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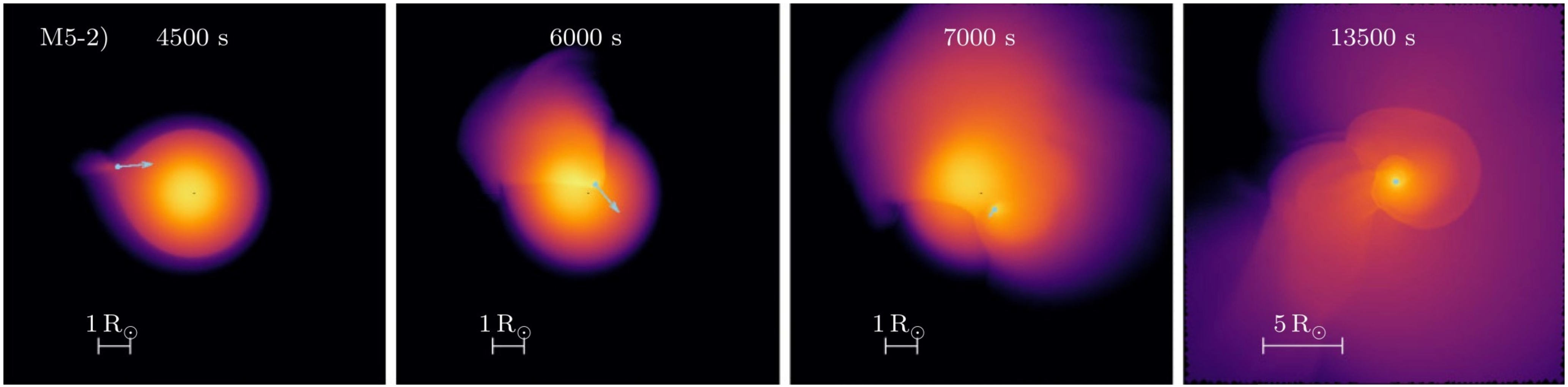
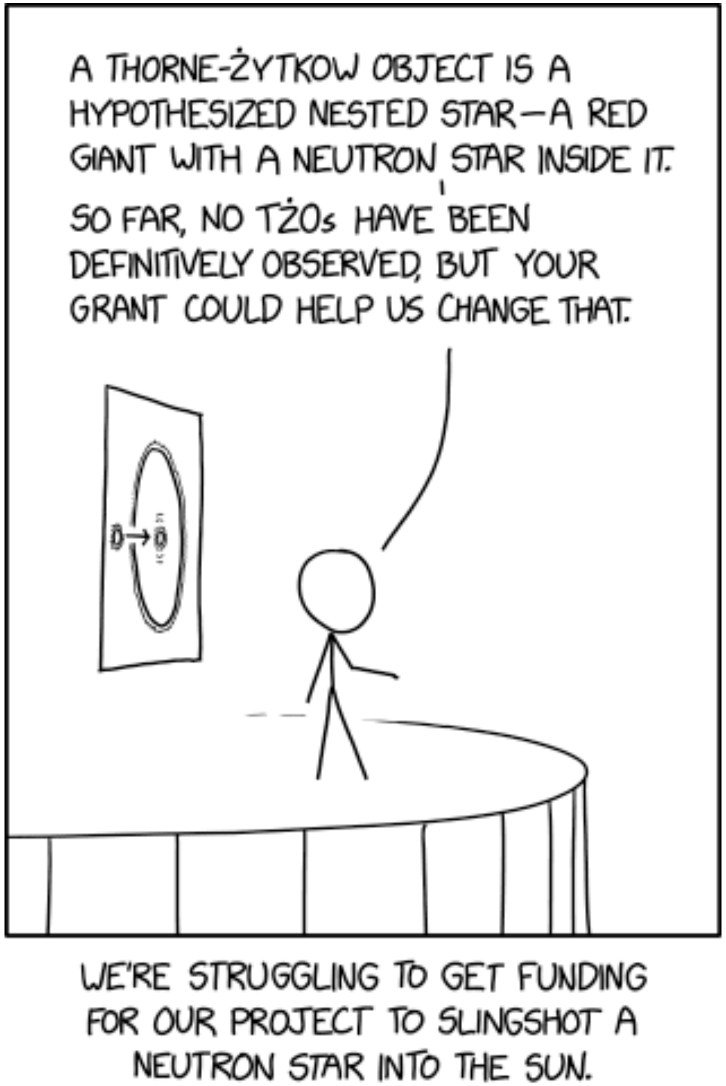
Galactic Chemical Evolution with Hybrid Stars – From Structural Assumptions to Yields

NAM2025
Durham - 09/07/25



“Ooh, basically, a star is a pretty simple thing…”
– Fred Hoyle

Thorne-Żytkow Objects



Landau stressed, as did Gamow, that a neutron core would "give an immediate answer to the question of the sources of stellar energy."
–D. G. Yakovlev

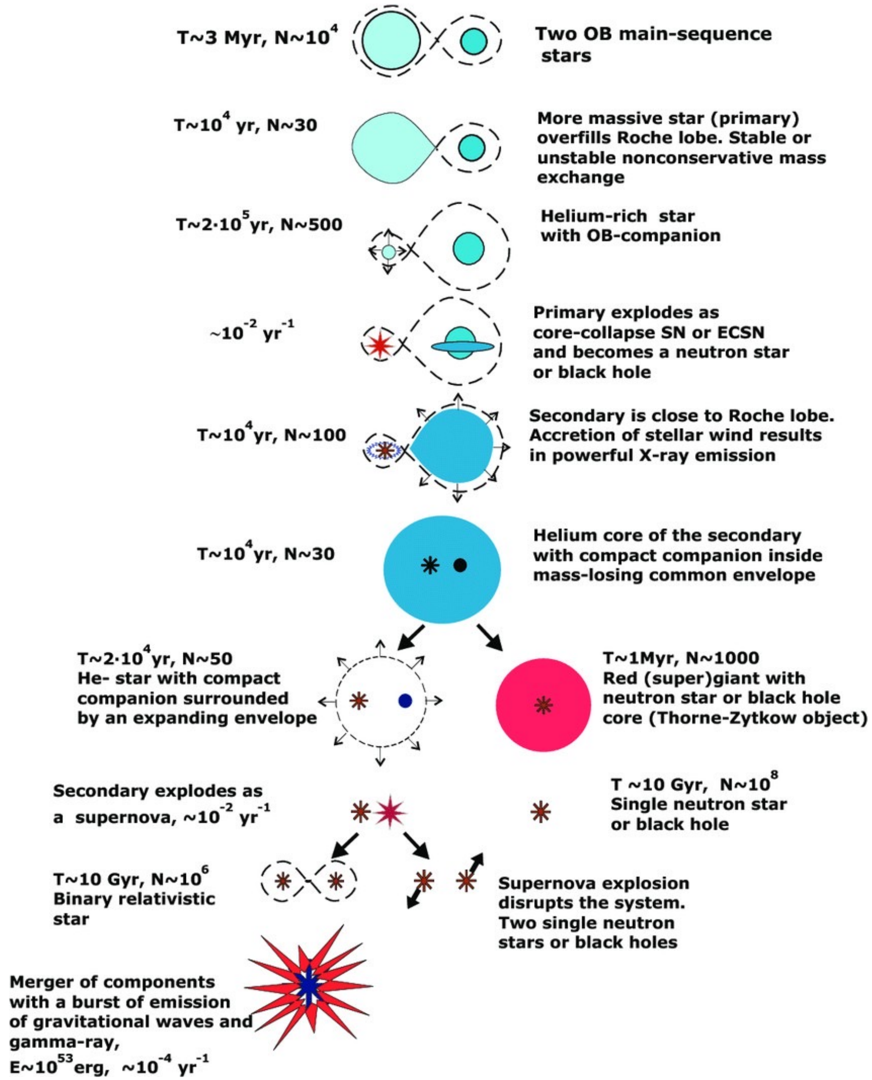
Formation

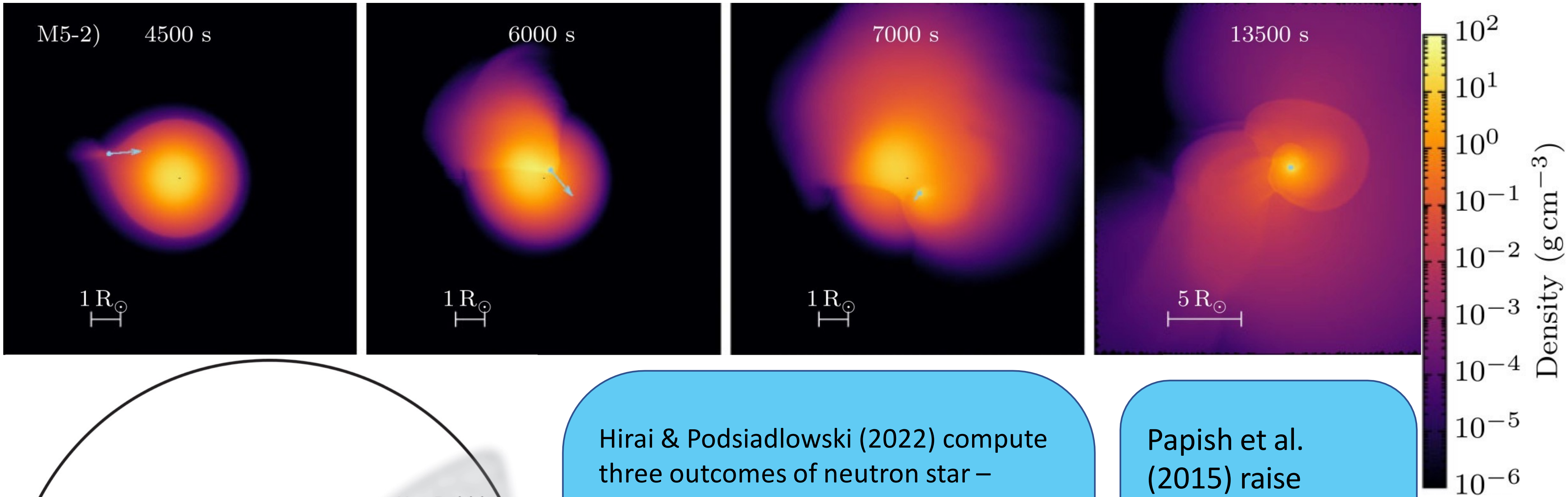
Hybrid Stars – Stars with some non-standard internal structure

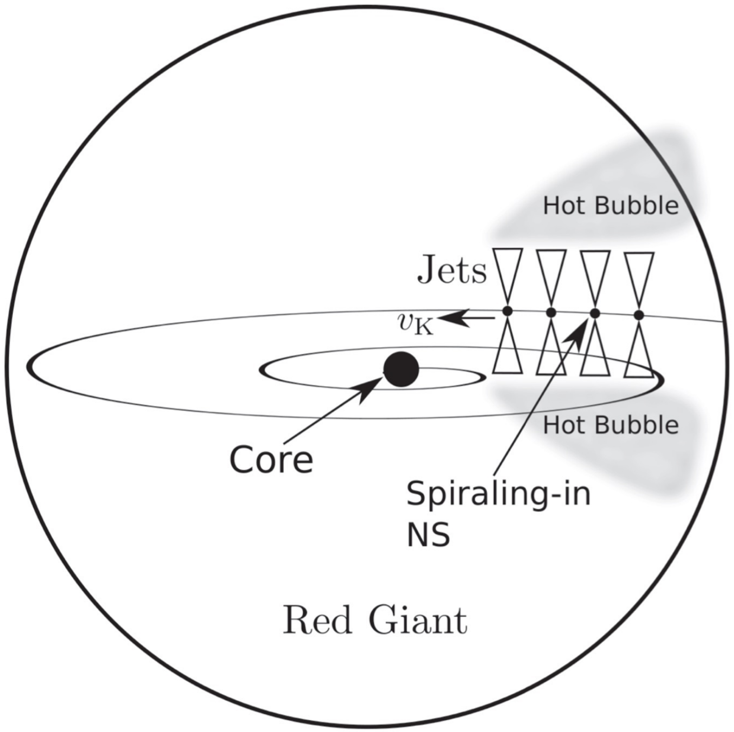
Thorne-Żytkow Objects (TŻOs) – a hybrid star consisting of a neutron star surrounded by a diffuse, giant envelope

Proposed formation mechanism – CEE of giant with neutron star (Podsiadlowski et al. 1996)

Possibility – a fraction (large? All?) of HMXB systems could be TŻO progenitors





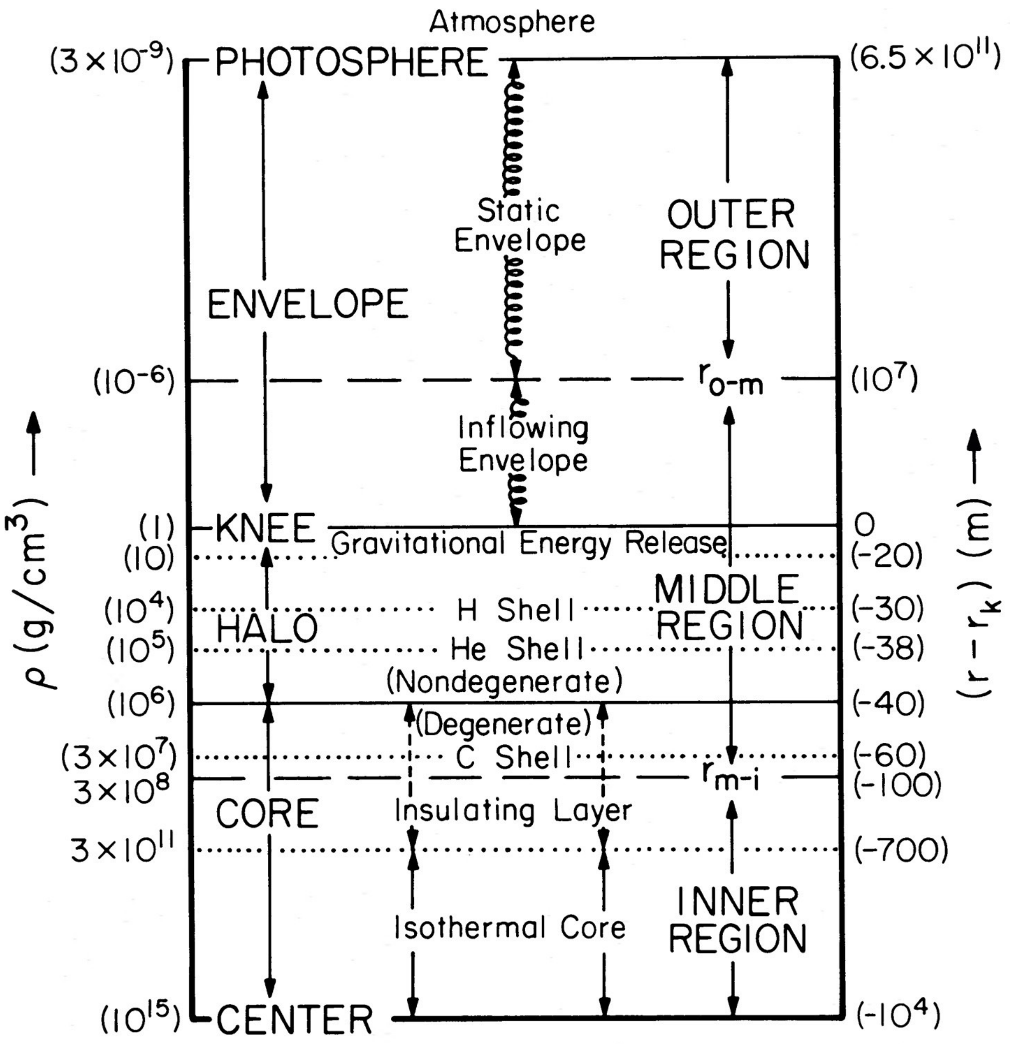


Hirai & Podsiadlowski (2022) compute three outcomes of neutron star – binary companion collisions:

1. NS does not intersect companion surface – tidal bulge excited, surface shock
2. Envelope penetration – partial TDE, material is carried away
3. Immediate merger (above) – NS never reemerges from the envelope, TŻO formed

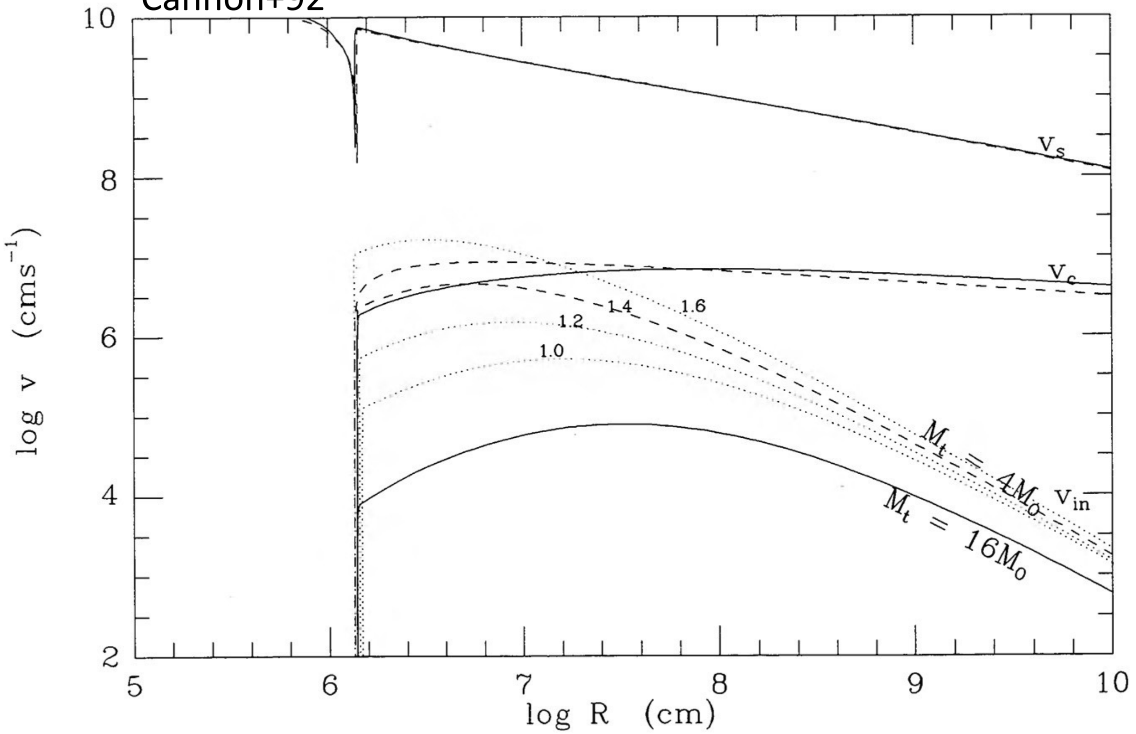
Papish et al. (2015) raise possibility of jets launched during formation ejecting envelope – but can retain or lose envelope, based on tuning (Soker et al. 2013)

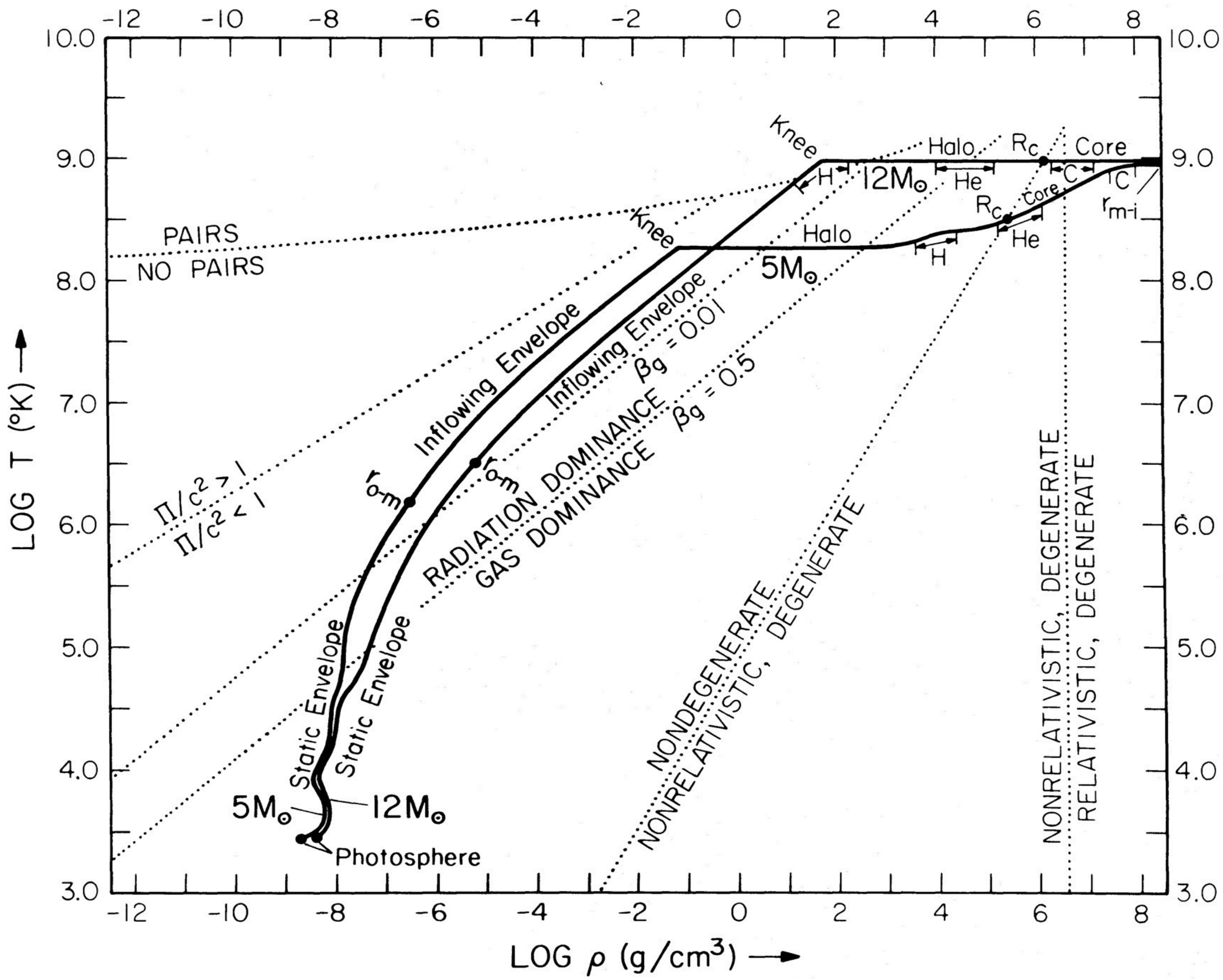
Canonical Structure



Thorne & Żytkow 77

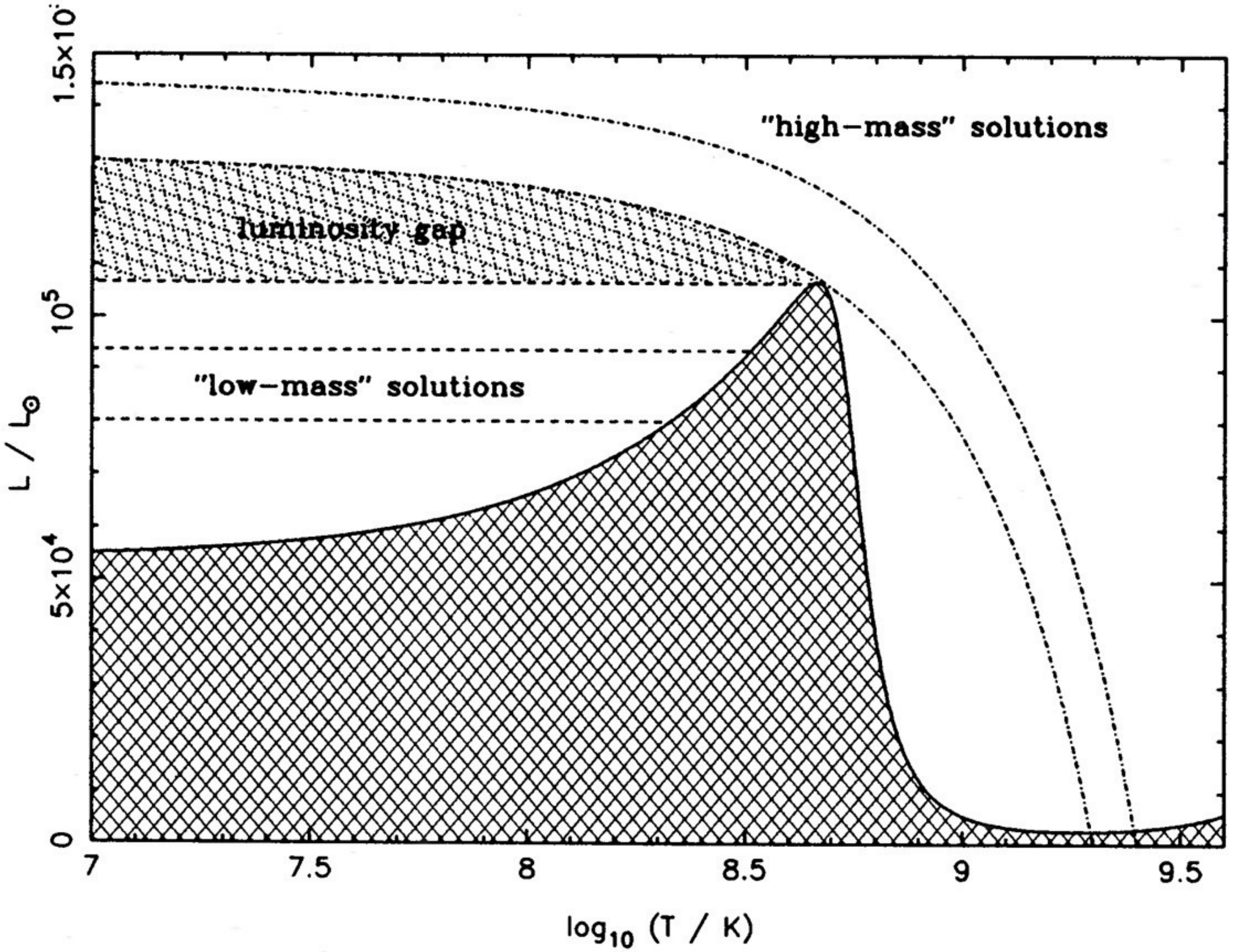
Cannon+92





TŻ & Cannon et al. Models – main features

- Static and inflowing envelope
- Knee – base of convective envelope
- Halo – radiative region reaching down to around 10x knee density – gravitational energy release
- Insulating layer – from e^- degeneracy to n drip line
- Isothermal neutron core



Cannon (1993)

TŻ & Cannon et al. Models – main features

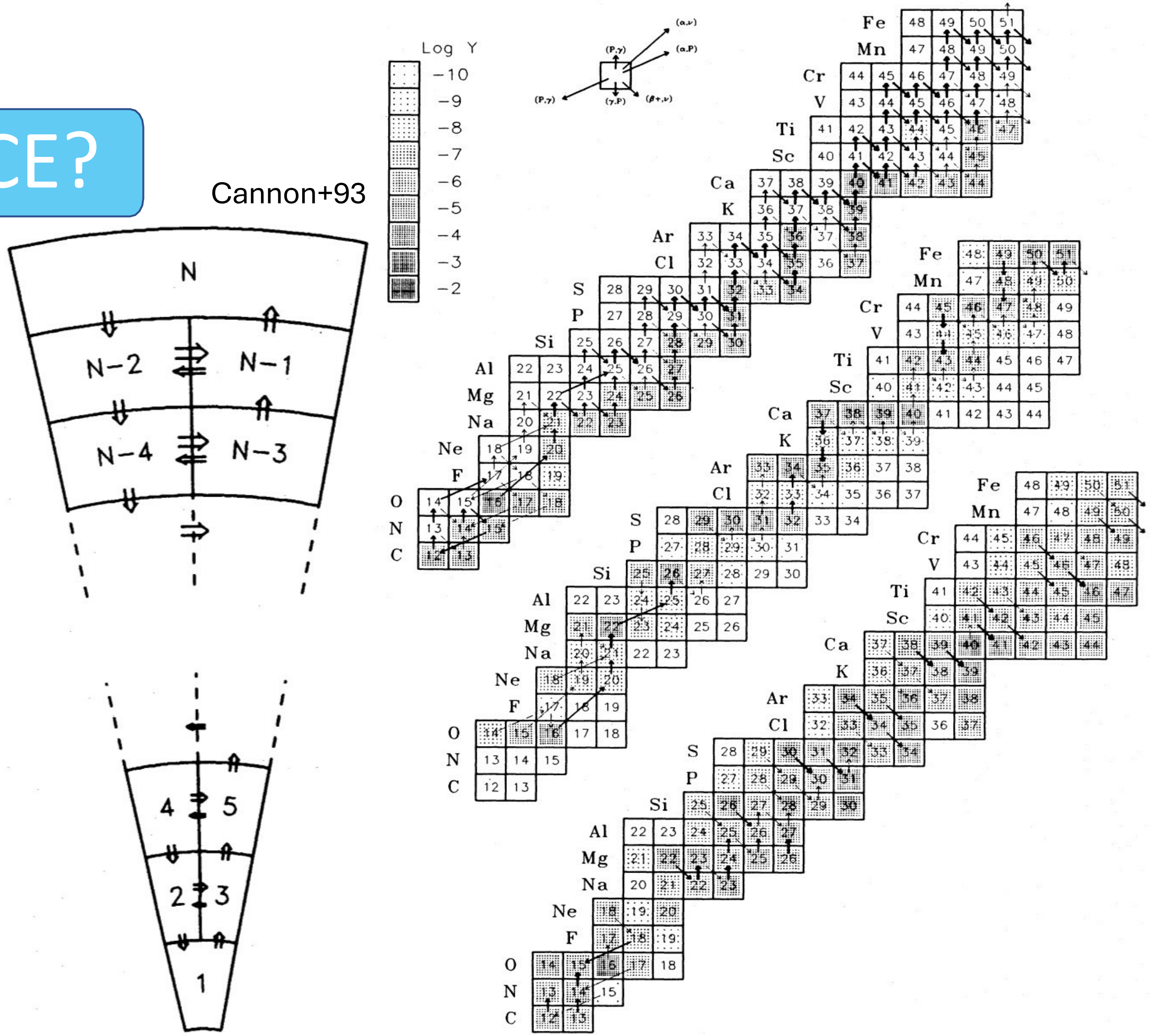
Two general classes of solutions

- Giants – Below around 9M$_\odot$ – energy generation dominated by ε_{grav} below the knee
- Supergiants – above around 13M$_\odot$ – energy generation dominated by ε_{nuc} H burning above the knee, He below

Applicable to GCE?

