Nordita Workshop, Stockholm, Sweden

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# An asteroseismic view of convective boundary mixing in massive stars

**Dominic Bowman**

Image credit: Hubble Space Telescope, NASA, ESA, STSCI/AURA

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# Importance of massive stars in astrophysics

- Radiative, chemical, kinematic feedback
- Progenitors of gravitational wave sources
- Laboratories for testing physics:
    - winds
    - binarity
    - magnetic fields
    - pulsations
    - rotation

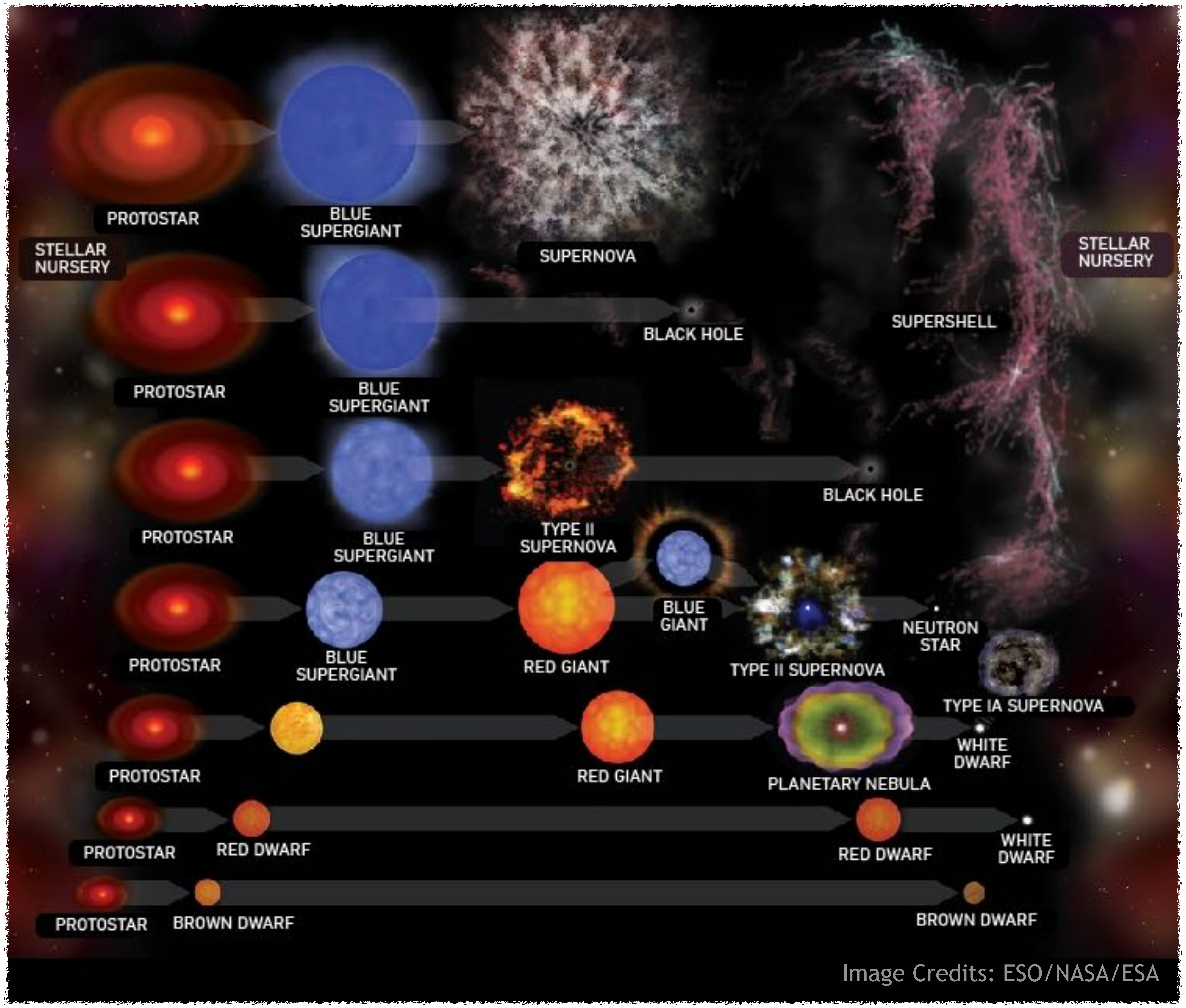
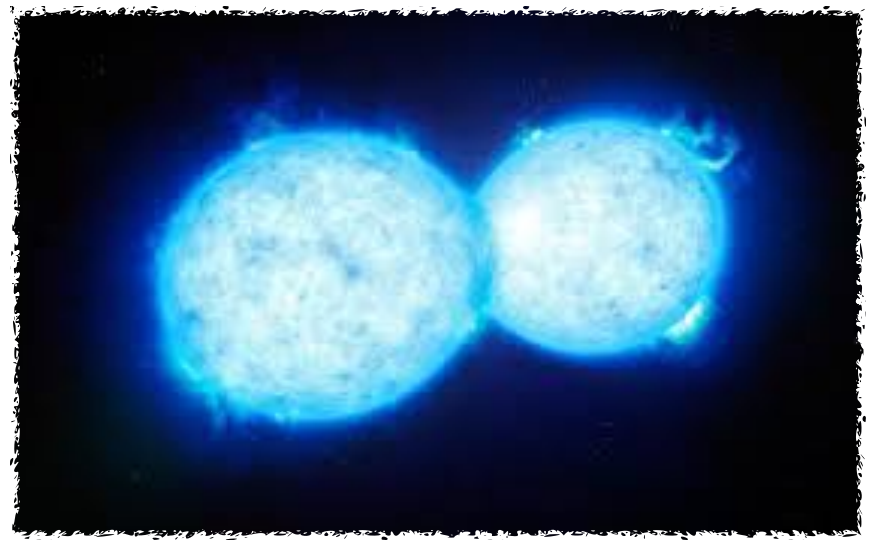


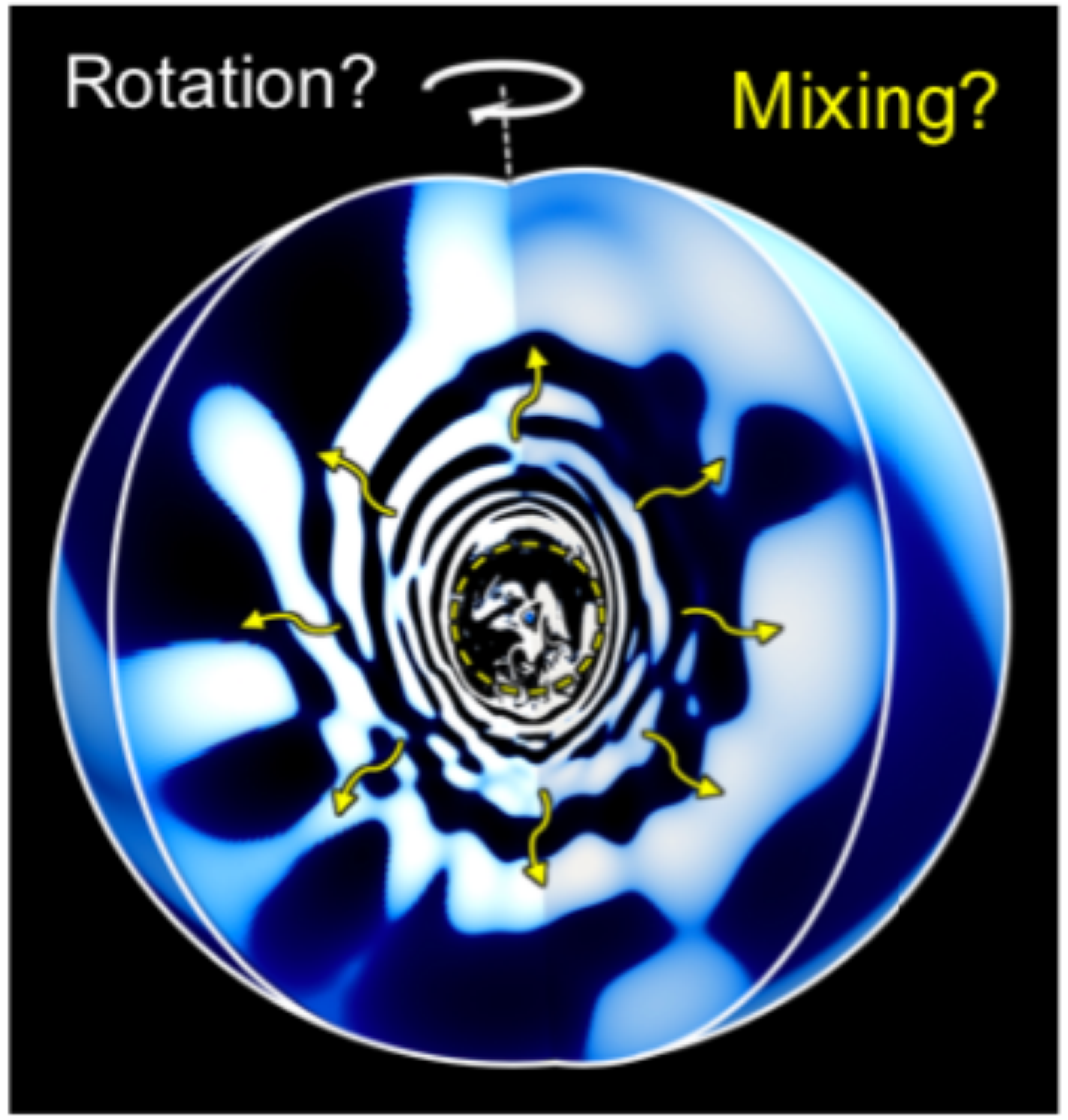
Image Credits: ESO/NASA/ESA



# Unconstrained physics of massive stars: mixing

Uncertainties in rotation and mixing propagate through evolution and strongly impact predictions of:

- compact remnant mass and spin
- supernova feedback to host galaxy



Edelmann et al. (2019)

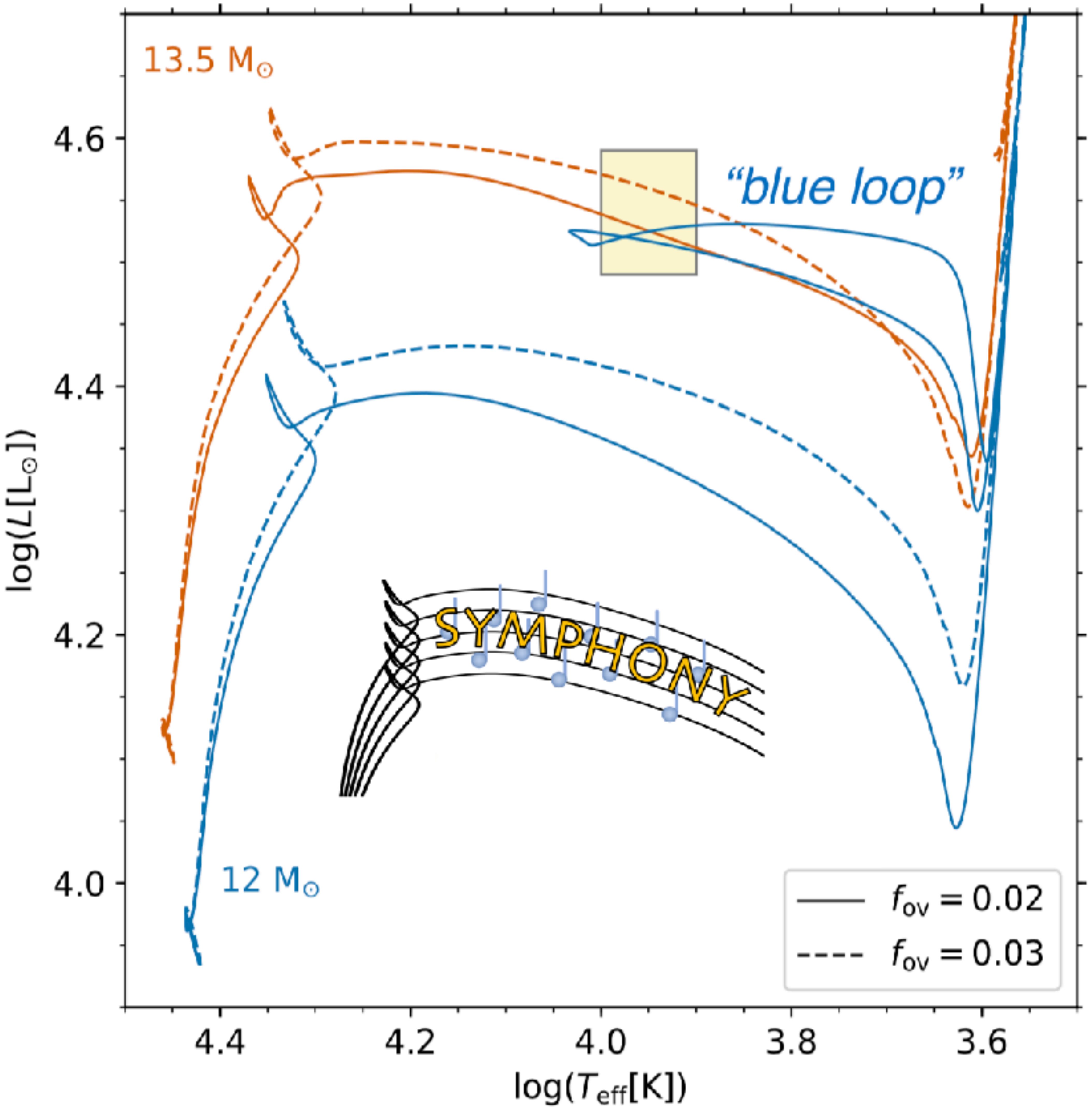
Unknown mixing means:

$\sigma(m_{cc}) > 50\%$

$\sigma(\text{age}) > 25\%$

already at the TAMS

Bowman (2020)



# Talk Outline

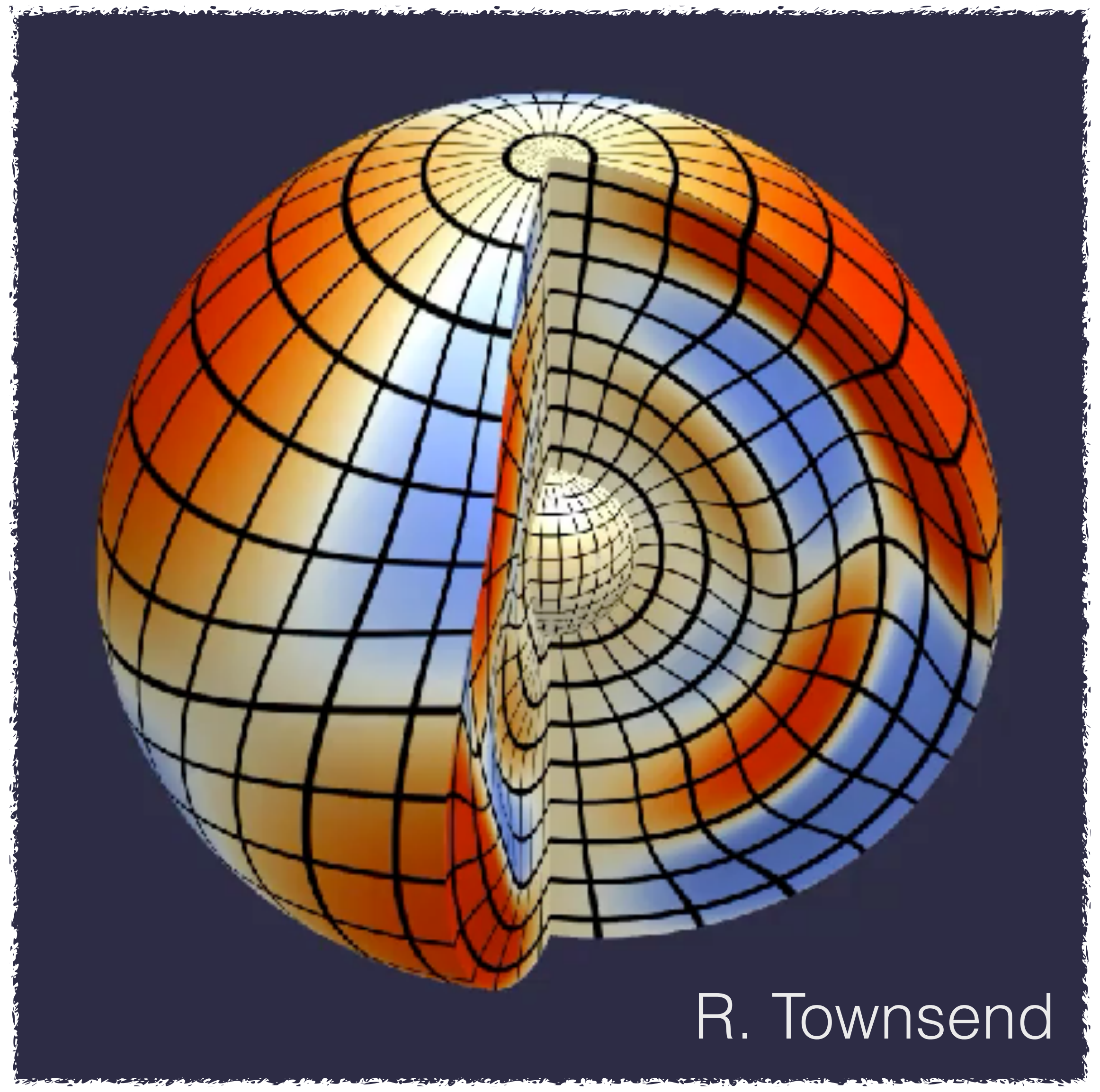
1. **Asteroseismology: types of pulsations and pulsators**

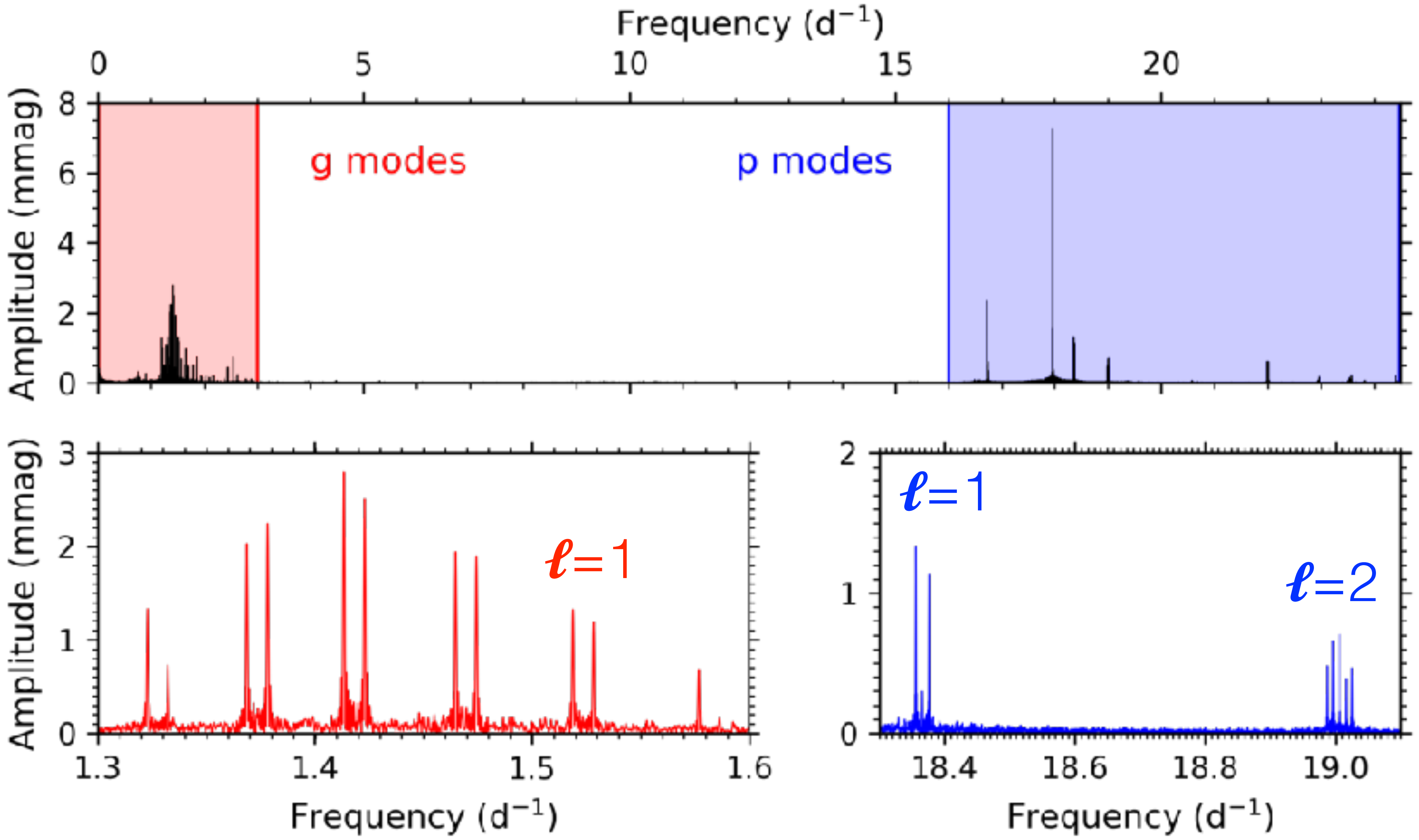
2. Insight from stellar pulsations: mixing and rotation

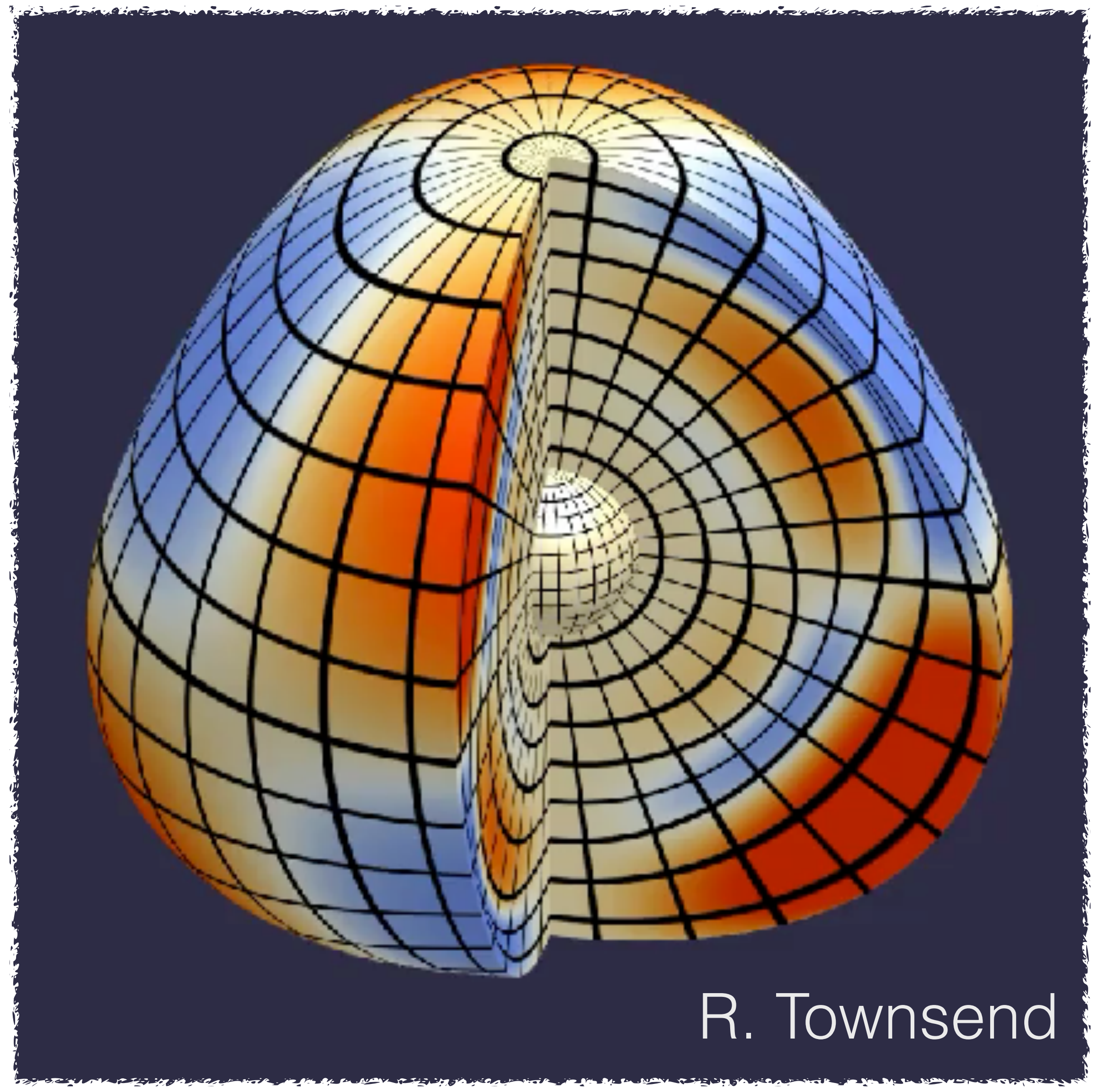
3. Magneto-asteroseismology: interior magnetic fields

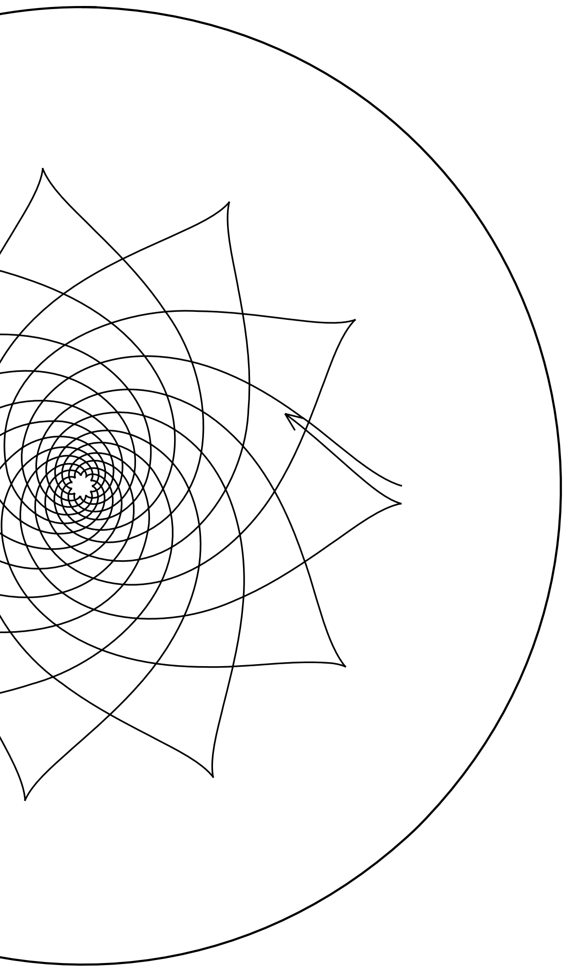
4. Stochastic low-frequency variability: gravity waves and turbulence

