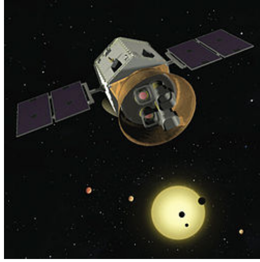
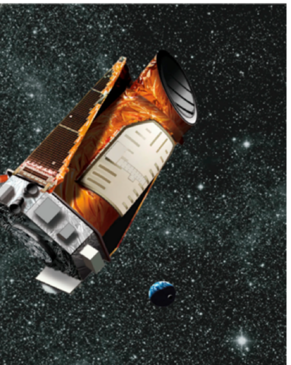


Solar-like oscillations

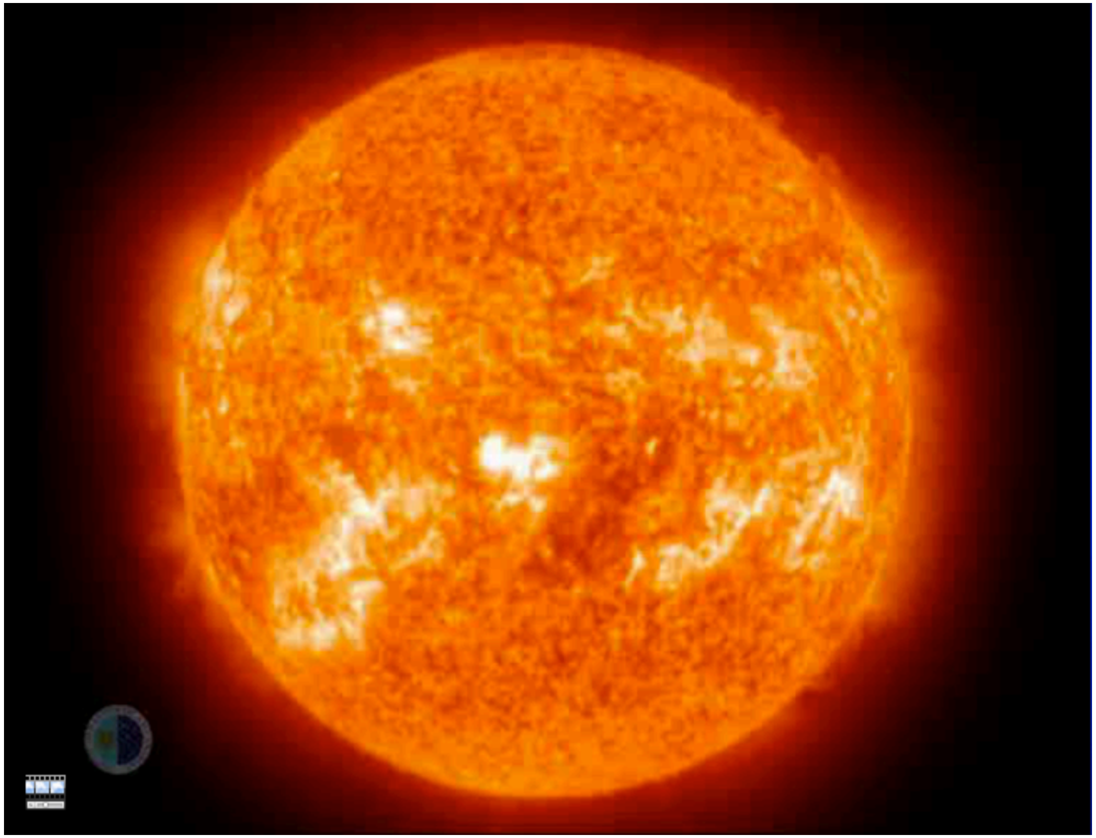
Asteroseismology: towards stellar revolution

