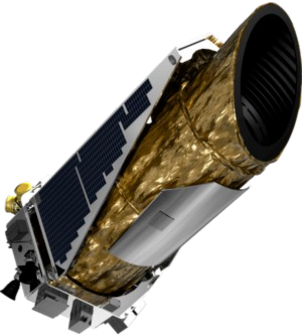
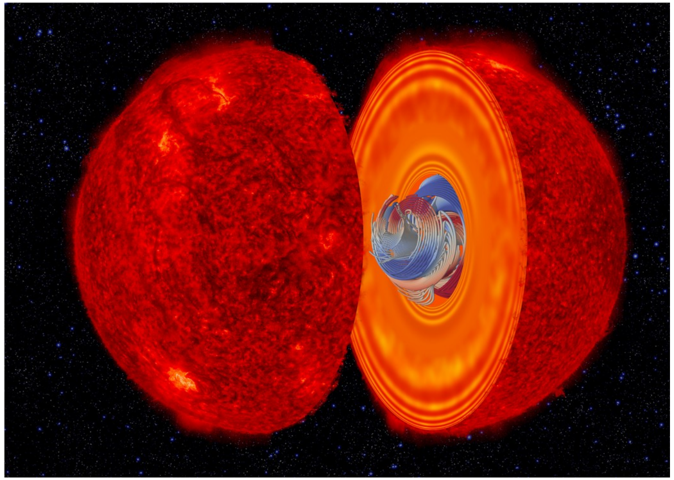
Sismologie : une nouvelle fenêtre sur les champs magnétiques internes des étoiles

Jérôme Ballot, François Lignières,
Sébastien Deheuvels, Gang Li,
Pascal Petit, Romane Cologni



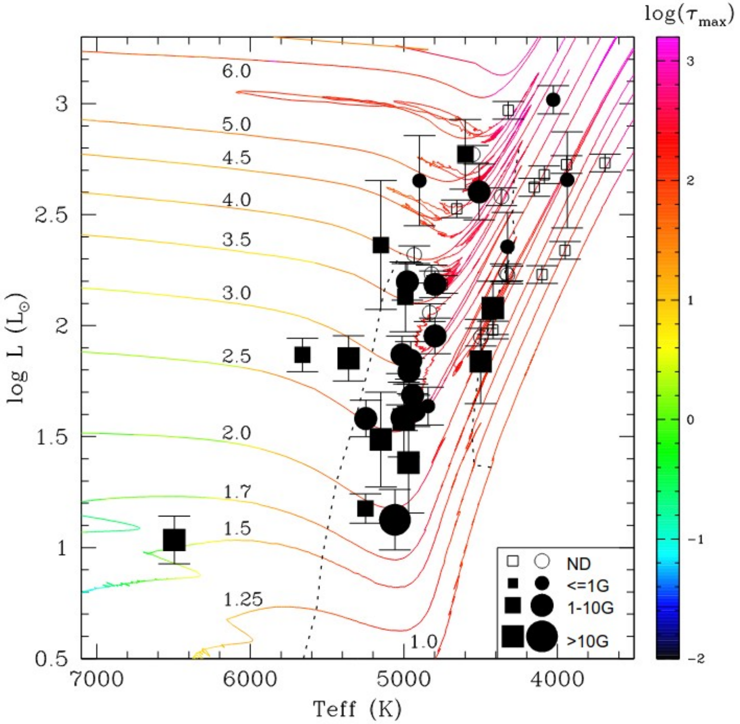


Surface magnetic fields of stars

- **Magnetic fields are ubiquitous in stars**
  - Detected *at the surface* of stars across the HR diagram
  - Example of Red giant stars →
- **Impact on stellar evolution:**
  - They redistribute ***angular momentum*** ⇒ reshape rotation profiles

    [Rüdiger+15, Jouve+15, Fuller+19, Petitdemange+23]
  - They modify rotational mixing and thus the abundance of chemicals [Maeder & Meynet 2005]

    ⇒ impact on the age determination

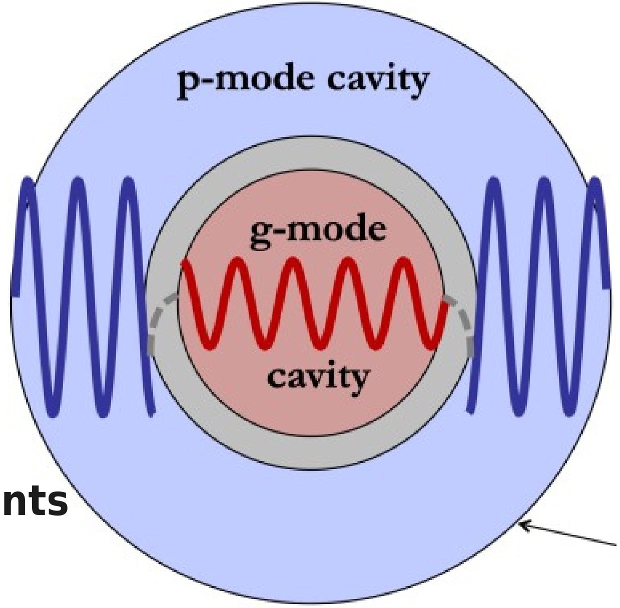


[Aurière+15]