# Asteroseismology unlocks stellar interiors


R. Townsend




R. Townsend

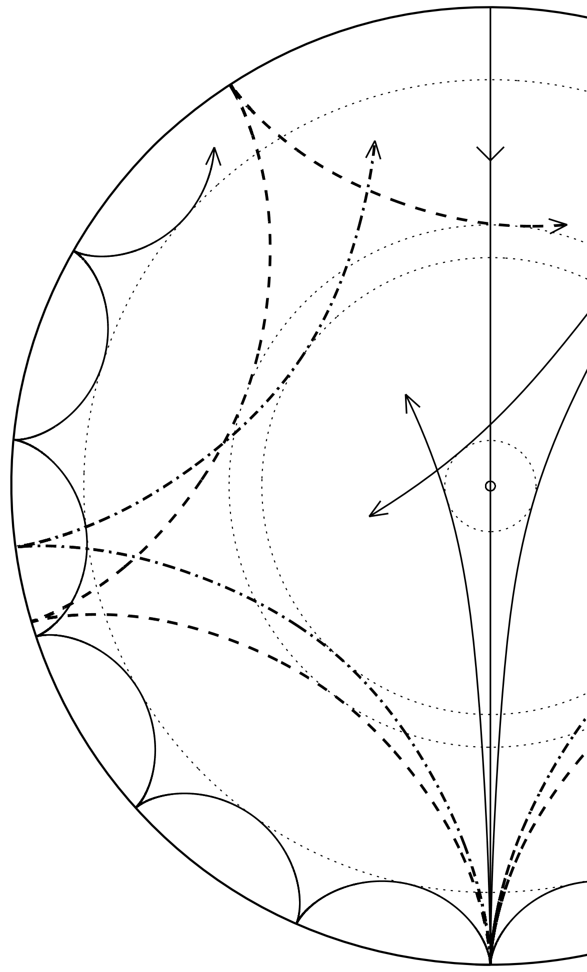


**Gravity (g) modes:**

- $n < 0$
- low frequency
- probe near-core
- non-radial
- equally-spaced in period

**Pressure (p) modes:**

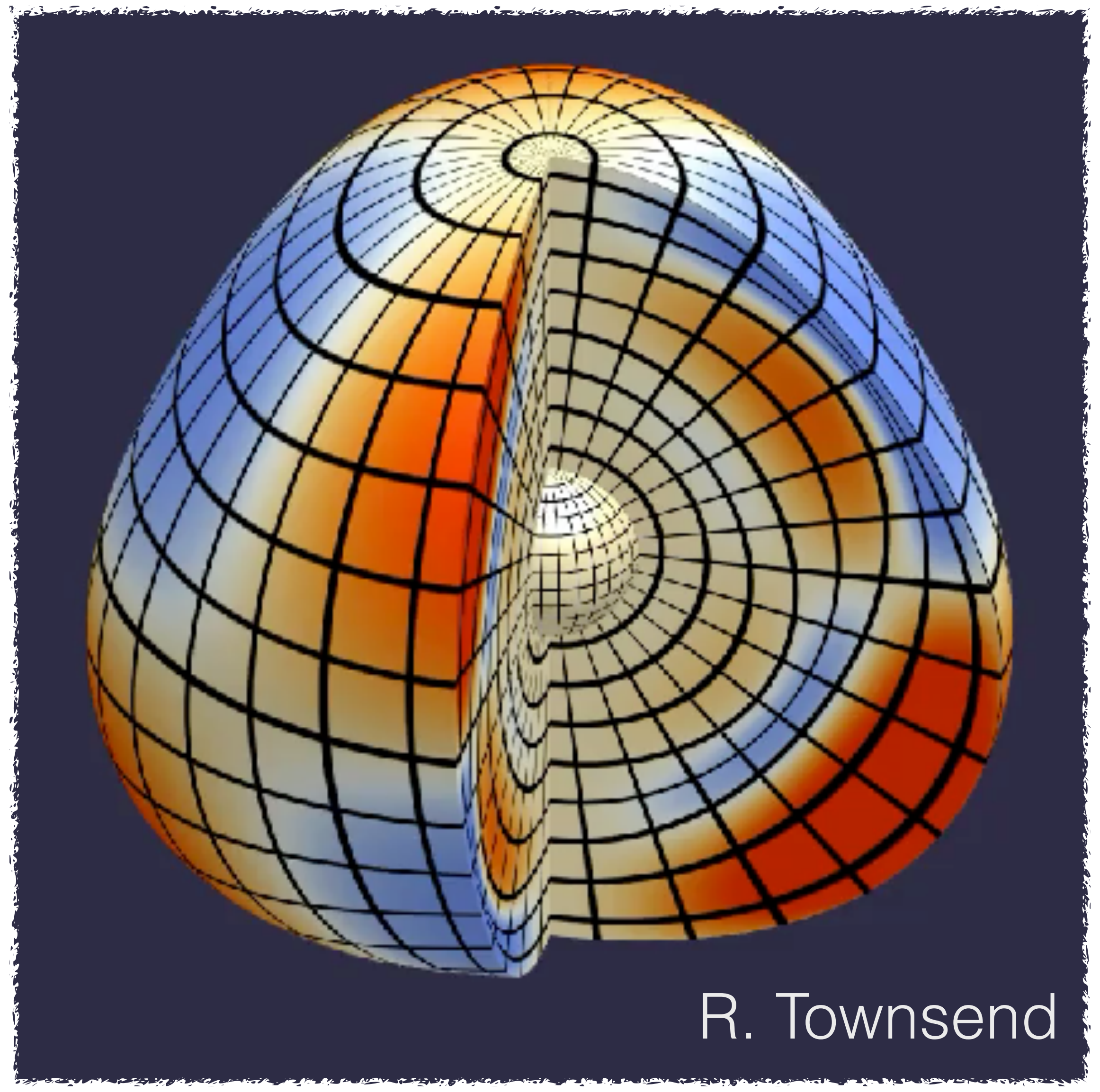
- $n > 0$
- high frequency
- probe near-surface
- radial and non-radial
- equally spaced in frequency



# Asteroseismology: pressure modes

Non-radial pressure modes probe the envelope physics:

- rotation rate from near-core to near-surface
- first-order caveat: applicable to slow rotators (<15% critical breakup)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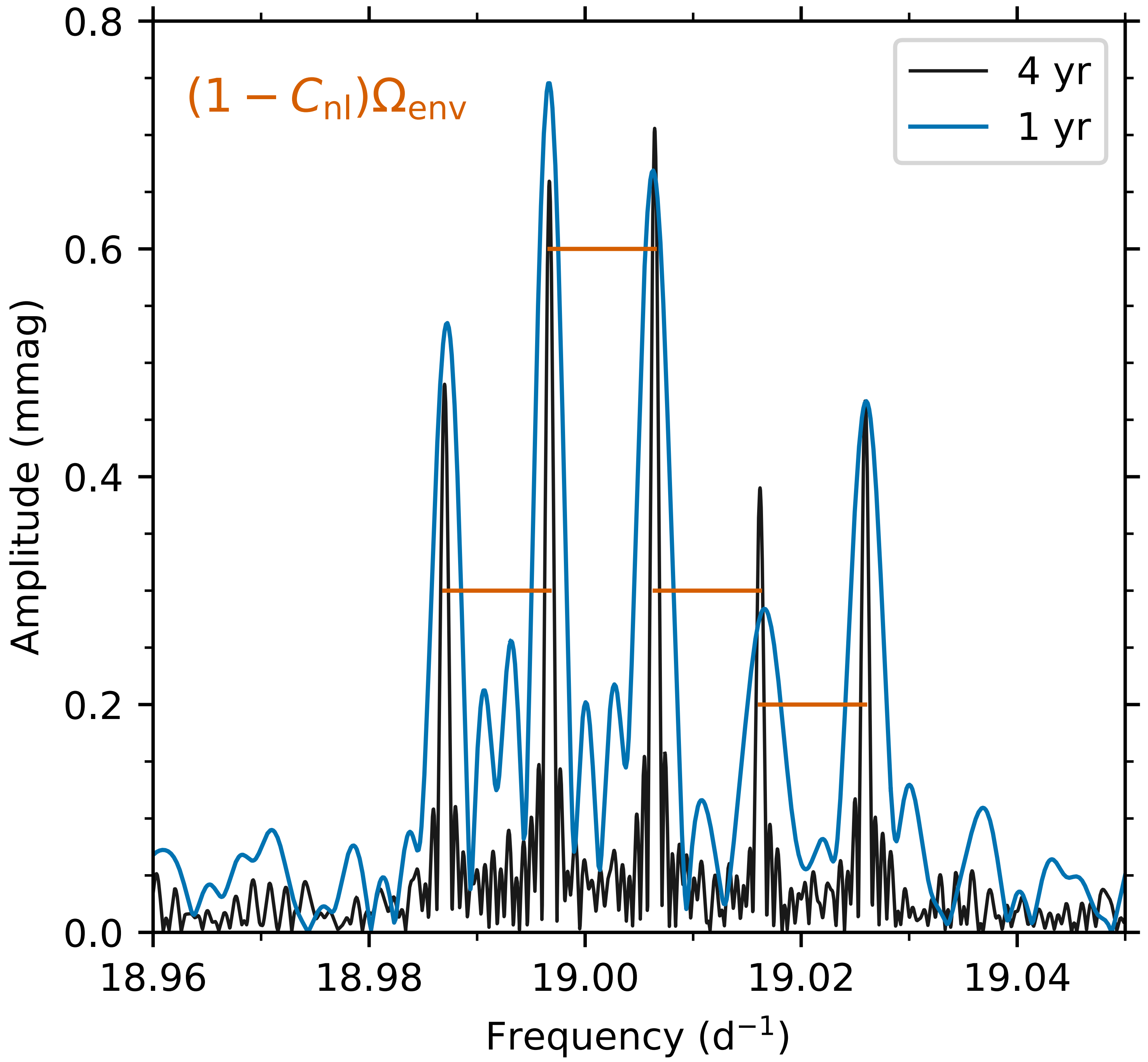


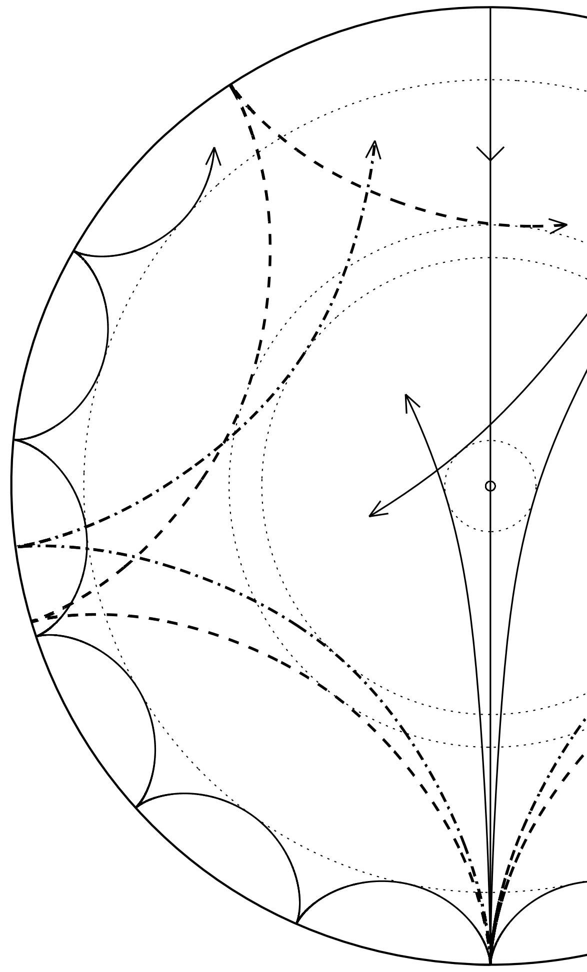
first-order Ledoux splitting:

$$\omega_{n\ell m} = \omega_{n\ell} + m\,(1 - C_{n\ell})\,\Omega$$

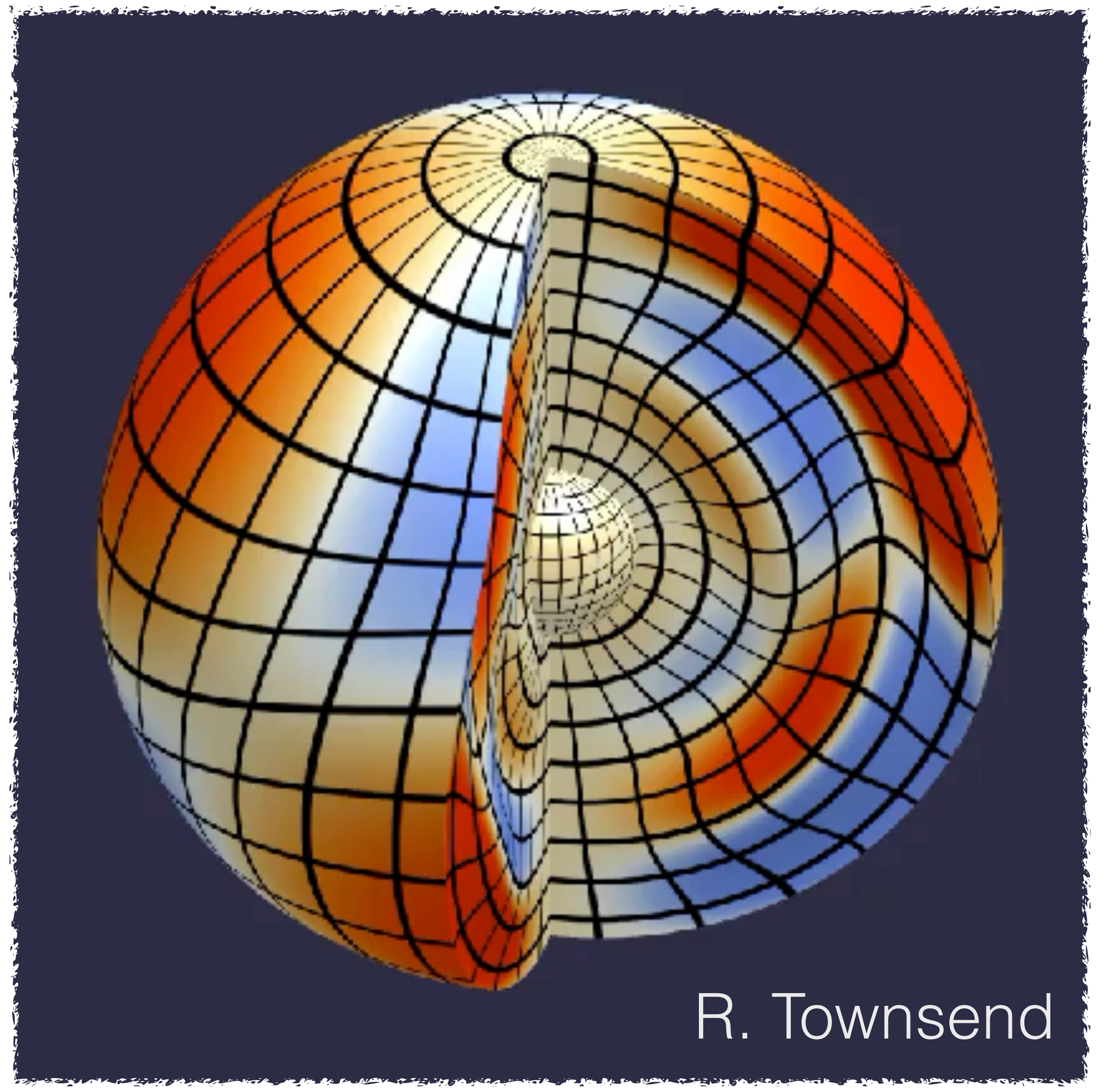
e.g. Kurtz et al. (2014) for AF stars
e.g. Aerts et al. (2003) for early-B stars

**Pressure (p) modes:**

- n > 0
- high frequency
- probe near-surface
- radial and non-radial
- equally spaced in frequency



# Asteroseismology: gravity modes



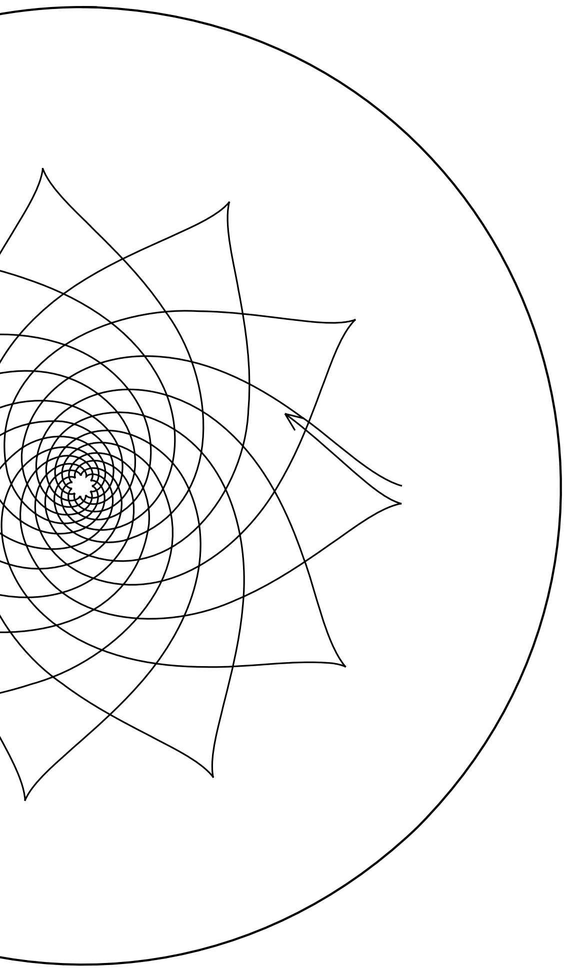
R. Townsend

Prograde dipole gravity modes most common geometry in observations:

- rotation and chemical mixing in near-core region
- Traditional approximation for rotation (TAR) up to ~90% critical breakup

$$P_{n\ell} = \frac{\Pi_0}{\sqrt{\ell\,(\ell+1)}}\,(|n|+\alpha)$$

$$\Pi_0 = 2\pi^2 \left( \int_{r_1}^{r_2} N(r) \frac{\mathrm{d}r}{r} \right)^{-1}$$



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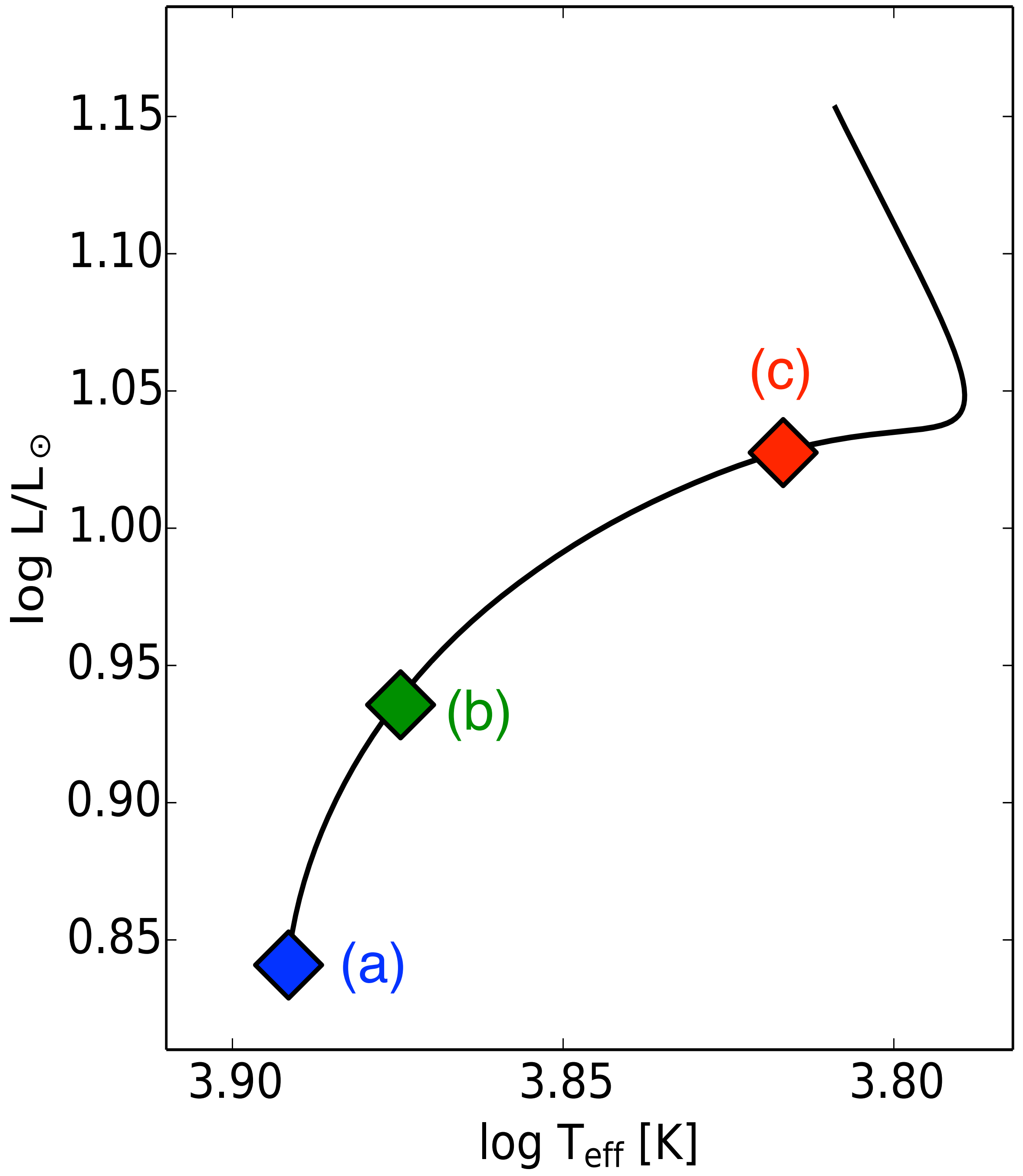
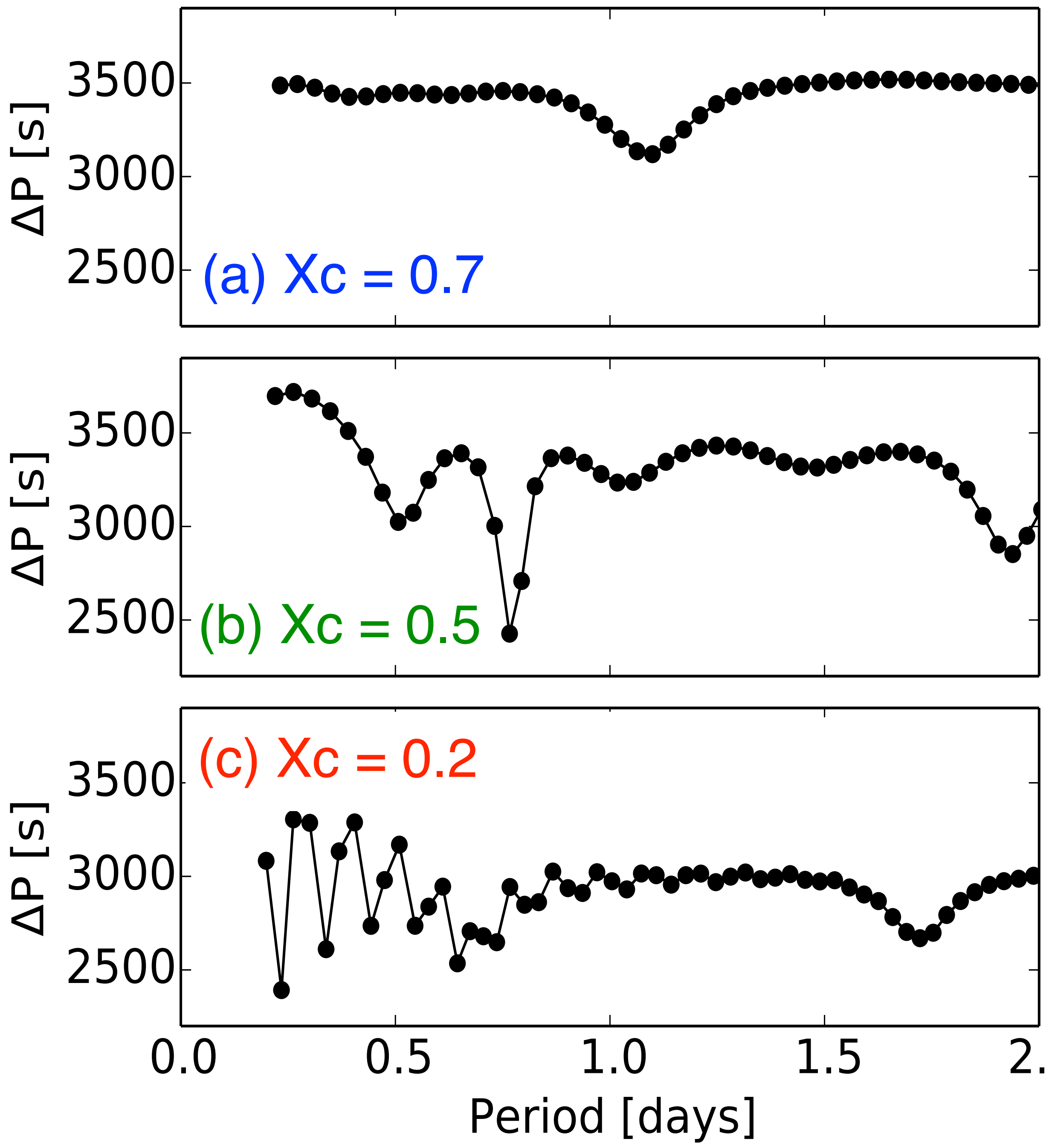
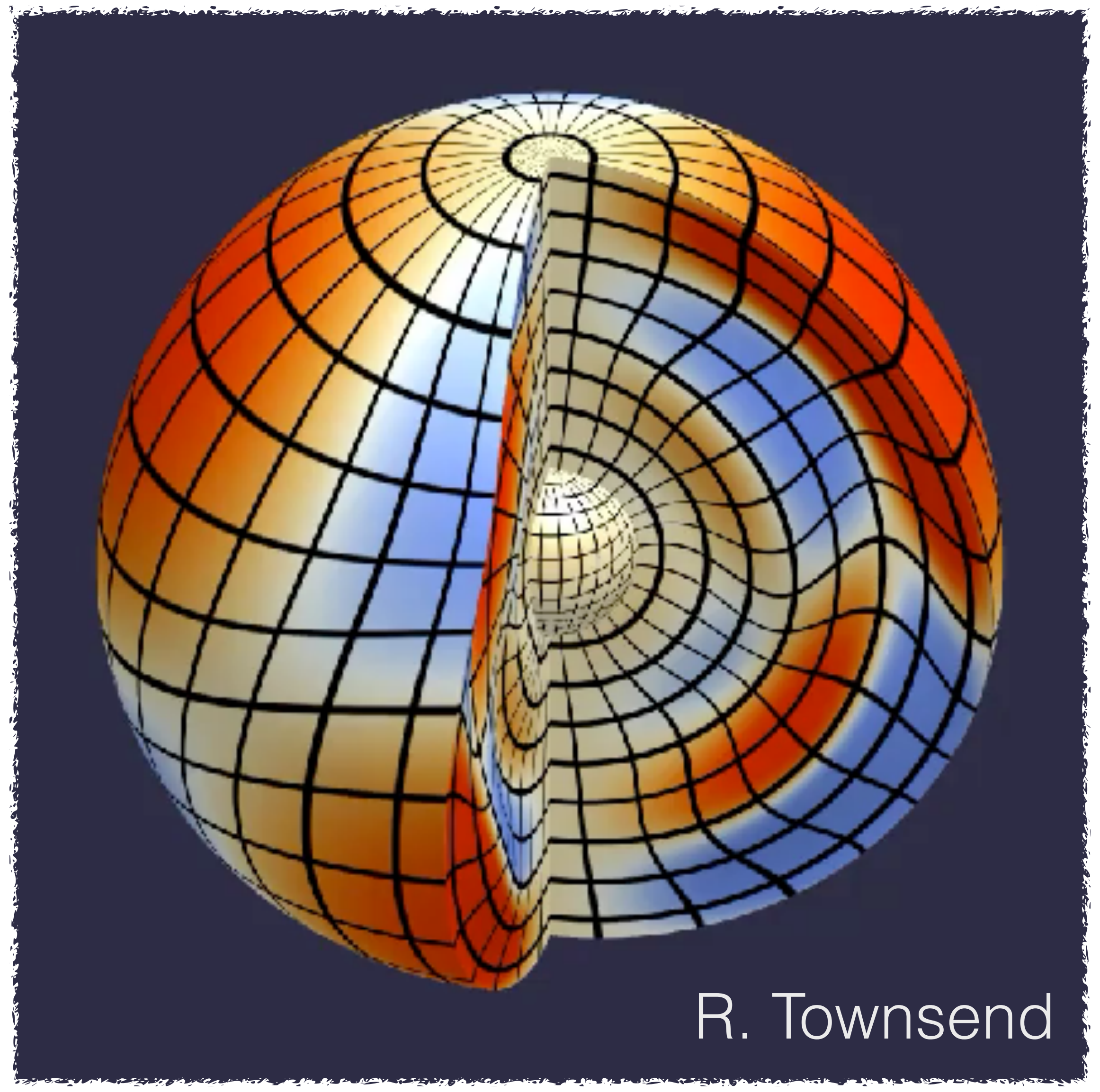


