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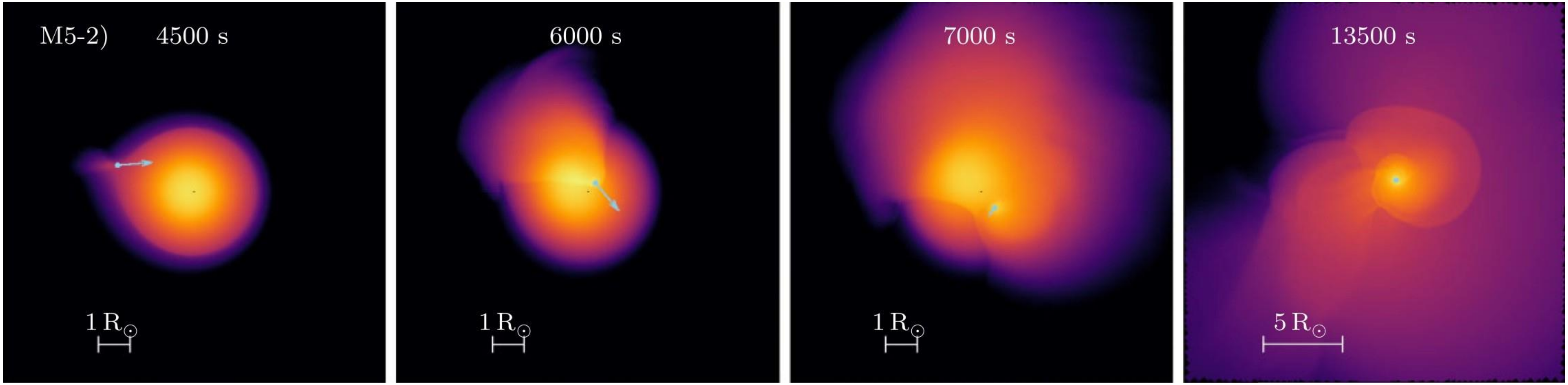
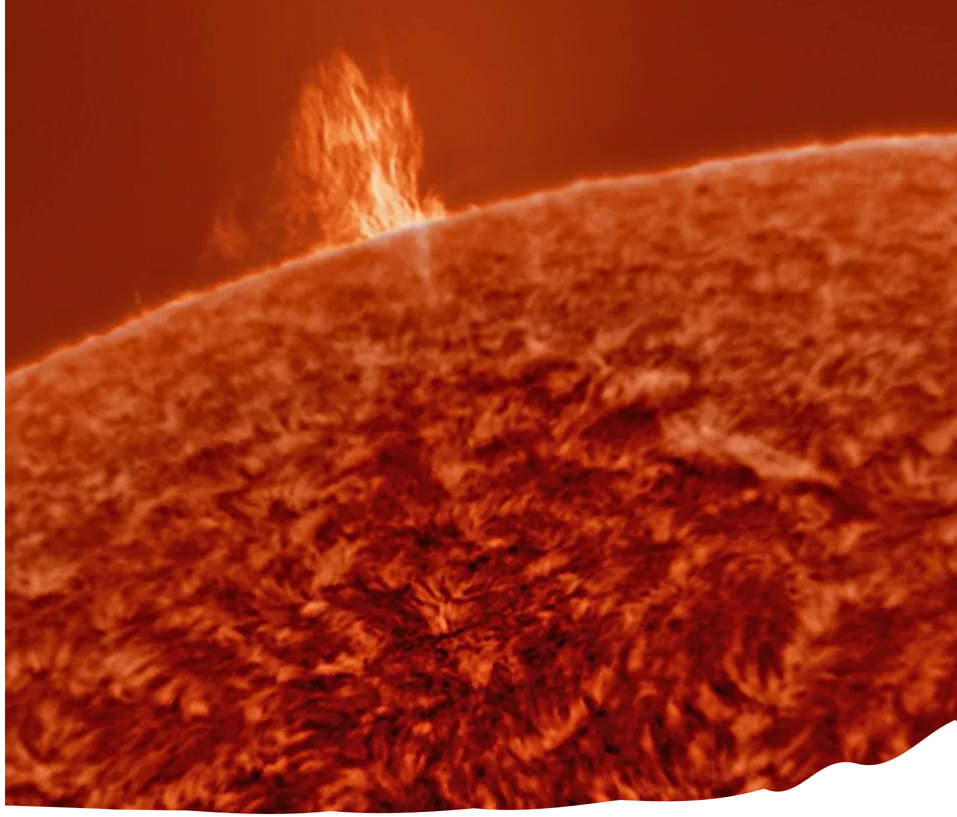
Exotic Stars – Near and Far



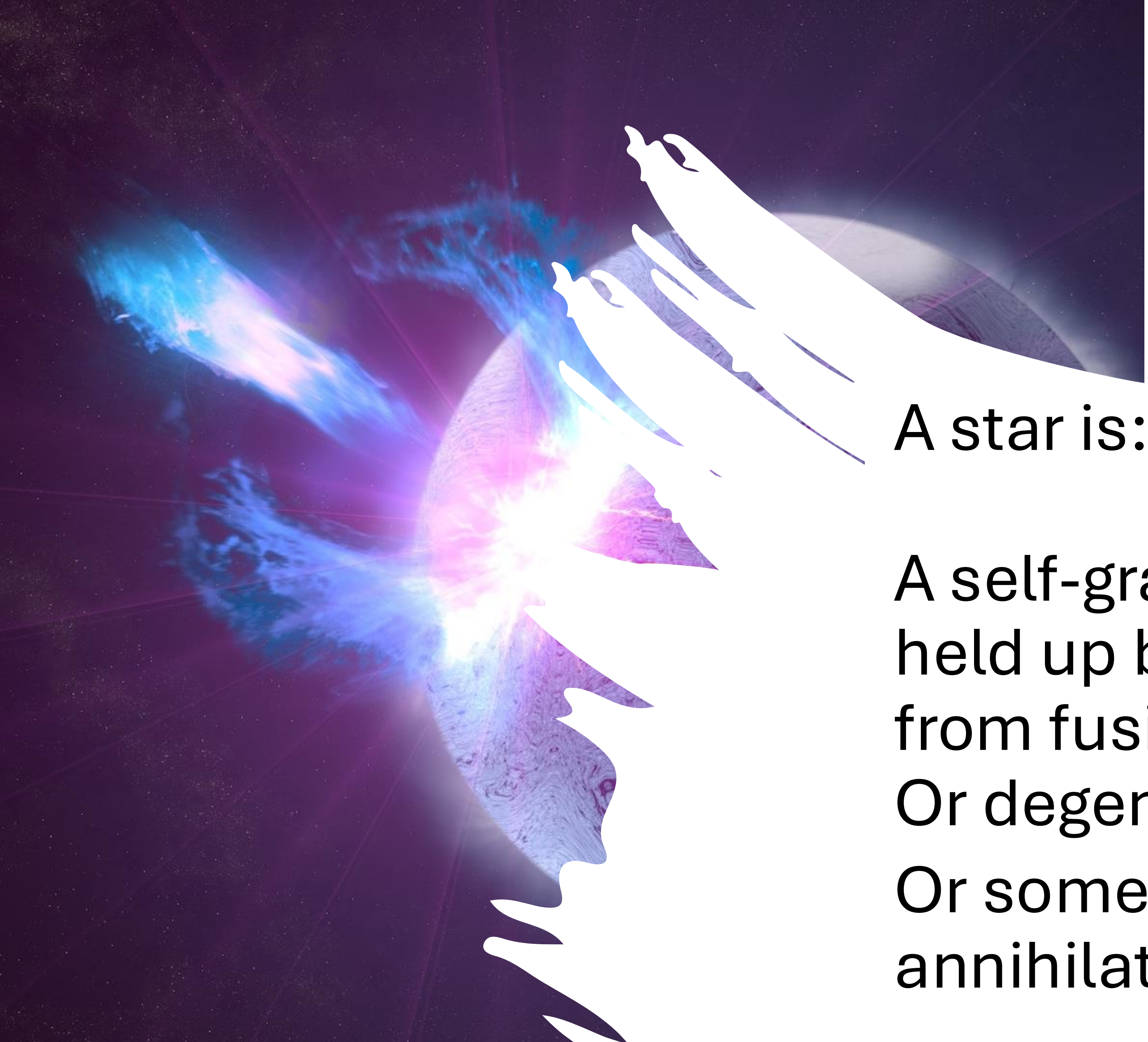
Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

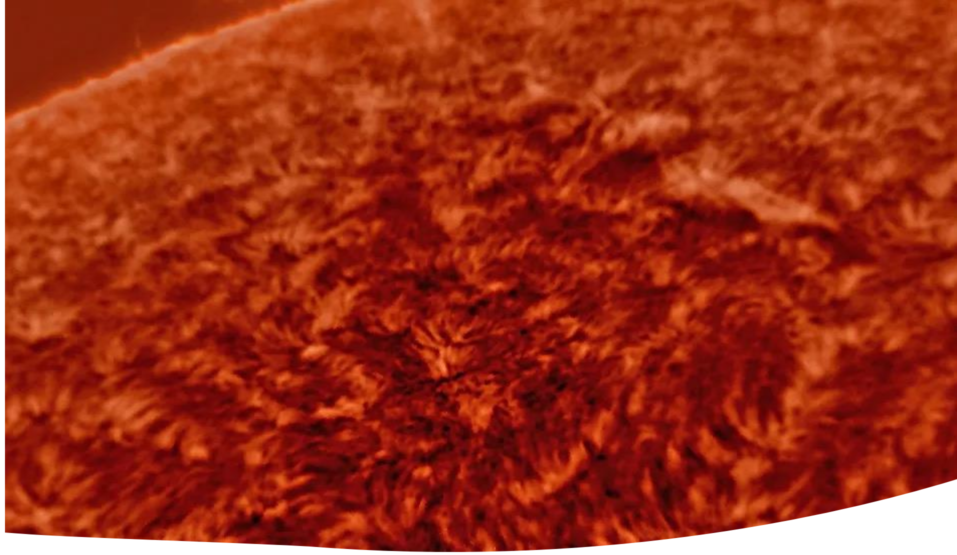
FZÚ – Division Seminar
22/05/25

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



Stellar Astrophysics for the Theorist in a Hurry



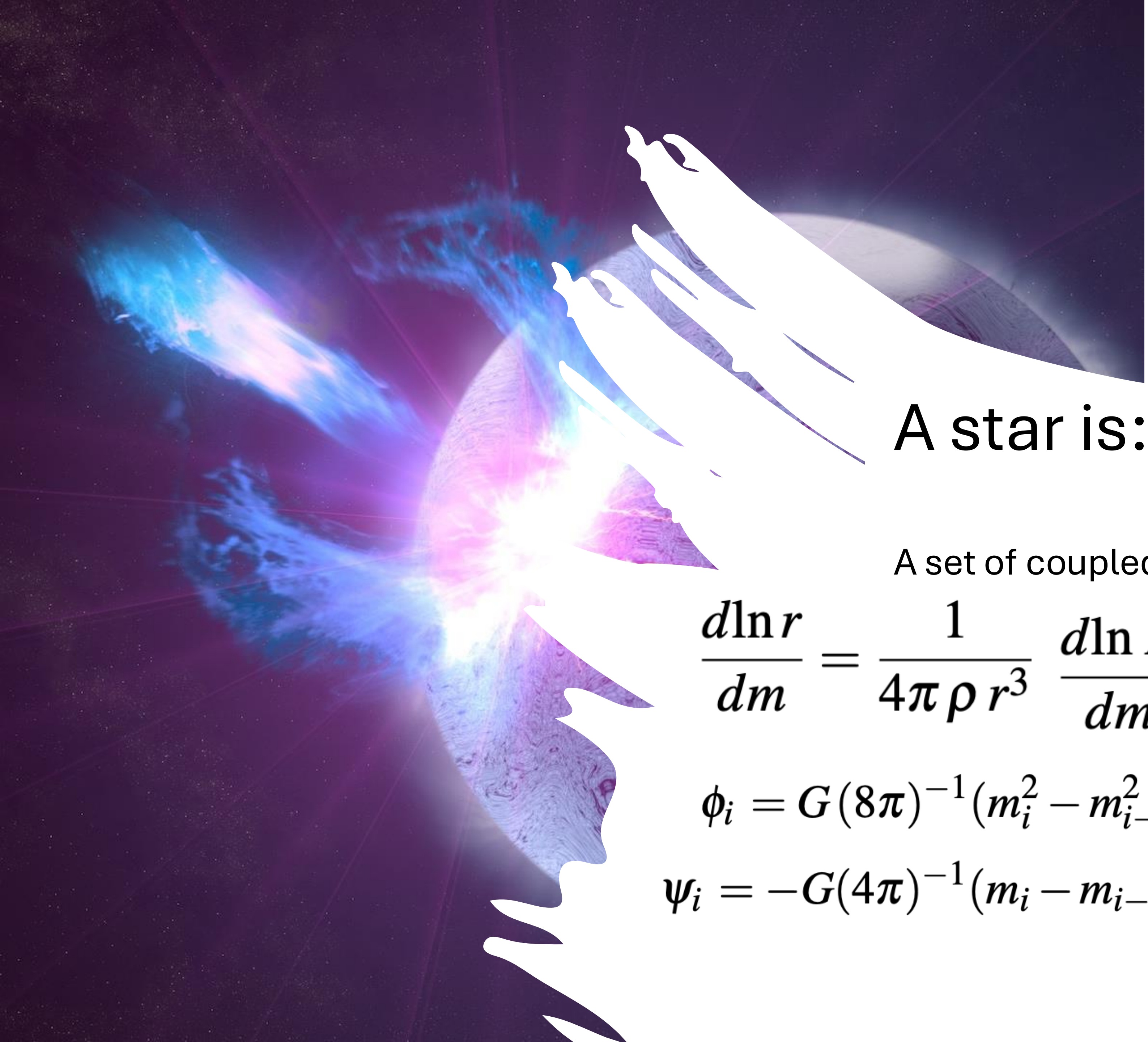


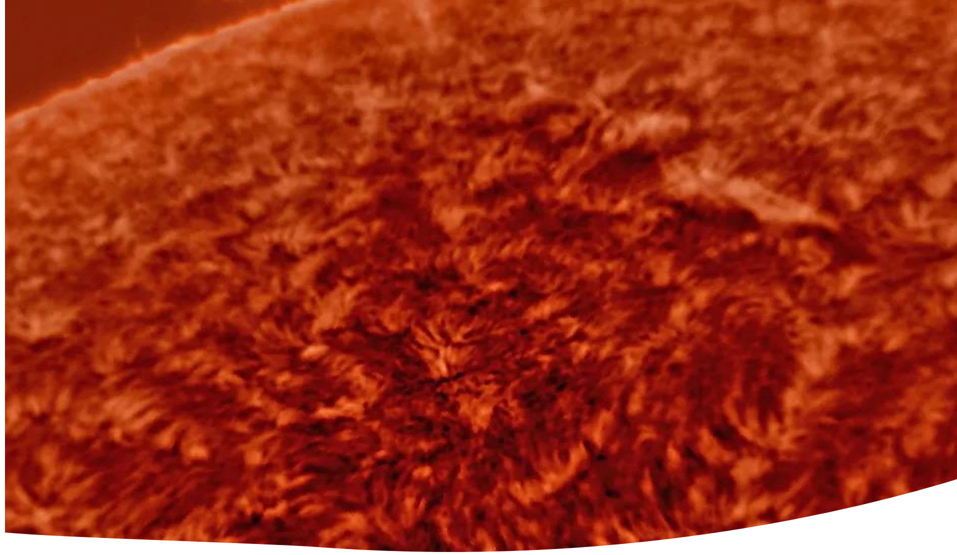
A star is:

A self-gravitating sphere of gas held up by thermal pressure from fusion?

Or degeneracy pressure...

Or some sort of DM annihilation?





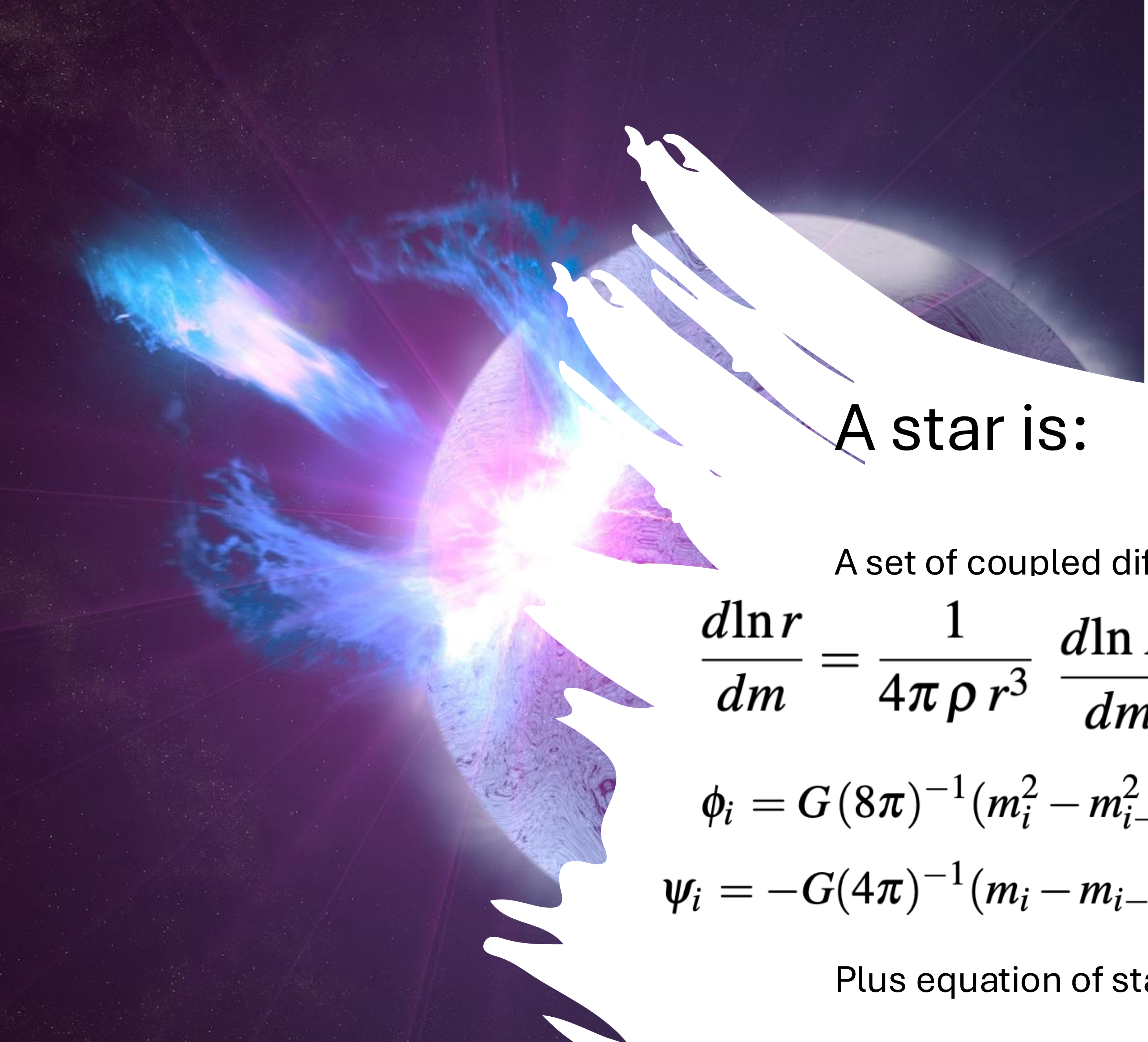
A star is:

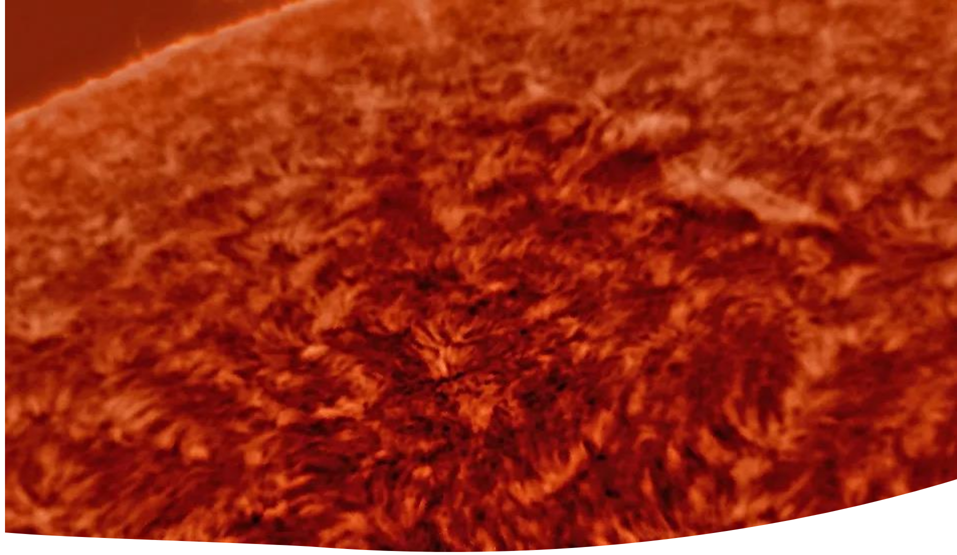
A set of coupled differential equations

$$\frac{d\ln r}{dm} = \frac{1}{4\pi \rho r^3} \quad \frac{d\ln P}{dm} = -\frac{Gm}{4\pi P r^4}$$

$$\phi_i = G(8\pi)^{-1}(m_i^2 - m_{i-1}^2)e^{-\frac{1}{2}(y_i+y_{i-1})-2(x_i+x_{i-1})} + y_i - y_{i-1}$$

$$\psi_i = -G(4\pi)^{-1}(m_i - m_{i-1})e^{-\frac{3}{2}(x_i+x_{i-1})-\frac{1}{2}(q_i+q_{i-1})} + x_i - x_{i-1}$$





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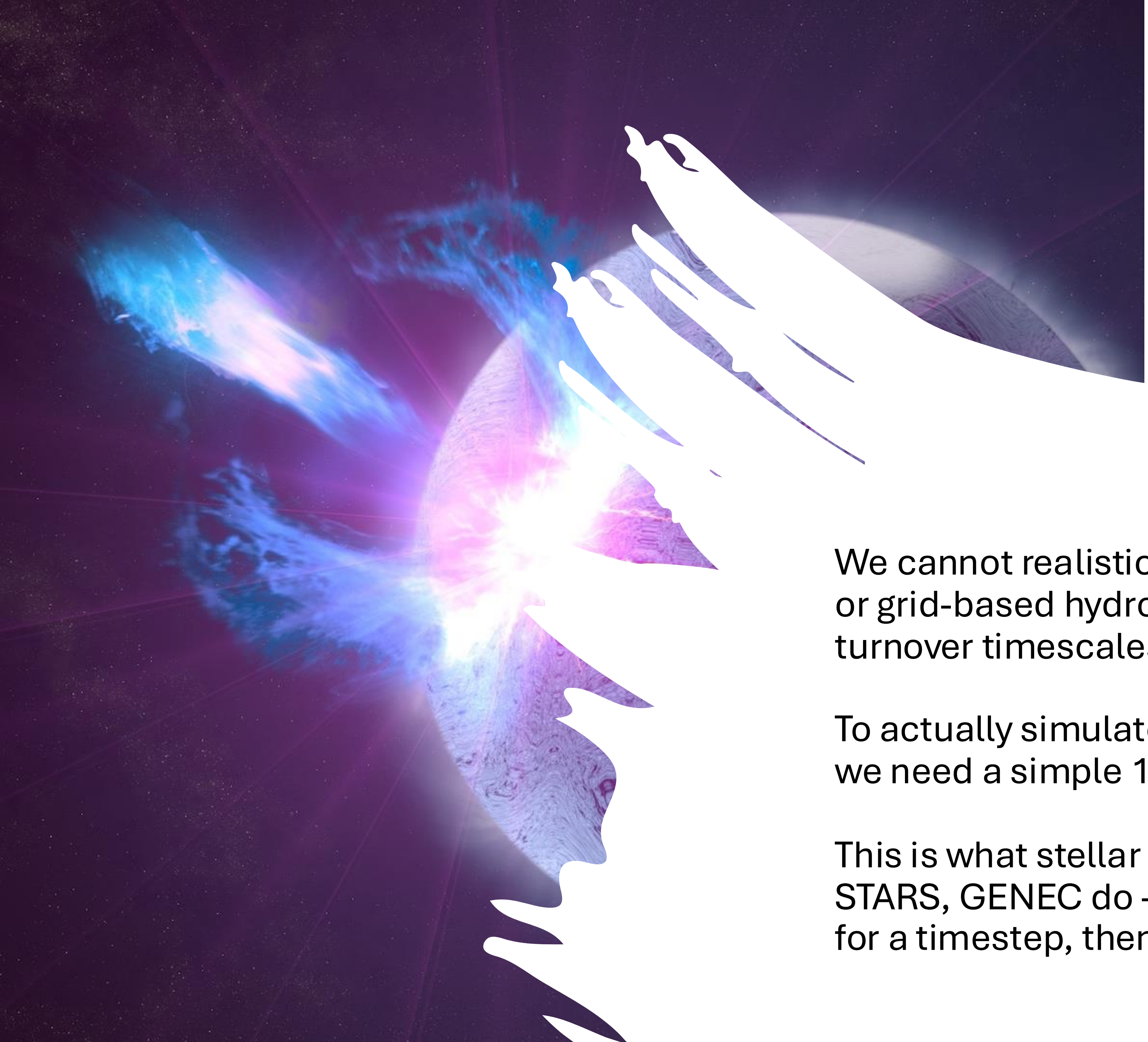
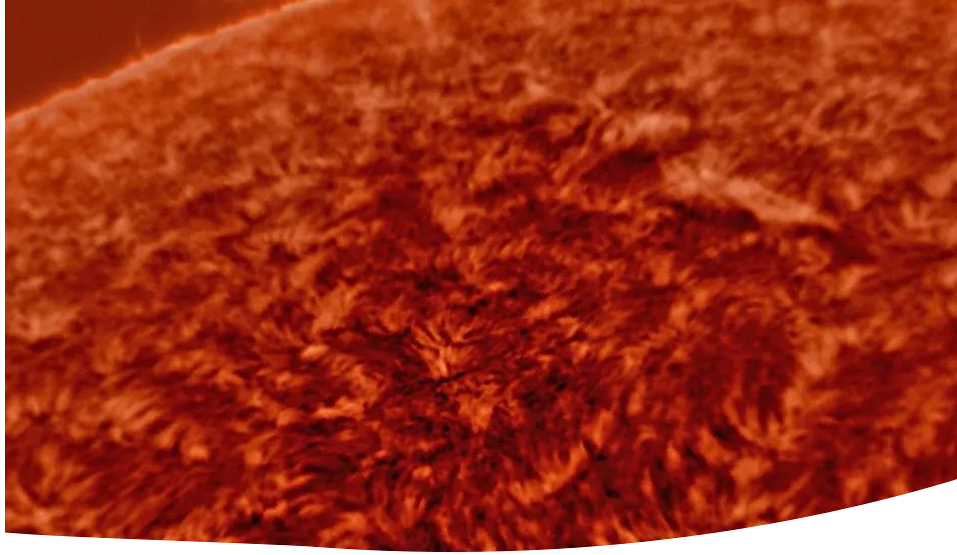
Plus equation of state, opacities, nuclear reaction network...



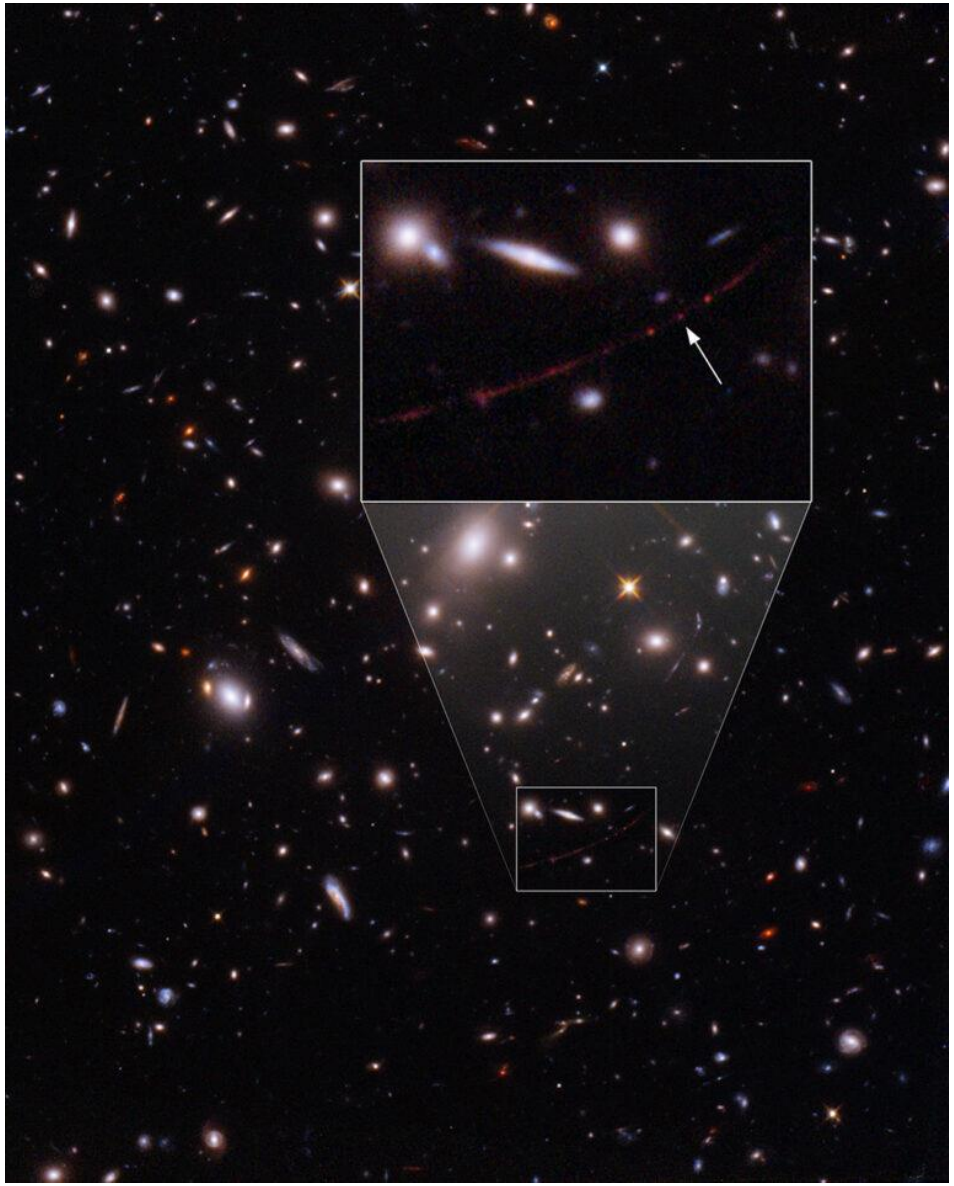


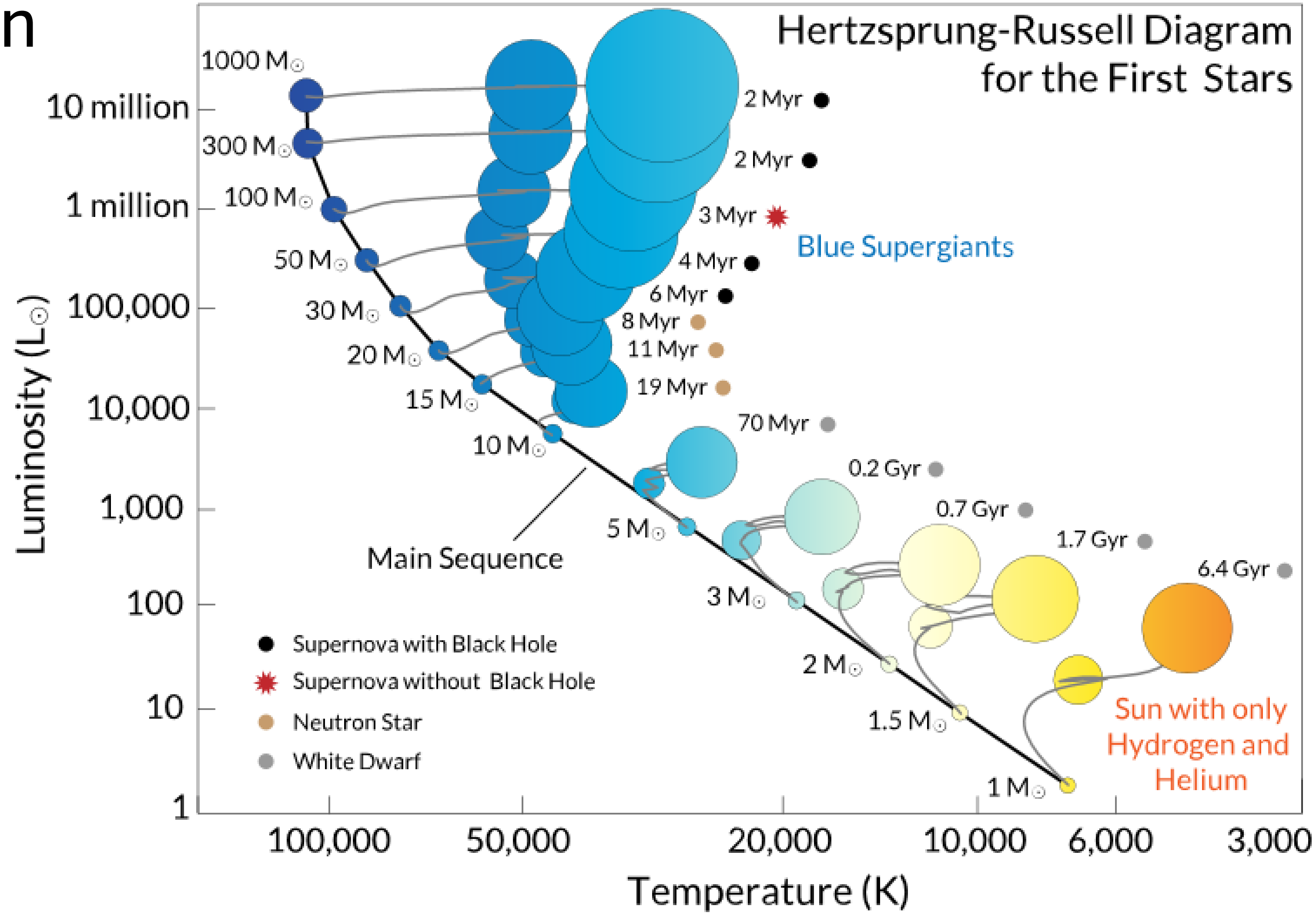
We cannot realistically simulation the entire star in 3D SPH or grid-based hydro – not for more than a few convective turnover timescales…

To actually simulate a star over the stars nuclear timescale, we need a simple 1D, relaxation based solution

This is what stellar evolution codes such as e.g. MESA, STARS, GENEC do – take a stellar structure, and permute it for a timestep, then do a Henyey relaxation to converge

Massive Stars and Reionization





Earendel – Highly lensed star at $z_{phot} \approx 6.2$

How do such objects affect the Universe at First Light?

