Gravitational-wave progenitors

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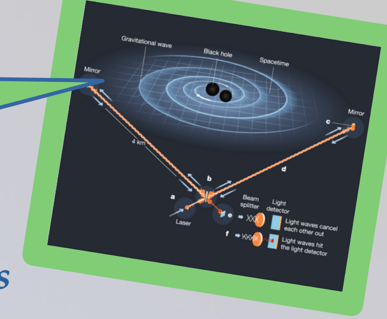
Lecture #8

NCU, Summer Semester 2022

Previously
on GW-progenitors...

To form very heavy BHs
(which go on to merge & emit GWs),
low-metallicity is needed.



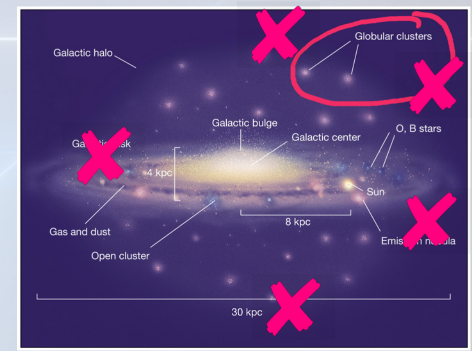
massive stars have strong, Z-dependent winds

Where can we find stars*

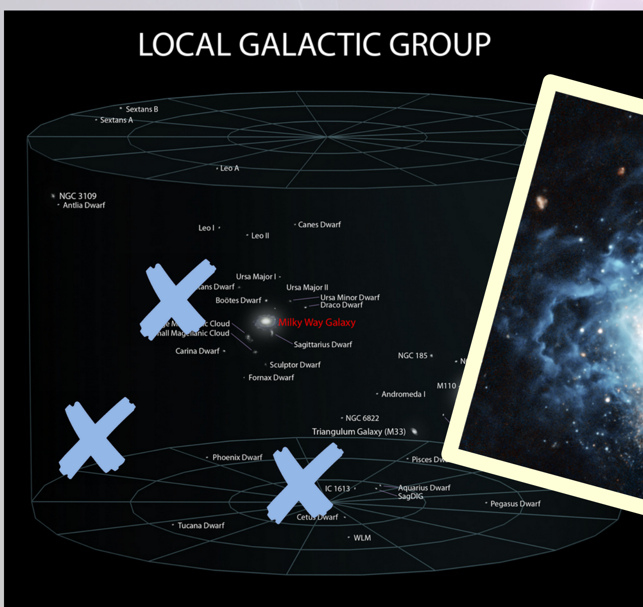
*gas/galaxies/anything: “*environments*”

with sub-Solar Z?

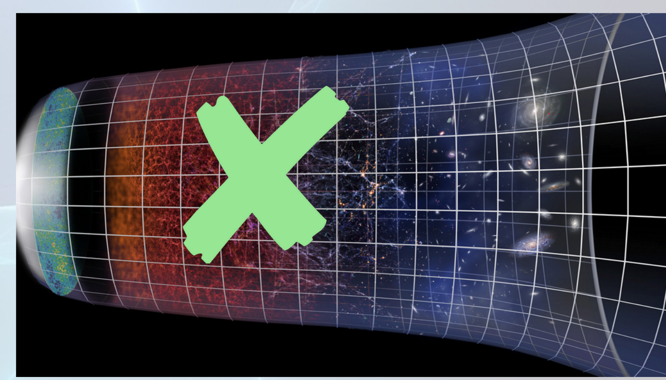
Globular clusters



Dwarf galaxies



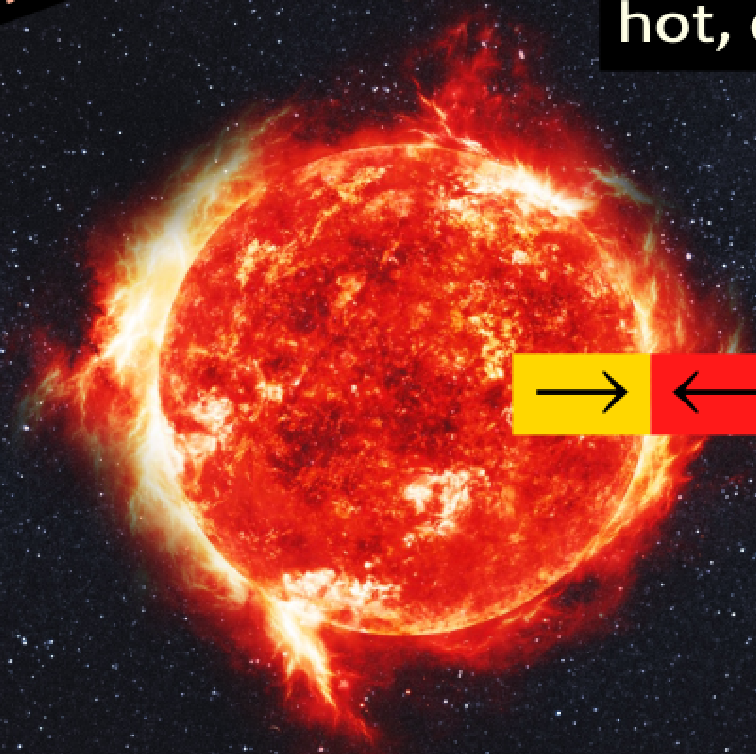
Early Universe



What is a star?

surface?
→ photons escape
"photosphere"

hot, dense plazma



→ ←

equilibrium: pressure gradient gravity

Theoretical modelling of the stellar structure

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

mass conservation

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

momentum conservation

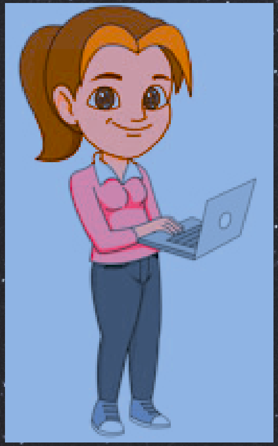
$$\frac{\partial L_r}{\partial m_r} = \epsilon_{\mathrm{pl}} - T\frac{\partial S}{\partial t} \qquad (3)$$

energy conservation

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

transport of energy

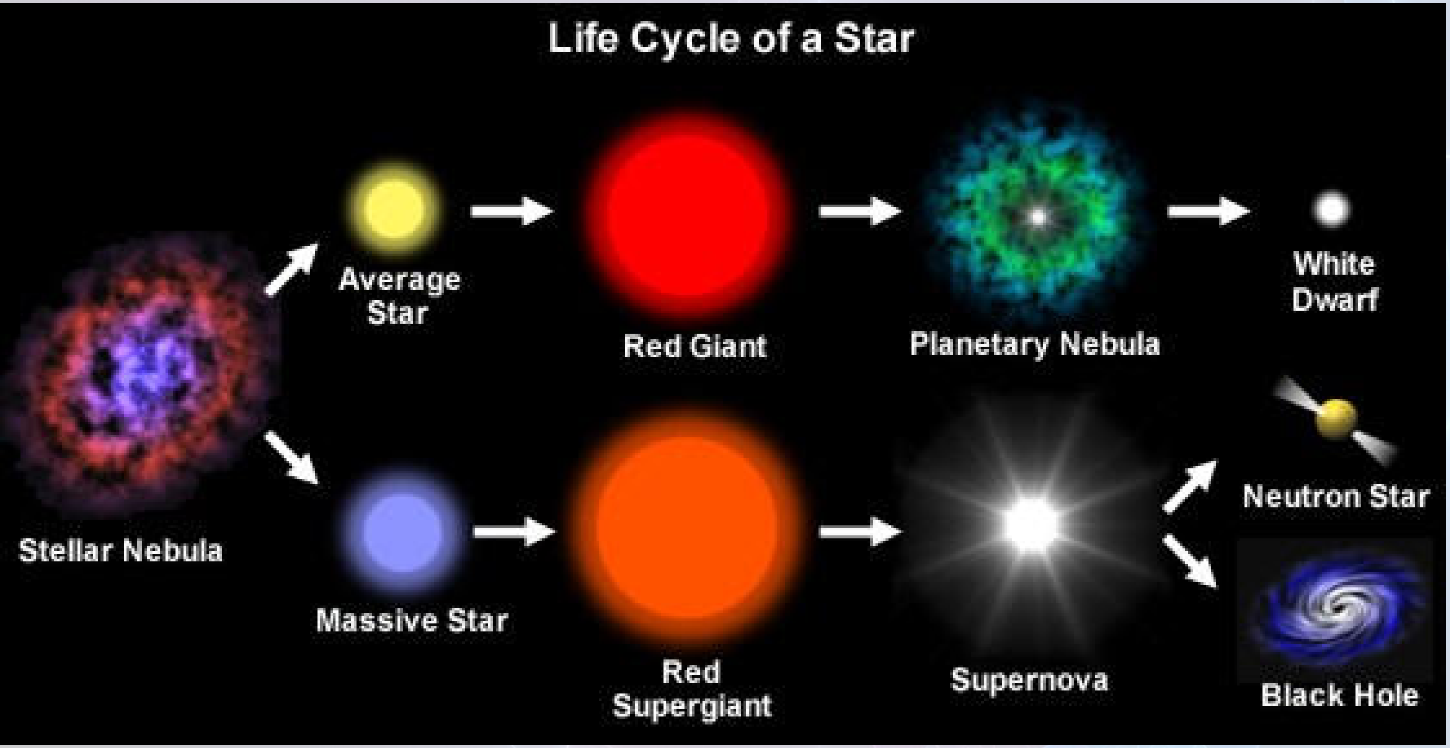
Guilera+ 11



composition change due to nuclear burning:

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

stars evolve
→ stellar evolution



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

massive: $> 8\ M_\odot$

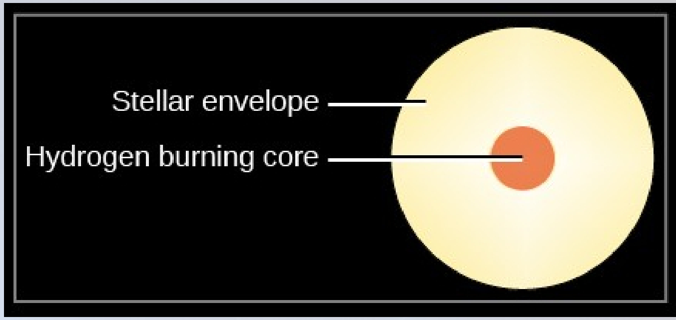
(simplistic…)

Our strategy is/has been:

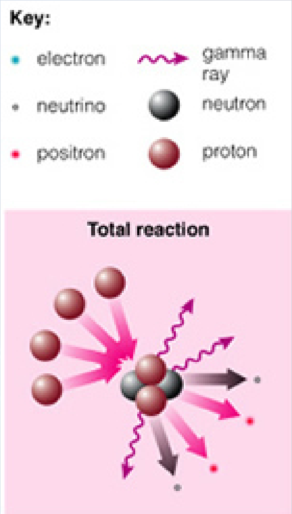
start with
Massive Stars at Solar Z

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

Longest phase of stellar evolution: MS

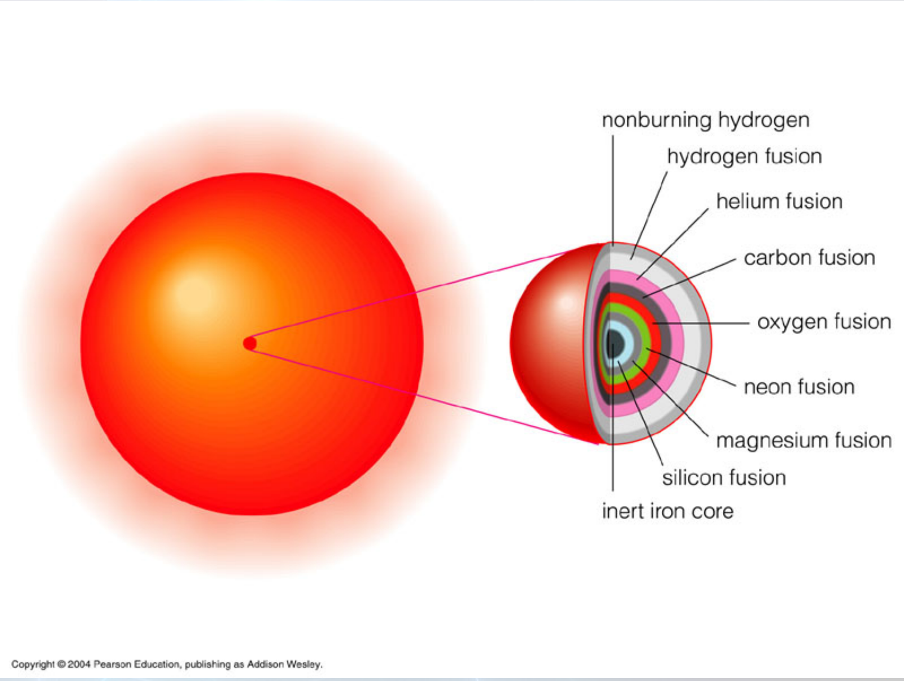


- Main Sequence
  - ***core***-hydrogen-burning phase
- lasts for ~90% of the lifetime (longest of them all)
- core temperatures: ~40M K
- in massive stars: CNO cycle
  - low-mass stars like the Sun: pp-chain
- $4\,{}^{1}H \rightarrow {}^{4}He + \gamma$
- end of MS: Terminal-Age Main Sequence (TAMS)

