The way forward to study stellar oscillations in HPC simulations

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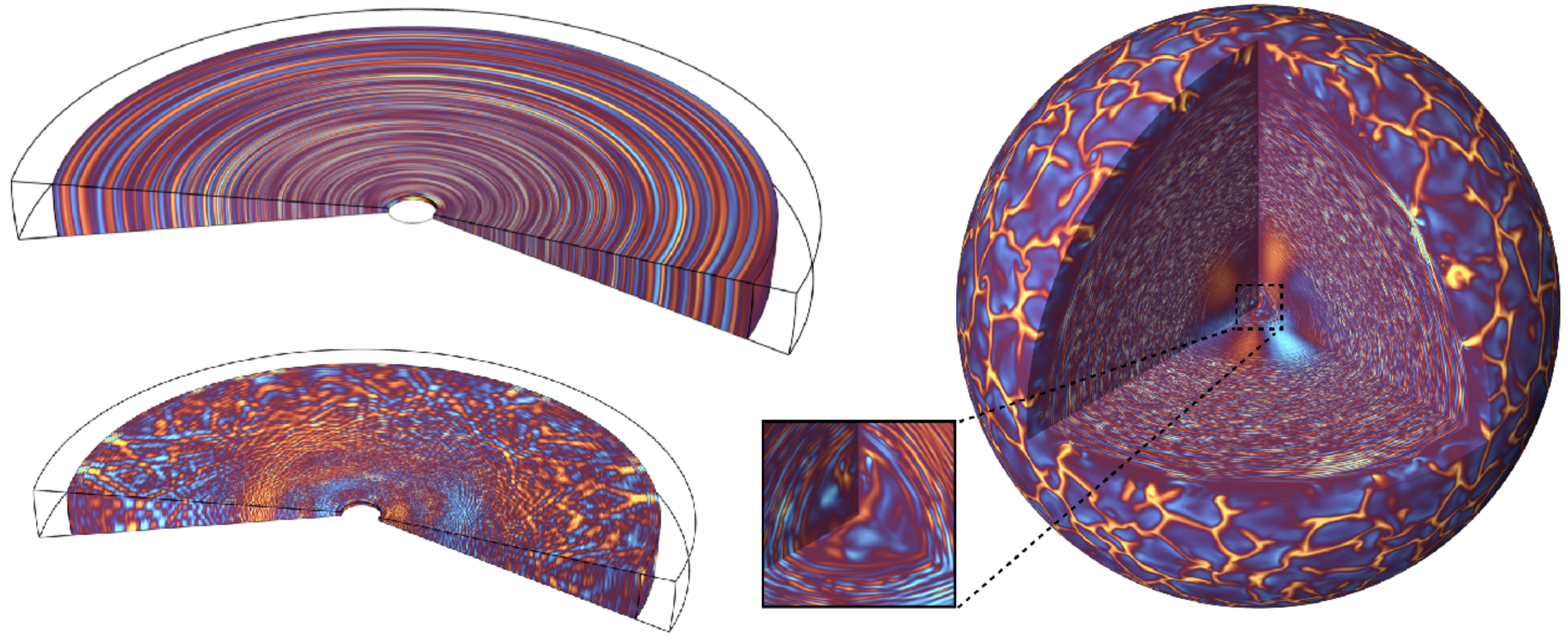

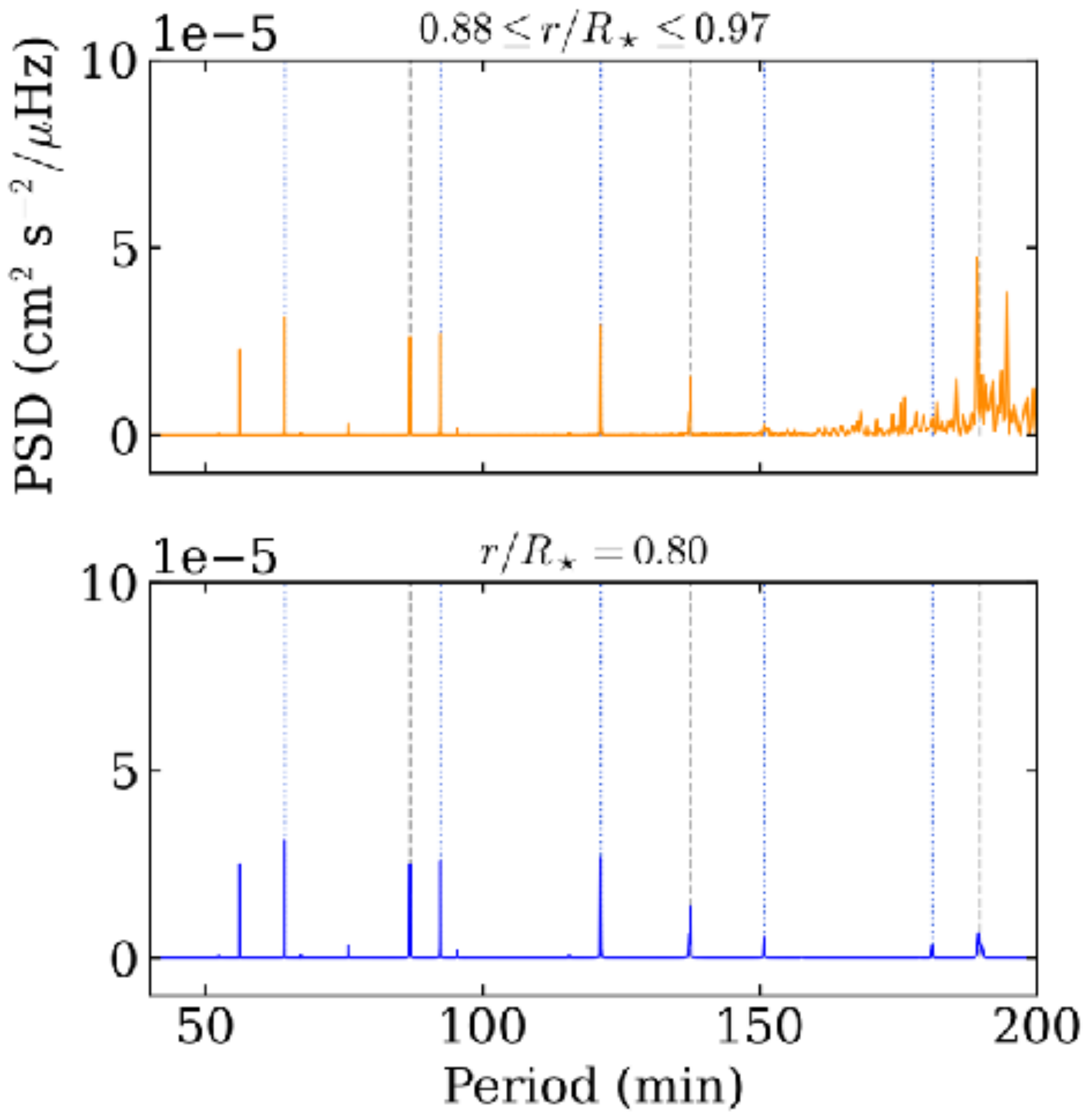

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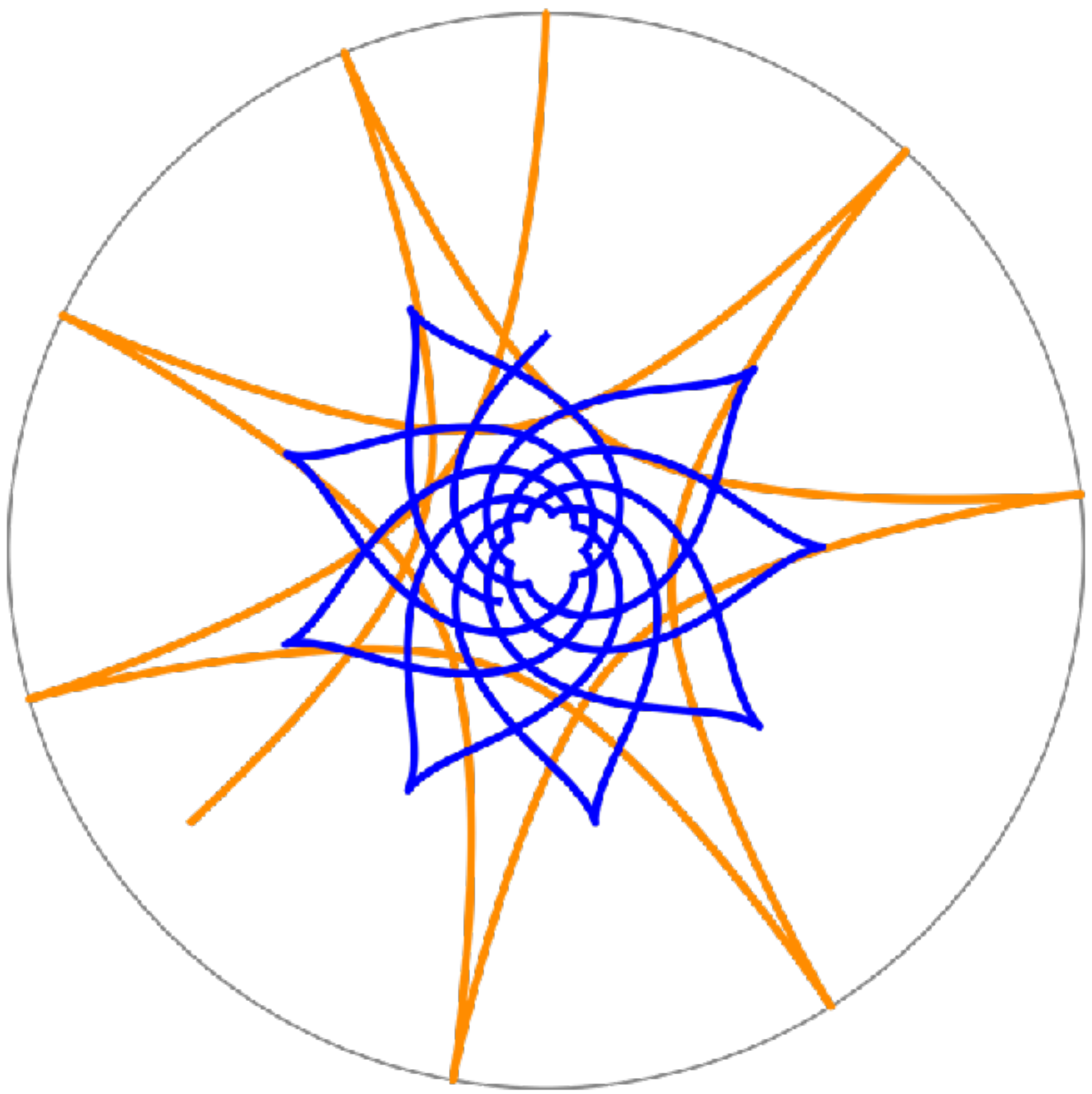
17 Décembre 2025

Stellar oscillations

≡

standing modes of waves propagating in **stellar interiors**



Acoustic modes ↔ pressure gradient

Gravity modes ↔ buoyancy

Inertial modes ↔ Coriolis force

Our only direct window on stellar interiors !

