

*Pulsations on the Main Sequence:
constraining Ω profiles and μ gradients*

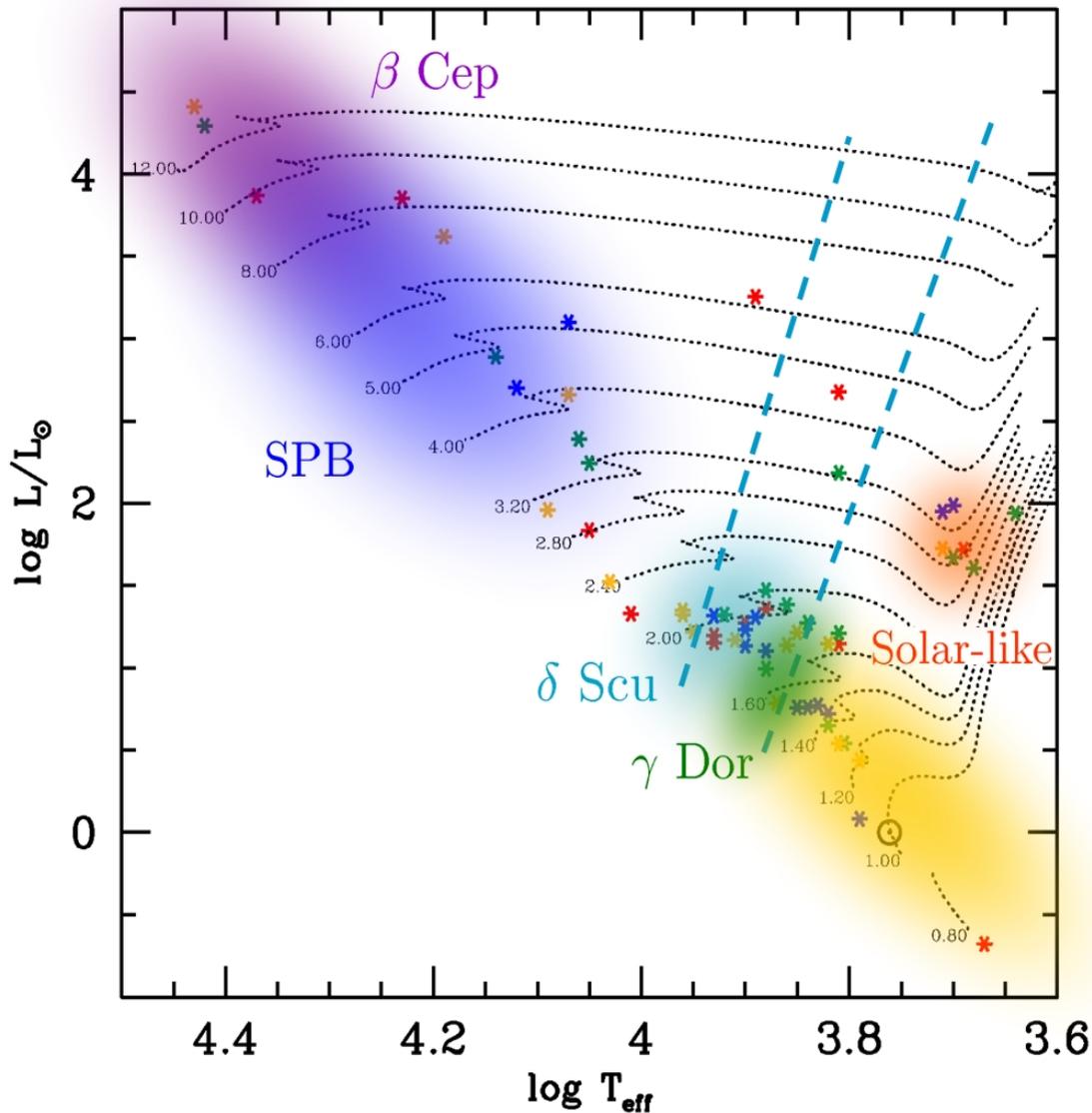
Sébastien Salmon



European Research Council
Established by the European Commission

23rd April 2020

The pulsating HR diagram:

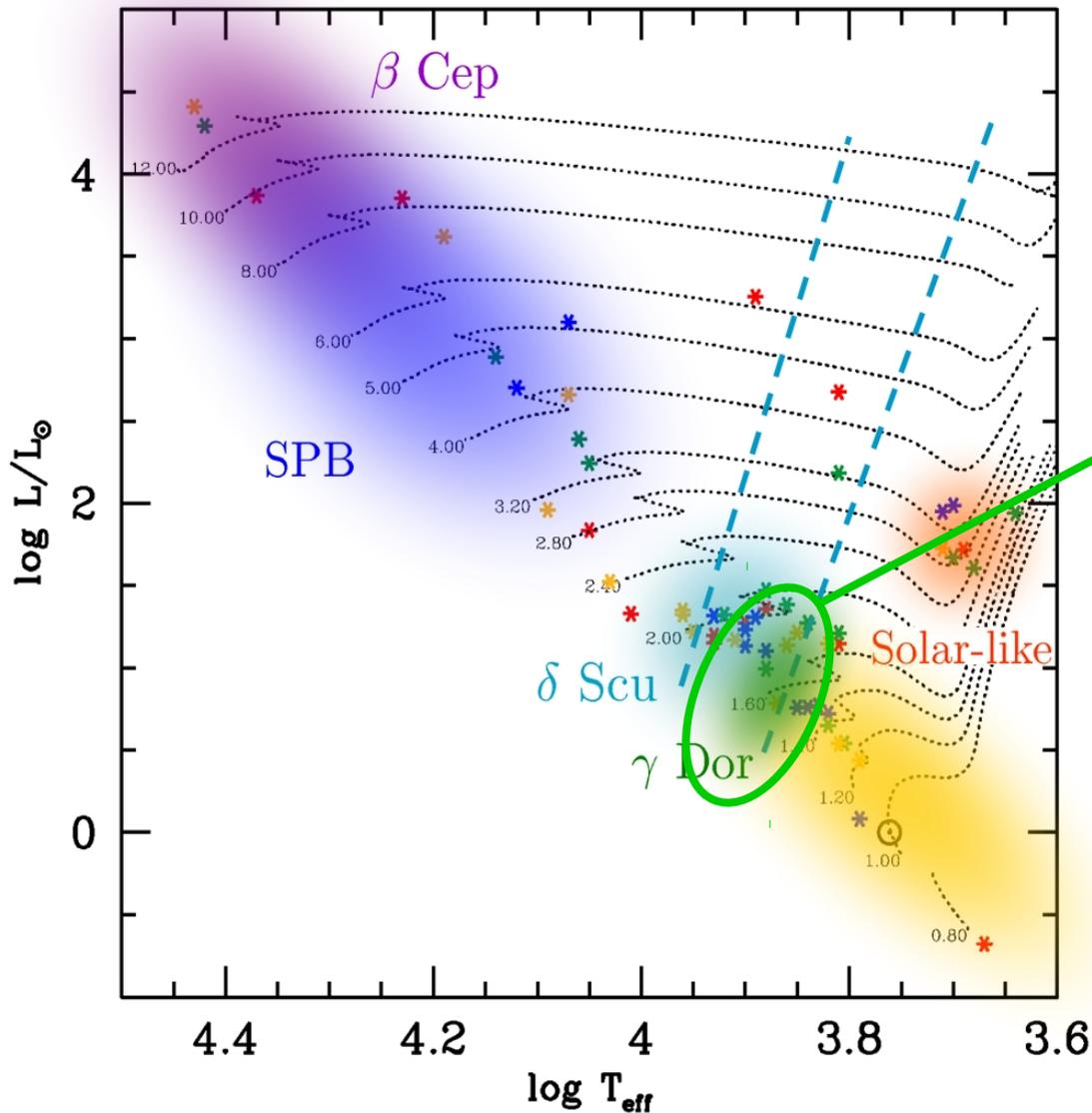


Many stars on the main sequence and in more advanced phases present pulsations

=> access to different processes and structures with stellar asteroseismology

The pulsating HR diagram:

focus on the γ Dor stars

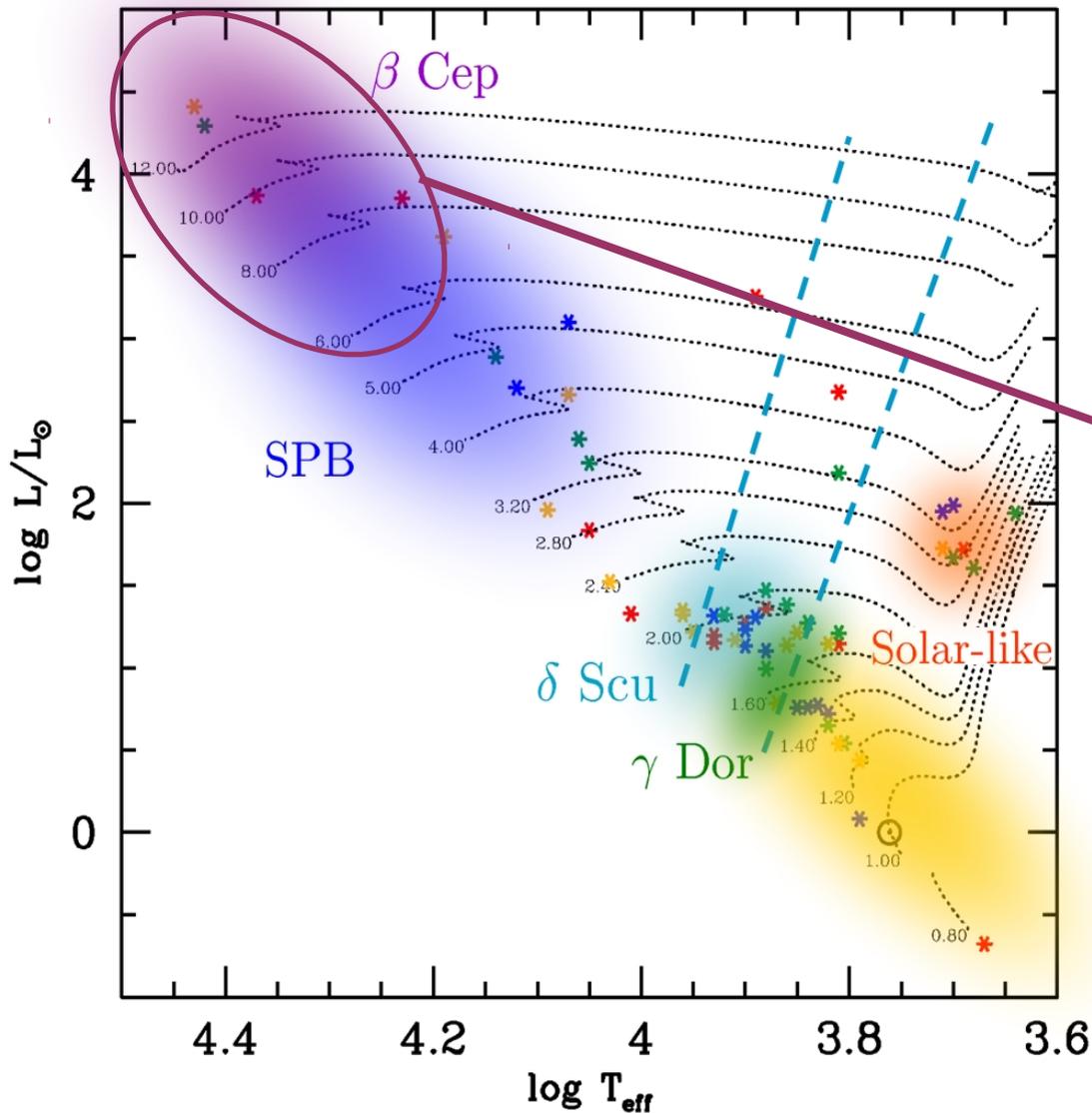


γ Dor stars:

- A5-F0 spectral types
- $M \sim 1.2-2 M_{\odot}$
- high-order g modes with periods $\sim 0.3-3$ d
- presence of convective core
- evolve to red giants

The pulsating HR diagram:

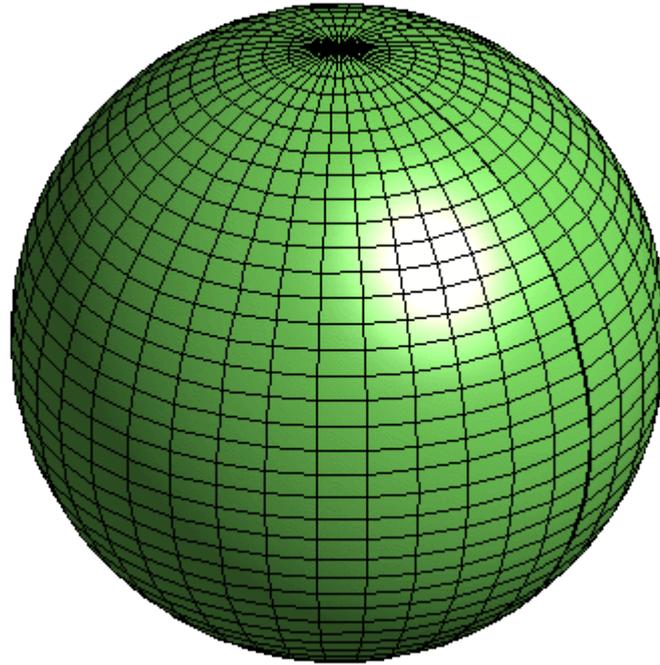
focus on the γ Dor stars



β Cephei stars present low-order p and g modes:

- masses $\sim 8\text{-}20 M_{\odot}$
- pulsations excited by κ mechanism
- periods $\sim 2 - 8$ hours

A short intro on stellar pulsations

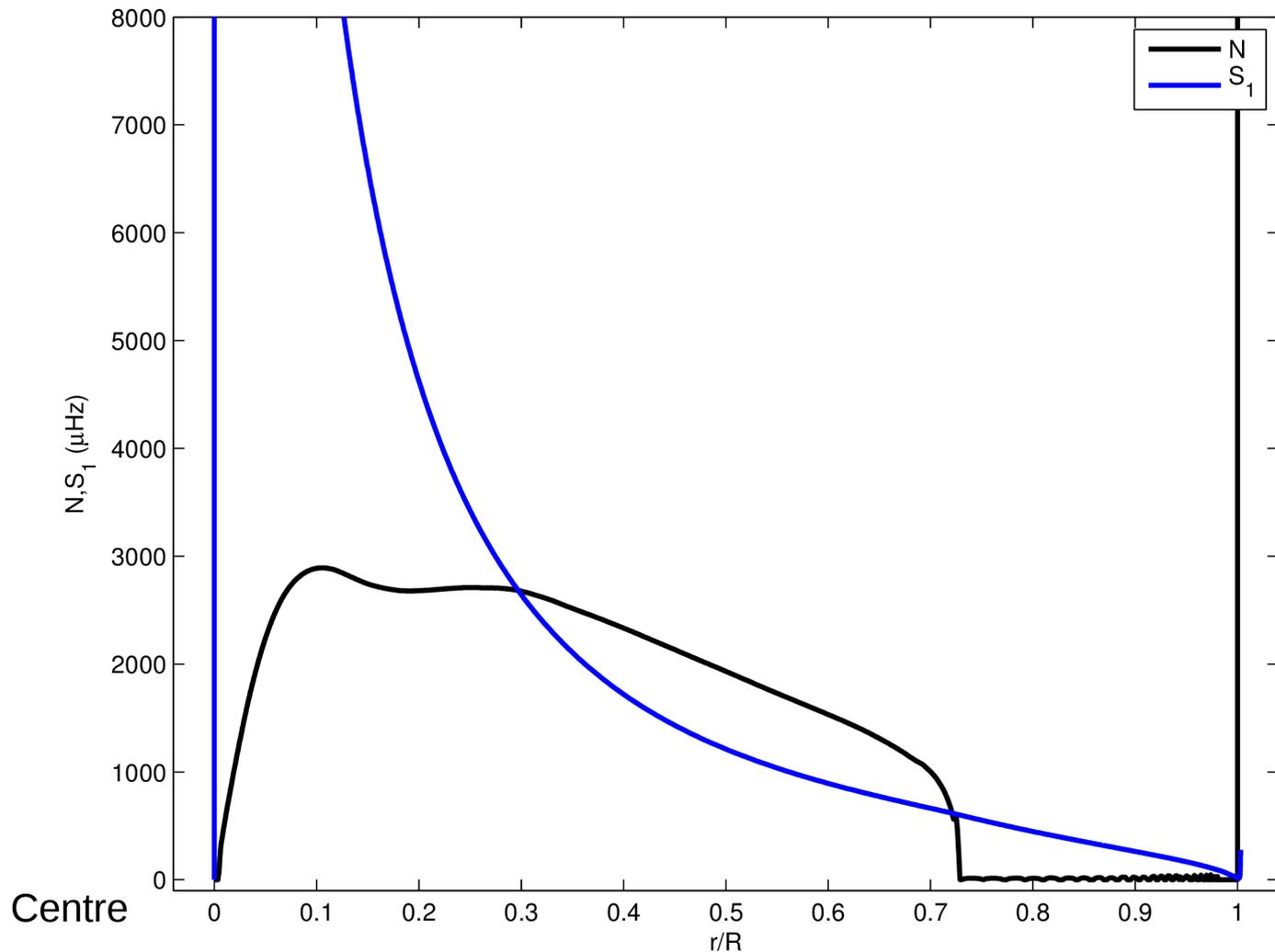


Pulsation (unrealistic amplification) of a star: 3 characteristic numbers, n ℓ m

A short intro on stellar pulsations

Equation of stellar oscillation in a (rough) approximation:

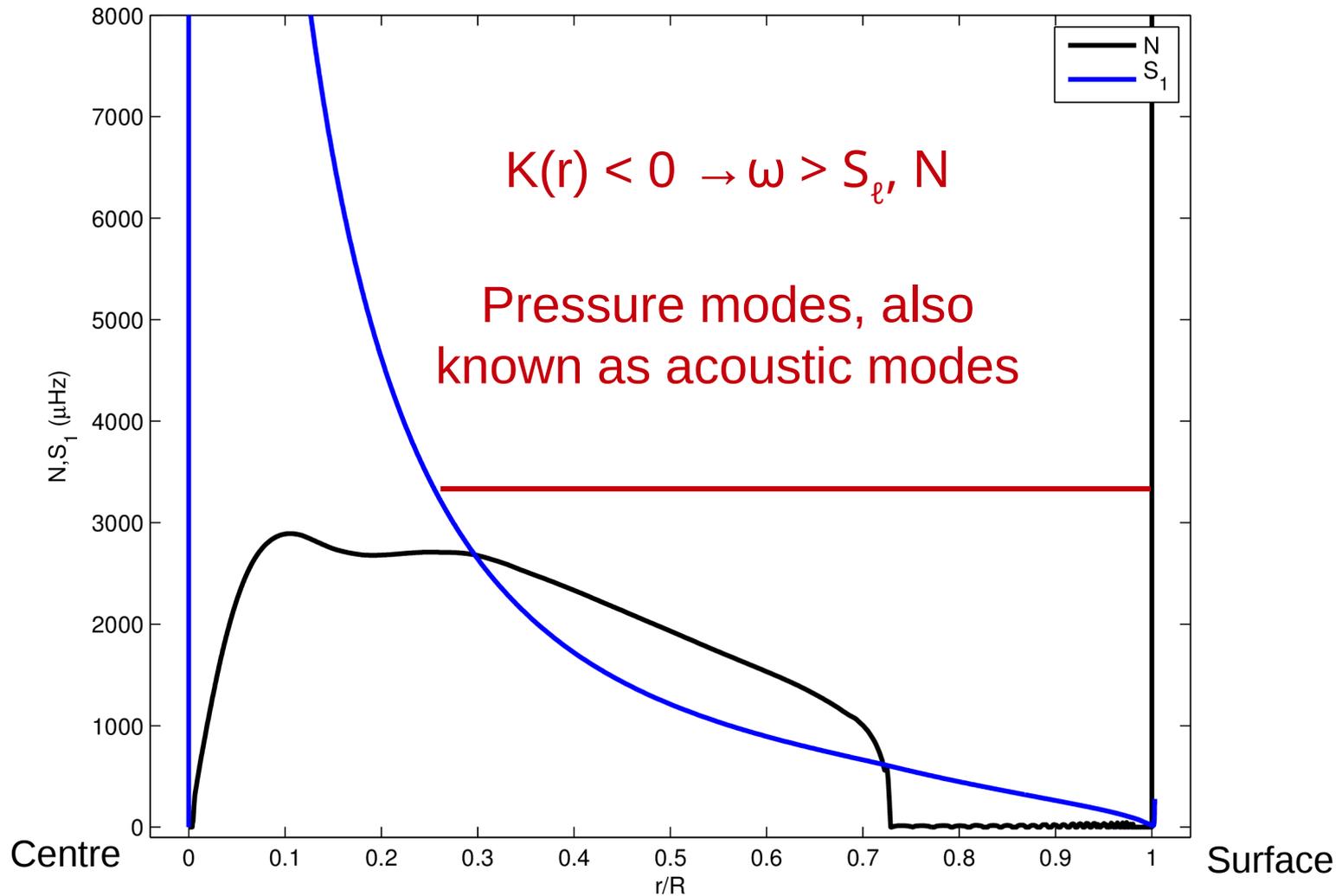
Brunt-Väisälä frequency $\frac{d^2 \xi_r}{dr^2} = \frac{\omega^2}{c^2} \left(\frac{N^2}{\omega^2} - 1 \right) \left(\frac{S_\ell^2}{\omega^2} - 1 \right) \xi_r = -K(r) \xi_r$ Lamb frequency



Typical structure of a solar-like star

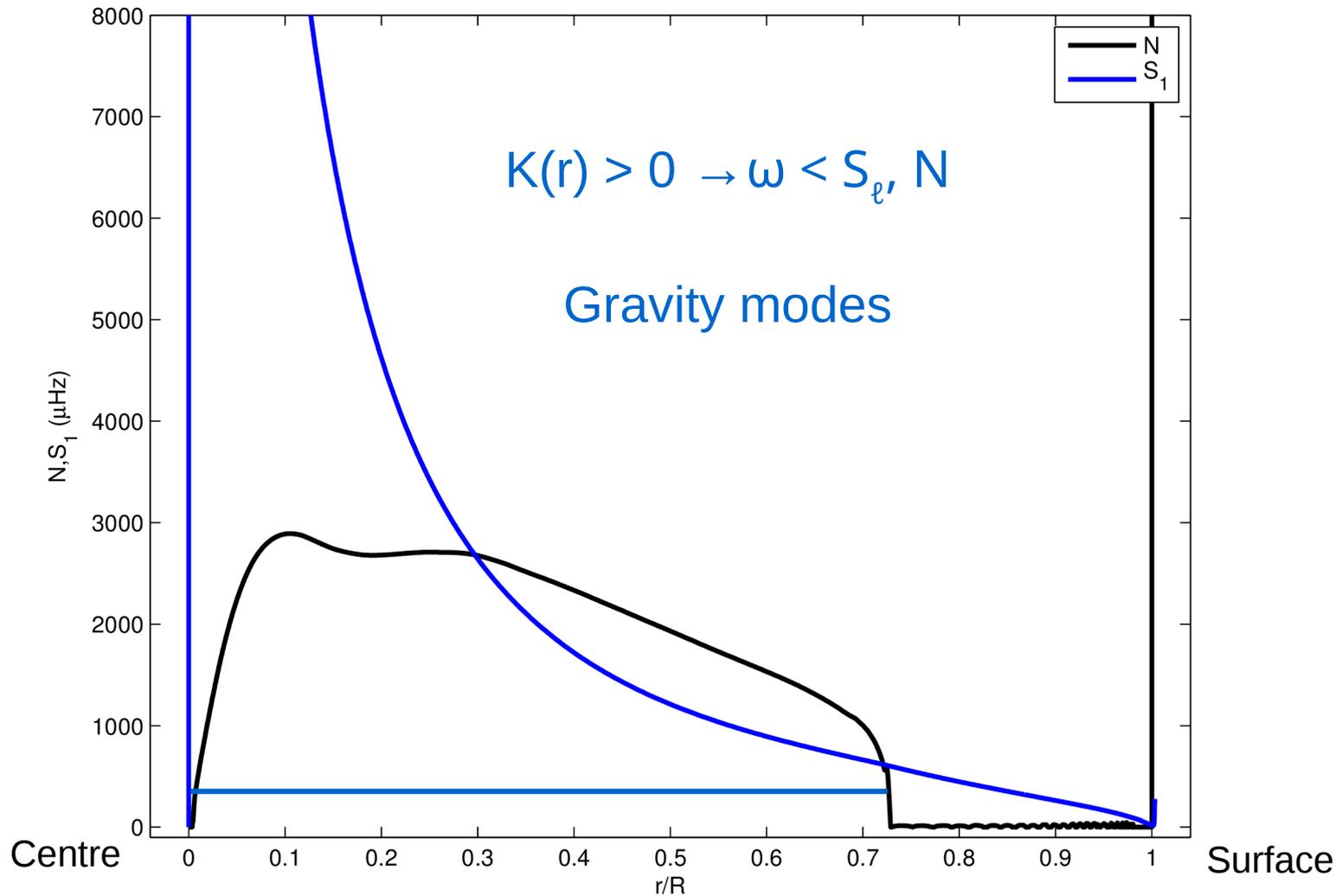
A short intro on stellar pulsations

$$\frac{d^2 \xi_r}{dr^2} = \frac{\omega^2}{c^2} \left(\frac{N^2}{\omega^2} - 1 \right) \left(\frac{S_\ell^2}{\omega^2} - 1 \right) \xi_r = -K(r) \xi_r$$



A short intro on stellar pulsations

$$\frac{d^2 \xi_r}{dr^2} = \frac{\omega^2}{c^2} \left(\frac{N^2}{\omega^2} - 1 \right) \left(\frac{S_\ell^2}{\omega^2} - 1 \right) \xi_r = -K(r) \xi_r$$



Plan

- I. The γ Dor stars: a key to reveal deep-layer rotation in A and F stars
- II. β Cephei stars: a testbed for chemical mixing and rotation in massive stars

I. The γ Dor stars: a key to reveal deep-layer rotation in A and F stars

a) Why studying γ Dor ?

