CENTER FOR SPACE SCIENCE NYUAD

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Seismic measurements for main sequence stars and subgiants

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Asteroseismology with PLATO

Support exoplanet science, e.g.

- Planet mass and radius
- Characterize habitable zone
- Constraints on spin-orbit angle

Improve understanding of stellar physics, e.g.

- Stellar rotation
- Internal stellar structure
- Stellar evolution
- Identification of missing physics

- **Requirements on Precision (and Accuracy) for stars:**
  - Few % for Radius
  - 10% for Mass
  - ~10% in Age

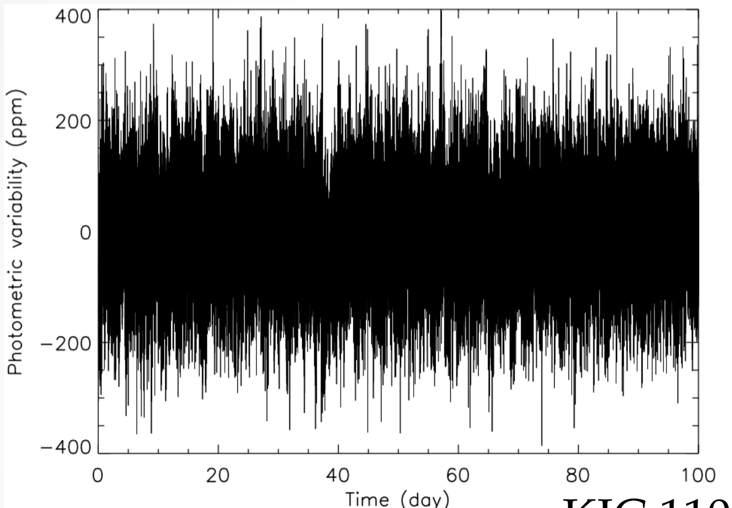
- **Requires:**
  - Accurate stellar models
  - Accurate and Precise spectroscopic parameters
  - Accurate and Precise asteroseismic constraints (mostly frequencies)

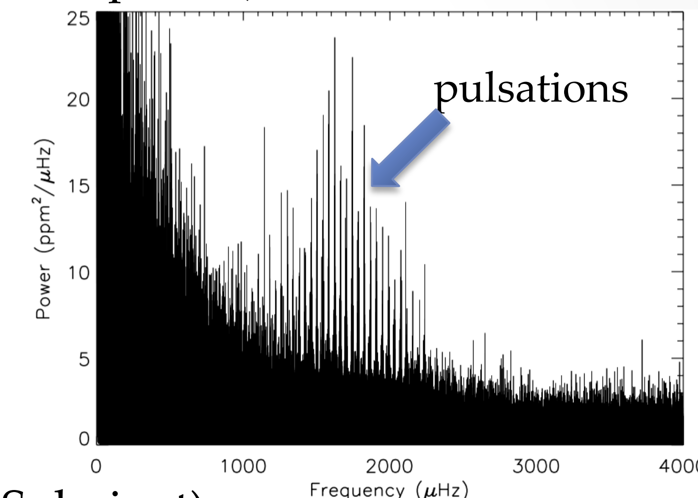
Solar-like stars

Analysis of stellar pulsations

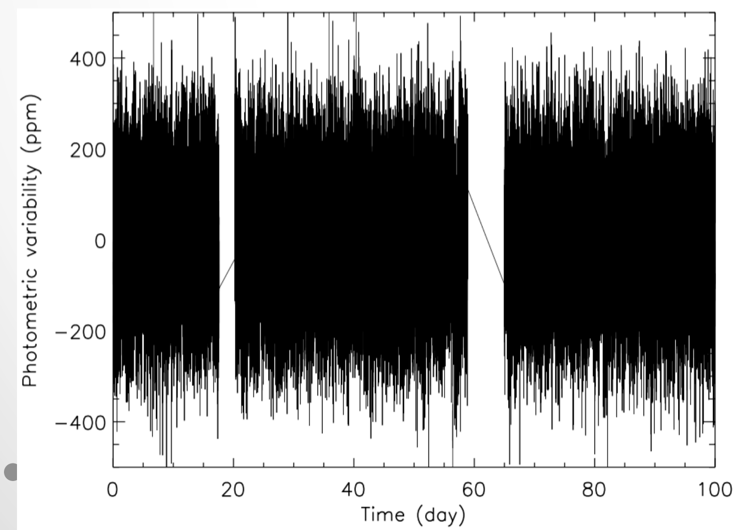
- **<u>Analysis mostly made on the power spectrum:</u>**
  - Clear mode pulsations
  - Power spectrum of a Solar-like pulsations well understood

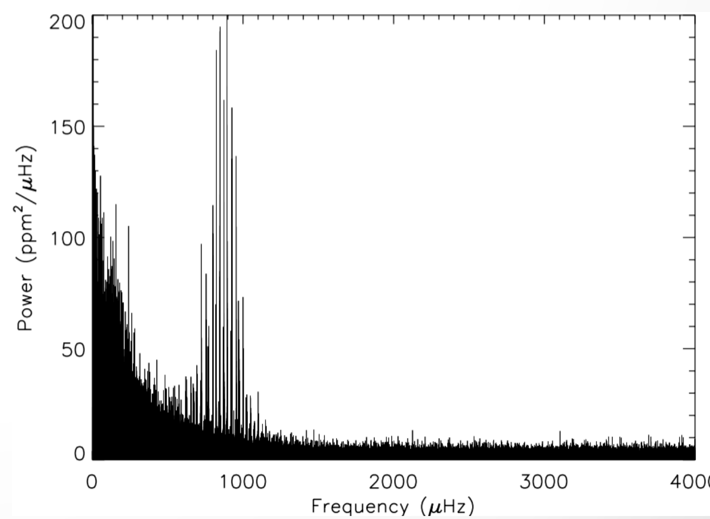
KIC 9139163 (Main Sequence)





KIC 11026764 (Subgiant)





Dealing with the Power Spectrum

1. Signal Statistics

2. Model for pulsations

➢ Fit the power spectrum: extract the mode parameters

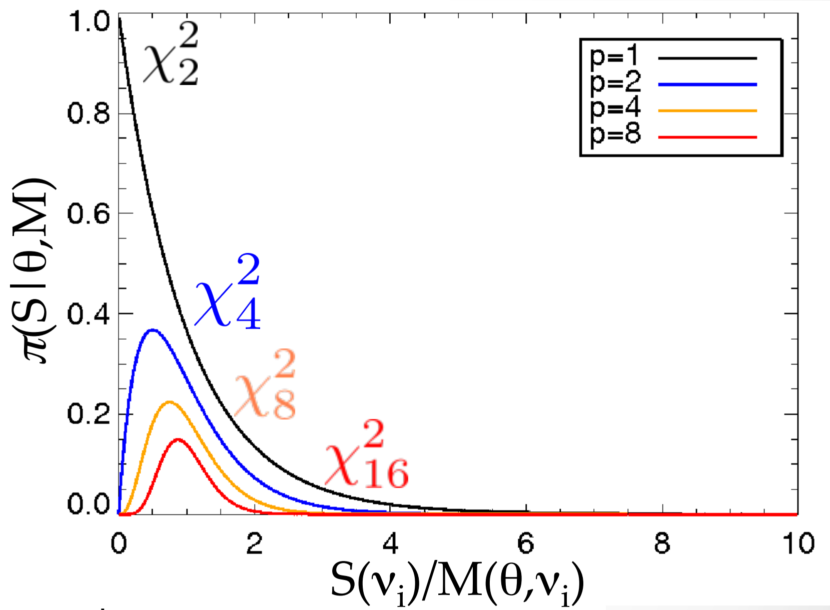
- Noise: Intrinsic stochastic noise due to the stochastic nature of the excitation function of the modes ➔ for each point, noise following a χ^2_2 statistic.

Power Spectrum

Likelihood: $$\pi(S|\theta,M) = \prod_i \frac{e^{-\frac{S(\nu_i)}{M(\boldsymbol{\theta},\nu_i)}}}{M(\boldsymbol{\theta},\nu_i)}$$

Appourchaux+ (1998)

Model for pulsations



- If you are a Bayesian use of *priors* on the parameters :

Posterior probability density

Priors

$$\pi(\boldsymbol{\theta}|S,M) \propto \pi(S|\boldsymbol{\theta},M)\,\pi(\theta|M)$$

➢ Best Fit: MLE, MAP, MCMC

Dealing with the Power Spectrum

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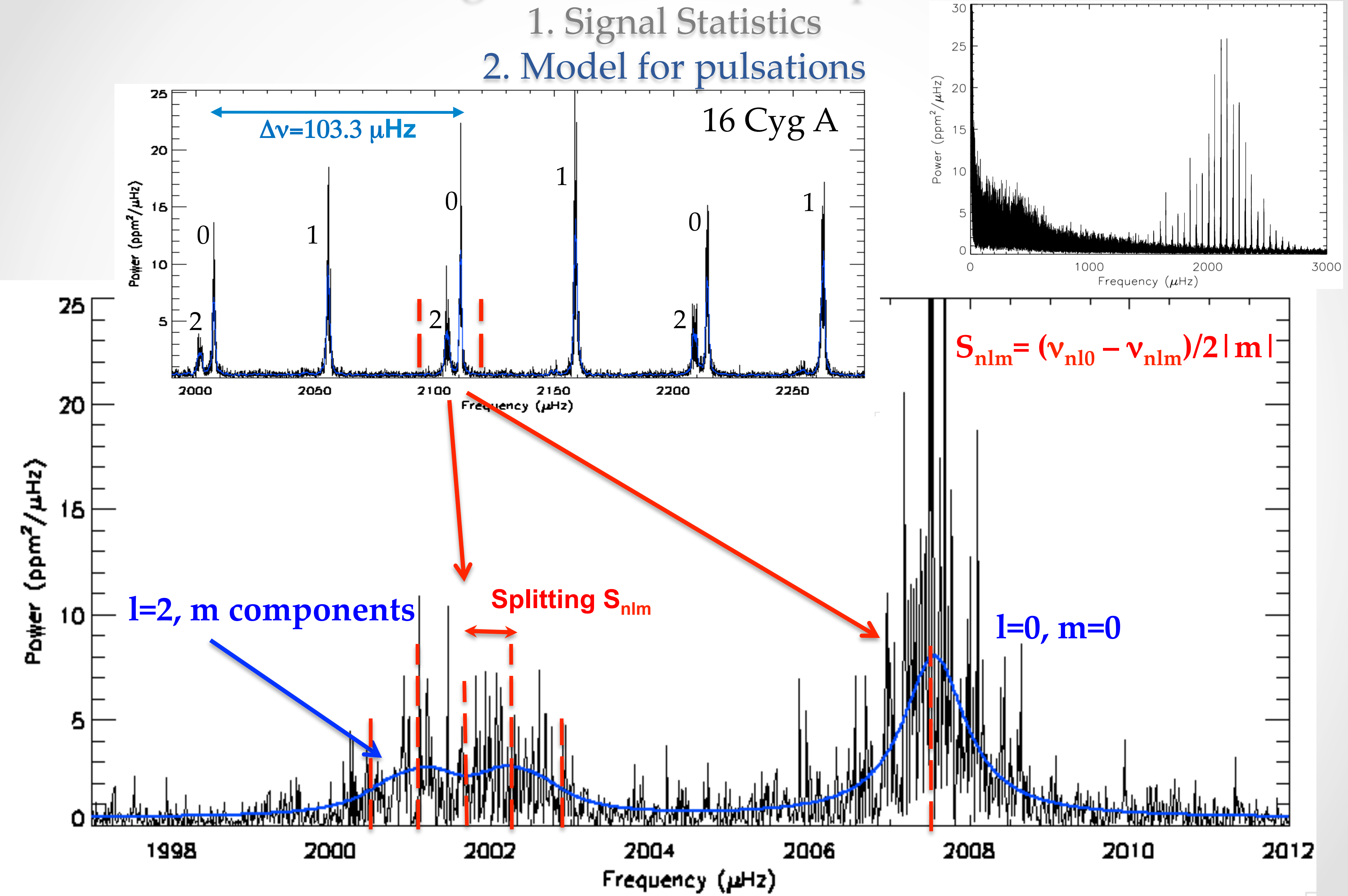


