Gravitational-wave progenitors

Dorottya Szécsi

dorottya.szecsi@gmail.com

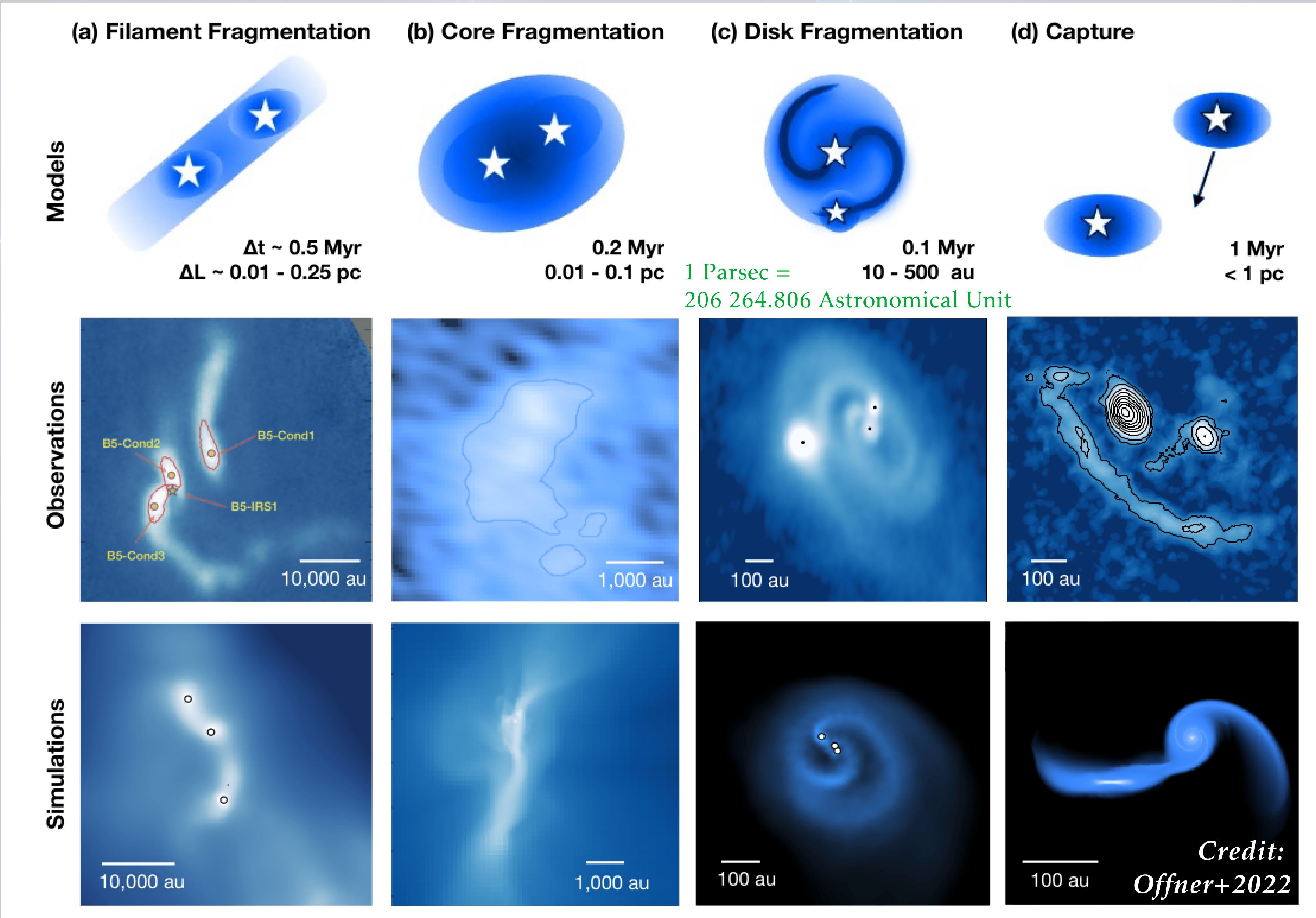
Lecture #10

NCU, Summer Semester 2022

Previously
on GW-progenitors…

Stars sometimes form in *multiples*

binaries, triples, quadruples…



Our strategy is/has been:

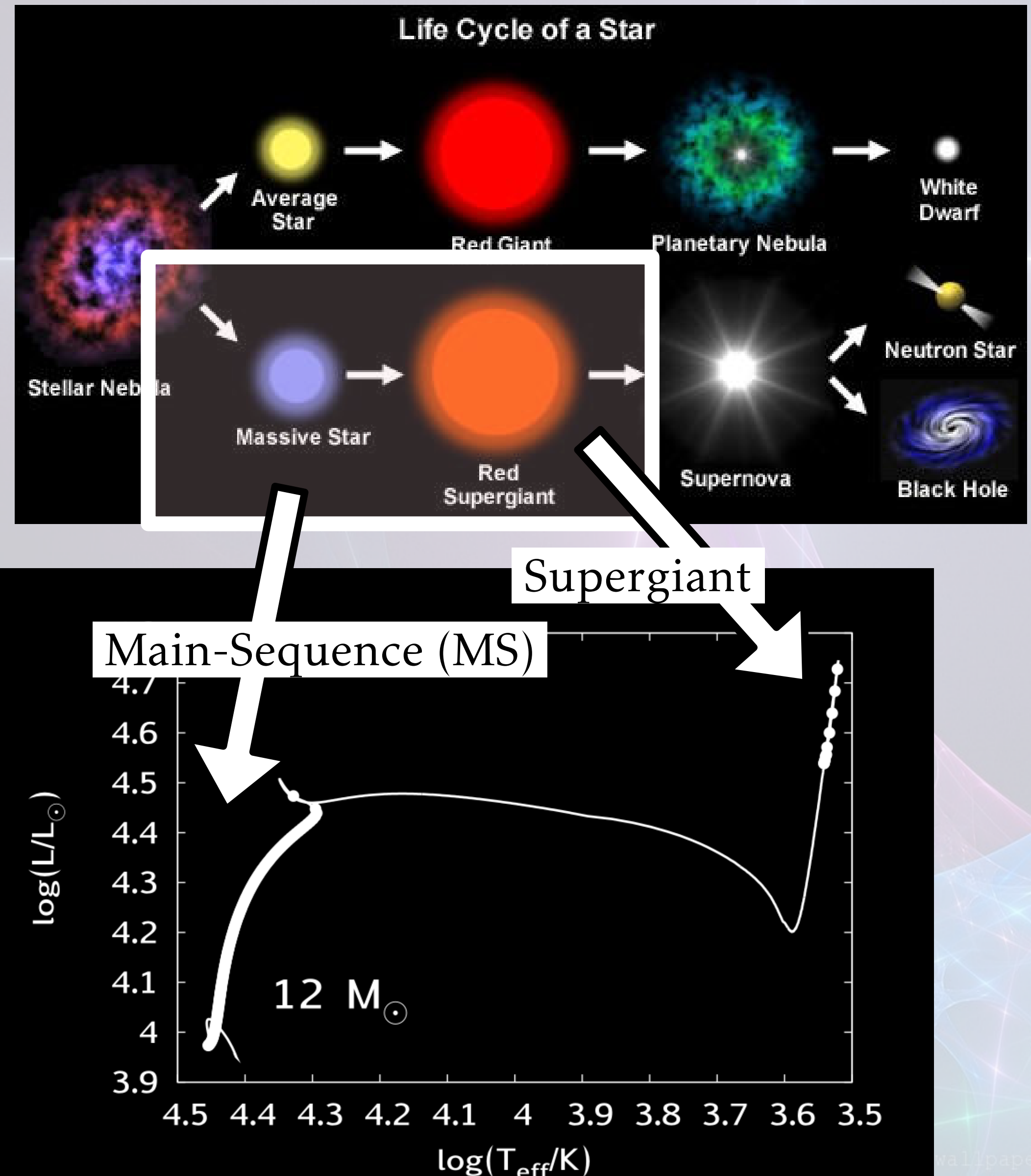
start with
Massive Stars at Solar Z

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

Imagine two (massive) stars!

with Solar Z, no rotation

One (massive) star alone:

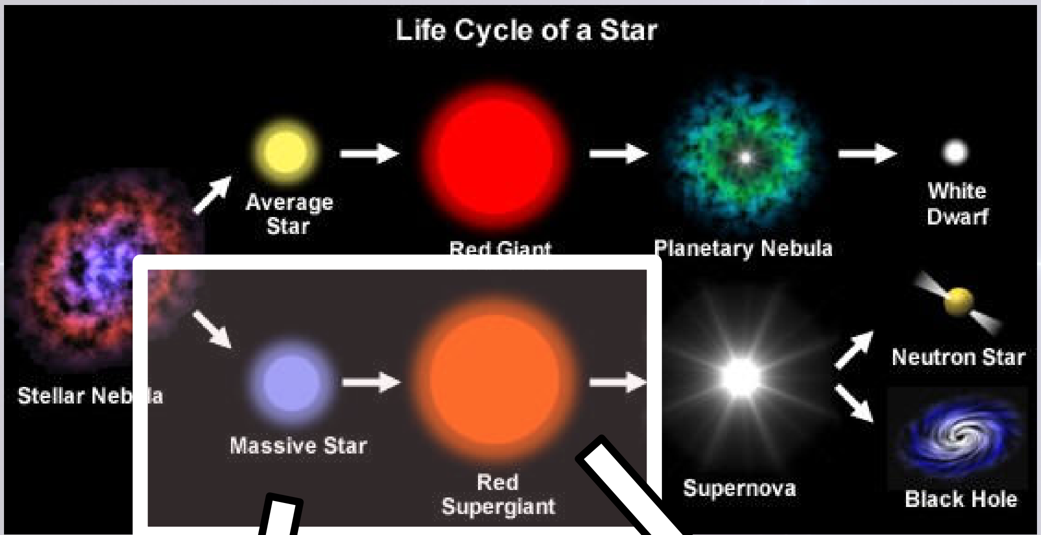


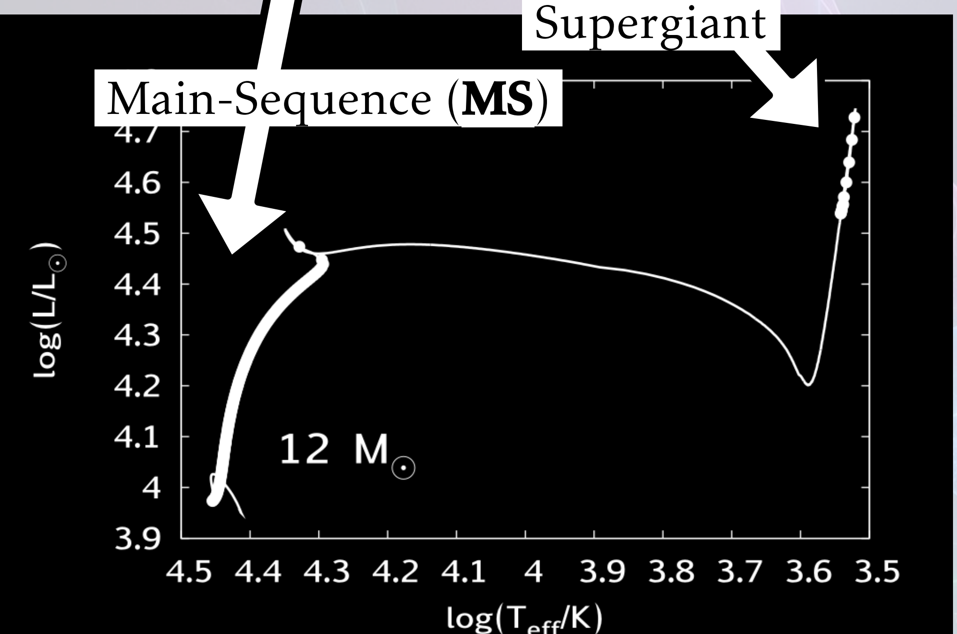
Two of them next to each other:

with Solar Z, no rotation

Imagine two (massive) stars!

