Journées SF2A Strasbourg – 20/06/2023

Strong magnetic fields discovered in red giant cores using seismology

G. Li, S. Deheuvels, J. Ballot, F. Lignières, 2022, Nature 610, 43

S. Deheuvels, G. Li, J. Ballot, F. Lignières, 2023, A&A Letter, 670, 16

G. Li, S. Deheuvels, T. Li, J. Ballot, F. Lignières, submitted to A&A

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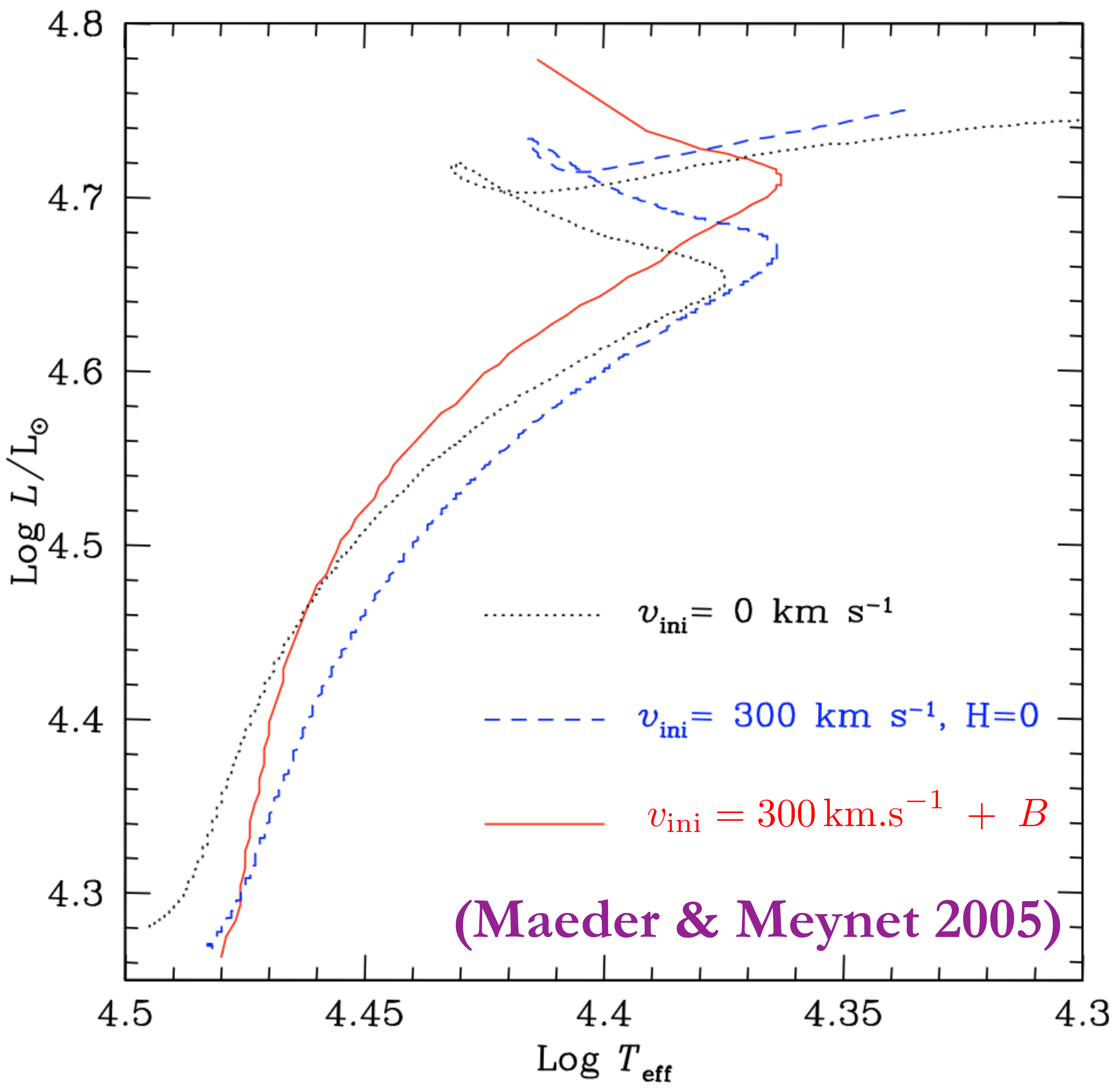
Magnetic fields & stellar evolution

- Magnetic fields are **ubiquitous in stars** (star formation + all stage of stellar evolution)

- They redistribute **angular momentum** (e.g., **Rüdiger+15, Jouve+15, Fuller+19**)
  ⇒ they reshape **rotation profiles**

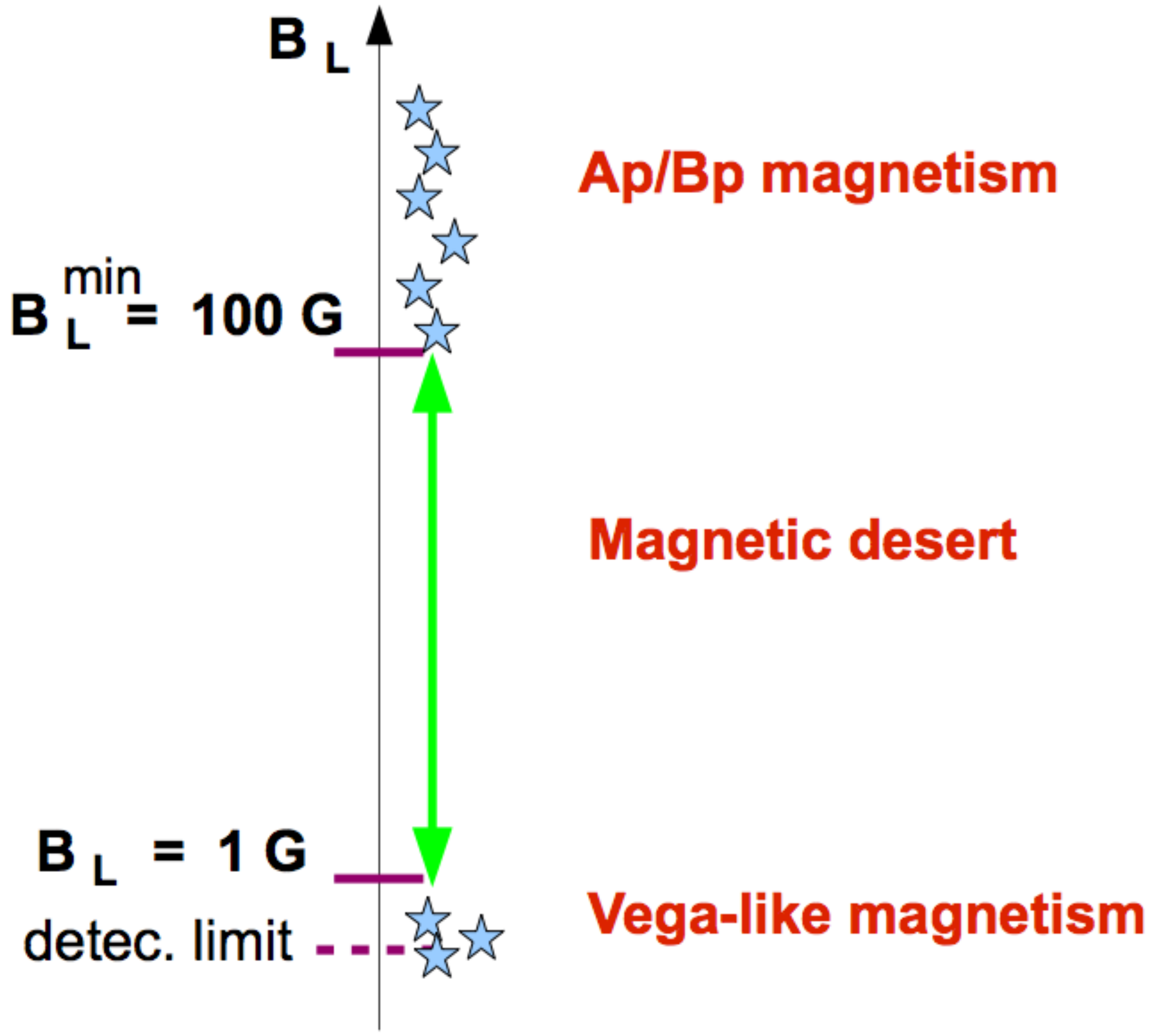
- They modify **rotational mixing** and thus the abundance of chemicals (**Maeder & Meynet 2005**)

- They influence stellar evolution (**stellar ages**)



Surface magnetic fields

- Magnetic fields in stars with **radiative envelopes**: dichotomy between
  - 5 to 10% of stars with strong ($\gtrsim 100\,\mathrm{G}$) dipolar fields (**Ap/Bp stars**)
  - Other stars with much weaker fields ($\lesssim 1\,\mathrm{G}$): **Vega-like** magnetism



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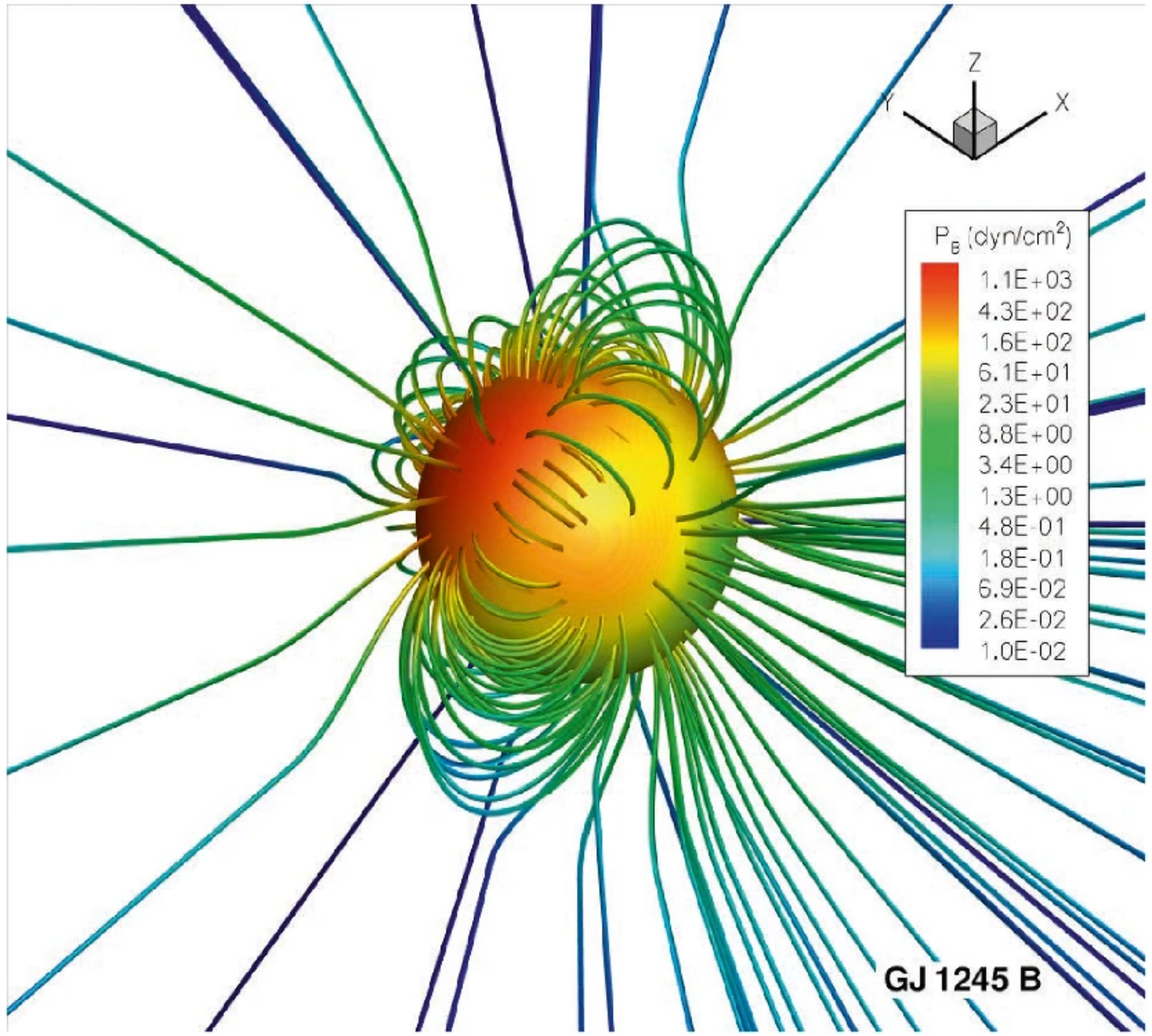
- Magnetic fields in stars with **convective envelopes**
  - Fields produced by **dynamo** in the convective envelope



(Vidotto+13)

Surface magnetic fields

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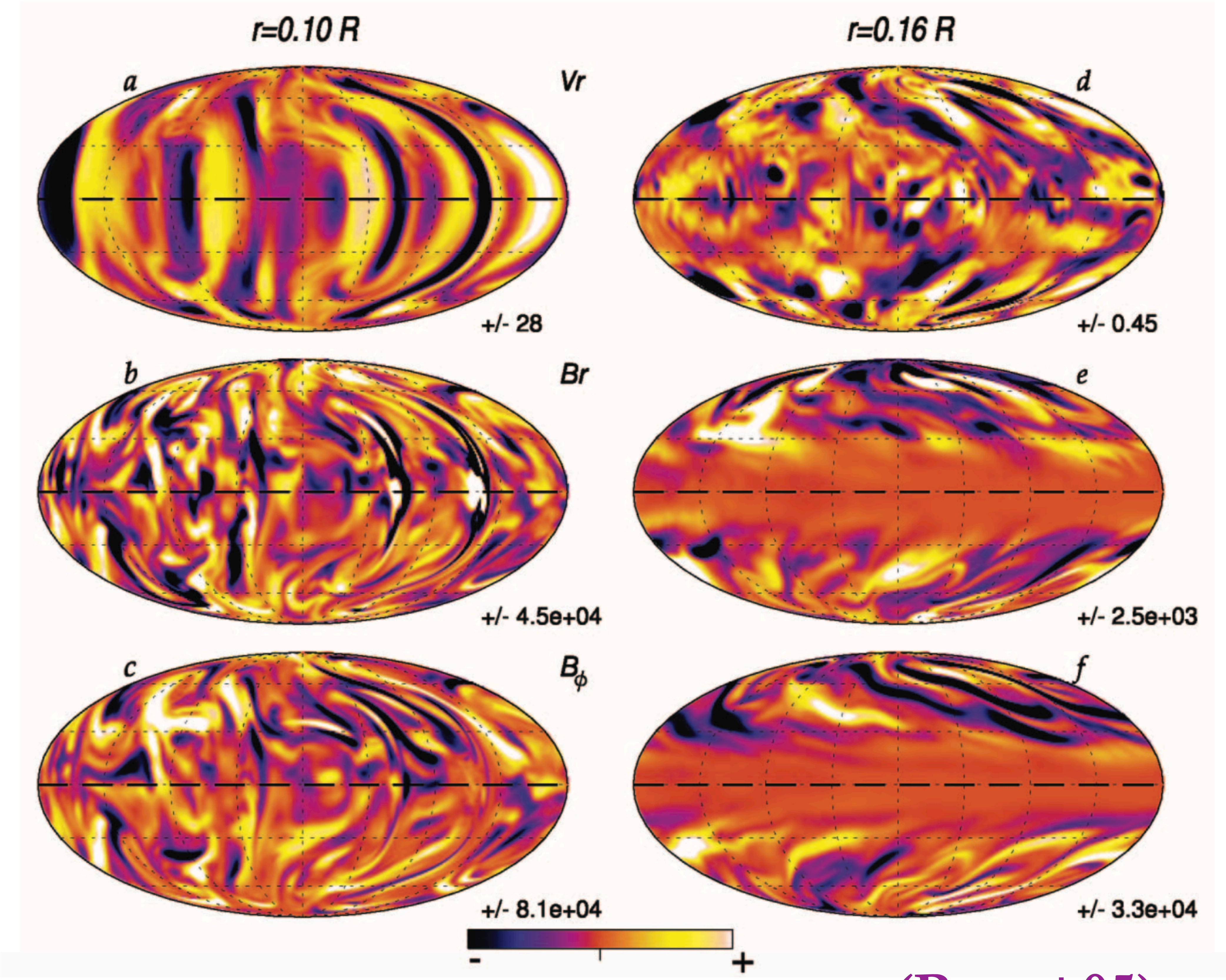
- Magnetic fields in stars with **convective envelopes**
  - Fields produced by **dynamo** in the convective envelope
  - Dynamo-generated fields also expected in **convective cores** (e.g., Brun+05)