Dealing with the Power Spectrum

1. Signal Statistics

2. Model for pulsations

Solar-like stars: each mode can be described as a damped oscillator, stochastically excited

$$\frac{1}{\omega^2_{n,l,m}}\frac{d^2}{dt^2}\xi(t)+\frac{2\pi\,\Gamma_{n,l,m}}{\omega^2_{n,l,m}}\frac{d}{dt}\xi(t)+\xi(t)=f(t)$$

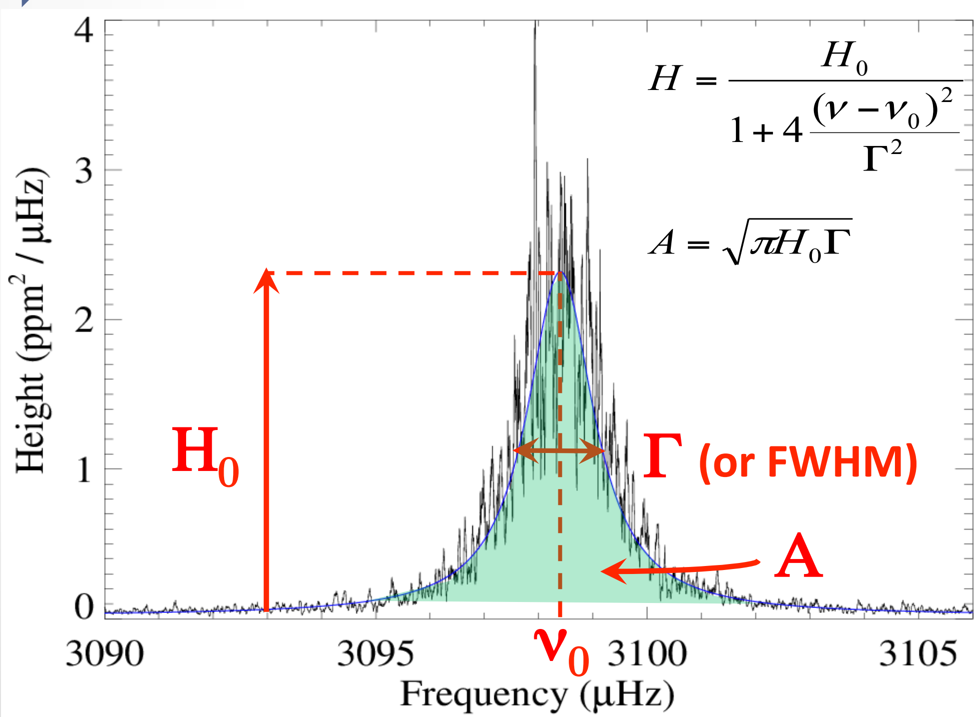
Damping coefficient ($\Gamma_{n,l,m}$)

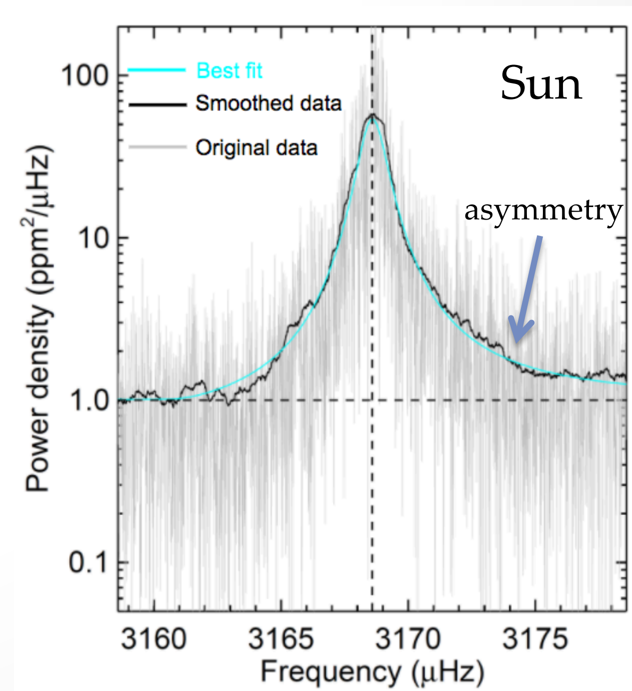
Pulsation frequency ($\omega_{n,l,m}$)

Displacement ($\xi(t)$)

Stochastic function (excitation) ($f(t)$)

Power spectrum: the solution is a Lorentzian



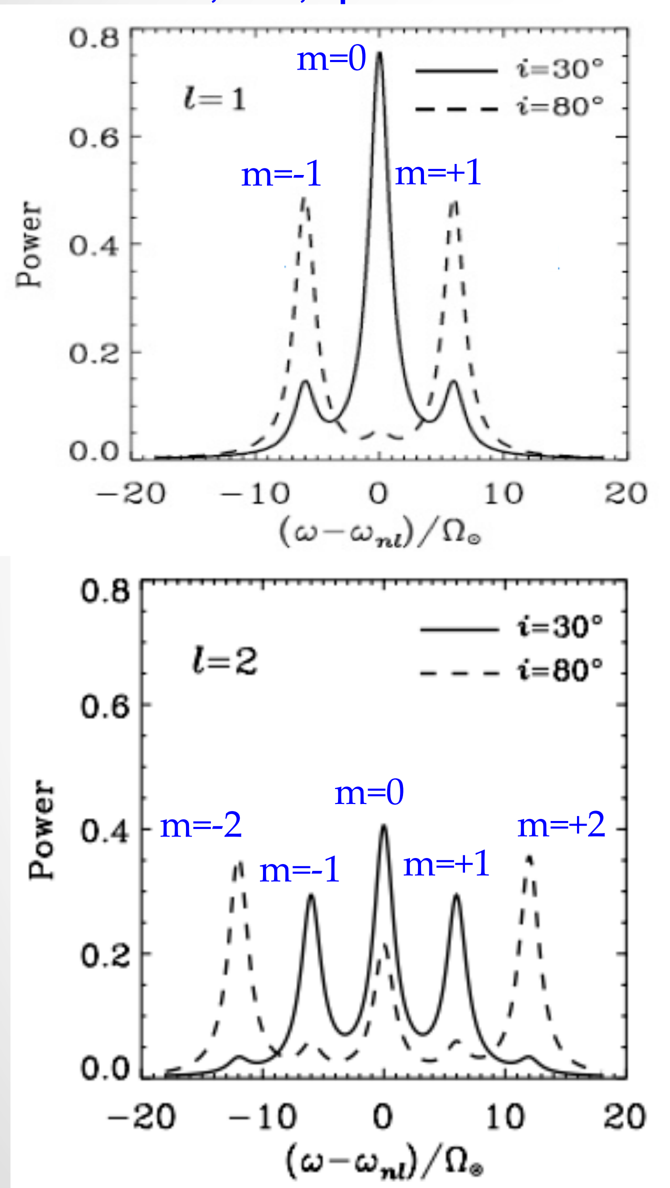


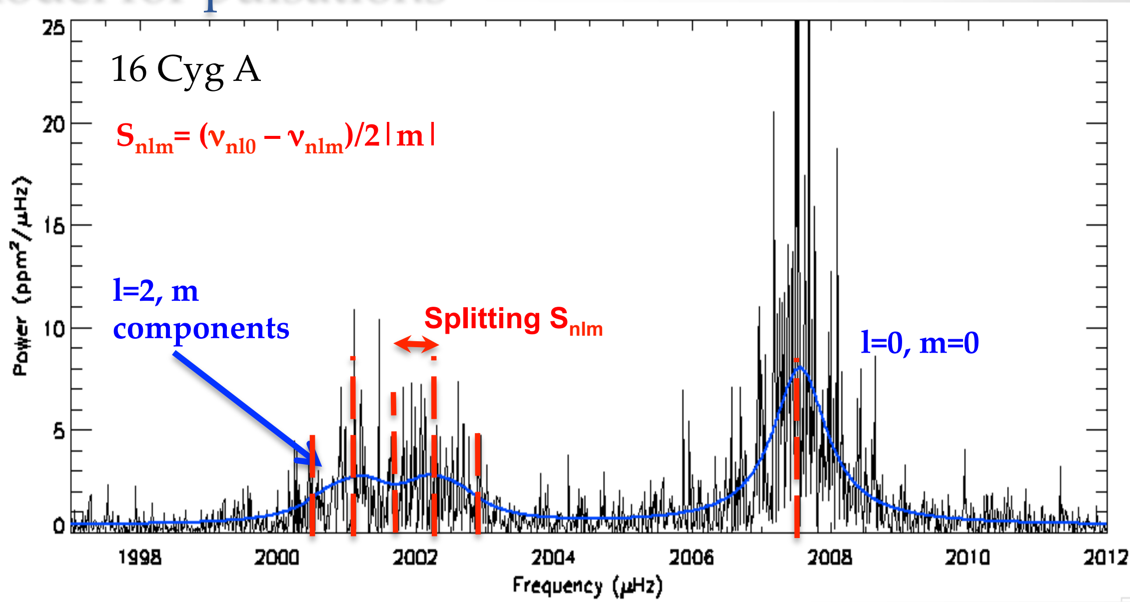
Dealing with the Power Spectrum

1. Signal Statistics

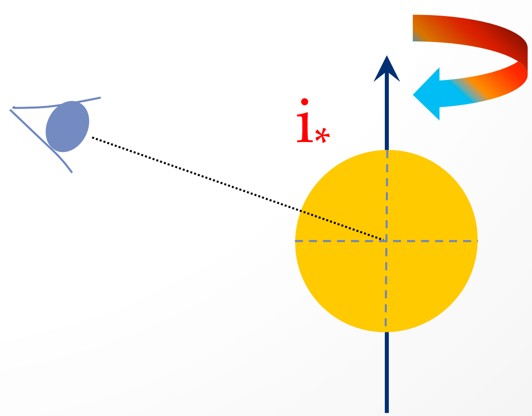
2. Model for pulsations

Gizon & Solanki, 2003, ApJ





- For l>0, m component height is modulated by the stellar inclination
- The mean splitting measures the average internal rotation