One (massive) star alone:





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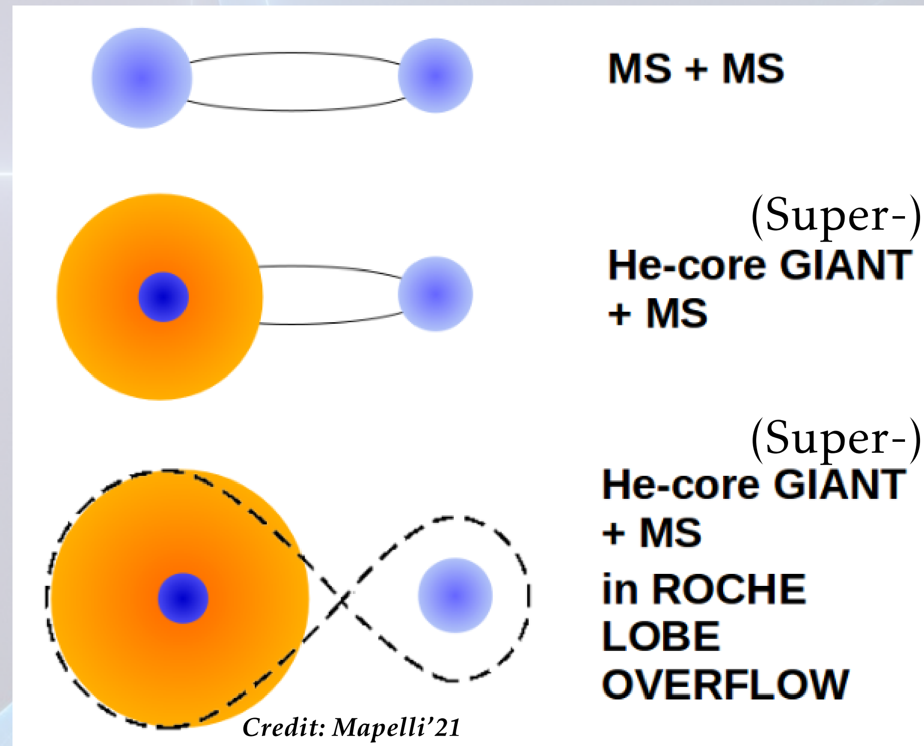
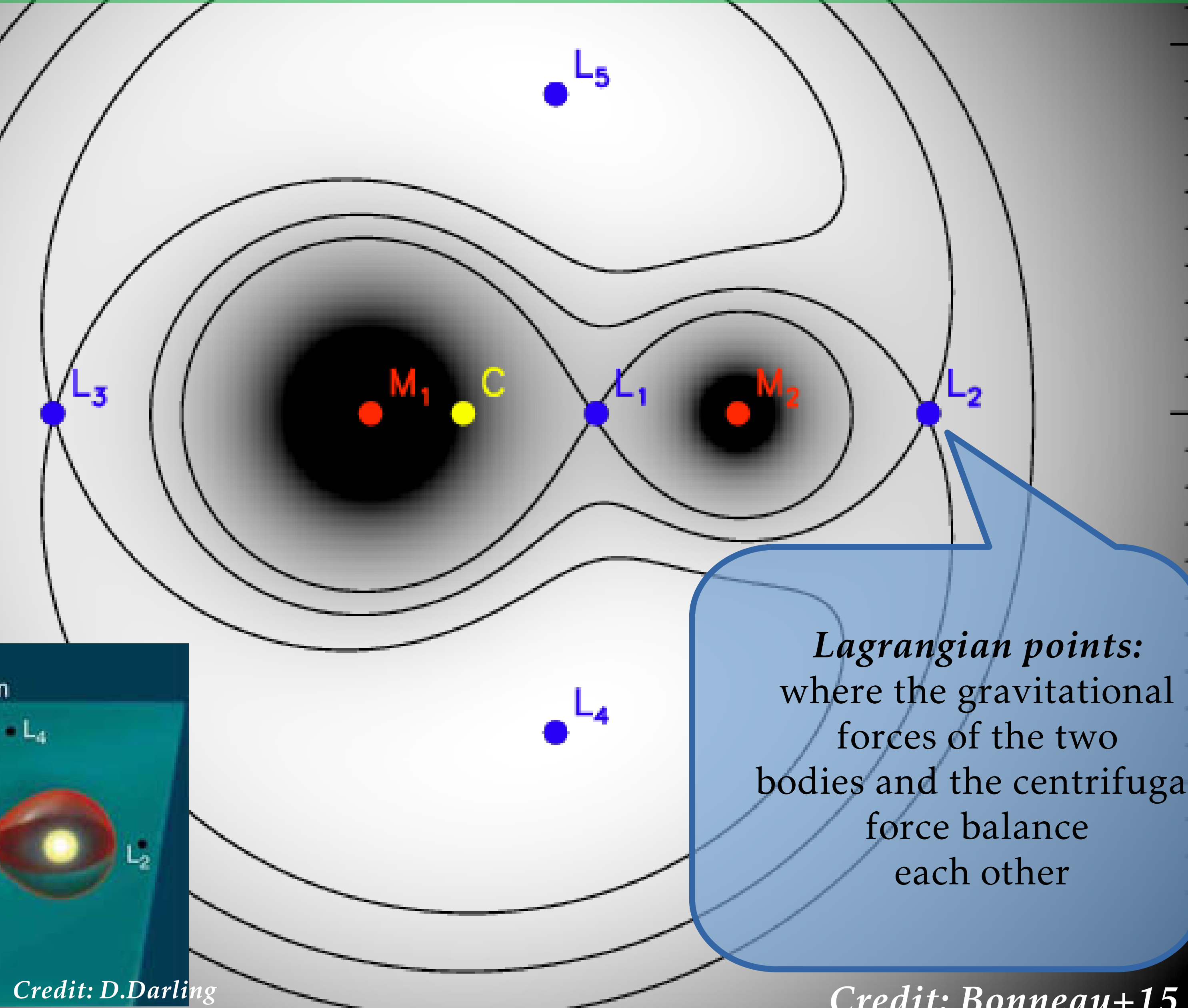


Credit: Mapelli'21

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

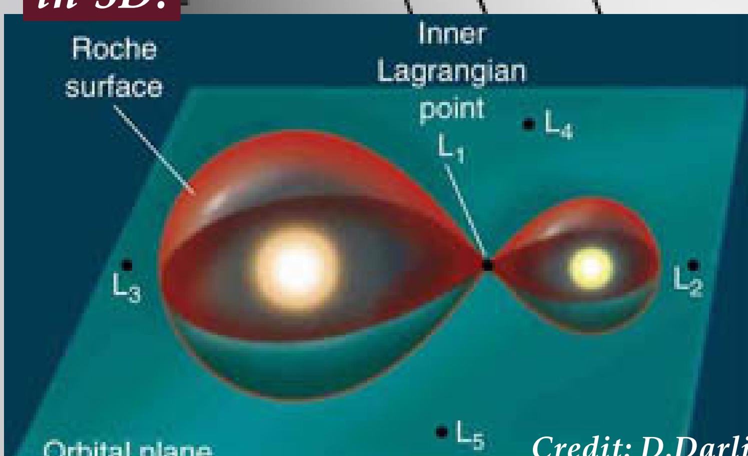
The most important concept:
Roche-lobe



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

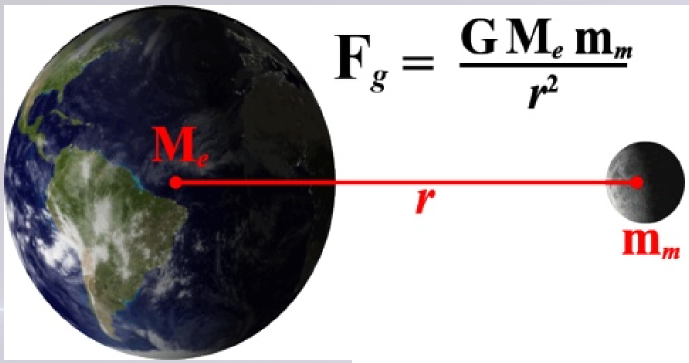
Credit: Bonneau+15

in 3D:



Credit: D.Darling

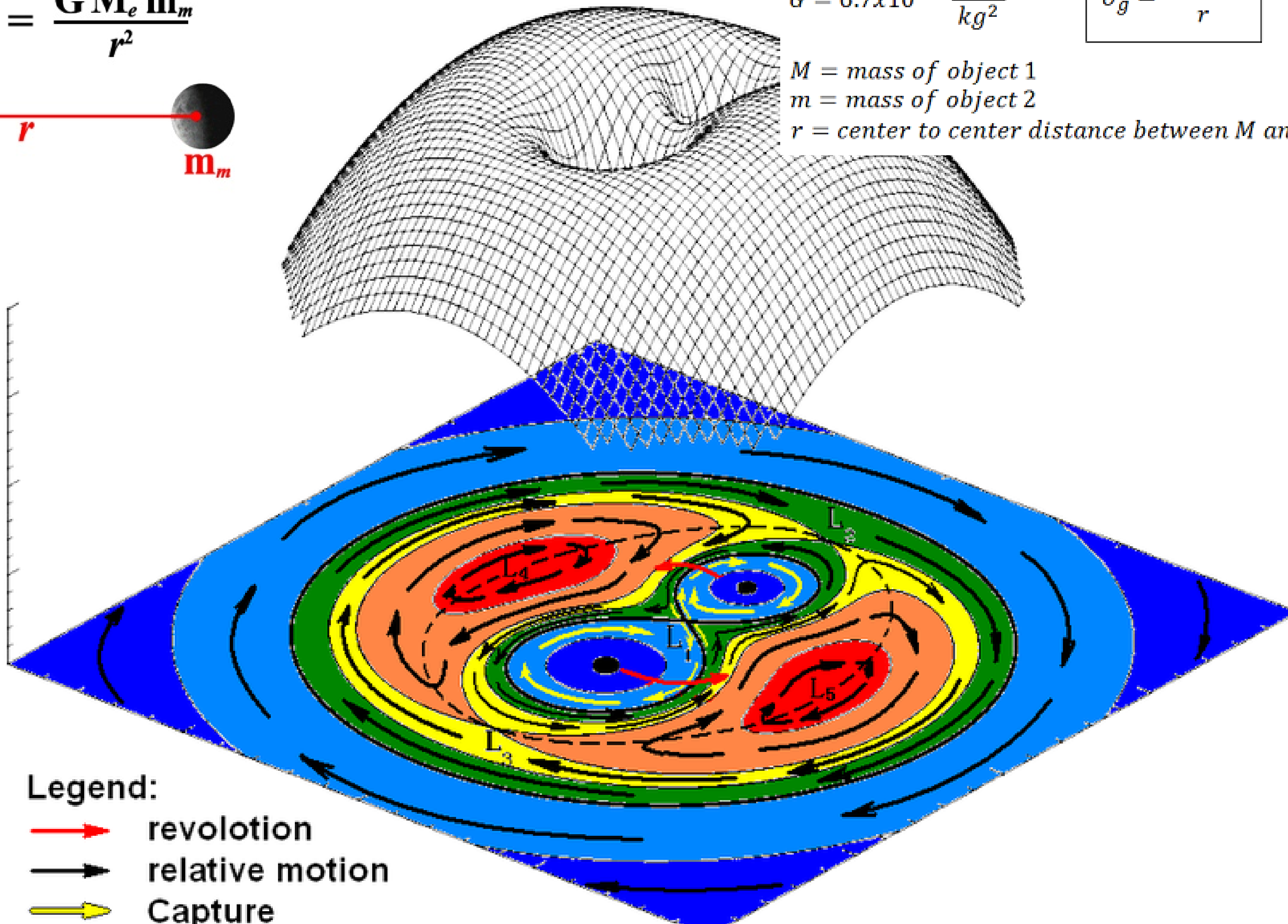
Gravitational equipotential surfaces



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

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

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



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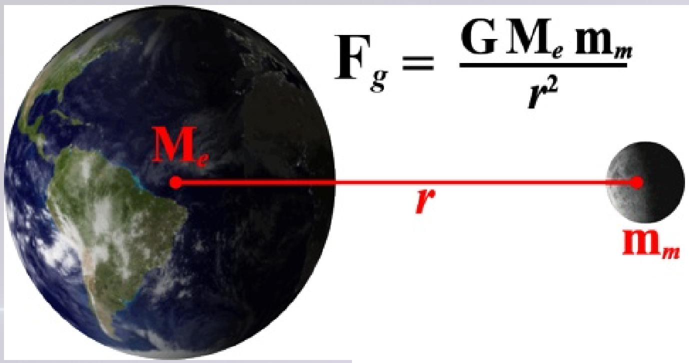

