Colloque de prospective PNPS

Jeudi 11 janvier 2024

Explorer la dynamique interne d'étoiles au cours de leur évolution grâce à des simulations hydrodynamiques

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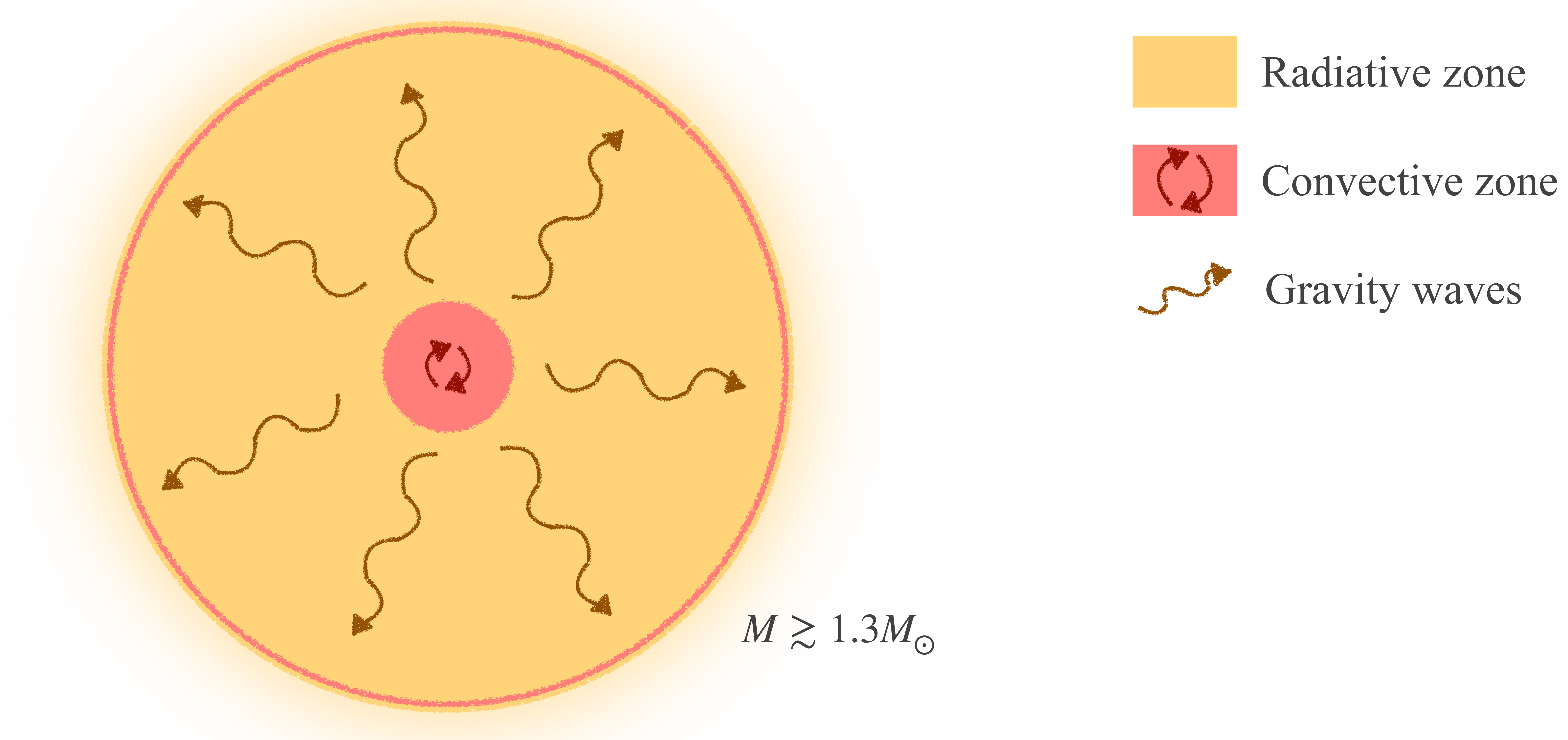
J. Pratt (Livermore), T. Goffrey (Warwick)

Stellar structure



Open questions linked to stellar internal structure and dynamics:

➡ Convective boundary mixing, rotationally induced transport, IGWs properties, double diffusive convection…

Importance in stars → Affect all stars with $M \geq 0.35 M_\odot$

Convective boundary mixing (CBM)

- Drives chemical mixing, link with rotation and magnetic field in low-mass stars
- Affect core size, lifetime, evolution and surface abundances of core convective stars

→ Can simulations of CBM helps to explain observations?

Internal Gravity Waves (IGWs)

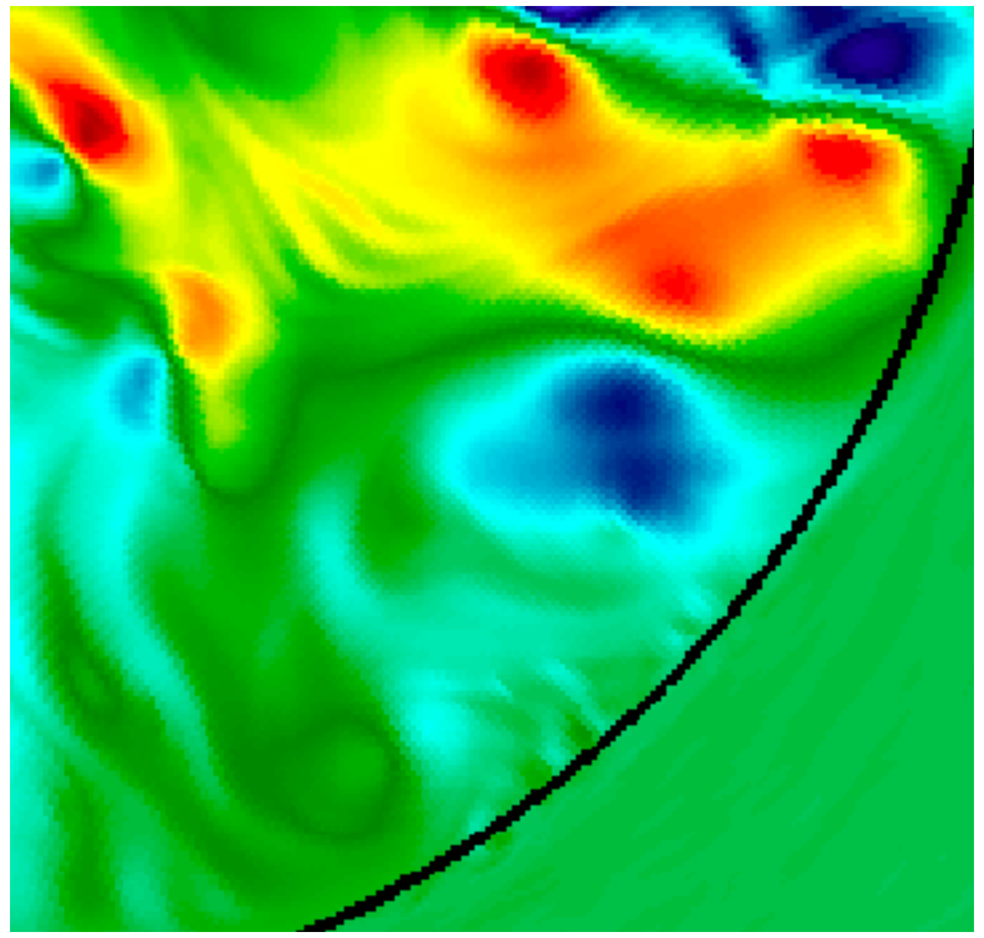
- Transport of chemical elements, angular momentum (AM) and energy in radiative zones of stars
- Get insight on the internal structure and dynamics of stars

→ Can we detect IGWs excited by core convection in intermediate mass stars?

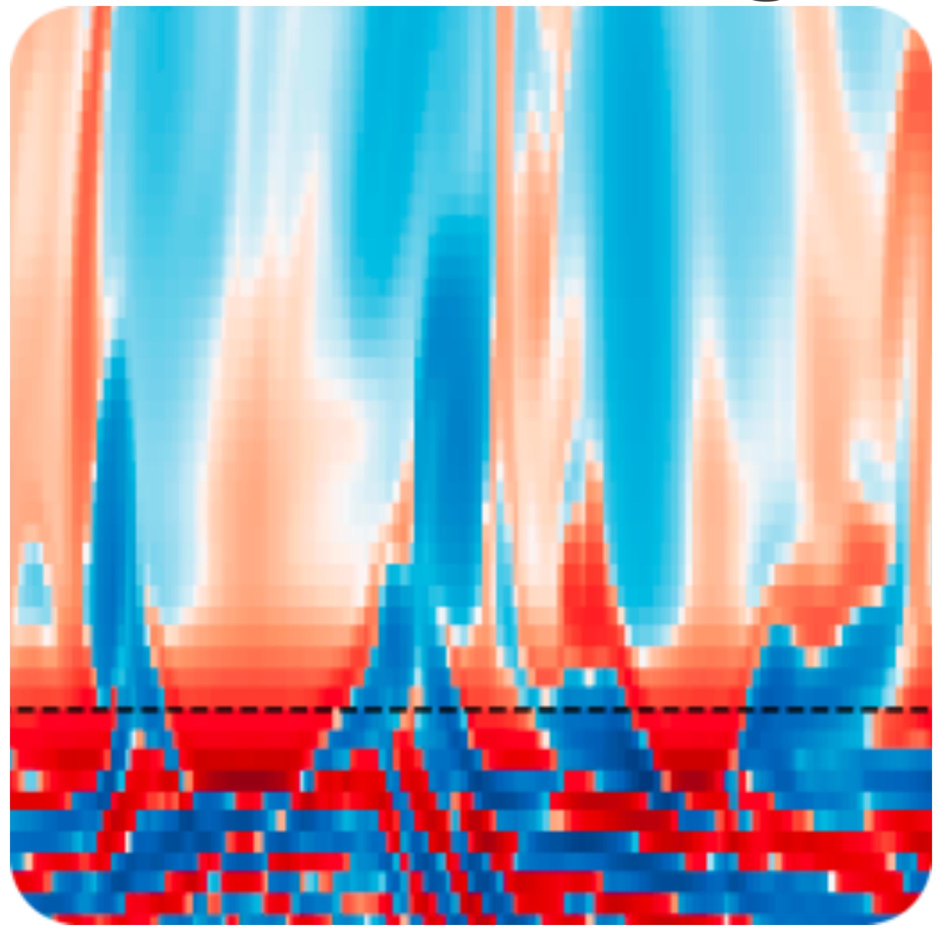
MUSIC: MUltidimensional Stellar Implicit Code

e.g. Viallet *et al.* 2011, 2013, 2016; Geroux *et al.* 2016; Goffrey *et al.* 2017; Pratt *et al.* 2016, 2017