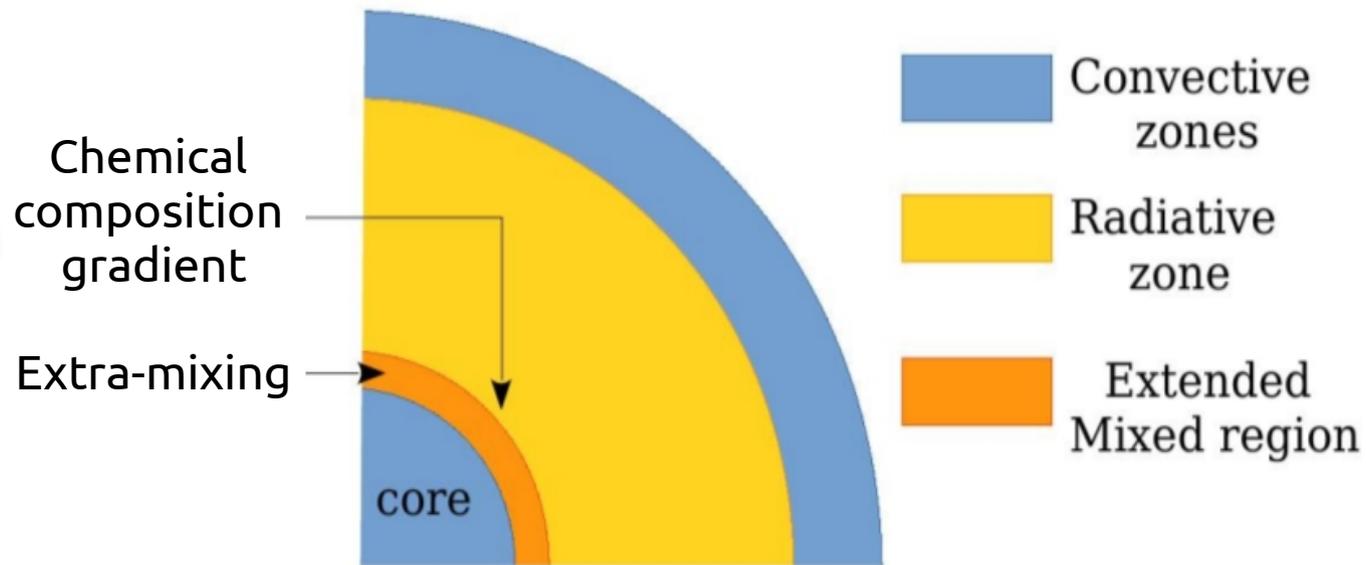
- the asteroseismic potential
- filling a gap in the evolution of low-mass stars

b) The Kepler view of γ Dor stars

c) New seismic diagnostic to probe rotation

d) Current results and future prospect

I.a The γ Dor asteroseismic potential



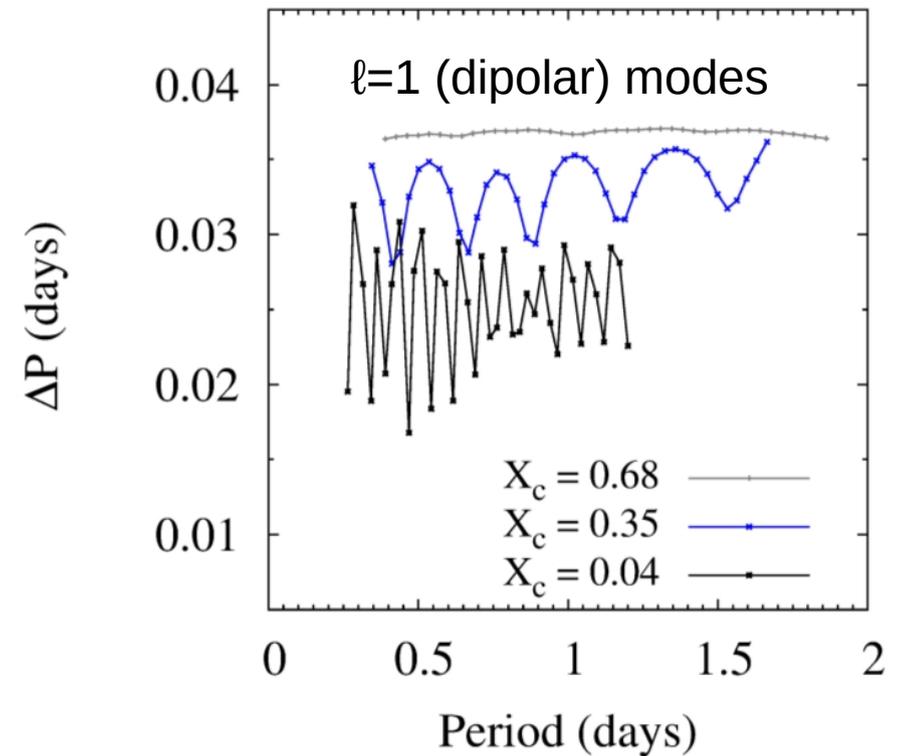
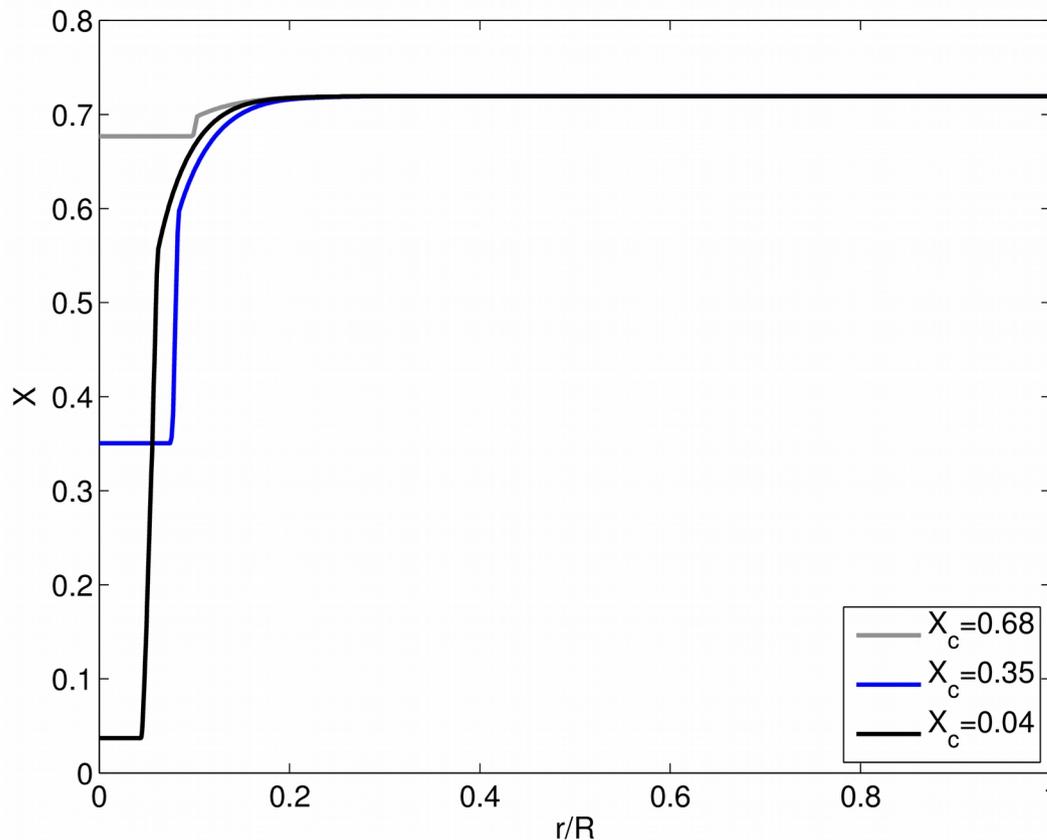
A typical γ Dor profile

I.a The γ Dor asteroseismic potential

Effect of the evolution

=> presence of a chemical composition gradient

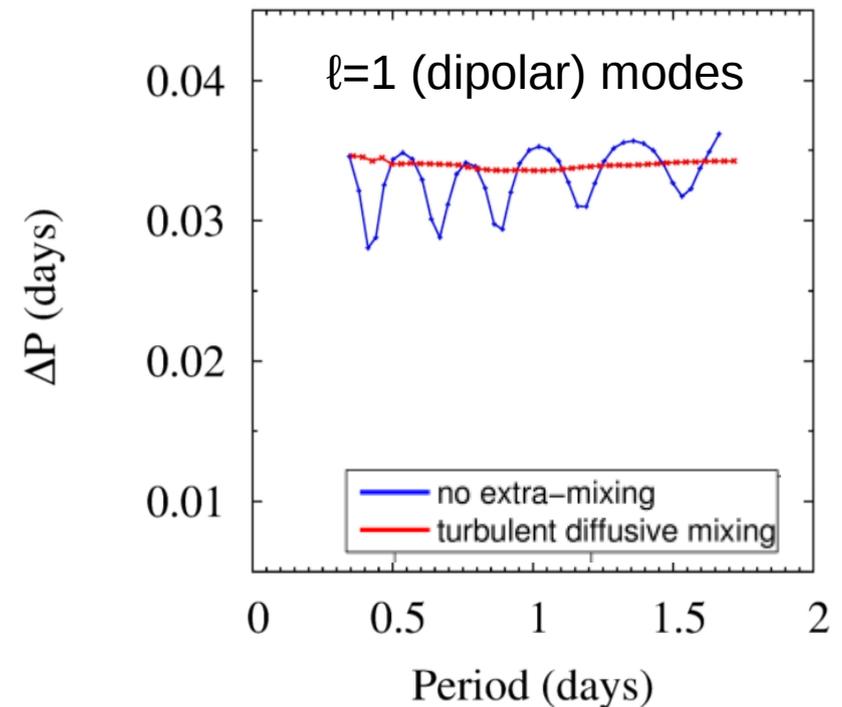
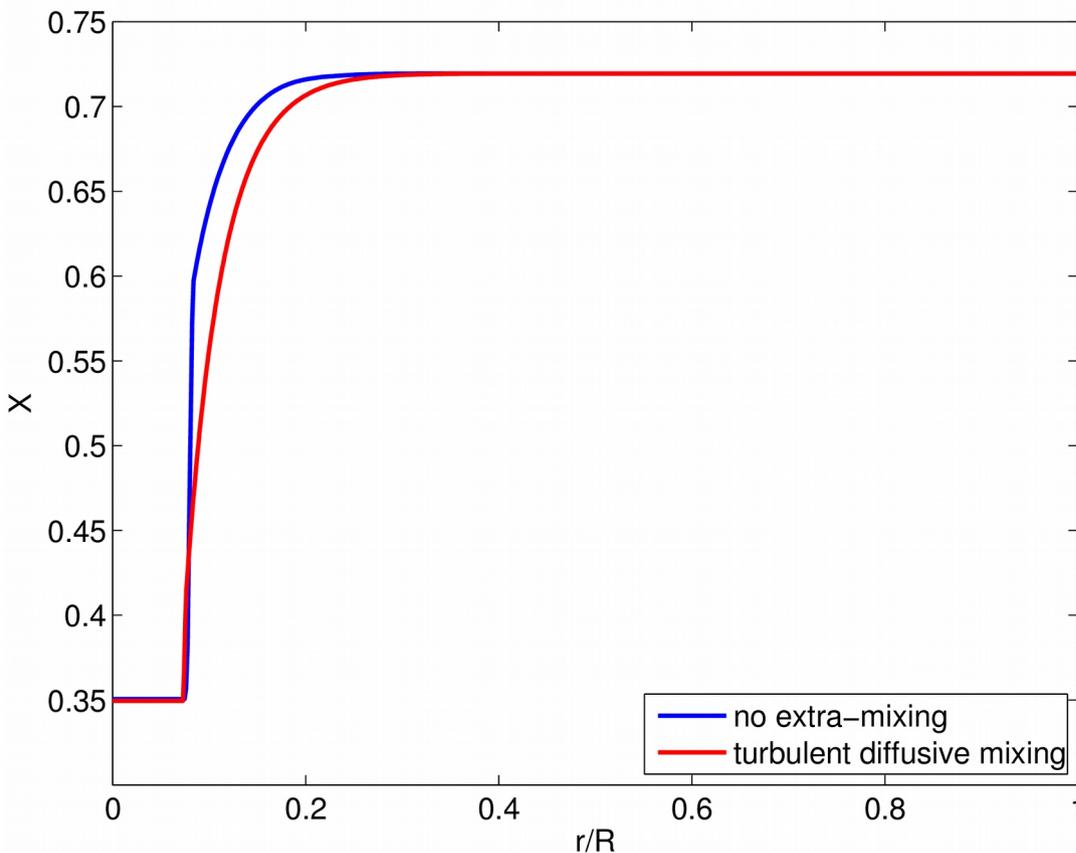
=> oscillations in the period spacing pattern (Miglio et al. 2008)



1.6 M \odot stellar model

I.a The γ Dor asteroseismic potential

Considering rotation mixing resulting as a diffusive process
=> tends to smooth the chemical gradient in the stellar structure
=> damping of the oscillation in the period spacing pattern (Miglio et al. 2008)



1.6 M_{\odot} stellar model

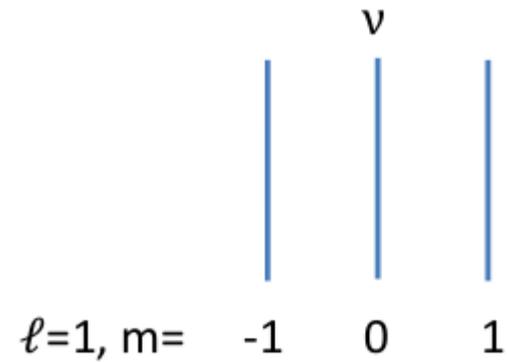
I.a The γ Dor asteroseismic potential

Rotation lifts the degeneracy on the azimuthal order (m) of the oscillations



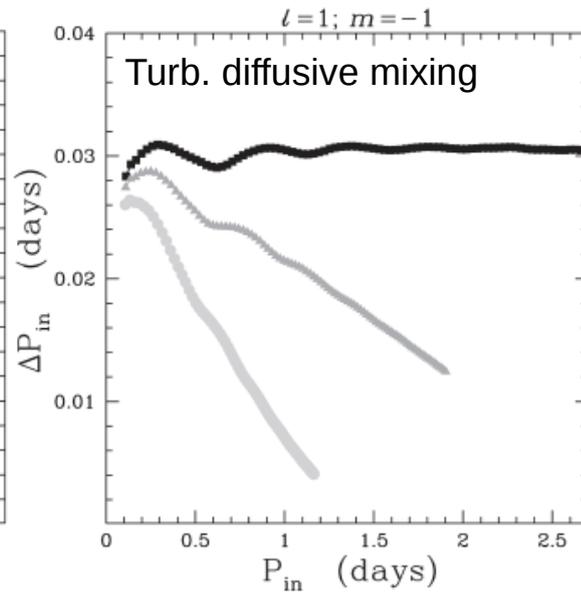
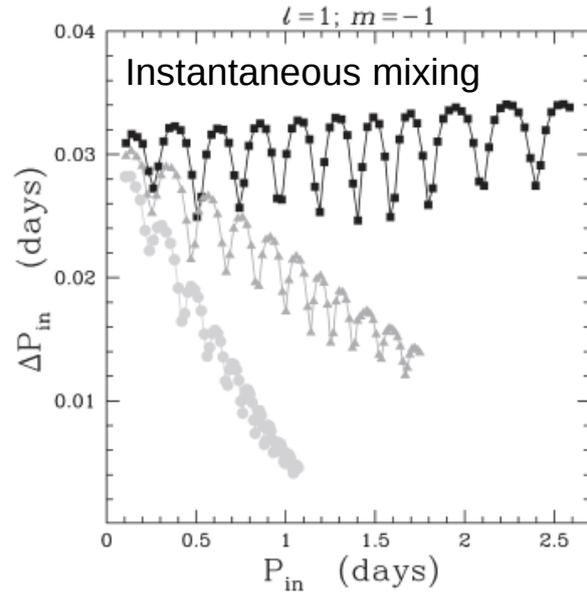
1.a The γ Dor asteroseismic potential

Rotation lifts the degeneracy on the azimuthal order (m) of the oscillations



1.a The γ Dor asteroseismic potential

Depending on the azimuthal order, the period spacing follows a different trend (illustrated for γ Dor stars by Bouabid et al. 2014)



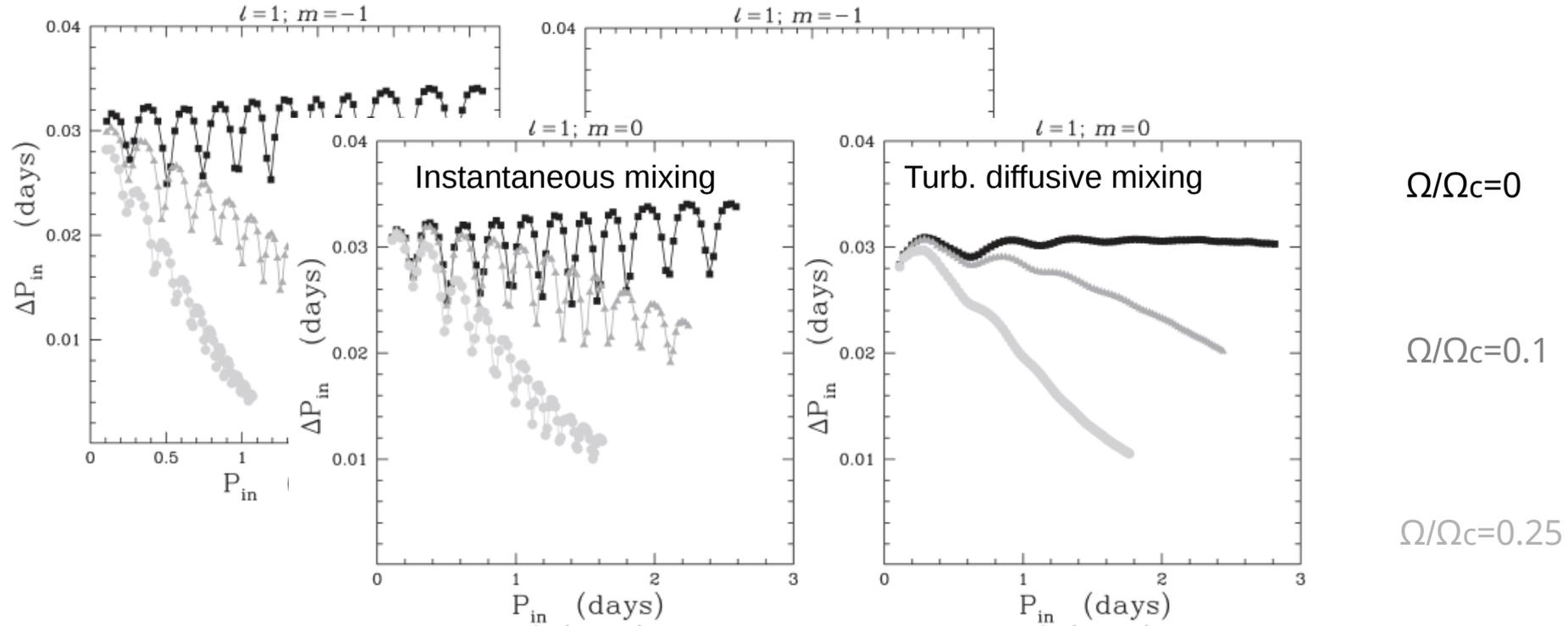
$\Omega/\Omega_c=0$

$\Omega/\Omega_c=0.1$

$\Omega/\Omega_c=0.25$

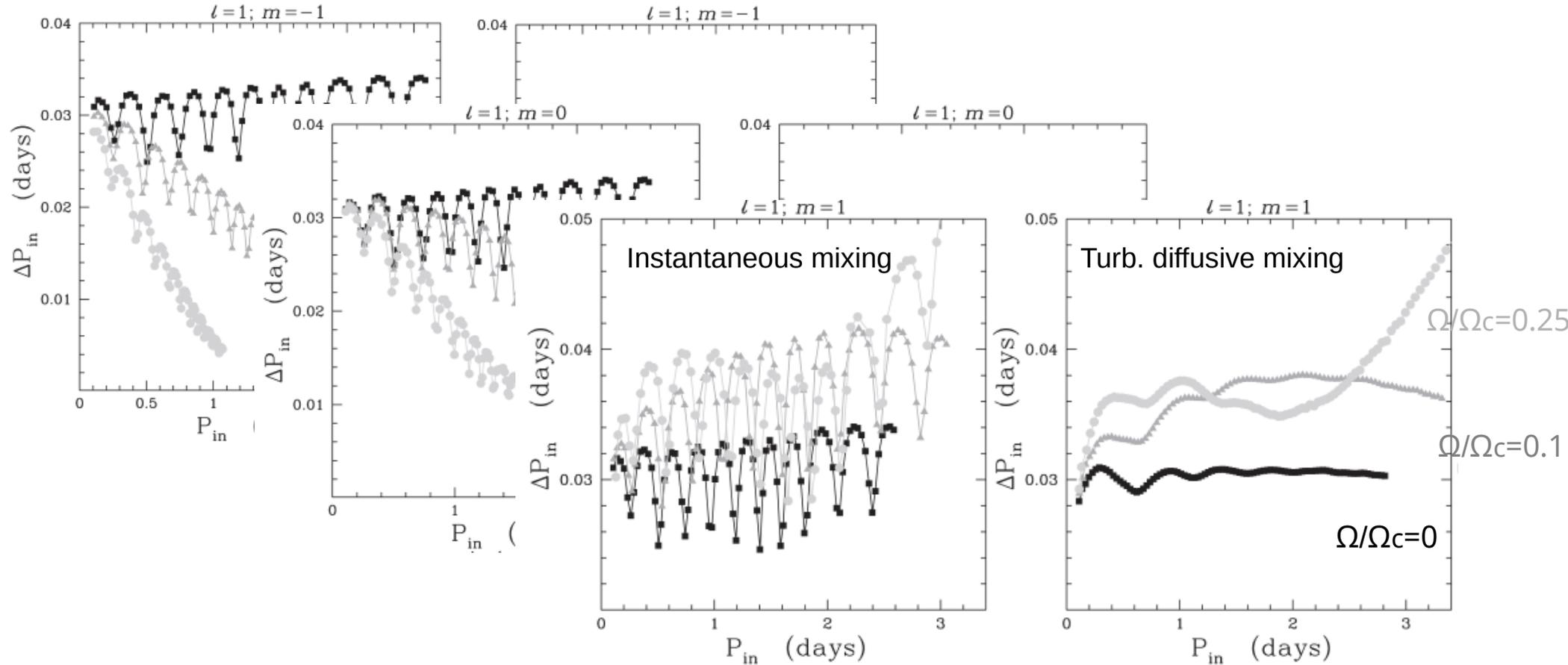
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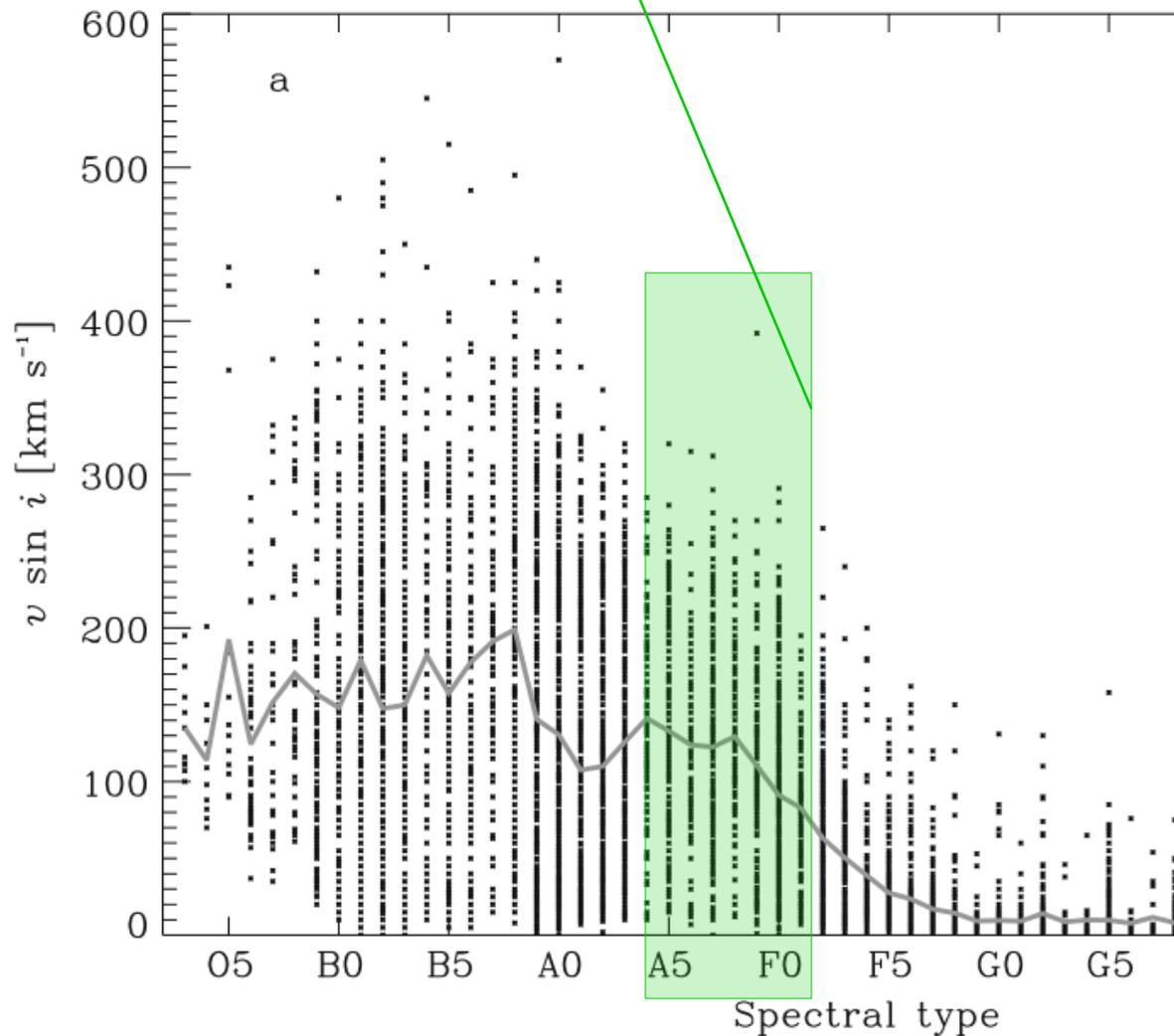
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I.a γ Dor stars in the context of stellar evolution with rotation

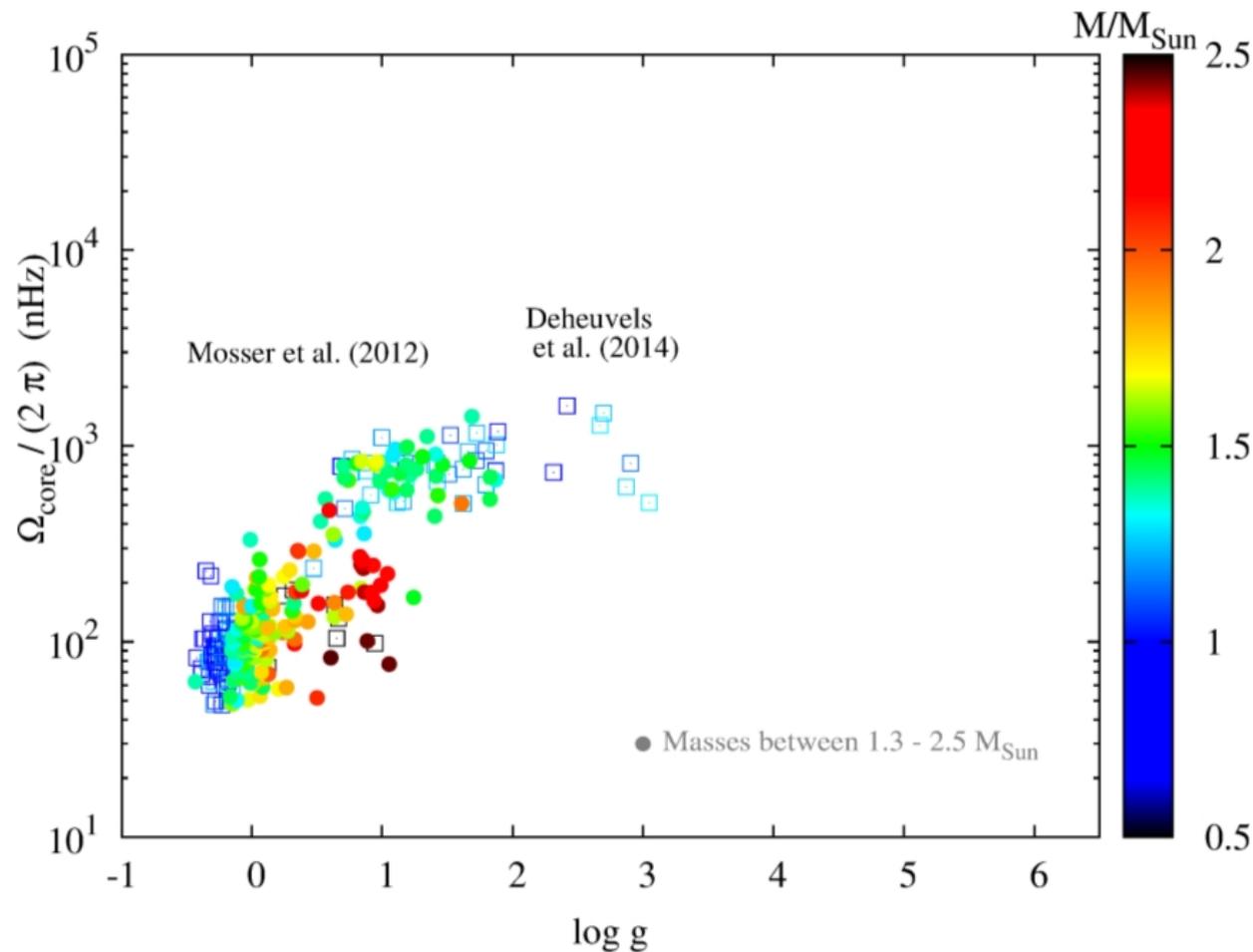
γ Dor: moderate to fast rotators



Adapted from
Royer 2009

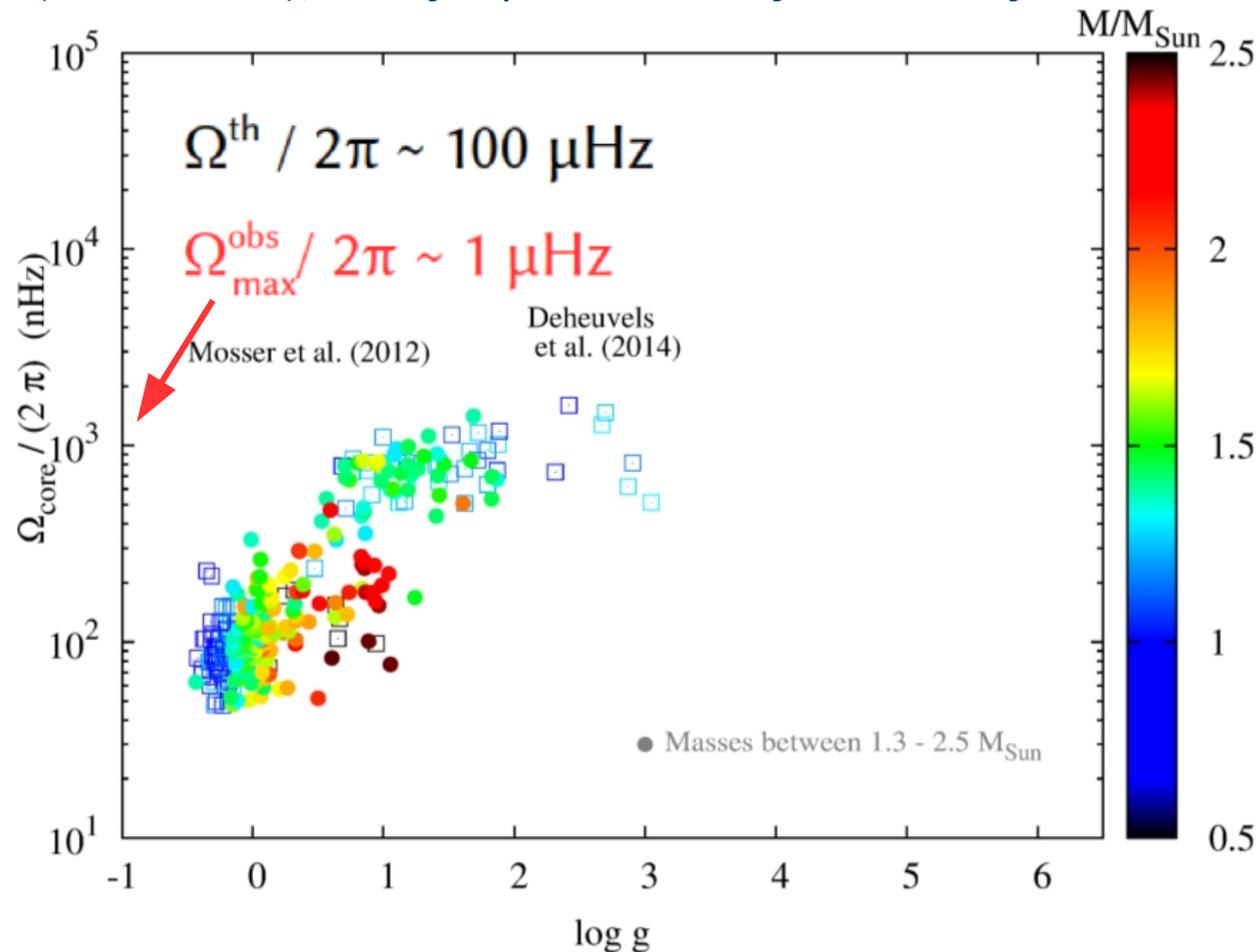
1.a γ Dor stars in the context of stellar evolution with rotation