Savita Mathur

Instituto de Astrofísica de Canarias

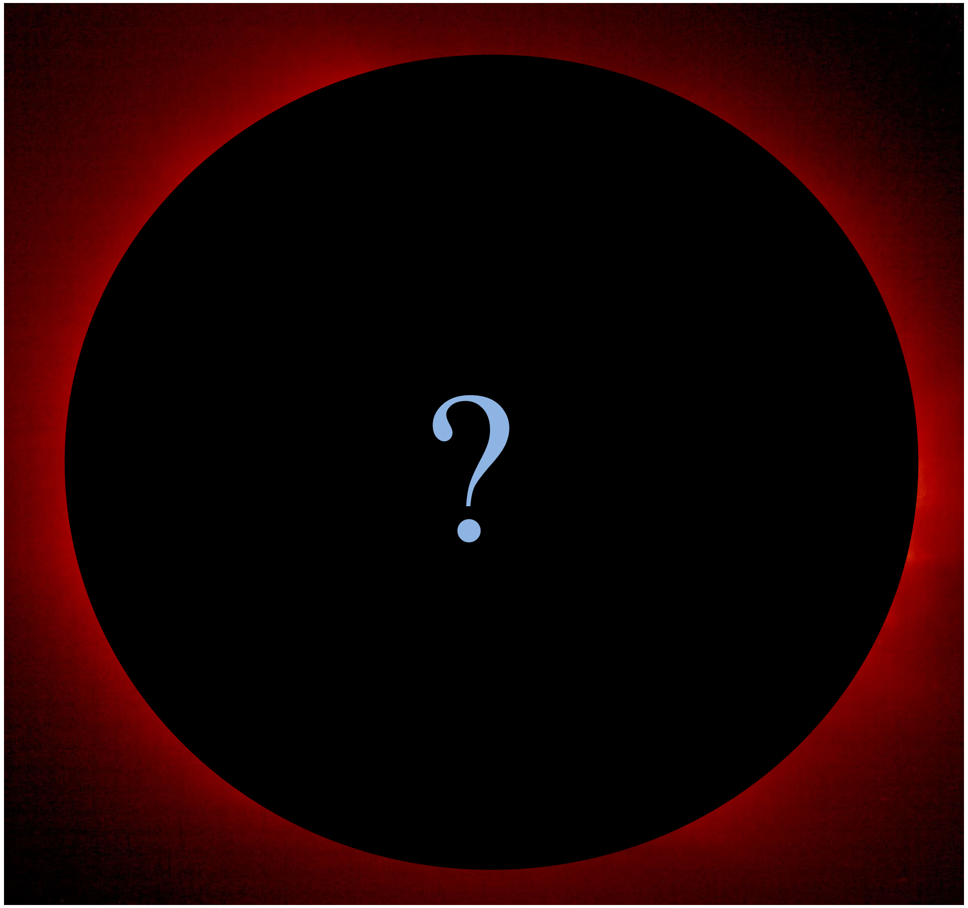


Introduction

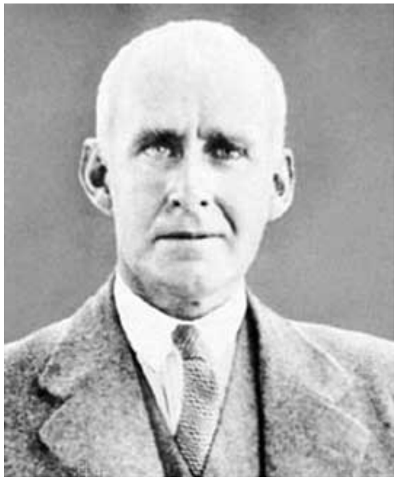


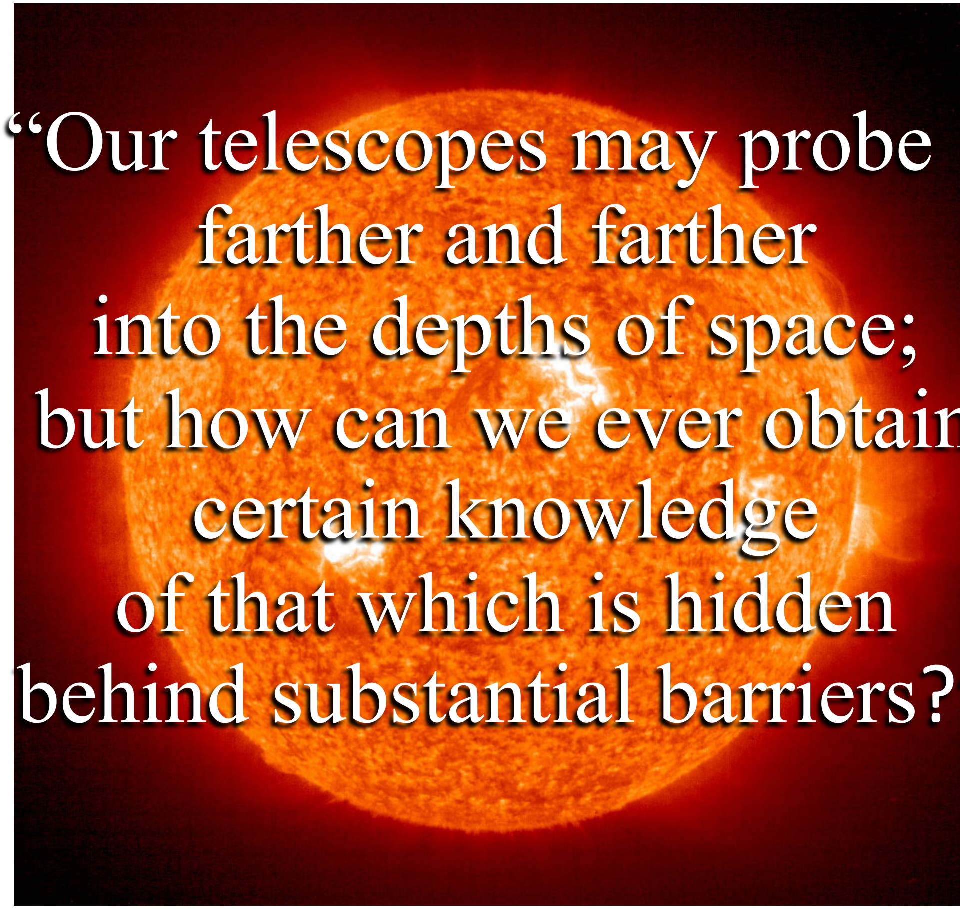
How can we study the interior of the Sun and the stars?