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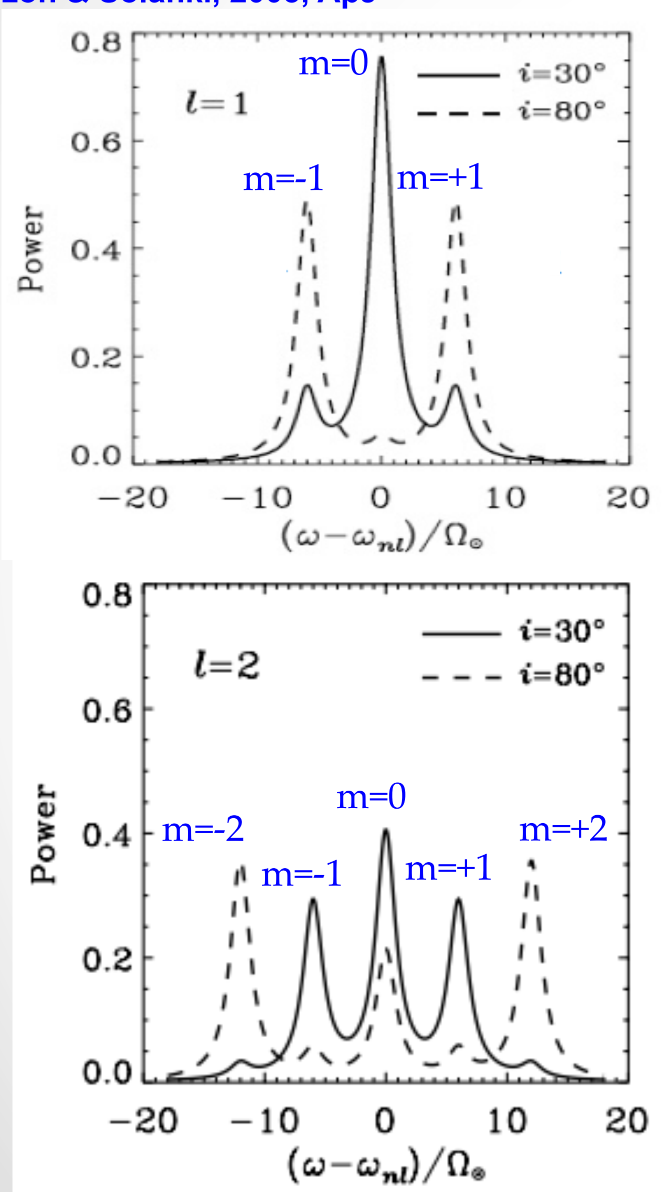
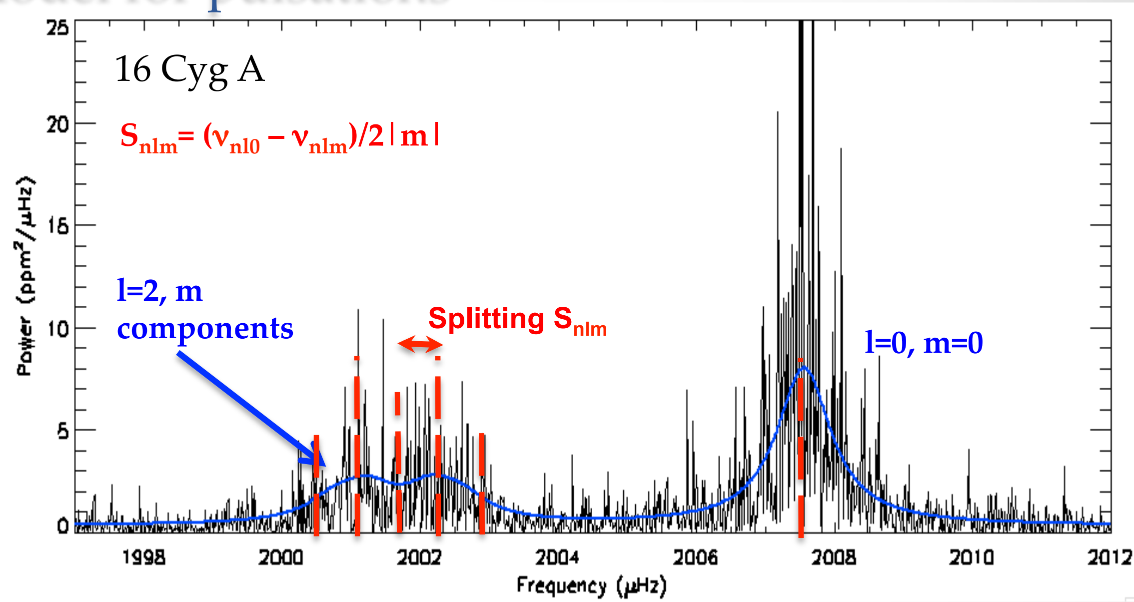




Basic model for a mode:

$$P_{n,l,m}(\nu) = R(i,m) . \frac{H_{n,l}}{1+\left(\frac{\nu-\nu_{n,l,m}}{\Gamma_{n,l,m}/2}\right)^2}$$

Inclination factor

Maximal height

Eigen frequency

FWHM

In practice, fitting this does not provide robust estimates… need assumptions

Current common recipe for MS/SG: Global fitting

$$P_{n,l,m}(\nu) = R(i,m).\frac{H_{n,l}}{1+\left(\frac{\nu-(\nu_{n,l}+m.\nu_s)}{\Gamma_{n,l}/2}\right)^2}$$

Maximal height ($H_{n,l}$)

Inclination factor ($R(i,m)$)

Eigen frequency ($\nu_{n,l}$)

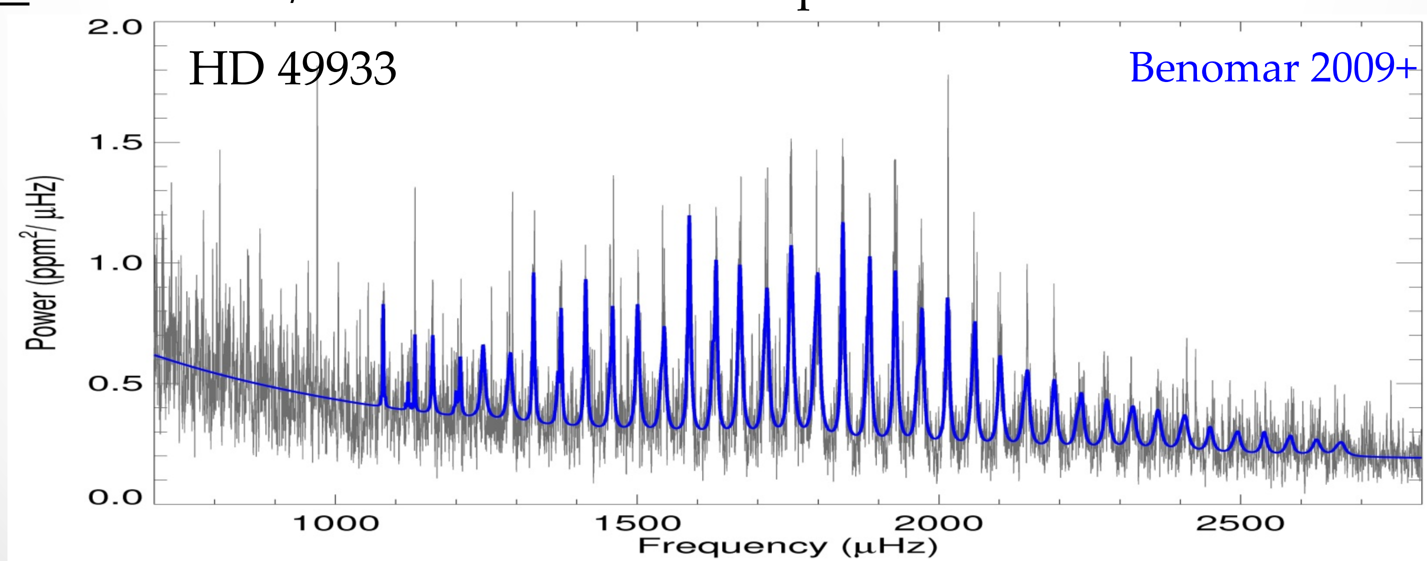
FWHM ($\Gamma_{n,l}$)

$$M(\nu) = \sum_{n=n_0}^{N_{\max}} \sum_{l=0}^{L_{\max}} \sum_{m=-l}^{m=+l} P_{n,l,m}(\nu) + N(\nu)$$

Assumptions (built on the CoRoT experience):

1. Common inclination (single spin axis)
2. Common splitting (near solid-body rotation)
3. Power law for Noise background (Harvey profile)
4. Interpolating FWHM (damping) of l>0 from l=0 widths for main-sequence stars (Analogy to the Sun)
5. Due to geometrical properties + Limb-darkening: $H_{n,l>0} \propto H_{n,l=0}$

Global Fit: More robust/Reliable estimate of all parameters than local fit



Summary/Perspectives

- A lot of experience accumulated by analysing CoRoT and Kepler data
- With multi-year observations, some assumptions may not be anymore required:
  - Evaluating radial/latitudinal differential rotation: Drop assumption 2 (e.g. Nielsen+ 2017)
  - Test of excitation and damping of modes: Drop assumptions 3 and 4
  - Measuring the Limb-darkening effect: Drop assumption 5
- Still room for many improvements in our methods of analysis before PLATO
  - Need to get faster: Currently ~1 day / star for MCMC analysis
  - Need to get (semi)-automatic pipelines for defining priors / inputs of fit parameters