Thanks to the Kepler mission, access to deep rotation in subgiants (Deheuvels et al. 2012, 2014) and red giants (Beck et al. 2012 ; Mosser et al. 2012 ; Deheuvels et al. 2015 ; Di Mauro et al. 2016)

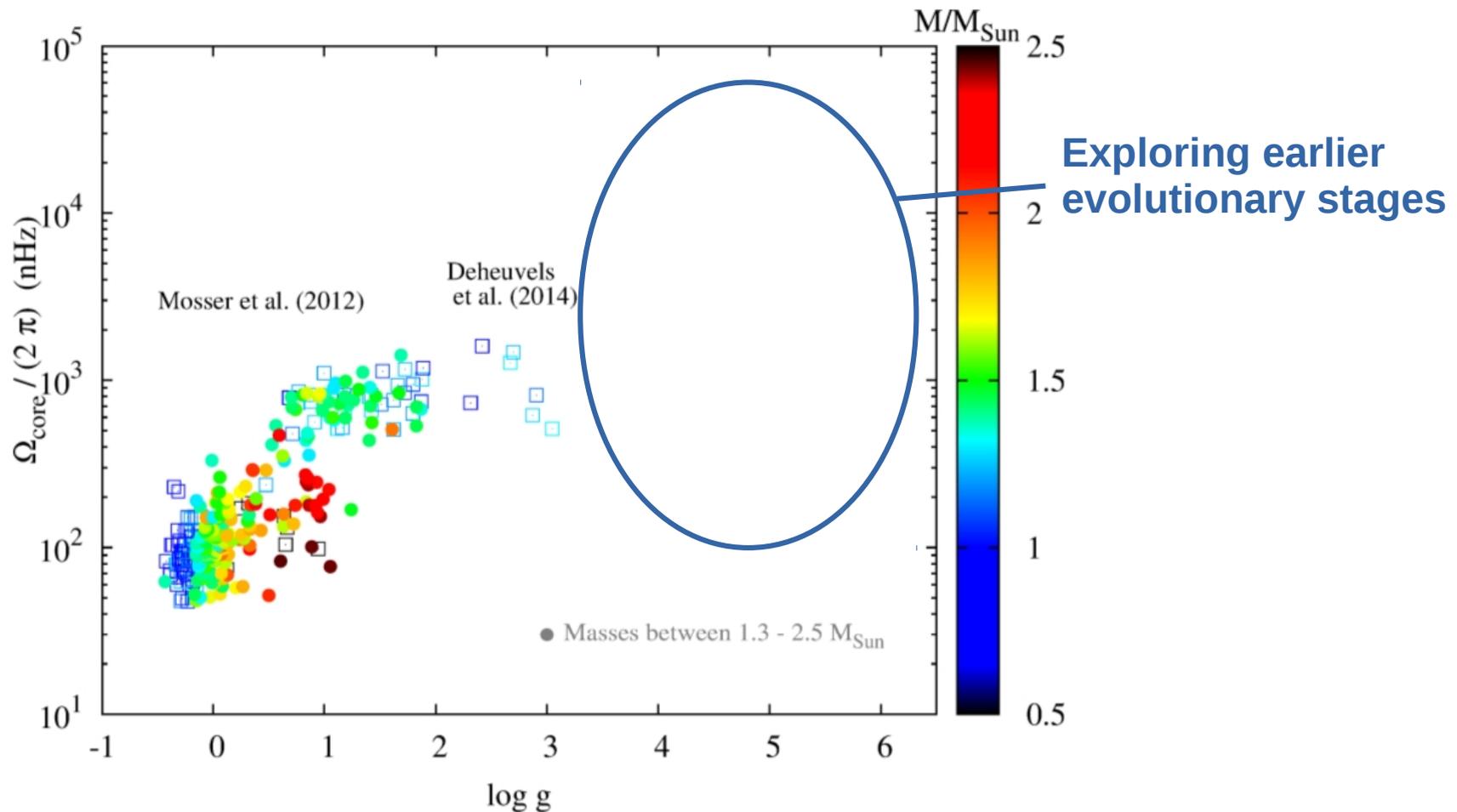


1.a γ Dor stars in the context of stellar evolution with rotation

- Led to discrepancy with core rotation expected from theoretical models
=> need of additional angular momentum transport (eg. Eggenberger et al. 2012, 2016, 2019b)
- Solutions? Tayler-Spruit dynamo impact on rotation (Cantiello et al. 2014), transport by IGW (Fuller et al. 2014, Pinçon et al. 2017) transport by mixed oscillation modes (Belkacem et al. 2015), Tayler instability revised prescription (Fueller 2019), none yet provides a fully satisfactory solution

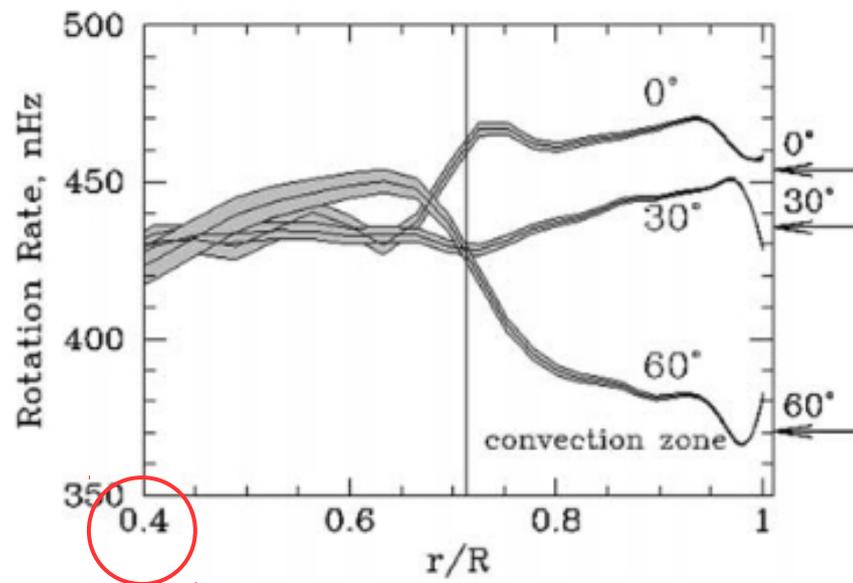


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I.a γ Dor stars in the context of stellar evolution with rotation

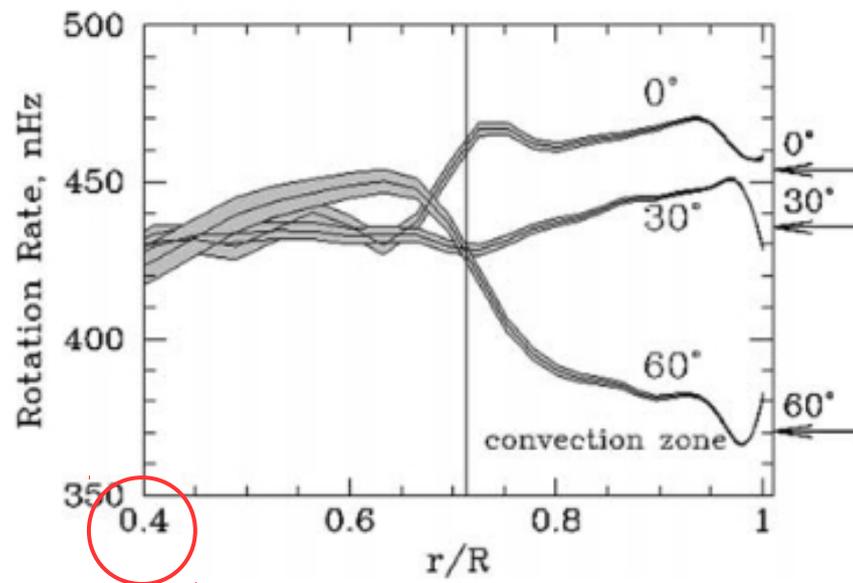
- Sun (e.g. Brown et al. 1989 ; Elsworth et al. 1995 ; Kosovichev et al. 1997 ; Schou et al. 1998 ; Garcia et al. 2007)
- Now also in other solar-like stars (Lund et al. 2014 ; Benomar et al. 2015 ; Nielsen et al. 2015) but the information is tied to the superficial layers.



Kosovichev et al. 1997

1.a γ Dor stars in the context of stellar evolution with rotation

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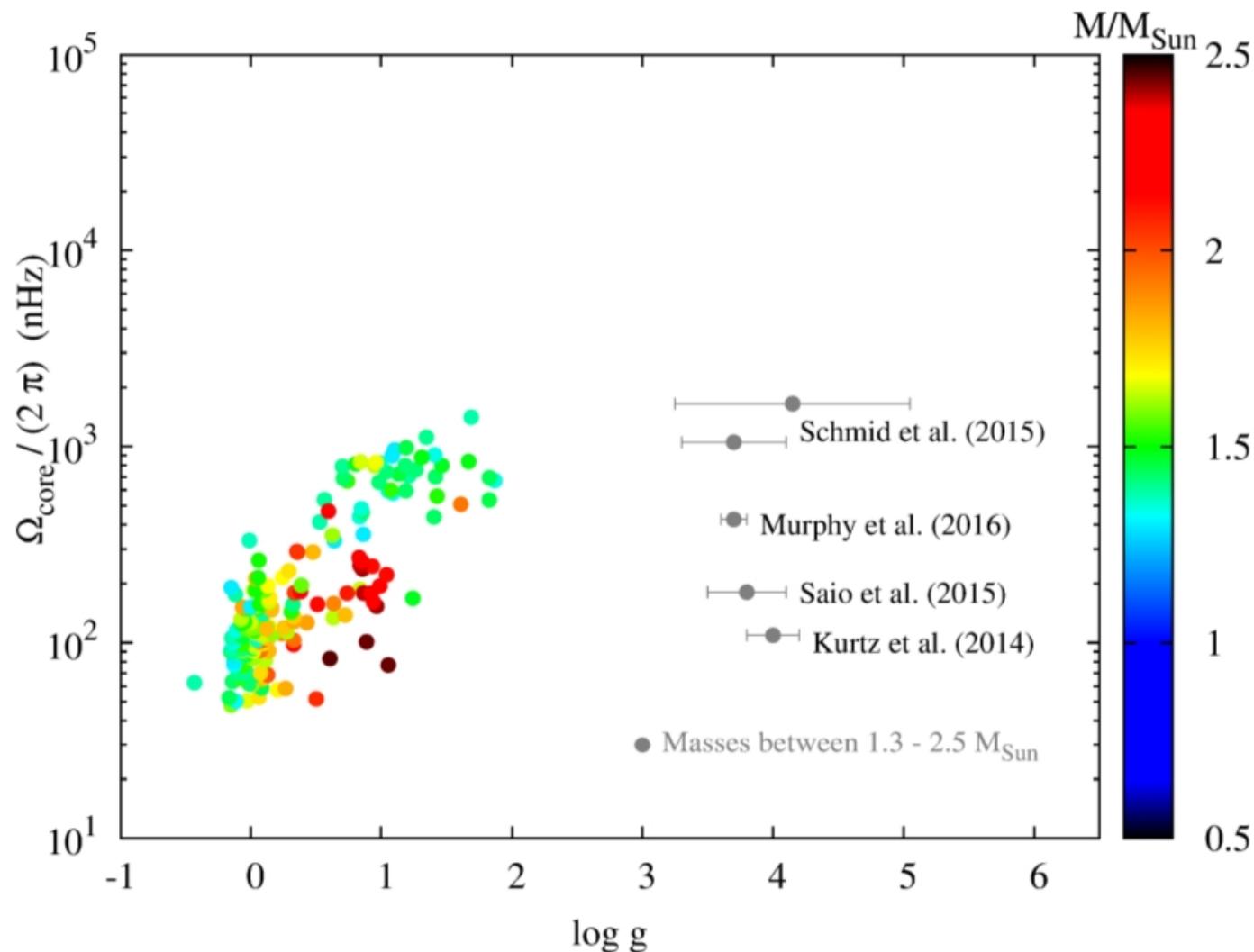


Kosovichev et al. 1997

=> γ Dor (and hybrid delta Scuti) stars

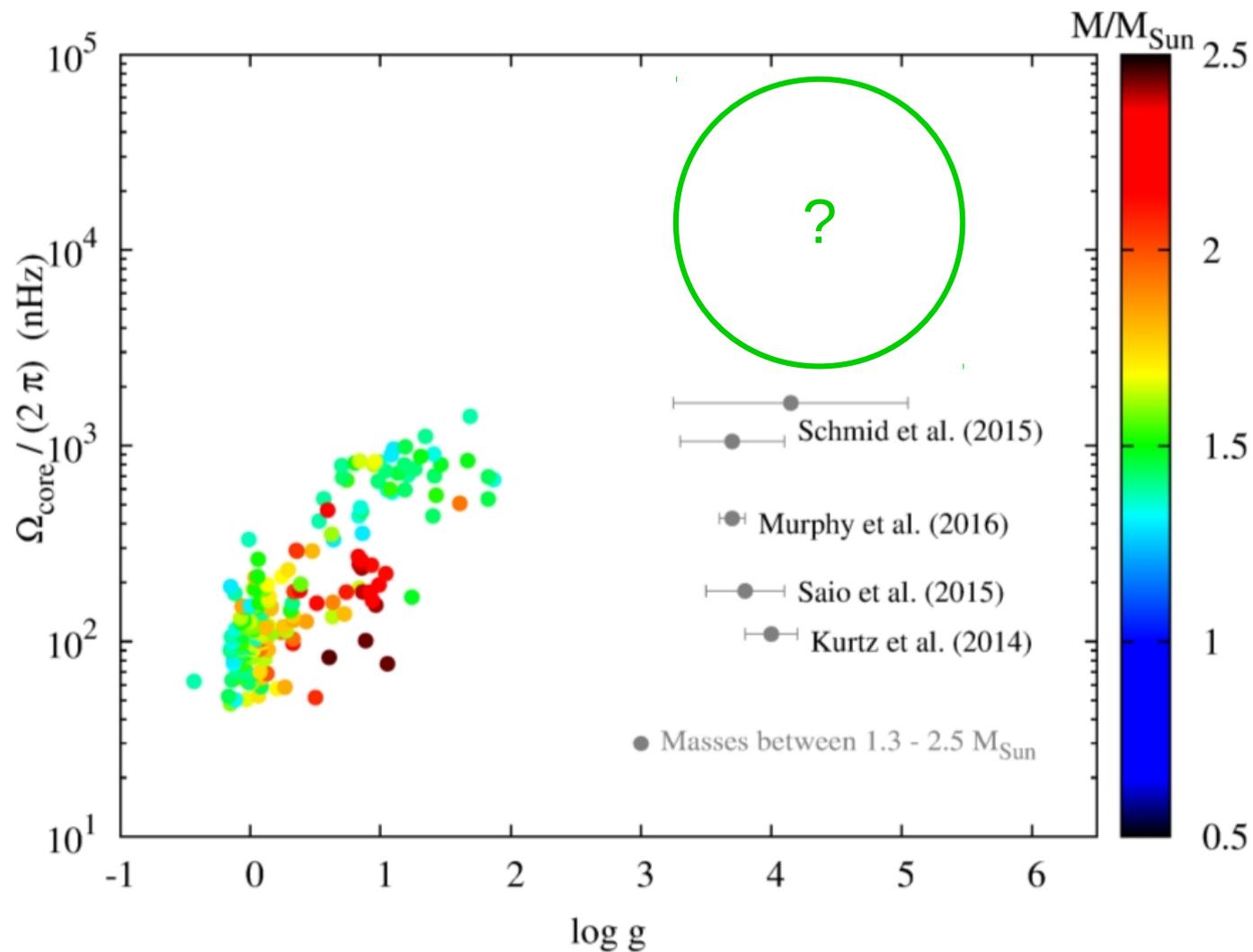
I.a γ Dor stars in the context of stellar evolution with rotation

First promising results with Kepler: hybrid δ Scuti/ γ Dor Stars ($v \sin i \sim 10$ km/s) showing nearly uniform rotation

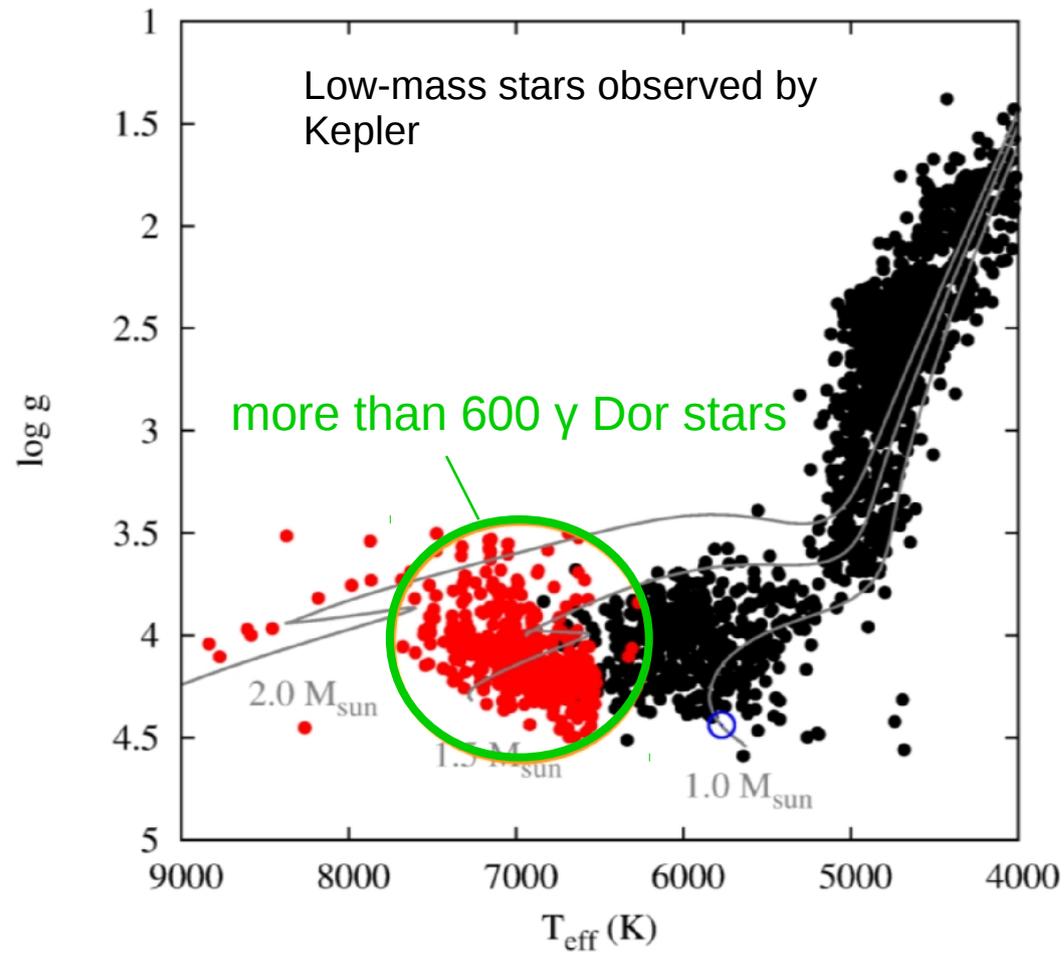


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I.b Rotating γ Dor as observed by Kepler



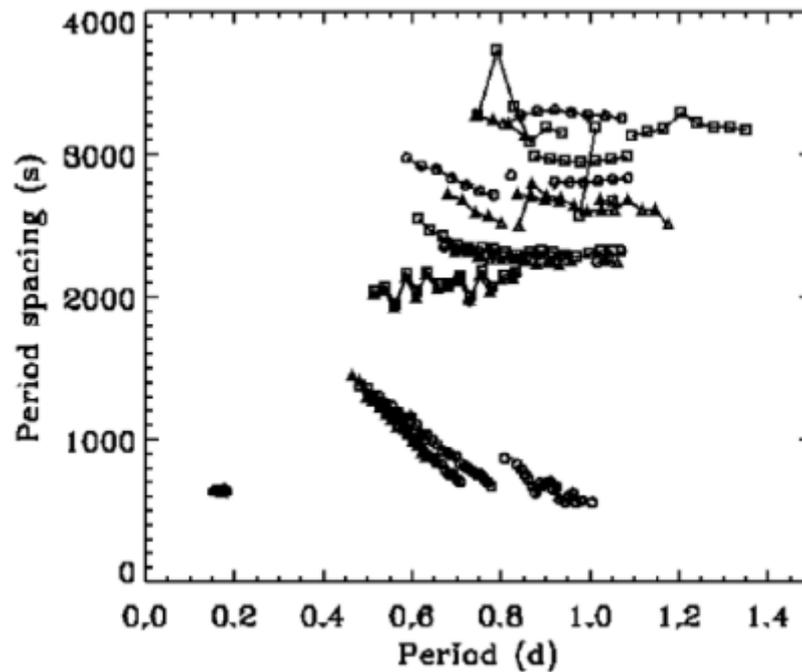
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Do we observe consecutive mode sequences allowing to derive period spacings?

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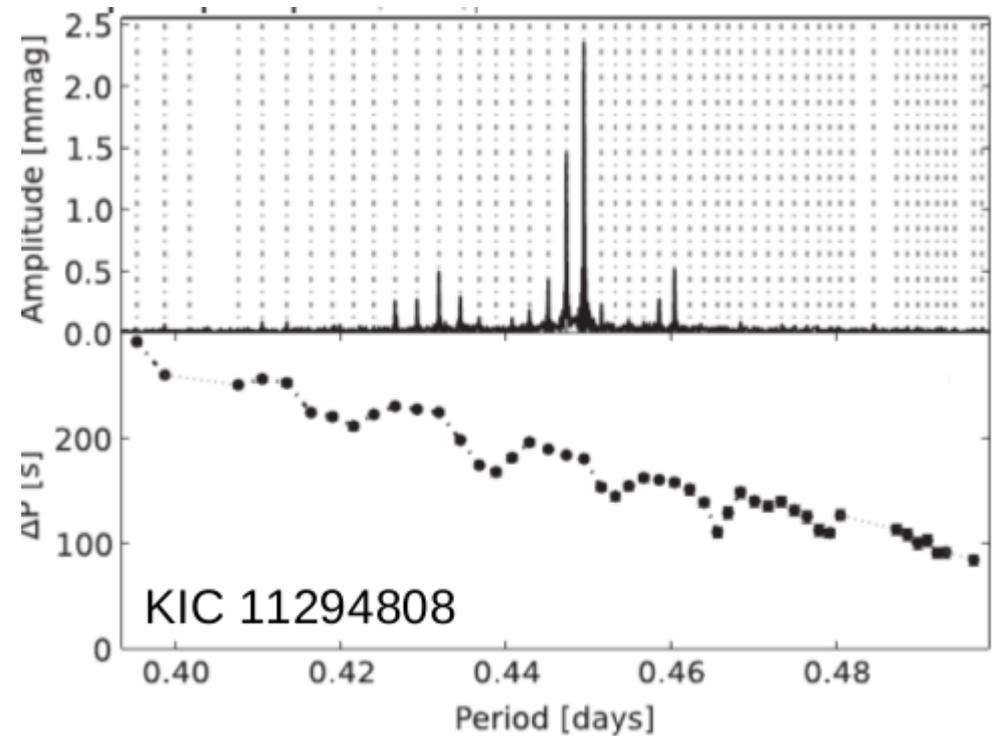
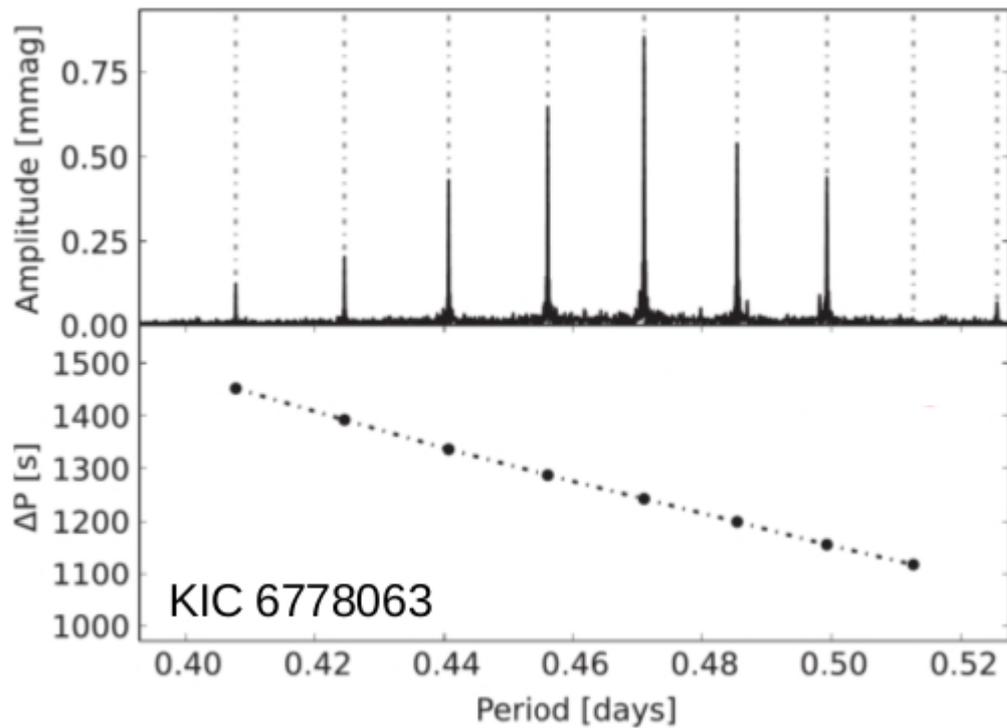


Bedding et al. 2015

I.b Rotating γ Dor as observed by Kepler

Do we observe period-spacing sequences?

