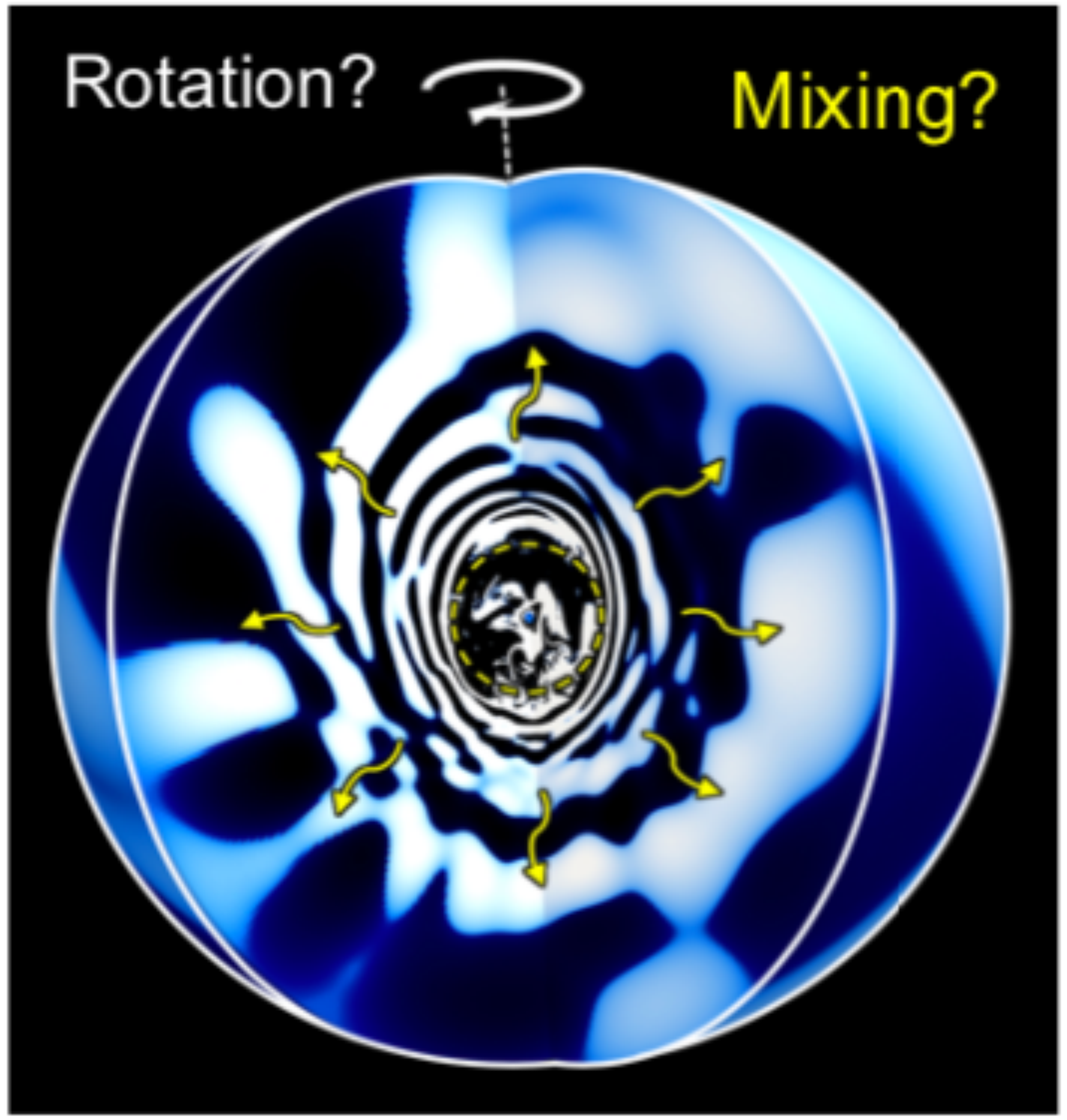
# Asteroseismology: new developments and open questions

Dominic Bowman

# Important physics of early-type stars

*Talk to Dominic Bowman*

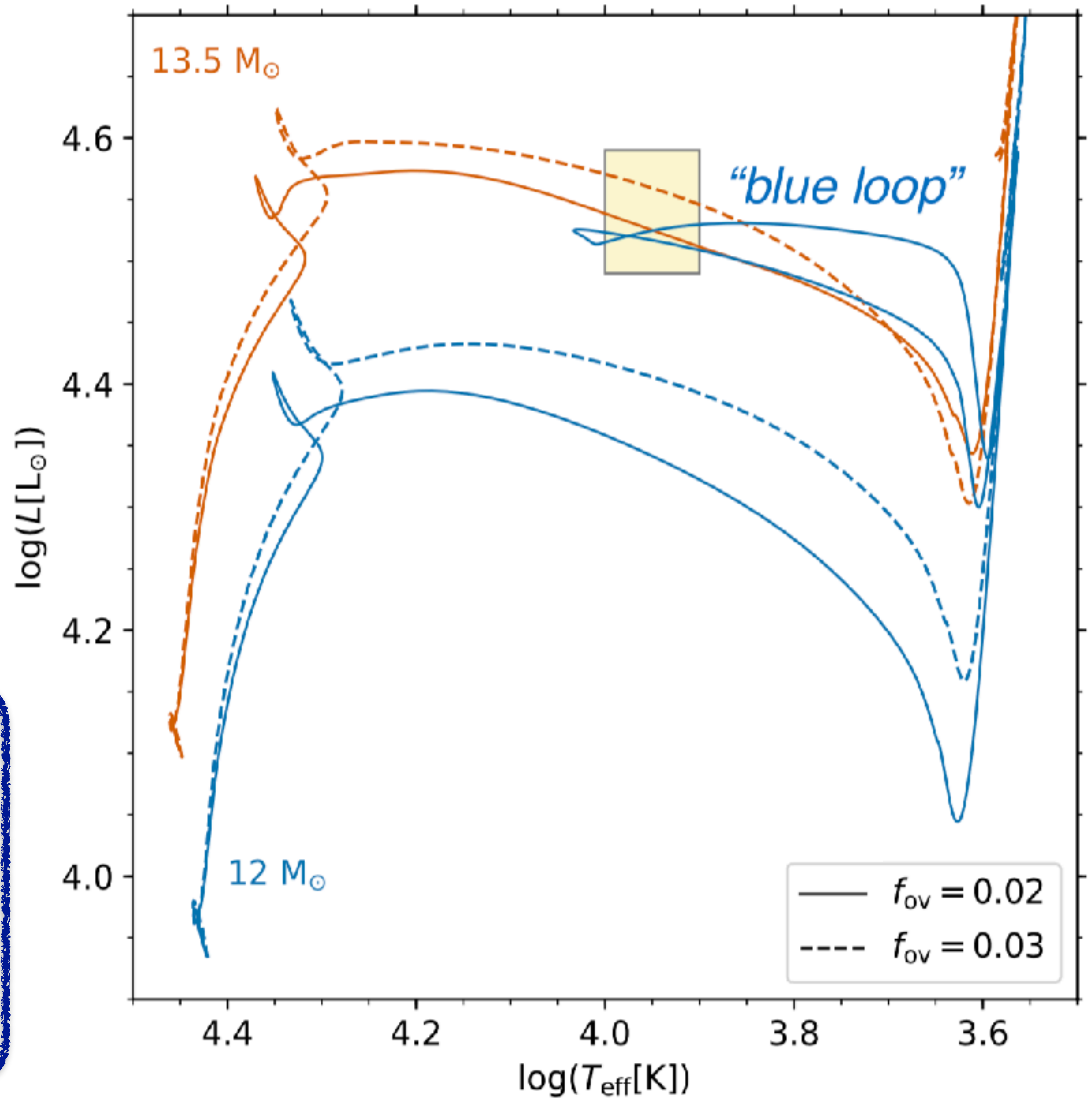
Large uncertainties in rotation and mixing propagate from main-sequence into post-main sequence and have drastic consequences!




Edelmann et al. (2019, ApJ 876)

Unknown mixing means:
$\sigma(m_{cc}) > 50\%$
$\sigma(\text{age}) > 25\%$

Bowman (2020, Fron. Ast. Space Sci. 7)



# Pulsating early-type stars

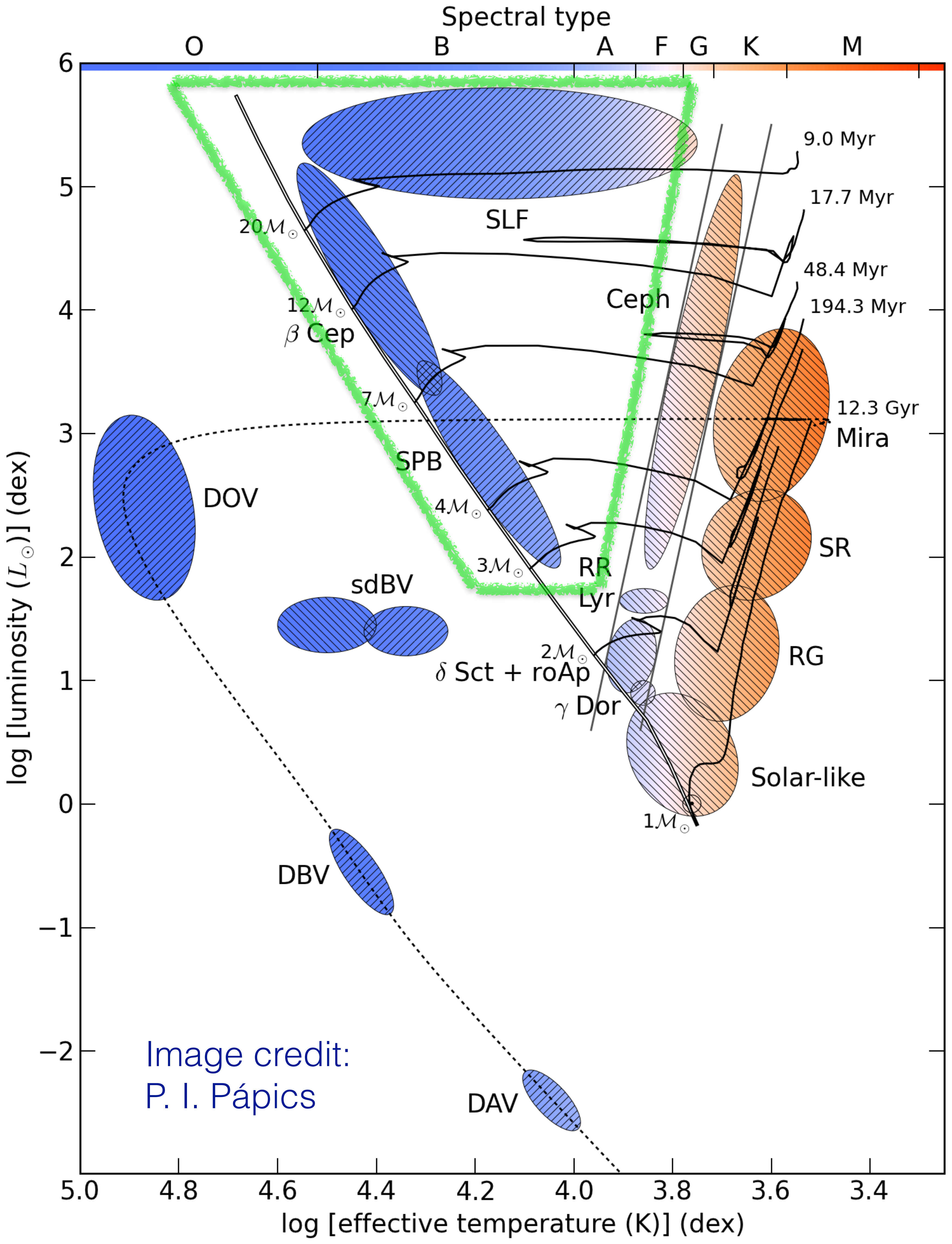


Image credit: P. I. Pápics

**SLF**: Stochastic low-frequency variability

- Broad period range between minutes and several days
- Seemingly near-ubiquitous in OB 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 $M_\odot$

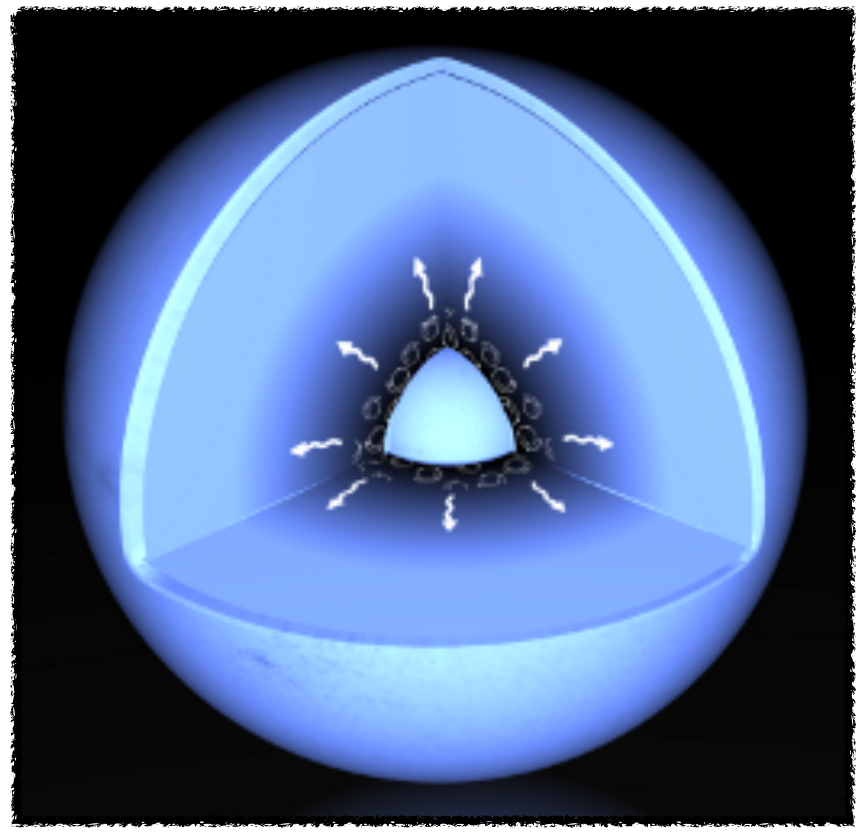
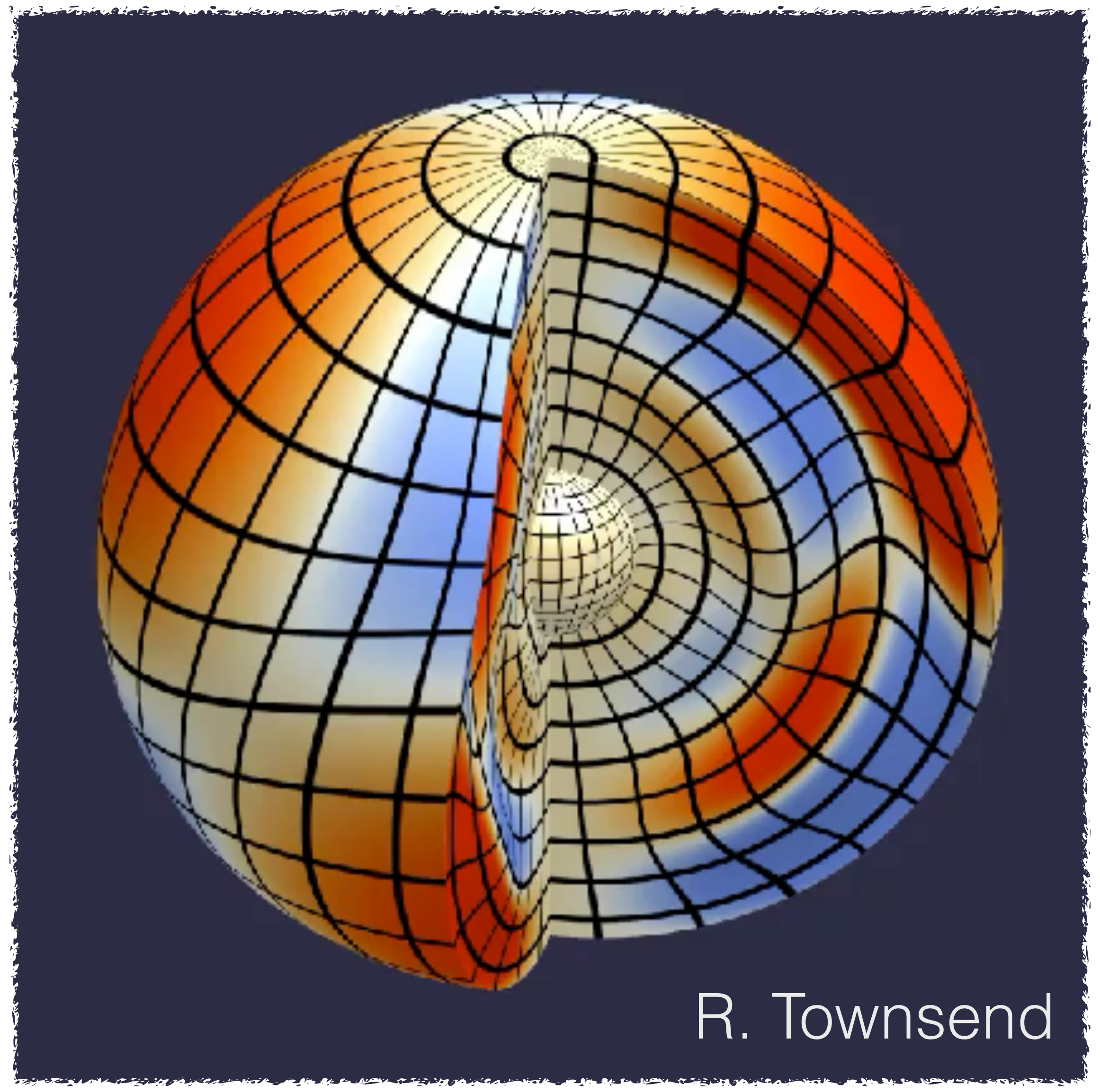
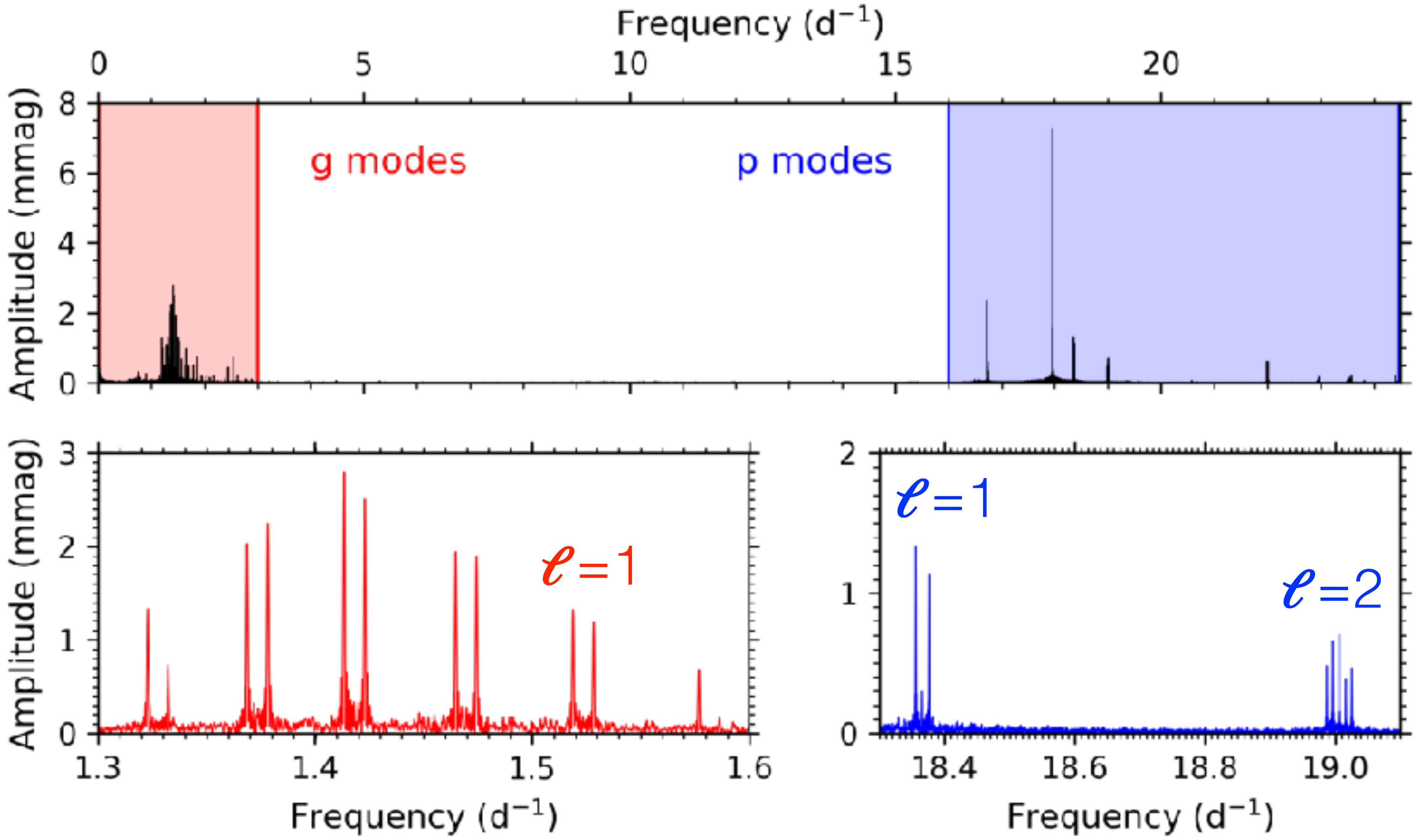
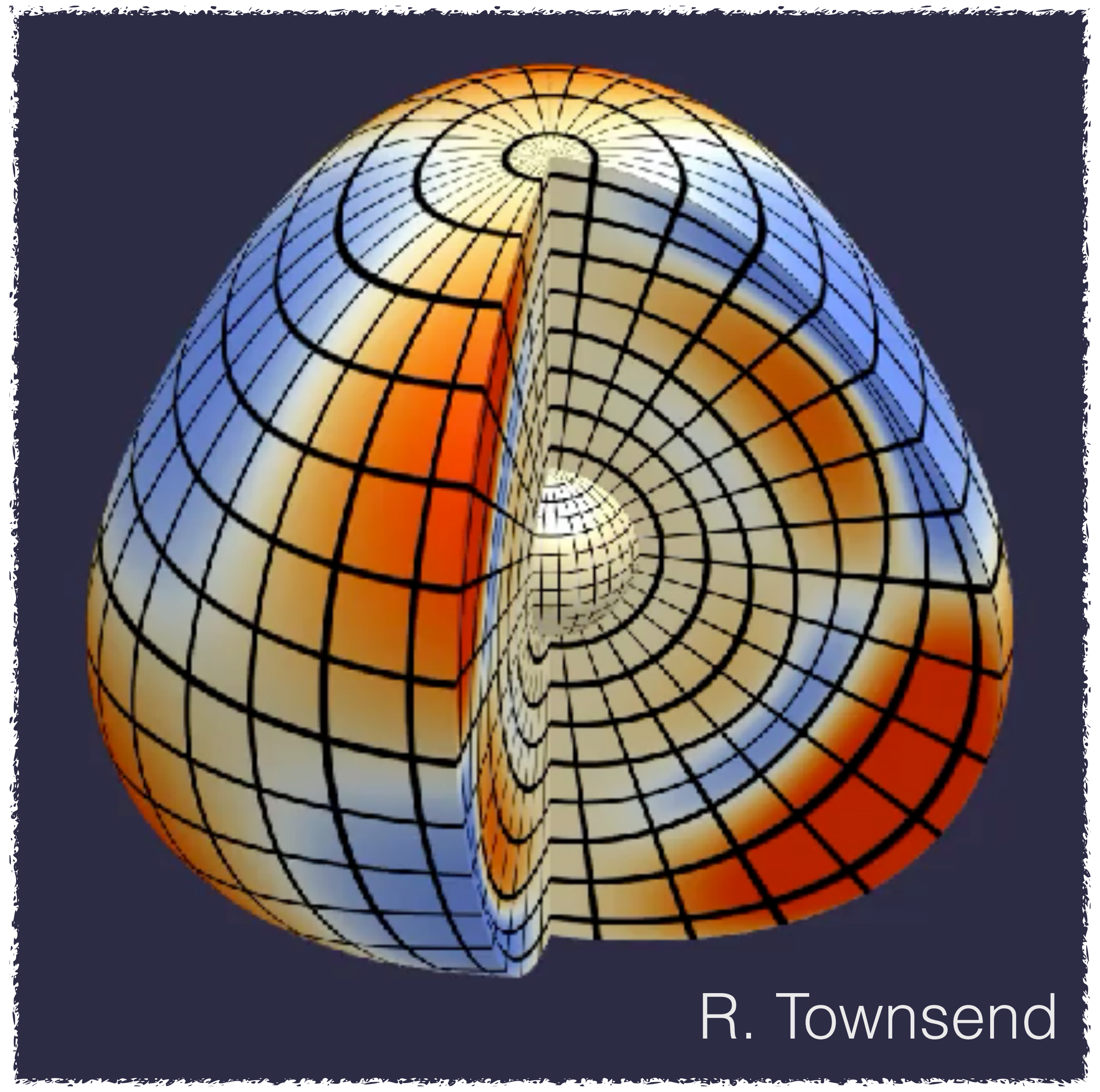


