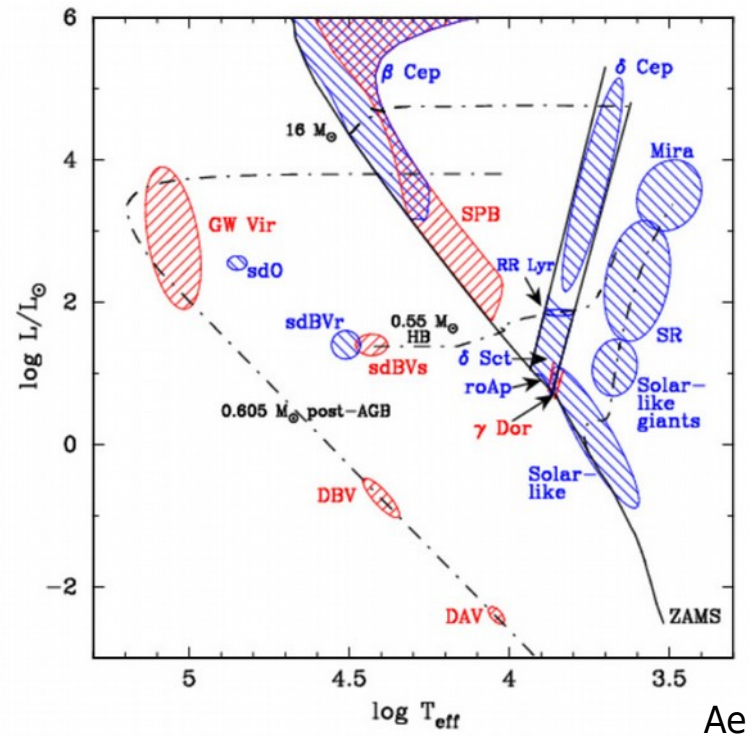
# Seismology of solar-like stars: Legacy of CoRoT & Kepler

Jérôme Ballot

# “Solar-like” stars

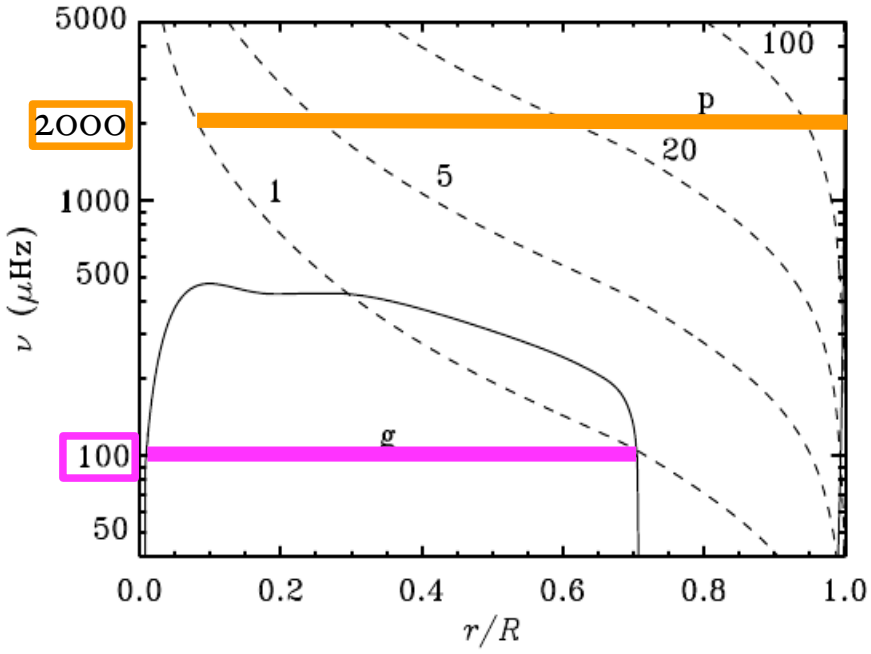
- **“Solar-like” for a seismologist ↔ stars with a convective envelope**
  - Acoustic modes stochastically excited by a convective surface
- **Late F, G, K main sequence stars + subgiants**
- **Red giant stars**




Aerts+10

# Nature of Oscillations

- **Acoustic = pressure = p modes**
- **Gravity = g modes ?**
  - Only controversial claims for the Sun
    [Turck-Chièze+ 04, García+ 07, Fossat+ 17]
- **Mixed modes**
  - A few in subgiants
  - All dipolar modes red giants have mixed properties



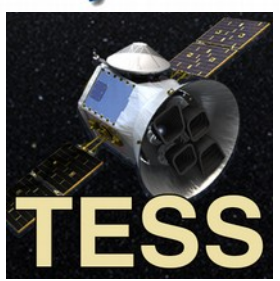
# CoRoT and Kepler

- **Photometric surveys – Synergy with exoplanet finders**
- **CoRoT (Convection, Rotation et Transits planétaires): 2006-2012**
  - CNES
- **Kepler: 2009-2013**
  - NASA
  - K2 mission: 2014-2018
- **TESS (Transiting Exoplanet Survey Satellite): 2018-…**
  - NASA
- **PLATO (PLAnetary Transits and Oscillations of stars): 2026-…**
  - ESA

