

# Asteroseismology:

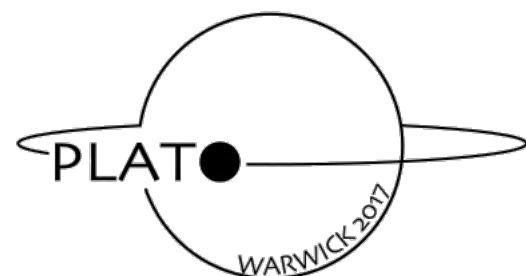
## How to deal with rapid rotation?

**Jérôme Ballot**

with F. Lignières, M. Rieutord, D. Reese, M. Pasek, V. Prat,  
B. Evano, B. Putigny, S. Christophe, R.M. Ouazzani

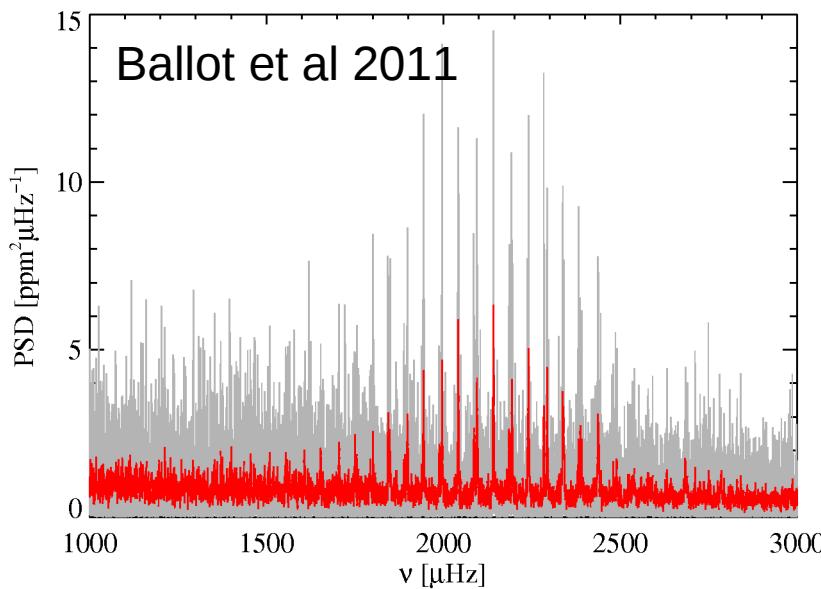
and the SoFAR team

**PLATO 2017, Warwick**

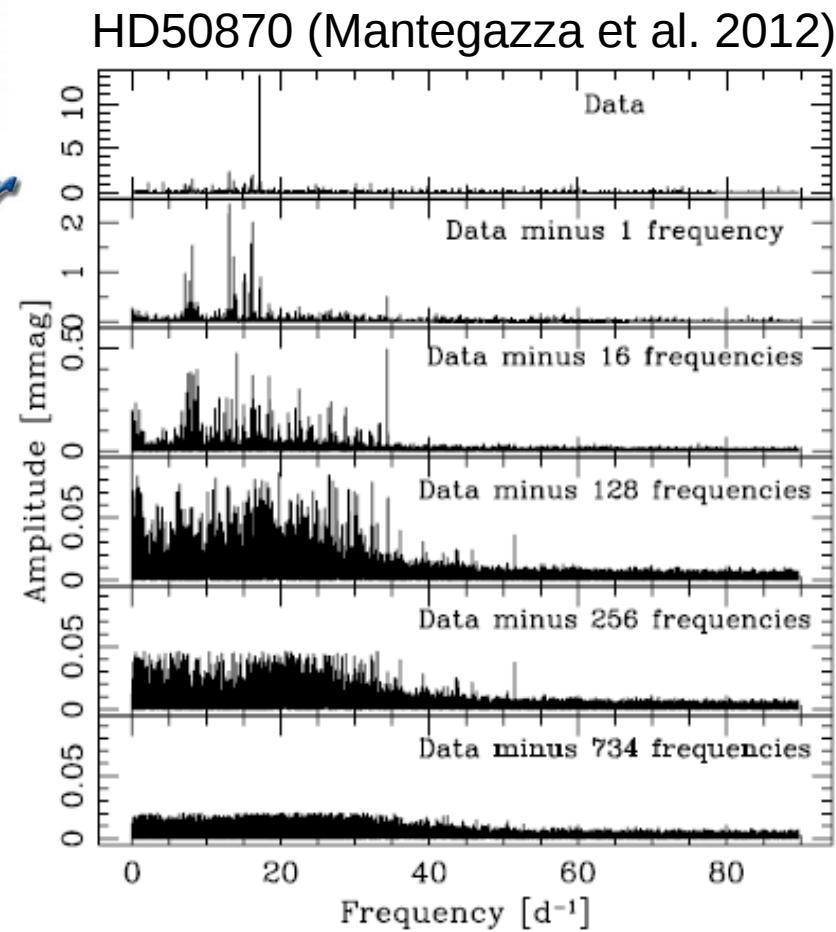


