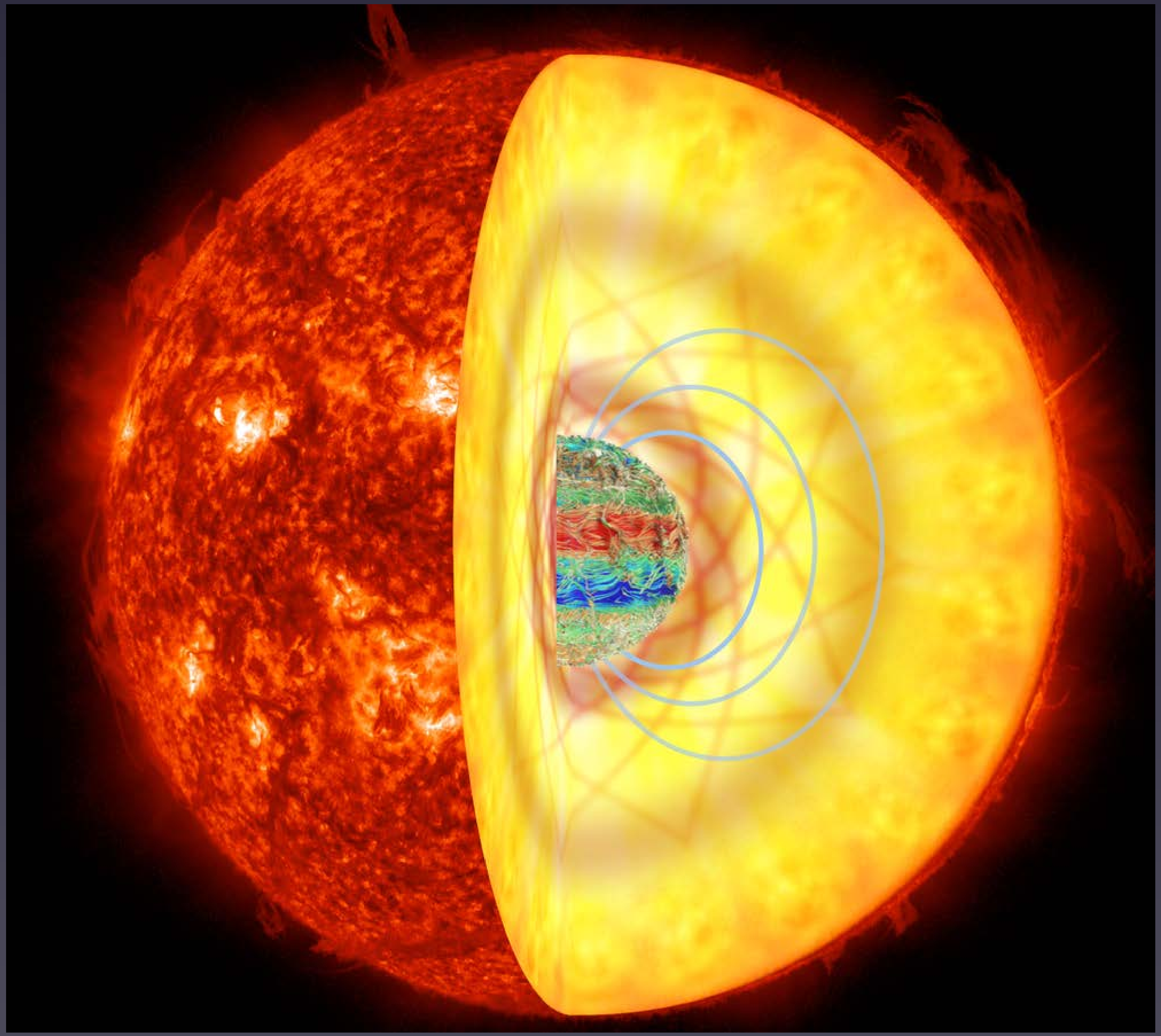
Surprising Impacts of ~~Gravitational~~ Gravity Waves

Jim Fuller

Caltech



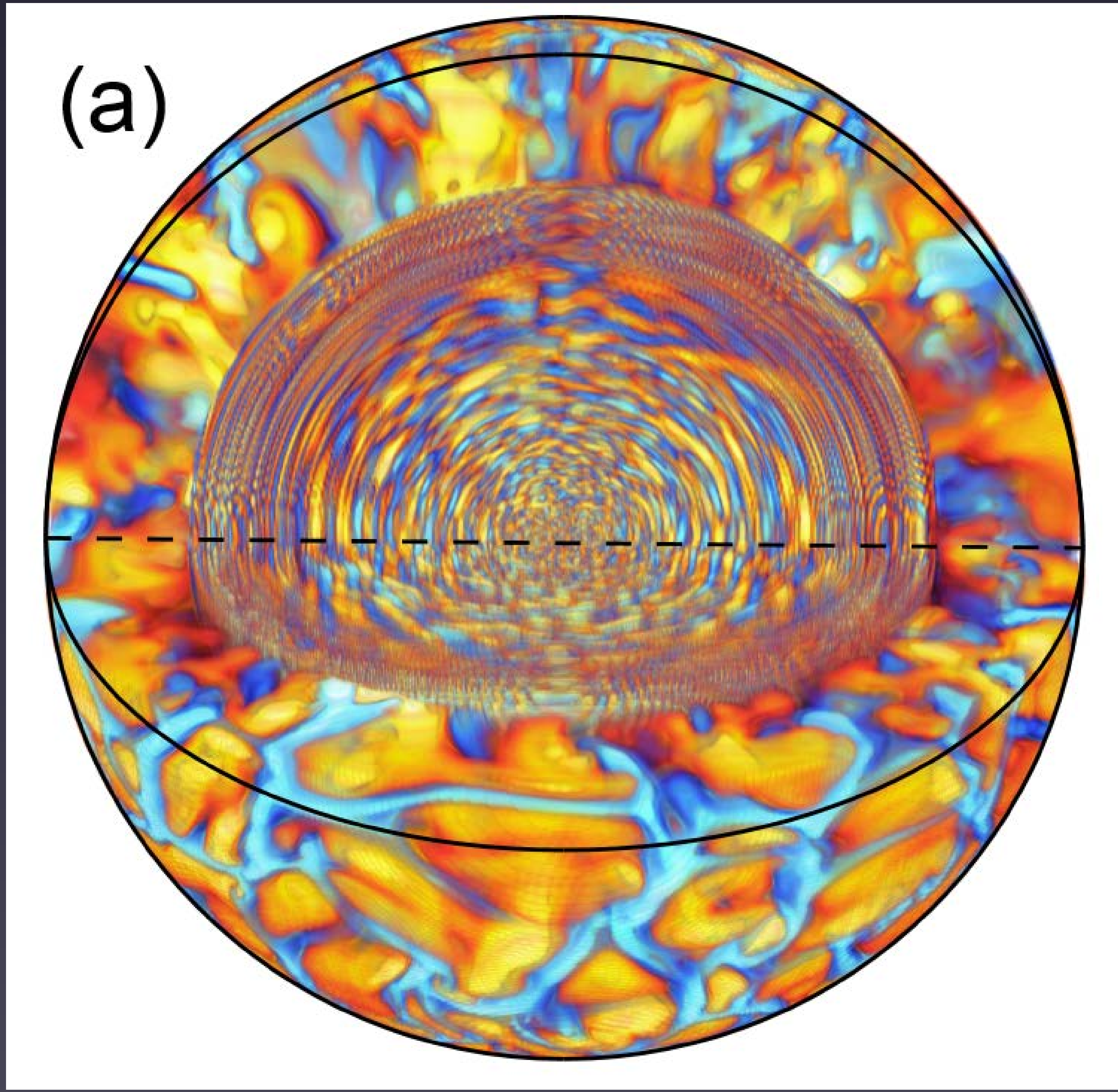
Why you should care about gravity waves

Gravity waves are everywhere in astrophysics
- Stars, planets, disks, galaxy clusters

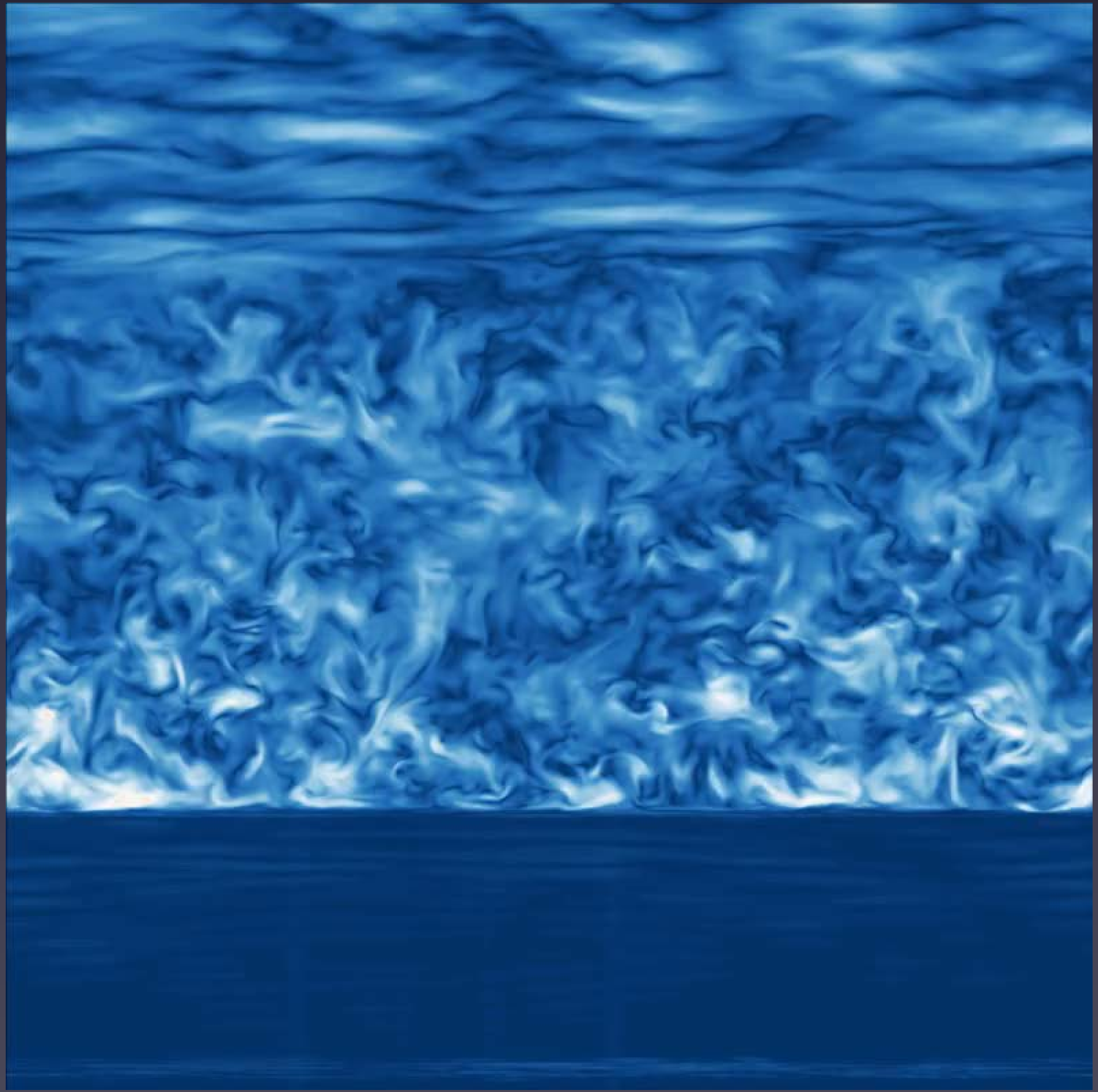
Gravity waves carry information
- Asteroseismology

Gravity waves carry energy and angular momentum
- Effect on evolution of stars, planets, moons

Gravity Waves are Ubiquitous



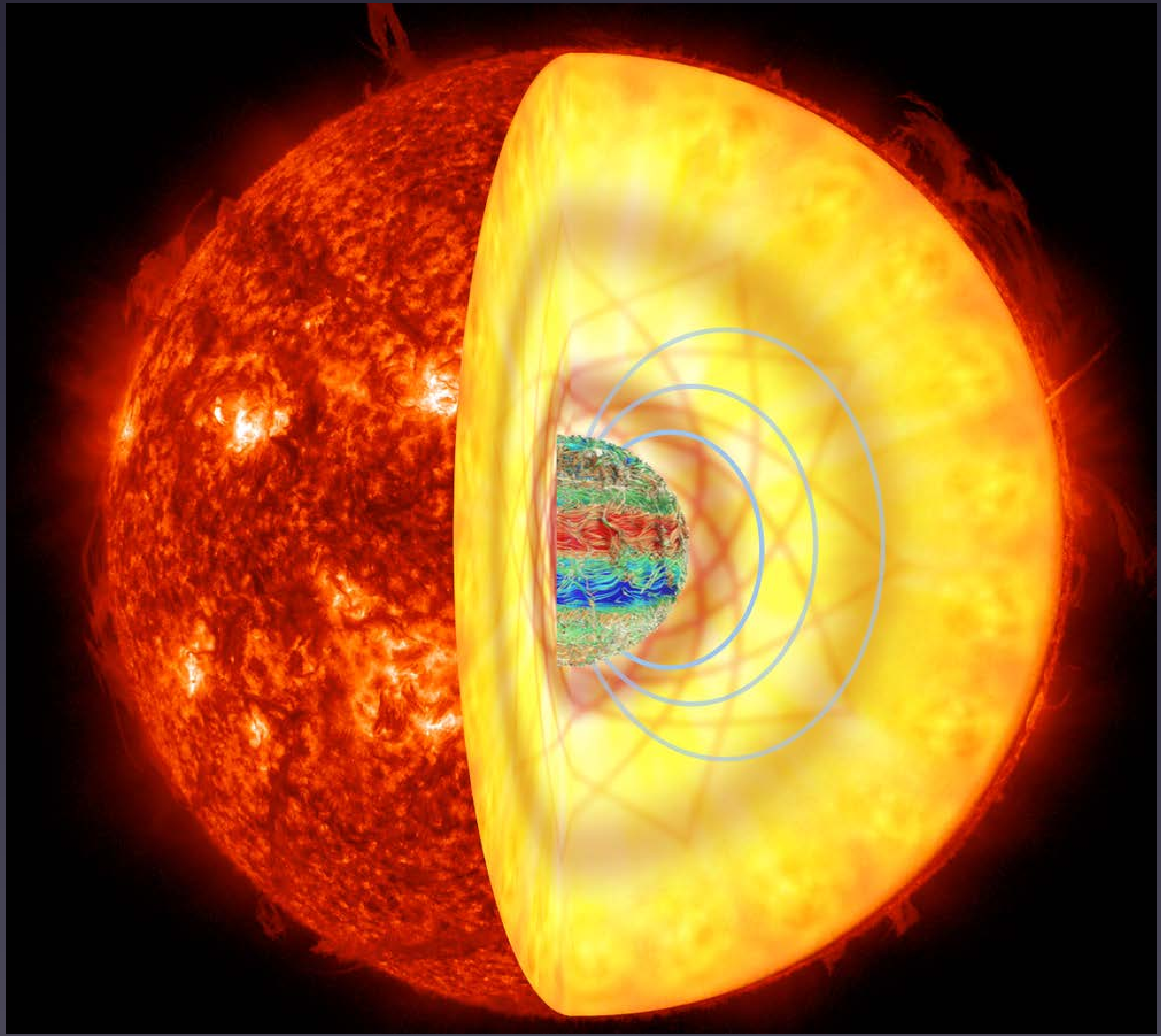
Alvan et al. 2014



Credit: Andrea Cristini

Magnetoasteroseismology

Very little known about magnetic fields inside of stars



Collaborators

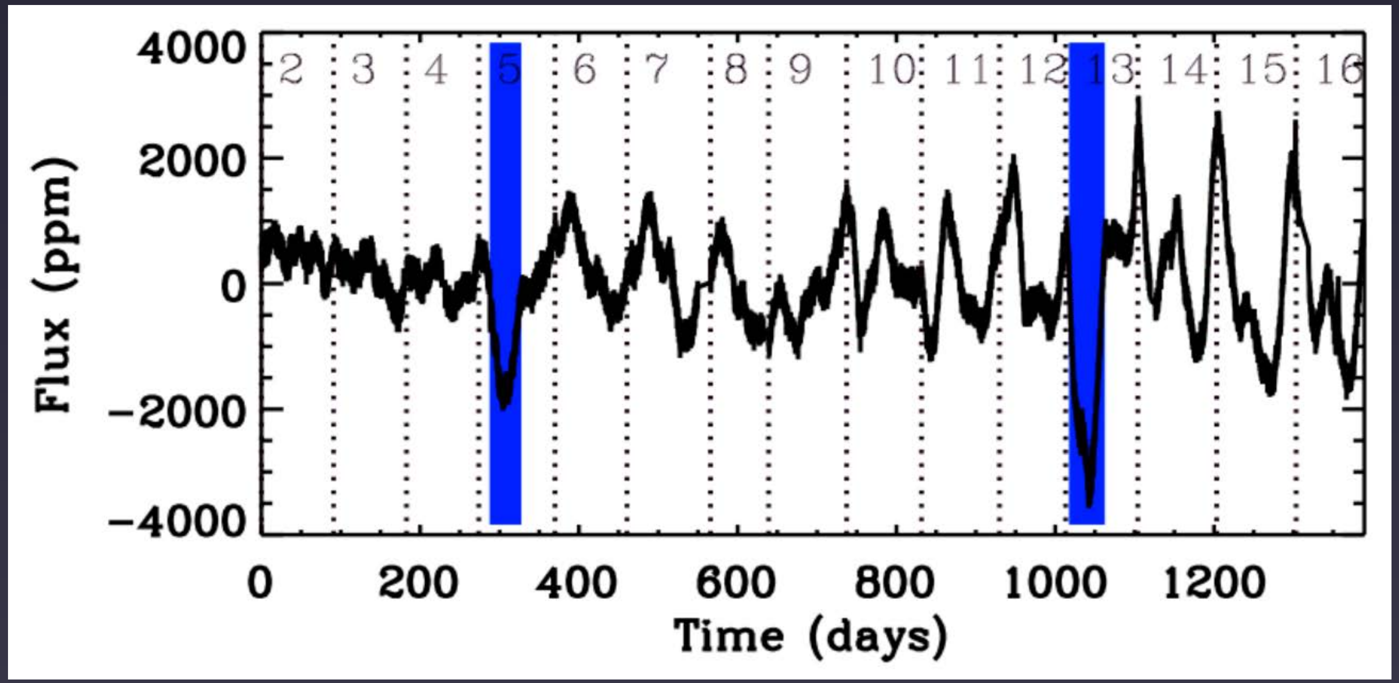
Matteo Cantiello

Dennis Stello

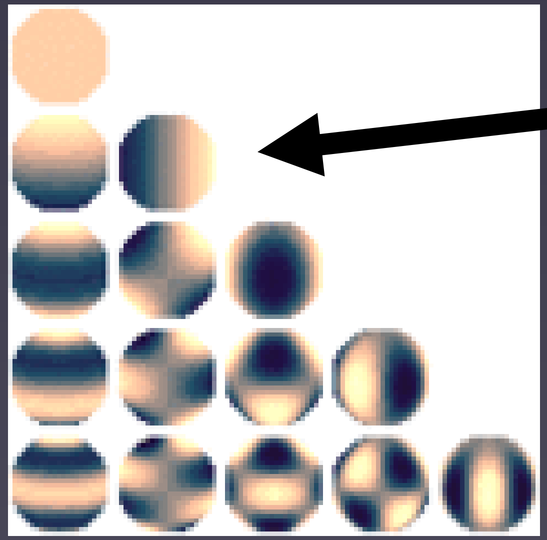
Daniel Lecoanet

Lars Bildsten, Rafael Garcia, Tim Bedding, Daniel Huber, Victor Silva Aguirre

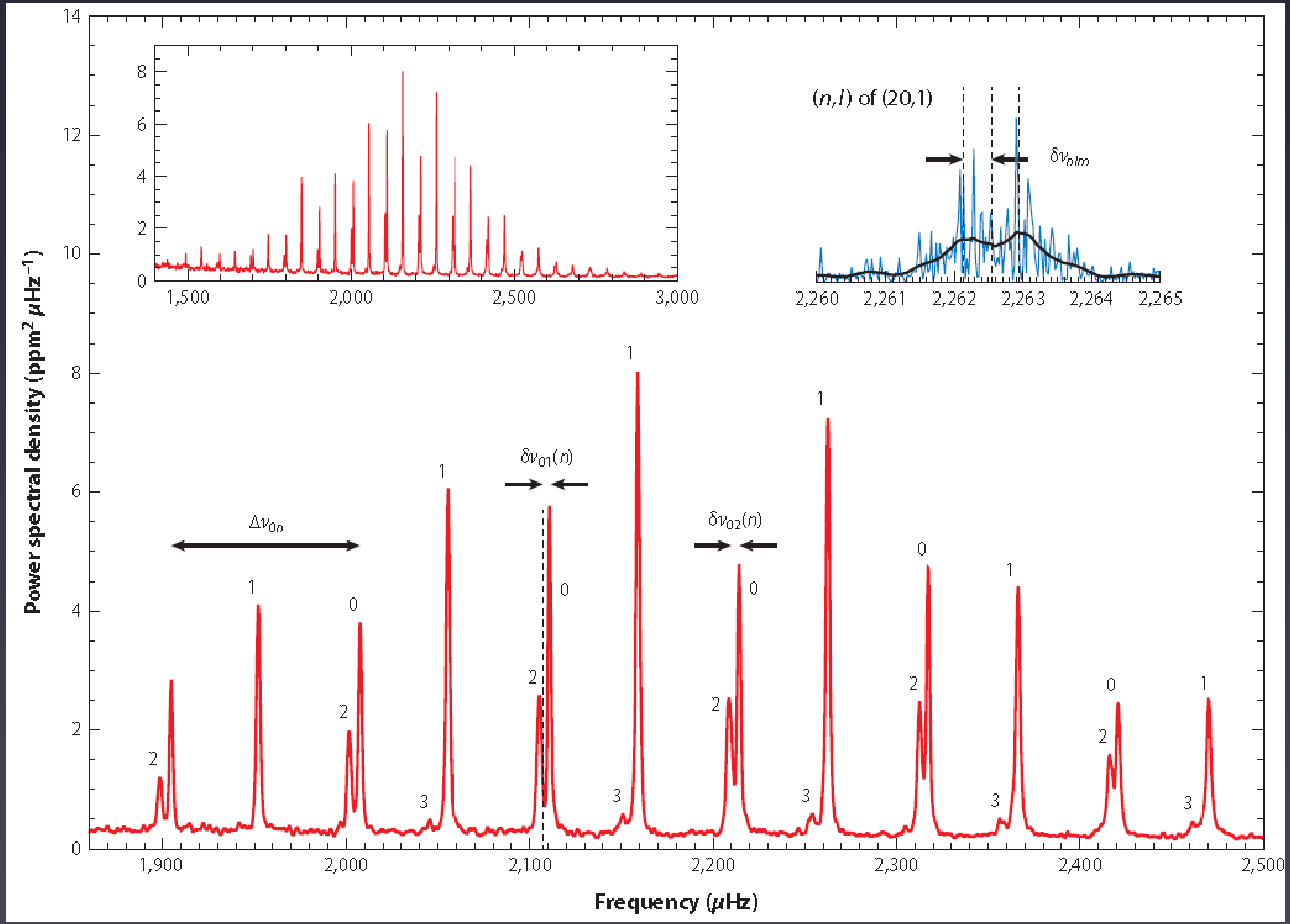
Asteroseismology Basics



Fourier Transform



l=1 dipole modes



Chaplin & Miglio 2013

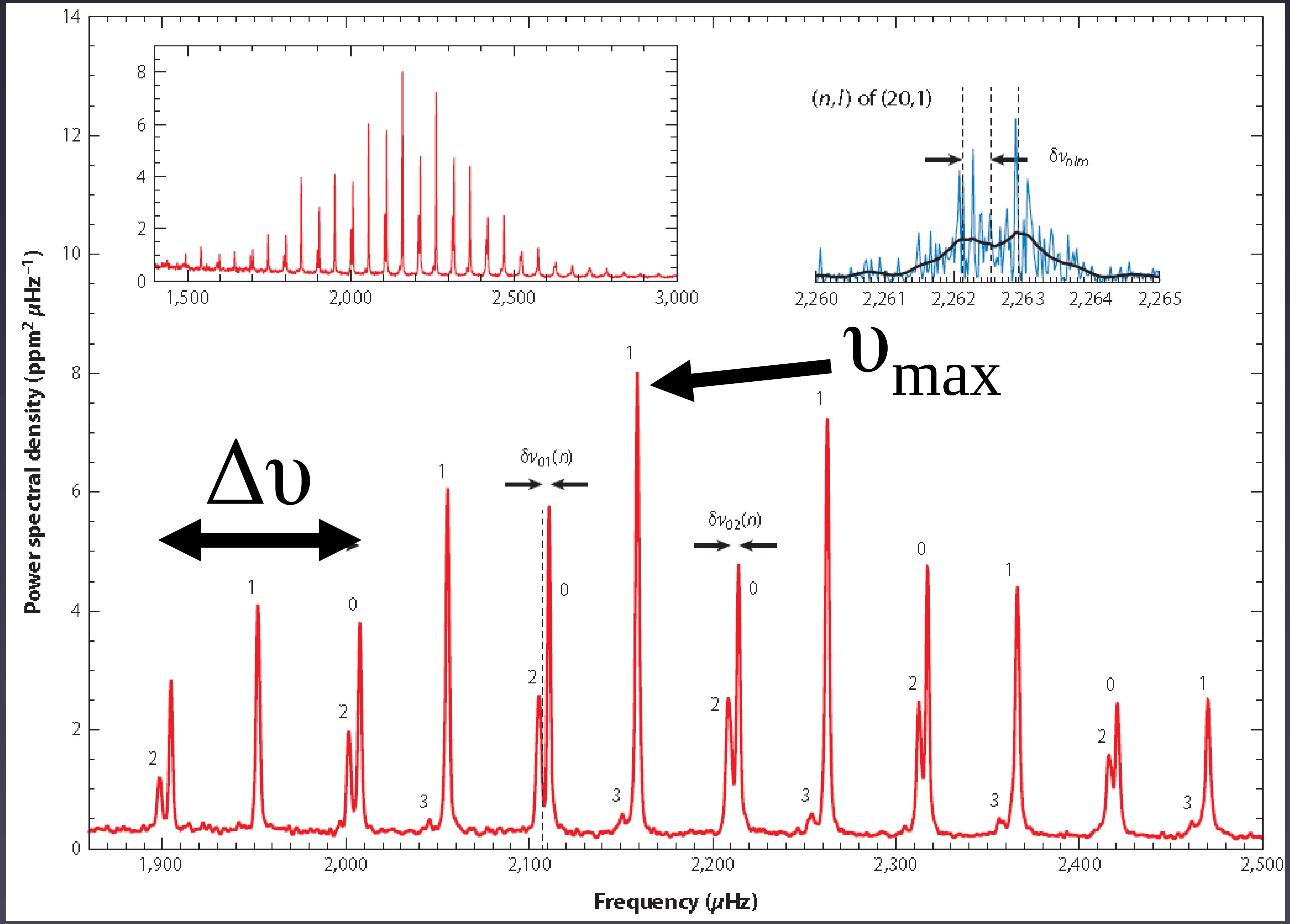
Asteroseismology basics, continued

Oscillations excited by convection, with frequency near dynamical frequency of stellar atmosphere:

$$\nu_{\rm max} \propto \nu_{\rm ac} \propto \frac{c}{H} \propto g\, T_{\rm eff}^{-1/2}$$

