Gravitational-wave progenitors

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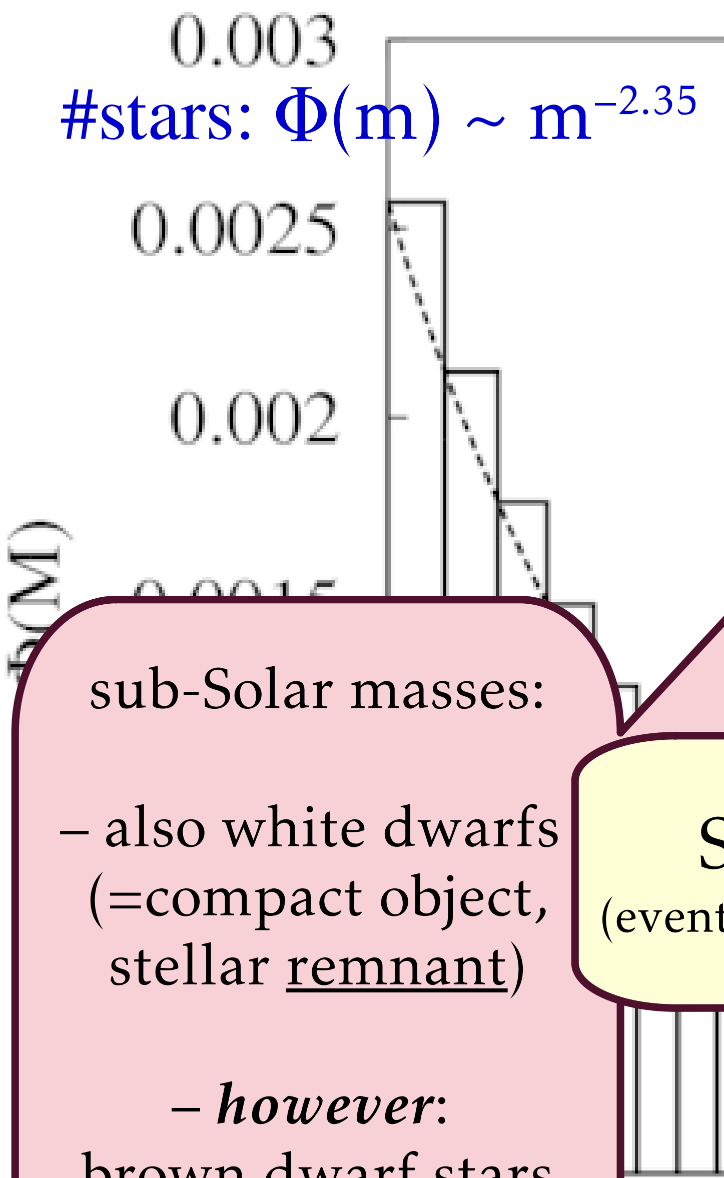
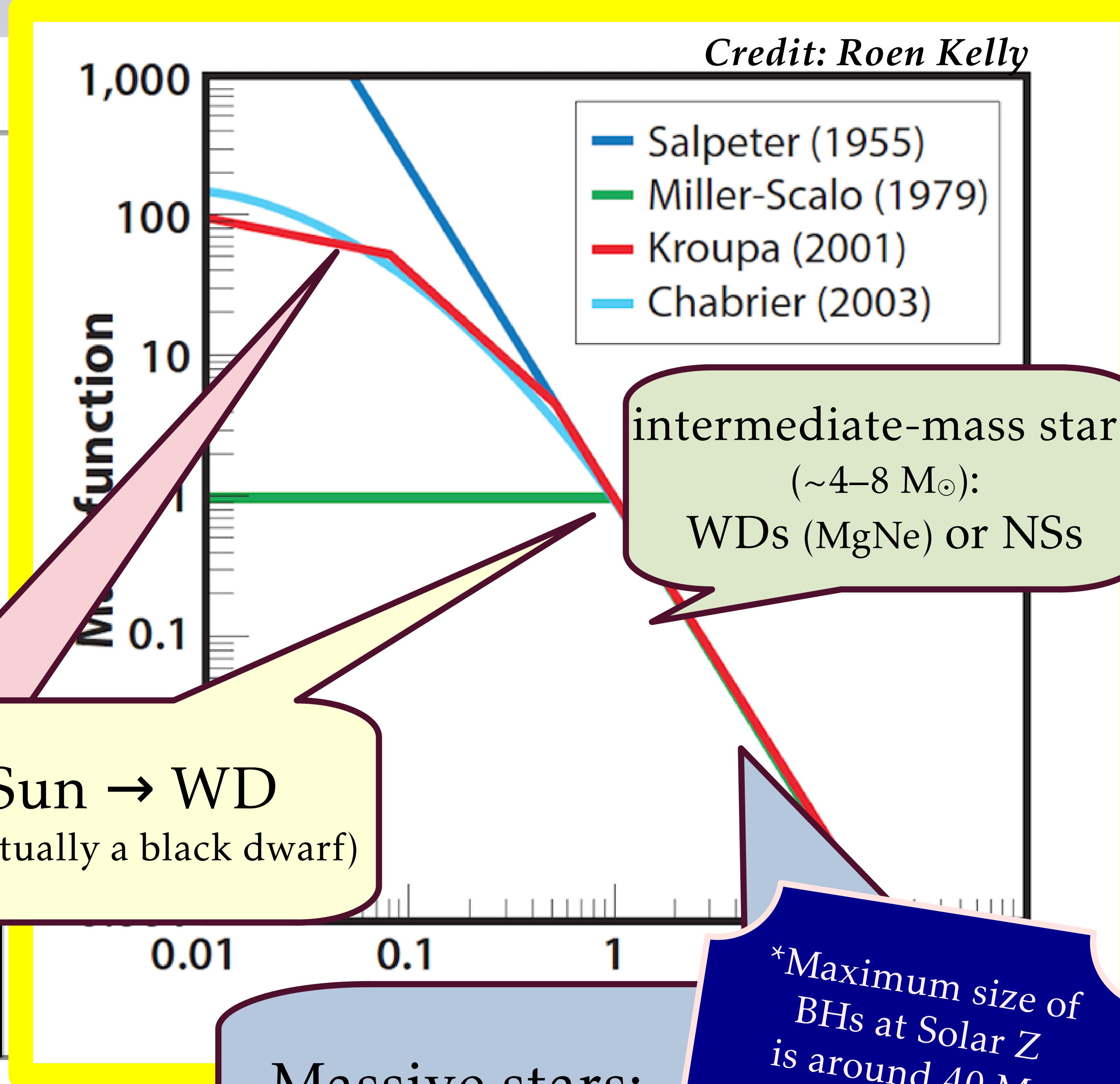
Lecture #7

NCU, Summer Semester 2022

Previously on GW-progenitors…

#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*

*Maximum size of BHs at Solar Z is around 40 $M_\odot$ due to strong mass loss of the massive star progenitor

What are compact objects?

stellar 'corpses' **= remnants**

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

(white dwarf and 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

Explosion types?

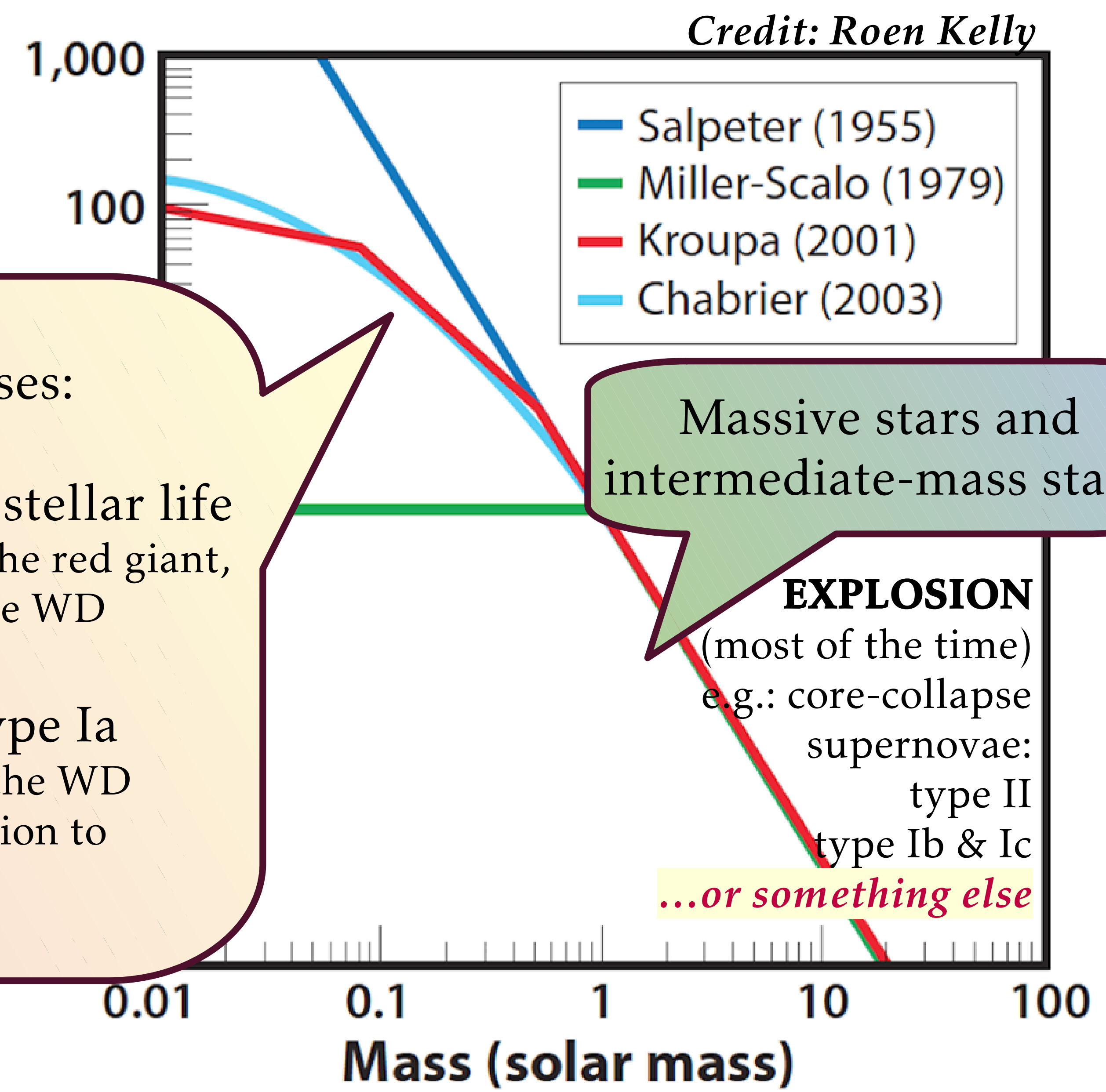
Sun & sub-Solar masses:

– no explosion at the end of stellar life
i.e. ejection of the outer layers of the red giant, planetary nebula around the WD

– ***LATER:*** supernova type Ia
thermonuclear explosion of the WD
IF there is a binary companion to transfer mass onto it

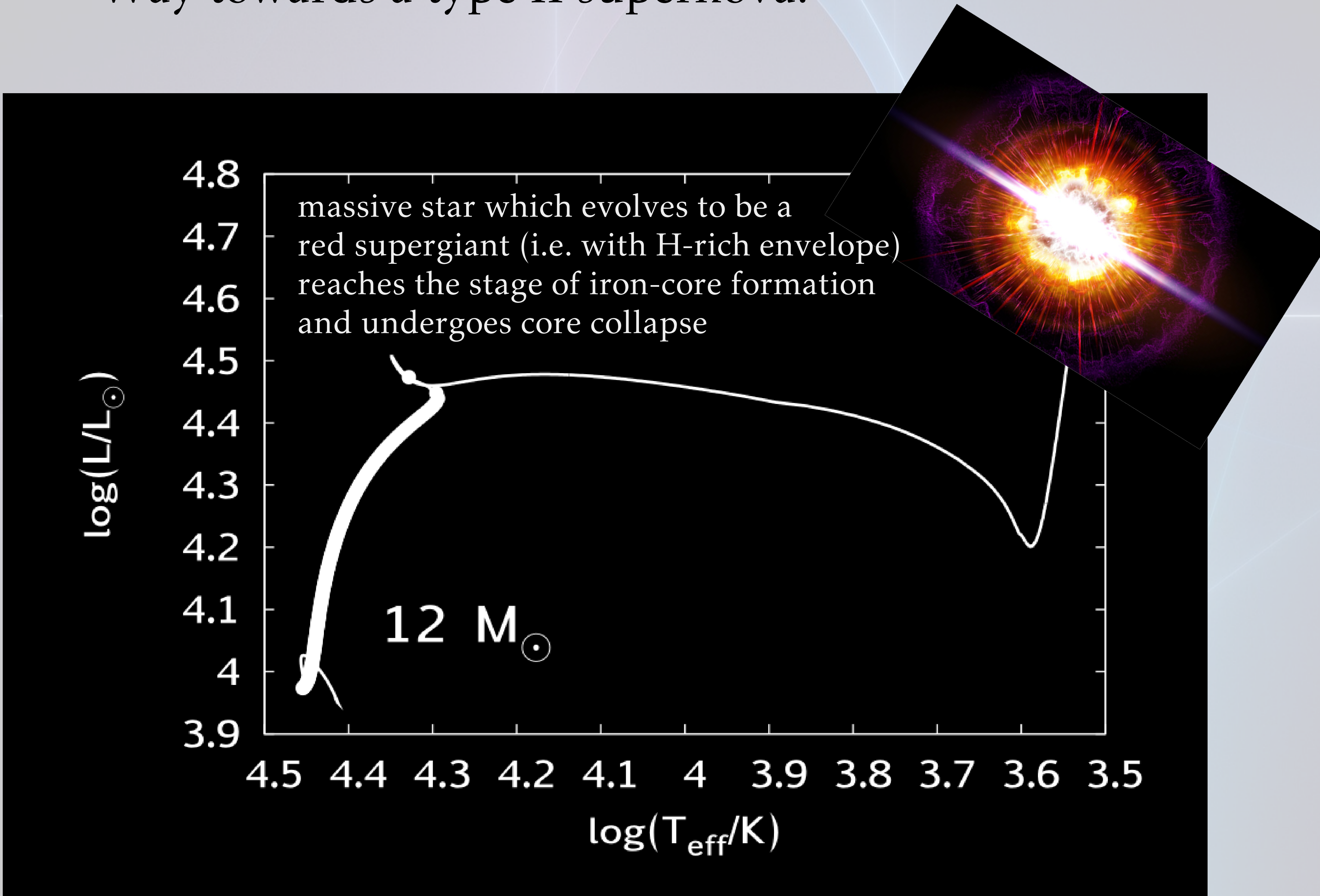
Massive stars and intermediate-mass stars?

EXPLOSION
(most of the time)
e.g.: core-collapse supernovae:
type II
type Ib & Ic
...or something else



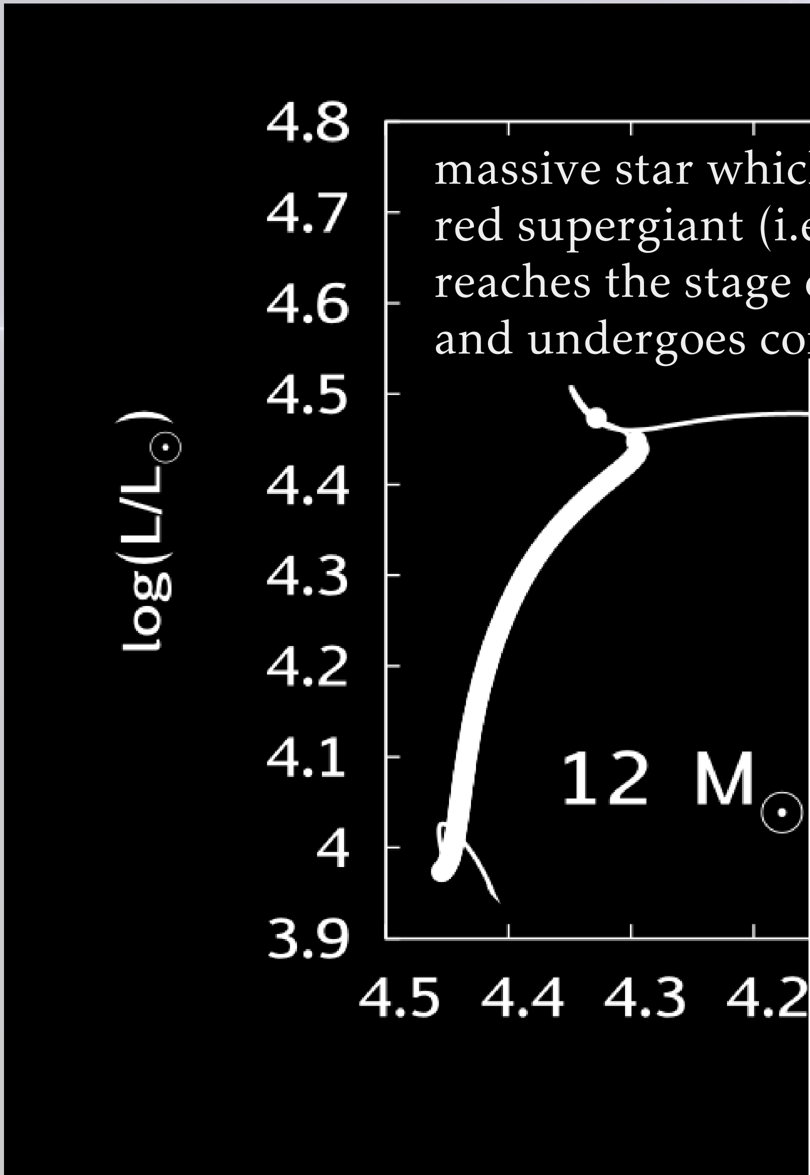
Side-note: type Ia Sne are standard candles in cosmology

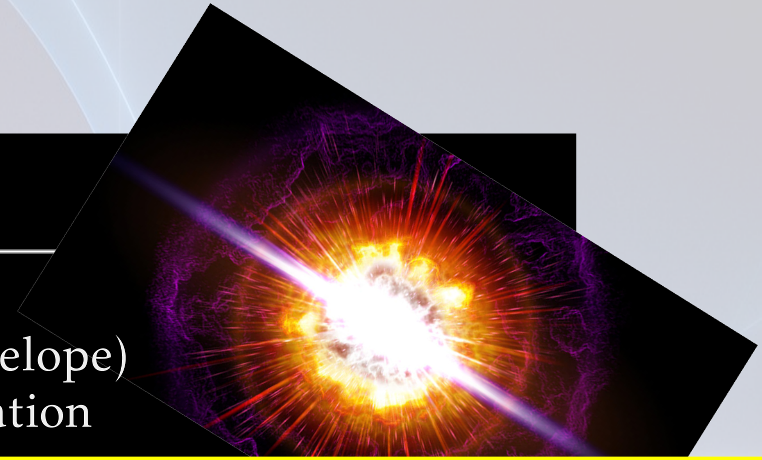
Way towards a type II supernova:

