Gravitational-wave progenitors

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Lecture #11

NCU, Summer Semester 2022

Previously

on GW-progenitors...

‘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 stellar classes O, B, A, F… or supernova classification type Ia, Ib, II…) – useful to know even if its getting outdated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

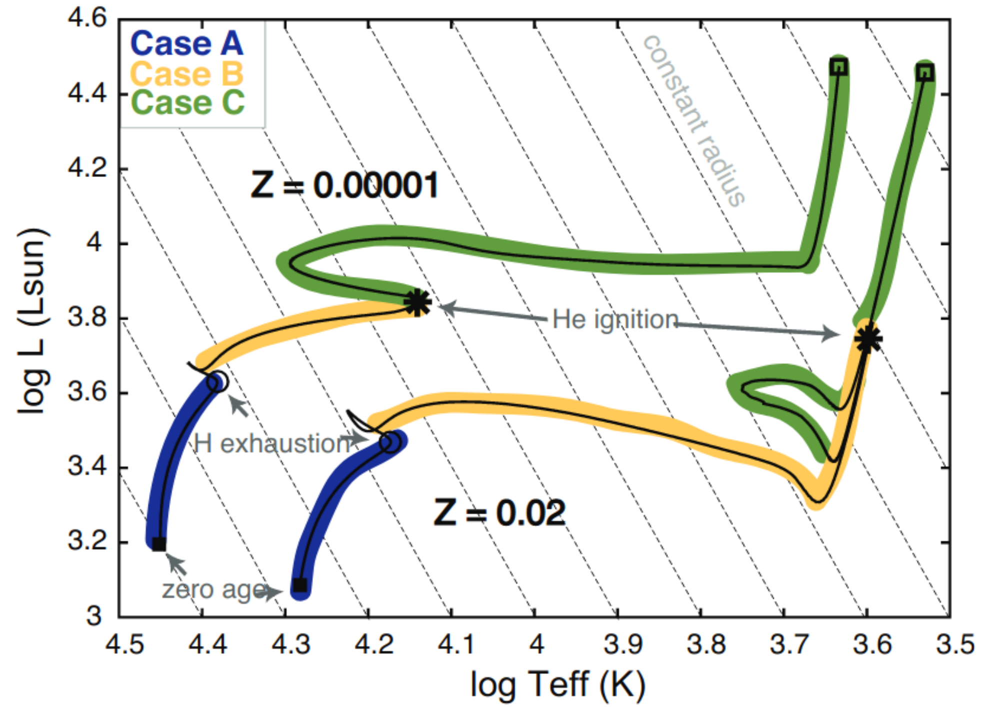

Figure 1.1: *Evolutionary tracks in the HR-diagram of a 6* $M_\odot$ *star illustrating the effect of metallicity on the occurrence of the different cases of mass transfer. The dashed diagonal lines indicate lines of constant radii. Cases A, B and C are defined in the text of Section 1.5.1. Figure adapted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

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even if its getting outdated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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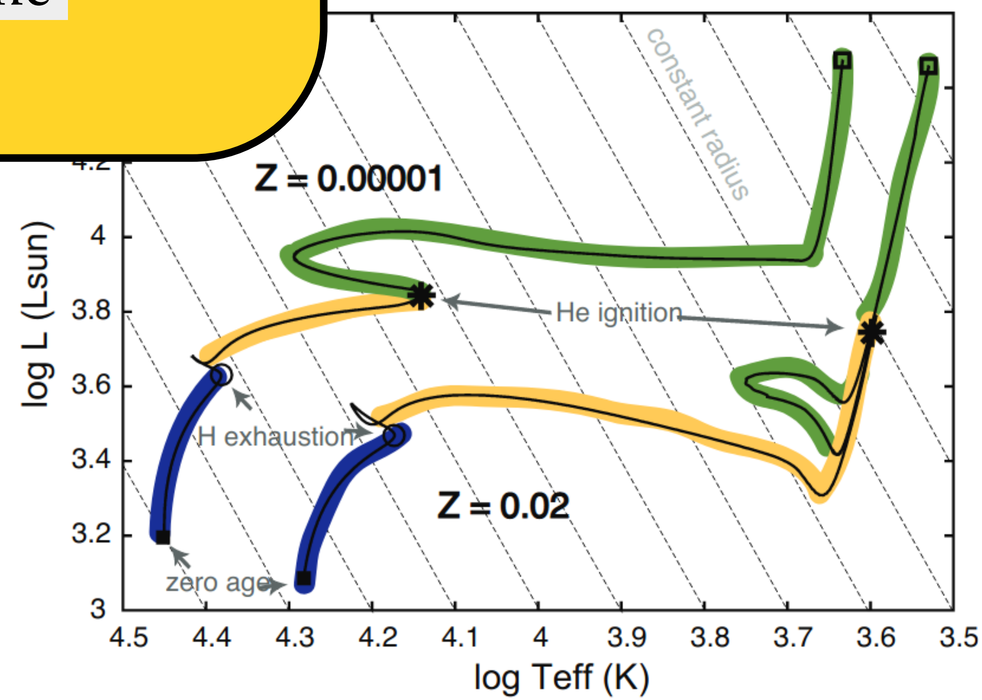

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Sidenote: TIMESCALES

- 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.

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

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

and winds carry away ang.mom. too

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

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

orbital separation: A

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

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

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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

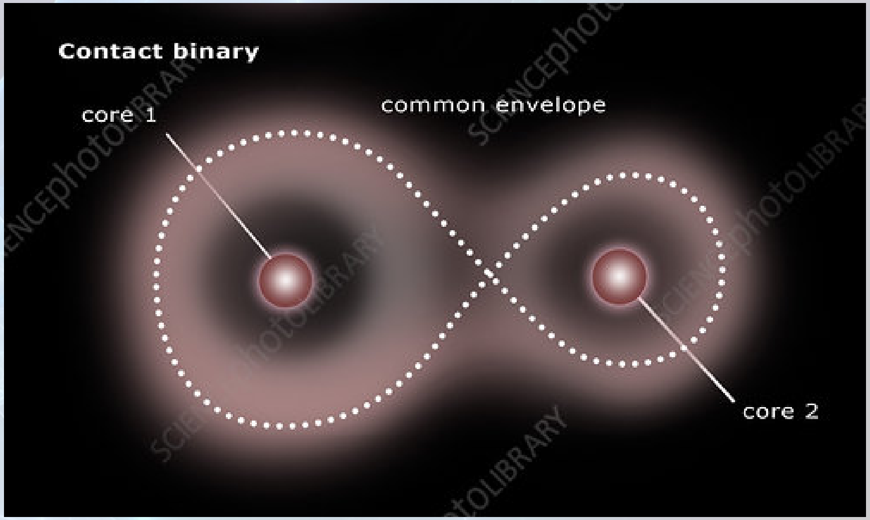
$\tau_{nuc} \gg \tau_{KH} \gg \tau_{dyn}$

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



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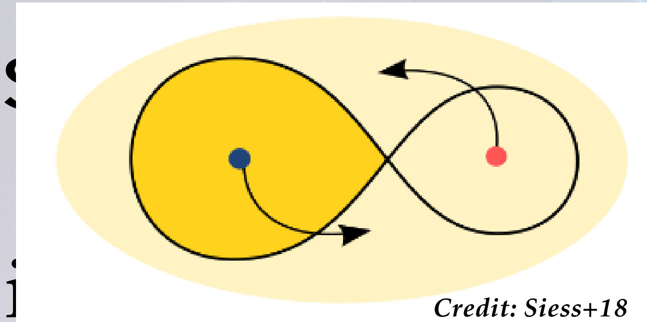
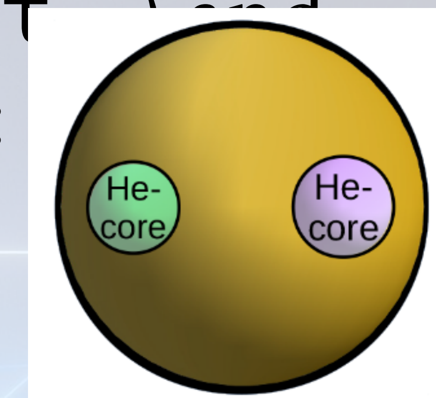
Uns -transfer



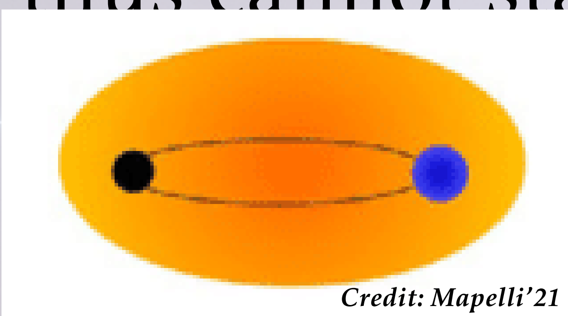
Credit: Siess+18

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

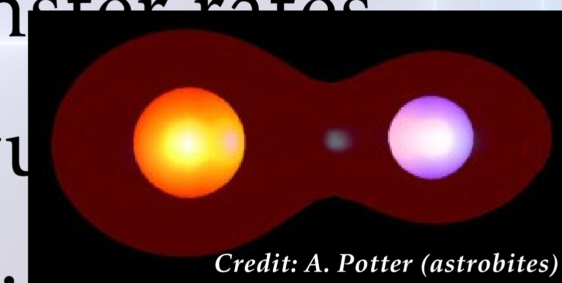


Credit: Yours Truly ;) [Vigna-Gomez+18]

ss-tran



Credit: Mapelli’21



Credit: A. Potter (astrobites)

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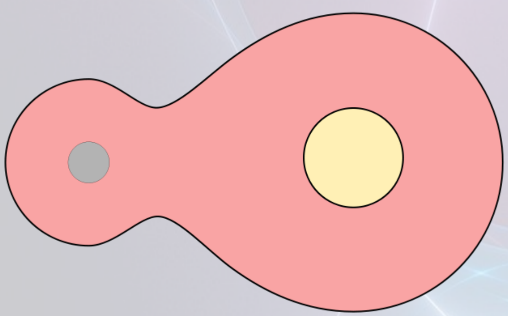
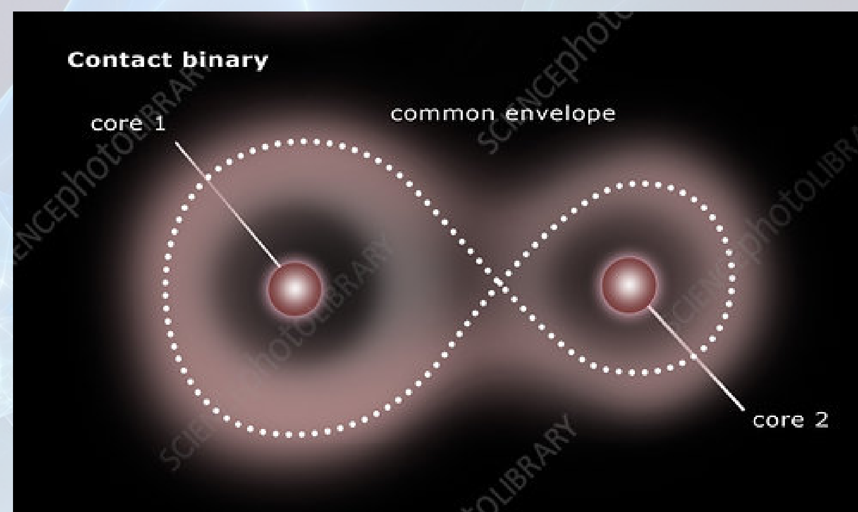


Credit: Wikipedia



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

What we know about CE

- short lived phase
  - observed?? how??

Movies :)

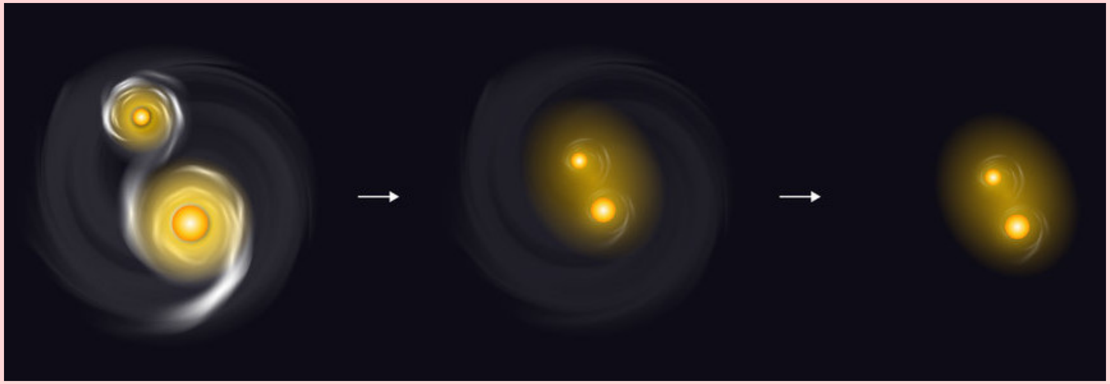
Passy+12: 0.88 $M_\odot$ (RG) + 0.15 $M_\odot$ companion	*Moreno+21:* 10 $M_\odot$ (RSG) + BH companion

- 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

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of the two stellar cores

Let's play!

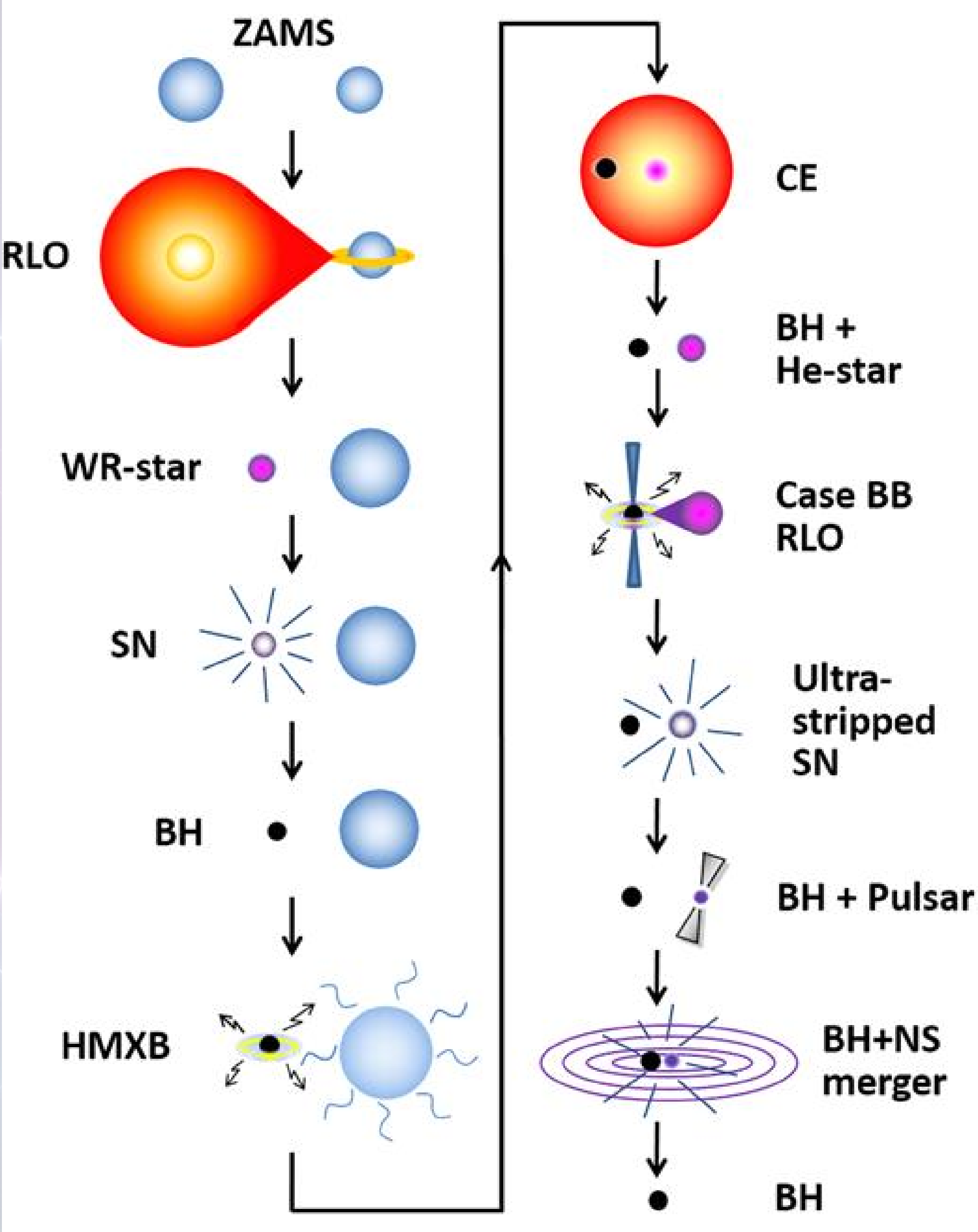
Zero-age Main Seq.

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 star)

GRAV. WAVES!!!

Credit: Kruckow+18

…t′s play!

This is just one possible scenario, actually.