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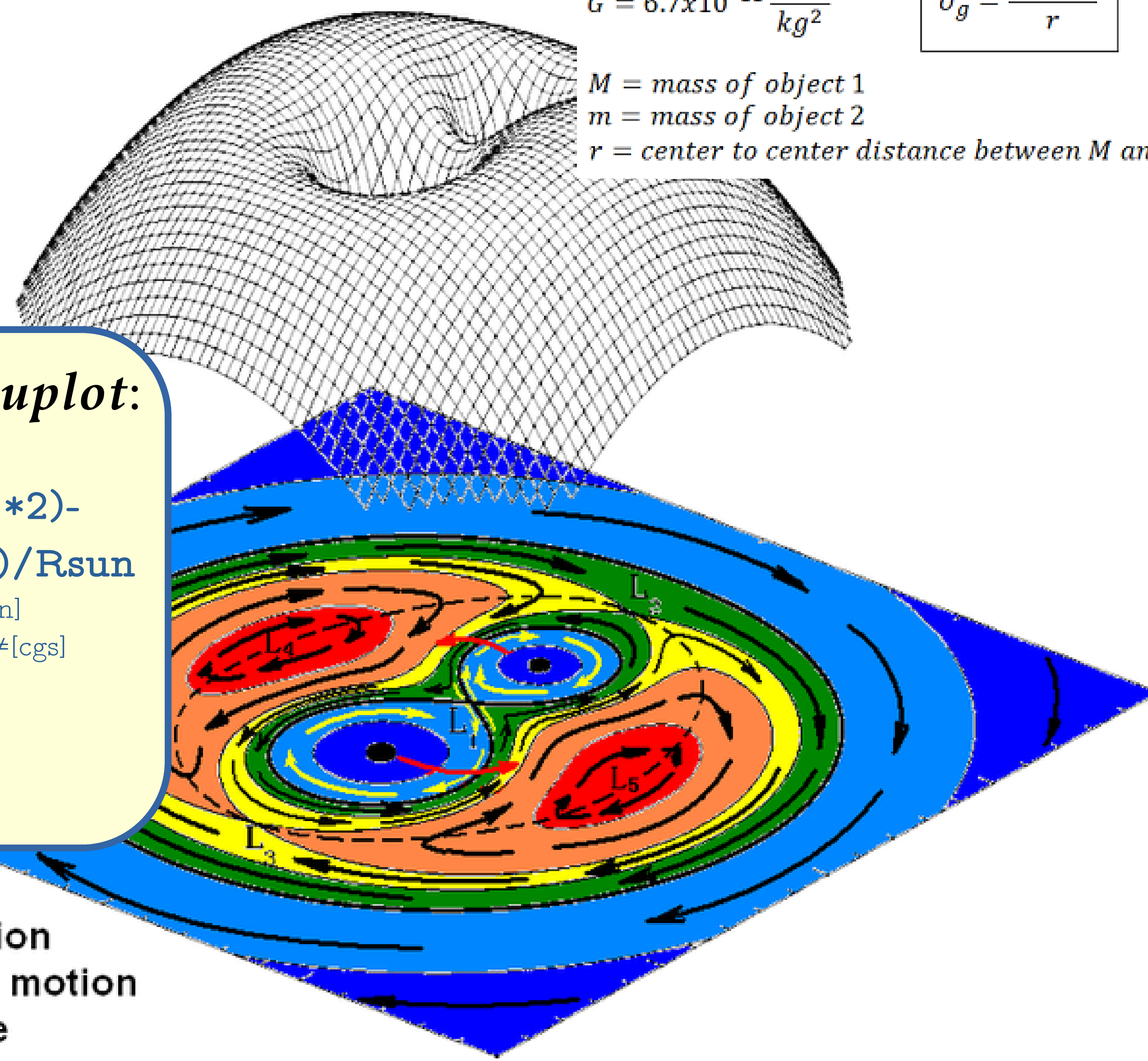