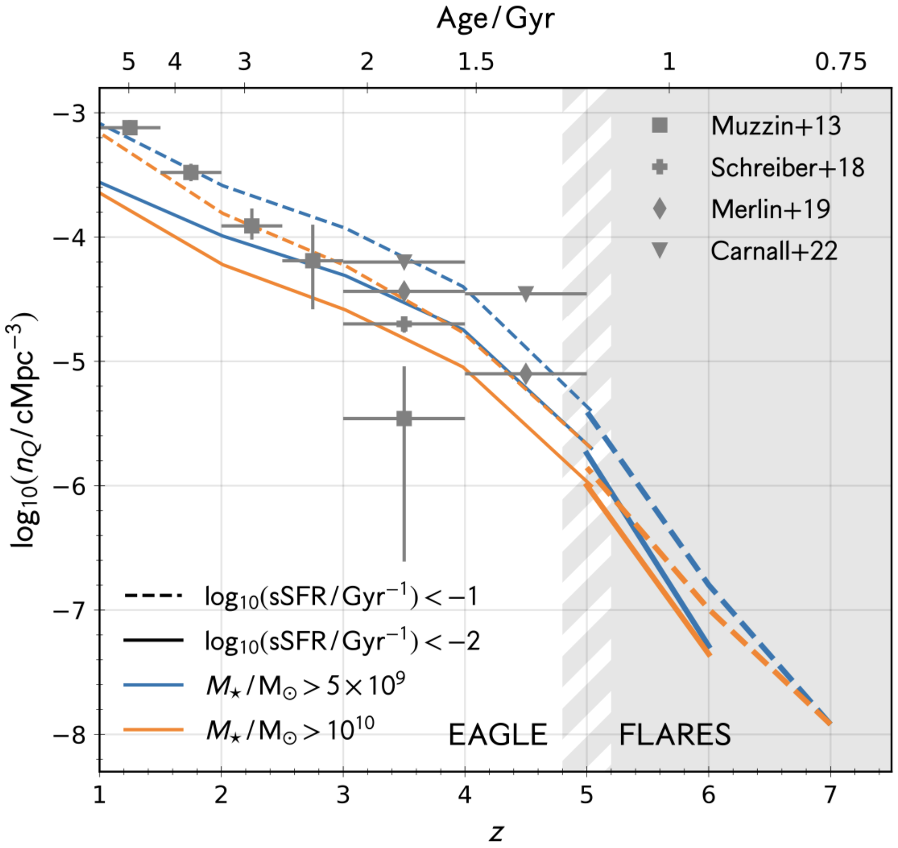
How can we model them?

Courtesy of F. X. Timmes

Massive Stars and Reionization

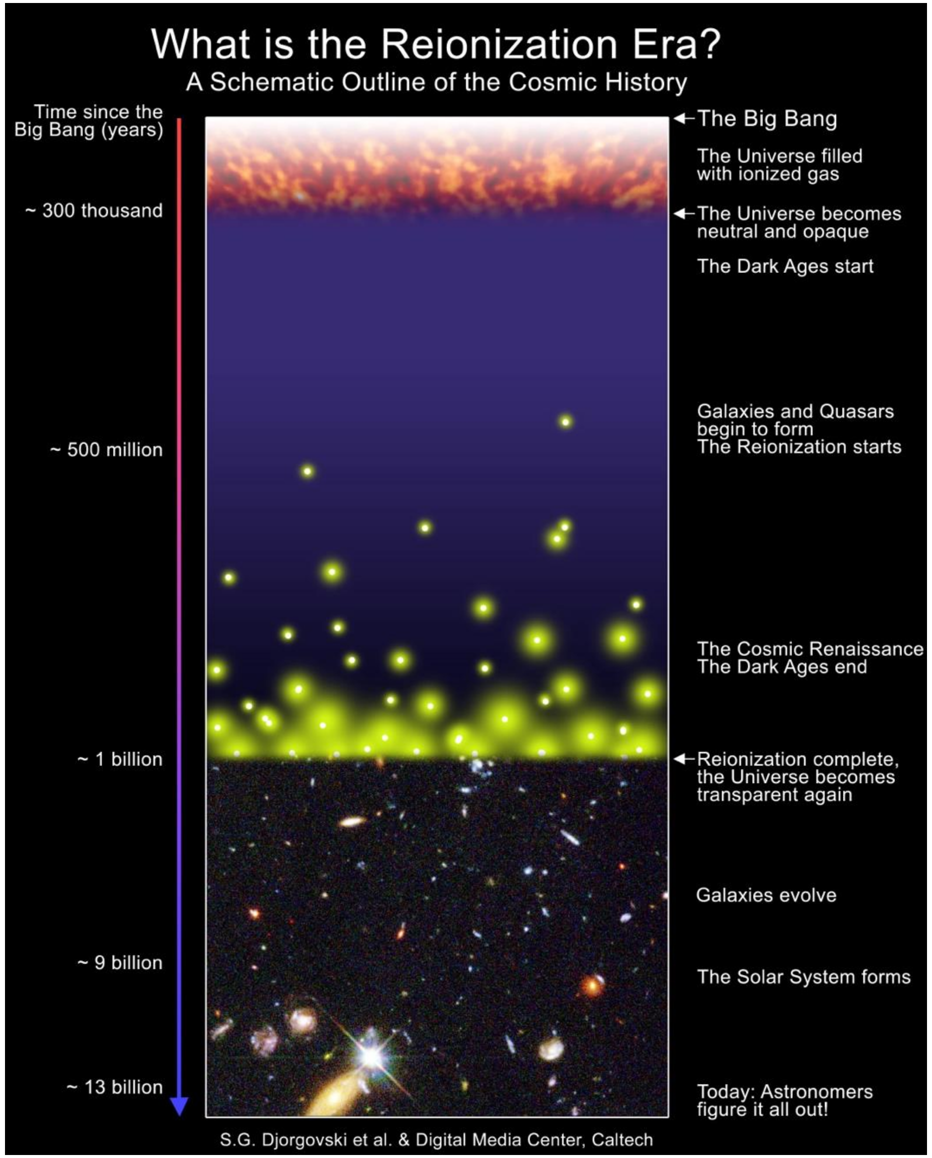
Reionization, and the evolution of galaxies at early times

Subject of simulations like FLARES (Lovell+23)



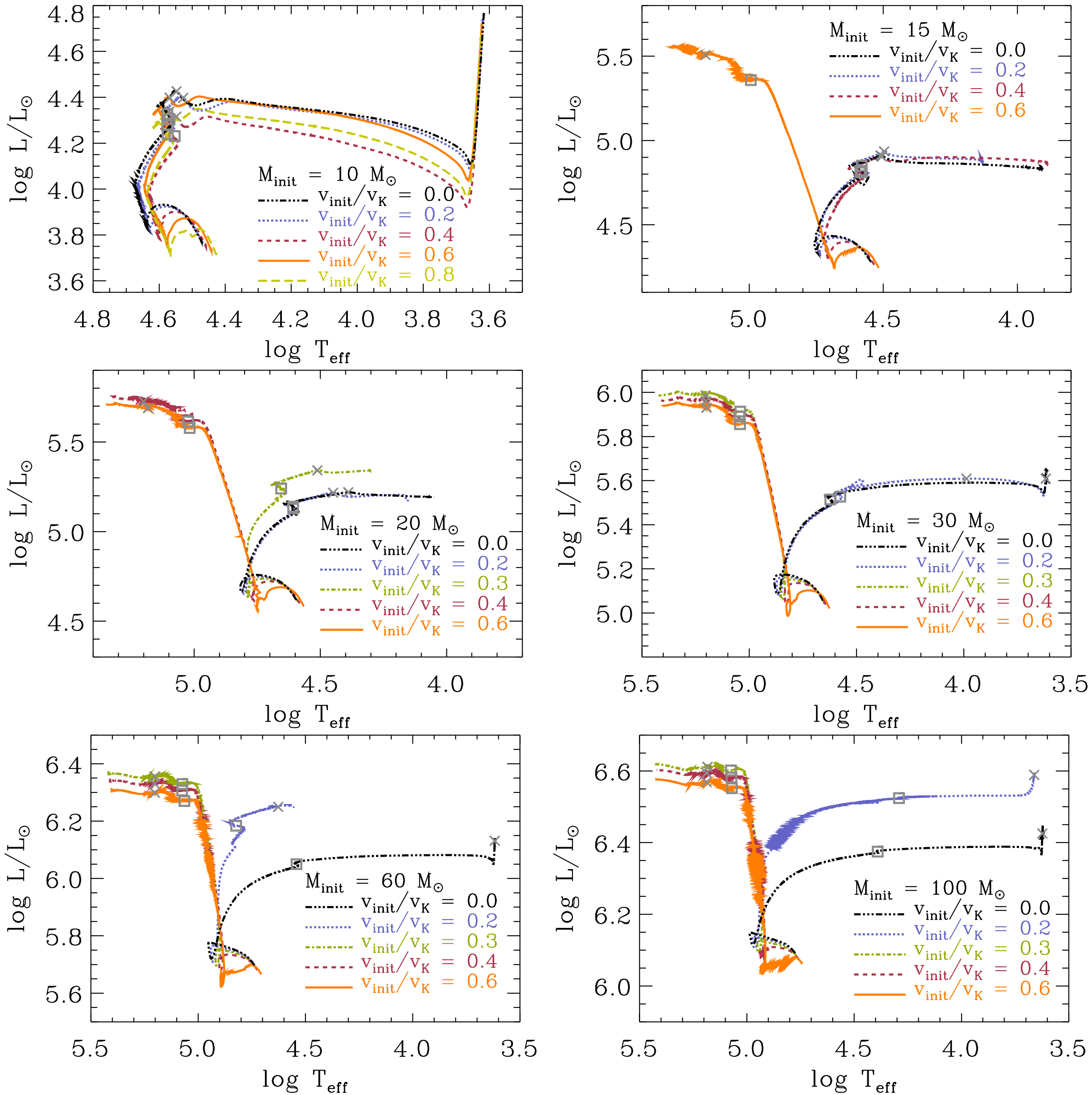
Subgrid physics is vital
How important was the light from Population III stars for reionization?

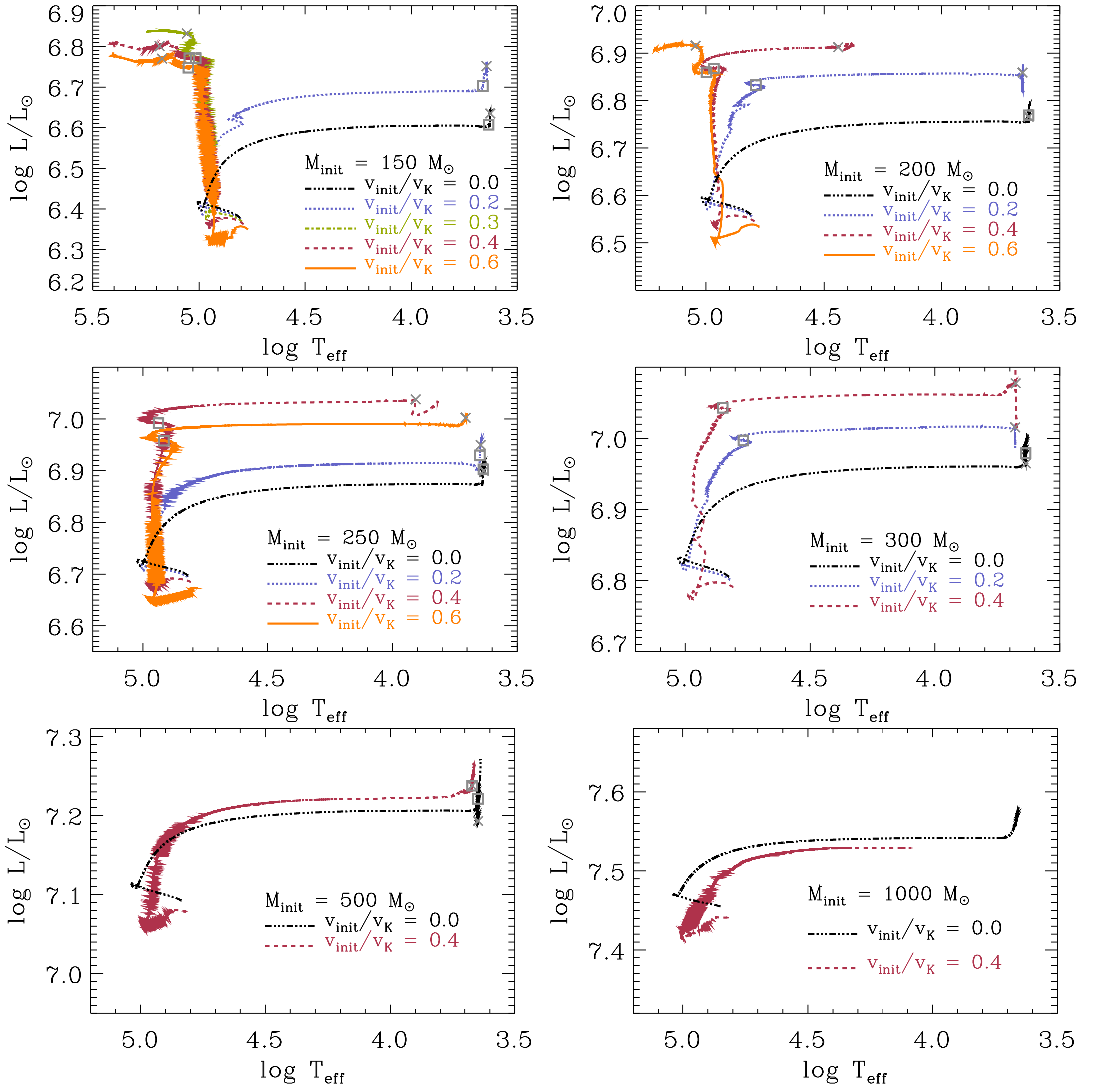
The first stars were metal-free and very massive – lack of metal for cooling & fragmentation (Klessen+23, Chantavat+23 etc.)



Massive Stars and Reionization

Yoon+12





Examples: rotating Pop III HRDs are very different from metal-enriched populations

Massive Stars and Reionization

Reionization, and the evolution of galaxies at early times

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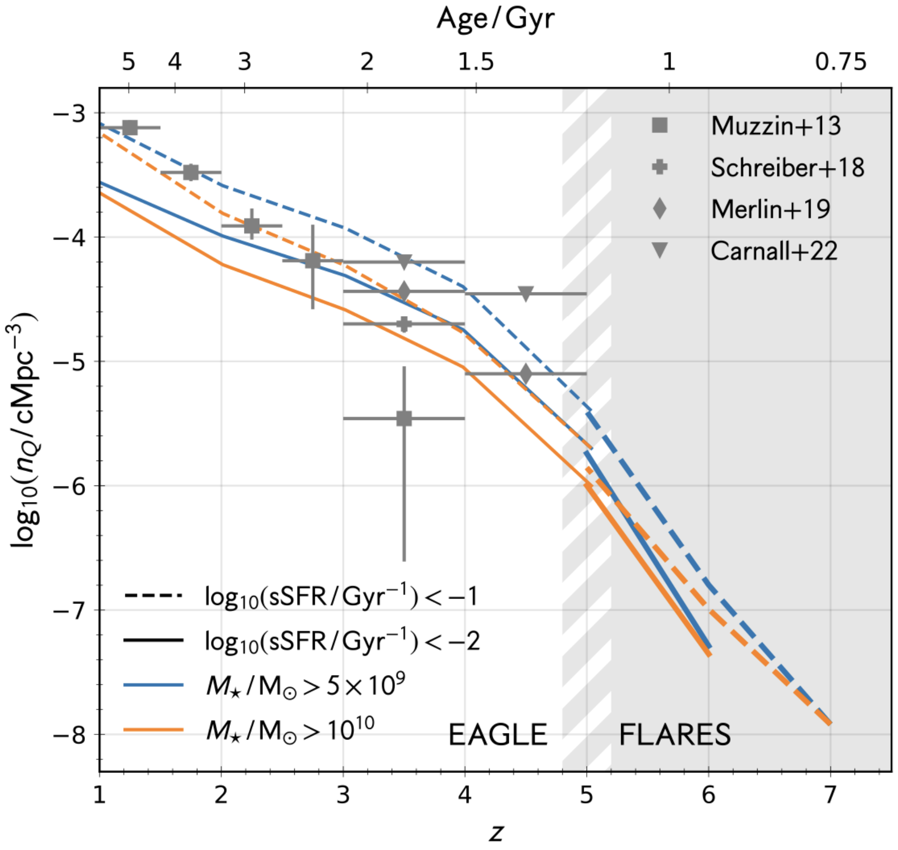

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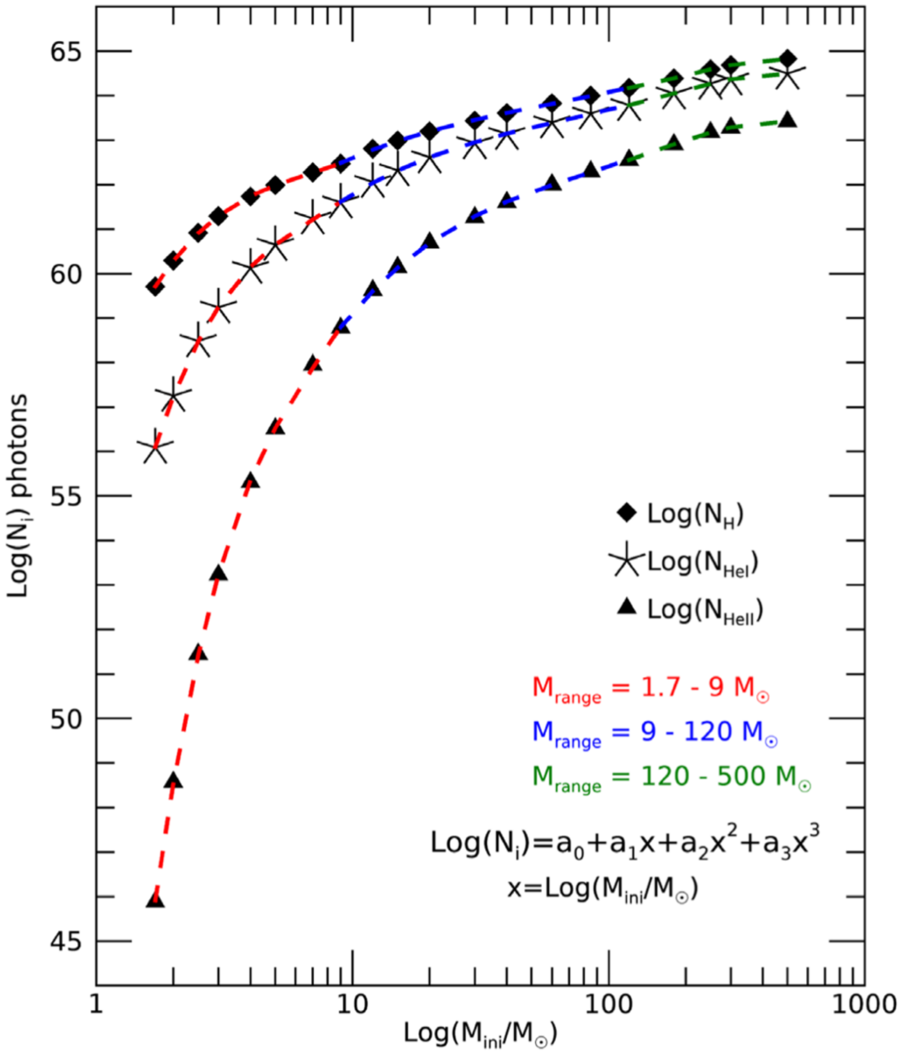
How important was the light from Population III stars for reionization?



Geneva simulations suggest simple cubic relation (Murphy+21)

Massive Stars and Reionization

Reionization, and the evolution of galaxies at early times

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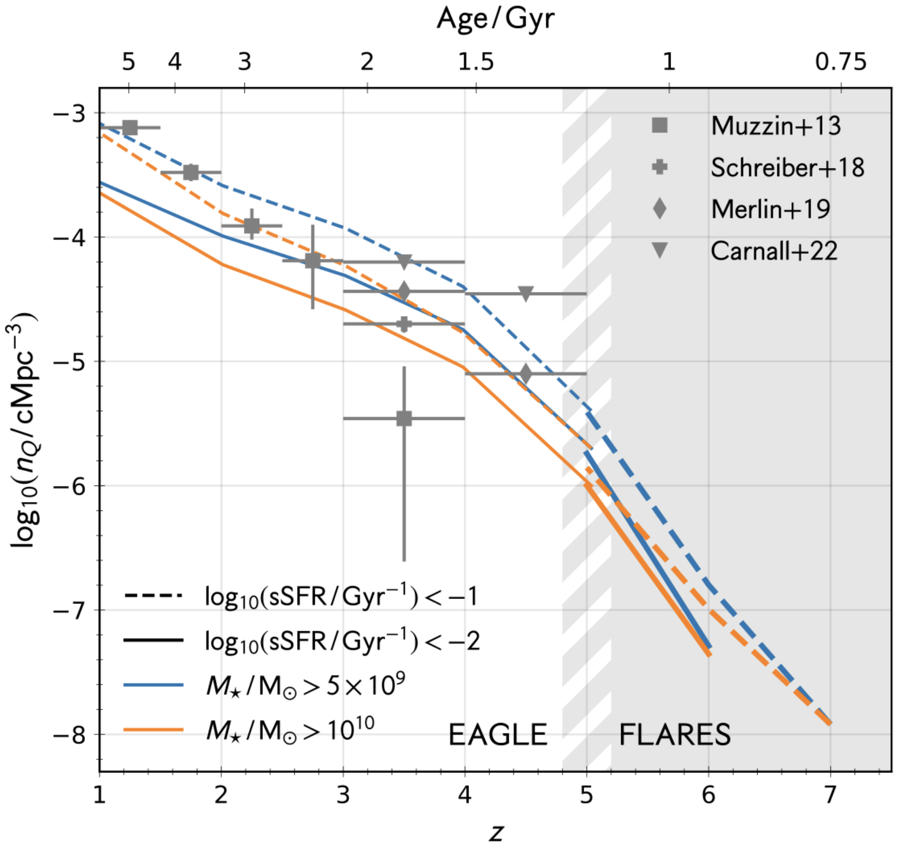
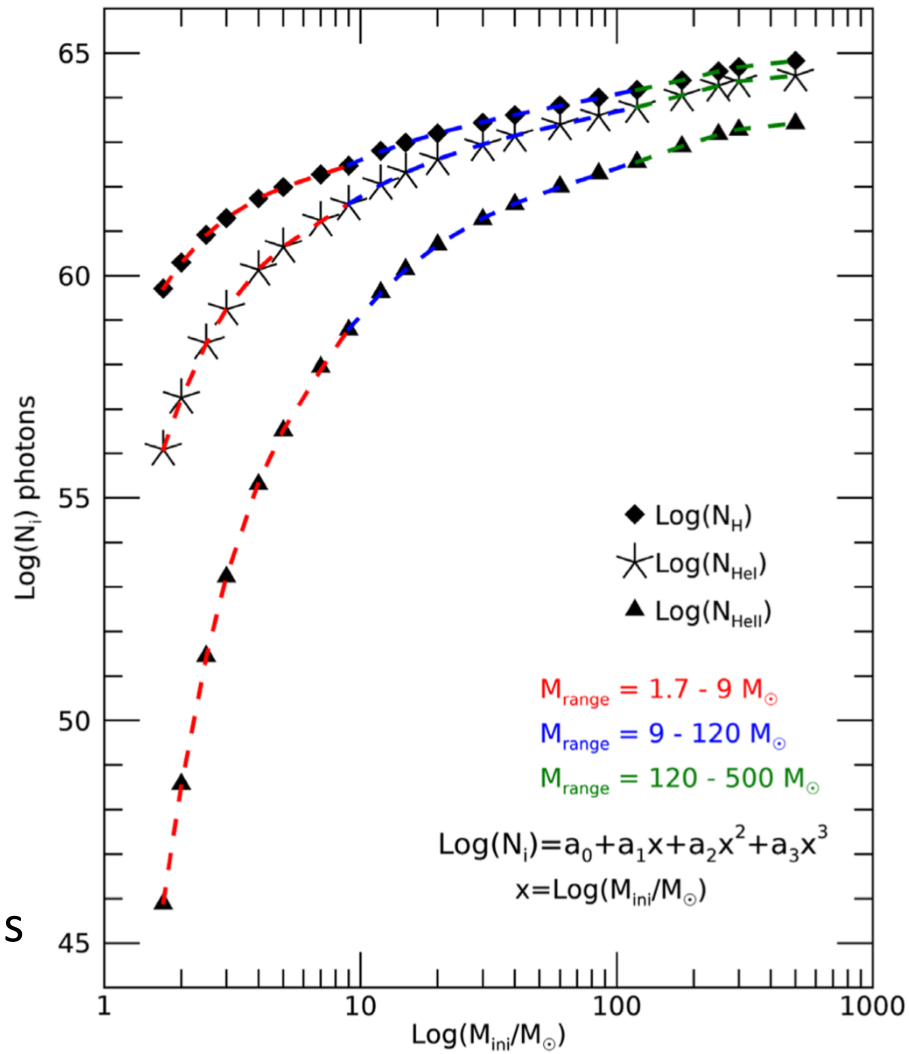


Subgrid physics is vital
How important was the light from Population III stars for reionization?

Input physics for our stellar models depend on

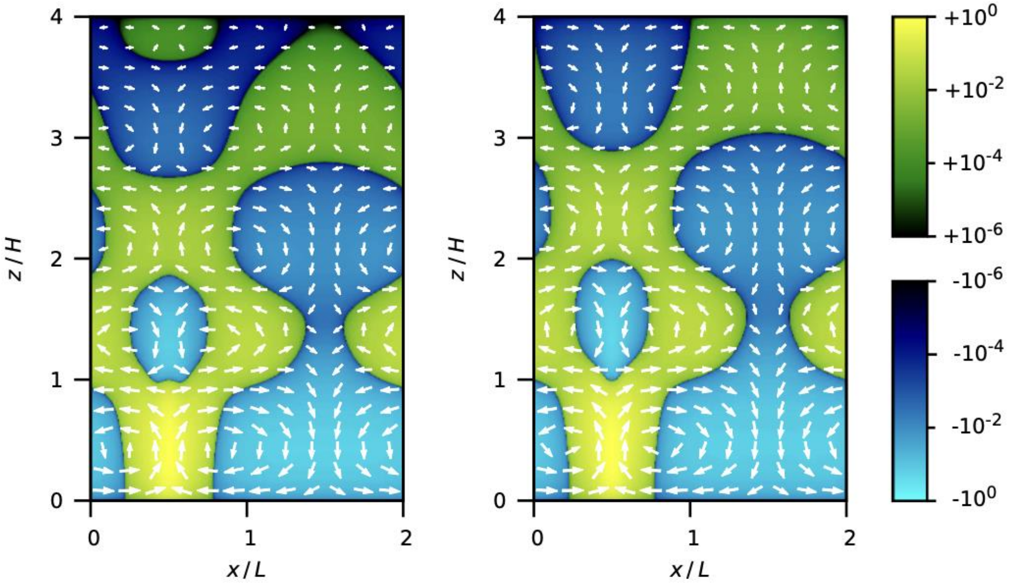
Initial Mass
IMF
Rotation
Convective Overshoot



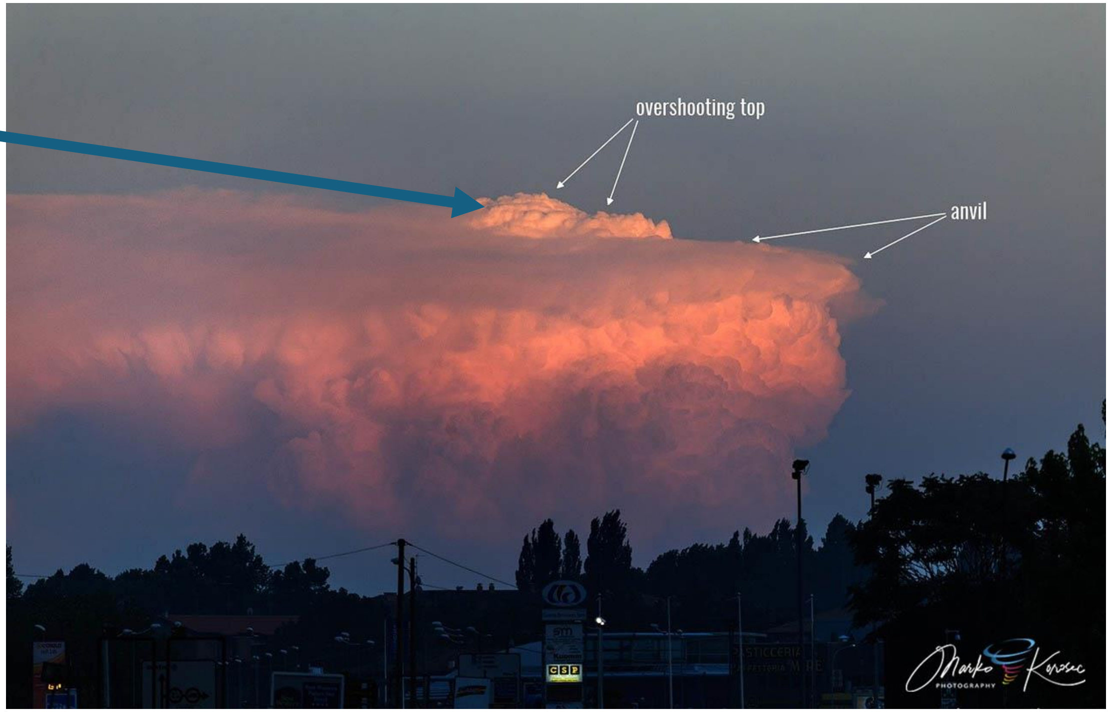
Geneva simulations suggest simple cubic relation (Murphy+21)

Massive Stars and Reionization

Overshooting – physically and observationally motivated



Observed originally in thunderclounds!



