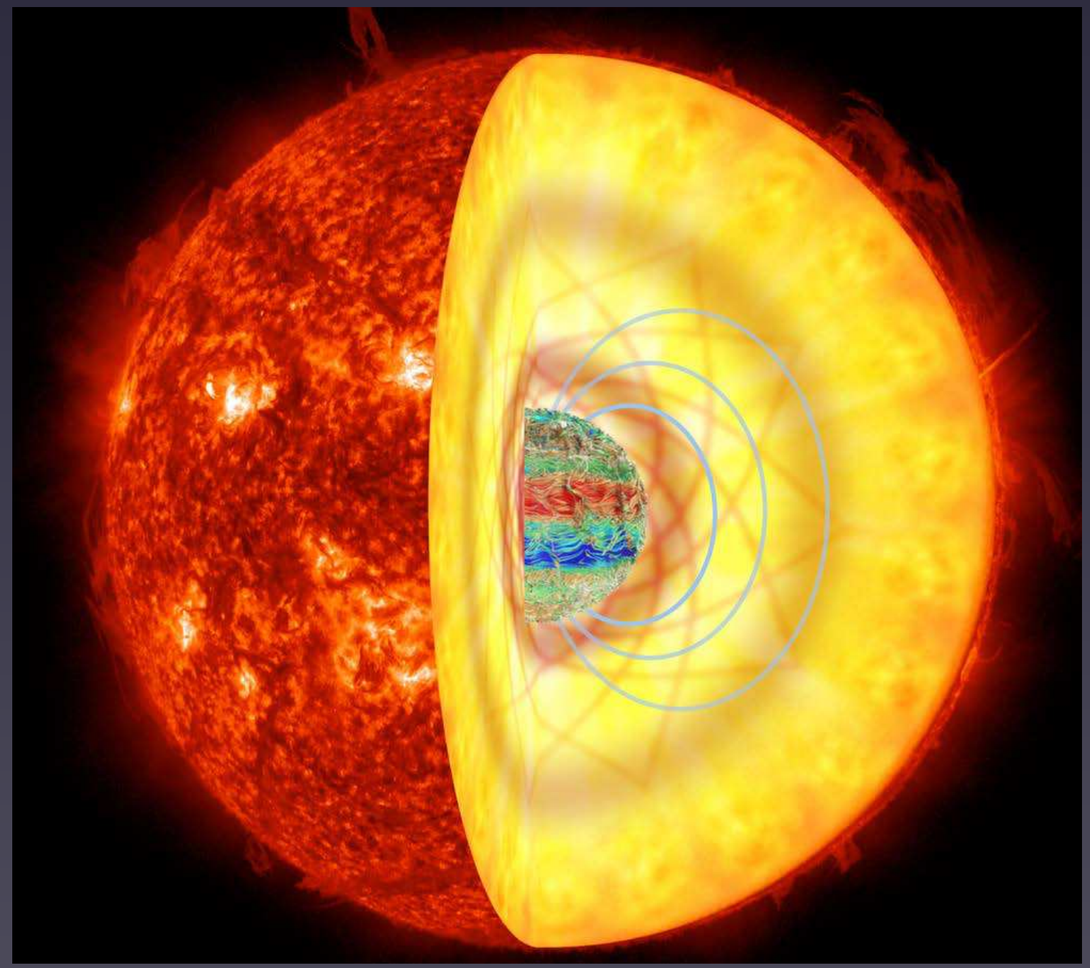
Shocking Consequences of Waves on Massive Stars

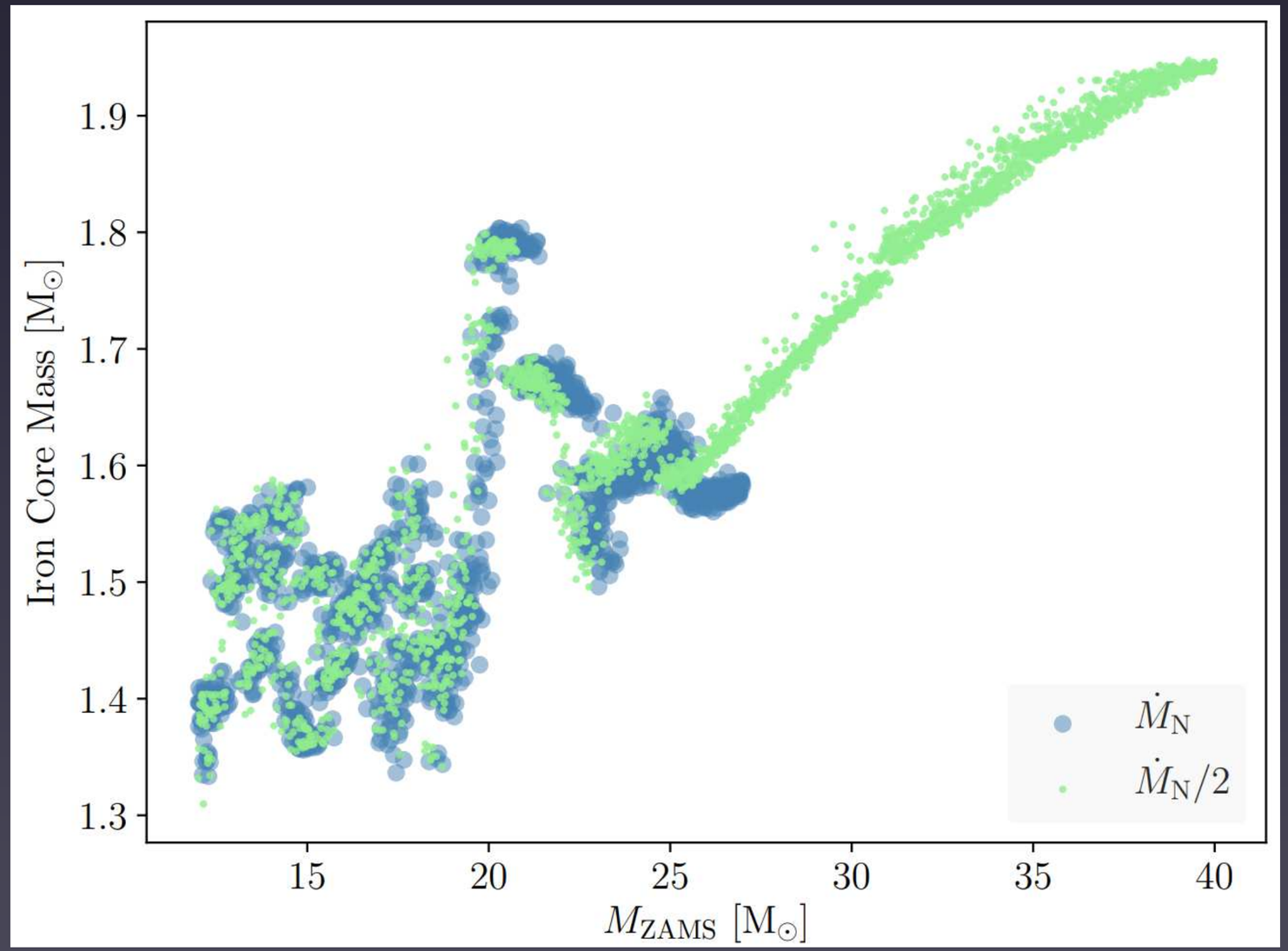
Jim Fuller

Caltech



Massive Star Evolution

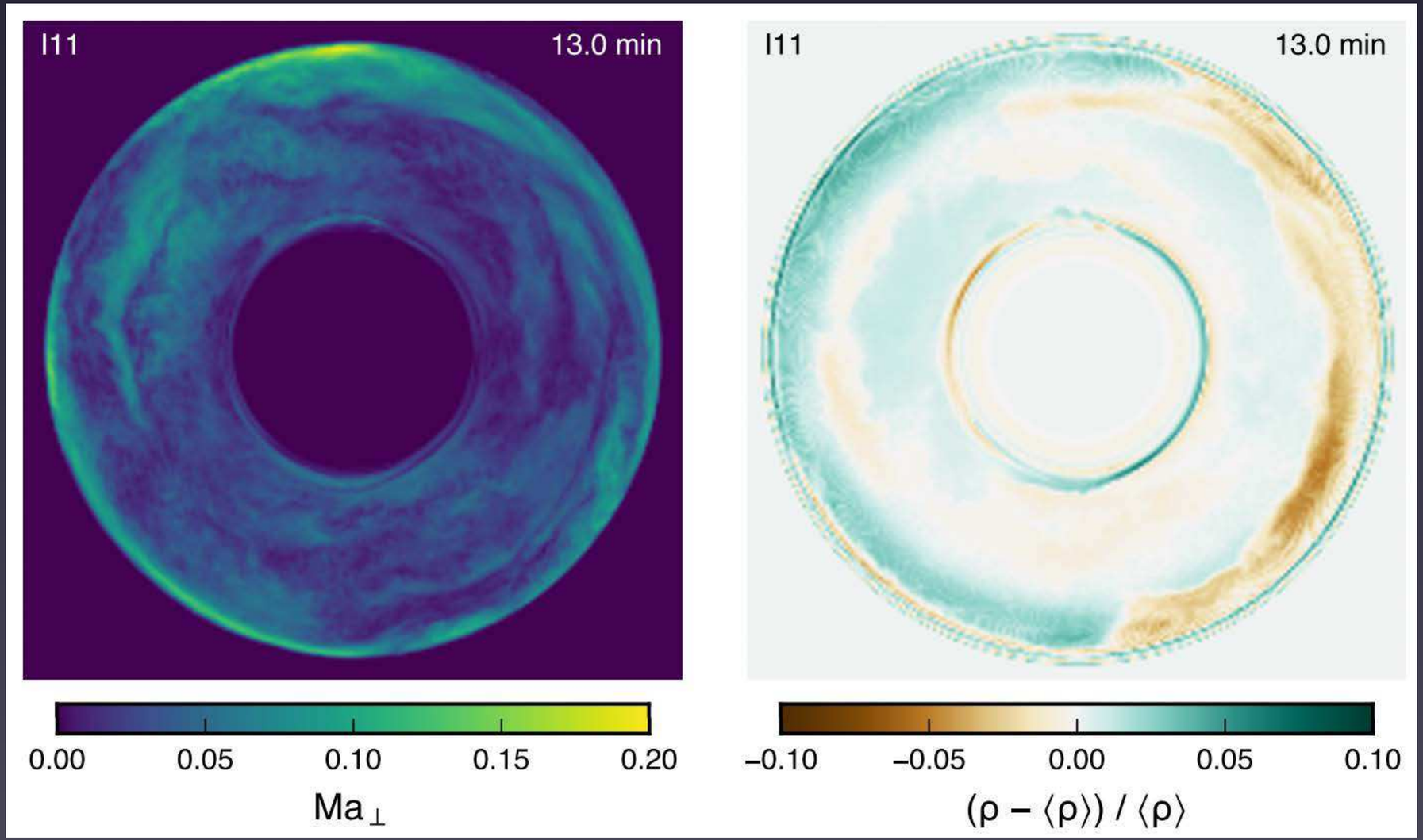
- Large suites of models
  - “Chaotic” stellar evolution
- Wind mass loss
  - Mass loss rates ~1/3 of previous estimates
- Binary evolution
  - Ubiquitous
  - See talk by Marchant



Sukhbold, Woosley, Heger 2017

Multi-dimensional modeling

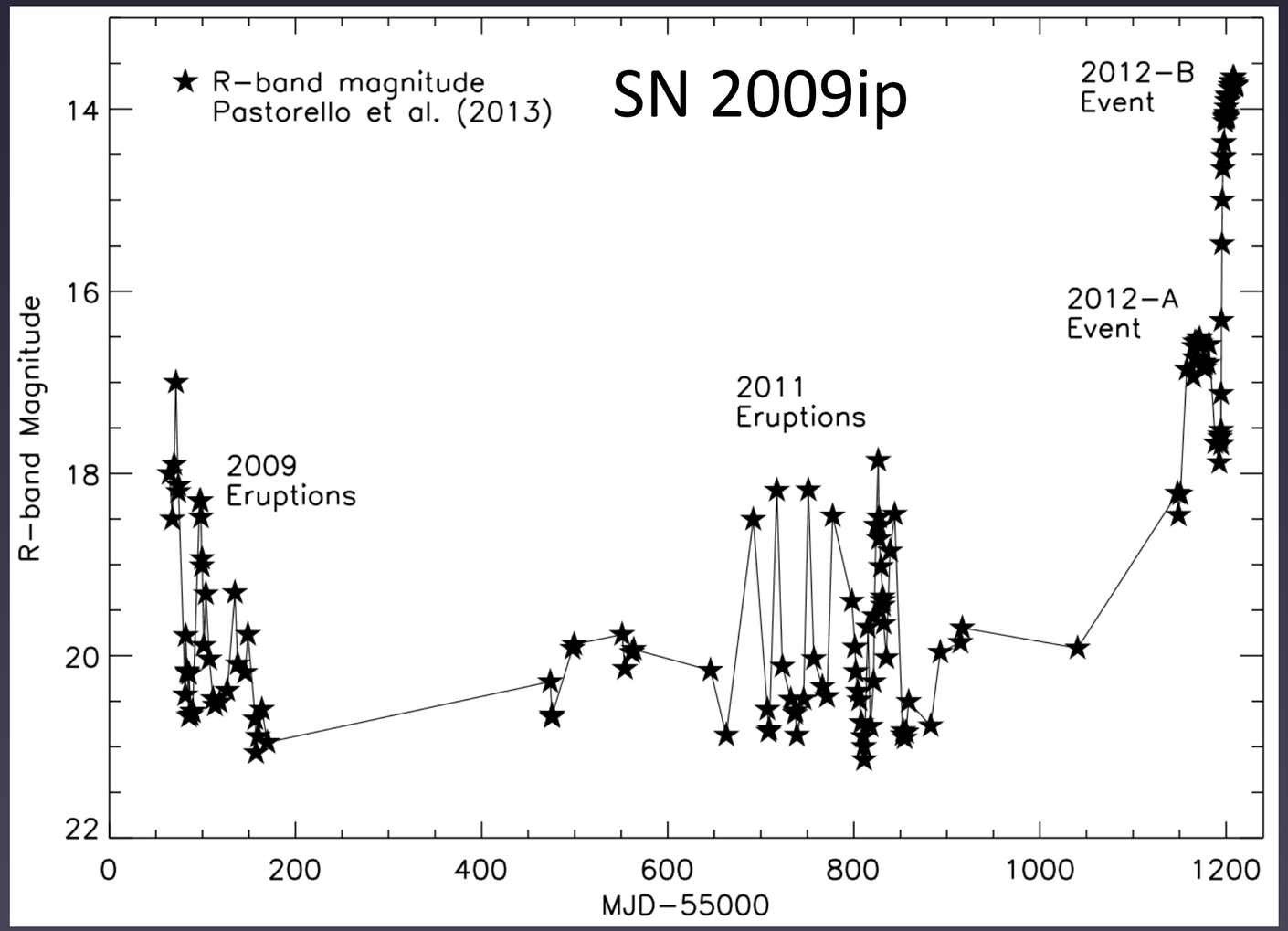
- Simulations of late burning stages possible
- More mixing, larger convective velocities?
- Effects on supernova explosion?



Adrassy+ 2018

Pre-Supernova Outbursts

- Pre-SN outbursts occur in many types of SNe
  - Occur in last ~years of star's life
  - Mass loss rates enhanced by factors of ~10^3, can be >> 10^{-3} M_{sun}/yr

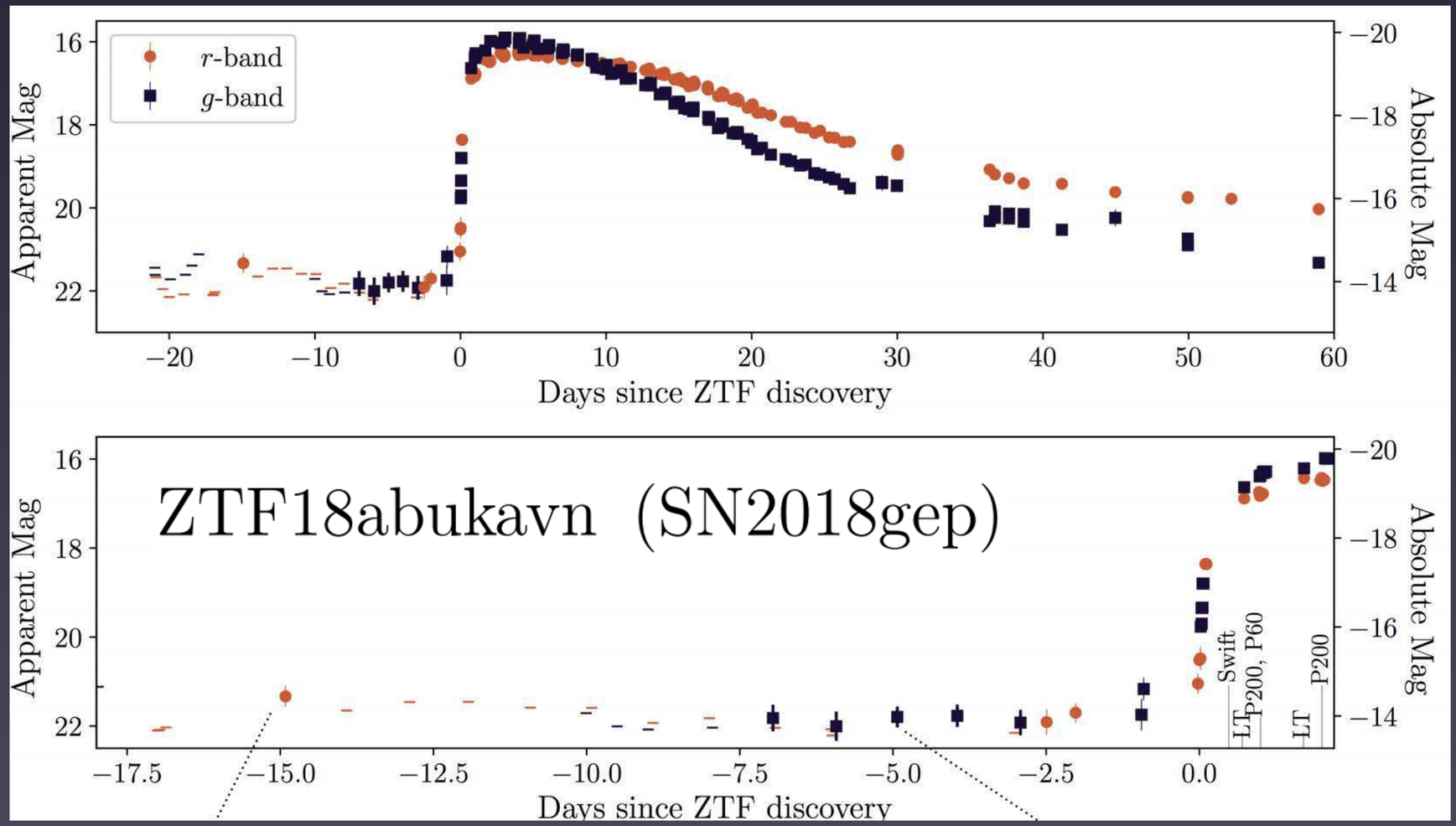


Graham et al. 2014

Wave-driven Pre-Supernova Outbursts

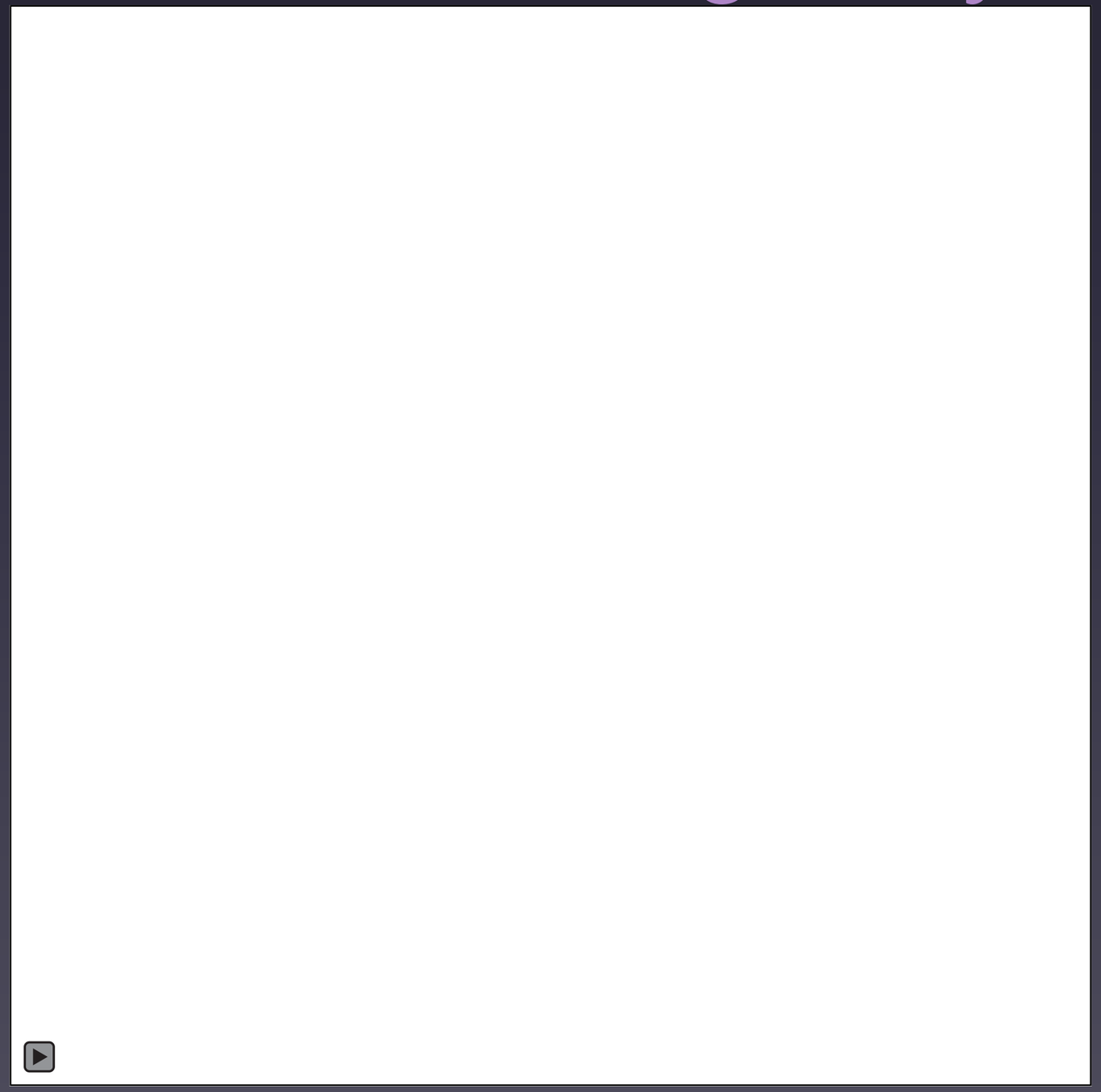
- Waves may be cause

  Quataert & Shiode (2012)
  Shiode & Quataert (2014)



Ho, Goldstein +, 2019

Convection excites gravity waves



Movie made by
Andrea Cristini

Wave Power

Convection puts energy into waves at a rate

$$L_{\rm wave} \sim \mathcal{M}_{\rm con} L_{\rm con}$$

Goldreich & Kumar 1990
Lecoanet et al. 2013
Rogers et al. 2013

Where the convective Mach number is

$$\mathcal{M}_{\rm con} = \frac{v_{\rm con}}{c_{\rm sound}} \ll 1$$

The convective velocity can be estimated from mixing length theory

Late Stage Massive Stellar Evolution

During late burning stages, neutrinos cool core, causing burning timescales to be short

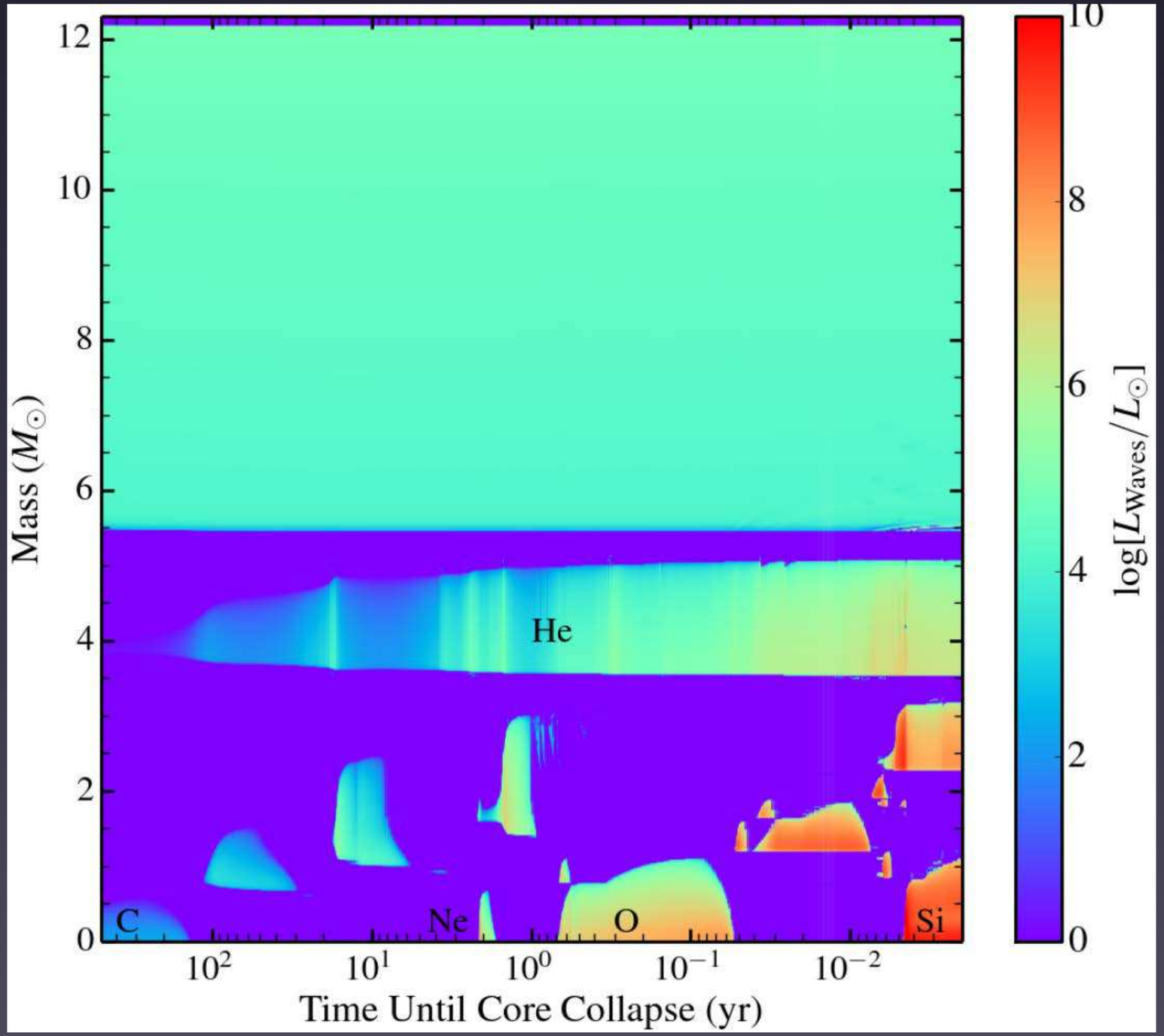
$$t_{\rm dyn} \ll t_{\rm nuc} \ll t_{\rm therm}$$

$$L_{\rm nuc} \gg L_*$$

Consequently, there are situations where

$$L_{\rm wave} \gg L_*$$

Waves can transport energy to surface on timescale of ~ $t_{\rm dyn}$



Wave Power in Massive Stars

$$E_{\rm waves} \sim 10^{47-48}\,{\rm erg}$$

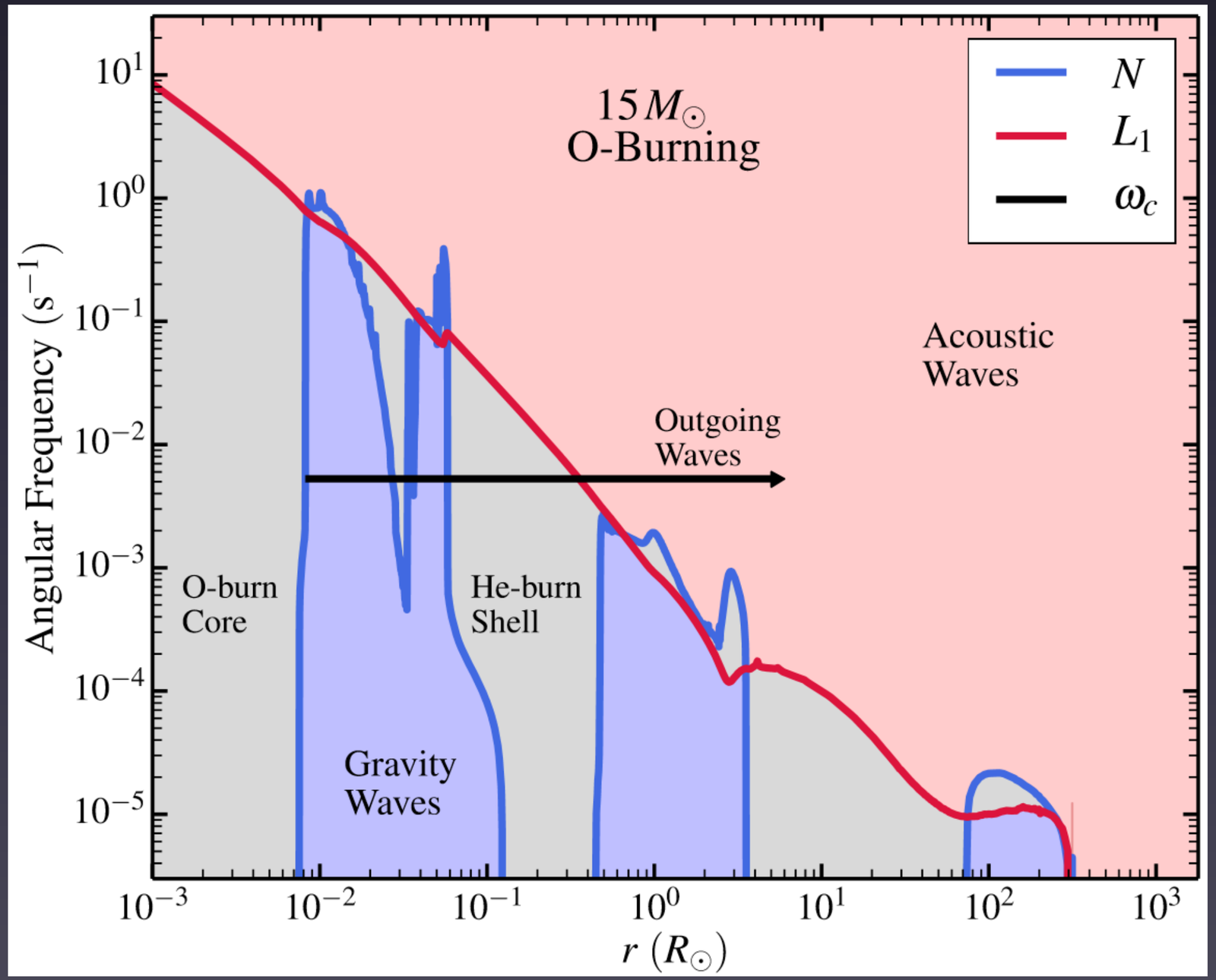
Wave Propagation

Gravity excited in core must tunnel into stellar envelope as acoustic waves

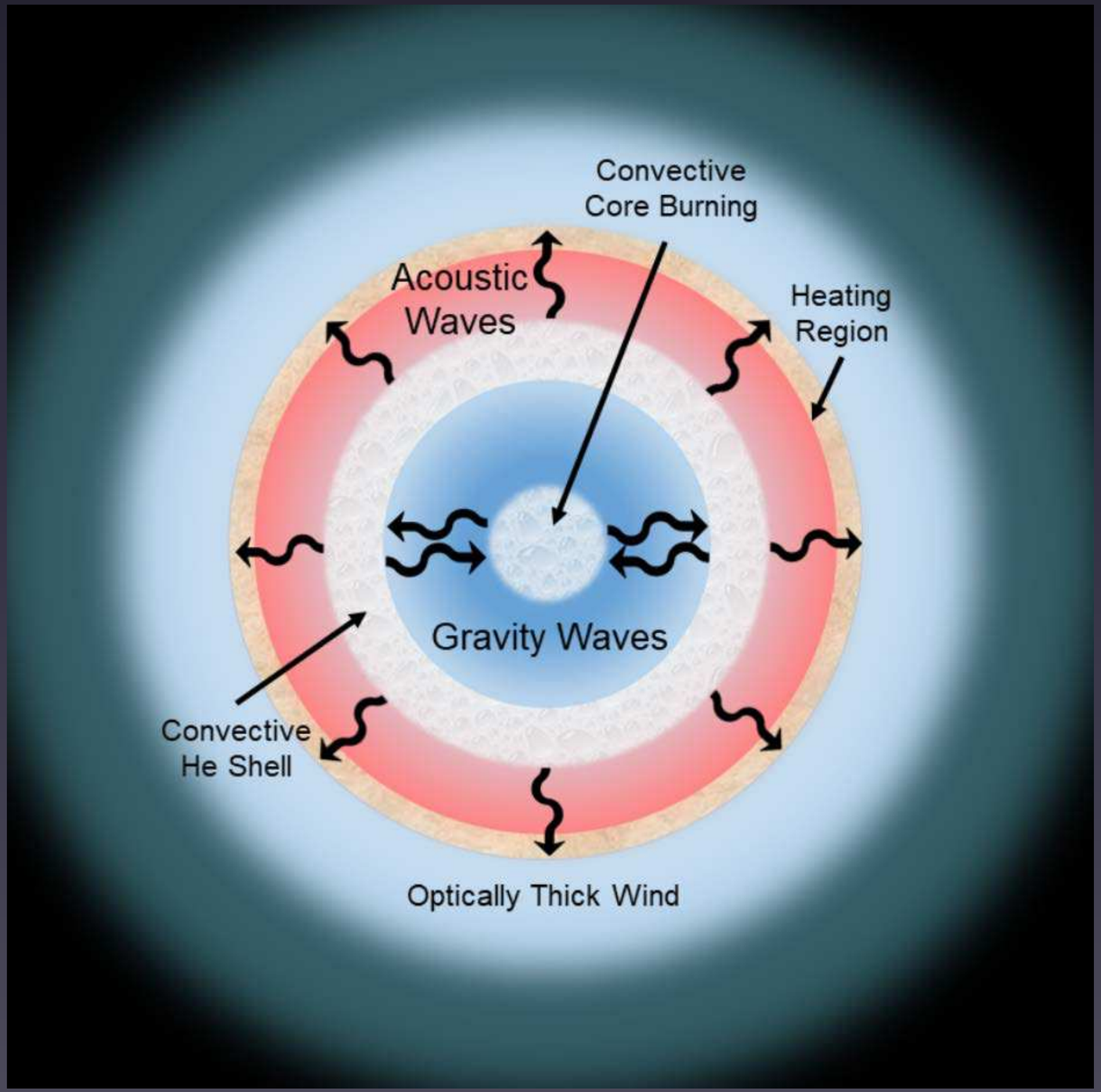
Acoustic waves damp in envelope, converting wave energy to thermal energy

$$v_{\rm con} = \left[L_{\rm con}/(4\pi\rho r^2)\right]^{1/3}$$

$$\omega_{\rm con} = 2\pi \frac{v_{\rm con}}{2\alpha_{\rm MLT} H}$$



Fuller 2017



Fuller & Ro 2018

Methods

- Run MESA models including the effects of wave energy transport

$$\gamma_\nu = \frac{\delta\epsilon_\nu}{\varepsilon} \simeq \frac{\Gamma_1^2 \nabla_{\rm ad}^2 g^2}{N^2 c_s^4} \left(\frac{\partial \ln \epsilon_\nu}{\partial \ln T} \right)_\rho \epsilon_\nu$$

- At each time step, compute:

$$L_{\rm heat} = f_{\rm esc} L_{\rm wave} = \left[1 + \frac{T_{\rm shell}^2 + x_\nu}{T_{\rm min}^2} \right]^{-1} L_{\rm wave}$$

  - Wave generation by nuclear burning convective zones in core

$$T_{1,2}^2 = \exp\left(-2 \int_{r_1}^{r_2} |k_r| dr \right)$$

  - Wave propagation and fraction of energy tunneling into the envelope

$$k_r^2 = \frac{\left(N^2 - \omega_2\right)\left(L_l^2 - \omega^2\right)}{\omega^2 c_s^2}$$

