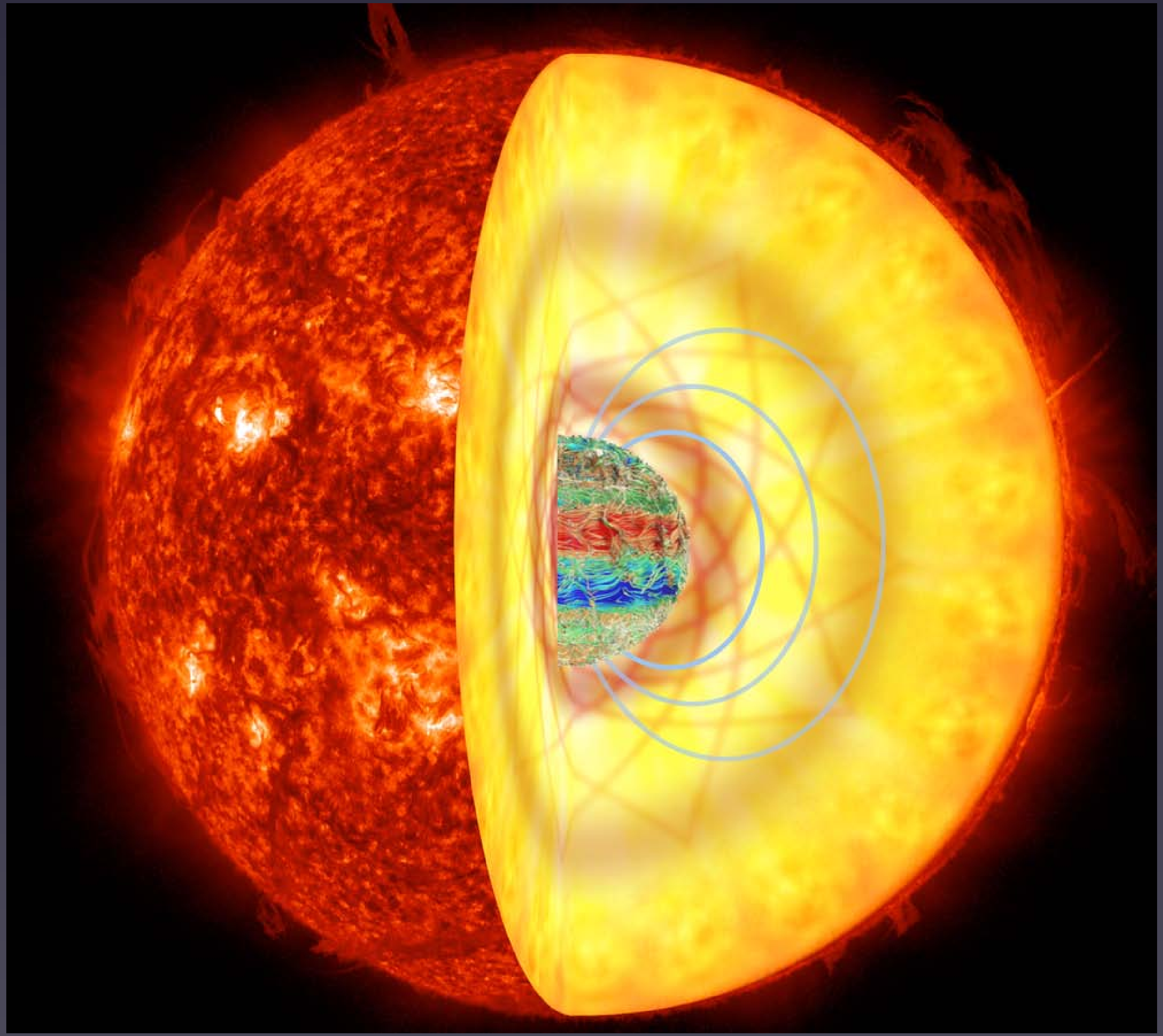
Asteroseismic Windows into Stellar Cores

Jim Fuller

Caltech/KITP



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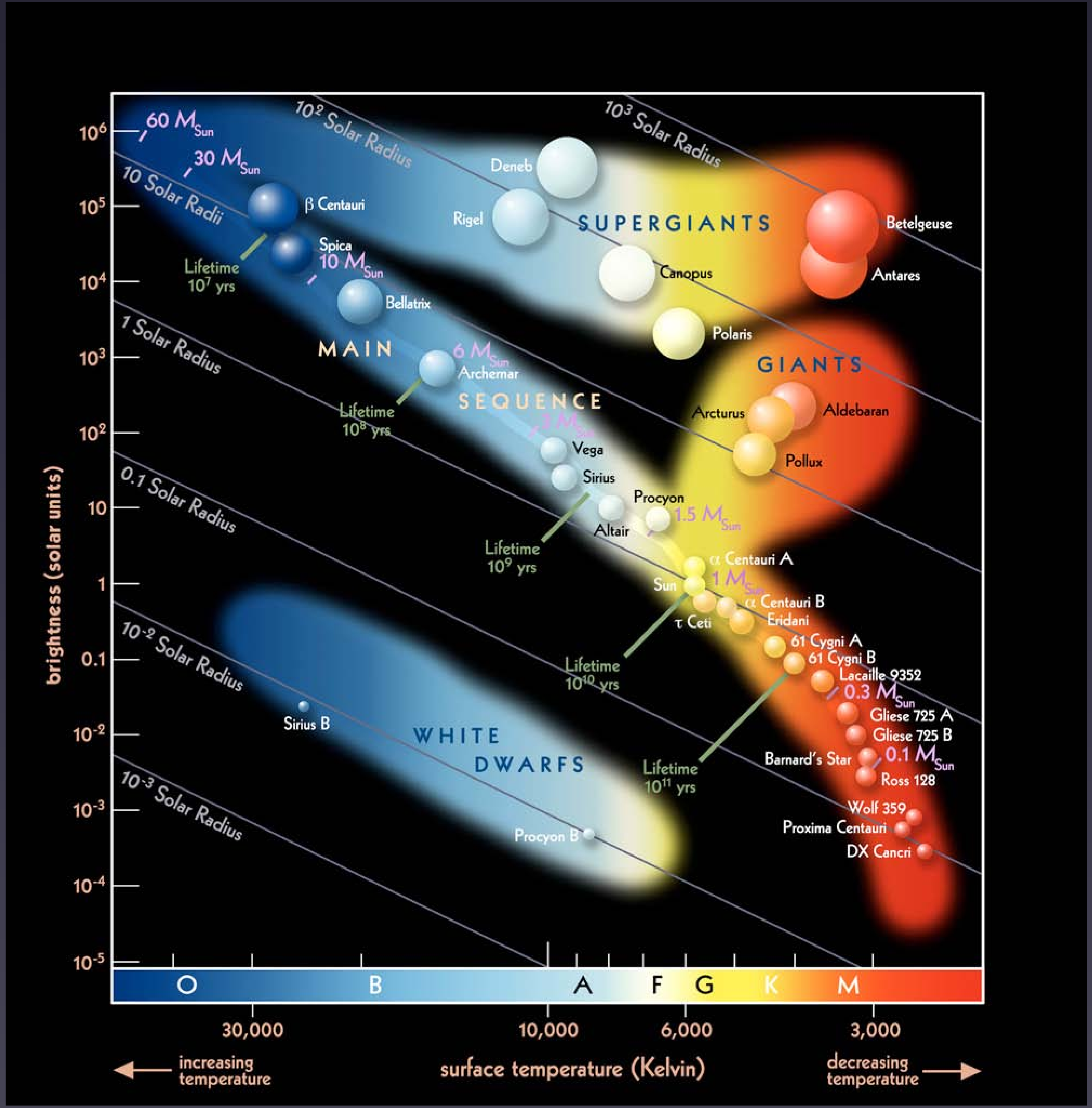
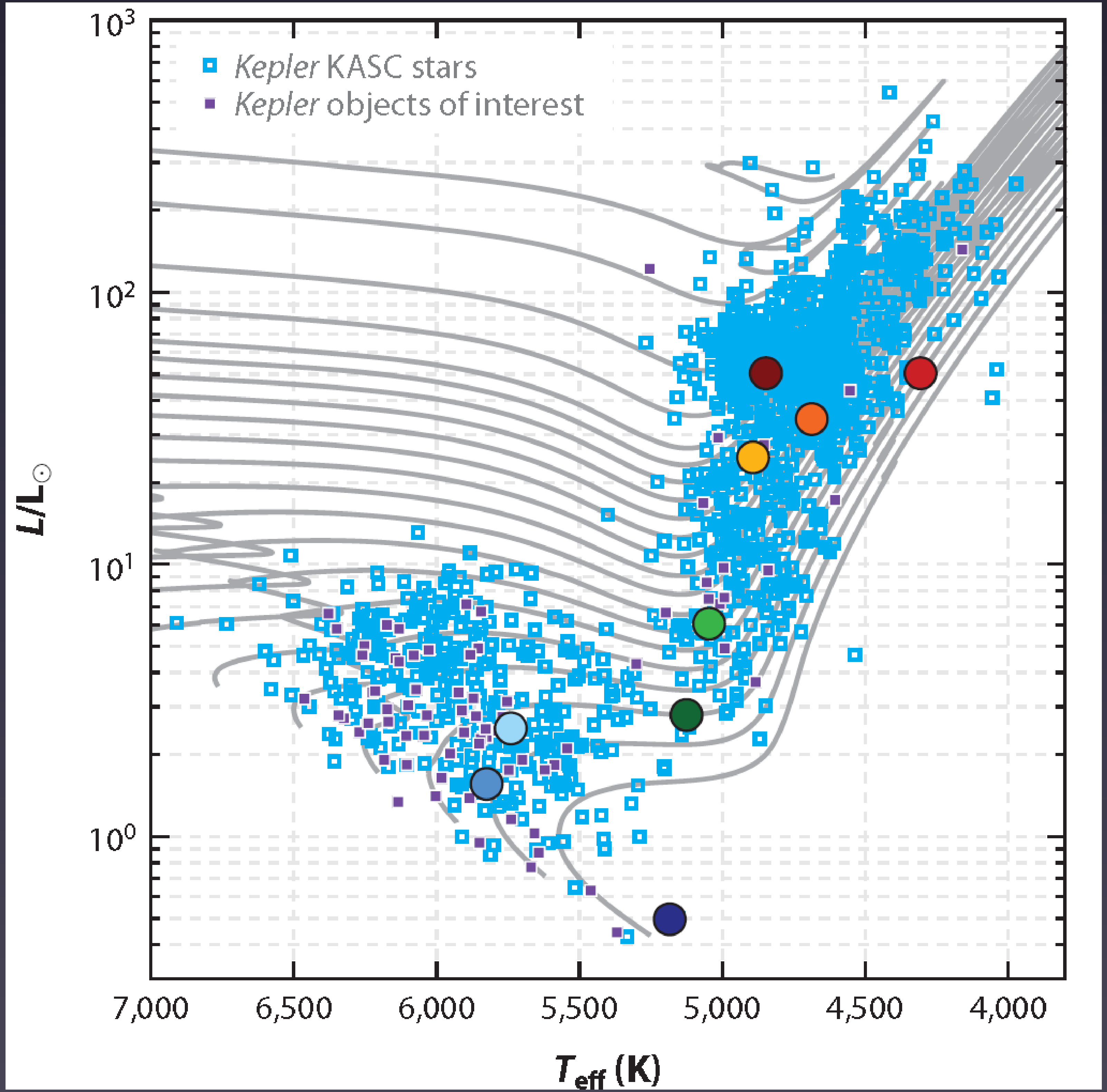
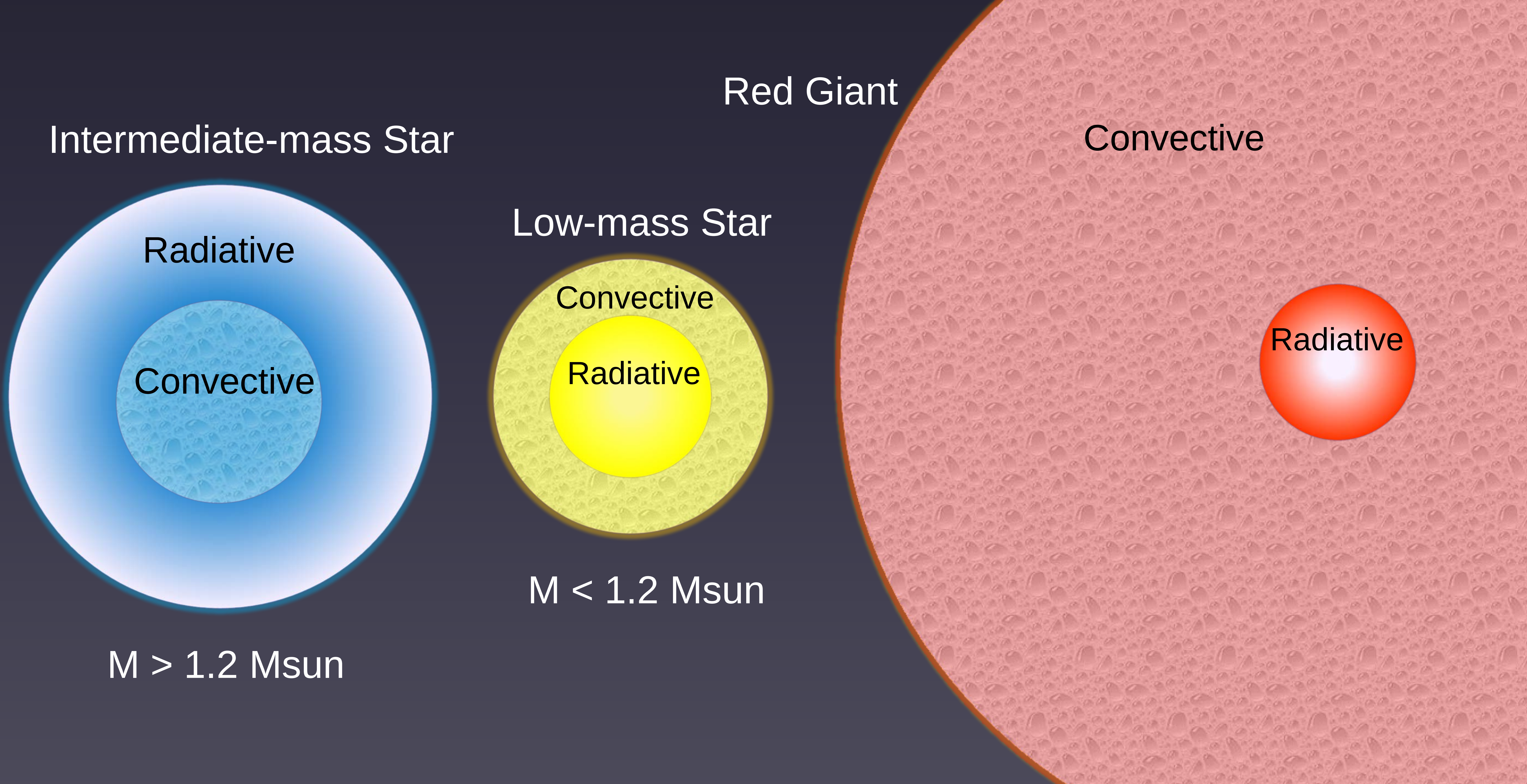
Stellar evolution and *Kepler* Asteroseismology





Chaplin & Miglio 2013

Stellar Structure



Intermediate-mass Star

Radiative

Convective

M > 1.2 Msun

Low-mass Star

Convective

Radiative

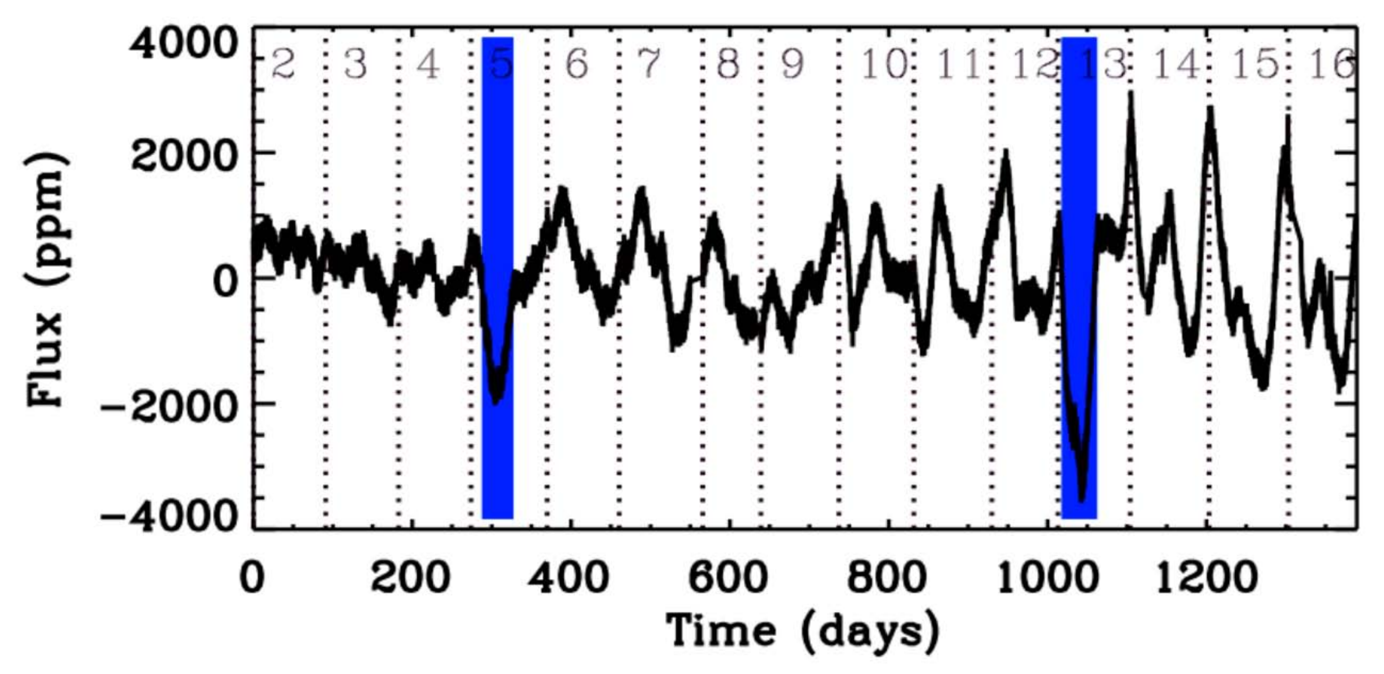
M < 1.2 Msun

Red Giant

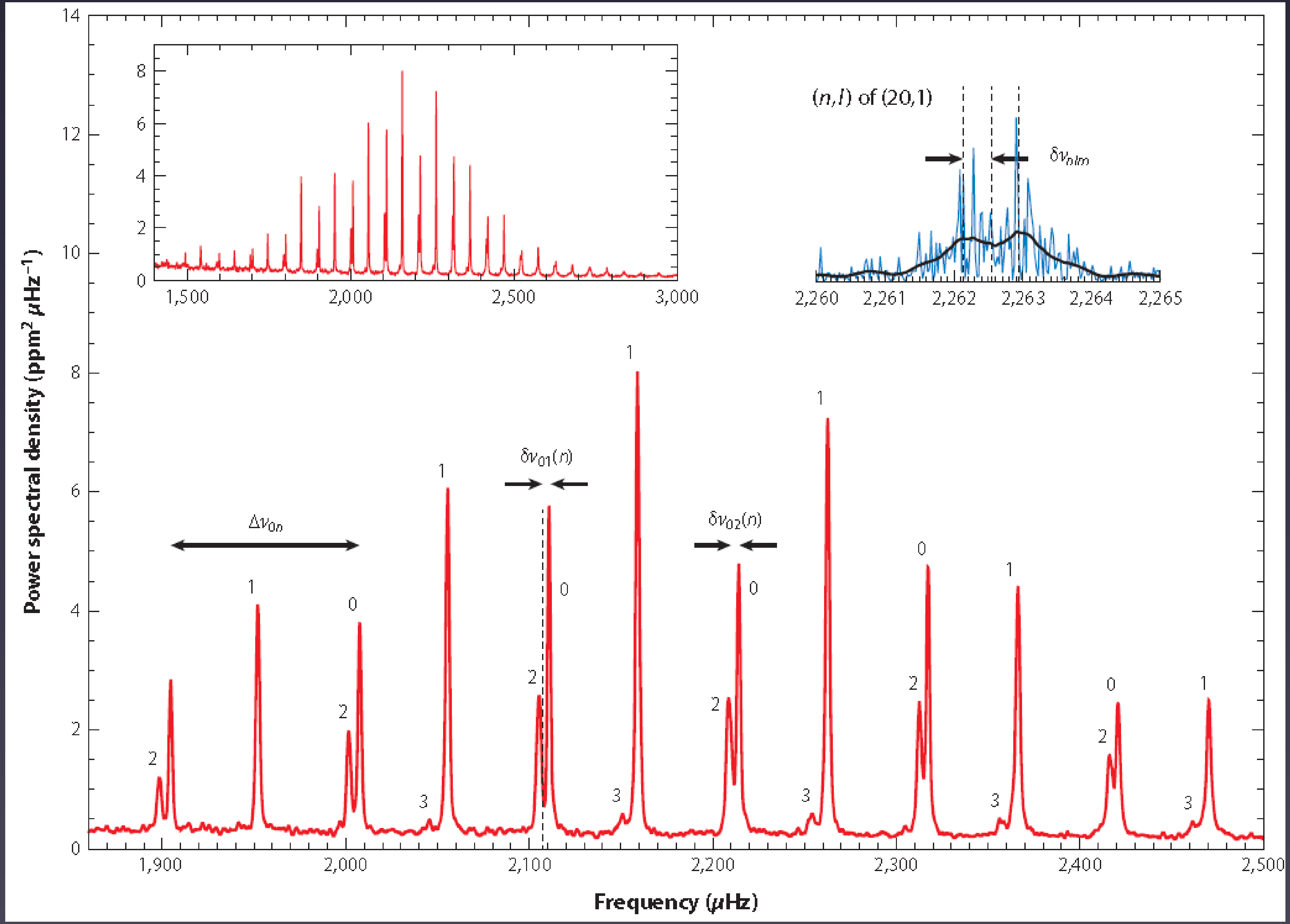
Convective

Radiative

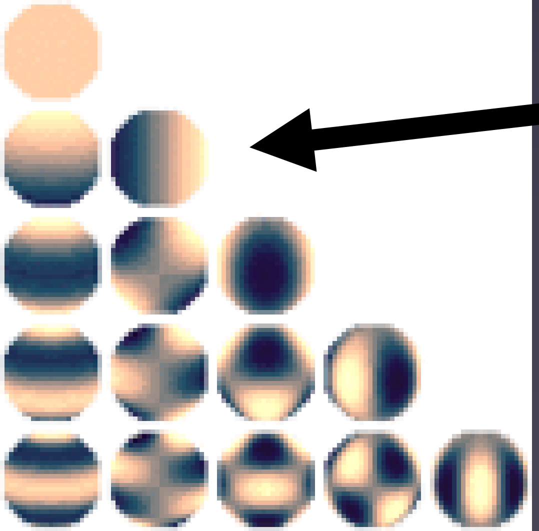
Asteroseismology Basics



Fourier Transform



Chaplin & Miglio 2013



l=1 dipole modes

Asteroseismology basics, continued

Oscillations excited by convection, with frequency near :

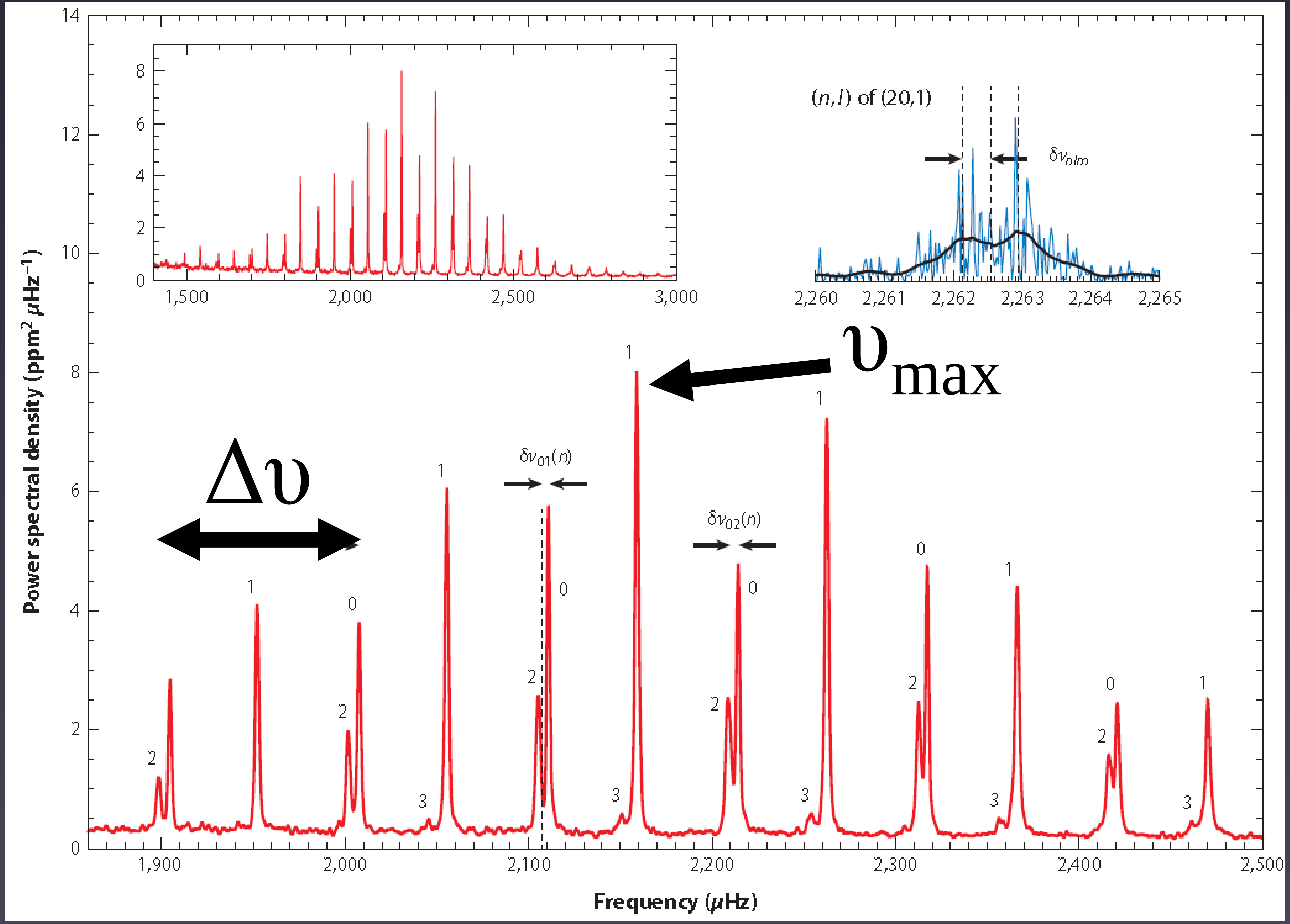
$$\nu_{\max} \propto \nu_{\mathrm{ac}} \propto \frac{c}{H} \propto g\, T_{\mathrm{eff}}^{-1/2}$$

Oscillations separated by dynamical frequency of star:

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

Combine to determine mass and radius via scaling relations (e.g., Brown et al. 1991, Huber et al. 2011)