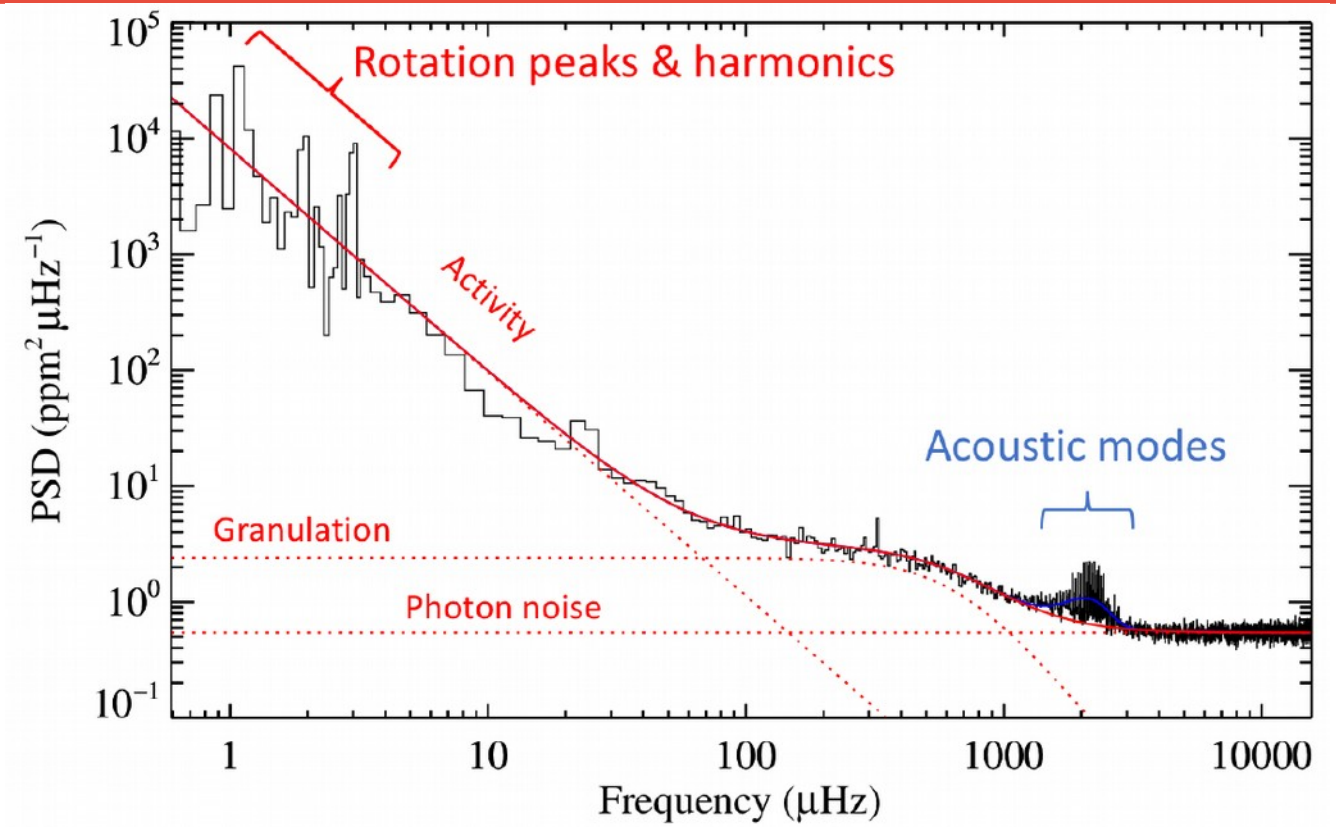
Pioneer

4-year high precision data





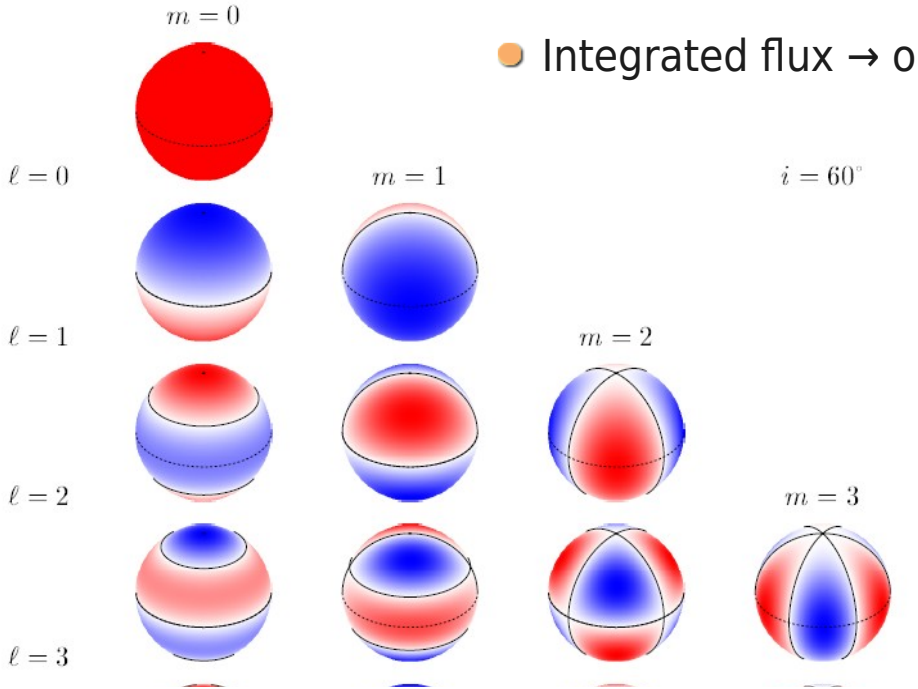
# Structure of an observed oscillation spectrum

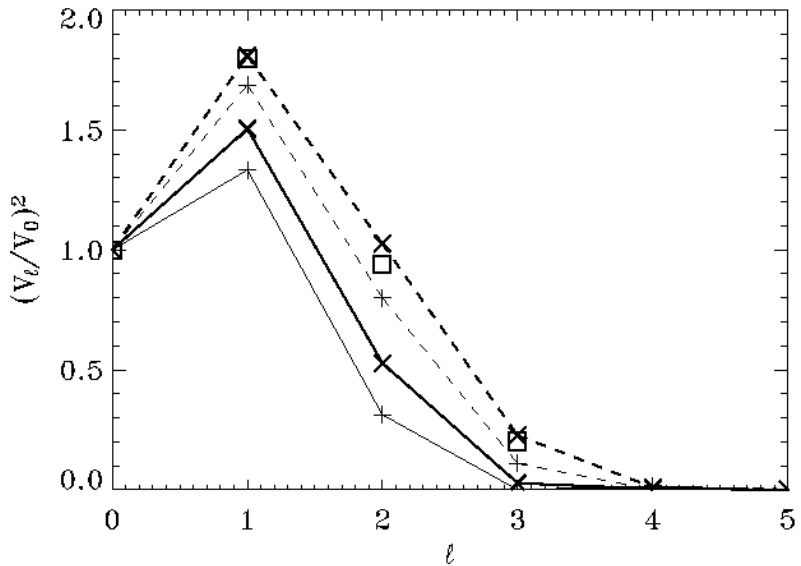



GB19

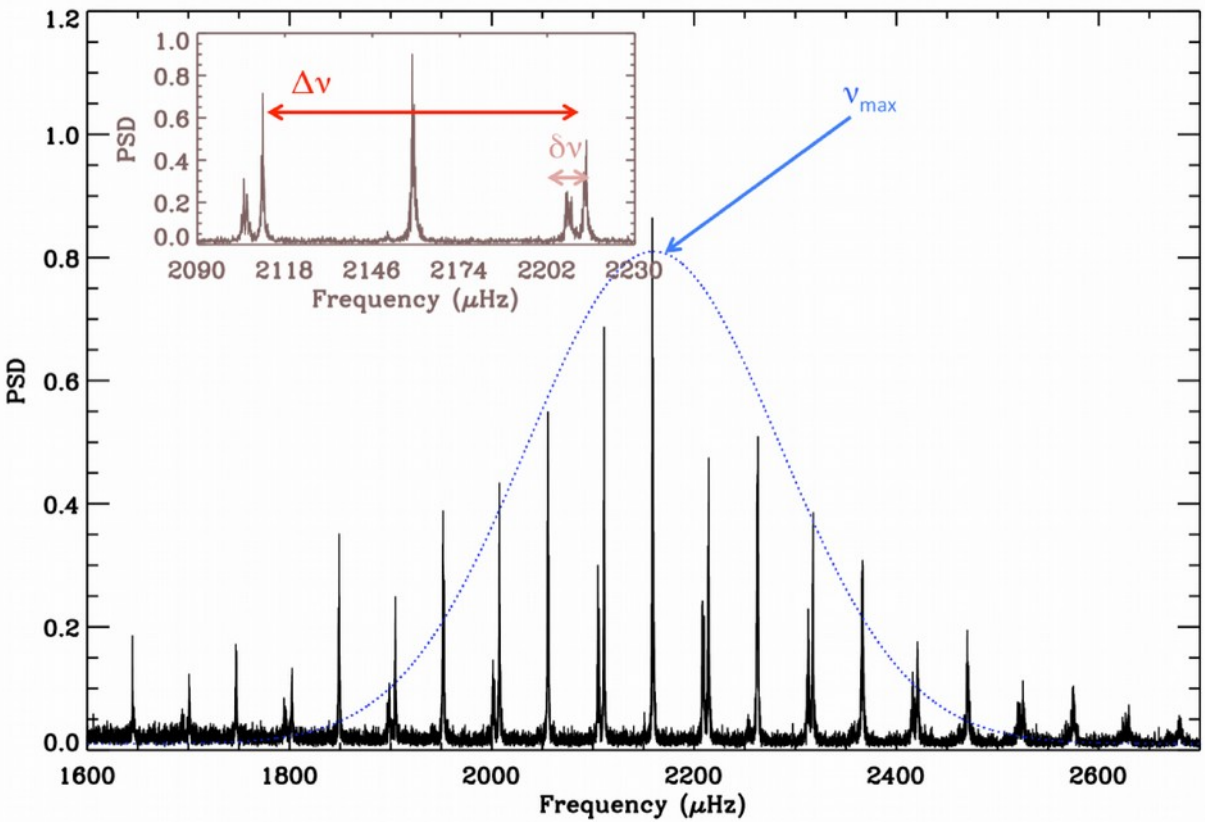
# Low-degree modes

- **Modes defined by 3 quantum numbers: n,l,m**
  - Integrated flux → only low degree (l) are observed (≠ *the Sun*)