Introduction



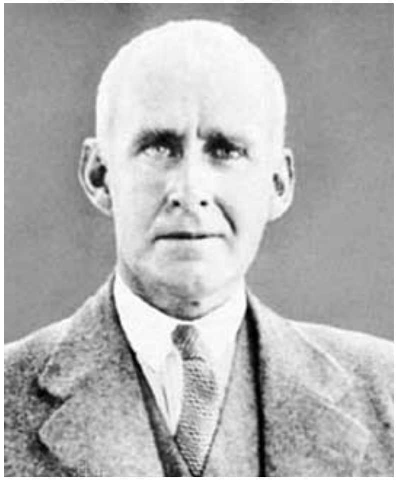
Introduction

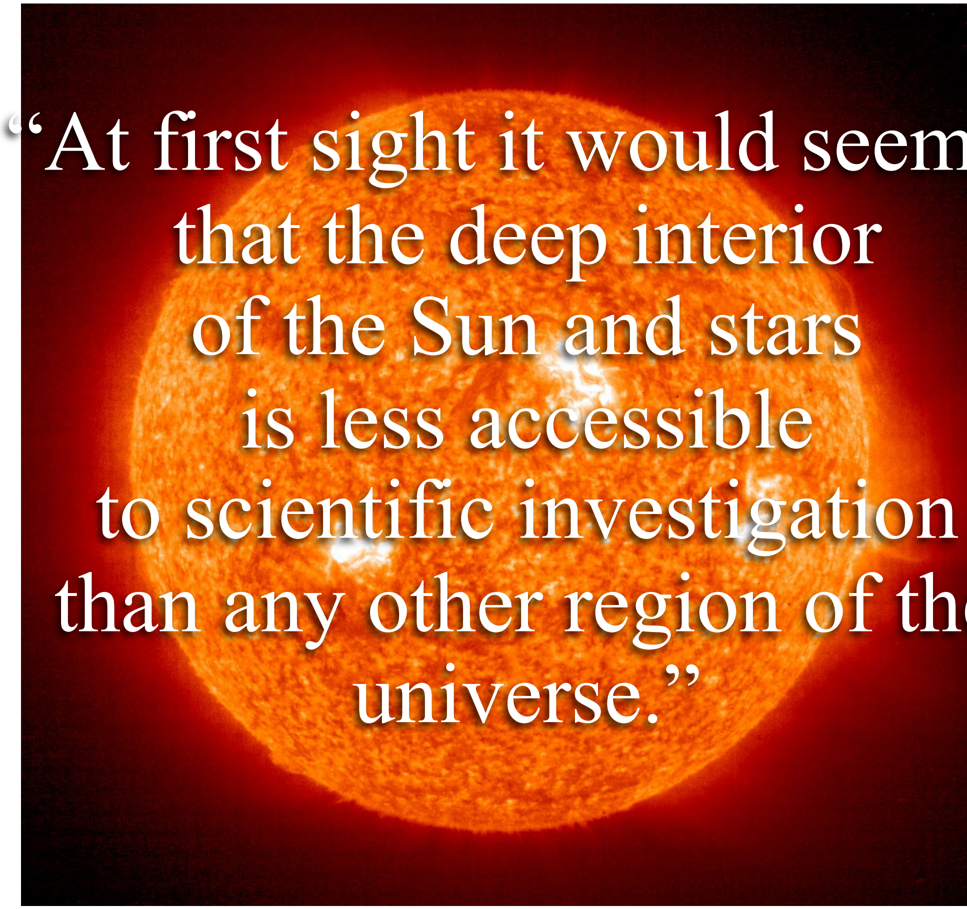




[The Internal Constitution of Stars, Eddington, 1926]

Introduction

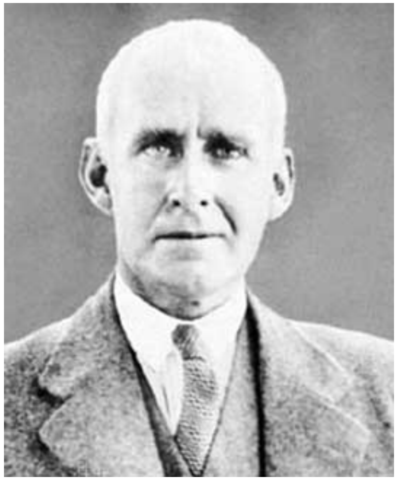