See poster by Meredith Rawls



Chaplin & Miglio 2013

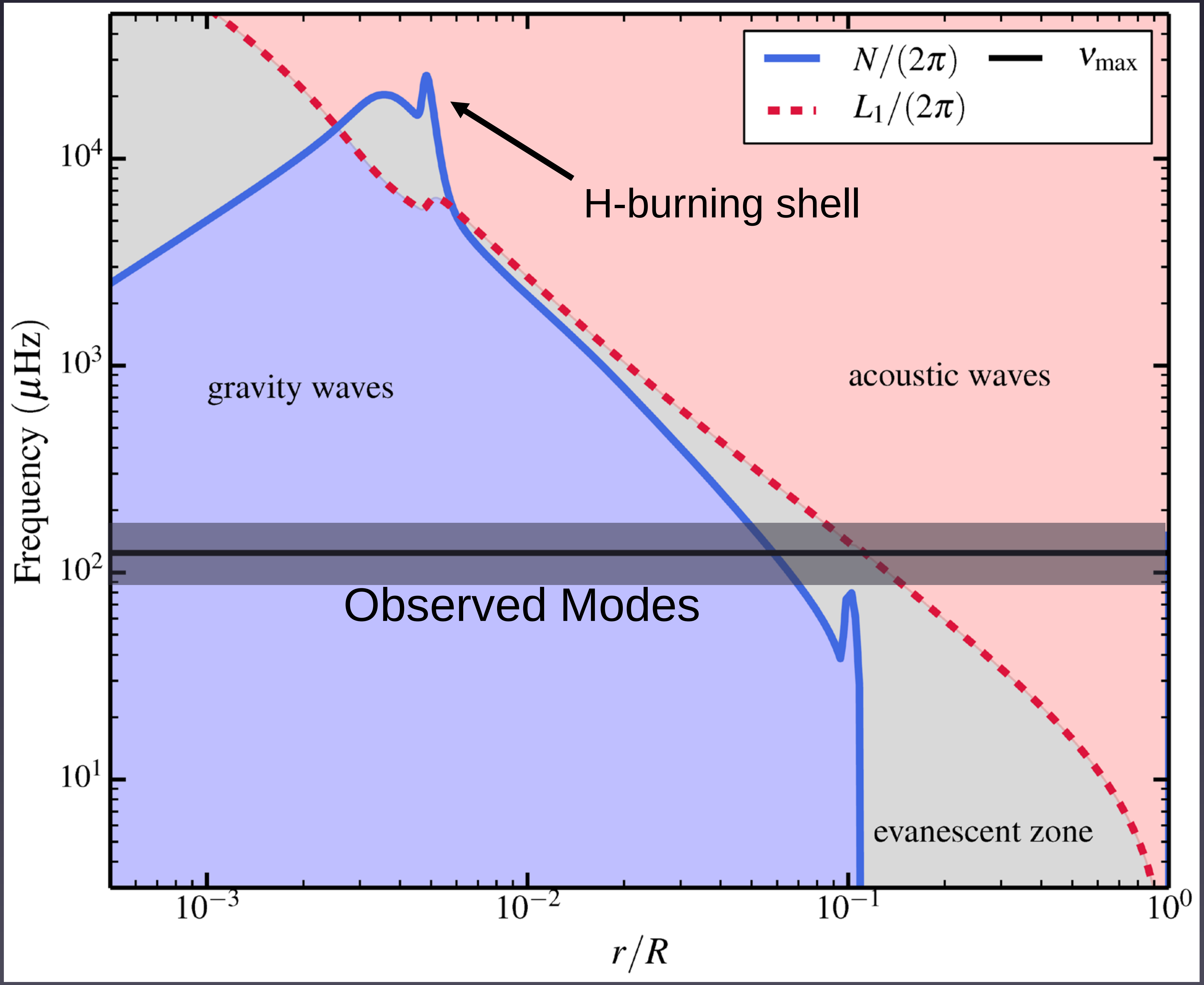
Wave Propagation in the Red Giants

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

$$k_r \simeq \frac{\omega}{v_s}$$

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

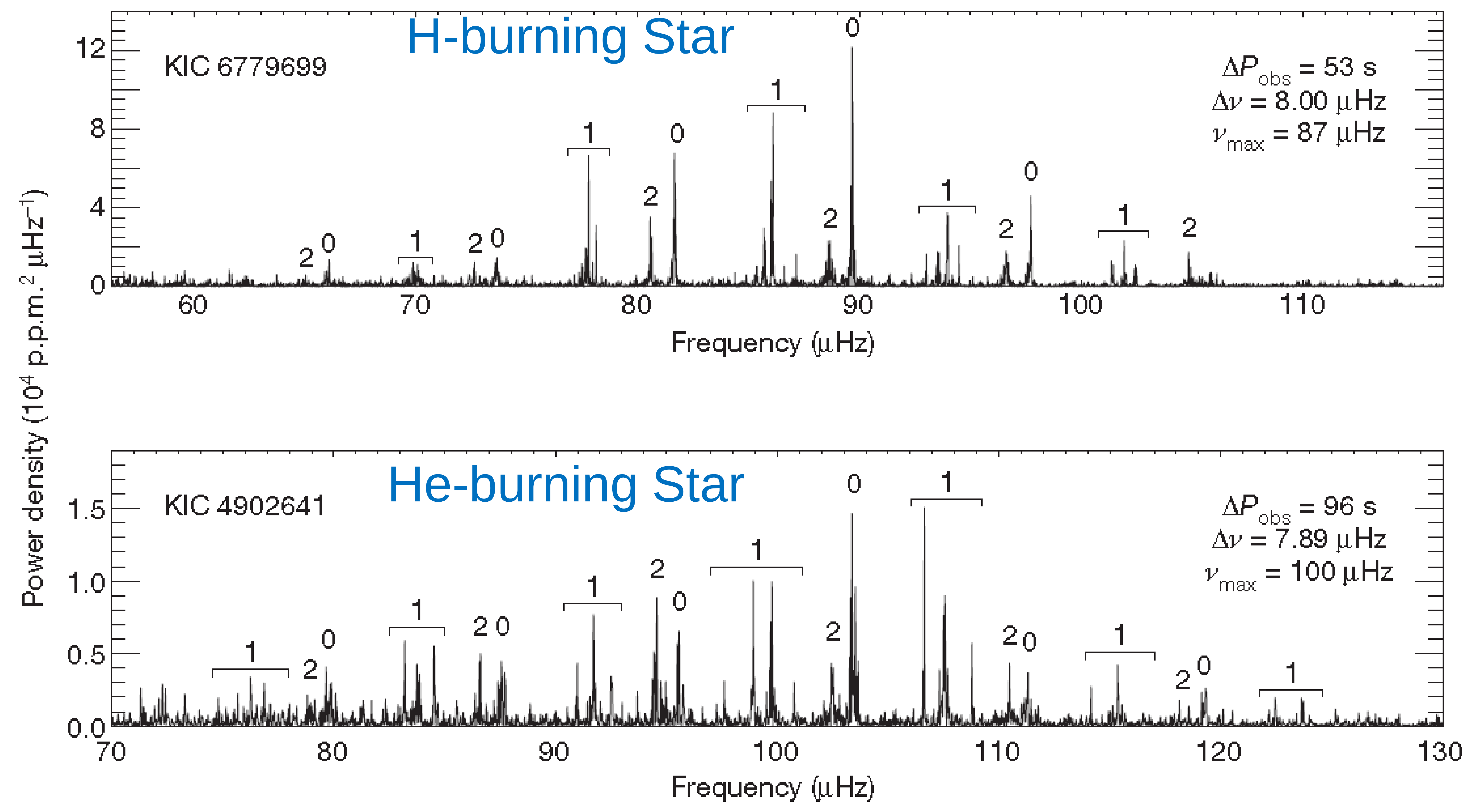
$$k_r \simeq \frac{\ell N}{\omega r}$$



H-burning shell

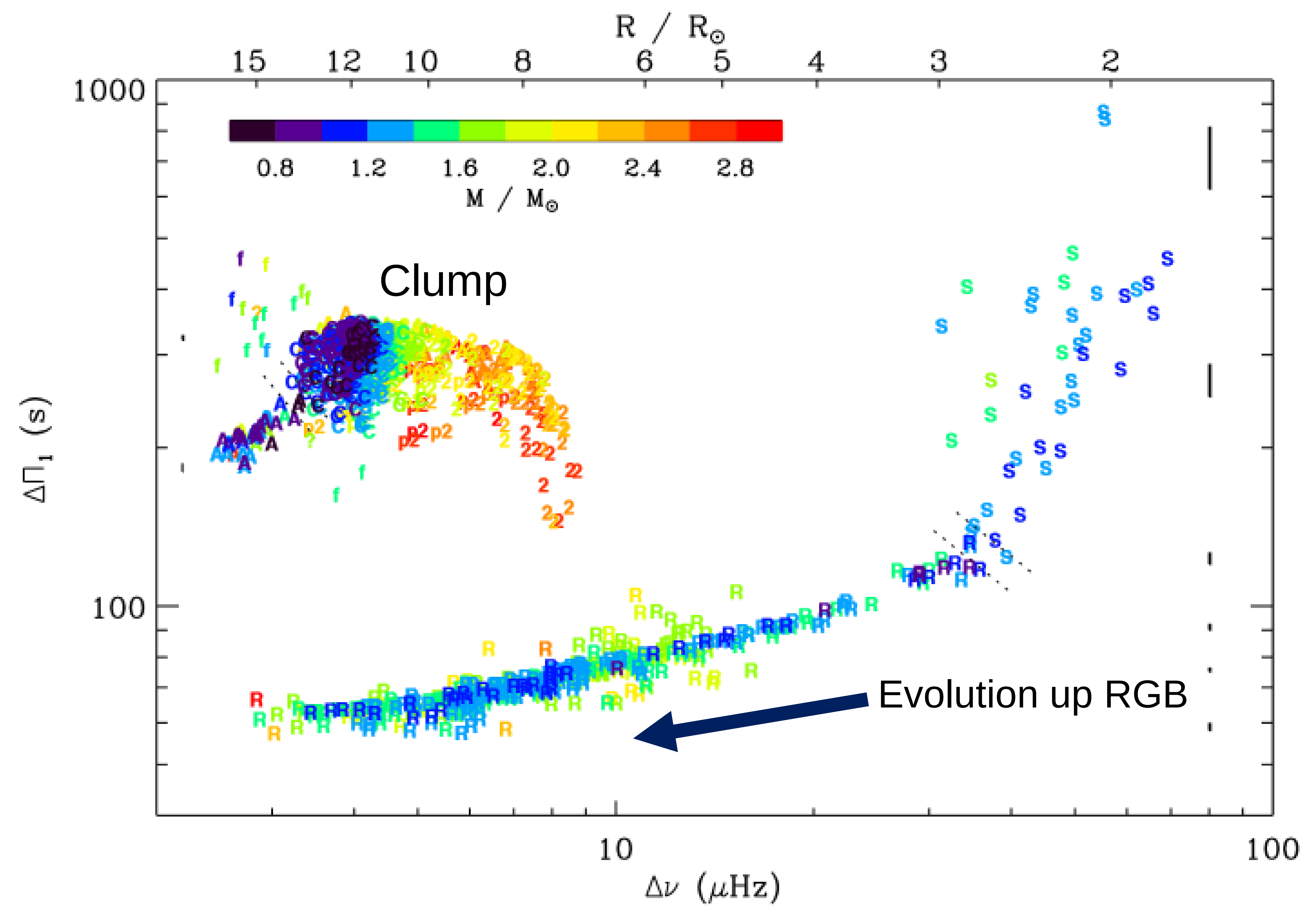
Observed Modes

Determining Evolutionary Status



Bedding et al. 2011

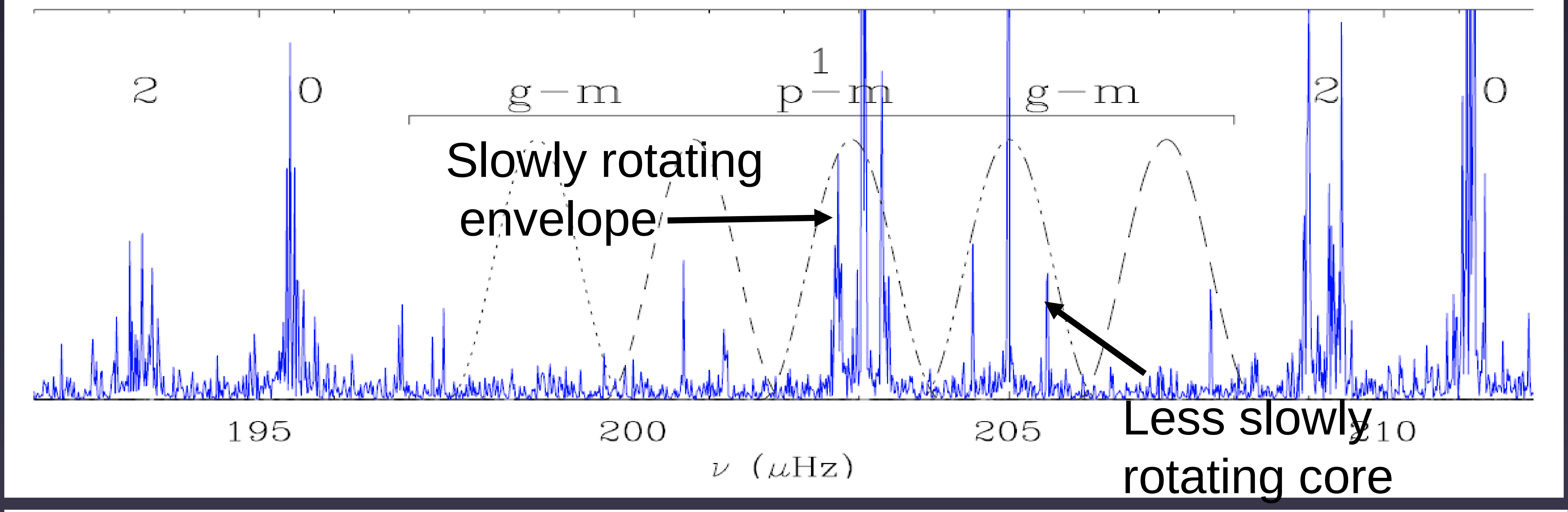
Charting Stellar Populations



Mosser et al. 2014

Internal Rotation and Angular Momentum Transport

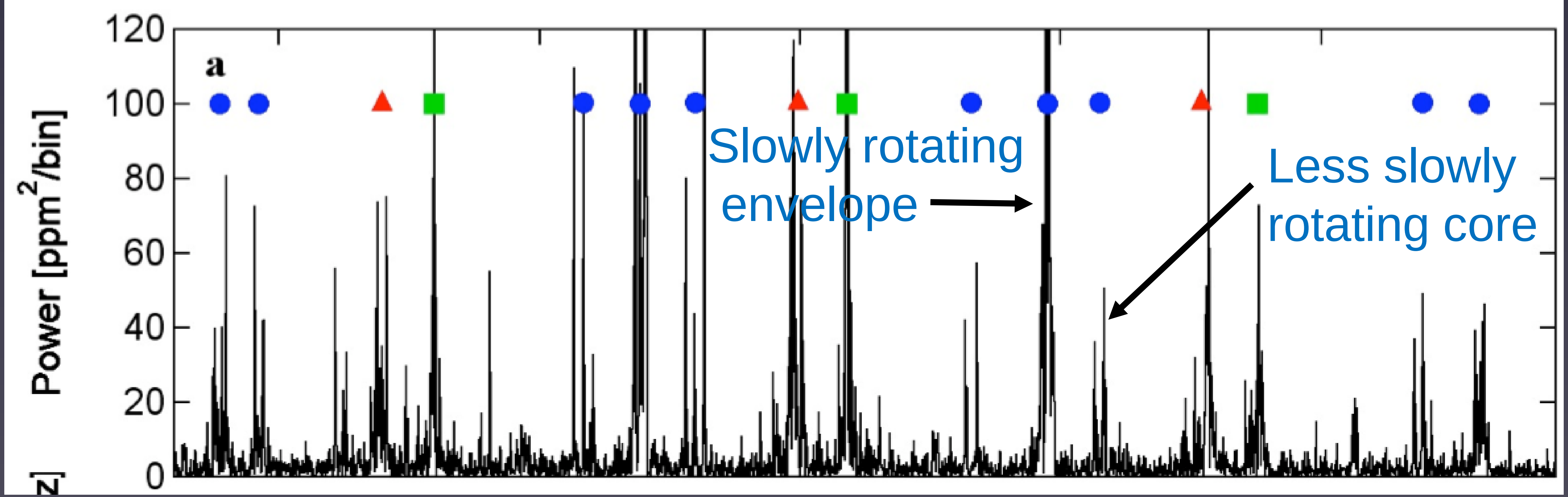
Measuring Core Spin from Rotational Splitting



Slowly rotating envelope

Less slowly rotating core

Mosser et al. 2012

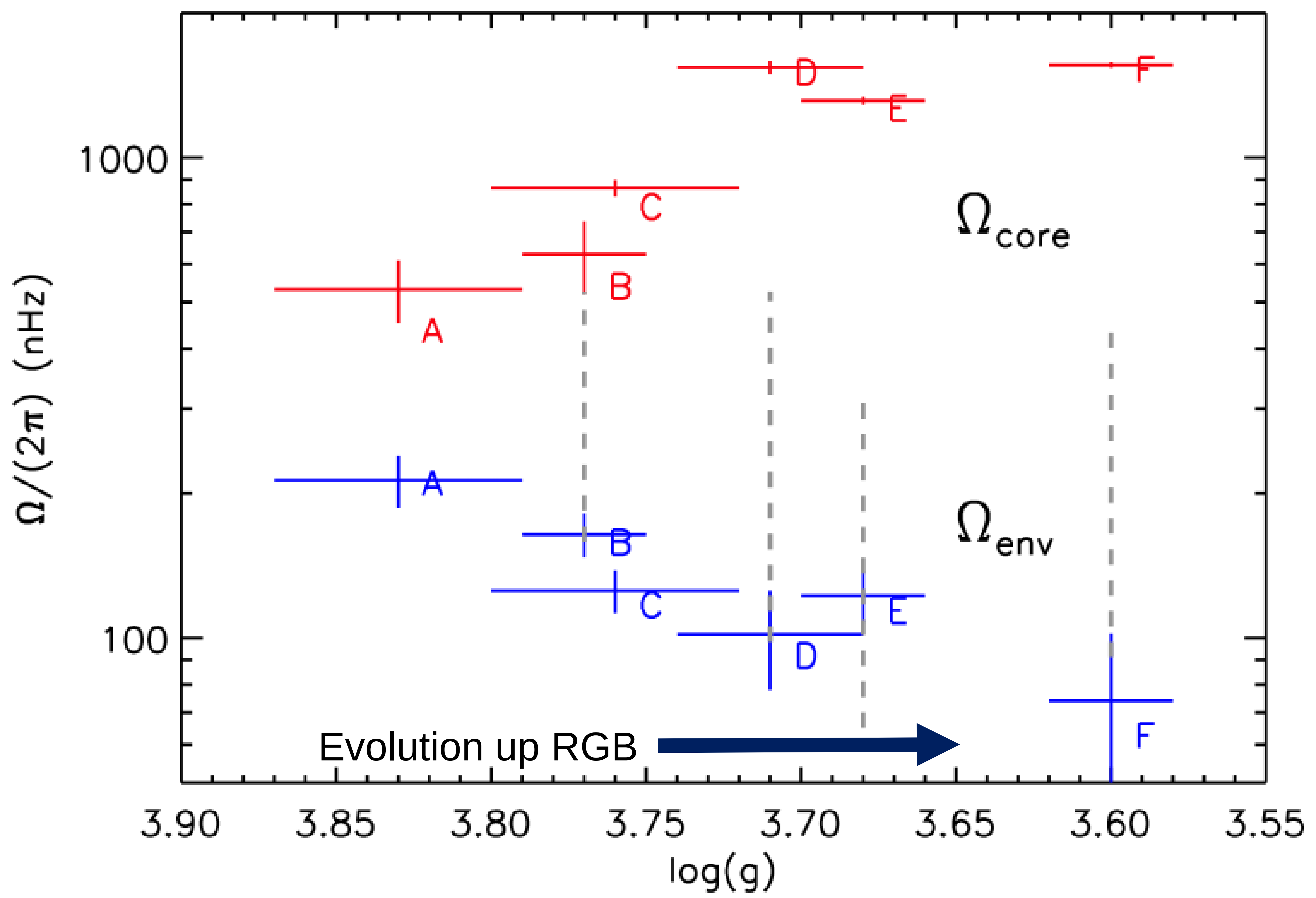


Slowly rotating envelope

Less slowly rotating core

Beck et al. 2012

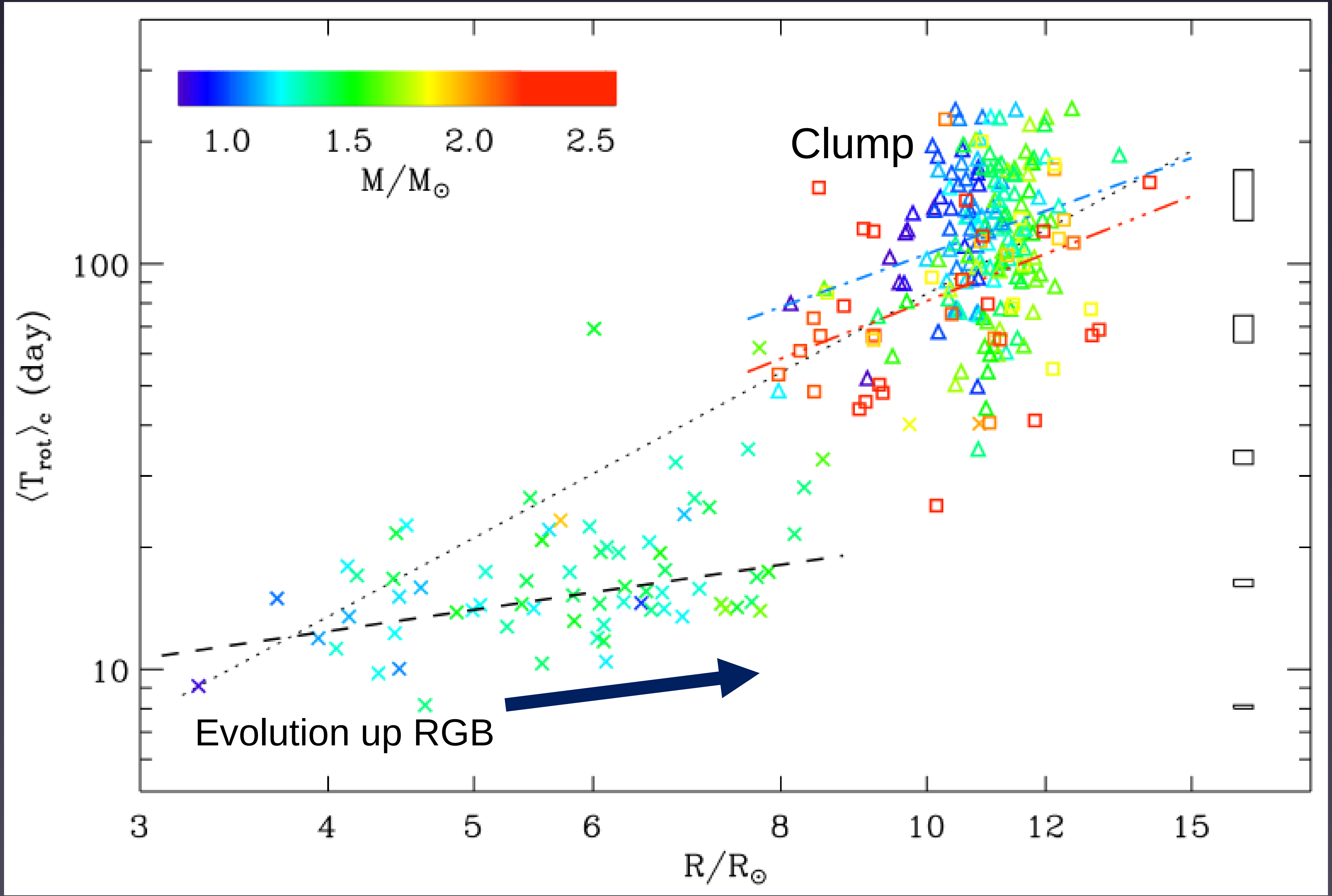
Growth of Differential Rotation



Deheuvels et al. 2014

See Tayar & Pinsonneault 2013, Spada et al. 2016

Core Spin-Down

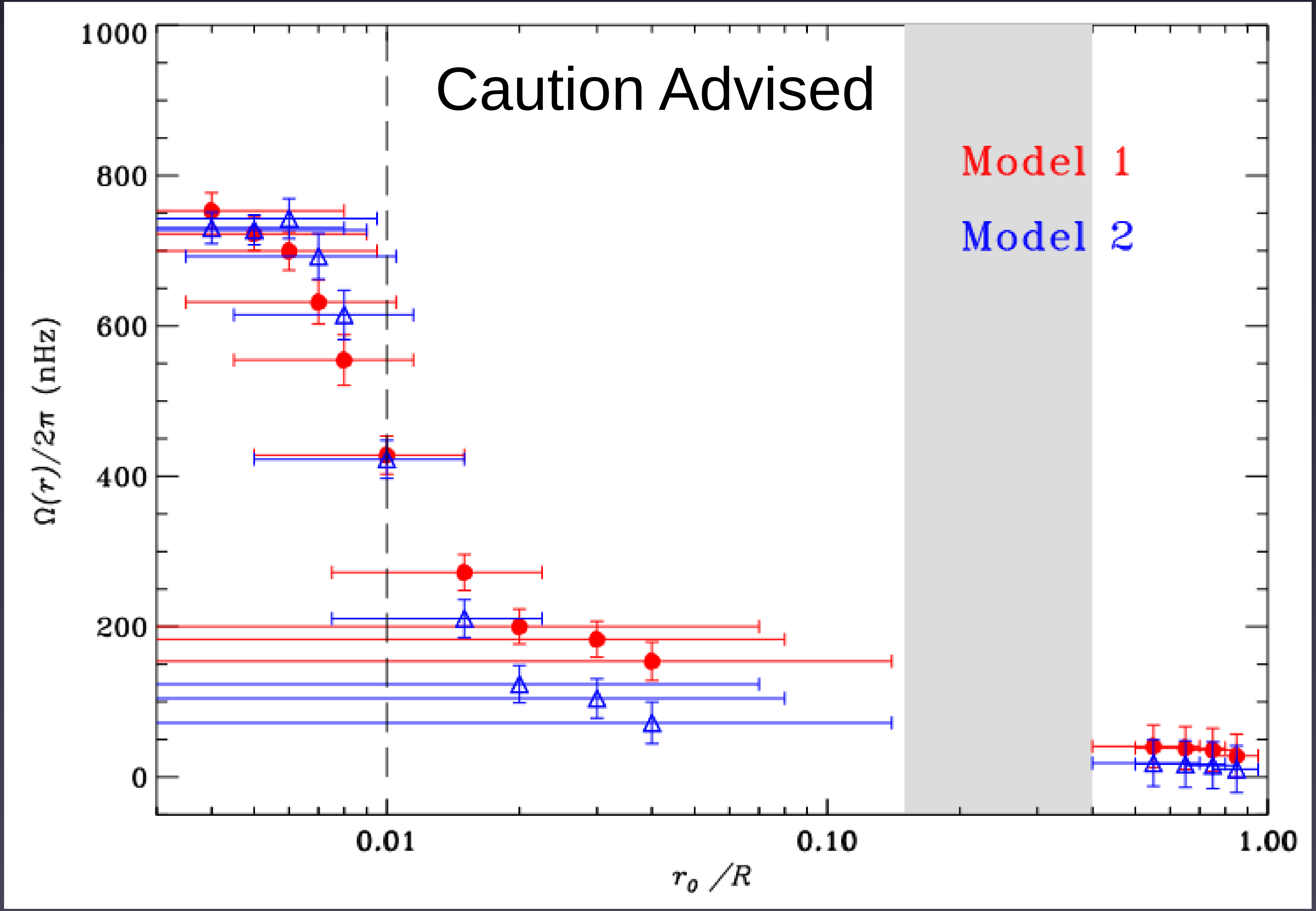


Evolution up RGB

Mosser et al. 2012

Rotation Profiles

Tentative evidence that differential rotation occurs near hydrogen burning shell (Di Mauro et al. 2016, Klion et al. 2016)



Di Mauro et al. 2016

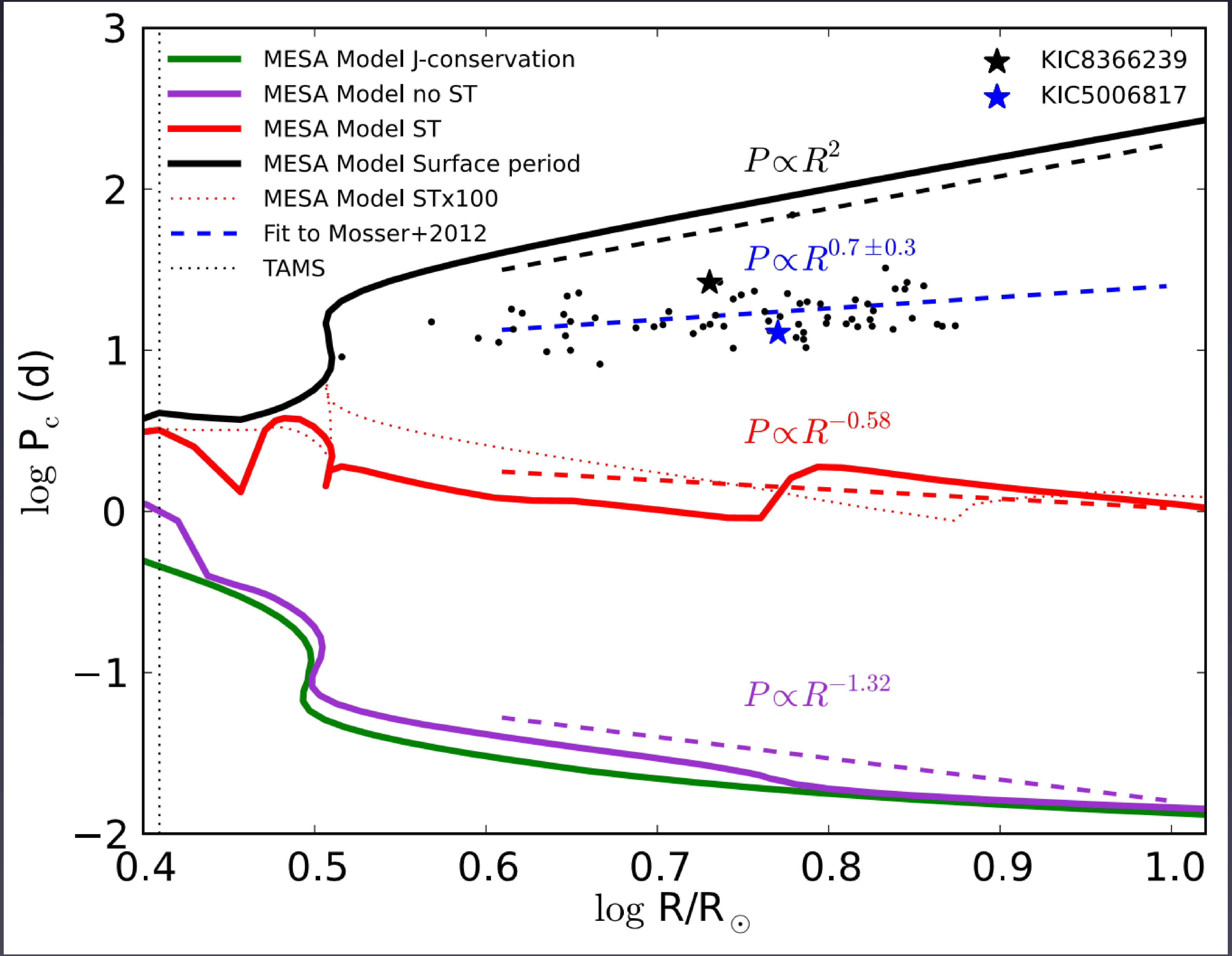
Cores rotate too slowly

Core rotation cannot be explained by non-magnetic angular momentum transport mechanisms

Taylor-Spruit Dynamo gets closer but still falls short

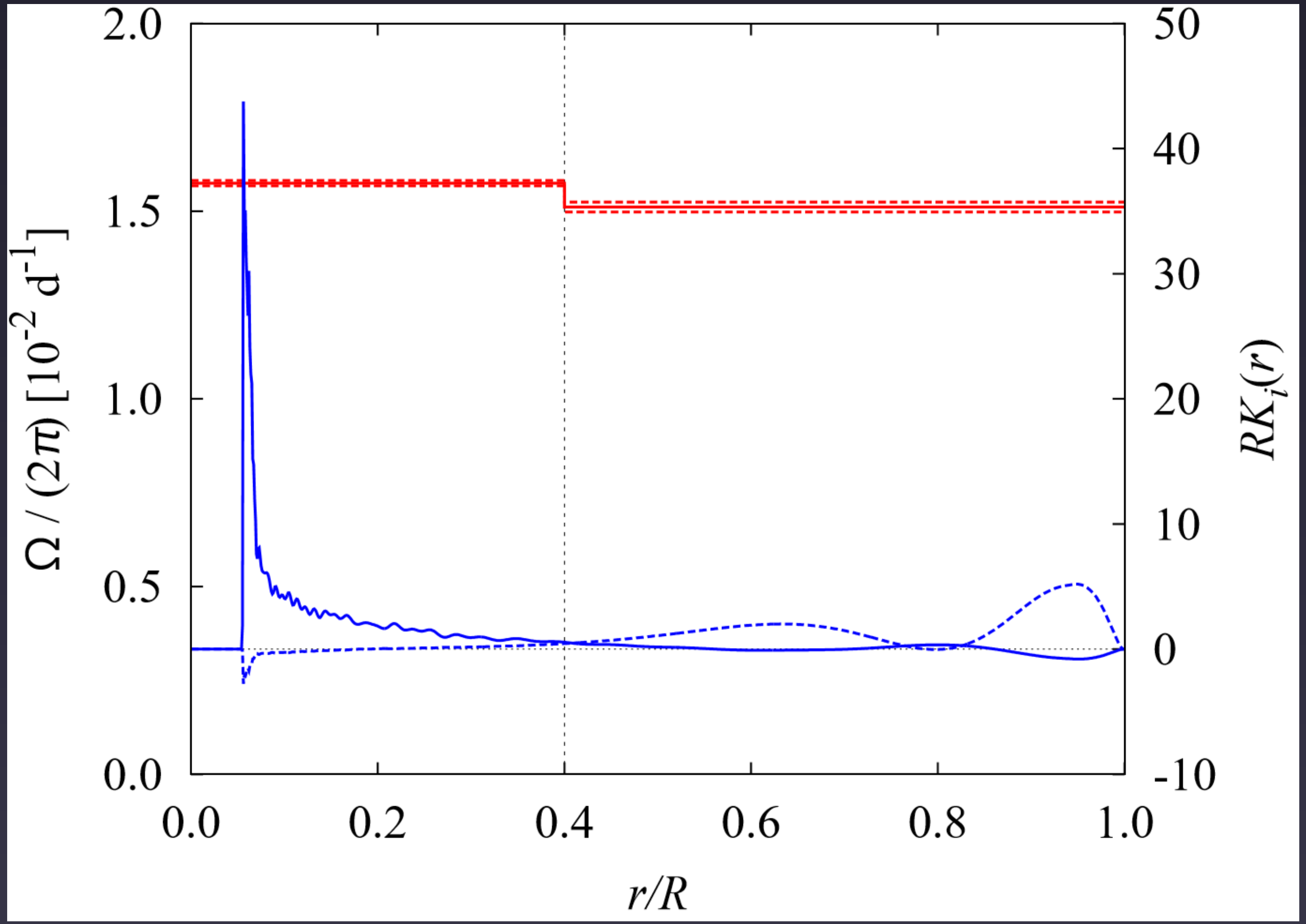
Possible explanations

- Fossil fields?
- MRI or other magnetic instability?
- Observational bias? (Tayar et al. 2015)



