L2: Observations of Stars

T.M. Rogers

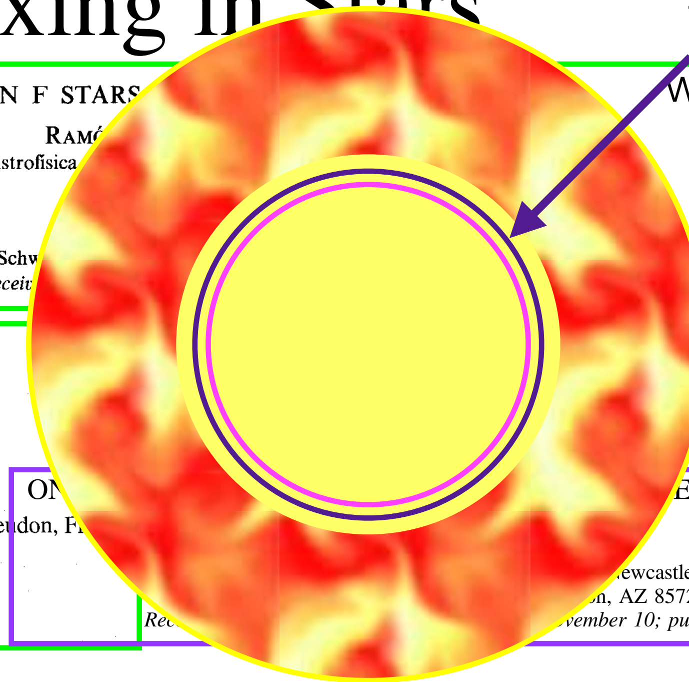
Waves, Instabilities and Turbulence in GAFD, 8-14 July 2019 Cargese

Solar Neutrinos

RADIATIVE AND OTHER EFFECTS FROM INTERNAL WAVES IN SOLAR AND STELLAR INTERIORS[1]

WILLIAM H. PRESS
Harvard–Smithsonian Center for Astrophysics; and Department of Physics, Harvard University
Received 1980 March 31; accepted 1980 October 16

Mixing in Stars



Li DEPLETION IN F STARS

Instituto de Astrofísica
Max-Planck-Institut für Astrophysik, Karl-Schw

Mixing by internal waves

I. Lithium depletion in the Sun

J. Montalbán
DASGAL, Observatoire de Paris-Meudon, F-92195 Meudon, F
MESIOA::MONTALBAN (SPAN)
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The Dynamical Tide in Close Binaries

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otation

E MAIN-SEQUENCE STARS

ewcastle University, UK
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vember 10; published 2015 December 18

- Until very recently all observational constraints about mixing/angular momentum transport in stars came from measuring surface abundances/rotation
- Surface abundances of Lithium for F/G stars (solar type) are lower than expected (big bang values)
- Measurements used to measure/place constraints on mixing beyond nominal convective-radiative boundary

Macroturbulence

OBSERVATIONAL SIGNATURES OF CONVECTIVELY DRIVEN WAVES IN MASSIVE STARS

C. AERTS[1,2] AND T. M. ROGERS[3,4]
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[2] Department of Astrophysics/IMAPP, Radboud University Nijmegen, 6500 GL Nijmegen, The Netherlands
[3] Department of Mathematics and Statistics, Newcastle University, Newcastle upon Tyne, UK
[4] Planetary Science Institute, Tucson, AZ 85721, USA
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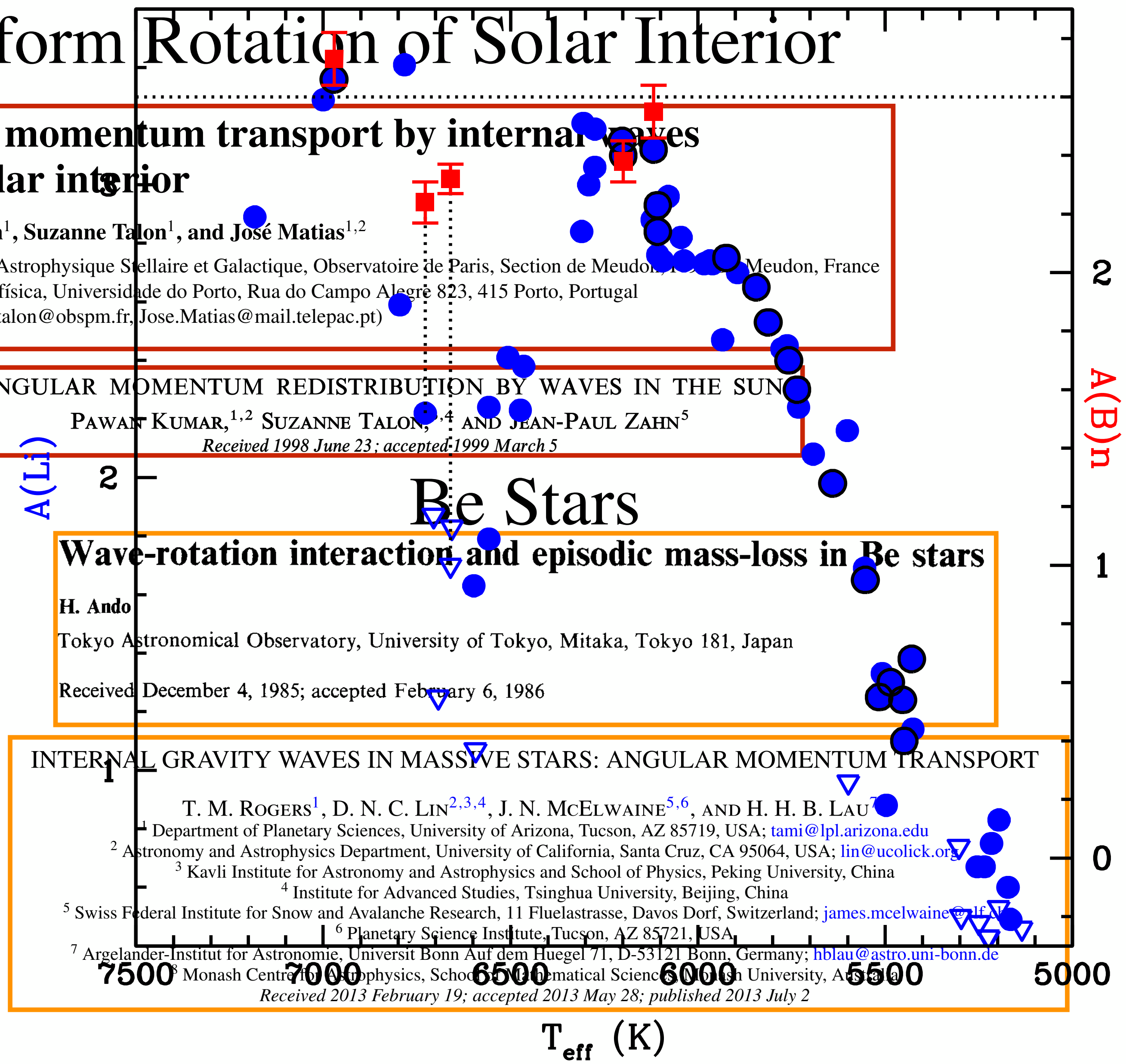
Uniform Rotation of Solar Interior



Angular momentum transport by internal waves in the solar interior

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[1] Département d'Astrophysique Stellaire et Galactique, Observatoire de Paris, Section de Meudon, Meudon, France
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ANGULAR MOMENTUM REDISTRIBUTION BY WAVES IN THE SUN

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Received 1998 June 23; accepted 1999 March 5

Be Stars

Wave-rotation interaction and episodic mass-loss in Be stars

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INTERNAL GRAVITY WAVES IN MASSIVE STARS: ANGULAR MOMENTUM TRANSPORT

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[7] Argelander-Institut for Astronomie, Universit Bonn Auf dem Huegel 71, D-53121 Bonn, Germany; hblau@astro.uni-bonn.de
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Received 2013 February 19; accepted 2013 May 28; published 2013 July 2