Applicable to GCE?

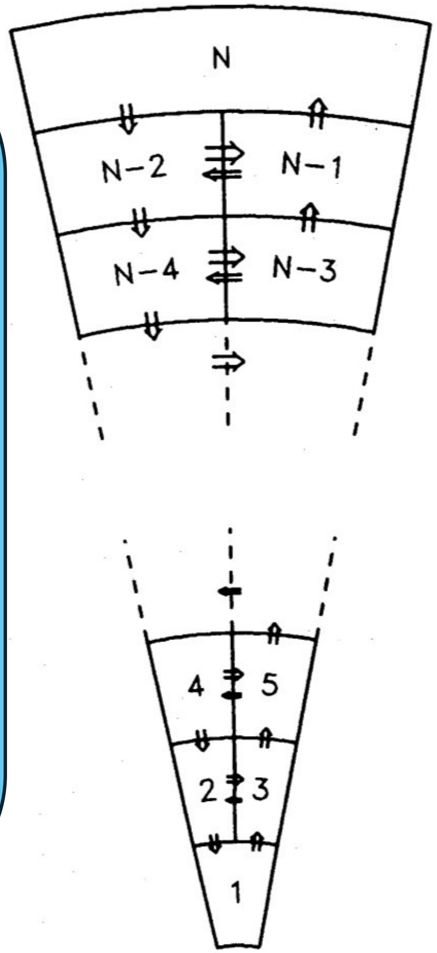
Cannon+93

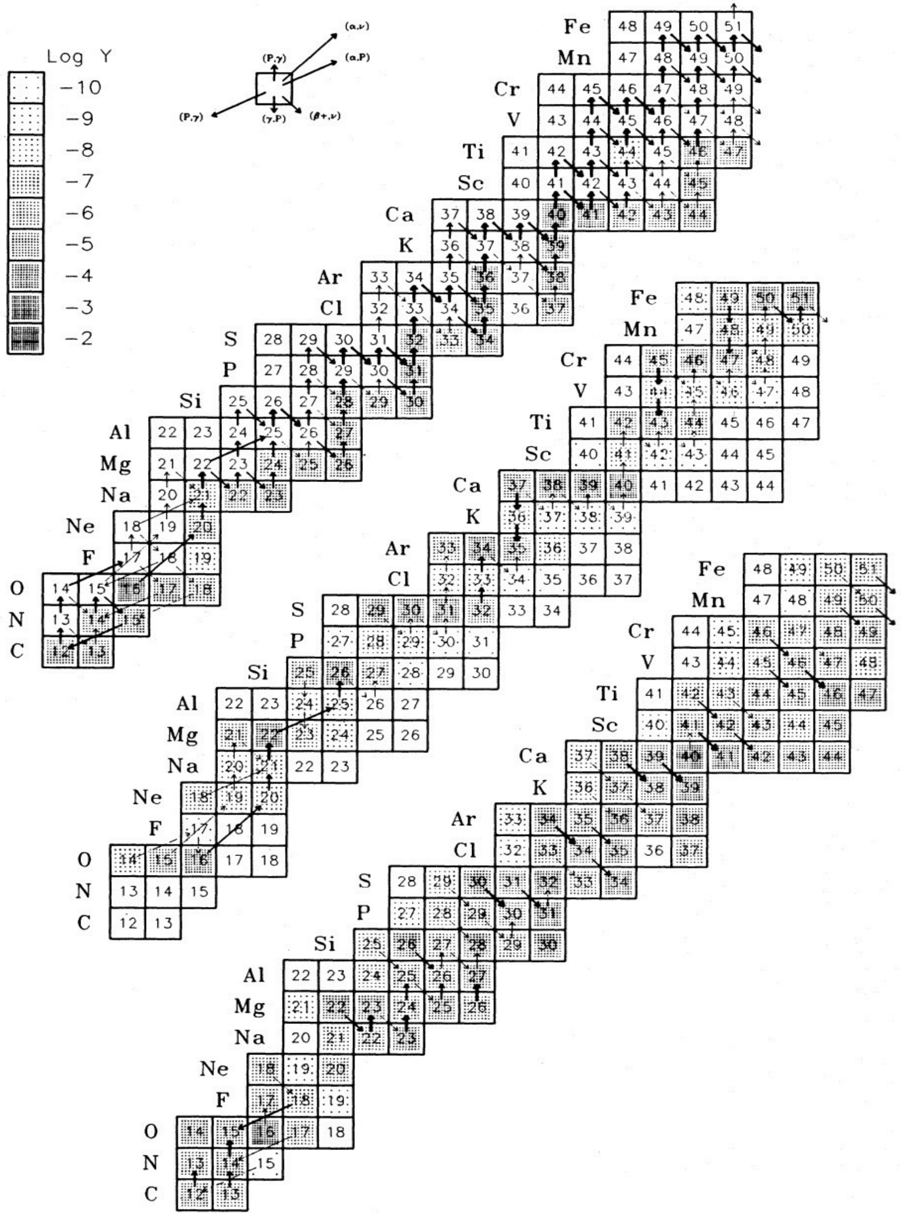


Applicable to GCE?

- TŻO knee → potential environment for **i**nterrupted **r**apid **p**roton process (**irp**-process)
- Products brought to the surface with convection → observational signature?
- (observationally) extreme M stars → strong wind mass loss

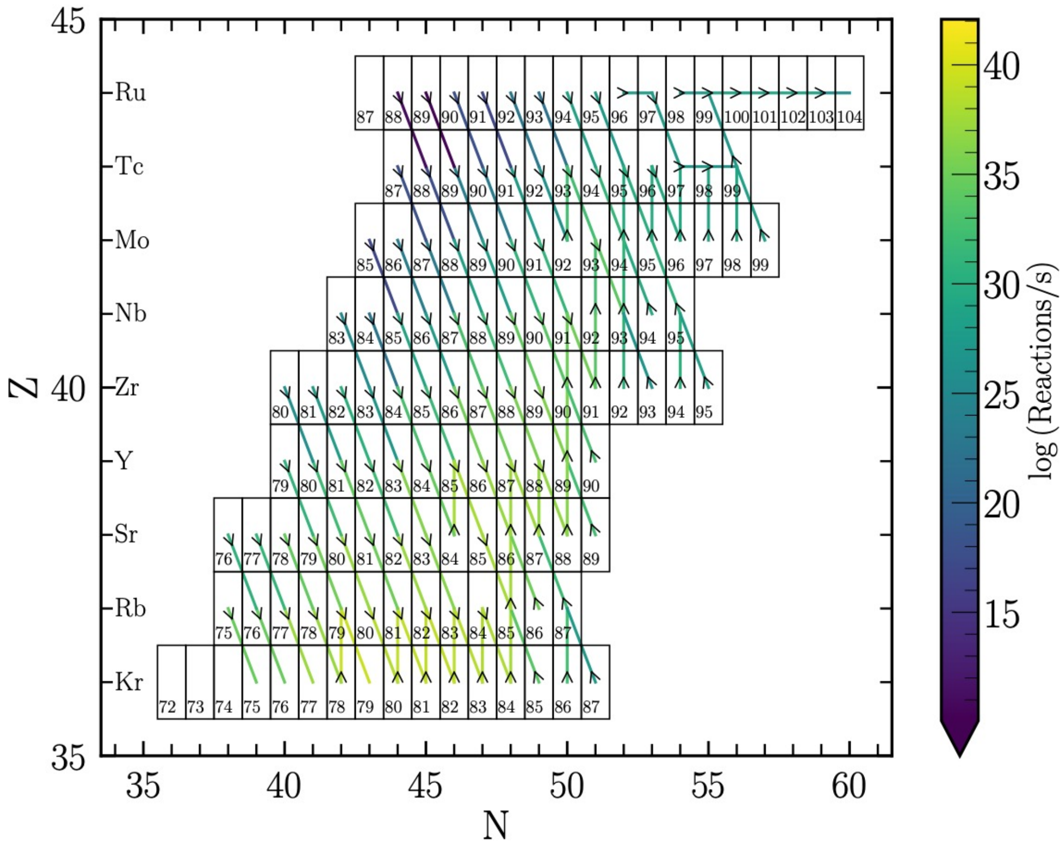
Cannon+93

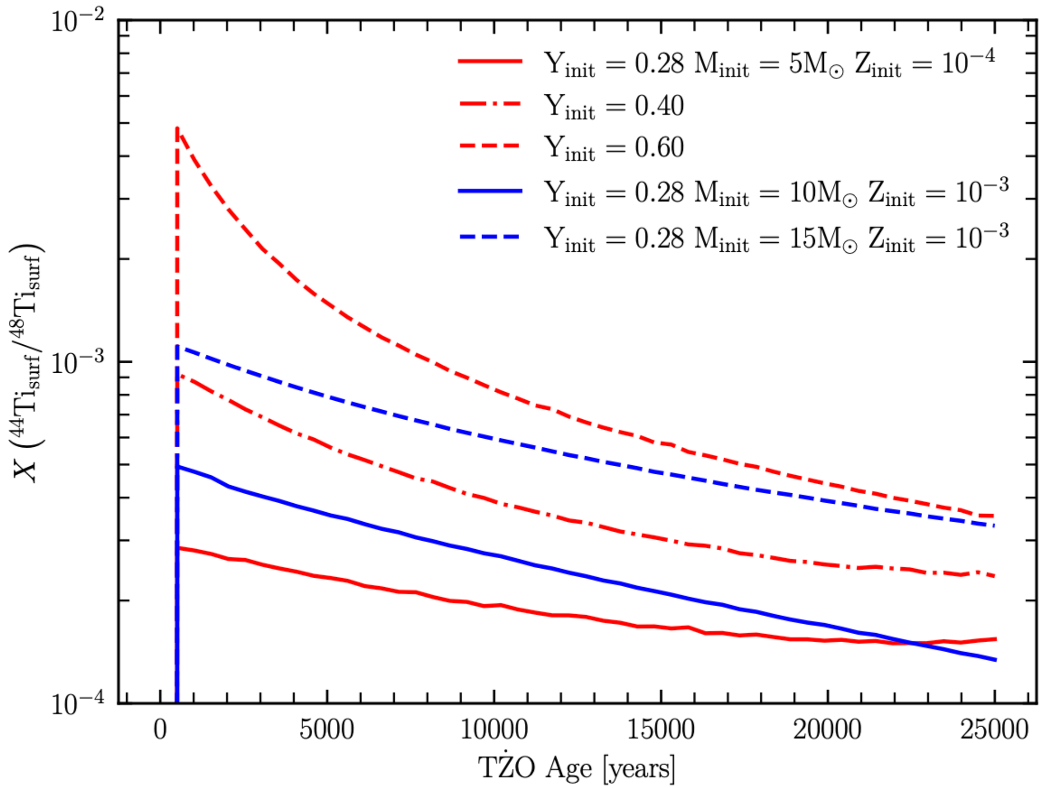




Applicable to GCE?

Farmer+23





Applicable to GCE?

Of course, can get chemical enrichment in a more explosive way...

Applicable to GCE?

Short τ_{acc}

10^{39} erg s^{-1} plateau for a few years, then go faint – vanished stars

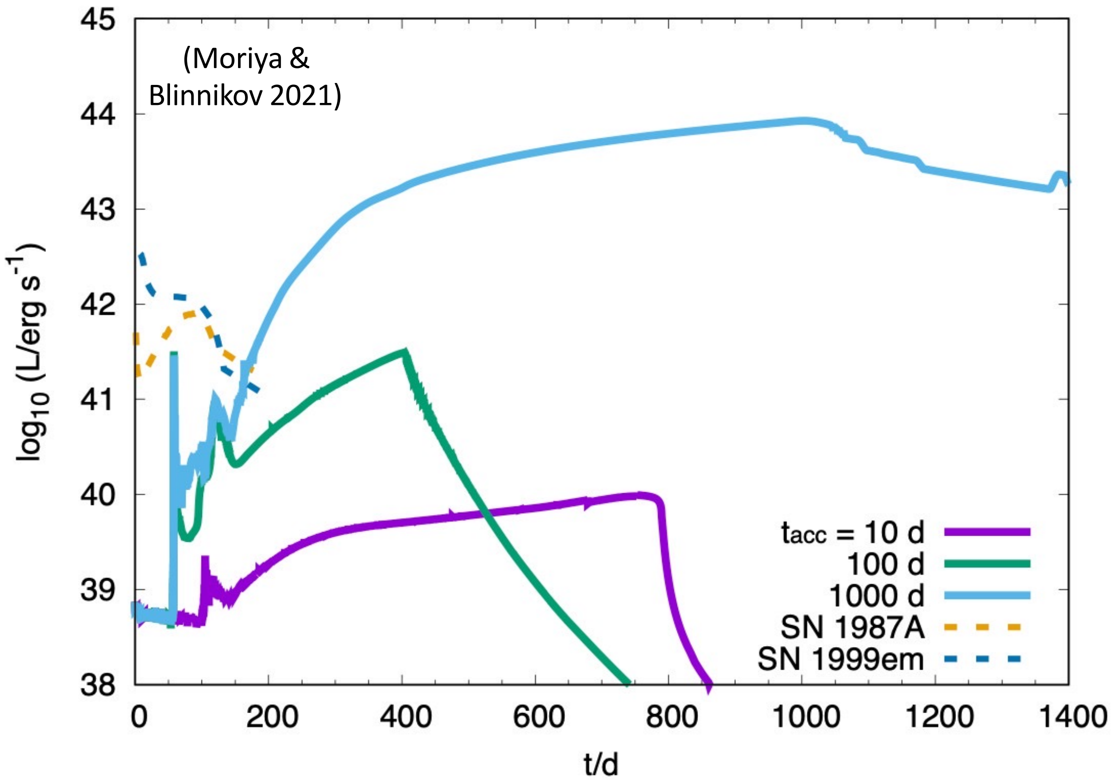
Long τ_{acc}

Supernova-like brightness

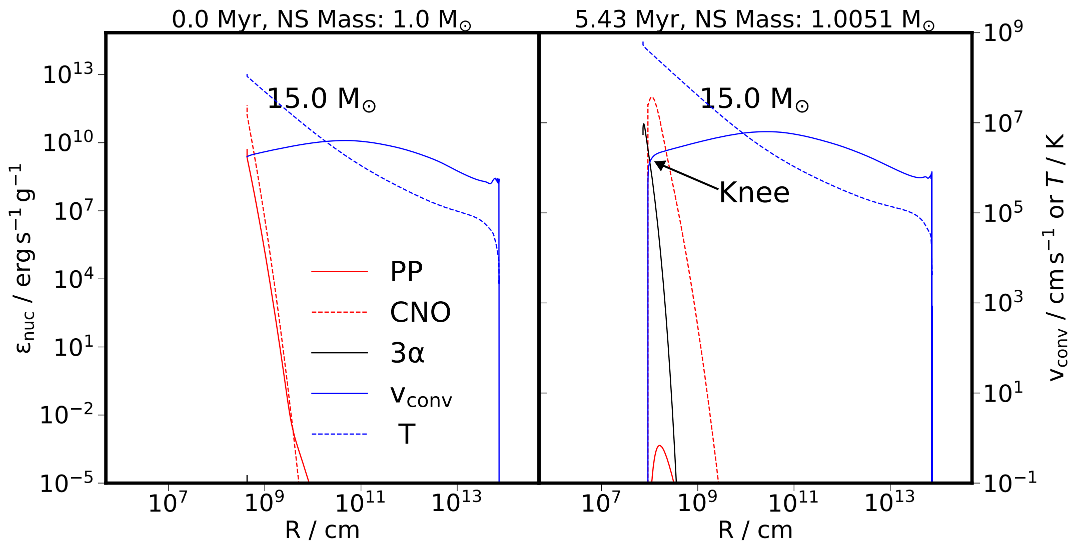
10^2 yr rise-time – low photospheric velocity – 2000 km s^{-1}