Stellar oscillations in red giants

- **Non-radial oscillation modes in red giants are mixed modes, behaving as:**
  - Pressure modes (p modes) in the envelope
  - Gravity modes (g modes) in the core
- **Detectable at the surface (p-mode) and probe the core (g-mode)**
  - Mixed modes have been detected in thousands of red giants observed with CoRoT, *Kepler*, TESS
- **Successfully probe the internal structure and dynamics of Red Giants**
  - Disentangle H-shell burning / core-He burning giants [Bedding+11, Mosser+11]
  - Detect stellar merger remnants [Rui & Fuller 21, Deheuvels+22, Y. Li+22]
  - Probe the internal rotation of red giants

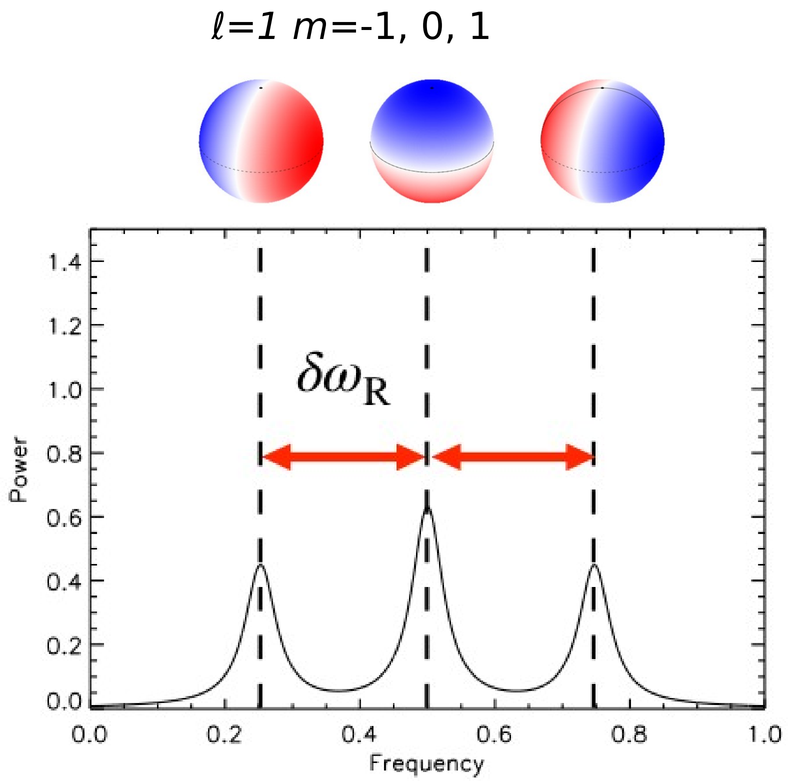
    [e.g., Beck+12, Deheuvels+12, Gehan+18, Kuszlewicz+23]
    - Core rotation is too slow compared to models ⇒ extra processes are needed



Modes are excited in the outer convective envelope

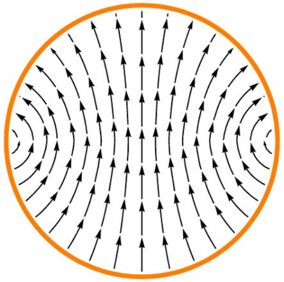
Seismology of red giants: rotation

- **Measuring oscillation mode frequencies**
  - Light curve –(Fourier T.)→ oscillation spectrum
- **Observed mixed modes: mainly dipole (ℓ=1) modes**
  - Rotation lifts the degeneracy between the frequencies of modes with same degree ℓ and different azimuthal orders m
  - Red giants are slow rotators
    ⇒ generally symmetric multiplets

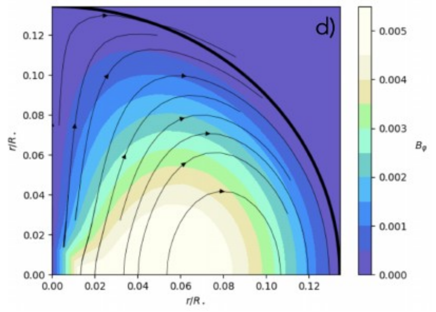


Effects of magnetic field on oscillations

- **First-order perturbation**
- **Theoretical predictions for**
  - the Sun [Gough & Thompson 90],
  - g-mode pulsators [Hasan+05],
  - Red giant stars
    - for axisymmetric dipolar fields [Gomes & Lopes 20, Mathis+21, Bugnet+21],
    - for inclined dipolar fields [Loi 21],
    - **for general fields [Li+22].**