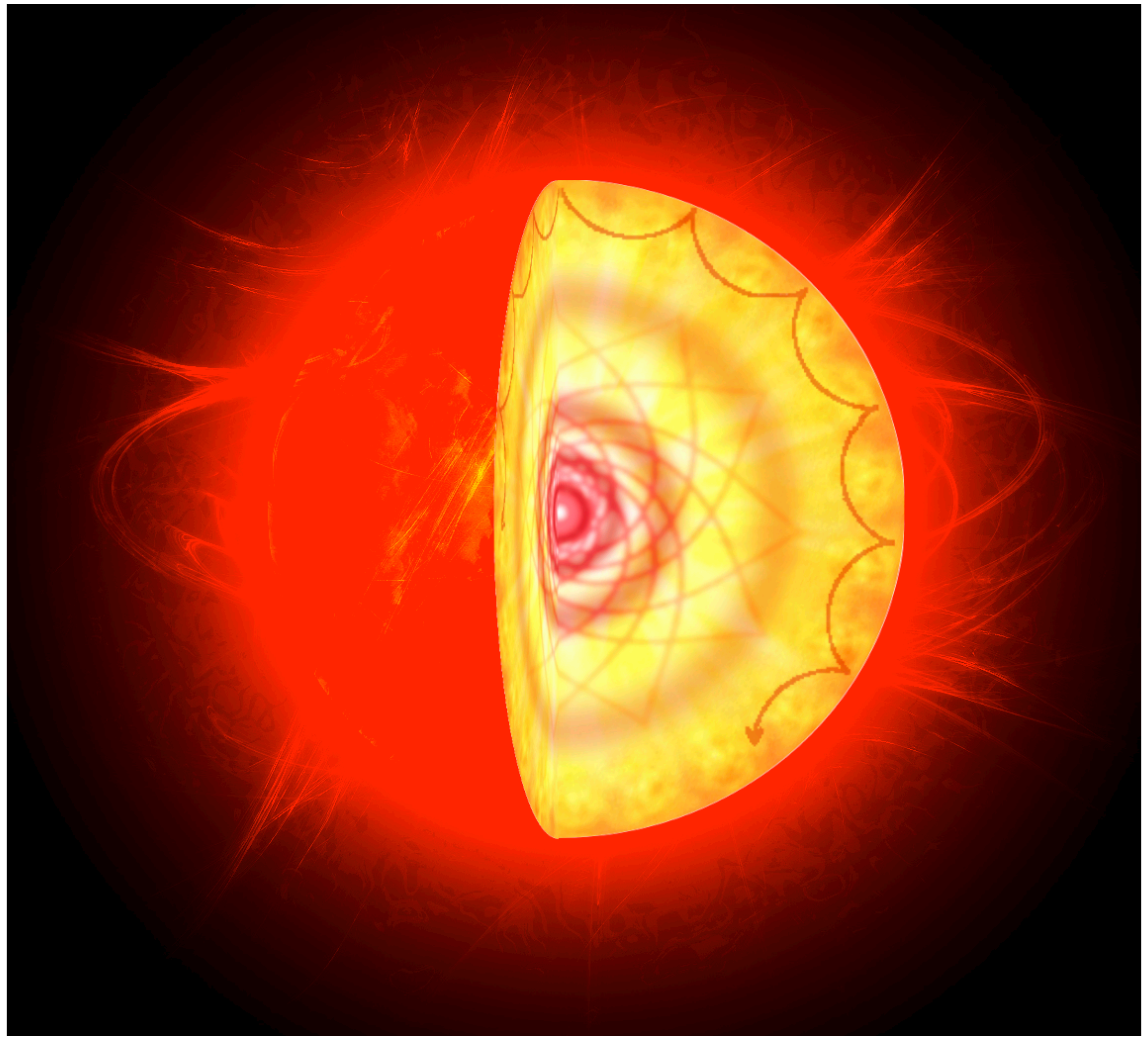


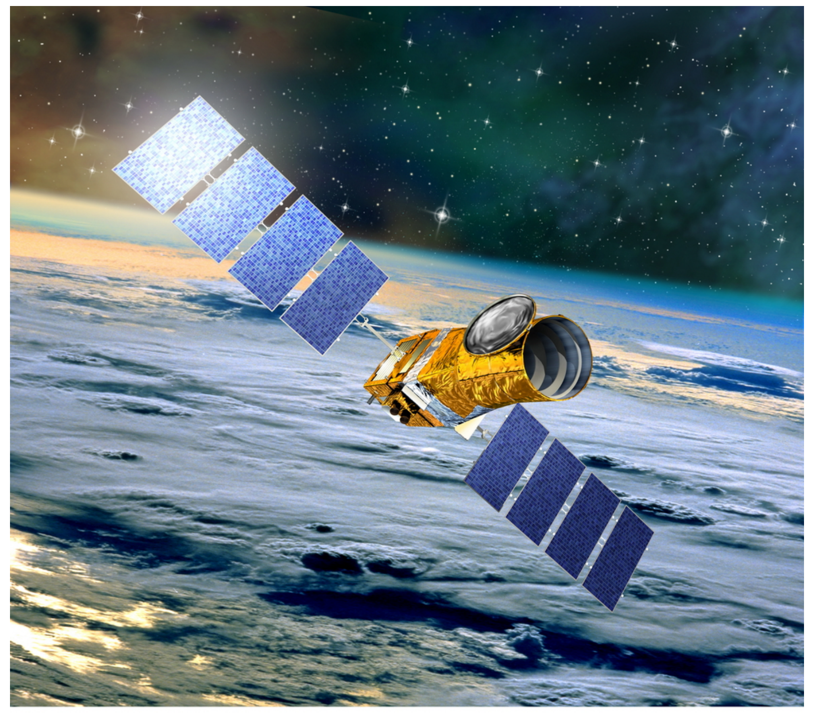
(Brun+05)

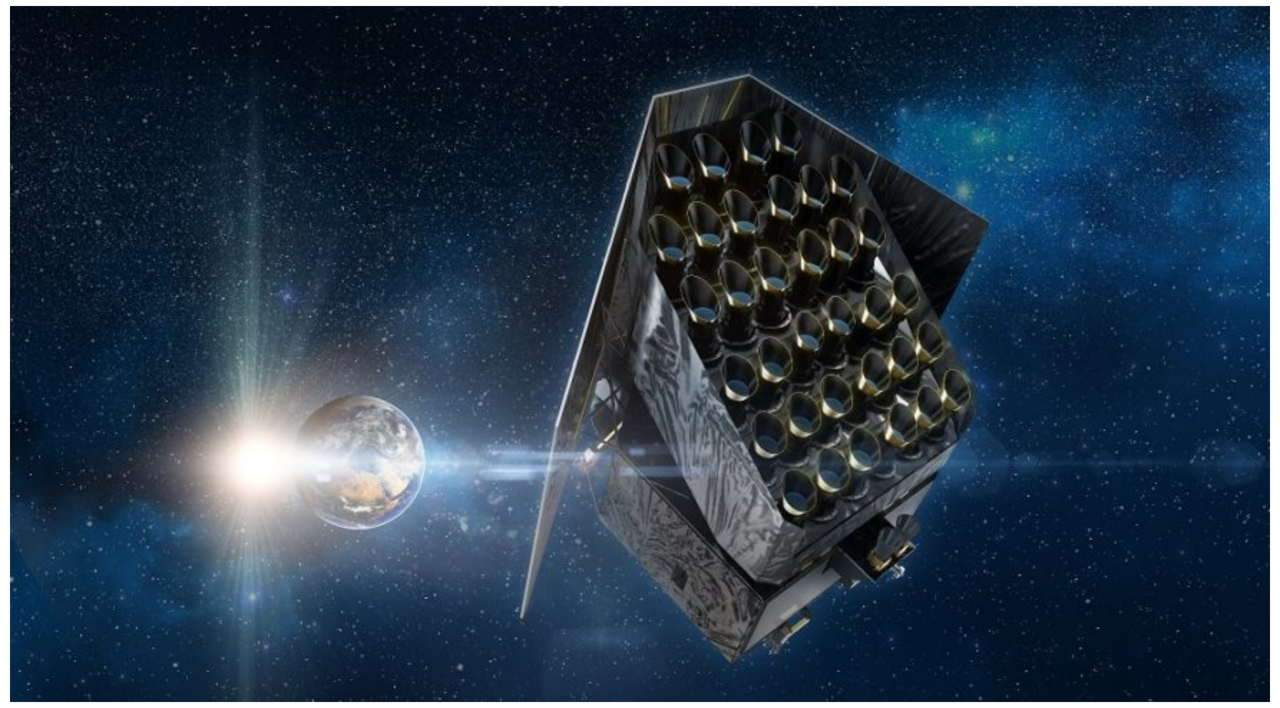
Asteroseismology from space

- **Asteroseismology** is a unique tool to **probe the interior of stars** and **test stellar structure and evolution models**

- Space missions (partly) dedicated to asteroseismology have revolutionized the discipline (CoRoT, Kepler, TESS + PLATO)







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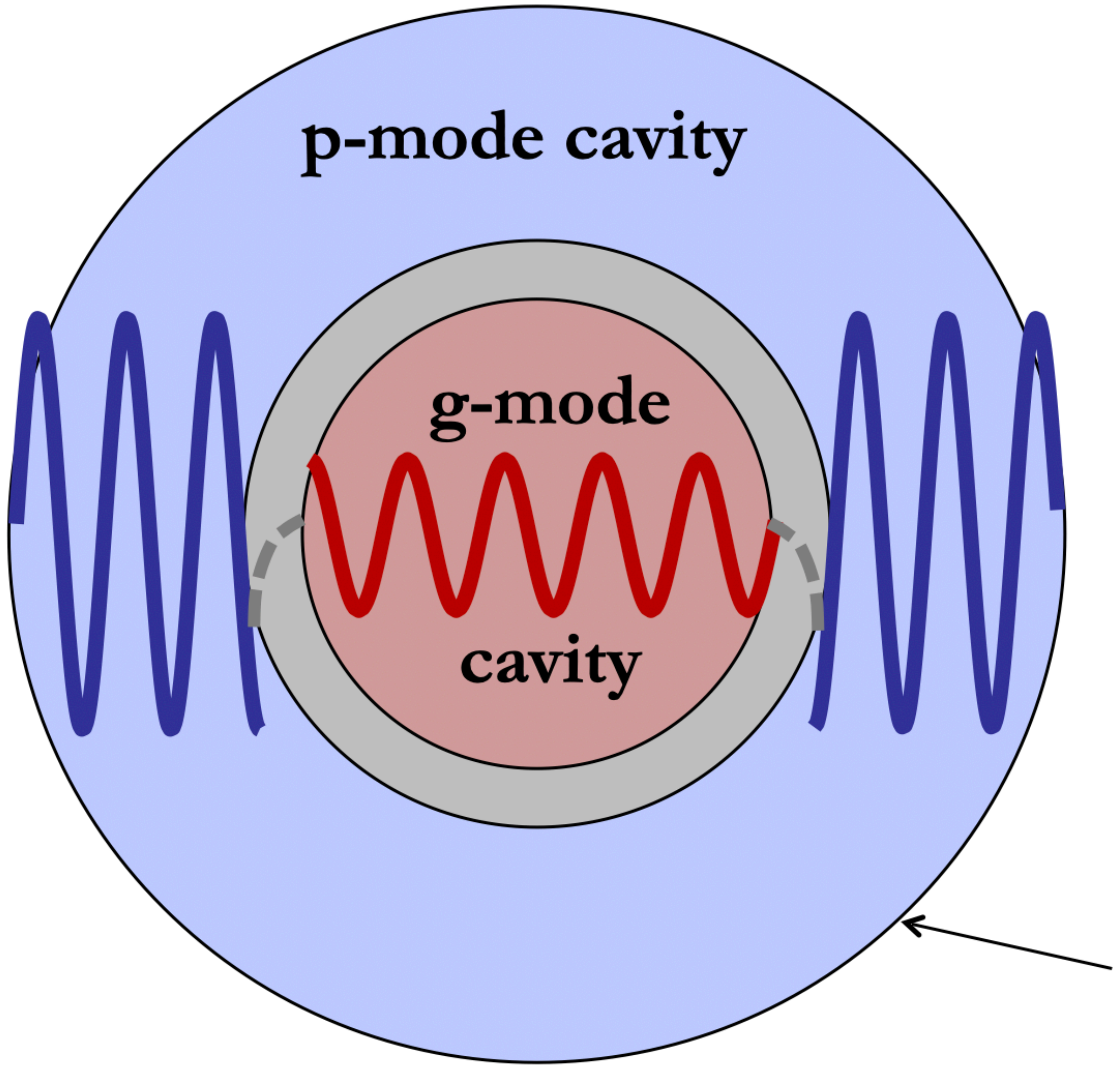
Stellar oscillations in red giants

- Different types of oscillation modes
  - **Pressure modes**, or p-modes (give information on the mean stellar density, the local sound speed velocity, envelope rotation, …)
  - **Gravity modes**, or g-modes (give information on the core properties, e.g. chemical composition, core rotation, …)



