Astronomical Institute of the Czech Academy of Sciences

Physics of Extreme Massive Stars
Marie-Curie-RISE project funded by the European Union

Evolution of massive stars post the main sequence

ambiguities & assessments

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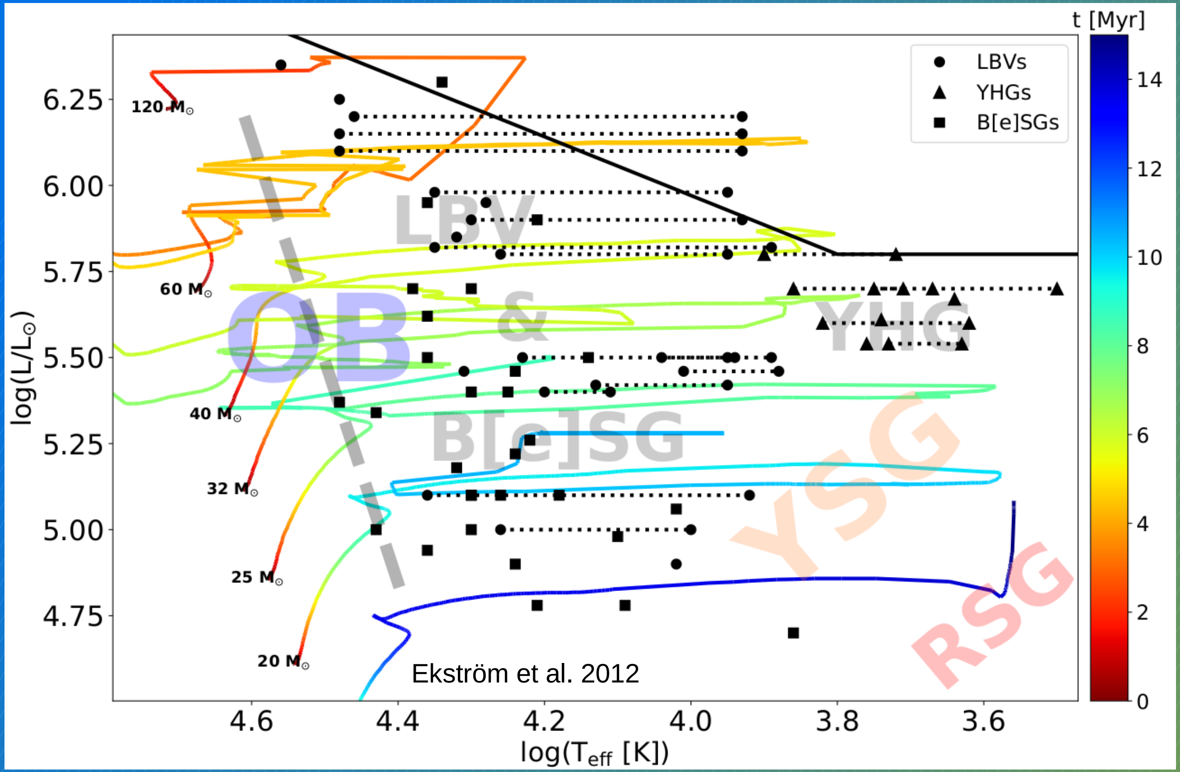
The post-main sequence evolution



- ✔ **Post main-sequence evolution is short but impacting for the stellar fate**
- ✔ **Uncertainties at early stages propagate to the late stages**
- ✔ **Certain stellar types may emerge by various channels**

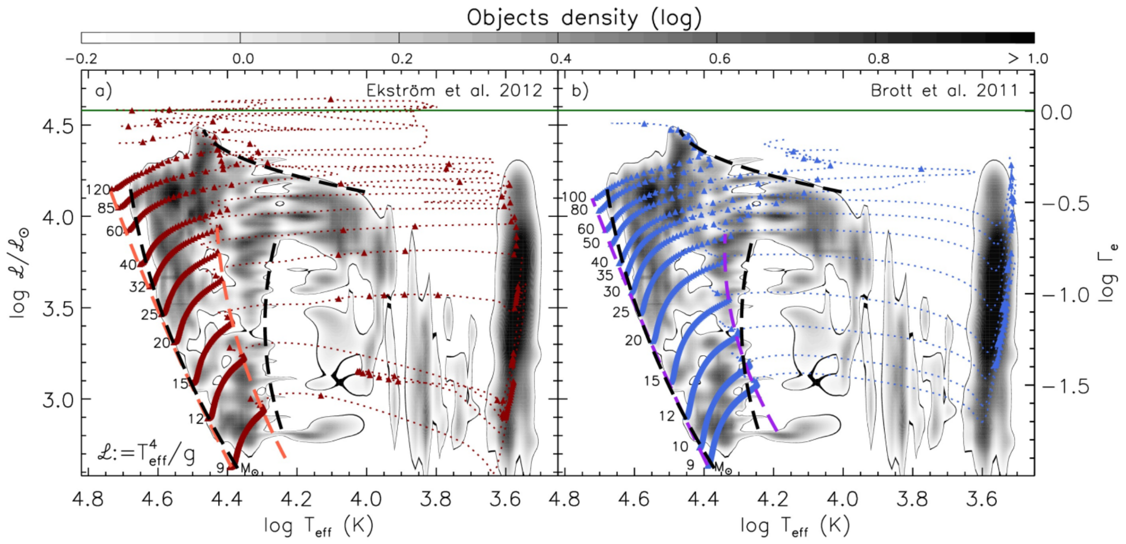
Nevertheless !!

- ✔ **Evolved stars are well accessible, thus ideal for high-resolution studies**
- ✔ **Study of their variability give access to interior, atmosphere and environmental properties**

The BSG problem

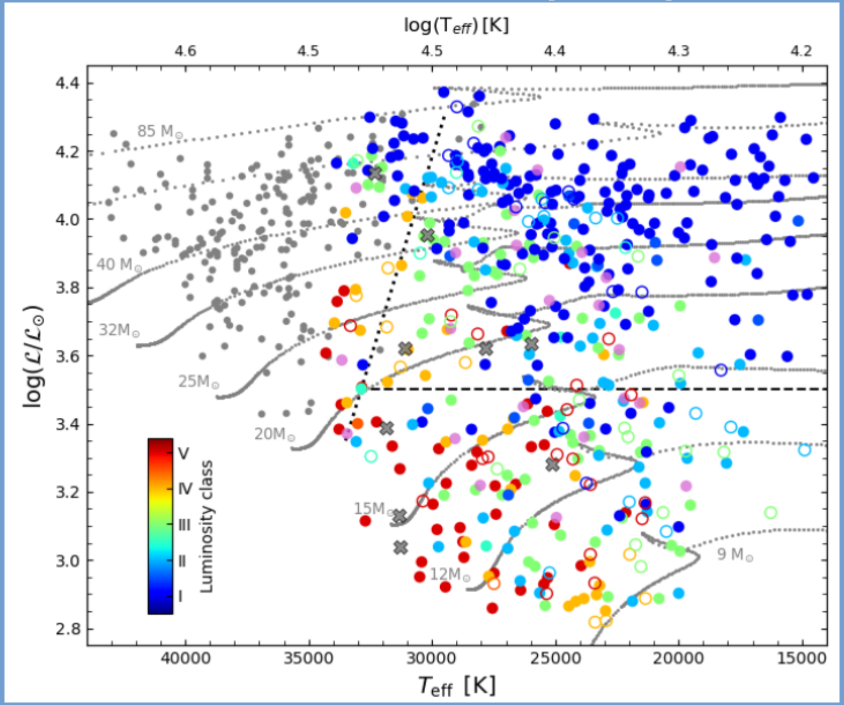
… or what is the origin of BSGs ?