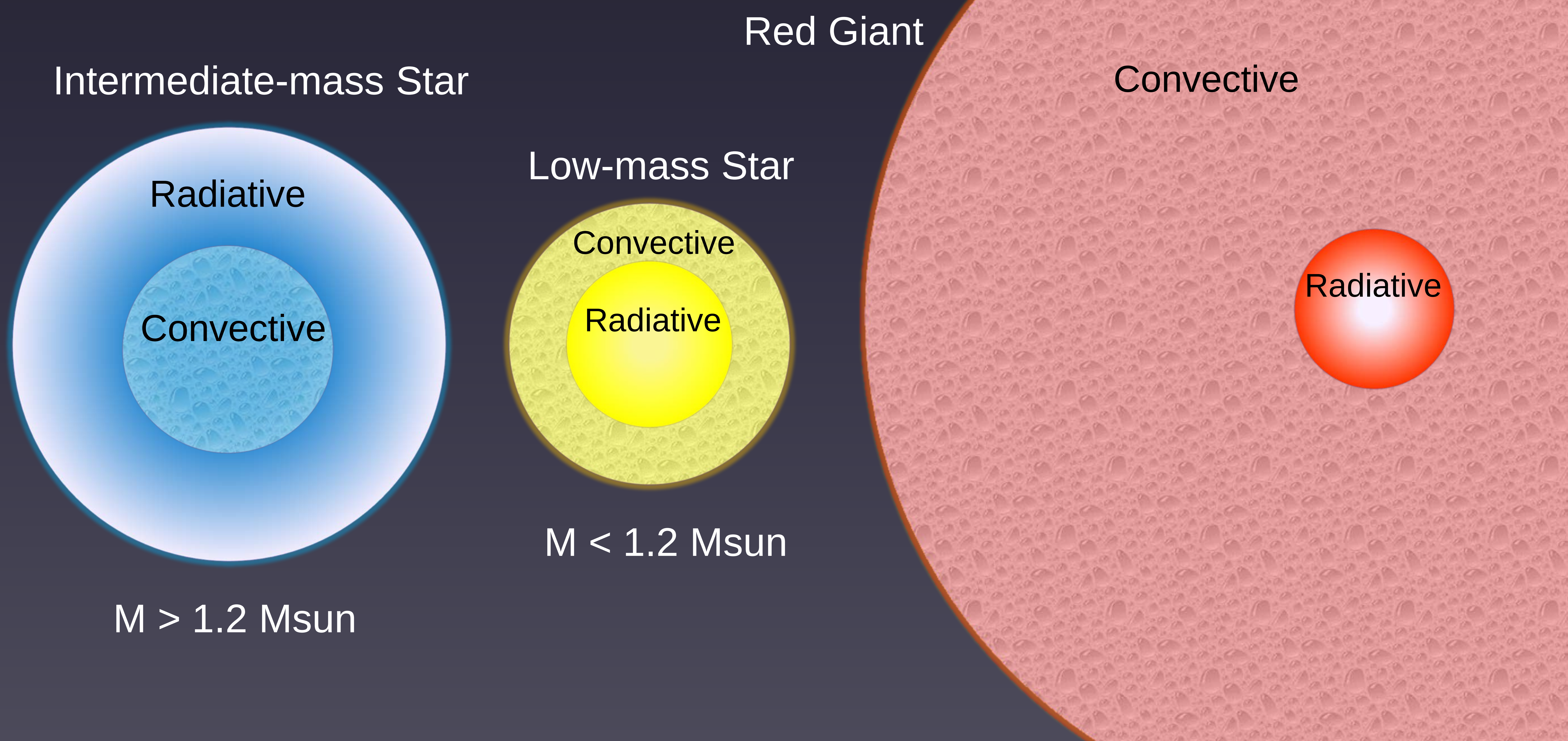
Oscillations separated by dynamical frequency of star:

$$\Delta\nu = \left(2\int_0^R \frac{dr}{c}\right)^{-1} \sim \sqrt{G\rho}$$



Chaplin & Miglio 2013

Stellar Structure



Wave Propagation in the Red Giants

- Dispersion relation:

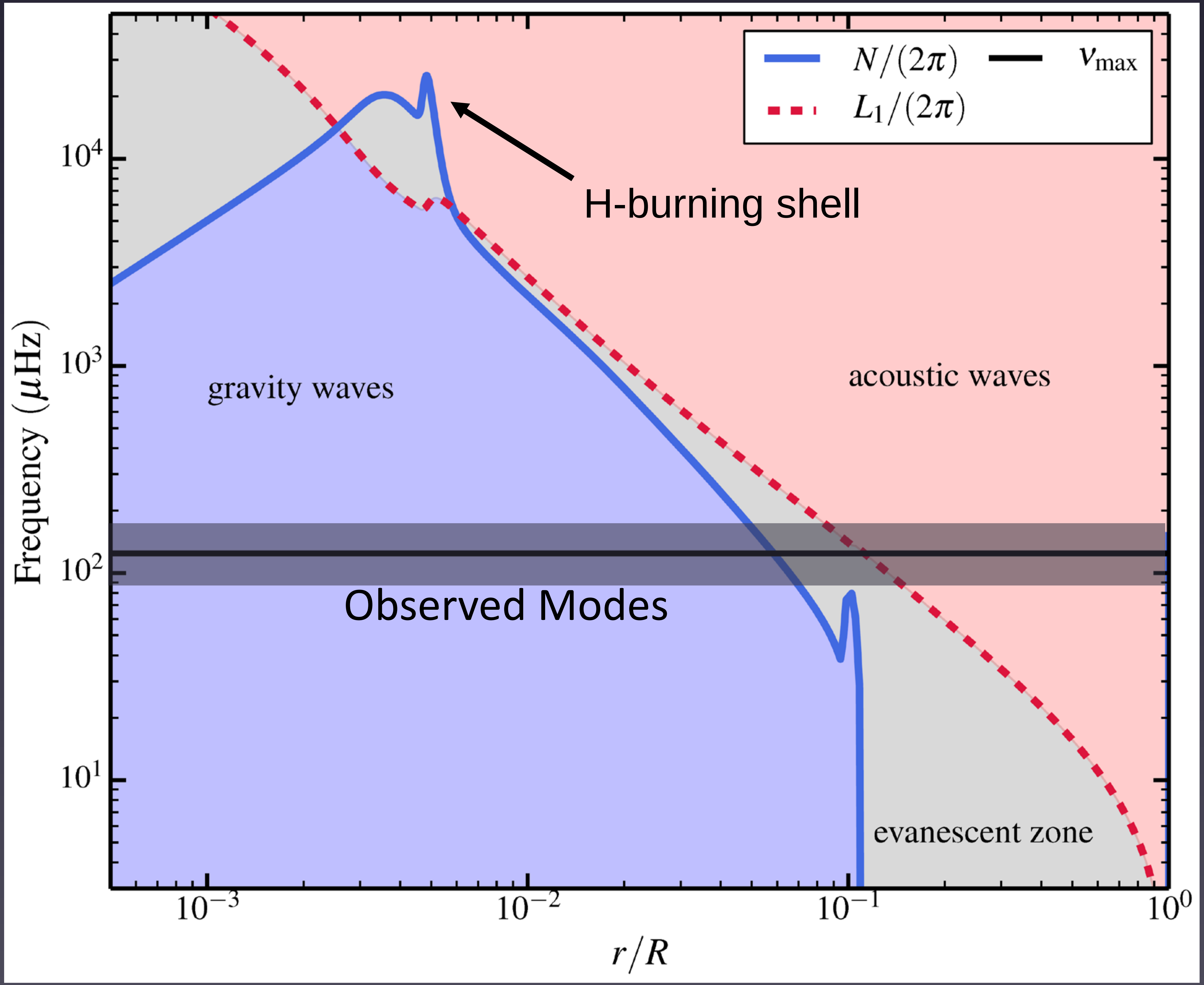
$$k_r^2 = \frac{\left(N^2 - \omega_{\text{wave}}^2\right)\left(L_\ell^2 - \omega_{\text{wave}}^2\right)}{\omega_{\text{wave}}^2 c_s^2}$$

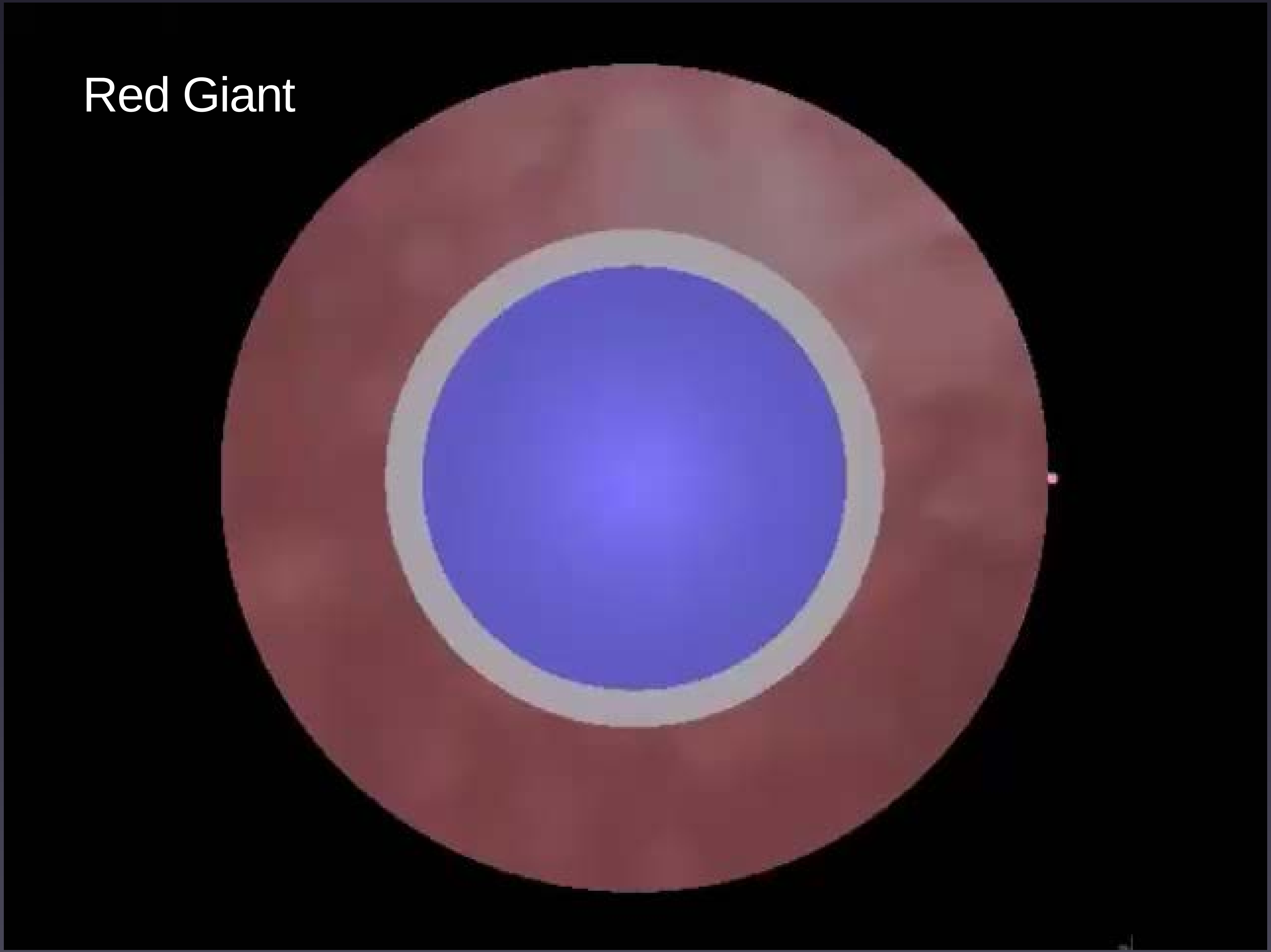
- Acoustic waves propagate where $\omega > N$, $\omega > L_l$

$$k_{r,\text{ac}}^2 \simeq \frac{\omega_{\text{wave}}^2}{c_s^2}$$

- Gravity waves propagate where $\omega < N$, $\omega < L_l$

$$k_{r,\text{IGW}}^2 \simeq \frac{\ell(\ell+1)N^2}{\omega_{\text{wave}}^2 r^2}$$




Red Giant

The Mixed Mode Spectrum

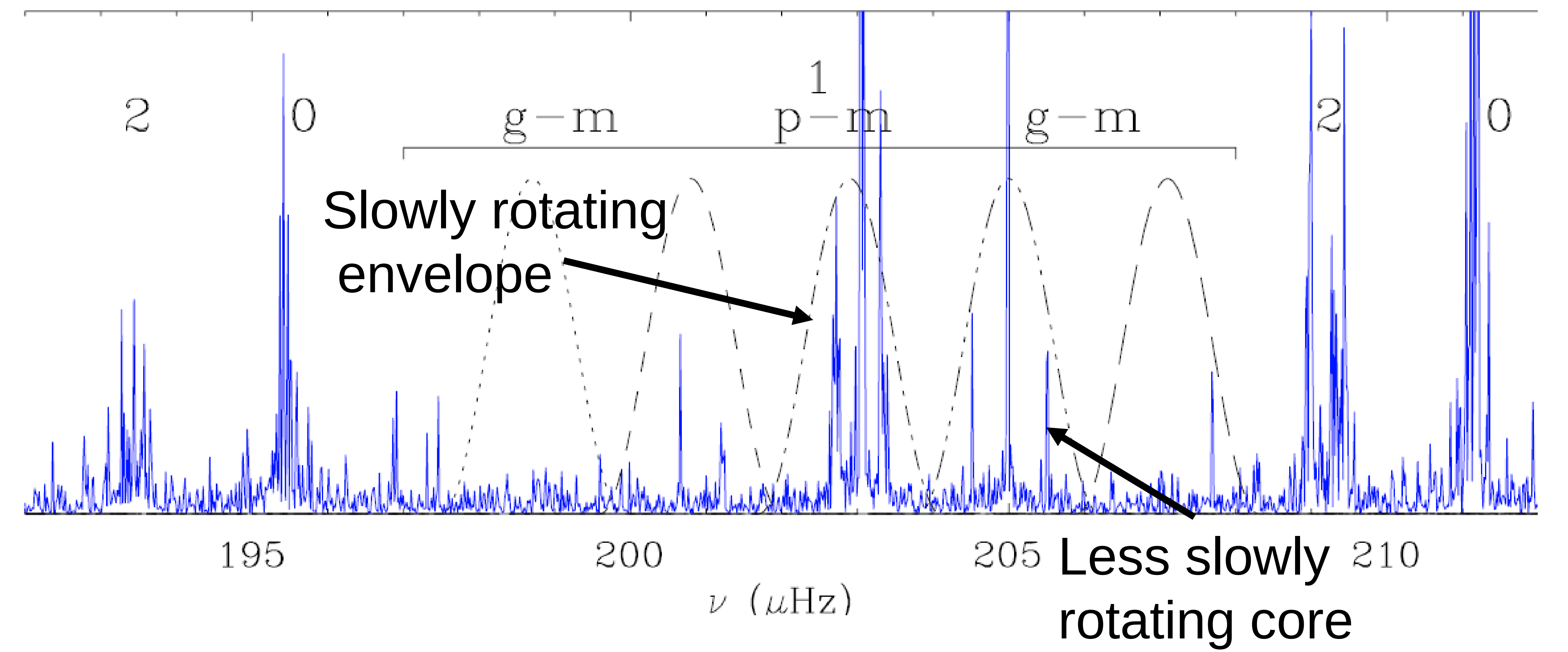


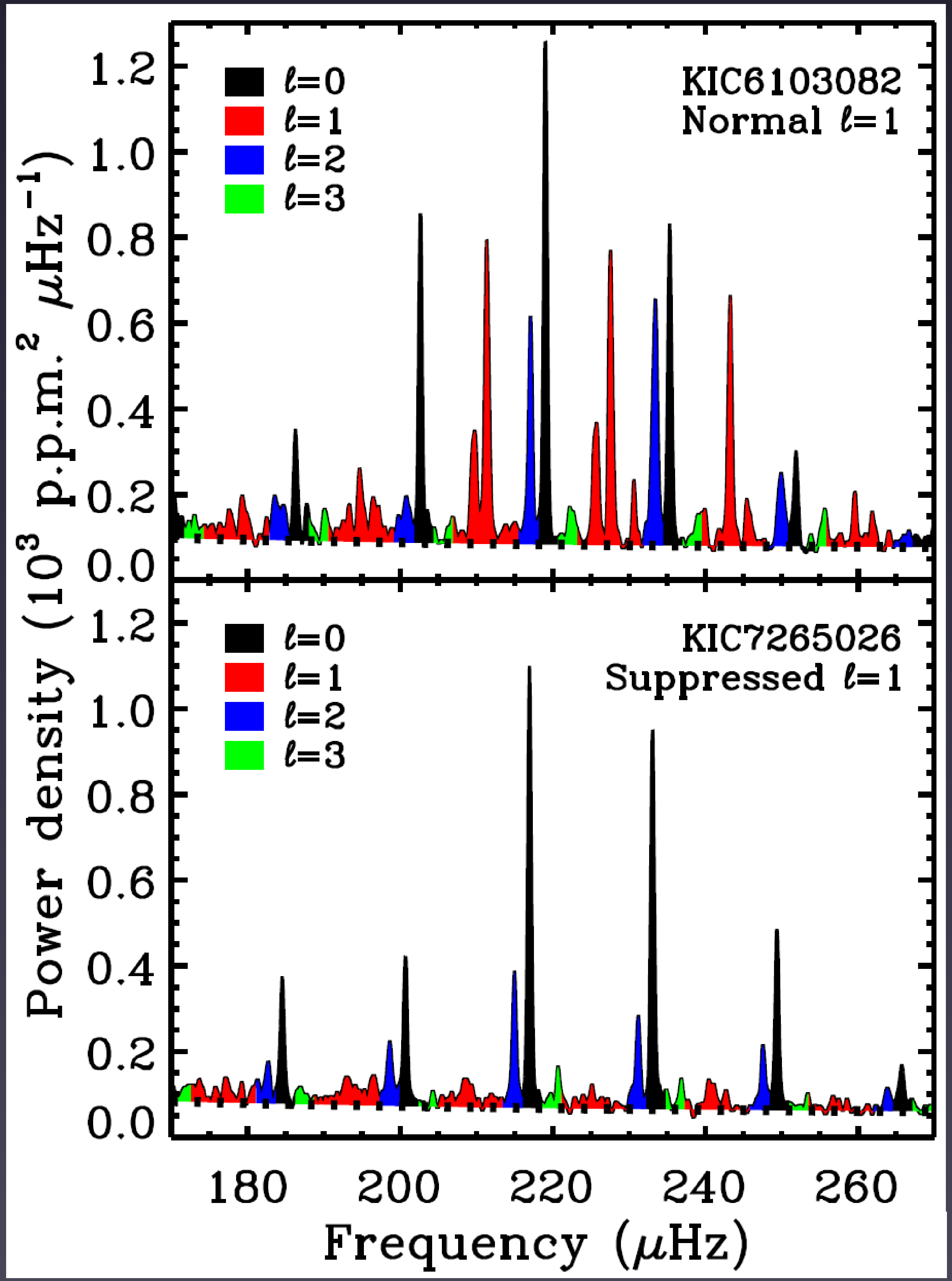
Fig. 3. Zoom on the oscillation spectrum of the target KIC 10777816. Different narrow filters centered in the $\ell = 1$ mixed mode range, indicated with different line styles, allow us to measure a local rotational splitting in each filter. For clarity, only those filters centered on possible multiplets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

Mosser et al. 2012

A mystery arises…

A class of red giants with extremely low amplitude, “suppressed” dipole modes

Mosser et al. 2011

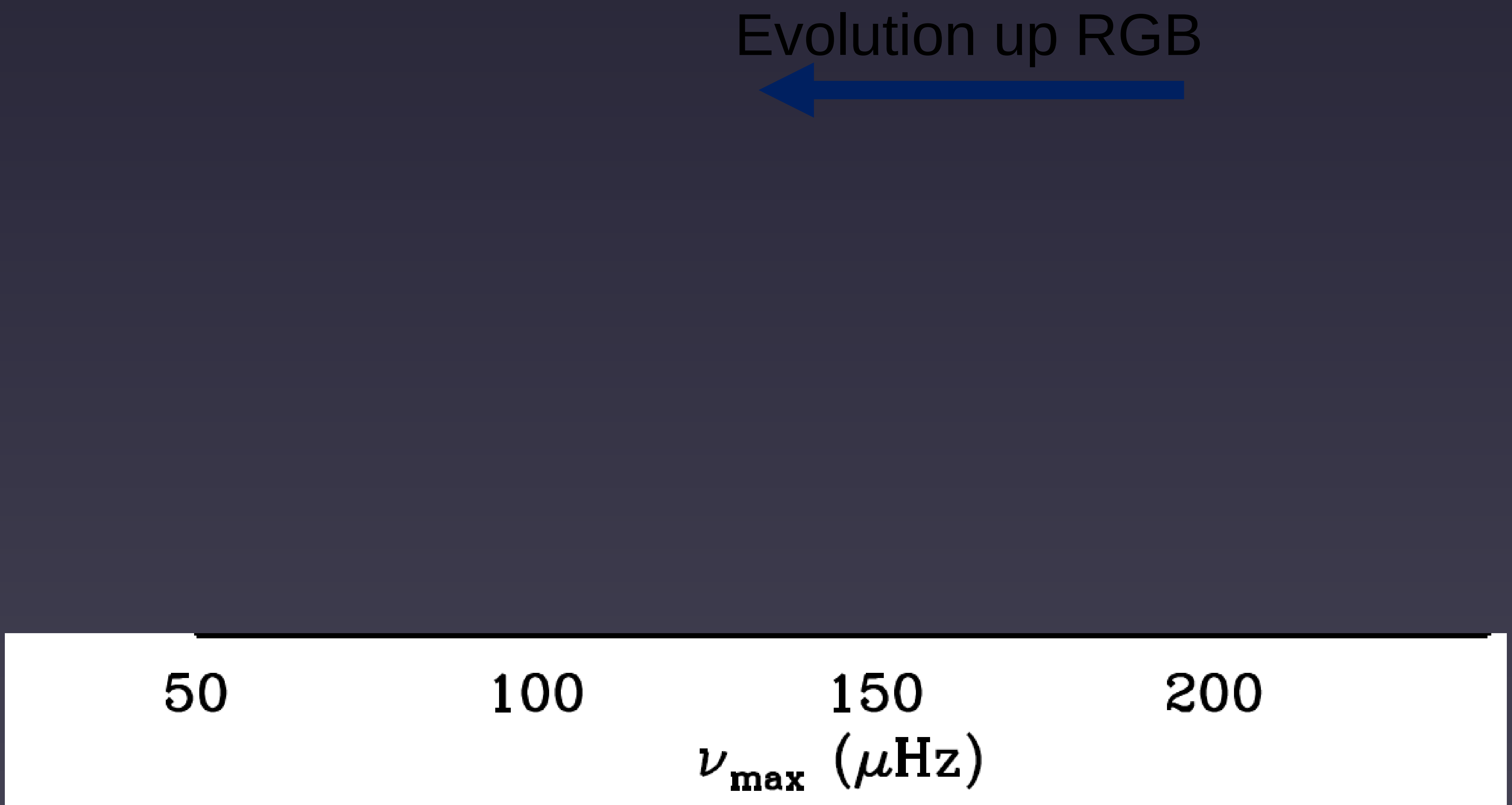


Stello, Cantiello, **Fuller** + 2016

The plot thickens…

- The dipole suppressed stars are common, occurring in ~20% of red giants

- The visibility of dipole modes depends on the evolutionary state of the star



Stello, Cantiello, **Fuller** + 2016

An idea develops…

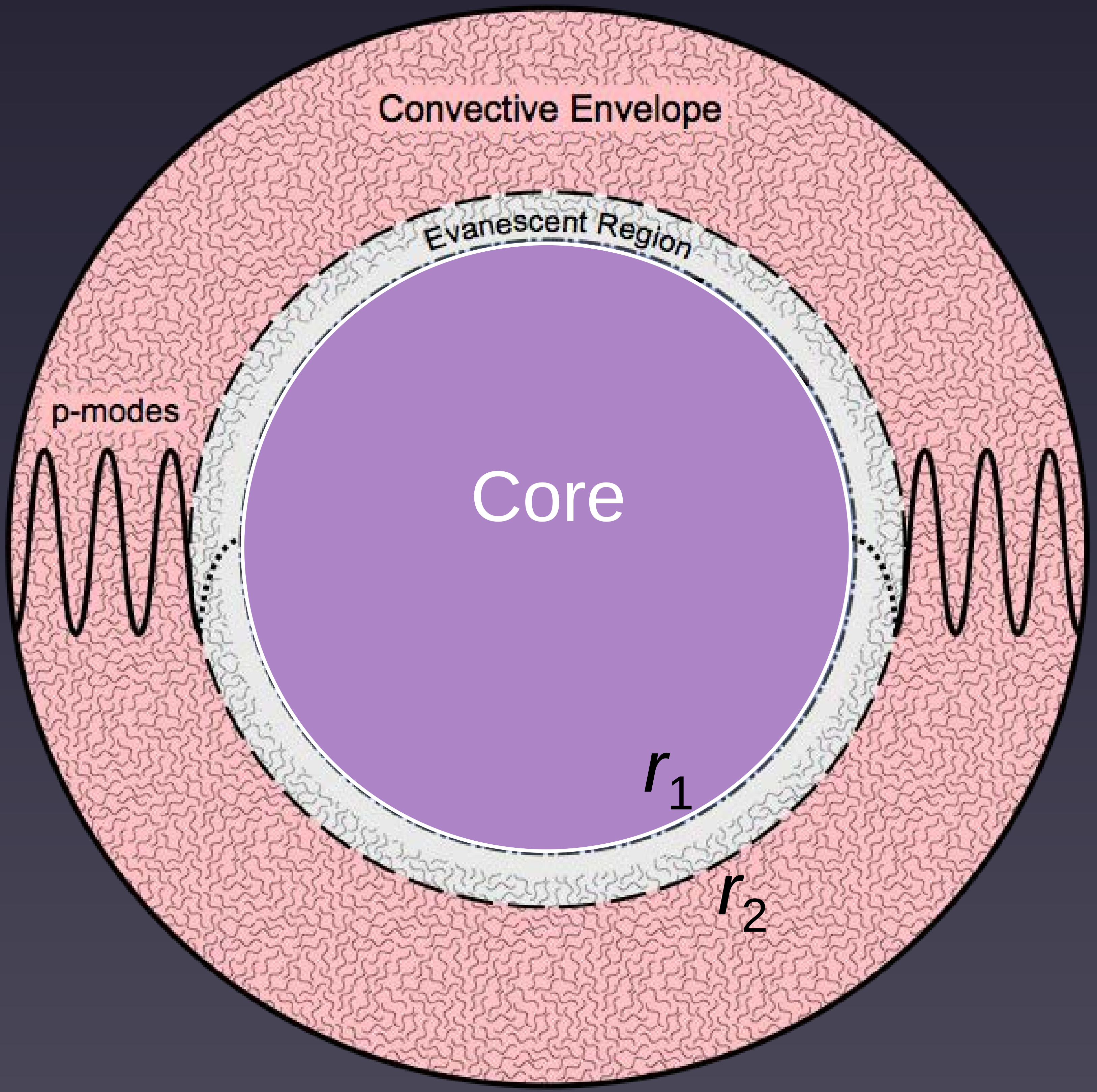
In equilibrium: $\dot{E}_{\rm in} = \dot{E}_{\rm out} = E_\alpha \gamma_\alpha$