Try it for yourself! E.g. in ***gnuplot***:

```
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

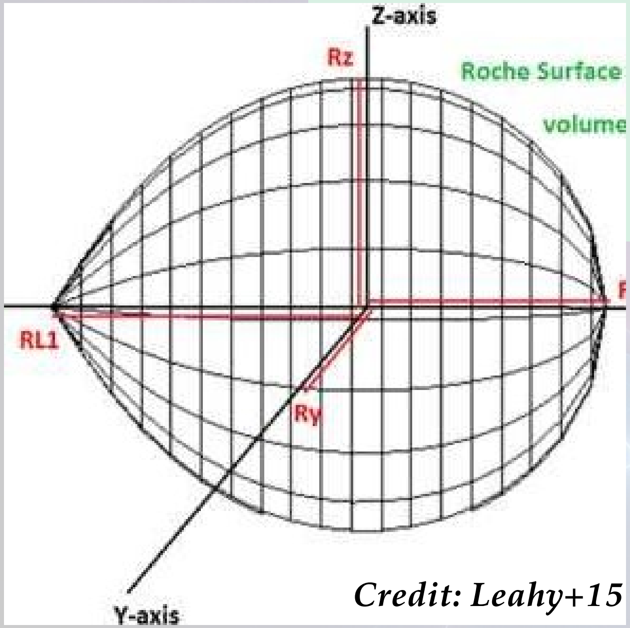
- we can plot is but we cannot explicitely derive it

$\Longrightarrow$ 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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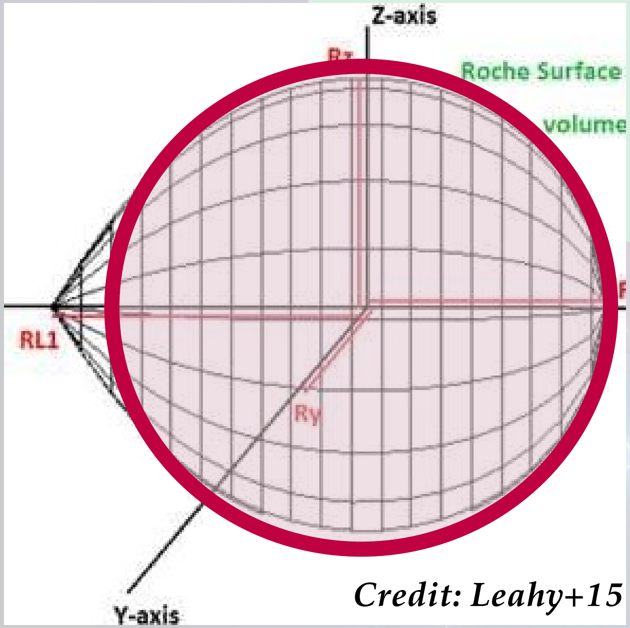
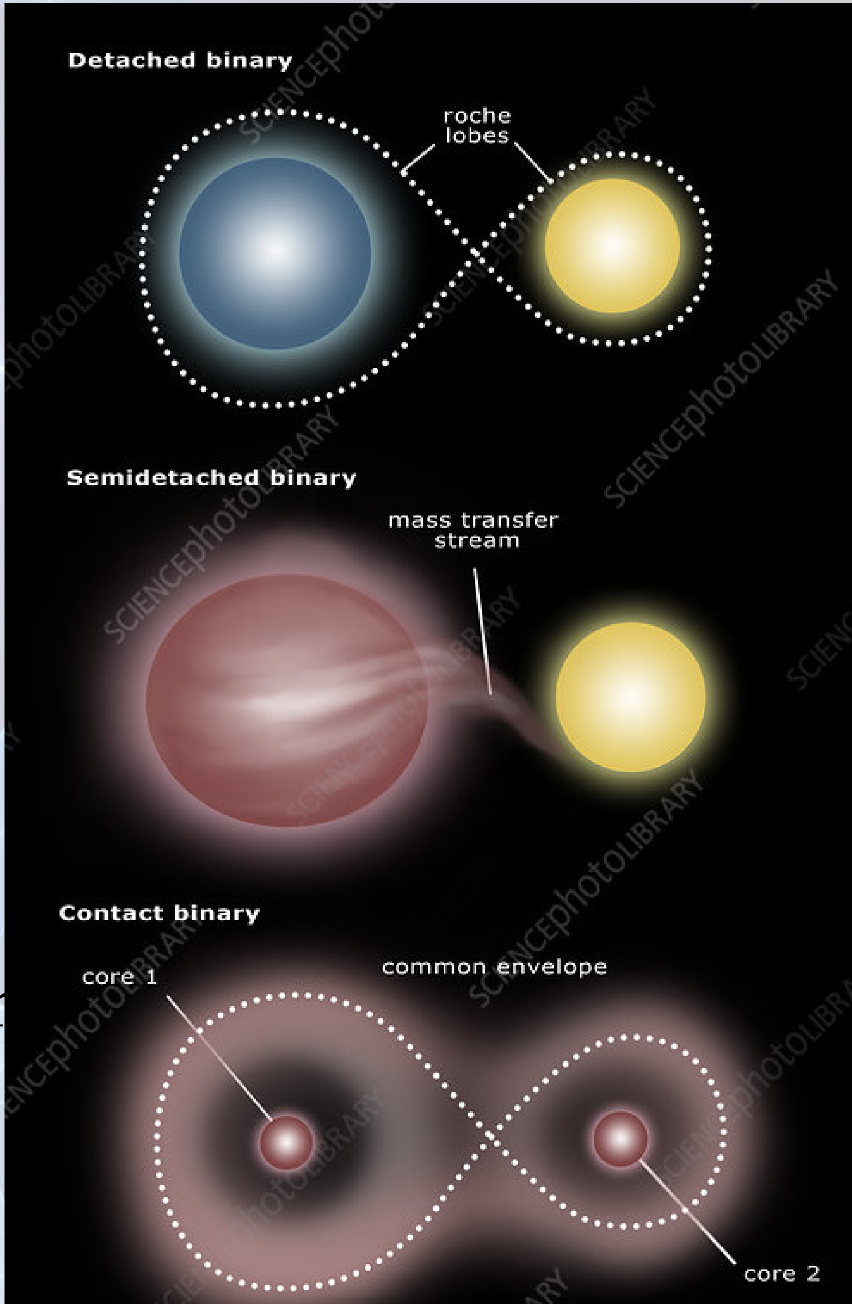


Credit: Leahy+15

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' (...)

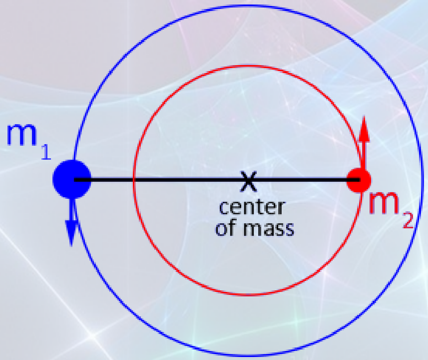
▶ *stellar* envelope



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:



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

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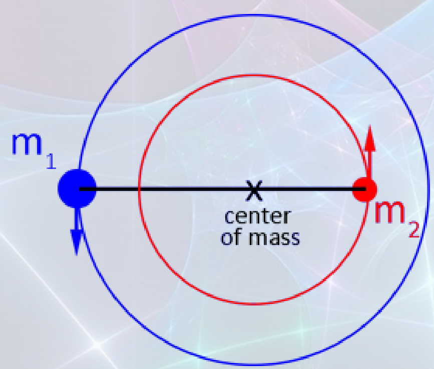
- Connection between distance & period?

Eccentricity, circular orbit
Inclination (orbital)
Orbital parameters
Semi-major axis ‘a’
Semi-minor axis ‘b’
Mass ratio, $q=m_2/m_1$
orbital angular momentum

Kepler's 3rd law:



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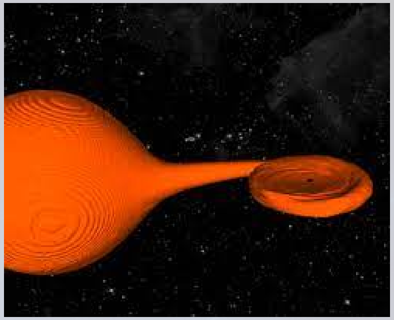
What happens when the Roche-lobe is overflown?



- Mass transfer

  ~ mass exchange

  ~ (binary) interaction

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

Today.

‘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’, ‘Case B’, ‘Case C’ mass transfer

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

    (donor’s evolutionary status)

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

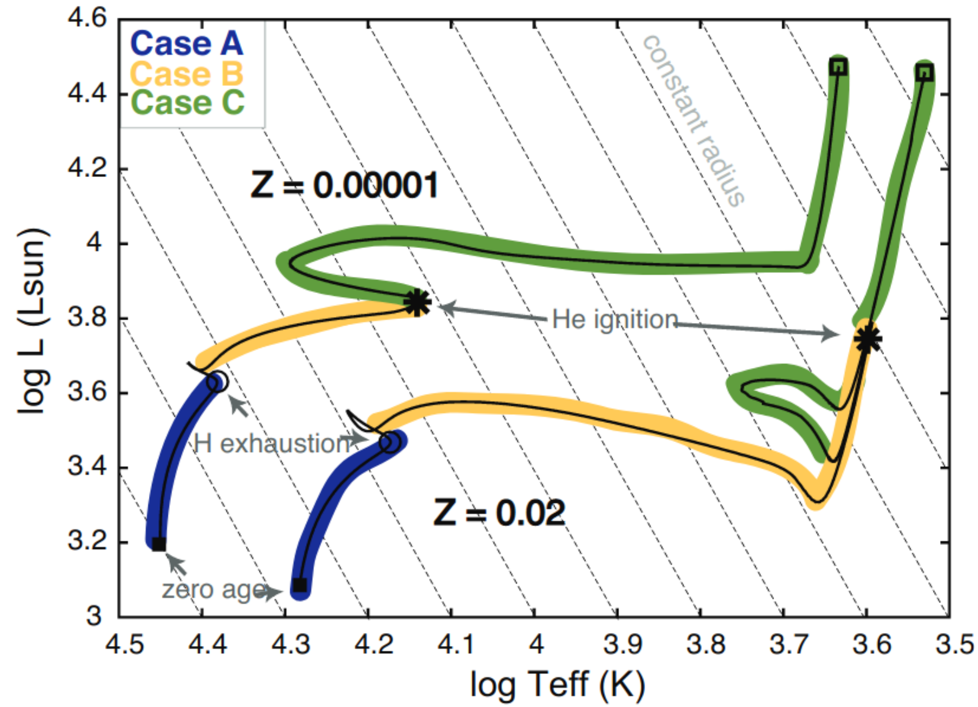

Figure 1.1: *Evolutionary tracks in the HR-diagram of a 6 $M_\odot$ star illustrating the effect of metallicity on the occurrence of the different cases of mass transfer. The dashed diagonal lines indicate lines of constant radii. Cases A, B and C are defined in the text of Section 1.5.1. Figure adapted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

