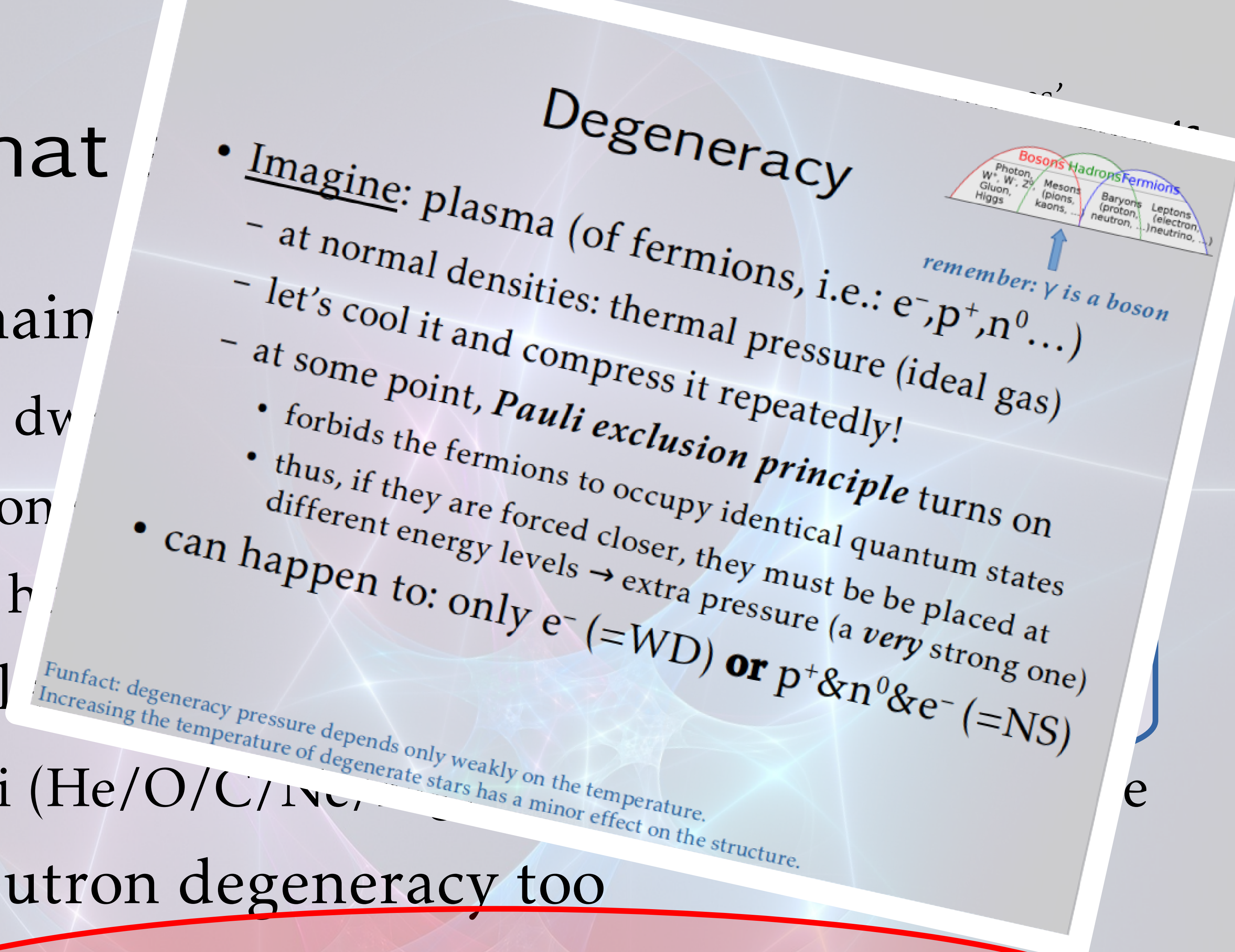
composition depends on mass (i.e. stellar evolution of the low-mass star in question)

- NSs: neutron degeneracy too

degeneracy pressure → **stability** against (self-)gravity

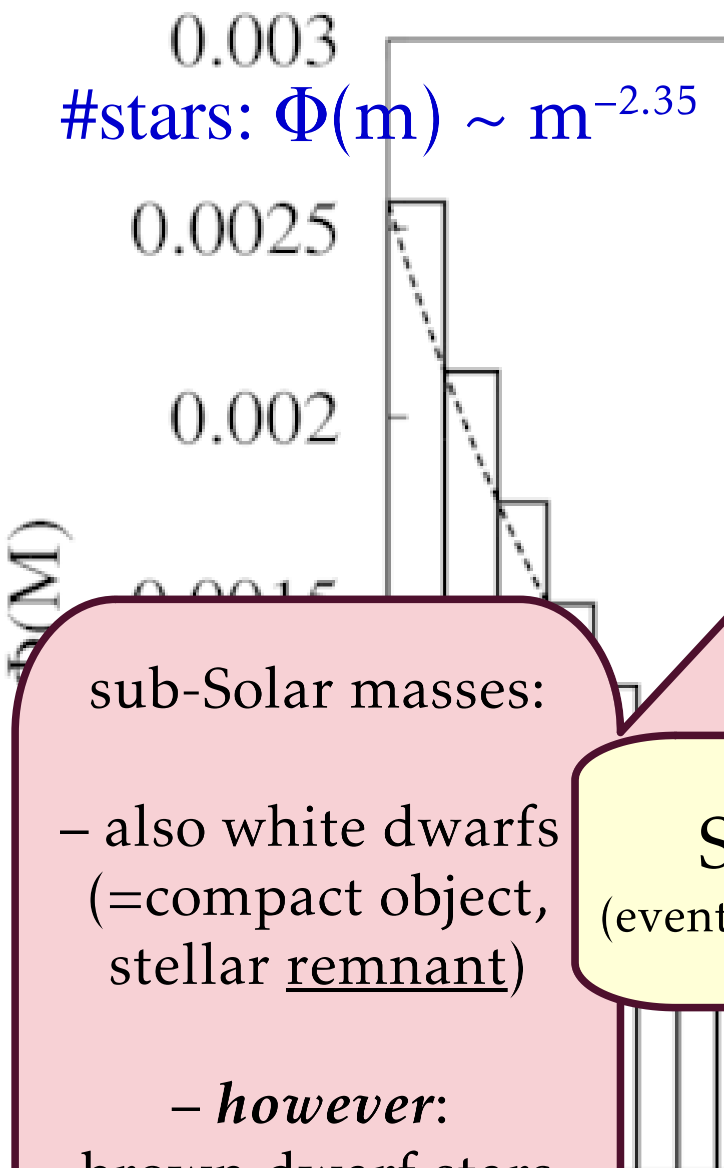
What

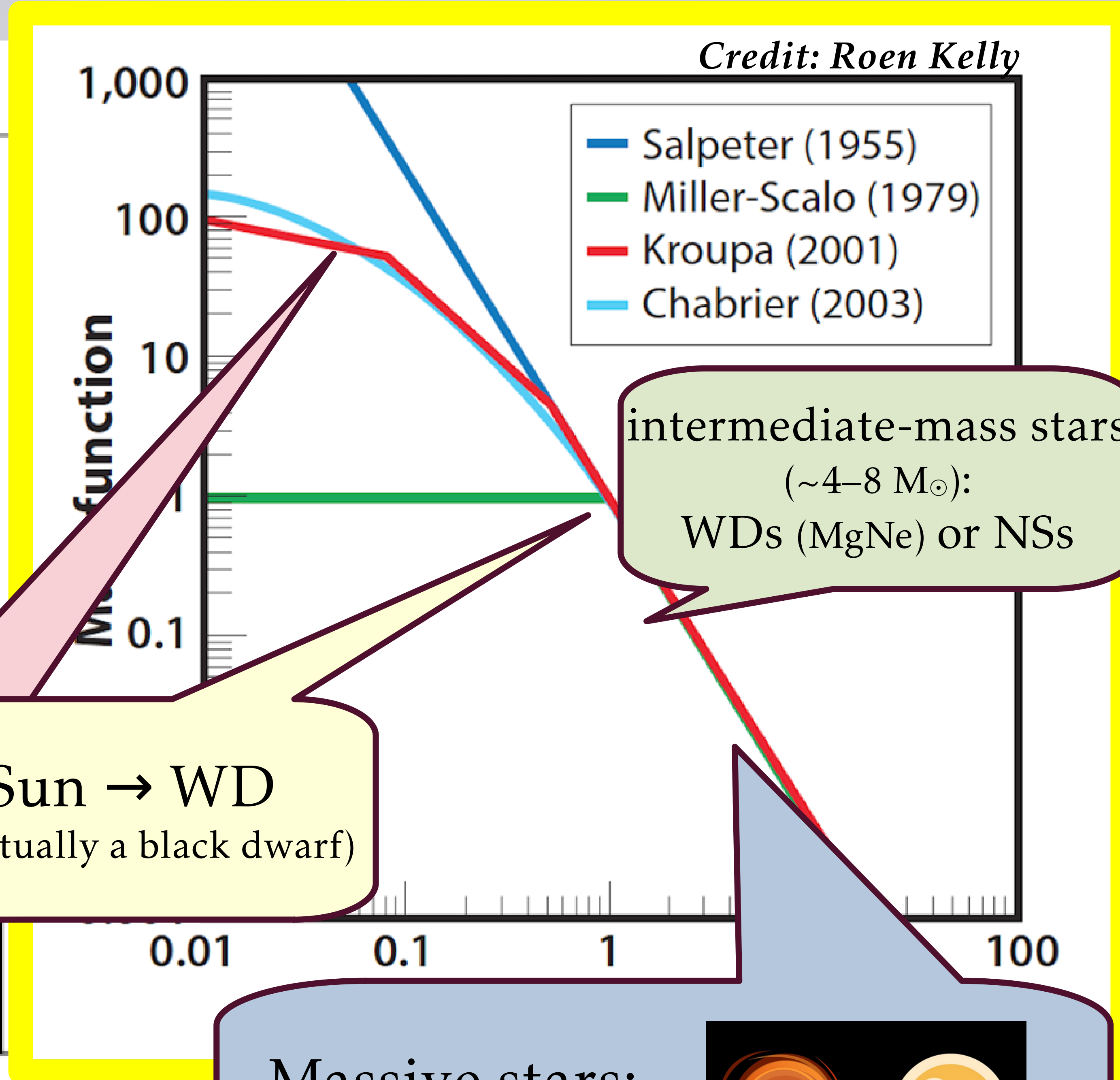
- three main
  - white dw
  - neutron
  - black h
- WDs: el
  - nuclei (He/O/C/Ne/ … e
- NSs: neutron degeneracy too



degeneracy pressure → **stability** against (self-)gravity

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





sub-Solar masses:

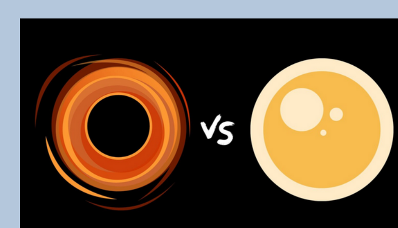
– also white dwarfs (=compact object, stellar remnant)

– ***however***: brown dwarf stars may live longer than the Universe…

Sun → WD
(eventually a black dwarf)

intermediate-mass stars
(~4–8 $M_\odot$):
WDs (MgNe) or NSs

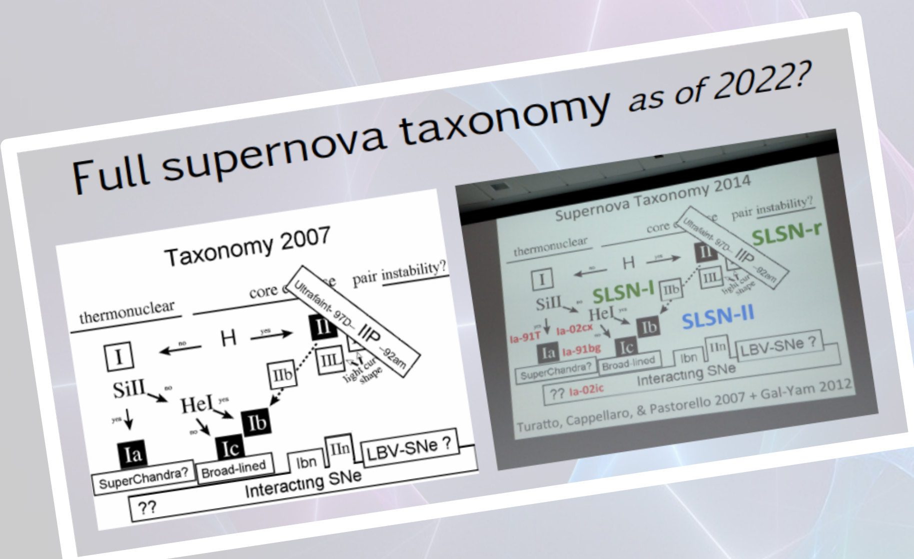
Massive stars:
NSs or BHs*



THIS HAS BEEN:

single massive stars' lives at solar metallicity

(without rotation)



***Our strategy:** start with*
Massive Stars at Solar Z

→ sub-Solar metallicities?
→ fast-rotating stars?
→ stars in a binary system?

Sub-Solar metallicities

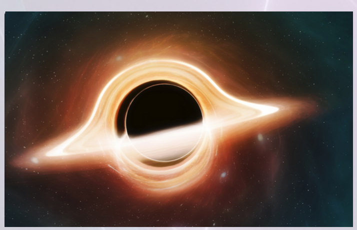
(and still no rotation and no binary companion)

- Main effect: mass loss becomes WEAKER

  → stars live their lives with more mass retained

  → also ***end*** their lives with more mass retained

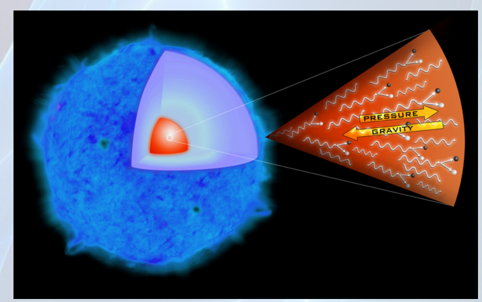
Consequence #1:



direct fall-in into
a black hole
(of mass ~20-40 $M_\odot$)

key question: is there something to STOP the collapse?   if yes: CCSN (type II, Ib/c)
if no: direct fall-in into a BH (no explosion)

Consequence #2:

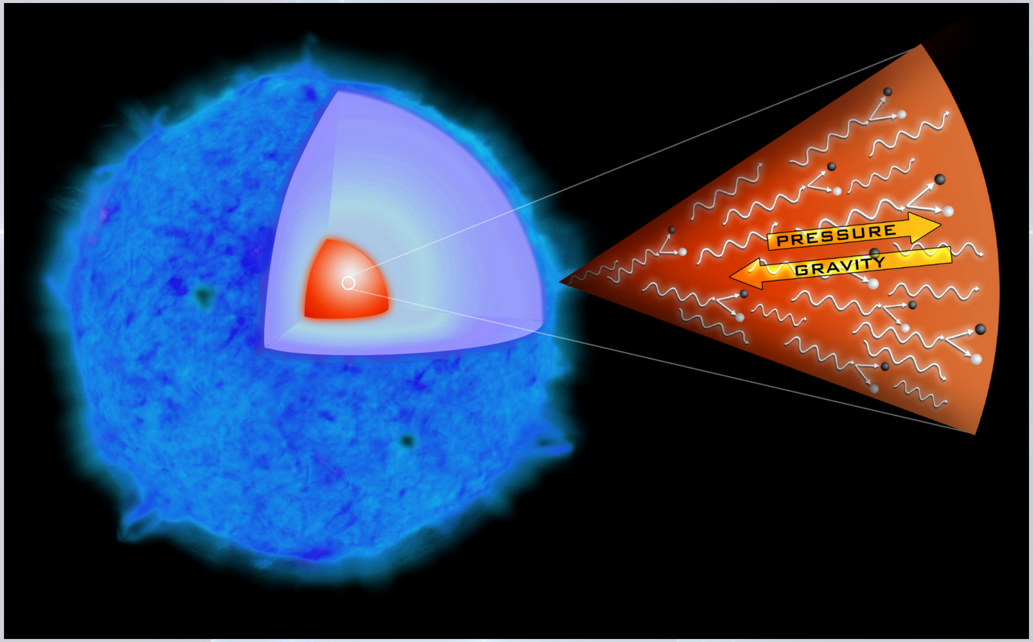


pair-instabiliy developing, leading to
a PISN (or maybe a pPISN)
or again to direct fall-in to a BH
(but this will be a very heavy BH with >150 $M_\odot$)

Why?

Pair Instability

happens in ***quite*** massive stellar cores
mass values quoted here mean M_{ZAMS}



Photon pressure drops due to $\gamma\gamma \rightarrow e^- \; \& \; e^+$

can happen already in stars with $\gtrapprox 60\ M_\odot$

Collapse

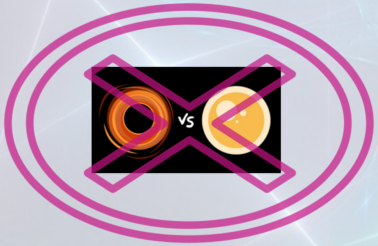
key question, as always:
is there something to stop it?
…if not:

Explosive O-burning
→ supernova

happens with stars ~140-260 $M_\odot$

pair-instability supernova (PISN)

No remnant!



above 260 M$_\odot$:
again direct collapse into BH
(gravity wins)

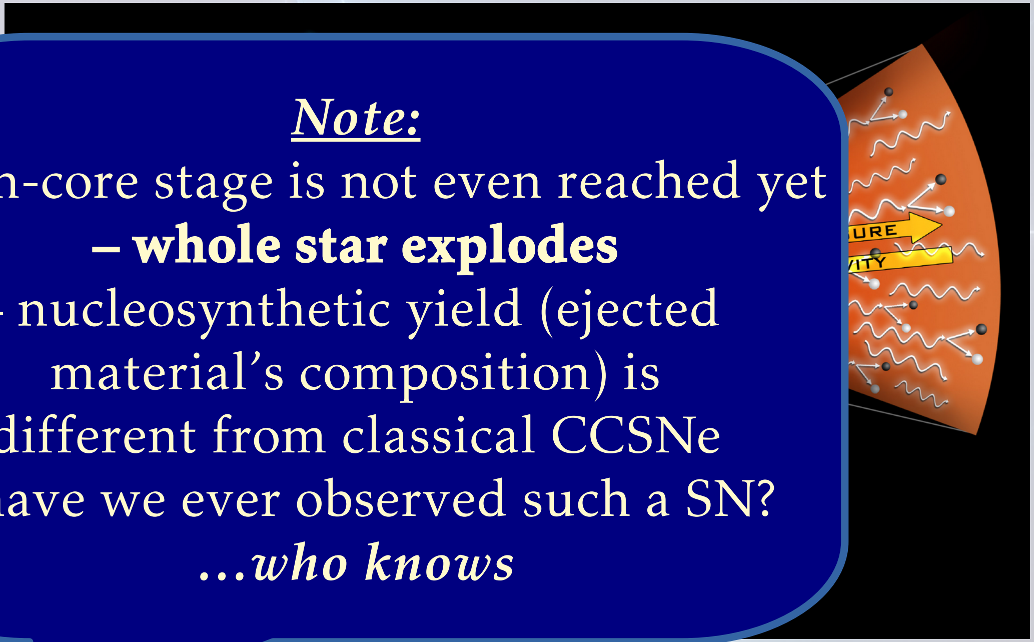
Pair Instability

happens in ***quite*** massive stellar cores

mass values quoted here mean M_{ZAMS}

Photon pressure drops due to
γγ → e- & e+

can happen already in stars with ≳ 60 M$_\odot$



Note:

– iron-core stage is not even reached yet

– whole star explodes

– nucleosynthetic yield (ejected material's composition) is different from classical CCSNe

– have we ever observed such a SN?