Obliquities of Hot Jupiters

INTERNAL GRAVITY WAVES MODULATE THE APPARENT MISALIGNMENT OF EXOPLANETS AROUND HOT STARS

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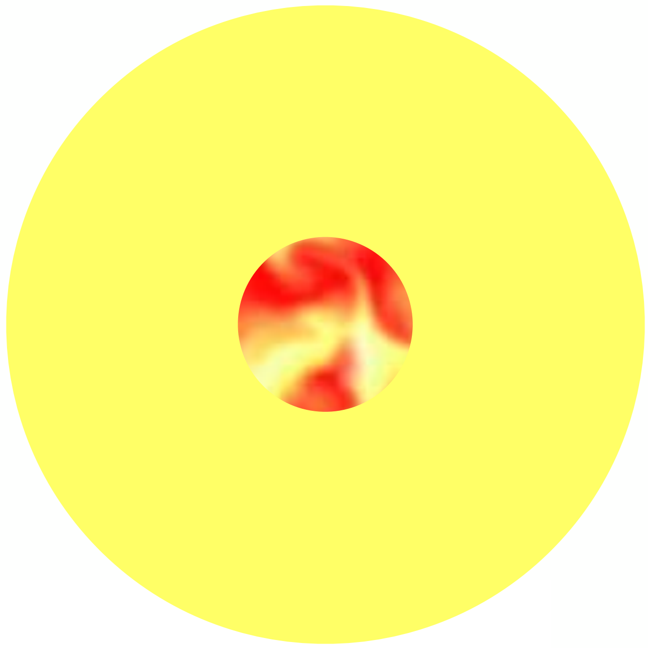
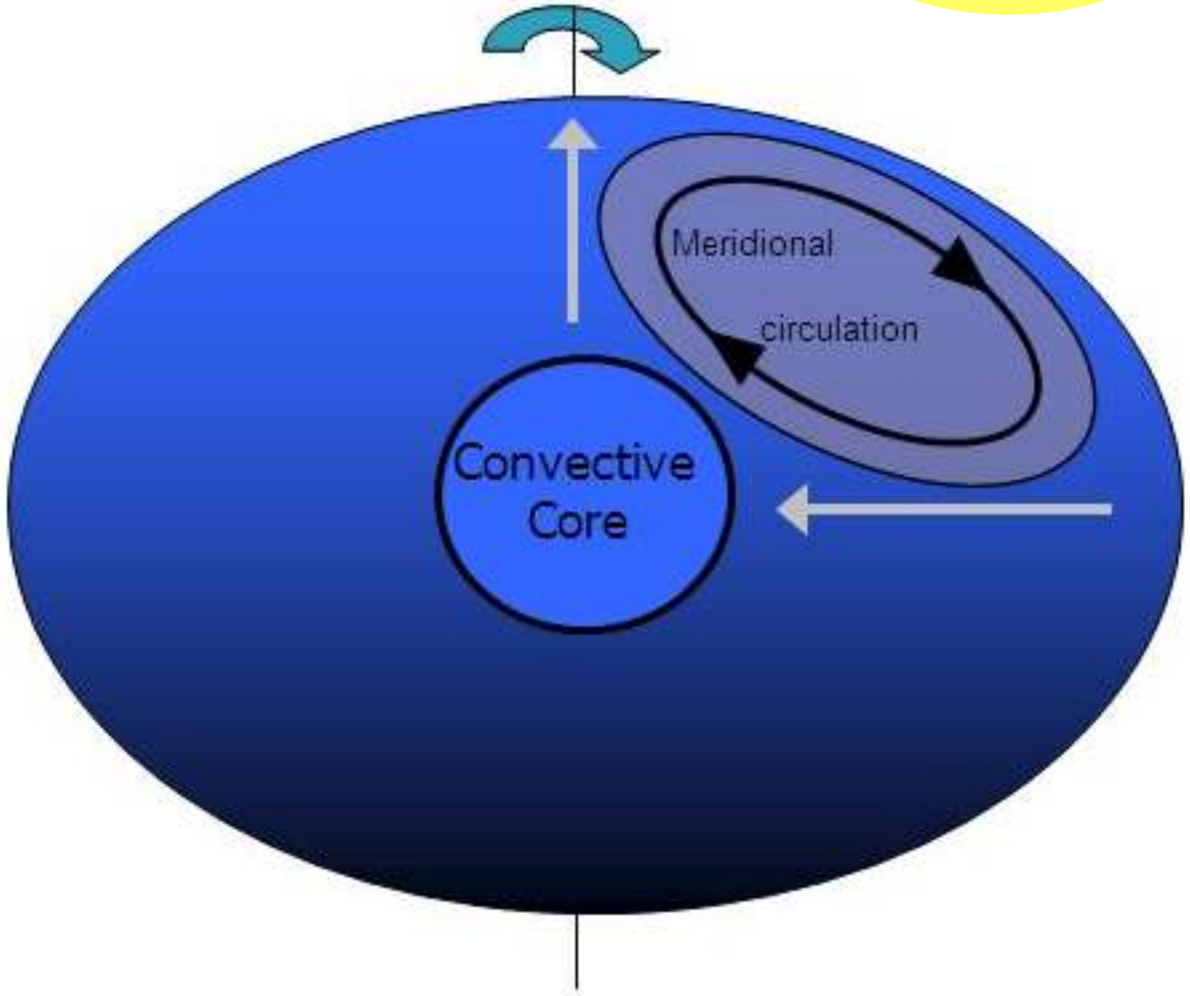
Eddington-Sweet circulation

- Rotation causes temperature differential between pole and equator - causes meridional circulation
- Timescale inversely proportional to rotation - > fast rotation -> shorter timescales -> more efficient mixing

$\tau_{ES\odot} \approx 10^{12}$ Not Important

$\tau_{ESB} \approx 10^{8}$ Probably Important



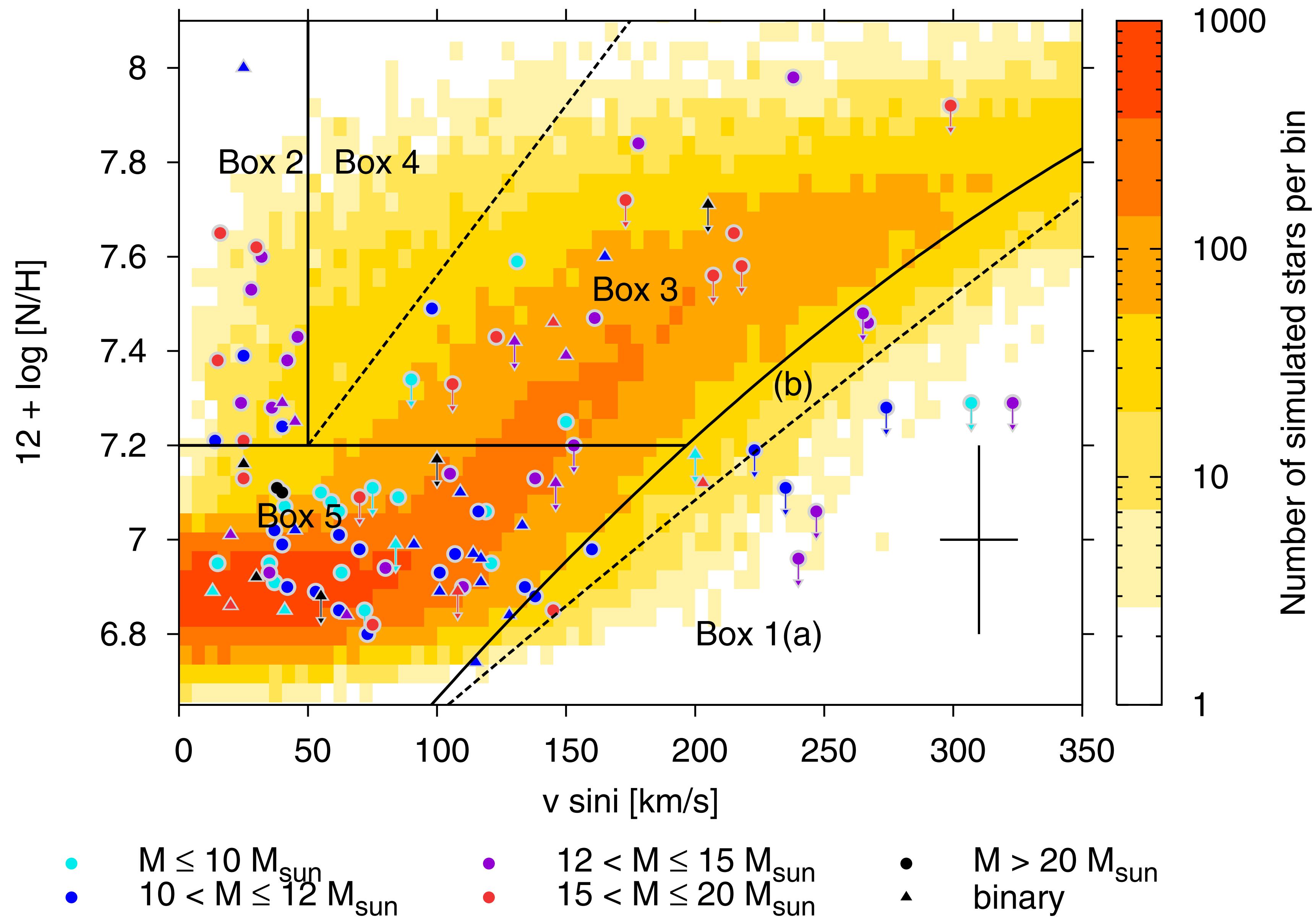


$$\tau_{ES} = \frac{G^2 M^3}{\Omega^2 R^4 L}$$

Chemical Mixing: Nitrogen Abundances

Brott et al. 2011

- Nitrogen is produced in the core of massive stars via burning: a surface enhancement of Ni would imply mixing through the (large) radiative envelope
- Mixing in massive stars (mostly radiative) is generally thought to be dominated by rotational mixing (Eddington-Sweet circulation)
- If this is the case one would expect strong Nitrogen enhancement at the surface of rapid rotators and no enhancement at surface of slow rotators
- This is generally seen but there are a lot of outliers : fast rotators with no enhancement + slow rotators which are enhanced



Solar Neutrinos

Helioseismology-

Then along came this!

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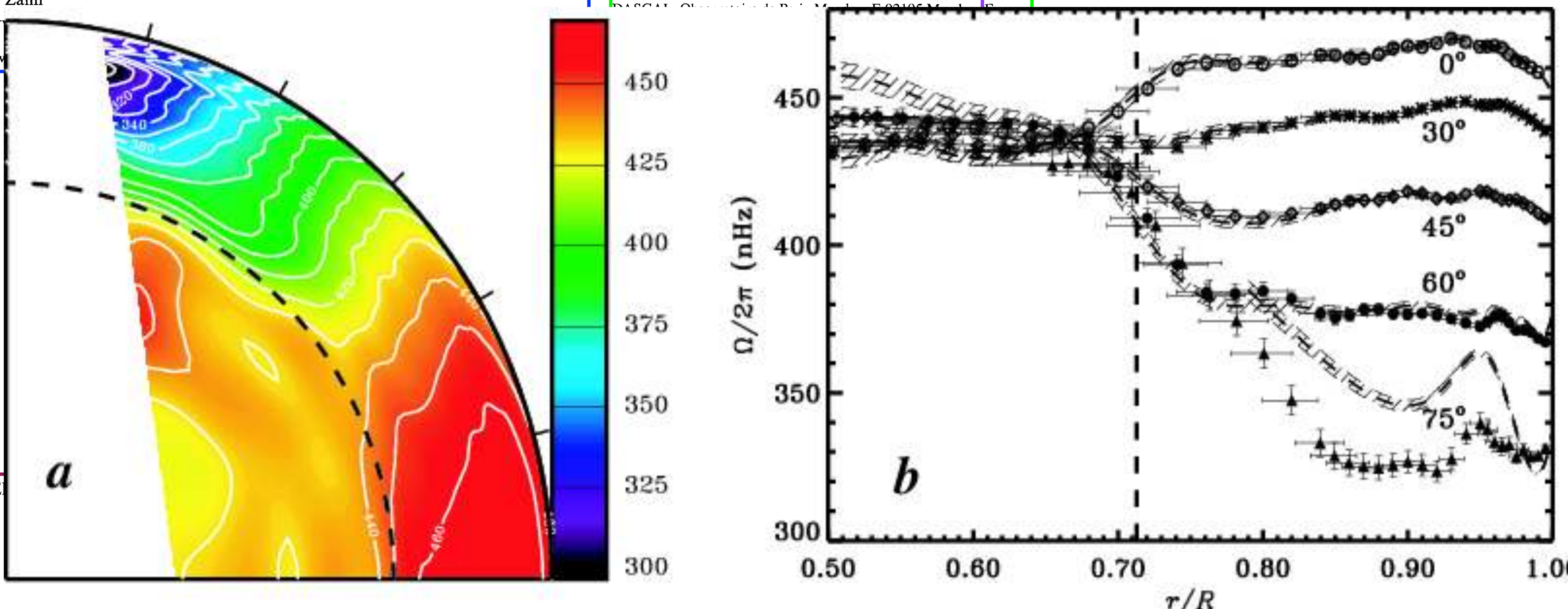