Modes are excited in the outer convective envelope

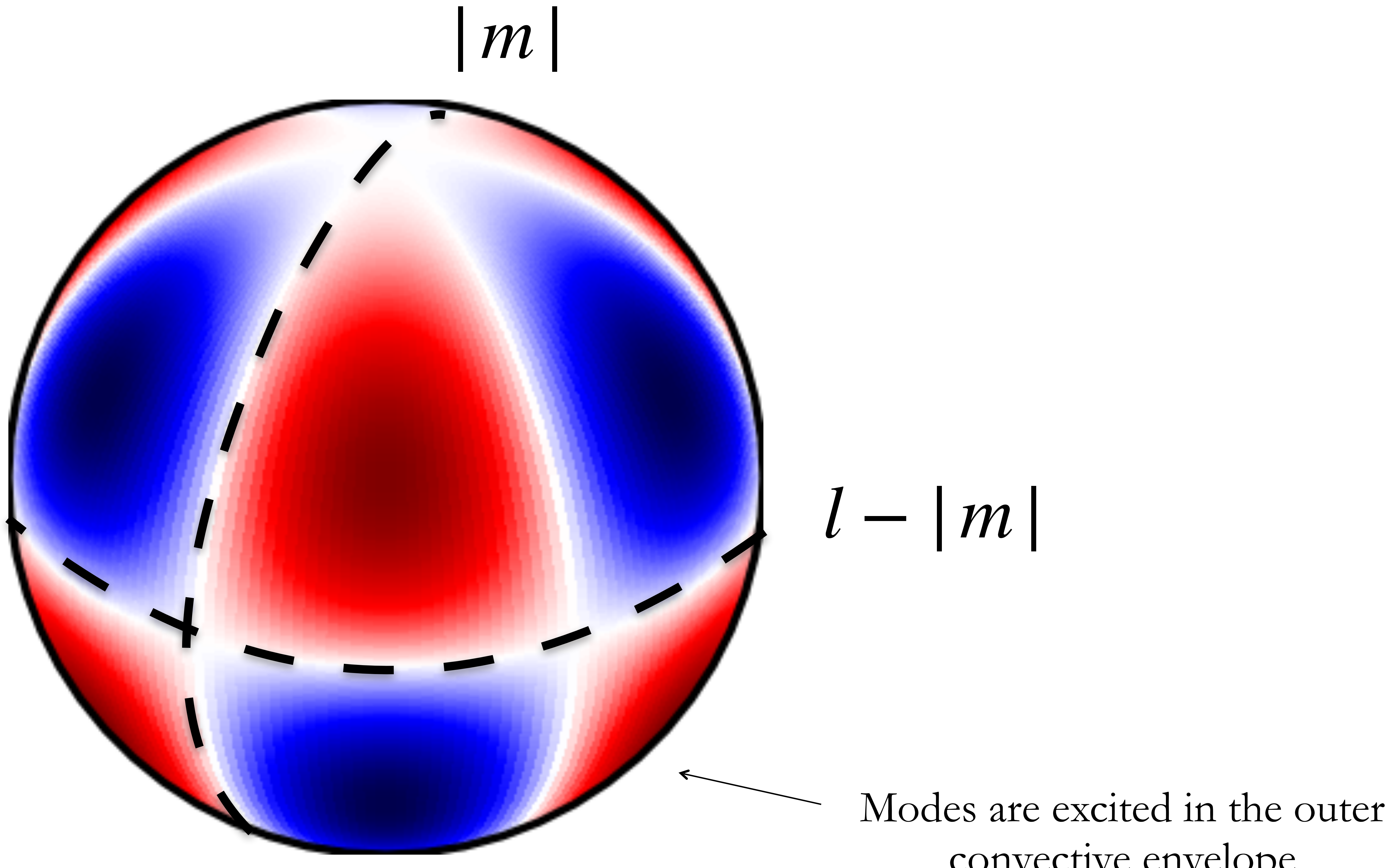
- Oscillation modes in a **subgiants** and **red giants**

$$\omega_p \sim \omega_g$$

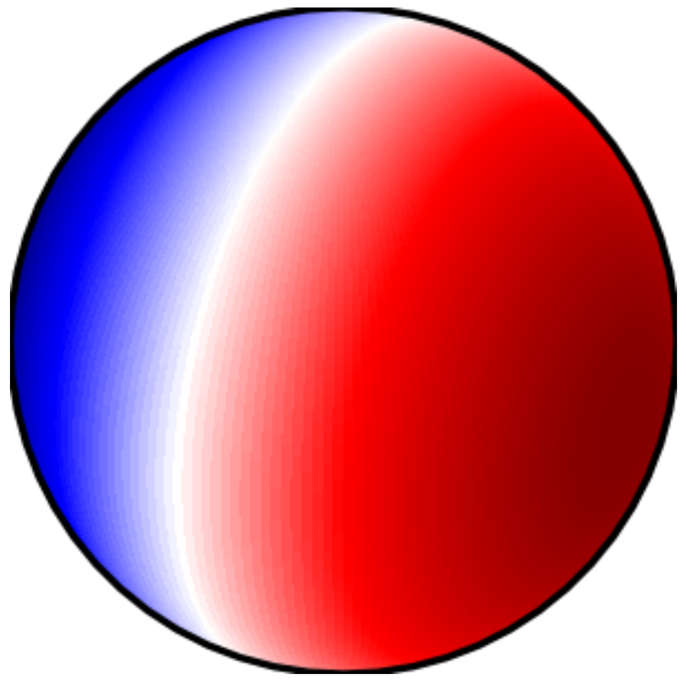
  - **Non-radial modes become mixed!**

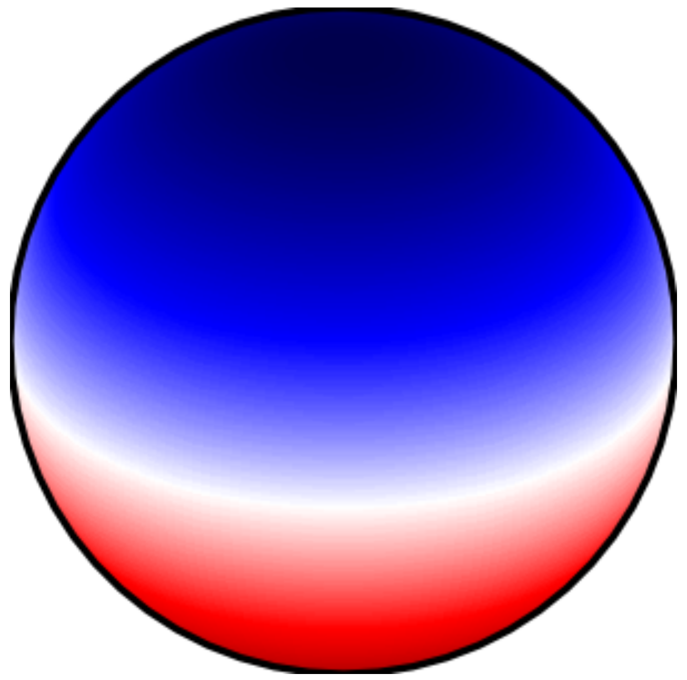
Stellar oscillations in red giants

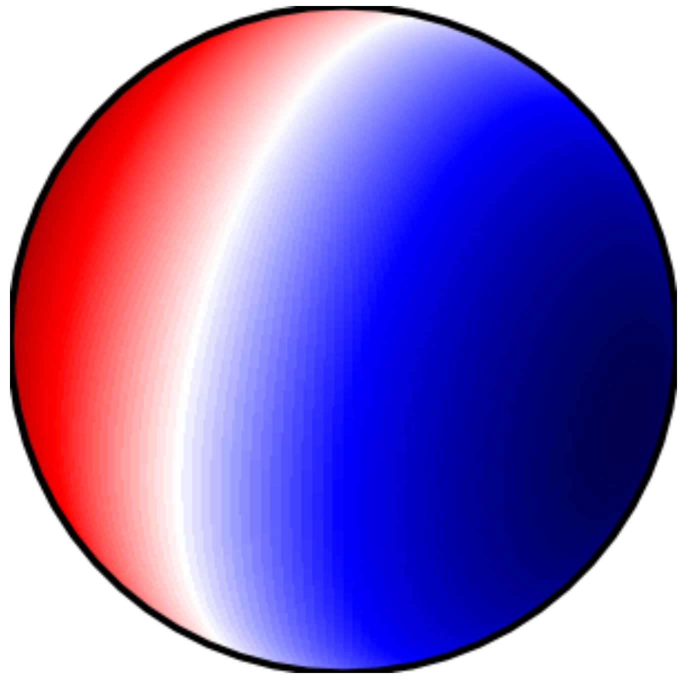
- For slow rotators, horizontal part of oscillations modes corresponds to spherical harmonics Y_l^m
  - Degree l = number of nodal lines
  - Azimuthal order m ($|m| \leqslant l$)



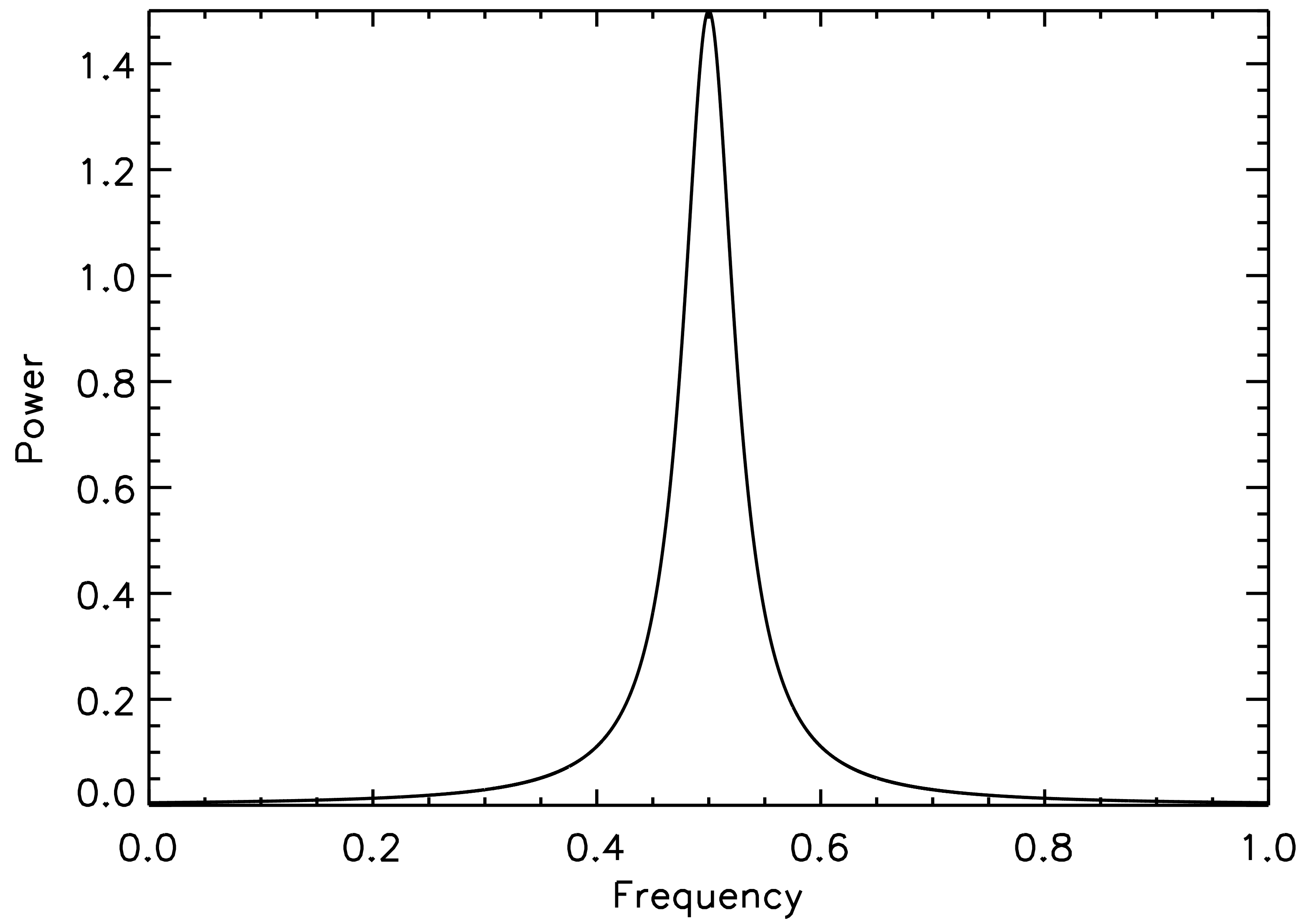
Effects of rotation on oscillation modes







Without rotation, all modes with same degree (number of nodal lines) have the same frequency



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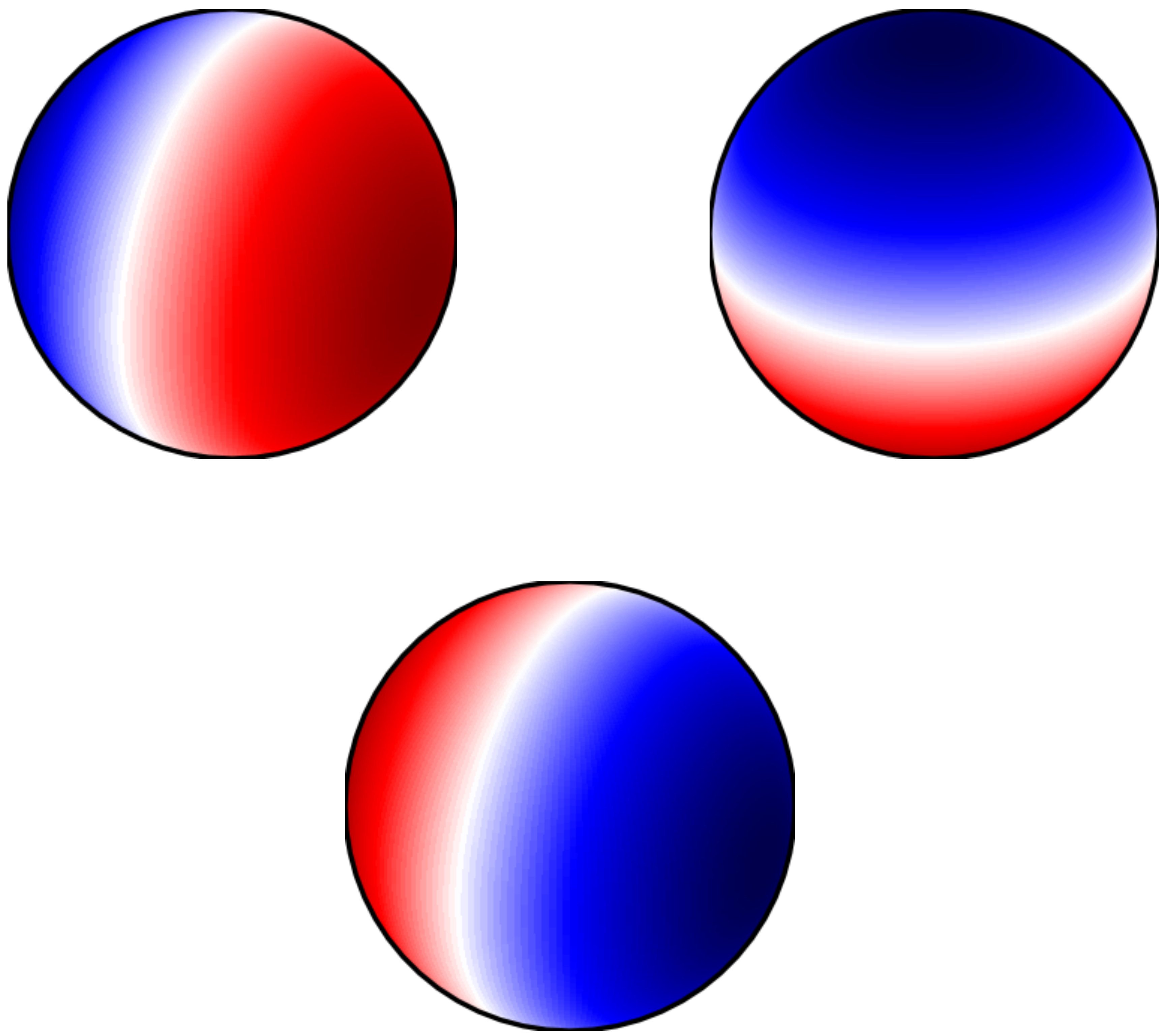
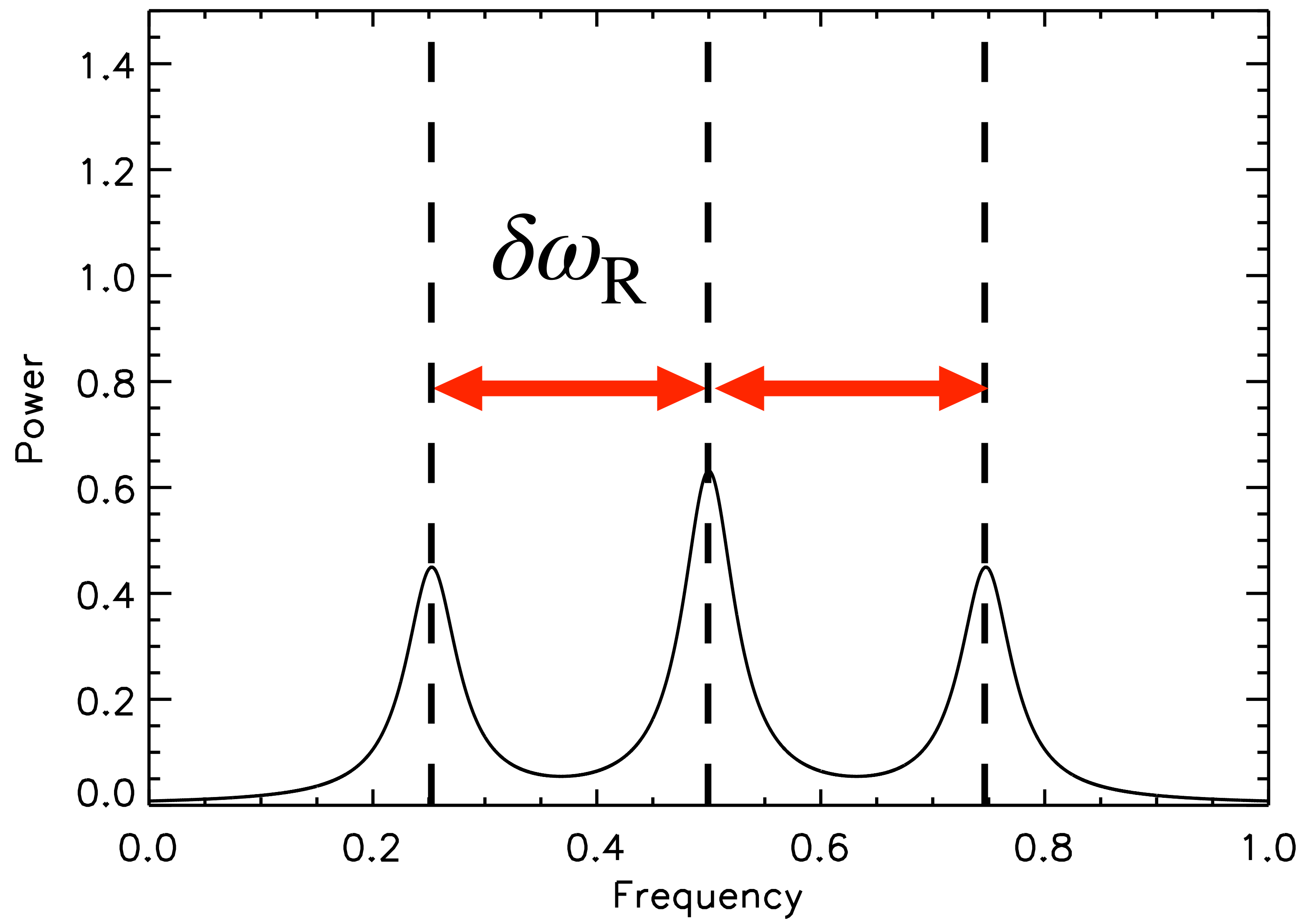