More Methods

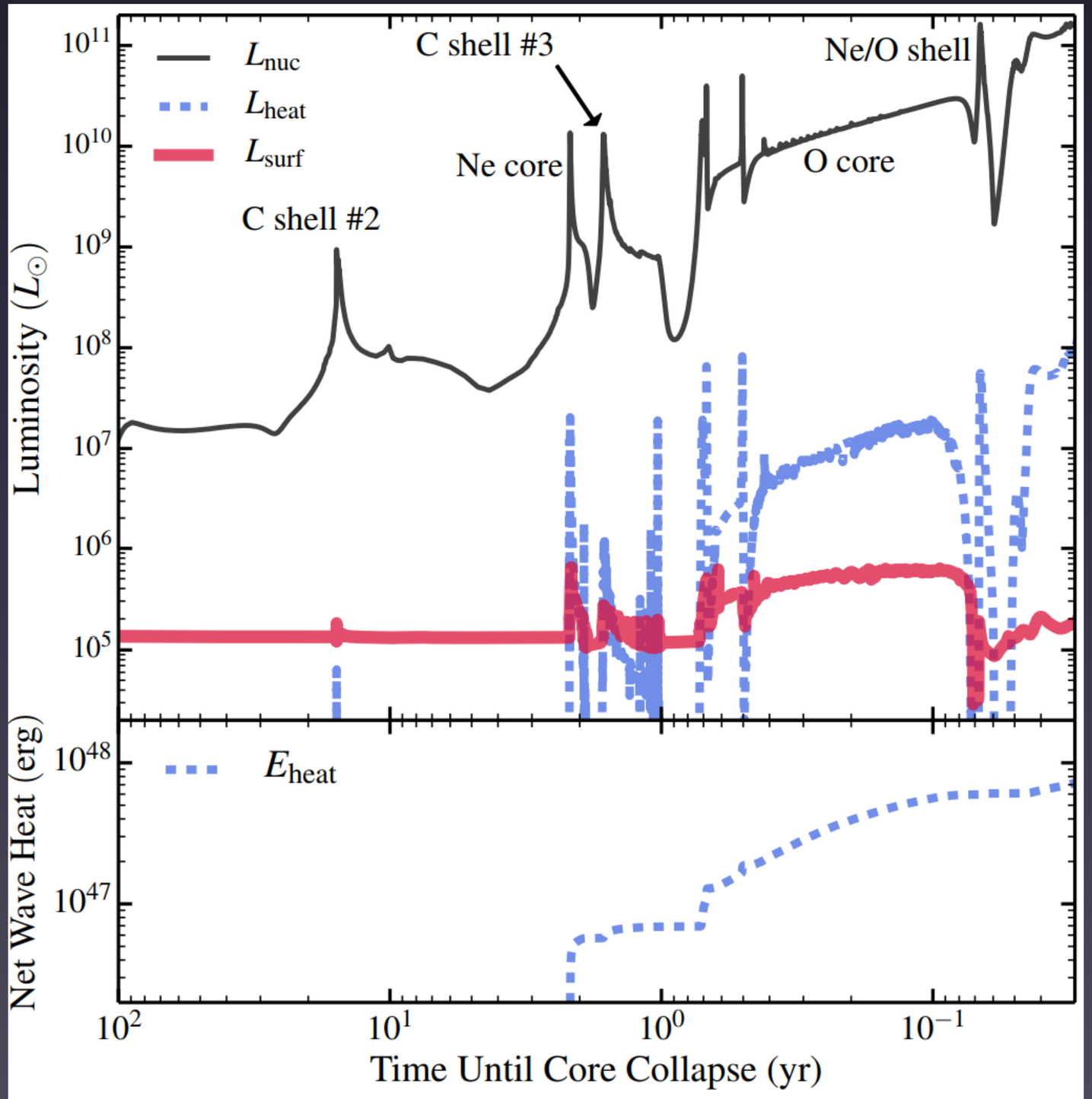
- Run MESA models including the effects of wave energy transport

$$\frac{dL_{\rm wave}}{dM} = -\frac{L_{\rm wave}}{M_{\rm damp}}$$

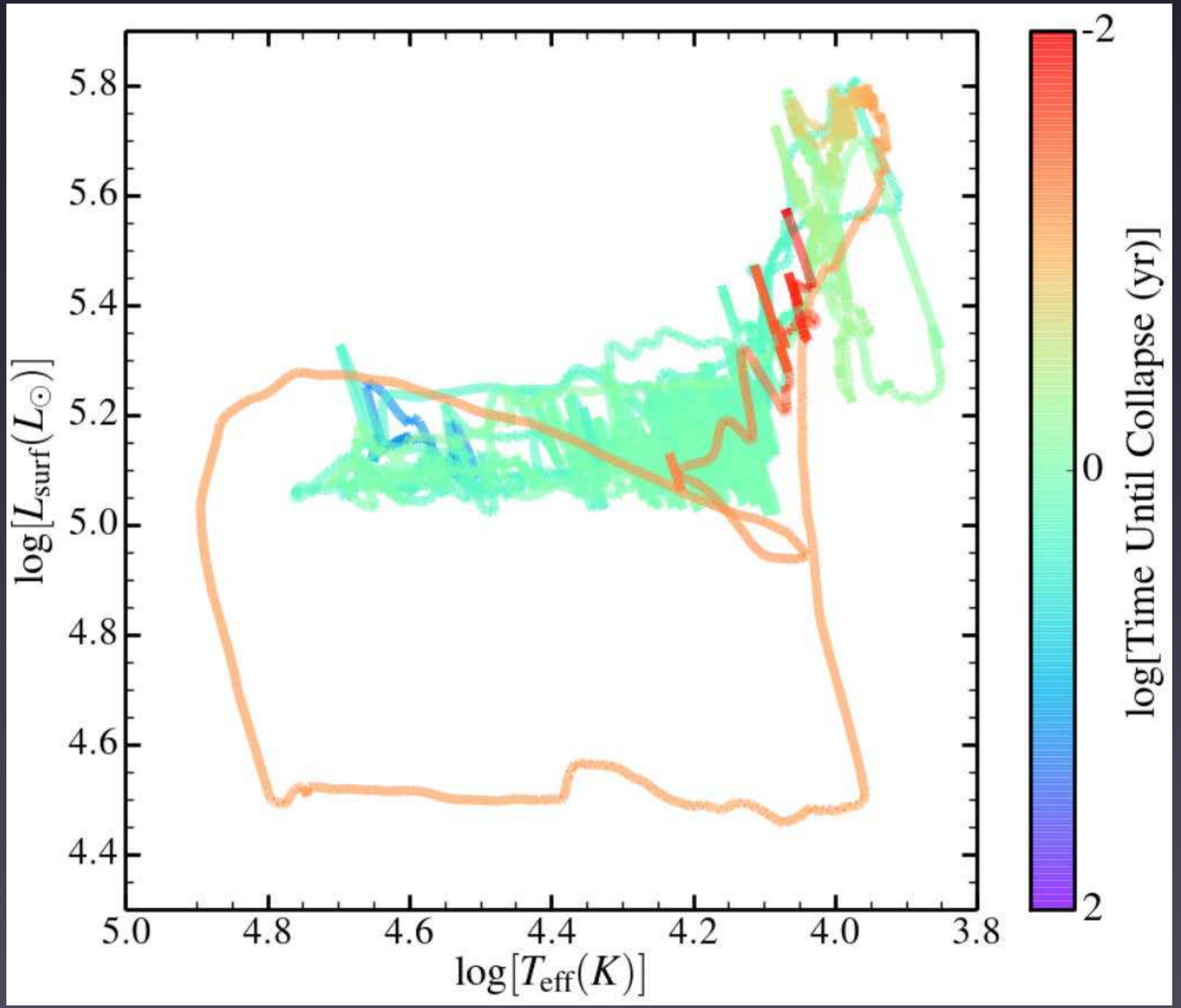
- At each time step, compute
  - Wave energy deposition rate per unit mass in stellar envelope

$$M_{\rm damp} = \frac{4\pi\rho r^2 c_s^3}{\omega^2 K} = \frac{3\pi\rho^3 r^2 c_s^3 c_p \kappa}{4\sigma_{\rm SB}\omega^2 T^3}$$

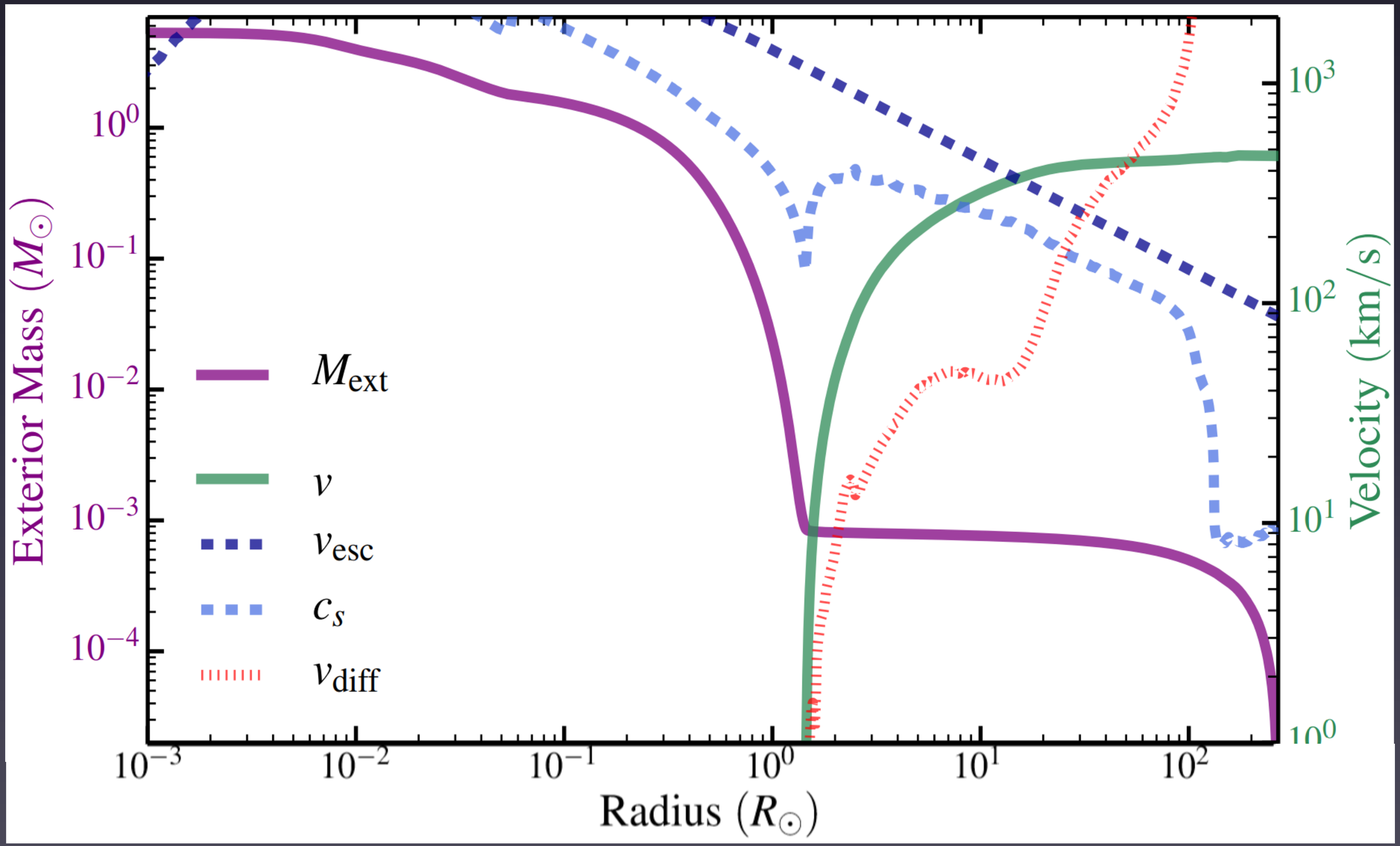
- Use hydrodynamic version of MESA to allow for high velocity flows



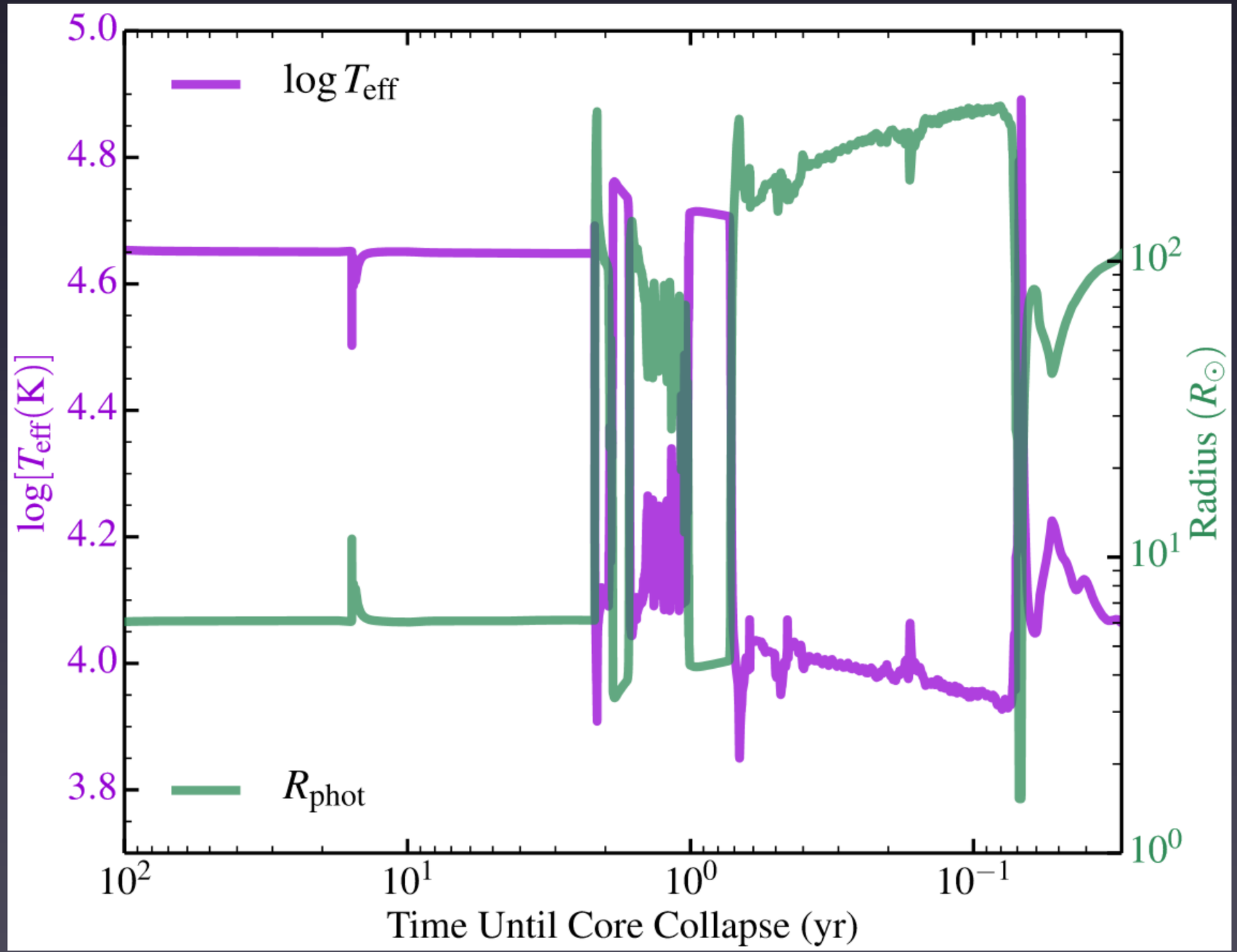
Fuller & Ro 2018



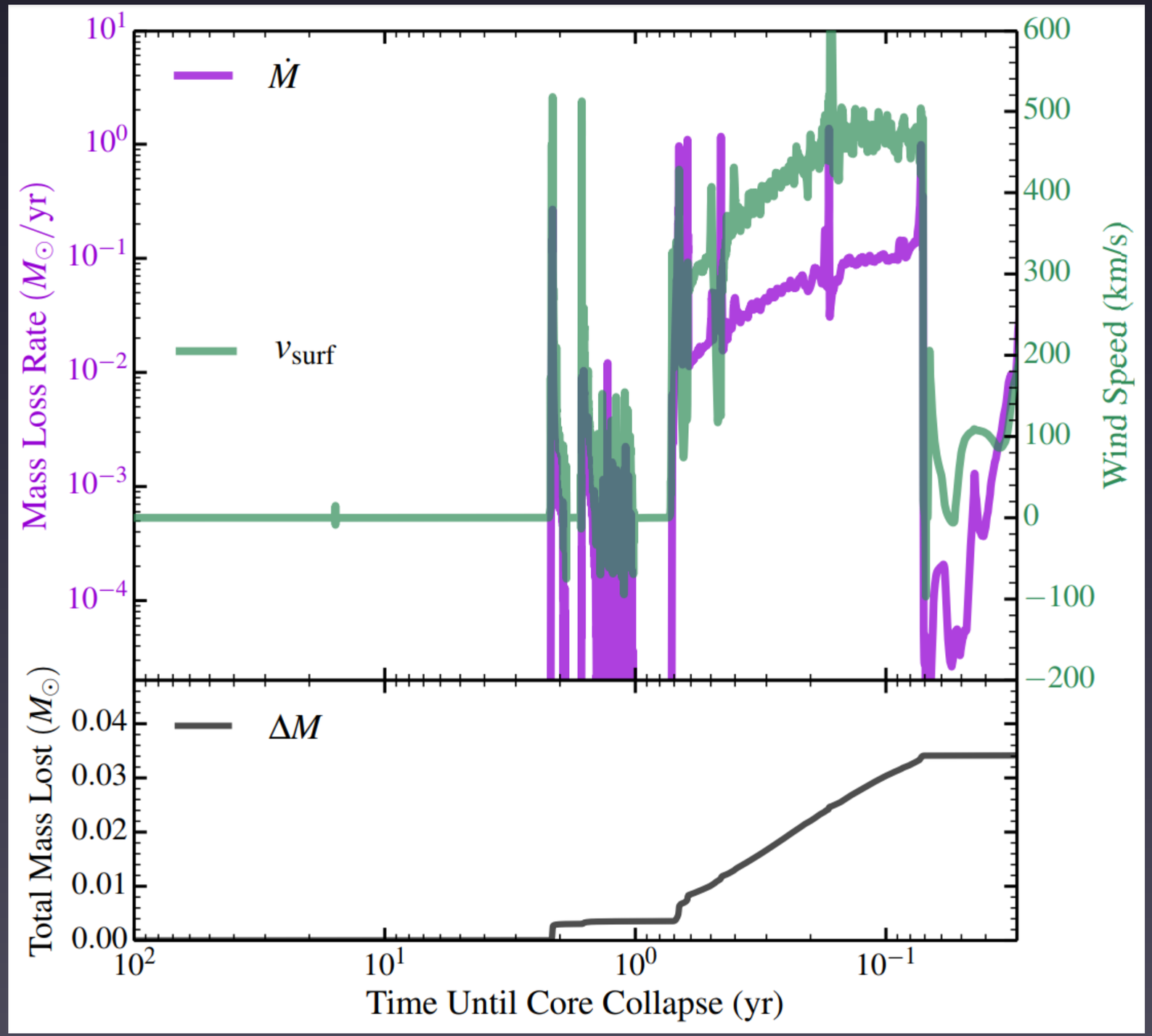
Fuller & Ro 2018



Fuller & Ro 2018



Fuller & Ro 2018



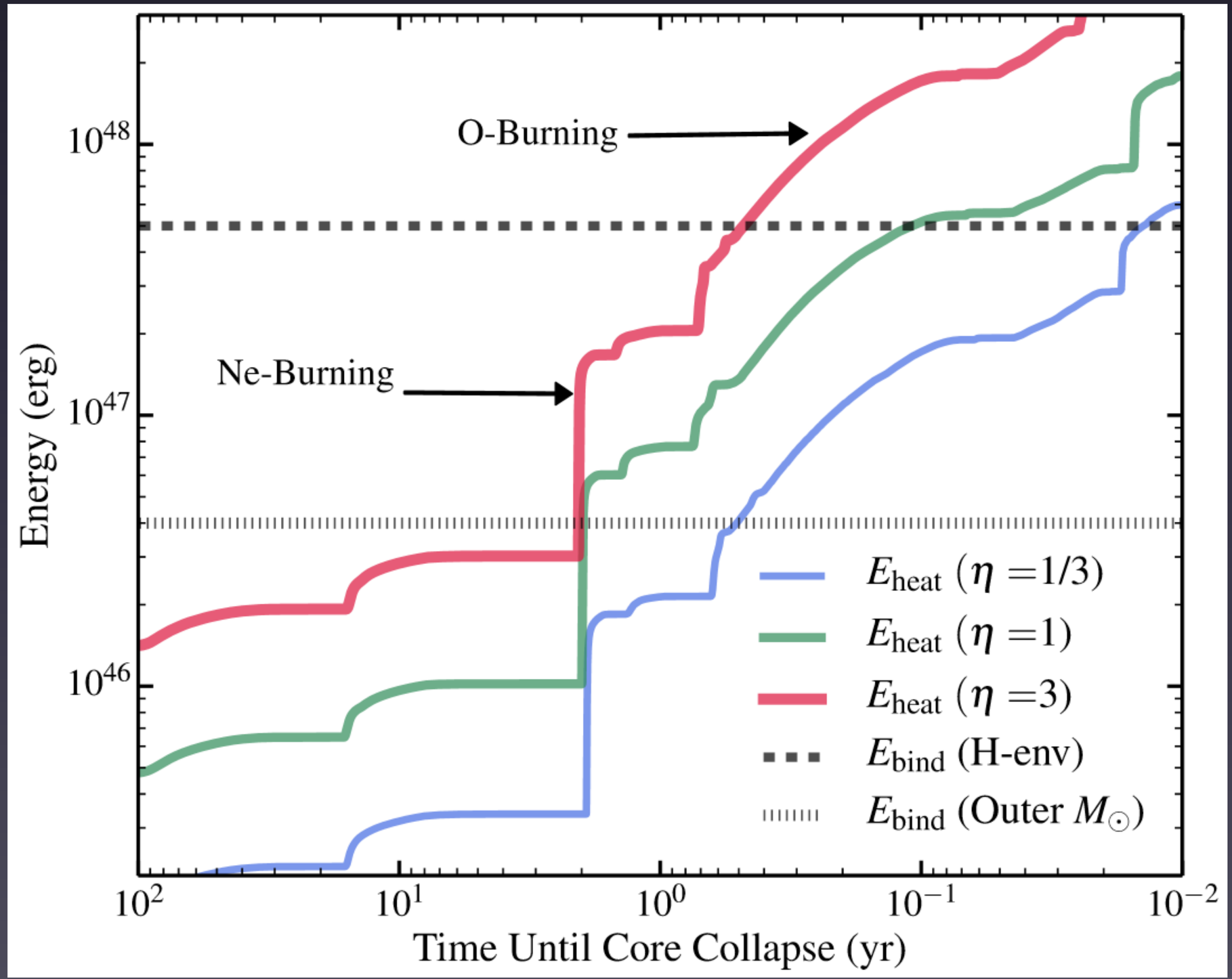
Fuller & Ro 2018

Hydrogen-rich stars

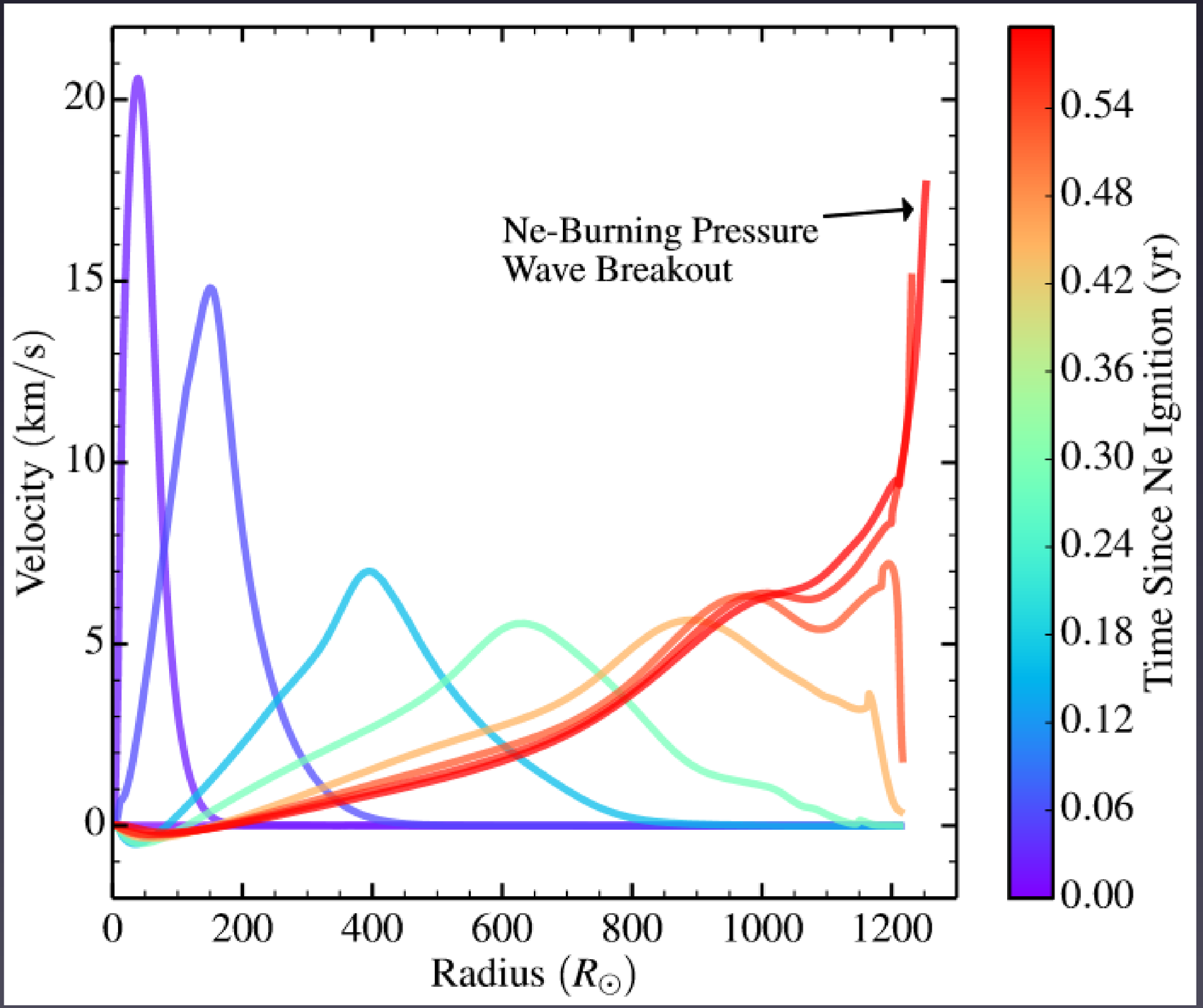
- Waves damp at base of H-envelope
- Wave heat launches acoustic pulse that expands surface layers



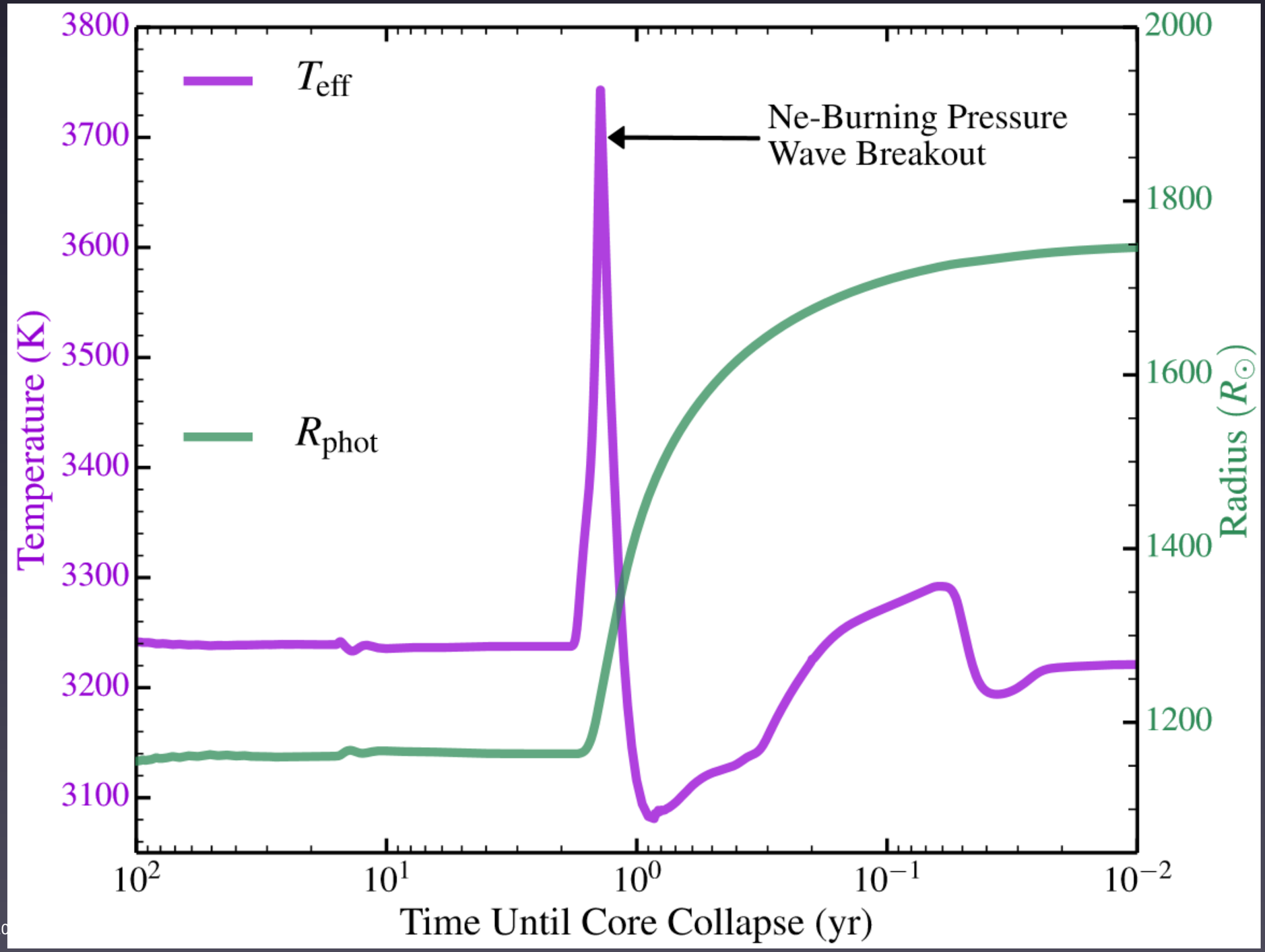
Fuller & Ro 2018


O-Burning
Ne-Burning
10^{48}
10^{47}
10^{46}
Energy (erg)
$E_{\rm heat}$ (η =1/3)
$E_{\rm heat}$ (η =1)
$E_{\rm heat}$ (η =3)
$E_{\rm bind}$ (H-env)
$E_{\rm bind}$ (Outer $M_\odot$)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
Time Until Core Collapse (yr)

Fuller 2017

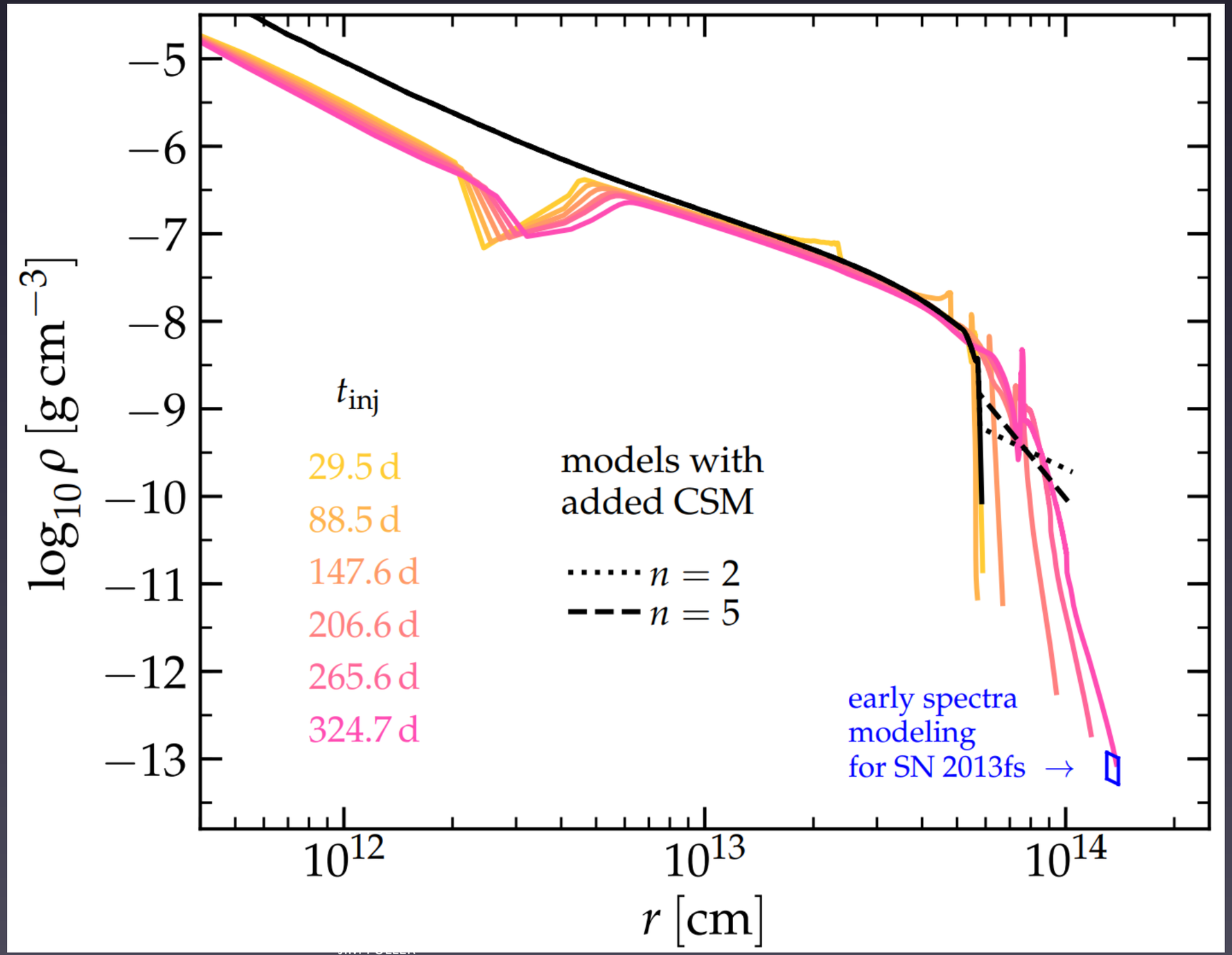

Ne-Burning Pressure
Wave Breakout
Velocity (km/s)
Radius ($R_\odot$)
Time Since Ne Ignition (yr)
0
5
10
15
20
0
200
400
600
800
1000
1200
0.00
0.06
0.12
0.18
0.24
0.30
0.36
0.42
0.48
0.54

Fuller 2017


$T_{\rm eff}$
$R_{\rm phot}$
Ne-Burning Pressure
Wave Breakout
Temperature (K)
Radius ($R_\odot$)
Time Until Core Collapse (yr)
3800
3700
3600
3500
3400
3300
3200
3100
2000
1800
1600
1400
1200
10^2
10^1
10^0
10^{-1}
10^{-2}

