Massive stars from various simulations: why so different?

Nagytömegű csillagok 1D szimulálása: mi okozza a különbségeket a modellekben?

Dorottya Szécsi
Assistant professor at Nicolaus Copernicus University, Poland
Humboldt Fellow, University of Cologne, Germany

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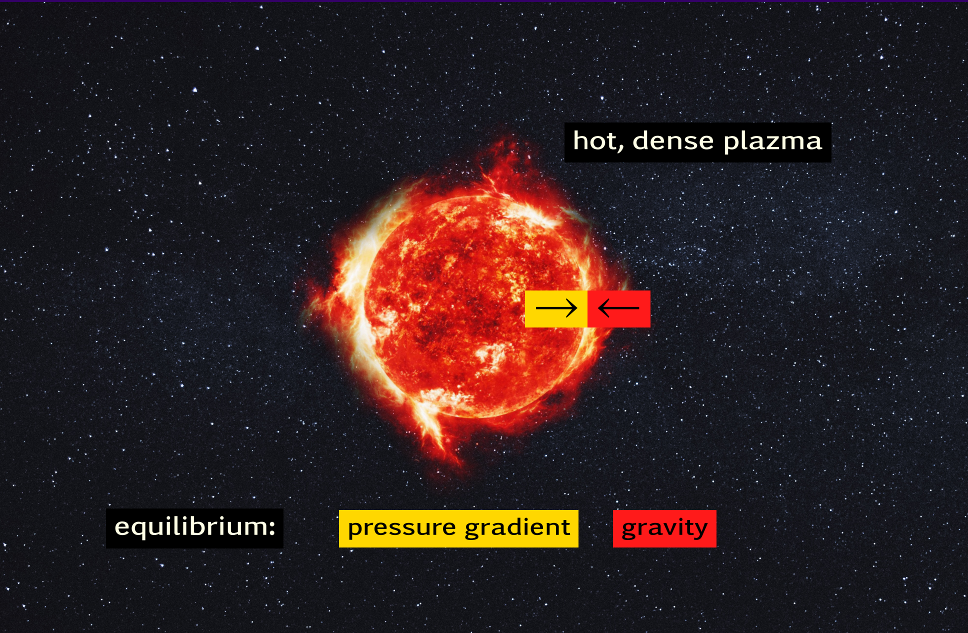
What is a star?