Spectroscopic HR diagram of 600 Galactic massive stars



Castro et al. 2014

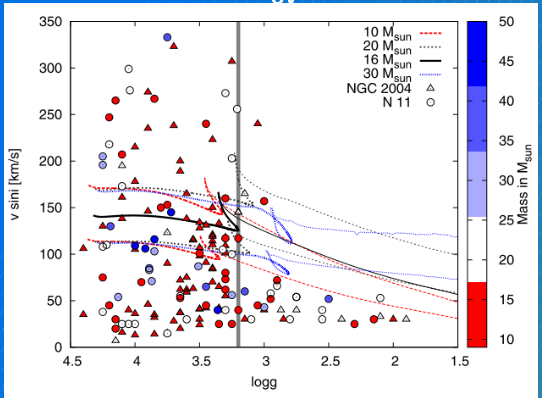
500 Galactic O9–B9 (LC I-II)



de Burgos et al. 2023

Internal mixing - binarity

assessing f_{ov} from vsini

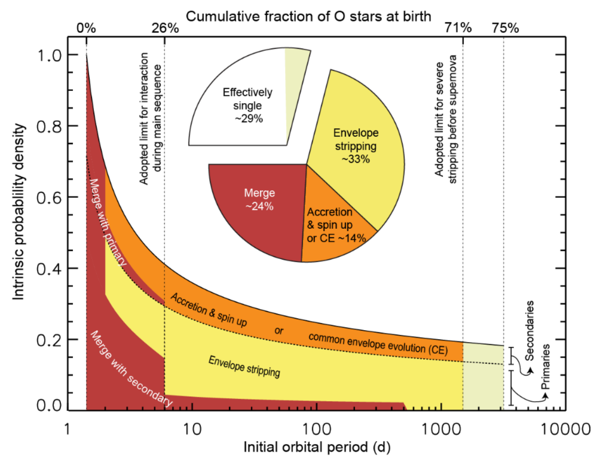


Brott et al. 2011

Core mass fraction regulated by

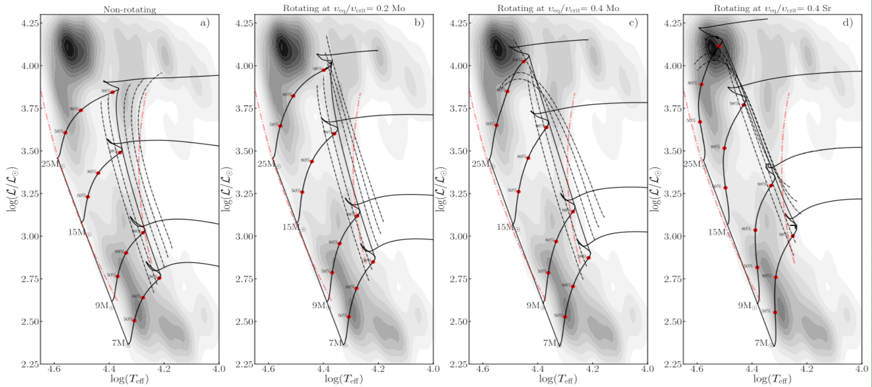
- Convective overshooting
- Rotationally induced mixing (depending e.g. on *Z* and binarity)

O-type multiplicity and interactions



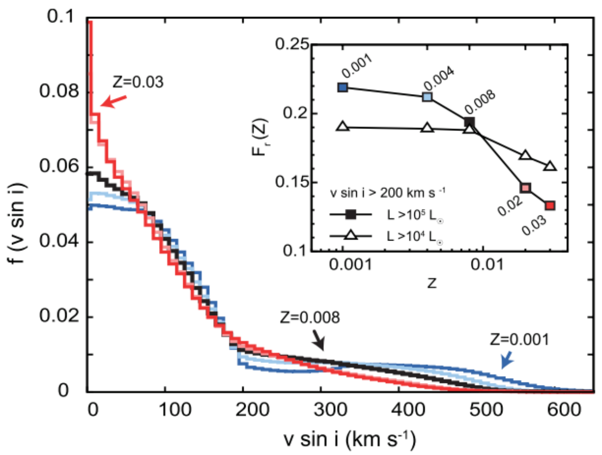
Sana et al. 2012

sHRD for different α and ang.mom. transport



Martinet et al. 2021

fast rotators = interacting binaries ?



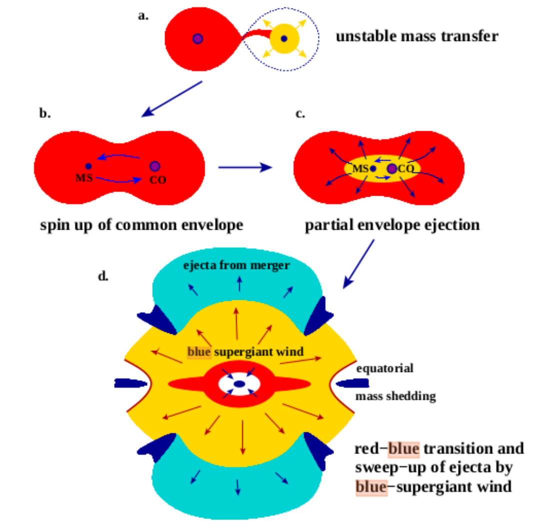
de Mink et al. 2013

BSGs as SN progenitors

SN 1987A (NASA/ESA HST)