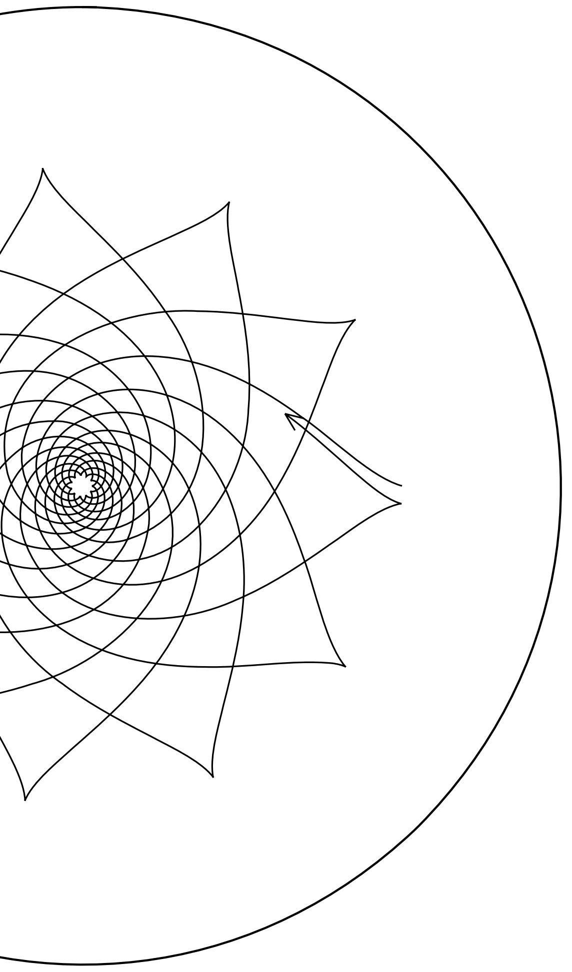
Image credit: P. Degroote

# Asteroseismology



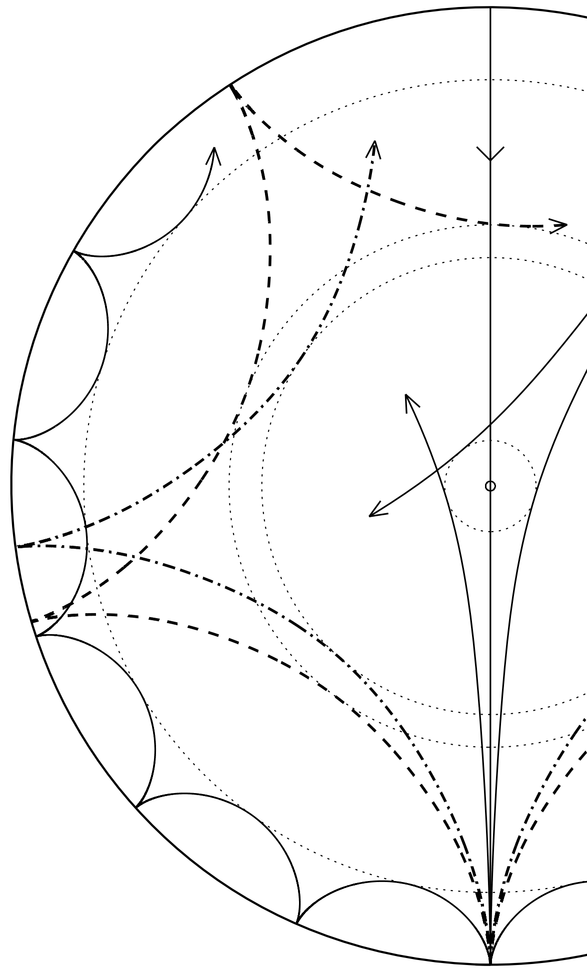



**Gravity (g) modes:**
- $n < 0$
- low frequency
- probe near-core
- non-radial
- equally-spaced in period

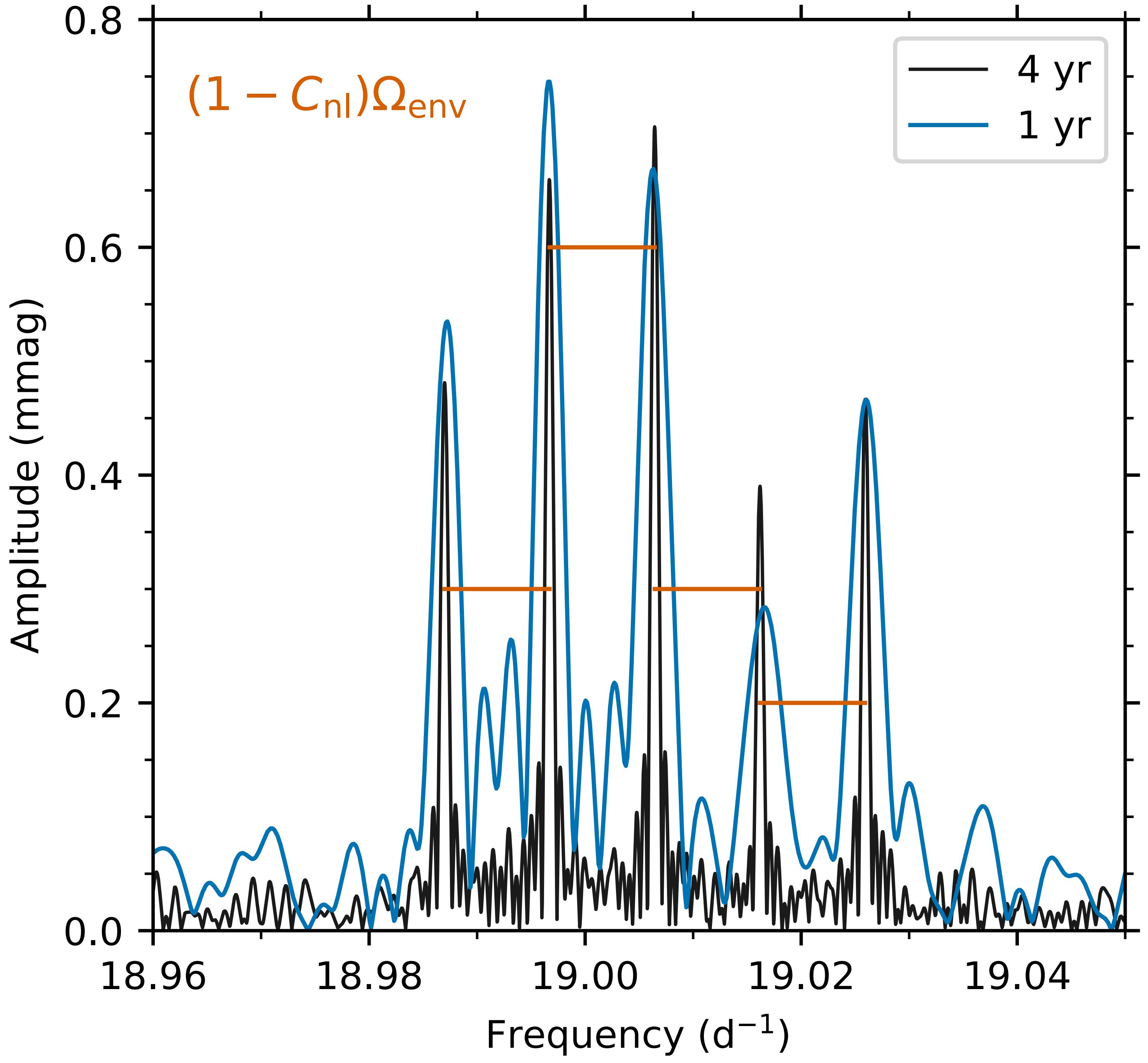
**Pressure (p) modes:**
- $n > 0$
- high frequency
- probe near-surface
- radial and non-radial
- equally spaced in frequency



# Asteroseismology: pressure modes

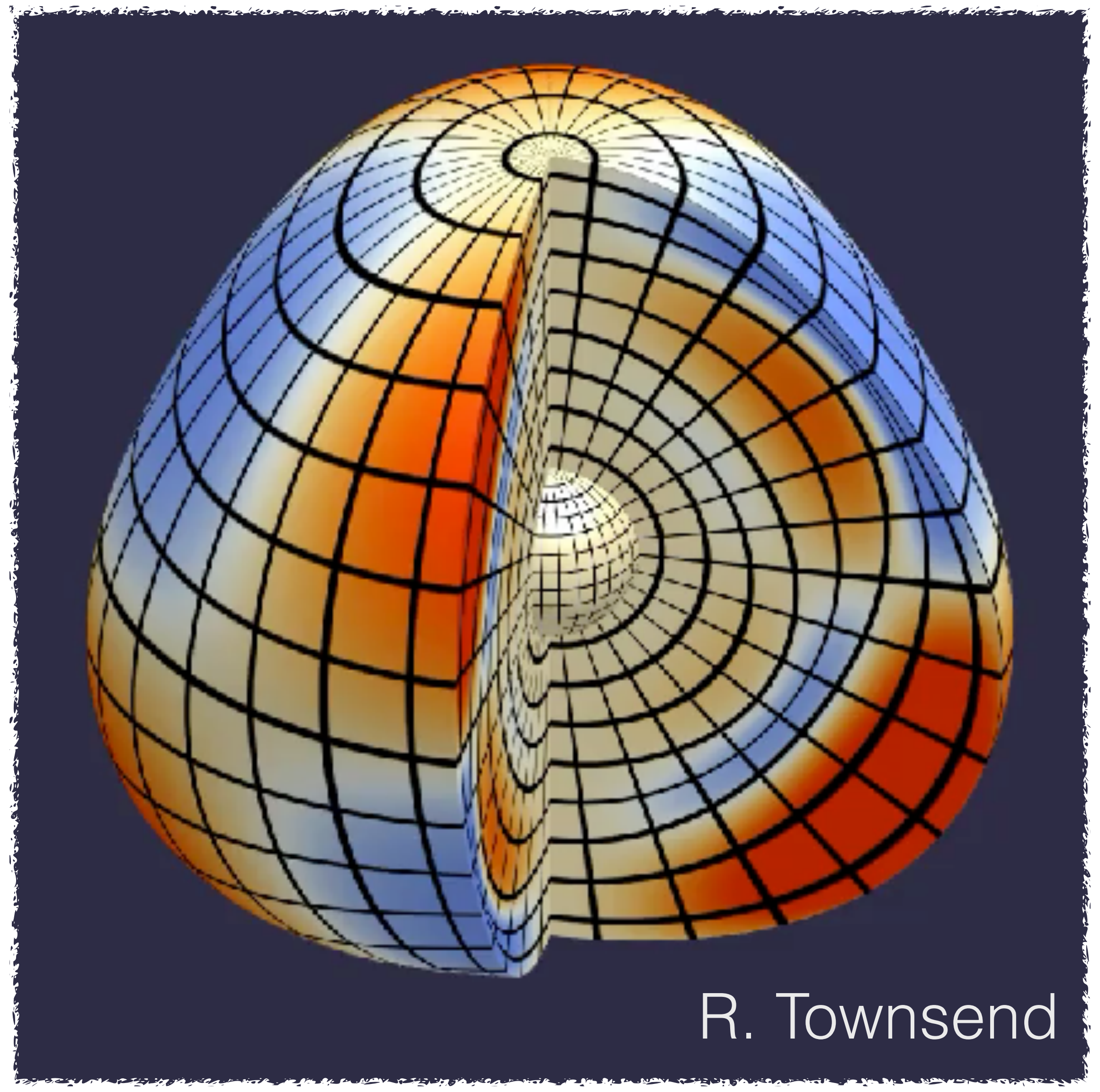
Non-radial pressure modes probe the envelope physics:

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




first-order Ledoux splitting:

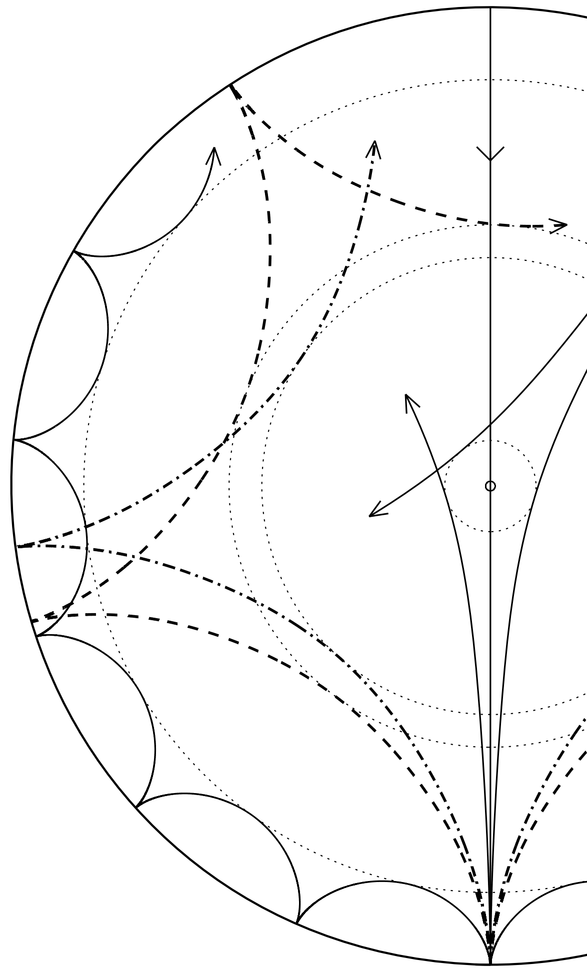
$$\omega_{n\ell m} = \omega_{n\ell} + m\,(1 - C_{n\ell})\,\Omega$$




e.g. Kurtz et al. (2014, MNRAS 444) for AF stars
e.g. Aerts et al. (2003, Science 300) for early-B stars

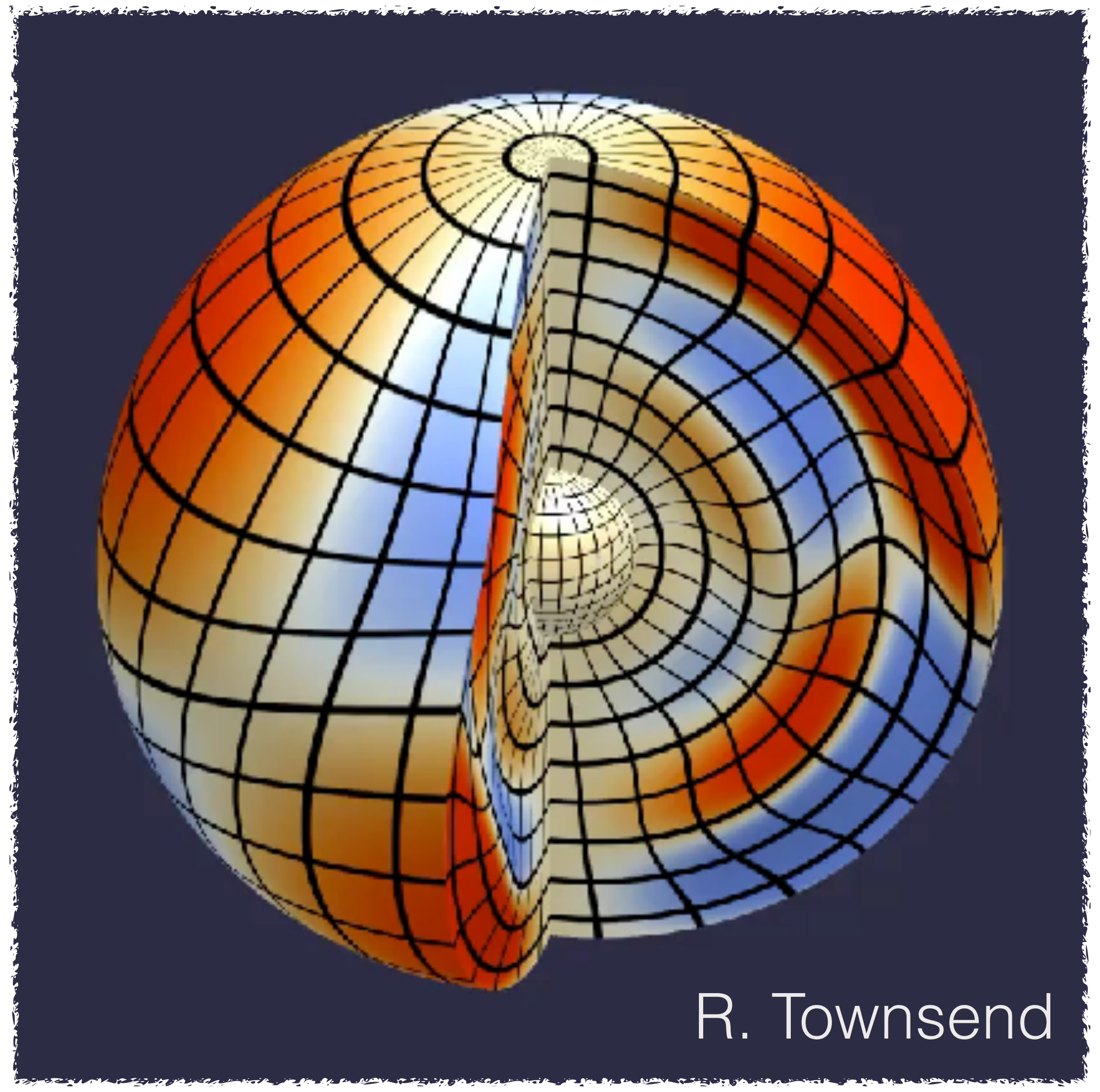
**Pressure (p) modes:**

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



# Asteroseismology: gravity modes

*Talk to Timothy Van Reeth*

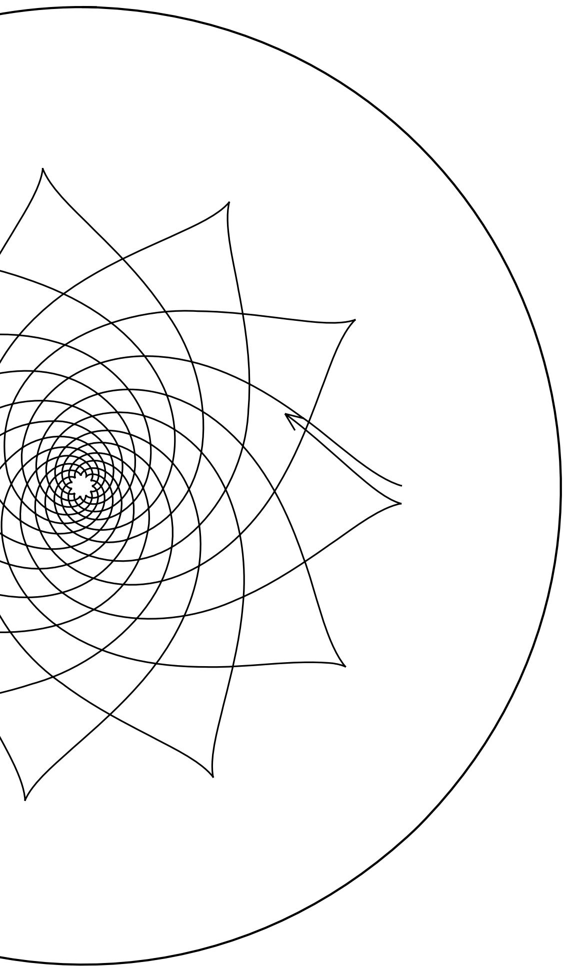



Prograde dipole gravity modes most common geometry in observations:

- rotation and chemical mixing in near-core region
- Traditional Approximation for Rotation (TAR) up to ~80% critical breakup

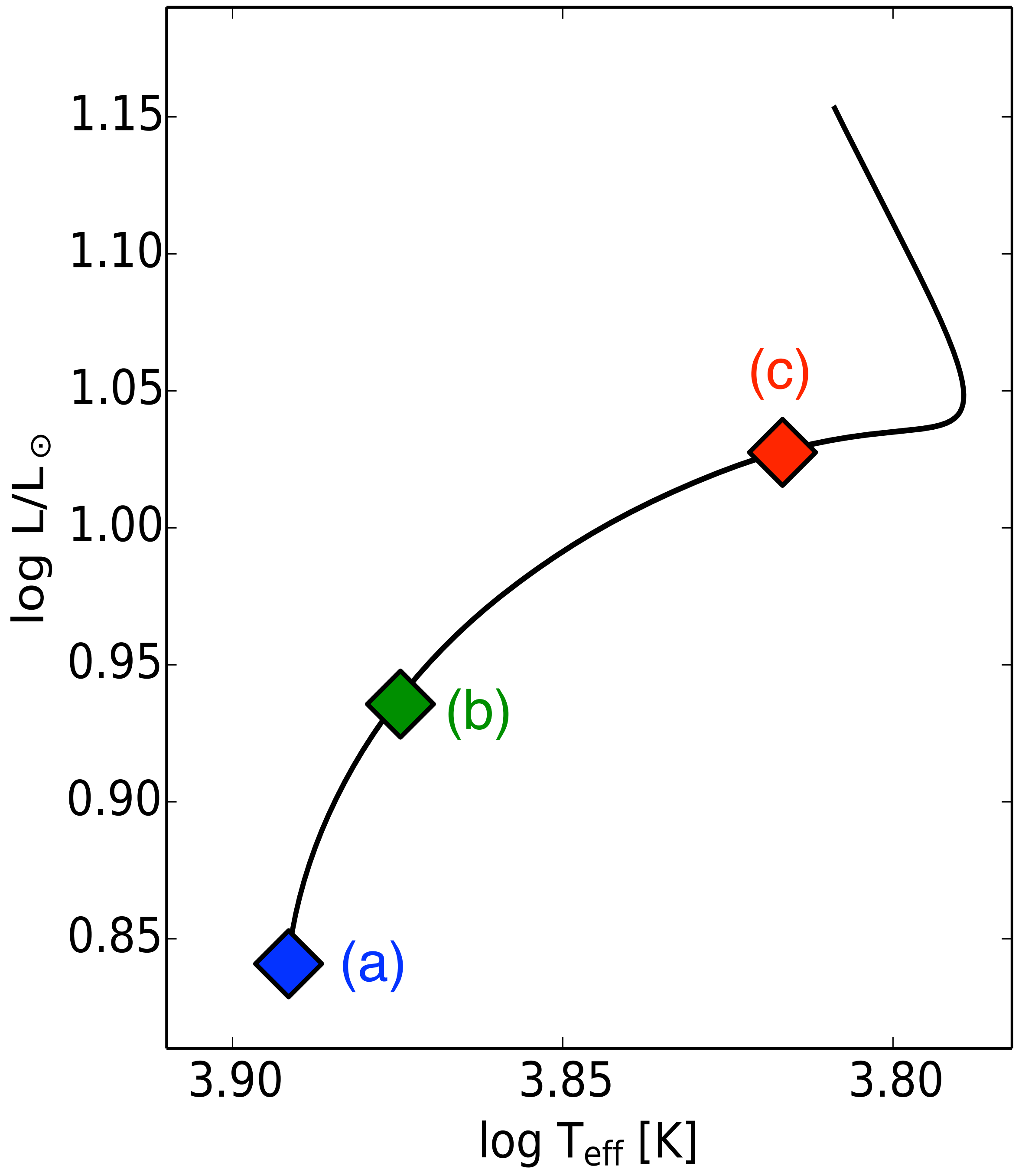
$$P_{n\ell} = \frac{\Pi_0}{\sqrt{\ell(\ell+1)}}(|n| + \alpha)$$