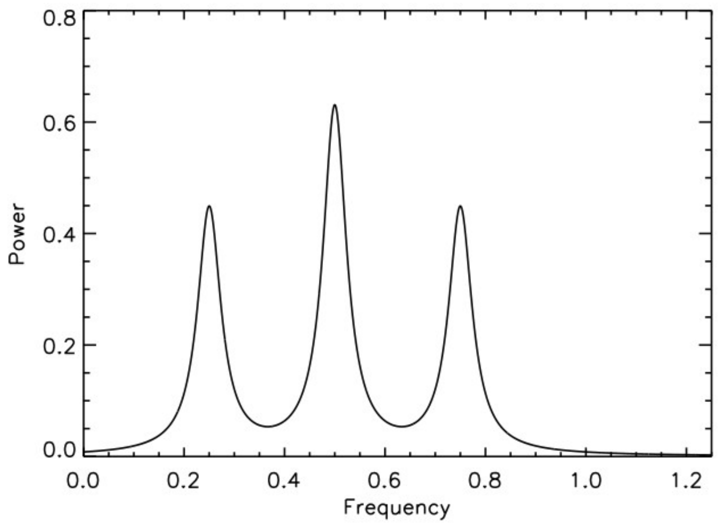
Gomes+20



Bugnet+21

Effects of magnetic field on oscillations

- **Effects on ℓ=1 modes**
  - If effects of non-axisymmetry of the field are negligible, multiplets mainly undergo:

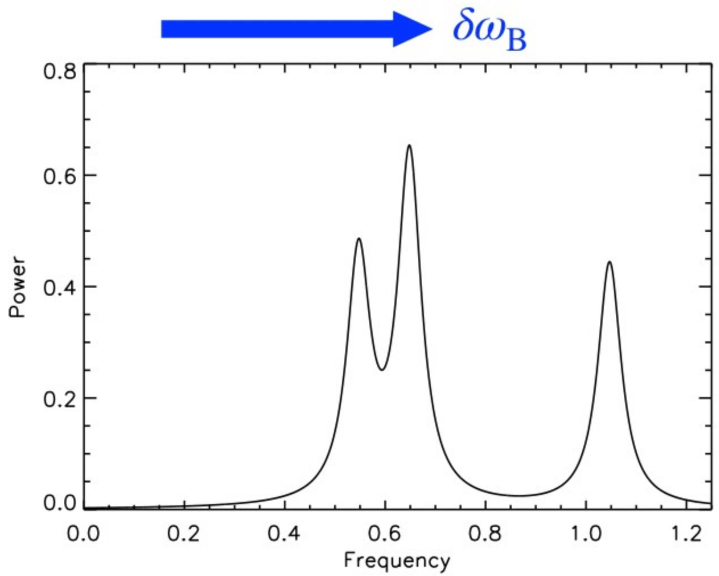


Effects of magnetic field on oscillations

Effects on ℓ=1 modes

- If effects of non-axisymmetry of the field are negligible, multiplets mainly undergo:

  – a global frequency shift $\delta\omega_B \sim \omega^{-3}$



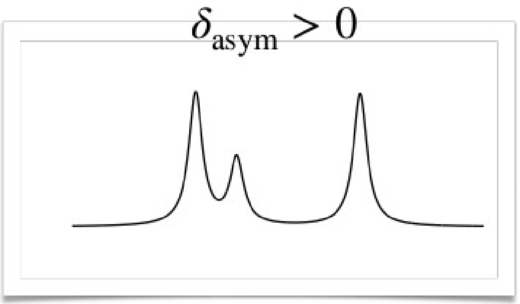
Effects of magnetic field on oscillations

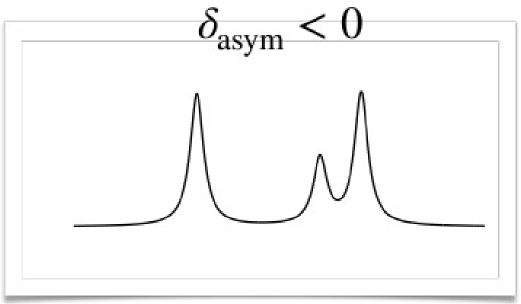
- **Effects on ℓ=1 modes**
  - If effects of non-axisymmetry of the field are negligible, multiplets mainly undergo:

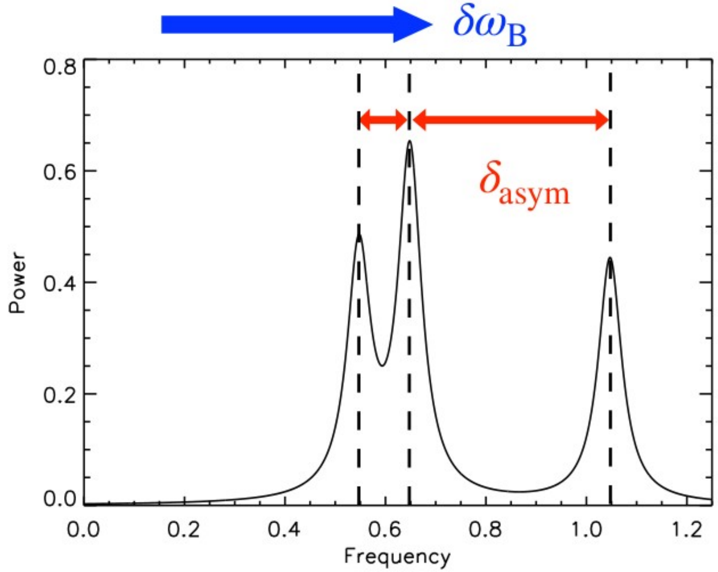
– a global frequency shift $\delta\omega_B \sim \omega^{-3}$

