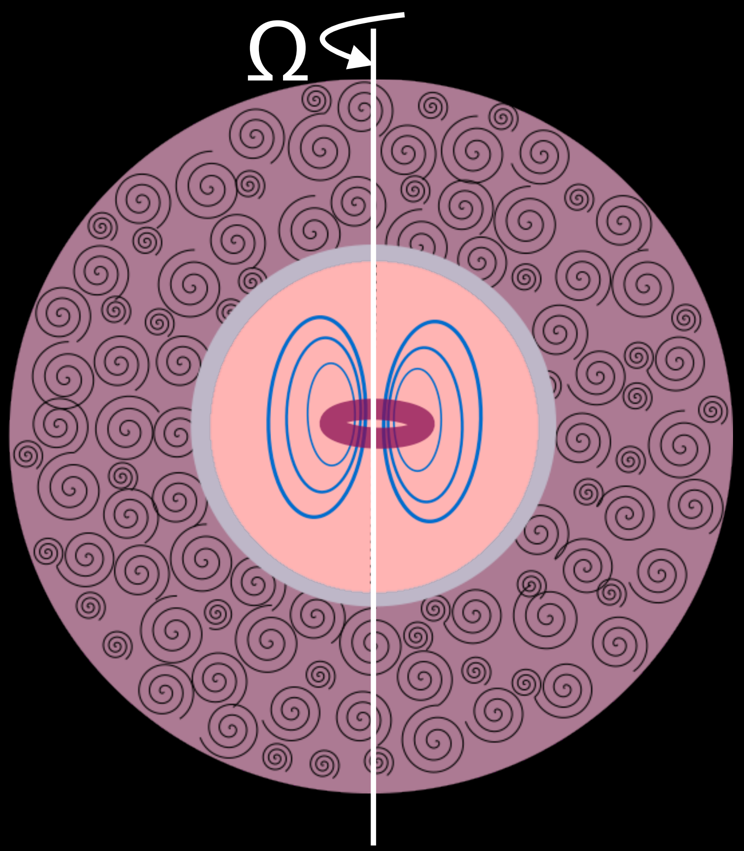
Lisa Bugnet

Supervision:
R.A. García, S. Mathur (Data analysis)
S. Mathis (Theoretical works)
Main collaborations : V. Prat, G. Davies, A. Astoul, K. Augustson, C. Neiner

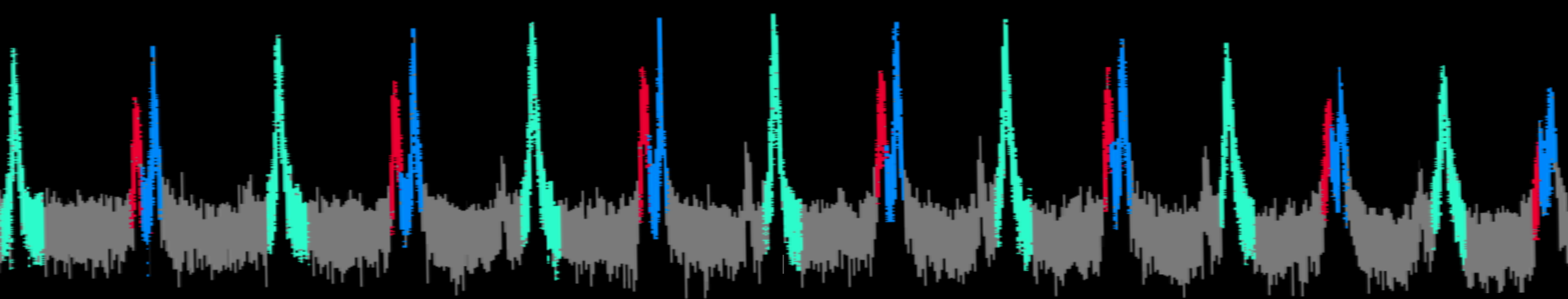
GLOBAL CHARACTERISATION OF SOLAR-TYPE STARS AND INTERNAL MAGNETISM ALONG THE EVOLUTION



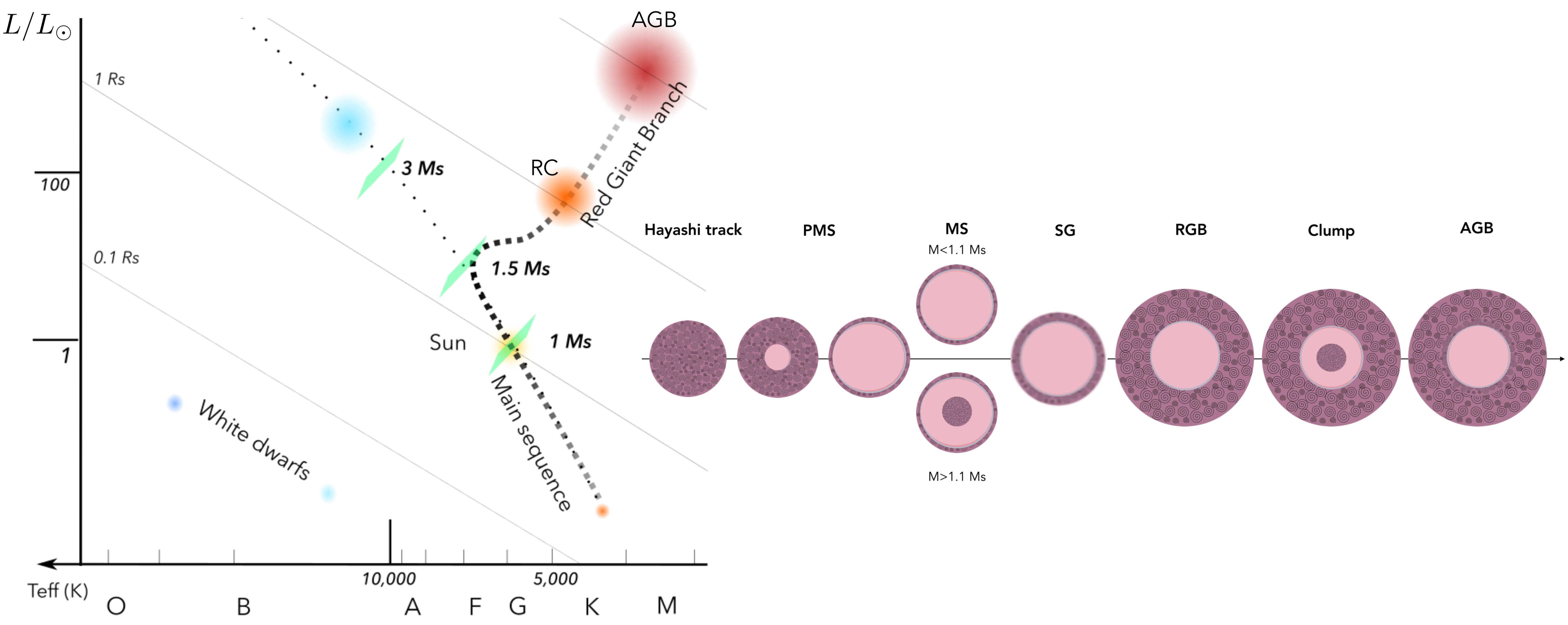
Machine learning for global asteroseismology

and

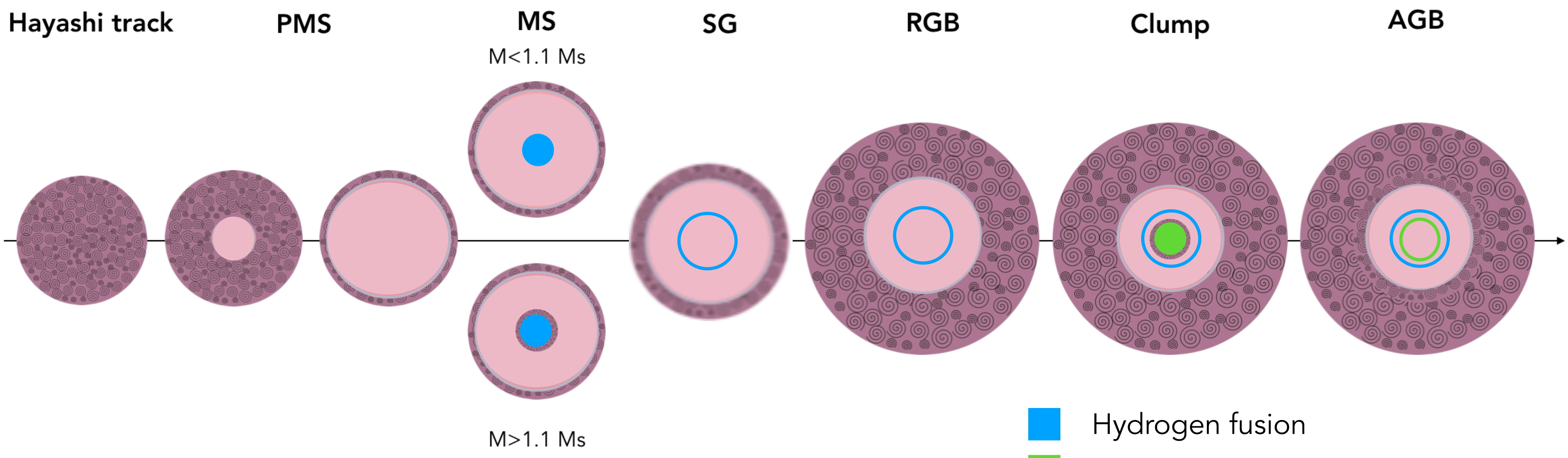
New diagnosis for internal magnetic fields



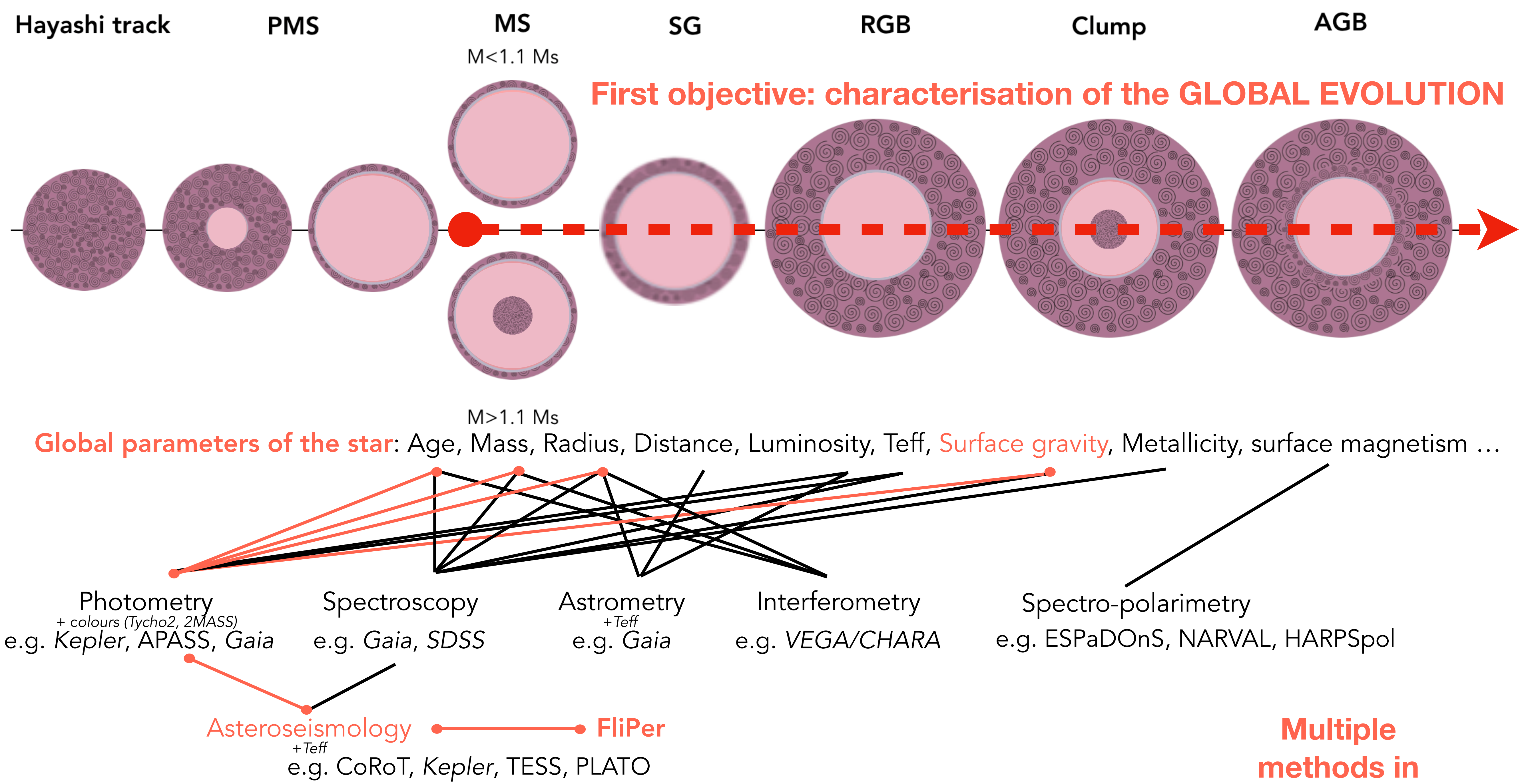
SOLAR-TYPE STARS ALONG THE EVOLUTION



SOLAR-TYPE STARS ALONG THE EVOLUTION



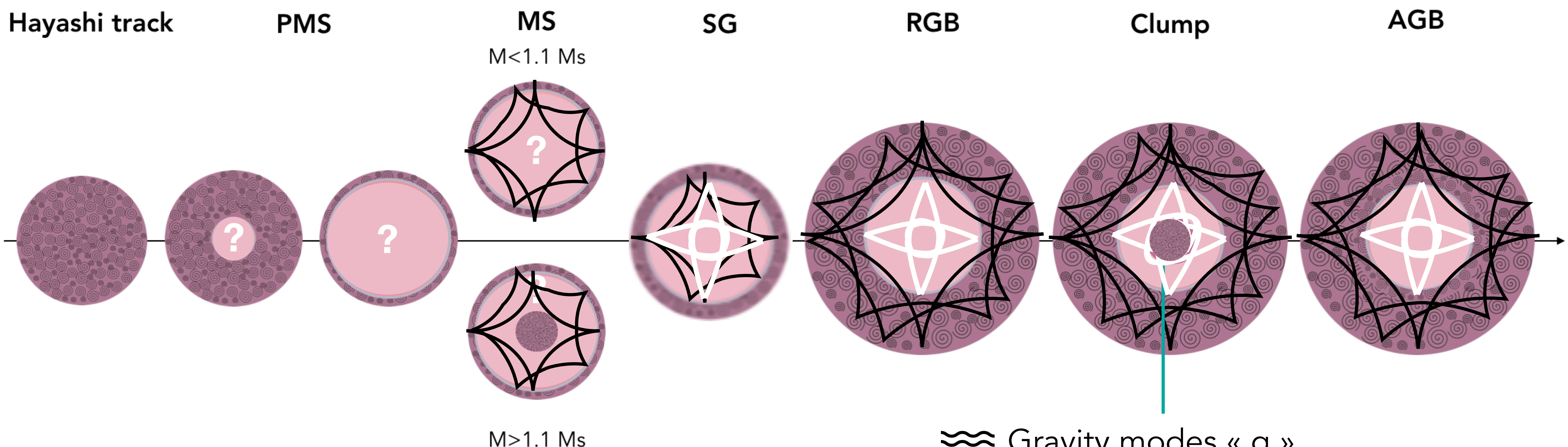
SOLAR-TYPE STARS ALONG THE EVOLUTION



[Bugnet et al., 2018, 2019]

Multiple methods in synergy

DETECTABLE STELLAR OSCILLATIONS (ALONG THE EVOLUTION)

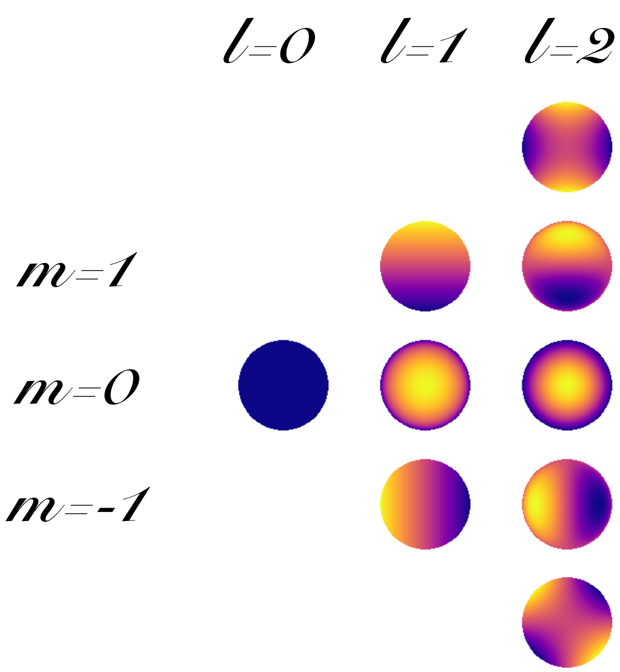


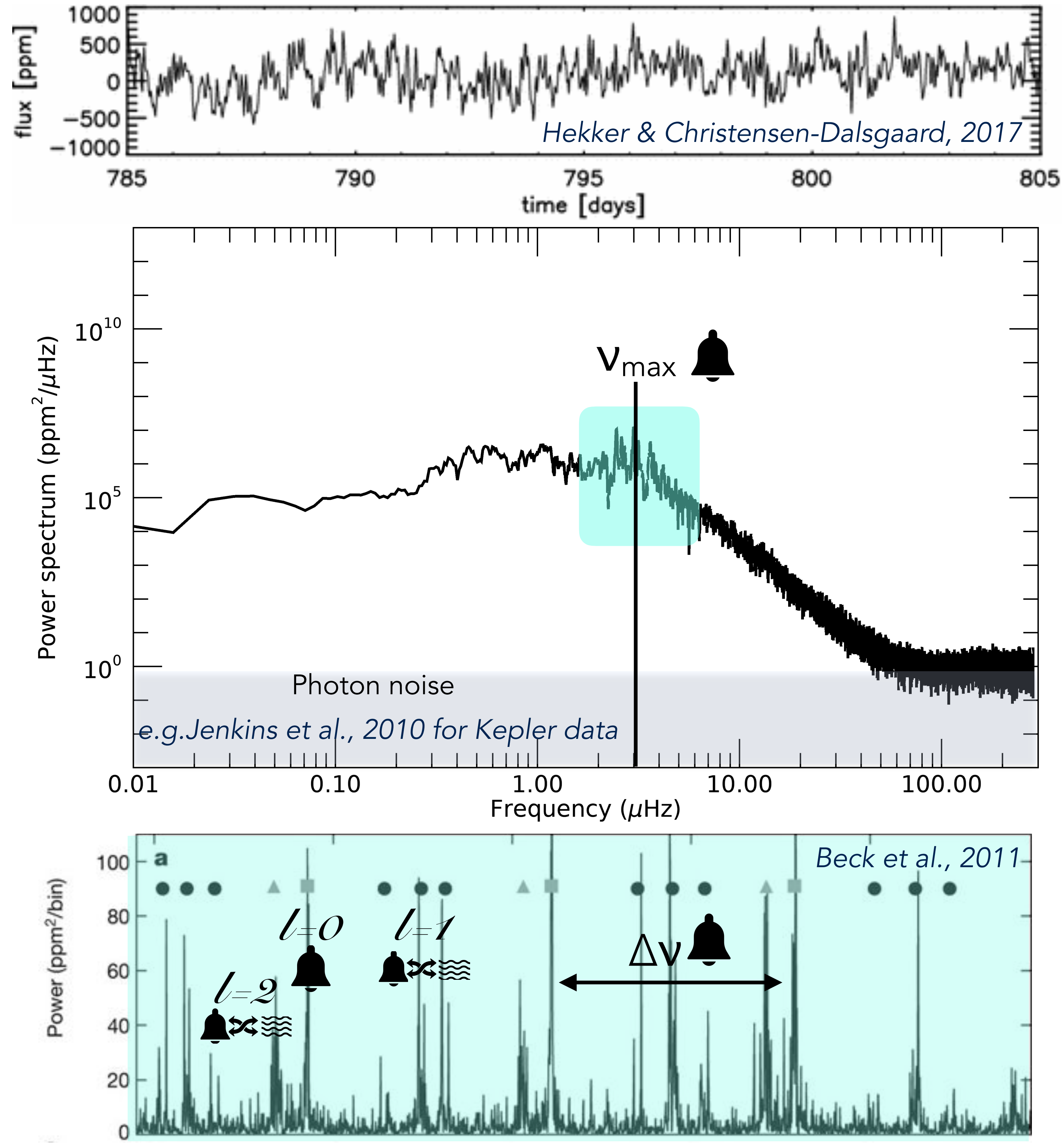
Gravity modes « g »
Restoring force: Archimede
Excitation: interface radiative/convective
Propagation location: radiative interior