<u>Assumptions (built on the CoRoT experience):</u>

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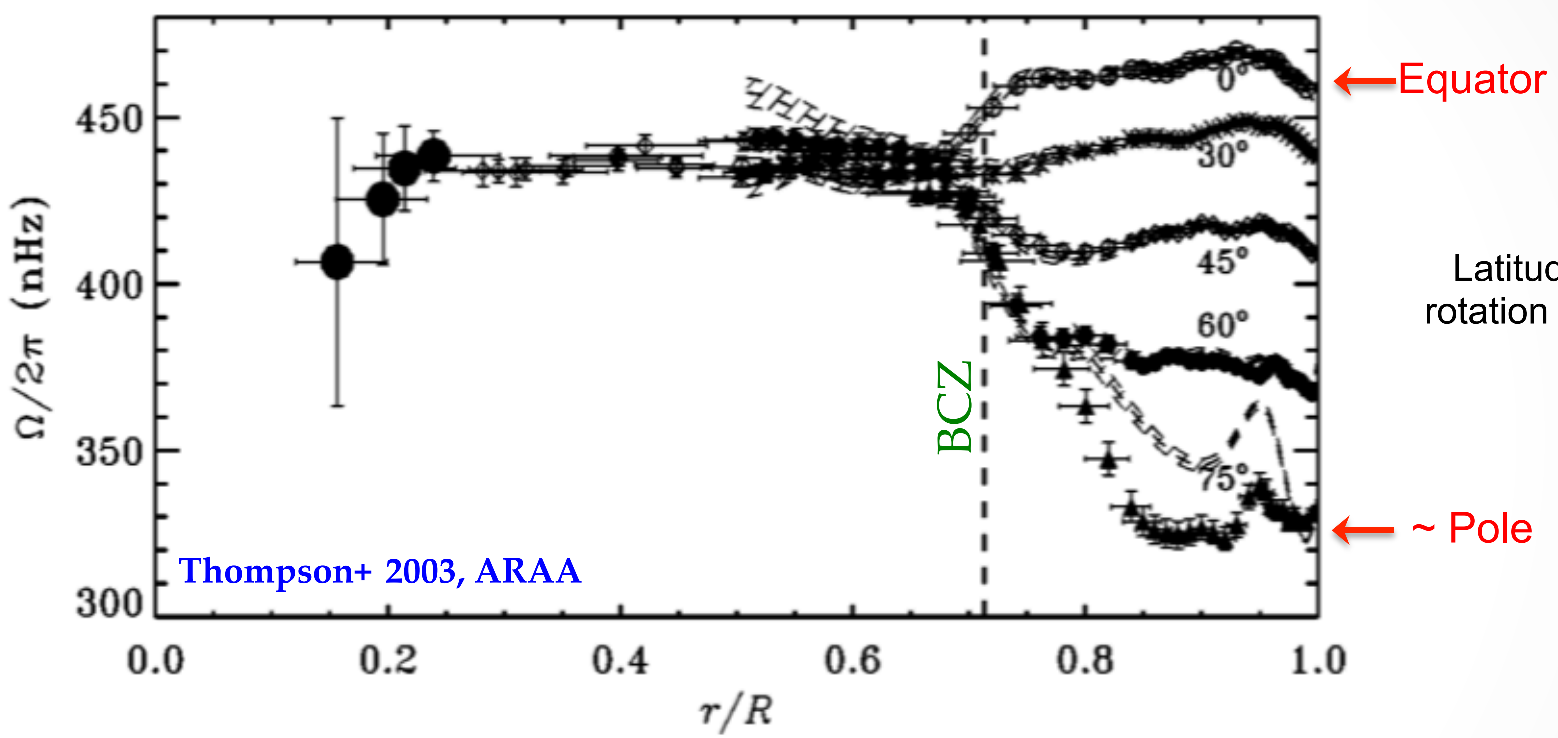
END

Questions?

Rotation: Main sequence solar-like stars

Rotation and Rotational splitting: The Sun



Latitudinal differential rotation does not exceed ~30%

Nearly-uniform rotation for the Sun but…

What mechanism(s)? Rotation induced, magnetics fields, internal waves,…?
Is the Sun peculiar?

Benomar+2015 ➔ Nearly Uniform rotation for the vast majority of solar-like stars
But what about the latitudinal rotation in the envelope of stars?

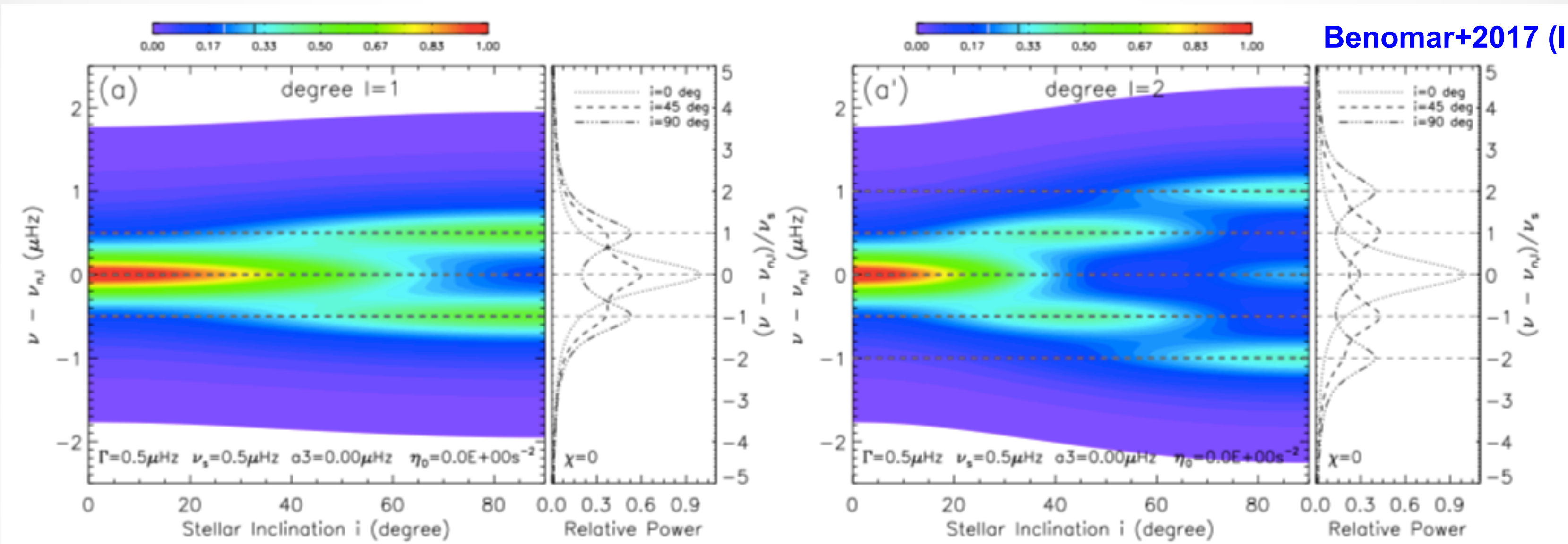
Rotation: Asphericity and latitudinal rotation effects