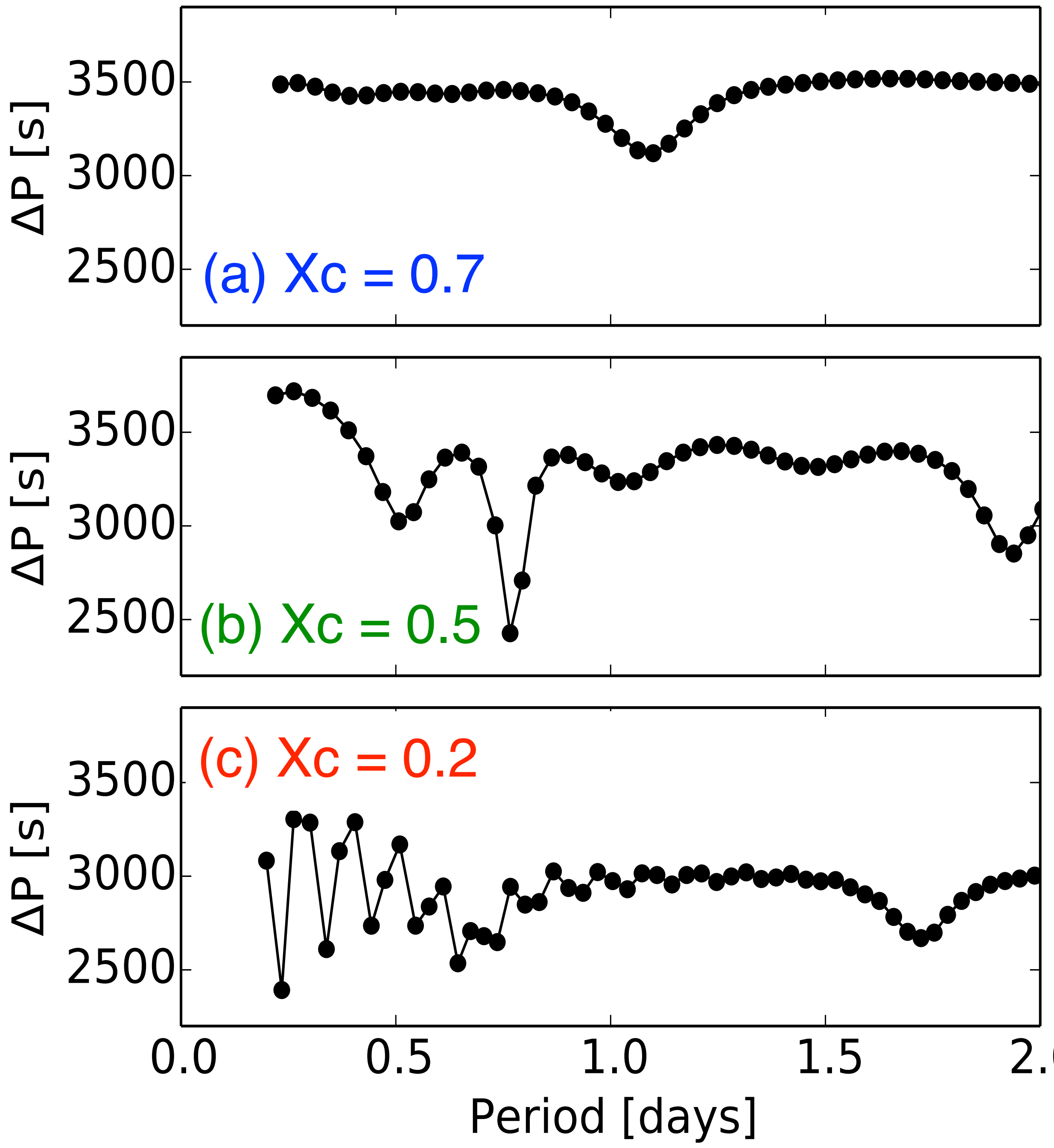
$$\Pi_0 = 2\pi^2 \left( \int_{r_1}^{r_2} N(r) \frac{\mathrm{d}r}{r} \right)^{-1}$$



**Gravity (g) modes:**

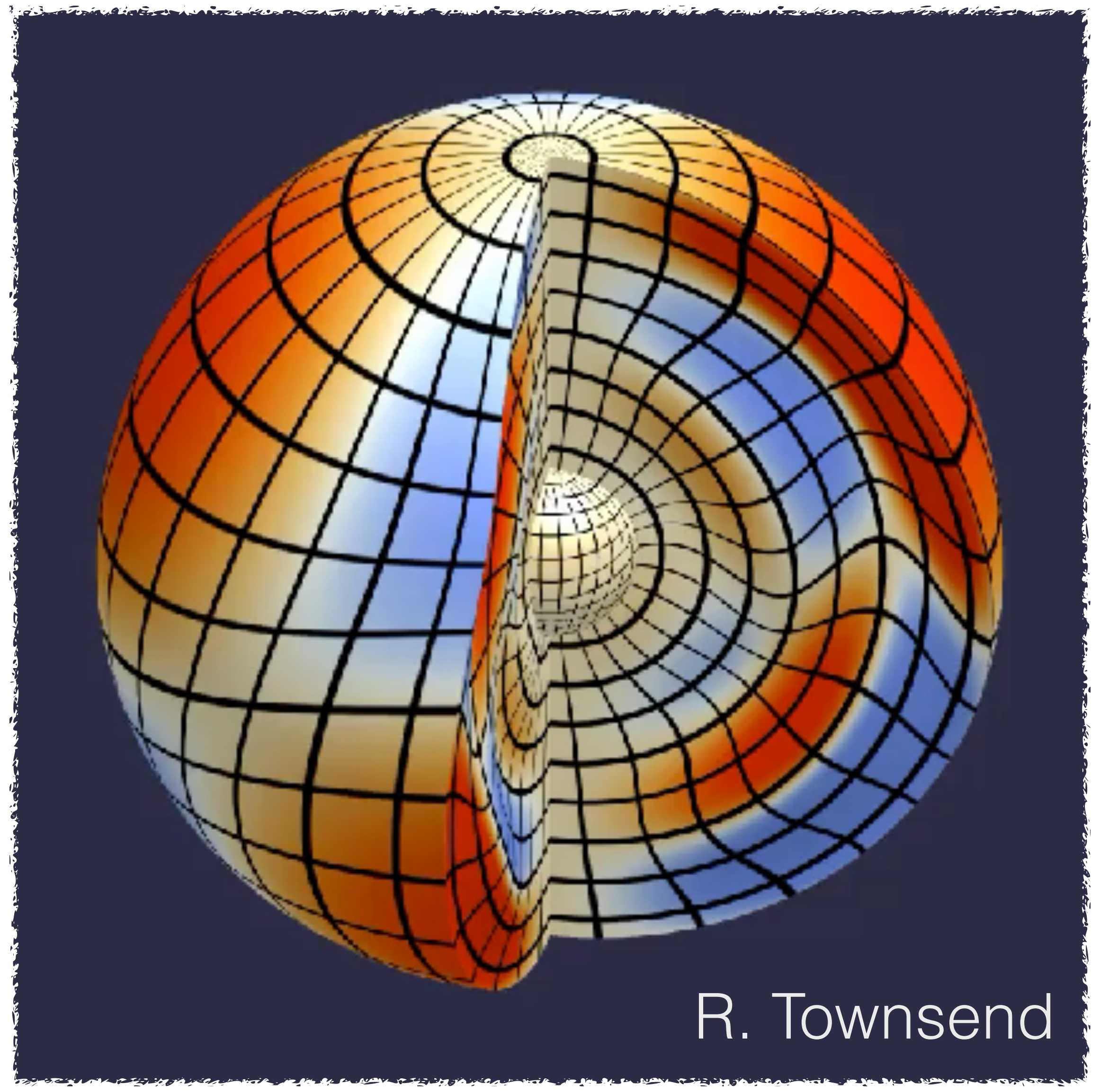
- $n < 0$
- low frequency
- probe near-core
- non-radial
- equally-spaced in period



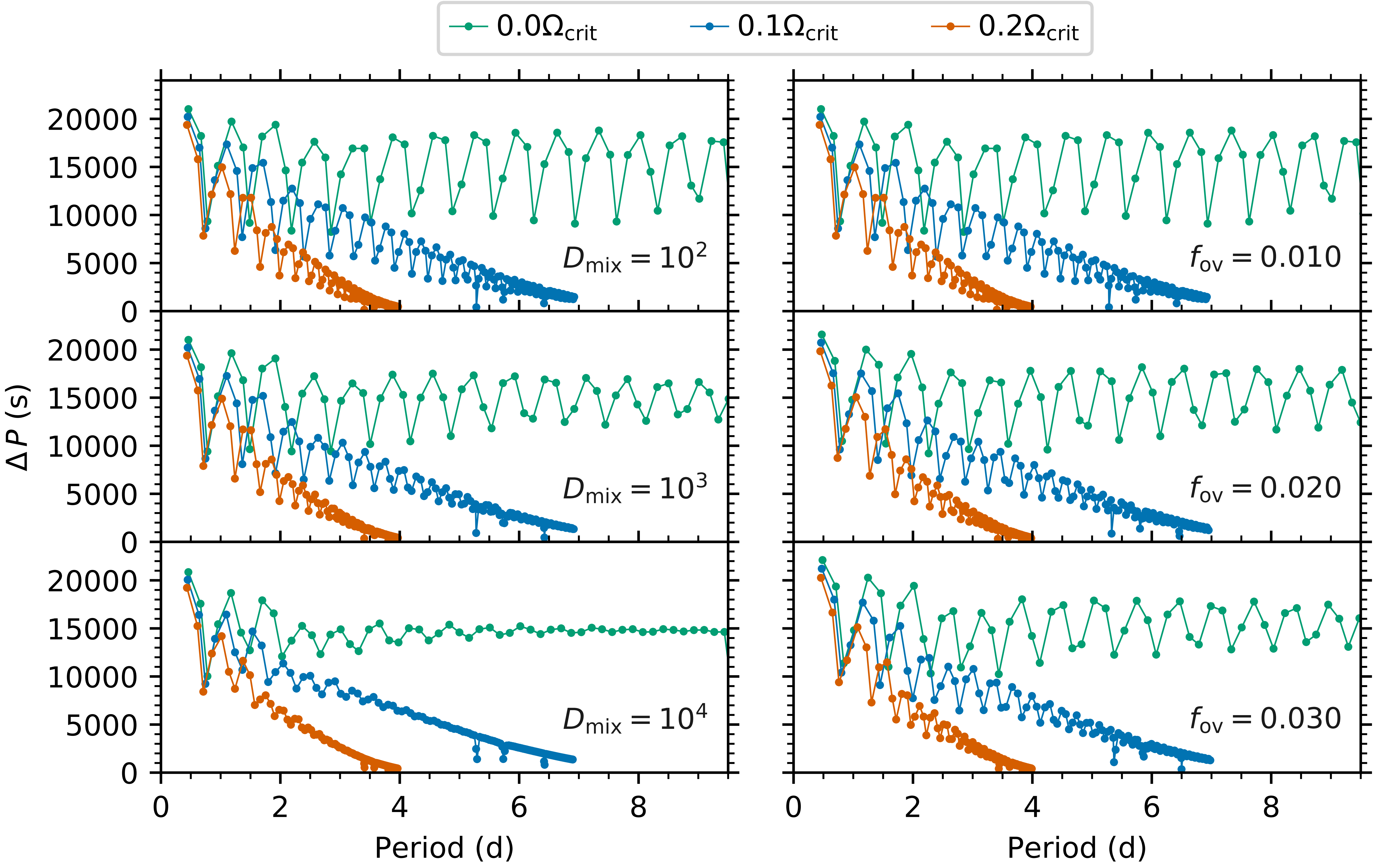



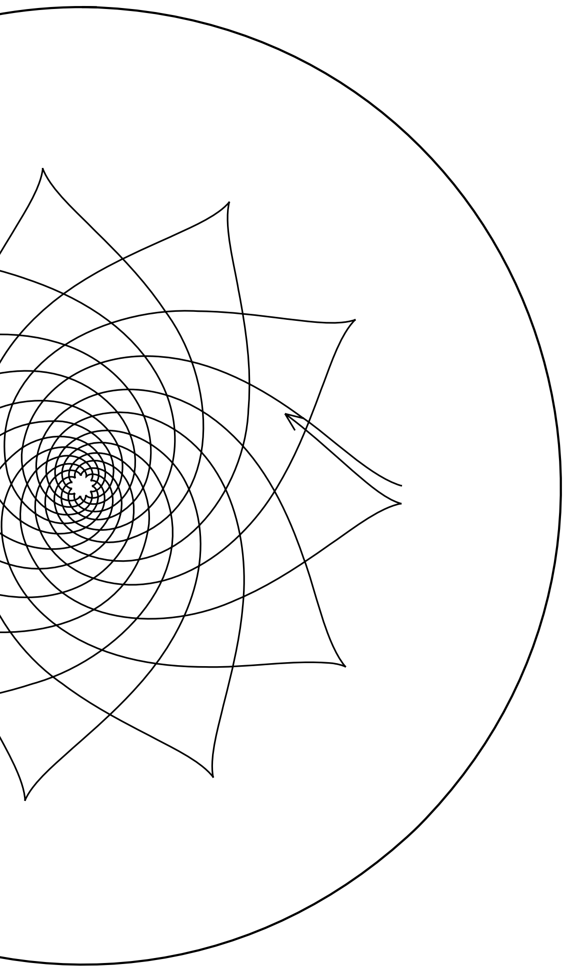

Van Reeth et al. (2015, ApJS 218)

# Asteroseismology: gravity modes




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



**Gravity (g) modes:**

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

Bowman (2020, Fron. Ast. Space Sci. 7)

# Discussion Points / Open Questions

1. **Interior rotation:** what is the missing AM transport mechanism(s)?

2. Envelope mixing in MS stars: why is there a large diversity?

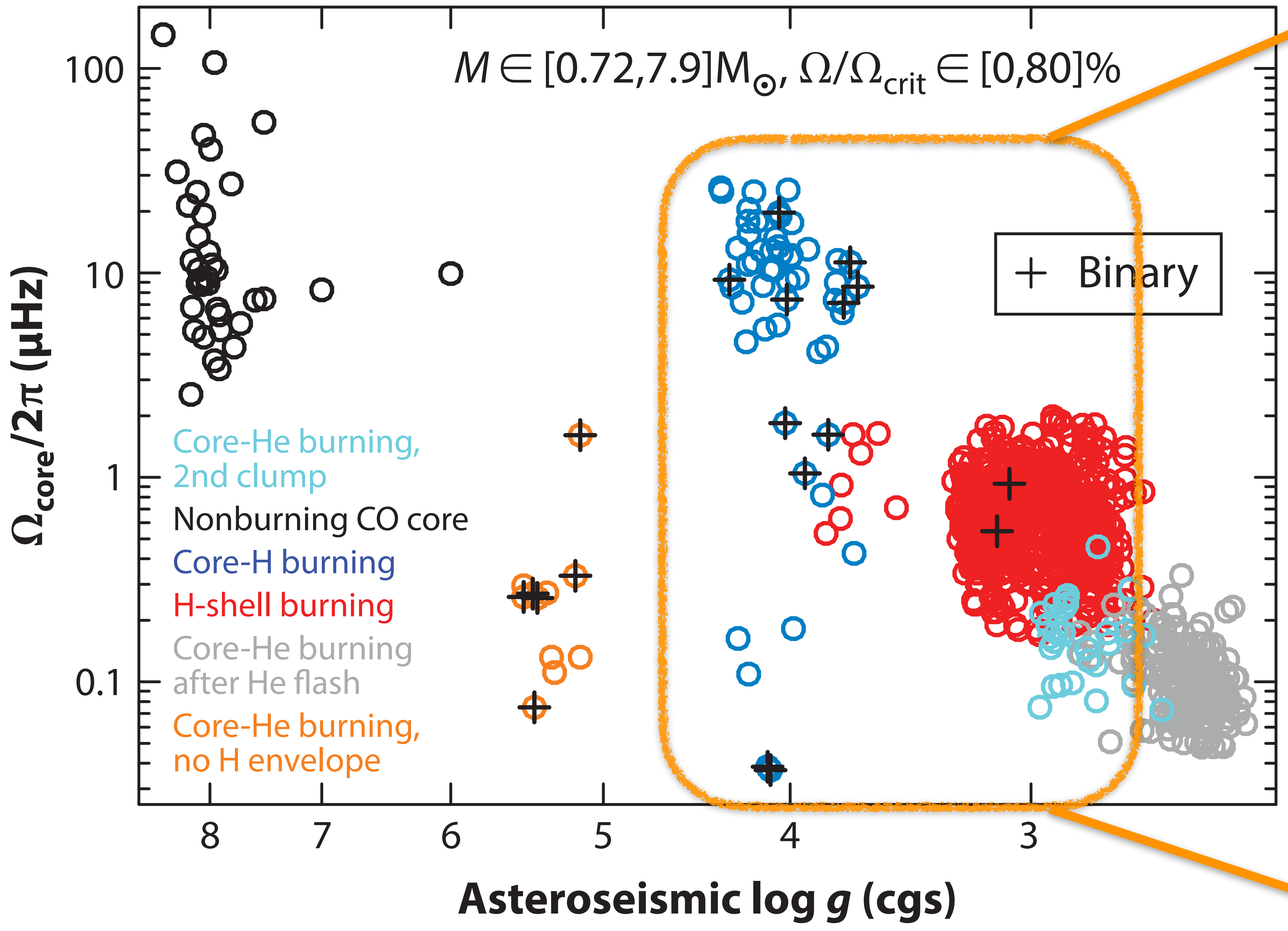
3. Core Boundary Mixing: what is the best shape in 3D -> 1D?

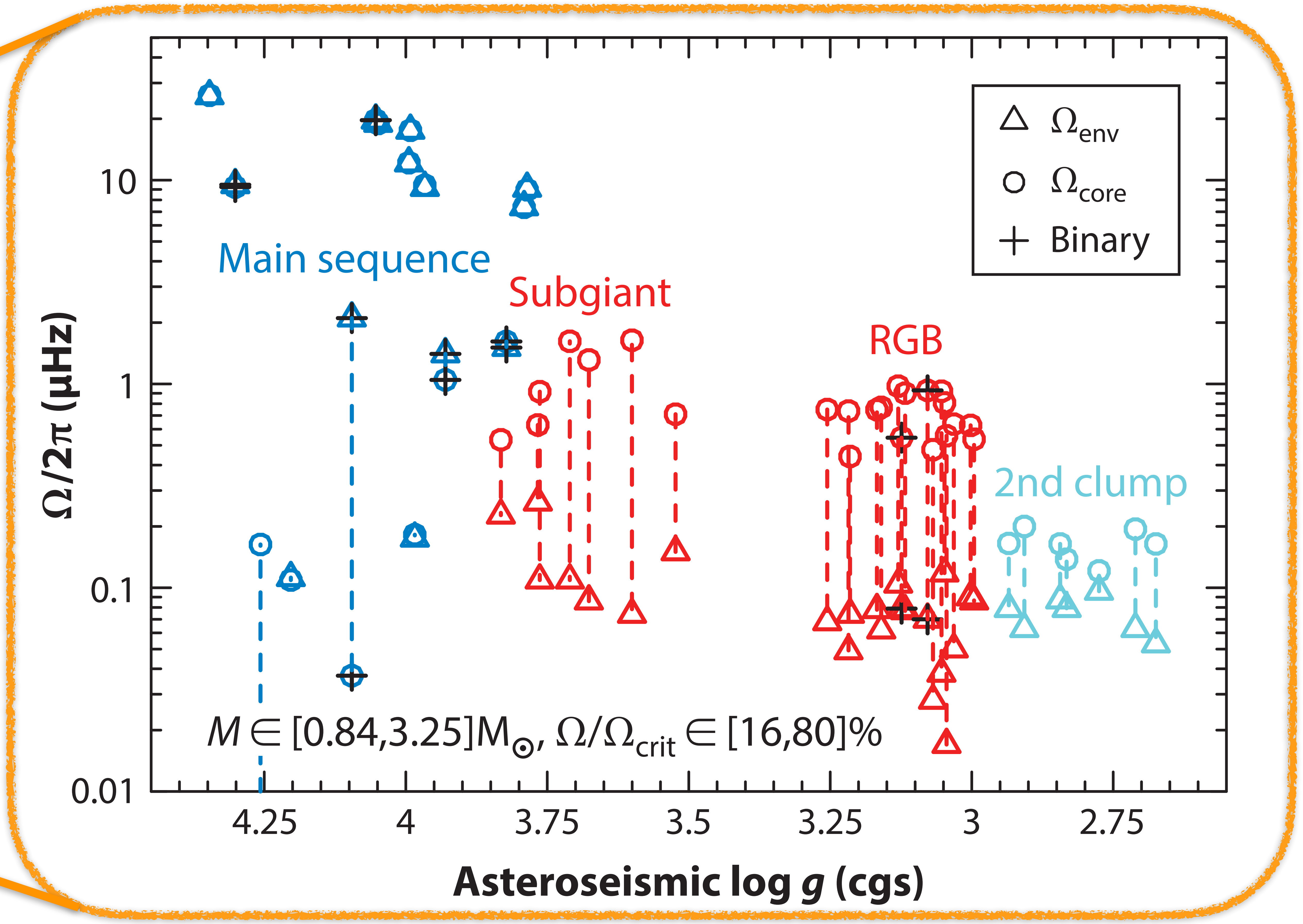
4. Magnetic Cores: can we measure field strengths with pulsations?

5. Gravity Waves: what are the excitation mechanisms and effects of transport?

# Interior rotation and angular momentum transport

*Talk to Jamie Tayar*




What is the missing angular momentum transport mechanism(s) to explain rigid-body main sequence stars?