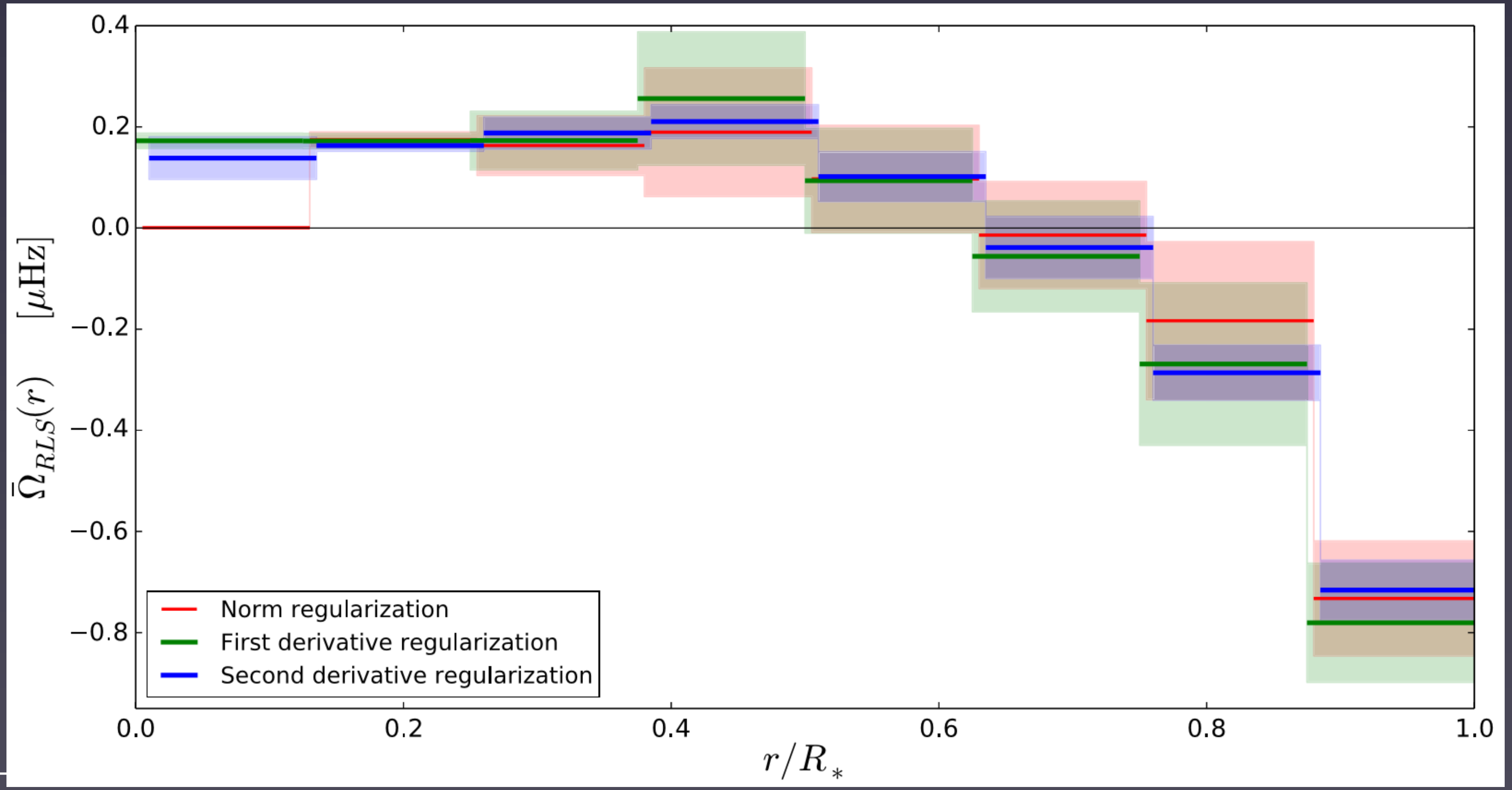
Cantiello et al. 2014

Efficient Angular Momentum Transport

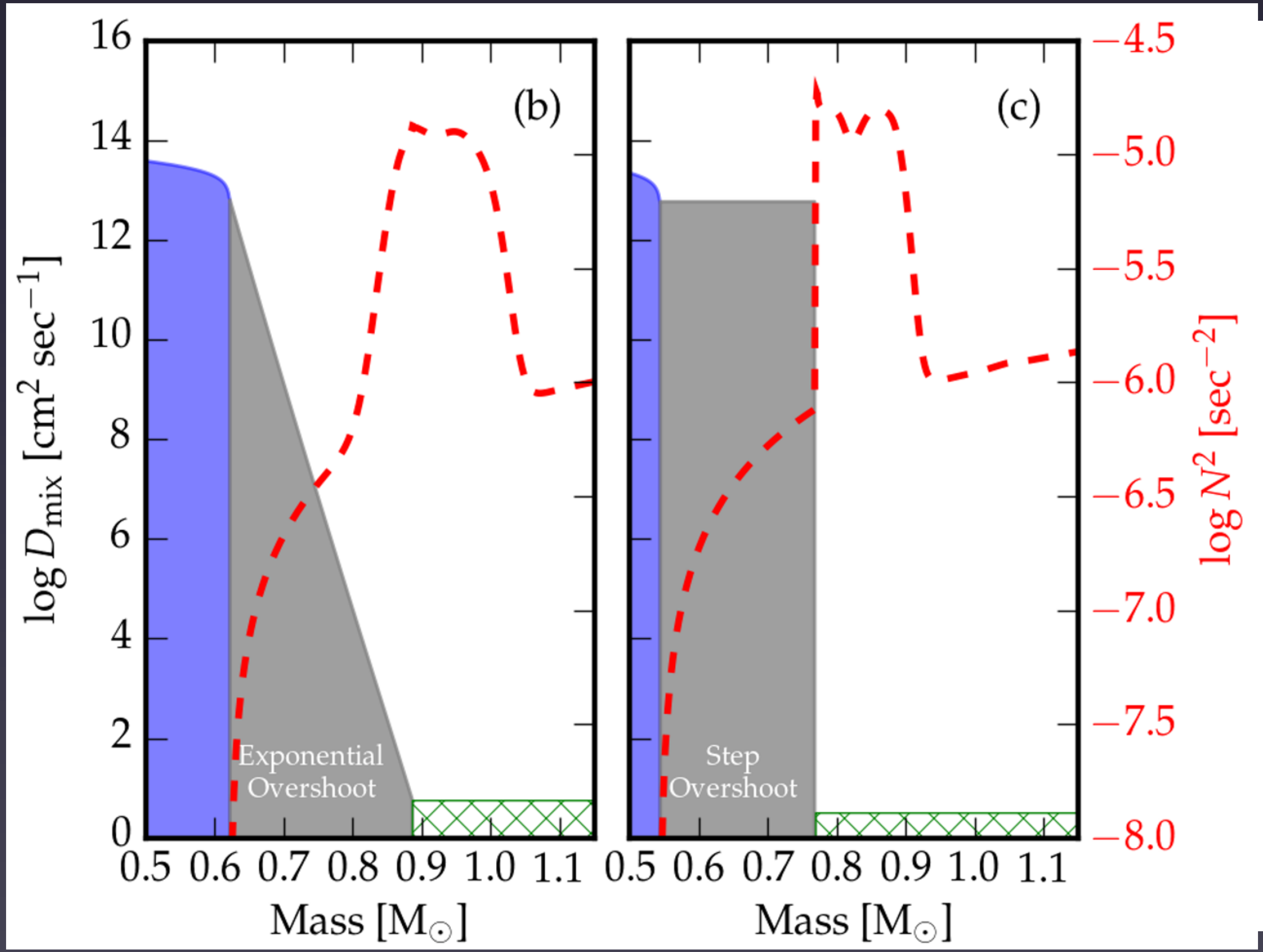


Little evidence for “large” amounts of differential rotation in main sequence stars

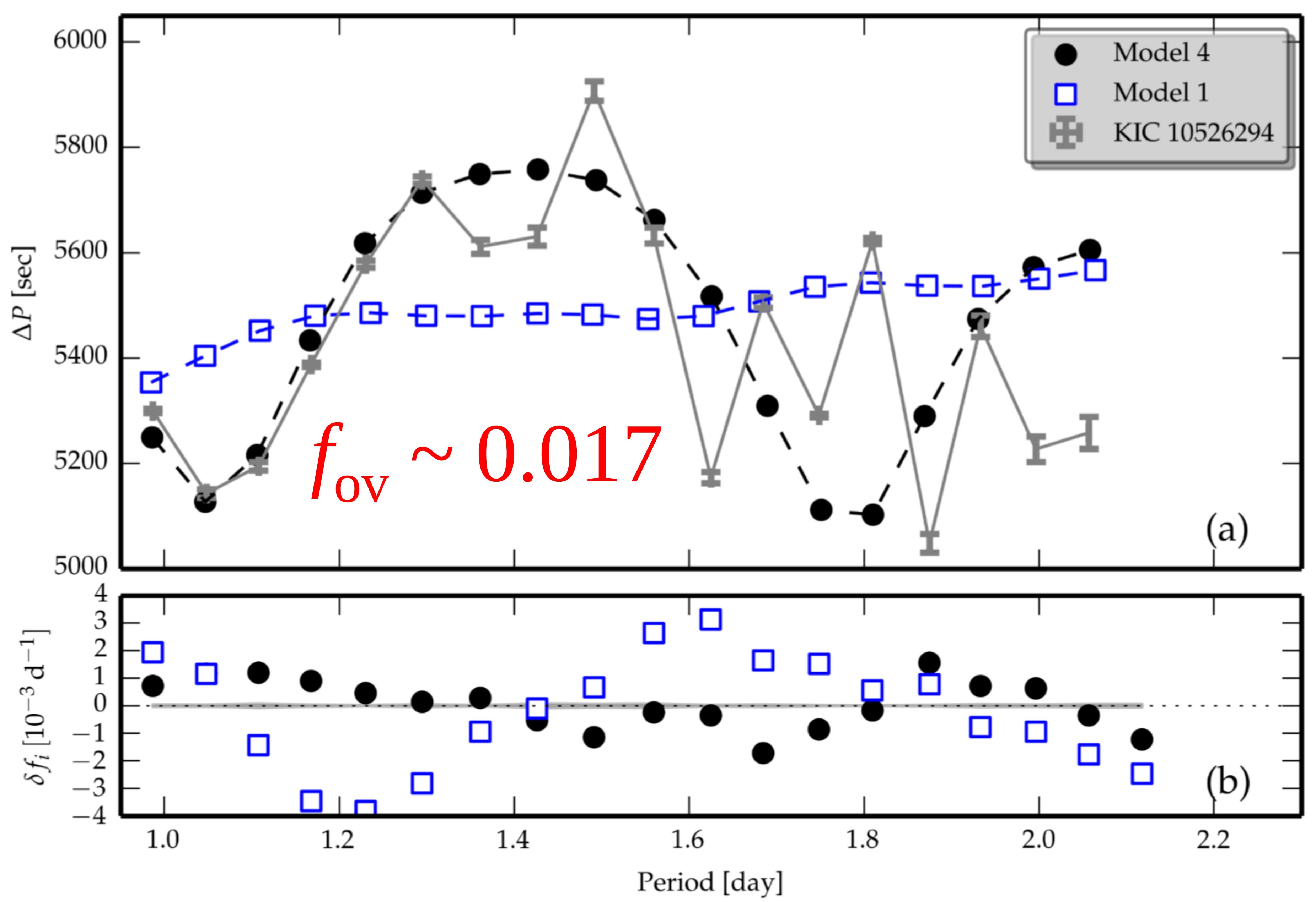
Kurtz et al. 2014, Saio et al. 2015, Nielsen et al. 2014, Benomar et al. 2015, Van Reeth et al. 2016



Internal Mixing and Convective Overshoot

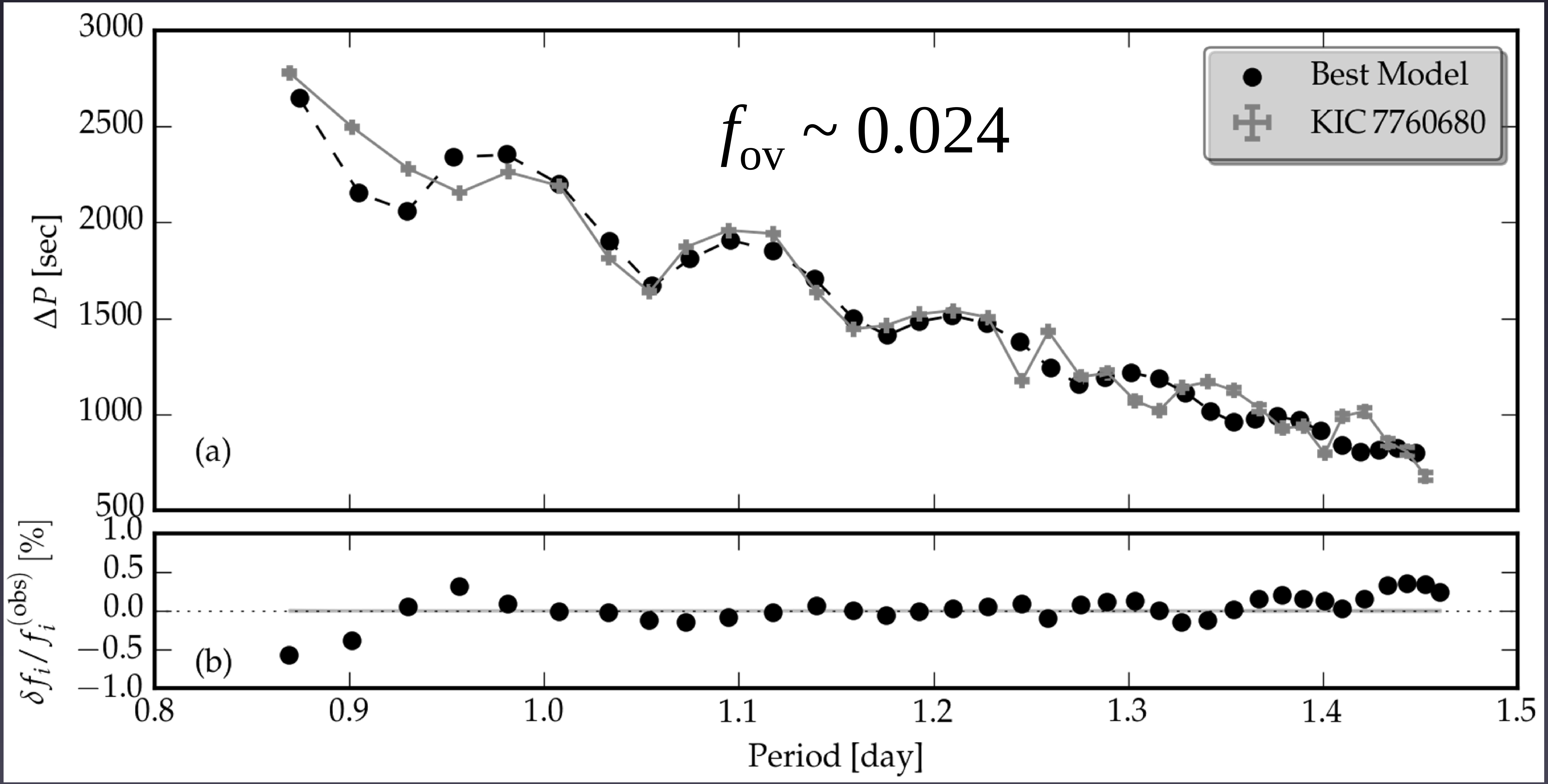


Moravveji et al. 2016

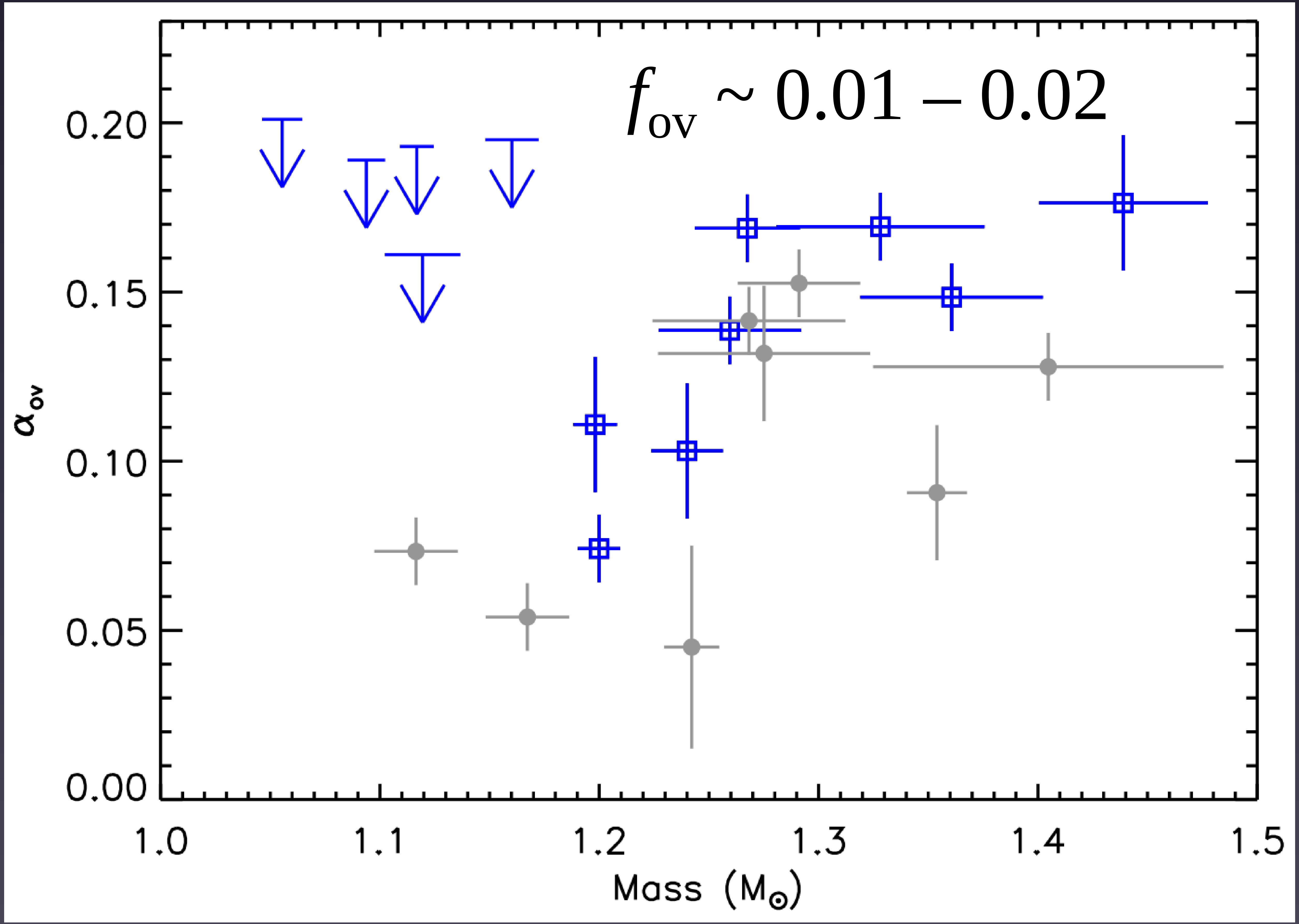


$f_{ov} \sim 0.017$

Moravveji et al. 2015



Moravveji et al. 2016



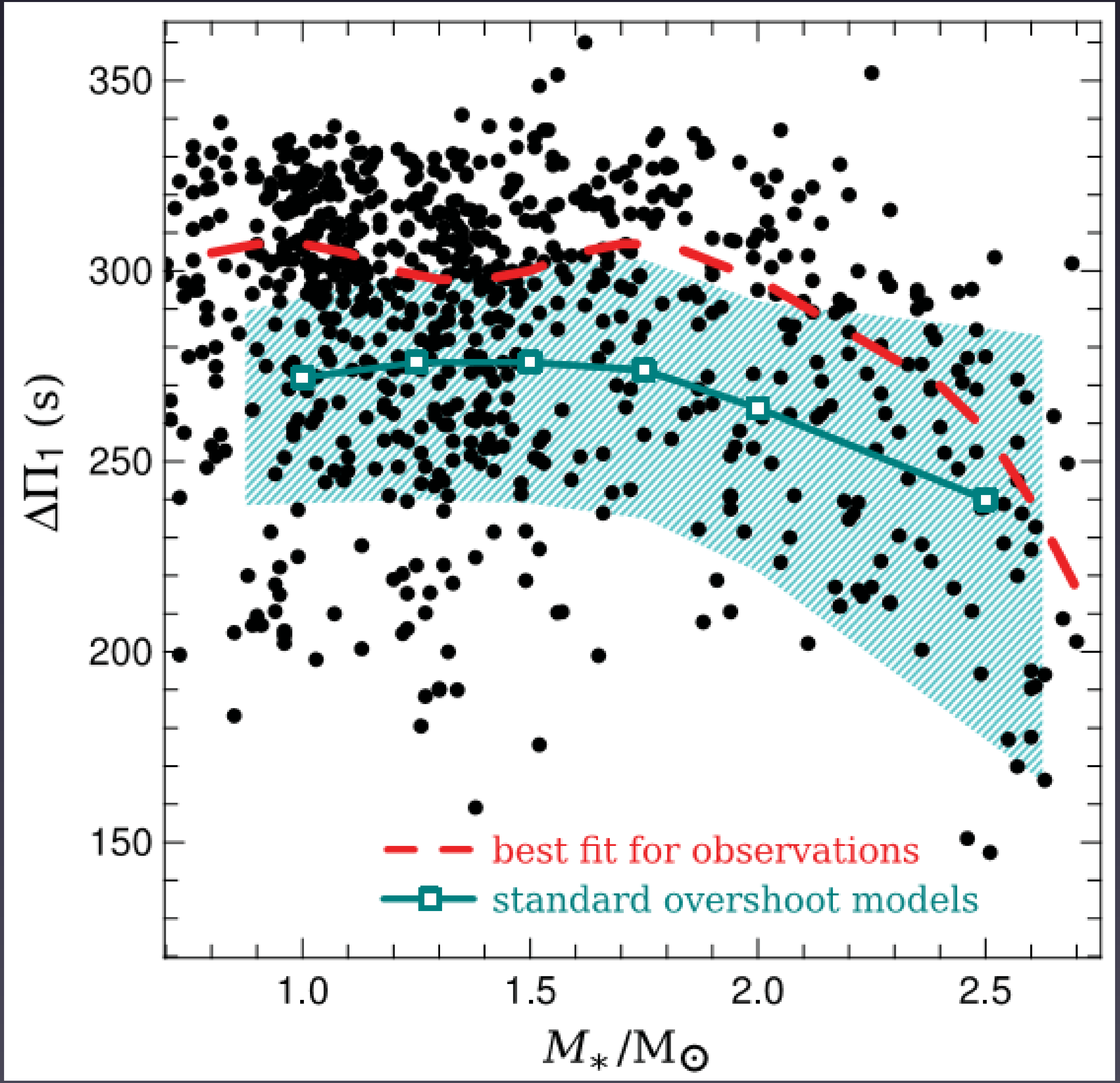
$f_{ov} \sim 0.01 - 0.02$

Deheuvels et al. 2016

Convective Overshoot In He-burning Stars

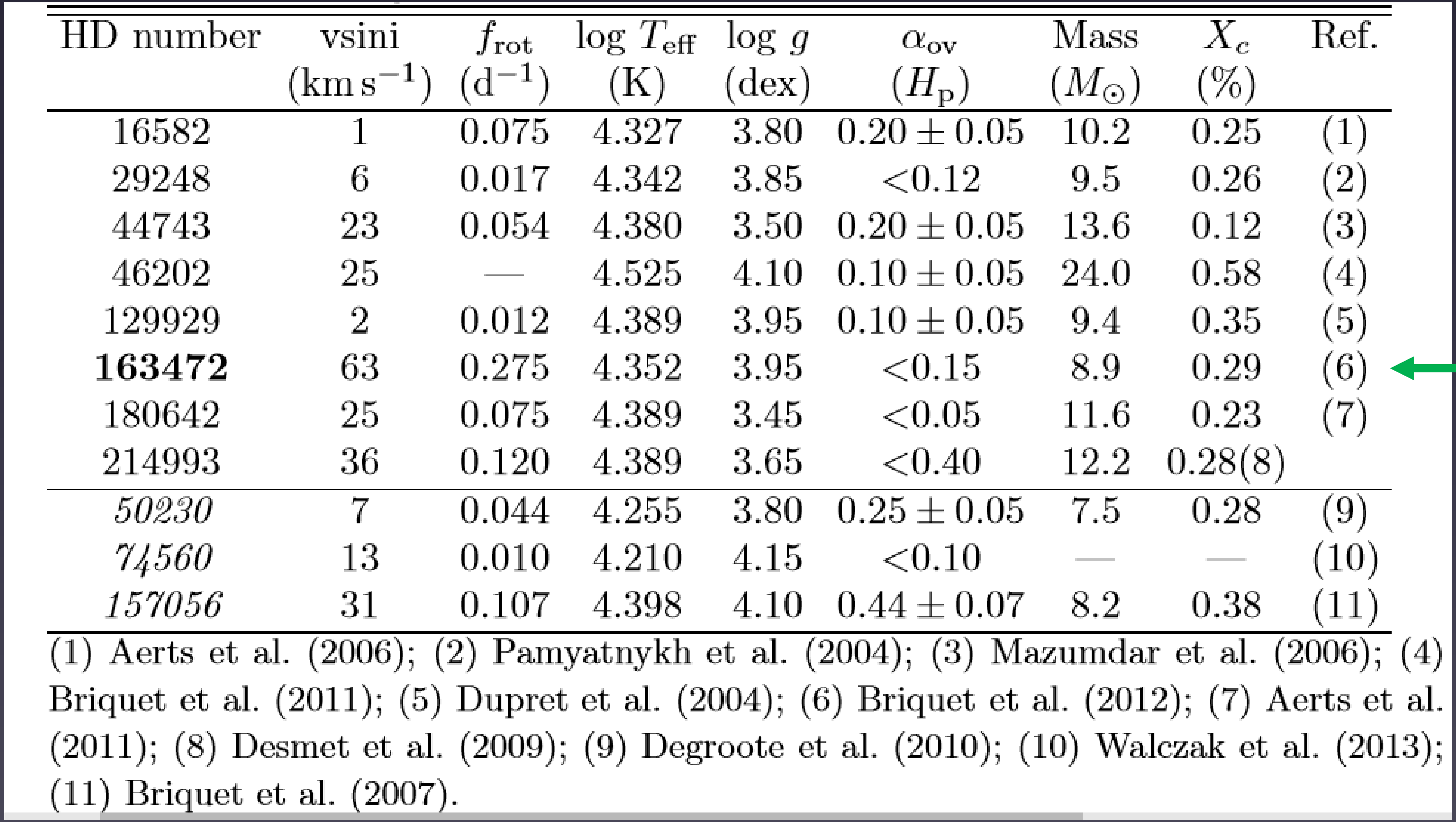
- Evidence for large convective cores in both red giants and sdB stars

- May indicate large amounts of convective overshoot (Bossini et al. 2015, Constantino et al. 2015, Van Grootel et al. 2010a,2010b, Charpinet et al. 2011b, Schindler et al. 2015)



Constantino et al. 2015

Few robust results for massive stars



HD number	vsini (km s^{-1})	$f_{\rm rot}$ (d^{-1})	log $T_{\rm eff}$ (K)	log g (dex)	$\alpha_{\rm ov}$ ($H_{\rm p}$)	Mass ($M_\odot$)	X_c (%)	Ref.
16582	1	0.075	4.327	3.80	0.20 ± 0.05	10.2	0.25	(1)
29248	6	0.017	4.342	3.85	<0.12	9.5	0.26	(2)
44743	23	0.054	4.380	3.50	0.20 ± 0.05	13.6	0.12	(3)
46202	25	—	4.525	4.10	0.10 ± 0.05	24.0	0.58	(4)
129929	2	0.012	4.389	3.95	0.10 ± 0.05	9.4	0.35	(5)
163472	63	0.275	4.352	3.95	<0.15	8.9	0.29	(6)
180642	25	0.075	4.389	3.45	<0.05	11.6	0.23	(7)
214993	36	0.120	4.389	3.65	<0.40	12.2	0.28(8)	
50230	7	0.044	4.255	3.80	0.25 ± 0.05	7.5	0.28	(9)
74560	13	0.010	4.210	4.15	<0.10	—	—	(10)
157056	31	0.107	4.398	4.10	0.44 ± 0.07	8.2	0.38	(11)

(1) Aerts et al. (2006); (2) Pamyatnykh et al. (2004); (3) Mazumdar et al. (2006); (4) Briquet et al. (2011); (5) Dupret et al. (2004); (6) Briquet et al. (2012); (7) Aerts et al. (2011); (8) Desmet et al. (2009); (9) Degroote et al. (2010); (10) Walczak et al. (2013); (11) Briquet et al. (2007).

← Magnetic!