Schou+ 1994, ApJ

In case of a solid-body rotation of a sphere: $S_{nlm} = S_{nl-m} = \delta\nu_s$

$\delta\nu_s$ is the average rotation rate of the star

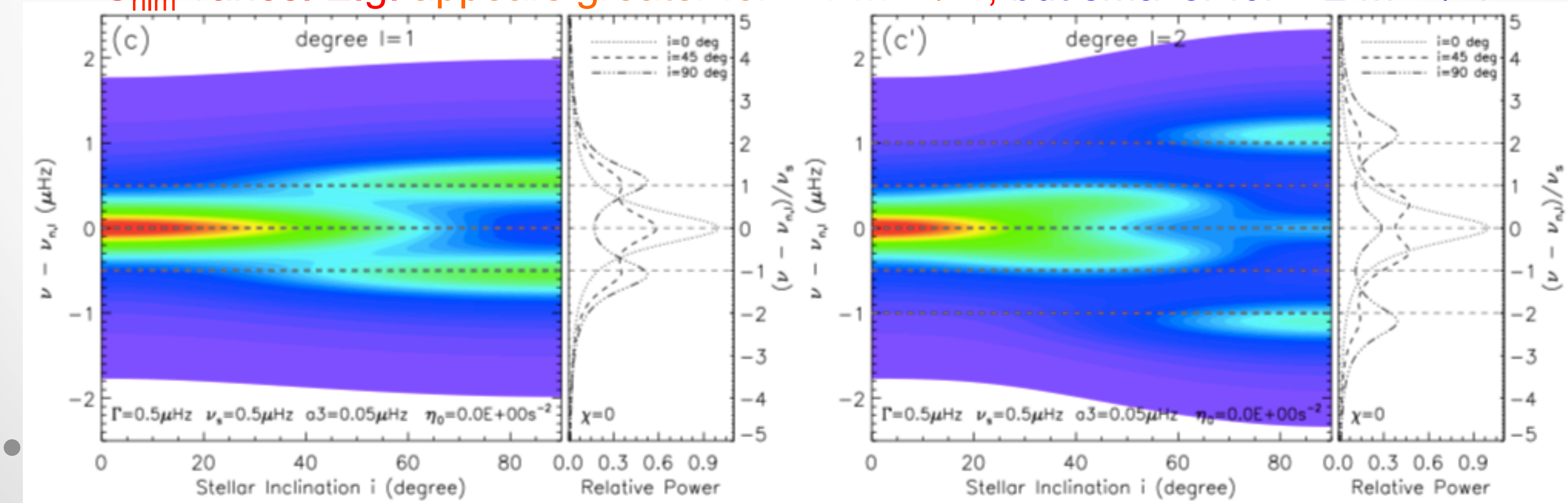
Higher frequency



In case of a latitudinal rotation of a sphere

S_{nlm} varies. E.g. appears greater for l=1 m=+/-1, but smaller for l=2 m=+/-1

Higher frequency



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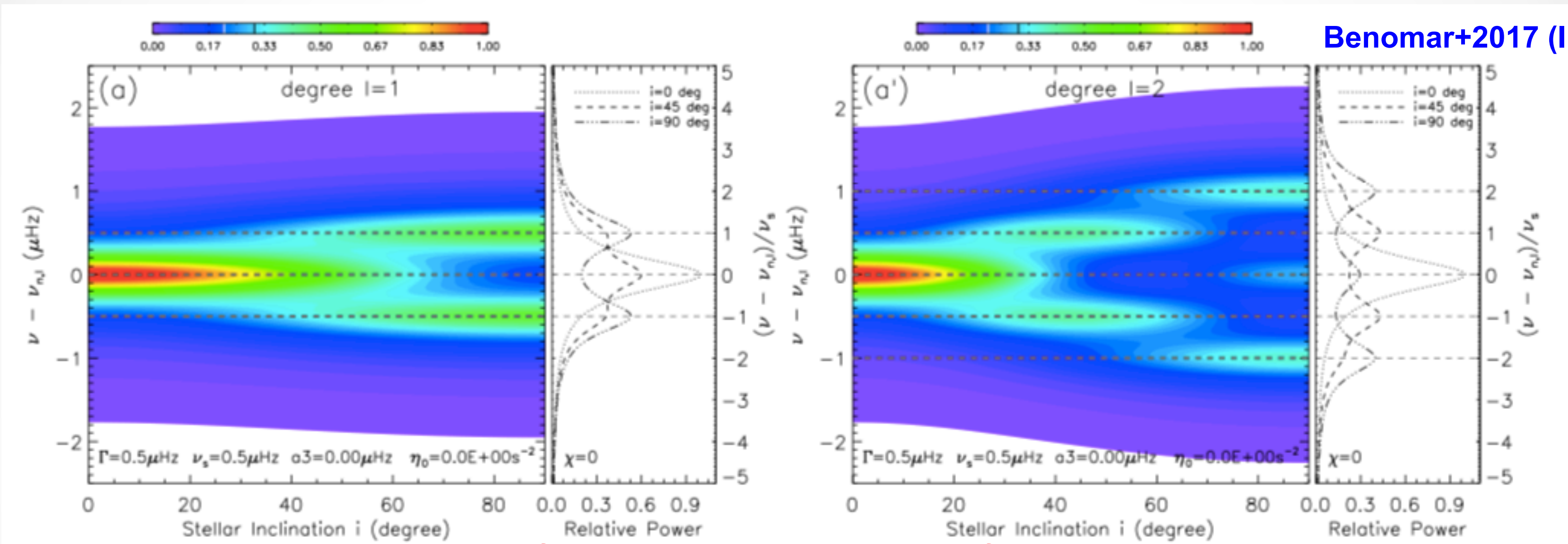
Benomar+2017 (In prep)

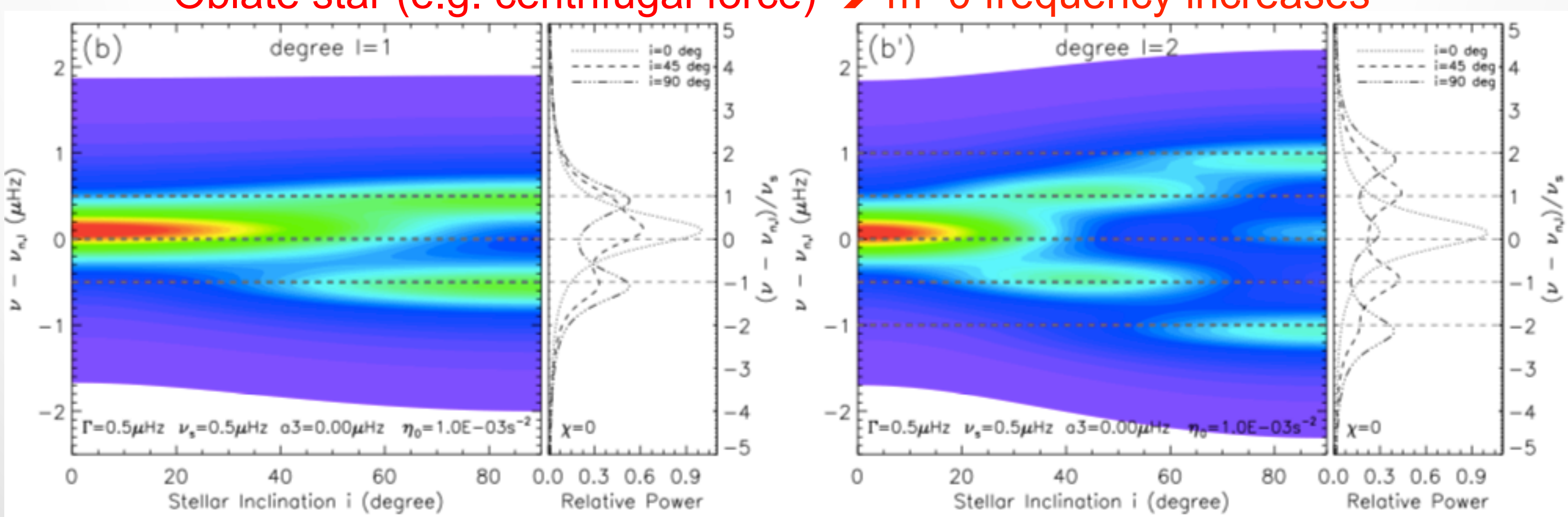
Higher frequency



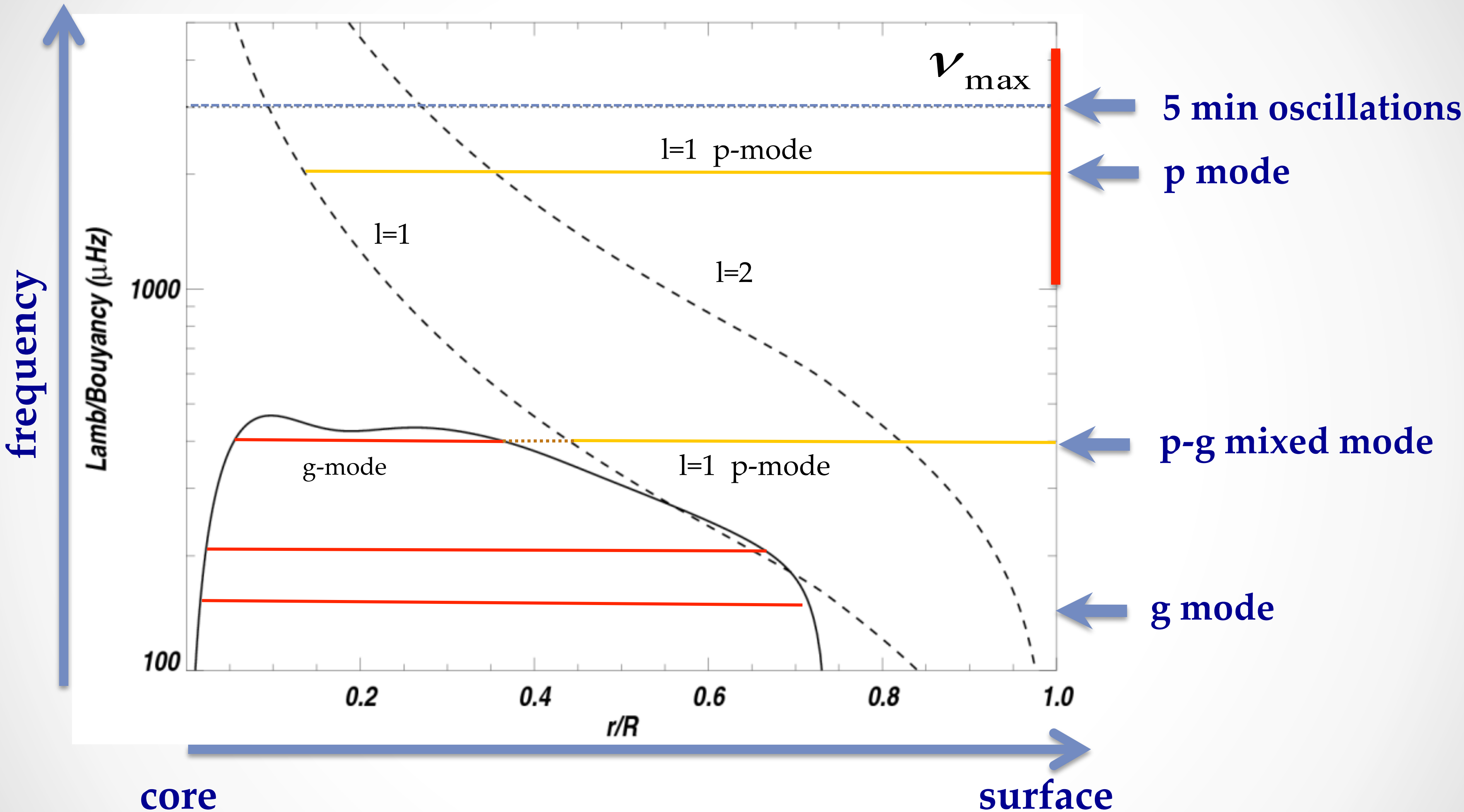
In case of a solid-body rotation of a spheroid

Oblate star (e.g. centrifugal force) ➔ m=0 frequency increases

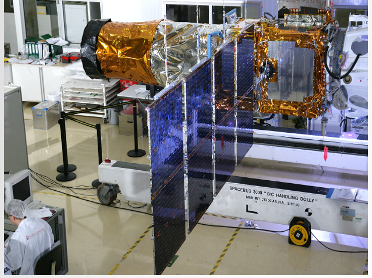
Higher frequency



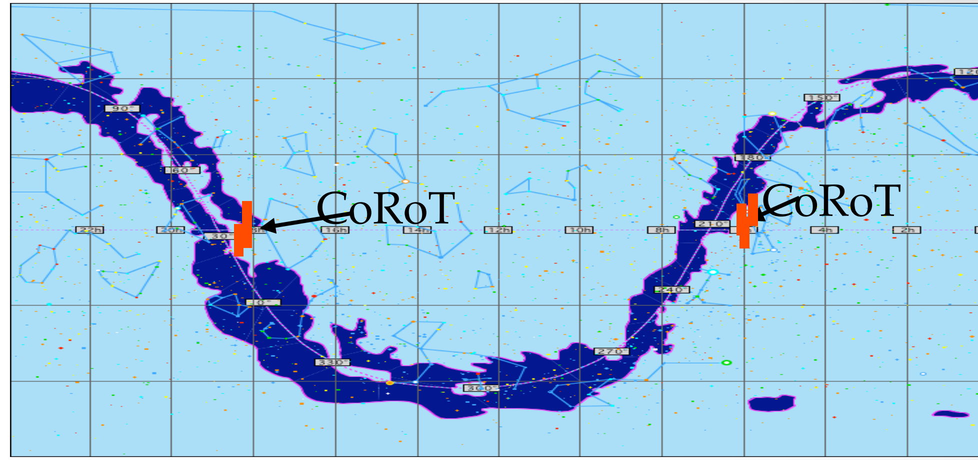
Propagation diagram of the Sun



Lamb frequency: delimits the p modes cavities
Brunt Vaisala frequency: delimits the g modes cavity