Acoustic modes « p »
Restoring force: pressure
Excitation: turbulent layers of the convection zone
Propagation location: whole star

Inside evolved stars the propagation cavities are very close: coupling of the modes
Mixed modes « p-g »

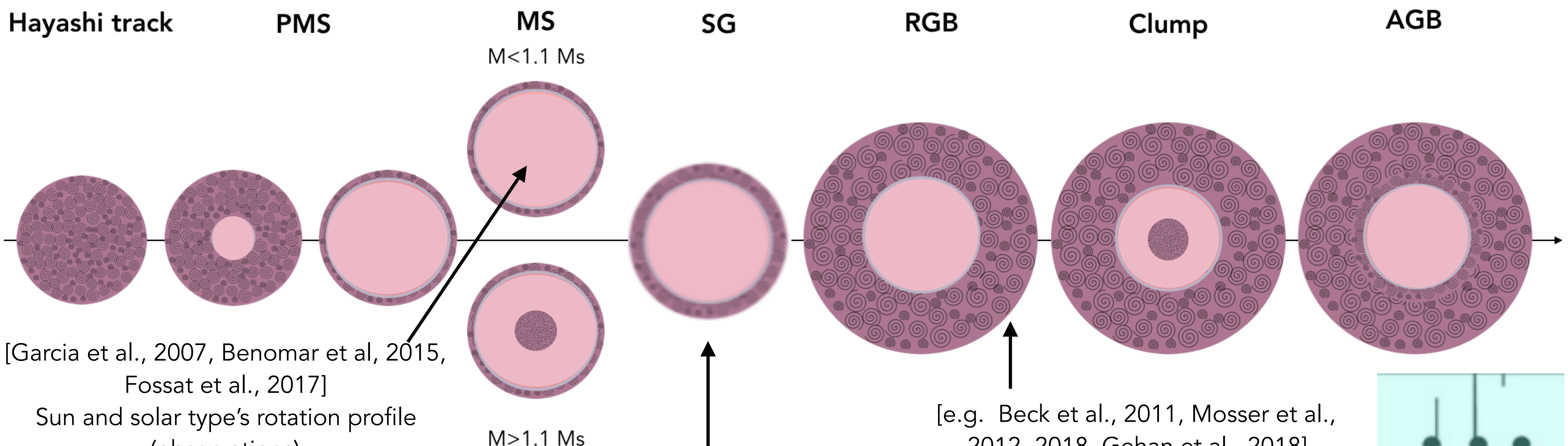
ASTEROSEISMOLOGY
OF SOLAR-TYPE STARS
(IN A NUTSHELL)





Mixed modes = access to internal dynamics

Internal rotation of stars (along the evolution)



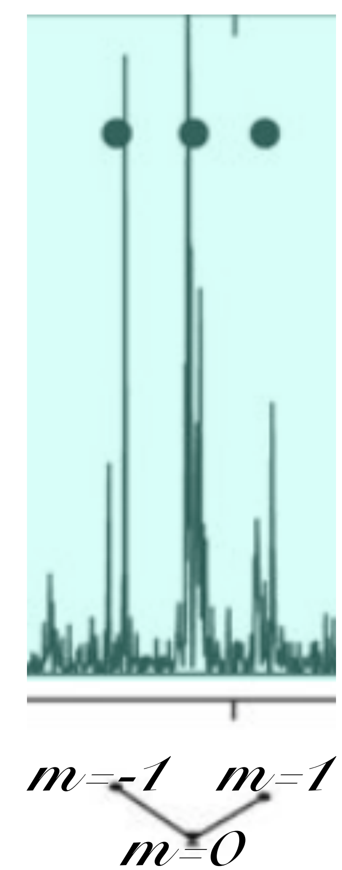
[Garcia et al., 2007, Benomar et al, 2015, Fossat et al., 2017]
Sun and solar type's rotation profile (observations)
$\Omega_{env} \sim \Omega_{core}/[1-4]$

Candidate for the Sun

[Van Reeth et al., 2015, 2016, 2018]
Intermediate mass rotation rate above the convective core

[e.g. Deheuvels et al., 2012, 2014, 2020]
Sub-giants rotation profile (observations)
$\Omega_{env} \sim \Omega_{core}/[1-10]$

[e.g. Beck et al., 2011, Mosser et al., 2012, 2018, Gehan et al., 2018]
Red giants rotation profile (observations)



Beck et al., 2011

Rotation: internal mixing → Galactic evolution
Magnetism and activity
star/planet interactions

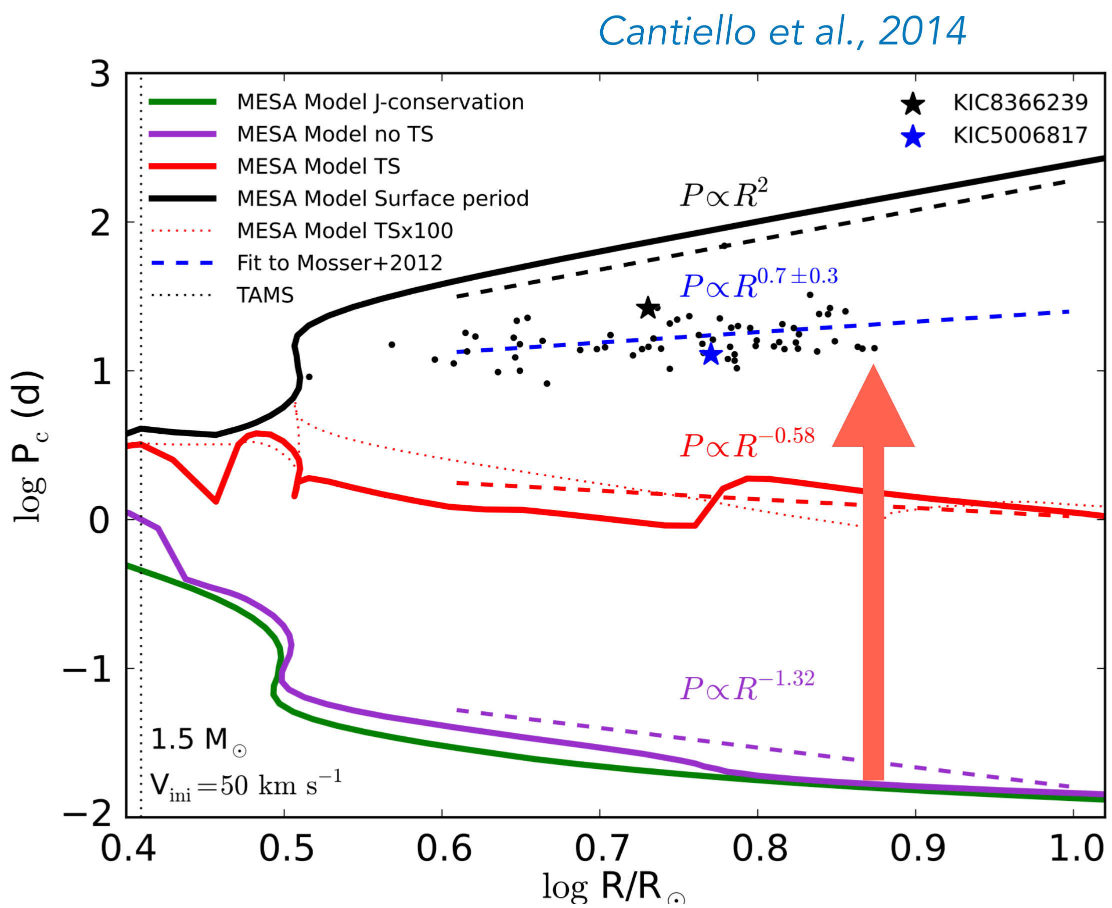
CHALLENGING QUESTIONS

Mosser et al., 2012
Deheuvels et al., 2012, 2014,2015
Gehan et al., 2018
Eggenberger et al., 2012
Ceillier et al., 2013
Marques et. al., 2013
Cantiello et al., 2014

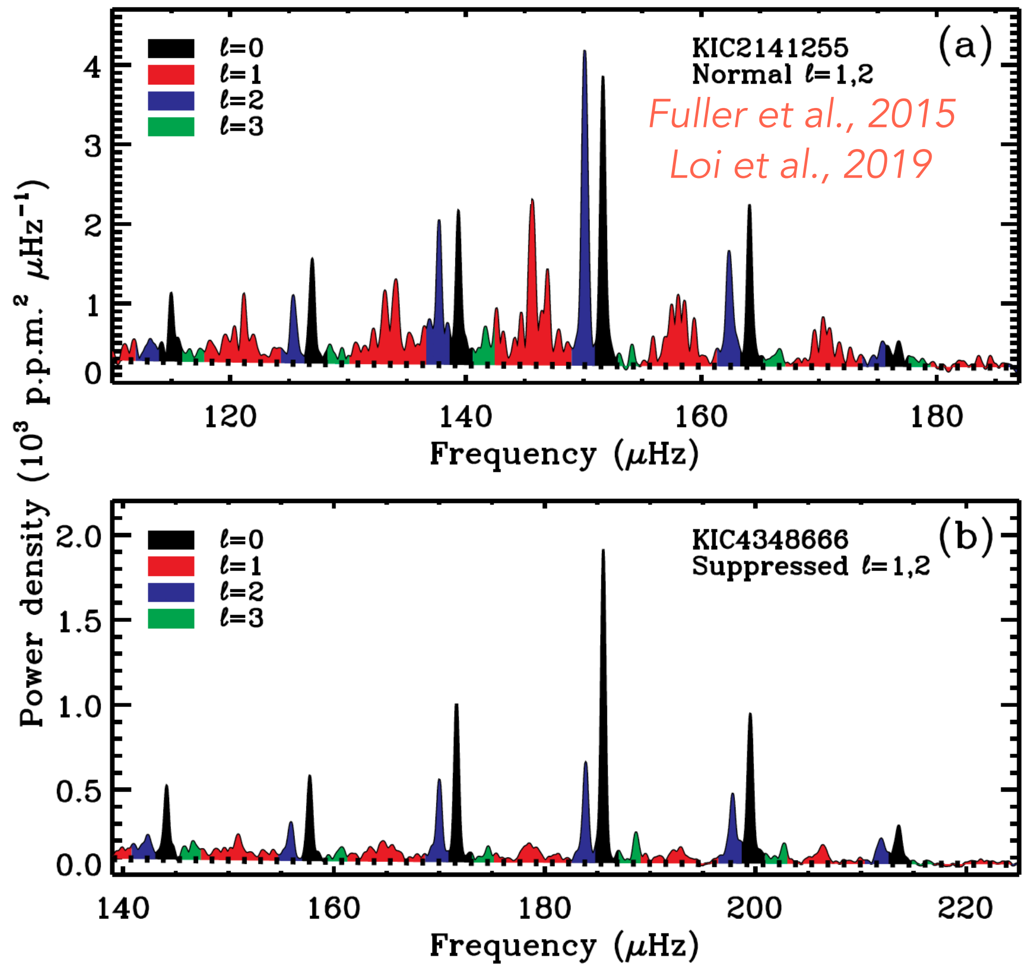
Angular momentum transport problem along the evolution

Low-amplitude l=1 mixed modes

Garcia et al., 2014
Mosser et al., 2017
Fuller et al., 2015
Cantiello et al., 2016



The rotation rate of RG cores is about **2 orders of magnitude lower** than the value predicted by the standard theory of angular momentum

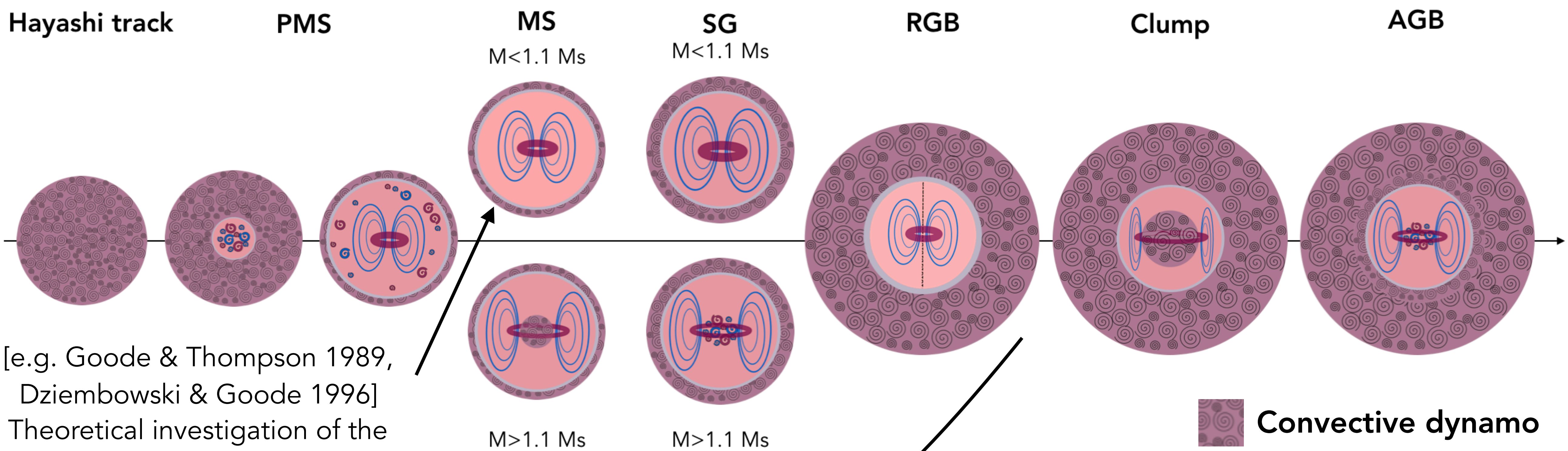


How can we explain the lack of power observed in dipolar modes ?

MAGNETIC FIELD IS ONE OF THE MOST PROMISING CANDIDATE

INTERNAL MAGNETISM INSIDE STARS (ALONG THE EVOLUTION)

Second objective: characterisation of the internal magnetic field



Convective dynamo

Relaxation phase

Fossil magnetic field

[e.g. Goode & Thompson 1989, Dziembowski & Goode 1996] Theoretical investigation of the internal magnetism of the Sun through p modes

[Bigot 2000]: RoAp stars Theoretical investigation of the magnetic field configuration

[Prat et al, 2019, Van Beeck et al., 2020]: Theoretical investigation of the internal magnetism of rapidly rotating stars through g modes

[Bugnet et al., *in prep*, Mathis et al., *in prep*]: Theoretical investigation of the internal magnetism of evolved solar-like stars

Mixed modes = access to core rotation

Access to core magnetism ?

What is the impact of a buried magnetic field on mixed-mode *frequencies* ?

Complementary Methods in synergy

⊕

Advanced observational analysis

→ Constrain

← Predict

Theoretical stellar modeling

Photometric & Asteroseismic analyses:
Red giants and Solar-like stars PSD analysis

with **Machine learning**:
Random Forest, Neural network

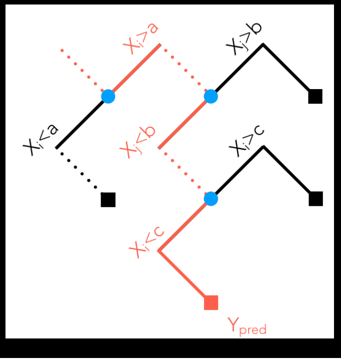
Theory of stellar pulsation including the effects of stellar rotation and magnetism

Theory for the transport of angular momentum

Stellar evolution model MESA

Stellar pulsation model GYRE

1 FliPer (Flicker in Power)

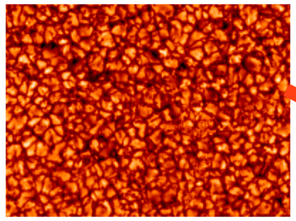


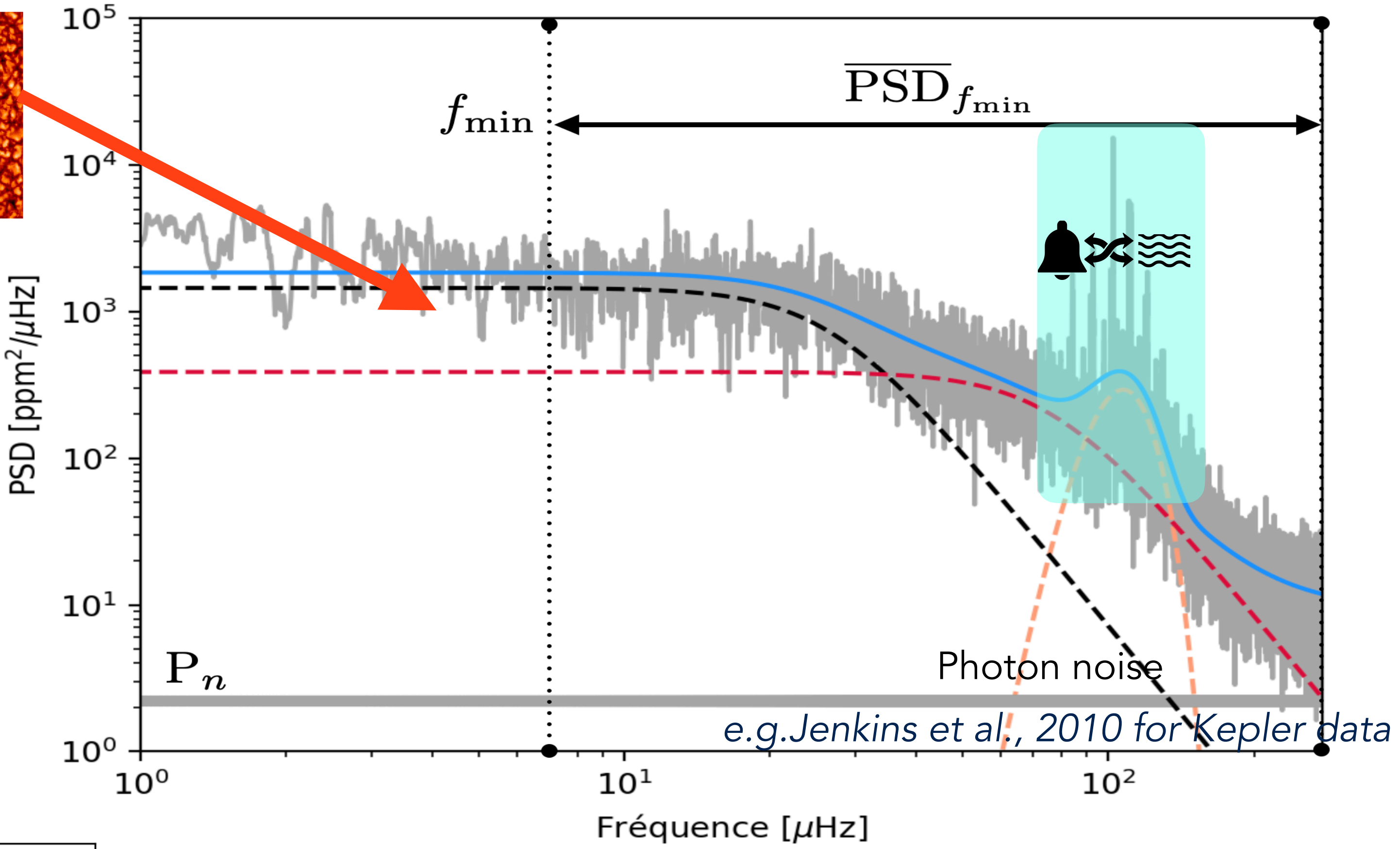
Convection as a proxy of surface gravity

