~~Sailing on the winds of massive stars with ULYSSES~~ ⇒

The *dirty secrets* of stellar evolution modelling

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It is a truth universally acknowledged, that

many people use stellar evolutionary models in their research.

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- *Massive* star models (“~~tracks~~”):
  - libraries / grids, e.g. Geneva models, Bonn models…
  - DIY with MESA

massive: > 8 $M_\odot$

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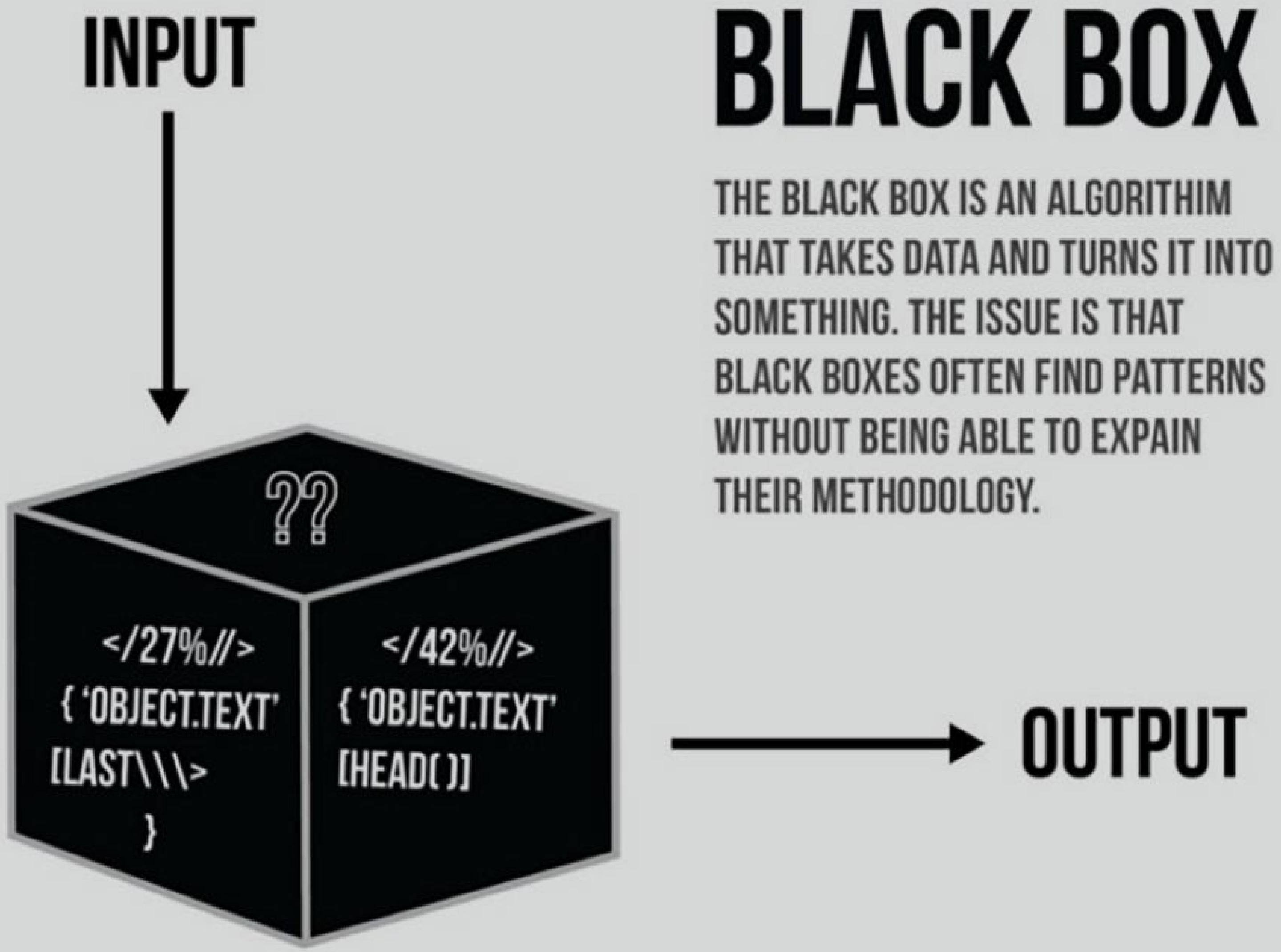
- …maybe even you?
- *Massive* star models ("~~tracks~~"):
  - libraries / grids, e.g. Geneva models, Bonn models…
  - DIY with MESA
- Really wide range of usage:
  - obtaining mass & age etc. of observed stars
  - star-formation simulations, starcluster formation studies
  - chemical evolution of the Universe
  - binary population synthesis → gravitational-wave event rates

massive: > 8 $M_\odot$

What do *you* do?

just examples, there are more

Necessarily, the models are – most of the time – used as a black box.



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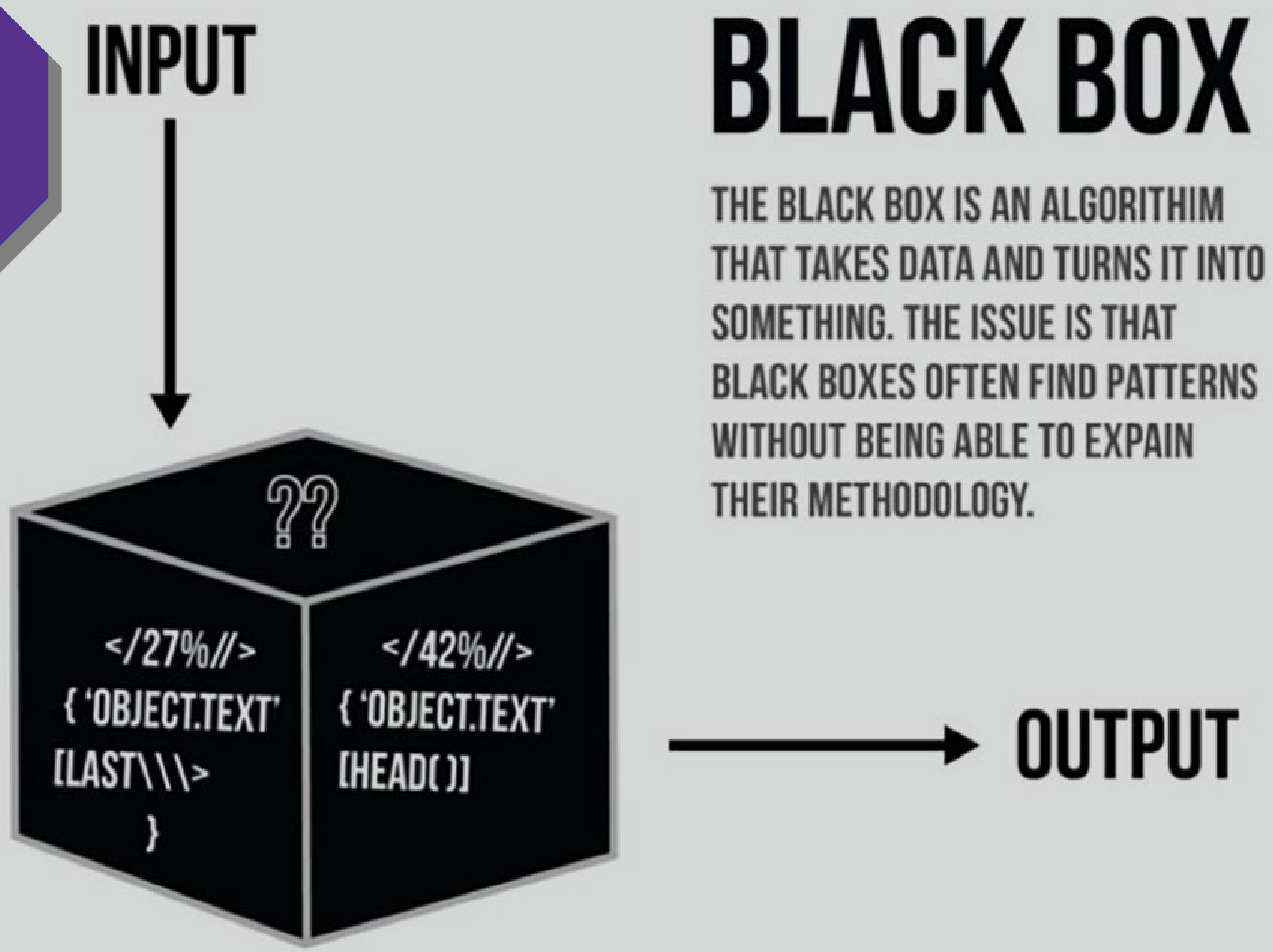
Which is fine.