…who knows

Collapse

key question, as always:
is there something to stop it?
…if not:

stars between 60–140 M$_\odot$:
collapse is stopped by the star re-gaining its hyrostatic stability

might* lead to a
'pulsational pair-instability supernova' (pPISN)

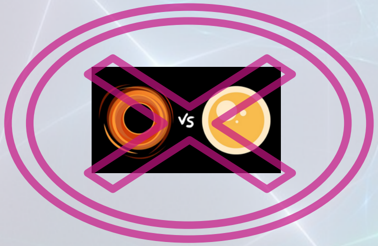
because layers lost in the pulsations ***might*** collide and emit light

Explosive O-burning
→ supernova

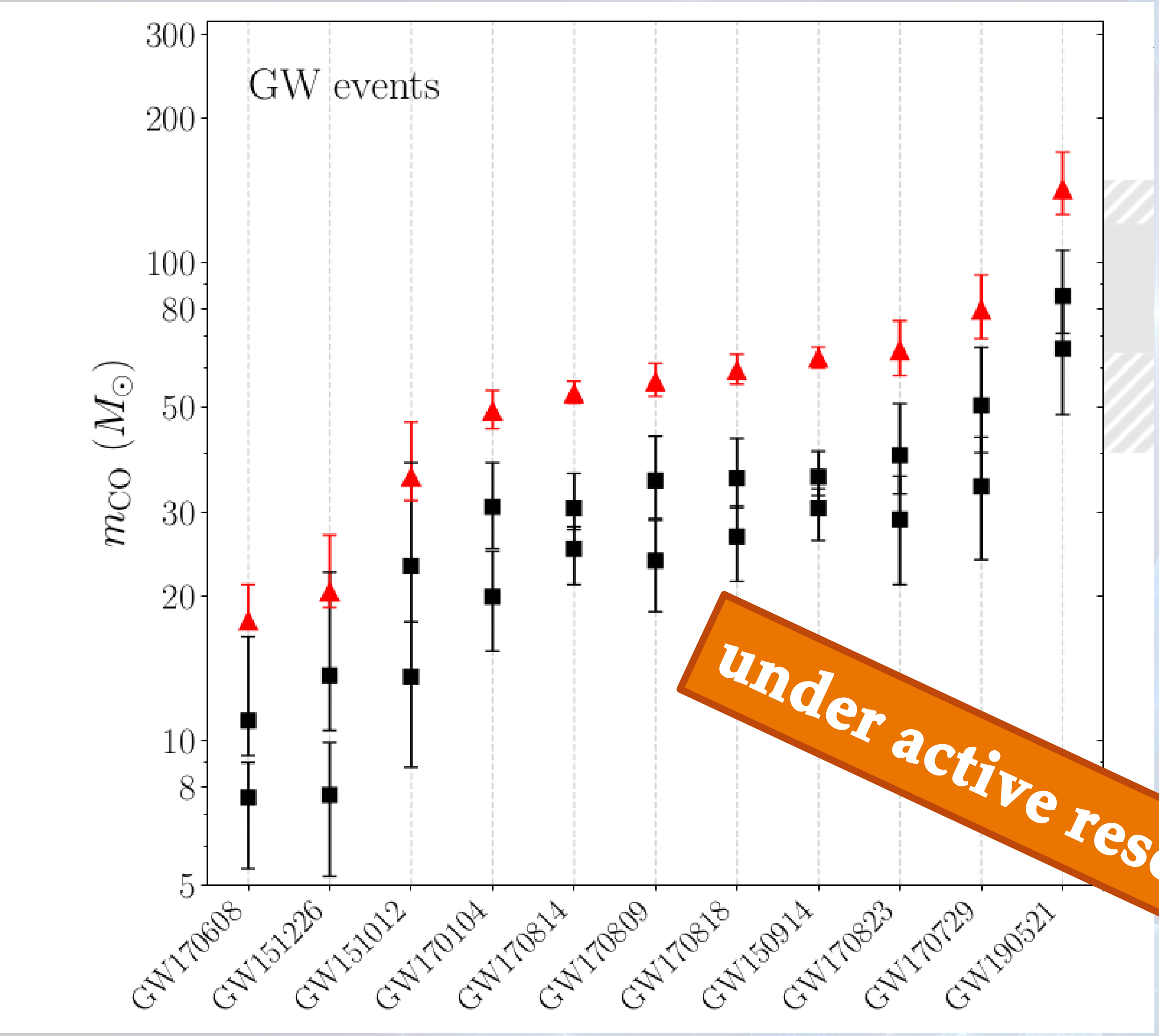
happens with stars ~140-260 M$_\odot$

pair-instability supernova (PISN)

No remnant!



The BHs of GW190521 shouldn't exist...



under active research

BH no go zone

GW190521:

m1 = 85 (+21/−14) Msun

m2 = 66 (+17/−18) Msun

What happens at

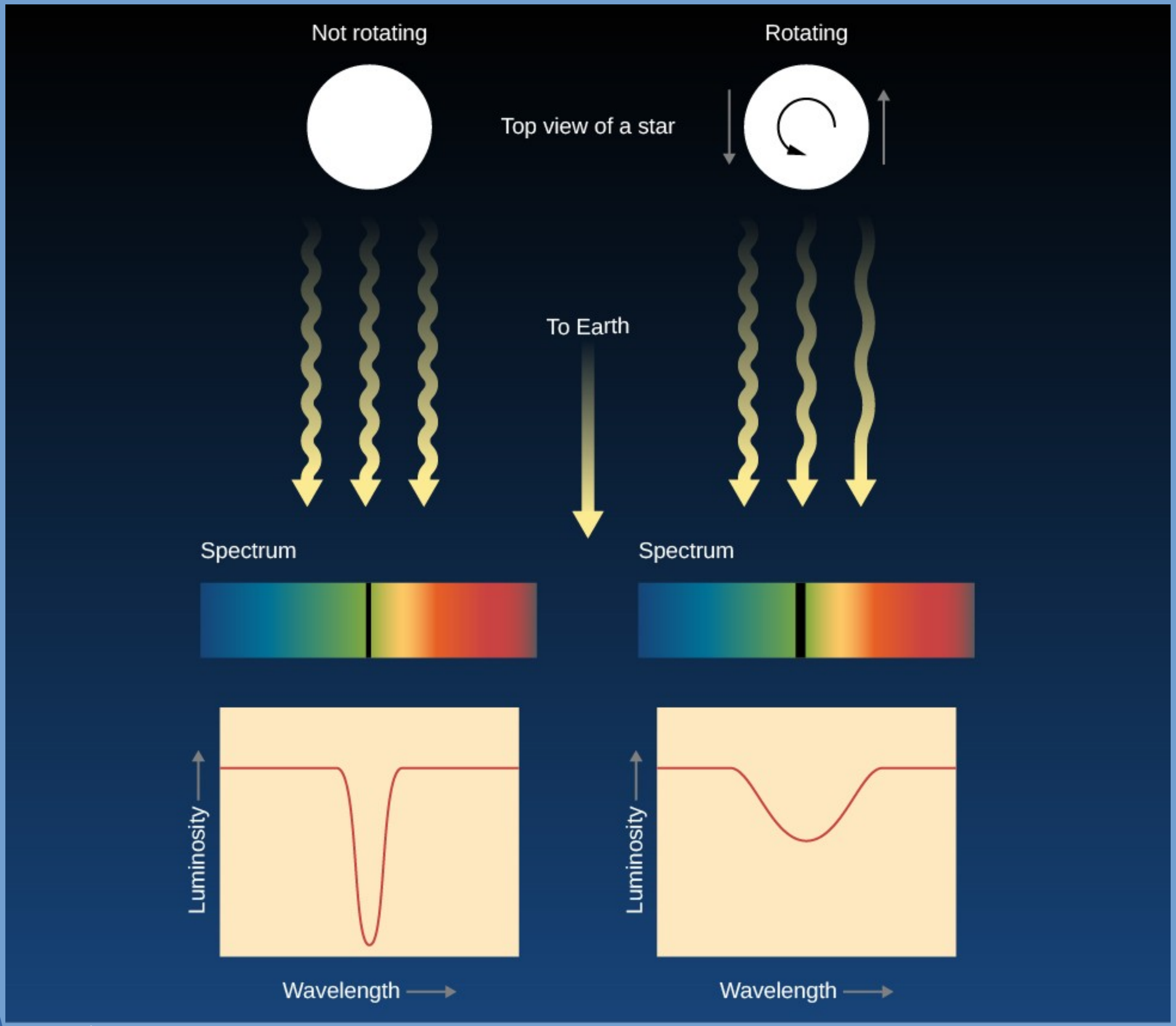
→ sub-Solar metallicities? ✓

→ fast-rotating stars?

→ stars in a binary system?

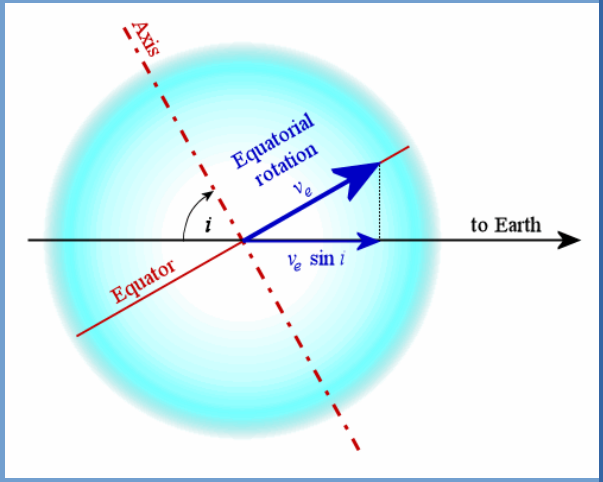
Massive stars rotate… sometimes quite fast

How do we know that? → line profile



Credit: LumenLearning Astronomy

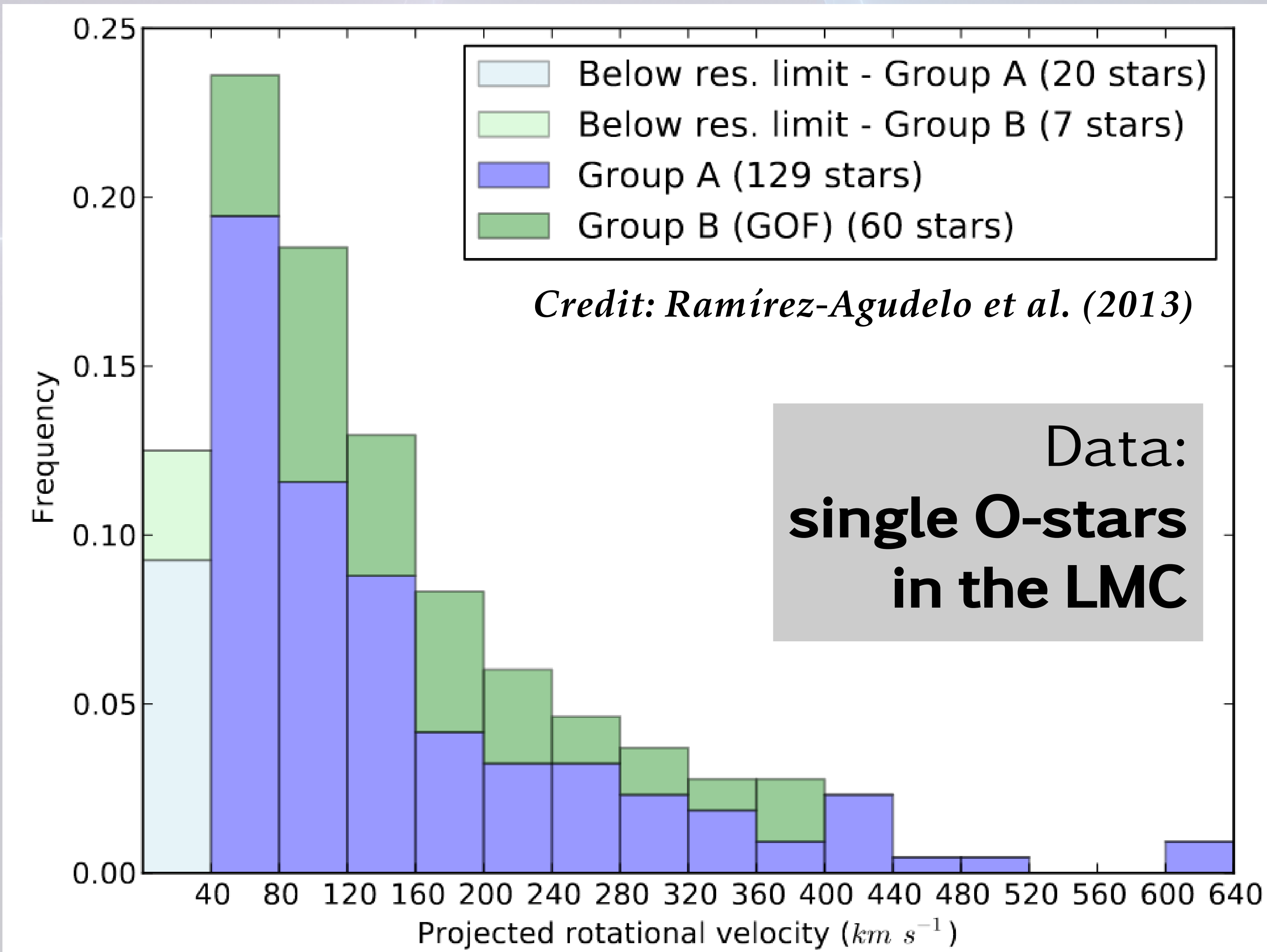
inclination?



v*sin(i)
("projected rotational velocity")

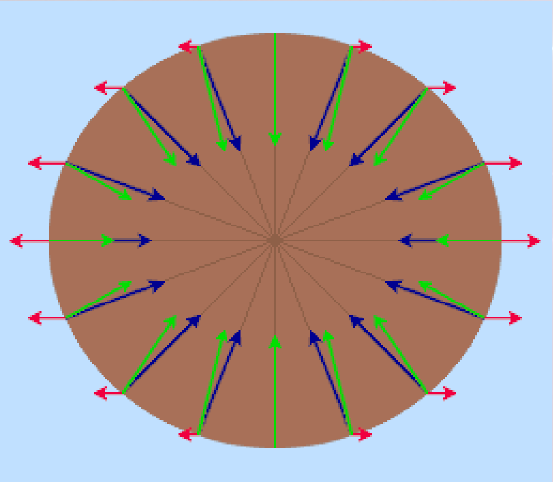
Massive stars rotate… sometimes quite fast

especially at low Z!



Theoretically considered:

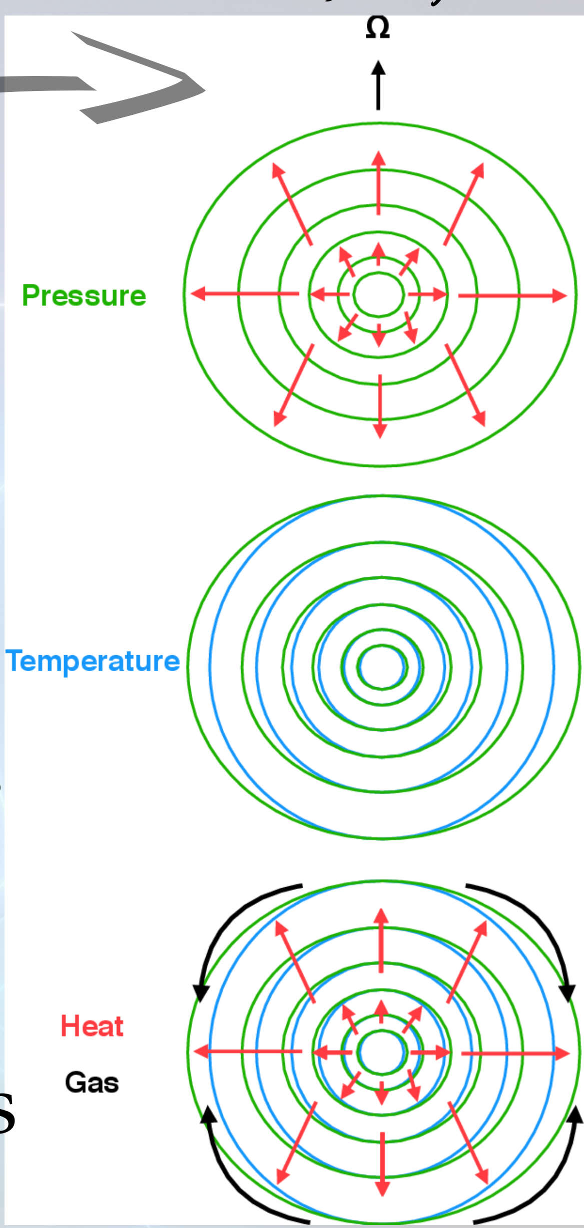
Rotation can effect the structure



- centrifugal force
  - oblate shape
  - extra mixing inside!
- extreme case:
  - "break-up" rotation
  - $F_{cen} \geq F_{grav}$ "critical rotation" "Keplerian break-up frequency"
  - leads to extra mass los
  - mass dependent

    e.g. "B[e] star" phenomenon

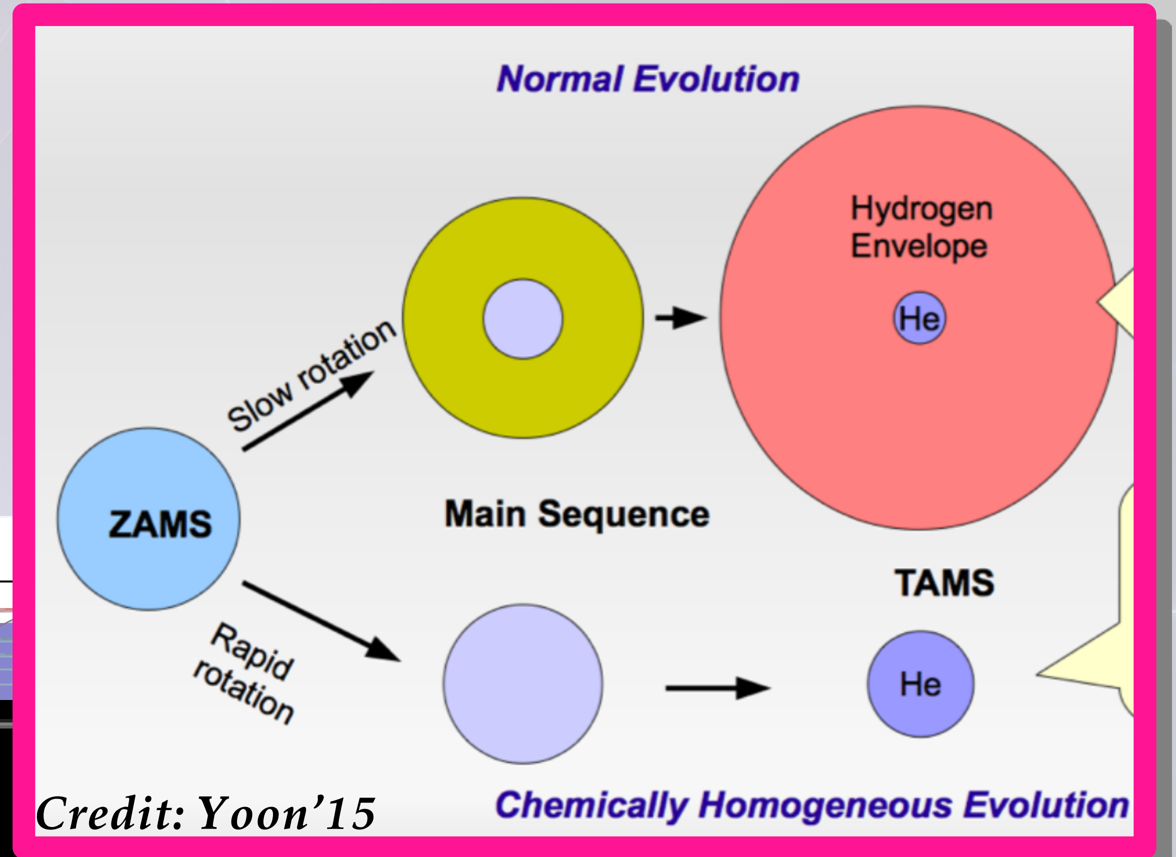
Credit: *Jermyn+18*



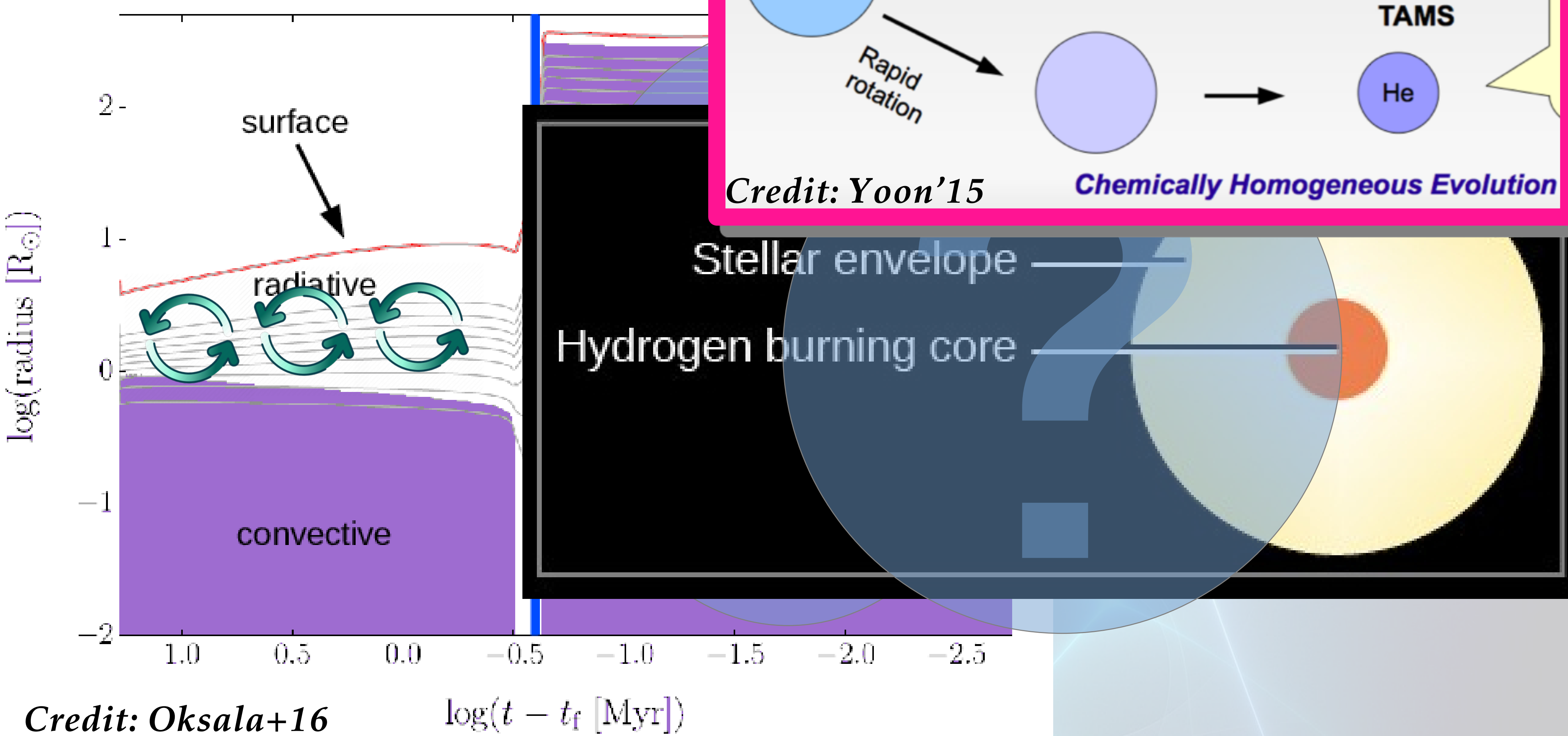
- non-extreme case: mixing & mass loss

Rotational mixing

…but depends on Z too:
metallicity   mass loss;
mass loss → angular momentum loss