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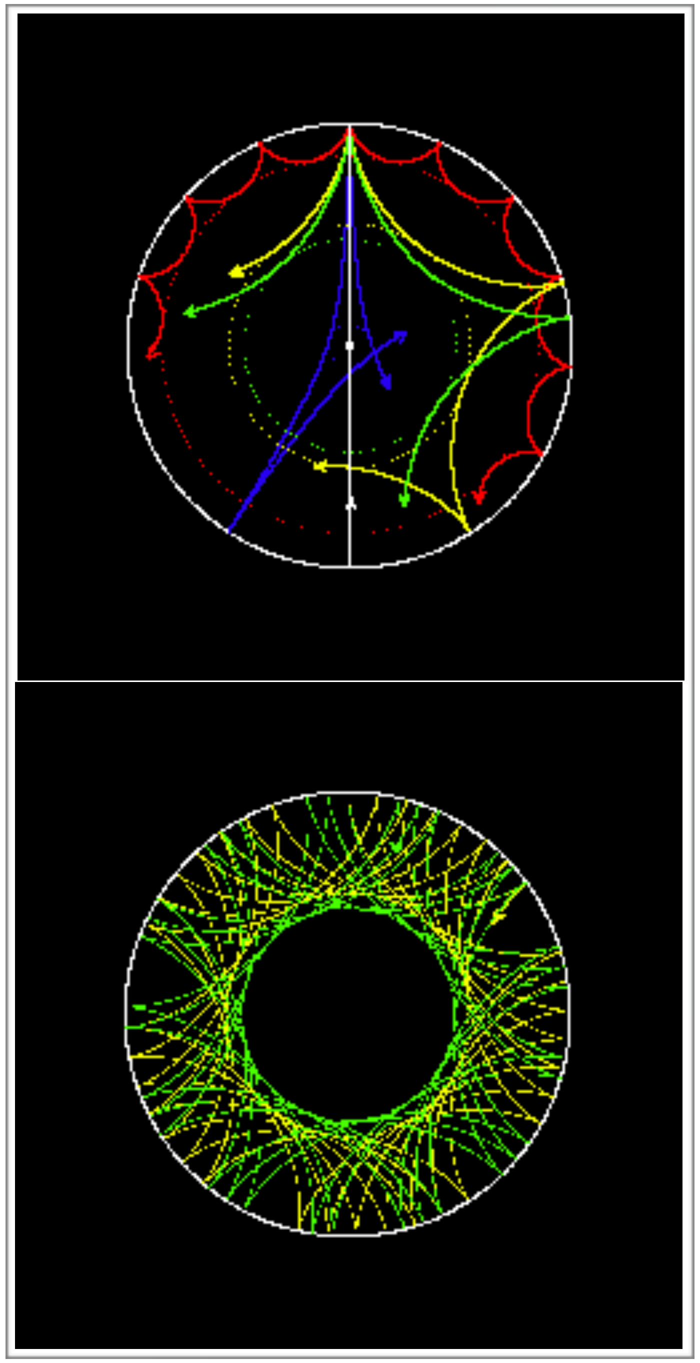
- Radiative interior rotating uniformly
- Convective envelope rotating differentially
- Very thin layer between (tachocline)

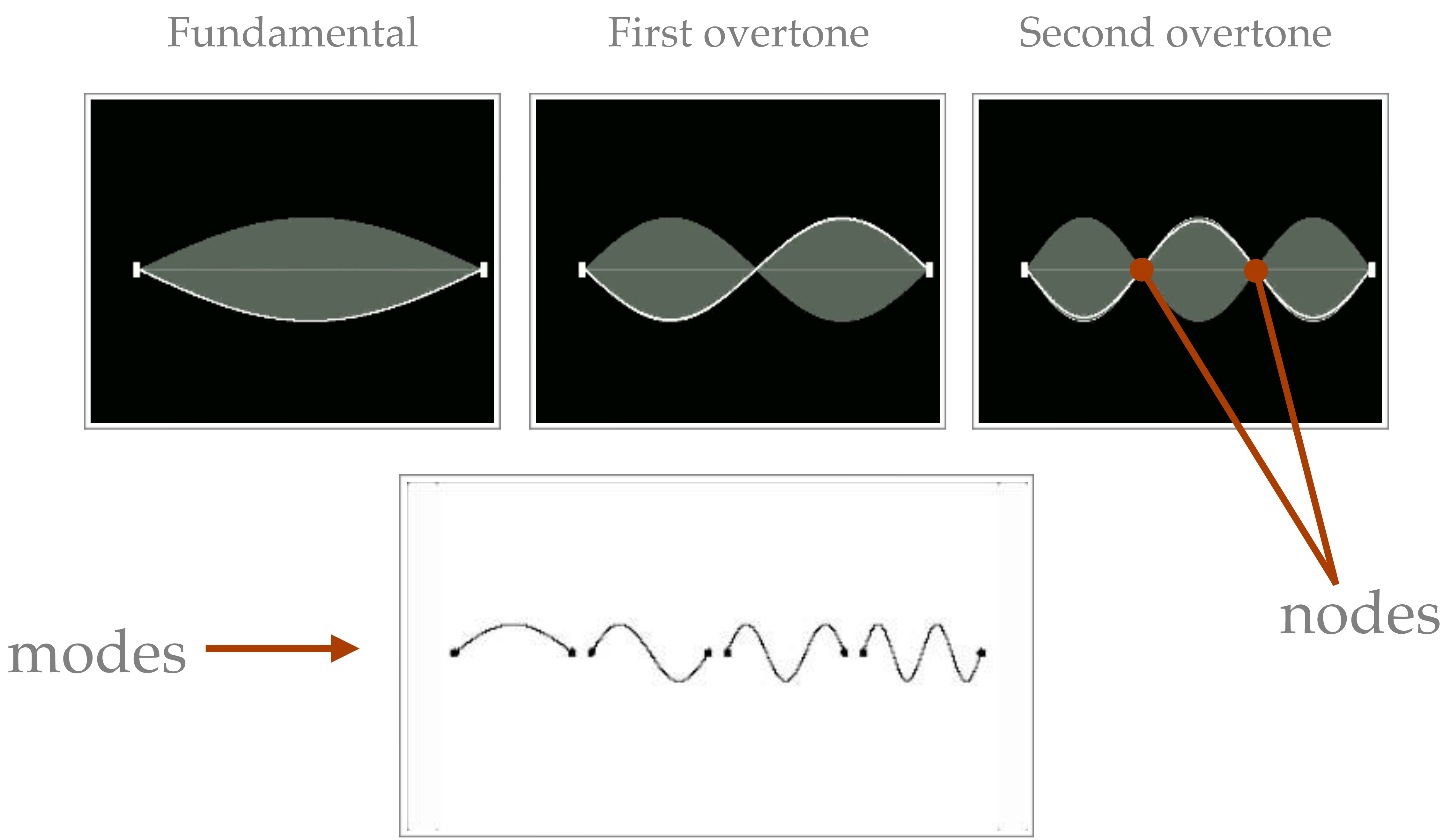
Asteroseismology

aster ⟶ star
seismos ⟶ oscillation
logos ⟶ discourse

The analysis of stellar oscillations enables the study of the stellar interior because different modes penetrate to different depths inside the star



Asteroseismology 101

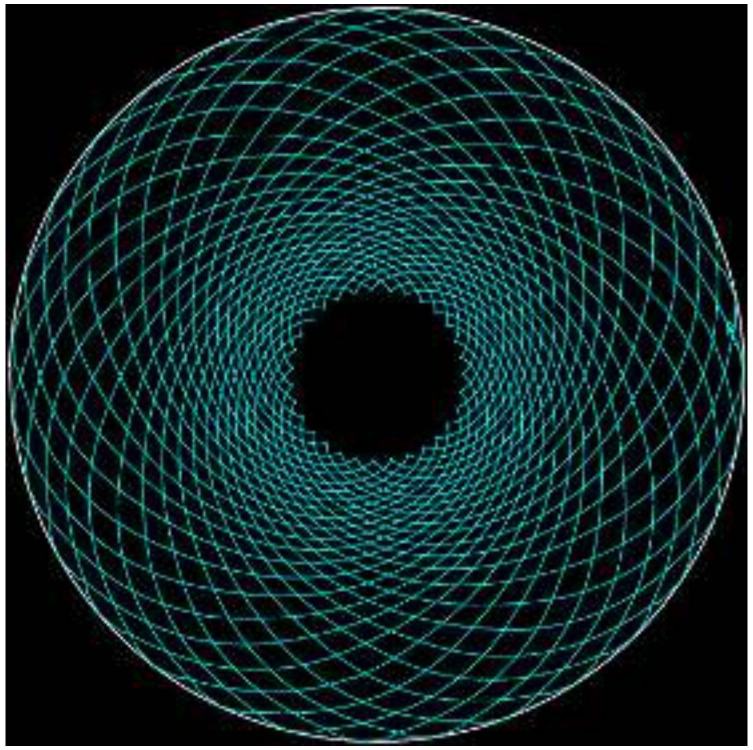


Asteroseismology

- **Oscillations = solutions of perturbed SSE in terms of periodic eigenfunctions**
- **Each oscillation mode described as spherical harmonic & frequency:**

$$\sqrt{4\pi}\Re\left\{\left[\tilde{\xi}_r(r)Y_l^m(\theta,\phi)\boldsymbol{a}_r + \tilde{\xi}_\mathrm{h}(r)\left(\frac{\partial Y_l^m}{\partial\theta}\boldsymbol{a}_\theta + \frac{1}{\sin\theta}\frac{\partial Y_l^m}{\partial\phi}\boldsymbol{a}_\phi\right)\right]\exp(-\mathrm{i}\omega t)\right\}$$