Problem – overshooting calibrated to solar models

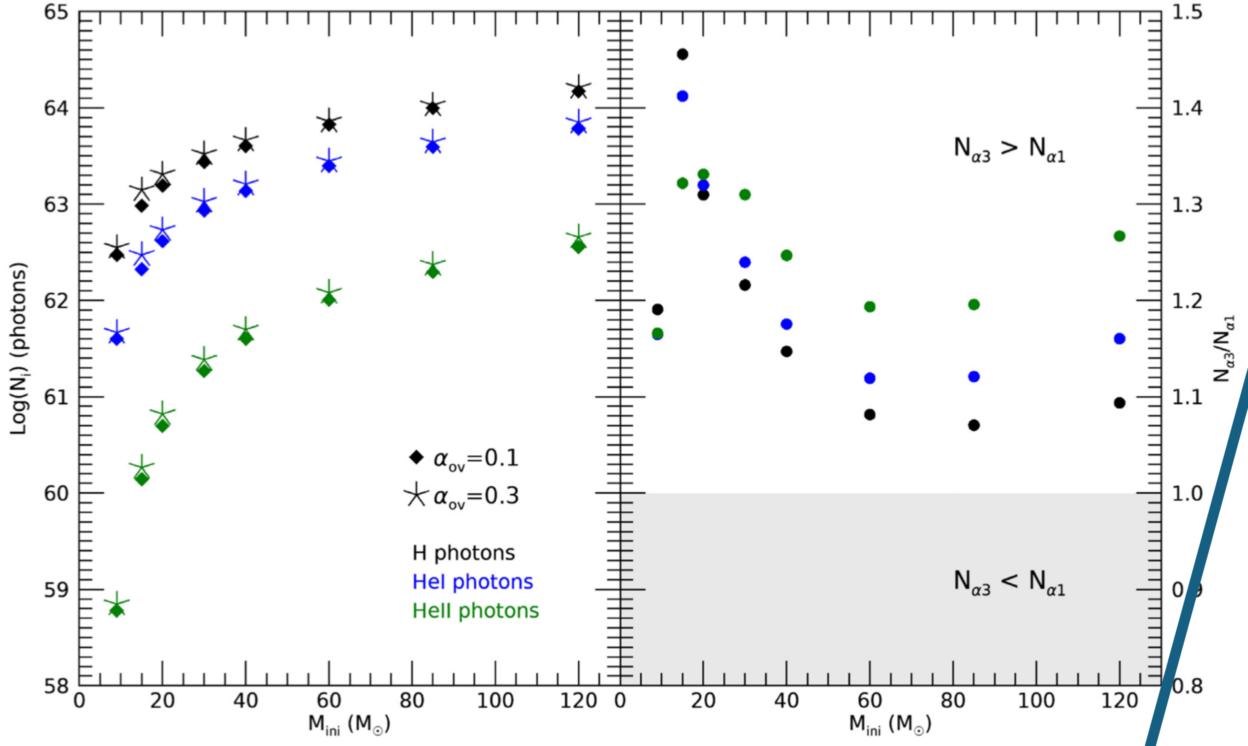
Safe to extrapolate to 100s $M_\odot$?

Momentum of convective material continues beyond convective boundary

Massive Stars and Reionization

Mass range from $9M_{\odot} \leq M_{initial} \leq 120M_{\odot}$

1 million solar mass starburst



Ionizing photon production function of overshooting

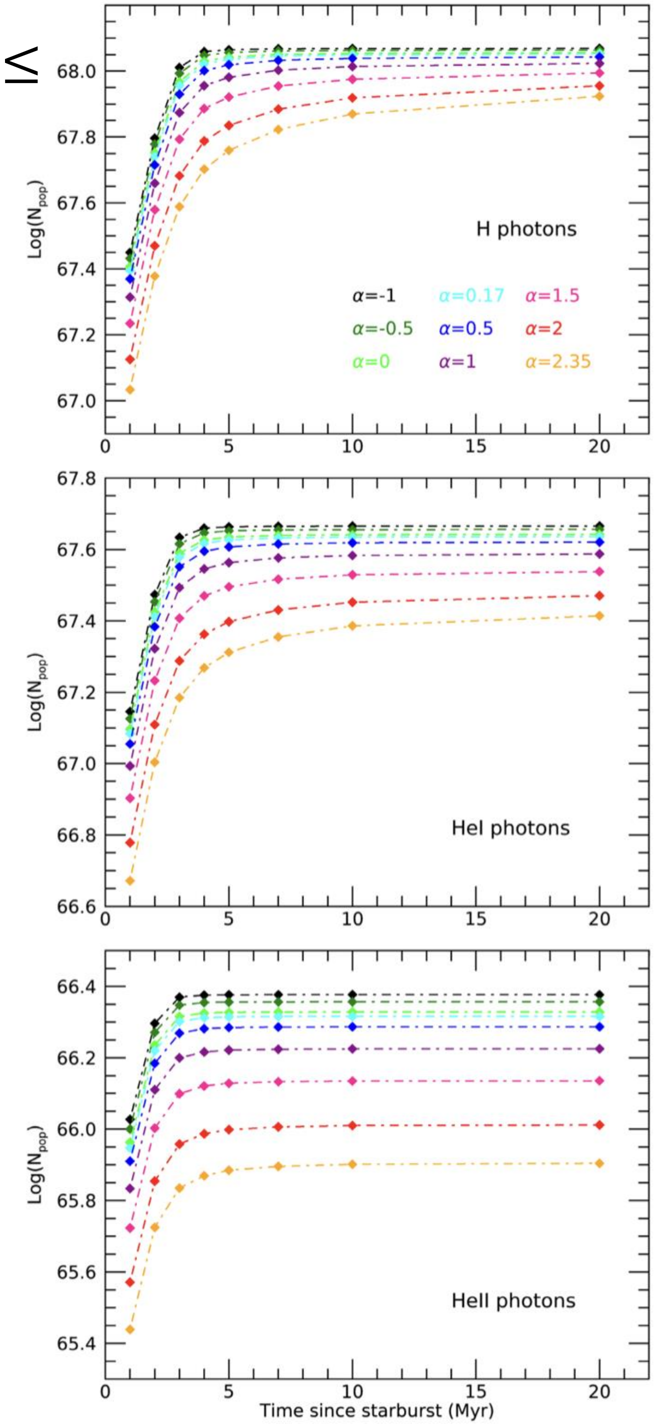
Of course – will be strongly dependant on IMF

Assume Salpeter/Salpeter-like?

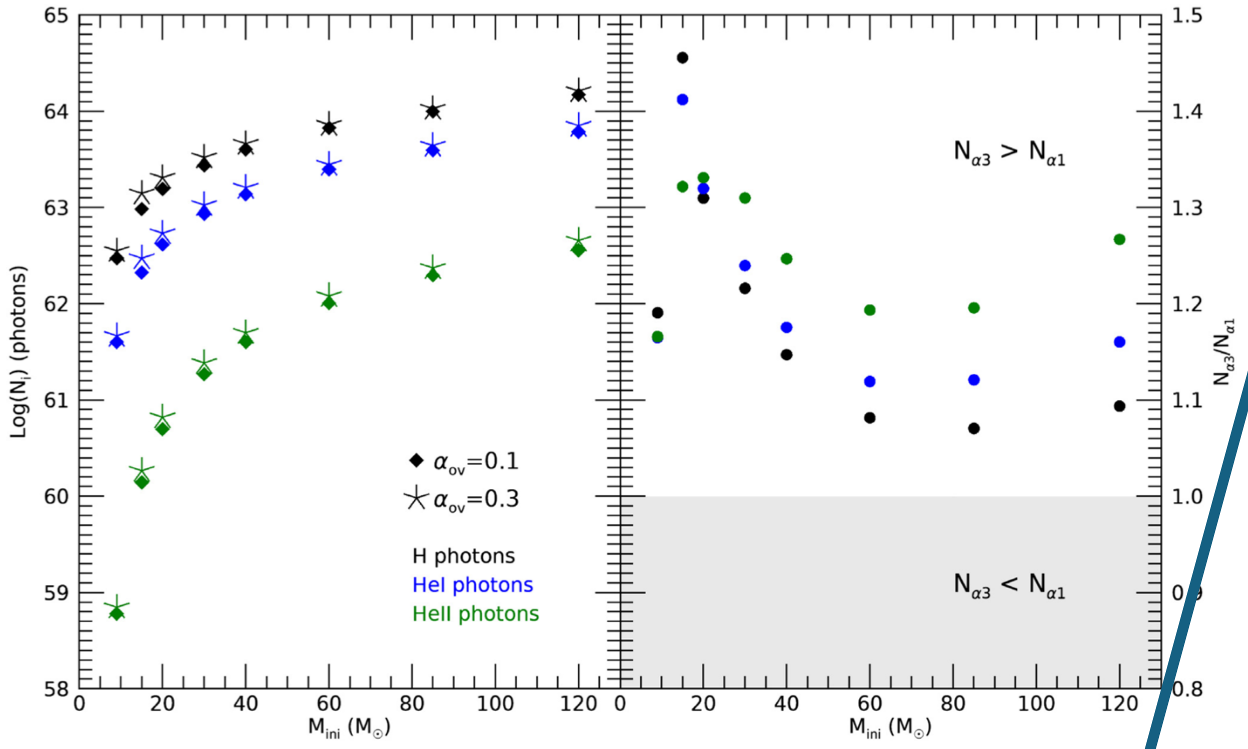
Key conclusions

Higher overshooting increases ionizing photon production

Not just from increased L and T_{eff}, but mainly *increased lifespan*



Massive Stars and Reionization



Ionizing photon production function of overshooting

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Assume Salpeter/Salpeter-like?

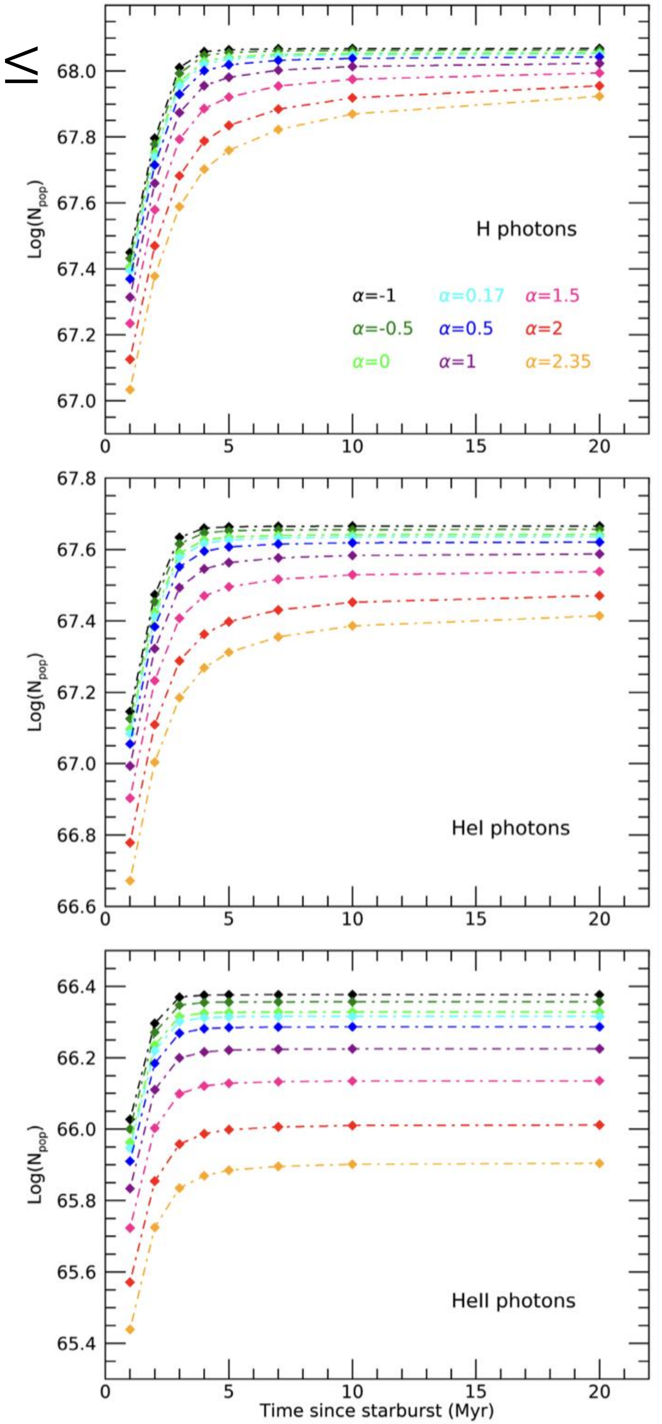
Mass range from $9M_\odot \leq M_{initial} \leq 120M_\odot$

1 million solar mass starburst

Key conclusions

Top-heavy IMFs produce more ionizing photons

Dominated by higher initial masses



Massive Stars and Reionization

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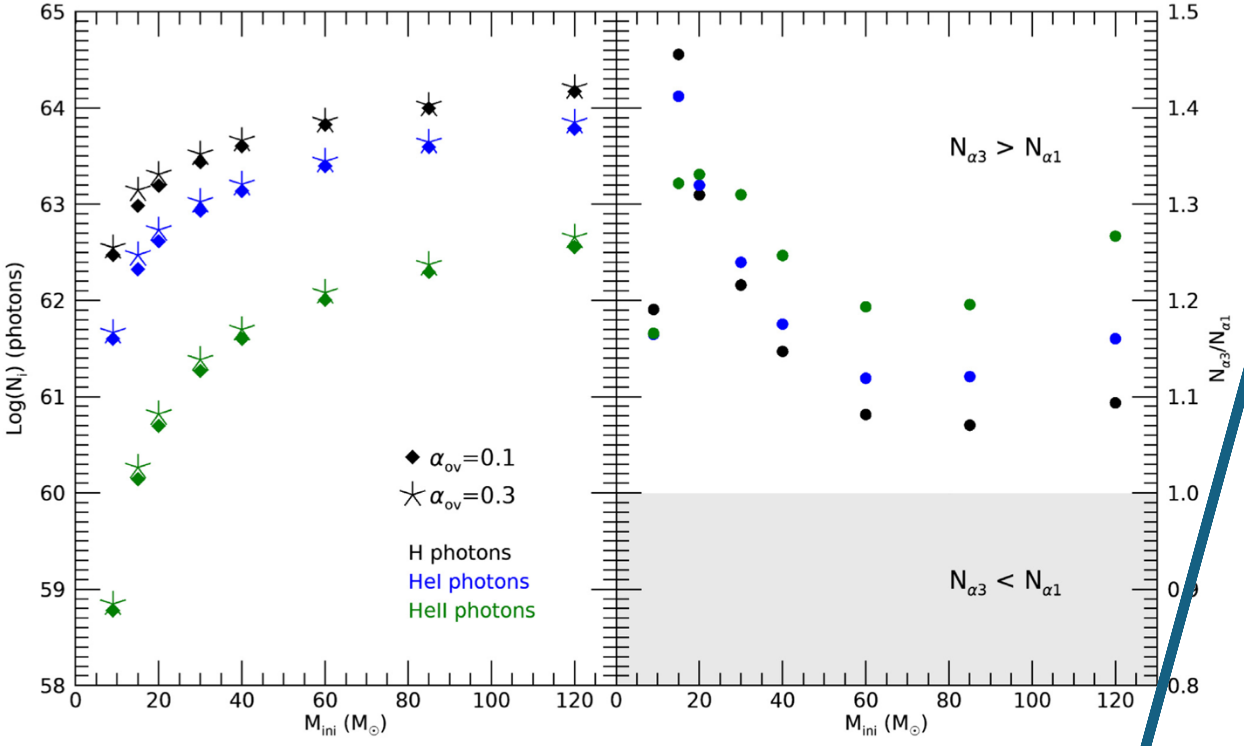

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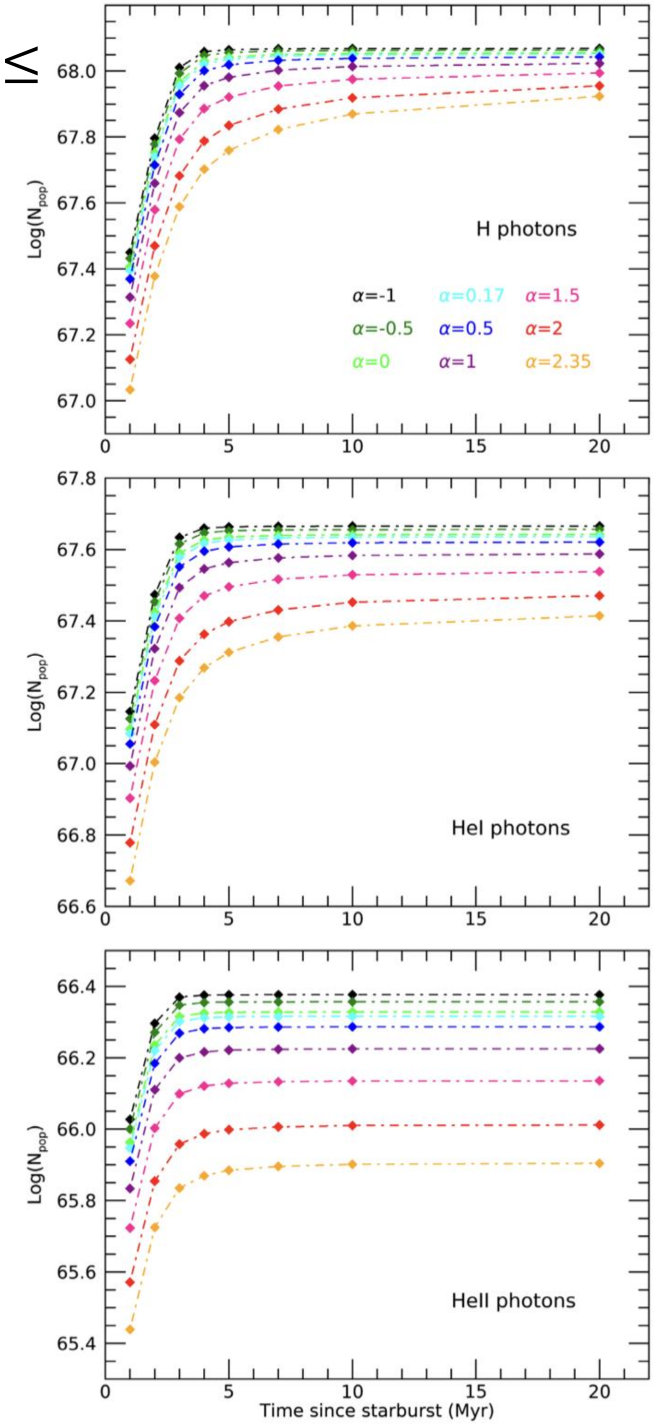
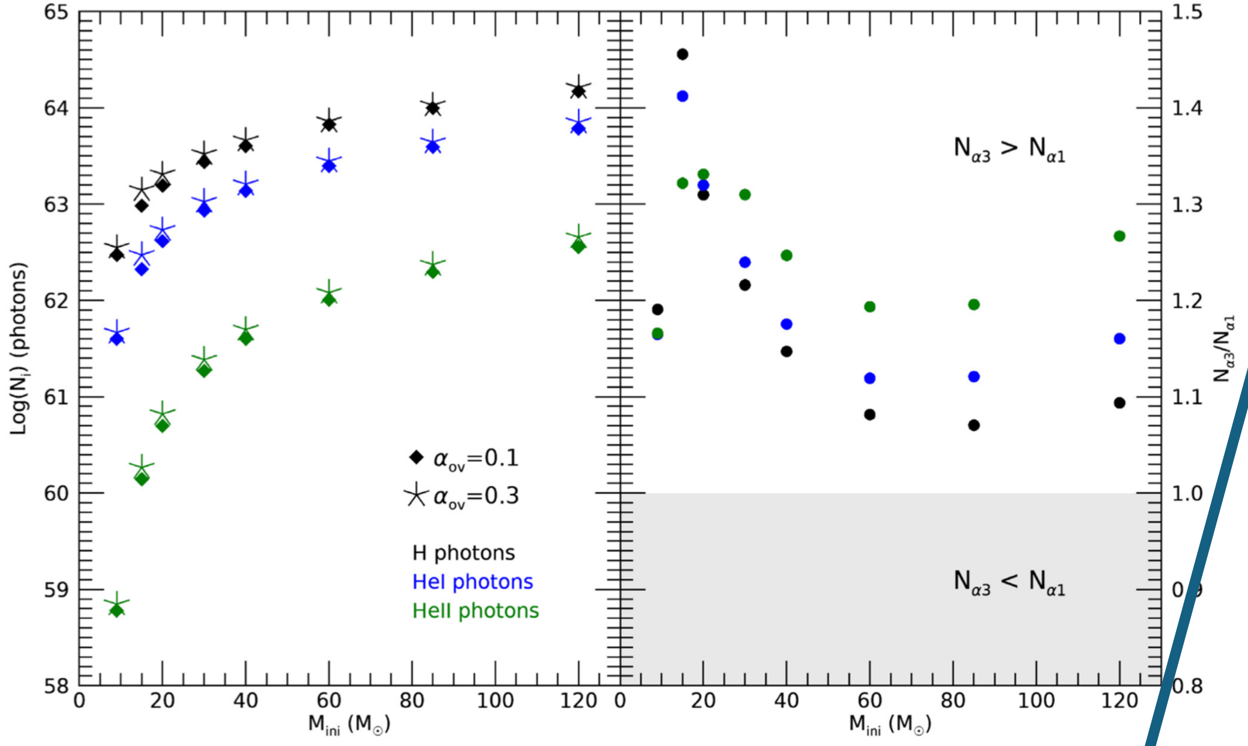


Key conclusions

Top-heavy IMFs produce more ionizing photons

Steeper-slope IMFs also take *longer* to produce their photons – more low-mass, long-lived stars

Massive Stars and Reionization



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Of course – will be strongly dependant on IMF

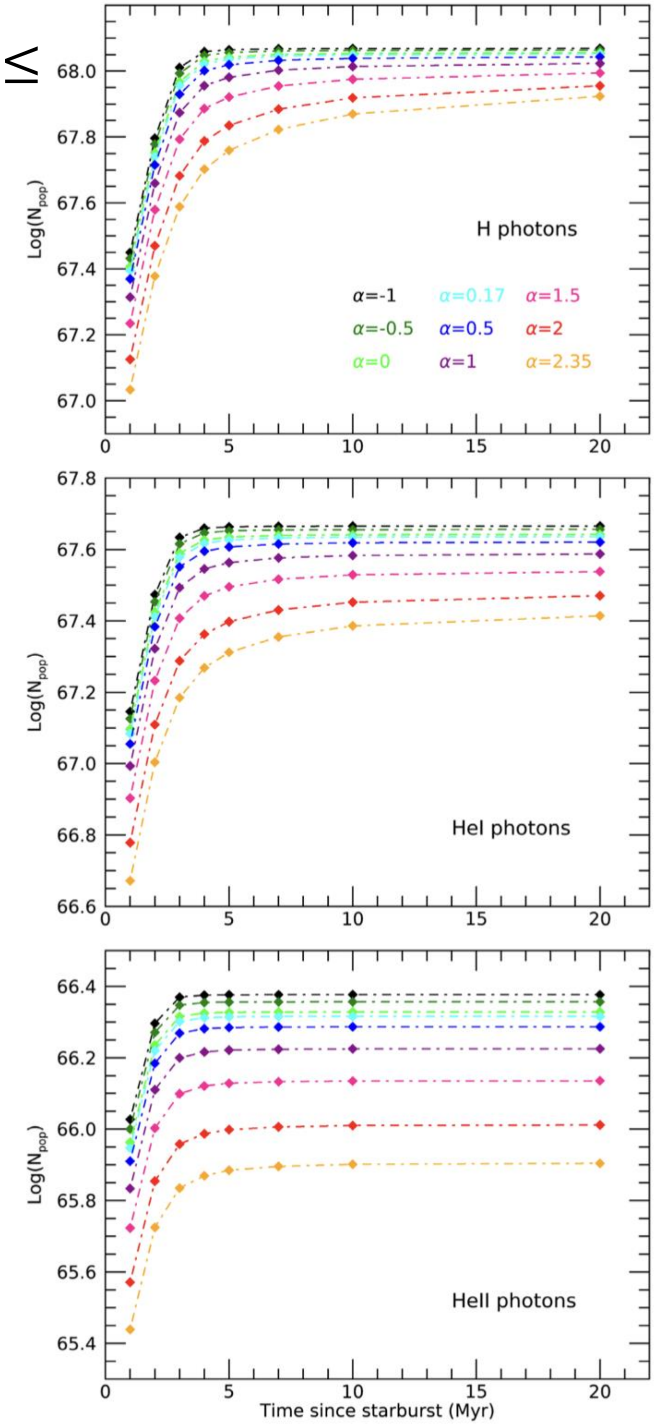
Assume Salpeter/Salpeter-like?

Mass range from $9M_\odot \leq M_{initial} \leq 120M_\odot$

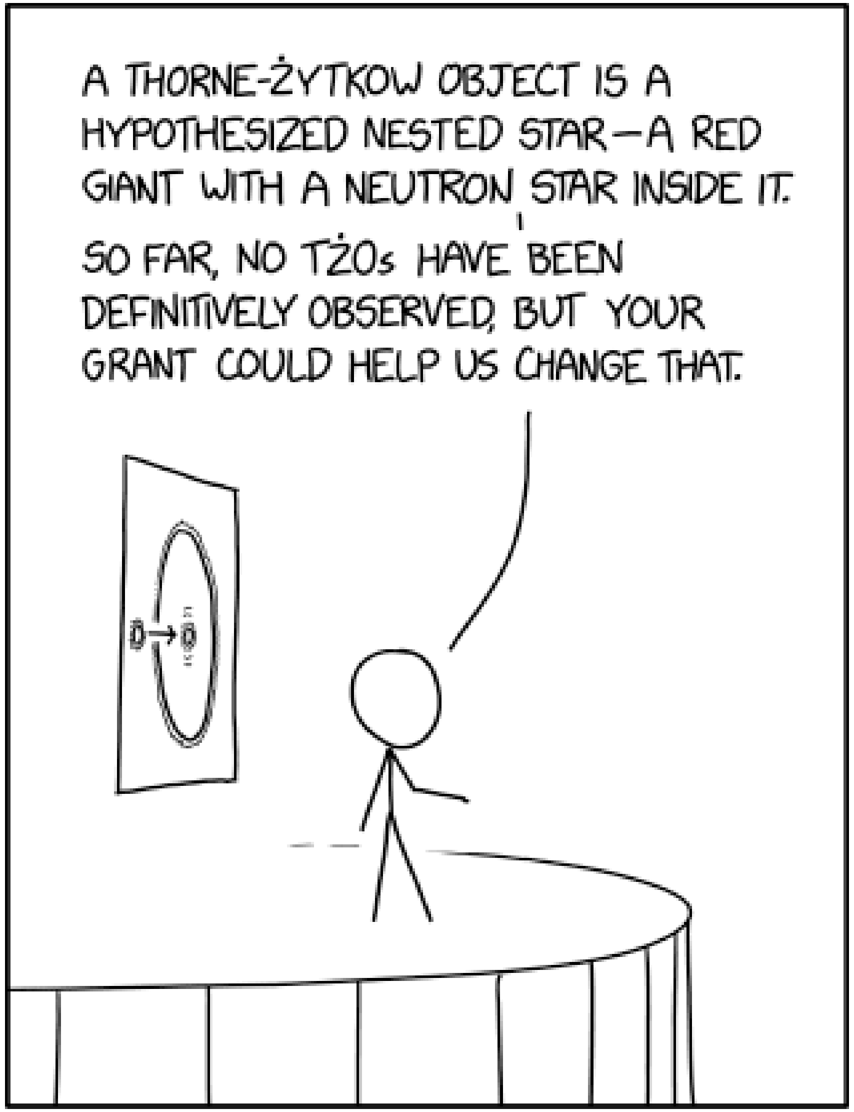
1 million solar mass starburst

Key conclusions

Stars that undergo *chemically homogenous evolution* (CHE) produce ~1.5 dex more ionizing photons



Thorne-Żytkow Objects



WE'RE STRUGGLING TO GET FUNDING FOR OUR PROJECT TO SLINGSHOT A NEUTRON STAR INTO THE SUN.

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

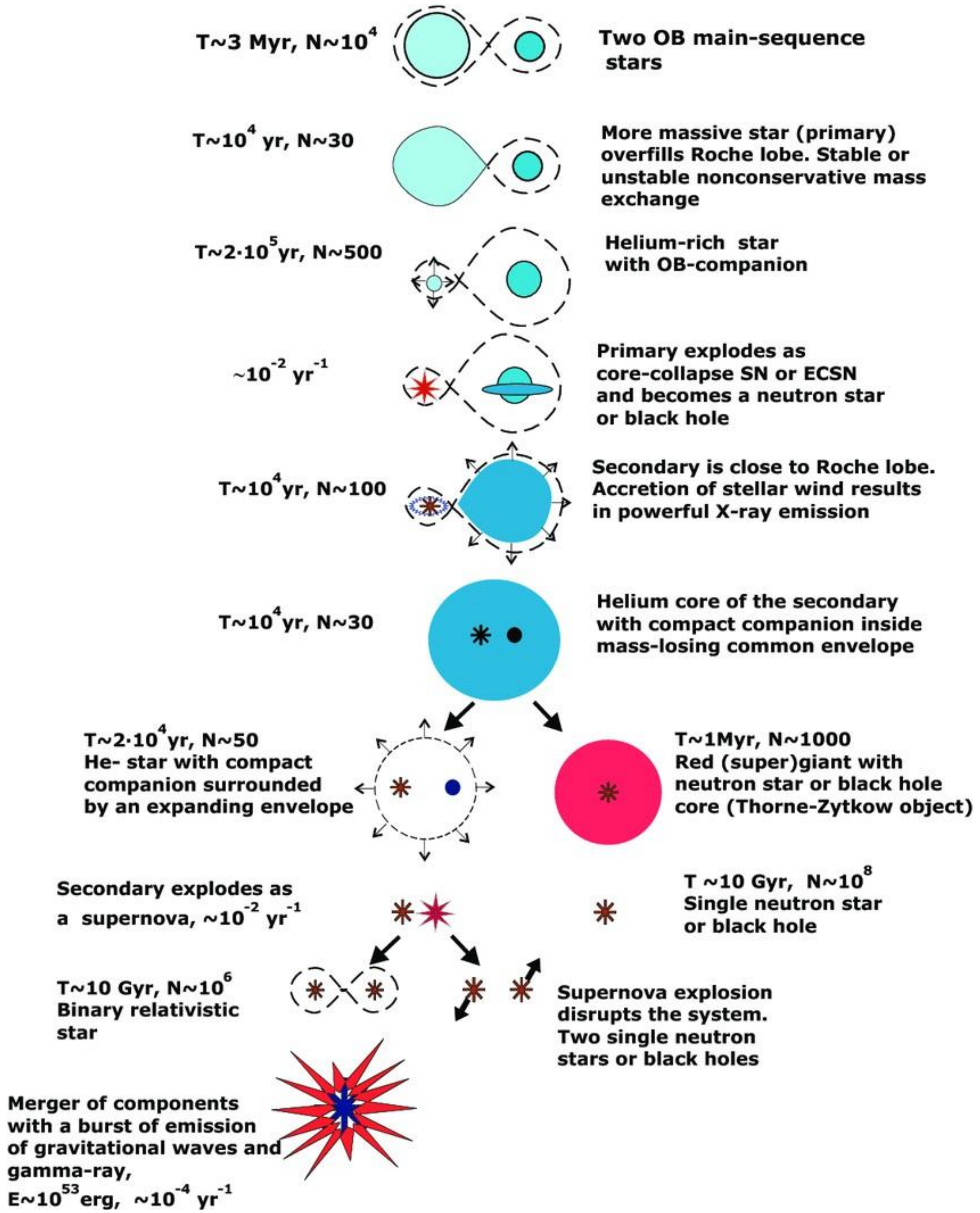
Formation

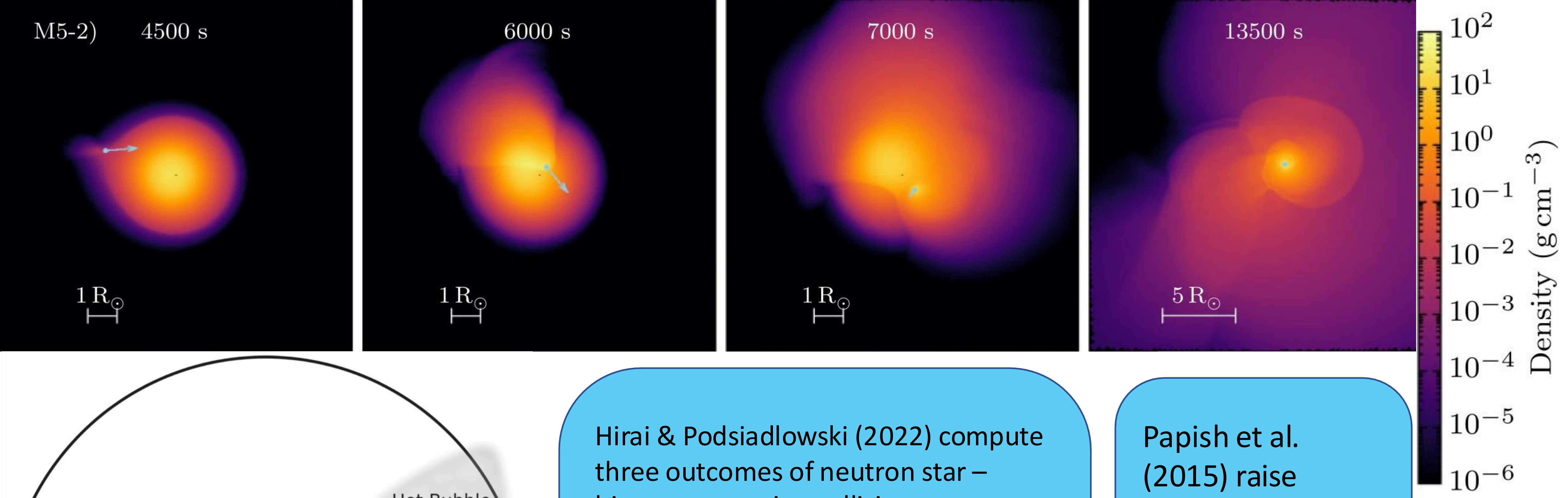
Hybrid Stars – Stars with some non-standard internal structure