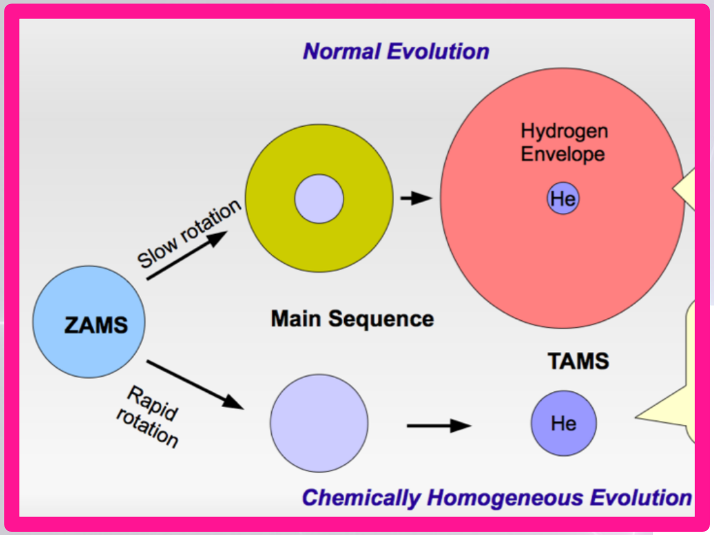
Credit: Yoon'15



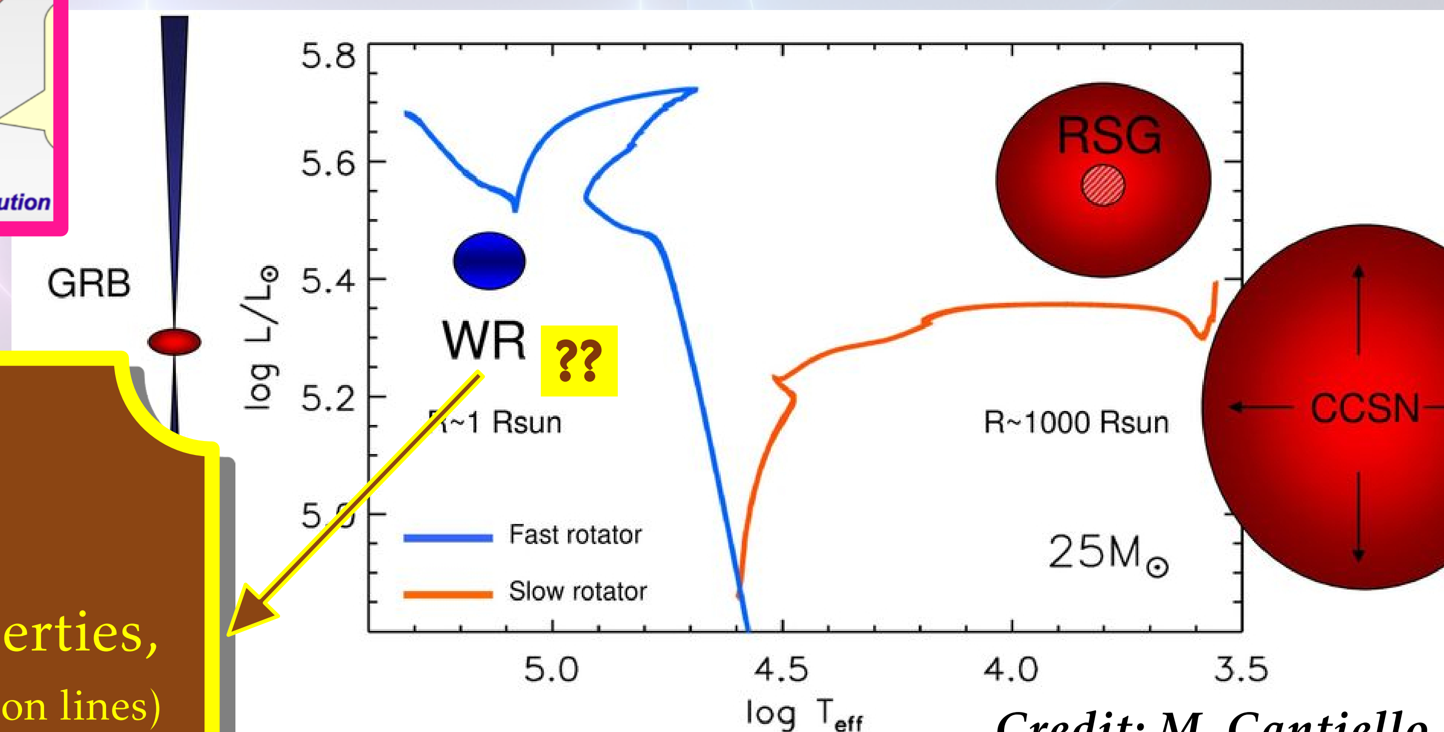
Credit: Oksala+16

Chemically homogeneous evolution

= *Quasi-chemically homogeneous evolution*



In the Hertzsprung–Russell diagram:



Credit: M. Cantiello

a hot, He-rich star

depending on wind properties, might be a WR star (emission lines) or something else? (absorbtion lines)

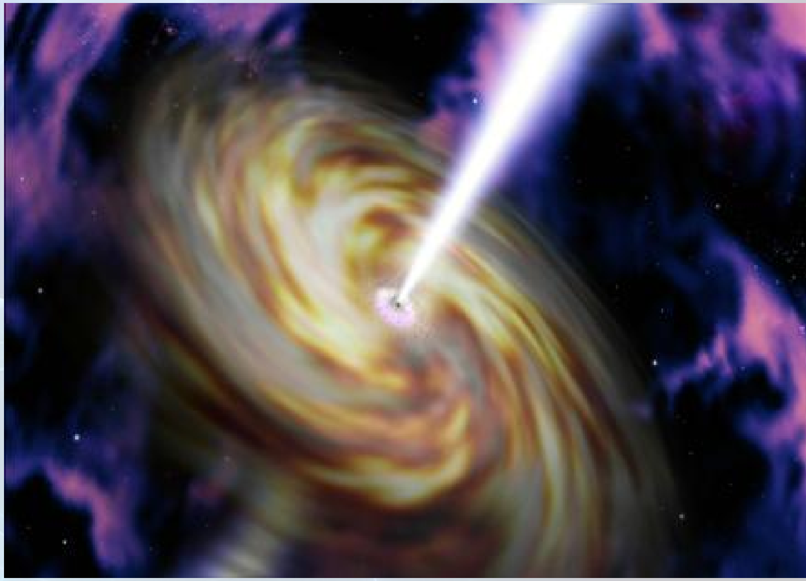
Type of final explosion?
type Ib/Ic (core collapse)
but ROTATING!! → a 'collapsar'

Collapsar

- "core collapse" ≠ "collapsar"
- core collapse + fast rotation = collapsar
- collapsar → accretion disc & jets
- if the jet aligns with the line of sight: **long-duration gamma-ray burst** may be observed (L-GRB)
  - accompanied by a SN Ib/Ic
- if not aligned: SN Ib/Ic

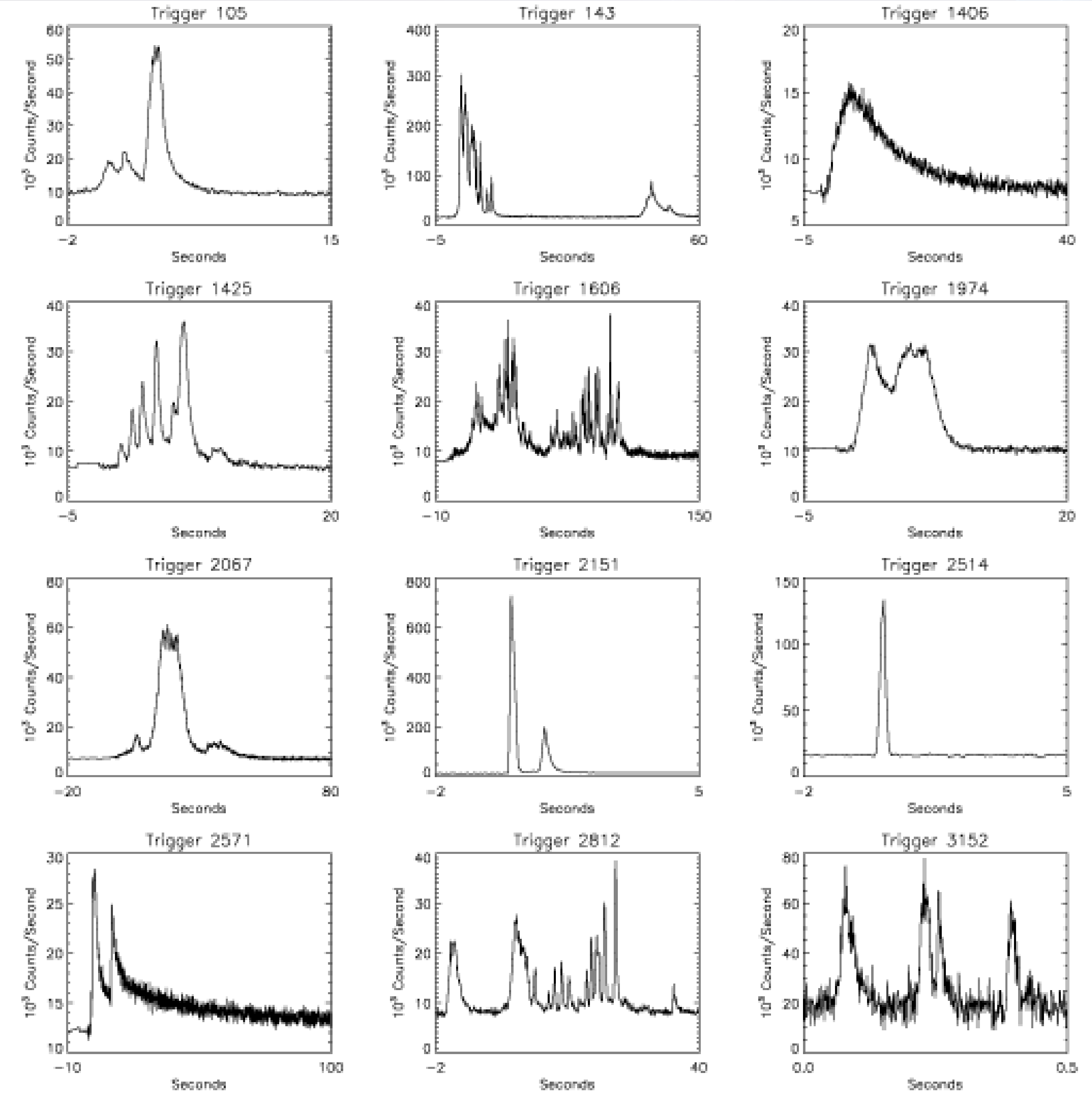
A BH or a NS forms in the middle. The proto-NS is probably highly magnetized.

Synchrotron radiation accelerated in the jet. γ-rays emitted.



What are GRBs?

Observationally...



– during the cold war…

– today: satellite missions
e.g.:
Fermi Gamma-ray Space Telescope
Neil Gehrels Swift Observatory etc.

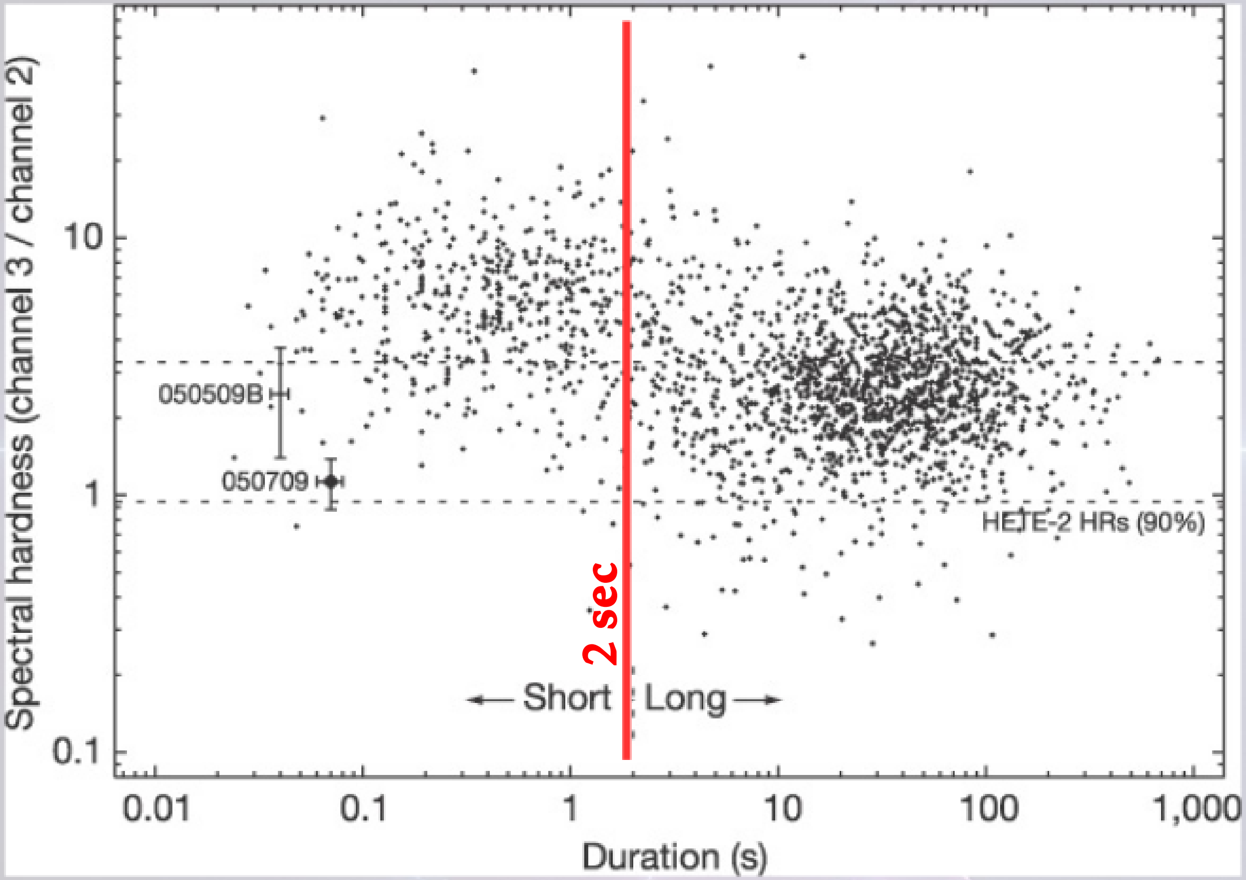
– daily observations

– majority of the energy is measured in γ-rays

– there is a so-called "afterglow" observed at softer wavelength (X-ray, optical, IR, radio…) after the prompt γ-emission

What are GRBs?

At least two, physically distinct types of objects

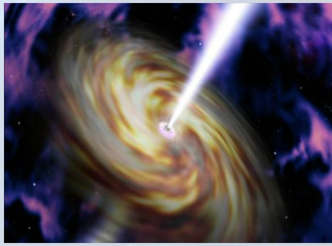


Credit: Hjorth+2005

Long/soft:

Massive Stars at collapse

a "collapsar"



binarity!

GWs!

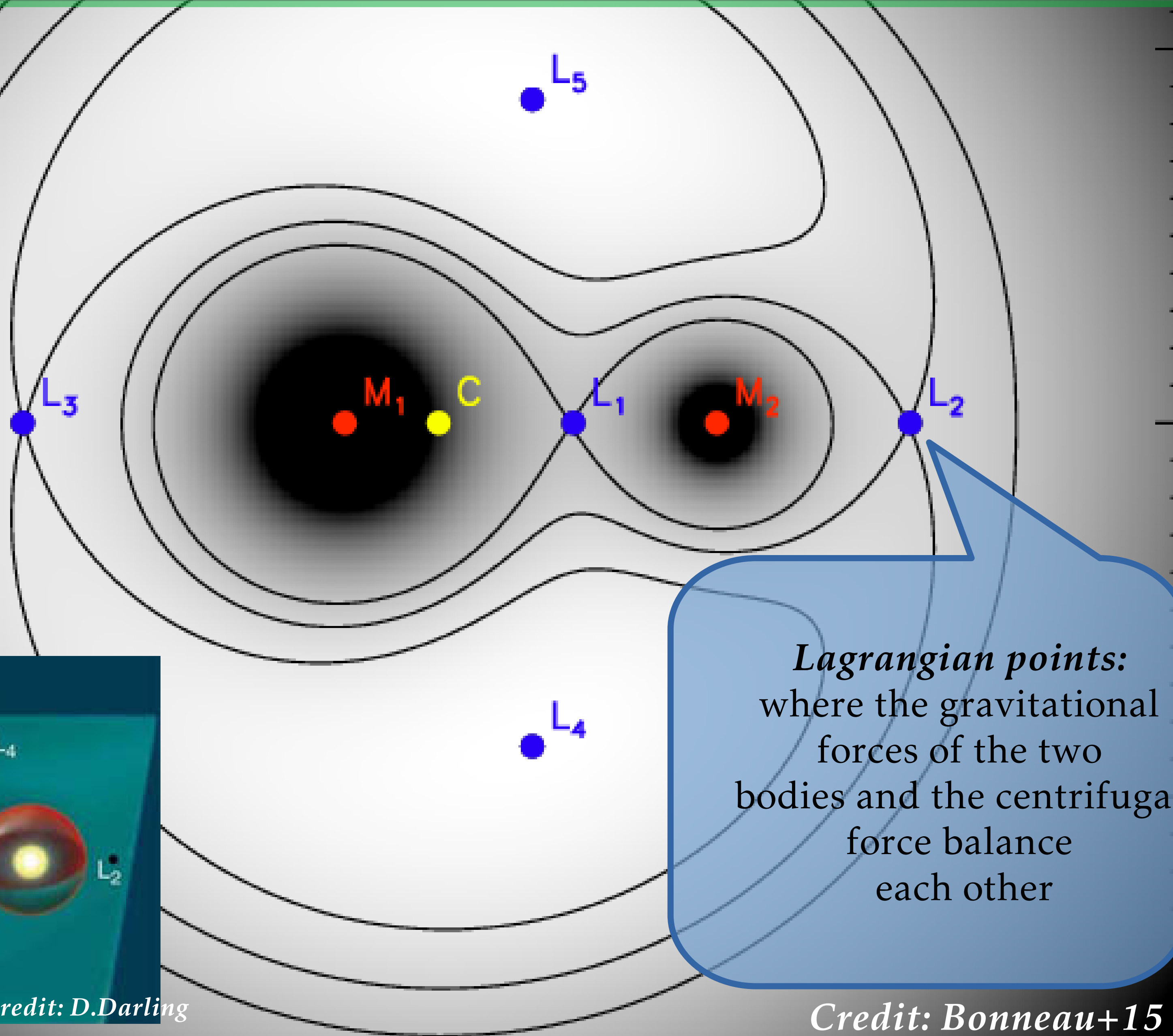
Short/hard: two Compact Objects at merger

Our strategy:

start with
Massive Stars at Solar Z

→ sub-Solar metallicities?
→ fast-rotating stars?
→ stars in a binary system?