Theoretical modelling of the stellar structure

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

mass conservation

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

momentum conservation

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

energy conservation

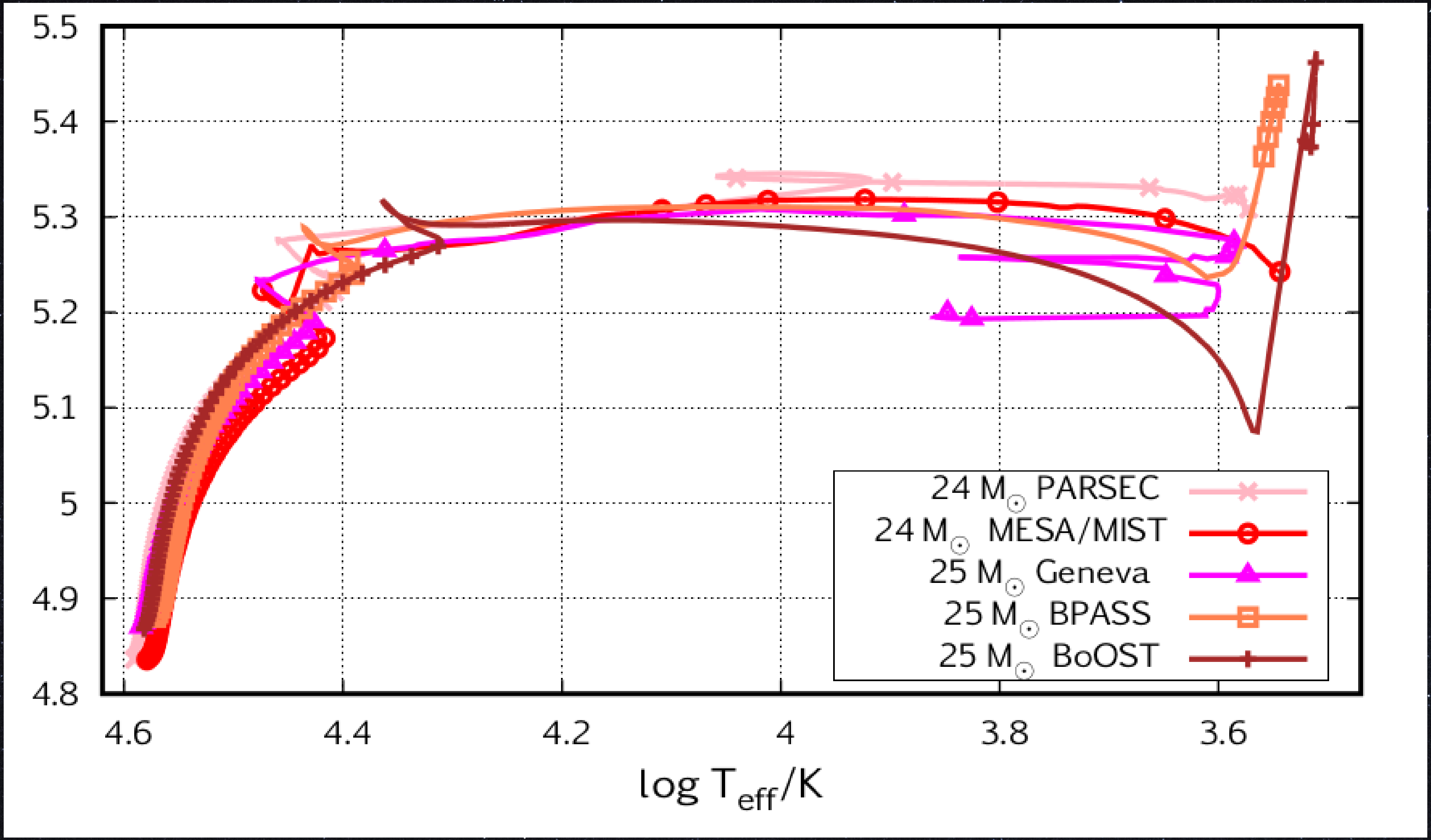
$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla \qquad (4)$$

transport of energy

Guilera+ 11

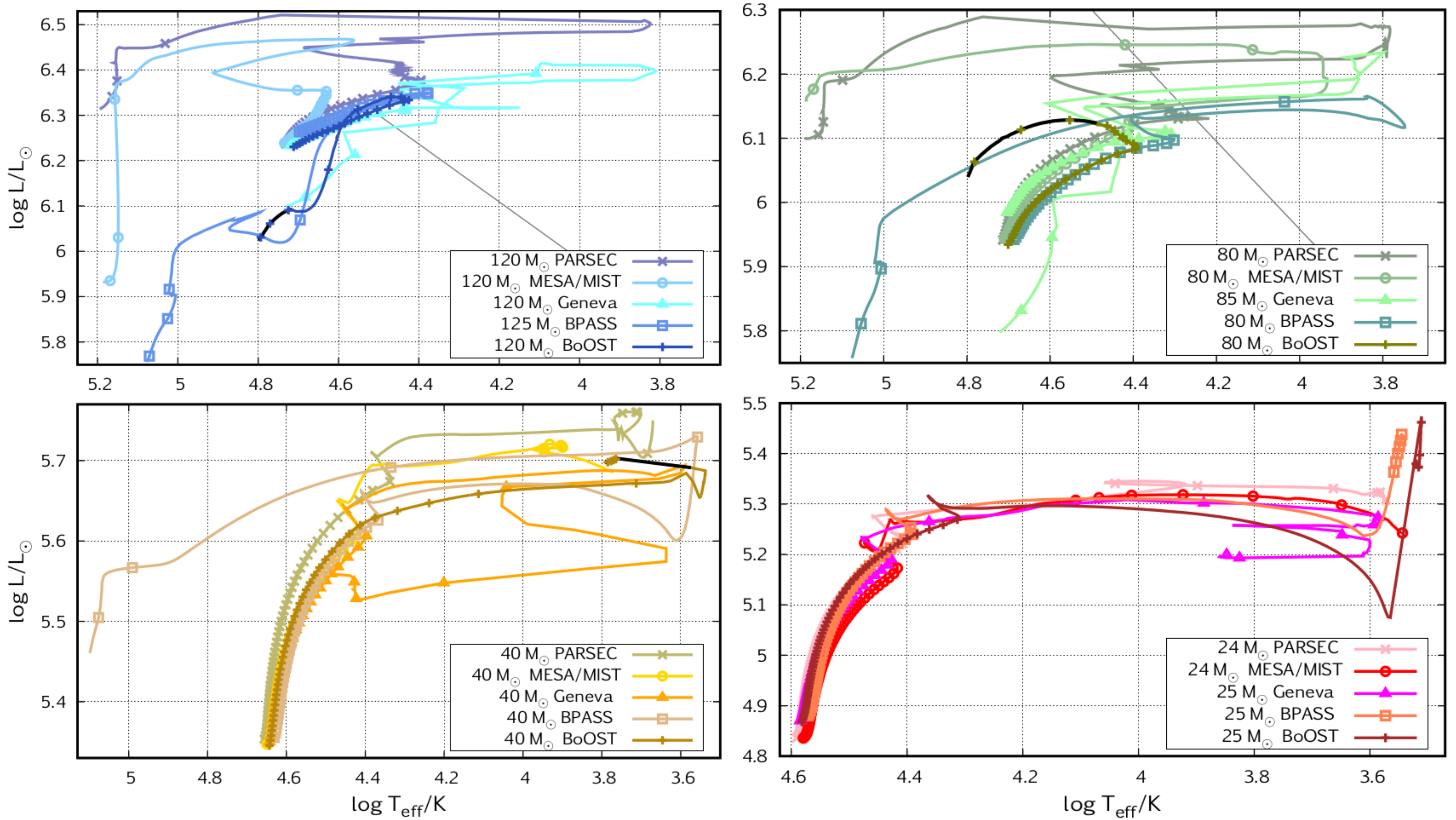
composition change due to nuclear burning:

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



P. Agrawal (2021, *PhD thesis*)

Szécsi & Agrawal (2021, *in prep.*)



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When the equilibrium* is compromized:

the Eddington limit

** between*
gravity & radiation pressure

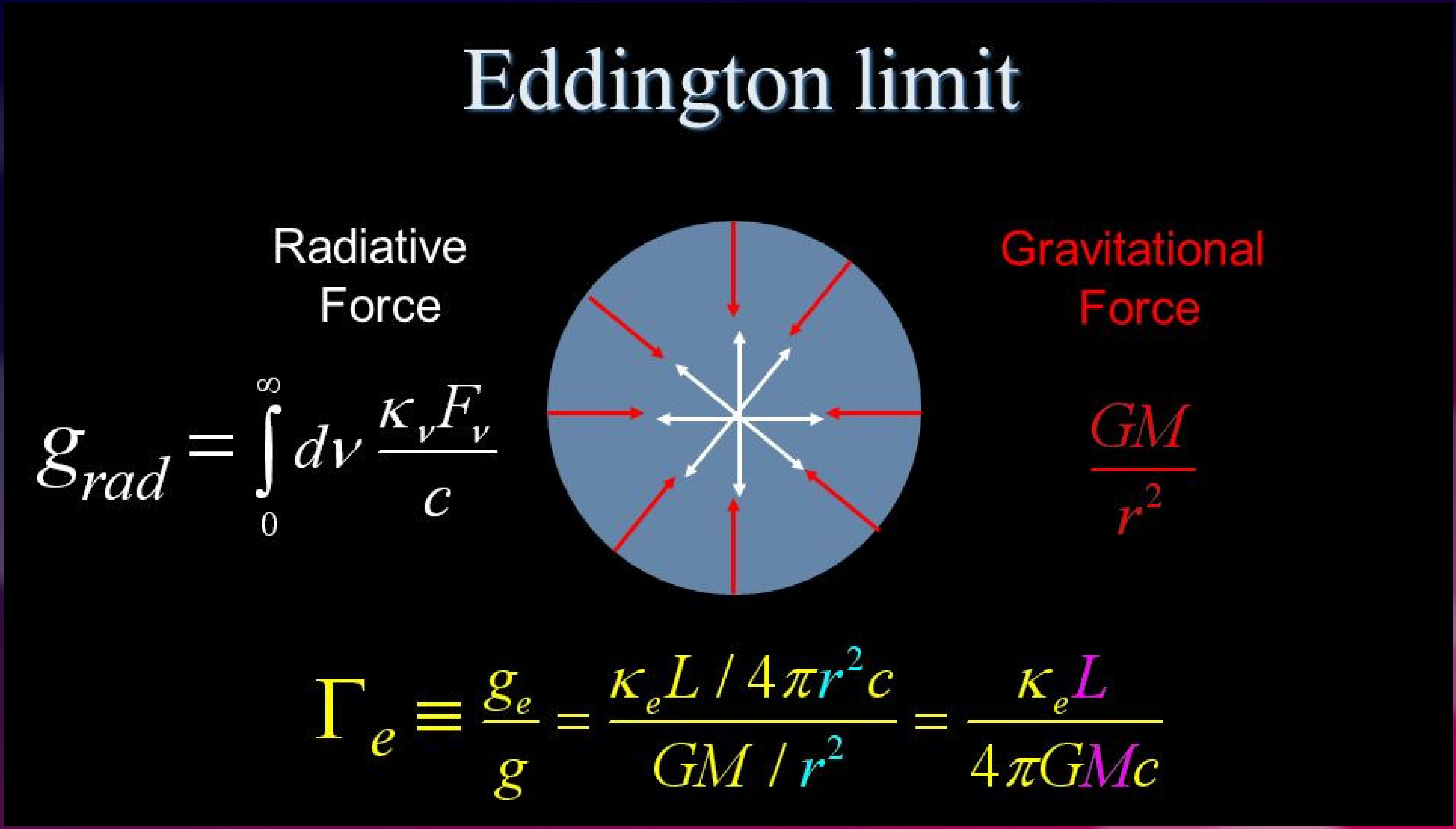
Other reasons for falling out of equilibrium:

- 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...
- ...

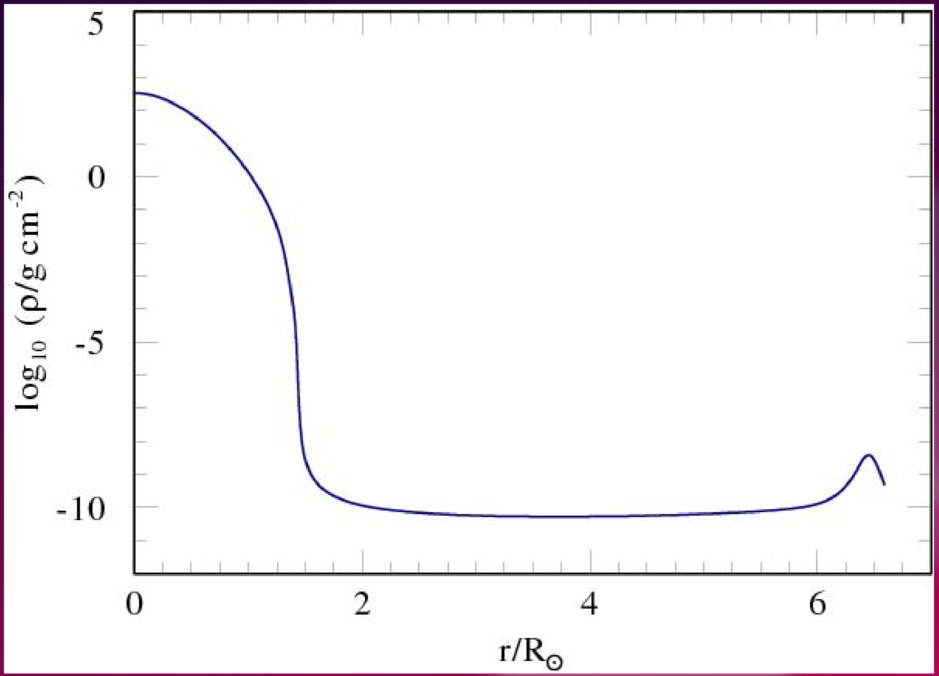


Credit: Stan Owocki

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**

credit: Götz Gräfener

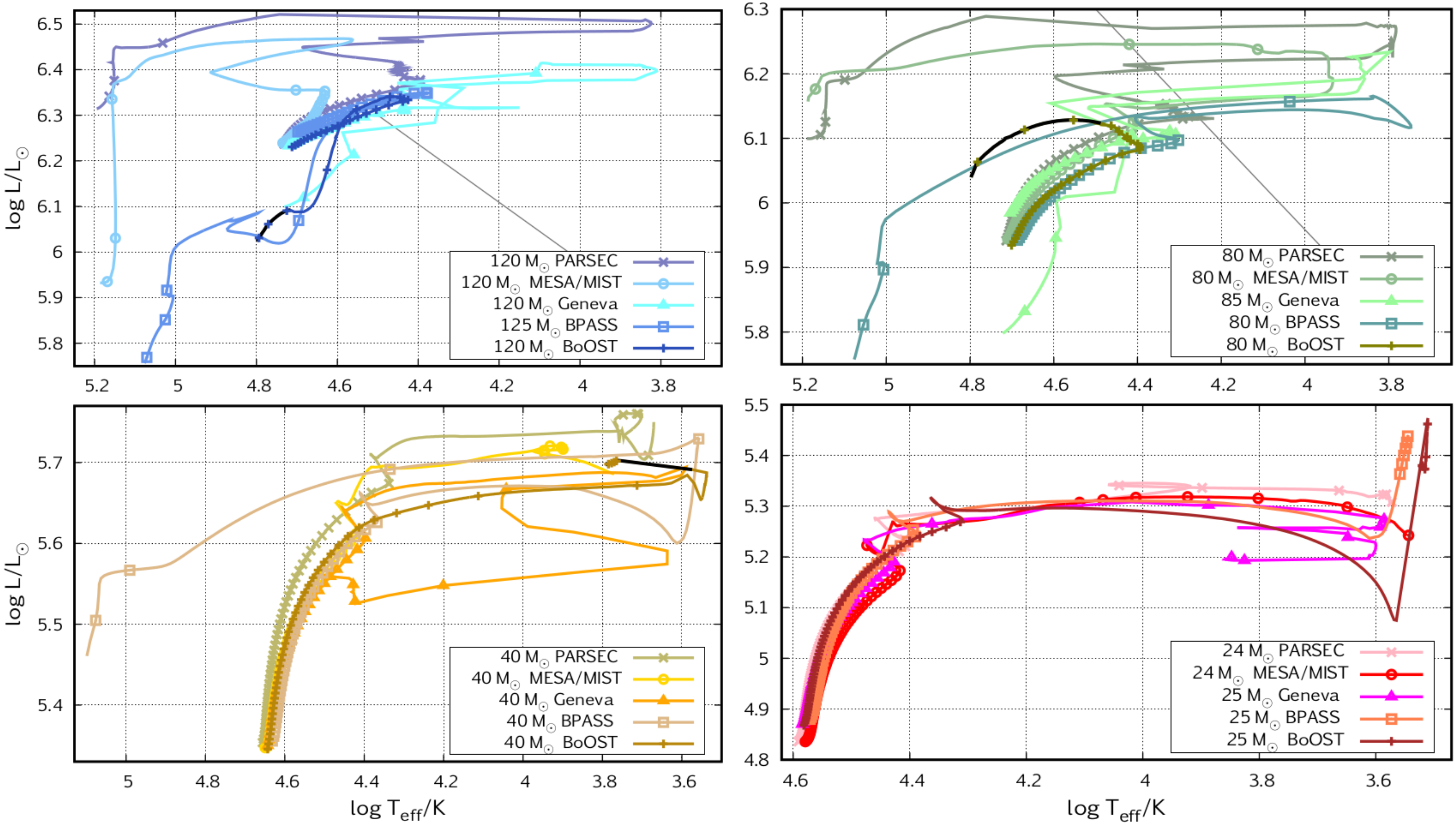
Is there a solution?

- several “tricks” in the literature
  - various codes use various tricks & methods
  - *cf.* Agrawal (*PhD Thesis*), Szécsi & Agrawal (‘21, *in prep.*)
- 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

  (‘Geneva’ and BPASS:) **artificially enhanced mass loss at the right moment**
- BoOST (‘Bonn’) **inflated envelope & post-processing with ‘normal’ mass loss**



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Ionizing flux...

Table 1. Ionizing photon number flux [s^{-1}] in the Lyman continuum emitted *on average* by the stellar models during their lives, cf. Sect. 2.3. 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	3.7e48	1.3e49	5.5e49	1.0e50	1.08e54
MIST	3.3e48	1.5e49	5.1e49	1.1e50	1.06e54
Geneva	3.5e48	1.2e49	4.6e49	7.8e49	9.27e53
BPASS	3.6e48	1.3e49	4.5e49	7.7e49	9.34e53
BoOST	3.7e48	1.2e49	4.4e49	7.4e49	9.14e53

up to 15% difference!