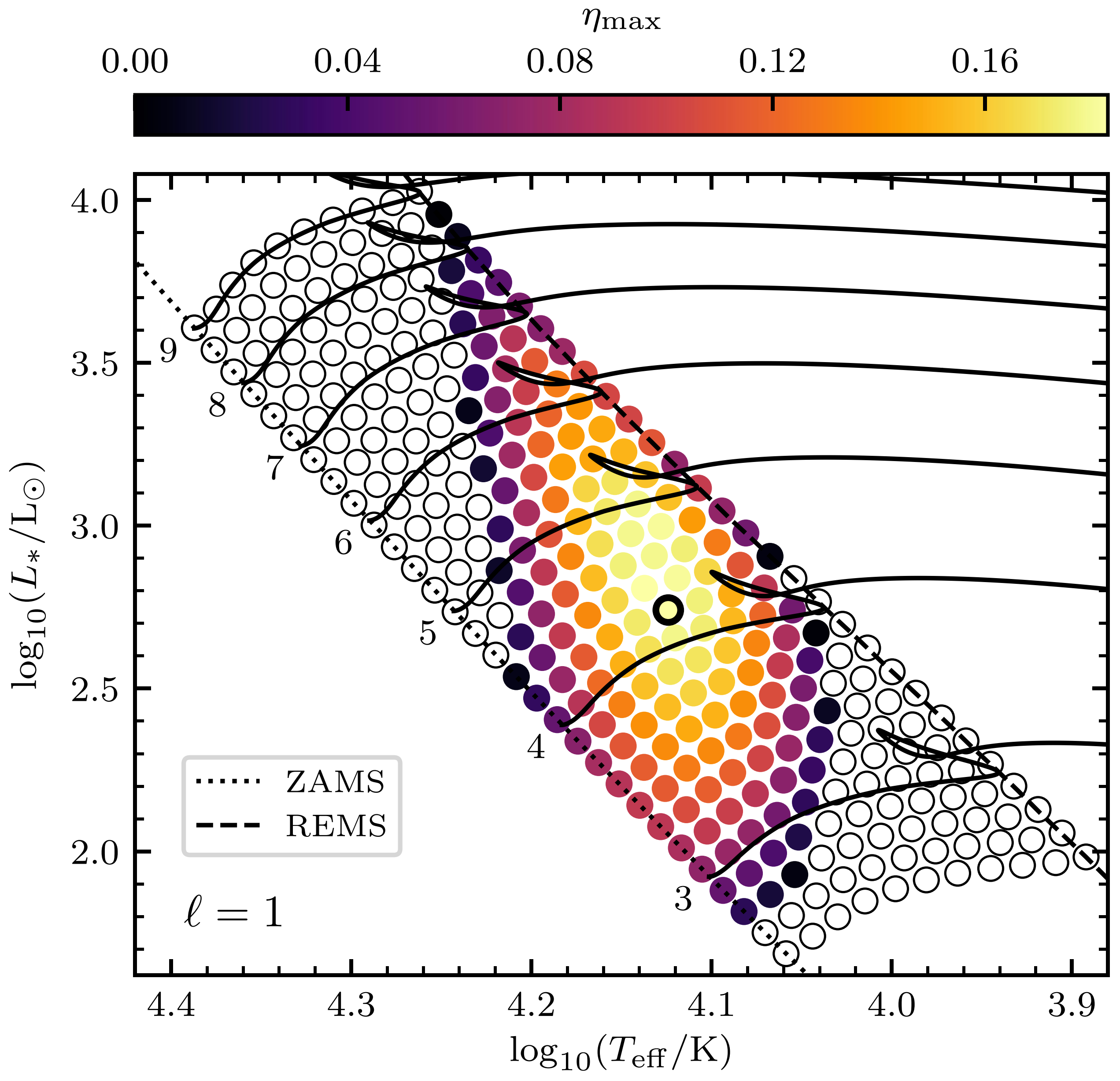
Aerts, Mathis, & Rogers (2019, ARAA 57)

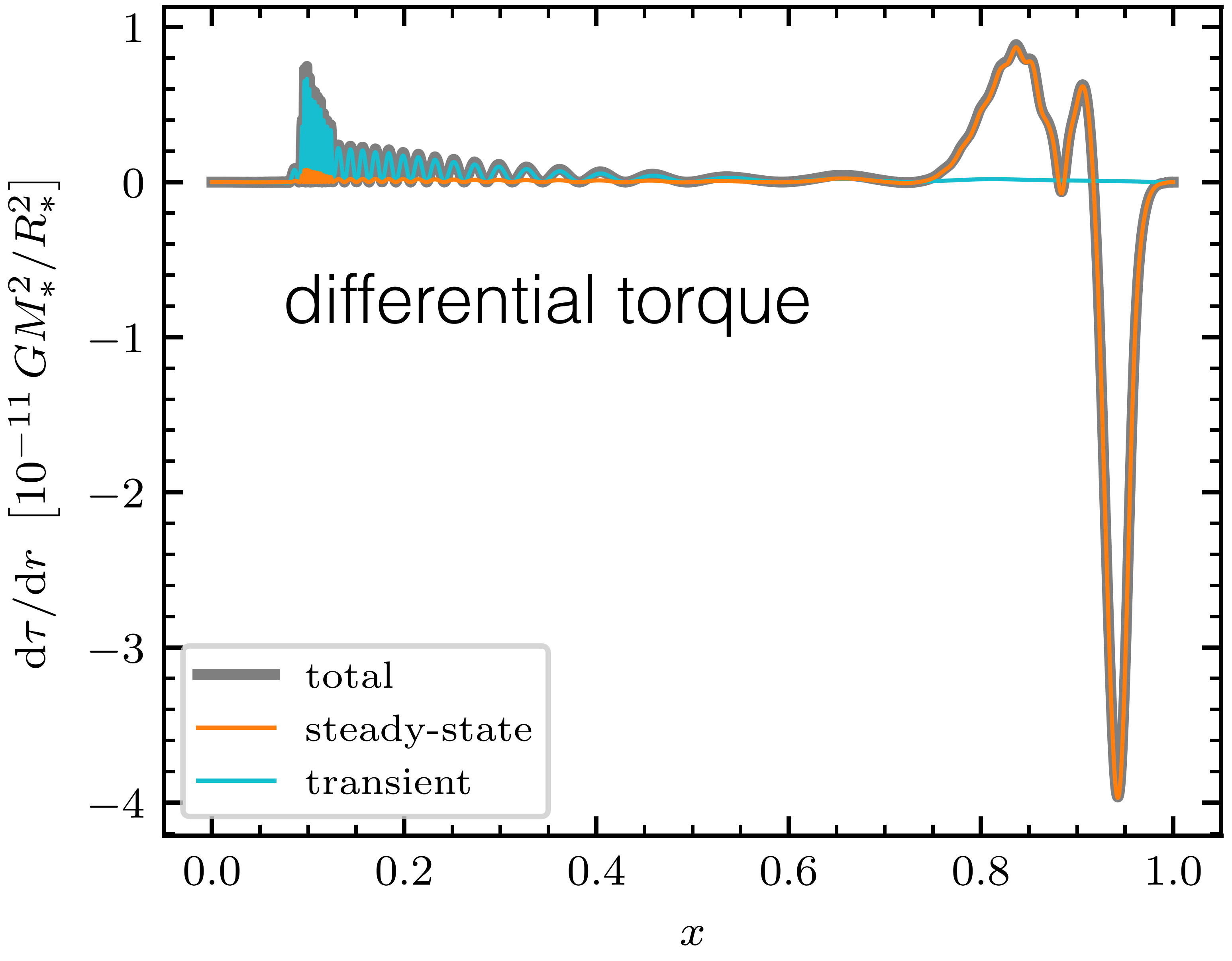
# Interior rotation and angular momentum transport

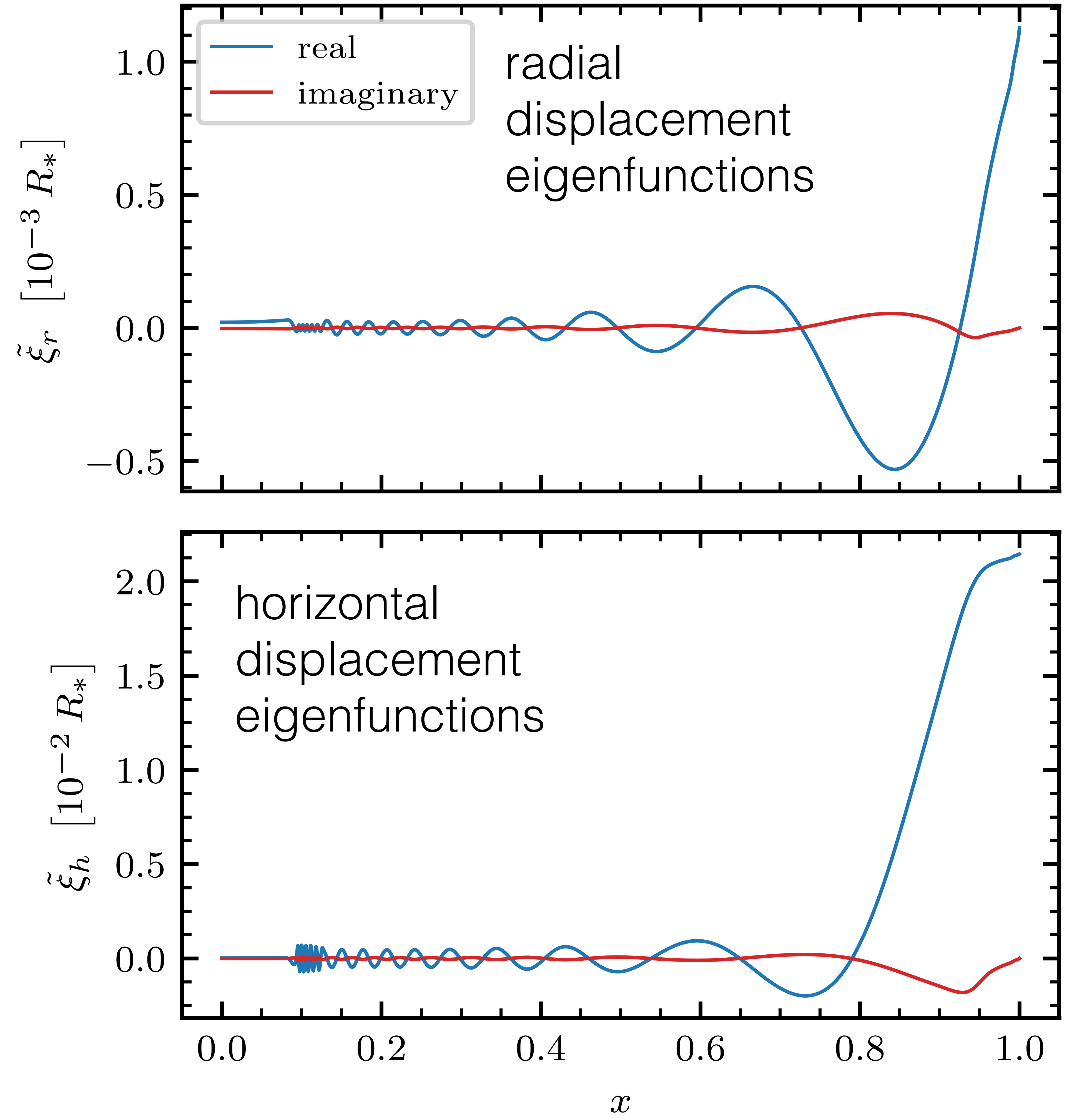
Differential torque of gravity modes in main sequence 4.2 M star very efficient at angular momentum transport.

Magnetism counterbalances angular momentum transport.

Do pulsating, slowly-rotating, massive stars also have internal magnetic fields?




Townsend et al. (2018, MNRAS 475)

# Discussion Points / Open Questions

1. Interior rotation: what is the missing AM transport mechanism(s)?

2. **Envelope mixing in MS stars:** why is there a large diversity?

3. Core Boundary Mixing: what is the best shape in 3D -> 1D?

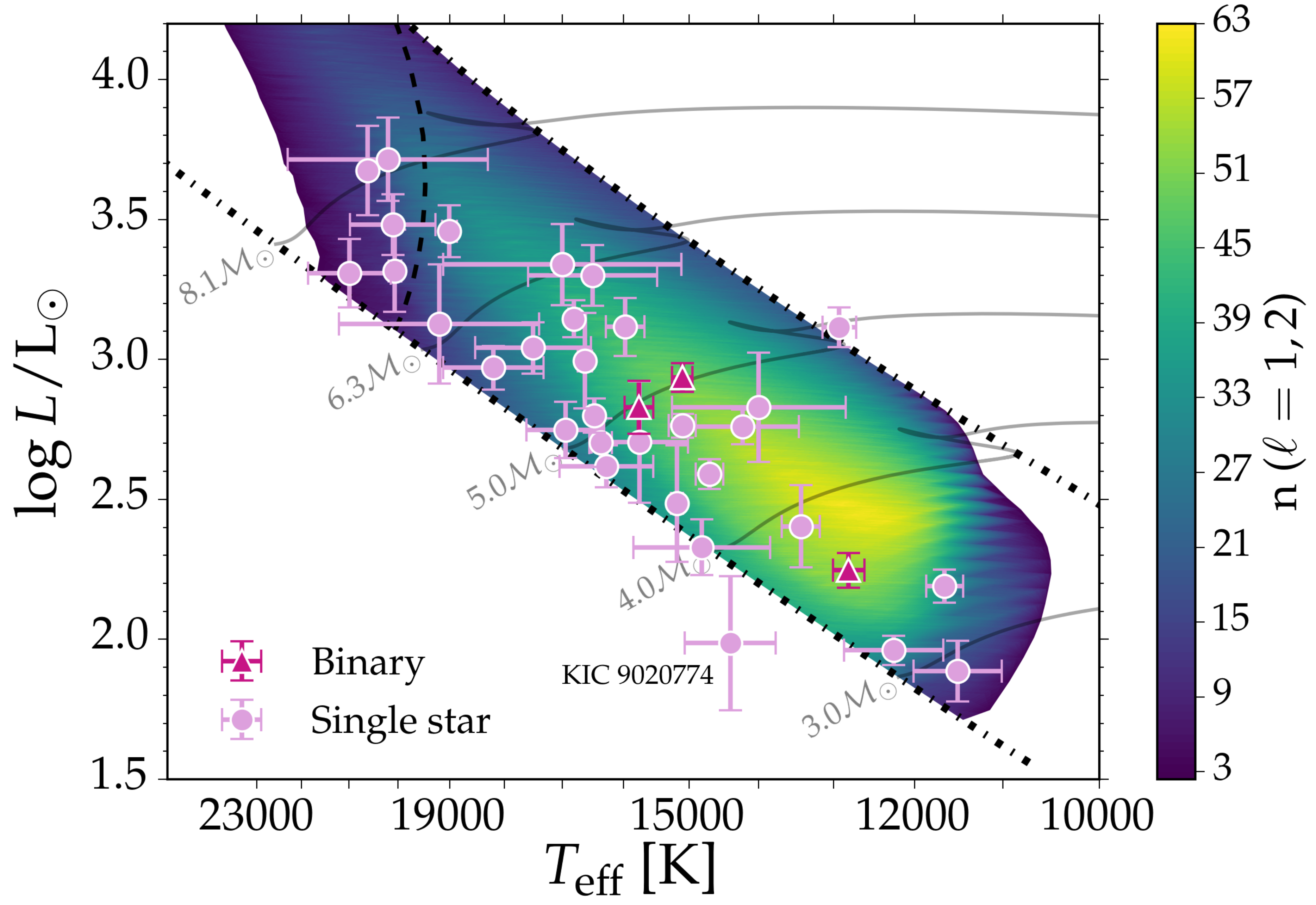
4. Magnetic Cores: can we measure field strengths with pulsations?

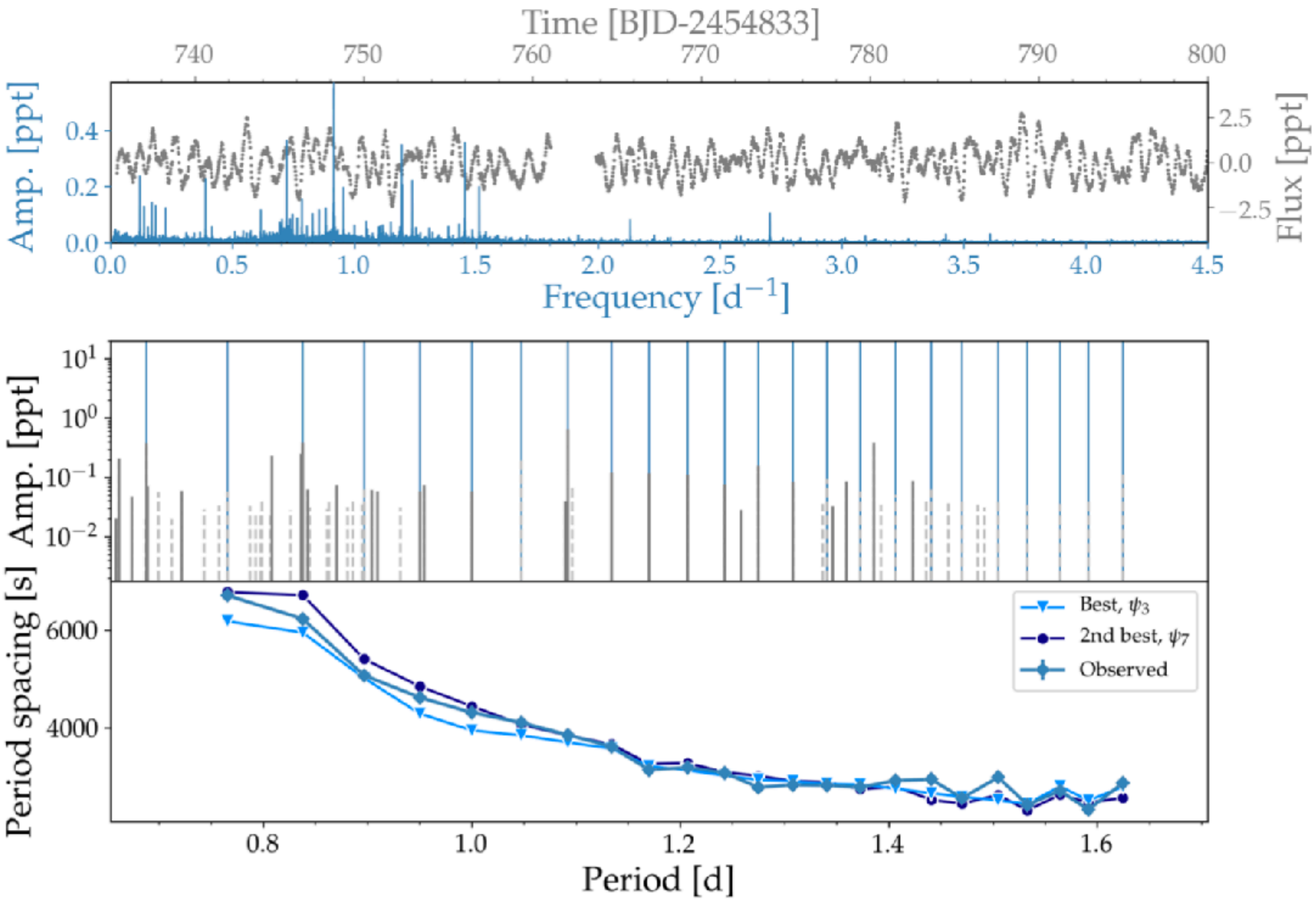
5. Gravity Waves: what are the excitation mechanisms and effects of transport?

# Envelope Mixing

*Talk to May Pedersen*

*Kepler* Space Telescope had good coverage of the SPB instability region.



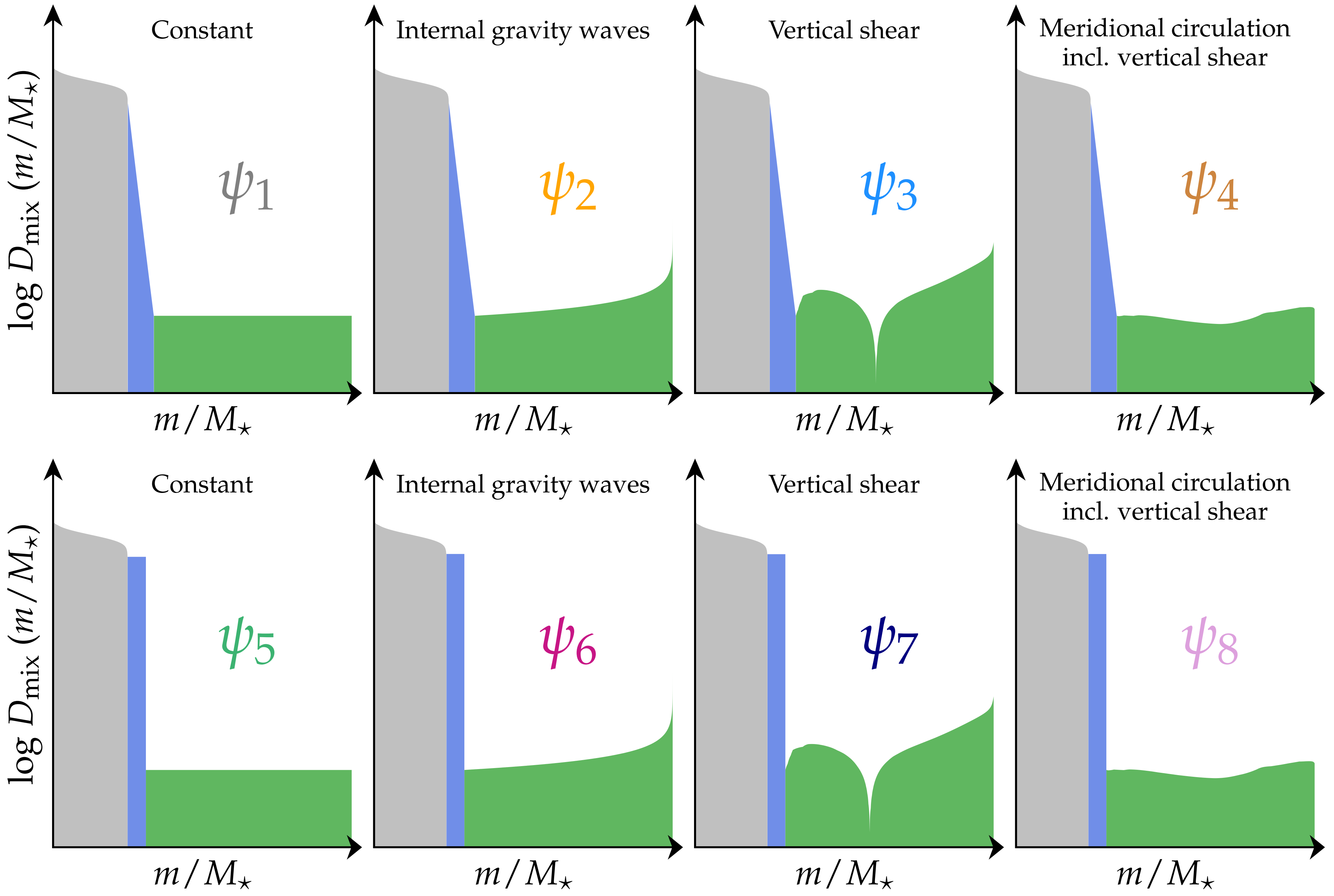




Pedersen et al. (2020, MNRAS 495)
Pedersen et al. (2021, NatAst 5)

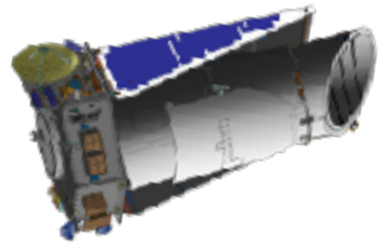
# Envelope Mixing

*Talk to May Pedersen*

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




$f_{\rm ov}$ Z $M_\star$ $X_c$
$M_{cc}$ $D_{\rm mix}(r)$ $\Omega(r)$



light curve → frequency analysis → identify mode geometry → forward seismic modelling → stellar properties