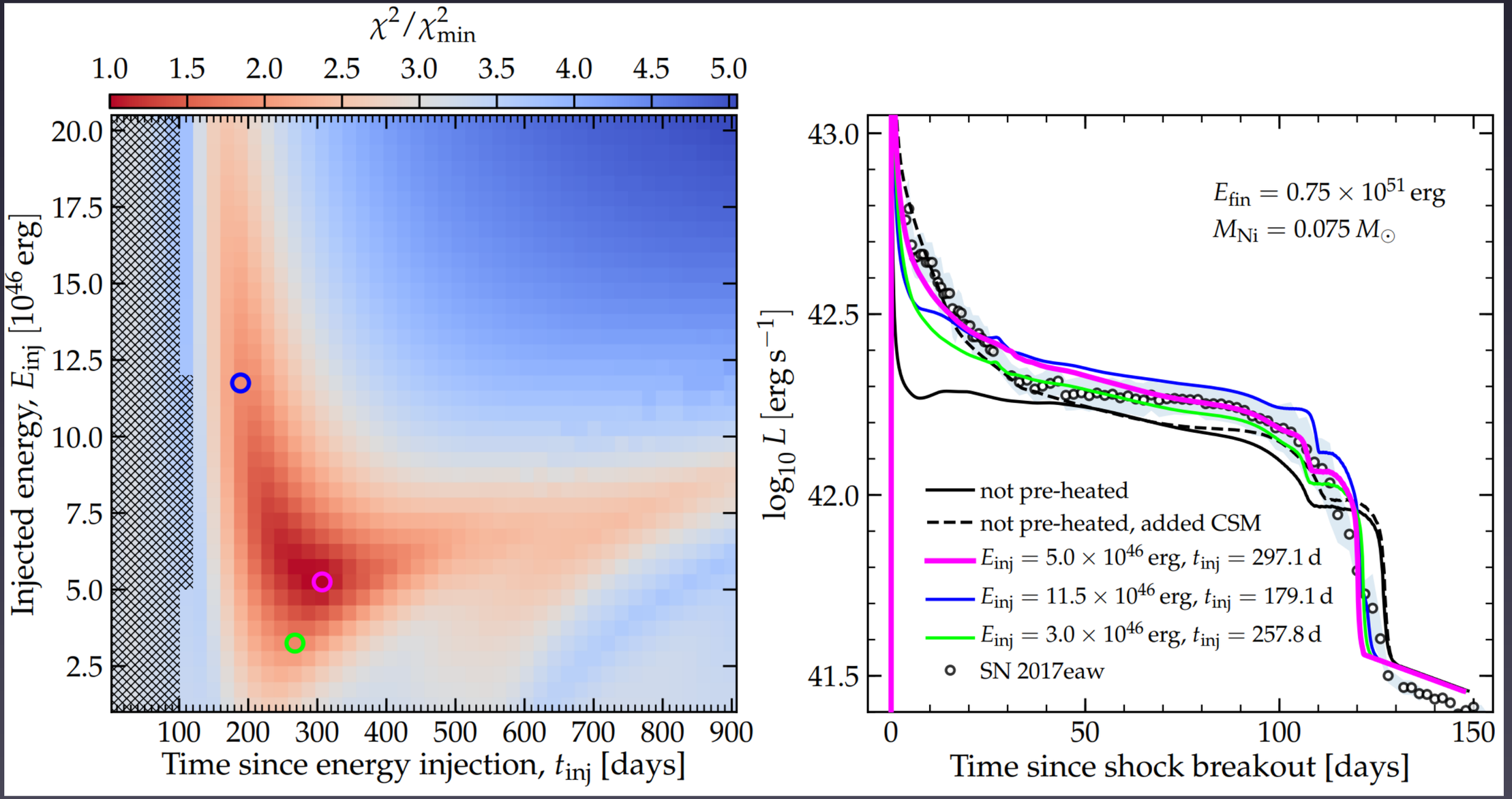
Fuller 2017

- Altered density profile



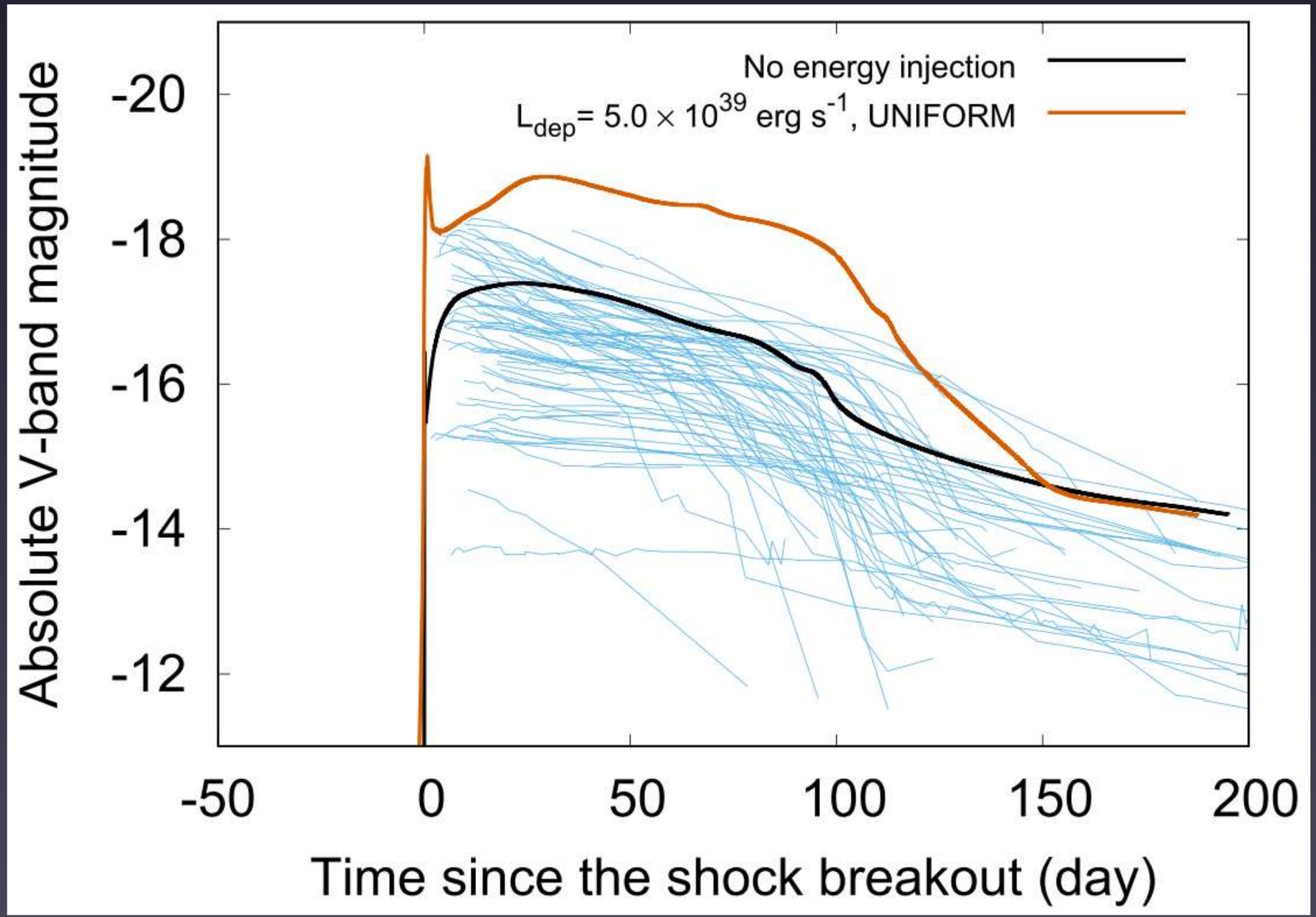
Morozova +, submitted

Effects on Supernova



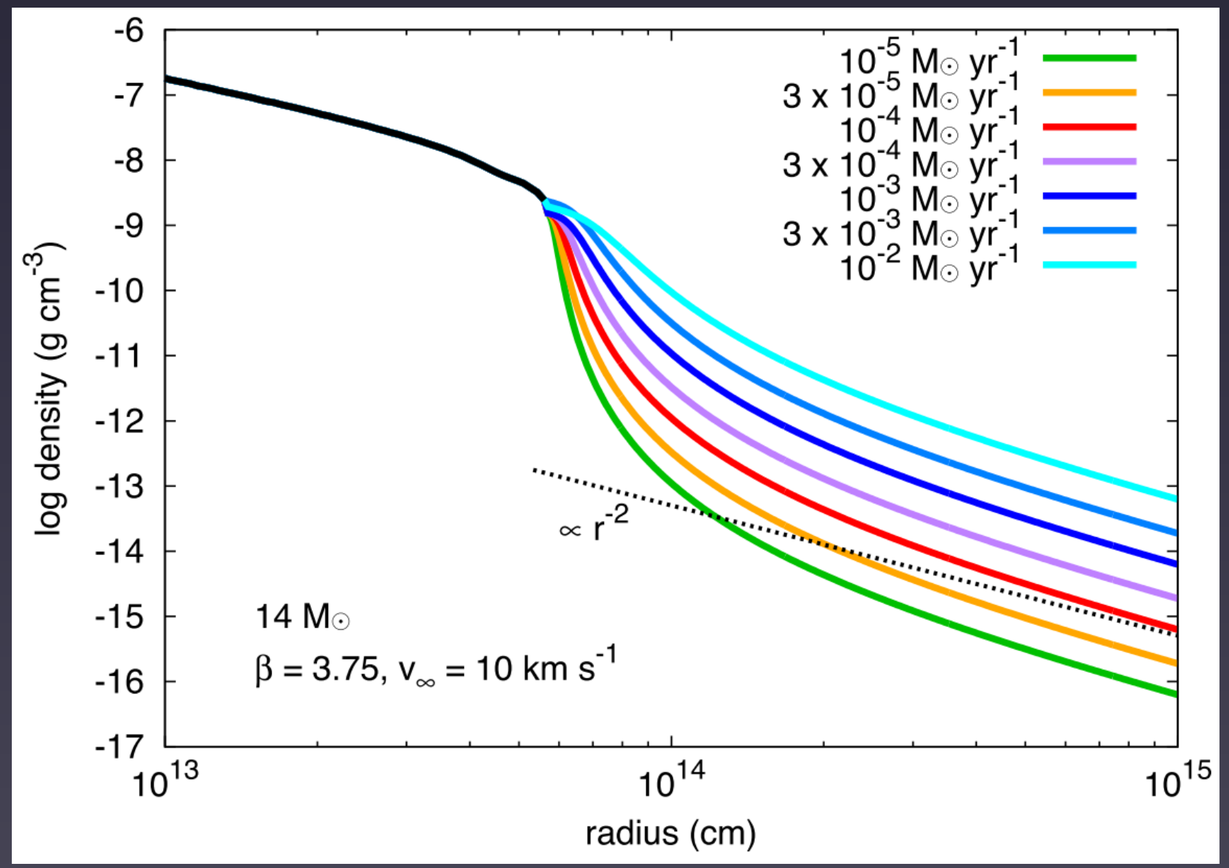
Morozova +, submitted

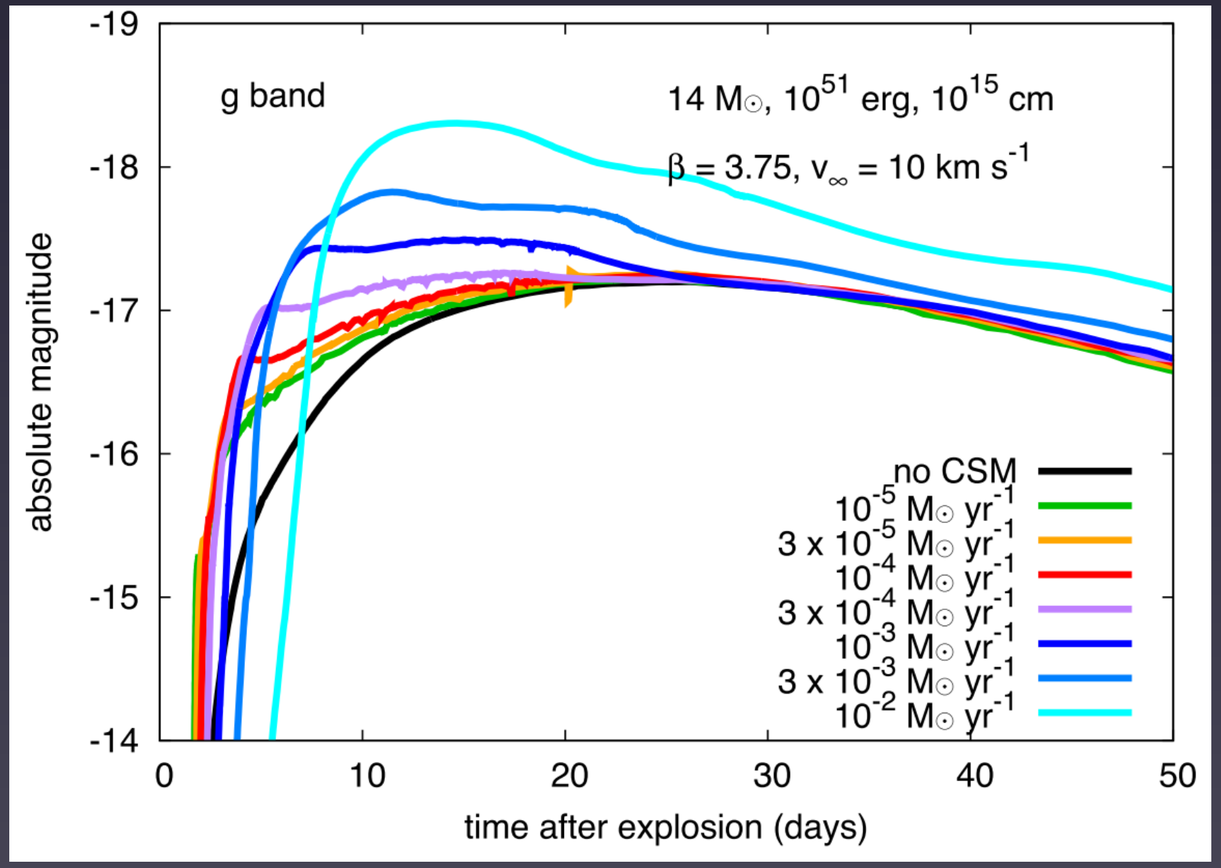
- Rate of energy deposition important
- Light curves inconsistent with gradual energy deposition



Ouchi & Maeda, 2019

Stellar corona or wind acceleration?

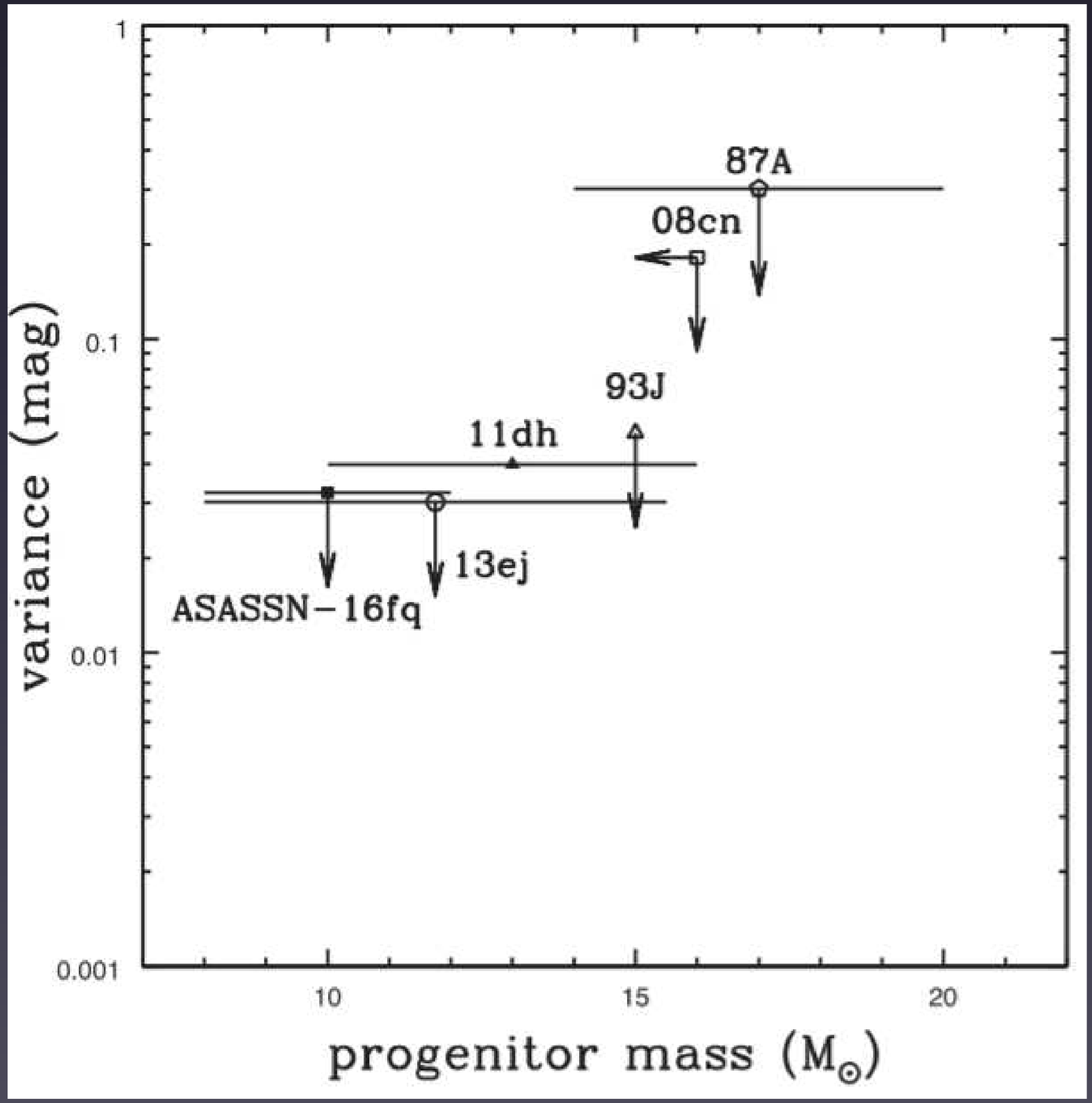




Moriya+ 2018

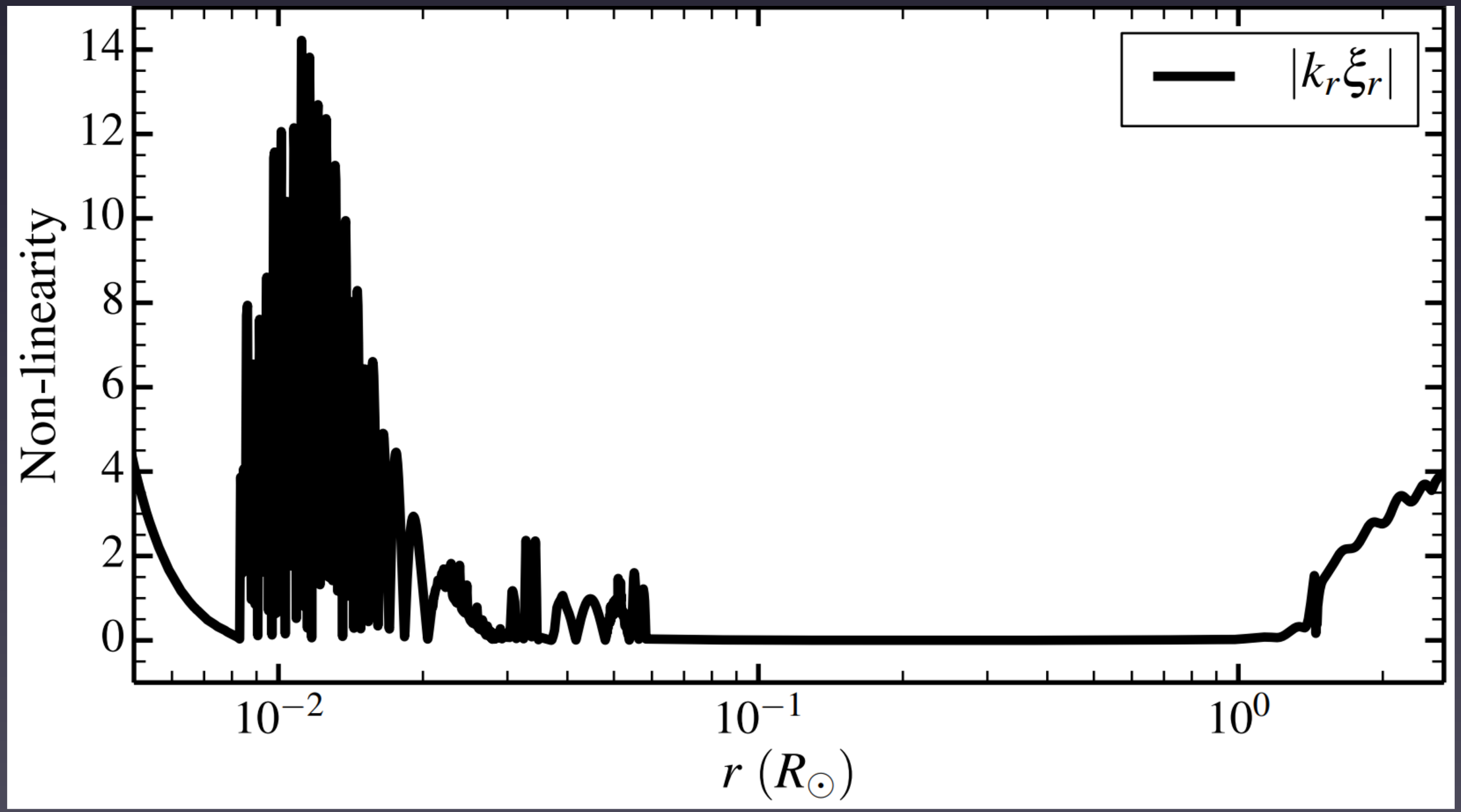
Variability of Progenitors

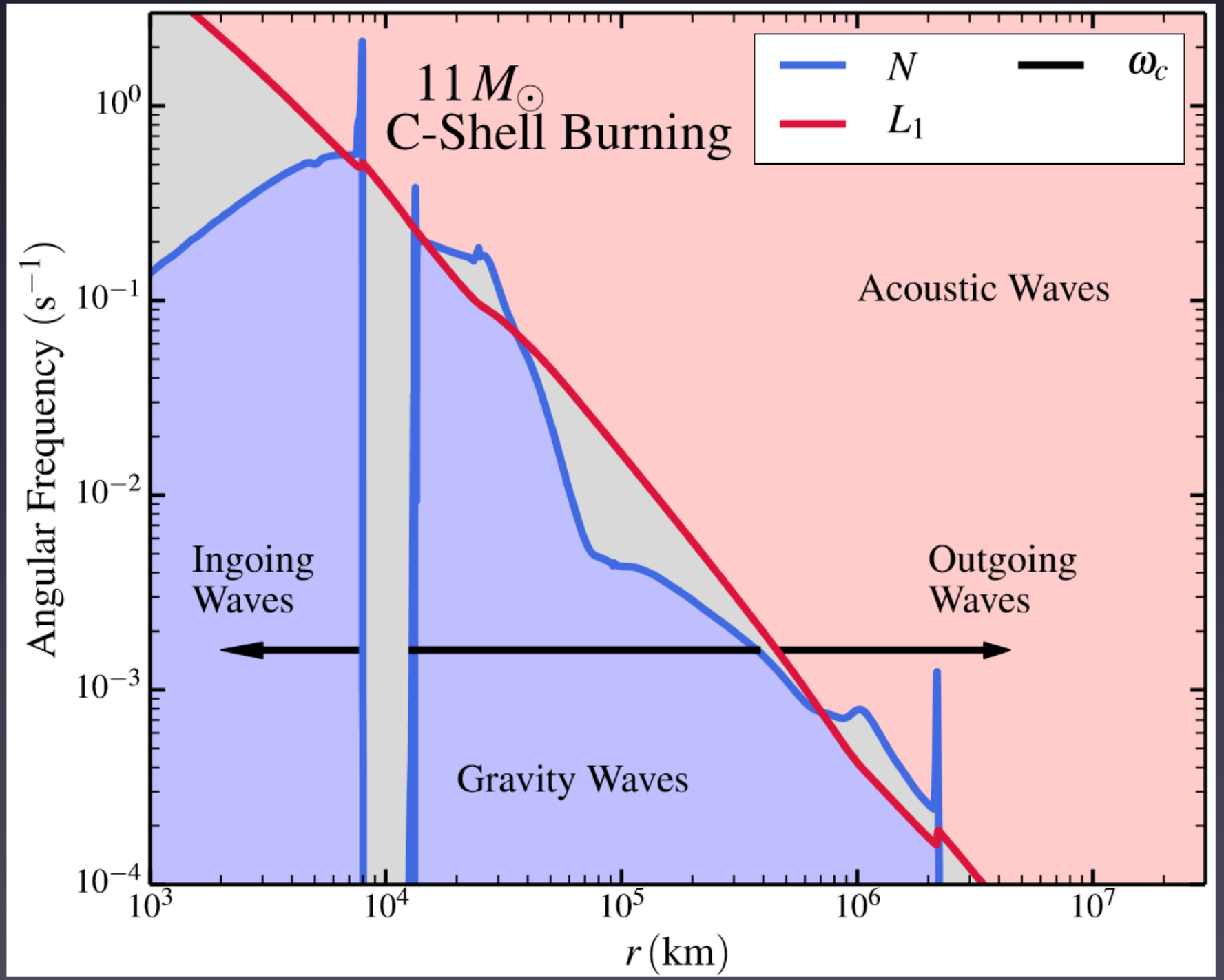
- Outbursts may be uncommon

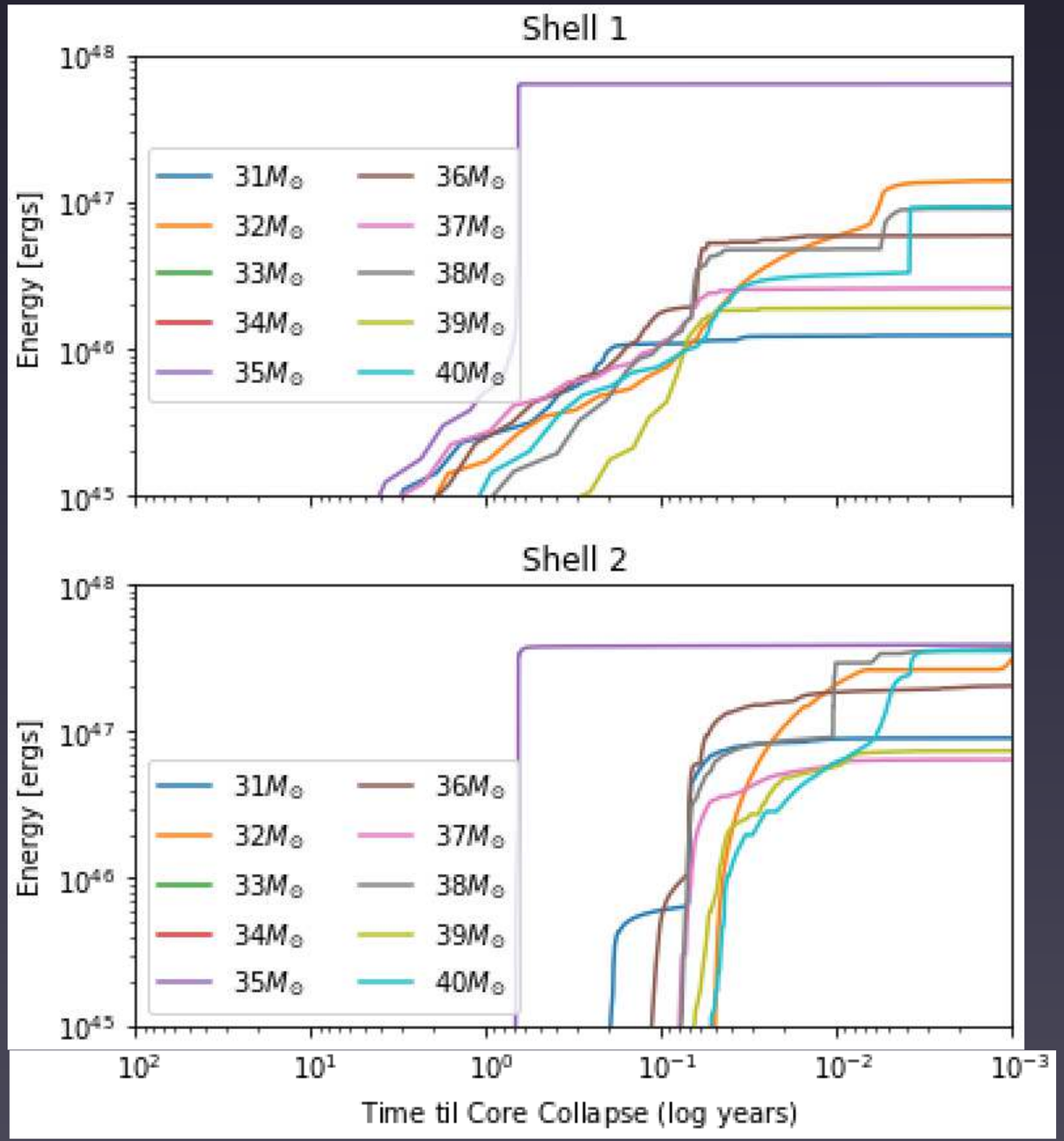


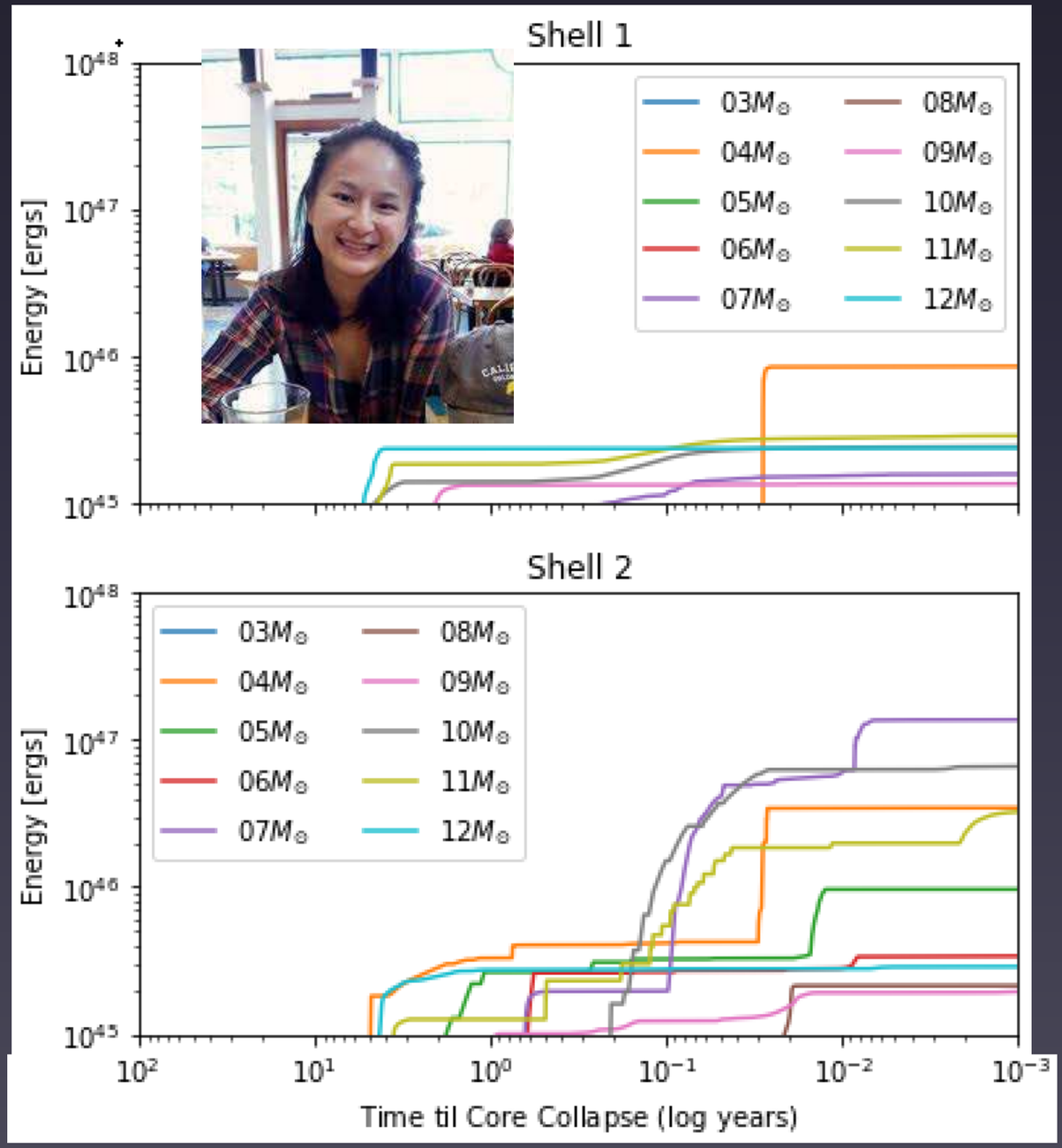
Kochanek et al. 2017

Problem: waves are non-linear



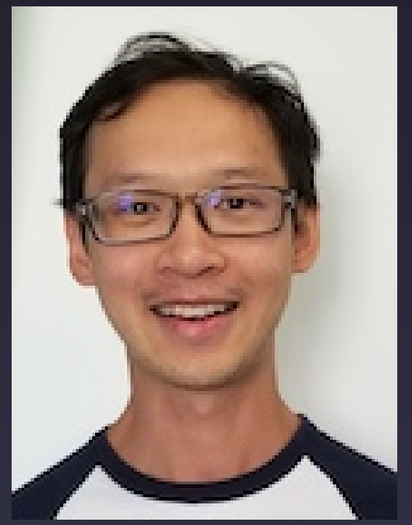

$11\,M_\odot$
C-Shell Burning
N
ω_c
L_1
Acoustic Waves
Ingoing
Waves
Outgoing
Waves
Gravity Waves
Angular Frequency (s^{-1})
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^3
10^4
10^5
10^6
10^7
$r\,(\mathrm{km})$