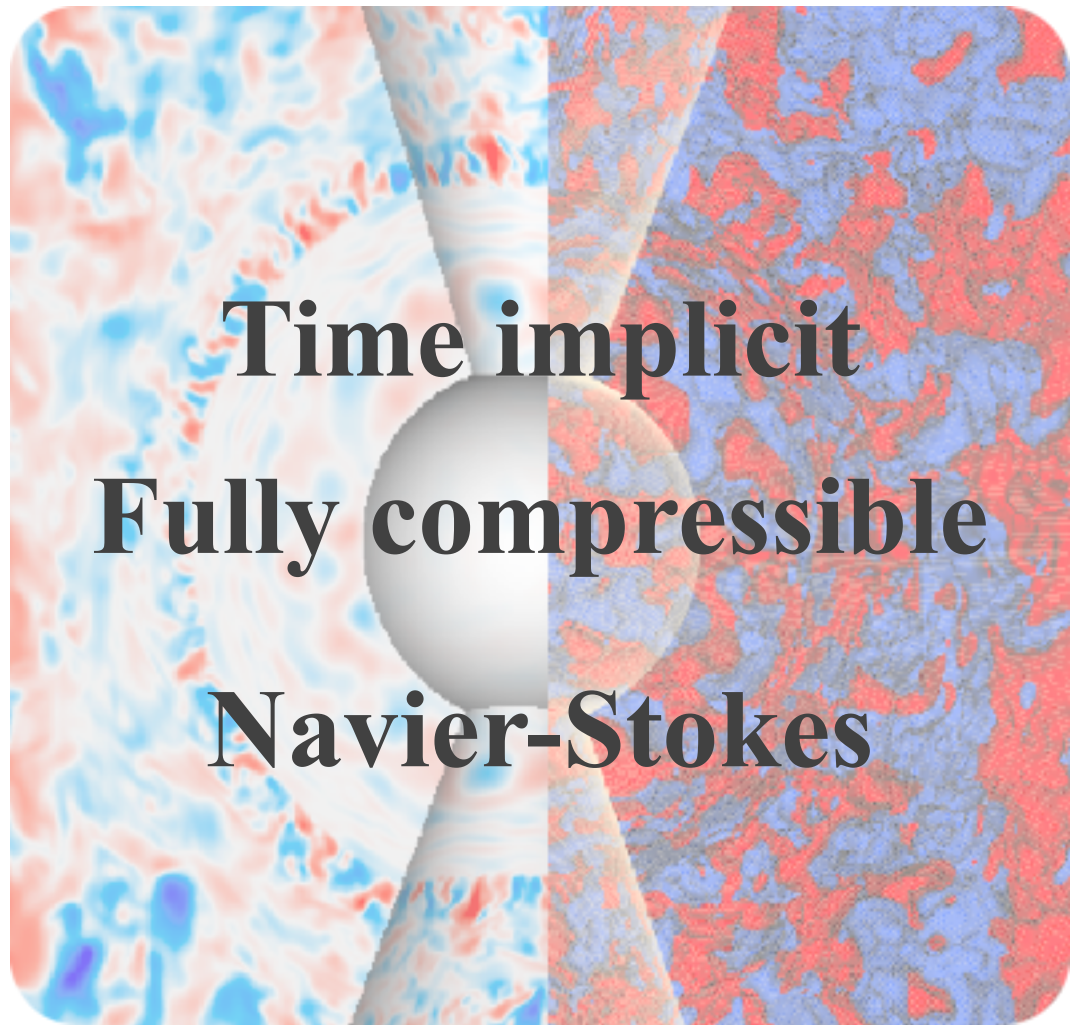
Convection



Overshooting



MUSIC



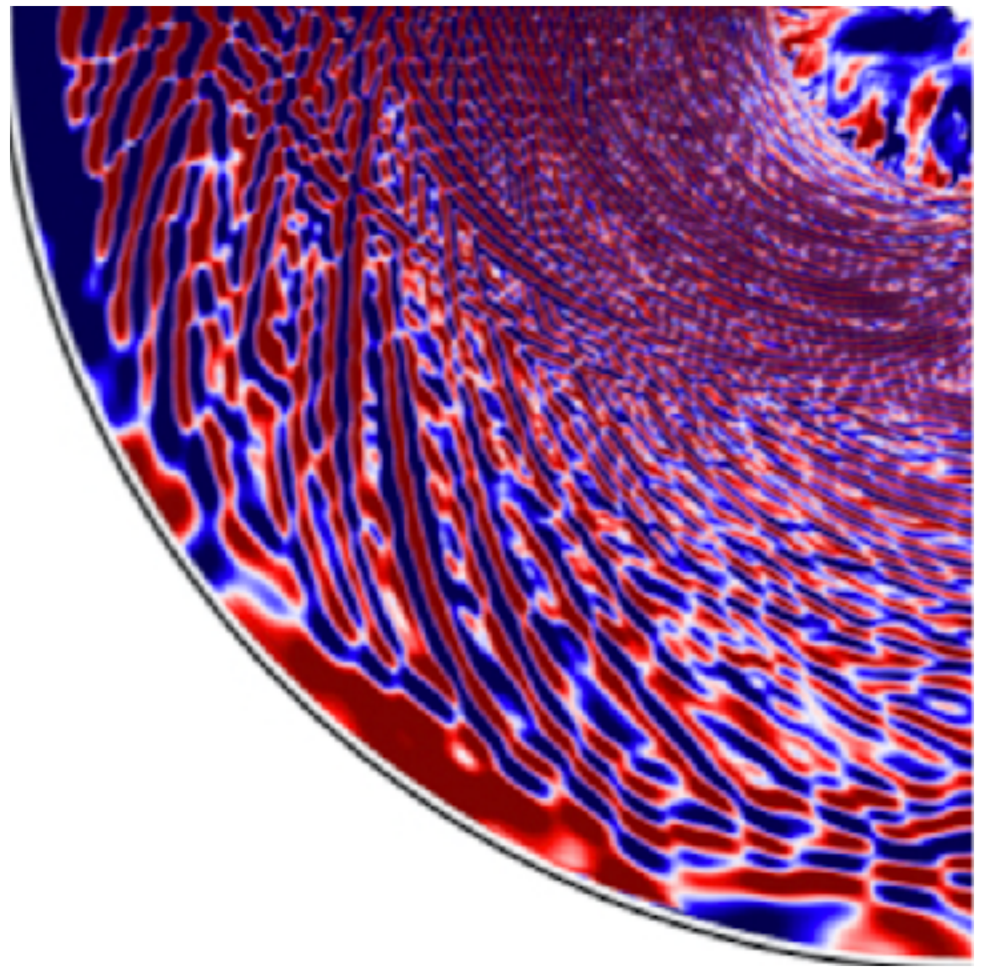
Spherical and Cartesian staggered grids

Realistic EoS and opacities, radiative diffusion

Passive and active scalars

Rotation, MHD, viscosity, chemical diffusion…

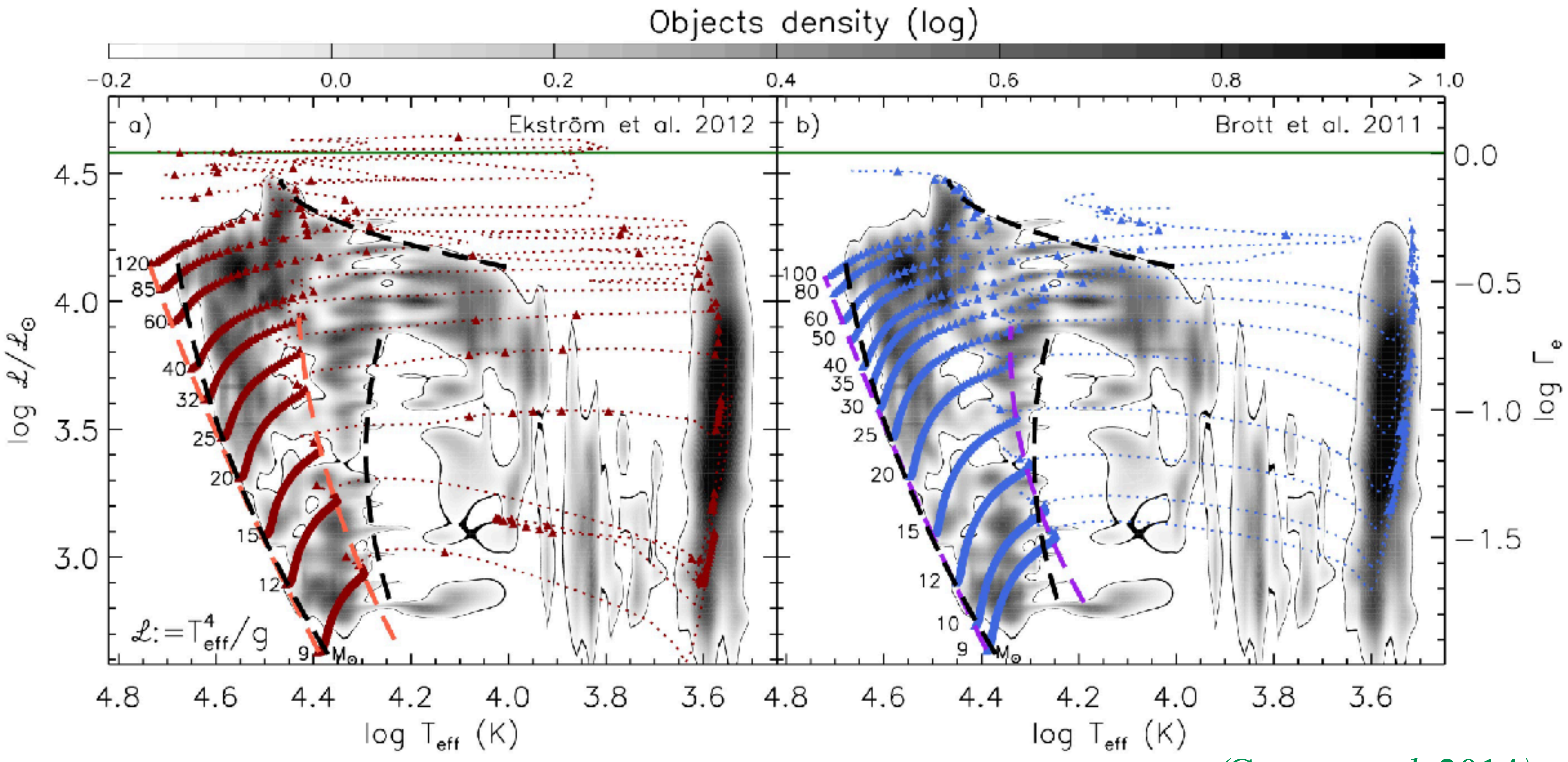
Waves



Transport & Mixing

Credits: T. Guillet

Need for extra mixing at the convective boundary



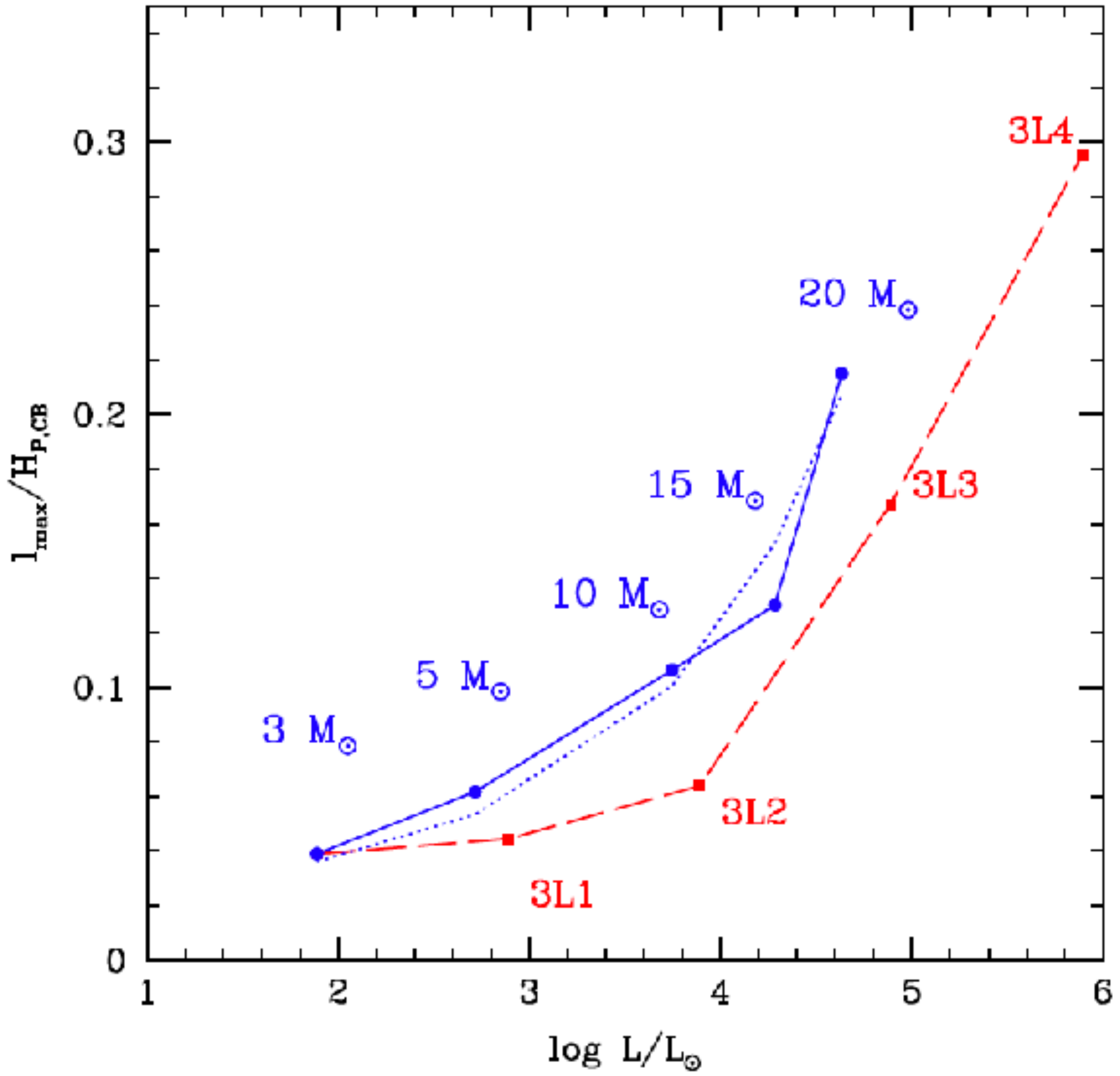
(Castro et al. 2014)

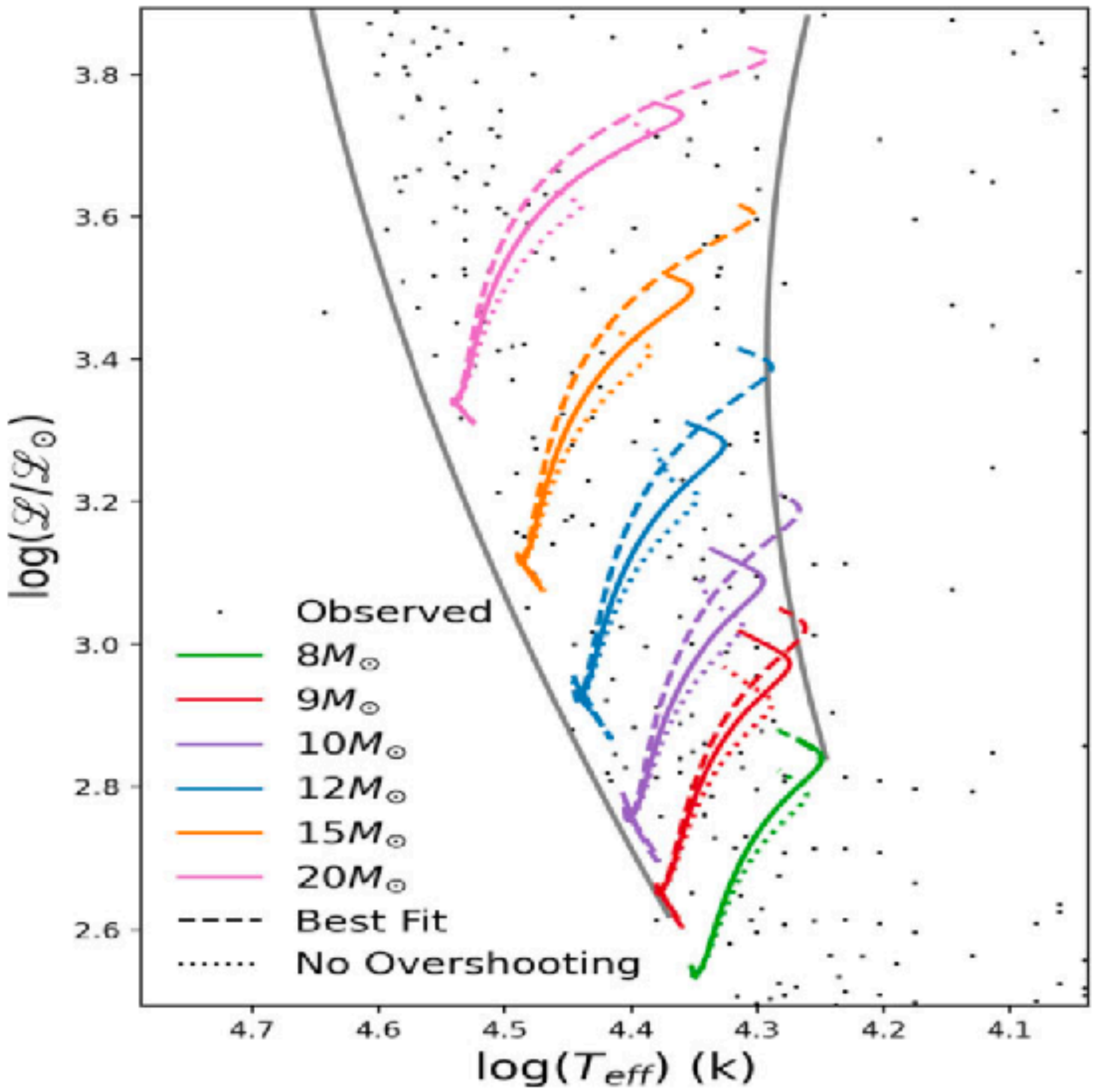
Current models cannot explain the width of the Main-Sequence for intermediate/high mass stars

Dependence of core overshooting on stellar mass

Run 9 simulations:
$3M_\odot$ (x4), $5M_\odot$, $10M_\odot$, $15M_\odot$, $20M_\odot$

$$\frac{d_{\rm ov}}{H_{P,\rm conv}} = 3.05 \times 10^{-3} \left(\frac{L}{L_\odot}\right)^{1/3} \left(\frac{r_{\rm conv}}{H_{P,\rm conv}}\right)^{1/2} + 0.02$$





Baraffe *et al.* (2023)

Important to scale $d_{\rm ov}$ with L

Still difficult to explain observations… rotation? impact of stellar evolution? extra mixing (waves)?