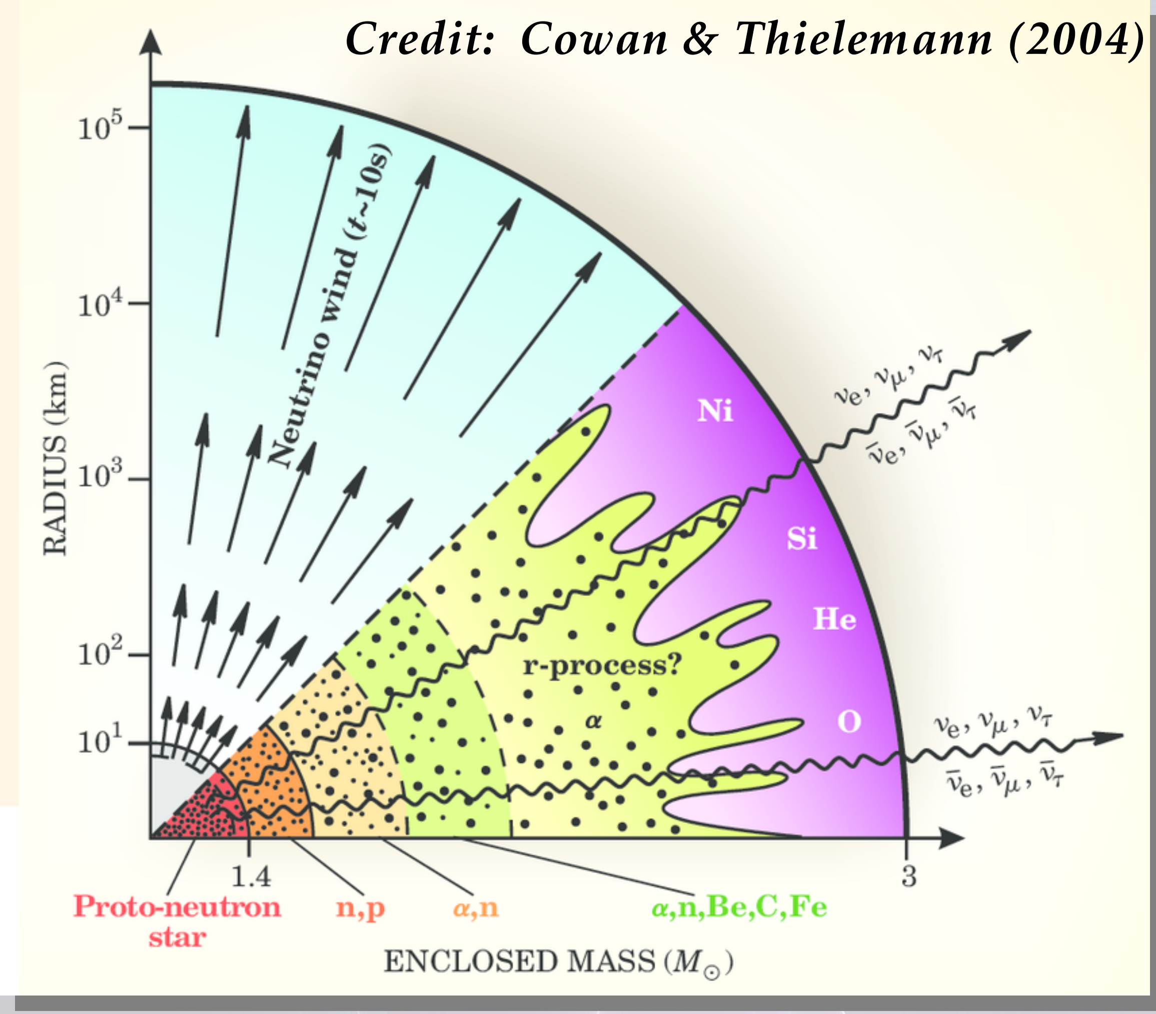


Post-MS

- Includes:
  Temp.
  - 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

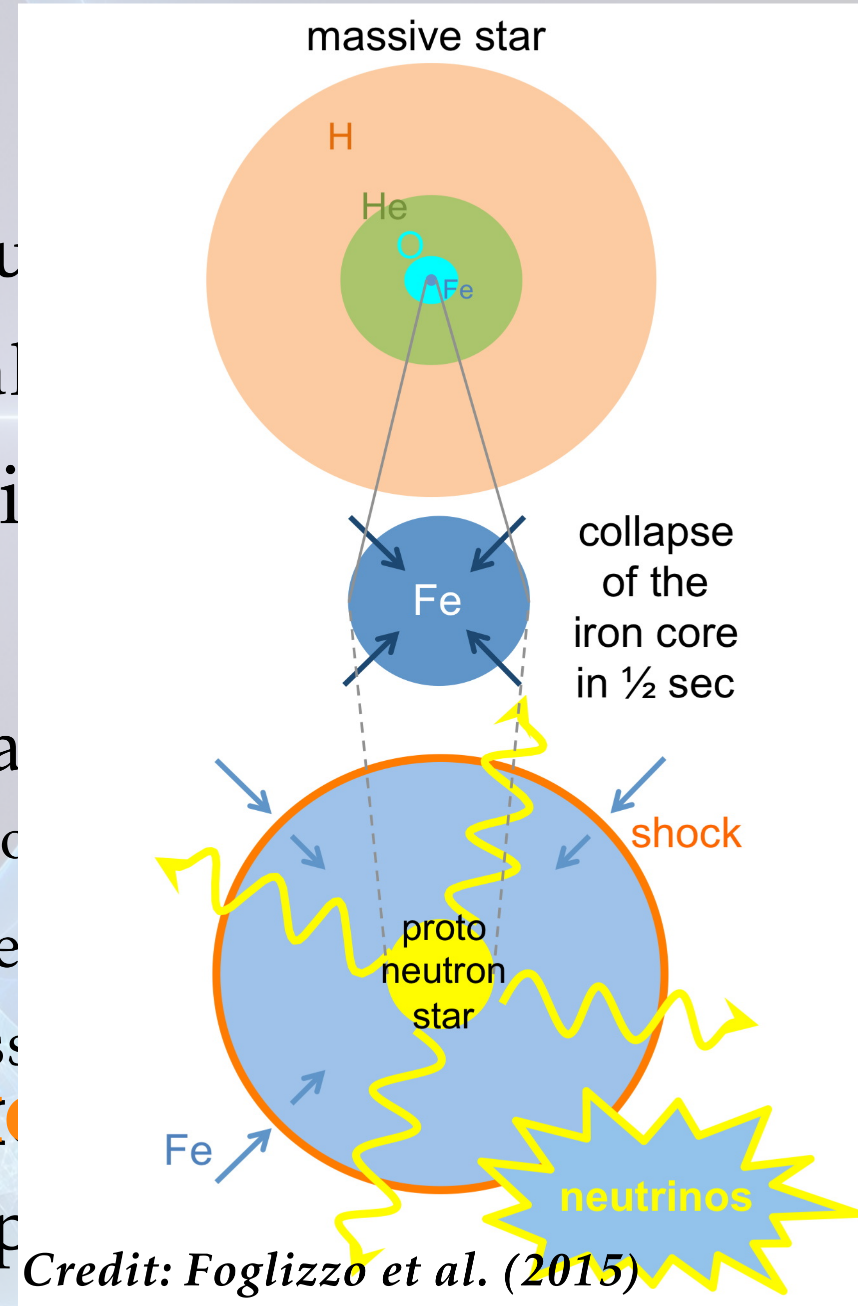


apse

forms in the center ("proto-neutro

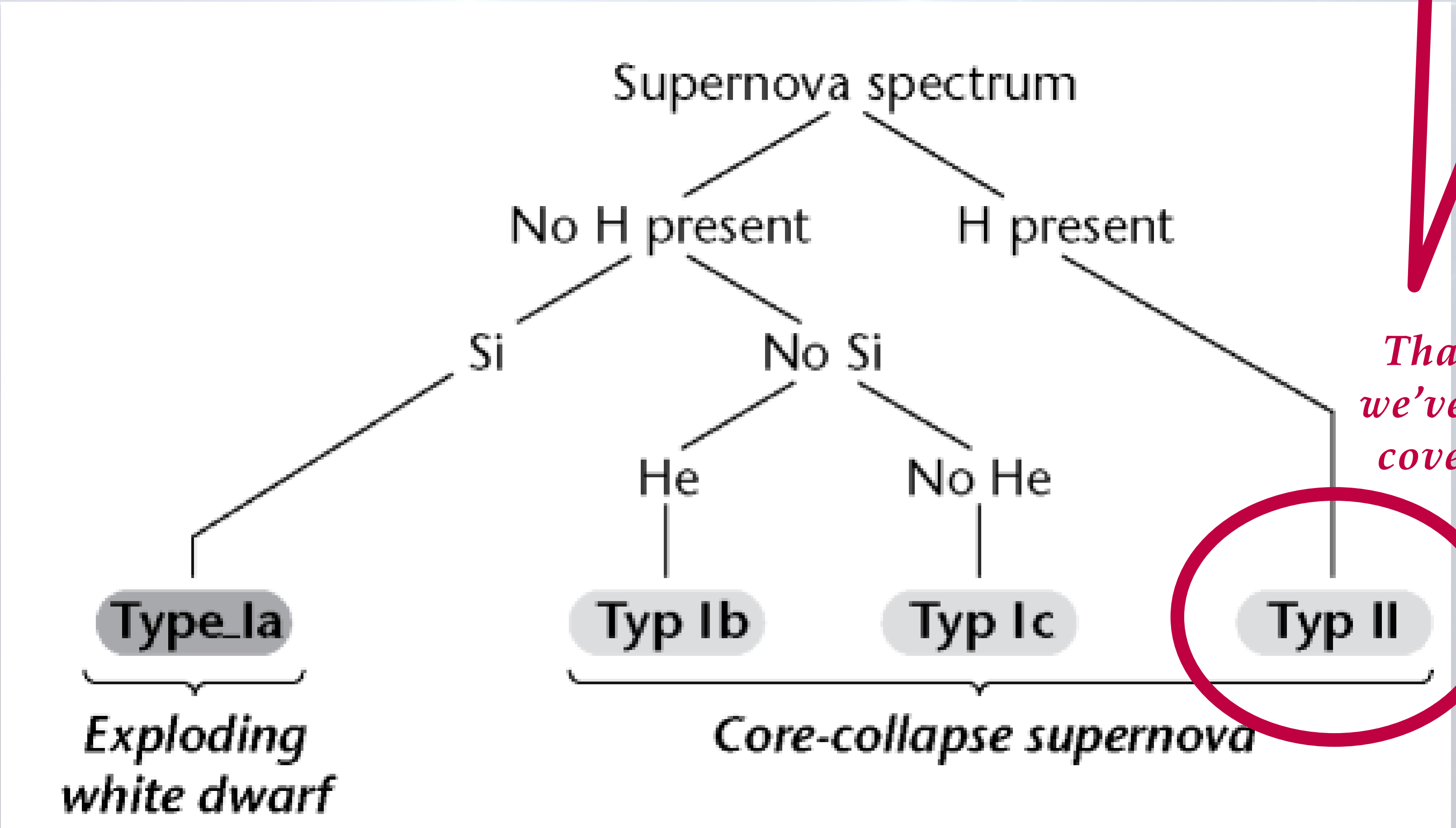
- a neutron star is: one giant nucle
- bounce-back, shock waves, emiss light = **SUPERNOVA EXPLOSI**

– technically: a core-collapse sup



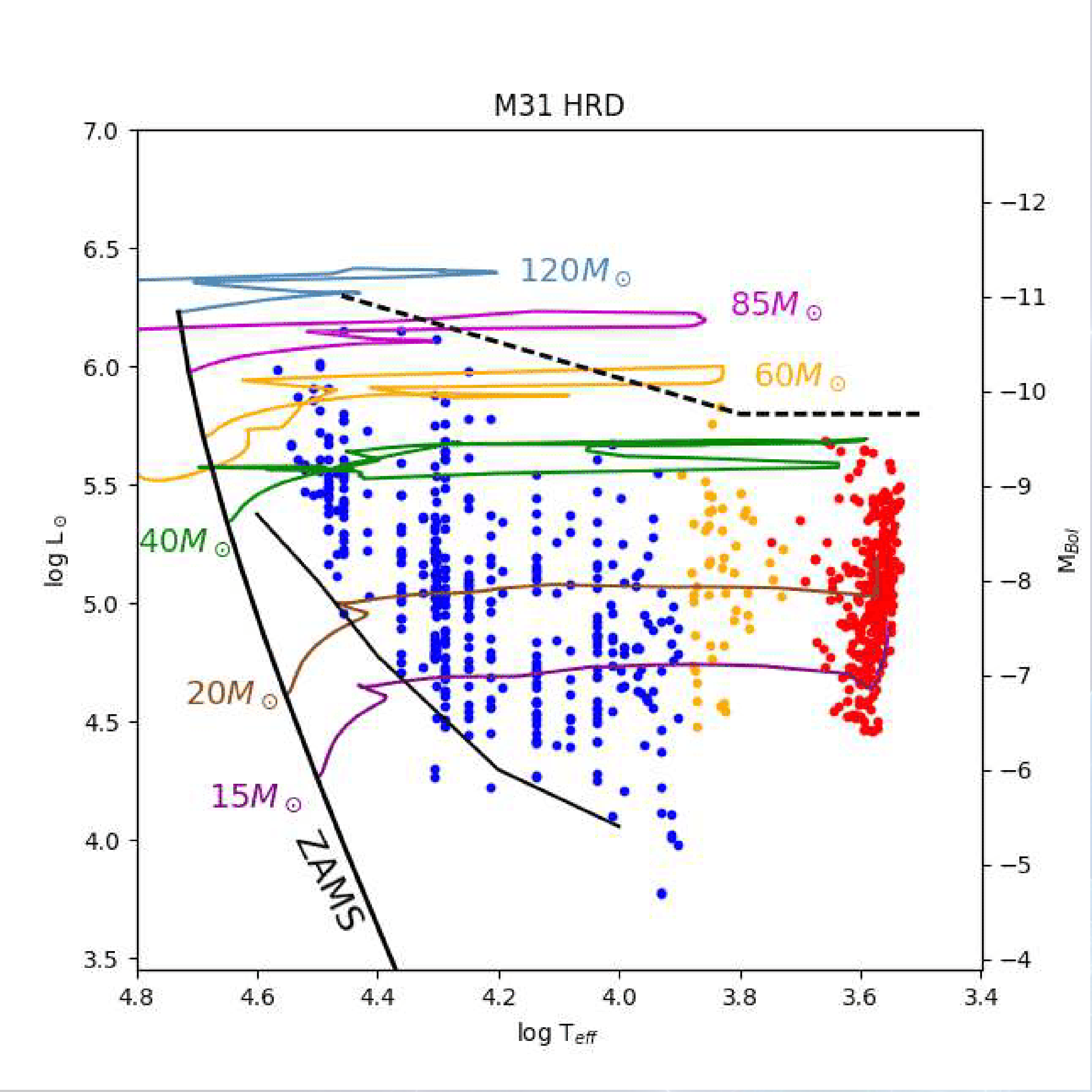
So far: core-collapse SNe

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



Progenitor:
a massive star with a H-rich envelope

That's what we've actually covered here



*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**

Credit: Roberta Humphreys & al. (2017, ApJ. 844.)