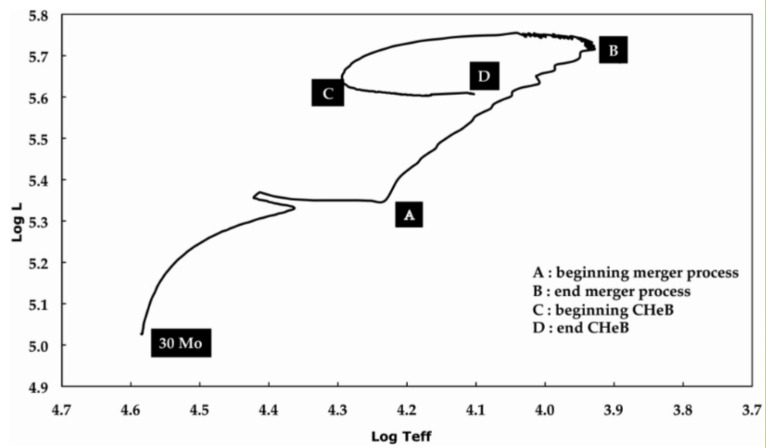
Binary mergers are needed for providing

- rapid rotating supergiants
- H supply to the envelope

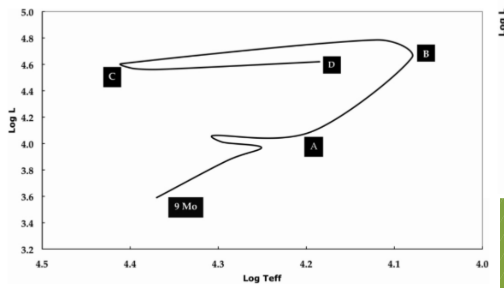


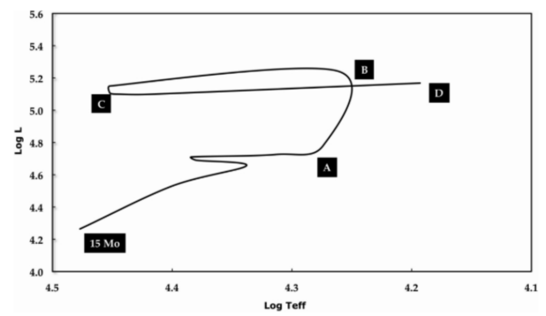
Morris & Podsiadlowski 2007

Evolutionary track of a 30+20 Mo Case B merger



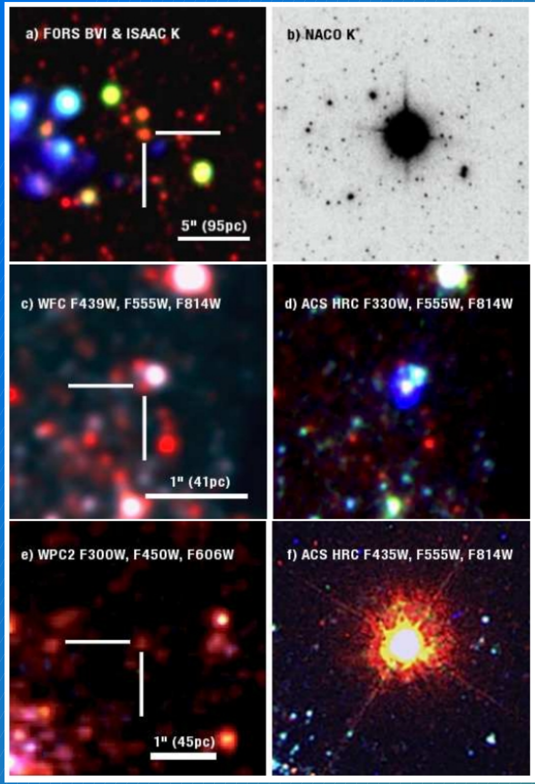
Vanbeveren et al. 2013



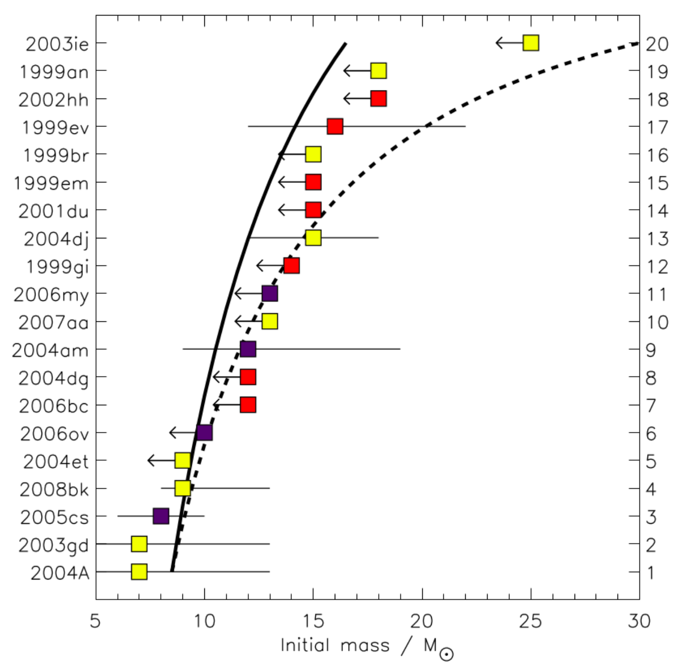


The RSG problem

..or how do stars with M > 20 M_o die ?