Extensive 1D linear theory but we desperately need more understanding of their **behaviour in a non-linear context** (e.g. excitation by convection)

→ **2D/3D simulations**

Let's illustrate this with a case study !

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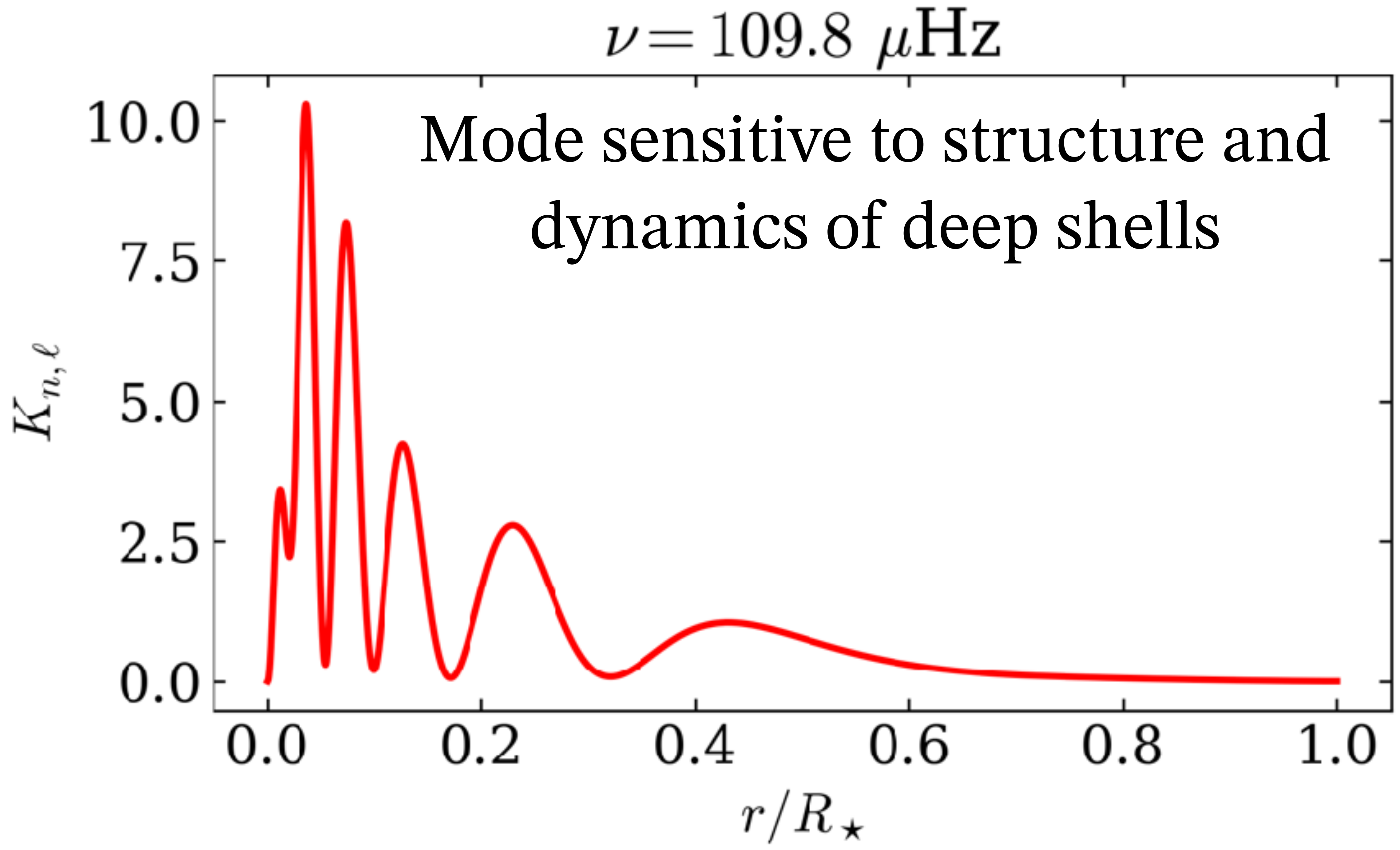
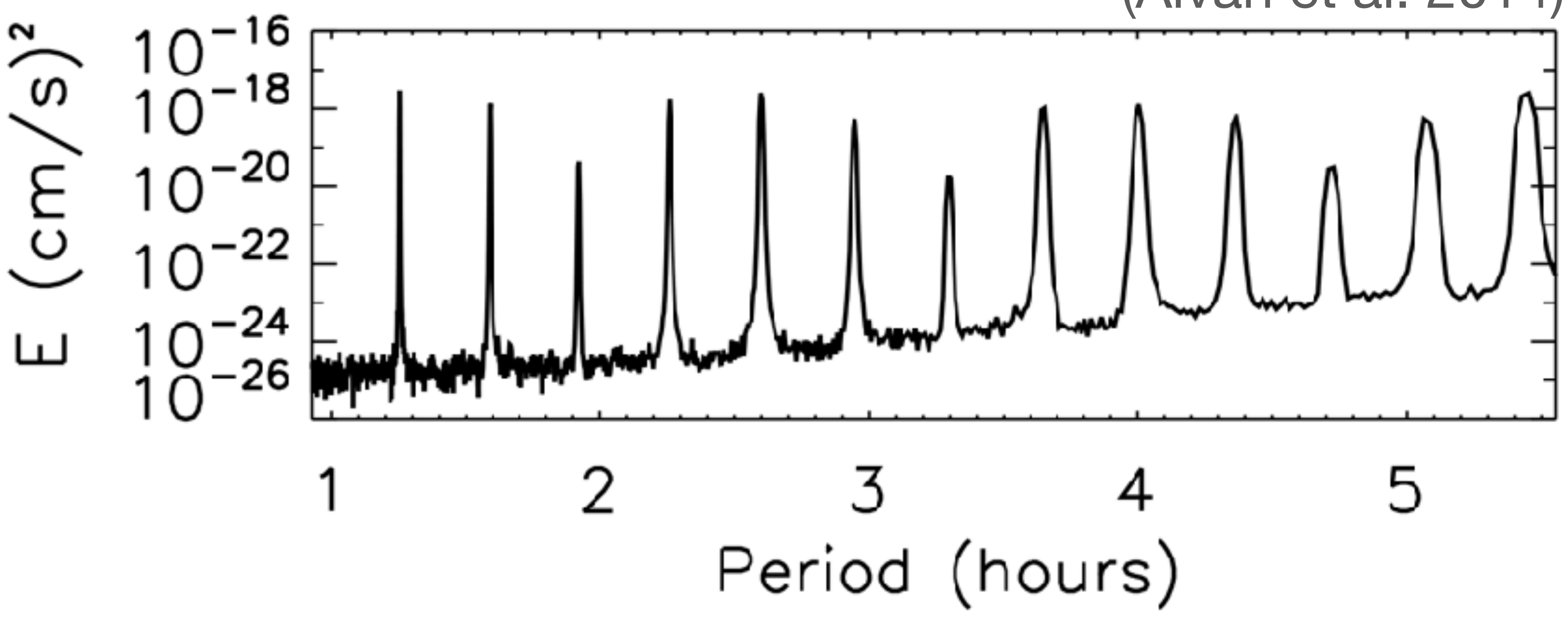
Probing deep stellar dynamics with gravity modes



(Alvan et al. 2014)



Evanescent in **convective** regions !