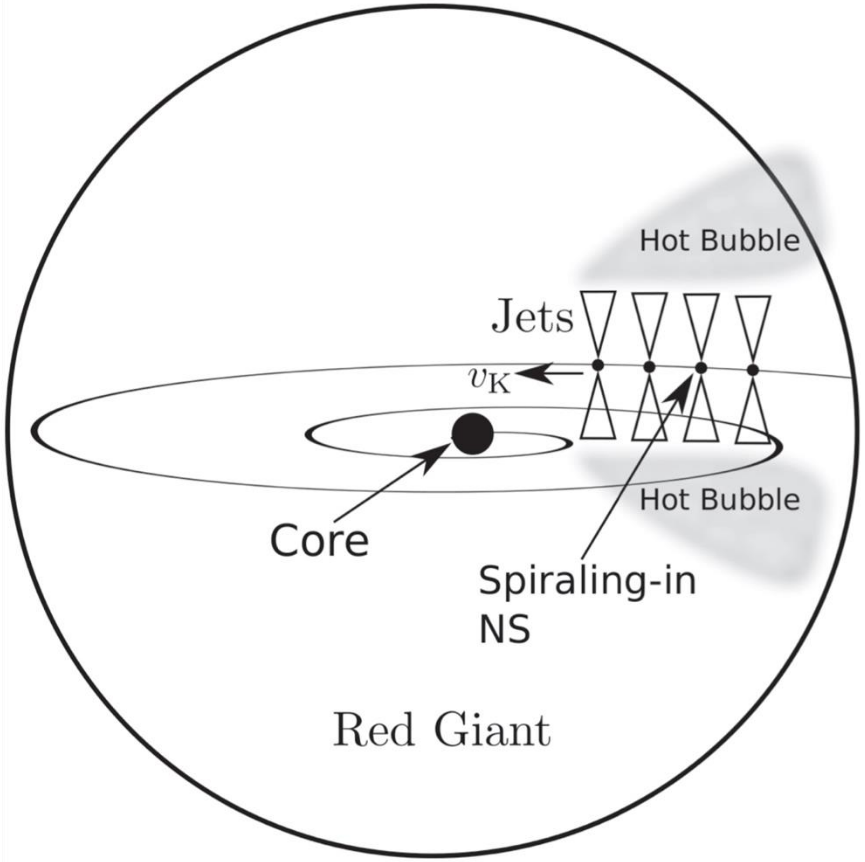
Thorne-Żytkow Objects (TŻOs) – a hybrid star consisting of a neutron star surrounded by a diffuse, giant envelope

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





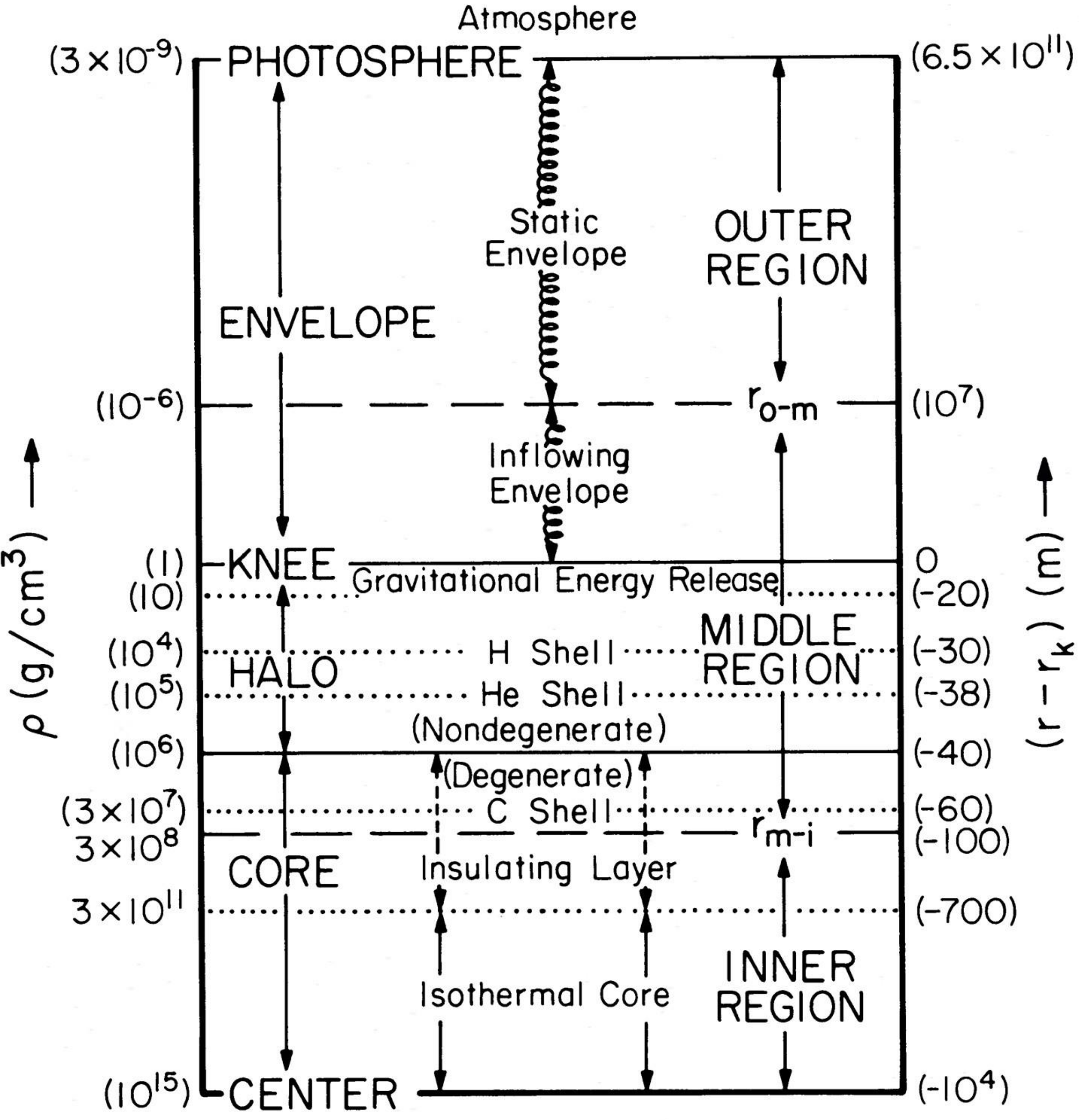


Hirai & Podsiadlowski (2022) compute three outcomes of neutron star – binary companion collisions:

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

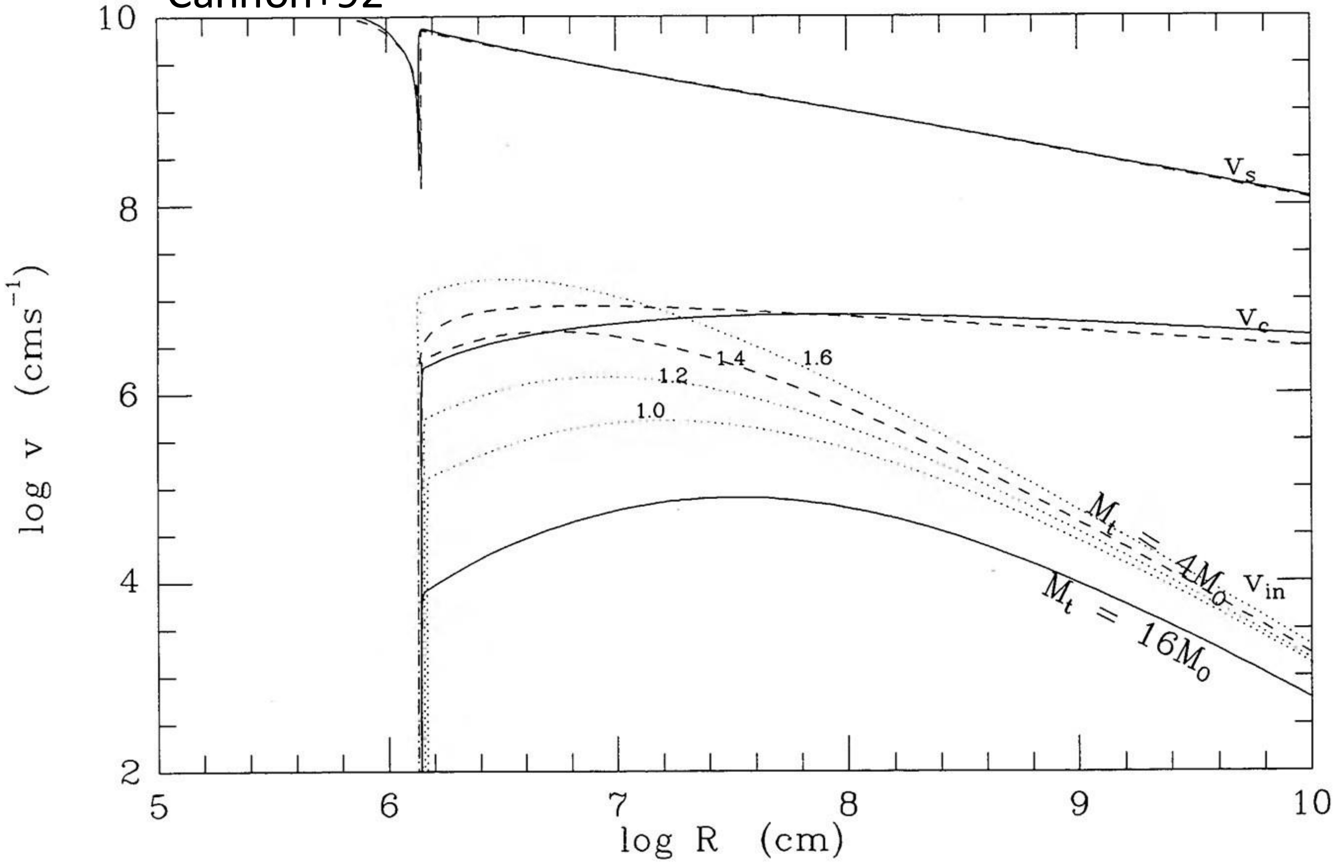
Papish et al. (2015) raise possibility of jets launched during formation ejecting envelope – but can retain or lose envelope, based on tuning (Soker et al. 2013)

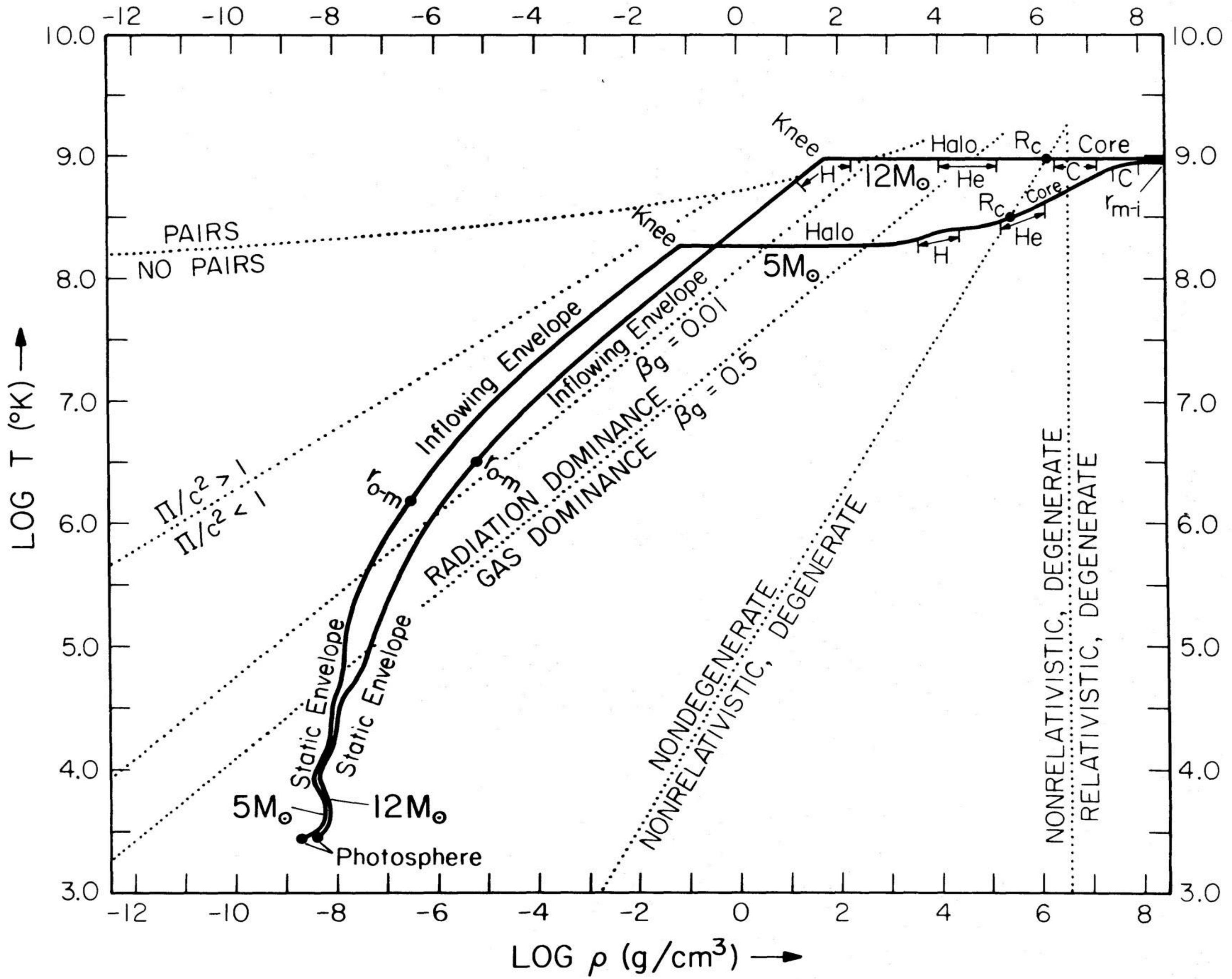
Canonical Structure



Thorne & Żytkow 77

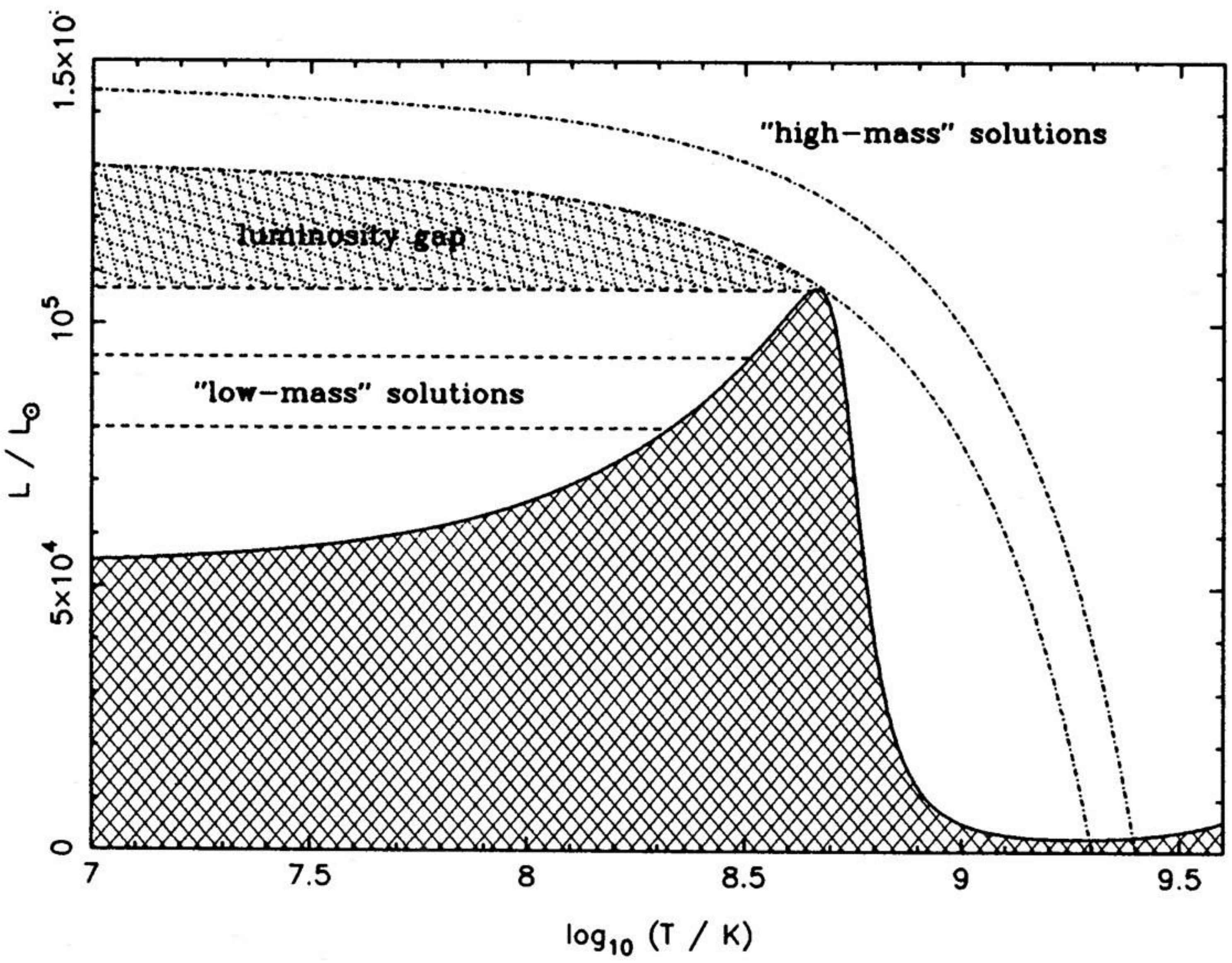
Cannon+92





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

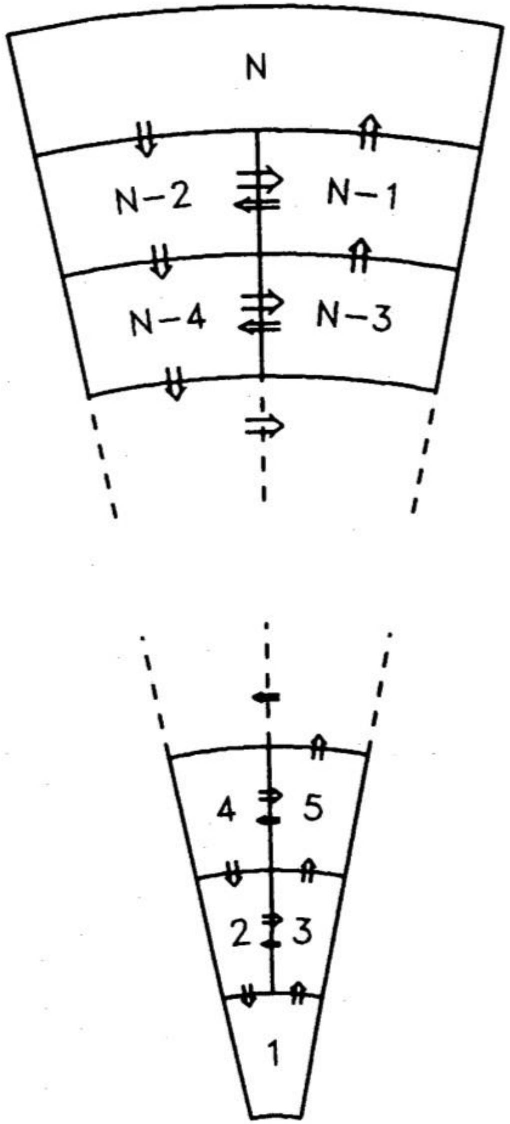
Two general classes of solutions

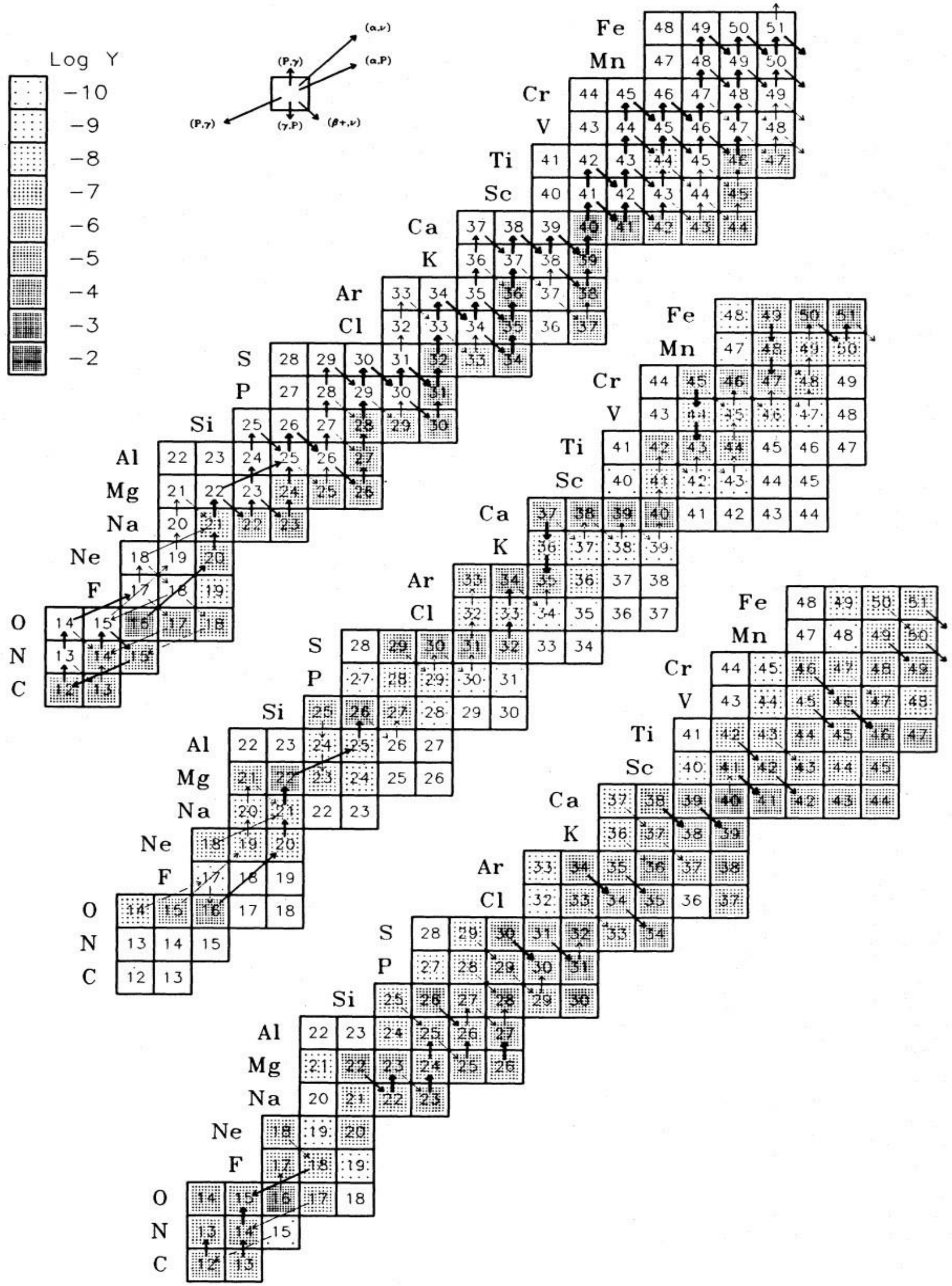
- Giants – Below around $9M_\odot$ – energy generation dominated by ε_{grav} below the knee
- Supergiants – above around $13M_\odot$ – energy generation dominated by ε_{nuc} H burning above the knee, He below

Applicable to GCE?

Applicable to GCE?

Cannon+93

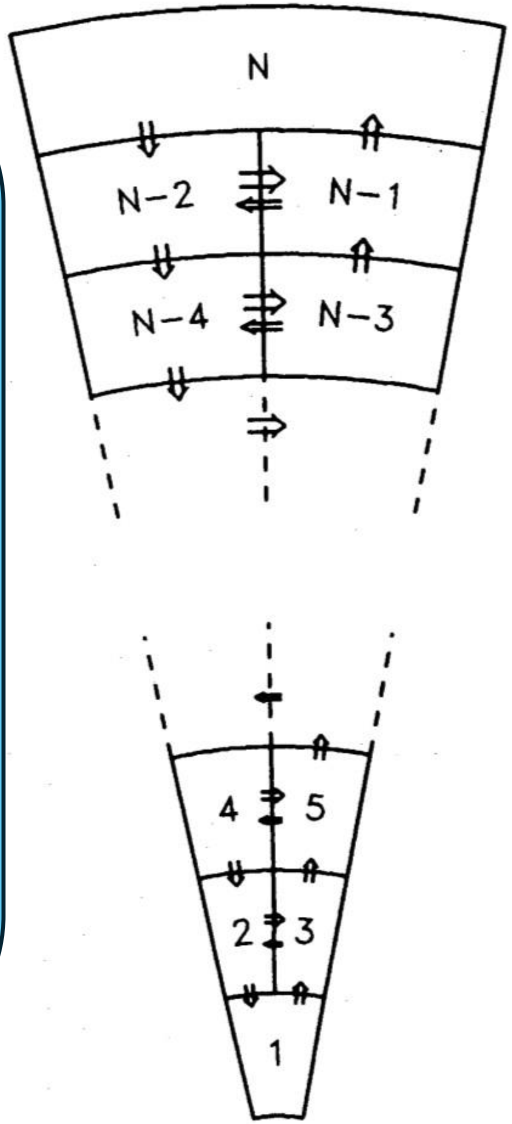


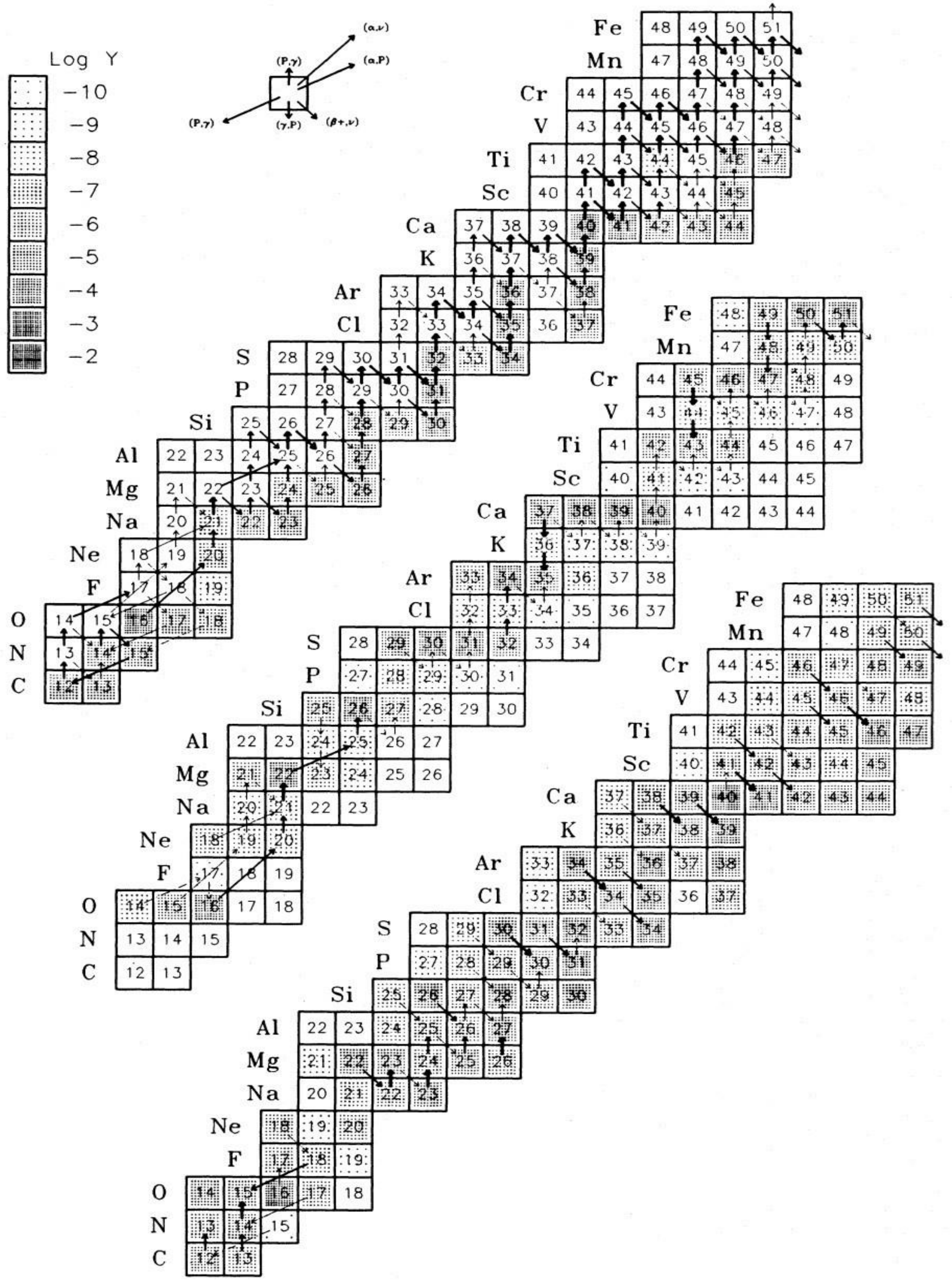


Applicable to GCE?

