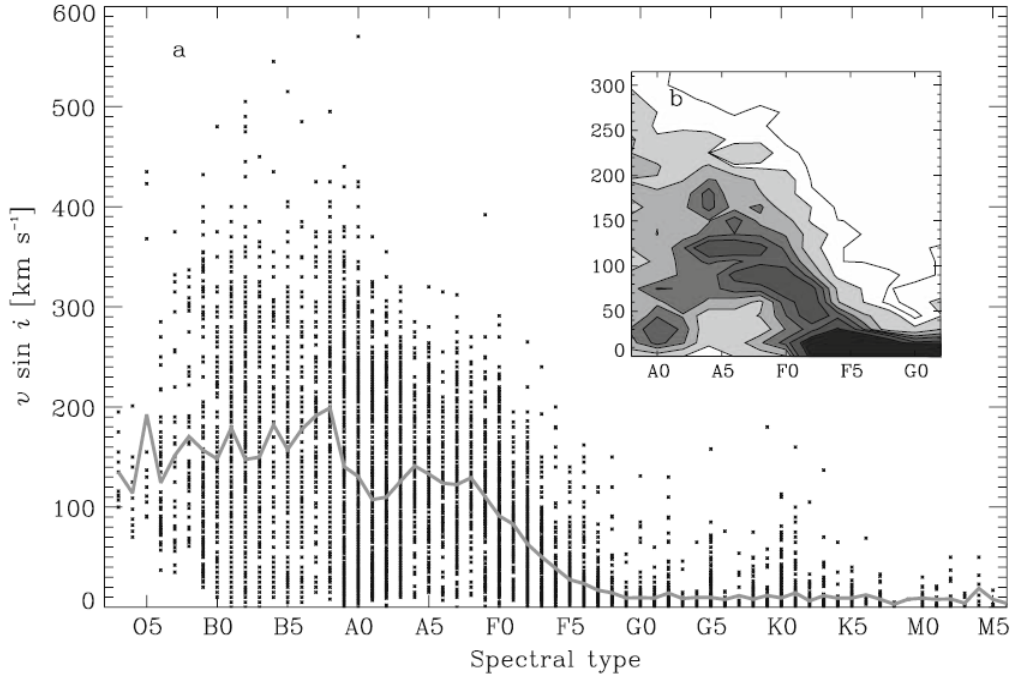
Seismology of rapidly rotating stars

Jérôme Ballot
F. Lignières,
V. Prat,
D. R. Reese,
M. Rieutord,
G. Mirouh

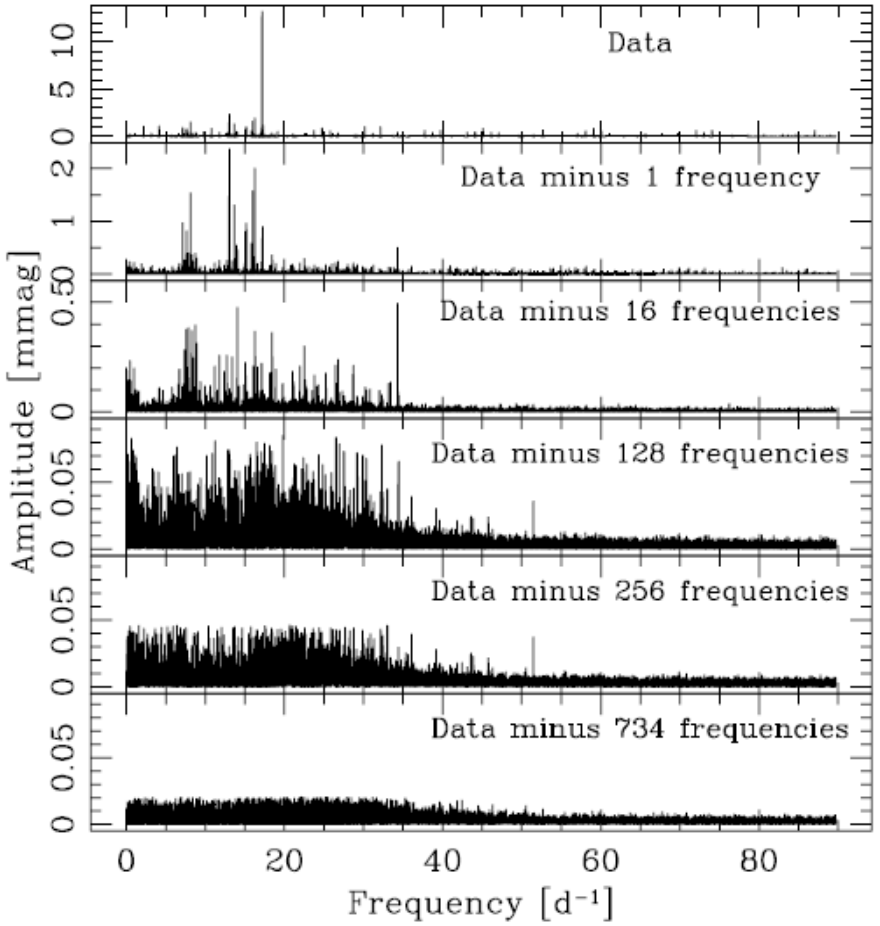
Prospective PNPS - Besançon - 25.02.2014

Rapid rotation

- **High rotation is common in intermediate- and high-mass stars**
  - δScuti, γDor, SPB...
- **Complicated spectra**



Royer (2009)



Garcia-Hernandez et al 2012

δScuti

What is a “rapid rotation”?