There are more.

stable mass transfer

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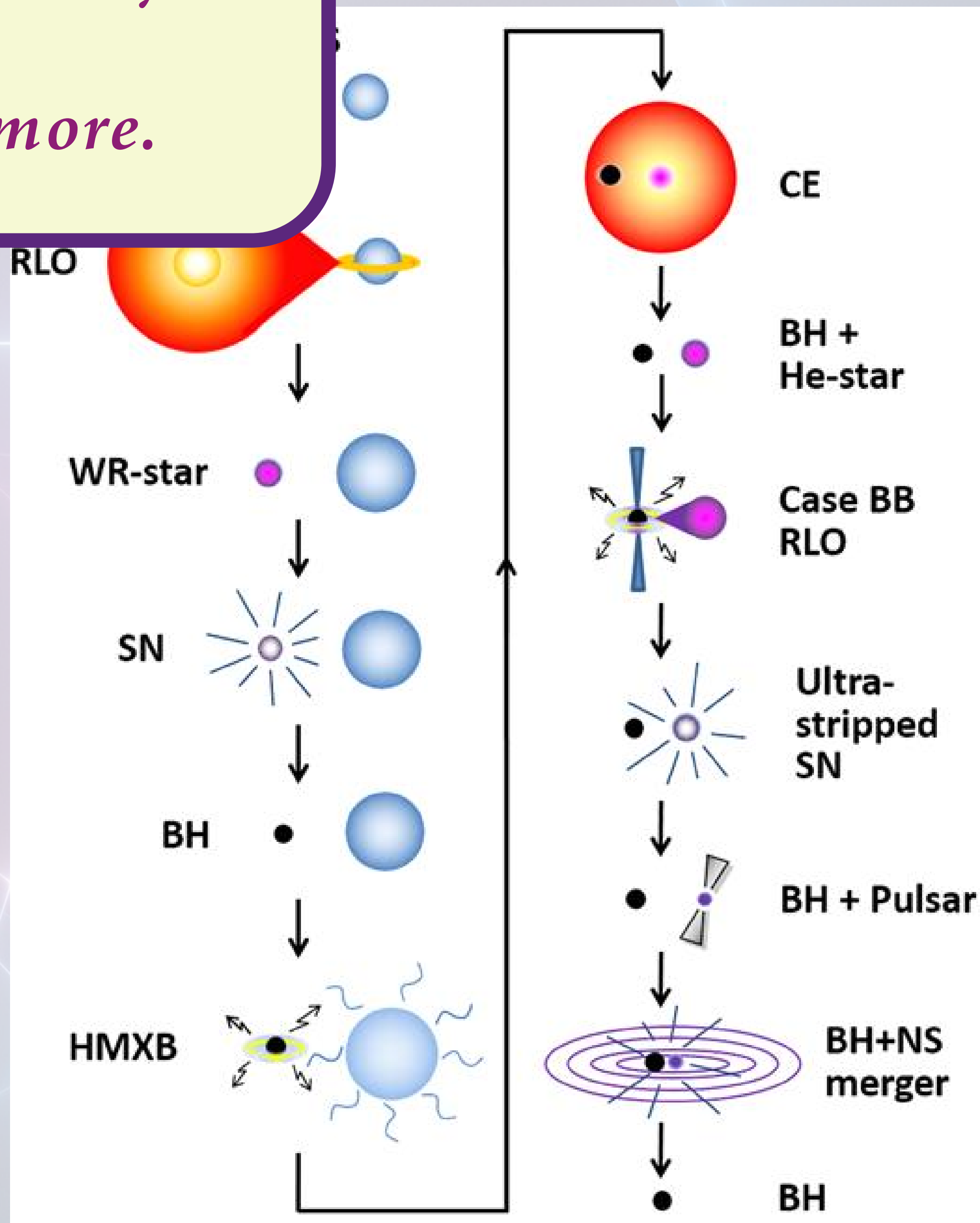

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Today:
some more scenarios

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some more scenarios

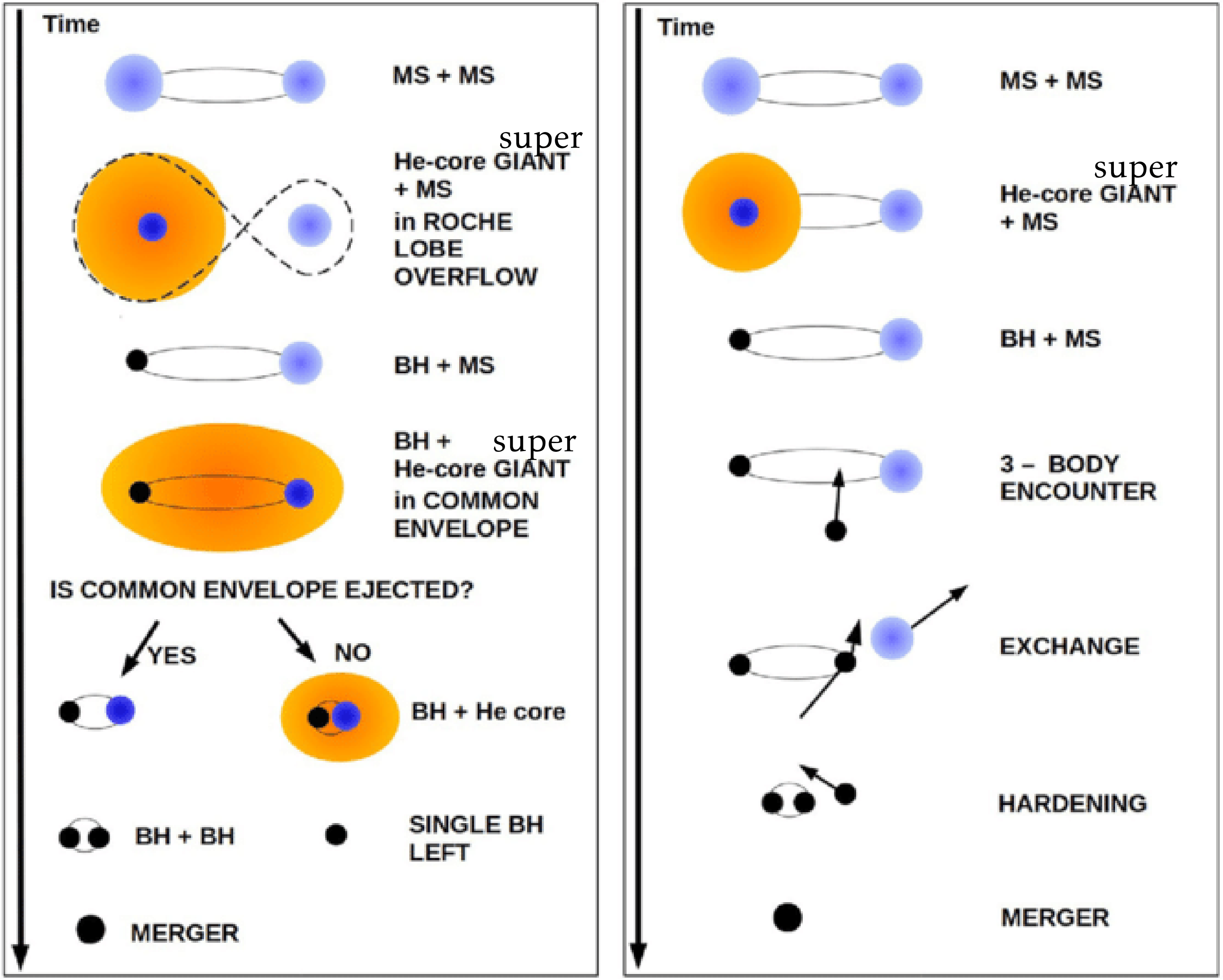
Followed by:

NSs & degeneracy
HMXBs, AGNs, jets

After that: effects of metallicity & rotation:
GW-progenitors without the common envelope scenario
(spoiler: chemically homogeneous evolution)

Next time: why statistics is important →
population synthesis (including SN kicks)
vs. evolutionary models of binary systems

Some other scenarios...

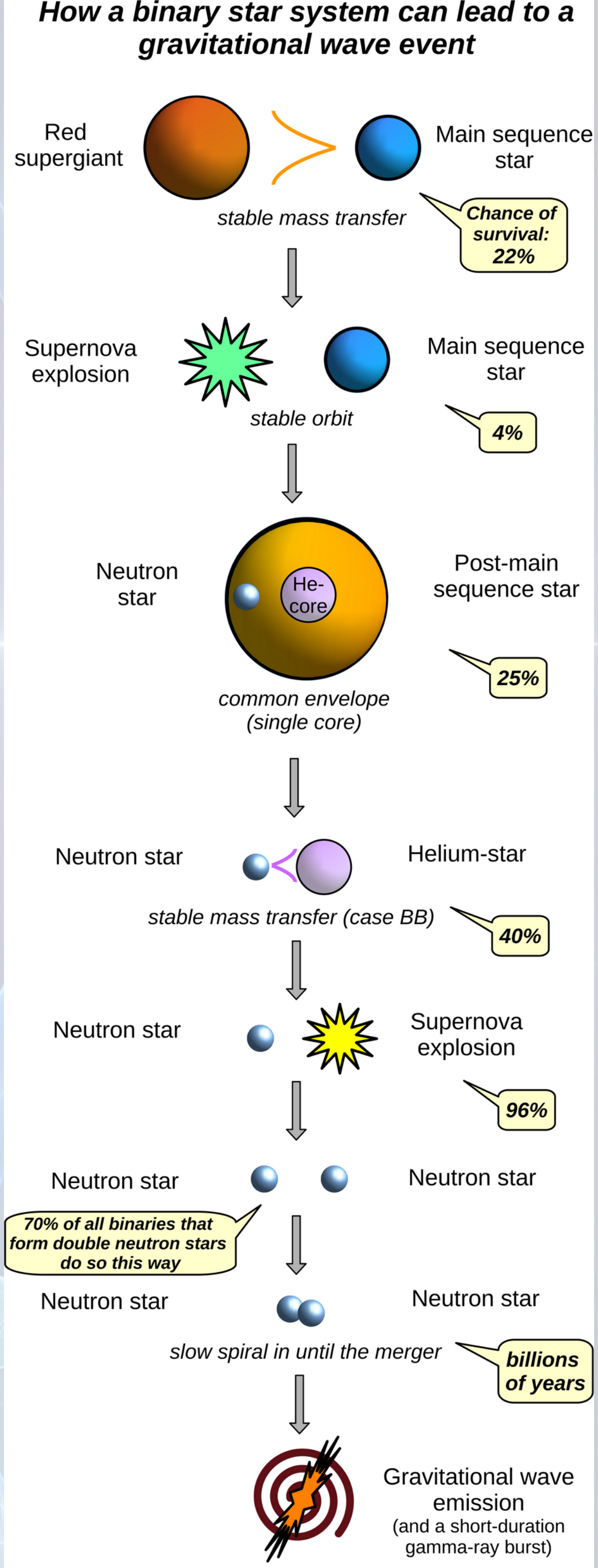


a triple!

= orbit shrinks

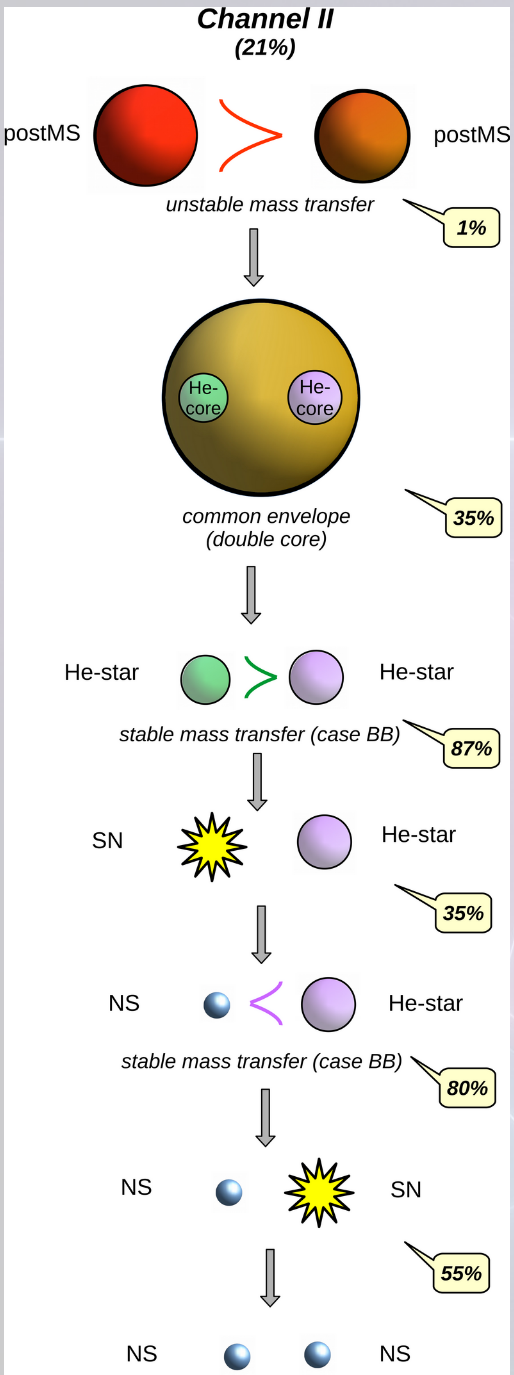
Credit: Mapelli'21

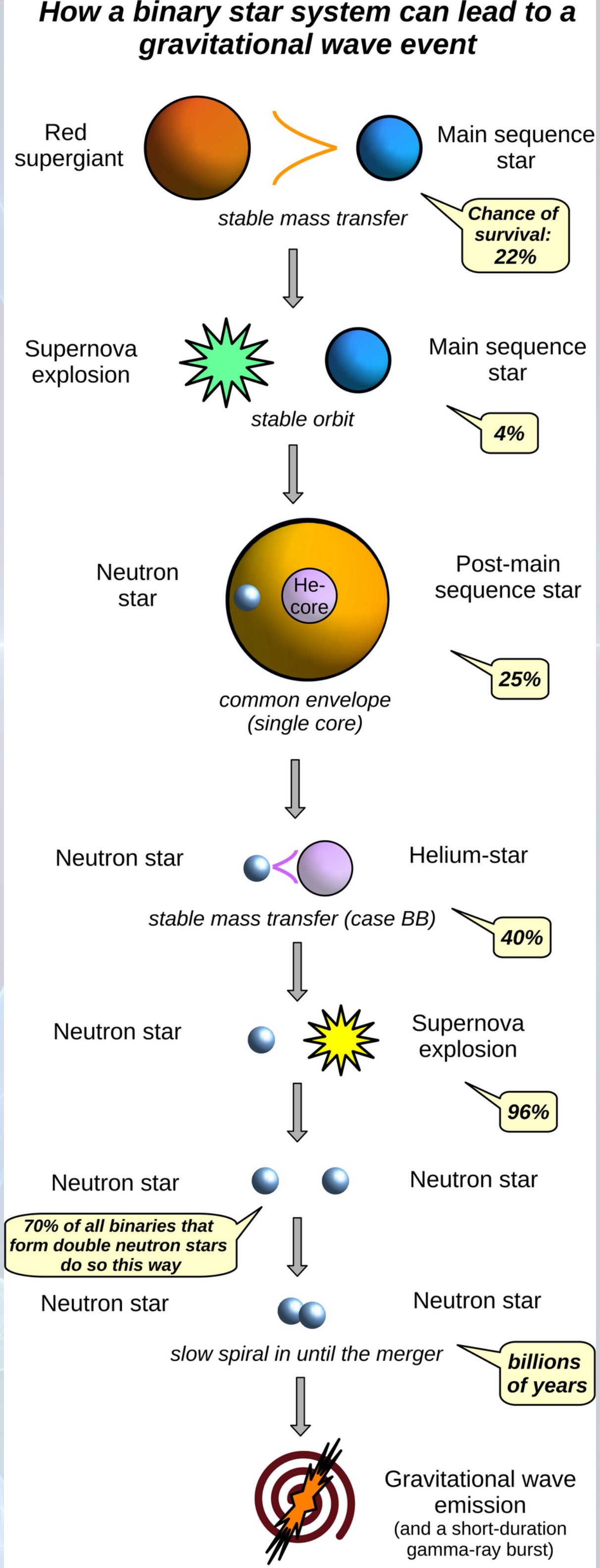
There are more… :D



Credit: Vigna-Gomez+18

There are more... :D

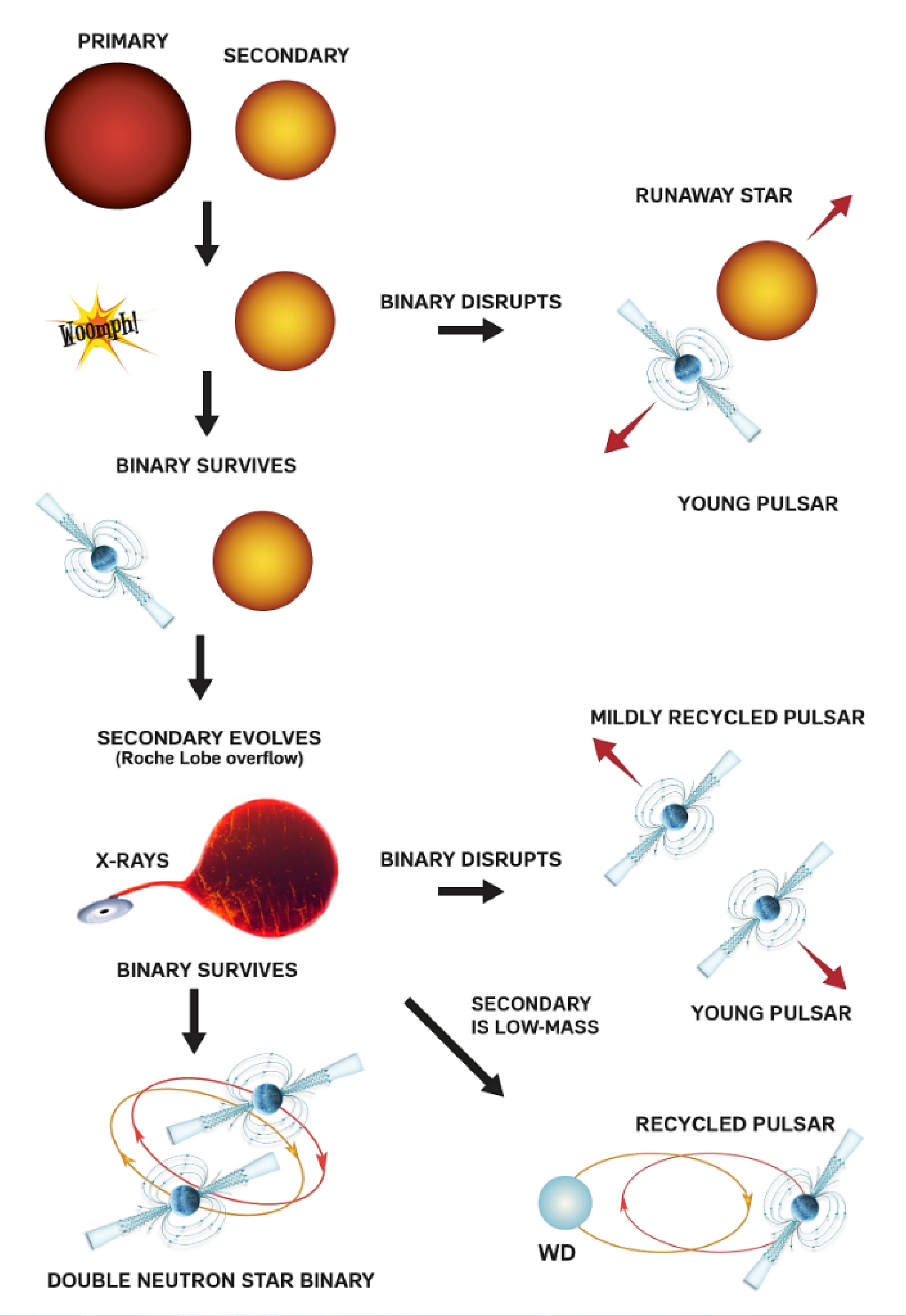




Credit: Vigna-Gomez+18

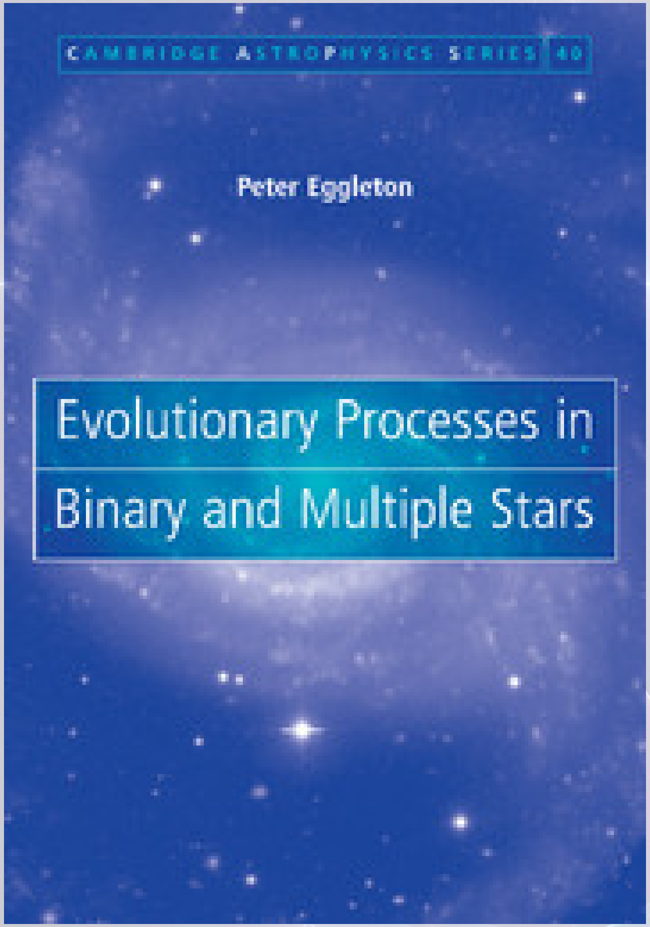
And even more…

This one makes it clear that there are various outcomes based on the SN kick.