- **Dominance of restoring force?**
  1. **pressure (acoustic waves)**
  2. **buoyancy (gravity waves)**
  3. **Coriolis (inertial waves)**
  4. **Lorentz (Alfvén waves)**
  5. **tidal (tidal waves)**



Gravity waves propagating in radiative zone of a massive star, from surface to core

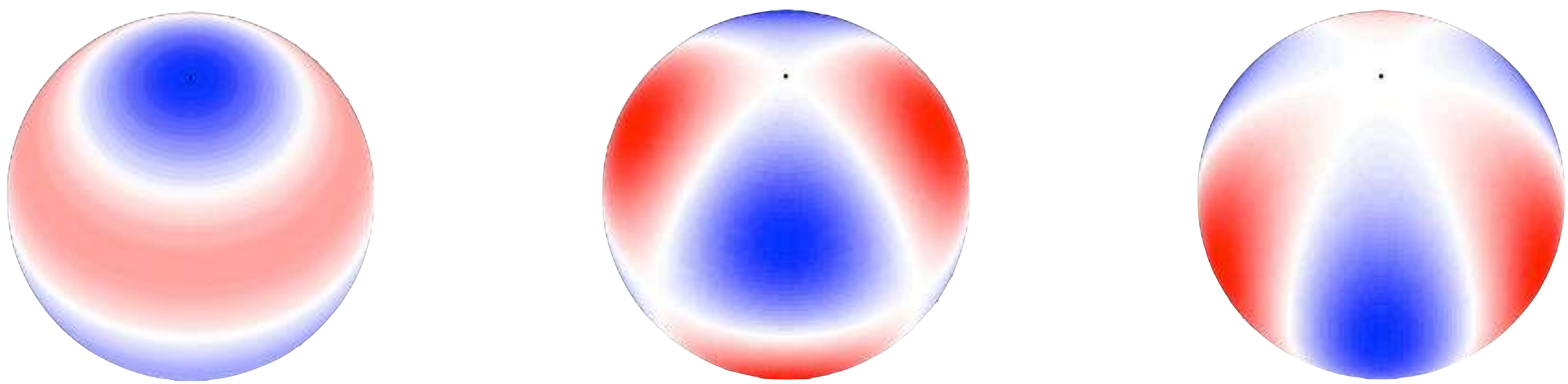
Asteroseismology 301

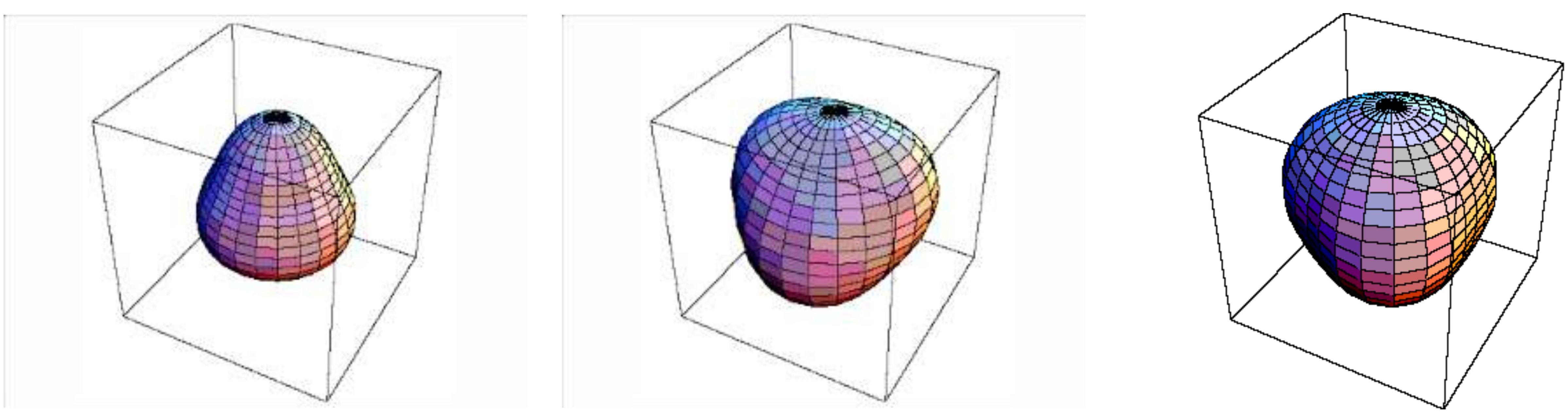
(l,m)=(3,0) axisymmetric

(l,m) = (3,2) tesseral

(l,m)=(3,3) sectoral

Blue: Moving towards Observer   Red: Moving away from Observer





Asteroseismology

time ⟶ frequency (period of mode)

geometry ⟶ spherical harmonic+radial order

$$\xi(r,\theta,\phi,t) = [(\xi_{r,nl} e_r + \xi_{\mathrm{h},nl} \nabla_{\mathrm{h}}) Y_l^m(\theta,\phi)] \exp(-\mathrm{i}\omega t)$$

Inferences of properties of stellar interiors via modes

a) requires frequencies & identification of (l,m) of as many modes as possible from data (+ n from models)

b) can only probe regions where modes propagate

Wave Equation

$$\frac{d^2\xi_r}{dr^2} = \frac{\omega^2}{c^2}\left(1 - \frac{N^2}{\omega^2}\right)\left(\frac{S_l^2}{\omega^2} - 1\right)\xi_r$$

$S_l =$ Lamb Frequency

$N =$ Brunt Vaisala Frequency

$c =$ Sound Speed

$\omega =$ Wave Frequency

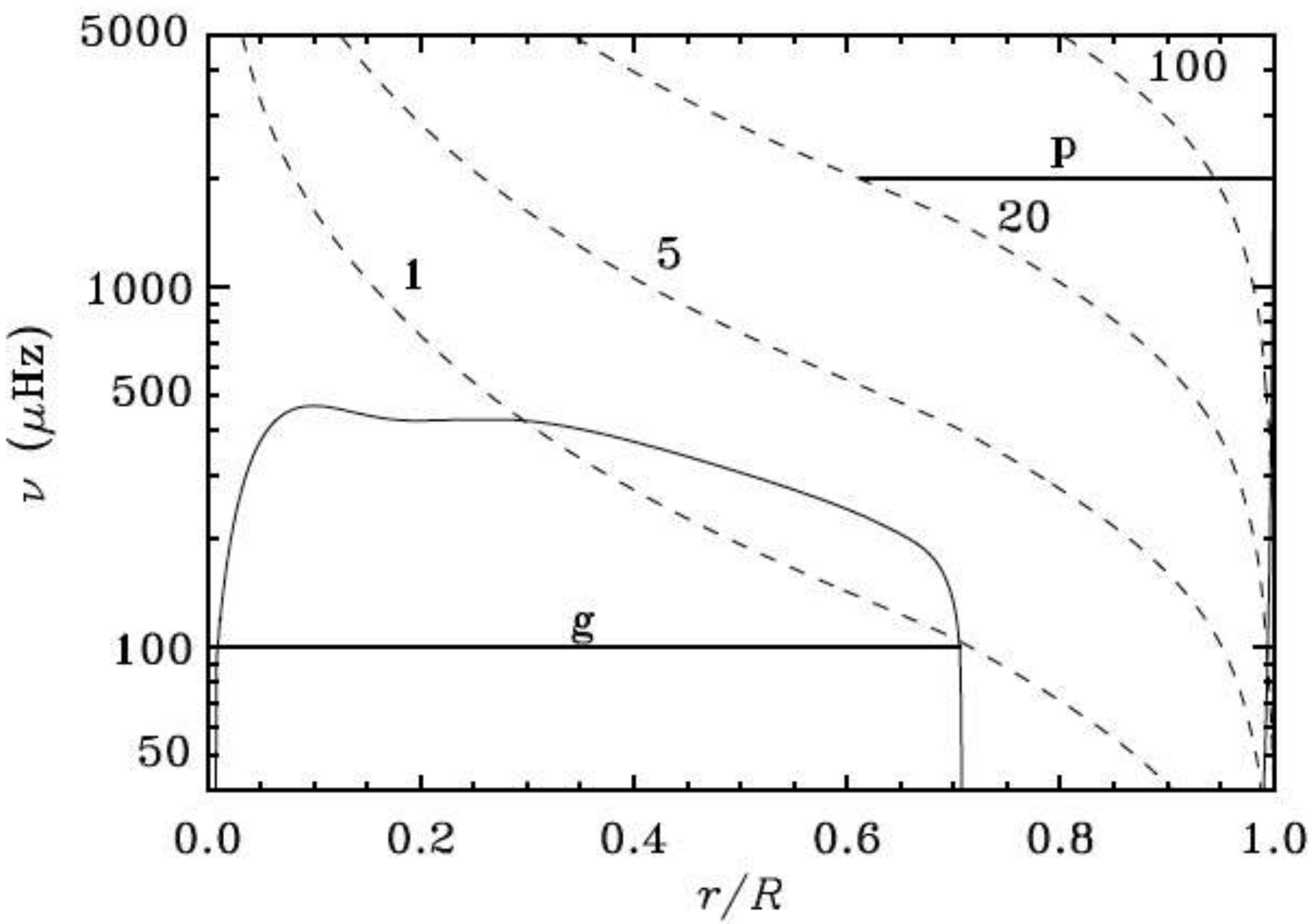
$|\omega| > |N|$ and $|\omega| > |S_l|$ **p-modes**