– Multiplet asymmetry δ_{asym}

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





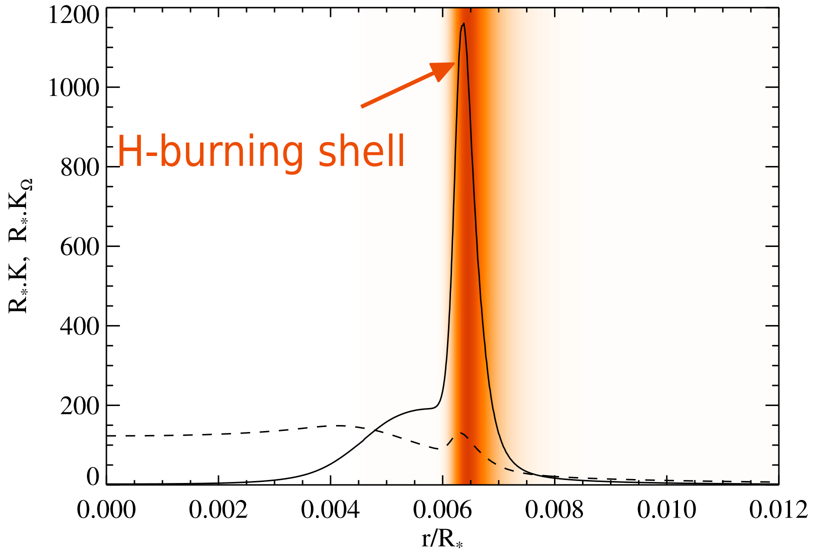


Asymmetric multiplets

Linking observable with physical properties

- **We show that in a very general case that:**
  - global frequency shift $\delta\omega_B \propto \frac{1}{\omega^3}\int_g K(r) B_r^2 dr$ [Mathis+21, Li+22]

    it measures an average of the squared radial field in and below the H-burning shell.



Linking observable with physical properties

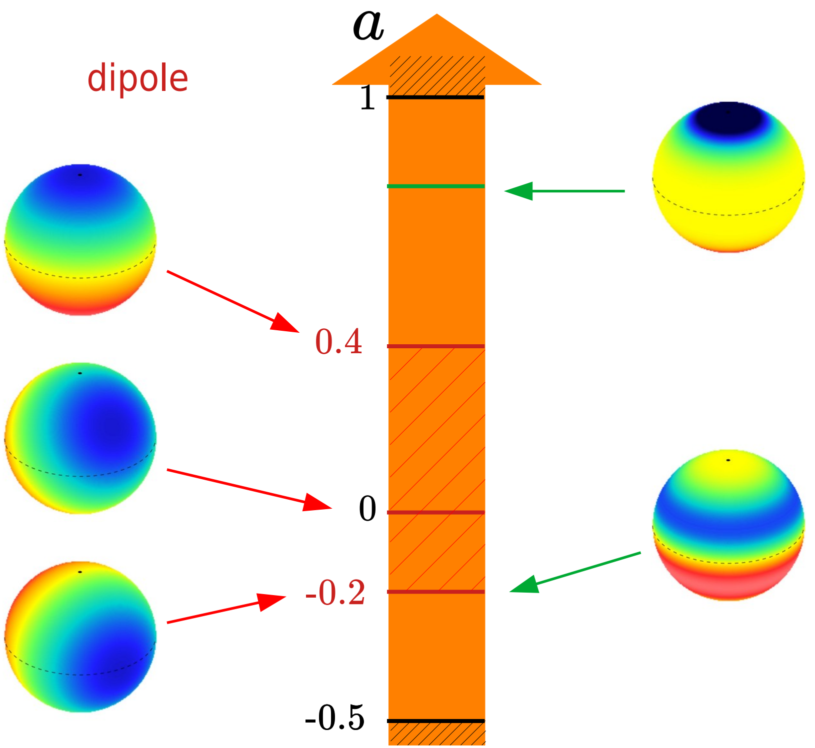
- **We show that in a very general case that:**
  - global frequency shift $\delta\omega_B \propto \frac{1}{\omega^3}\int_g K(r) B_r^2 dr$

    it measures an average of the squared radial field in and below the H-burning shell.
  - asymmetry $\delta_{asym} = 3\, a\, \delta\omega_B$

    [Li+22]