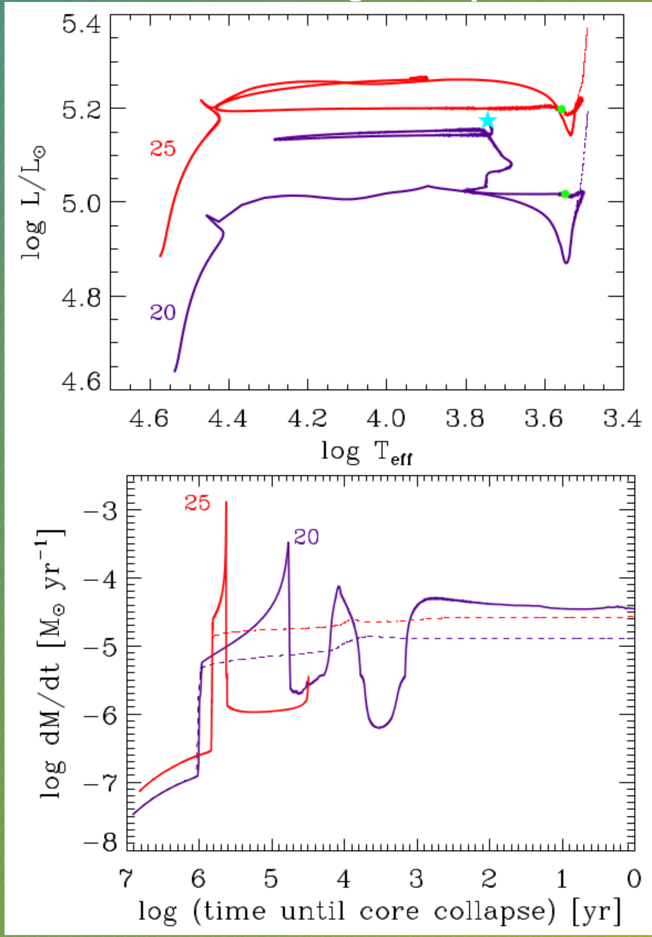


pre/post-SN imaging



Smartt 2009

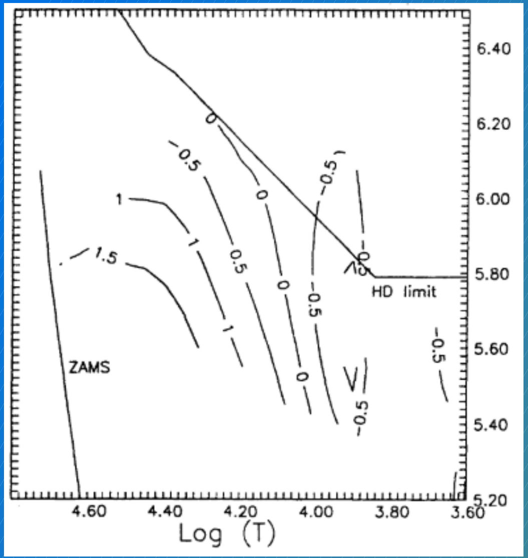
mass-loss during RSG phase



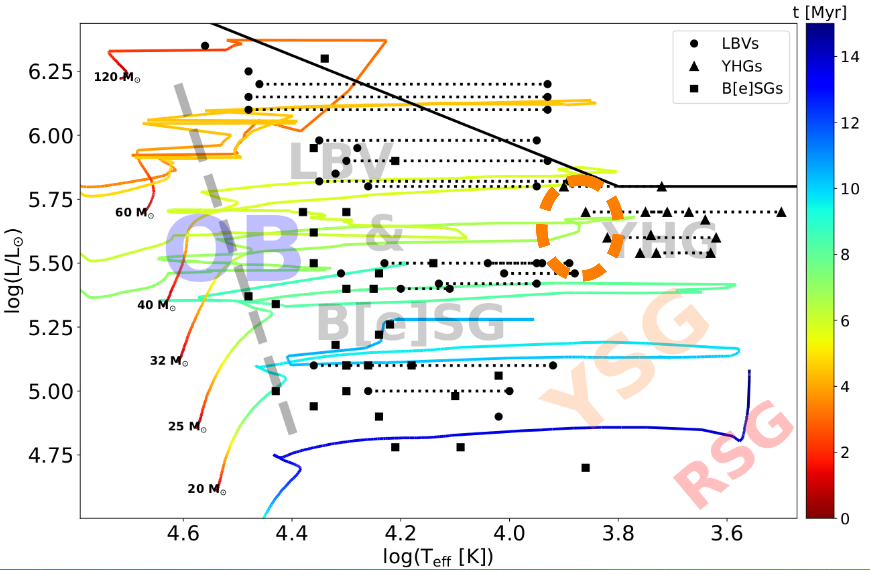
Yoon & Cantiello 2010

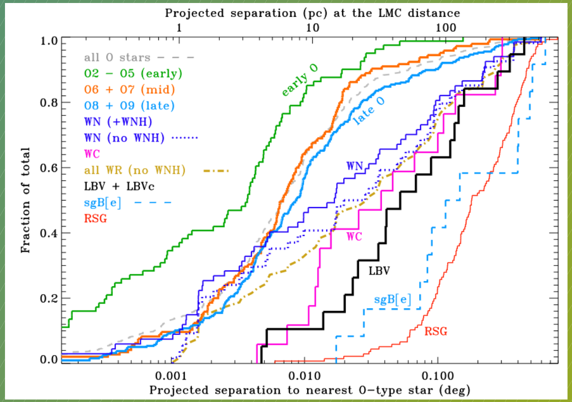
Post-RSG evolution & instability

Mapping $\log g_{eff}$ in postRSG

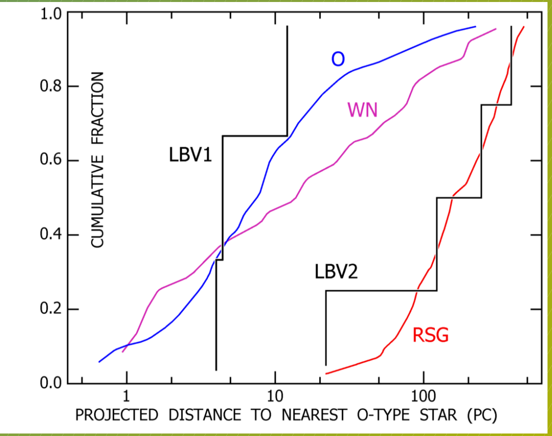


Nieuwenhuijzen et al. 1995





Smith & Tombleson et al. 2015



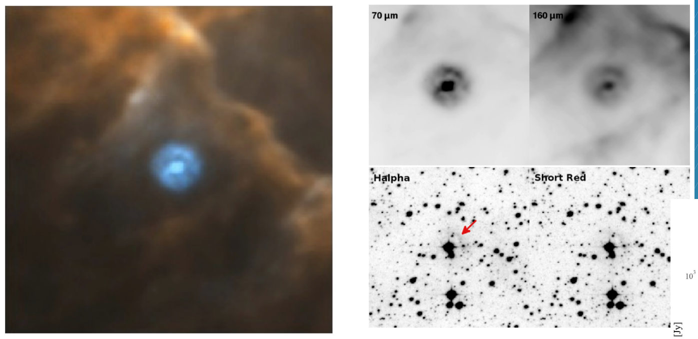
Humphreys et al. 2016

- ✔ Post-RSG evolution is linked to states where atmospheres become highly unstable
- ✔ Fraction of transition-phase massive stars are thought to be in a post-RSG phase

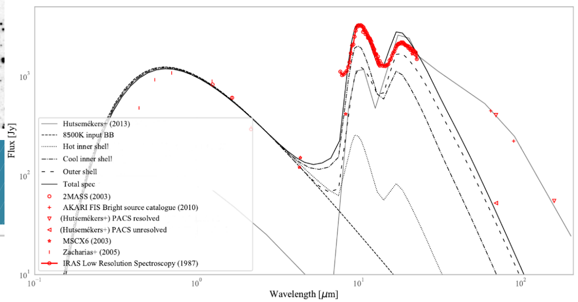
Observational assessments

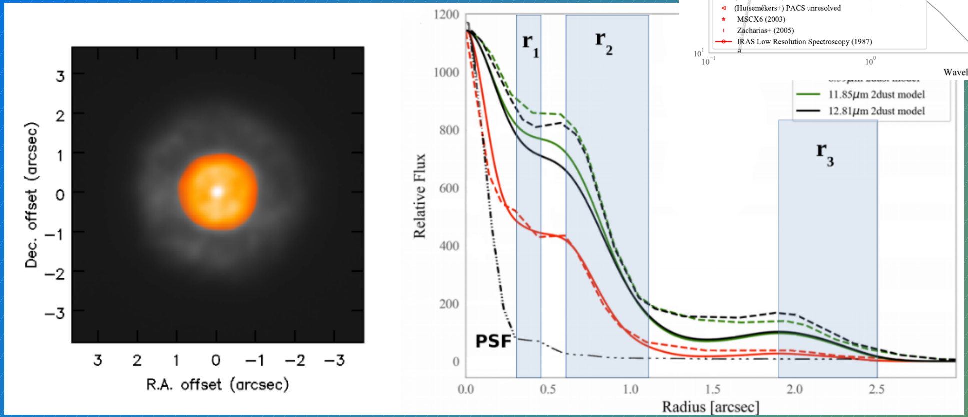
Dusty surroundings of post-RSGs

Hutsemekers et al. 2013



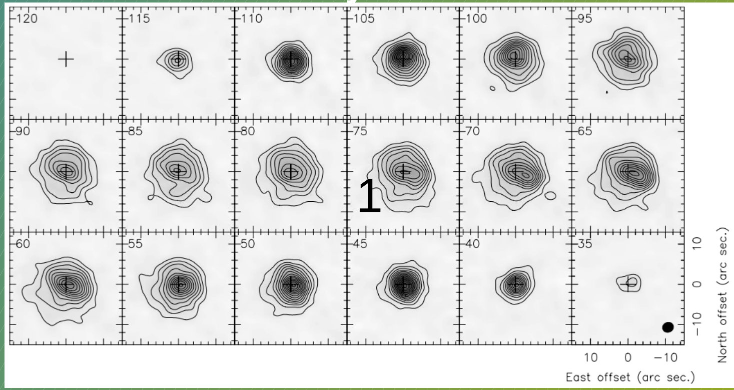
Hen 3-1379: The Fried Egg nebula





Koumpia et al. 2020

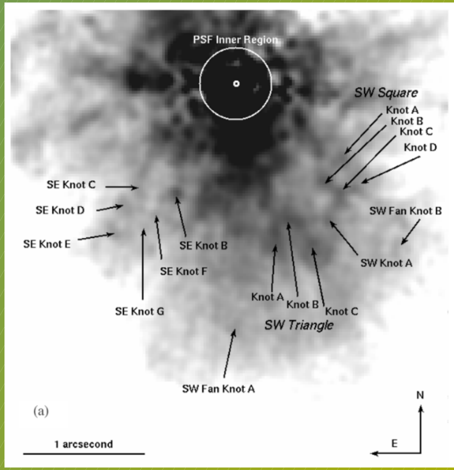
Interferometry of IRC+10420



Castro-Carrizo et al. 2007

- ✔ Complex ejecta
- ✔ Shells tracing mass-loss events
- ✔ Distinct embedded features