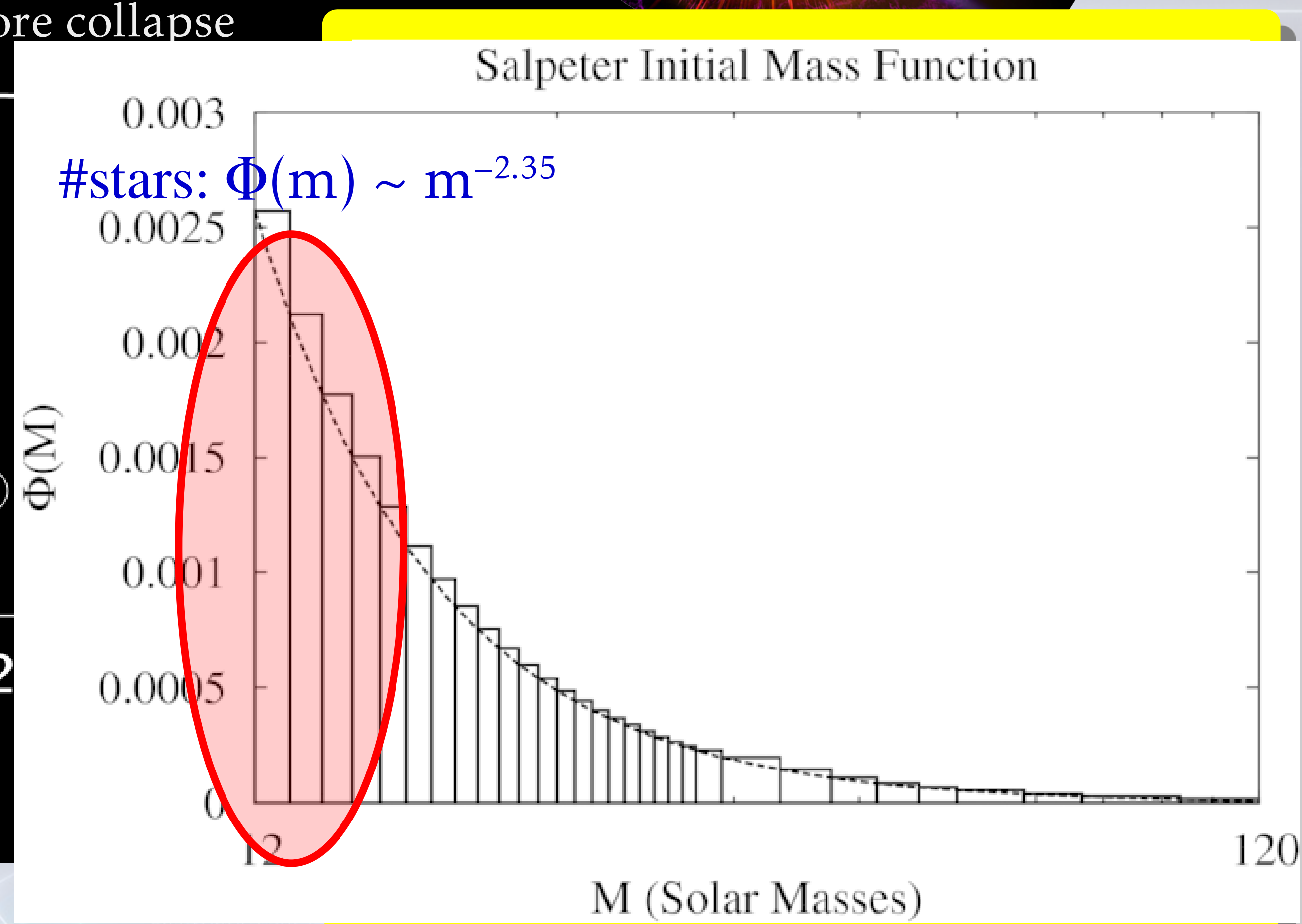


Way towards a type II supernova:

massive star which evolves to be a red supergiant (i.e. with H-rich envelope) reaches the stage of iron-core formation and undergoes core collapse

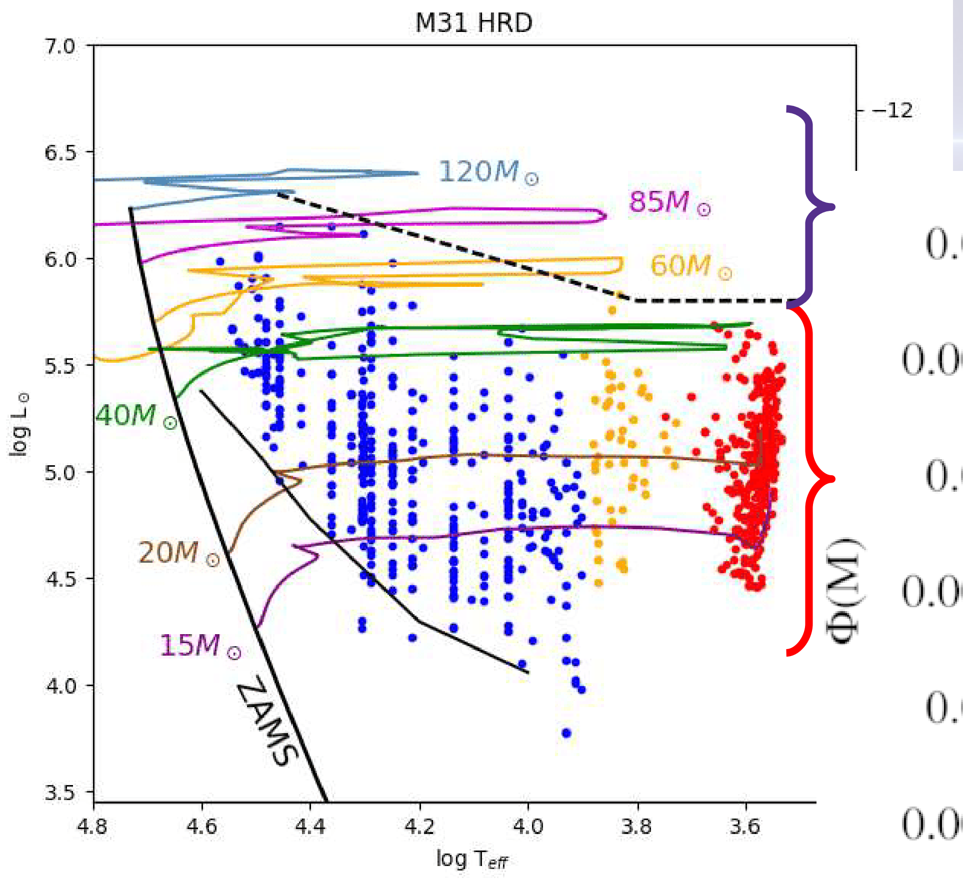


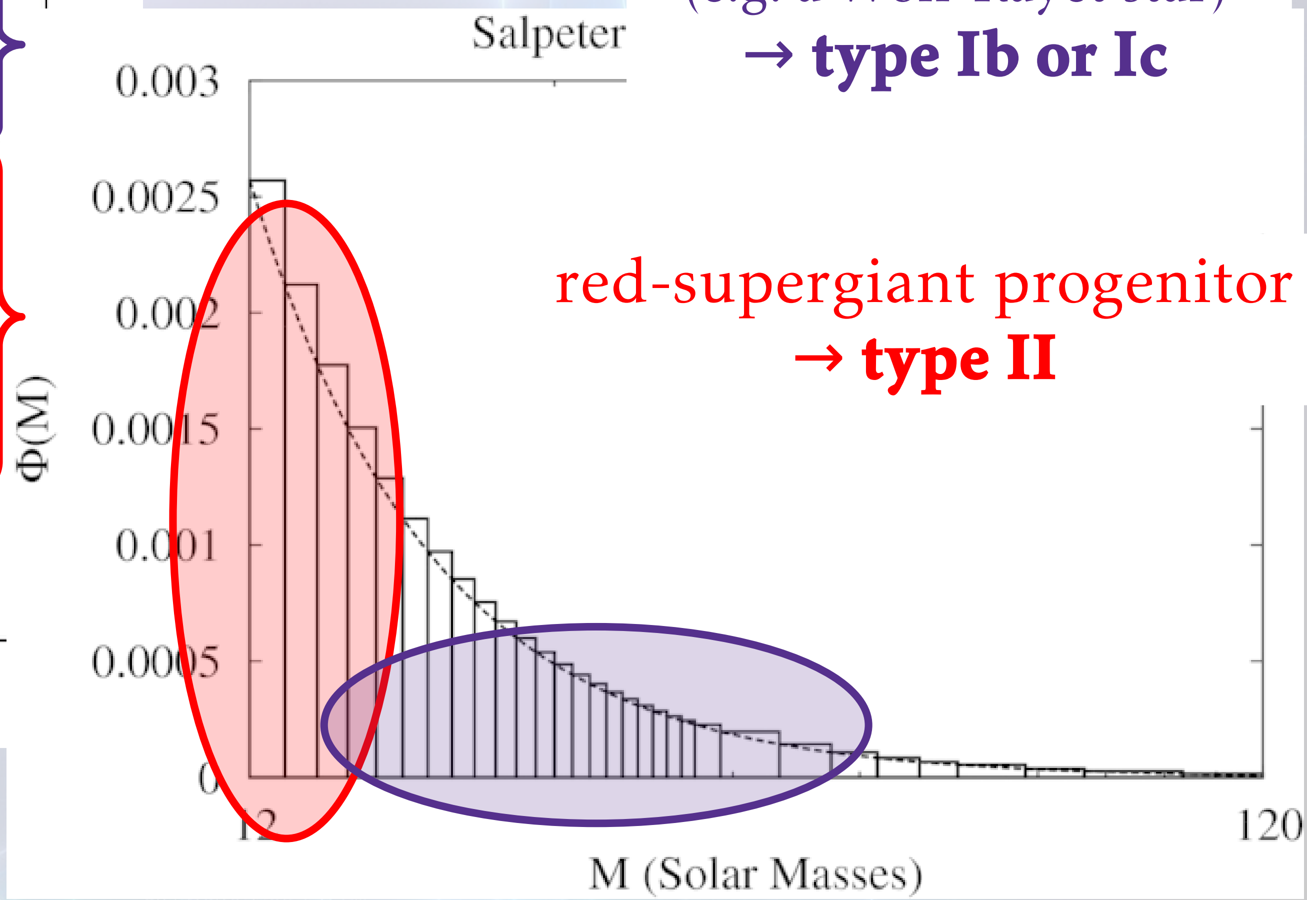




This is only true: single stars
at solar metallicity
no (or slow) rotation

*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

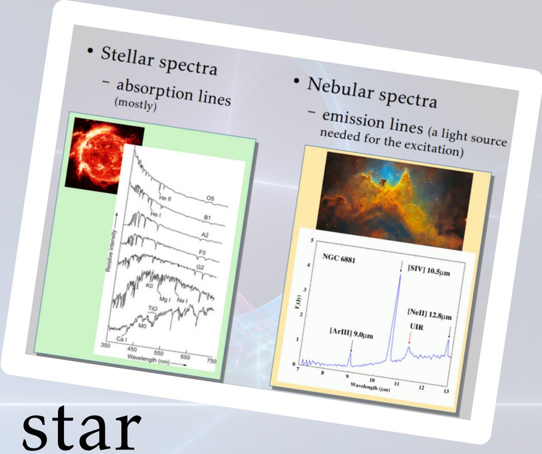




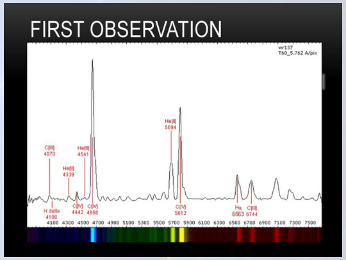
'stripped' progenitor*
(e.g. a Wolf-Rayet star)
→ **type Ib or Ic**

red-supergiant progenitor
→ **type II**

Side-notes on Wolf-Rayet stars



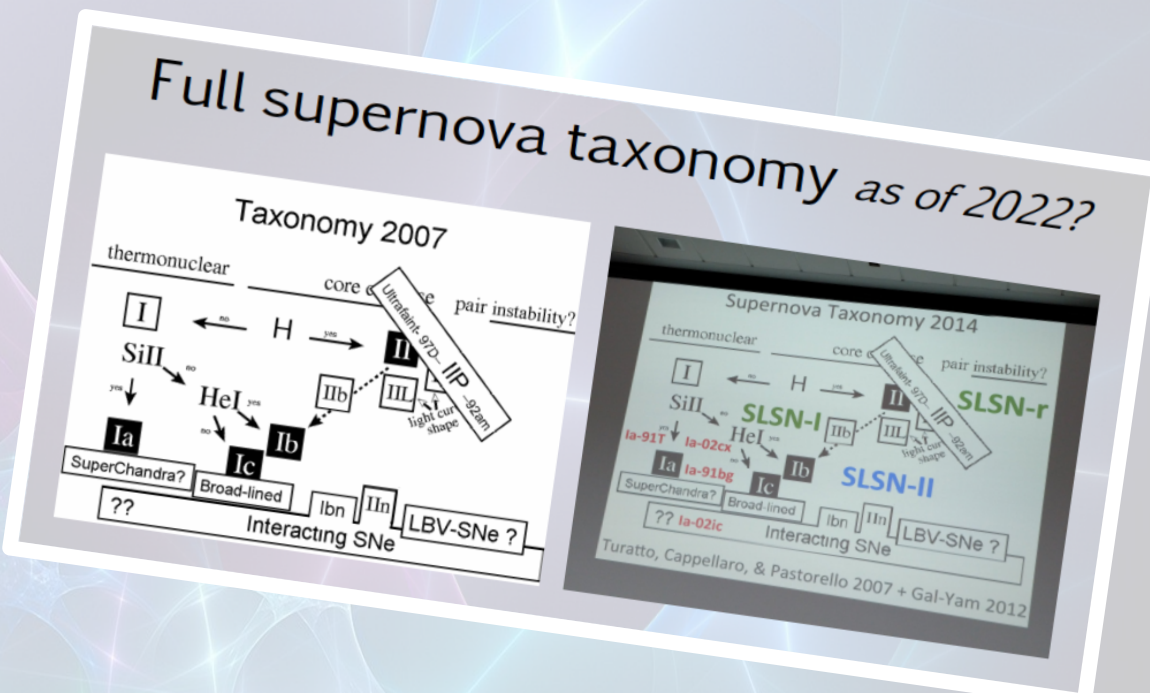
- Observationally:
  - broad emission lines in the spectrum
  - meaning there is a nebula around the star
  - composition: (usually) H-free



- 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.)

What happens at

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



Sub-Solar metallicities

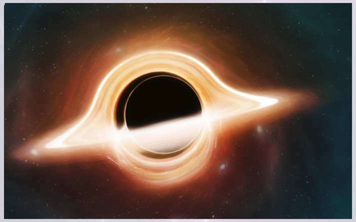
(and still no rotation and no binary companion)

- Main effect: mass loss becomes WEAKER

  → stars live their lives with more mass retained

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

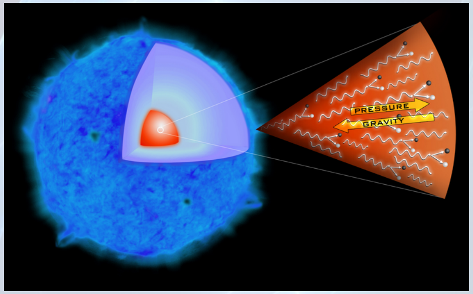
Consequence #1:



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?

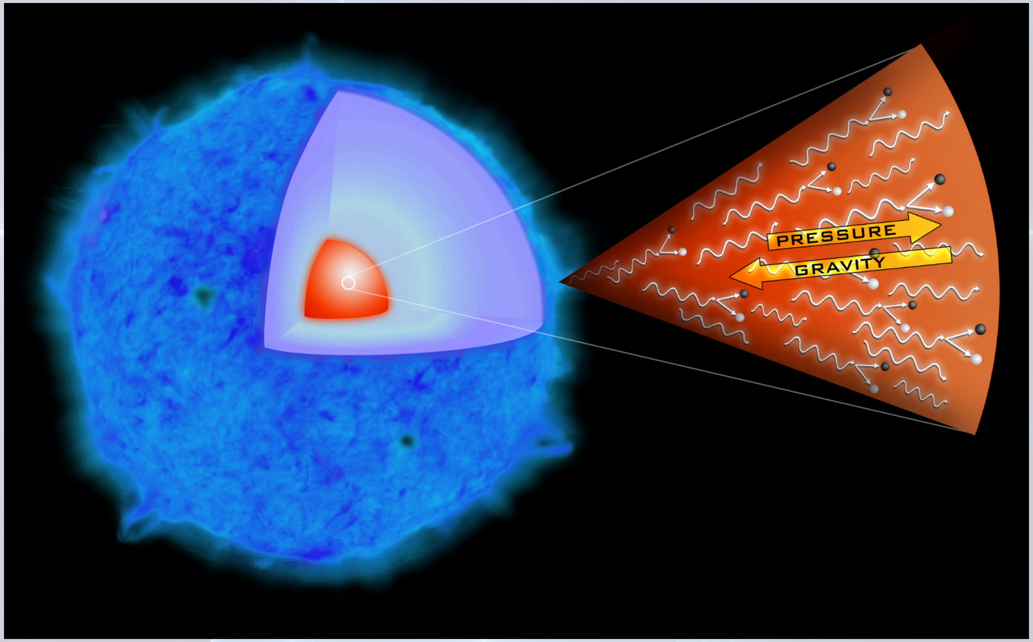
Pair Instability

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

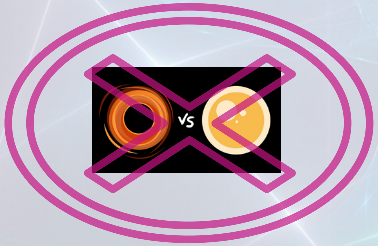
key question, as always:
is there something to stop it?
…if not:

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

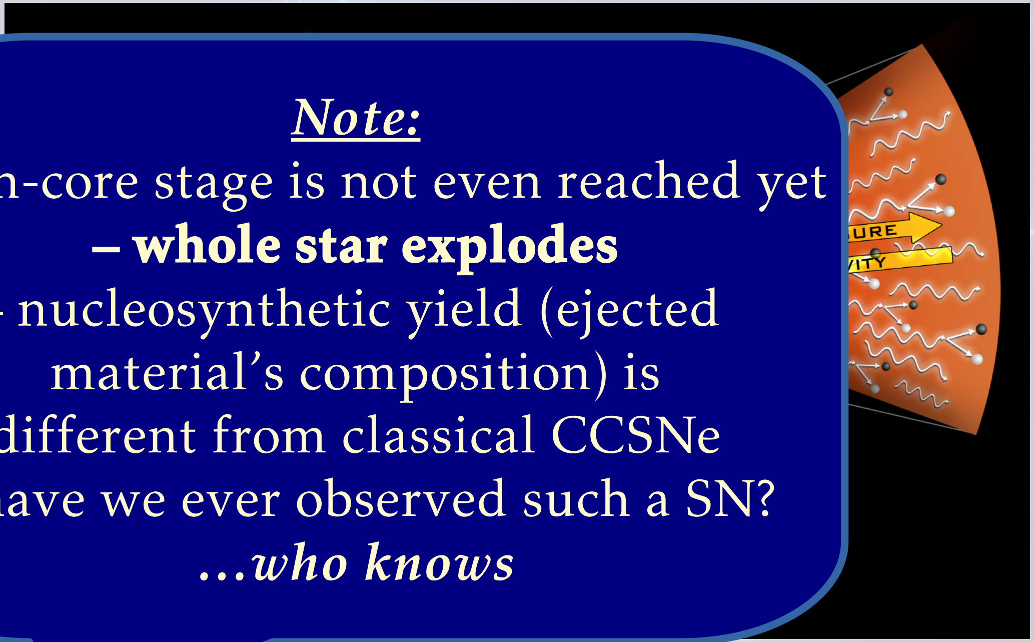
happens in ***quite*** massive stellar cores
mass values quoted here mean M_{ZAMS}

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

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

Collapse

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



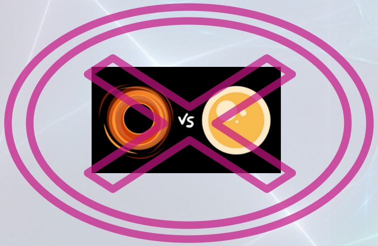
Note:
– iron-core stage is not even reached yet
– whole star explodes
– nucleosynthetic yield (ejected material's composition) is different from classical CCSNe
– have we ever observed such a SN?
…who knows

Explosive O-burning
→ supernova

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

pair-instability supernova (PISN)

No remnant!