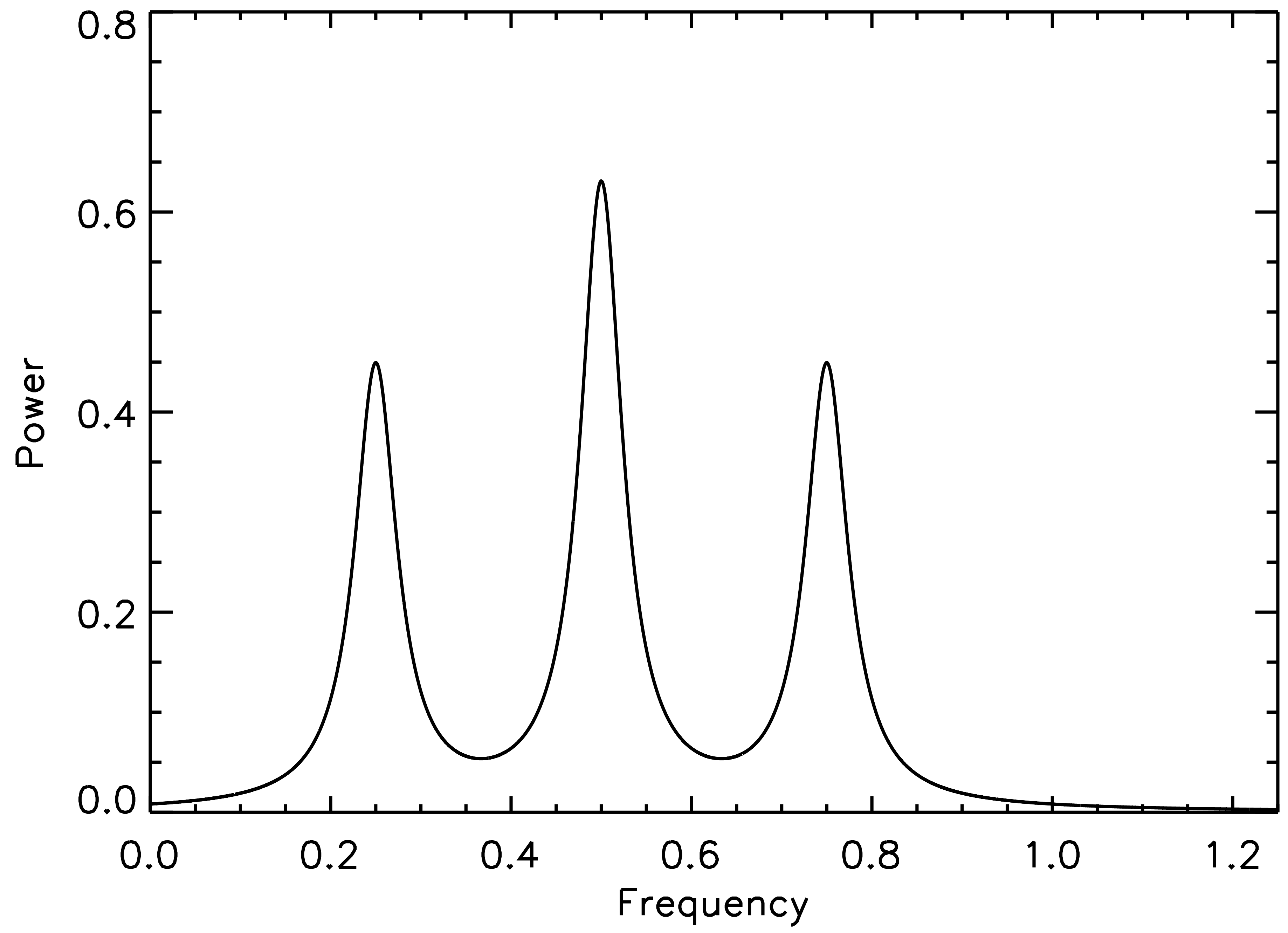
With rotation, dipole modes
are split into triplets



Symmetric multiplets

Effects of magnetic field on oscillations

- Studied for the Sun (**Unno+89, Gough & Thompson 90**) and g-mode pulsators (**Hasan+05**)
- If effects of non-axisymmetry of the field are negligible, multiplets mainly undergo:



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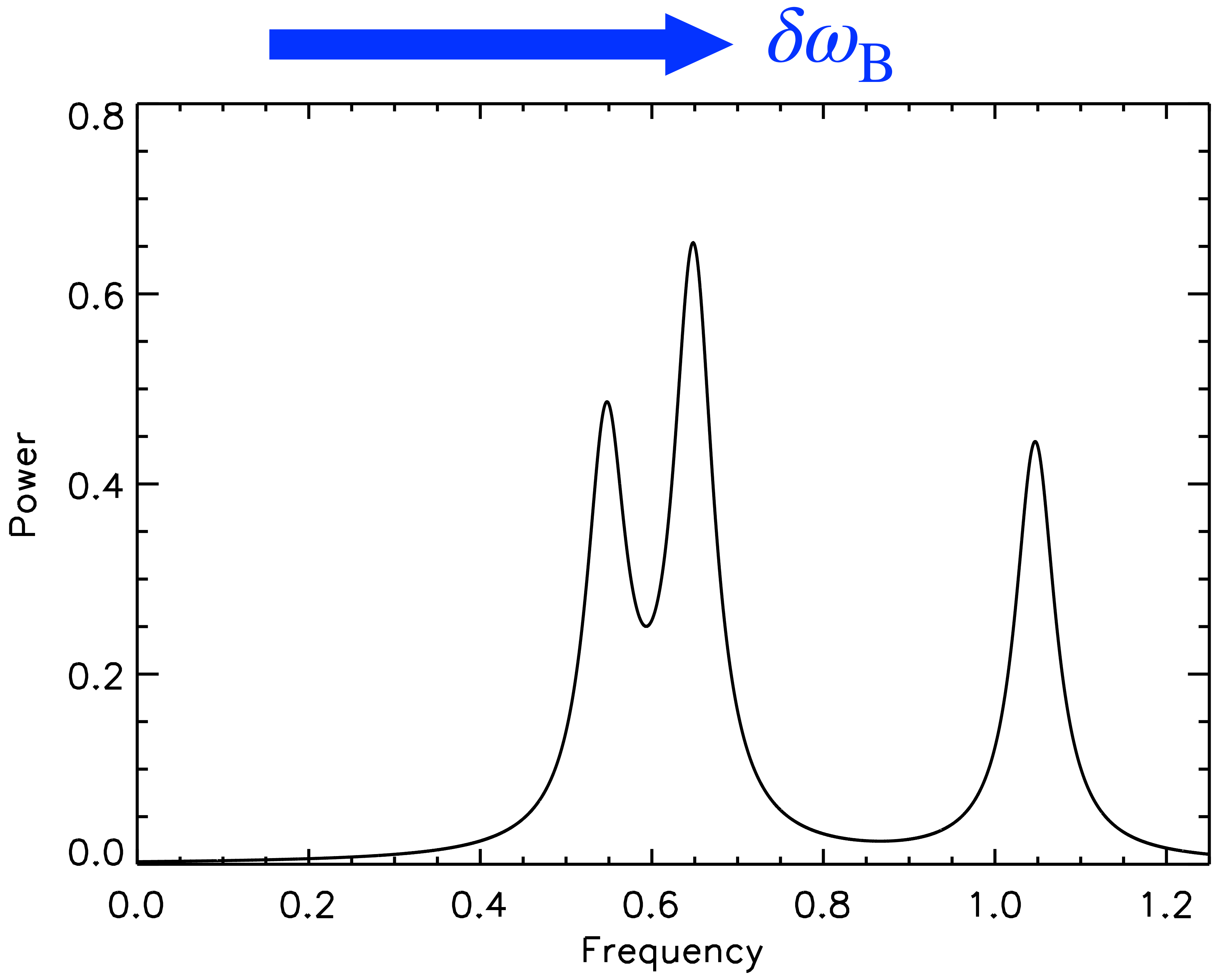

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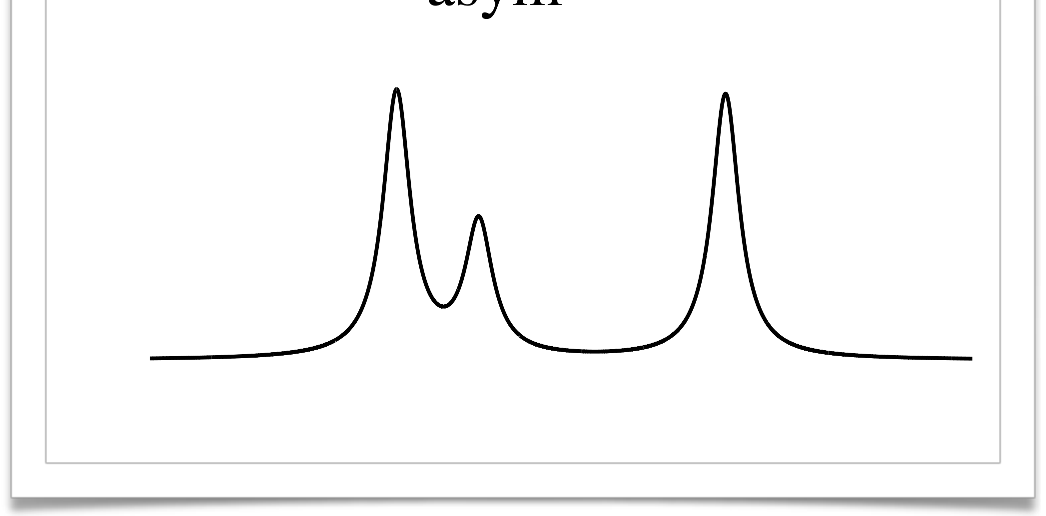
  - A **global frequency shift** $\delta\omega_B \sim \omega^{-3}$
  - **Multiplet asymmetry** δ_{asym}

$$\delta_{asym} = \omega_{m=-1} + \omega_{m=-1} - 2\omega_{m=0}$$

$\delta_{asym} > 0$



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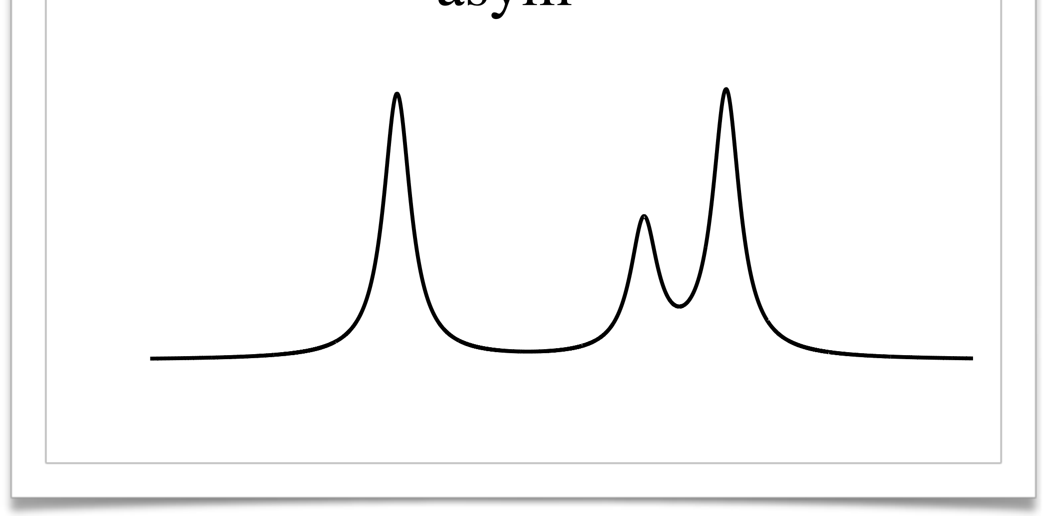
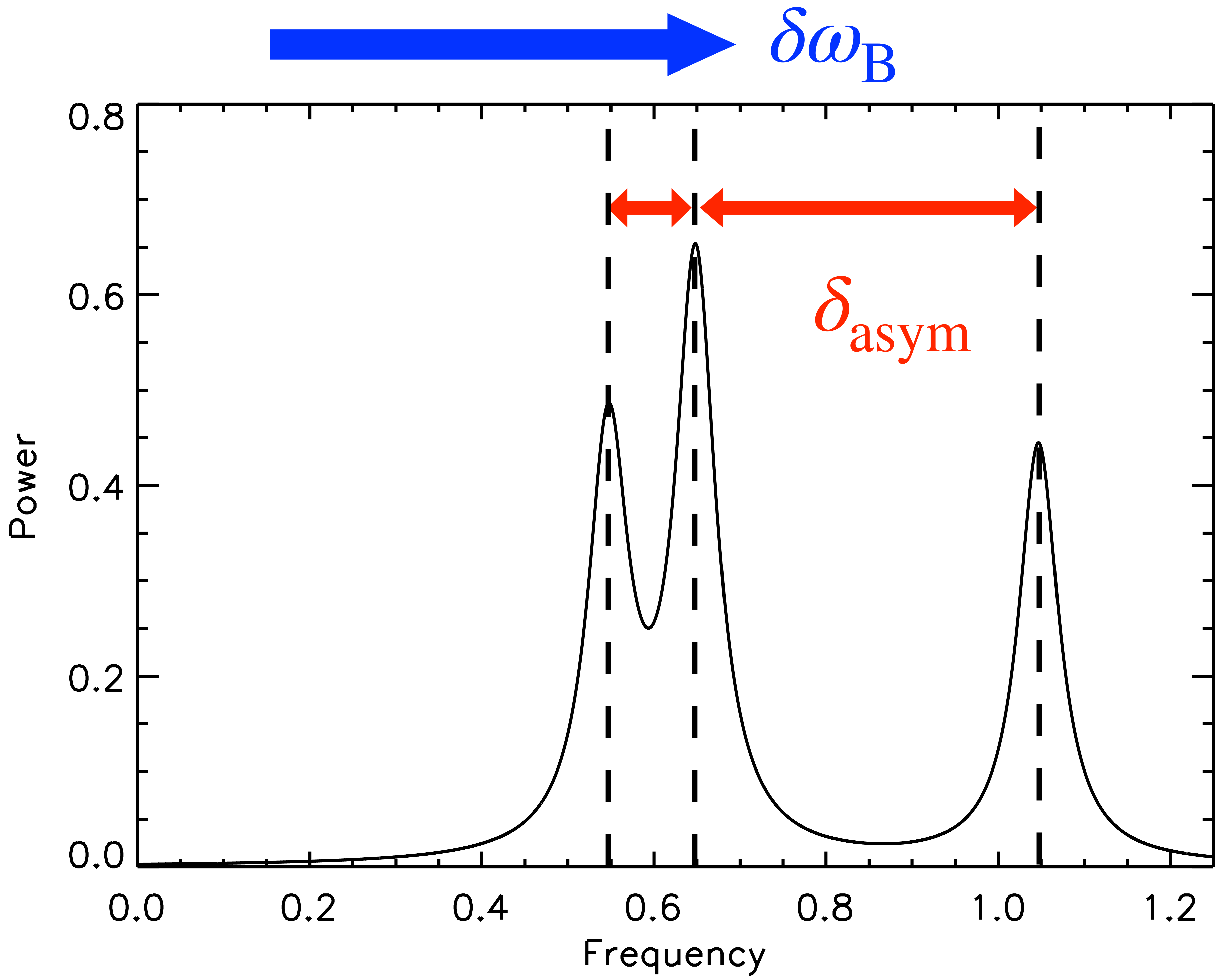