Yes (~4-yr long observations)



Van Reeth et al. 2015, 2016

I.c Tools to infer rotation in γ Dor: setting the stage

- In a non-rotating case, oscillations are described by :

$$\delta\vec{r}(r, \theta, \phi, t) = \vec{\xi}(r)Y_{\ell,m}(\theta, \phi)\exp(i\omega t)$$

- In γ Dor stars, $\Omega \sim \omega_{puls}$, and perturbative approach is not appropriate. We use here 3 methods, aiming at stars presenting moderate to fast rotation :

1) Traditional Approximation of Rotation (Eckart 1963 ; Berthomieu et al. 1978)

Rigid rotation – Spherical models – Cowling approximation – Coriolis terms in $\Omega \sin \theta$ neglected

$$\Theta_{\ell,m,\eta}(\theta) \exp(i\Phi + i\omega t)$$

$$\delta\vec{r}(r, \theta, \phi, t) = \vec{\xi}(r)Y_{\ell,m}(\theta, \phi)\exp(i\omega t)$$

I.c Tools to infer rotation in γ Dor: setting the stage

2) Asymptotic TAR (e.g. Townsend 2003b) \Rightarrow radial order $n \gg \ell$

$$P_{\text{co}}(n) = \frac{2\pi^2(n + \frac{1}{2})}{\sqrt{\lambda_{\ell, m, \eta}} \int_{r_0}^{r_1} \frac{N}{r} dr}$$

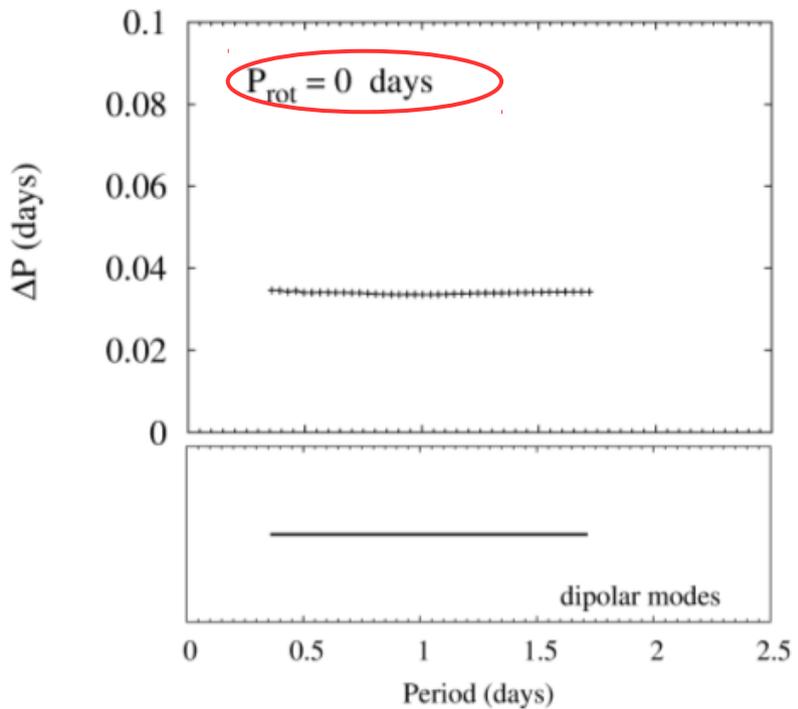
3) 2D non-perturbative codes (TOP - Reese et al. 2006; ACOR Quazzani et al. 2012b). Resolution of the complete eigenvalue problem

$$\delta\vec{r}(r, \theta, \phi, t) = \sum_{\ell \geq |m|}^{\infty} \tilde{\xi}_{r, n, \ell}(r) Y_{\ell}^m(\theta, \varphi) e^{i\sigma t}$$

“Accuracy” versus computing effort: switching between methods

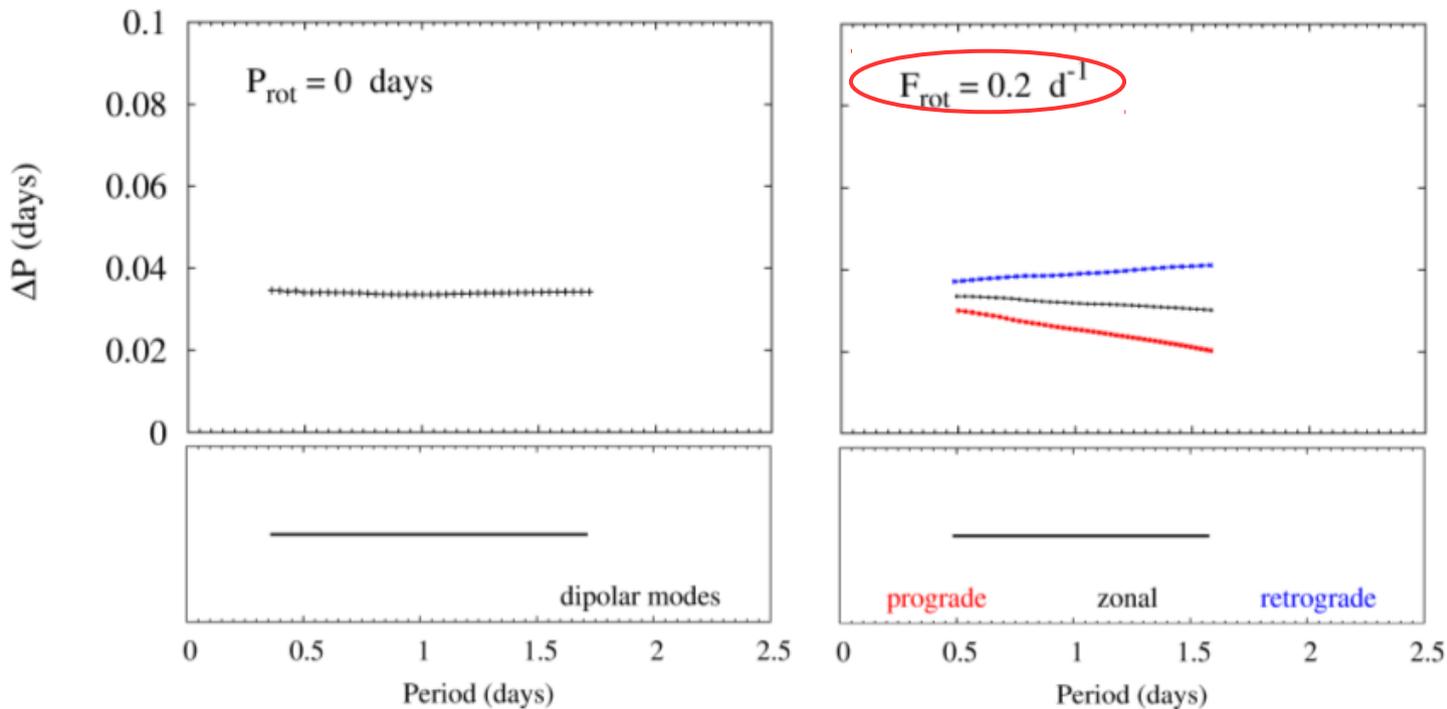
I.c Tools to infer rotation in γ Dor: the slope of the period spacing relation

Typical γ Dor model (including turbulent diffusive mixing)



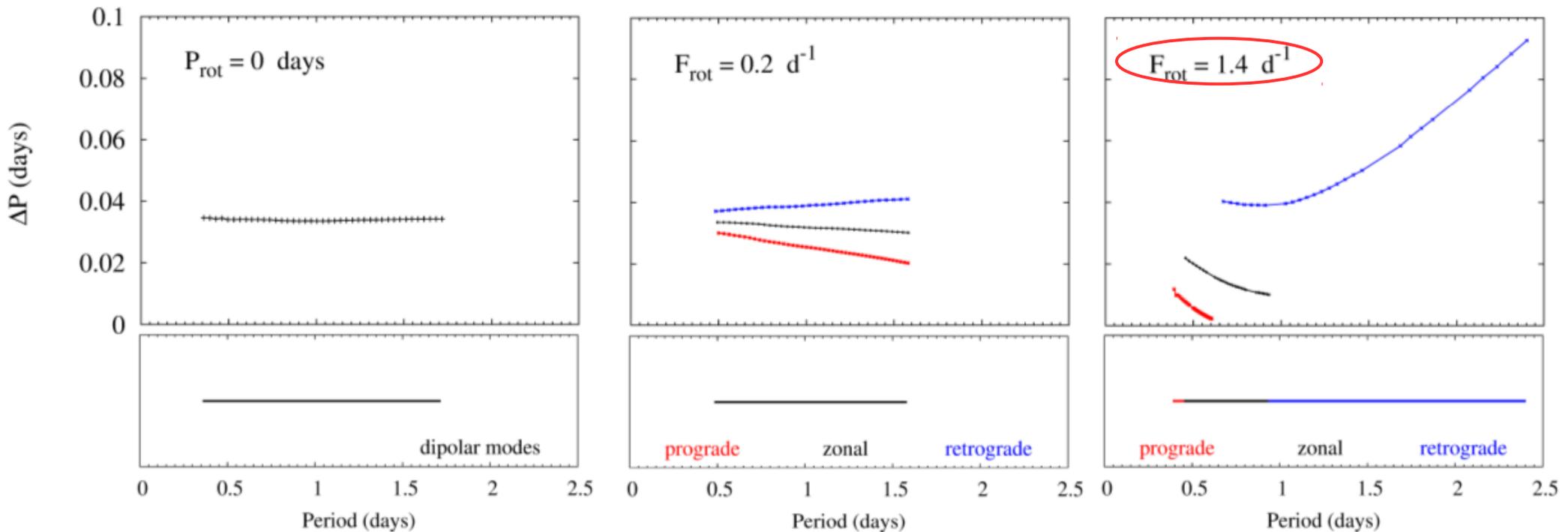
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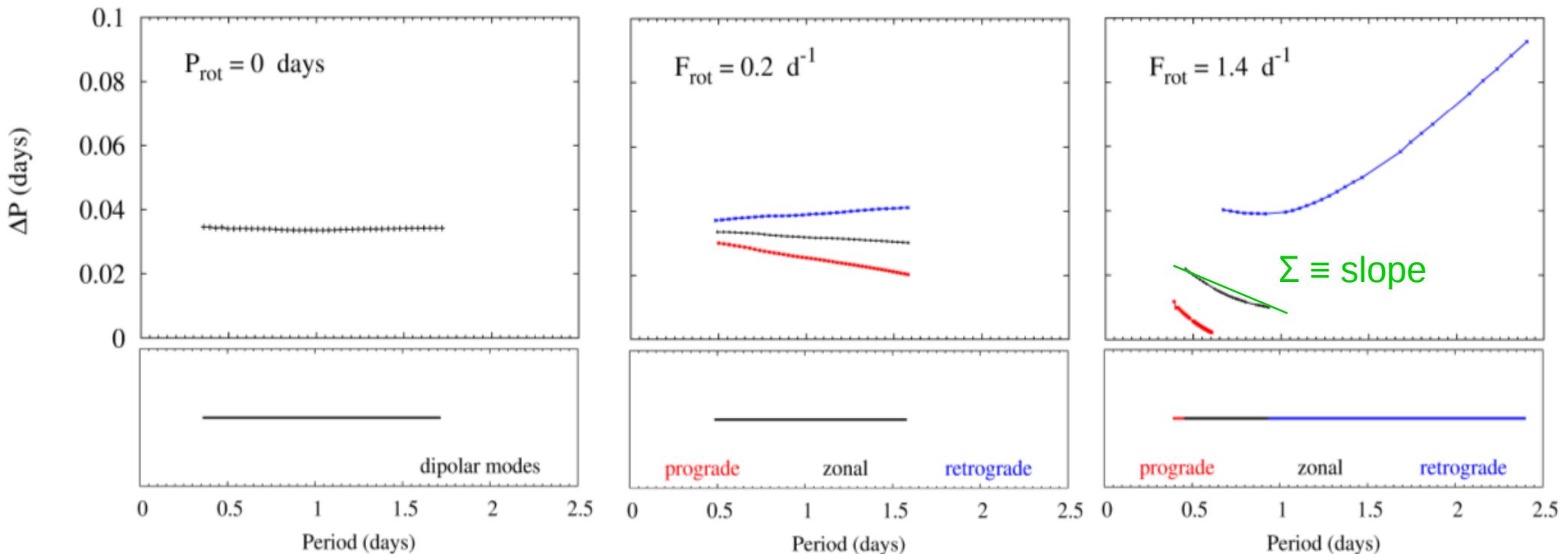
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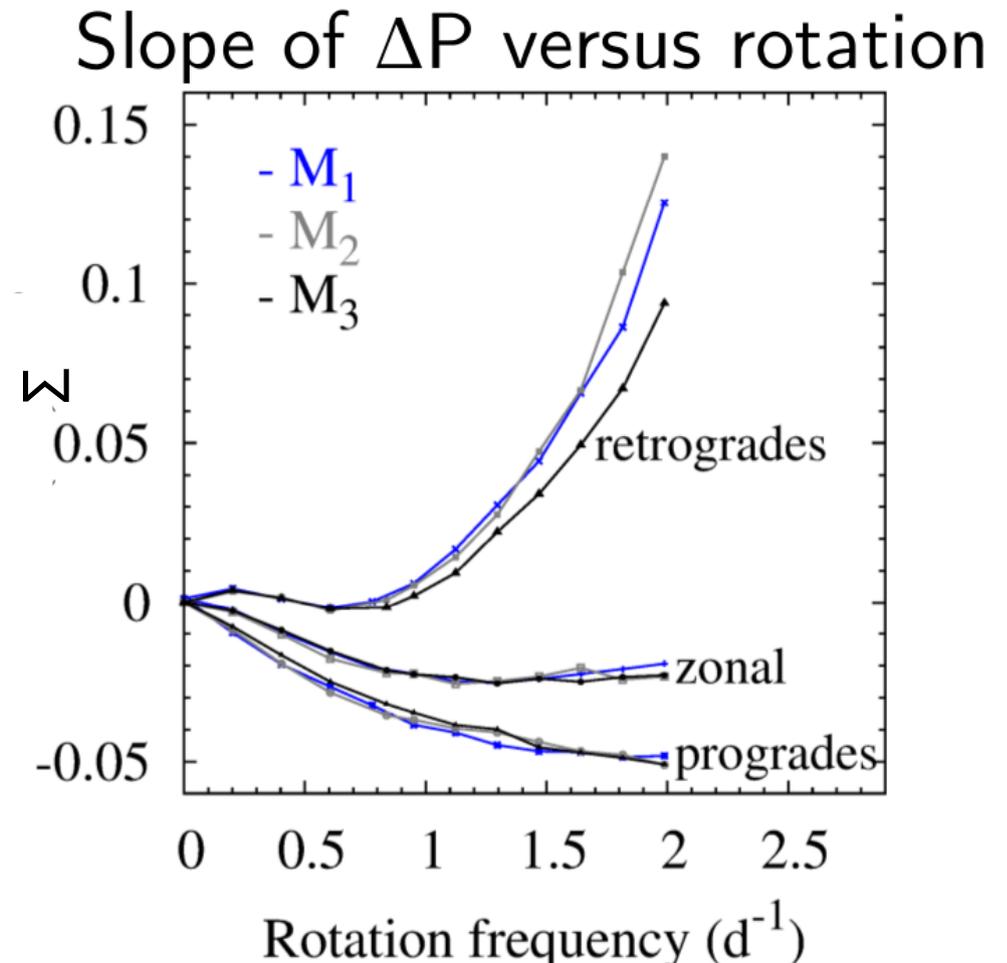
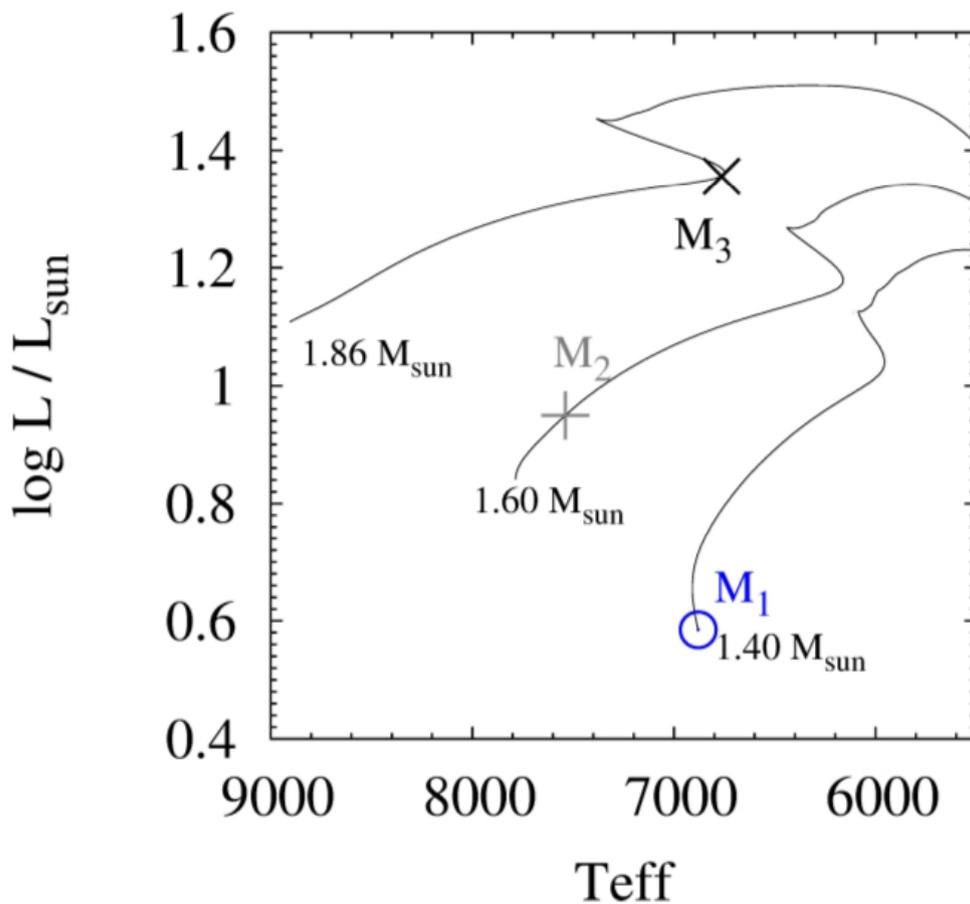
I.c Tools to infer rotation in γ Dor: the slope of the period spacing relation

Is there a one-to-one relation between Σ and Ω ?



In Tools to infer rotation in γ Dor: a one-to-one relation?

Three γ Dor models at different masses and ages: rigid rotation (up to 220km/s) with ACOR



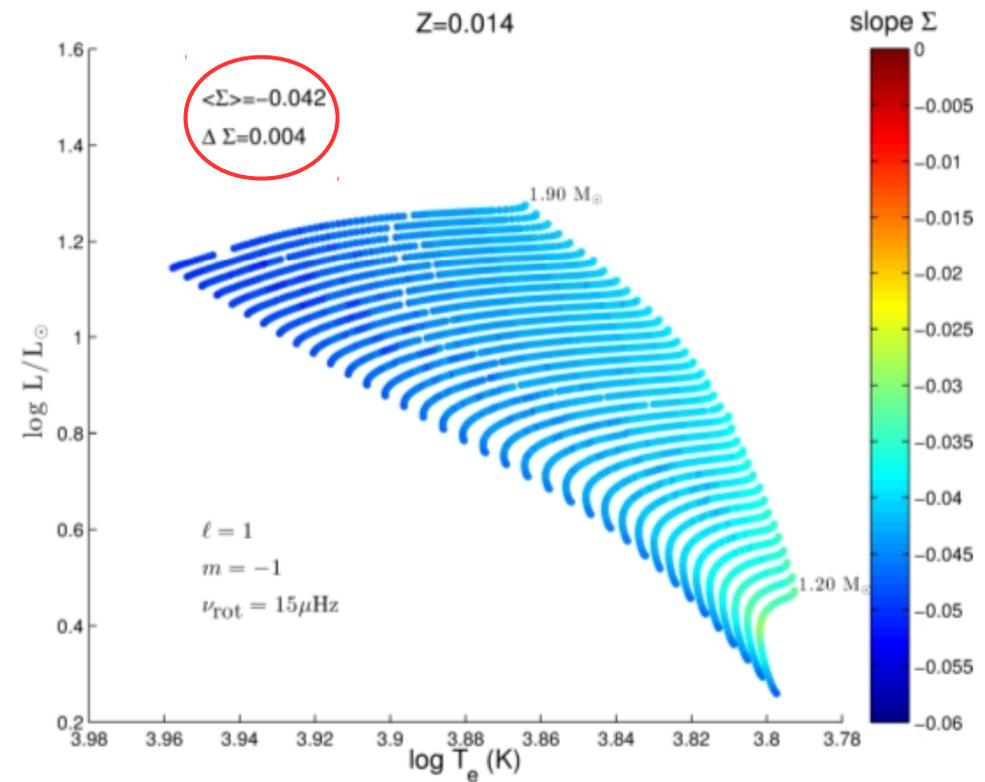
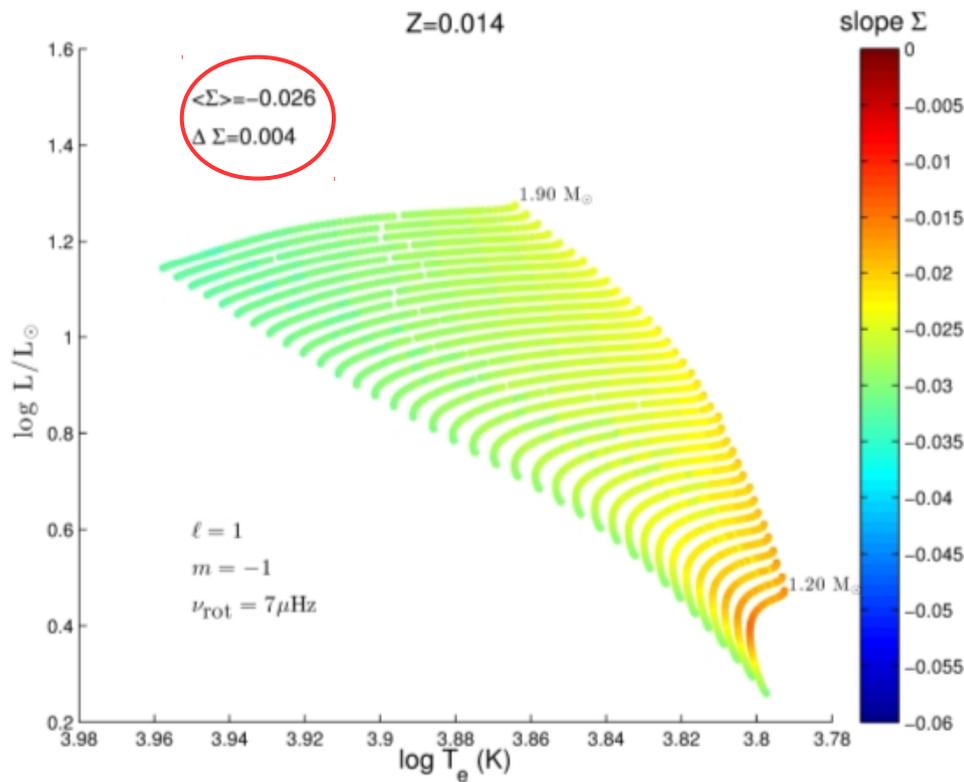
I.c Tools to infer rotation in γ Dor: a one-to-one relation?

We check the sensitivity of Σ on a grid of stellar models (Liège stellar code), using TAR Asymptotic

M/M_{\odot}	1.20-1.90	0.02
Z	0.010- 0.018	0.004
α_{MLT}	1.70	–
$\nu_{\text{rot}} (\mu\text{Hz})$	0.0 - 23.0	2.0
$D_t (\text{cm}^2\text{s}^{-1})$	0/700	–
α_{ov}	0/0.2	–

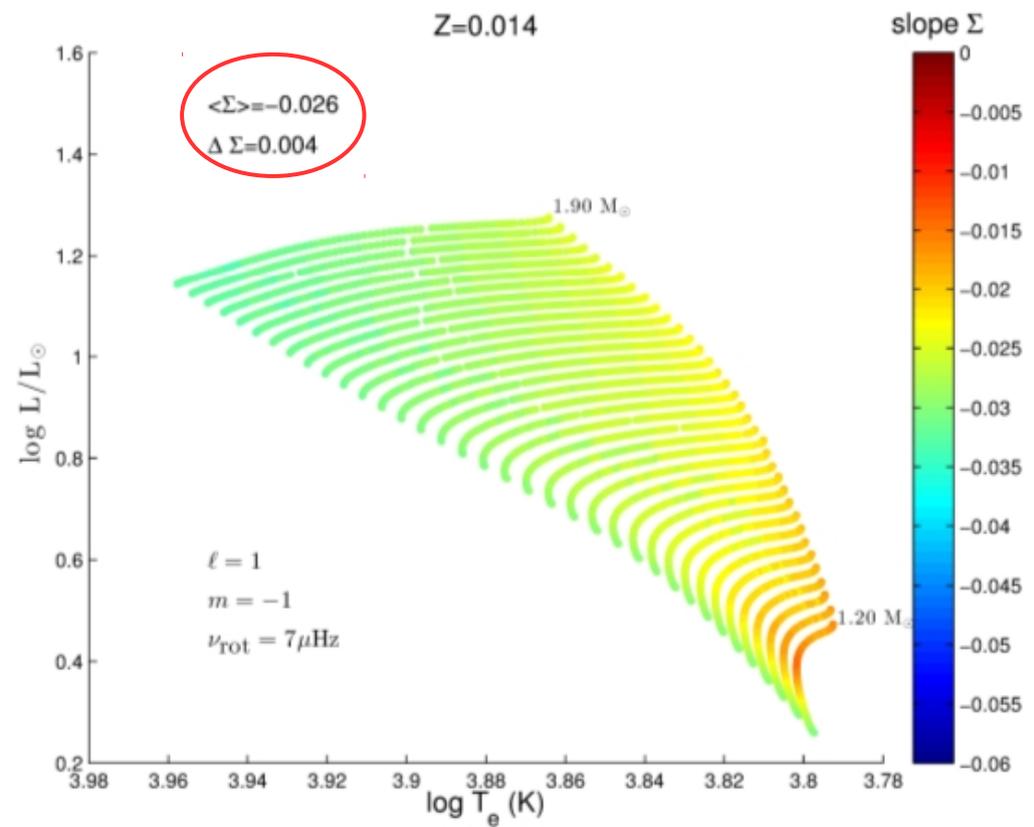
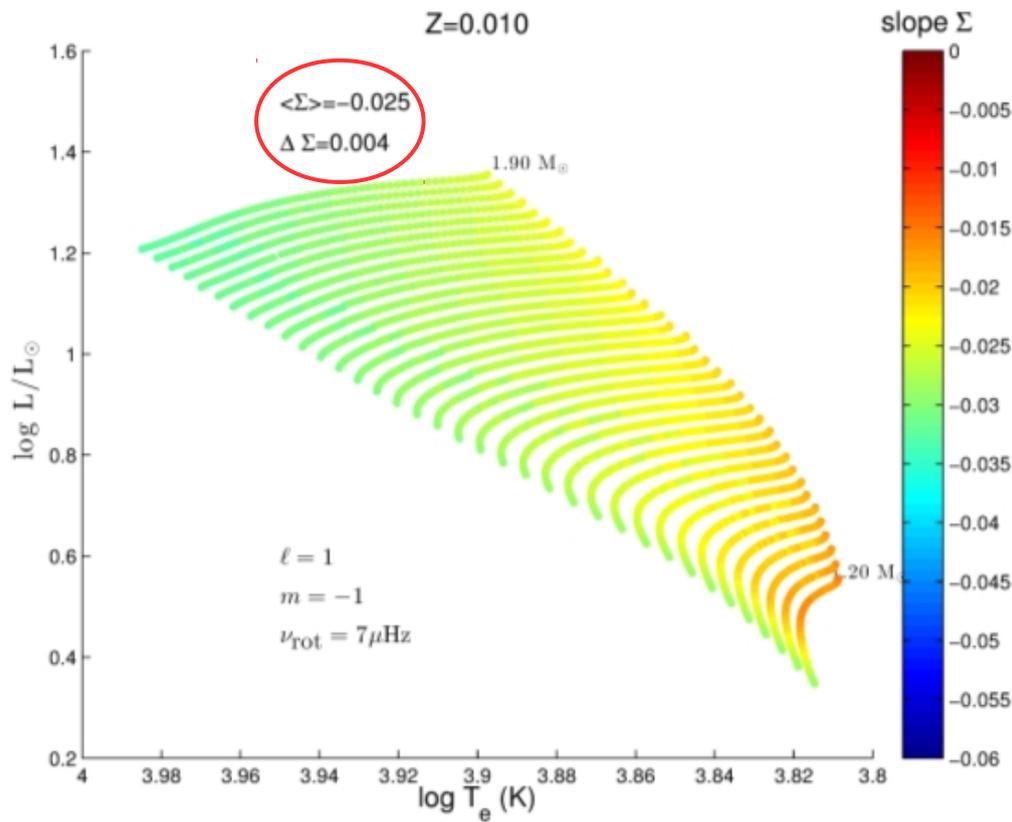
I.c Tools to infer rotation in γ Dor: a one-to-one relation?