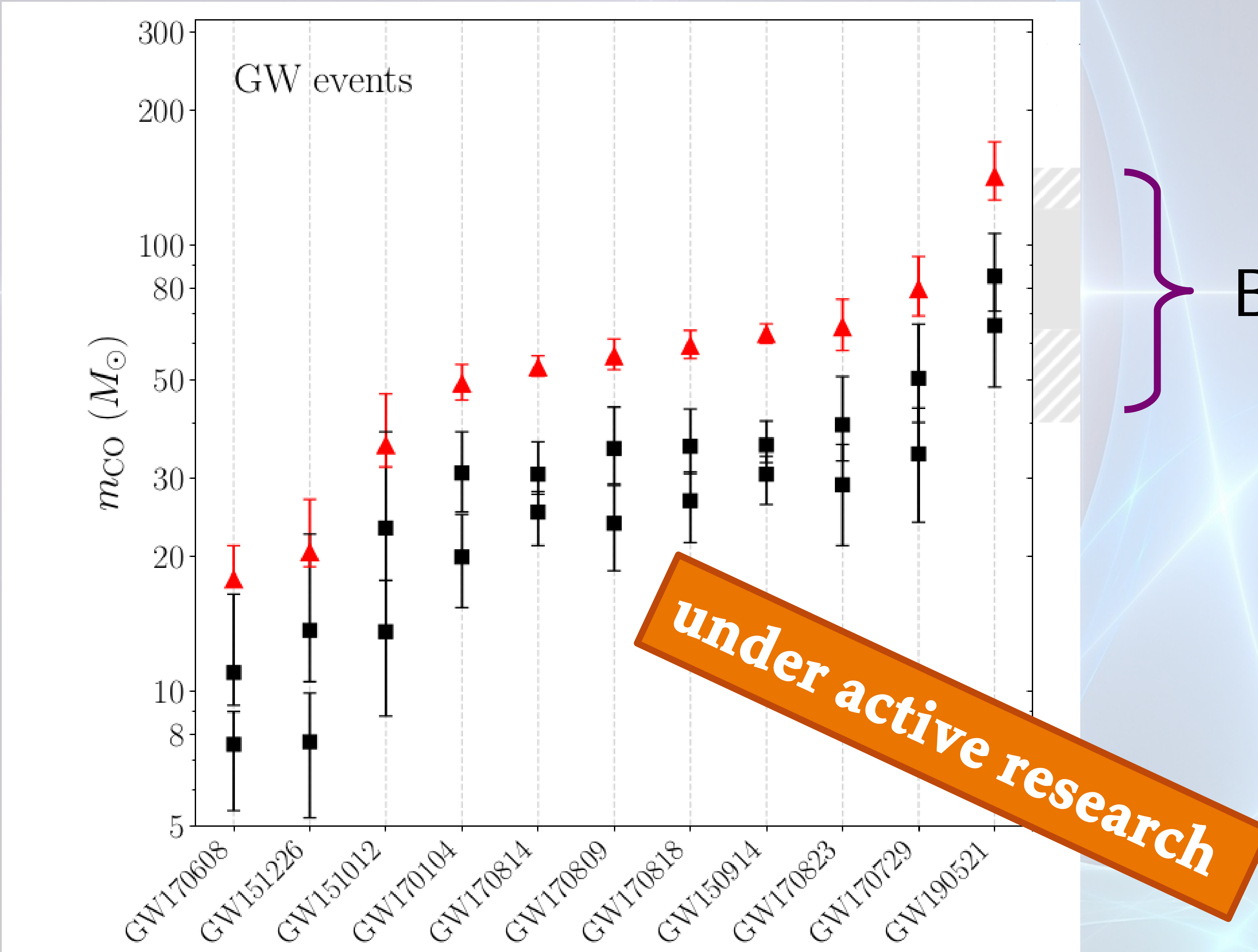


stars between 60–140 $M_\odot$:
collapse is stopped by the star re-gaining its hyrostatic stability

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

because layers lost in the pulsations
might collide and emit light

The BHs of GW190521 shouldn't exist...



BH no go zone

GW190521:

m1 = 85 (+21/−14) Msun

m2 = 66 (+17/−18) Msun

Today...

What happens at

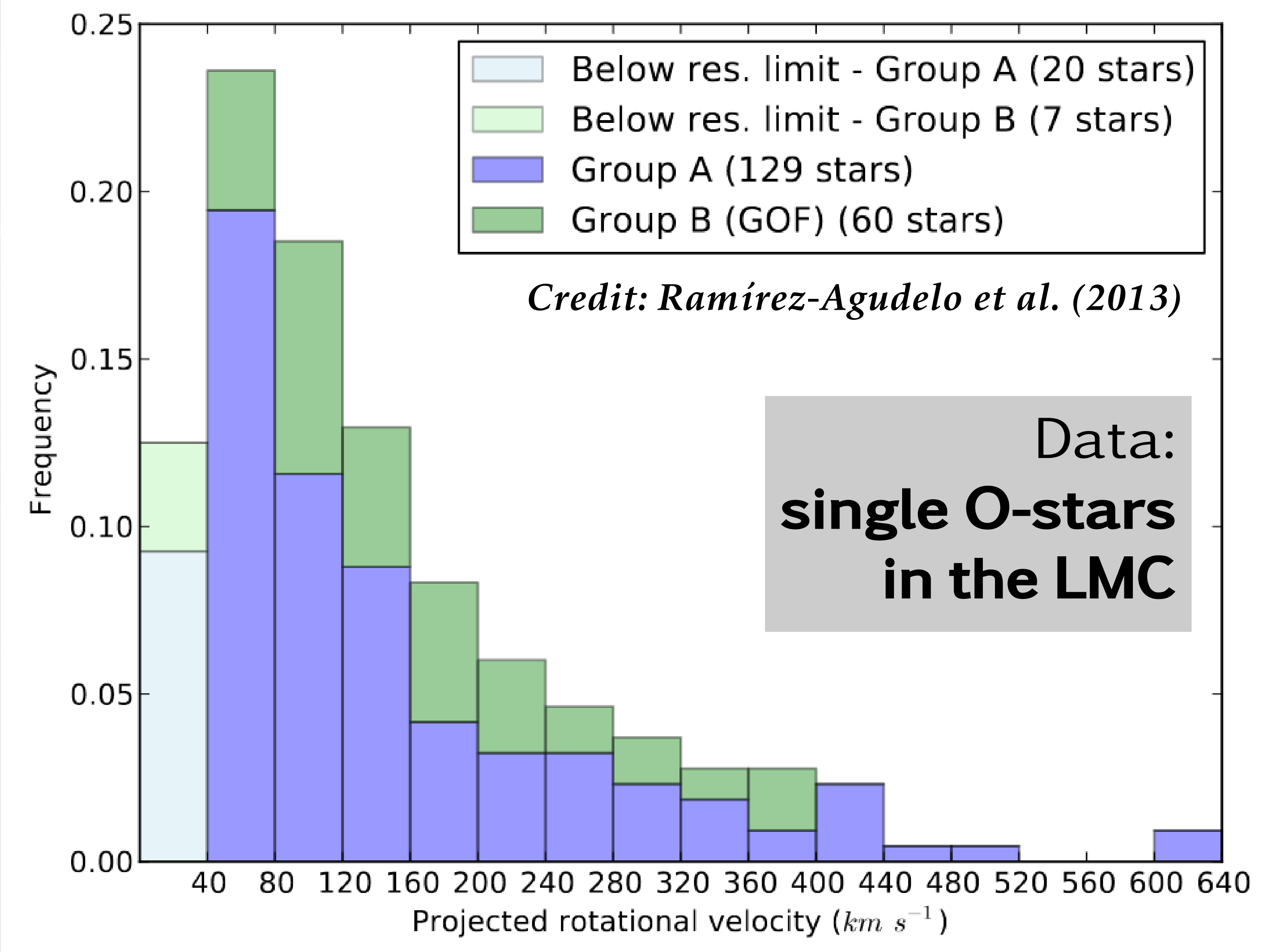
→ sub-Solar metallicities? ✓

→ fast-rotating stars?

→ stars in a binary system?

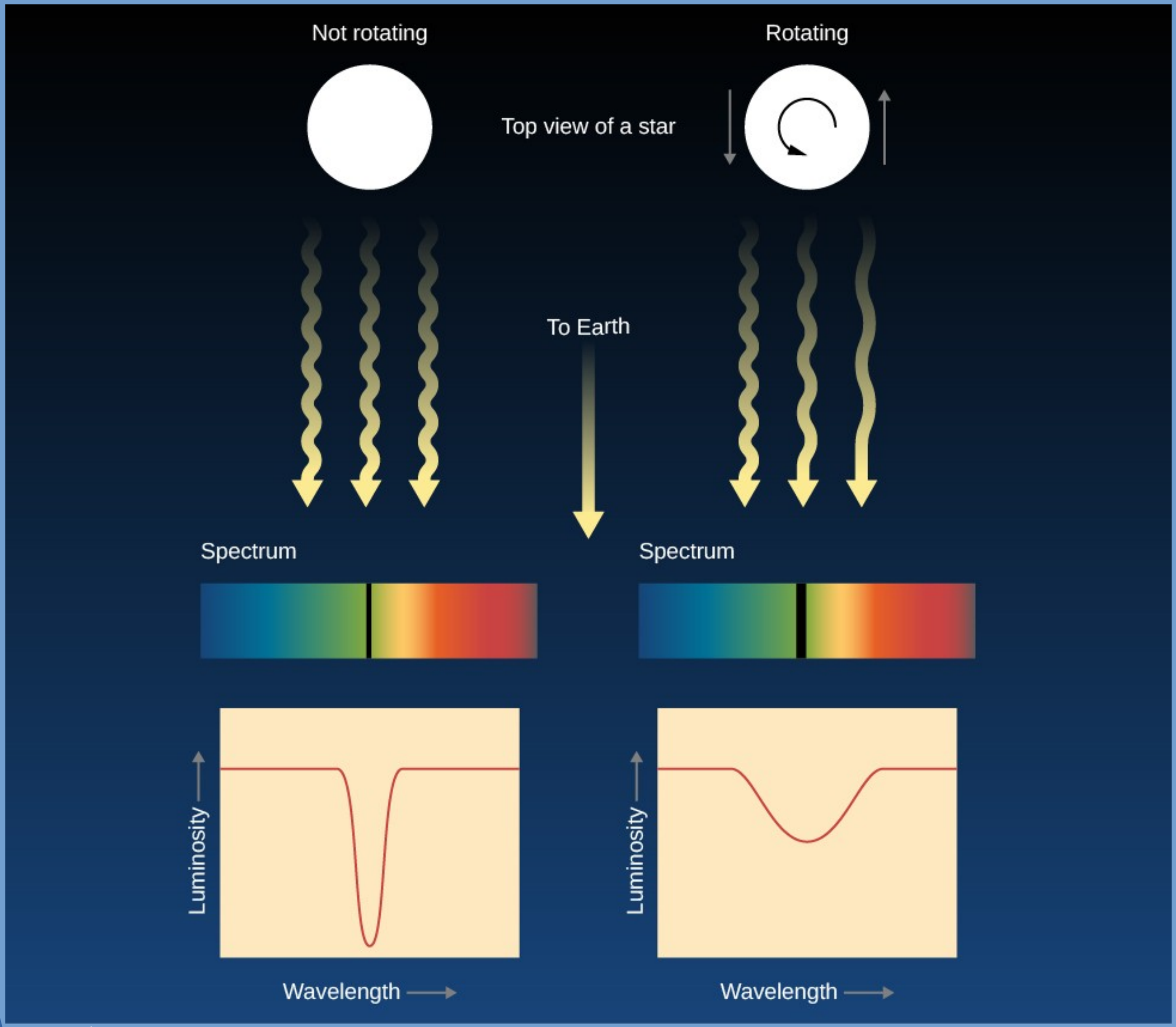
Massive stars rotate… sometimes quite fast

especially at low Z!



Massive stars rotate… sometimes quite fast

How do we know that? → line profile



Credit: LumenLearning Astronomy

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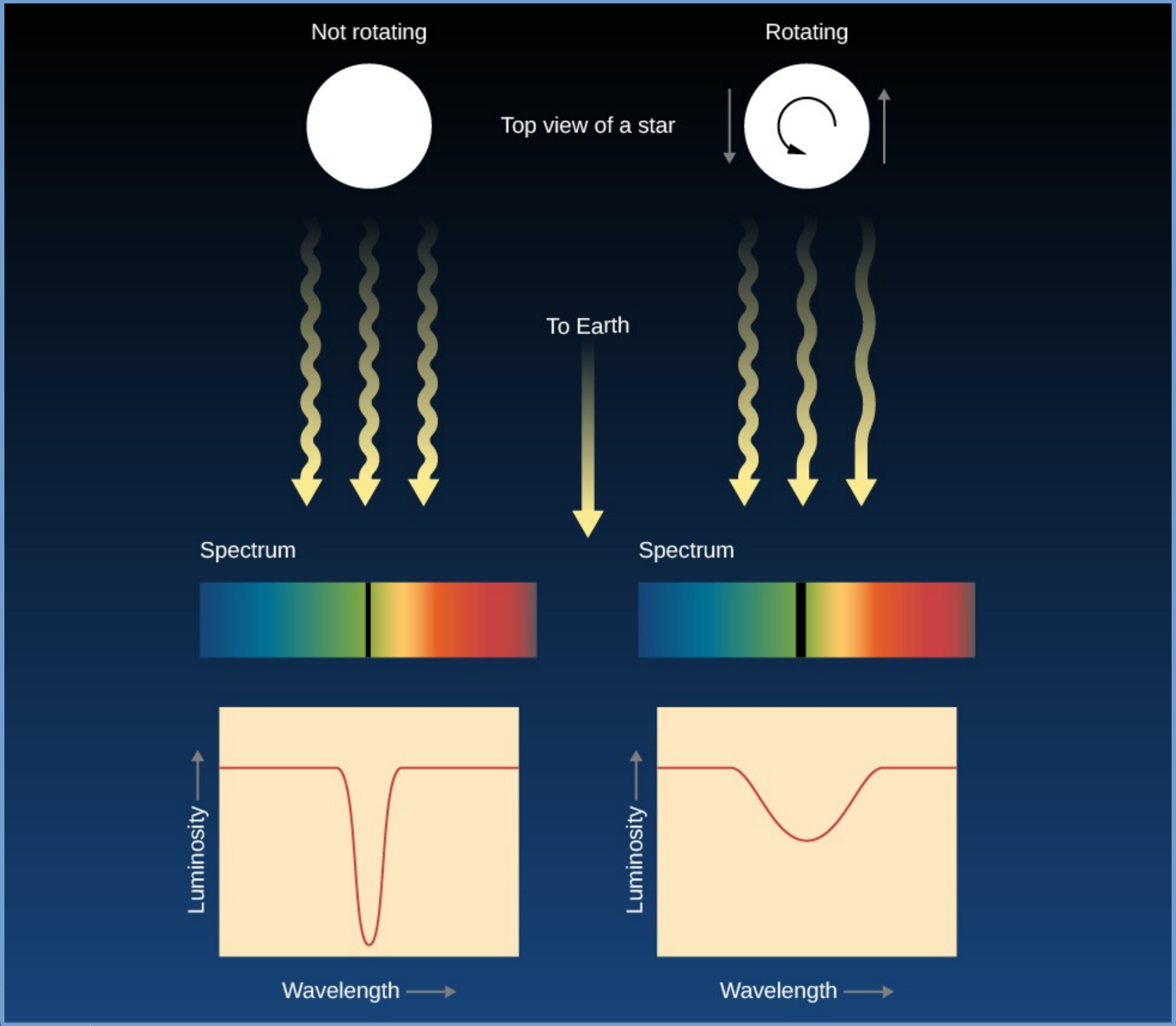

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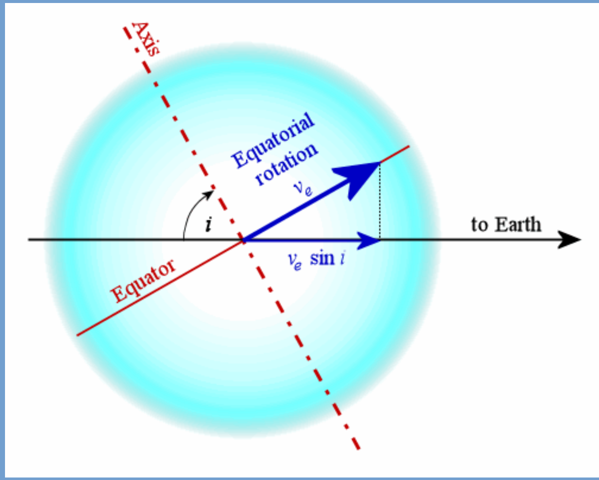
inclination?

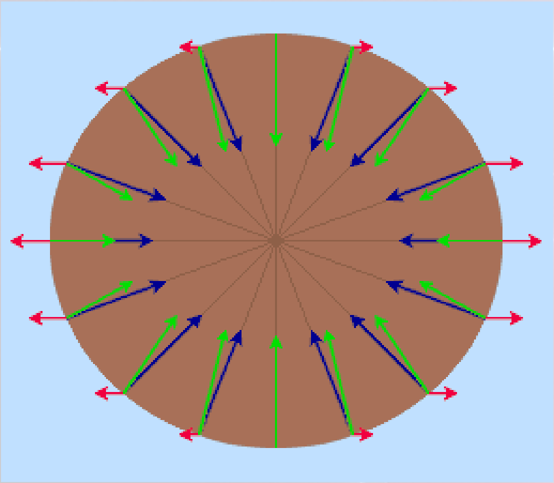


v*sin(i)
("projected rotational velocity")

Theoretically considered:

Rotation can effect the structure

- centrifugal force
  - oblate shape
  - extra mixing inside!