"At first sight it would seem that the deep interior of the Sun and stars is less accessible to scientific investigation than any other region of the universe."

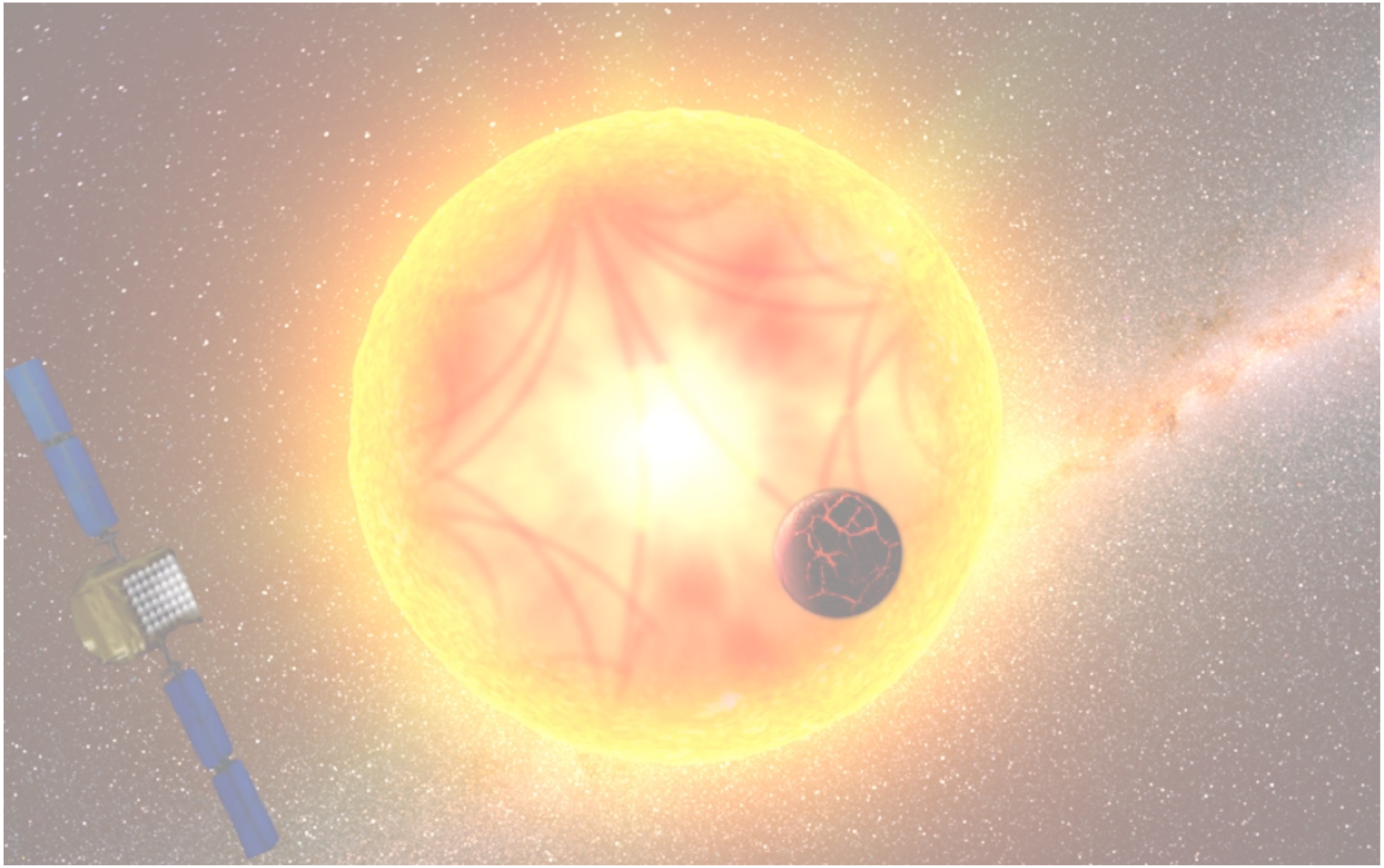
[The Internal Constitution of Stars, Eddington, 1926]