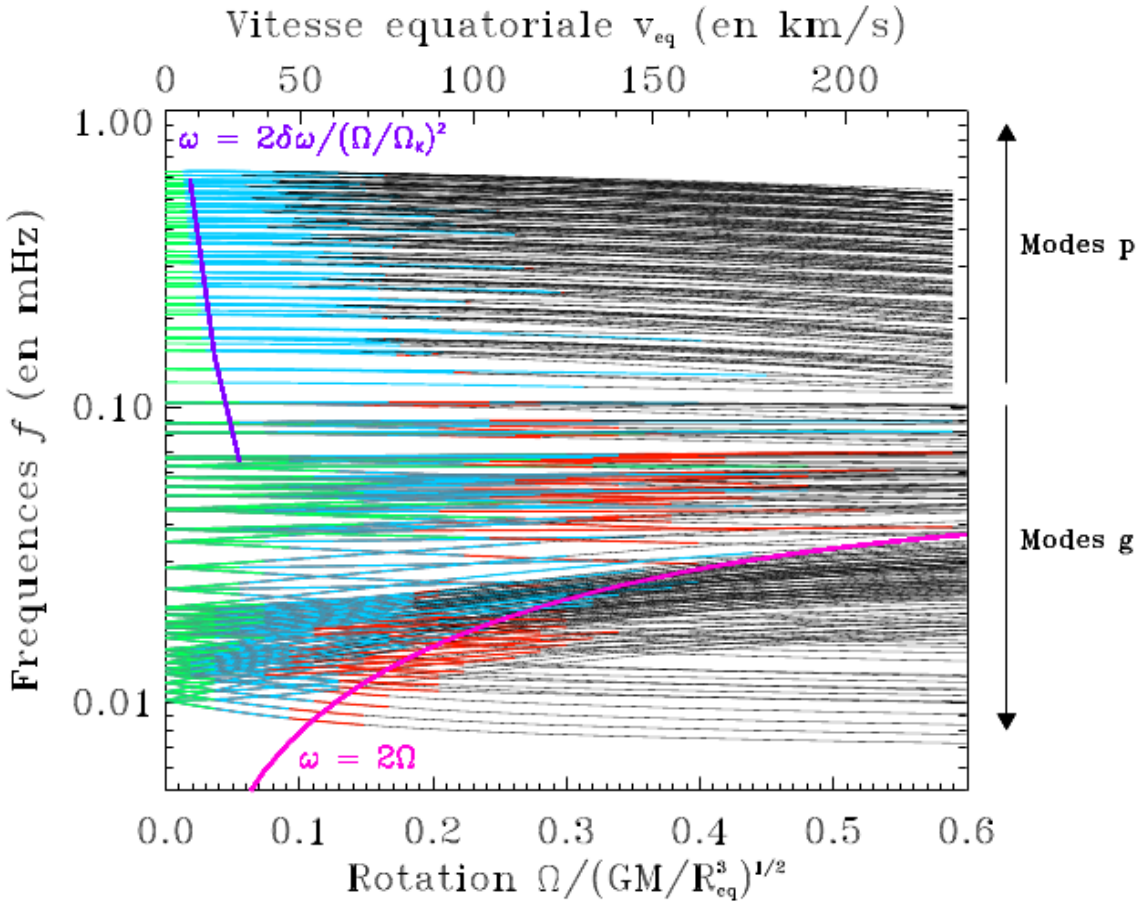
- **Perturbative developments**

$$\omega_{nlm} = \omega_{nl0} + C^1_{nlm}\Omega + C^2_{nlm}\Omega^2 + C^3_{nlm}\Omega^3$$

  - Valid as long as $\boxed{\Omega \ll \omega}$ and $\boxed{\Omega \ll \Omega_K}$

Coriolis force Centrifugal force

What does “negligeable” mean in practice?

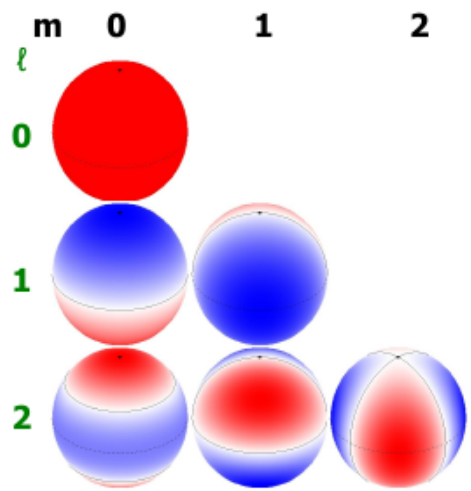


Reese et al. 2006
Ballot et al. 2010
Ballot, Lignières, Reese 2013

Computing oscillation modes

- **Governing Equations**

$$\partial_t \rho + \nabla \cdot (\rho_0 \mathbf{u}) = 0,$$
$$\rho_0 \partial_t \mathbf{u} + 2\rho_0 \Omega \wedge \mathbf{u} = -\nabla P + \rho \mathbf{g}_0 - \rho_0 \nabla \psi,$$
$$\partial_t P + \mathbf{u} \cdot \nabla P_0 = c_s^2 \left(\partial_t \rho + \mathbf{u} \cdot \nabla \rho_0\right),$$
$$\Delta \psi = 4\pi G \rho,$$