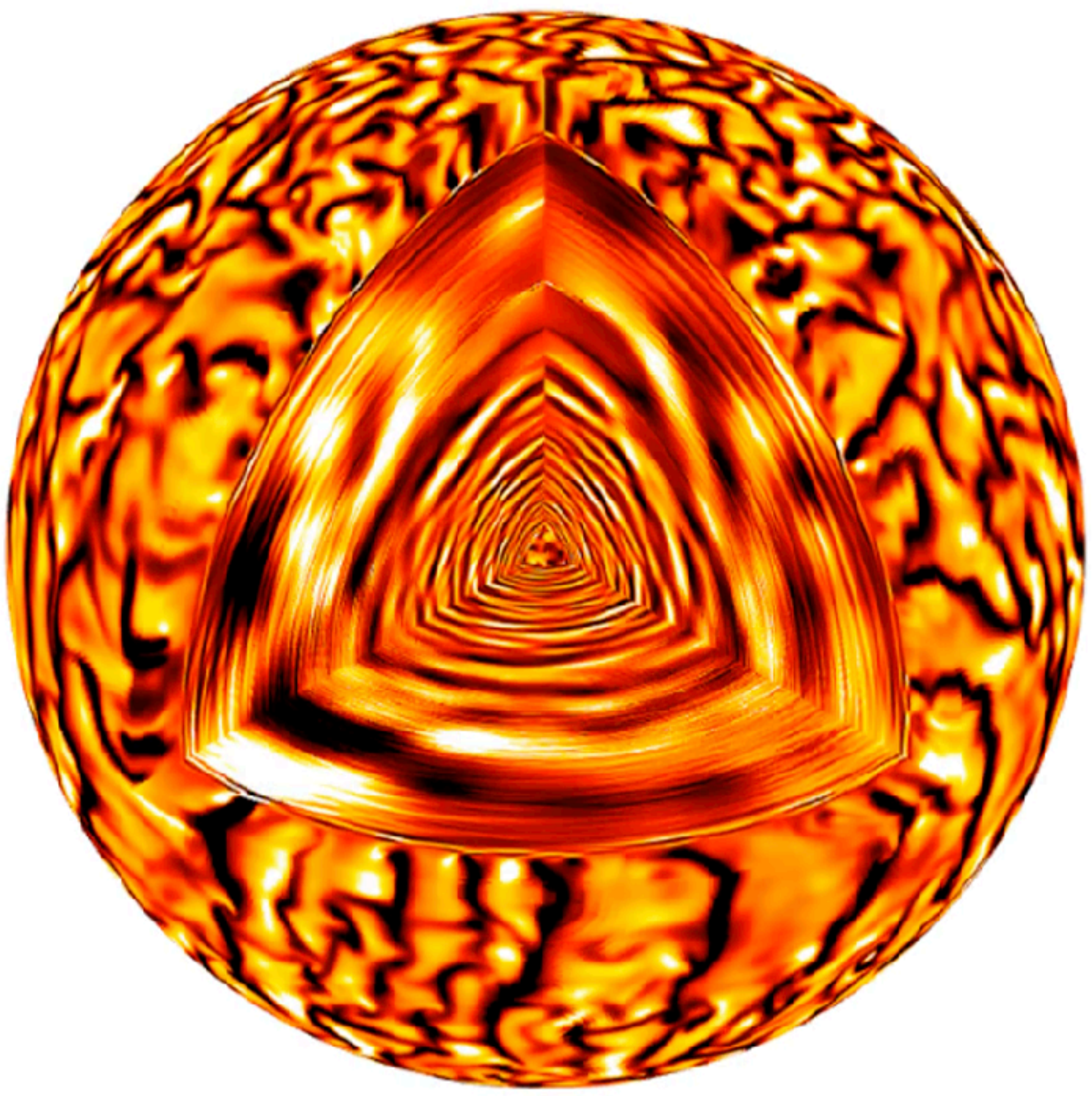
→ Low surface amplitude

Can g modes be observed in main-sequence solar-type stars ?

(e.g. García et al. 2007, Belkacem et al. 2022, Breton et al. 2023)

3D simulations of gravity mode non-linear excitation

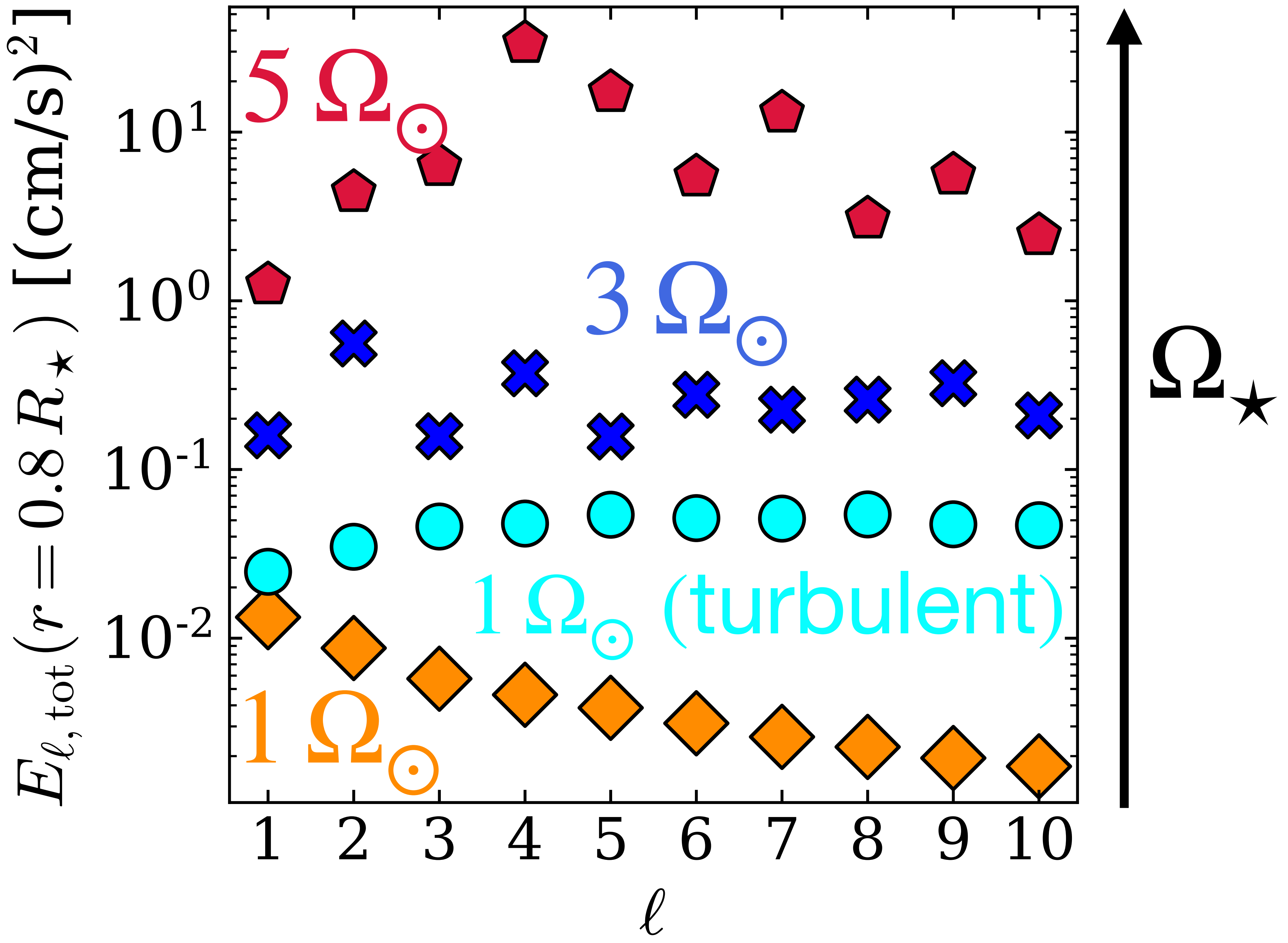
1.3 $M_\odot$ F-type star



A first simulation **without** the convective core

(Breton et al. 2022)

Key role of **rotation** in the mode **excitation**



(Breton et al. 2022)

Spherical **anelastic** setup with the ASH code

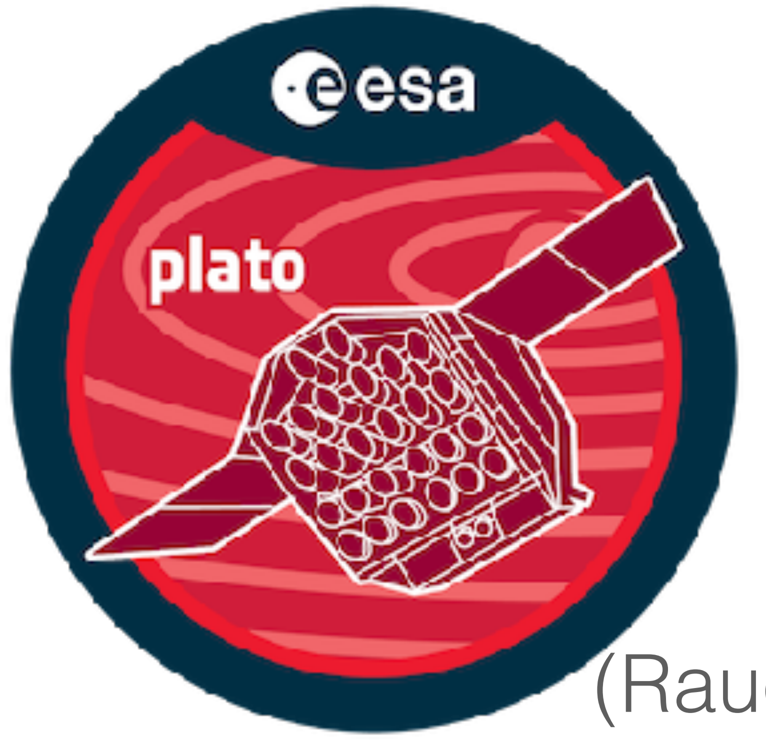
(Clune et al. 1999, Brun et al. 2004)

Including the convective core in the picture

A lot of stars in the **PLATO mission core sample** will have this structure. (Goupil et al. 2023)

→ It is critical to understand better their dynamics !