or

$|\omega| < |N|$ and $|\omega| < |S_l|$ **g-modes**

Otherwise waves are evanescent

Propagation Cavity in the Sun

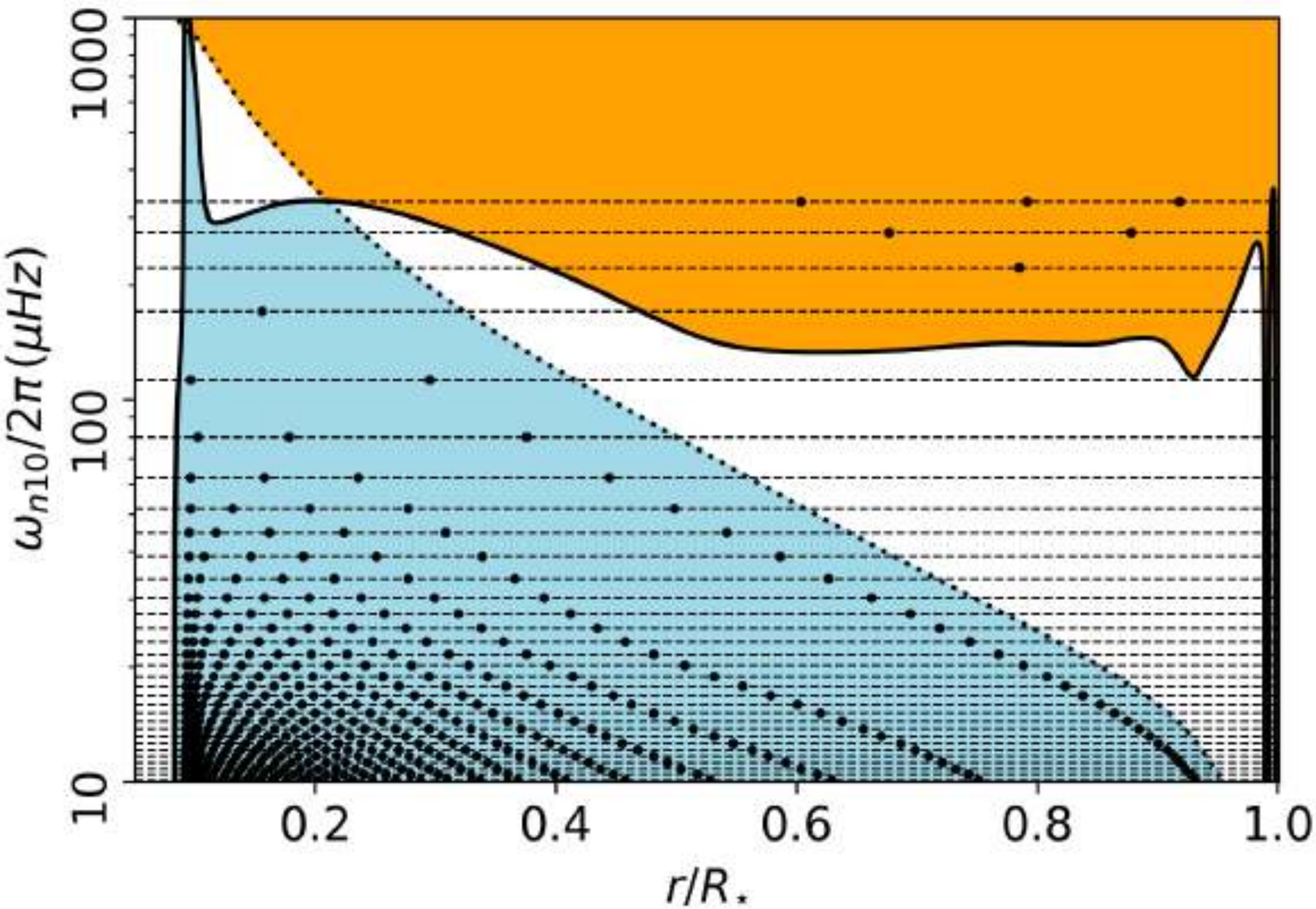


$$S_l^2 = \frac{l(l+1)c^2}{r^2}$$

$$N^2 \simeq \frac{g^2 \rho}{p}(\nabla_{\rm ad} - \nabla + \nabla_\mu)$$

All helioseismology is done with p-modes

Probing power in F stars (H burning in core)



p modes

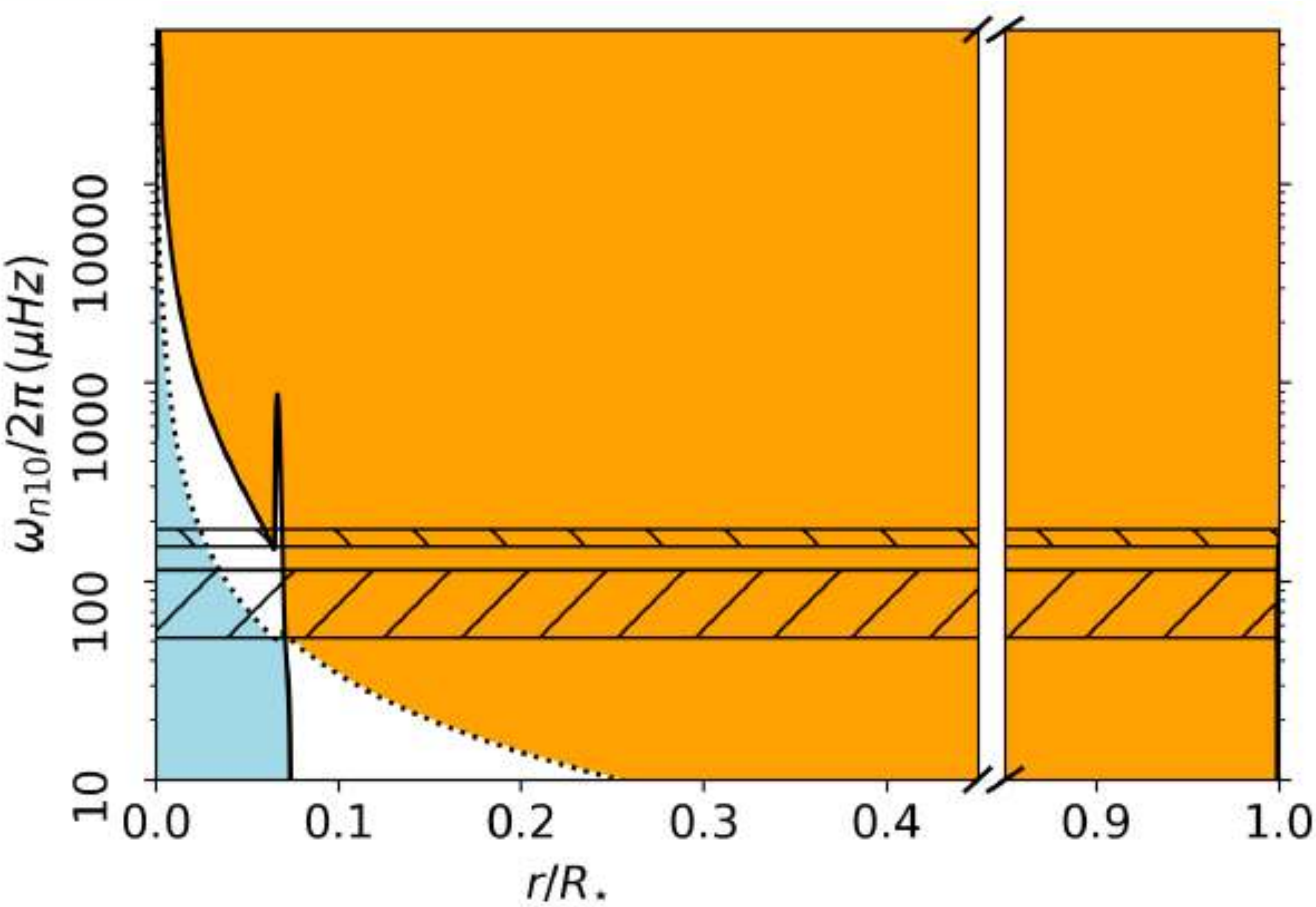
g modes

p- and g-modes probe different regions throughout evolution

Figure courtesy of Joey Mombarg used in Aerts et al. (2019) ARAA, in press

Probing power on Red Giant Branch (H exhausted in core, burning in shell)

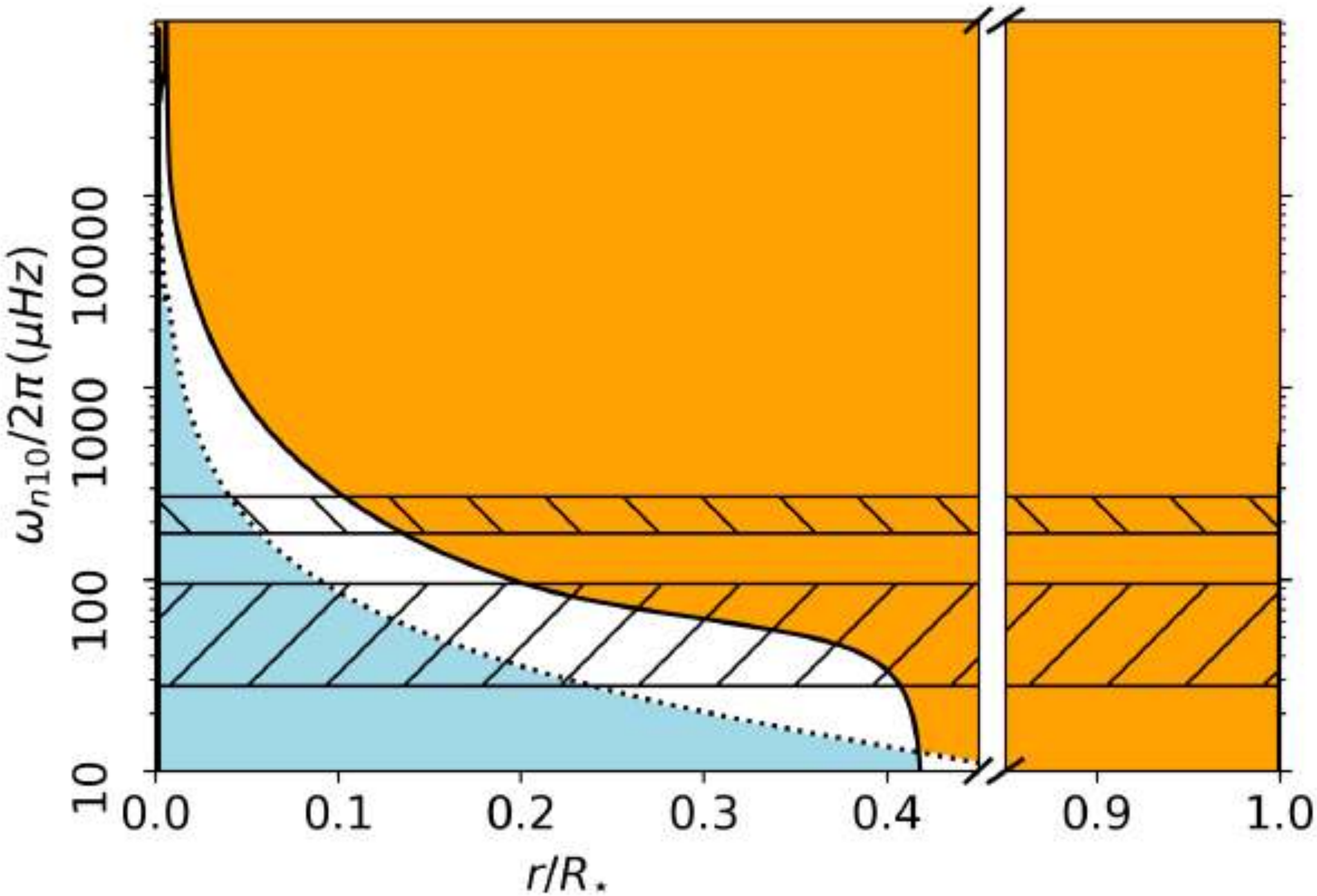
Main Sequence (H burning in core)