# Observed stellar oscillation spectra

Solar type stars, Red giants

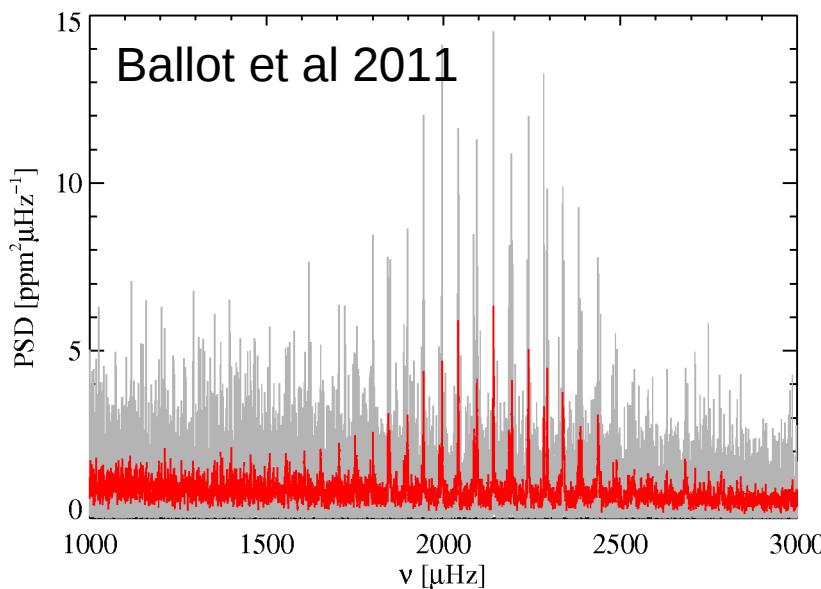


$\delta$  Scuti



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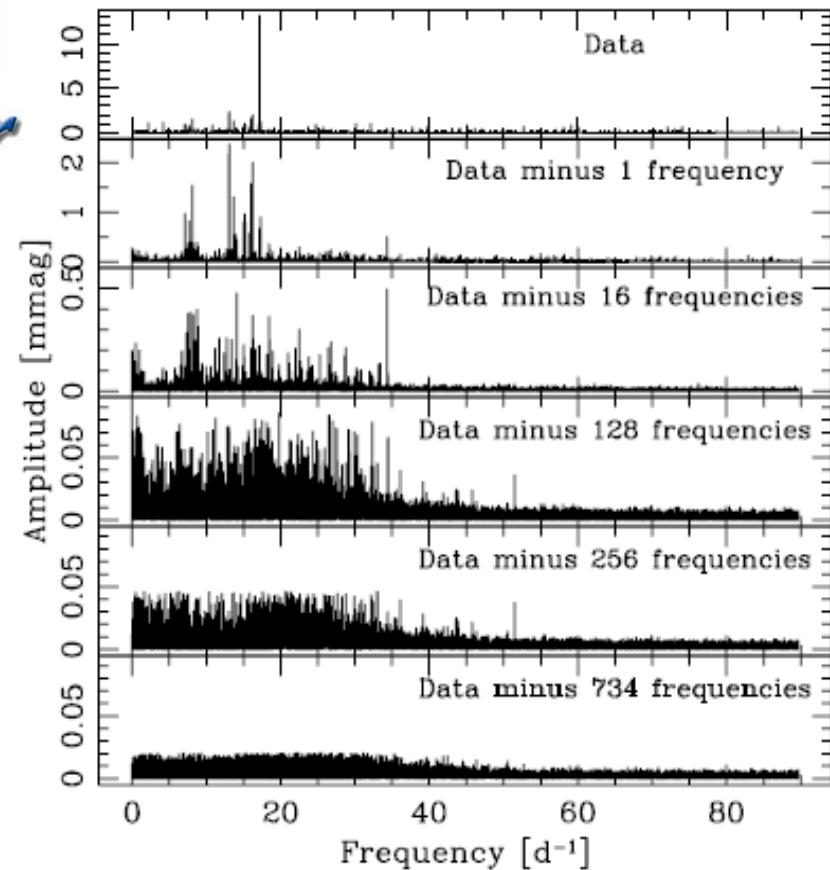


Simple, regular,  
Well-understood



$\delta$  Scuti

HD50870 (Mantegazza et al. 2012)



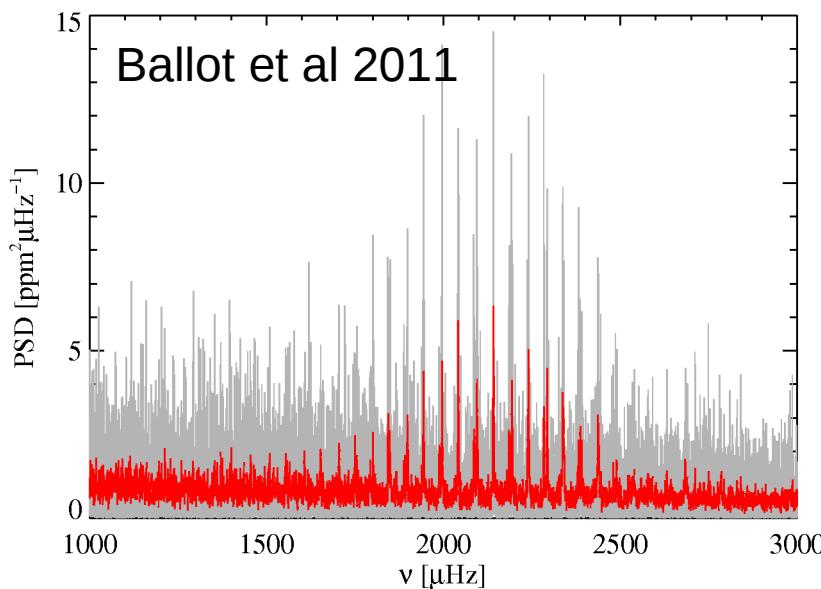
Why?

Complex...