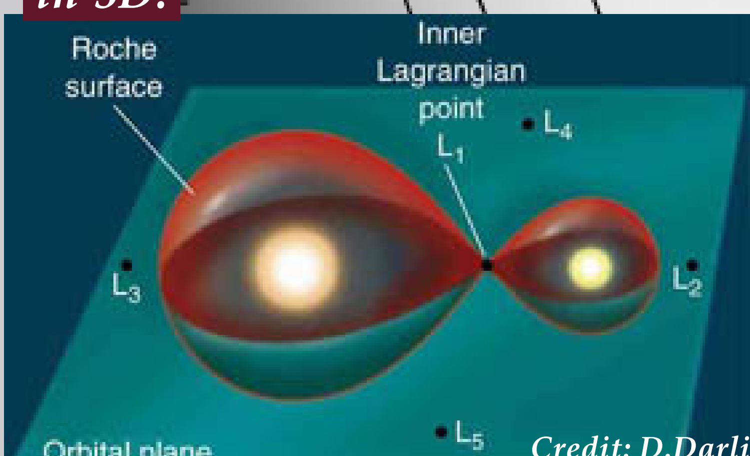
The most important concept:
Roche-lobe



Lagrangian points:
where the gravitational forces of the two bodies and the centrifugal force balance each other

Credit: Bonneau+15

in 3D:

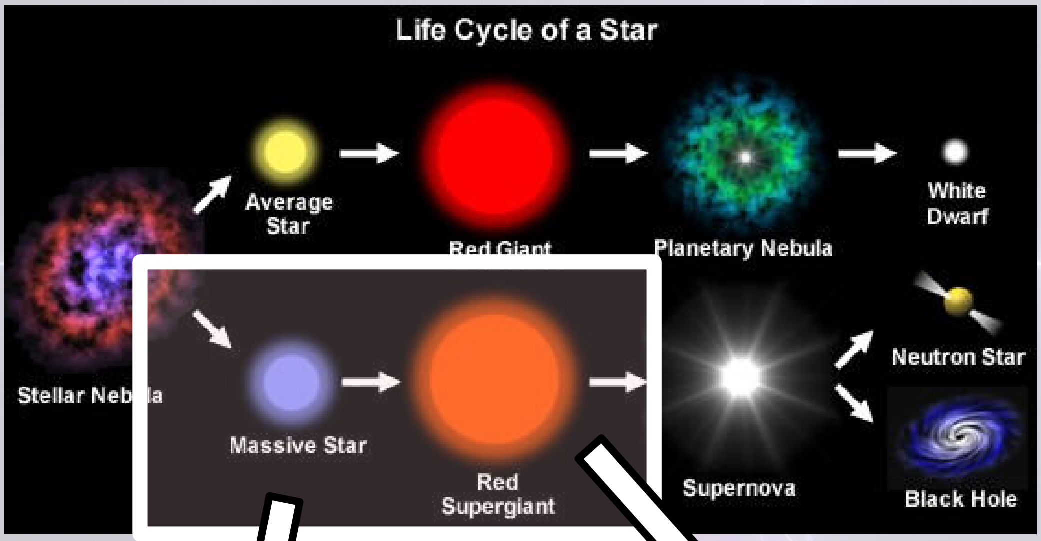


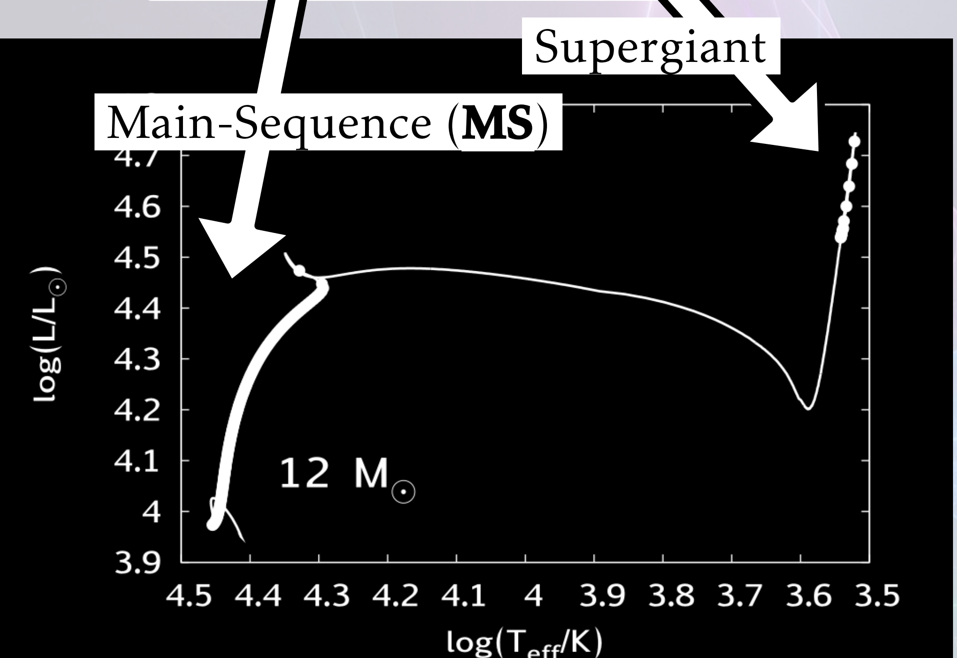
Credit: D.Darling

with Solar Z, no rotation

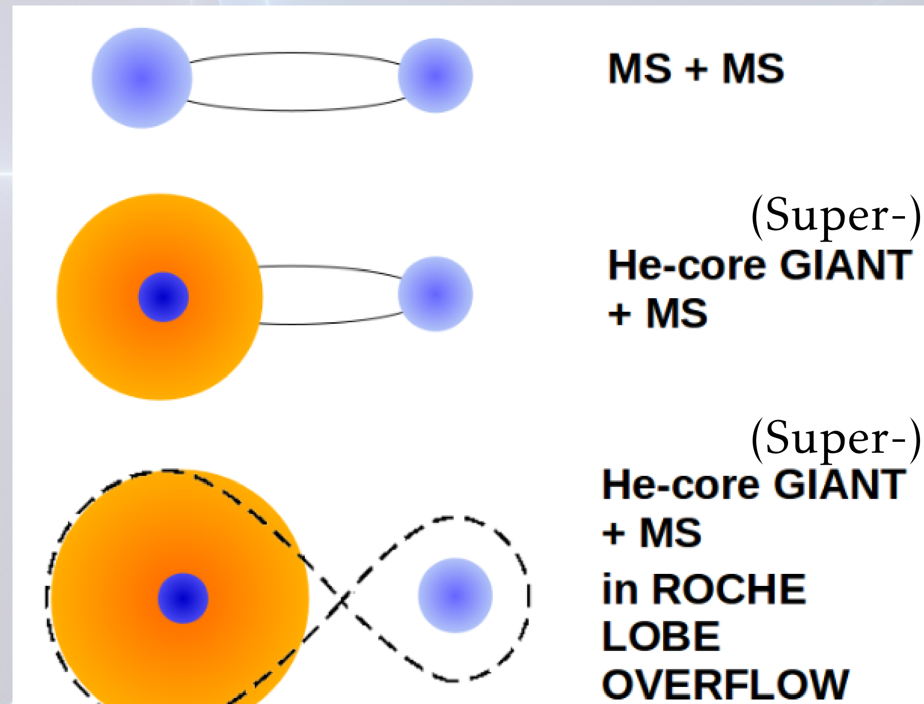
Imagine two (massive) stars!

One (massive) star alone:





Two of them next to each other:



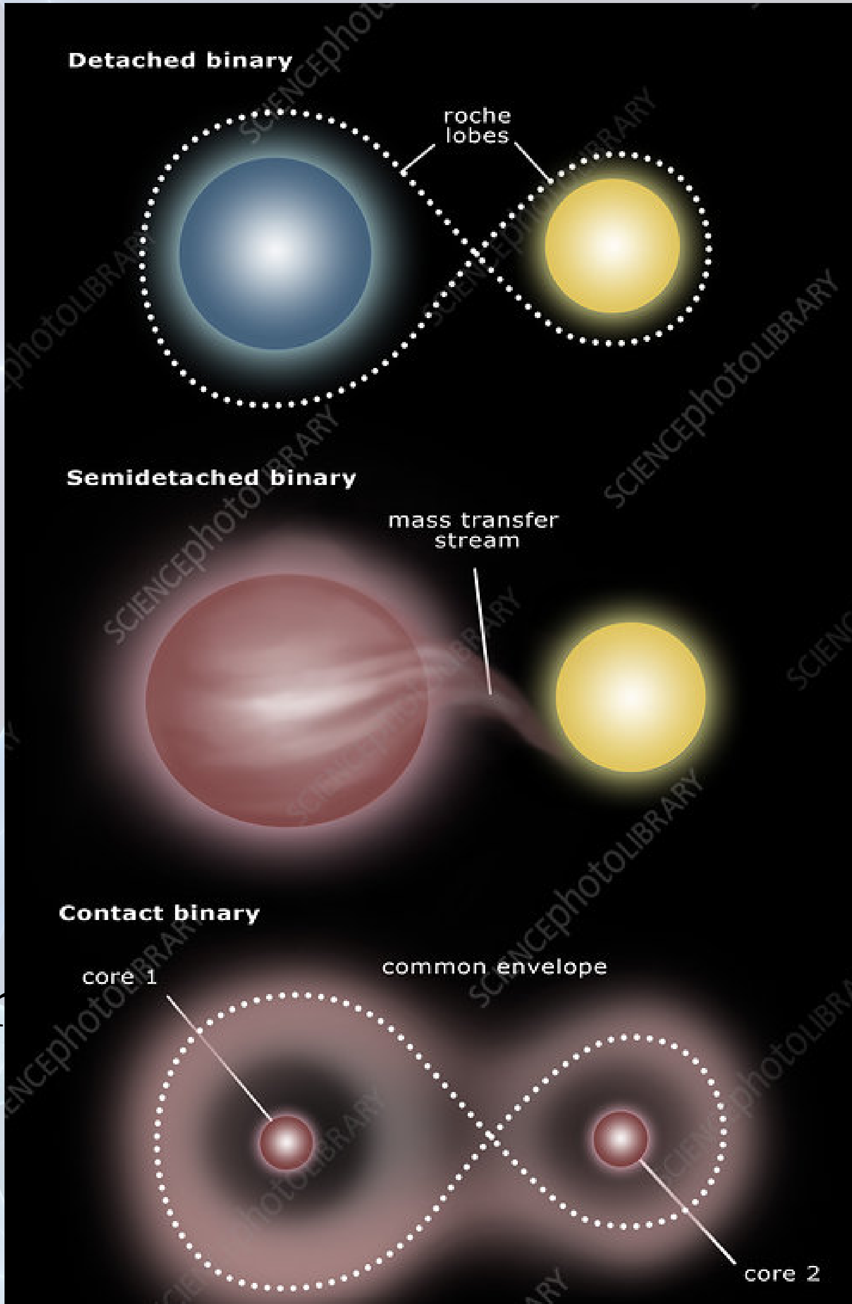
Credit: Mapelli'21

- $\tau(m) \sim m^{-2.5}$
  - Sun's lifetime: ~$10*10^9$ yrs
  - an 8 $M_\odot$ star's lifetime: ~ $5*10^7$ yrs
  - a 100 $M_\odot$ star's lifetime: ~ $2*10^6$ yrs

Why does the Roche-lobe matter?

- Mass transfer.
- Some important terms:
  - primary/secondary (companions)
  - donor/accretor mass gainer
  - M_1/M_2 losing mass / gaining mass
  - detached system
  - Roche-lobe overflow
  - semi-detached, contact system
  - 'common envelope' (...)

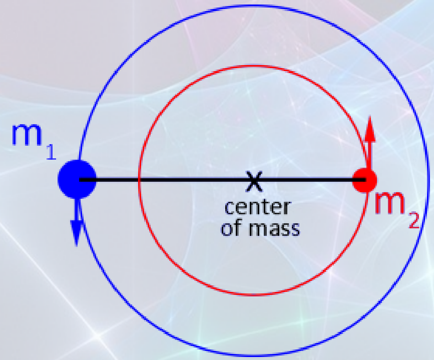
▶ *stellar* envelope



Some more terms

- orbital separation = orb. distance
- period = orbital period
    - ≠ rotational period!!
      (though cf. ***synchronization***)
      e.g. due to tidal forces
- <u>initial</u> orbital separation ***vs.*** <u>actual</u>
- <u>initial</u> period ***vs.*** <u>actual</u>
- Connection between distance & period?

Kepler's 3rd law:



$$P^2 = \frac{4\pi^2}{G(M_1+M_2)} r^3$$

‘Case A’, ‘Case B’, ‘Case C’ mass transfer

- Historical categorization (cf. stellar classes O, B, A, F… or supernova classification type Ia, Ib, II…) – useful to know even if its getting outdated

  - case A: MS
  - case B: HG
  - case C: He-b.

  (donor’s evolutionary status)

MS = Main Sequence
HG = Hertzsprung-gap
He-b. = helium-burning

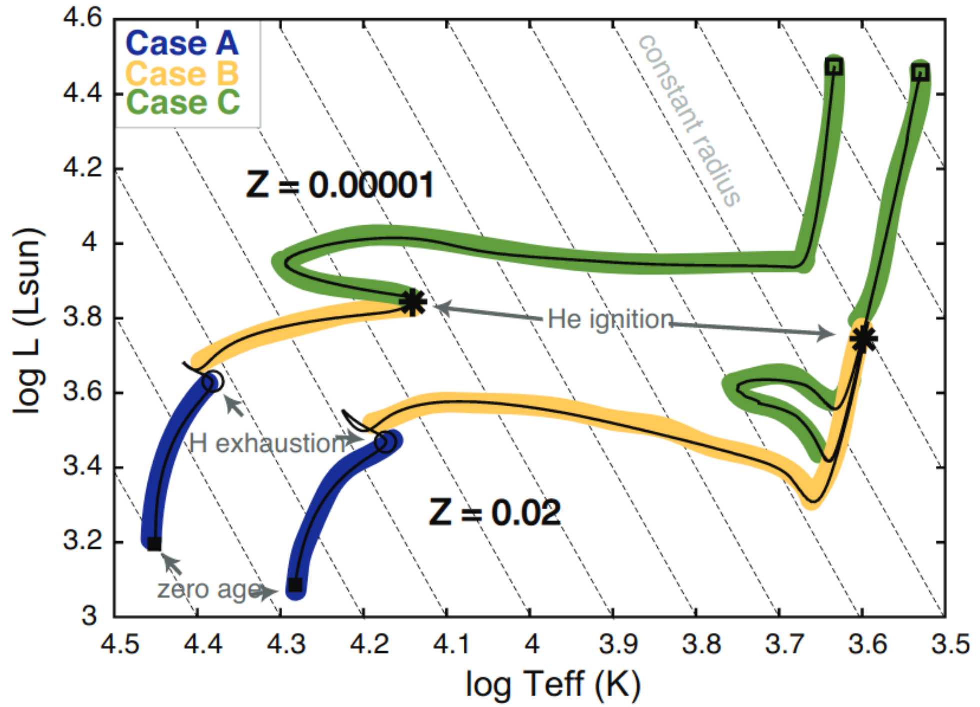


Figure 1.1: *Evolutionary tracks in the HR-diagram of a 6 $M_\odot$ star illustrating the effect of metallicity on the occurrence of the different cases of mass transfer. The dashed diagonal lines indicate lines of constant radii. Cases A, B and C are defined in the text of Section 1.5.1. Figure adapted from De Mink et al. (2008b).*

Orbital evolution during mass transfer

- suppose conservative mass transfer:
  - orbit shrinks if $M_{donor} > M_{acc}$
  - orbit expands if $M_{donor} < M_{acc}$

cf. prof. Onno Pols' lecture notes on binaries [LINK]

- if the mass transfer is non-conservative:
  - then we also need to take into account how much angular momentum is lost from the system…
- Roche-lobe is effected:

$\Longrightarrow$ approximation of Roche lobe (*Eggleton 1983*) $q = m_1/m_2$

$$RL_1 = A \frac{0.49 q^{2/3}}{0.6 q^{2/3} + ln(1 + q^{1/3})}$$

orbital separation: A

- And remember: massive stars have <u>WINDS</u>…

  and winds carry away ang.mom. too

What happens to the donor after losing layers?

- Can the donor regain its stability after RLOF?
  - if yes: ***stable*** mass transfer – or detachement (depending also on RL-evolution)
  - if no: ***unstable*** mass transfer (😳)
- Stable mass transfer:
  - donor remains in thermal equilibrium while continuing mass transfer driven by stellar evolution related expansion (or by orbital shrinkage due to ang. mom. loss)
  - donor does not remain in thermal eq. but the mass transfer may still be stable, driven (self-regulatingly) by thermal readjustment of the donor

hardcore stuff

$\tau_{nuc} \gg \tau_{KH} \gg \tau_{dyn}$

What happens to the donor after losing layers?

- Can the donor regain its stability after RLOF?
  - if yes: ***stable*** mass transfer – or detachement (depending also on RL-evolution)
  - if no: ***unstable*** mass transfer
- Stable mass transfer:
  - donor remains in ther... ...ibrium while continuing mass ...tion related expansion (or by ...s)
  - ...ut the ...n ...ment of the donor

Detailed calculations show that stars with **radiative envelopes** shrink rapidly (τ_{dyn}) in response to mass loss, while stars with **convective envelopes** tend to expand or keep a roughly constant radius (τ_{KH}).

hardcore stuff

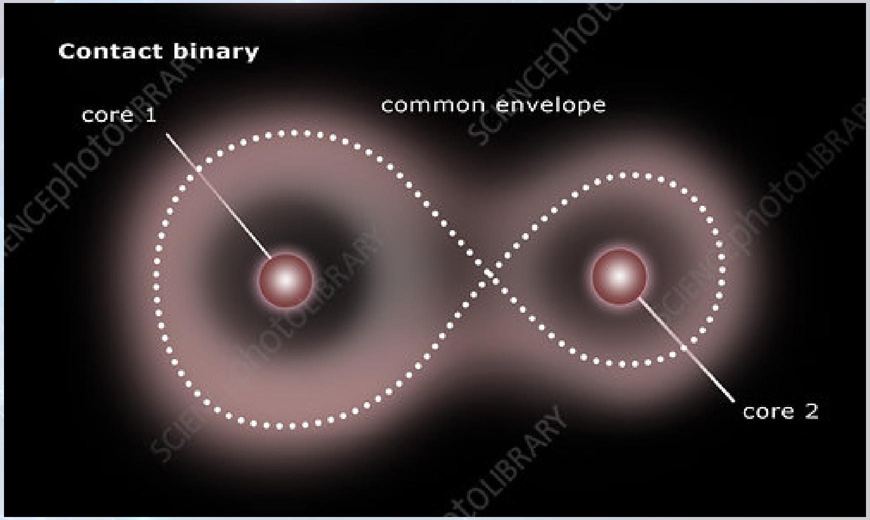
$\tau_{nuc} \gg \tau_{KH} \gg \tau_{dyn}$

Unstable mass-transfer

- if the donor is expanding too quickly ($\tau_{\rm dyn}$) and thus cannot stay within its Roche lobe: ever-increasing mass-transfer rates
- this is an unstable, runaway situation

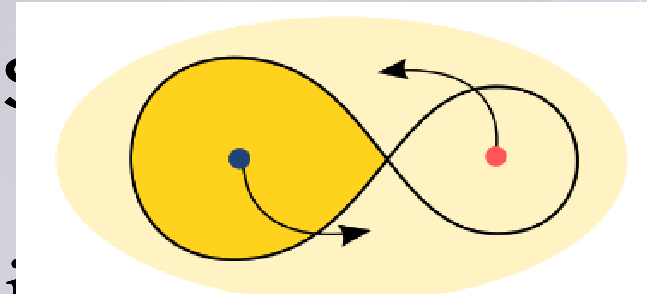
secondary cannot accrete fast enough

- has dramatic effects: “common envelope” situation

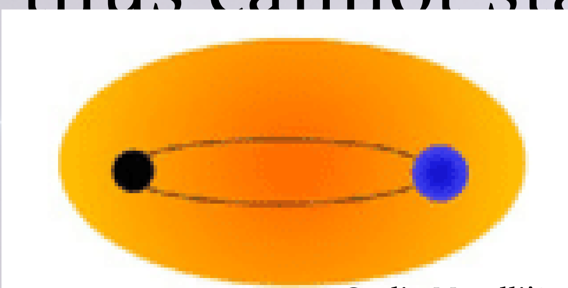


$\tau_{\rm nuc} \gg \tau_{\rm KH} \gg \tau_{\rm dyn}$

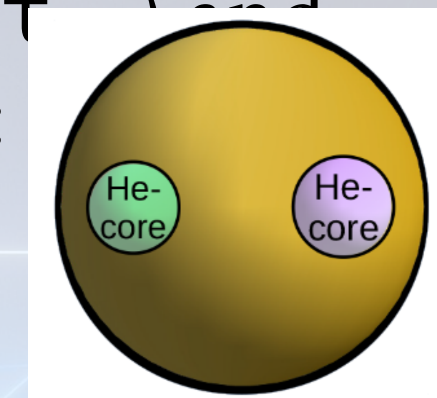
Uns… -transfer


Credit: Siess+18

- if the donor i… quickly (τ…) and thus cannot stay within its Roche lobe: …ss-transfer rates