- 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

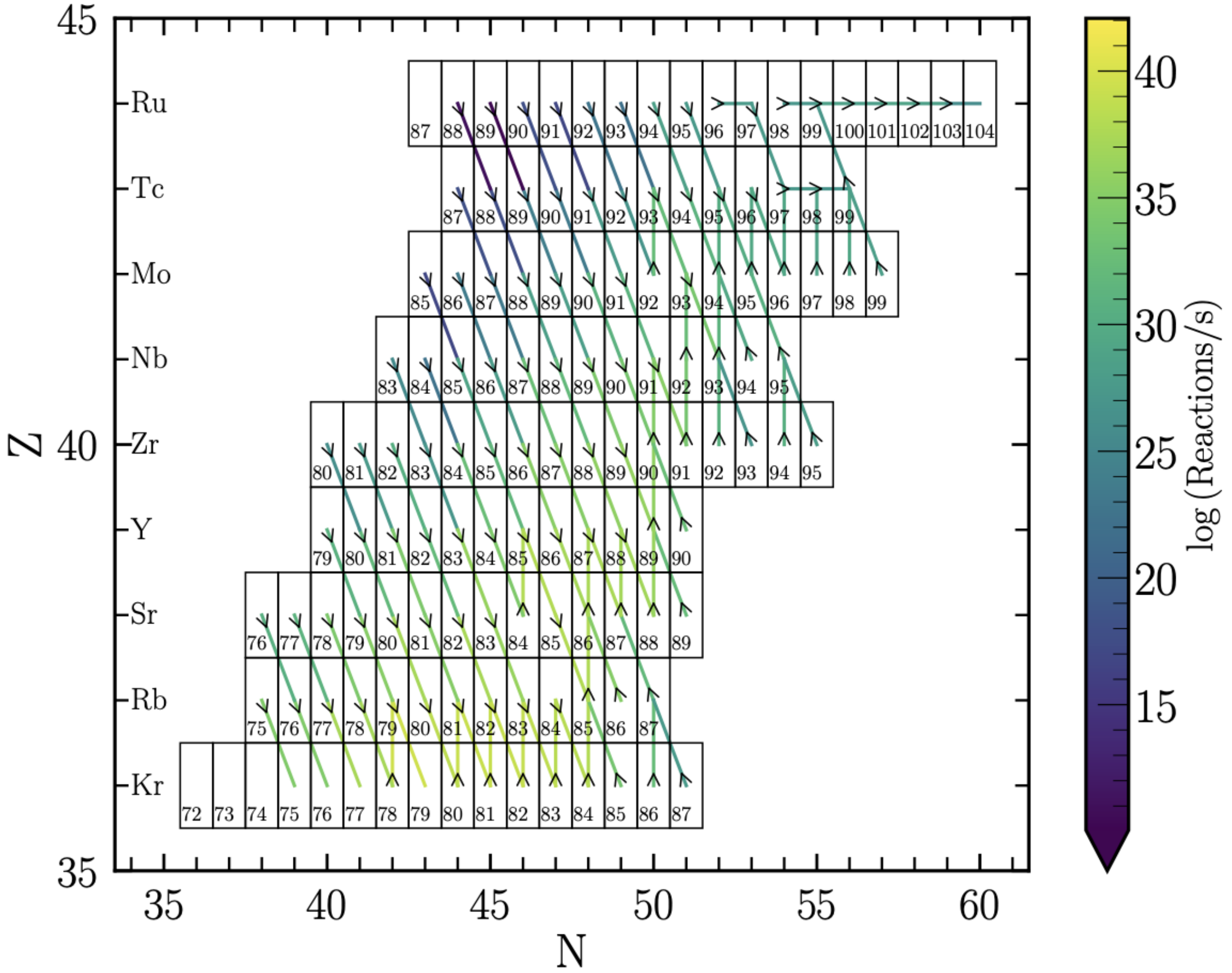
Cannon+93

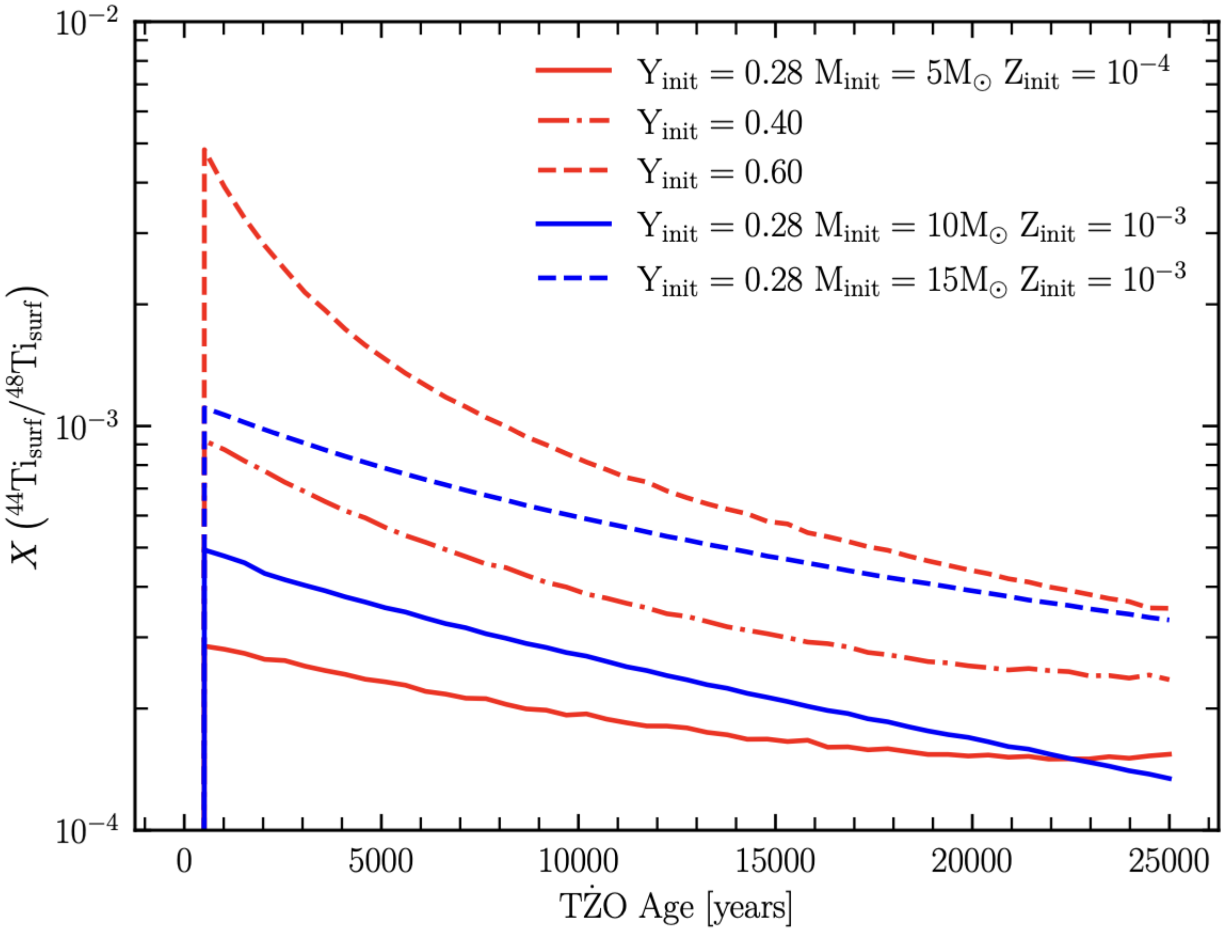




Applicable to GCE?

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

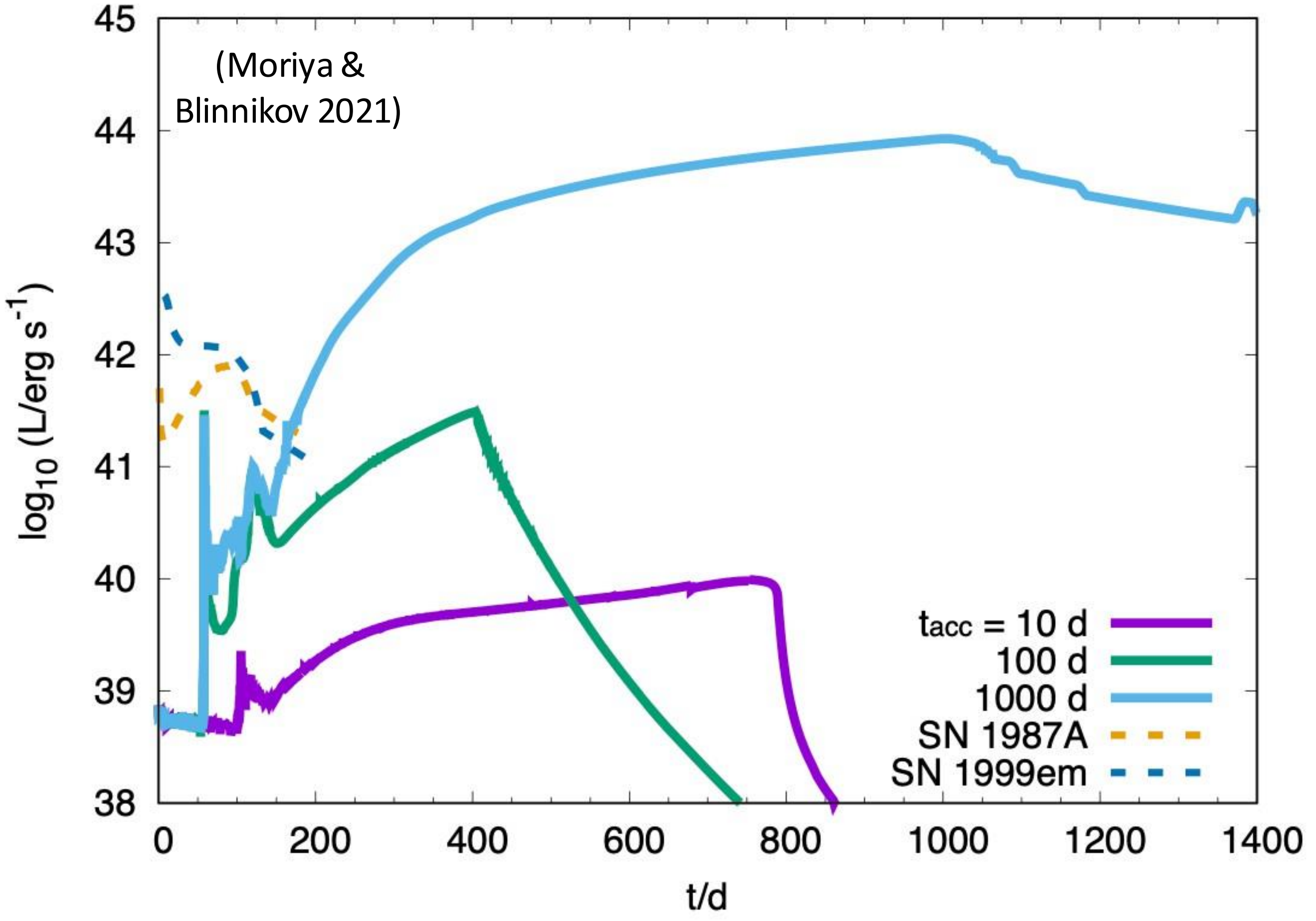
Long τ_{acc}

Supernova-like brightness

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

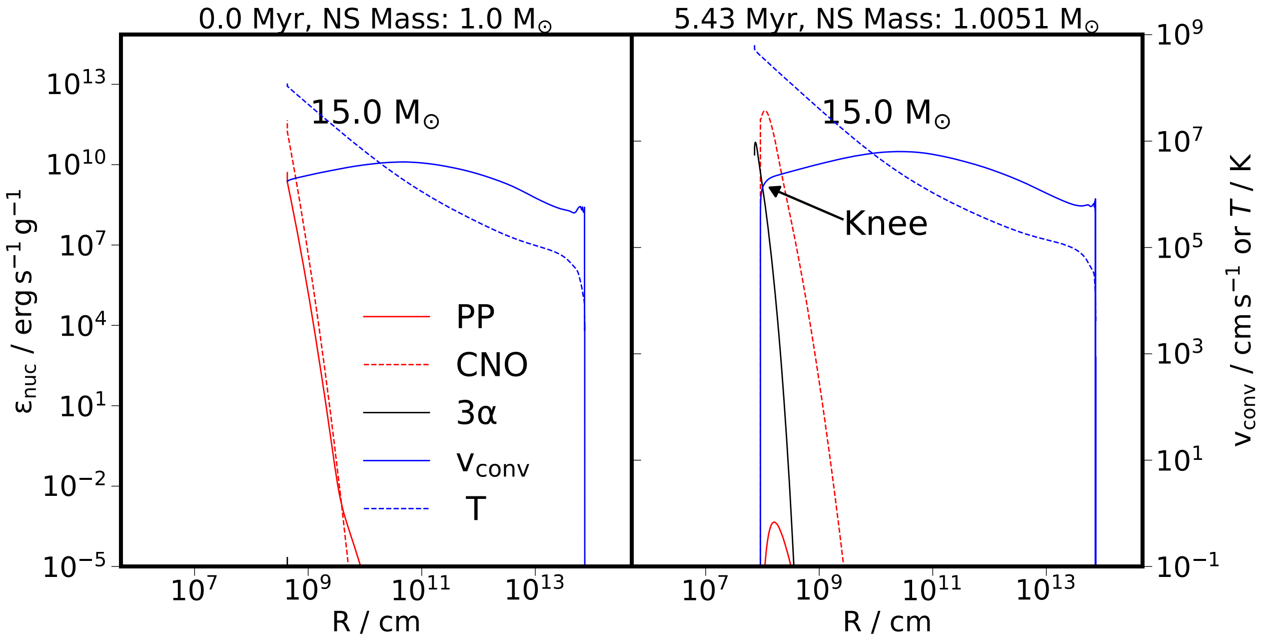
- Accretion terminates at some point – outflowing energy – parameterize with τ_{acc}

- 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

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

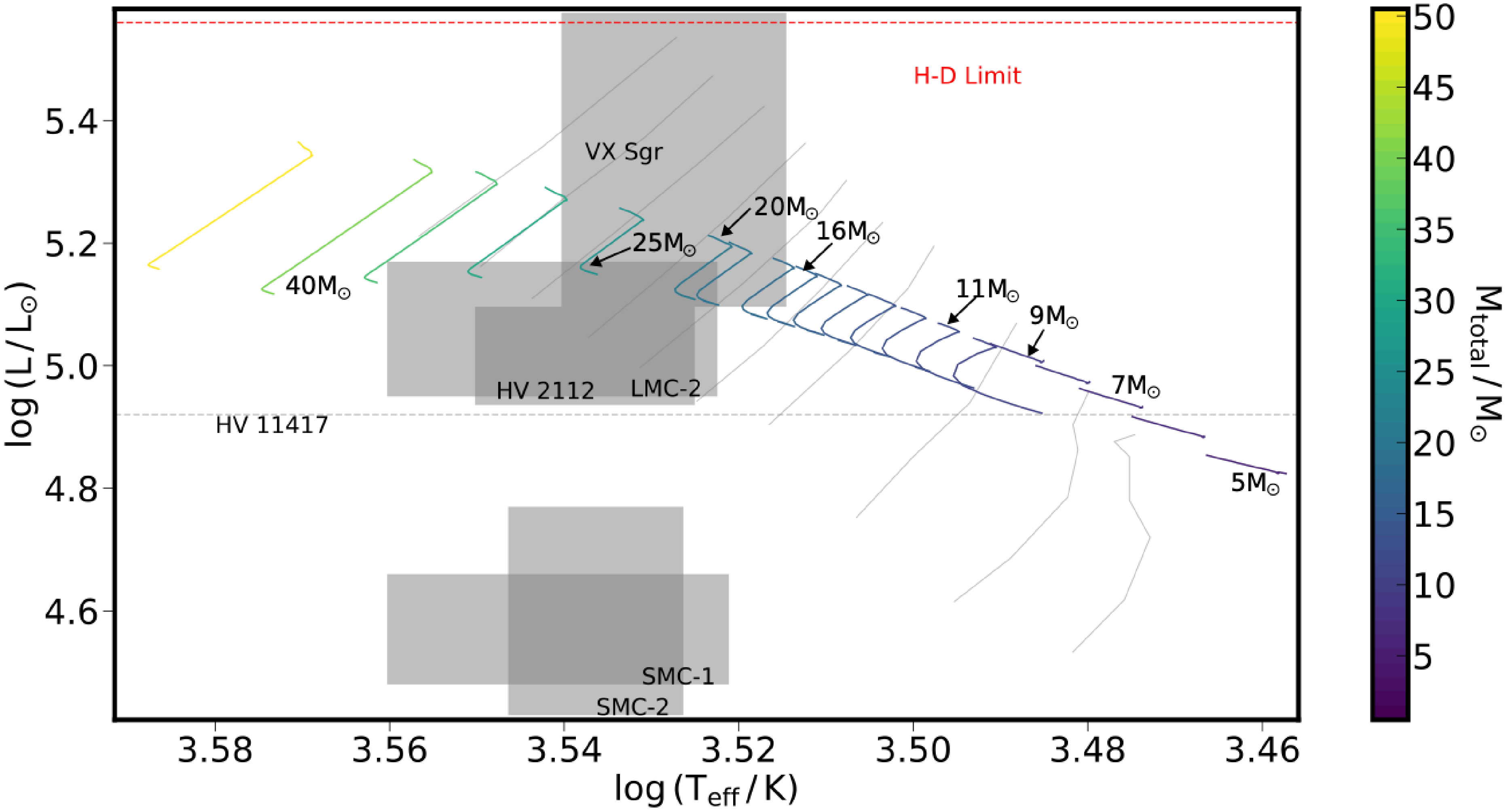
$$L_{\rm knee} = L_r^{\rm crit} \equiv 4\pi c G M_r \kappa^{-1}$$

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

via contact with Thorne (1977) form in Newtonian Limit

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

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



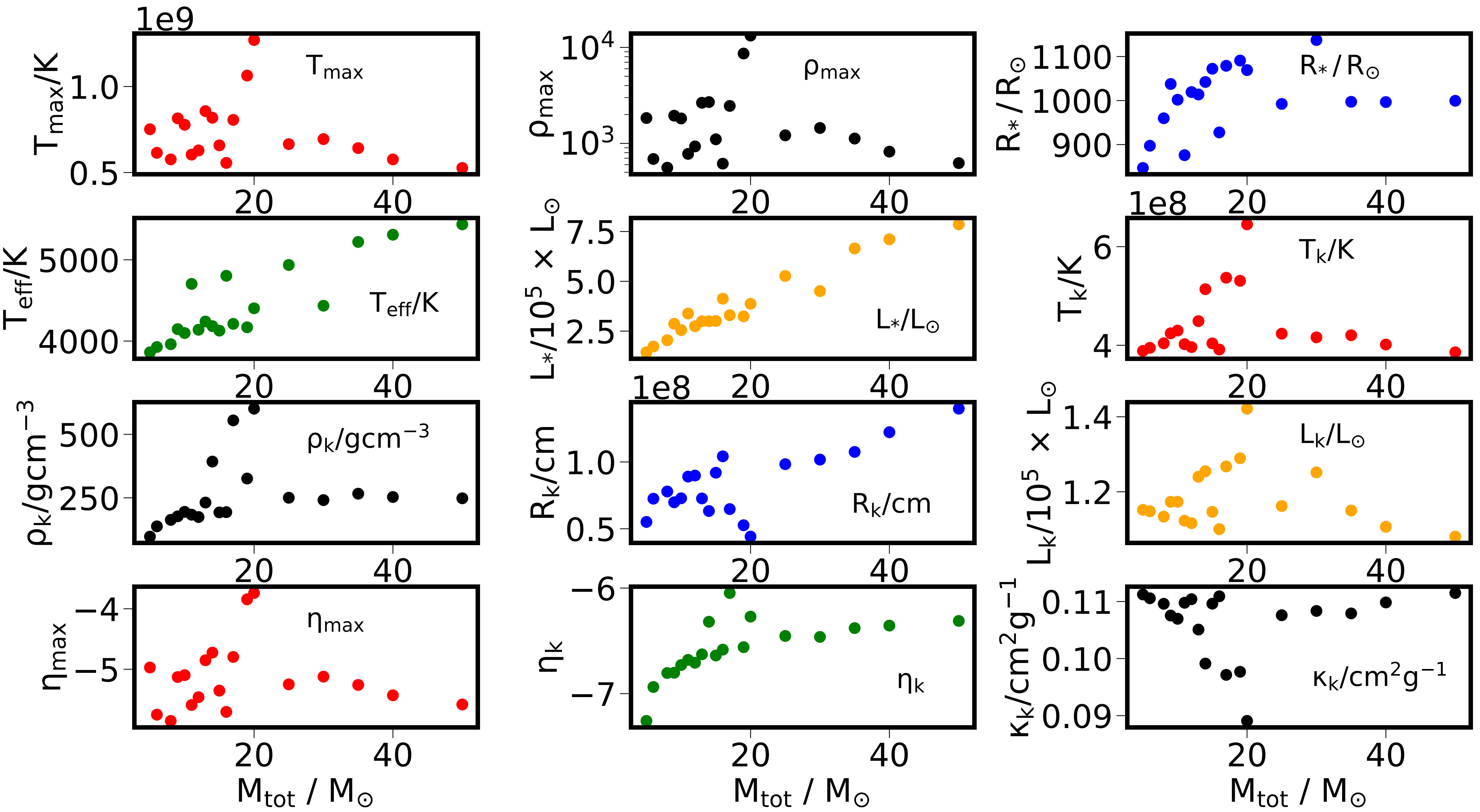
HRD tracks are consistent with some TŻO candidates

Most prominently HV2112 and VX Sgr

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

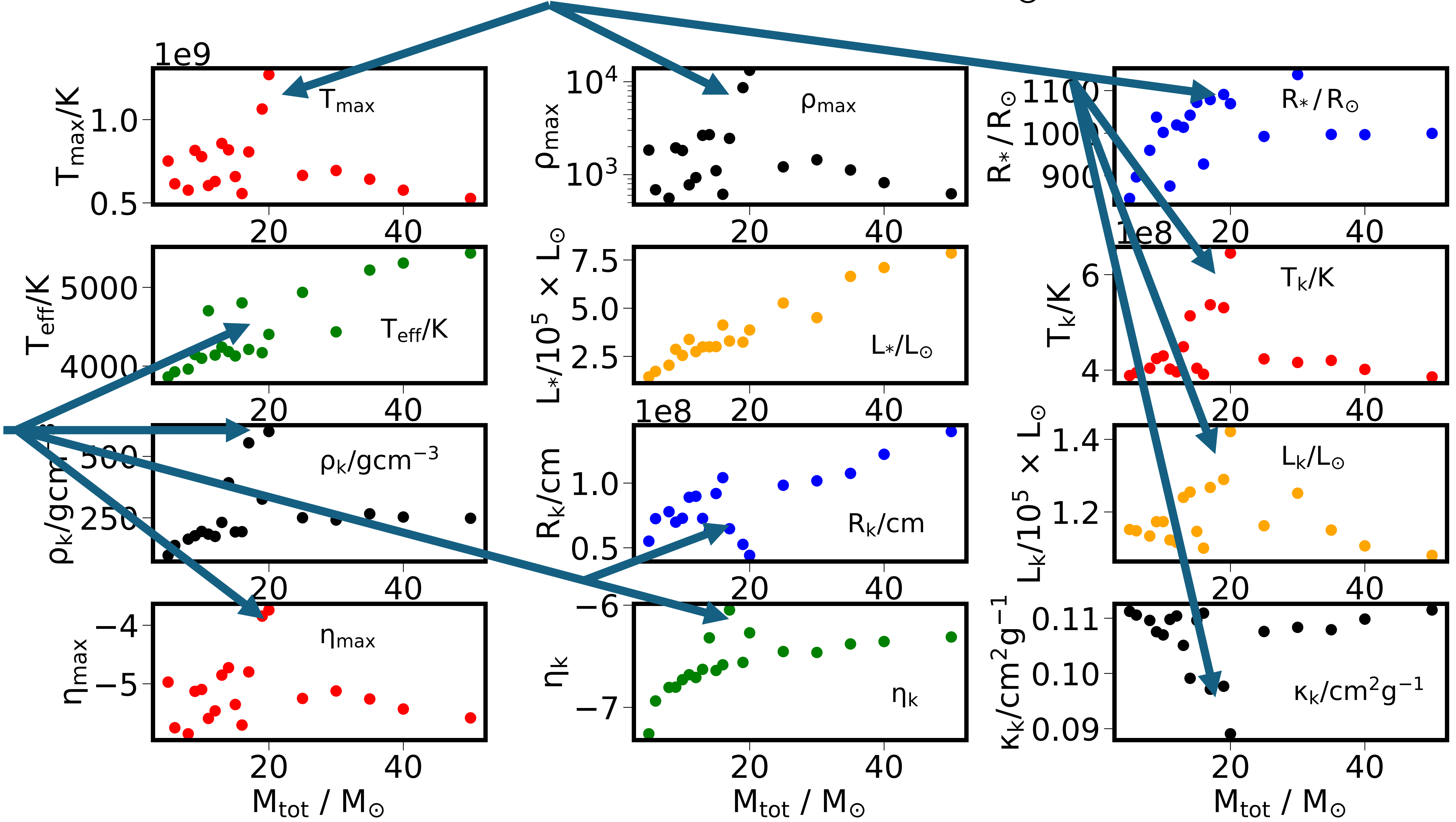
Coloured Tracks → our models
Greyscale Tracks → Cannon et al.-style models

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



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

Strange discontinuities at around $20 M_\odot$?



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

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

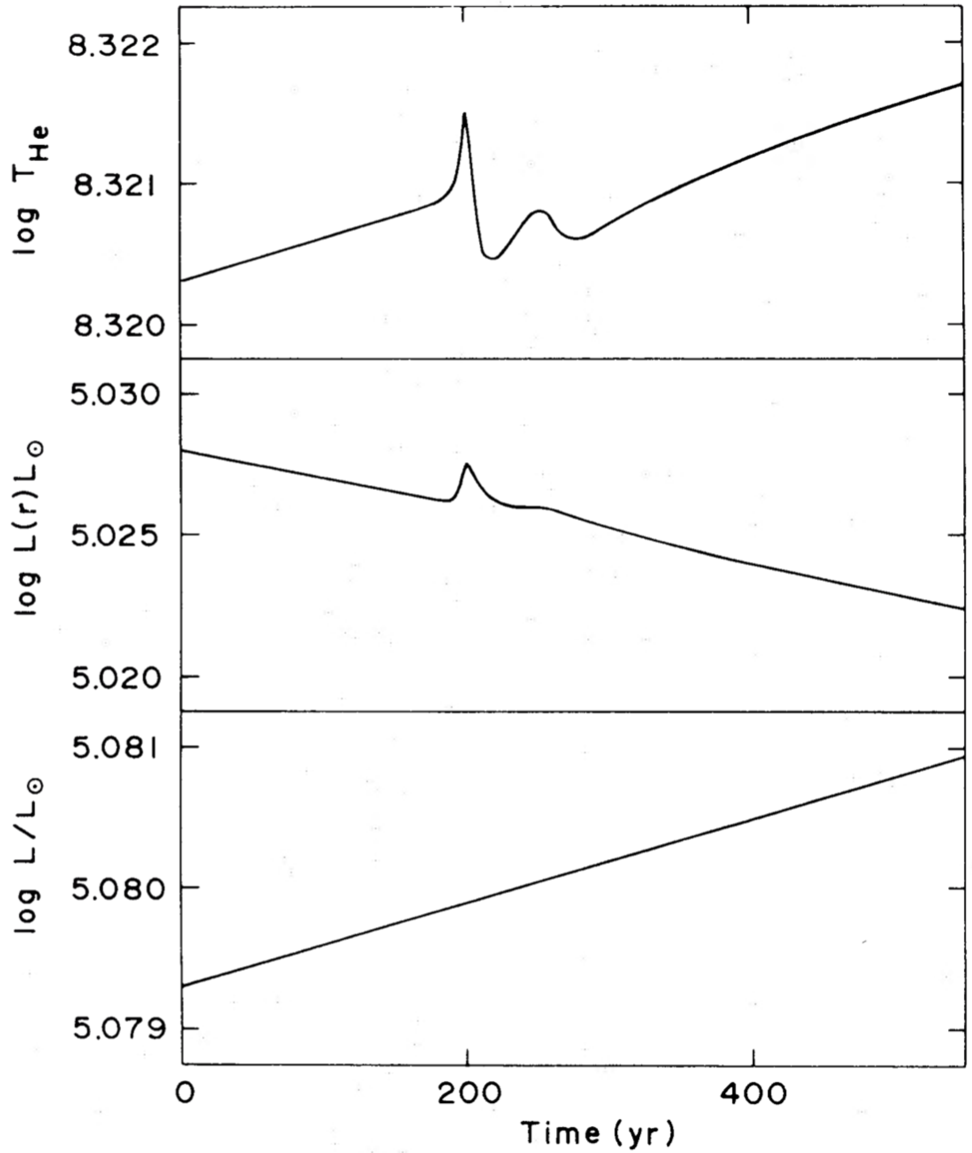
where

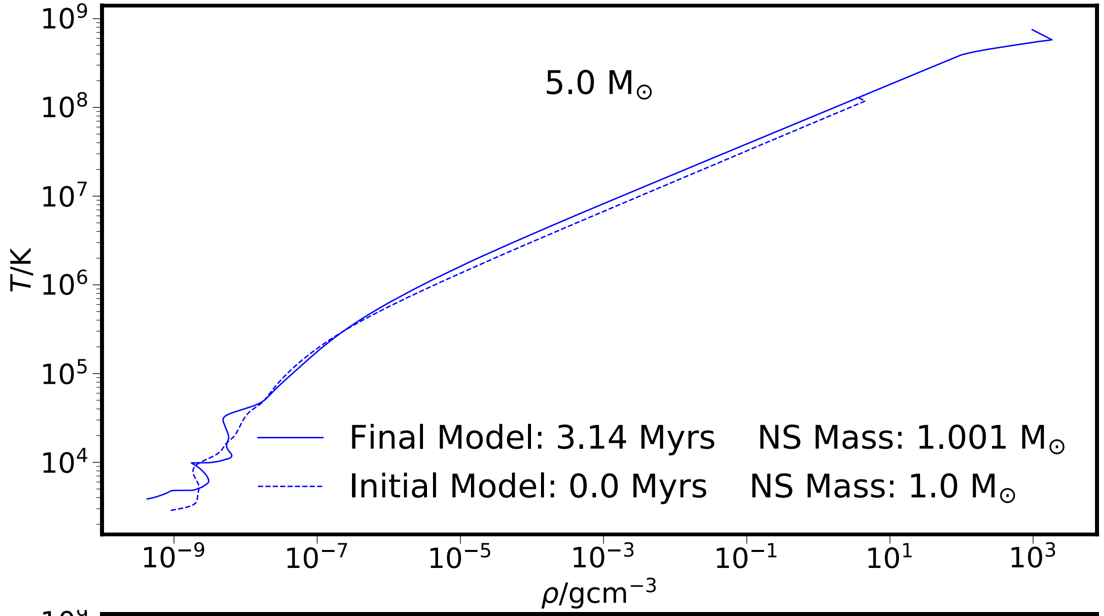
$$f(\beta) = \frac{\beta\left(32/3 - 8\beta - \beta^2\right)}{32/3 - 16\beta + 6\beta^2},$$

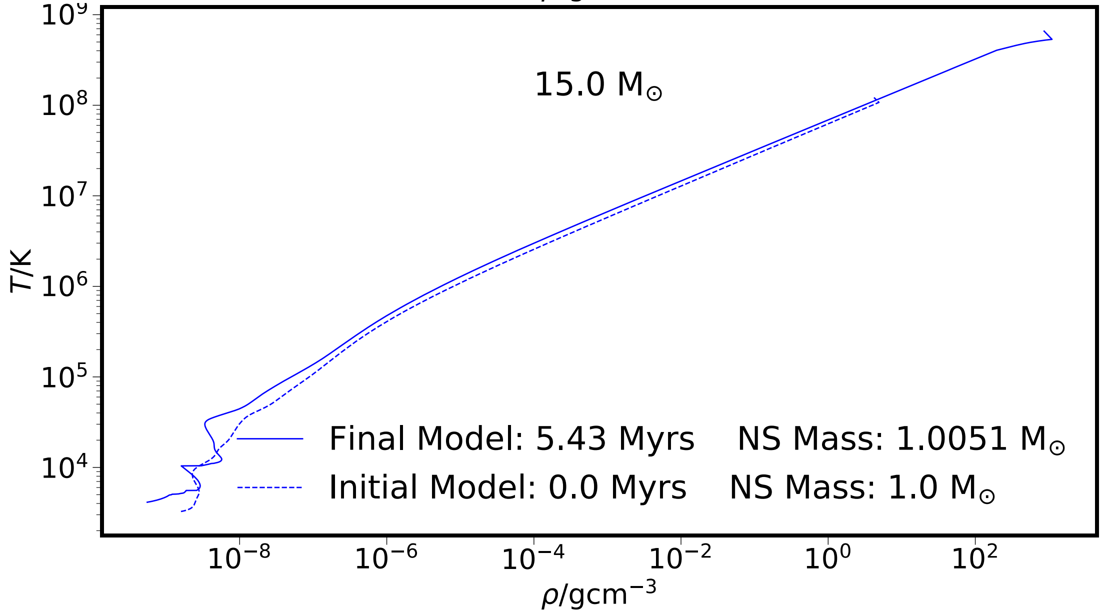
where Q is defined as by Schwarzschild & Härm (1965)

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

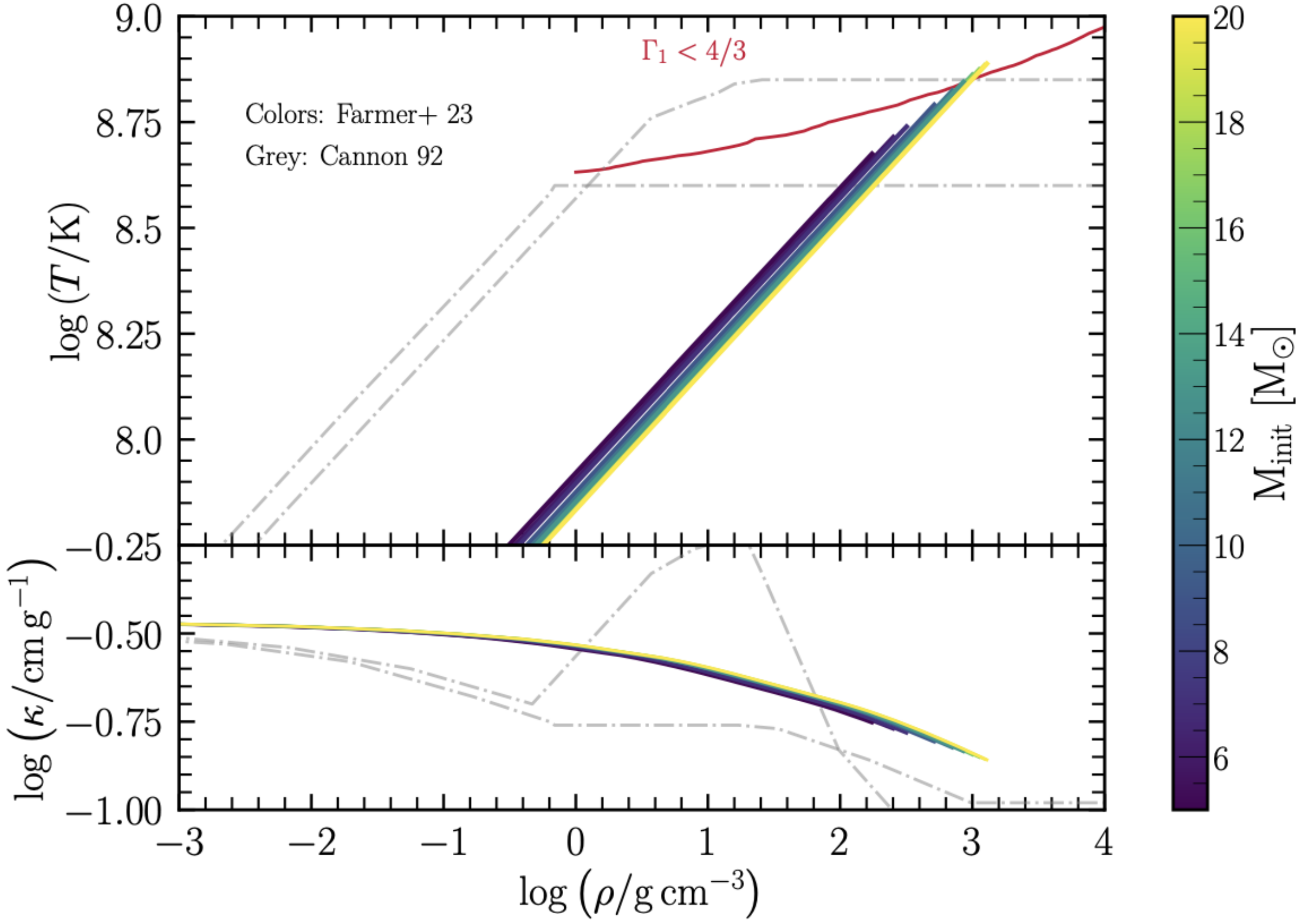
Find our shells are comfortably stable, but likely subject to the "flickering" instability (Stothers & Wen Chin 1973)