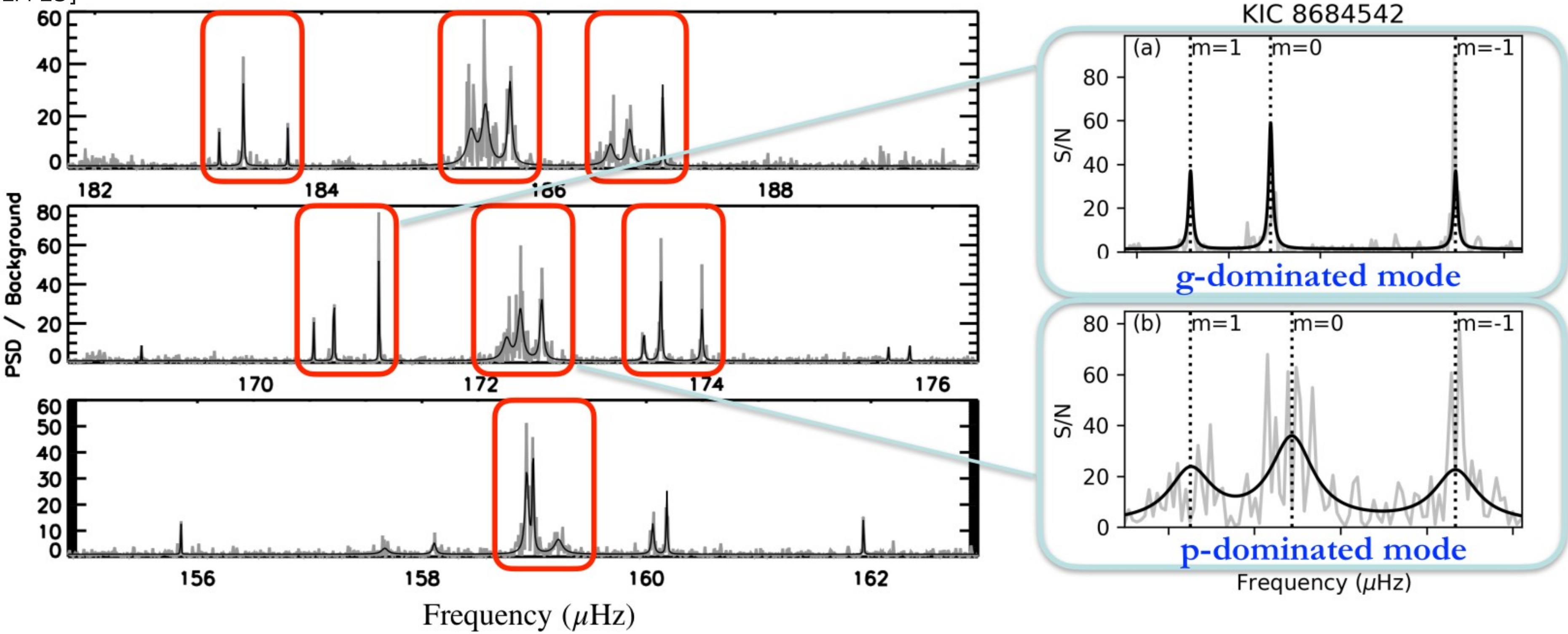
    with $a \propto \iint B_r^2 P_2(\cos\theta) \sin\theta d\theta d\phi$

    a measures B_r^2 in polar caps vs B_r^2 in equatorial band:
    - a maximal (>0) for fields concentrated on the polar
    - a minimal (<0) for fields concentrated on the equator
    - a = 2/5 for an axisymmetric dipolar field



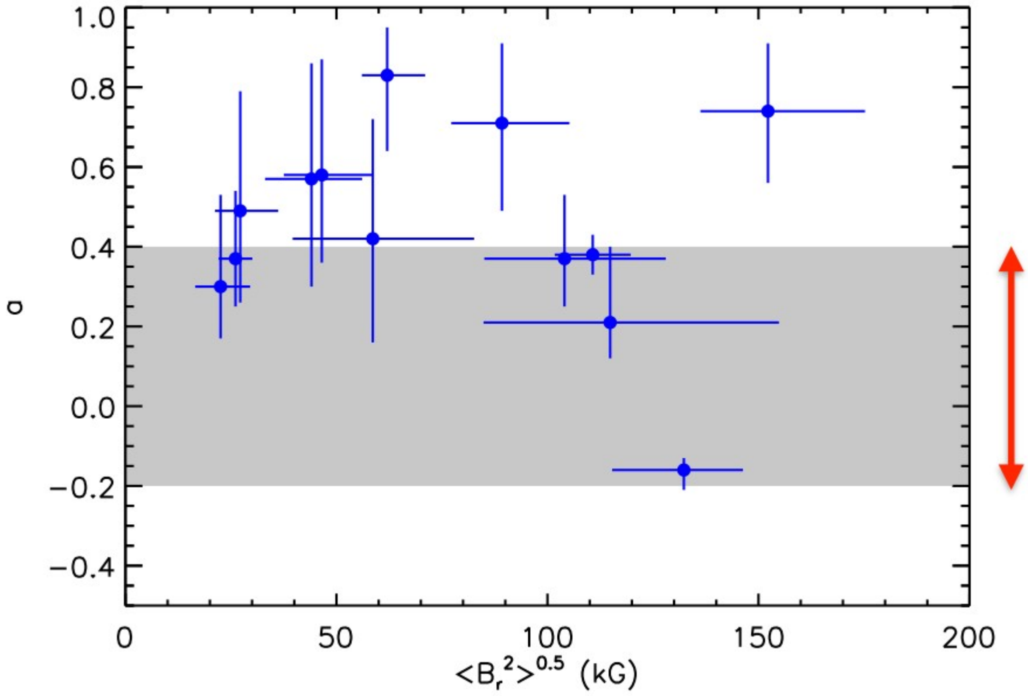
Detection of asymmetries in Kepler red giants