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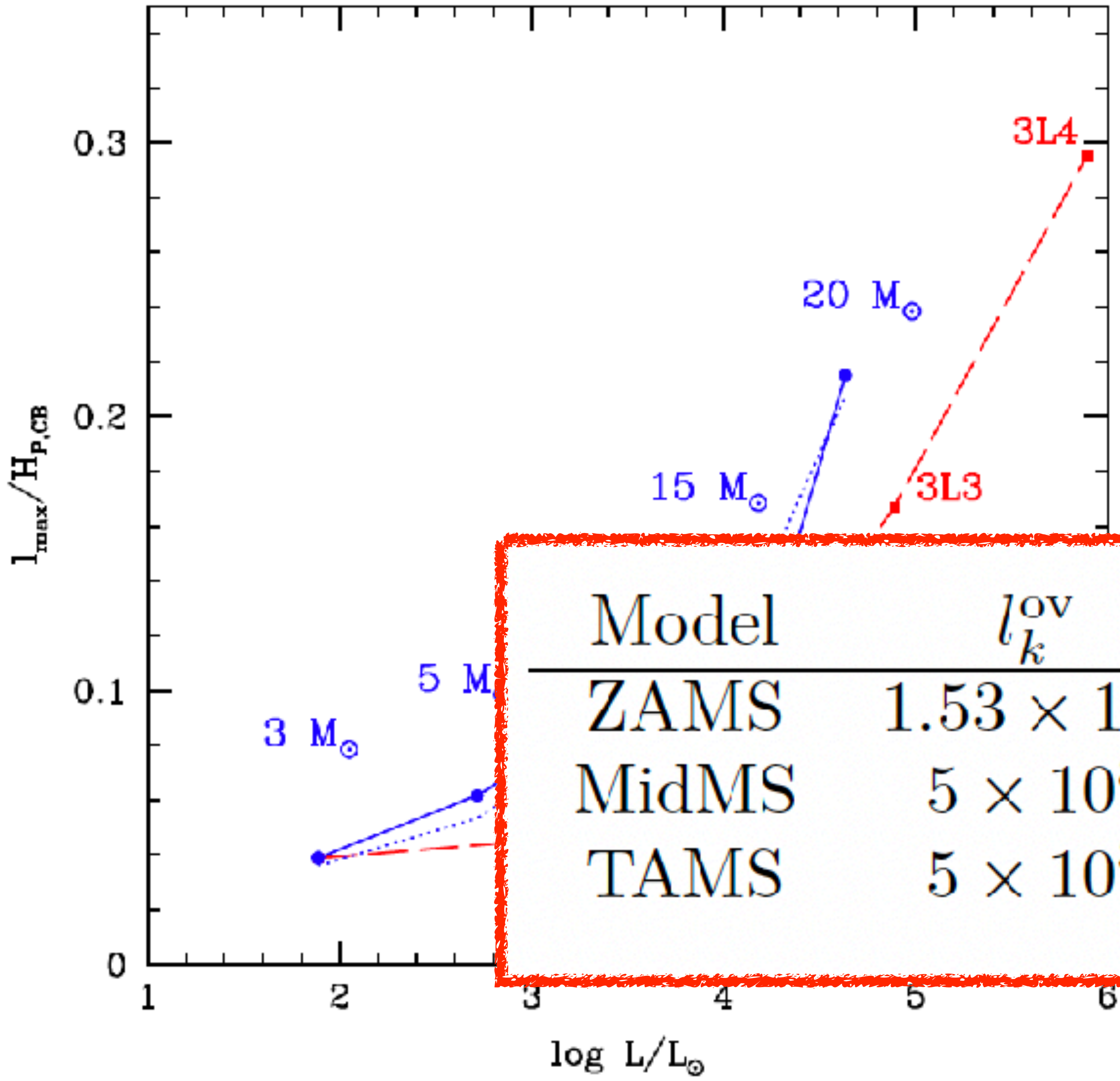
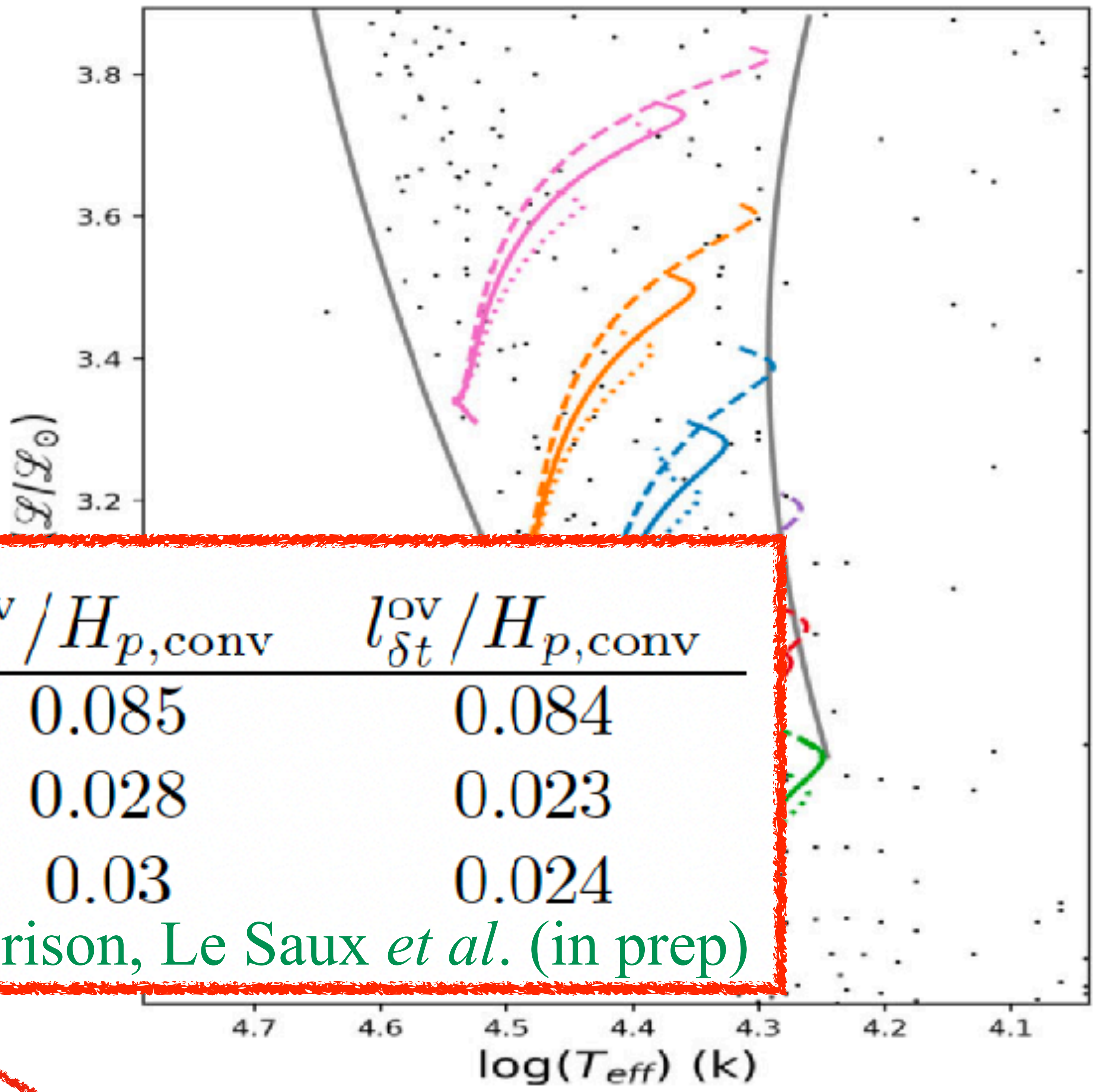


Model	$l_k^{\rm ov}$	$l_{\delta t}^{\rm ov}$	$l_k^{\rm ov}/H_{p,\rm conv}$	$l_{\delta t}^{\rm ov}/H_{p,\rm conv}$
ZAMS	1.53×10^9	1.51×10^9	0.085	0.084
MidMS	5×10^8	4×10^8	0.028	0.023
TAMS	5×10^8	4×10^8	0.03	0.024

Morison, Le Saux *et al.* (in prep)



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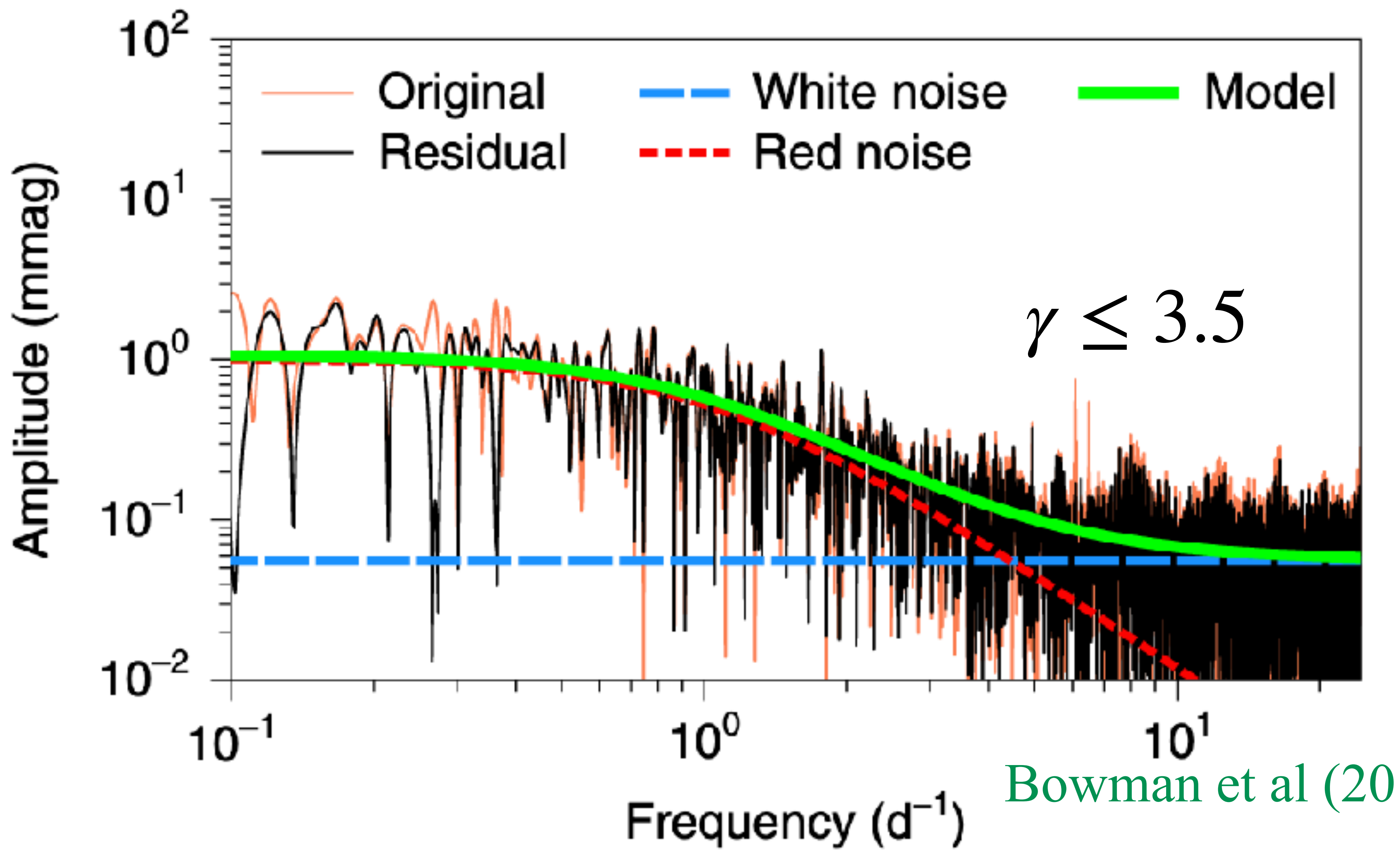
Observations of IGWs in intermediate-mass stars?

Detection of a low-frequency power excess in photometric observations by CoRoT and TESS of O and B type stars

IGWs generated by core convection
Aerts & Rogers (2015)
Bowman et al (2019, 2020)
Thompson et al (2022)

$$P(f) = \frac{\alpha}{1 + (2\pi\tau f)^{\gamma}}$$



Bowman et al (2019)

Subsurface CZ
Cantiello et al (2009, 2019)
Lecoanet et al (2019, 2021)

If CC generated IGWs:
- Low ω damped by radiative diffusion
- IGWs reflected by subsurface CZ?