- Accretion terminates at some point – outflowing energy – parameterize with τ_{acc}

- TŻO explosions are then long duration transients – years



New approach to converging equilibrium solutions for hybrid stars:
Remove assumption of smooth core-envelope interface artifice (Cannon et al. 1993)



Use opacity (Eddington)-limited accretion prescription to link envelope – core

$$L_{\rm grav} = \frac{G M_{\rm c} \dot{M}}{R_{\rm c}}$$

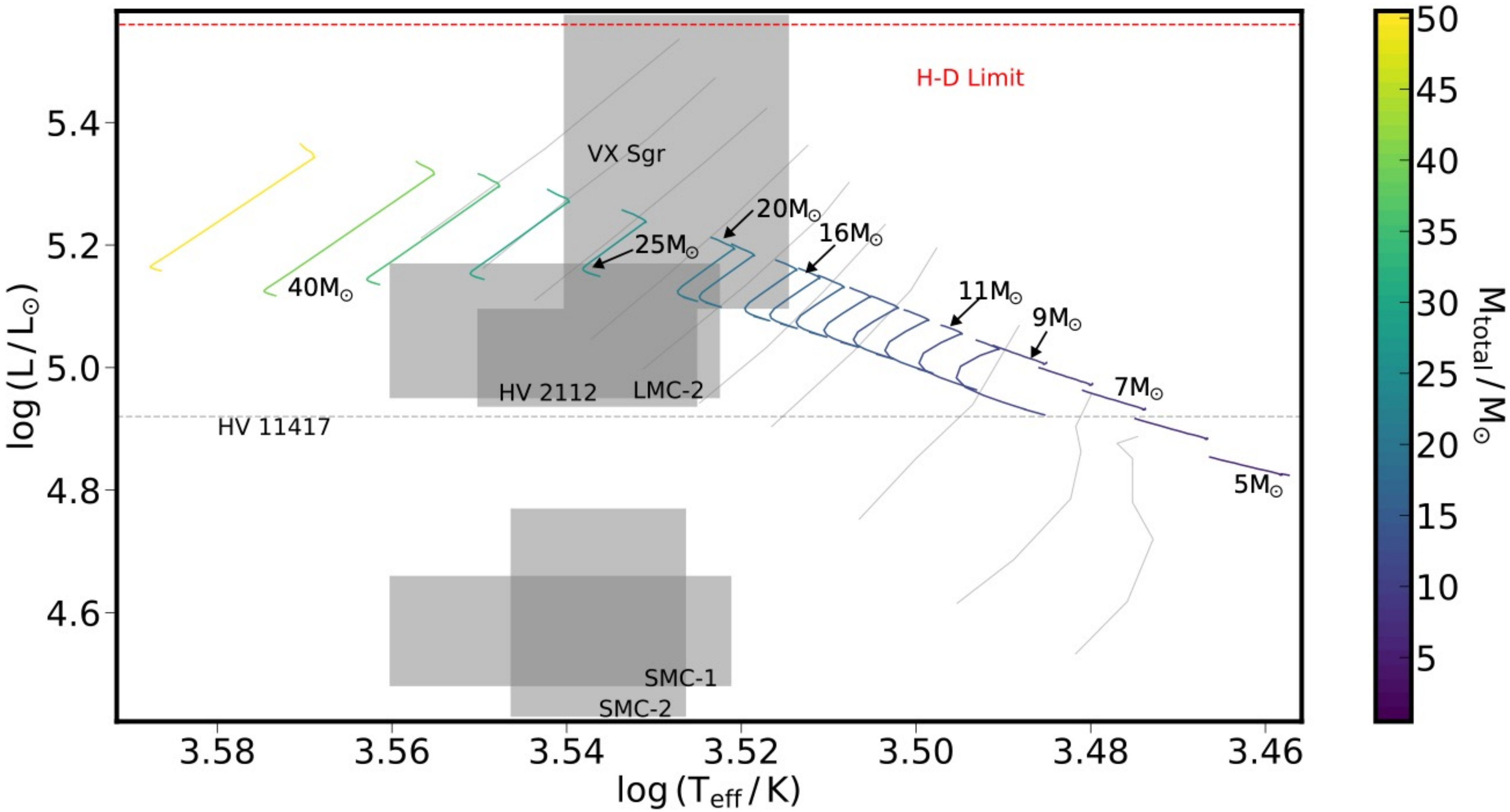
$$L_{\rm knee} = L_r^{\rm crit} \equiv 4\pi c G M_r \kappa^{-1}$$

$$\epsilon_{\rm grav} = -T\frac{ds}{dt} = -TC_P\left[\left(1-\nabla_{\rm ad}\chi_T\right)\frac{d\ln T}{d\ln t} - \nabla_{\rm ad}\chi_\rho\frac{d\ln\rho}{dt}\right]$$

via contact with Thorne (1977) form in Newtonian Limit

$$L_r = \dot{M}\left(\Pi + \frac{P}{\rho} - B + \phi\right) + \text{(conv burn)}$$

$$\frac{\partial}{\partial r}\left(\frac{\mathscr{R}^2 L_r}{c^2} - \left(\frac{\partial M_r}{\partial t}\right)_r \mathscr{H}\mathscr{R} + \left(\frac{\partial M_{tr}}{\partial t}\right)_r \mathscr{V}\mathscr{R}\right) = 0.$$



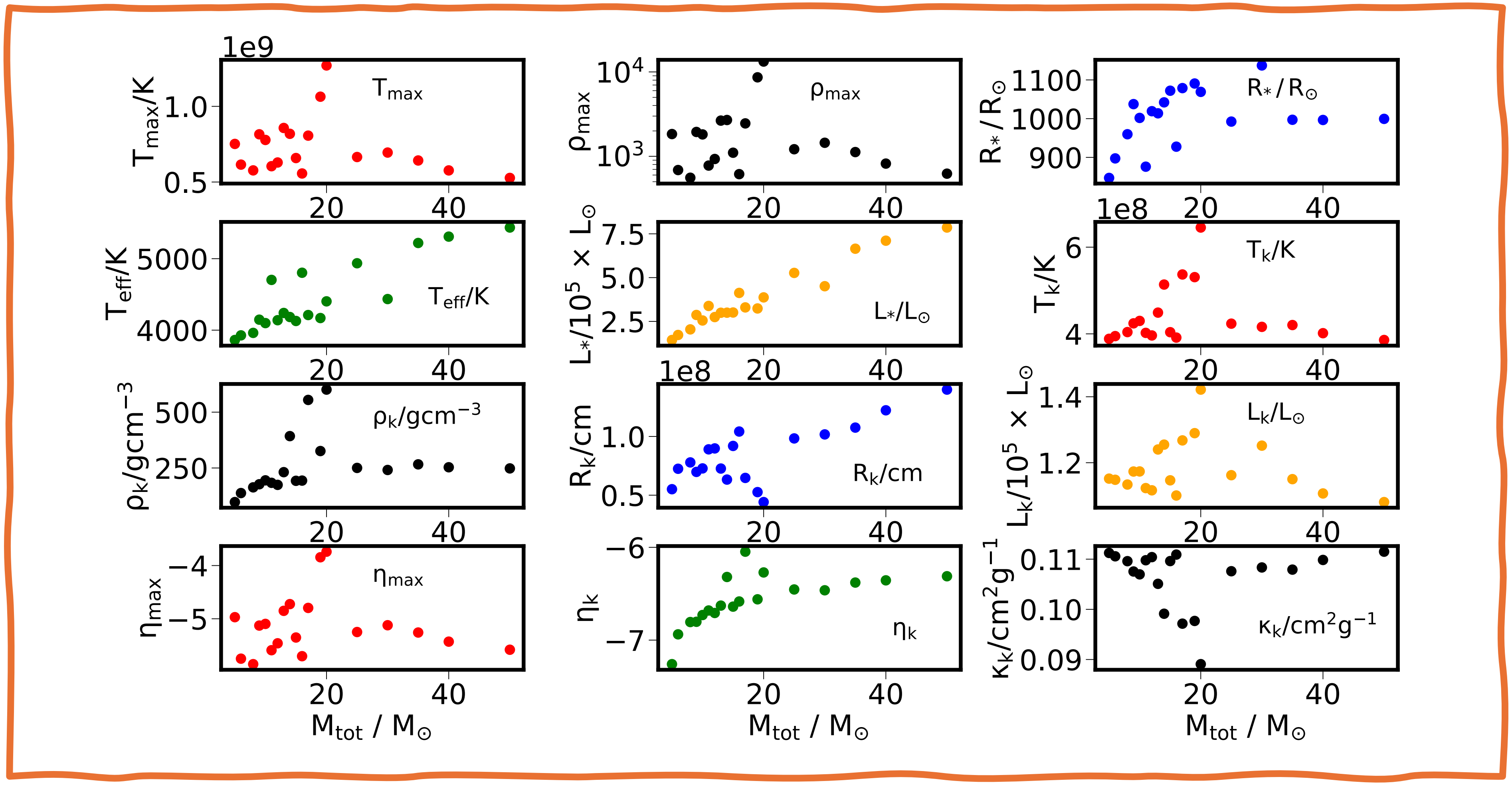
HRD tracks are consistent with some TŻO candidates

Most prominently HV2112 and VX Sgr

But also many SAGB candidates from O'Grady+22,23!

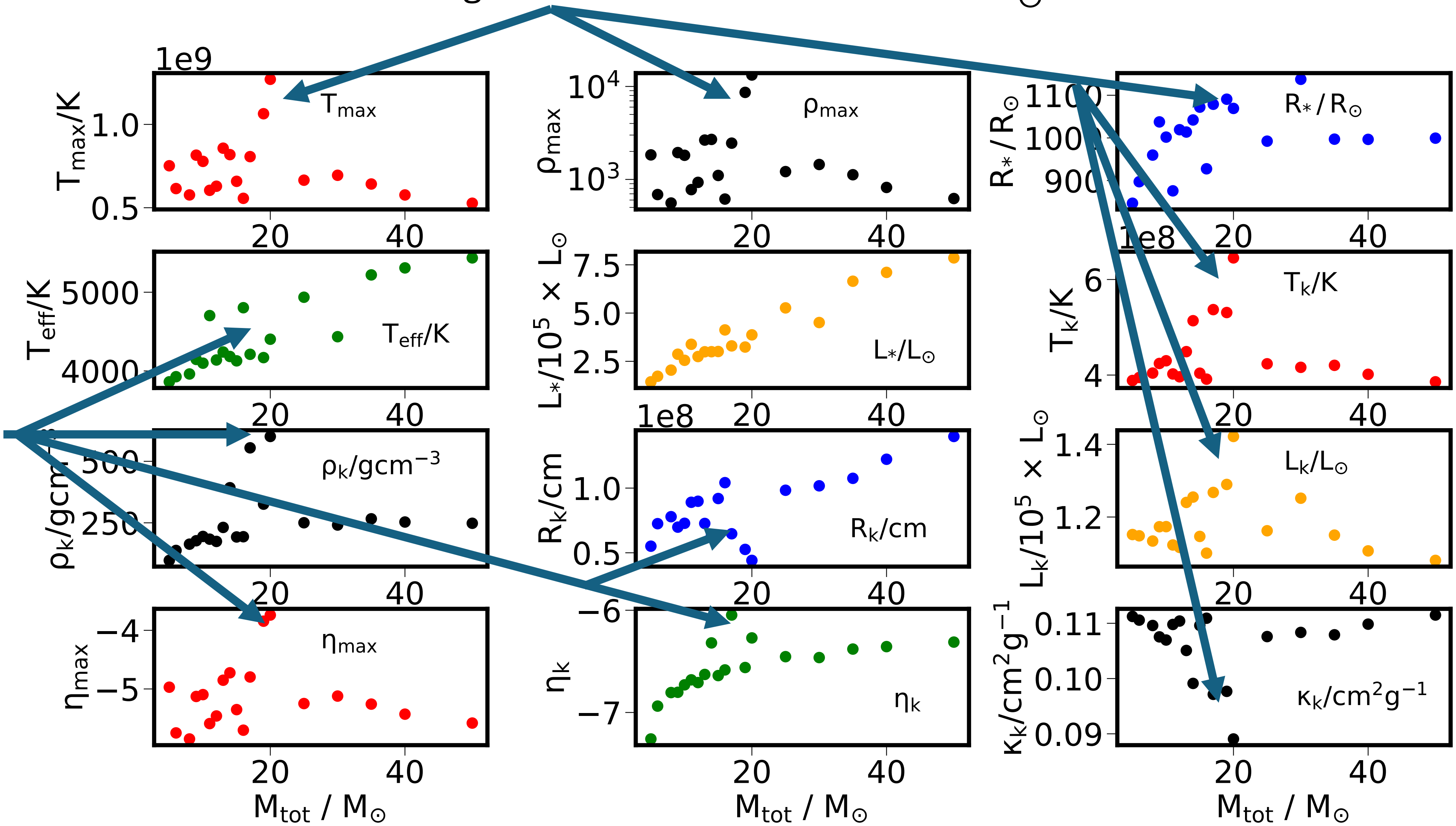
Coloured Tracks → our models
Greyscale Tracks → Cannon et al.-style models

Qualitative differences in internal structure have little effect on quantitative behaviour in the HRD



1e9
T_{max}/K
T_{max}
ρ_{max}
$R_*/R_\odot$
T_{eff}/K
$L_*/10^5 \times L_\odot$
$L_*/L_\odot$
1e8
T_k/K
ρ_k/gcm^{-3}
R_k/cm
$L_k/10^5 \times L_\odot$
$L_k/L_\odot$
η_{max}
η_k
κ_k/cm^{2}g^{-1}
M_{tot} / $M_\odot$

Strange discontinuities at around $20M_\odot$?