Sub-categories exist…

– case BA: mass transfer is initiated during helium core burning

– case BB: initiated after helium core burning is terminated, but before the ignition of carbon

’ mass transfer

ellar classes O, B, A, F… or

- useful to know

even if its getting outdated

– case B: HG

– case C: He-b.

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MS = Main Sequence
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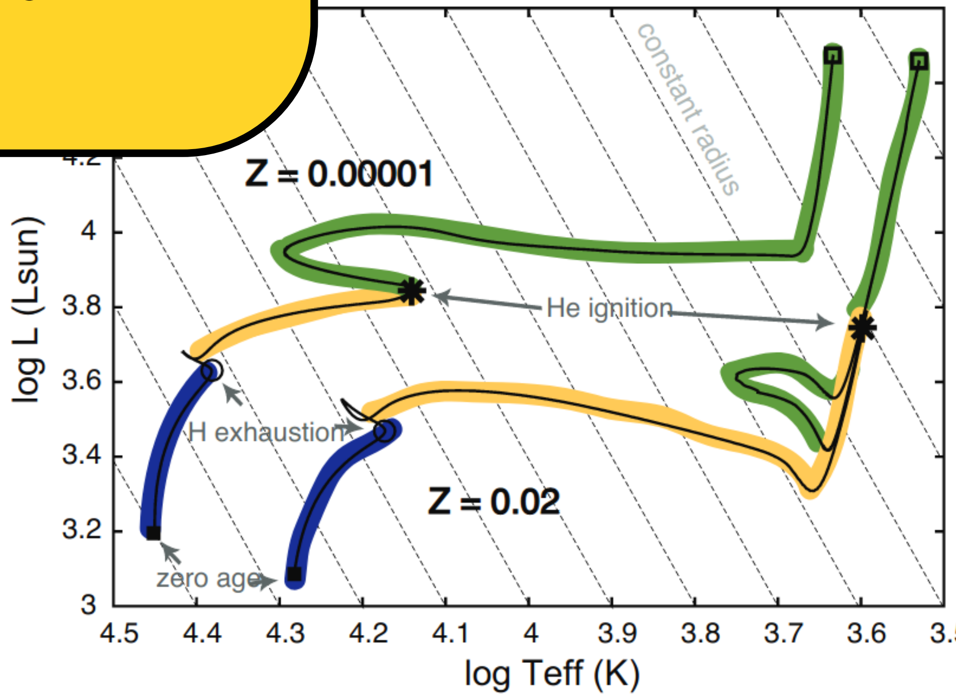

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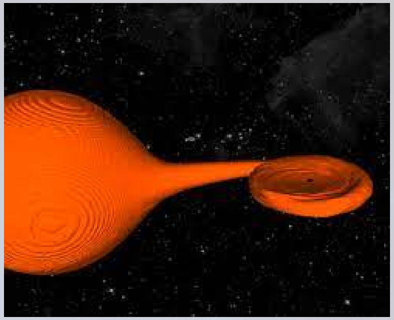
Sidenote: TIMESCALES

- The **dynamical timescale**. How long would it take for the star to expand or contract if the balance between pressure gradients and gravity was suddenly disrupted? Same as the "free-fall time scale". For the Sun, it is about half an hour.
- The **thermal timescale**. Also known as the Kelvin-Helmholtz timescale. Suppose nuclear reactions were suddenly cut off in the star (but the stability somehow stays intact). The thermal timescale is the time required for the star to radiate all its reservoir of thermal energy away. For a Sun-like star the thermal timescale is ~10 Myr.
- The **nuclear timescale**. This is the evolutionary timescale of a star. As the star evolves the composition of the core changes due to nuclear burning. The nuclear timescale is the time for the star to change its core composition by a factor of order unity. For a Sun-like star the nuclear timescale is ~10 Gyr.

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

What happens when the Roche-lobe is overflown?