Sub-Solar metallicities

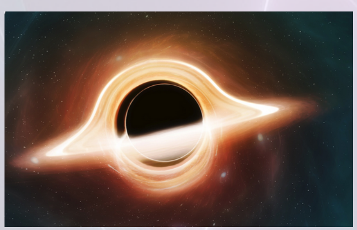
(and still no rotation and no binary companion)

- Main effect: mass loss becomes WEAKER

  → stars live their lives with more mass retained

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

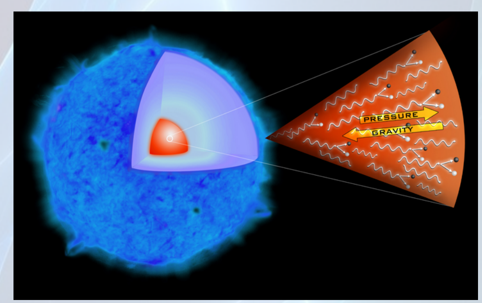
Consequence #1:



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

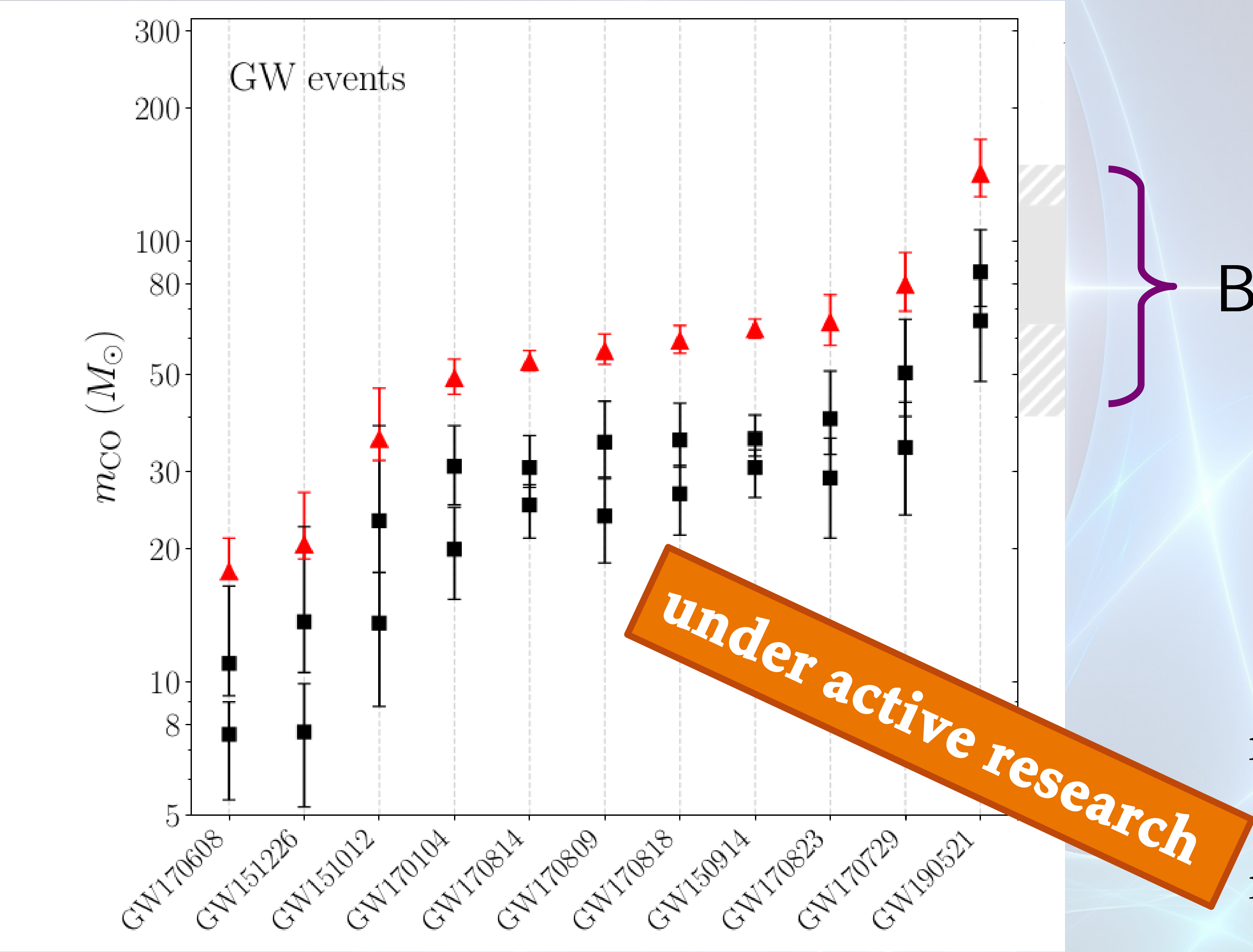
key question: is there something to STOP the collapse? if yes: CCSN (type II, Ib/c)
if no: direct fall-in into a BH (no explosion)

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 $M_\odot$)

The BHs of GW190521 shouldn't exist...



BH no go zone

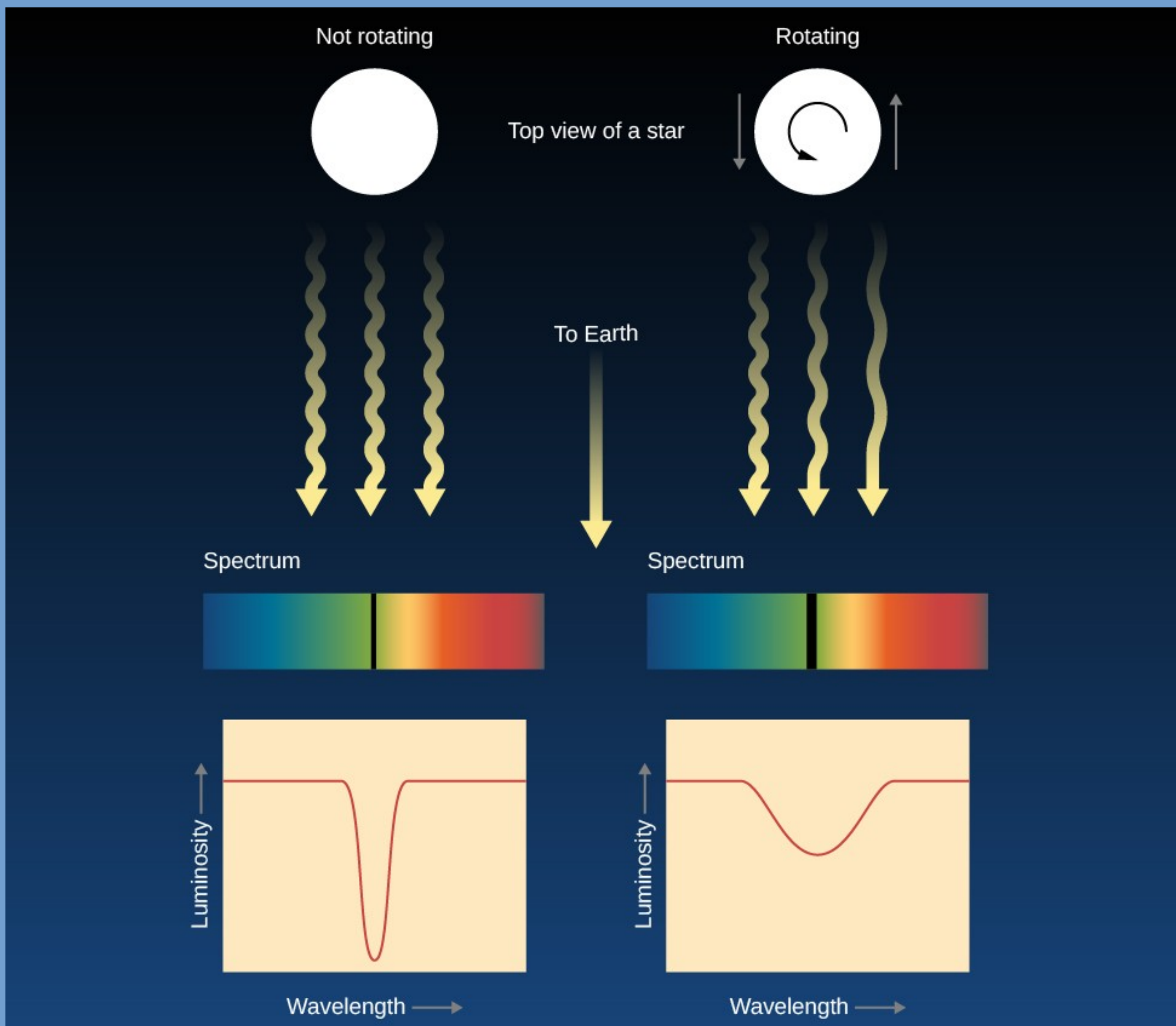
GW190521:

m1 = 85 (+21/−14) Msun

m2 = 66 (+17/−18) Msun

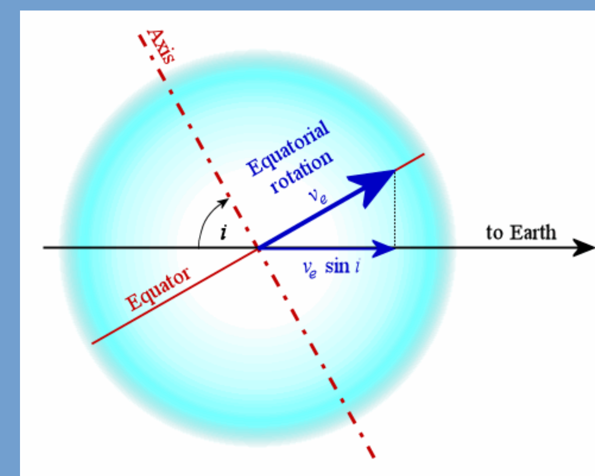
Massive stars rotate… sometimes quite fast

How do we know that? → line profile



Credit: LumenLearning Astronomy

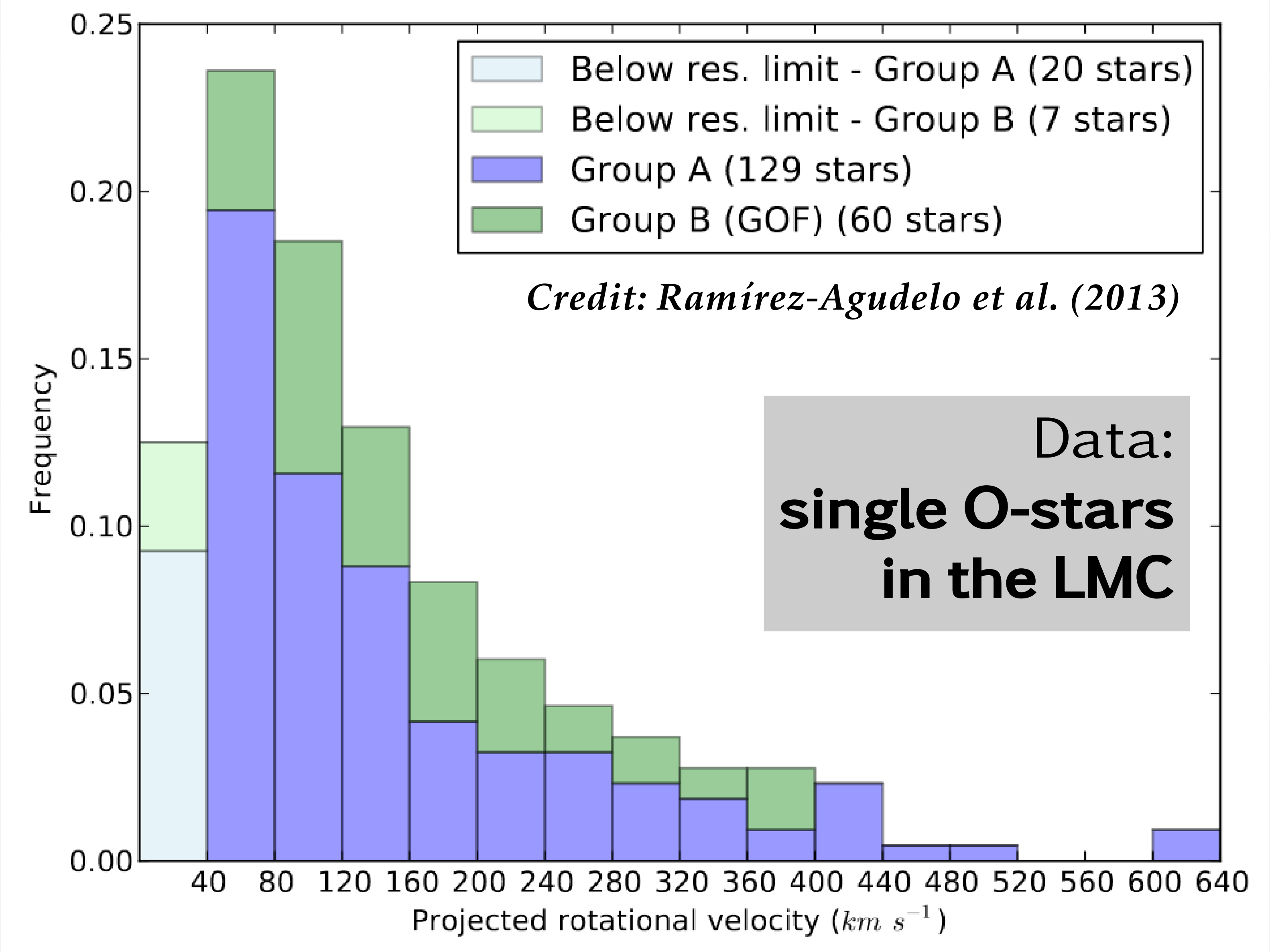
inclination?



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

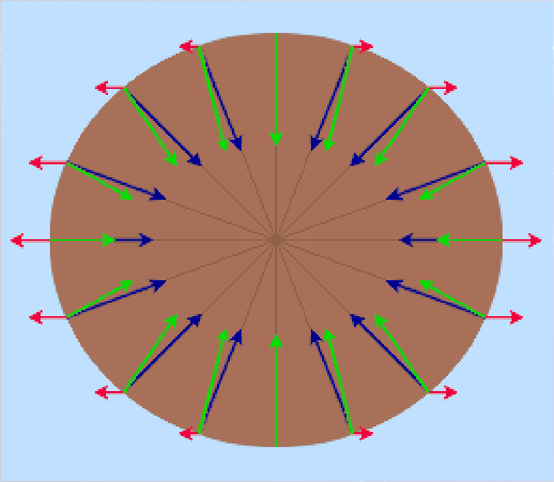
Massive stars rotate... sometimes quite fast

especially at low Z!



Theoretically considered:

Rotation can effect the structure

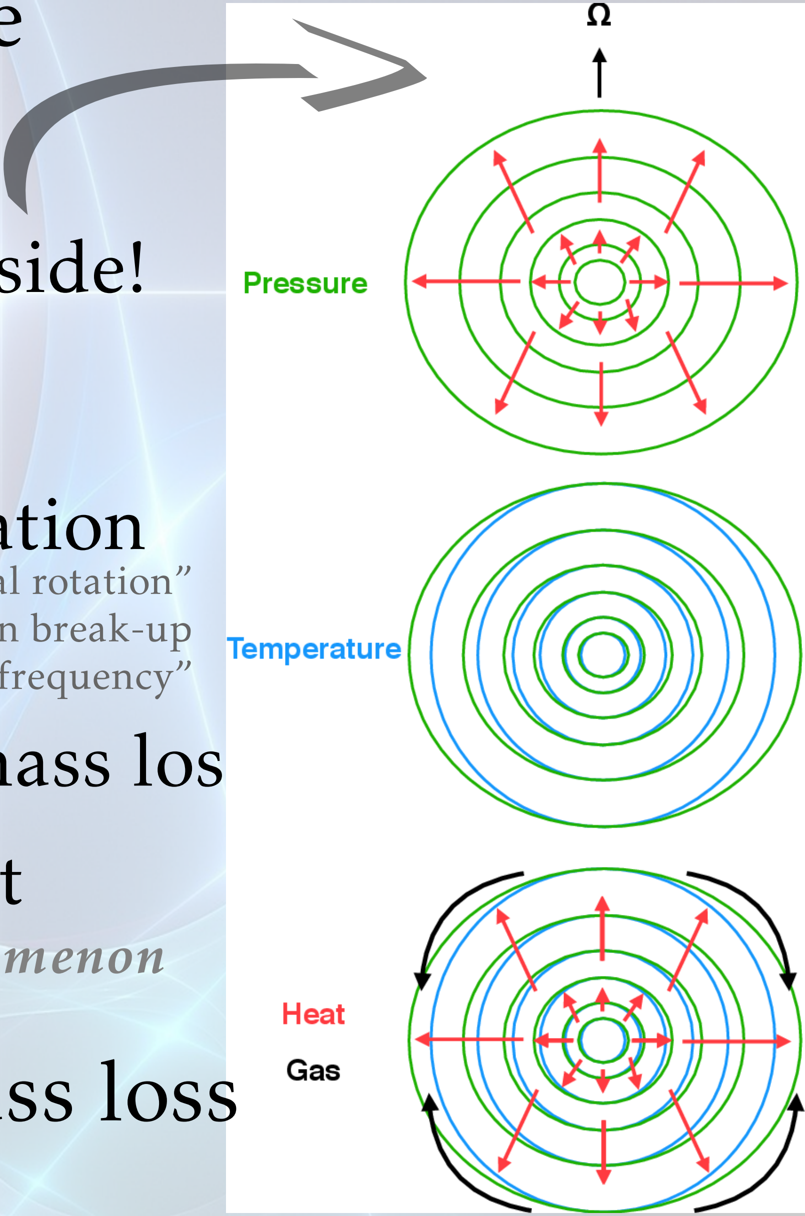


- centrifugal force
  - oblate shape
  - extra mixing inside!
- extreme case:
  - "break-up" rotation
  - $F_{cen} \geq F_{grav}$ "critical rotation" "Keplerian break-up frequency"
  - leads to extra mass los
  - mass dependent