# Structure of a Spectrum




- **Asymptotic expression**
  - $\nu_{nl}=\Delta\nu(n+l/2+\varepsilon)$ [Tassoul 80]
- **Comb structure**
  - Large separation Δν
- **Stochastic excitation**
  - Bell-shape amplitude envelope
  - Centred around $\nu_{max}$

16 Cyg A
Garcia 15

# Relation for $\nu_{max}$

- **$\nu_{max}$ driven by the properties of surface convection**
- **$\nu_{max} \propto \nu_c$ (cut-off frequency)** [Belkacem et al. 2011, 2013]

$$\nu_{max} \propto \frac{c_s}{4\pi H_p} \propto \left(\frac{p}{\rho}\right)^{1/2} \frac{g\rho}{p}$$

$$\nu_{max} \propto g T_{\rm eff}^{-1/2}$$

$$\boxed{\nu_{max} \propto M R^{-2} T_{\rm eff}^{-1/2}}$$

# Relation for Δν

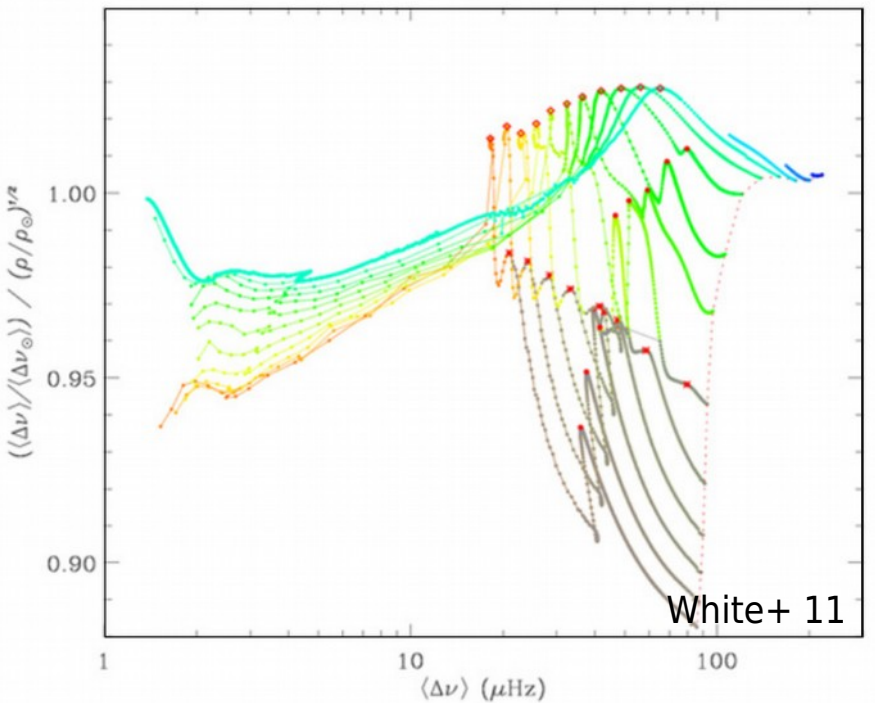
- **According to asymptotic development**

$$\Delta\nu \approx \left(2\int \frac{dr}{c}\right)^{-1}$$

- **Free-fall frequency** $\nu_0 \approx < G\rho >^{1/2}$
- **For 2 homologous stars, one shows**

$$\frac{\Delta\nu}{\Delta\nu'} \propto \nu_0/\nu_0'$$

$$\boxed{\Delta\nu \propto M^{1/2}R^{-3/2}}$$




Stars are not homologous, but law verified <5%

# Seismic Masses and Radii

- **Radius**

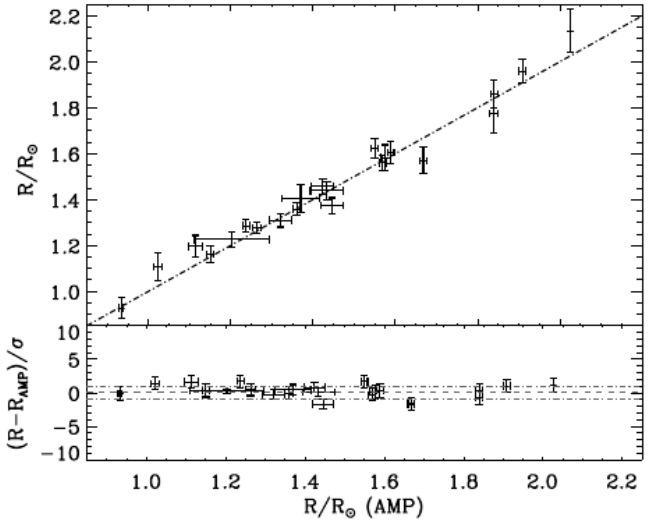
$$\frac{R}{R_\odot} = \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_\odot}\right)^{1/2}$$

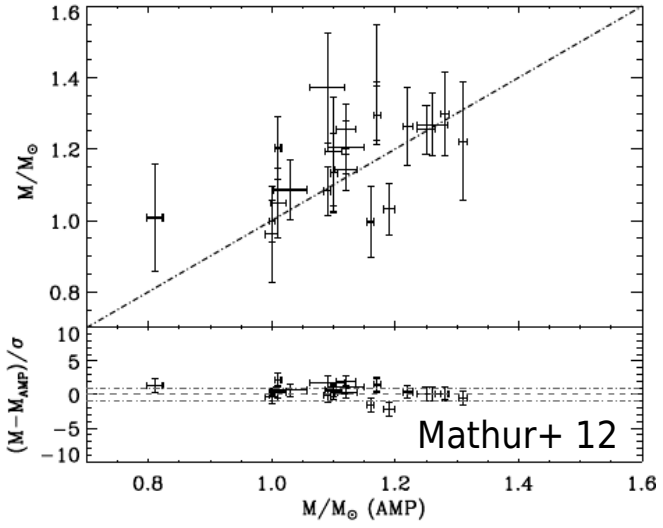
- **Mass**

$$\frac{M}{M_\odot} = \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)^{3} \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{\rm eff}}{T_\odot}\right)^{3/2}$$