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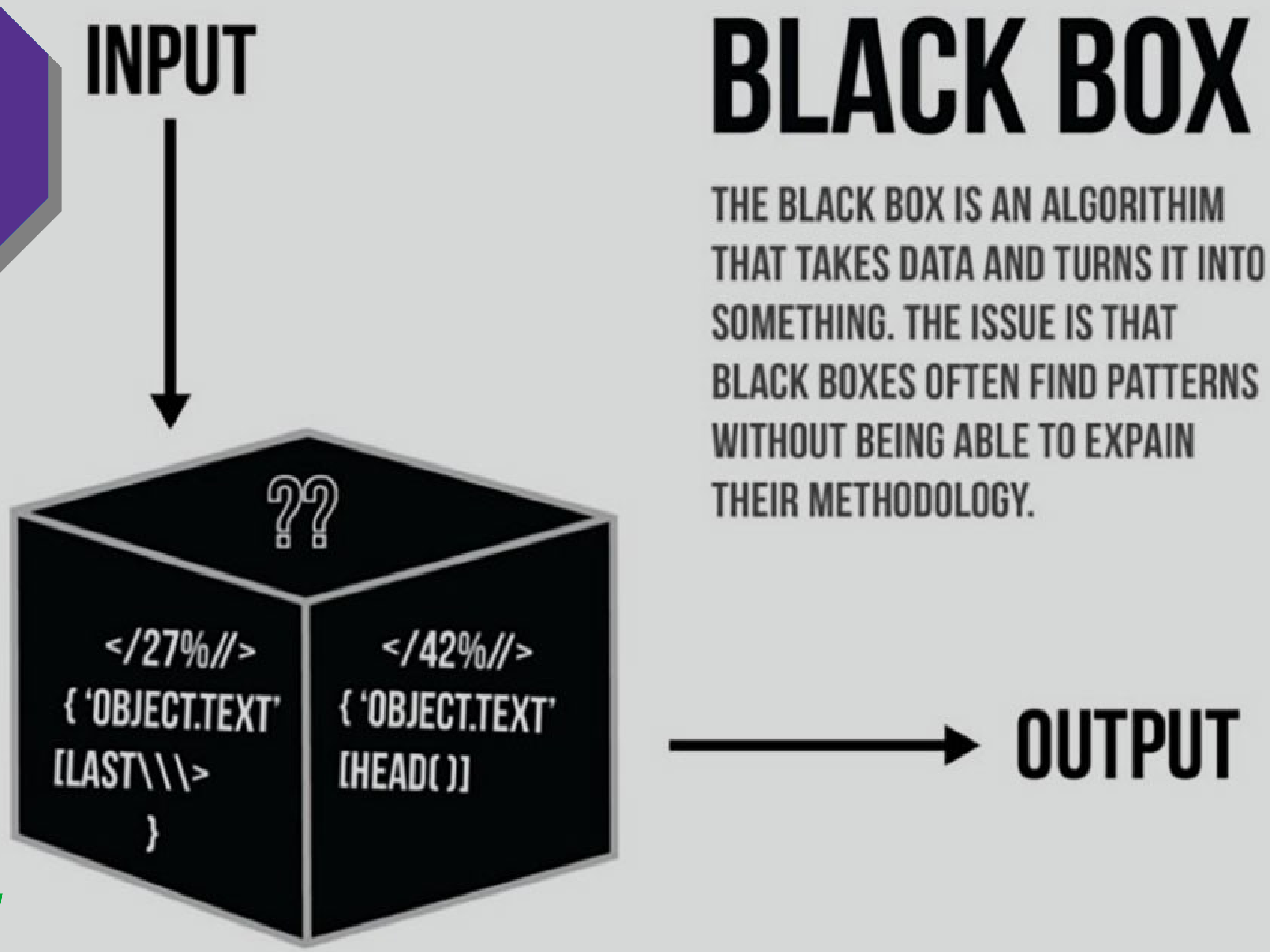

However...

Let’s peek into to box!

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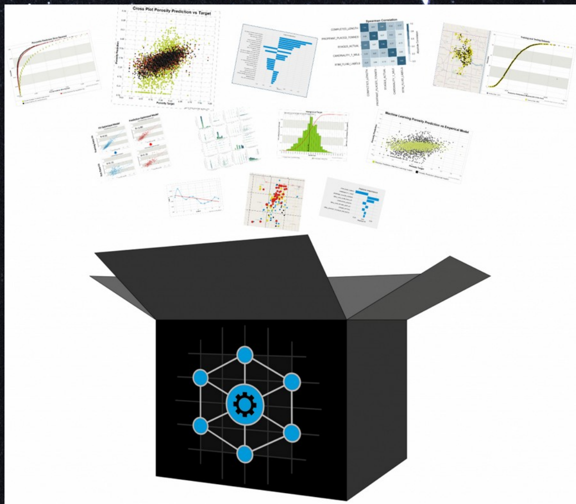
Agrawal & Szécsi et al. (2022, MNRAS)

also see:
Martins & Palacios 2013
Jones et al. 2015



Agrawal & Szécsi et al. (2022, MNRAS):

We compare 5 sets of stellar evolutionary models from 5 independent projects/codes

– so that you don’t have to ;)

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- PARSEC (Padova code)
- MIST (MESA code)
- Geneva code
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- BoOST project (Bonn code)

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- PARSEC (Padova code)
- MIST (MESA code)
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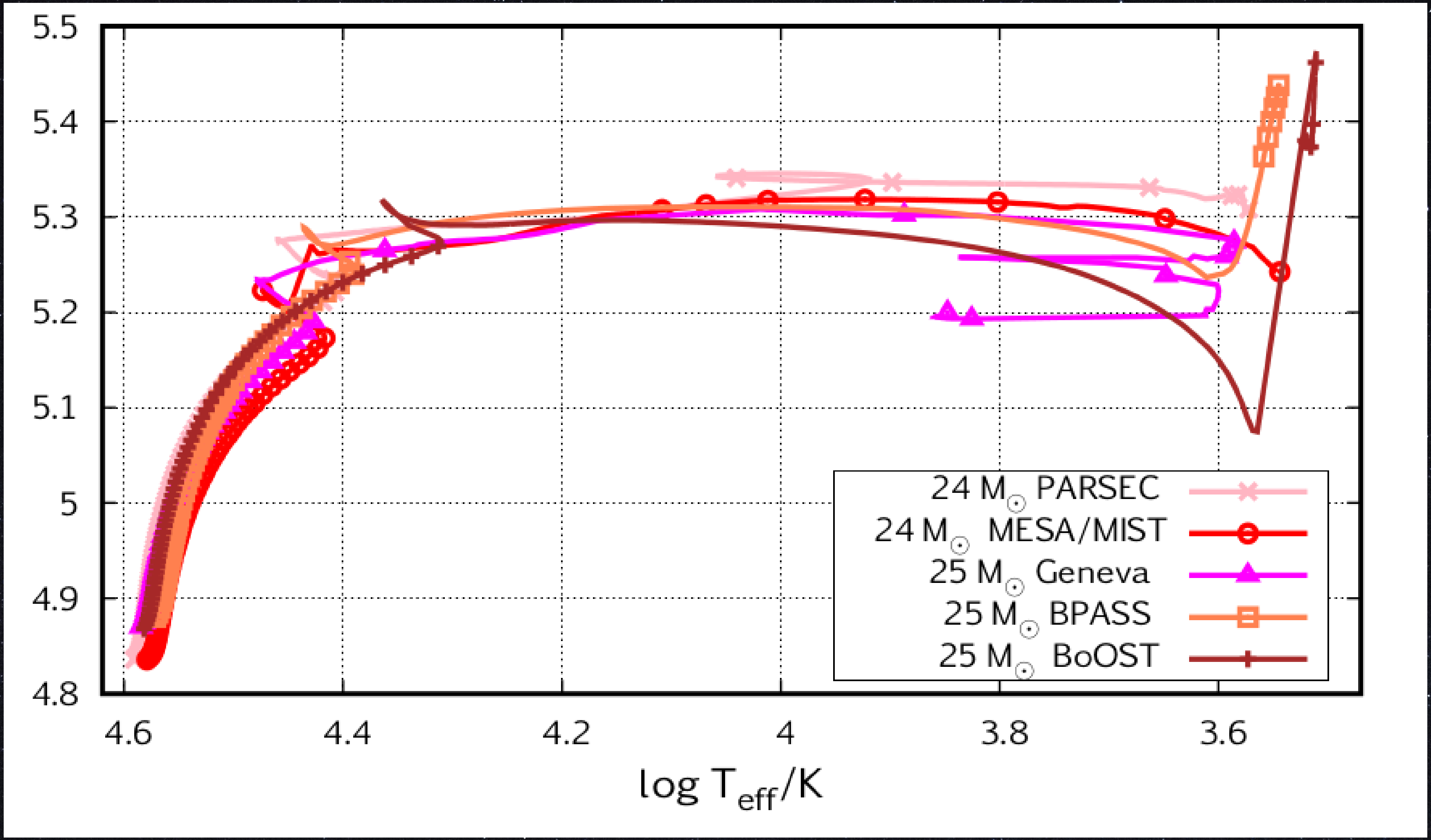
Only comparing:

models with the same mass and composition*
(single stars with no or slow rotational rate)

*namely, Solar


Agrawal & Szécsi et al. (2022, MNRAS)