1) Varying the rotation frequency : from 0.6 to 1.3 c/d



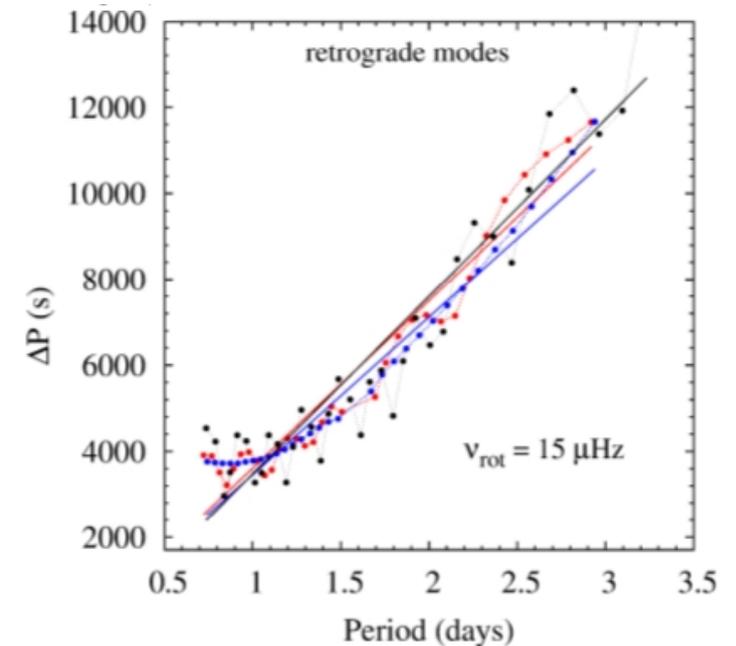
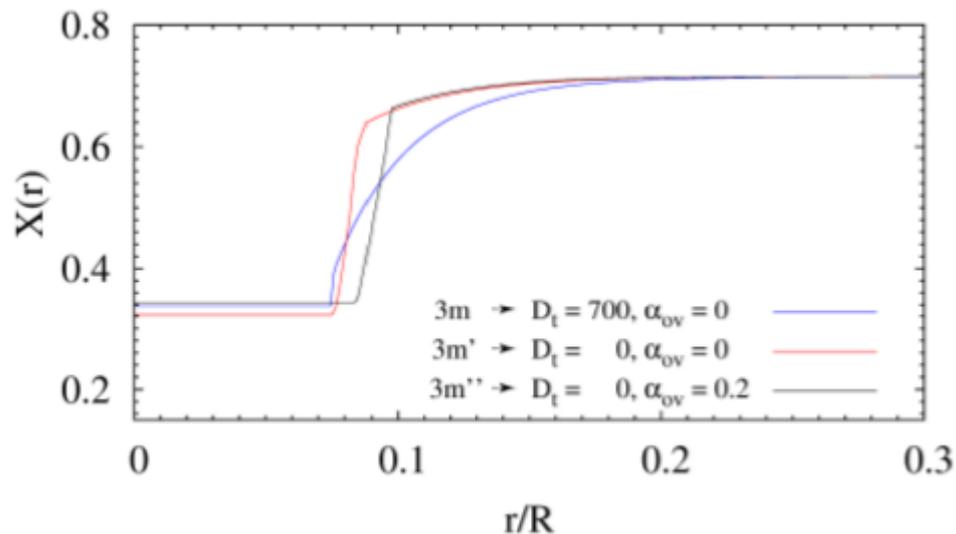
I.c Tools to infer rotation in γ Dor: a one-to-one relation?

2) Varying the metallicity $Z=0.010$ and $Z=0.014$



I.c Tools to infer rotation in γ Dor: a one-to-one relation?

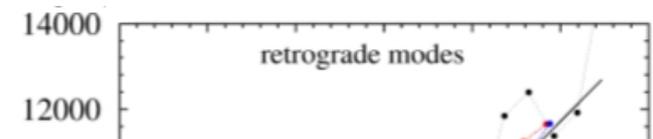
3) Sensitivity to the nature of the extra-mixing: "worst" case – retrograde modes



Model	Slope Σ
3m	4.24×10^{-2}
3m'	4.50×10^{-2}
3m''	4.77×10^{-2}

I.c Tools to infer rotation in γ Dor: a one-to-one relation?

3) Sensitivity to the nature of the extra-mixing: "worst" case – retrograde modes

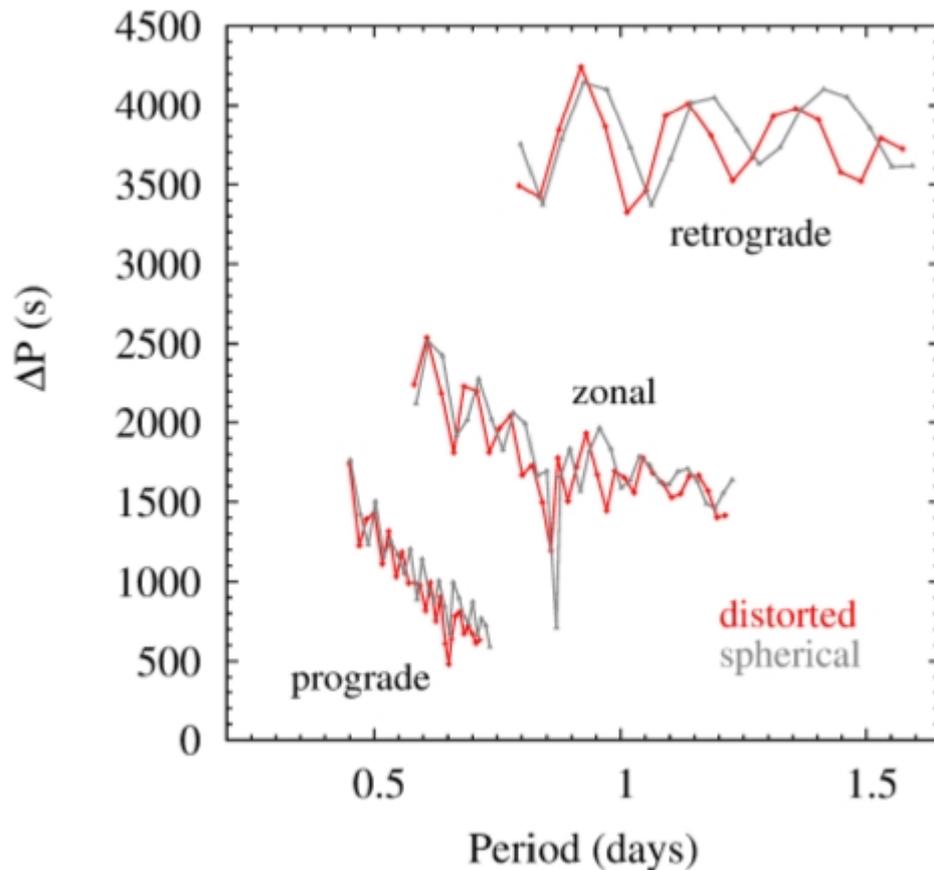


**Similar to a shift of the model in the HR diagram
=> effect included in the dispersion on the Σ -HR plots**

3m	4.24×10^{-2}
3m'	4.50×10^{-2}
3m''	4.77×10^{-2}

I.c Tools to infer rotation in γ Dor: a one-to-one relation?

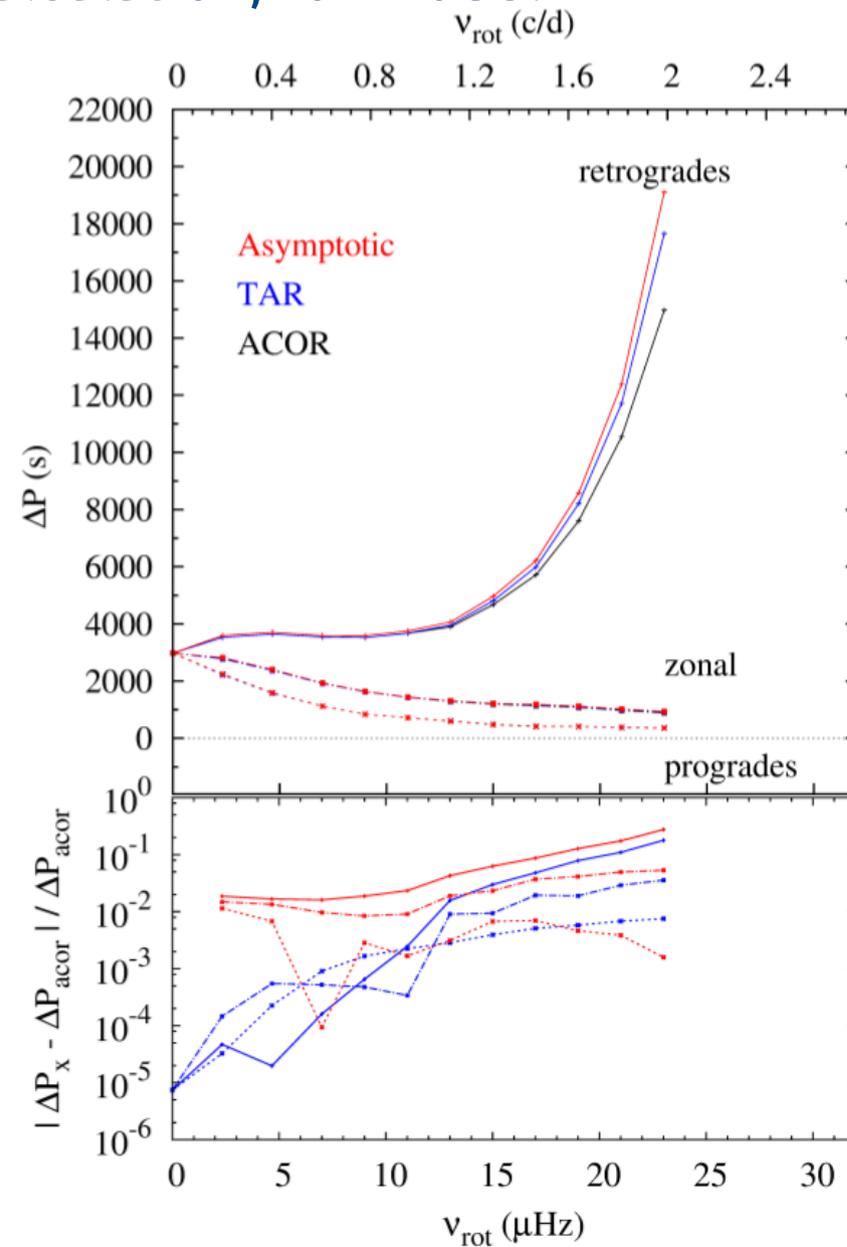
- 4) Impact of the centrifugal distortion (ACOR) :
- model M3 distorted following Roxburgh 2006
 - for a rotation profile 0.6 c/d in surface - 1.5 c/d in the core



modes	Σ_{1D}	Σ_{2D}
prograde	-0.035	-0.041
zonal	-0.012	-0.013
retrograde	0.0010	0.0009

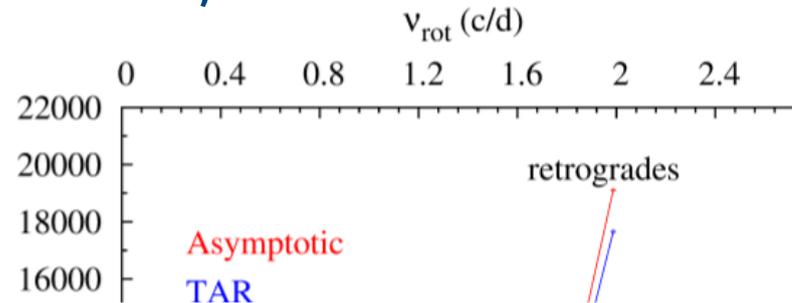
1.c Tools to infer rotation in γ Dor: a one-to-one relation?

5) TAR vs complete calculation, for model M1

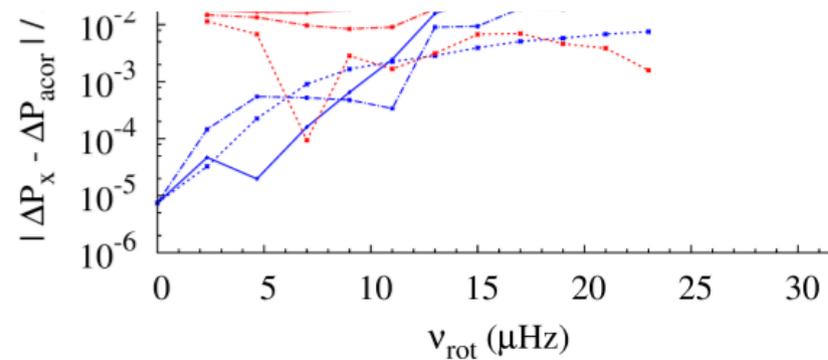


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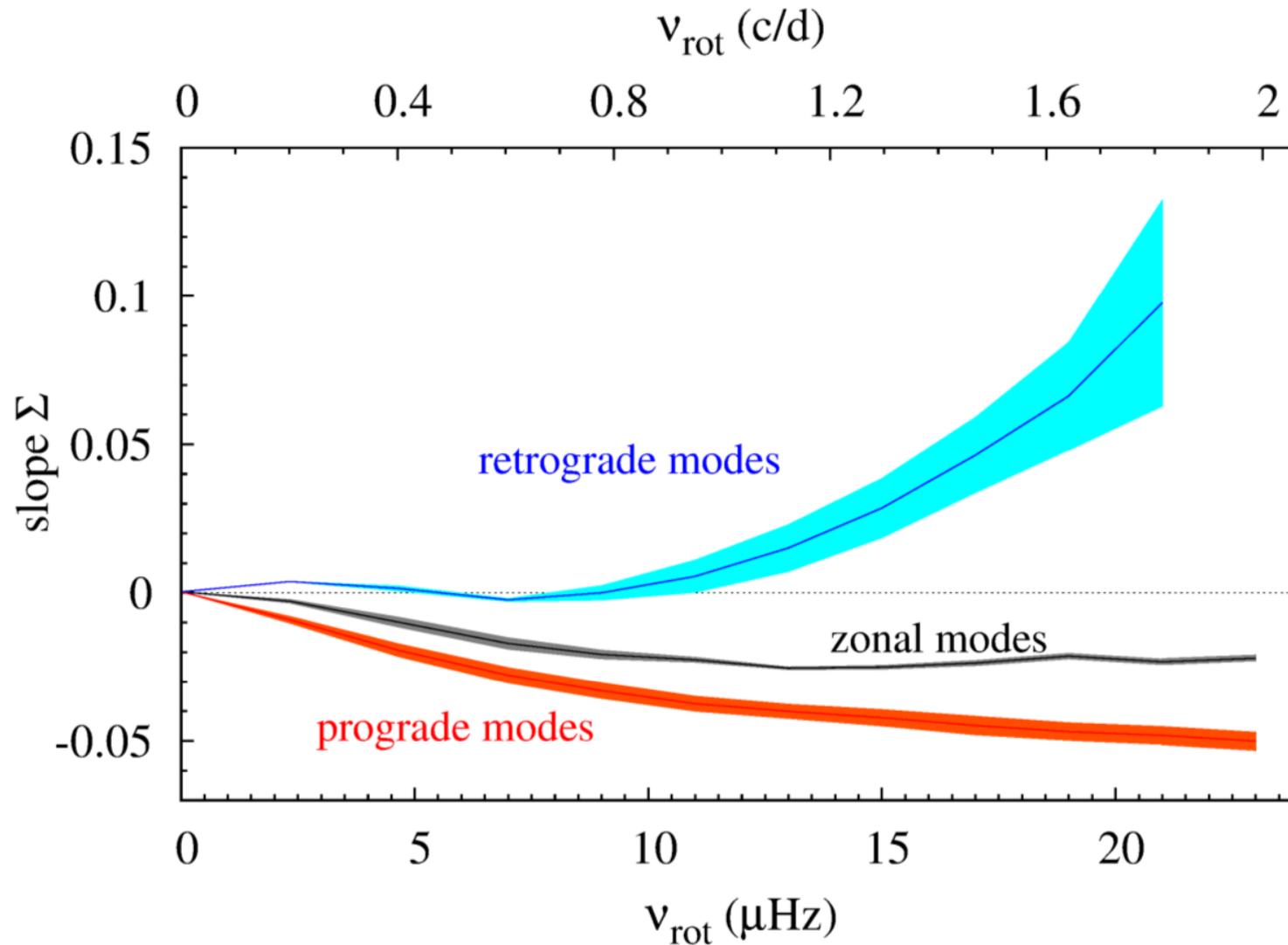


To obtain a Σ - Ω relation, we use the results of the complete 2D oscillation computations (ACOR) and estimate the uncertainty from the dispersion in the Σ -HR plots (TAR Asymptotic)

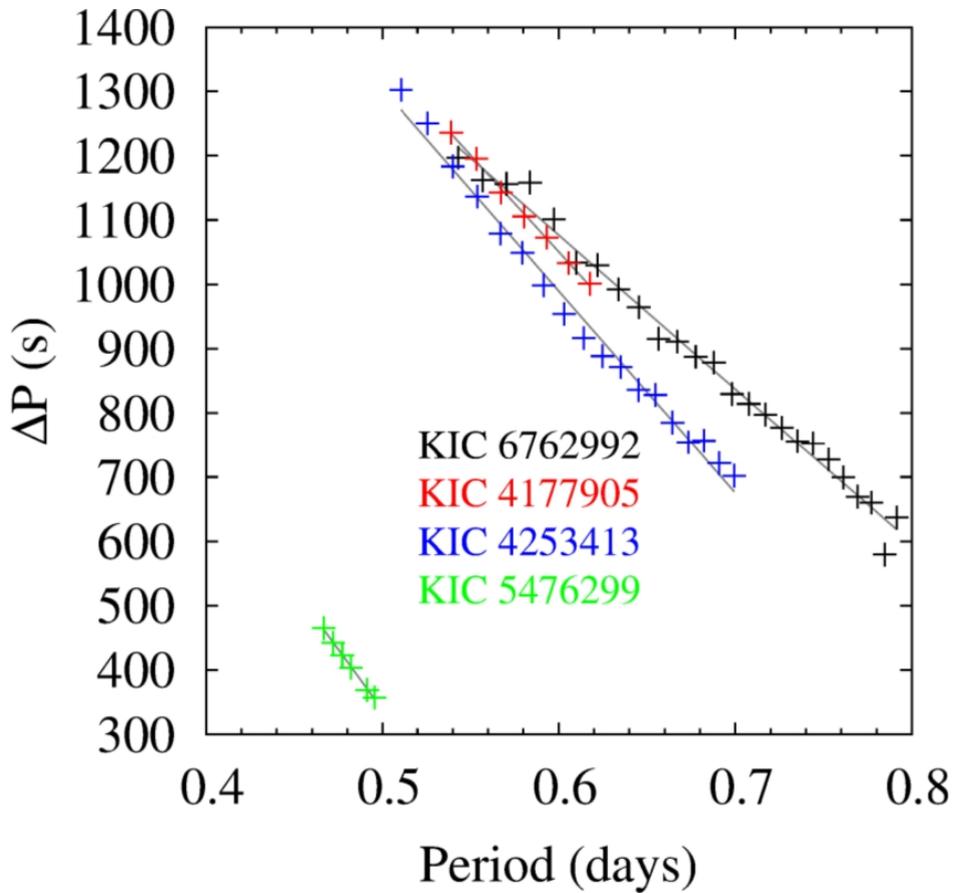


I.c Tools to infer rotation in γ Dor: the Σ - Ω relation

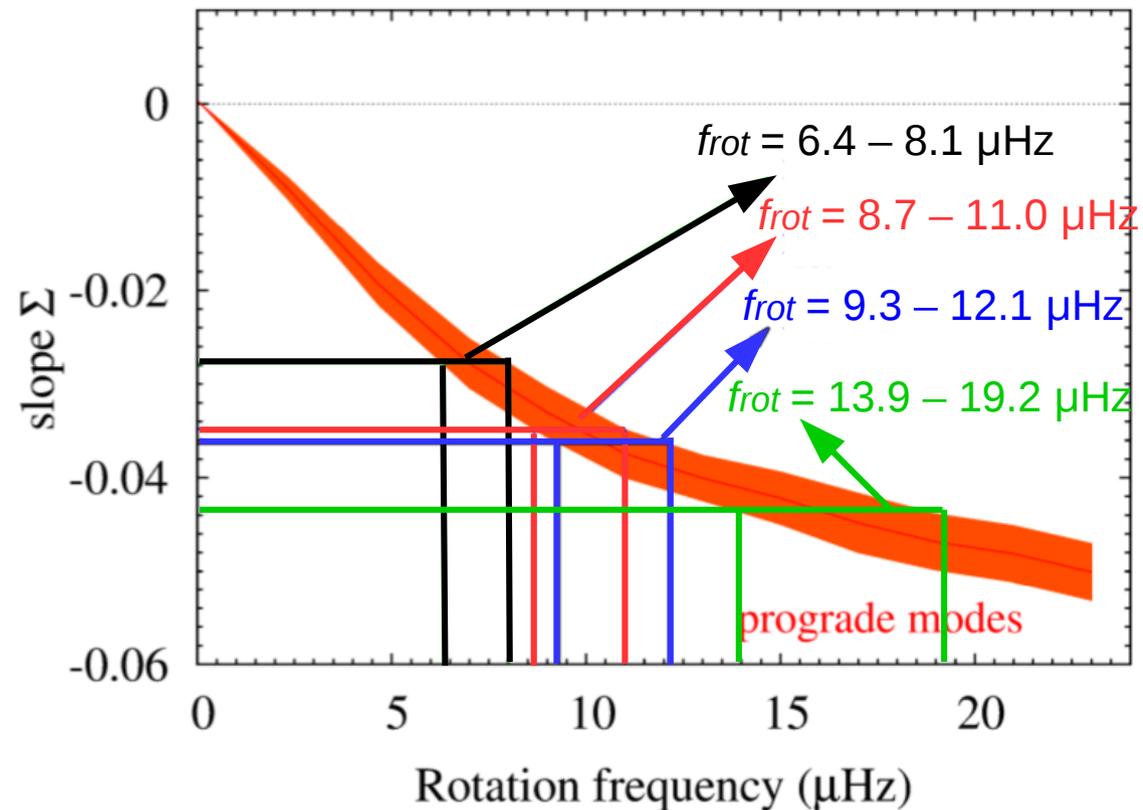
Ouazzani, Salmon et al. 2017



I.c Applying Σ - Ω relation to observations



In addition to the slope Σ , use of the mean period spacing and observed range of periods to identify the mode nature => prograde sectoral



I.c Exploiting asymptotic relation: the stretched periodogram

Another way to infer rotation and buoyancy radius: method developed in Christophe et al. 2018 (see also similar method by Takata et al. 2020)

Based on constant spacing of periods, back in the corotating referential :

$$\sqrt{\lambda_{\ell,m}(s)} P_{n,\ell,m}^{\text{co}} \approx P_0 (n + \epsilon)$$

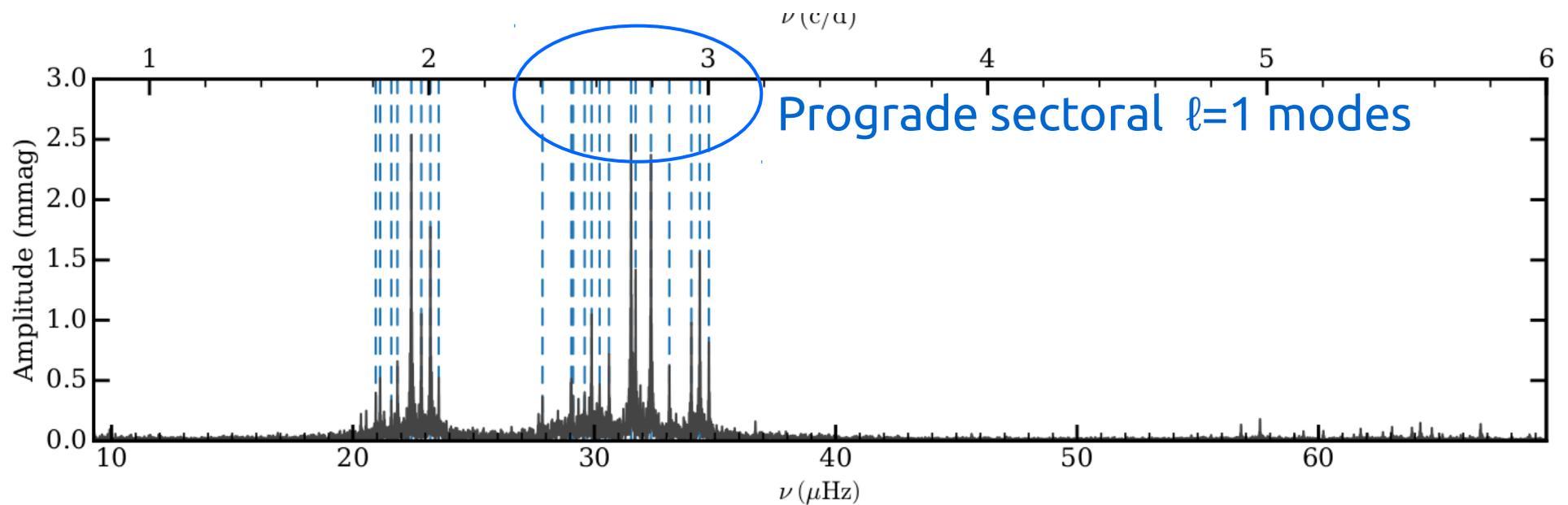
I.c The stretched periodogram

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Christophe et al. 2018 then propose to compute discrete Fourier transform varying Ω and P_0

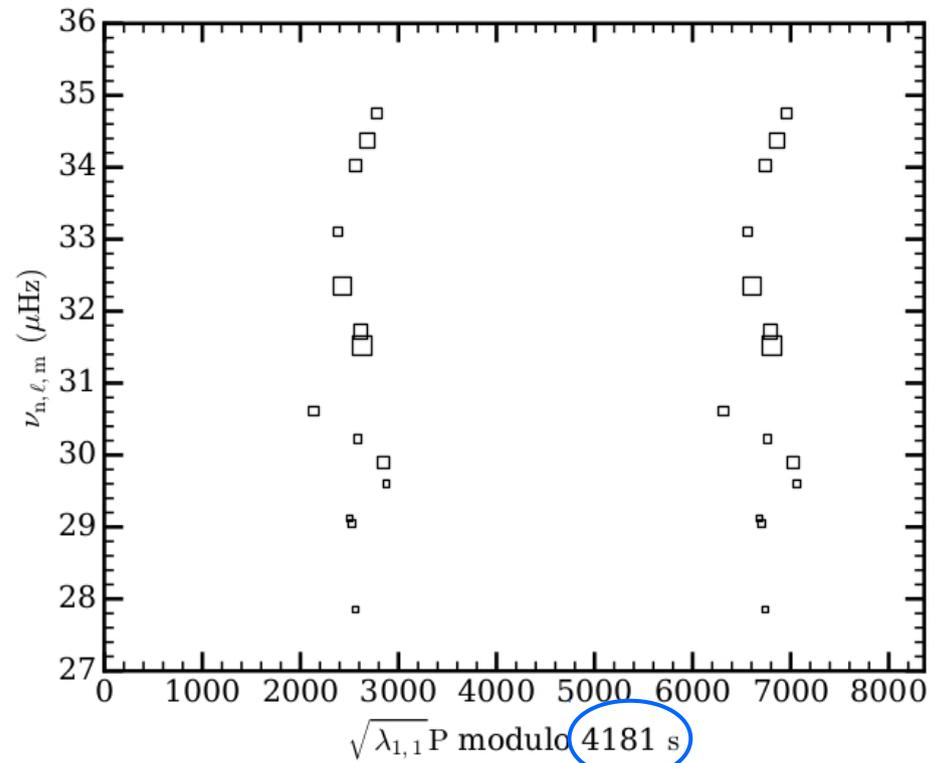
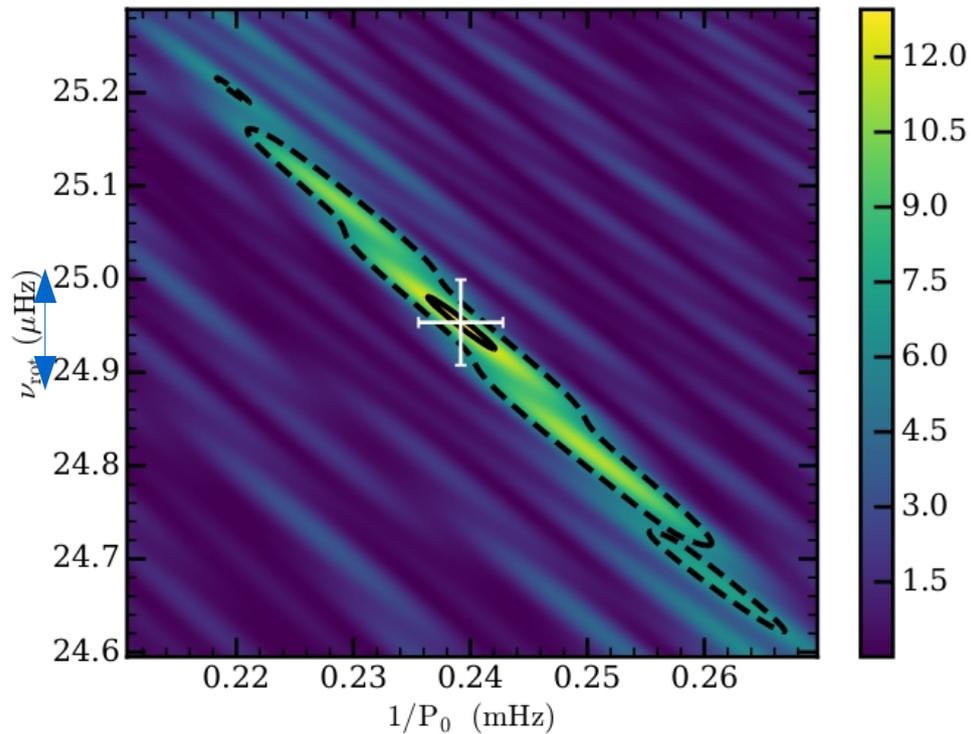
$$\left| \text{DFT} \left(\sqrt{\lambda_{\ell,m}} P_{\text{co}} \right) \right|^2 (f) = \frac{1}{N} \left| \sum_{i=1}^N e^{i2\pi f \sqrt{\lambda_{\ell,m}} P_i^{\text{co}}} \right|^2$$