p- and g-modes probe different regions throughout evolution

Figure courtesy of Cole Johnston used in Aerts et al. (2019) ARAA, in press

Probing power on Red Clump (He burning in core)



p- and g-modes probe different regions throughout evolution

Figure courtesy of Cole Johnston used in Aerts et al. (2019) ARAA, in press

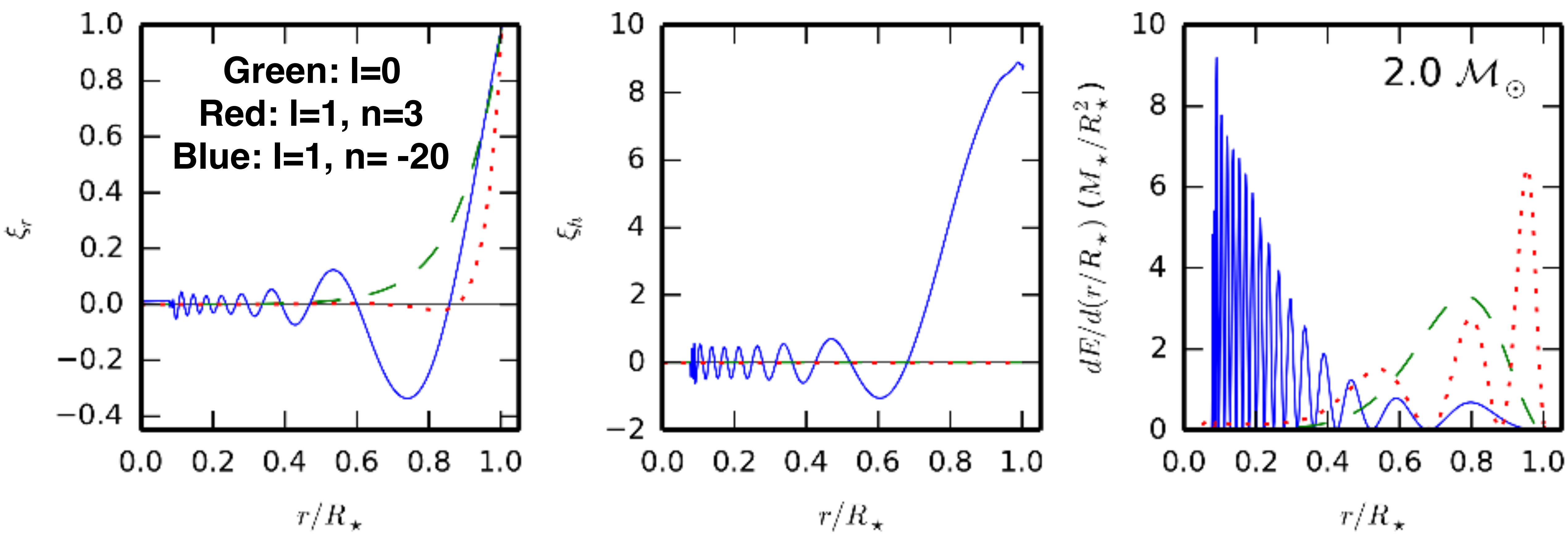
Probing power of p- and g-modes

p-modes: dominantly radial ξ

g-modes: dominantly tangential ξ