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

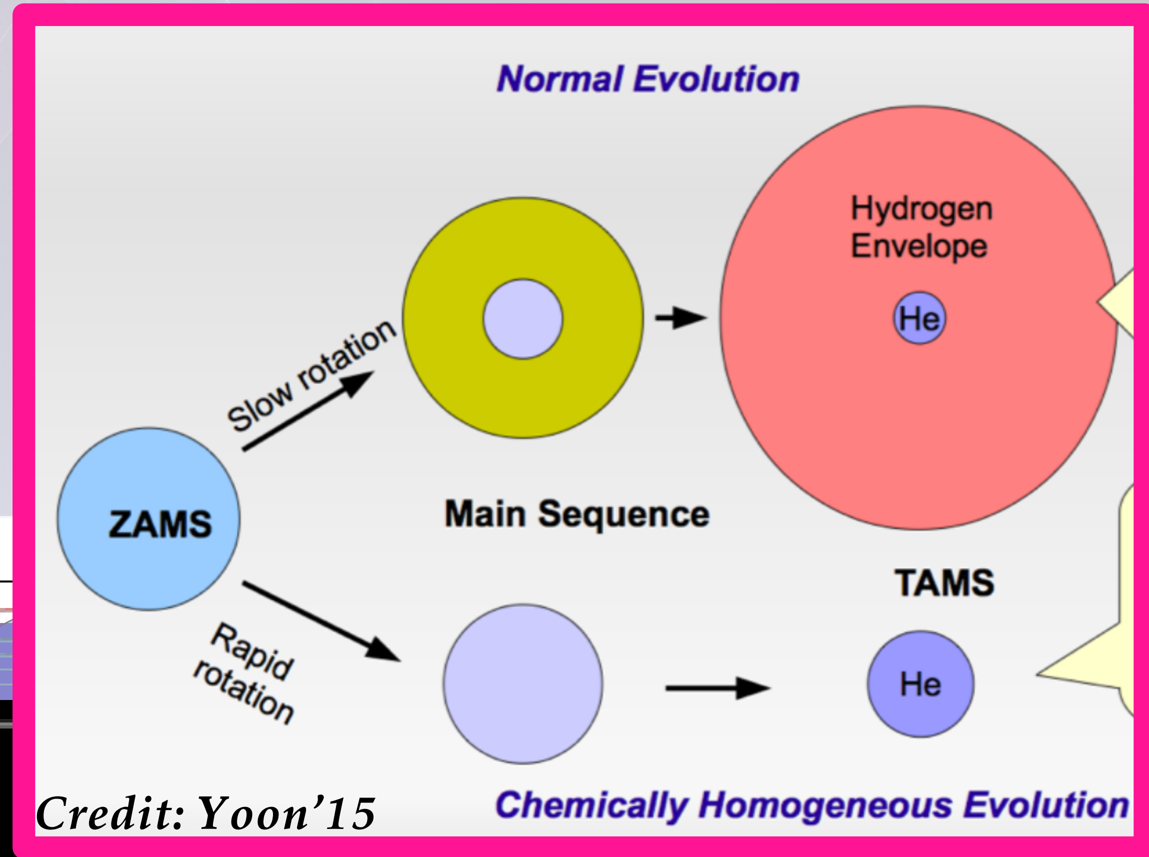
- non-extreme case: mixing & mass loss

Credit: Jermyn+18

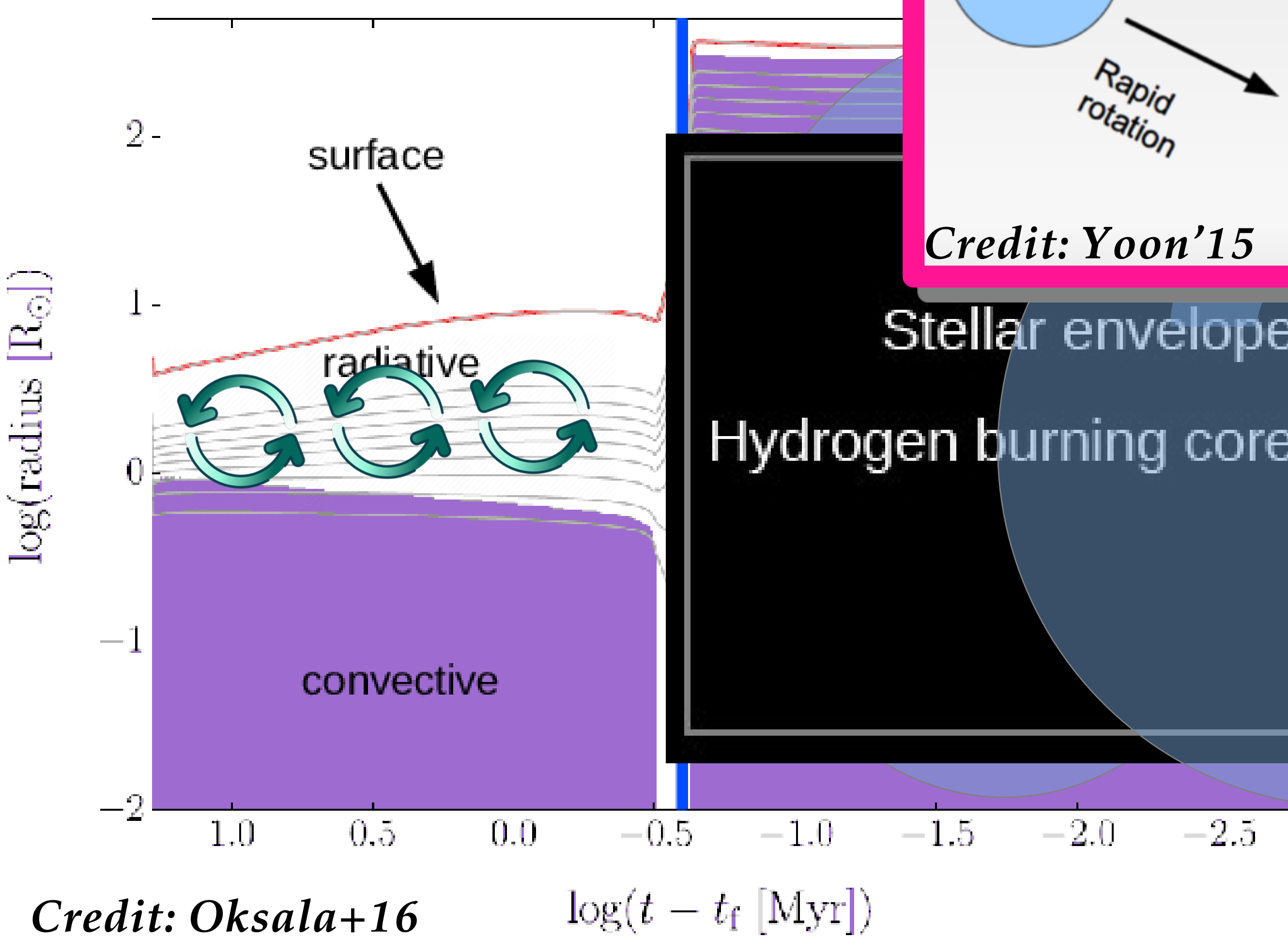


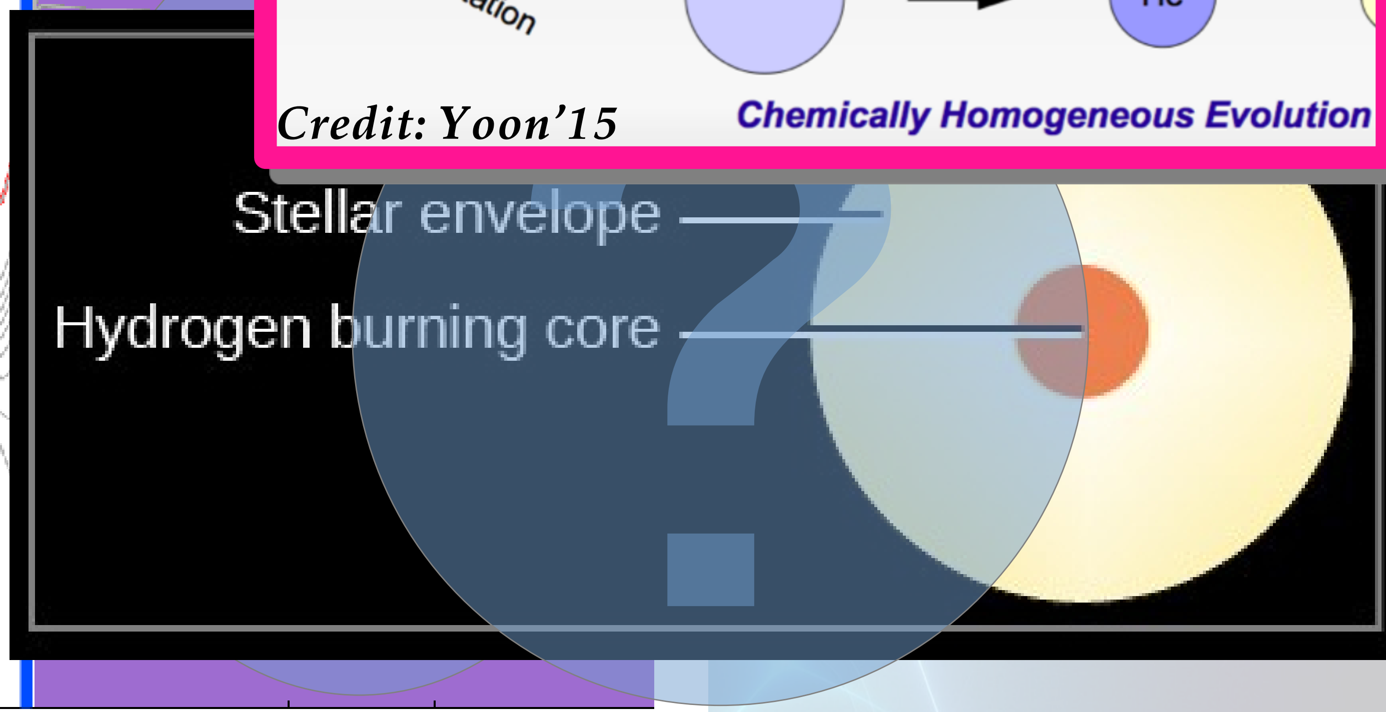
Rotational <u>mixing</u>

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



Credit: Yoon'15

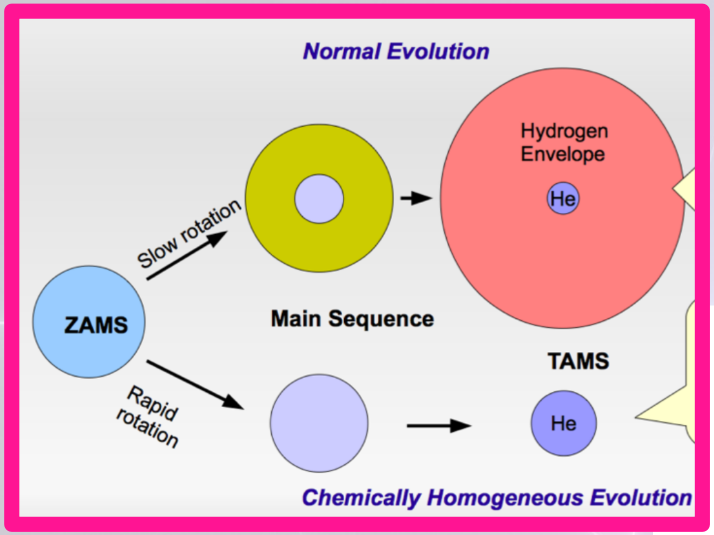




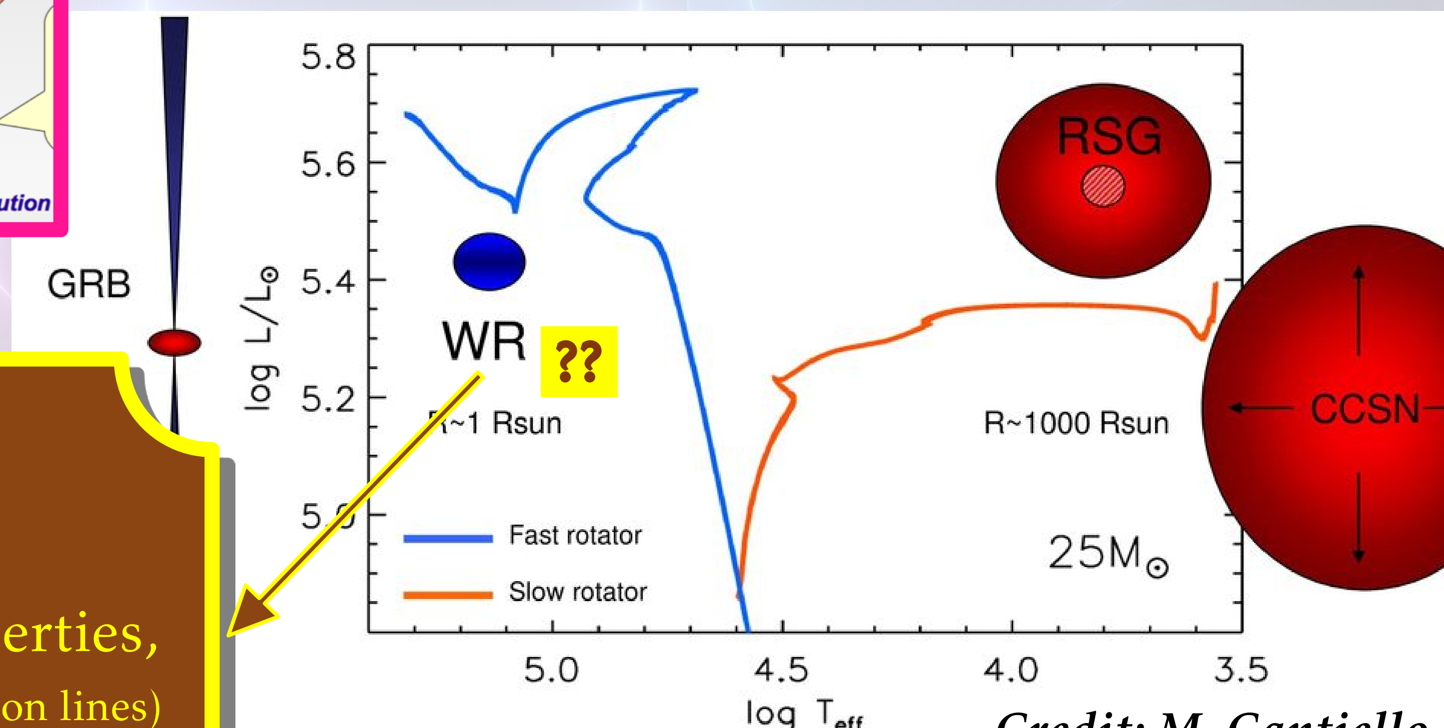
Credit: Oksala+16

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)