Credit: Alice Froll

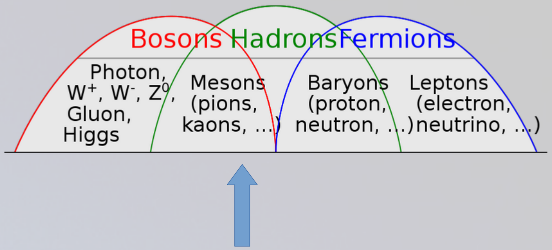
Further reading:



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

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

Degeneracy



remember: γ is a boson

- Imagine: plasma (of fermions, i.e.: e^{-},p^{+},n^{0}…)

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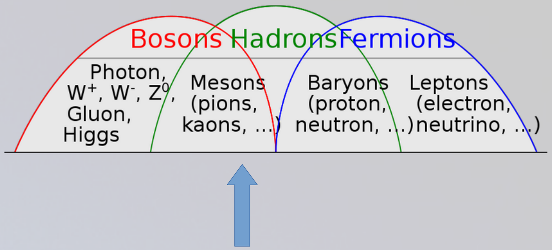

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  - let's cool it and compress it repeatedly!

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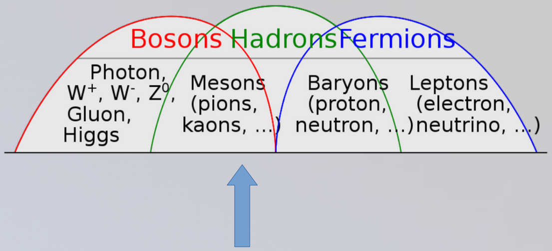

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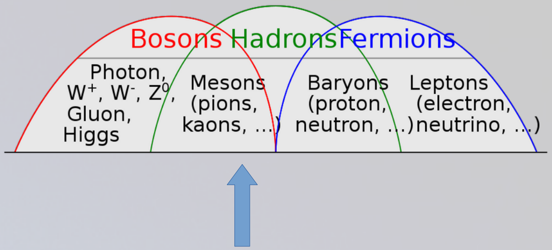

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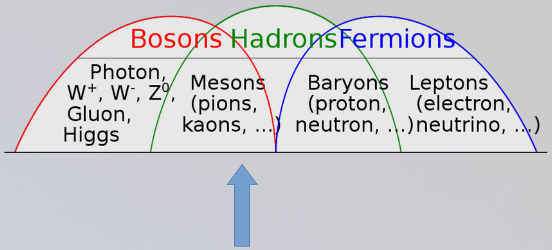

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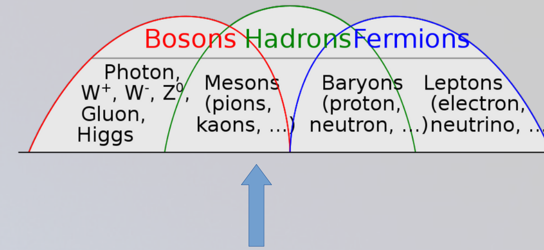
- can happen to: only e^- (=WD) **or** p^+&n^0&e^- (=NS)

Degeneracy



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- Imagine: pl… e^-,p^+,n^0…)
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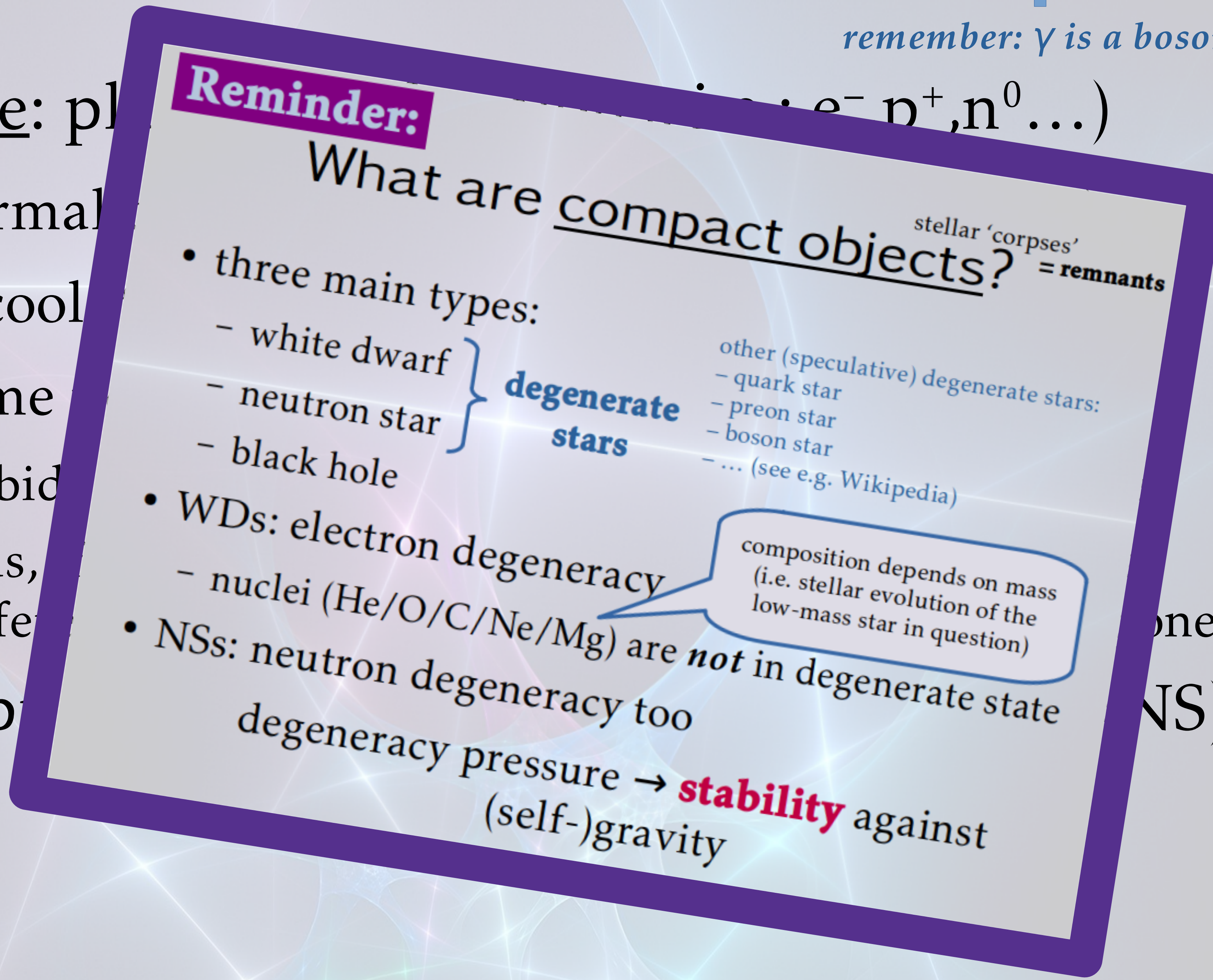
  - let's cool …
  - at some …
    - forbid…
    - thus, … diffe… …one)
- can hap… …NS)



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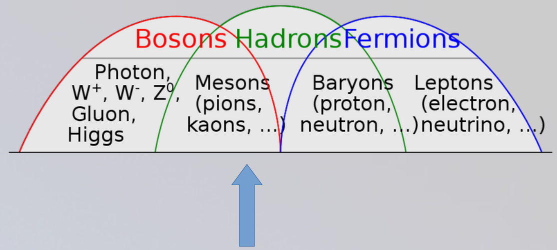

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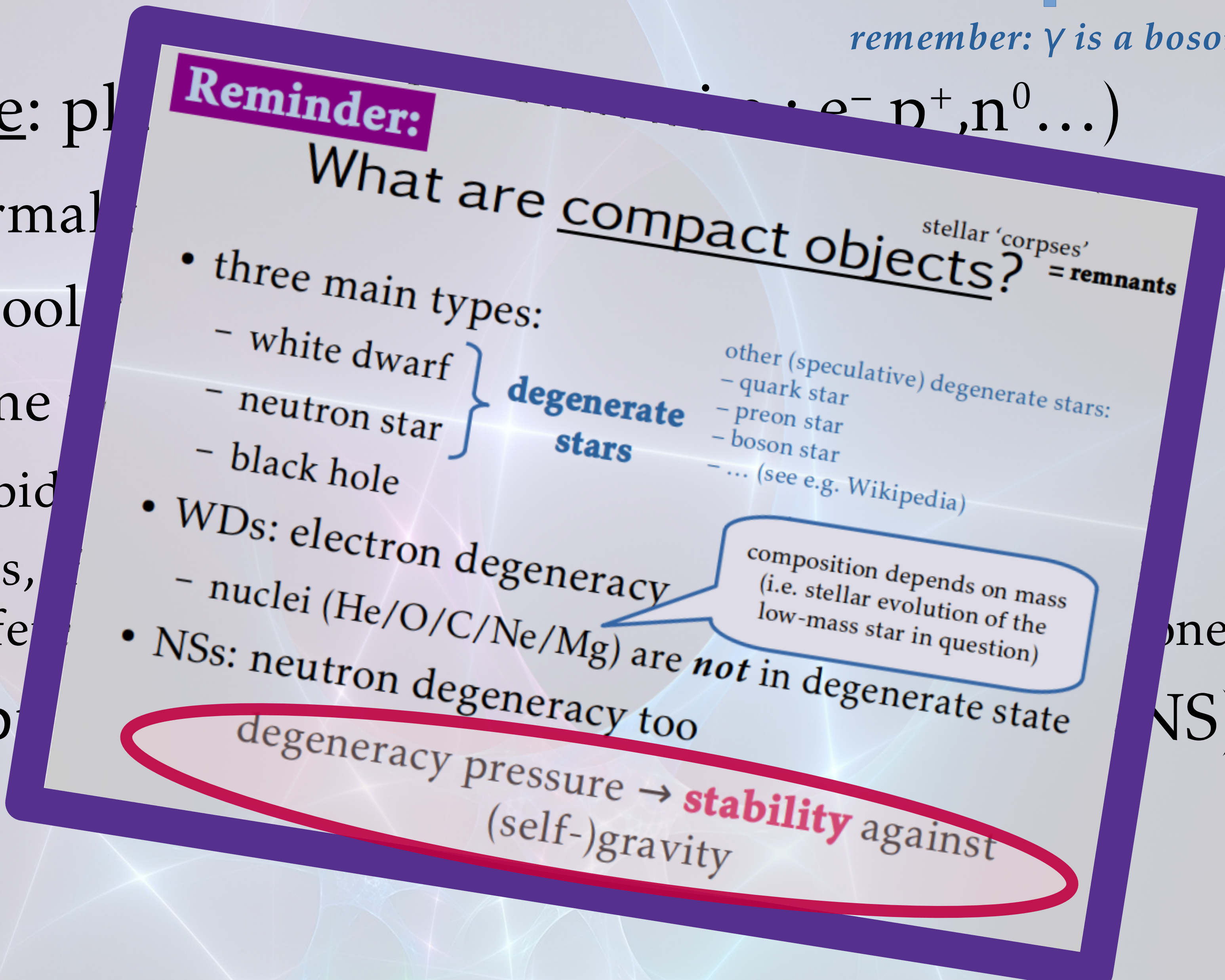

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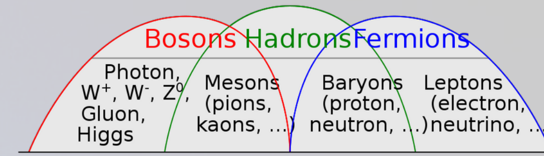

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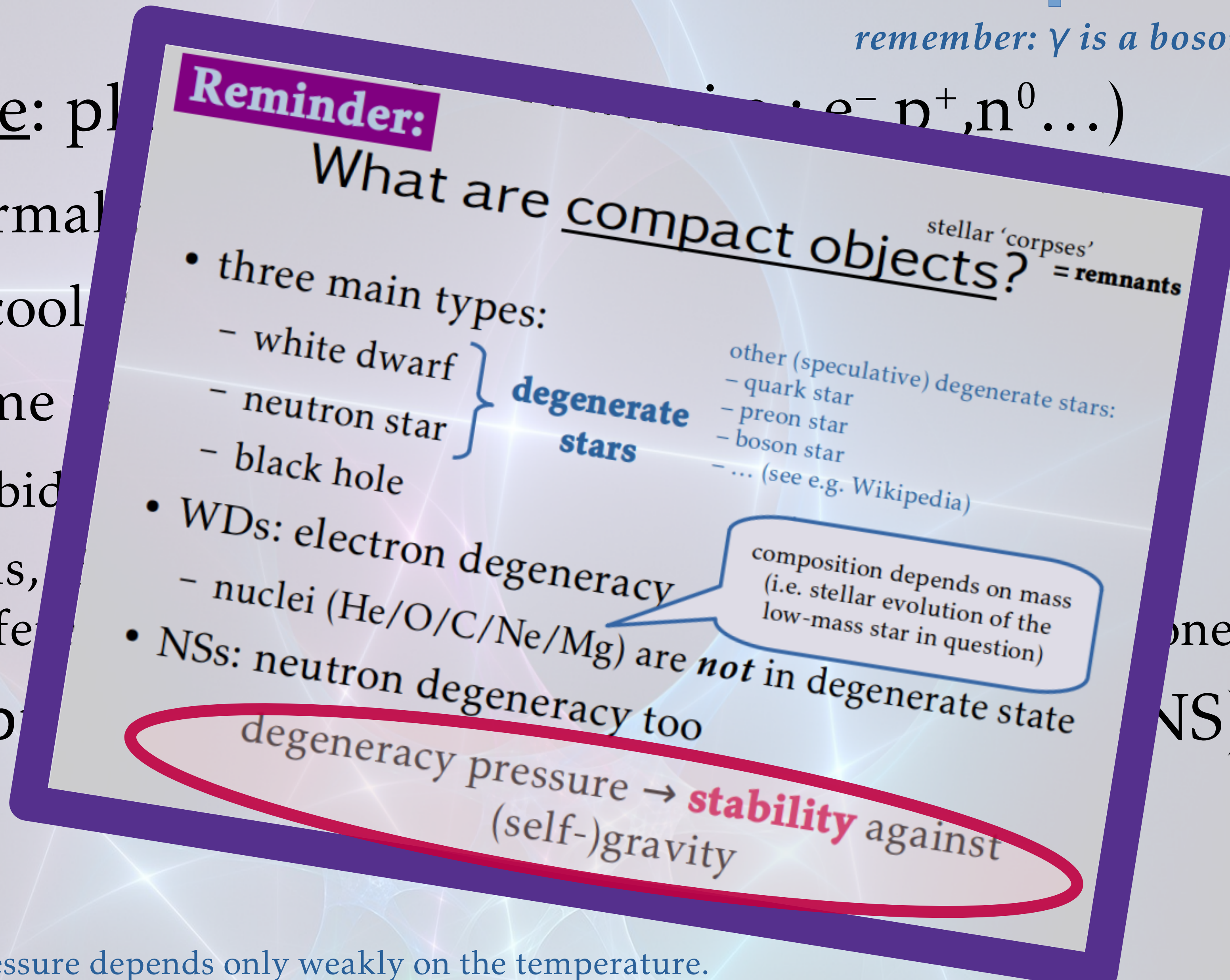
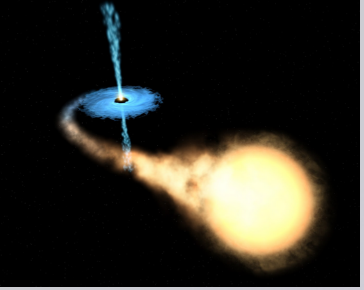
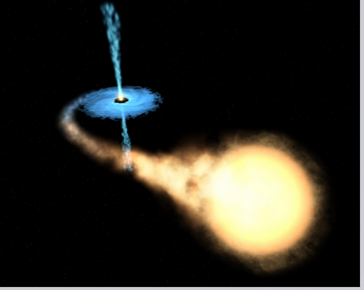


Funfact: degeneracy pressure depends only weakly on the temperature.
Increasing the temperature of degenerate stars has a minor effect on the structure.