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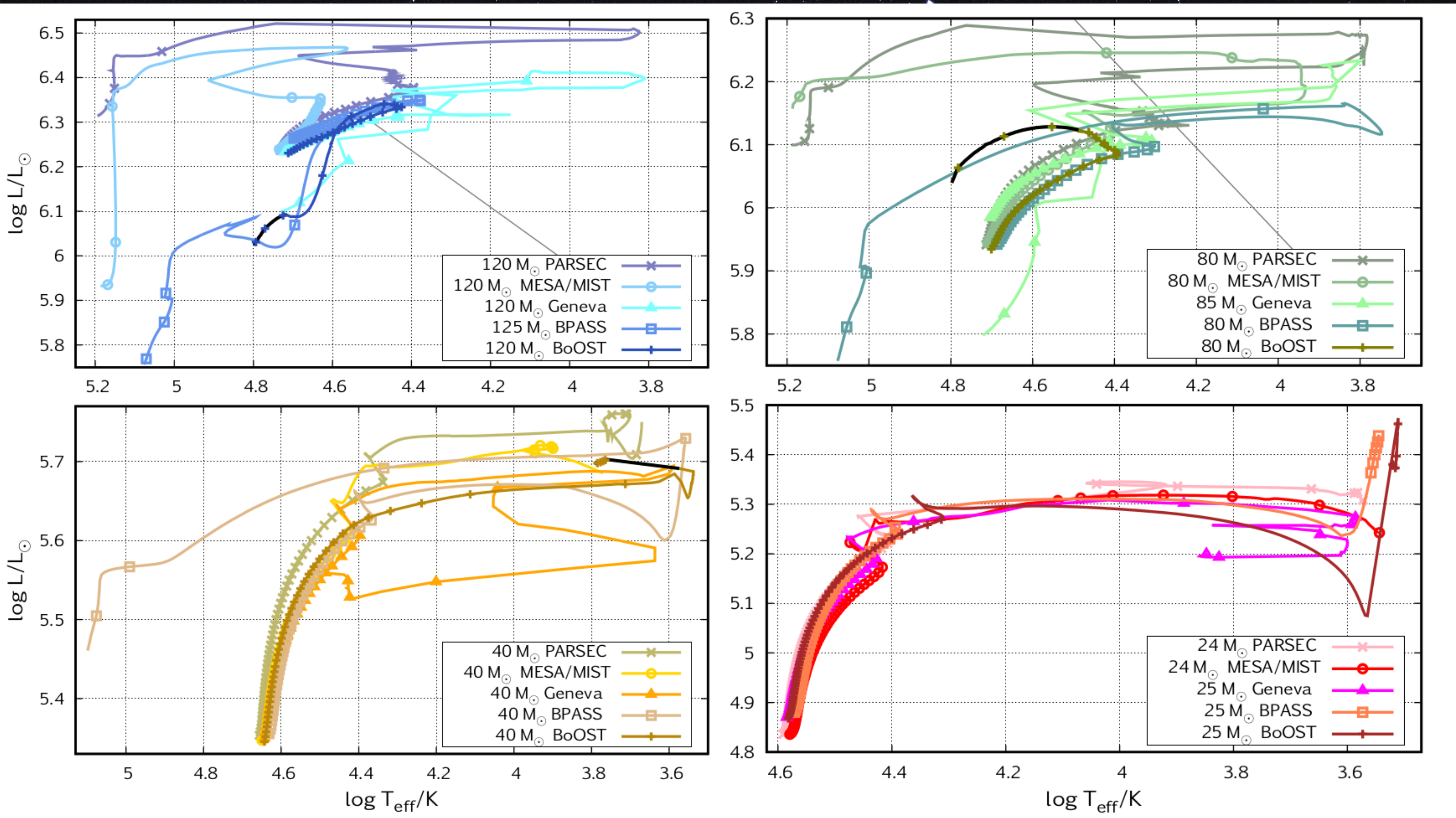

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What about other predictions?

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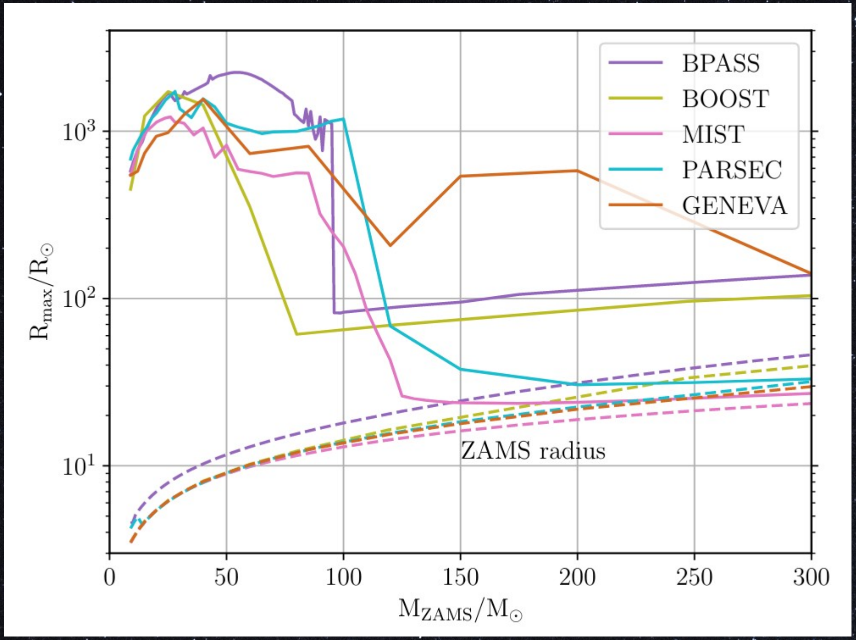
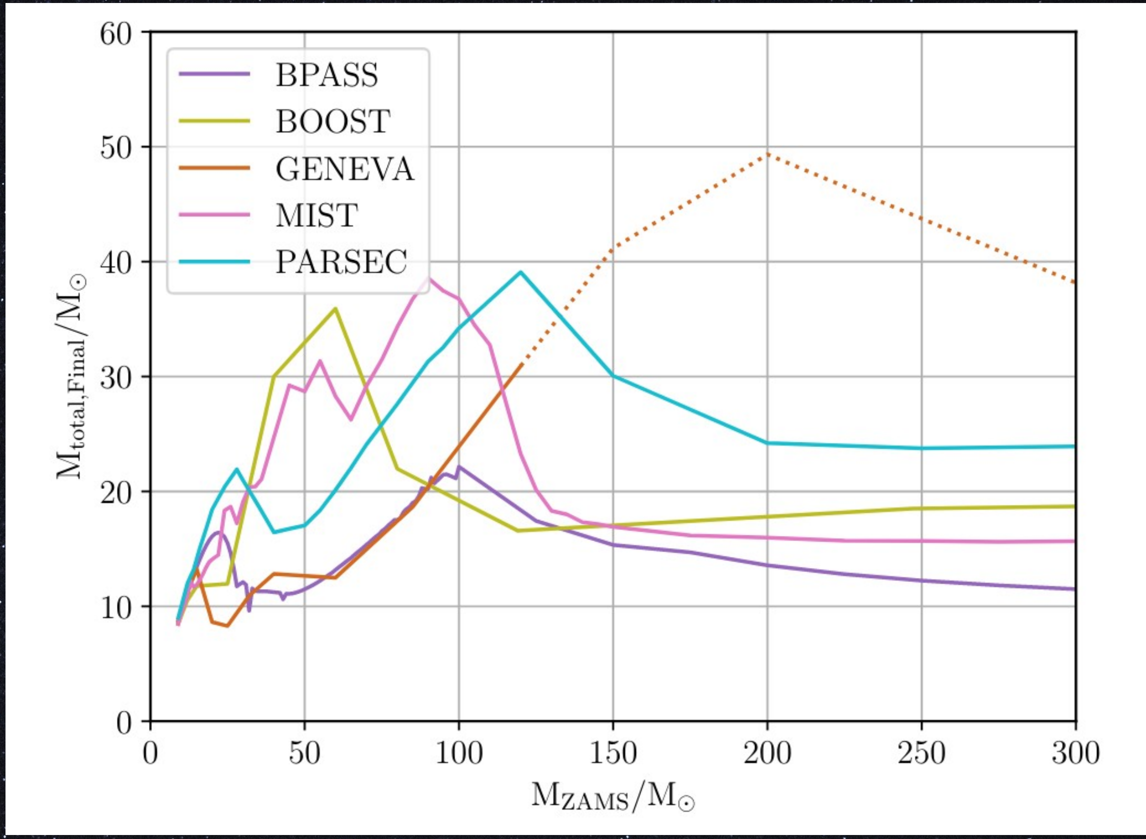




Agrawal & Szécsi et al. (2022, MNRAS)

O-okay, but… why??

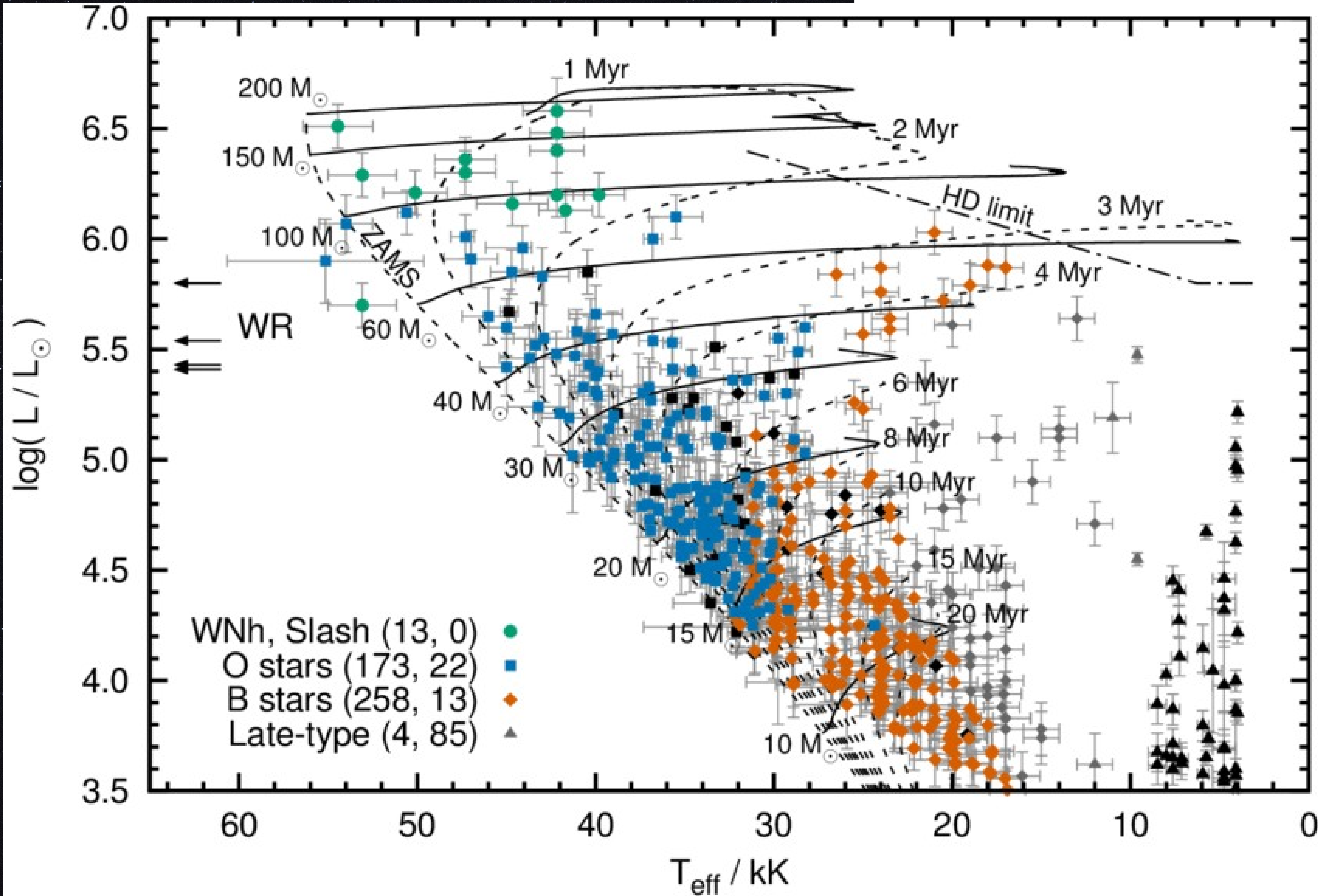
Agrawal & Szécsi et al. (2022, MNRAS)

Quick and dirty answer:

we don’t really understand massive star physics that well. (Yet.)