Spectroscopy → forward seismic modelling

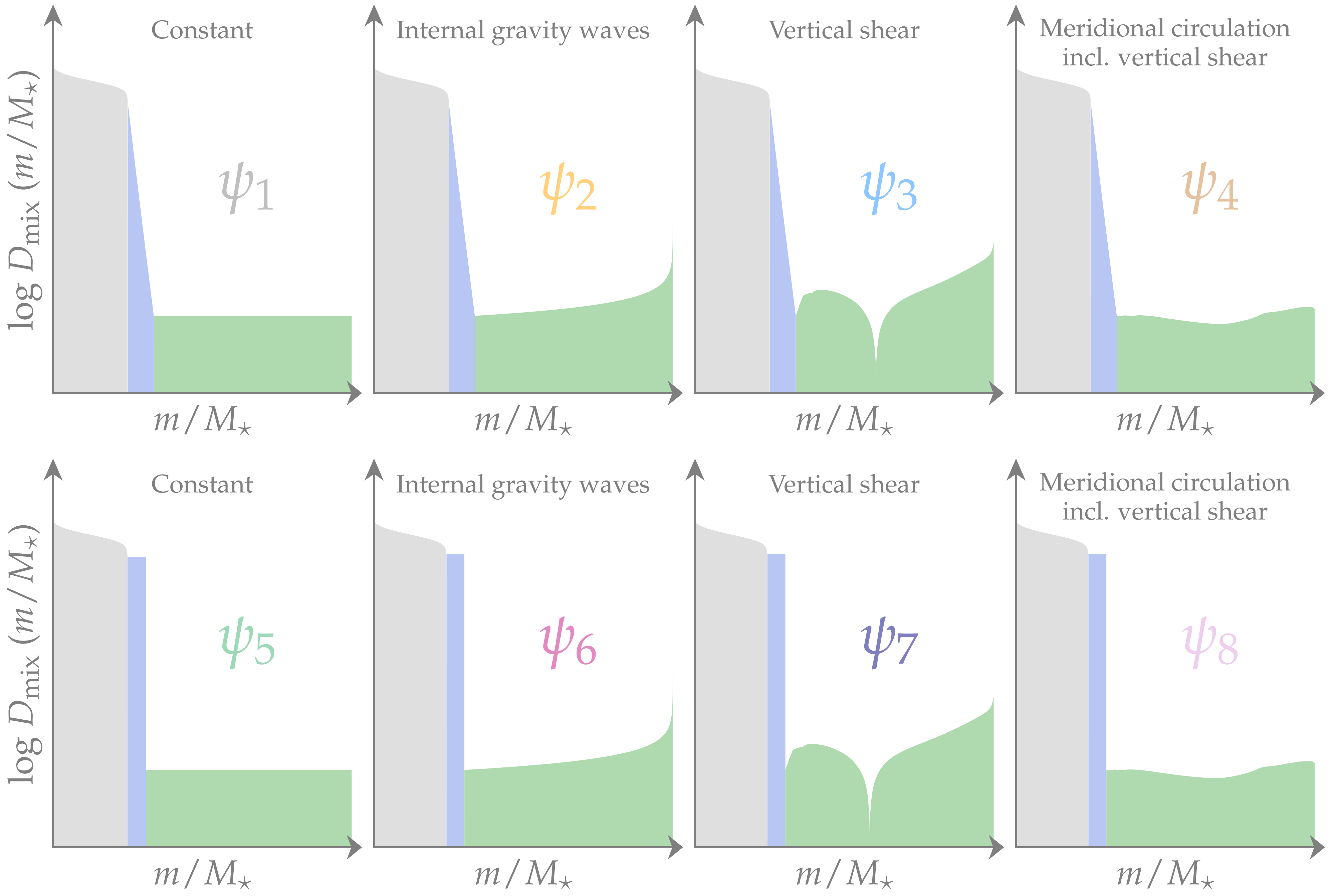
Pedersen et al. (2021, NatAst 5)

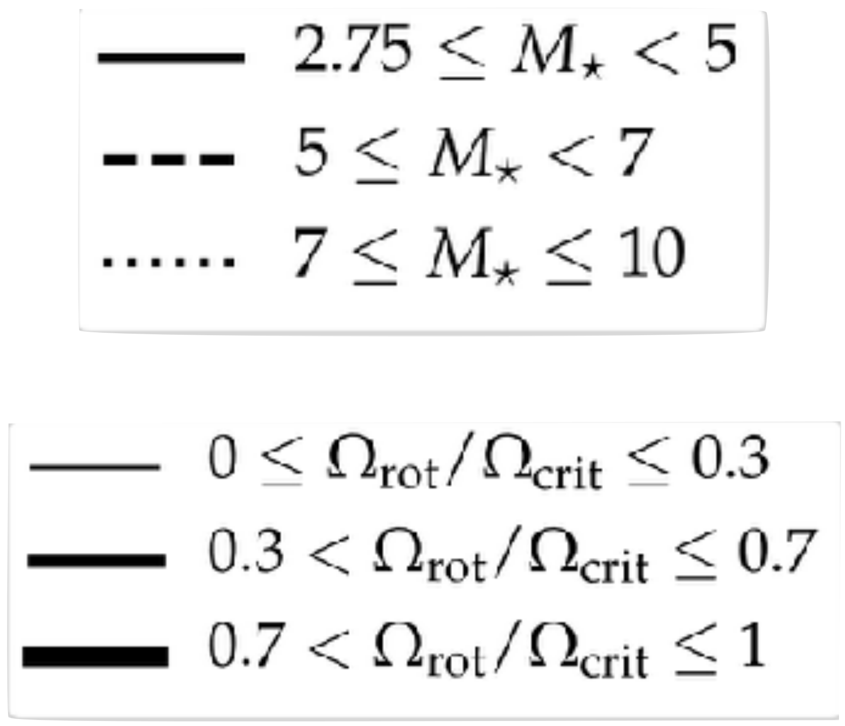
# Envelope Mixing

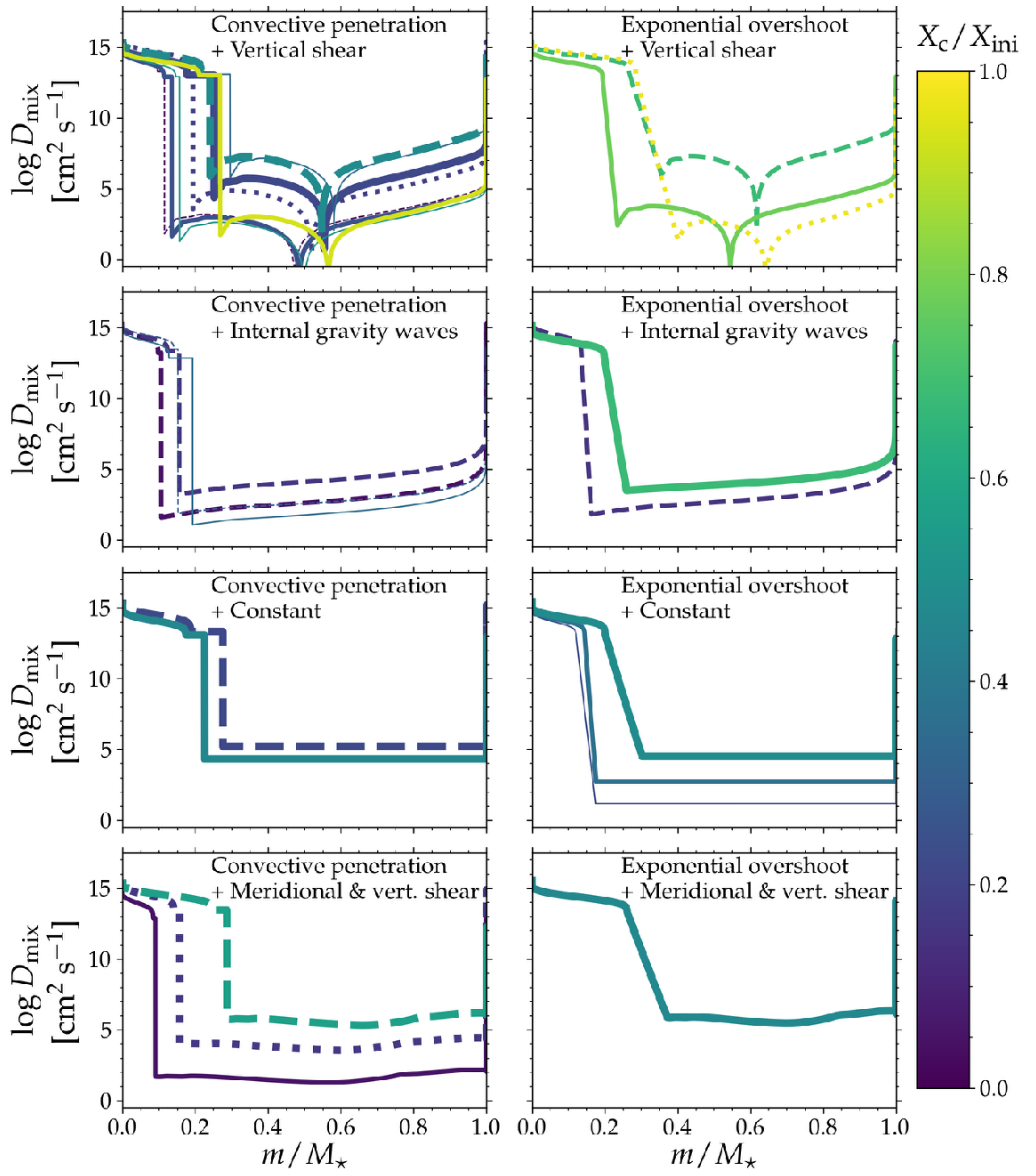
*Talk to May Pedersen*

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

Why is there a large diversity in mixing profiles?




Pedersen et al. (2021, NatAst 5)

# Discussion Points / Open Questions

1. Interior rotation: what is the missing AM transport mechanism(s)?

2. Envelope mixing in MS stars: why is there a large diversity?

3. **Core Boundary Mixing:** what is the best shape in 3D -> 1D?

4. Magnetic Cores: can we measure field strengths with pulsations?

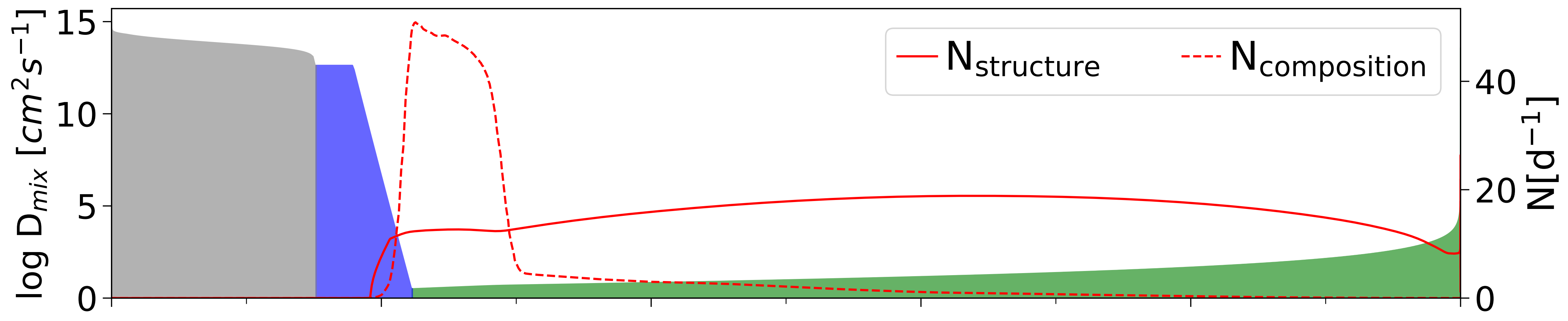
5. Gravity Waves: what are the excitation mechanisms and effects of transport?

# Core-Boundary Mixing

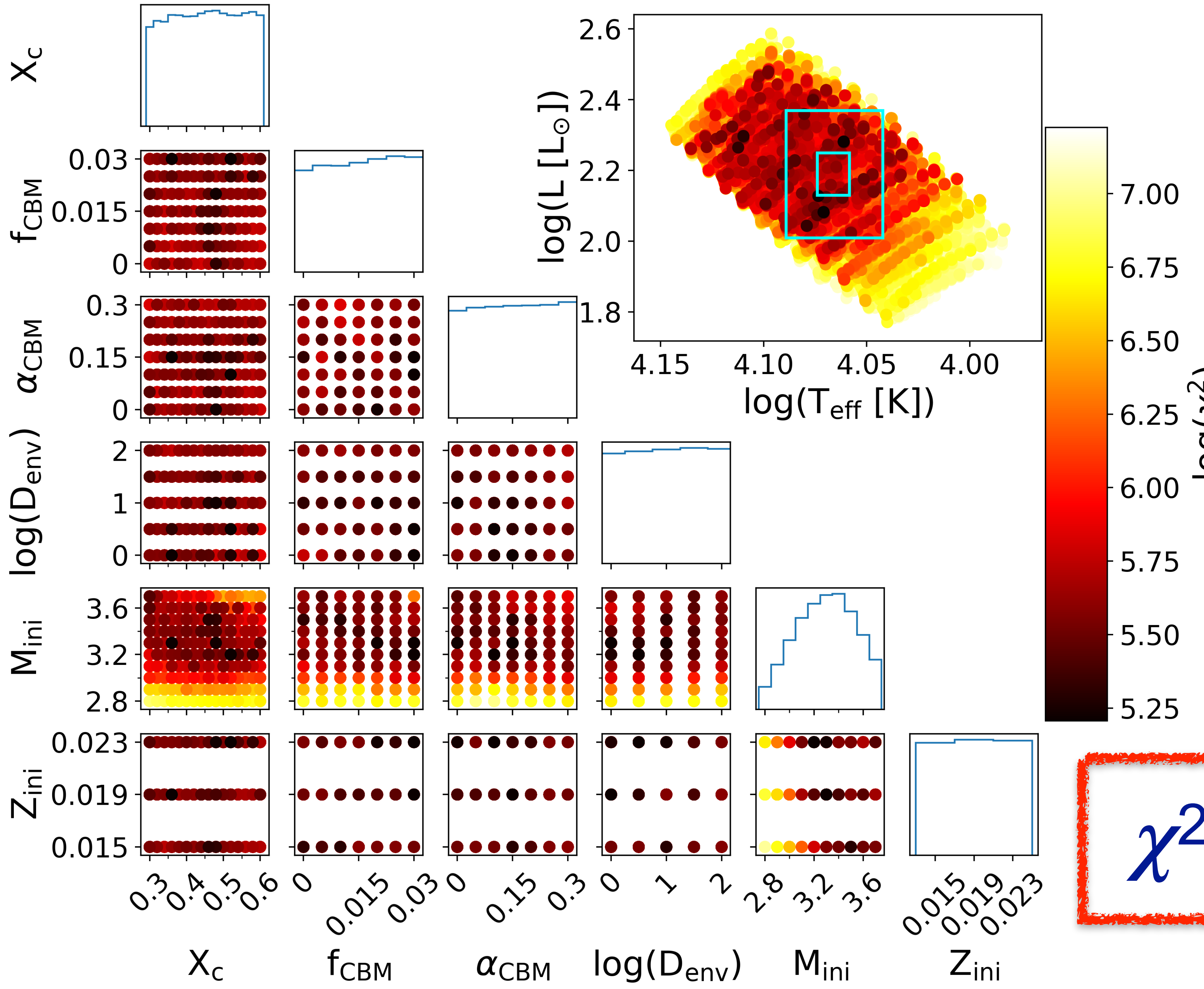
*Talk to Mathias Michielsen*

Advanced modelling requires Mahalanobis Distance instead of $\chi^2$ as merit function:

- theoretical uncertainties
- parameter correlations and degeneracies




Michielsen et al. (2021, A&A 650)




KIC 7760680

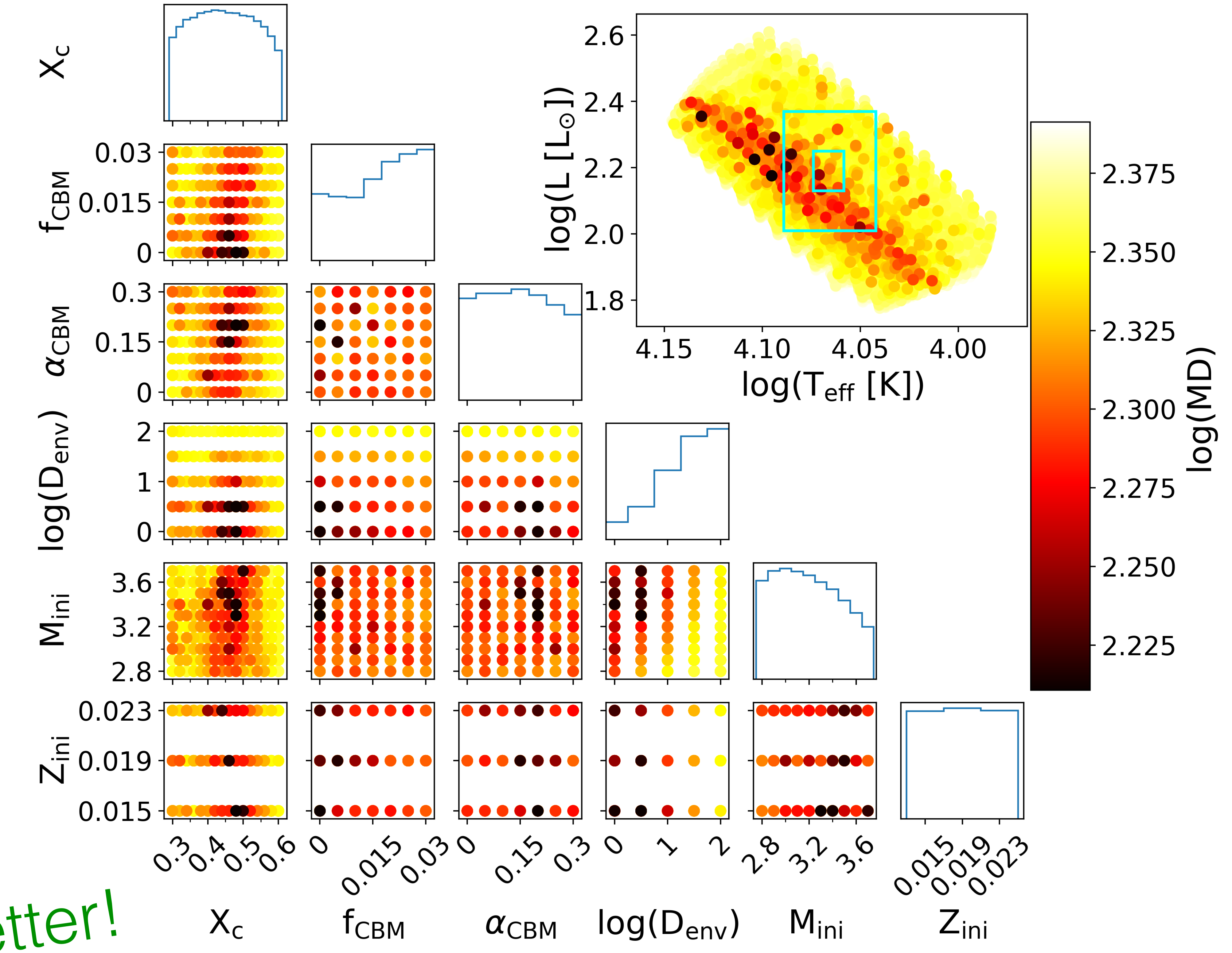
Kepler SPB

36 g modes

($\ell$=1)

$\chi^2$ → MD

better!

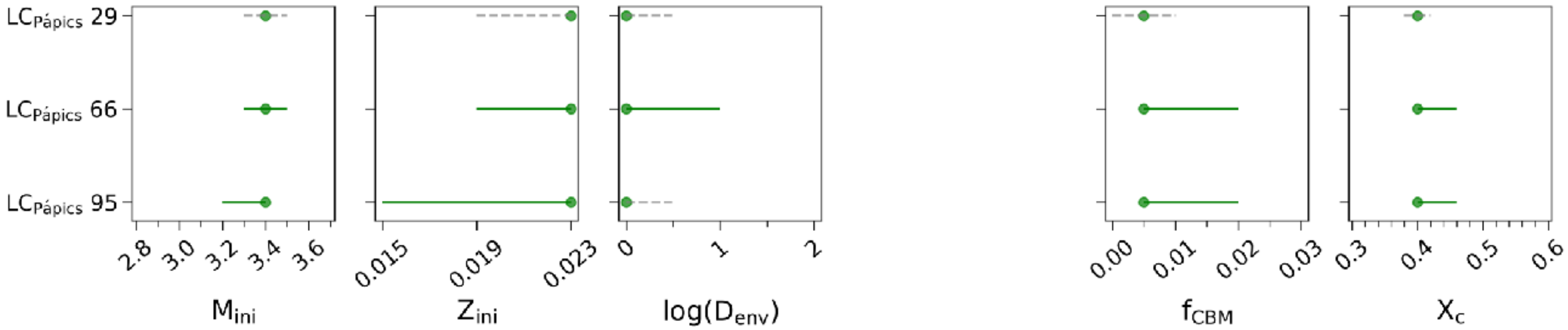


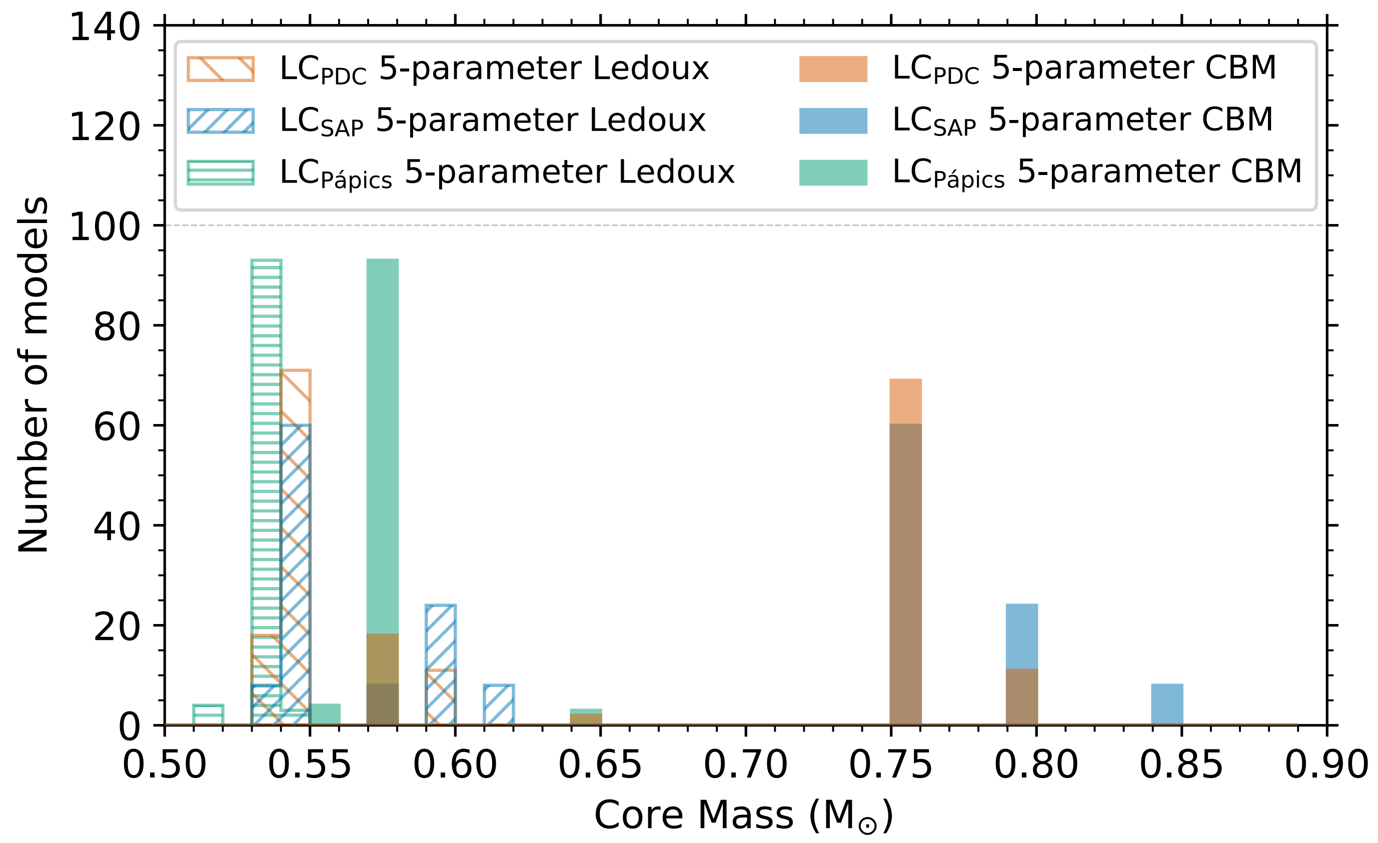
# Core-Boundary Mixing

Difference in 1- and 2-parameter asteroseismic modelling for CBM:

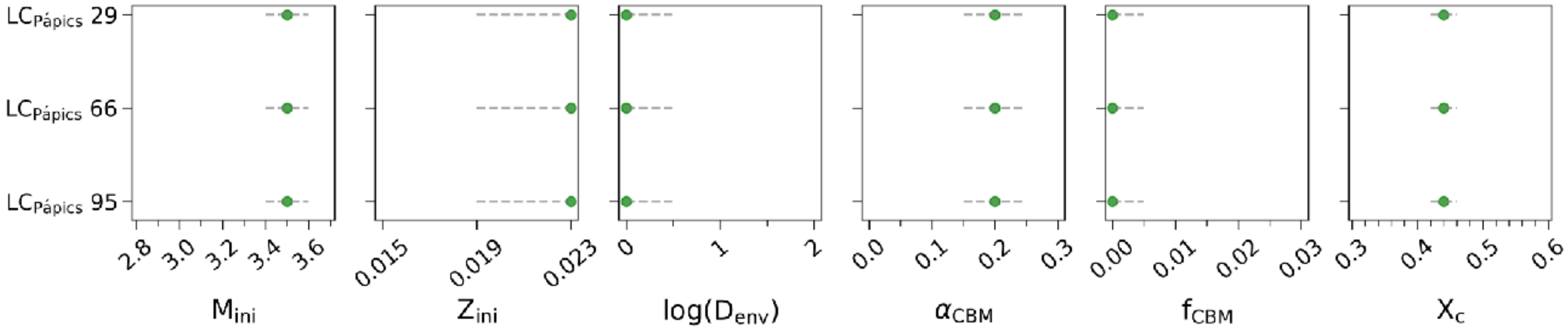
What is the best overshooting prescription for 1D models?