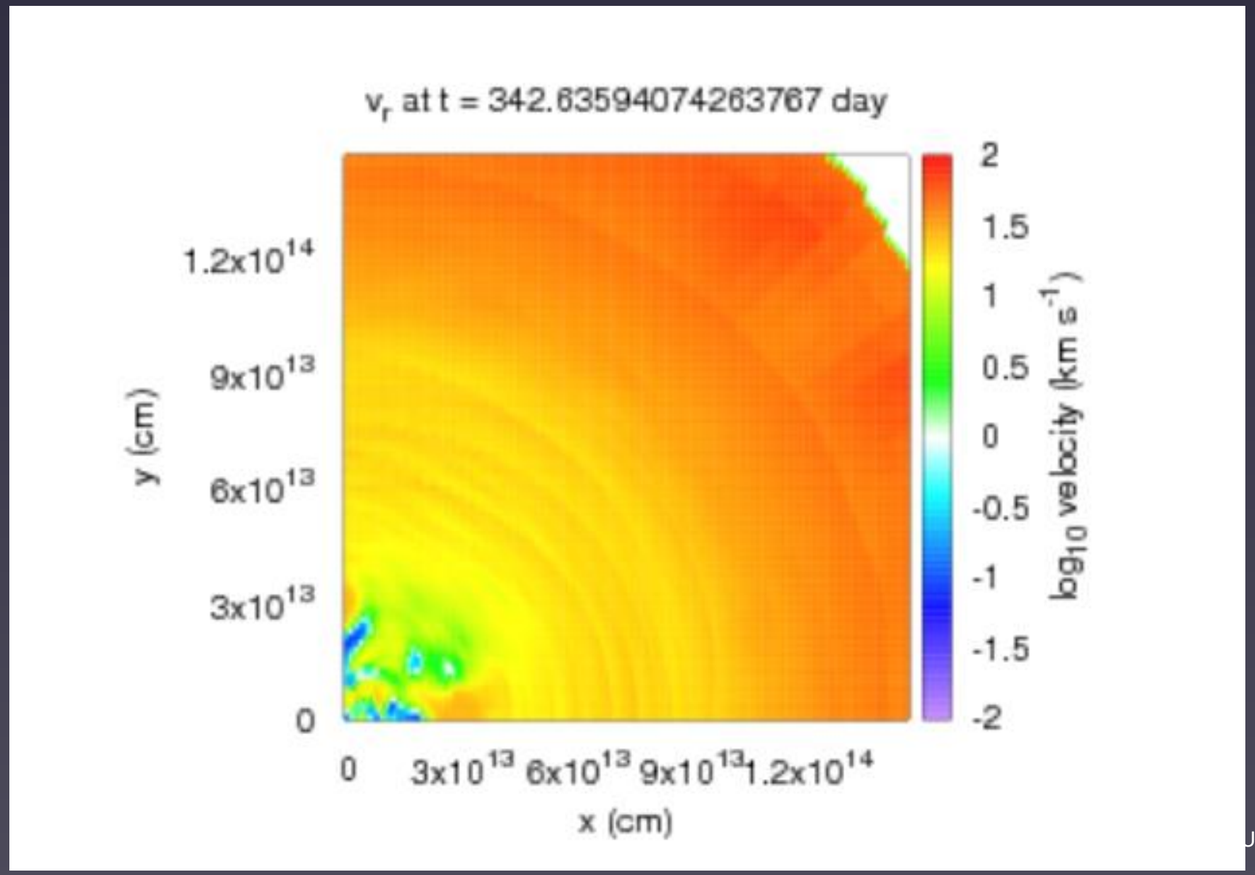


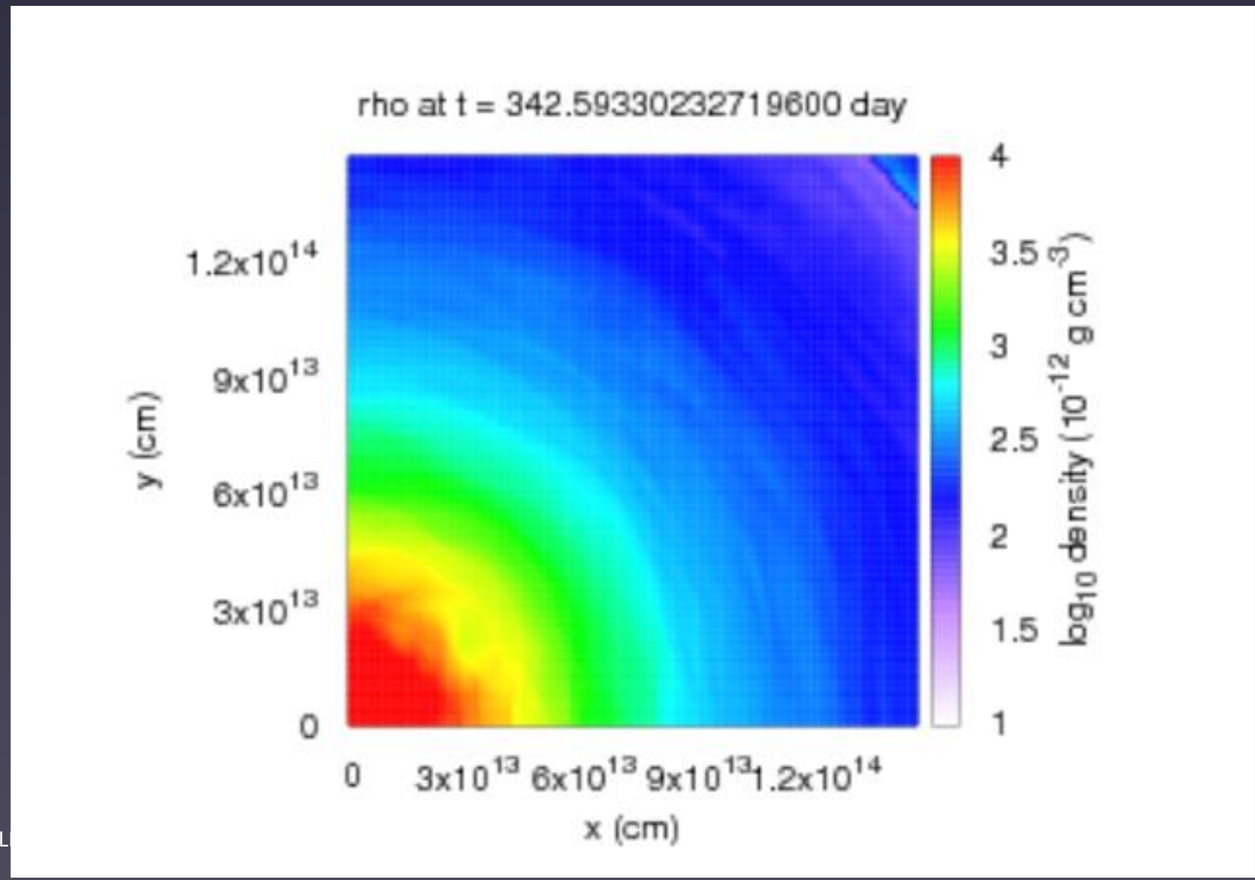


Wu & Fuller, in prep

Simulating Outbursts







Wave-driven Phenomena

- Wave heating in may cause pre-SN outbursts
  - Wave heating unlikely to lead to most luminous Type IIn Sne
- Wave heating is good candidate to create:
  - Flash-ionized SNe
  - Type II-L SNe
  - Type Ibn and transitional Ib/IIn Sne
  - Fast Blue Optical Transients (FBOTs)
- Unlikely to substantially alter core structure (binding energy ~10^{51} erg)

Caveats

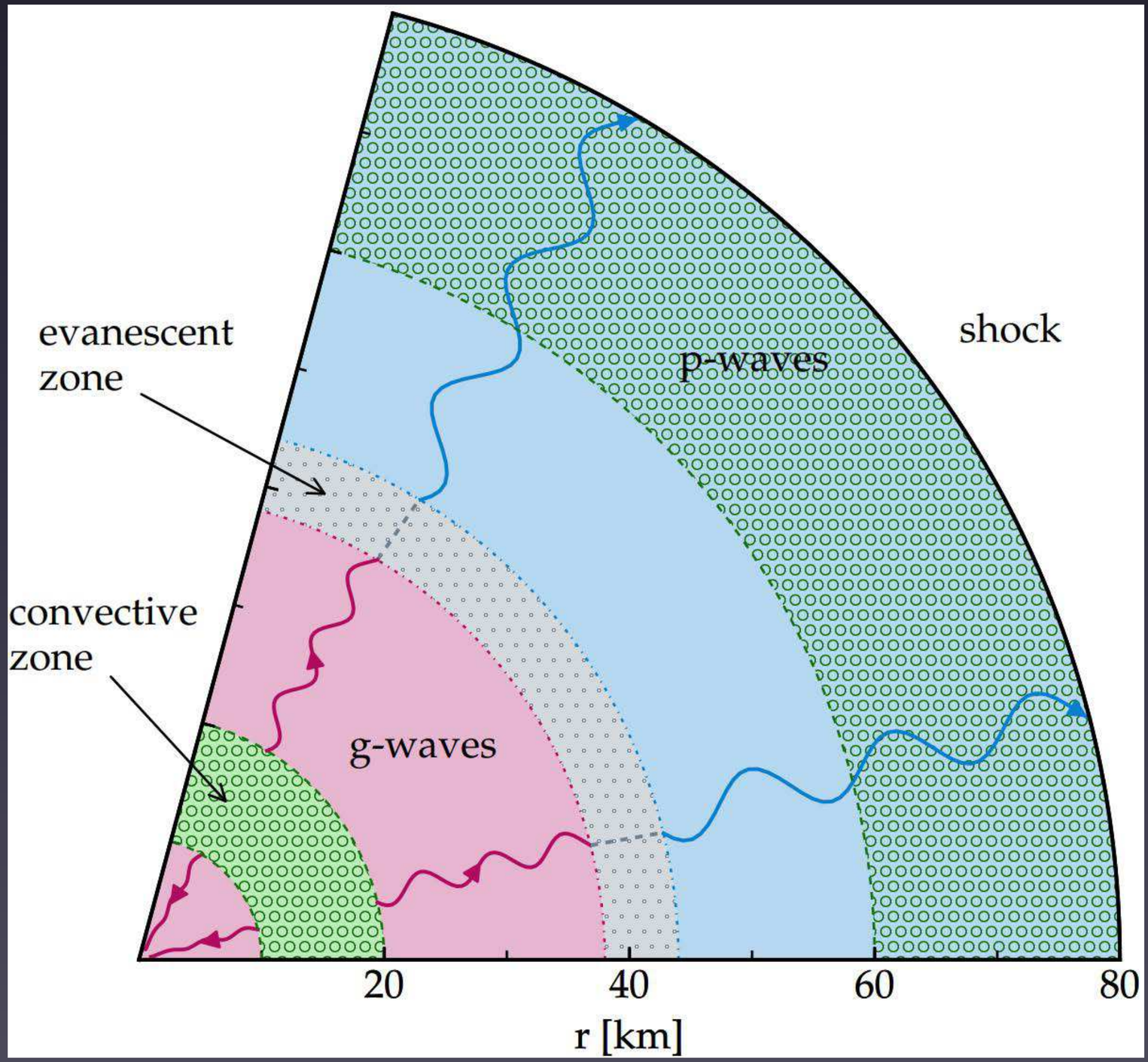
- Wave excitation very uncertain
  - Amplitude, frequency, and wavenumber spectrum needs to be included
- Non-linear effects may damp wave energy in core
- Convective response to wave heating is uncertain
  - How fast can envelope convection accelerate in response to wave heating?

Gravity waves can help stars explode

- Neutron star binding energy converted to explosion energy via wave energy transport

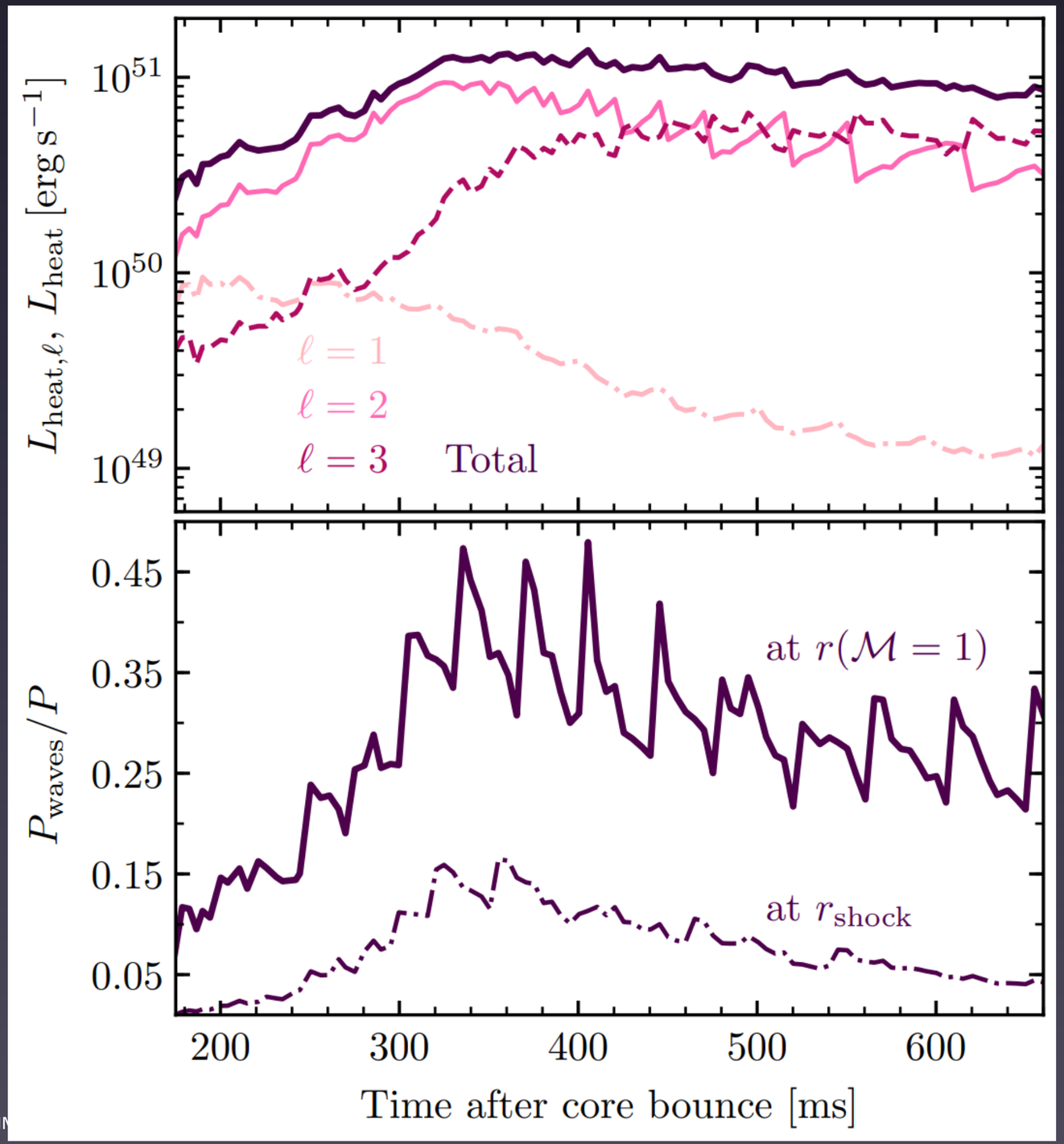


Gossan, Fuller, & Roberts 2019



Wave Energetics

- Waves can deliver ~10^{51} erg of energy to gain region
- Can contribute > 10% of pressure on shock



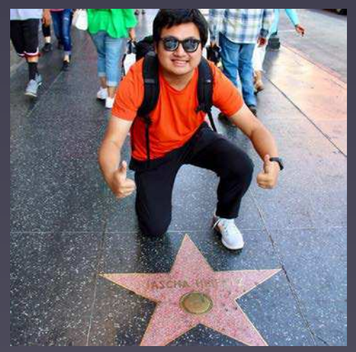
Gossan, Fuller, & Roberts 2019

The Spin of Stellar Cores

- Cores contract and spin up, generating shear
- MHD Instabilities transport angular momentum, slowing rotation of the core
- Determines spins of compact objects







Asteroseismology to the Rescue

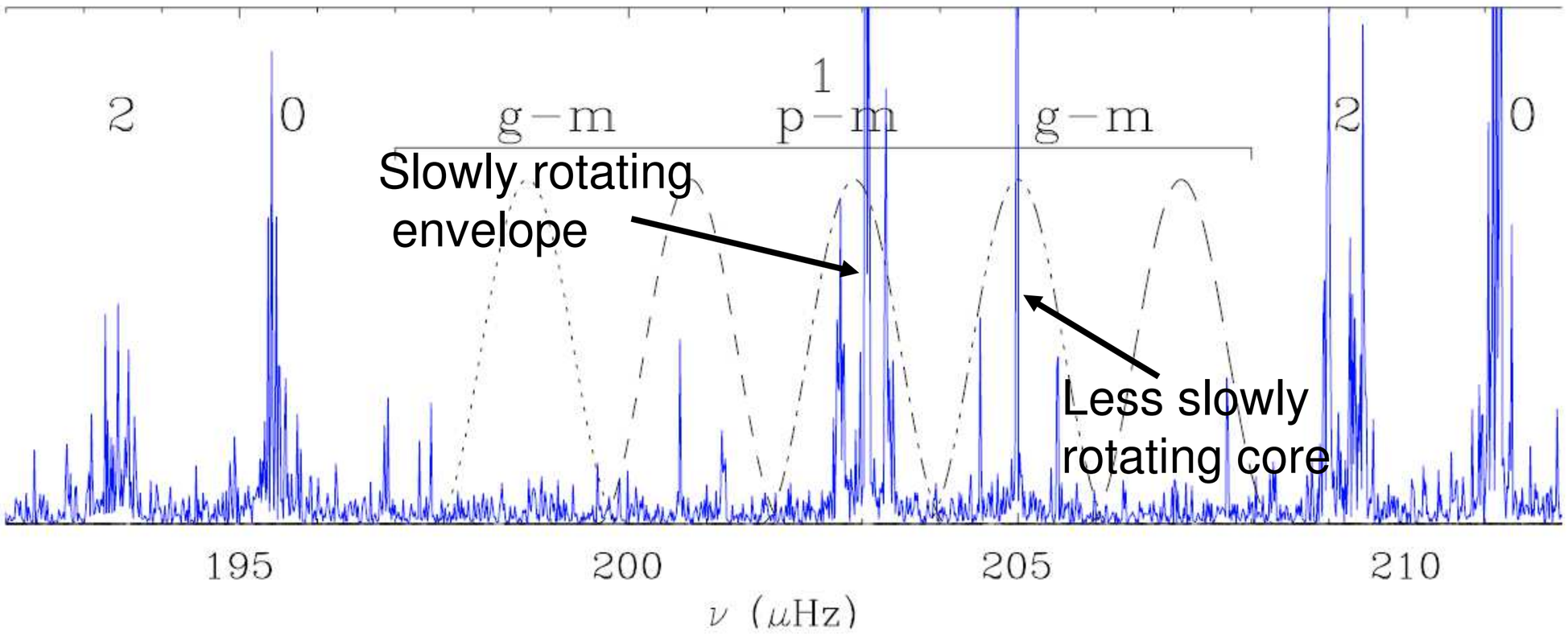
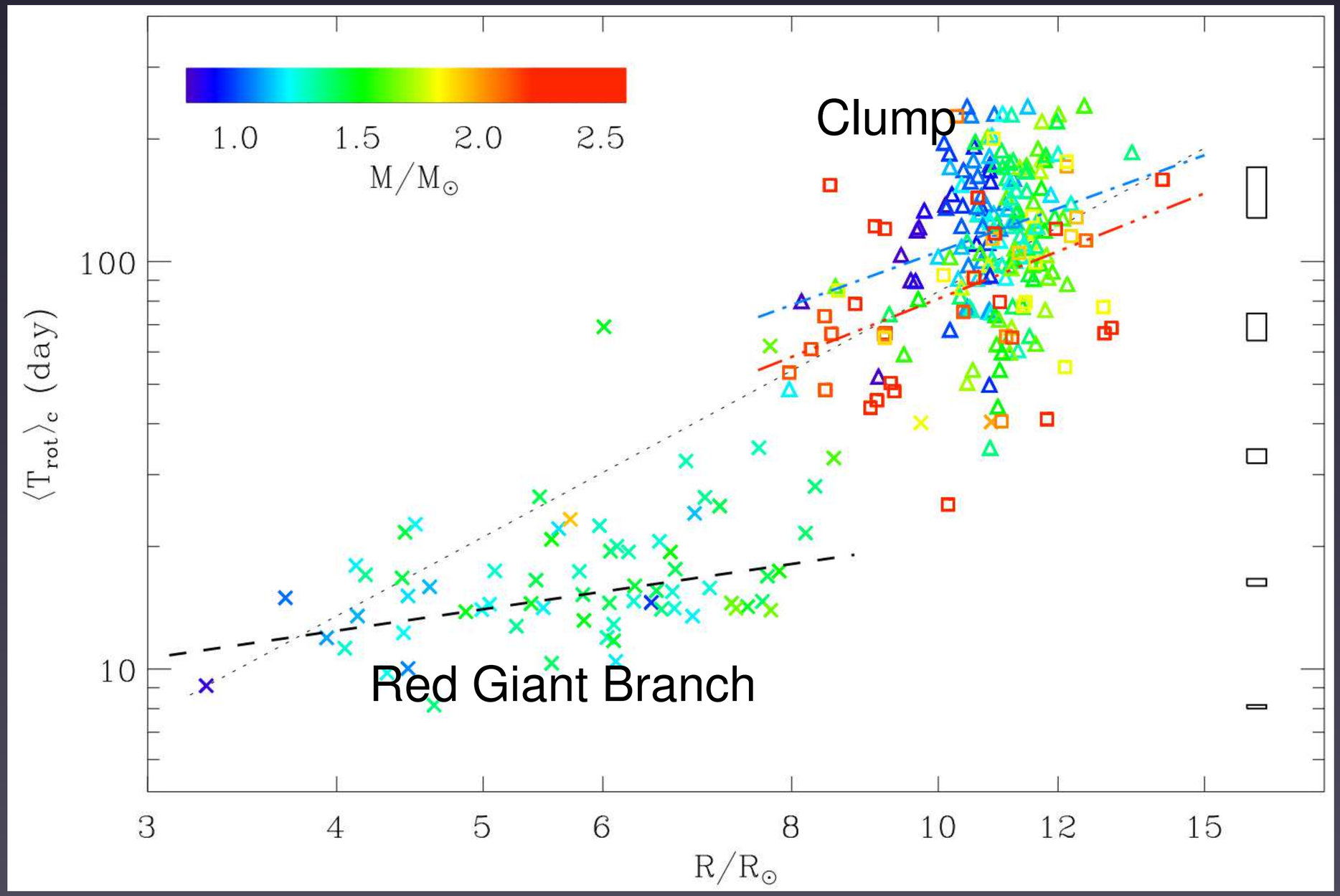


Fig. 3. Zoom on the oscillation spectrum of the target KIC 10777816. Different narrow filters centered in the $\ell = 1$ mixed mode range, indicated with different line styles, allow us to measure a local rotational splitting in each filter. For clarity, only those filters centered on possible multiplets have been represented.

Mosser et al. 2012

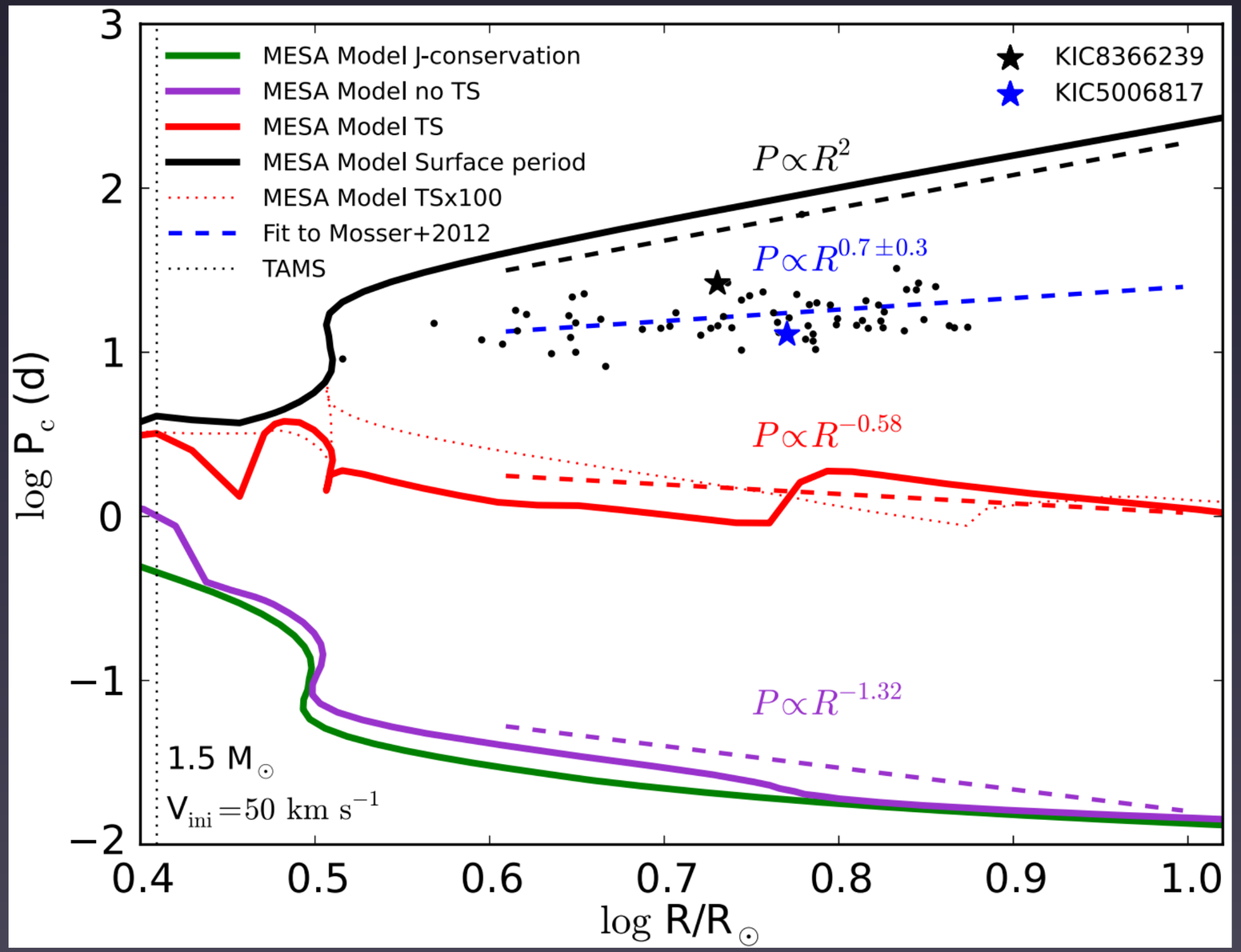
Asteroseismic Spin Rates



Mosser et al. 2012

AM transport: failure of theory

- Hydrodynamic instabilities hopeless
- MRI suppressed by stable stratification
- Tayler-Spruit dynamo provides most AM transport, but is suppressed by composition gradients



Cantiello et al. 2014

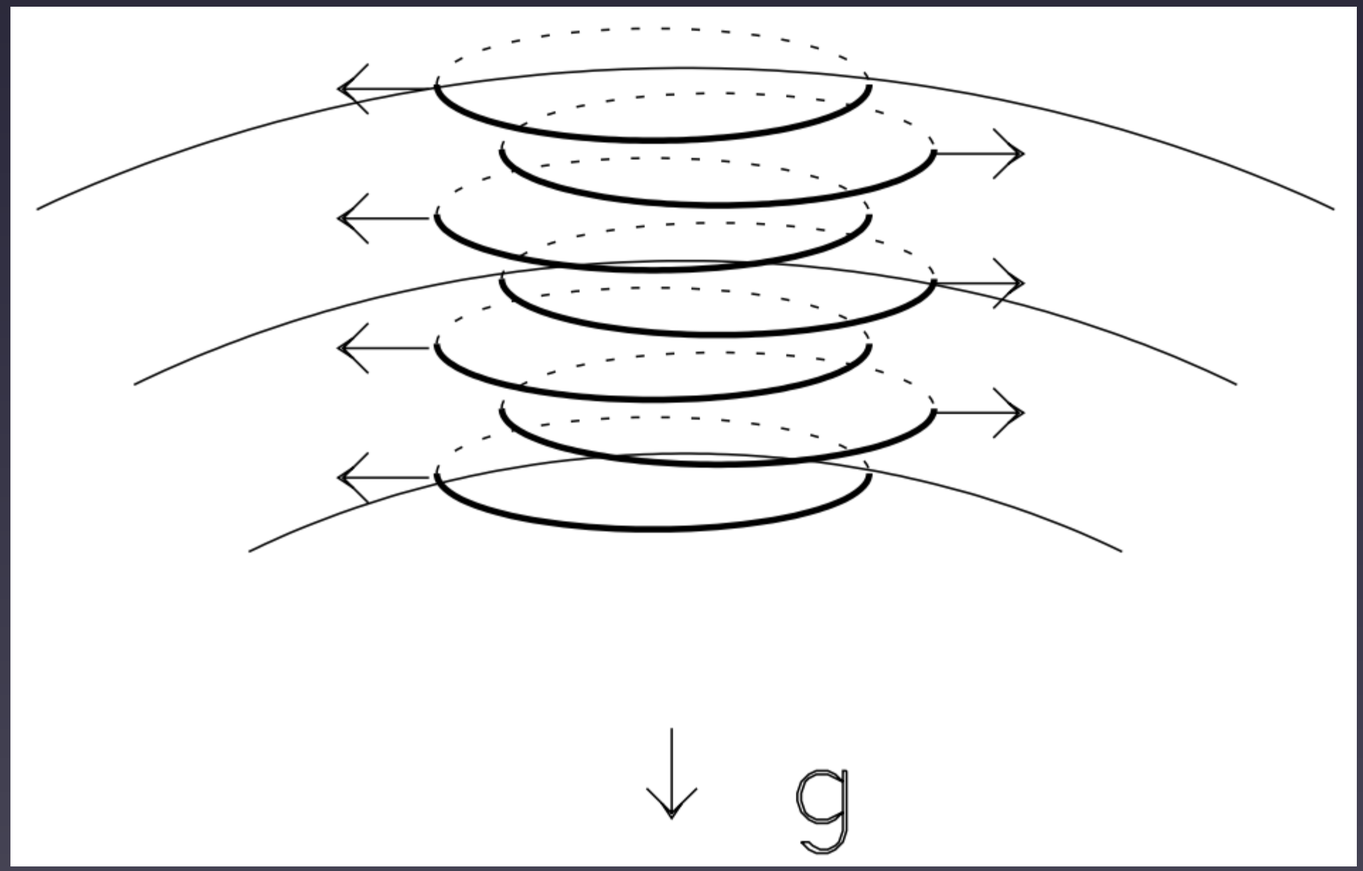
Tayler-Spruit Dynamo

- Weak radial magnetic field wound up by differential rotation
- Toroidal field slips sideways, regenerates radial field
- According to Spruit 2002, instability creates net torque

$$\nu_{\rm e0} = r^2 \Omega q^2 \left(\frac{\Omega}{N} \right)^4$$

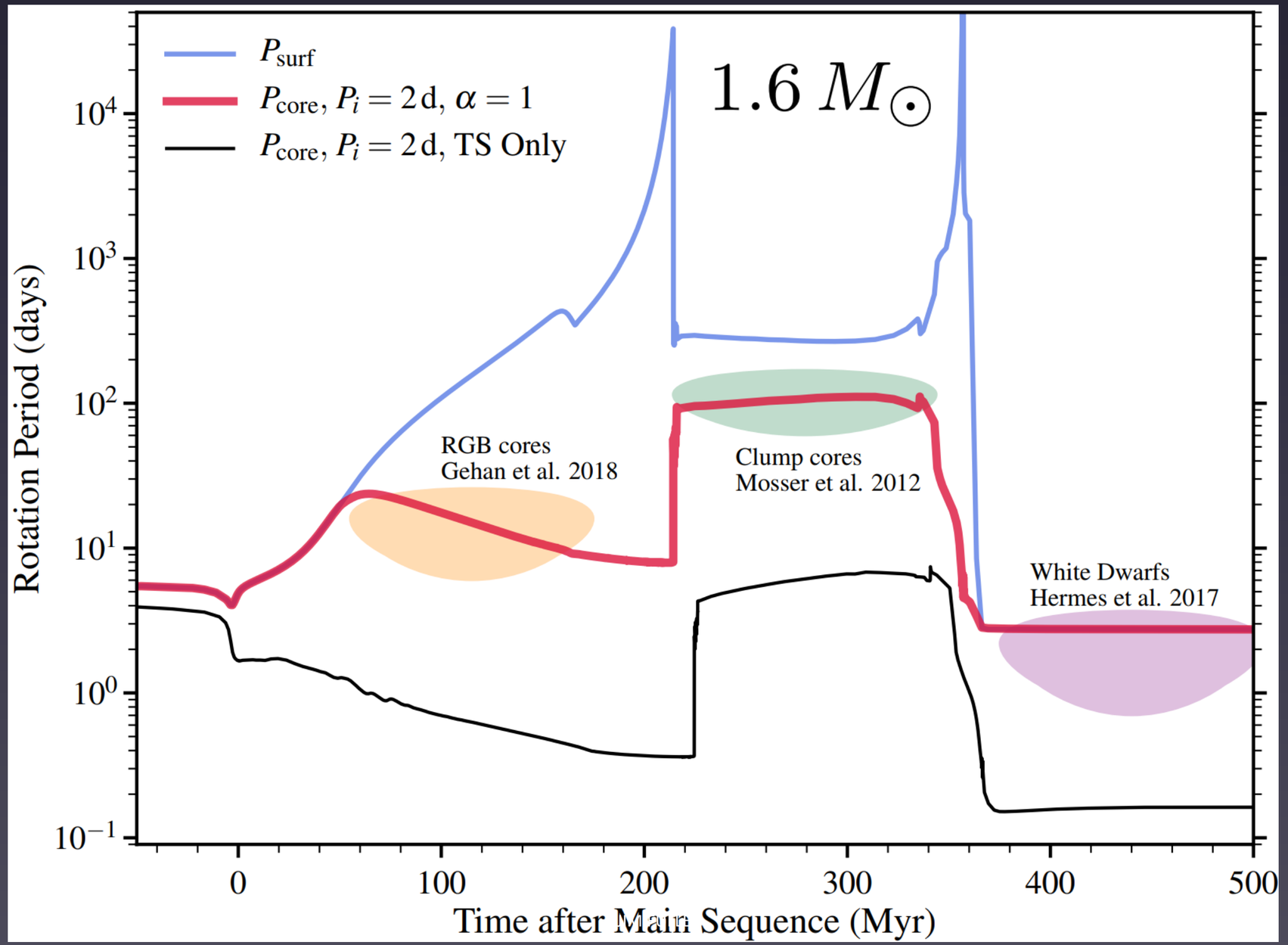
- Updated prediction:

$$\nu_{\rm AM} = \alpha^3 r^2 \Omega \left(\frac{\Omega}{N_{\rm eff}} \right)^2$$