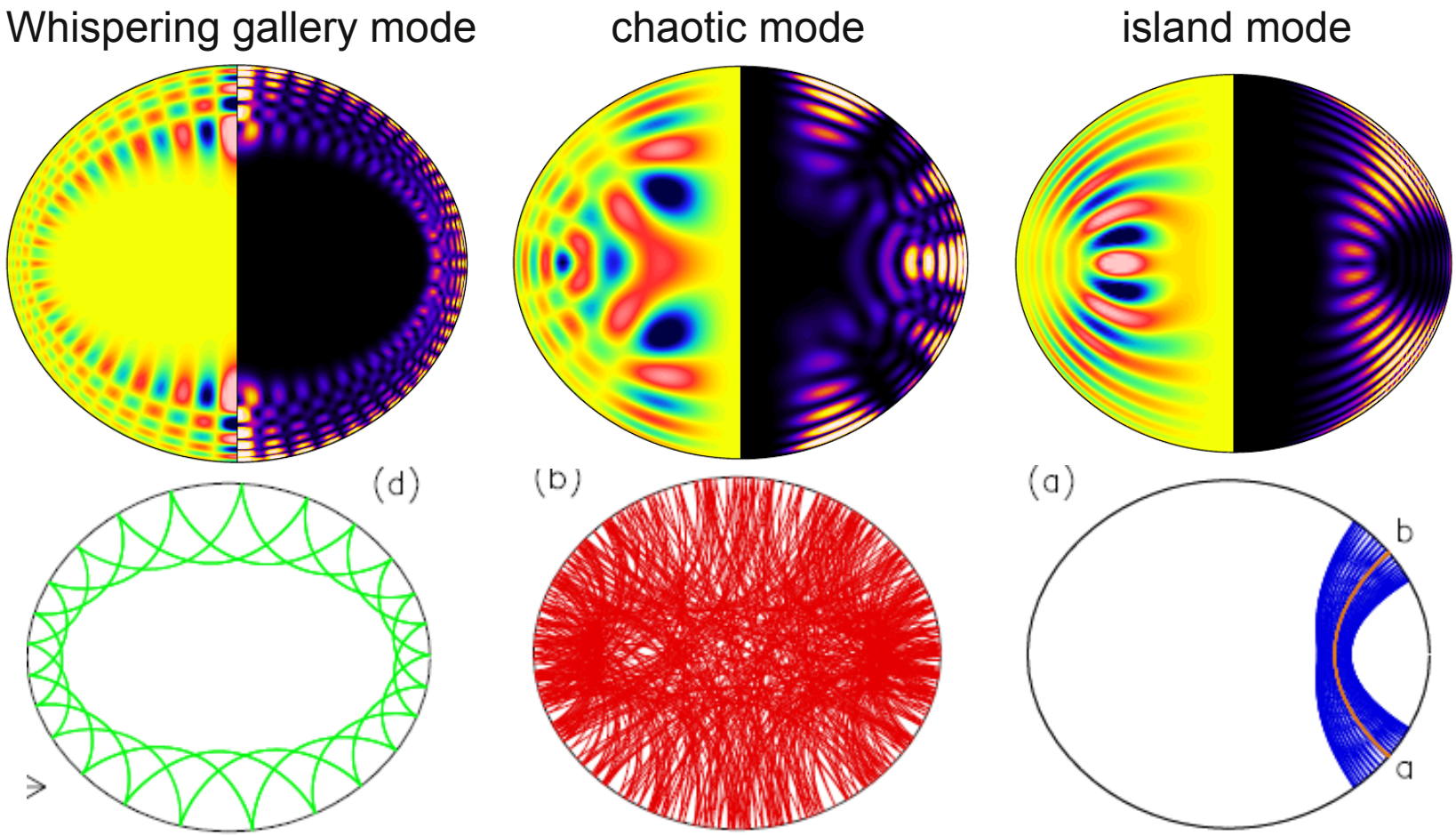
- **Ω=0 → spherical symmetry**
  - Solutions in the form $g(\vec{x}) = f(r) P_\ell^m(\theta) \exp(im\phi)$, with $P_\ell^m(\theta) \exp(im\phi) = Y_{\ell m}$
  - → 1D eigenvalue problem
- **Ω≠0 → axial and equatorial symmetry**
  - Solutions in the form $g(\vec{x}) = f(\vec{x}_M) \exp(im\phi)$
  - → 2D eigenvalue problem (2D models needed!)
  - → to be solved with the TOP code (Reese et al 2006)
    ACOR code (Ouazzani 2012)

2D models are needed

- **Computation from 1-D structure models**
  - No distortion / 2nd order perturbation
- **Polytropic 2-D models**
  - Intensively used to explore spectra
- **Realistic 2-D models: ESTER code**
  [Espinosa Lara & Rieutord 2007, 2012, Rieutord & Espinosa Lara 2009, 2013]
  - 2-D structures of massive stars
    - M, Ω, X_c
  - Code under GPL
    - Web: `www.ast.obs-mip.fr/users/rieutord/ESTER.html`
      `http://code.google.com/p/ester-project/`

p modes

- **New families of modes (Spectrum = Σ subspectra)**



  - classification with ray theory (Lignières & Georgeot 2008,2009)