Wave energy leaks into core at rate:

$$\dot{E}_{\rm leak} = E_{\rm ac} \frac{T^2}{2 t_{\rm cross}}$$

Transmission coefficient is:

$$T \sim \left(\frac{r_1}{r_2} \right)^{\sqrt{\ell(\ell+1)}}$$

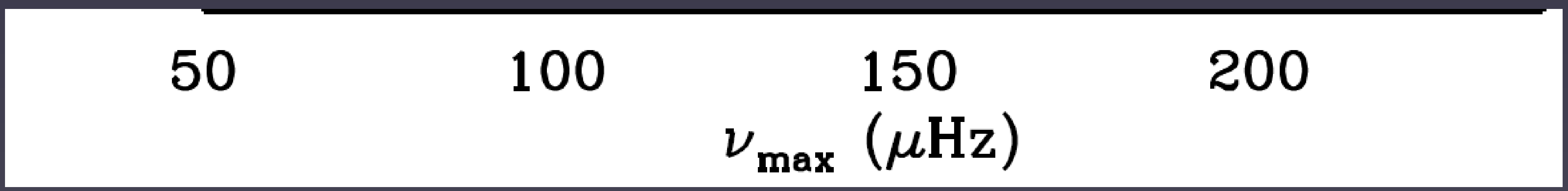


A (partial) solution emerges…

Evolution up RGB

- Mode amplitudes can be explained by wave energy leakage into the core

$$\frac{V^2_{\rm sup}}{V^2_{\rm norm}} = \left[1 + T^2 \Delta\nu\tau\right]^{-1}$$



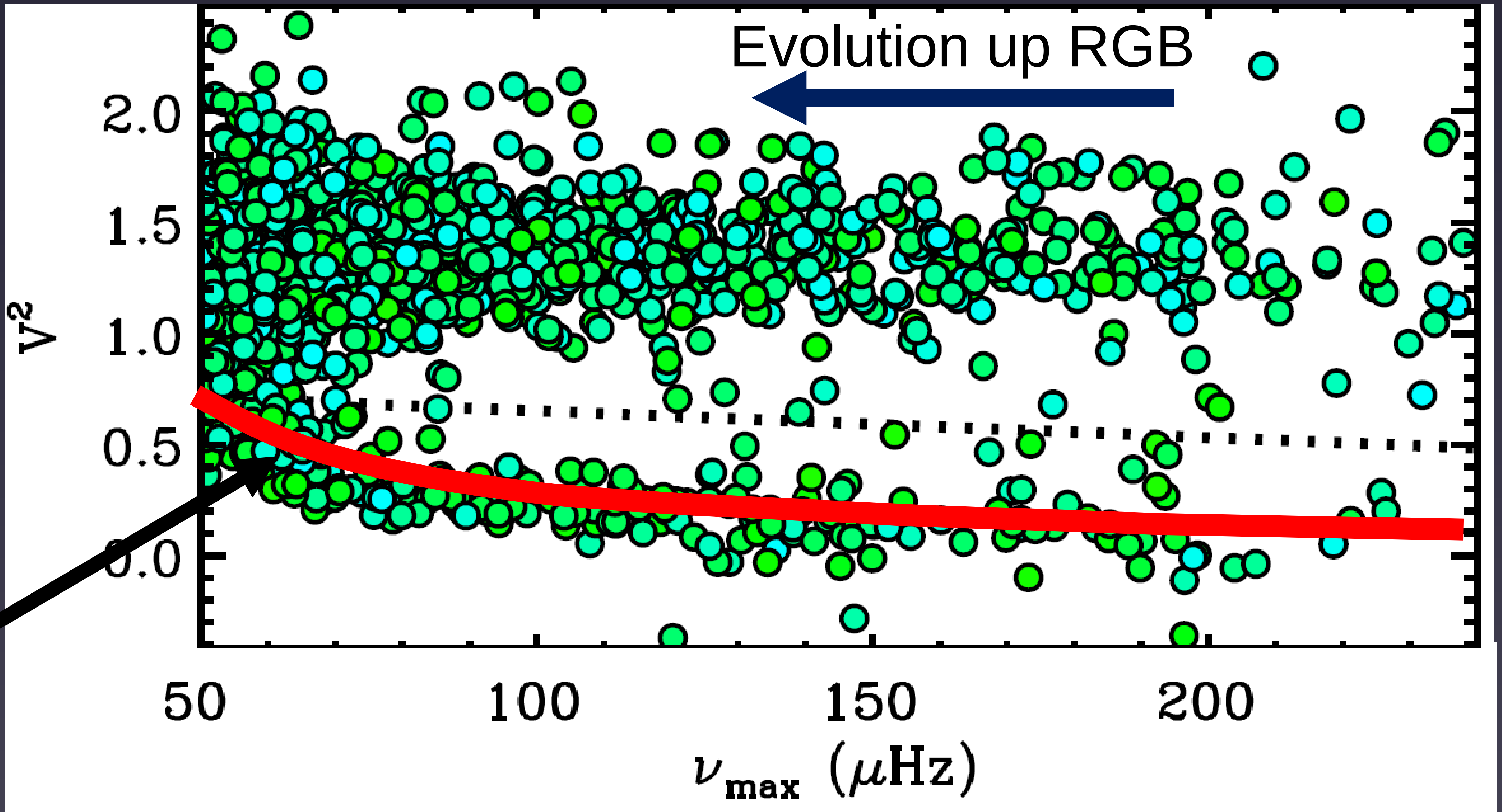
Stello, Cantiello, **Fuller** + 2016

A (partial) solution emerges…

- Mode amplitudes can be explained by wave energy leakage into the core

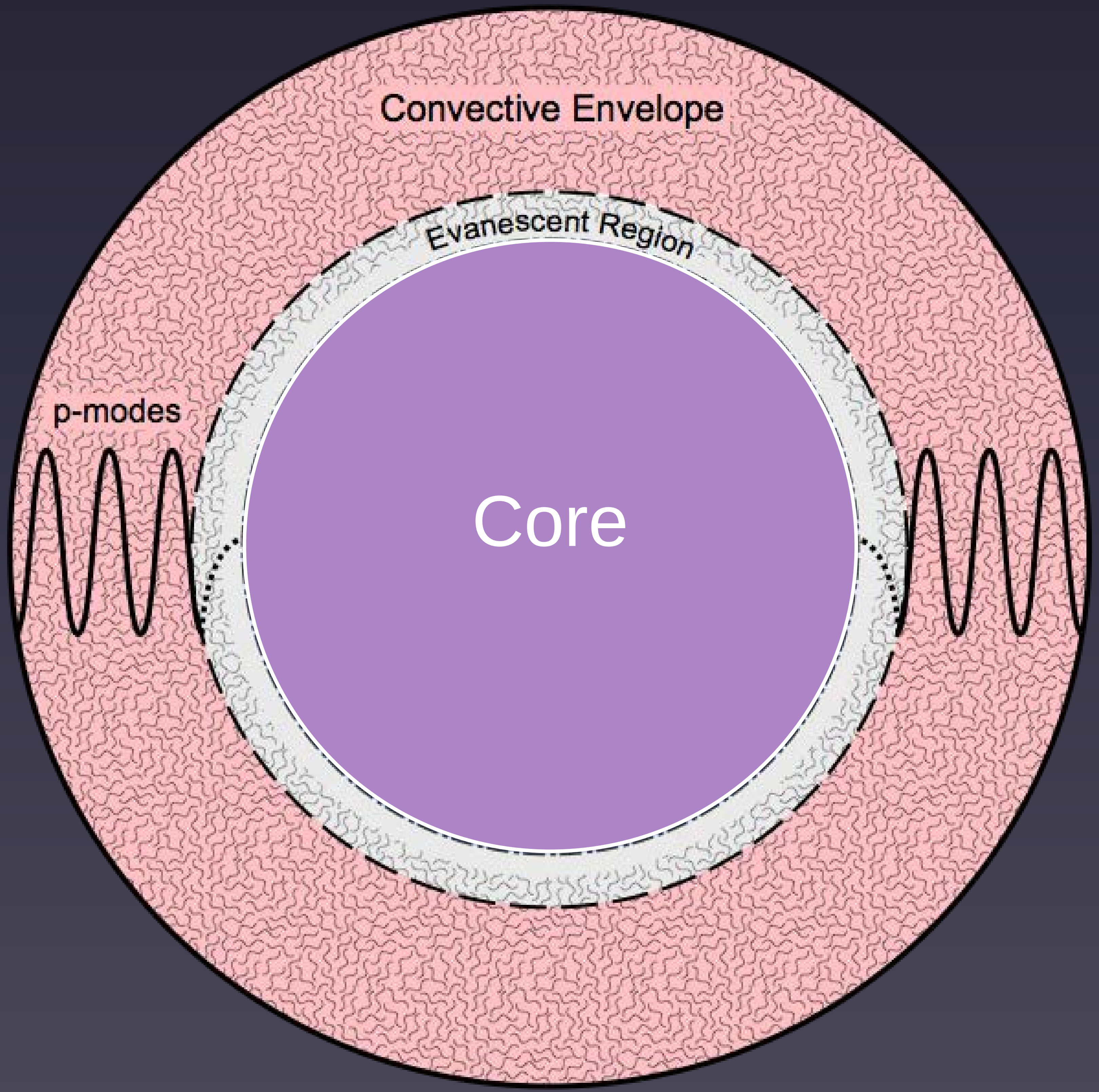
$$\frac{V^2_{\rm sup}}{V^2_{\rm norm}} = \left[1 + T^2 \Delta\nu\tau\right]^{-1}$$

Small correction required, see Mosser et al. 2016

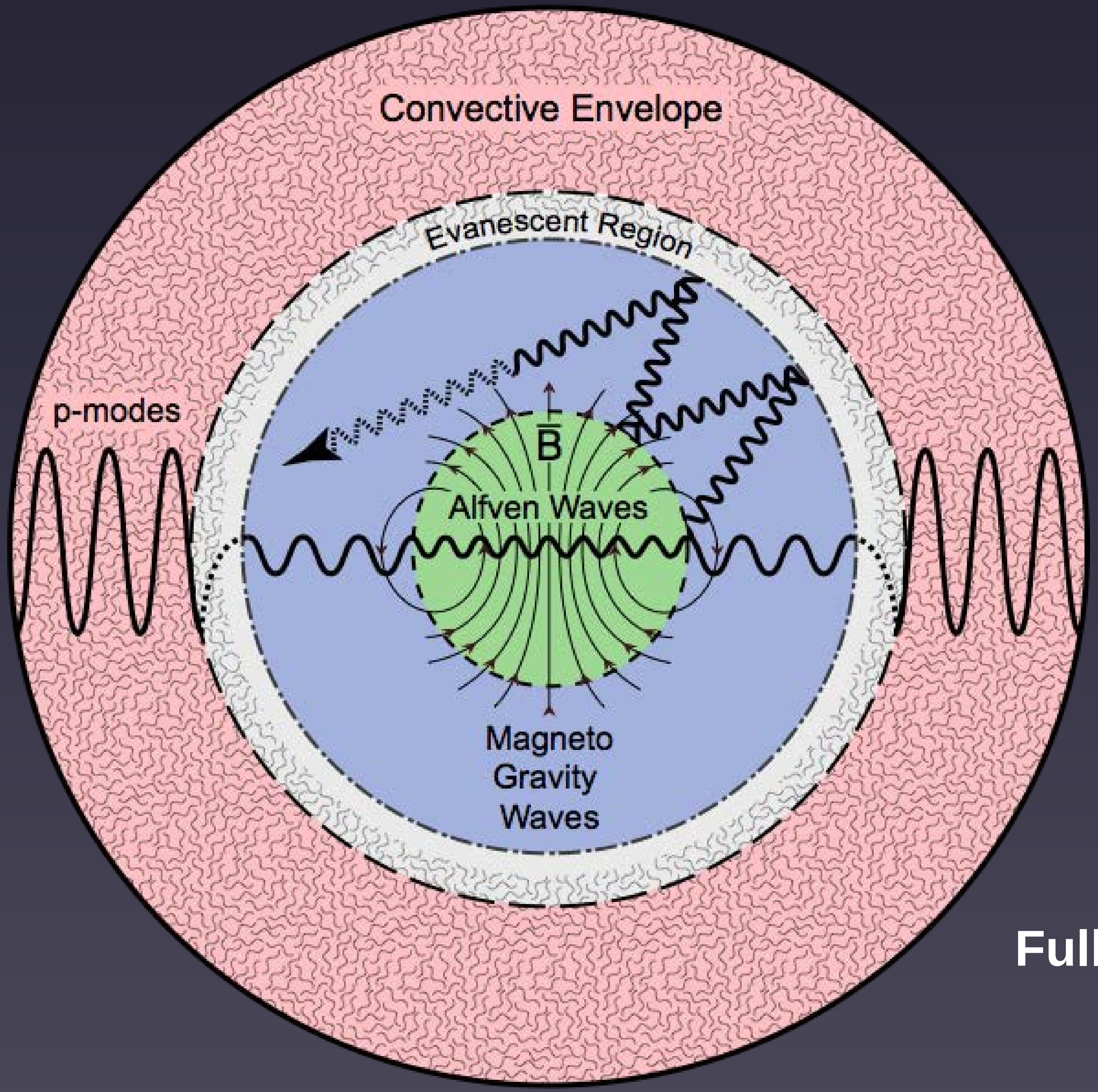


Stello, Cantiello, **Fuller** + 2016

What causes wave dissipation in core?



The Magnetic Greenhouse Effect



Fuller & Cantiello + 2015

Magnetic Forces

- In the presence of strong B-fields, magnetic tension forces can become comparable to buoyancy
- Modified dispersion relation for magneto-gravity waves

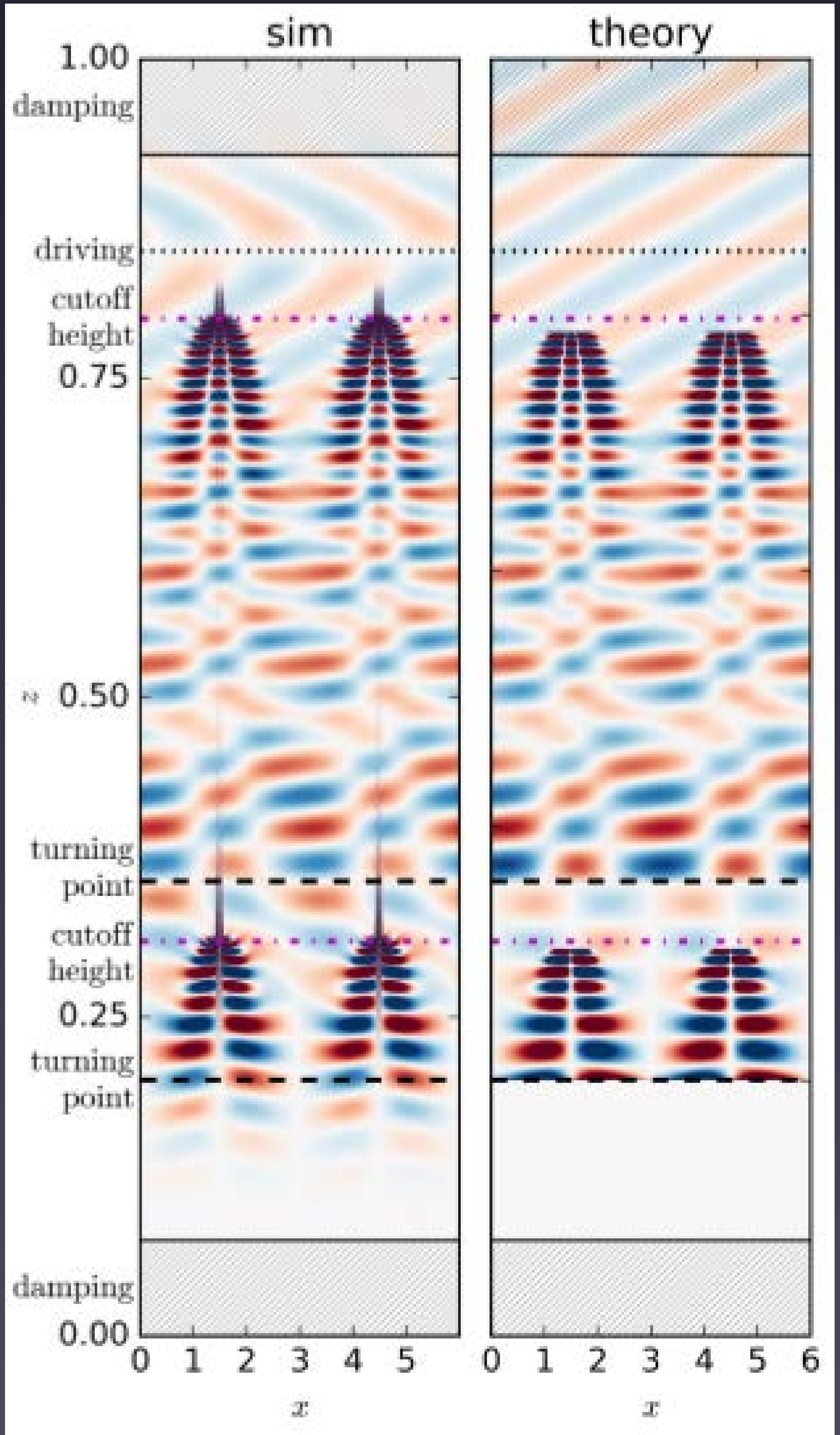
$$k^2 = \frac{\omega^2}{2 v_A^2 \mu^2} \left[1 \pm \sqrt{1 - \frac{4 \mu^2 v_A^2 N^2 k_\perp^2}{\omega^4}} \right]$$

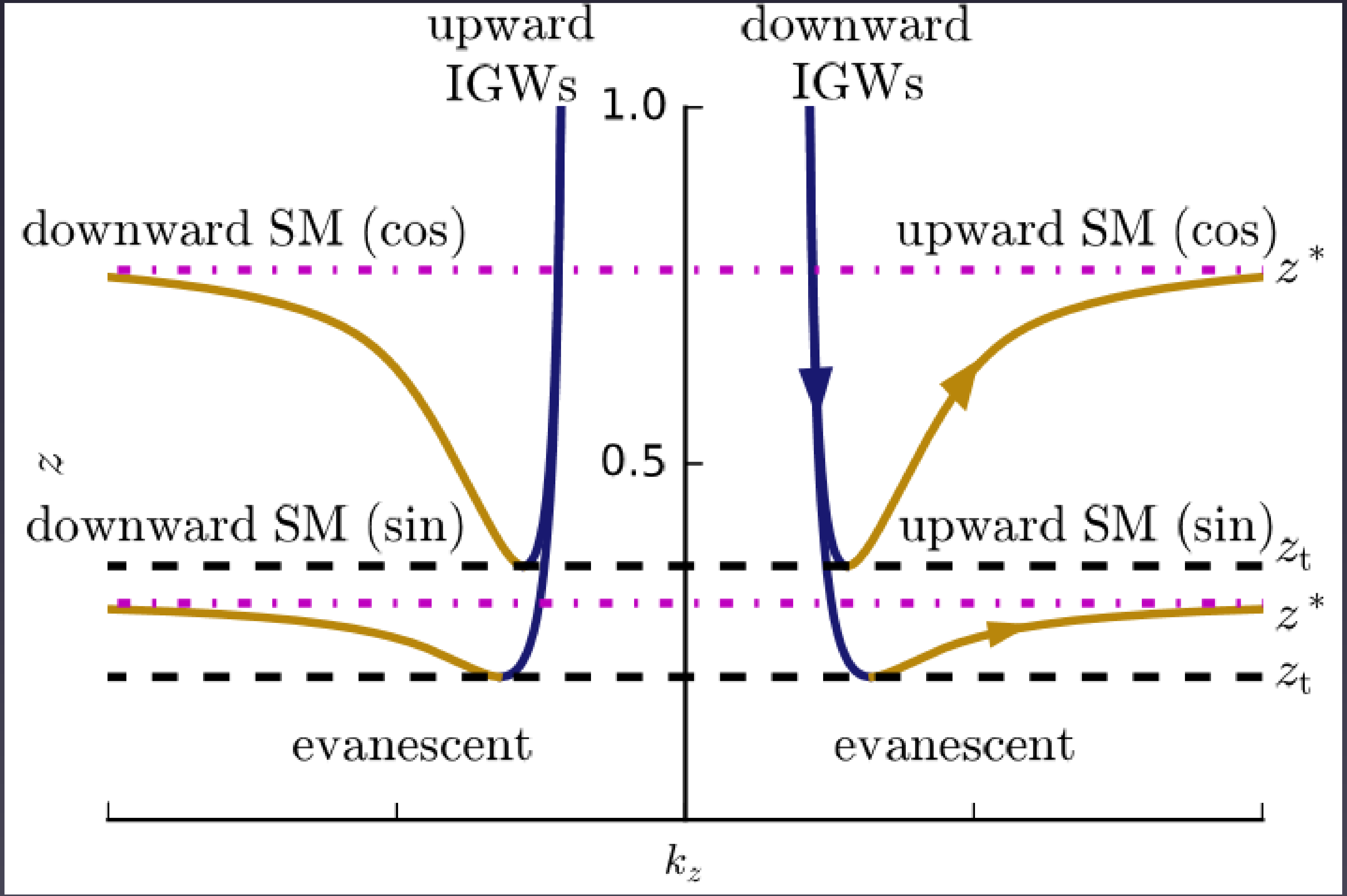
- Equate tension force with buoyancy Force

$$\Rightarrow \quad B_c = \sqrt{\frac{\pi \rho}{2}} \, \frac{\omega^2 r}{N}$$

- Occurs when Alfven speed ~ gravity wave group velocity

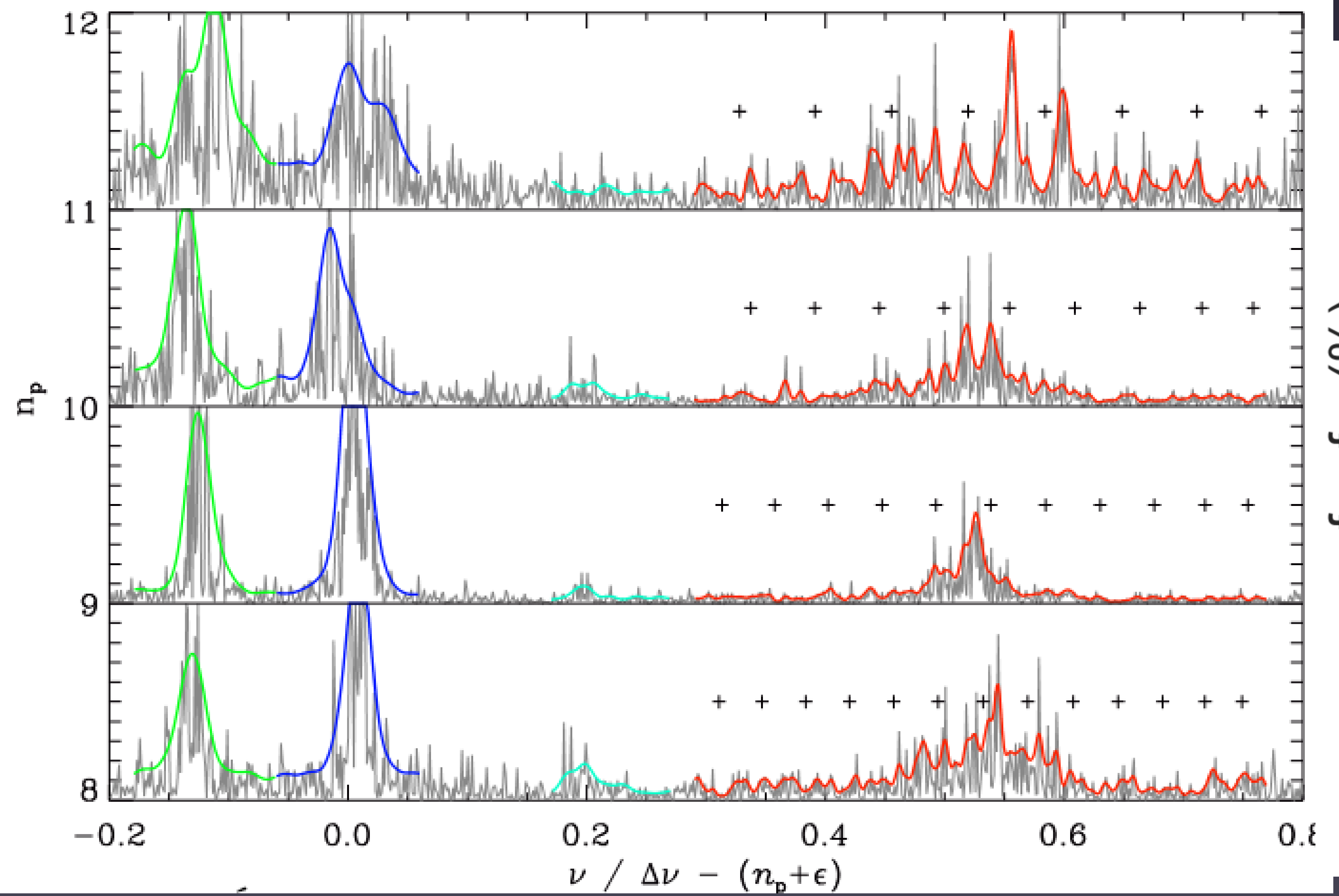
Magnetic Mirror Effect



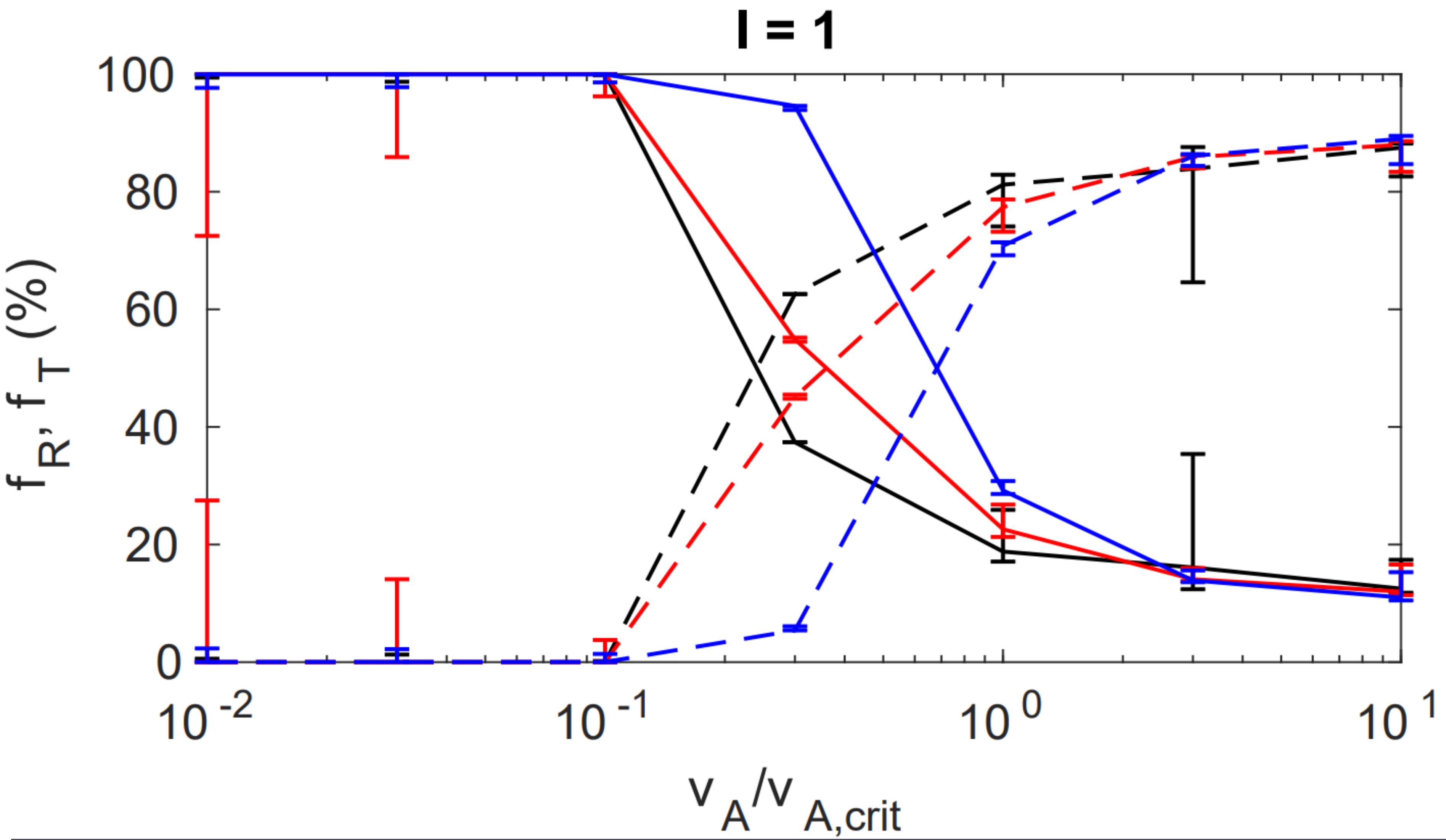


Lecoanet, Vasil,
Fuller+ 2016

Survival of Mixed Modes?