Introduction



[The Internal Constitution of Stars, Eddington, 1926]

Introduction



- Seismology : stratified information of internal structure and dynamics of stars

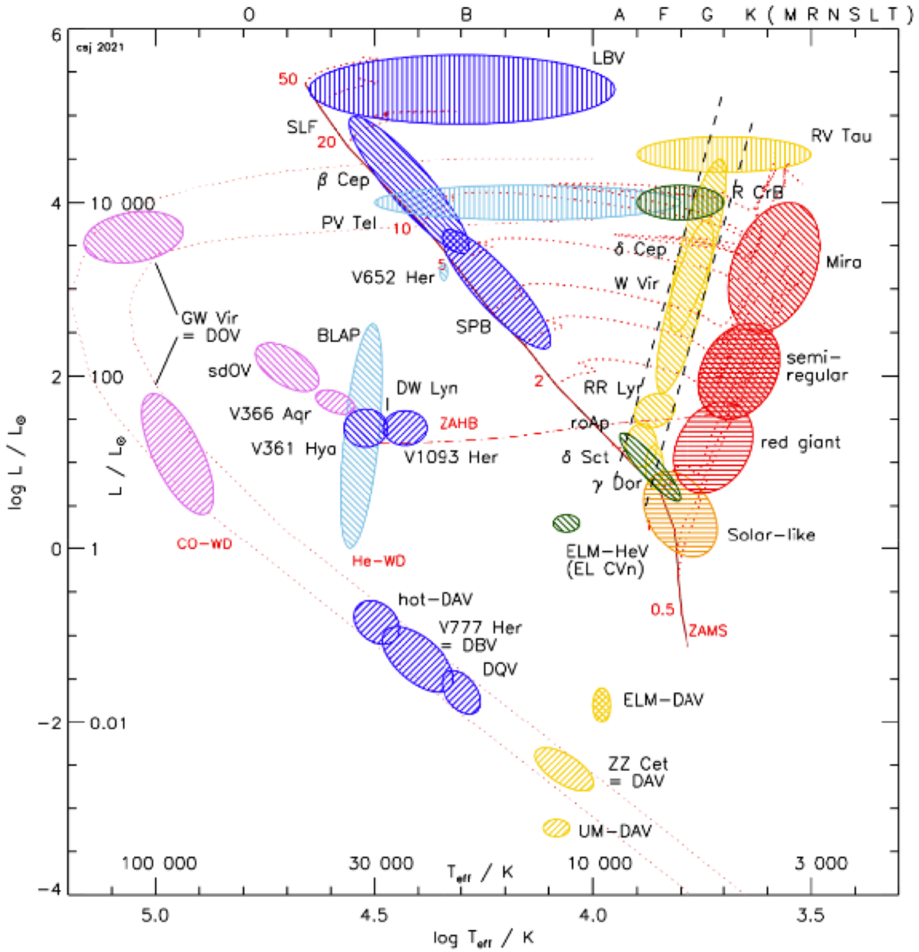
Instead of looking at stars we need to listen to them