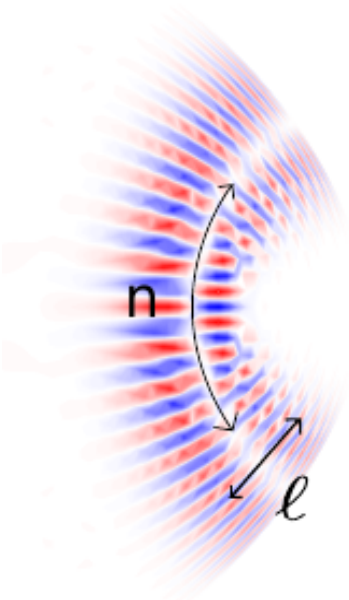
p-mode regularities

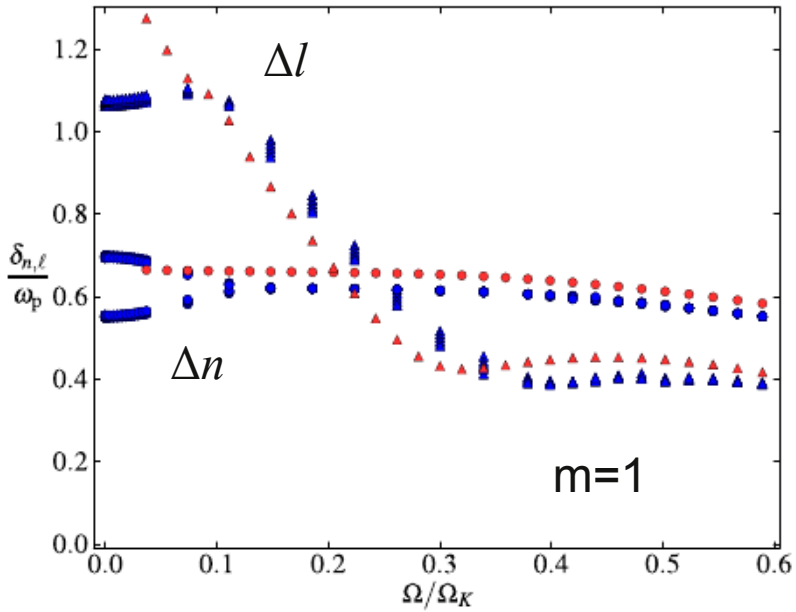
- **Regularities derived for non-rotating stars are lost, new regularities (for island modes) emerge**
  - Empirical relations (e.g. Lignières et al. 2006, Reese et al. 2006, 2009)

$$\omega_{n,\ell,m} = n\Delta_n + \ell\Delta_\ell + |m|\,\Delta_m + \alpha^{\pm}$$

  - Asymptotic theory (Pasek et al. 2011, 2012)