HMXB = High-mass X-ray binary

- sister object: LMXB = Low-mass X-ray binary



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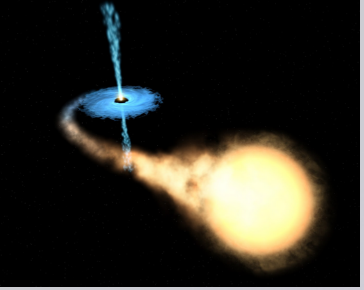

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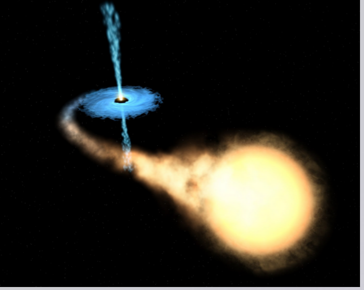
  - if it's a massive star: HMXB



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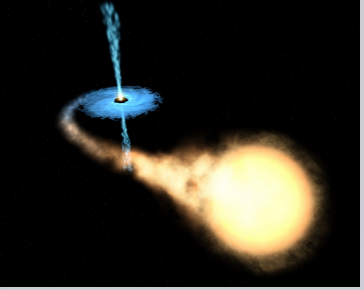
Observed:
~ 200 LMXB in the MW
some more in other gals.
> 100 HMXB in MW
e.g. ***Cygnus X-1***

periodic X-ray pulses



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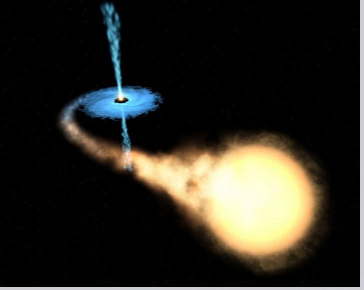

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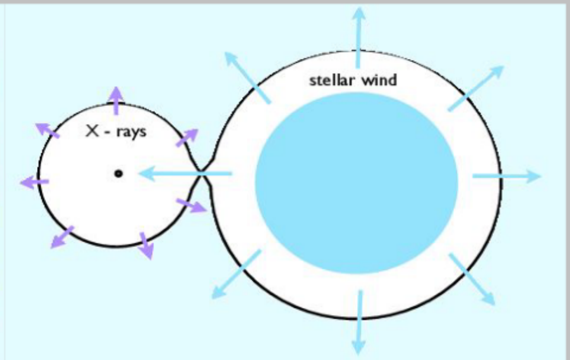
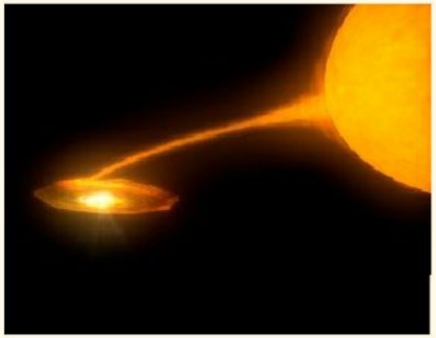
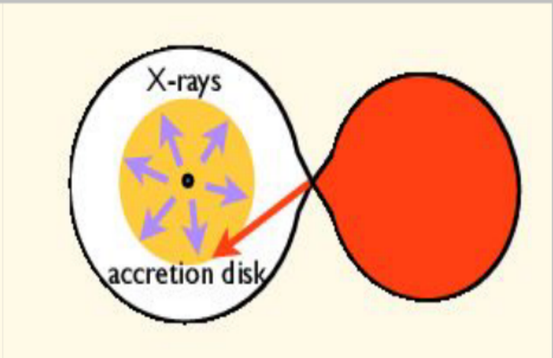
HMXB's | **LMXB's**

Credit: Palit 2020







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

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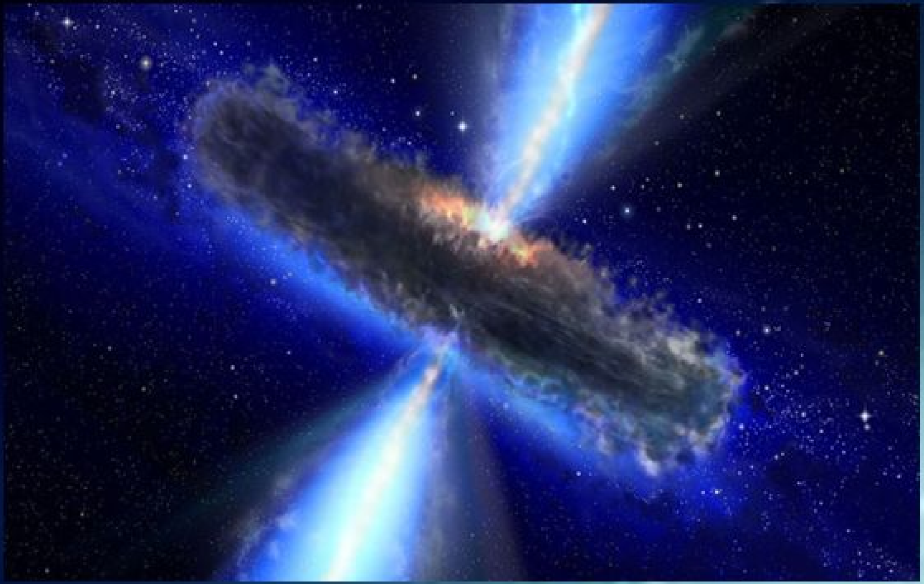
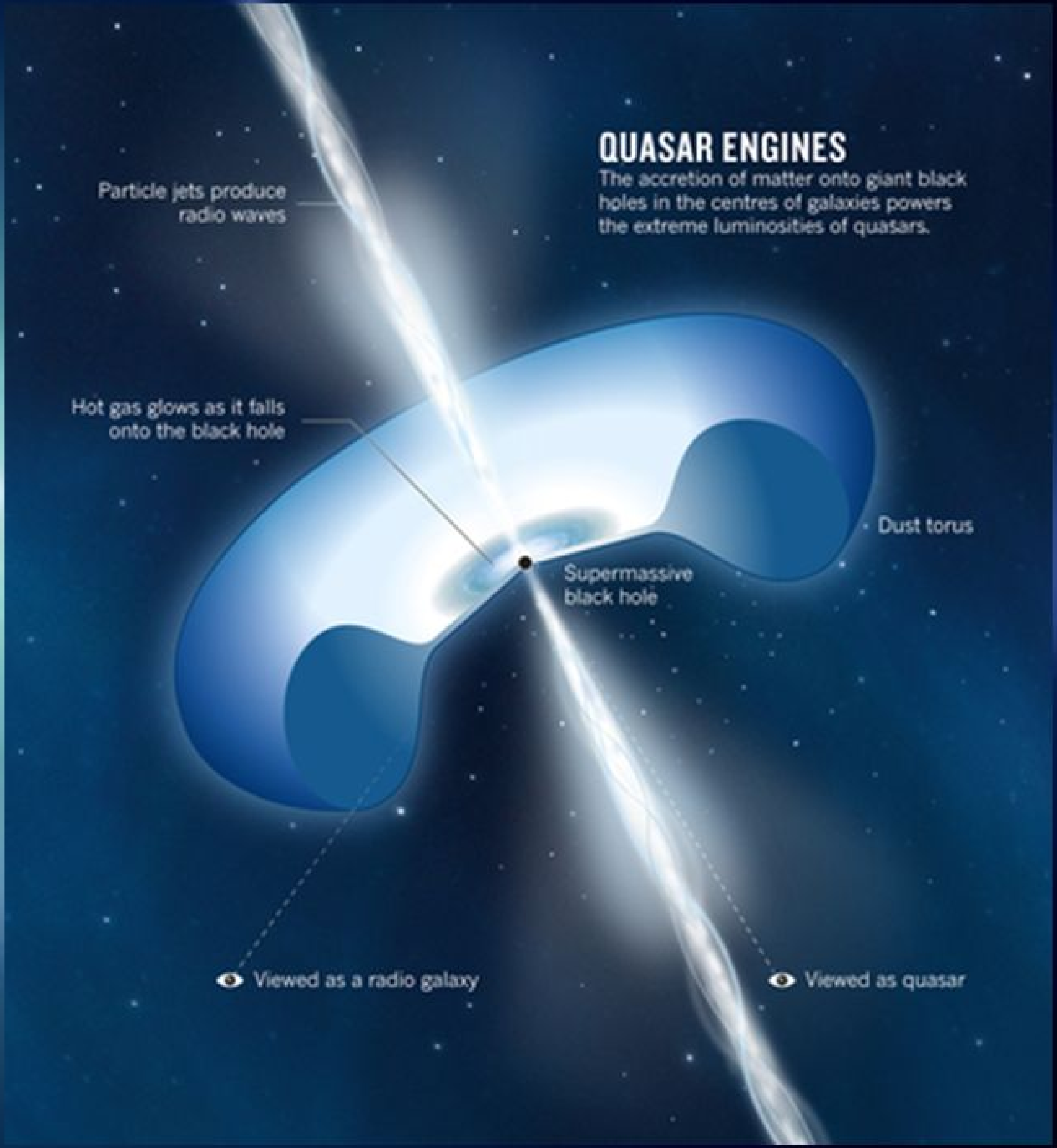
- name comes from 'quasars'

  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)




z = 4.75


QUASAR ENGINES
The accretion of matter onto giant black holes in the centres of galaxies powers the extreme luminosities of quasars.
Particle jets produce radio waves
Hot gas glows as it falls onto the black hole
Dust torus
Supermassive black hole
Viewed as a radio galaxy
Viewed as quasar

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)

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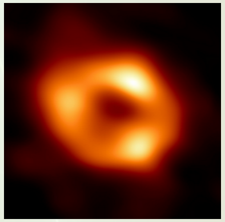
  - **THIS WEEK'S MOST EXCITING NEWS!!**
    Capturing our MW's central BH by the "Event Horizon Telescope" (not a real telescope; but a collaboration of radio observatories & clevera data reduction techniques :D)



Sgr A*
4×10^6 $M_\odot$

not a very active nucleus (fortunately)

- basically

  - the sou ... next slide)

  - Cygnus

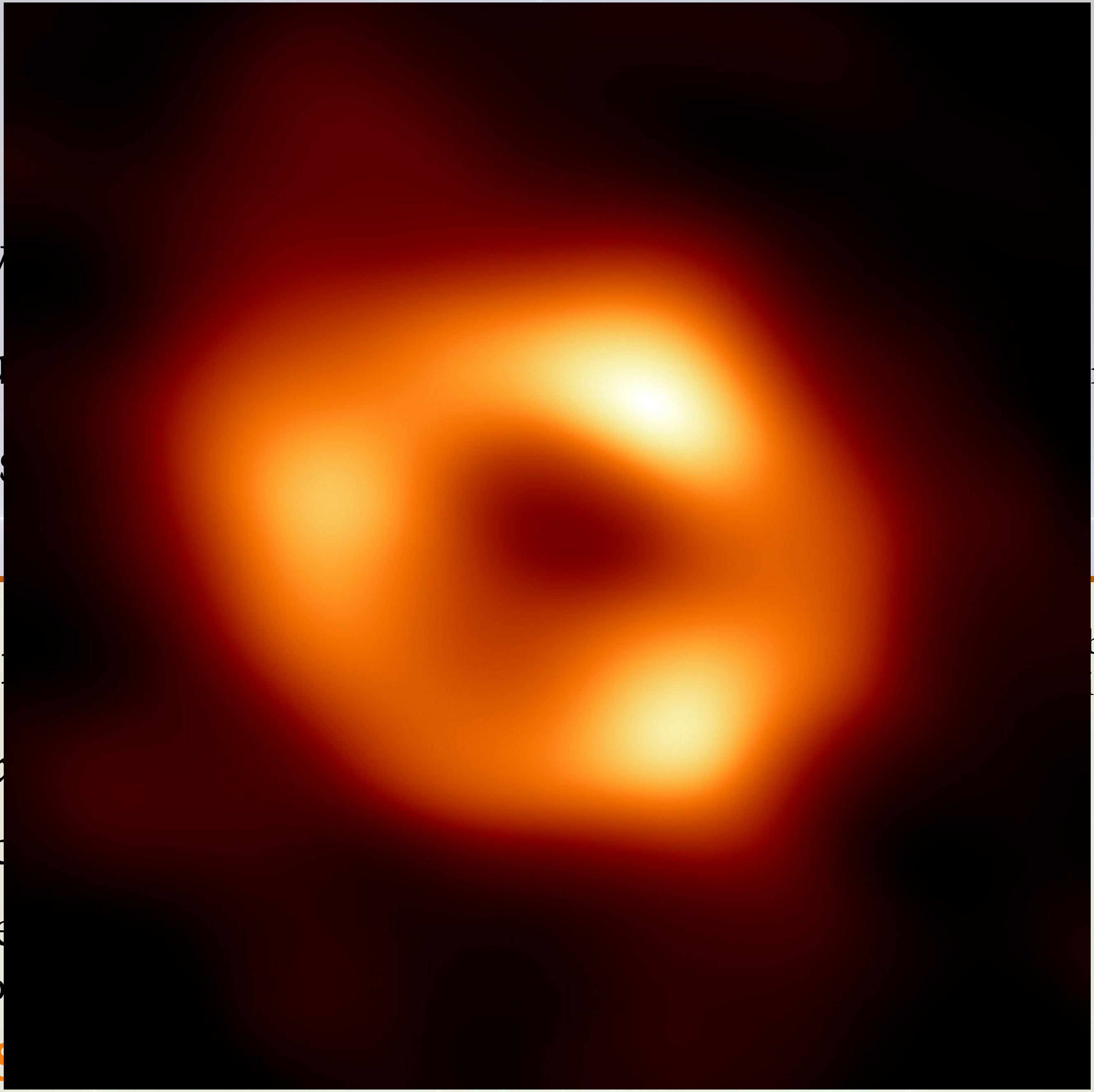
- name co ... bject" (QSO) ... io sources of

  - *gala*

  - → ac

  - powe
    (as op

  - **THIS**



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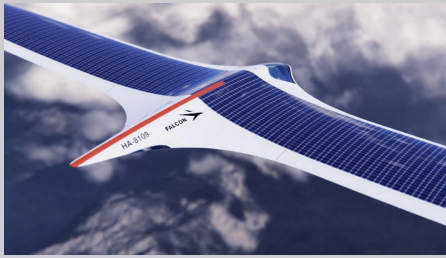
Jets (in astronomy)



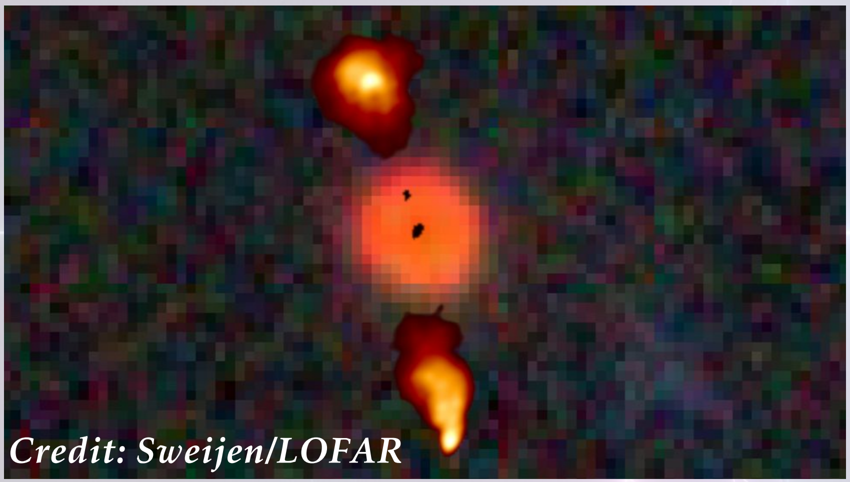
Jets (in astronomy)

AGNs

GRBs

Jets (in astronomy)

Actual observation (2021, LOFAR):

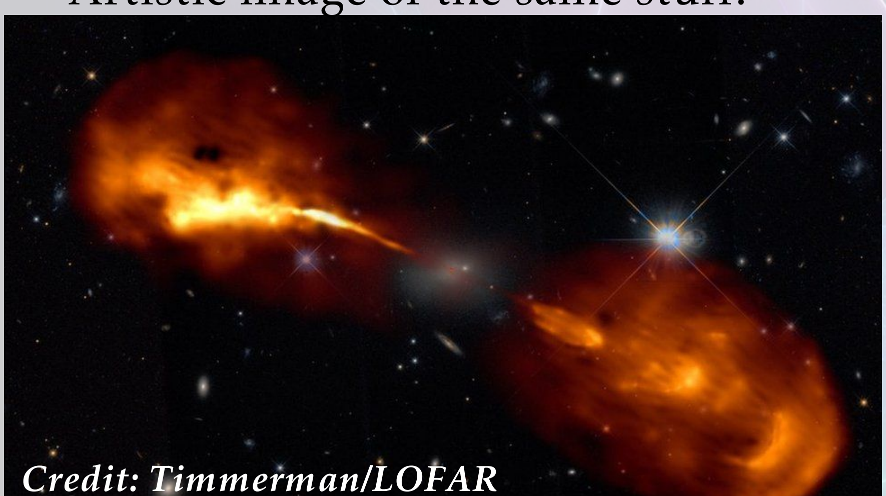


Credit: Sweijen/LOFAR

AGNs

GRBs

Artistic image of the same stuff:



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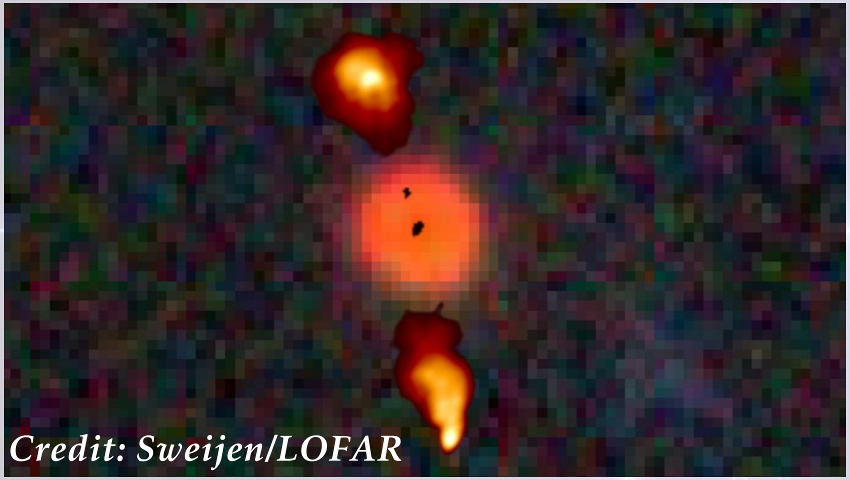

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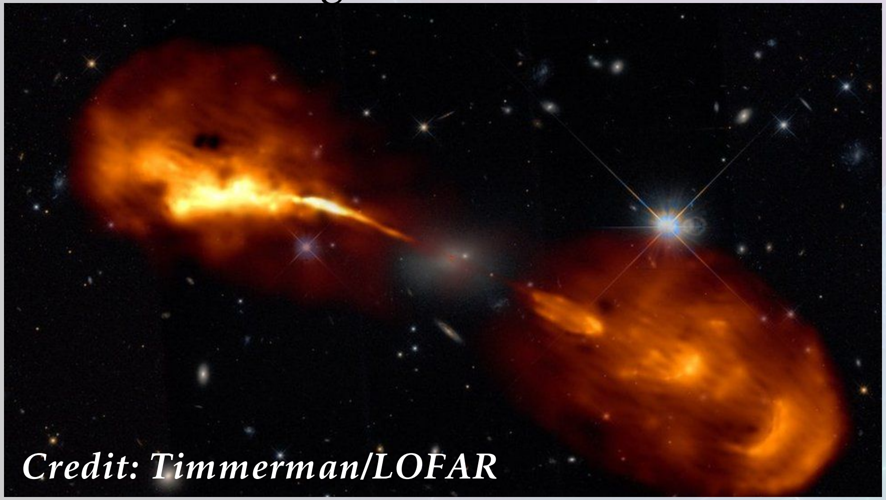