Outline

I. Pulsations in the HRD
II. Wave propagation
   a. Theory of waves
   b. Oscillations properties
III. Asteroseismology: from the observations to the stellar parameters
IV. New discoveries with asteroseismology

Pulsations in the HR diagram

Pulsations of stars

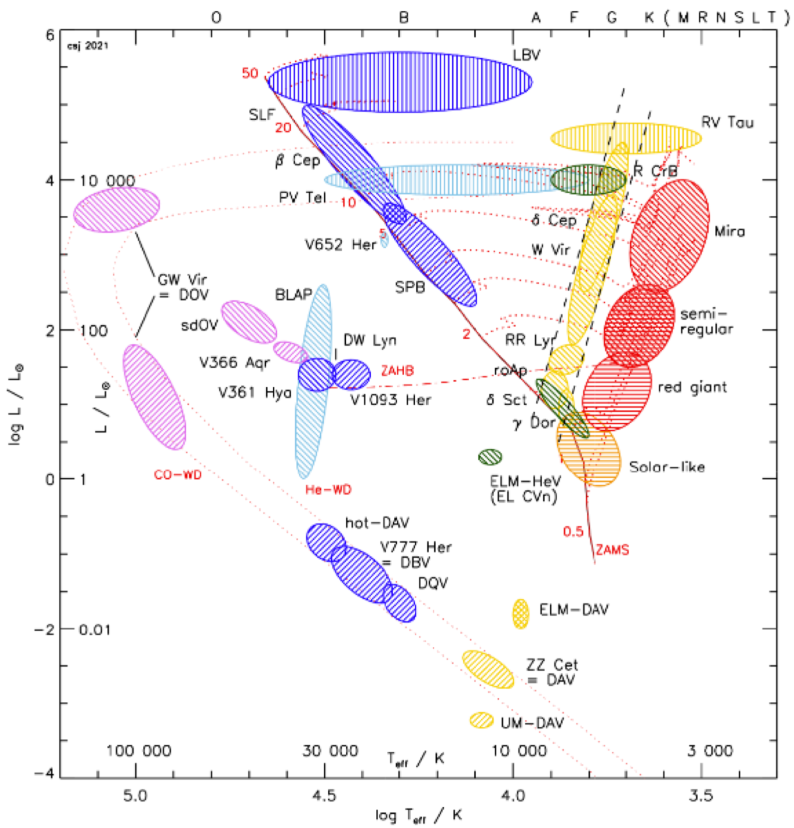


\\\ p modes
/// g modes
≡ stochastically driven modes
||| strange modes

[Kurtz 2022, ARA&A]

Different types of pulsations

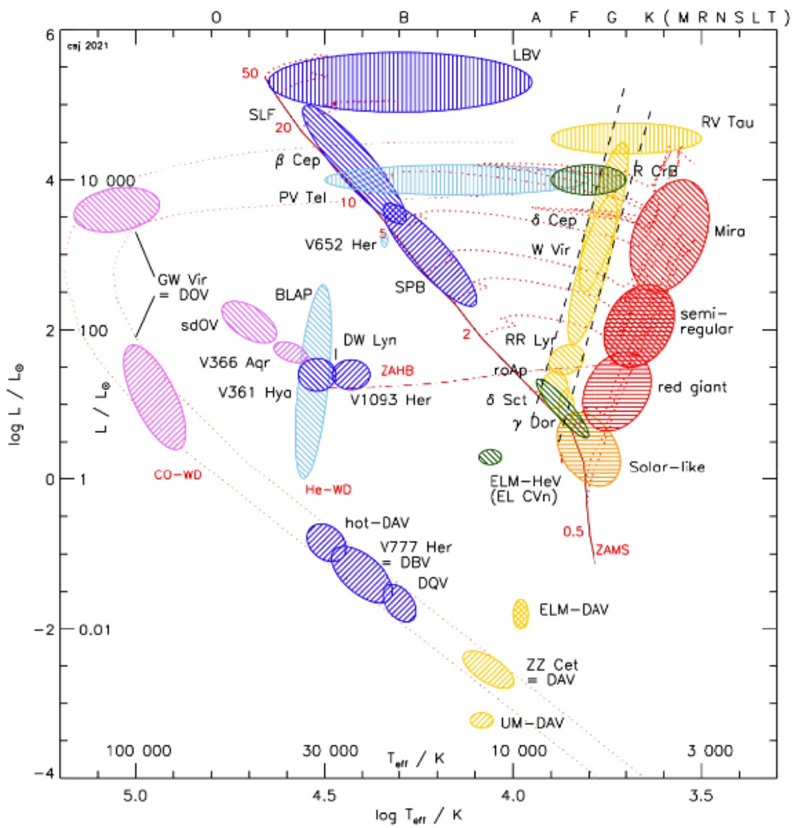
- Modes excited by:
  - K mechanism: opacity (heat engine mechanism)
    - Ceph, RR Lyr, delta Scuti: second He ionization zone
    - SPB, beta Cep: iron-group elements
    - roAp: high-order acoustic modes tied to large-scale magnetic field