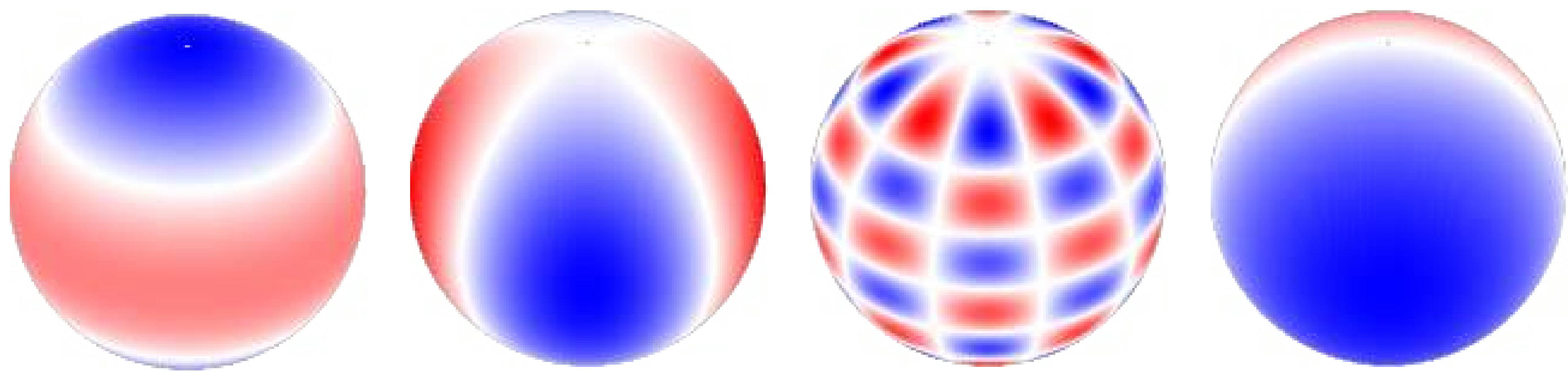
p-modes: probe envelope physics

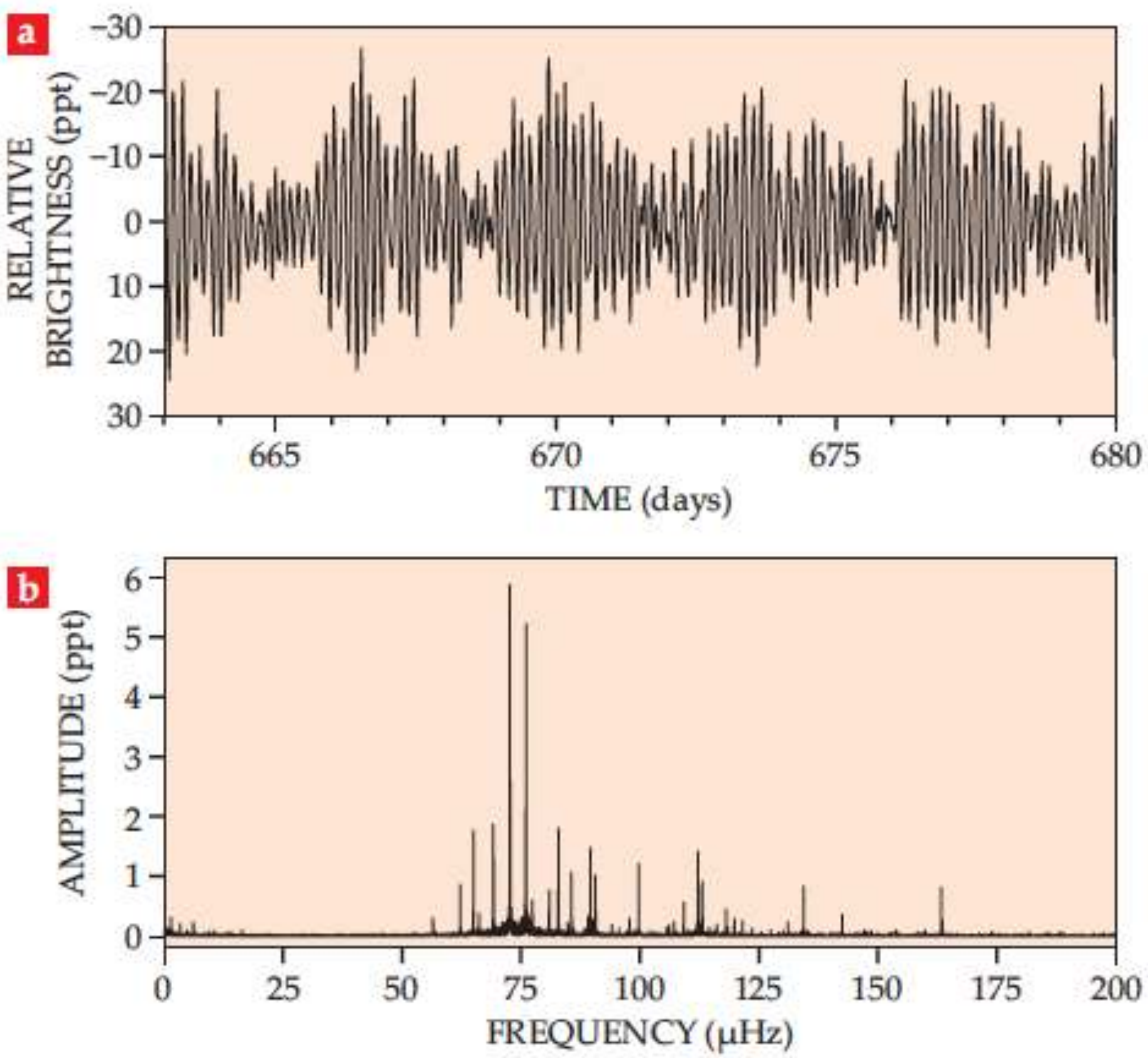
g-modes: probe near-core region

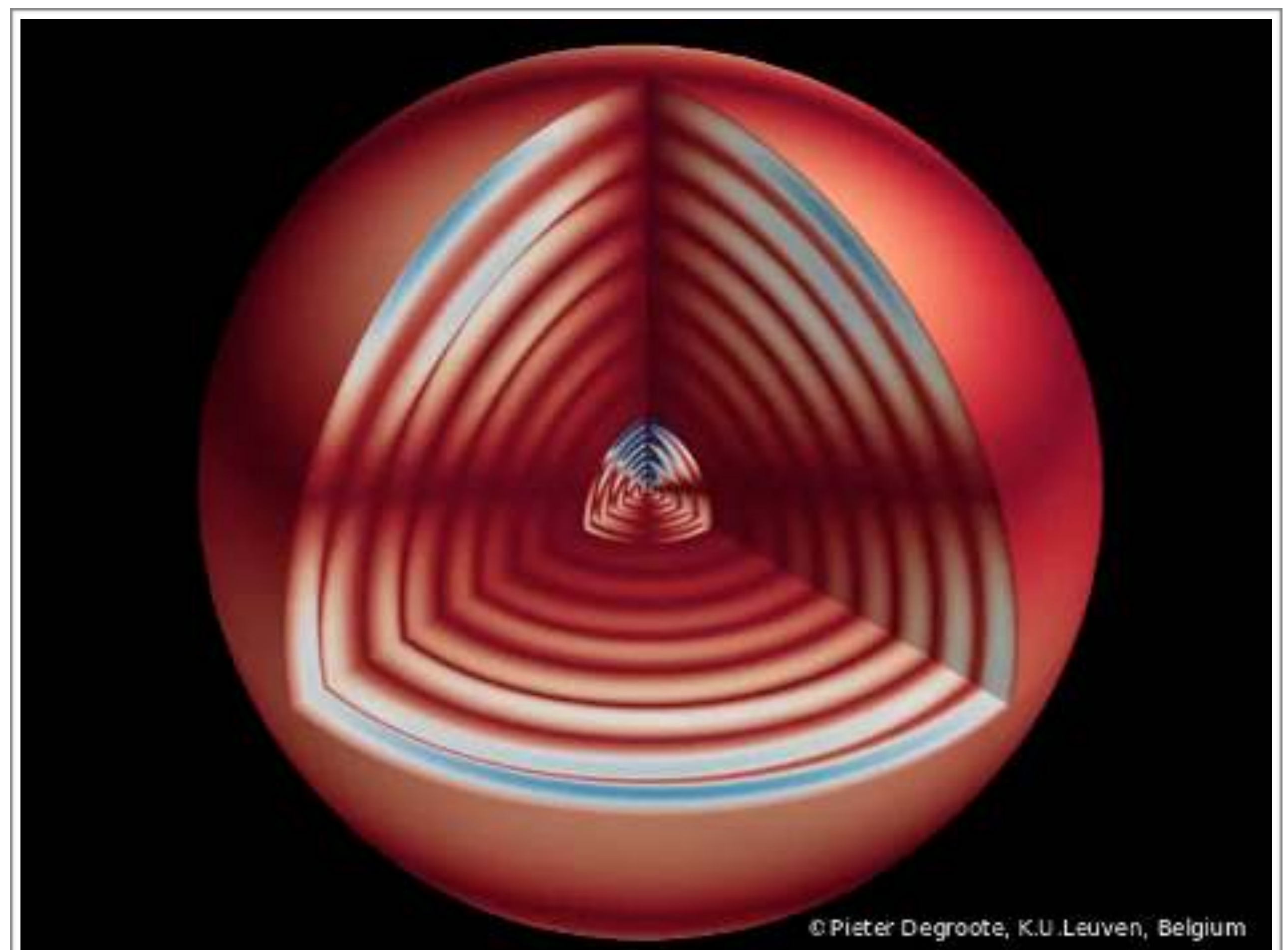


Schmid & Aerts (2016)

Starquakes and Asteroseismology

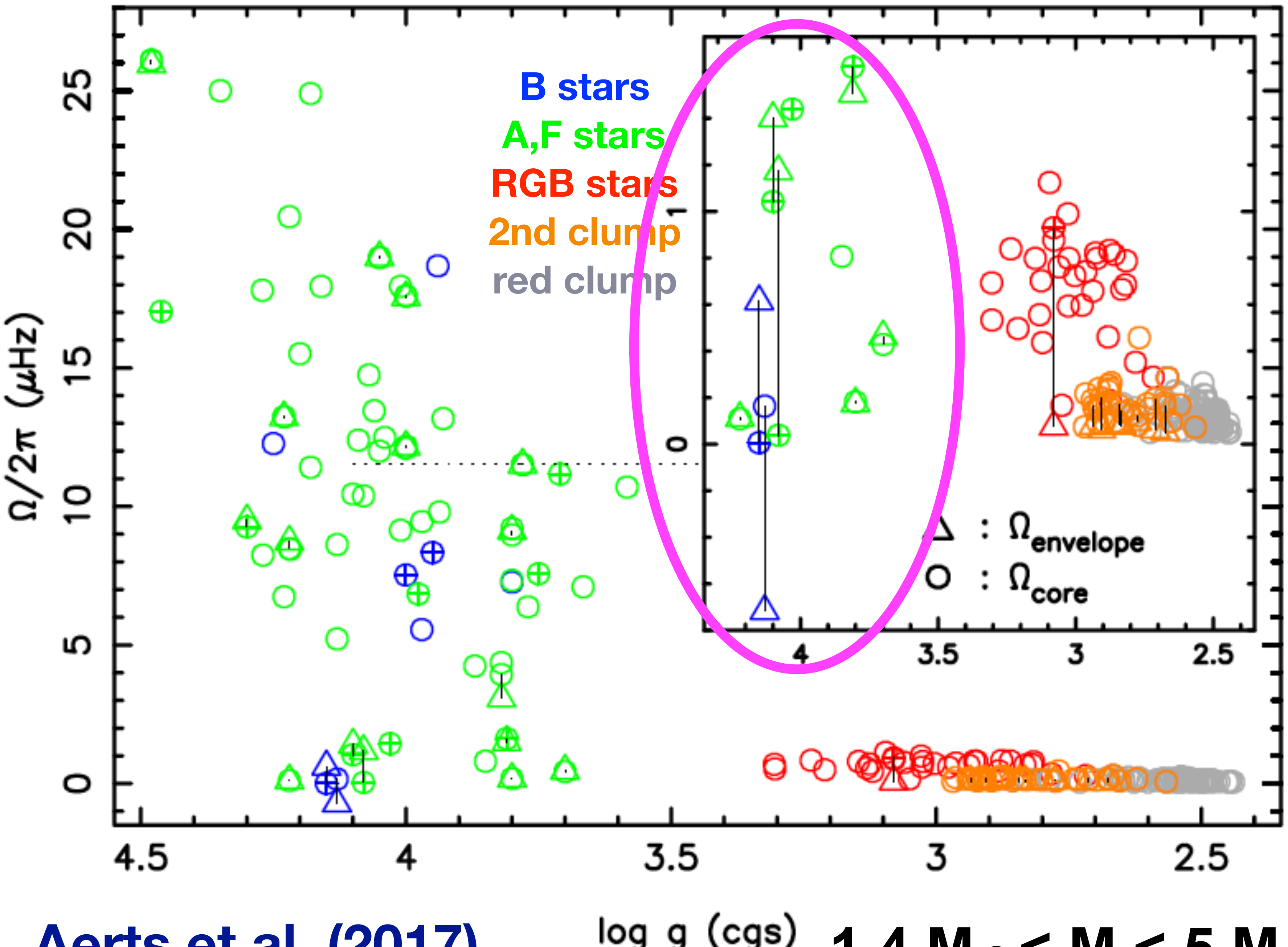






Rotation (and differential rotation) across the HR diagram

stars on the main sequence mostly rotate uniformly (in radius)*



Aerts et al. (2017)