Aerts 2013

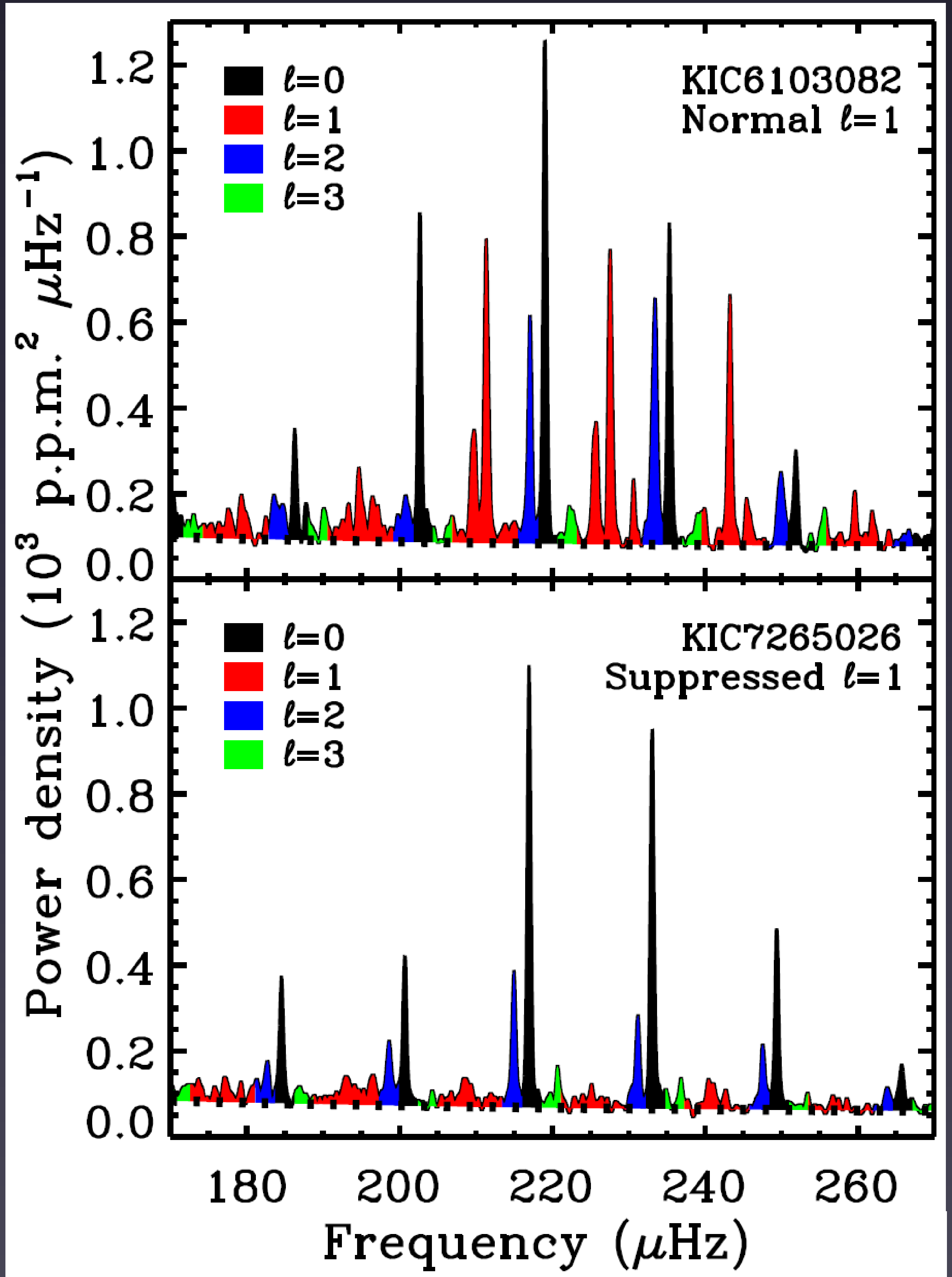
Internal Magnetic Fields

Matteo Cantiello & Dennis Stello
Daniel Lecoanet, Lars Bildsten, Rafael Garcia

A mystery arises…

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

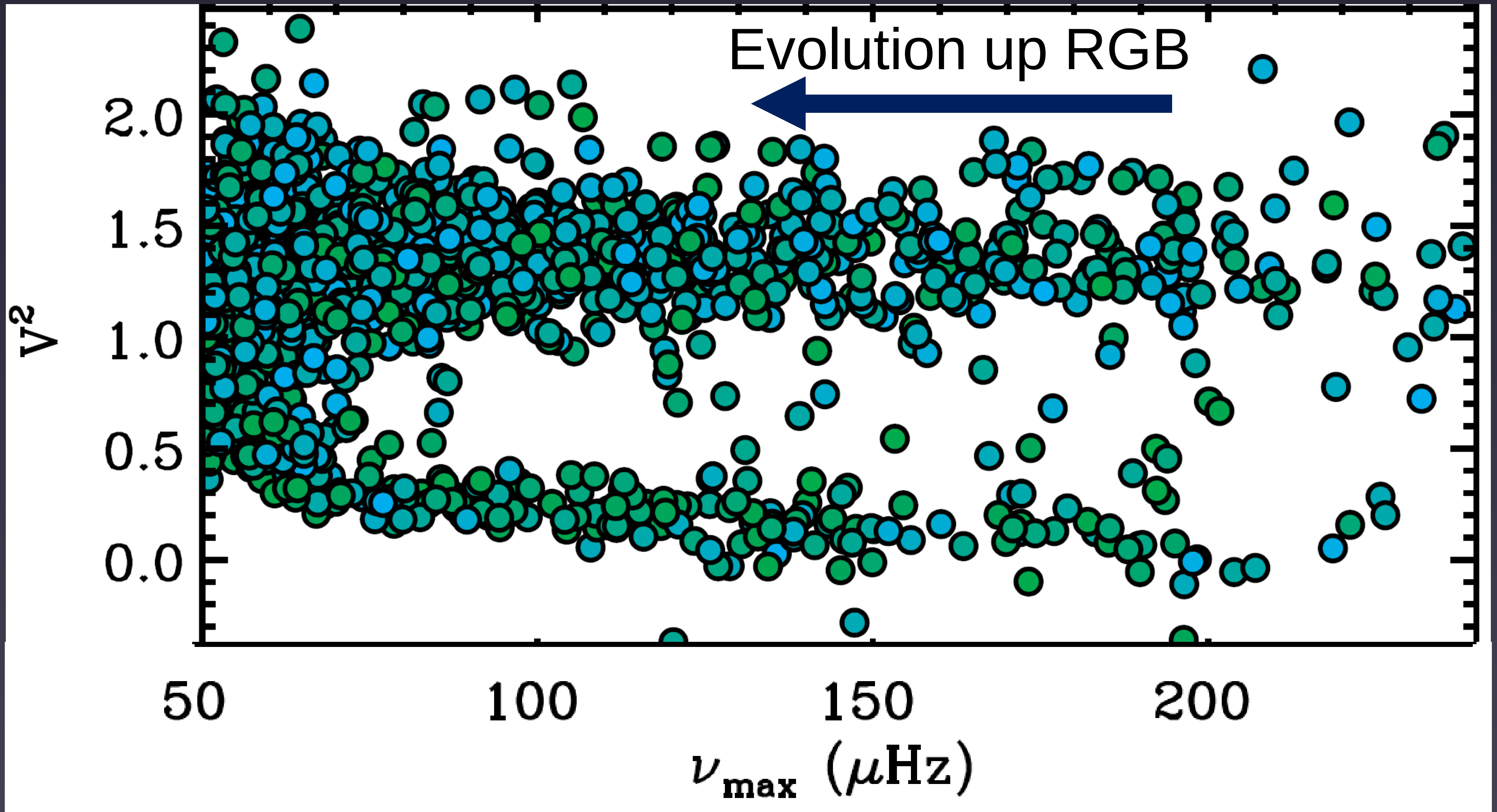
Mosser et al. 2011



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…

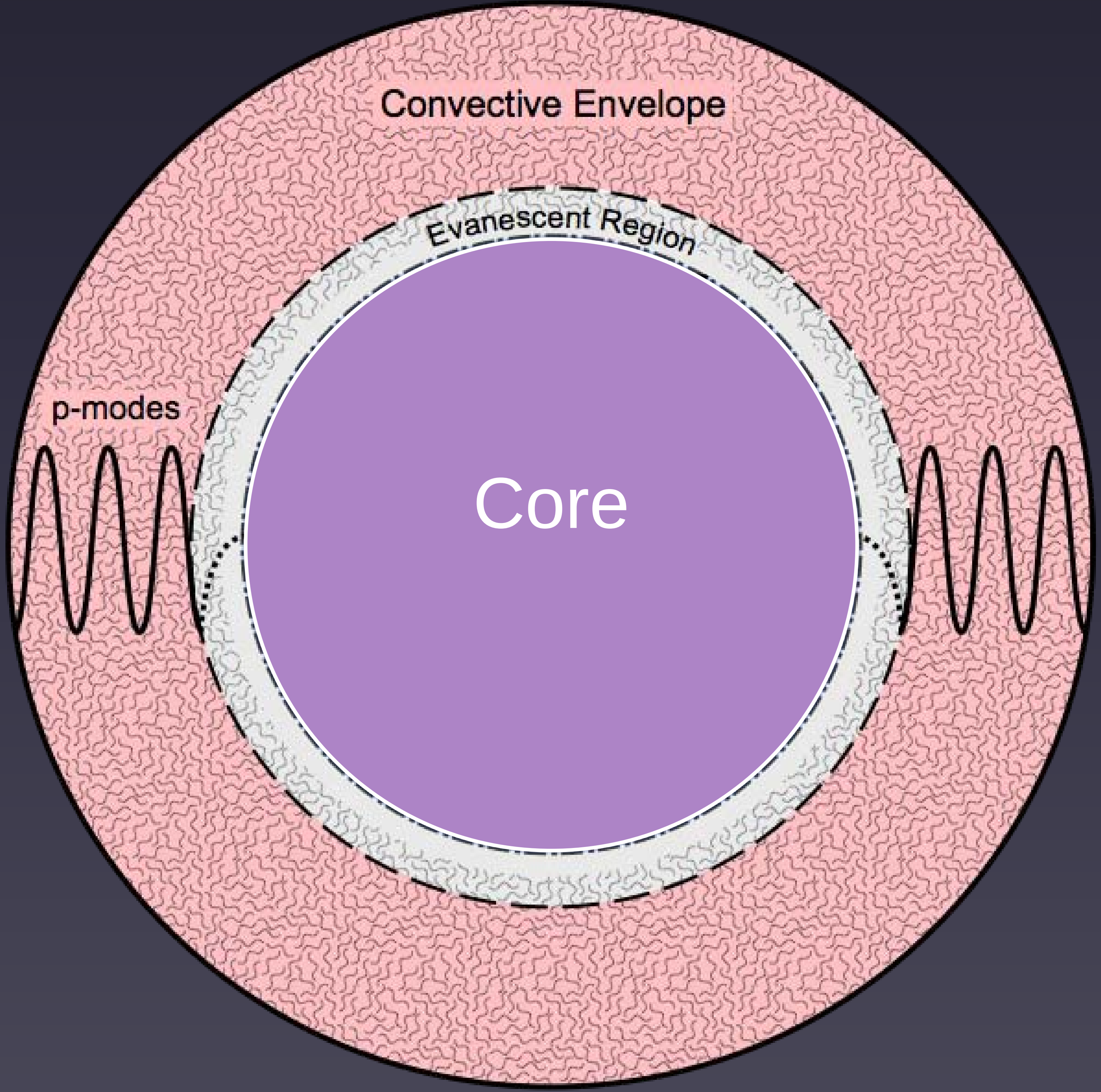
- Wave energy leaks into core at rate

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

- Ratio of suppressed mode to non-suppressed mode is

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

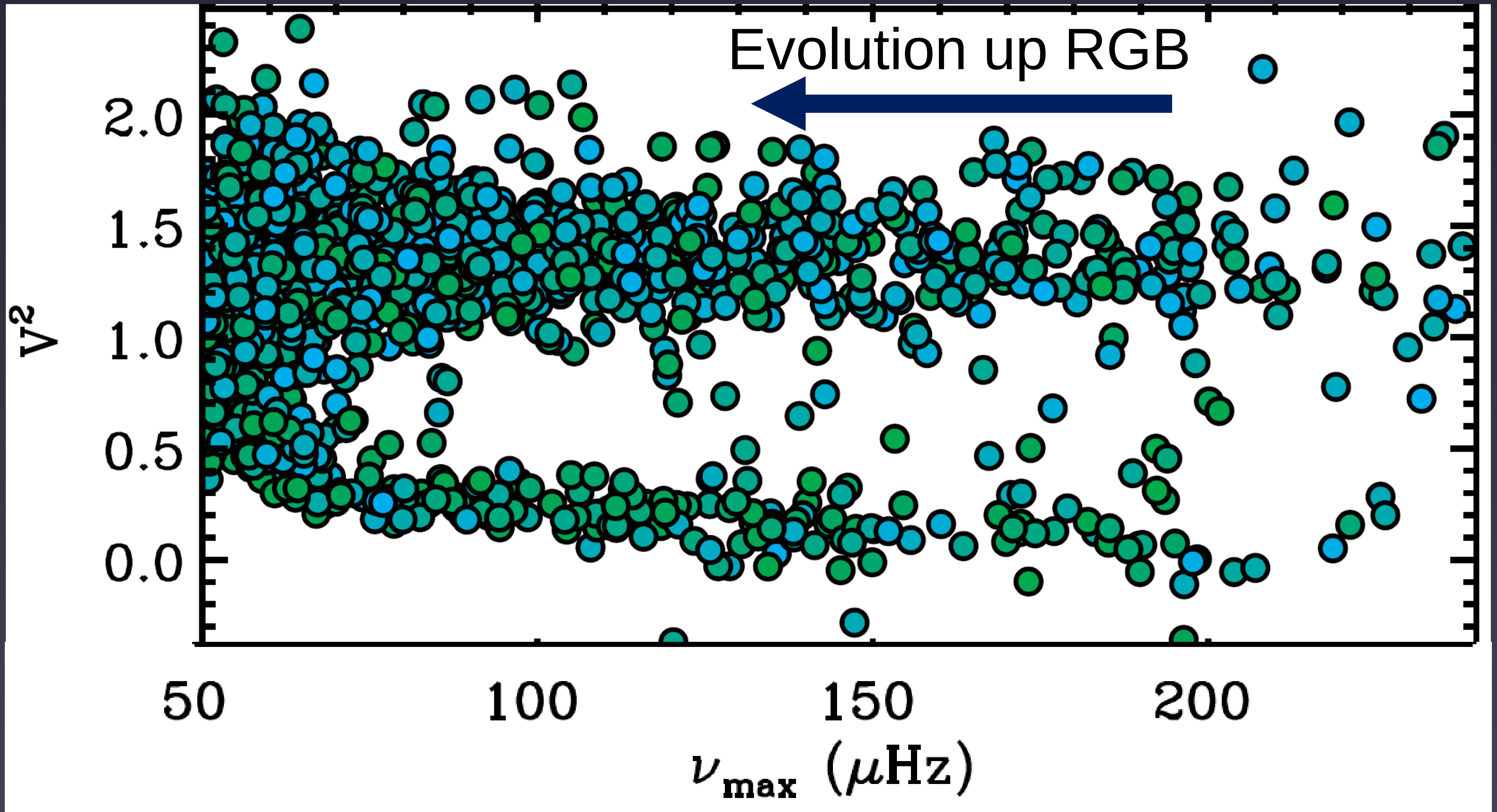
Radial mode lifetime



A (partial) solution emerges…

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

$$\frac{V_{\rm sup}^2}{V_\alpha^2} = \left[1 + \Delta\nu\tau_{\rm ac}T^2\right]^{-1}$$



Stello, Cantiello, Fuller + 2016

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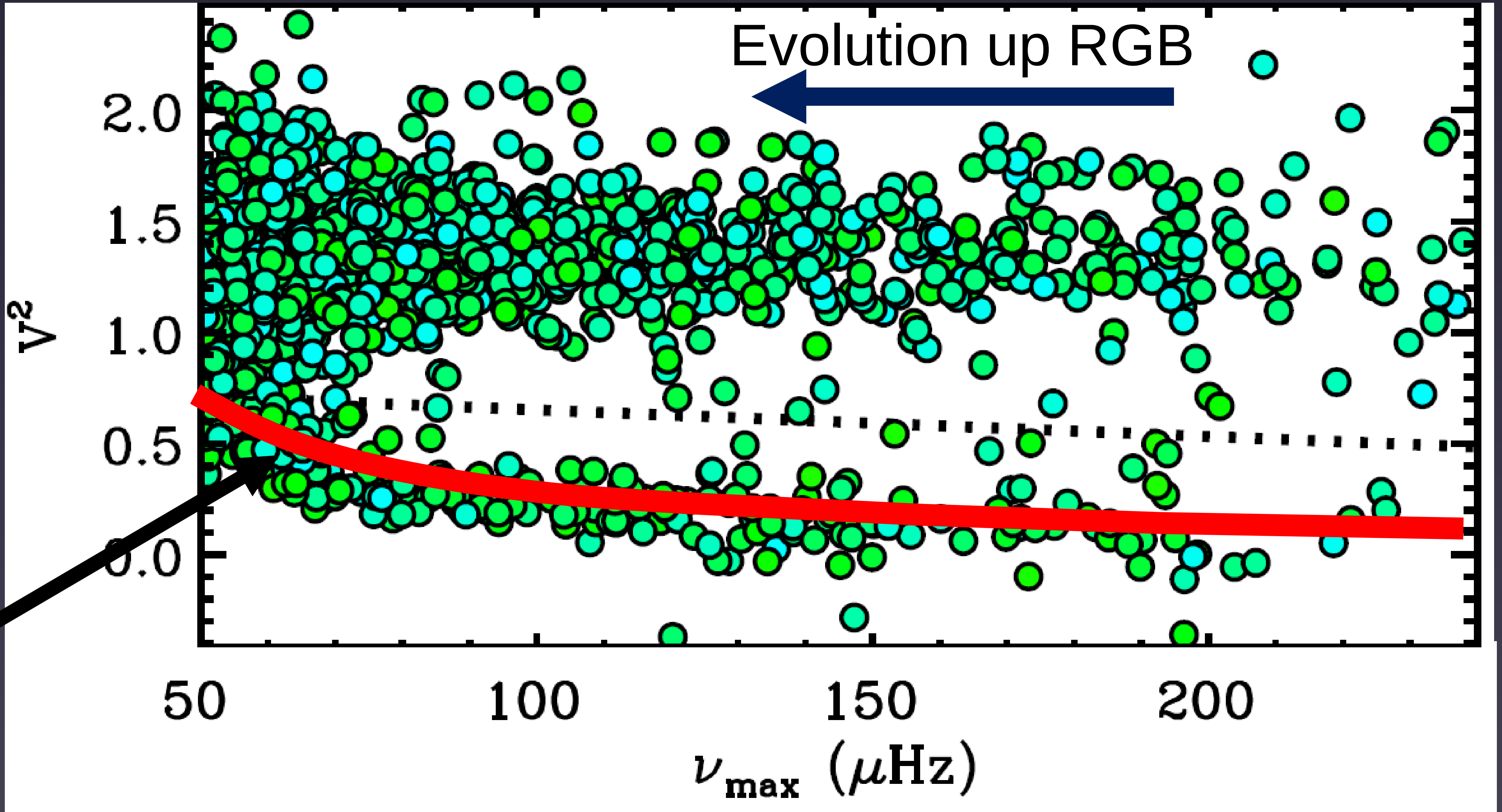
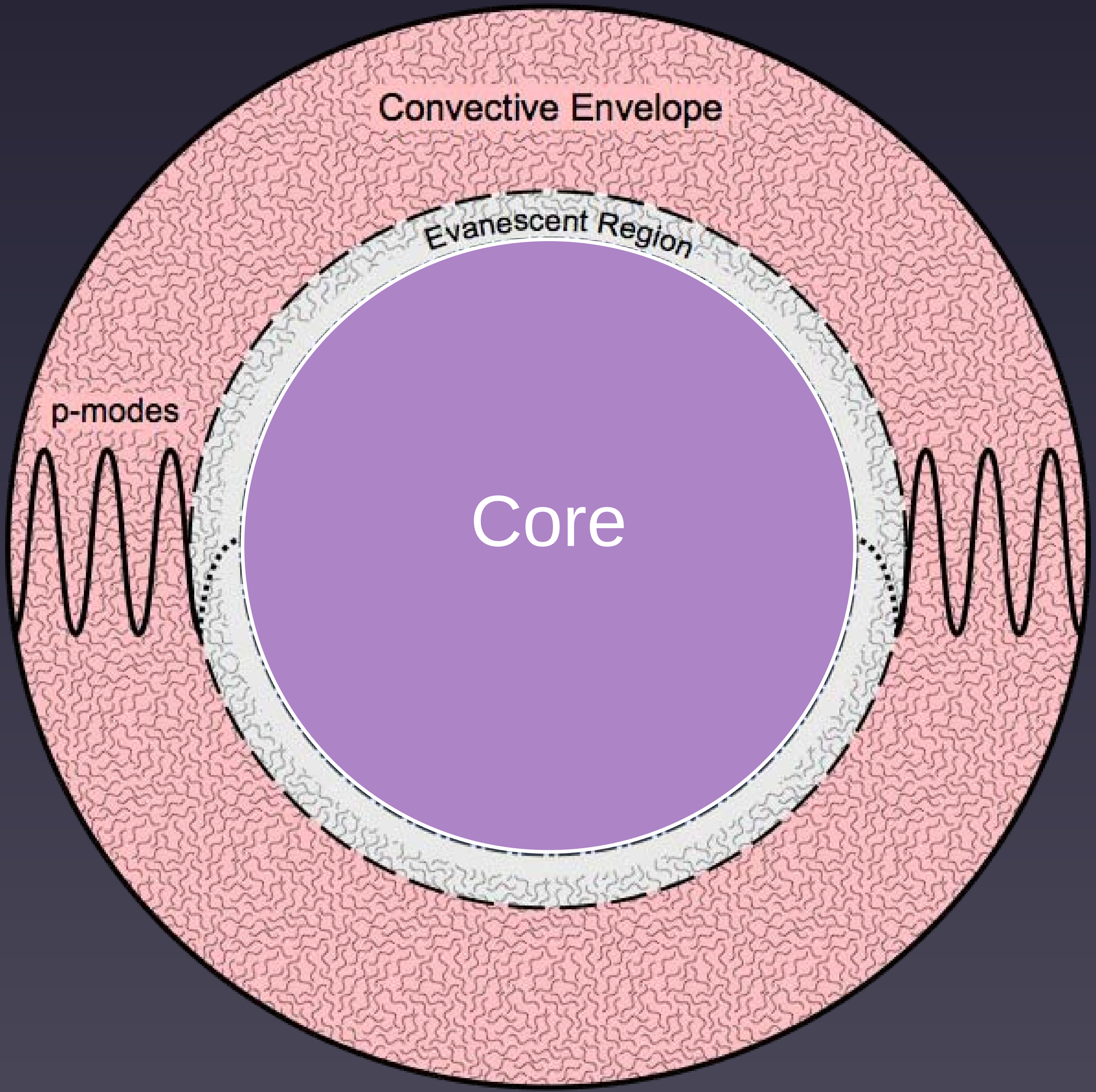
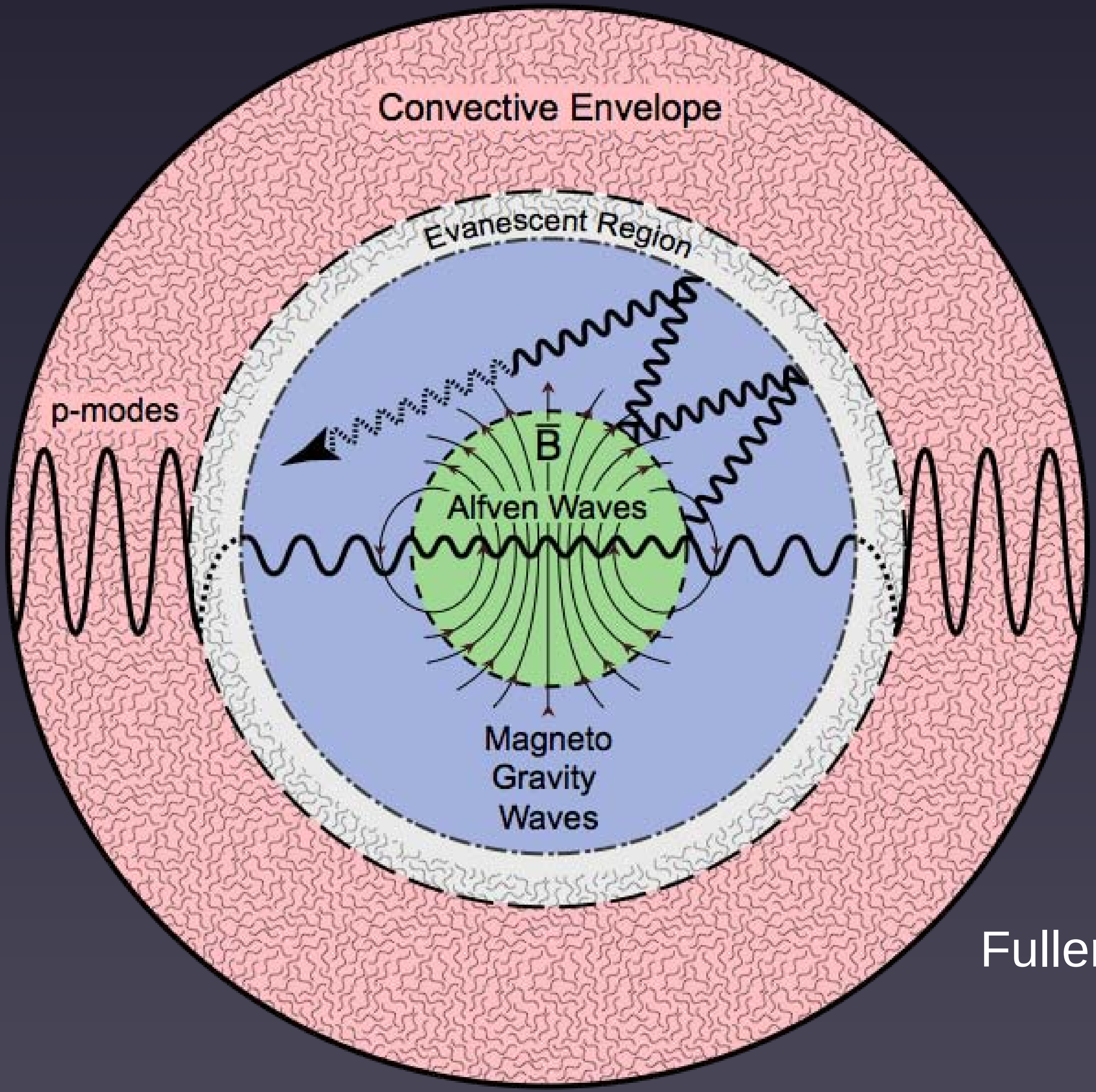


Stello, Cantiello, Fuller + 2016

What causes wave dissipation in core?



Magnetic Fields



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

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

- Equate tension force with buoyancy Force

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

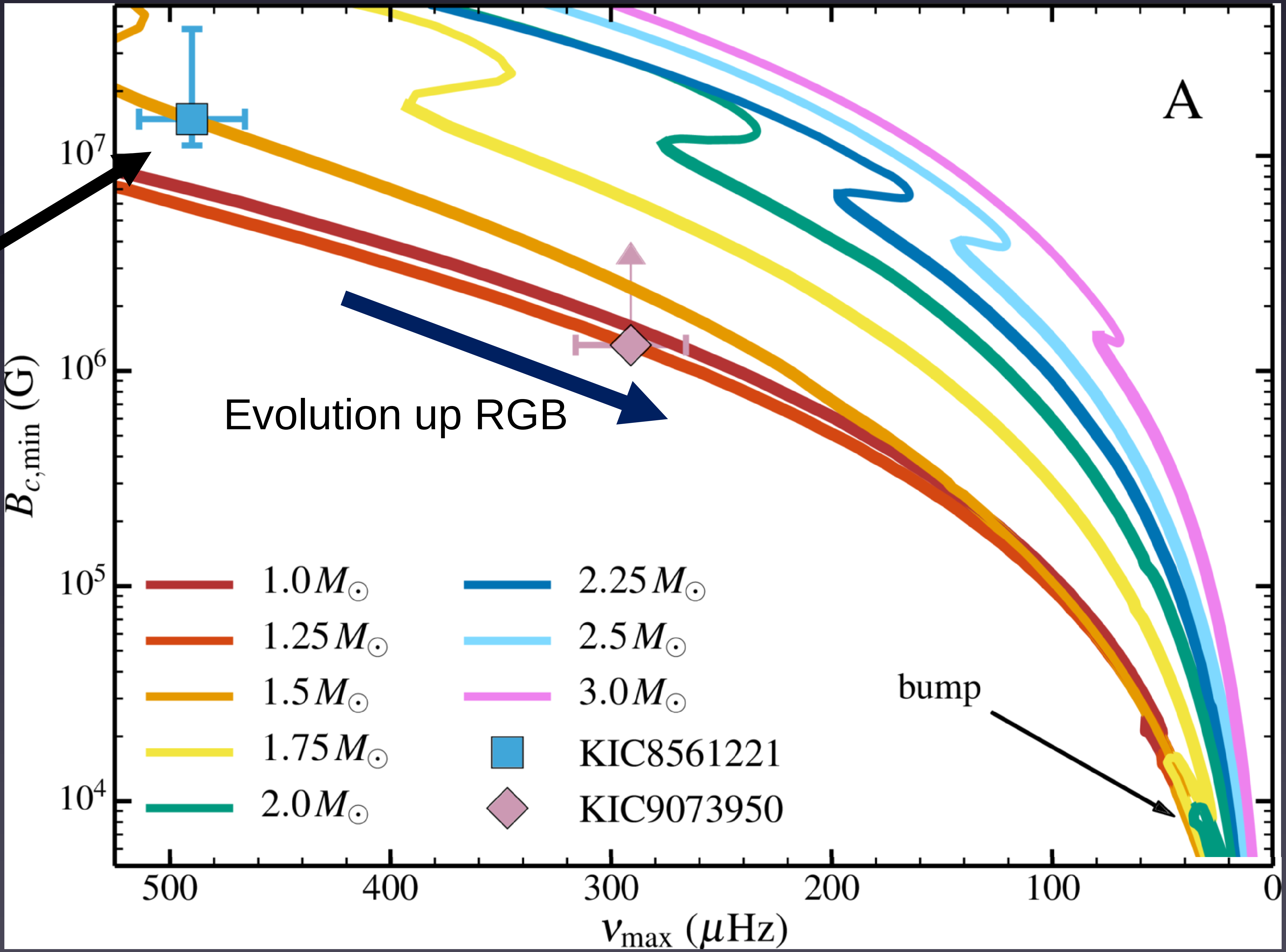
- Occurs when Alfven speed ~ gravity wave group velocity

Rogers & MacGregor 2010,2011

Minimum magnetic field for magnetic greenhouse effect to operate

Droopy

Garcia et al. 2014



Fuller & Cantiello + 2015

Cantiello & Fuller + 2016

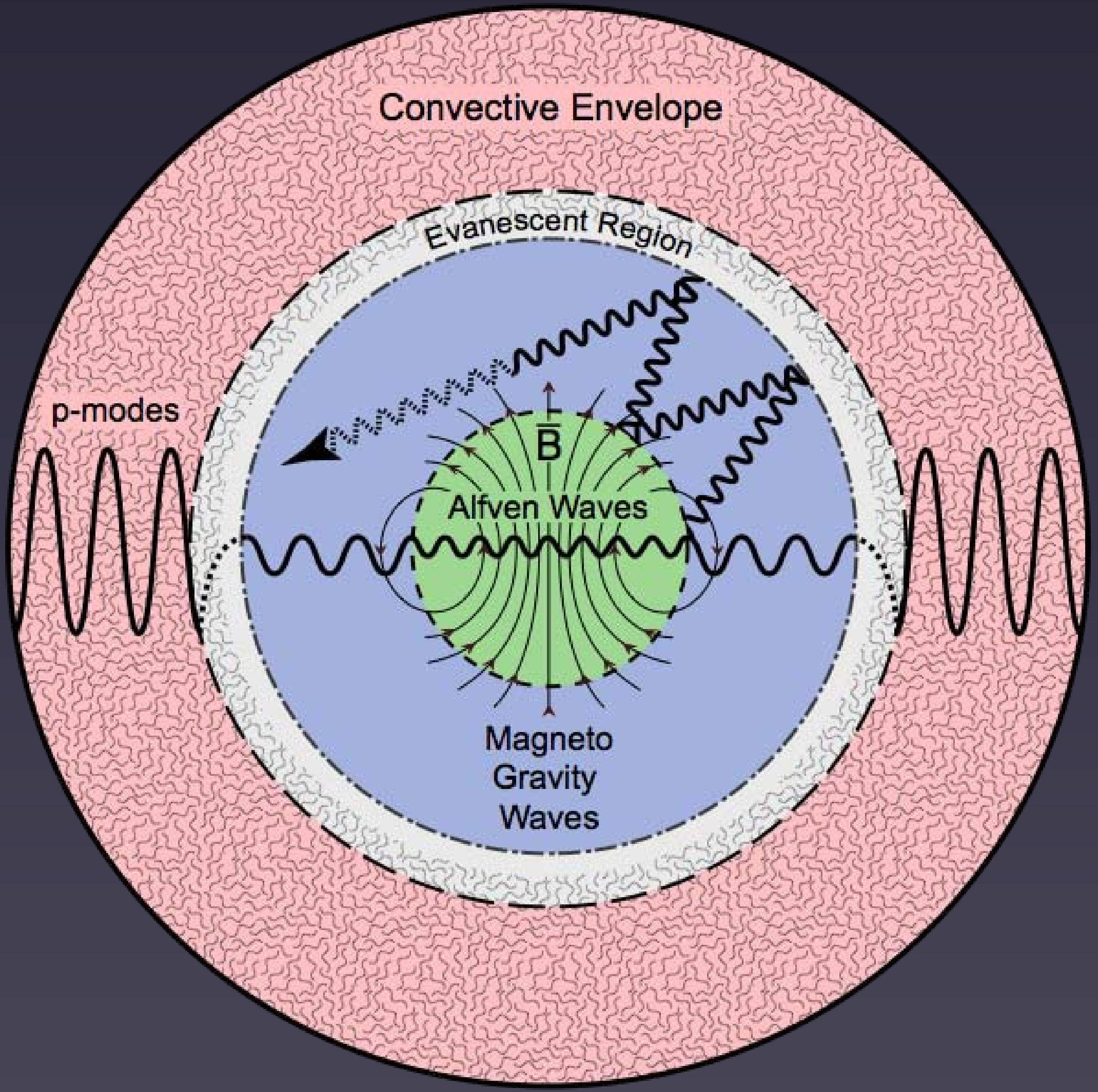
Magnetic Greenhouse Effect → Magnetic Mirror Effect

- Waves excited by turbulent convection near stellar surface, travel inward, and tunnel into radiative core

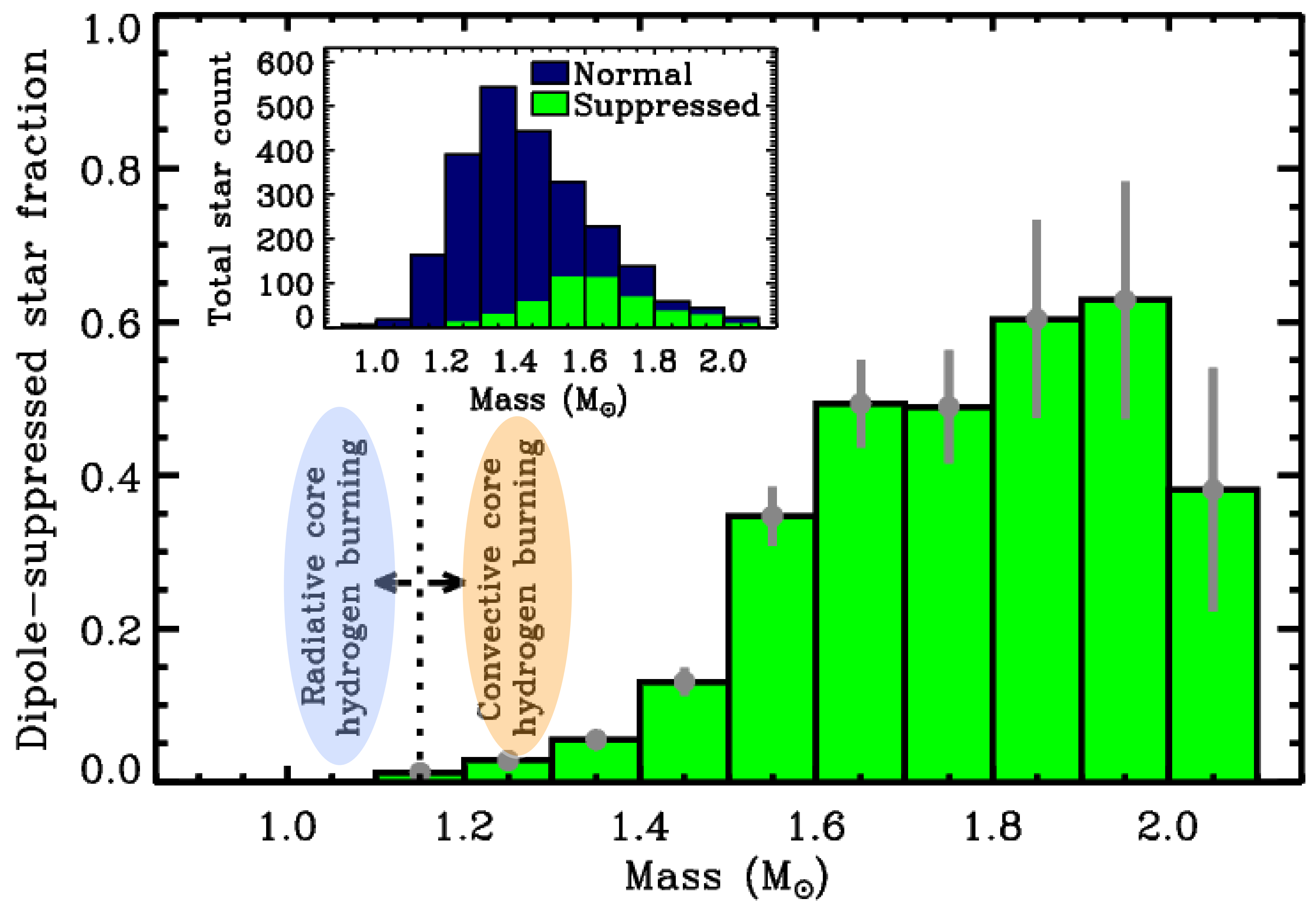
- Ingoing waves reflect off regions of high field strength

- Magnetic mirror converts gravity waves into Alfven waves (Lecoanet et al. 2016)