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

- Mass transfer

  ~ mass exchange

  ~ (binary) interaction

Material of the star becomes unbound. It might flow off.
(outer layers)

If it does, where does it end up?

(1) – on the top of the companion ('transfer')
(2) – in the surroundings (non-conservative mass "transfer")
in reality: a mix of (1)+(2) or some other option (e.g. an accretion/decretion disc?)
((disc: circumstellar or circumbinary))

What happens when the Roche-lobe

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tch:
af4s

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What happens to the <u>donor</u> after having lost some layers?

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How does the orbit (and thus the Roche-lobe) change?

…

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]

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orbital separation: A

- And remember: massive stars have WINDS…

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 (😳)

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- 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

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

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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

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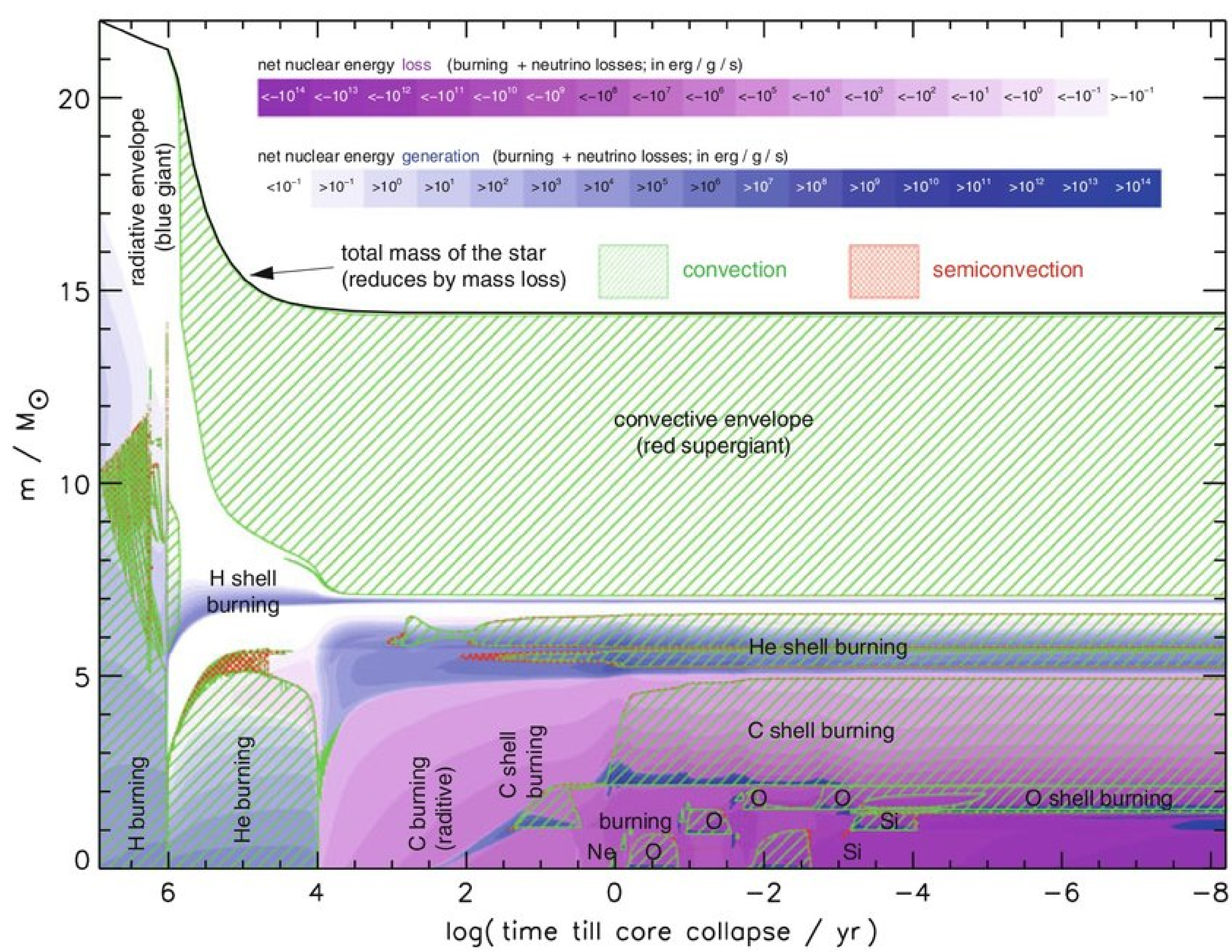
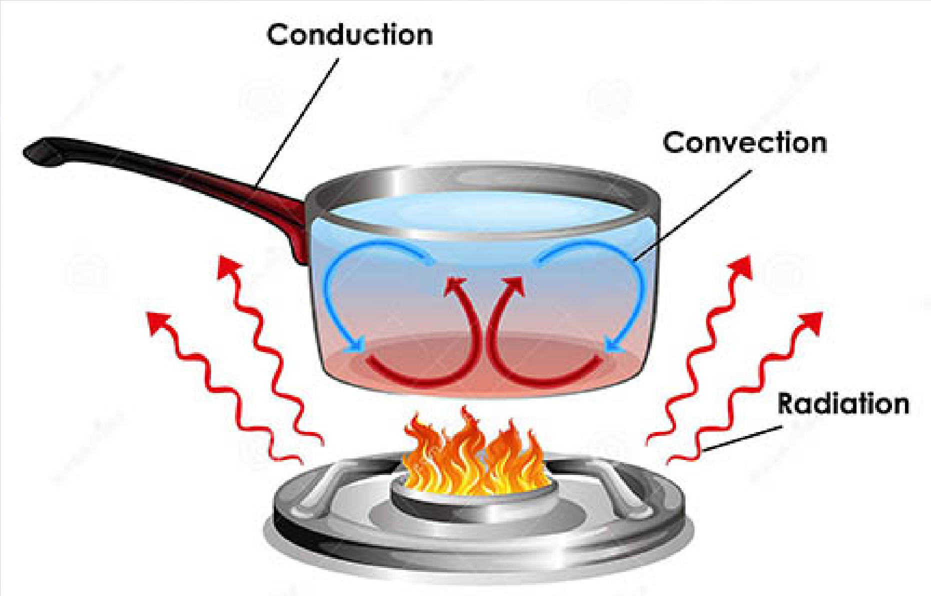
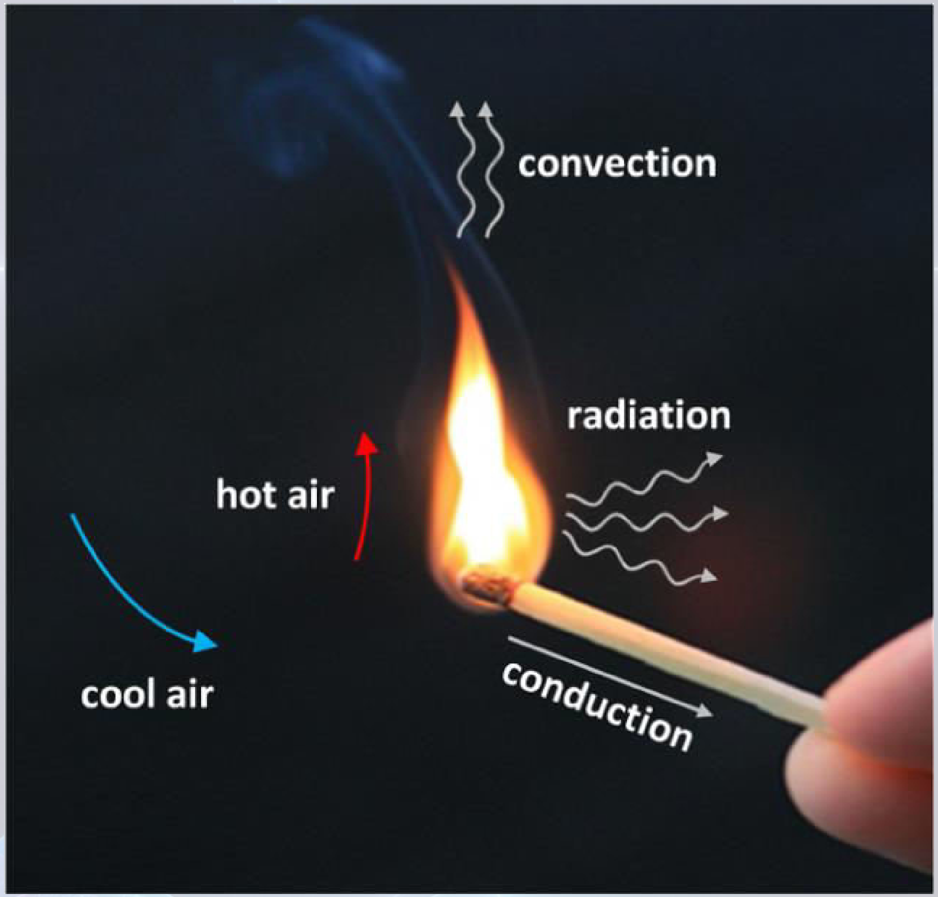
Remeinder: Kippenhahn diagram



Remeinder: 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)

Remeinder: convection

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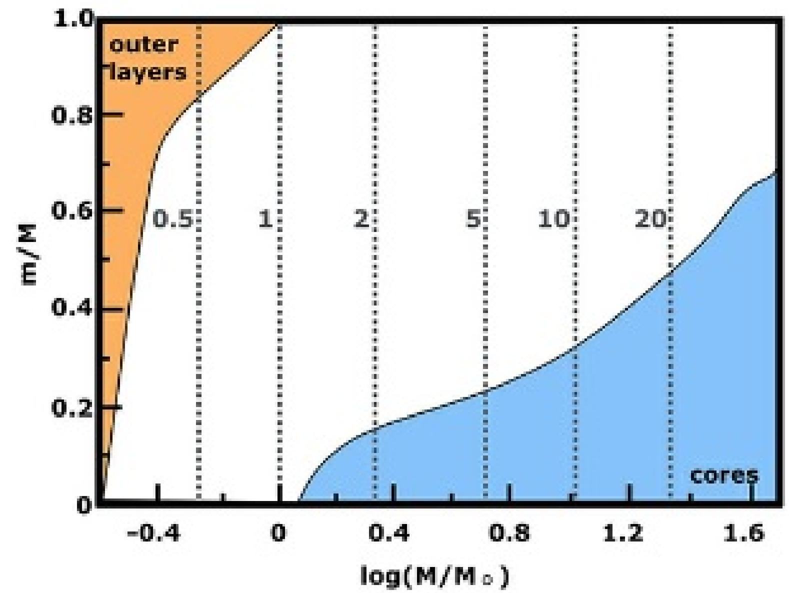
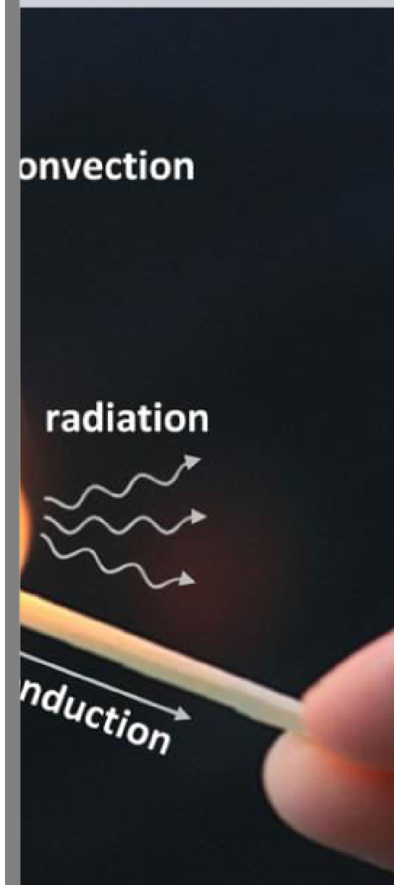