*"Period spacing pattern"*

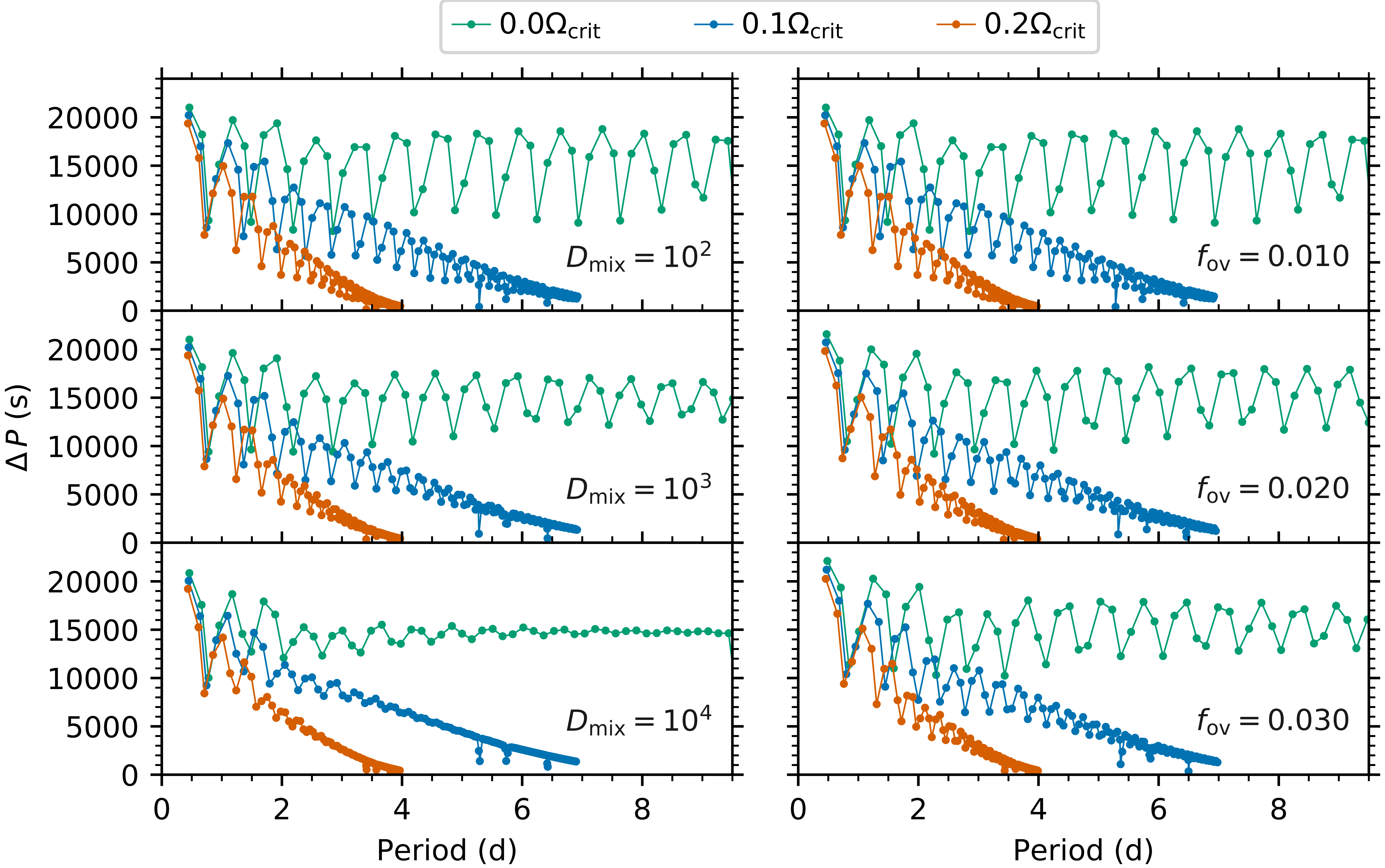


Van Reeth et al. (2015)

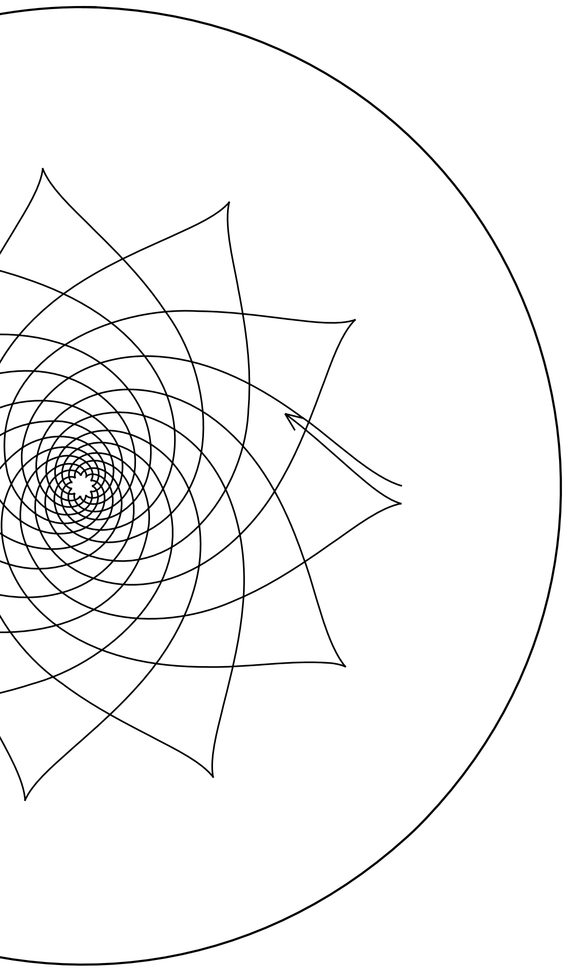
# Asteroseismology: gravity modes



Increased mixing decreases *"dips"* in g-mode period spacing pattern.



Bowman (2020)



**Gravity (g) modes:**

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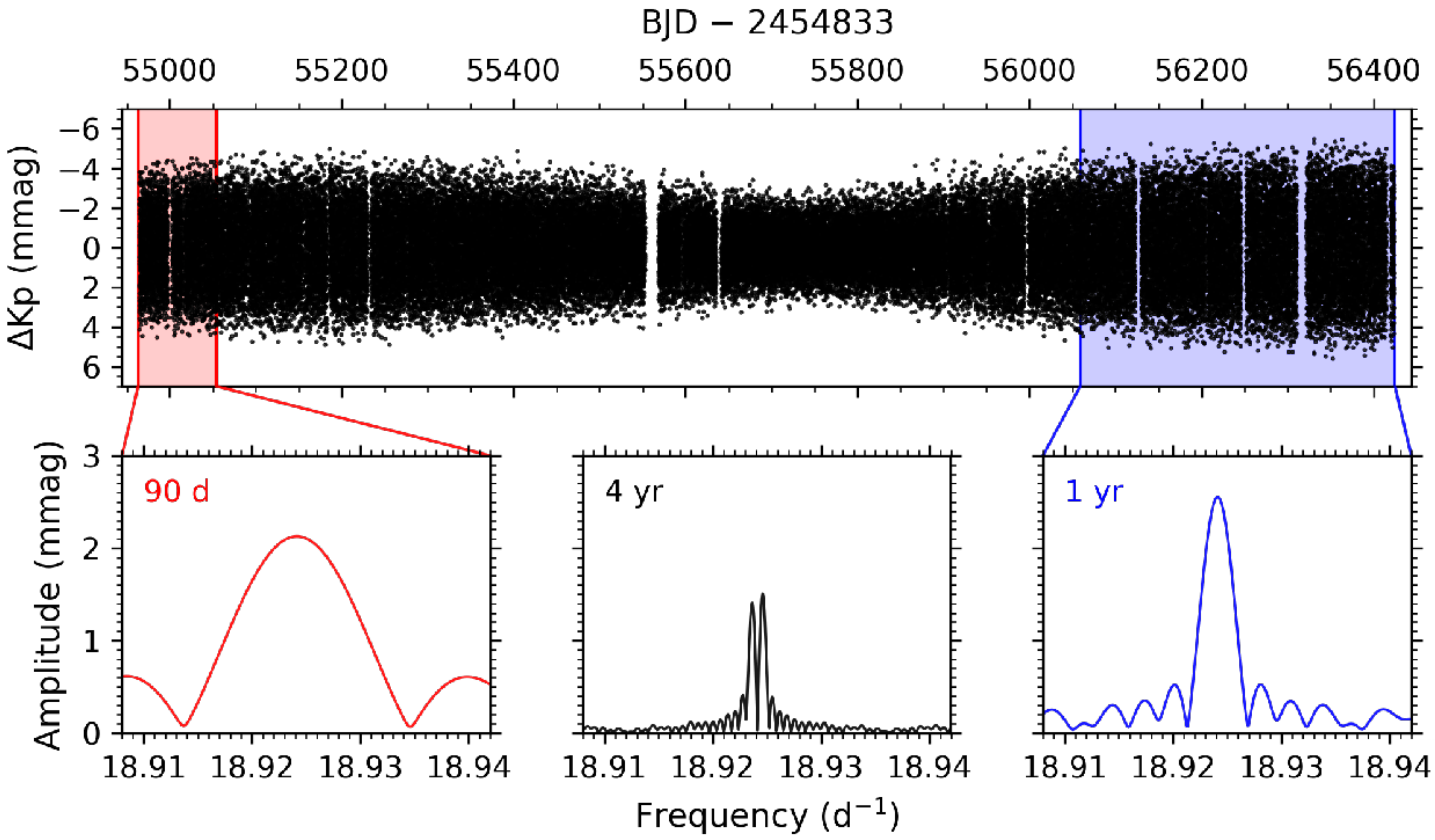
# Space photometry revolution

Long-term, continuous, high-precision light curves are needed to resolve individual pulsation modes.



# Types of pulsating massive stars

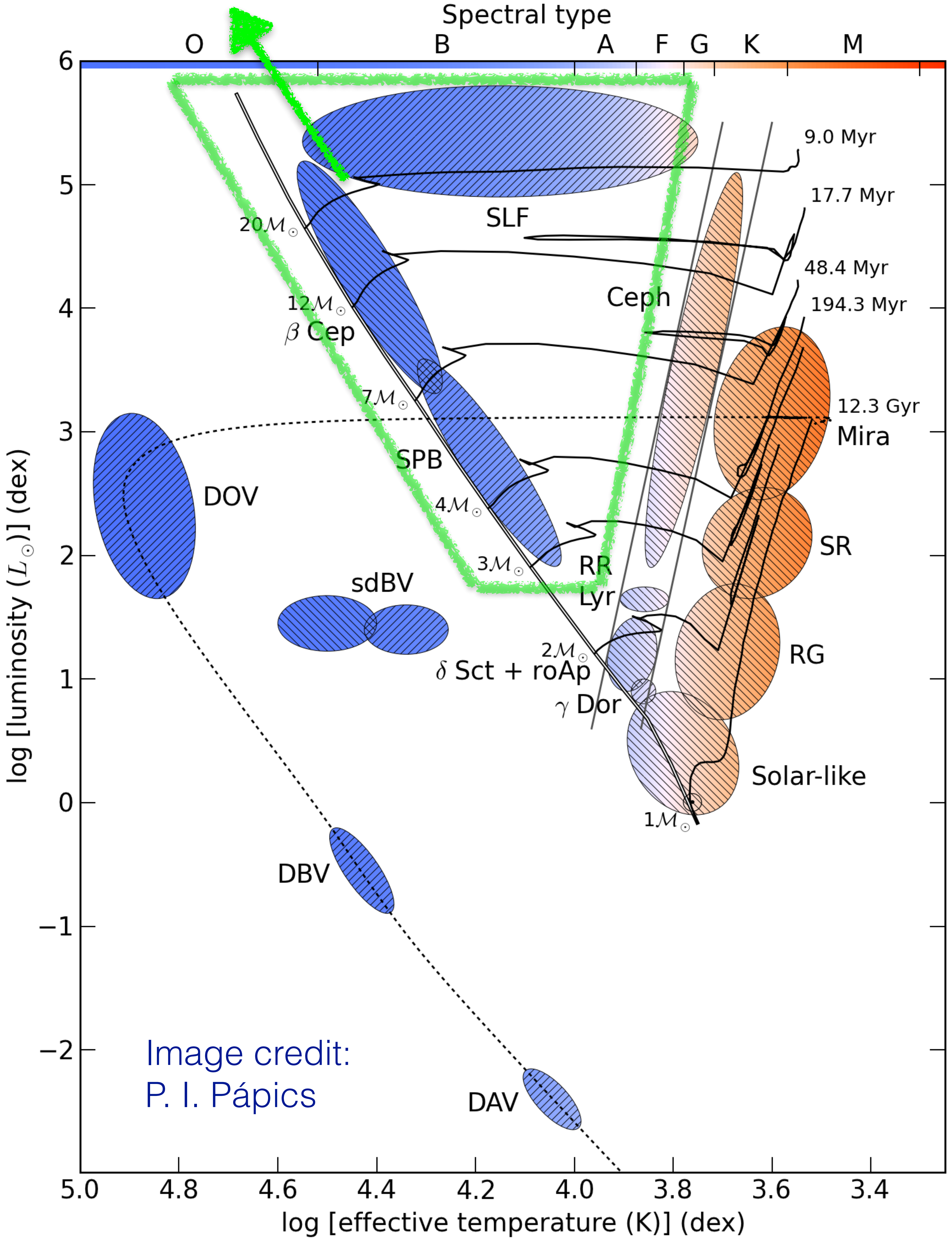


Image credit:
P. I. Pápics

**SLF:** Stochastic low-frequency variability

- Broad period range between minutes and several days
- Seemingly near-ubiquitous in massive stars

**β Cephei stars:**

- Periods of order several hours
- Low radial order coherent p and g modes
- Masses above ~8 $M_\odot$

**Slowly Pulsating B stars:**

- Periods of order days
- High radial order g modes
- Masses between 3 and 9 $M_\odot$

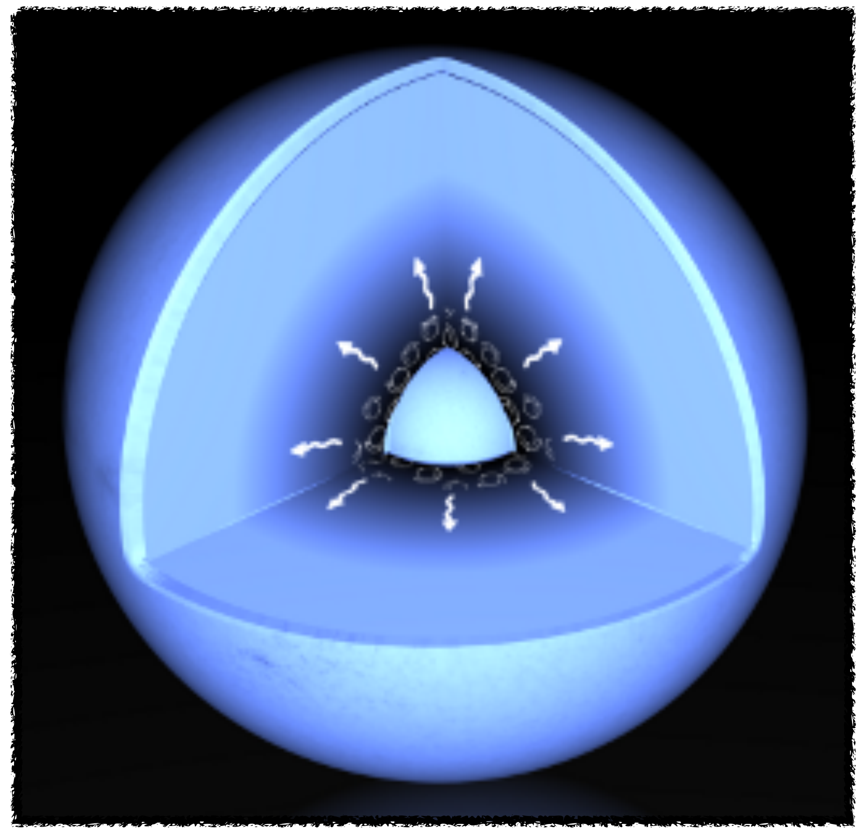


Image credit: P. Degroote

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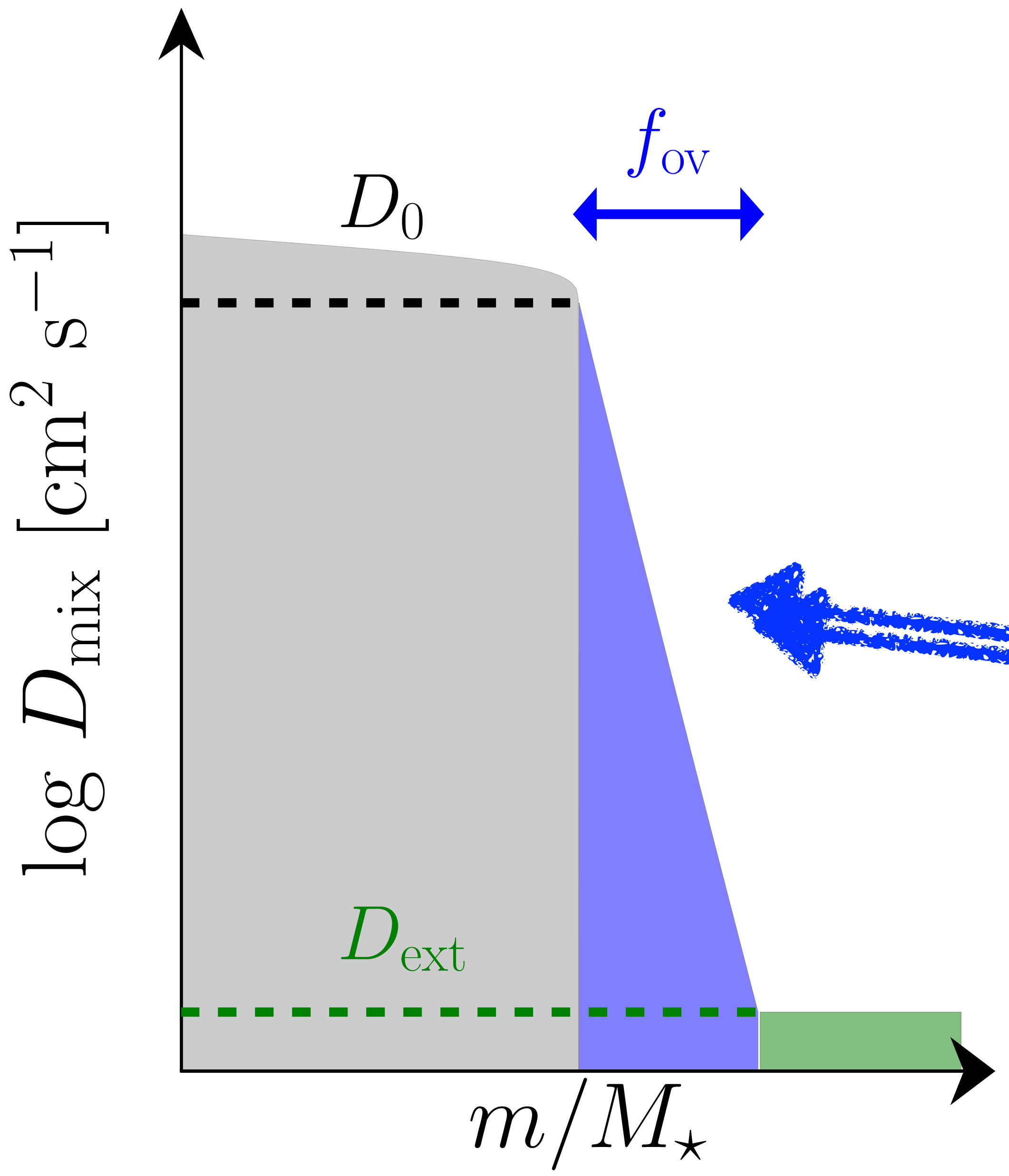
# Asteroseismic results for interior mixing

From a large grid of **stellar evolution models** and their pulsation mode frequencies determine:

- Convective core boundary mixing: $\boldsymbol{f}_{\mathrm{ov}}$
- Stellar parameters: $Z$, $M_\star$, $X_c$, $M_{cc}$
- Envelope Mixing: $D_{\mathrm{mix}}(r)$

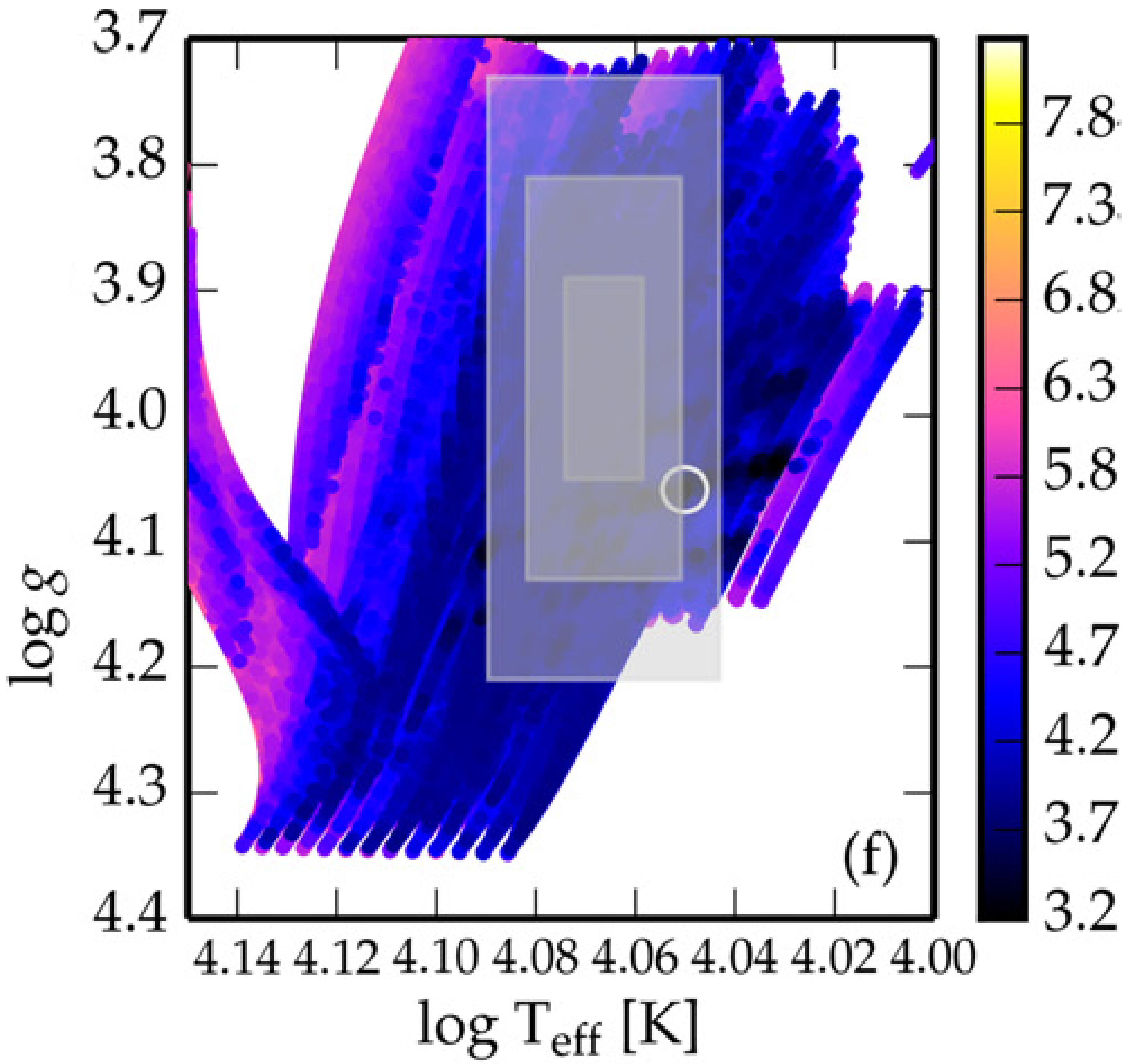
Very important for post-main sequence evolution!



What is the shape of the overshooting and the temperature gradient in the boundary mixing region?