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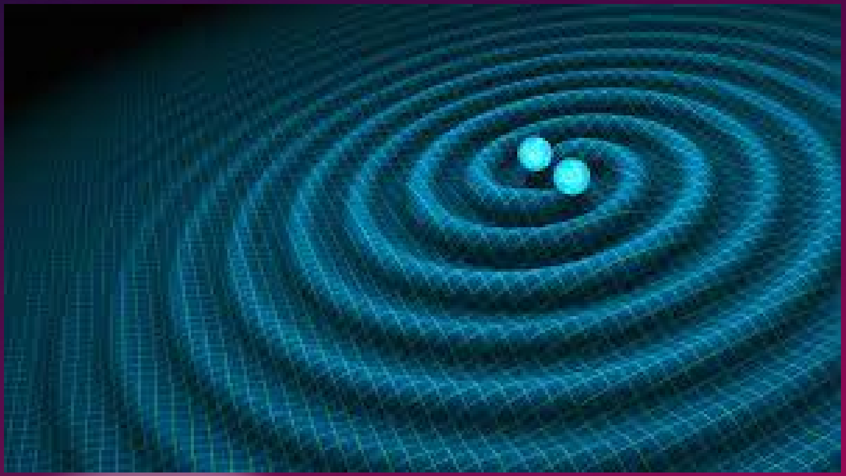
Gravitational waves:
compact object mergers (e.g. black holes)



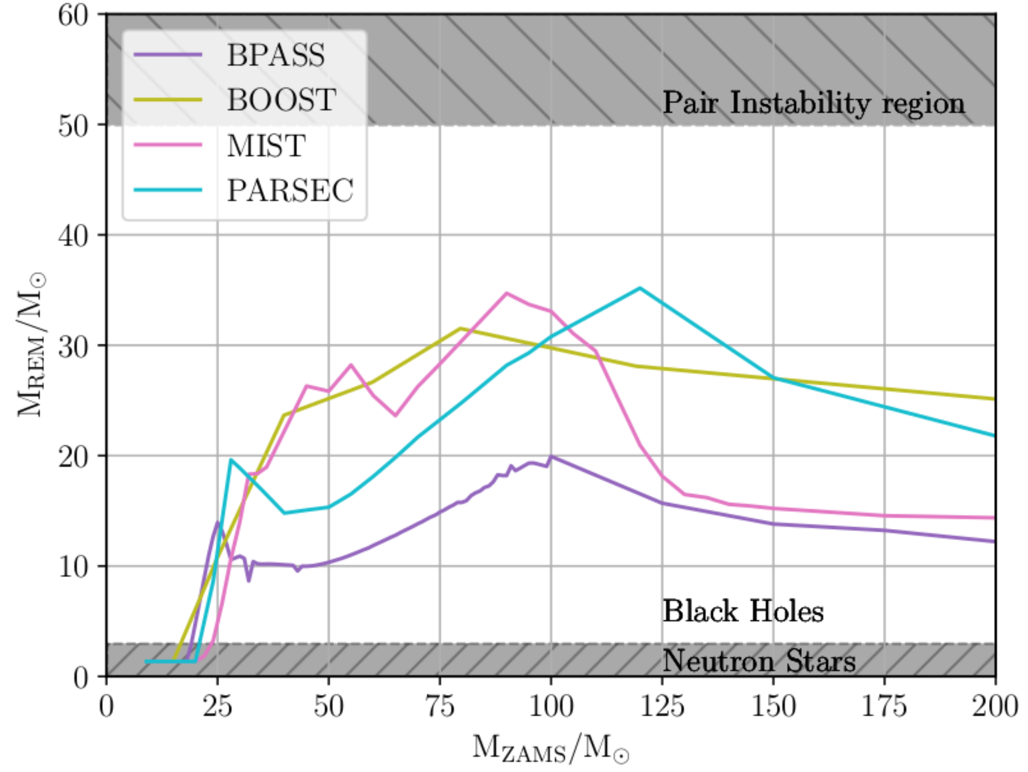


Figure 2. Mass of stellar remnant as a function of the initial mass of the star (near-solar composition). Differences in the assumptions in massive star modelling can cause a variation of up to 20 $M_\odot$ in the remnant masses between simulations. Choosing to apply one of these simulations over the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

up to 20 $M_\odot$ difference!

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Take away messages

- Eddington limit is a thing :)
- stellar evolution above 40 $M_{\odot}$ has

not reached consensus

- use stellar models with extra caution, be flexible for updates

Thanks!