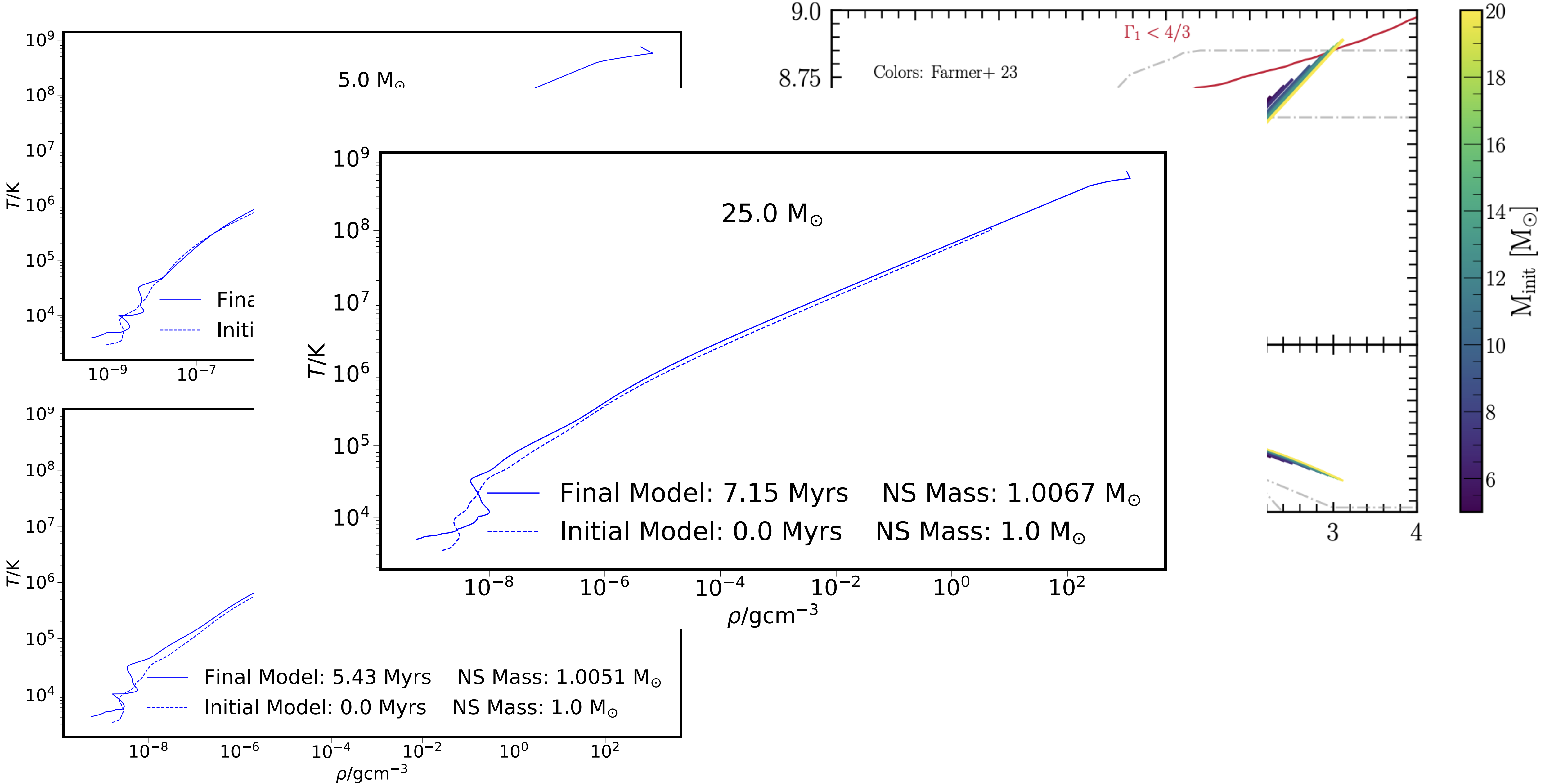




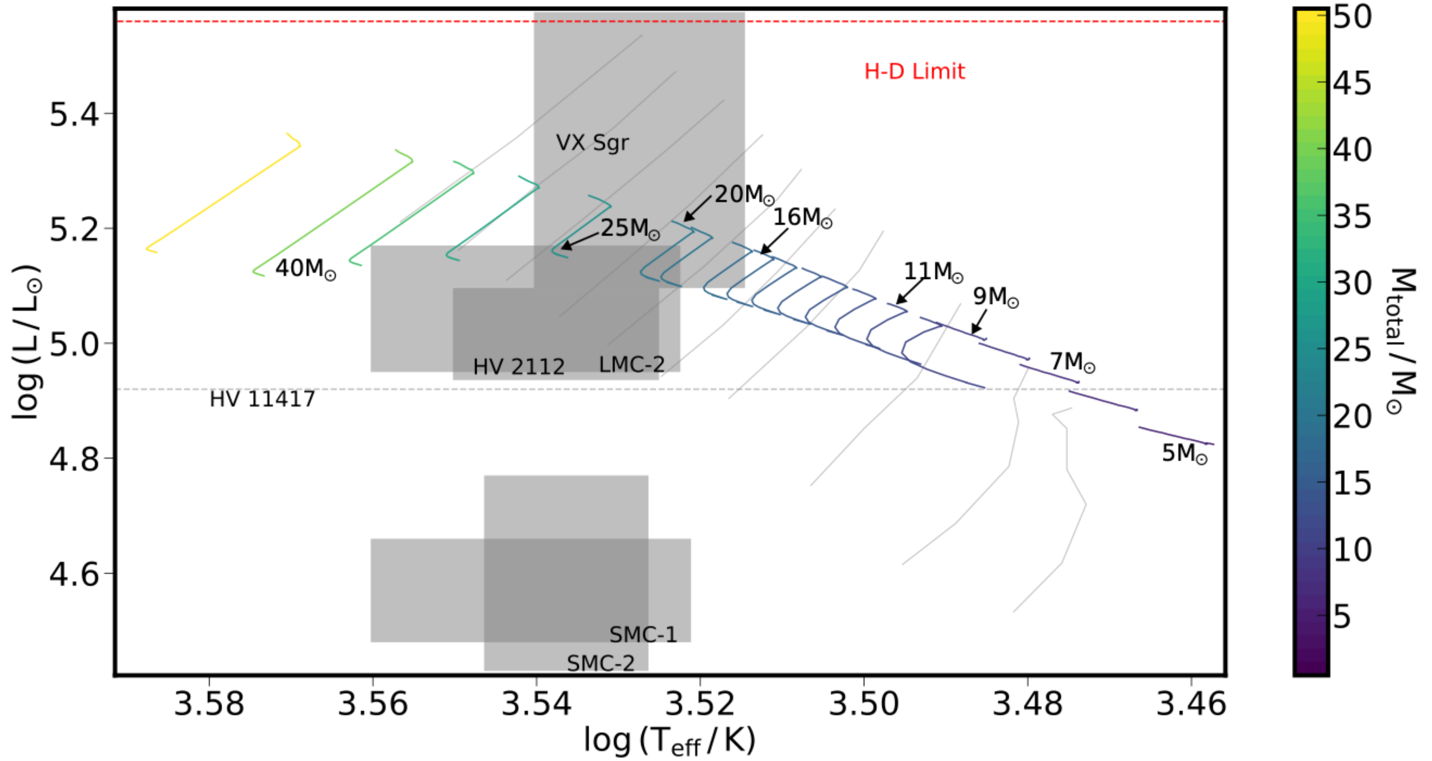
Farmer+23



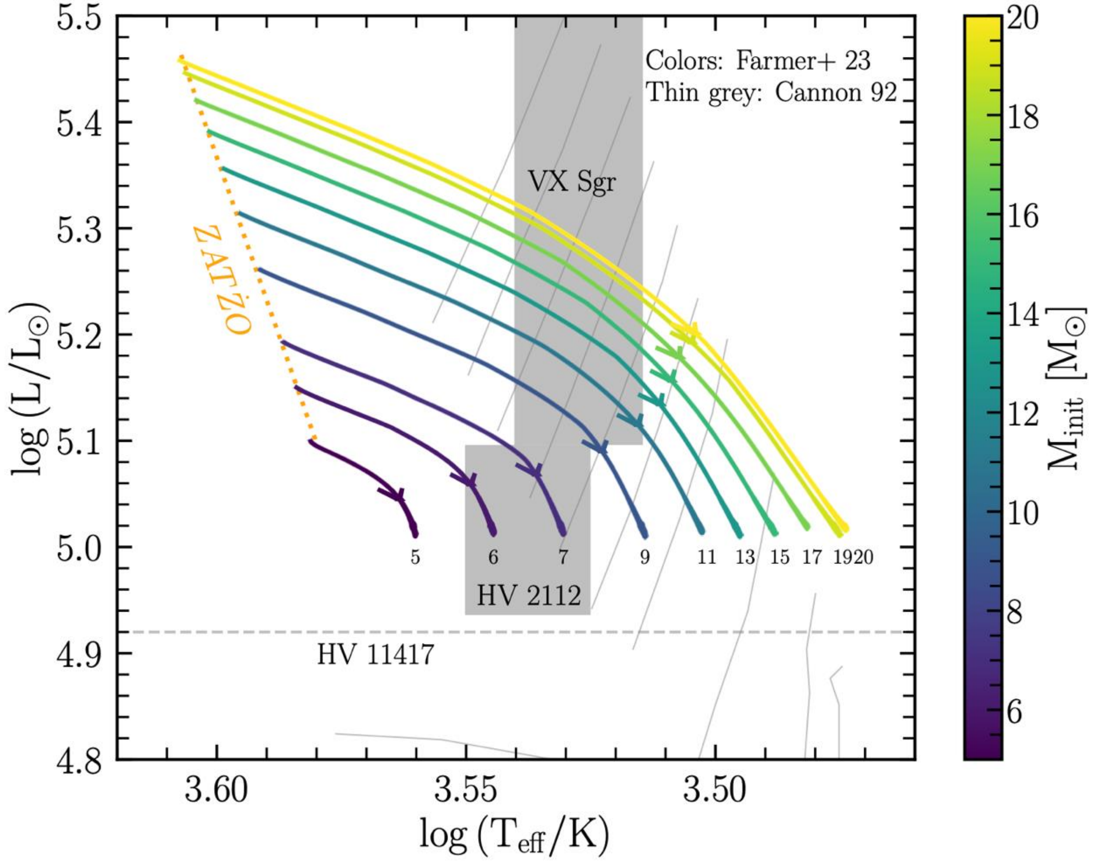
How do we differ from Farmer+23?
We place the innermost BC at the NS surface, not at 600km above

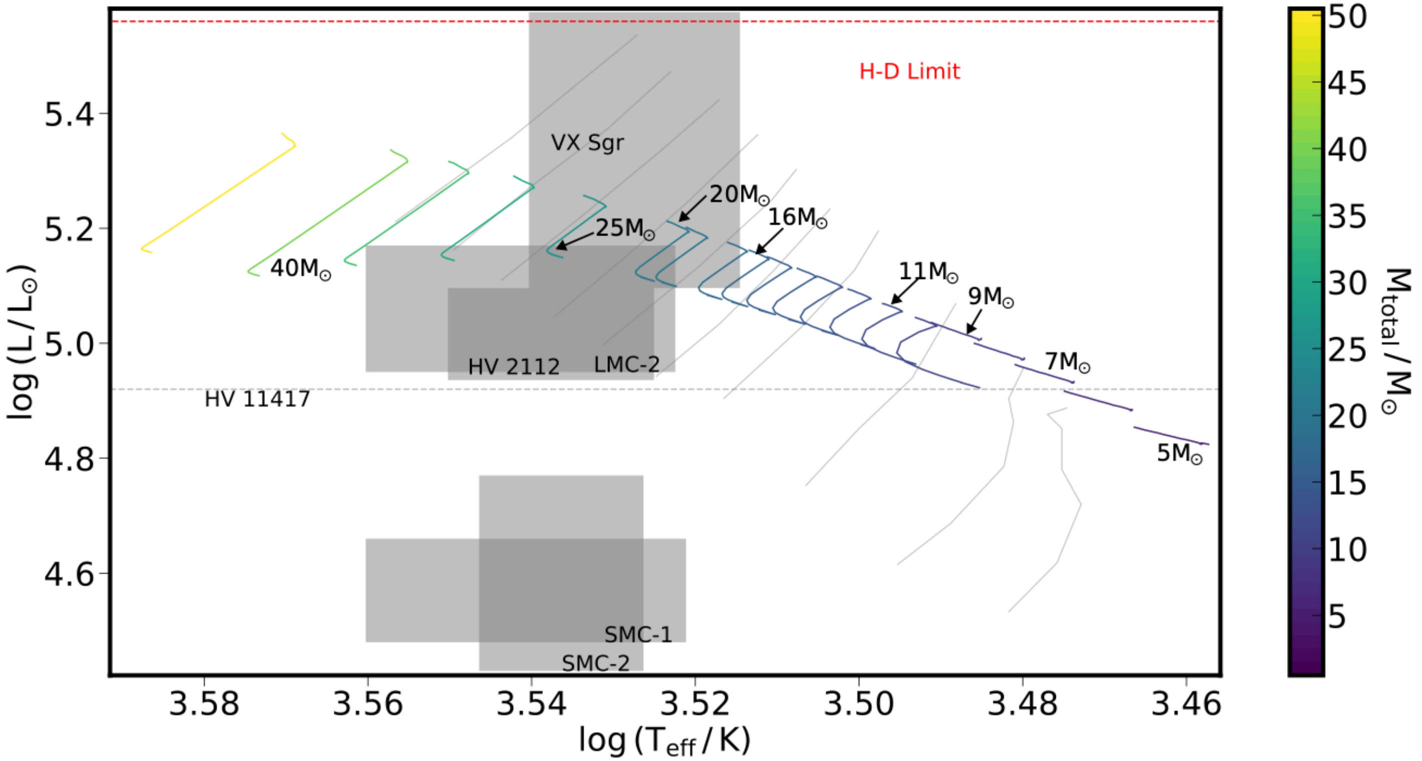


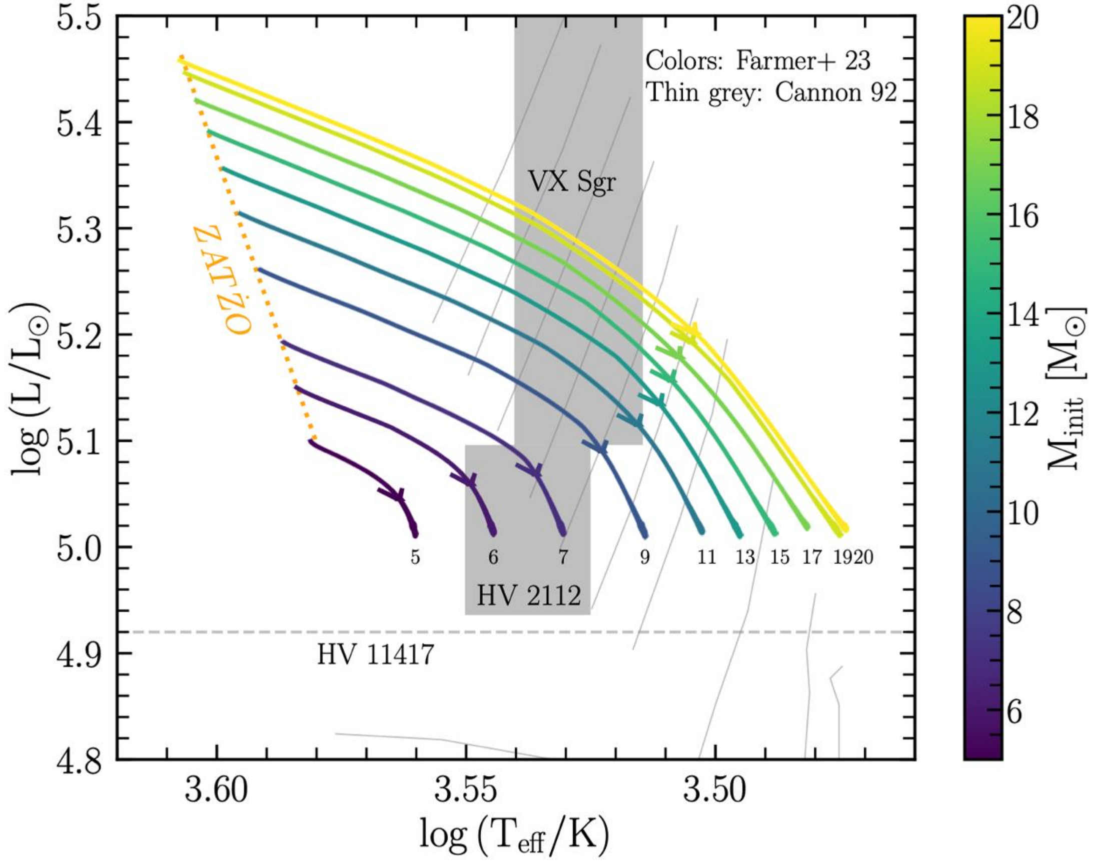
5.0 M⊙
25.0 M⊙
Final Model: 7.15 Myrs NS Mass: 1.0067 M⊙
Initial Model: 0.0 Myrs NS Mass: 1.0 M⊙
Final Model: 5.43 Myrs NS Mass: 1.0051 M⊙
Initial Model: 0.0 Myrs NS Mass: 1.0 M⊙
T/K
ρ/gcm⁻³
Γ₁ < 4/3
Colors: Farmer+ 23
M_init [M⊙]



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



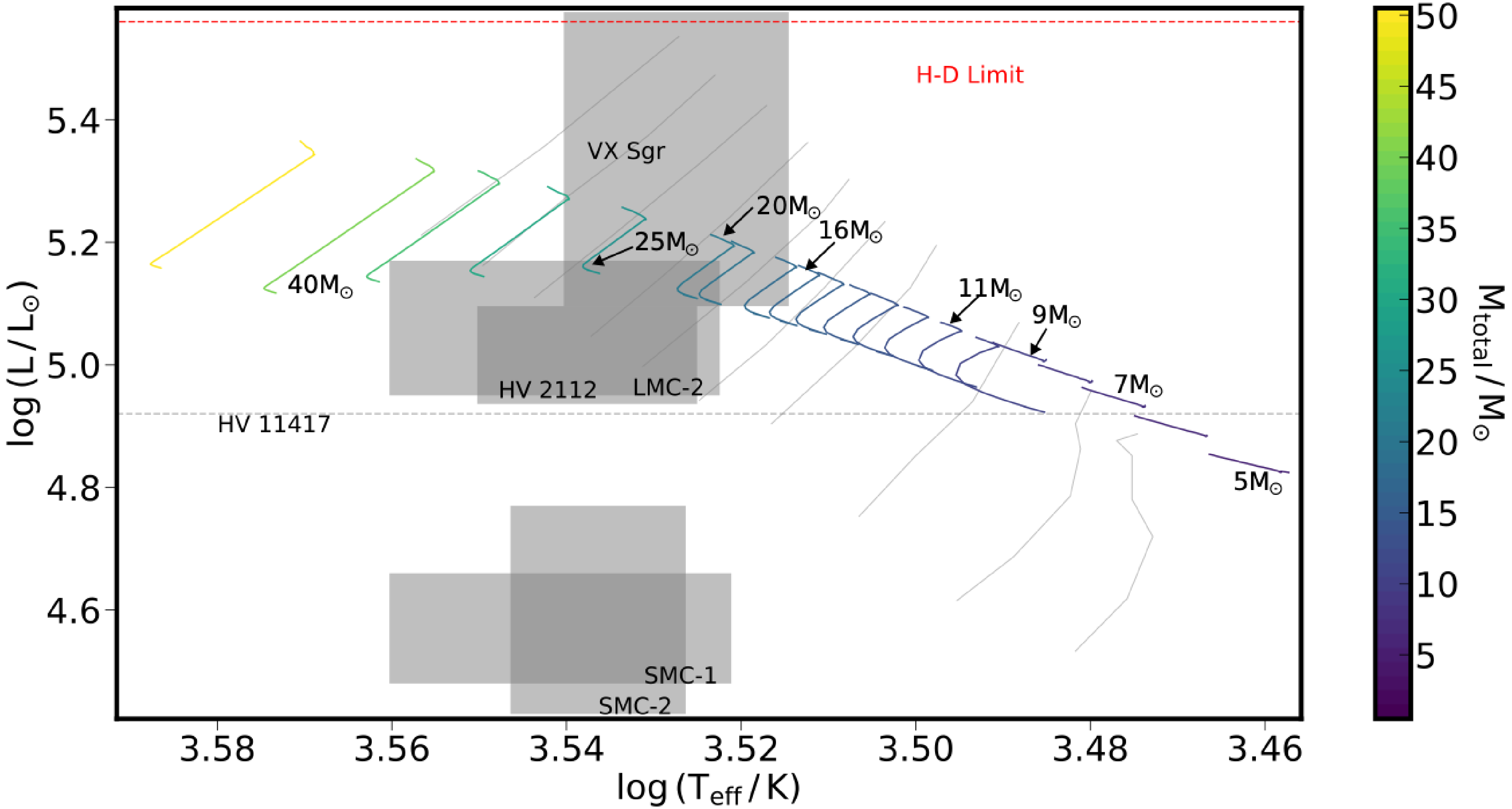




Moving boundary conditions from inside halo into convective envelope → explains dramatic changes

Concern: choice of BC changes chemical yields

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



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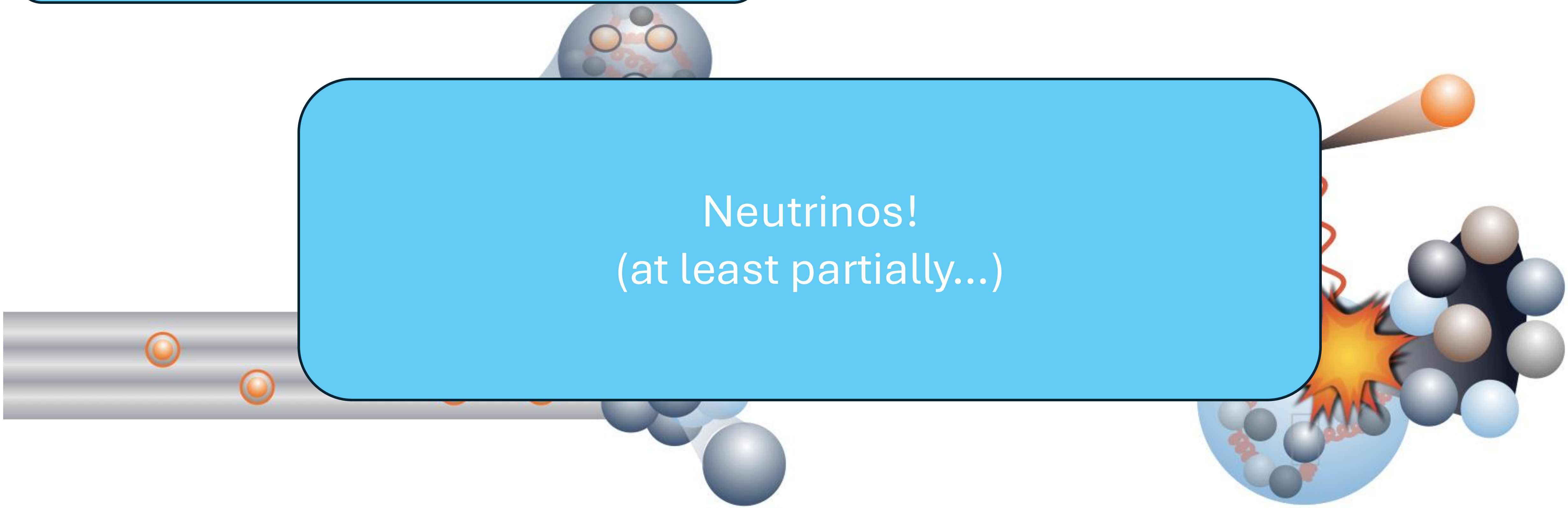
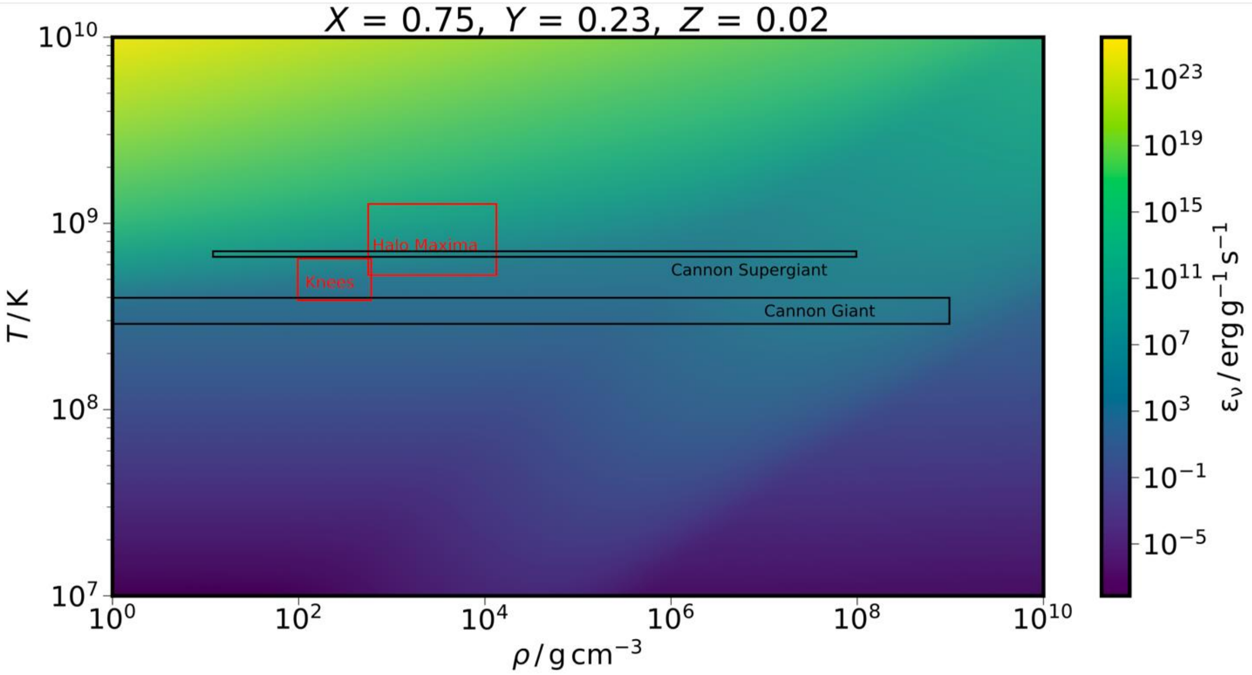
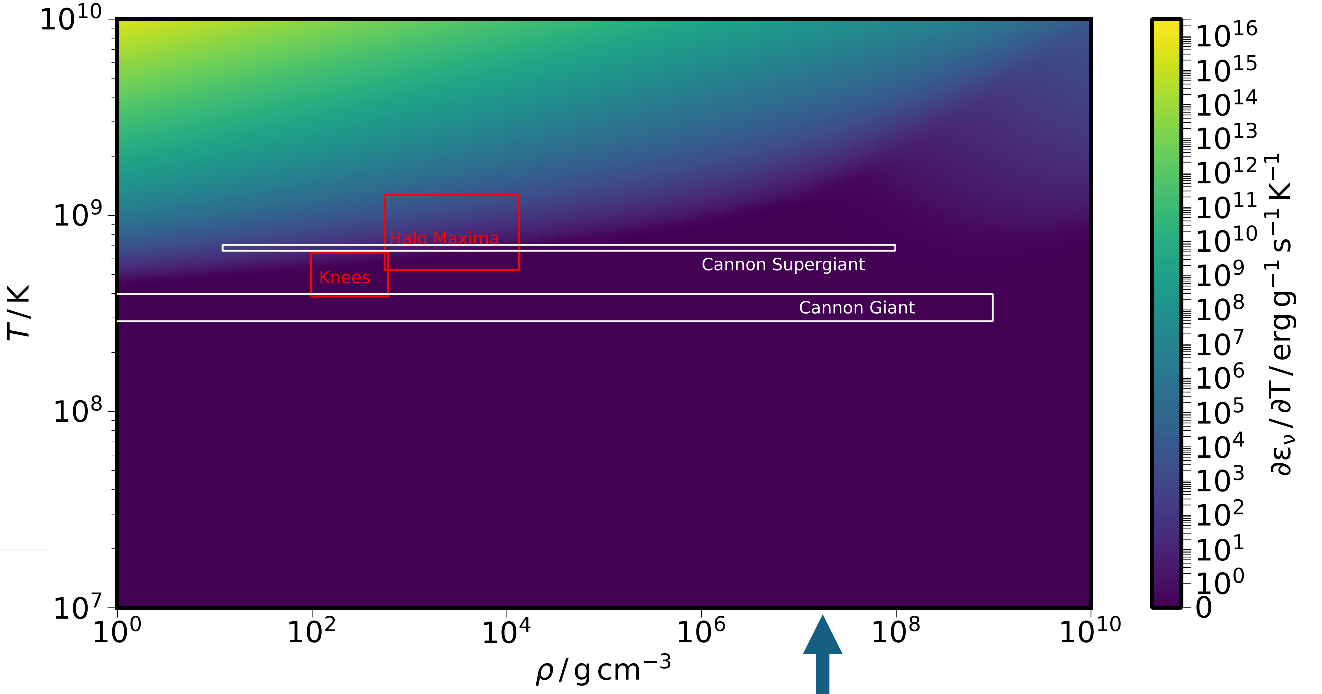


Neutrinos!
(at least partially...)