Quick sanity check on our haloes,
Helium burning shell (Dennis 1971):

$$\Delta r/r < f(\beta)|Q|^{-1},$$

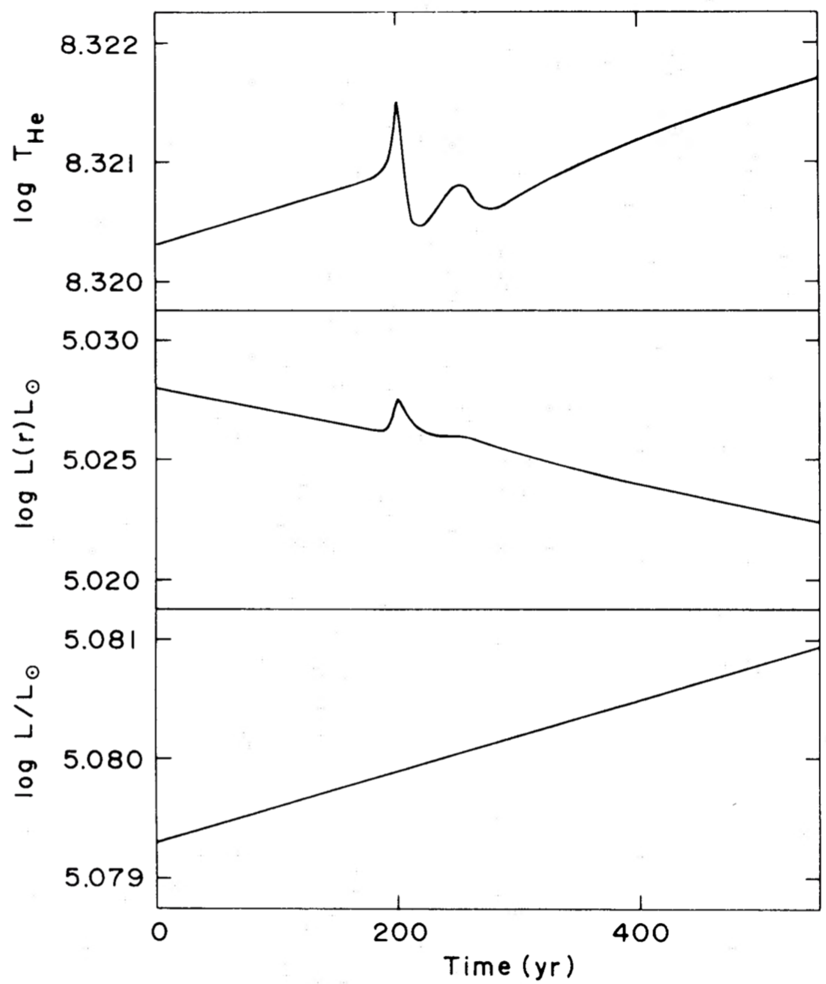
where

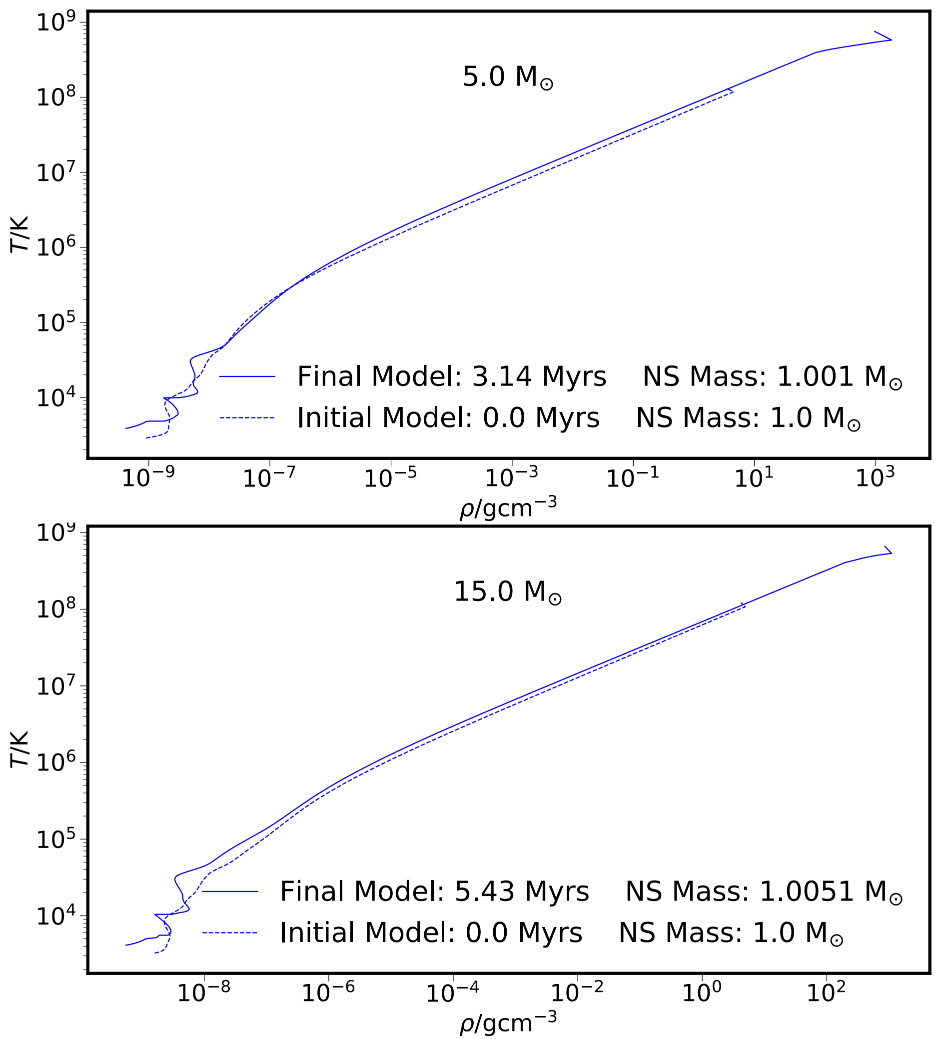
$$f(\beta) = \frac{\beta\left(32/3 - 8\beta - \beta^2\right)}{32/3 - 16\beta + 6\beta^2},$$

where Q is defined as by Schwarzschild & Härm (1965)

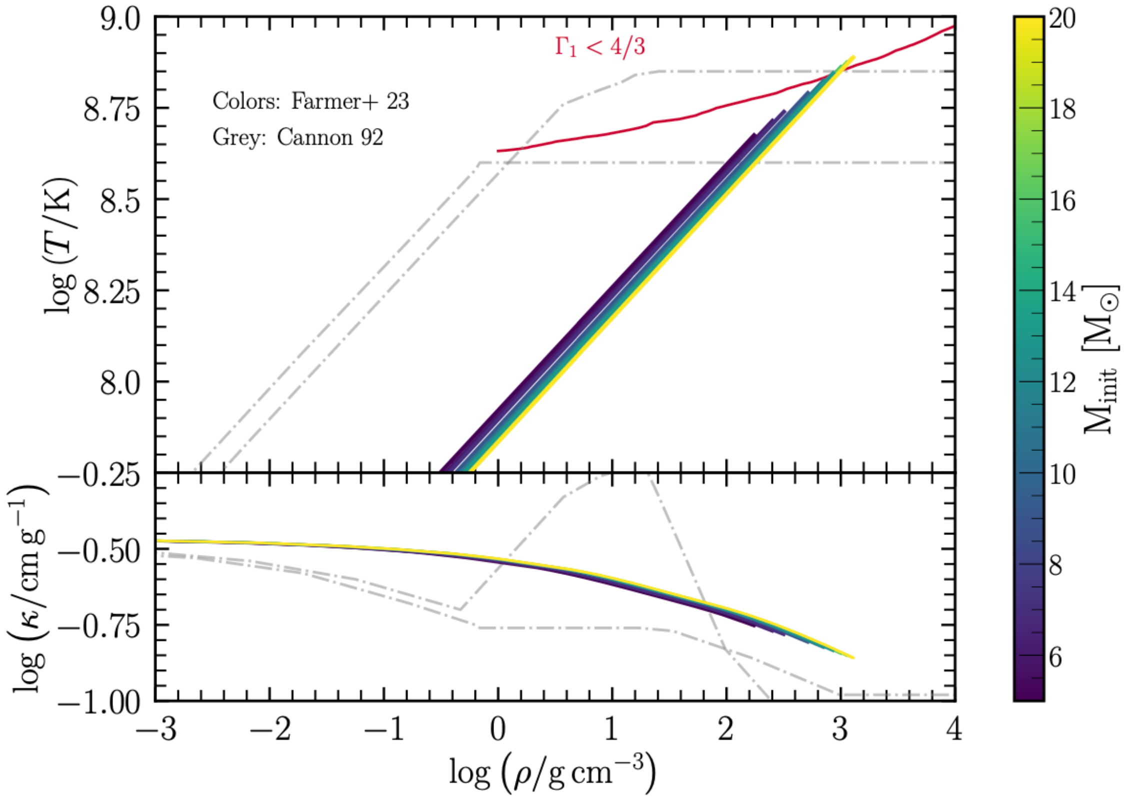
$$Q = \left(\left(\frac{\delta r}{r}\right)_2 \Big/ \left(\frac{\delta P}{P}\right)_2 - \left(\frac{\delta r}{r}\right)_1 \Big/ \left(\frac{\delta P}{P}\right)_1\right)^{-1},$$

Find our shells are comfortably stable, but likely subject to the "flickering" instability (Stothers & Wen Chin 1973)