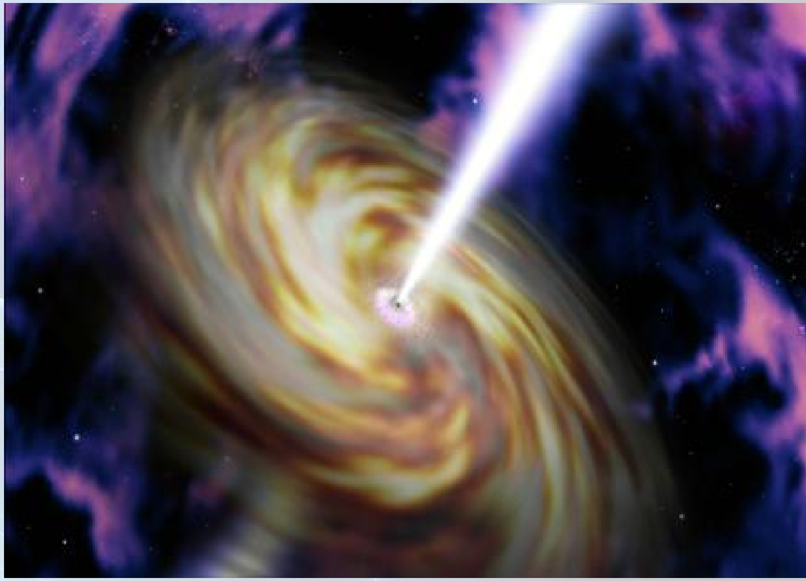
Type of final explosion?
type Ib/Ic (core collapse)
but ROTATING!! → a 'collapsar'

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

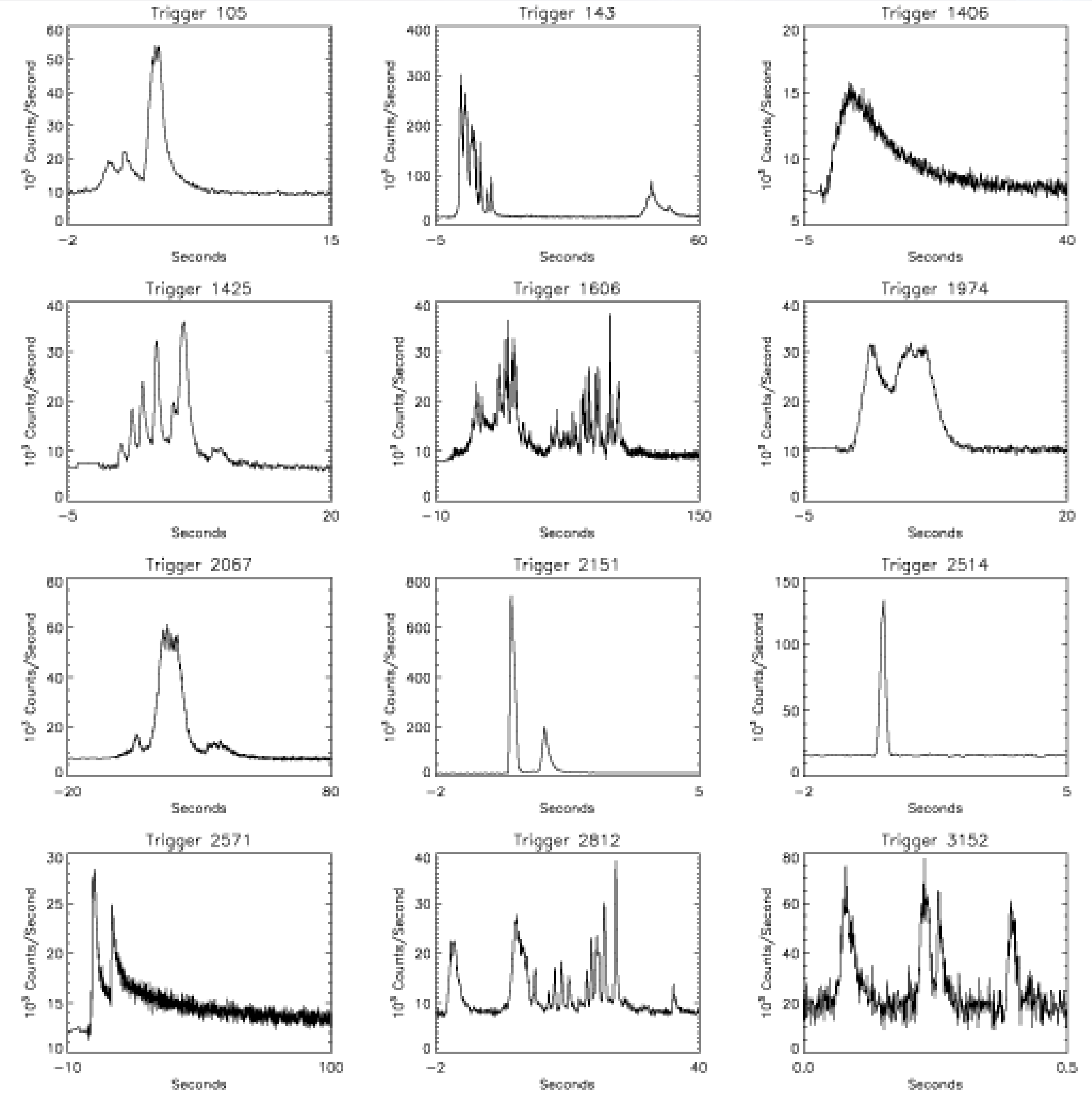
A BH or a NS forms in the middle.
The proto-NS is probably highly magnetized.

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.

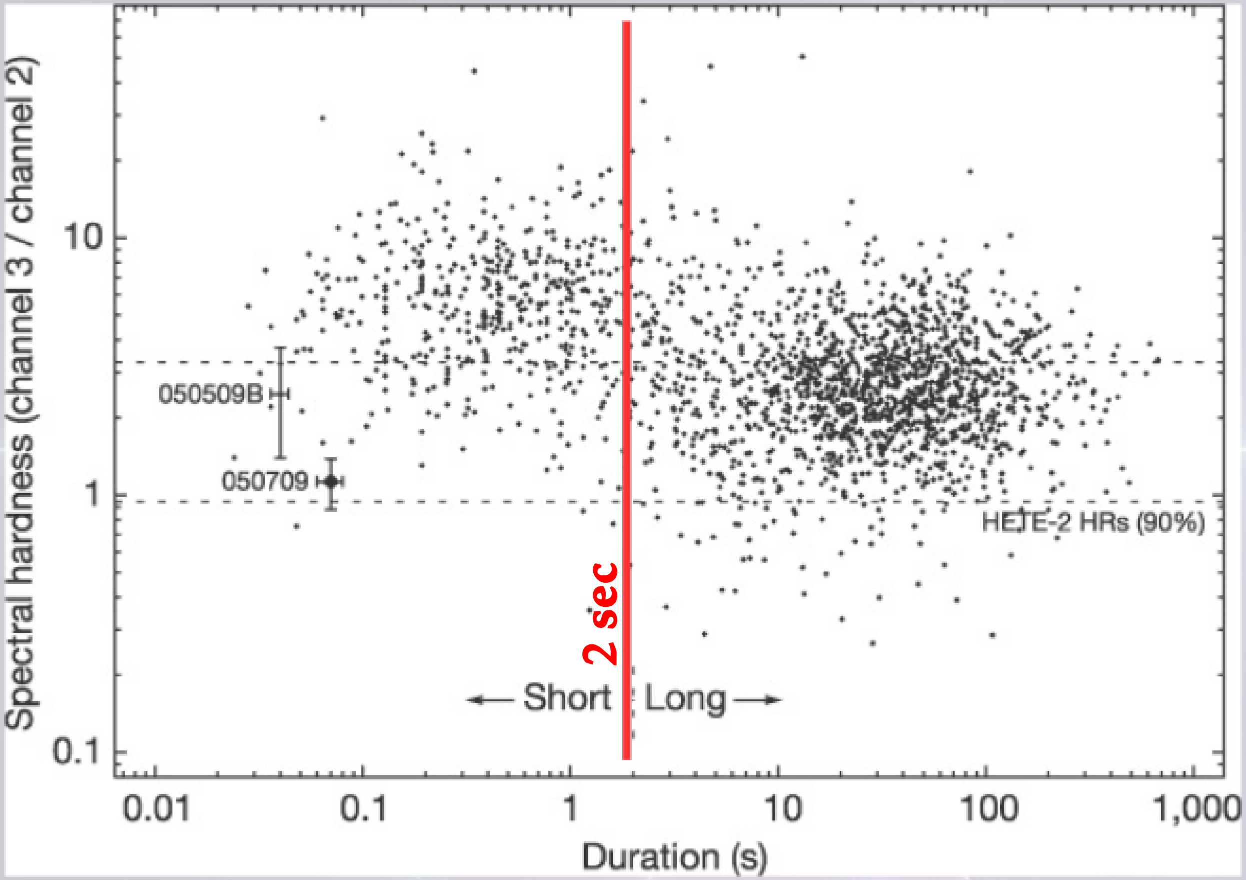
– daily observations

– 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

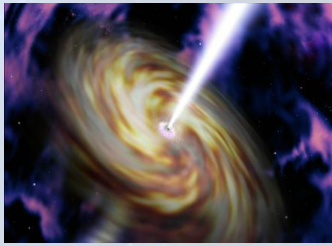


Credit: Hjorth+2005

Long/soft:

Massive Stars at collapse

a "collapsar"



Short/hard: **two Compact Objects at merger**

binarity!

GWs!

→ sub-Solar metallicities? ✓

→ fast-rotating stars? ✓

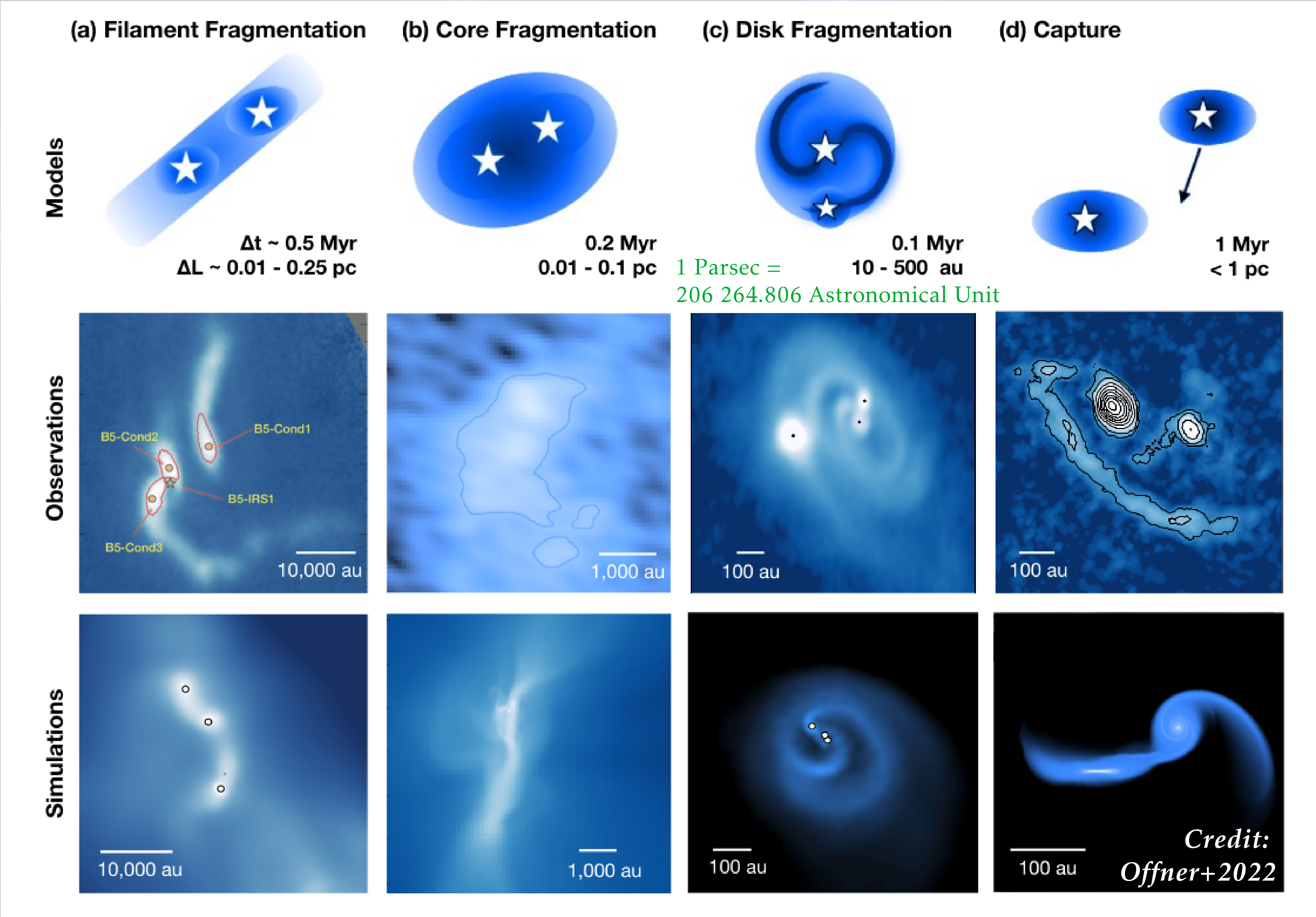
→ stars in a binary system? **Coming today! :)**