- Alfven waves dissipate in regions with small magnetic fields

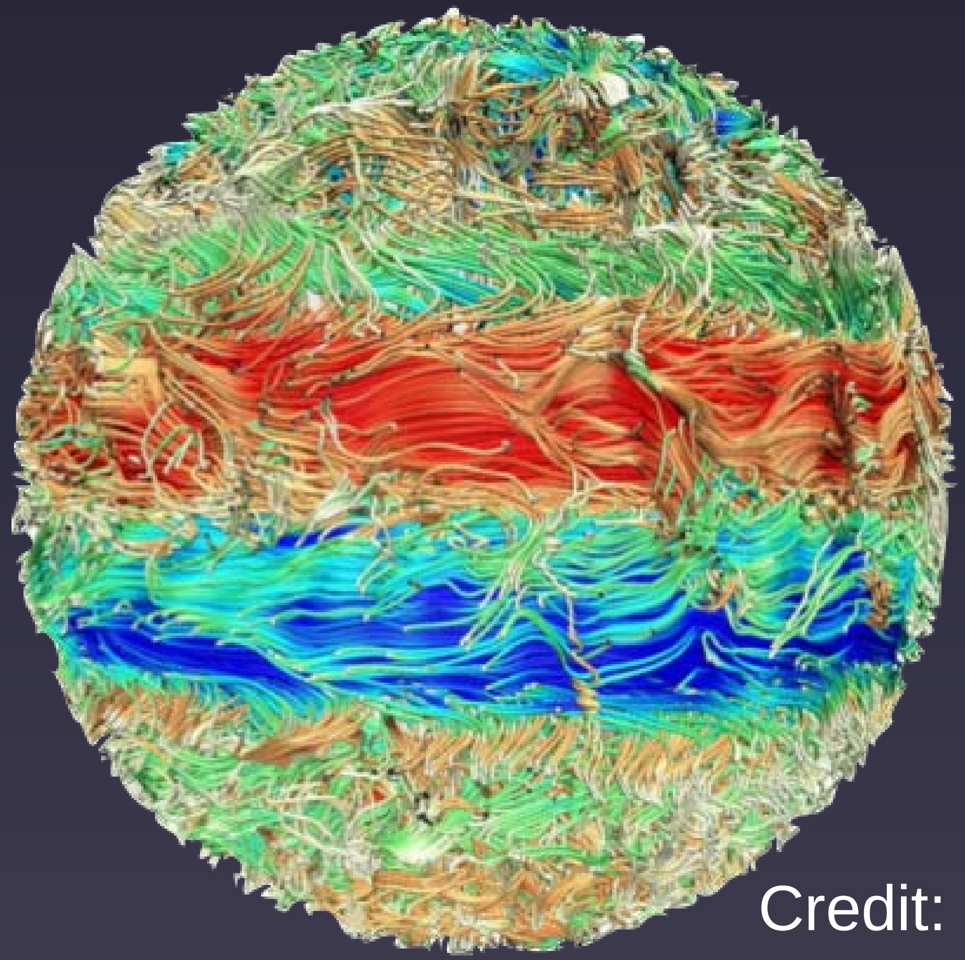


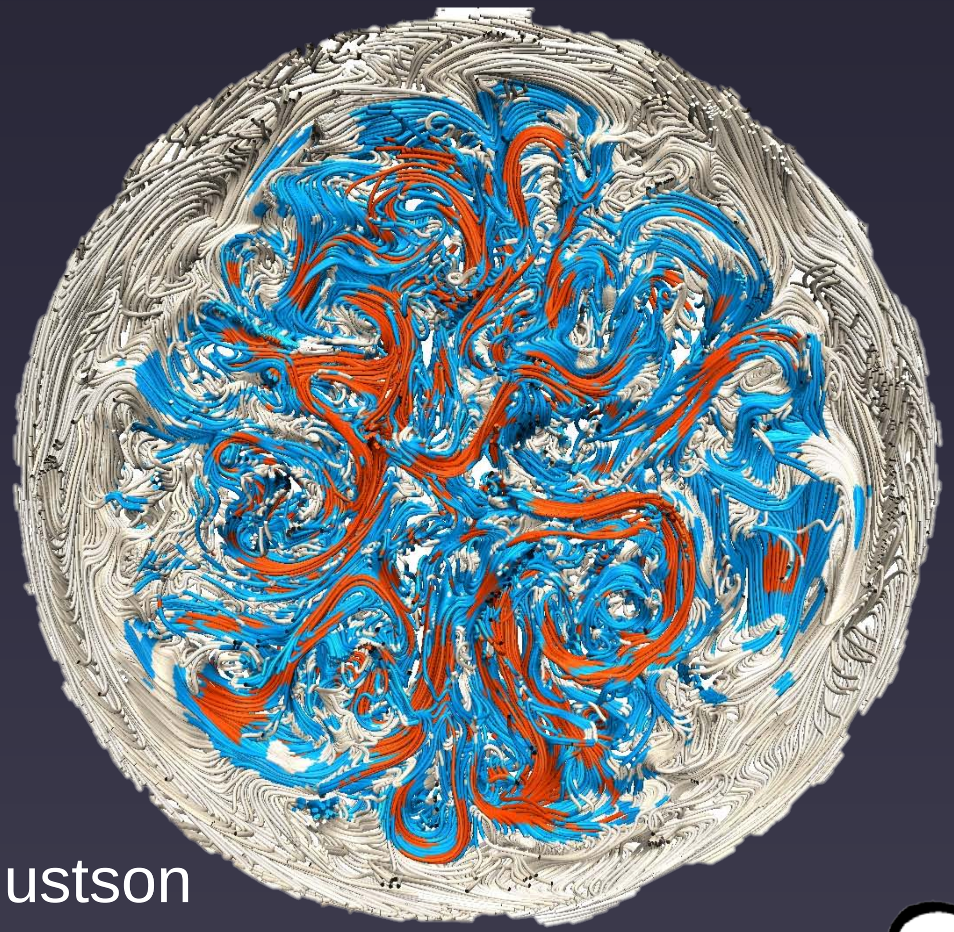
Incidence of core fields is mass-dependent



Stello, Cantiello, Fuller+, 2016

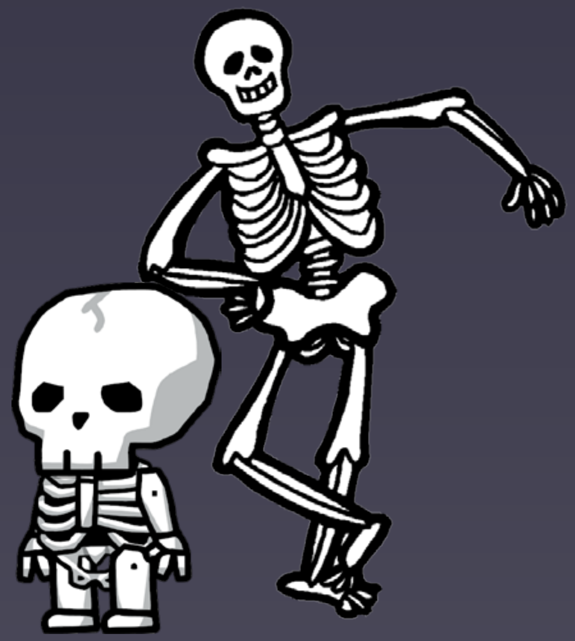
Evidence for convective core dynamos



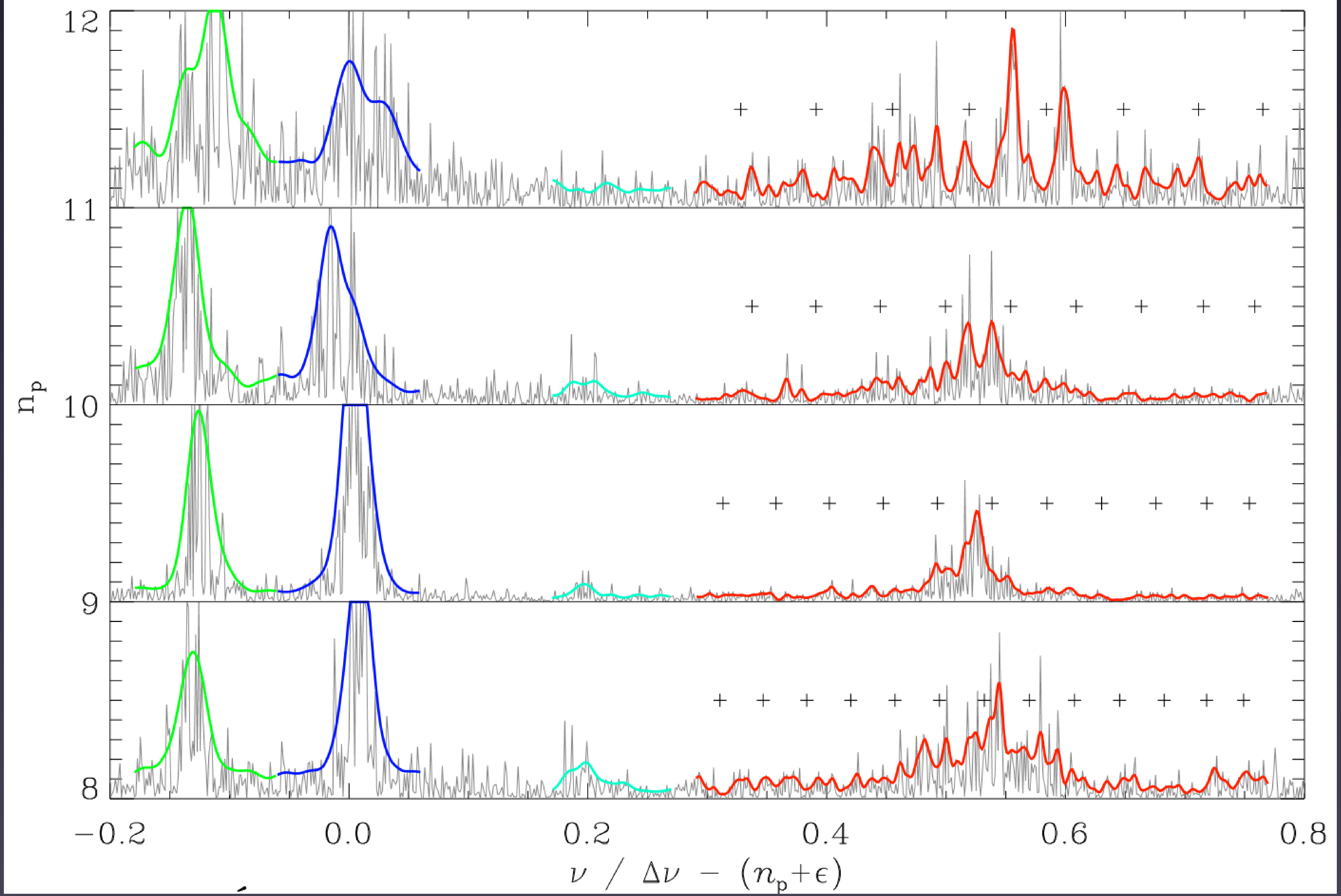


Credit: Kyle Augustson

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



Mixed modes in stars with suppressed dipole modes may indicate another mechanism is at work (see Mosser et al. 2017)



Mosser et al. 2017

Conclusions

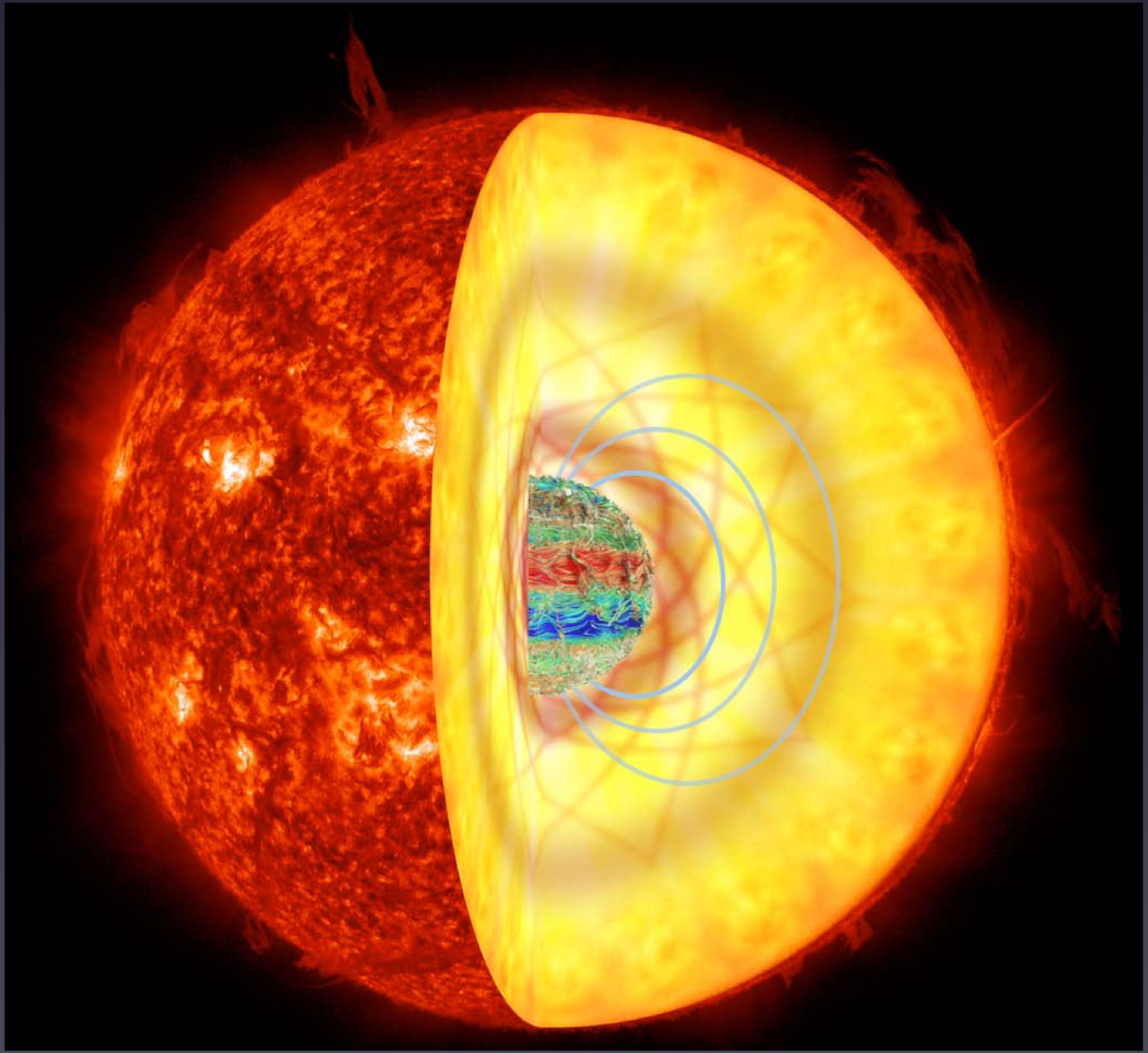
Asteroseismology indicates:

- Mixing is efficient
  - Schwarzschild criterion + overshoot matches observations best
  - Overshoot $f_{\rm ov}$~0.02 should be used in massive star evolution

- Angular momentum transport is efficient
  - Magnetic and/or wave transport likely required
  - Massive star cores rotate slower than predicted by past models

- Strong internal magnetic fields may be common
  - Internal dynamo-generated fields may persist to later phases
  - Neutron star magnetic fields may be inherited from progenitor

Thanks!



Bonus Material!

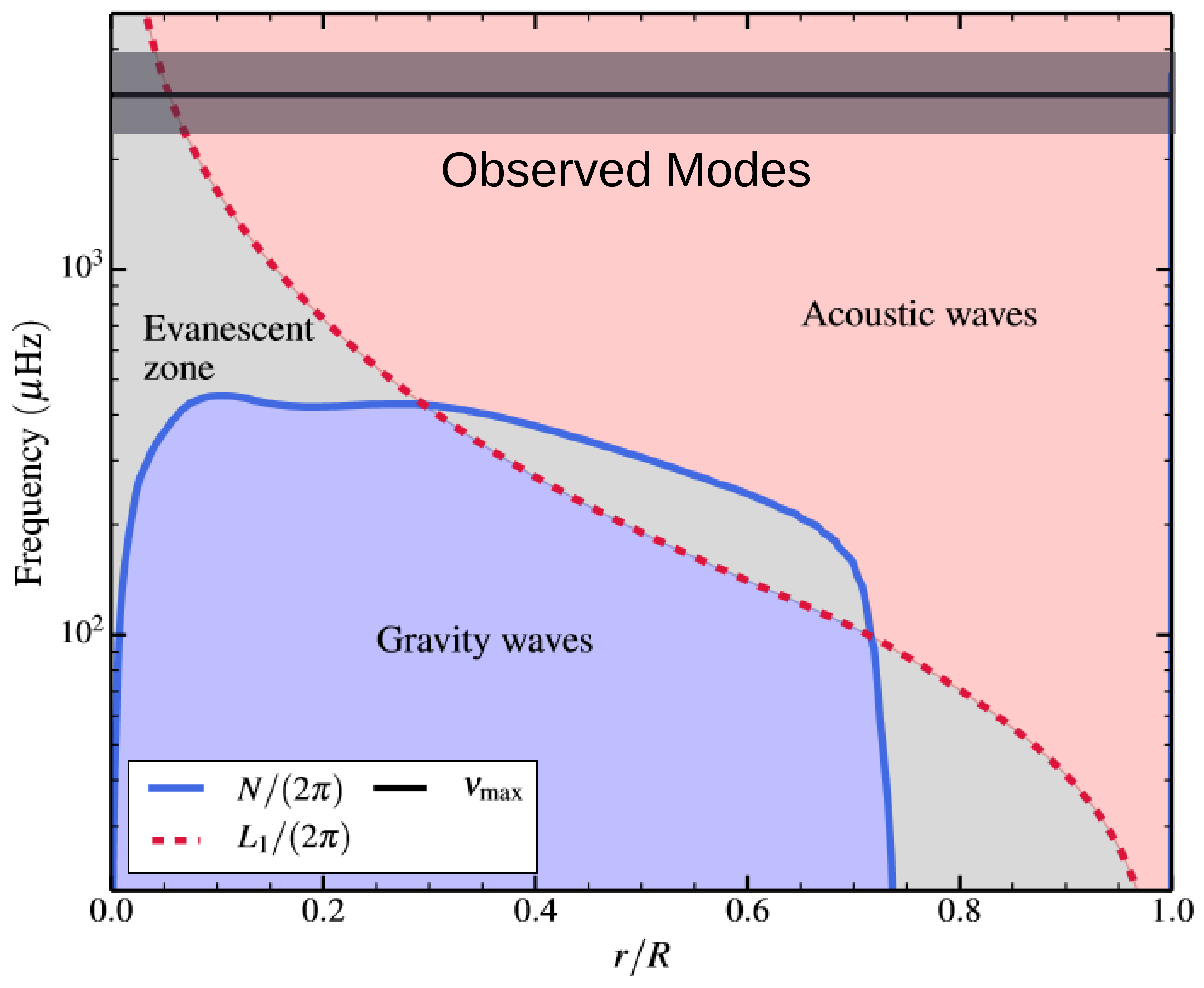
Wave Propagation in the Sun

- Acoustic waves propagate where ω>N, ω>L_l

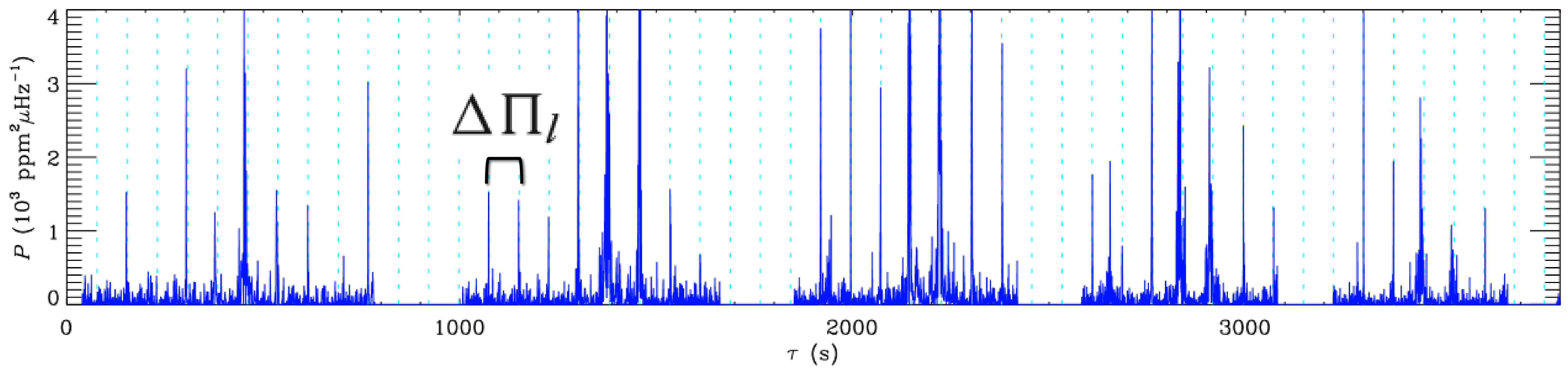
$$k_r \simeq \frac{\omega}{v_s}$$

- Gravity waves propagate where ω<N, ω<L_l

$$k_r \simeq \frac{\ell N}{\omega r}$$



The Mixed Mode Forest



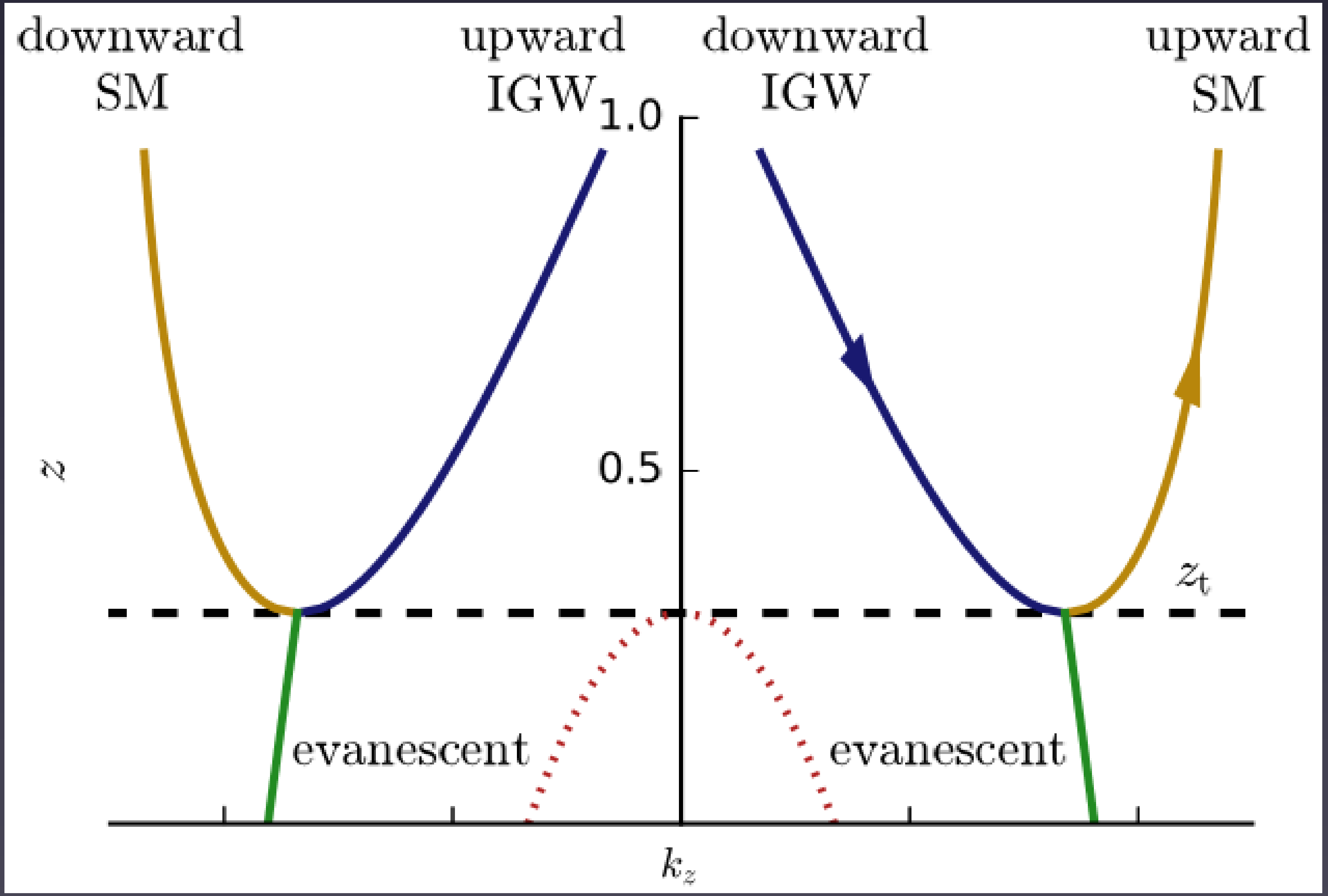
Vrard et al. 2016

- Mixed modes have constant period spacing determined by core properties

$$\Delta\Pi_l = \frac{2\pi^2}{\sqrt{l(l+1)}}\left(\int_{r_1}^{r_2} N\,\frac{\mathrm{d}r}{r}\right)^{-1}$$

Magnetic Wave Conversion

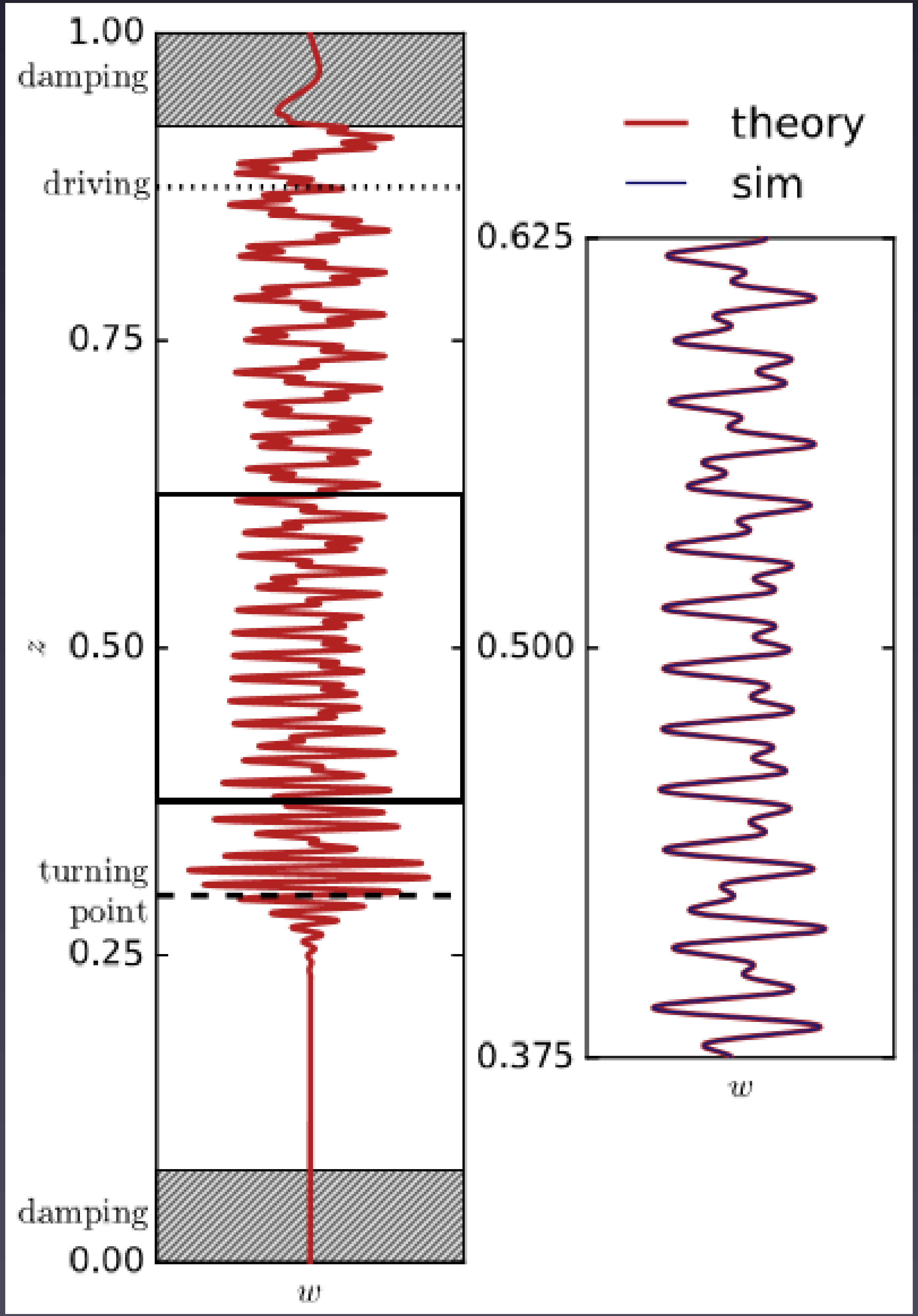
- Downward propagating gravity waves have positive wave number
- Wavenumber does not go through zero at critical point, i.e., waves do not reflect
- Waves refract into upgoing Alfvenic waves



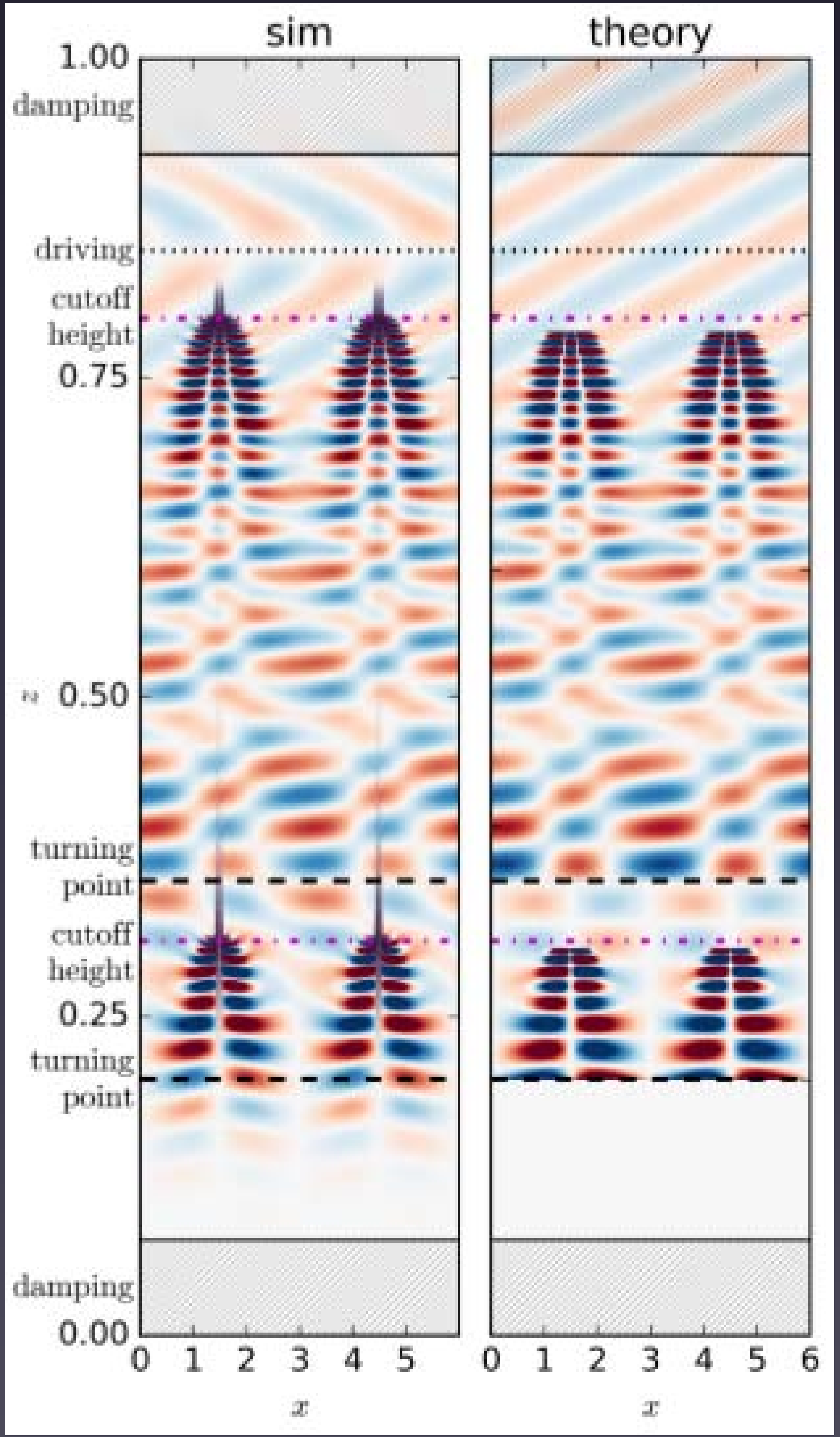
Lecoanet, Vasil, Fuller+ 2016

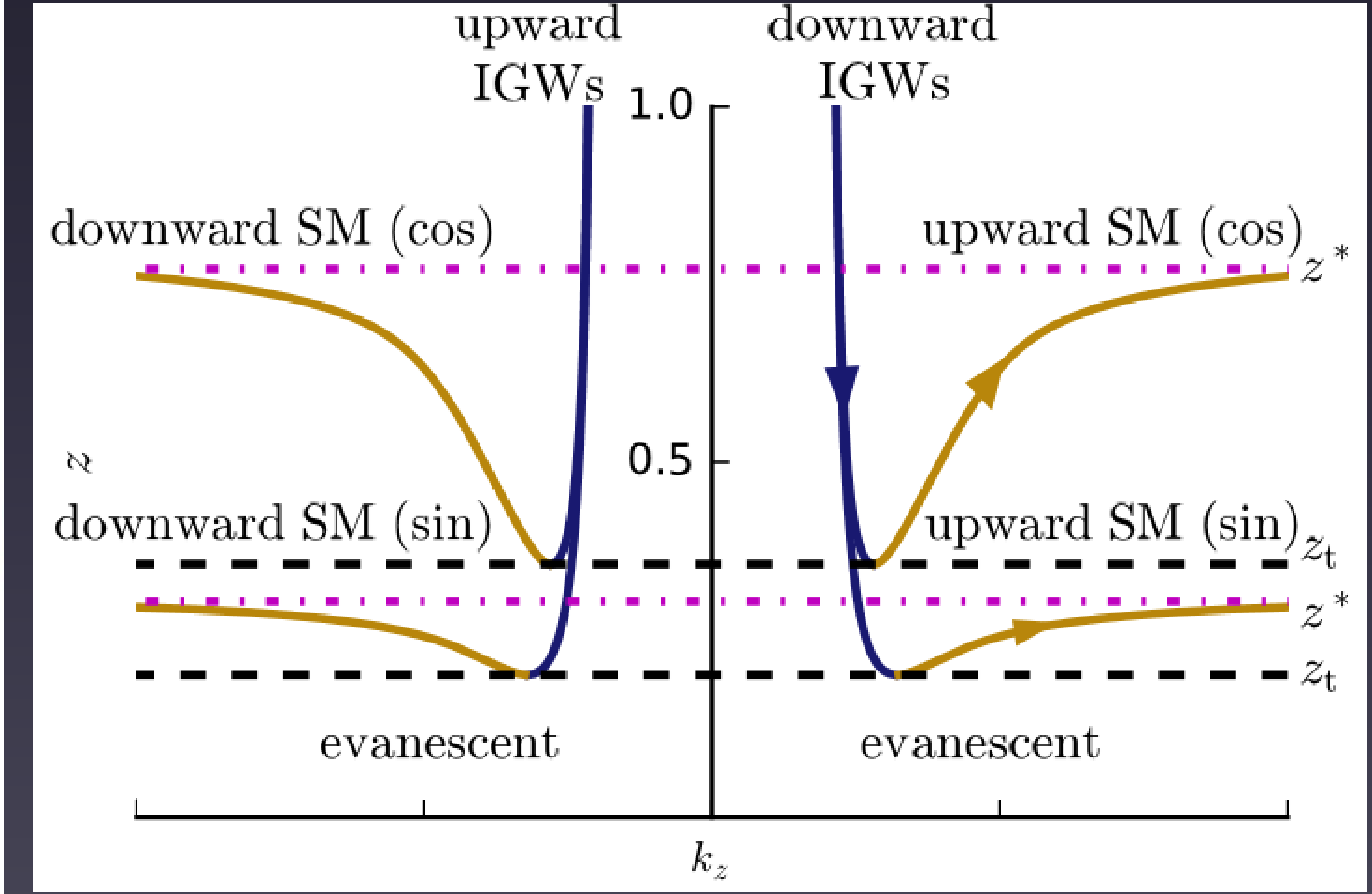
Fate of Magnetic Waves

- Alfven waves increase wavenumber as they propagate outwards into region with weak field
- For non-uniform magnetic field, waves reach ‘Alfven cut-off height’ where wavenumber diverges
- Waves likely damp deep within star