Agrawal & Szécsi et al. (2022, MNRAS)

30 Doradus star-cluster in the Large Magellanic Cloud galaxy (VFTS survey, 2018)



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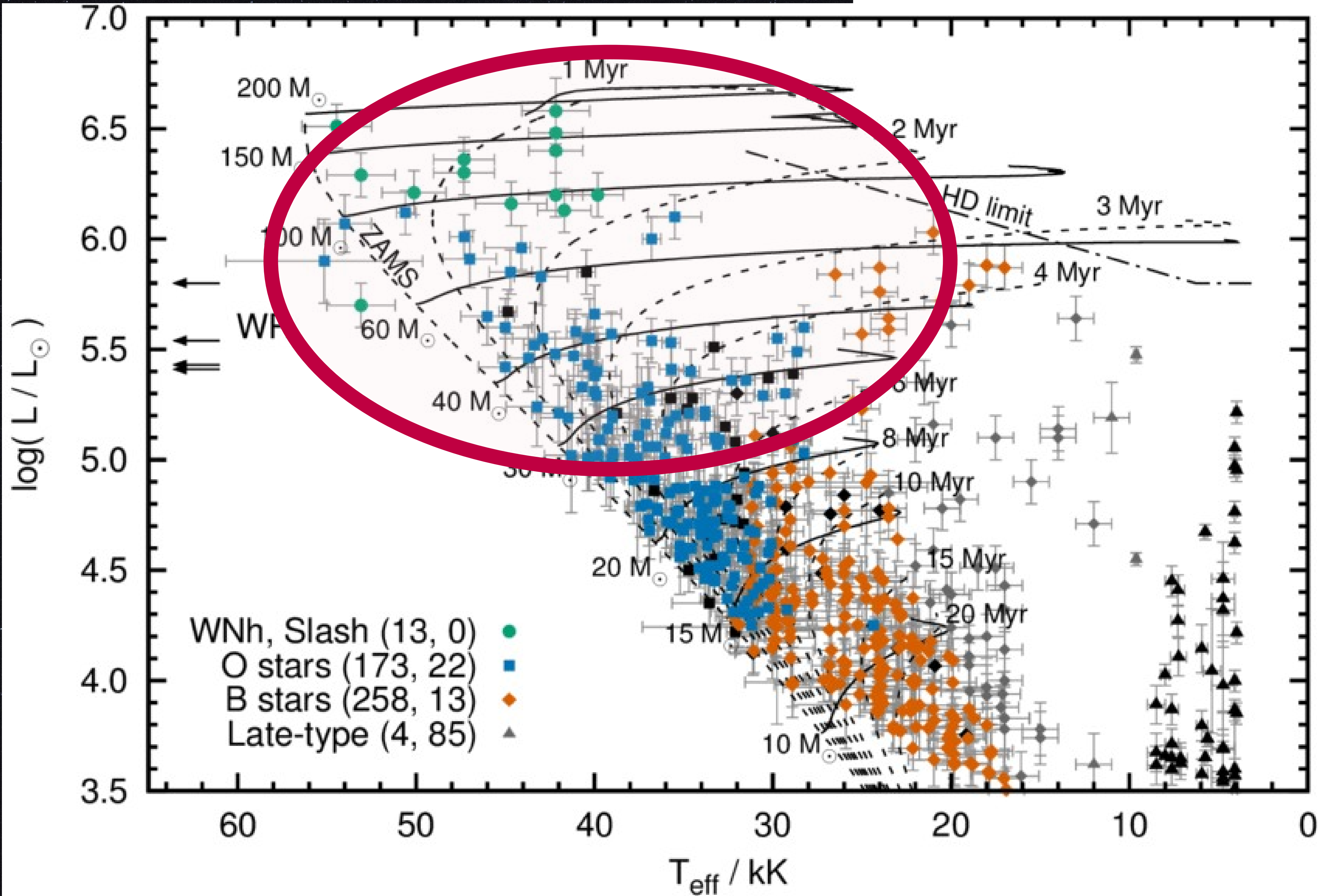

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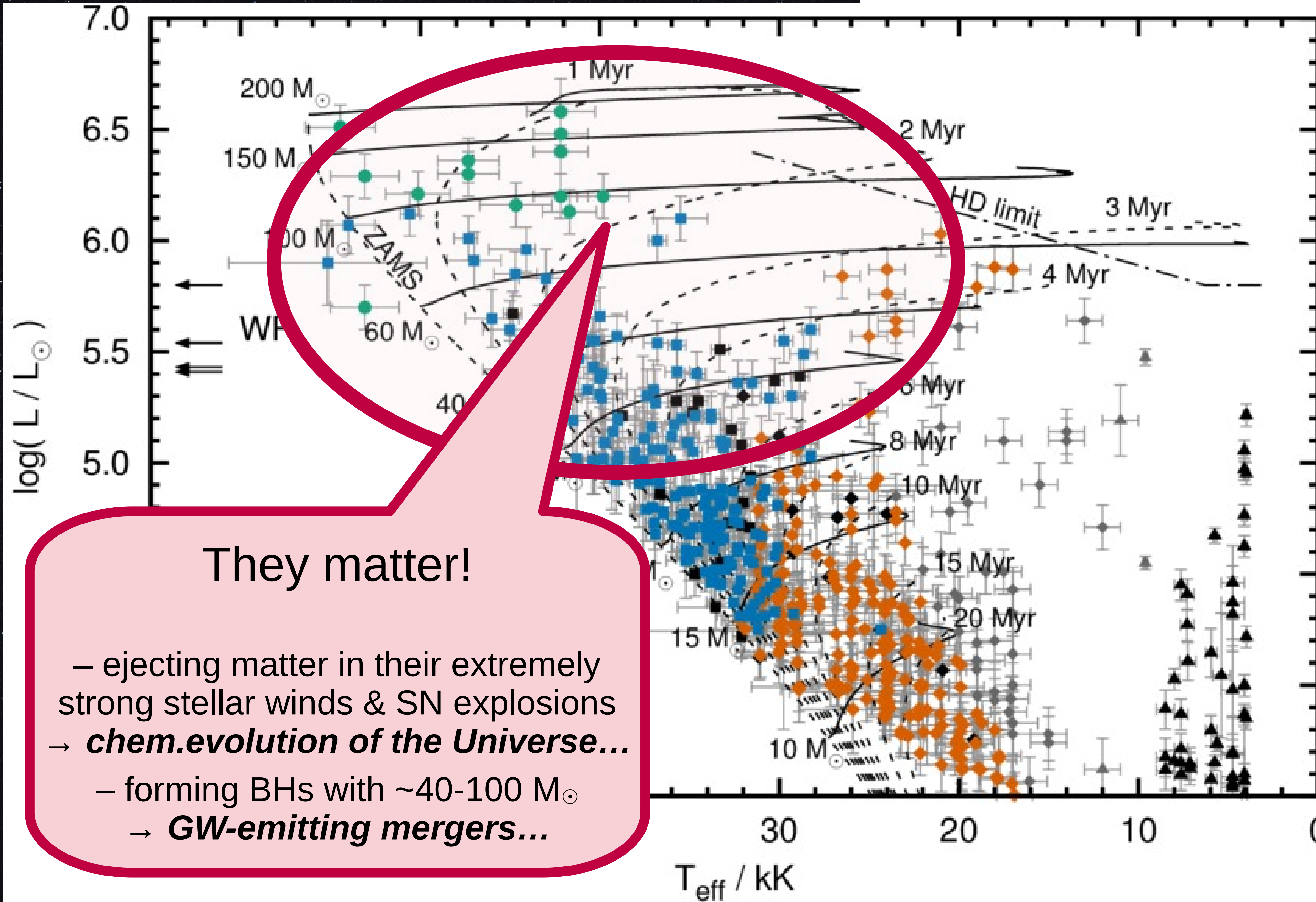

They matter!

– ejecting matter in their extremely strong stellar winds & SN explosions
→ ***chem.evolution of the Universe…***

– forming BHs with ~40-100 M☉
→ ***GW-emitting mergers…***

Again…
different, but why??

Long answer…

Agrawal & Szécsi et al. (2022, MNRAS)

What is a star?