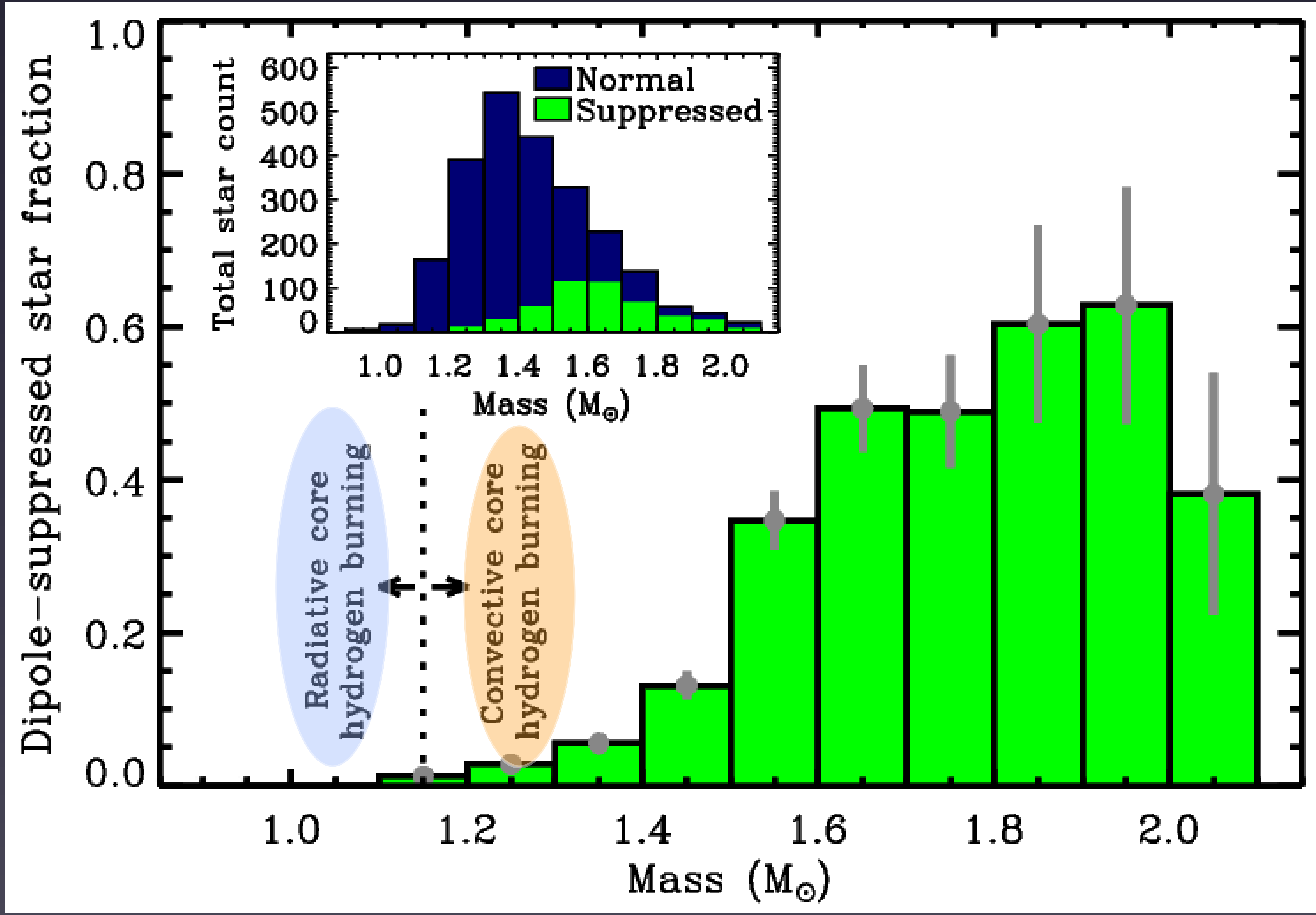


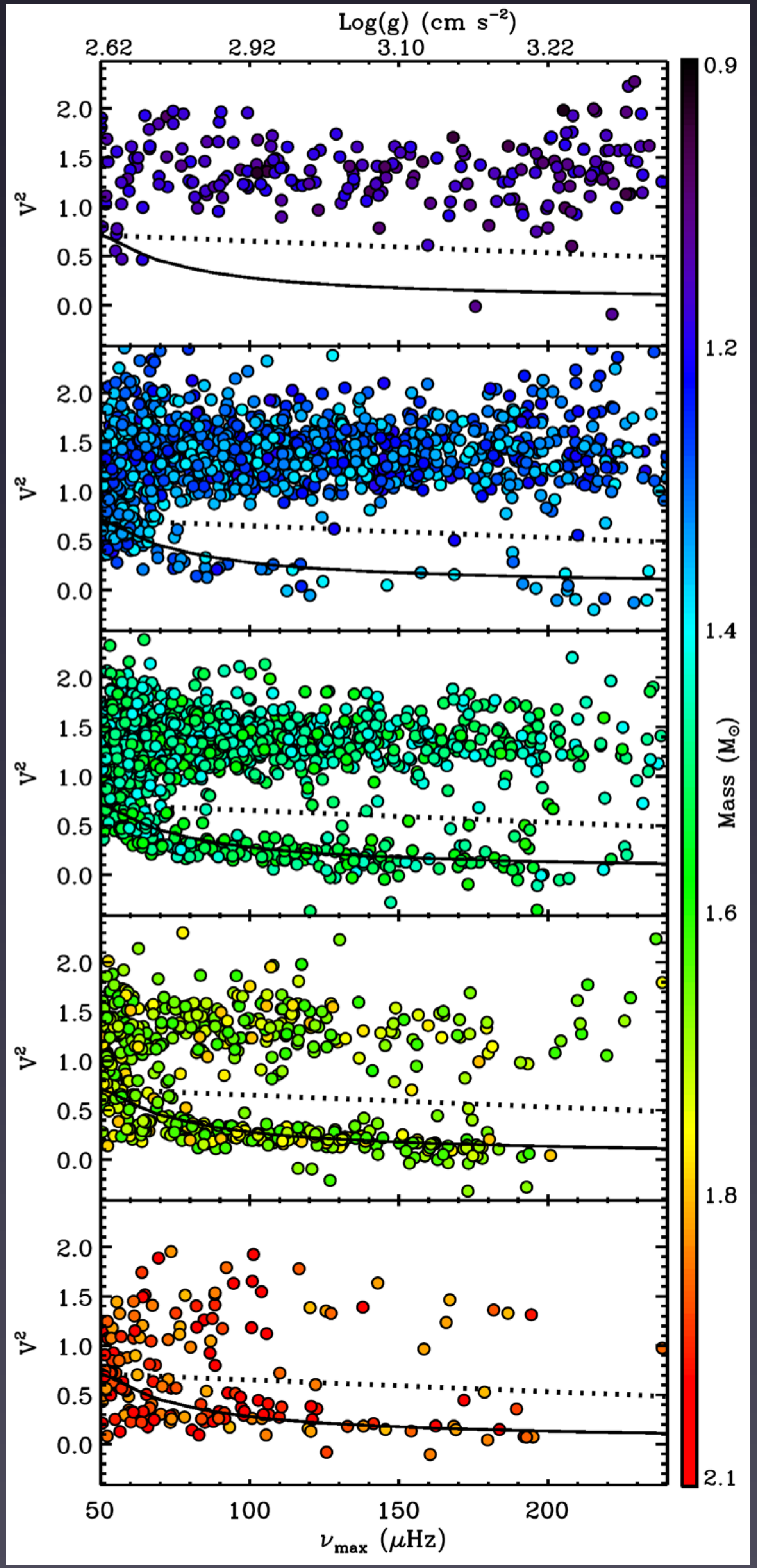
Mosser et al. 2016



Loi 2020

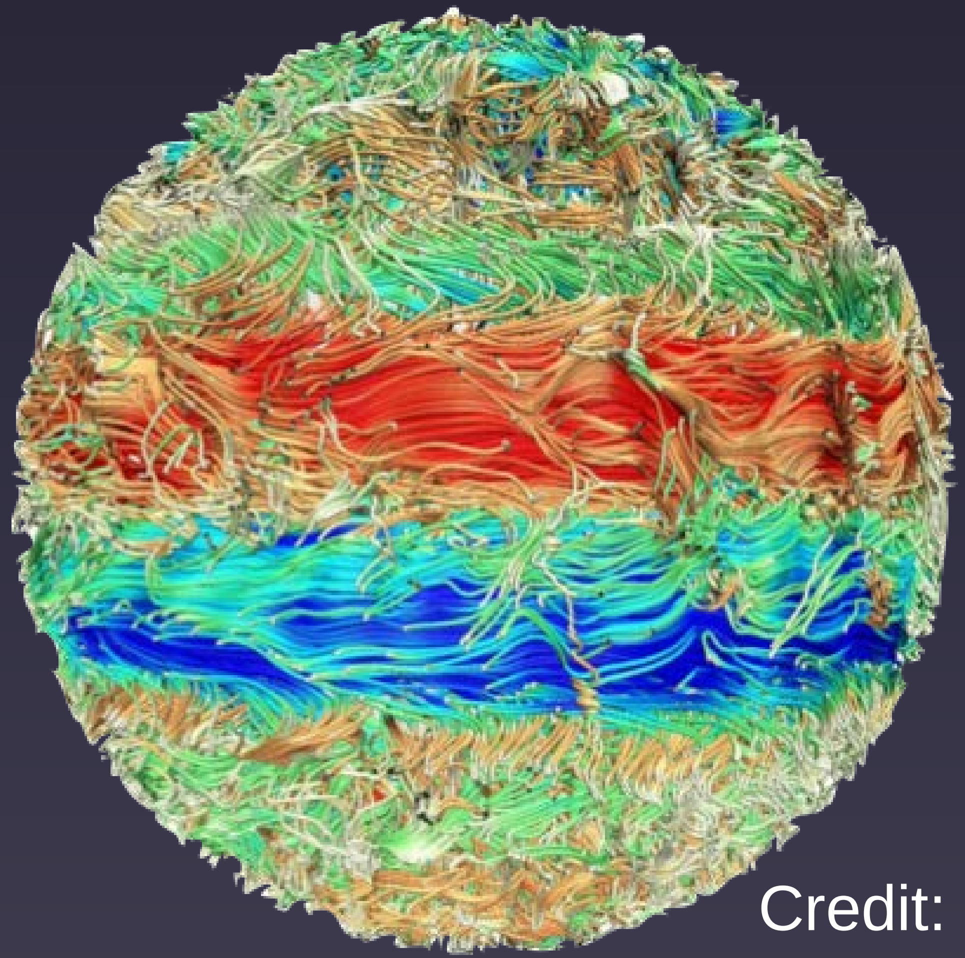
Incidence of core fields is mass-dependent

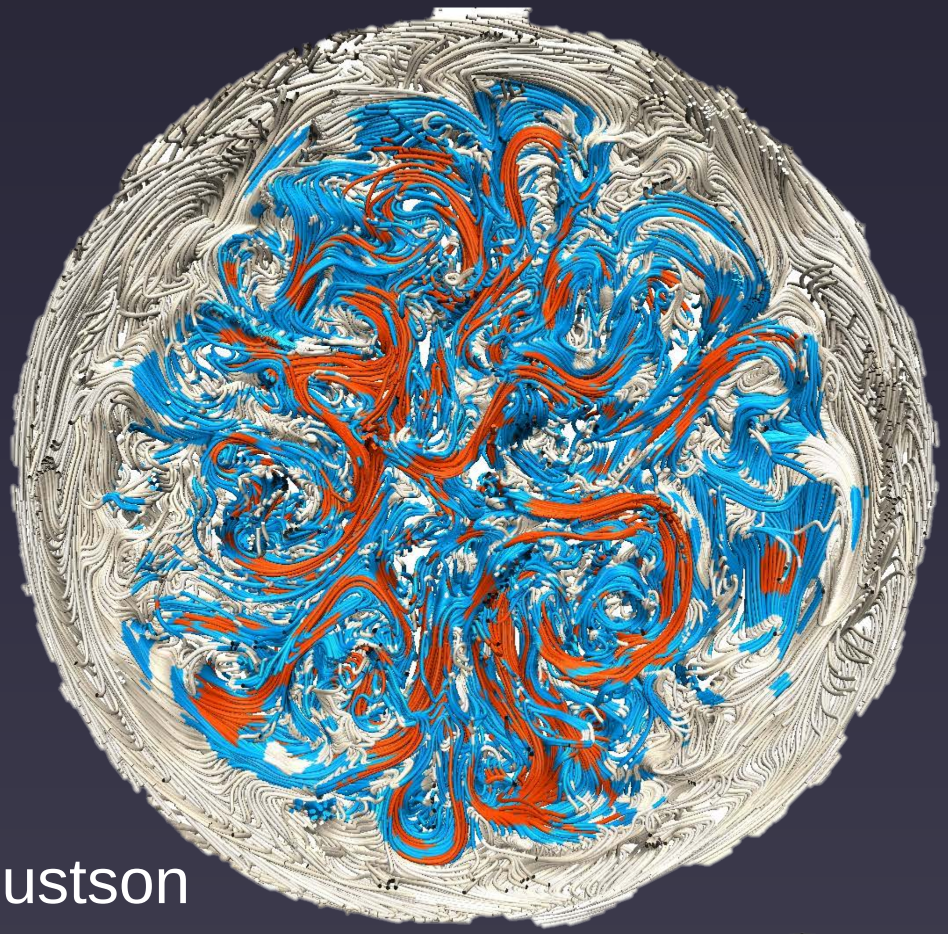




Stello, Cantiello, **Fuller** + 2016

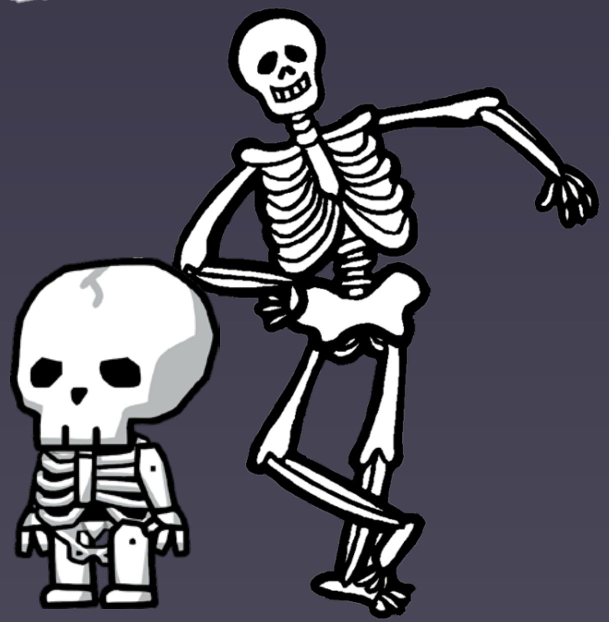
Evidence for convective core dynamos





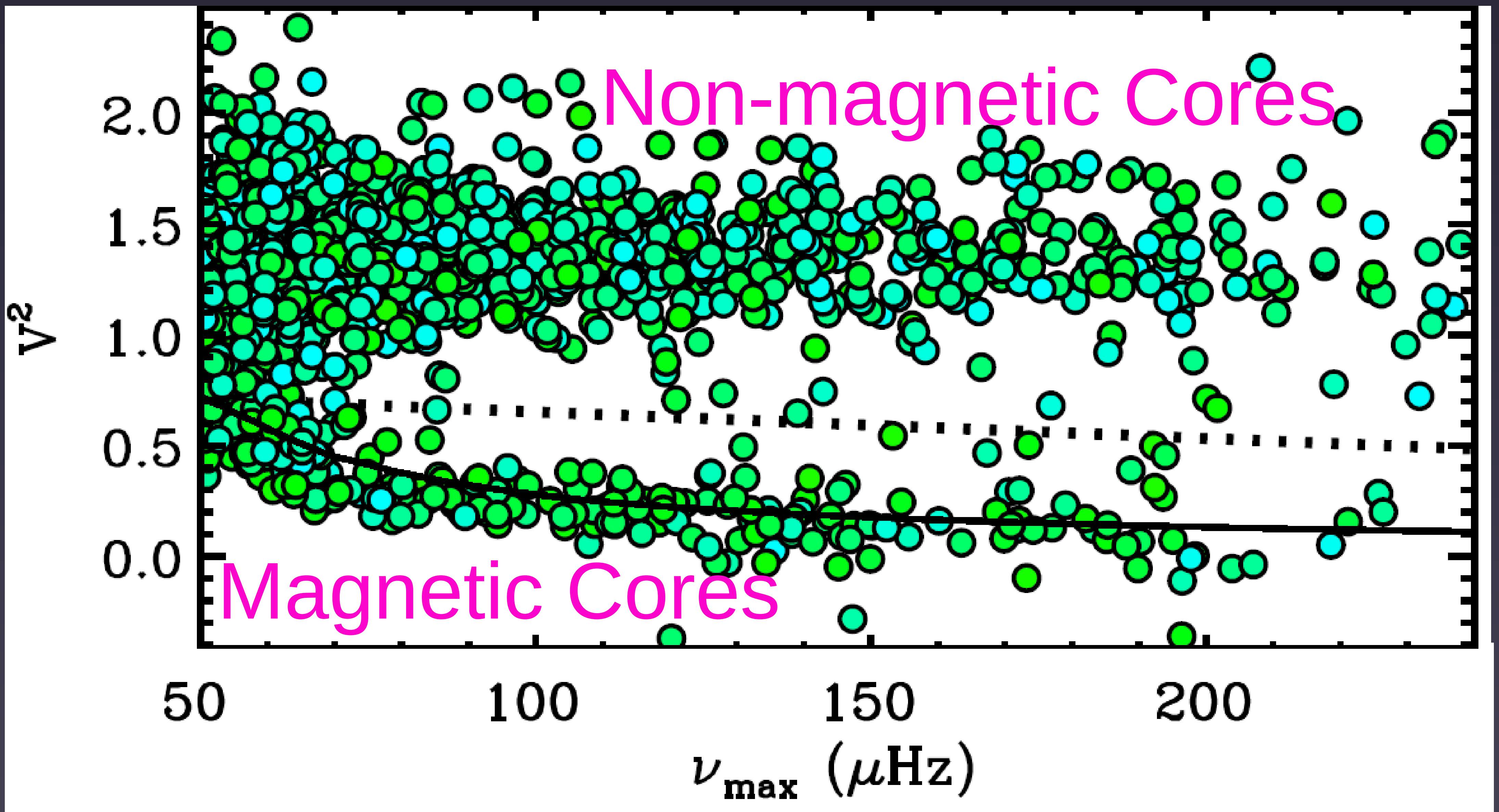
Credit: Kyle Augustson

- Strong fields in red giants are "skeleton" fields which are remnants of main sequence dynamos



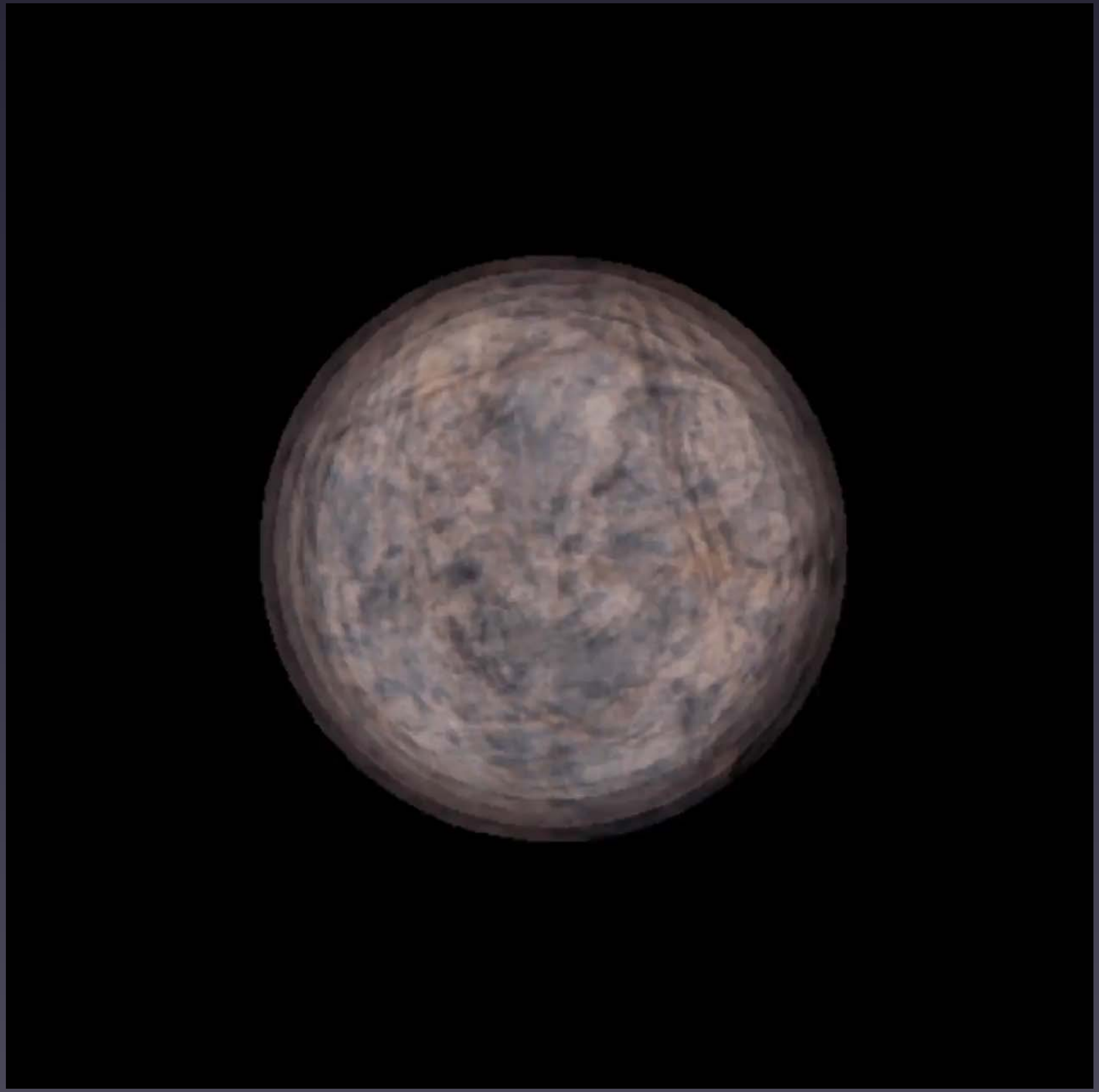
Implications

- Magnetic stars identified by low dipole mode visibility
- Sun-like stars have weak internal fields
  - Radial field strengths less than ~10^3 G
- Core-dynamo fields may be common
  - Magnetic white dwarfs
  - Magnetars
- Magnetic fields may not always be explanation for depressed modes (Mosser et al. 2016)