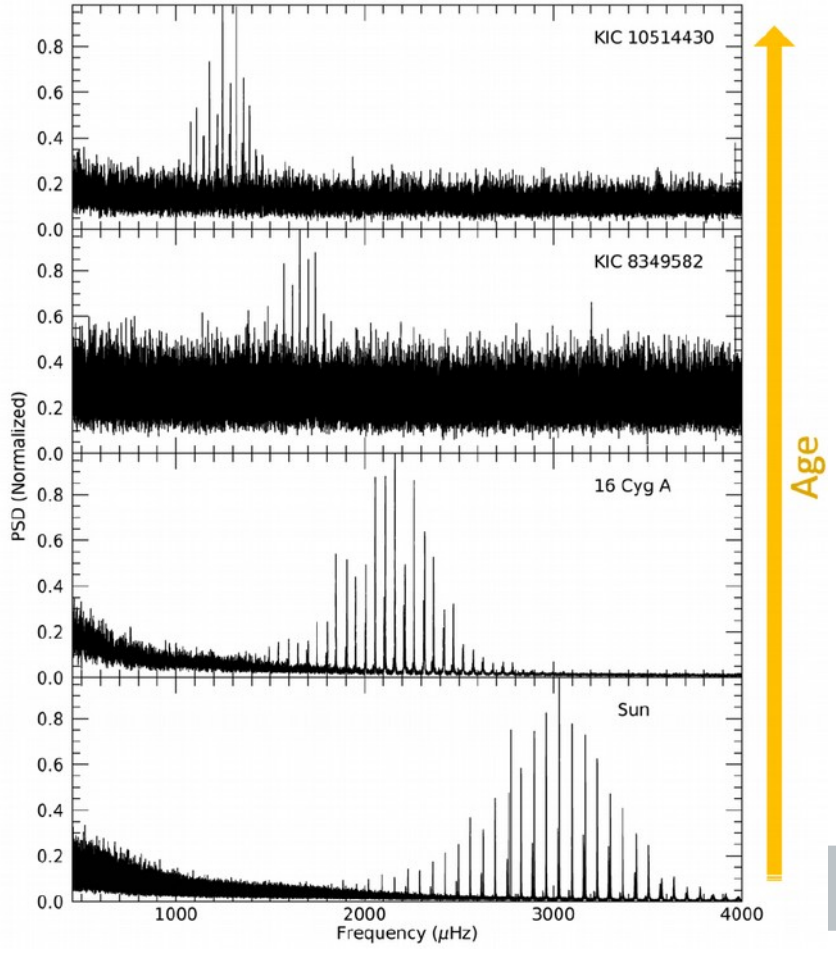
  - Reference “Sun” = a collection of stars

- $\Delta\nu \propto M^{-1/4}\, T_{\rm eff}^{3/8}\, \nu_{\rm max}^{3/4}$



# Sequence of solar analogs

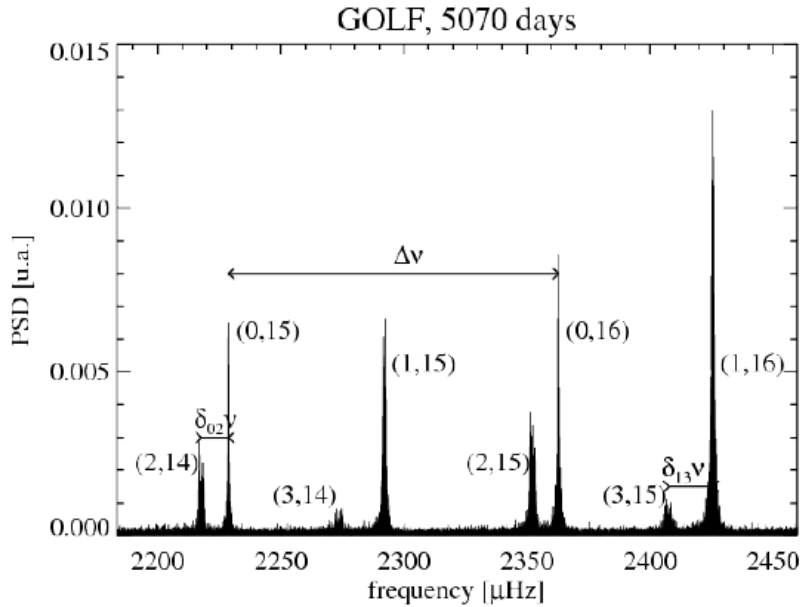


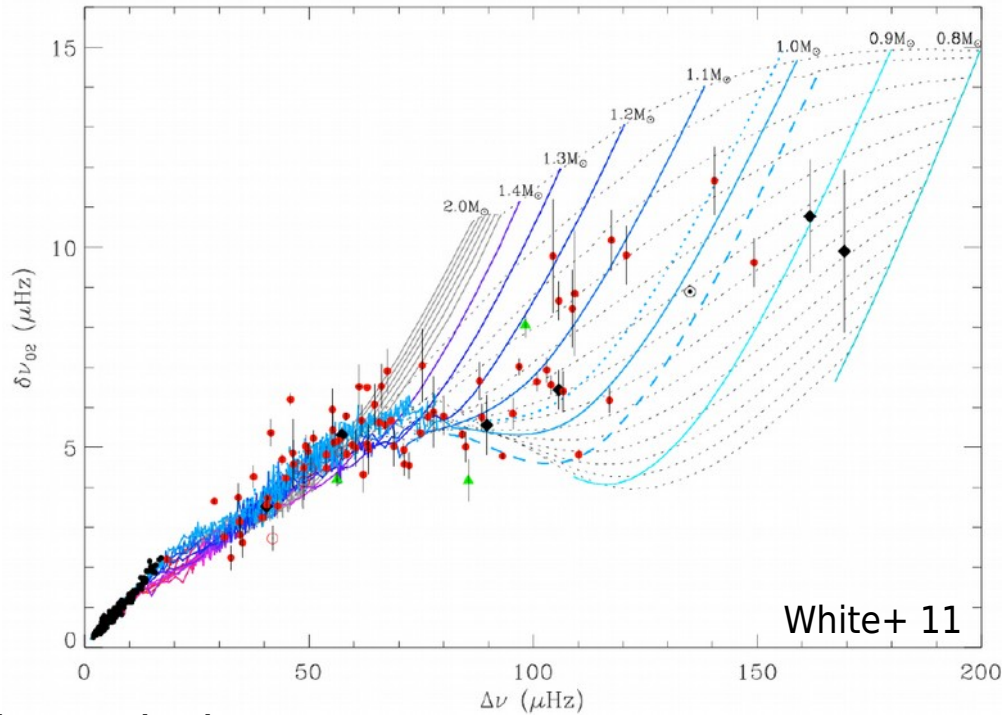

BG19

- **Building evolutive sequence of a star from a collection of stars.**
- **Example of solar analogs:**
  - the Sun (SoHO/VIRGO/SPM)
  - 16 Cyg A (1.011 ± 0.02 $M_{\odot}$)
  - KIC 8349582 (1.068 ± 0.02 $M_{\odot}$)
  - KIC 10514430 (1.059 ± 0.04 $M_{\odot}$)

  [Metcalfe+12; Silva Aguirre+ 2015]

# Finer structure: small separations

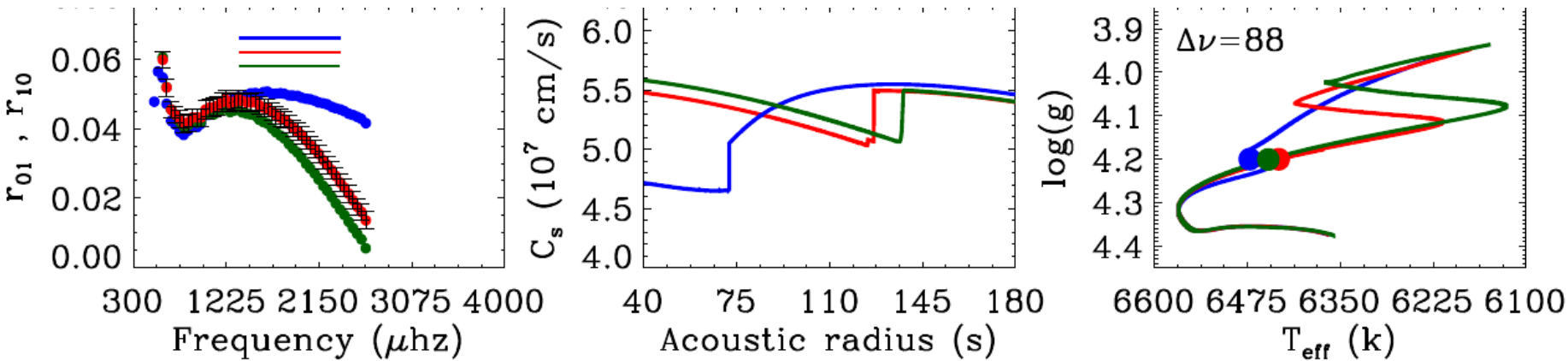



Small separations sensitive to core, ie evolutionary stages
Accurate age → detailed modelling required