Bowman & Michielsen (2021)
Michielsen, Aerts & Bowman (2021)

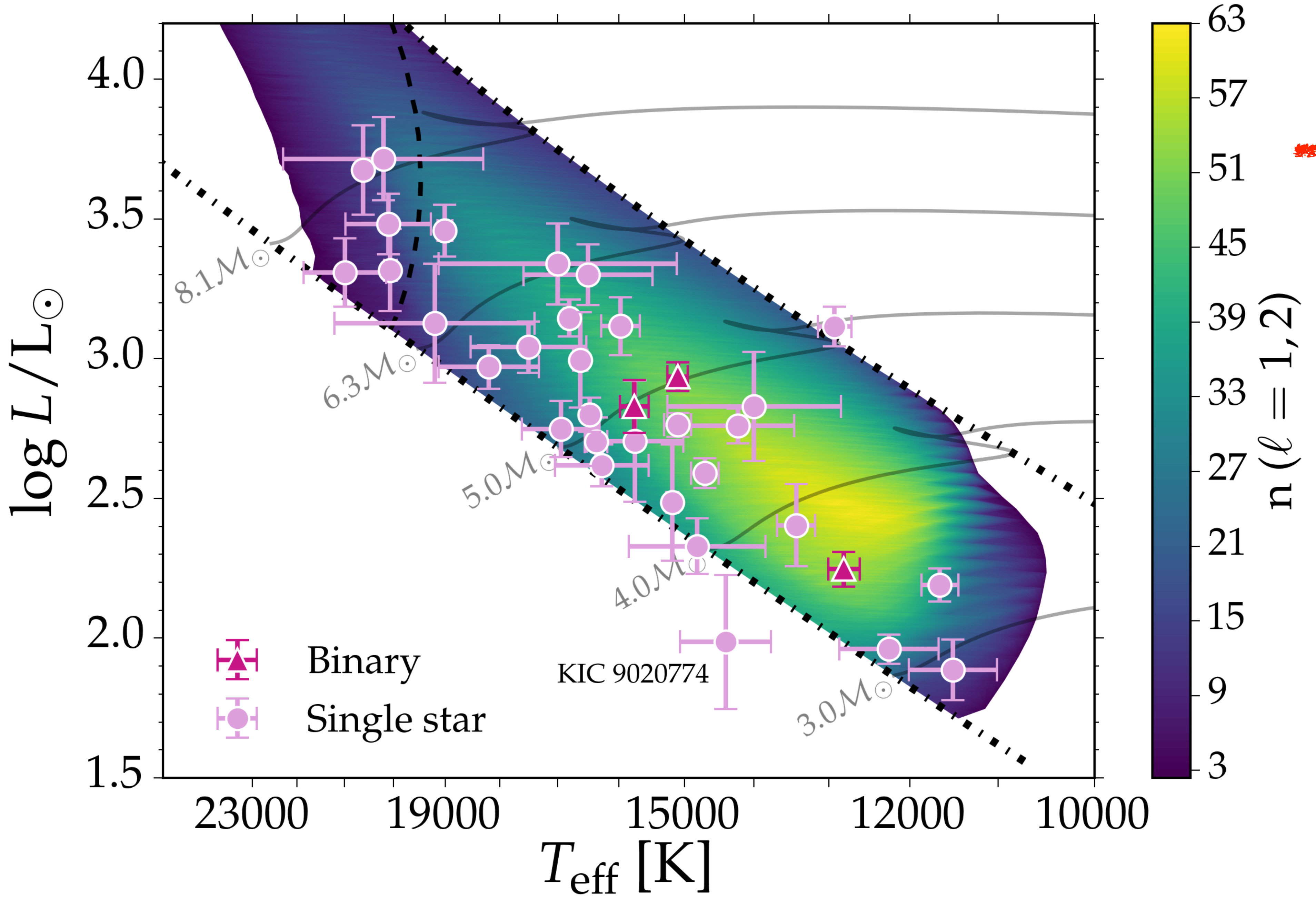
MESA + GYRE



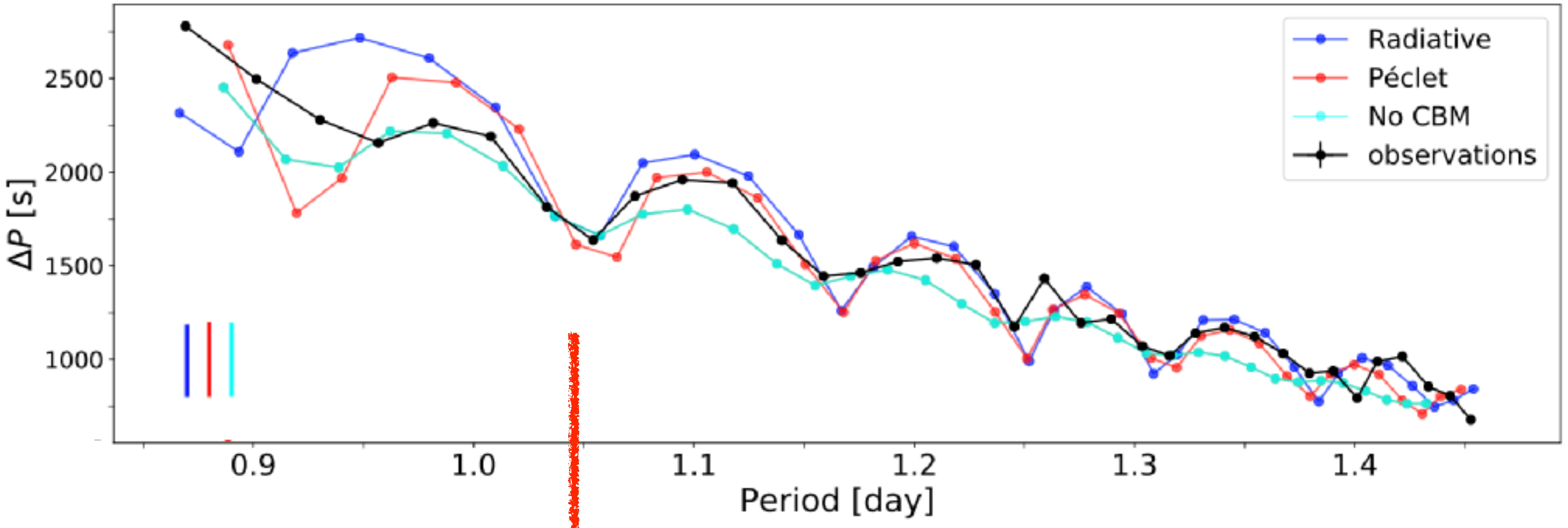
Moravveji et al. (2015)
Moravveji et al. (2016)

# Asteroseismic results for interior mixing: SPB stars

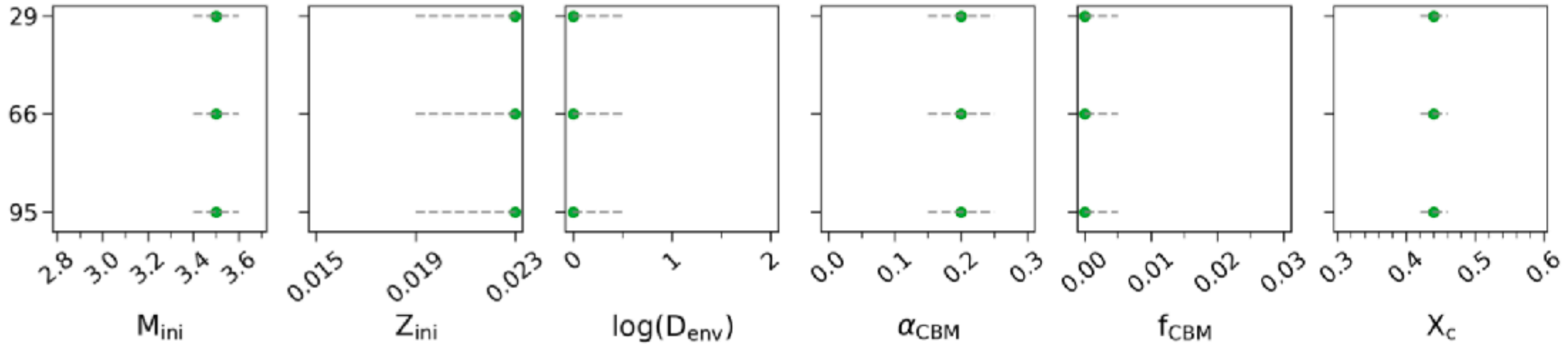
*Kepler* space telescope had good coverage of **SPB stars**:



Michielsen, Aerts, Bowman (2021)



KIC 7760680: confidence intervals of an excellent SPB star:



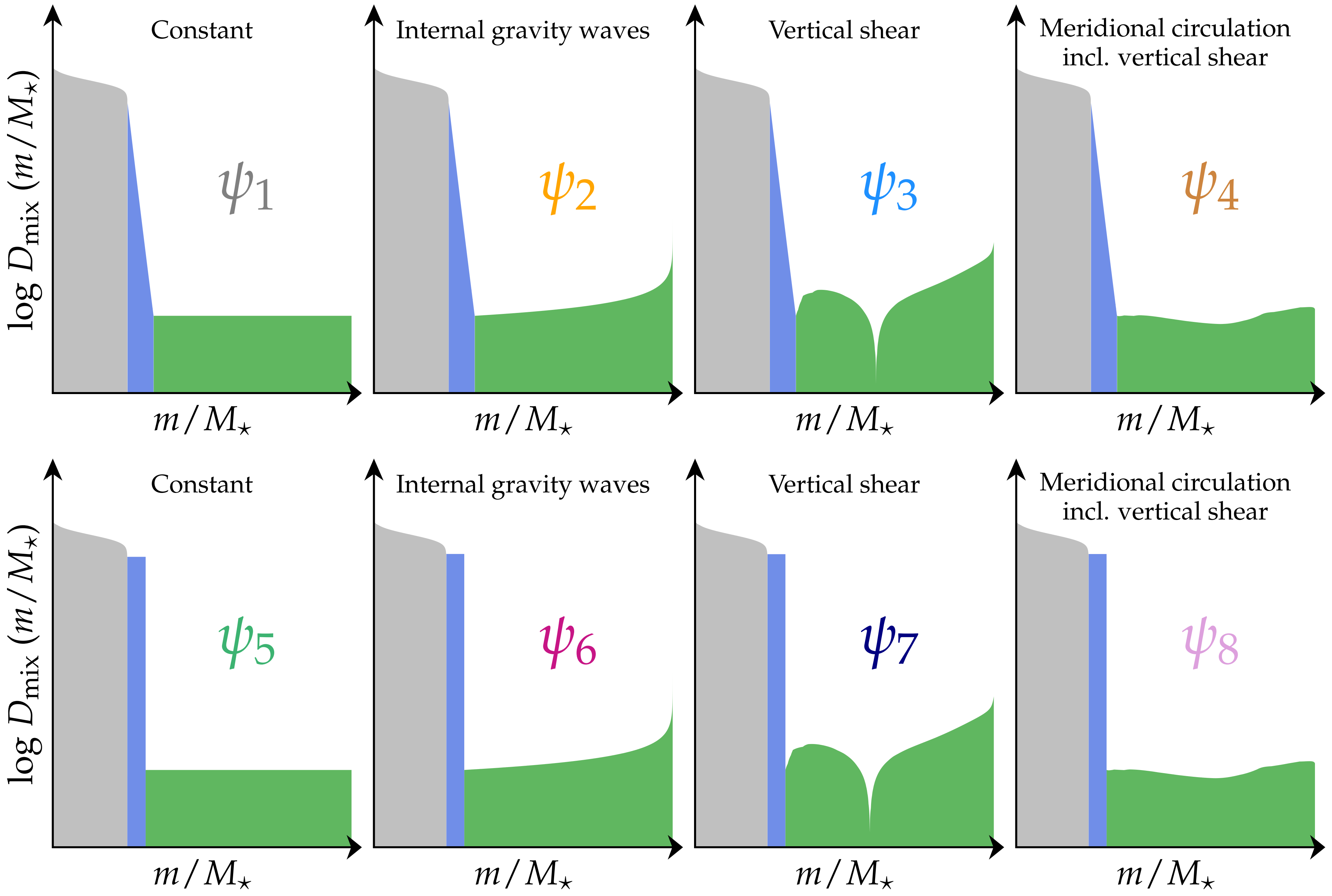
Bowman & Michielsen (2021)

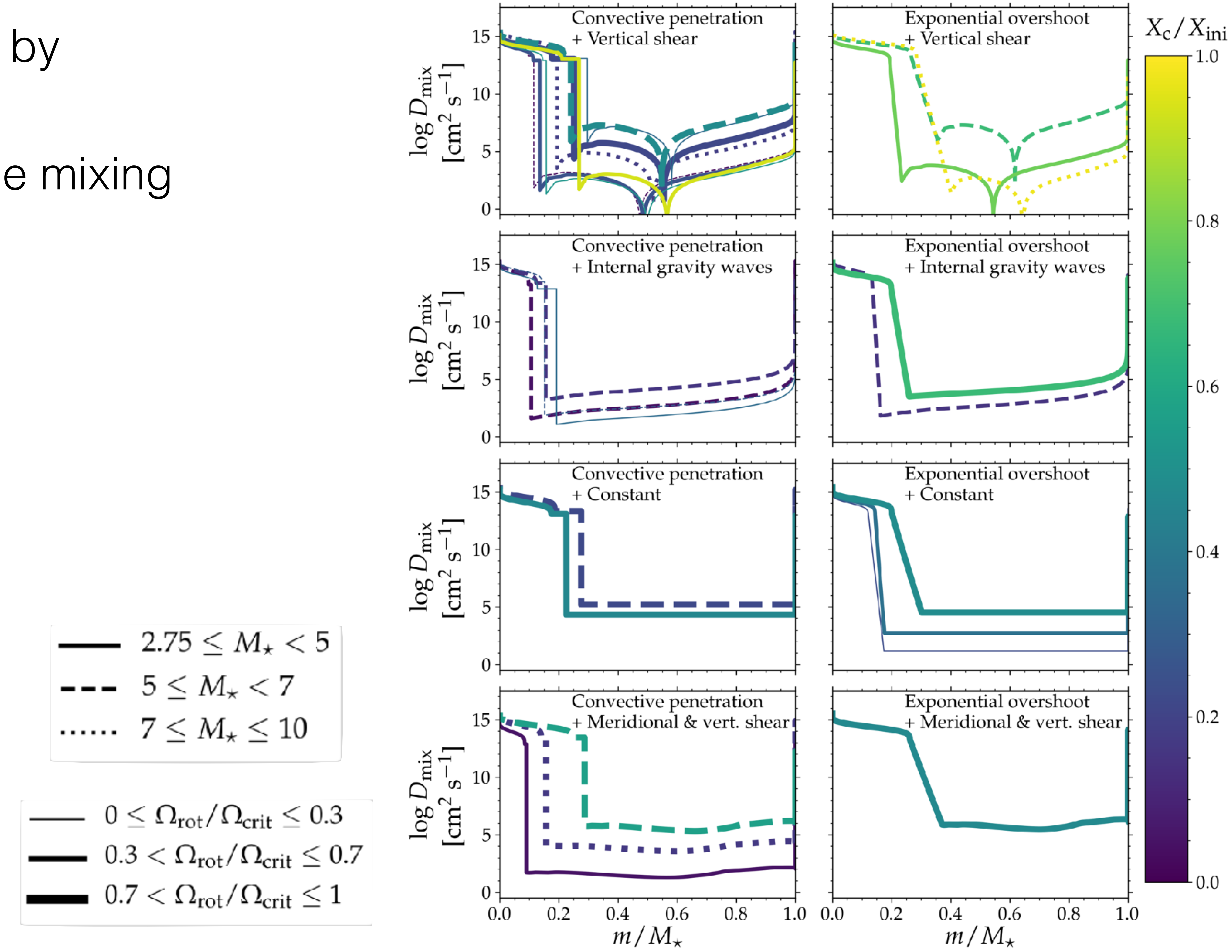
See also:
Pápics et al. (2017)
Pedersen et al. (2020, 2021)

# Asteroseismic results for interior mixing: SPB stars

Ensemble modelling of 26 SPBs observed by *Kepler* reveals interior mixing profiles:

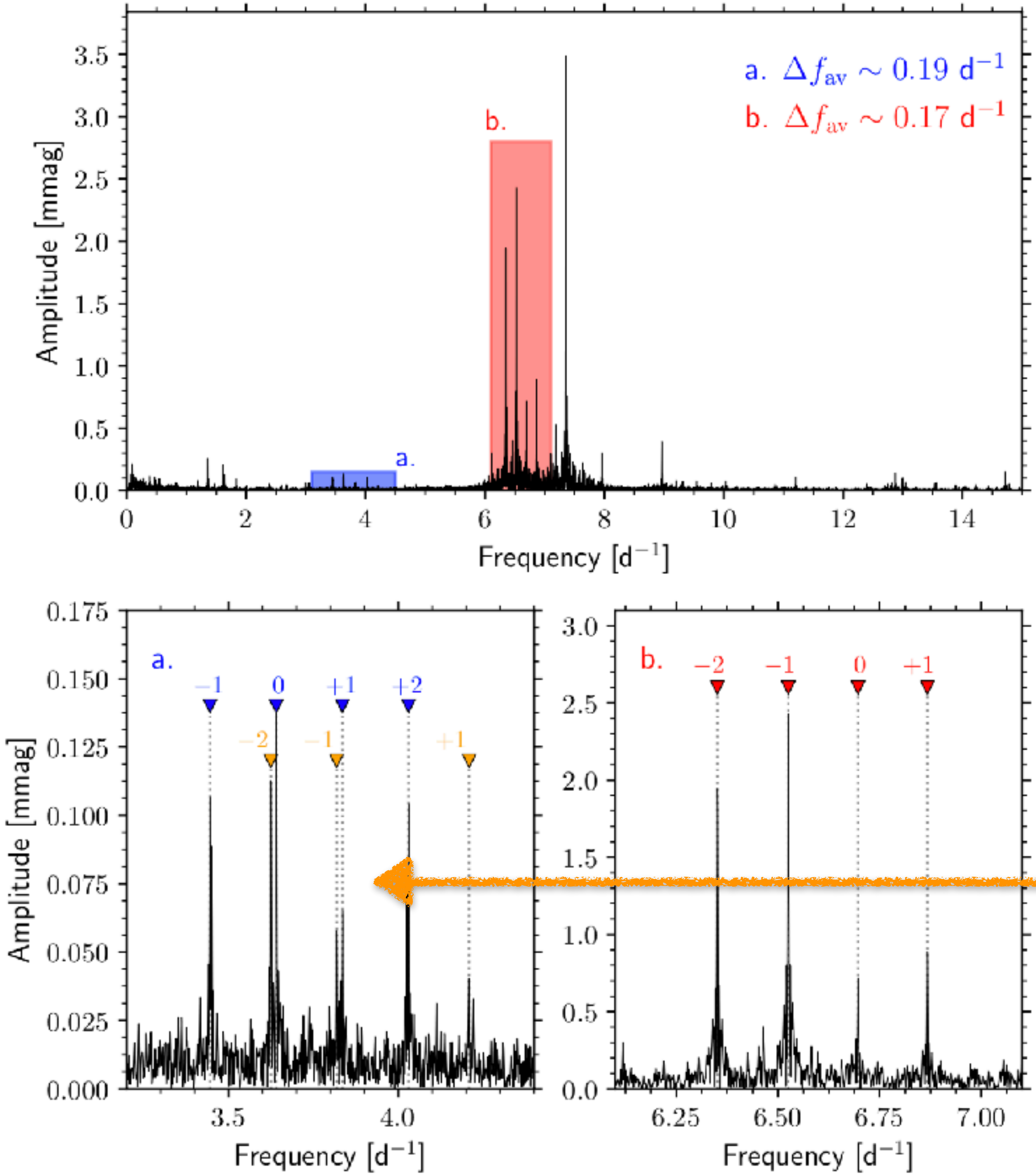
- diverse *shape* and *amount* of envelope mixing
- quasi-rigid rotation





Pedersen et al. (2021)

# HD192575: a new β Cep star with TESS



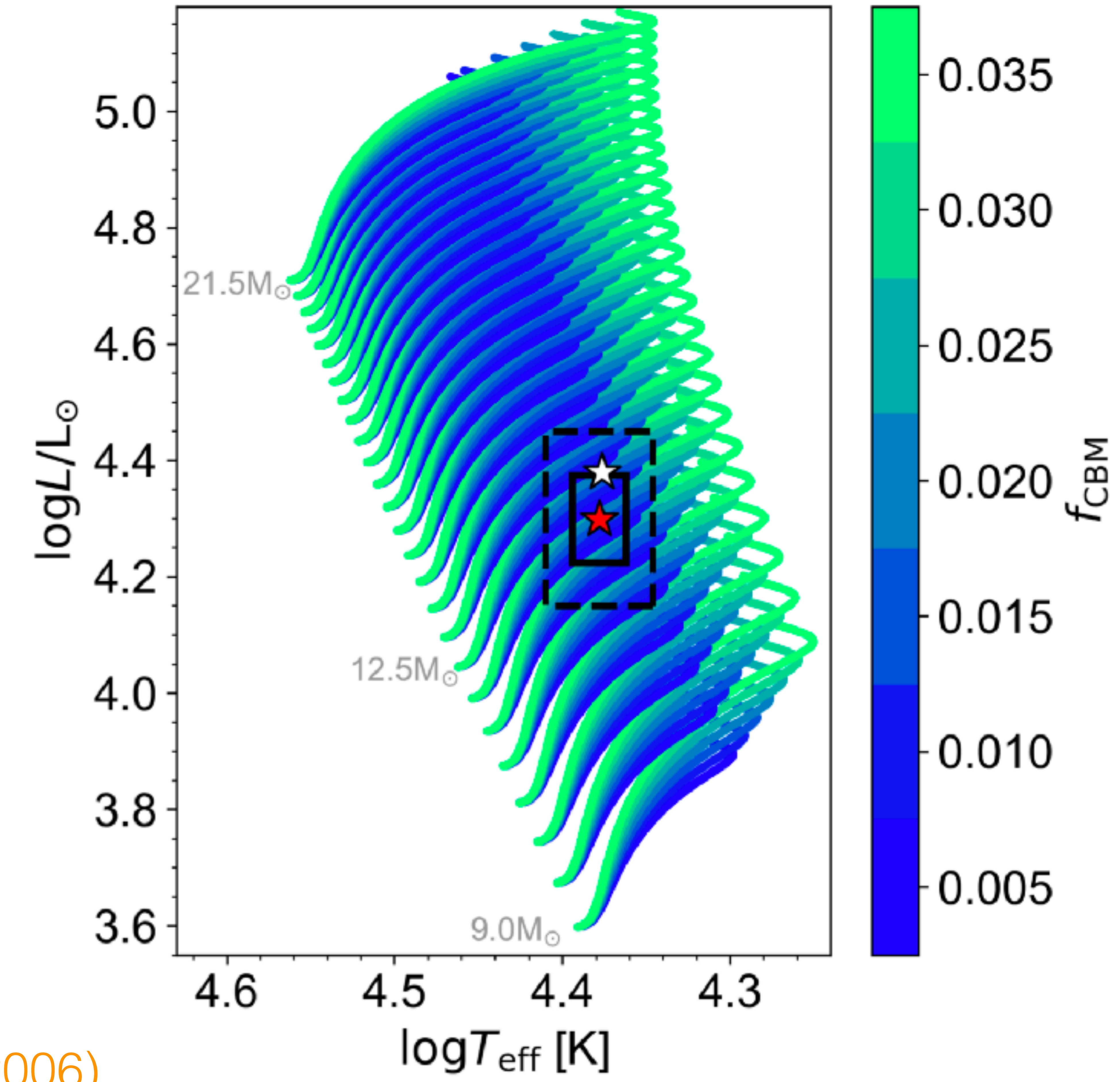
pressure mode
rotational multiplet

gravity mode
rotational multiplet

avoided crossing
between two ℓ = 2
gravity-mode
rotational multiplets

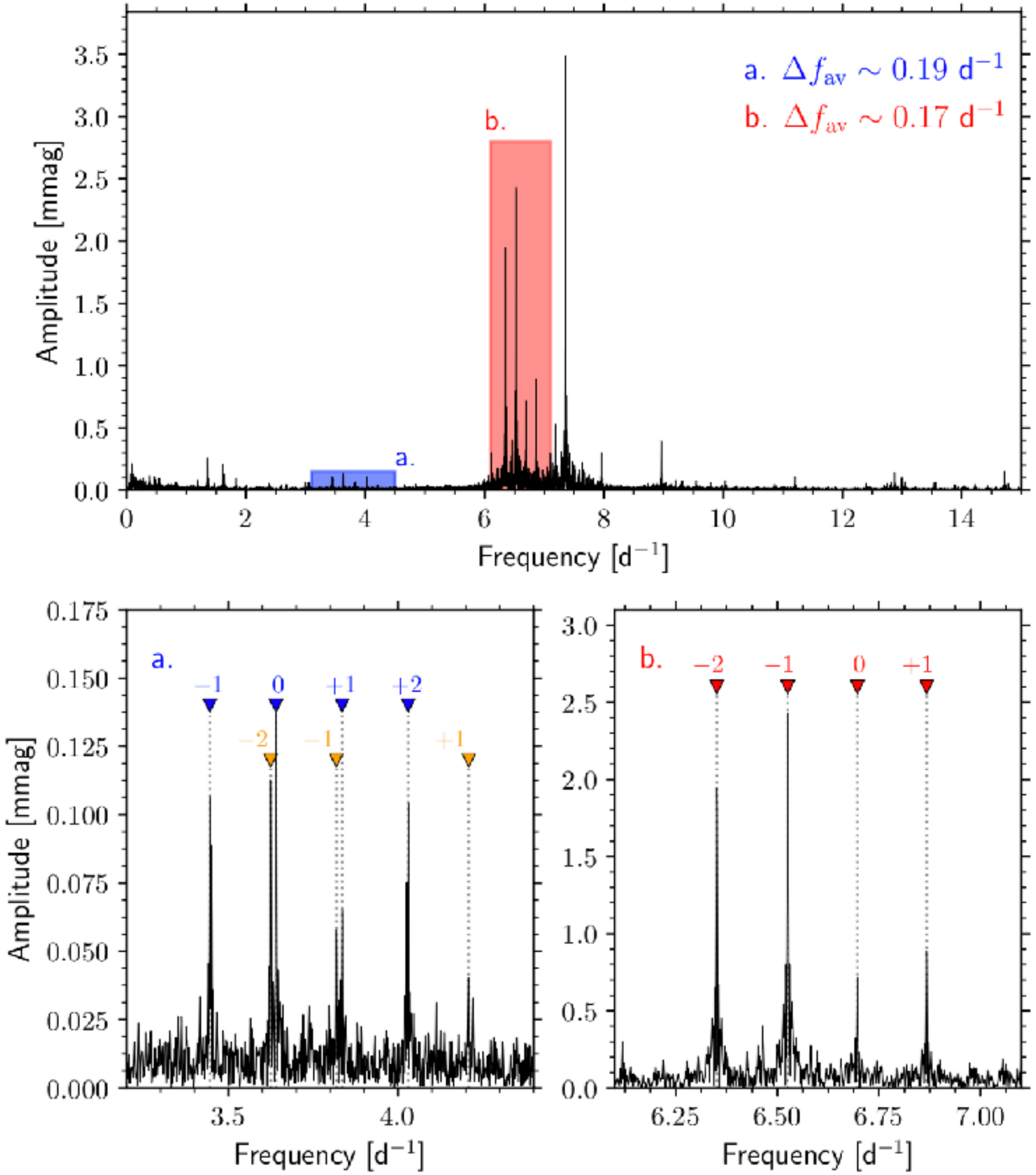
(e.g. Mazumdar et al. 2006)

Grid of 1D **MESA** models:



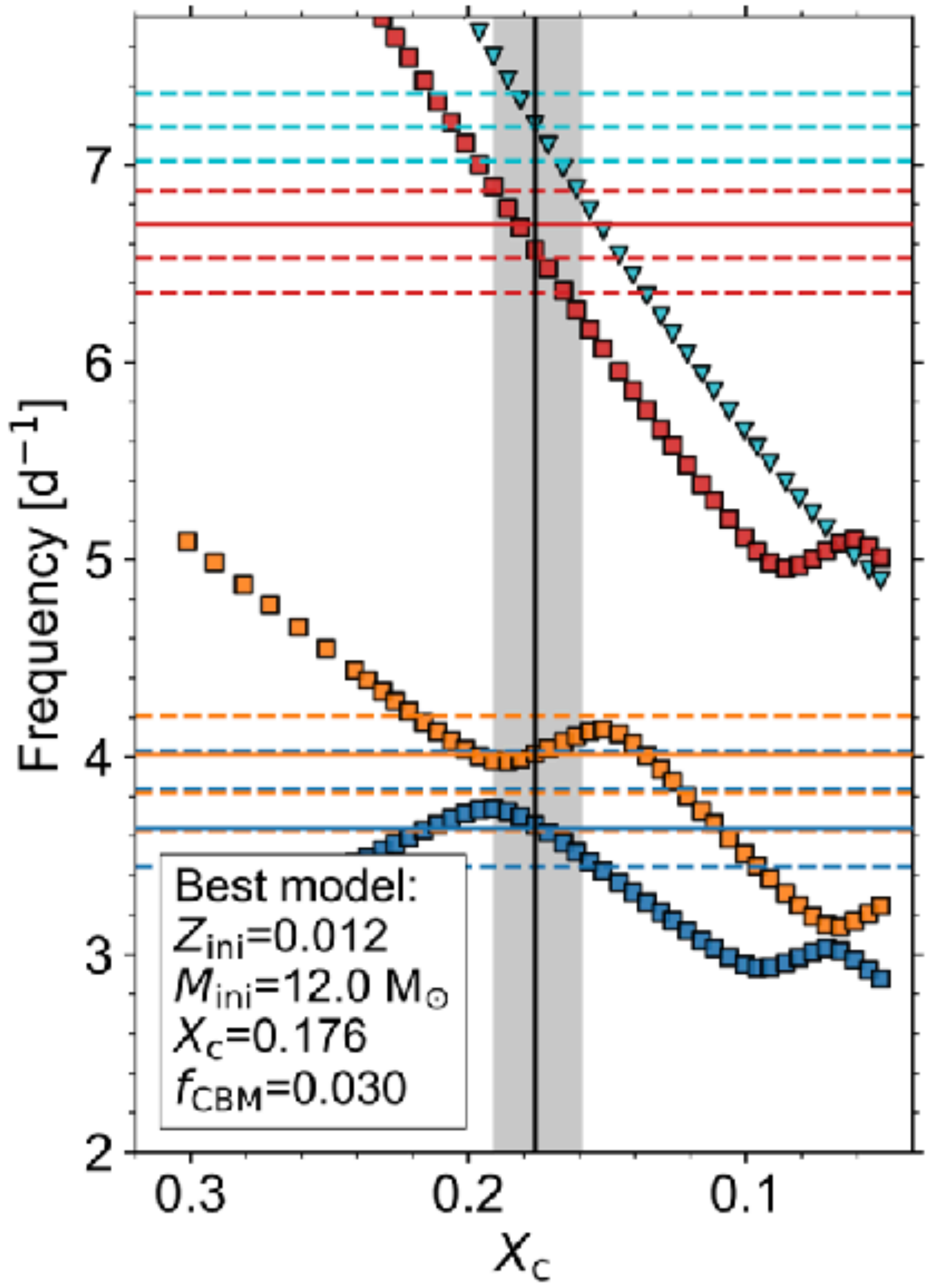
Burssens, Bowman et al. (2023)

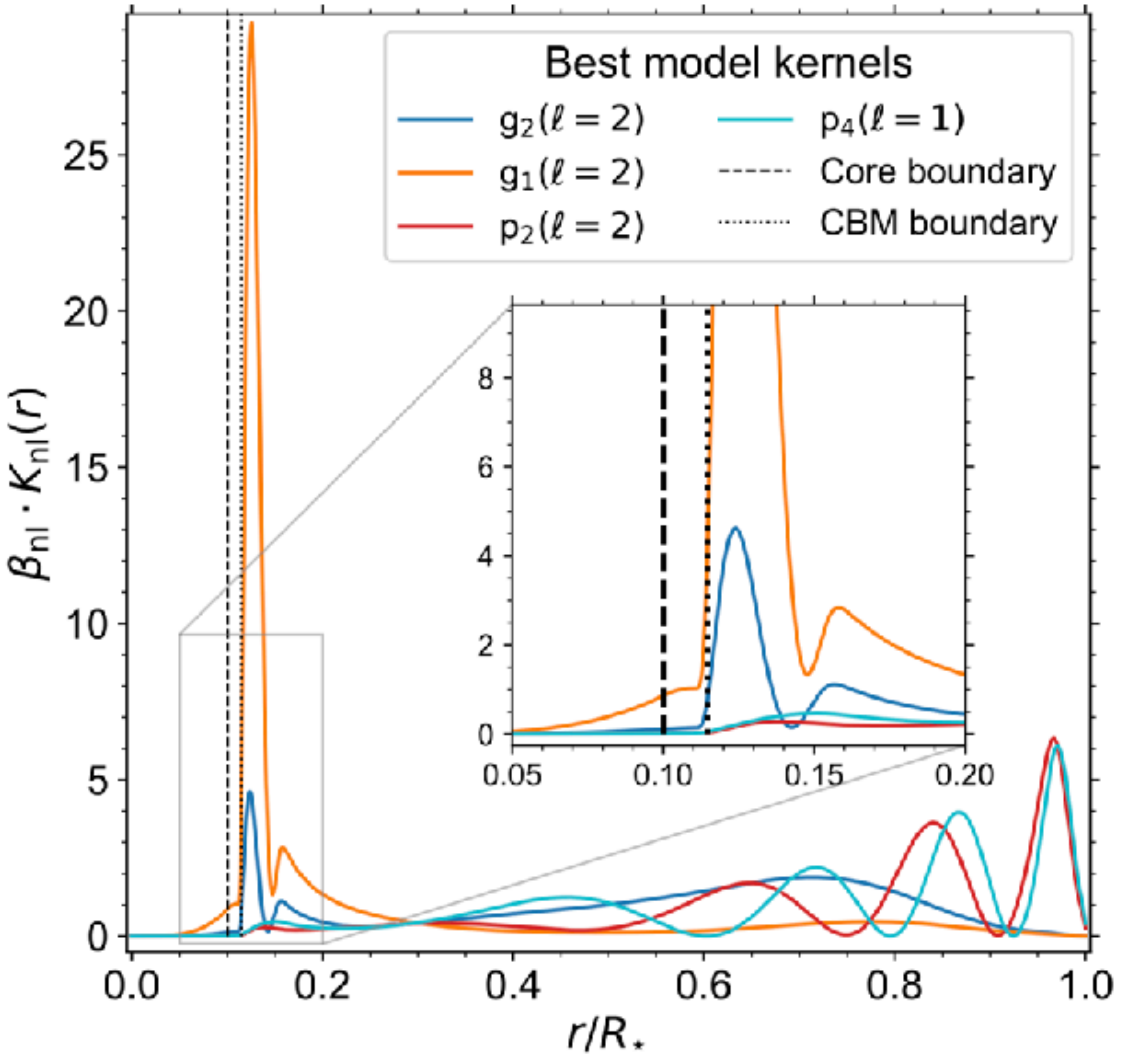
# HD192575: avoided crossing of multiplets



**Avoided crossing** among rotational multiplets:

- very(!) tight age constraint
- full core-to-surface rotation profile





Burssens, Bowman et al. (2023)

# HD192575: forward asteroseismic modelling

**Mahalanobis Distance** superior to $\chi^2$ as merit function:

$$\mathrm{MD_j} \equiv \left(\boldsymbol{Y}_\mathrm{j}^\mathrm{theo} - \boldsymbol{Y}^\mathrm{obs}\right)^\mathrm{T} (\mathrm{V} + \Sigma)^{-1} \left(\boldsymbol{Y}_\mathrm{j}^\mathrm{theo} - \boldsymbol{Y}^\mathrm{obs}\right)$$

➔ includes theoretical uncertainties

➔ penalises parameter correlations and degeneracies

**2σ confidence intervals:**

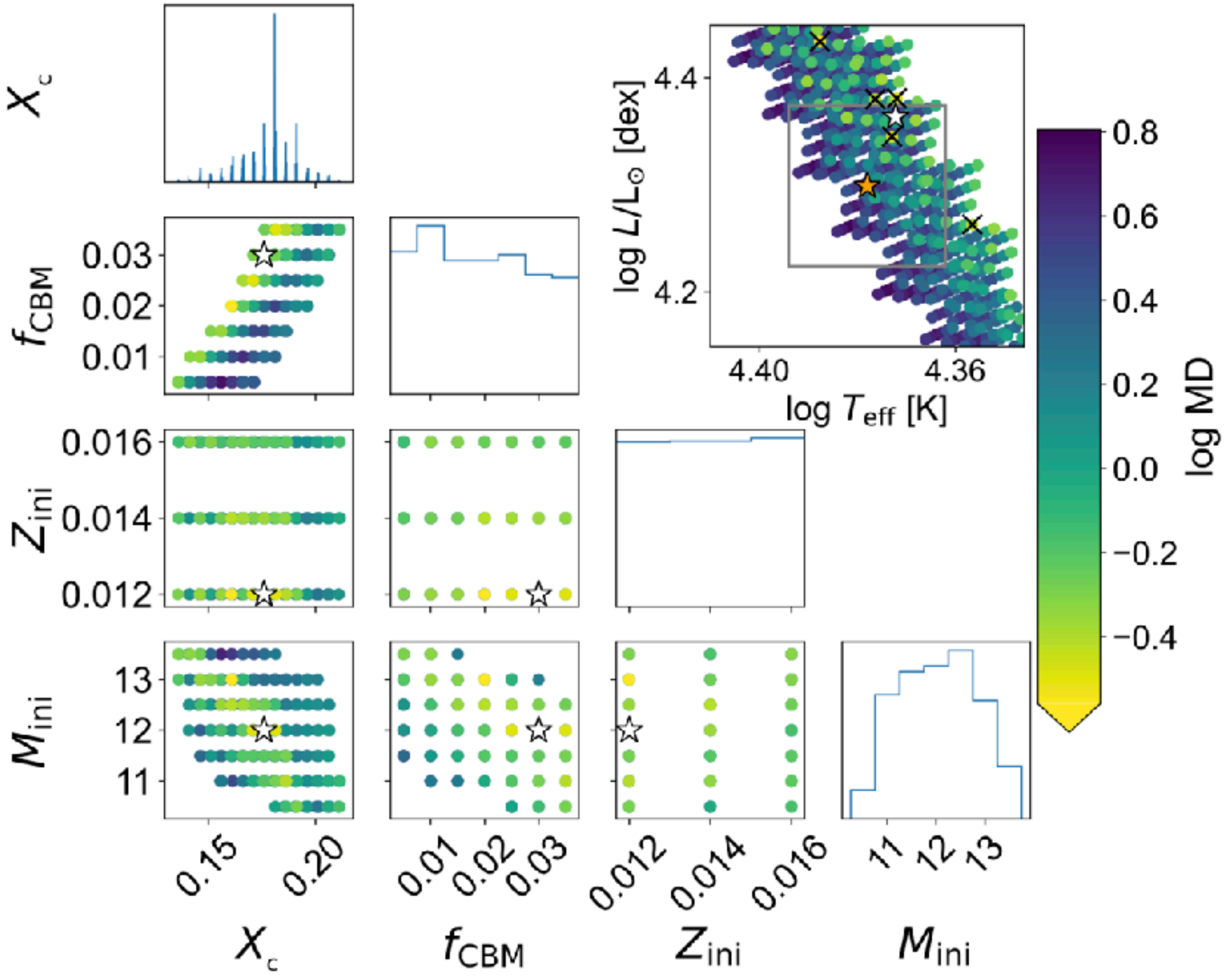
| | |
|---|---|
| $Z_\mathrm{ini}$ [dex] | $0.012^{+0.004}_{-0.000}$ |
| $M_\mathrm{ini}$ [M$_\odot$] | $12.0^{+1.5}_{-1.5}$ |
| $X_\mathrm{c}$ | $0.176^{+0.035}_{-0.040}$ |
| $f_\mathrm{CBM}$ | $0.030^{+0.005}_{-0.025}$ |
| Age [Myr] | $17.0^{+4.7}_{-5.4}$ |
| $M_\mathrm{cc}$ [M$_\odot$] | $2.9^{+0.5}_{-0.8}$ |
| $R_\mathrm{cc}$ [R$_\odot$] | $0.91^{+0.11}_{-0.15}$ |
| $R_{\star,\mathrm{seism}}$ [R$_\odot$] | $9.1^{+0.8}_{-1.7}$ |

From only 1-year TESS light curve:

1σ (age) < 15%

1σ (mass) < 10%

1σ (m$_\mathrm{core}$) < 15%



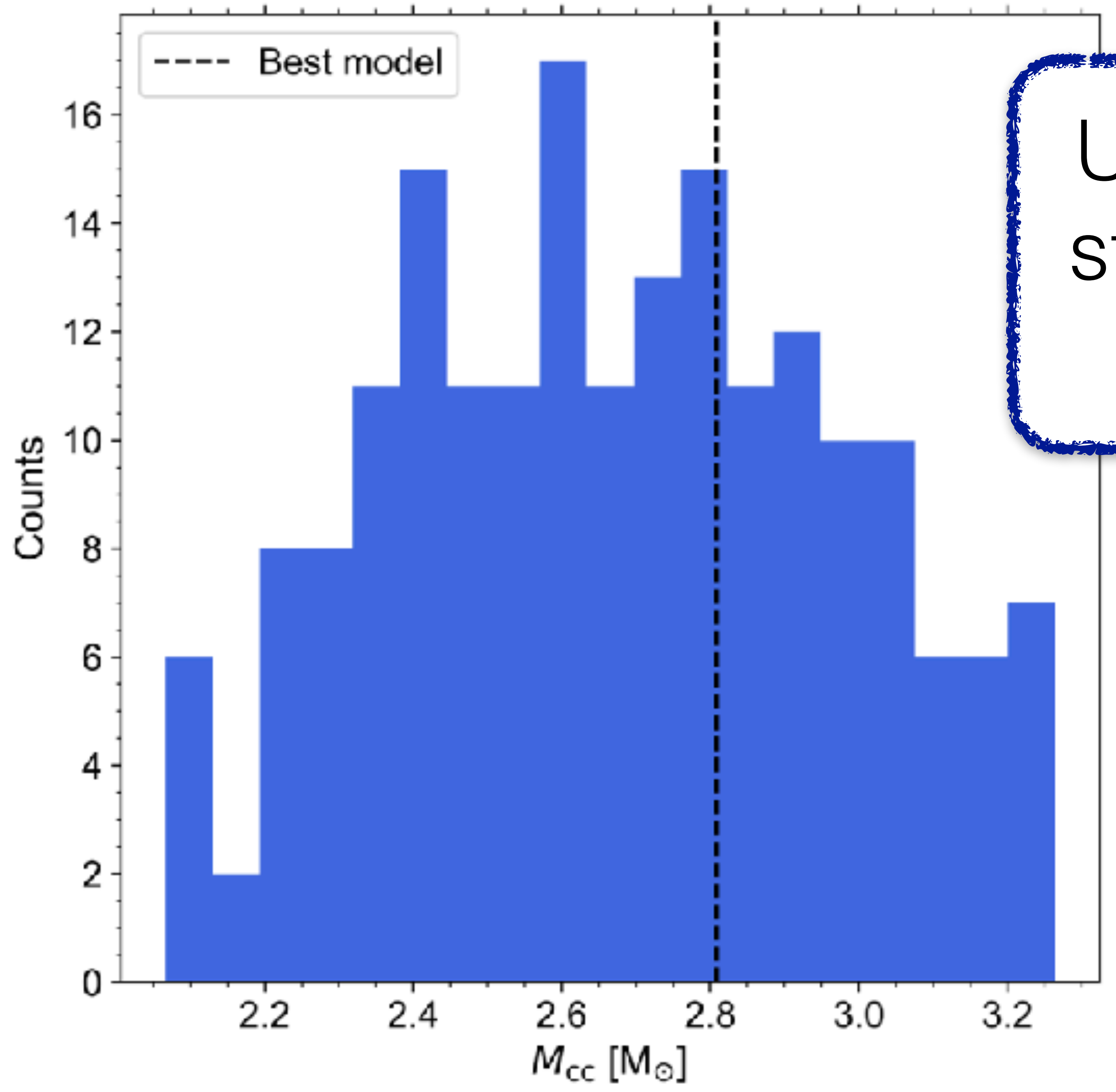
Burssens, Bowman et al. (2023)

# Interior rotation and mixing profiles

**Mahalanobis Distance** superior to $\chi^2$ as merit function:

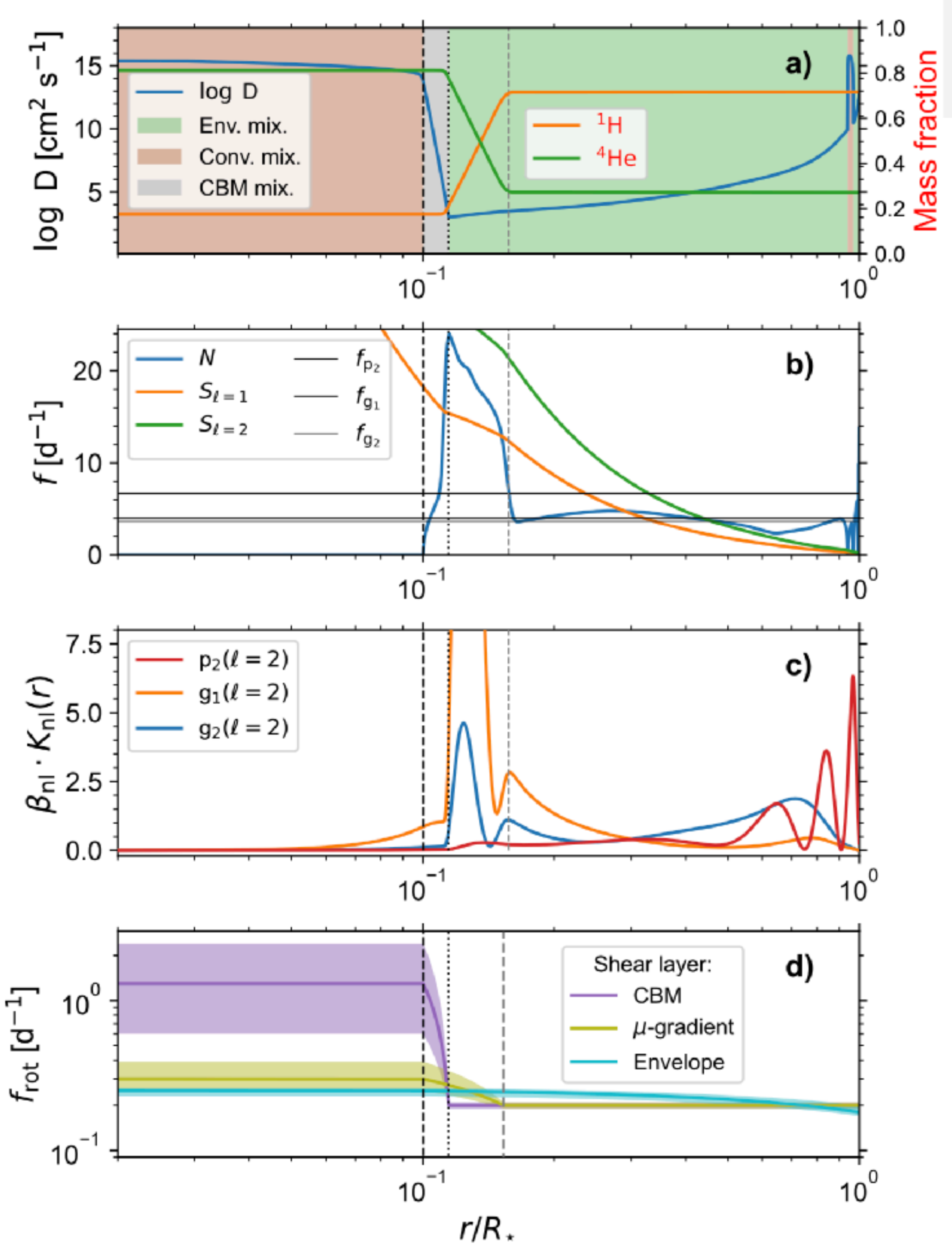
➔ includes theoretical uncertainties

➔ penalises parameter correlations and degeneracies



Uncertainties based on statistical sampling and full error propagation

$\Omega_{core} / \Omega_{env} = 1.5 \pm 0.4$



Burssens, Bowman et al. (2023)

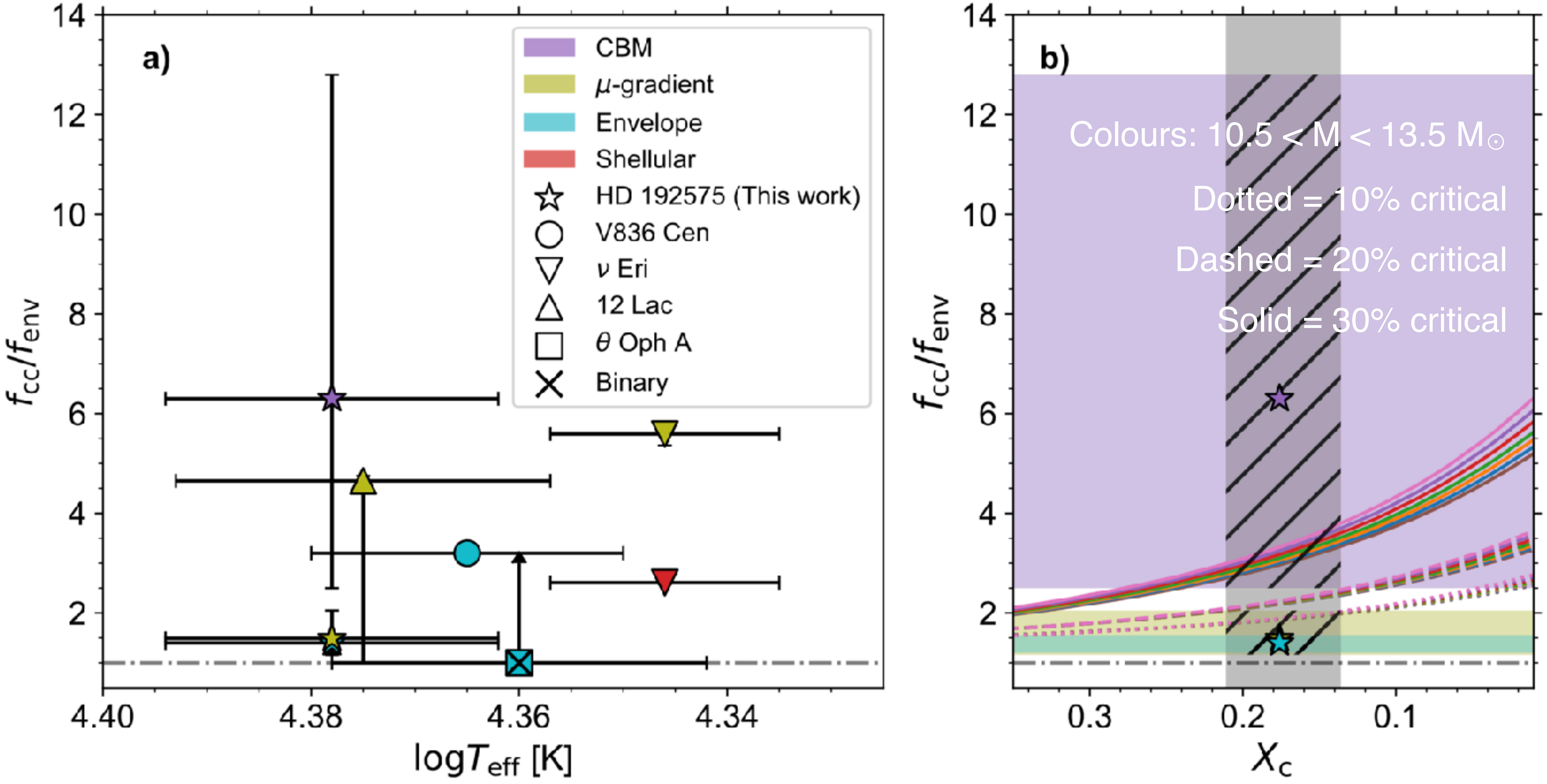
# Efficiency of angular momentum transport

Near-rigid rotation profile:

**$\Omega_{\mathrm{core}} / \Omega_{\mathrm{env}} = 1.5 \pm 0.4$**

Very efficient **angular momentum transport** compared to rotating models

**μ gradient zone** most likely shear layer



Colours: $10.5 < M < 13.5\ M_\odot$

Dotted = 10% critical

Dashed = 20% critical

Solid = 30% critical

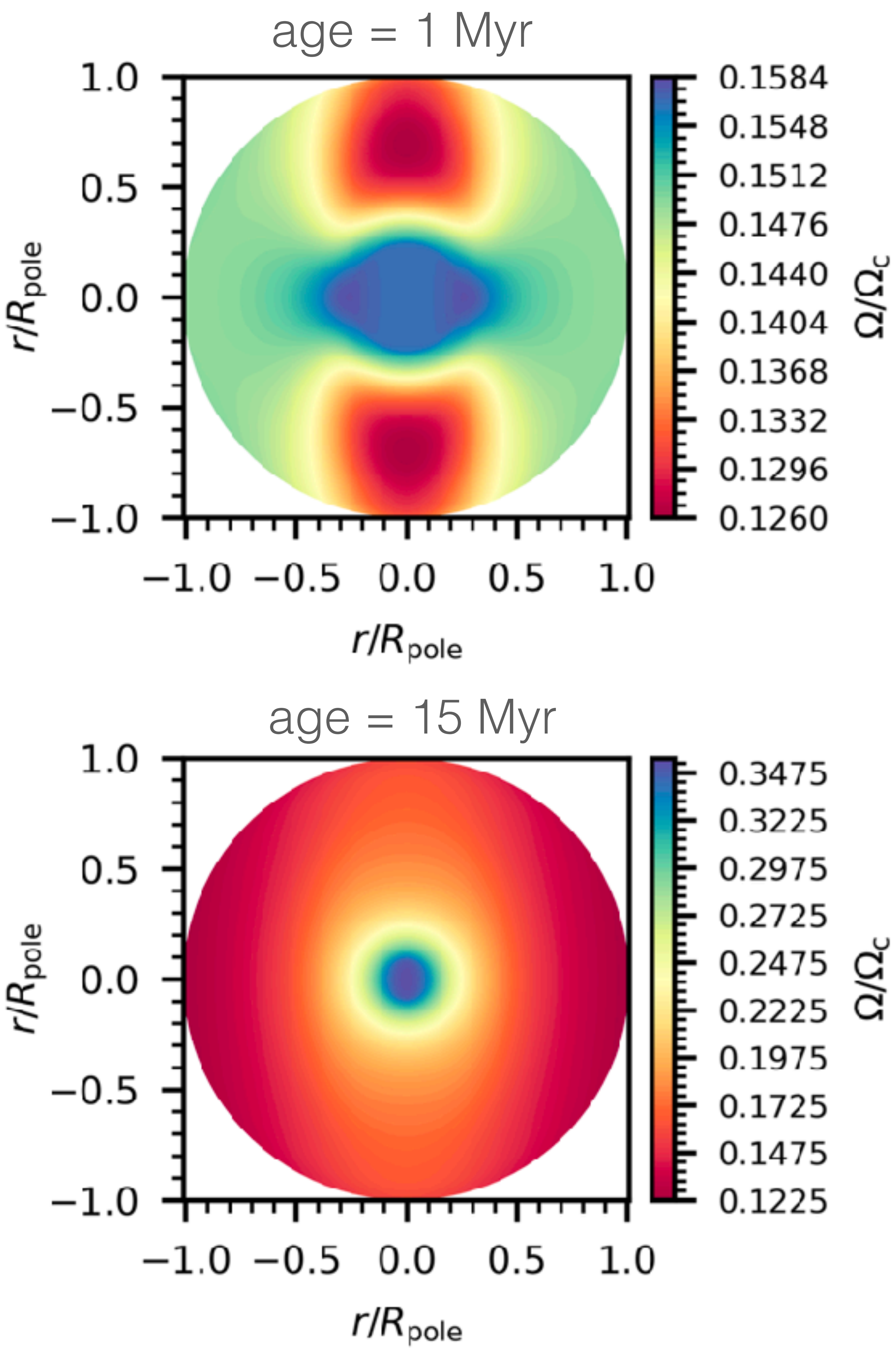
Burssens, Bowman et al. (2023)