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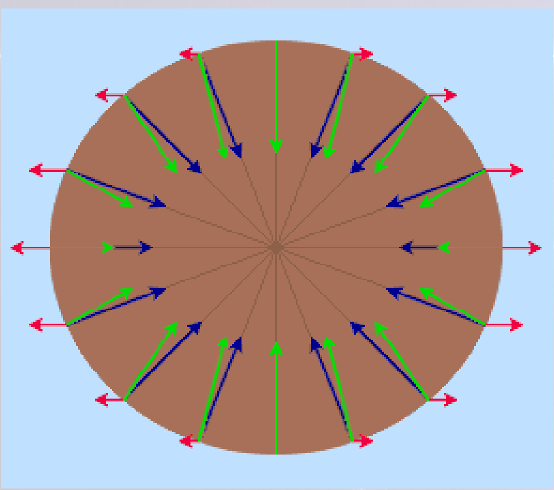
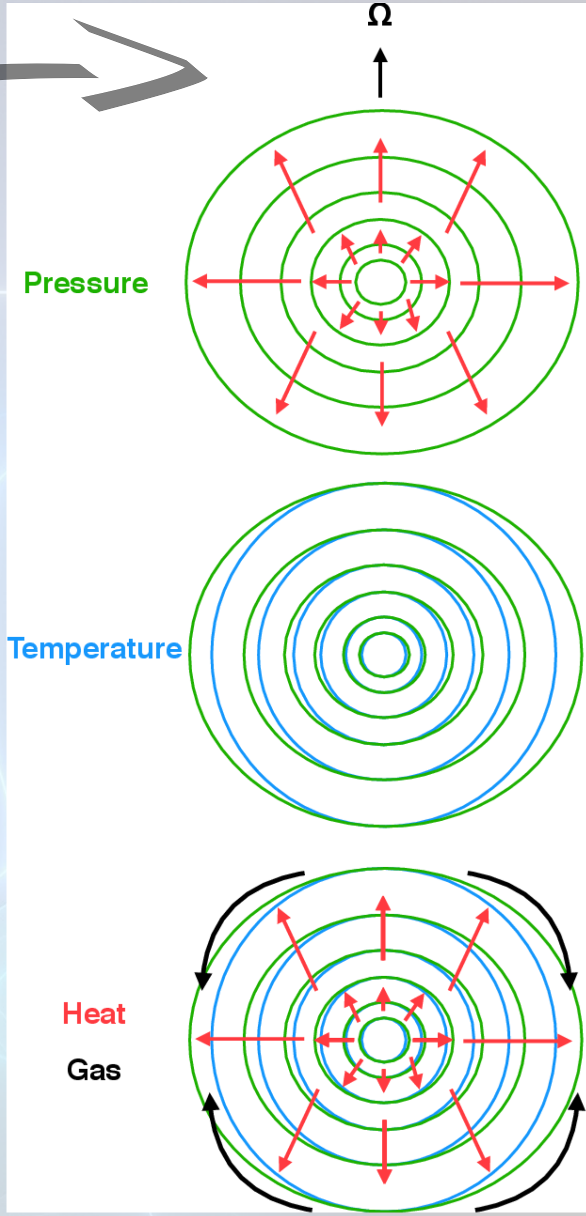


Credit: Jermyn+18



Theoretically considered:

Rotation can effect the structure

- centrifugal force
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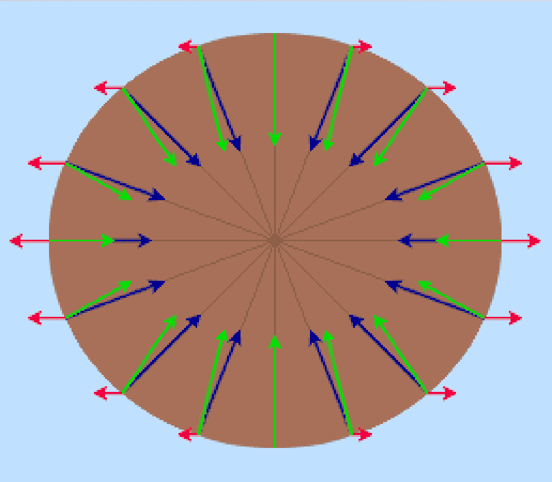
  - extra <u>mixing</u> inside!
- extreme case:
  - "break-up" rotation
    "critical rotation"
  - $F_{cen} \geq F_{grav}$
    "Keplerian break-up frequency"
  - leads to extra mass los
  - mass dependent
    e.g. "B[e] star" phenomenon



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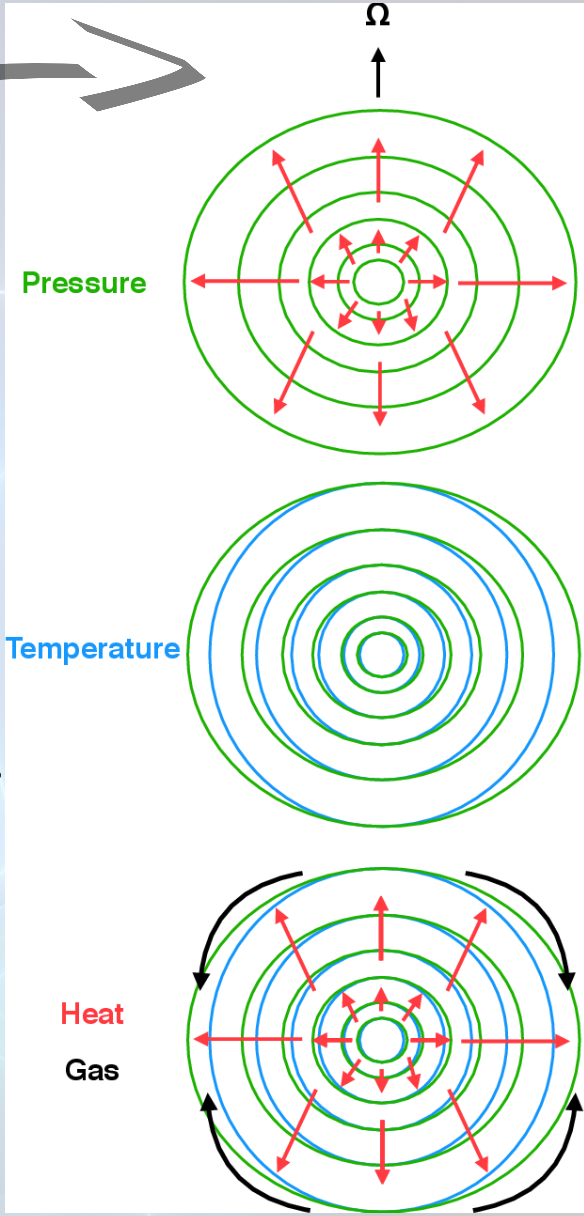

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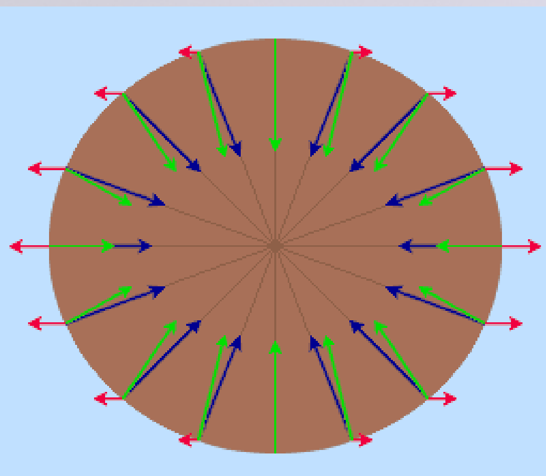

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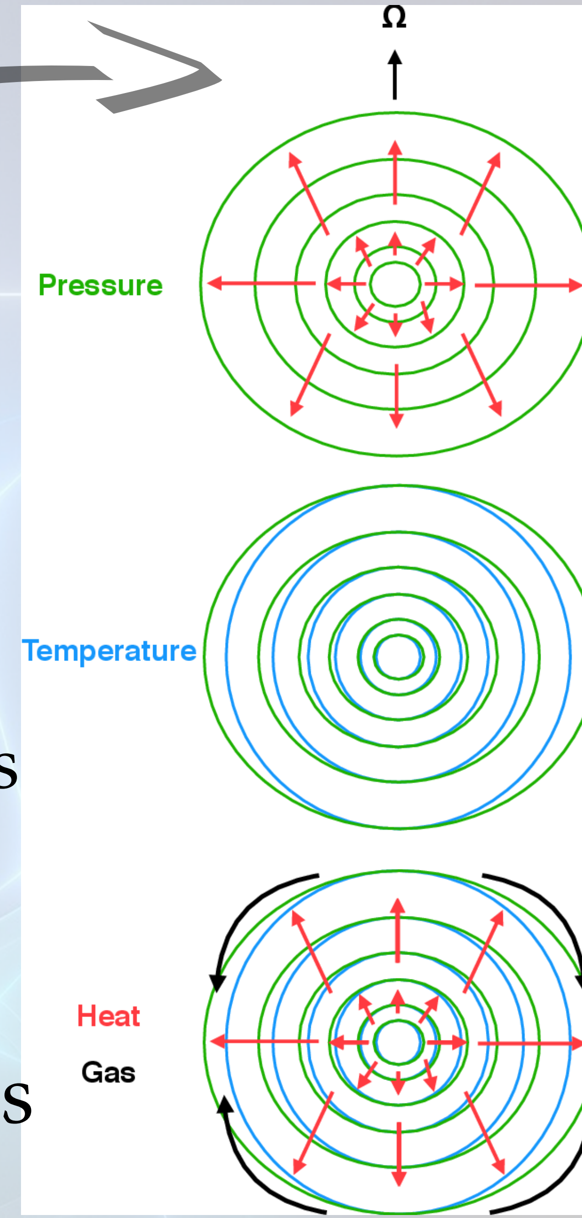
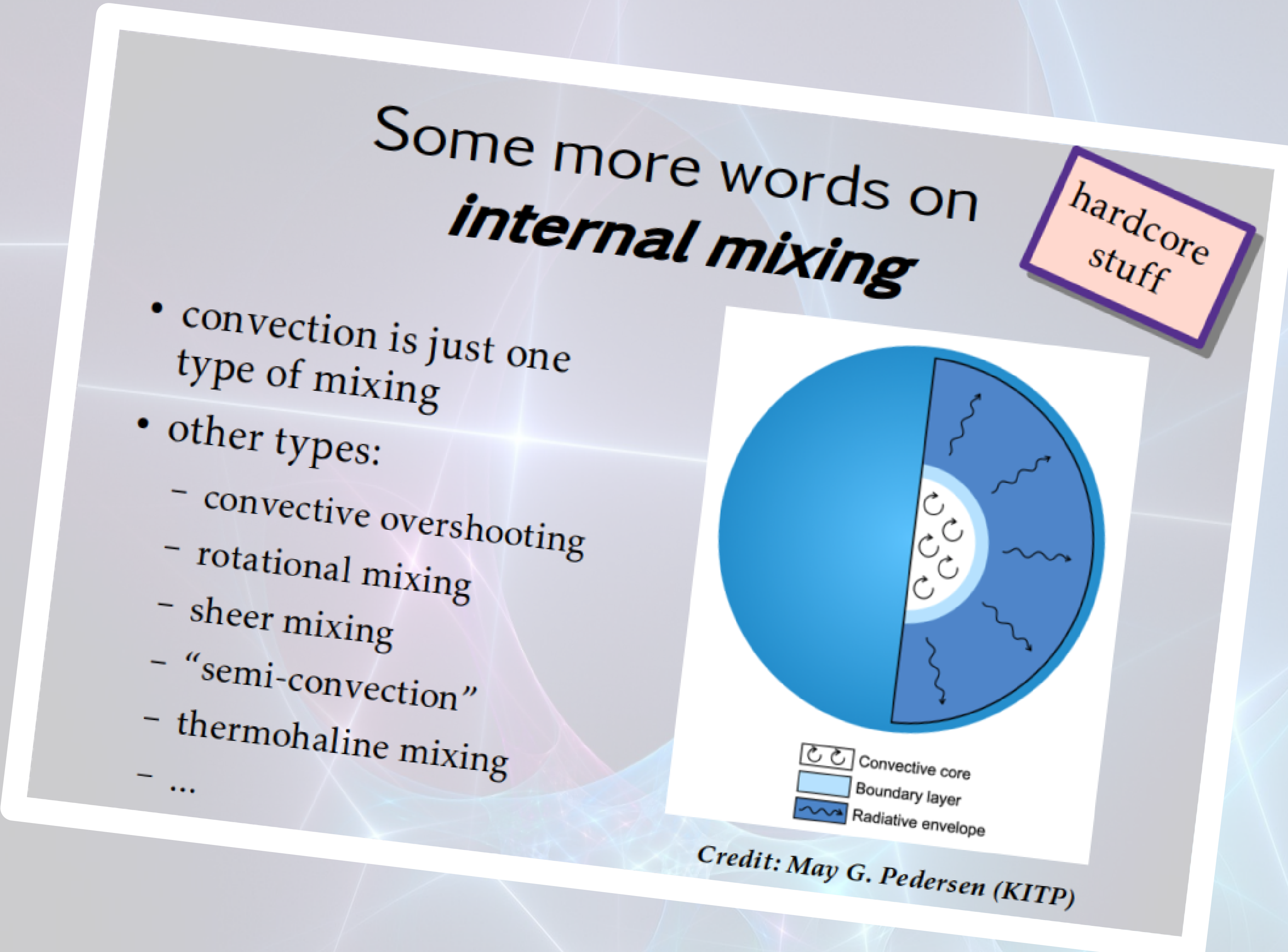


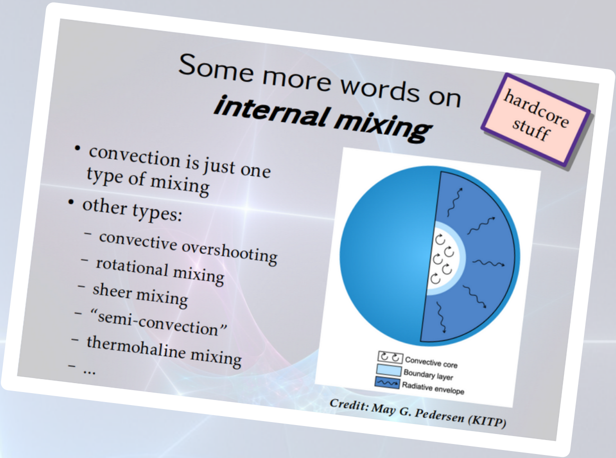
- non-extreme case: mixing & mass loss

Rotational <u>mixing</u>

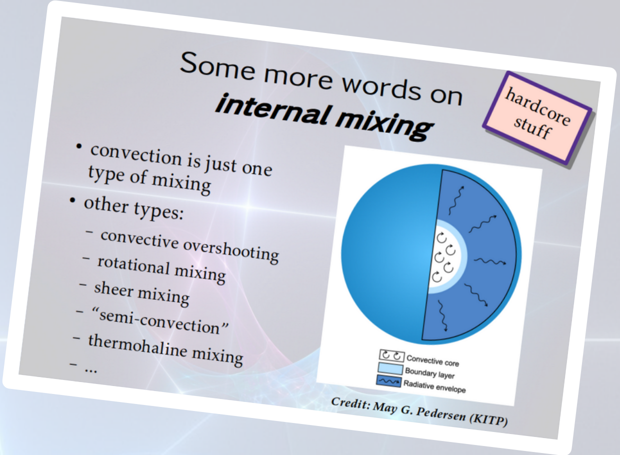
Rotational <u>mixing</u>

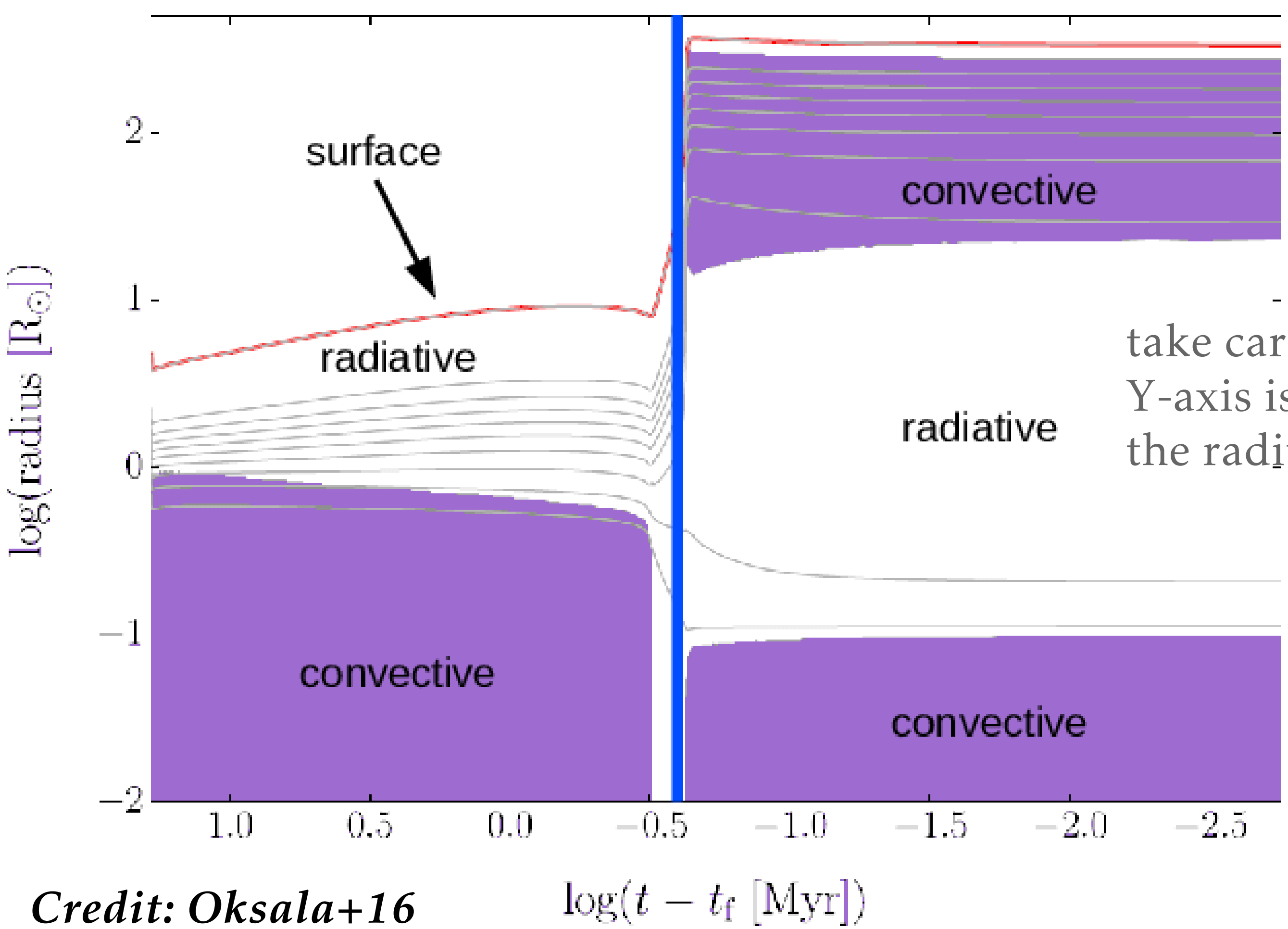


Rotational <u>mixing</u>



Rotational mixing

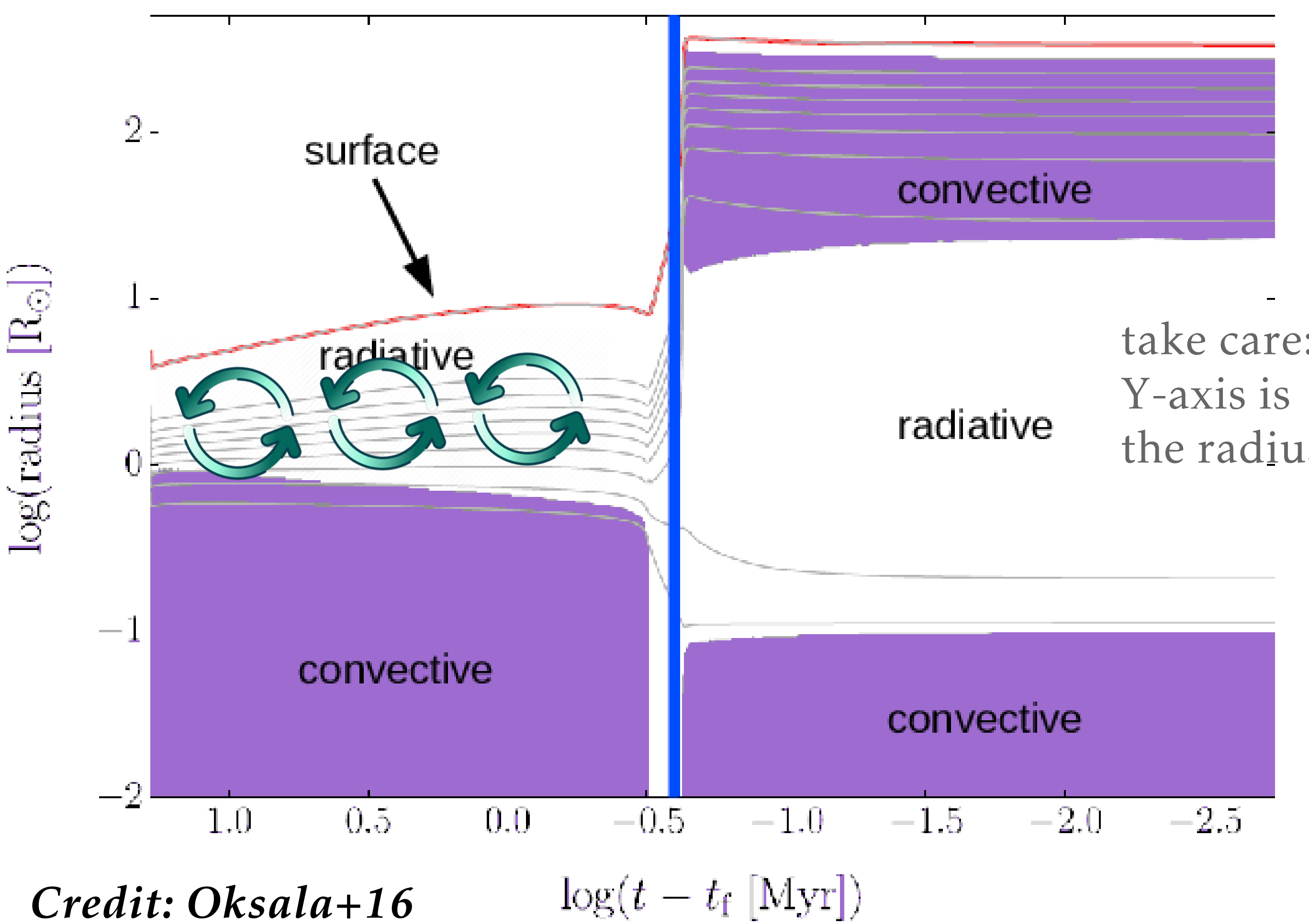




take care:
Y-axis is
the radius!