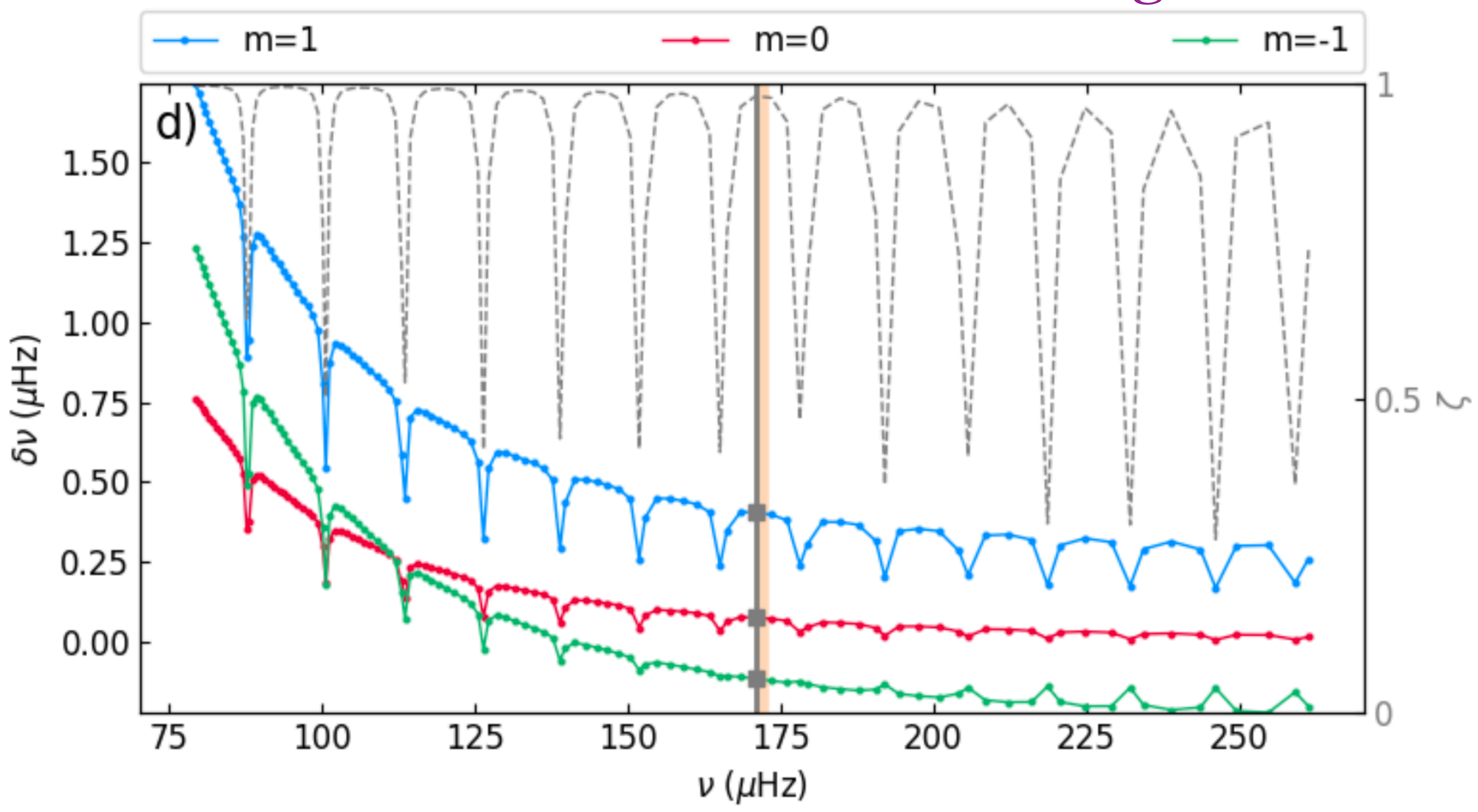


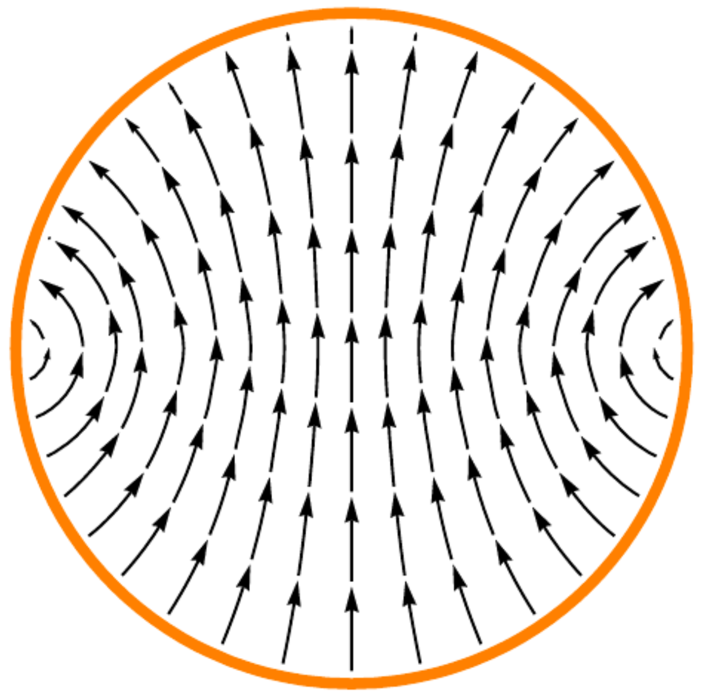
Asymmetric multiplets

Effects of magnetic fields on mixed modes

- Prior to their detection, the effects of **magnetic fields on mixed modes** in red giants had been addressed in several studies:
  - Axisymmetric dipolar field configurations (**Gomes+20, Mathis+21, Bugnet+21**)
  - Inclined dipoles **(Loi+21)**

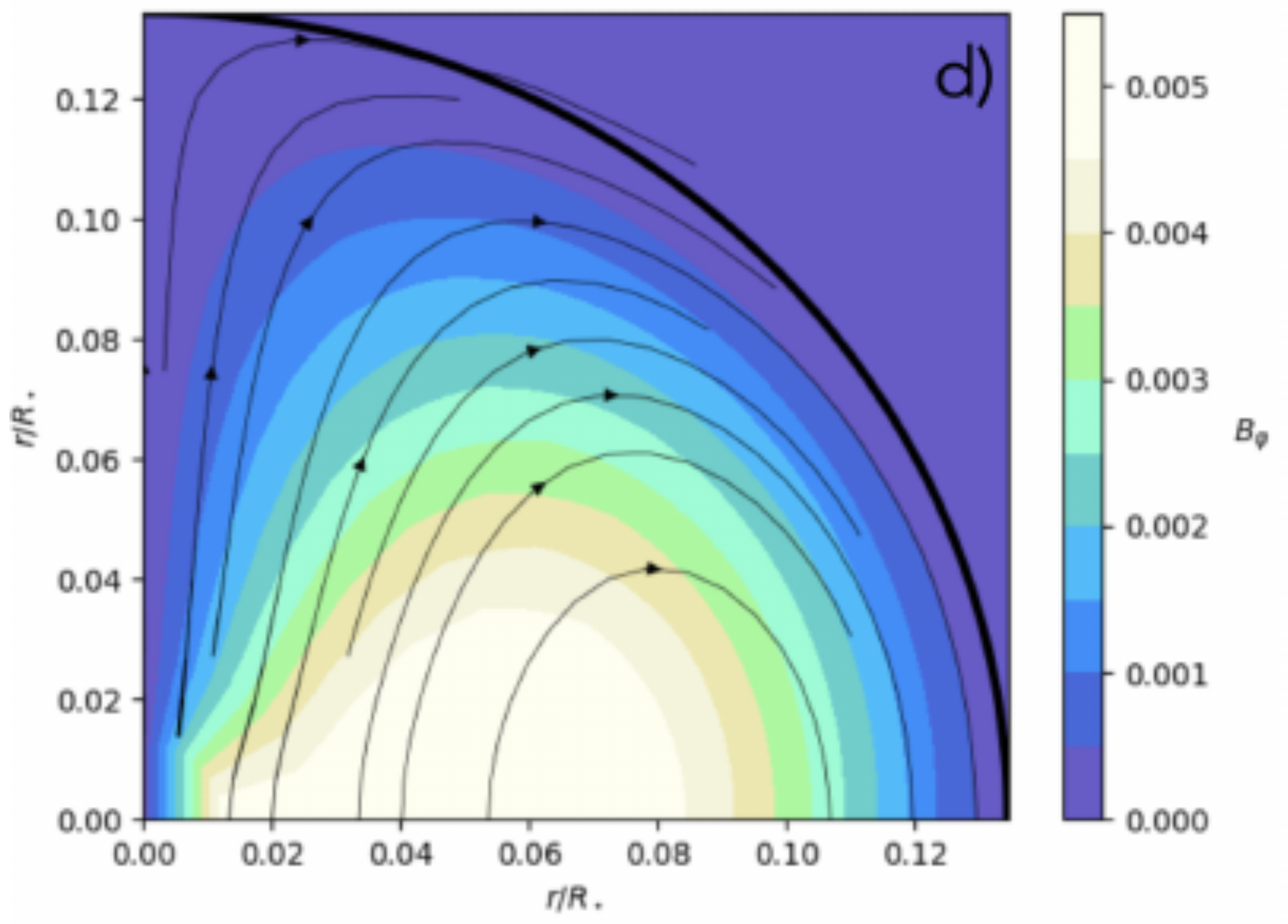
Bugnet+21





(Gomes+20)