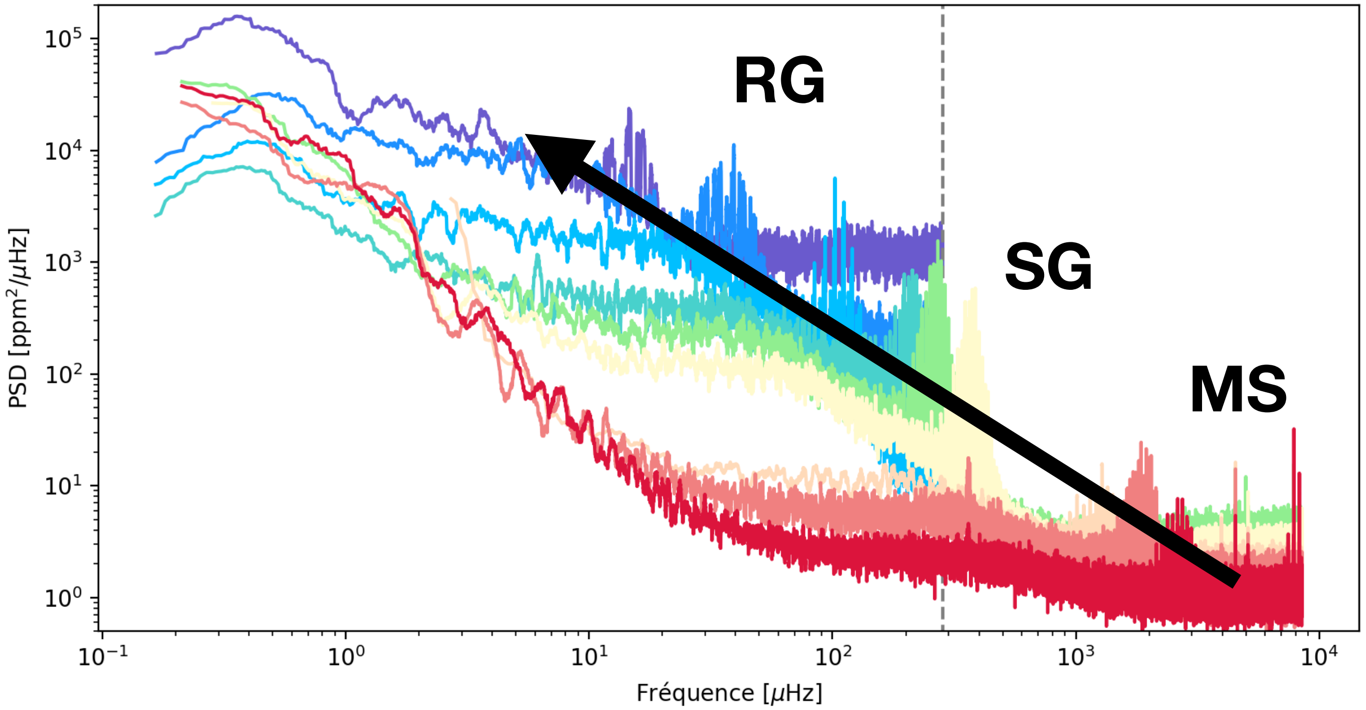
e.g. Mathur et al., 2012
Flicker: Bastien et al., 2015

$$F_p = \overline{PSD} - P_n$$

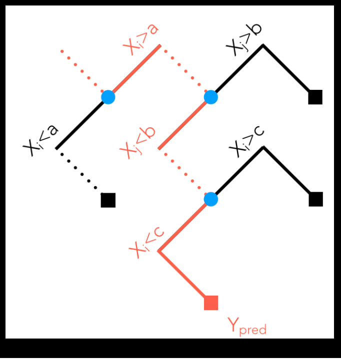
Bugnet et al., 2018







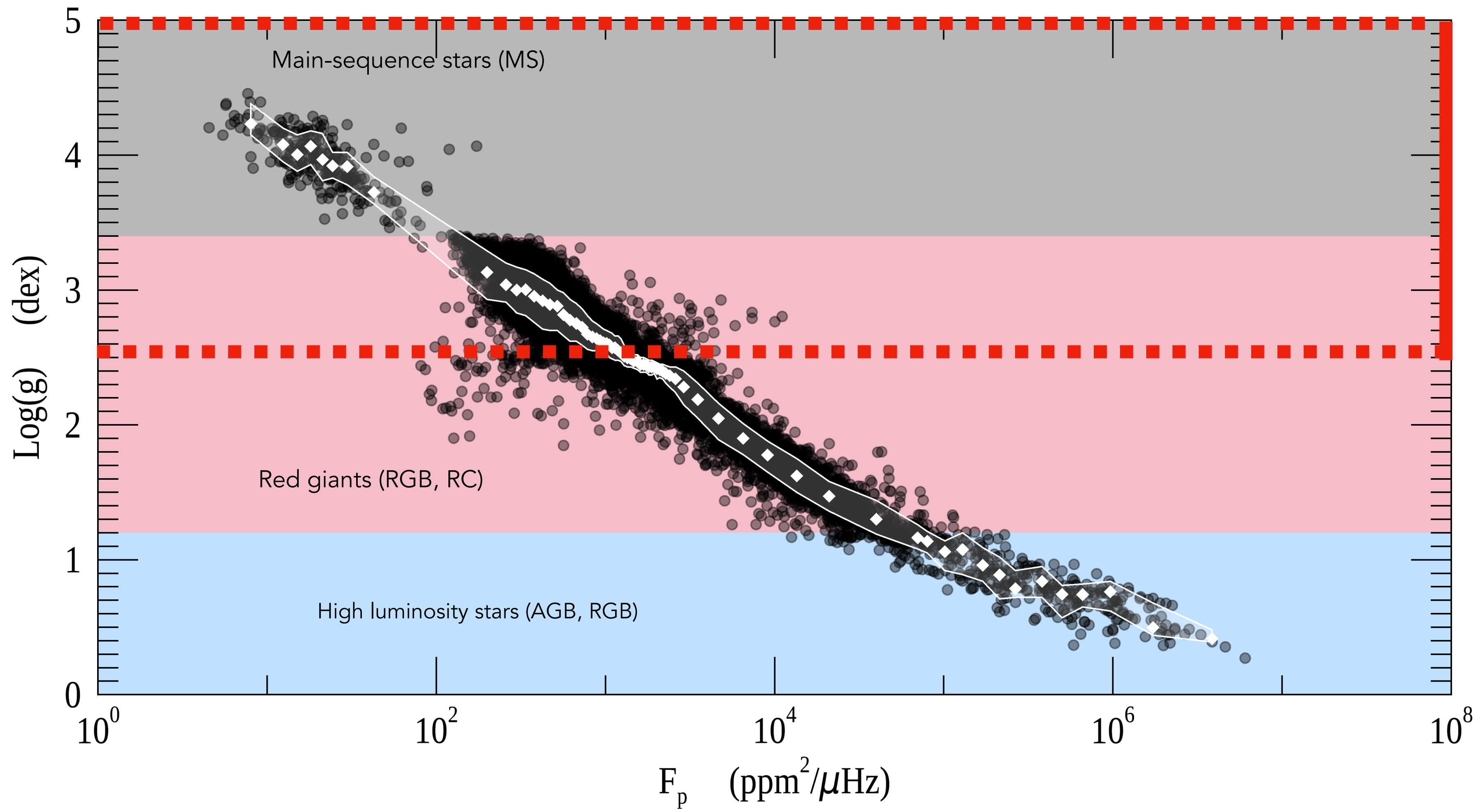
1 FliPer (Flicker in Power): Solar-like stars characterisation



$$F_p = \overline{PSD} - P_n$$

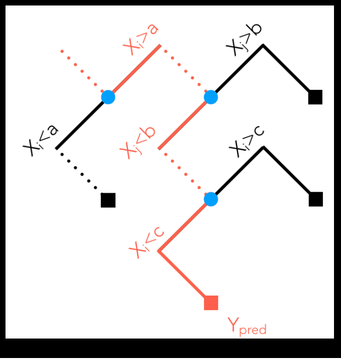
Bugnet et al., 2018

~ 15,000 Solar-like stars studied with the A2Z Mathur et al., 2010 pipeline to estimate log(g)



Applicability range of the flicker

FliPer (Flicker in Power): Solar-like stars characterisation



$$F_p = \overline{PSD} - P_n$$

Bugnet et al., 2018

~ 15,000 Solar-like stars studied with the A2Z pipeline to estimate log(g)

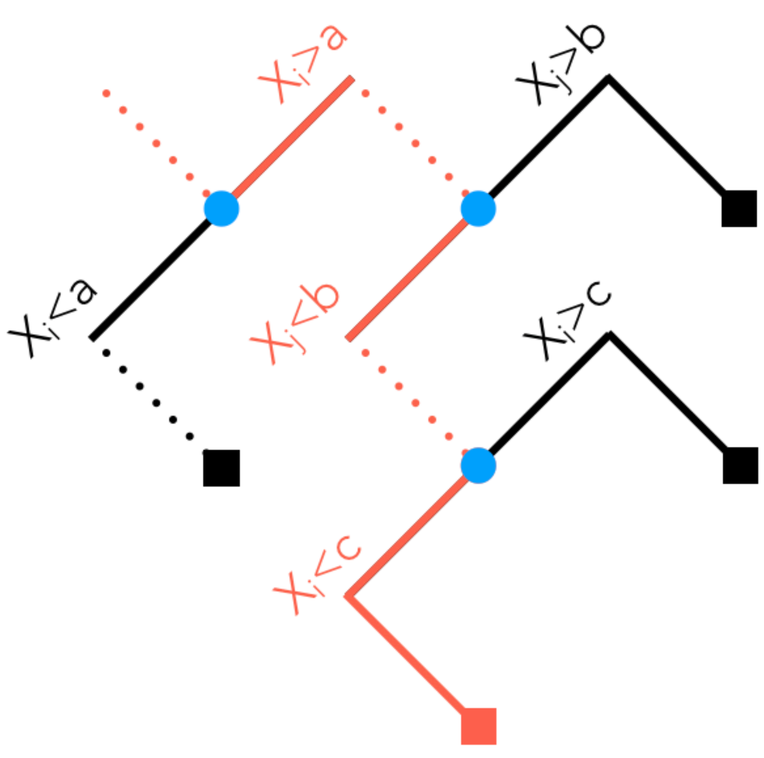
Mathur et al., 2010

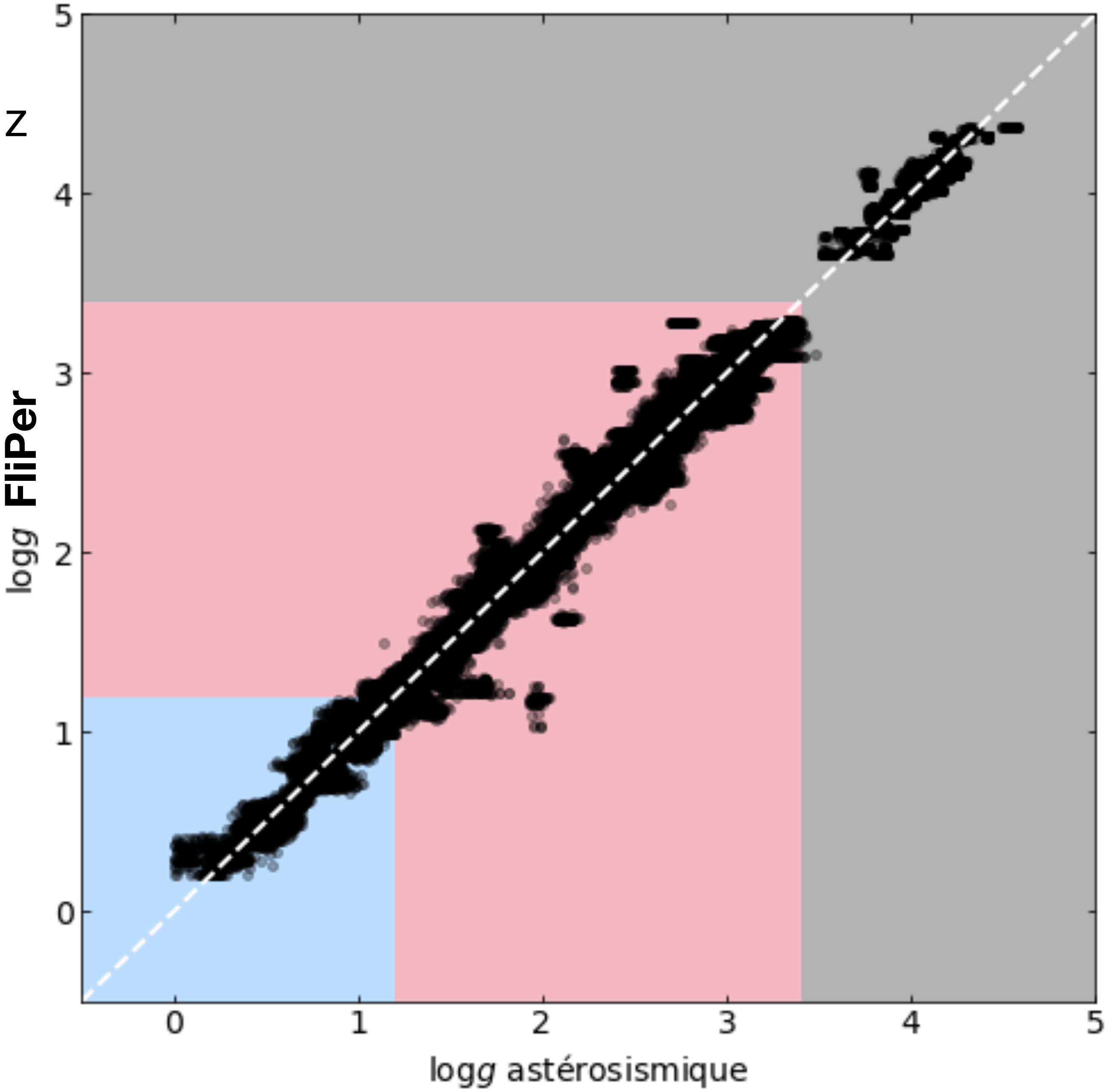
Parameters: BP-RP (Gaia) or T_{eff}

$F_{p,i}$ i in [0.2, 0.7, 7, 20, 50]μHz

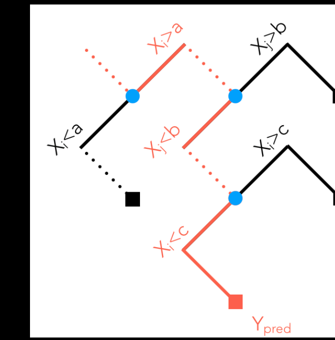
Method: Random Forests

Breiman, 2001



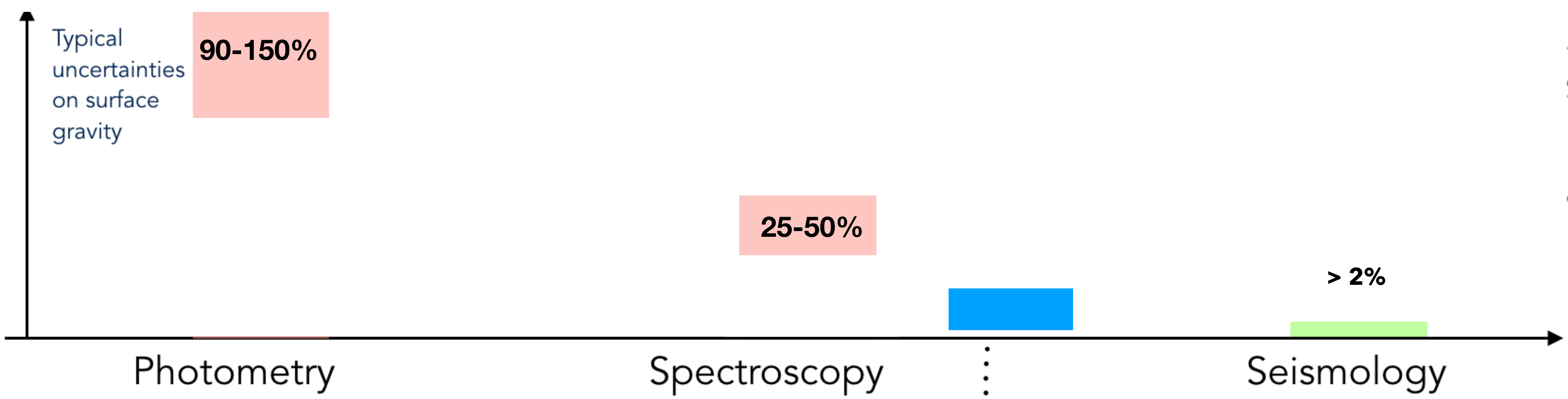


1 FliPer (Flicker in Power): Solar-like stars characterisation



New method to rapidly **estimate log g or ν_{max} of stars with 0.1dex precision directly from the power spectrum density,** from MS to high-luminosity RGB

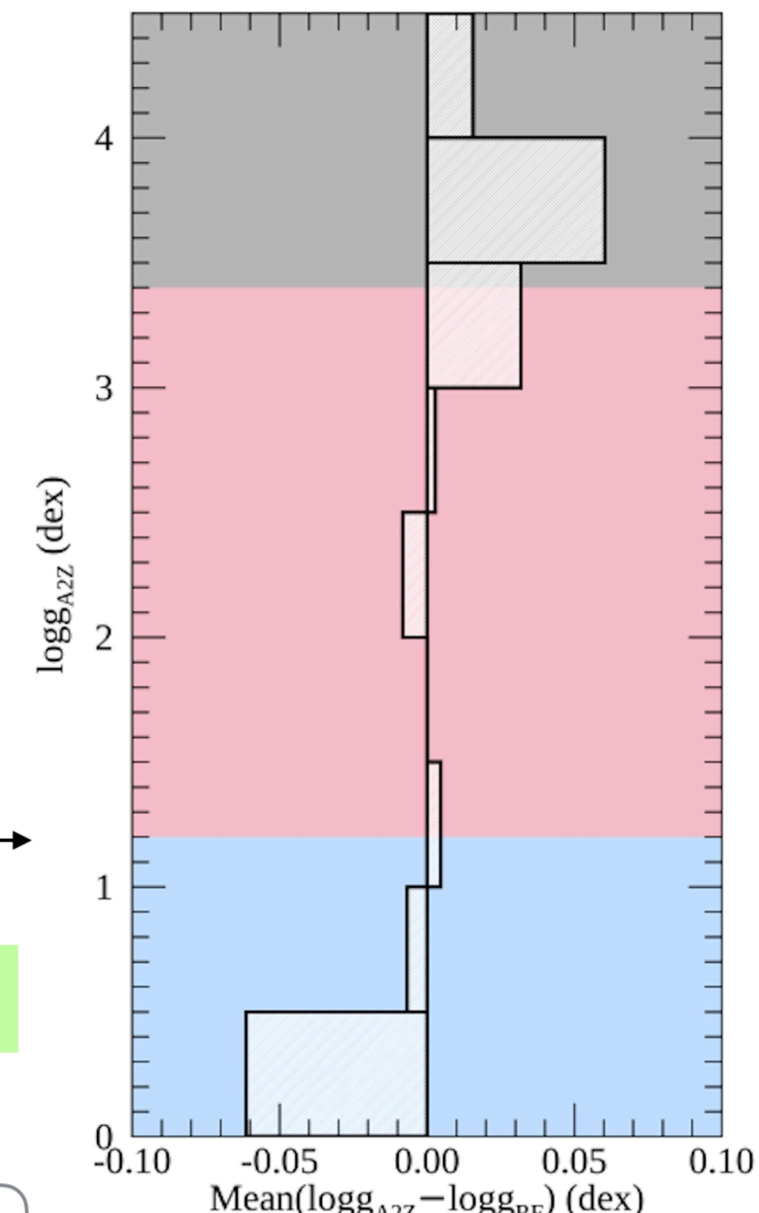
Included as a sub-module in the PLATO WP Stellar rotation and activity measurement to estimate log g