Lecoanet, Vasil, Fuller+ 2016





Lecoanet, Vasil,
Fuller+ 2016

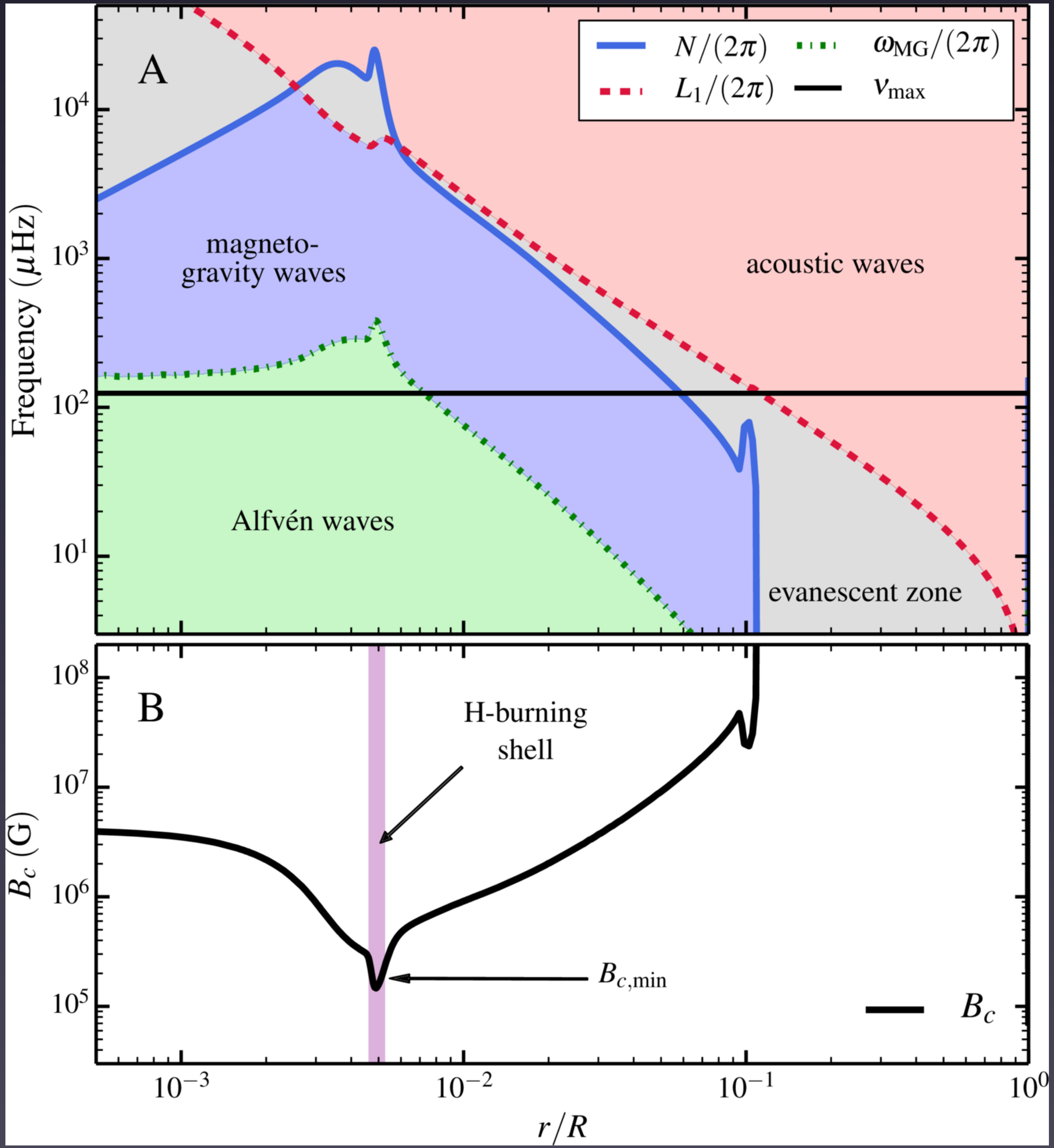
Magnetic Tension Forces

- Critical field strength for magnetic tension to dominate buoyancy as wave restoring force

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

- Gravity waves cannot propagate below cutoff frequency

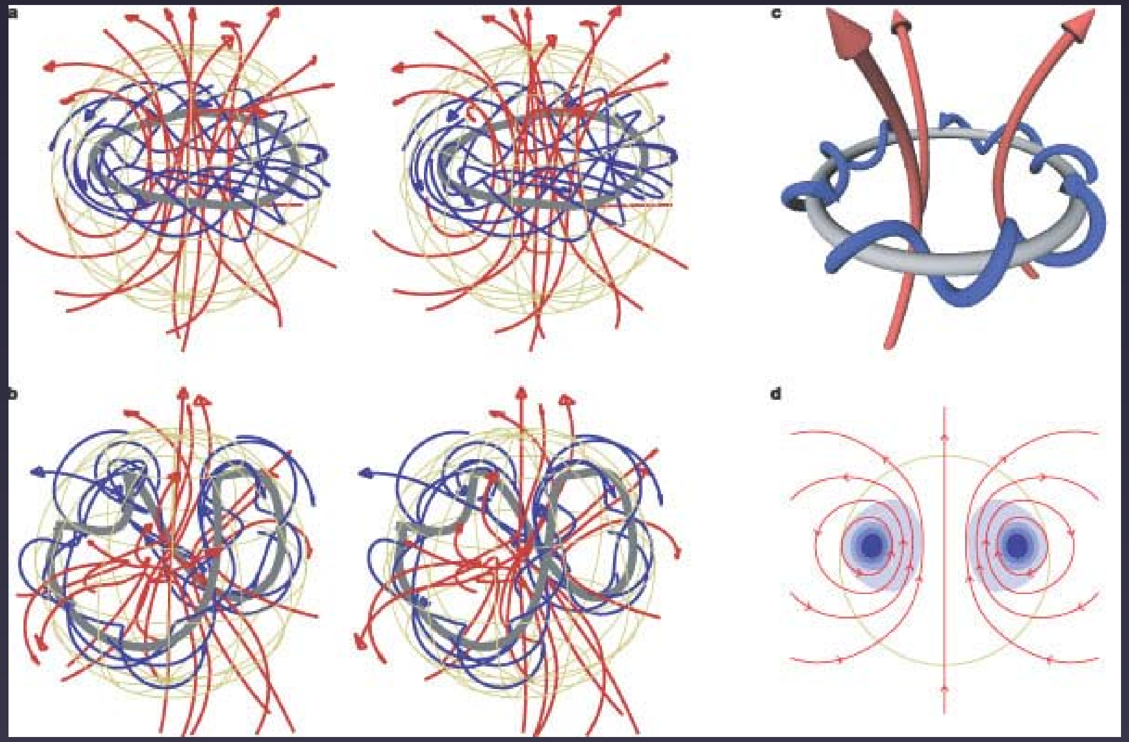
$$\omega_{\rm MG} = \left[\frac{2}{\pi}\frac{B_r^2 N^2}{\rho r^2}\right]^{1/4}$$



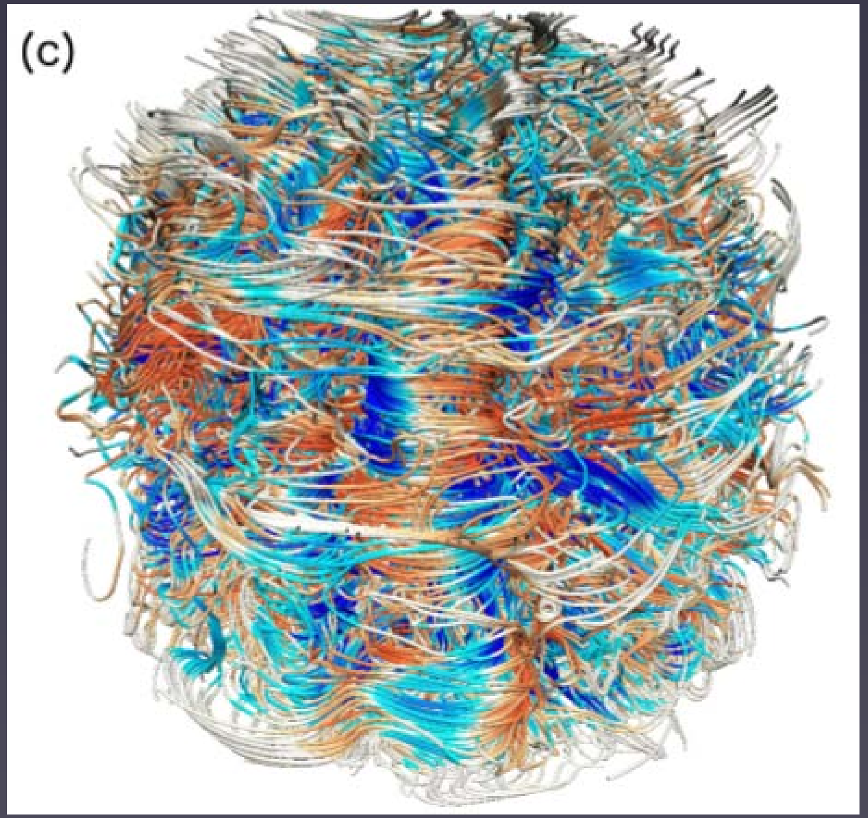
Fuller & Cantiello + 2015

Magnetic field topology may be complex

- Stable magnetic configurations of interlocked poloidal+toroidal fields exist in radiative regions
- Convective core dynamos on the MS: B_{eq}~10^5 G
- Flux conservation leads to B~10^7 G on the RGB

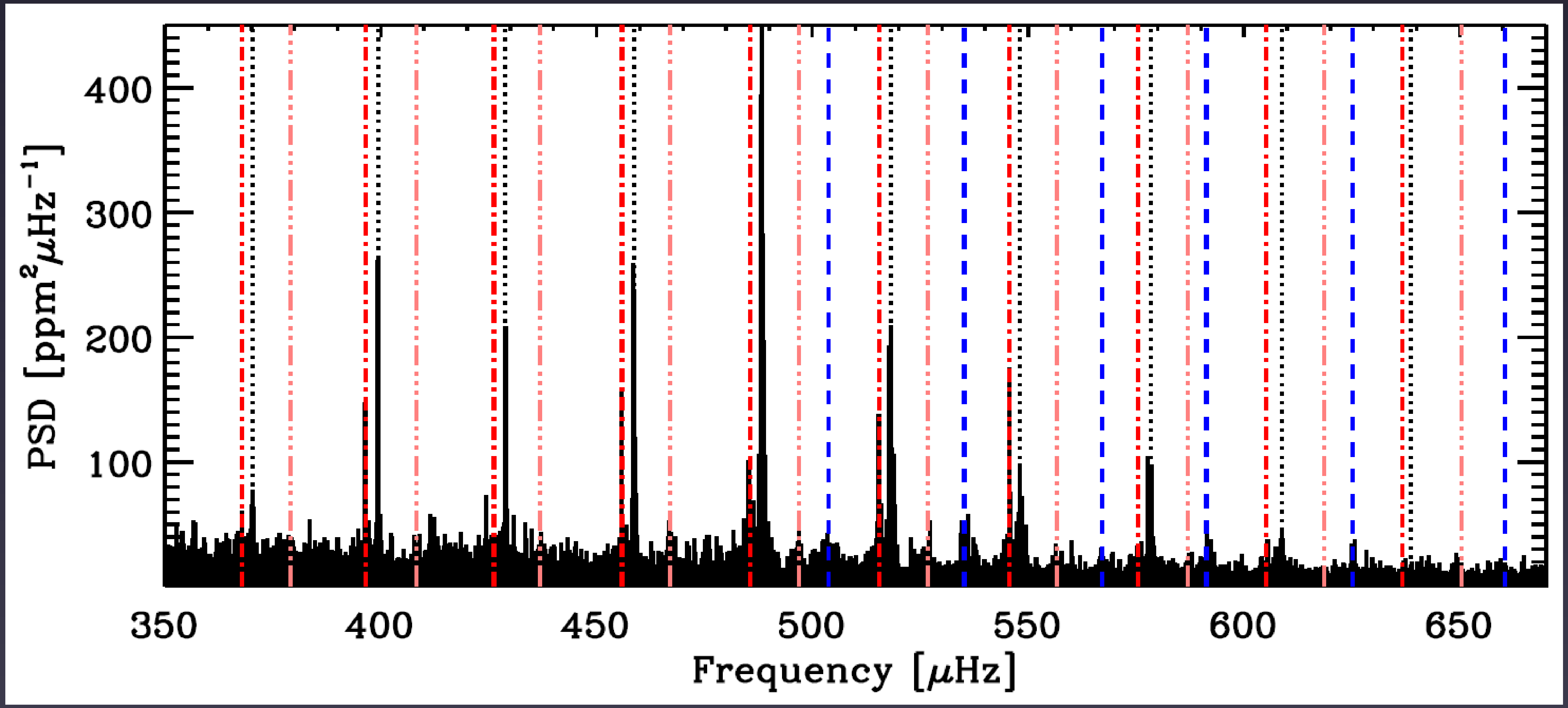


Braithwaite & Nordlund 2006

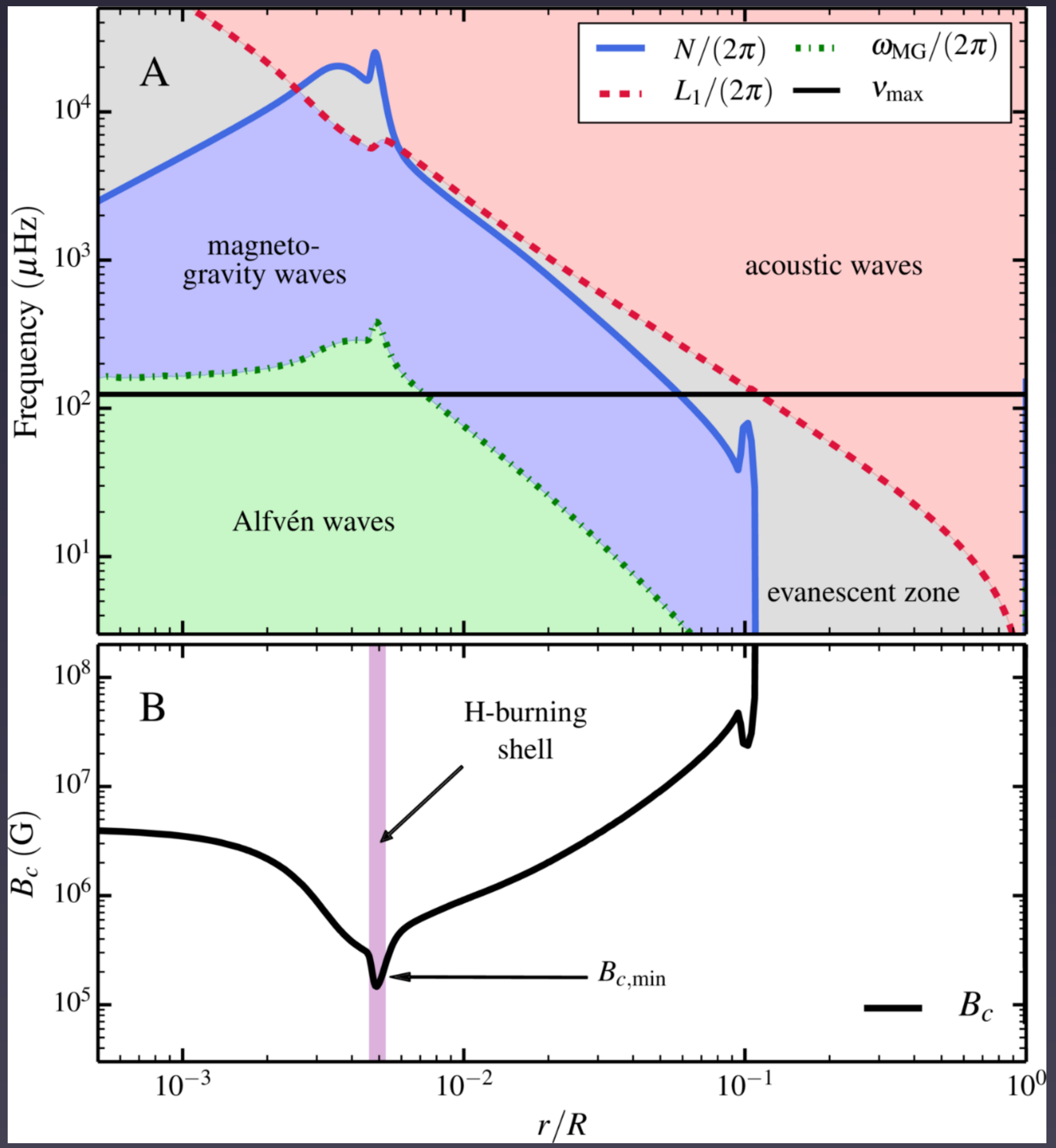


Kyle Augustson

Measurement of magnetic field in Droopy



Garcia et al. 2014



- Modes above cutoff frequency not suppressed:

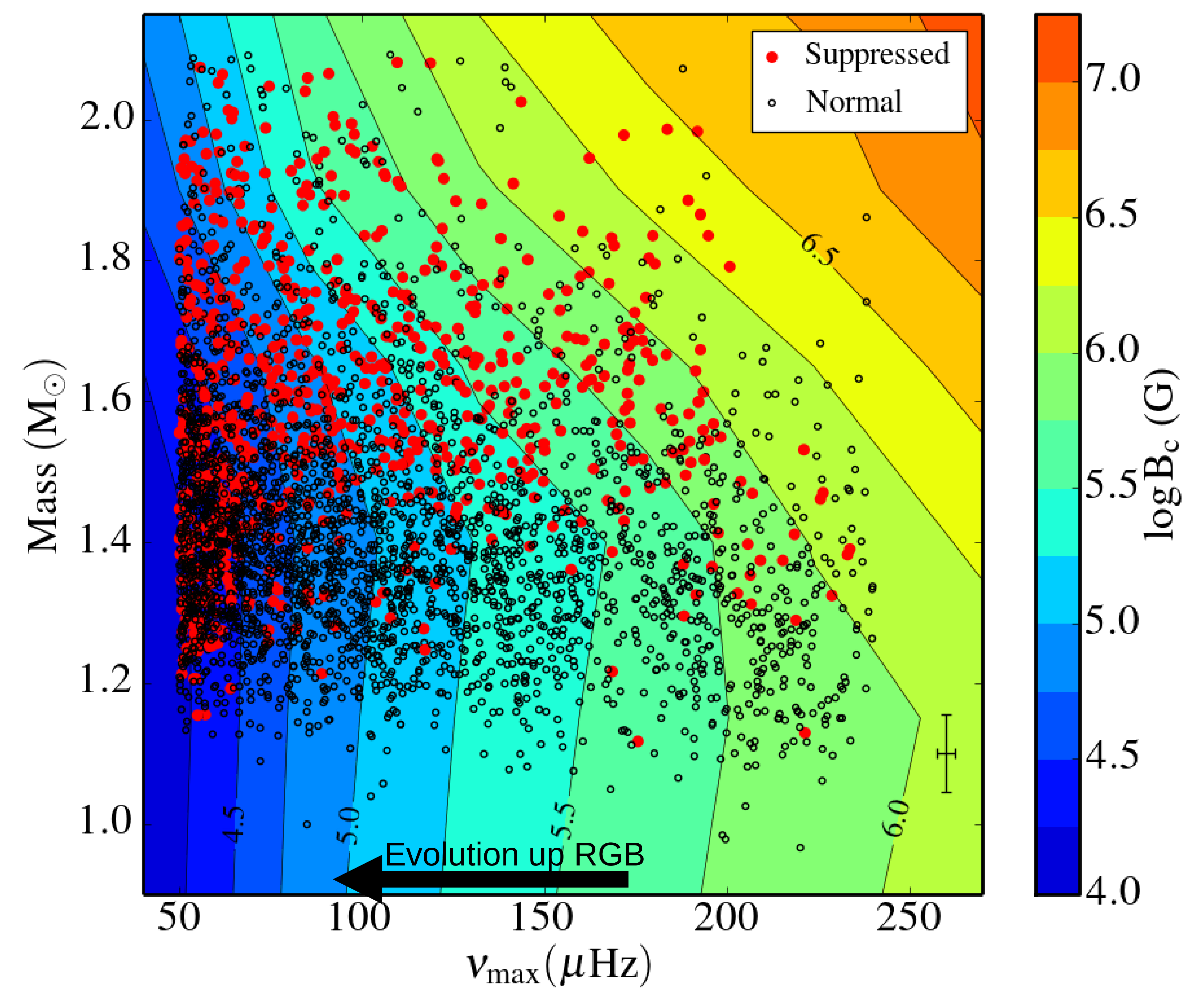
$$\omega_{\rm MG} = \left[\frac{2}{\pi}\frac{B_r^2 N^2}{\rho r^2}\right]^{1/4}$$

- Measurement of cutoff frequency yields B-field at H-burning shell: $B_c = \sqrt{\frac{\pi\rho}{2}}\frac{\omega^2 r}{N}$ ≈10^7 G

Magnetic fields in thousands of stars

- No evidence of point at which magnetic greenhouse effect "turns on"

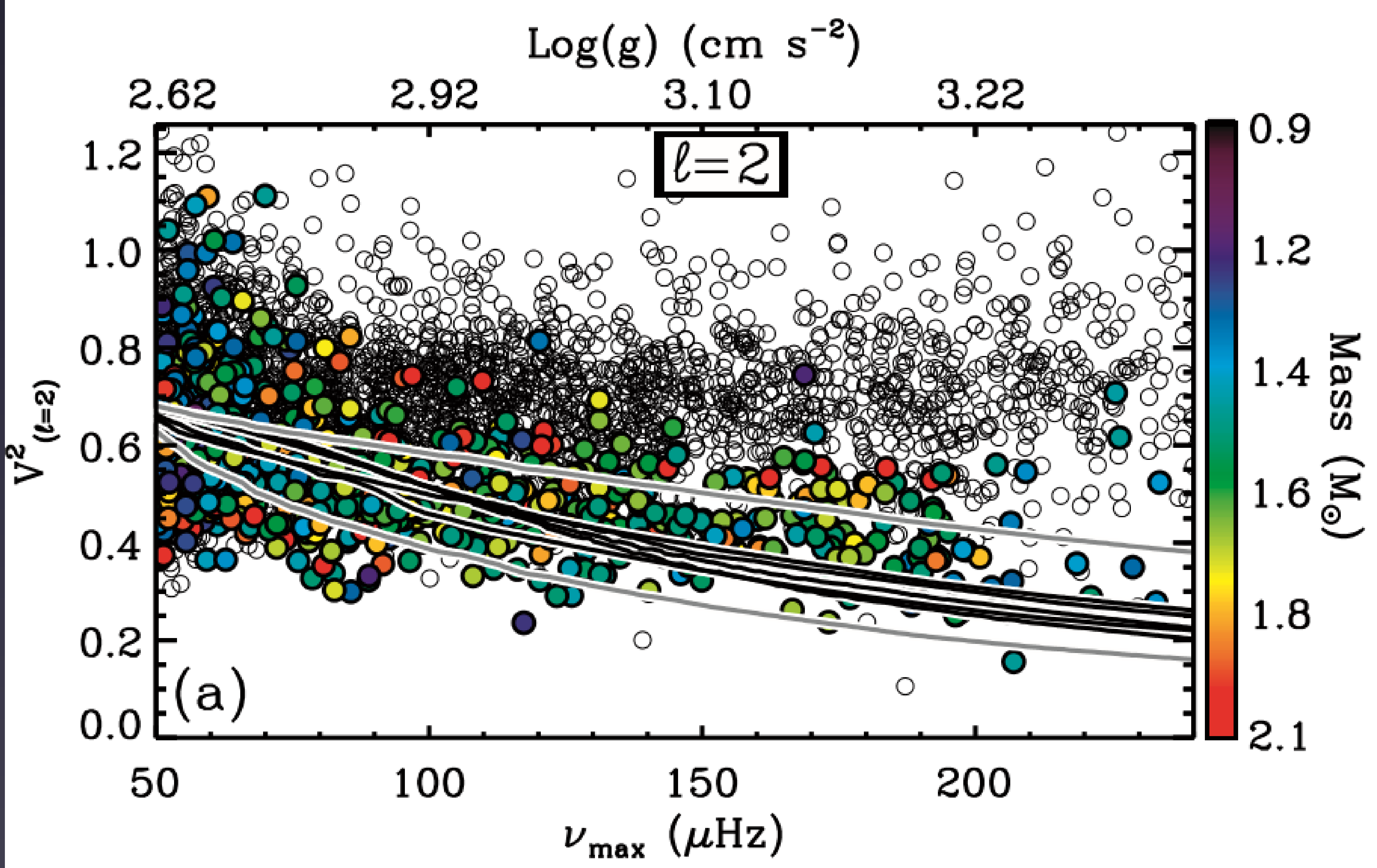
- No evidence of maximum attainable field strength



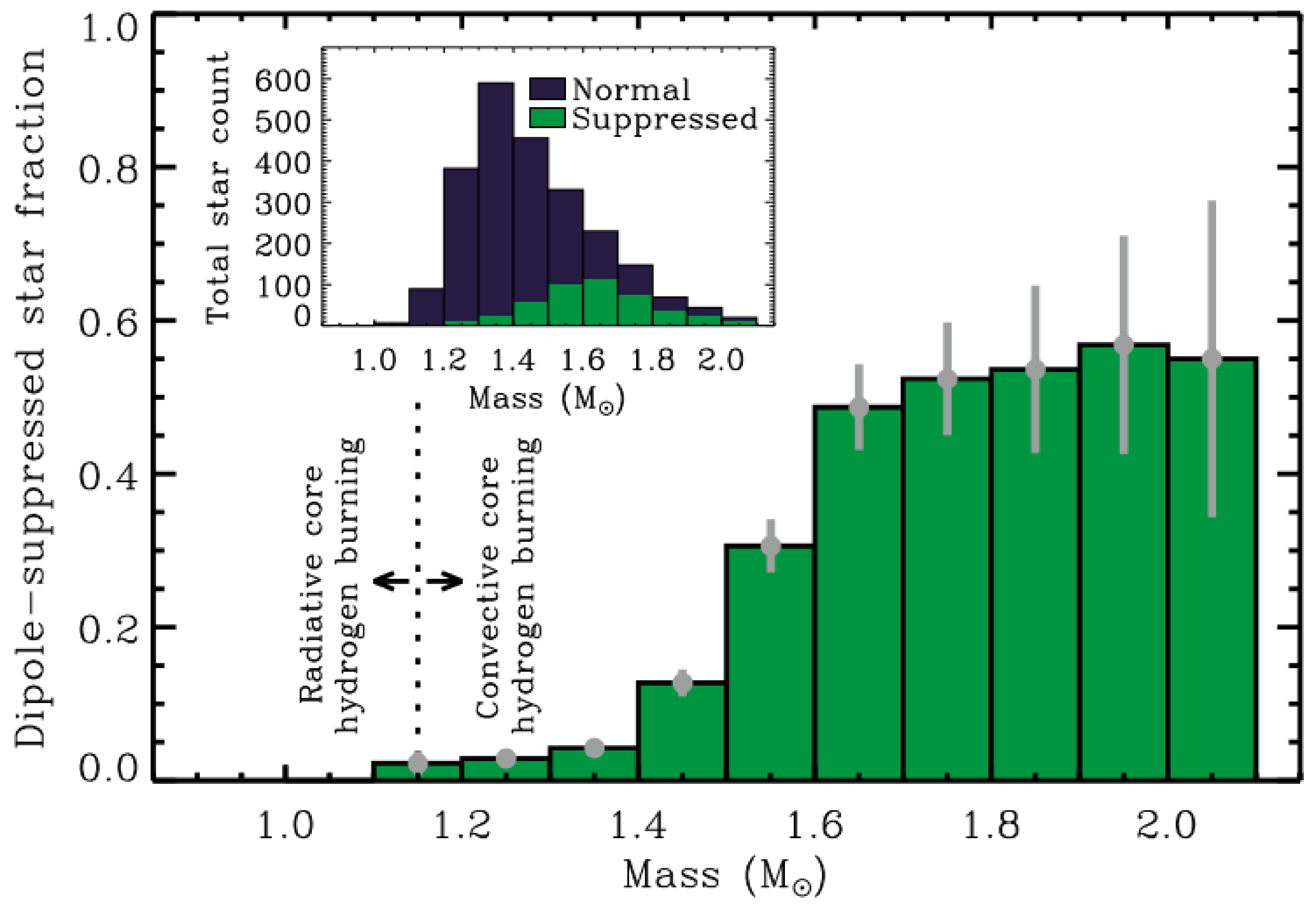
Stello, Cantiello, Fuller + 2016,

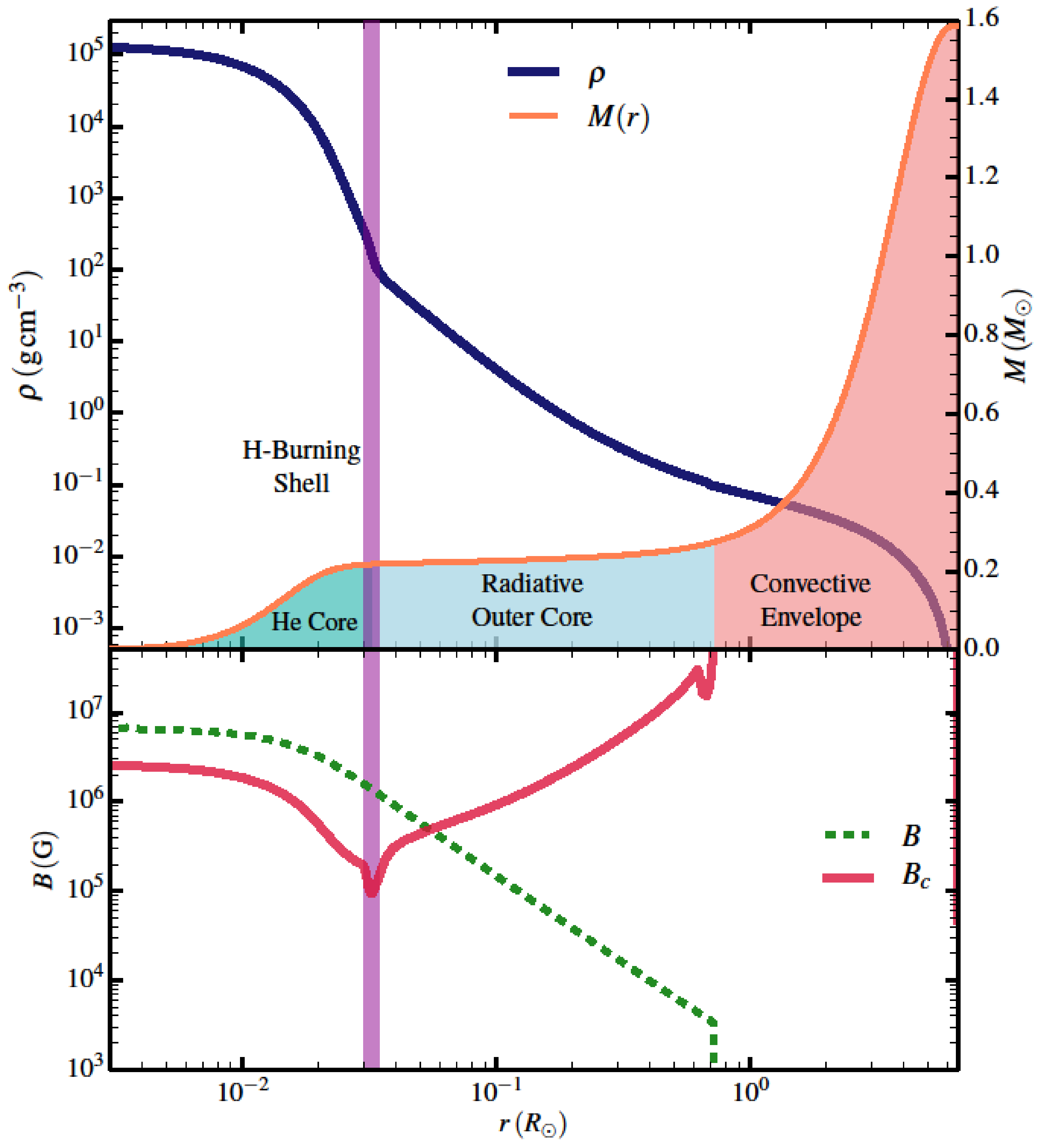
Predictions

- Quadrupole modes mildly suppressed
- Magnetic He-burning stars should be detectable
    - Does He flash wipe out strong fields?
- Surface rotation rates need not be fast
- Surface magnetic fields need not be strong