$\Delta \leftrightarrow$ structure

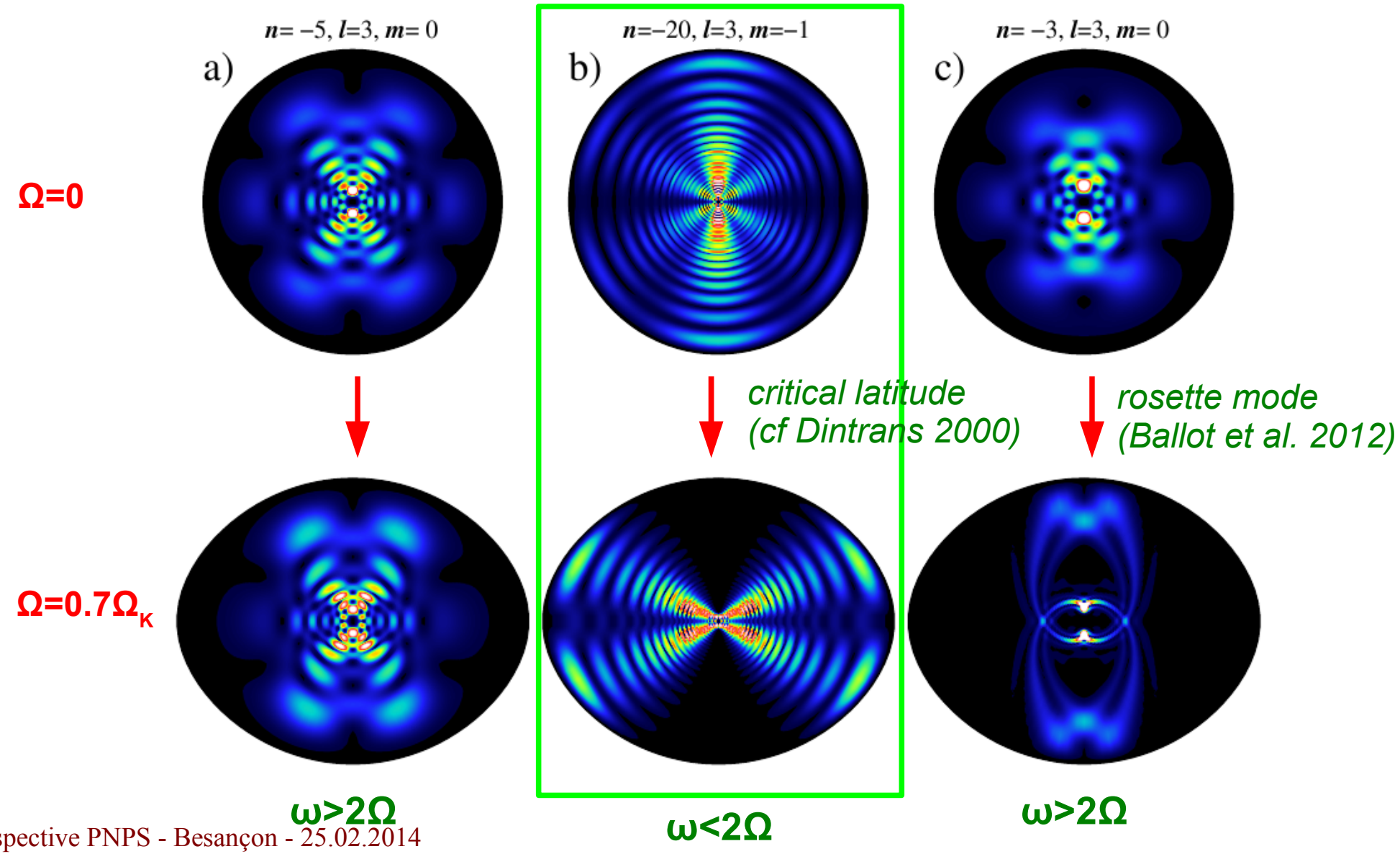




Pasek et al 2012

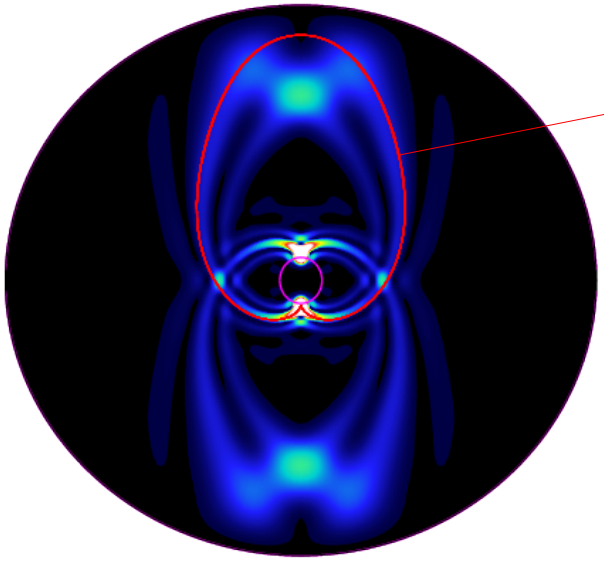
g modes in rotating stars

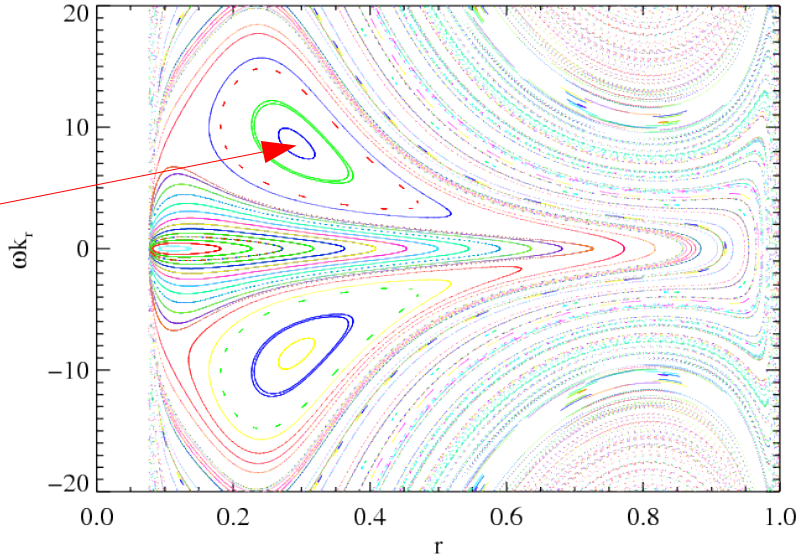
- **Different behaviours**



Rosette modes

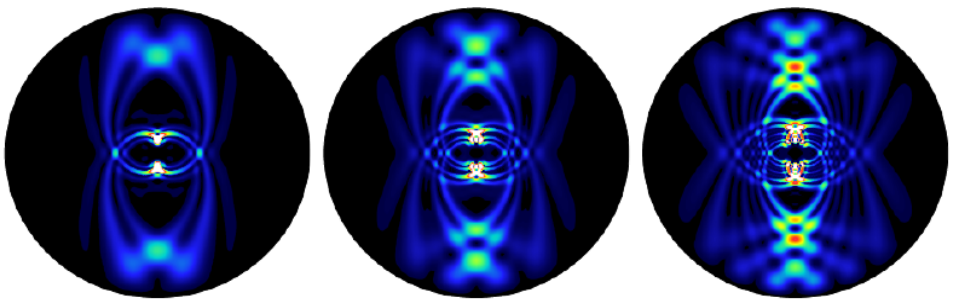
- **Rosette modes are associated with stable trajectories**