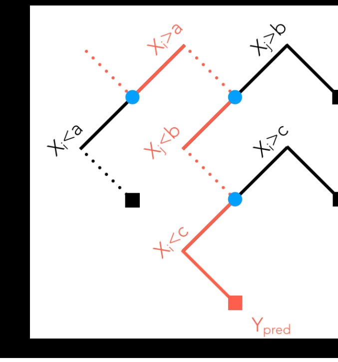
Not precise enough to properly constraint models

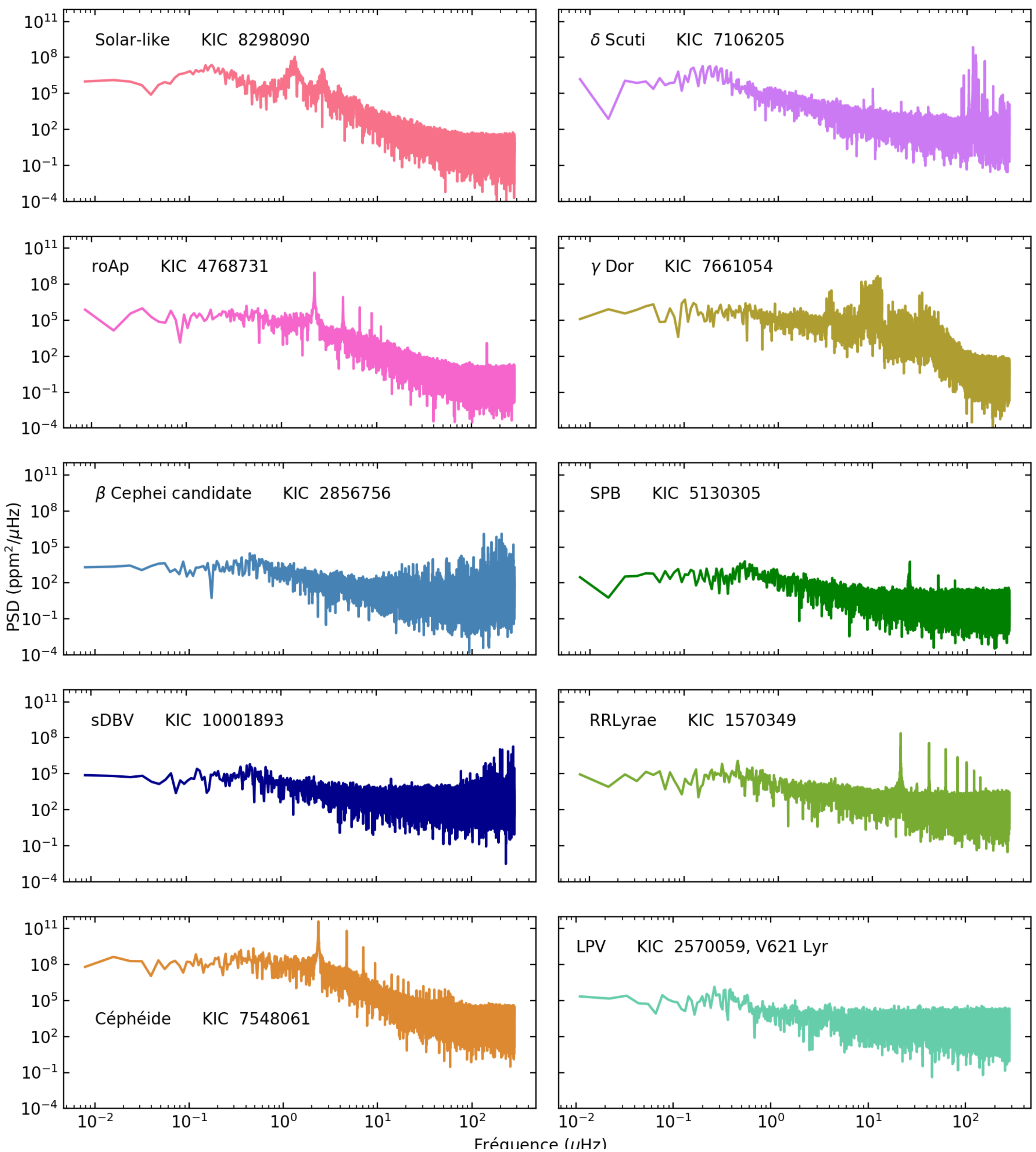
Only for stars with visible modes in the PSD

FliPer (Flicker in Power)
Bugnet et al., 2018
down to logg=0.1 dex



1 FLIPER$_{CLASS}$: SOLAR-LIKE STARS AUTOMATIC DETECTION

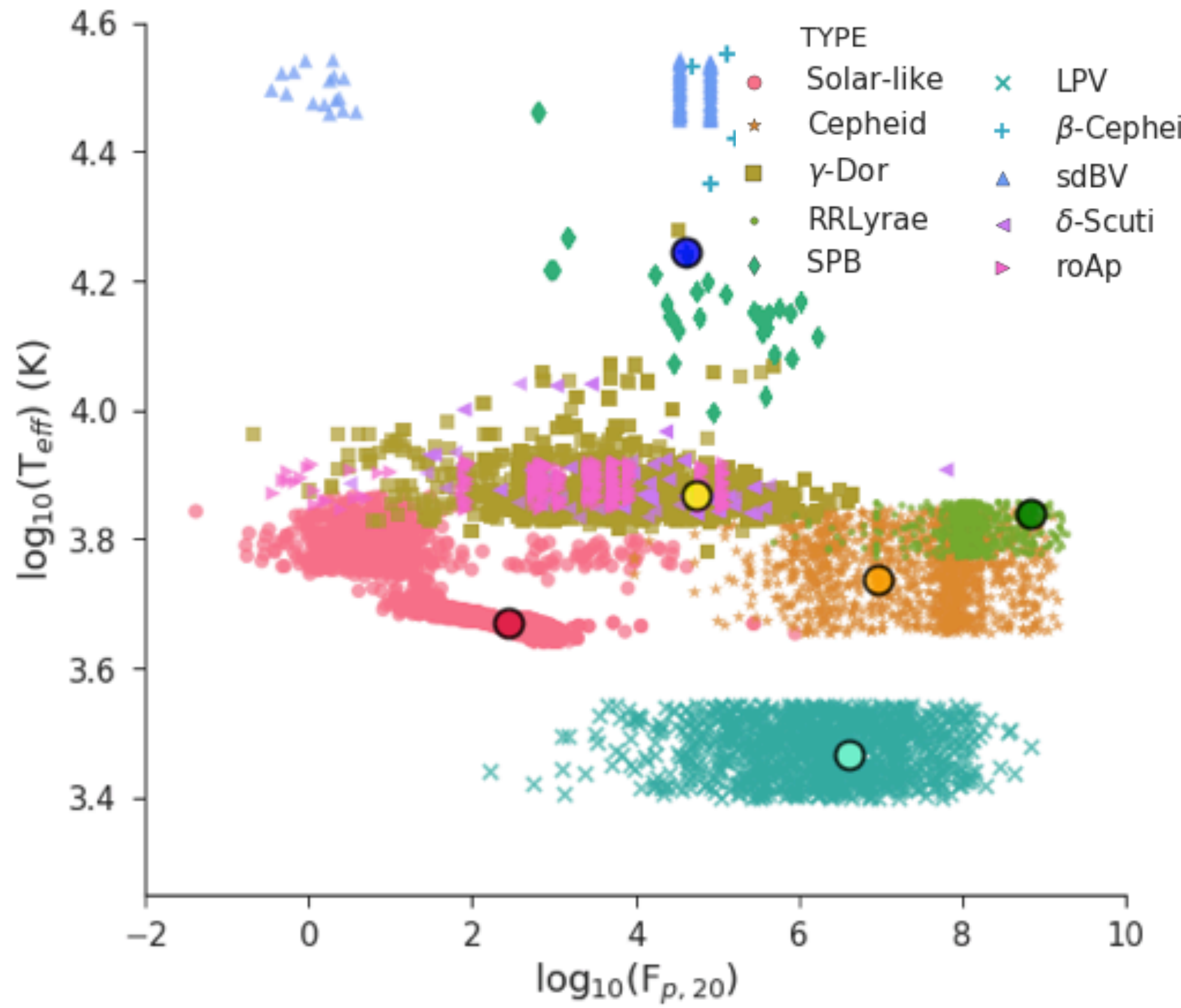




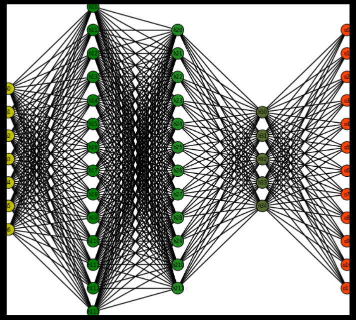
Classification of solar-type pulsators among other stars

Included in the T'DA classification pipeline for TESS targets

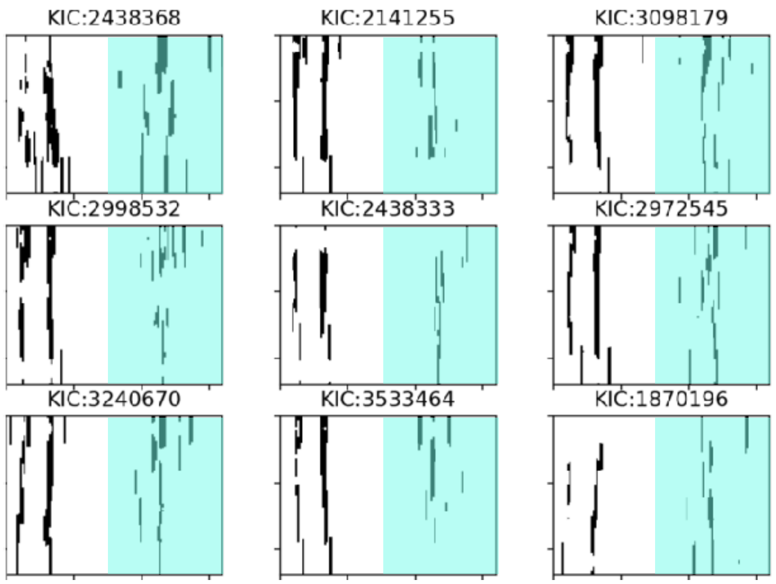
extension to K2 data, work in progress.



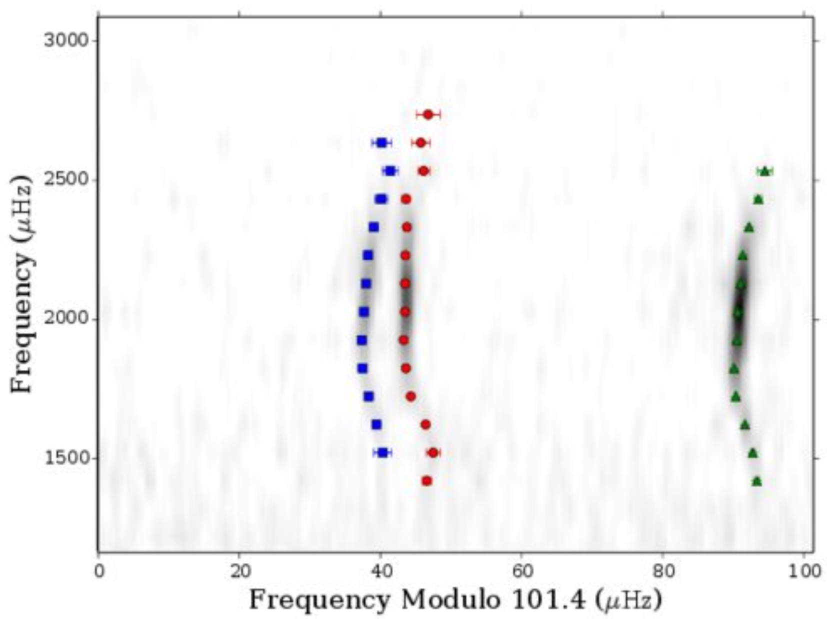
1 LOW-AMPLITUDE L=1 MIXED MODES AUTOMATIC DETECTION

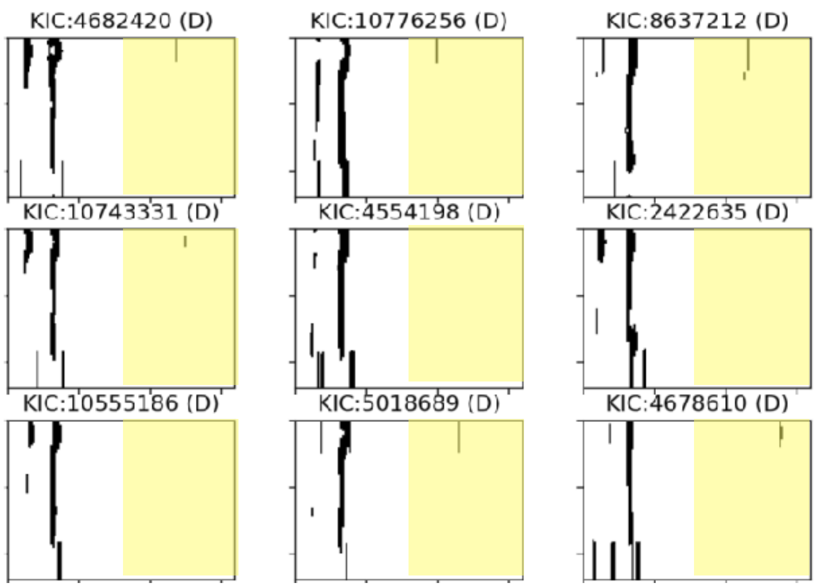


Le Saux, Bugnet et al., *in prep*



Normal RG





Low-amplitude RG detected

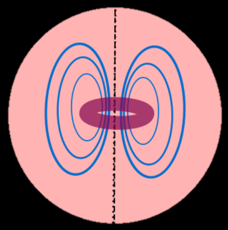
Automatic detection of low-amplitude mixed-modes: sample on which to study the frequency pattern: signature of internal magnetic field ?

Detection of stars with partial low amplitude: work in progress

Garcia et al., 2014

To understand observations:

2 Effect of an axisymmetric fossil magnetic field aligned with rotation axis on mixed-mode frequencies



TOPOLOGY

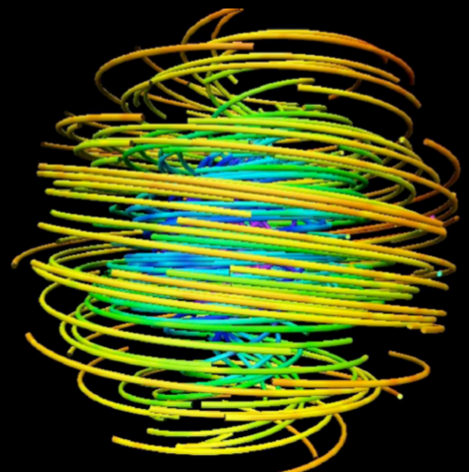
For M>1.3 Ms, convective core on the MS: **dynamo-generated field that can persist through the RGB as a fossil field in the core.**
Stello et al., 2016

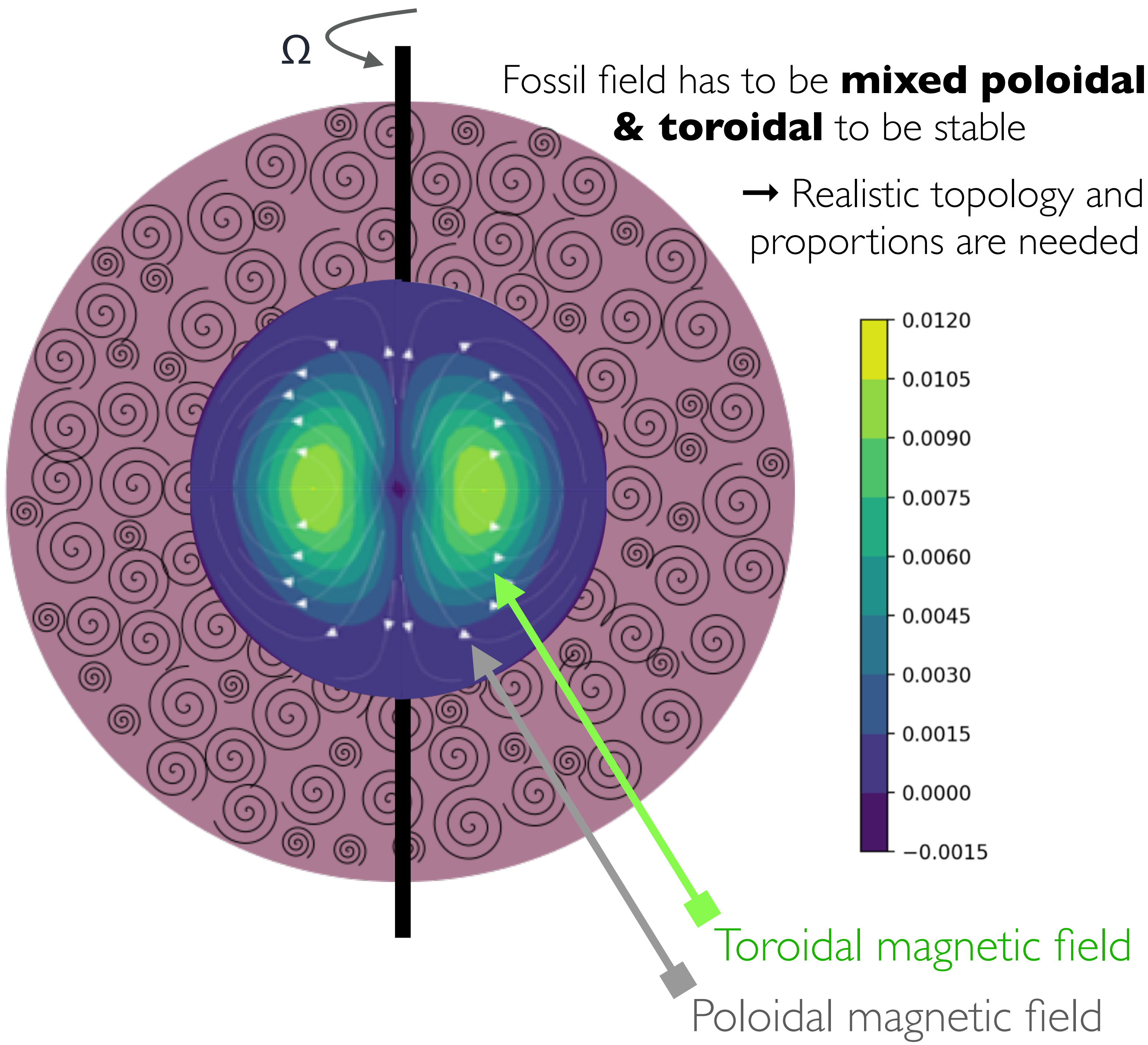
Simulation: formation of a fossil field

Braithwaite & Spruit 2004

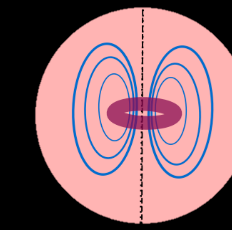
Closest semi-analytic description

Duez et al., 2010



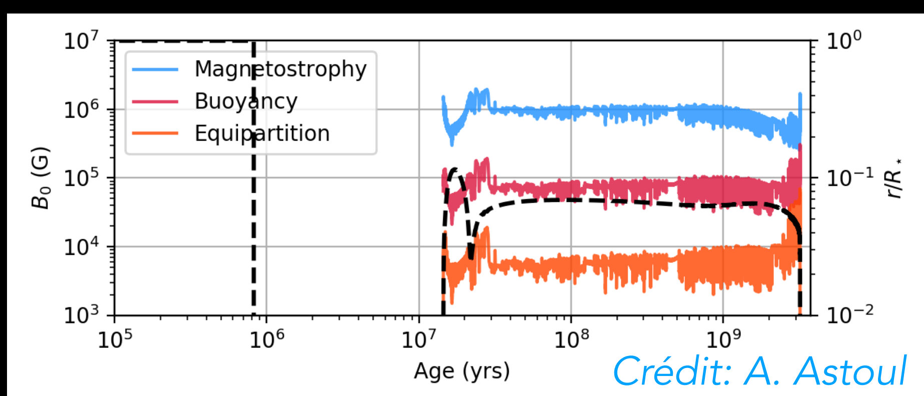


2 EFFECT OF AN AXISYMMETRIC FOSSIL MAGNETIC FIELD ALIGNED WITH ROTATION AXIS ON MIXED-MODE FREQUENCIES



AMPLITUDE

For M>1.3 Ms, convective core on the MS: **dynamo-generated field that can persist through the RGB as a fossil field in the core.**
Stello et al., 2016