Credit: Oksala+16

Rotational mixing



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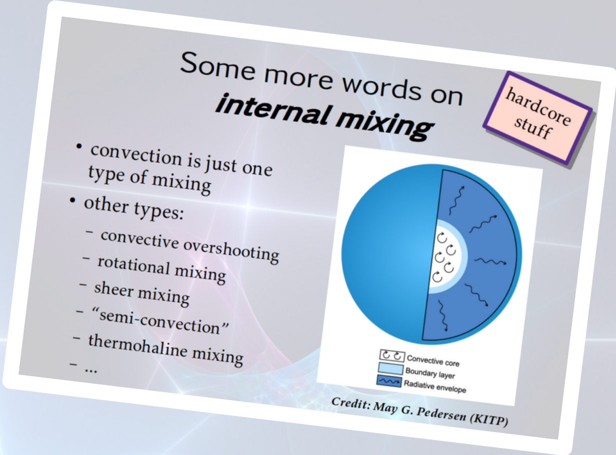

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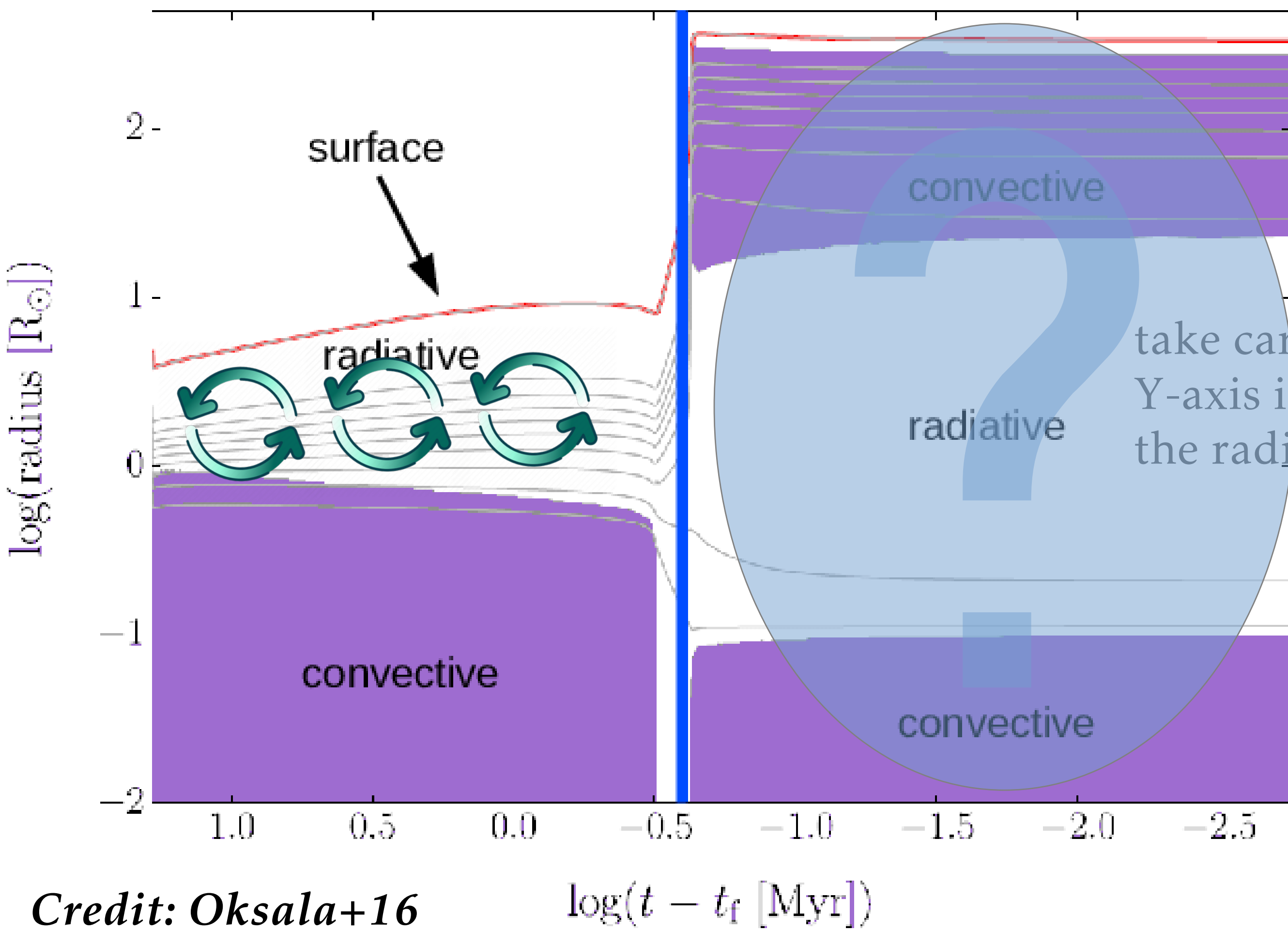

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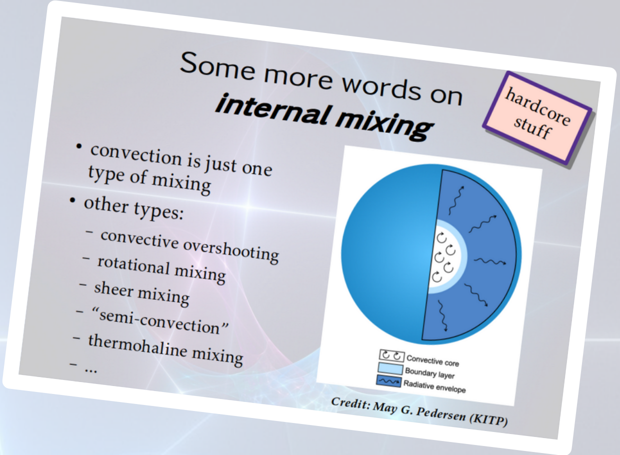
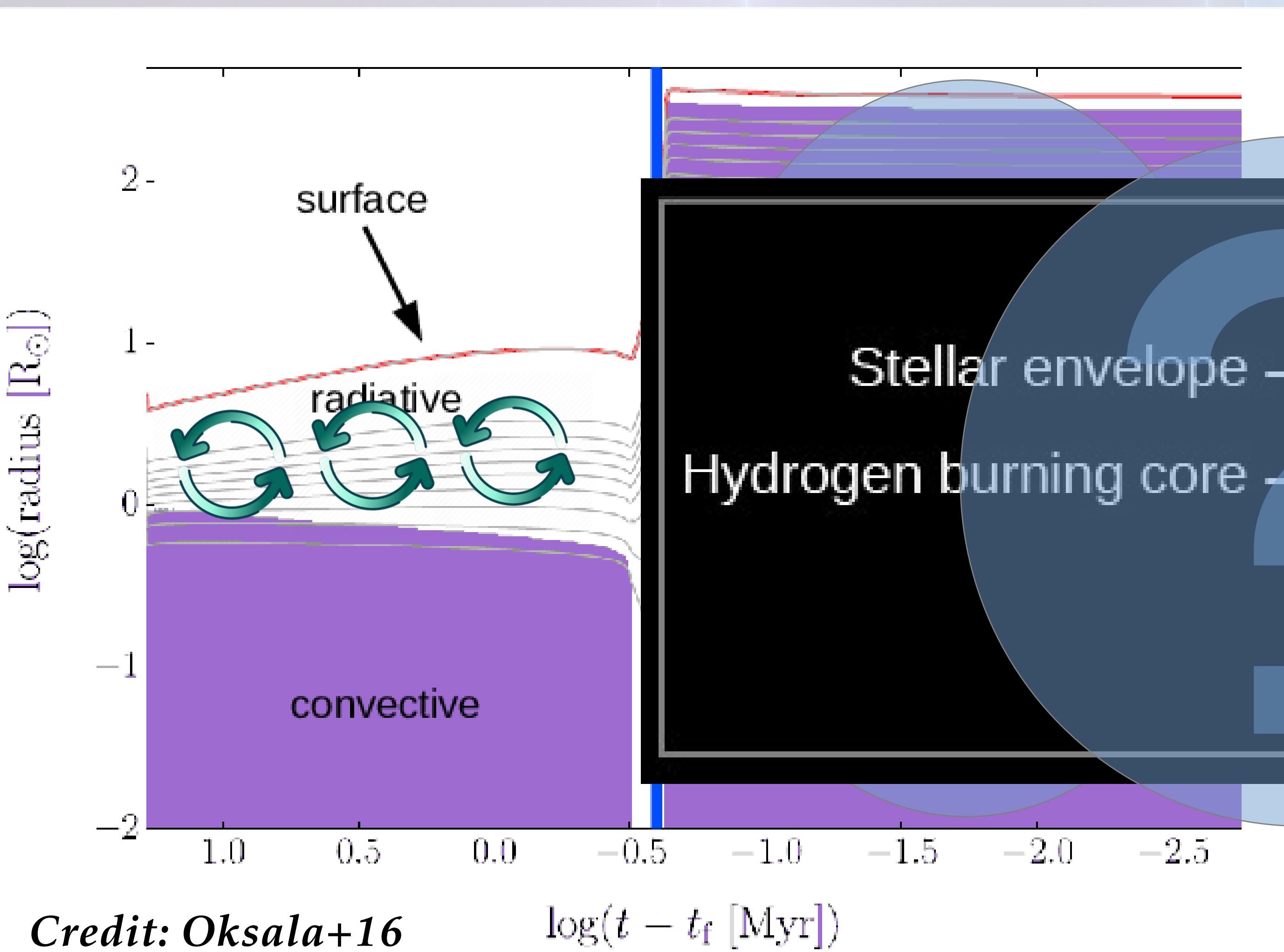


Rotational mixing



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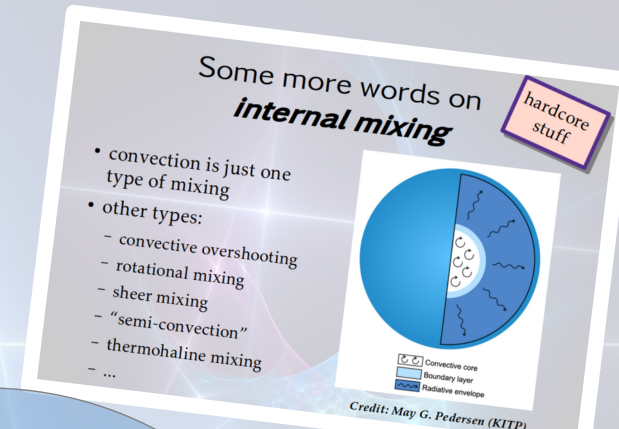
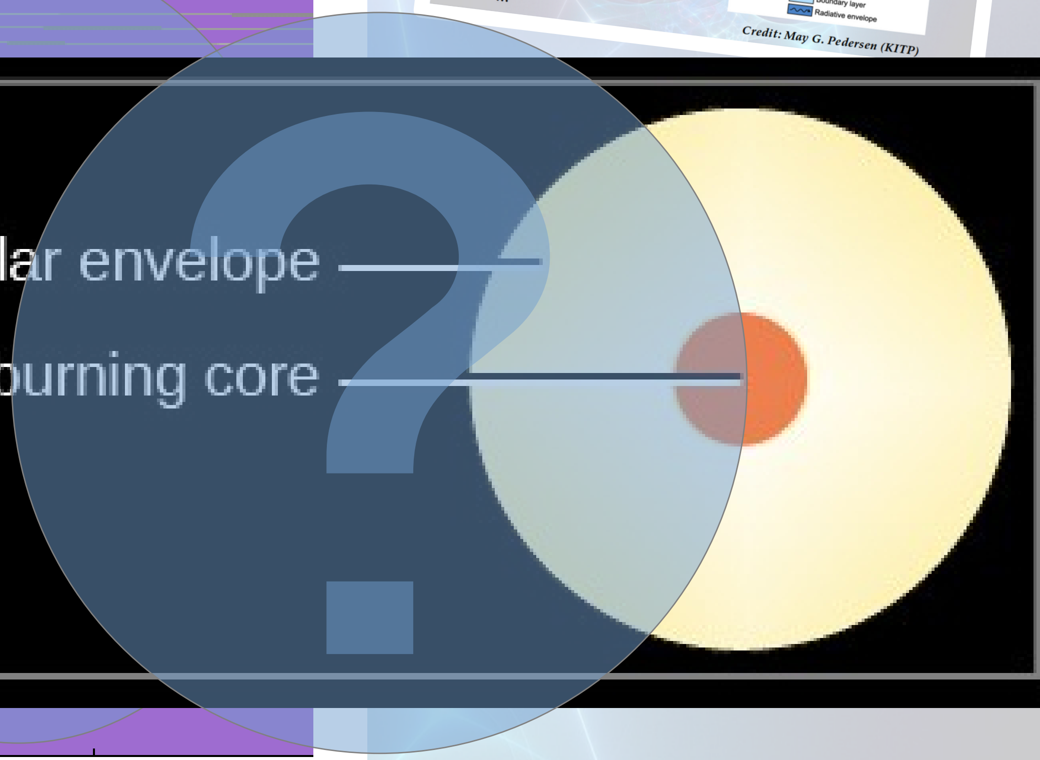
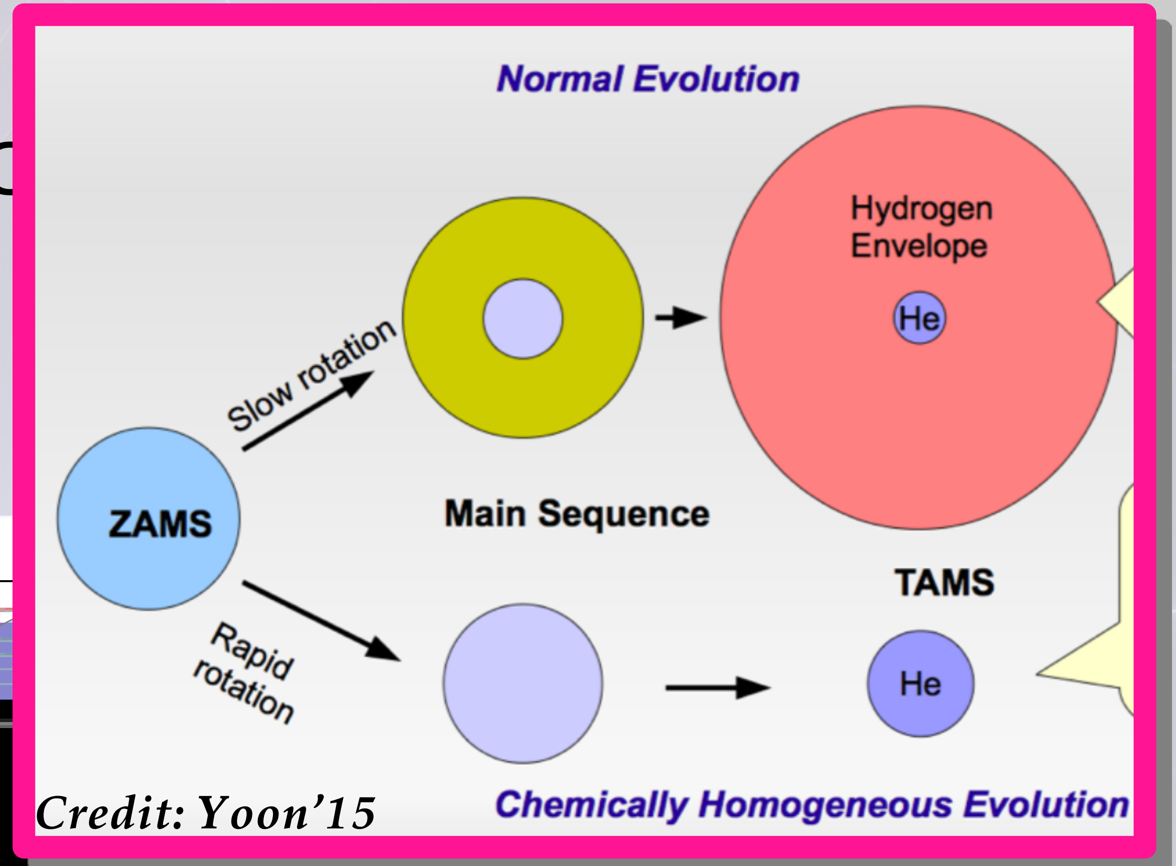
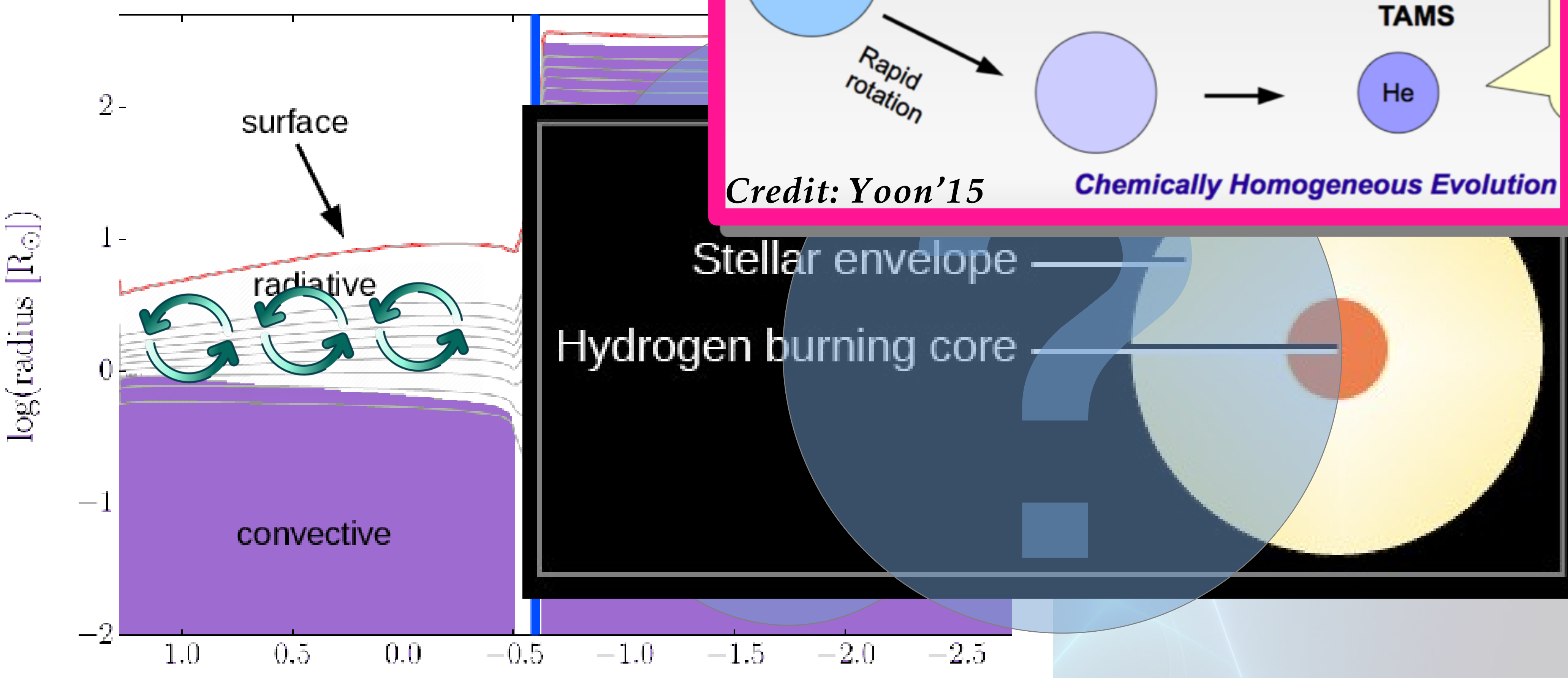