Non-magnetic rotating **`GENEC`** models from: Georgy et al. (2013)

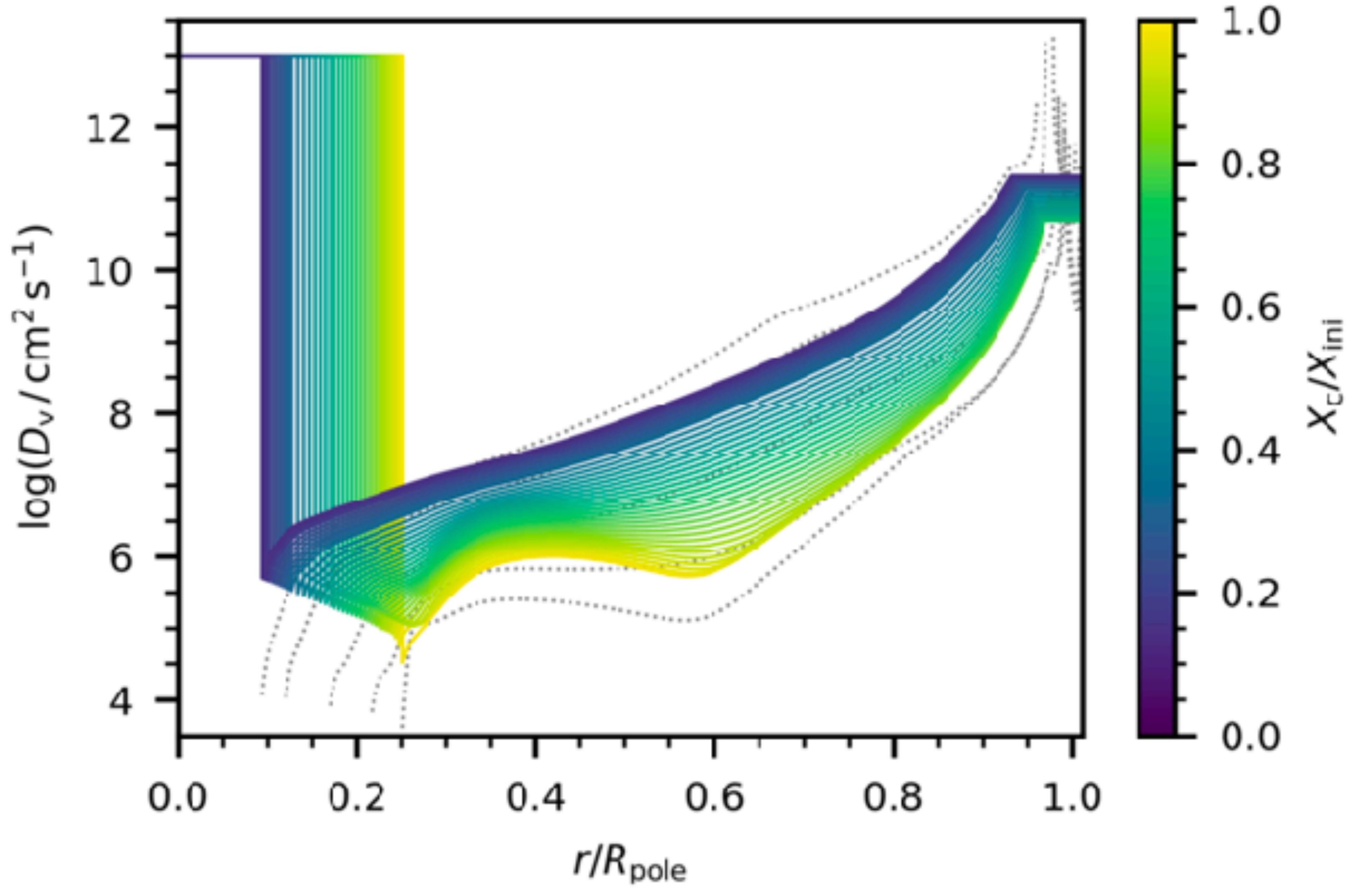
# 2D stellar evolution models

Rotation results from forward asteroseismic modelling using 1D `MESA` models consistent with **rotating 2D `ESTER`** models:

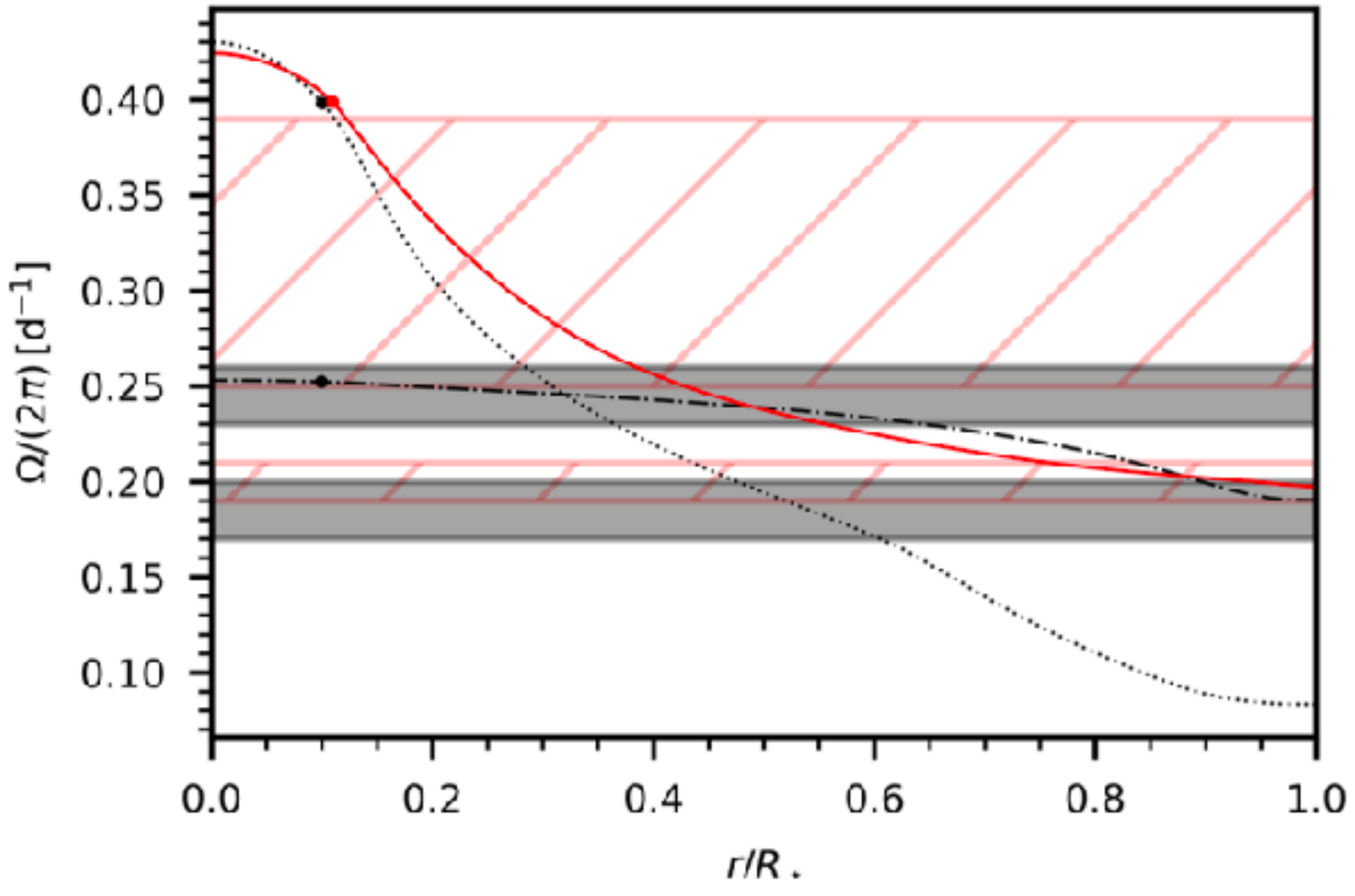
- non-rigid rotation profile
- shear layer is the μ-gradient zone



Interior mixing profile:

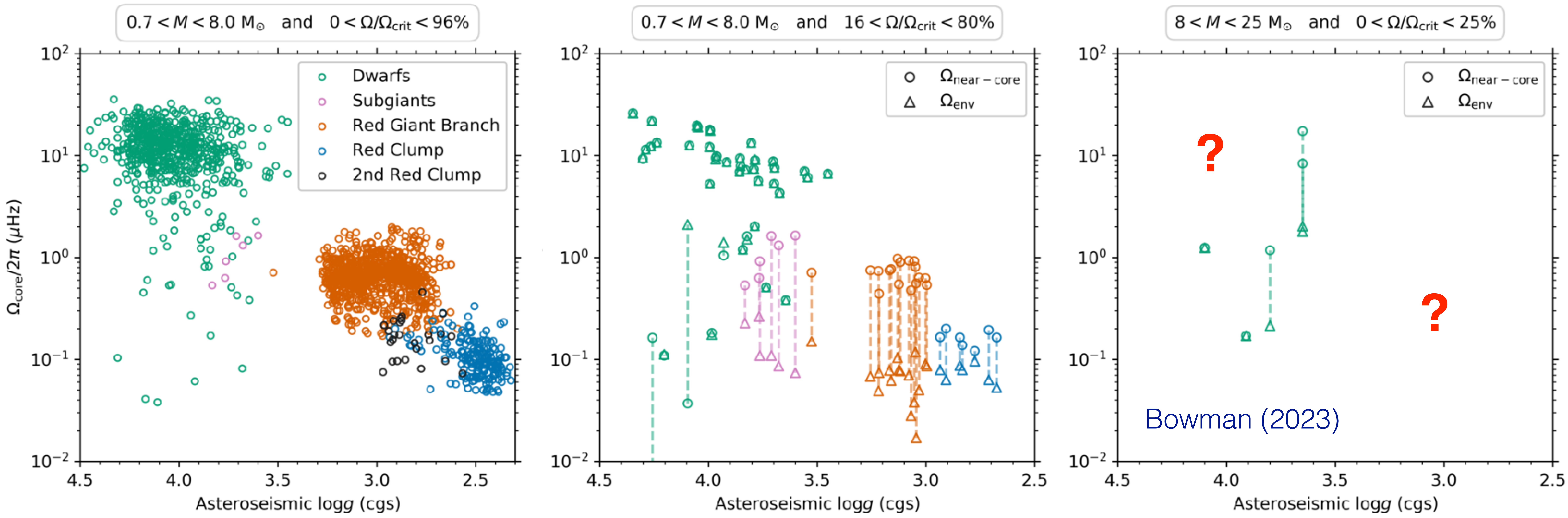


Interior rotation profile:



Mombarg, Rieutord, Espinosa Lara (2023)

# Asteroseismic results for interior rotation



Quasi-rigid interior **rotation** measurements across stellar evolution mandate strong **angular momentum transport** mechanism(s)

based on:
Aerts, Mathis, & Rogers (2019)
Li et al. (2019)
Bowman (2020)
Pedersen et al. (2021)

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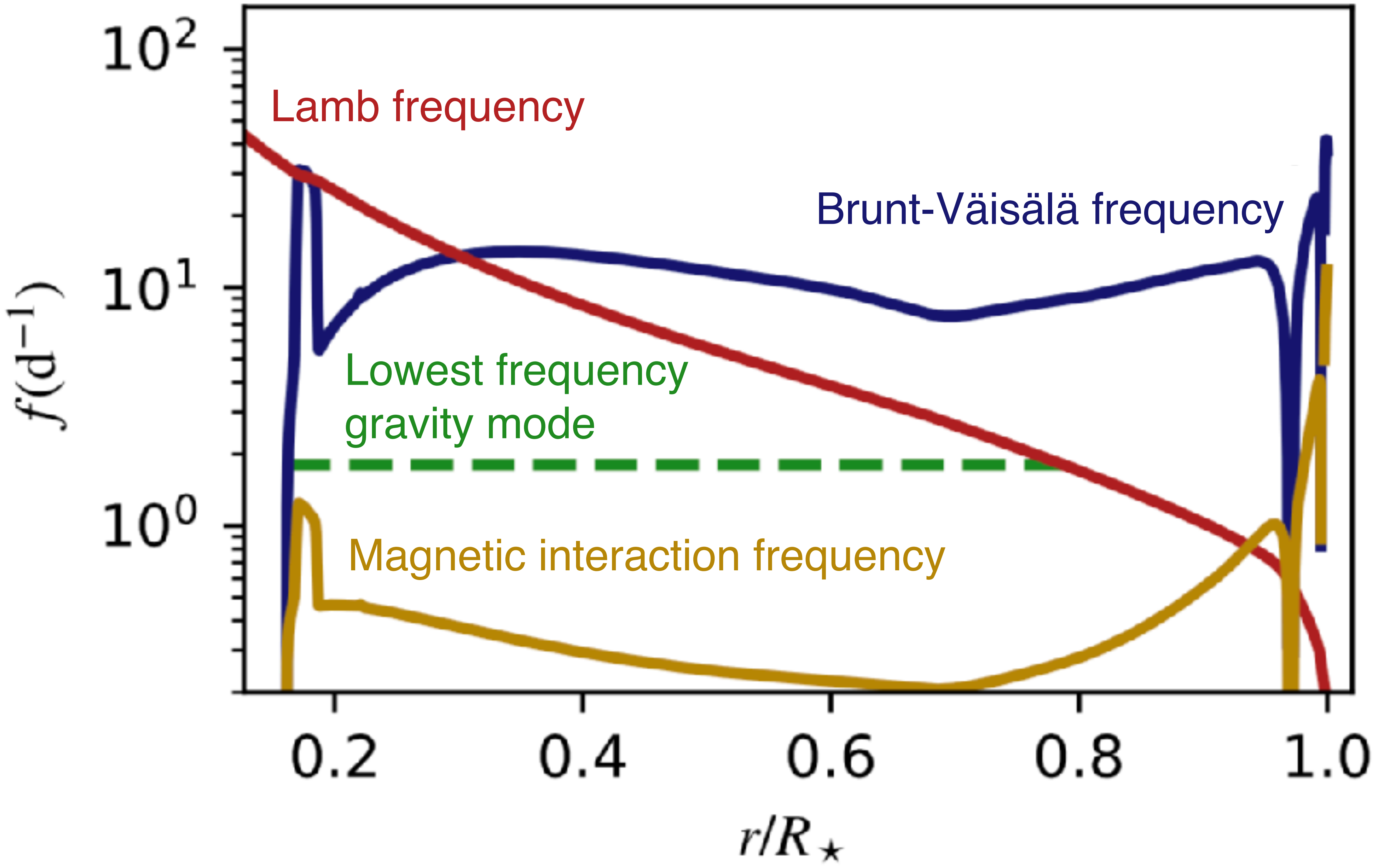
4. Stochastic low-frequency variability: gravity waves and turbulence

# What about magnetic fields?

Case study of **magnetic SPB star** HD 43317:

- perturbation of pulsation frequency
- damping of pulsation standing wave
- suppression of pulsation excitation mechanism



Magnetic field **damps** standing gravity wave if:

$$f \lesssim f_B = \frac{1}{2\pi}\sqrt{\frac{B_r}{\pi\rho}\frac{N\Lambda}{r}} \quad \text{where: } \Lambda = \sqrt{\ell(\ell+1)}$$

Assuming:

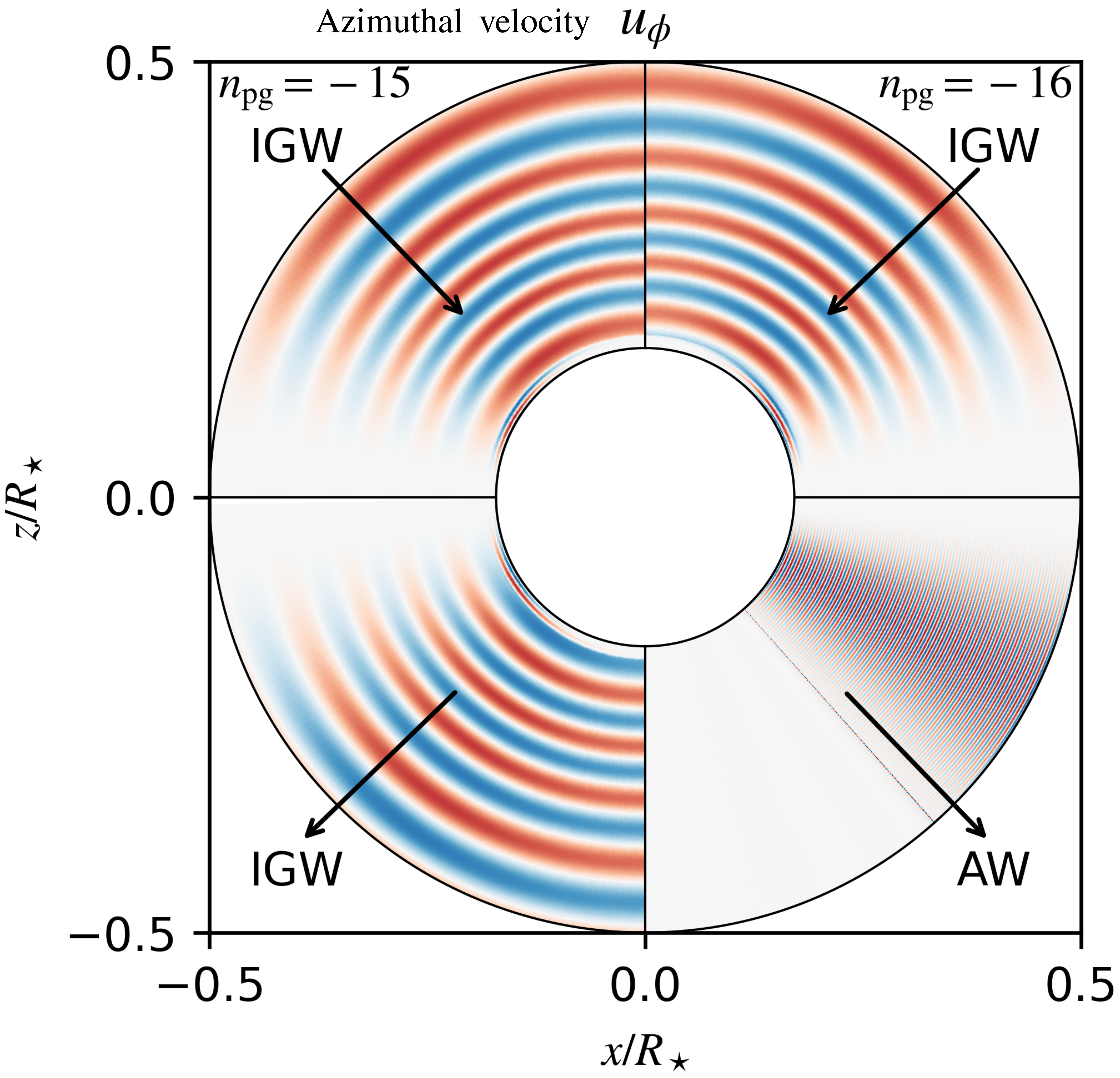
- dipolar magnetic field geometry ($\propto 1/r^3$)
- range of self-excited gravity modes

Upper limit for **near-core magnetic field**:

$$B_r \simeq 4.7 \times 10^5 \mathrm{G} \text{ at } r = 0.18 R_\star$$

Buysschaert et al. (2018)
Lecoanet, Bowman, Van Reeth (2022)

# MHD simulations of magnetic SPB star HD43317



Magnetic field needed to damp gravity modes:

➔ rotating MHD simulations with the `DEDALUS` code

eigenvalue problem solved using WKBJ approximation

High radial order g modes (i.e. |n| >>1) strongly interact with the magnetic field:

- not possible to set up a standing wave
- upper limit for magnetic field strength

Upper limit for **near-core magnetic field**:

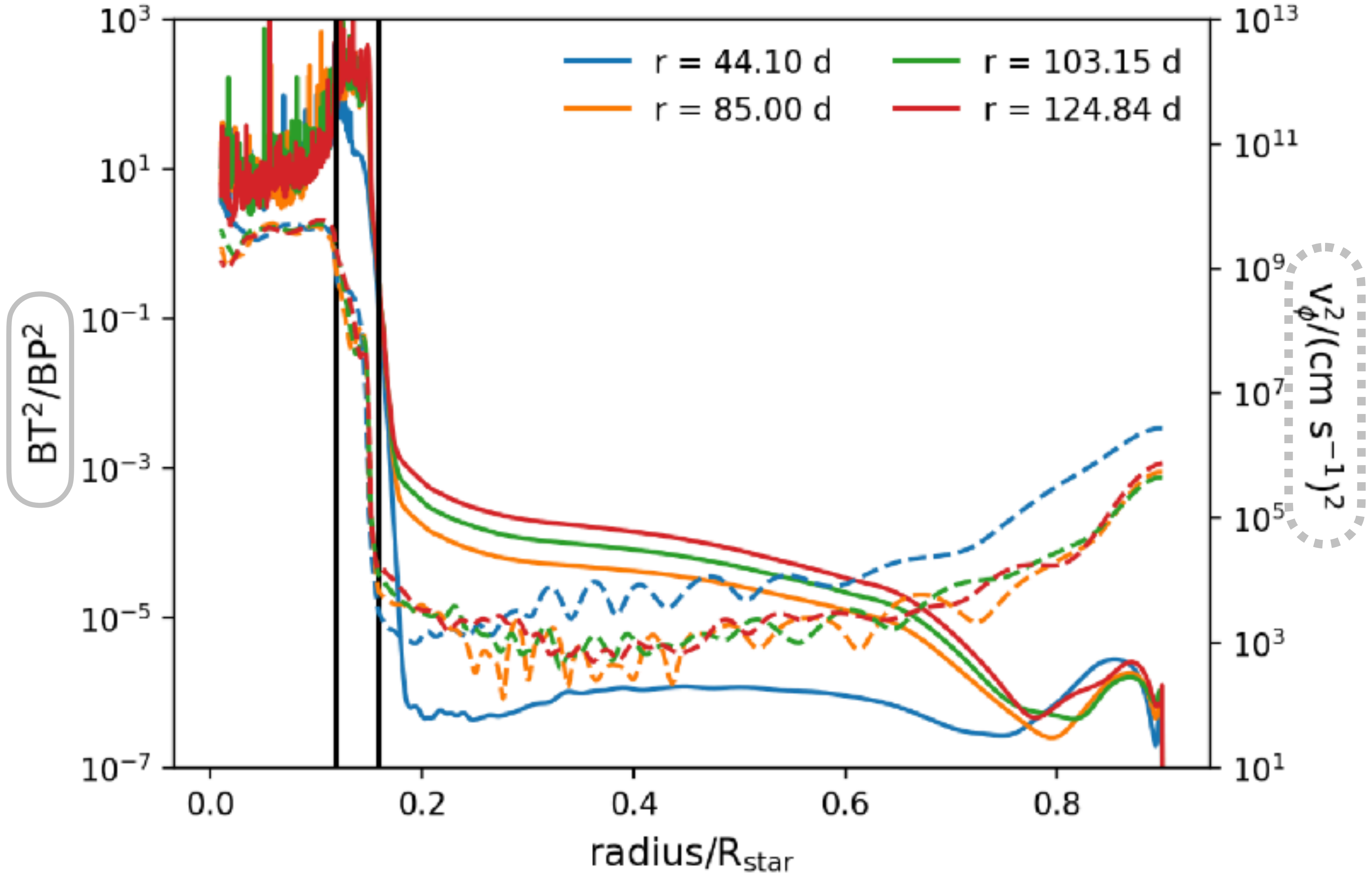
$$B_r \simeq 4.7 \times 10^5 \mathrm{G} \text{ at } r = 0.18 R_\star$$

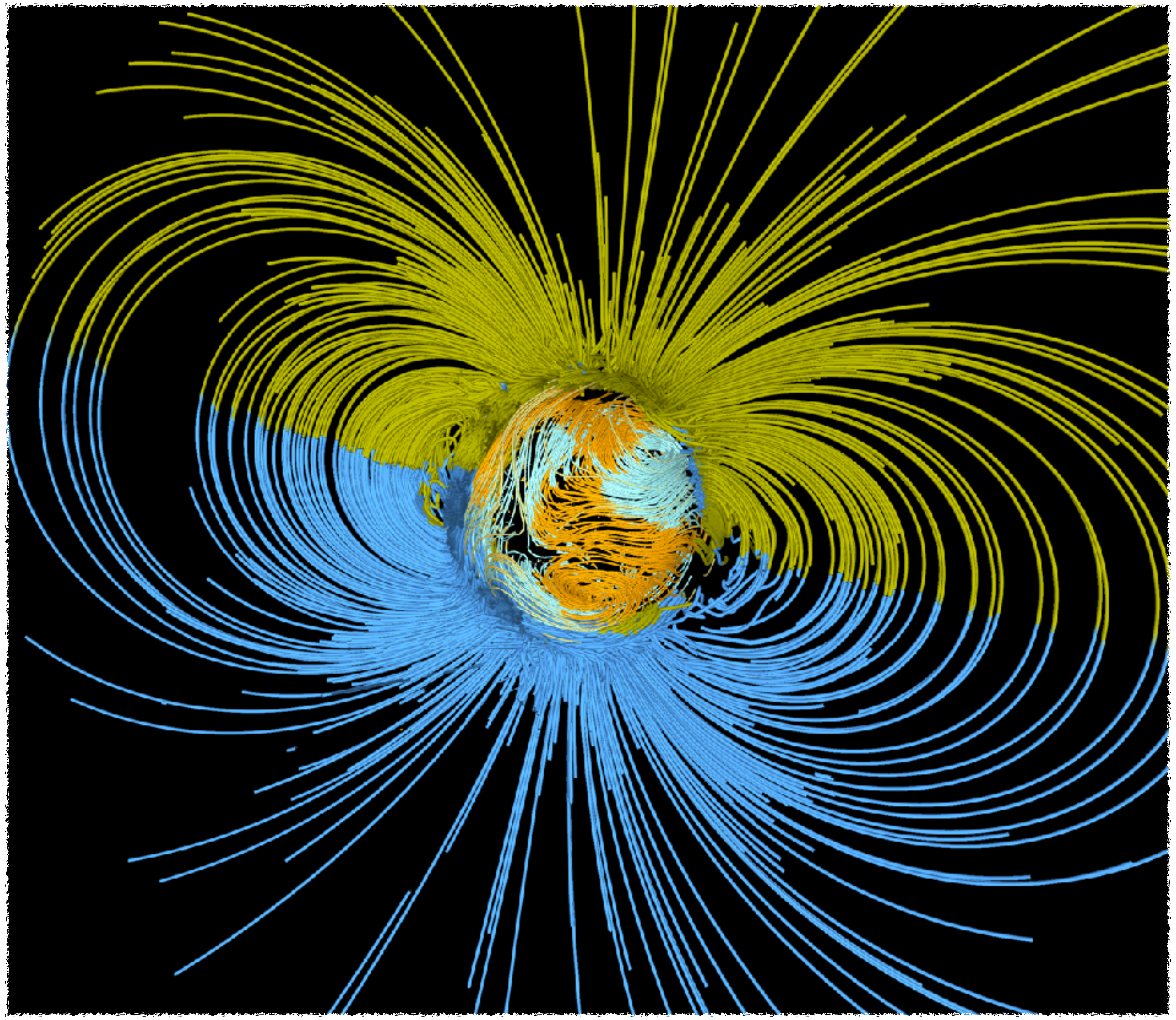
Lecoanet, Bowman, Van Reeth (2022)