Crédit: A. Astoul

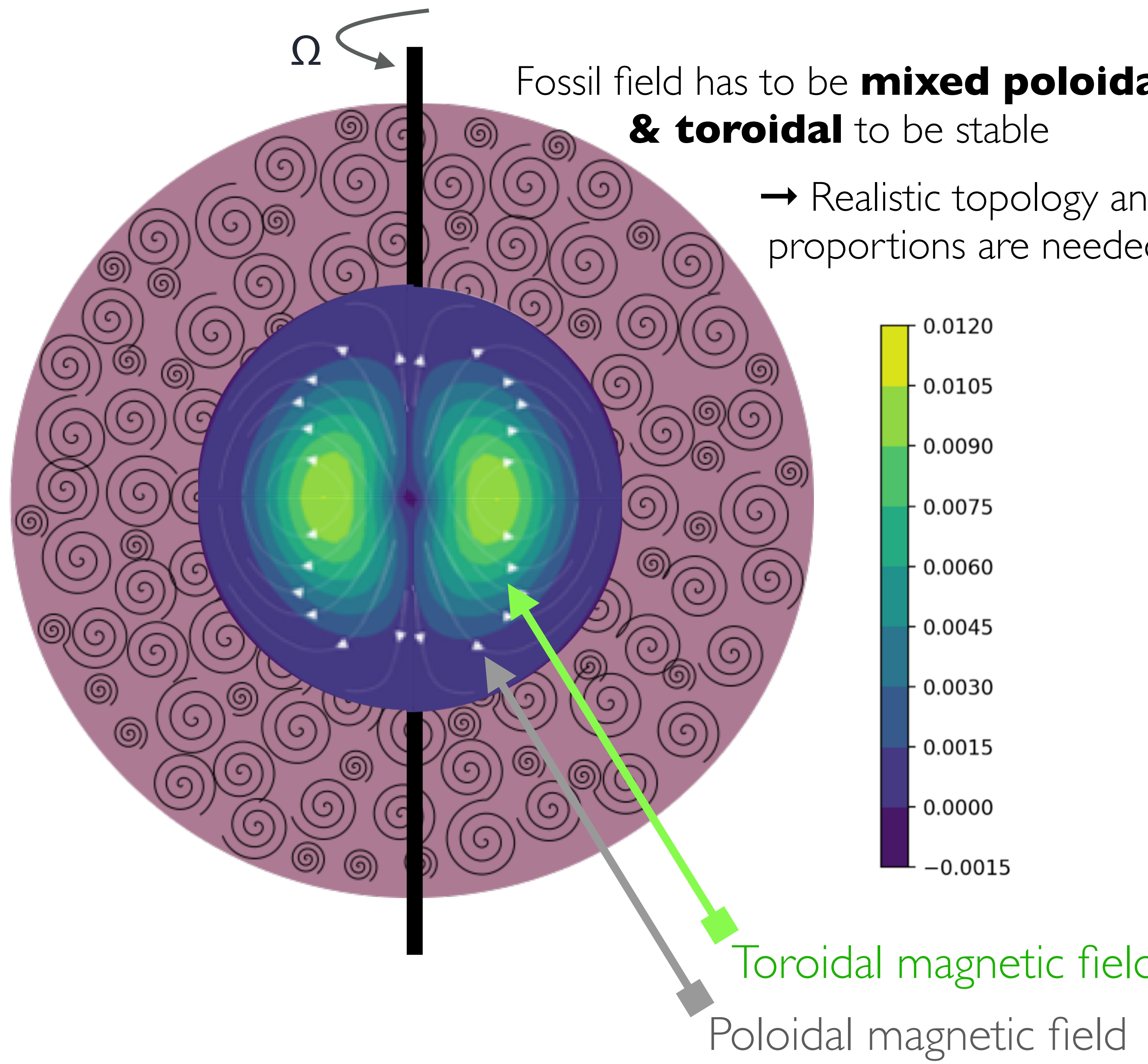
Internal magnetic field at the end of MS: amplitude 0.01-1MG

↓ *Magnetic flux conservation*

*Internal magnetic field on top of RGB: amplitude **0.1-10MG***

Fossil field has to be **mixed poloidal & toroidal** to be stable

→ Realistic topology and proportions are needed



Linearised momentum equation

Coriolis component

Perturbations

Change of frame

$$\omega^2 \boldsymbol{\xi} + i\omega \left(\boldsymbol{F_c}(\boldsymbol{\xi}) + \boldsymbol{F_f}(\boldsymbol{\xi}) \right) + \boldsymbol{F}(\boldsymbol{\xi}) = \boldsymbol{0}$$

Pressure and buoyancy forces

Magnetic field component *Perturbation*

Magnetic amplitude B_0=1MG coherent with dynamo action in the core of main-sequence stars *Duez et al., 2010*

Core rotation rate Ω_{core}=0.5 μHz
Envelope rotation rate Ω_{env}=0.05 μHz

Deheuvels et al., 2012
Gehan et al., 2018

ξ_0 *Paxton et al., 2011* *Townsend et al., 2013* MESA+GYRE

Mixed modes

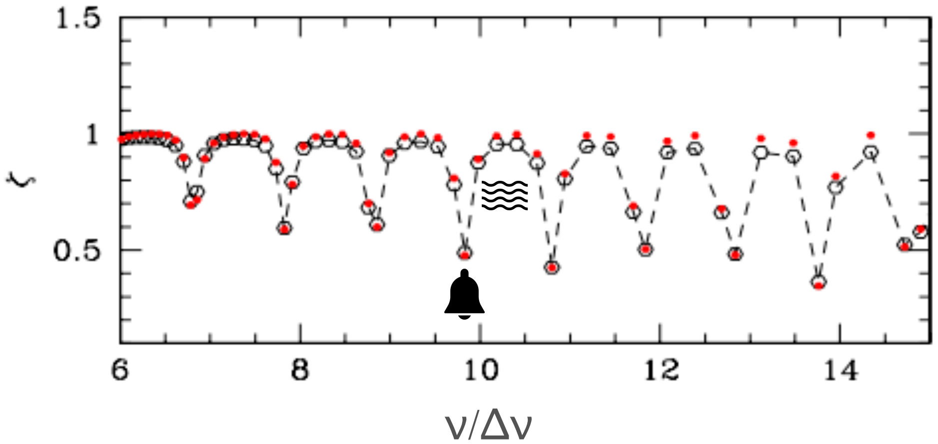
First-order perturbation:

$$\omega_1 = -\frac{\langle \boldsymbol{\xi}_0, \delta \boldsymbol{F}_L(\boldsymbol{\xi}_0) \rangle + \langle \boldsymbol{\xi}_0, \boldsymbol{F}_c(\boldsymbol{\xi}_0) \rangle + \langle \boldsymbol{\xi}_0, \boldsymbol{F}_f(\boldsymbol{\xi}_0) \rangle}{2\omega_0 \langle \boldsymbol{\xi}_0, \boldsymbol{\xi}_0 \rangle}$$

2 Effect of Coriolis acceleration on mixed mode frequencies

$$\zeta = \frac{\mathcal{I}_{\text{core}}}{\mathcal{I}} = \frac{\int_0^{R_{\text{rad}}} \left(\xi_r^2 + \Lambda \xi_h^2\right) r^2 dr}{\int_0^{R_\star} \left(\xi_r^2 + \Lambda \xi_h^2\right) r^2 dr}$$

Goupil et al., 2013



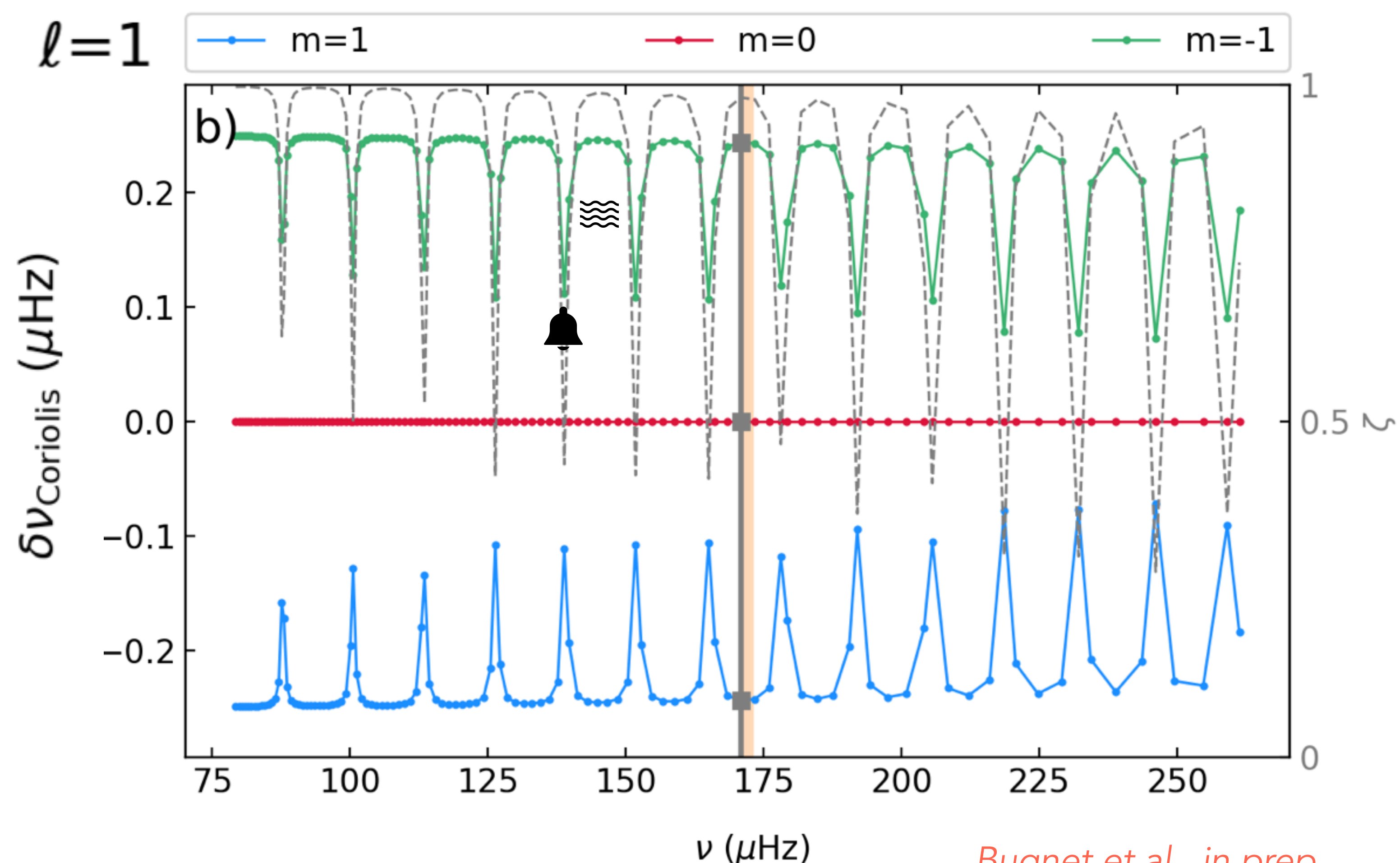
$$\delta \nu_{\text{rot}} \approx \frac{1}{2} \left\langle \frac{\Omega}{2\pi} \right\rangle_{\text{core}} \zeta$$

Core rotation rate Ω_{core}=0.5 μHz
Envelope rotation rate Ω_{env}=0.05 μHz

Deheuvels et al., 2012
Gehan et al., 2018

First-order perturbation:

$$\omega_1 = - \frac{\langle \boldsymbol{\xi}_0, \delta \boldsymbol{F}_L(\boldsymbol{\xi}_0) \rangle + \langle \boldsymbol{\xi}_0, \boldsymbol{F}_c(\boldsymbol{\xi}_0) \rangle + \langle \boldsymbol{\xi}_0, \boldsymbol{F}_f(\boldsymbol{\xi}_0) \rangle}{2\omega_0 \langle \boldsymbol{\xi}_0, \boldsymbol{\xi}_0 \rangle}$$

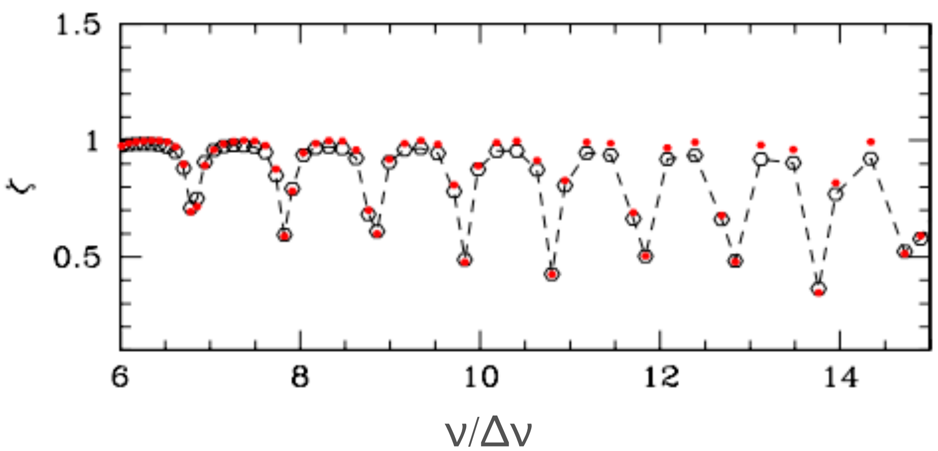


Bugnet et al., in prep

2 Effect of the change of frame on mixed mode frequencies

$$\zeta = \frac{\mathcal{I}_{\text{core}}}{\mathcal{I}} = \frac{\int_0^{R_{\text{rad}}} \left(\xi_r^2 + \Lambda \xi_h^2\right) r^2 dr}{\int_0^{R_\star} \left(\xi_r^2 + \Lambda \xi_h^2\right) r^2 dr}$$

Goupil et al., 2013



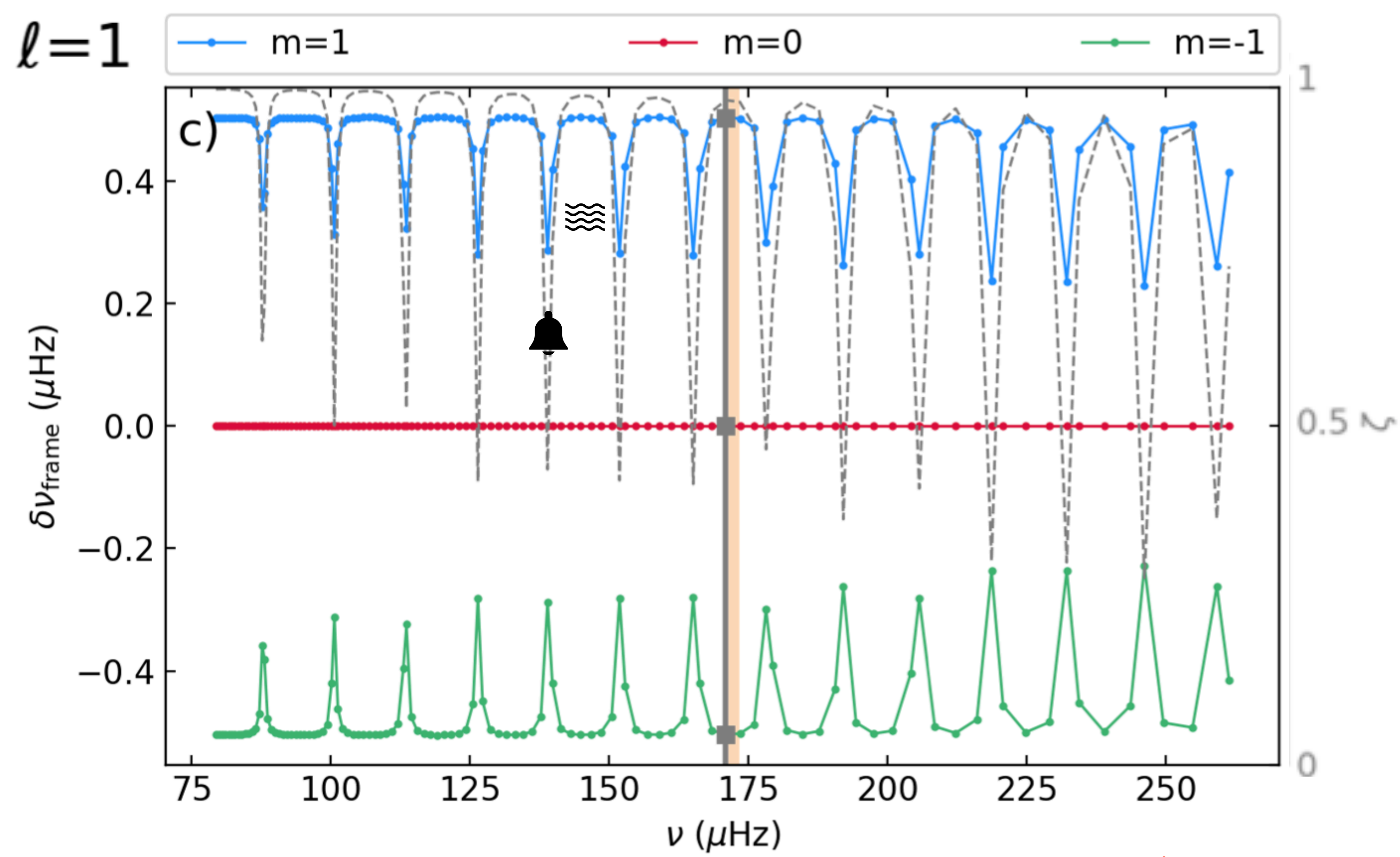
$$\delta \nu_{\text{rot}} \approx \frac{1}{2} \left\langle \frac{\Omega}{2\pi} \right\rangle_{\text{core}} \zeta$$