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



Magnetic field strength and topology

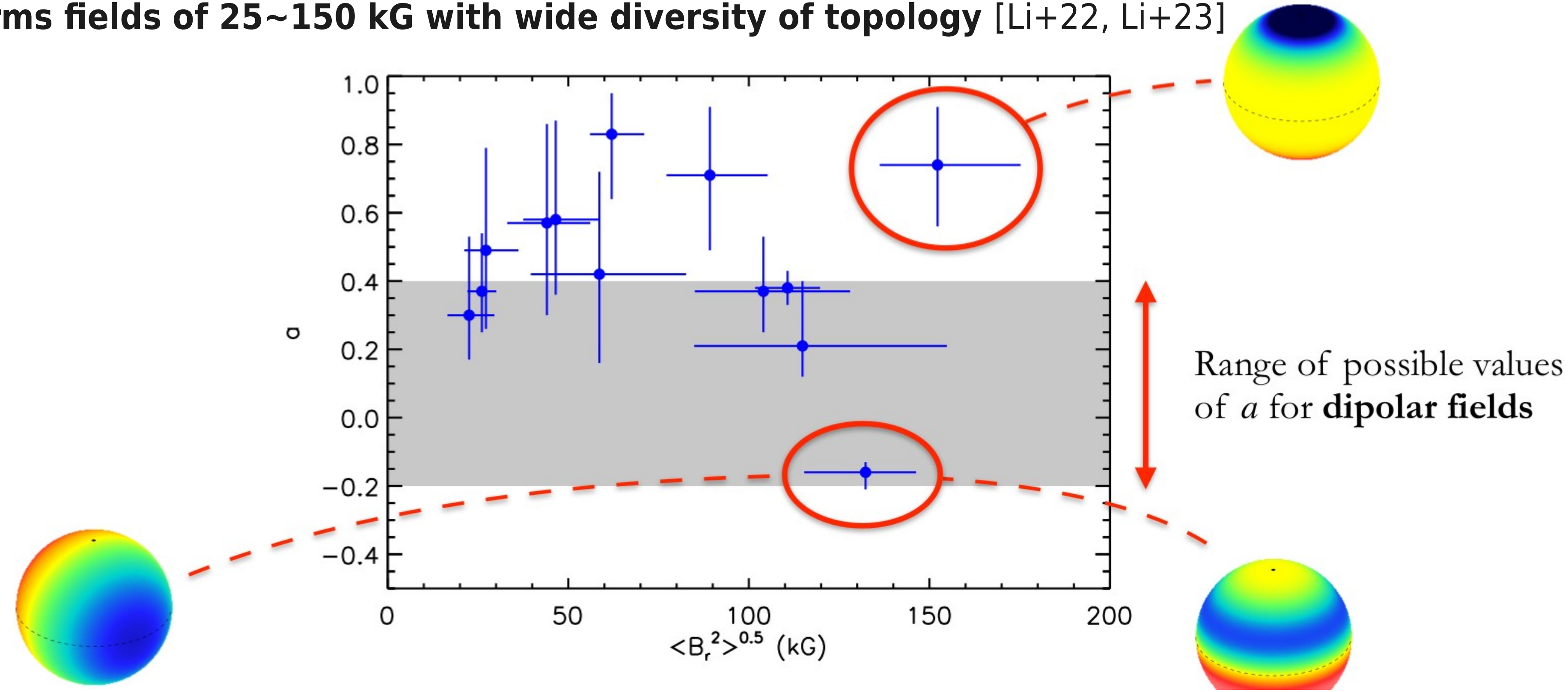
- **rms fields of 25~150 kG with wide diversity of topology** [Li+22, Li+23]



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

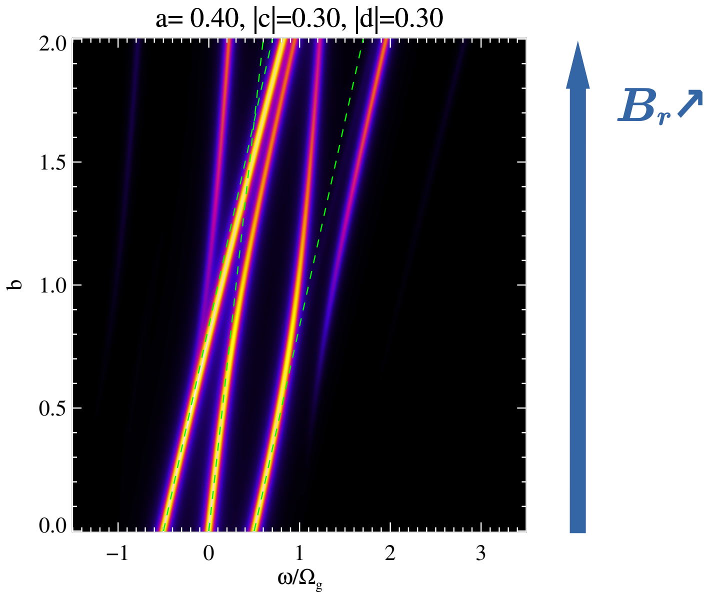
Magnetic field topology

- **rms fields of 25~150 kG with wide diversity of topology** [Li+22, Li+23]