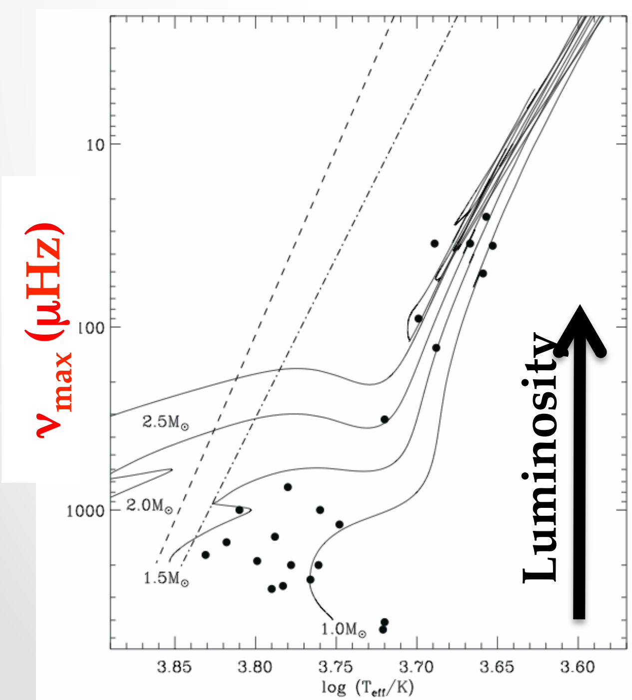


Instruments: CoRoT

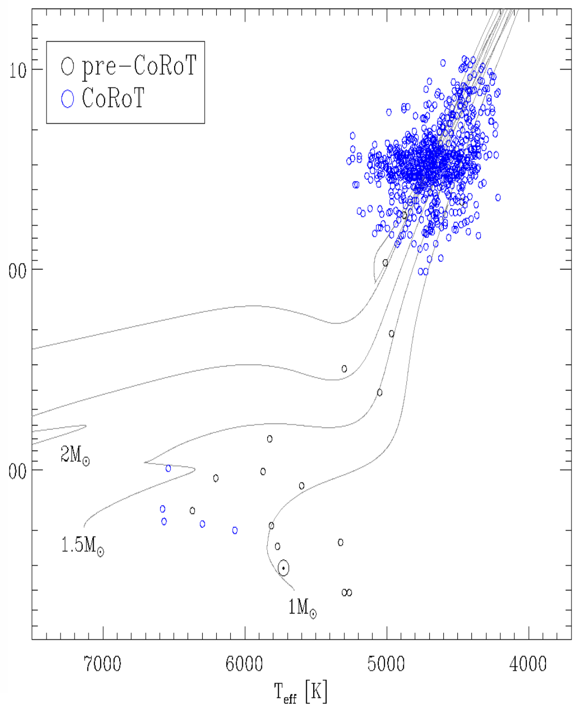


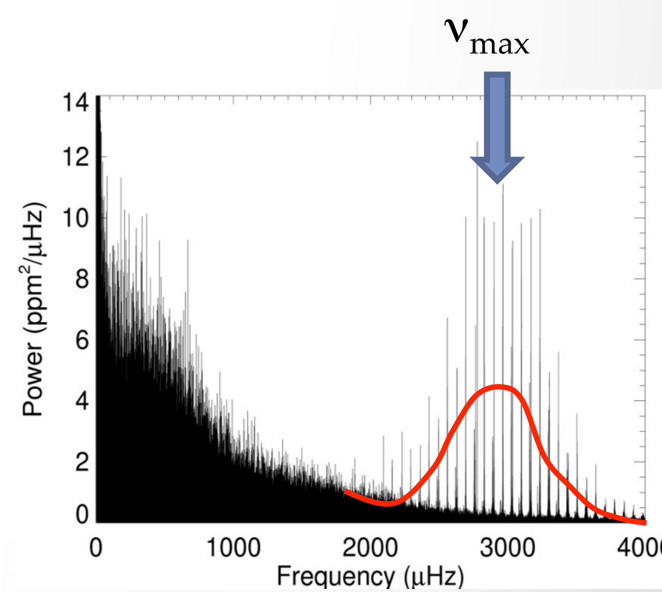
- Earth orbit since 27 Dec. 2007
- Observation duration: 60- 150 days
- Status: dead (02/11/2012), deorbiting

2007 Pre CoRoT



2009 Post CoRoT





Measuring pulsations implies improved precision

- Classical approaches: large uncertainties
  (e.g. spectroscopy only)

  - Radius :~10%
  - Mass :~20%
  - Age : >50%
- *Main uncertainty source: the internal stellar structure*
- *The Asterosismology:*
  - *Account of the internal structure*
  - *Allows to determine the physics inside the stars*

<u>We can reach uncertainties of:</u>

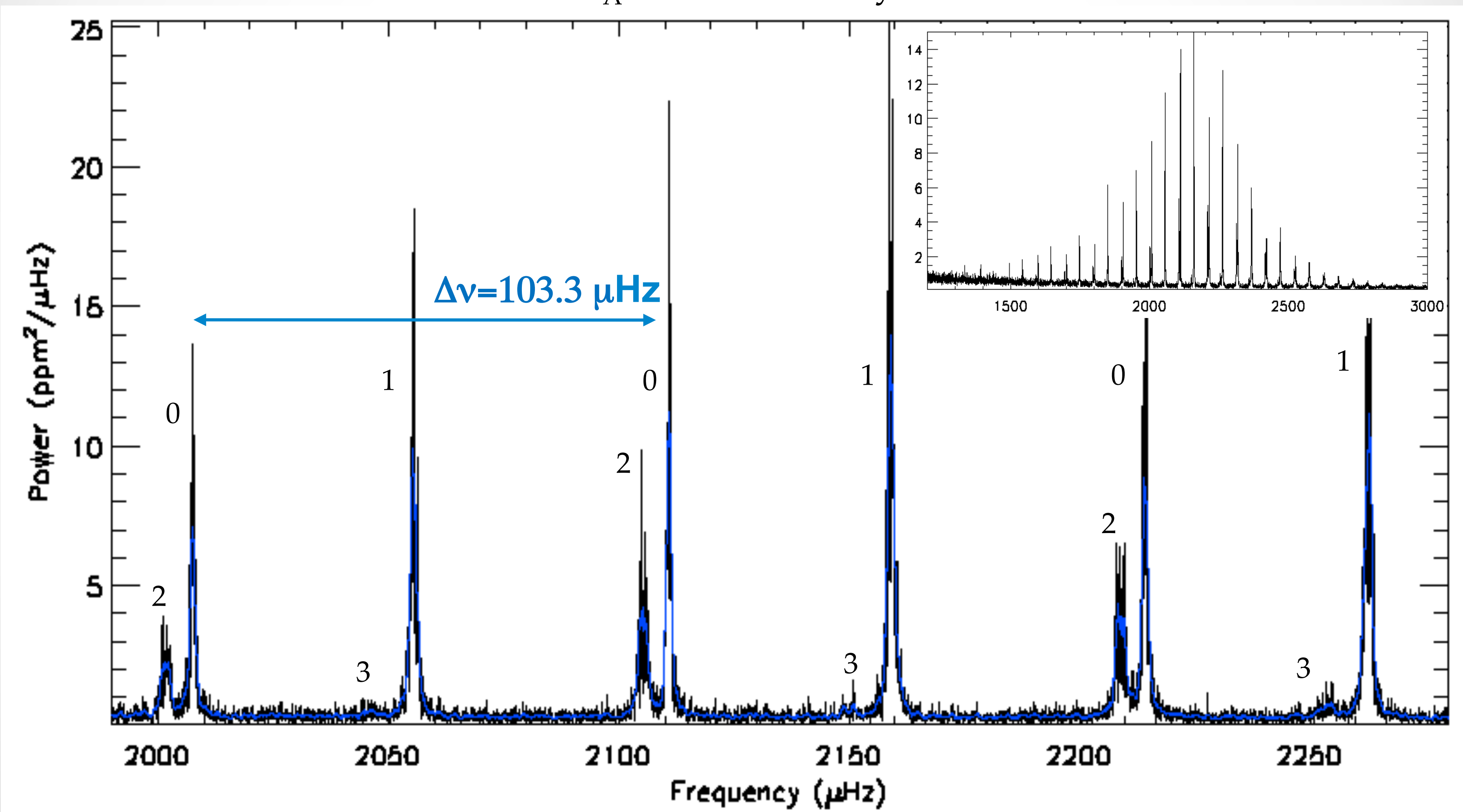
- 2% on radius
- 5% on the mass
- <20% on the age