Subsurface CZ can generate waves, macro turbulence and magnetic field (obs of bright spots)

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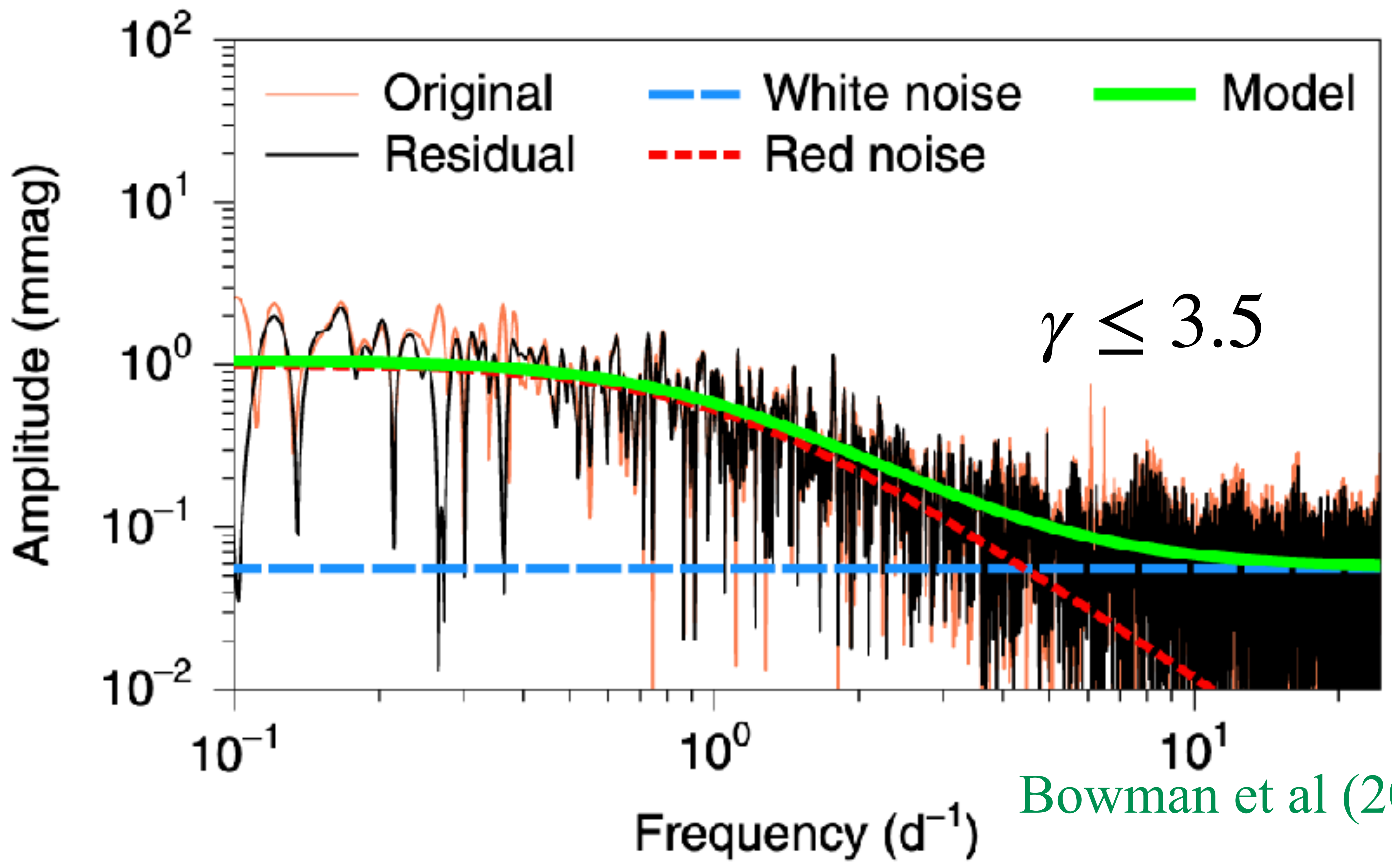

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Radiative damping of IGWs

$$\tau(r,\ell,\omega) = [\ell(\ell+1)]^{3/2} \int_{r_e}^{r} \kappa_{\rm rad} \frac{N^3}{\omega^4} \left(\frac{N^2}{N^2-\omega^2} \right)^{1/2} \frac{\mathrm{d}r}{r^3}$$

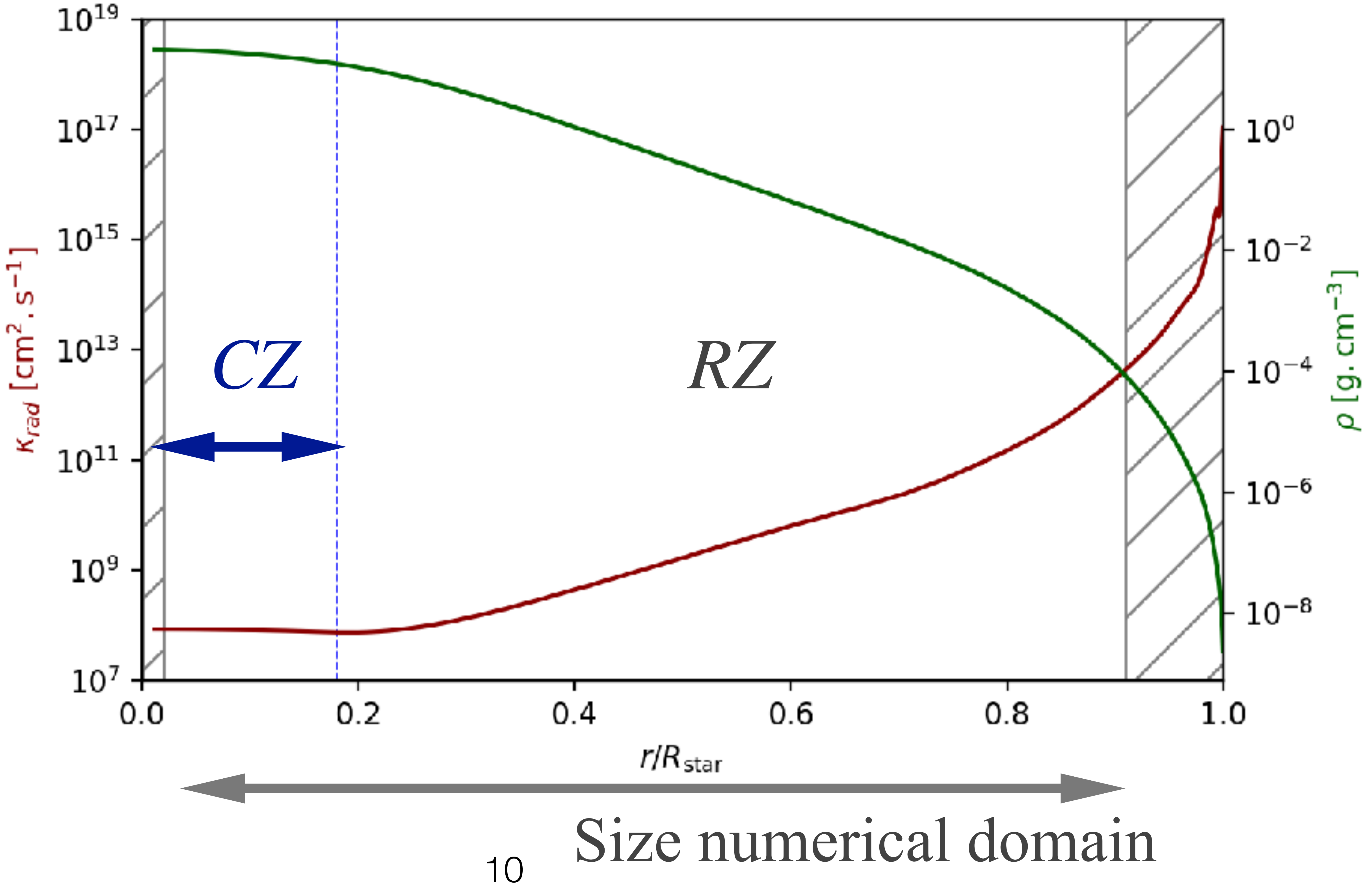
Based on Press (1981)

$$v_r(r,\ell,\omega) = v_0 \left(\frac{\rho}{\rho_0} \right)^{-1/2} \left(\frac{k_h}{k_{h,0}} \right)^{3/2} \left(\frac{N^2-\omega^2}{N_0^2-\omega^2} \right)^{-1/4} e^{-\tau/2}$$