Figure 7.6. Occurrence of convection in stars at the beginning of the core H-fusion phase (ZAMS). The mass of convective envelopes (orange) and convective cores (blue) is expressed as a fraction of the stellar mass, from $m/M = 0$ in the core to $m/M = 1$ at the surface. The vertical lines indicate the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



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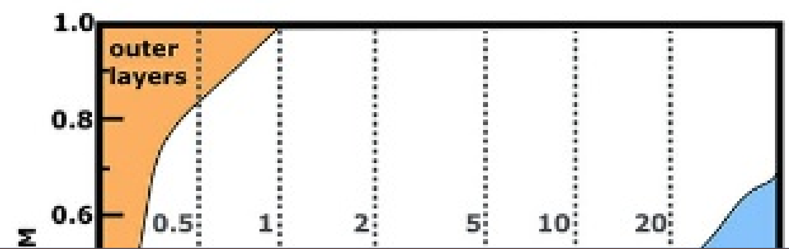

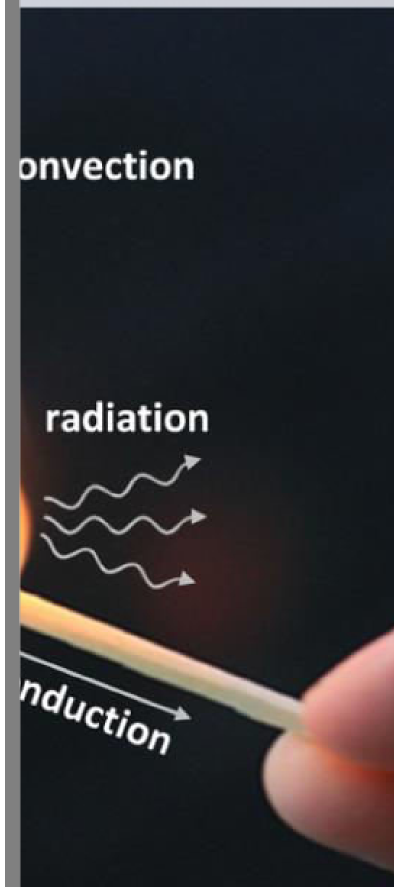

Make sure to remember:

– massive stars's cores are convective
(the Sun's core is radiative!)

– supergiants' (aka post-MS massive stars')
envelope is *also* convective
(will be important later, in binary interactions)

tly
d low-mass stars…

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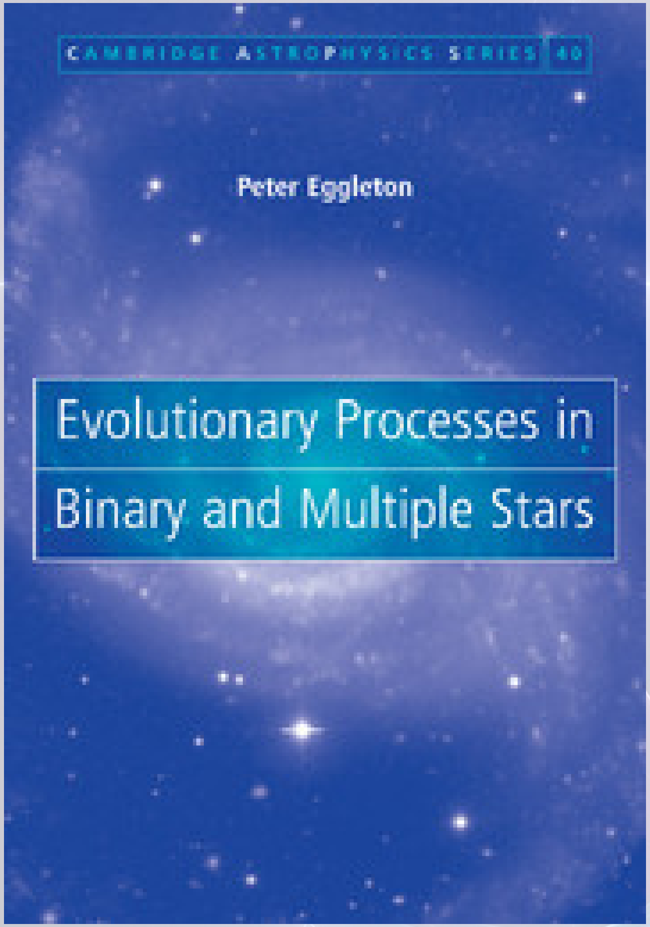
Further reading:



- Peter Eggleton: ***Evolutionary Processes in Binary and Multiple Stars*** (2006, Cambridge University Press)

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

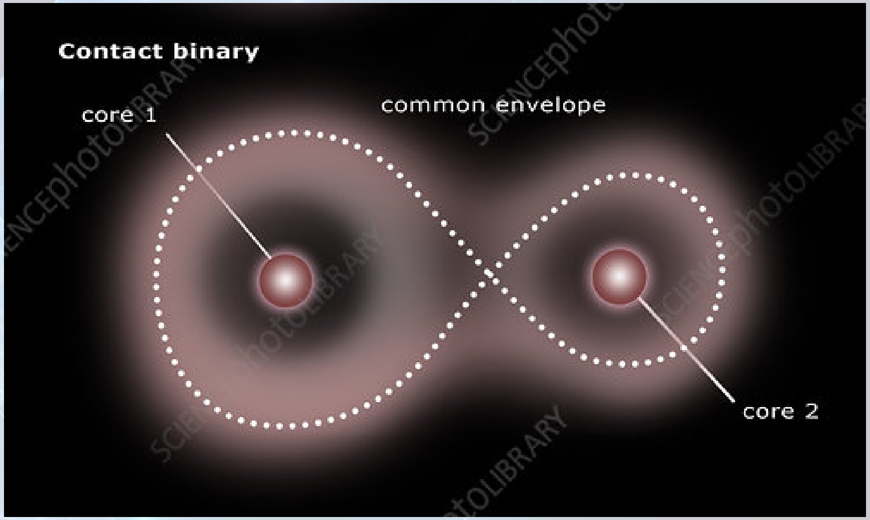
Unstable mass transfer

Unstable mass-transfer

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

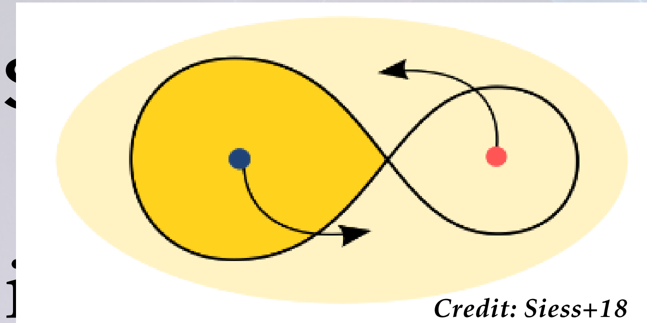
secondary cannot accrete fast enough

- has dramatic effects: “common envelope” situation

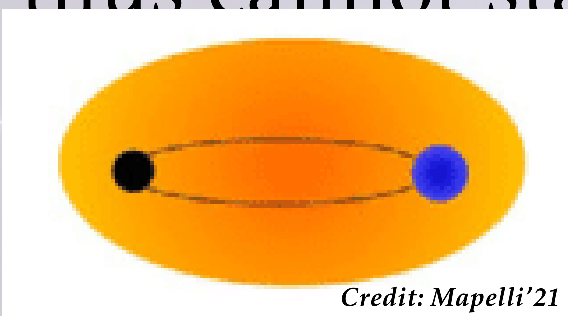


$\tau_{nuc} \gg \tau_{KH} \gg \tau_{dyn}$

Uns -transfer


Credit: Siess+18

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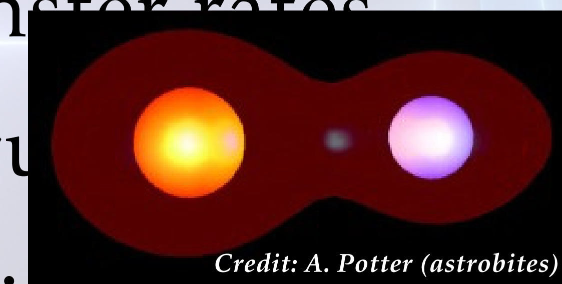
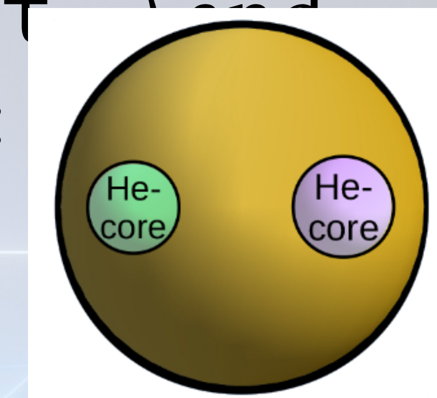
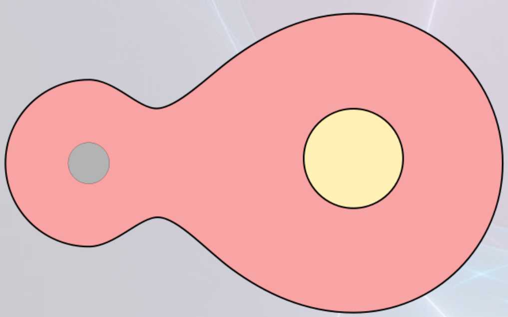
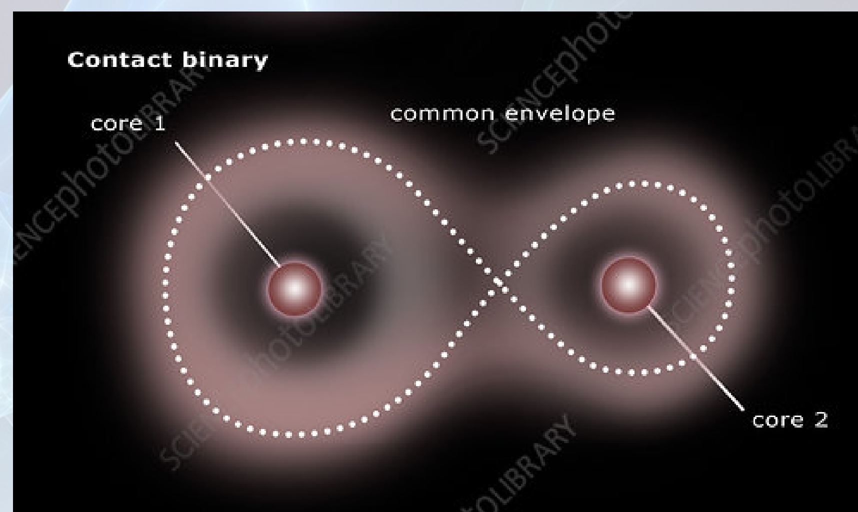

Credit: A. Potter (astrobites)



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

- able, ru on
- has dramatic effects: common envelope" situation