Core rotation rate Ω_{core}=0.5 μHz
Envelope rotation rate Ω_{env}=0.05 μHz

Deheuvels et al., 2012
Gehan et al., 2018

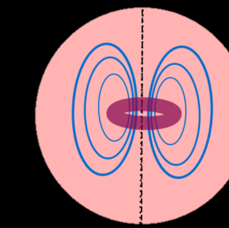
First-order perturbation:

$$\omega_1 = -\frac{\langle \boldsymbol{\xi}_0, \delta \boldsymbol{F}_L(\boldsymbol{\xi}_0)\rangle + \langle \boldsymbol{\xi}_0, \boldsymbol{F}_c(\boldsymbol{\xi}_0)\rangle + \langle \boldsymbol{\xi}_0, \boldsymbol{F}_f(\boldsymbol{\xi}_0)\rangle}{2\omega_0 \langle \boldsymbol{\xi}_0, \boldsymbol{\xi}_0 \rangle}$$



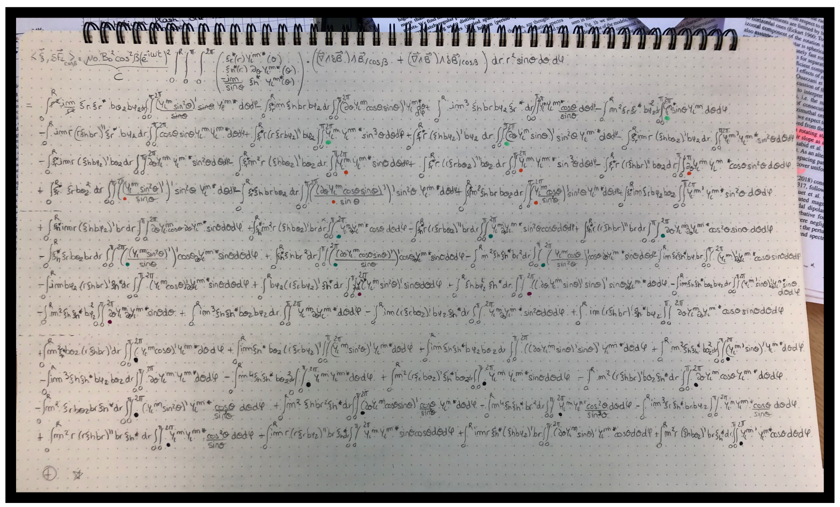
Bugnet et al., in prep

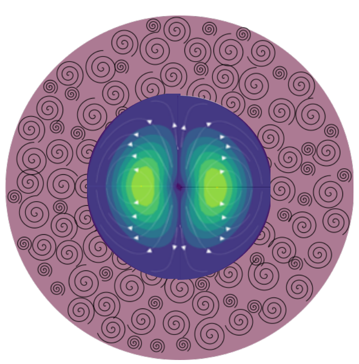
Effect of an axisymmetric fossil magnetic field on mixed mode frequencies



$$\delta\nu_{\rm mag} = \delta\nu_{\rm g,mag}\zeta + \delta\nu_{\rm p,mag}(1-\zeta)$$

Mathis, Bugnet et al., in prep



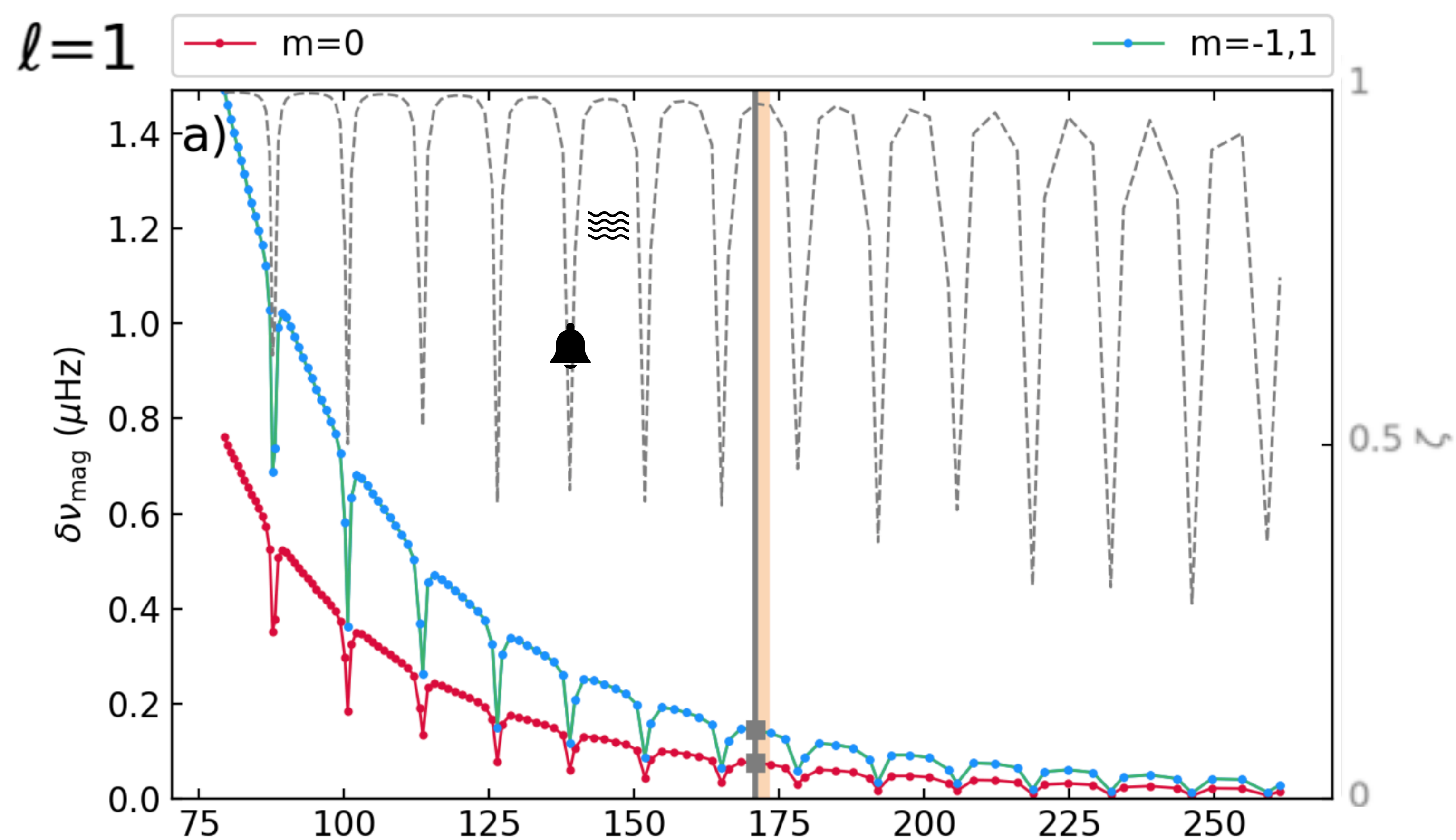


Duez et al., 2010

Magnetic field amplitude B_0=1MG coherent with dynamo action in the core of main-sequence stars

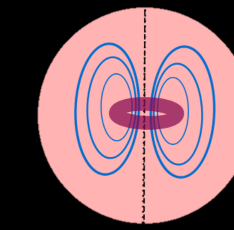
First-order perturbation:

$$\omega_1 = -\frac{\langle \boldsymbol{\xi}_0, \delta \boldsymbol{F}_L(\boldsymbol{\xi}_0)\rangle + \langle \boldsymbol{\xi}_0, \boldsymbol{F}_c(\boldsymbol{\xi}_0)\rangle + \langle \boldsymbol{\xi}_0, \boldsymbol{F}_f(\boldsymbol{\xi}_0)\rangle}{2\omega_0\langle \boldsymbol{\xi}_0, \boldsymbol{\xi}_0\rangle}$$



Bugnet et al., in prep

2 Effect of an axisymmetric fossil magnetic field on mixed mode frequencies: Asymptotic expression

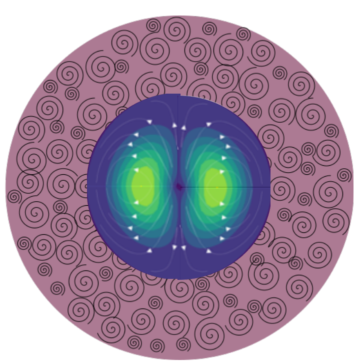


$$\delta\nu_{\rm mag} = \delta\nu_{\rm g,mag}\zeta + \delta\nu_{\rm p,mag}(1-\zeta)$$

Mathis, Bugnet et al., in prep

State of the art for rotation:

$$\left(\frac{\delta\omega}{\omega_0}\right)_{\rm g,rot} \propto \frac{\int_0^1 \frac{\Omega(x)N}{x}dx}{\int_0^1 \frac{N}{x}dx}$$

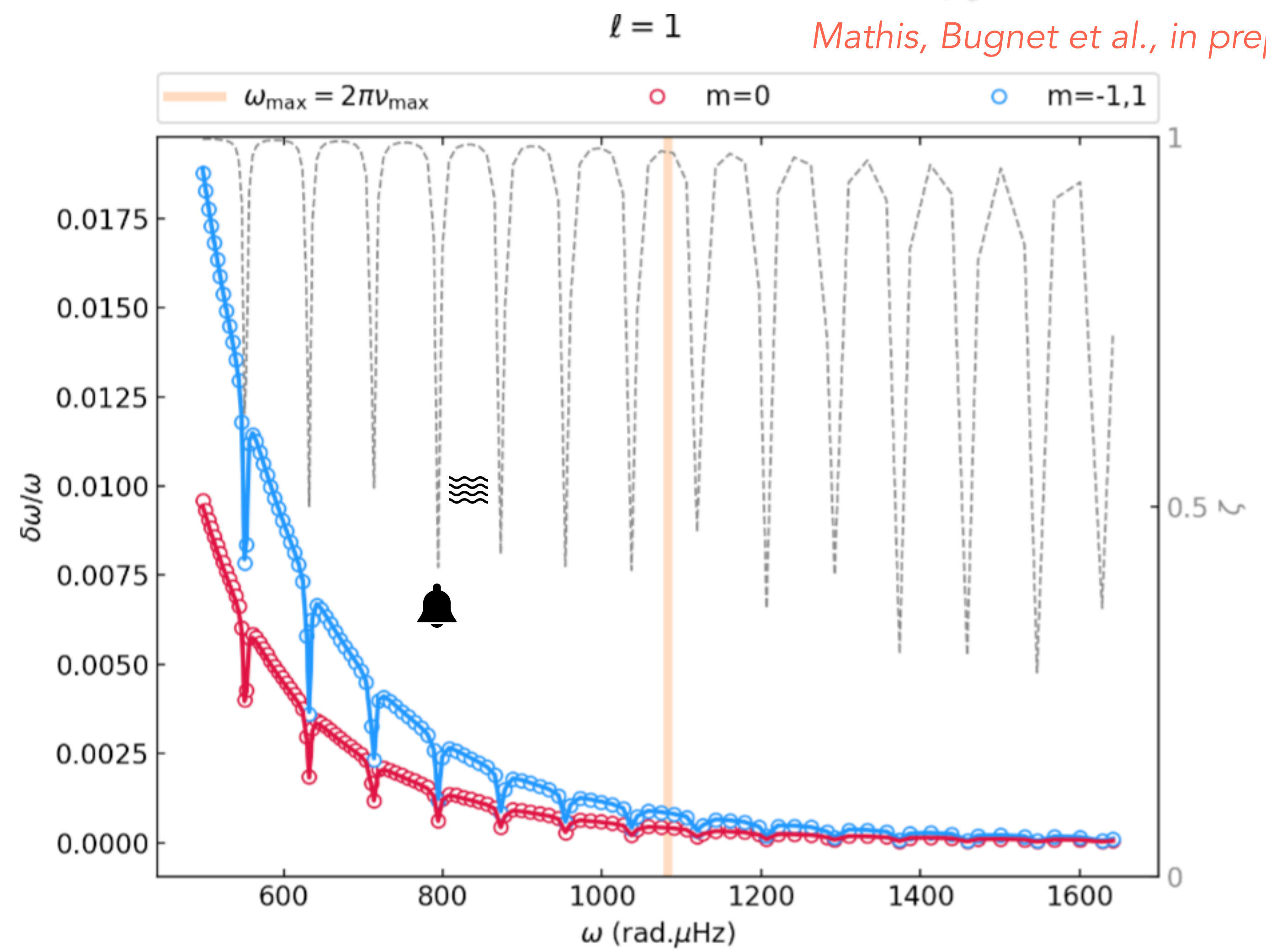


Duez et al., 2010

Magnetic amplitude B_0=1MG coherent with dynamo action in the core of main-sequence stars

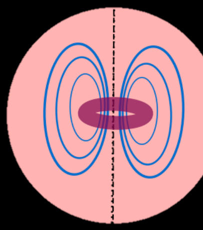
$$\left(\frac{\delta\omega}{\omega_0}\right)_g = \frac{1}{2}\frac{B_0^2}{4\pi\rho_c R^2\omega_0^2}\frac{N_{\rm max}^2}{\omega_0^2} l(l+1)\, C_{l,m} \frac{\int_0^1 \boxed{\frac{b_r^2\widehat{N}^2}{(\rho/\rho_c)\,x^2}}\widehat{N}\frac{{\rm d}x}{x}}{\int_0^1 \widehat{N}\frac{{\rm d}x}{x}}$$

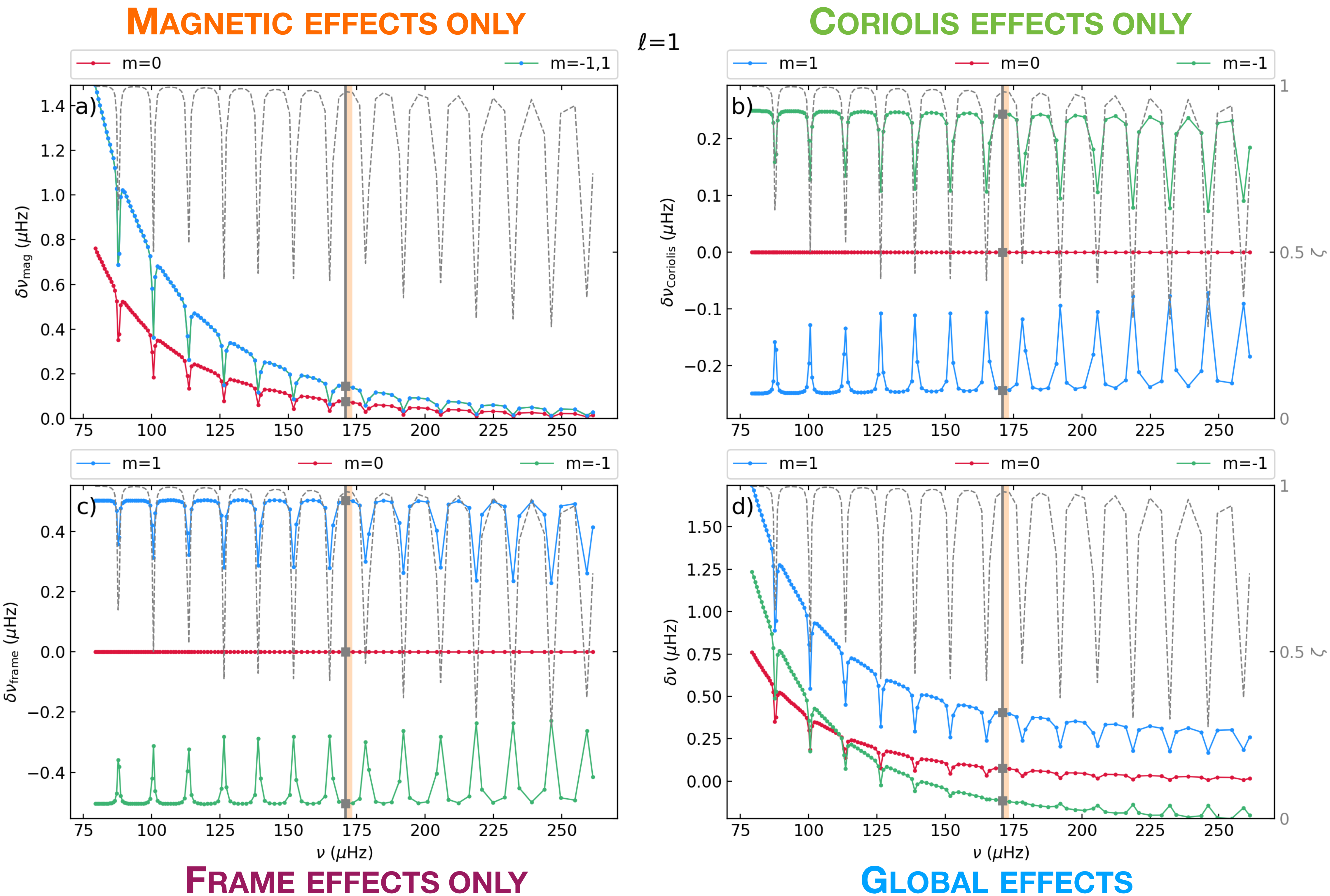
Mathis, Bugnet et al., in prep



May allow inversion of the magnetic field as for rotation…

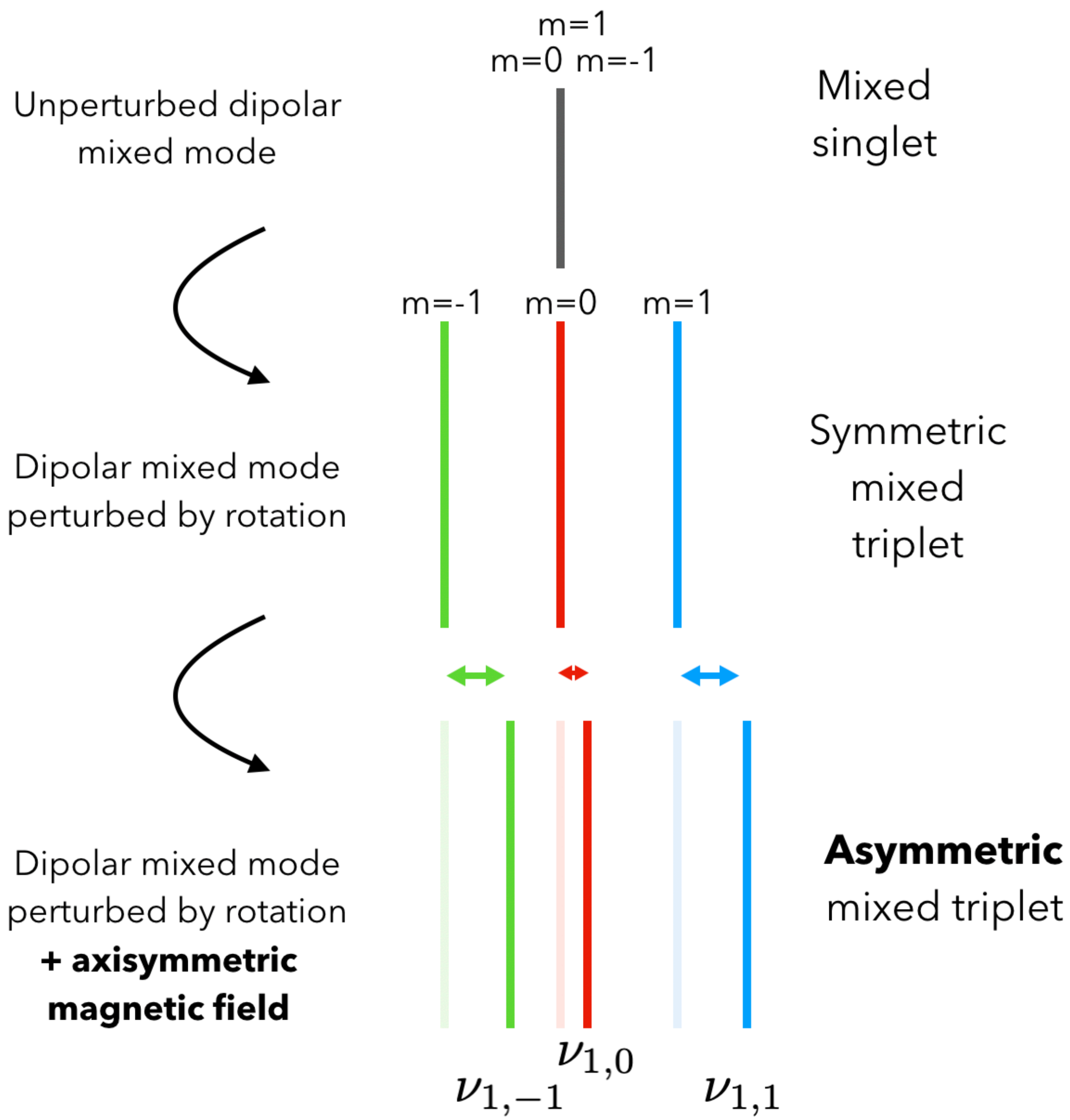
2 Mixed mode frequency shifts for a typical M =1.5M$_\odot$ red giant