Density

Radiative damping

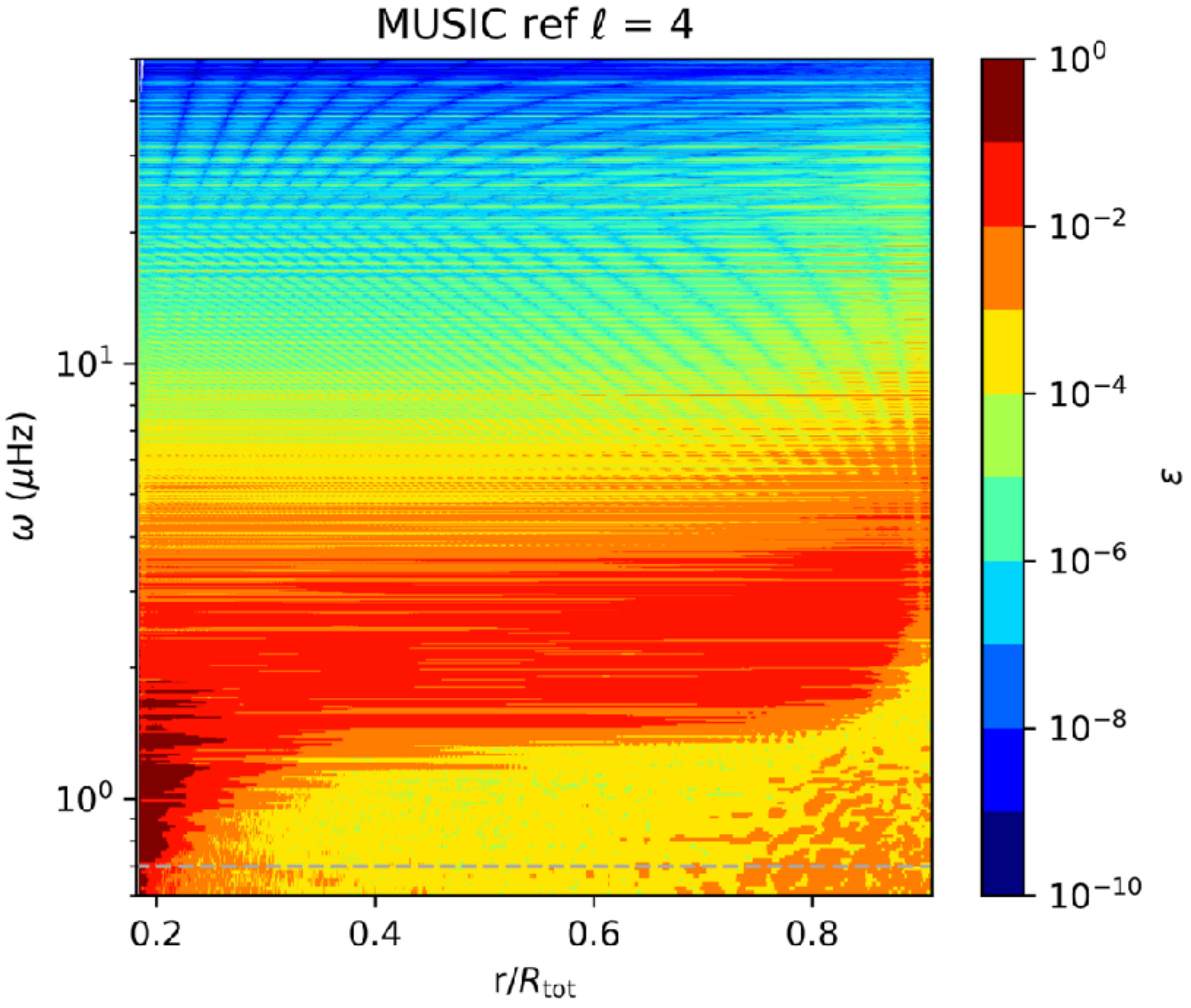
Simulation of 5 $M_\odot$ at ZAMS

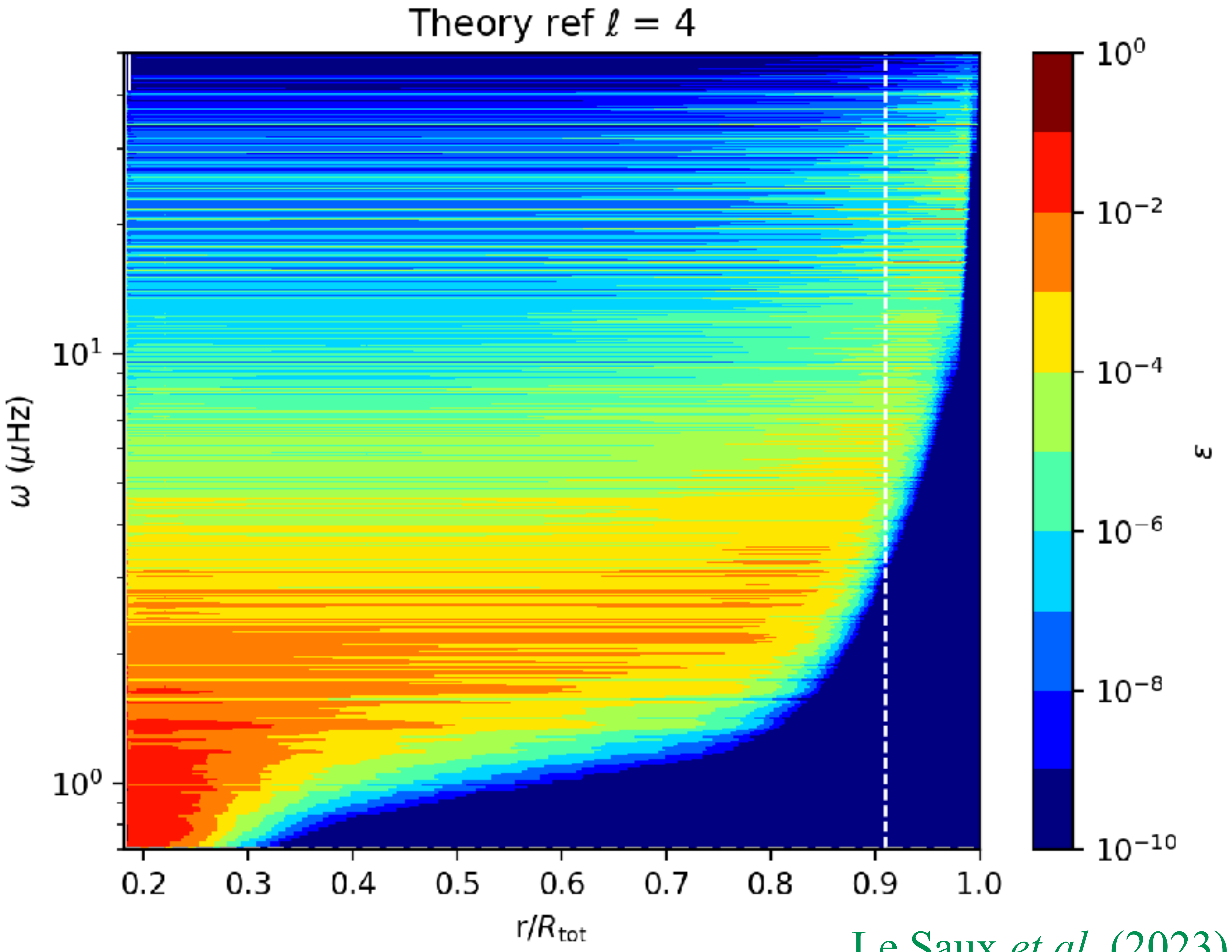


Radiative damping of IGWs

Radiative damping

$$\tau(r,\ell,\omega) = \int_r^{r_e} \kappa_{\rm rad} \frac{N^3}{\omega^4} \left(\frac{N^2}{N^2-\omega^2} \right)^{1/2} k_h^3 dr$$



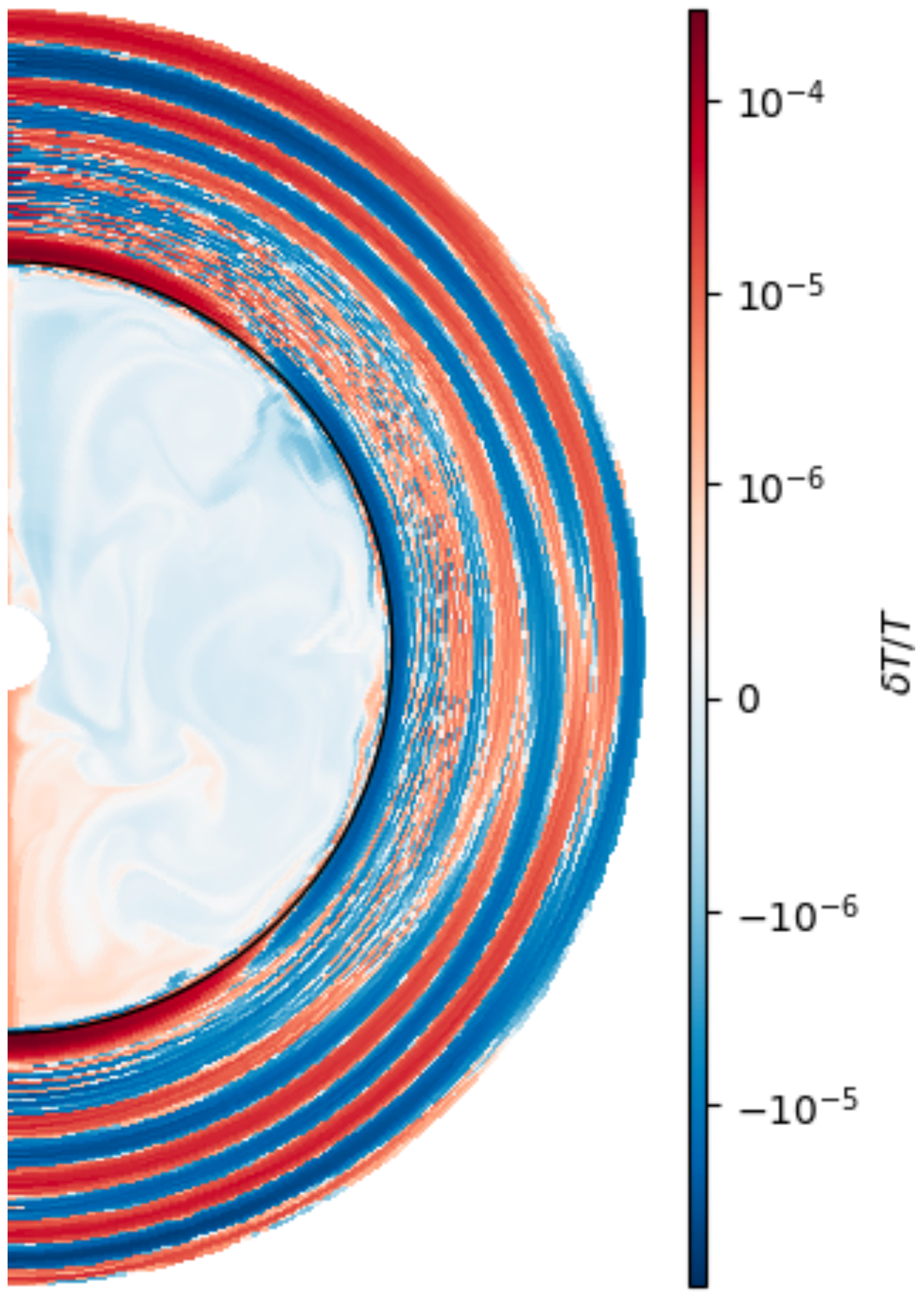


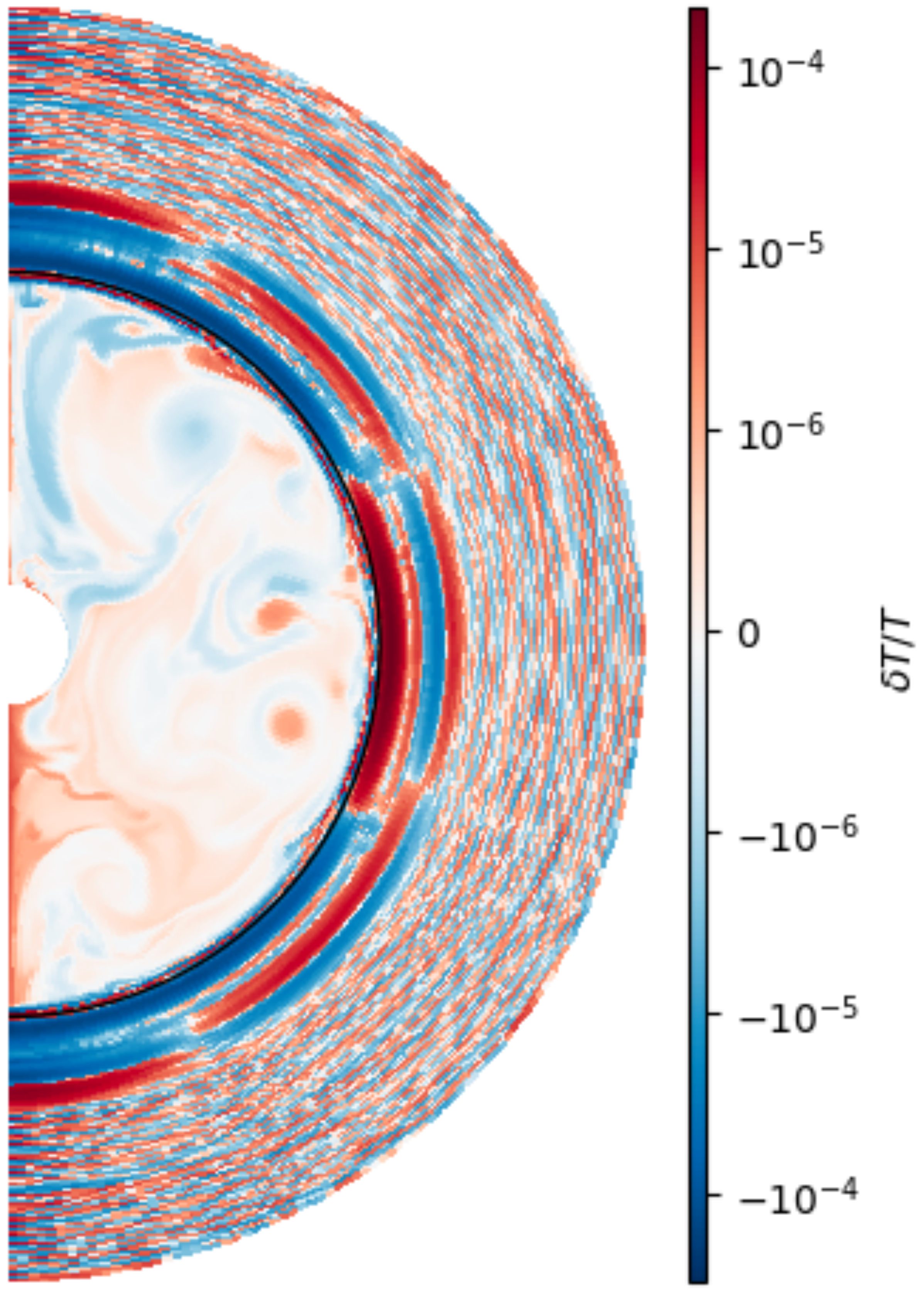
Le Saux *et al*. (2023)

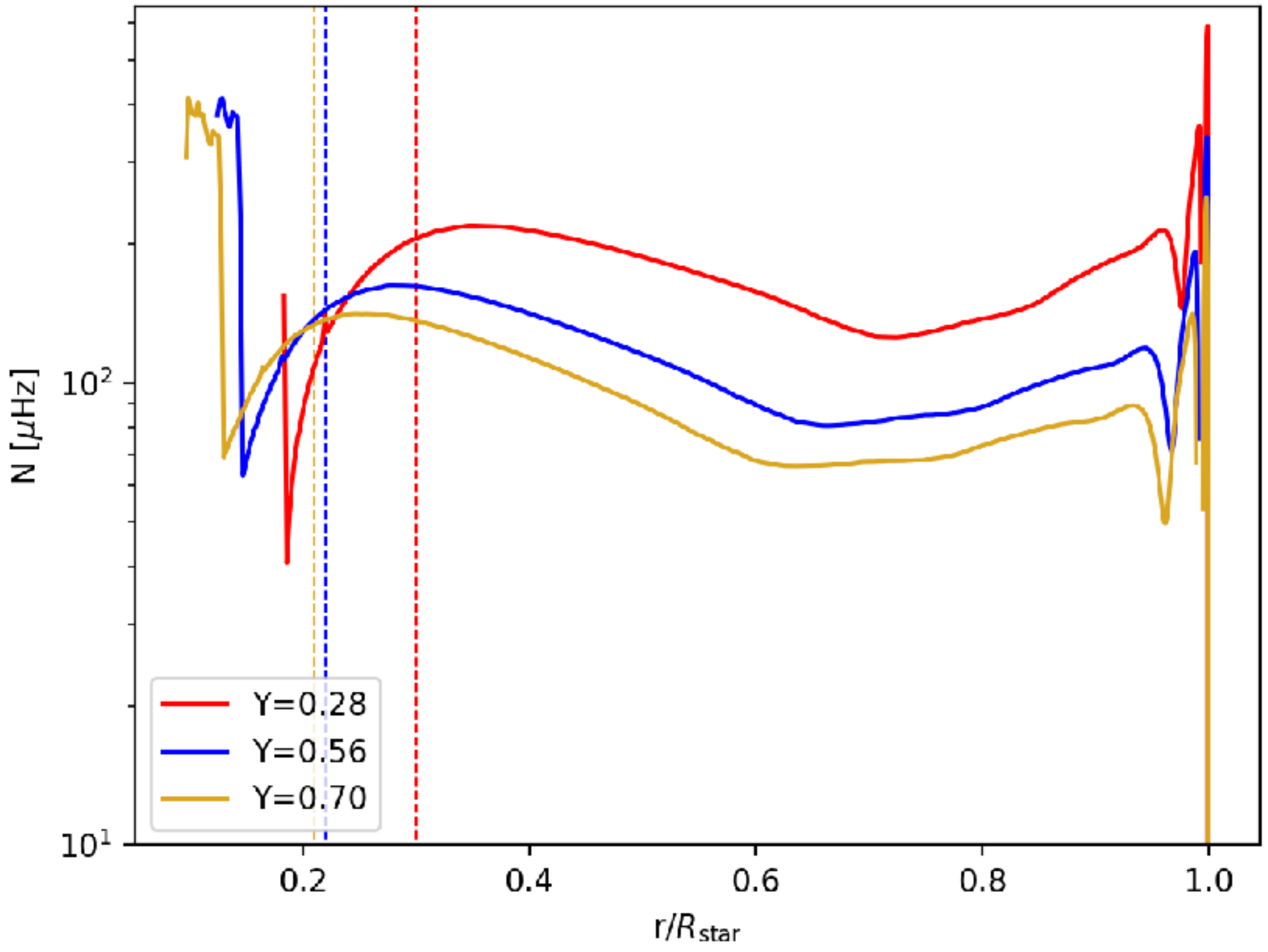
Results corroborated by Anders et al. (2023) with their 3D simulations.

What happens when the star evolves?