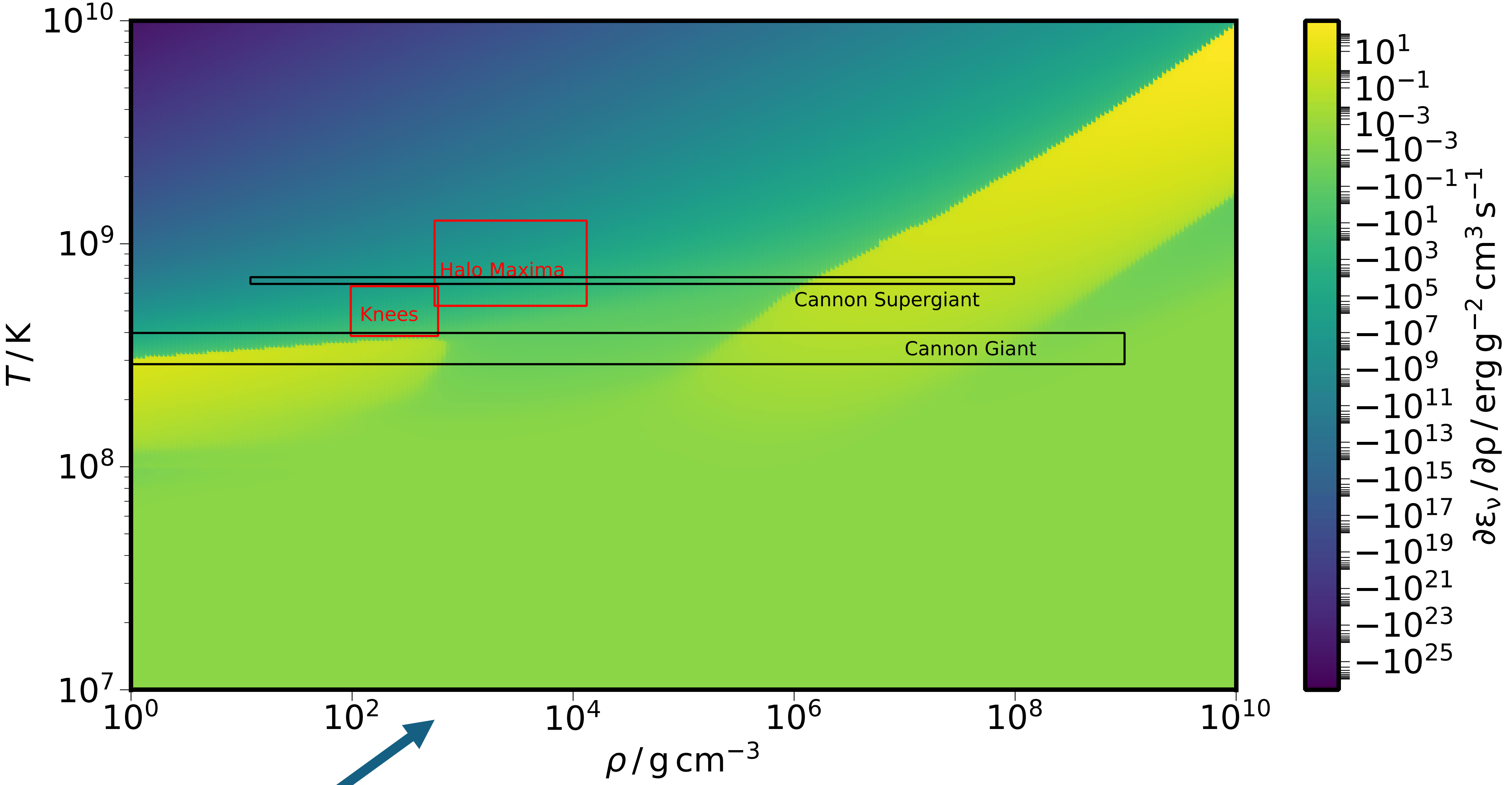
Neutrinos!

Luminosity

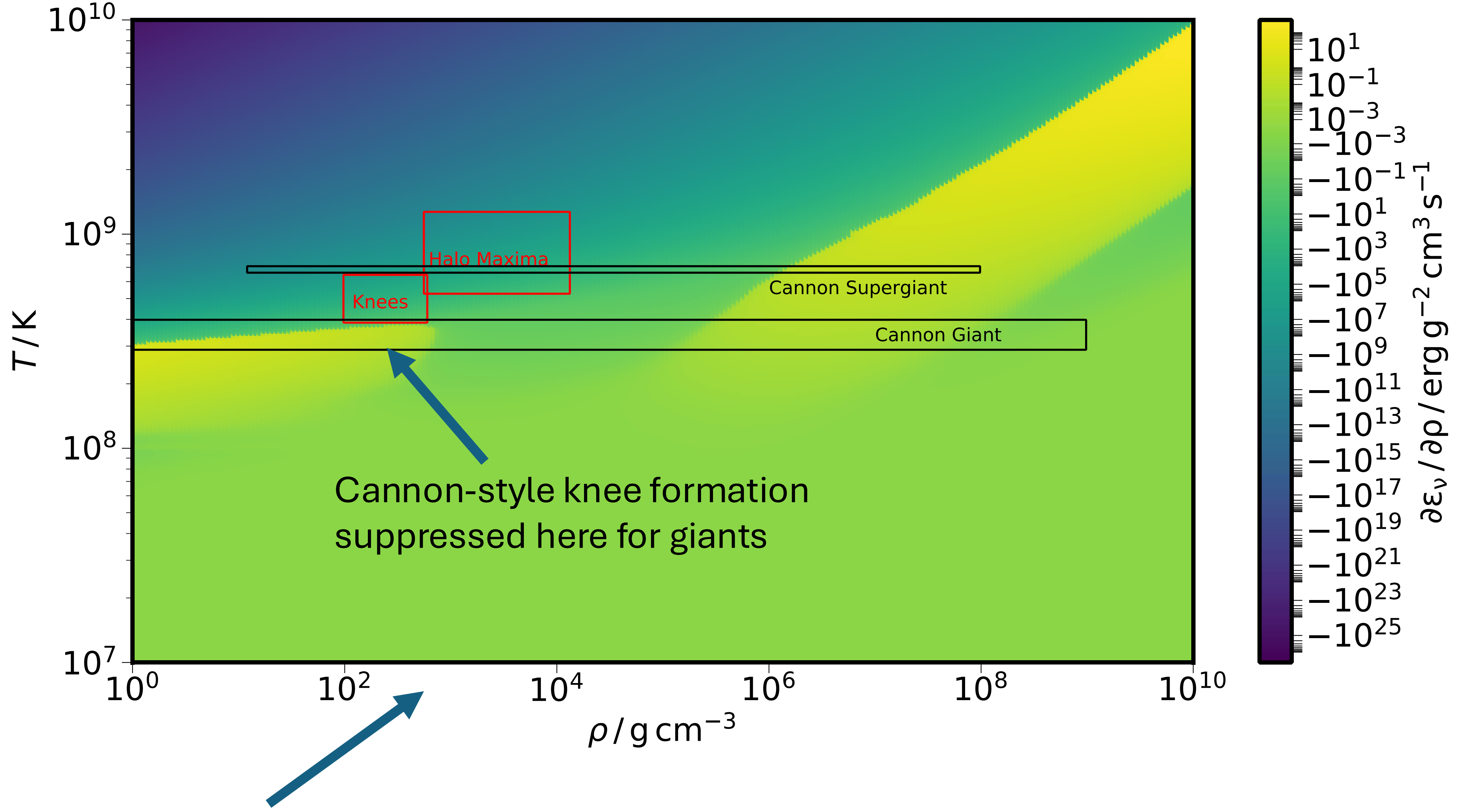




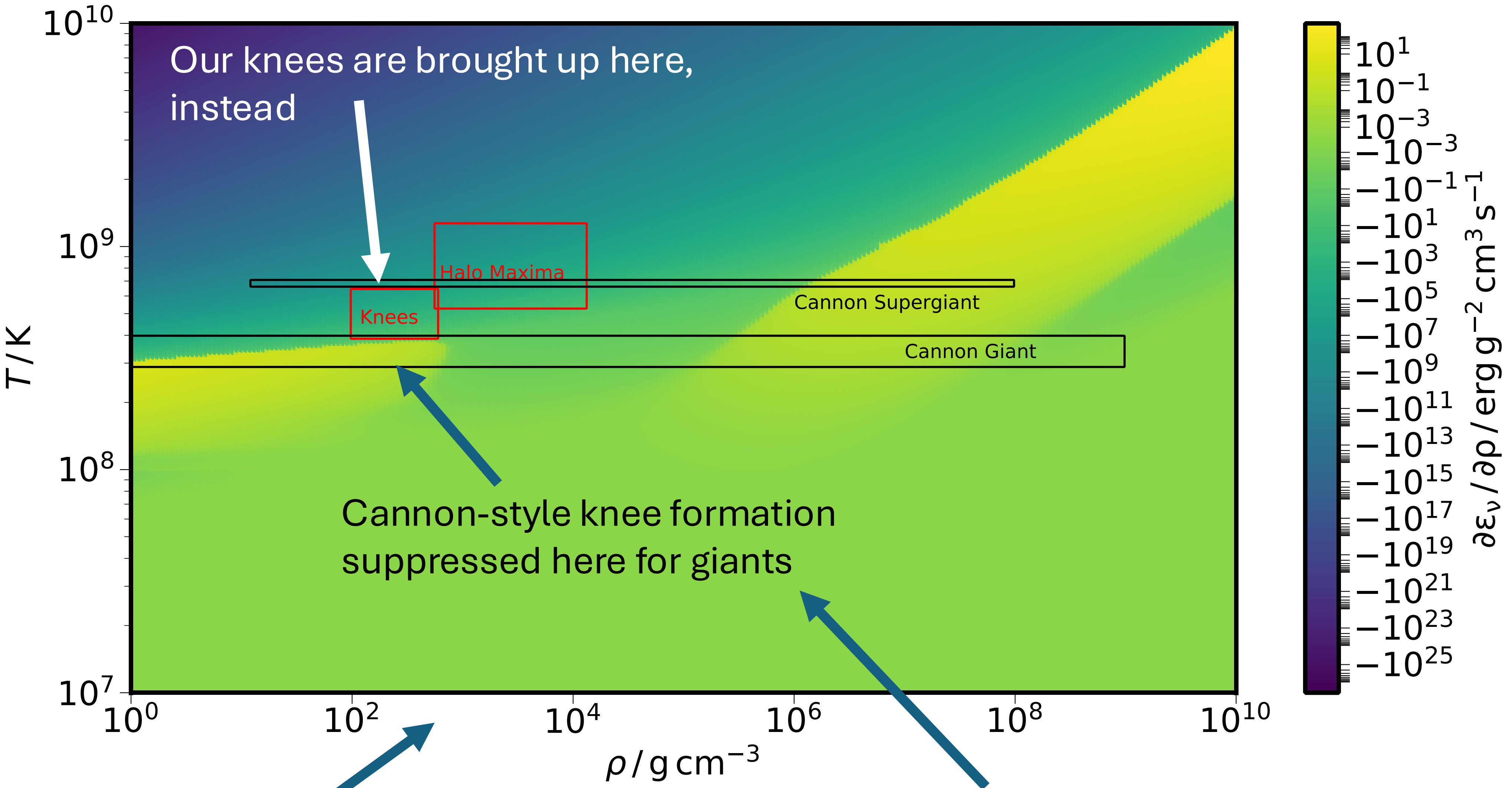
Partial w.r.t T



Partial w.r.t ρ



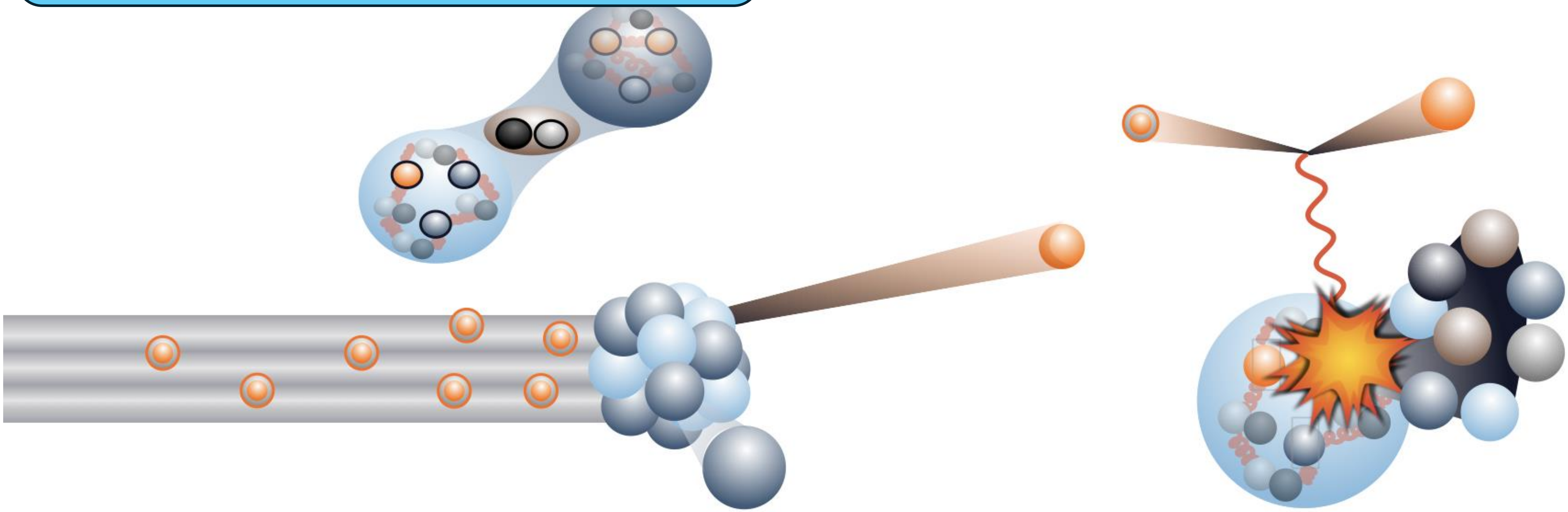
Partial w.r.t ρ



Partial w.r.t ρ

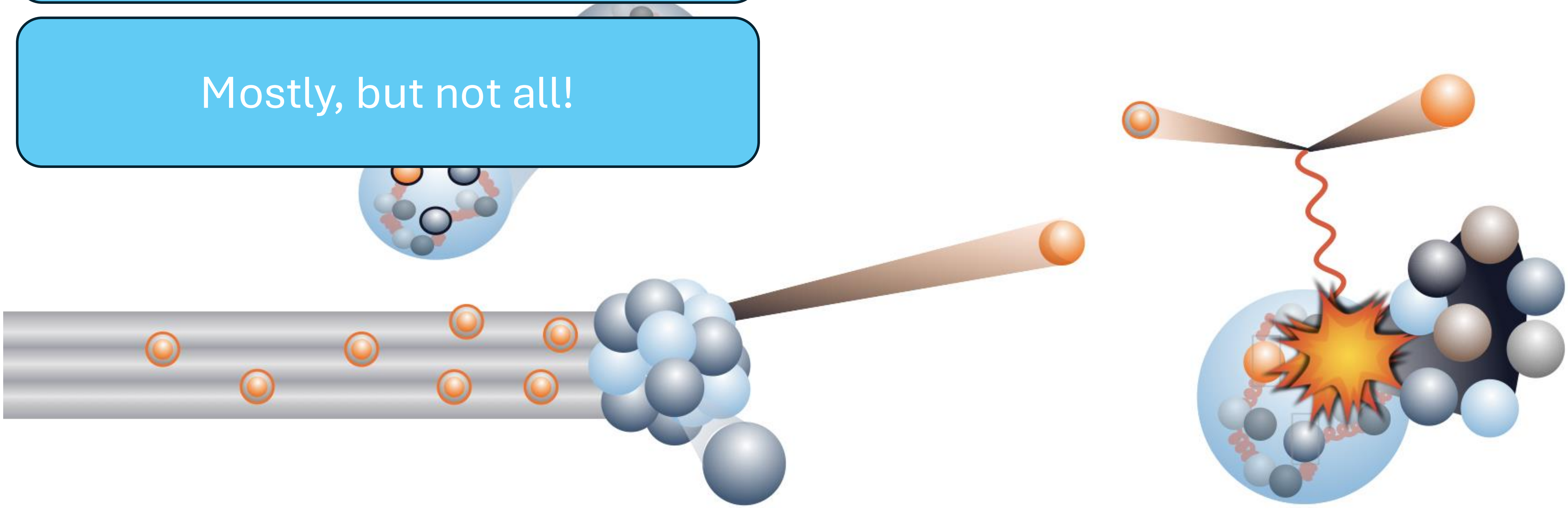
We **always** get supergiant configurations – even at low mass!!

Is it all neutrinos?

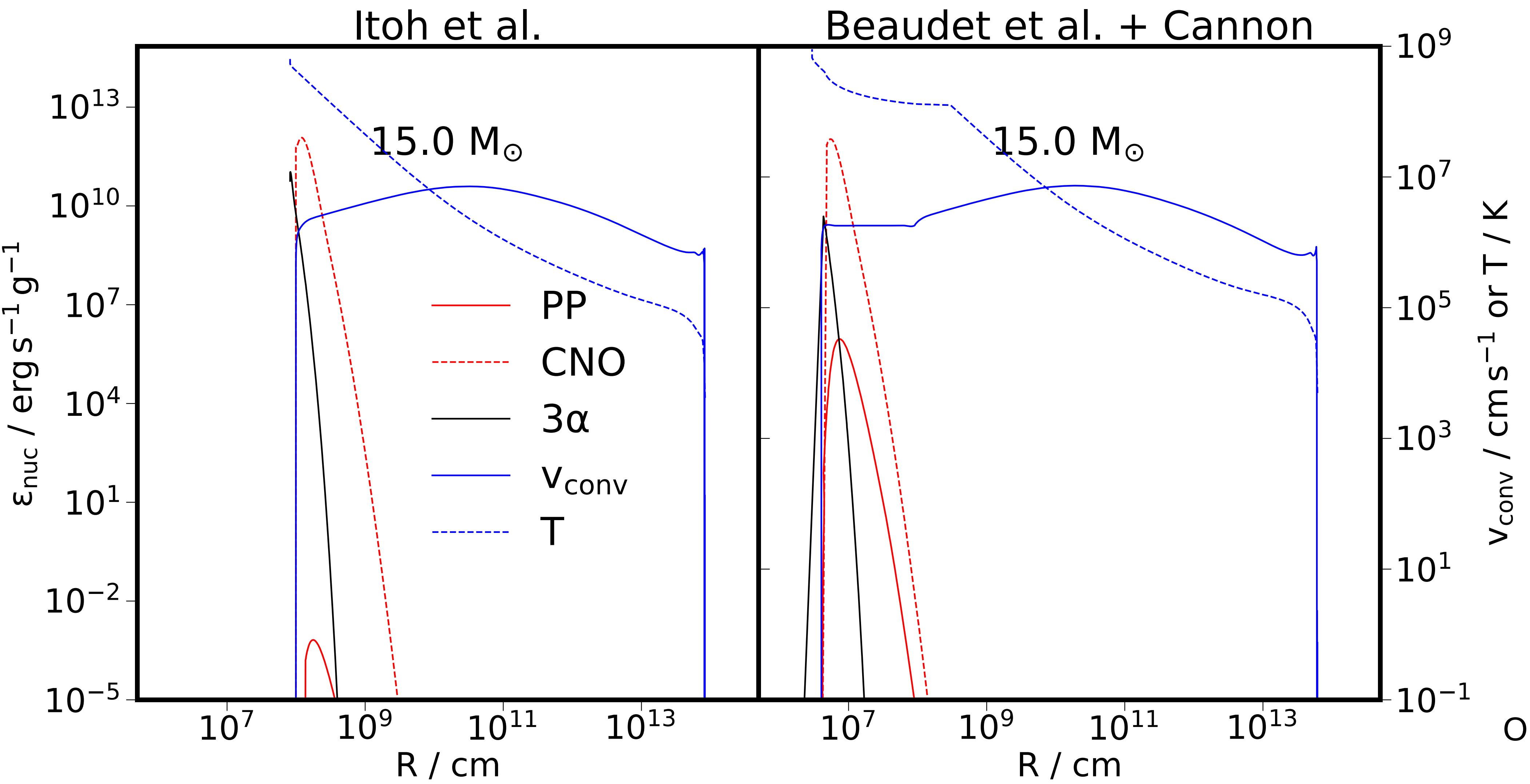


Is it all neutrinos?

Mostly, but not all!



Is it all neutrinos?

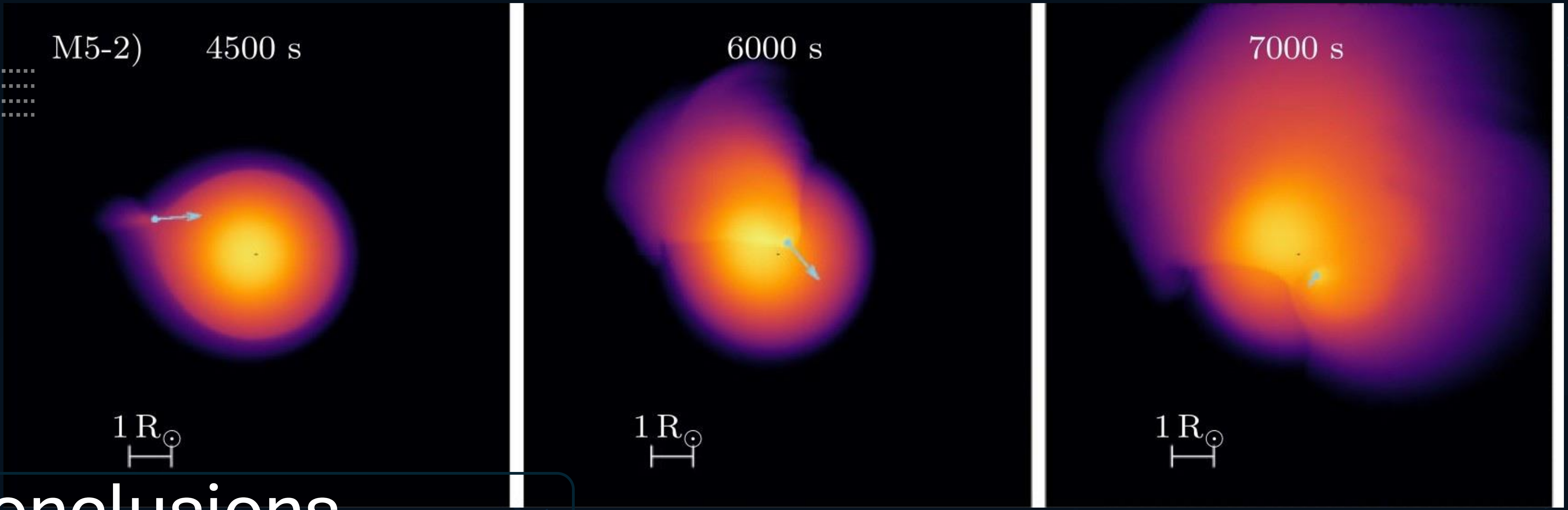


- Much more Cannon-esque now!
- But not identical
- Possible differences

Code structure

Reaction rates

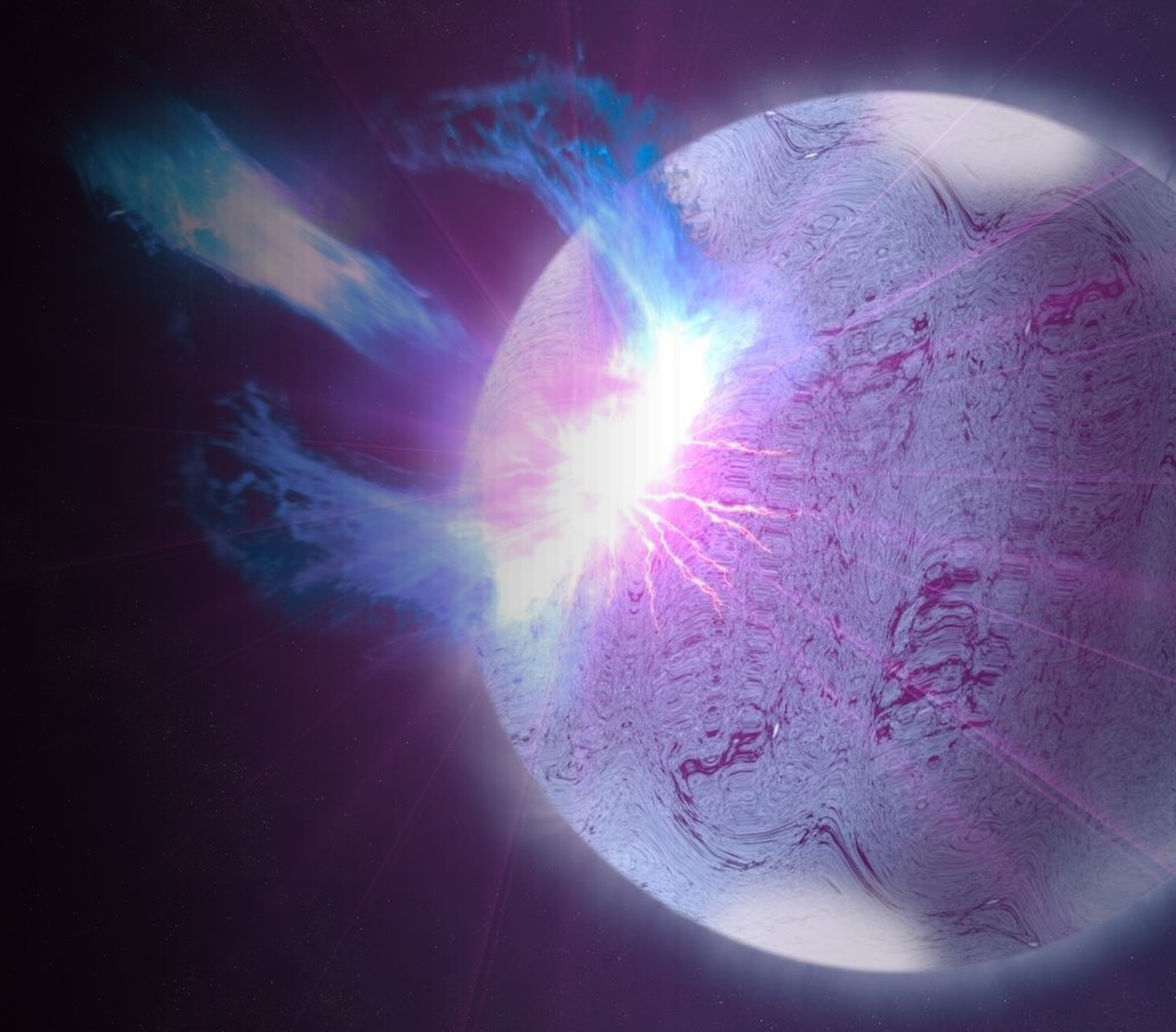
Opacities?



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?

Super-Chandrasekhar mass,
Highly magnetic WDs as progenitors of over-luminous Ia SNe



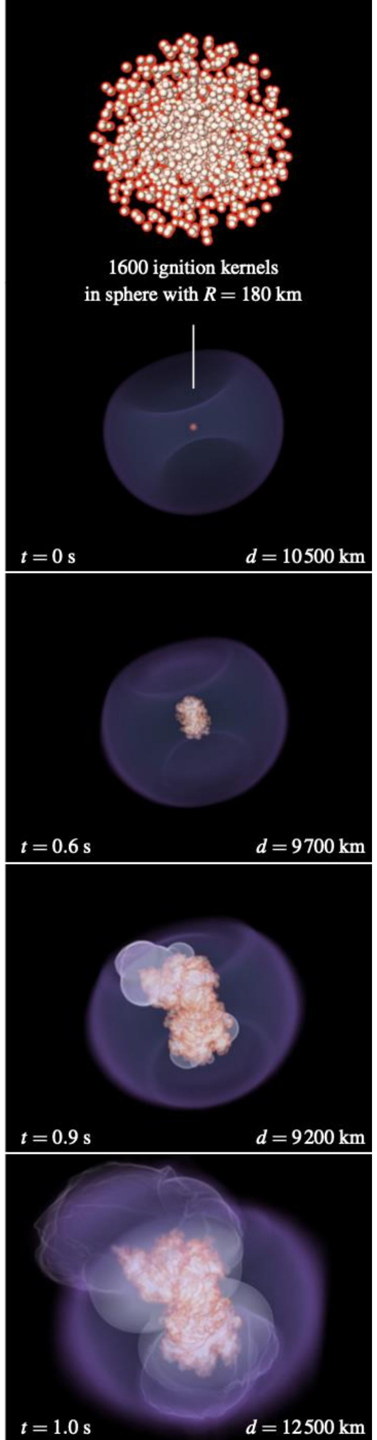
Surveys of Sne Ia show distinct subgroups

Some are superluminous, and have anomalous declines – sometimes by a full mag

SN 2006gz, SN 2009dc etc.

(Of course, could just be lensed e.g. Quimby+13)

Modelling (including by people at HITS e.g. Fink+18) suggest super-Chandrasekhar mass progenitors



How to make a super-Chandrasekhar mass WD?

Spin it up to (nearly) critical

Permeate it with an extreme magnetic field

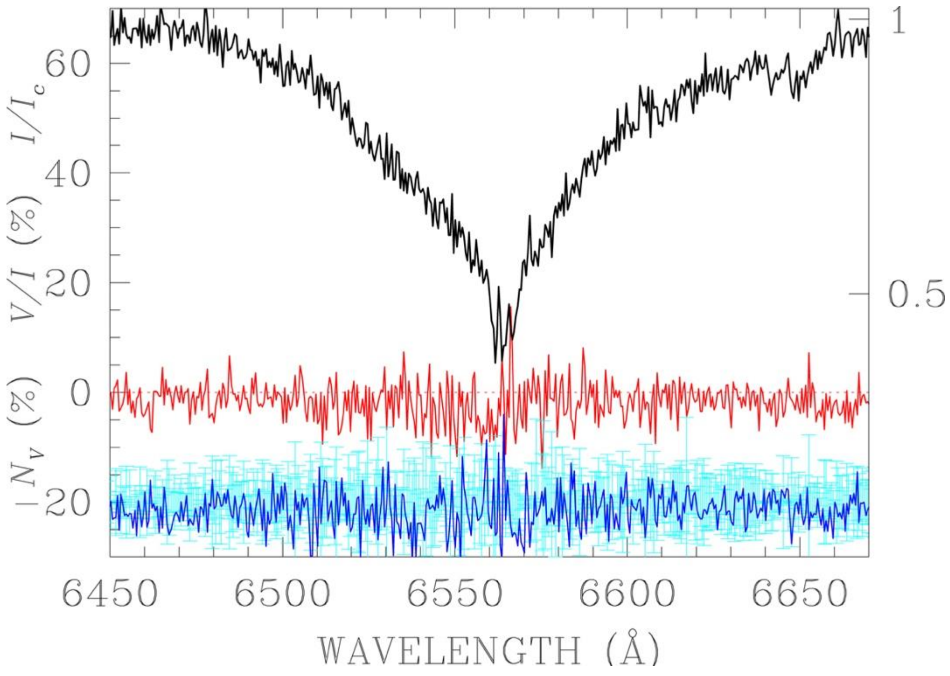
Can we model this?

Das+12 shows new EoS from Landau quantization

Can implement without needing GR if $\zeta \lesssim 0.01$

Roughly corresponds to

$$B_c \approx 10^{14} G$$



Landstreet+19 found kilogauss fields in WD 1105–340 – very close by!

Our implementation?