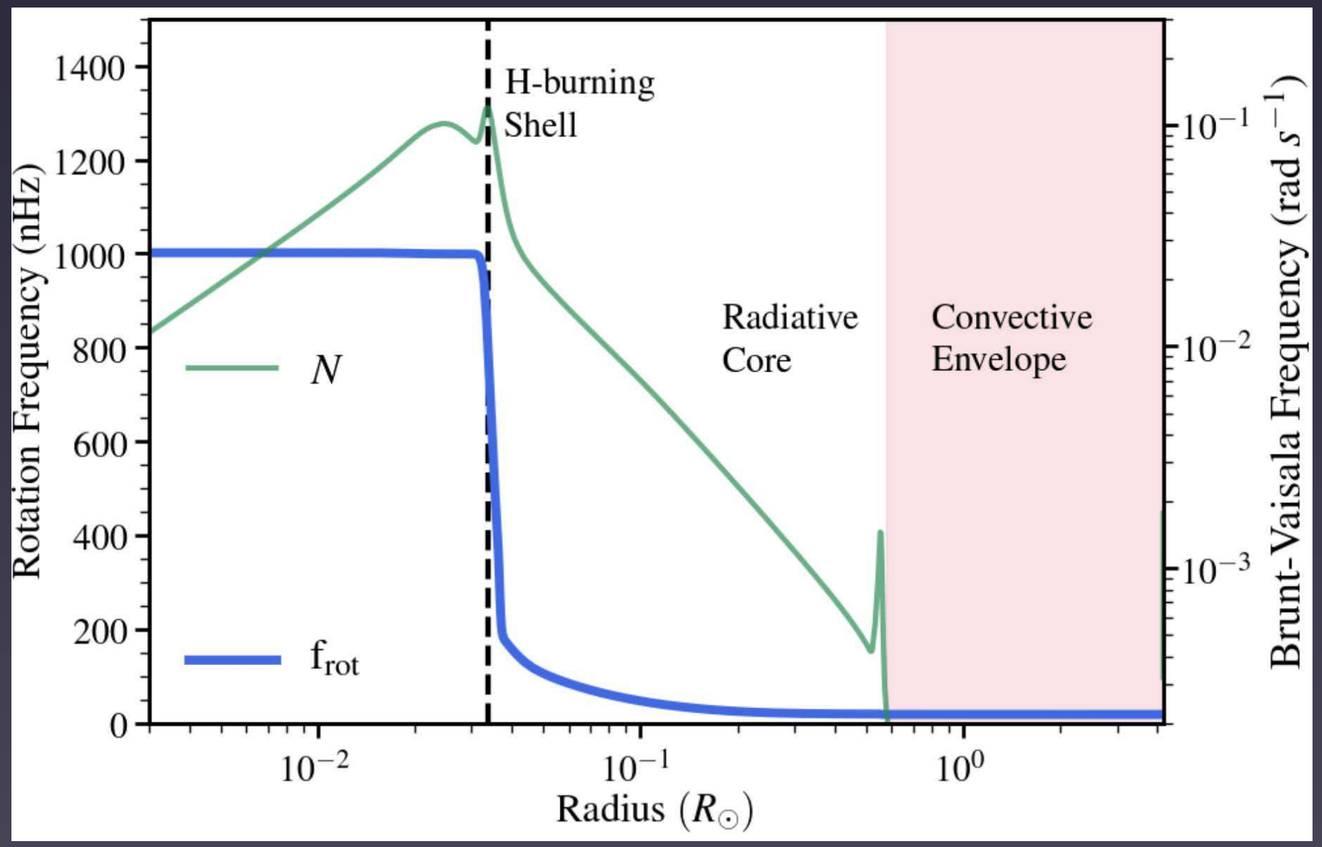
Spruit 1999

Rotational Evolution

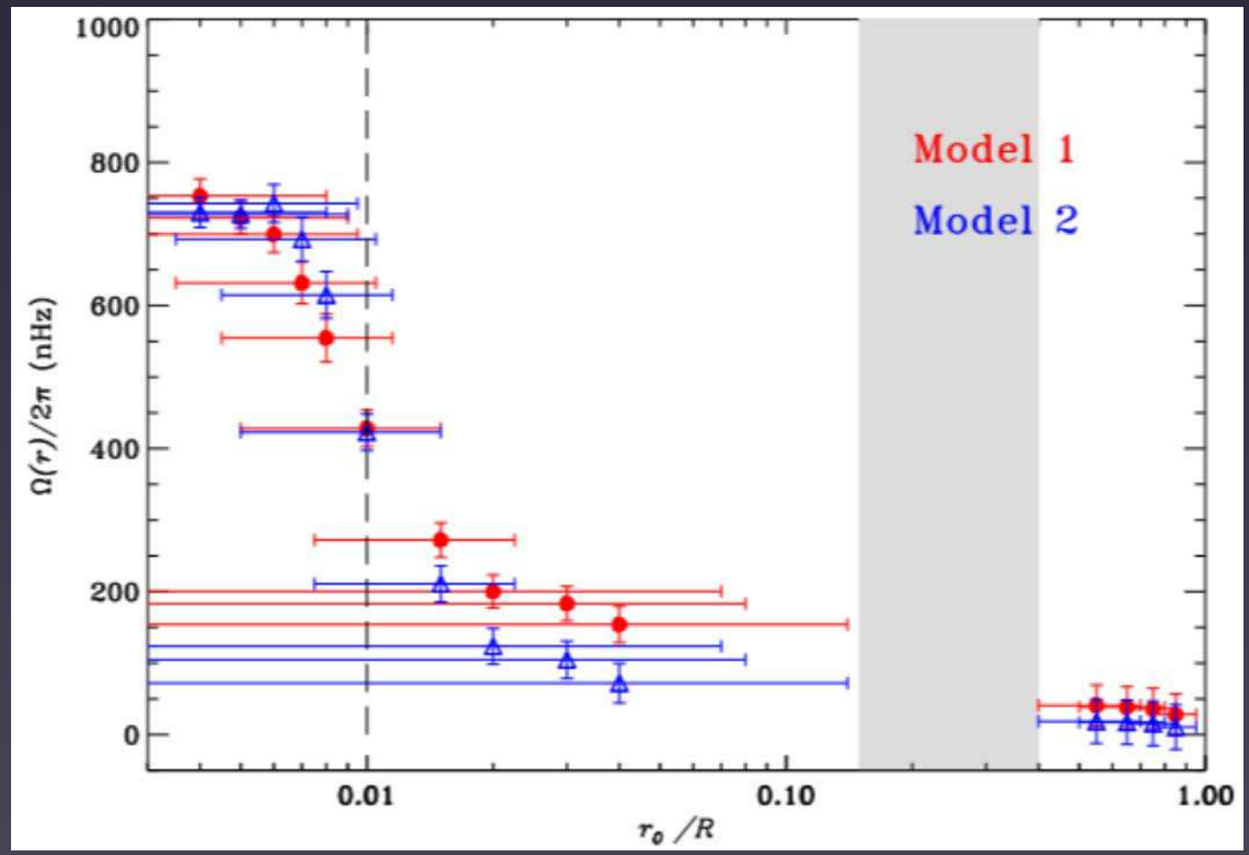


Fuller+ 2019

Rotation Profile



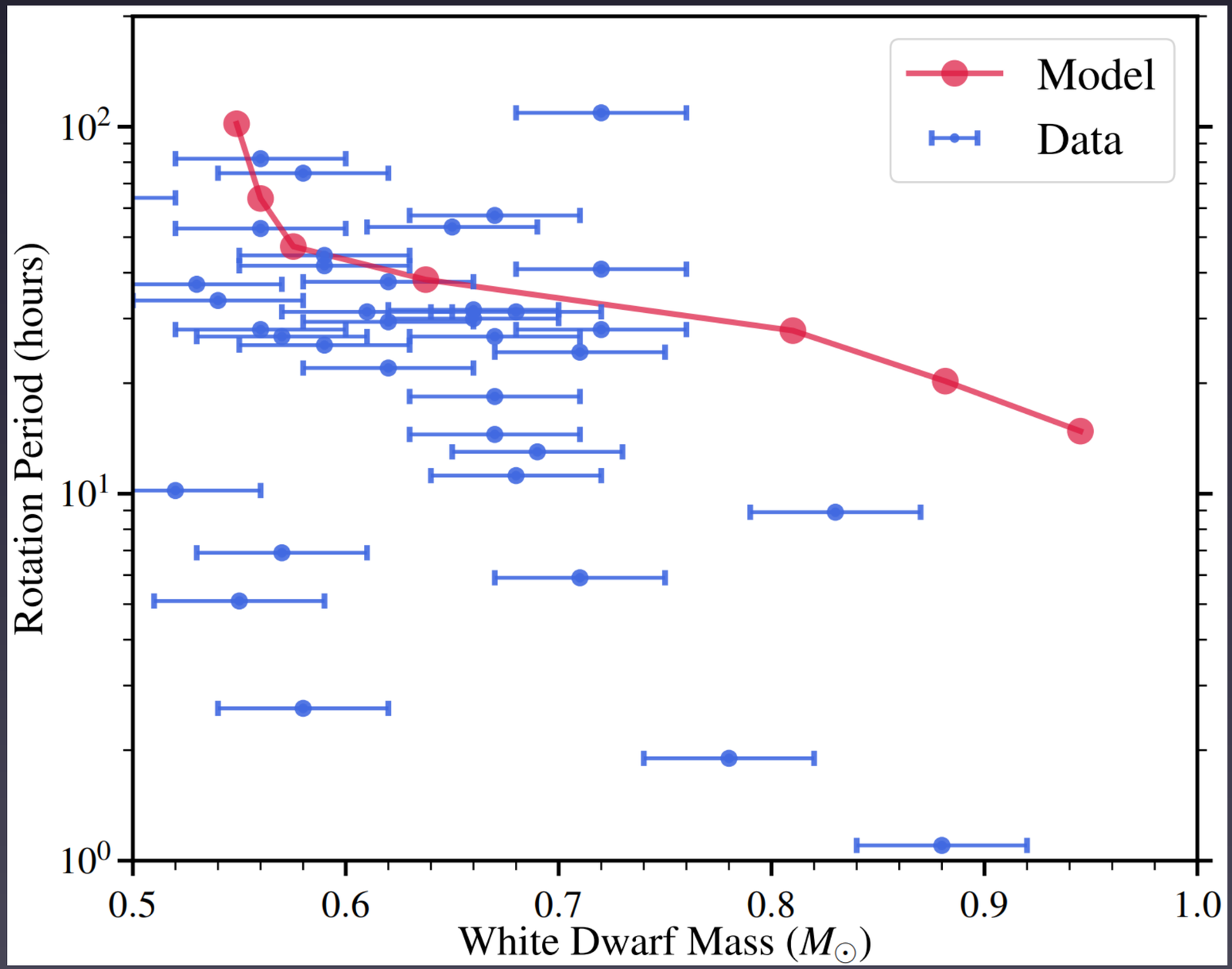
Fuller+ 2019



Di Mauro et al. 2017

White Dwarfs

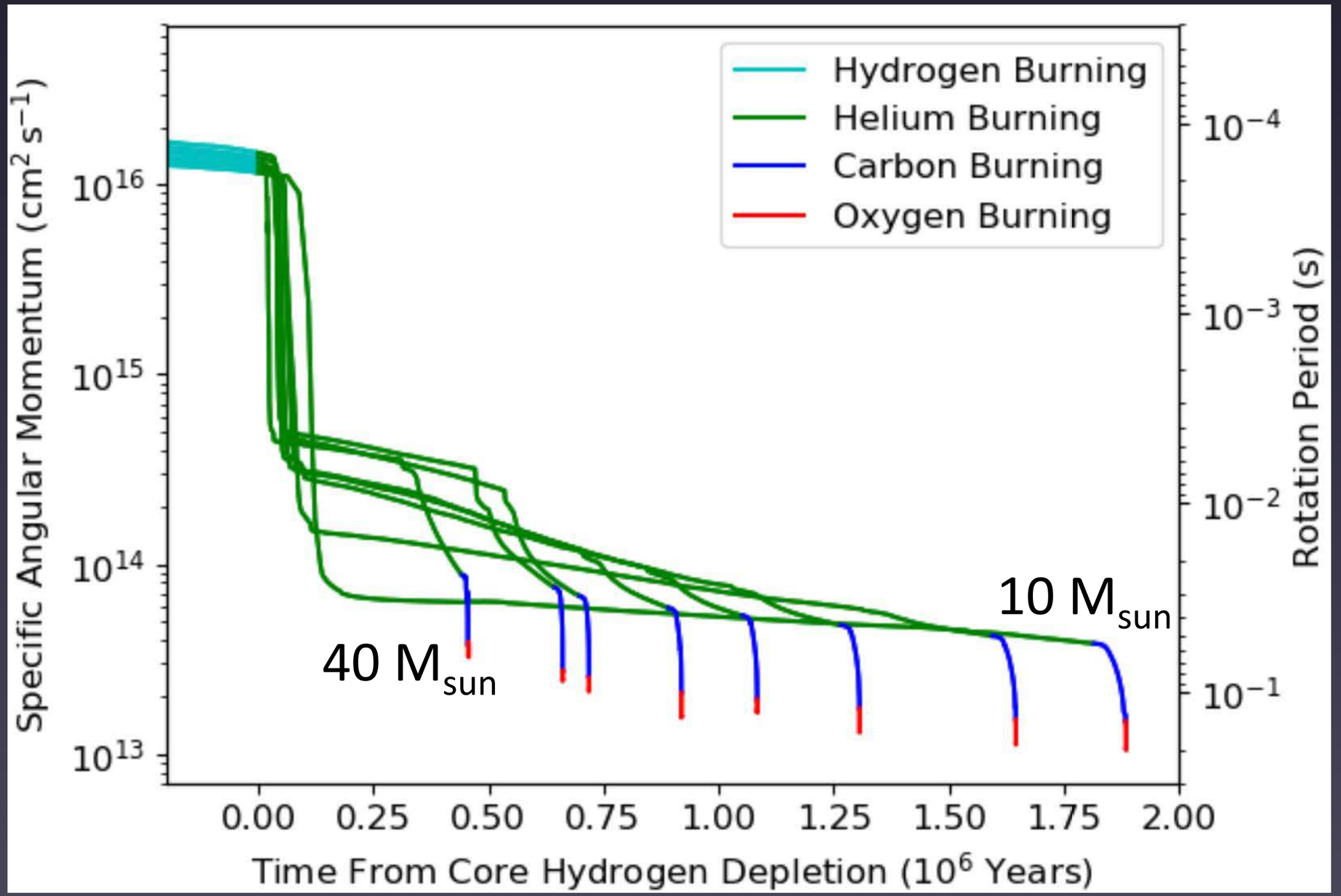
- WD rotation rates previously unexplained
- Massive WDs appear to rotate faster



Fuller+ 2019

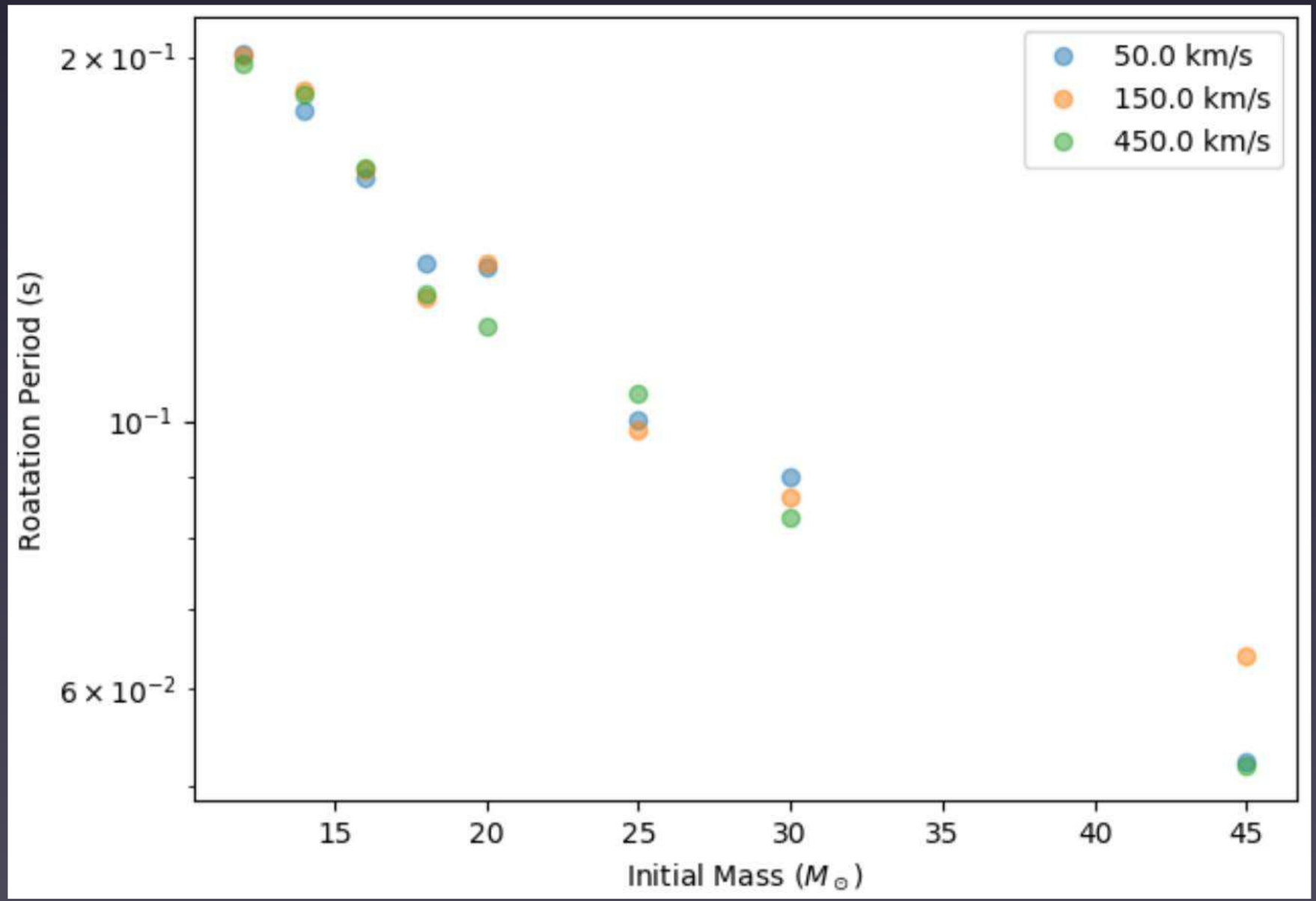
Massive Stars

- AM of inner core lost upon He core contraction after main sequence

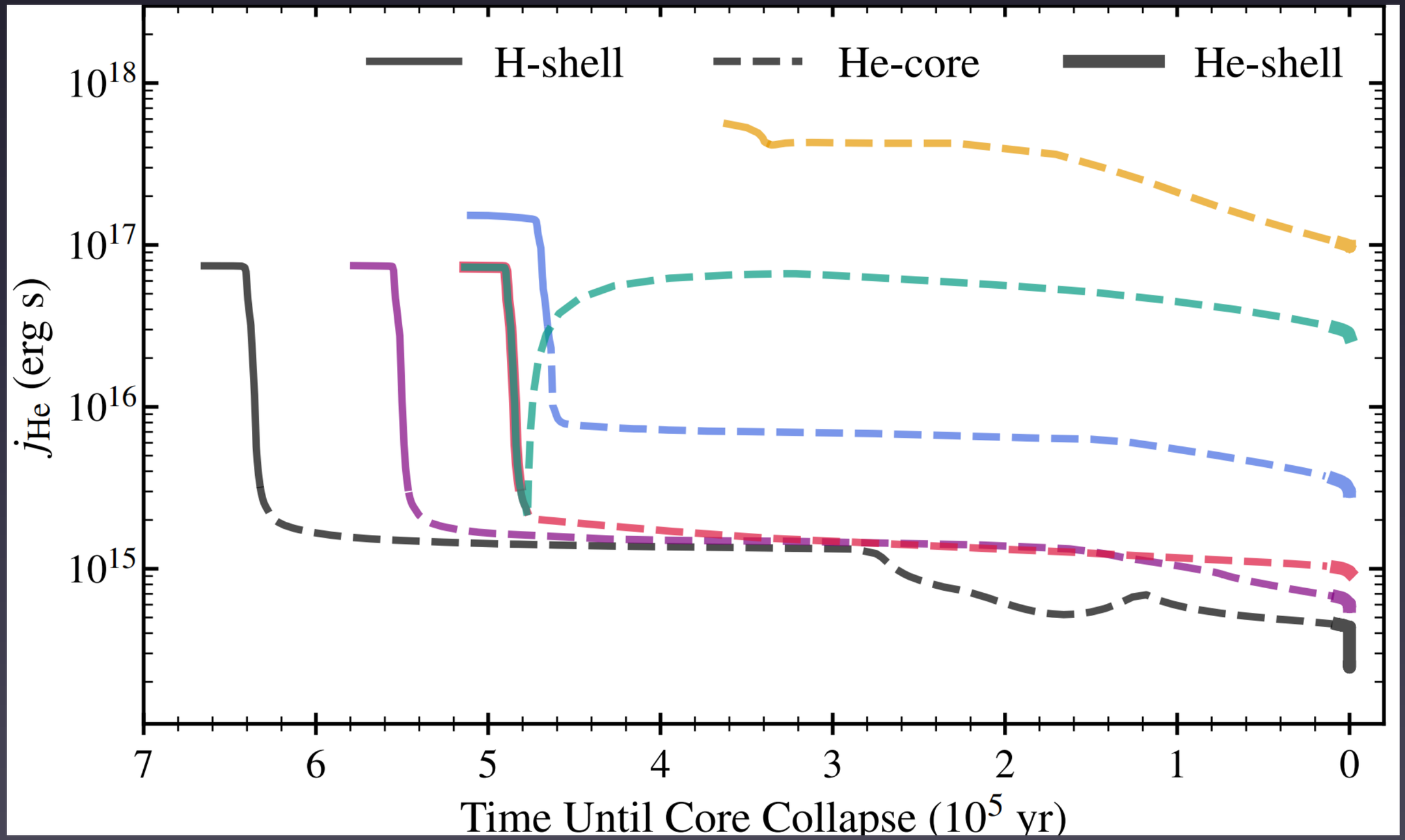


Ma & Fuller 2019

Neutron Stars Slowly Rotating



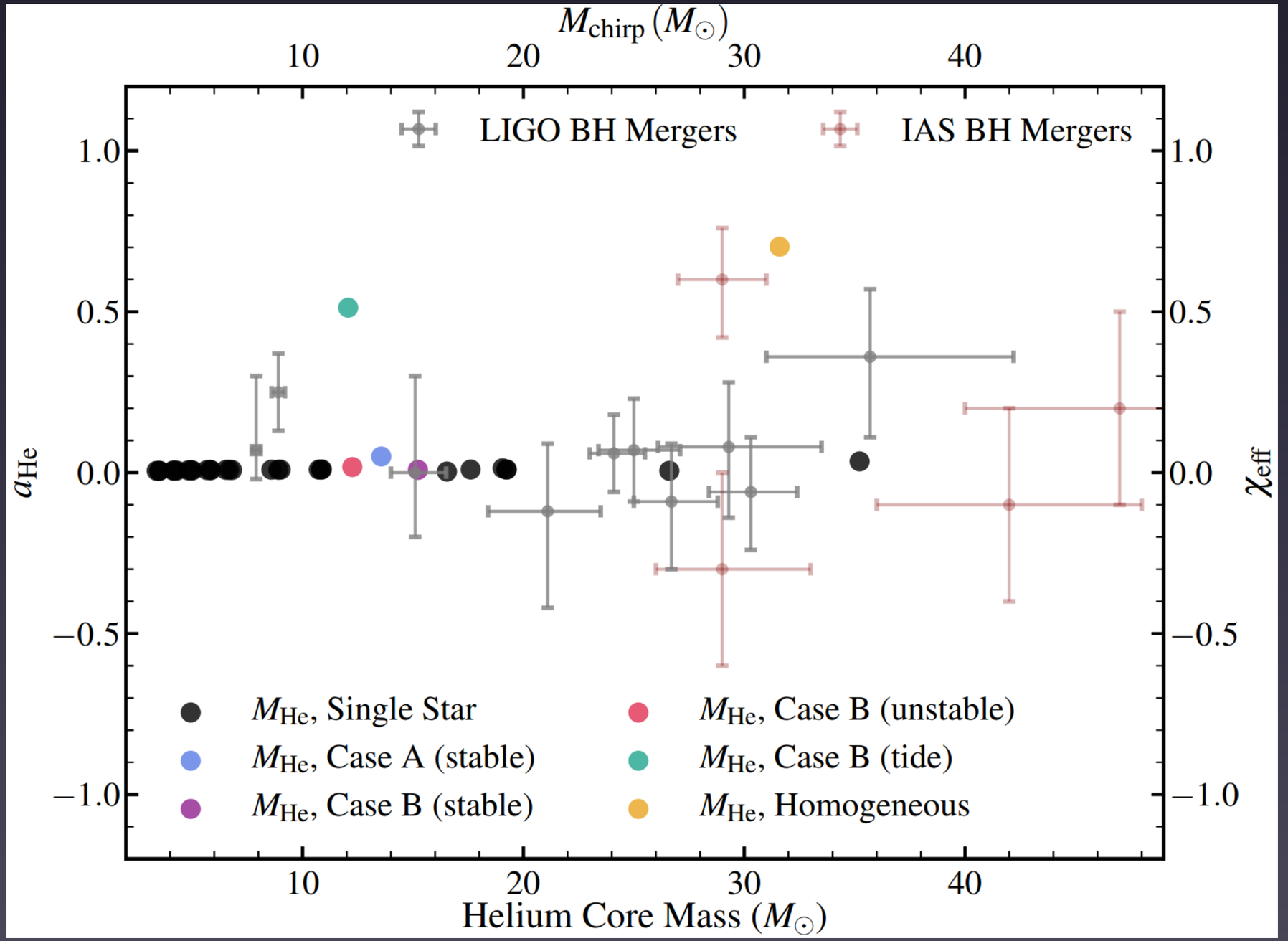
Ma & Fuller 2019



Fuller & Ma 2019

Compact Objects

- Black holes detected by LIGO appear to rotate slowly
- Binary scenarios with tidal spin-up can produce rapidly rotating BHs

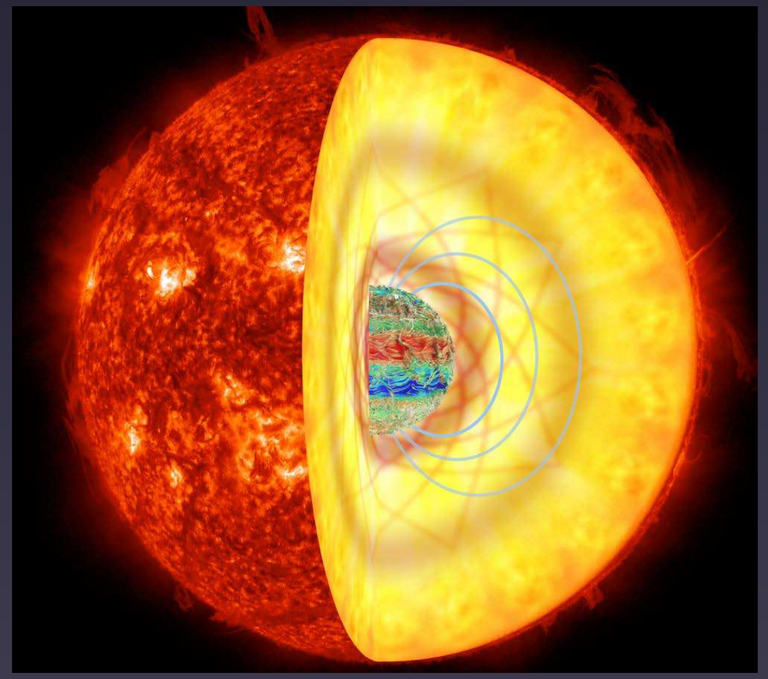


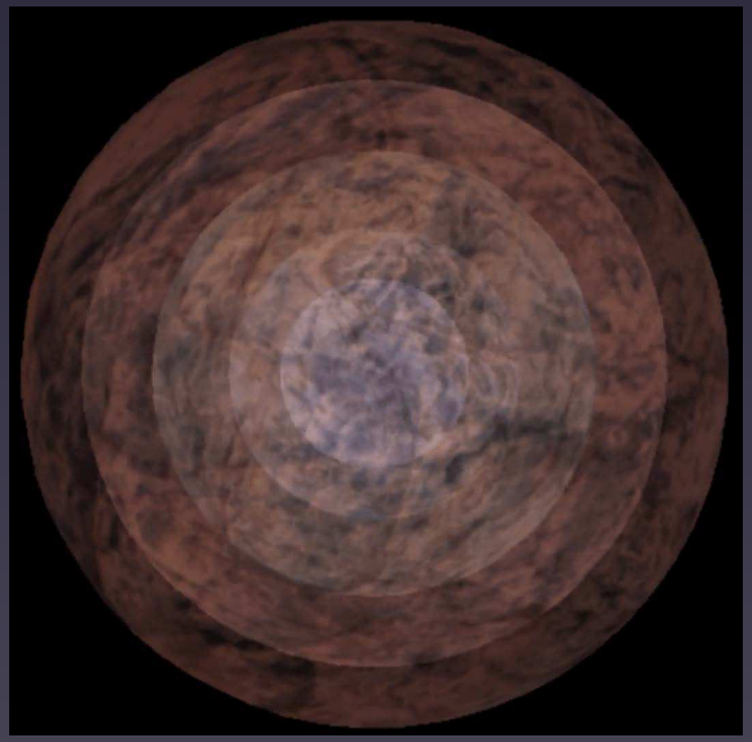
Fuller & Ma 2019

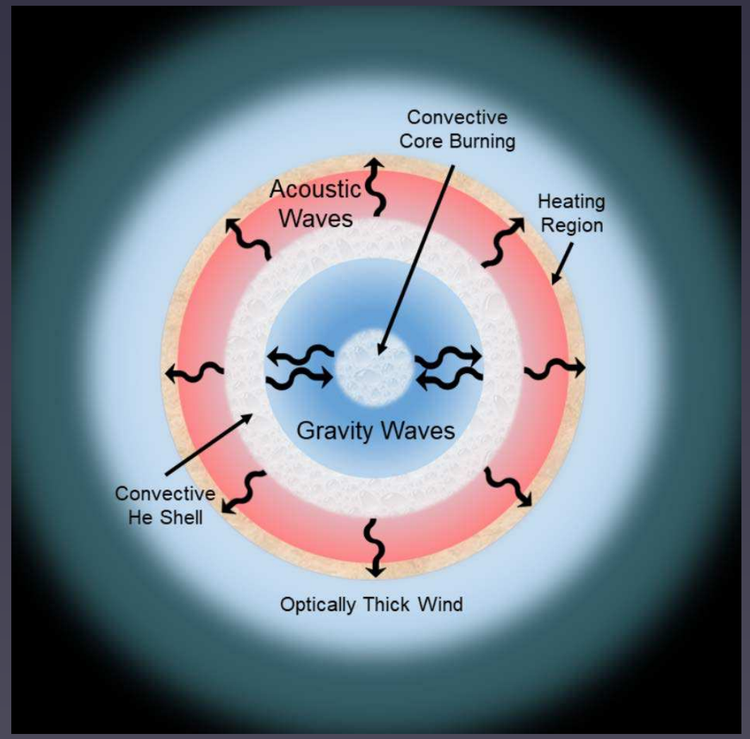
Postdictions

- White dwarfs rotate extremely slowly (~10^{-4} breakup)
- Black holes and neutron stars rotate very slowly (~10^{-2} breakup)
- Rapidly rotating magnetars and black holes mostly originate from tidally spun up binaries

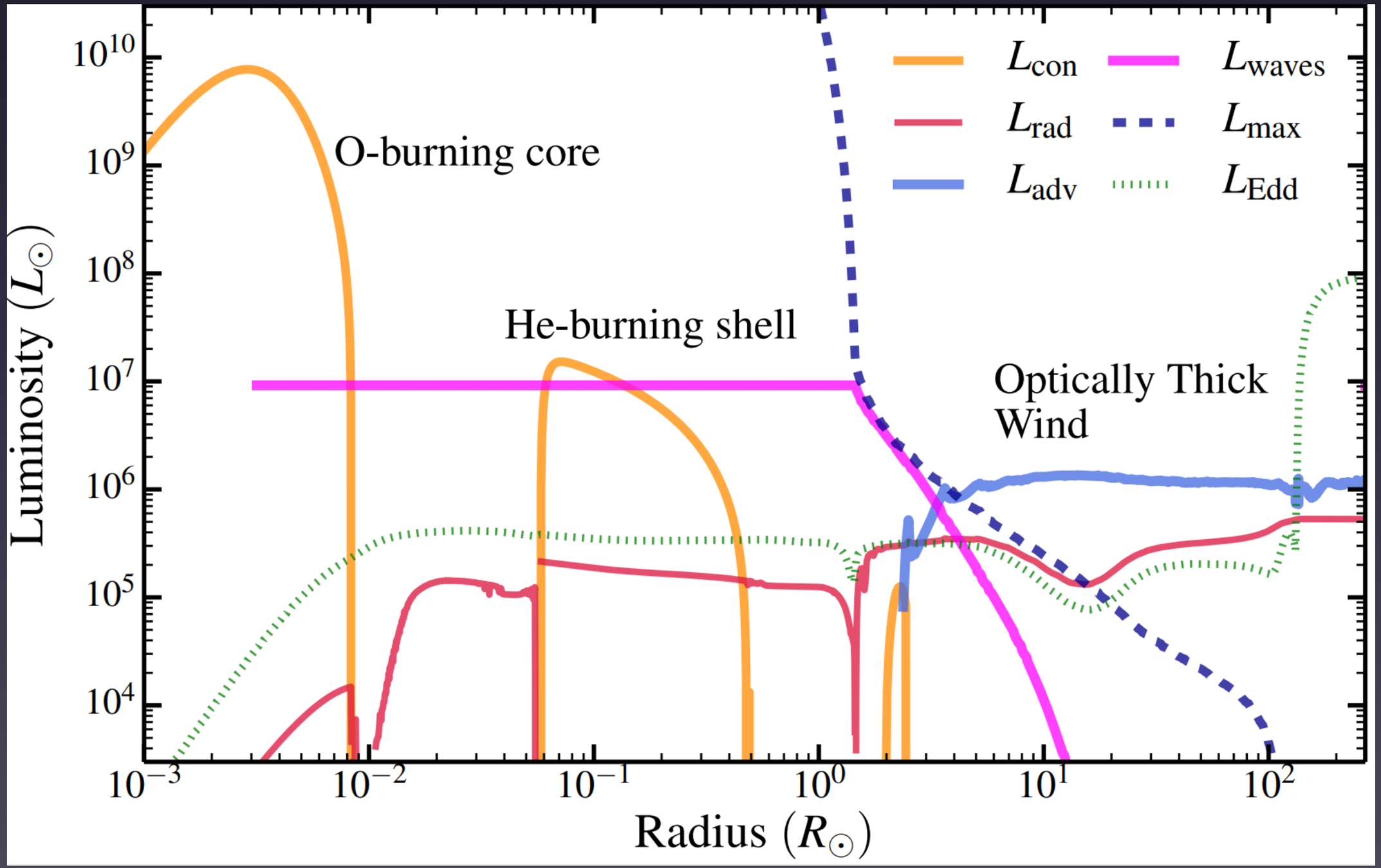
Thanks!





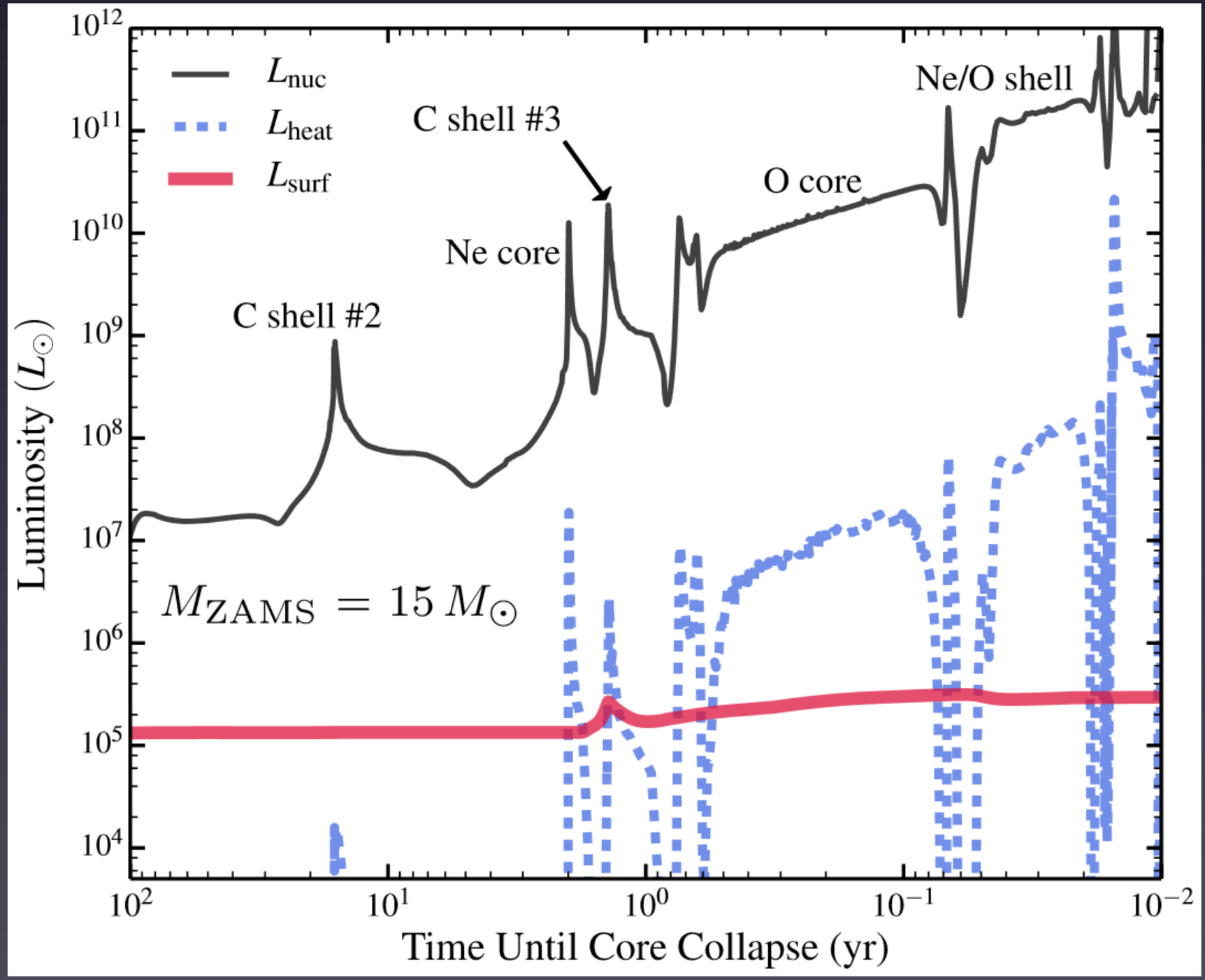

Convective
Core Burning
Acoustic
Waves
Heating
Region
Gravity Waves
Convective
He Shell
Optically Thick Wind

Bonus Material!