Two new models of a $5M_\odot$ at Y=0.56 and Y=0.70





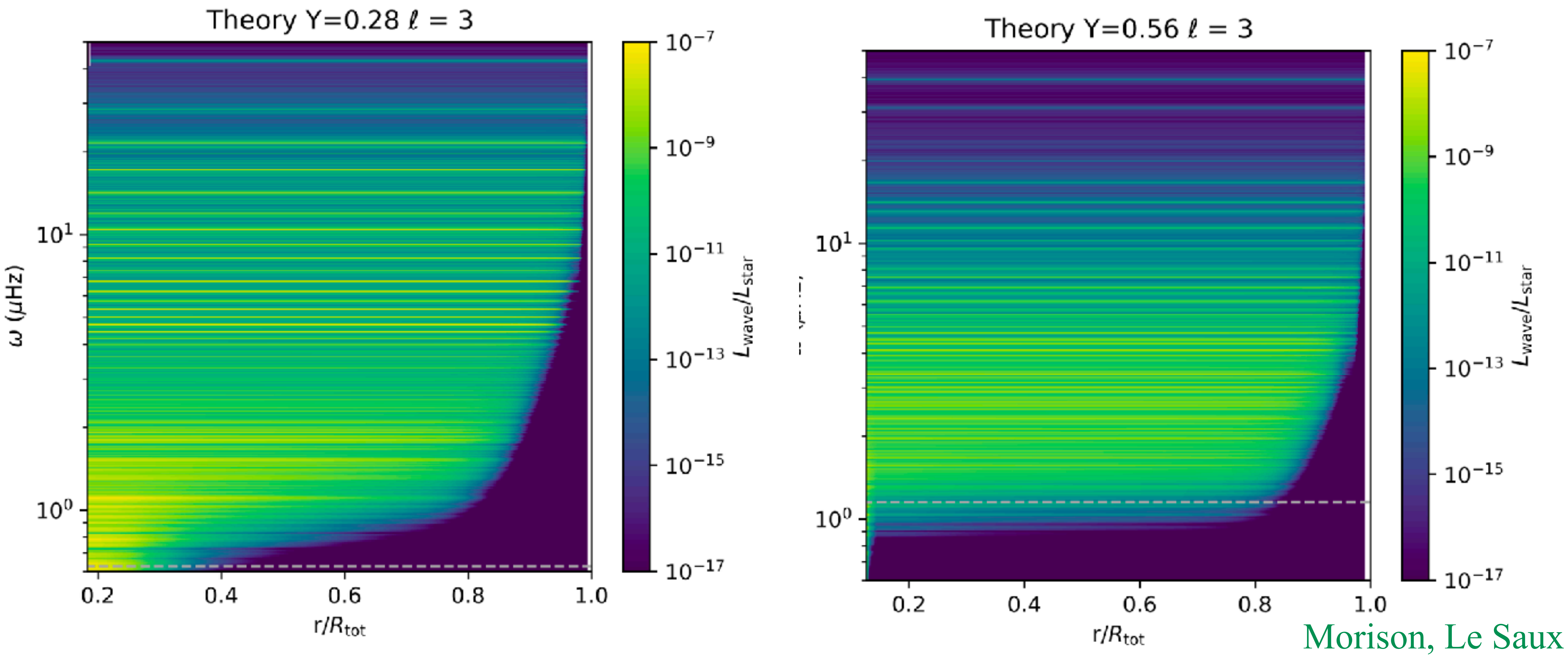


Along the Main-Sequence

Radiative damping

$$\tau(r,\ell,\omega) = \int_r^{r_e} \kappa_{\rm rad} \frac{N^3}{\omega^4} \left(\frac{N^2}{N^2-\omega^2} \right)^{1/2} k_h^3 dr$$

Two new models of a $5M_\odot$ at Y=0.56 and Y=0.70



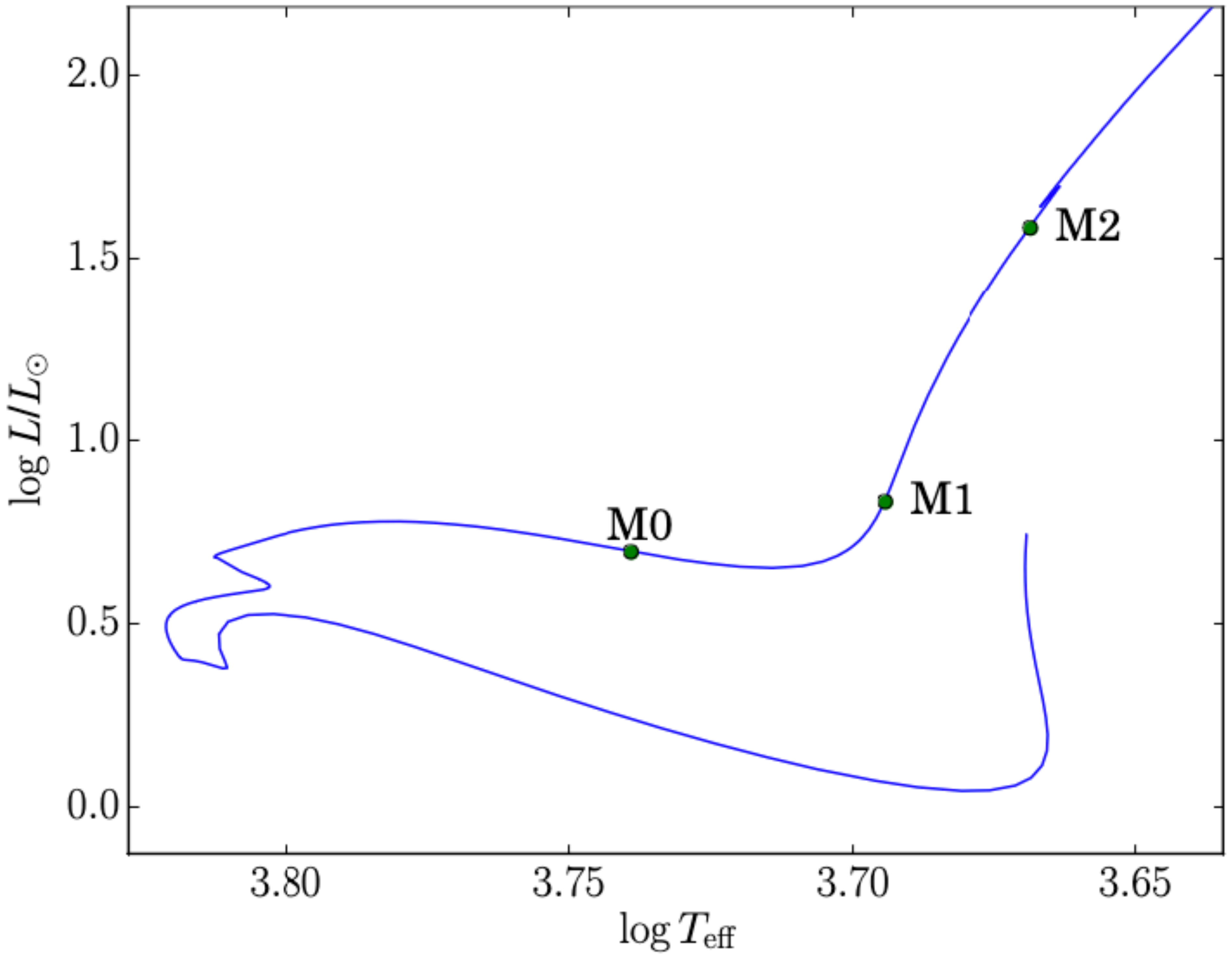
Morison, Le Saux *et al.* (in prep)

Overshooting less efficient as stars evolve

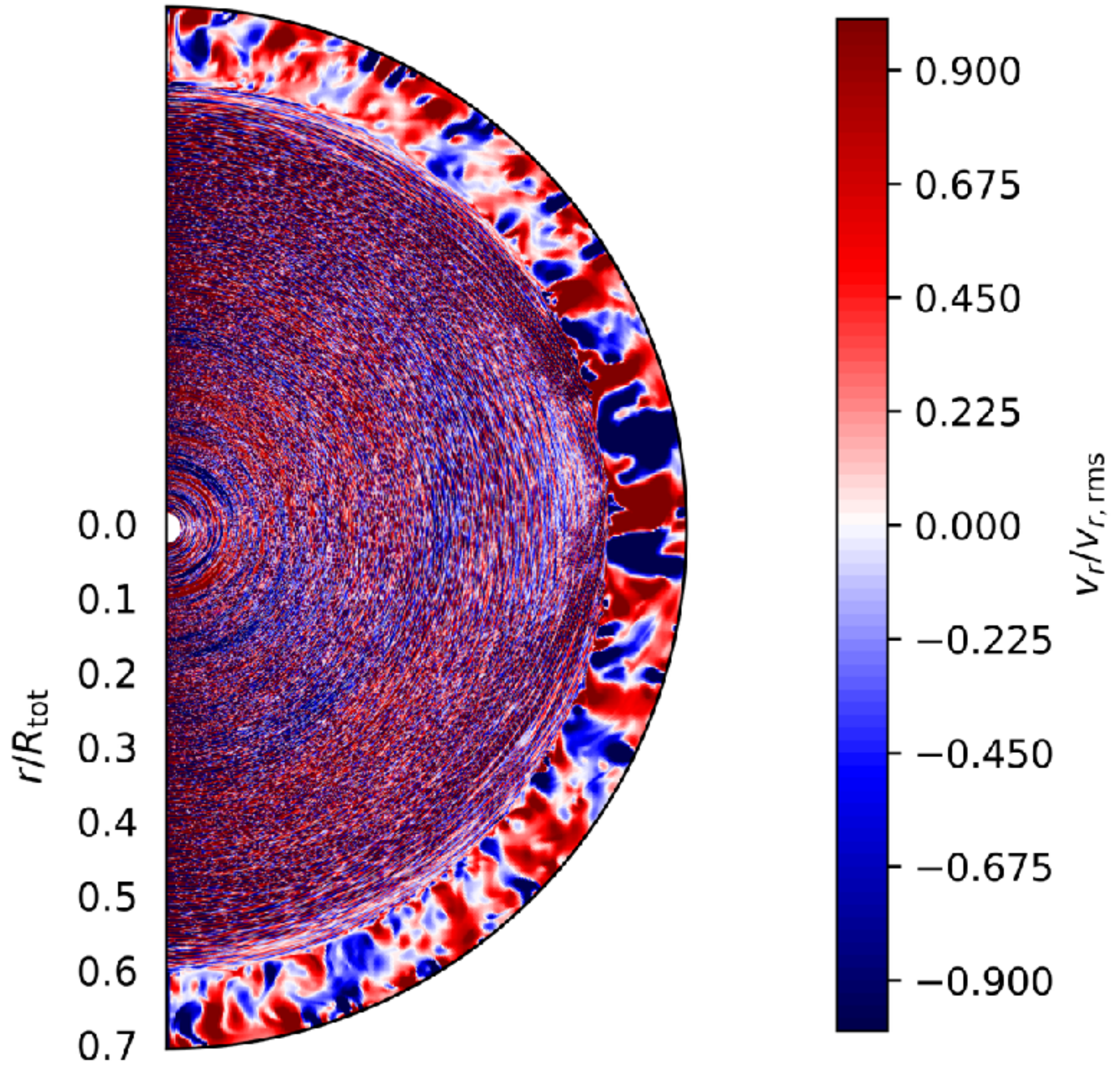
Less likely to observe waves along the MS (low freq. power excess = subsurface CZ?)

Beyond Main-Sequence

Waves in a $1.3M_\odot$ subgiant model



Belkacem *et al*. (2015b)