Opacity

EoS

$$\kappa_B \approx 5.5\times 10^{31}\,\rho\,/\,\mathrm{g\,cm^{-3}}\,(T\,/\,\mathrm{K})^{-3/2}(\mathrm{B}\,/\,\mathrm{G})^{-2}\mathrm{cm^2\,g^{-1}}$$

Potekhin magnetic opacity (Potekhin+01, Ventura+01)
Add to ordinary (OPAL) opacity in inverse

Radial magnetic field profile (Gupta+20)
Modified with cutoff radius

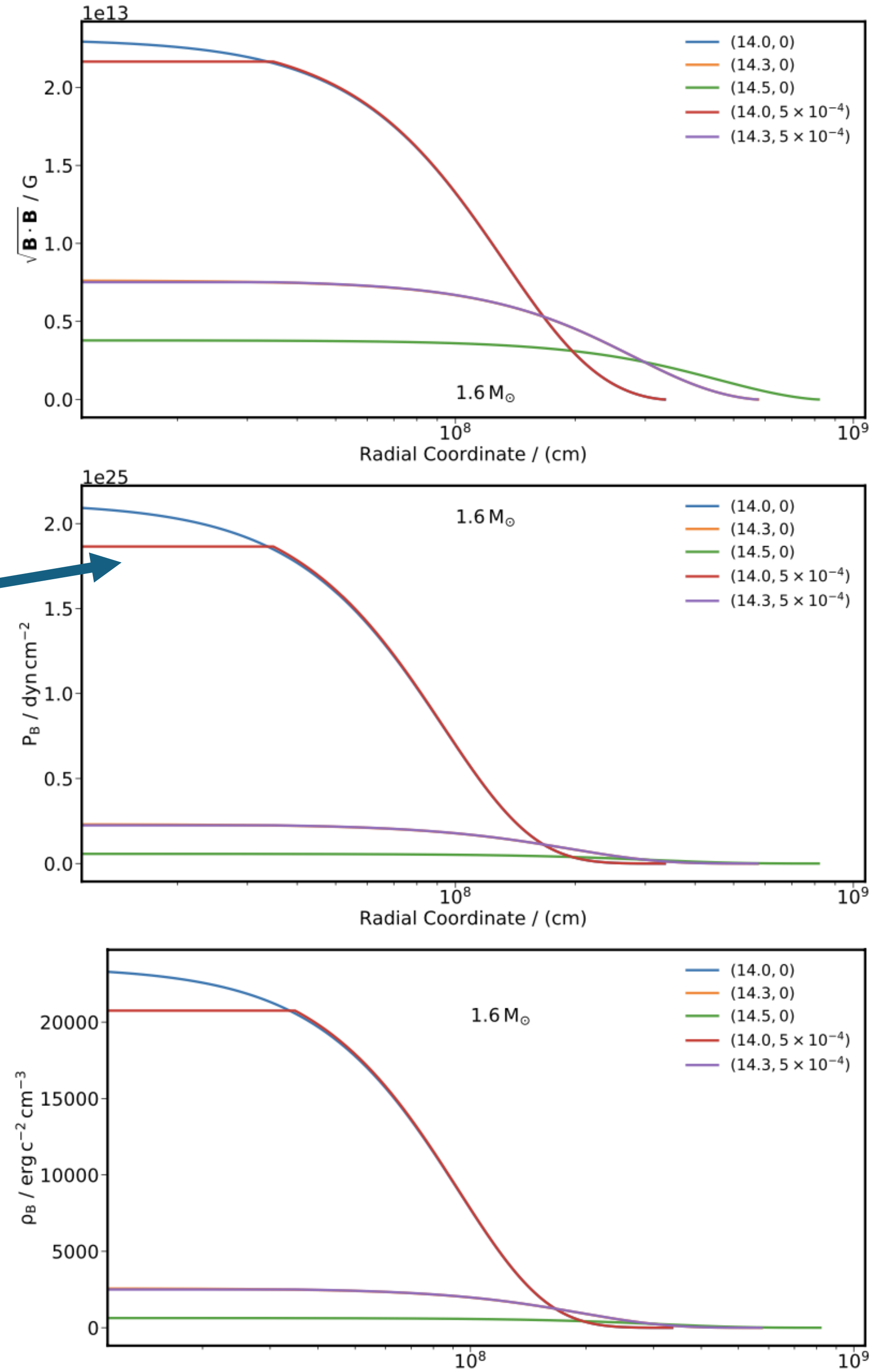
$$B\left(\frac{\rho}{\rho_0}\right) = \begin{cases} B_S + B_0\left[1-\exp\left(-\eta\left(\frac{\rho}{\rho_0}\right)^{\gamma}\right)\right] & r \le R_c \\ B_S + B_0\left[1-\exp\left(-\eta\left(\frac{\rho_c}{\rho_0}\right)^{\gamma}\right)\right] & r > R_c \end{cases}$$

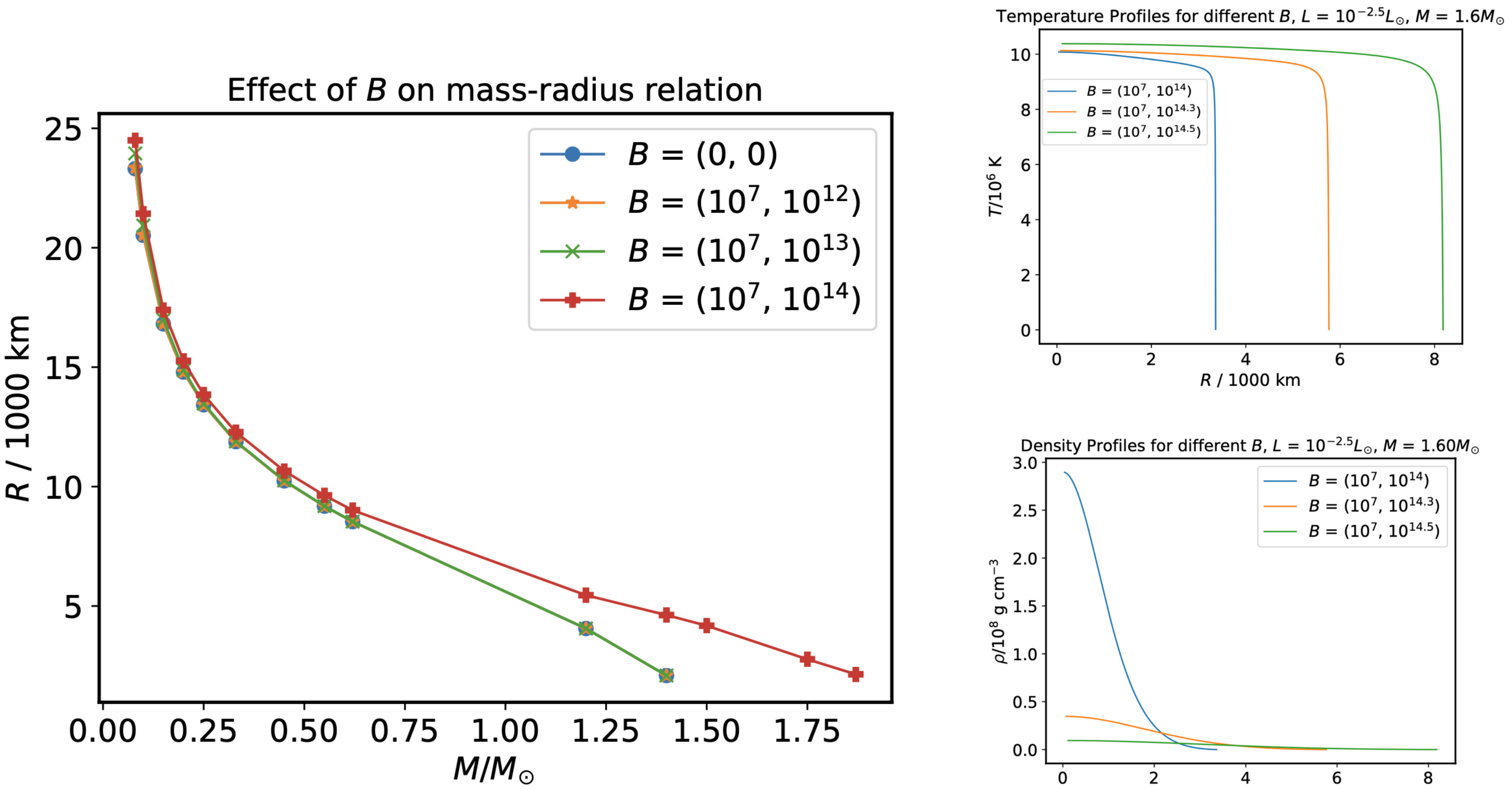
Why cutoff?

Chatterjee+17 – all positive radial field gradient →

Unphysical current sheath at small radii

It works: even with large cutoff radii – surface observables retained!





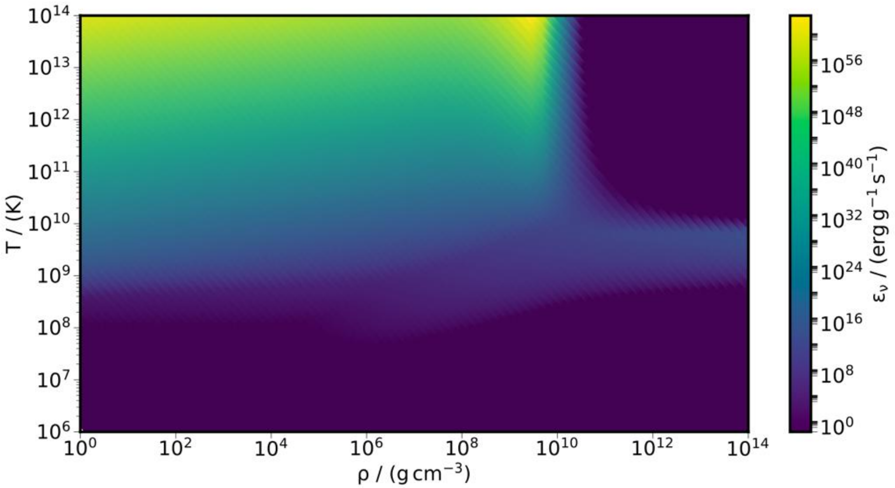
Effect of B on mass-radius relation
B = (0, 0)
B = (10^7, 10^{12})
B = (10^7, 10^{13})
B = (10^7, 10^{14})
R / 1000 km
$M/M_\odot$
Temperature Profiles for different B, $L = 10^{-2.5}L_\odot$, $M = 1.6M_\odot$
B = (10^7, 10^{14})
B = (10^7, $10^{14.3}$)
B = (10^7, $10^{14.5}$)
$T/10^6$ K
R / 1000 km
Density Profiles for different B, $L = 10^{-2.5}L_\odot$, $M = 1.60M_\odot$
B = (10^7, 10^{14})
B = (10^7, $10^{14.3}$)
B = (10^7, $10^{14.5}$)
$\rho/10^8$ g cm^{-3}
R / 1000 km

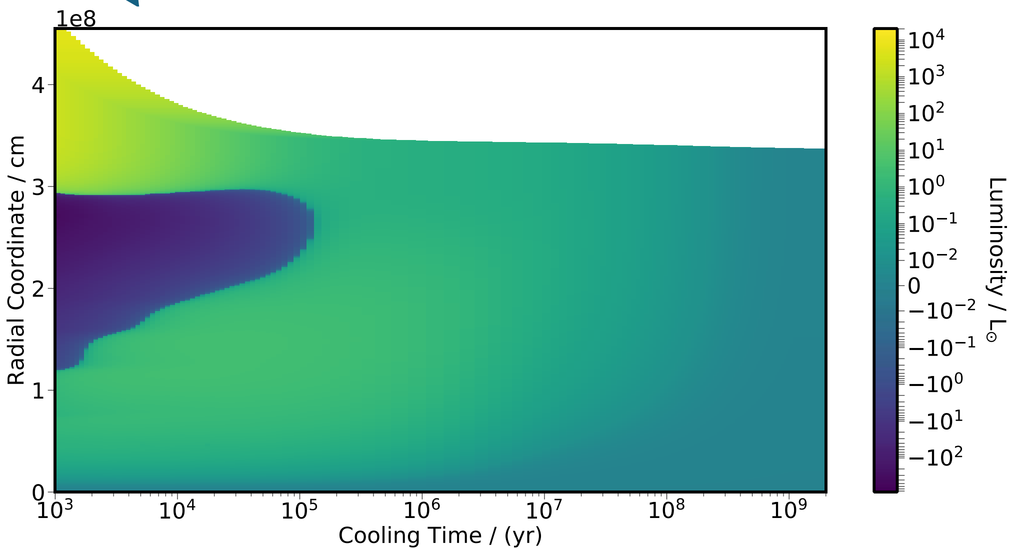
Cooling

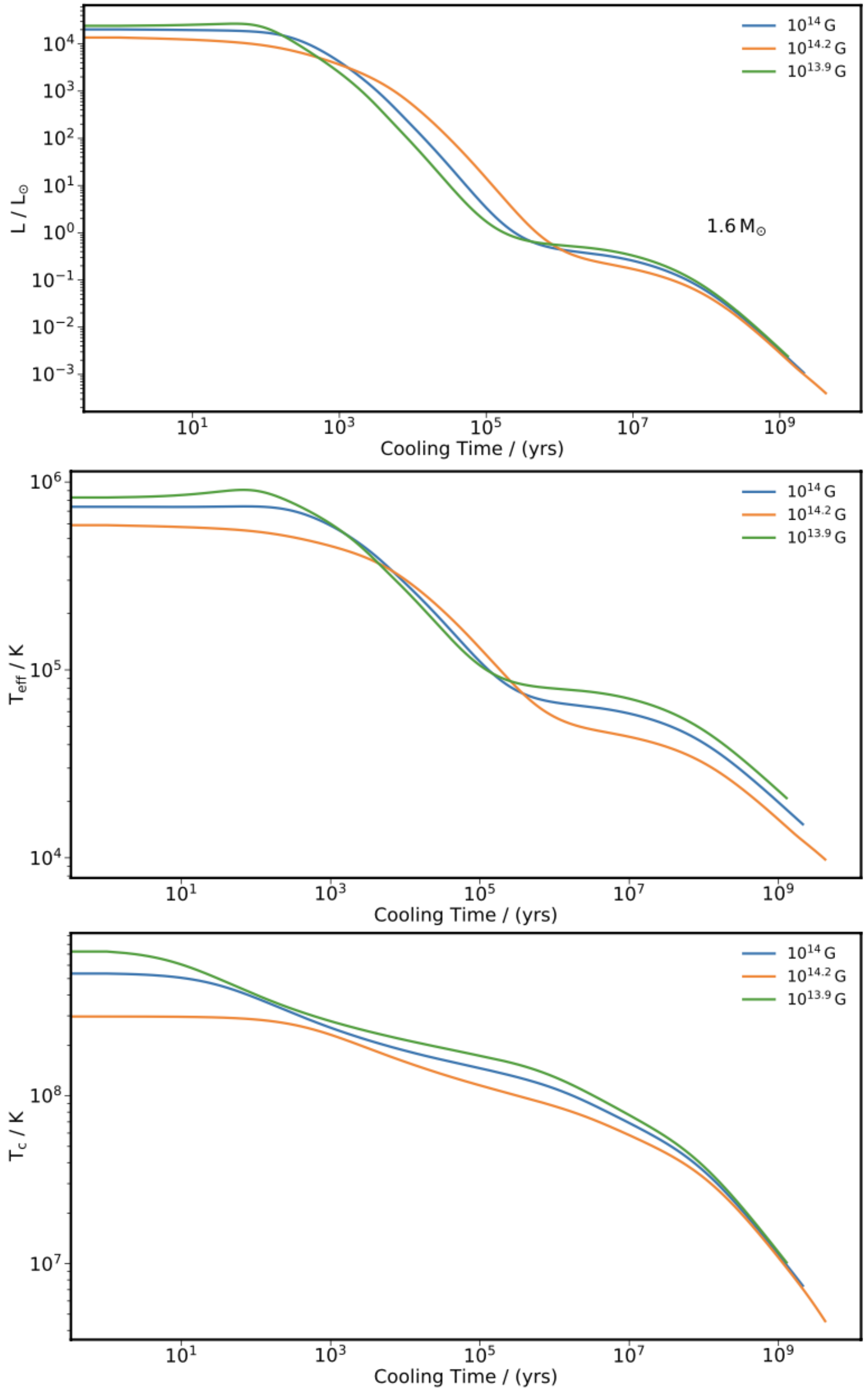
Early times

Long term cooling

Thermal neutrinos

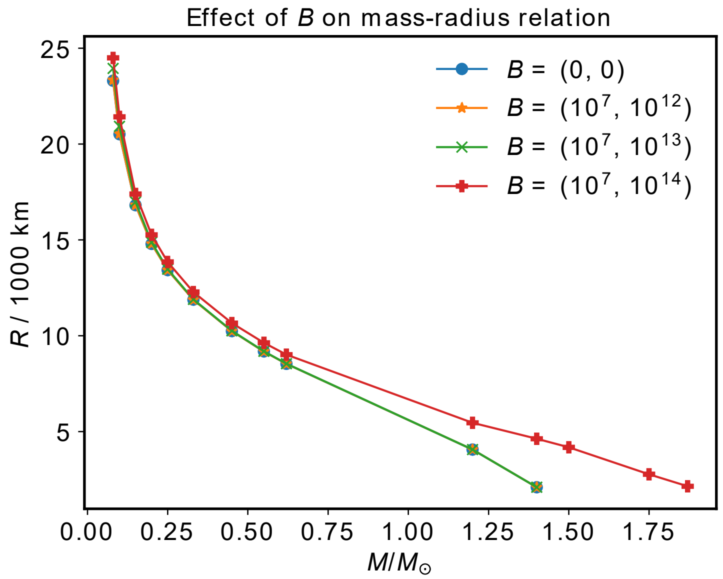




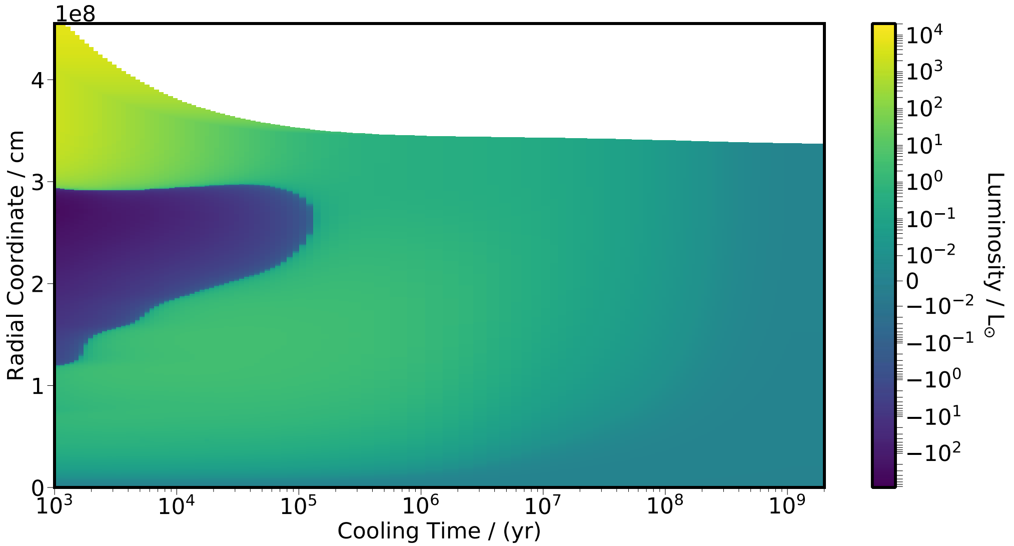


Super-Chandrasekhar mass, highly magnetic WDs as progenitors of over-luminous Ia SNe

We see overly luminous supernovae Ia (e.g. Chornock+13)



M-R Relationship for B-WDs



Internal cooling for $1.6M_\odot$
$B_0 = 10^{14}G$ max internal field

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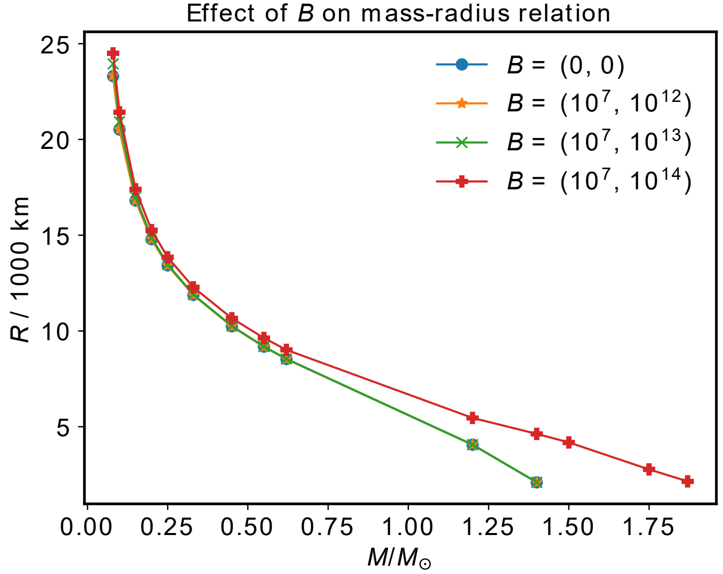
↓

Could be the result of **lensing** (Quimby+13)



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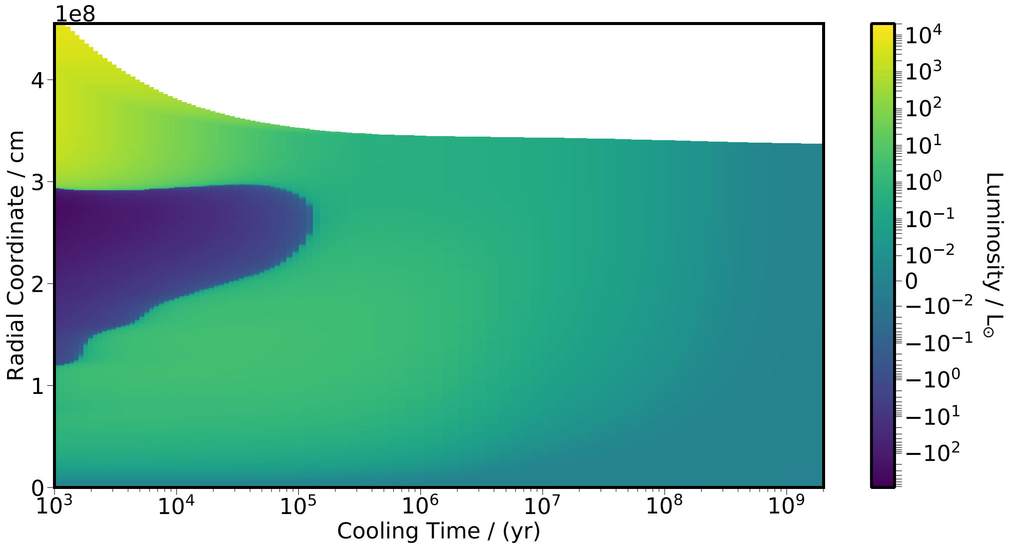

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- Spin-up to near critical
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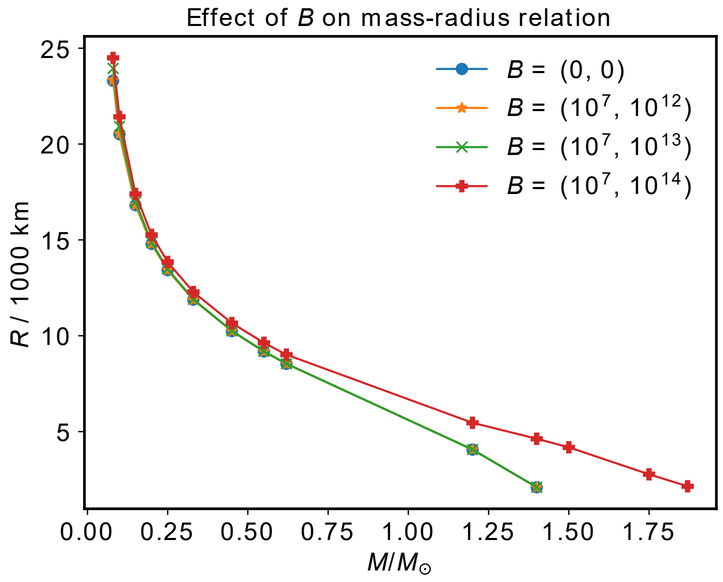

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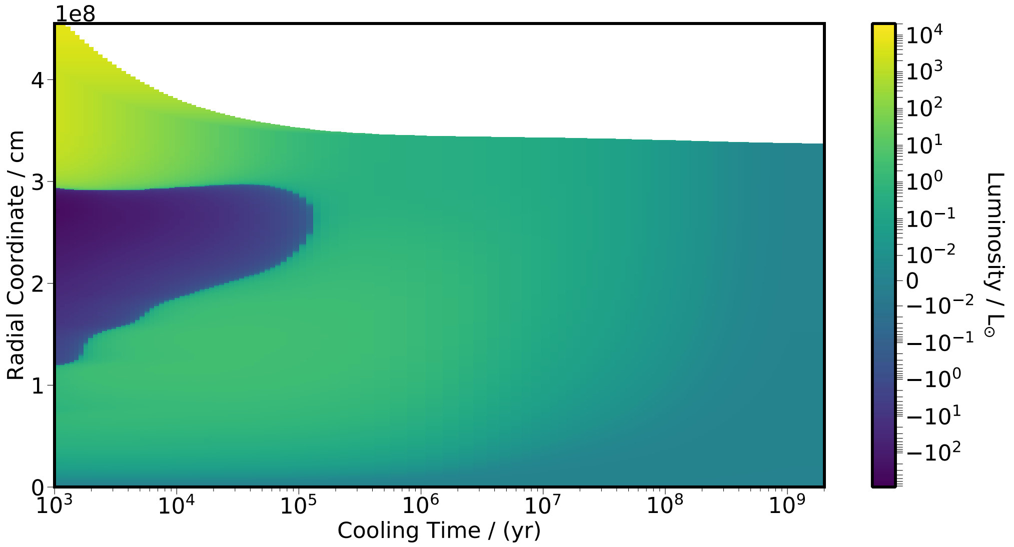

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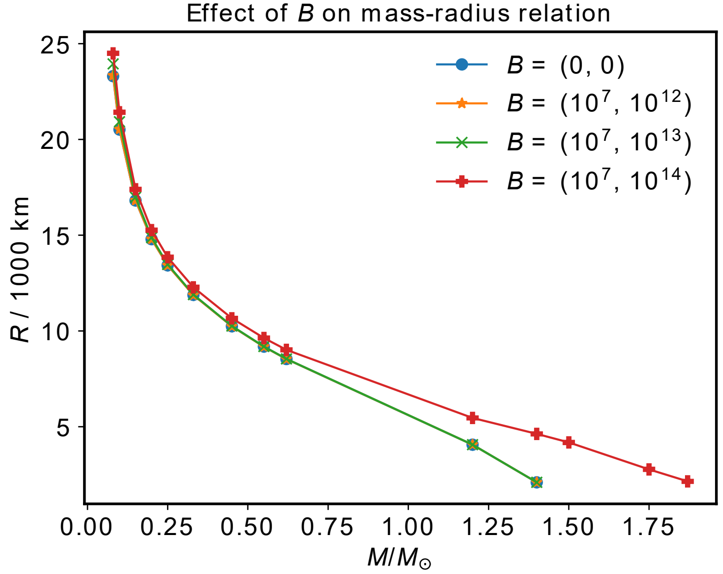

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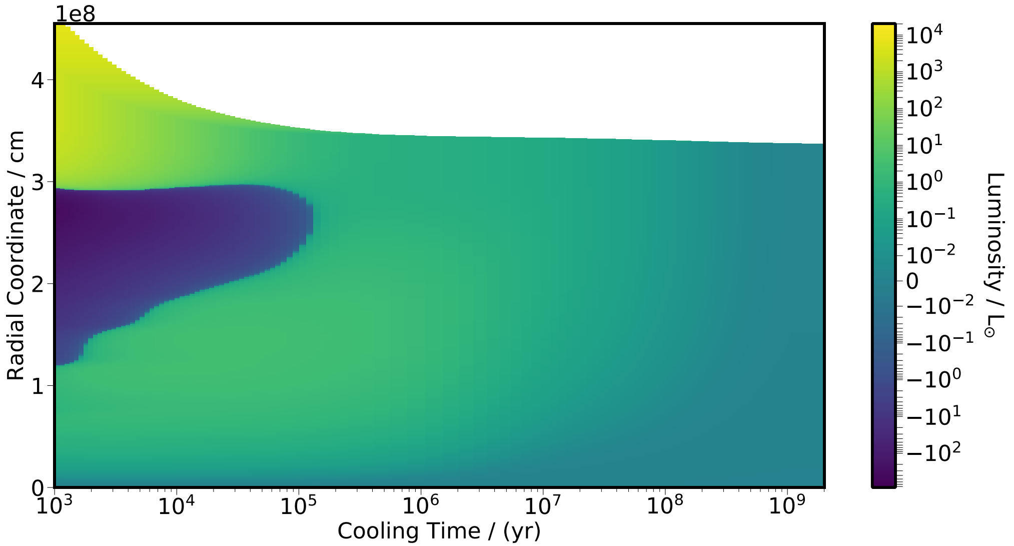

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(B_s, B_0)/G	$\rho_c/10^6\,\mathrm{g\,cm^{-3}}$	R/1000km	Max Mass/$M_\odot$
(0, 0)	2210	2.1177	1.4397
$(10^7, 10^{11})$	2257	2.1196	1.4358
$(10^7, 10^{12})$	2280	2.1227	1.4358
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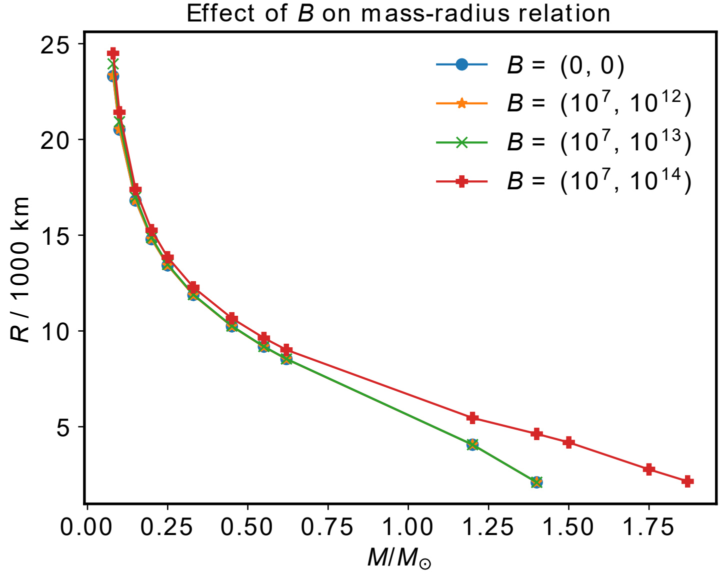
Use a magnetic field profile (Bandyopadhyay+97 & many others)



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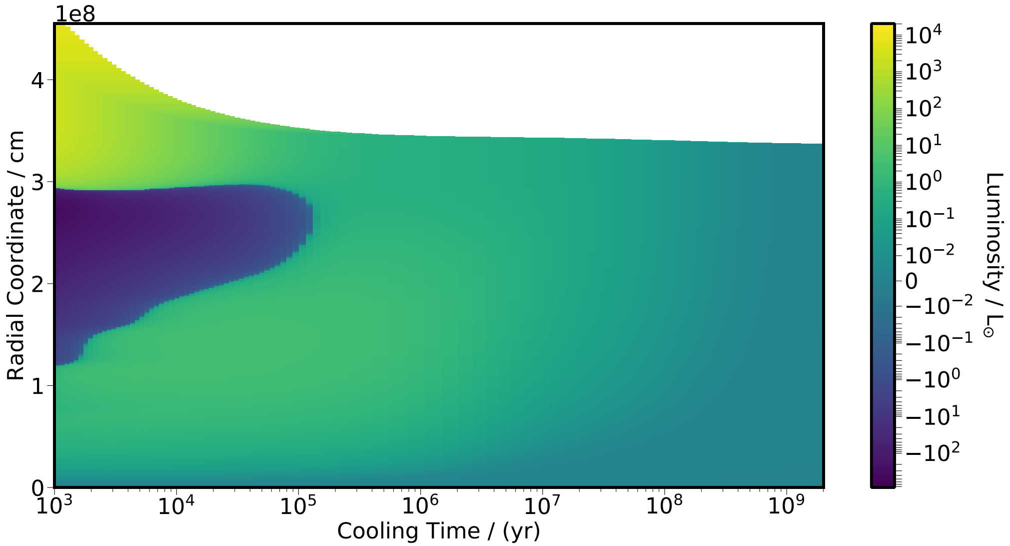

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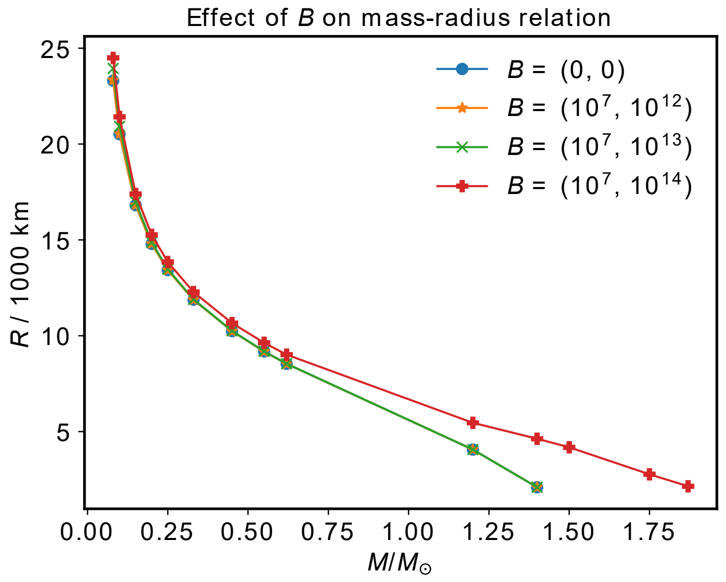

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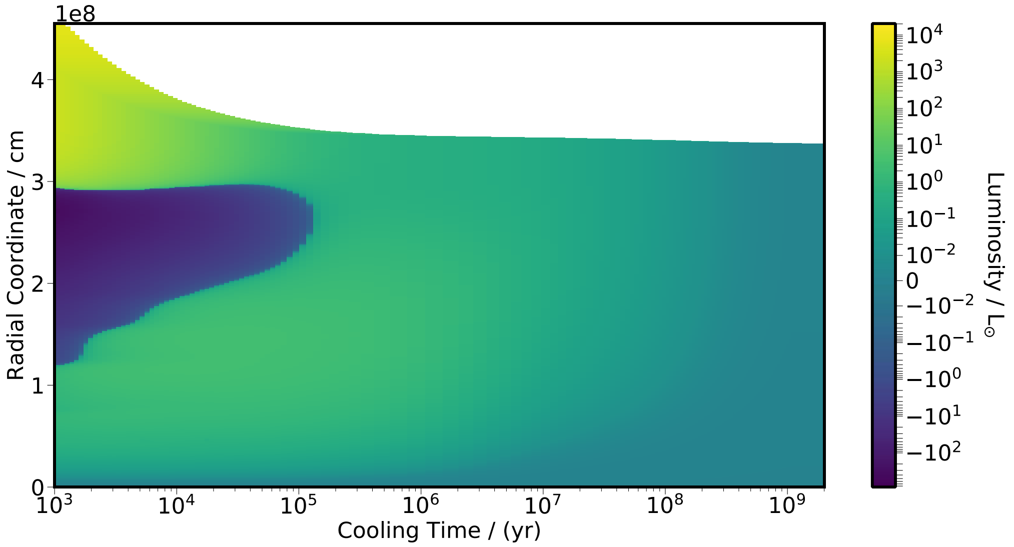

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Use a magnetic field profile (Bandyopadhyay+97 & many others)

Problem!
Profile implies unphysical current sheath at small radii

Solution
Introduce radius cutoff alongside density cutoff

No change in observables

"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