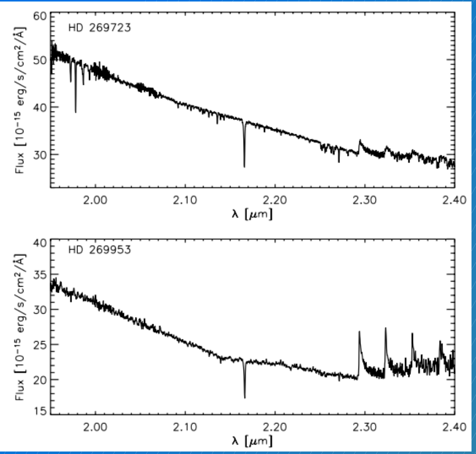
HST imaging IRC+10420



Tiffany et al. 2010

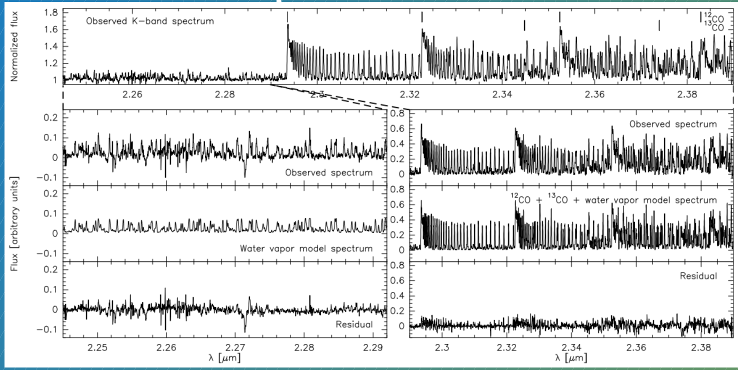
Ejected molecules from post-RSGs

CO disk around LMC YHGs ?