I.c The stretched periodogram applied to KIC 12066947

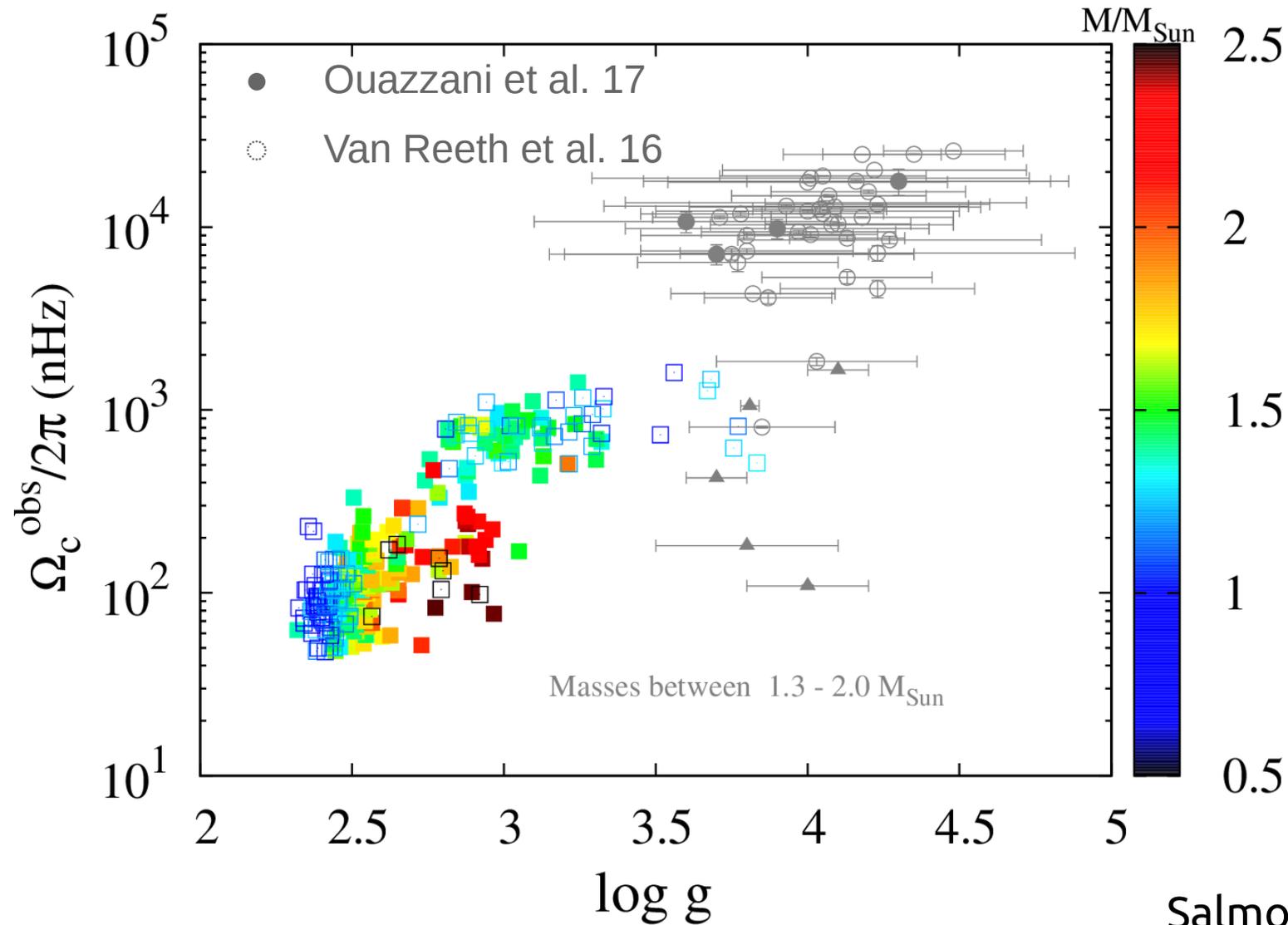


Christophe et al. 2018

V. New prospects: the stretched periodogram for KIC 12066947



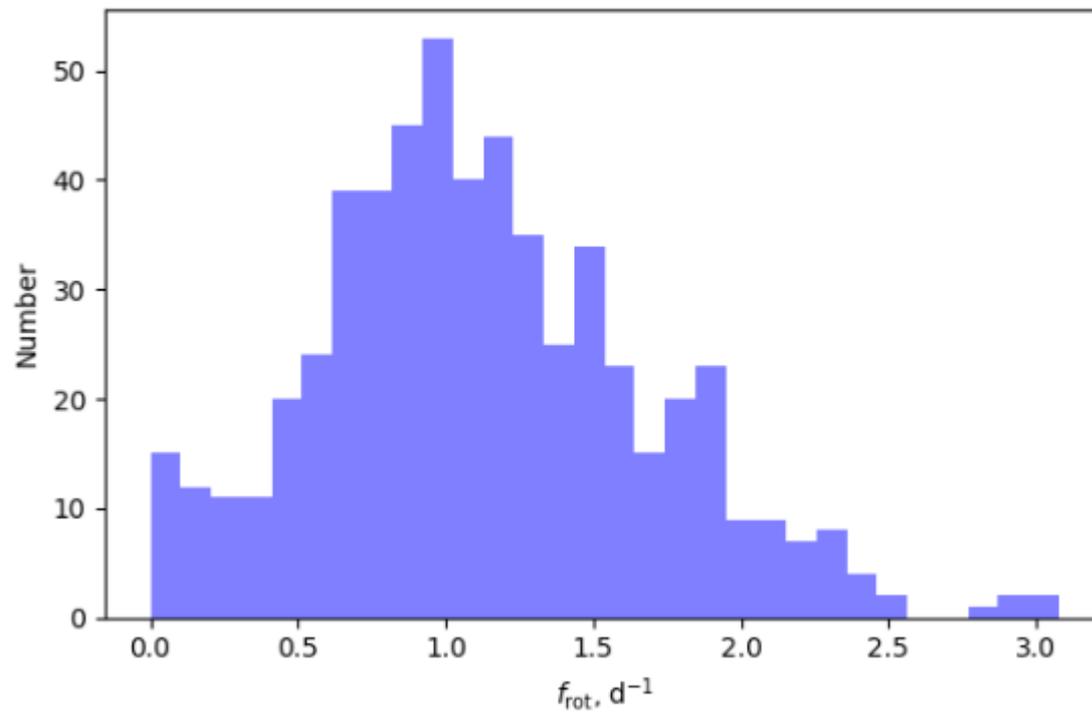
1.d First results



1.d New prospects: updating the core rotation – evolution diagram

- 33 more stars were analyzed with Christophe's method and presented in Ouazzani et al. 2019
- fast evolution of the sample: Li et al. 2019b claim identification of period spacing patterns in 611 Kepler stars in the γ Dor region of the HR diagram

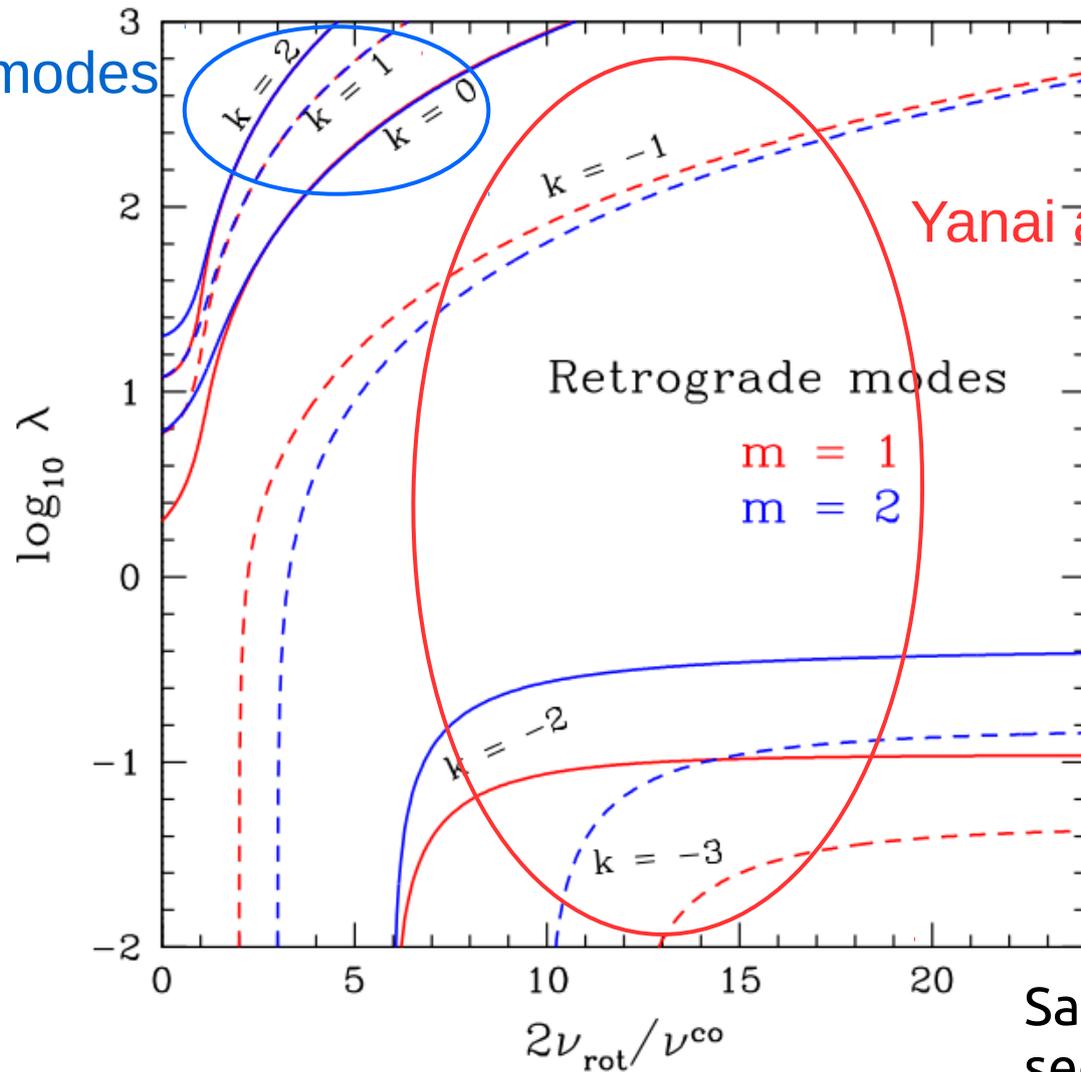
1.d New prospects: updating the core rotation – evolution diagram



Near-core rotations from the sample of Li et al. 2019b

1.d New prospects: additional constraints from the Rossby modes

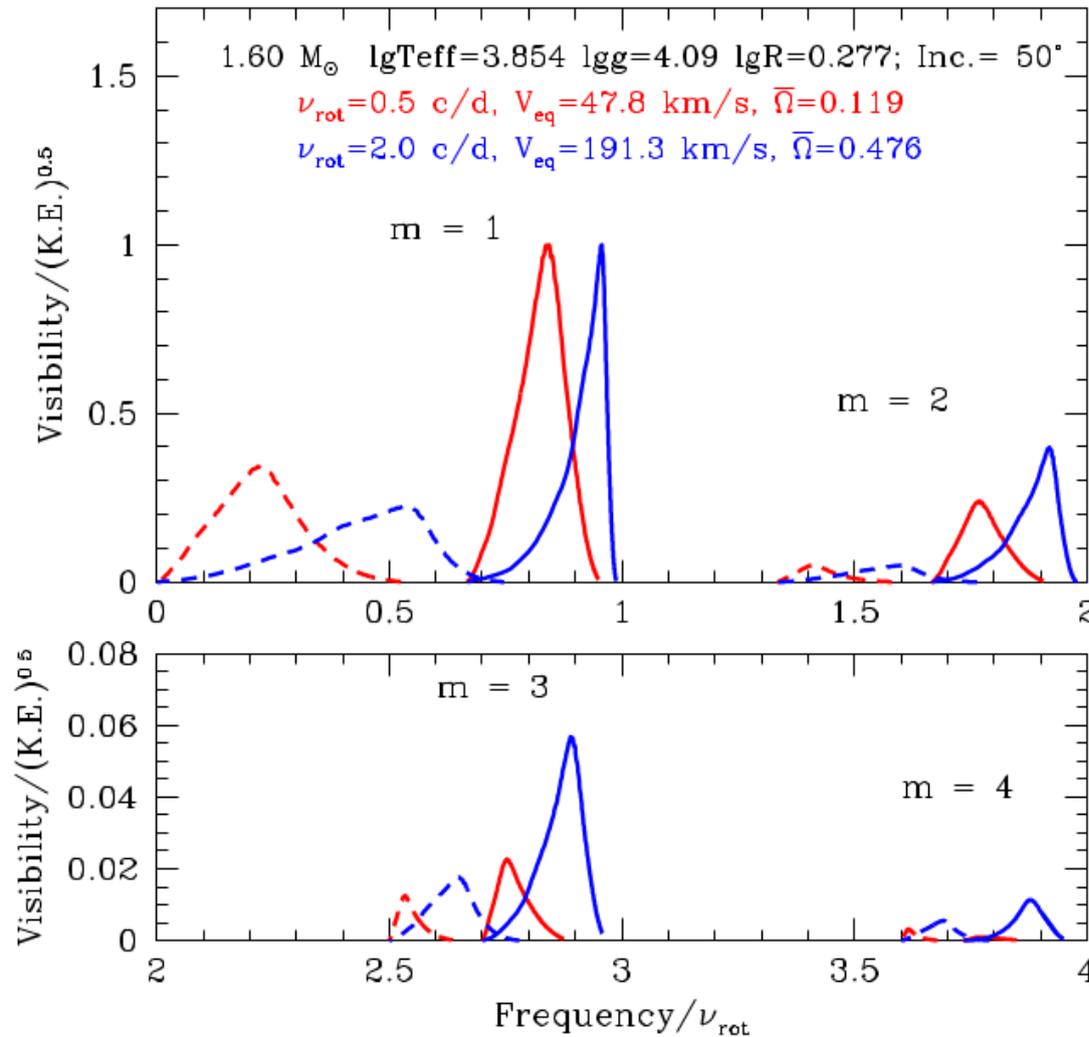
gravito-inertial modes



Yanai and Rossby modes:
Coriolis force is the
restoring force

Saio et al. 2018
see also Lee & Saio 1997

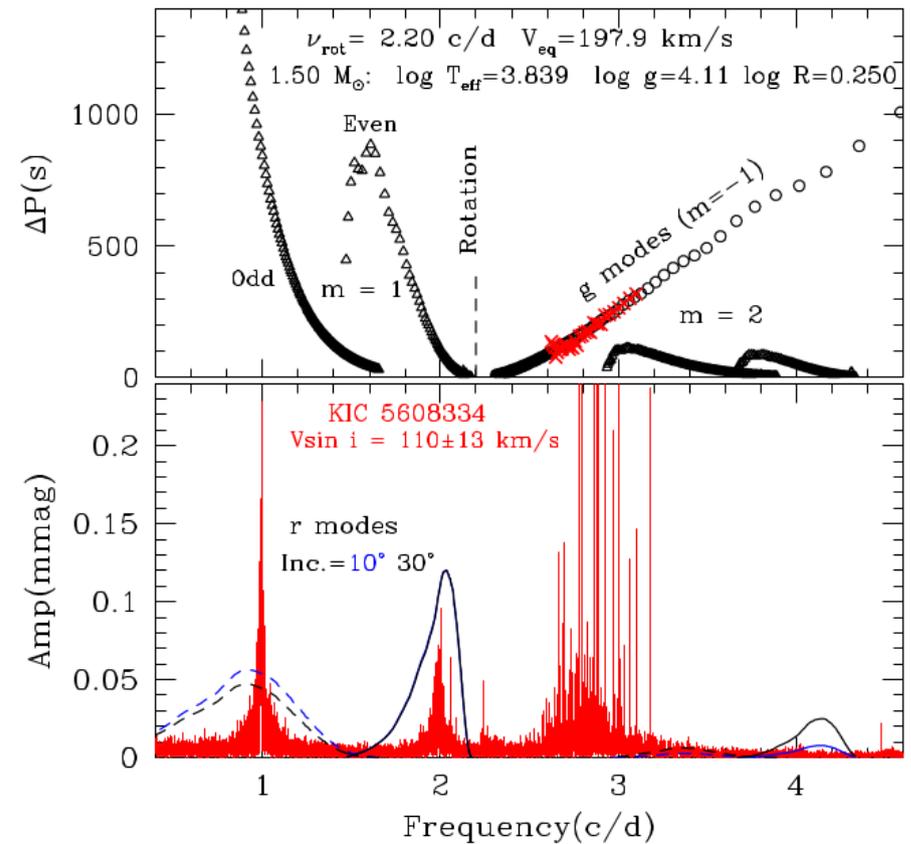
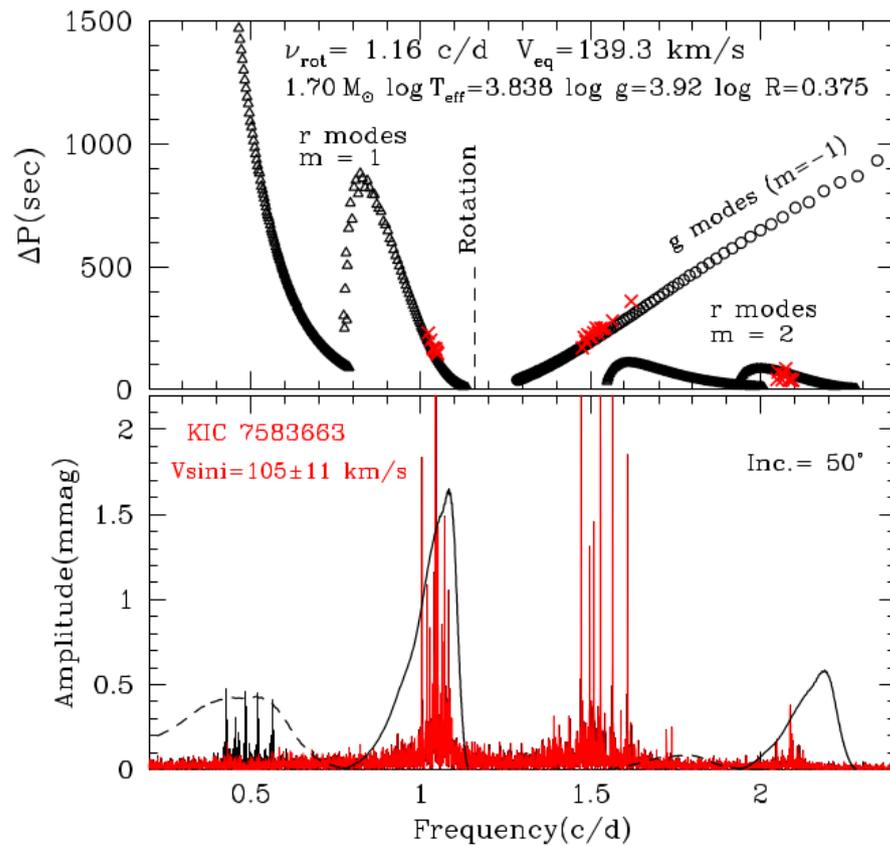
1.d New prospects: the Rossby modes



$f(\text{r modes}) < m f(\text{rotation})$

Saio et al. 2018

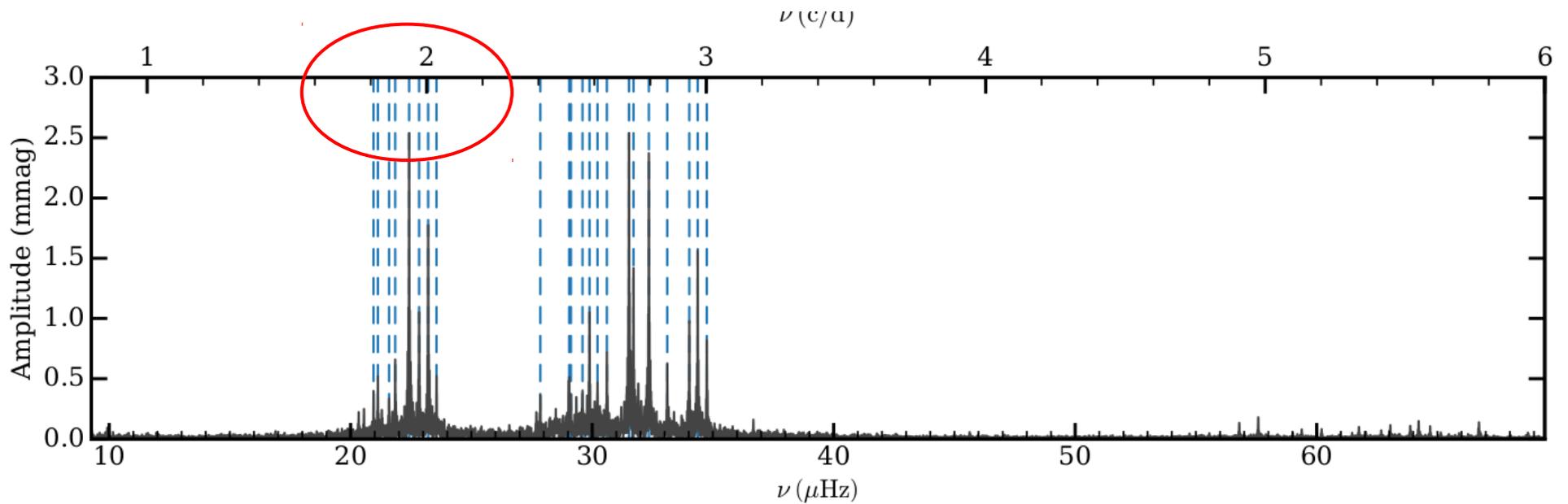
1.d New prospects: Rossby modes



Saio et al. 2018

1.d New prospects: Rossby modes also suspected in KIC 12066947

Rossby $m=1$ modes



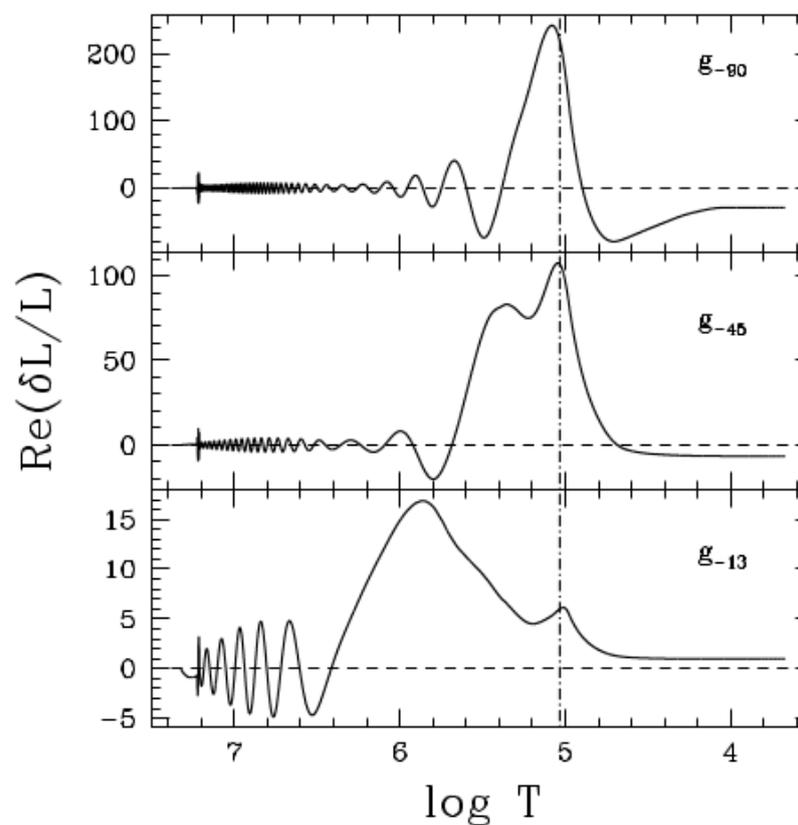
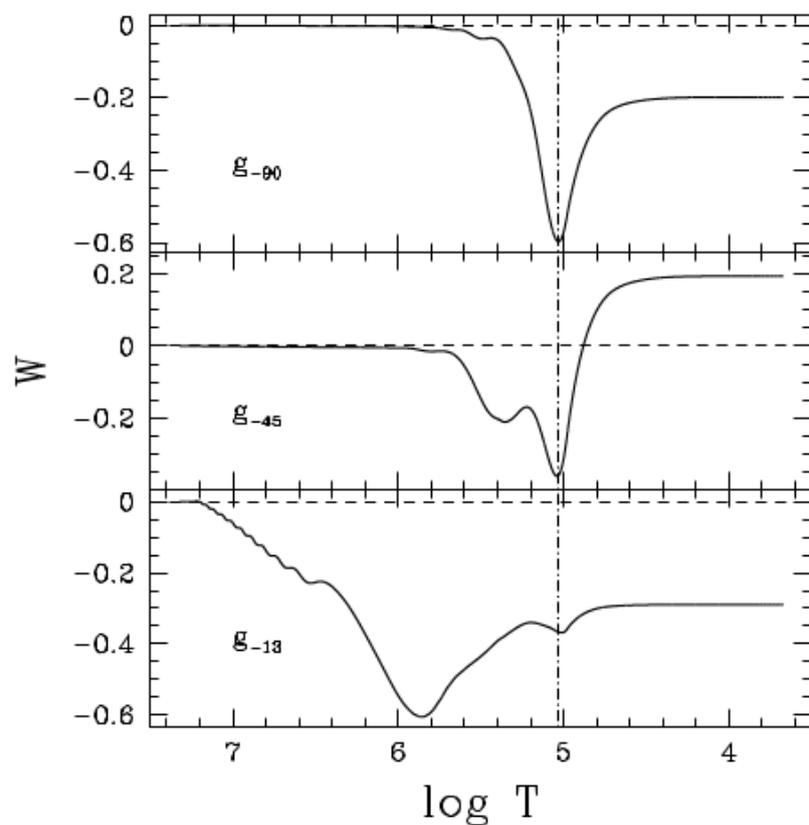
Christophe et al. 2018