Stello, Cantiello, **Fuller** + 2016

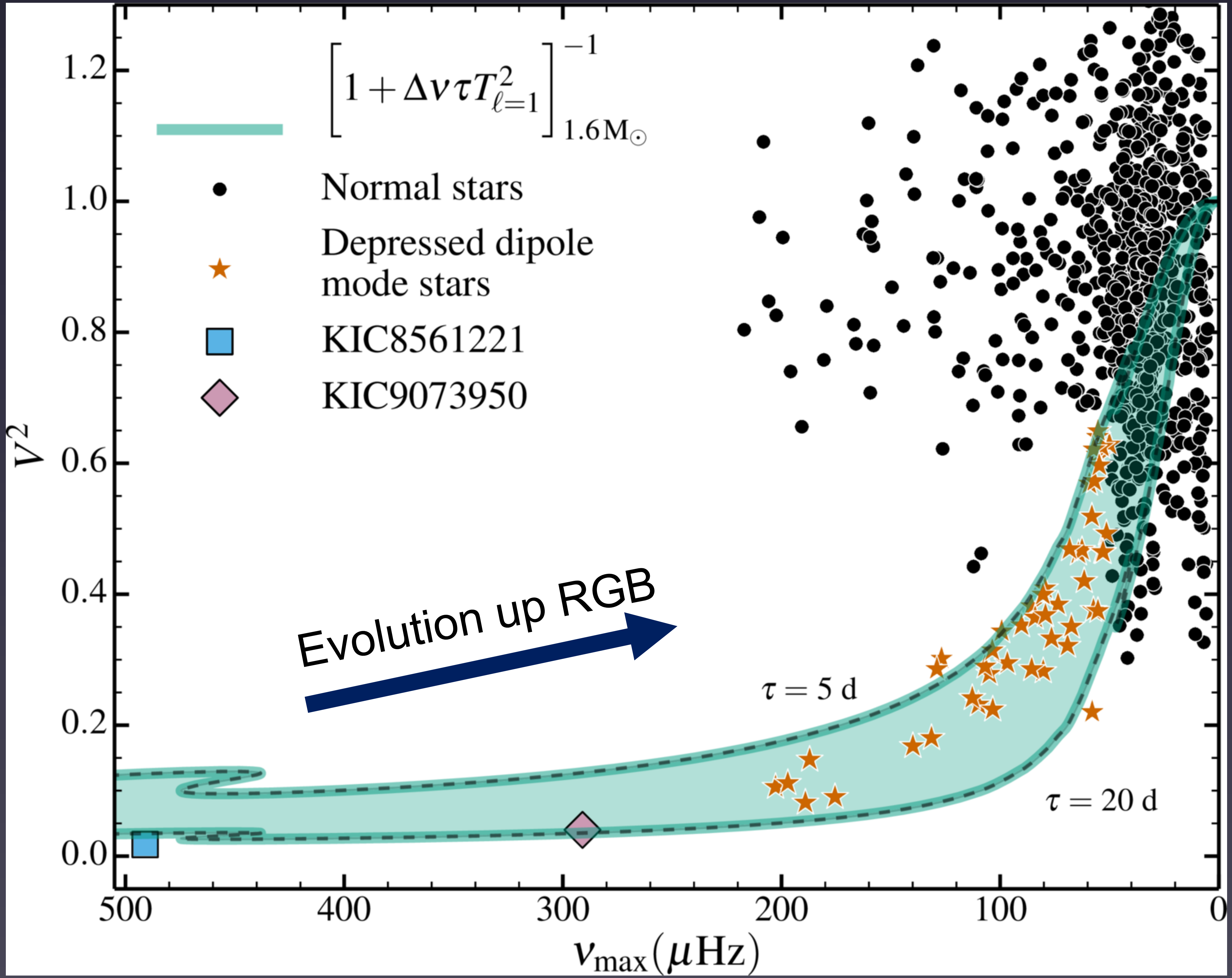

Dipole−suppressed star fraction
1.0
0.8
0.6
0.4
0.2
0.0
1.0
1.2
1.4
1.6
1.8
2.0
Mass (M$_\odot$)
Radiative core hydrogen burning
Convective core hydrogen burning
Total star count
600
500
400
300
200
100
0
Normal
Suppressed
1.0
1.2
1.4
1.6
1.8
2.0
Mass (M$_\odot$)



ρ
$M(r)$
H-Burning Shell
He Core
Radiative Outer Core
Convective Envelope
$\rho\,(\mathrm{g\,cm^{-3}})$
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
$M\,(M_\odot)$
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
B
B_c
$B\,(\mathrm{G})$
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{-2}
10^{-1}
10^{0}
$r\,(R_\odot)$

A (partial) solution emerges…

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



Fuller & Cantiello + *Science*, 2015

Wave Dispersion Relations

Acoustic waves:

$$\omega = c_s k_r$$

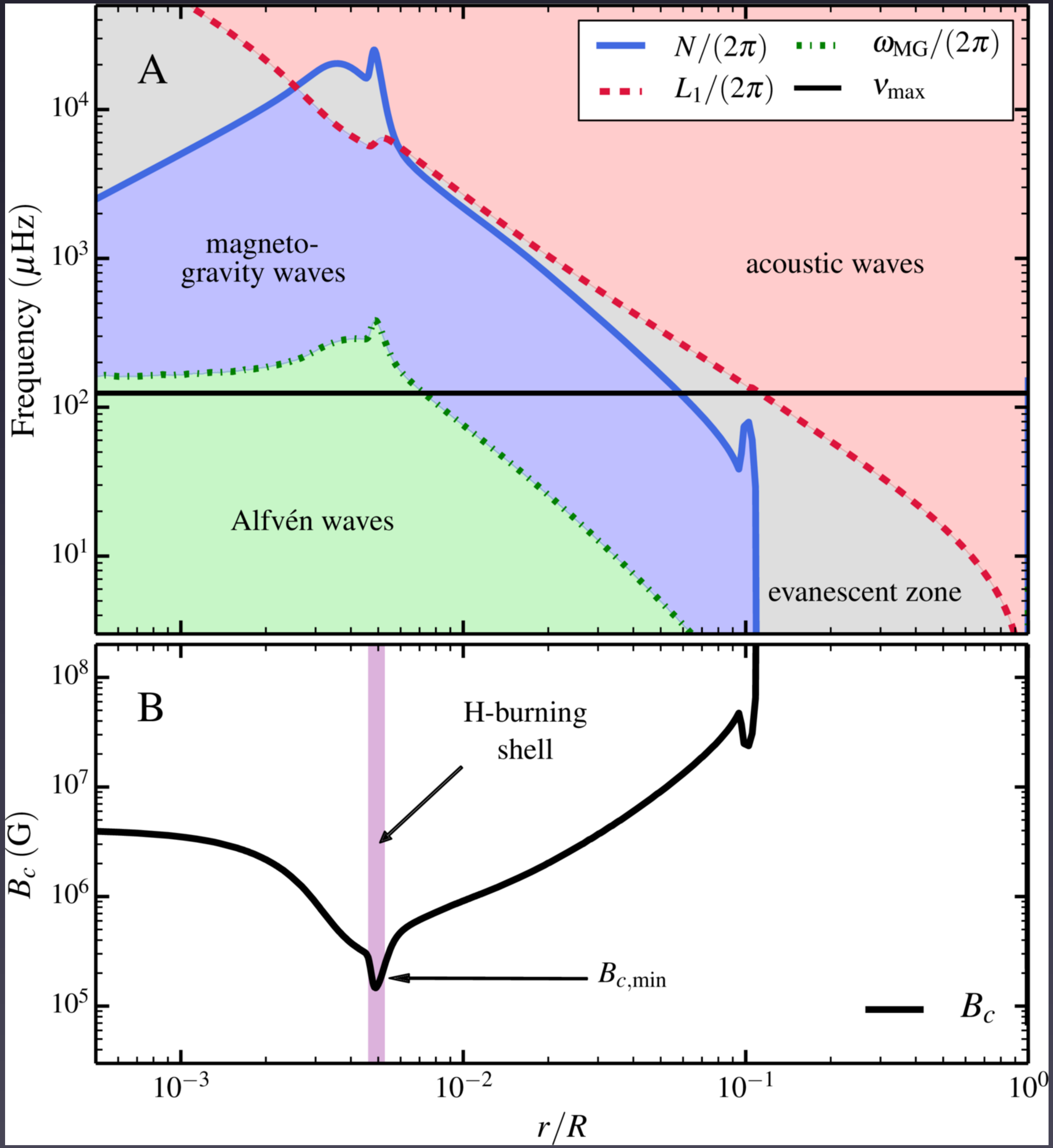
Gravity Waves

$$k_r^2 \approx \ell(\ell+1)N^2/r^2\omega^2$$

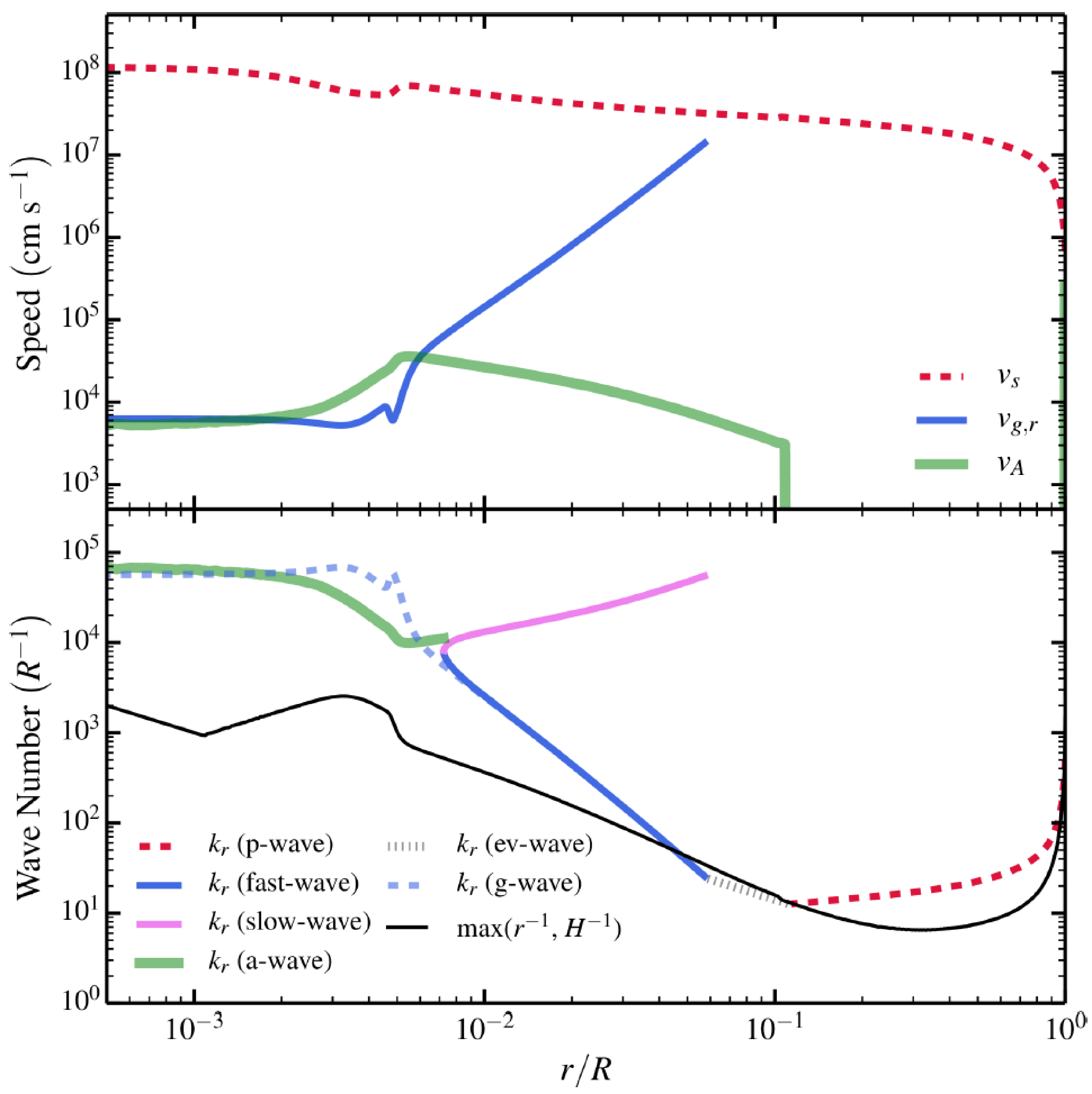
Magneto-gravity Waves:

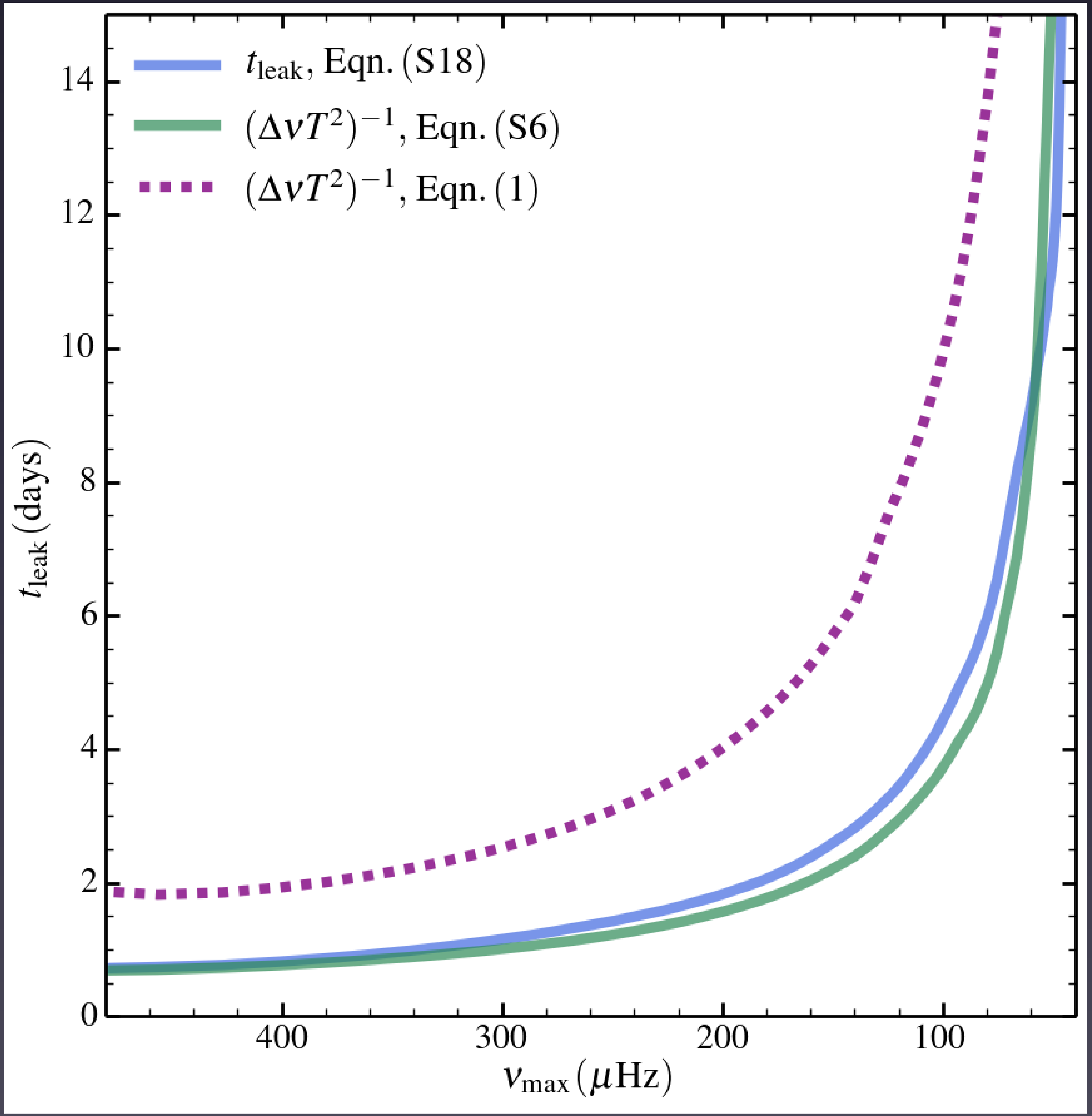
$$k^2 = \frac{\omega^2}{2v_A^2\mu^2}\left[1 \pm \sqrt{1 - \frac{4\mu^2 v_A^2 N^2 k_\perp^2}{\omega^4}}\right]$$

Alfven Waves: $$k^2 = \frac{\omega^2}{\mu^2 v_A^2}$$



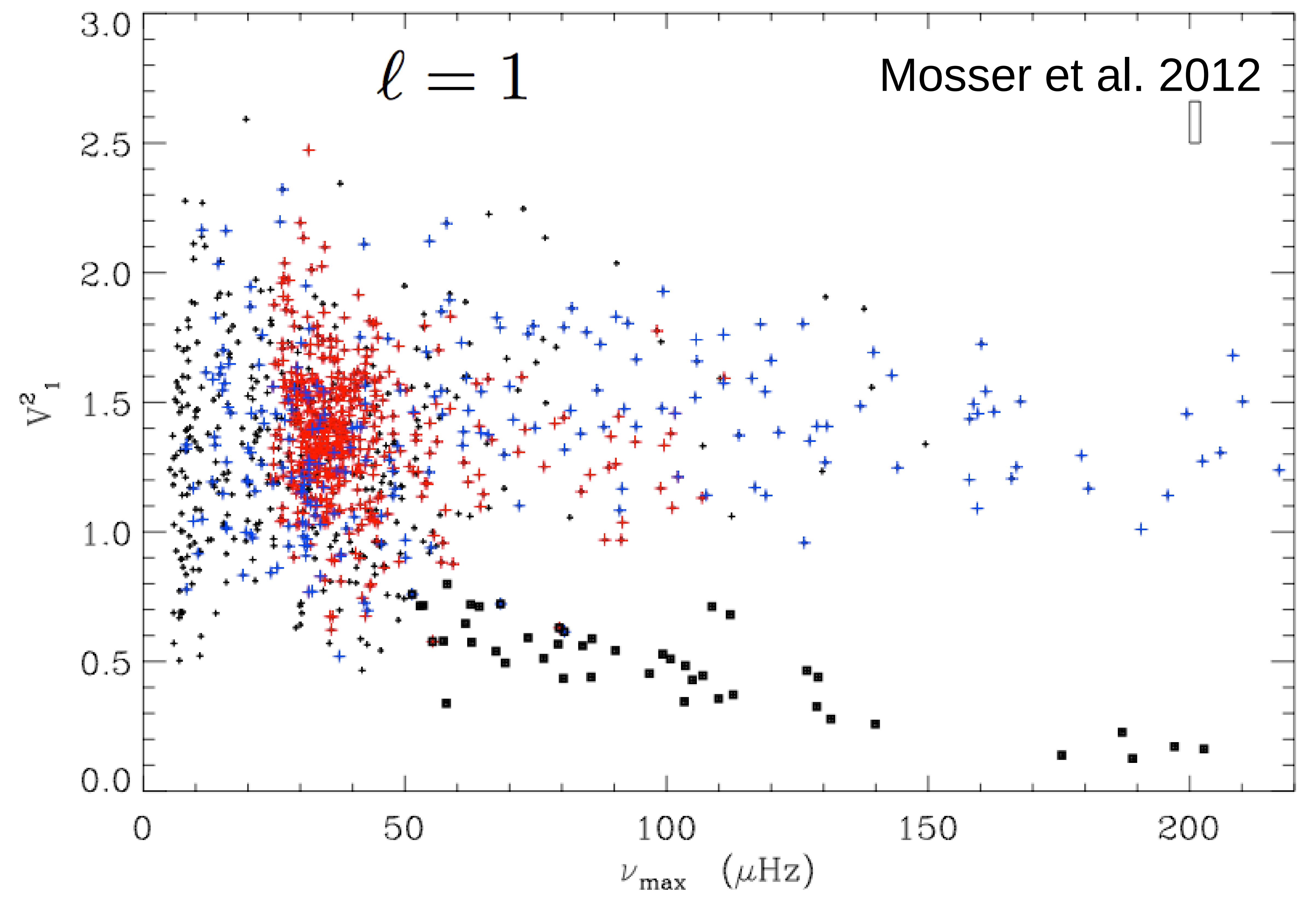
Fuller & Cantiello +
Science, 2015


10^8
10^7
10^6
10^5
10^4
10^3
Speed (cm s^{-1})
v_s
$v_{g,r}$
v_A
10^5
10^4
10^3
10^2
10^1
10^0
Wave Number (R^{-1})
k_r (p-wave)
k_r (fast-wave)
k_r (slow-wave)
k_r (a-wave)
k_r (ev-wave)
k_r (g-wave)
max(r^{-1}, H^{-1})
10^{-3}
10^{-2}
10^{-1}
10^0
r/R



$t_{\rm leak}$, Eqn. (S18)
$(\Delta\nu T^2)^{-1}$, Eqn. (S6)
$(\Delta\nu T^2)^{-1}$, Eqn. (1)
$t_{\rm leak}$ (days)
0
2
4
6
8
10
12
14
400
300
200
100
$\nu_{\rm max}$ (μHz)

Dipole mode suppression somewhat common in red giants

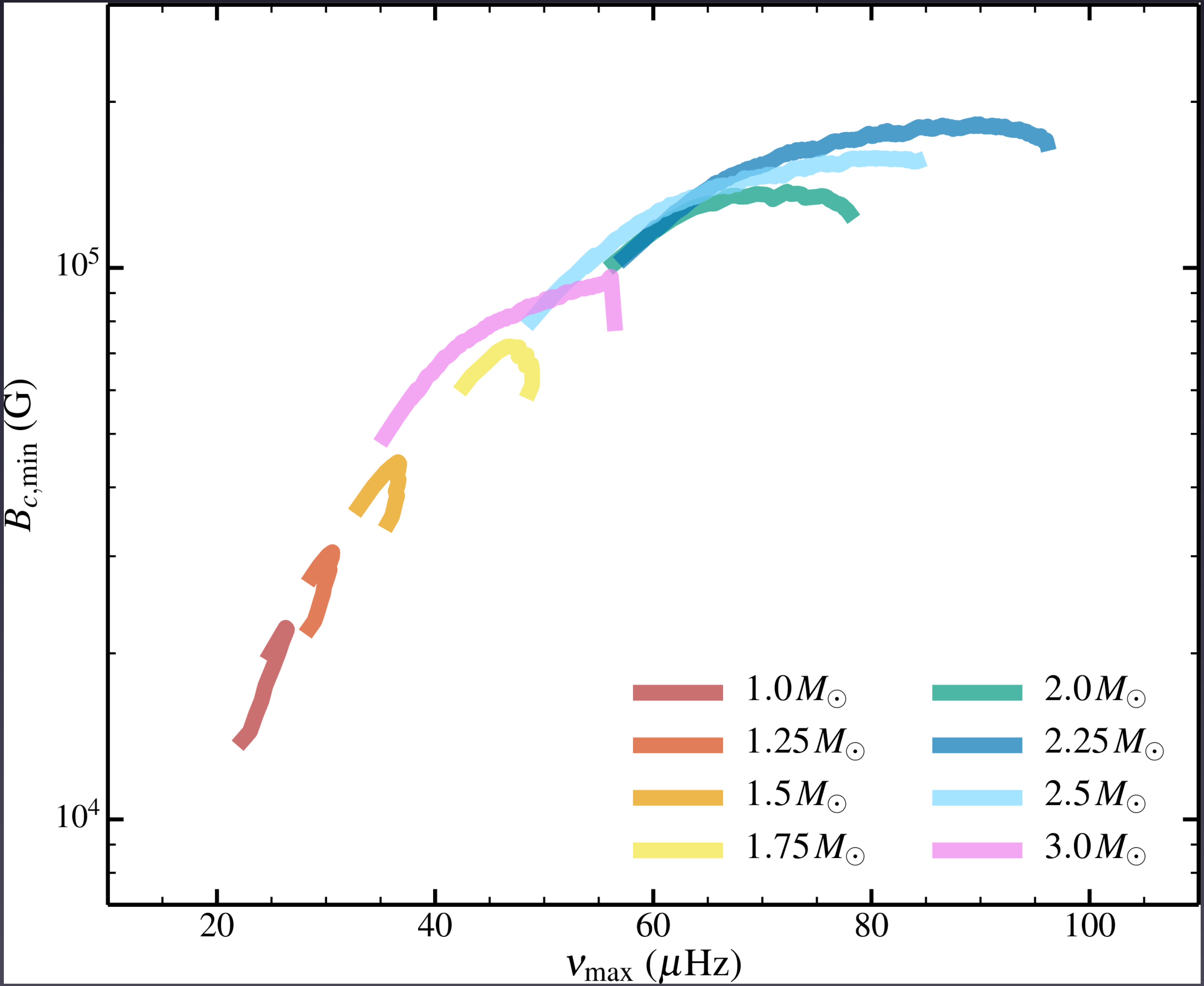


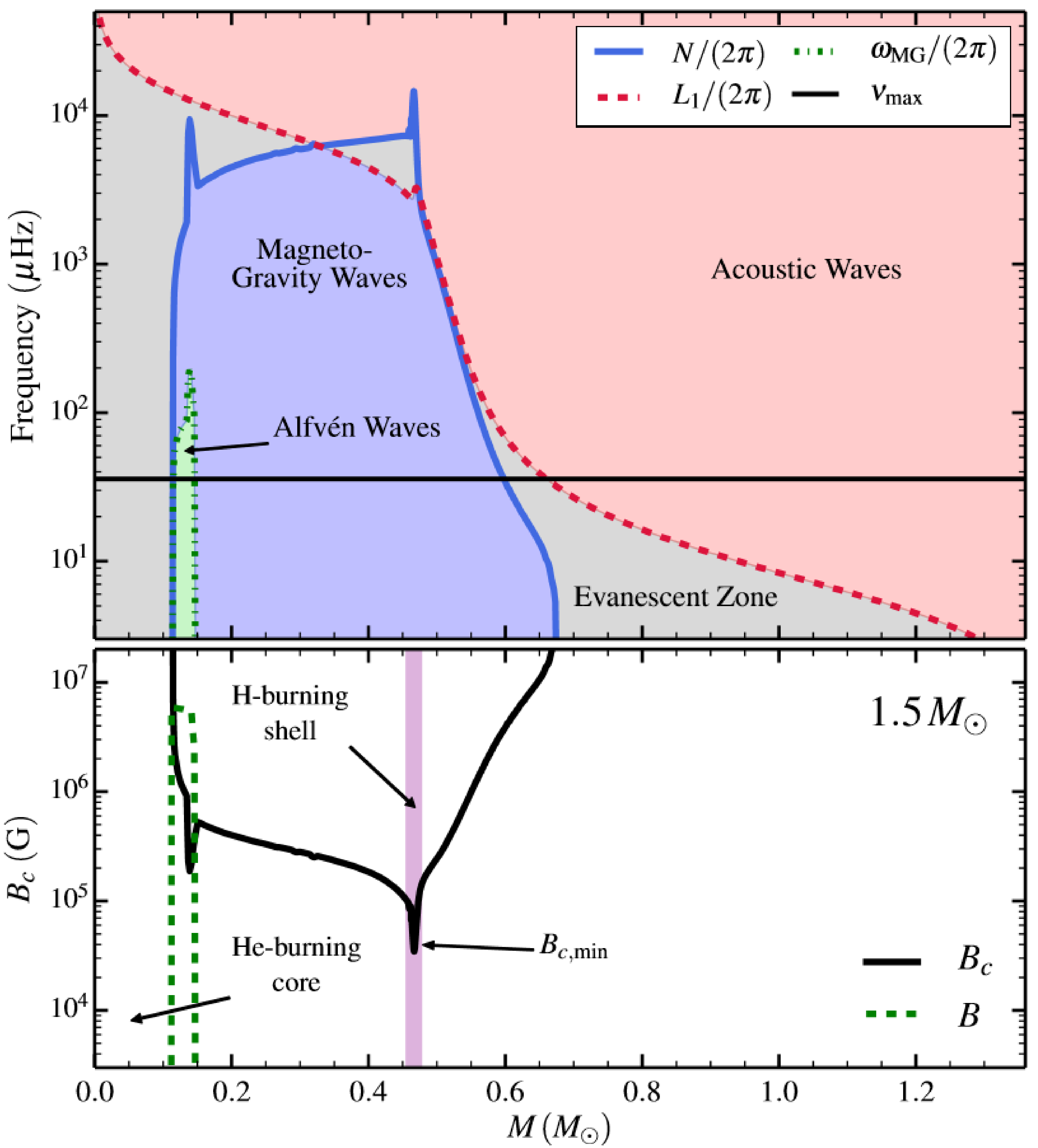
Role of Joule Heating

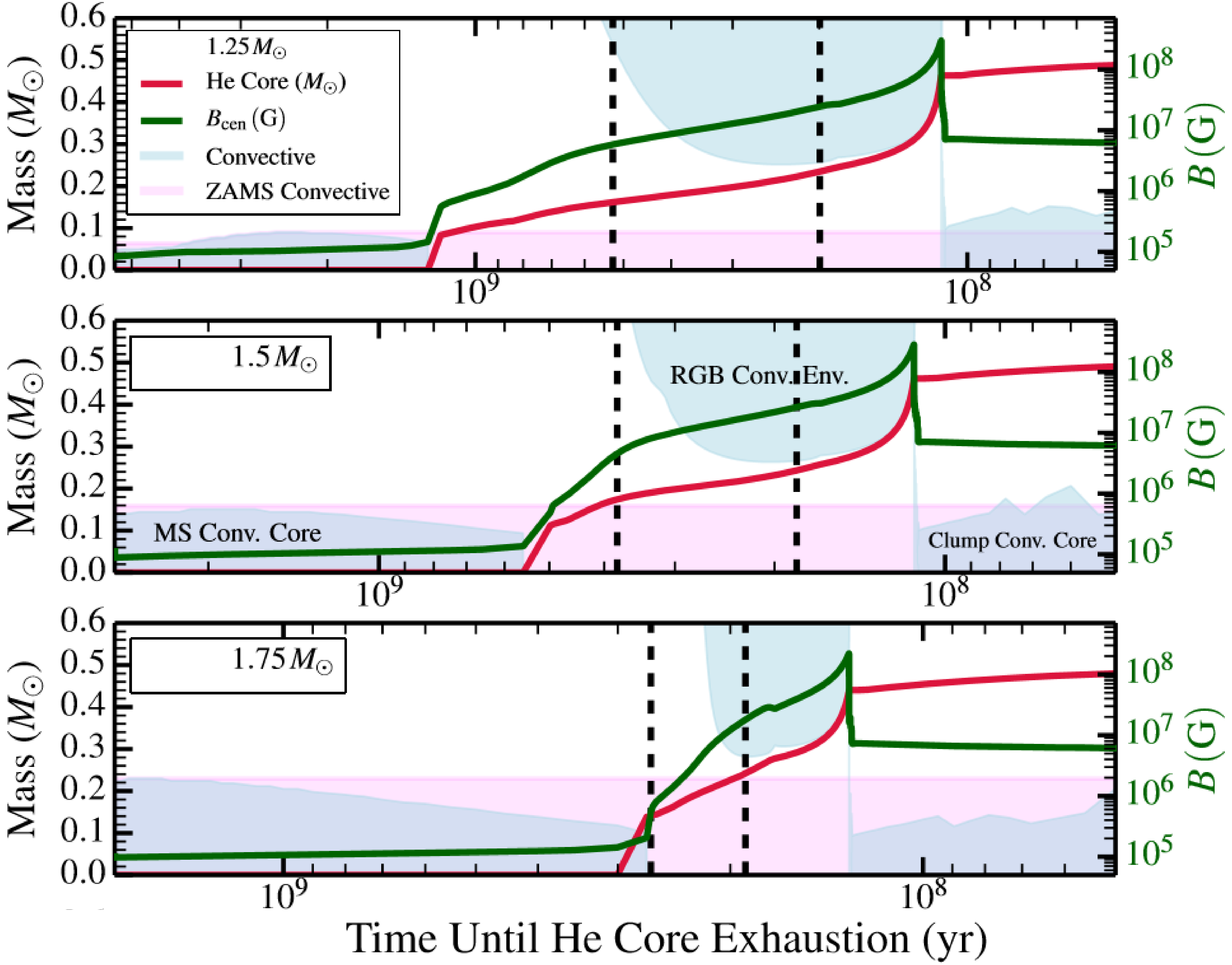
$$\Gamma_B = \frac{\eta B^2 k_r^4}{(4\pi)^2 \rho \omega^2}$$

$$\frac{\Gamma_B}{\Gamma_r} = \frac{\eta}{\kappa} \frac{B^2 k_r^2}{(4\pi)^2 \rho \omega^2} = \frac{\eta}{\kappa} \frac{l(l+1) B^2 N^2}{(4\pi)^2 \rho r^2 \omega^4}$$