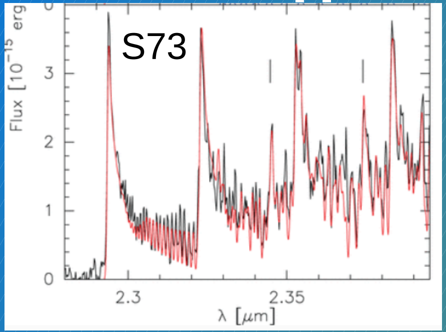
Oksala et al. 2013

Water vapor around HD269953



Kraus et al. 2022

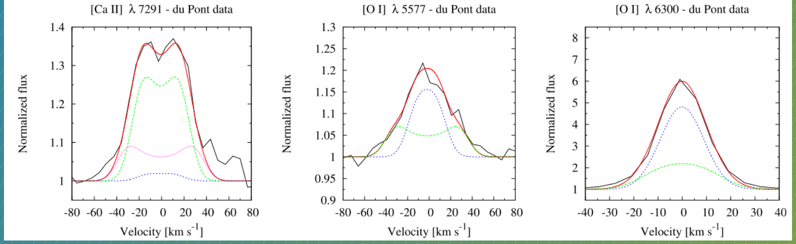
CO¹³ around B[e]SGs



Liermann et al. 2010

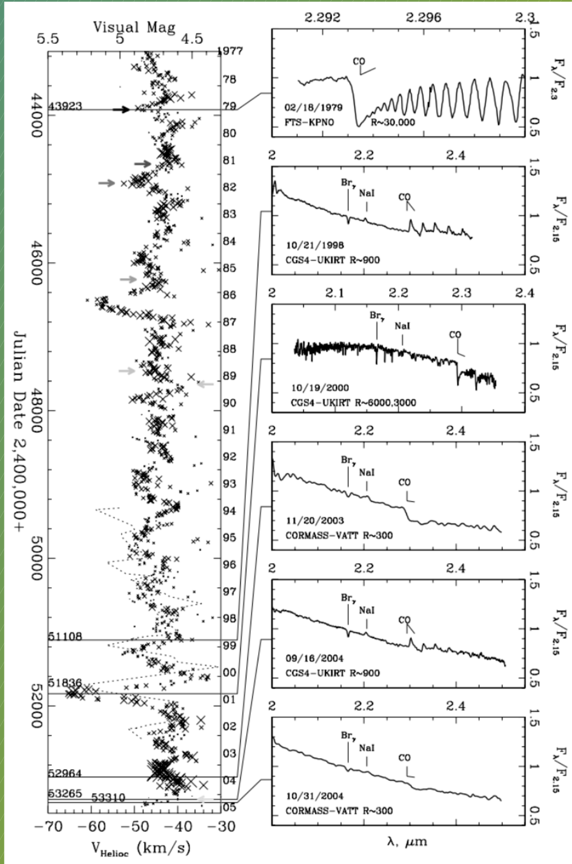
Disks/rings around post-RSGs

Forbidden optical lines tracing rings in S 35



Torres et al. 2018

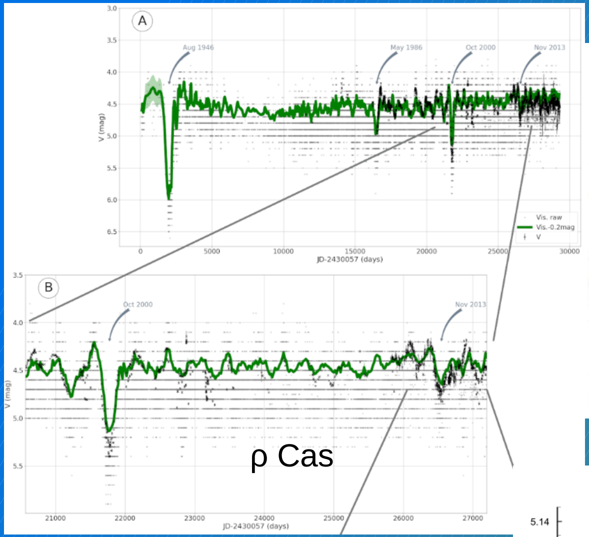
Pulsations on CO gas of ρ Cas



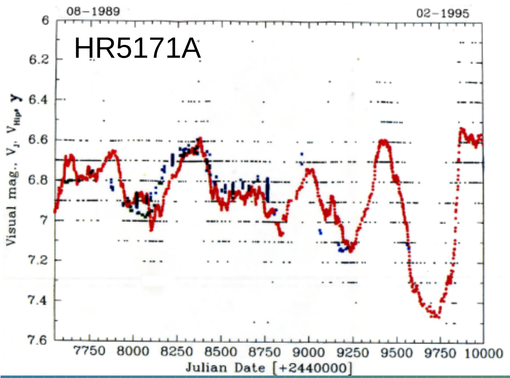
Gorlova et al. 2006

Observed pulsations in post-RSGs

Maravellias & Kraus 2021

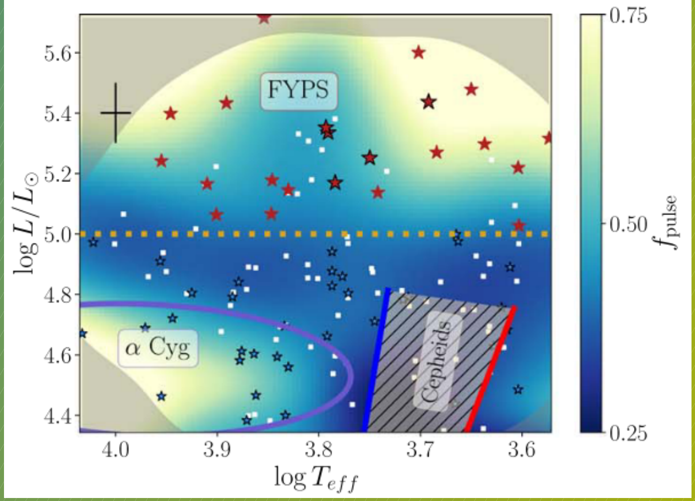


van Genderen et al. 2019

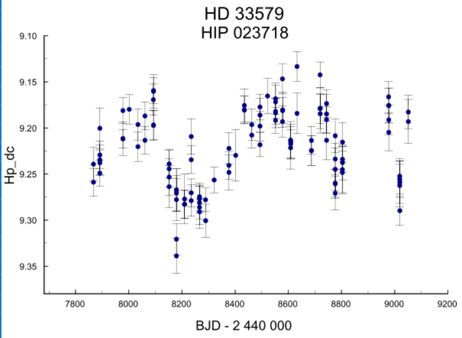


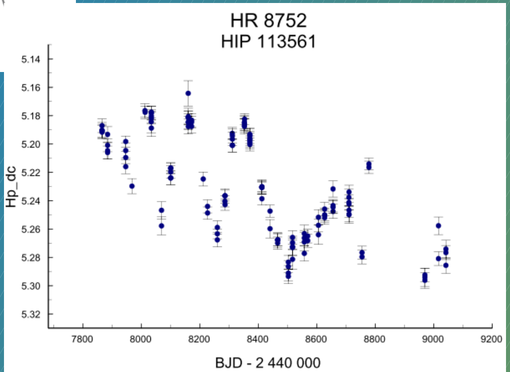
- Most, if not all, YHGs exhibit pulsations with poorly-understood nature
- Pulsating properties change based on the location/direction of the YHG on the HRD
- How does the pulsating activity change in YHGs compared to YSGs ?

Are post-RSGs fast pulsators ?



Dorn-Wallenstein et al. 2022



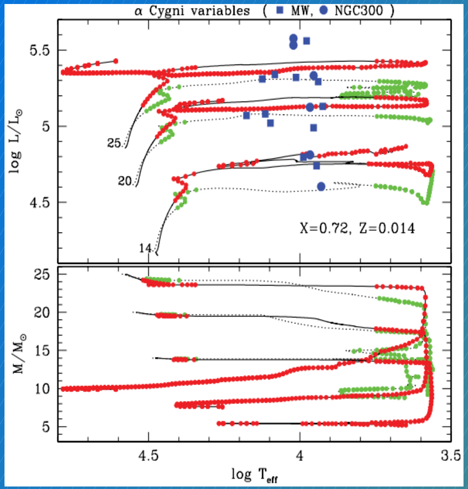


Nieuwenhuijzen & de Jager 2000

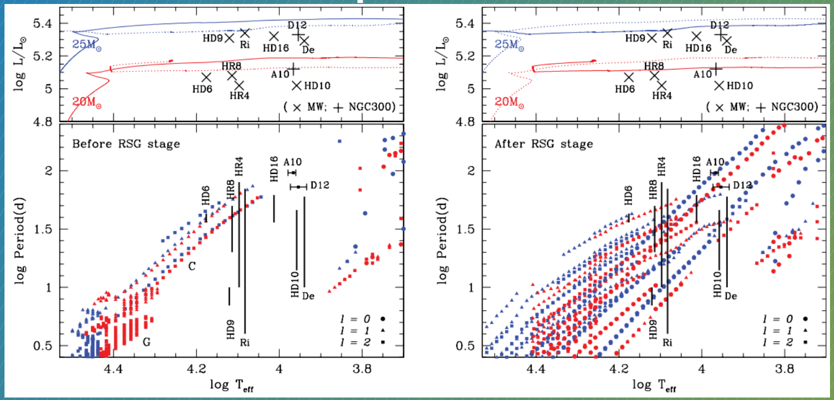
Strange modes in post-RSGs

- For L/M ratios above 10^4, the strange mode instabilities persist over the entire range of Teff (Glatzel & Kraus 2024)
- Radial (strange-mode) pulsations are excited in models that had been RSGs previously (Saio et al. 2013)

Excitation of radial mode

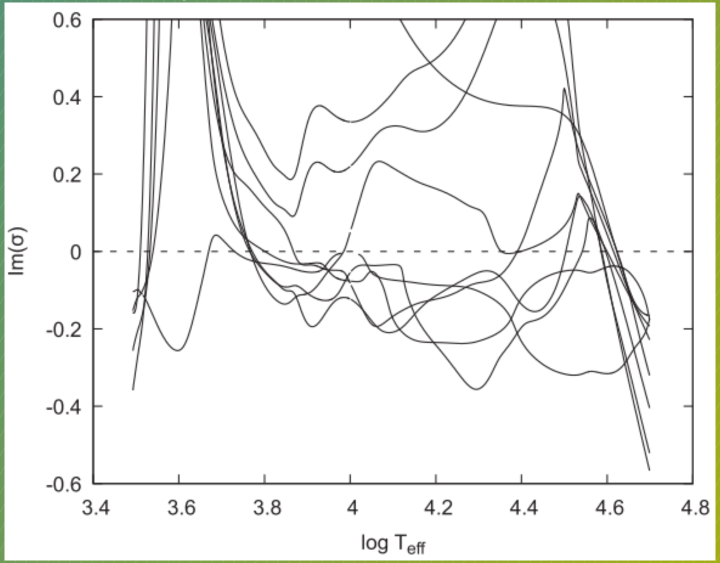


Periods of pulsations excited



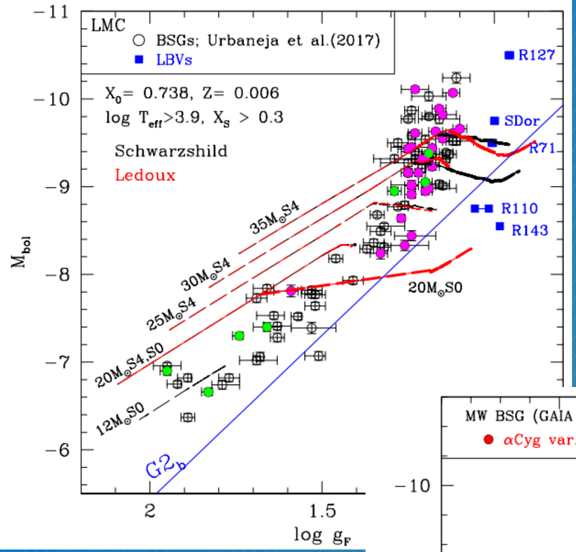
Saio et al. 2013

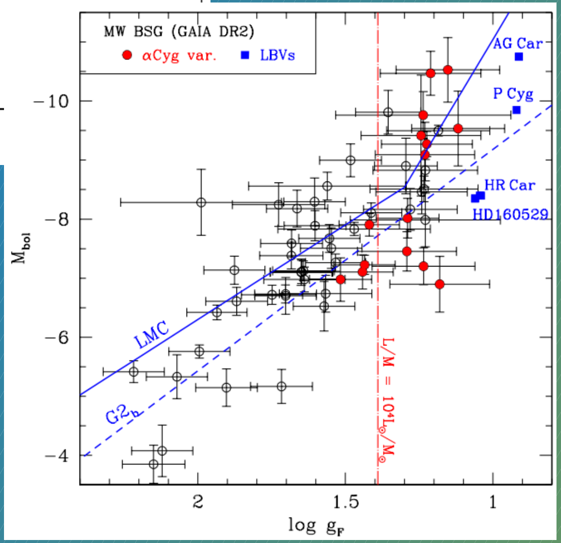
M = 25 M_O, $\log(L/L_O) = 5.3$, LMC metal/ty