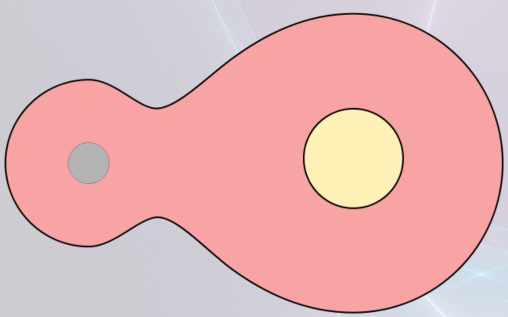

Credit: Mapelli'21

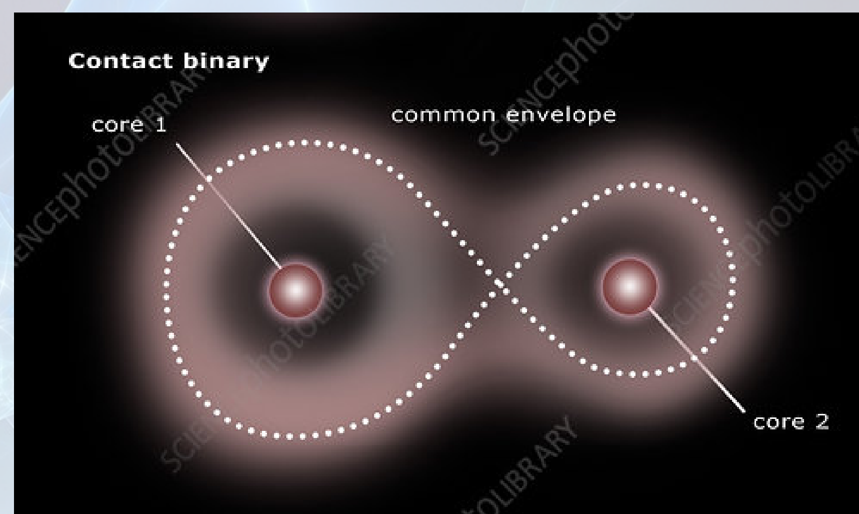

Credit: A. Potter (astrobites)



Credit: Yours Truly ;) [Vigna-Gomez+18]

- …able, ru… on
- has dramatic effects: “common envelope” situation


Credit: Wikipedia



$\tau_{\rm nuc} \gg \tau_{\rm KH} \gg \tau_{\rm dyn}$

What we know about CE

- short lived phase
  - observed?? how??

Movies :)

Passy+12: 0.88 $M_\odot$ (RG) + 0.15 $M_\odot$ companion	*Moreno+21:* 10 $M_\odot$ (RSG) + BH companion

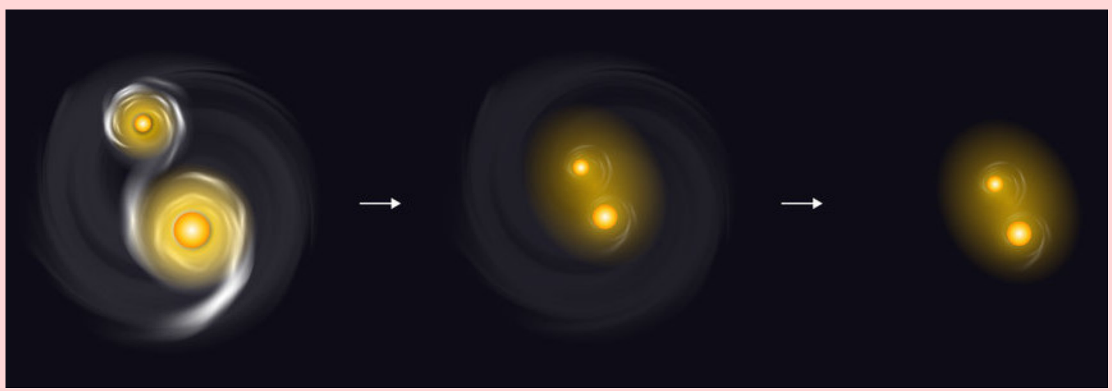
- but it probably occurs
  - explaining close white dwarf-binaries (WD=ex-Red Giant: no other way to get that close)
- 3D simulations are still very expensive
  - in practice: derived relations between orbital energy & binding energy of the envelope
- Result: envelope is (probably?) ejected due to friction. (If not: merger. *No GW possible.*)

  of the two stellar cores

What we know about CE

Leads to the 'hardening' (=shrinking) of the orbit.

(If the system survives, and not merge.)



Credit: MPIA

sult: envelope is (probably?) ejected due to

ction. (If not: merger. ***No GW possible.***)

of the two stellar cores

Let's play!

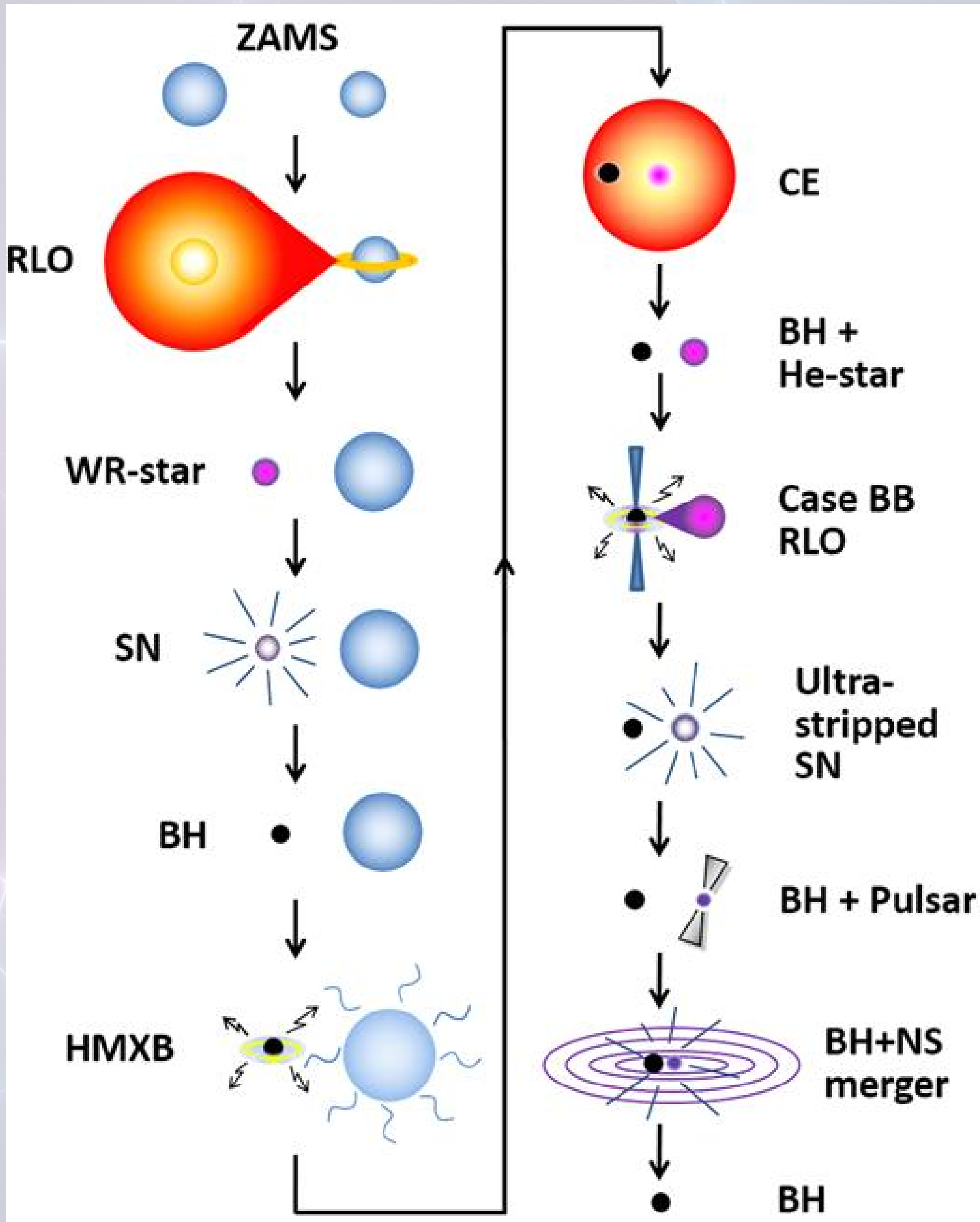
Zero-age Main Seq.

Roche-lobe overflow:
stable mass transfer

Wolf-Rayet star
(naked He-star with
strong emission lines)

Supernova may kick out
the companion! Survival
rate?

Accreting black hole:
High-Mass X-ray Binary
(observed: periodic
pulsations in X-rays)



Common Envelope! 😳

Probably a HMXB?

Stripped = type Ib
Ultra-stripped = type Ic

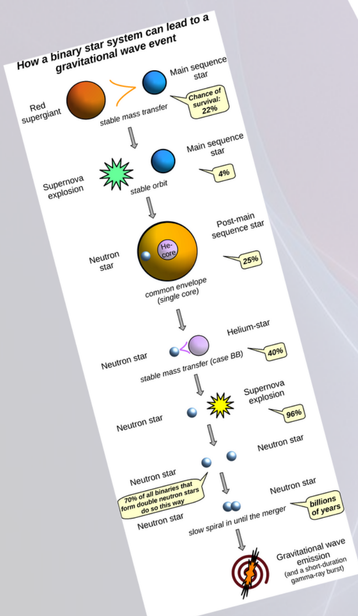
(Pulsar: a rotating,
magnetized neutron sta

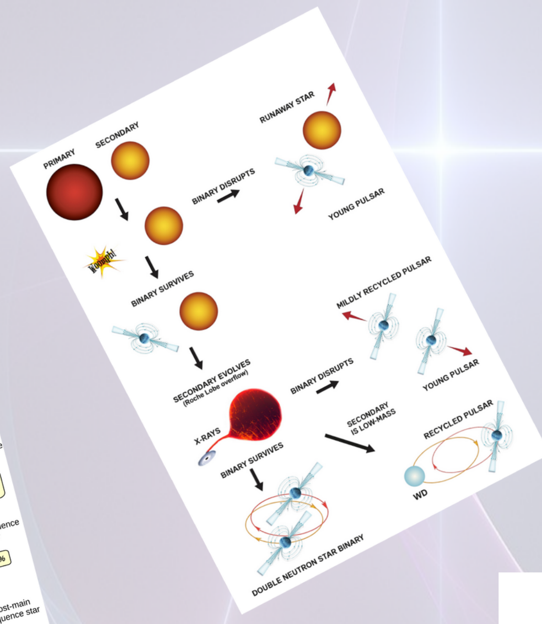
GRAV. WAVES!!!

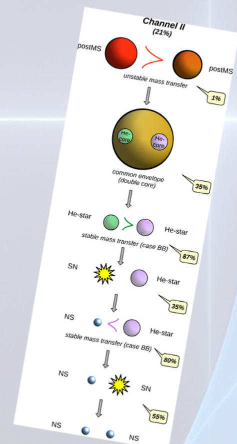
Credit: Kruckow+18

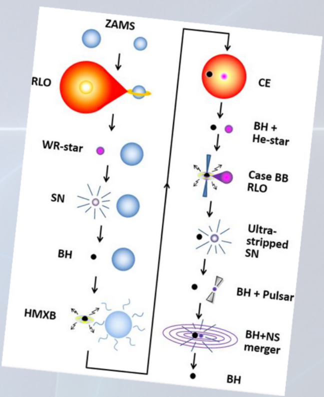
Possible exam question ;)

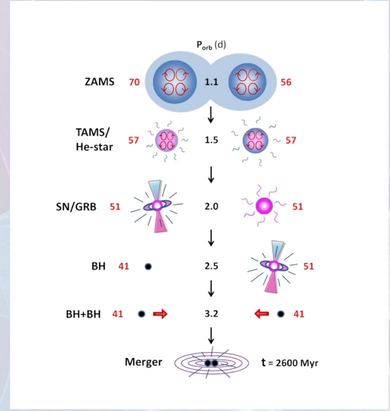
- explain a binary evolution cartoon scientifically!

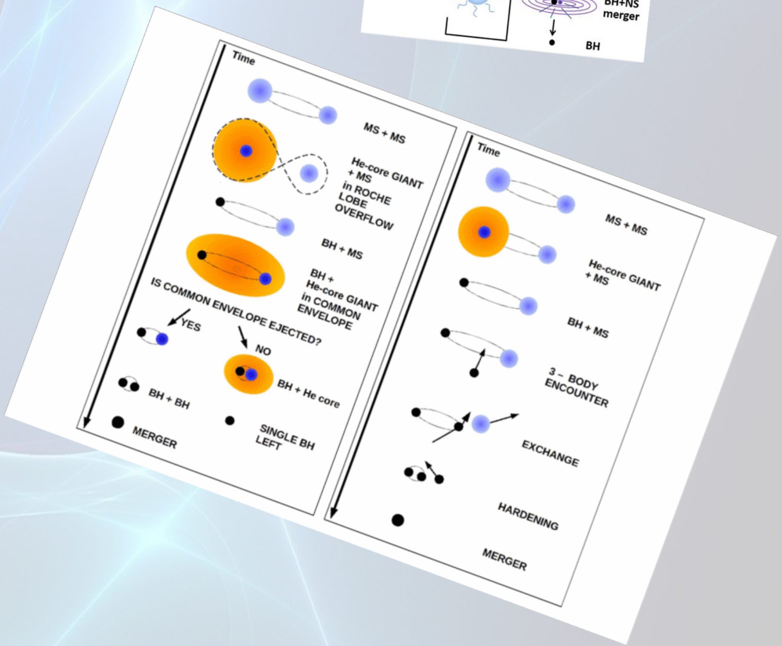






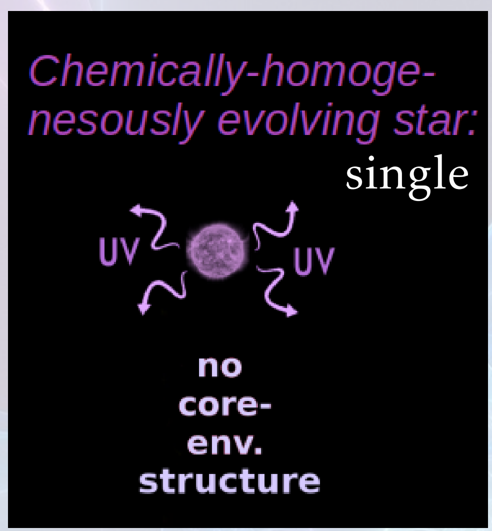






→ sub-Solar metallicities?
→ fast-rotating stars?
→ stars in a binary system?

What about a metal-poor, fast rotating binary system?



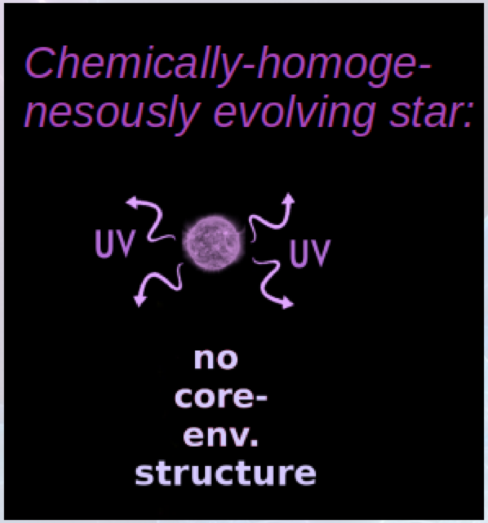
→ sub-Solar metallicities? ✓

→ fast-rotating stars? ✓

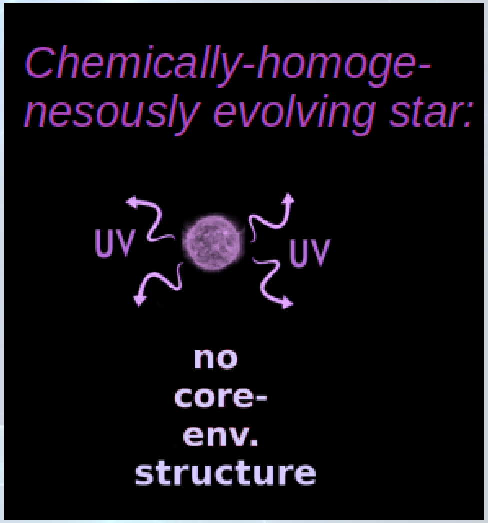
→ stars in a binary system? ✓

What about a metal-poor, fast rotating binary system?

Let's put two of them next to each other on a (very) close orbit!