# Interior magnetic fields of massive stars

3D spherical `Rayleigh` MHD simulations:

- **toroidal field** dominates over poloidal field in the core and near core regions
- shear layer is the **μ-gradient zone**





Ratnasingam et al. (2024, under review)

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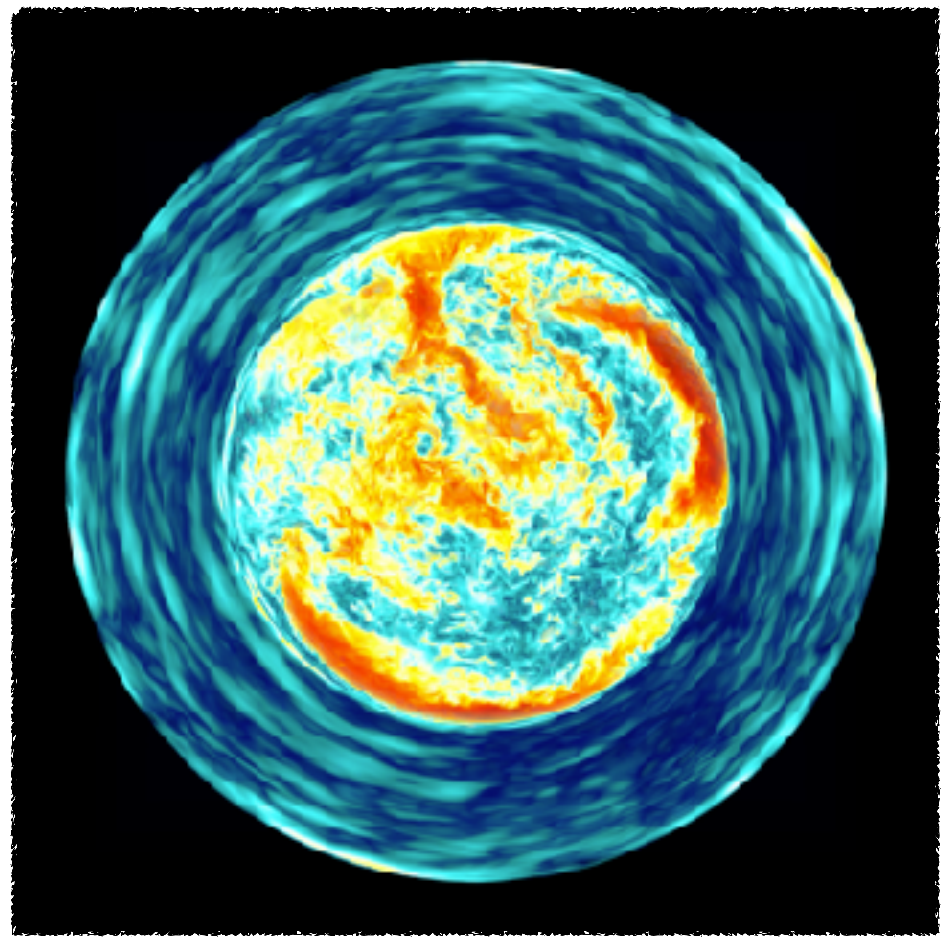
# Stochastic Low-Frequency (SLF) variability

Gravity waves from core, surface (both?), and/or winds

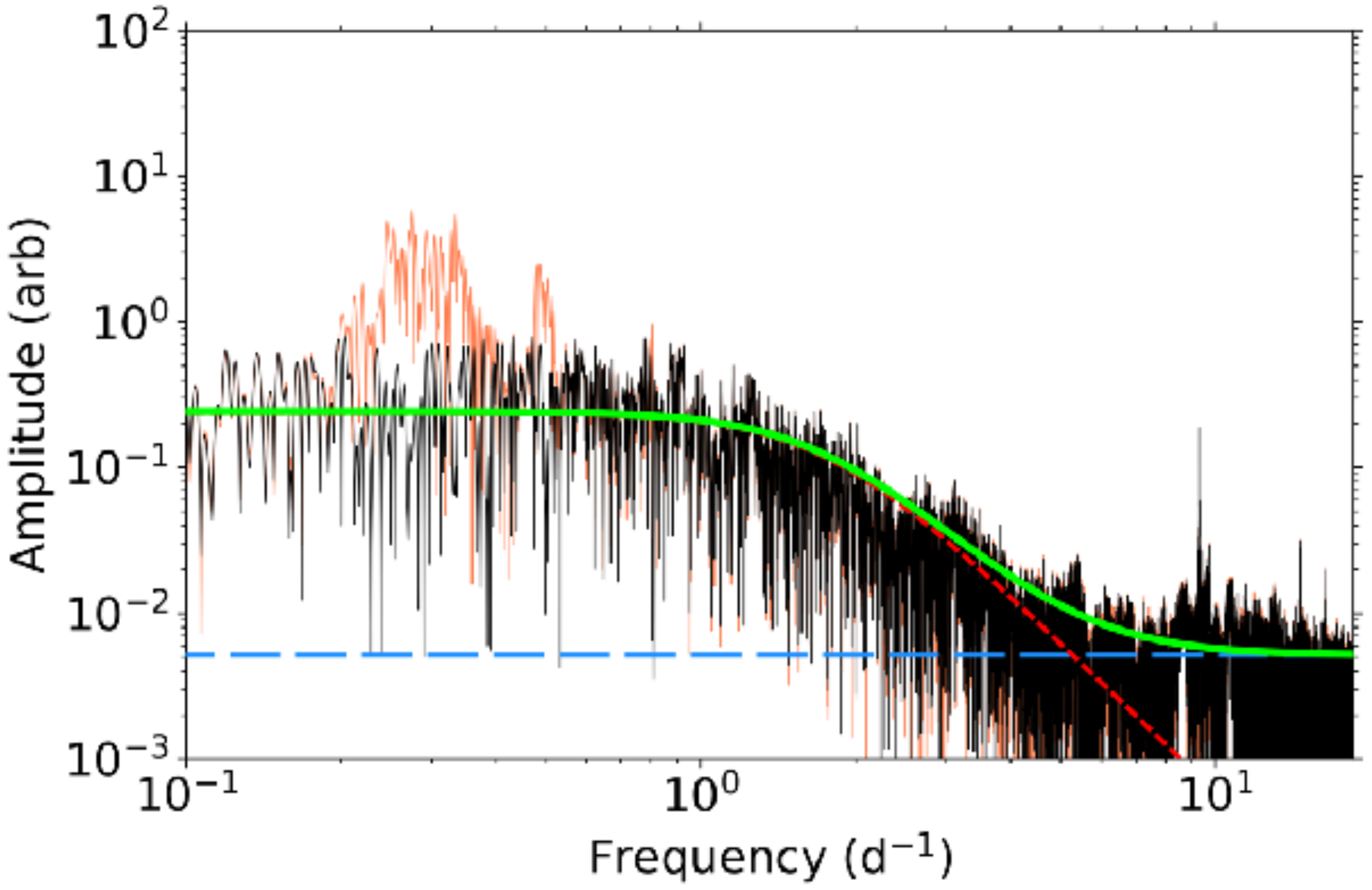
(Rogers et al. 2013, 2015;
Edelmann et al. 2019;
Horst et al. 2020; Ratnasingam et al. 2020;
Vanon et al. 2023; Thompson et al. 2024;
Lecoanet et al. 2019, 2021; Anders et al. 2023;
Krtička & Feldmeier 2021)

Sub-surface convection is **metallicity dependent:** exist in SMC stars?
(Jermyn et al. 2022, Bowman et al. 2024)

**3D hydro simulation of core convection in 25 $M_\odot$ star**



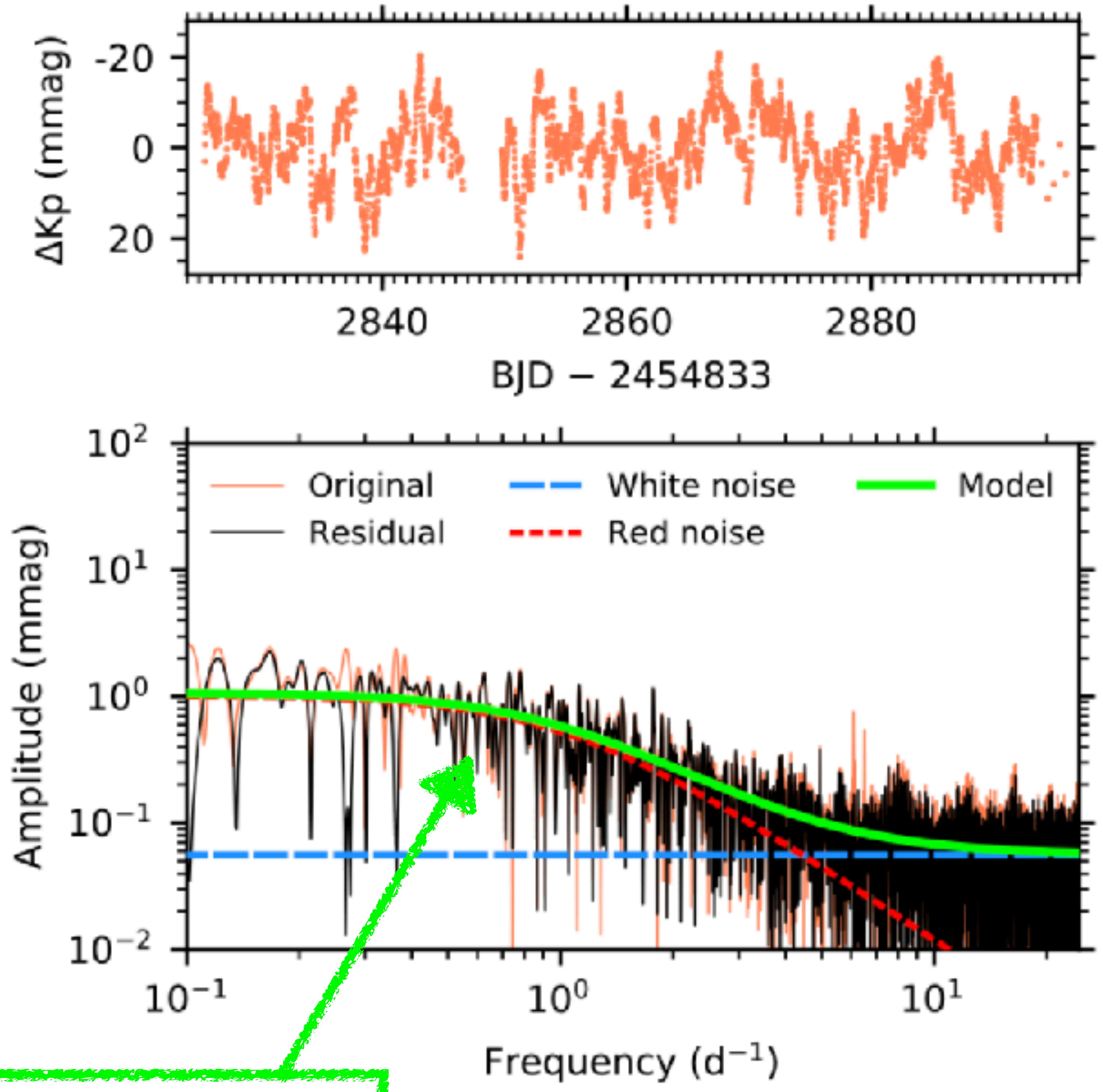
Herwig et al. (2023)



Amplitude spectrum fit:

$$\alpha(\nu) = \frac{\alpha_0}{1 + (\frac{\nu}{\nu_c})^\gamma} + C$$

**Observed 25 $M_\odot$ star**

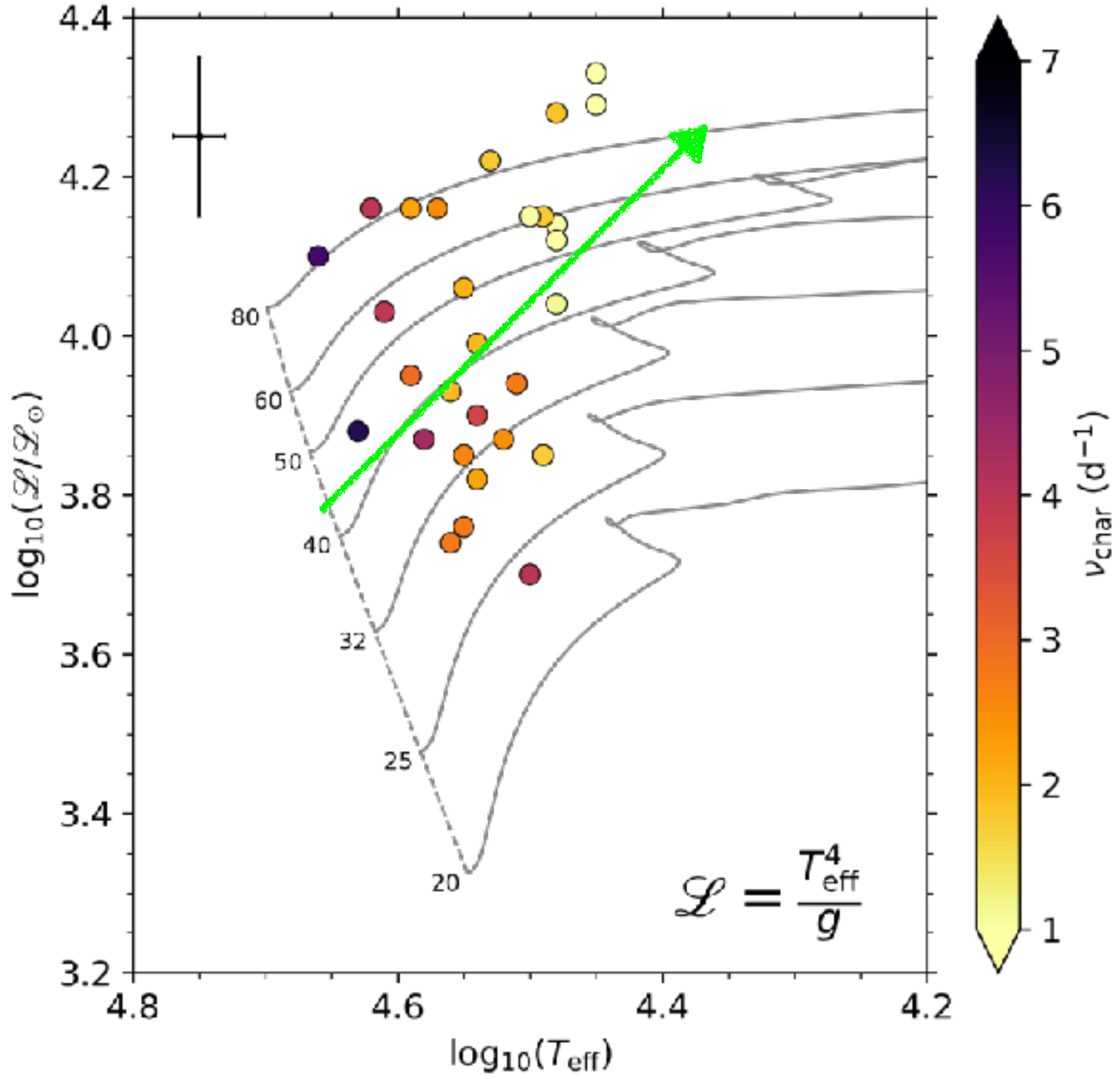


Bowman et al. (2019a, 2019b, 2020)

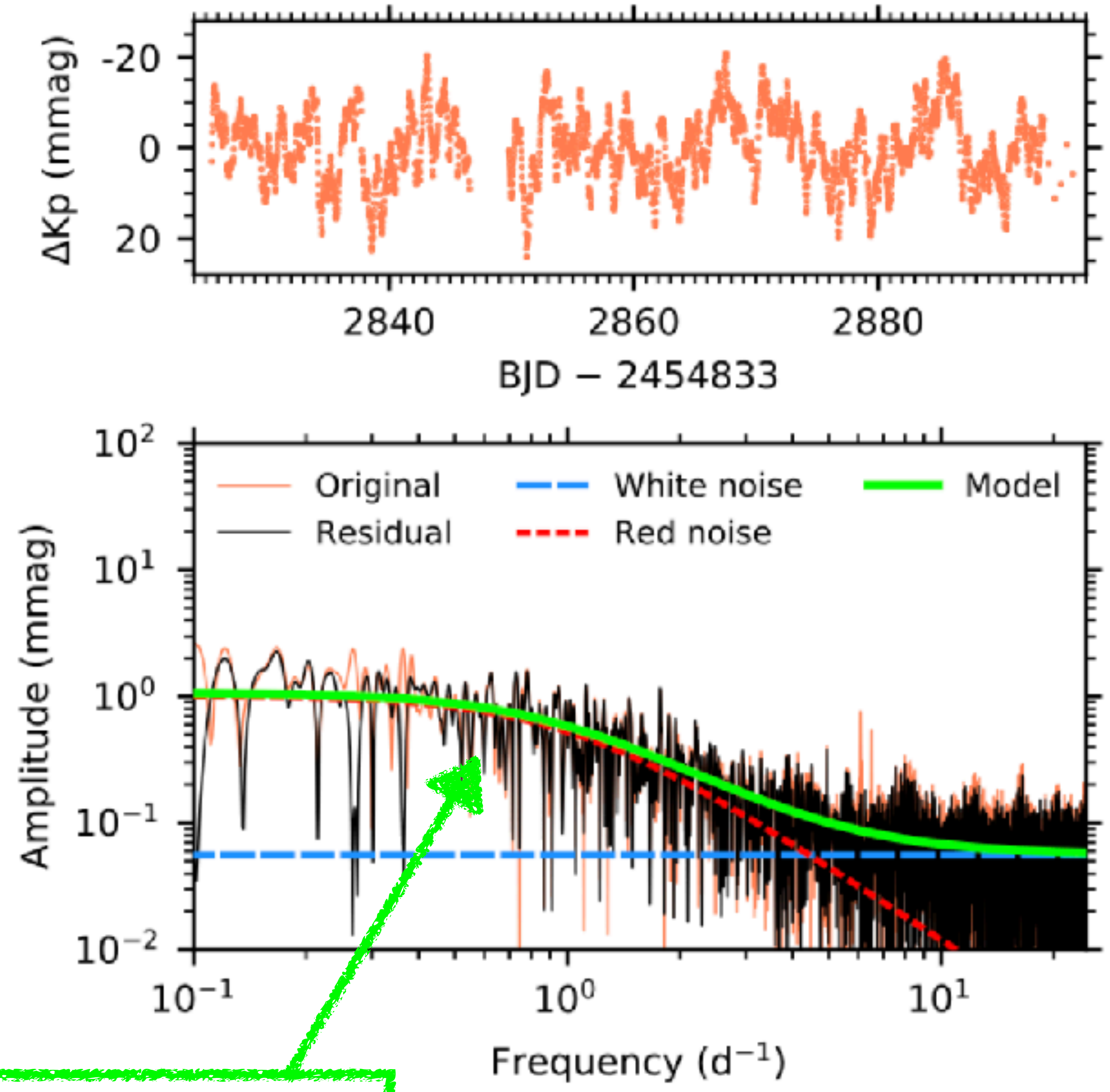
# SLF variability across the HR diagram

SLF variability morphology probes
**mass** and **age** of a massive star:

↑M and ↑age = ↑ $\alpha$ and ↓ $\nu_{char}$



Bowman et al. (2020)



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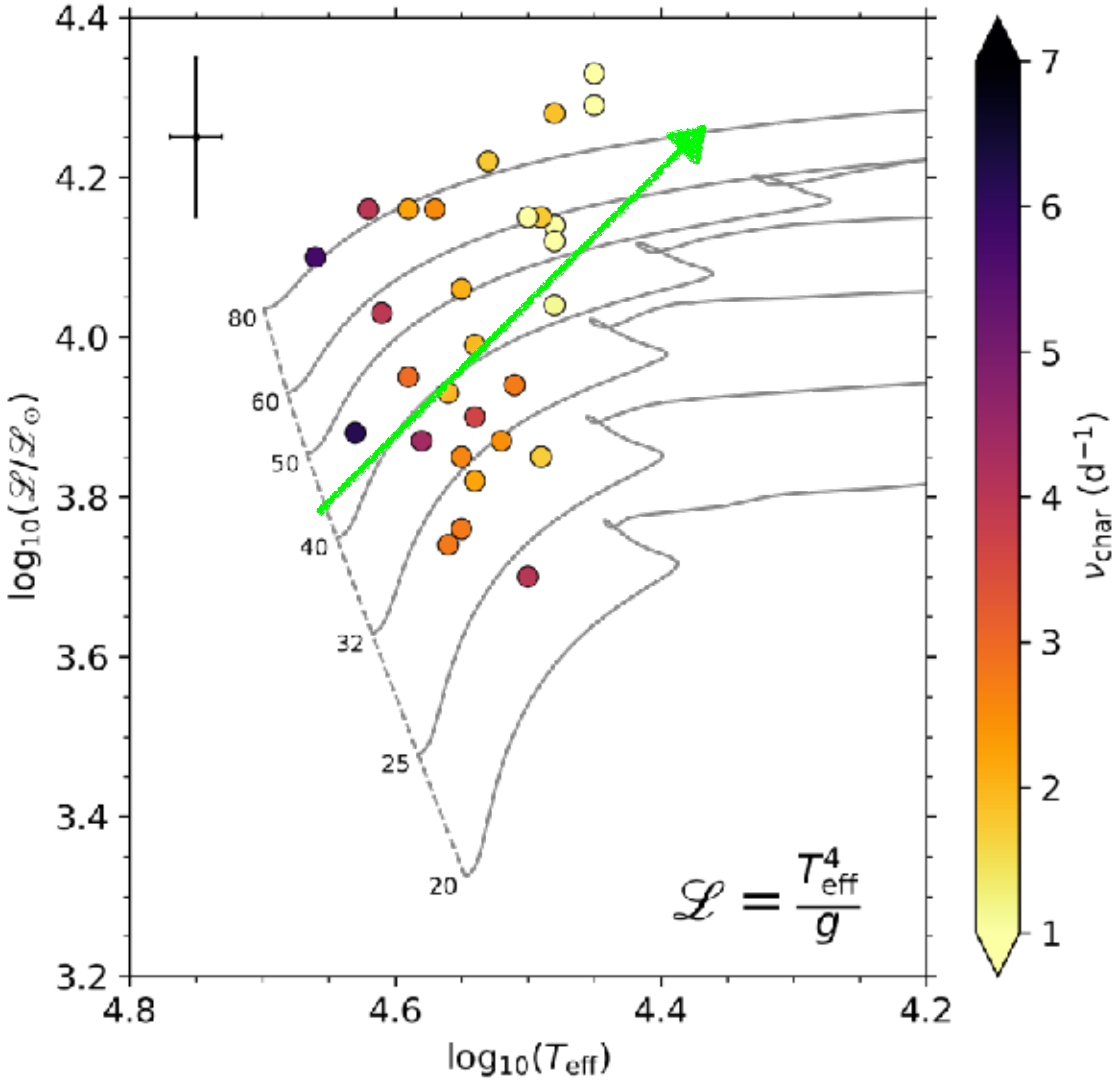
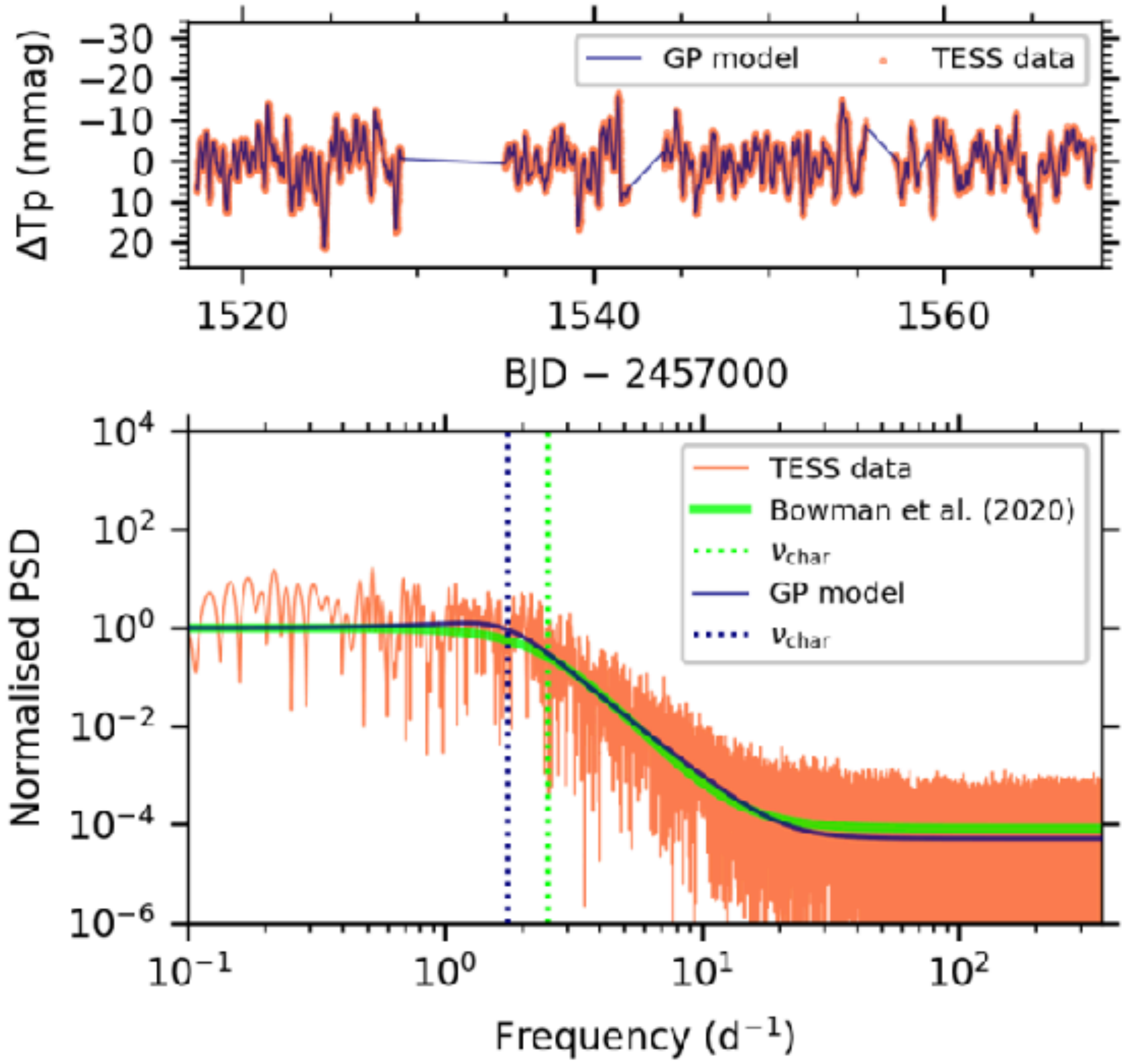