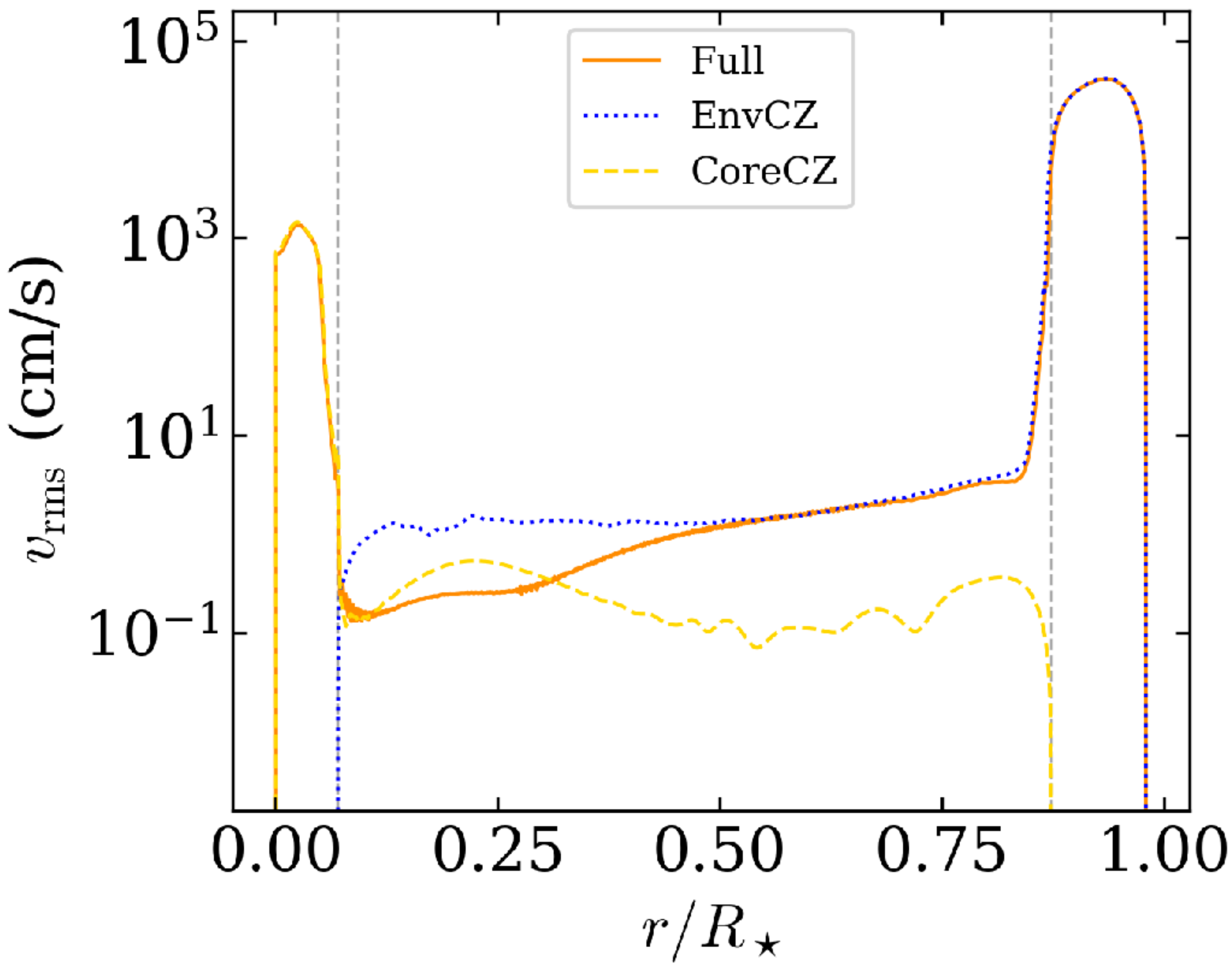
(Determination of **their age** and the one of their **planets** !)



Launch early 2027, we are getting close !

(Rauer et al. 2025)

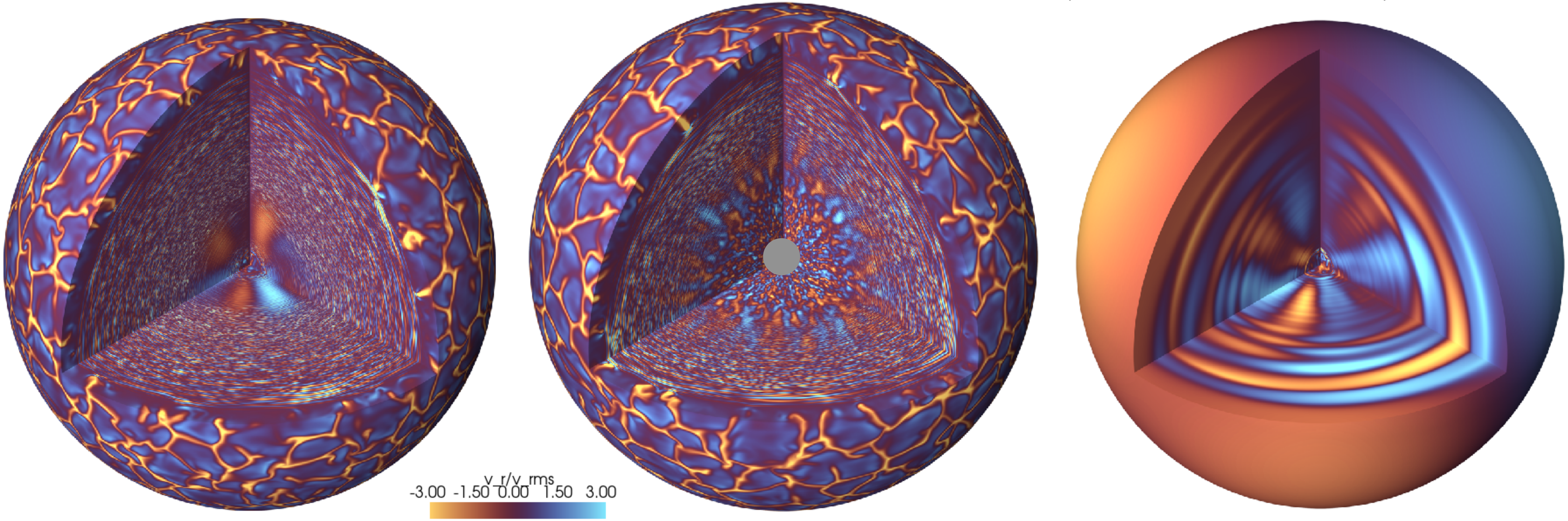
(Breton et al. submitted)



Including the convective core in the picture

A comparative analysis

(Breton et al. submitted)