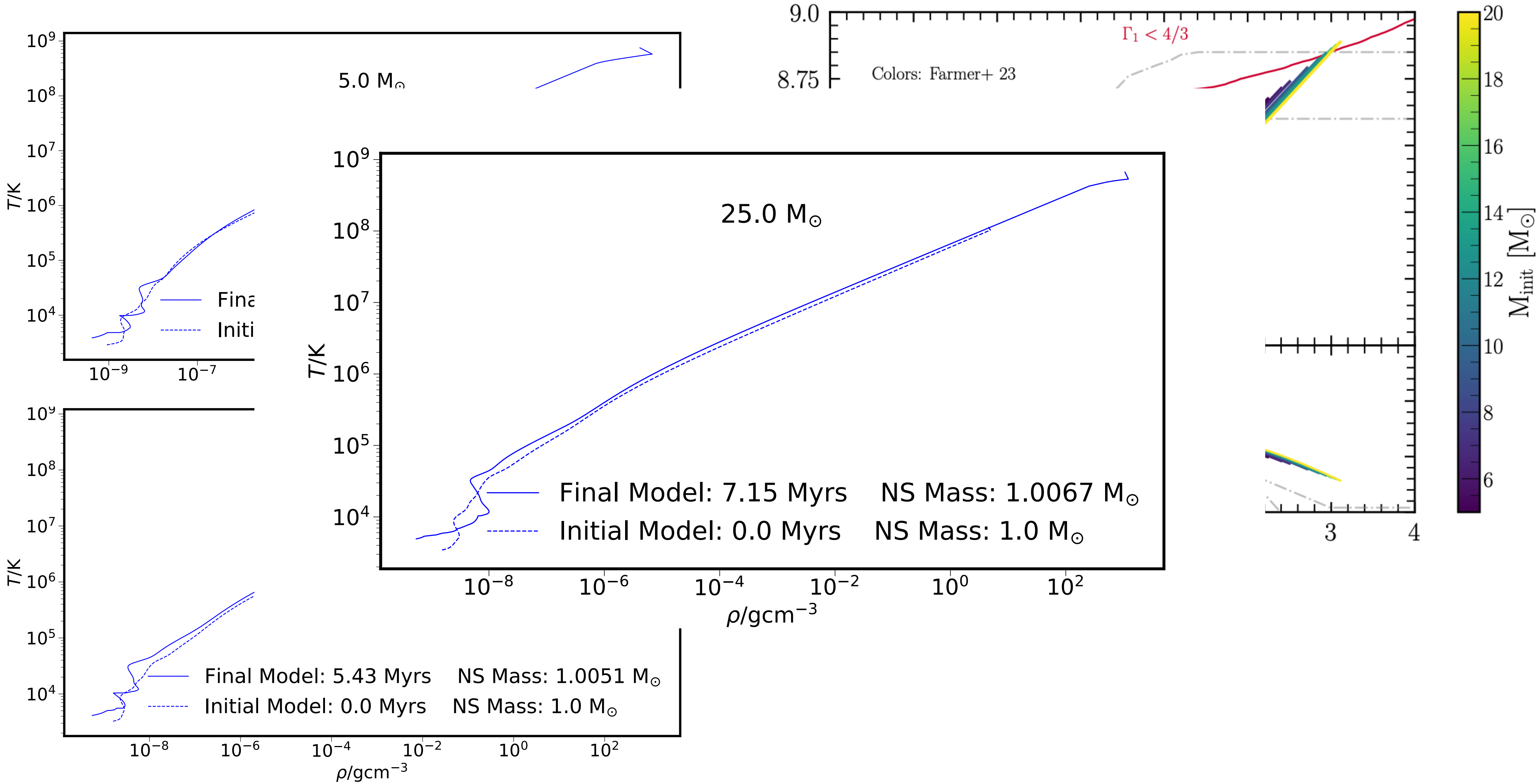




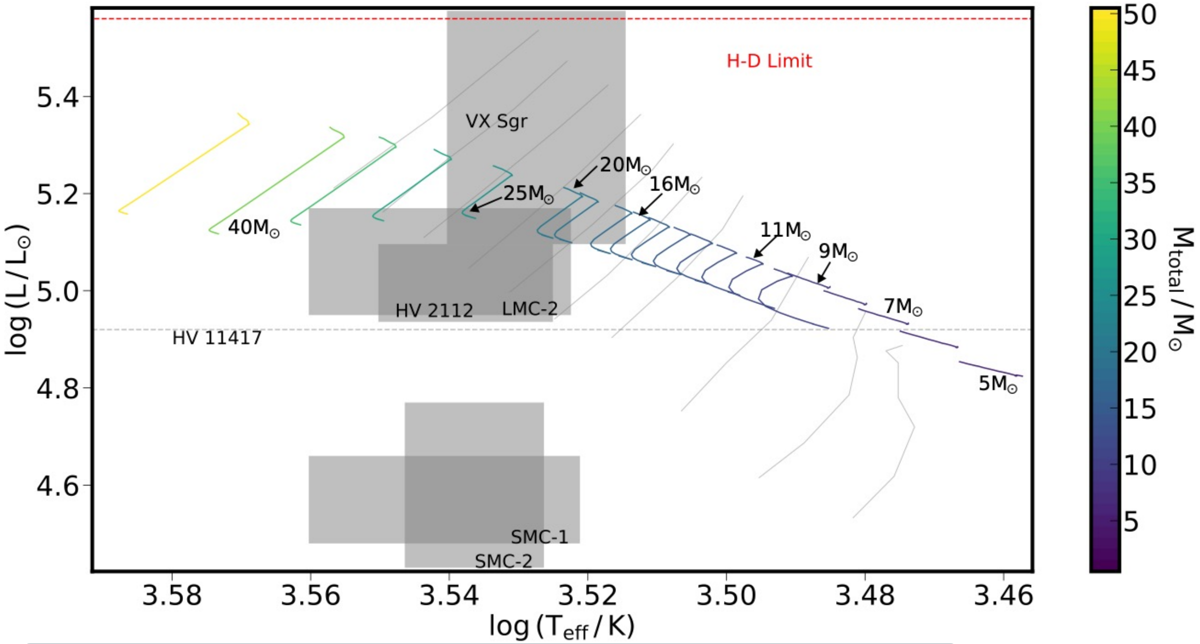
Farmer+23



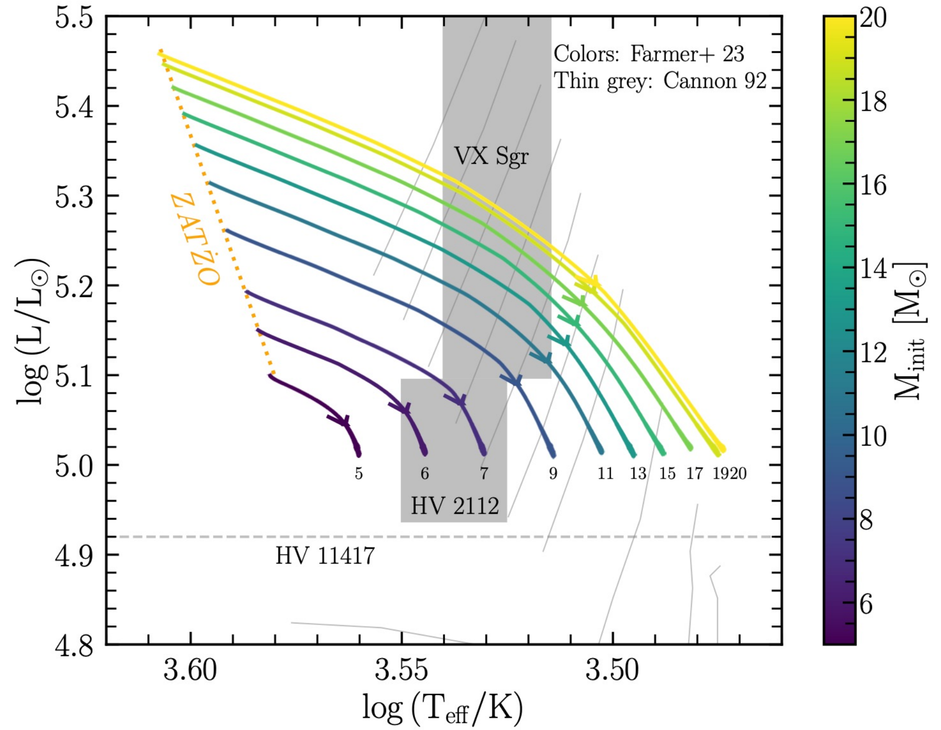
How do we differ from Farmer+23?
We place the innermost BC at the NS surface, not at 600km above

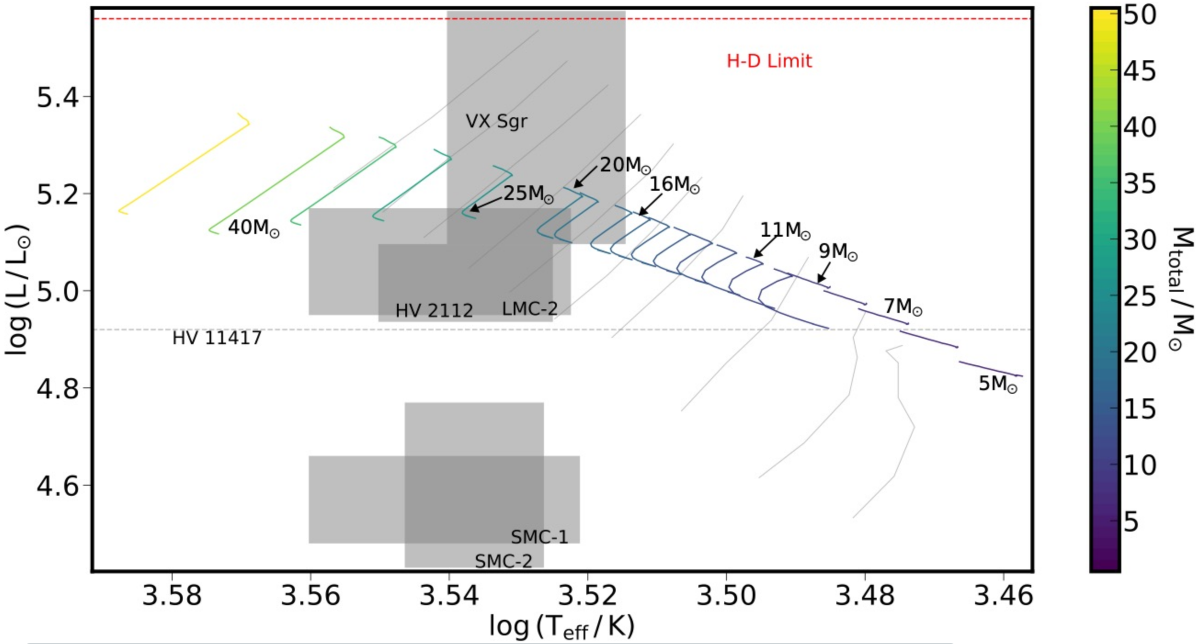


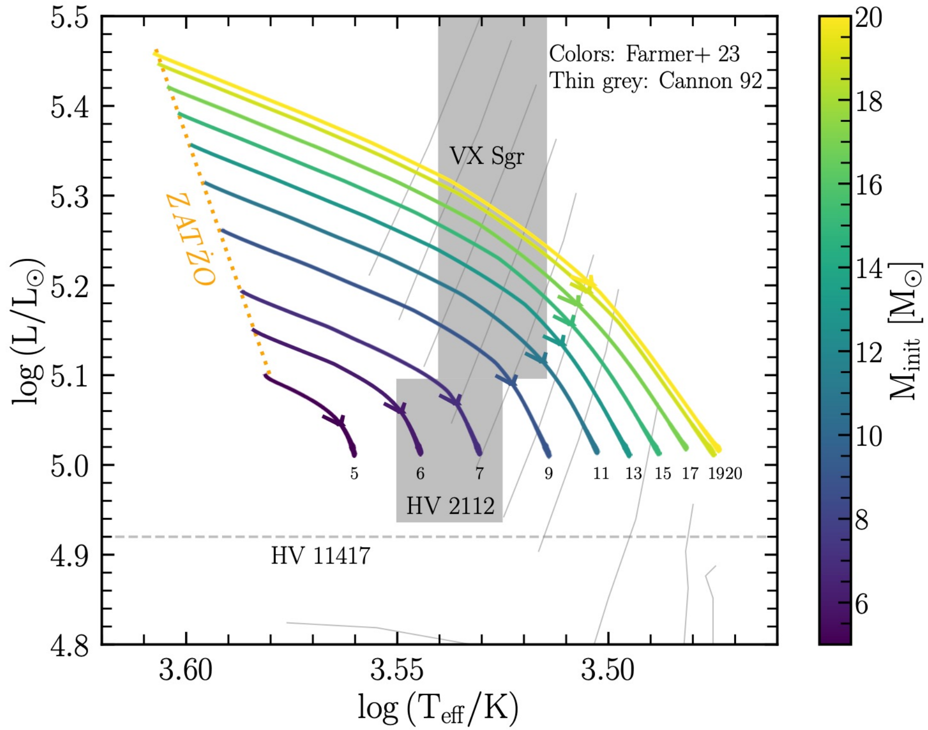
5.0 M⊙
25.0 M⊙
Final Model: 7.15 Myrs NS Mass: 1.0067 M⊙
Initial Model: 0.0 Myrs NS Mass: 1.0 M⊙
Final Model: 5.43 Myrs NS Mass: 1.0051 M⊙
Initial Model: 0.0 Myrs NS Mass: 1.0 M⊙
T/K
ρ/gcm⁻³
Γ1 < 4/3
Colors: Farmer+ 23
M_init [M⊙]



Moving boundary conditions from inside halo into convective envelope → explains dramatic changes



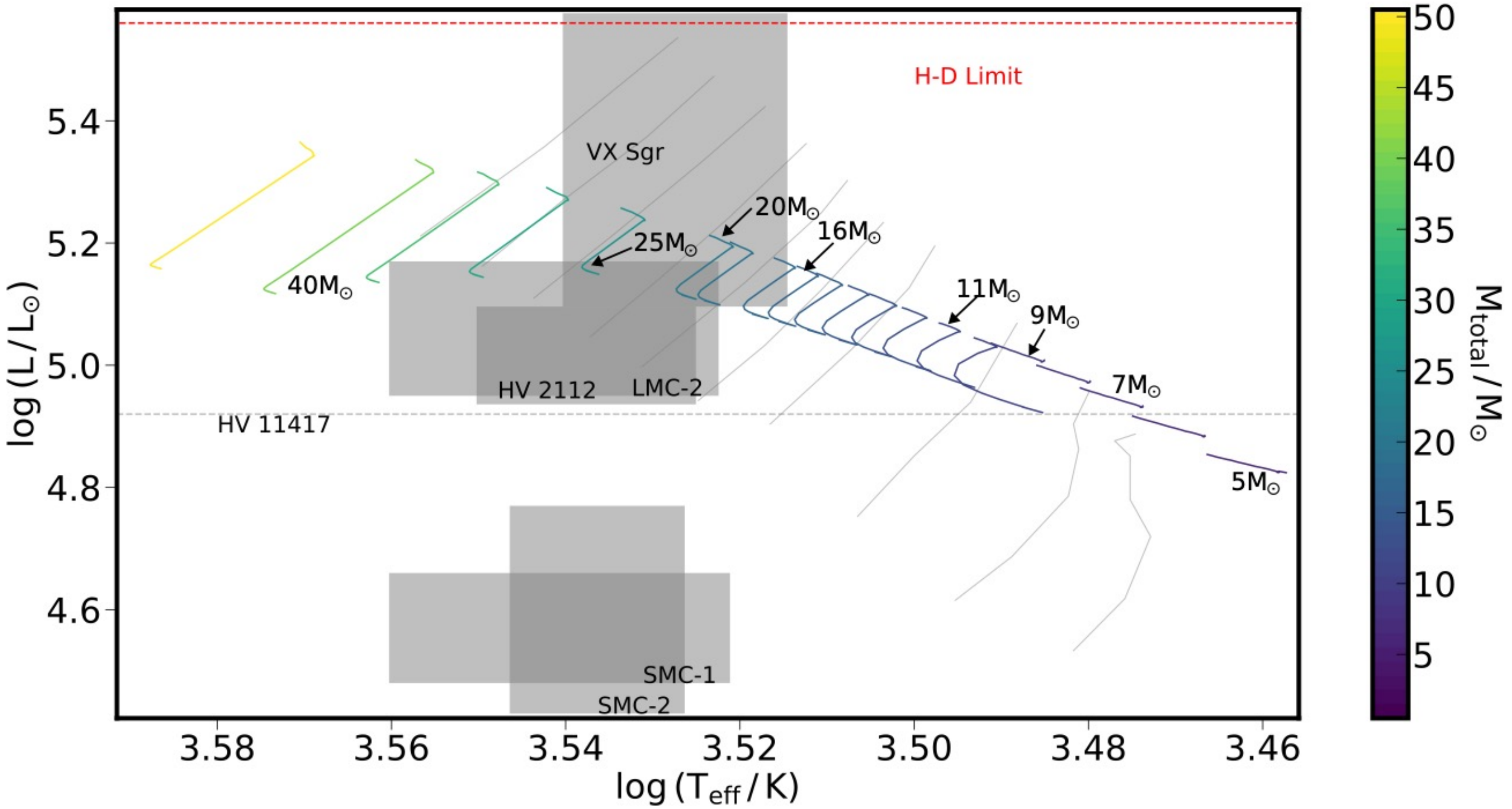




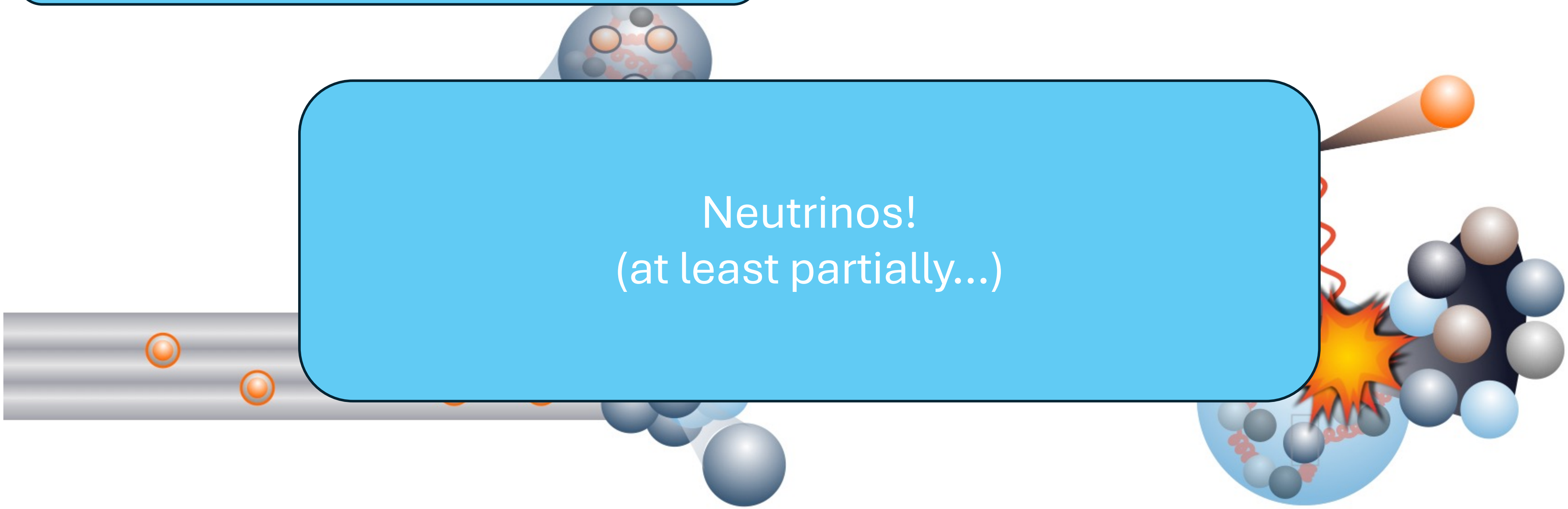
Moving boundary conditions from inside halo into convective envelope → explains dramatic changes

Concern: choice of BC changes chemical yields

Why do we disagree with the Cannon et al.-style models?