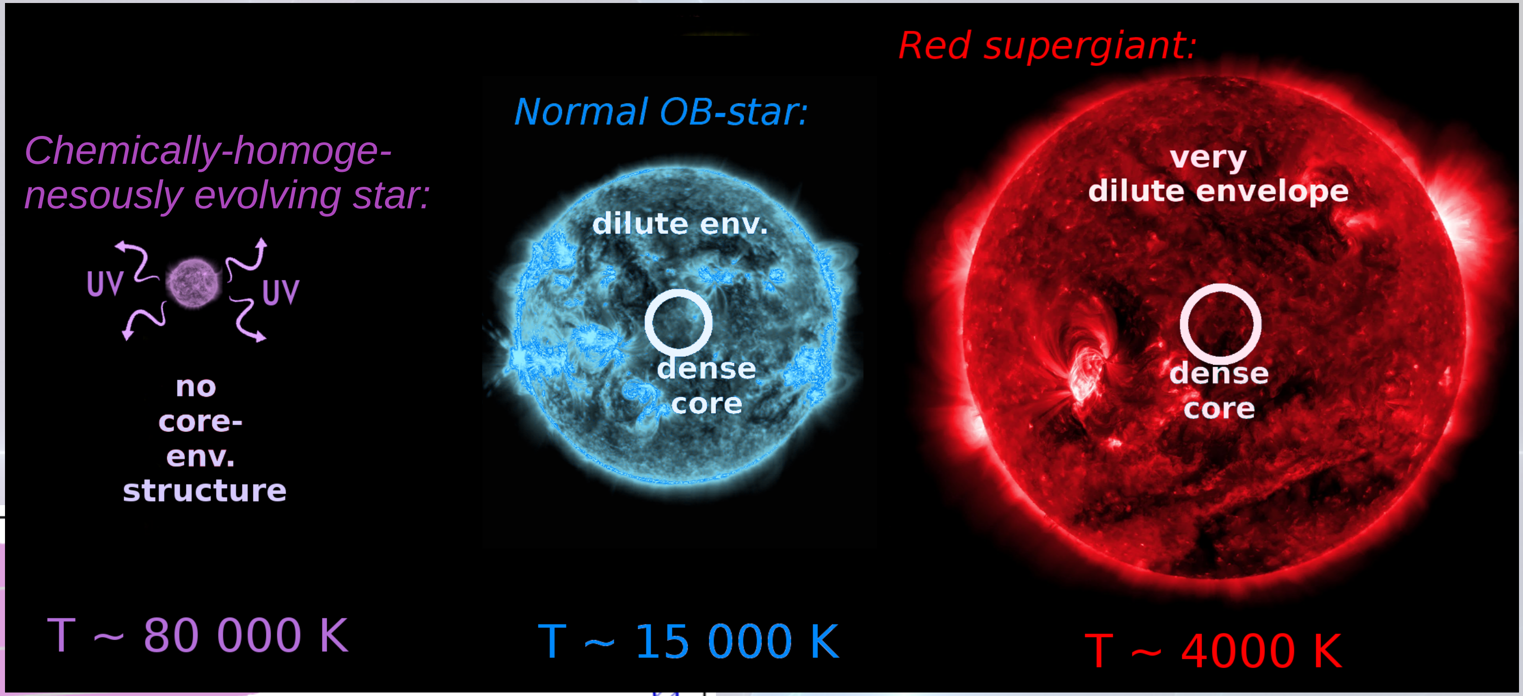


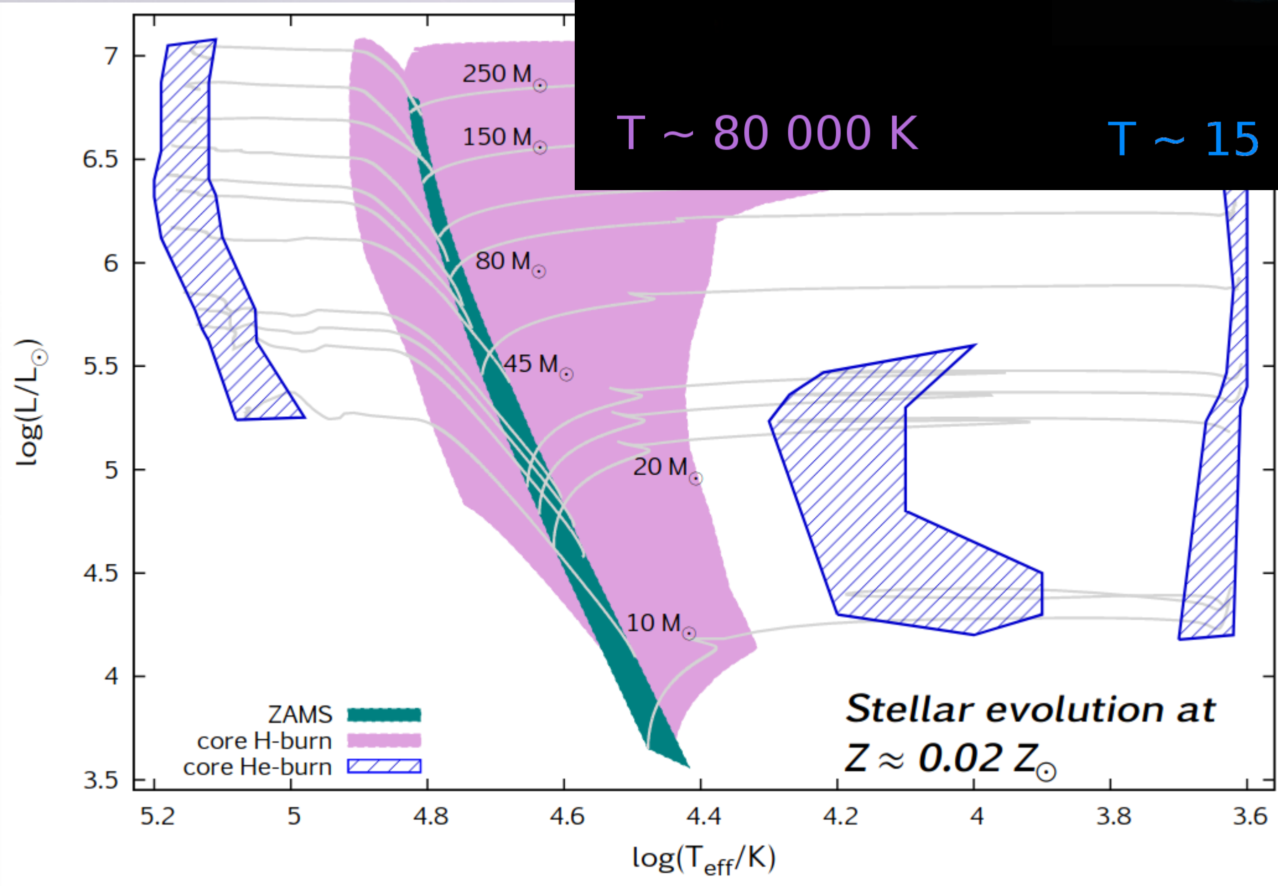
+

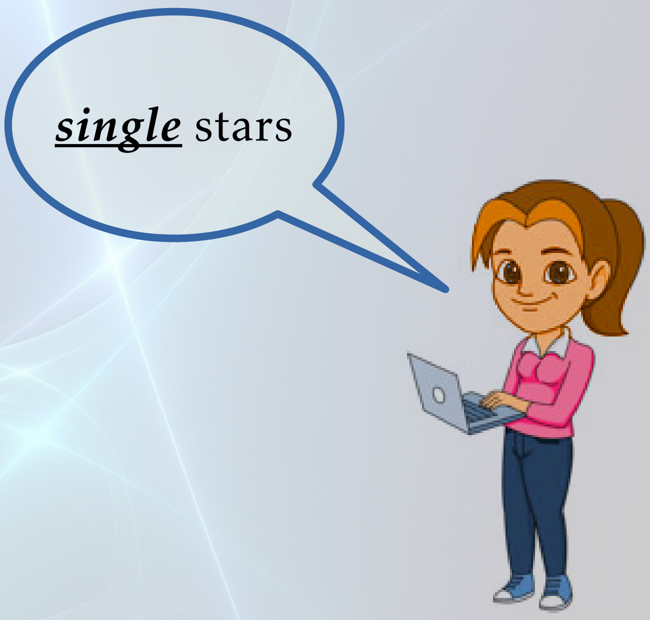


= ?

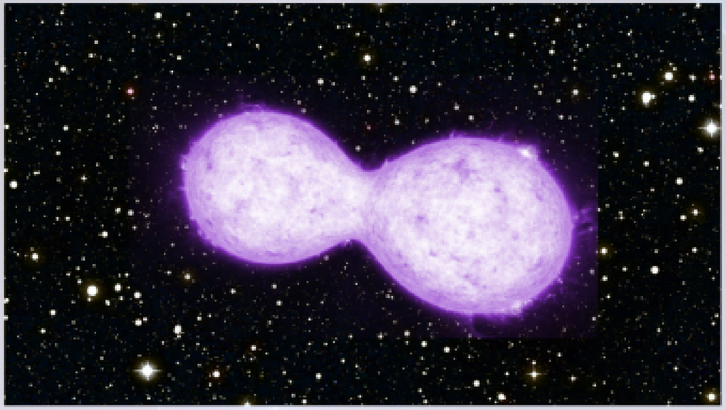
What do chem.hom. evolving stars look like?







Gravitational waves... theoretical origin!



e.g. **Szécsi**'17a

Szécsi'17b

Bagoly,**Szécsi**+16

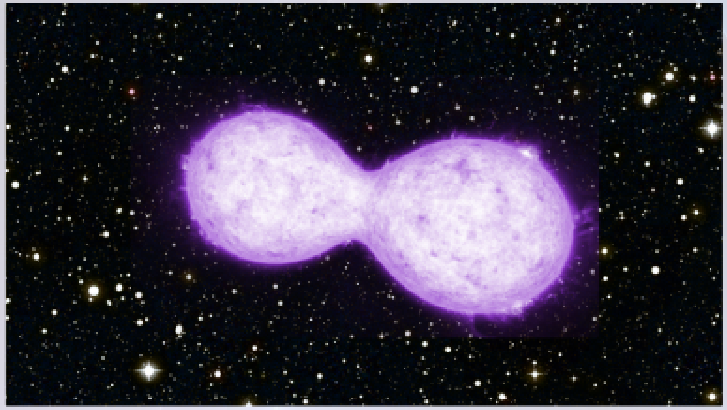
Marchant+16,17

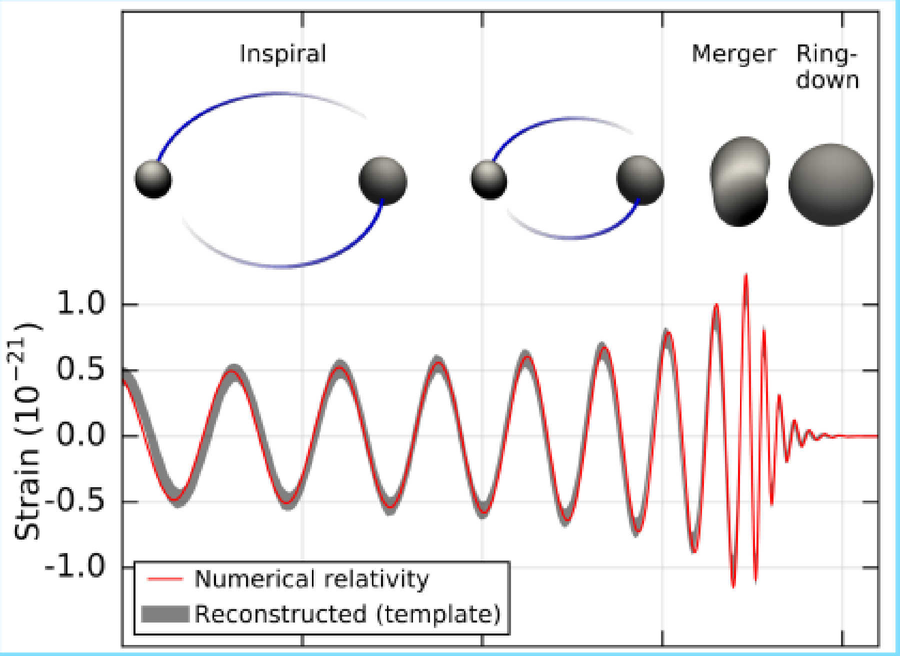
Gravitational waves... theoretical origin!

Life — Massive binaries

Death — Explosions

Afterlife — 2 Black Holes (or Neutron Stars)





Credit: http://gallatin.physics.lsa.umich.edu

'Second death'

Merger

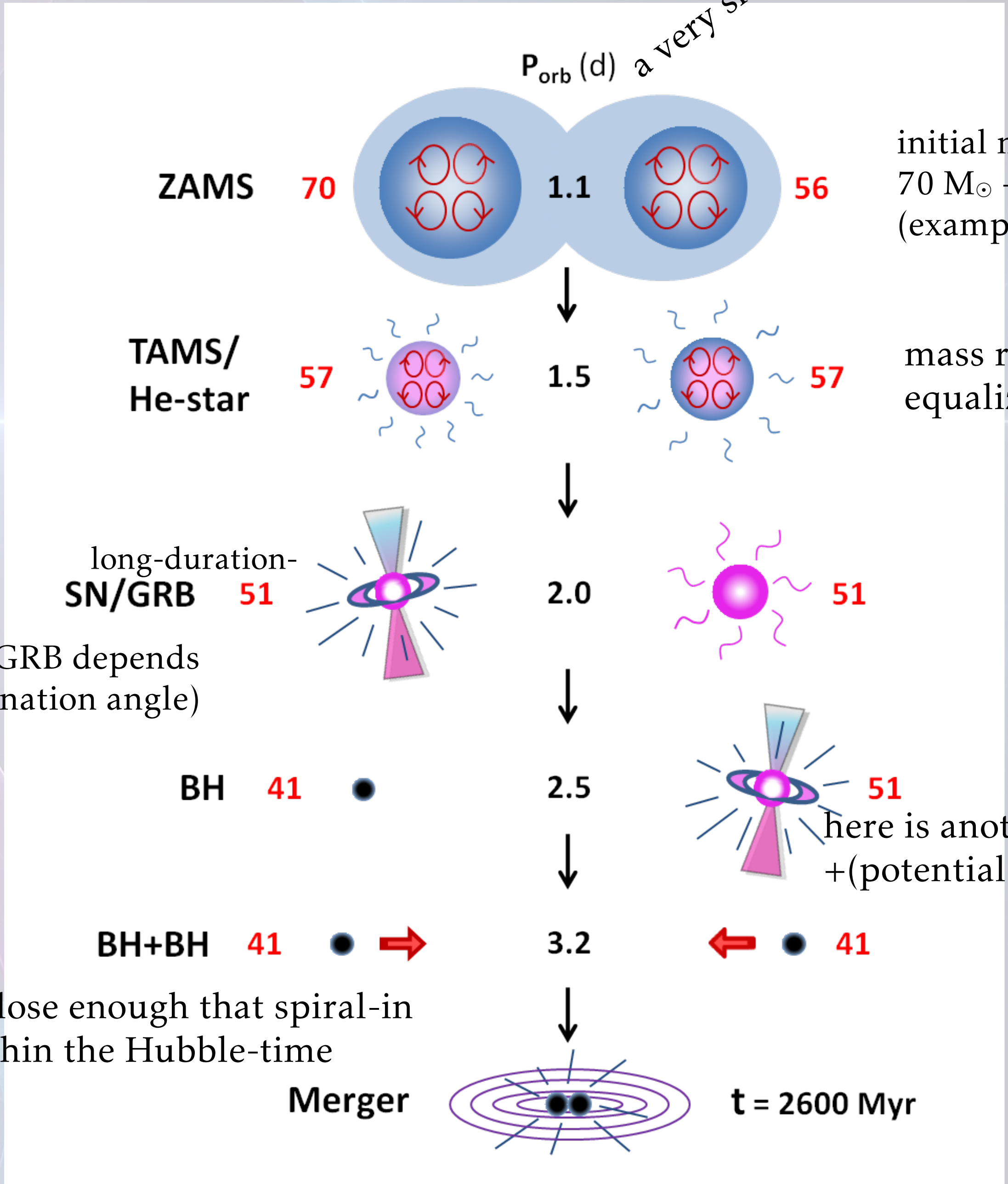
e.g. Szécsi'17a

Szécsi'17b

Bagoly,Szécsi+16

Marchant+16,17

To "cartoonize" the scenario:



initial masses
70 $M_\odot$ + 56 $M_\odot$
(example)

mass ratio (q)
equalizes

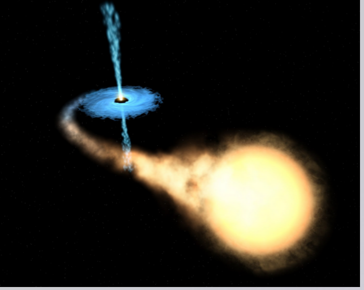
(seeing the L-GRB depends on the inclination angle)

Remember: to see a GRB, we need to look right into the jet!

here is another SN +(potential) L-GRB

system is still close enough that spiral-in can happen within the Hubble-time

Credit: Marchant+16



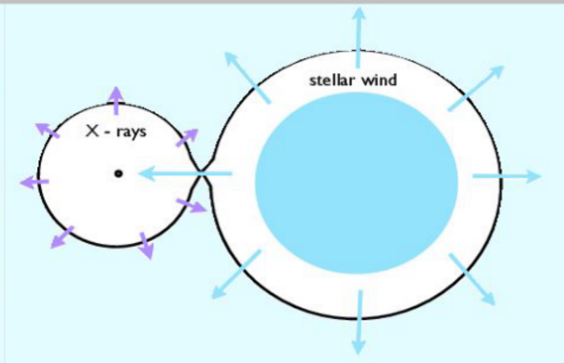
HMXB = High-mass X-ray binary

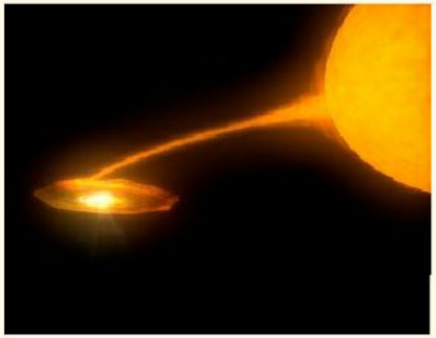
Observed:
~ 200 LMXB in the MW
some more in other gals.
> 100 HMXB in MW
e.g. ***Cygnus X-1***

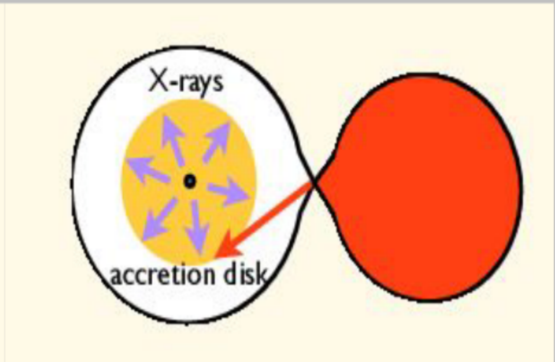
- sister object: LMXB = Low-mass X-ray binary
- X-rays are produced by the matter falling from the (stellar) companion to the NS or BH
  - if the companion is a low-mass star (or a WD): LMXB
  - if it's a massive star: HMXB
- Massive stars have strong winds! It contributes.

periodic X-ray pulses

HMXB's | **LMXB's**



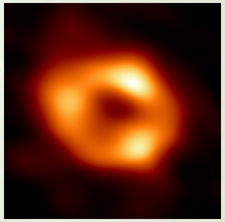




Microquasars

- basically HMXBs which also emit in radio
  - the source of the radio emission is two jets* (*see next slide)
  - Cygnus-X1 is also a microquasar

- name comes from 'quasars' also known as 'quasi-stellar object" (QSO) – discovered in the 50s as radio sources of unknown origin
  - ***galaxies where the central BH eats up the stars…***
  - → active galactic nucleus (AGN)
  - powered by a ***supermassive*** BH ($\gtrsim 10^6$–10^9 $M_\odot$)
    (as opposed to a ***stellar mass*** BH as in a HMXB/microquasar)
  - **THIS WEEK'S MOST EXCITING NEWS!!**
    Capturing our MW's central BH by the "Event Horizon Telescope" (not a real telescope; but a collaboration of radio observatories & clevera data reduction techniques :D)



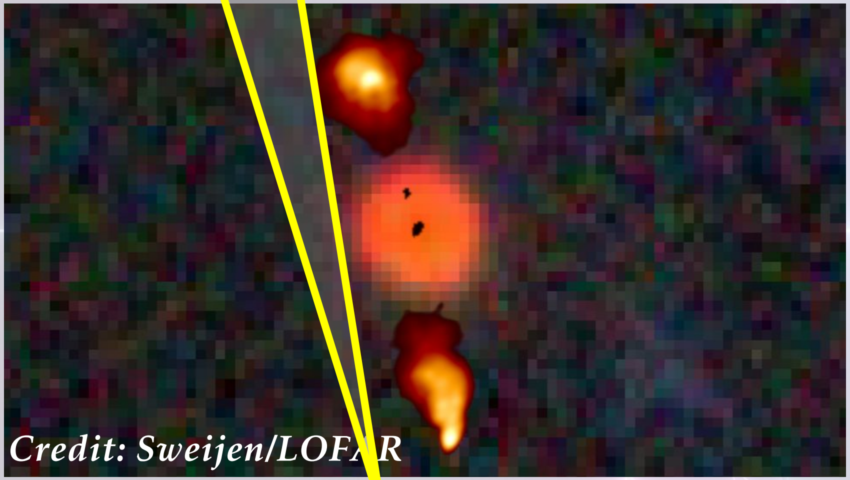
Sgr A*
4×10^6 $M_\odot$

not a very active nucleus (fortunately)

Jets (in astronomy)

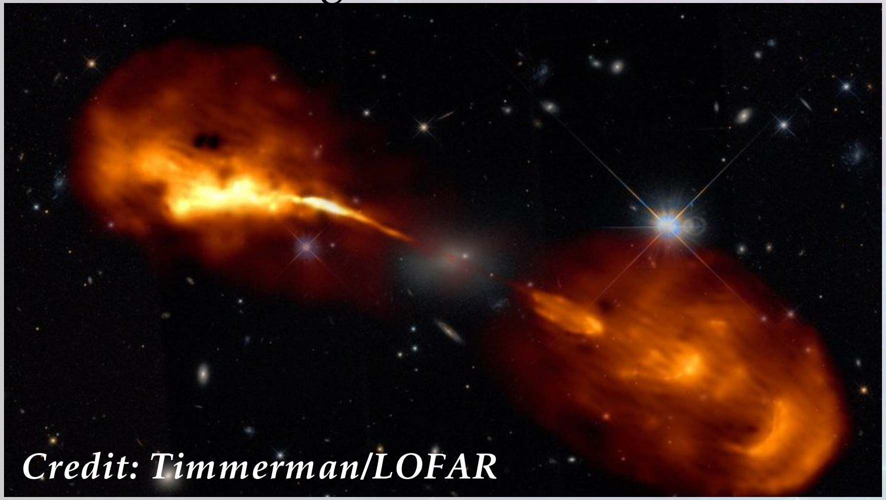
And also microquasars, of course.

Actual observation (2021, LOFAR):



AGNs

Artistic image of the same stuff:



long-living

short-living

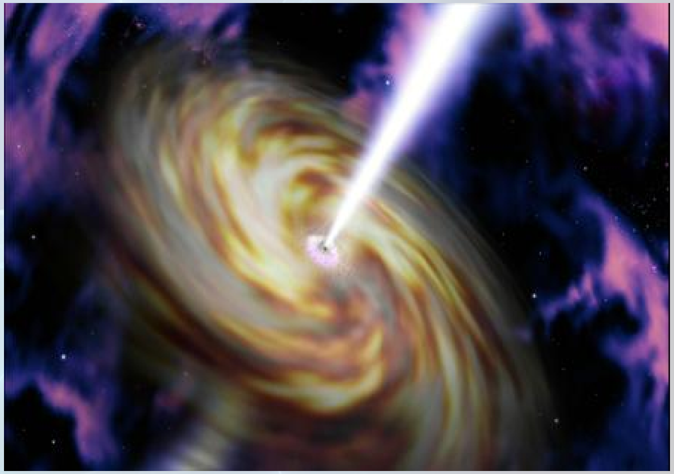
(timescales
are proportional
to the mass
of the central BH)

??