# Size of convective core

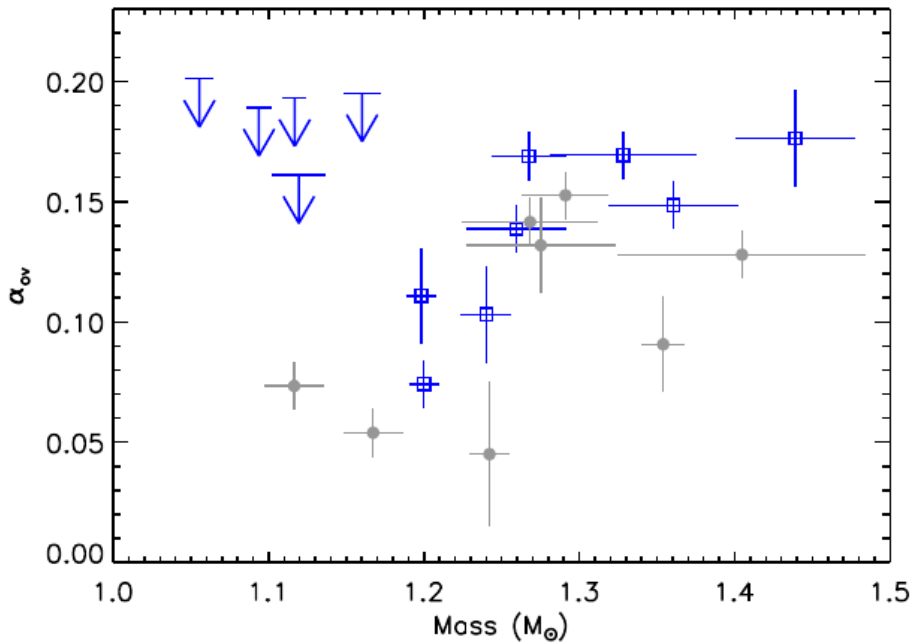
- **Convective core in solar-like stars (M>1.2$M_\odot$)**
  - The Sun cannot be used
  - Extent of the mixed region? → impact on lifetime on MS




Silva Aguirre+ 11

# Size of convective core

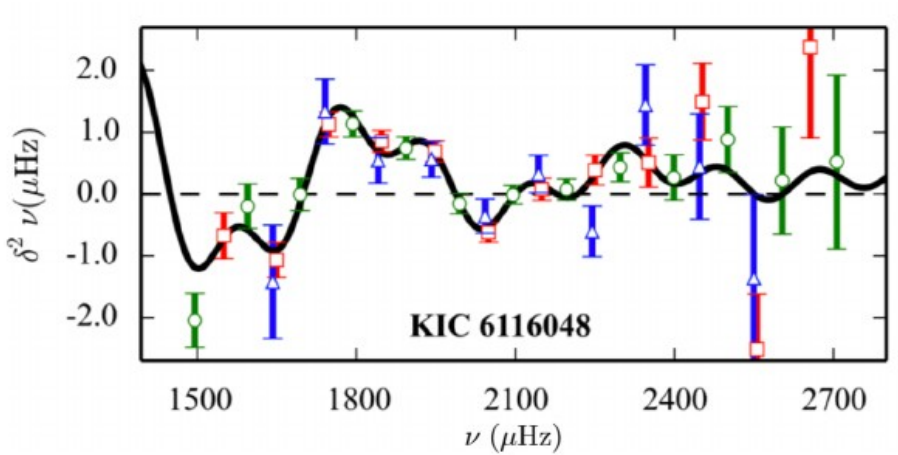
- **Constraints on overshoot parameter**
  - Mass dependency

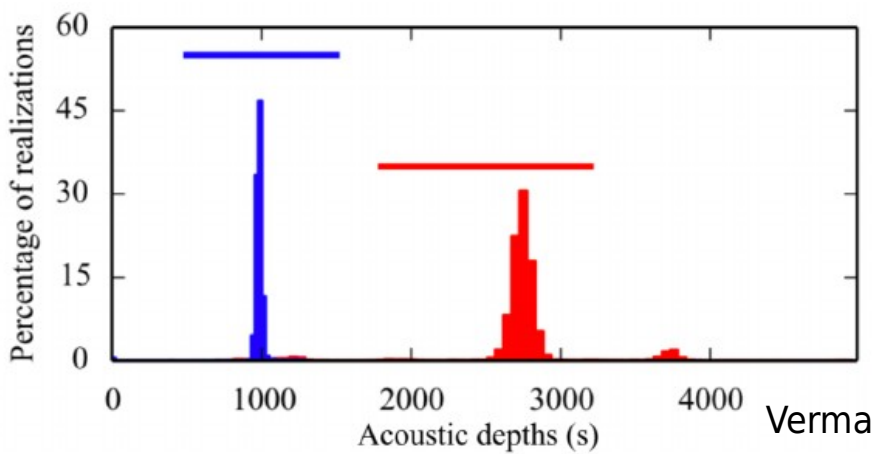



Deheuvels+ 16

# Convective envelope

- **Sun**
  - depth of convective envelope well defined by sound-speed inversion
- **For other stars: “glitches” in low-*l* modes**
  - Depth of CE + constraints on He abundances