Different types of pulsations

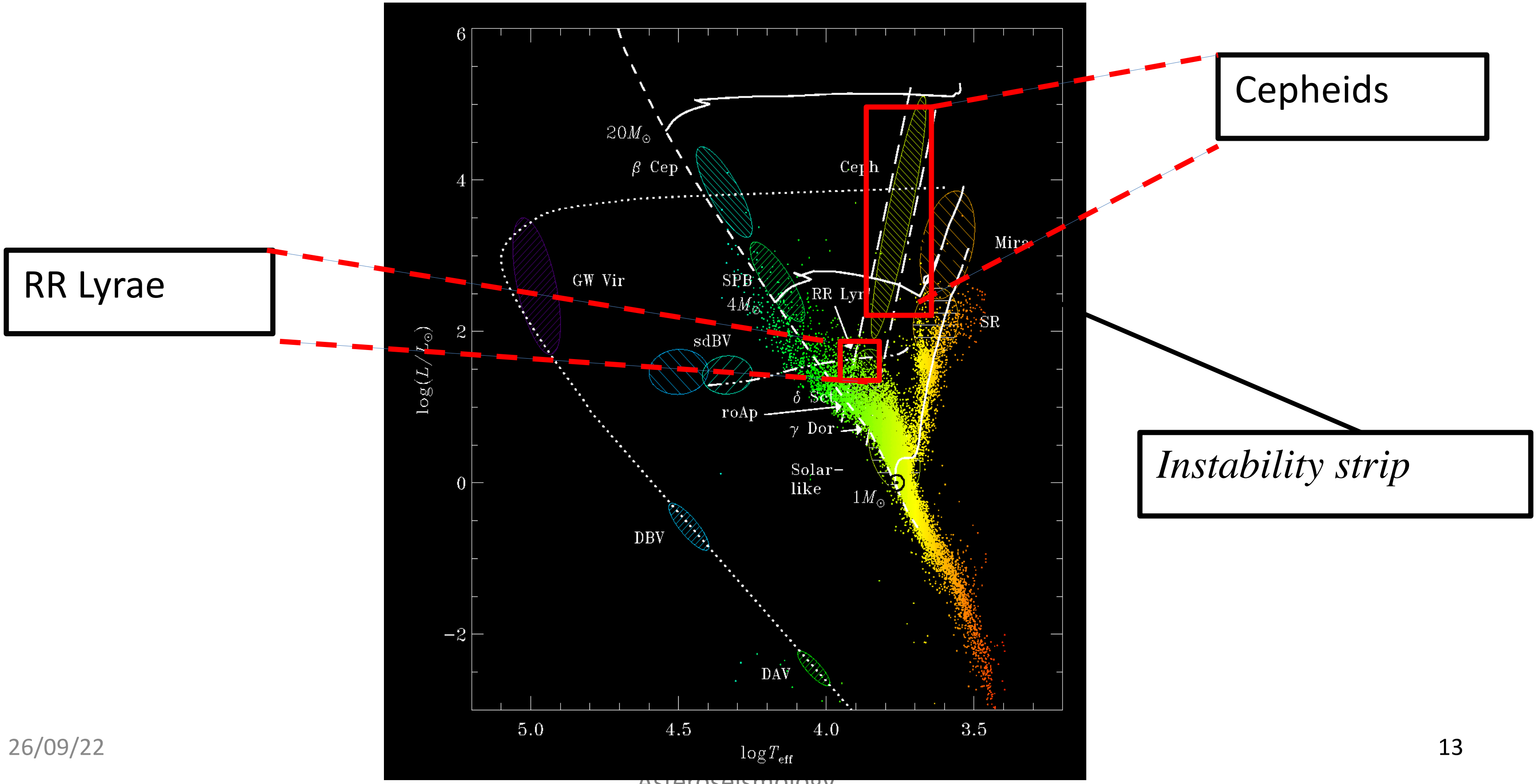
- Modes excited by:
  - K mechanism: opacity mechanisms (heat engine mechanism)