# Observed stellar oscillation spectra

Solar type stars, Red giants

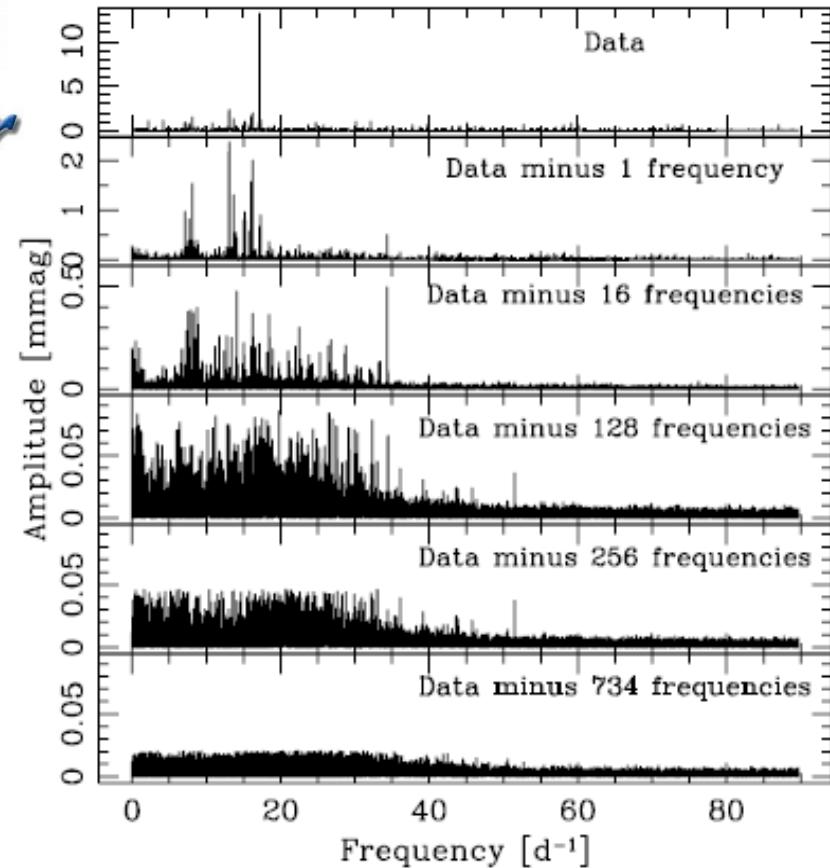


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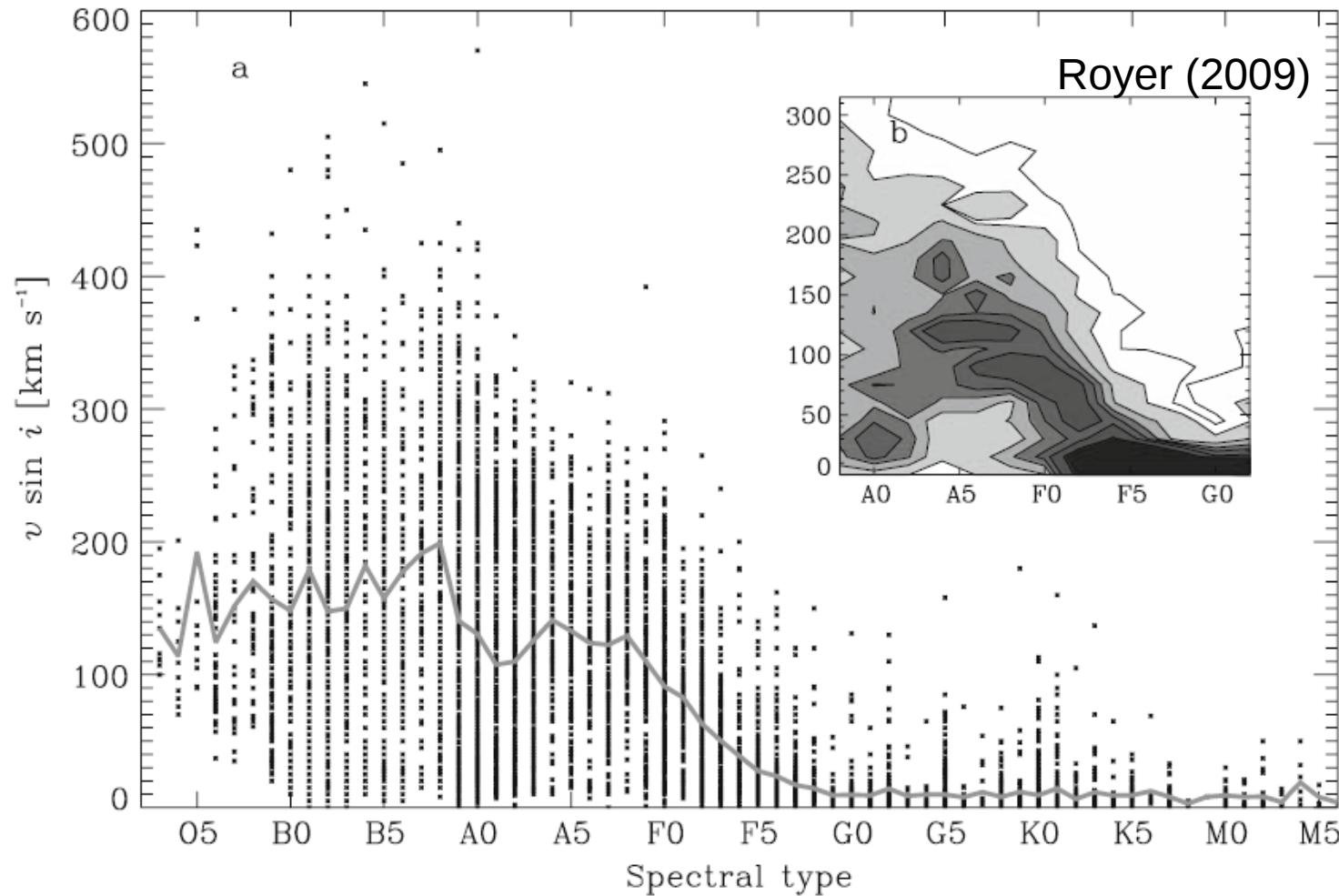
1. No theory predicting mode amplitudes
2. Effects of rotation

Why?

Complex...



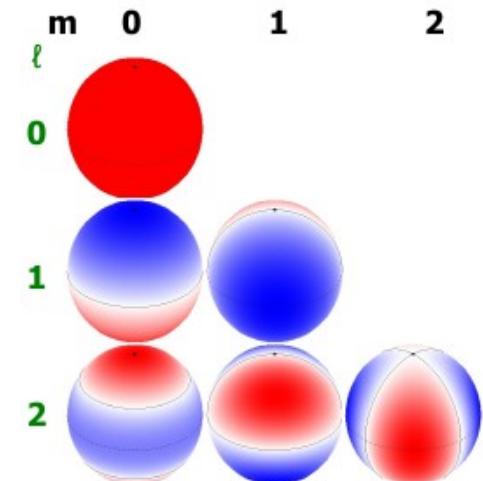
# Stellar rotation velocity



➤ High-mass and intermediate-mass stars rotate fast.

➤  **$\Omega=0 \rightarrow$  spherical symmetry**

- ◆ modes  $g(\vec{x}) = f(r)P_\ell^m(\theta) \exp(im\phi)$
- ◆  $\rightarrow$  1-D Problem