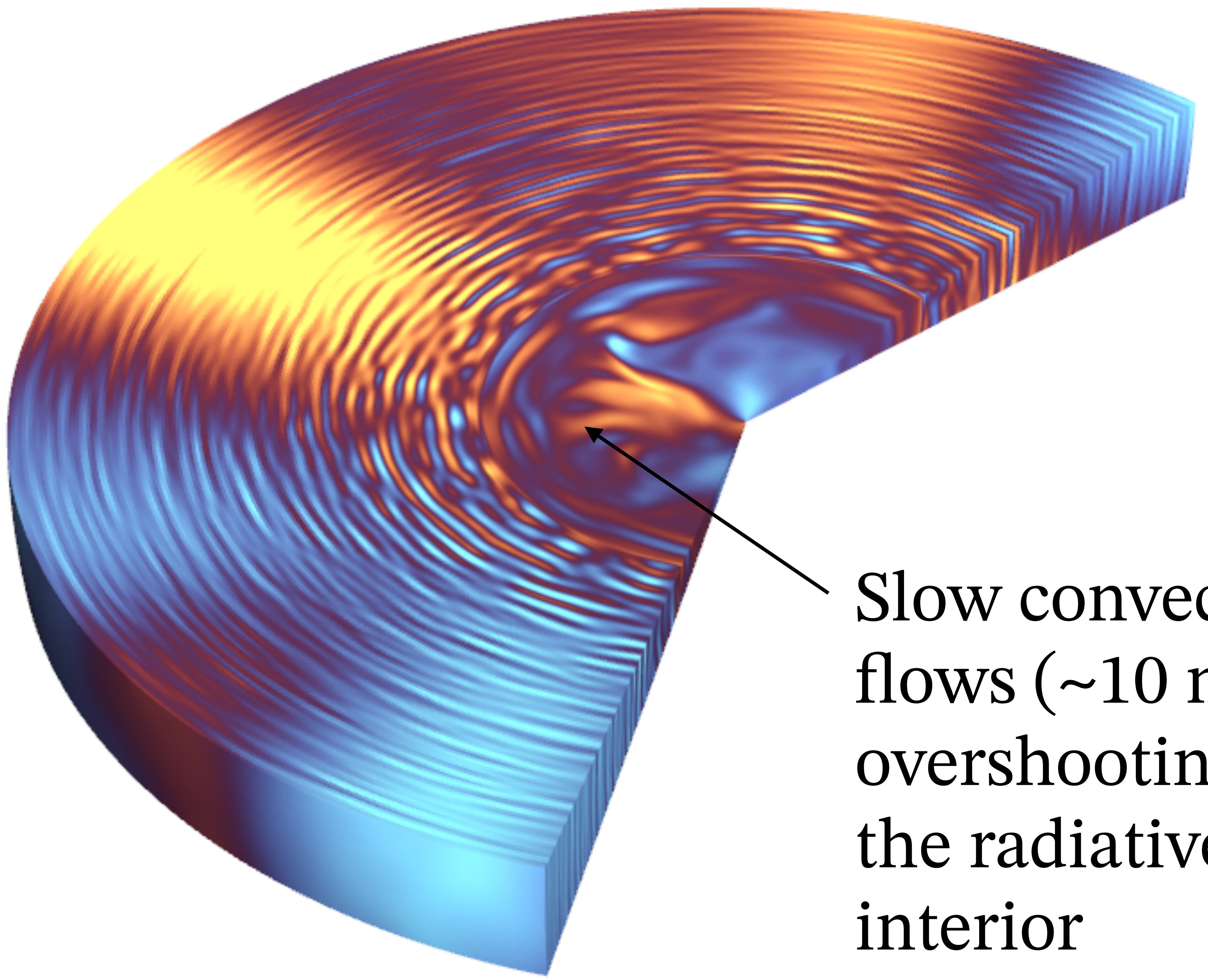


Full interior

No core

No envelope

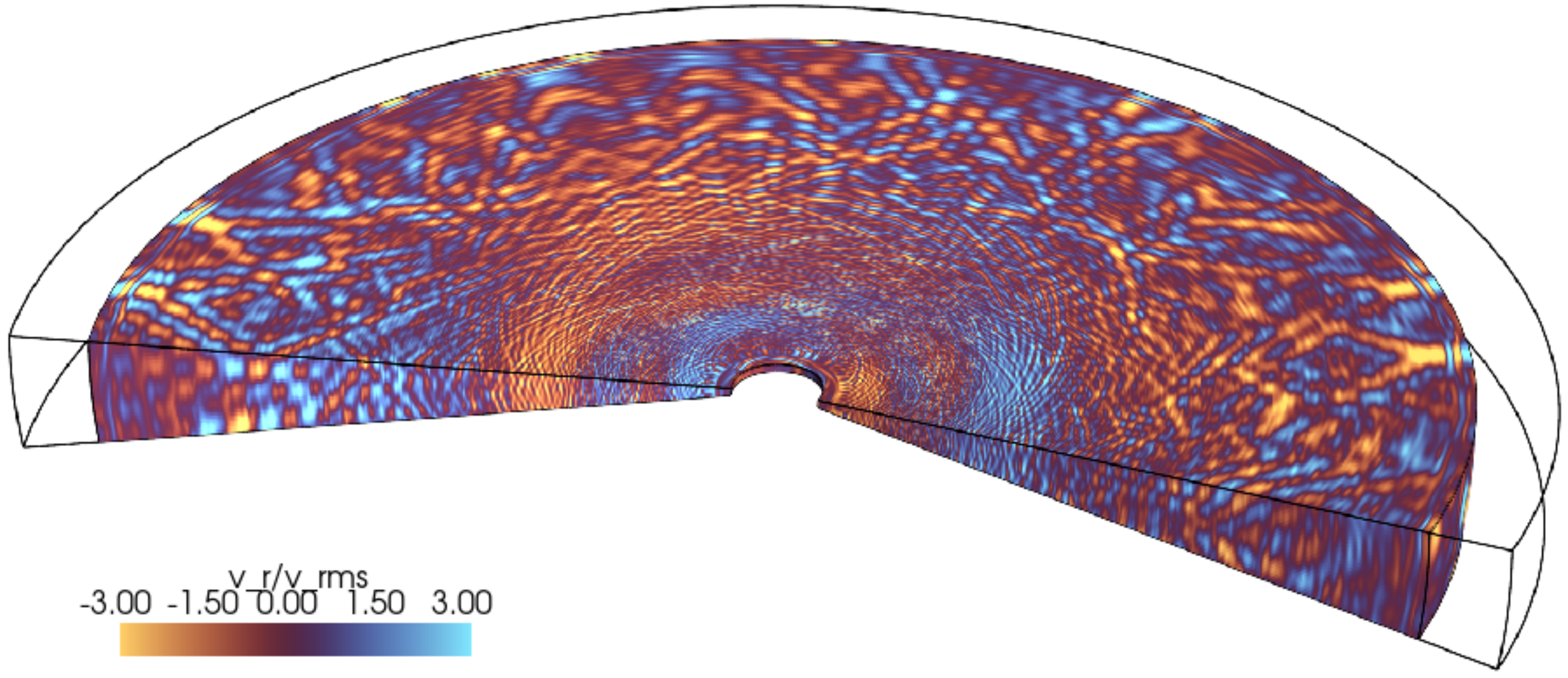
A few dynamical highlights



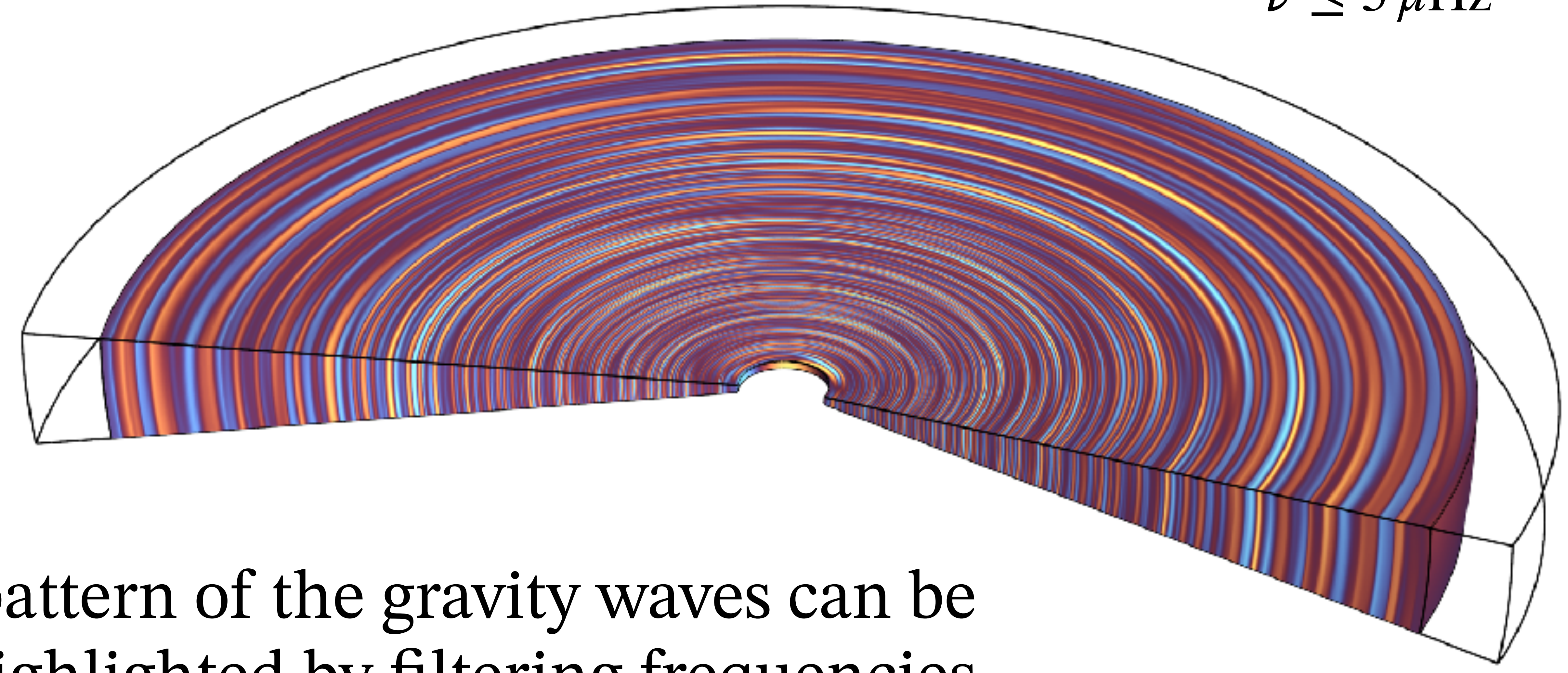
Slow convective flows (~10 m/s) overshooting in the radiative interior

(Breton et al. submitted)