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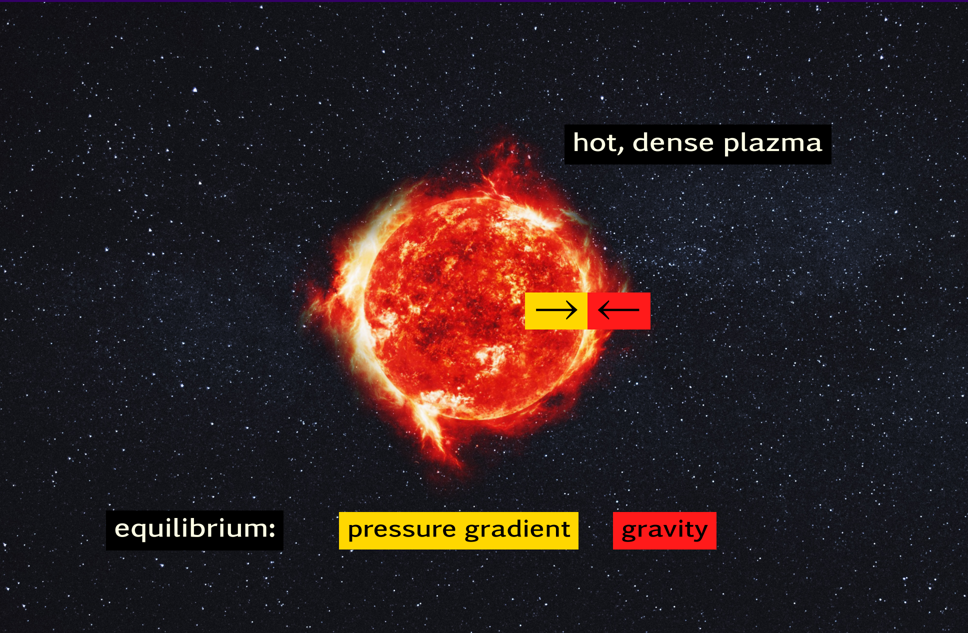

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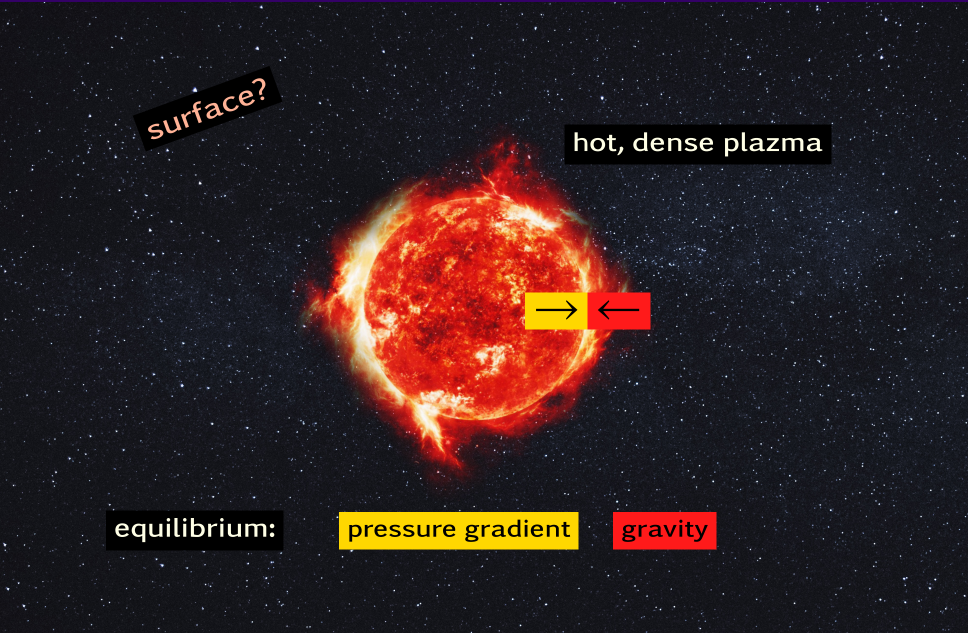
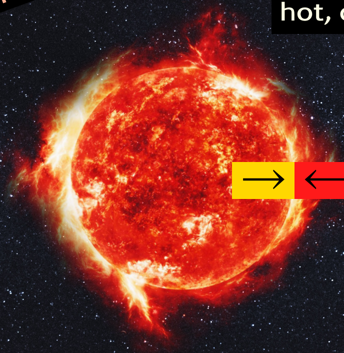


What is a star?

surface?
→ photons escape
"photosphere"

hot, dense plazma



→ ←

equilibrium: pressure gradient gravity

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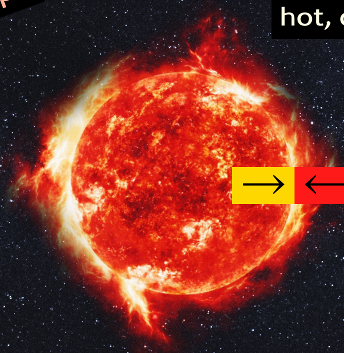

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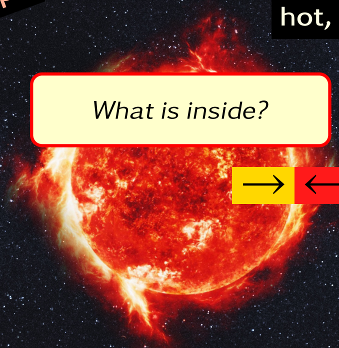

What is inside?

$\longrightarrow$ $\longleftarrow$

equilibrium: pressure gradient gravity

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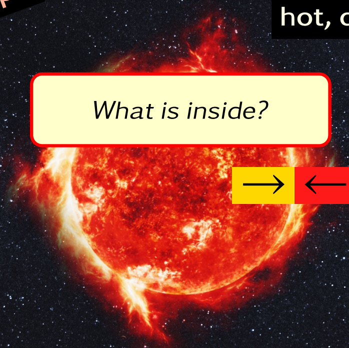

What is inside?

theoretical modelling of the stellar structure

equilibrium: pressure gradient → ← gravity

Theoretical modelling of the stellar structure

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho} \quad \text{equation of definition of mass} \quad (1)$$

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4} \quad \text{equation of hydrostatic equilibrium} \quad (2)$$

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{\mathrm{pl}} - T\frac{\partial S}{\partial t} \quad \text{equation of energetic balance} \quad (3)$$

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla \quad \text{equation of energy transport,} \quad (4)$$

Guilera+ 11

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equation of energy transport,

Guilera+ 11

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transport of energy

Guilera+ 11

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Guilera+ 11

composition change due to nuclear burning:

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transport of energy

Guilera+ 11

composition change due to nuclear burning:

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

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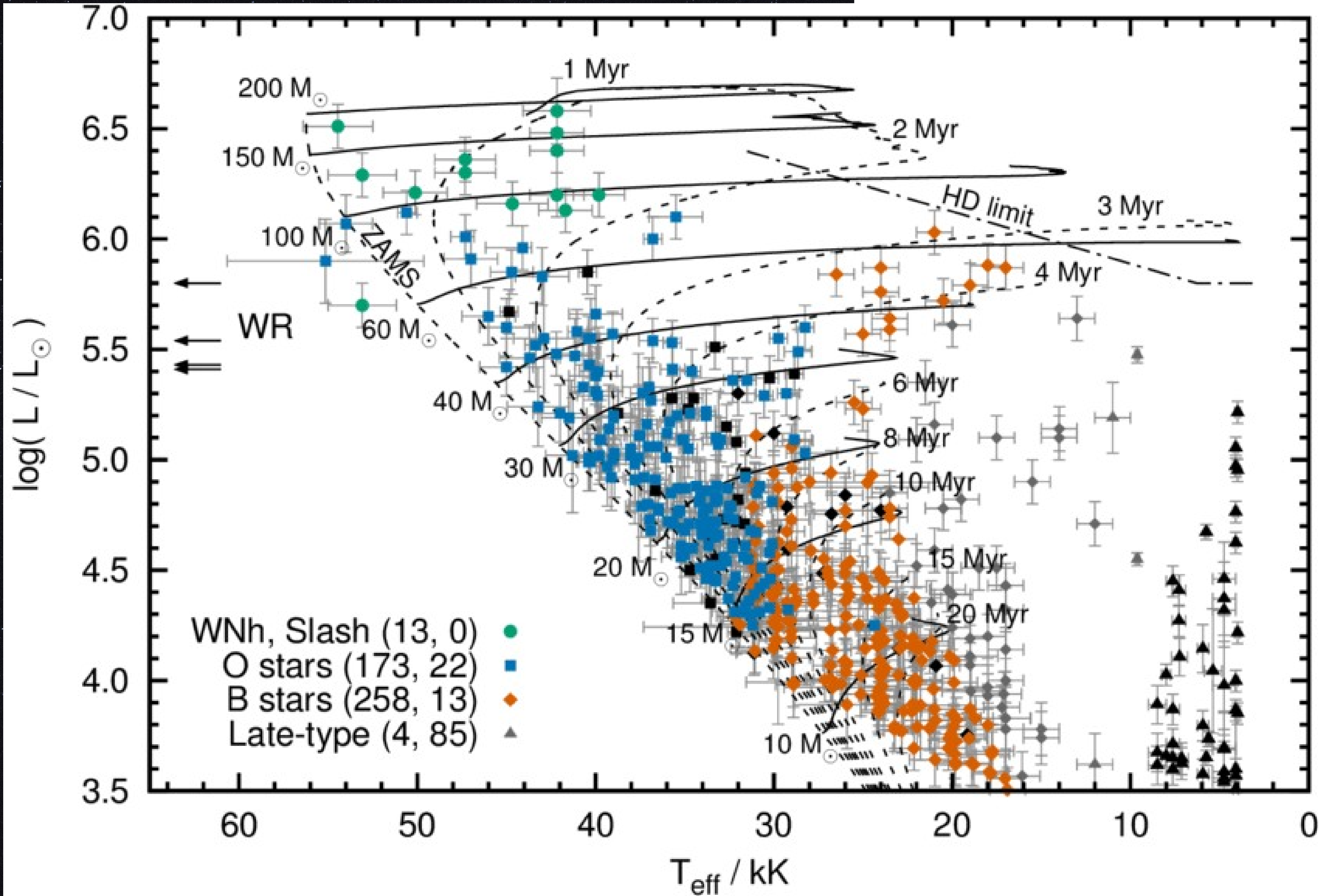