Impact of non-axisymmetric magnetic fields

- **Extra components appear in multiplets** [e.g. Gough &Thompson 90, Loi 21]
  - For ℓ=1 modes, those effects are fully described by 2 extra parameters (c, d) [Li+22]
  - Their impacts depend on $b = \dfrac{\text{Magnetic shift}}{\text{Rotation splitting}}$
  - For $b \lesssim 1$, even for high values of $|c|$ and $|d|$, 3 components dominate the multiplets
  - For high values of b, more complex patterns may appear and can be misinterpreted or rejected by current pipeline.
    → *to be considered in future analyses*

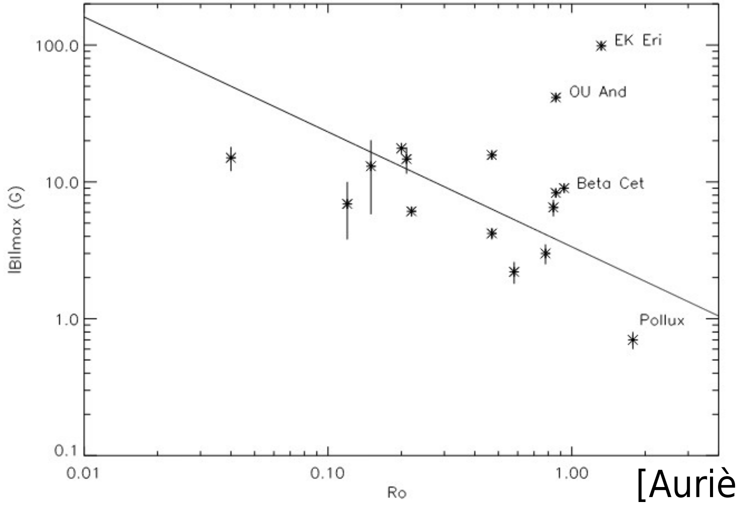


Origin of these detected magnetic fields

- **Field produced by dynamo action in main sequence convective core?**
  - Fields detected in stars with masses ranging from ~1.05 $M_\odot$ to 1.6 $M_\odot$
    - Convective core at the ZAMS
  - Assuming conservation of magnetic flux, our field measurements in the core would correspond to field strengths ~ 1 to 30 kG at ZAMS
  - Numerical simulations of dynamo-generated fields in convective cores [Brun+05]
    - Br ~ 45 kG within the core
    - Br ~ 2.5 kG at the edge of the core
- **Fields inherited from fossil magnetic fields?**

What is the incidence of red giants with magnetic core?

- **Asymmetries in a dozen of stars among the thousands of red giants**
  - abnormal stars with atypical history?
  - or normal stars, other reasons explaining the rarity of the field detections:
    - Impact of the topology (especially non-axisymmetric effects that make spectra more complex)
    - Weak values of parameter a
    - Critical field
- **Are the surface magnetic fields of these stars normal, or not?**
  - Especially the star with negative asymmetries (and M ~ 1.6$M_\odot$)
  - Rotation are known with seismology

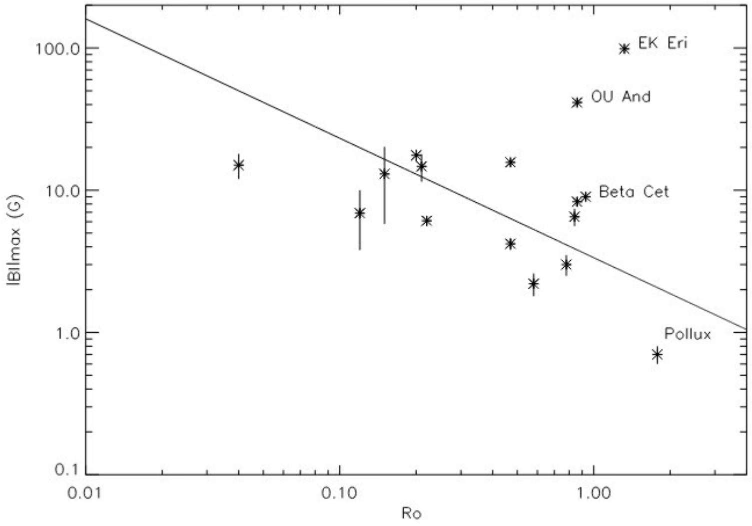


[Aurière+15]

Spectropolarimetric observations

- **ESPaDOnS @ CFHT, 2023A**
  - The two brightest targets (V<11.5), including the one with a<0

[Aurière+15]