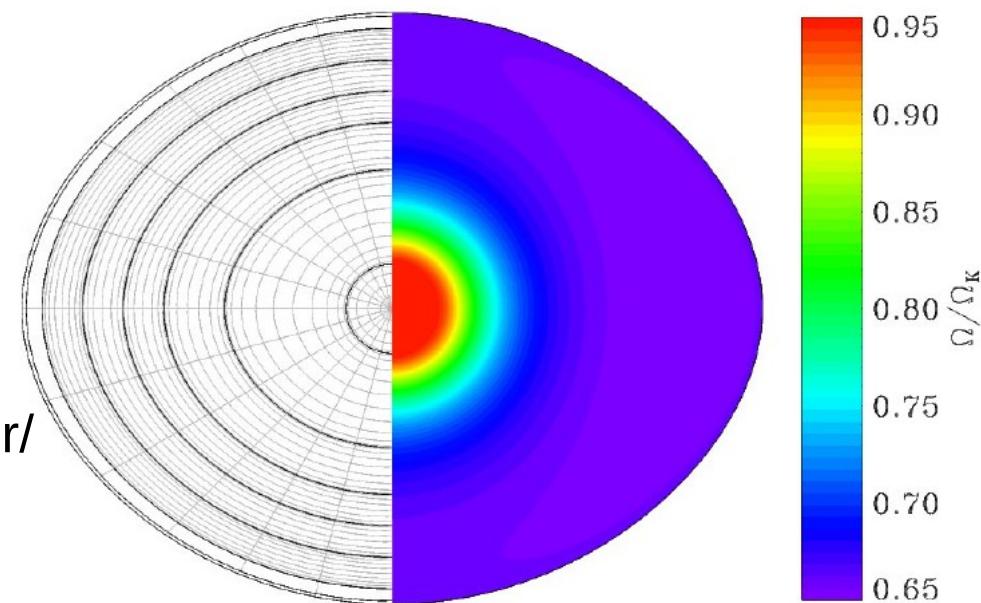


➤  **$\Omega \neq 0 \rightarrow$  centrifugal distortion + Coriolis force  
 $\rightarrow$  axial symmetry**

- ◆ modes  $g(\vec{x}) = f(\vec{x}_M) \exp(im\phi)$
- ◆  $\rightarrow$  2-D Problem

# What models must we use?

- **1-D models** → may be ok for some g modes...
- **2-D models**
  - ◆ Simplified models (polytropes)
  - ◆ Distorted 1-D stellar evolution models [Roxburgh 2006]
  - ◆ 2-D Stellar structures → ESTER code [Rieutord et al. 2016]
    - Self-consistent
    - Up-to-date microphysics
    - Valid for massive stars
    - Simplified evolution
    - Open source code developed @ IRAP  
<http://ester-project.github.io/ester/>



# How to compute modes?

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## ➤ Reduce a 2-D problem to a set of 1-D problems

- ◆ Perturbative methods

- Only valid if  $\Omega \ll \omega$  and  $\Omega \ll \Omega_K = \sqrt{GM/R^3}$

Coriolis

Centrifugal force

- ◆ For g modes: Traditional Approximation [Eckart 1960]

- Solid rotation, neglecting distortion & terms in Coriolis force

## ➤ Complete 2-D computations

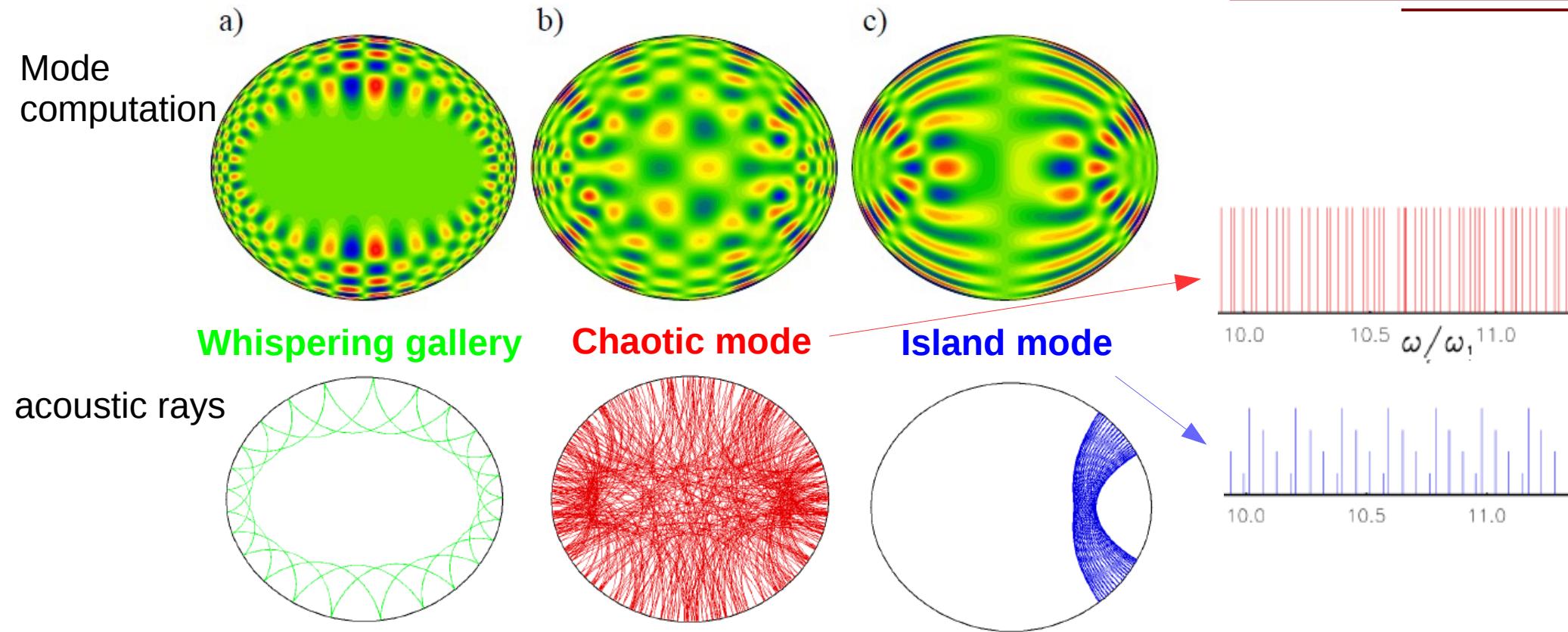
- ◆ TOP code [Reese et al. 2006]

- ◆ ACOR code [Ouazzani et al. 2012]