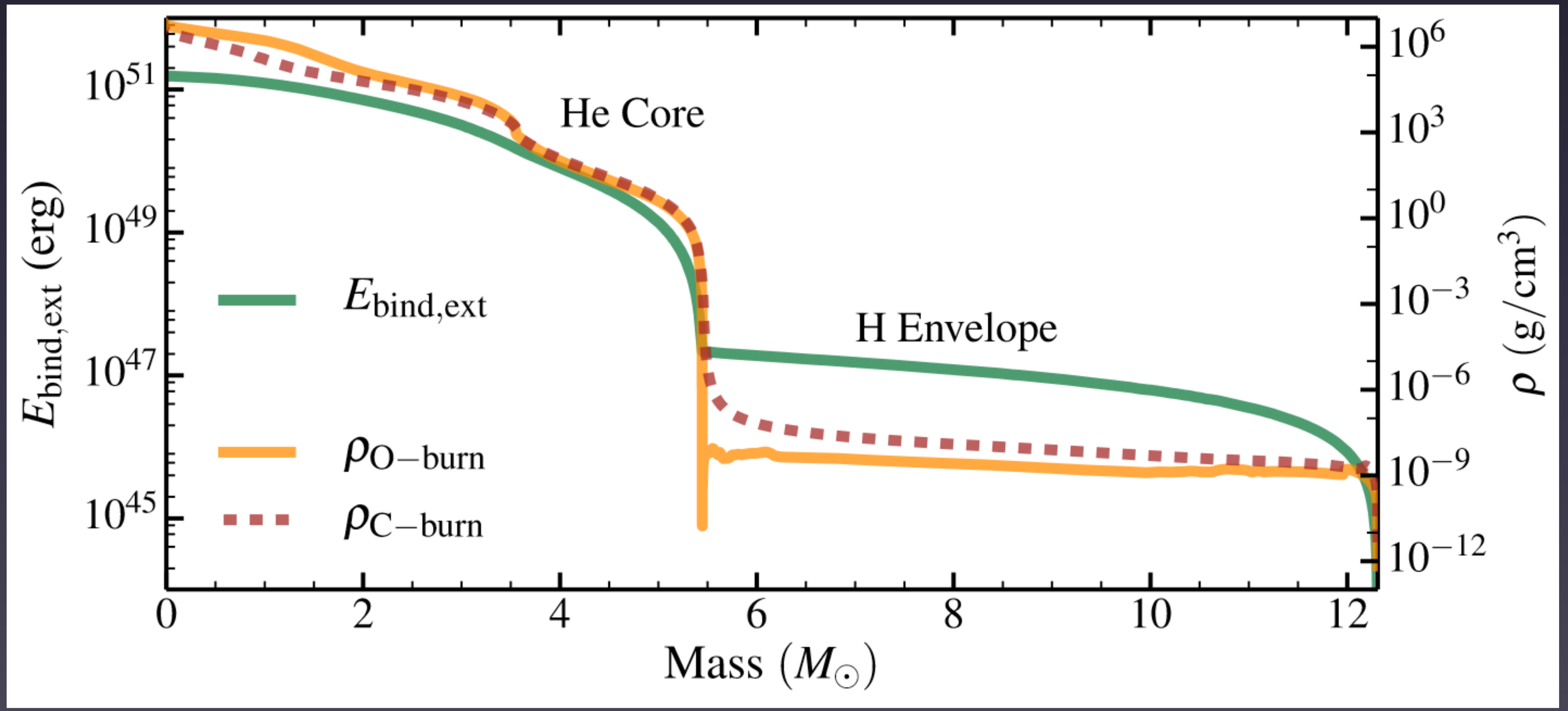


Fuller & Ro 2018

Wave Power

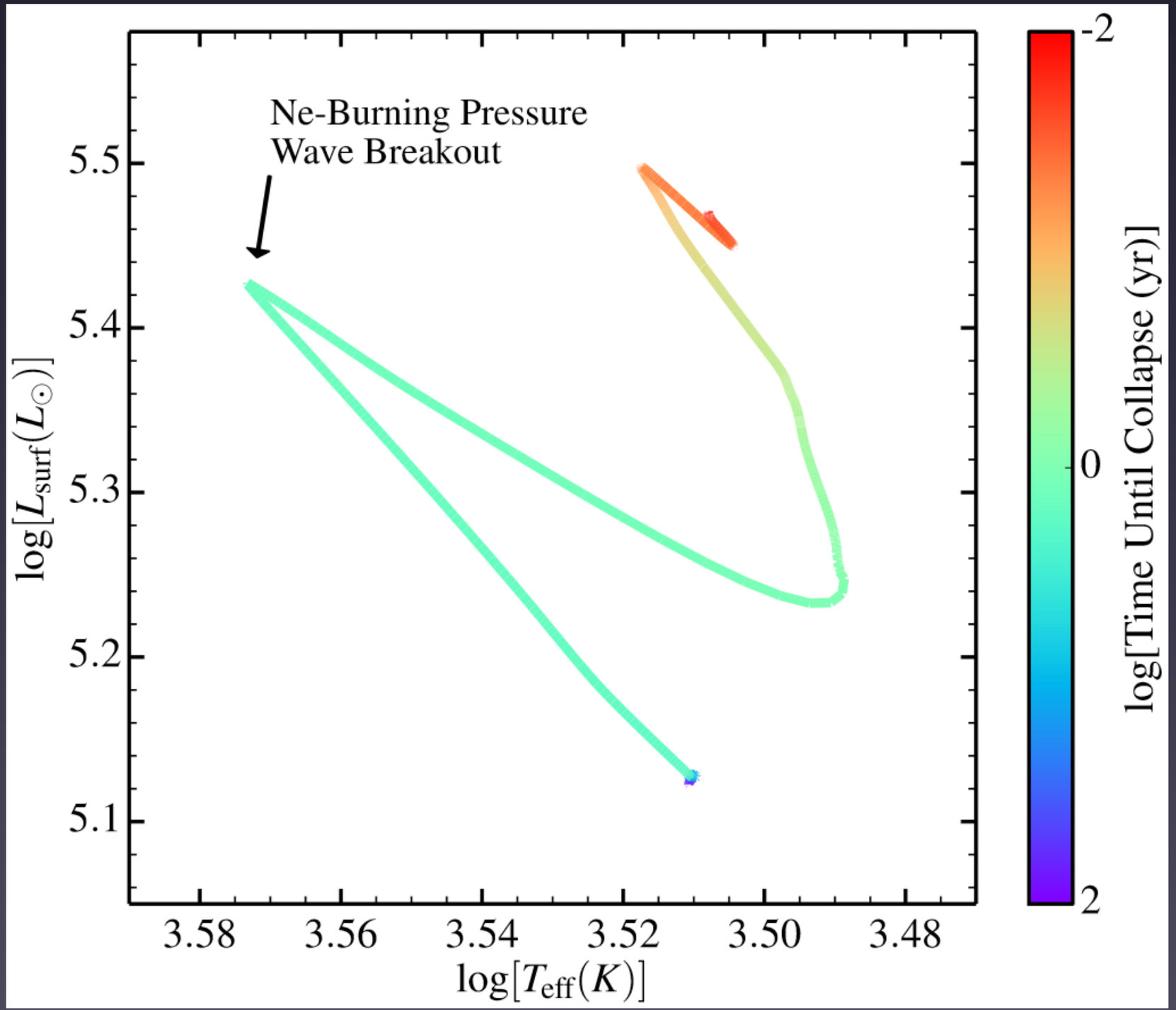


Fuller 2017


He Core
H Envelope
$E_{\rm bind,ext}$
$\rho_{\rm O-burn}$
$\rho_{\rm C-burn}$
$E_{\rm bind,ext}$ (erg)
ρ (g/cm^3)
Mass ($M_\odot$)
10^{51}
10^{49}
10^{47}
10^{45}
10^{6}
10^{3}
10^{0}
10^{-3}
10^{-6}
10^{-9}
10^{-12}
0
2
4
6
8
10
12

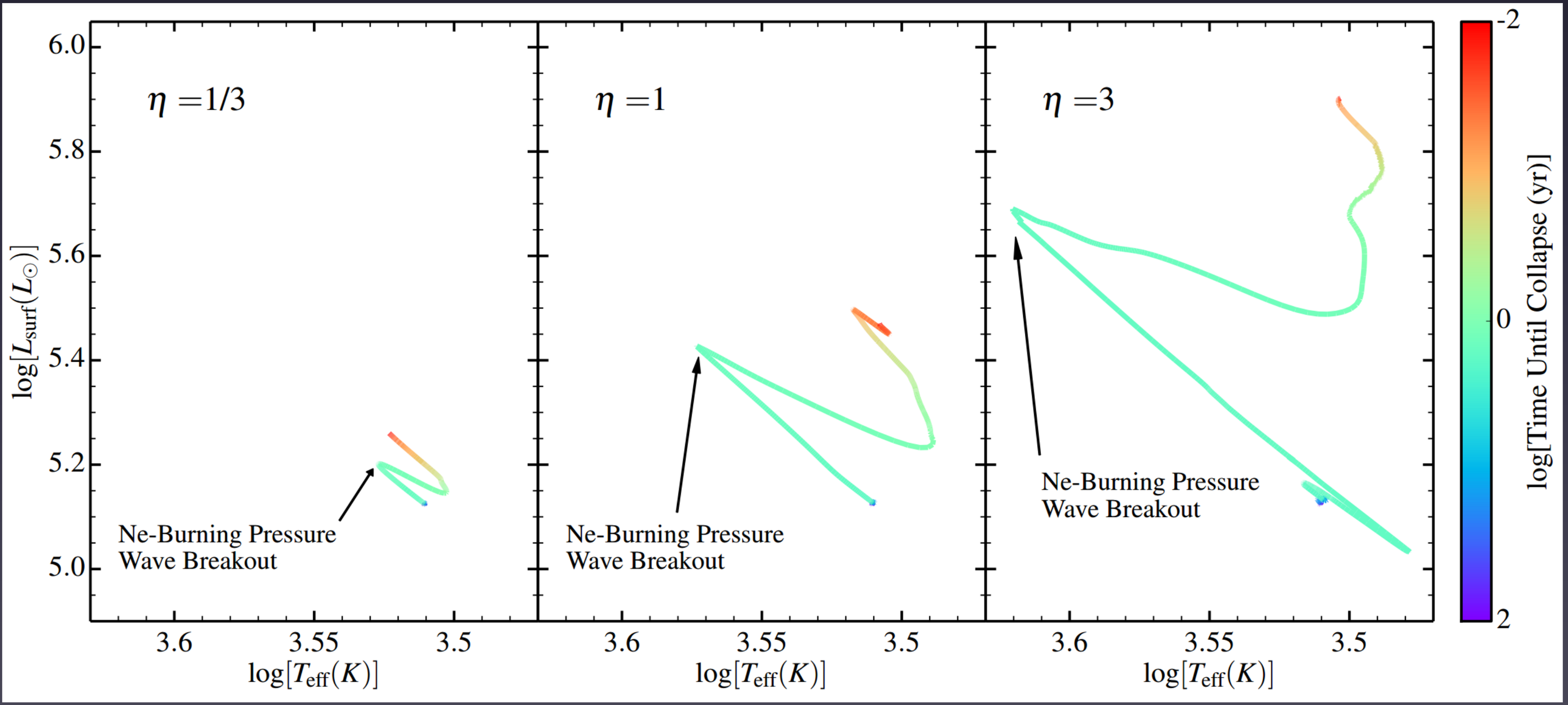
15 M_{Sun} Red Supergiant

2/27/2020



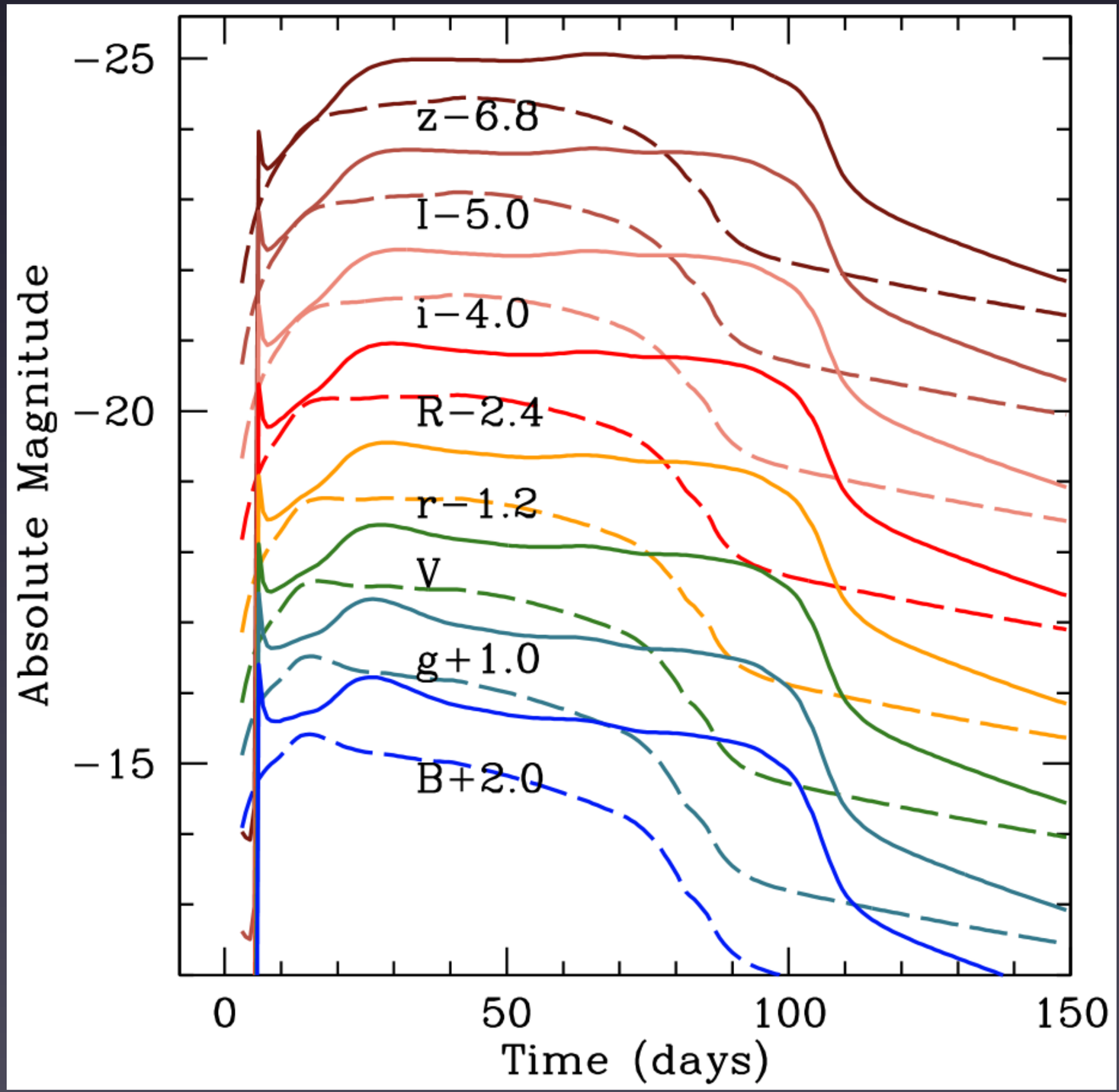
Brightening/dimming by factor of a few in last couple years

Fuller 2017

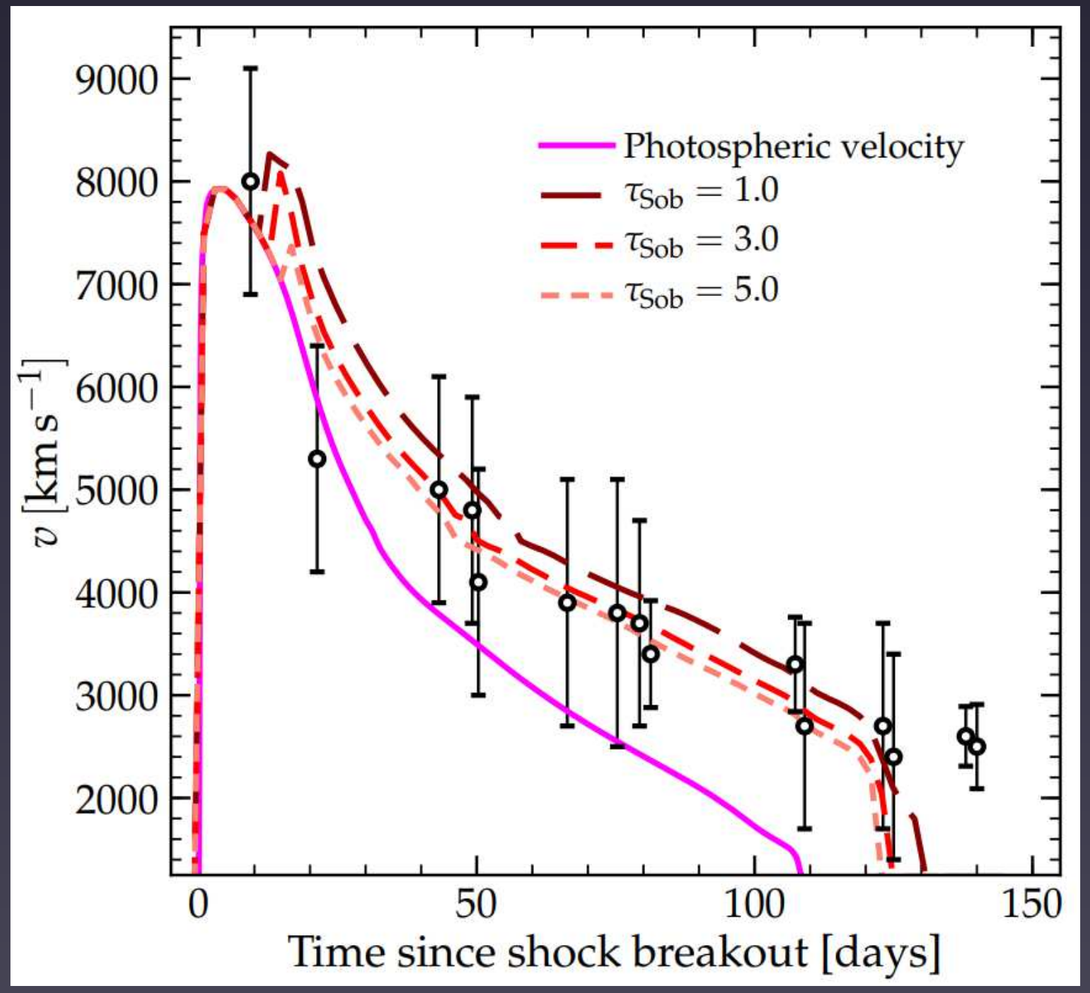

η =1/3
η =1
η =3
Ne-Burning Pressure
Wave Breakout
Ne-Burning Pressure
Wave Breakout
Ne-Burning Pressure
Wave Breakout
log[L_surf(L⊙)]
6.0
5.8
5.6
5.4
5.2
5.0
log[T_eff(K)]
3.6
3.55
3.5
log[Time Until Collapse (yr)]
-2
0
2

Fuller 2017

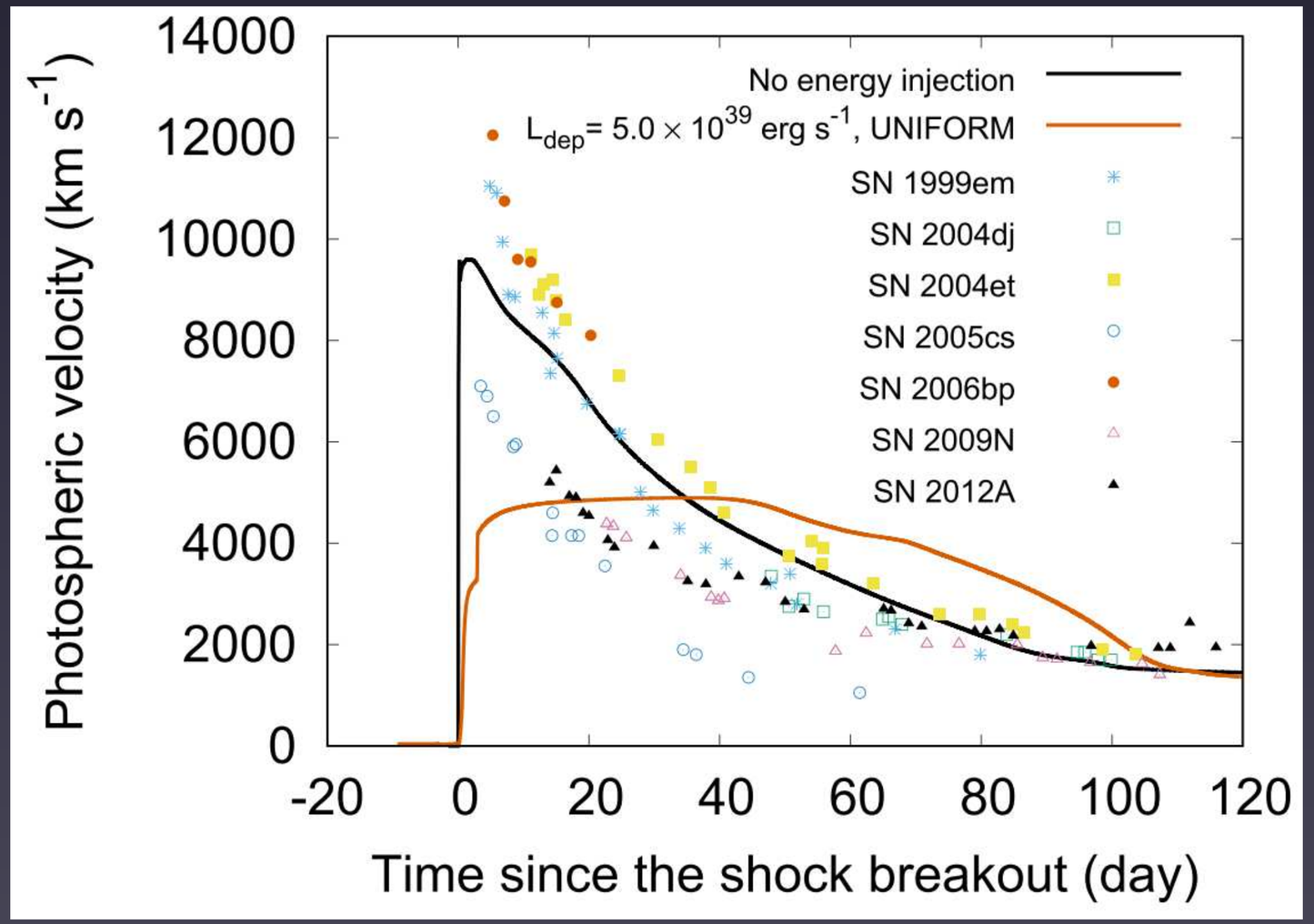
Effect on Supernova Lightcurve



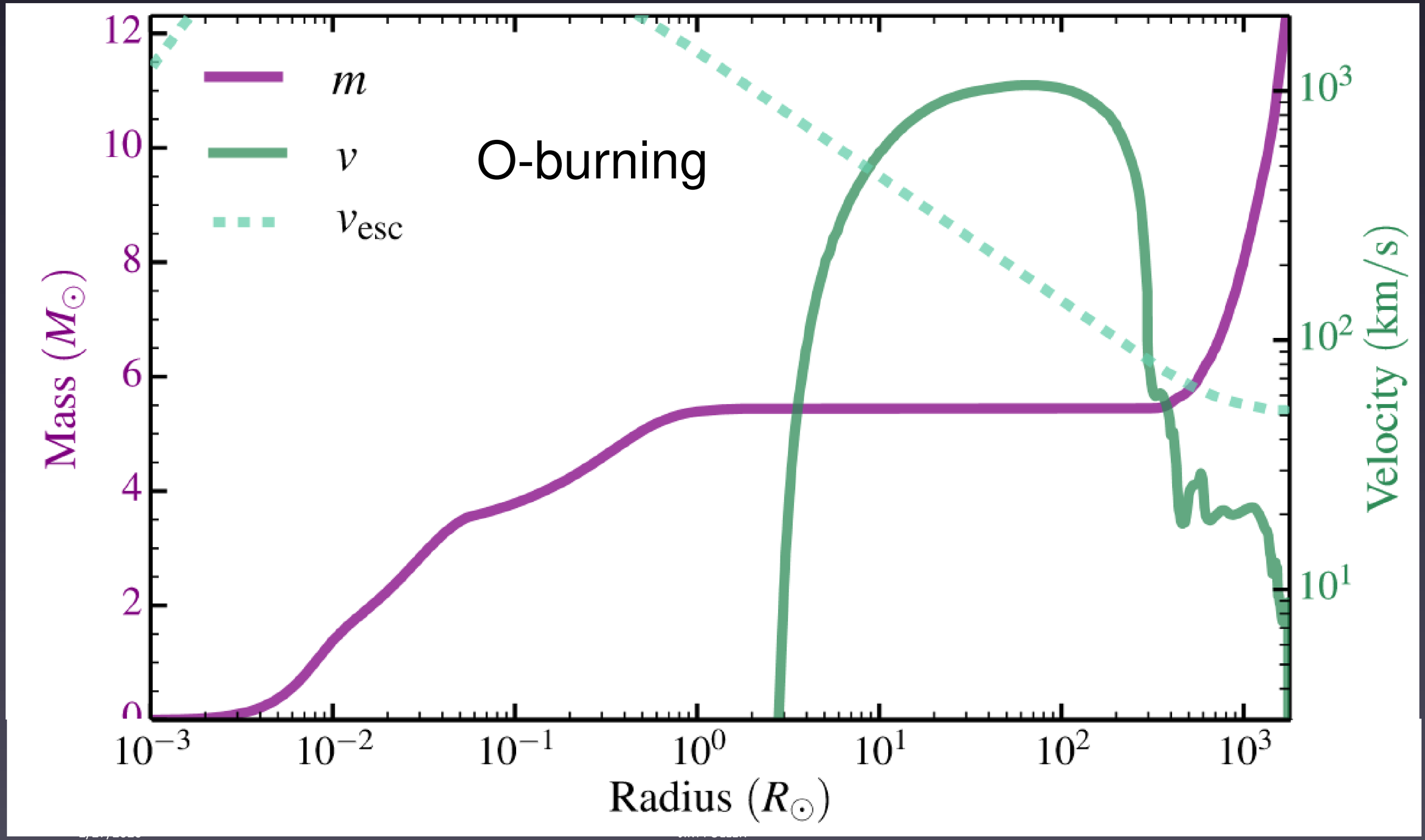
Credit:
Tony Piro



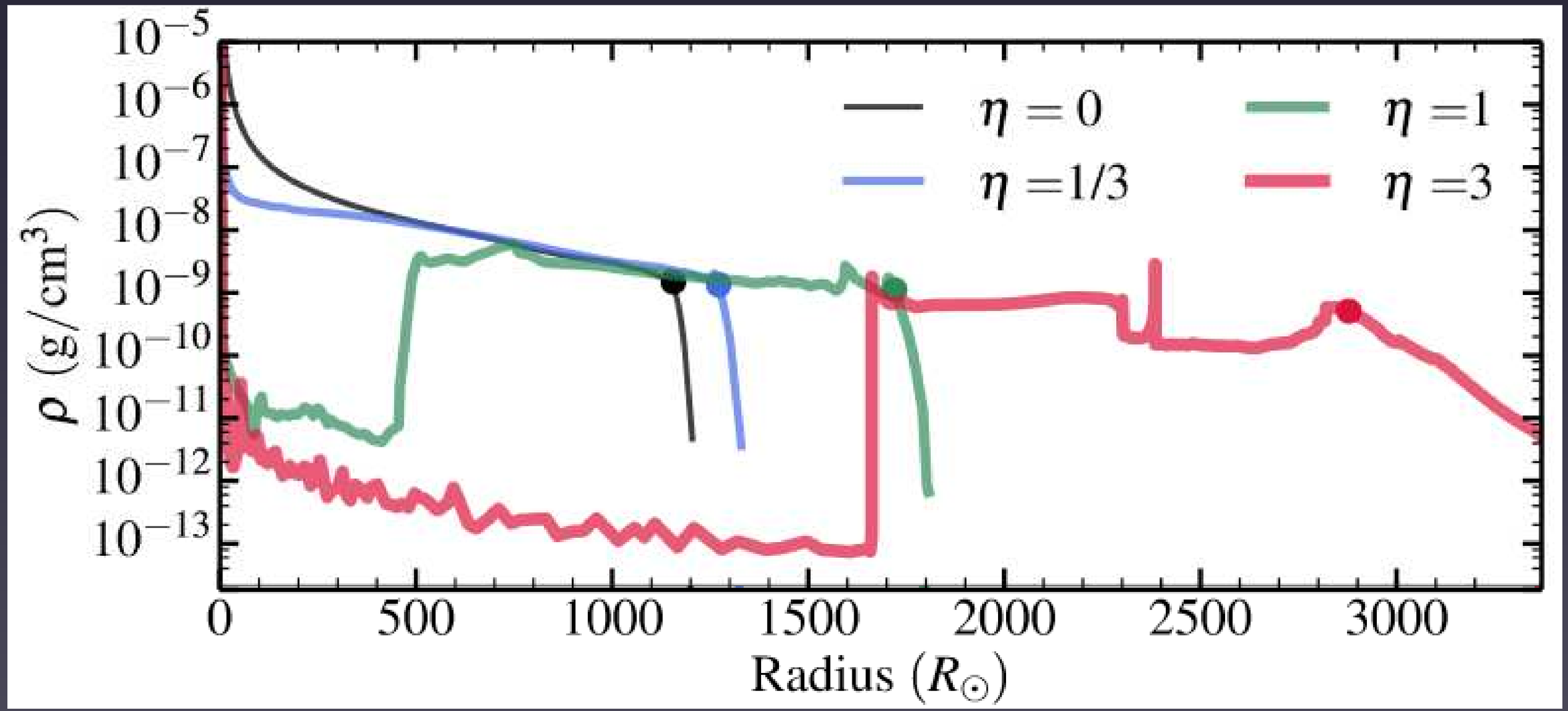
Morozova+ 2020

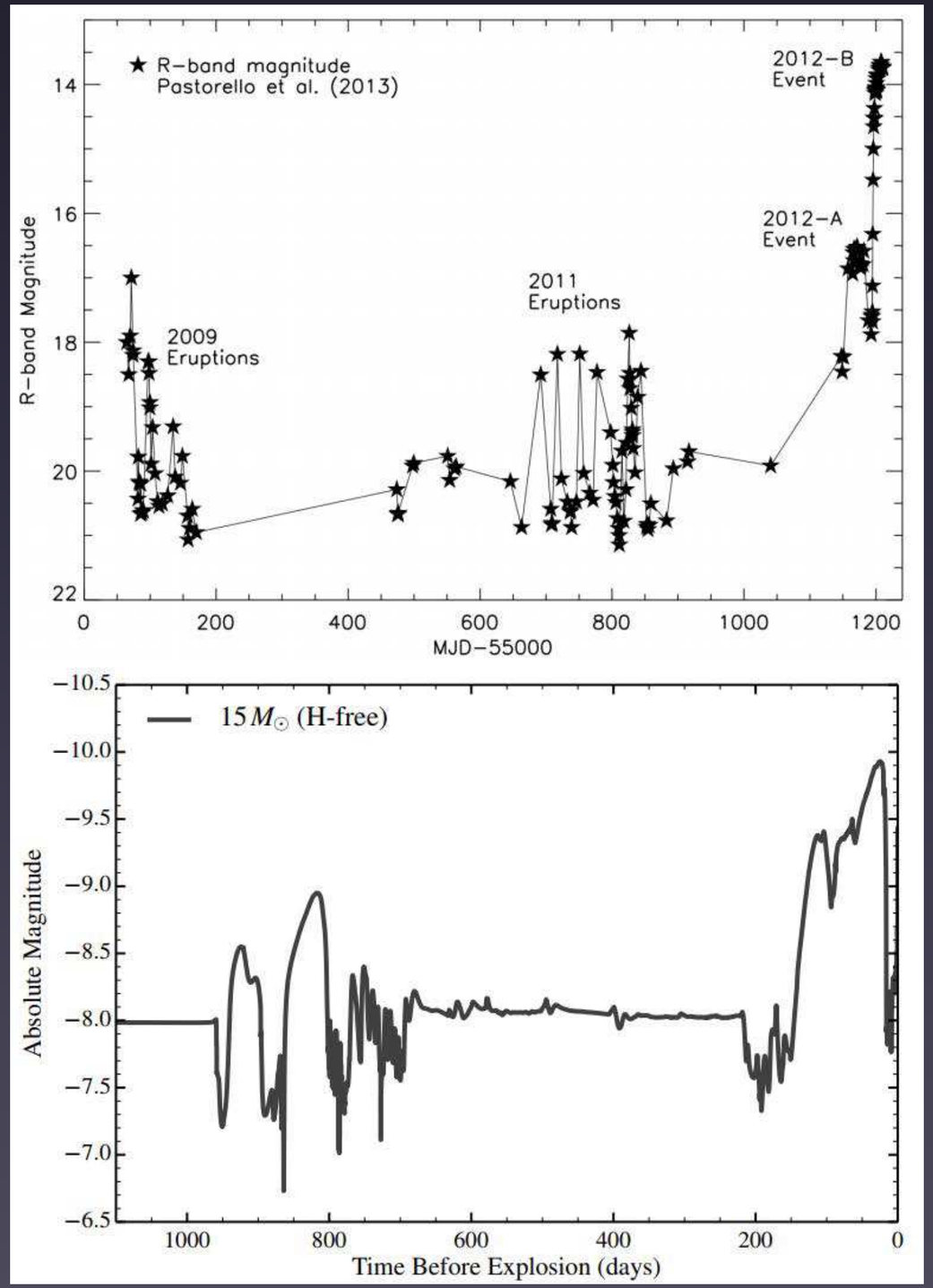


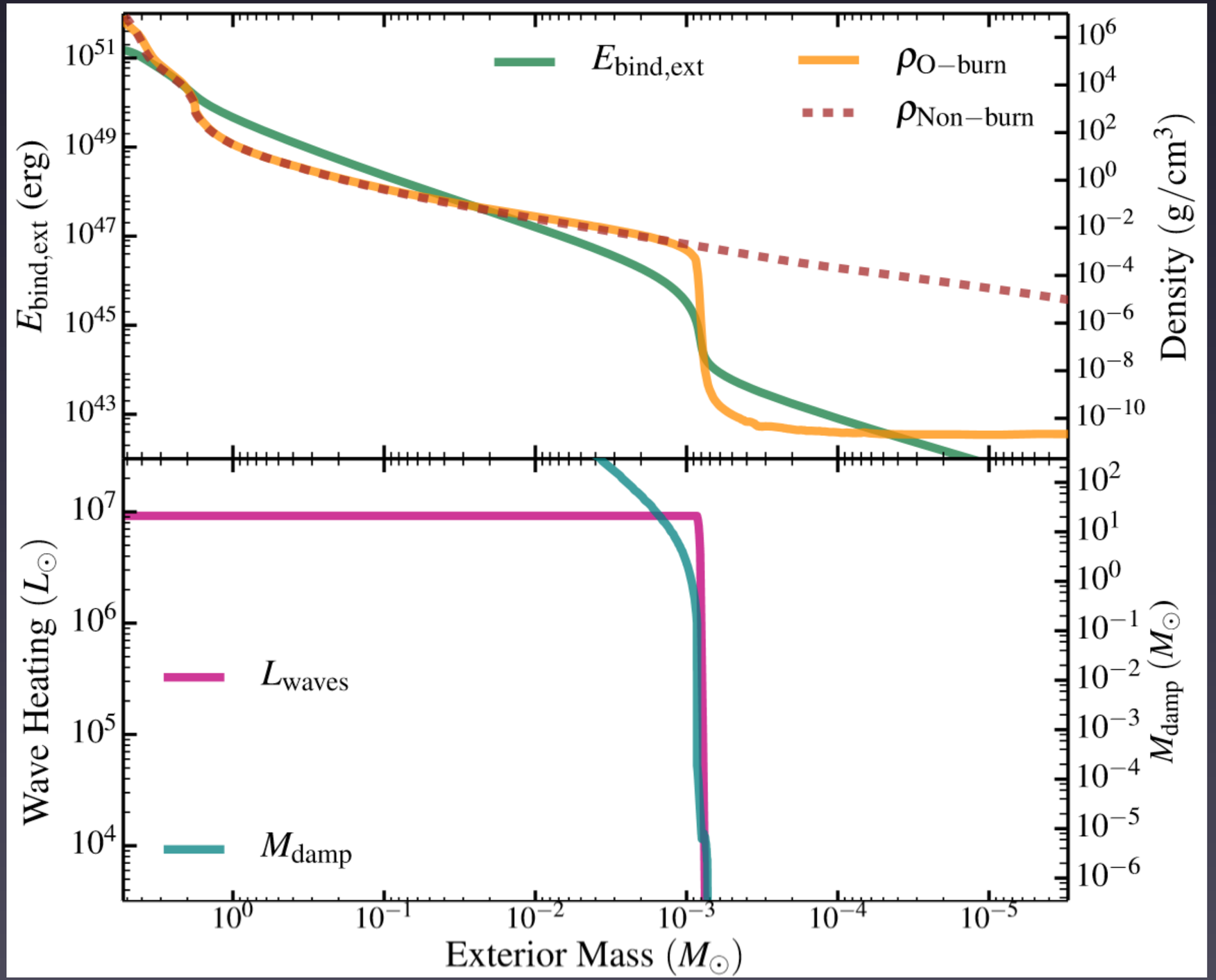
Ouchi & Maeda 2019

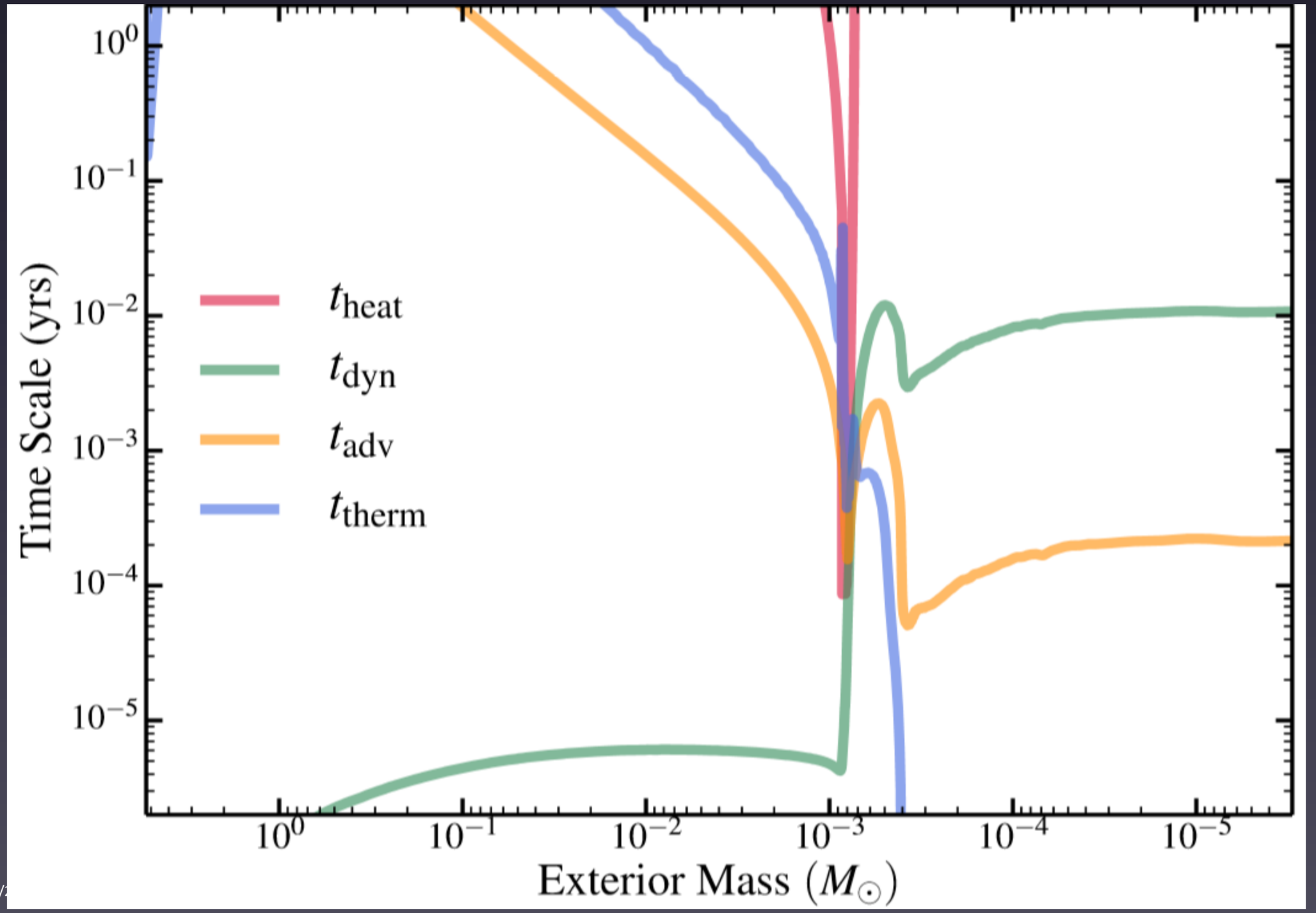

O-burning
m
v
v_{esc}
Mass ($M_\odot$)
Velocity (km/s)
Radius ($R_\odot$)
0
2
4
6
8
10
12
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{1}
10^{2}
10^{3}