Binaries

…and other multiple systems

Stars sometimes form in multiples

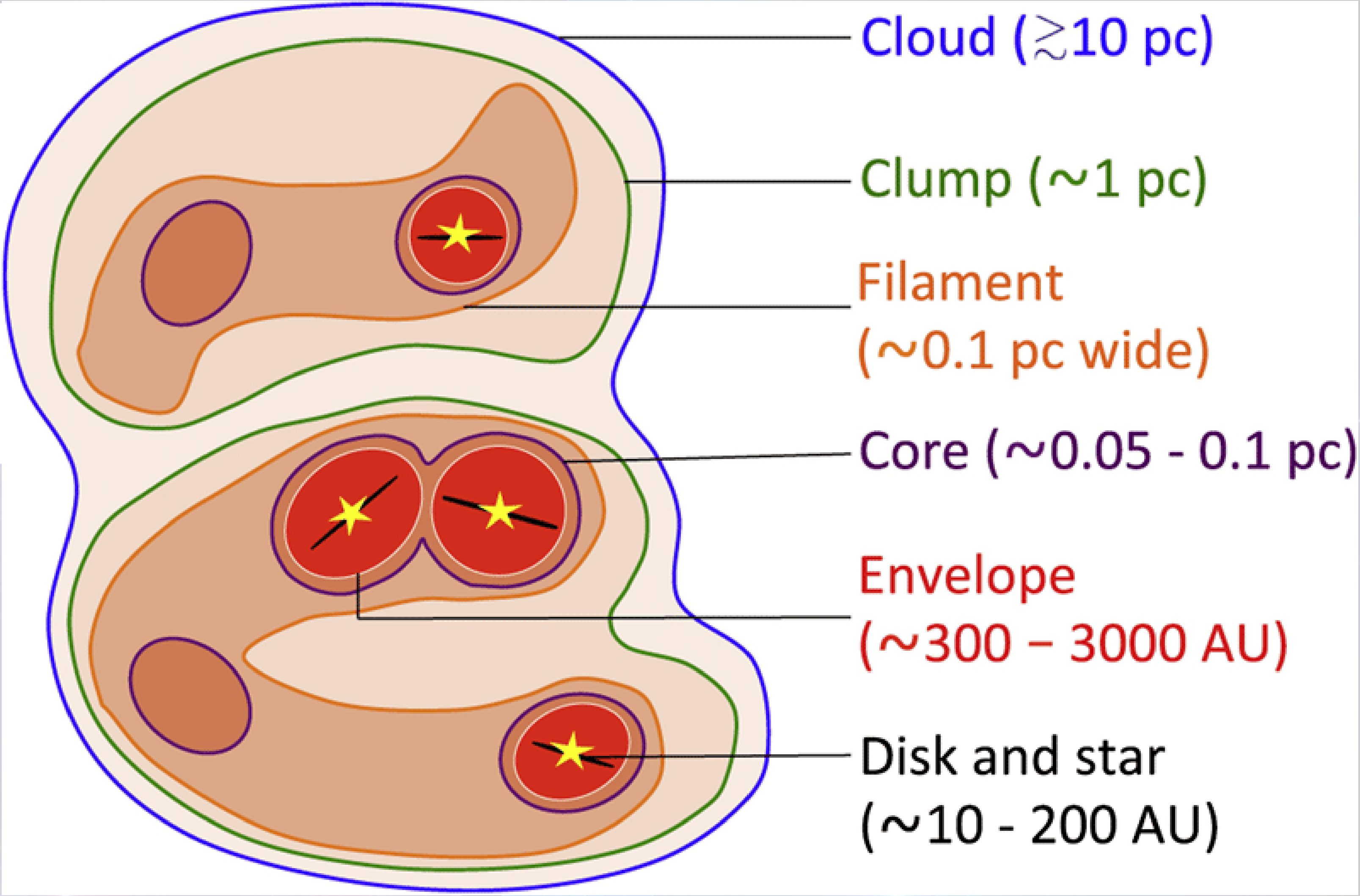
binaries, triples, quadruples…



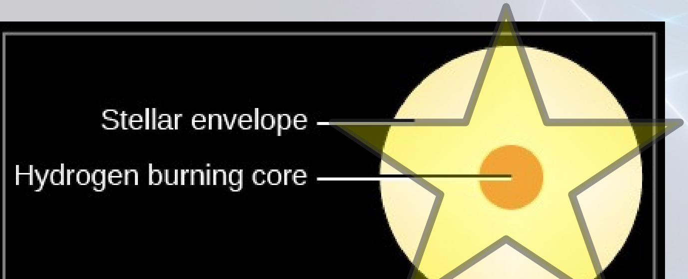
1 Parsec =
206 264.806 Astronomical Unit

Reminder:

Structure of a molecular cloud (where stars are born)

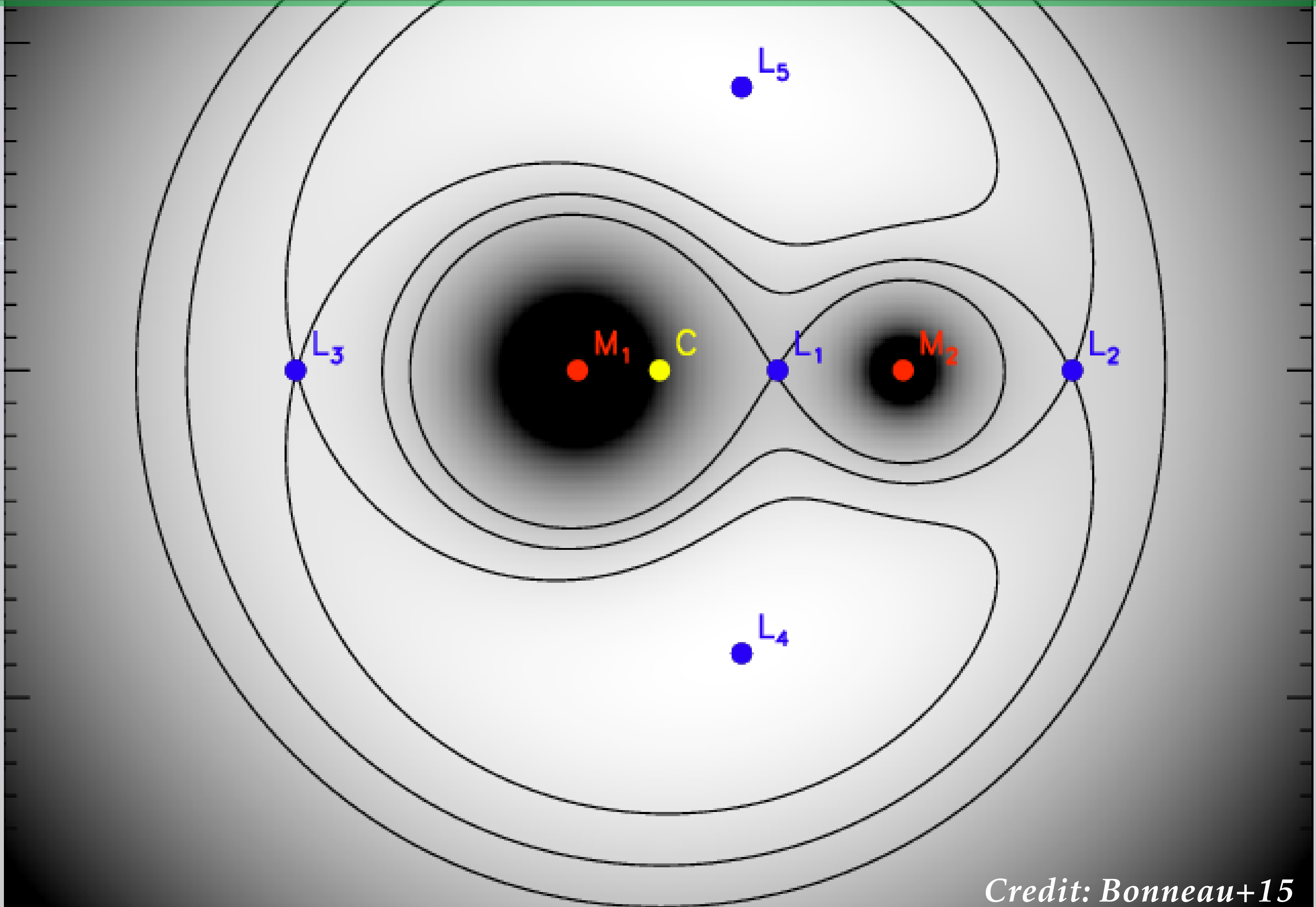


Credit: A. L. Rosen et al. (2020)



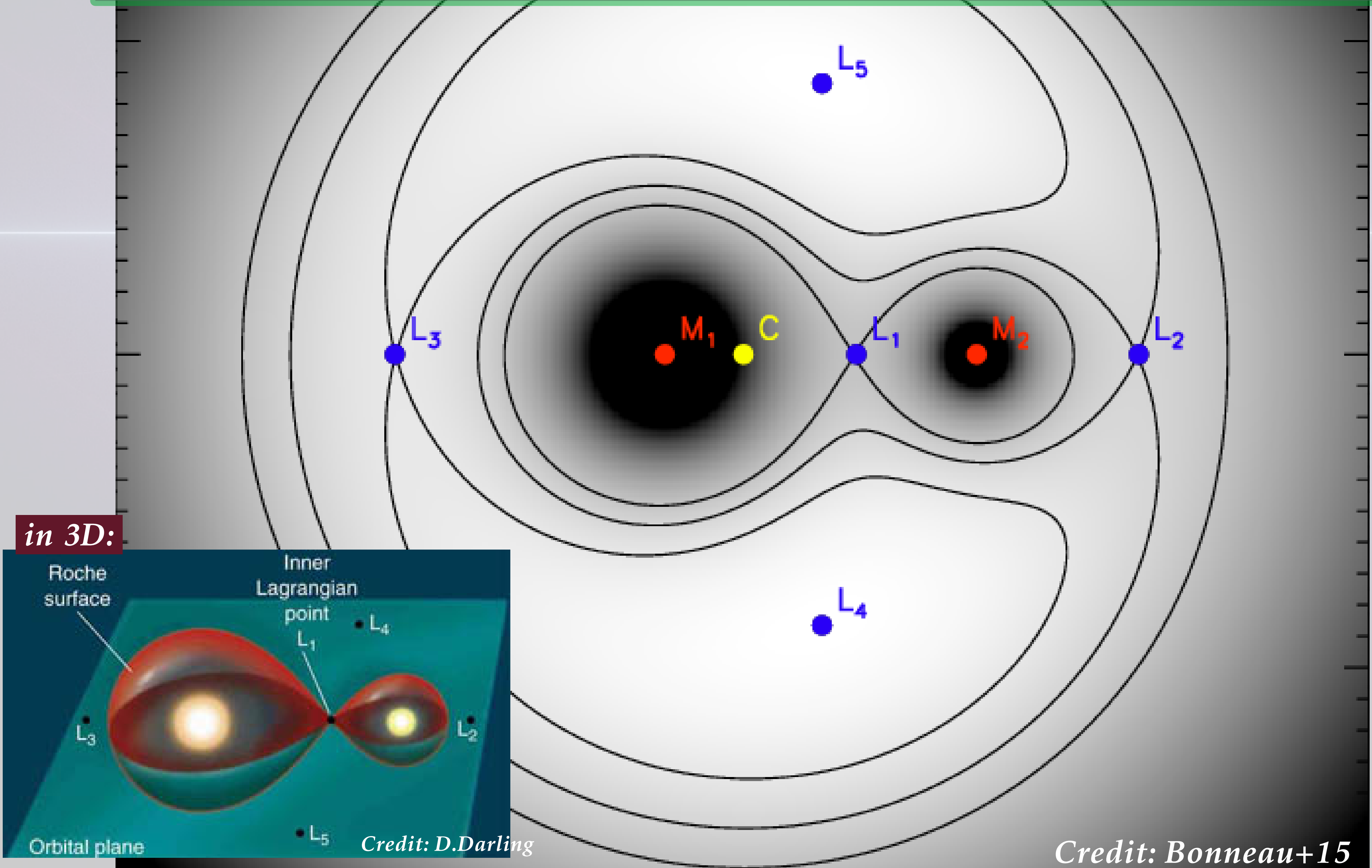
‘envelope’ here ≠ stellar envelope
‘core’ here ≠ stellar core

The most important concept:
Roche-lobe



Credit: Bonneau+15

The most important concept: **Roche-lobe**

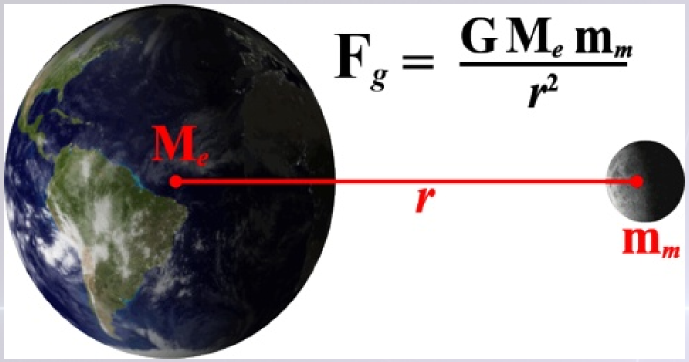


Credit: Bonneau+15

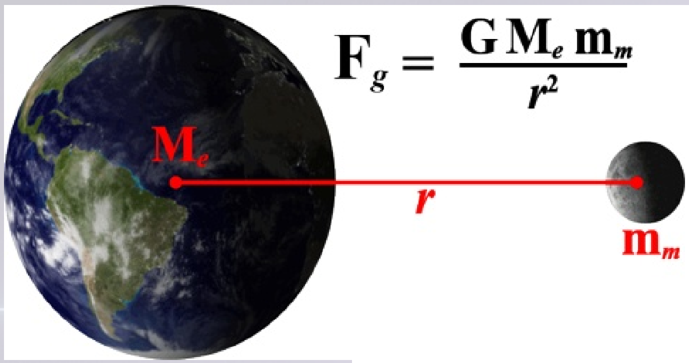
in 3D:

Credit: D.Darling

Gravitational equipotential surfaces



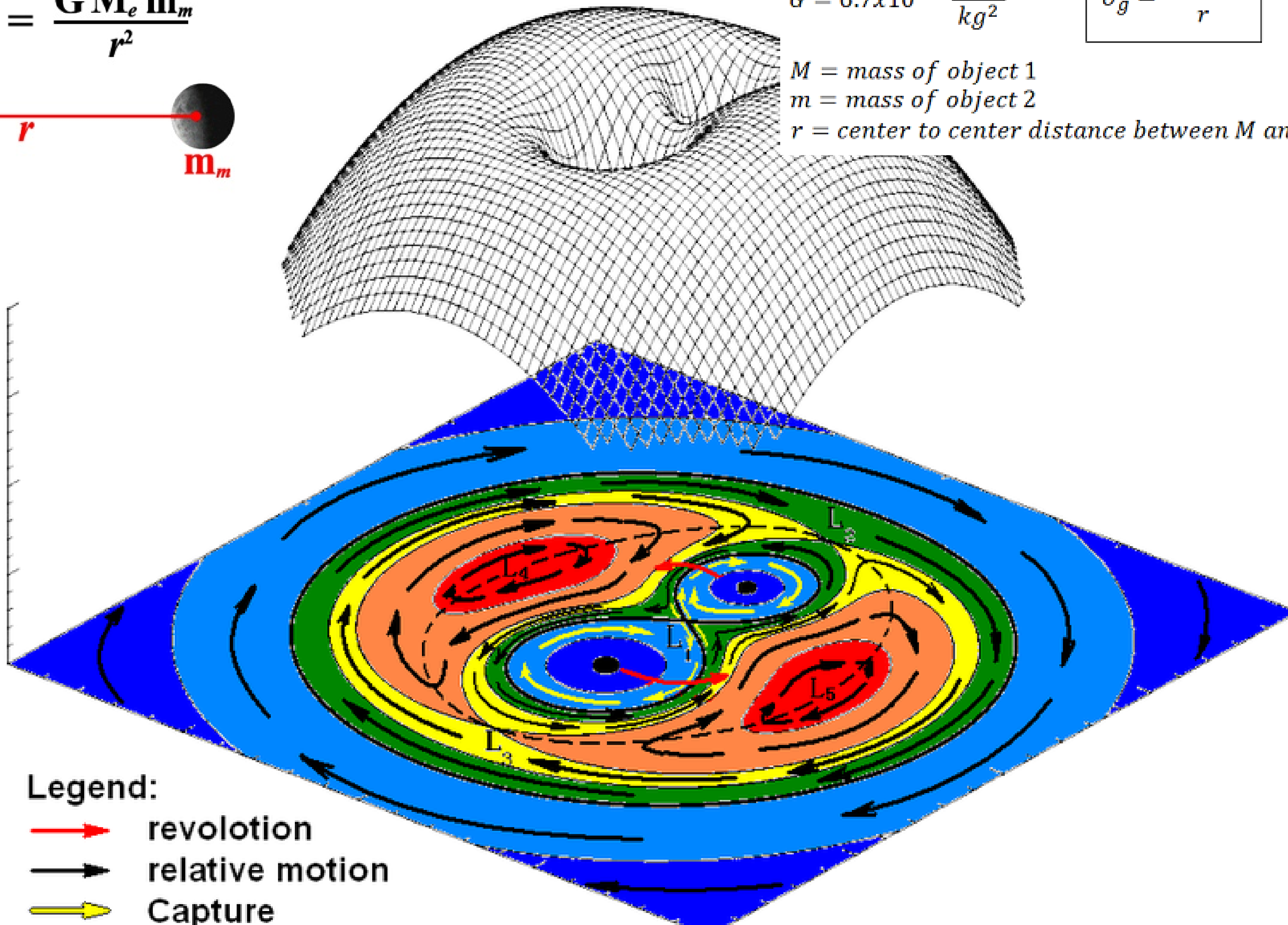
Gravitational equipotential surfaces



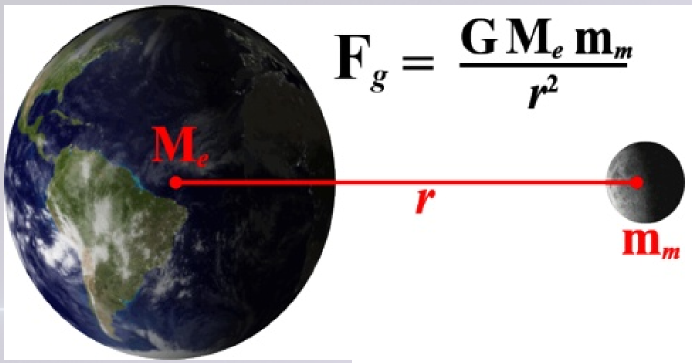
$G = 6.7x10^{-11} \frac{Nm^2}{kg^2}$

$$U_g = \frac{-GMm}{r}$$

M = mass of object 1
m = mass of object 2
r = center to center distance between M and m