Bugnet et al., in prep

2 CHARACTERISATION OF THE ASYMMETRY OF THE MULTIPLET



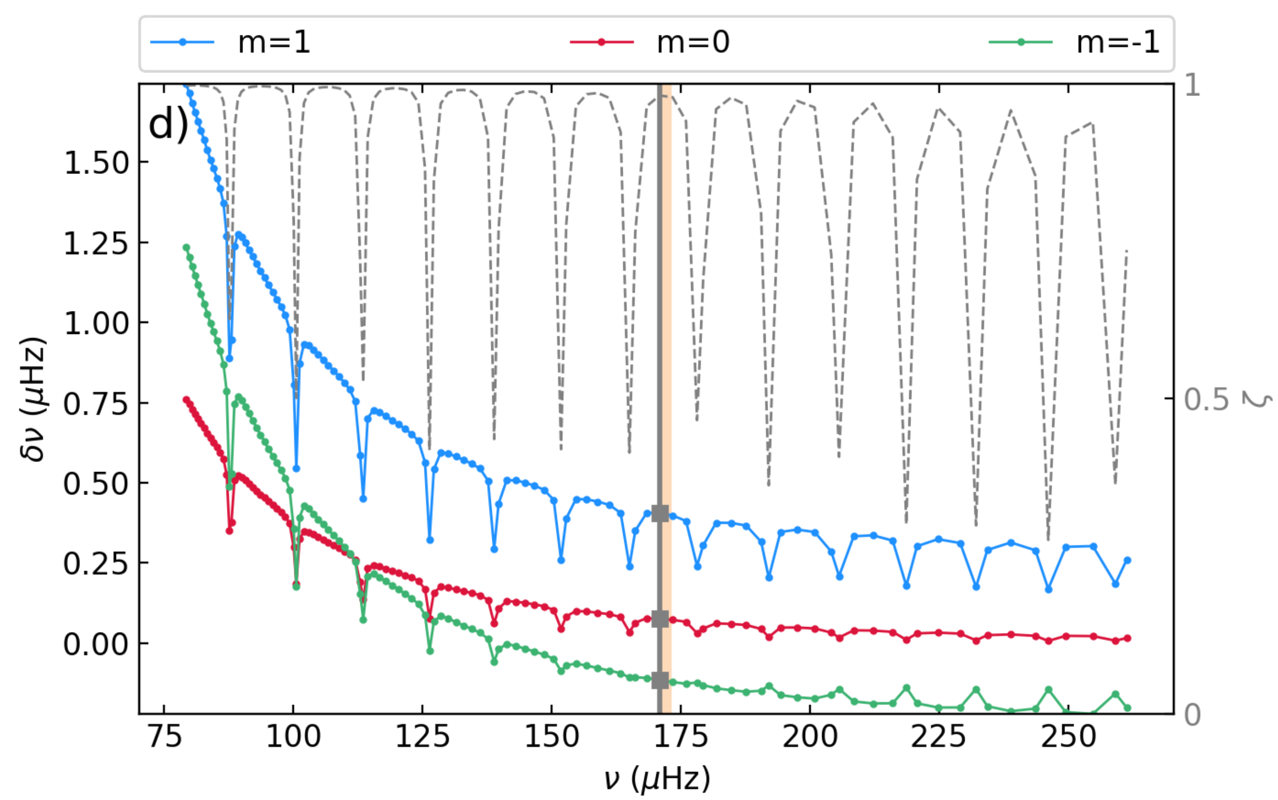
Magnetic splitting asymmetry degree:

$$\delta_{\ell,m} = \frac{\nu_{\ell,m} + \nu_{\ell,-m} - 2\nu_{\ell,0}}{\nu_{\ell,m} - \nu_{\ell,-m}}$$

Other known sources of asymmetry:

<u>Easily distinguishable:</u> Non-degenerate effects

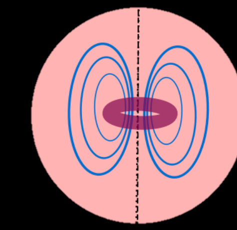
<u>Negligible:</u> second-order rotational effects, buoyancy glitches, latitudinal differential rotation

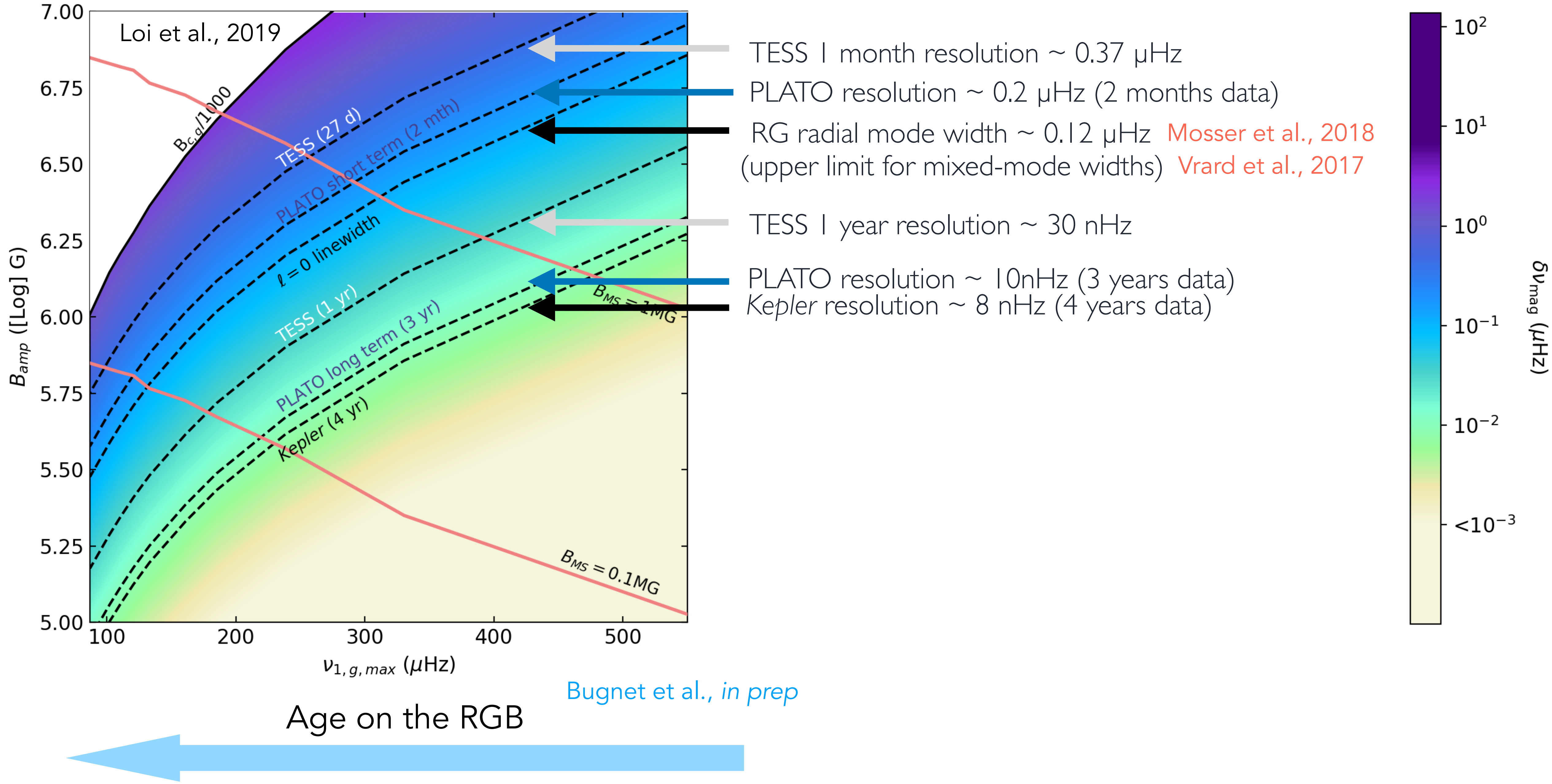


GLOBAL EFFECTS

Bugnet et al., in prep

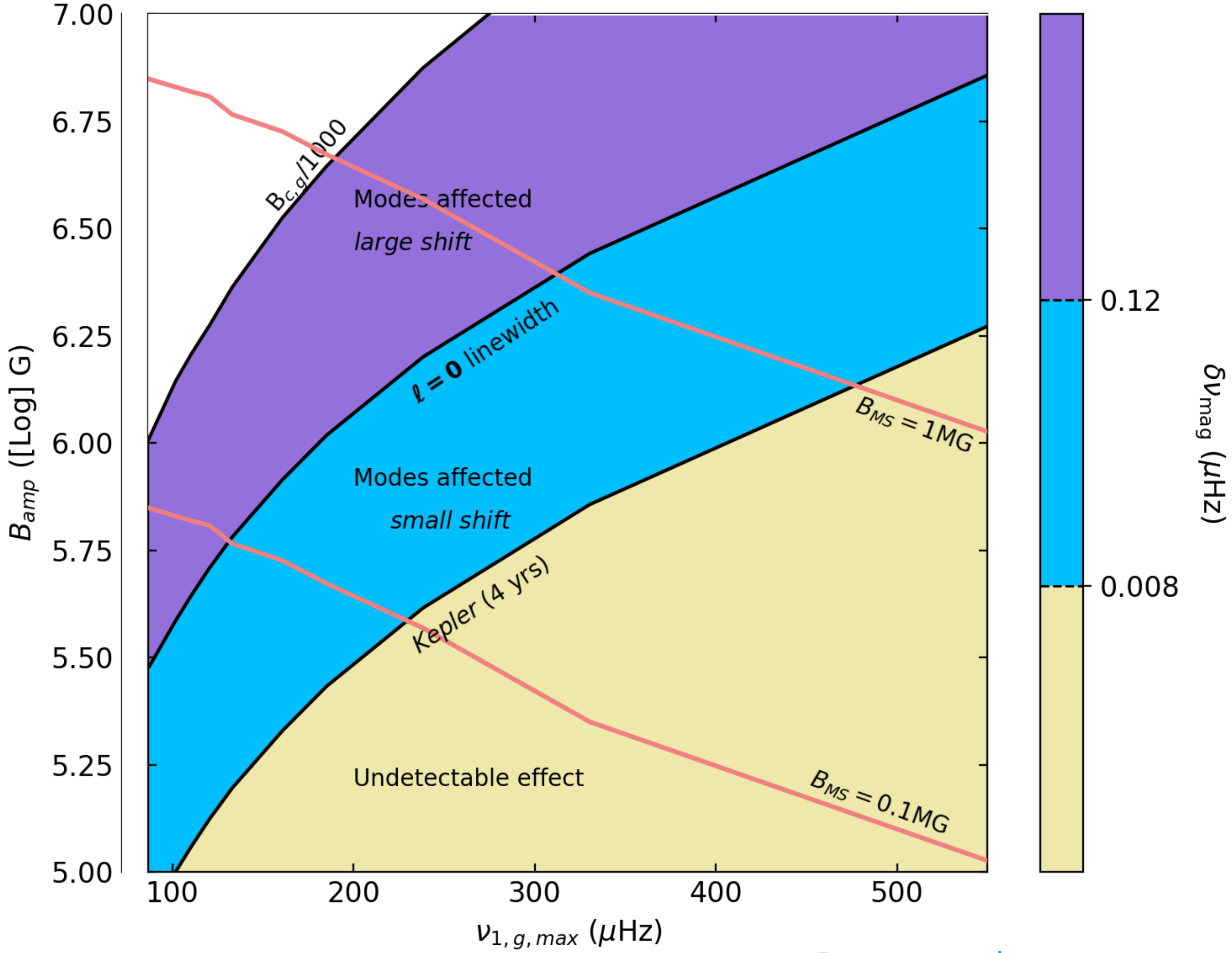
2 MIXED MODE MAGNETIC FREQUENCY SHIFTS EVOLUTION ON THE RGB FOR A TYPICAL M =1.5M$_\odot$, Z=0.02 RED GIANT





Bugnet et al., *in prep*

2 MIXED MODE MAGNETIC FREQUENCY SHIFTS EVOLUTION ON THE RGB FOR A TYPICAL M =1.5M$_\odot$, Z=0.02 RED GIANT



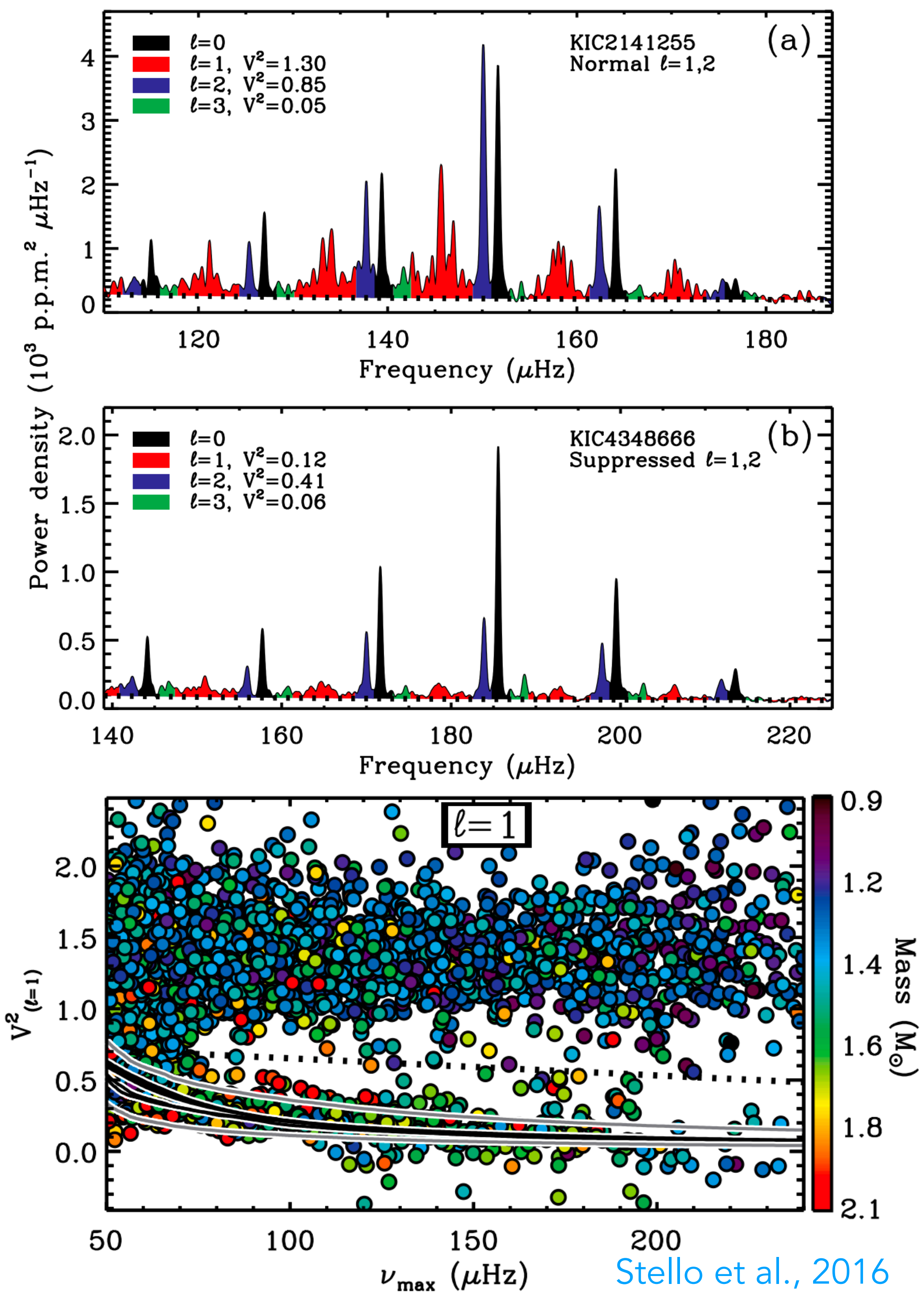
Bugnet et al., *in prep*

Age on the RGB

2

Challenging question 1:

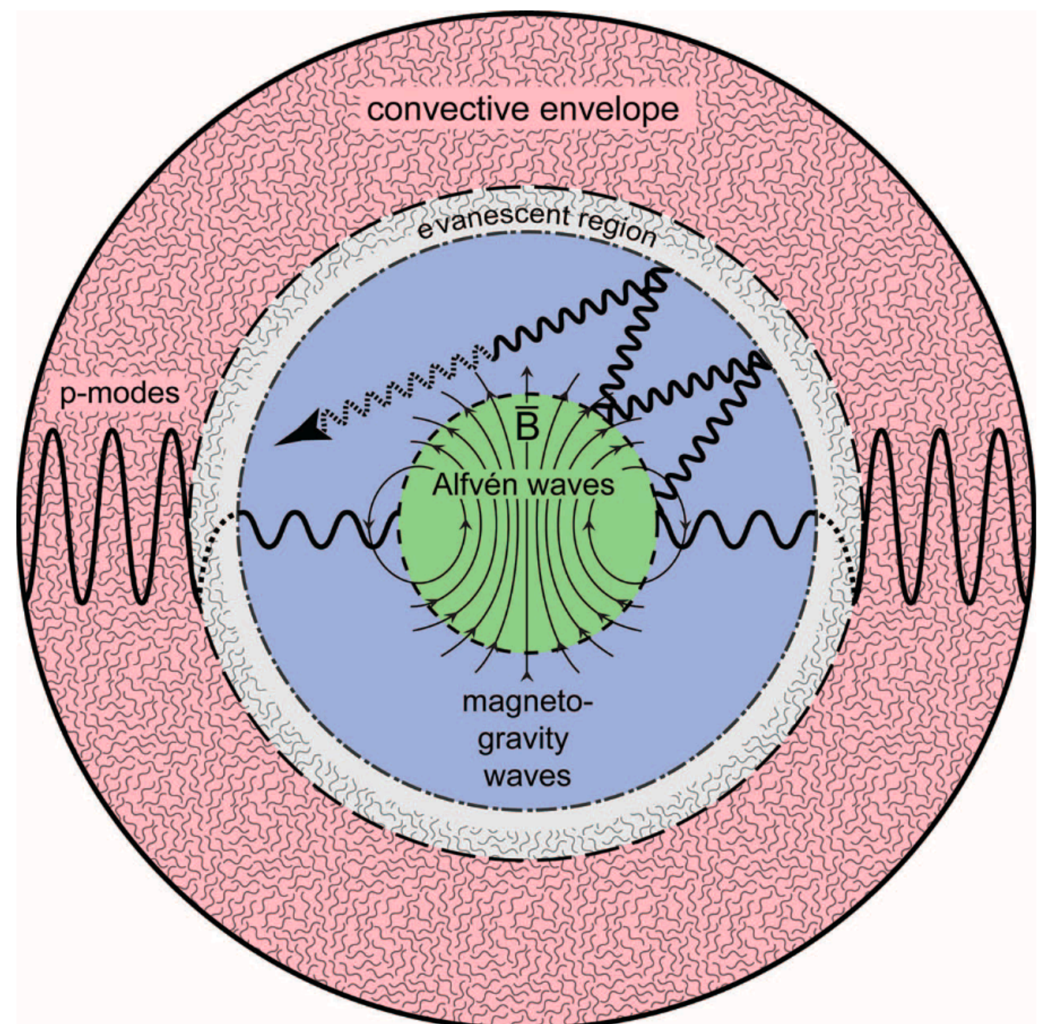
How can we explain the lack of power observed in dipolar modes ?