Rotatio



Credit: Yoon'15

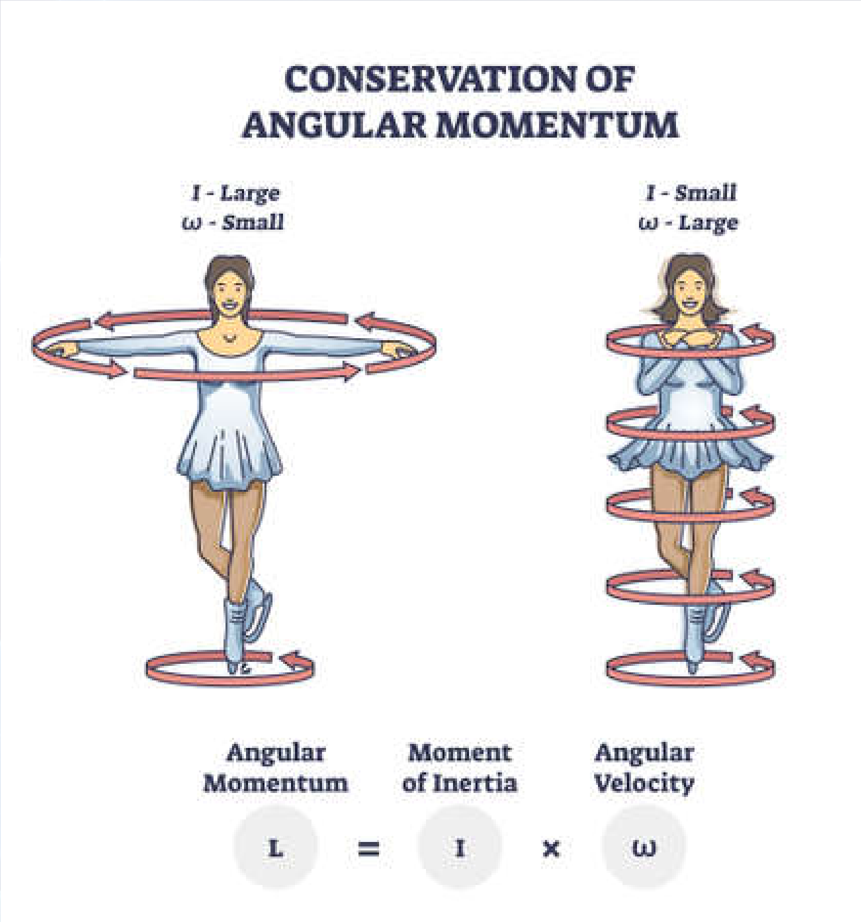


$\log(t - t_f\ [\mathrm{Myr}])$

Credit: Oksala+16

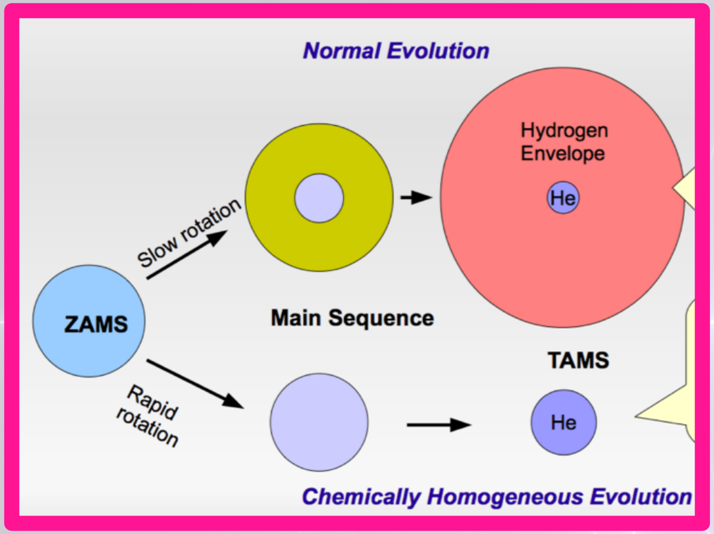
But: metallicity is important

- metallicity   mass loss
  - high Z → high dM/dt
- mass loss → angular momentum loss
- rotational mixing becomes important at lower metallicities
  - Solar Z: fast spin-down



Chemically homogeneous evolution

= *Quasi-chemically homogeneous evolution*



In the Hertzsprung–Russell diagram?

Credit: M. Cantiello

Chemically homogeneous evolution

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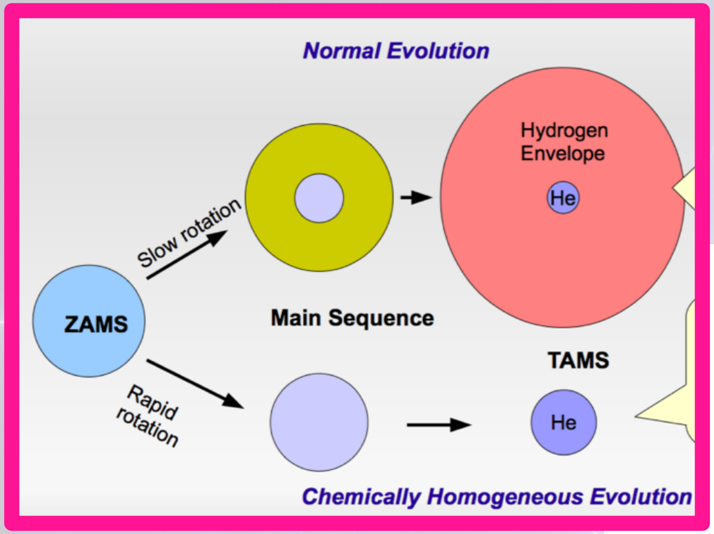

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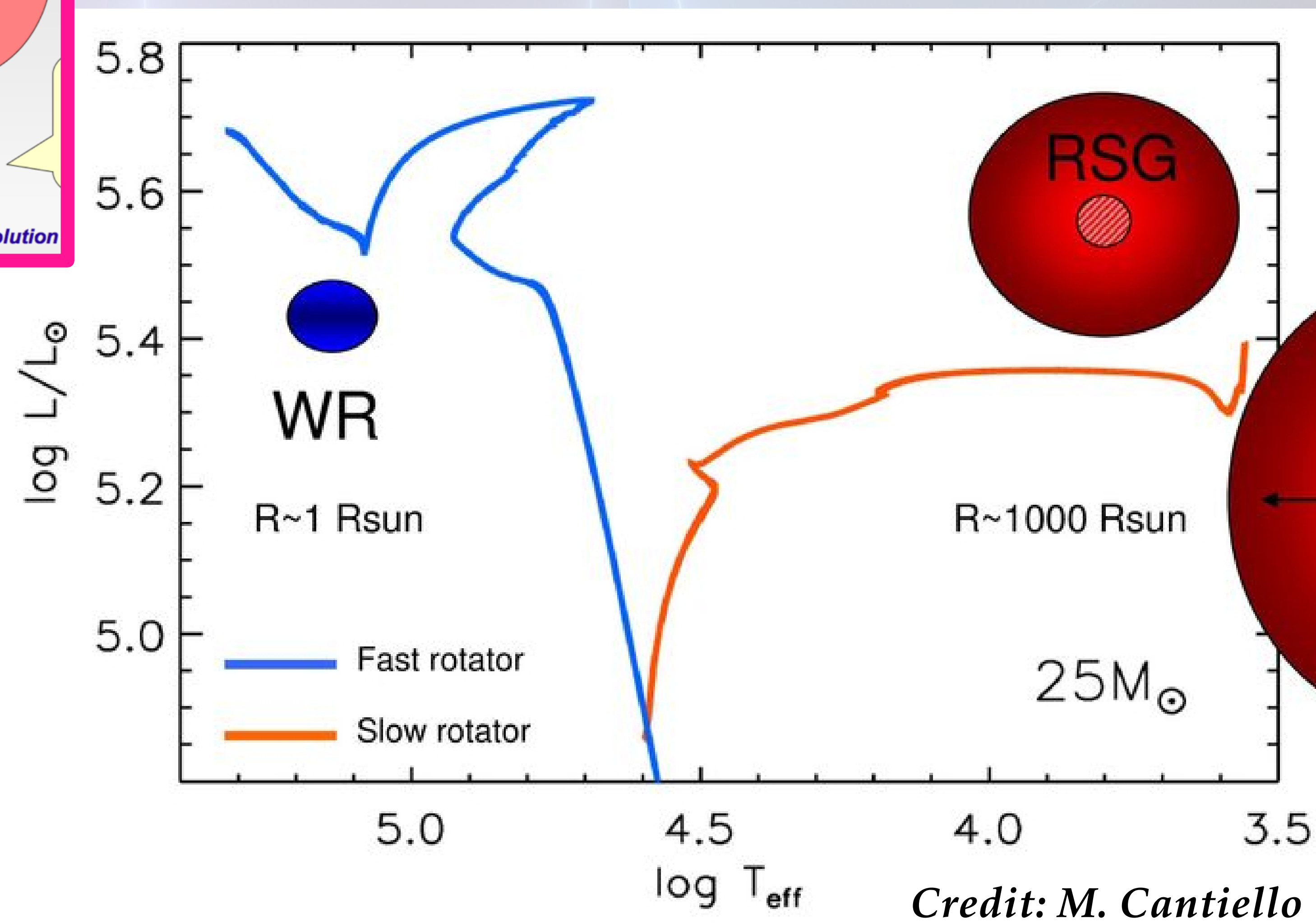

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Chemically homogeneous evolution

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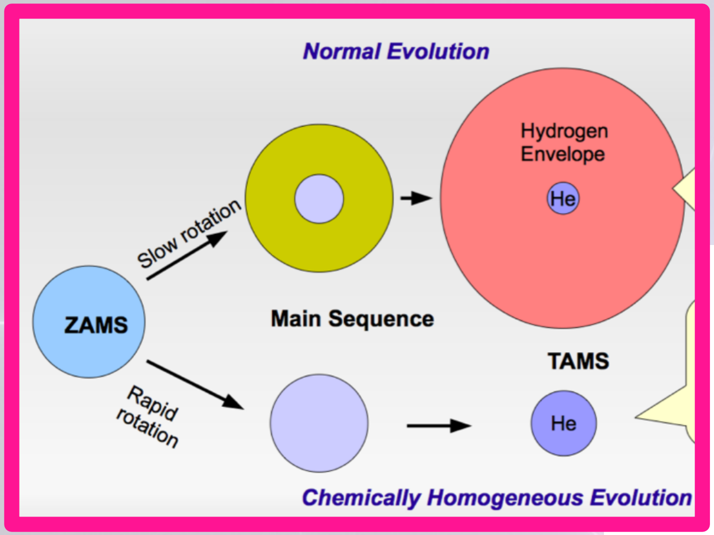

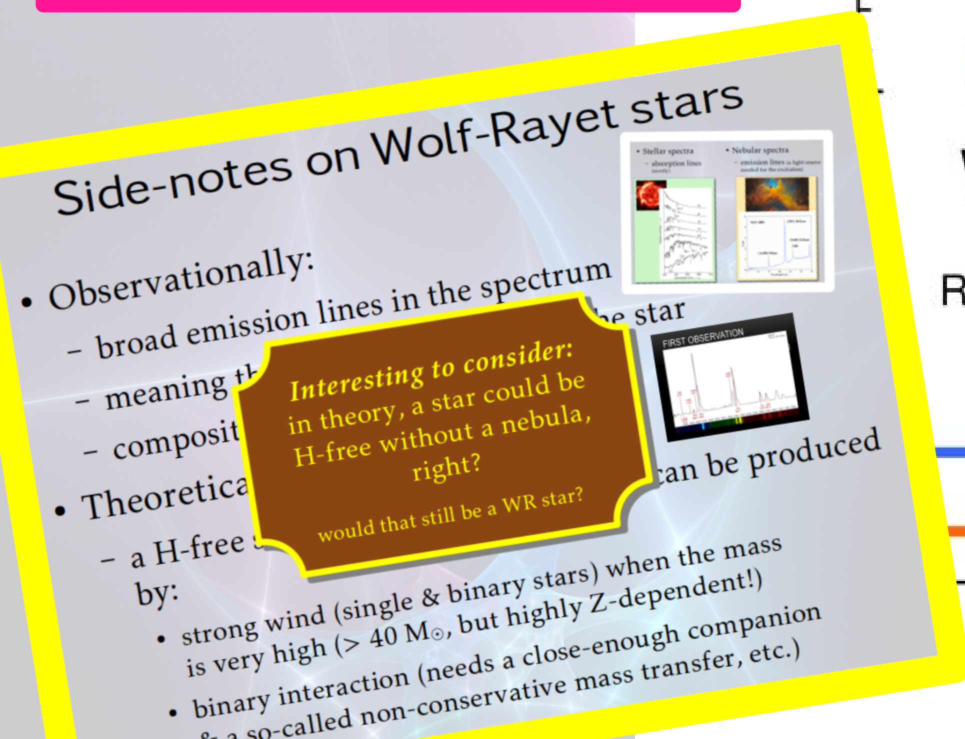

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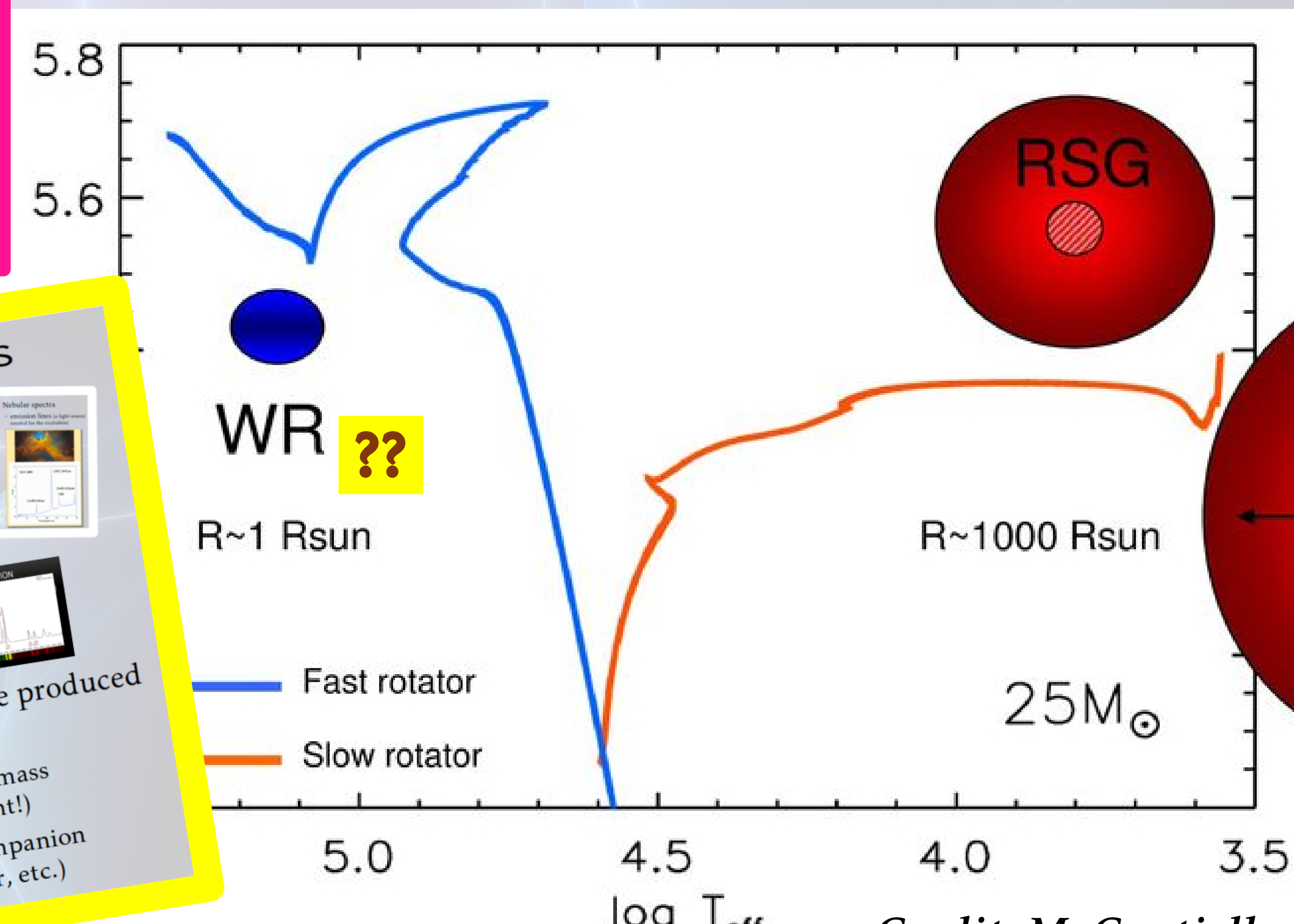

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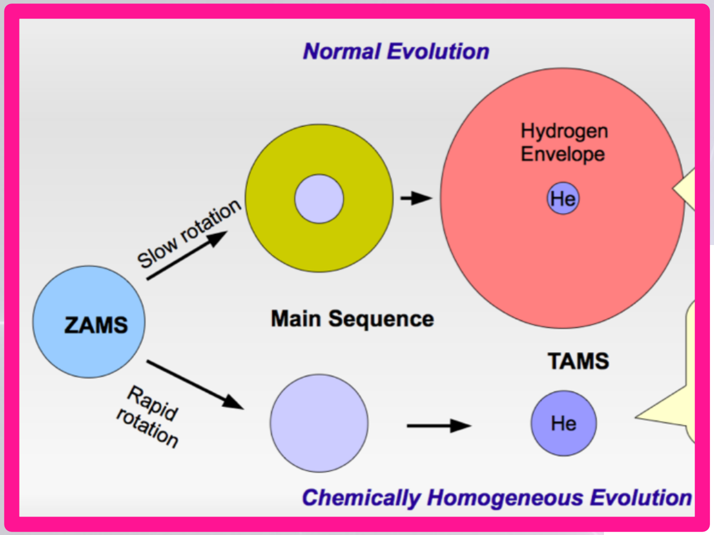