Beyond Main-Sequence

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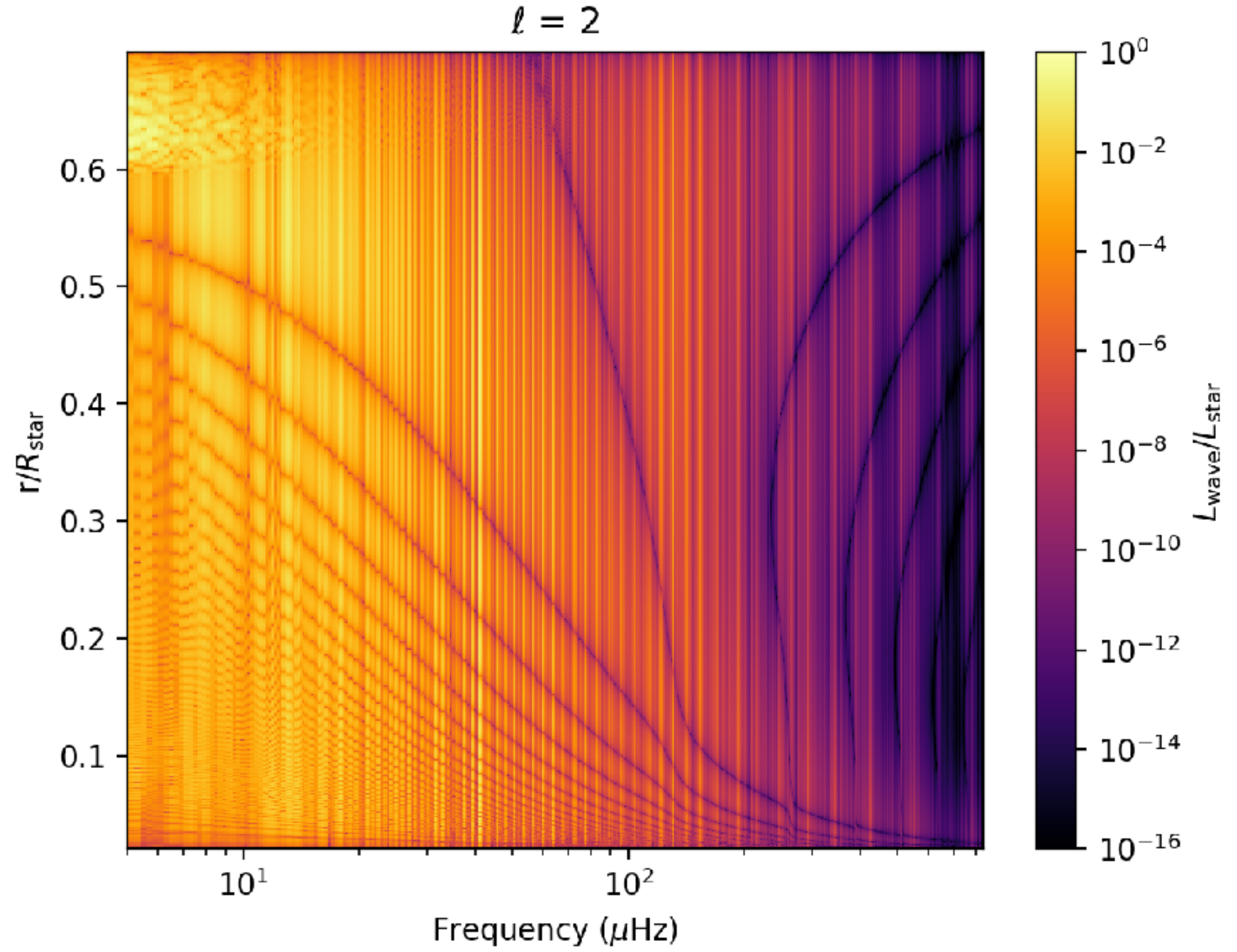
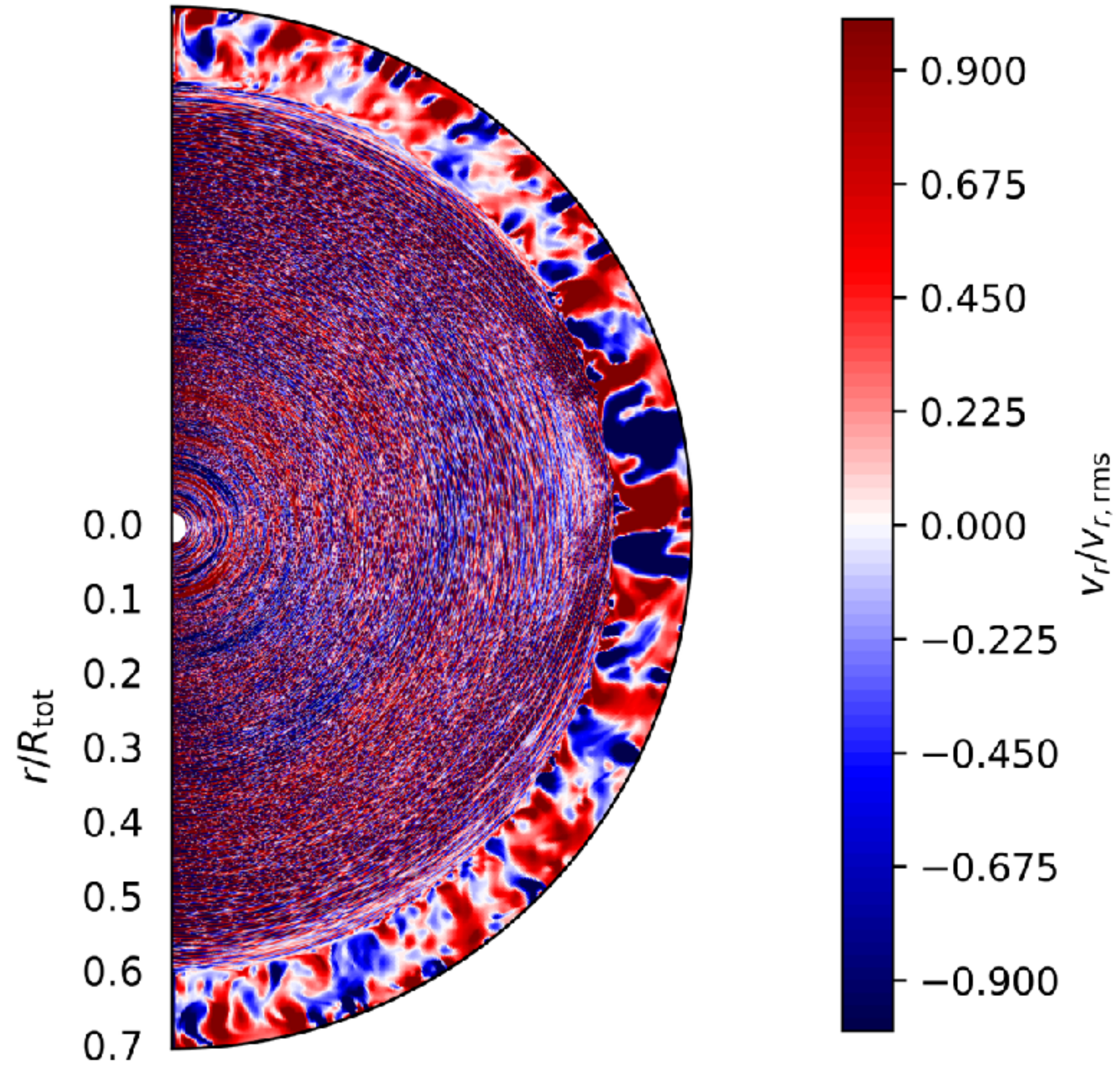
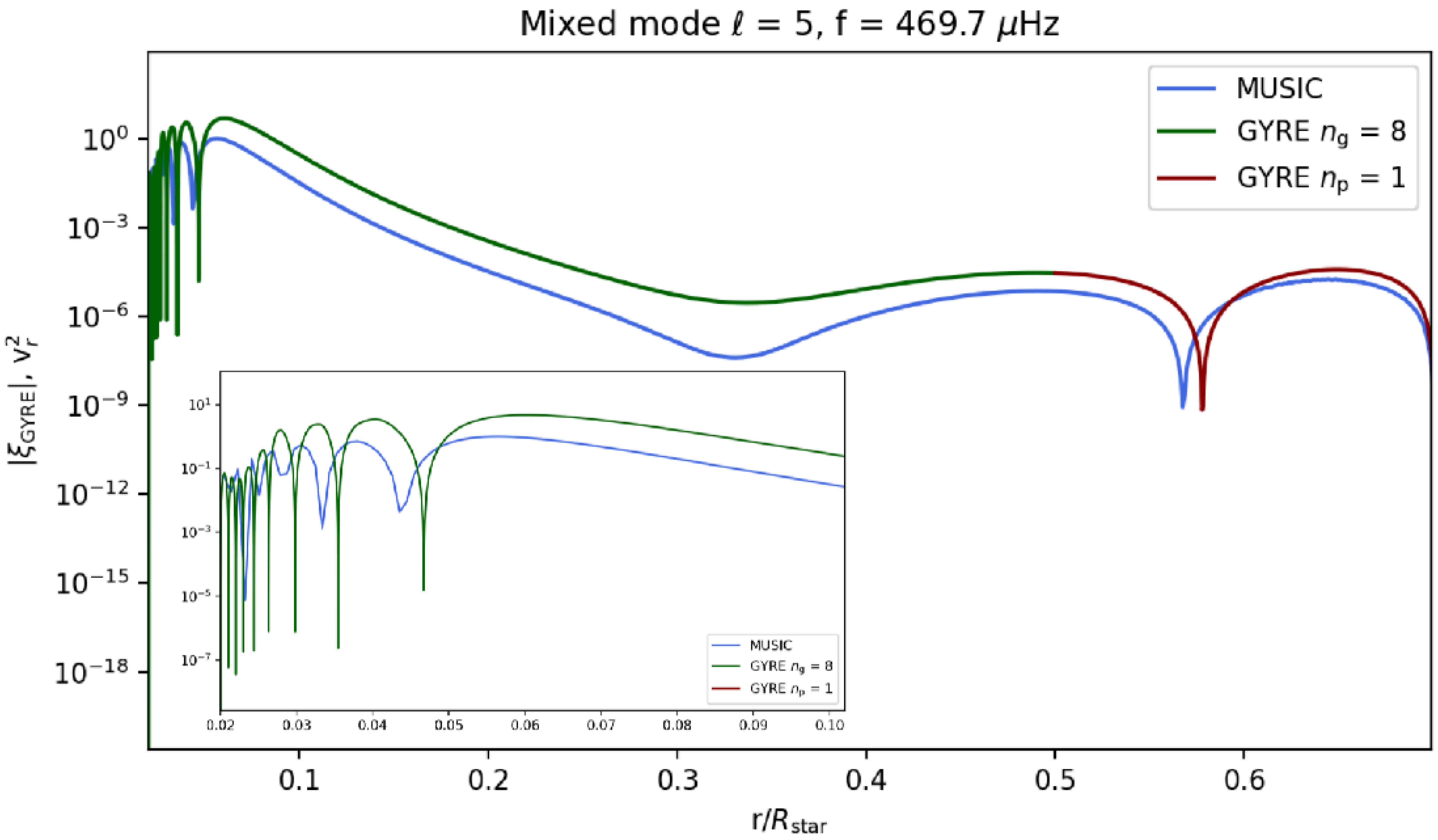




Modelling mixed modes with MUSIC

Waves in a $1.3M_\odot$ subgiant model



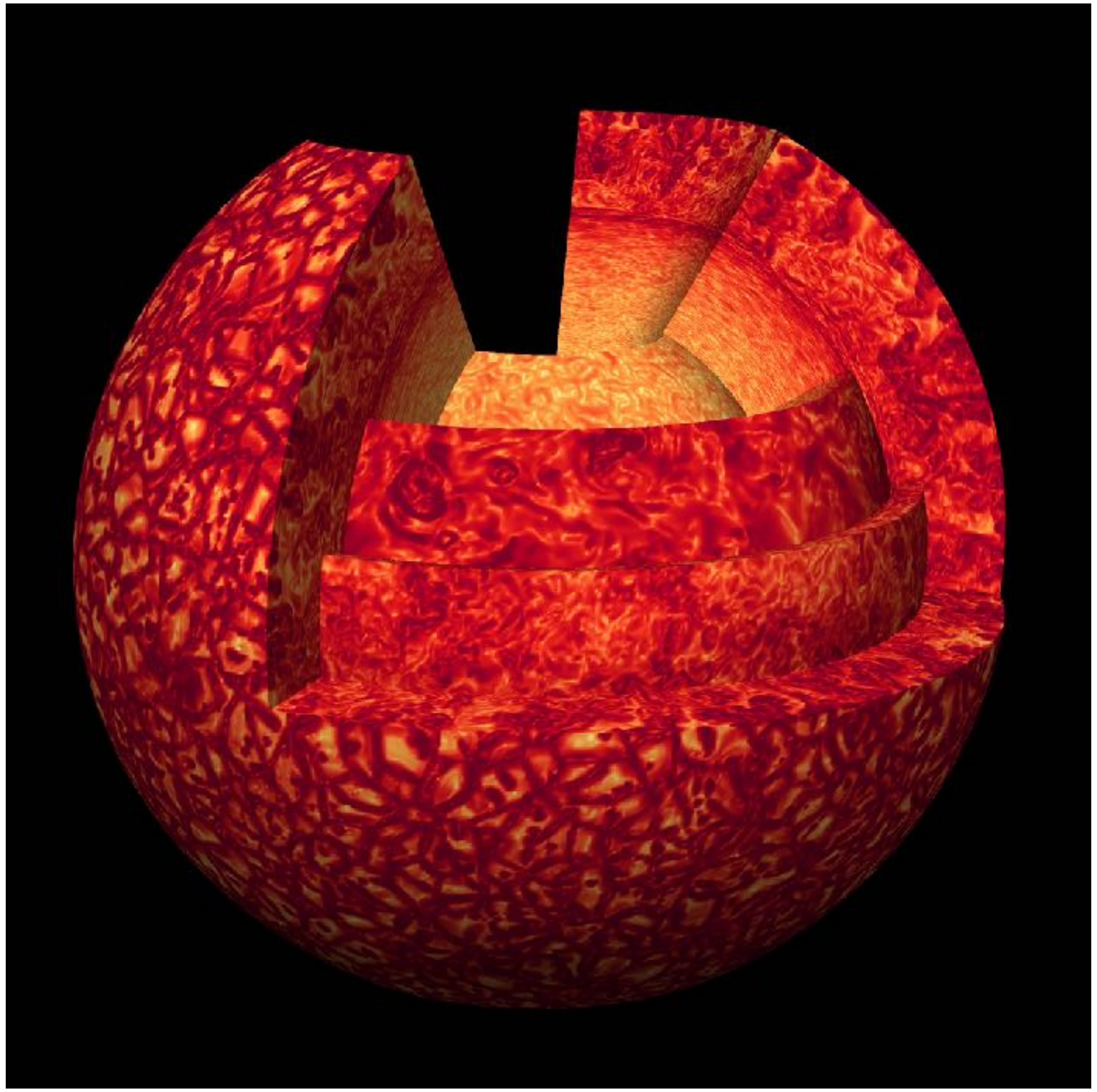
Identification using the oscillation code GYRE (Townsend et al. 2013, 2016)

Compute theoretical eigenfunction and compare to mode measured in MUSIC simulations