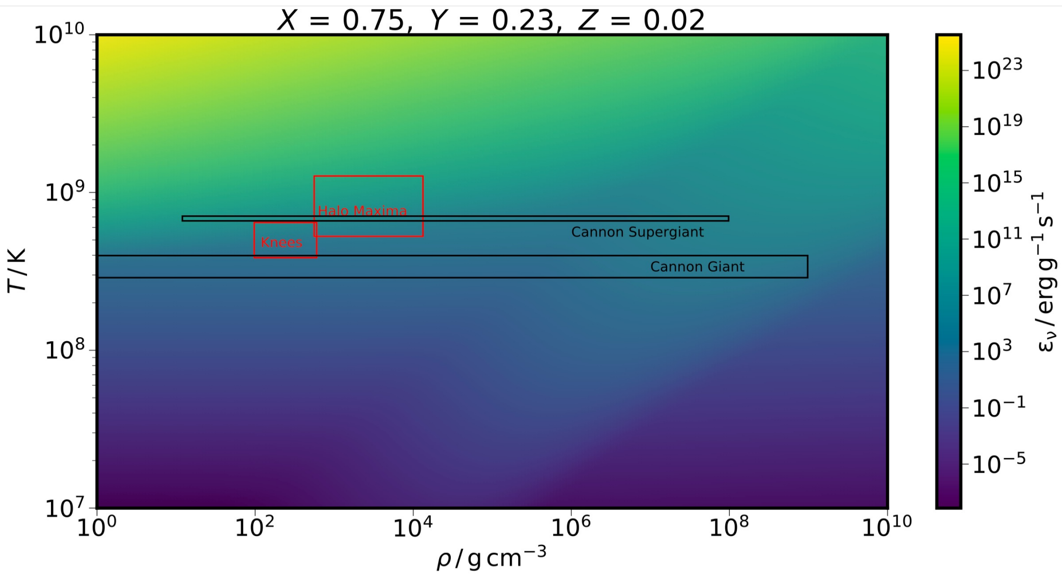
Why do we disagree with the Cannon et al.-style models?

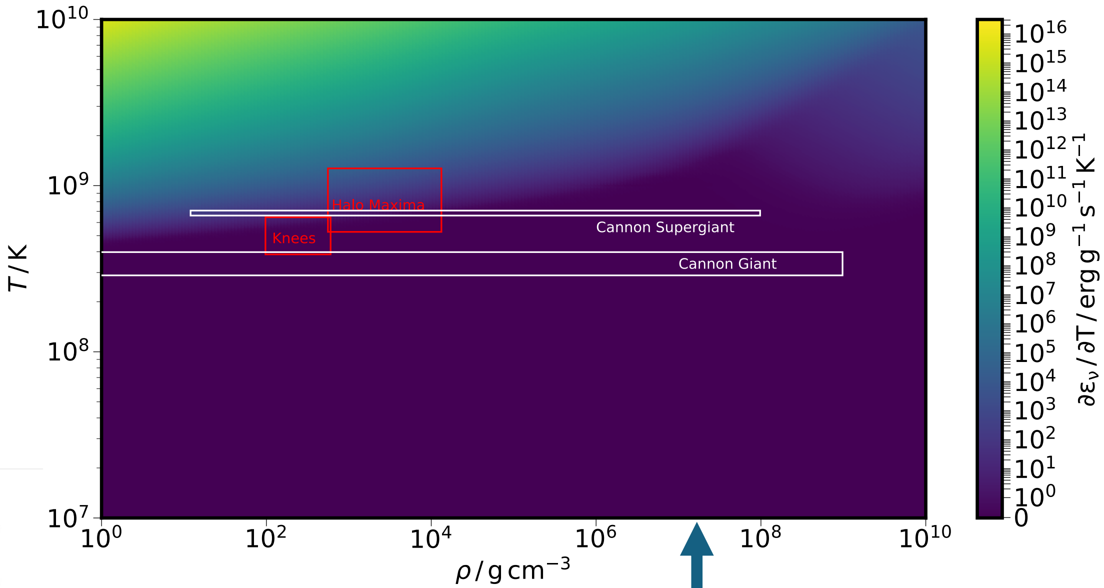


Neutrinos!
(at least partially...)

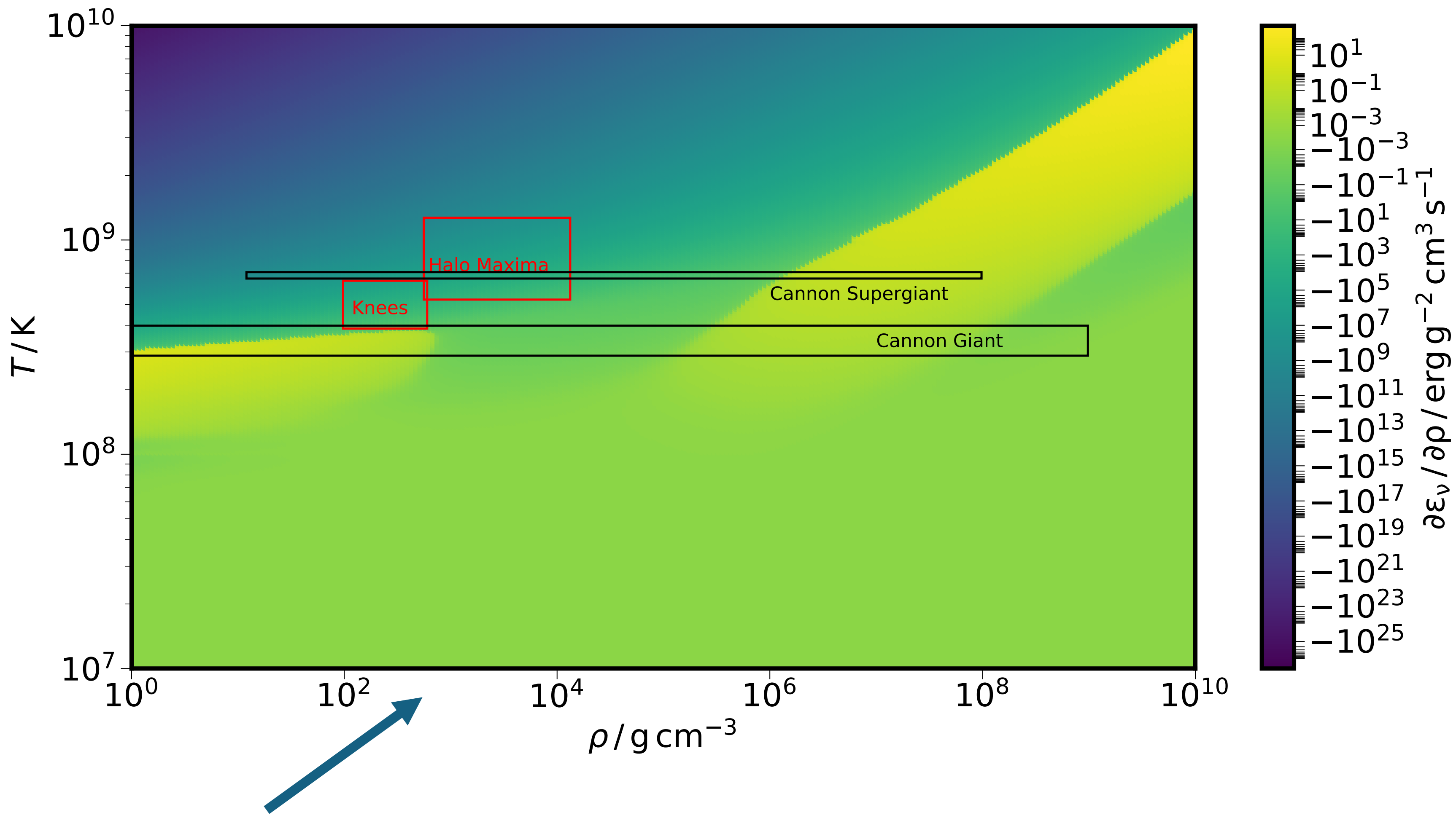
Neutrinos!