- *Better characterisation of exoplanets:*
  Mass, Radius, composition

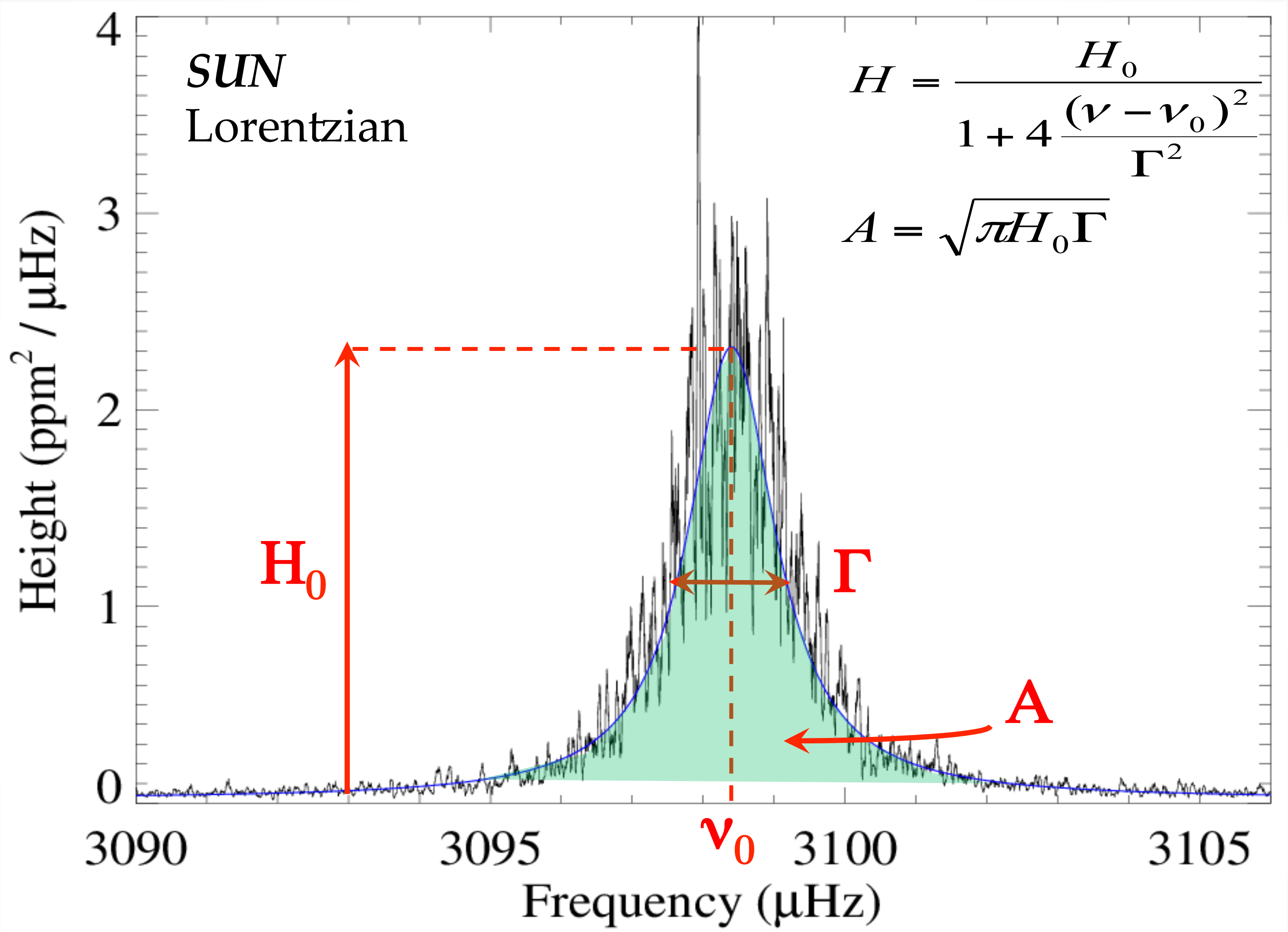
16 Cyg A : The brightest star of the Kepler Field

M_A=1.08 +/- 0.02 M_{sun}
R_A= 1.229 +/- 0.008 R_{sun}
t_A=7.07 +/- 0.26 Gyrs

Metcalfe+ 2015
Davies+ 2015



Lorentzian profiles of the modes



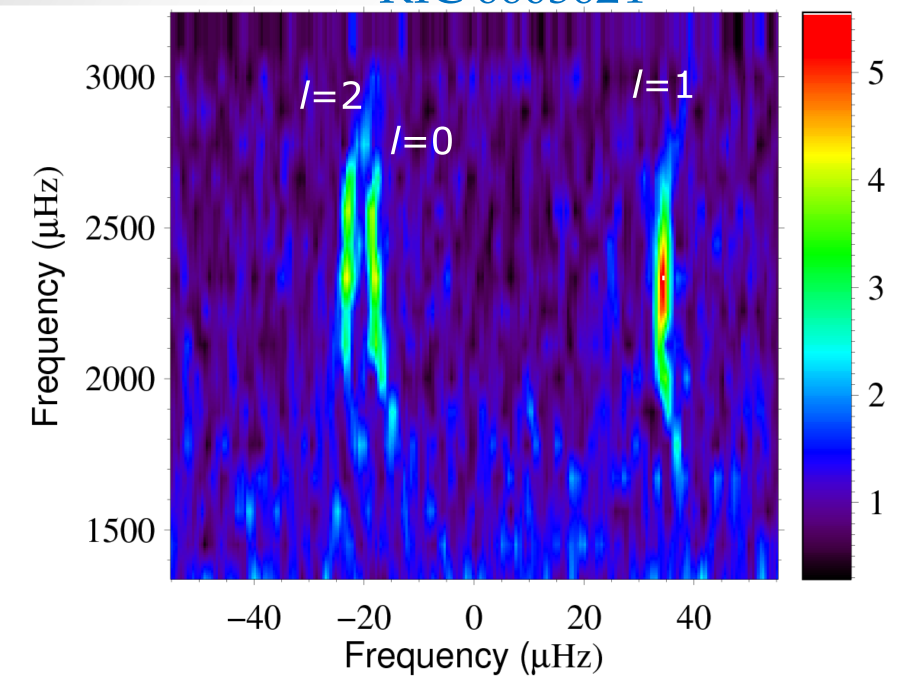
Measure of mode parameters (H_0, Γ_0, A, ν_0) requires spectrum fitting

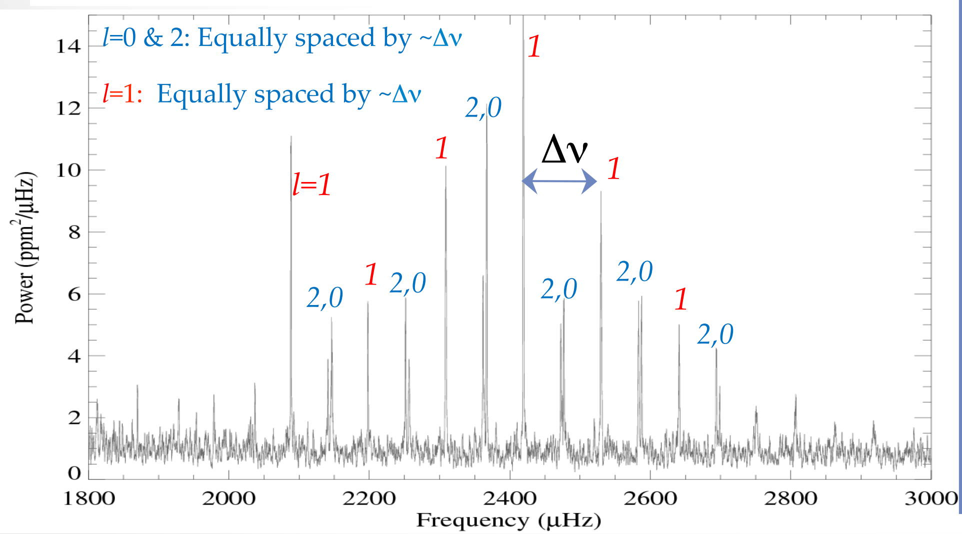
H_0, Γ_0, A: Quantities sensitive to the