When the equilibrium* is compromized:

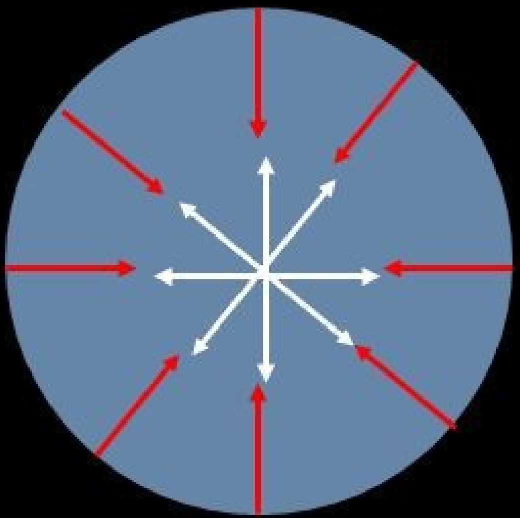
the Eddington limit

** between gravity & radiation pressure*

Eddington limit

Radiative Force

$$g_{rad} = \int_0^\infty d\nu \, \frac{\kappa_\nu F_\nu}{c}$$



Gravitational Force

$$\frac{GM}{r^2}$$

$$\Gamma_e \equiv \frac{g_e}{g} = \frac{\kappa_e L / 4\pi r^2 c}{GM / r^2} = \frac{\kappa_e L}{4\pi G M c}$$

Credit: Stan Owocki

Other reasons for falling out of equilibrium:

- iron core

  → gravitational collapse & SN (due to bounce-back)

- pair-instability

  → grav. collapse & subsequent thermonuclear explosion (PISN) or pulsations (puls-PISN)

- end of a burning phase

  → restructuring, crossing the Herzsprung-gap...

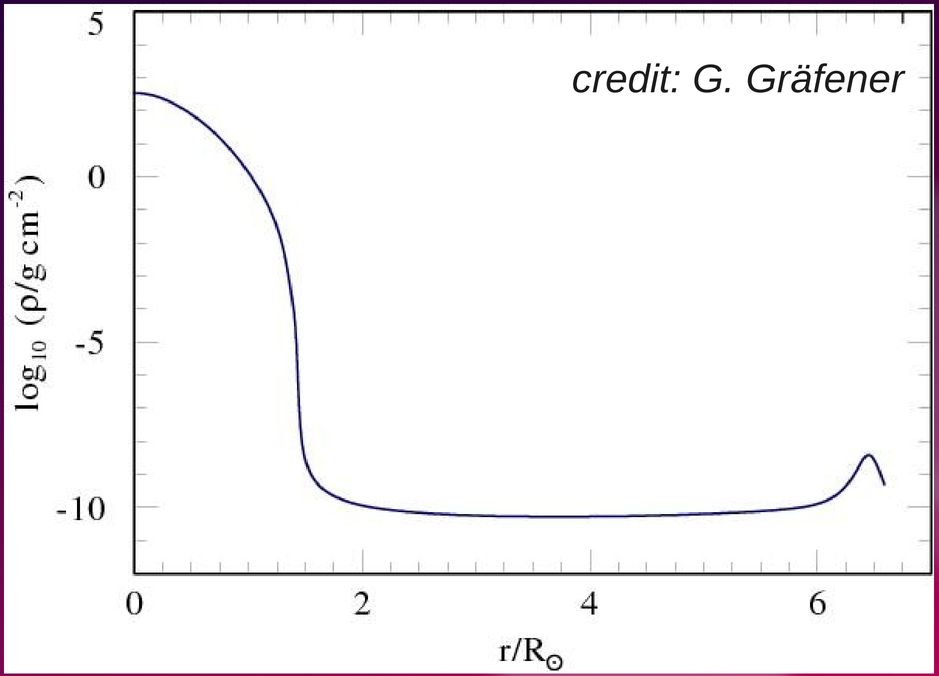
- ...

of approaching the Eddington-limit

Consequences for the stellar interior

- density (and pressure) <u>inversion</u> *in the envelope*
- no efficient energy transport mechanism here (weak convection)
- → envelope “<u>inflation</u>”
- numerical difficulties...

density inversion:



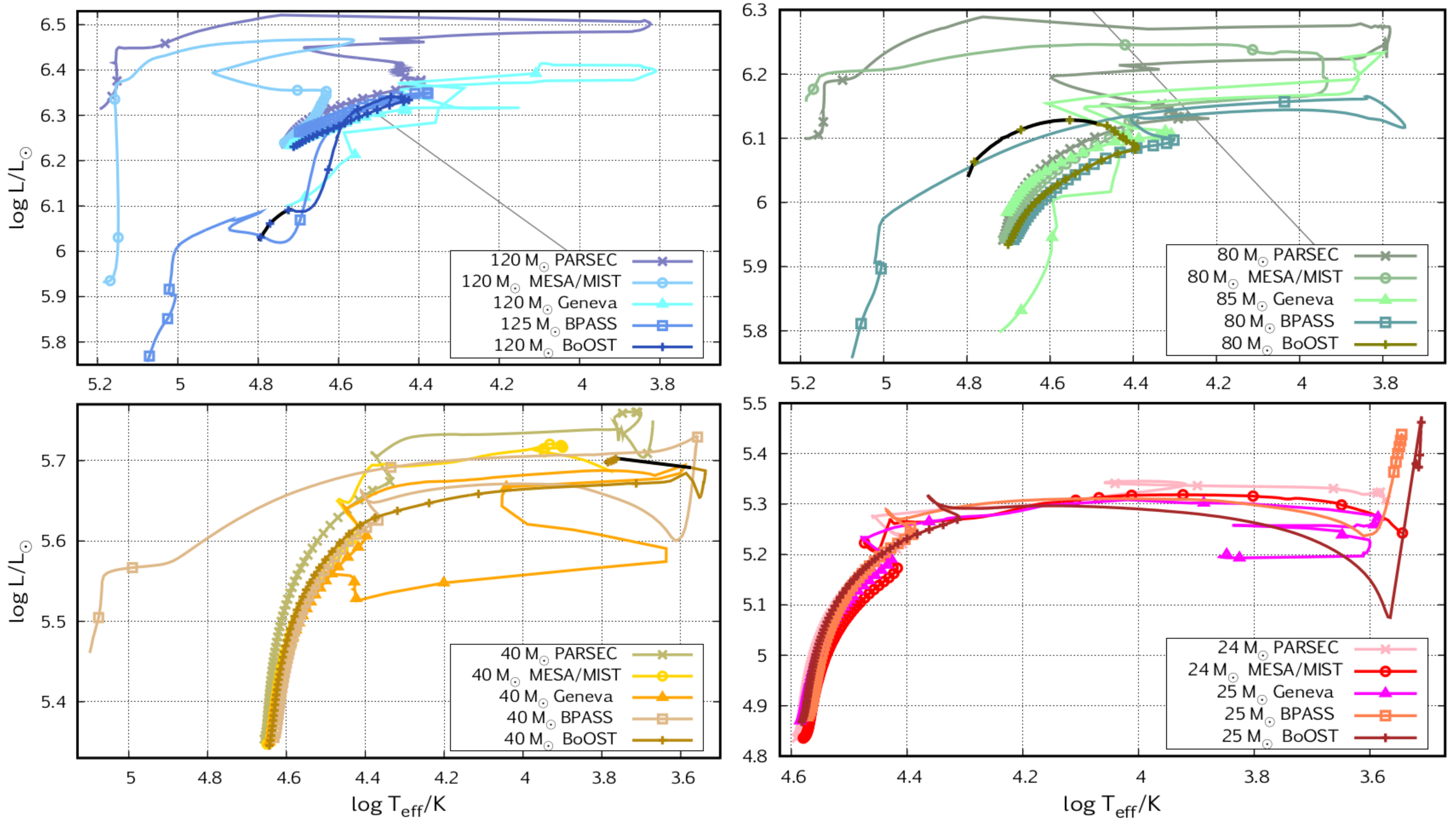
CORE **ENVELOPE**

How do the codes deal with that?

- several "tricks" in the literature
  - various codes use various tricks & methods
  - *cf.* Agrawal & Szécsi+22 (MNRAS)
- PARSEC ('Padova') **artificially limiting the temp. gradient**
- MIST (MESA) **MLT++ formalism *(limiting the superadiabacity*)***
  =changing how convection is treated**
  **difference between the isothermal and adiabatic temperature gradient*
  ***a type of internal mixing*
- 'Geneva'
- BPASS

artificially enhanced mass loss at the right moment

- BoOST ('Bonn') **inflated envelope & post-processing with 'normal' mass loss**



Agrawal & Szécsi et al. (2022, MNRAS)

Ionizing flux...

Table 2. Time averaged ionizing photon number flux [s^{-1}] in the Lyman continuum emitted by the stellar models during their lives *on average*, cf. Section 4.2. The last column provides the amount of Lyman radiation (number of photons [s^{-1}]) that a $10^7\,M_\odot$ population (e.g. a starburst galaxy or a young massive cluster in the Milky Way) containing these massive stars would emit.

M_{ini} [$M_\odot$]	24/25	40	80/85	120/125	pop.
PARSEC	3.7×10^{48}	1.3×10^{49}	5.5×10^{49}	1.0×10^{50}	1.08×10^{54}
MIST	3.3×10^{48}	1.5×10^{49}	5.1×10^{49}	1.1×10^{50}	1.06×10^{54}
Geneva	3.5×10^{48}	1.2×10^{49}	5.1×10^{49}	8.5×10^{49}	9.90×10^{53}
BPASS	3.6×10^{48}	1.3×10^{49}	4.5×10^{49}	7.7×10^{49}	9.34×10^{53}
BoOST	3.7×10^{48}	1.2×10^{49}	4.2×10^{49}	6.9×10^{49}	8.89×10^{53}

up to 18% difference!