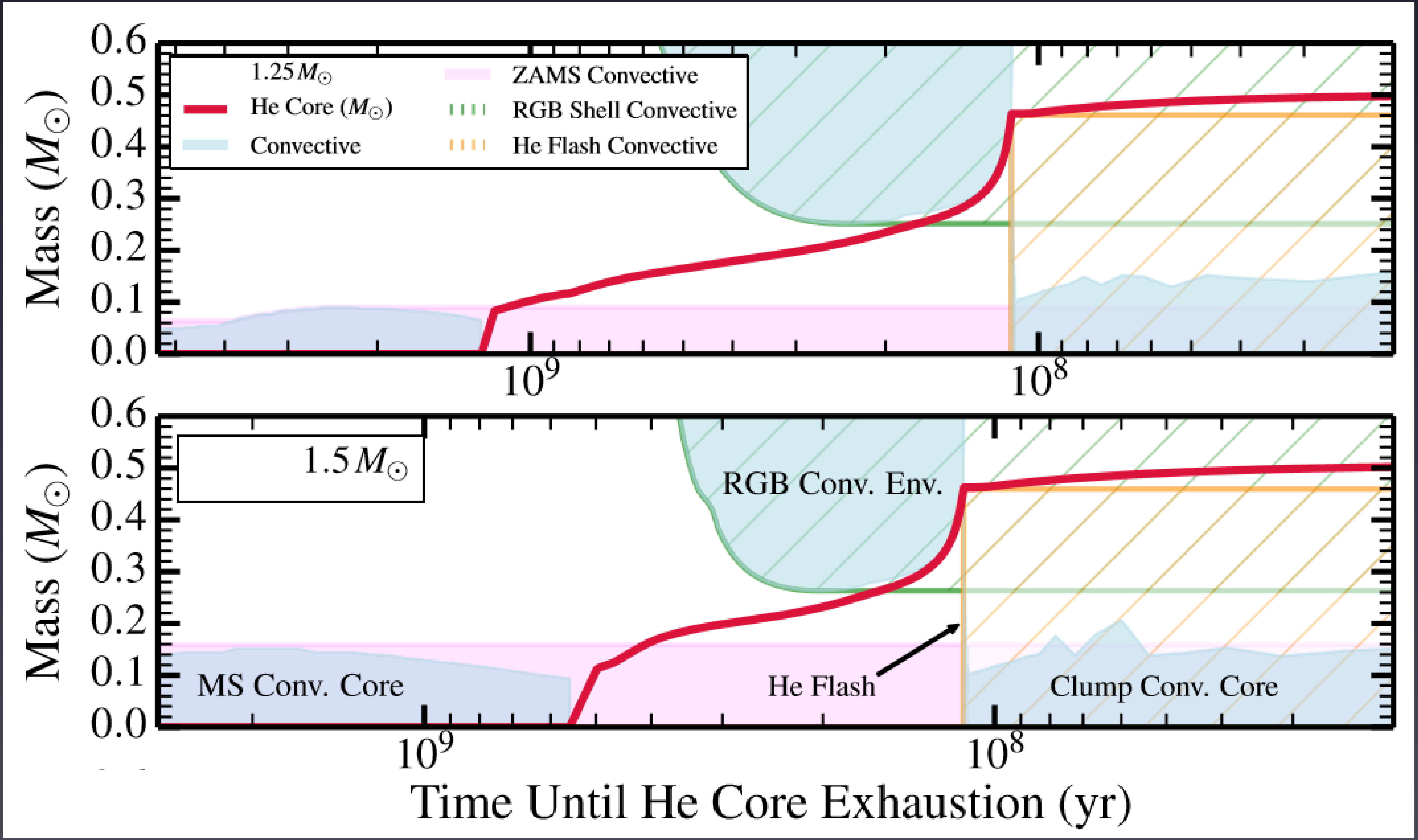
$$\frac{\Gamma_B}{\Gamma_r} = \frac{1}{16\pi} \frac{\eta}{\kappa}$$ <<1

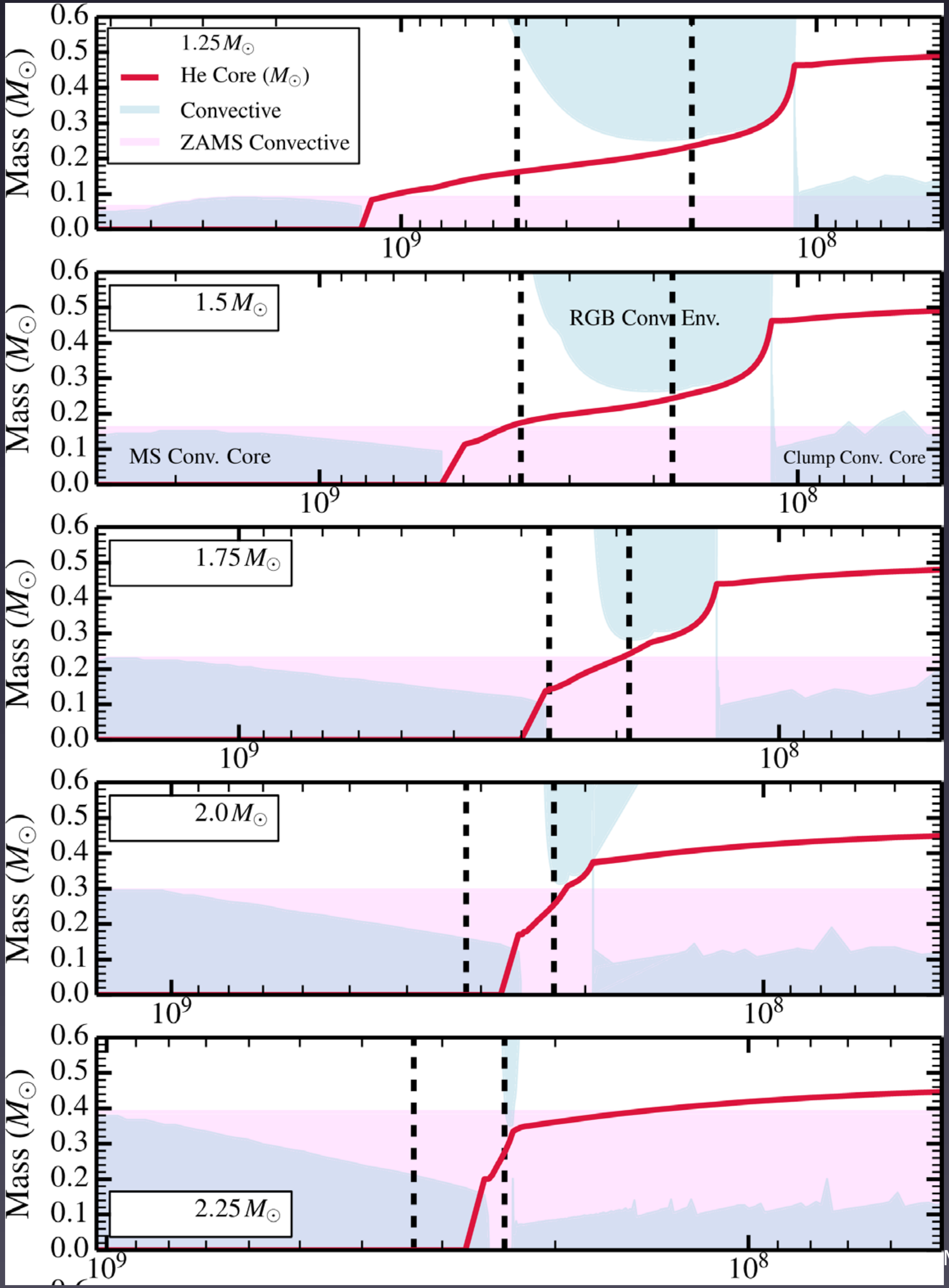

$B_{c,\mathrm{min}}$ (G)
10^5
10^4
20
40
60
80
100
ν_{max} (μHz)
$1.0\,M_\odot$
$1.25\,M_\odot$
$1.5\,M_\odot$
$1.75\,M_\odot$
$2.0\,M_\odot$
$2.25\,M_\odot$
$2.5\,M_\odot$
$3.0\,M_\odot$


$N/(2\pi)$
$\omega_{\rm MG}/(2\pi)$
$L_1/(2\pi)$
$\nu_{\rm max}$
Frequency (μHz)
10^4
10^3
10^2
10^1
Magneto-Gravity Waves
Acoustic Waves
Alfvén Waves
Evanescent Zone
B_c (G)
10^7
10^6
10^5
10^4
H-burning shell
$1.5\,M_\odot$
$B_{c,\rm min}$
He-burning core
B_c
B
0.0
0.2
0.4
0.6
0.8
1.0
1.2
$M\,(M_\odot)$

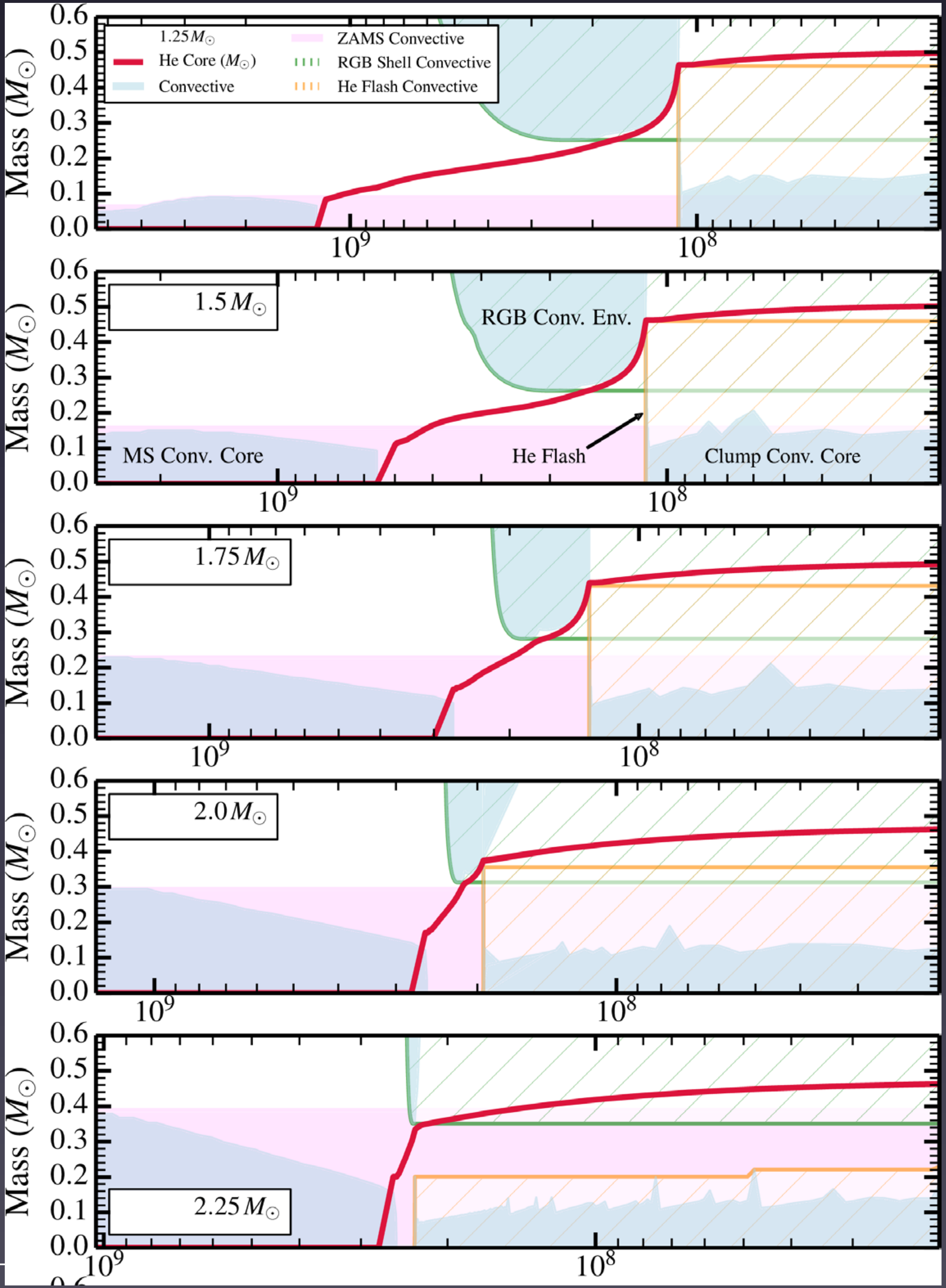


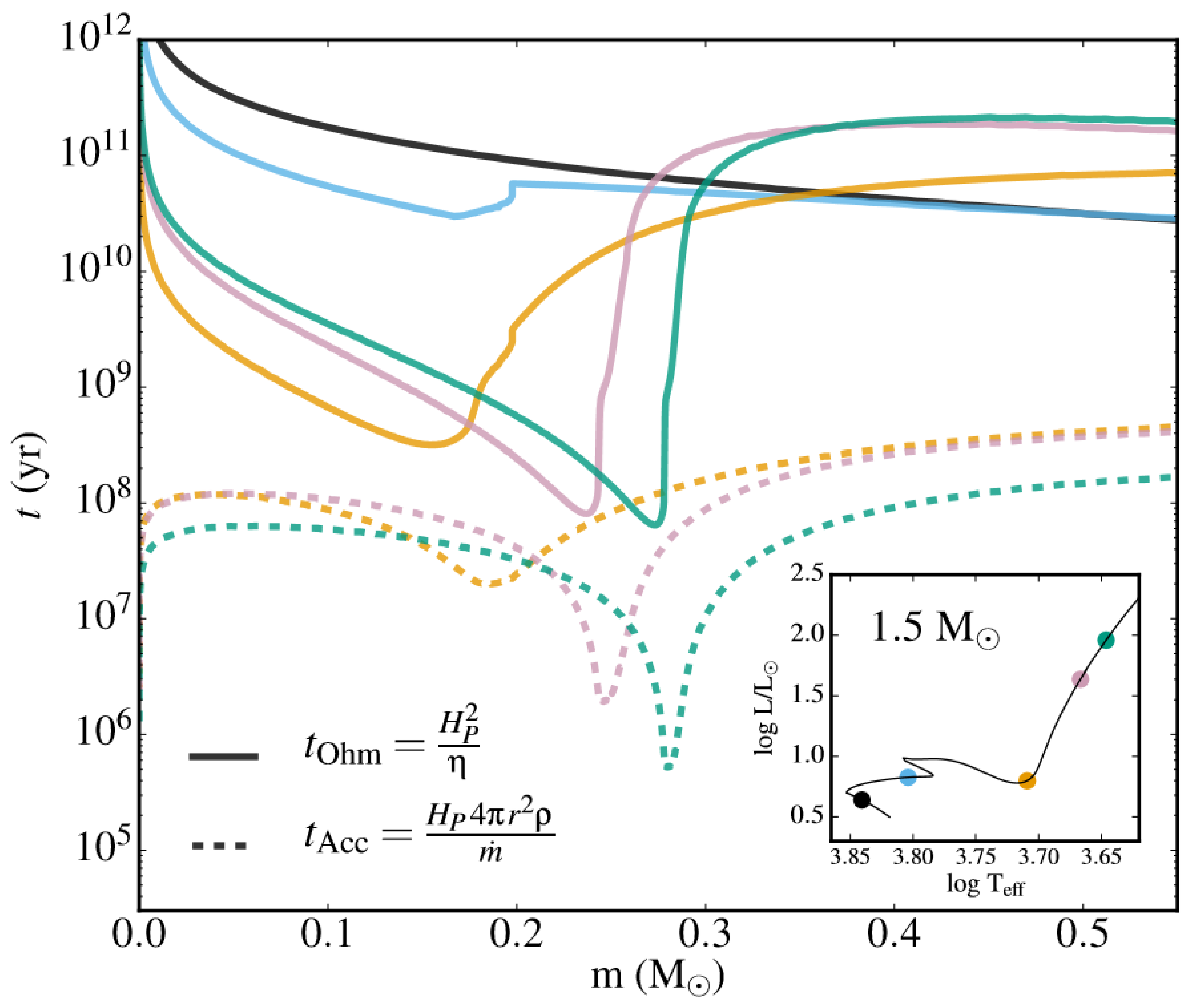
$1.25\,M_\odot$
He Core ($M_\odot$)
$B_{\rm cen}$ (G)
Convective
ZAMS Convective
$1.5\,M_\odot$
RGB Conv. Env.
MS Conv. Core
Clump Conv. Core
$1.75\,M_\odot$
Mass ($M_\odot$)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
B(G)
10^5
10^6
10^7
10^8
10^9
10^8
Time Until He Core Exhaustion (yr)


1.25 $M_\odot$
He Core ($M_\odot$)
Convective
ZAMS Convective
RGB Shell Convective
He Flash Convective
Mass ($M_\odot$)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
10^9
10^8
1.5 $M_\odot$
RGB Conv. Env.
MS Conv. Core
He Flash
Clump Conv. Core
Time Until He Core Exhaustion (yr)

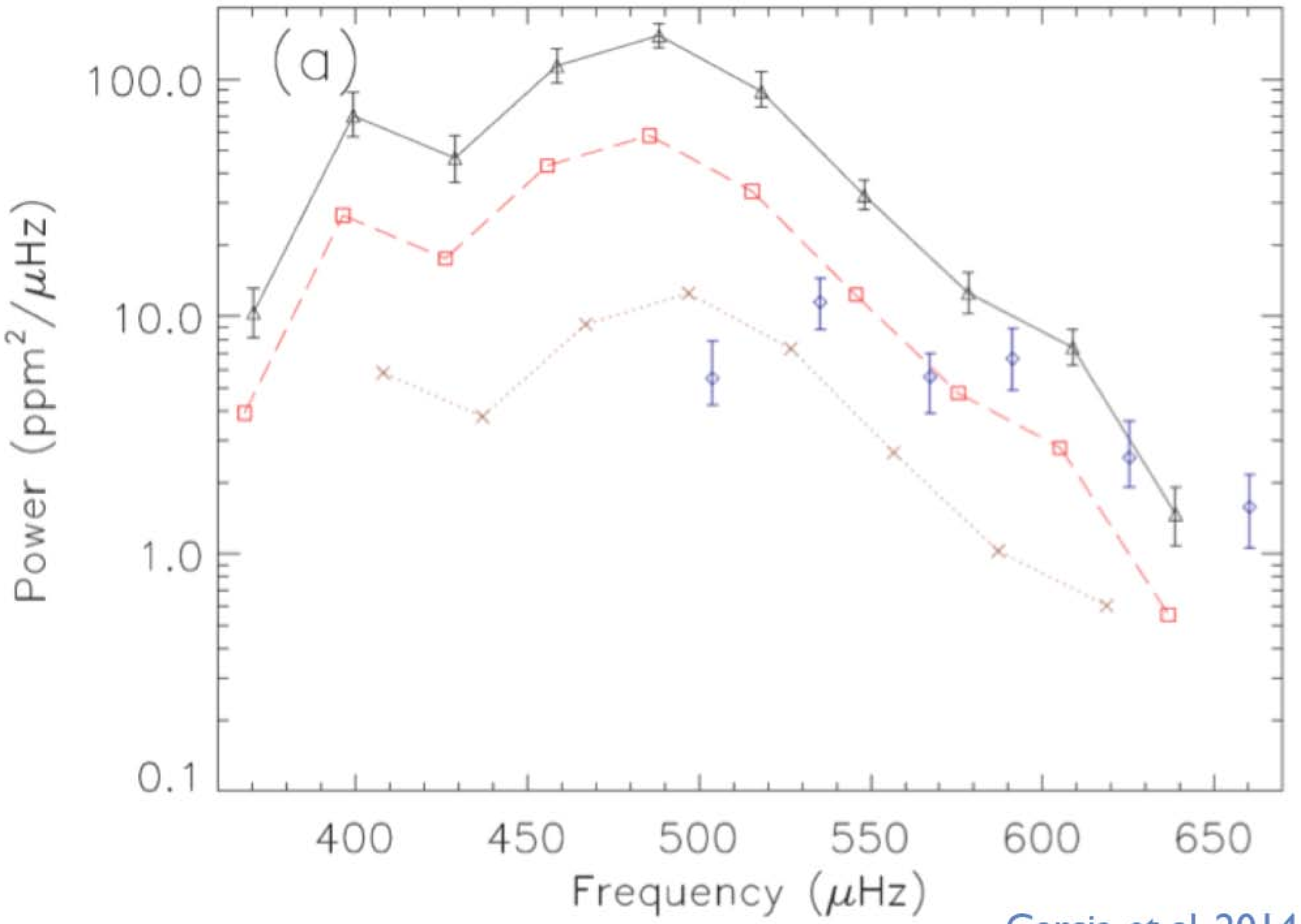

1.25$M_\odot$
He Core ($M_\odot$)
Convective
ZAMS Convective
1.5$M_\odot$
RGB Conv. Env.
MS Conv. Core
Clump Conv. Core
1.75$M_\odot$
2.0$M_\odot$
2.25$M_\odot$
Mass ($M_\odot$)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
10^9
10^8

M FULL

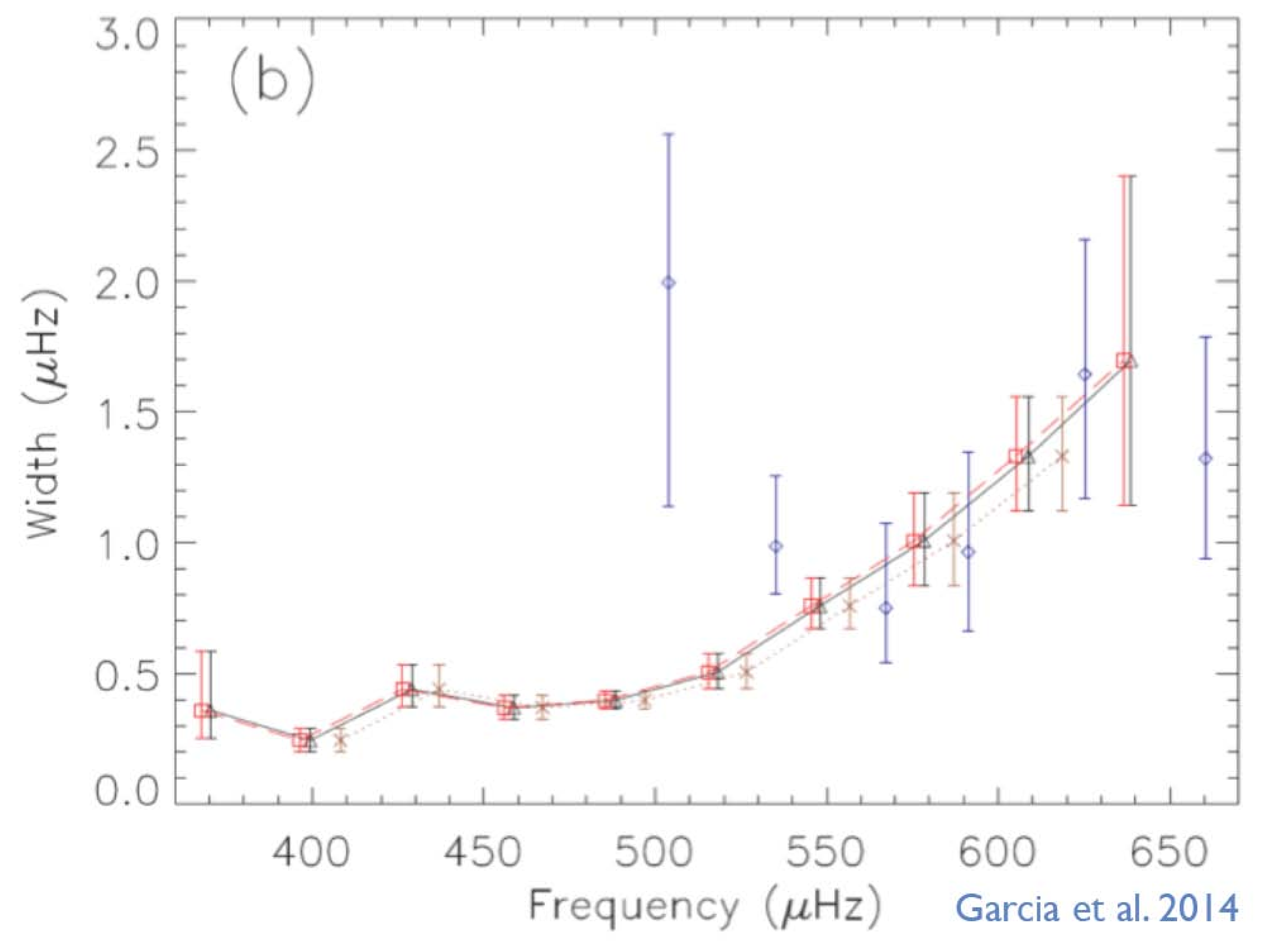

1.25$M_\odot$
He Core ($M_\odot$)
Convective
ZAMS Convective
RGB Shell Convective
He Flash Convective
1.5$M_\odot$
RGB Conv. Env.
MS Conv. Core
He Flash
Clump Conv. Core
1.75$M_\odot$
2.0$M_\odot$
2.25$M_\odot$
Mass ($M_\odot$)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
10^9
10^8



10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
t (yr)
0.0
0.1
0.2
0.3
0.4
0.5
m (M$_\odot$)
$t_{\rm Ohm} = \frac{H_P^2}{\eta}$
$t_{\rm Acc} = \frac{H_P 4\pi r^2 \rho}{\dot{m}}$
1.5 M$_\odot$
log L/L$_\odot$
log T$_{\rm eff}$
2.5
2.0
1.5
1.0
0.5
3.85
3.80
3.75
3.70
3.65



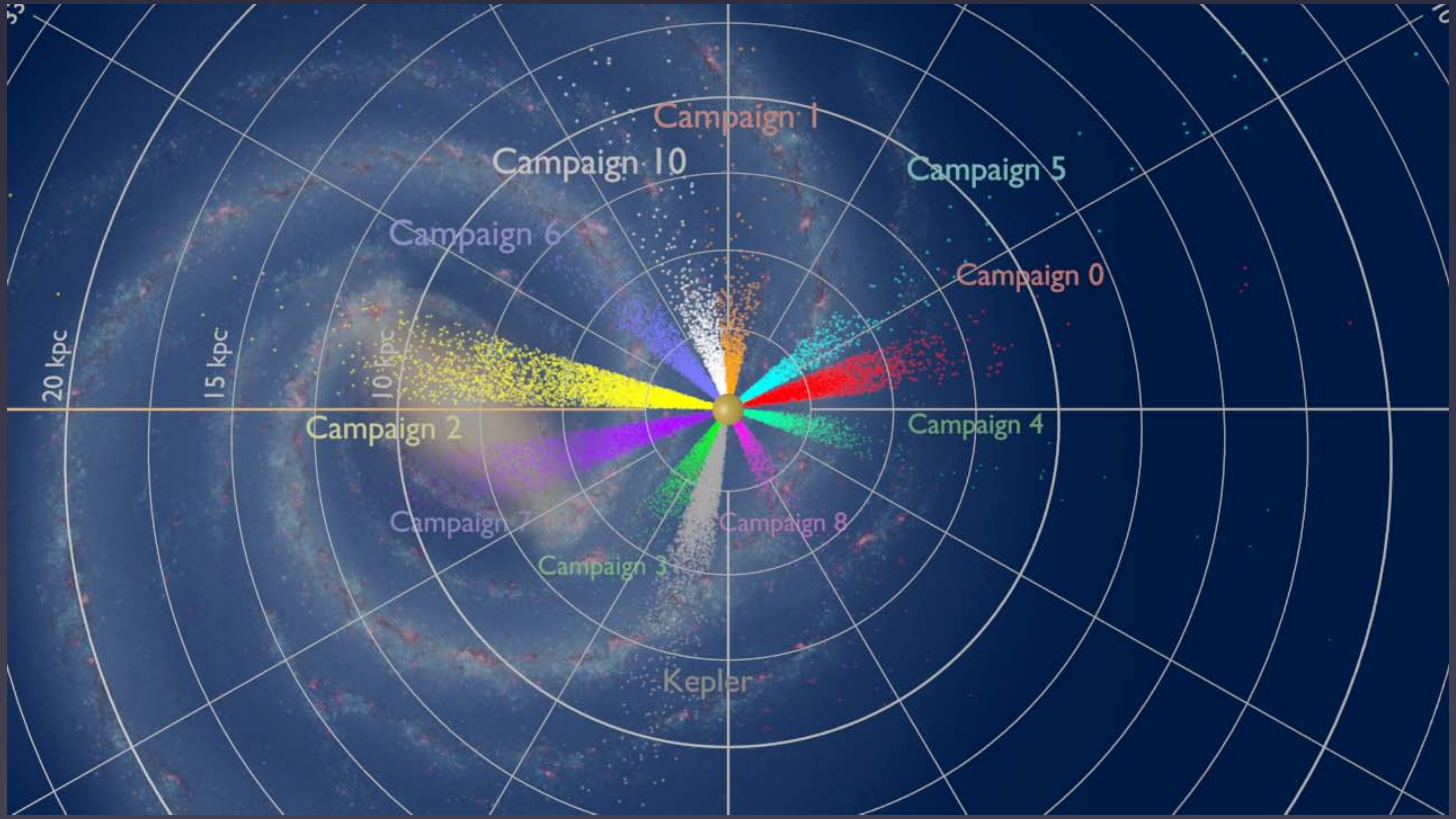
Garcia et al. 2014



Garcia et al. 2014

Additional Prospects

- Galactic archaeology
  - Combine measurements of mass and radius to infer distance and age



- Characterizing planets
- Fun with binaries
- K2, TESS, Plato → tens of thousands of stars