Stello, Cantiello, Fuller + *Nature* 2016

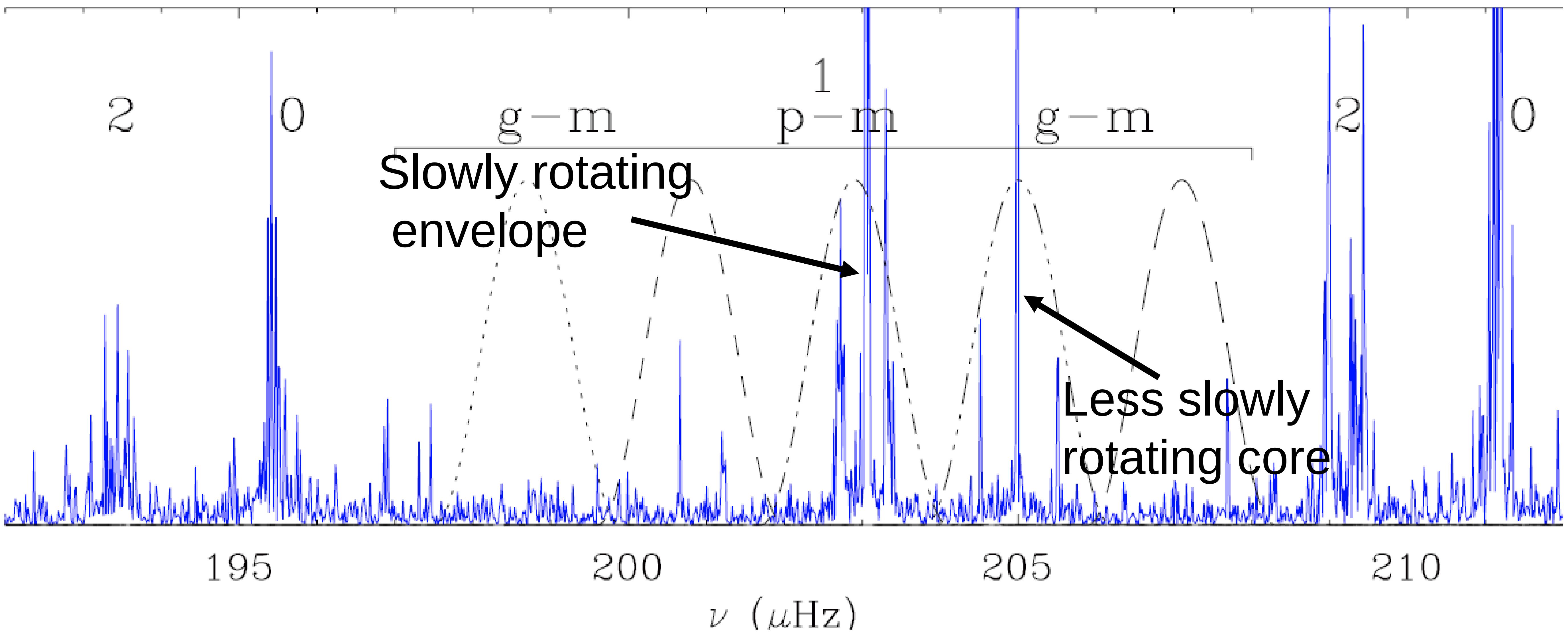
The Spin of Stellar Cores



- 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



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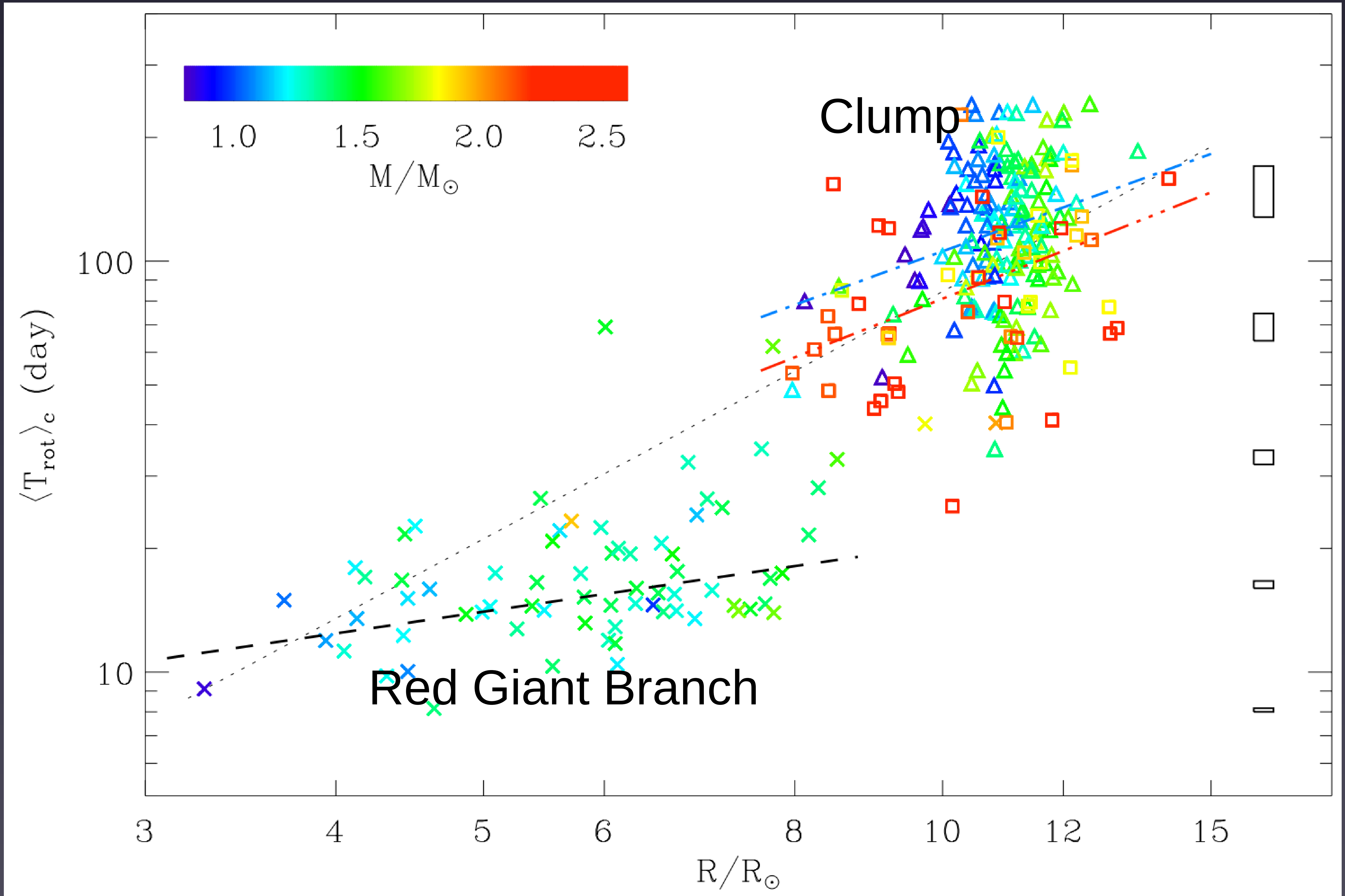
Mosser et al. 2012

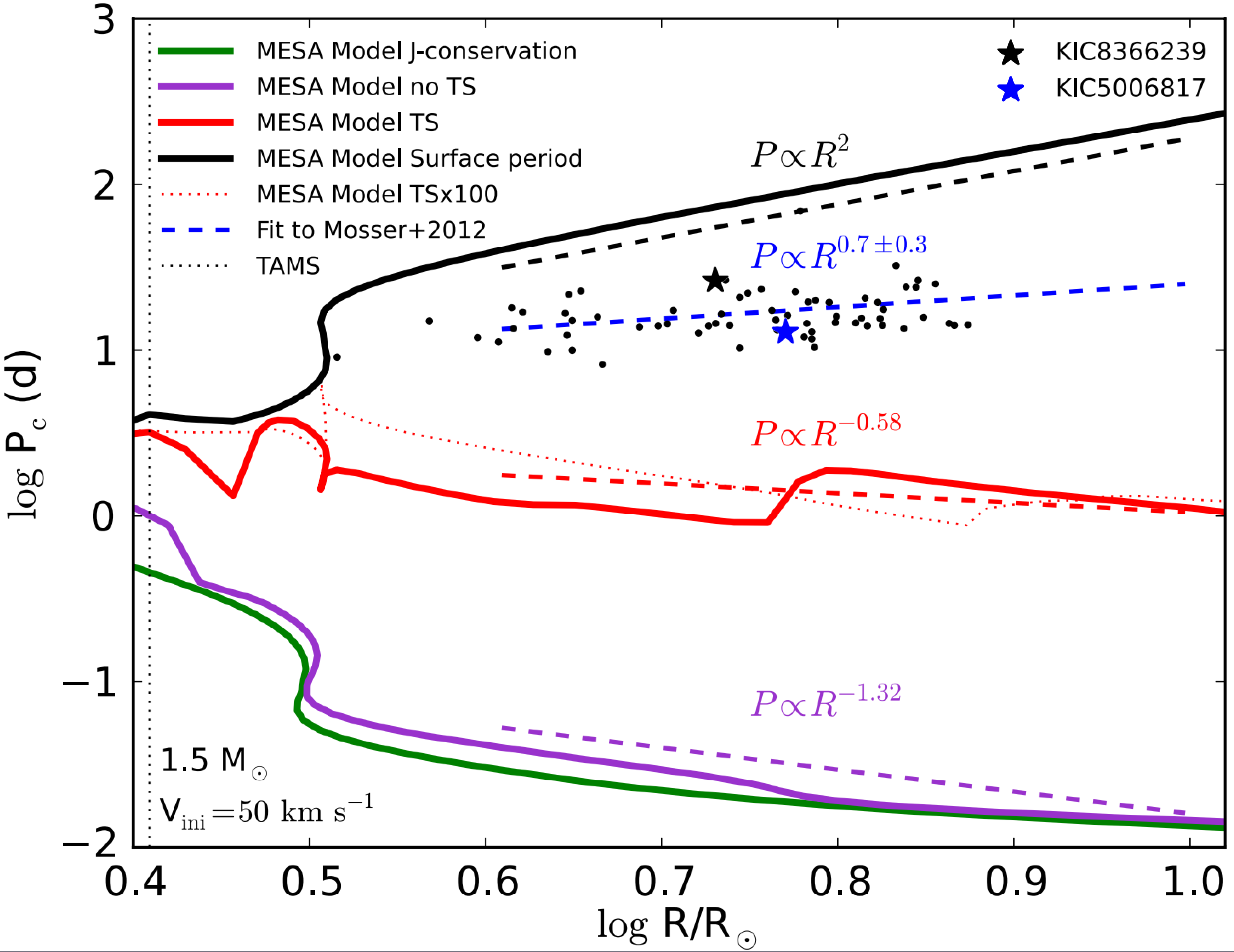
Asteroseismic Spin Rates



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

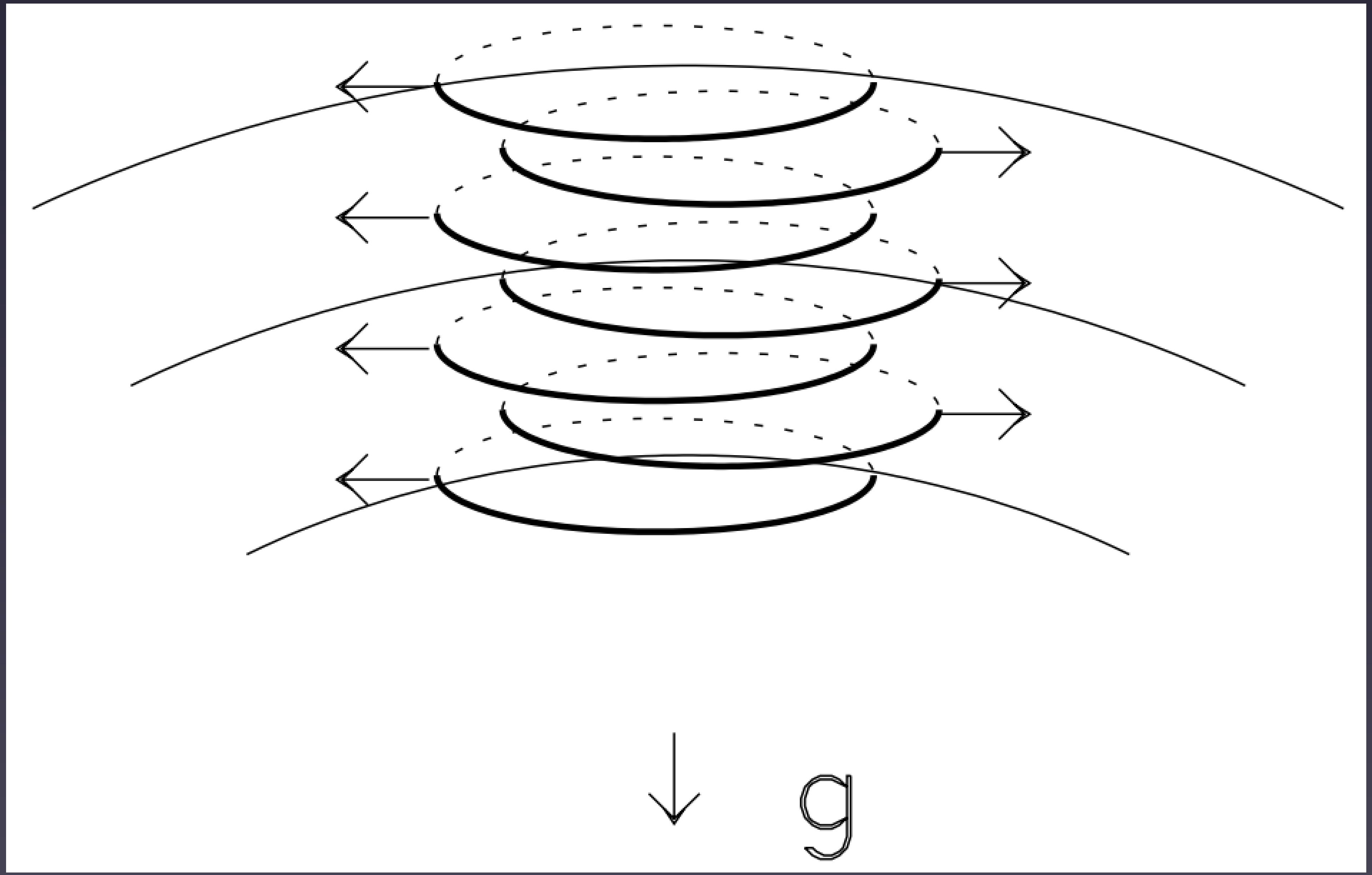
- Toroidal field slips sideways, regenerates radial field

- According to Spruit 2002, instability creates net torque

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

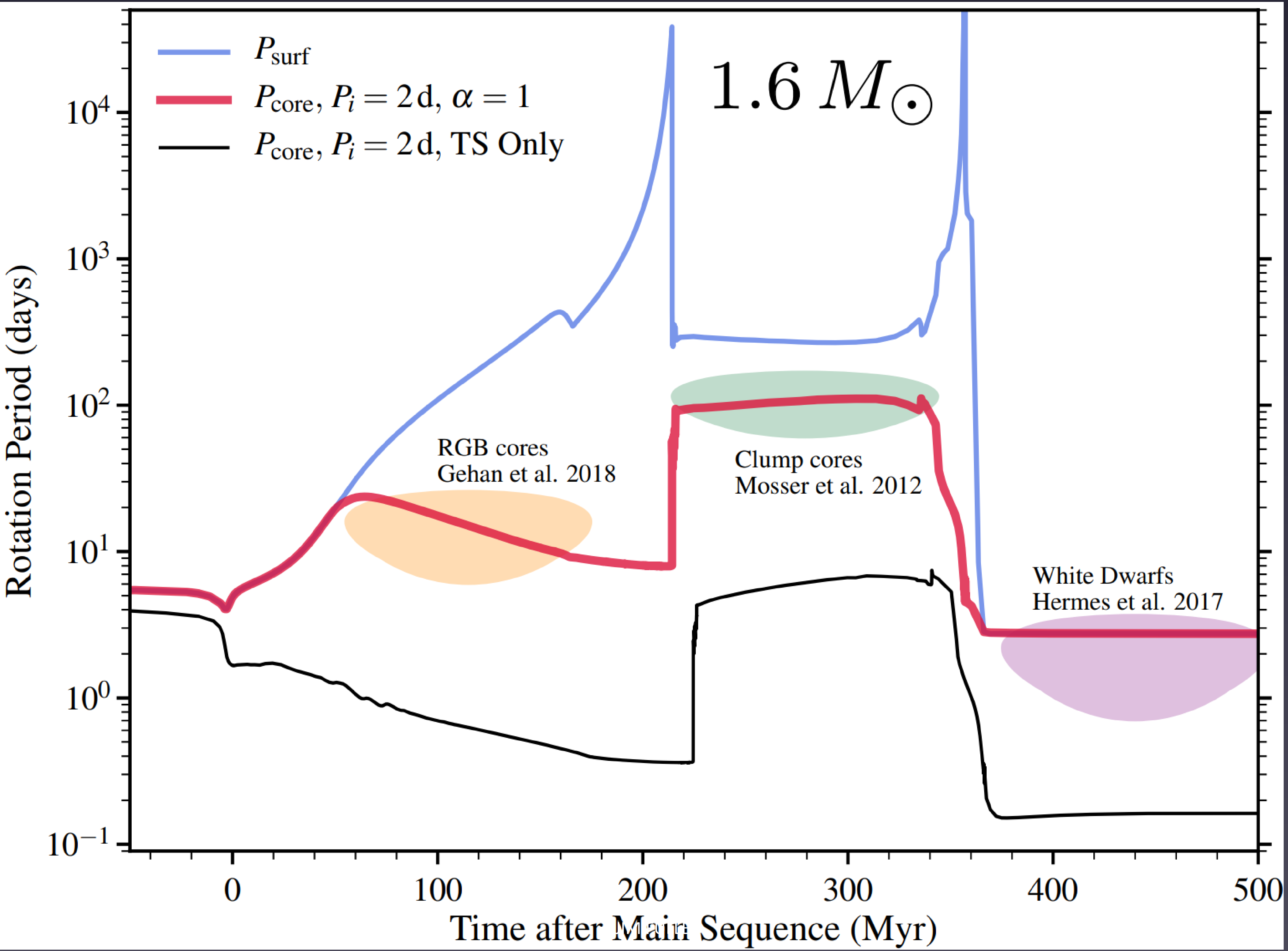
- Updated prediction:

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



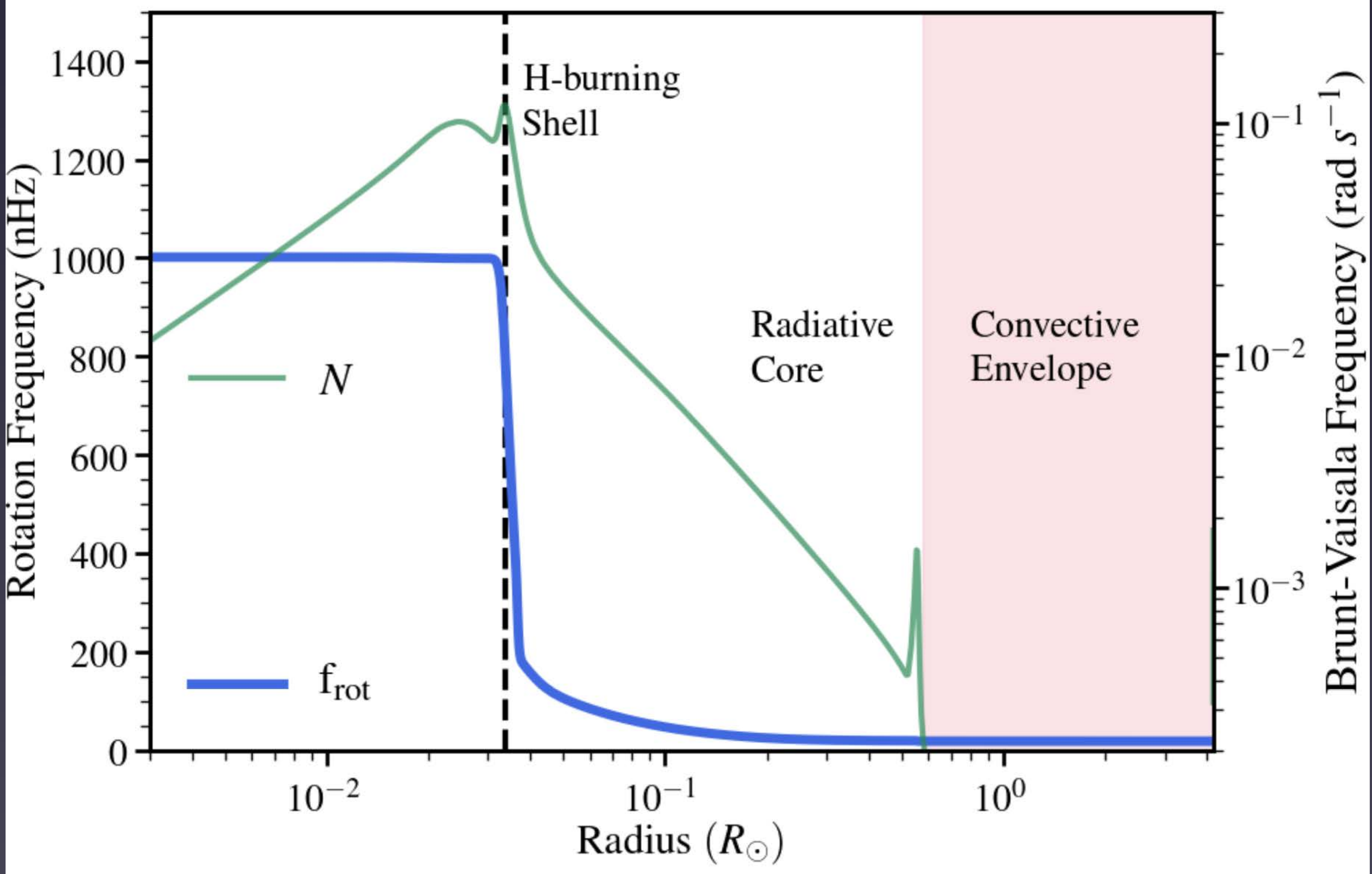
Spruit 1999

Rotational Evolution

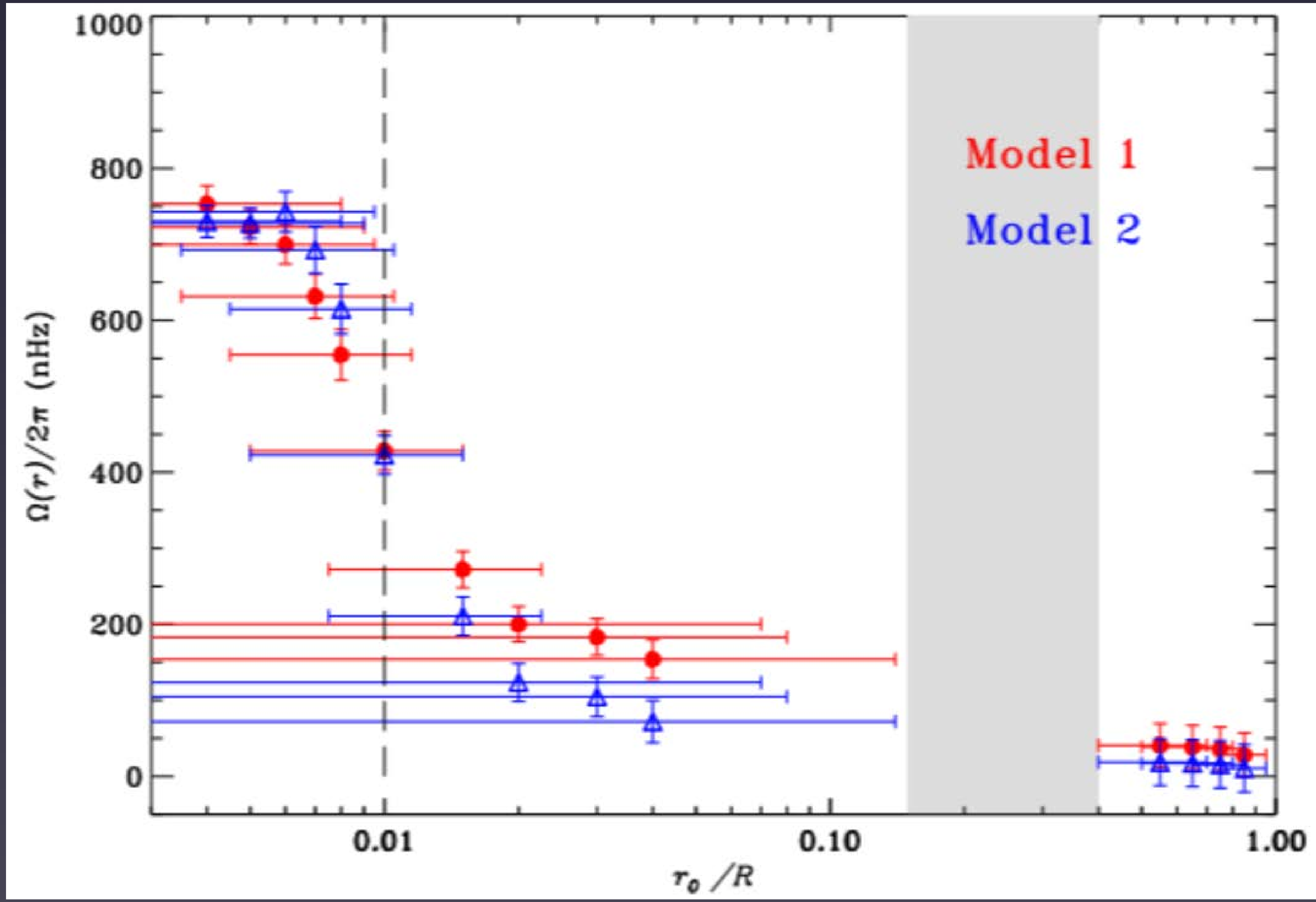


Fuller+ 2019

Rotation Profile



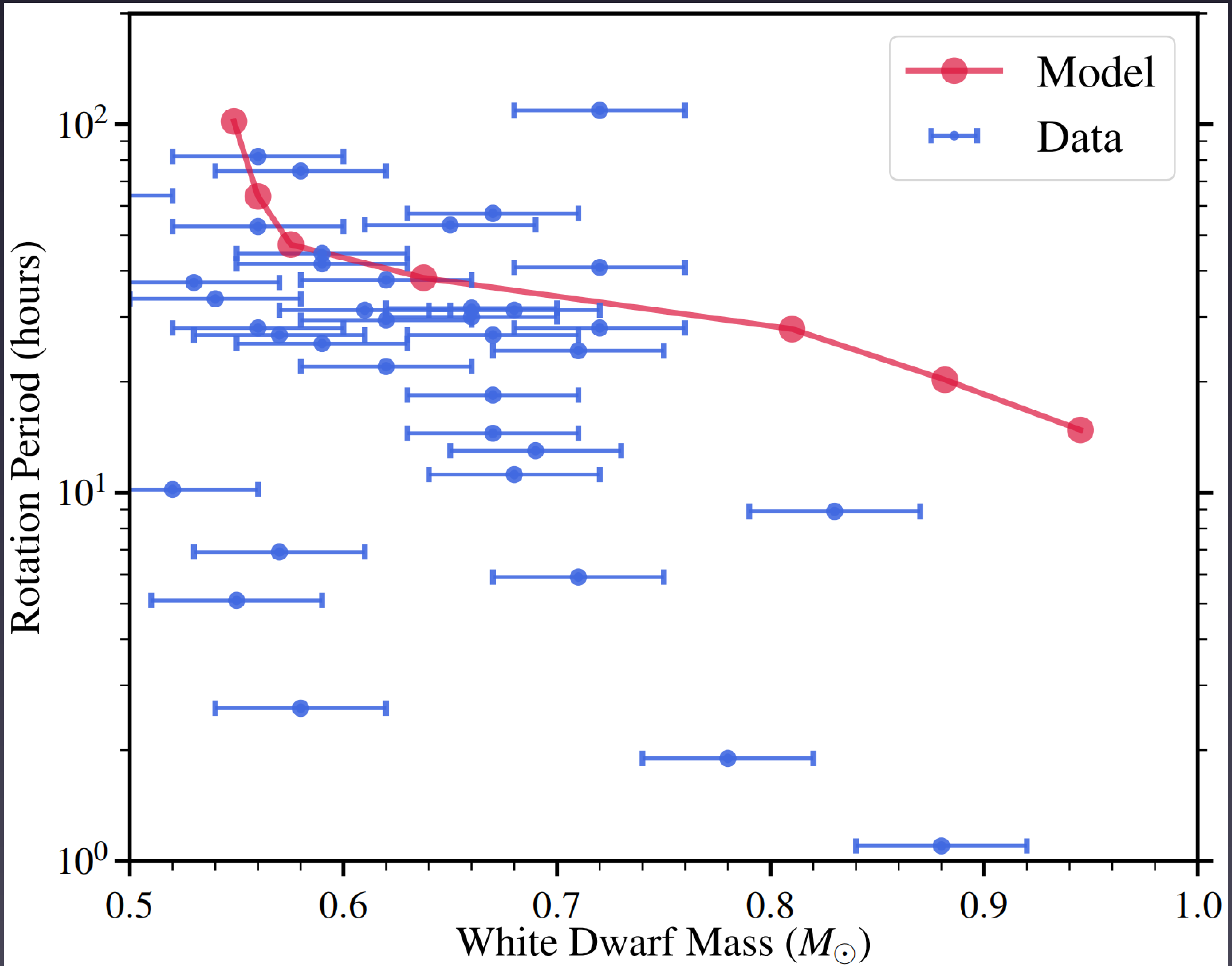
Fuller+ 2019



Di Mauro et al. 2017

White Dwarfs

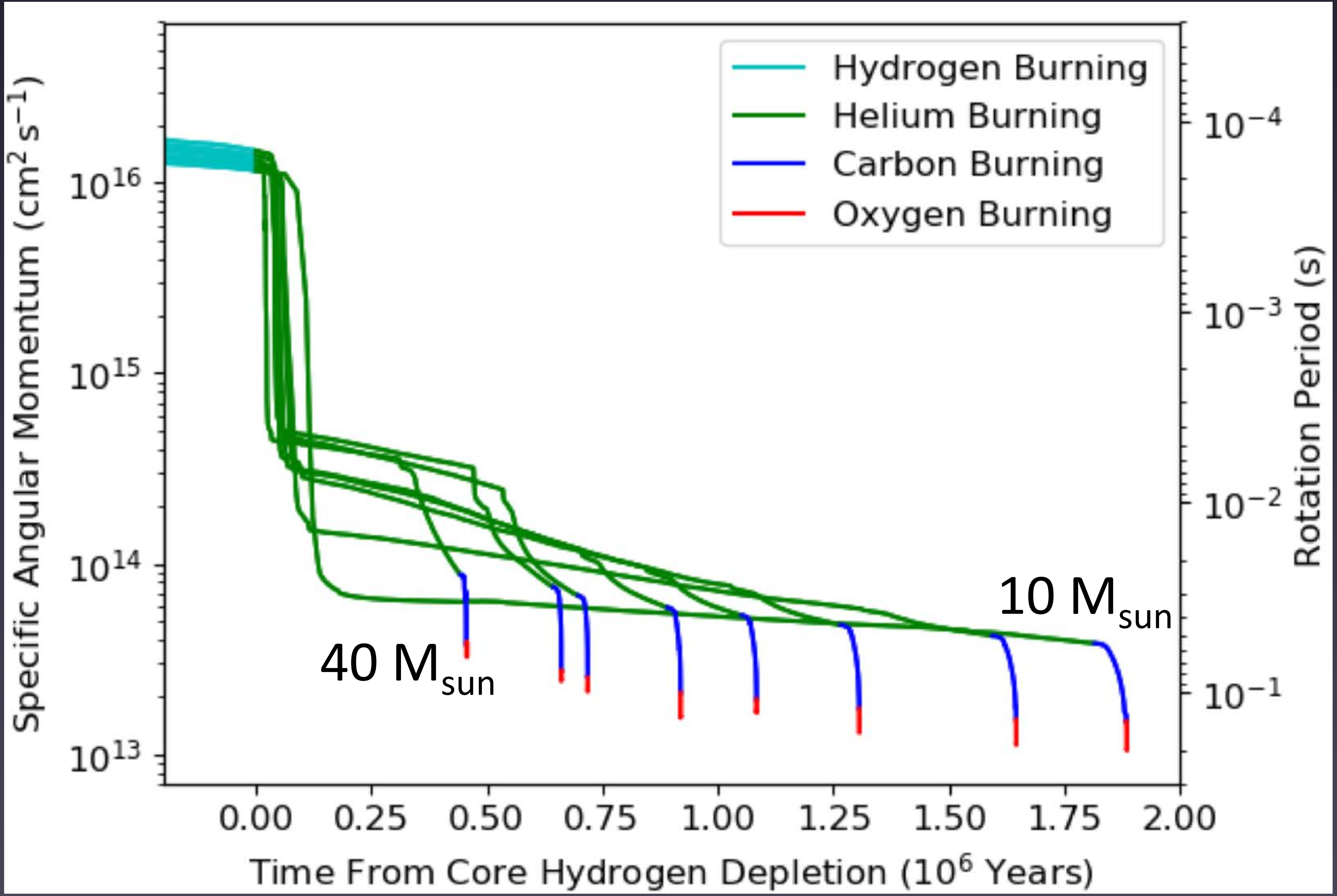
- WD rotation rates previously unexplained
- Massive WDs appear to rotate faster



Fuller+ 2019

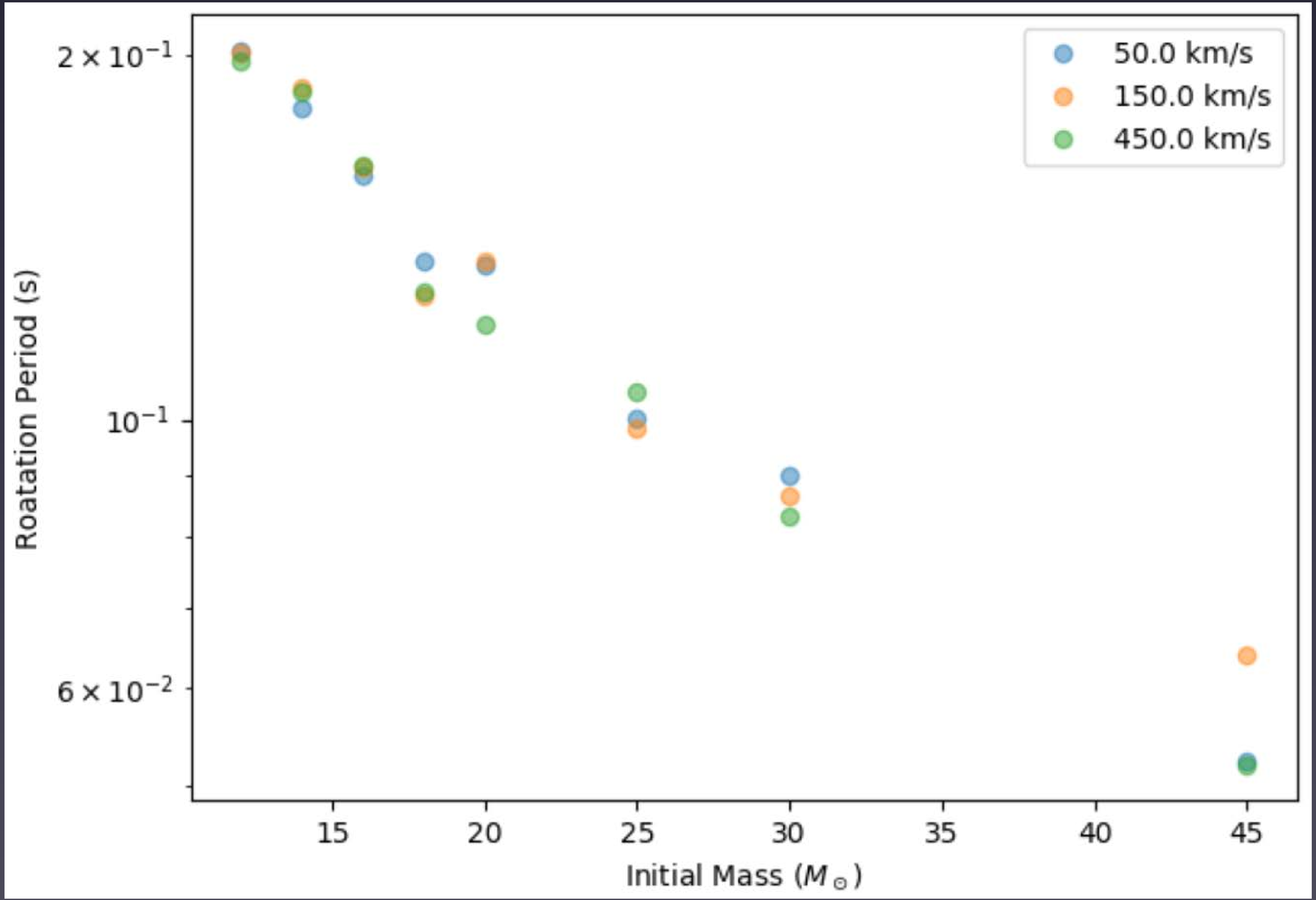
Massive Stars

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

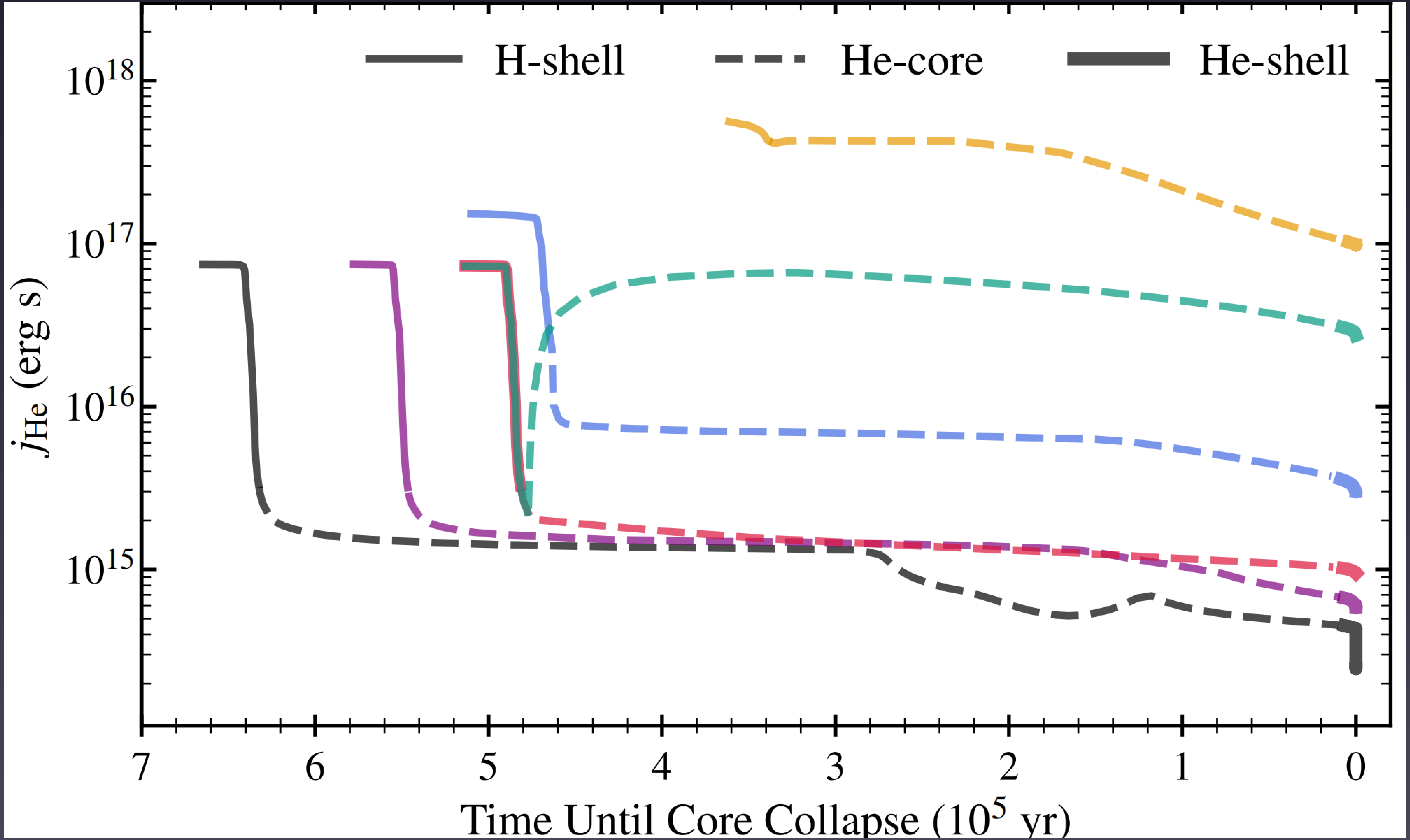


Ma & Fuller 2019

Neutron Stars Slowly Rotating



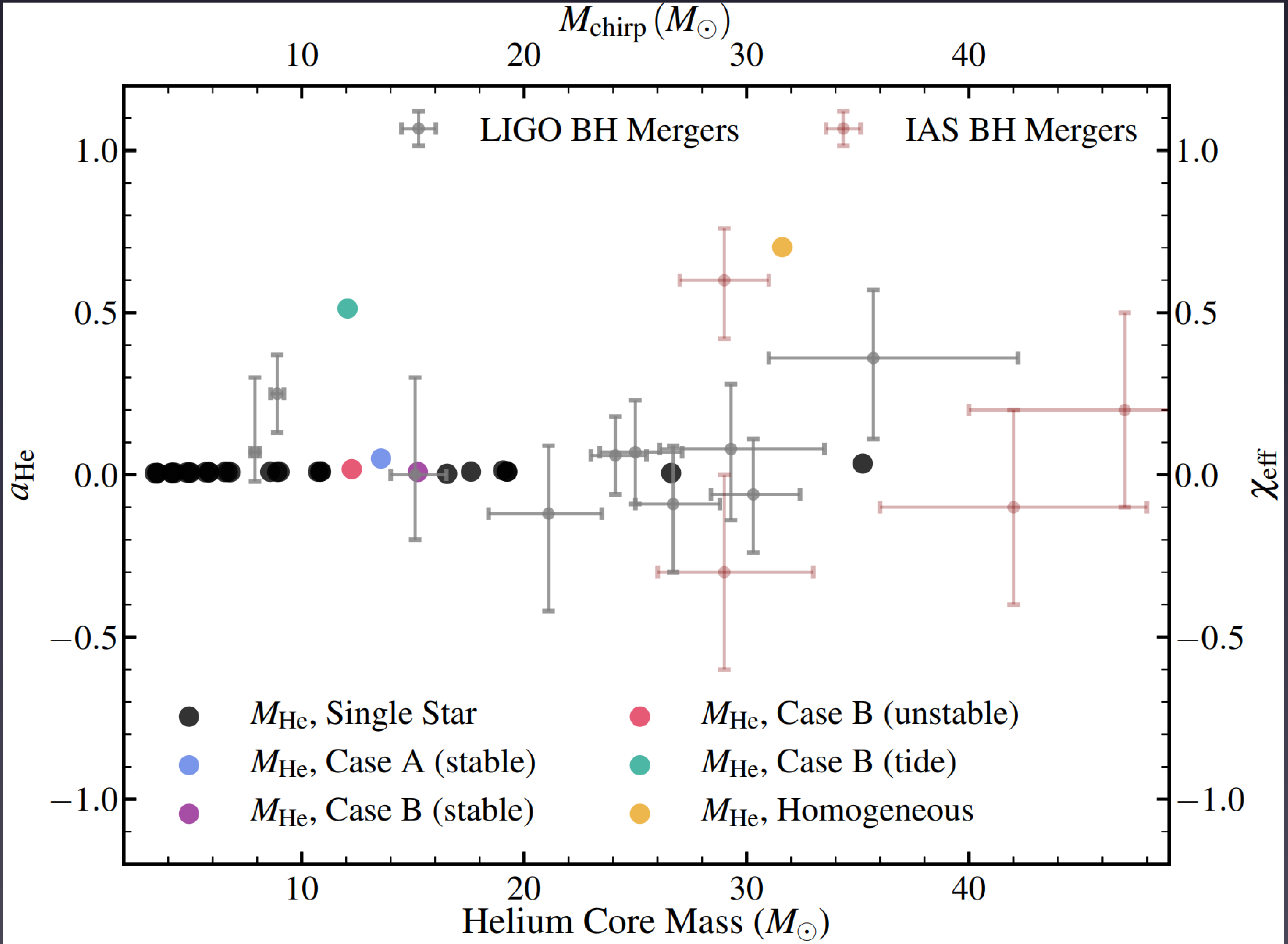
Ma & Fuller 2019



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

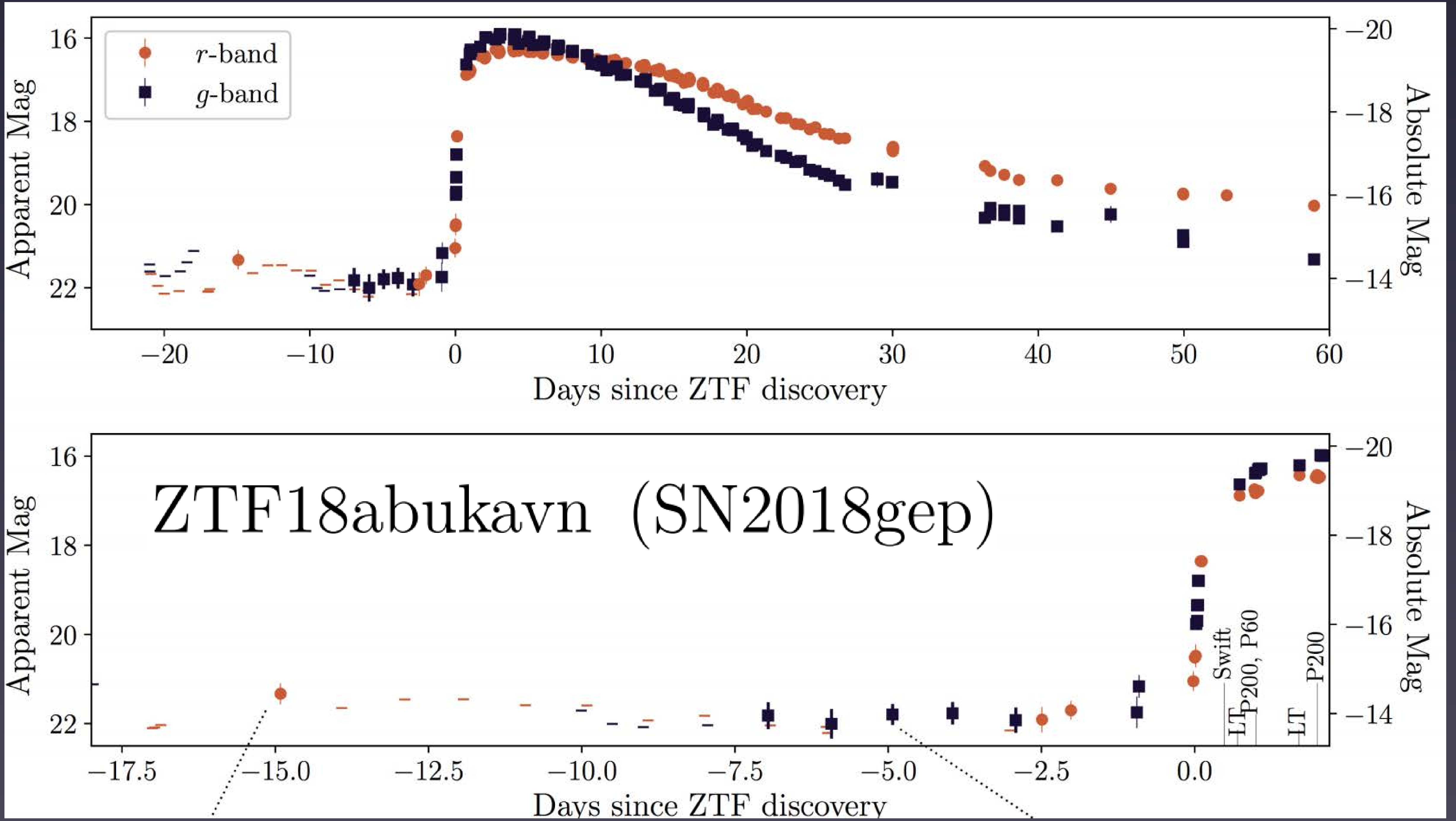
Postdictions

- 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

Wave-driven Pre-Supernova Outbursts

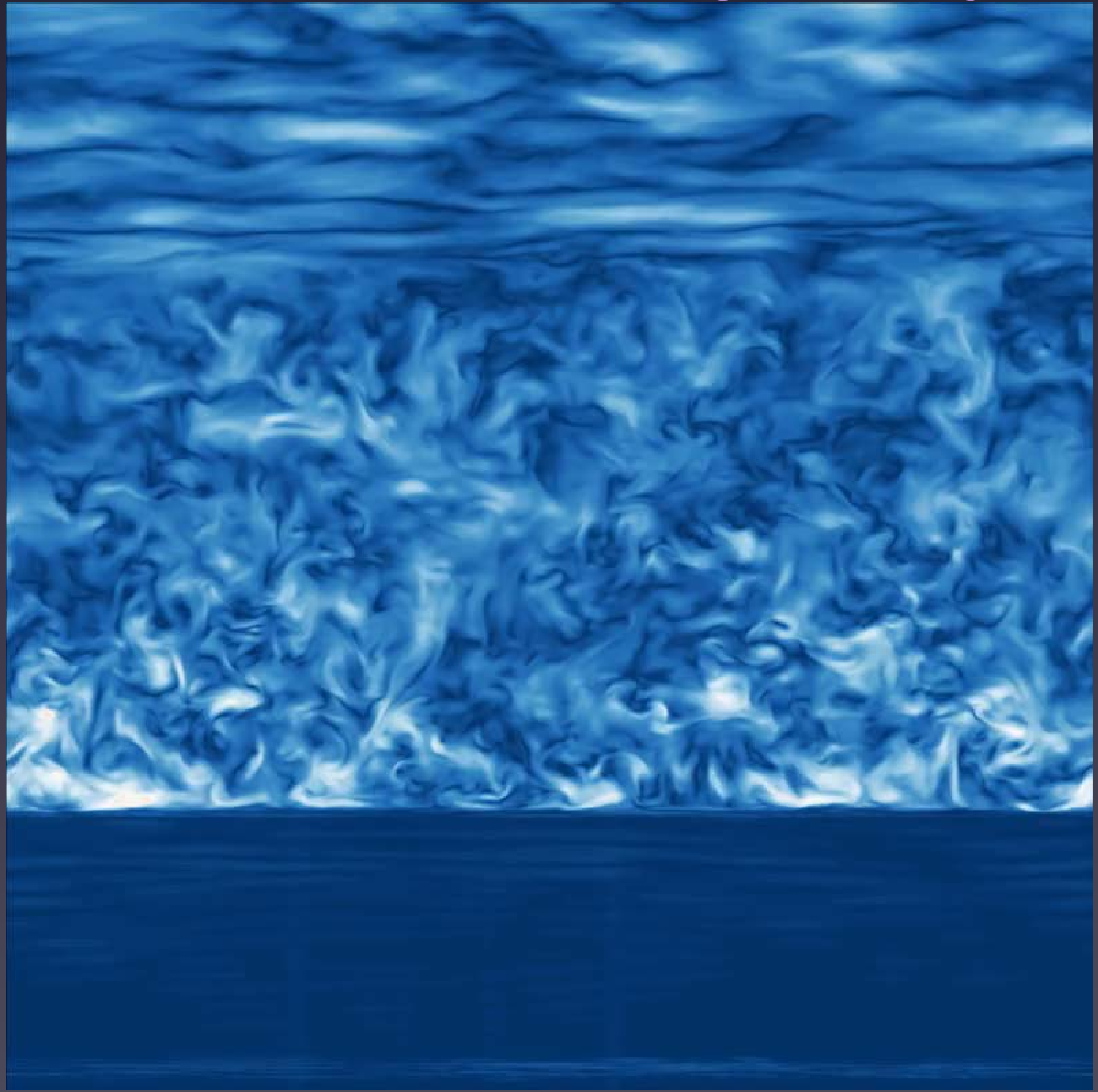
- Pre-SN outbursts common in many types of SNe
  - Occur in last ~years of star's life
  - Mass loss rates enhanced by factors of ~10^3
- Waves may be cause

  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

Huge energy fluxes during late burning phases

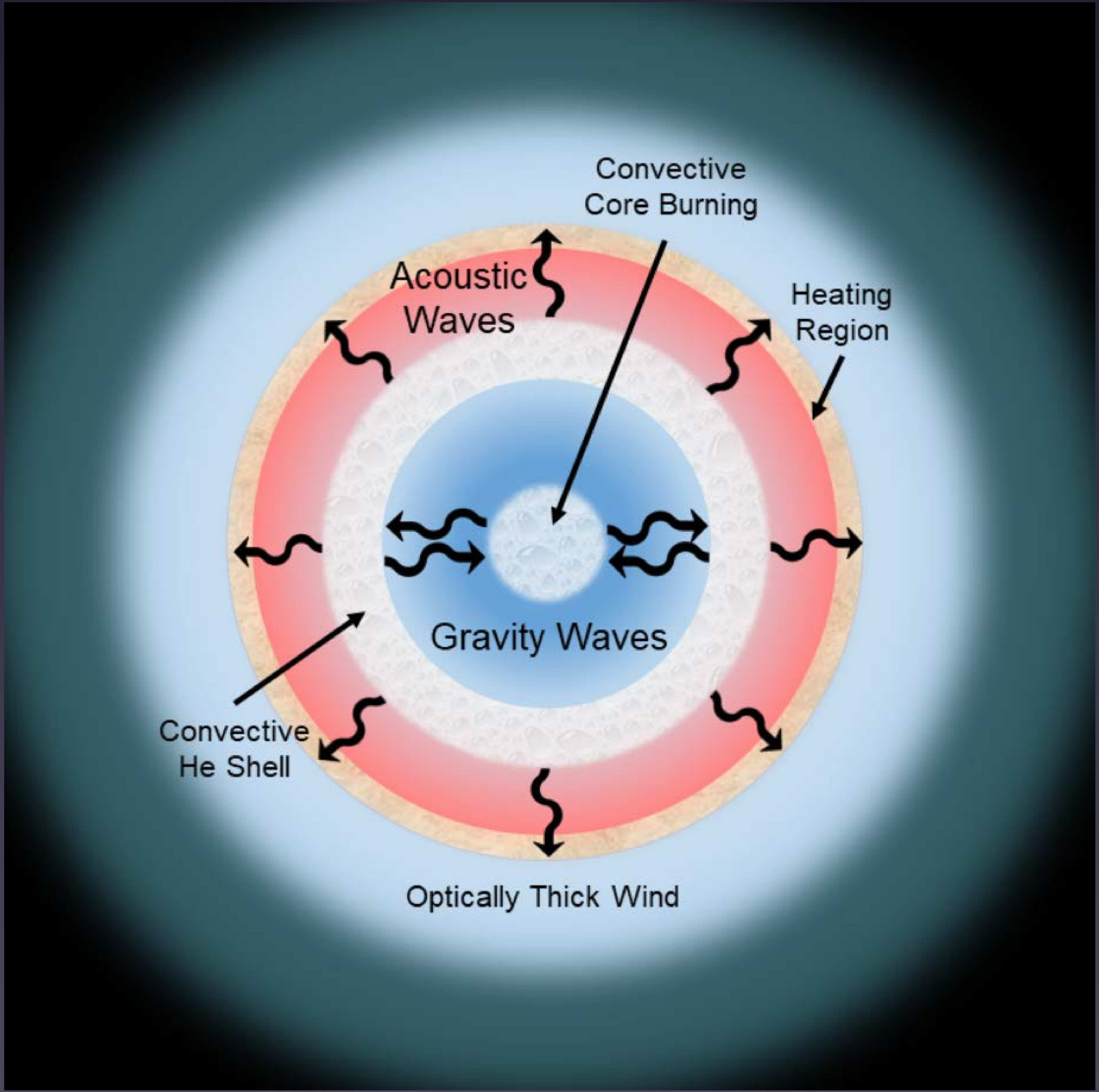
$$L_{\rm wave} \sim \mathcal{M}_{\rm conv} L_{\rm conv} \sim 10^8 \left(\frac{L_{\rm conv}}{10^{10}\,{\rm L}_\odot} \right) \left(\frac{\mathcal{M}_{\rm conv}}{0.01} \right) {\rm L}_\odot$$

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

Table 1. Late stages of massive stellar evolution.