Glatzel & Kraus 2024

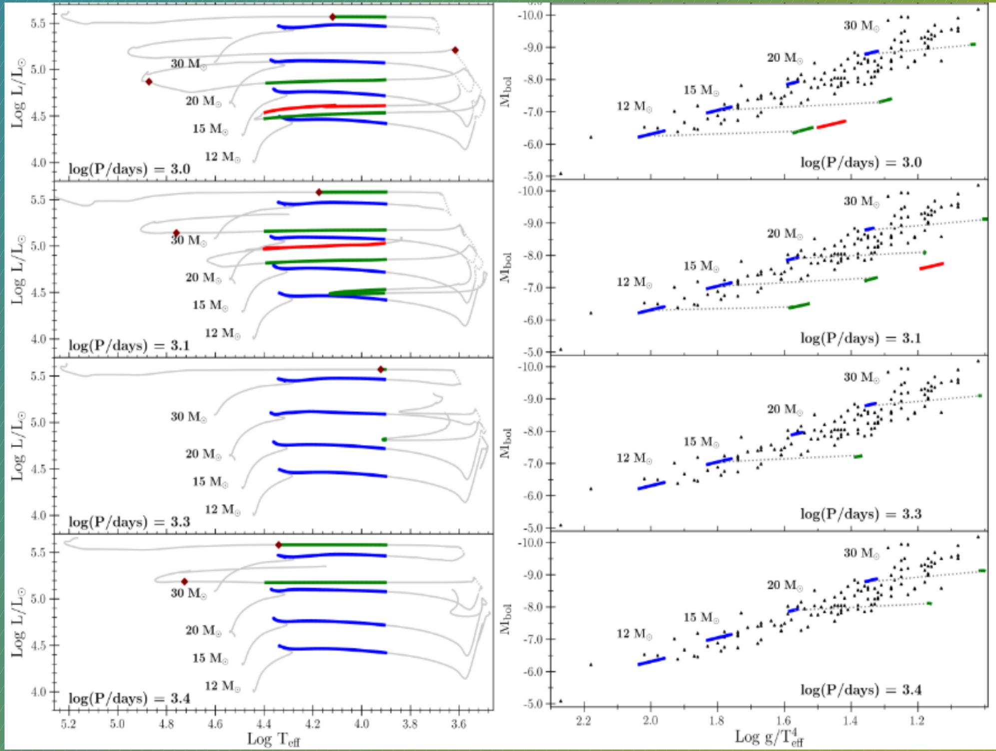
Flux-weighted gravity–luminosity relation





Georgy et al. 2021

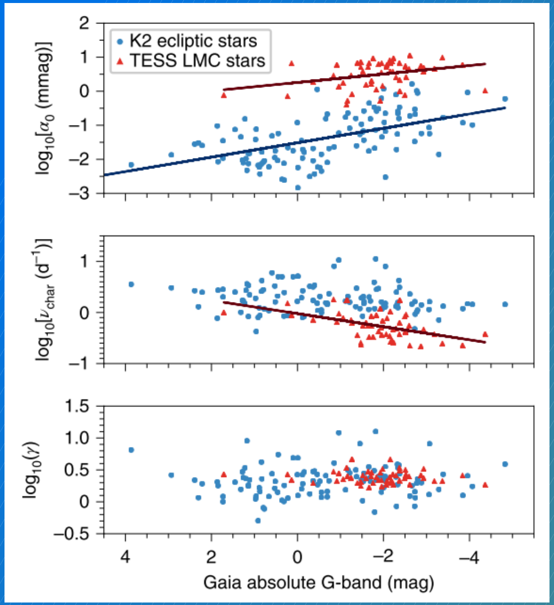
$$g_{\mathrm{F}} = \frac{g}{(T_{\mathrm{eff}}/10^4\ \mathrm{K})^4}$$



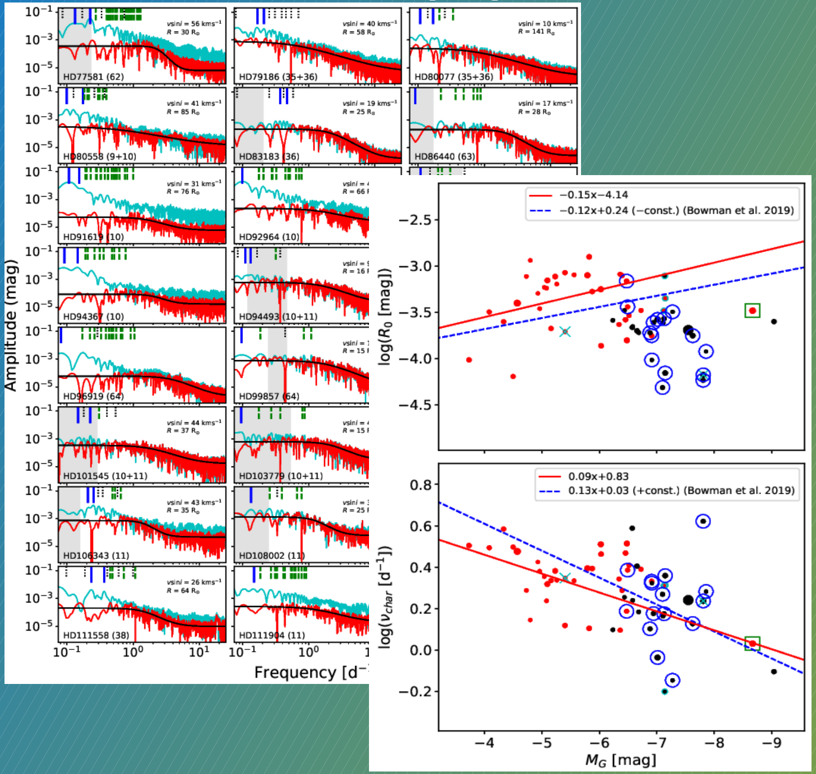
Farrell et al. 2019

Internal gravity waves

Bowman et al. 2019



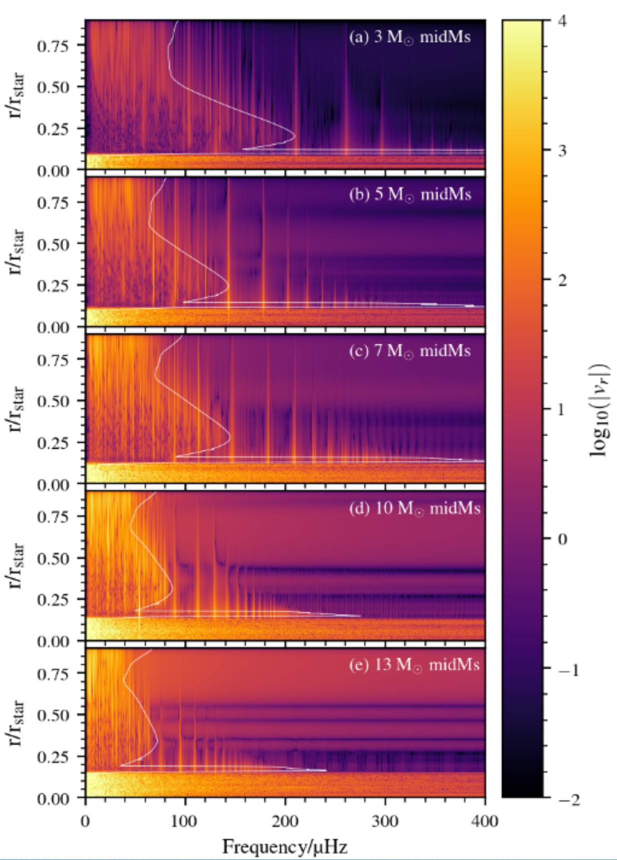
Kourniotis et al. in prep.