Gravitational equipotential surfaces



$G = 6.7x10^{-11} \frac{Nm^2}{kg^2}$

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M = *mass of object* 1
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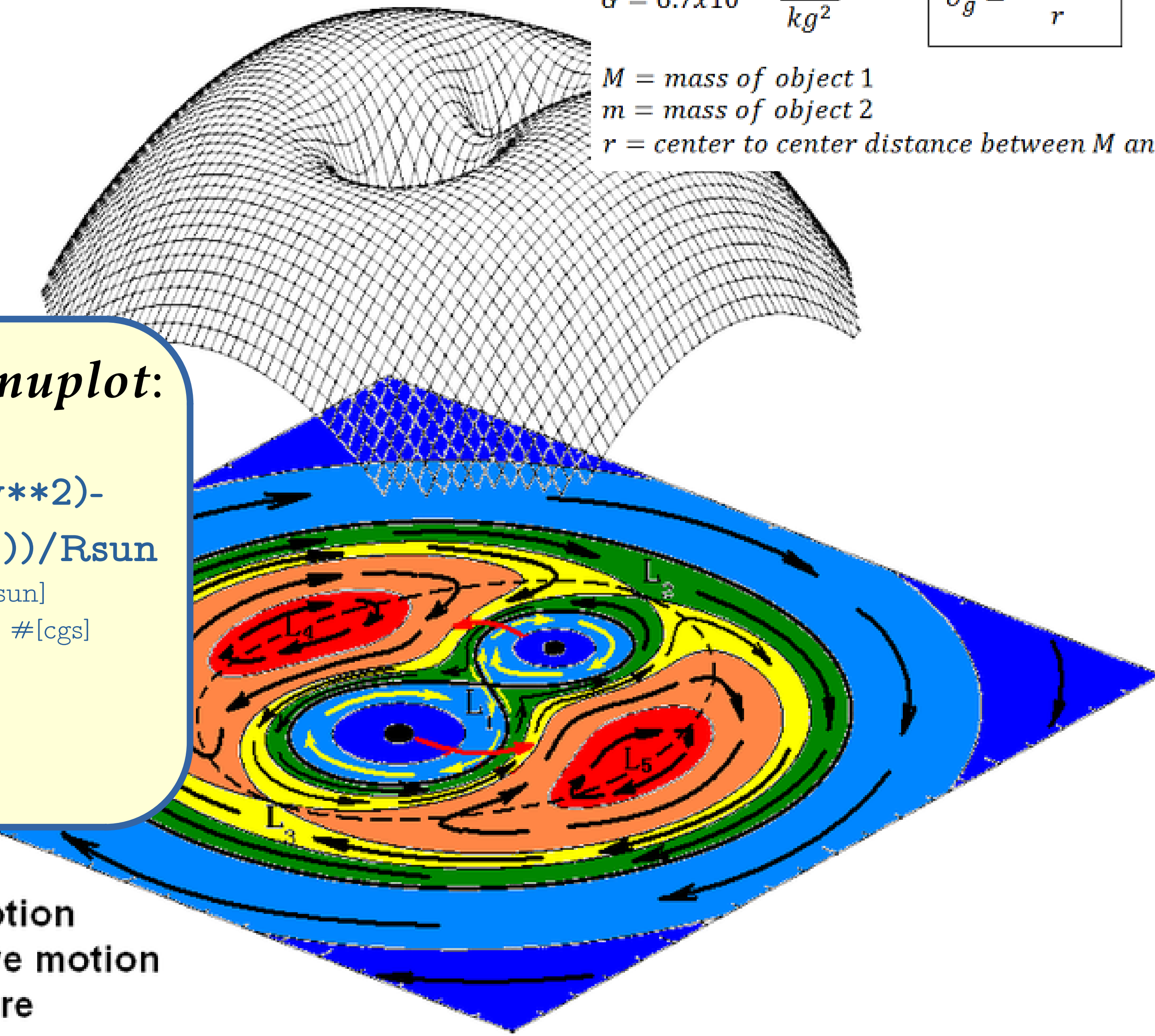
r = *center to center distance between* M *and* m



Try it for yourself! E.g. in ***gnuplot***:

```
U(x,y)=(-G*m1/sqrt(x**2+y**2)-
G*m2/sqrt((x-orbsep)**2+y**2))/Rsun
m1=20; m2=15; orbsep=5 #[Msun],[Rsun]
G=6.6743*10**(-8); Rsun=6.957*10**(10) #[cgs]
set isosamples 60,60
set pm3d
splot U(x,y)
```

Roche-lobe facts

- we can plot is but we cannot explicitely derive it

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

from numerical fit

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

orbital separation: A

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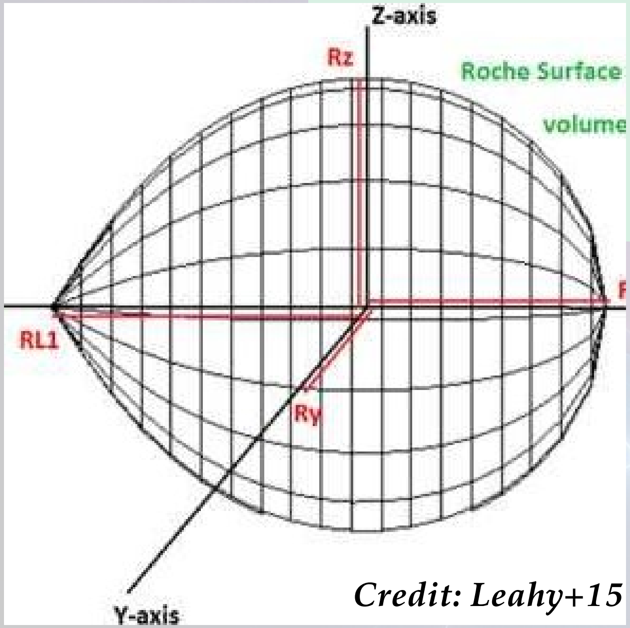

Credit: Leahy+15

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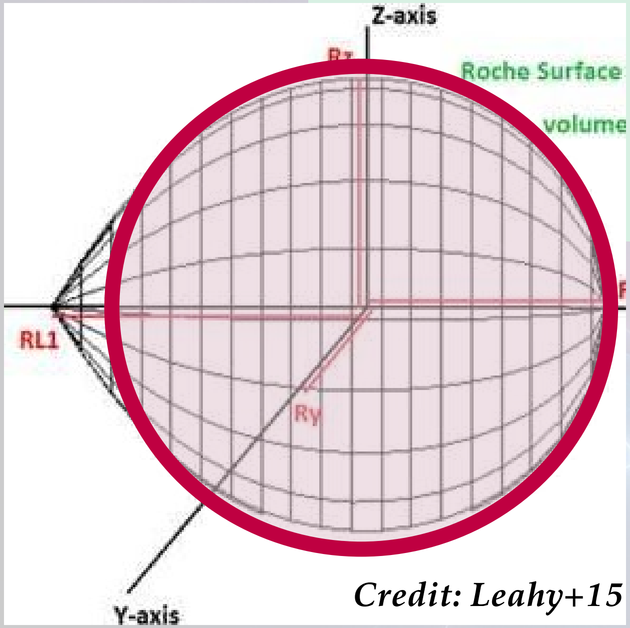

Credit: Leahy+15

Why does the Roche-lobe matter?

- Mass transfer.

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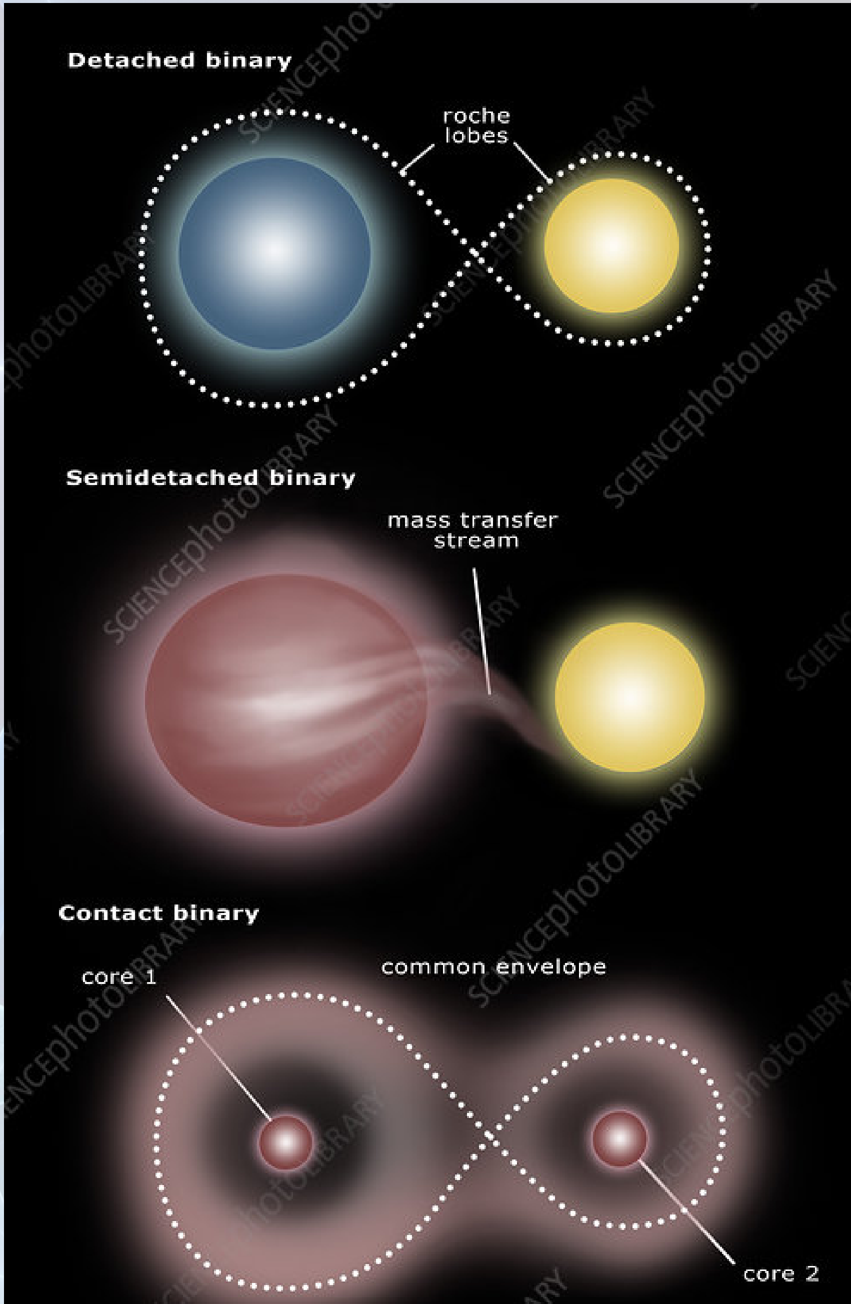
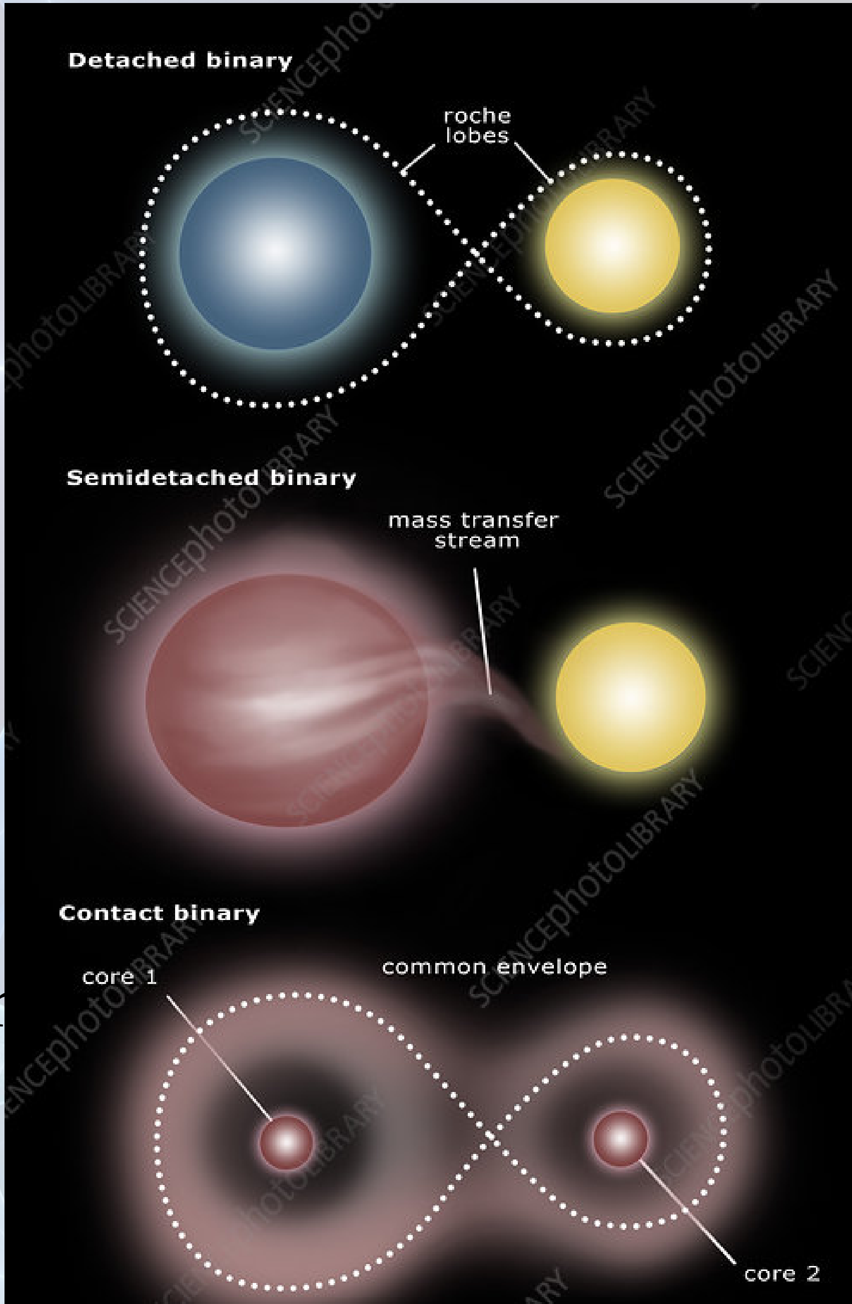


Why does the Roche-lobe matter?