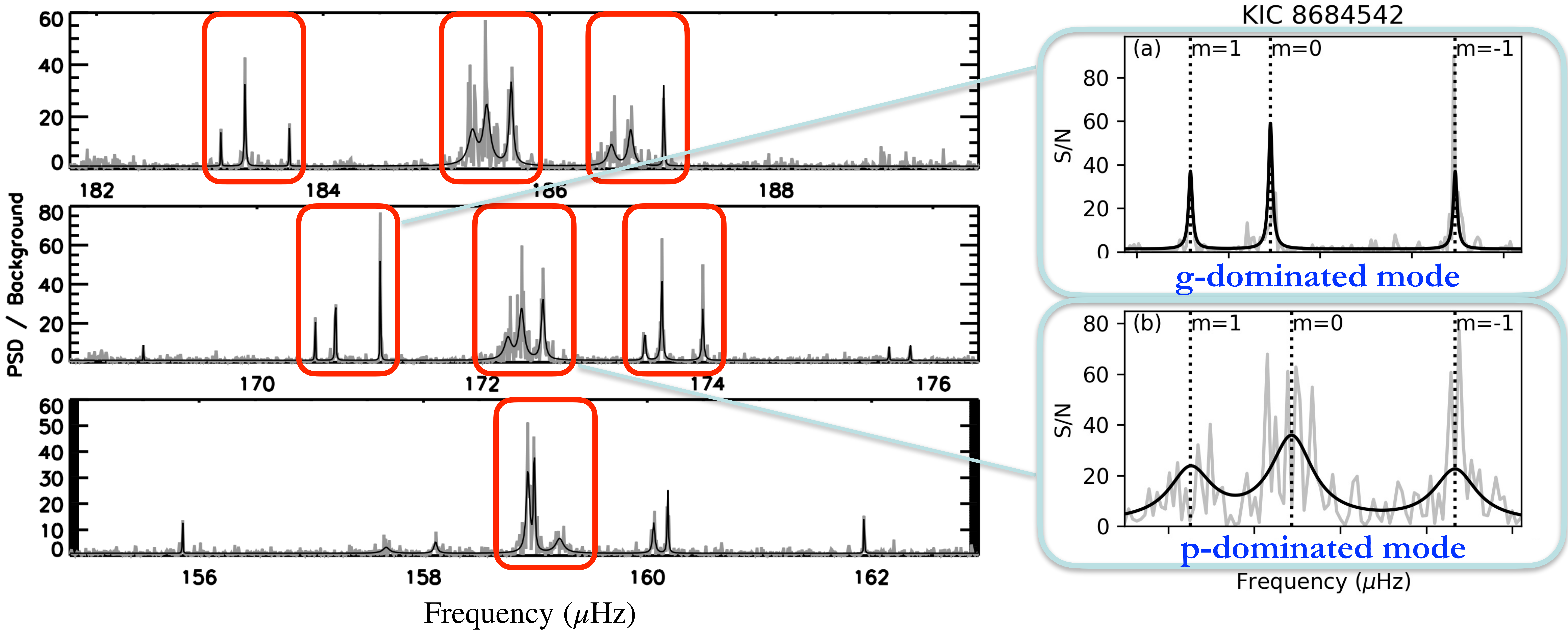
Prendergast solution **(Bugnet+21)**



- Axisymmetric dipolar fields, correspond to **positive asymmetries**

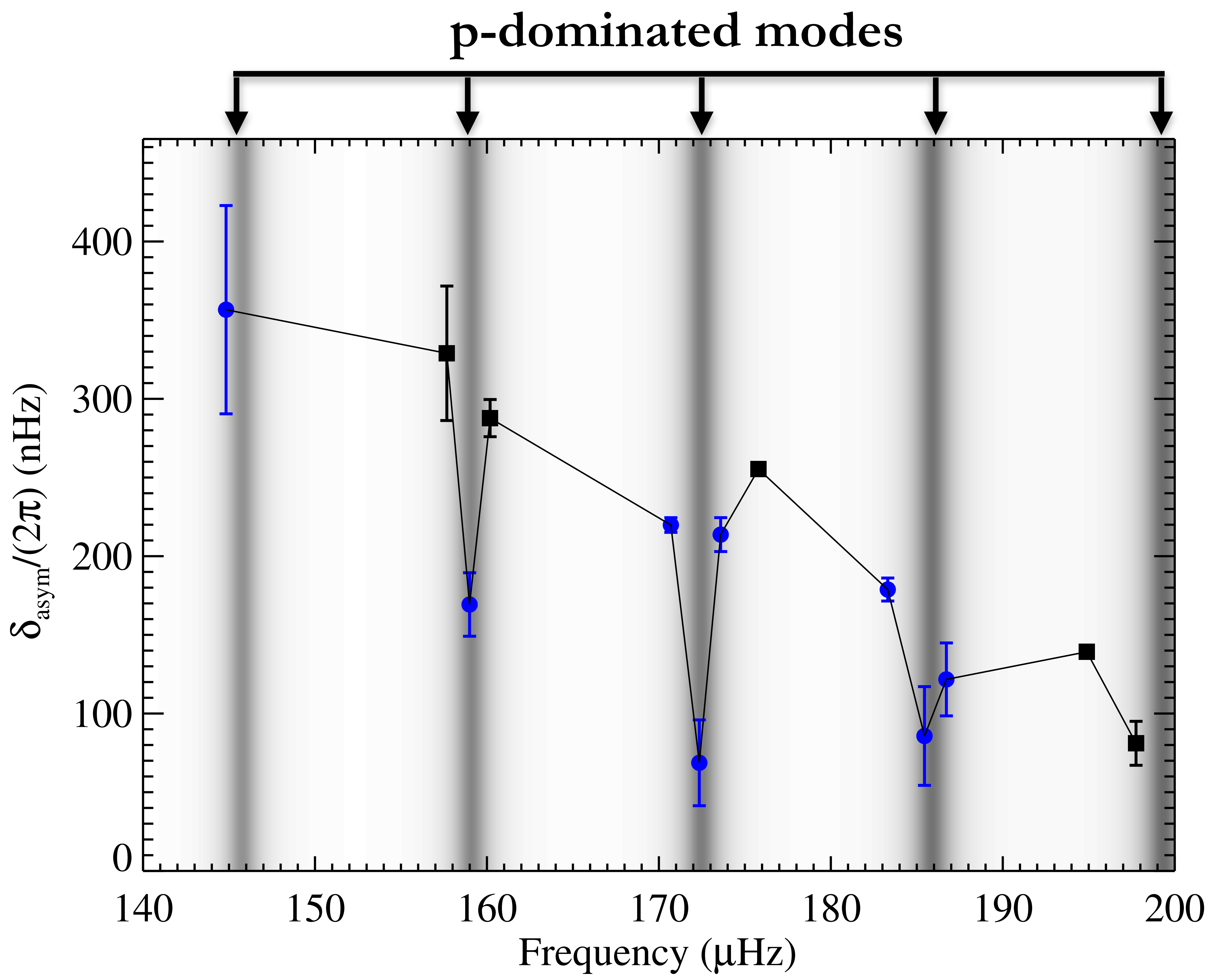
Detection of asymmetries in Kepler red giants

- **Clear asymmetries** in the rotational multiplets of dipolar modes for **13 *Kepler* red giants** (Li+22, Li+23)



Properties of the detected asymmetries

- **Positive** asymmetries (**12 targets**)



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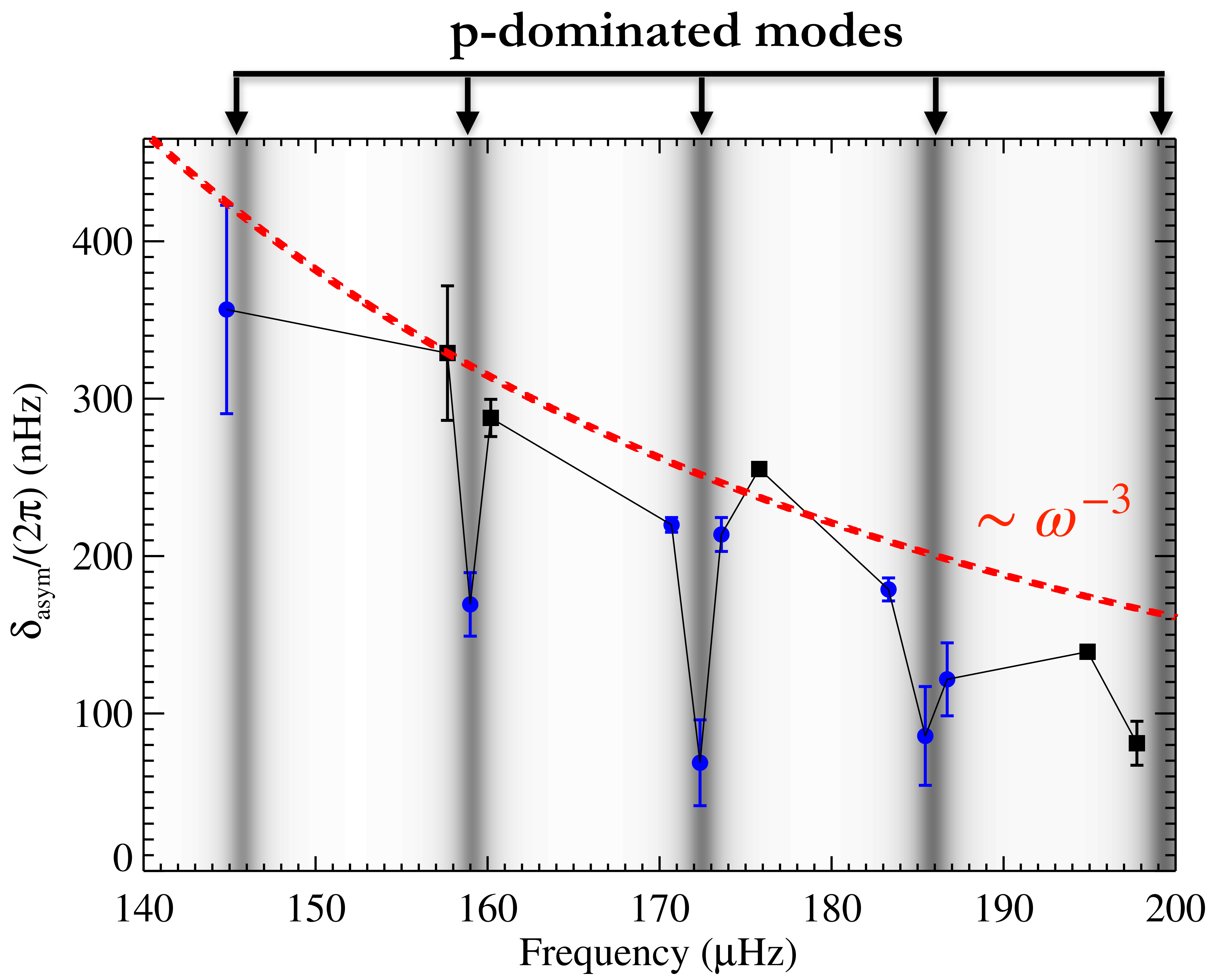

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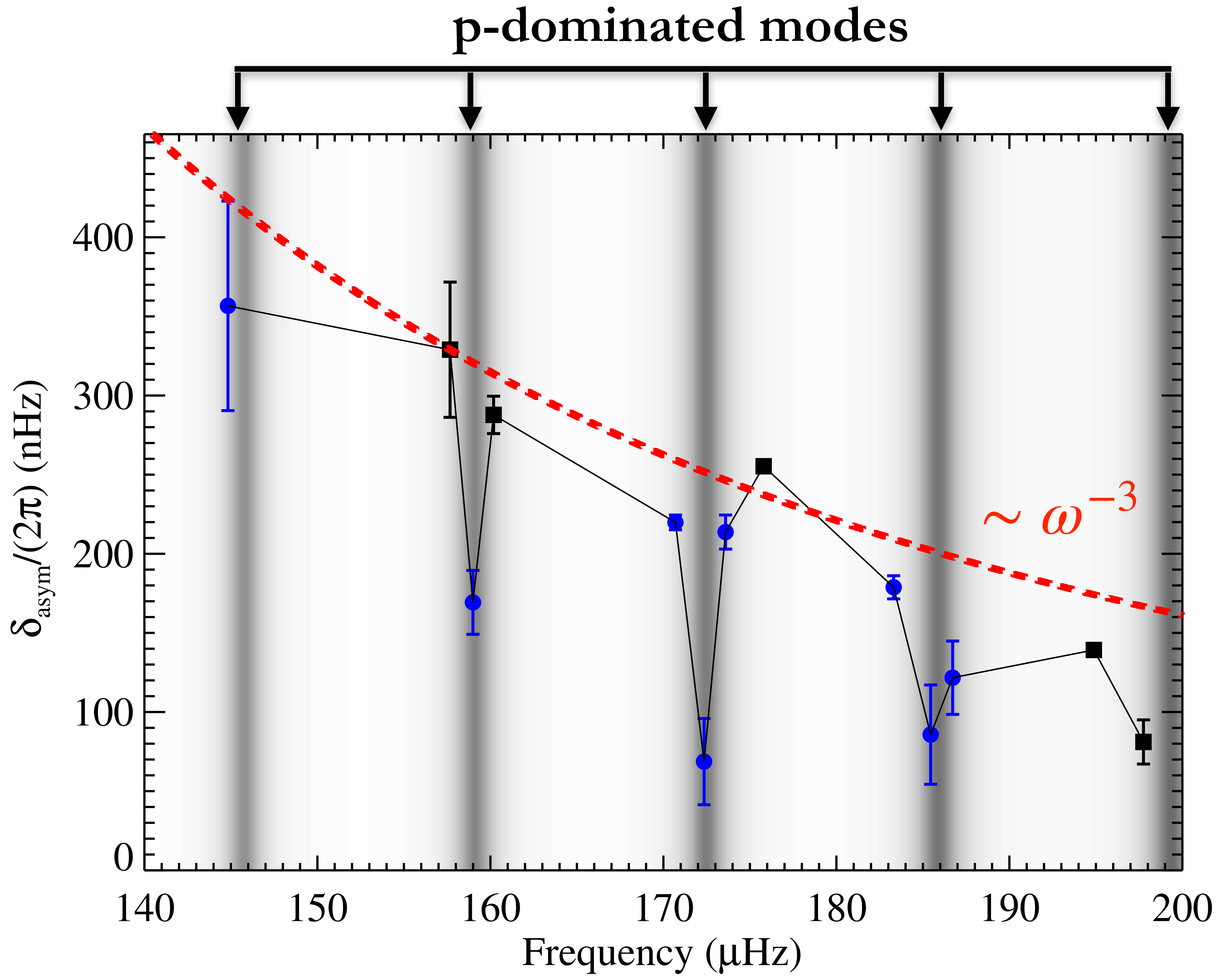
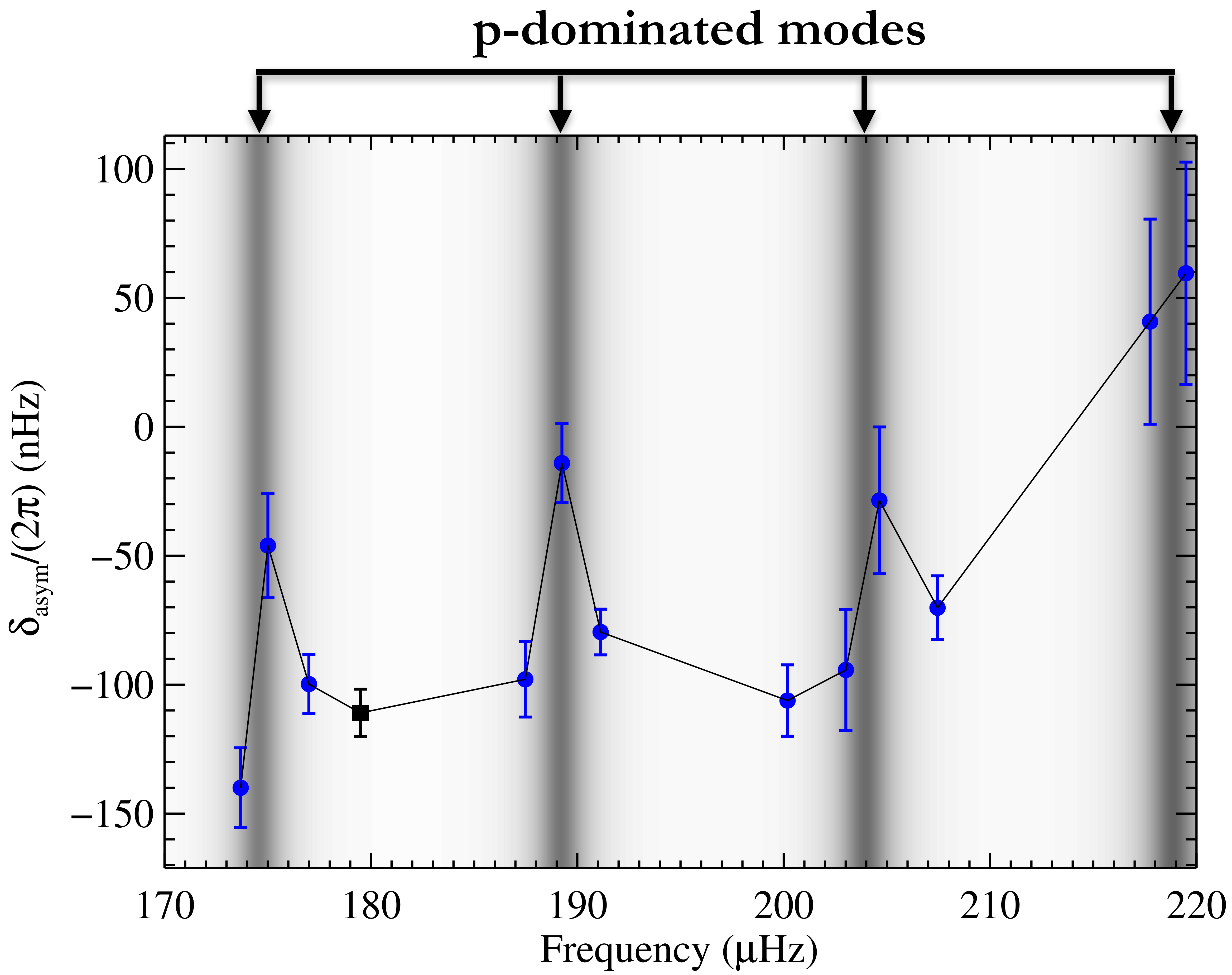


- **Negative** asymmetries (**1 target**)