## ➤ Ray theory

~ geometrical optics

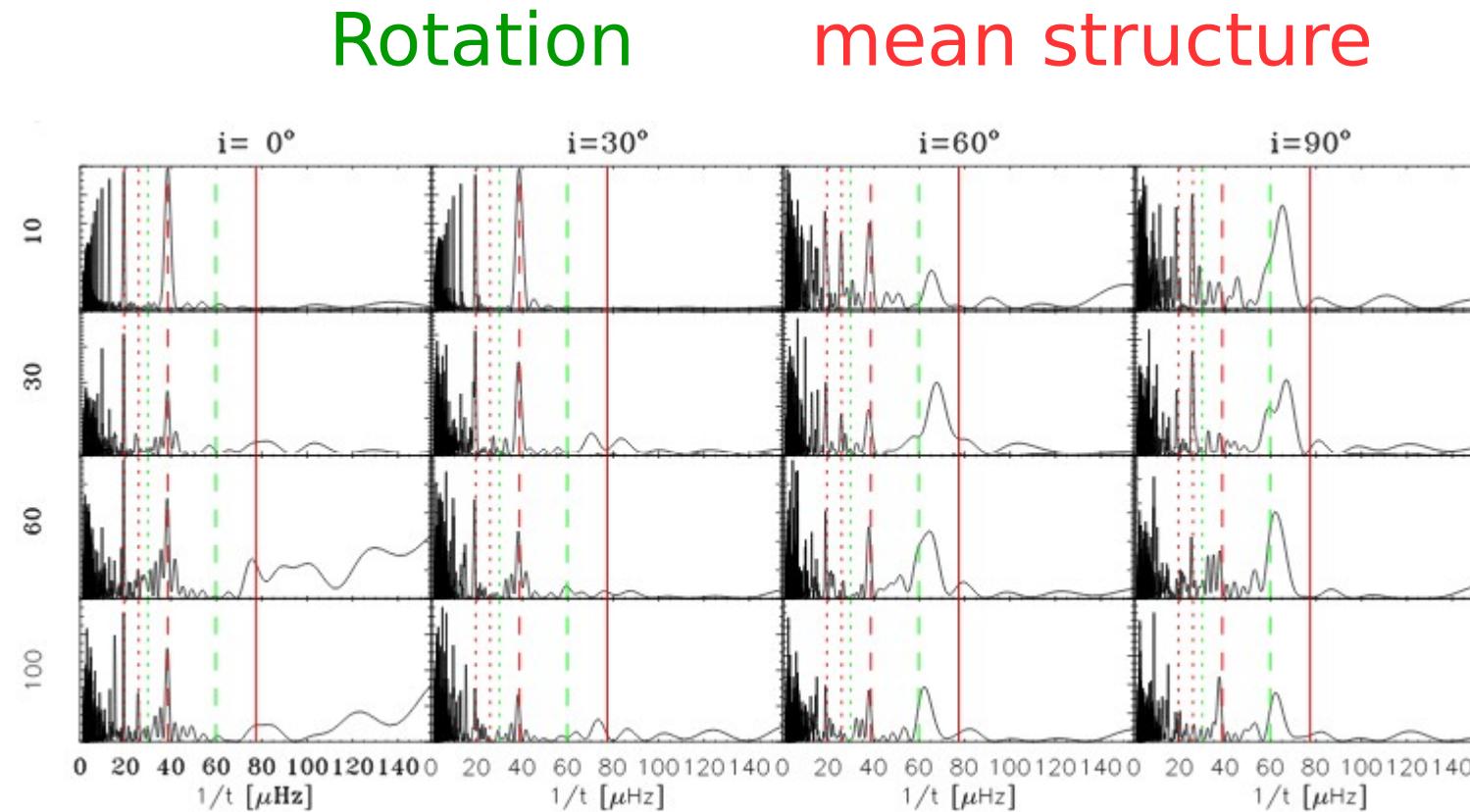
# p modes: classification and regularities



- **Numerical computation interpreted with ray theory**  
(Lignières & Georgeot 2008, 2009)
- **Regularities are found and understood for Island & chaotic modes** (LG2009, Reese et al. 2008, Pasek et al. 2011, 2012, Evano PhD Th.)

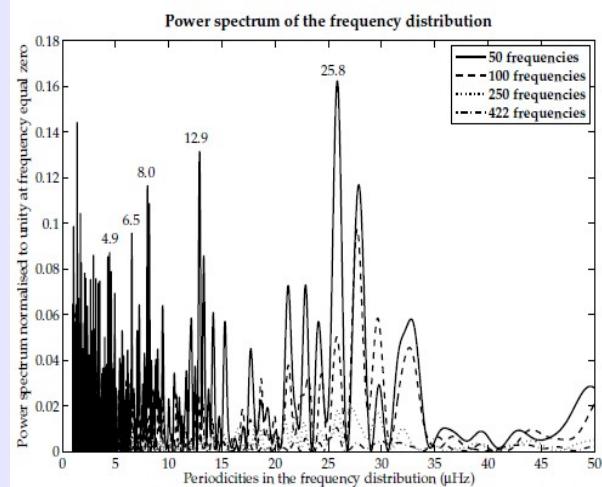
# Finding such regularities

- Tests on synthetic spectra (based on 2D models)
  - ◆ Methods based on autocorrelation, Fourier transform
  - ◆ Recovered spacings:  $2\Omega$  &  $\Delta/2$