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

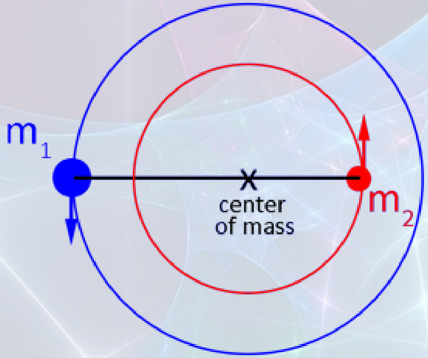
▶ *stellar* envelope



Some more terms

- orbital separation = orbital 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?

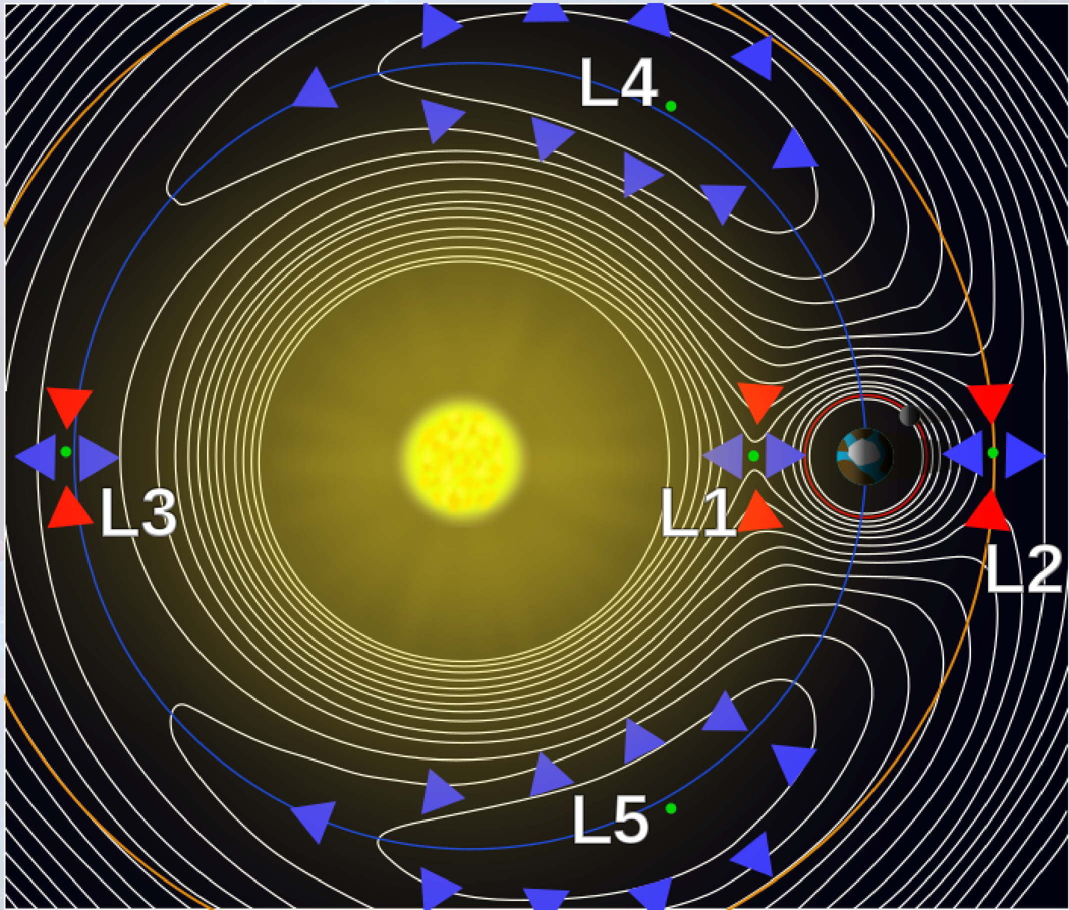
Kepler's 3rd law:



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

Some more terms *part #2*

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



Imagine two (massive) stars!

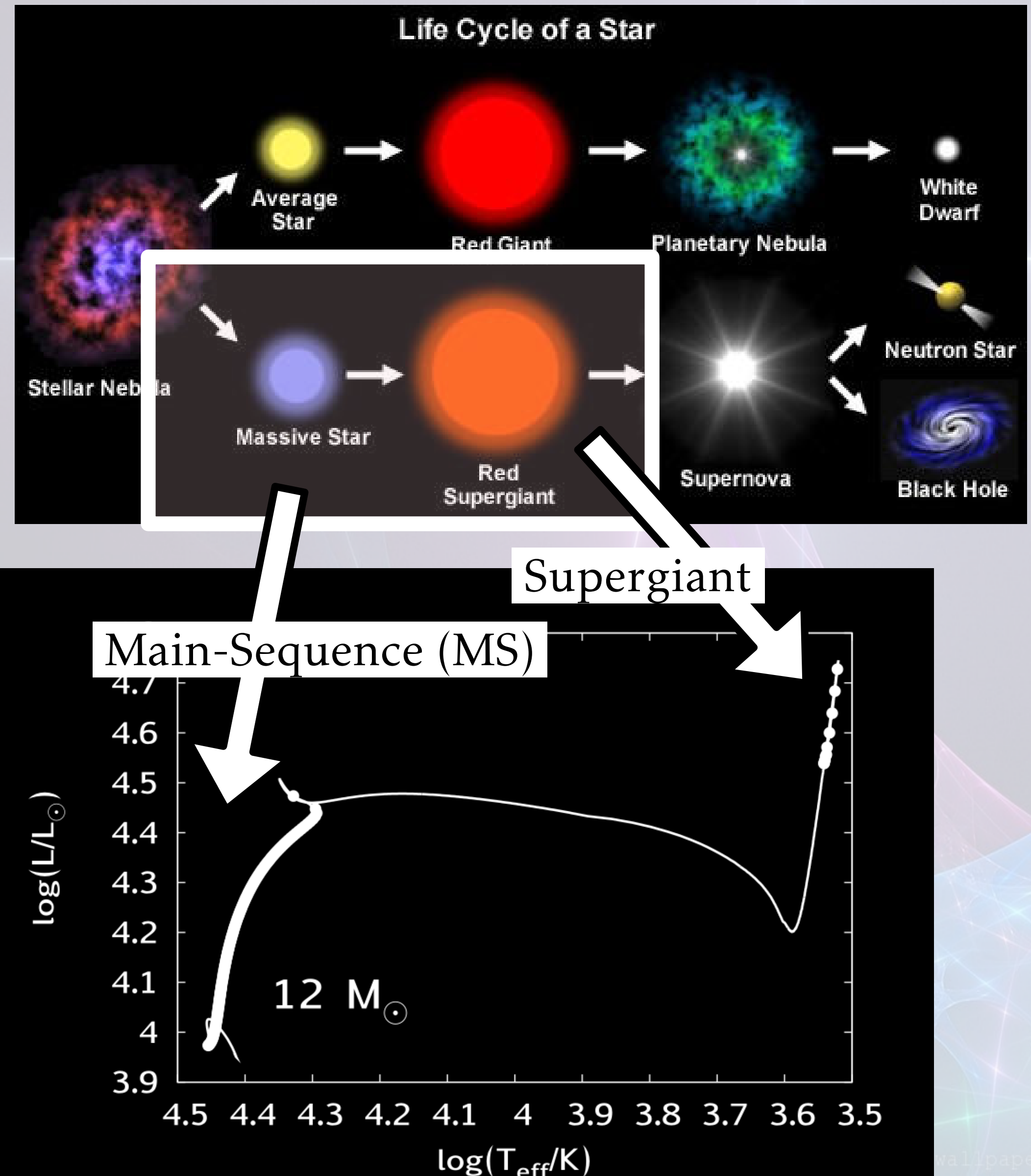
with Solar Z, no rotation

Imagine two (massive) stars!

with Solar Z, no rotation

Imagine two (massive) stars!

One (massive) star alone:

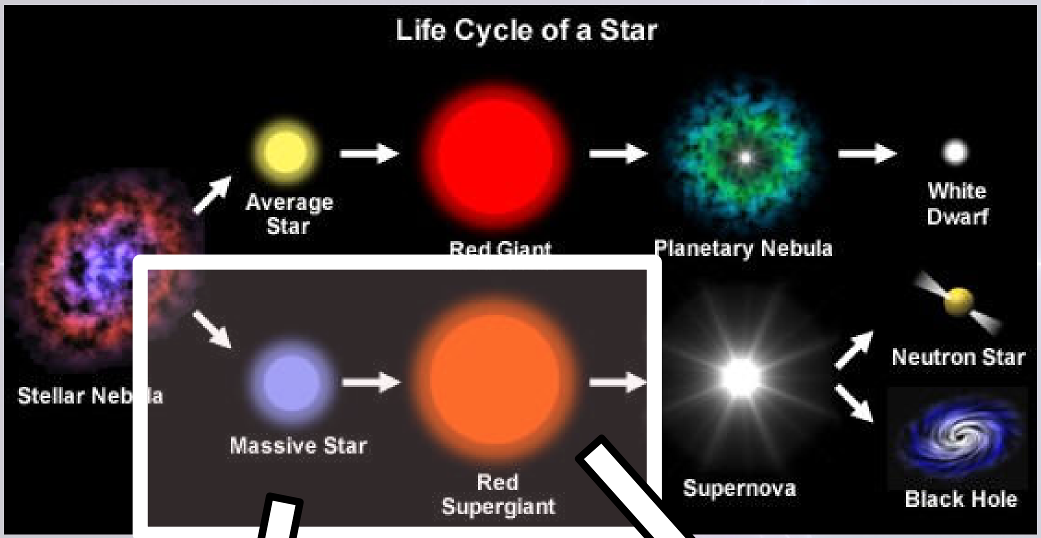


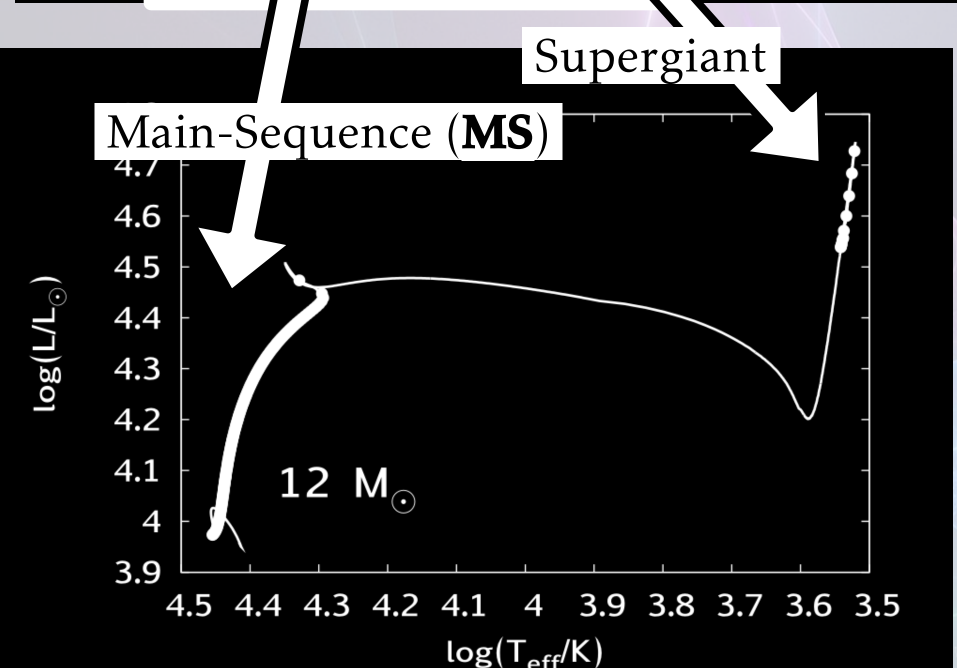
Two of them next to each other:

Imagine two (massive) stars!

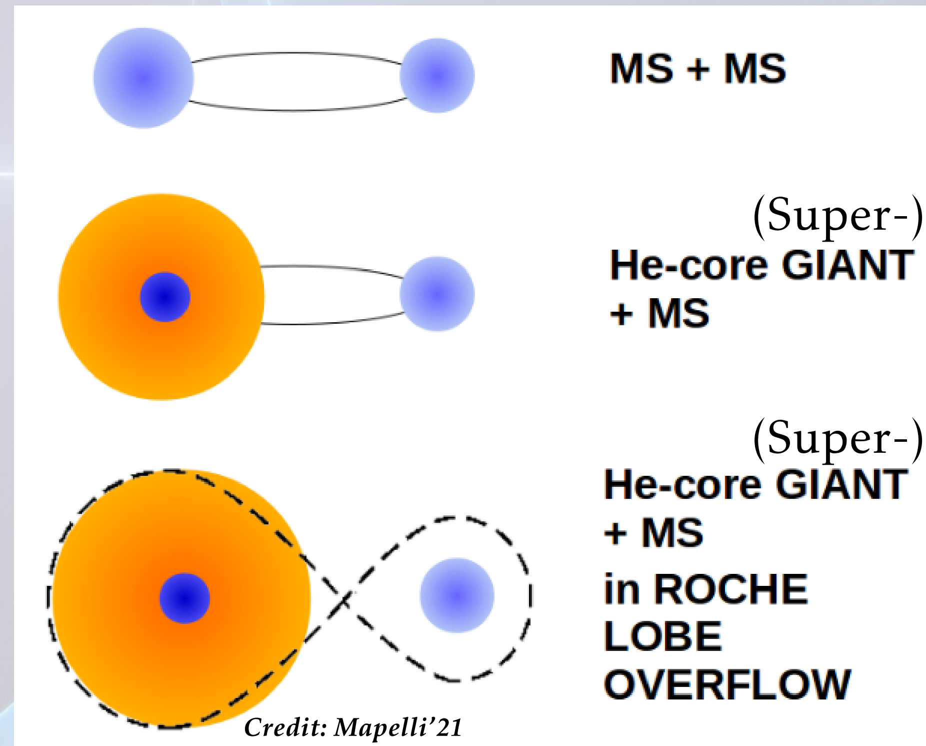
with Solar Z, no rotation

One (massive) star alone:



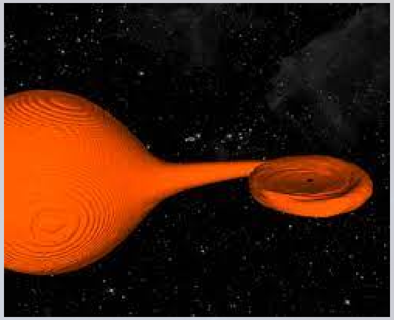


Two of them next to each other:



- $\tau(m) \sim m^{-2.5}$
  - 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

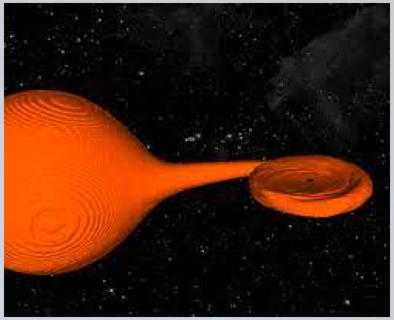
What happens when the Roche-lobe is overflown?



- Mass transfer
  - = mass exchange
  - = (binary) interaction

Youtube video to watch:
youtube.com/watch?v=xAjq7VGnf4s

What happens when the Roche-lobe is overflown?



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- Mass transfer
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Next time.