- Internal gravity waves, which are excited by core convection, are suggested as source of the low-frequency signal in massive stars.
- The red noise level scales with the stellar luminosity.
- Metallicity and evolutionary state of BSGs are currently explored.

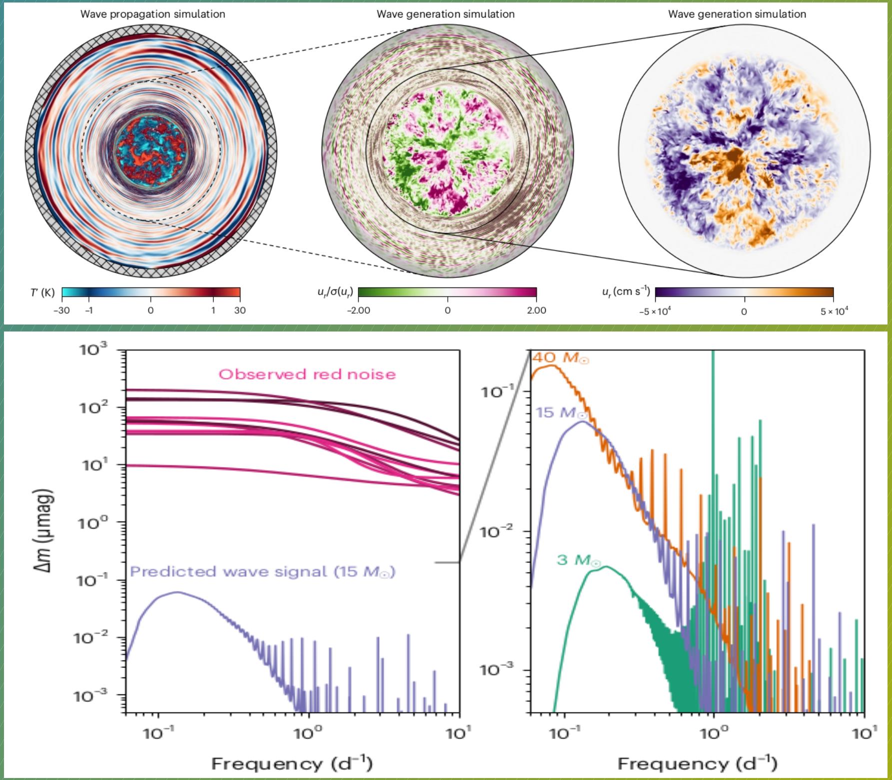
Modeling core convection

2D int. fluid evolution (3-13 Mo)



Ratnasingam et al. 2023

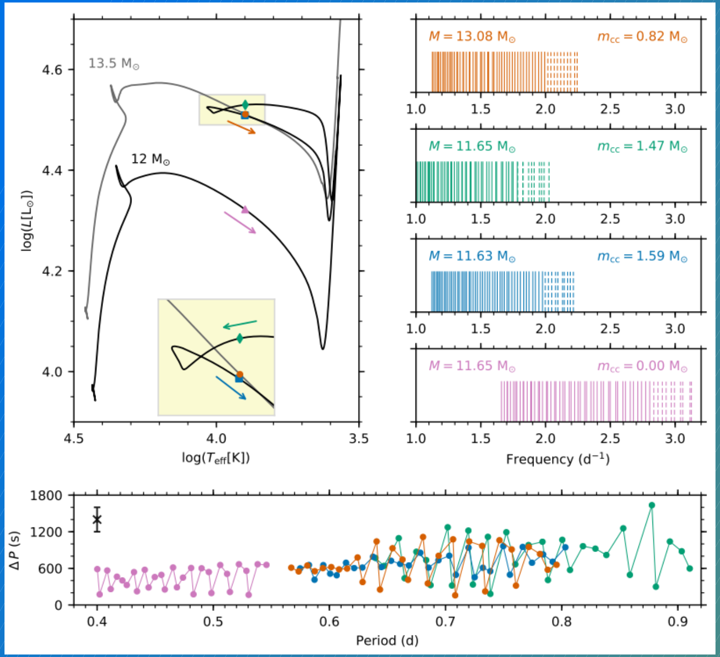
Interior 3D simulations of 15 Mo star



Anders et al. 2023

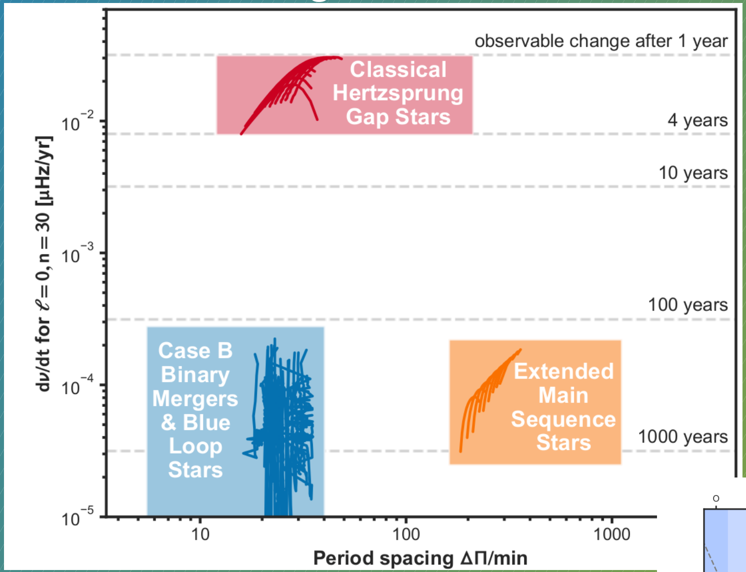
The asteroseismic potential

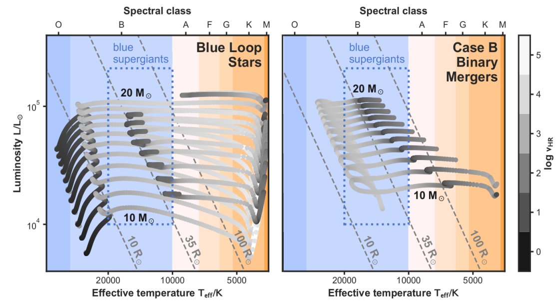
Bowman et al. 2019

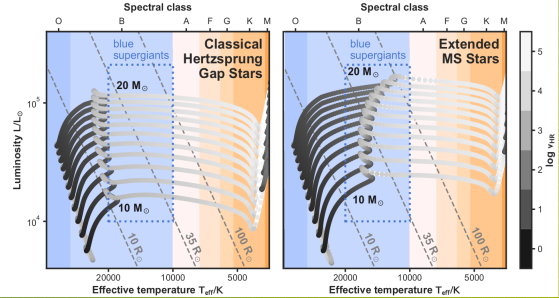


- f_{ov}=0.02, X = 0.72
- MESA + GYRE
- Adiabatic dipole zonal frequencies
- p-mode (dashed), g-mode (dotted)

Bellinger et al. 2023







- Stars with H cores, ΔΠ∼200m.
- Stars with He cores, ΔΠ∼20 min.
- Stars with H shell, frequency chances of the order 10^{-2} μHz/yr.

Conclusions

- Understanding the post-main sequence distribution of massive stars on the evolutionary diagram still poses a major challenge.
- Large theoretical uncertainties already at the earliest phases of stellar evolution propagate to the predictions of the later stages.
- With several free parameters and strong degeneracies describing the evolutionary modeling, tight constraints are needed from the observations.
- Asteroseismology is the key tool in mapping the stellar interior and distinguishing between the different evolutionary scenaria.
- Simulations that integrate large spectrum of massive star physics are needed.