Effect on Stellar Structure




R-band magnitude
Pastorello et al. (2013)
2012-B
Event
2012-A
Event
2011
Eruptions
2009
Eruptions
R-band Magnitude
MJD-55000
14
16
18
20
22
0
200
400
600
800
1000
1200
15 $M_\odot$ (H-free)
Absolute Magnitude
Time Before Explosion (days)
−10.5
−10.0
−9.5
−9.0
−8.5
−8.0
−7.5
−7.0
−6.5
1000
800
600
400
200
0


$E_{\rm bind,ext}$
$\rho_{\rm O-burn}$
$\rho_{\rm Non-burn}$
$E_{\rm bind,ext}$ (erg)
Density (g/cm^3)
$L_{\rm waves}$
$M_{\rm damp}$
Wave Heating ($L_\odot$)
$M_{\rm damp}$ ($M_\odot$)
Exterior Mass ($M_\odot$)


Time Scale (yrs)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$t_{\rm heat}$
$t_{\rm dyn}$
$t_{\rm adv}$
$t_{\rm therm}$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Exterior Mass ($M_{\odot}$)

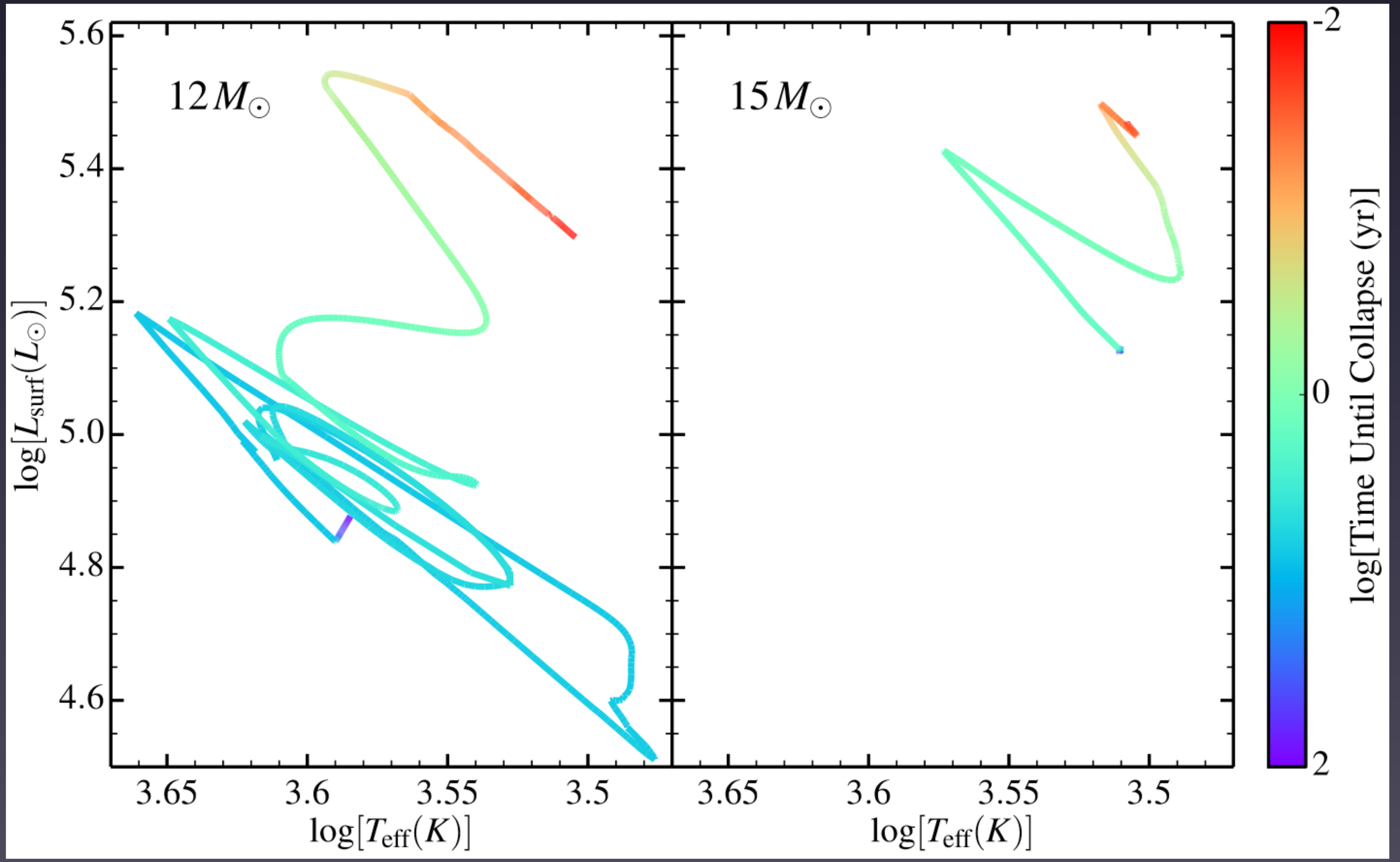
Caveats

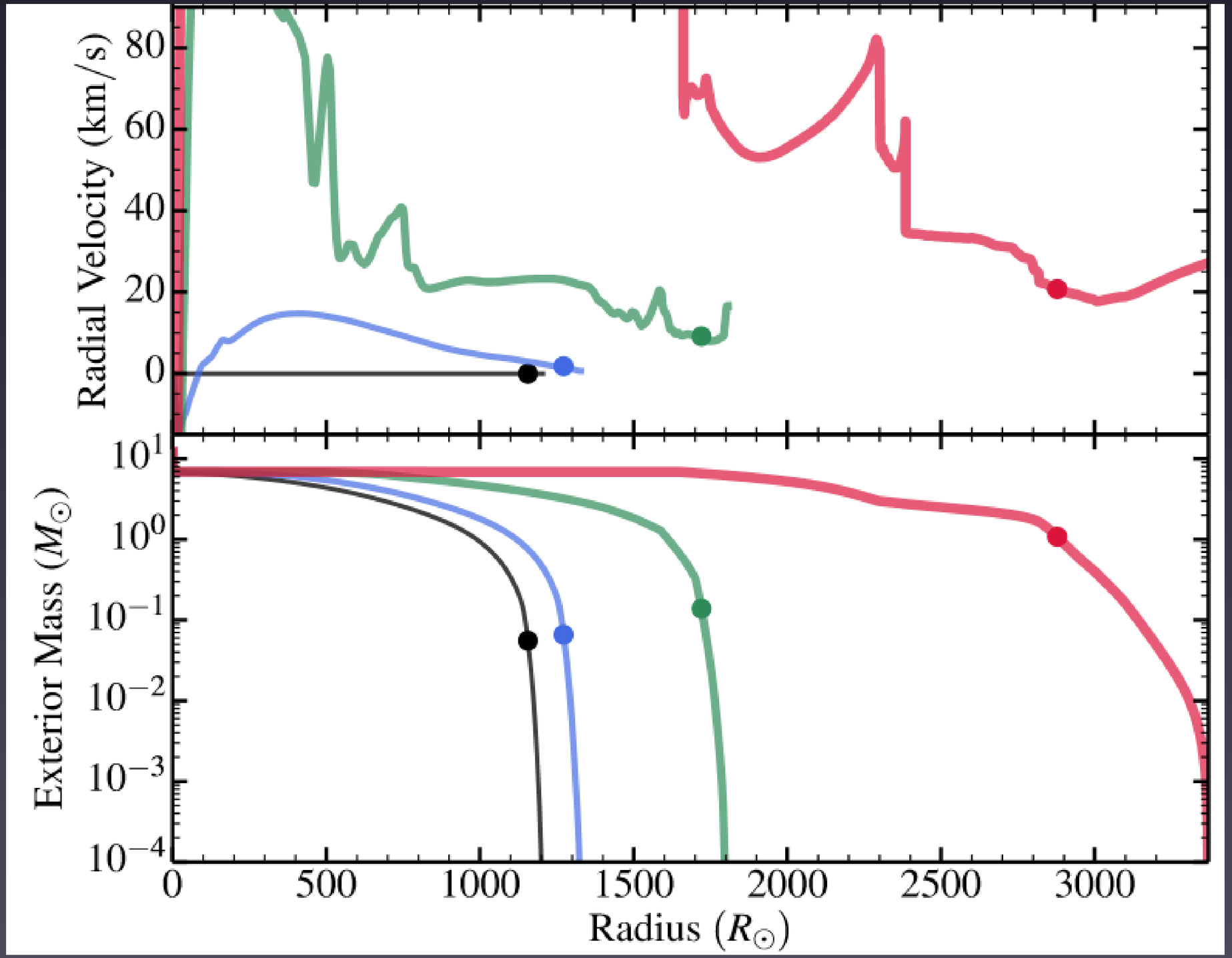
- Binaries, rotation, and magnetic fields
  - Radial expansion may trigger binary interaction → IIn supernova (Mcley & Soker 2014)
  - Core magnetic fields can inhibit gravity wave propagation (talk by Cantiello)

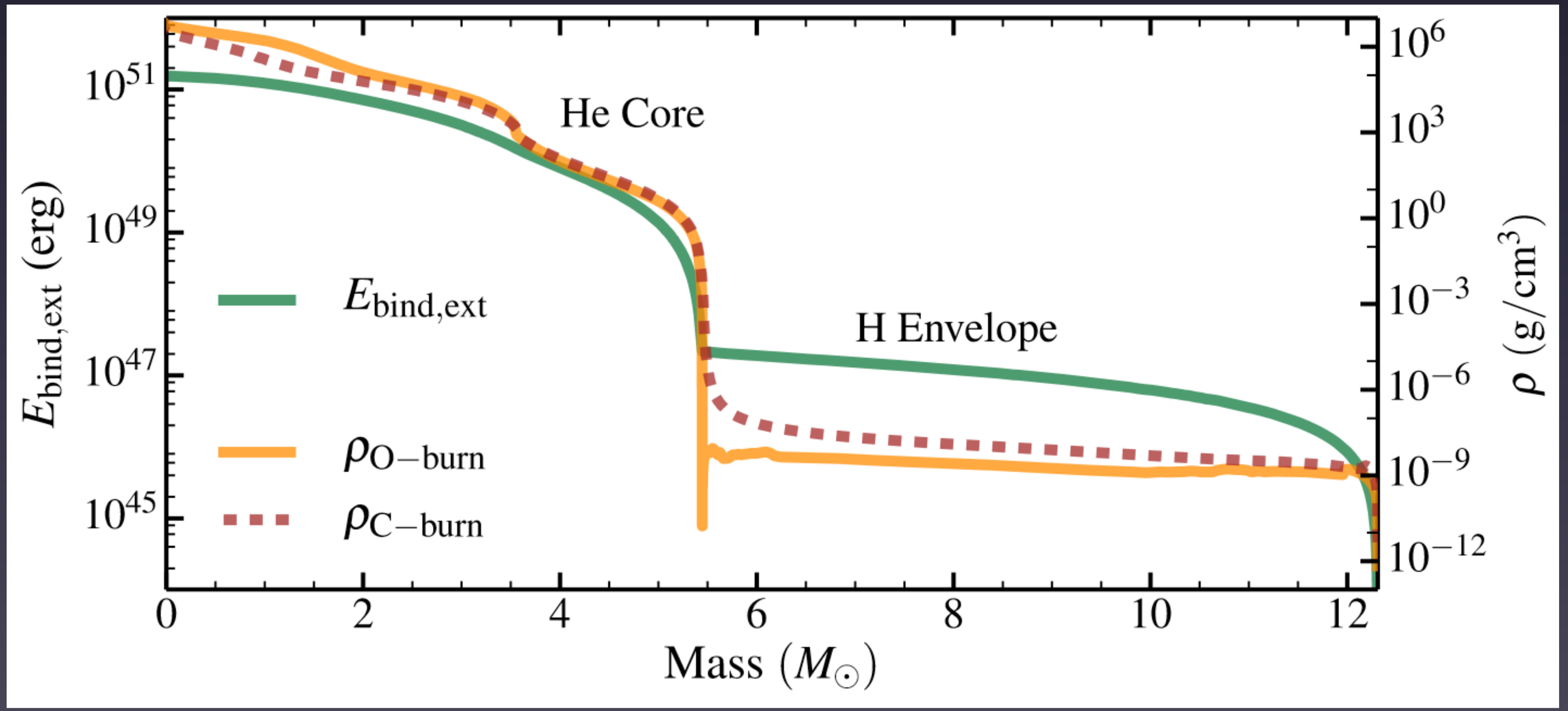
- Hard to explain IIbs, small variability of 2011dh (Szczygieł et al. 2012, Hosseinzadeh et al. 2015), small radius/mass loss of iPTF2013bvn (Cao et al. 2013)

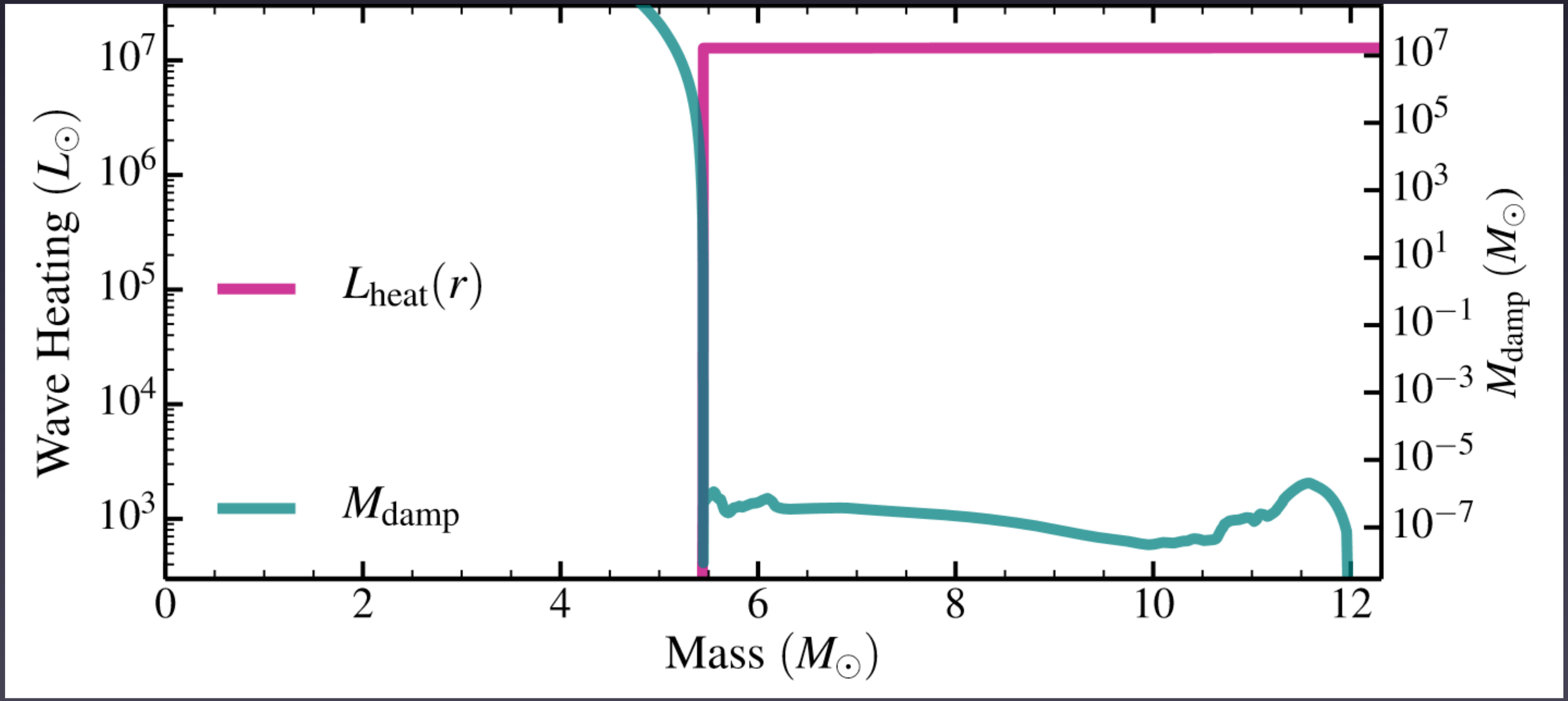
- Progenitor landscape is complex

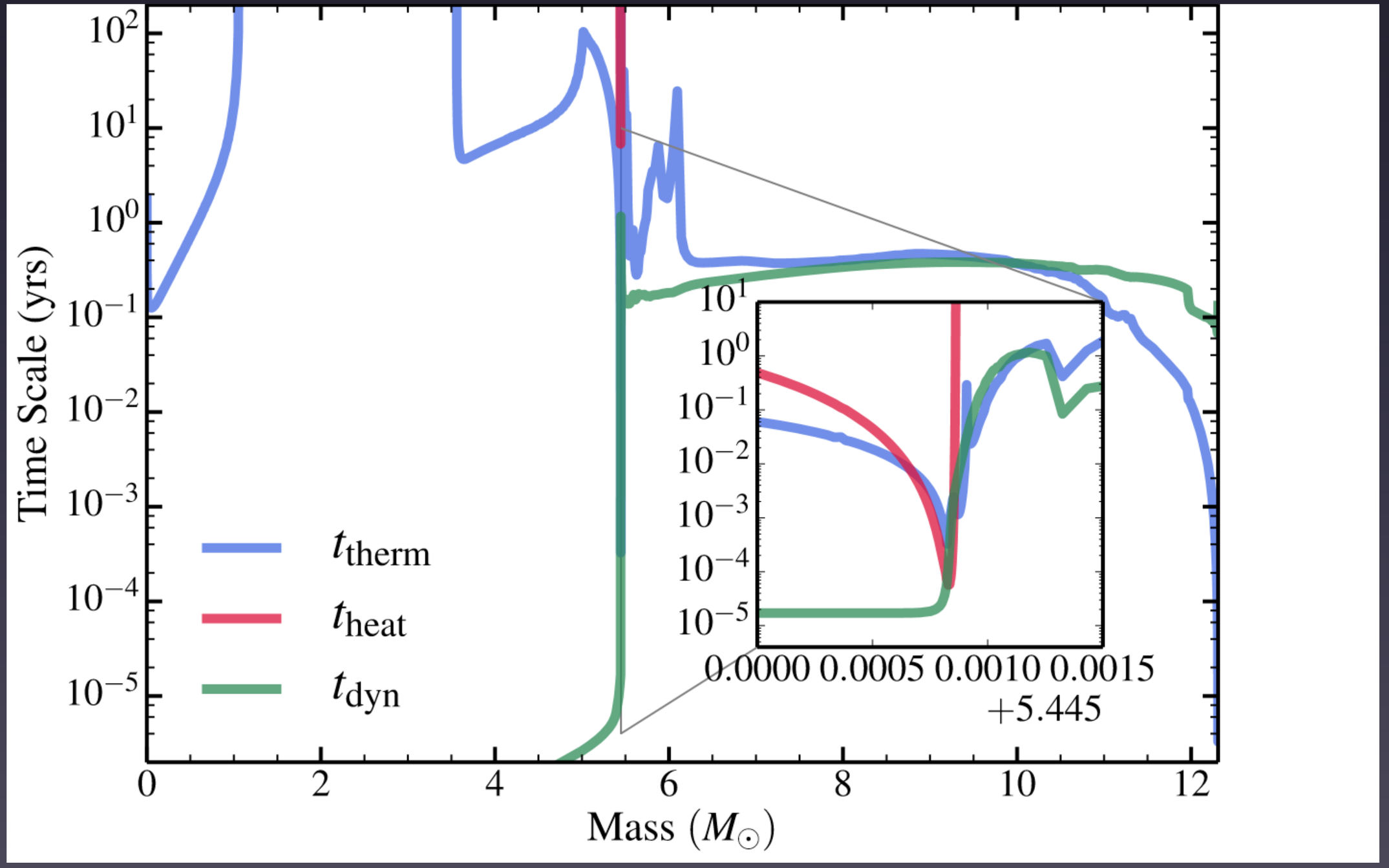
- Burning instabilities also possible (e.g., Meakin & Arnett 2006,2007,2016, Smith & Arnett 2014, Woosley & Heger 2015, Soker & Gilkis 2016,)

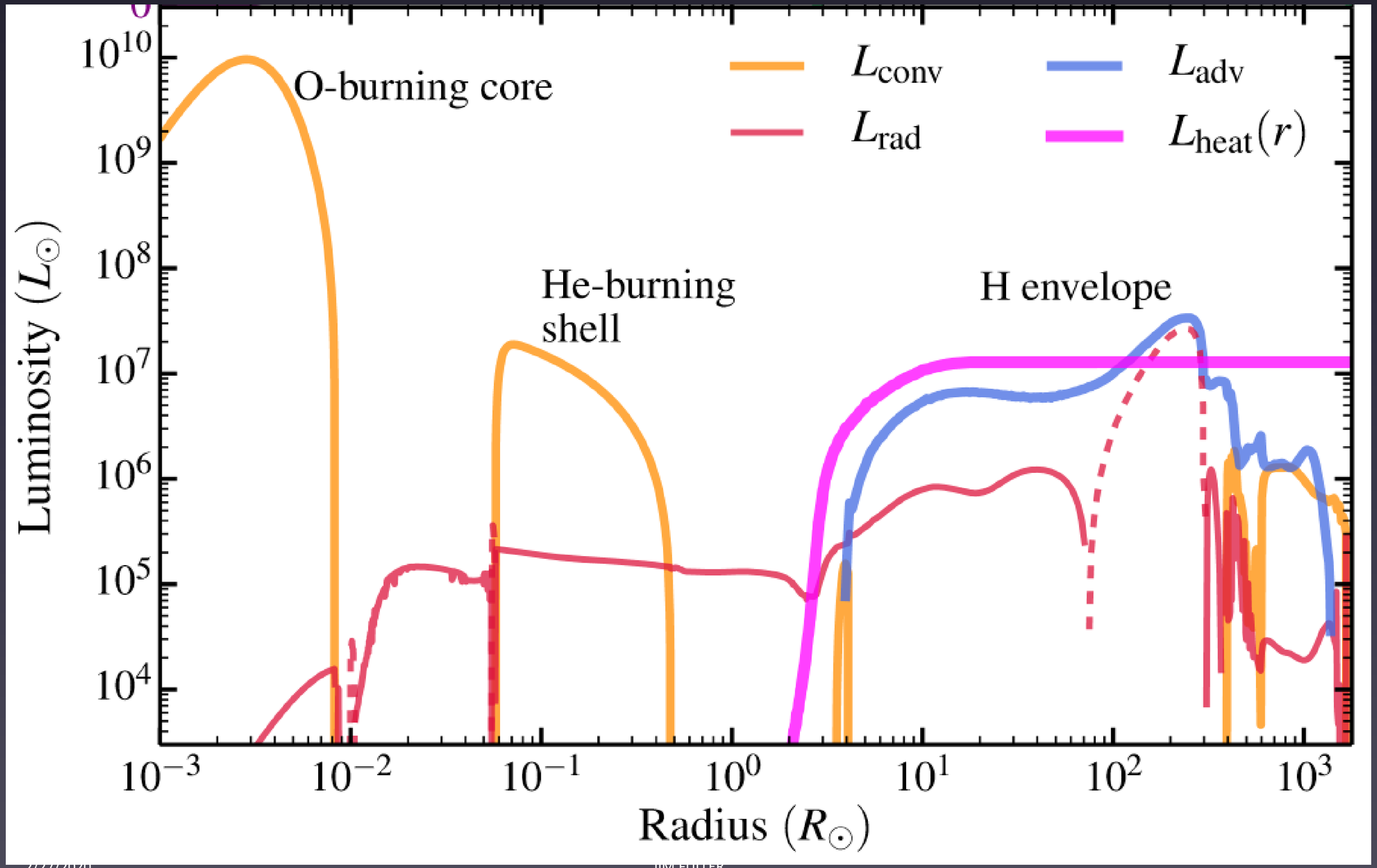

12 $M_\odot$
15 $M_\odot$
5.6
5.4
5.2
5.0
4.8
4.6
log[$L_{surf}(L_\odot)$]
3.65
3.6
3.55
3.5
log[$T_{eff}(K)$]
-2
0
2
log[Time Until Collapse (yr)]

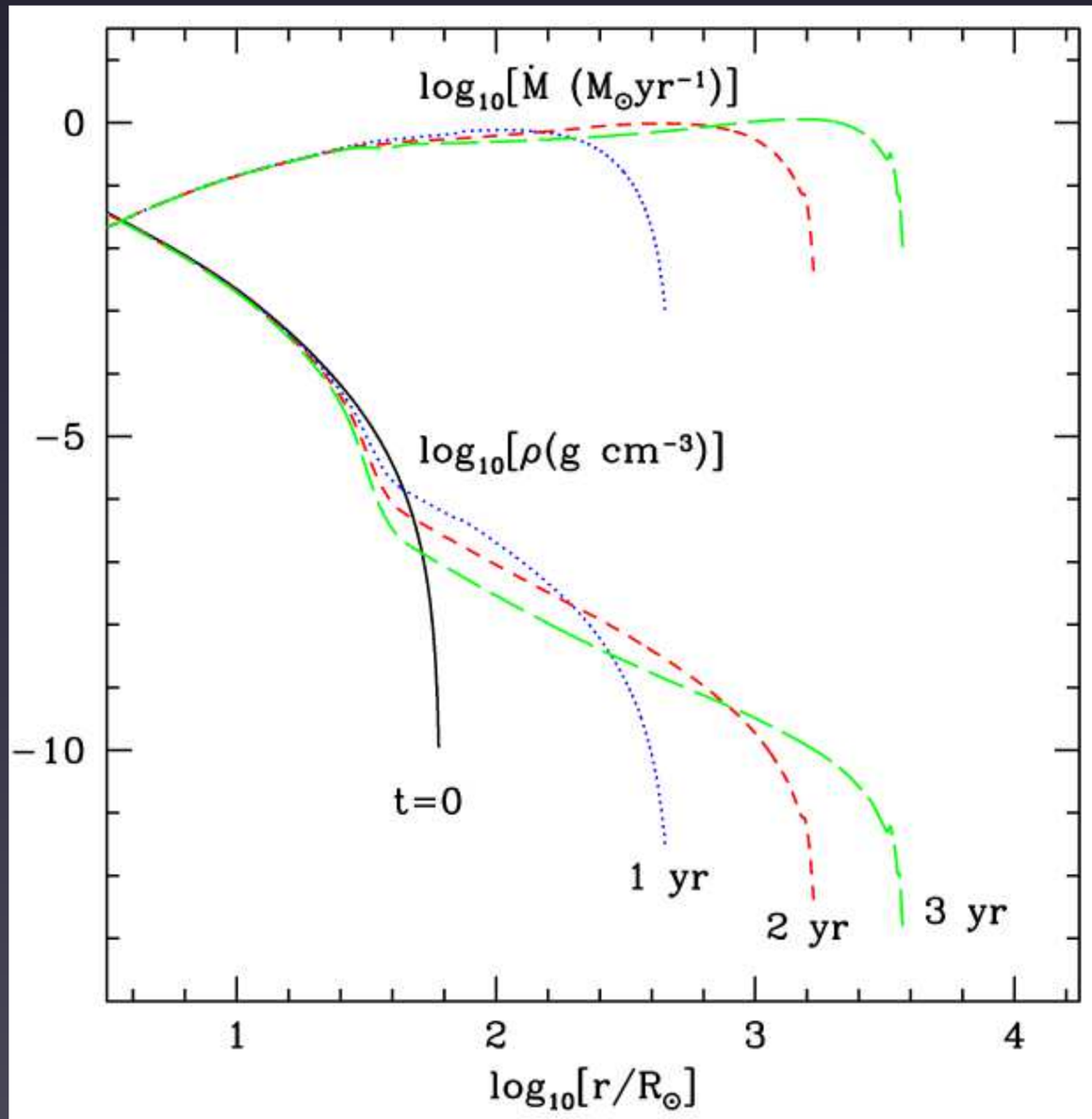

Radial Velocity (km/s)
80
60
40
20
0
Exterior Mass ($M_\odot$)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
500
1000
1500
2000
2500
3000
Radius ($R_\odot$)

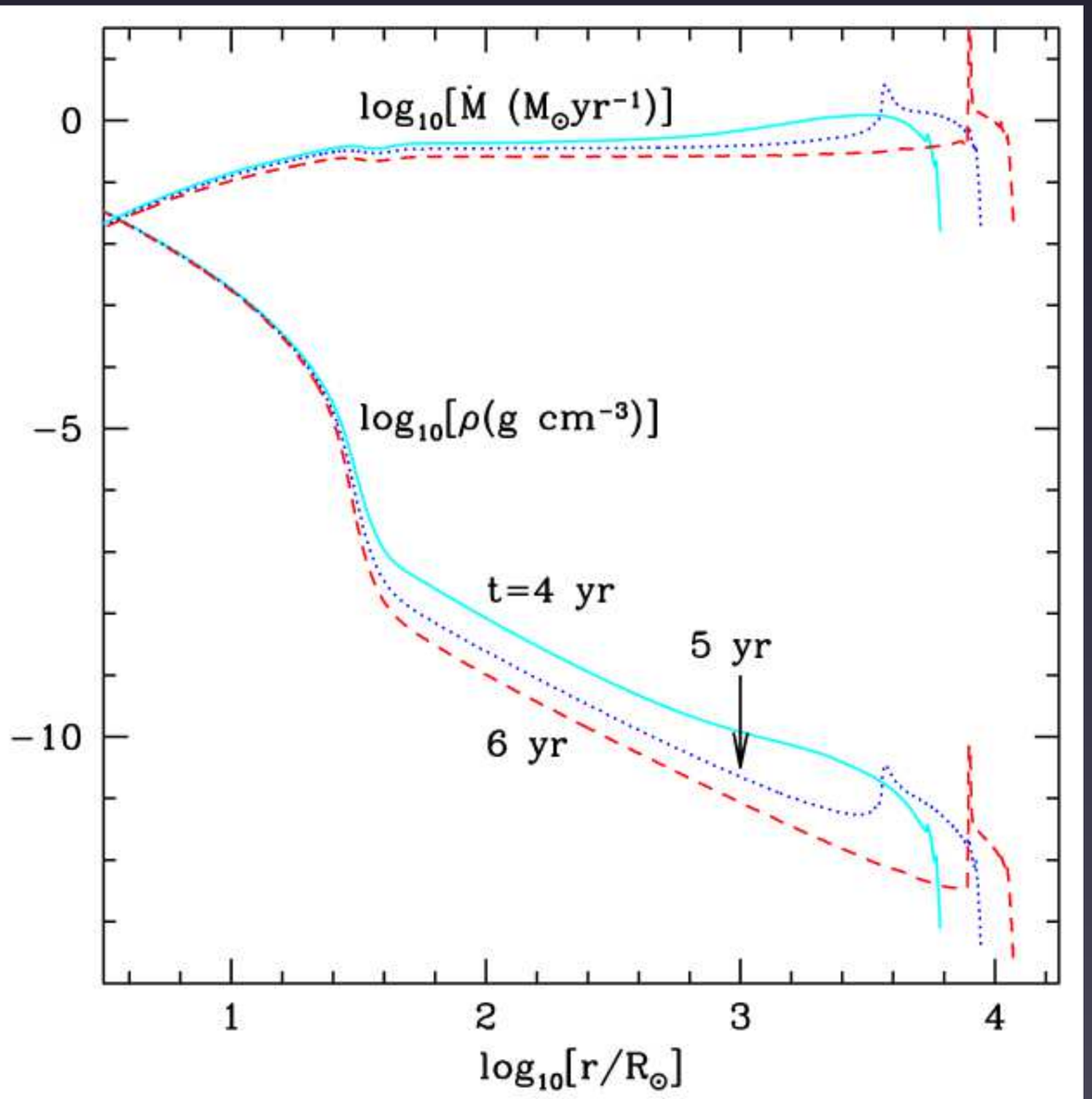

He Core
H Envelope
$E_{\rm bind,ext}$
$\rho_{\rm O-burn}$
$\rho_{\rm C-burn}$
$E_{\rm bind,ext}$ (erg)
ρ (g/cm^3)
Mass ($M_\odot$)
10^{51}
10^{49}
10^{47}
10^{45}
10^{6}
10^{3}
10^{0}
10^{-3}
10^{-6}
10^{-9}
10^{-12}
0
2
4
6
8
10
12

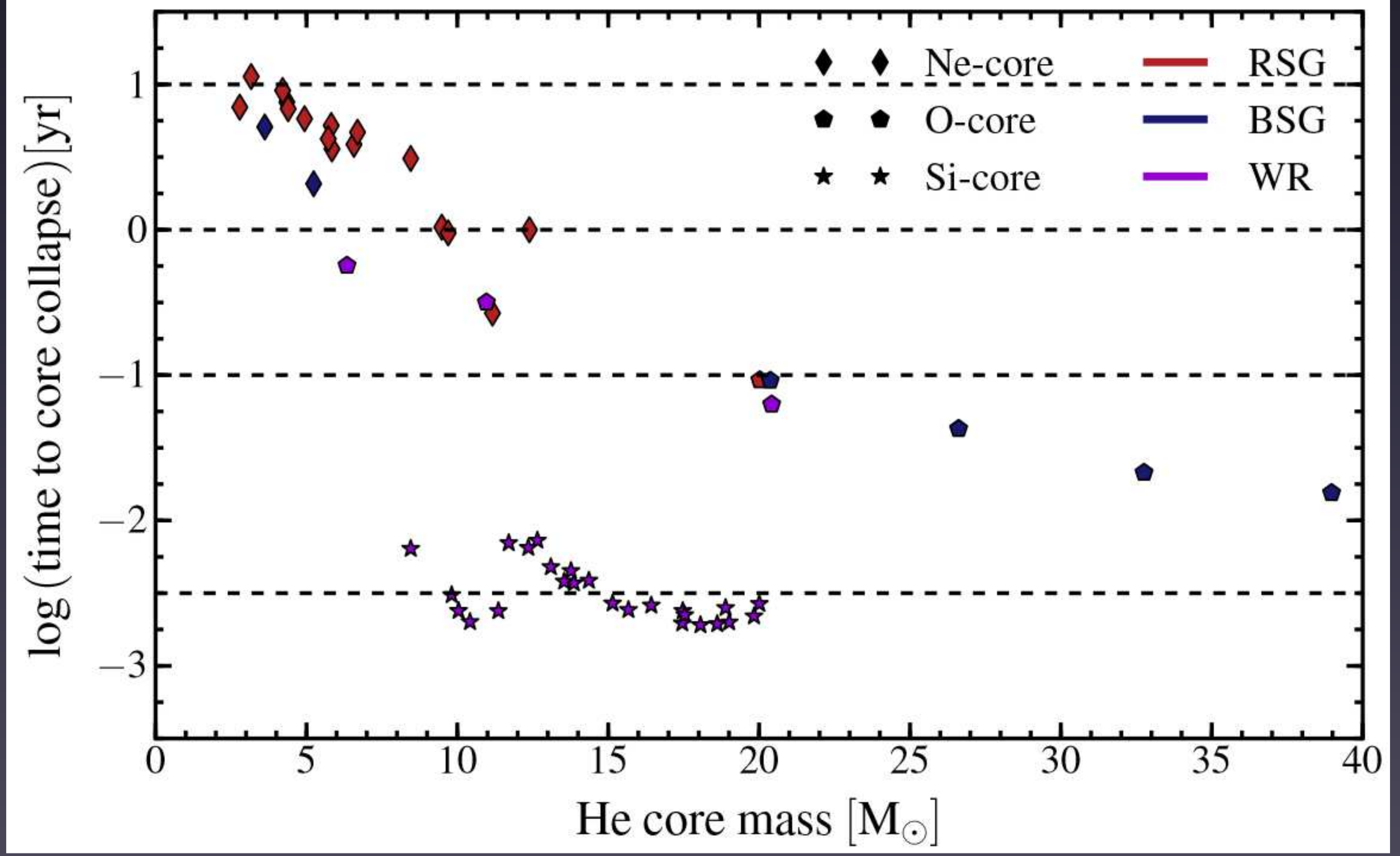

Wave Heating ($L_\odot$)
10^7
10^6
10^5
10^4
10^3
$L_{\rm heat}(r)$
$M_{\rm damp}$
0
2
4
6
8
10
12
Mass ($M_\odot$)
10^7
10^5
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
$M_{\rm damp}$ ($M_\odot$)