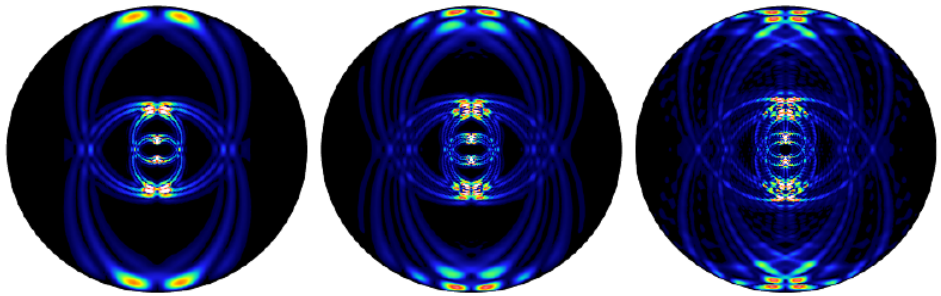




Ballot et al. 2012

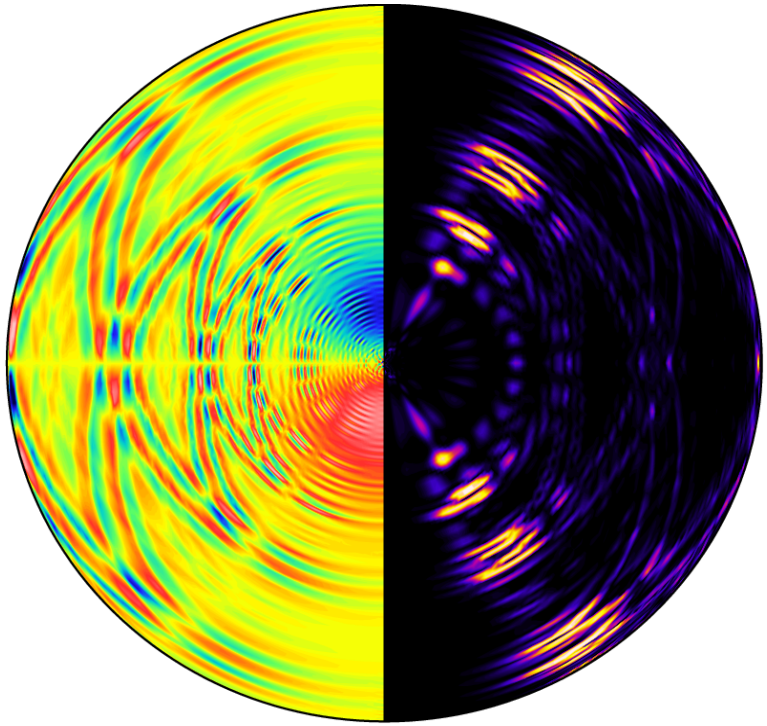
- **Several families of rosette modes**



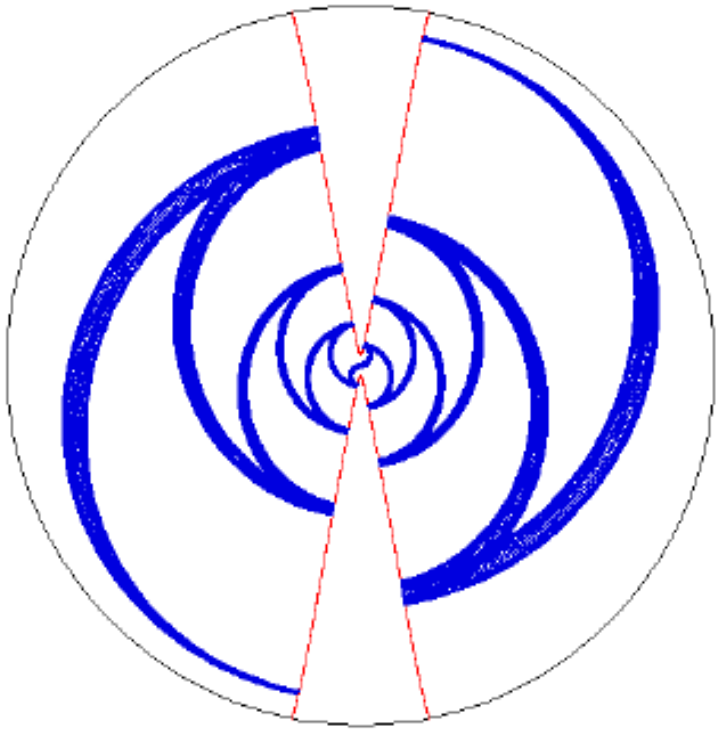


Bat-modes

- **Modes in the inertial domain also associated to stable trajectories**



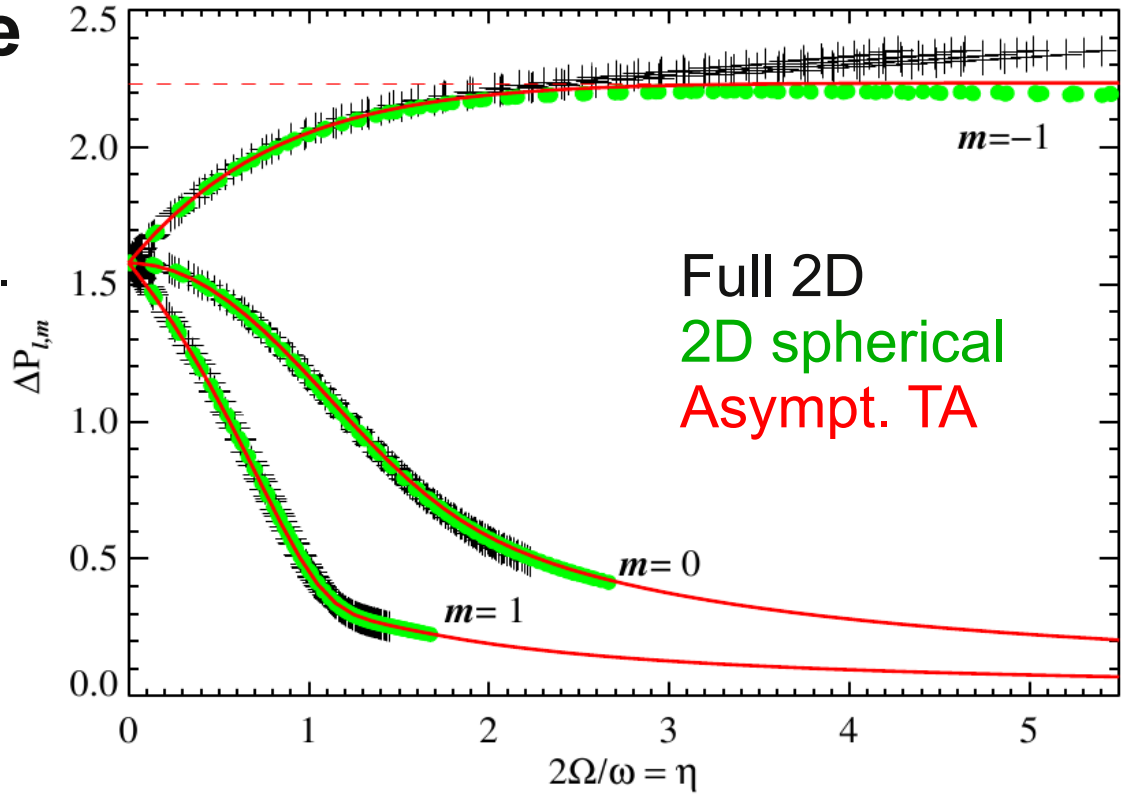
Ballot et al., en prep.