Stello et al., 2016

Magnetic « Green house » effect

Controversial

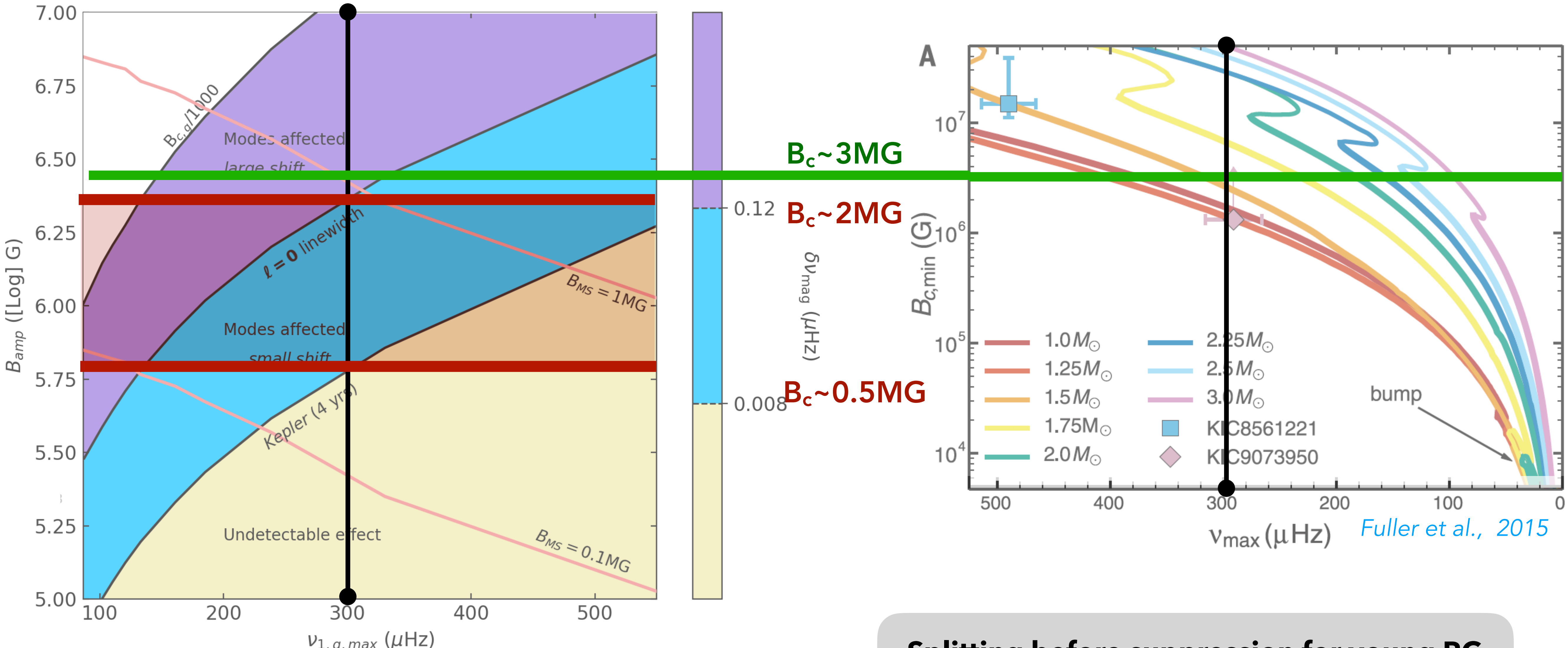


Fuller et al., 2015

2 Comparison with critical field for mode suppression for a typical M =1.5M$_\odot$, Z=0.02, ν_{max}=300 μHz red giant

Critical field for mode shifting

Critical field for mode suppression



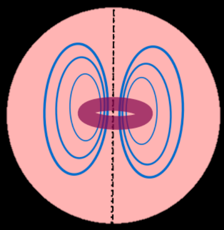
Bugnet et al., *in prep*

Age on the RGB

Splitting before suppression for young RG

2 **Challenging question 2:**

The rotation rate of RG cores is about 2 orders of magnitude lower than the value predicted by the standard theory of angular momentum. How can we explain observations ?



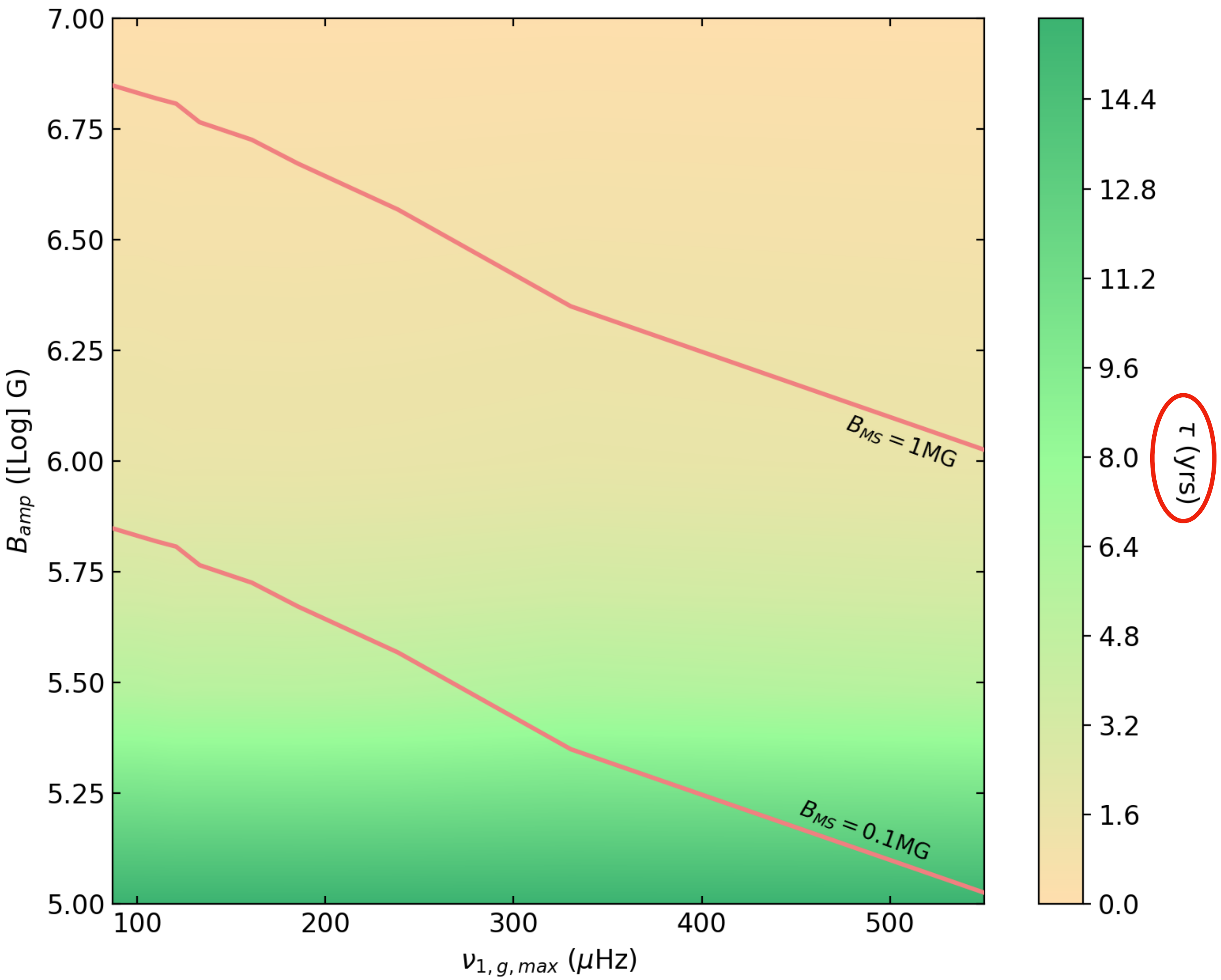
Characteristic time for the magnetic torque to flatten the rotational profile of the radiative interior

$$v_{A,p} = \frac{|B_p|}{\sqrt{4\pi\rho}}$$

$$\tau_{AM} = \frac{R_{\Delta\Omega}}{v_{A,p}}$$

Mestel et al., 1987

Very fast redistribution of angular momentum



Other important works:
Fuller et al, 2019, Eggenberger et al., 2020
for unstable fields that may transport AM efficiently

Data analysis: Machine learning for global asteroseismology

- **FliPer**: new independent global method for the recognition and estimation of surface gravity of solar-like stars
- **FliPer$_{\text{Class}}$**: new independent global method for the recognition and estimation of surface gravity of solar-like stars
- Neural network for the detection of low-amplitude dipolar mixed modes

Theoretical work on internal magnetism inside RG (and SG):

- Shift towards higher frequencies, asymmetry should be detectable in data. Increases with the star evolution.
- Critical observable axisymmetric fossil field aligned with rotation : ~1MG
- Critical field is of the same order of magnitude than field needed to suppress modes: splitting before suppression ?
- Redistribution of AM inside the radiative interior in about a year: magnetism very efficient to transport AM

Future & Prospects

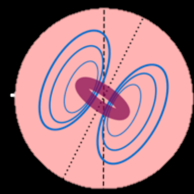
The search for **magnetic signature inside data:** Bayesian comparison of different fitting models to the data e.g. Benomar et a., 2008, Davies et. al., 2016

Estimation of the **rotation profile** for sub-giant stars presenting magnetic signature ? (if found)

Core
Method similar to Gehan et al., 2018

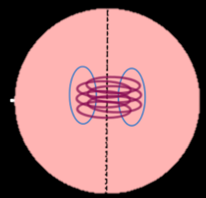
Surface
Application of ML to extract surface rotation rates
Impact on **gyrochronology**
Breton et al., *in prep*

Non-axisymmetric pattern: hyperfine structure expected



e.g. Goode & Thompson1989

Non-fossil field pattern: **rotation driven magnetism**

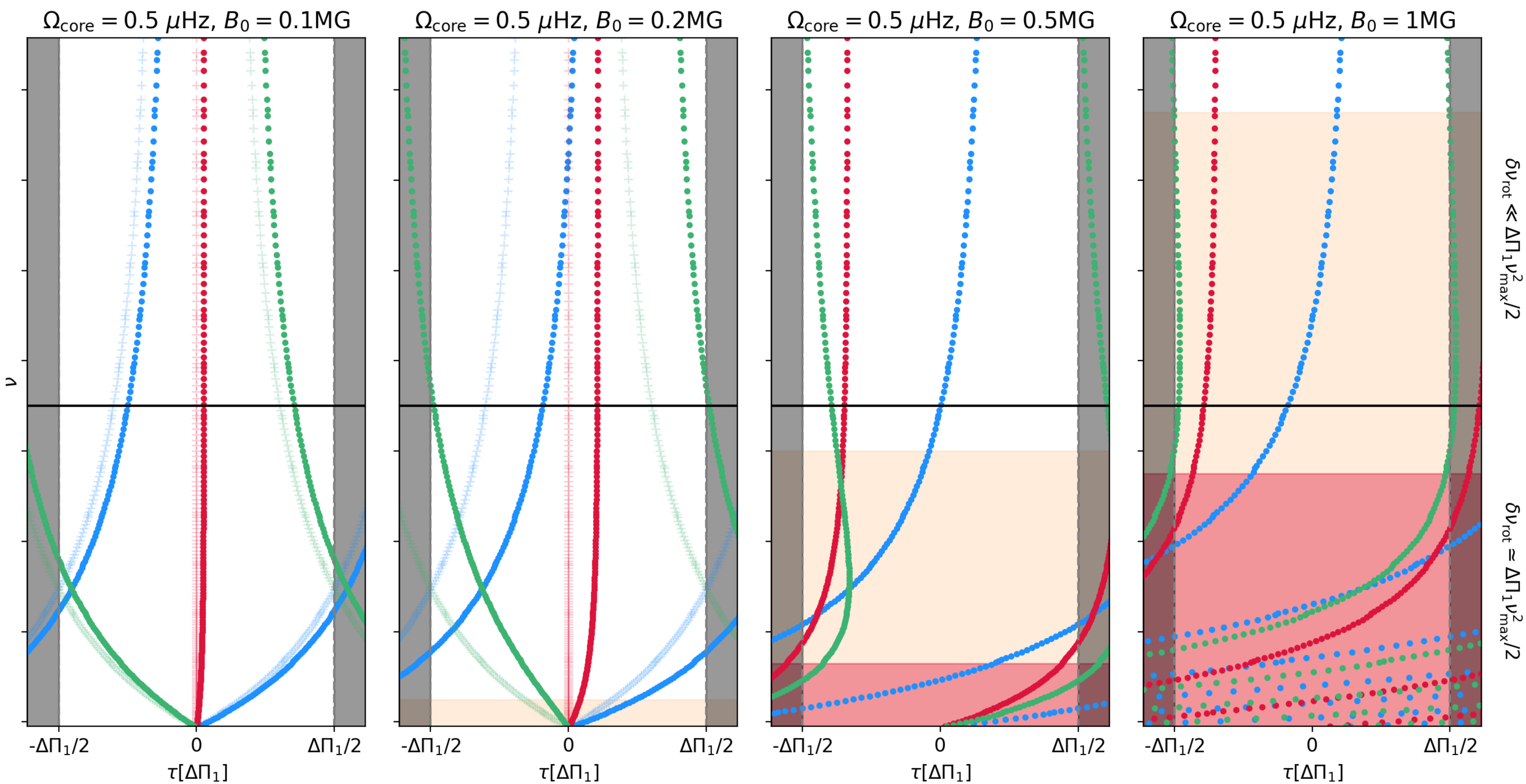


e.g. Fuller et. al., 2019

Expression of the **coupling factors** in presence of magnetism

SUPPLEMENTARY MATERIALS

2 Stretched echelle diagrams



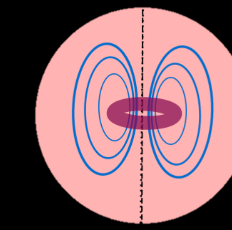
Stretched period: $\mathrm{d}\tau_m = \frac{1}{\zeta}\frac{\mathrm{d}\nu}{\nu}$

$$\Delta\tau_m = \Delta\Pi_1 \left(1 + 2\zeta \frac{\delta\nu_{\mathrm{rot,g},m} + \delta\nu_{\mathrm{mag,g},m}}{\nu}\right)$$

2

CHALLENGING QUESTION 2:

The rotation rate of RG cores is about **2 orders of magnitude lower** than the value predicted by the standard theory of angular momentum. How can we explain observations ?



Equation of motion:

$$\rho r^2 \sin^2\theta \frac{\partial \Omega}{\partial t} = \frac{1}{4\pi} \vec{B_p}.\vec{\nabla}[r \sin\theta B_\phi]$$

+ Equation of induction if B_p is constant

$$\frac{\partial B_\phi}{\partial t} = r(\vec{B_p}.\vec{\nabla})\Omega$$

➡Linear wave equation:

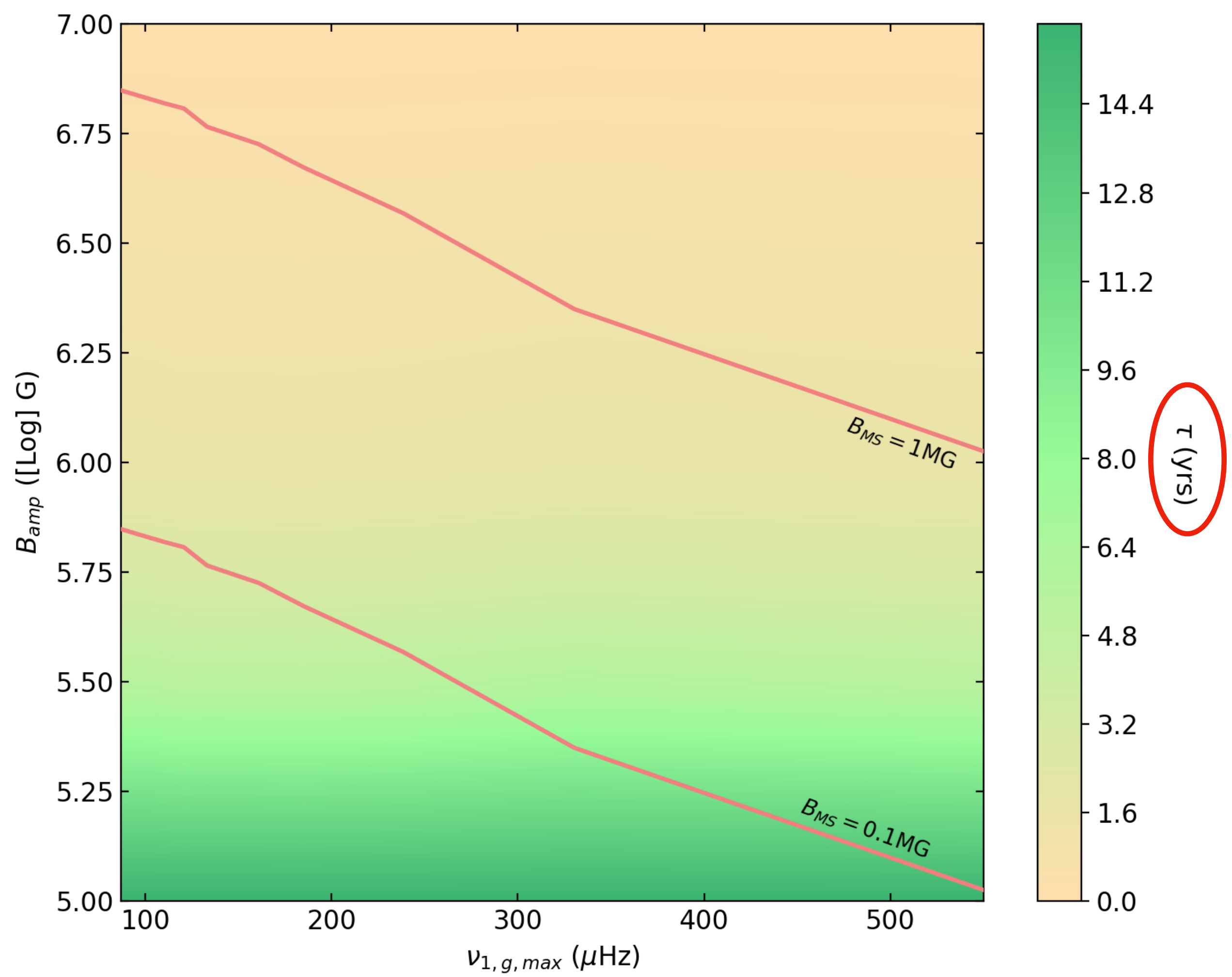
$$\rho r^2 \sin^2\theta \frac{\partial^2 \Omega}{\partial t^2} = \frac{1}{4\pi} \vec{B_p}.\vec{\nabla}[r^2 \sin^2\theta (\vec{B_p}.\vec{\nabla})\Omega]$$

Order of magnitude:

$$R^2 \frac{\Omega}{t_{AM}^2} = \frac{1}{4\pi\rho} \frac{B_p^2}{R_{\Delta\Omega}^2} R^2\Omega \qquad v_{A,p} = \frac{|B_p|}{\sqrt{4\pi\rho}}$$

$$\tau_{AM} = \frac{R_{\Delta\Omega}}{v_{A,p}}$$

Mestel et al., 1987



Very fast redistribution of angular momentum