Agrawal & Szécsi et al. (2022, MNRAS)

Remnant mass...

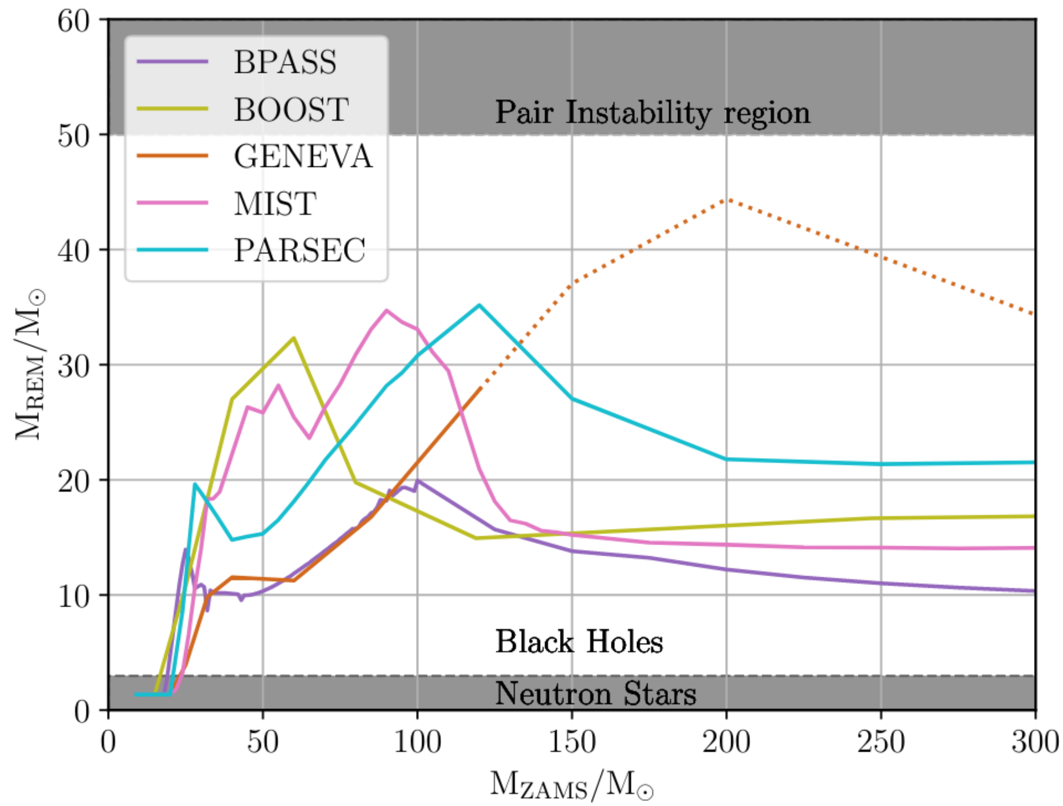
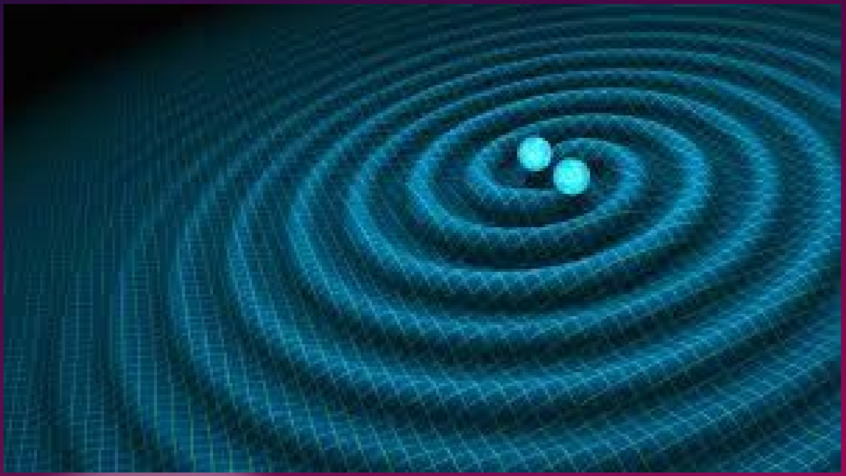


Figure 2. Mass of stellar remnant as a function of the initial mass of the star (near-solar composition). Differences in the assumptions in massive star modelling can cause a variation of up to 20 $M_{\odot}$ in the remnant masses between simulations. Choosing to apply one of these simulations over the others in e.g. gravitational-wave event rate predictions can lead to strikingly different results.

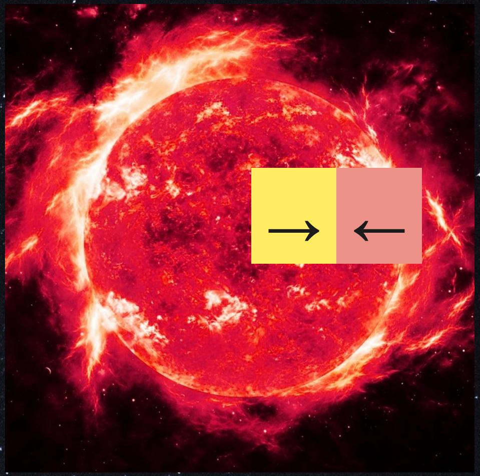
Gravitational waves:
compact object mergers (e.g. black holes)

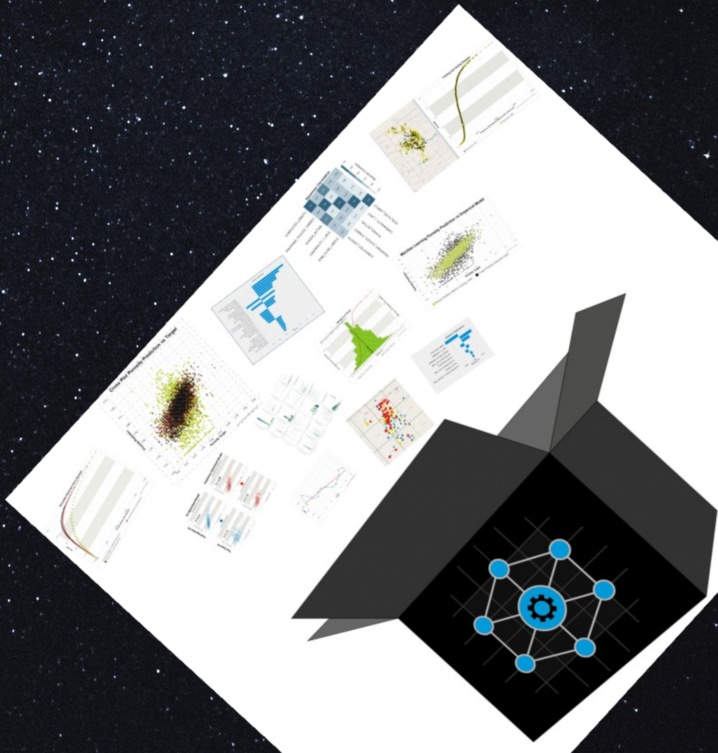


up to 20 $M_{\odot}$ difference!

Agrawal & Szécsi et al. (2022, MNRAS)

What we learned today by peeking into the black box:





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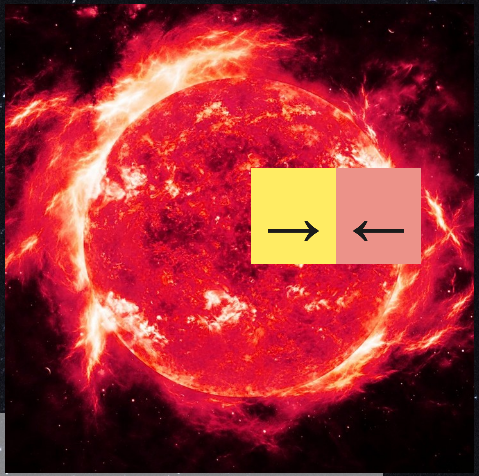

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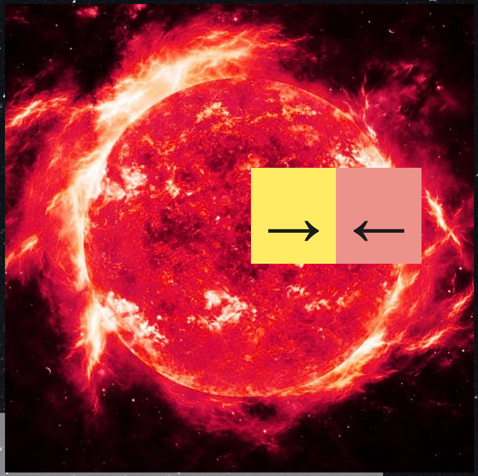

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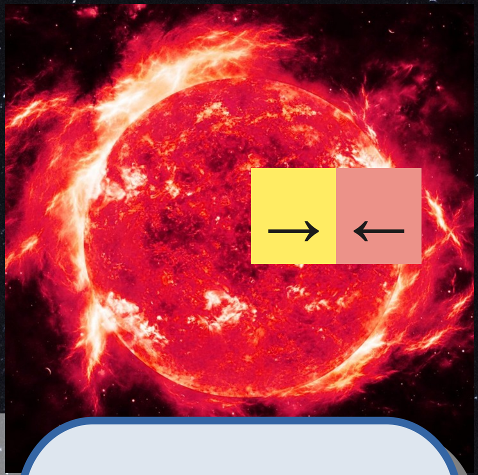

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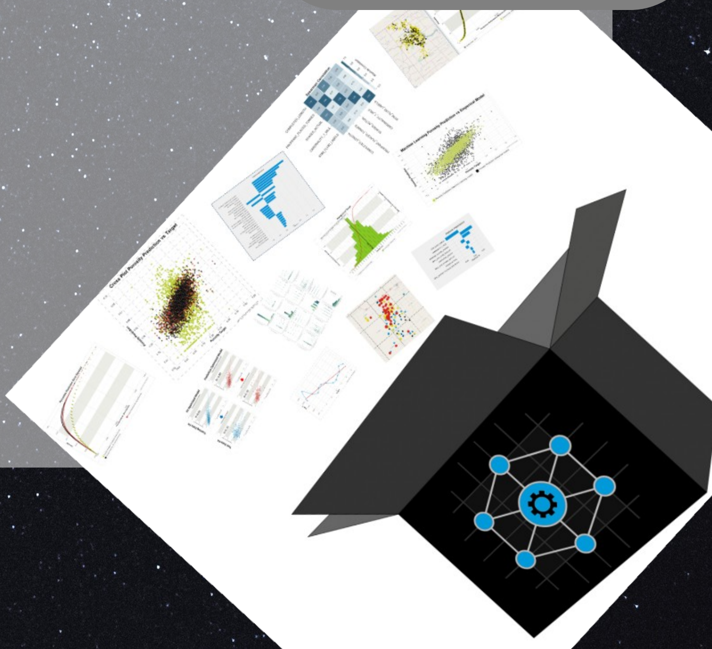
not even at Solar composition!

we didn't even touch low-metallicities...