Credit: Timmerman/LOFAR

??

spectral features (breaking)
high energies cannot be explained otherwise

GRBs

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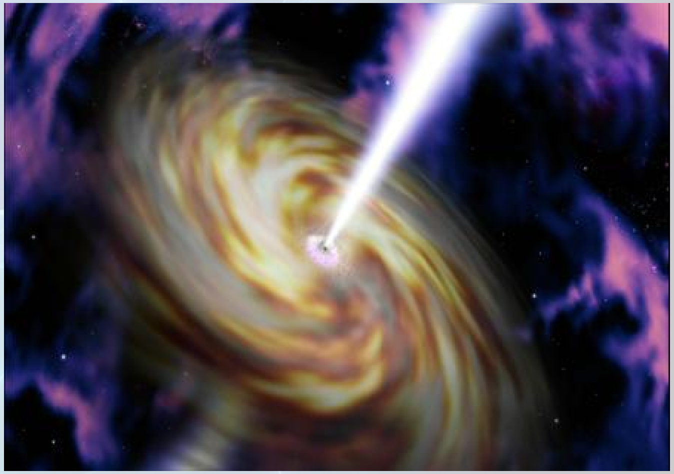

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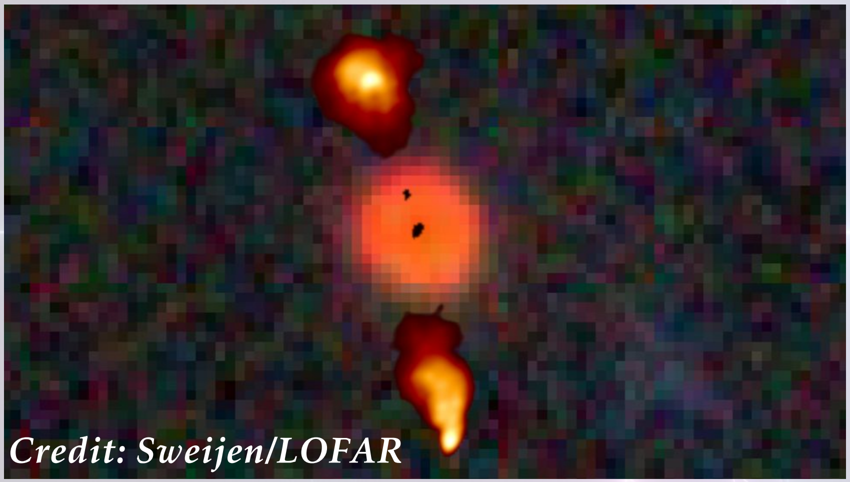

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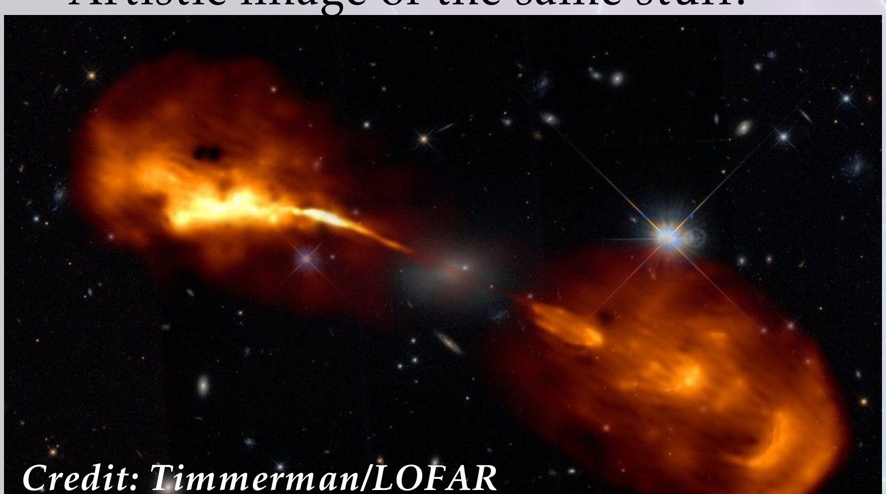

long-living

short-living

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

??

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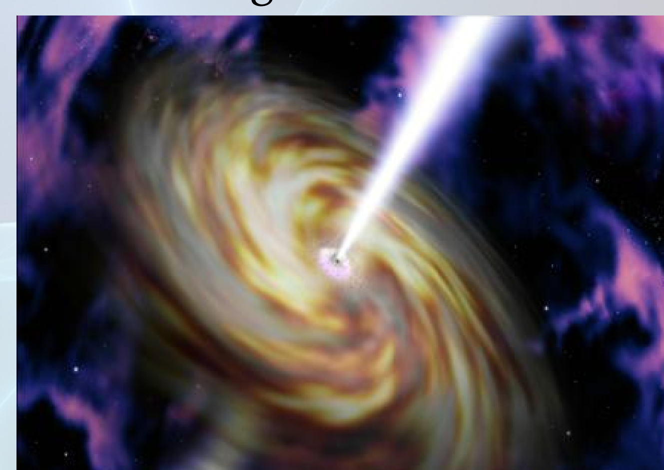

And also microquasars, of course.

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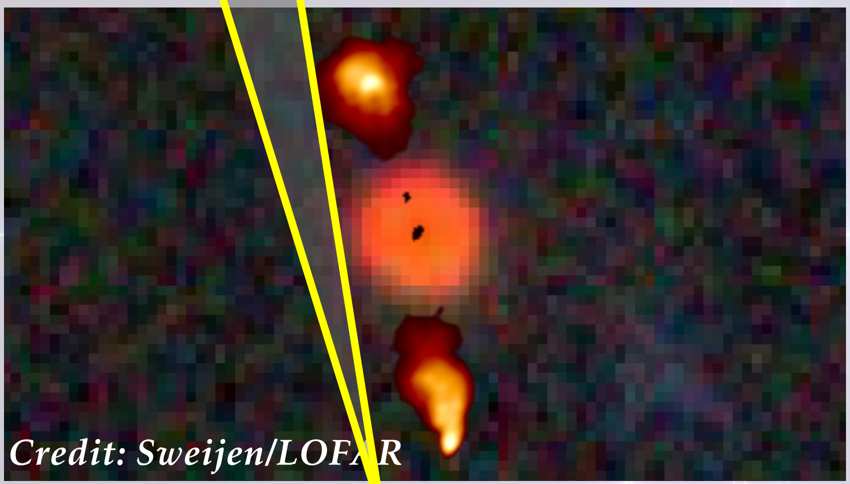

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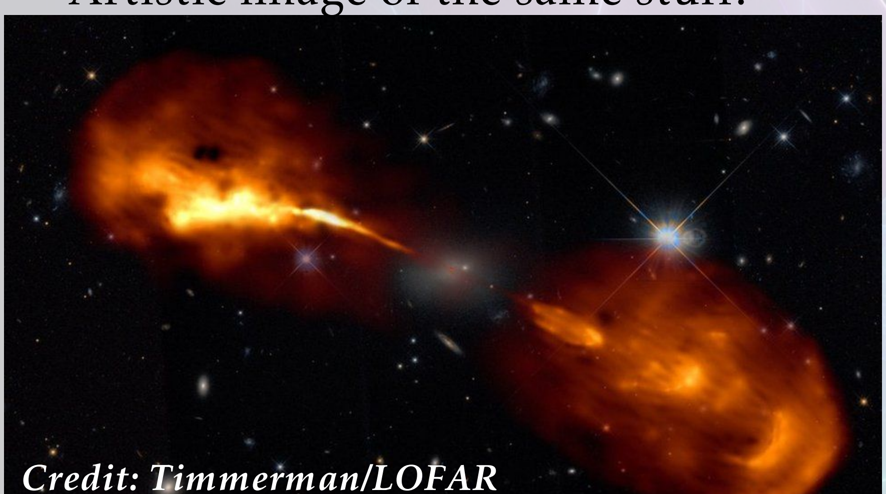

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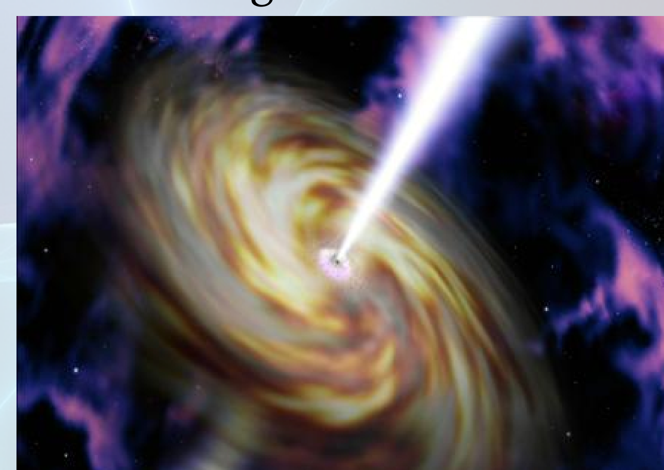

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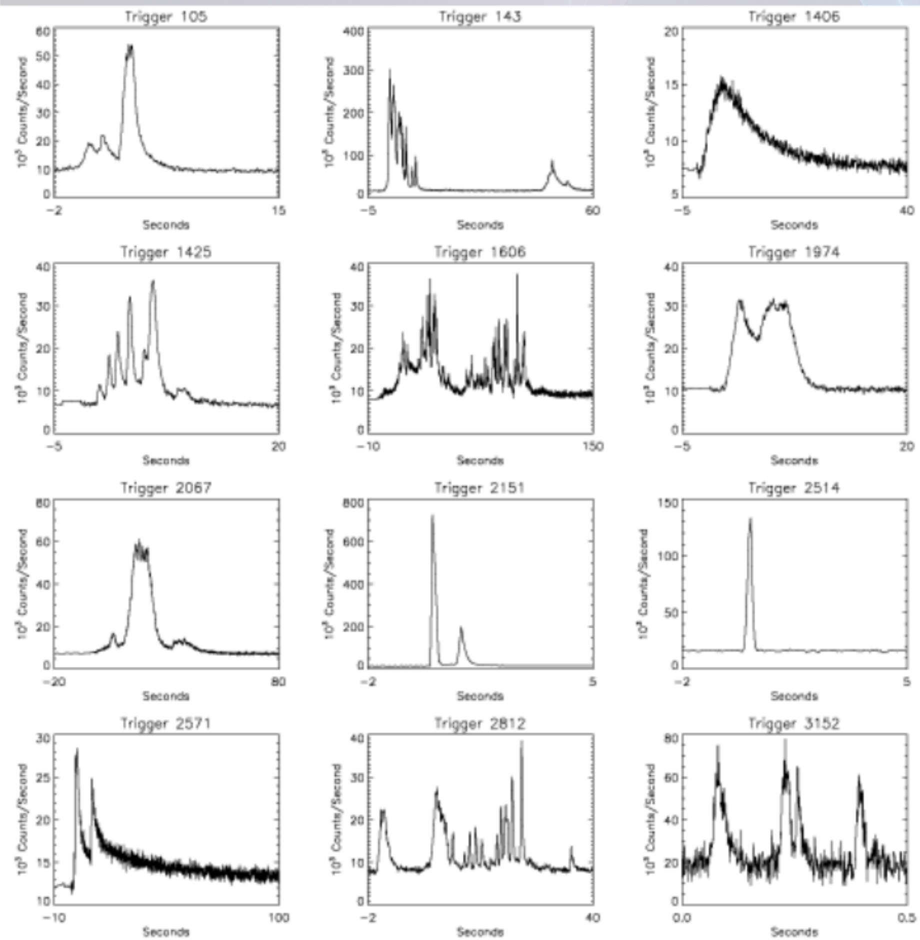
Jets (in astronomy)

What are GRBs?

Observationally...



– during the cold war…

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

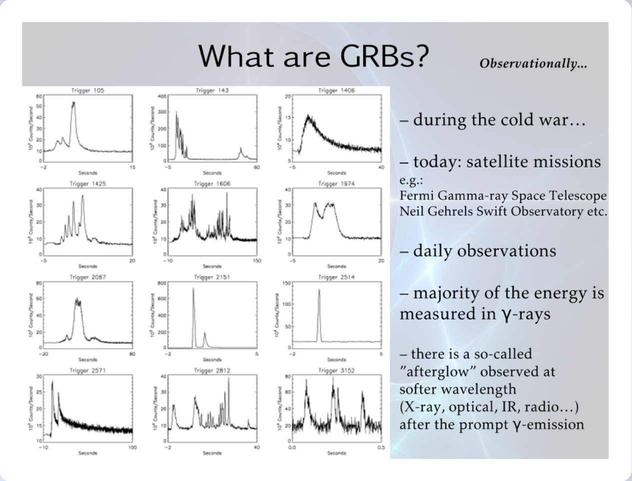
– daily observations

– 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

GRBs

Jets (in astronomy)



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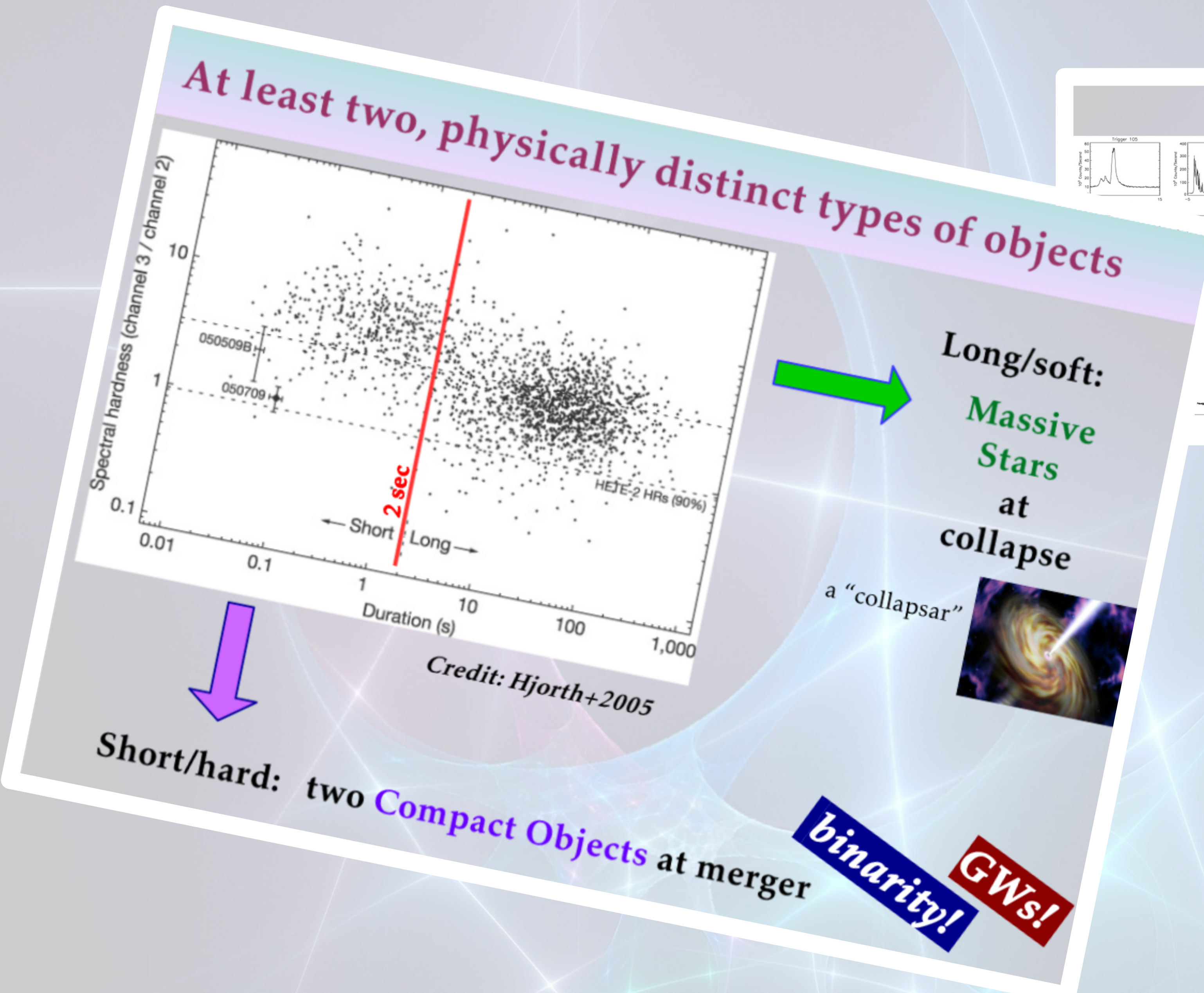

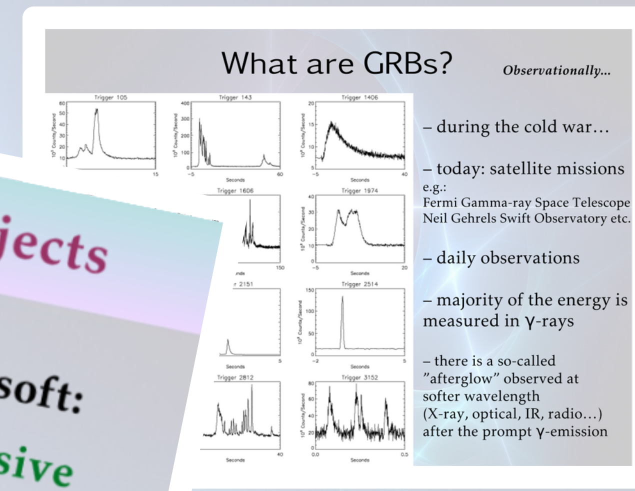

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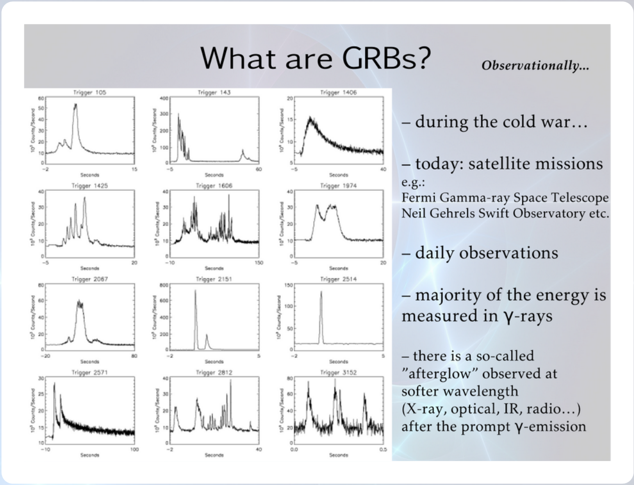