Time Scale (yrs)
Mass ($M_\odot$)
$t_{\rm therm}$
$t_{\rm heat}$
$t_{\rm dyn}$
+5.445


O-burning core
He-burning shell
H envelope
$L_{\rm conv}$
$L_{\rm rad}$
$L_{\rm adv}$
$L_{\rm heat}(r)$
Luminosity ($L_\odot$)
Radius ($R_\odot$)
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}


log10[Ṁ (M⊙yr⁻¹)]
log10[ρ(g cm⁻³)]
t=0
1 yr
2 yr
3 yr
0
−5
−10
1
2
3
4
log10[r/R⊙]


log10[Ṁ (M⊙yr⁻¹)]
log10[ρ(g cm⁻³)]
t=4 yr
5 yr
6 yr
0
−5
−10
1
2
3
4
log10[r/R⊙]


Ne-core
O-core
Si-core
RSG
BSG
WR
log (time to core collapse) [yr]
1
0
−1
−2
−3
0
5
10
15
20
25
30
35
40
He core mass [M⊙]

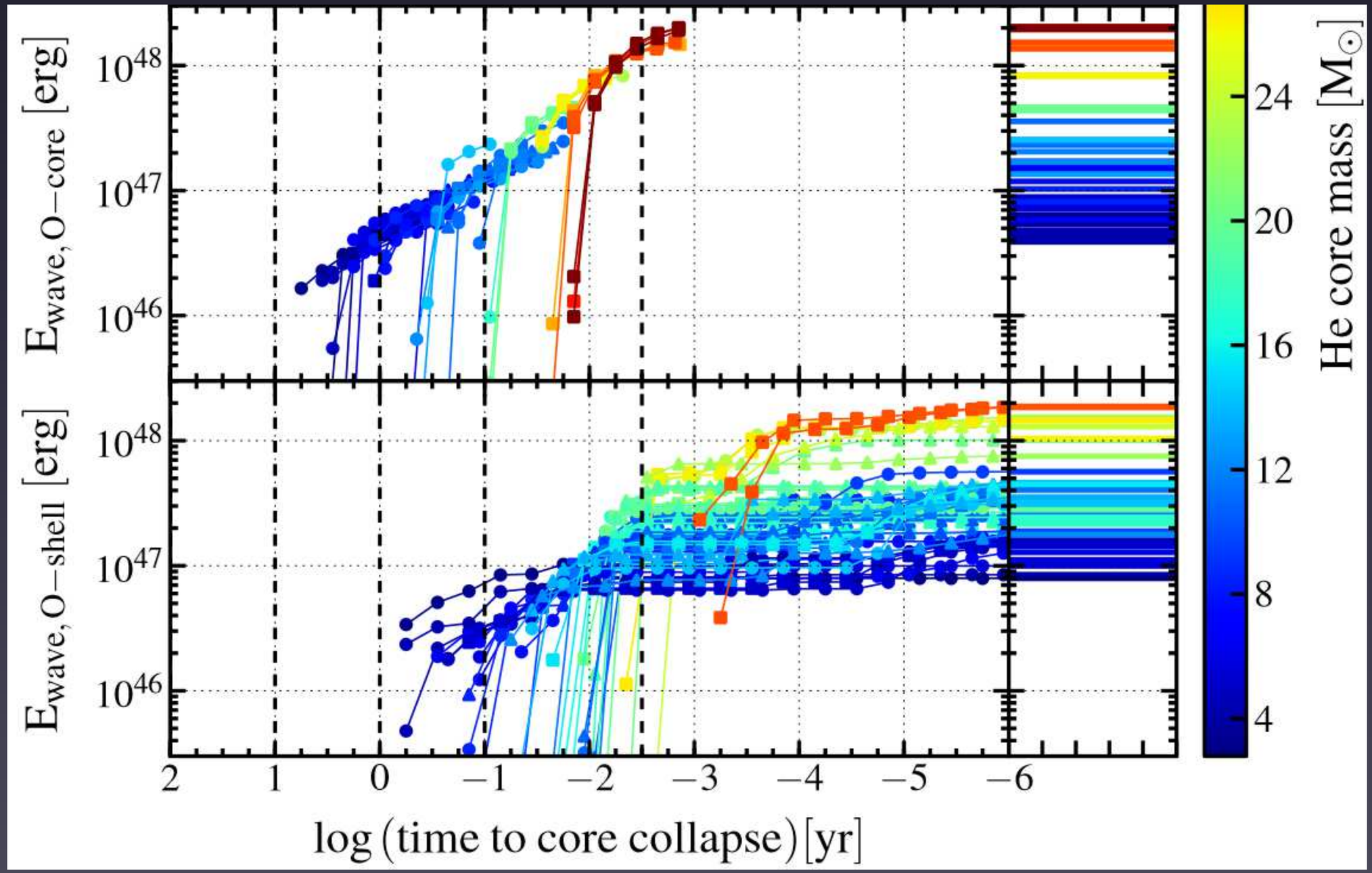
Wave Tunneling

To propagate into envelope of a massive star, waves must switch from gravity waves to pressure waves

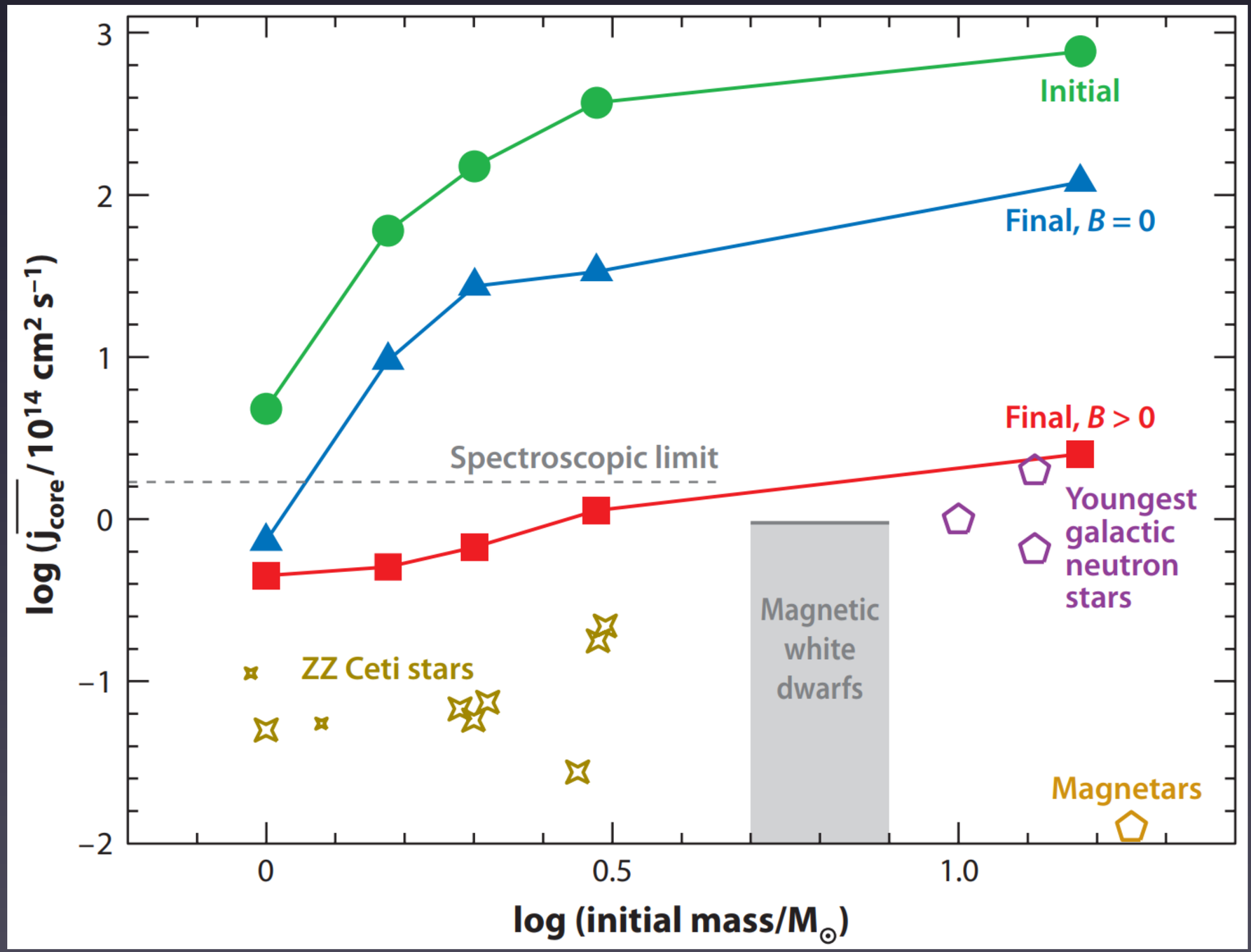
Waves “tunnel” through evanescent region separating gravity wave and sound wave cavities, analogous to particle tunneling in quantum mechanics

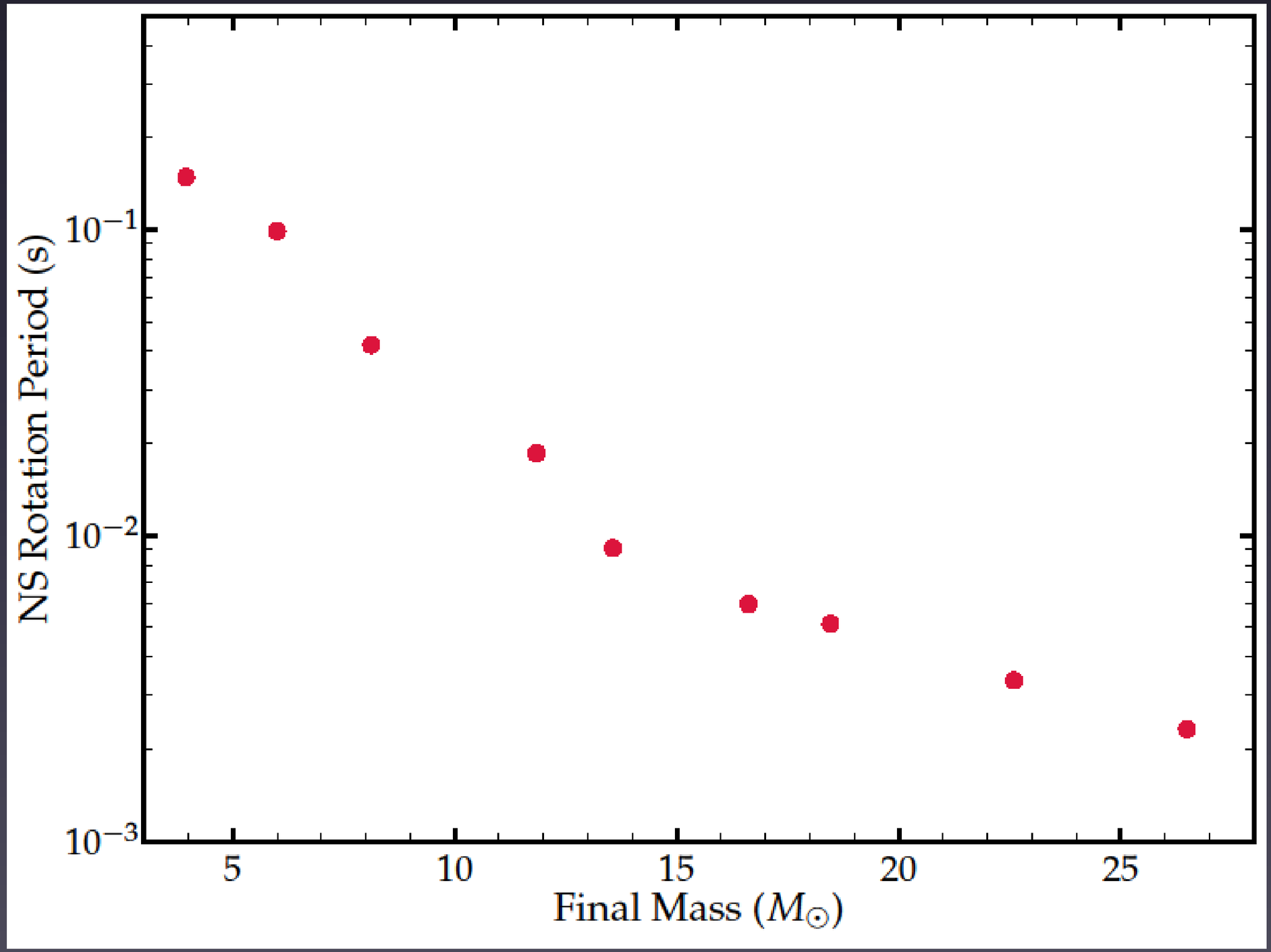
Fraction of wave energy that tunnels through evanescent region is

$$T^2 \sim \left(\frac{r_g}{r_p}\right)^{2l}$$

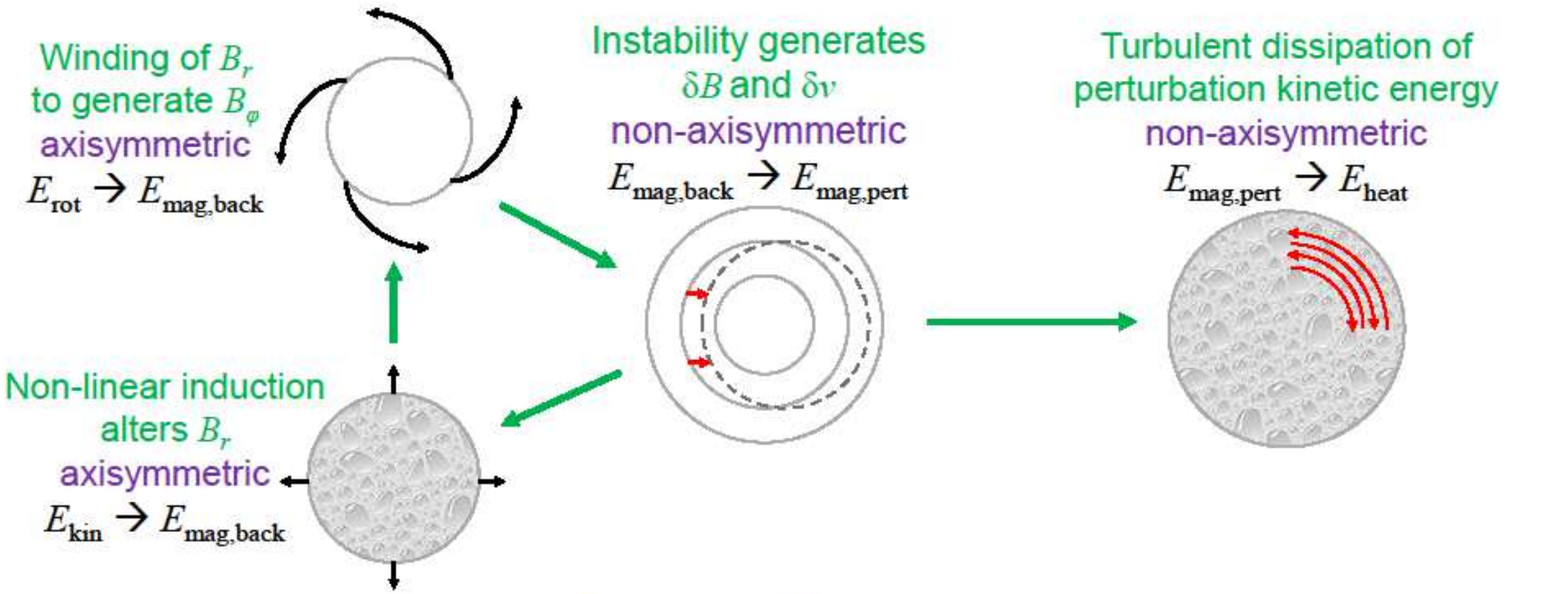


Shiode & Quataert (2014)

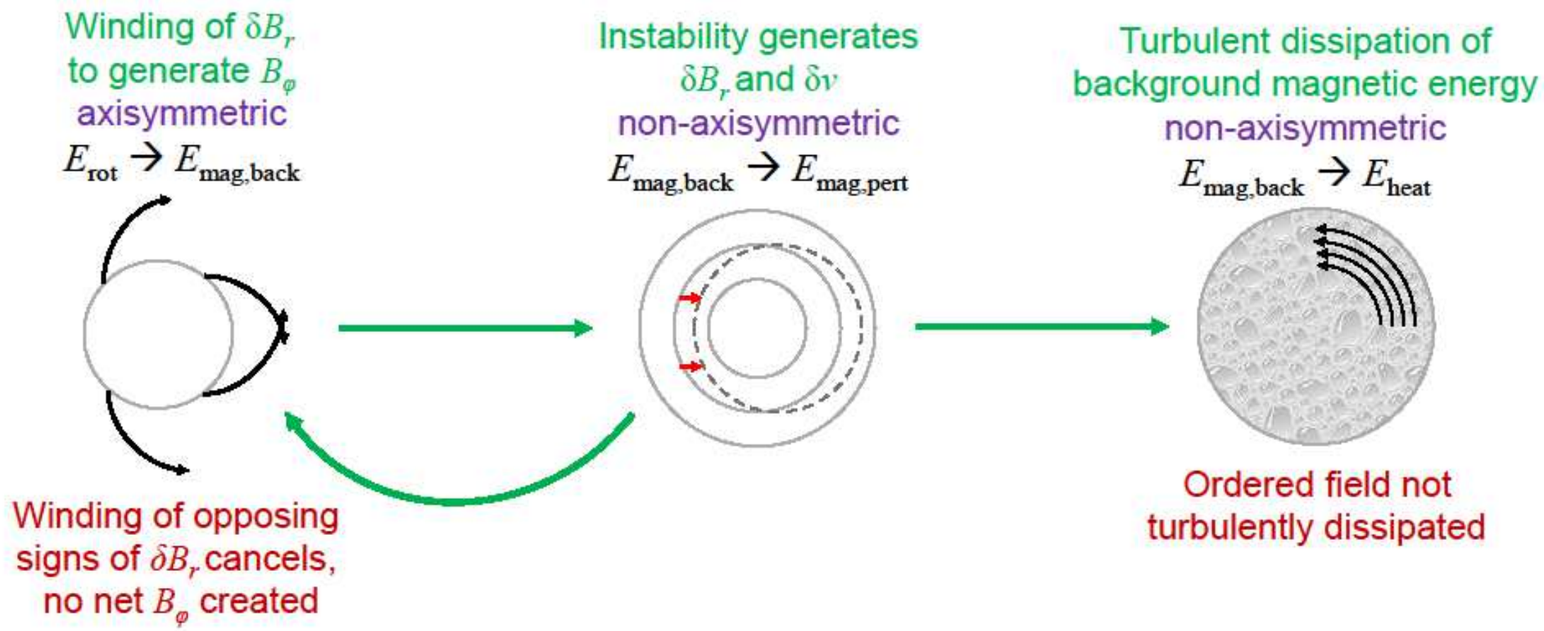

Initial
Final, $B = 0$
Final, $B > 0$
Spectroscopic limit
Youngest galactic neutron stars
Magnetic white dwarfs
ZZ Ceti stars
Magnetars
$\log (\overline{j_{core}}/10^{14}\ cm^2\ s^{-1})$
$\log$ (initial mass/$M_\odot$)
3
2
1
0
−1
−2
0
0.5
1.0


NS Rotation Period (s)
10^{-1}
10^{-2}
10^{-3}
5
10
15
20
25
Final Mass ($M_\odot$)

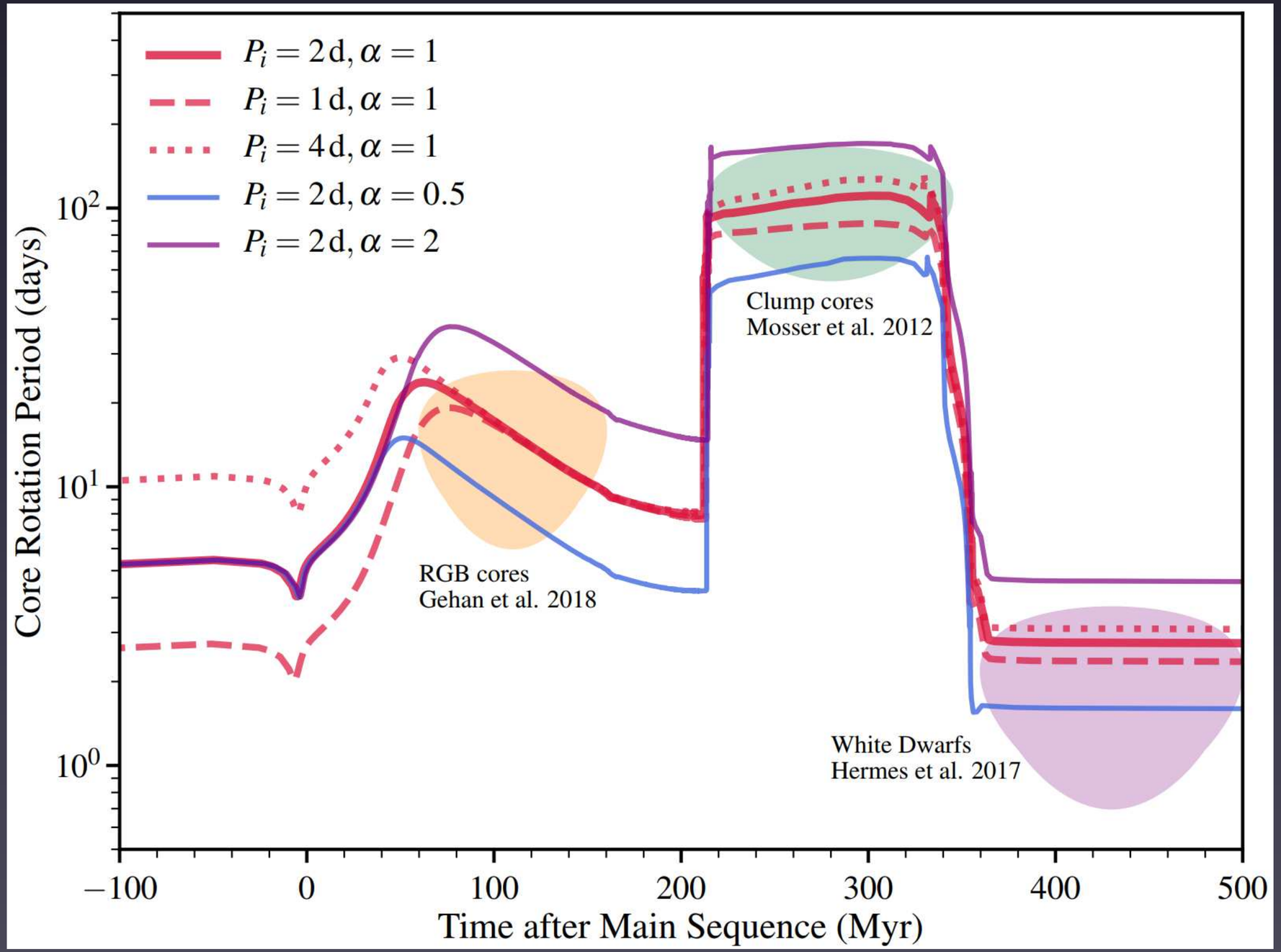
Our Picture

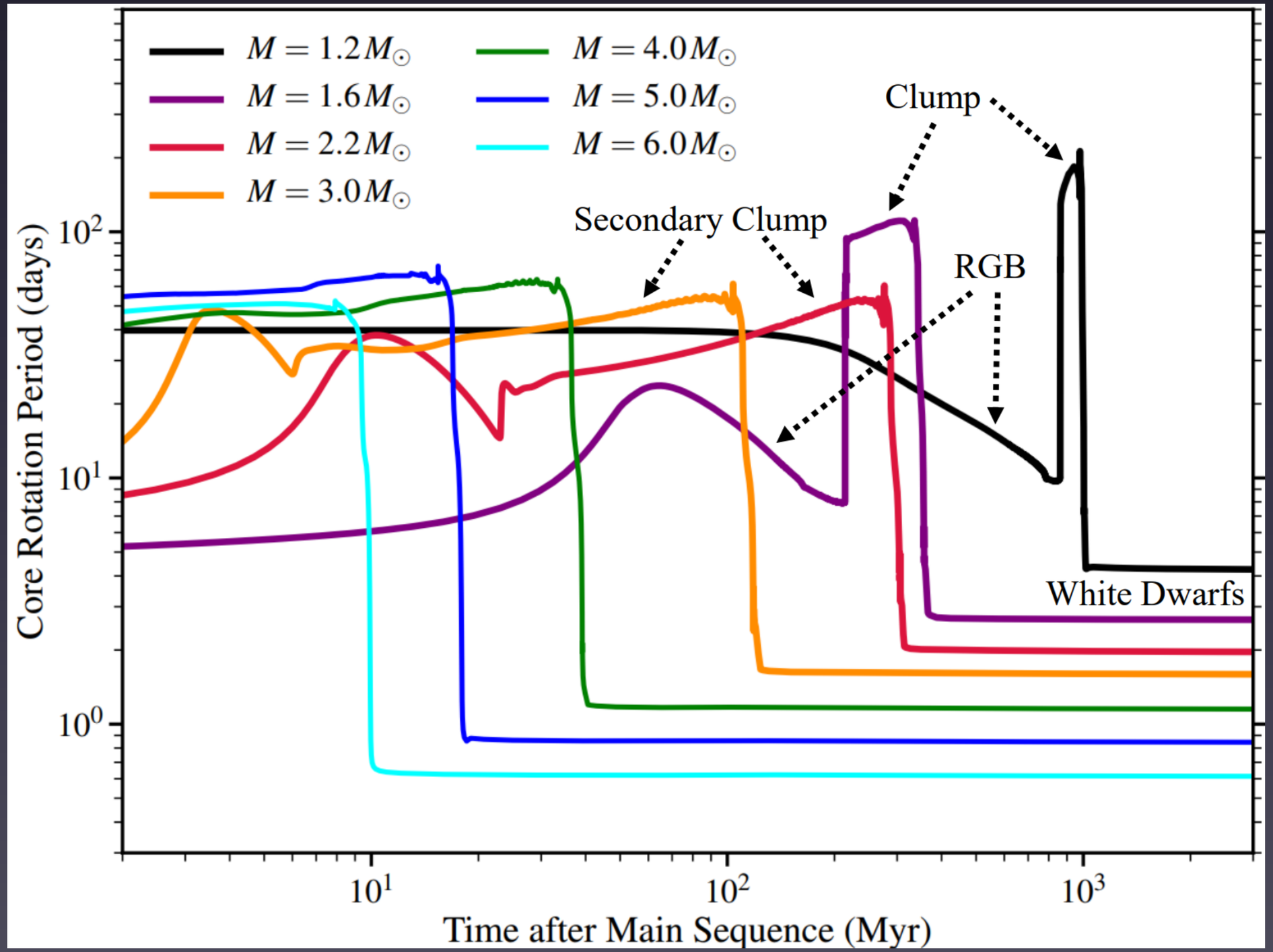


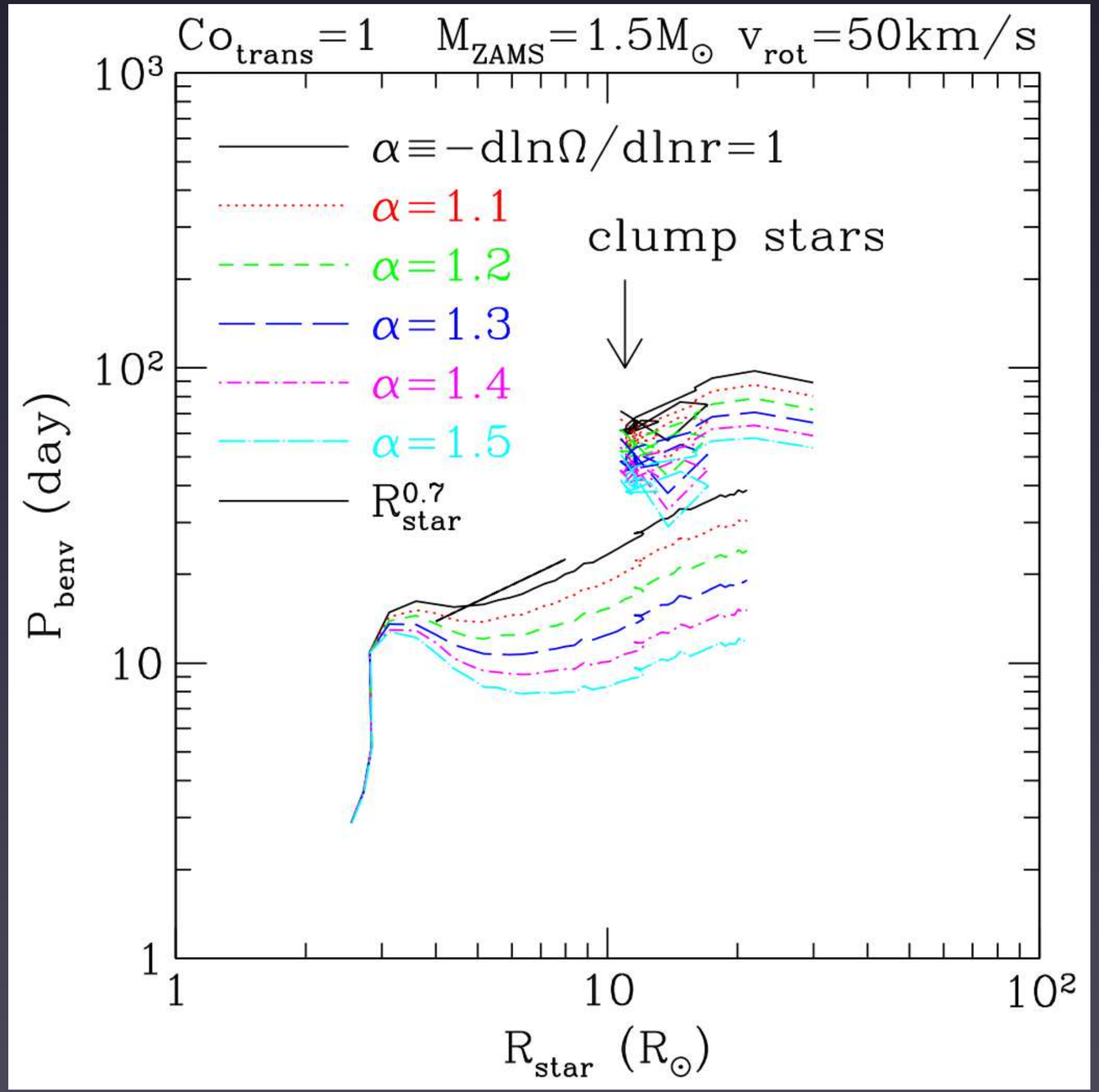
Spruit's Picture



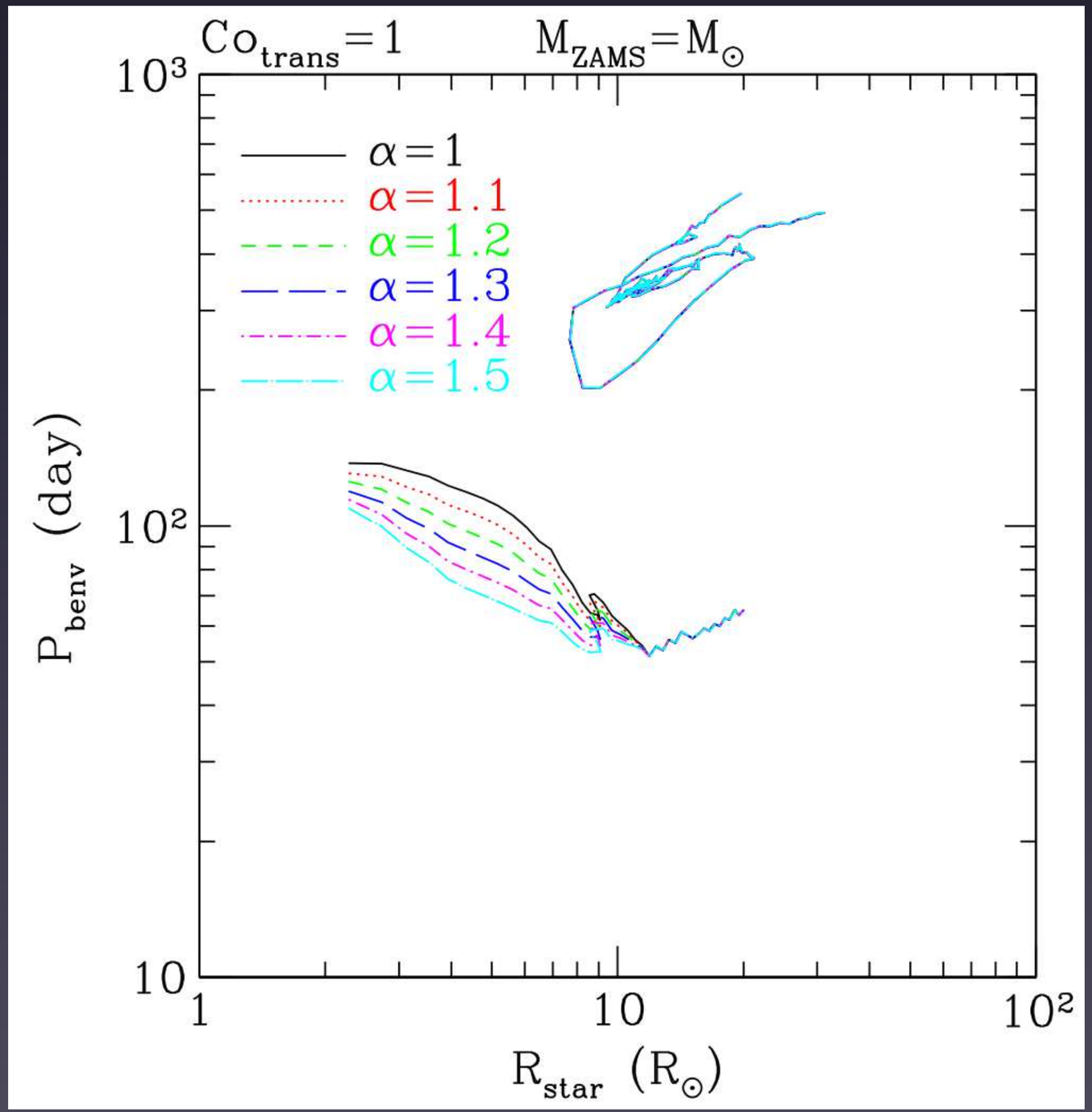
- Relatively insensitive to initial conditions
- Slight dependence on parameter α




$M = 1.2 M_\odot$
$M = 1.6 M_\odot$
$M = 2.2 M_\odot$
$M = 3.0 M_\odot$
$M = 4.0 M_\odot$
$M = 5.0 M_\odot$
$M = 6.0 M_\odot$
Clump
Secondary Clump
RGB
White Dwarfs
Core Rotation Period (days)
10^2
10^1
10^0
10^1
10^2
10^3
Time after Main Sequence (Myr)



Kissin & Thompson 2015



Kissin & Thompson 2015