$121\,\mu\text{Hz} \leq \nu \leq 123\,\mu\text{Hz}$



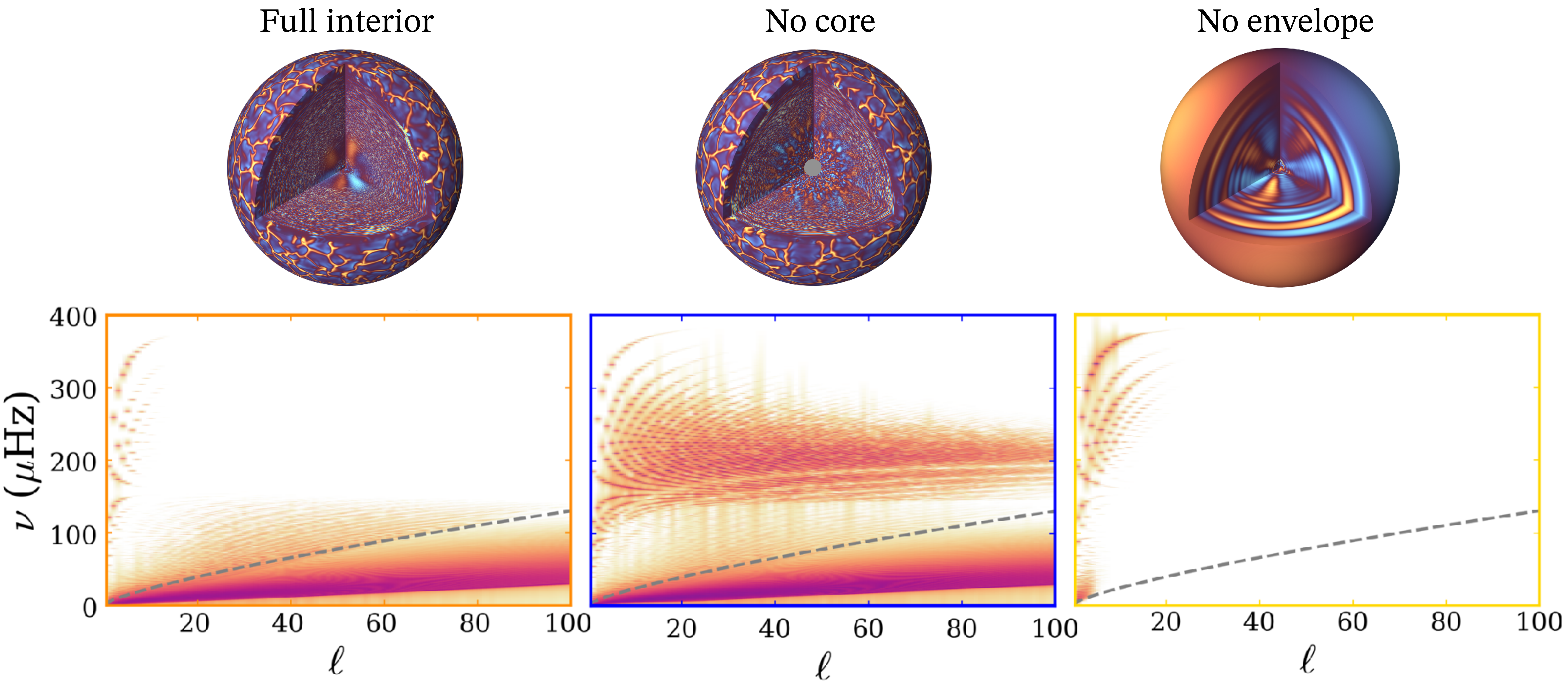
$\nu \leq 5\,\mu\text{Hz}$



Typical pattern of the gravity waves can be highlighted by filtering frequencies

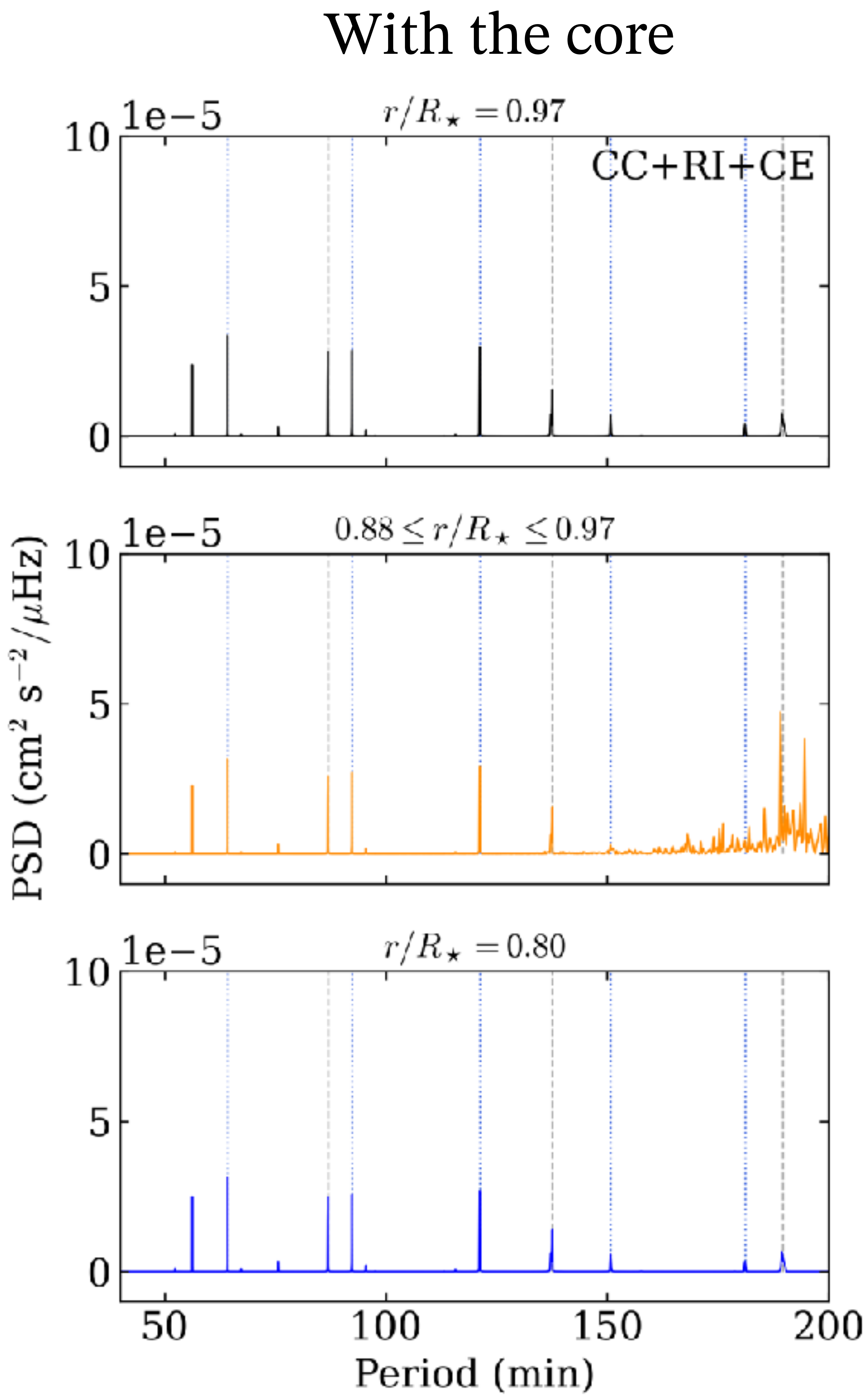
The power spectrum

(Breton et al. submitted)



Three very different spectra

Gravity mode signature



Power spectrum clearly exhibits the g mode signature **up to the top of the convective envelope** !

Observable ?

(Breton et al. submitted)

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Now let's take a few steps back to look at the broader picture !

What do we need to make this type of analysis **more systematic** and go **beyond the current state of the art** ?

(Ideally we would like to have a collection of simulation adapted to the **diversity of targets** that PLATO will observe !)

Challenge #1: high cadence time series

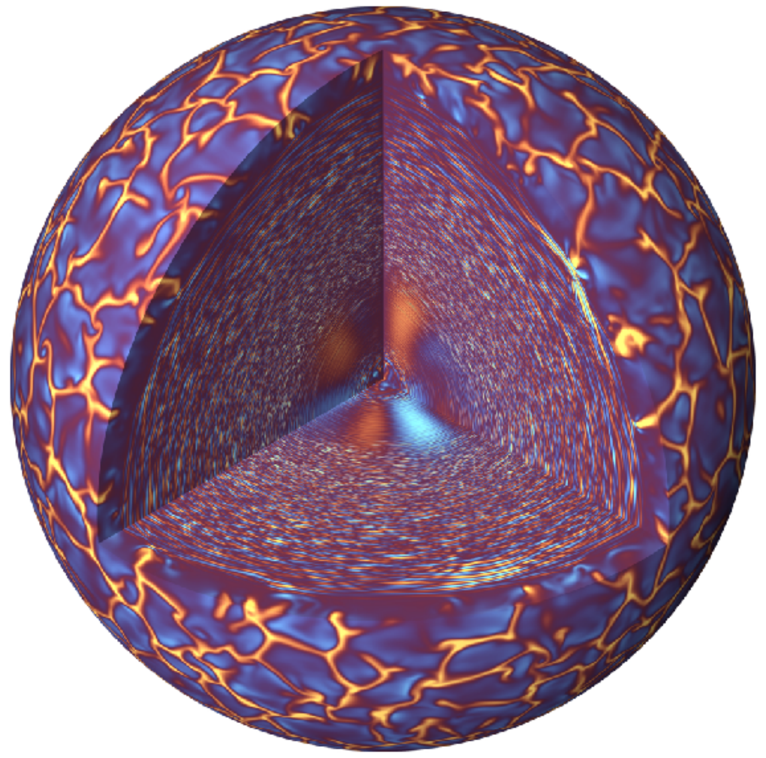
Main sequence solar-like stars

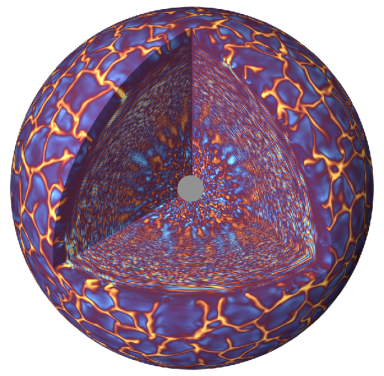
For gravity modes
1 output / ~ 600 seconds

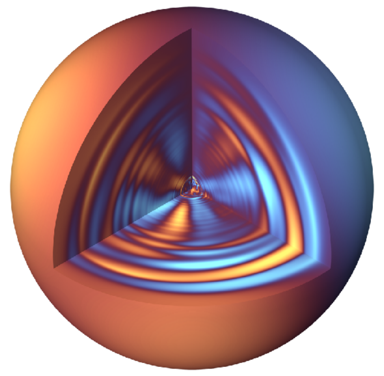
For acoustic modes (only fully compressible codes)
1 output / ~ 60 seconds !!!

We want time series of at least a few tenth of days

That's a lot of data to store !







→ in total close to **1 PB** of intermediate outputs before post-processing !