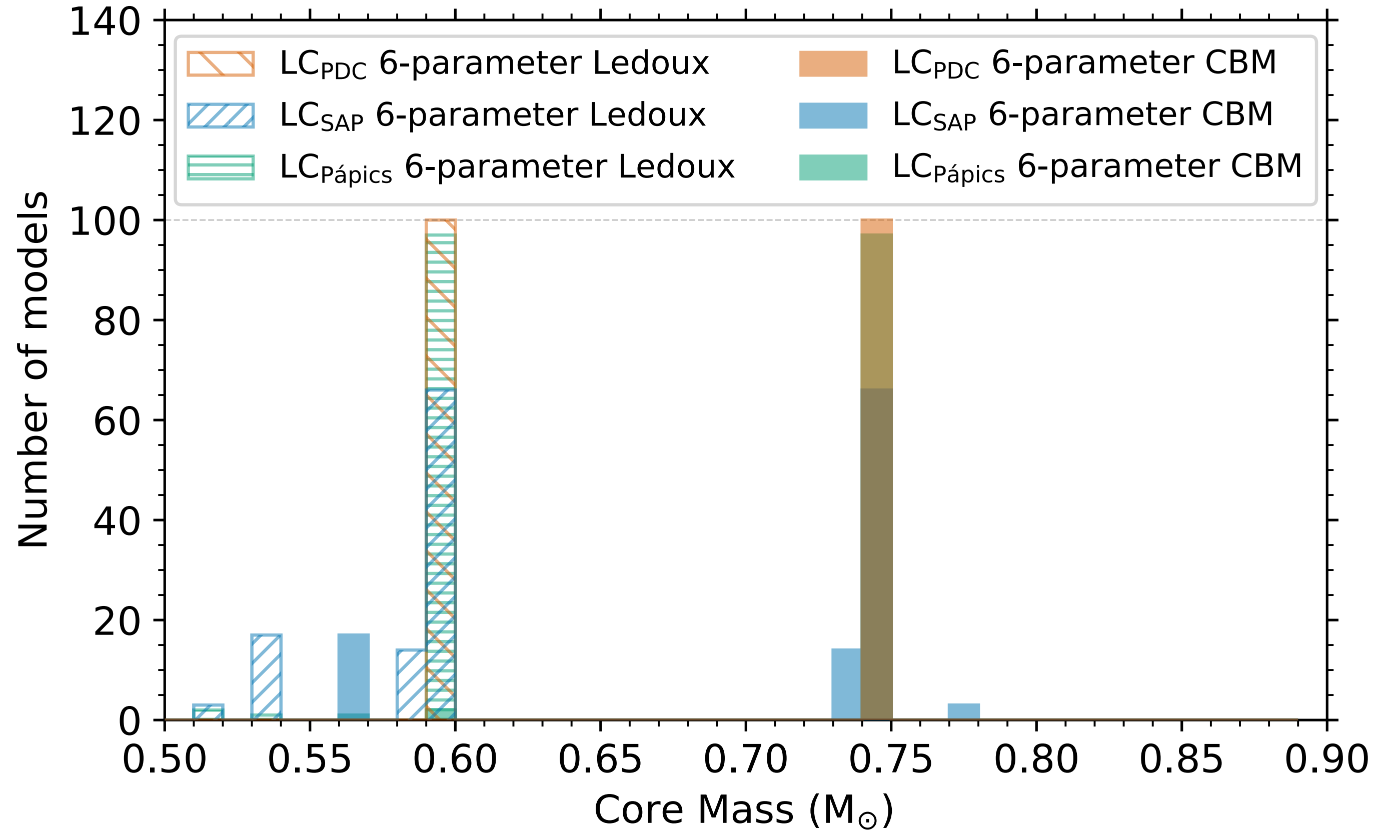
**5 parameters:**




**6 parameters:**




Bowman & Michielsen (2021, A&A *in press*)

# Discussion Points / Open Questions

1. Interior rotation: what is the missing AM transport mechanism(s)?

2. Envelope mixing in MS stars: why is there a large diversity?

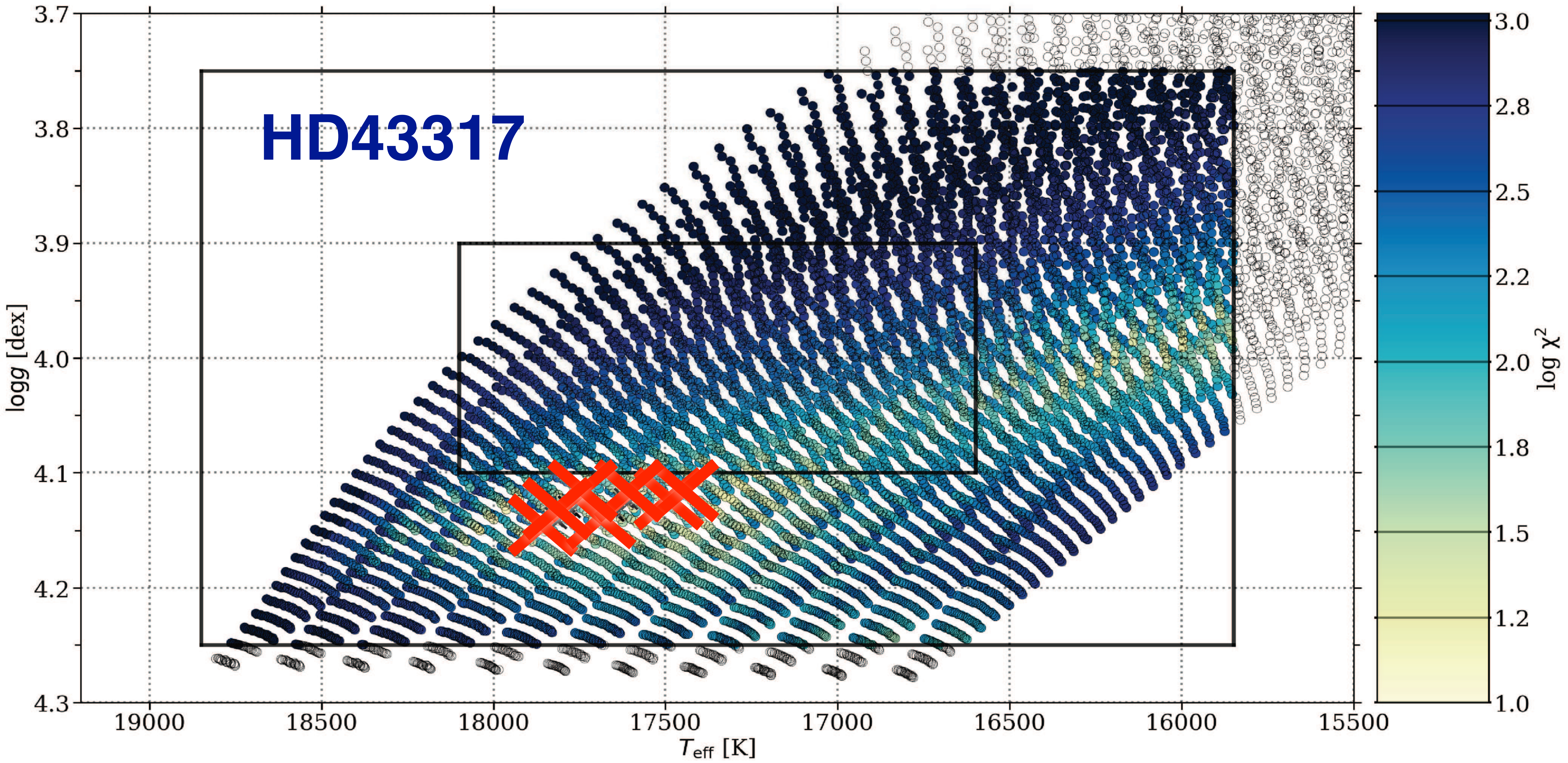
3. Core Boundary Mixing: what is the best shape in 3D -> 1D?

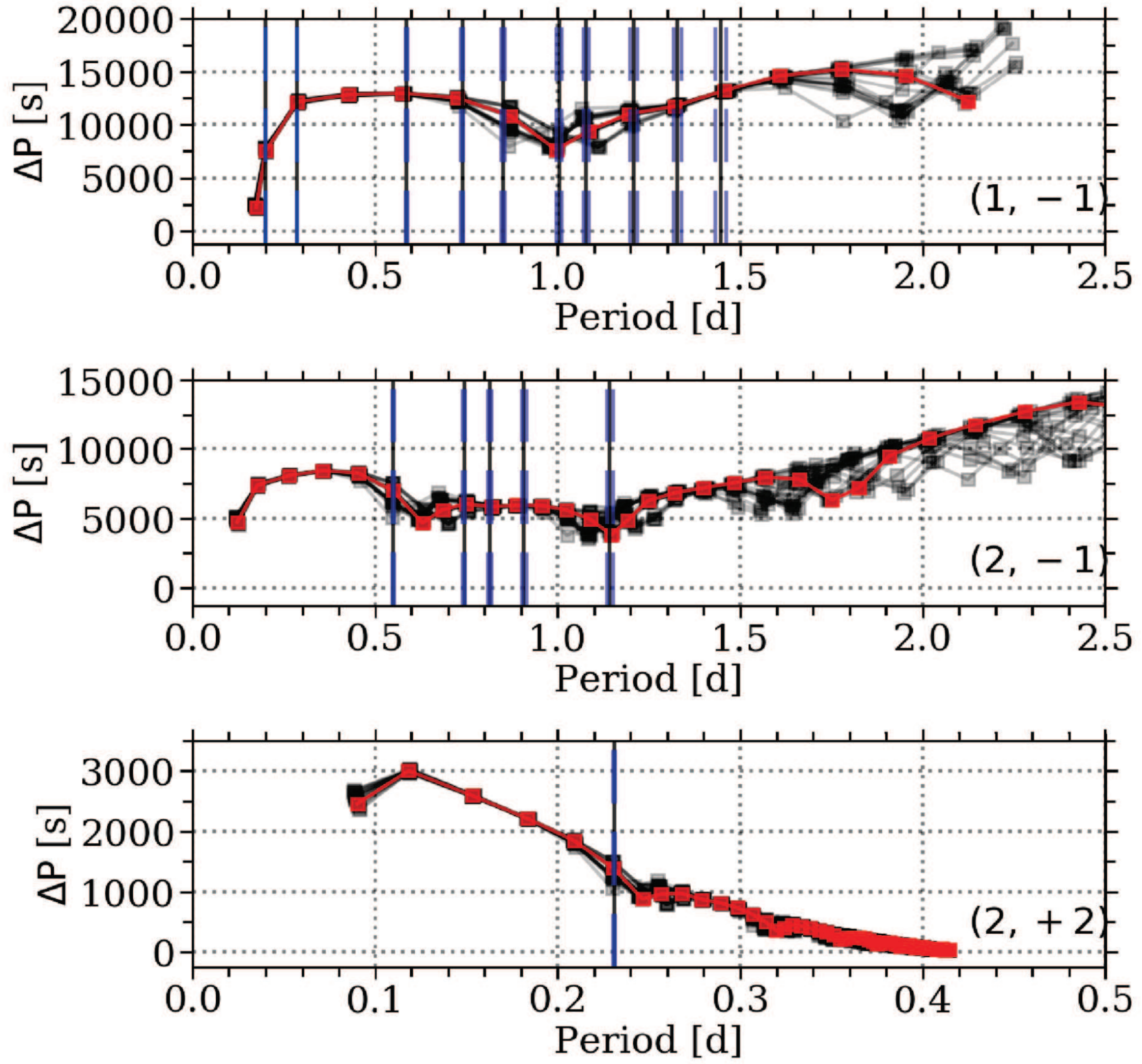
4. **Magnetic Cores:** can we measure field strengths with pulsations?

5. Gravity Waves: what are the excitation mechanisms and effects of transport?

# Magnetic cores: asteroseismology

*Talk to Dominic Bowman and Zsolt Keszthelyi*




Low overshooting because of core magnetic field?

Buysschaert et al. (2018, A&A 616)

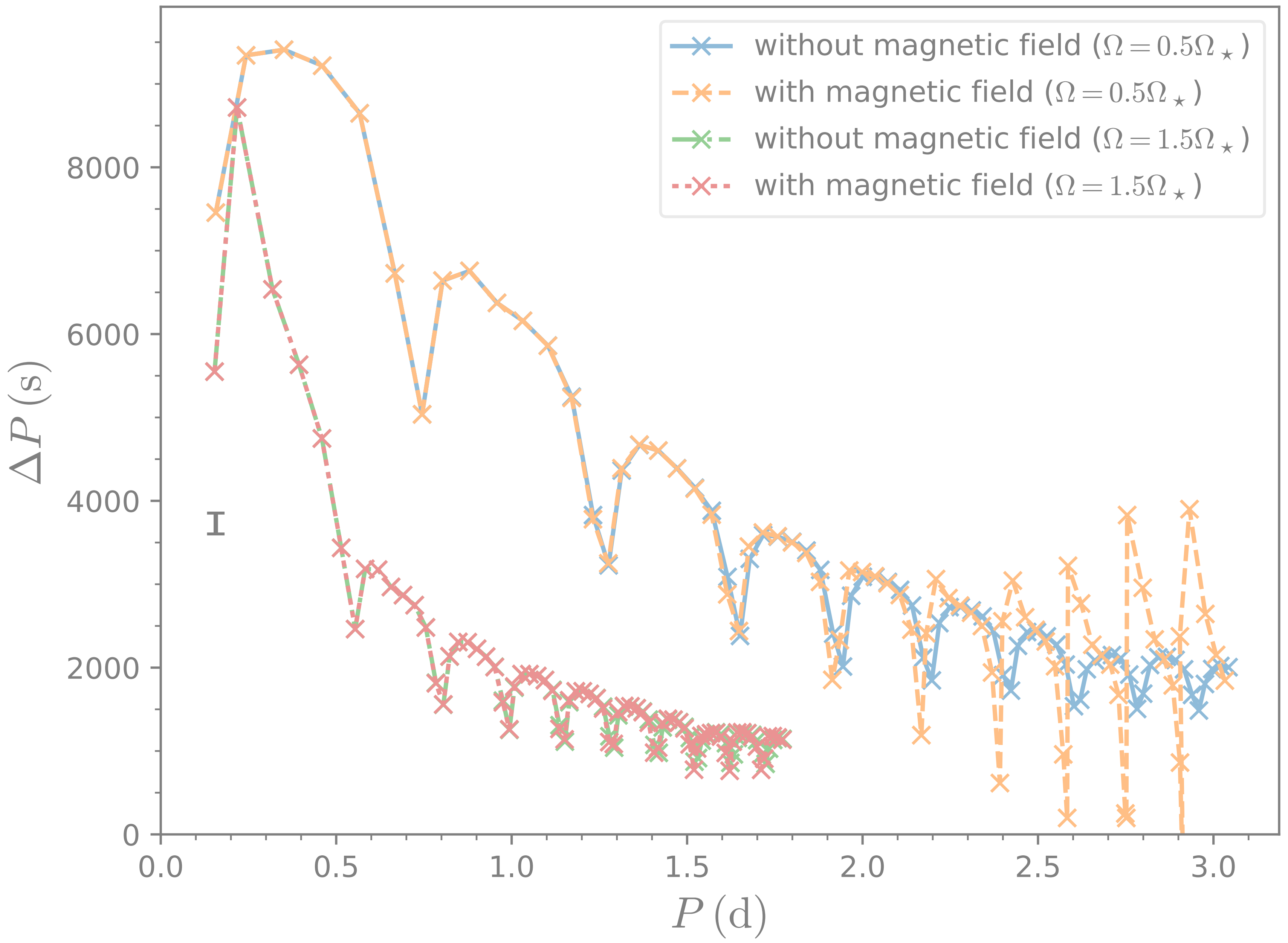
- $f_{\mathrm{ov}}$ = 0.004 ± 0.014
- $M_\star$ = 5.8 ± 0.2 $M_\odot$
- $X_c$ = 0.54 ± 0.02

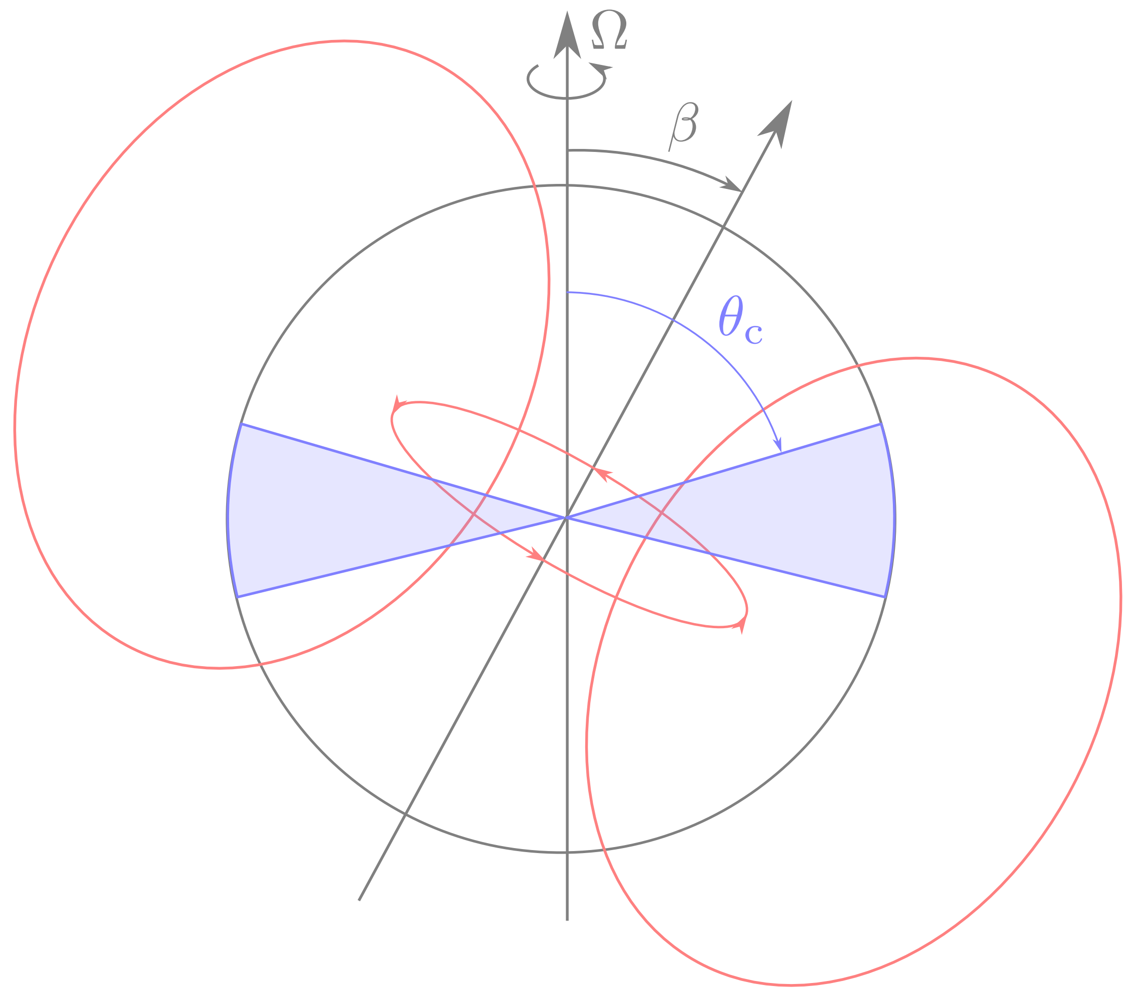
- $P_{\mathrm{rot}}$ = 0.897673 d
- $B_p$ = 1312 ± 332 G

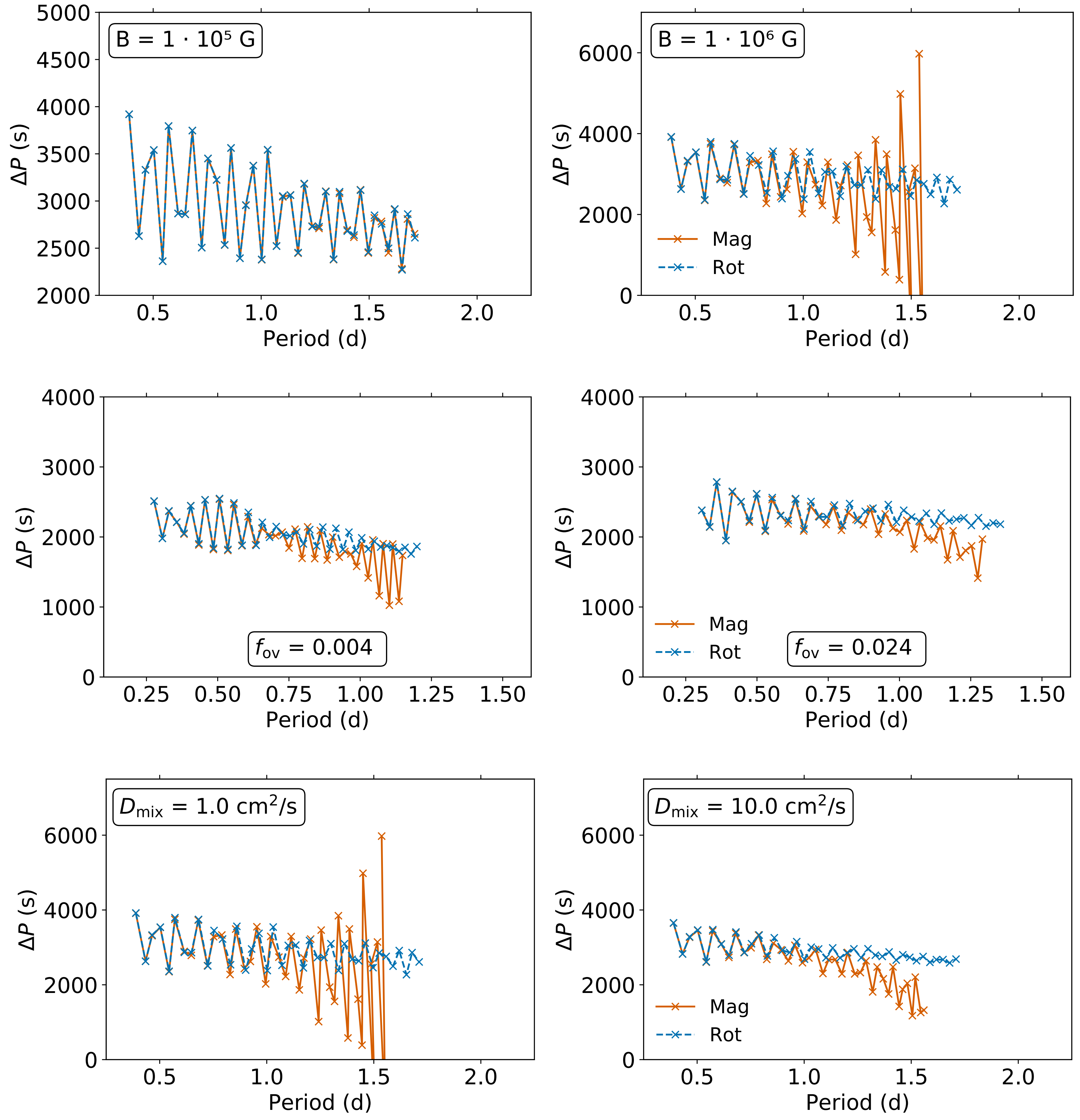
# Magnetic cores: asteroseismology

*Talk to Lisa Bugnet and Jordan Van Beeck*

Can we detect and characterise core magnetic field strengths from pulsations?