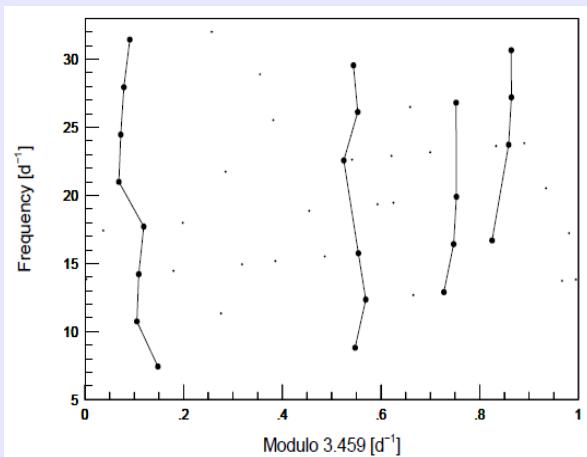
# Regularities in CoRoT & Kepler data

## FT of Spectra



García Hernández et al. 2009

## SSA sequence search algorithm

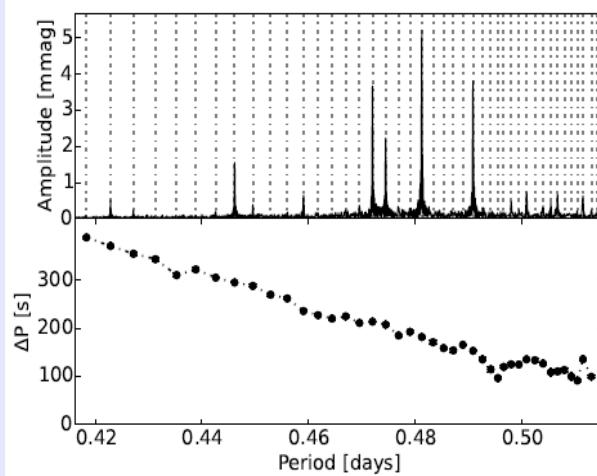


Paparó et al. 2016

## p modes ( $\delta$ Sct)

## g modes ( $\gamma$ Dor, SPB)

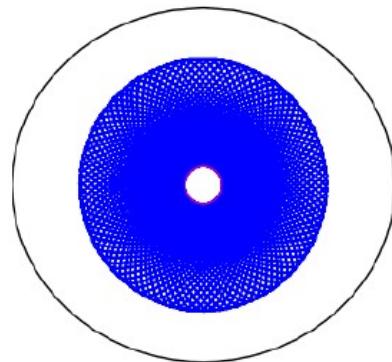
## Pattern search



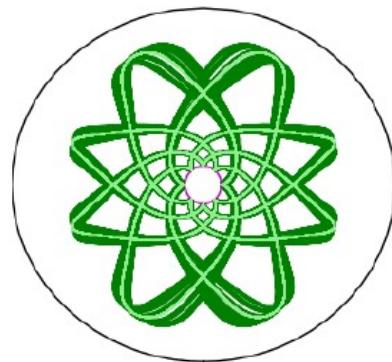
Van Reeth et al. 2015

# g modes classification

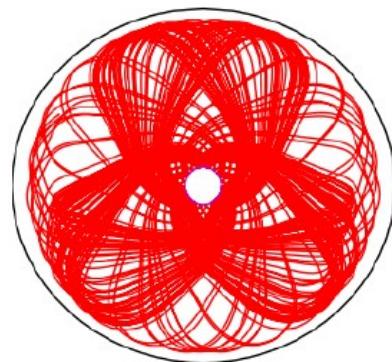
## Ray tracing



“normal” modes



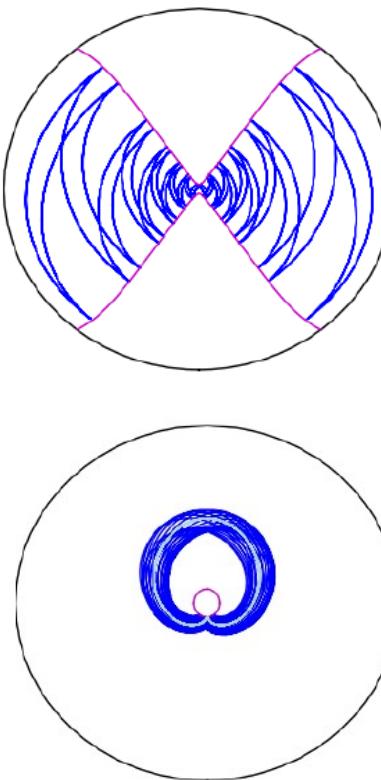
Island modes



Chaotic modes

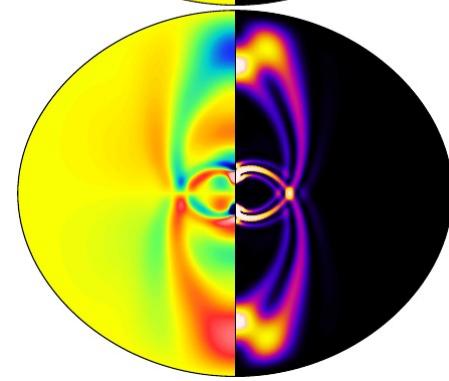
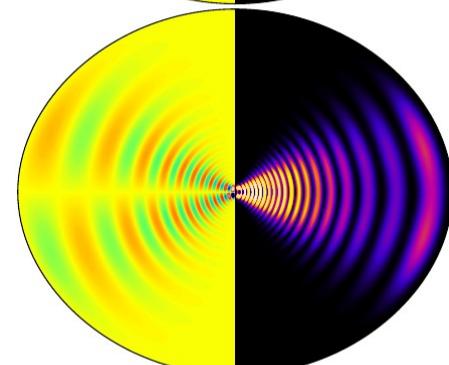
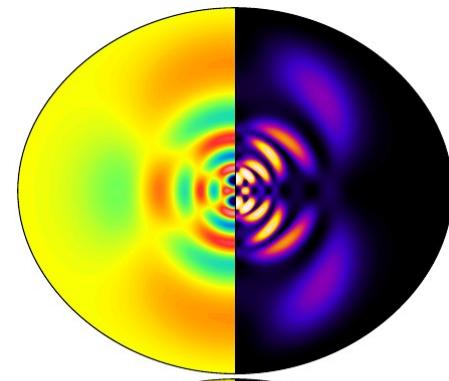
## Mode classification with ray theory

[Prat et al 2016, Ballot et al 2012]