→ Run crash because the scratch of the cluster saturated: ✔

Necessity to have **spherical degree ℓ** truncation **directly performed** by the HPC codes during the I/O procedures

Challenge #2: 3D to 1D connection

Challenge of **mode identification** from 1D linear predictions

→ equations may differ (e.g. no anelastic approximation implemented in the reference oscillation code GYRE)

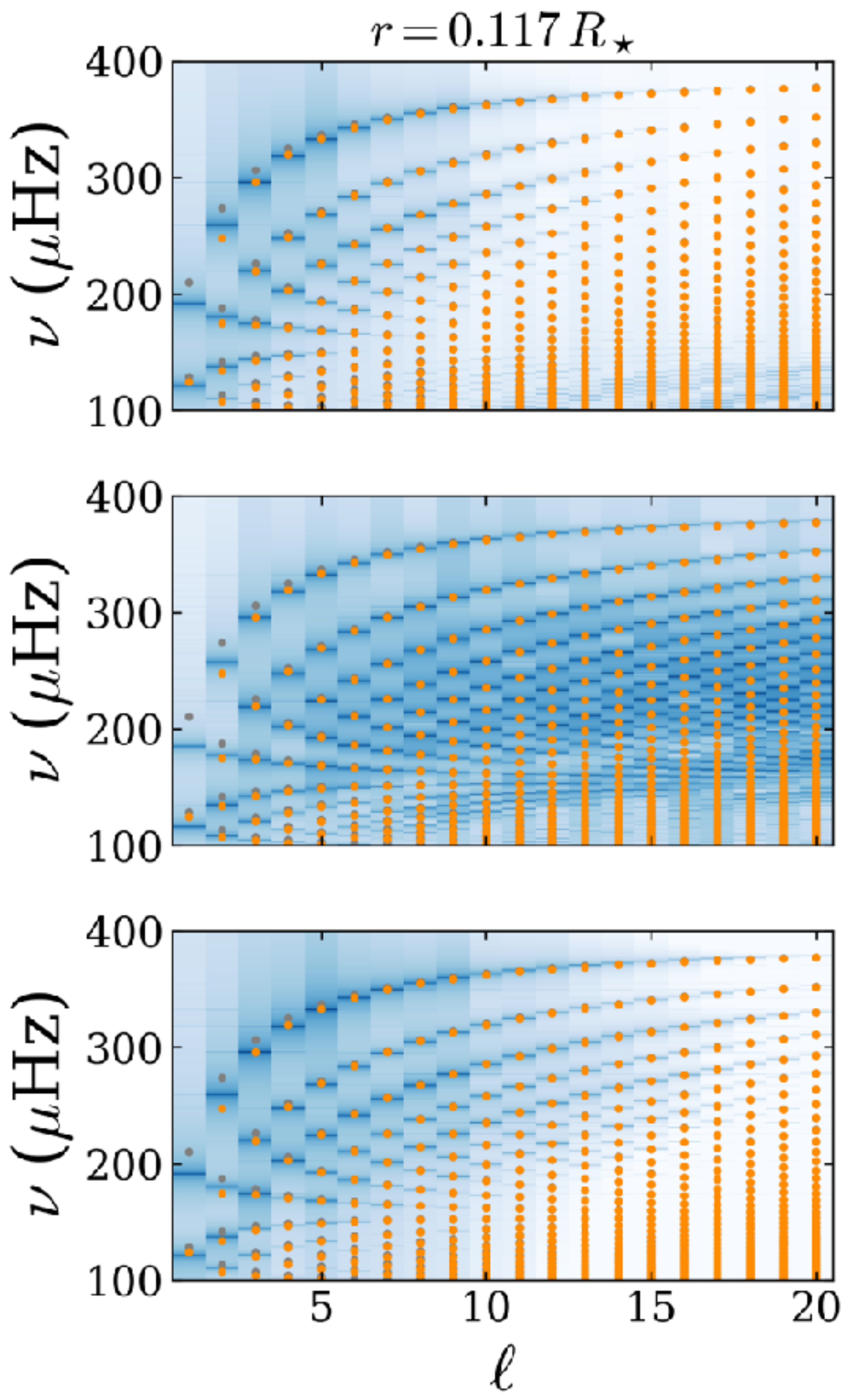
→ boundary conditions actually used in simulations not always implemented either

Retroaction of modes/internal waves on stellar dynamics: which strategies to go from 3D to 1D ?

→ angular momentum transport

→ chemical mixing

Better prescriptions in 1D stellar evolution codes
→ Better **stellar ages** !



(Breton et al. submitted)

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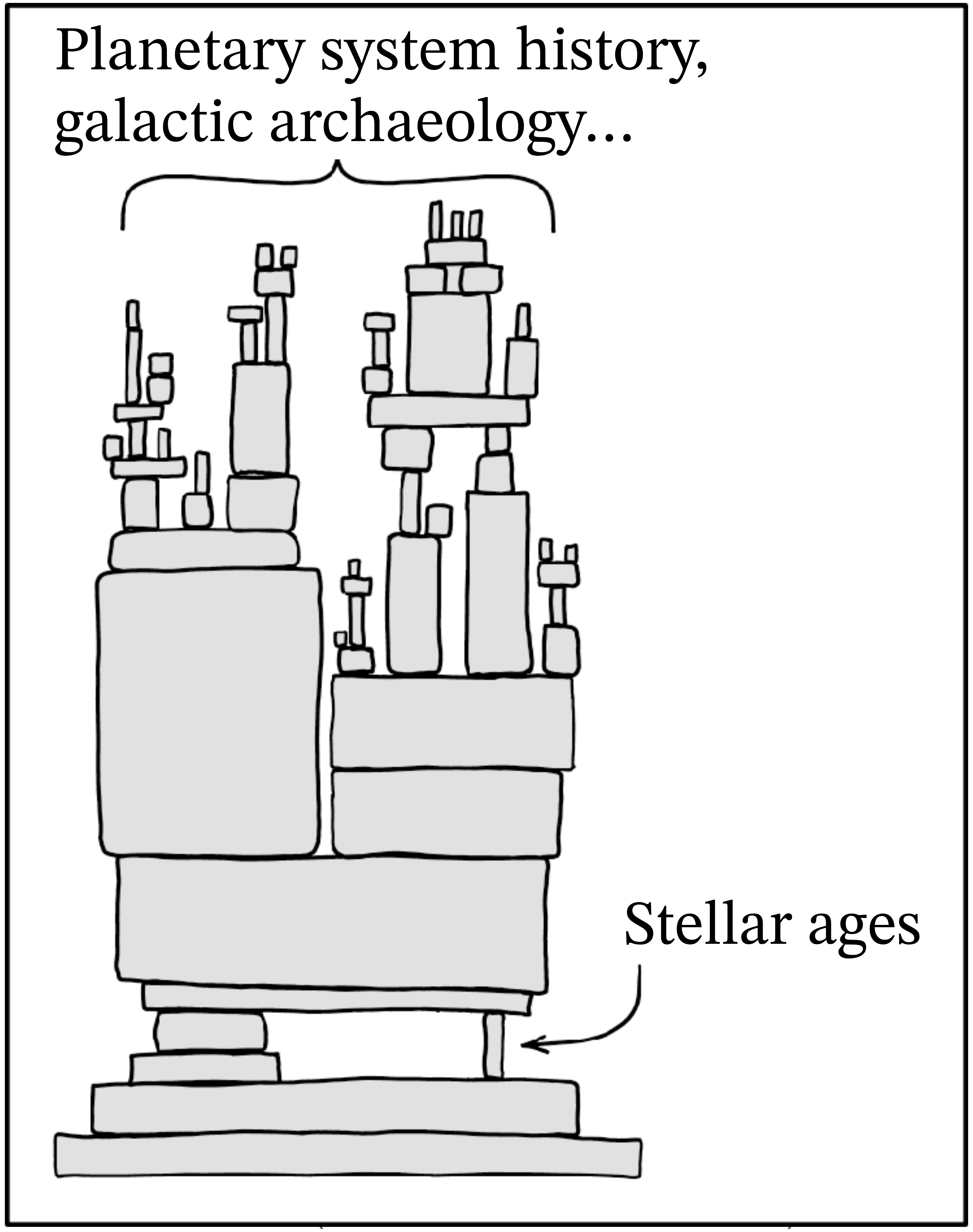

Challenge #3: More physics !

Equations: beyond anelastic convection

Solar type stars are acoustic mode pulsators: we need **acoustic waves** in the simulations !

→ Fortunately we are entering the era of **stellar global simulations with fully compressible setups** ! (e.g. dyablo, MUSIC)

Rotation

→ Coriolis force is **critical for (gravito)-inertial modes** (some of them recently discovered in the Sun, Löptien et al. 2018)

→ Rotation influences convection and therefore **excitation of every mode family** (acoustic, gravity, inertial) !

Some efforts in this direction

(e.g. Breton et al. 2022, Bekki et al. 2022, Blume et al. 2024, Souza-Gomes et al. 2025)

Magnetism

→ Strongly influences mode **excitation** and **damping**

→ Perturbs their frequencies with the **activity cycle**

Are we going to see anytime soon a 22-year long self-consistent simulation of the Sun with acoustic mode time series ?