Stage	Duration ($t_{\rm nuc}$)	$L_{\rm fusion}$ ($L_\odot$)	Mach ($\mathcal{M}_{\rm conv}$)	τ_c (s)
Carbon	$\sim 10^3$ yr	$\sim 10^6$	~ 0.003	$\sim 10^{4.5}$
Neon	~ 1 yr	$\sim 10^9$	~ 0.01	$\sim 10^3$
Oxygen	~ 1 yr	$\sim 10^{10}$	~ 0.02	$\sim 10^3$
Silicon	~ 1 d	$\sim 10^{12}$	~ 0.05	$\sim 10^2$

Quataert & Shiode (2012)



Fuller & Ro 2018

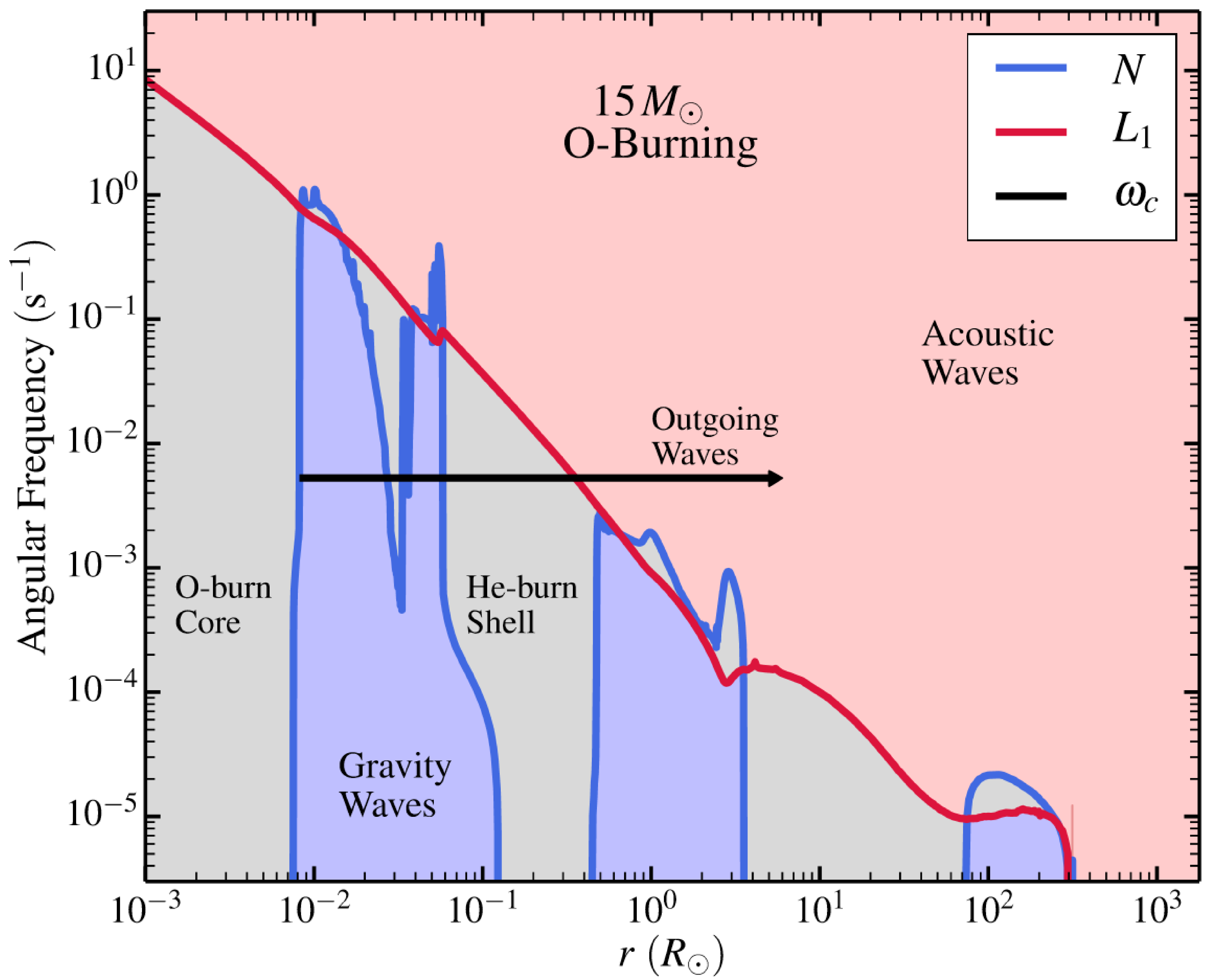
Wave Propagation

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

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:

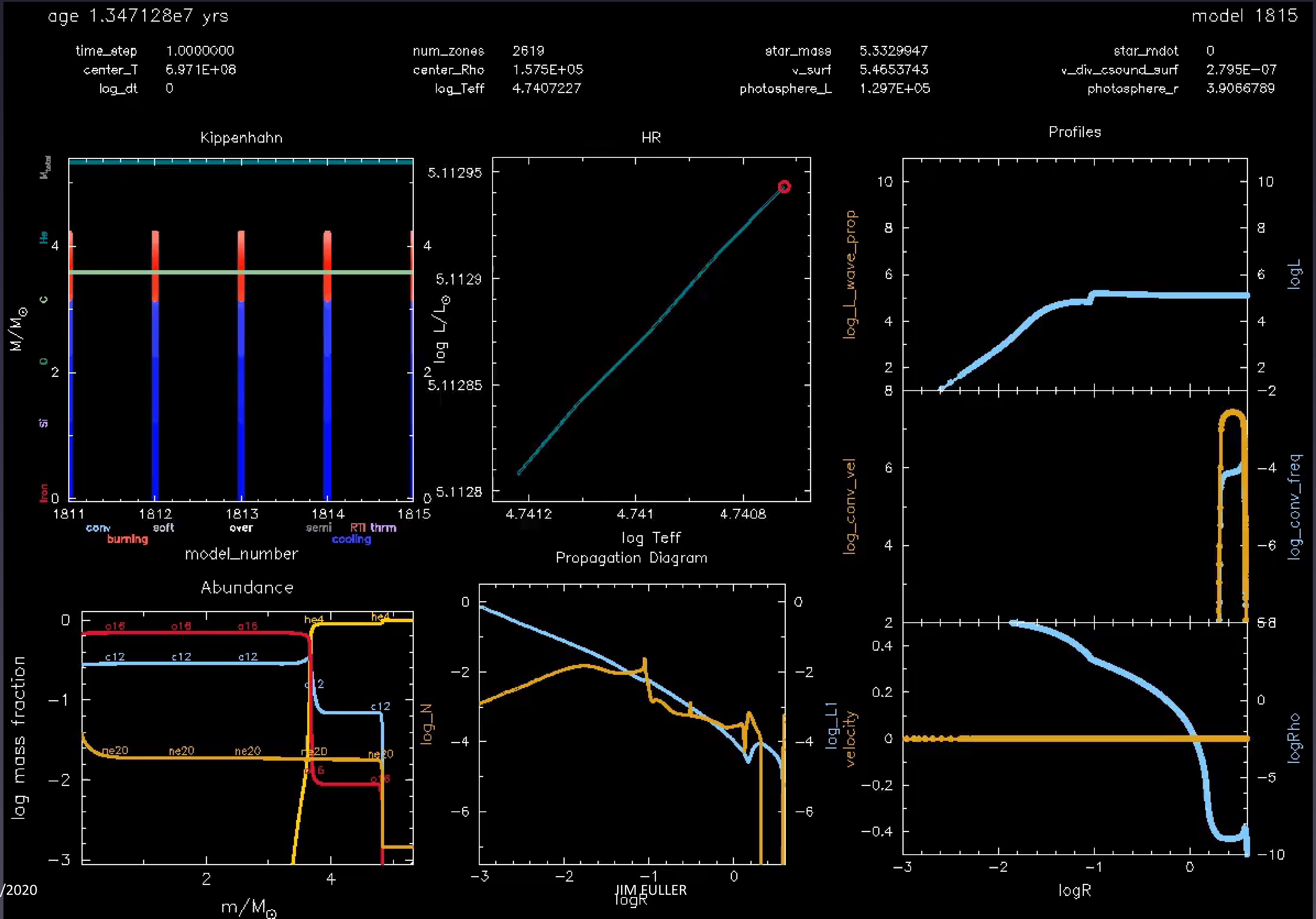
$$L_{\rm heat} = f_{\rm esc} L_{\rm wave} = \left[1 + \frac{T_{\rm shell}^2 + x_\nu}{T_{\rm min}^2} \right]^{-1} L_{\rm wave}$$

  - 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

$$k_r^2 = \frac{\left(N^2 - \omega_2\right)\left(L_l^2 - \omega^2\right)}{\omega^2 c_s^2}$$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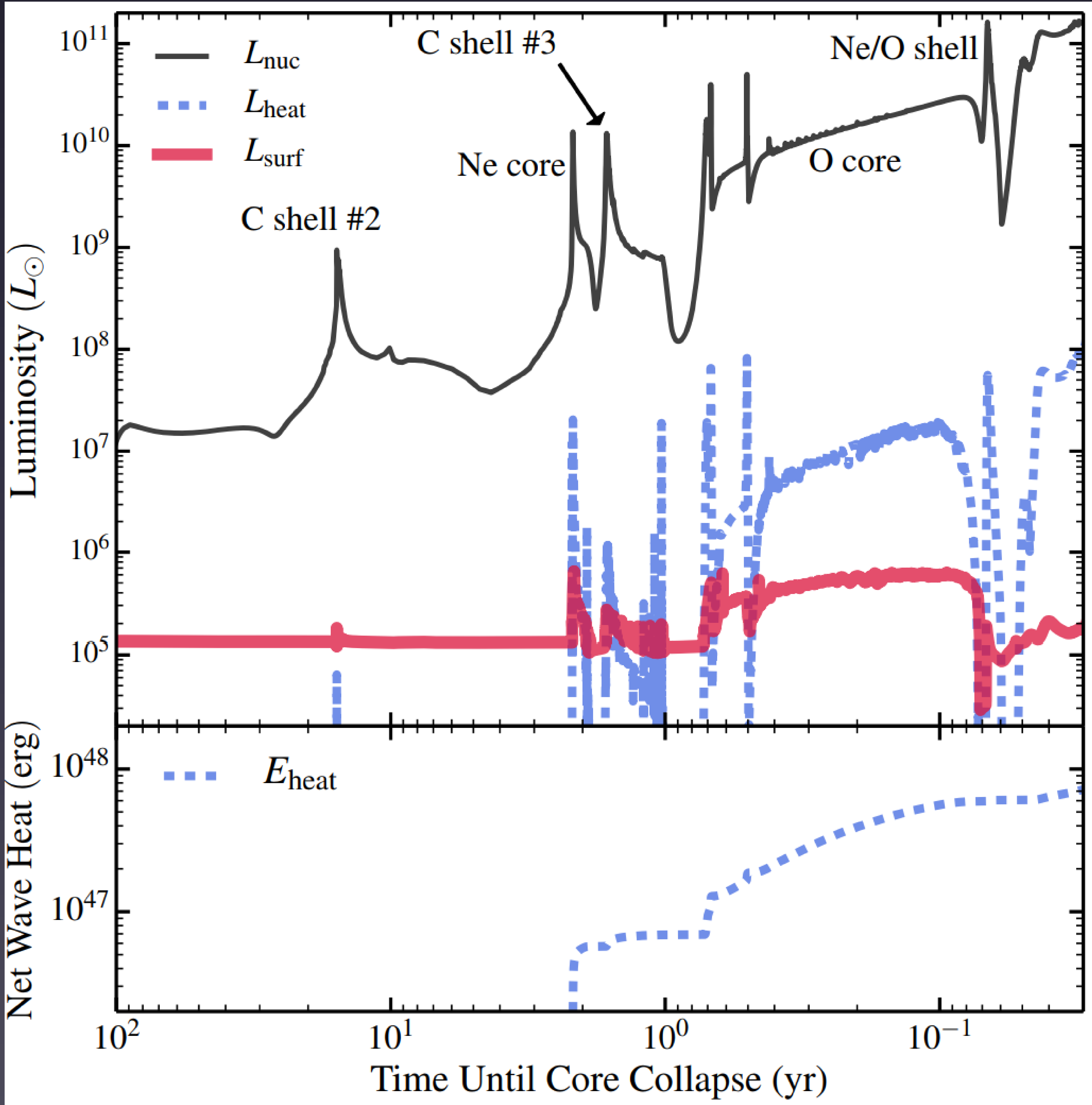
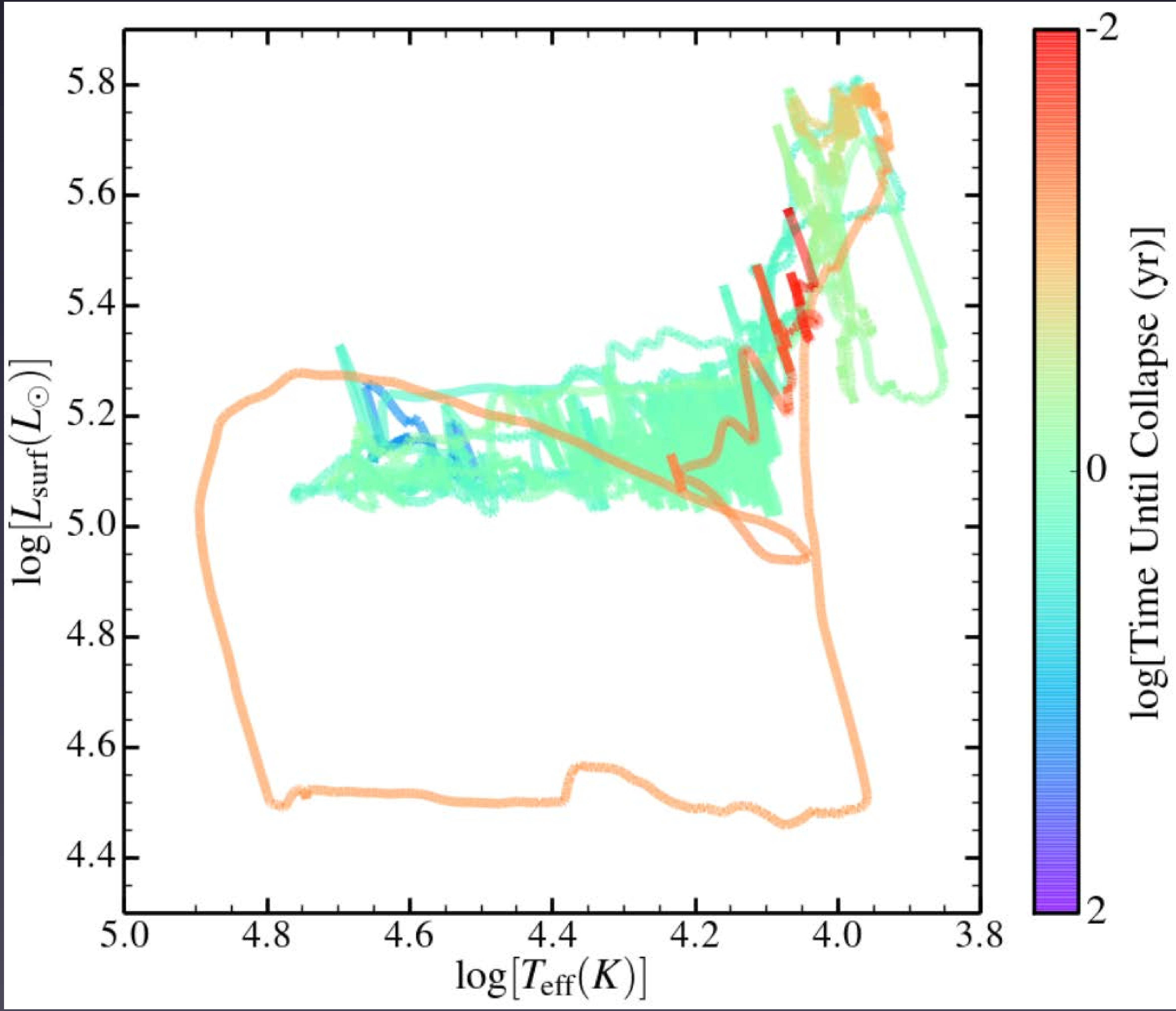
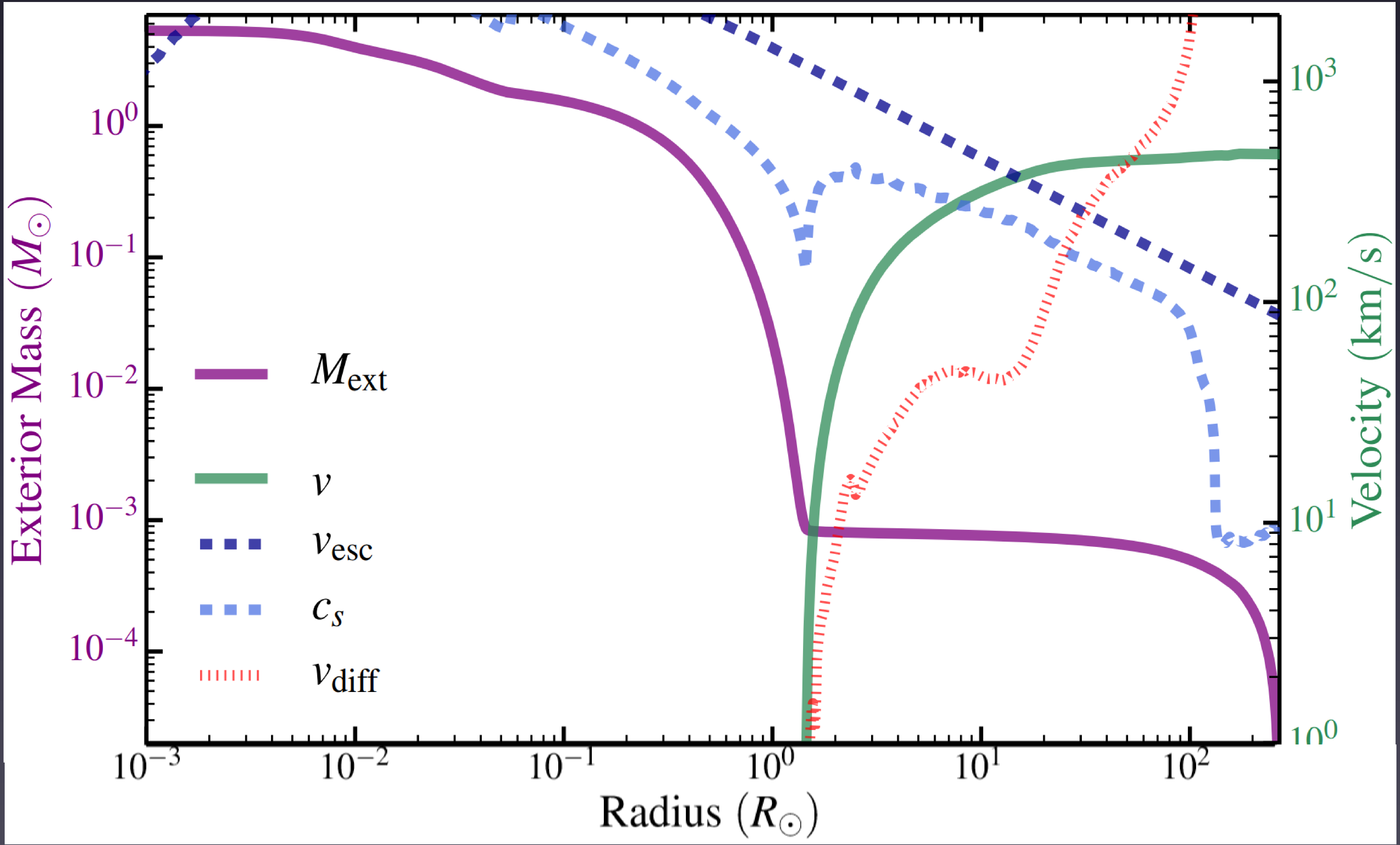
center_T 6.971E+08
log_dt 0
num_zones 2619
center_Rho 1.575E+05
log_Teff 4.7407227
star_mass 5.3329947
v_surf 5.4653743
photosphere_L 1.297E+05
star_mdot 0
v_div_csound_surf 2.795E−07
photosphere_r 3.9066789
Kippenhahn
HR
Profiles
M/M⊙
model_number
conv
burning
soft
over
semi
RTI thrm
cooling
log L/L⊙
log Teff
log_L_wave_prop
logL
log_conv_vel
log_conv_freq
Abundance
log mass fraction
m/M⊙
o16
c12
he4
ne20
Propagation Diagram
log_N
log_L1
logR
velocity
logRho