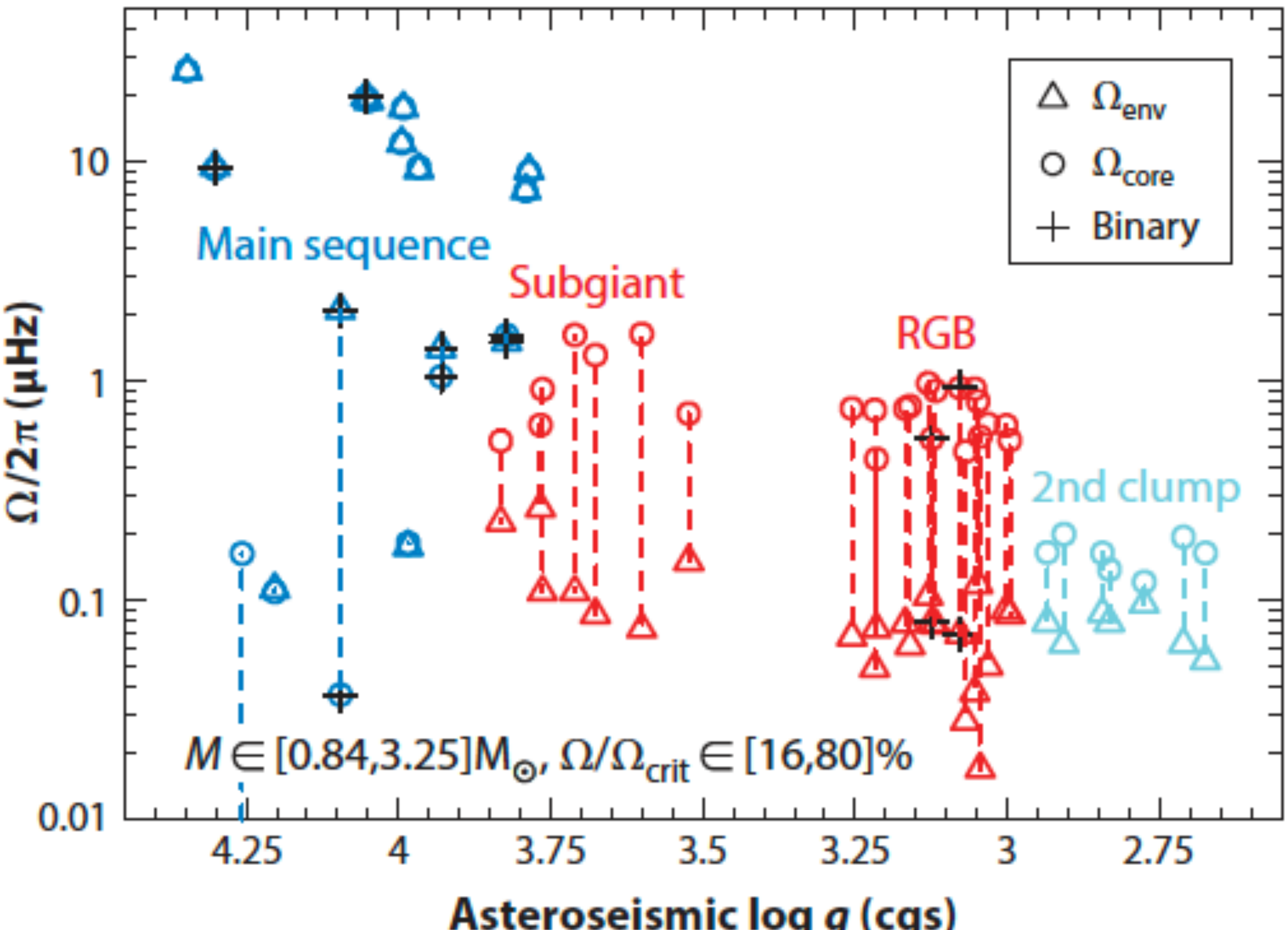
1.4 $M_\odot$ < M < 5 $M_\odot$

log g is a proxy for age

As stars age their cores spin up… but much less than expected

Must transfer angular momentum

Evolution of stellar rotation



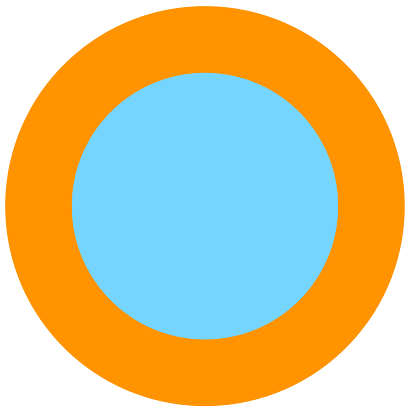
Core rotation much slower than expected (by 10-100) & Differential rotation decreases

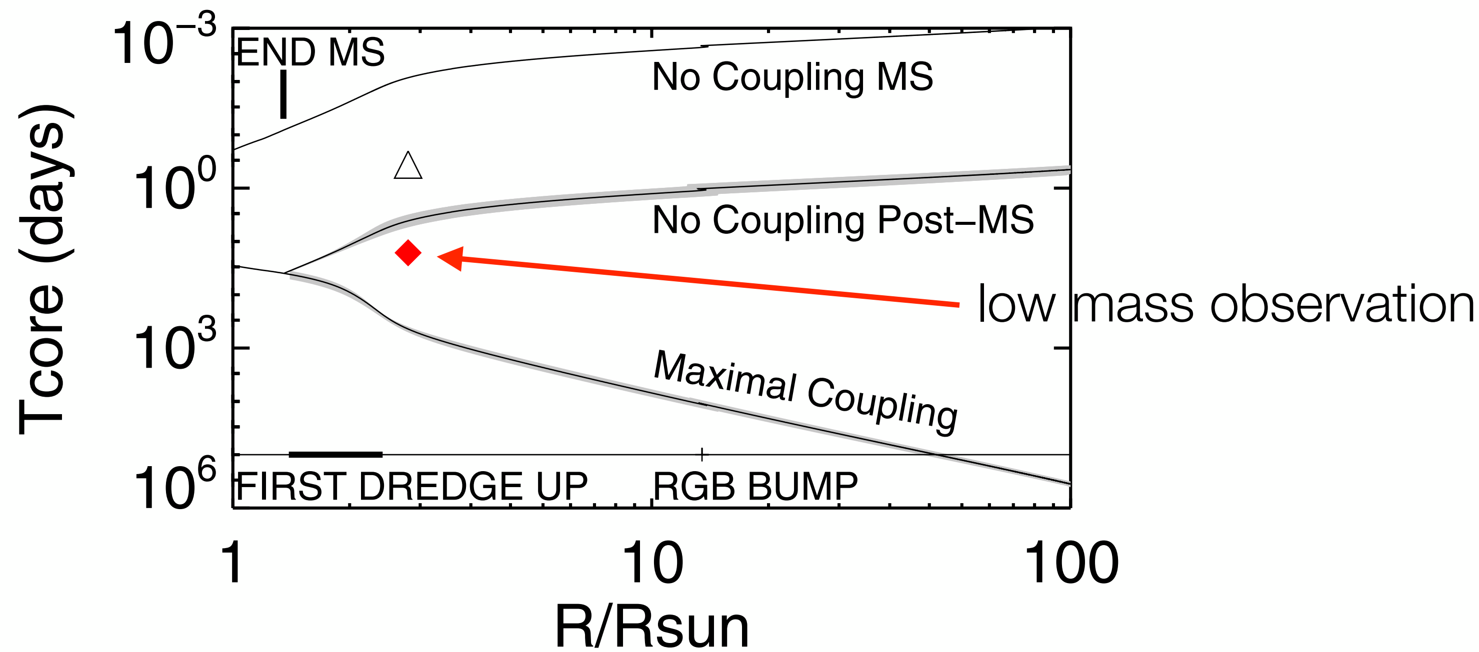
Aerts et al. (2019), ARAA, Vol. 57, in press

RiA via https://www.annualreviews.org/doi/pdf/10.1146/annurev-astro-091918-104359

Post Main Sequence Evolution

(happens for both low and high mass stars)

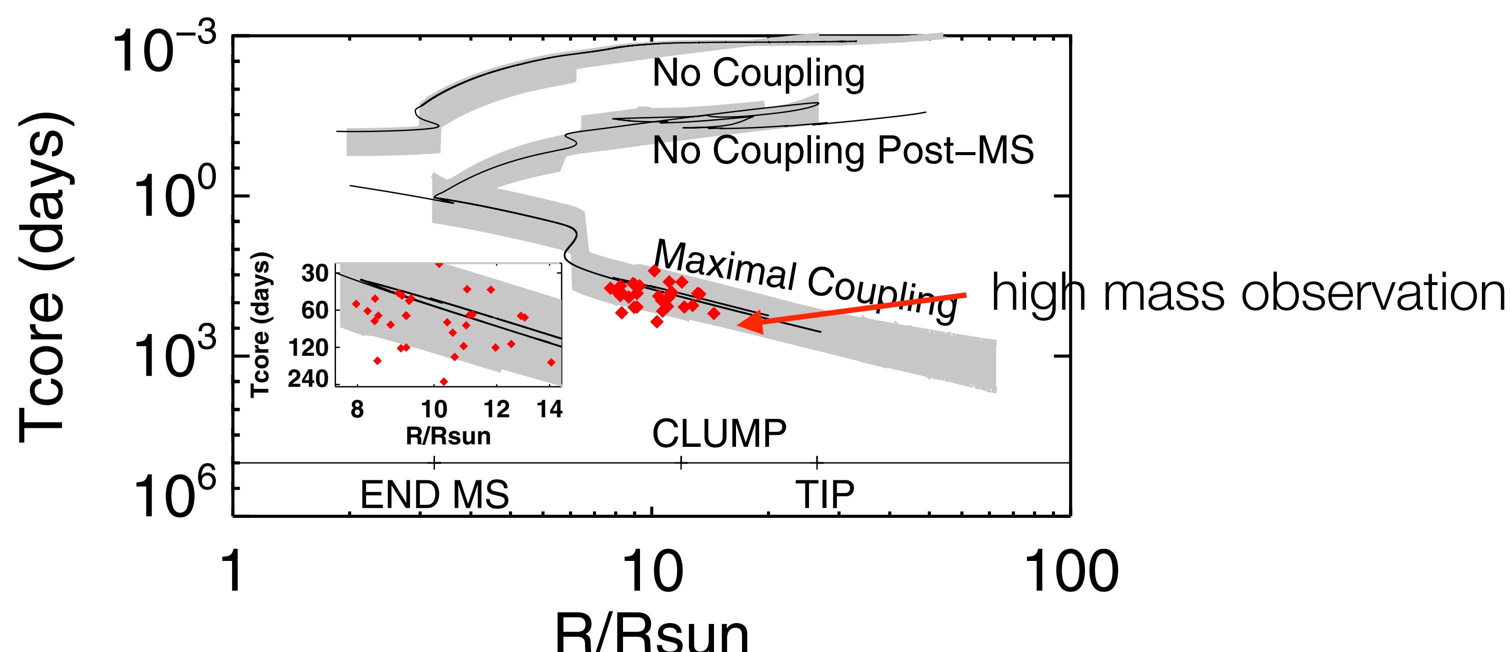




Energy source runs out in core; lose pressure support; core collapses

H starts burning in shell, causes outer layers to expand

To conserve AM core would spin up envelope would spin down
if no coupling



Tayar & Pinsonneault 2013

Important from IGW perspective

Summary of Observations

- Observations of surface abundances indicates unknown mixing in a variety of stars (low and high mass)
- Helioseismology indicates coupling between convective and radiative regions in Sun and an efficient AM transporter in radiative region to cause uniform rotation
- Asteroseismology indicates efficient AM transporter between convective and radiative regions across all ages and masses, though possibly more efficient in intermediate/high mass stars
- All of this indicates we need better descriptions of (magneto-)hydrodynamic processes in stellar interiors

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Macroturbulence

On the origin of macroturbulence in hot stars

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Obliquities of Hot Jupiters

INTERNAL GRAVITY WAVES MODULATE THE APPARENT MISALIGNMENT OF EXOPLANETS AROUND HOT STARS

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