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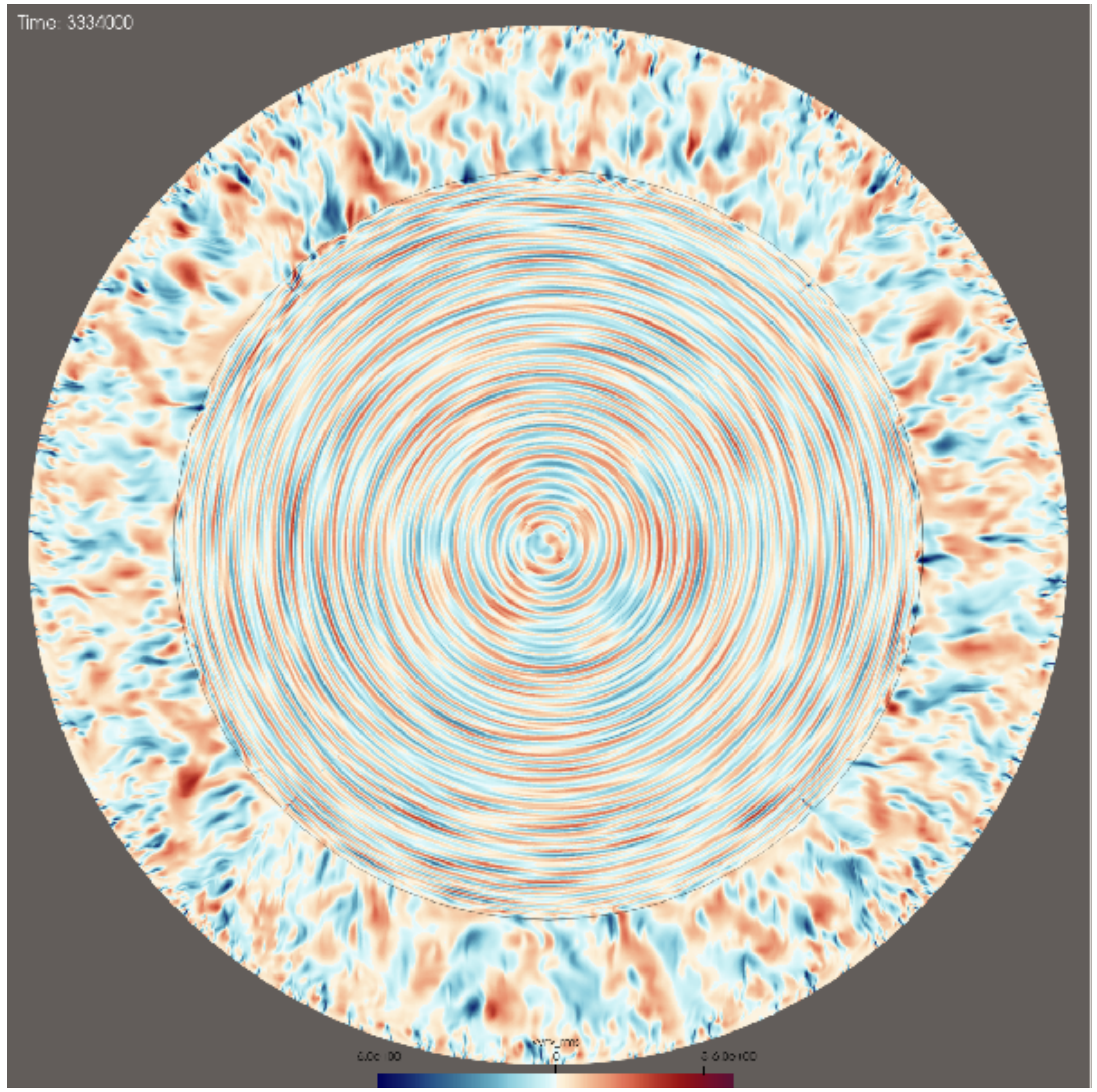
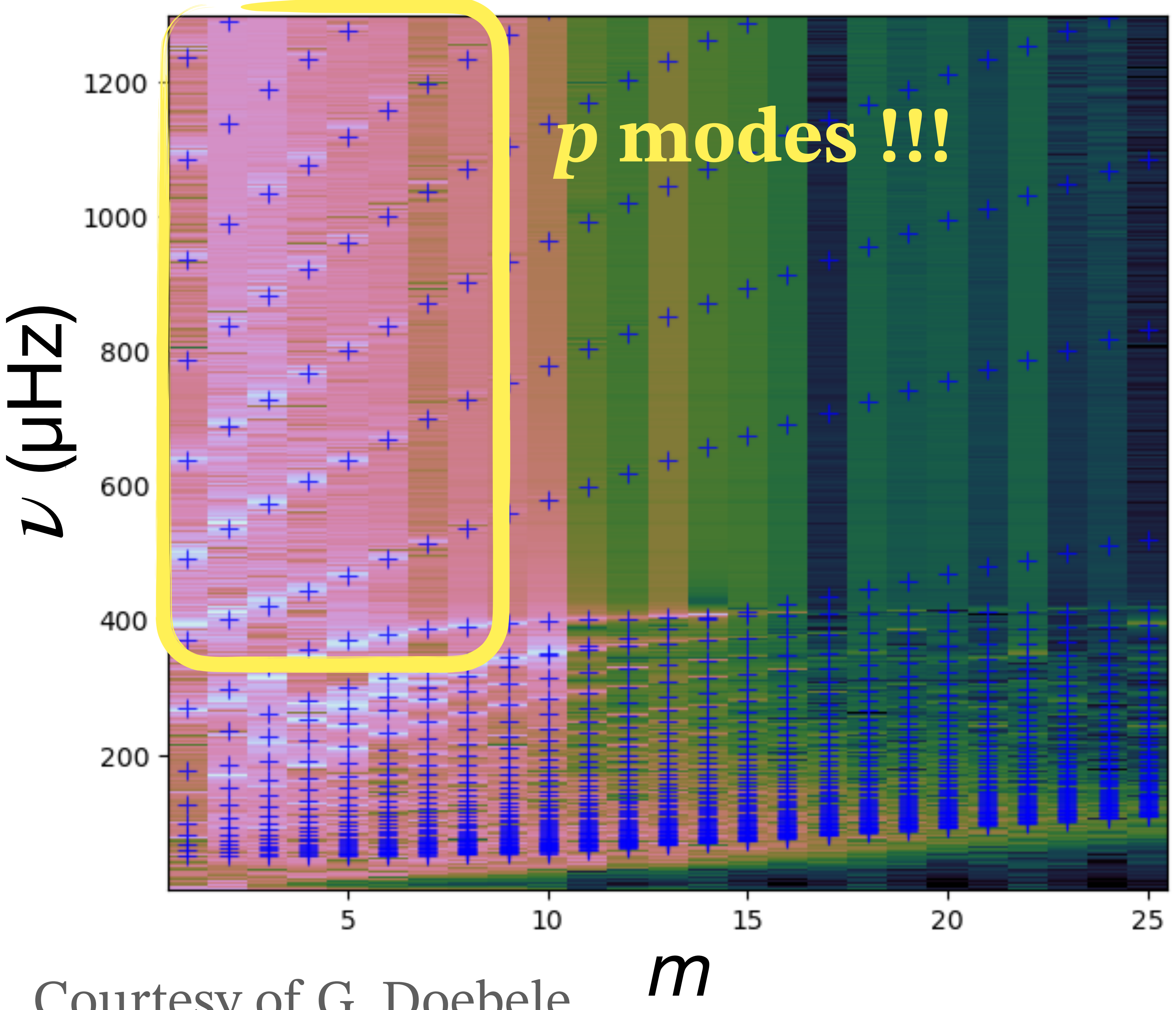
Time to board the dyablo train ! 🚂

Fully compressible dynamics + Adaptative mesh refinement !





Courtesy of G. Doebele

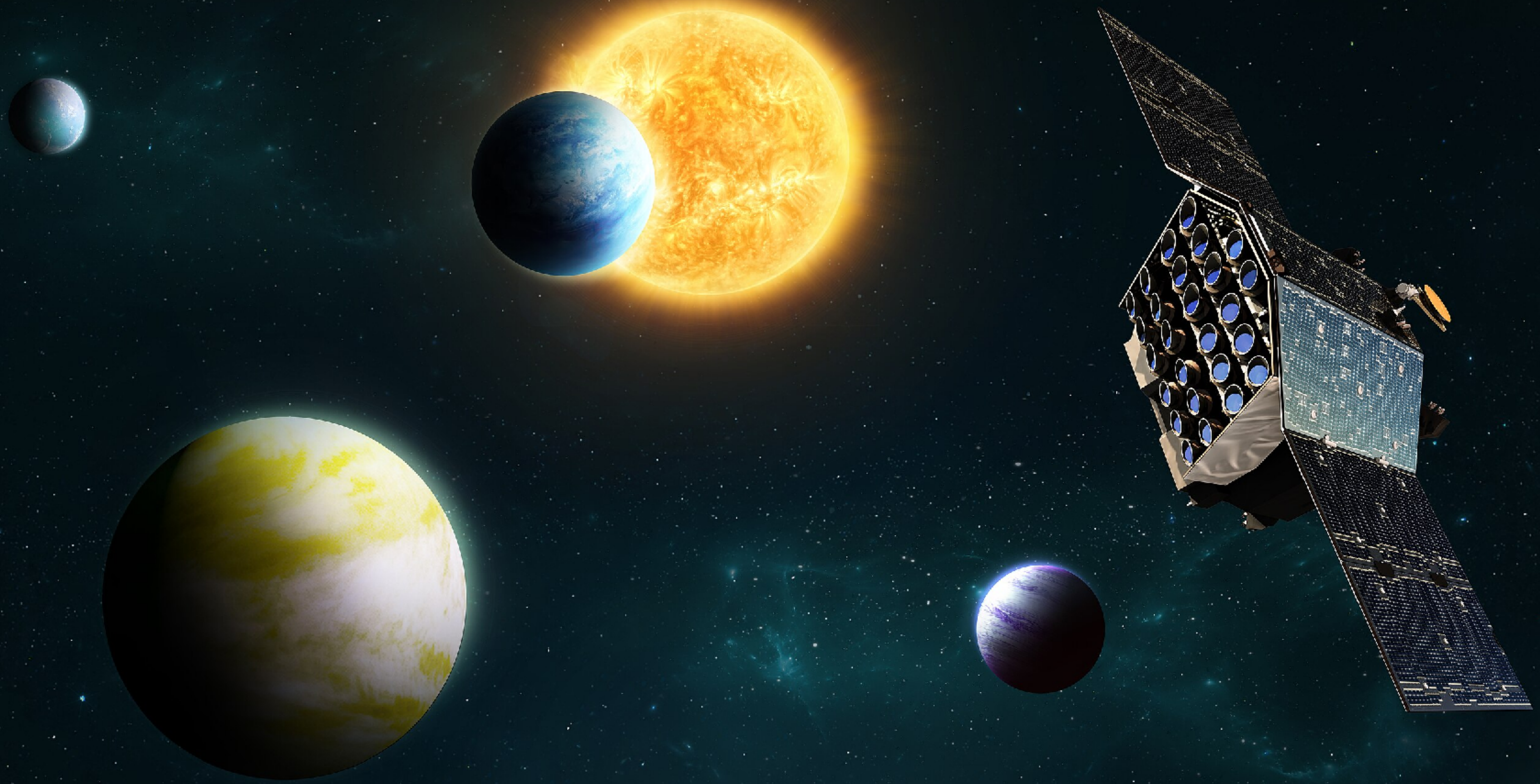
Talk from **Maxime** on Monday and talk from **Grégoire** just before mine

2D/3D spherical setups of convection on their way !
(Doebele et al. in prep.)

On the program

→ **Rotation** and internal waves

→ Oscillation in **evolved stars**



Thank you for your attention !