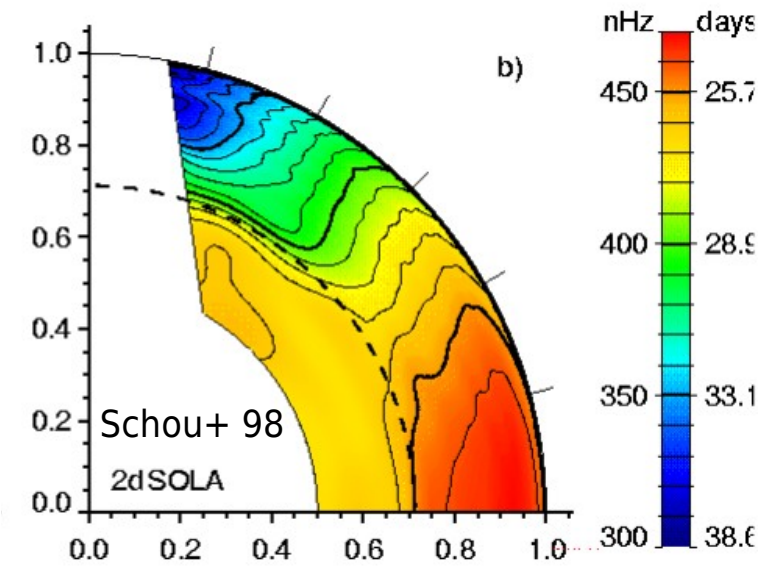


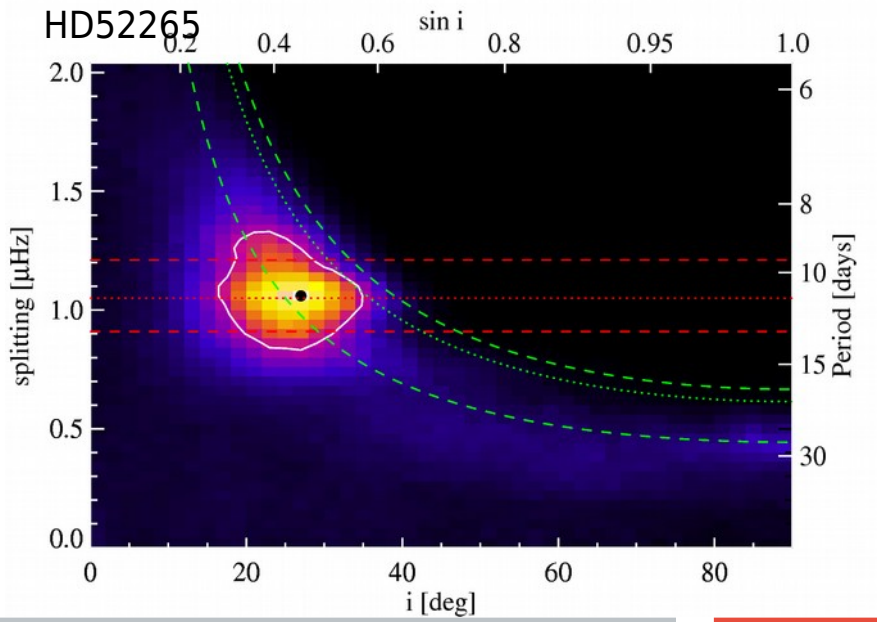




Verma+ 17

# Rotation

- **Sun= detailed inversion**
- **other MS solar-like stars: usually mean rotation in CE + inclination *i***



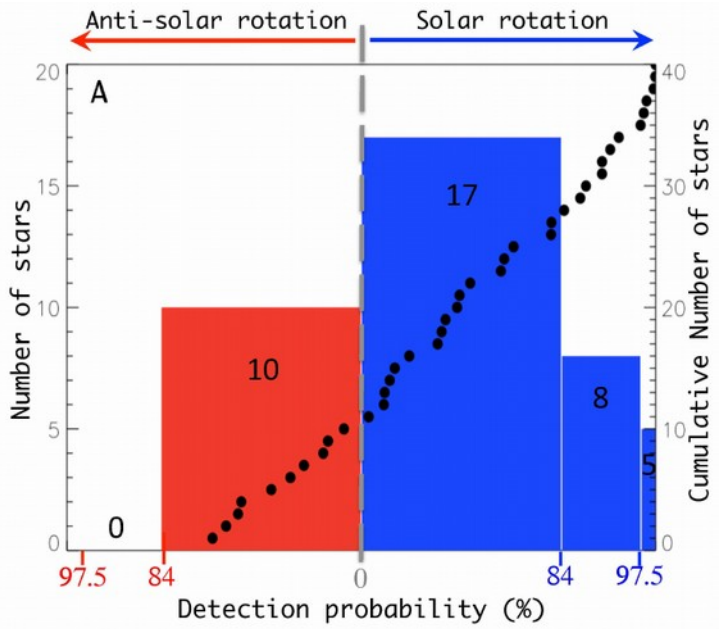




Spots: Ω

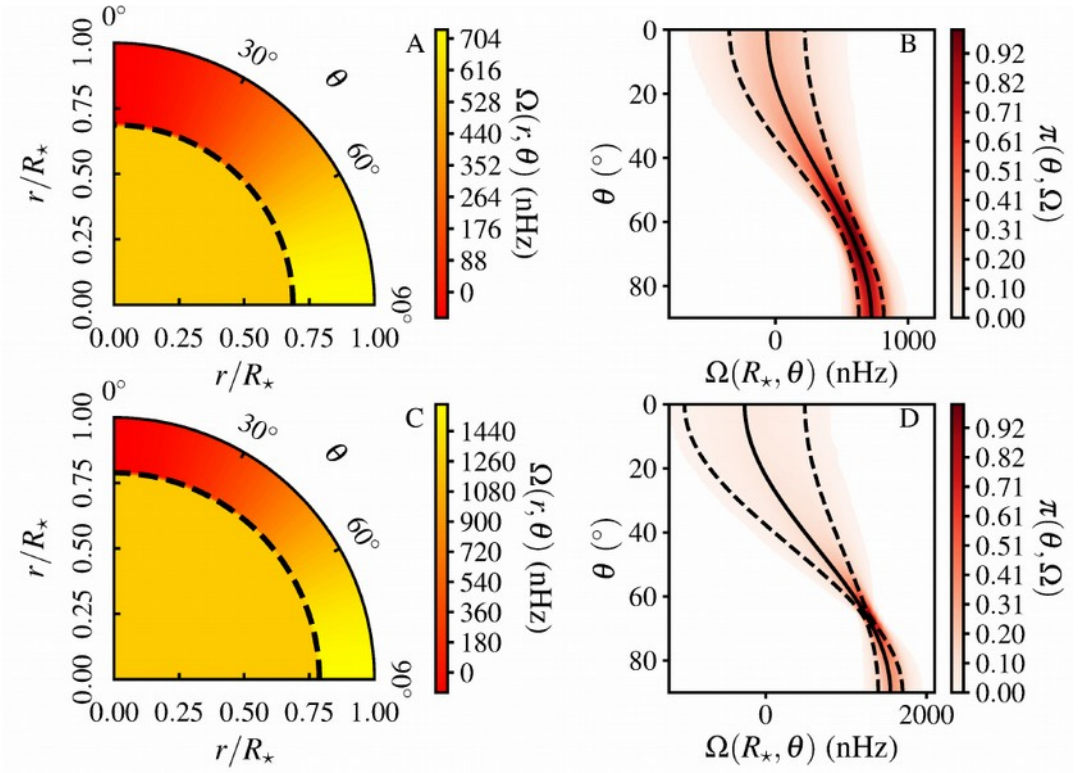
Spectro → (vsin*i*)
Seismo → R
→ Ω sin*i*