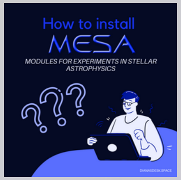
spectral features (breaking)
high energies cannot be explained otherwise

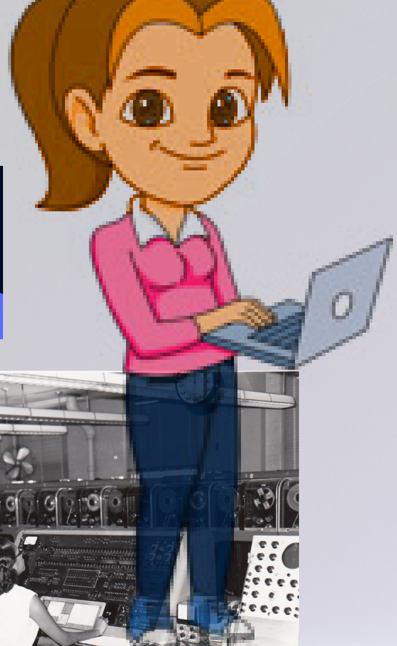
GRBs

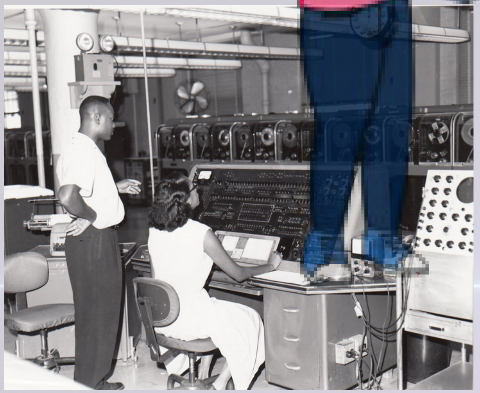
Artistic image:



From individual systems
to
populations







HR-diagram

Age, Mass, Radius, **T_{eff} [K]**, **$\log(L/L_{\odot})$**, Massloss rate…

```
# 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
         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         -6.6695769233523099E-009          4.6184809906170159E+000          0.0000000000000000E+000
         2.7736114895786840E+005          1.9999699193502106E+001         -6.6697558468033889E-009          4.6188749271645166E+000          0.0000000000000000E+000
         2.7760558384698193E+005          1.9999697555133814E+001         -6.6699347702544679E-009          4.6192688637120174E+000          0.0000000000000000E+000
         2.7785001873609552E+005          1.9999695916765514E+001         -6.6701136937055478E-009          4.6196628002595173E+000          0.0000000000000000E+000
```

IMPORTANT

Exam warning! :P

- Stellar evolution modelling
  - based on first principles ***(5 stellar equations)***
  - follows one star's life at the time
  - IMF is not yet considered
  - result is ***a line*** ('track') in the HR-diagram

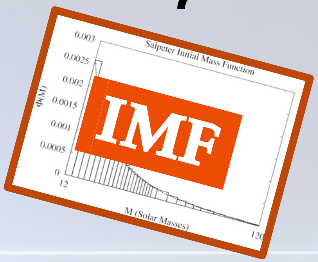
- Synthetic population modelling
  - ***relies*** on stellar evolution modelling
  - does not simulate the individual star's life (typically)
  - IMF is taken into account
  - result is a ***statistically meaningful*** prediction about a ***population***

under active research

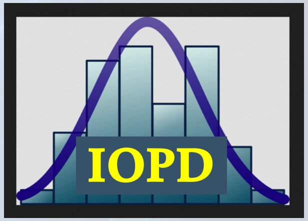
Population synthesis on ***binaries***

- 2 stars instead of 1
  - both have their individual IMFs

(related?)



- orbital separation!
  - Initial Orbital Period Distribution
    same kind of thing as the IMF but for the period,
    i.e. an observation-based statistical distribution

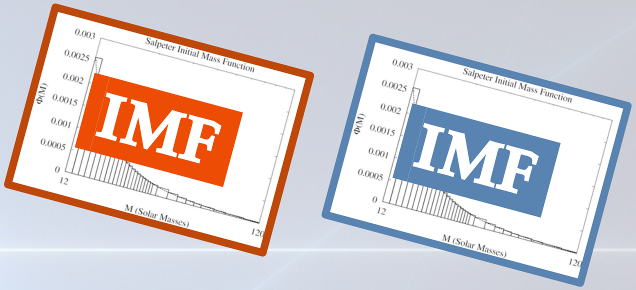


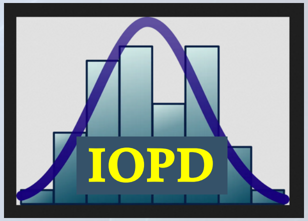
- plus a ***lot*** of assumptions about the evolution
  - mass transfer (stable/unstable? conservative/non-conservative? ...)
  - Common Envelope phase (outcome: merger or survival? separation afterwards?)
  - supernova physics… and the kick.

on top of what we already don't know about ***single*** stars' evolution

Star-formation history

- We need to know the ***history*** of how the stars are being born…

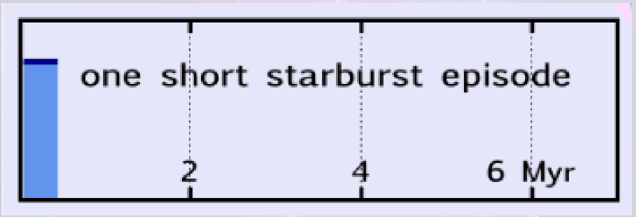




Not enough!

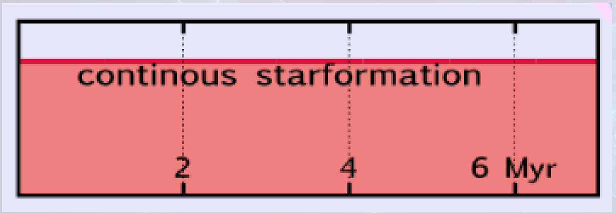
star-formation rate

SFR



or anything else

SFR

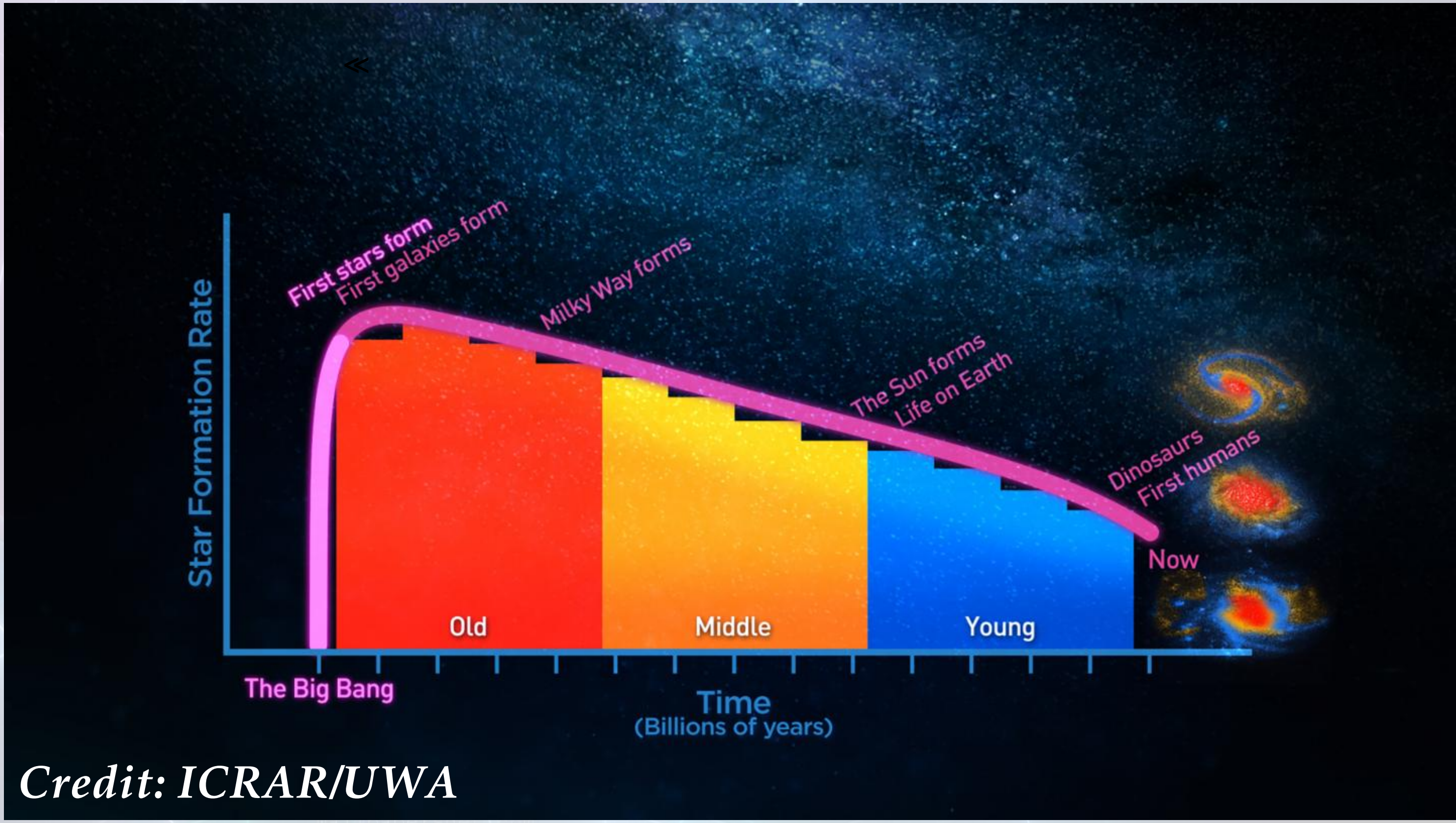


Unit: $M_\odot$/yr

We need all these to do (binary) population synthesis.

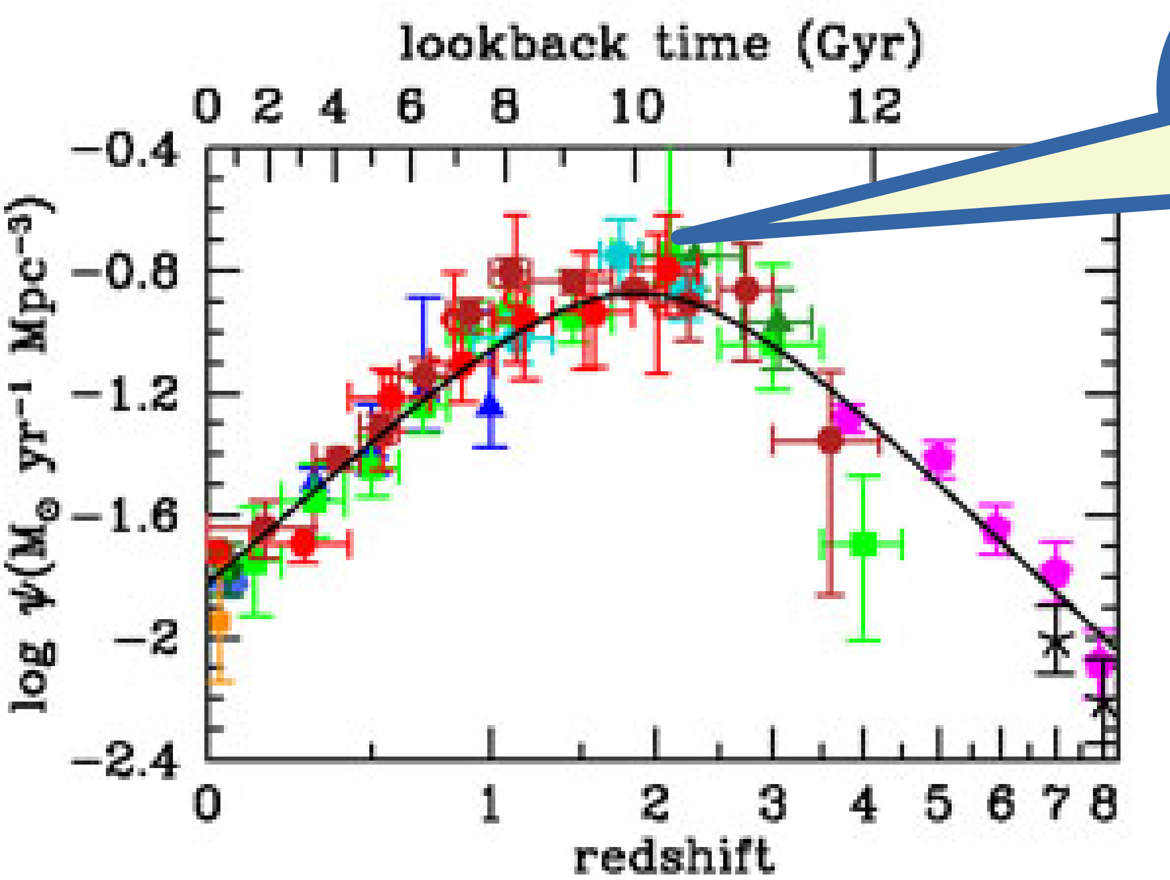
From star-formation history to ***cosmic*** star-formation history

- This is what we need to predict GW-event rates from synthetic populations



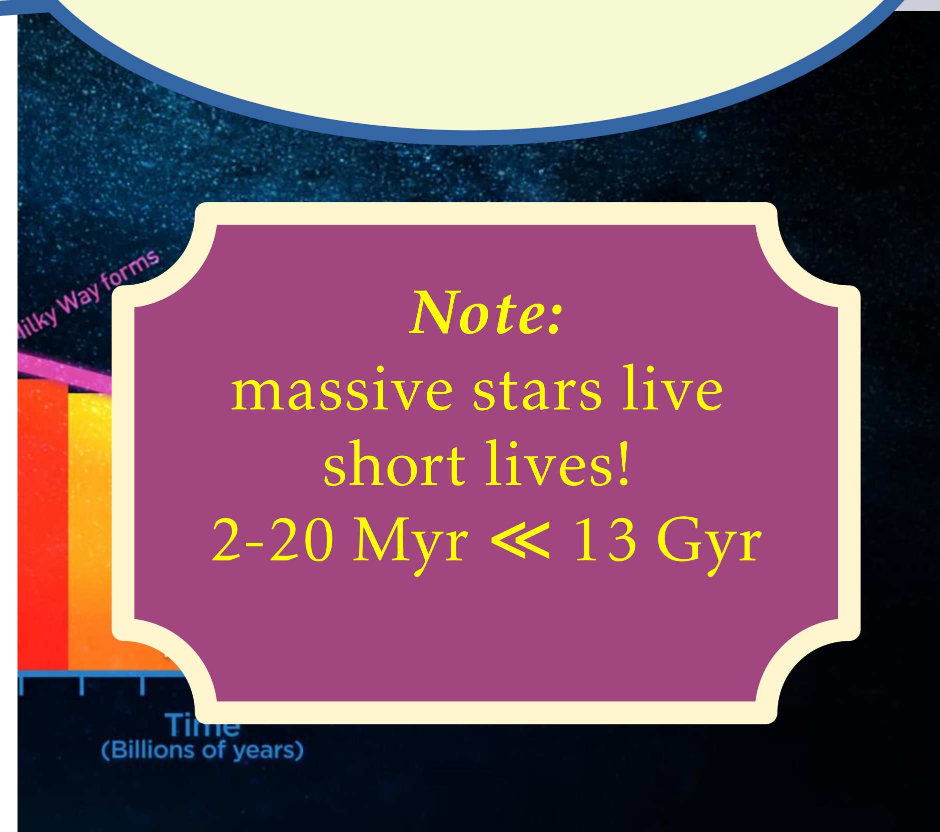
Credit: ICRAR/UWA

From star-formation history to ***cosmic*** star-formation history



Credit: Madau & Dickinson (2014)

Peaking: somewhere around z = 2, when the Universe was ~3.5 Gyr old

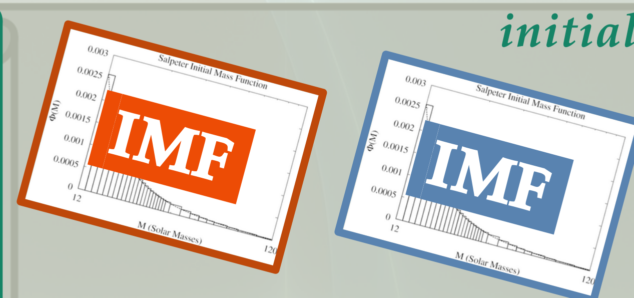


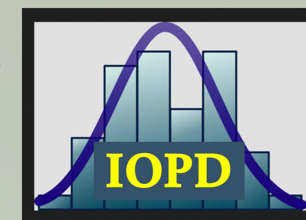
Note:
massive stars live short lives!
2-20 Myr ≪ 13 Gyr

Now we can answer the original *(kind of)* question of this whole lecture series

stellar models

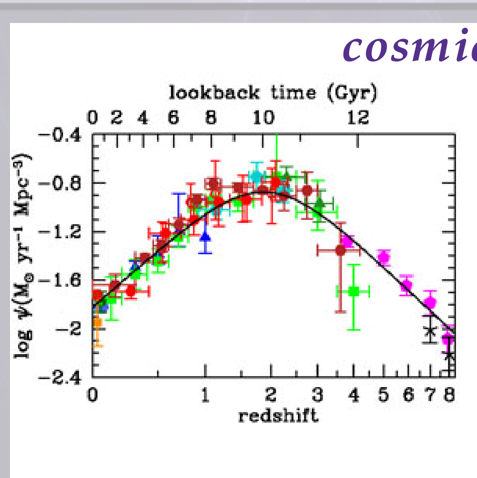
initial distributions

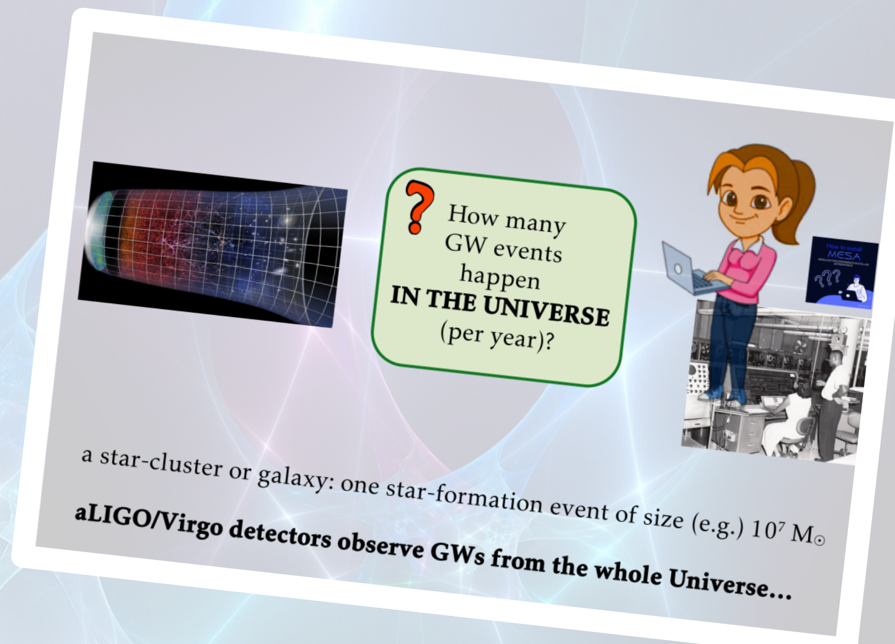




+ a lot of assumptions about binary physics

cosmic SFH

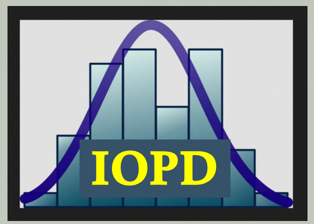




Now we can answer the original *(kind of)* question of this whole lecture series

stellar models

initial distributions



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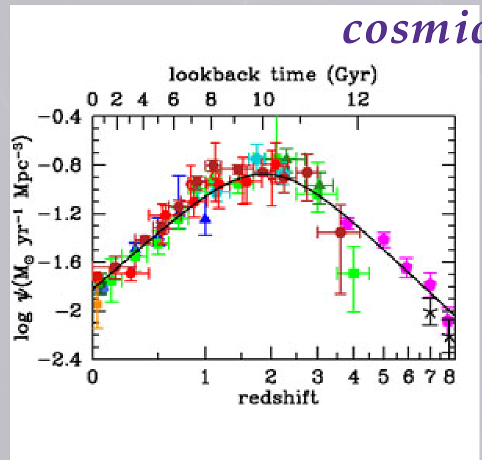
cosmic SFH



Important piece of math:

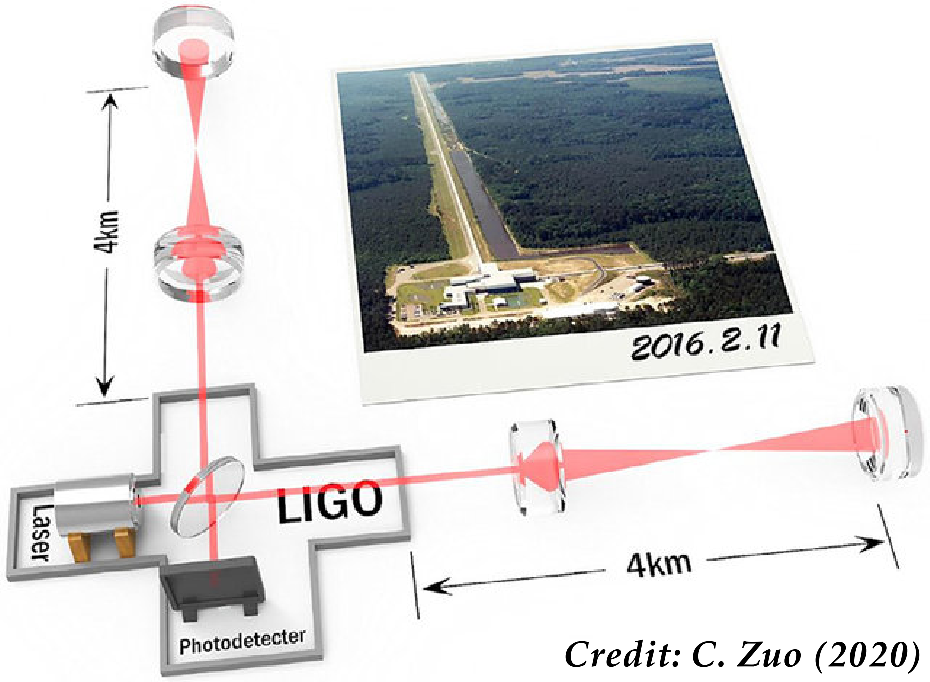
Convolution

of two functions

$$(f * g)(t) := \int_{-\infty}^{\infty} f(\tau)\, g(t-\tau)\, d\tau.$$

And some names you MUST know

- LIGO:
  - Laser Interferometer Gravitational-wave Observatory (USA)
- **aLIGO**
  - advanced LIGO
  - the current version
- **Virgo**
  - LIGO's important little sister in Europe



Credit: C. Zuo (2020)

The Einstein equations are canonical 2

Einstein equation!