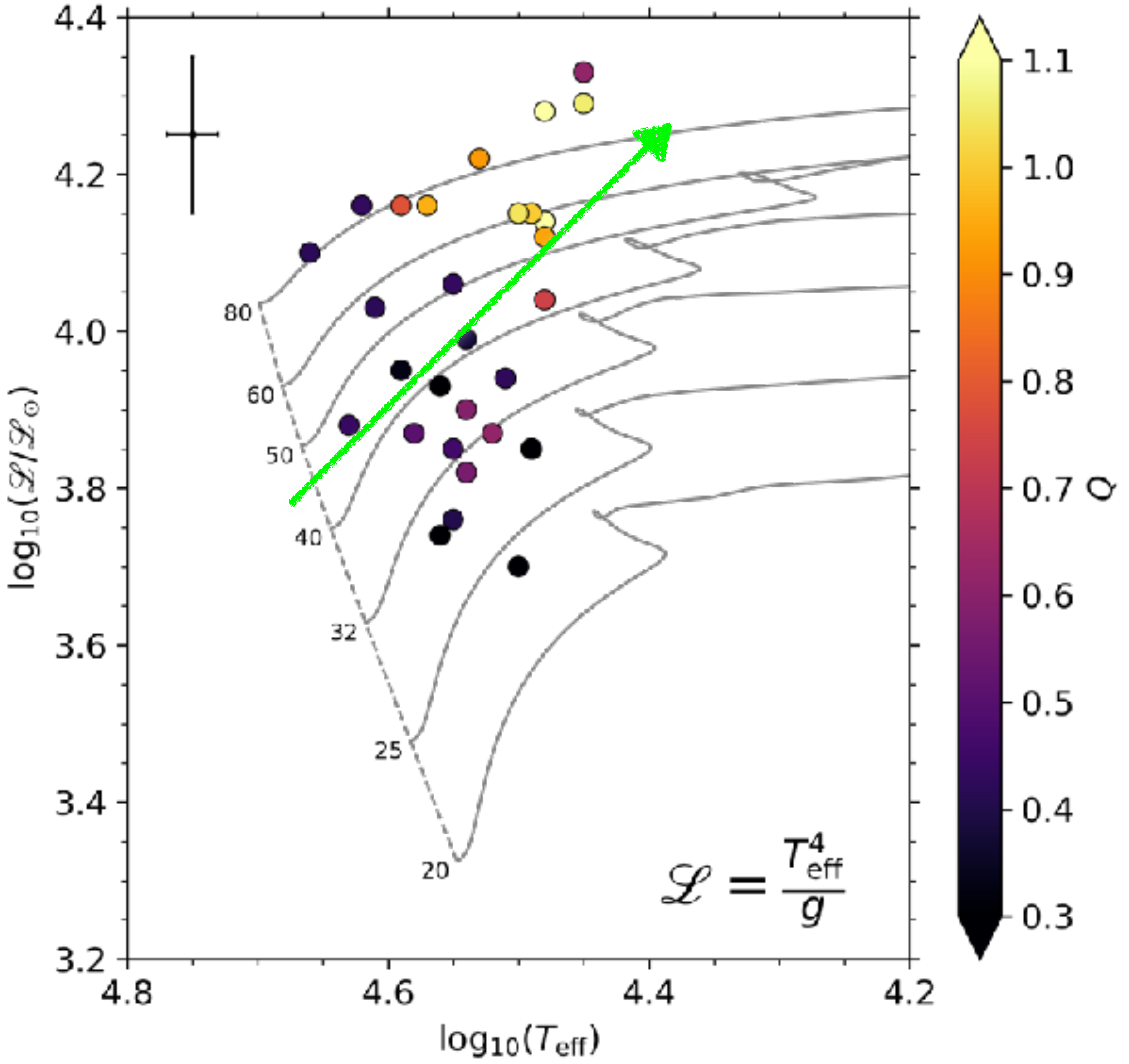
Bowman et al. (2020)



New method: light curve fit with **Gaussian Process (GP) regression** with damped SHO kernel

SLF variability transitions from **stochastic** to **quasi-periodic**:

↑M and ↑age = ↑ $Q$



Bowman & Dorn-Wallenstein (2022)

# SLF variability and macroturbulence

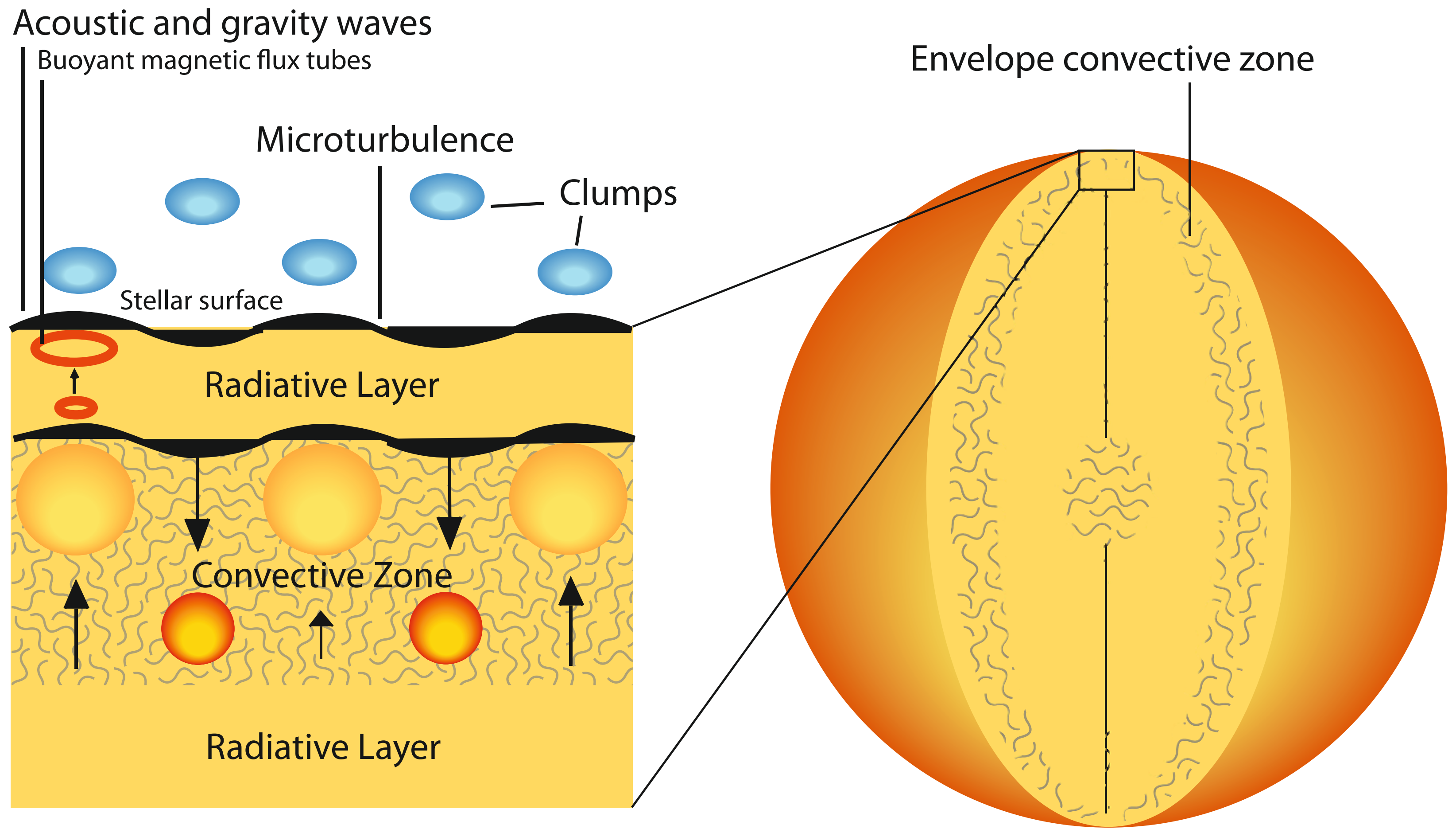
SLF variability morphology correlates with spectroscopic macroturbulence

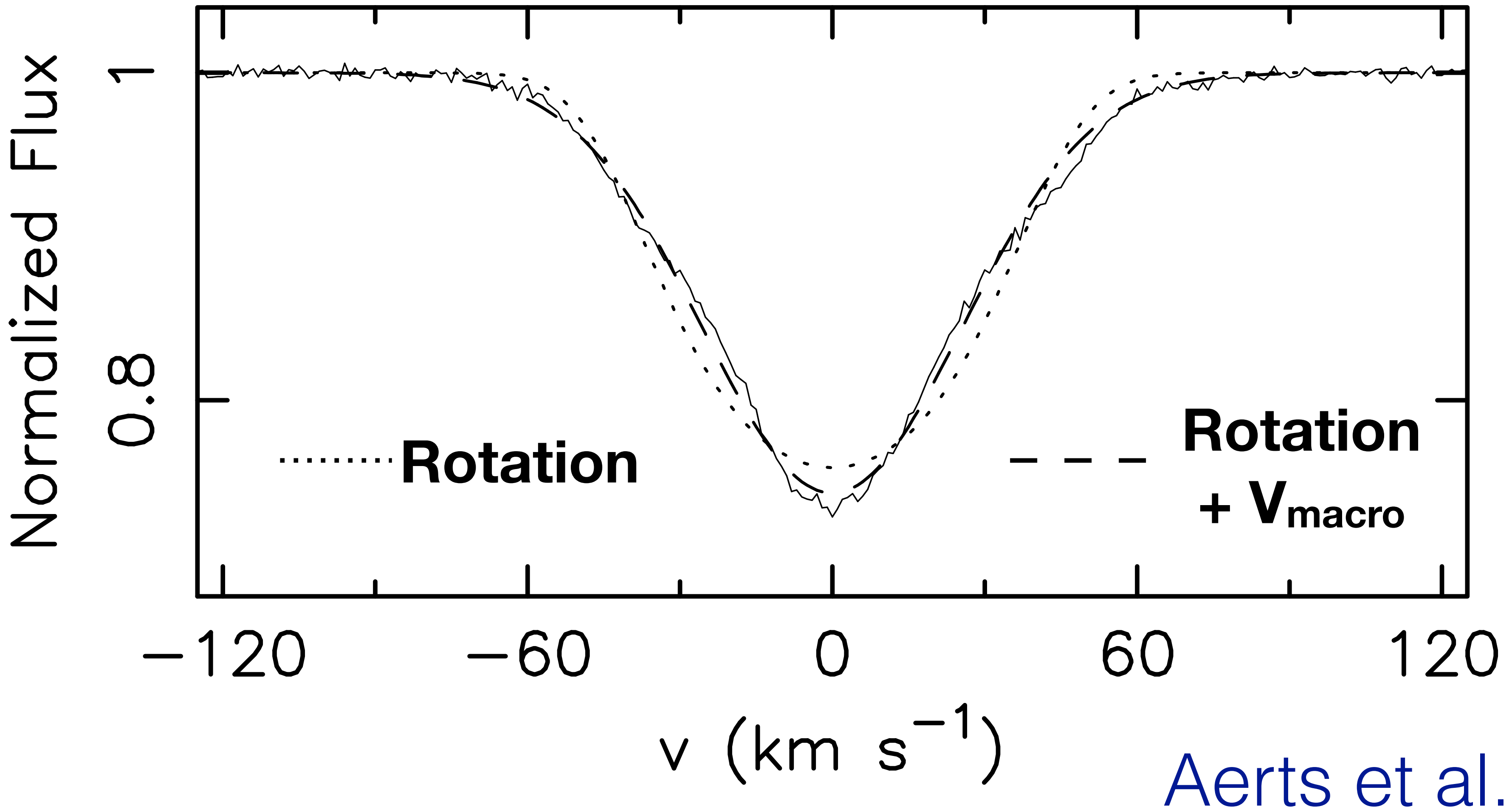
- **macroturbulence** = large-scale and anisotropic ($v_h / v_r >> 1$)
- **microturbulence** = small-scale and isotropic

$v_{macro}$ ~ 50-200 km s$^{-1}$

$v_{micro}$ ~ 2-15 km s$^{-1}$

Cantiello et al. (2009)





Aerts et al. (2009)

# SLF variability and macroturbulence

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SLF variability and macroturbulence:

↑M and ↑age = ↑ $v_{macro}$

↑ $\alpha$ and ↓ $v_{char}$ = ↑ $v_{macro}$

$v_{macro}$ ~ 50-200 km s$^{-1}$

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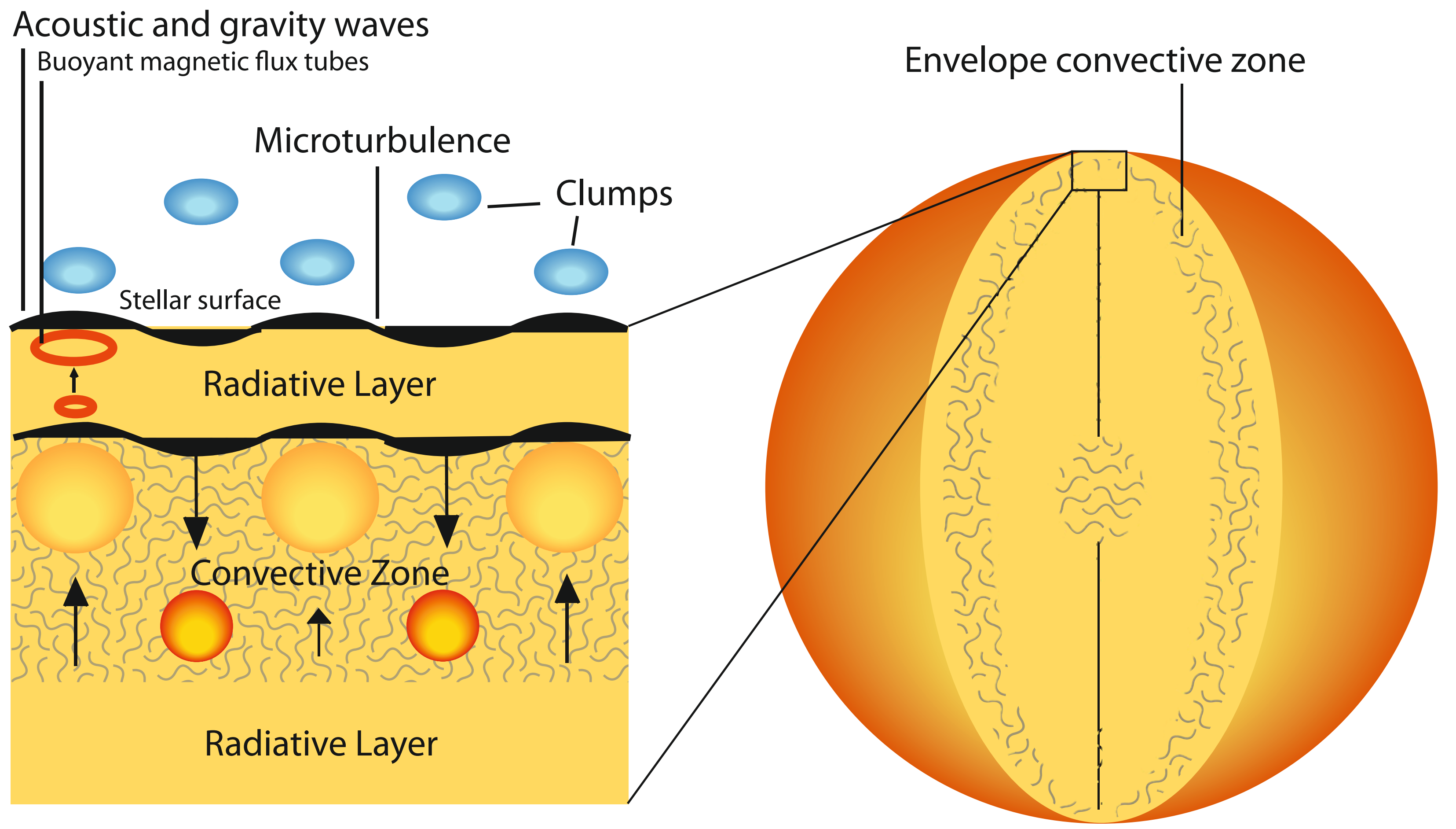
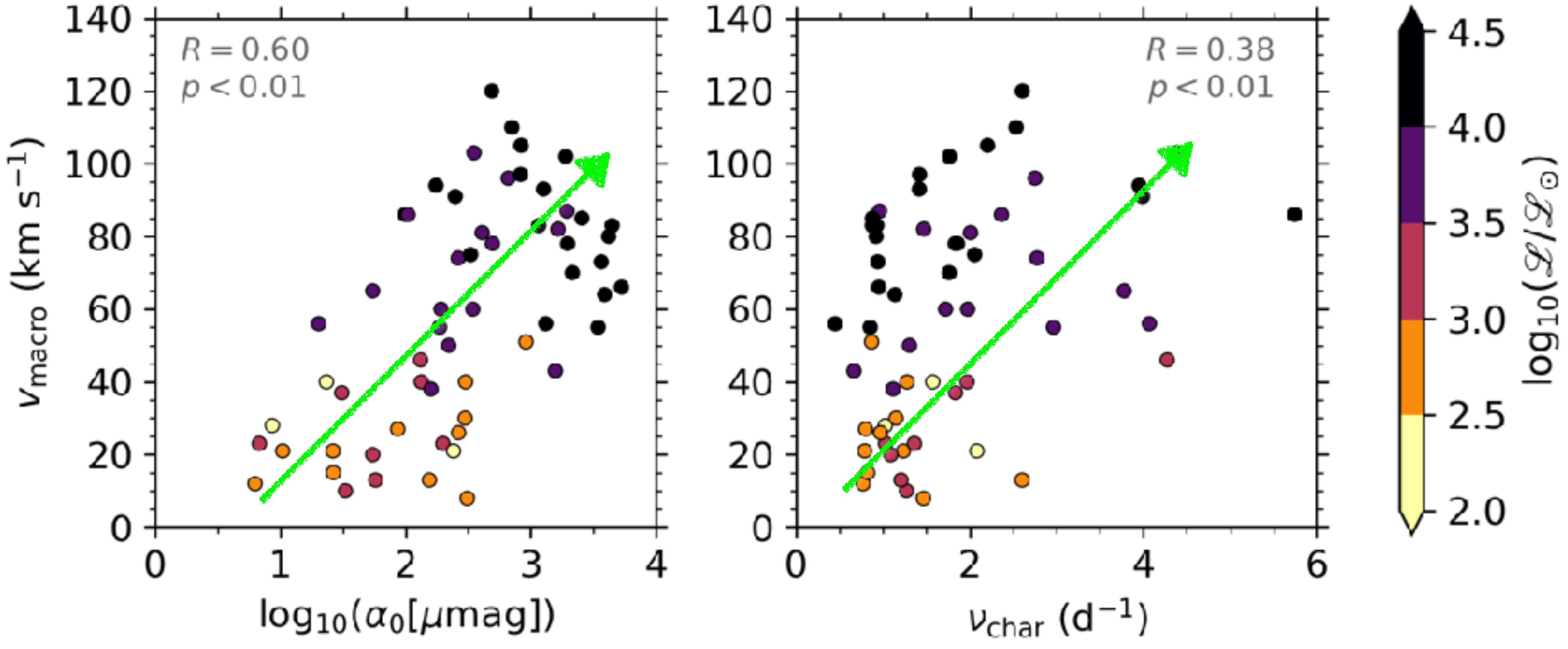
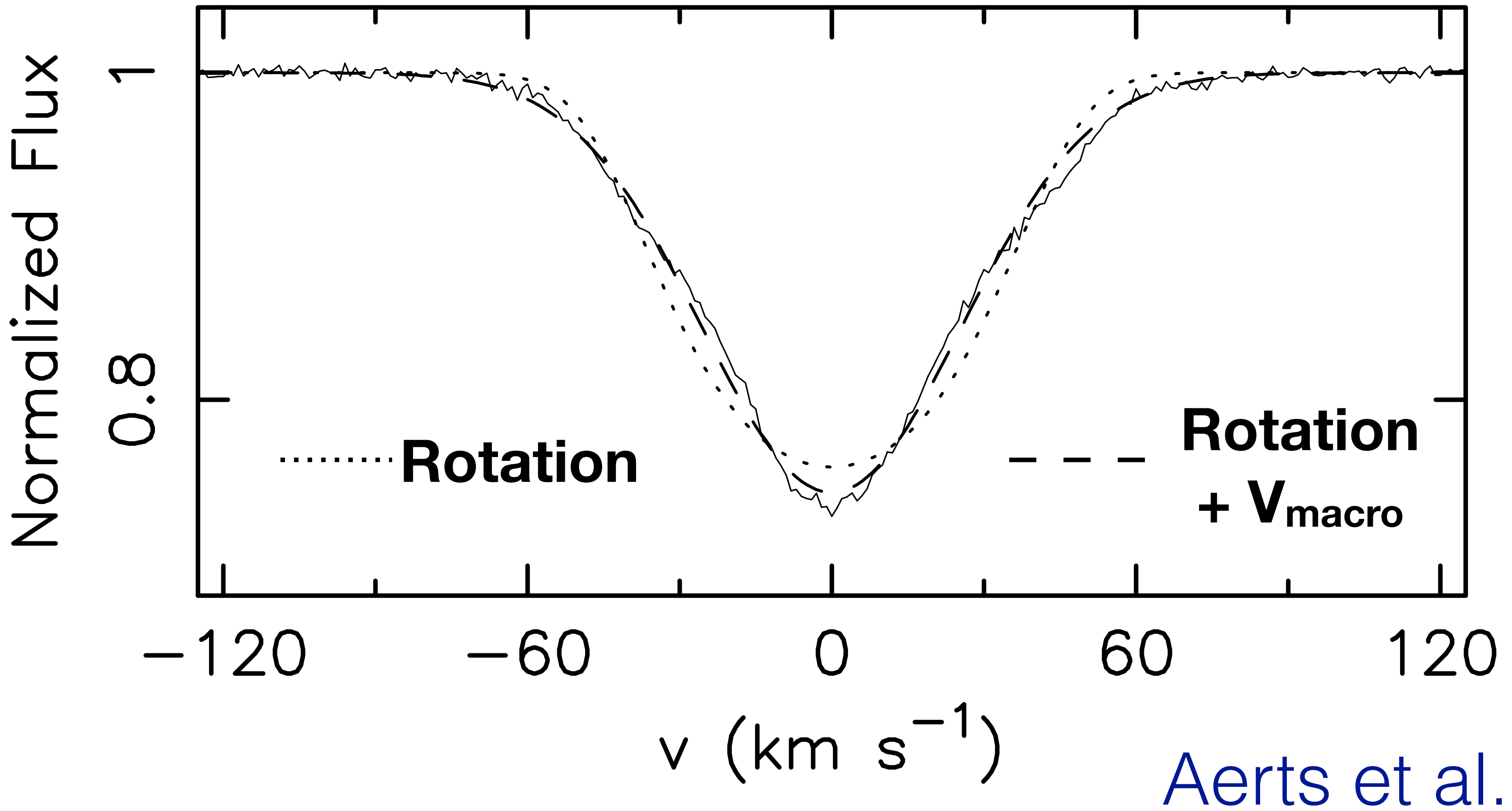
Cantiello et al. (2009)





Bowman et al. (2020)



Aerts et al. (2009)

# Conclusions and future prospects

- Asteroseismology of massive stars yields:
  - **quasi-rigid rotation profiles:** 0 → 90% critical
  - **boundary mixing:** $0.005 < f_{\mathrm{CBM}} < 0.040$
  - **envelope mixing:** $0 < \log(D_{\mathrm{env}}(r)) < 6$
  - **near-core magnetic field:** < 500 kG
- Asteroseismology of massive stars requires **Mahalanobis Distance** for precision and accuracy
- **SLF variability** probes mass and age, but origin remains unclear: core and/or envelope?
- Bright future for **(magneto)asteroseismology** thanks to several international projects:

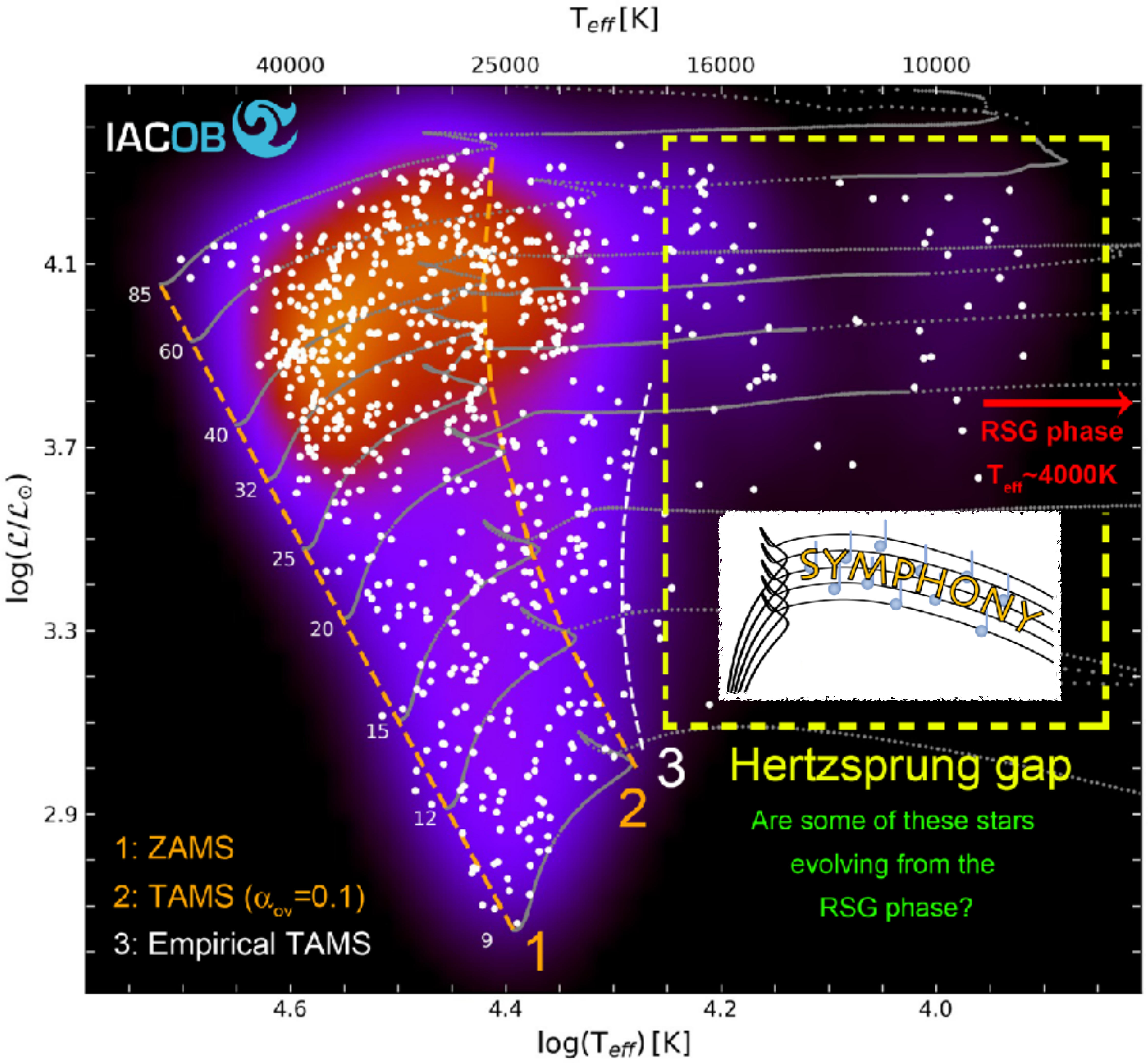


Figure courtesy of A. de Burgos & S. Simón-Díaz

# An asteroseismic view of convective boundary mixing in massive stars

*Thank you for your attention!*

**Dominic Bowman**

Image credit: Hubble Space Telescope, NASA, ESA, STSCI/AURA

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