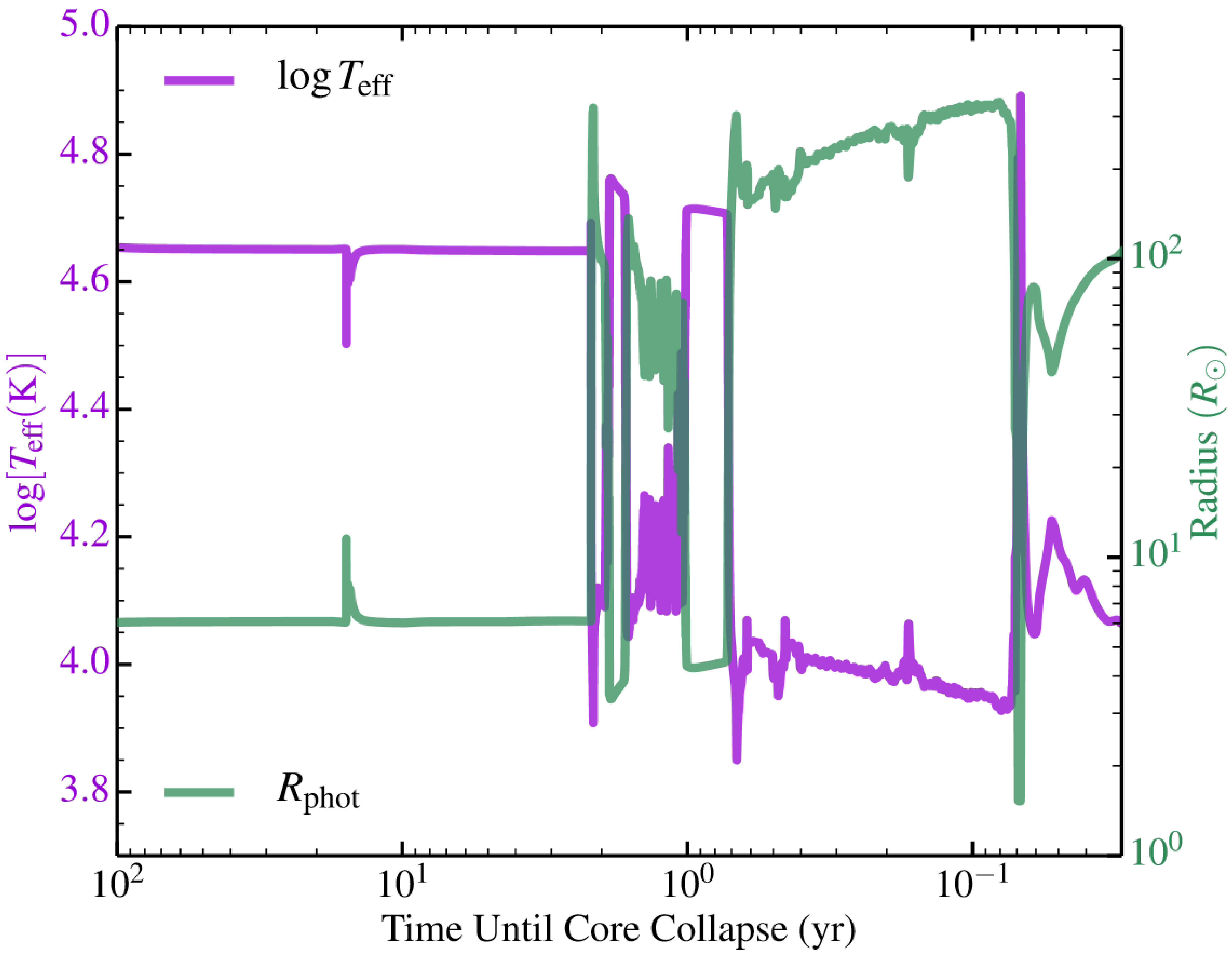
Fuller & Ro 2018



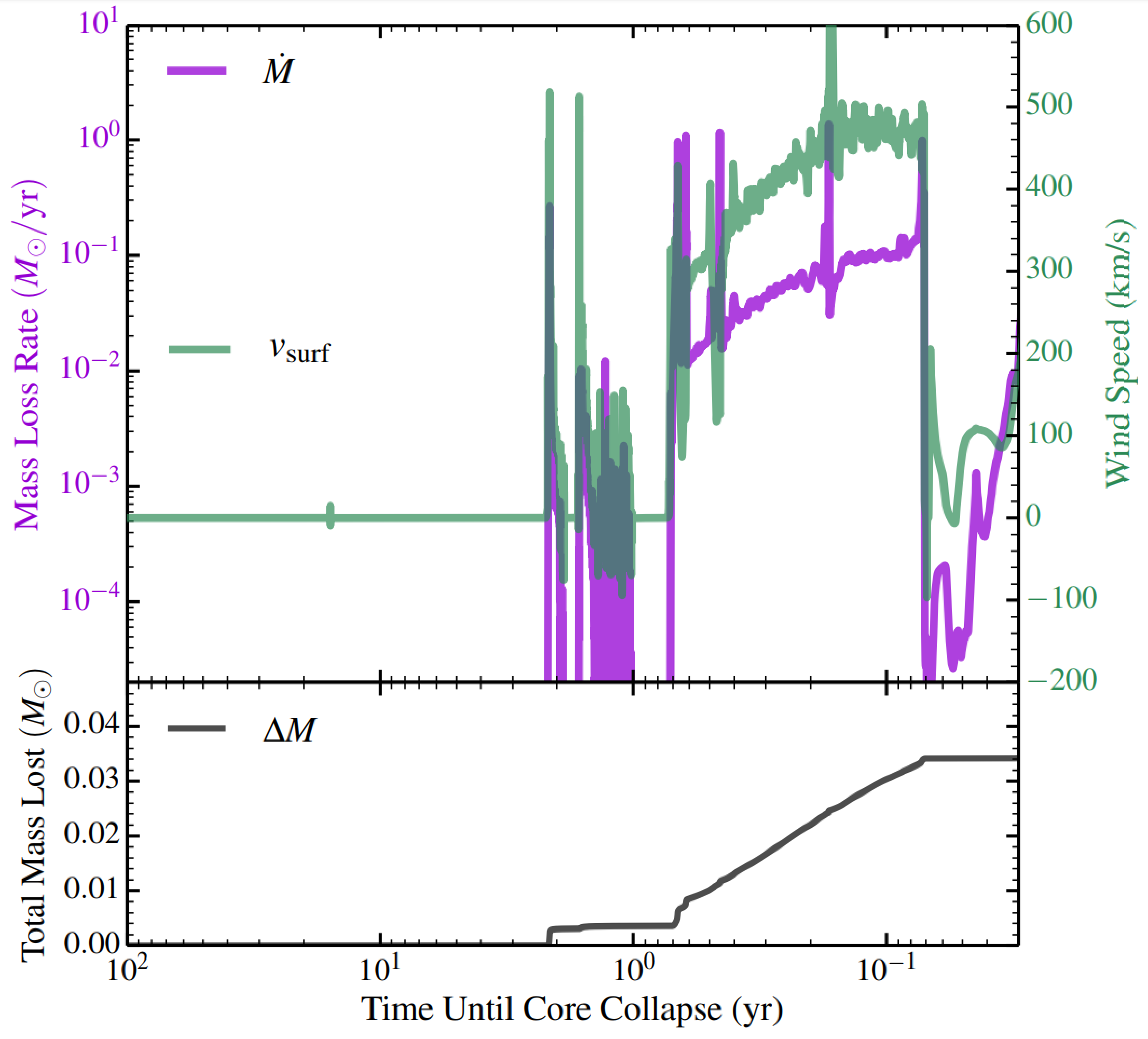
Fuller & Ro 2018



Fuller & Ro 2018



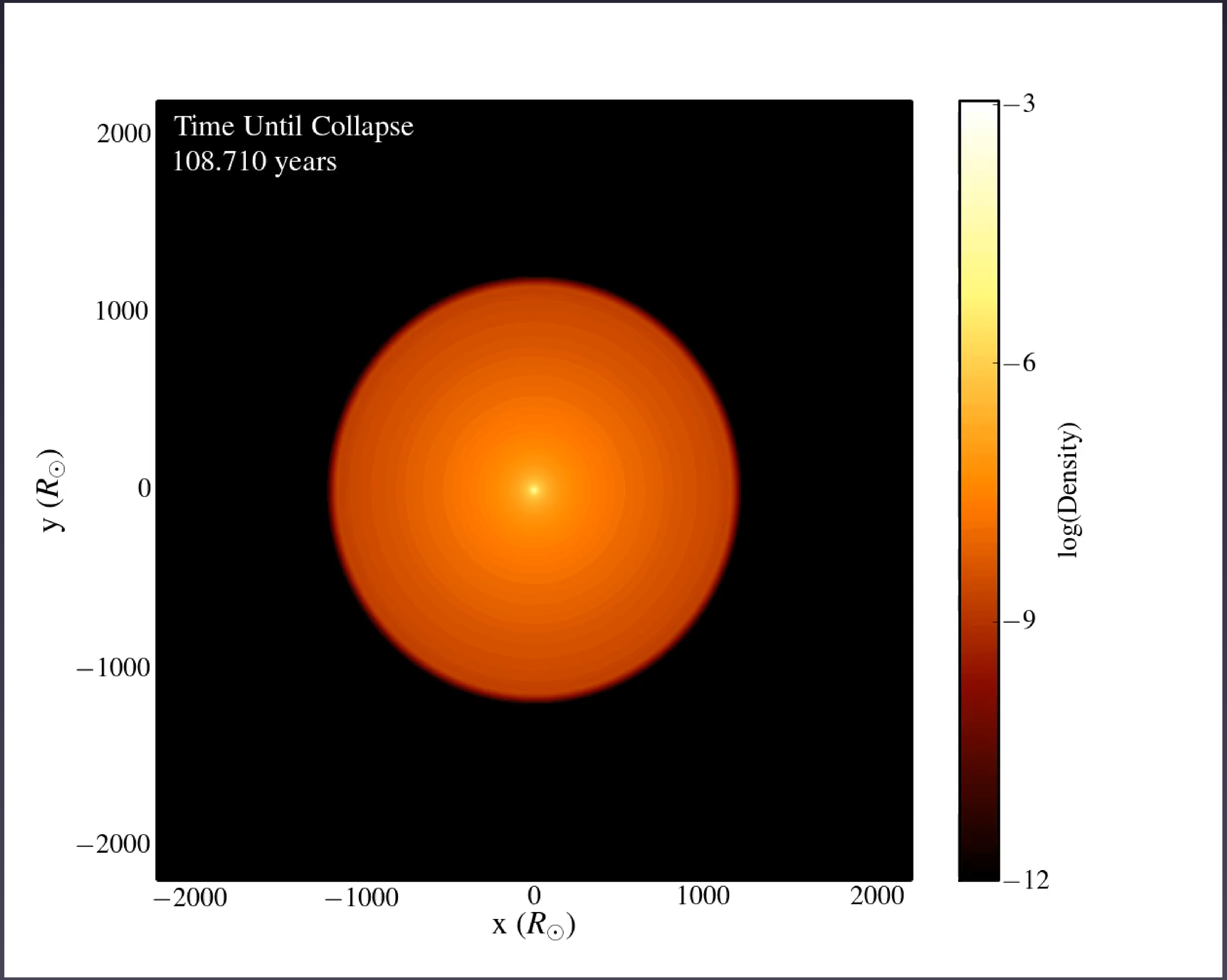
Fuller & Ro 2018



Fuller & Ro
2018

Hydrogen-rich stars

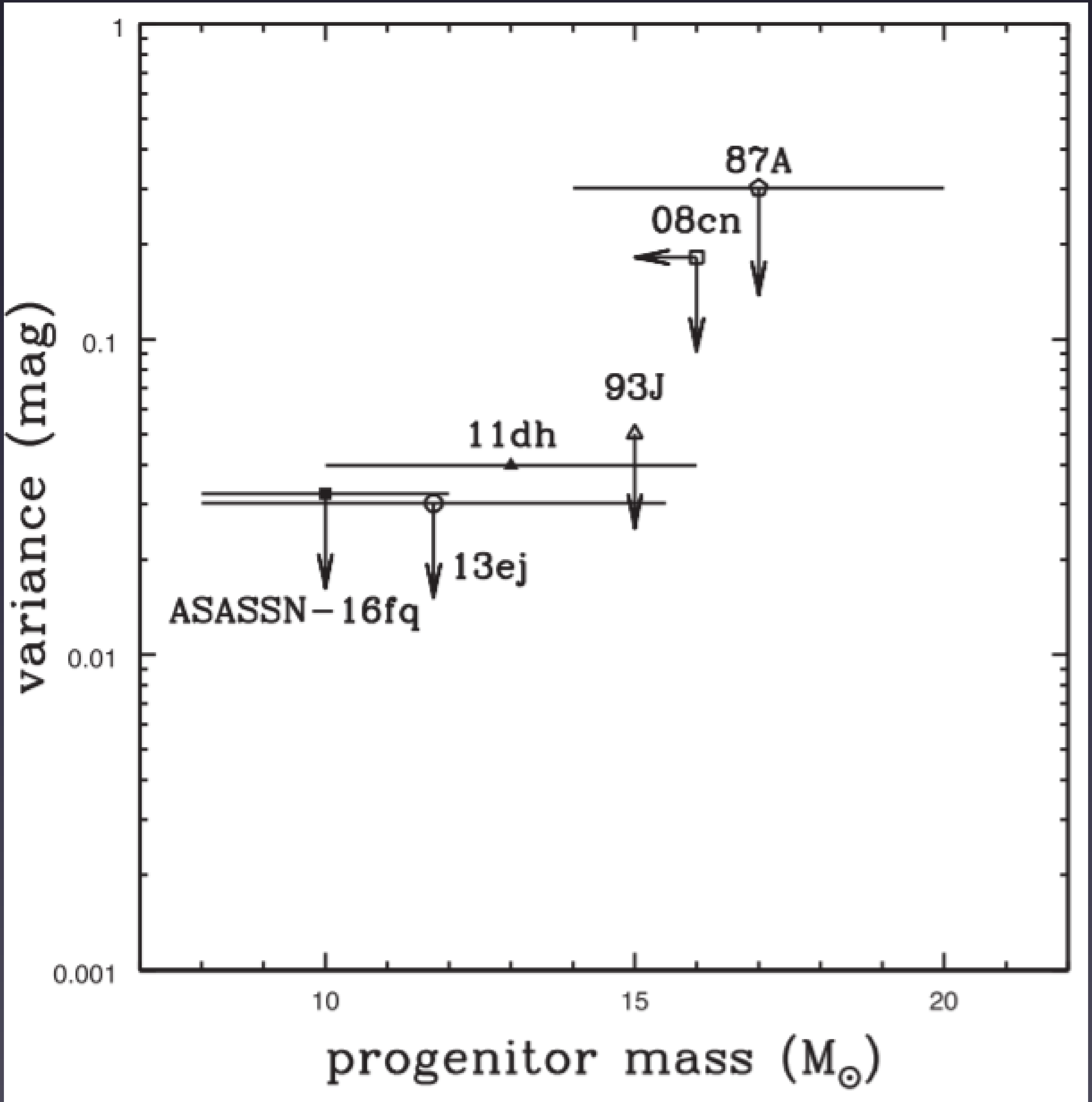
- Waves damp at base of H-envelope
- Wave heat launches acoustic pulse that nearly unbinds surface layers
- Envelope density profile, SN light curve are altered



Fuller & Ro 2018

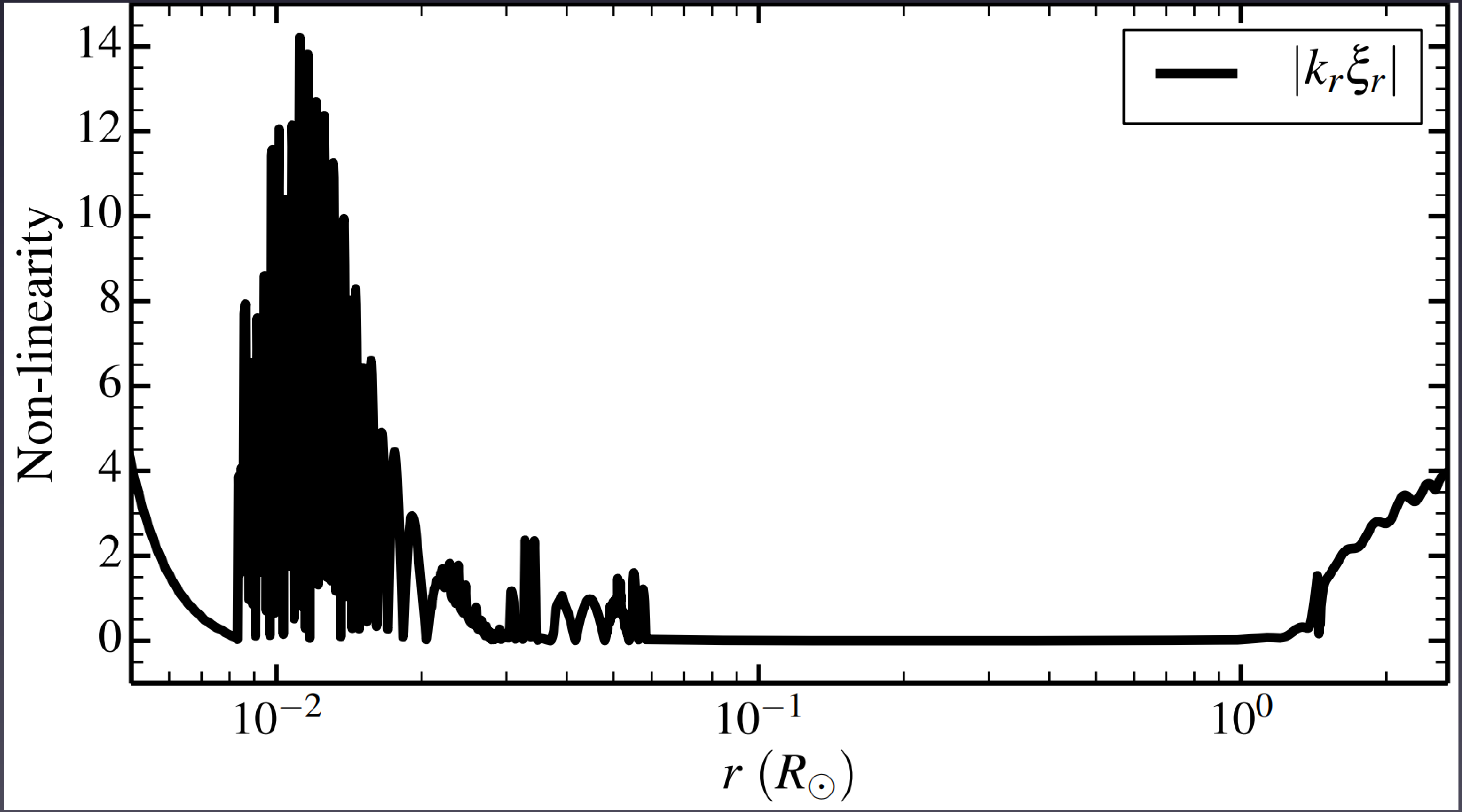
Variability of Progenitors

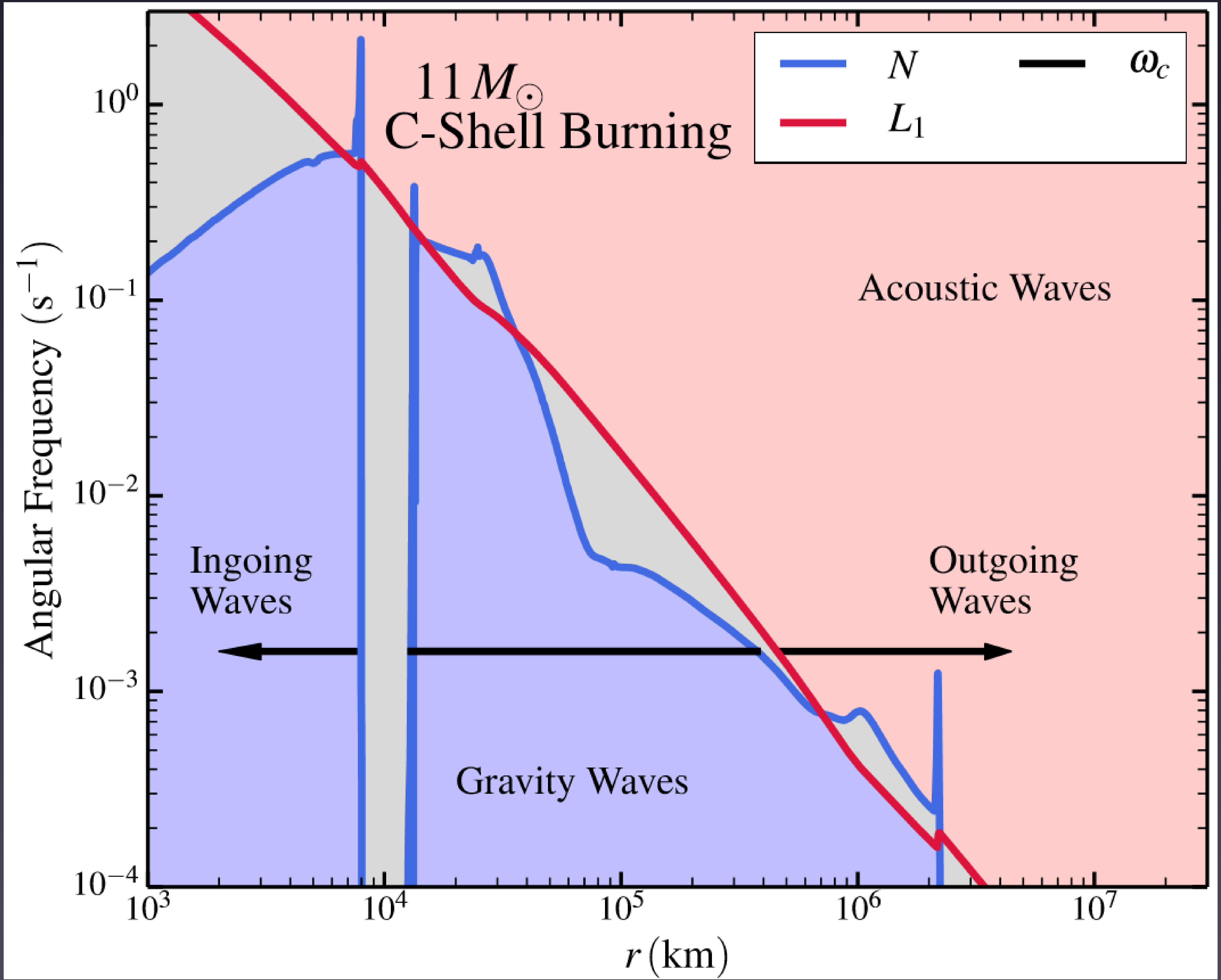
- Outbursts may be uncommon



Kochanek et al. 2017

Problem: waves are non-linear




11 $M_\odot$
C-Shell Burning
N
L_1
ω_c
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 (km)

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?

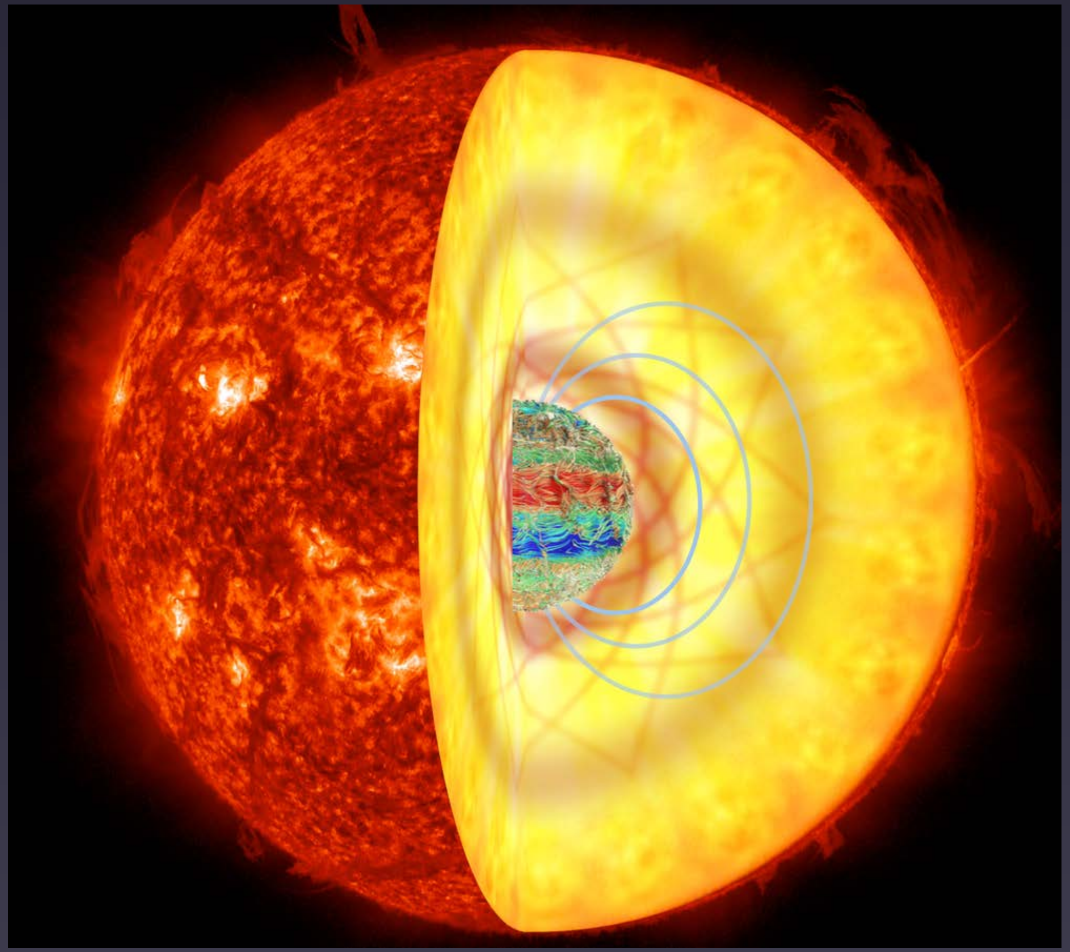
Conclusions and Discussion

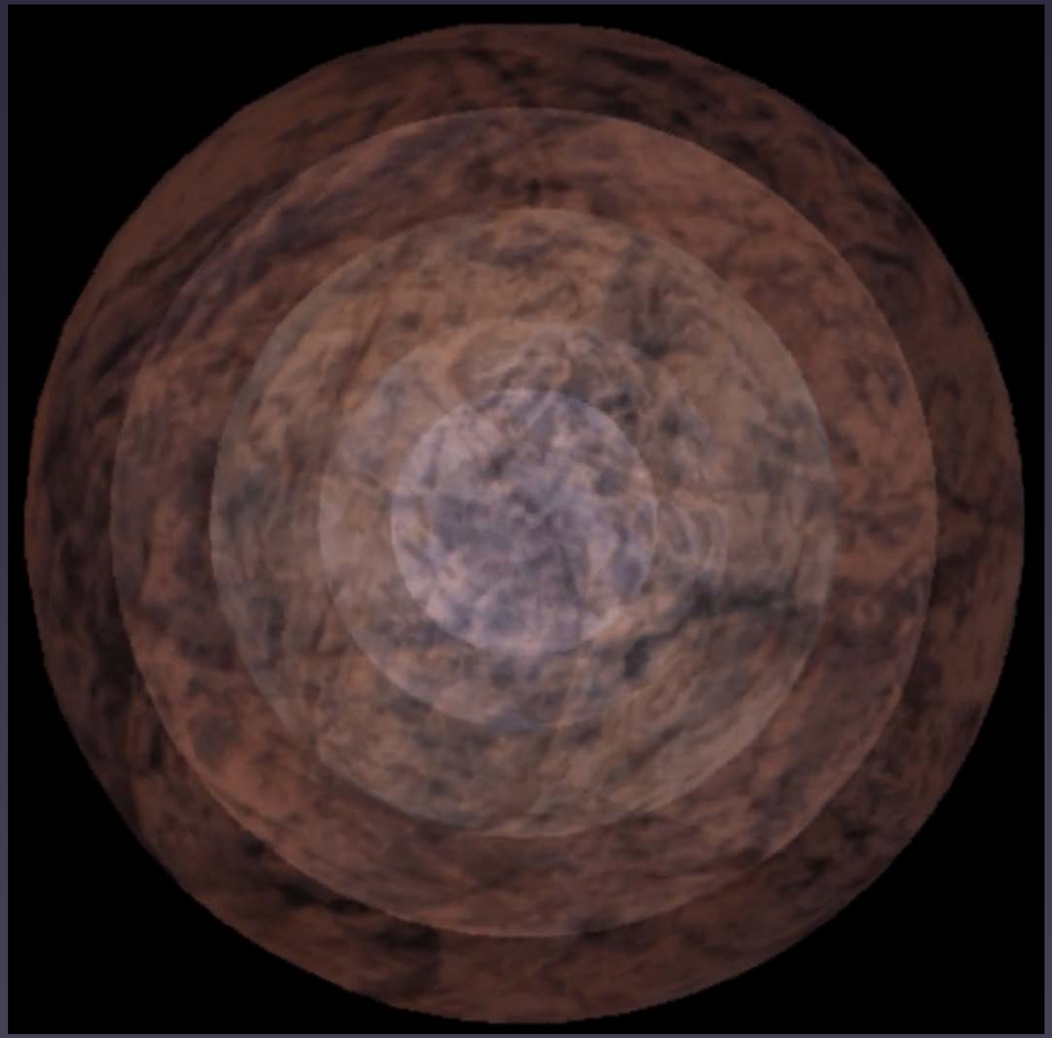
- Wave heating in may cause pre-SN outbursts
  - Wave heating unlikely to lead to most luminous Type IIn Sne

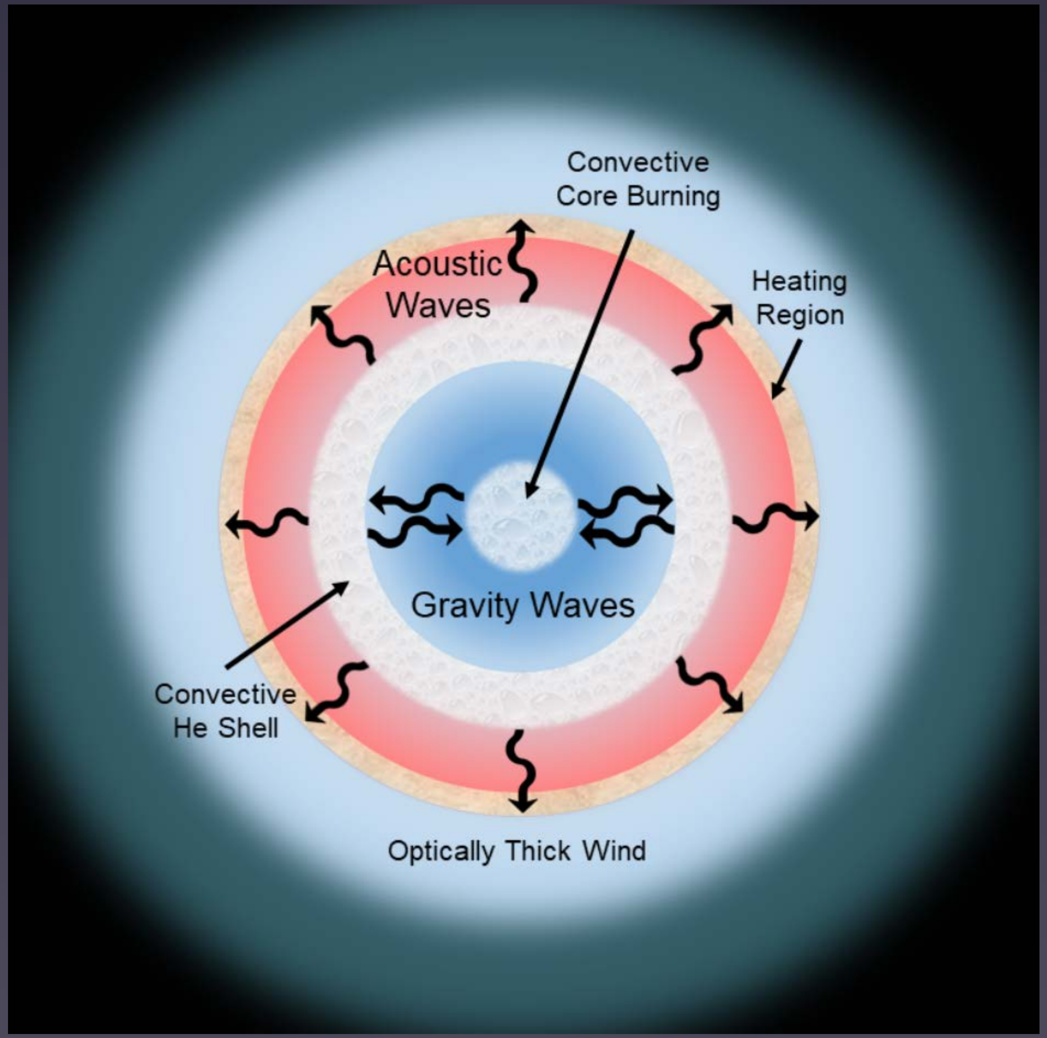
- Wave heating is good candidate to create:
  - Flash-ionized SNe
  - Type II-L SNe
  - Type Ibn and transitional Ib/IIn SNe

- Unlikely to substantially alter core structure (binding energy ~10^{51} erg)

Thanks!






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