Challenges & Prospectives

Towards more realistic stars: rotation, magnetic fields…

➡ MHD simulations in 3D



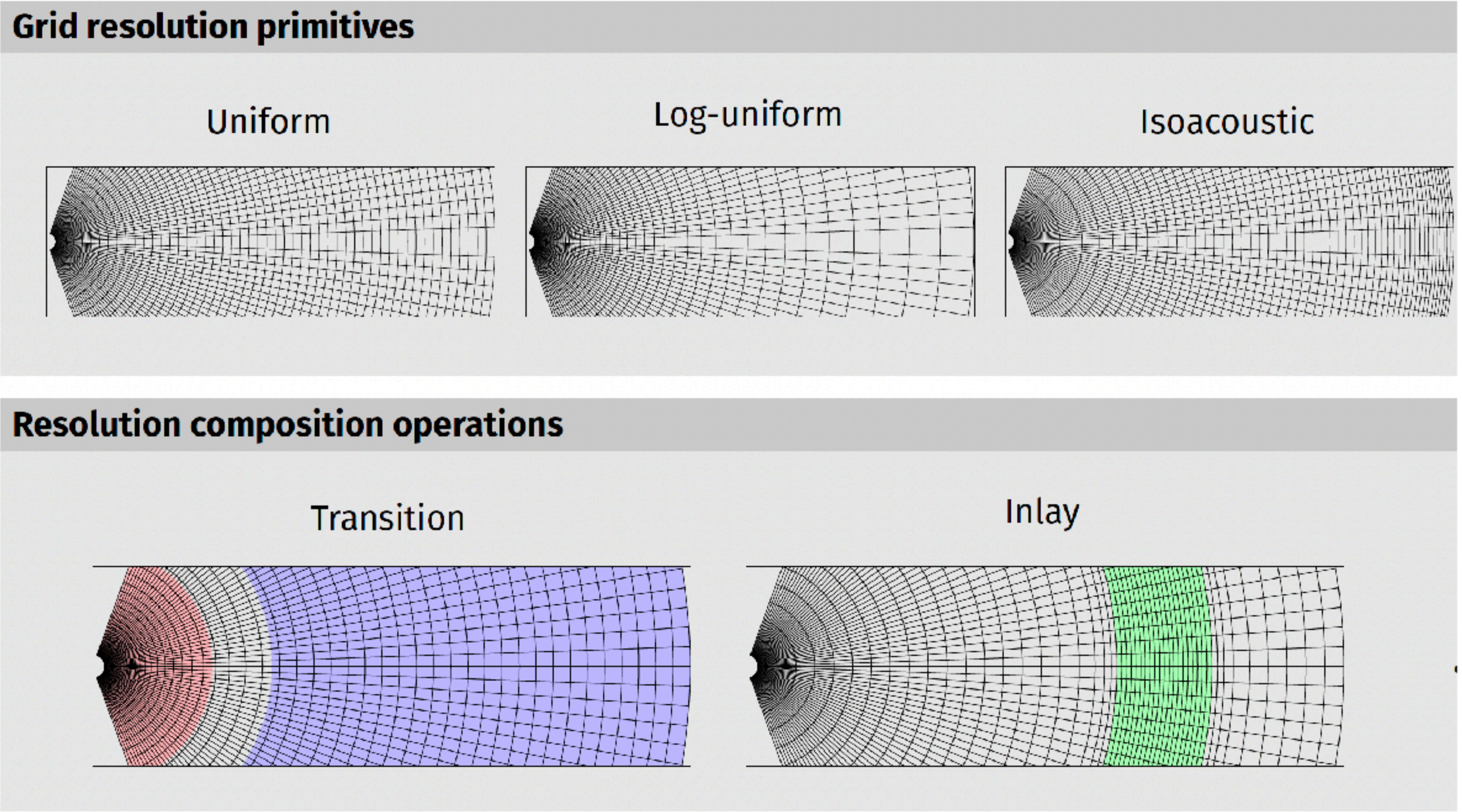
Credits: D. Vlaykov

First simulations currently analysed !

Challenges & Prospectives

Increase synergy with asteroseismology: CBM, mixed modes, extension up to R

→ Composable radially-mapped grids



Credits: T. Guillet

Challenges & Prospectives

Numerical methods become more complex and deal with more physics

→ Studying diffusion by internal gravity waves with tracers

Mixing possible through:

- Radiative damping
- Shear induced turbulence
- Non-linear wave breaking
- Non-linear mixing from Stokes drift

Challenges & Prospectives

Numerical methods become more complex and deal with more physics

→ Studying diffusion by internal gravity waves with tracers

Mixing possible through:

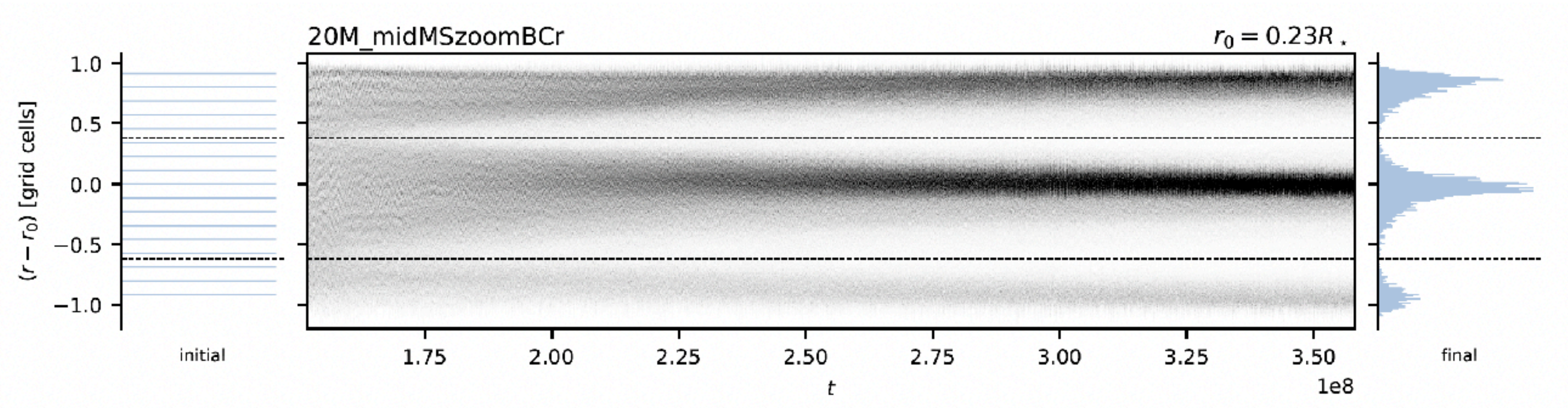
- Radiative damping ?
- ~~Shear induced turbulence~~
- Non-linear wave breaking ?
- Non-linear mixing from Stokes drift (small)

Simulations

Diffusive process (e.g. Higl et al. 2021, Varghese et al 2023): origin?

Spurious (methodology, numerical, …)?

Need to understand numerical methods better

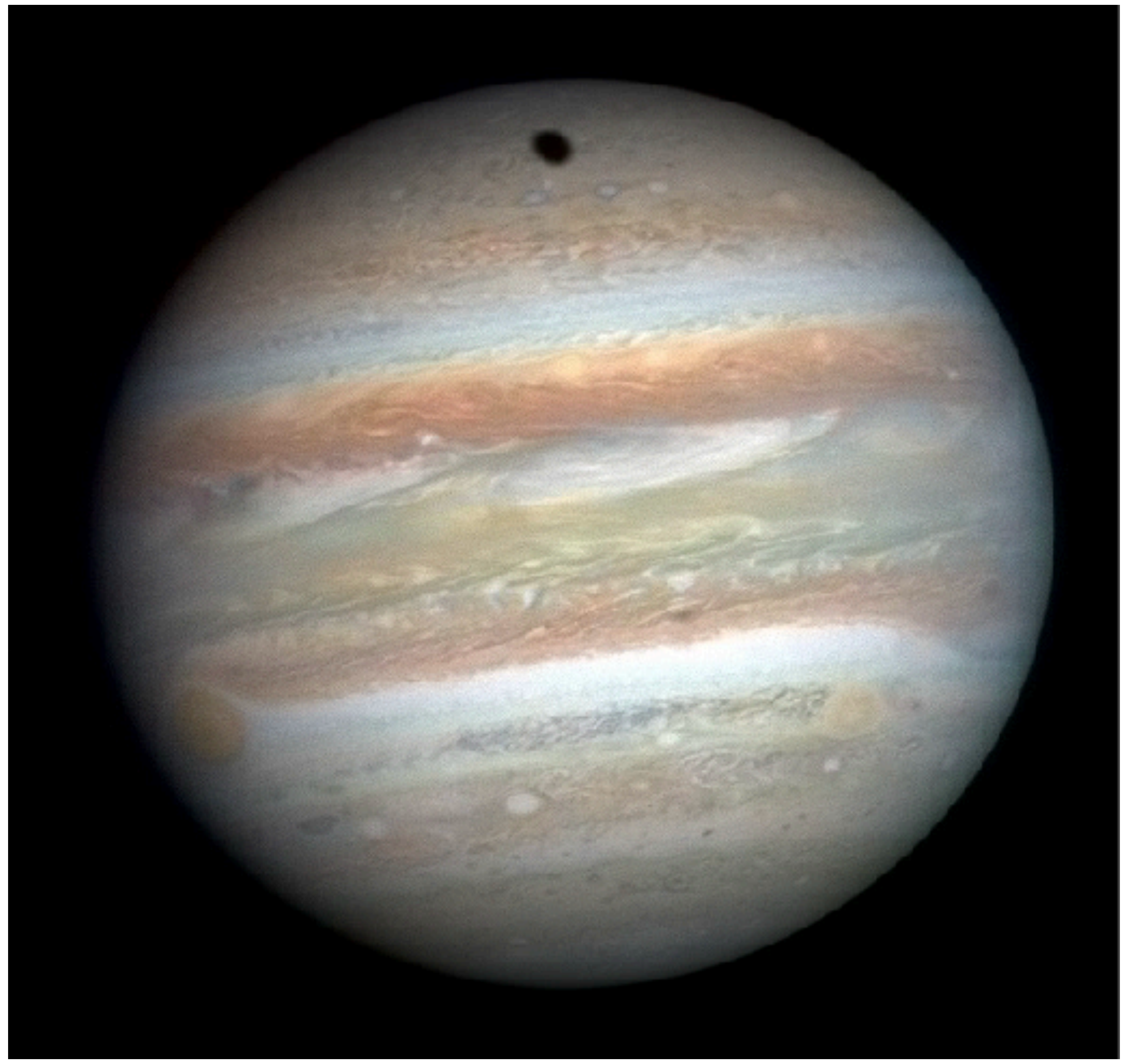


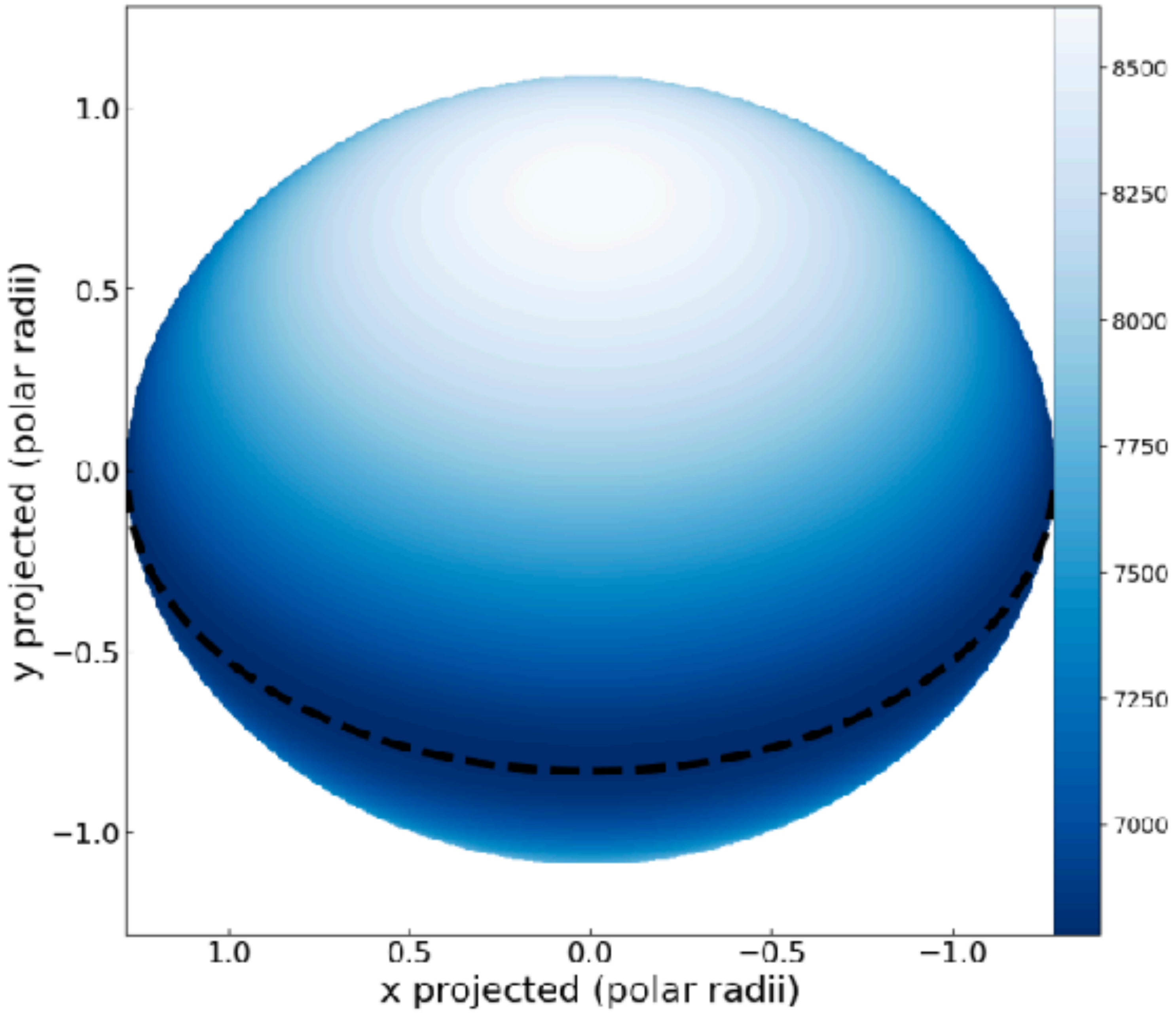
Credits: J. Morton

Challenges & Prospectives

Expanding application to new physical systems

→ Gas giants planets and rapidly rotating stars





Bouchaud *et al*. (2020)

Upcoming in MUSIC: simulating convection in rapidly rotating ESTER stars

Summary

Waves and CBM properties are inherently 3D, non-linear and anisotropic

→ **Need multi-dimensional simulations to test analytical models and guide observations!**

Upper layers particularly complex for wave analysis

→ **Direct comparison with observations is tricky**

Modelling and analysis of mixed modes, extension up to photosphere

→ Increase synergy with asteroseismology

Need to understand our numerical methods better

→ Studying diffusion by internal gravity waves with tracers

Expanding application to new physical systems

→ Gas giants planets and rapidly rotating stars

Compressibility effects matter:

Evolution of stratification, convective boundary mixing, acoustic and mixed modes, …