1.d Pursuing the effort on the Rossby modes

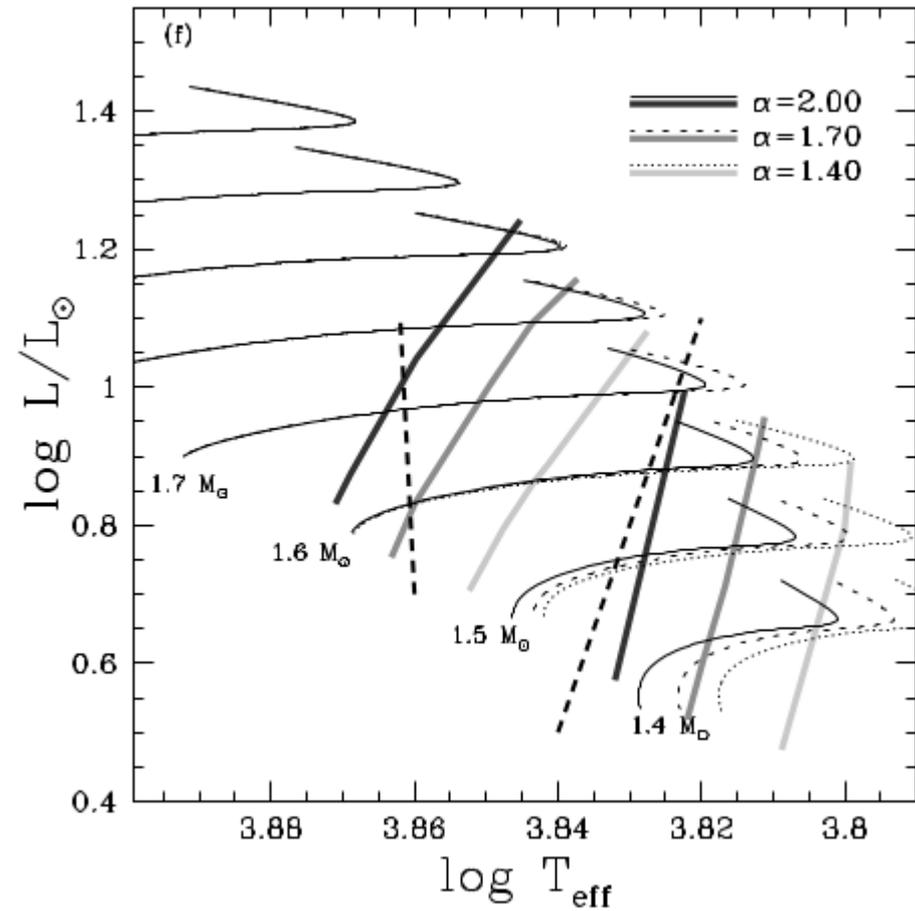
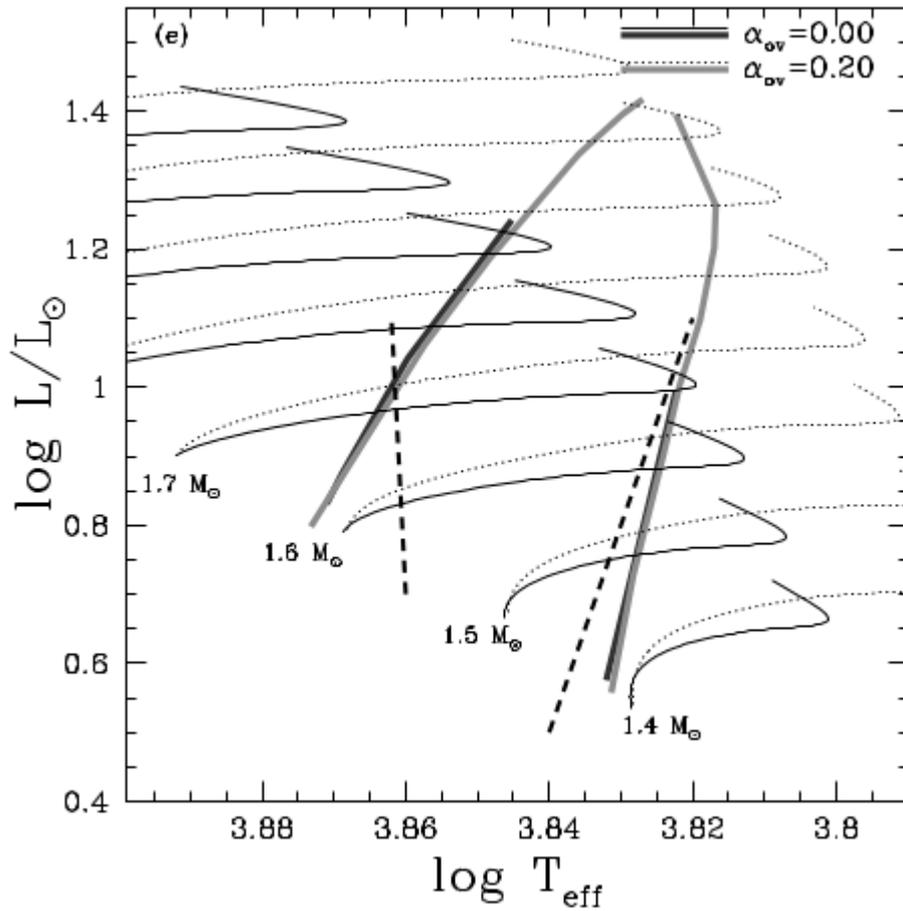
- Takata et al. (submitted) proposed to adapt the stretching method to Rossby modes. Applied to 2 Kepler stars, same rotation frequency than with gravito-inertial modes.
- Li et al. 2020 presents a sample of 82 stars with claimed detection of Rossby modes.
 - => need for another formalism to determine which region is probed by the Rossby modes
 - => providing a non-adiabatic analysis to get better constraints on the stellar parameters and understanding of the Rossby mode behaviour : work in progress

1.d Rossby modes: non-adiabatic computations

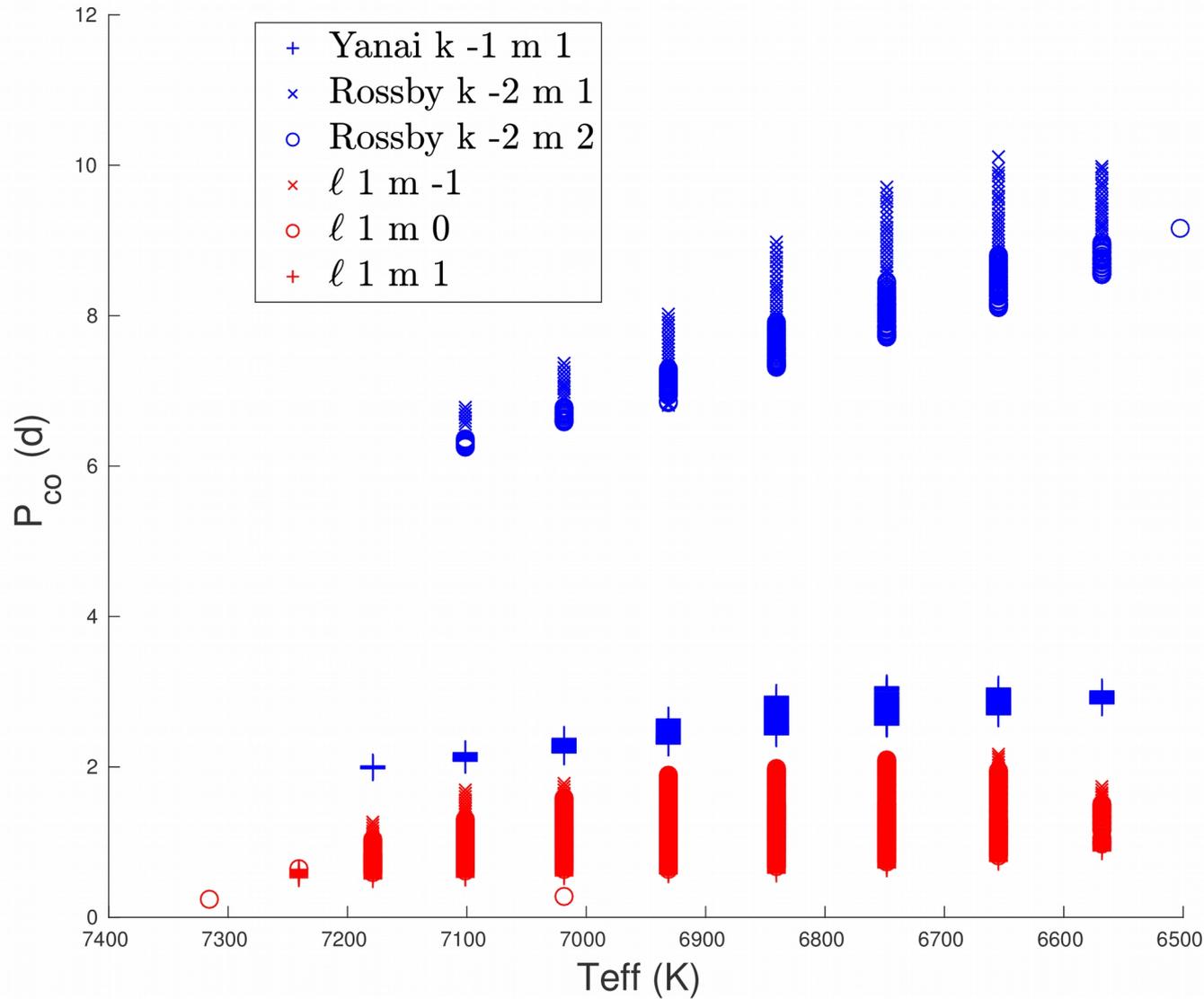
- Transition region: amplitude of the eigenfunction
- Competition with radiative damping



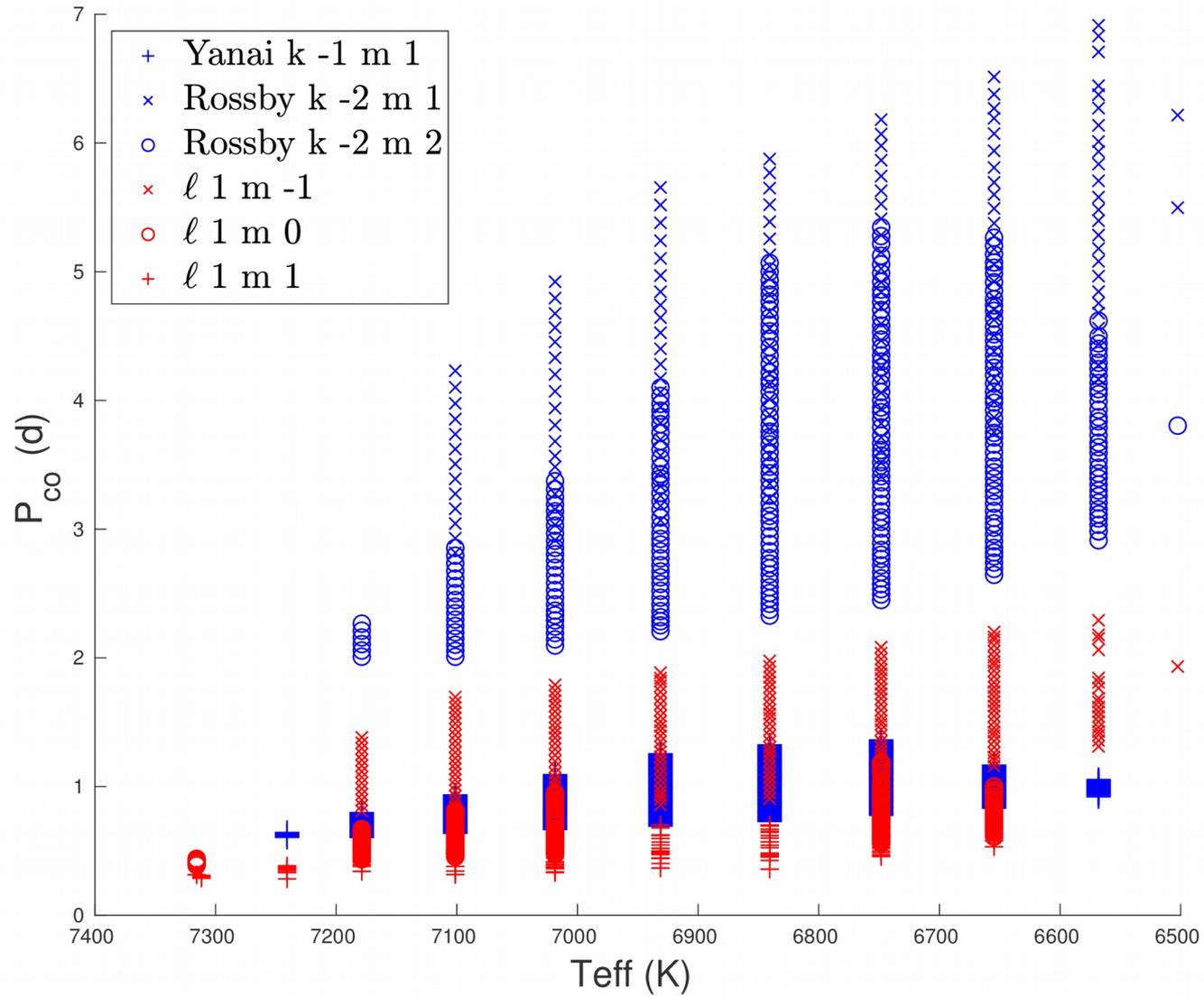
1.d Rossby modes: non-adiabatic computations



1.d Preliminary results : $\Omega/\Omega_c=0.10$; $1.50M_\odot$



I.d Preliminary results : $\Omega/\Omega_c=0.40$; $1.50M_\odot$



1.d Other questions

- 58 stars in the Li et al. 2019b sample presents variability associated to surface modulation => surface rotation frequency. Most are compatible with rigid rotation.

=> *quid* of the analysis assumptions (TAR asymptotic approach based on rigid rotation)

=> need to include refined treatment of rotation in TAR (e.g. Van Reeth et al. 2018, Mathis & Prat 2019)

=> ideal cases: full modelling of stars + full treatment of rotation (ACOR code)/inversion (Hatta et al. 2019). Additional observations to get fundamental parameters (Takada-Hidai et al. 2017, Mombarg et al. 2019)

1.d Other questions

- Nature of the mixing at the edge of the convective core. Detected period spacings have almost no oscillating pattern => diffusive mixing?

=> bias in the period spacing detection methods?

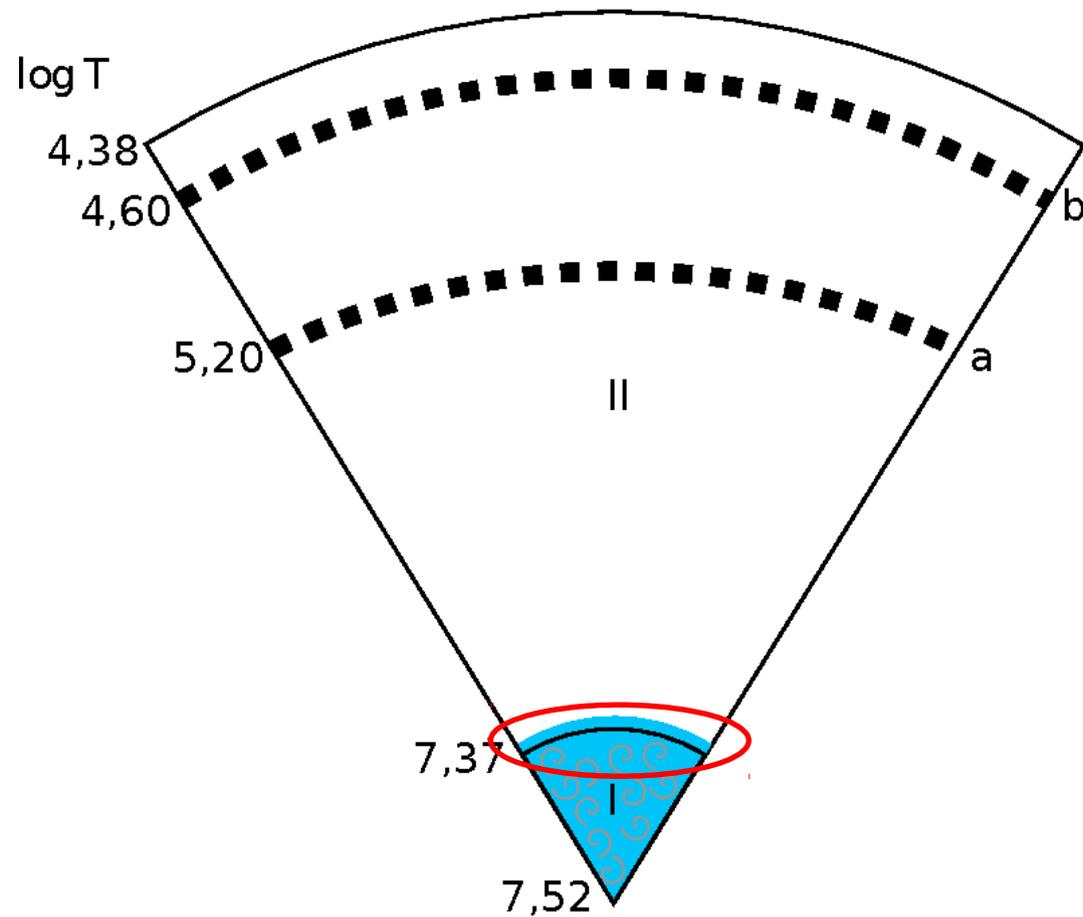
- The large samples of γ Dor stars already offer unique opportunities to compare to models with different angular momentum transport prescriptions.

II. Asteroseismology of β Cephei stars

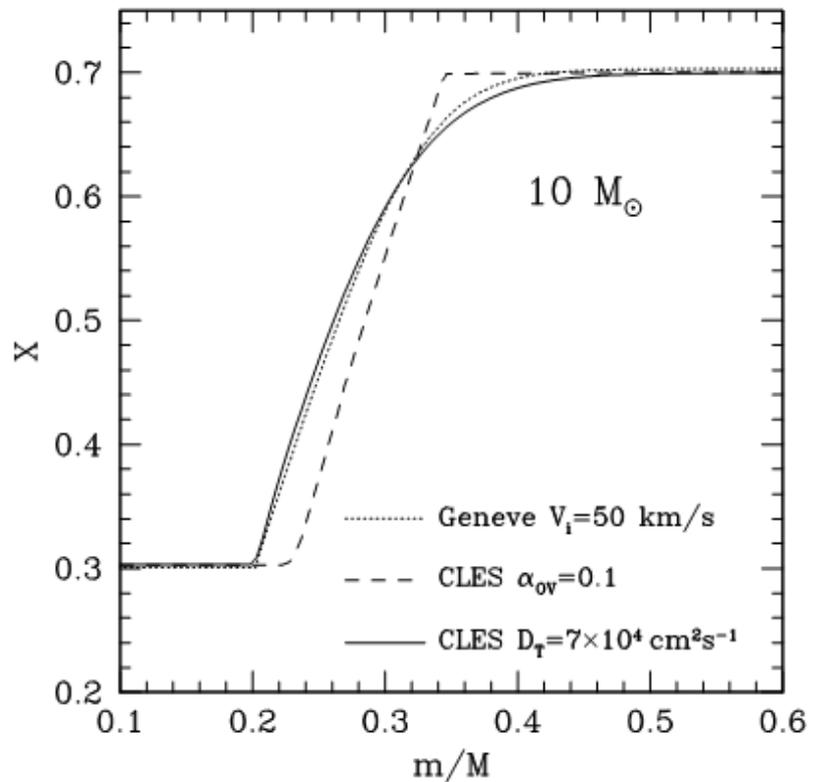
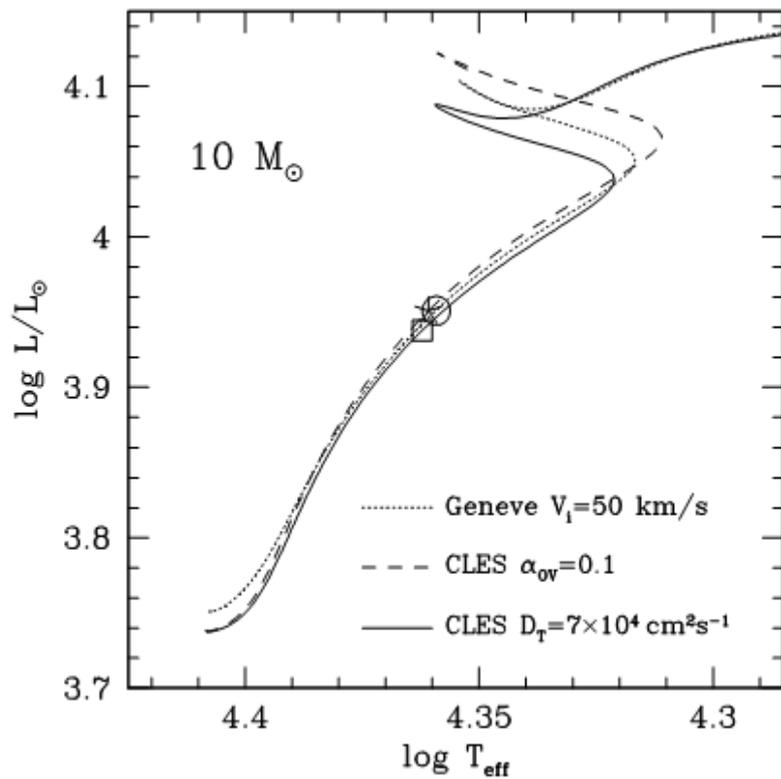
II. Asteroseismology of β Cephei stars

- a) The asteroseismic potential
- b) The model dependency and what is actually constrained
- c) Future prospect

II.a β Cephei stars: typical structure



II.a Different mixing processes



II.a A first asteroseismic legacy

Name	References	α_{ov}	$\Omega_{core}/\Omega_{surf}$	Surf. rotation
HD 129929	(Aerts et al. 2003, 2004; Dupret et al. 2004 ; Thoul et al. 2004)	0.10 ± 0.05	3.6	$v \sin i \lesssim 13$ km/s
ν Eri	(Handler et al. 2004 ; Aerts et al. 2004 ; De Ridder et al. 2004 ; Pamyatnykh et al. 2004; Dziembowski & Pamyatnykh 2008)	0 - 0.12	$\sim 3 - 5.8$	$v \sin i \lesssim 20$ km/s
β Canis Majoris	(Aerts et al. 1994 ; Shobrook et al. 2006 ; Mazumdar et al. 2006)	0.20 ± 0.05	-	$v_{eq} = 31 \pm 5$ km/s
δ Ceti	(Aerts et al. 1992, 2006)	0.20 ± 0.05	-	$v \sin i = 1 \pm 1$ km/s
V 1449 Aquilae	(Belkacem et al. 2009 ; Degroote et al. 2009 ; Aerts et al. 2011)	0-0.05	-	$v \sin i \lesssim 30$ km/s
12 Lac	(Handler et al. 2006 ; Desmet et al. 2007; Desmet et al. 2009; Dziembowski & Pamyatnykh 2008)	< 0.40	1.8 - 5	$v \sin i \lesssim 30$ km/s
θ Oph	(Handler et al. 2005; Briquet et al. 2005; Briquet et al. 2007)	0.44 ± 0.07	~ 1	$v \sin i = 36 \pm 2$ km/s
V 2052 Oph	(Neiner et al. 2003 ; Morel et al. 2006 ; Handler et al. 2012 ; Briquet et al. 2012)	0 - 0.15	-	$v \sin i \approx 71-75$ km/s

II.b What is actually constrained by asteroseismology

- Five free parameters to fit : M , X , Z , age, α_{ov} . Which accuracy can be expected, depending on the seismic constraints and the input physics?
- How about the central mixed layers? To which extent does it depend on the physics of the models used for the modelling
- Tests in hare and hound exercises

II.b Hare and hound exercise

- Merit function solely based on seismic constraints

$$\chi^2 = \frac{1}{N_{\text{obs}}} \sum_{i=1}^{N_{\text{obs}}} \frac{(\nu_{\text{obs},i} - \nu_{\text{th},i})^2}{\sigma_i^2}$$

- The fitting models from a grid adopting Asplund et al. 05 mixture.

Parameter	Range	Step
M (in M_{\odot})	7.6 – 18.6	0.1
X	0.68 – 0.74	0.02
Z	0.010 – 0.018	0.002
α_{ov}	0 – 0.50	0.05

II.b Hare and hound exercises

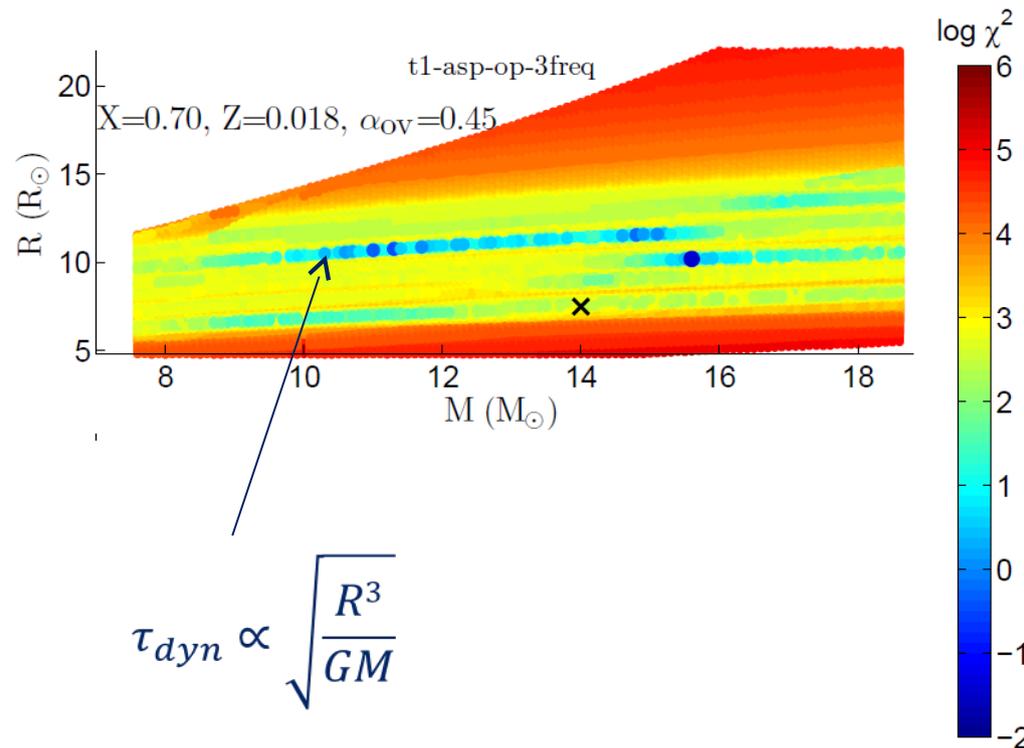
- The target stars are theoretical models with various physics, hence differing from that of the fit

Model	Mass (in M_{\odot})	R (in R_{\odot})	X	Z	α_{ov}	X_c	Diff	Solar mixture	Opacities	Atm	T_e (K)	$\log g$ (cm/s^2)
t1	14	7.48	0.70	0.014	0.2	0.288	N	AGS05	OP	Edd	27647	3.8364
t2	11	5.98	0.70	0.016	0.2	0.351	N	GN93	OP	K	25293	3.9258
t3	12	6.31	0.72	0.016	0.2	0.384	N	GN93	OPAL	K	25979	3.9163
t4	12	7.02	0.70	0.014	0	0.208	N	GN93	OPAL	K	25309	3.8245
t5	10	5.24	0.70	0.020	0	0.418	Y	GN93	OP	Edd	23906	3.9984
t6	10	4.020	0.70	0.014	0	0.388	Y	AGS05	OP	Edd	24487	4.0196
t7 [†]	9.4	4.62	0.715	0.016	0.1	0.473	N	AGS05+Ne	OPAL	K	23533	4.0818

II.b Testing the seismic constraints

Input model (« observed » star)	Fitting models
AGS05/OP	AGS05/OP

- t1, 3 frequencies, ℓ known (0,1,2)



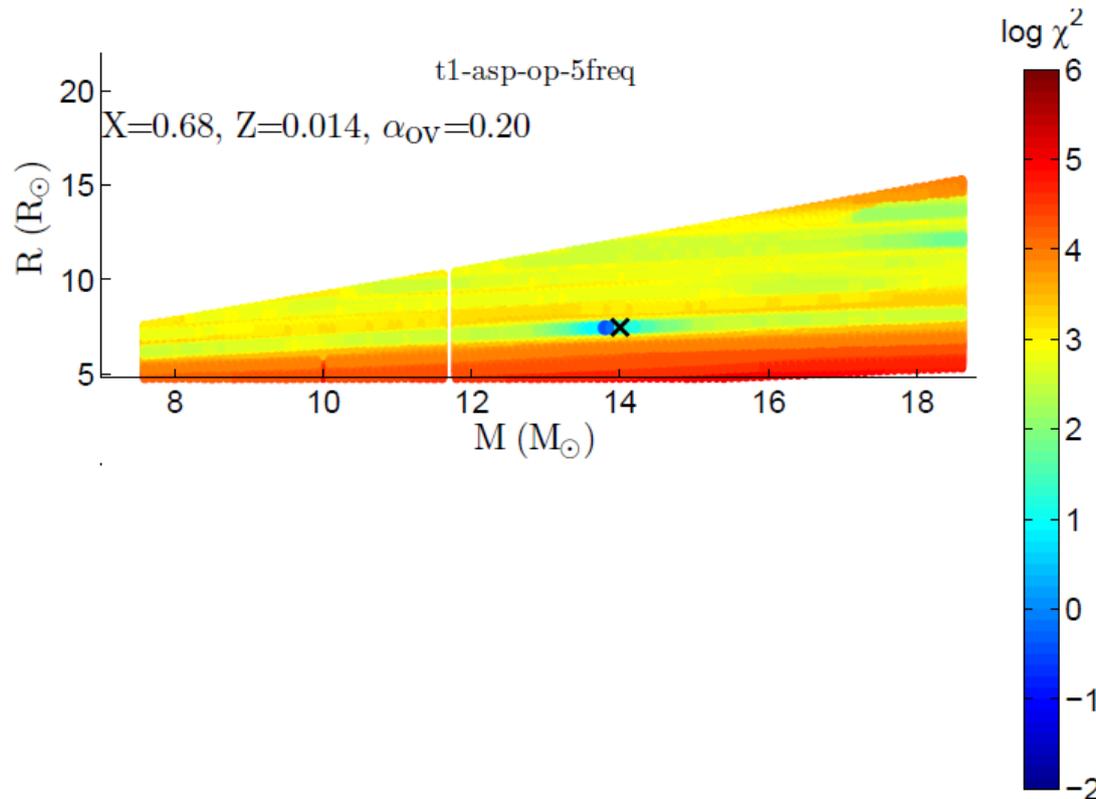
(radial mode constraint)