**Fossil field with poloidal and toroidal components**

Prat et al. (2019, A&A 627)

**Oblique dipolar fossil magnetic field**

Prat et al. (2020, A&A 636)

**Full parameter study for g-mode period spacing patterns**

Van Beeck et al. (2020, A&A 638)

# Discussion Points / Open Questions

1. Interior rotation: what is the missing AM transport mechanism(s)?

2. Envelope mixing in MS stars: why is there a large diversity?

3. Core Boundary Mixing: what is the best shape in 3D -> 1D?

4. Magnetic Cores: can we measure field strengths with pulsations?

**5. Gravity Waves:** what are the excitation mechanisms and effects of transport?

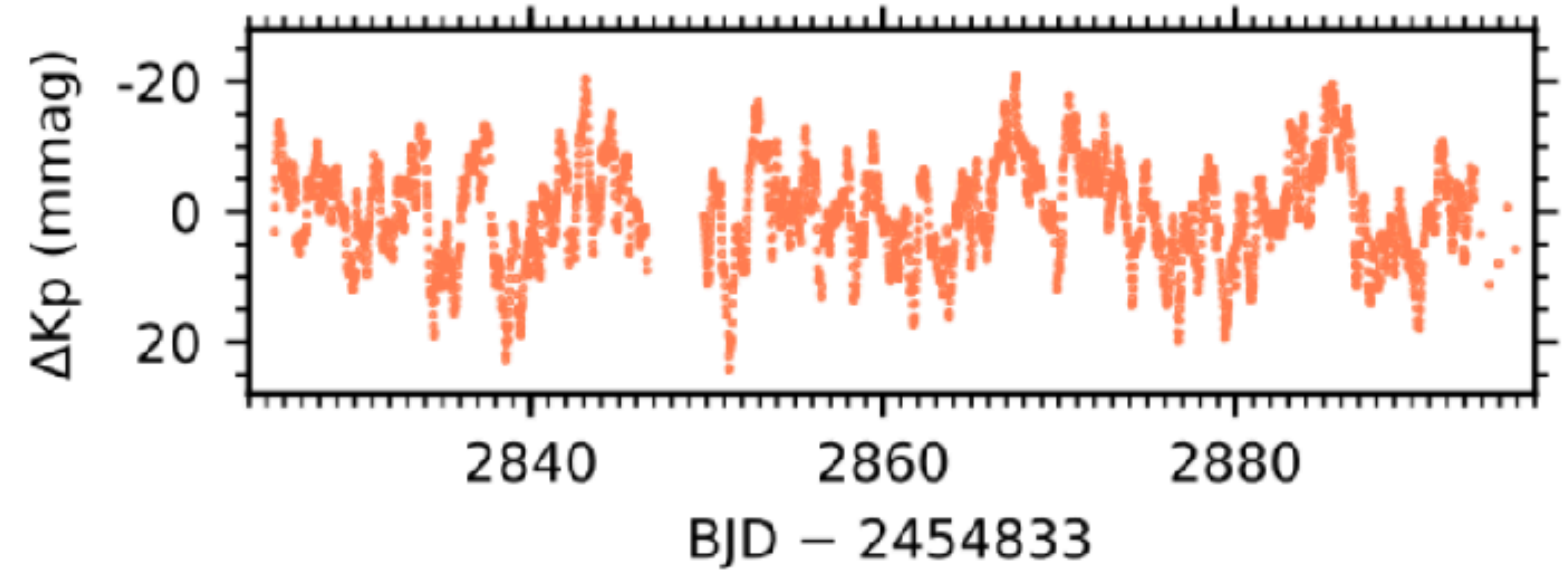
# Gravity Waves in Massive Stars

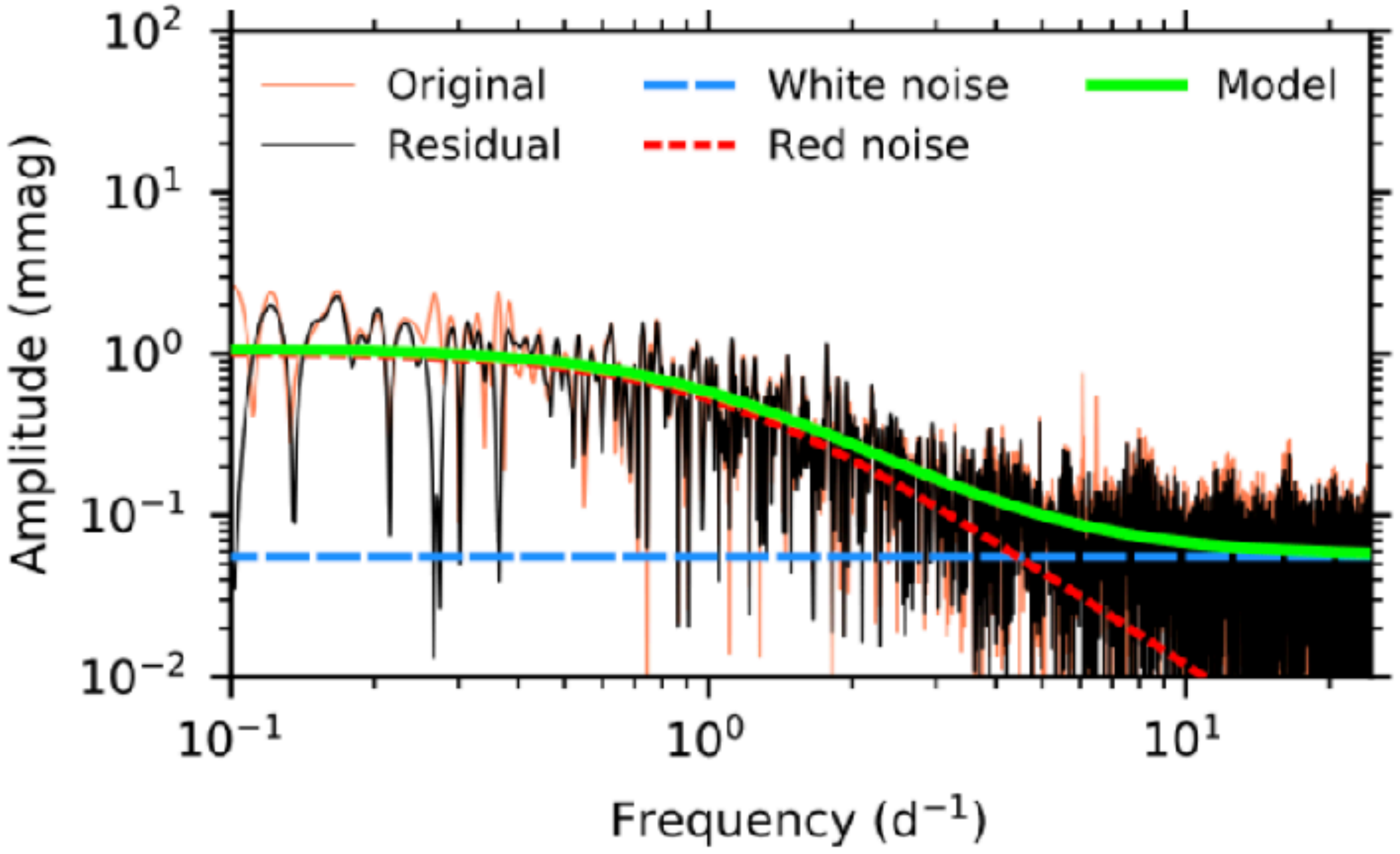
*Talk to Falk Herwig and Philipp Edelmann*

Ubiquitous Stochastic Low Frequency variability in OB stars:

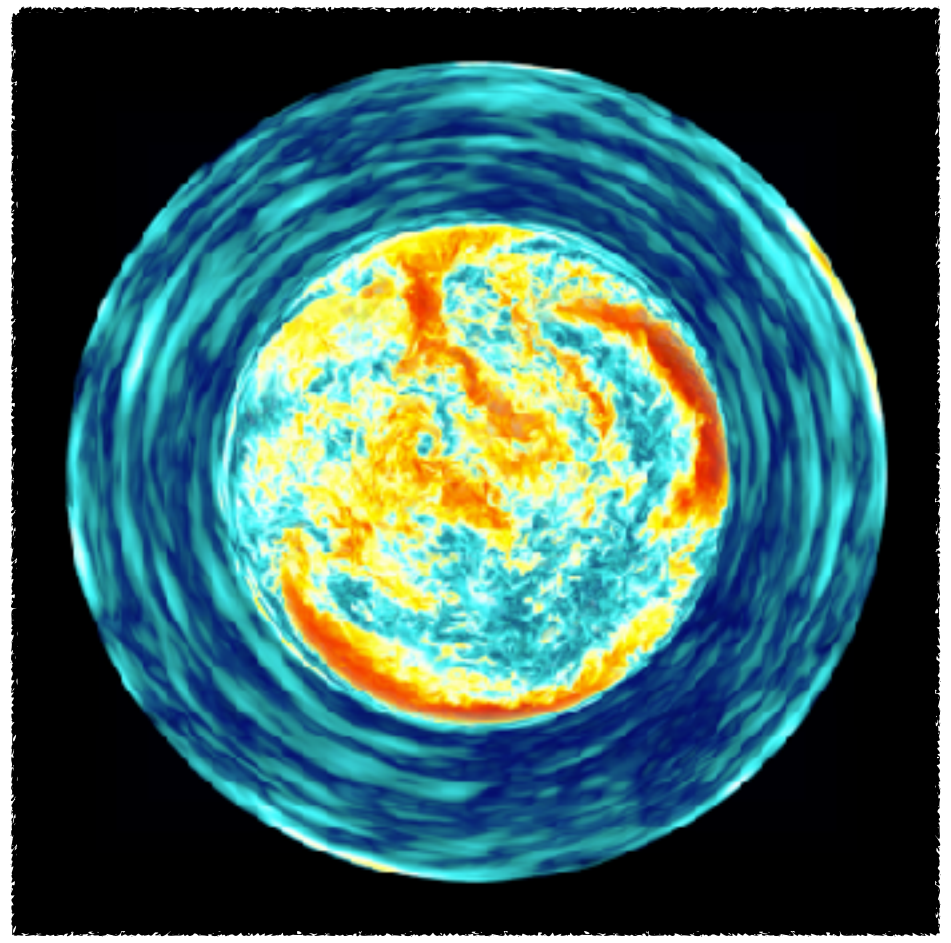
- waves from core convection or the surface (or both):
  (Rogers et al. 2013, ApJ 772; Shiode et al. 2013, MNRAS 430; Edelmann et al. 2019, ApJ 876; Horst et al. 2020, A&A 641; Lecoanet et al. 2019, ApJL 886; Cantiello et al. 2021, ApJ 915; Lecoanet et al. 2021, MNRAS 508)
- clumpy and aspherical winds:
  (e.g. Krtička & Feldmeier 2021, A&A 648)

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

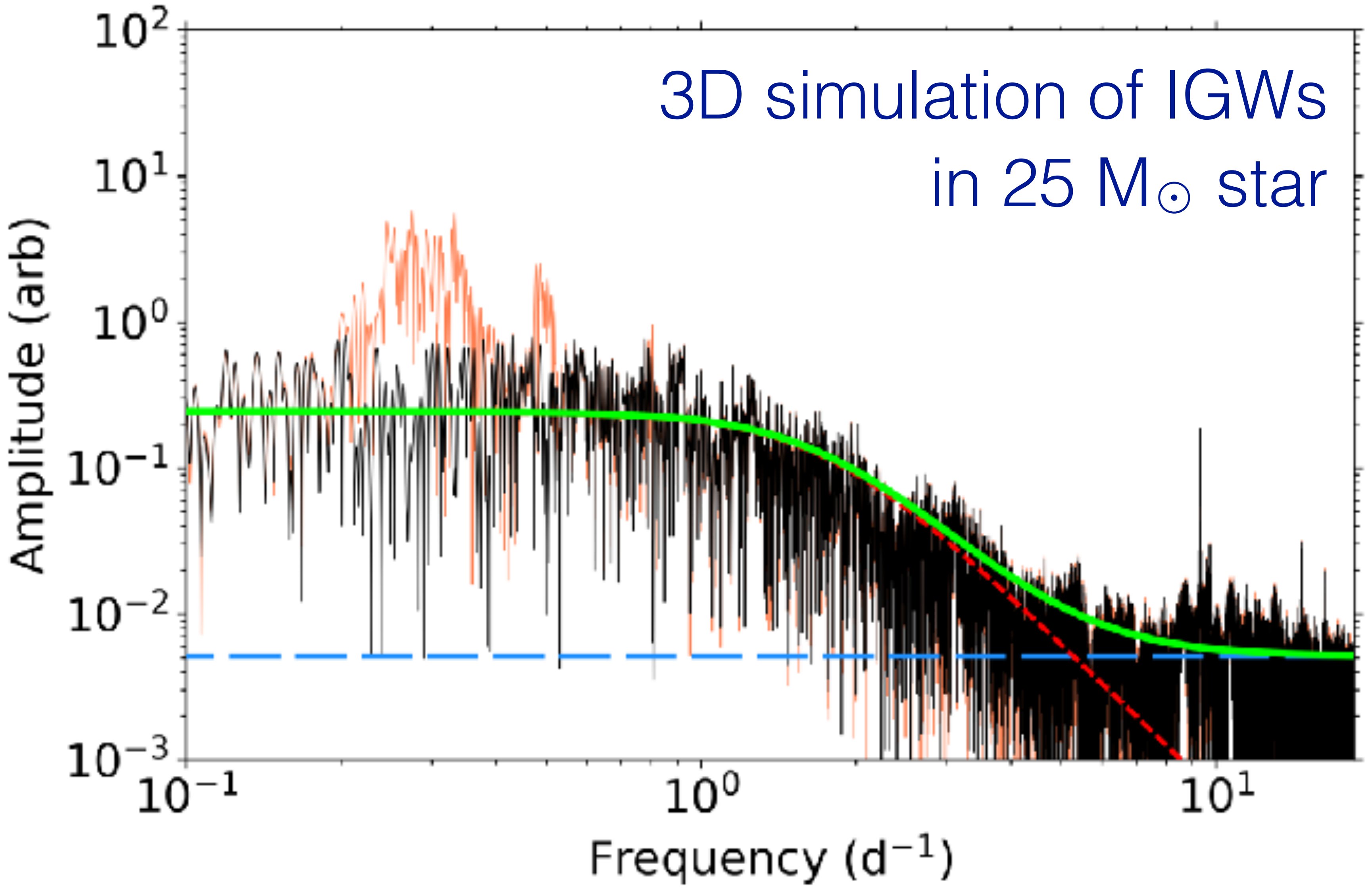



Bowman et al. (2019, Nature Astronomy 3)



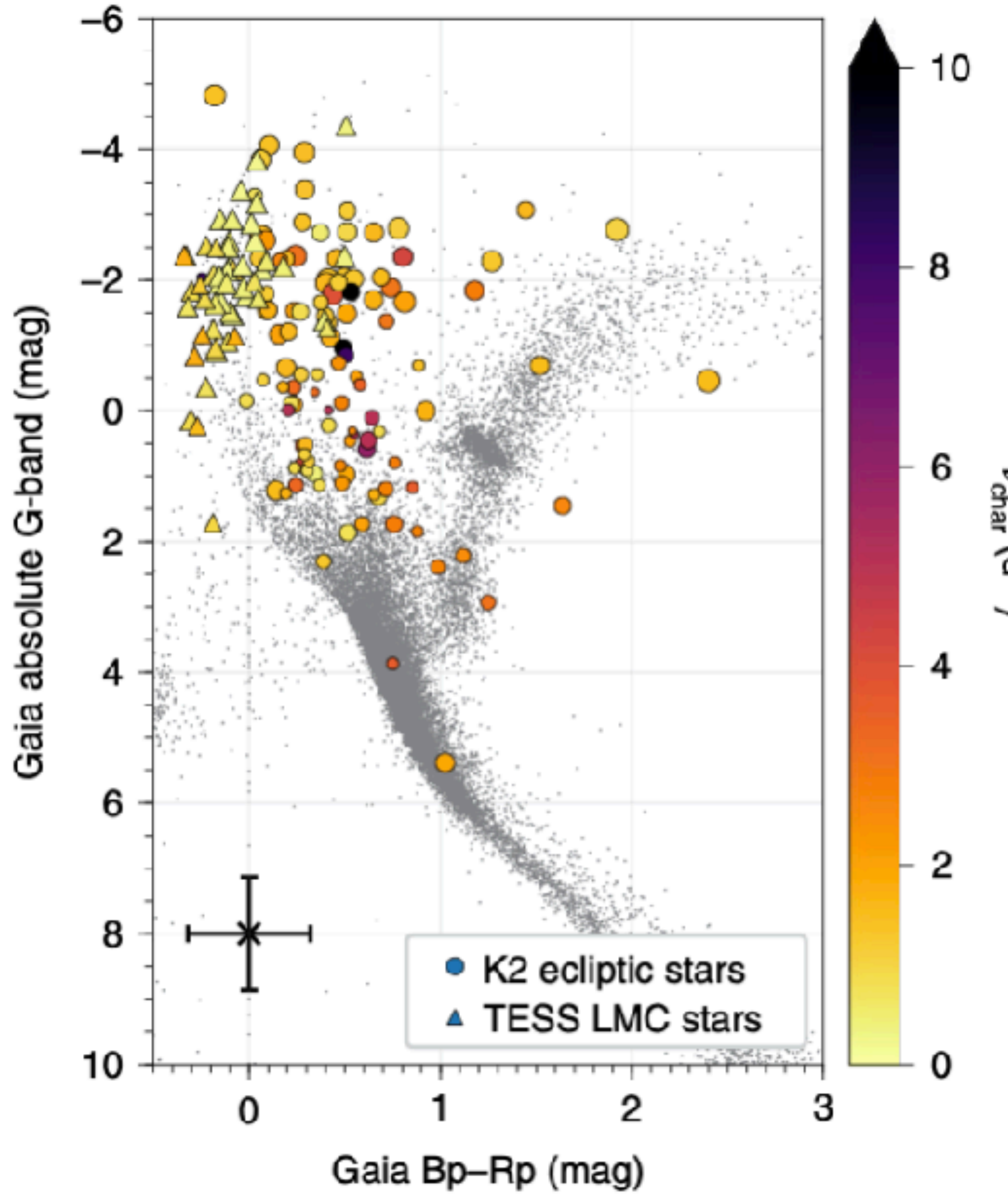
Courtesy of F. Herwig

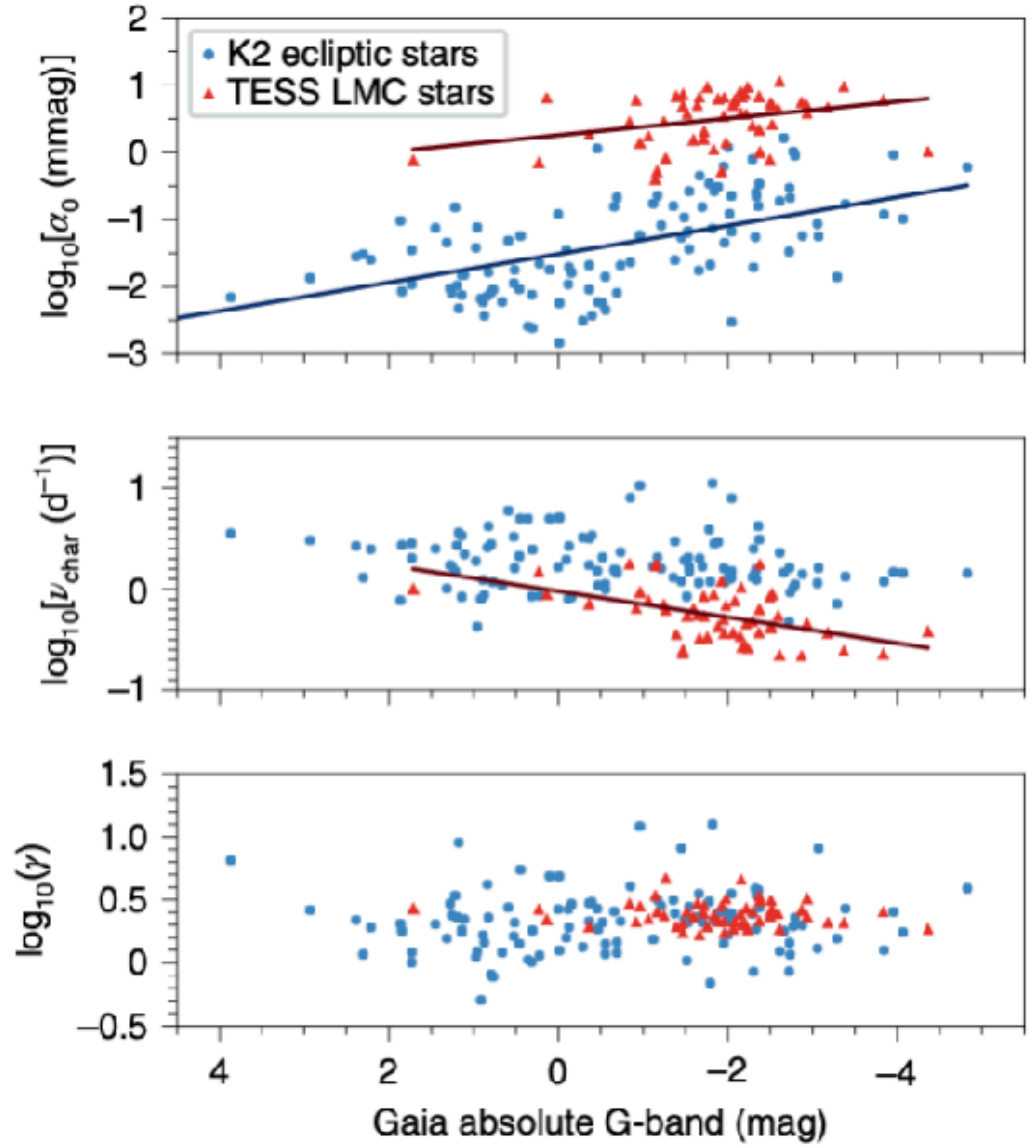


# Gravity Waves in Massive Stars

Ubiquitous Stochastic Low Frequency variability in OB stars:

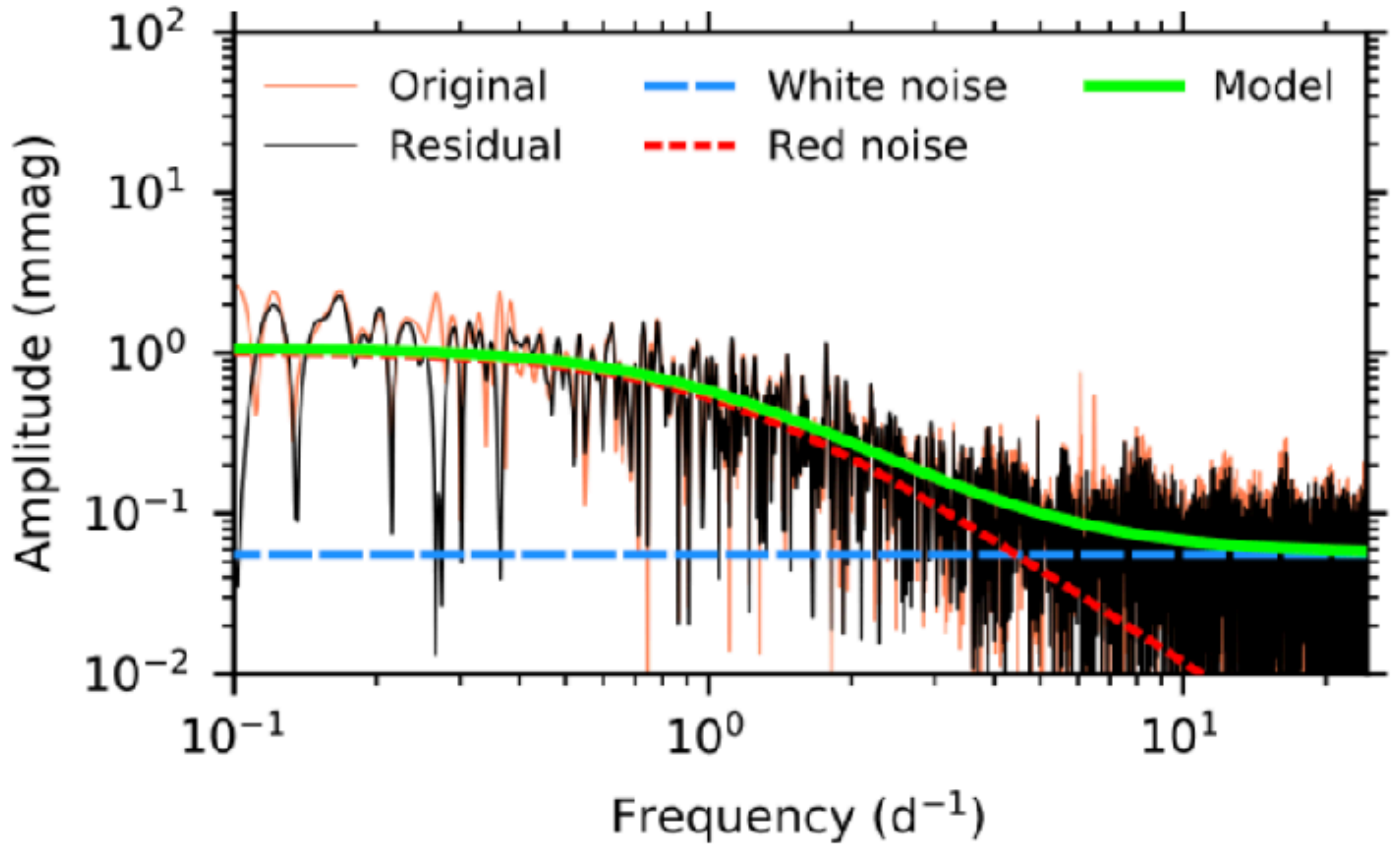
- waves from core convection or the surface (or both)
- metallicity independent (Bowman et al. 2019, NatAst 3)




Stochastic low-frequency model:

$$\boxed{\alpha(\nu) = \frac{\alpha_0}{1 + \left(\frac{\nu}{\nu_{\rm c}}\right)^{\gamma}} + C}$$




Bowman et al. (2019, Nature Astronomy 3)

# Gravity Waves in Massive Stars

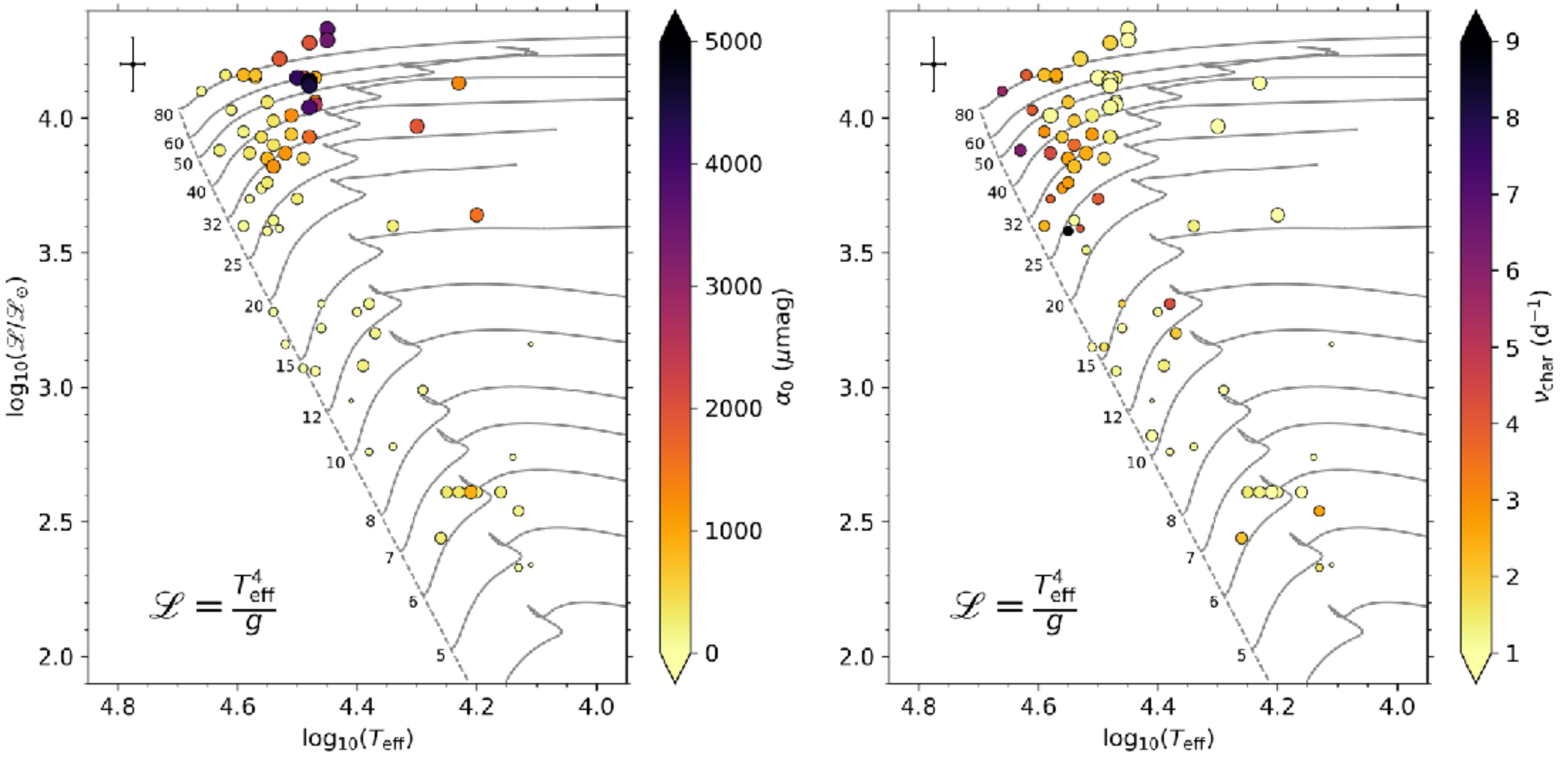
*Talk to Dominic Bowman, Matteo Cantiello and Daniel Lecoanet*

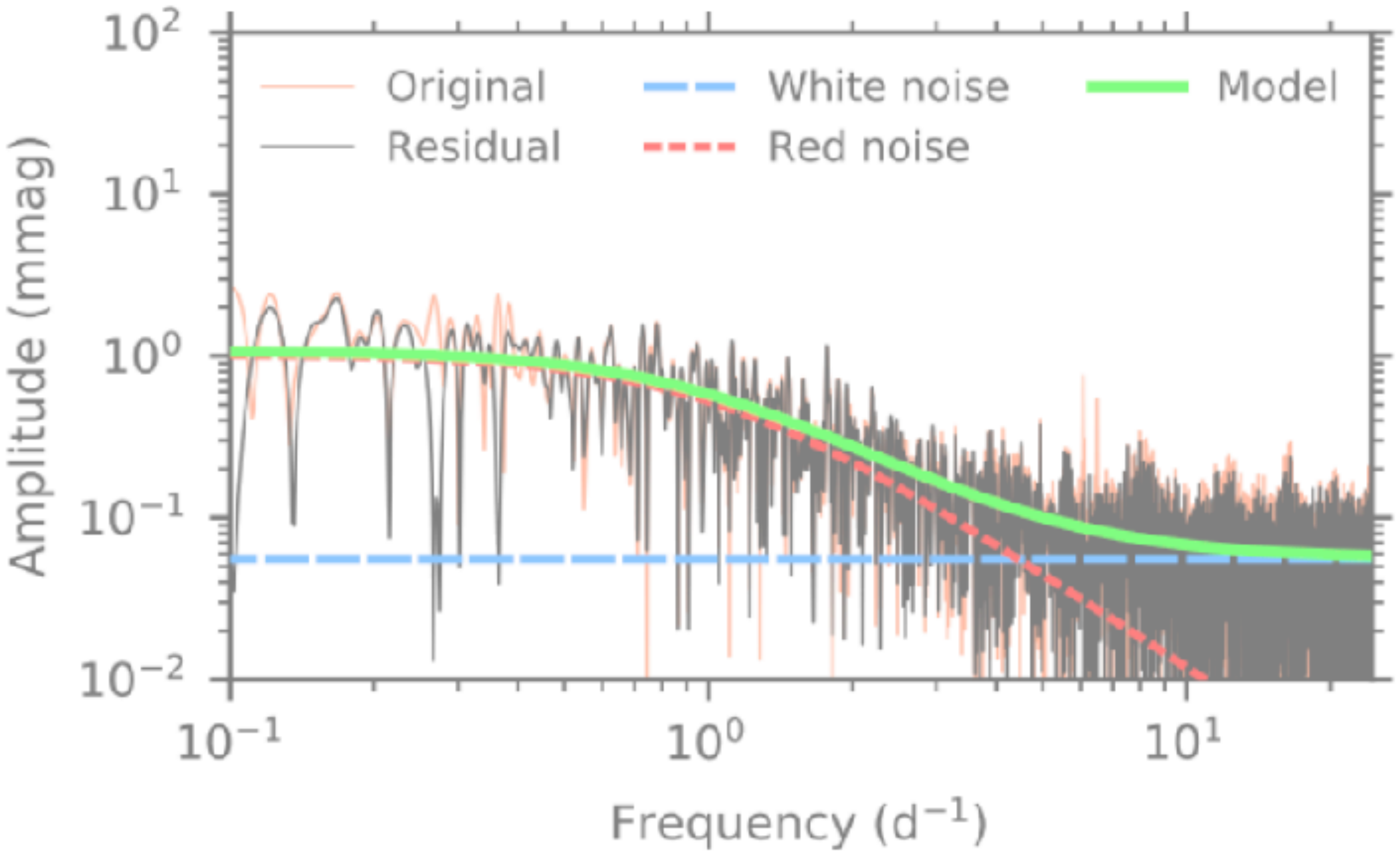
Ubiquitous Stochastic Low Frequency variability in OB stars:

- waves from core convection or the surface (or both)
- metallicity independent
- dependent on mass and age (Bowman et al. 2020, A&A 640)

What is the dominant cause of red noise in massive stars?

How can we fully exploit this new type of observation?



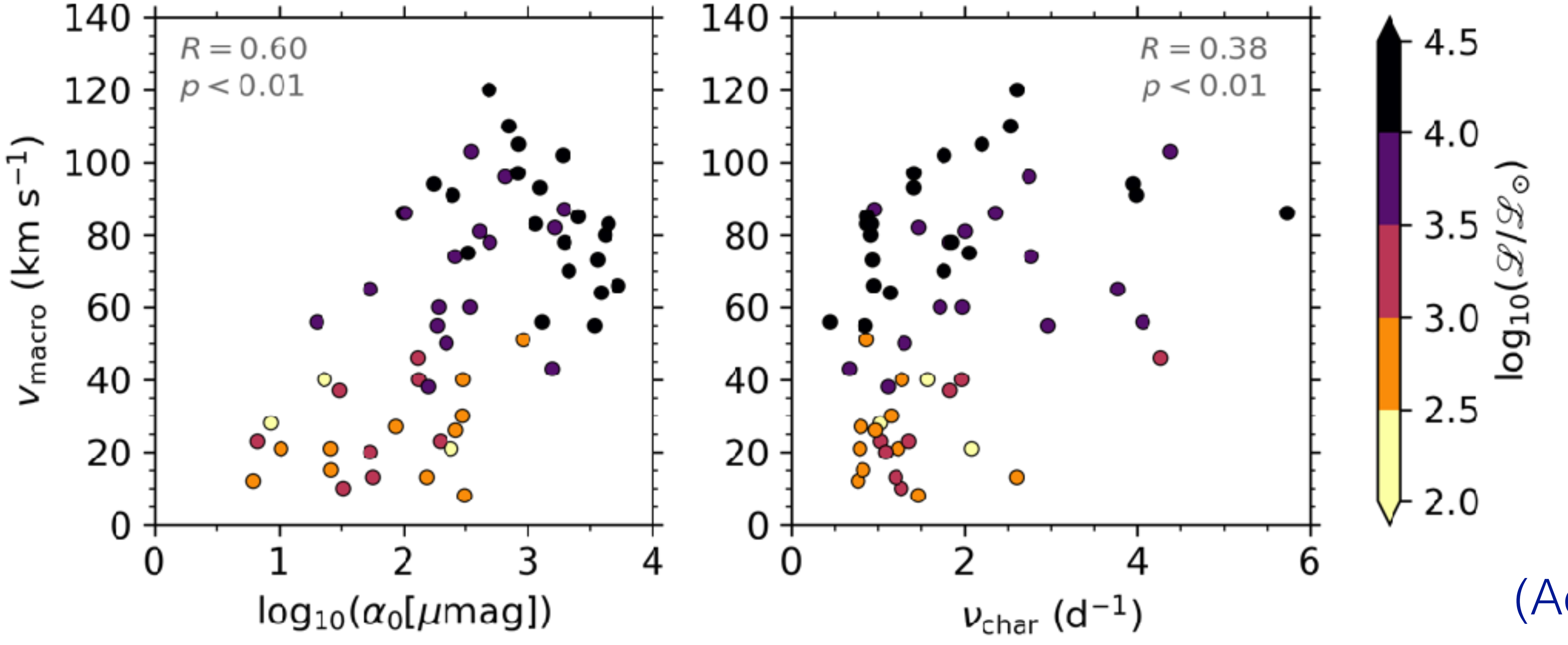



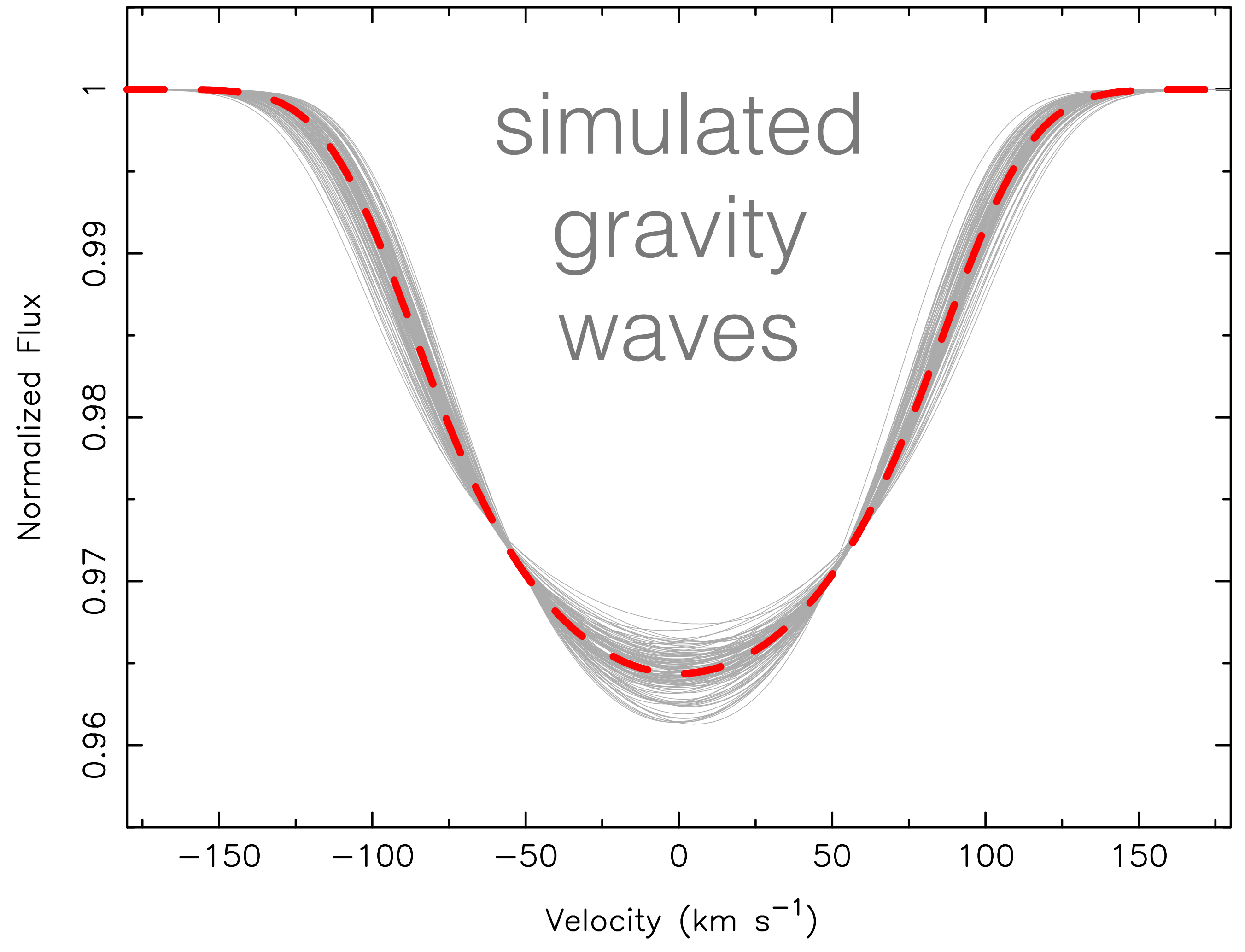

Bowman et al. (2019, Nature Astronomy 3)

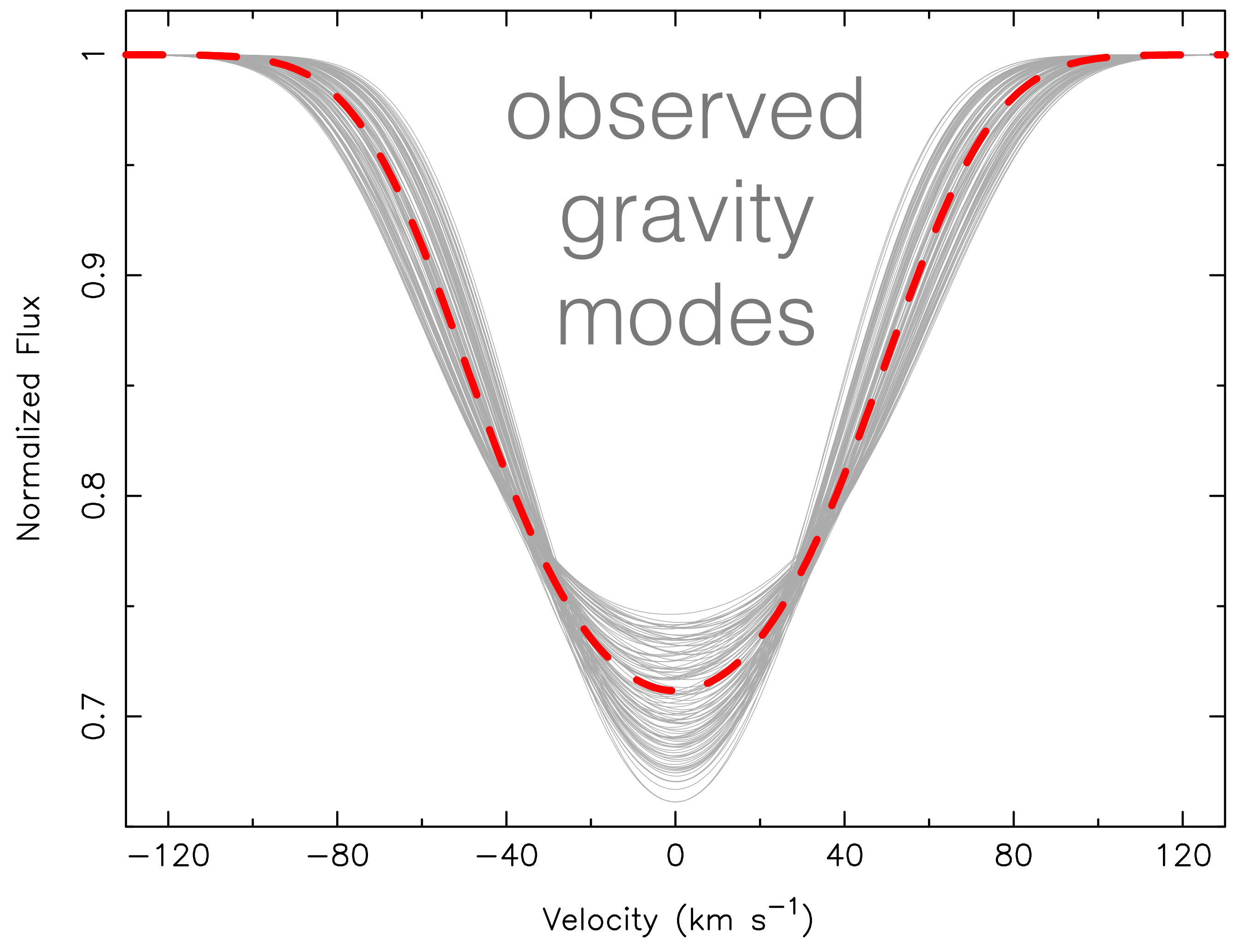
# Gravity Waves in Massive Stars

Ubiquitous Stochastic Low Frequency variability in OB stars:

- waves from core convection or the surface (or both)
- metallicity independent
- dependent on mass and age
- correlation between SLF properties and macroturbulence (Bowman et al. 2020, A&A 640)




(Aerts & Rogers 2015, ApJL 806; Aerts et al. 2009, A&A 508)