Effects of magnetic fields on mixed modes

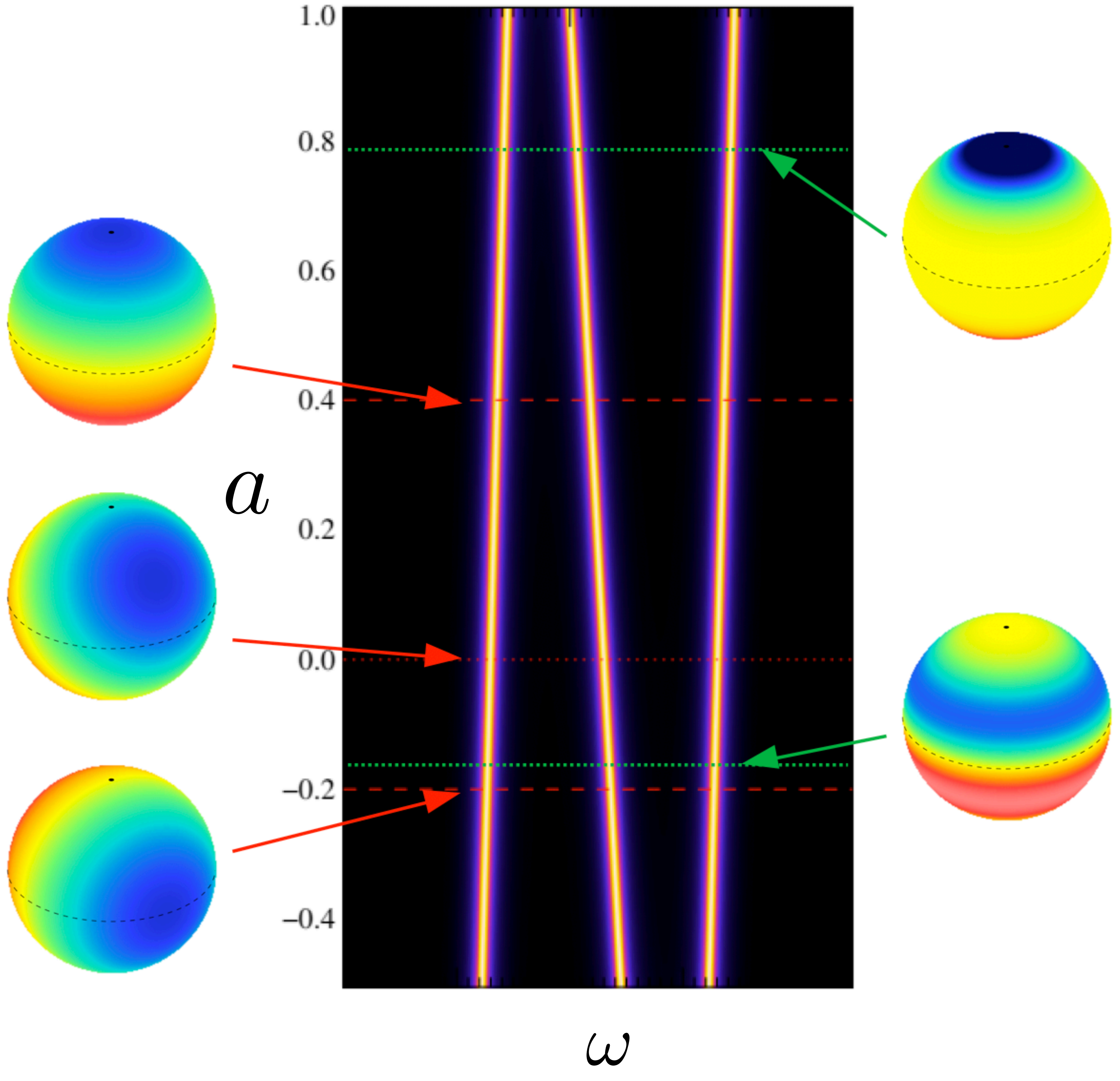
- Effects of **arbitrary** magnetic fields on mixed mode frequencies (**Li+22, Nature Supplement Material**)
  - **Global frequency shift ω_B: average radial field** in the core

$$\omega_B \propto \int_g K(r)\overline{B_r^2}\,dr$$

  - **Multiplet asymmetry $\delta_{asym} = 3a\omega_B$: horizontal average** of the magnetic field in the core

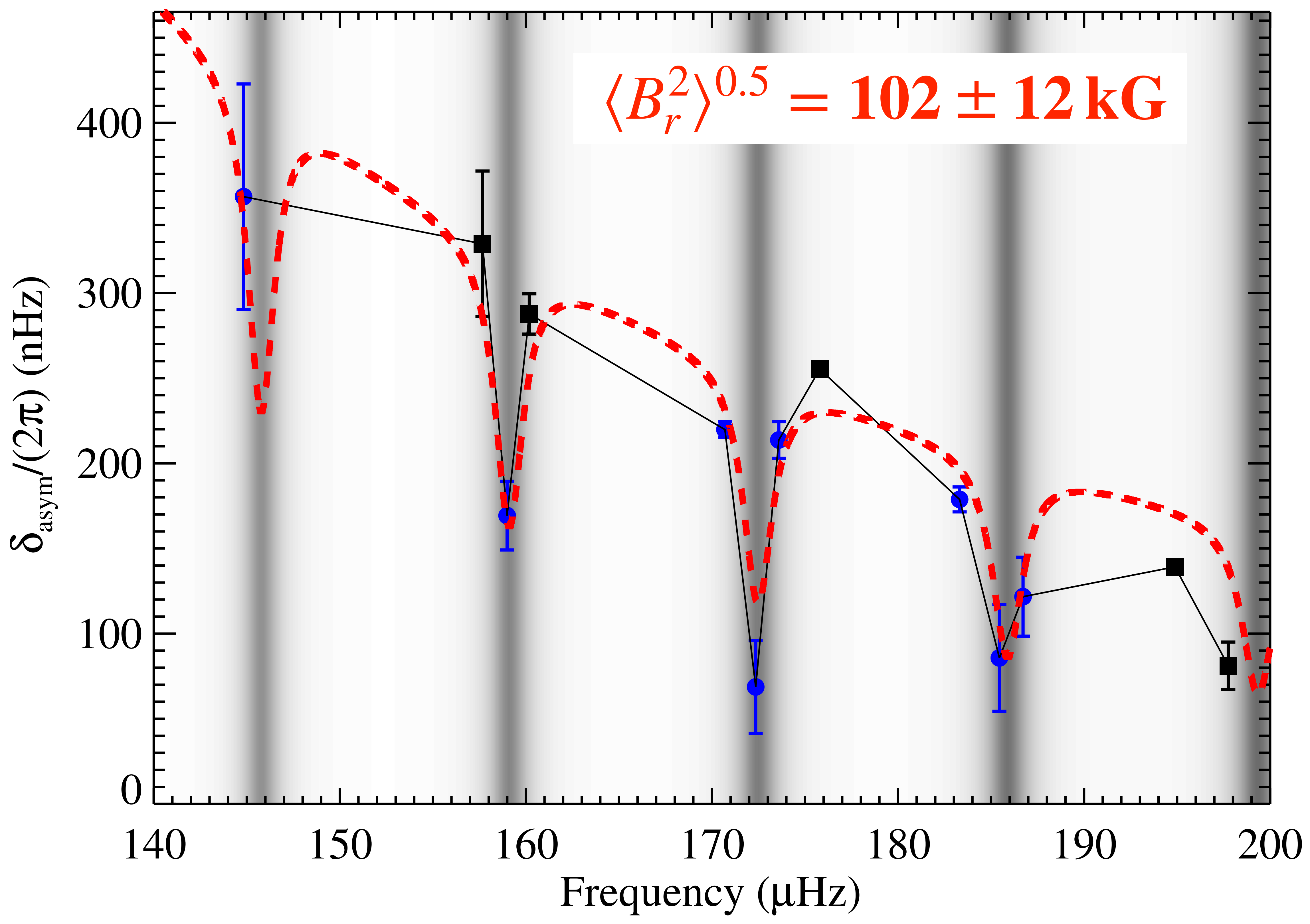
$$a \propto \iint B_r^2 P_2(\cos\theta)\sin\theta\,d\theta d\phi$$

    - a maximal (>0) for field concentrated on the **pole**
    - a minimal (<0) for field concentrated on the **equator**



Fit of the detected asymmetries

- **Positive** asymmetries (12 targets)



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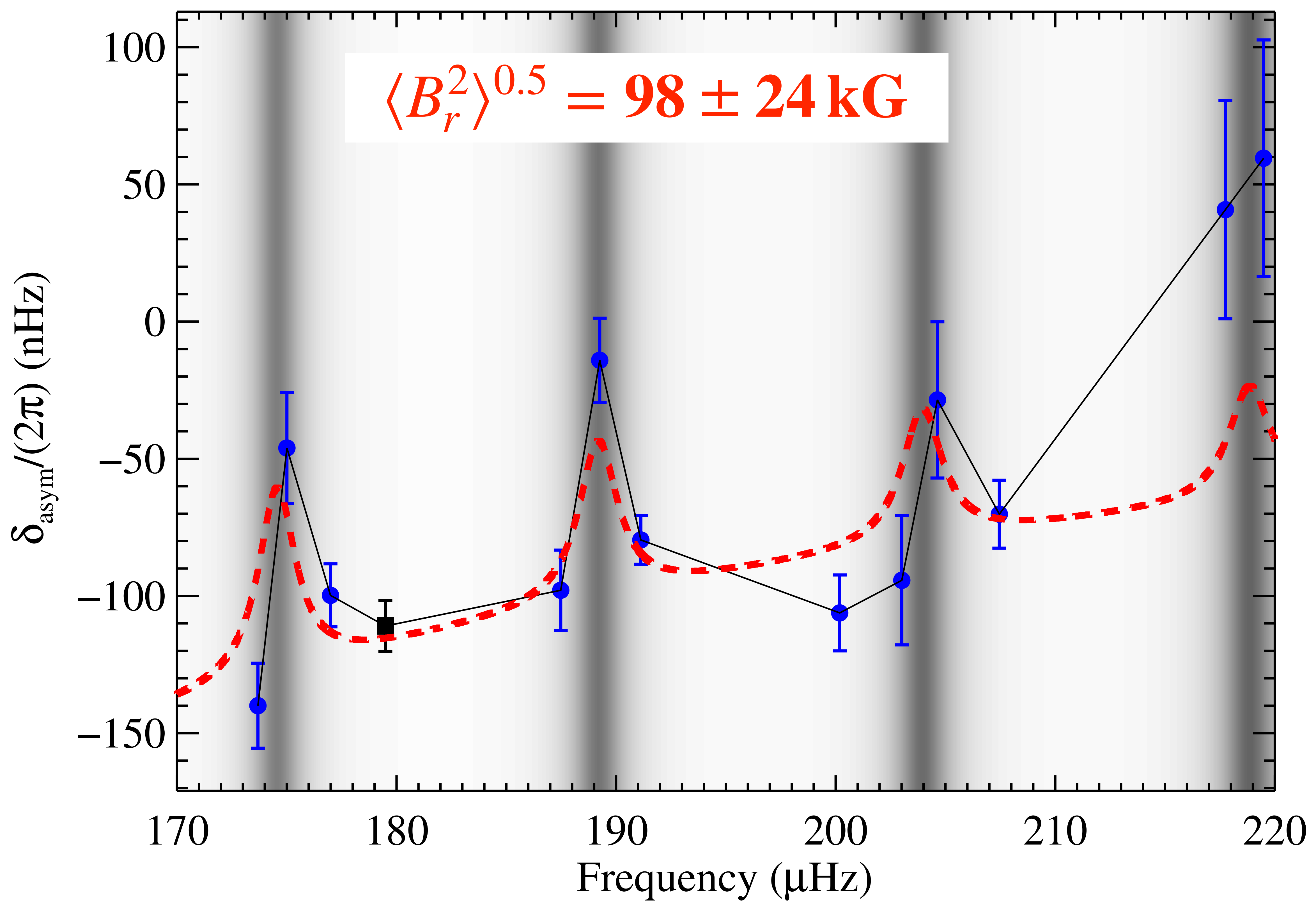
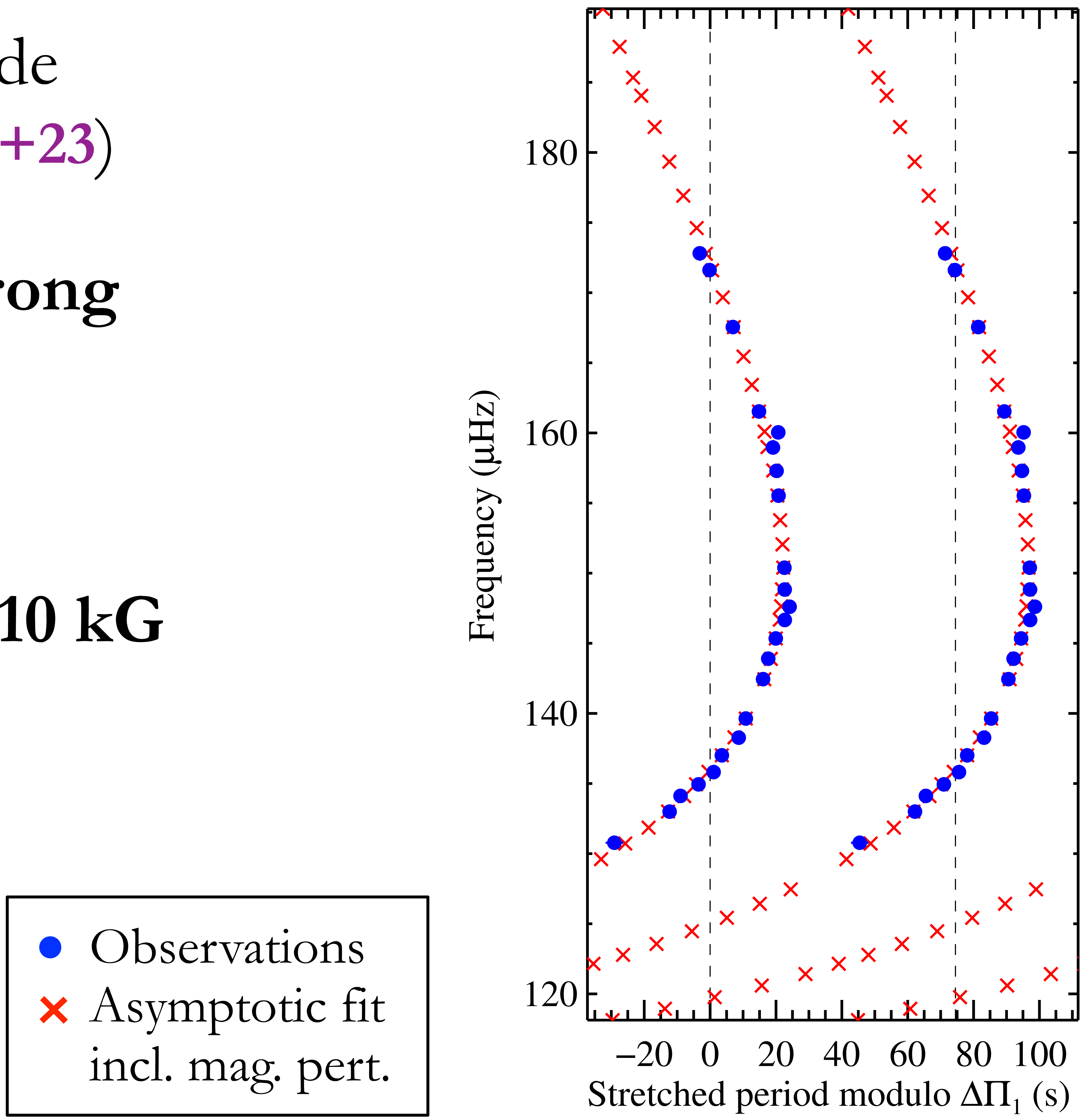