$G(g) = 8\pi T(g)$

$$R_{ab} - \frac{1}{2} S \cdot g_{ab} + \Lambda \cdot g_{ab} = 8\pi T_{ab}.$$

- Based on experience in physics, we want to have a differential equation, thus $\alpha \neq 0$ and we can assume $\alpha = 1$ by rescaling.
- The constant turns out to be 8π in our system of units.
- For the sake of simplicity, we will take $\Lambda = 0$ in this lecture.
- We have seen that the Ricci tensor tells us how the volumes change, which plays nicely with the interpretation of curvature as gravity.

The Einstein equations are hard so solve

In terms of the metric, the Einstein equation looks like this:[2]

$$g_{ab}(x) \equiv \begin{pmatrix} -1 & & & \\ & 1 & & 0 \\ & & 1 & \\ & & & 1 \end{pmatrix}$$

$$\frac{1}{2}g^{ab}\partial_a\partial_m g_{bn} + \frac{1}{2}g^{ab}\partial_a\partial_n g_{mb} - \frac{1}{2}g^{ab}\partial_a\partial_b g_{mn} - \frac{3}{2}g^{ab}\partial_m\partial_n g_{ab}$$
$$-\frac{1}{2}g^{bl}g^{ar}\partial_a g_{rl}\partial_m g_{bn} - \frac{1}{2}g^{bl}g^{ar}\partial_a g_{rl}\partial_n g_{mb} + \frac{1}{4}g^{bl}g^{ar}\partial_n g_{al}\partial_m g_{rb}$$
$$+\frac{1}{4|g|}g^{ab}\partial_b|g|\partial_n g_{ma} - \frac{1}{4|g|}g^{ab}\partial_b|g|\partial_a g_{mn} - \frac{1}{4|g|}g^{ab}\partial_b|g|\partial_m g_{an}$$
$$+\Lambda g_{mn} \qquad = 8\pi T_{mn}.$$

Finding solutions is hopeless except for **highly symmetric** situations (Minkowski, Schwarzschild, Robertson–Walker etc.) or with **extra conditions** (global hyperbolicity, Choquet-Bruhat etc.).

[2] The credit for the explicit formula goes to Ville Hirvonen from Profound Physics.

Linearization

This is where the linearized theory comes into play: suppose we have a "background" solution g_{ab} of the full Einstein equation

$$G(g) = 8\pi T(g)$$

and look for solutions of the form

$$g_{ab} + \epsilon h_{ab}$$

where h_{ab} is a symmetric tensor.

$$G(g + \epsilon h) = 8\pi T(g + \epsilon h)$$

$$G(g) + \epsilon \cdot \left.\frac{d}{d\epsilon}\right|_{\epsilon=0} G(g + \epsilon h) + O\left(\epsilon^2\right) = 8\pi T(g) + \epsilon \cdot 8\pi \cdot \left.\frac{d}{d\epsilon}\right|_{\epsilon=0} T(g + \epsilon h) + O\left(\epsilon^2\right)$$

Plane waves

constant matrix of amplitudes

wave number vector

- Plane wave ansatz:

$$\bar{h}_{ab} = A_{ab} \cos(k_m x^m)$$

- This is a single Fourier mode
- Divergence-freeness implies $k^a A_{ab} = 0$.

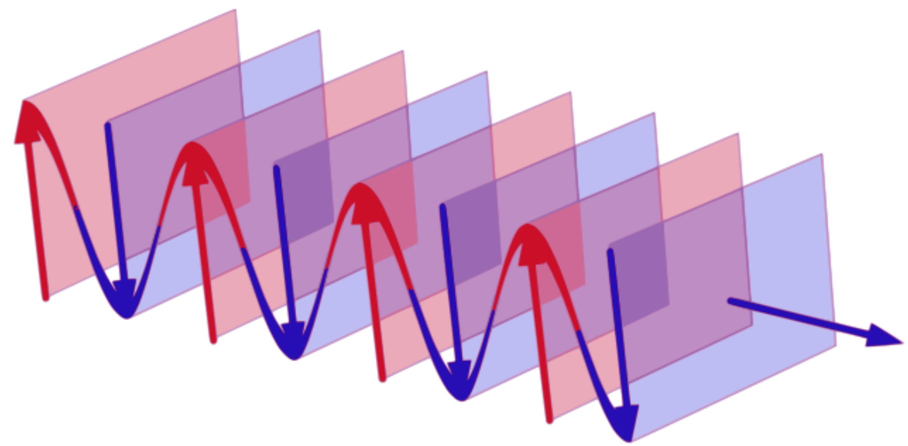


Image credit Wikipedia user Constant314

Our plane wave has only two degrees of freedom

Next suppose we orient our spatial coordinate axes so that the wave is travelling in the positive z-direction, i.e.

$$k^t = \omega, \quad k^x = k^y = 0, \quad k^z = \omega$$

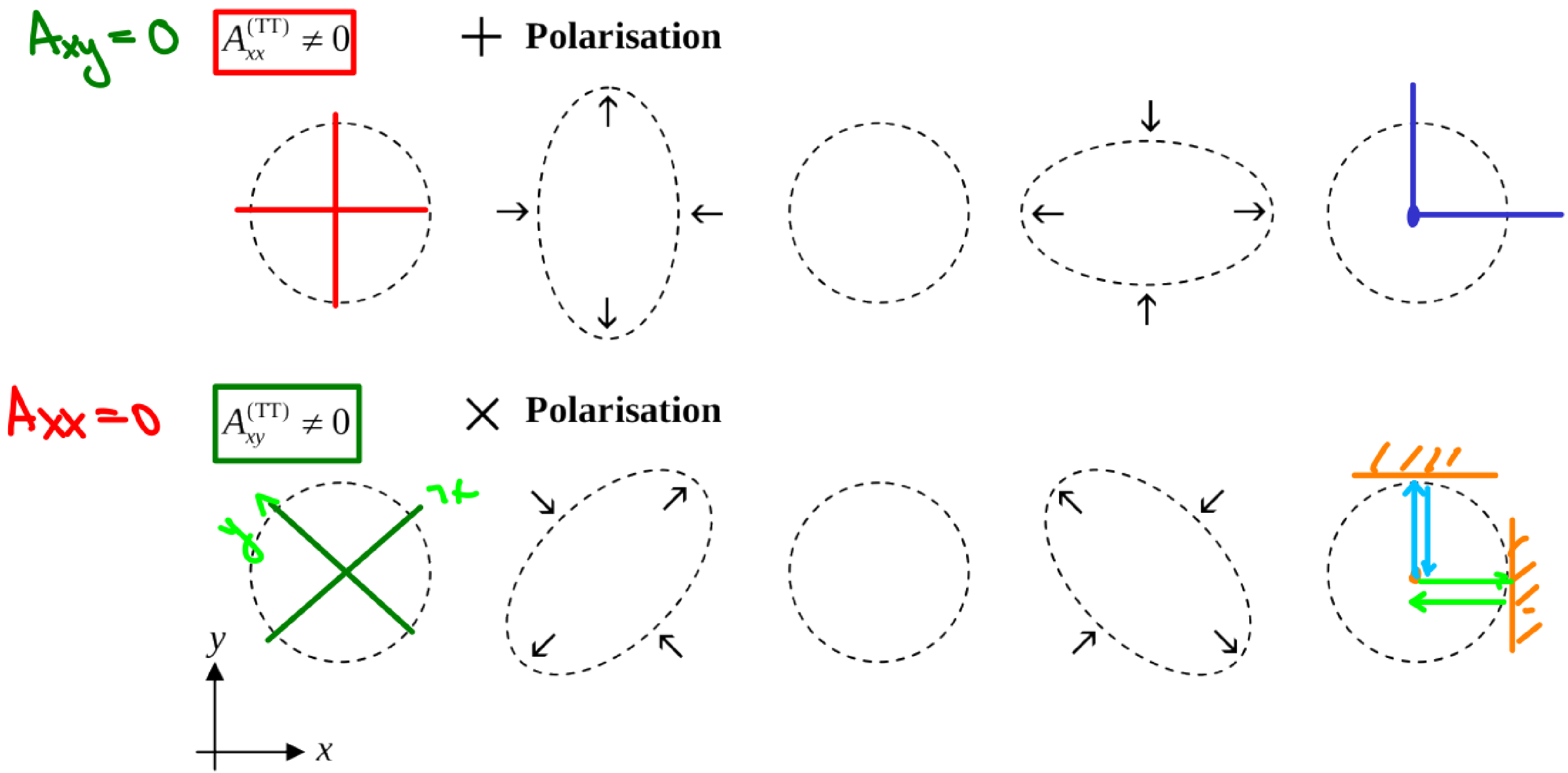
and

$$k_t = -\omega, \quad k_x = k_y = 0, \quad k_z = \omega$$

Then $A_{az} = 0$ for all a.
All in all, we obtain

$$\bar{h}_{mn} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & A_{xx} & A_{xy} & 0 \\ 0 & A_{xy} & -A_{xx} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cos(\omega(t - z))$$

Polarisation states



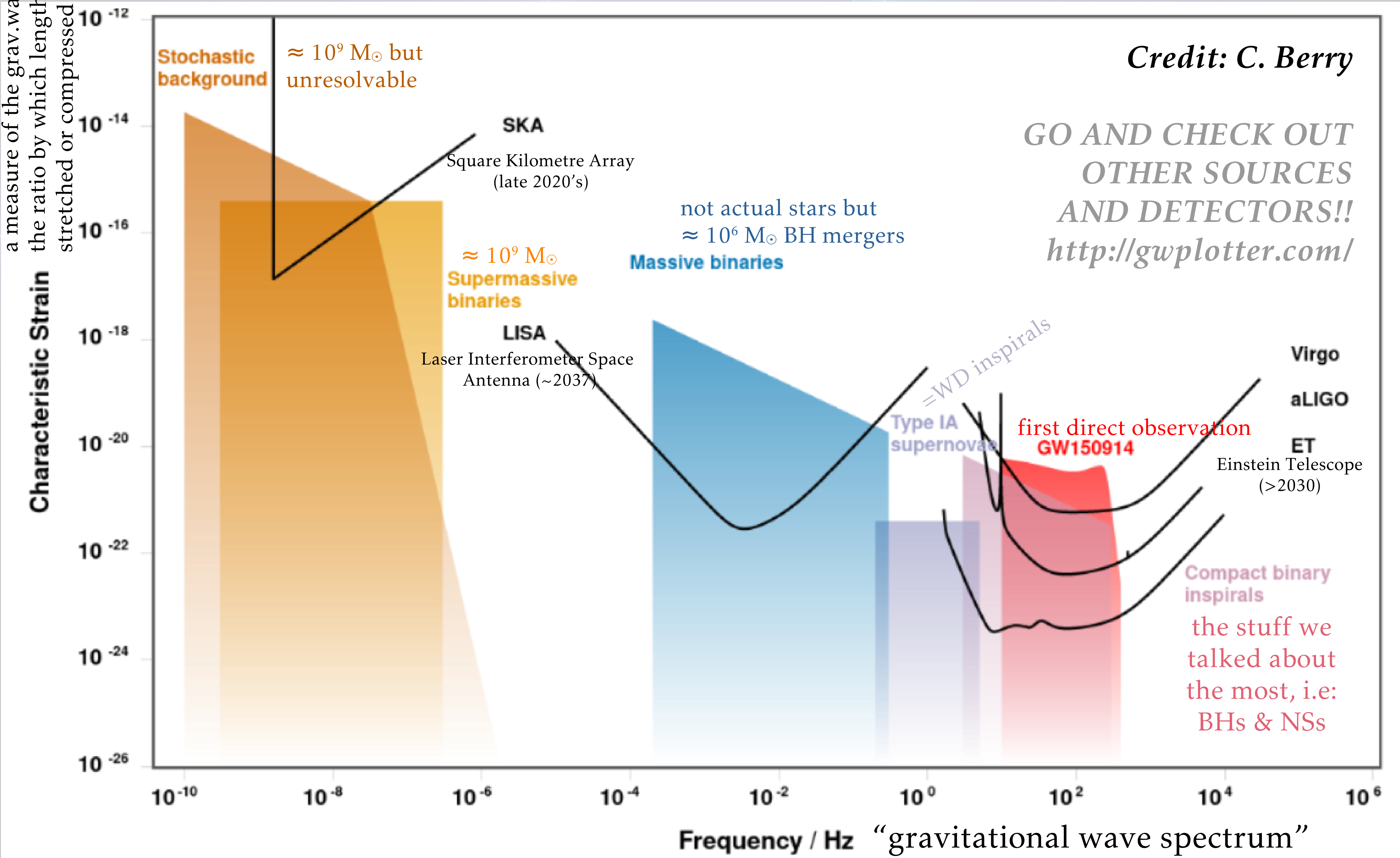
Suggested reading

calculation details about the plane wave

- Chapter 20 in R. D'Inverno, Introducing Einstein's relativity, Clarendon Press, 1998
- B. F. Schutz's lecture notes about Gravitational Waves at the 2011 Azores School on Observational Cosmology (online) ← he talks about detectors, too
- T. Matolcsi, Spacetime without reference frames, Minkowski Press, 2020 (online) ← a clean treatment of elementary spacetimes

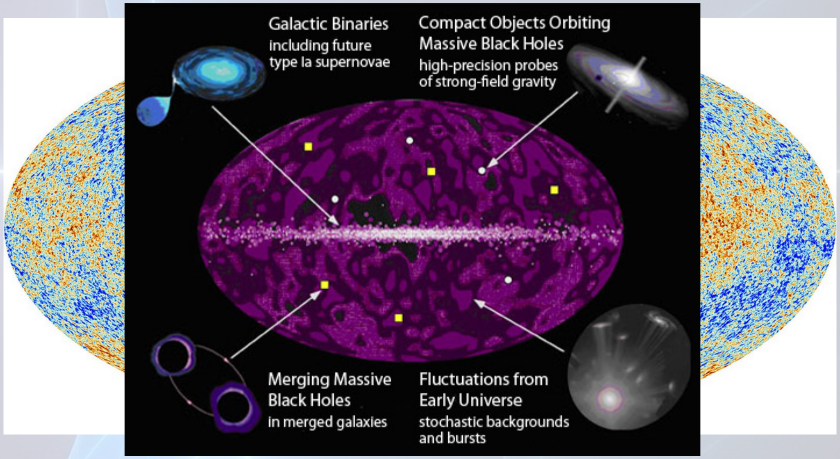
$$\Box h_{ab} + R * h = 0$$

Detector sensibility



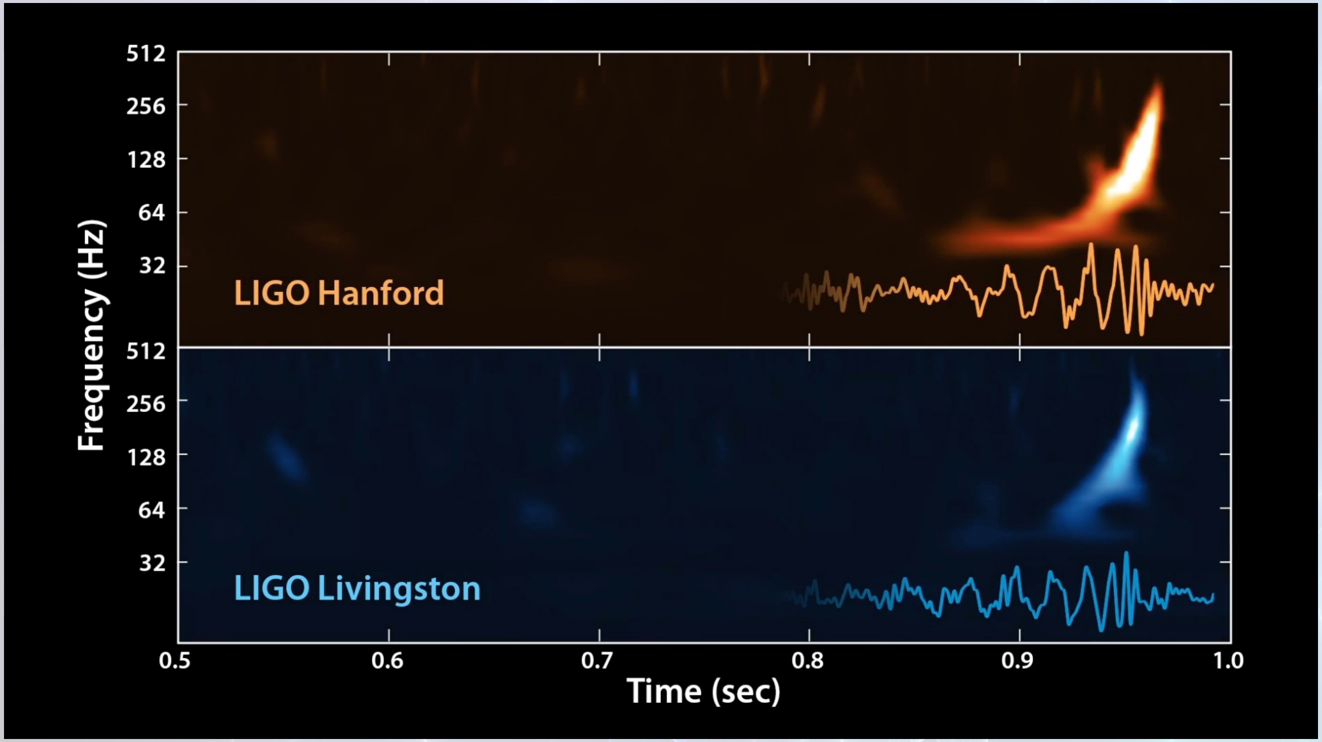
Cosmic grav.wave background

- Heard about the cosmic microwave background?
- GW-background:
  - undetected (yet)
  - cosmological sources
    - processes during e.g. the cosmic inflation (10^{-36}–10^{-33} sec after the Big Bang)
  - astrophysical sources
    - large number of ***unresolvable*** BH-BH (or BH-NS, or NS-NS) mergers; additional WD-WD mergers, supernova explosions…



The whispering of the Universe

https://www.youtube.com/watch?v=2PzbYK1x3Vo



'GW150914'

35 $M_\odot$ & 30 $M_\odot$

(BH+BH)

=

64 $M_\odot$

3 $M_\odot$ converted into GWs!