Luminosity

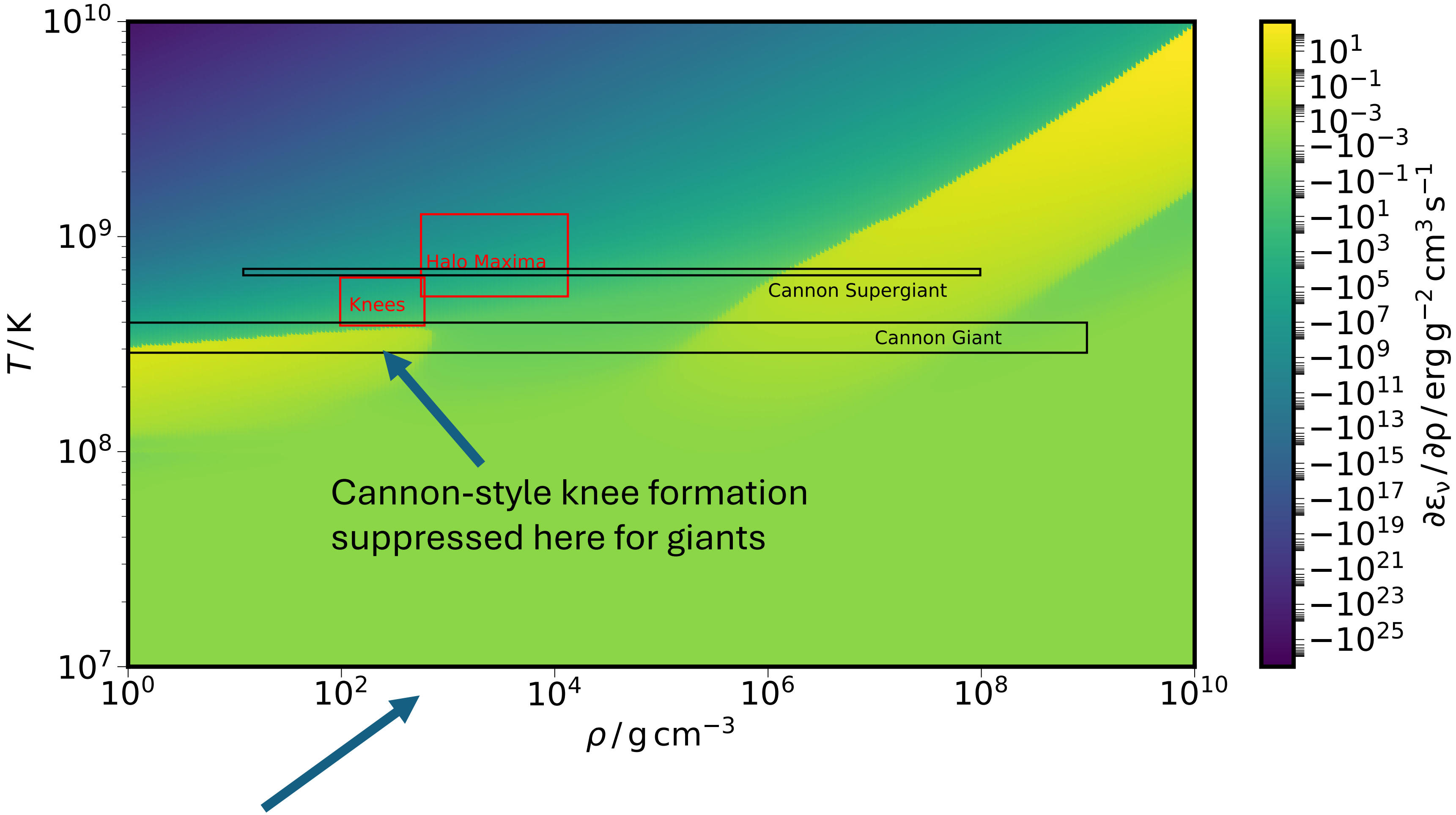




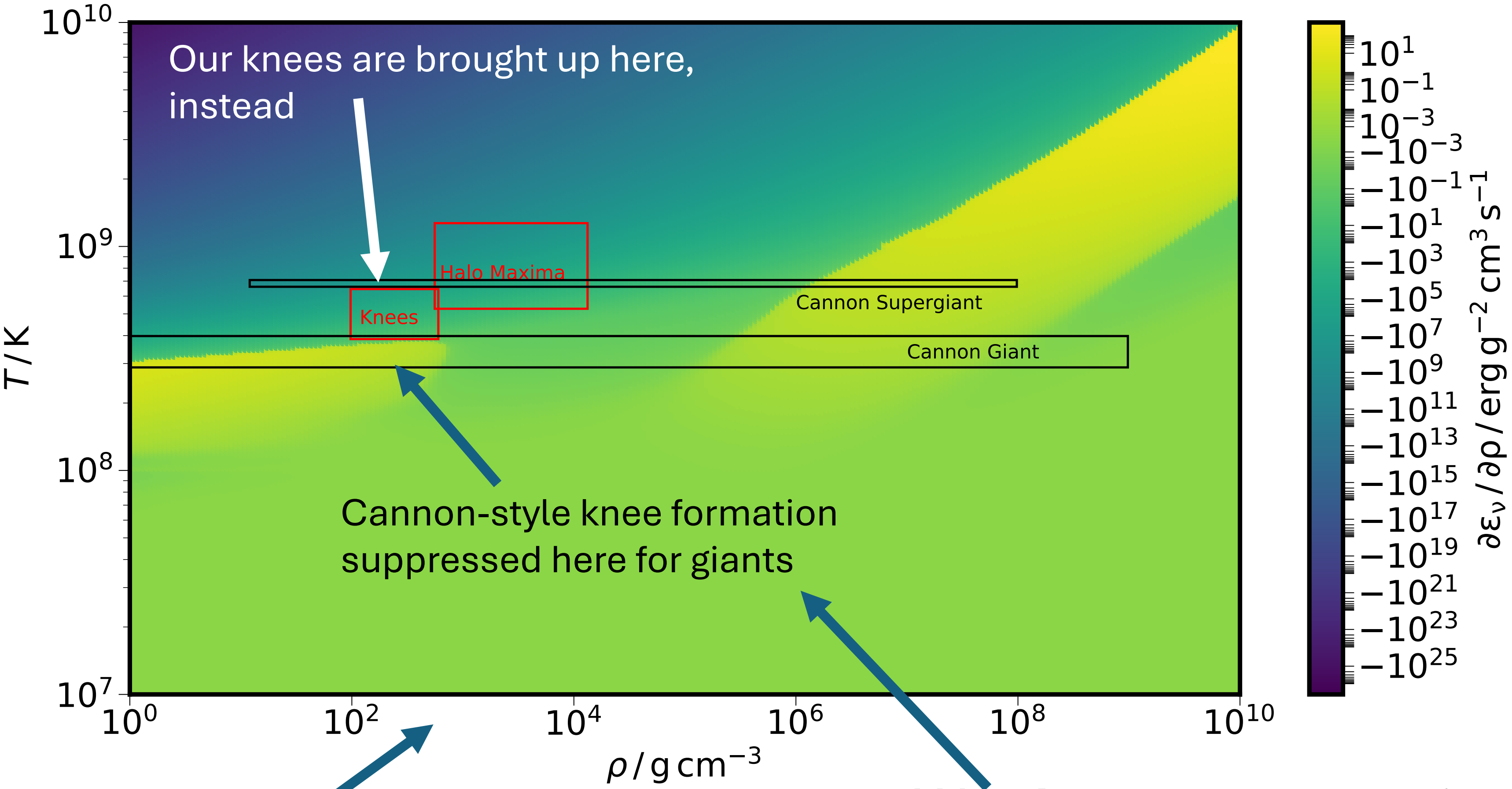
Partial w.r.t T



Partial w.r.t ρ



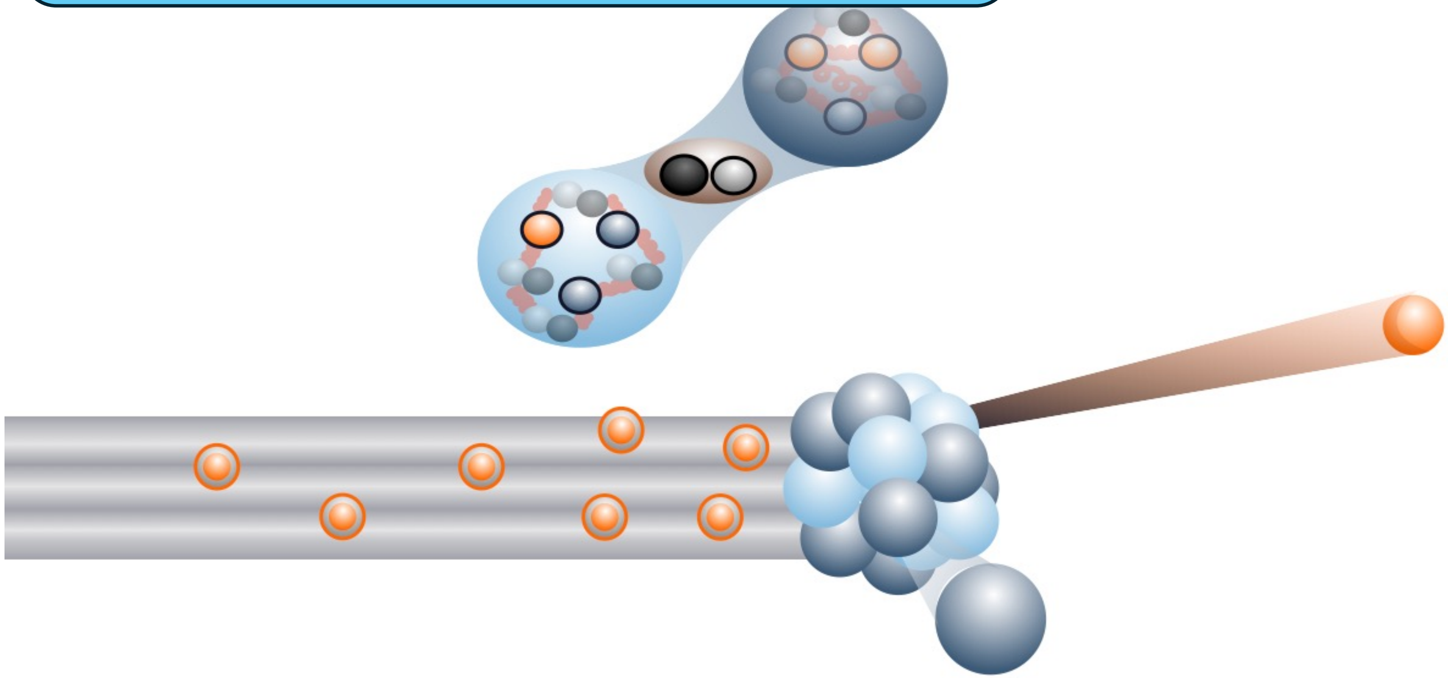
Partial w.r.t ρ

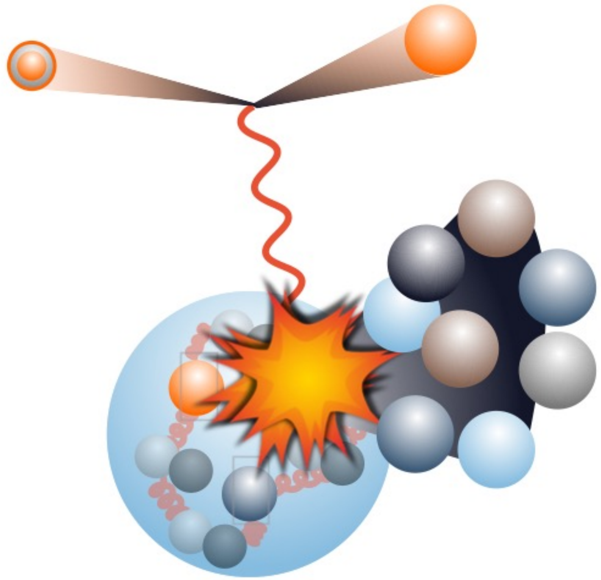


We **always** get supergiant configurations – even at low mass!!

Partial w.r.t ρ

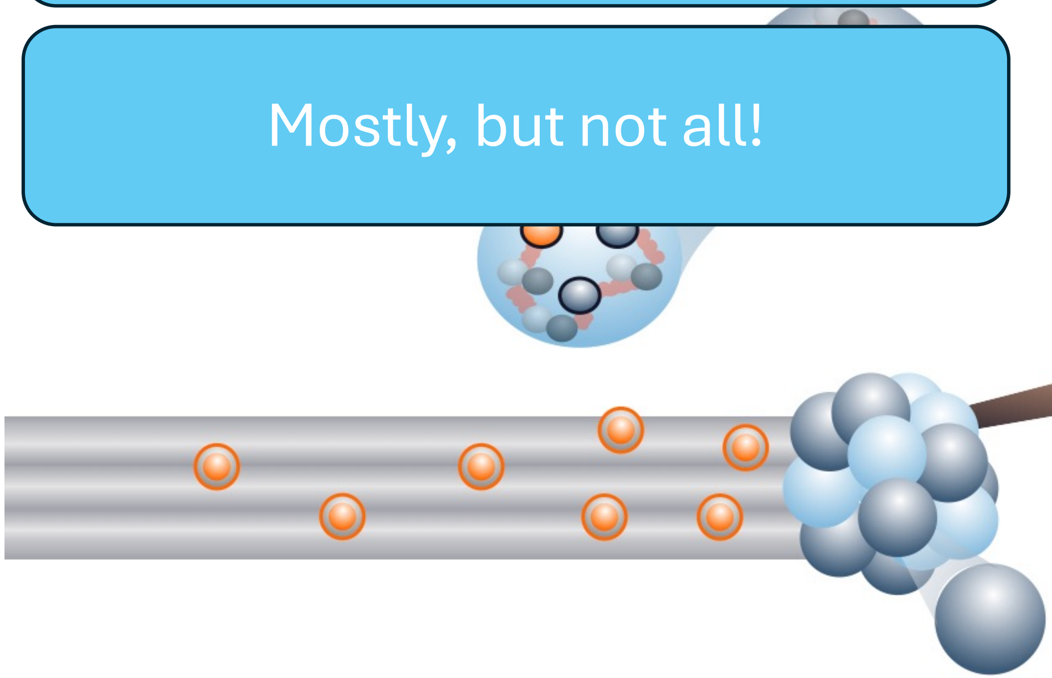
Is it all neutrinos?

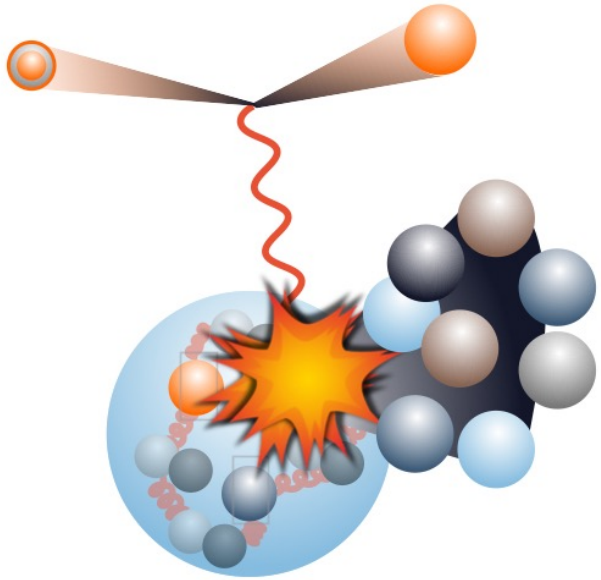




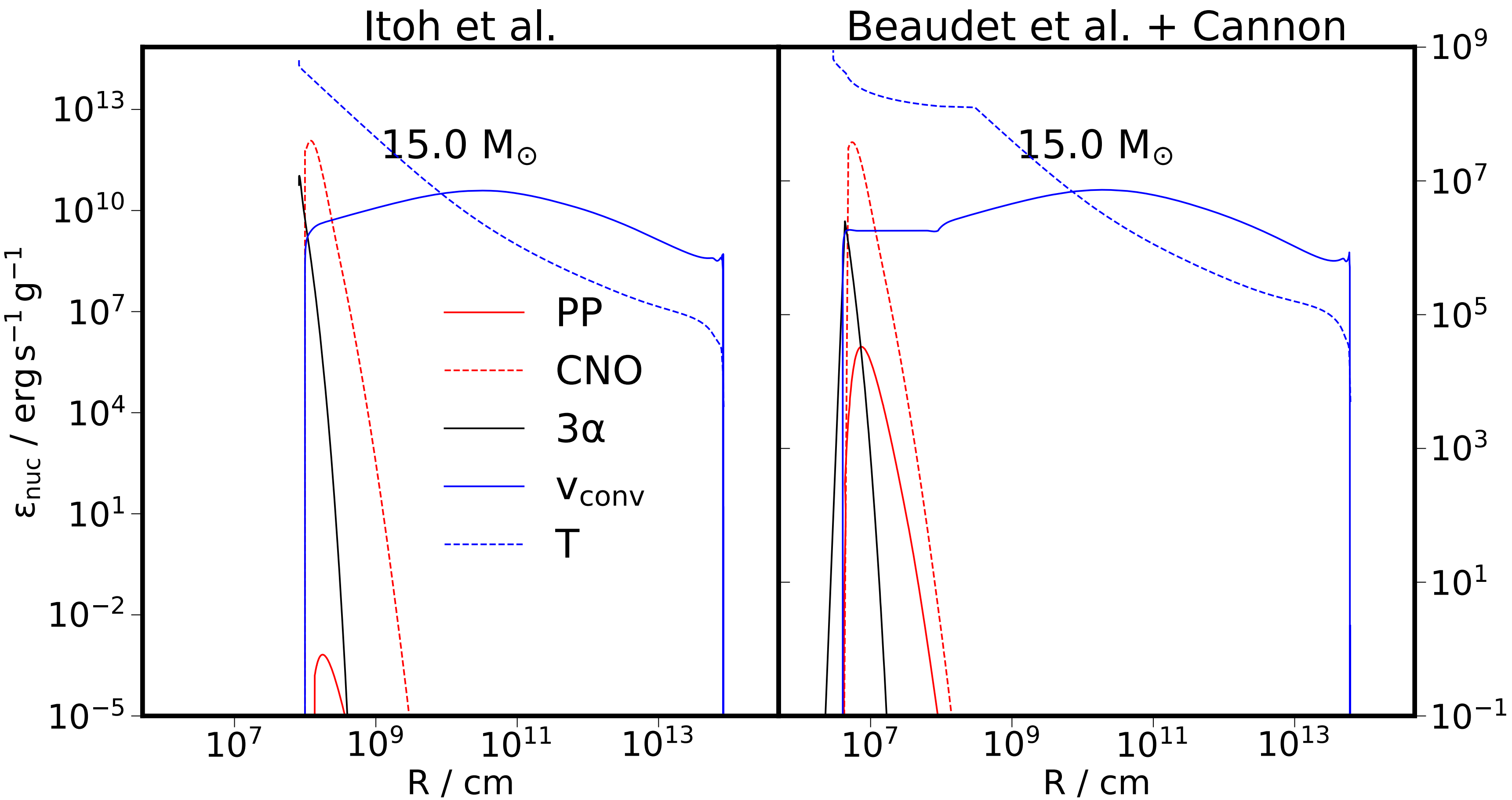
Is it all neutrinos?

Mostly, but not all!





Is it all neutrinos?

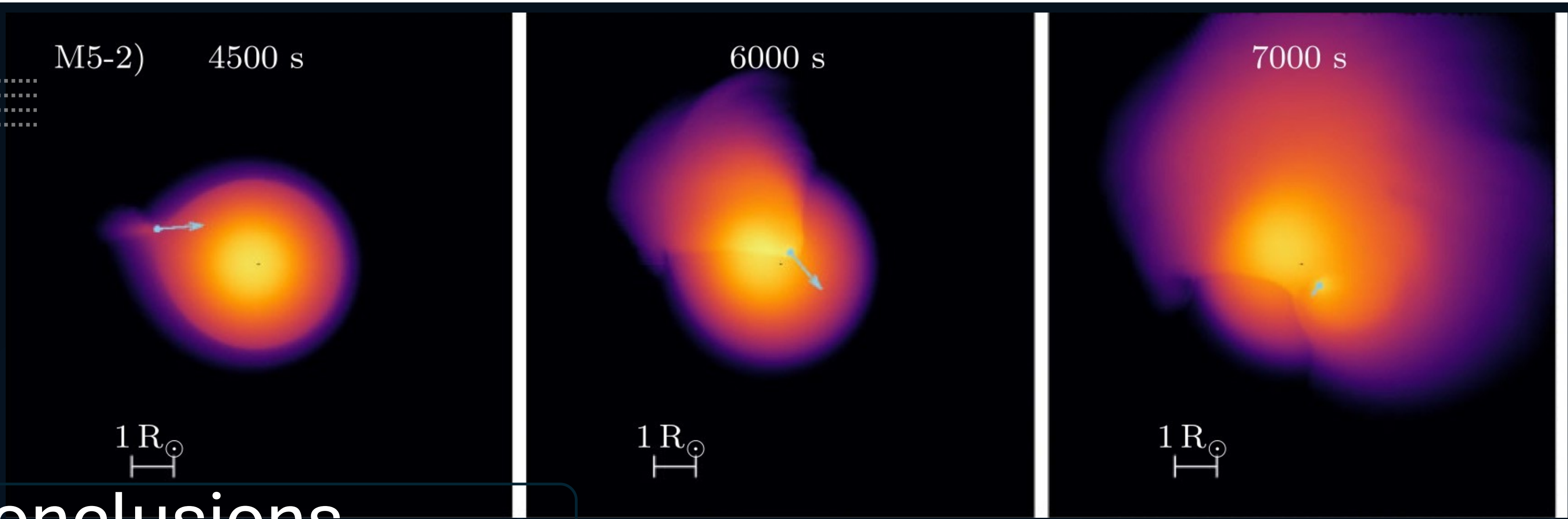


- Much more Cannon-esque now!
- But not identical
- Possible differences

Code structure

Reaction rates

Opacities?



Conclusions

- TŻOs are (sets of) solutions for stellar evolution equations involving a neutron star core surrounded by a diffuse giant envelope
- TŻOs might form at an almost zero rate, but could be common outcomes of (low-mass) XRBs – our predictions are very model dependent
- If TŻOs exist, they are likely to influence the chemical evolution of the Galaxy/MCs
- Multiple sets of model series with vastly different assumptions and predictions exist – how can we decide?

“Ooh, basically, a star is a pretty simple thing…”
– Fred Hoyle

"Ooh, basically, a star is a pretty simple thing…"
– Fred Hoyle

"Well, Fred, you'd look pretty simple too, from ten parsecs!"
– R. O. Redman