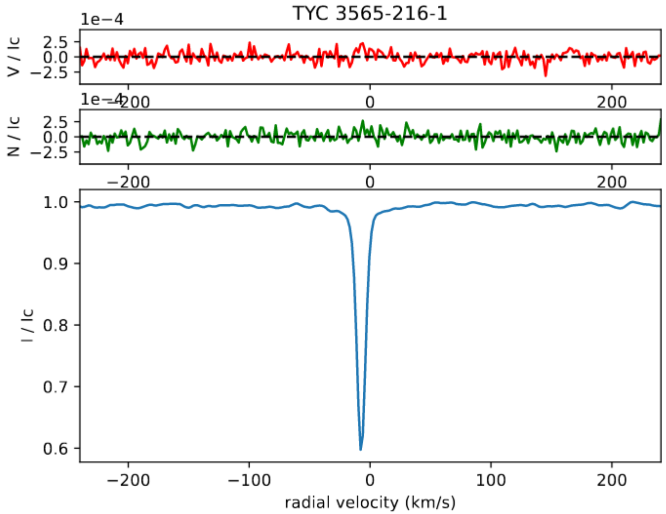
- **Preliminary results:**

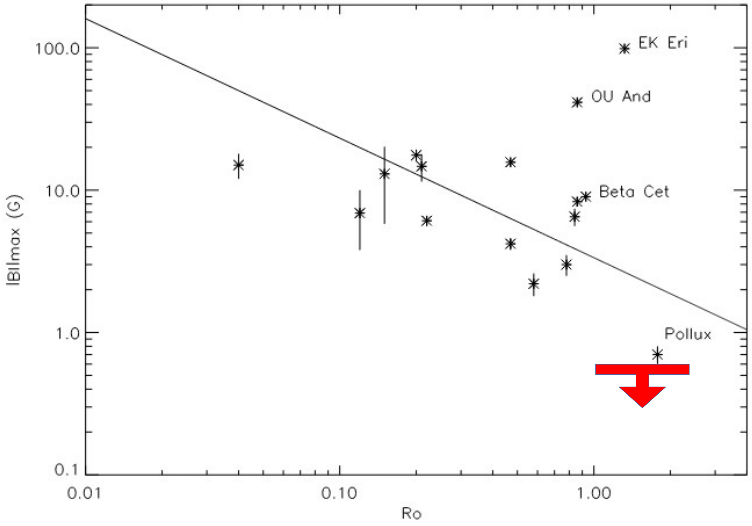
Spectropolarimetric observations

- **ESPaDOnS @ CFHT, 2023A**
  - The two brightest targets (V<11.5), including the one with a<0

[Aurière+15]

- **Preliminary results:**
  - Upper limit for B_{lon} of 0.6 G



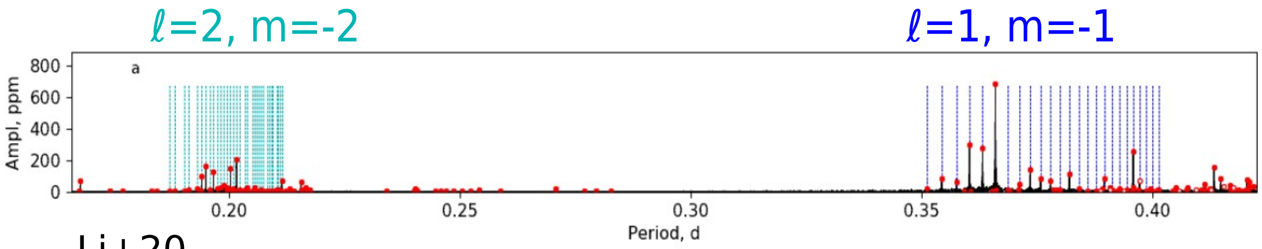


- **These stars look typical!**

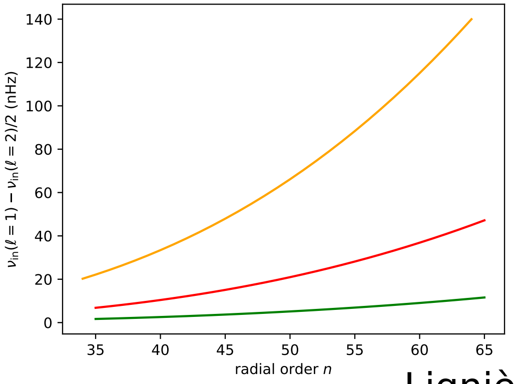
Looking for magnetic fields in core of their progenitors

- **Suited seismic targets: γ Doradus stars**
  - Main sequence stars with $1.4M_\odot \lesssim M \lesssim 1.8M_\odot$
  - Numerous g modes detected and identified in more than 600 stars with *Kepler* [e.g. VanReeth+15,16, Christophe+18, Li+19,20]
  - Fast rotators ($0.5d \lesssim P \lesssim 3d$)

- **Theoretical works**
  - perturbative B but non perturbative Ω (TAR)
    - Dipolar field [Prat+19,20]
    - General field [Lignières+23]
  - We propose new seismic indicators combining ℓ=1 and ℓ=2 modes



Li+20



Lignières+20

Conclusions & perspectives

- **Clear seismic detection of magnetic fields in the core of red giants**
  - Seismic detection of core fields in 24 red giants so far [Li+22, Li+23 + Deheuvels+23]
  - Field strength ($\langle B_r^2\rangle^{1/2}$) ranging from 20 to 600 kG
  - Constraints on field topology through parameter a
  - These stars have normal surface magnetic fields
- **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
  - Selection biases to be constrained
- **Looking for fields inside stars on MS (γ Dor)**
- **Effect of strong fields**
  - New approximation (“TAM” by Rui+23)
  - Complete 2D (then 3D) computations with ACOR and TOP (cf. PhD Thesis of A. Fort, LESIA)