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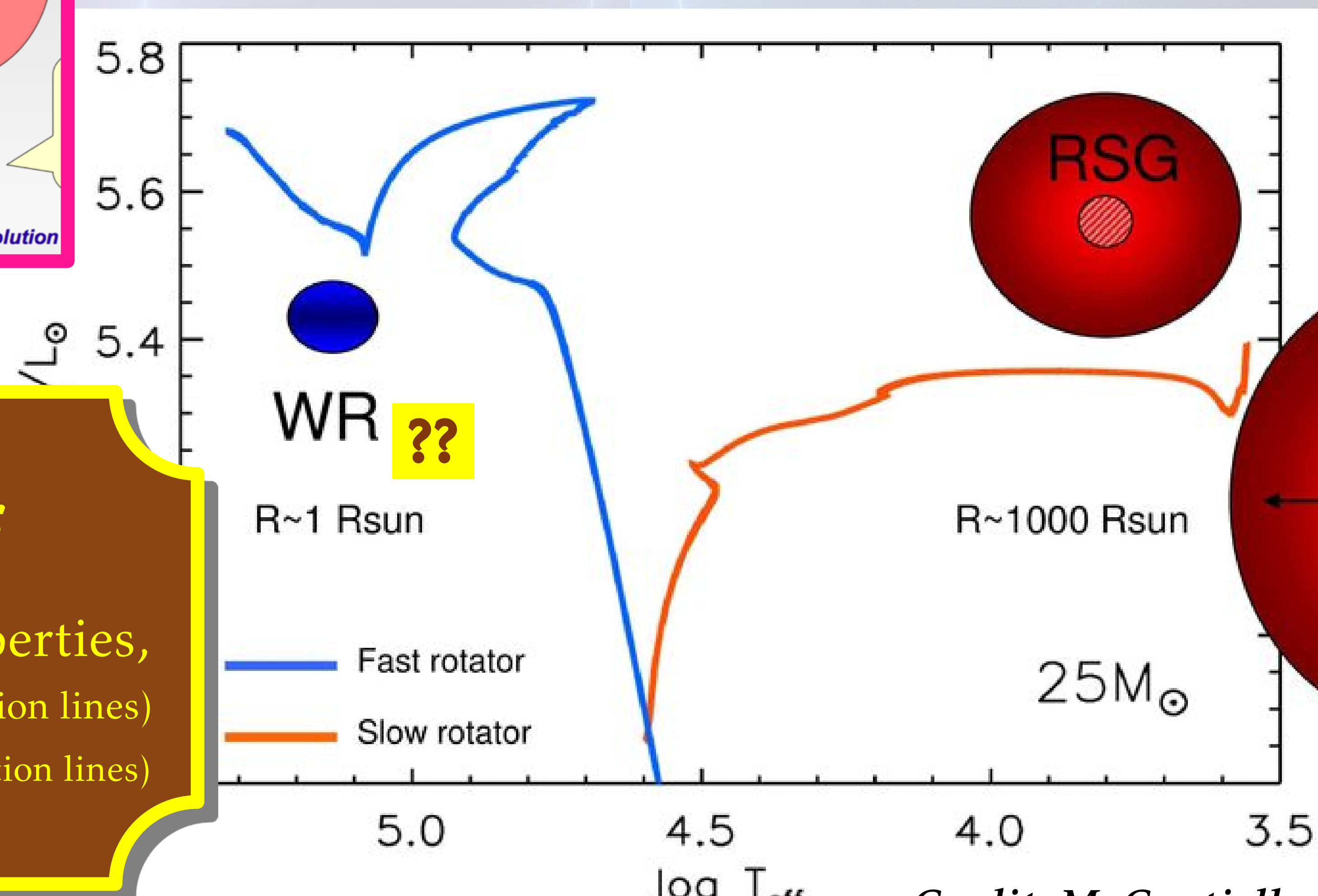


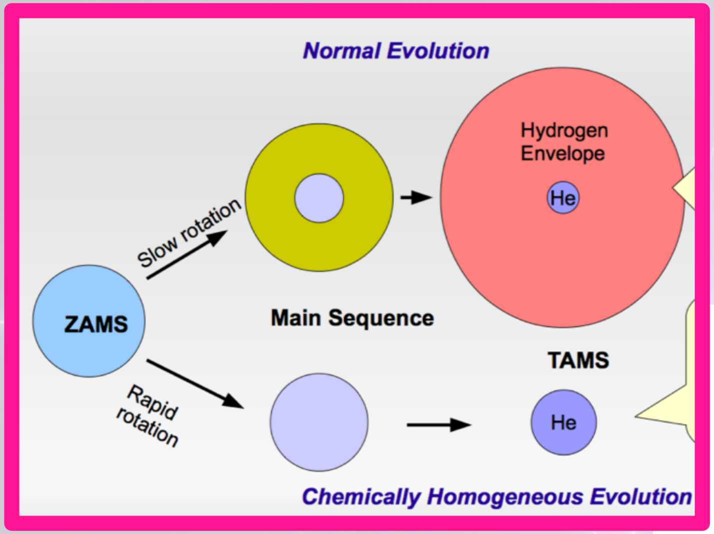
a hot, He-rich star

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

Credit: M. Cantiello

Chemically homogeneous evolution

= *Quasi-chemically homogeneous evolution*



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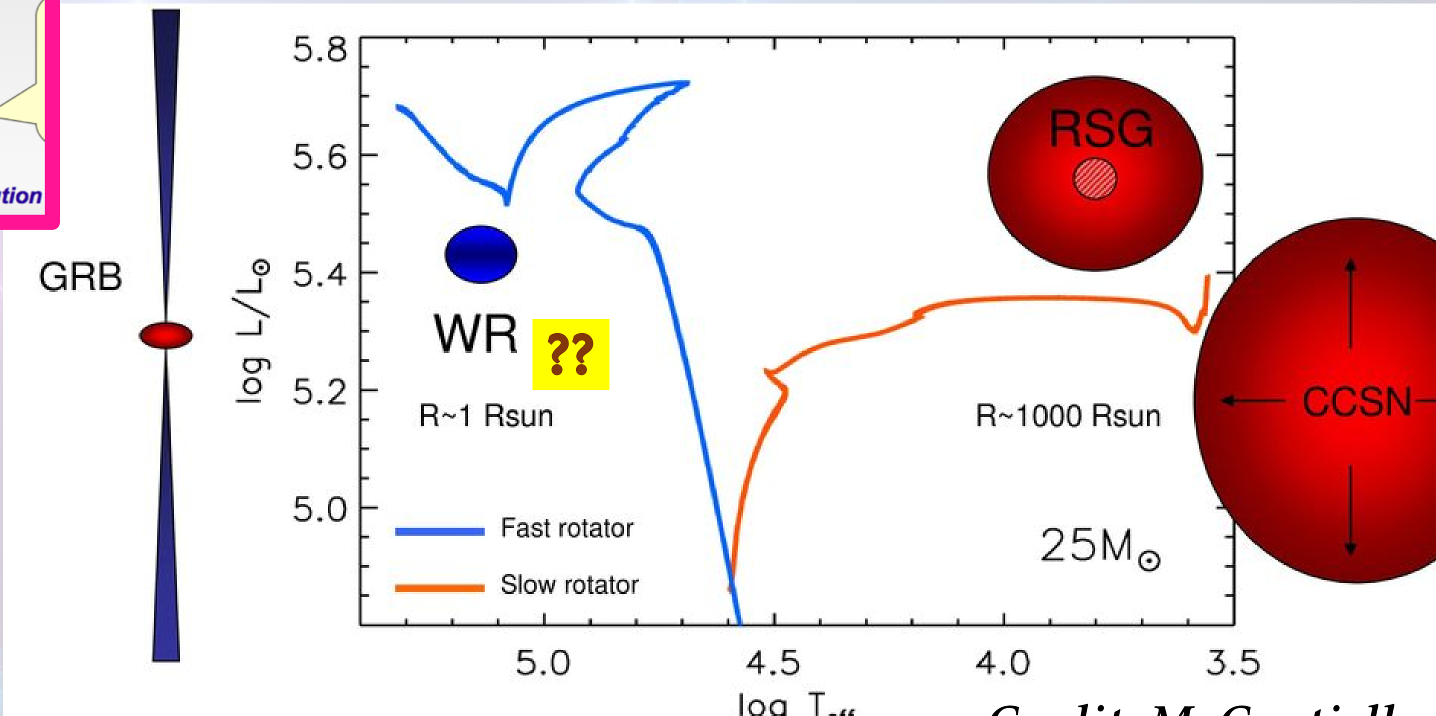


Credit: M. Cantiello

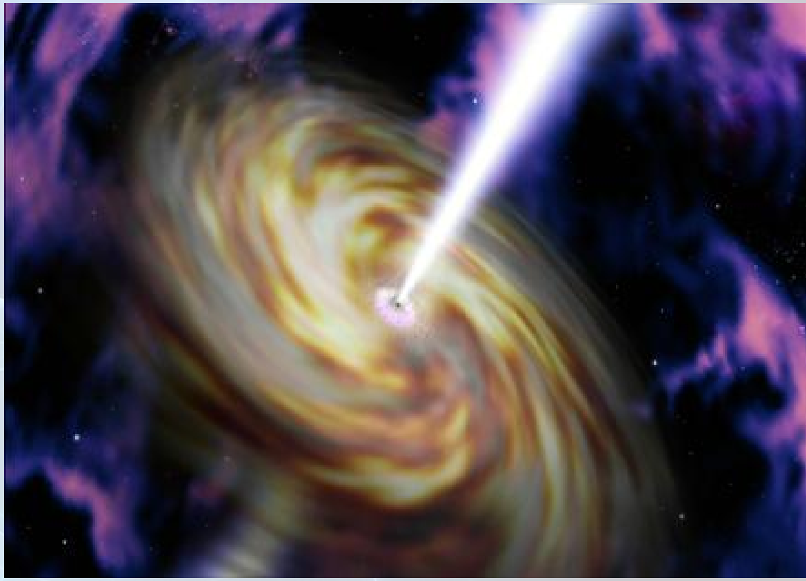
Type of final explosion?

type Ib/Ic
(core collapse)

but ROTATING!!

Collapsar

- "core collapse" ≠ "collapsar"



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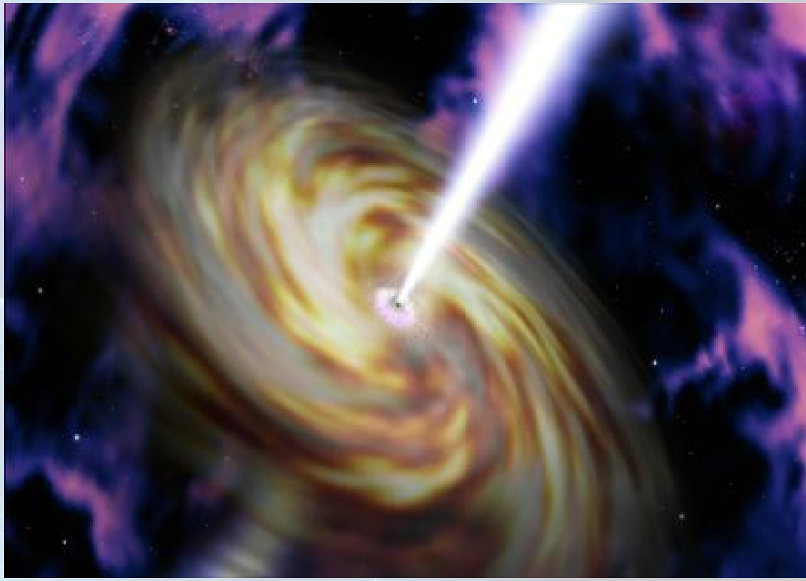

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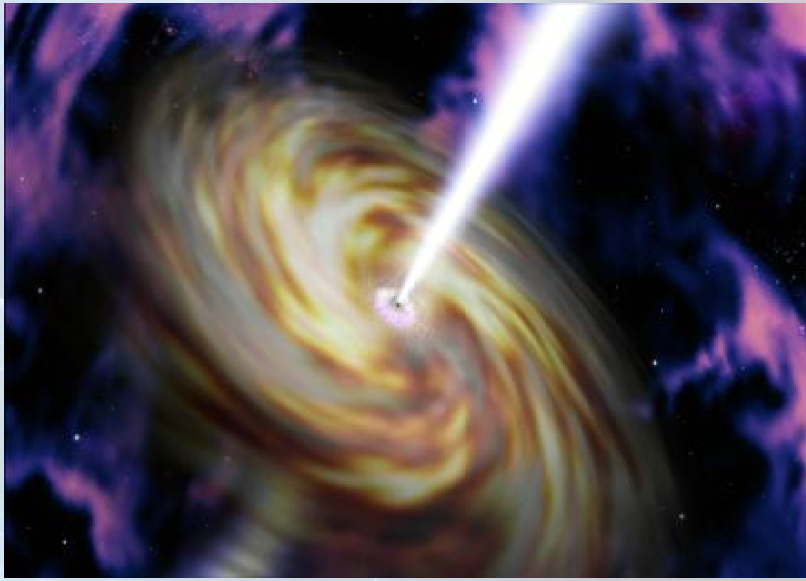
A BH or a NS forms in the middle. The proto-NS is probably highly magnetized.



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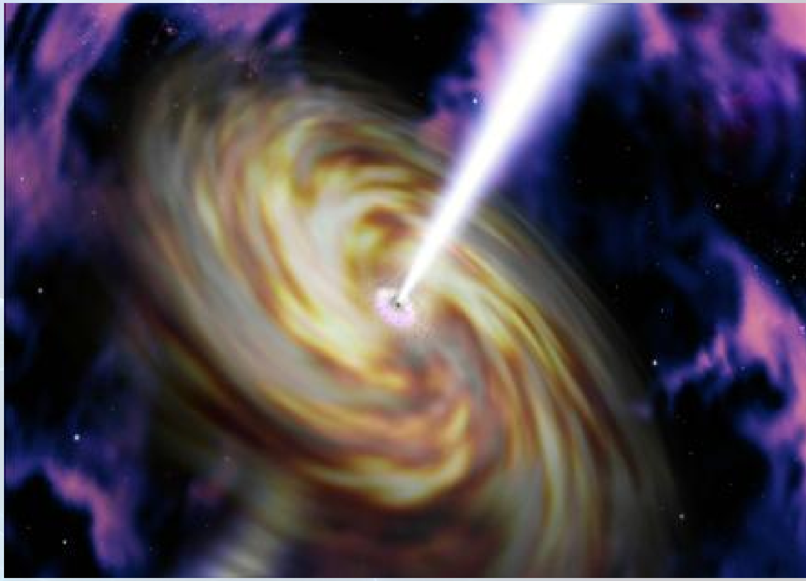

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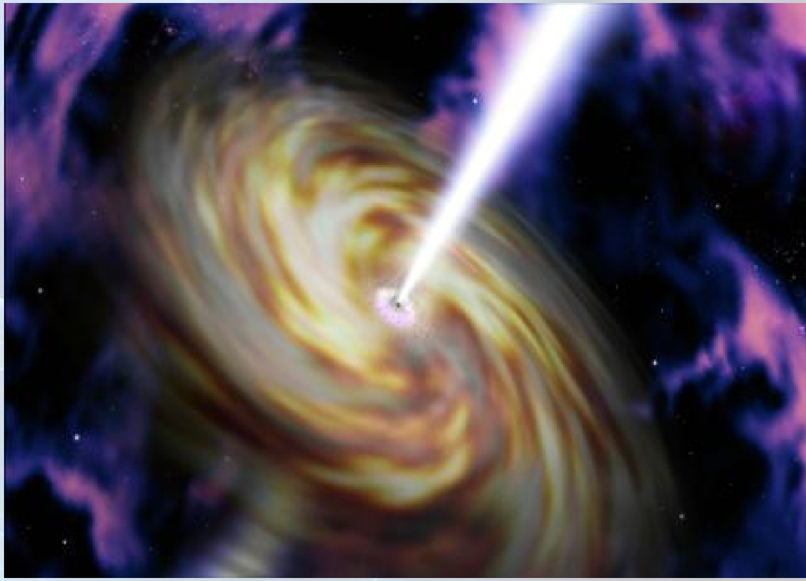

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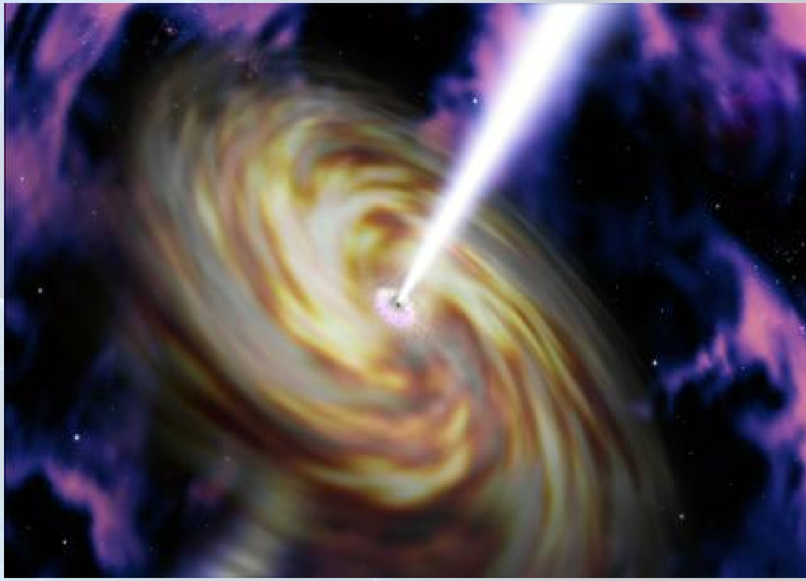

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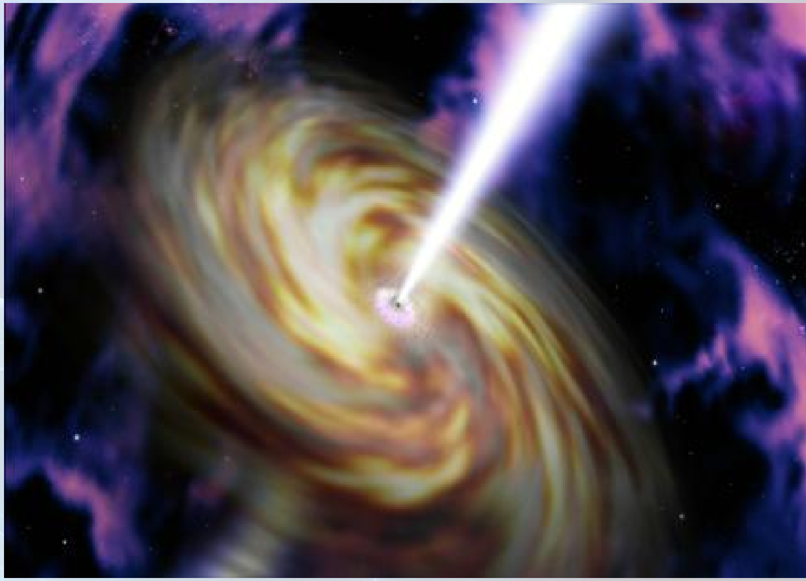
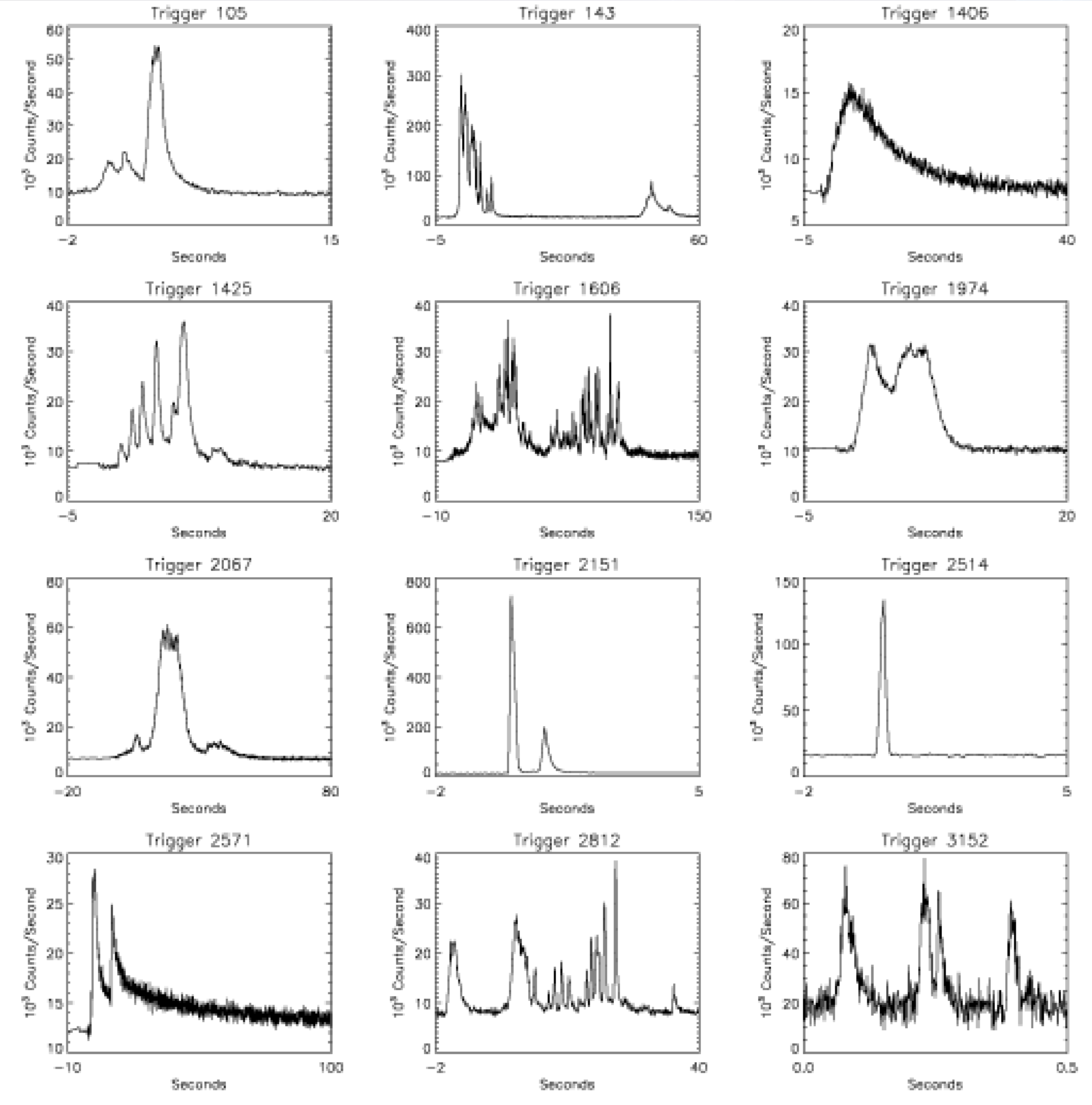


What are GRBs?