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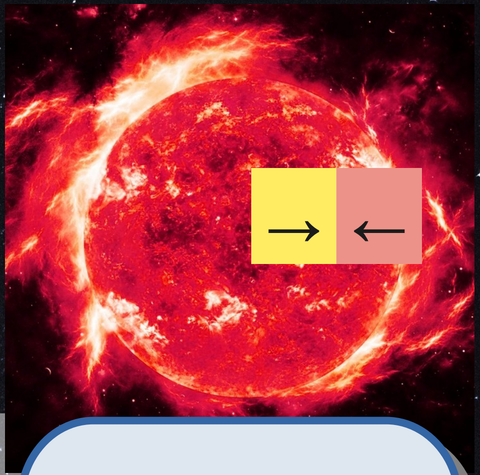

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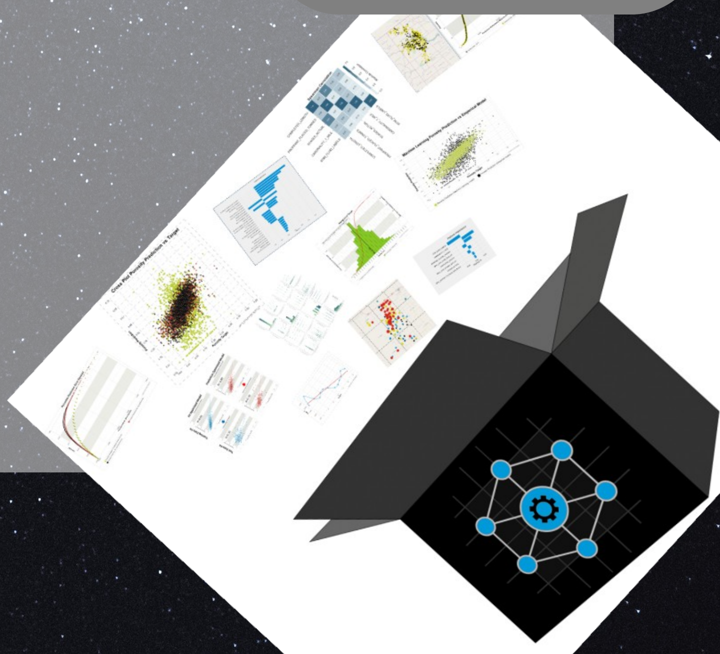

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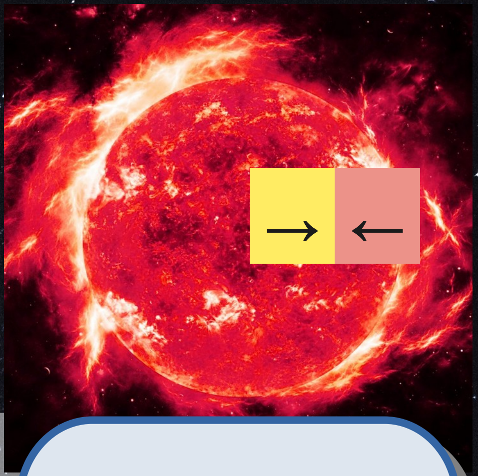

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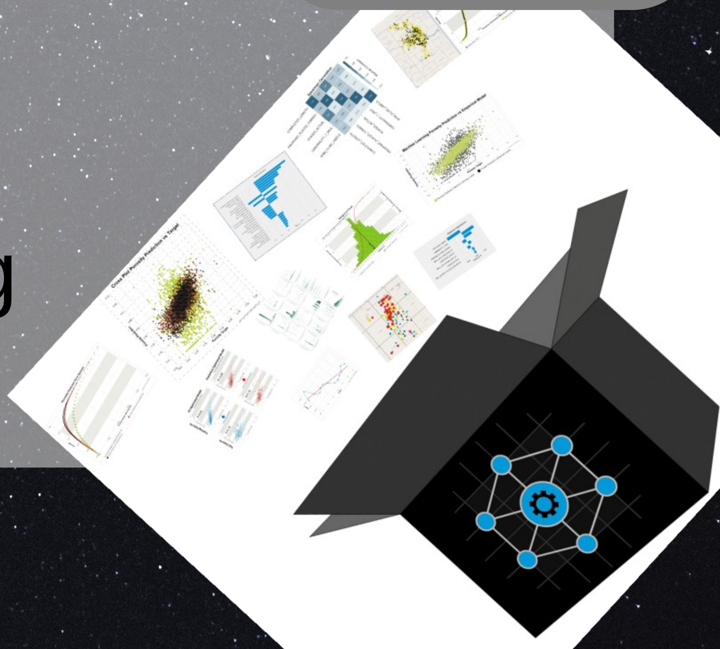
- use stellar models with extra caution, & be flexible for updates
- if you decide to DIY with MESA, **ask an expert** before publishing things! ***even better: hire one?***



My people :D

Dr Poojan Agrawal
(post-doc at Chapel Hill, NC)

Agrawal & Szécsi et al. (2022, MNRAS)

My people :D

In Toruń, Poland:

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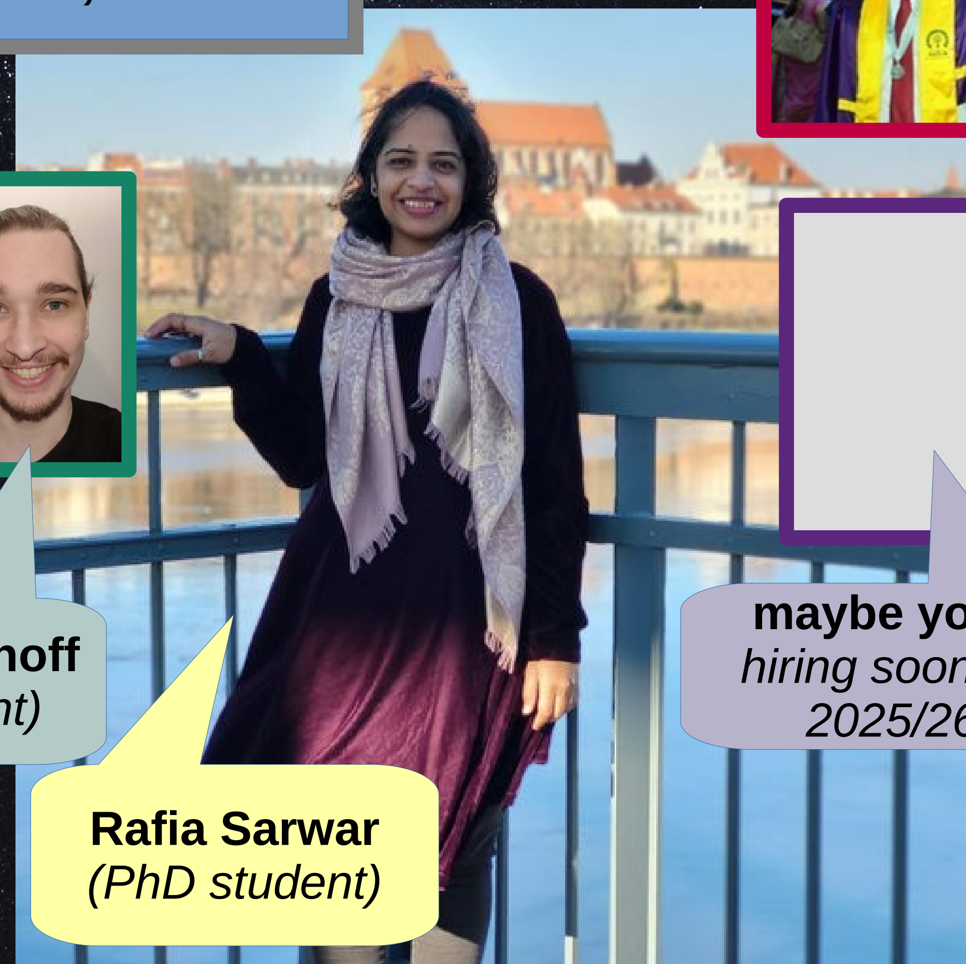
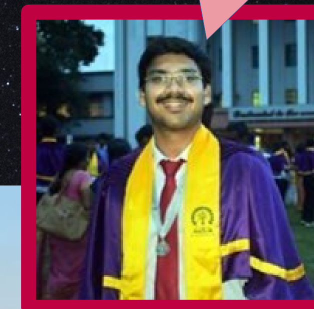
Agrawal & Szécsi et al. (2022, MNRAS)

Hanno Stinshoff
(PhD student)



Rafia Sarwar
(PhD student)



Dr. Koushik Sen
(post-doc)

maybe you?
hiring soon for 2025/26

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