# Differential rotation

- **A few measurements with *l*=2**

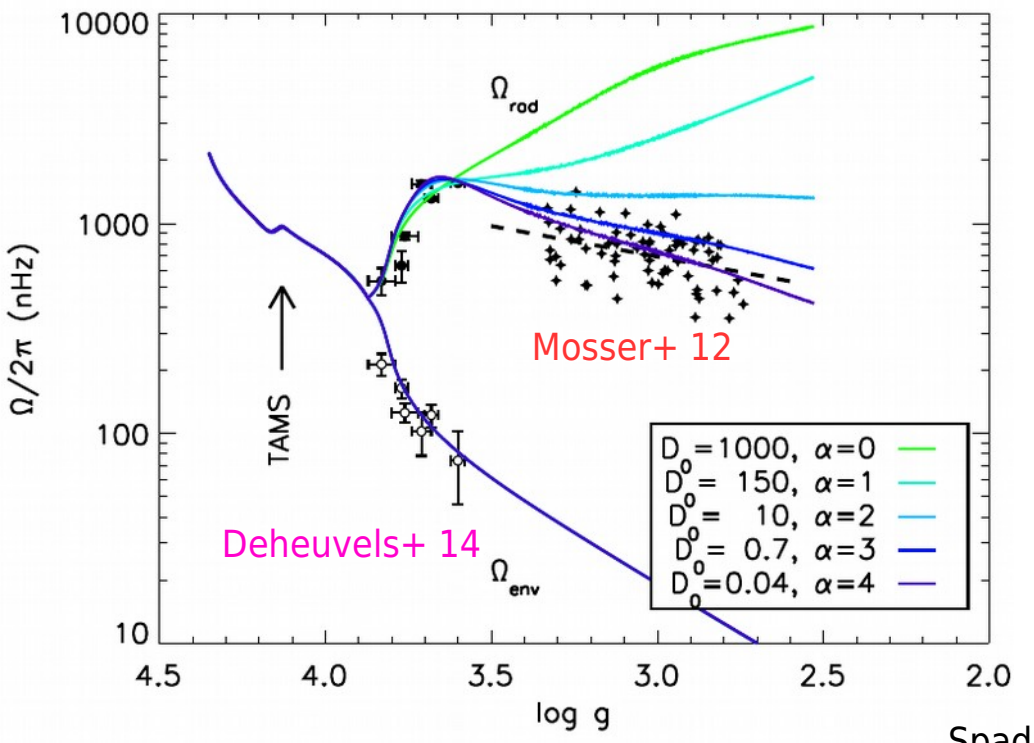



Benomar+ 18



# Core rotation from mixed modes

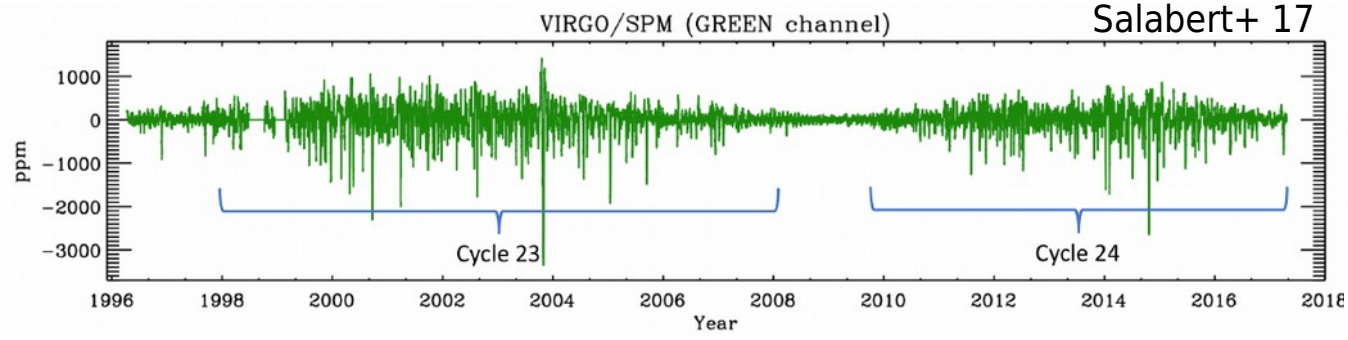
- **Subgiants: C+E**
  - Deheuvels+ 14
- **Giants: core**
  - Mosser+ 12, Gehan 18



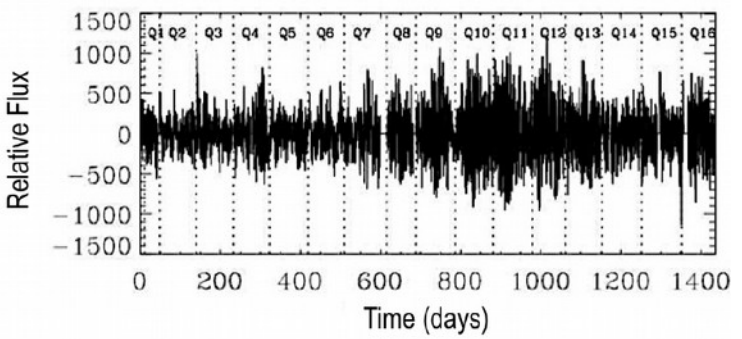

Spada+ 16

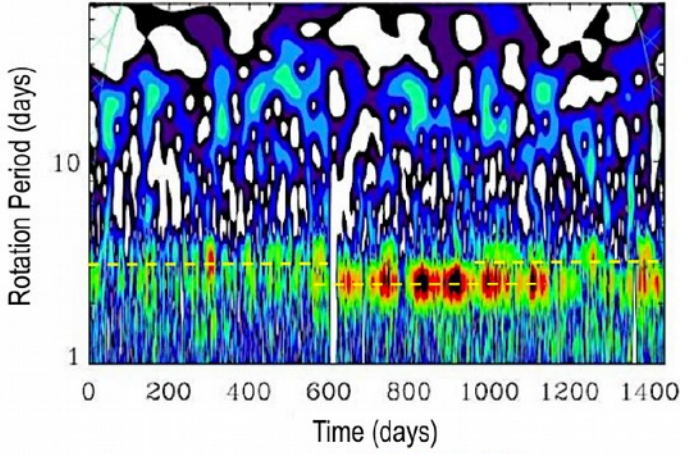
# Activity

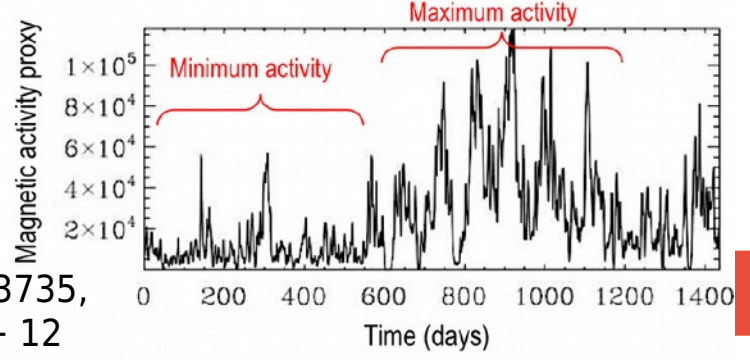
- **From photometry**
  - Light curve → $S_{ph}$




- **Warning**
  - Beating between close rotation frequencies (due to differential rotation) mimic activity-induced variations!