Credit: Wikipedia



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What we know about CE

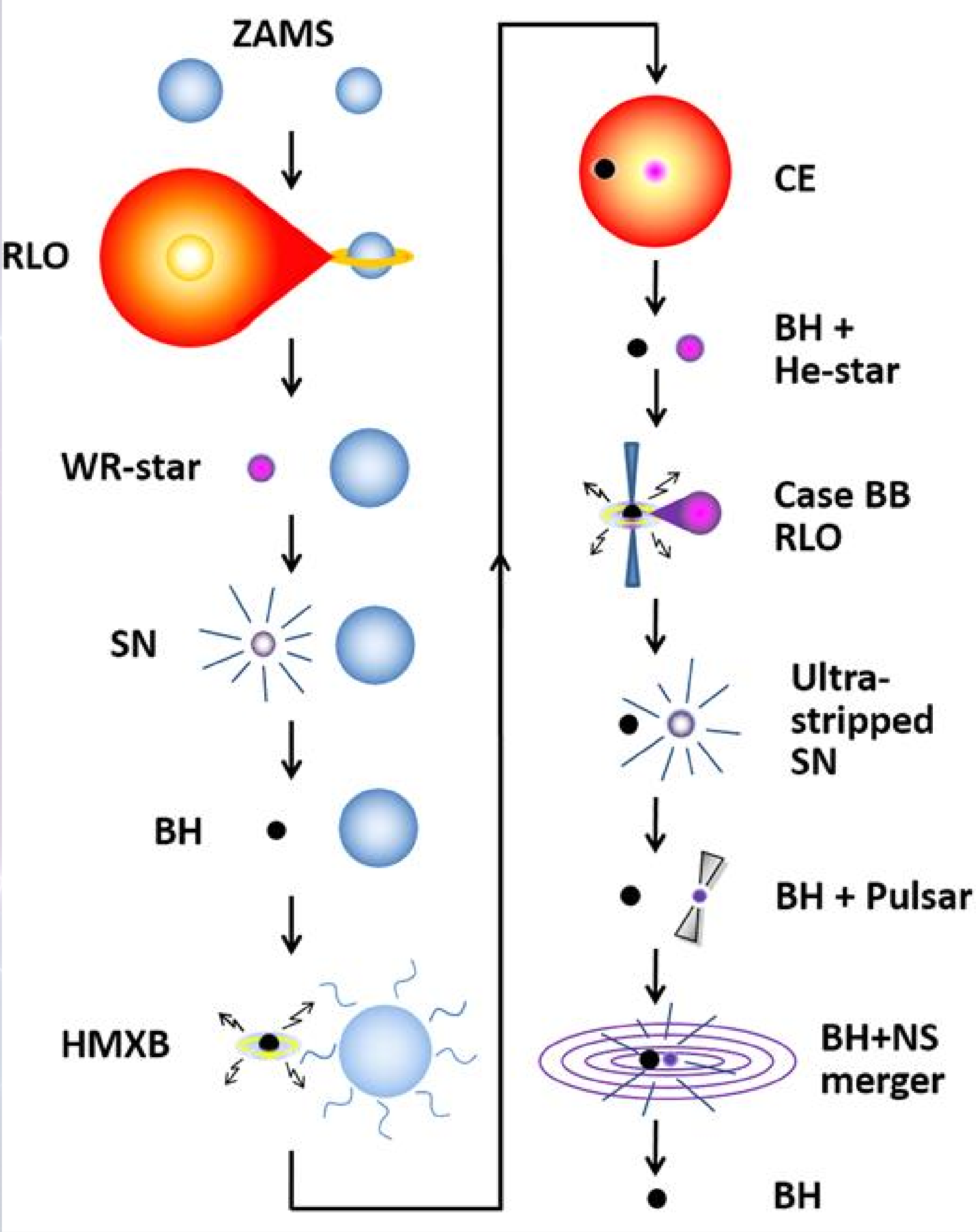
- short lived phase
  - observed?? how??
- but it probably occurs
  - explaining <u>close</u> white dwarf-binaries (WD=ex-Red Giant: no other way to get that close)
- 3D simulations are still very expensive
  - in practice: derived relations between orbital energy & binding energy of the envelope
- Result: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

Movies :)

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

Let's play!

Let's play!



Credit: Kruckow+18

Let's play!

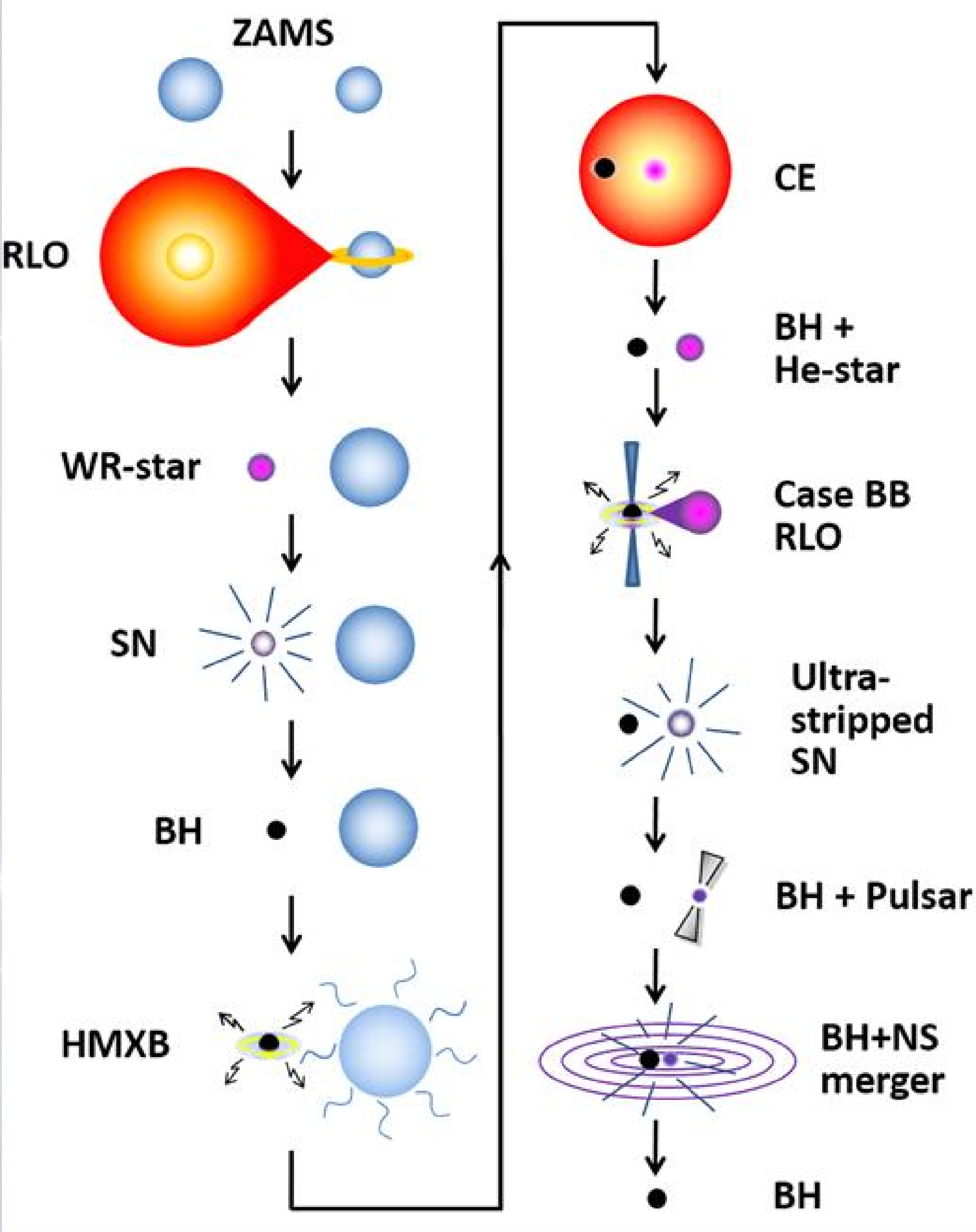
Zero-age Main Seq.

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 star)

GRAV. WAVES!!!

Credit: Kruckow+18

This is just one possible scenario, actually.

There are more.

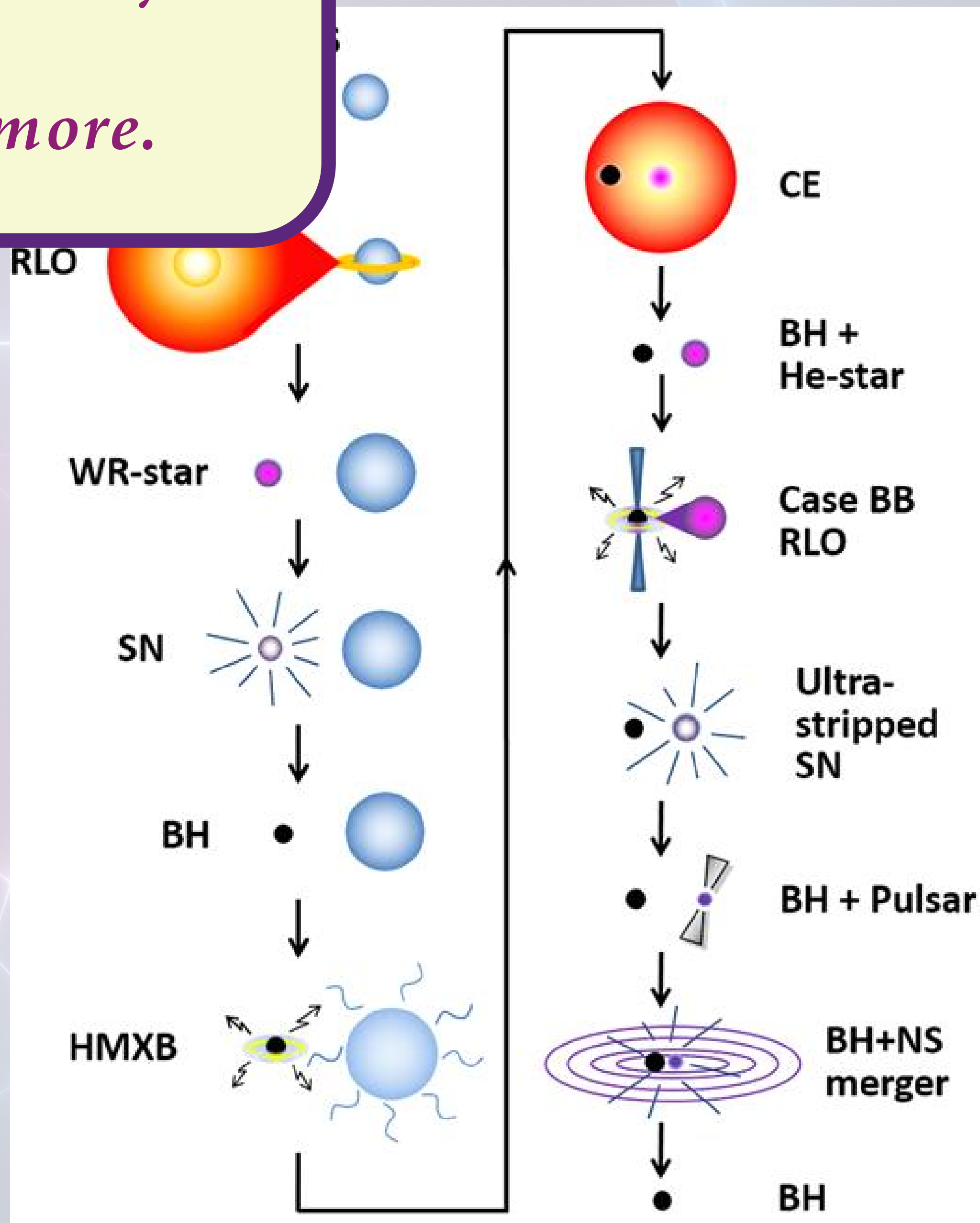
t's play!

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?

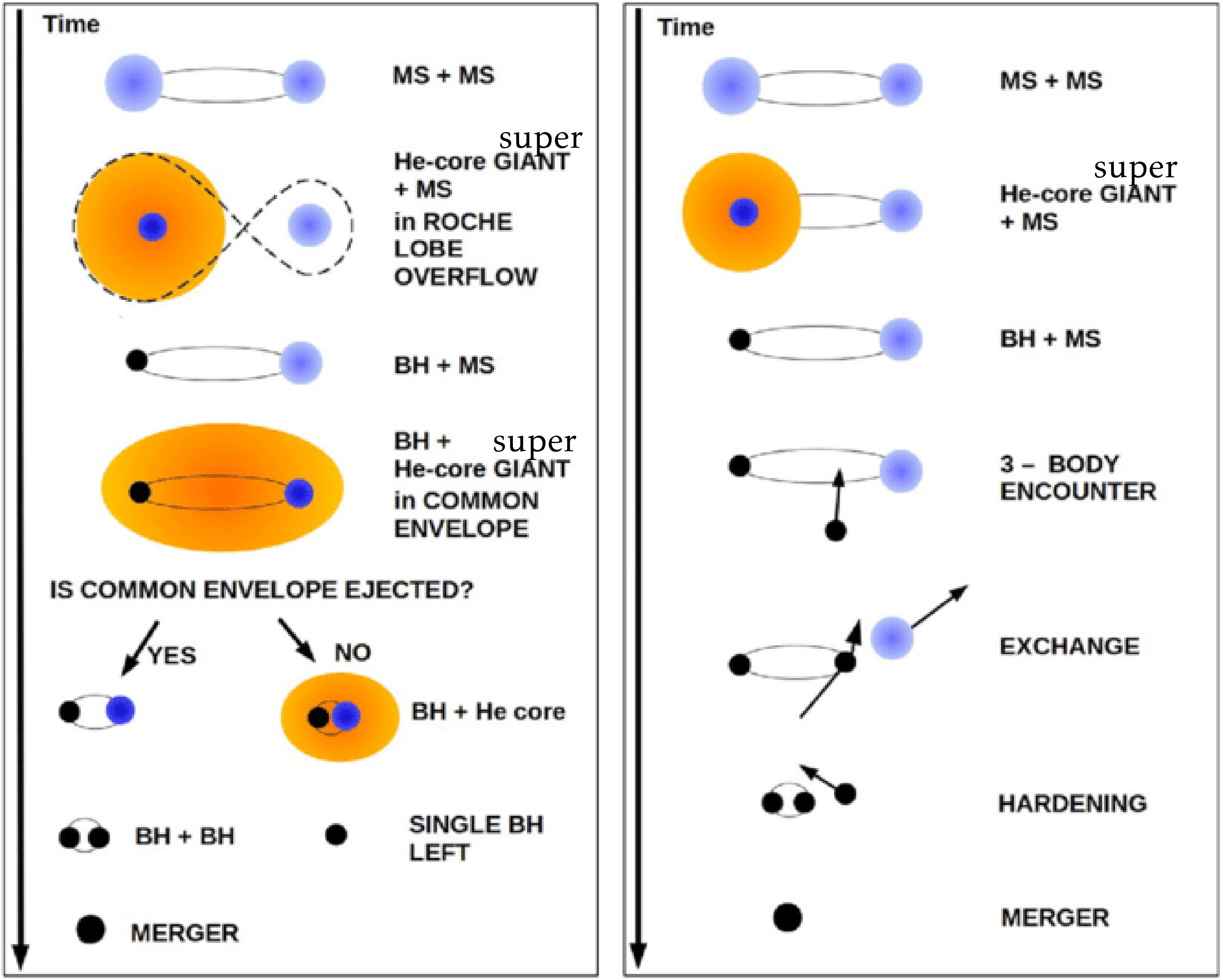
Stripped = type Ib
Ultra-stripped = type Ic

(Pulsar: a rotating, magnetized neutron star

GRAV. WAVES!!!

Credit: Kruckow+18

Some other scenarios...

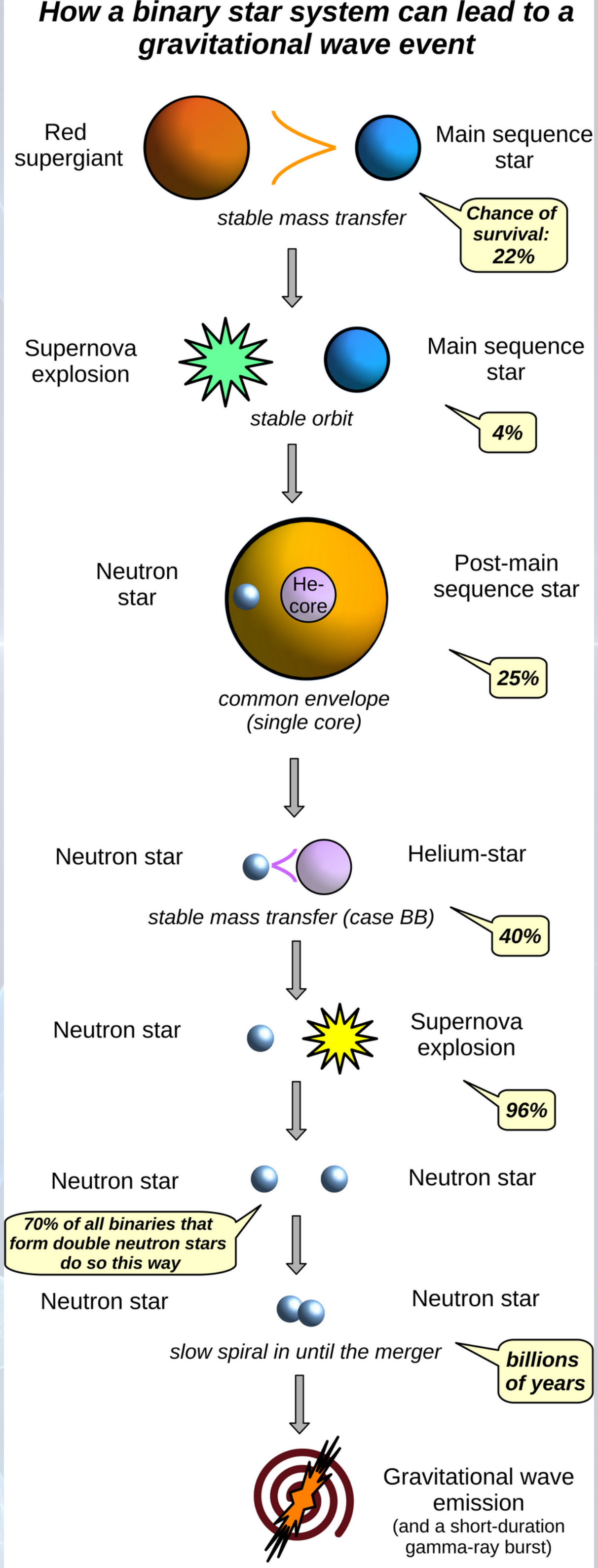


a triple!

= orbit shrinks

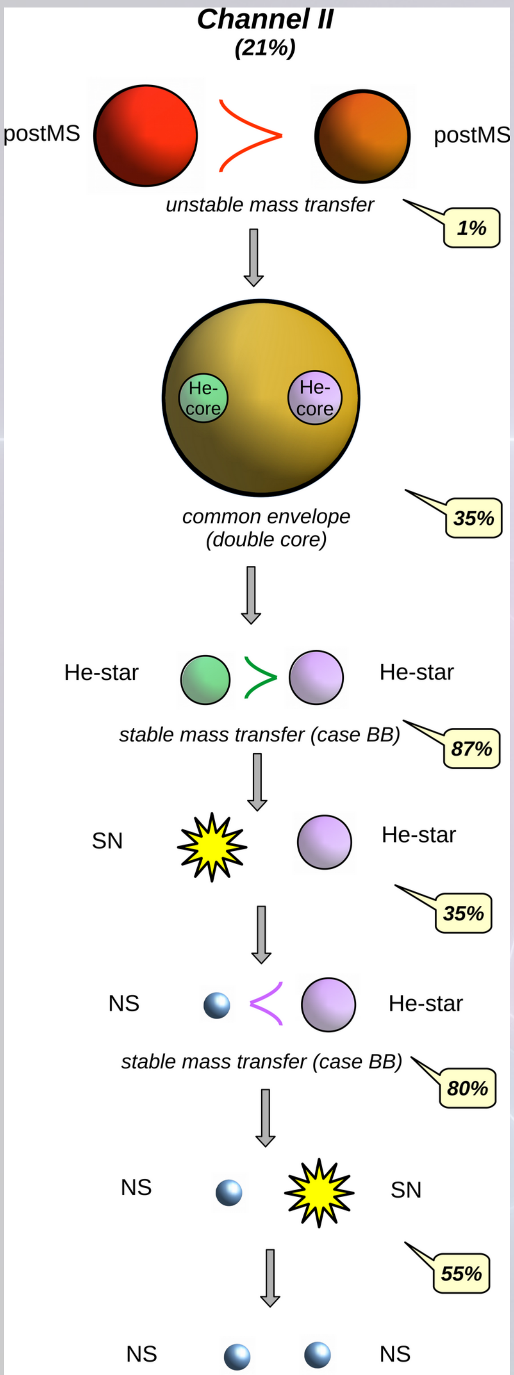
Credit: Mapelli'21

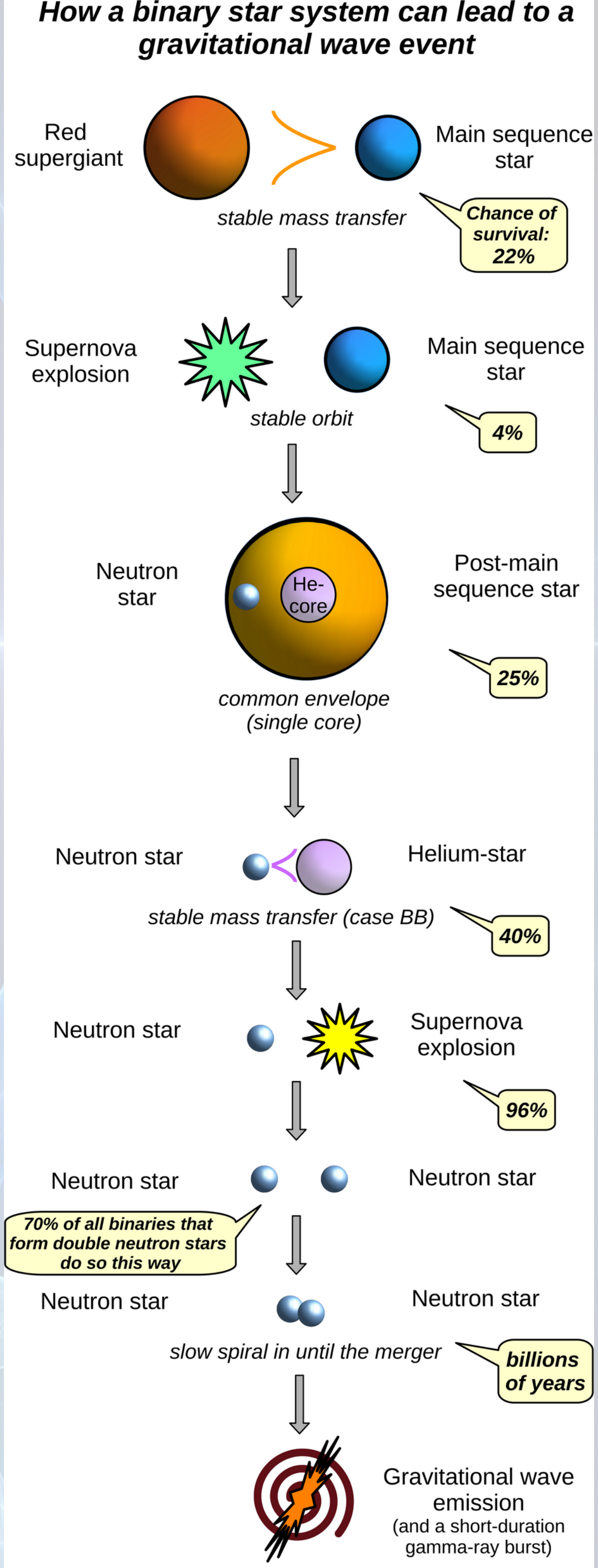
There are more... :D



Credit: Vigna-Gomez+18

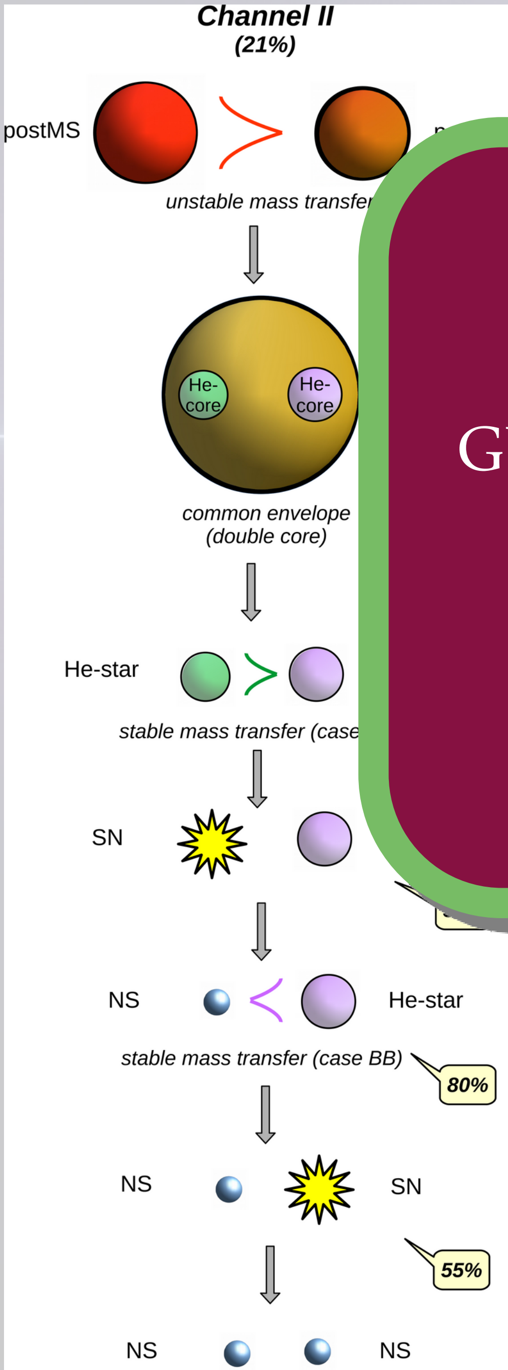
There are more... :D





Credit: Vigna-Gomez+18

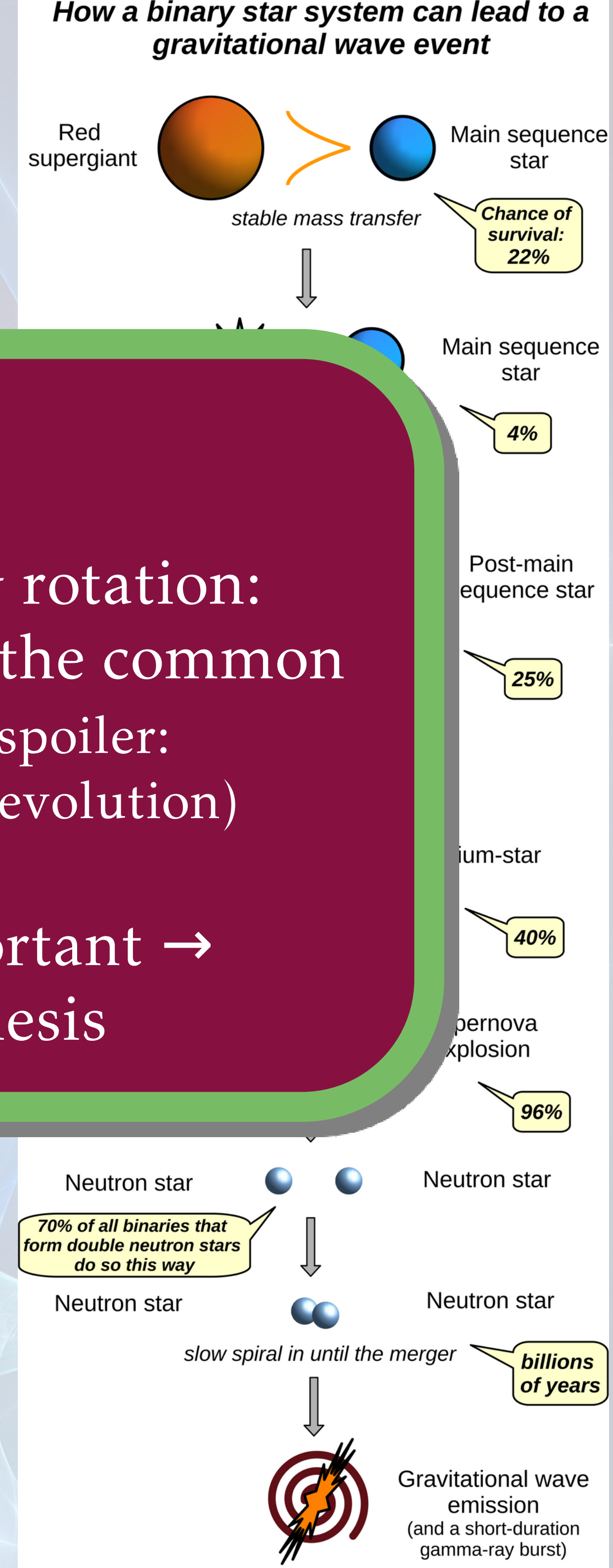
There are more… :D



Next time:

effects of metallicity & rotation: GW-progenitors <u>without</u> the common envelope scenario (spoiler: chemically homogeneous evolution)

why statistics is important → population synthesis



Credit: Vigna-Gomez+18