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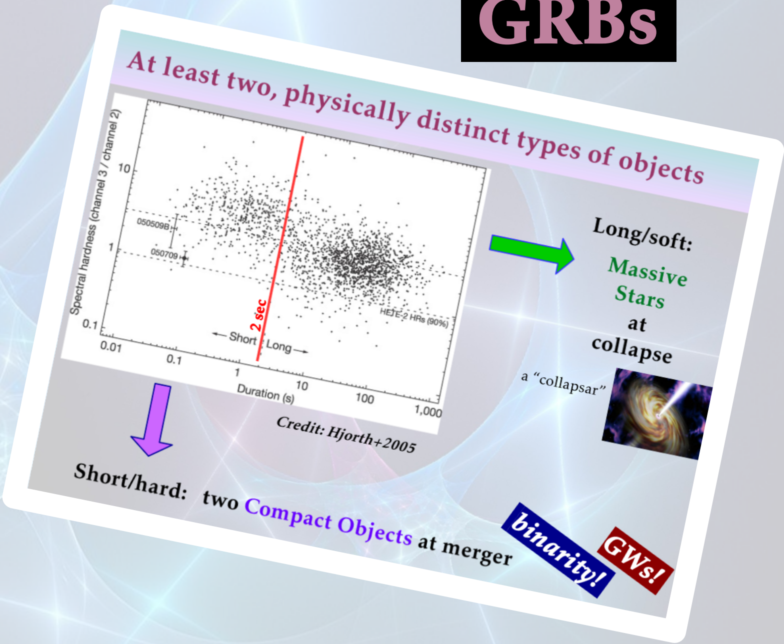

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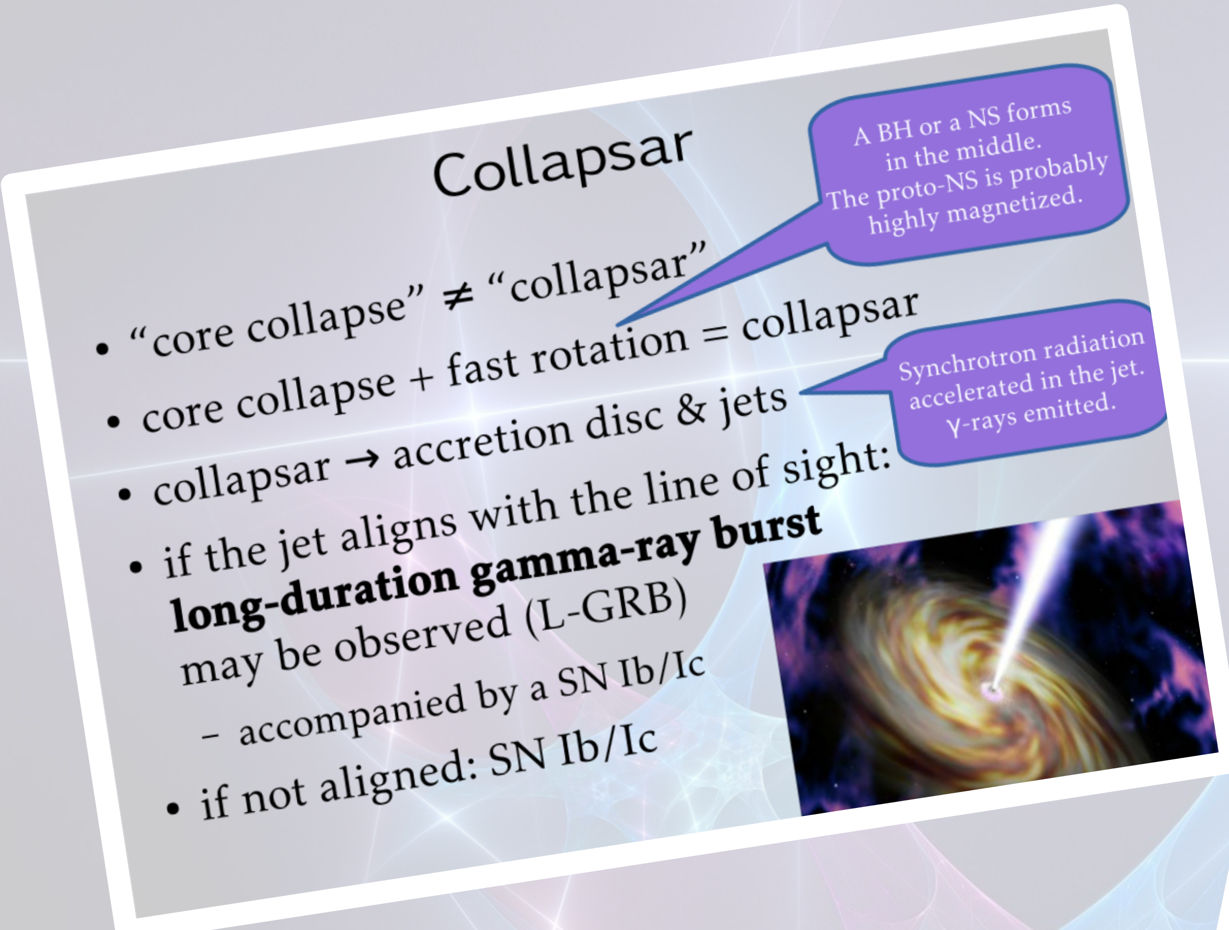

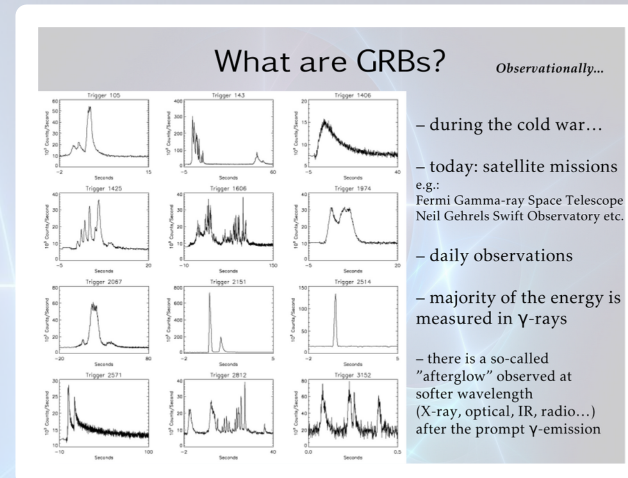

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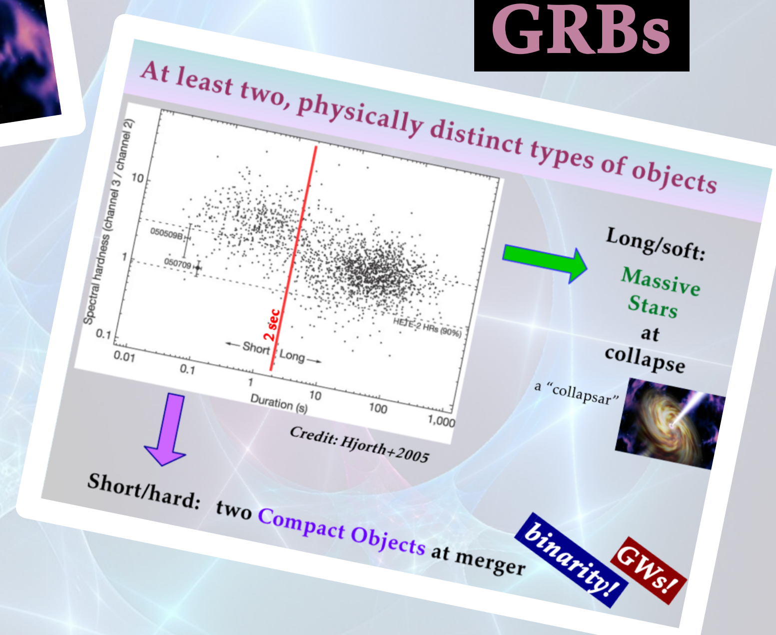
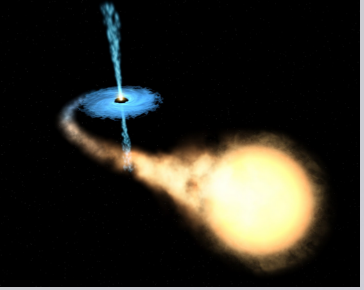


Going back to HMXBs…



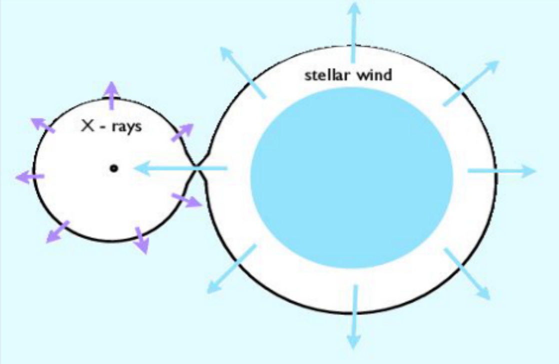
HMXB = High-mass X-ray binary

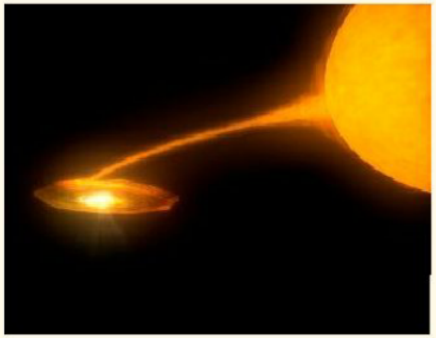
- sister object: LM
- X-rays are produced
  the (stellar) compani
  - if the companion is a
  - if it's a massive star:
- Massive stars have str

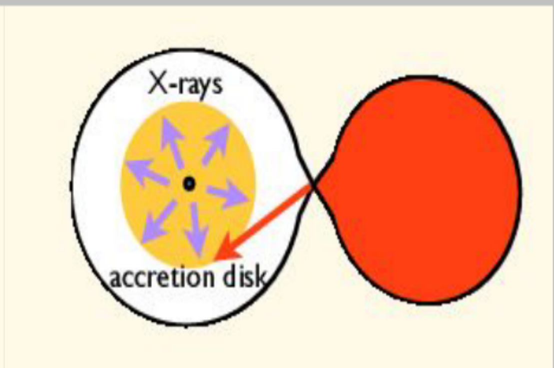
Question:

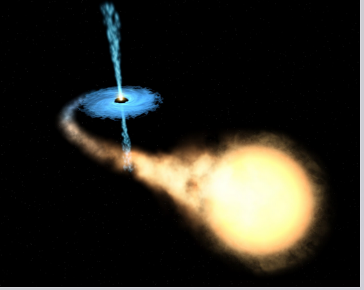
Would two 'naked' BHs produce X-ray radiation?

HMXB's **LMXB's**









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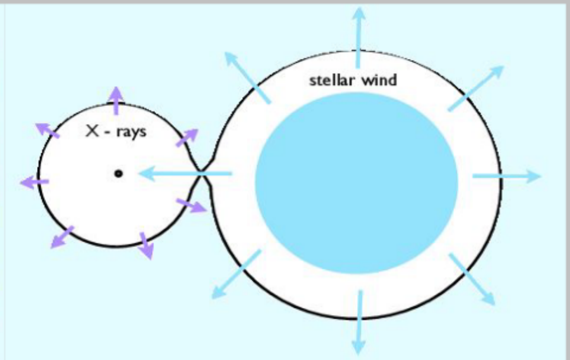
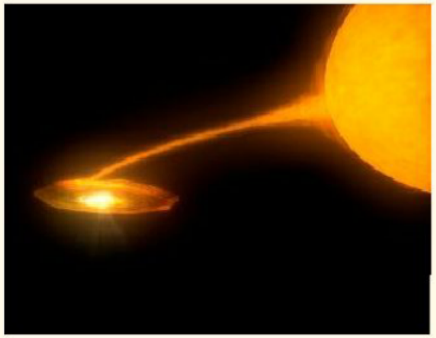
NO.

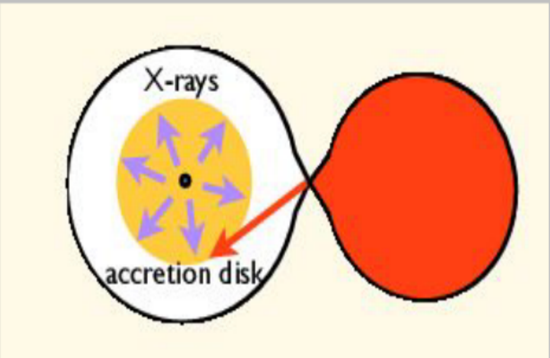
HMXB's

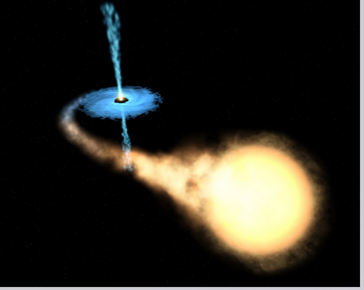
LMXB's

Credit: Palit 2020









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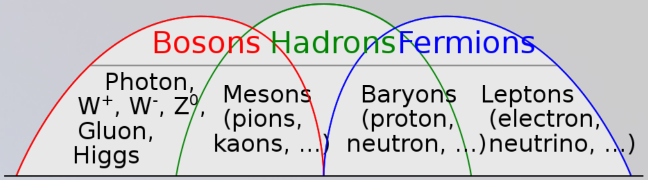

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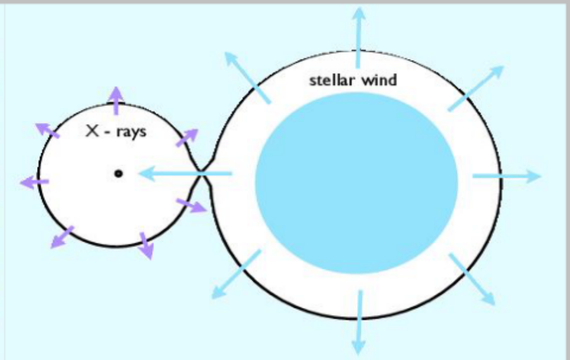
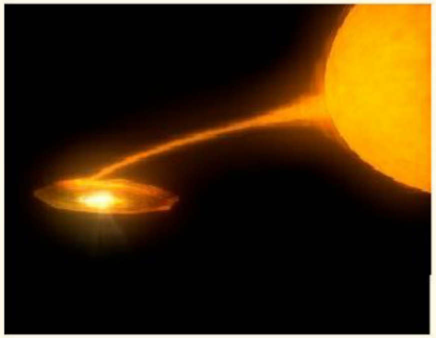
We need (barionic) matter to be accelerated to relativistic energies. **NO.**

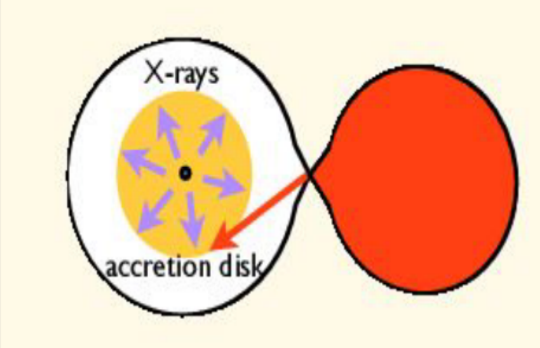
HMXB's

LMXB's

Credit: Palit 2020







Our strategy:

start with
Massive Stars at Solar Z

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

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

Reminder: single massive stars with fast rotation & low-Z

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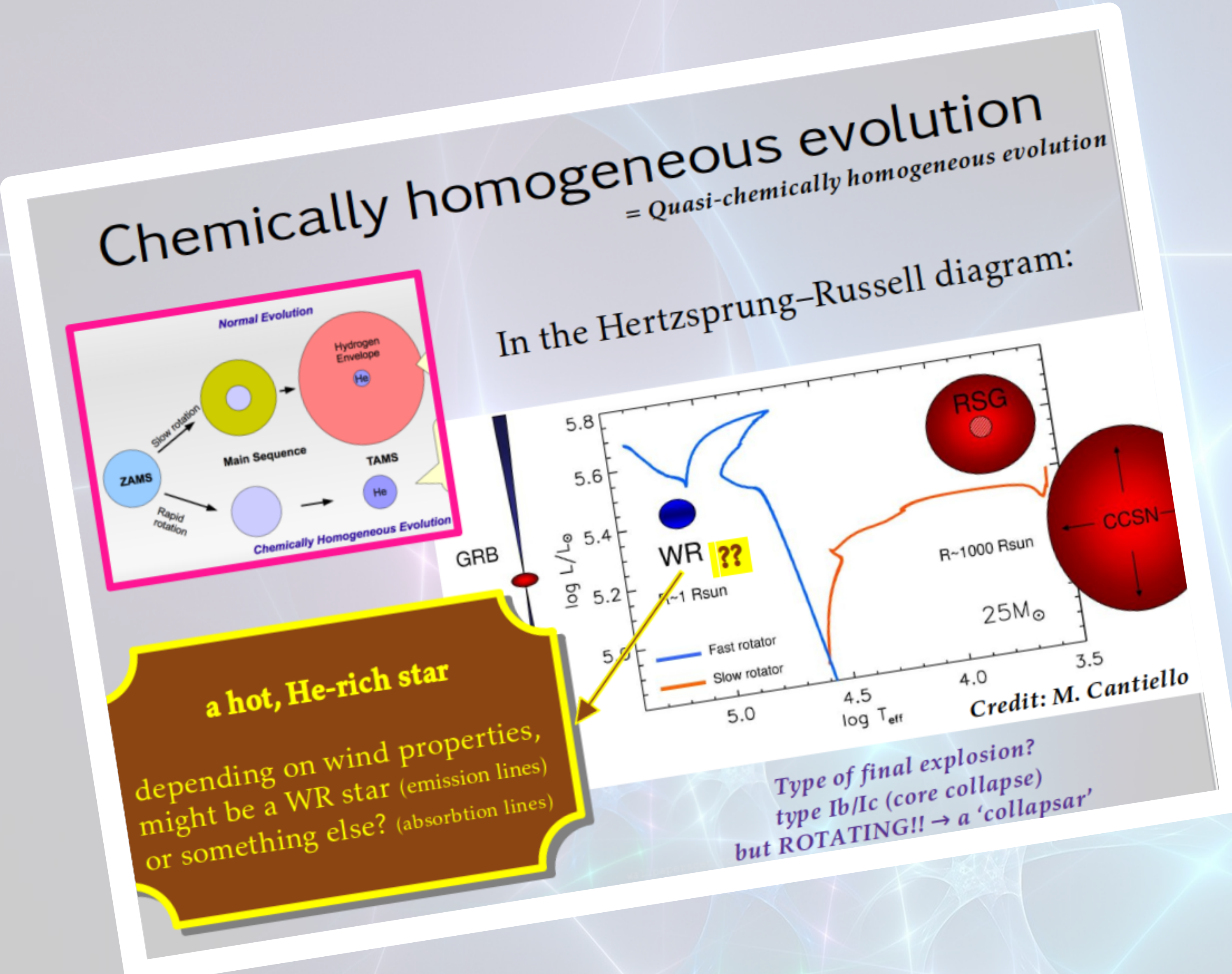
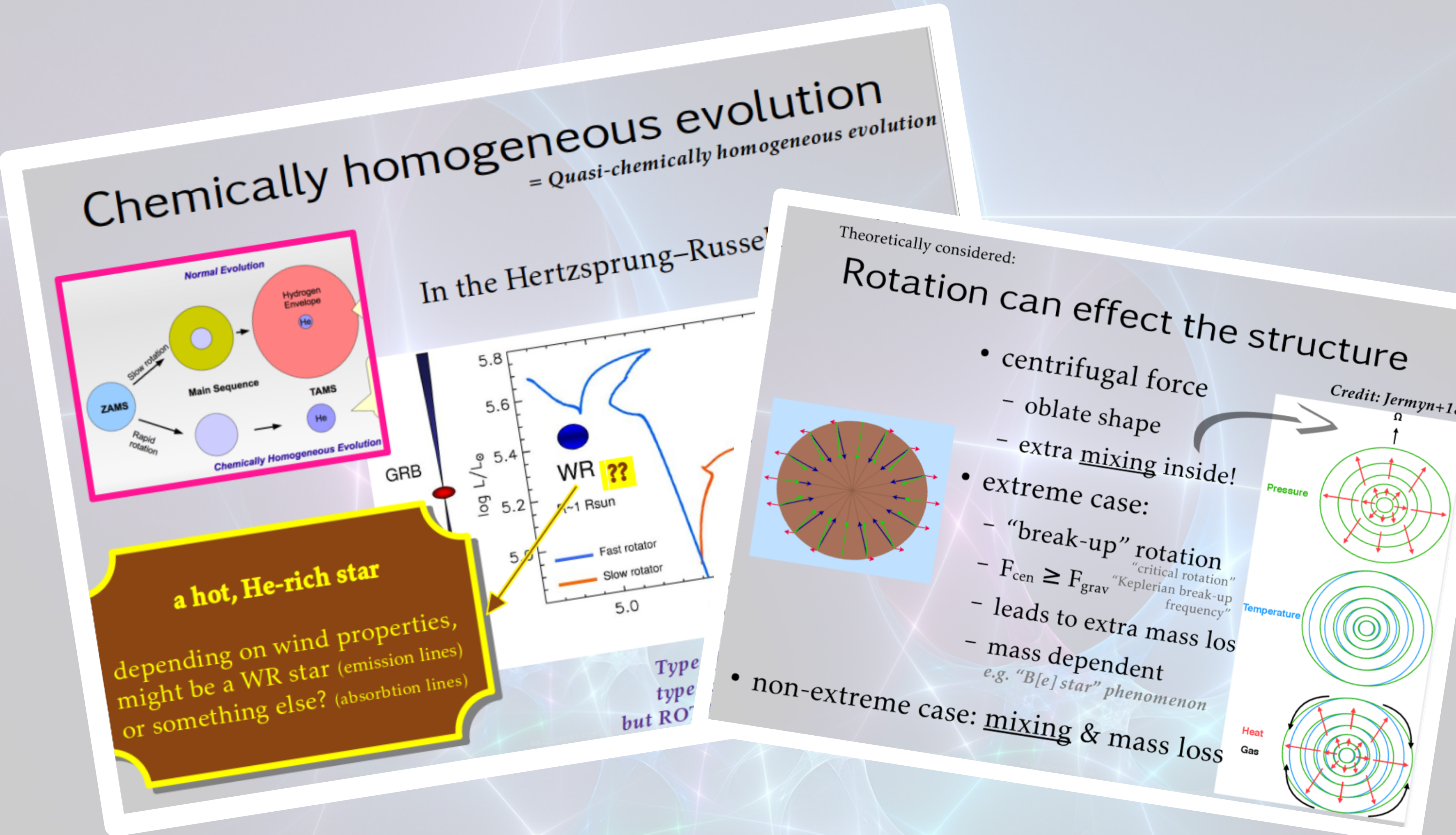
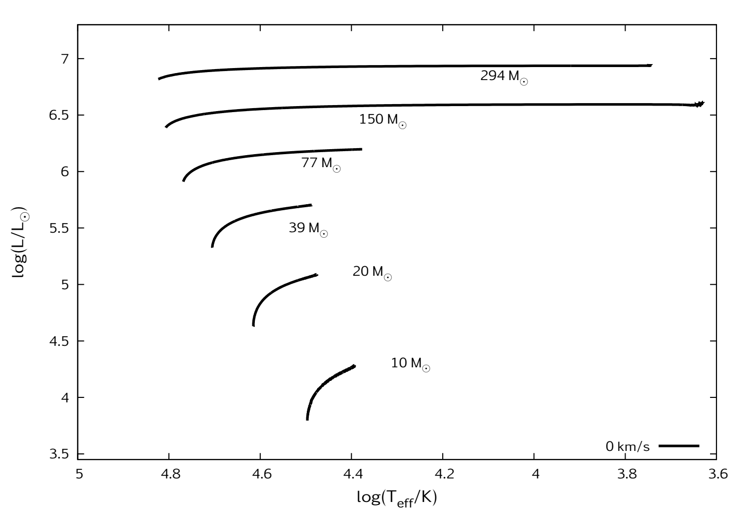


Reminder: single massive stars with fast rotation & low-Z



Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



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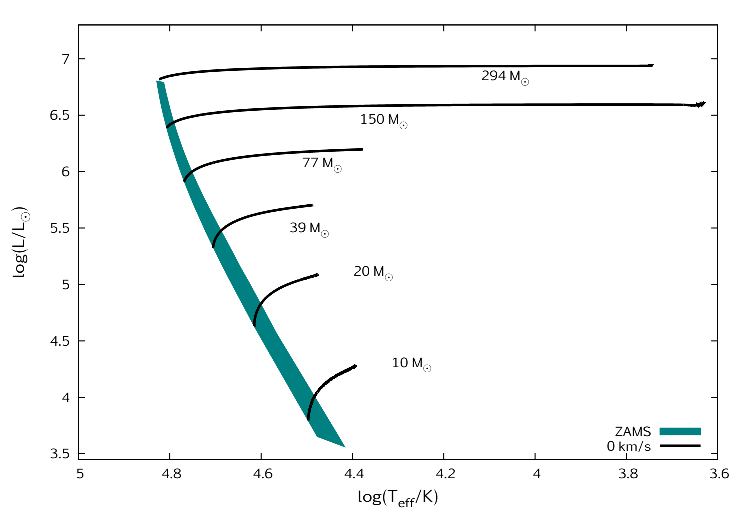

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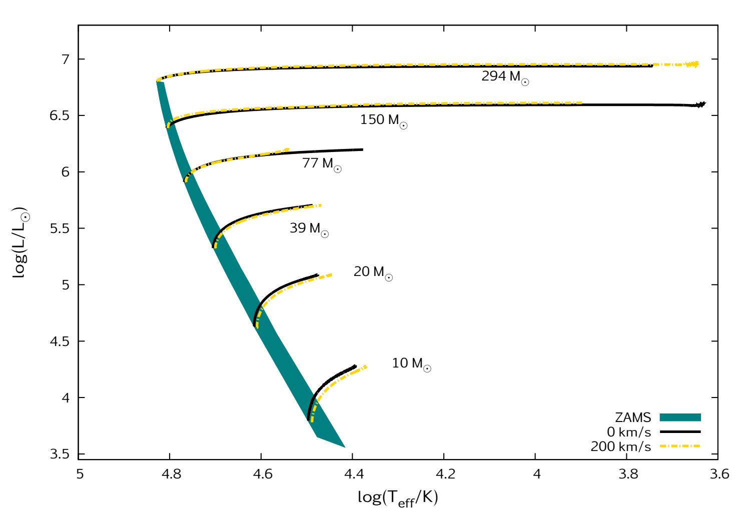

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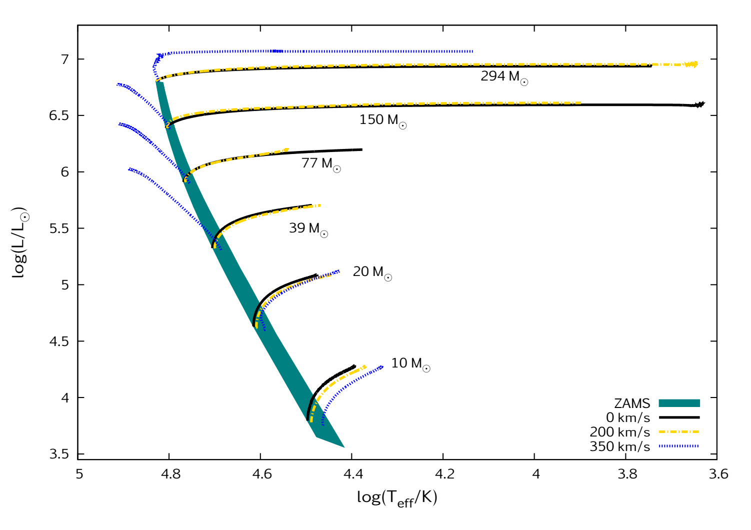

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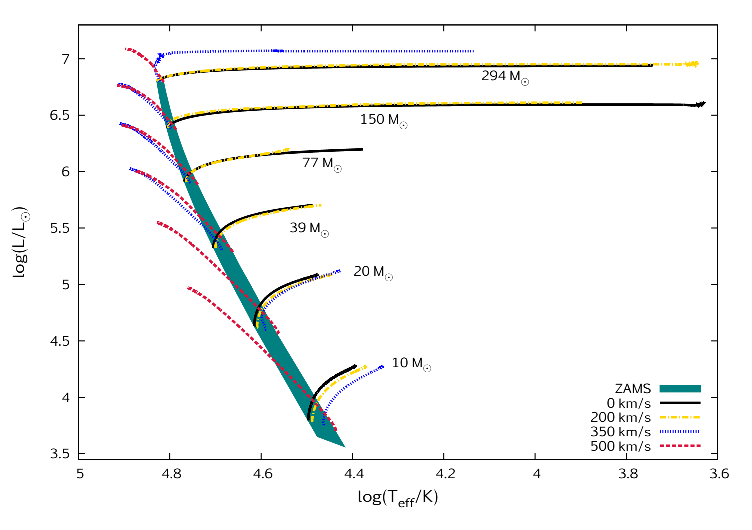

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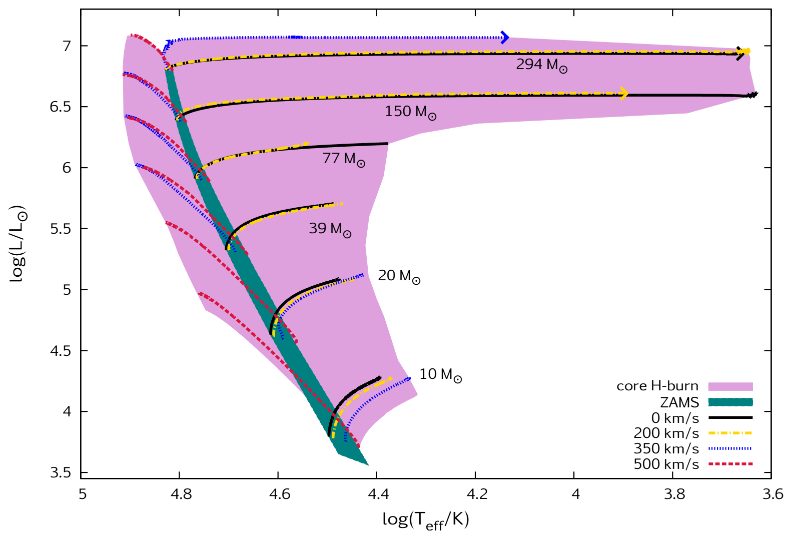
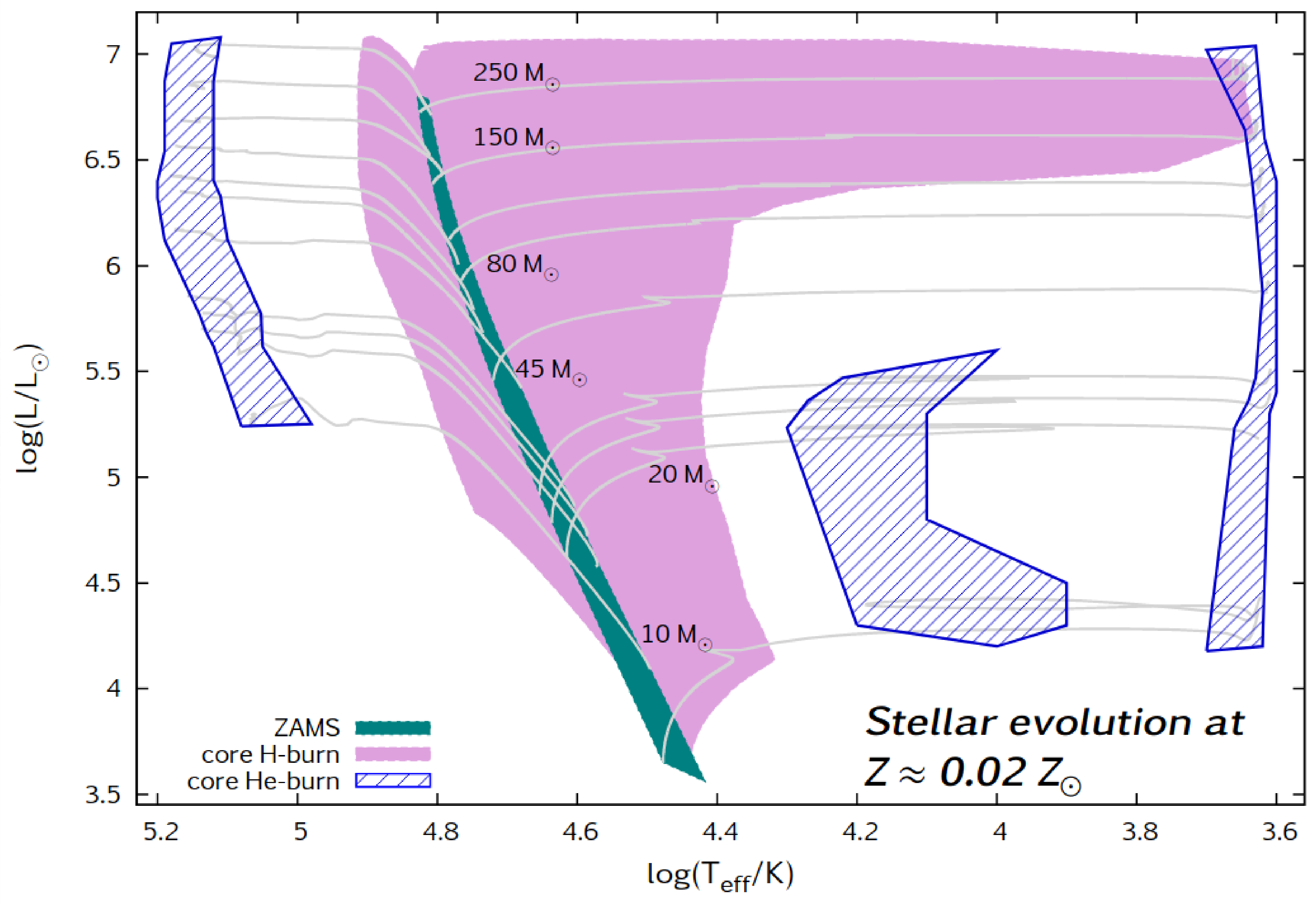