- By fitting all mode frequencies, we find **field strengths from 20 to 150 kG**

Strong magnetic fields in the cores of 11 *Kepler* giants

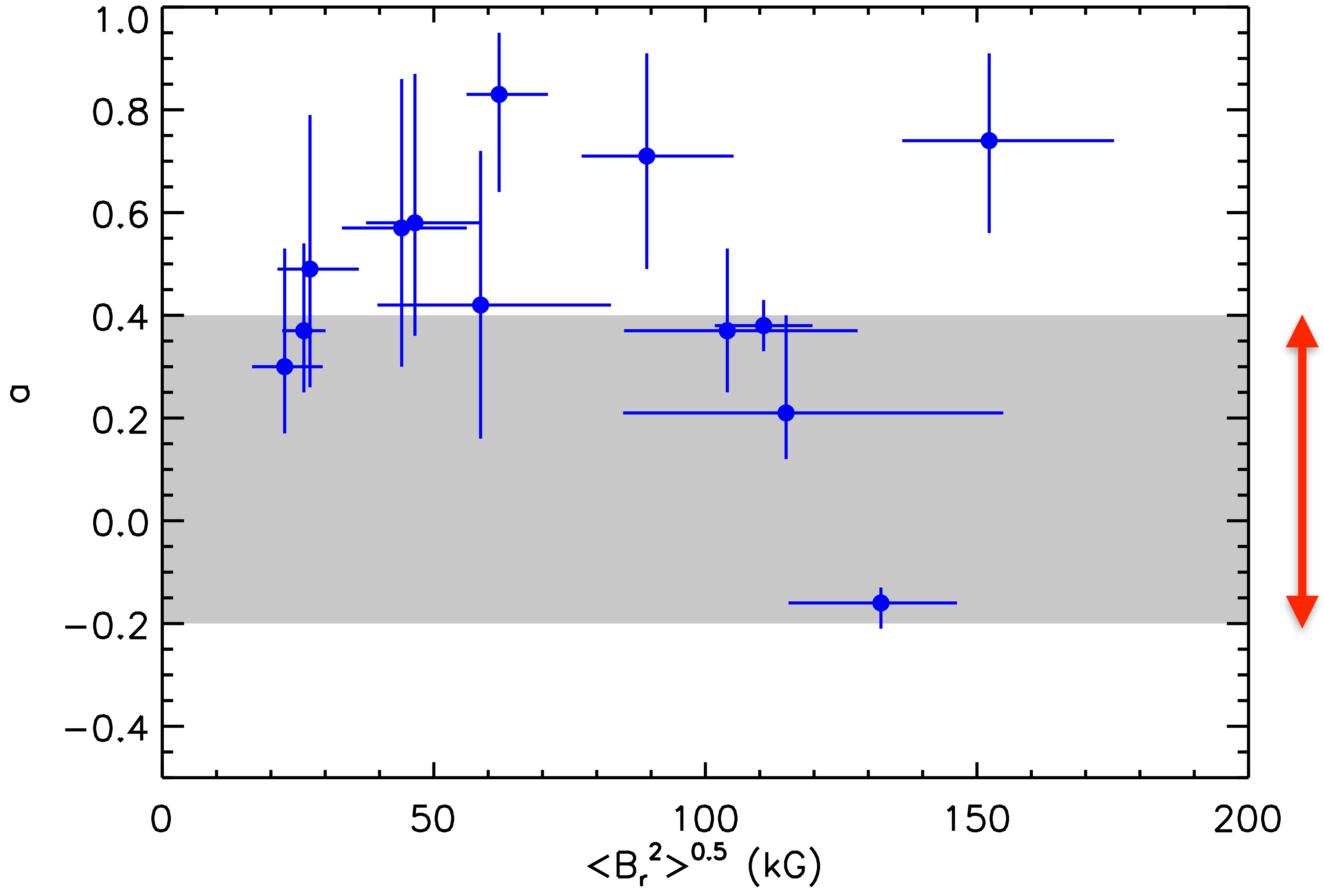
- Strong fields can alter the regularity of g-mode period spacings (**Li+22, Bugnet 22, Deheuvels+23**)
- **Detection of 11 Kepler red giants with strong deviations from regular period spacing** (**Deheuvels+23**)
- Minimal field strengths ranging from **40 to 610 kG**

Deheuvels+23



Magnetic field topology

- A **wide diversity of field topology** (**Li+22, Li+23**)



Range of possible values of *a* for **dipolar fields**

Magnetic field topology

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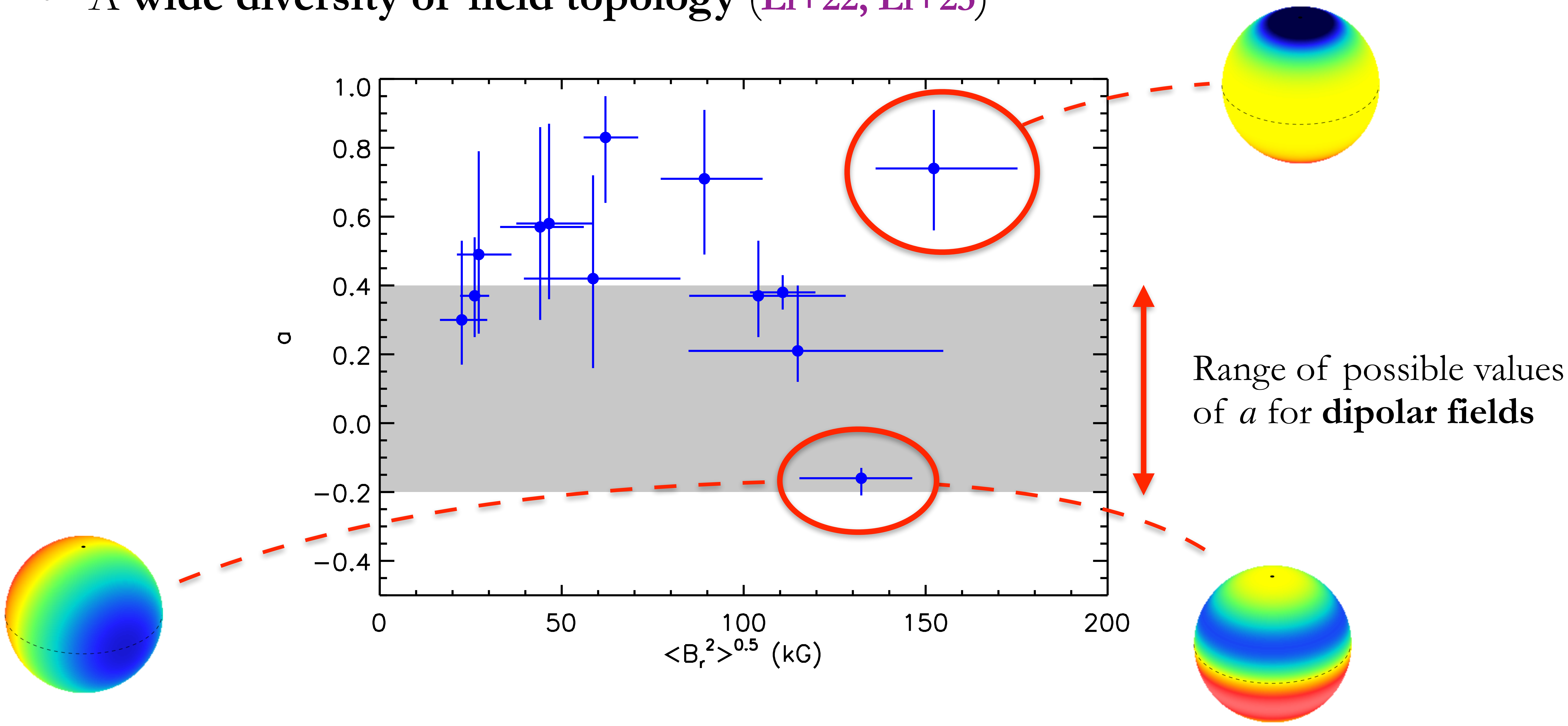
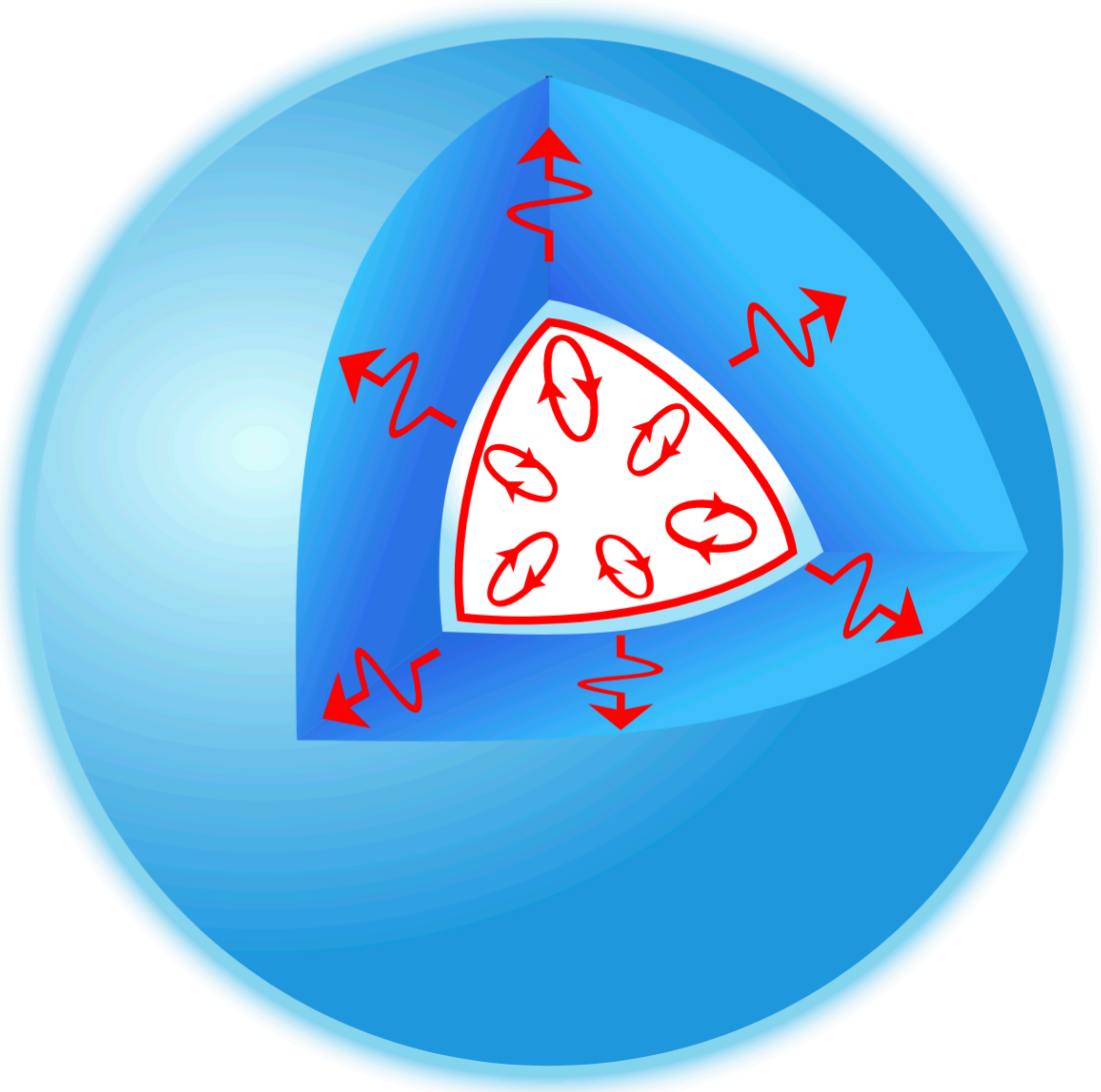


Origin of detected fields?

- What is the **origin of these magnetic field?**
  - Fields produced by **dynamo action** in main sequence **convective core**?



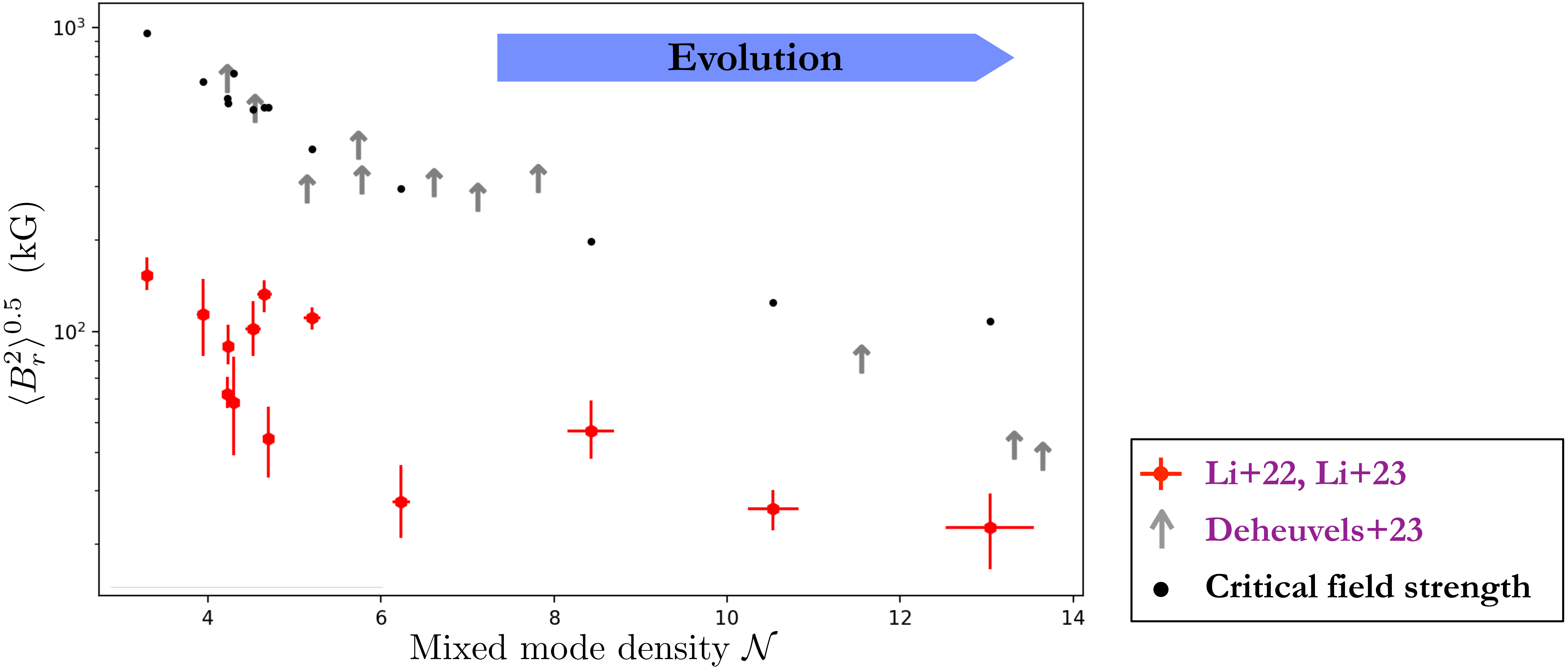
  - Fields detected in stars with masses ranging from $\sim 1.05\,M_\odot$ to $1.56\,M_\odot$
  - Assuming **conservation of magnetic flux**, our field measurements in the core would correspond to field strengths $\sim$ **1 to 30 kG** at ZAMS (**Li+22, Deheuvels+23**)
  - Numerical simulations of dynamo-generated fields in convective cores **(Brun+05)**

    $B_r \sim 45\,\mathrm{kG}$ within the core
    $B_r \sim 2.5\,\mathrm{kG}$ at the edge of the core

  - Fields inherited from **fossil magnetic fields**?

Magnetic field strength vs stellar evolution

- We observe a **decrease of the field strength with evolution** (**Deheuvels+23, Li+23**)
  - Potential link with critical magnetic fields (**Fuller+15**)



Perspectives and Conclusions

- Clear **seismic detection of magnetic fields in the core of red giants**
- Field strength ($\langle B_r^2 \rangle^{0.5}$) ranging from **20 to 600 kG in the core**
- Constraints on **field topology** through parameter *a*
- Seismic detection of core field in **24 red giants** so far **(Li+22, Deheuvels+22, Li+23)**

- **How frequent** are red giants with magnetic fields in the core?
  - ⇒ **Systematic search** for magnetic frequency shifts / asymmetries
- Search for seismic signatures of **non-axisymmetric magnetic fields**
- New constraints from **PLATO**?

- **We thank the PNPS for its support!**

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Ecole Evry Schatzman 2023

La physique stellaire avec Gaia

Oléron 2-6 octobre 2023

Comité d’organisation : C. Babusiaux, C. Reylé, Y. Lebreton, O. Creevey, N. Lagarde, B. Famaey

Il reste encore quelques places

Date limite 24 juin !

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