Prat 2010

Regularities of g modes: period spacings

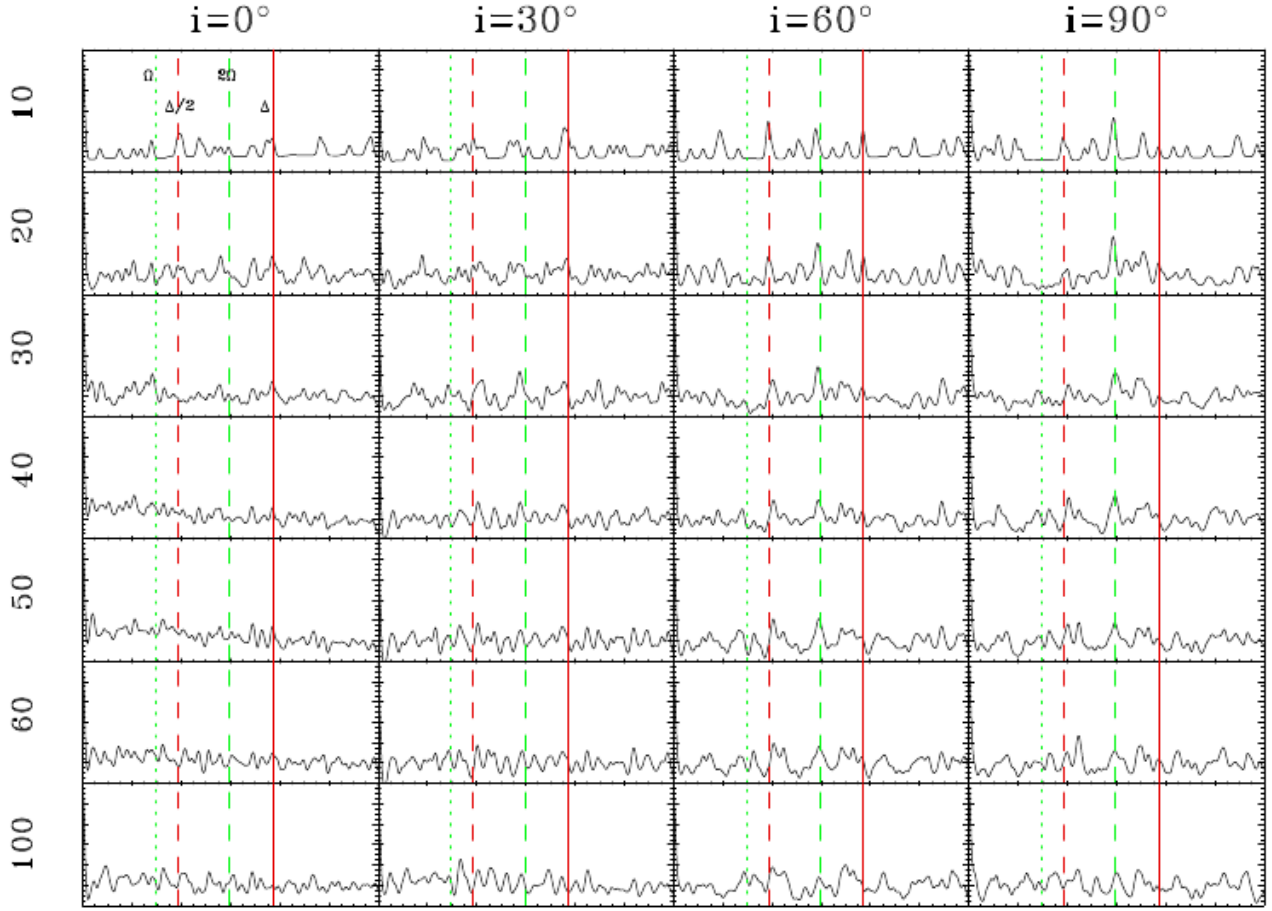
- **ΔP as a function of η = 2ΩP= 2Ω/ω**
  - **Spacings compatible with the Traditional approximation**
    [Eckart 1960, Berthomieu et al. 1978, Lee & Saio 1987]
  - **However**
    - T.A. cannot predict rosette/bat modes
    - T.A.: problem with convective core



[Ballot et al. 2012]

Comparison with observations

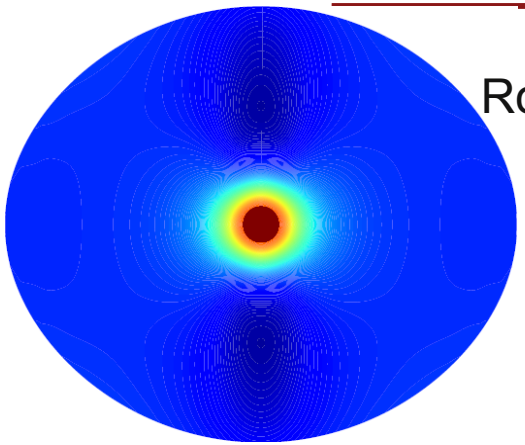
- **Looking for regularities**
  - AC, PSPS according to the configure contraction of Δ or Δ/2, sometimes 2Ω