- Excitation
- Damping (convective / radiative)
- Non adiabatic processes

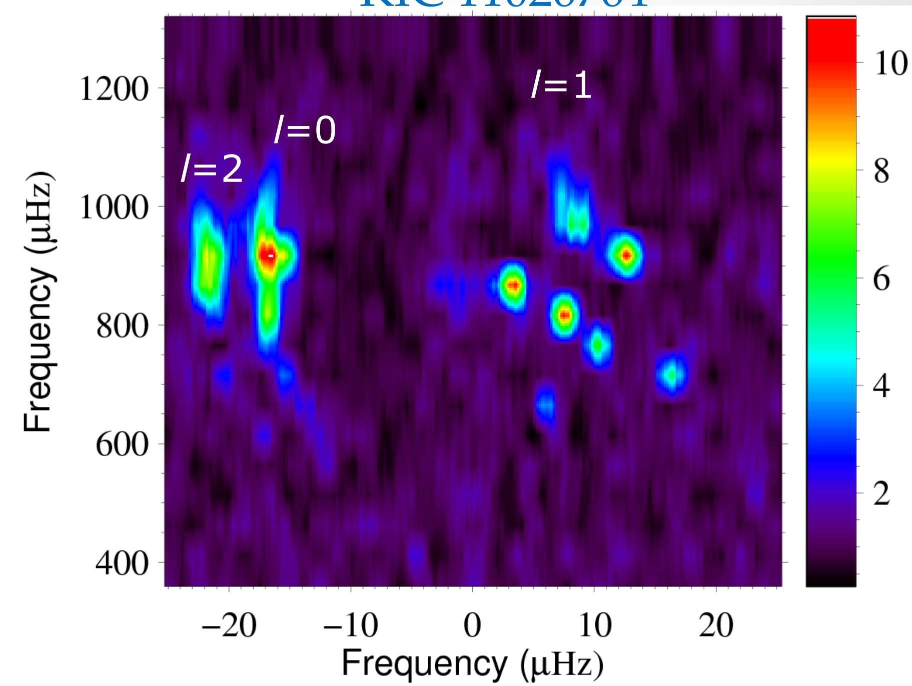
Main sequence vs Evolved stars

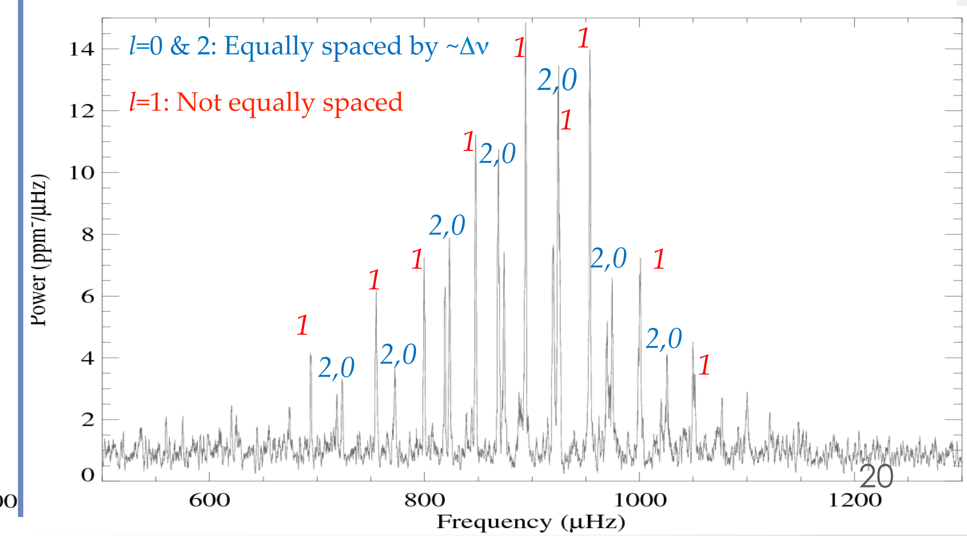
KIC 6603624





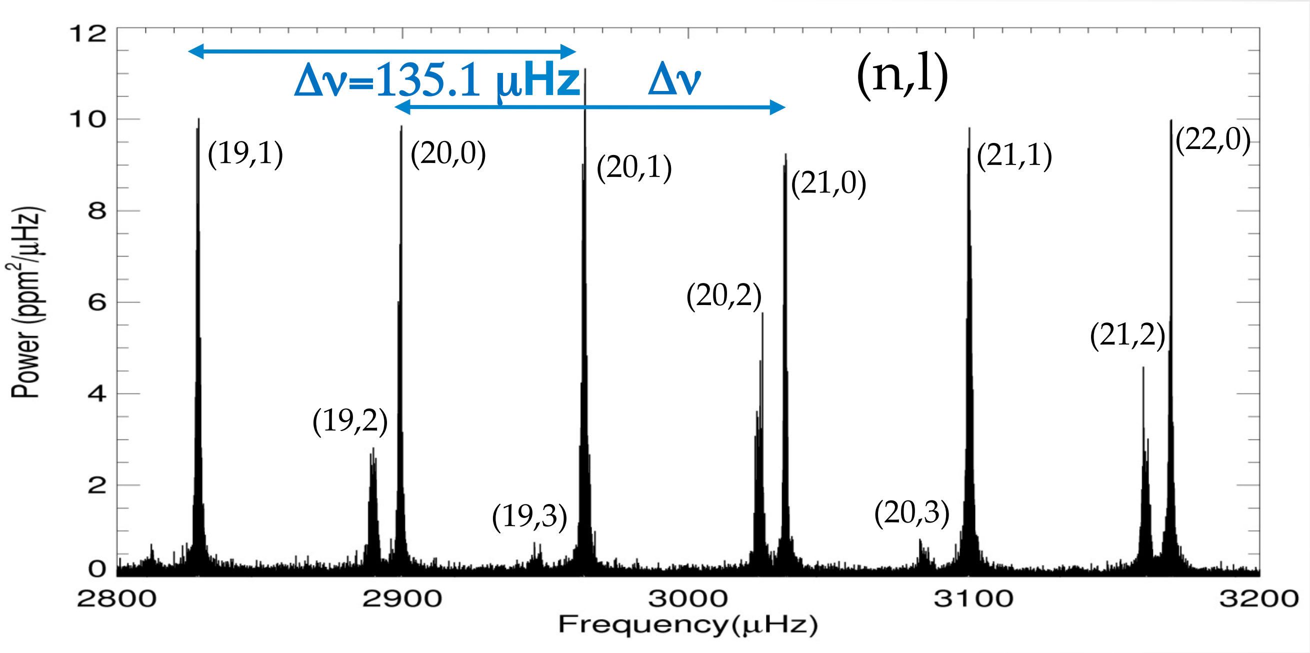
KIC 11026764





Stochastically driven modes

Sun observed by VIRGO (SoHo)



- Modes (n,l) are regularly spaced ➔ linear function $\nu(n,l) \propto (n + l/2)\Delta\nu$
- $\Delta\nu = \left[2\int_0^R \frac{dr}{c(r)}\right]^{-1} \propto \sqrt{\rho}$ mean density of the star
- Individual frequencies: information about structure changes within the star... Such as the Transition between convective zone/radiative zone

Rotation: Evolved solar-like stars

Rotation in evolved stars: Subgiants and (low-mass) early red giants

Observed splitting

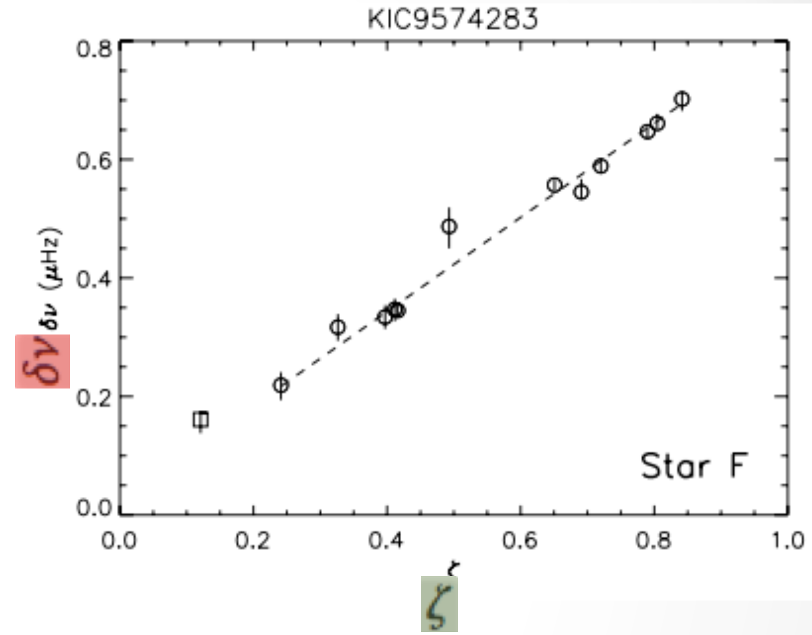
Core (g-cavity)

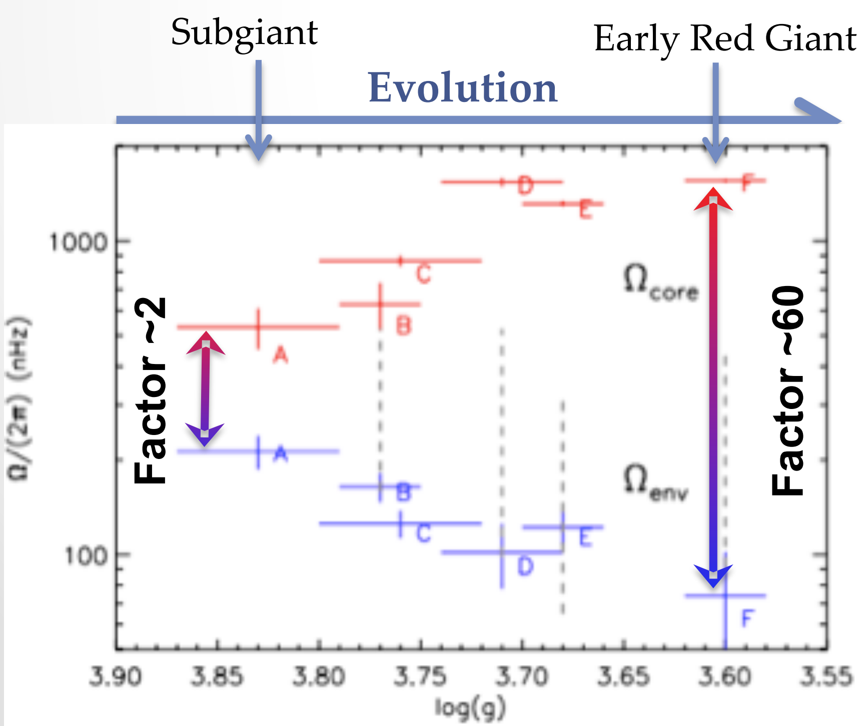
Outer layers (p-cavity)

$$\delta\nu = \zeta\left(\frac{1}{2}\left\langle\frac{\Omega_g}{2\pi}\right\rangle - \left\langle\frac{\Omega_p}{2\pi}\right\rangle\right) + \left\langle\frac{\Omega_p}{2\pi}\right\rangle$$

Kinetic energy in the core/Total kinetic energy (from model or theory)

Goupil+ 2013, A&A





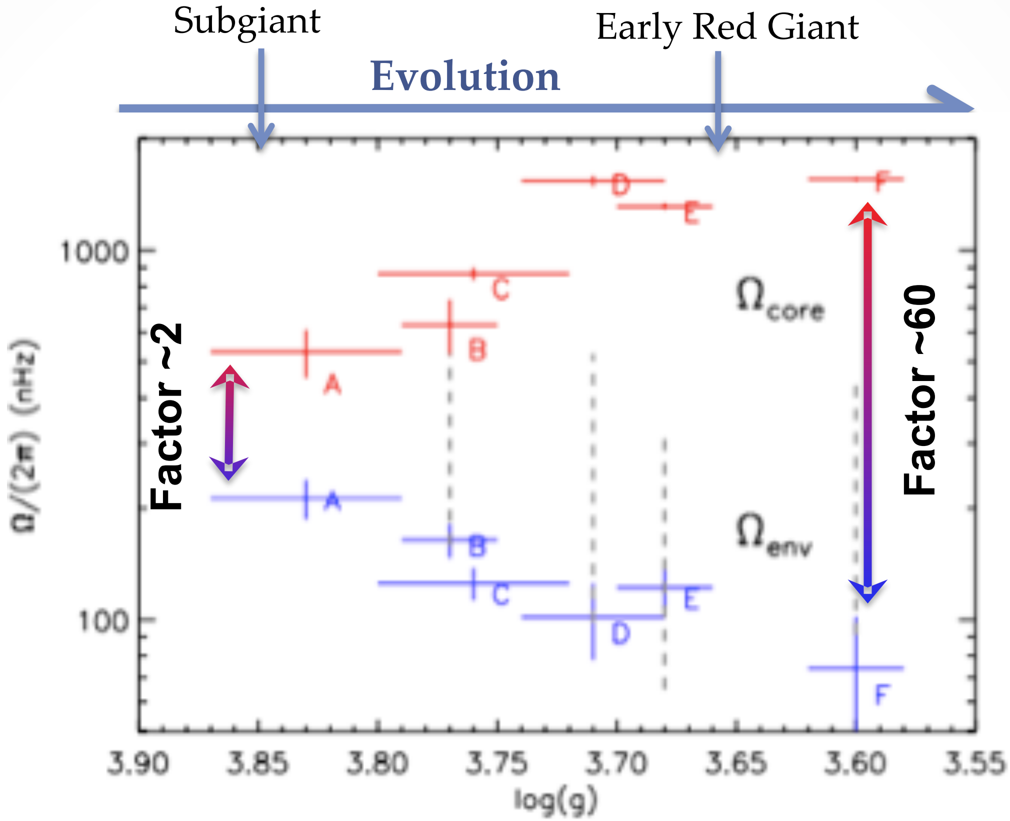
<u>During the subgiant/early red giant phase:</u>

- ✧ Spin-up of the core (core contraction)
- ✧ Spin-down of the envelope (envelope expansion)

Deheuvels+ 2014, A&A

Measure of Rotation: example on Evolved solar-like stars

Rotation in evolved stars: Subgiants and (low-mass) early red giants



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Deheuvels+ 2014, A&A

Low SNR cases

Robustness of fit requires global fitting (Appourchaux+ 2008, Benomar+ 2009)