Complete evolution of the same models



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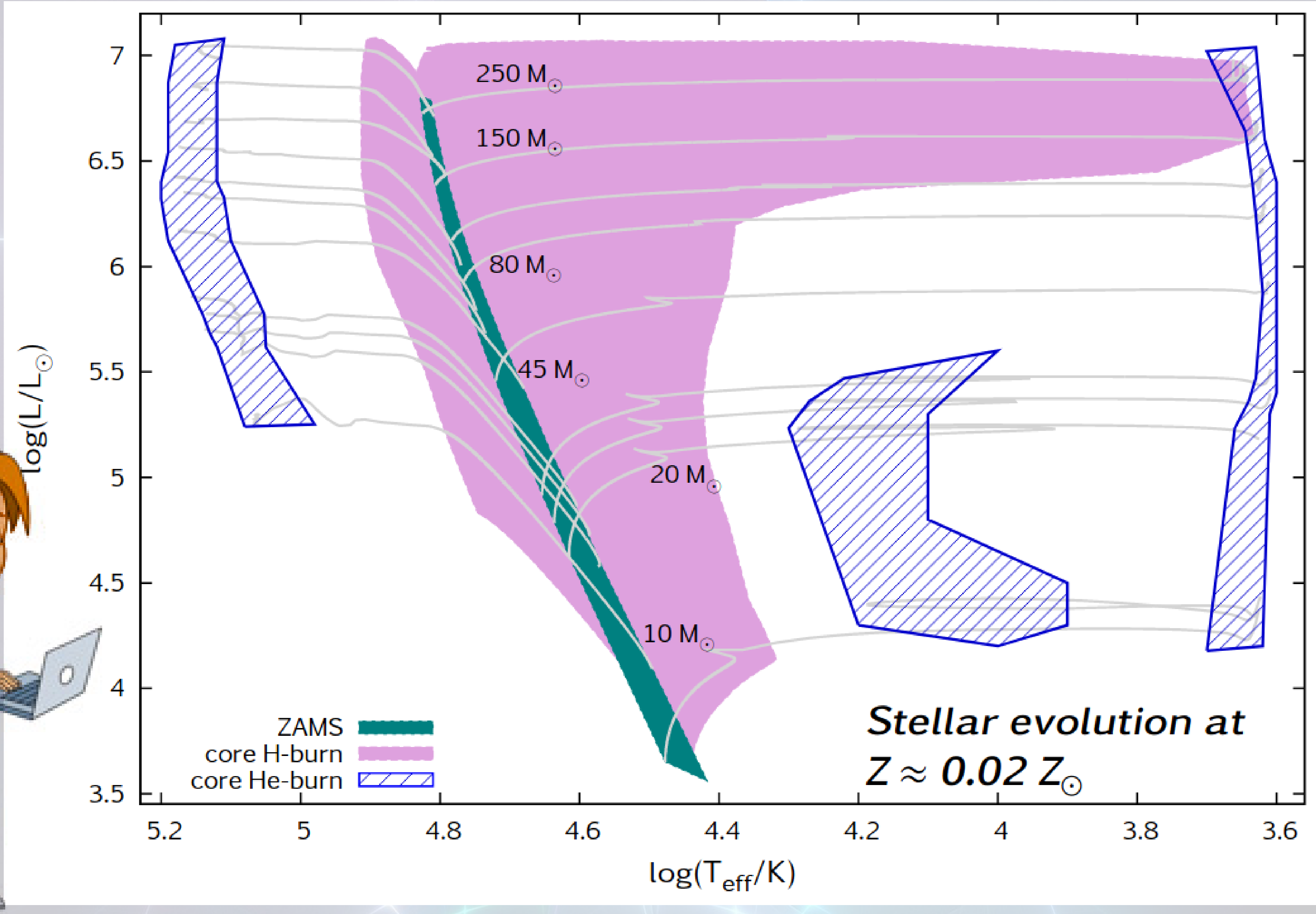
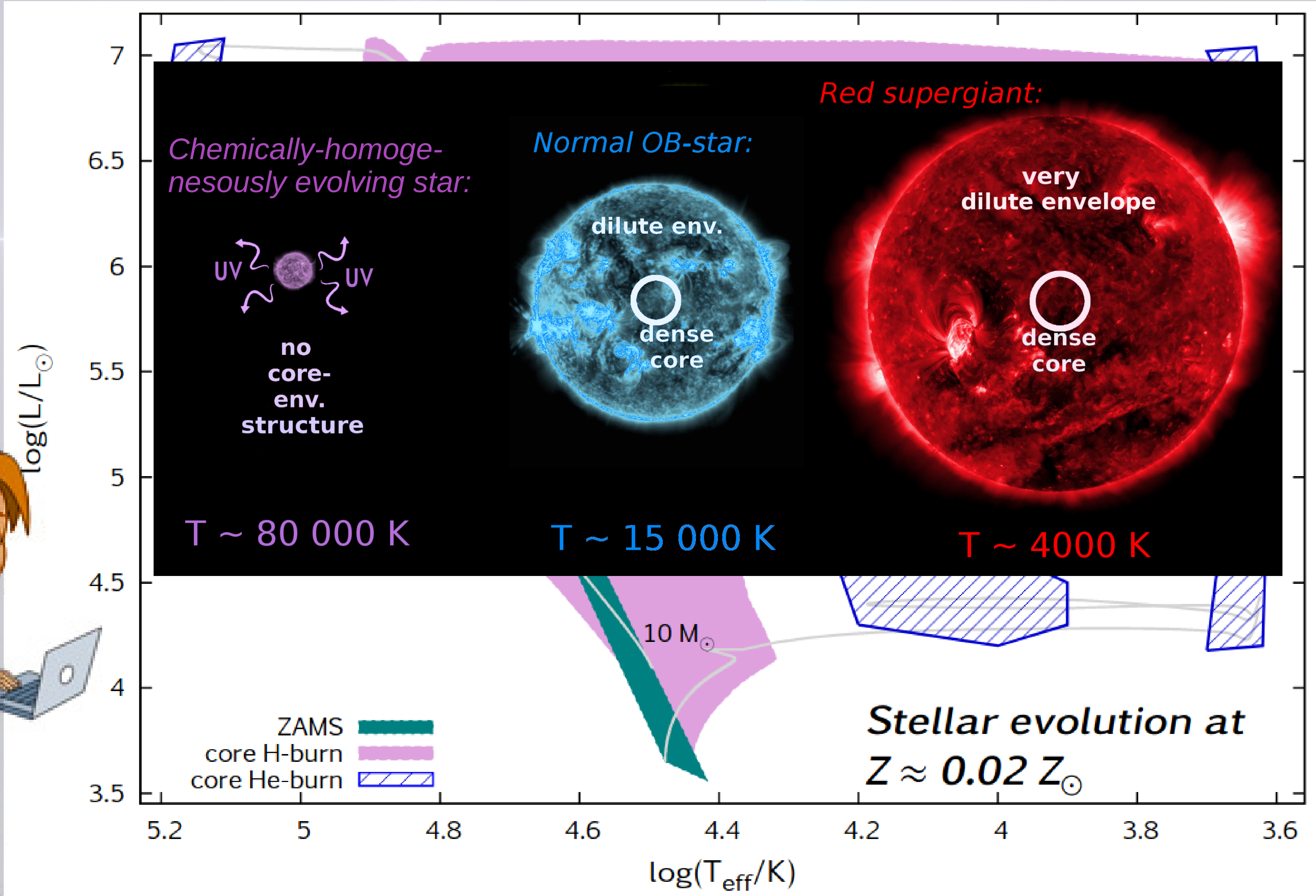
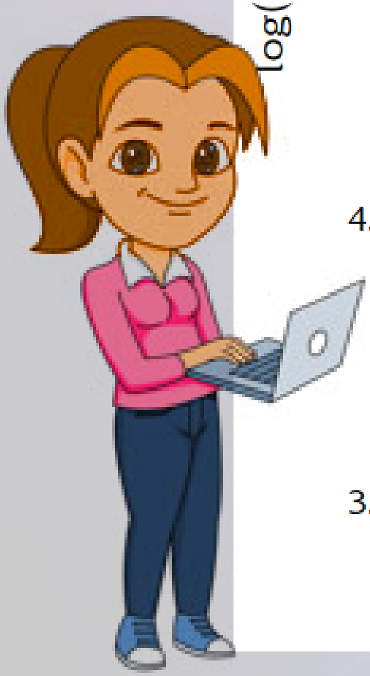


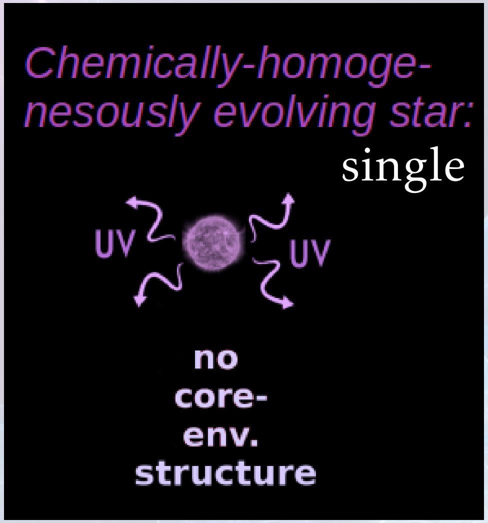
What do they look like?





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

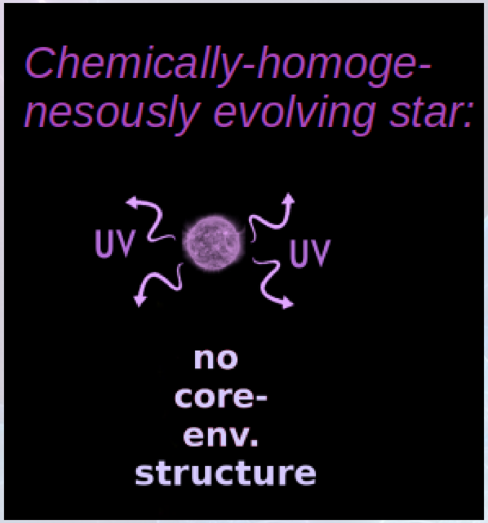
What about a metal-poor, fast rotating binary system?



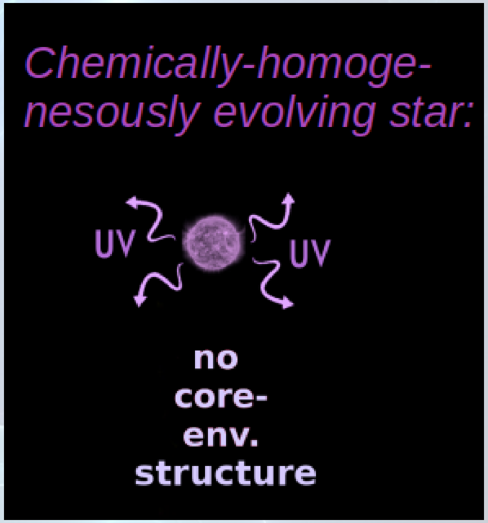
→ sub-Solar metallicities?
→ fast-rotating stars?
→ stars in a binary system?

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

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

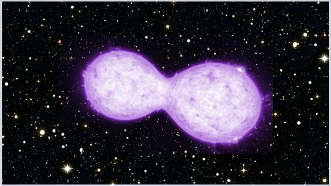


+



= ?

Gravitational waves... theoretical origin!



e.g. **Szécsi**′17a

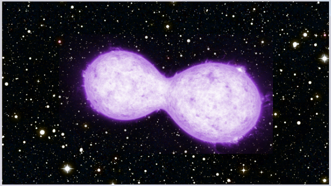
Szécsi′17b

Bagoly,**Szécsi**+16

Marchant+16,17

Gravitational waves... theoretical origin!

Life



Massive binaries

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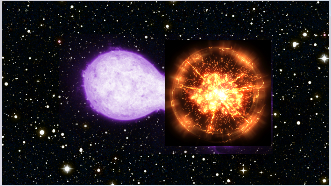
Life

Death



Massive binaries

Explosions

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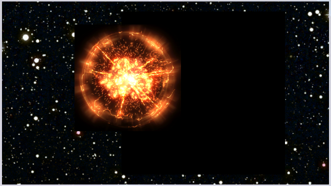

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Gravitational waves… theoretical origin!

Life — Massive binaries

Death — Explosions

Afterlife — 2 Black Holes (or Neutron Stars)

e.g. **Szécsi**′17a

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Bagoly,**Szécsi**+16

Marchant+16,17

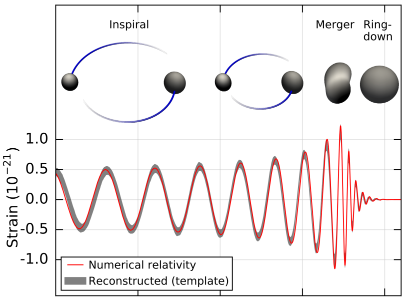
Gravitational waves... theoretical origin!

Life — Massive binaries

Death — Explosions

Afterlife — 2 Black Holes (or Neutron Stars)

'Second death' — **Merger**



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

e.g. **Szécsi**'17a

Szécsi'17b

Bagoly,**Szécsi**+16

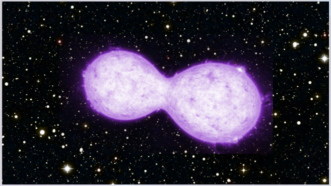
Marchant+16,17

Gravitational waves... theoretical origin!

Life — Massive binaries

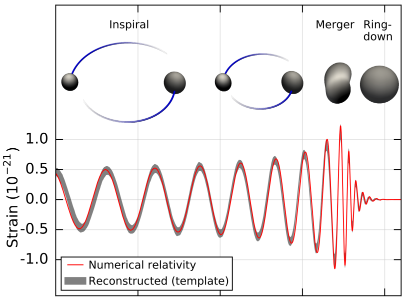
Death — Explosions

Afterlife — 2 Black Holes (or Neutron Stars)



'Second death'

Merger



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

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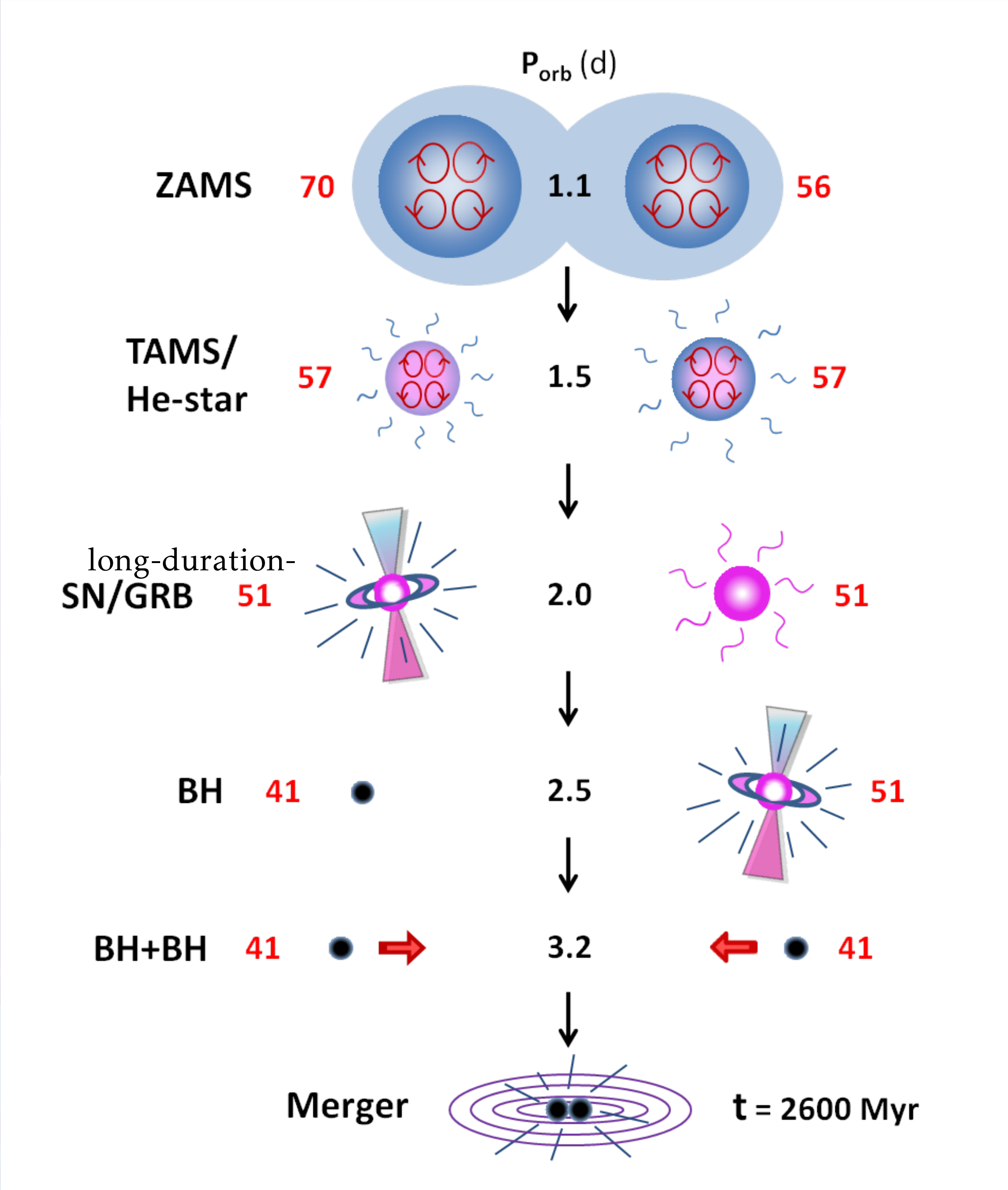
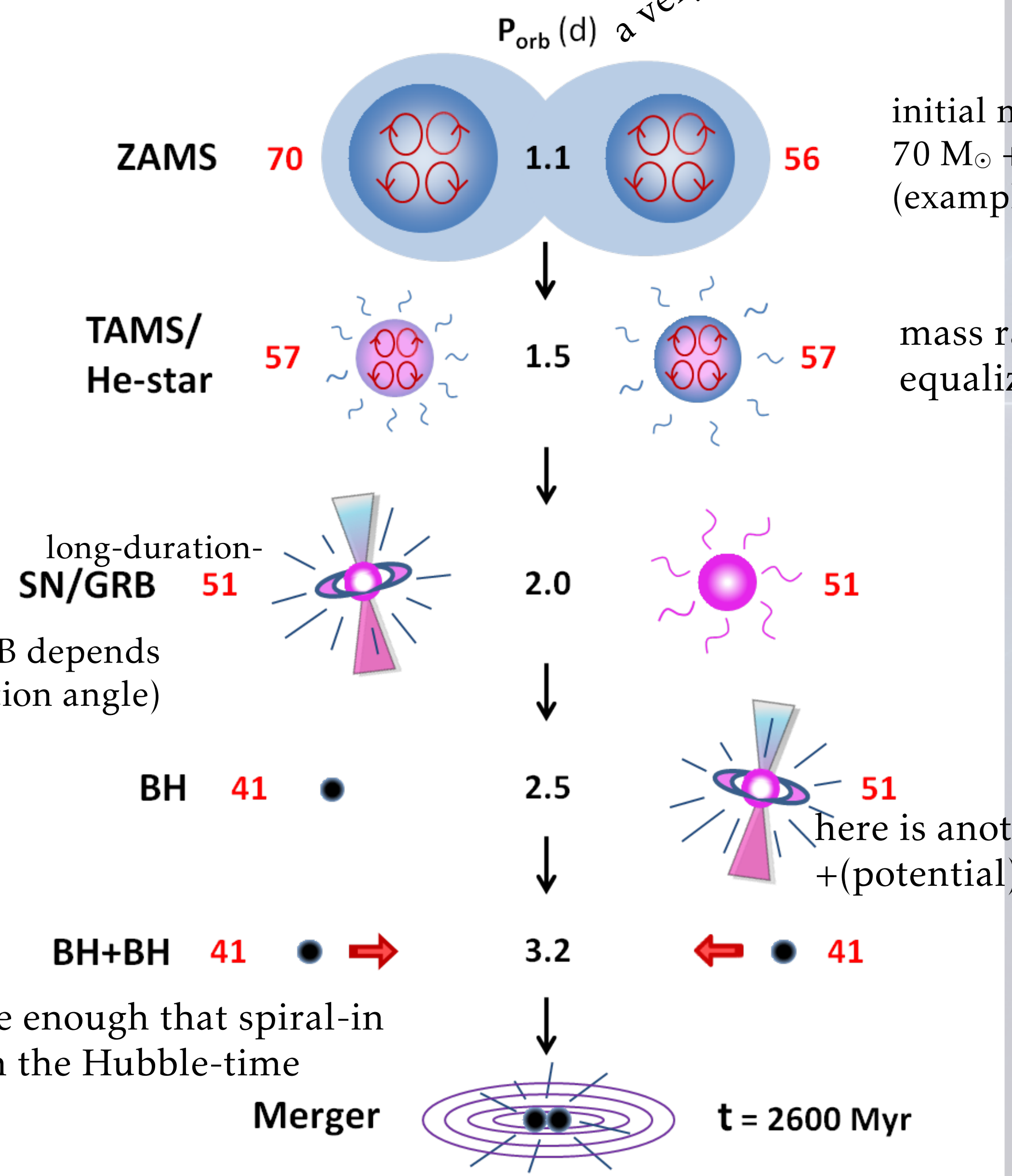
To "cartoonize" the scenario:



Credit: Marchant+16

To "cartoonize" the scenario:



a very short orb.period!

initial masses 70 M☉ + 56 M☉ (example)

mass ratio (q) equalizes

long-duration-

(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

Next time:

Today we dealt with:

NSs & degeneracy
HMXBs, AGNs, jets

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

Next time: why statistics is important →
population synthesis (including SN kicks)
vs. evolutionary models of binary systems