Parameter	Input	Fitting model
M (M_{\odot})	14	15.6
R (R_{\odot})	7.48	10.18
X	0.70	0.70
Z	0.014	0.018
α_{ov}	0.20	0.45
Xc	0.288	0.237

II.b Testing the seismic constraints

Input model (« observed » star)	Fitting models
AGS05/OP	AGS05/OP

- t1, 5 frequencies, ℓ known (0,1,2)

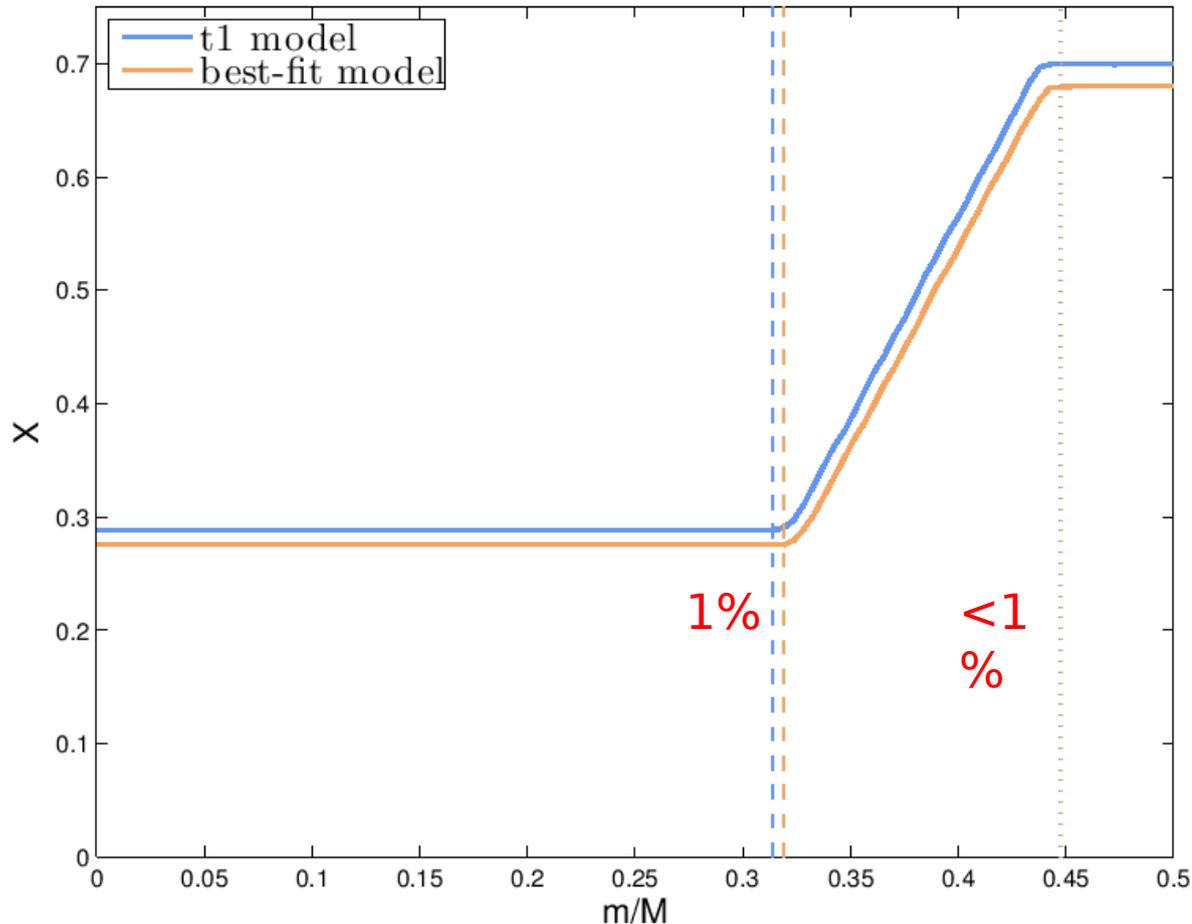


Paramete	Input	Fitting model
r		
M (M_{\odot})	14	13.8
R (R_{\odot})	7.48	7.45
X	0.70	0.68
Z	0.014	0.014
α_{ov}	0.20	0.20
Xc	0.288	0.274

II.b Testing the seismic constraints

Input model (« observed » star)	Fitting models
AGS05/OP	AGS05/OP

- t1, 5 frequencies, ℓ known (0,1,2)

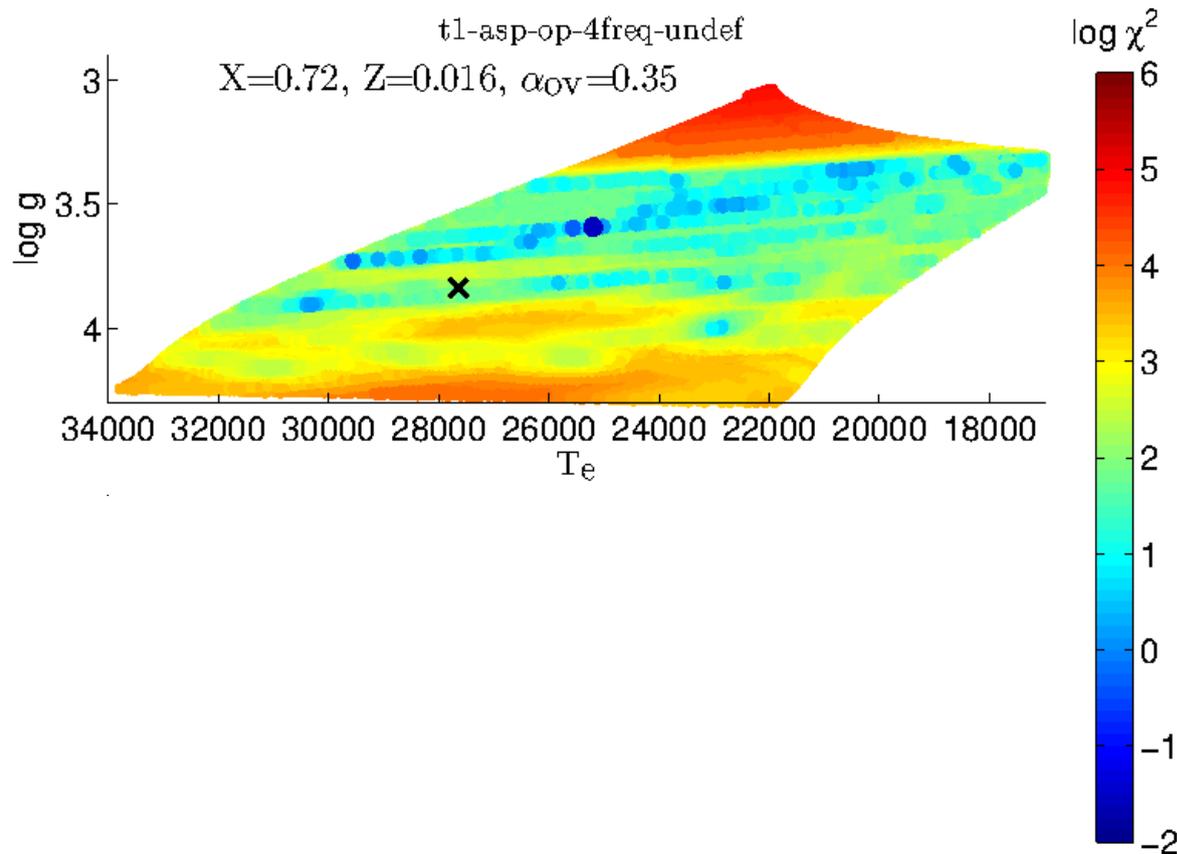


Parameter	Input	Fitting model
r		
$M (M_{\odot})$	14	13.8
$R (R_{\odot})$	7.48	7.45
X	0.70	0.68
Z	0.014	0.014
α_{ov}	0.20	0.20
X_c	0.288	0.274

II.b Testing the seismic constraints

Input model (« observed » star)	Fitting models
AGS05/OP	AGS05/OP

- t1, 4 frequencies, ℓ unknown

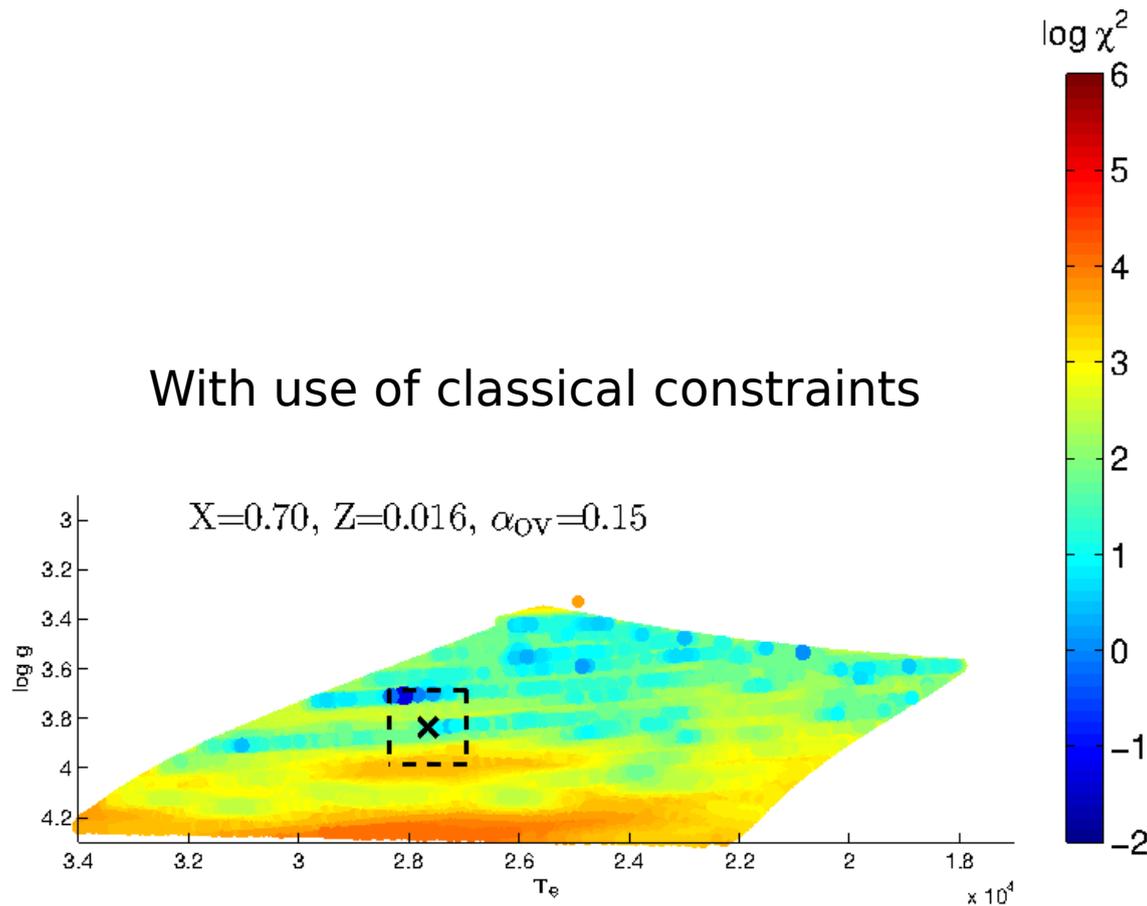


Parameter	Input	Fitting model
M (M_{\odot})	14	14.2
R (R_{\odot})	7.48	9.99
X	0.70	0.72
Z	0.014	0.016
α_{ov}	0.20	0.35
X_c	0.288	0.201

II.b Testing the seismic constraints

Input model (« observed » star)	Fitting models
AGS05/OP	AGS05/OP

- t_1 , 4 frequencies, τ unknown

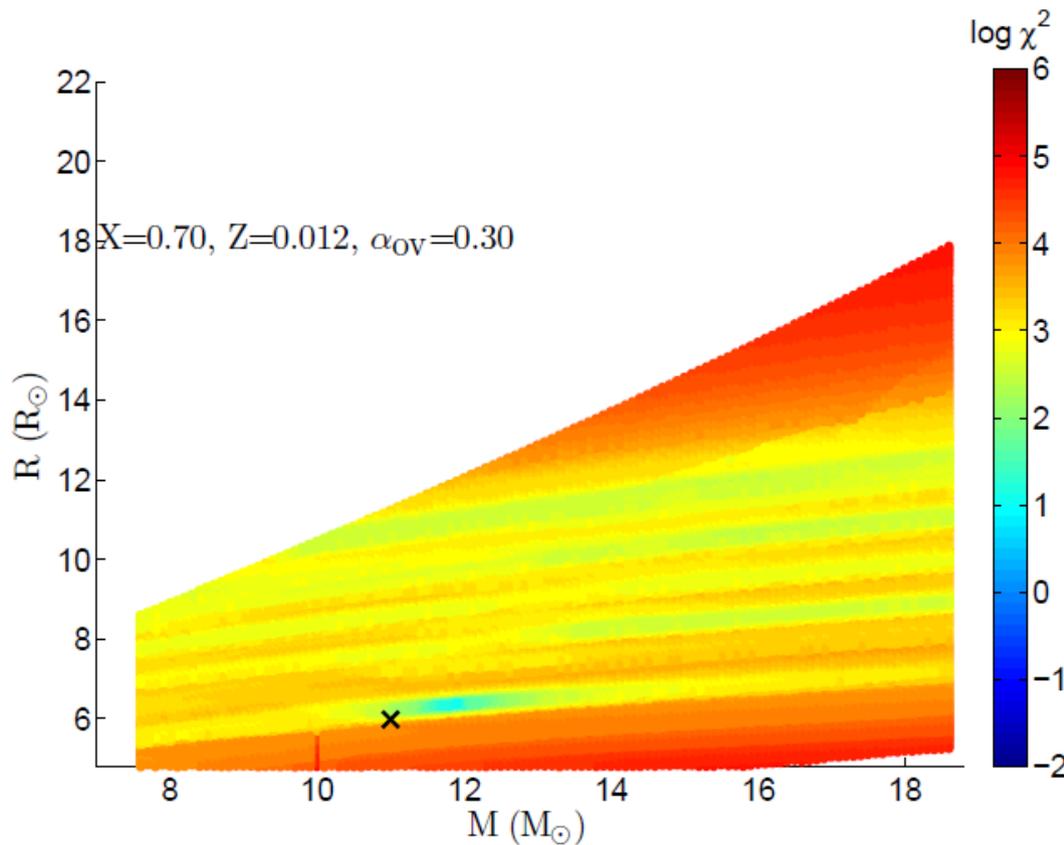


Parameter	Input	Fitting model
M (M_{\odot})	14	16.6
R (R_{\odot})	7.48	9.43
X	0.70	0.70
Z	0.014	0.016
α_{ov}	0.20	0.15
X_c	0.288	0.212

II.b Testing the physics

Input model (« observed » star)	Fitting models
GN93/OP	AGS05/OP

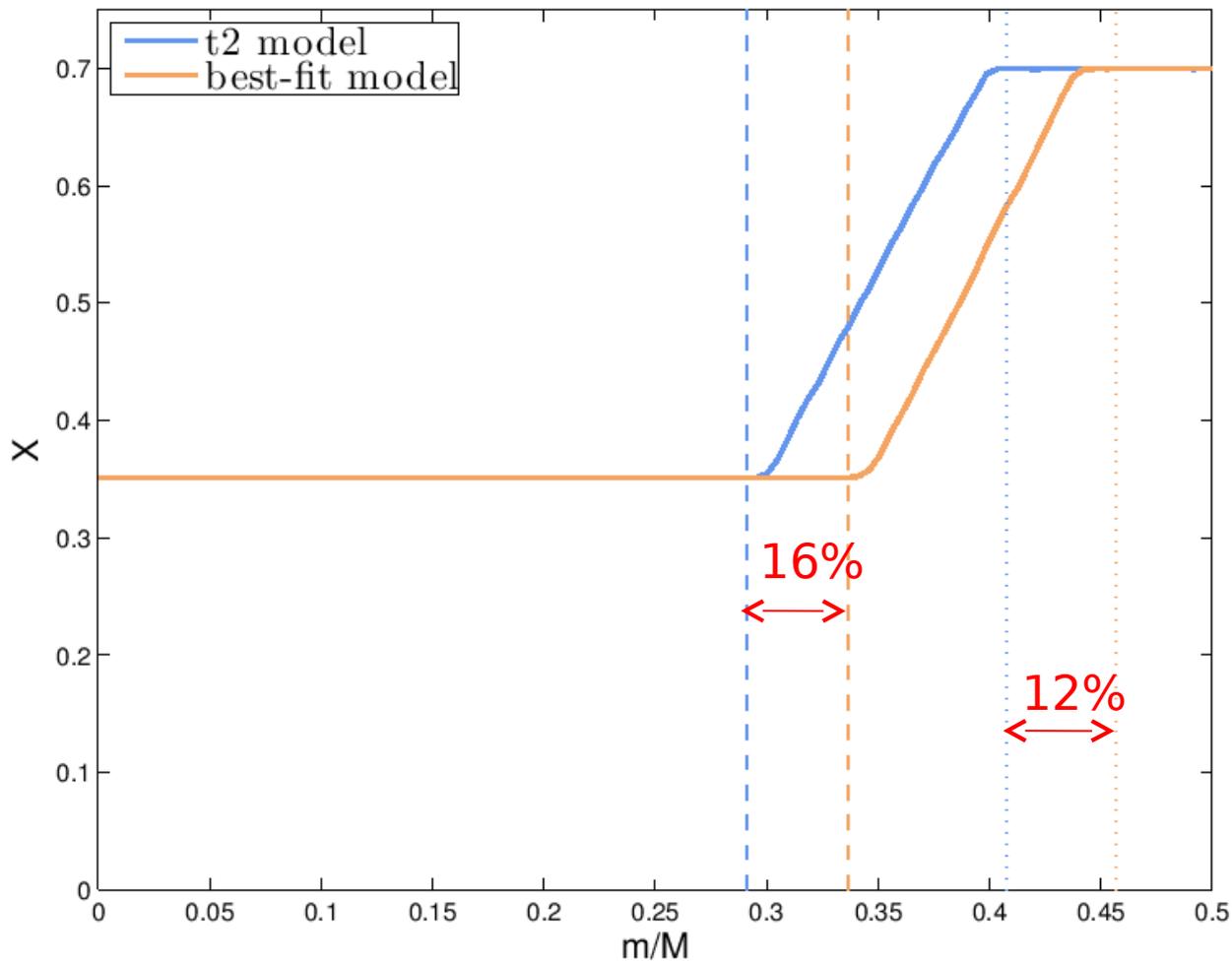
- t2, 6 frequencies, ℓ known (0,1,2)



Parameter	Input	Fitting model
M (M_{\odot})	11	11.4
R (R_{\odot})	5.98	6.07
X	0.70	0.70
Z	0.016	0.012
α_{ov}	0.20	0.30
X_c	0.351	0.354

II.b Testing the physics

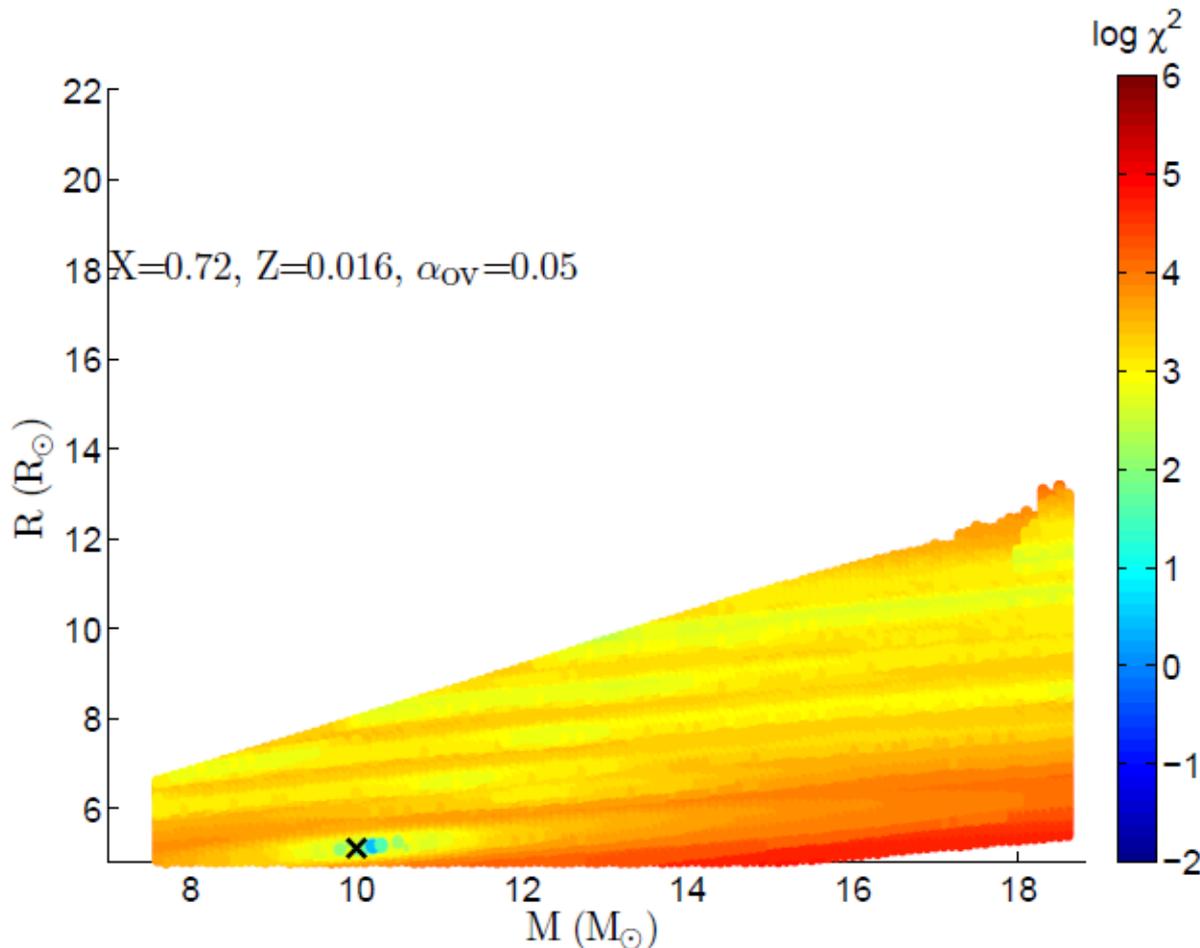
Input model (« observed » star)	Fitting models
GN93/OP	AGS05/OP



II.b Testing the physics

Input model (« observed » star)	Fitting models
AGS05/OP + diffusive mixing	AGS05/OP

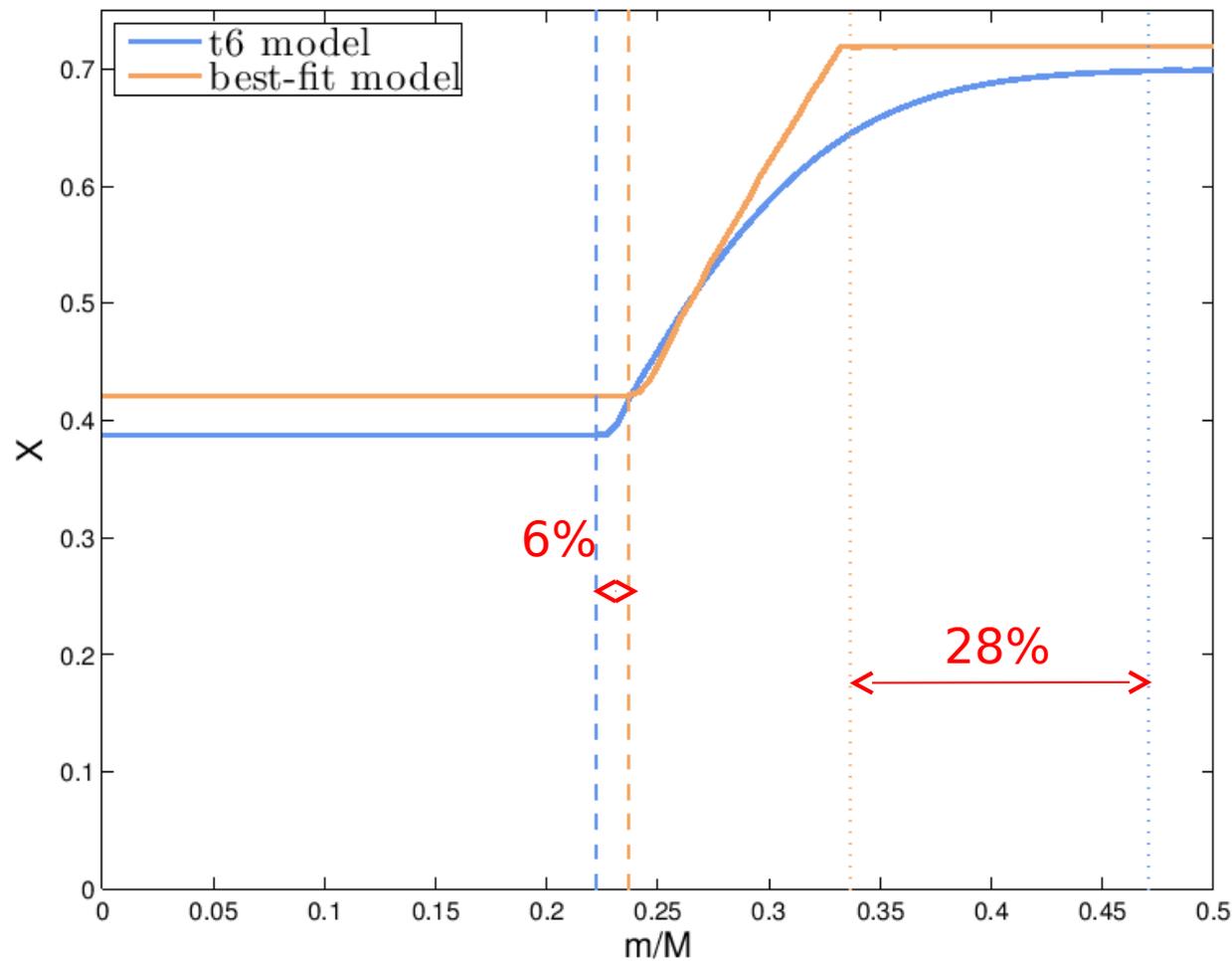
- t6, 8 frequencies, ℓ known (0,1,2)



Parameter	Input	Fitting model
M (M_{\odot})	10	10.2
R (R_{\odot})	5.12	5.16
X	0.70	0.72
Z	0.014	0.016
α_{ov}	0.05*	0.05
X_c	0.388	0.419

II.b Testing the physics

Input model (« observed » star)	Fitting models
AGS05/OP + diffusive mixing	AGS05/OP



II.b Results of the exercises

- Knowledge of the **angular degree** of frequencies detected
- Completing seismic data with other “classical” constraints, ideally the **detailed chemical mixture**
- Provided the **chemical mixture is known**, the extent of the fully mixed region can be accurately determined...
- ... but constraining **nature of extra-mixing** probably requests either introducing a new free parameter or focusing on hybrid stars (inner regions best probe by g modes).

II.c Prospects

Four β Cephei of interest:

- ν Eri (De Ridder et al. 2004): 13 frequencies, 7 with identified ℓ , 5 members of rotational triplets + 6 new g-mode frequencies from BRITE satellites (Handler et al. 2017)

- θ Oph (Briquet et al. 2007): 7 frequencies with identified ℓ , 1 triplet, and 3 members of a quintuplet + 19 new frequencies from BRITE (Walczak et al., 2019)

- HD129929 (Aerts et al. 2003): 6 frequencies with identified ℓ , 1 triplet, and 2 members of a quintuplet

- ν Lac (Desmet et al. 2009): 10 frequencies, 4 with identified ℓ , 2 members of a triplet

=> proposing to reanalyse them with a unique method and set of stellar models + comparison with prescriptions of mixing at the edge of the core

Thank you !