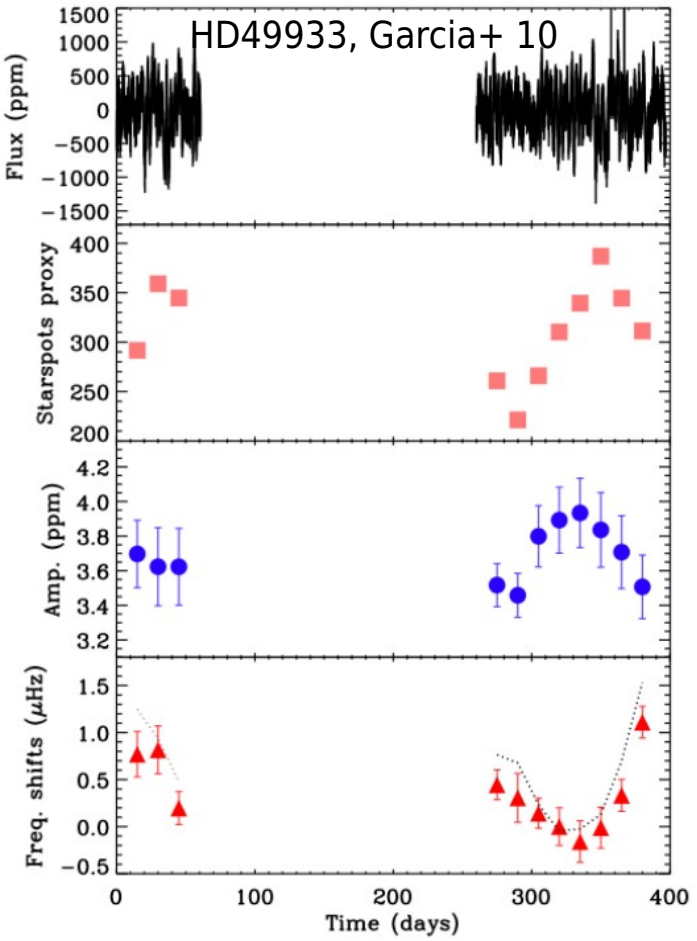



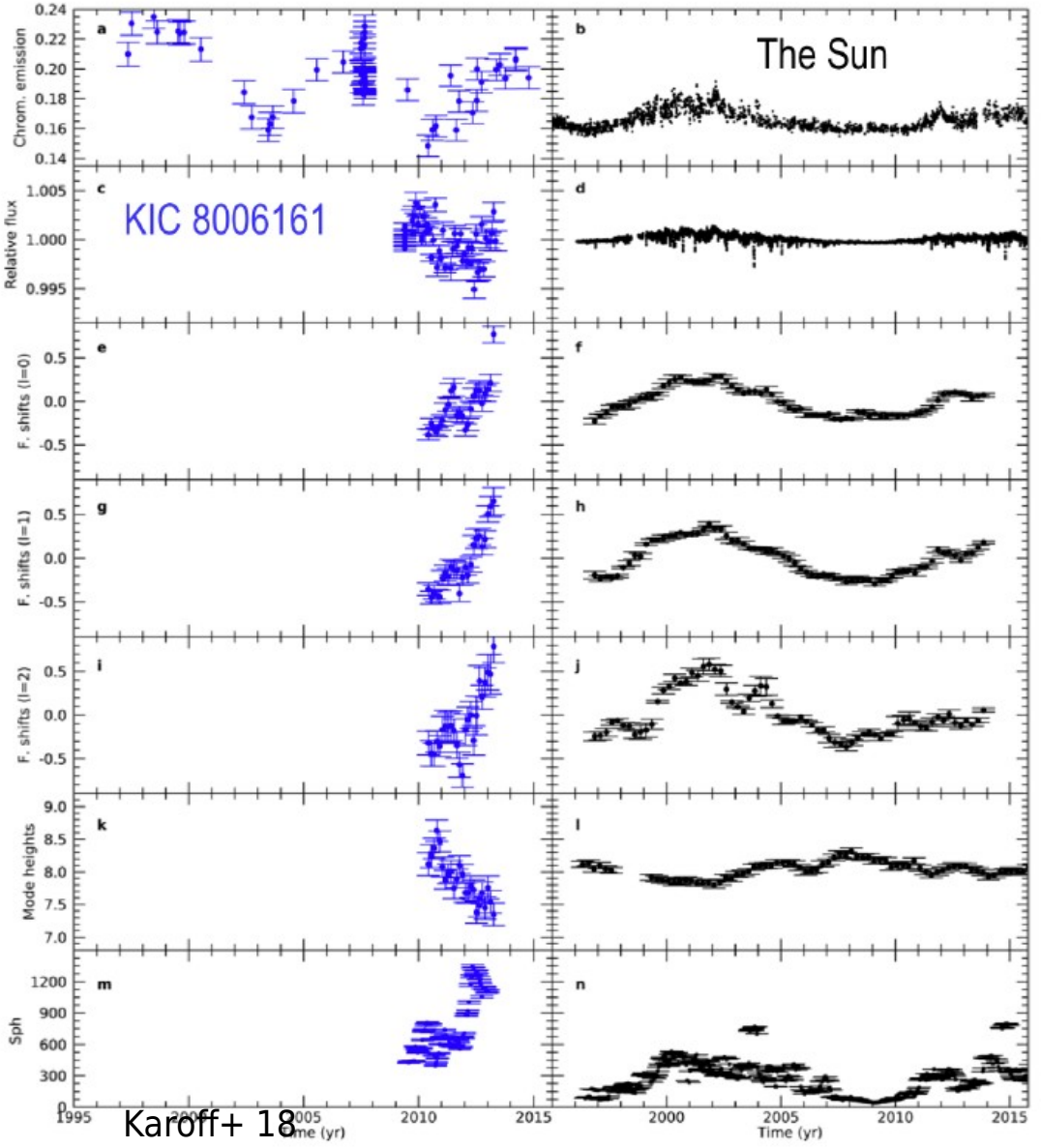




KIC 3733735, Mathur+ 12

# Activity seen with p modes

- Frequency shifts
- Damping

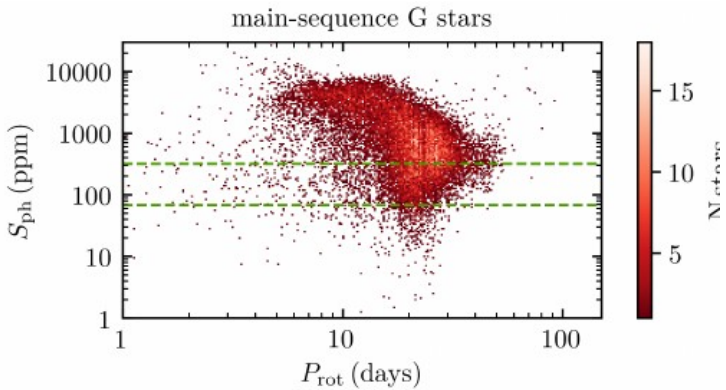


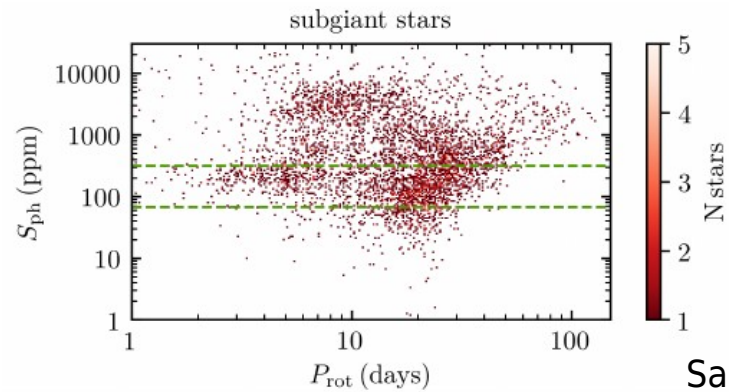



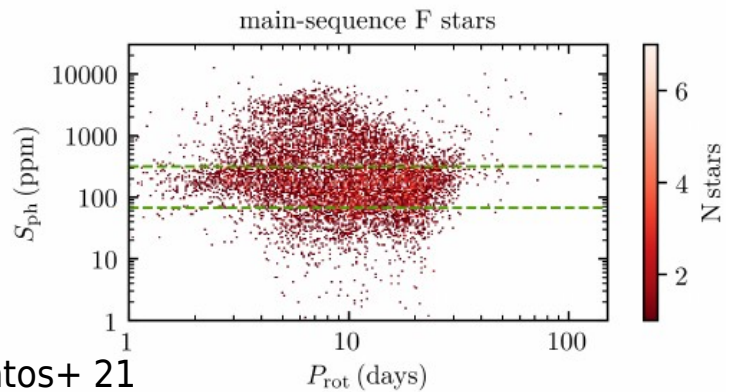

Karoff+ 18

# Rotation and activity: Ensemble analysis

- **Large sample analysis possible**
  - Activity level vs rotation
  - Example: F, K MS + subgiants




Santos+ 21

# Conclusions: seismology of solar-like stars, beyond the Sun

- **Analysis less fine than for the Sun**
  - intermediate- and high-degree modes missing
- **Sun = one point**
  - “Parameter study” possible
  - Ensemble analysis
  - Granulation, activity, rotation,...
- **Probe phenomenon that does not occur in the Sun**
  - Ex: convective core
- **Constraints from Red Giants on Main Sequence solar-type stars**