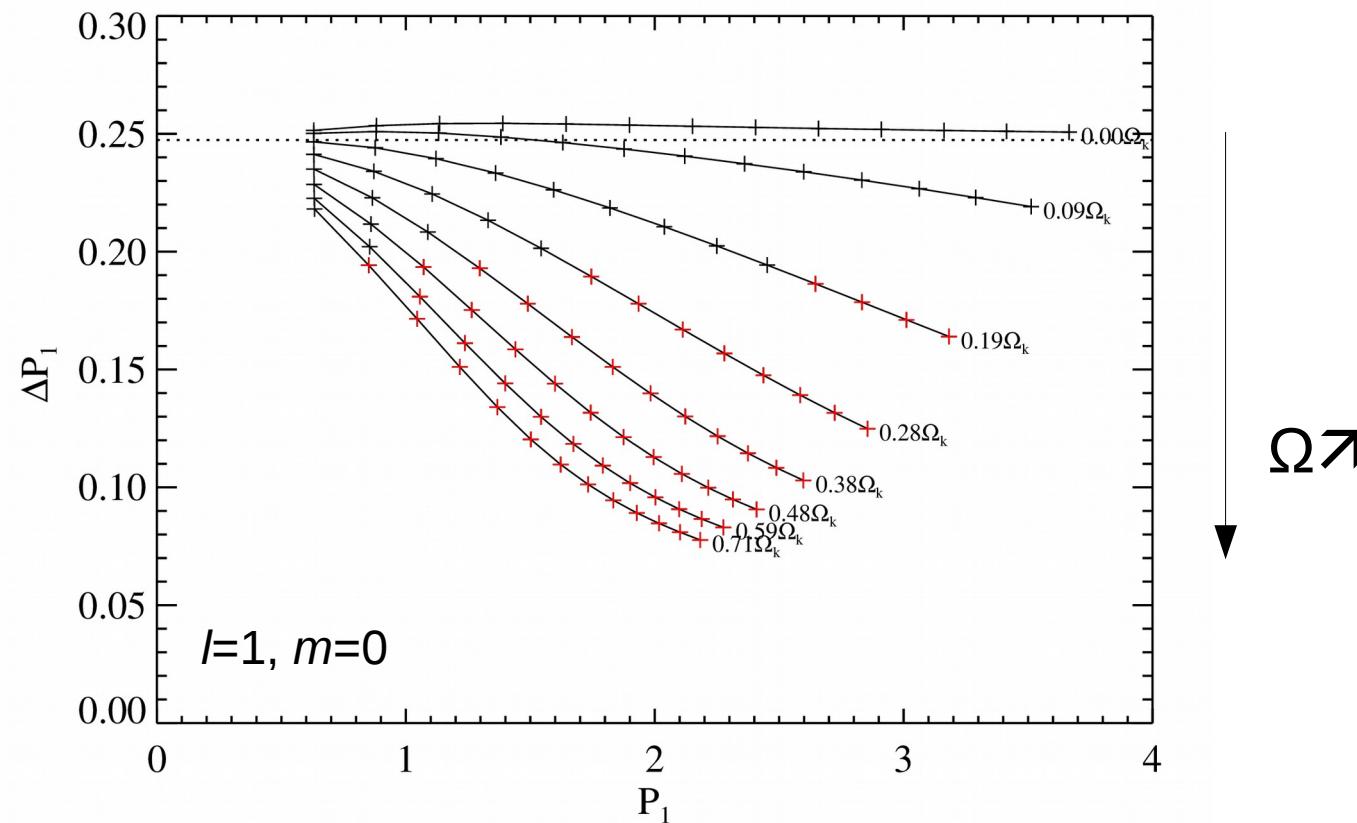
Rosette modes

## Numerical computations



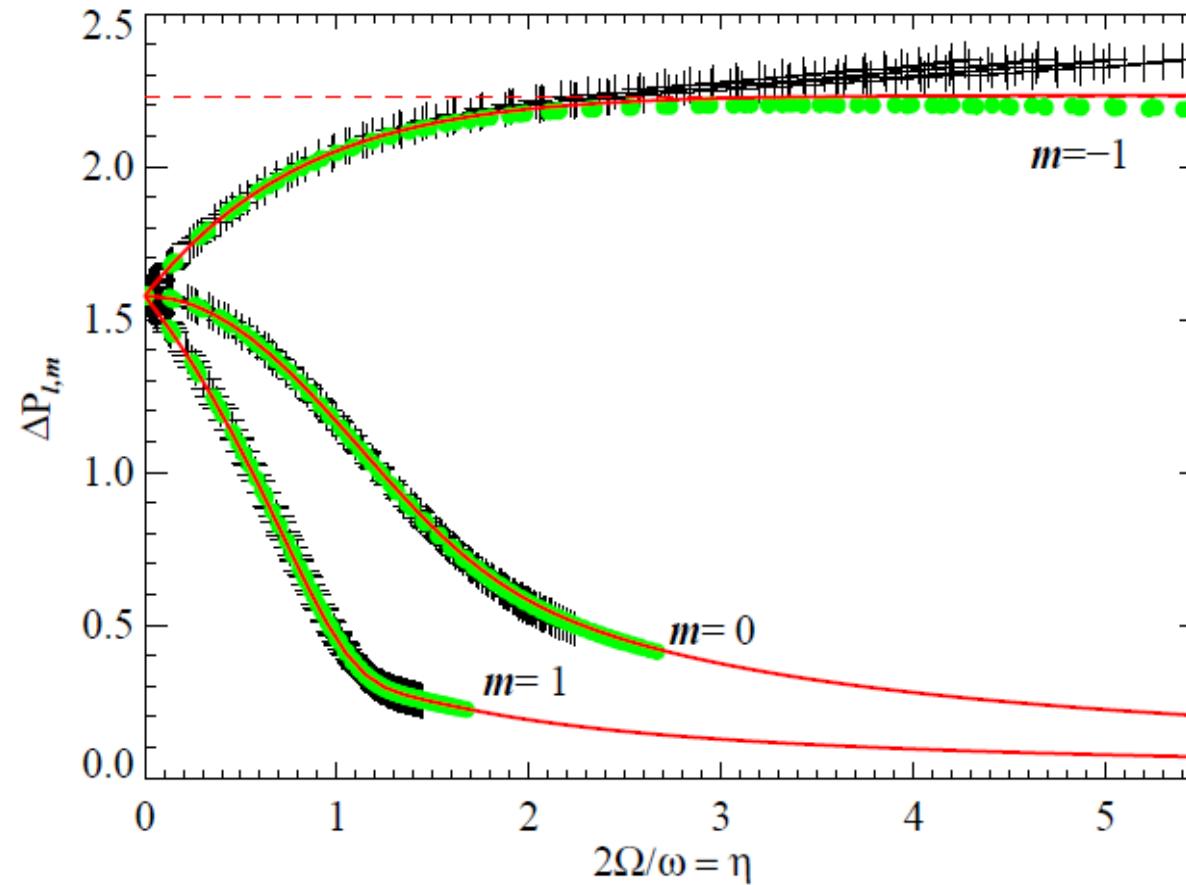
# g mode: regularities

- Evenly spaced in period without rotation ( $P_0$ )
  - ◆ Spacings are no more constant with rotation...