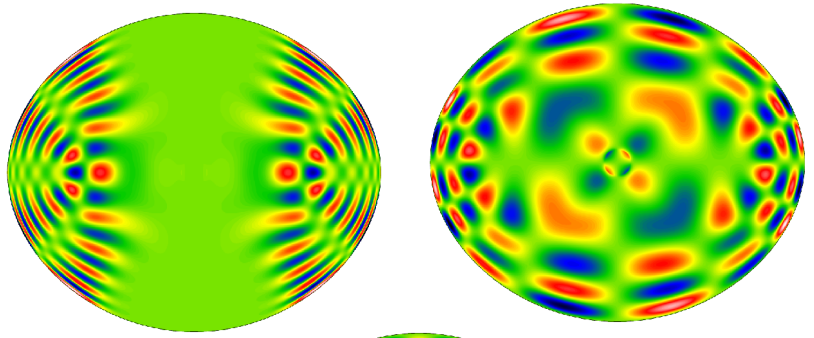
Reese et al. sub

Direct comparison

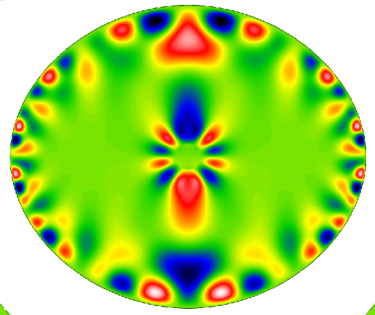
- **2D model of α Oph w. ESTER**
  - Observational constraints
    - Interferometry (Zhao et al. 2009)
- **Oscillations w. TOP**
  - Modes+visib.+damping
  - Observations (Monnier et al 2010)



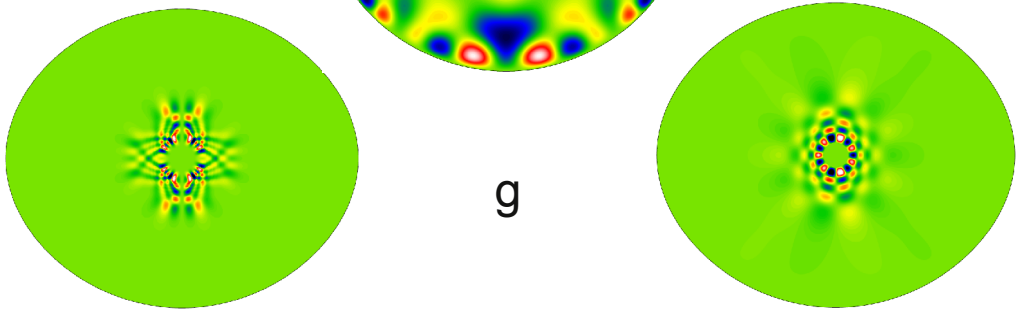
Rotation



p

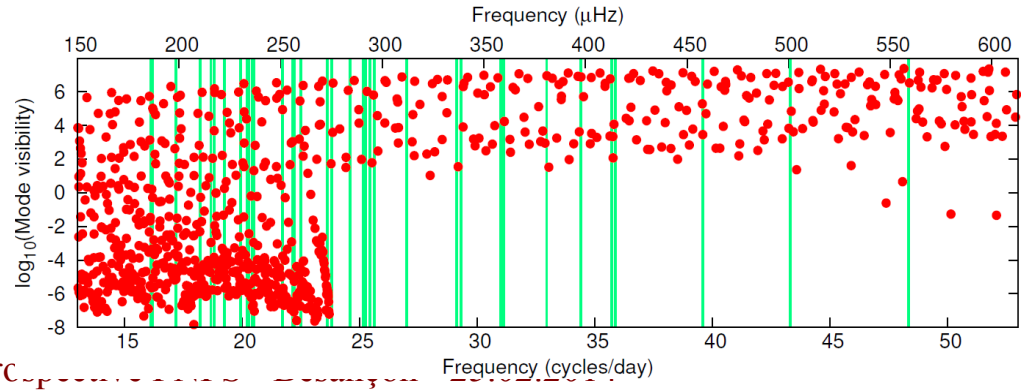


p-g



g

Mirouh et al. 2013



Summary

- **Better understanding of p- and g-mode spectra**
  - mode classification
  - regularities
- **Data exploitation**
  - Looking for regularities in spectra
    - simple to implement. Interpretation?
  - Direct comparison
    - time consuming. work in progress
  - Issue: predicting mode amplitudes

The Space Photometry Revolution

CoRoT Symposium 3, Kepler KASC-7 joint meeting

6-11 Jul 2014 Toulouse (France)

6-11 Jul 2014, Toulouse

http://corot3-kasc7.sciencesconf.org/

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- LIST OF PARTICIPANTS
- PRELIMINARY PROGRAMME
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VENUE

The conference will be held at ***Espaces Vanel*, Toulouse (France)**.

Situated in the South-West of France, close to the Pyrénées mountains, Toulouse is a friendly and attractive town benefiting from the sunny and mild weather of southern France. It can be easily reached by plane through Toulouse-Blagnac international airport (http://www.toulouse.aeroport.fr) located at 10 km from Toulouse city centre.

The access to the Espaces Vanel is easy. It is located in downtown Toulouse, a 5-minute walk away from the central train station (Toulouse Matabiau) and a 10-minute walk away from the historic centre.

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