Observationally...



– during the cold war…

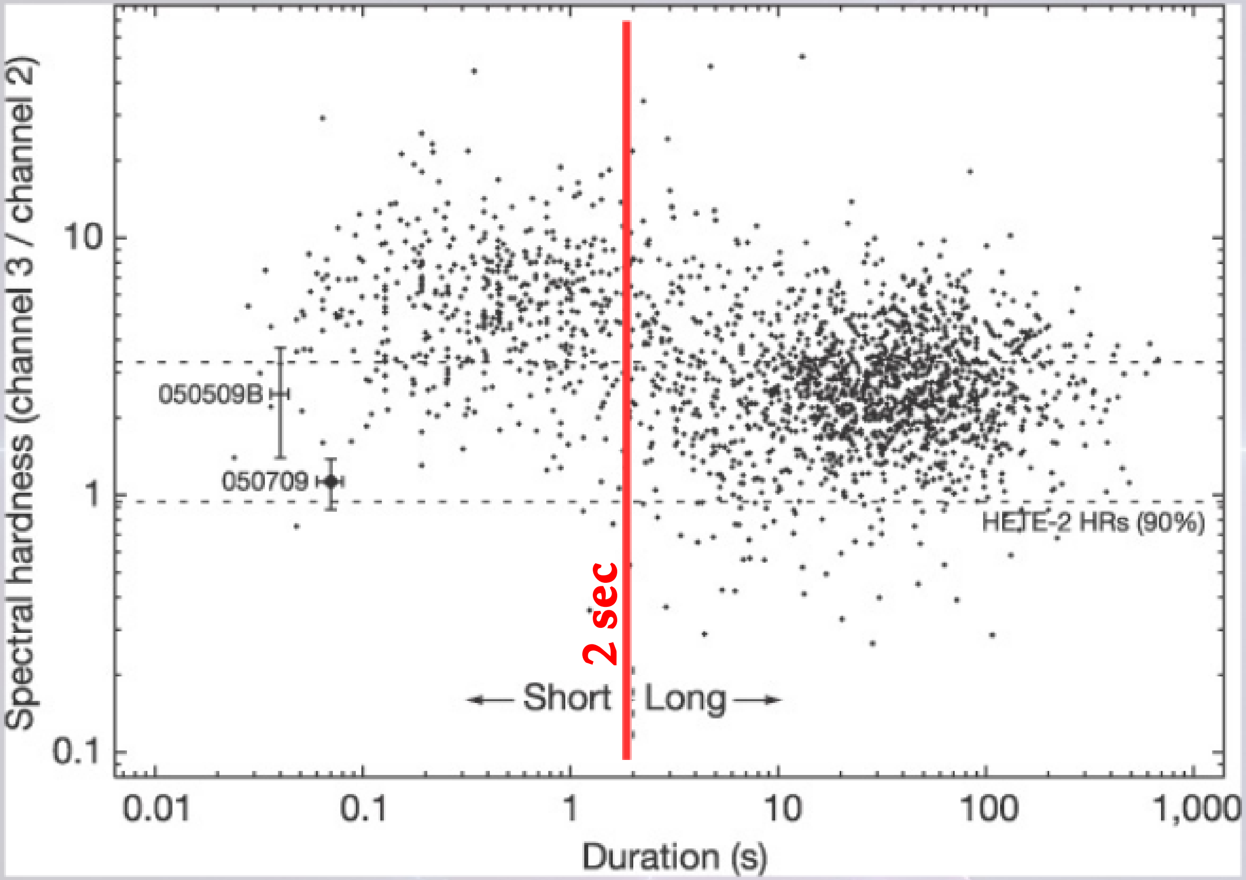
– today: satellite missions
e.g.:
Fermi Gamma-ray Space Telescope
Neil Gehrels Swift Observatory etc.

– 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

At least two, physically distinct types of objects



Credit: Hjorth+2005

Long/soft:

Massive Stars at collapse

Short/hard: two Compact Objects at merger

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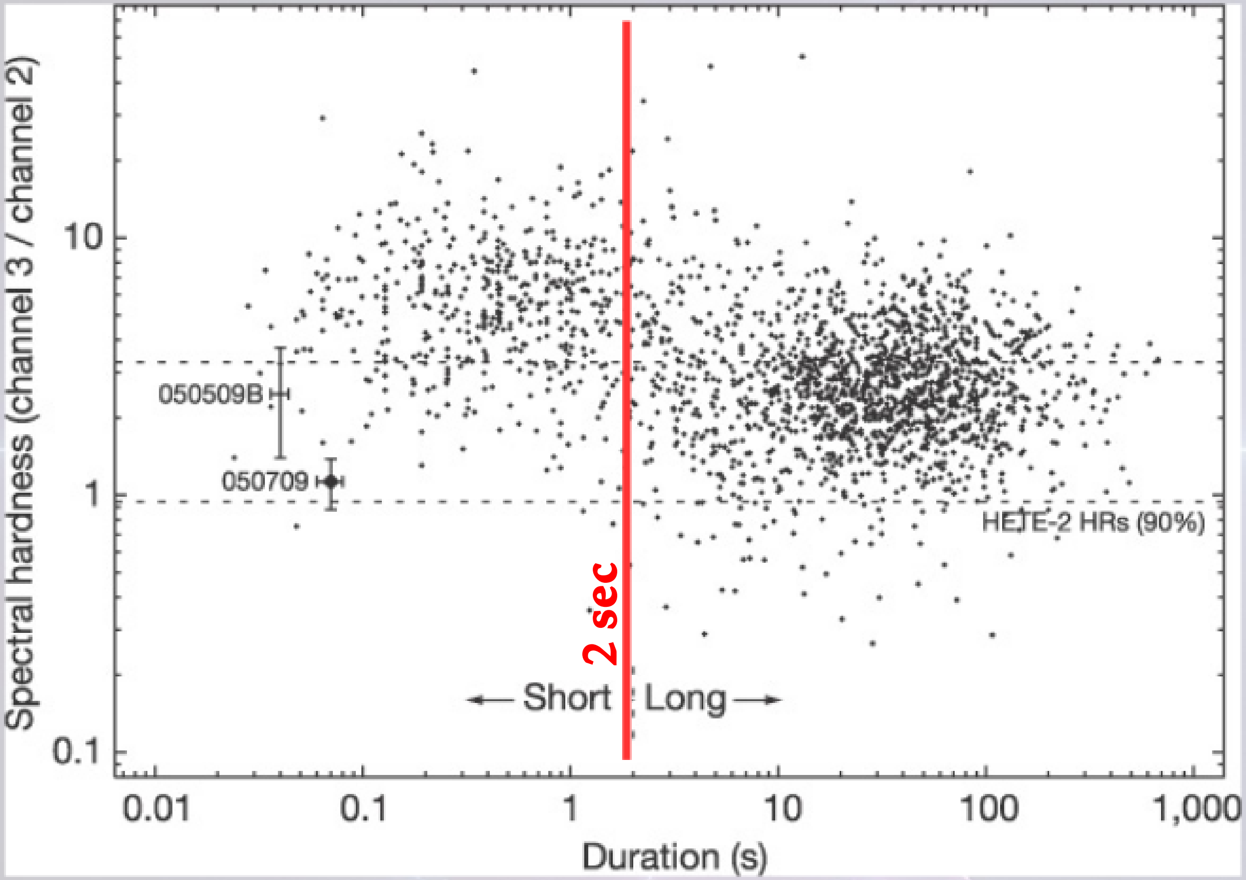

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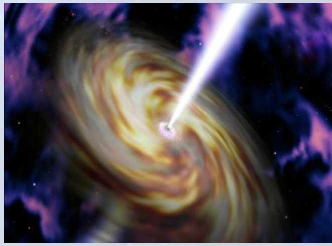

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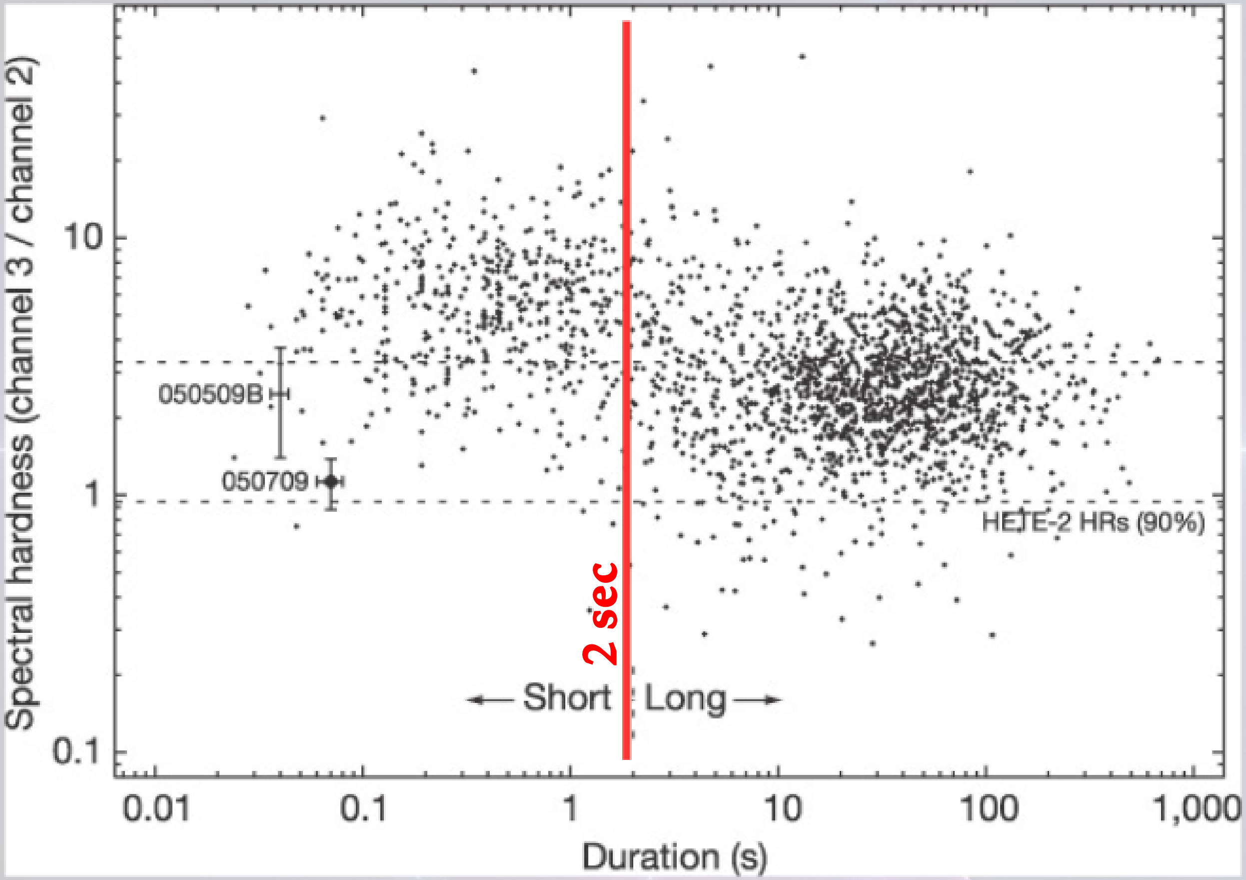

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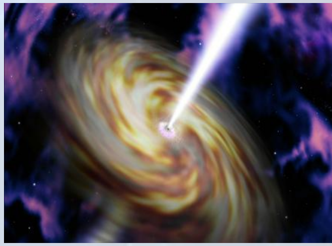

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binarity!

GWs!

→ sub-Solar metallicities? ✓

→ fast-rotating stars? ✓

→ stars in a binary system?

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- especially relevant at low Z (cf. the balerina)

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- might lead to chemically homogeneous evolution
  - if so: the star becomes a hot He-star (WR??)
  - if it survives until Fe-core, dies as a collapsar → L-GRB + SN Ib/c

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→ stars in a binary system? **Coming soon…**

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REMINDER

REMINDER: Exam & grading

Oral examination.
Assessment criteria:

- fail: below 50 pts (below 50%)
- satisfactory: 50 pts (50%)
- satisfactory plus: 60 pts (60%)
- good: 70 pts (70%)
- good plus: 75 pts (75%)
- very good: 80 pts (80%)

Extra options...

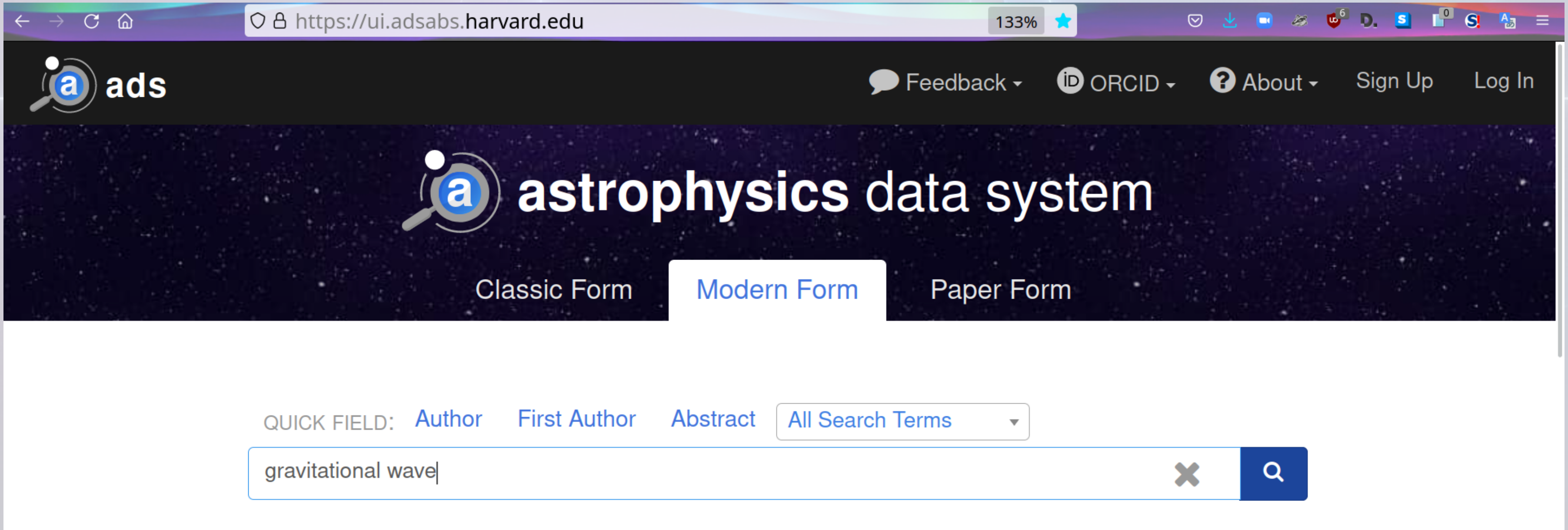
- active participation*: +20%
- paper presentation**: +40%

*asking questions during class, thinking out loud, showing interest

**chosing a GW-related paper from arXiv/ADS (accepted for publication after 24.01.2022) and giving a "journal club" style presentation (with slides) of ~30 min

Where to find the relevant papers?

- NASA ADS: https://ui.adsabs.harvard.edu/



- arXiv: https://arxiv.org/ (preprints...)

What is expected?

- 20 minutes + discussion

- WHICH MEANS:
  - don't need to explain the whole paper!!
  - explain what's in the **abstract** & main **conclusion**
  - show **1 figure** (the most important or interesting)

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  - explain what's in the **abstract** & main **conclusion**
  - show **1 figure** (the most important or interesting)
  - make it understandable & exciting
    - don't just boringly list the results
    - instead: build a ***narrative***

Tell a story!

A list of suggested examples

- But feel free to choose anything else you like!

Finke et al.: Modified gravitational wave propagation and the binary neutron star mass function
https://ui.adsabs.harvard.edu/abs/2022PDU....3600994F/abstract

Perna et al.: Host galaxies and electromagnetic counterparts to binary neutron star mergers across the cosmic time: detectability of GW170817-like events
https://ui.adsabs.harvard.edu/abs/2022MNRAS.512.2654P/abstract

Gao et al.: A higher probability of detecting lensed supermassive black hole binaries by LISA
https://ui.adsabs.harvard.edu/abs/2022MNRAS.512....1G/abstract

Rizzuto et al.: Black hole mergers in compact star clusters and massive black hole formation beyond the mass gap
https://ui.adsabs.harvard.edu/abs/2022MNRAS.512..884R/abstract

Mapelli et al.: The cosmic evolution of binary black holes in young, globular, and nuclear star clusters: rates, masses, spins, and mixing fractions
https://ui.adsabs.harvard.edu/abs/2022MNRAS.511.5797M/abstract

Korol et al.: Observationally driven Galactic double white dwarf population for LISA
https://ui.adsabs.harvard.edu/abs/2022MNRAS.511.5936K/abstract

Zou et al.: Gravitational-wave Emission from a Primordial Black Hole Inspiraling inside a Compact Star: A Novel Probe for Dense Matter Equation of State
https://ui.adsabs.harvard.edu/abs/2022ApJ...928L..13Z/abstract

Vigna-Gómez et al.: Stellar response after stripping as a model for common-envelope outcomes
https://ui.adsabs.harvard.edu/abs/2022MNRAS.511.2326V/abstract

Mohan et al.: Detectability of electromagnetic counterparts from neutron star mergers: prompt emission versus afterglow
https://ui.adsabs.harvard.edu/abs/2022MNRAS.511.2356M/abstract

Biscoveanu et al.: The effect of spin mismodelling on gravitational-wave measurements of the binary neutron star mass distri
https://ui.adsabs.harvard.edu/abs/2022MNRAS.511.4350B/abstract

Gualandris et al.: Eccentricity evolution of massive black hole binaries from formation to coalescence
https://ui.adsabs.harvard.edu/abs/2022MNRAS.511.4753G/abstract