# g mode: regularities

- Spacings for a family of modes depend on a function of  $\Omega^*P$

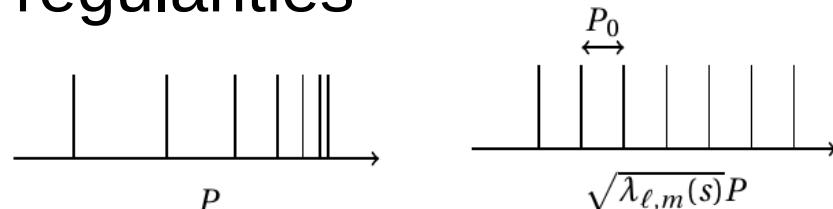


- ◆ Compatible with the traditional approximation

# Looking for regularities in g mode spectra

## Method:

- ◆ Assuming a rotation, stretch the spectrum and find for regularities

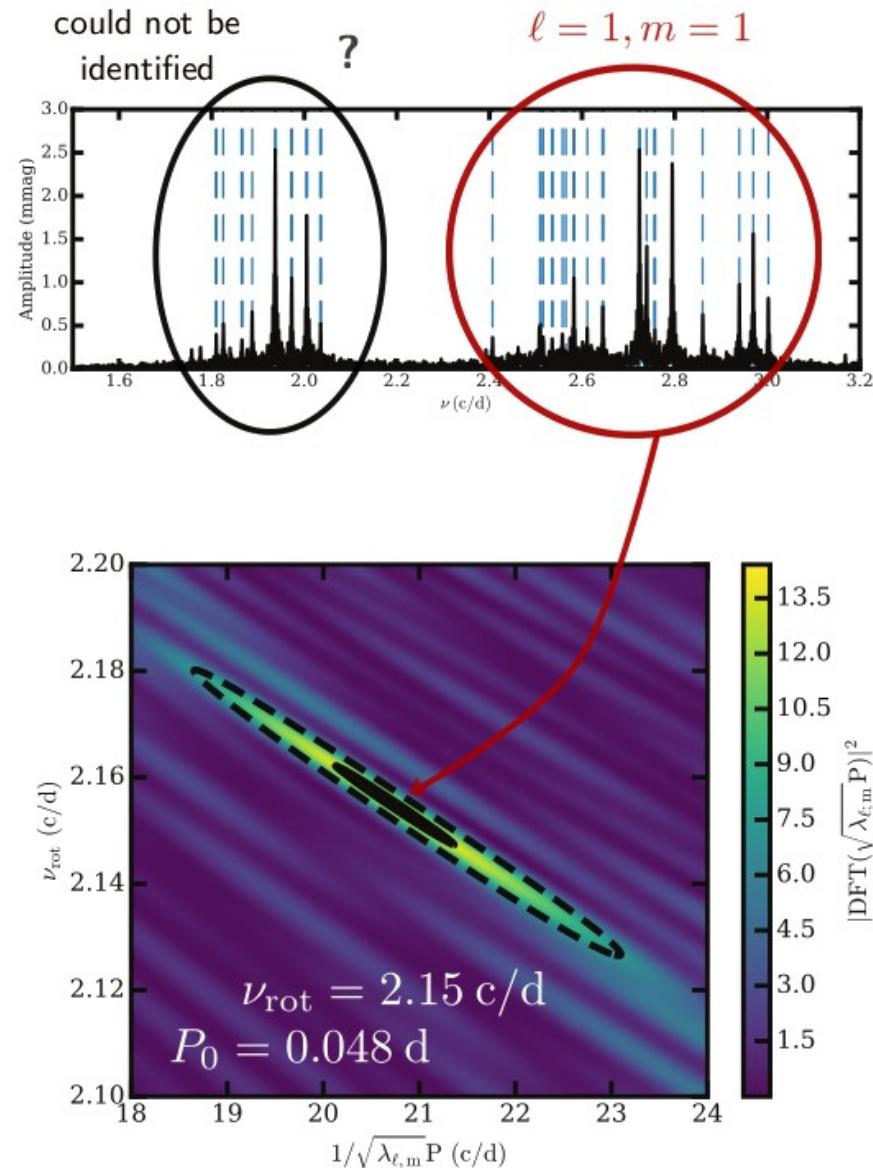


- ◆ Scan a rotation range

## Test on $\gamma$ Doradus and SPB observed by Kepler

- ◆ identify modes
- ◆ Rotation period recovered
- ◆  $P_0$  determined

## See Poster 28 [Christophe et al] !



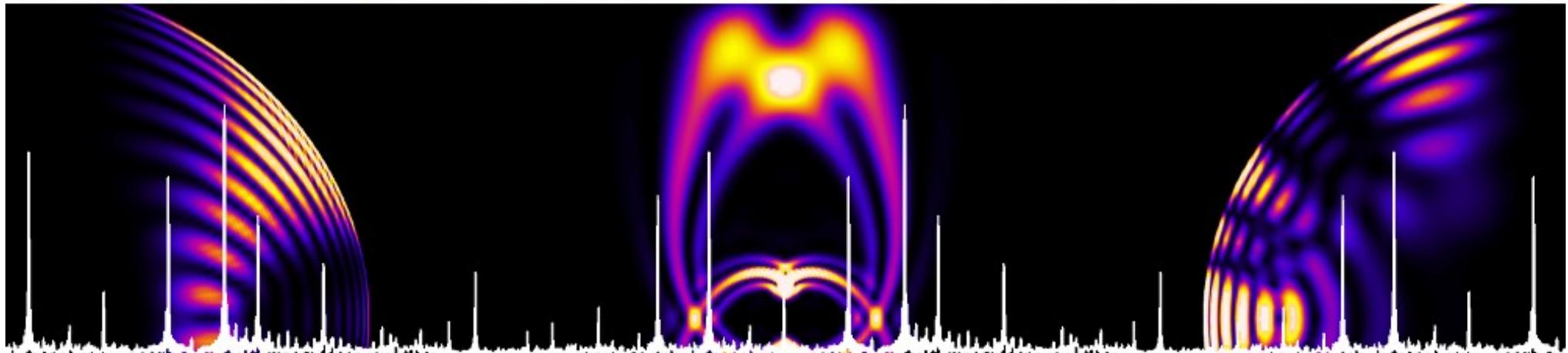
- **Convergence between theoretical developments and observations**
- **Further works**
  - ◆ p modes:
    - Identifying nature and origin of spacings (large spacing, rotation...)
    - Finer mode identification (chaotic modes, island modes...)
  - ◆ g modes:
    - Validity range of Traditional Approximation
    - Effects of differential rotation (Mirouh et al. 2016, Vincent's talk)  
(see also Aerts et al. 2017)
  - ◆ How to use 2D models to perform direct seismic analysis?
- **ISSI International team SoFAR**

# SoFAR – Seismology of Fast Rotating Stars



<http://www.issibern.ch/teams/sofar/>

International Team



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