  or
  - Stochastically by convective turbulence in outer layers of the star (solar-like oscillations): 0.8-1.5$M_\odot$ from MS to RGB



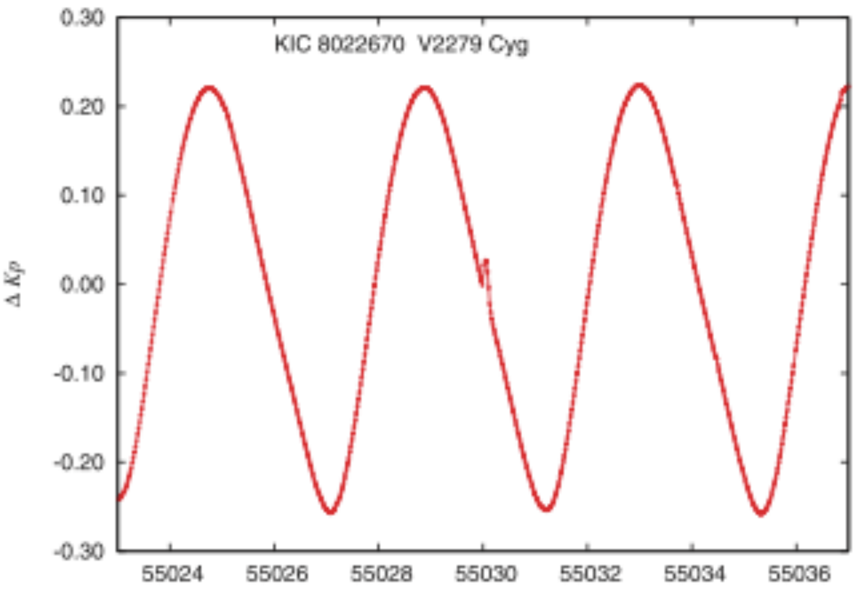
Different types of pulsations

- Variation of luminosity of stars
  - Due to intrinsic pulsations of the stars themselves
  - K mechanism: Cepheids, long period variables
  - Radial modes



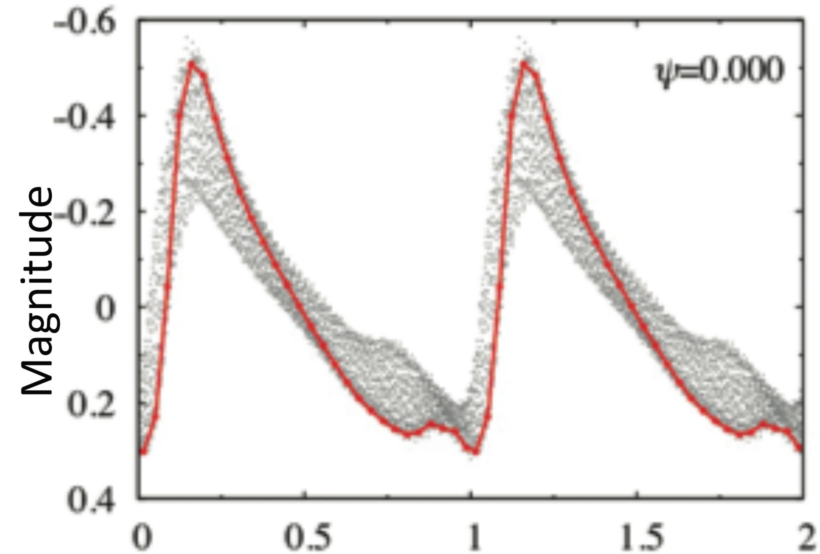
Cepheids and RR Lyrae

Cepheid



Time

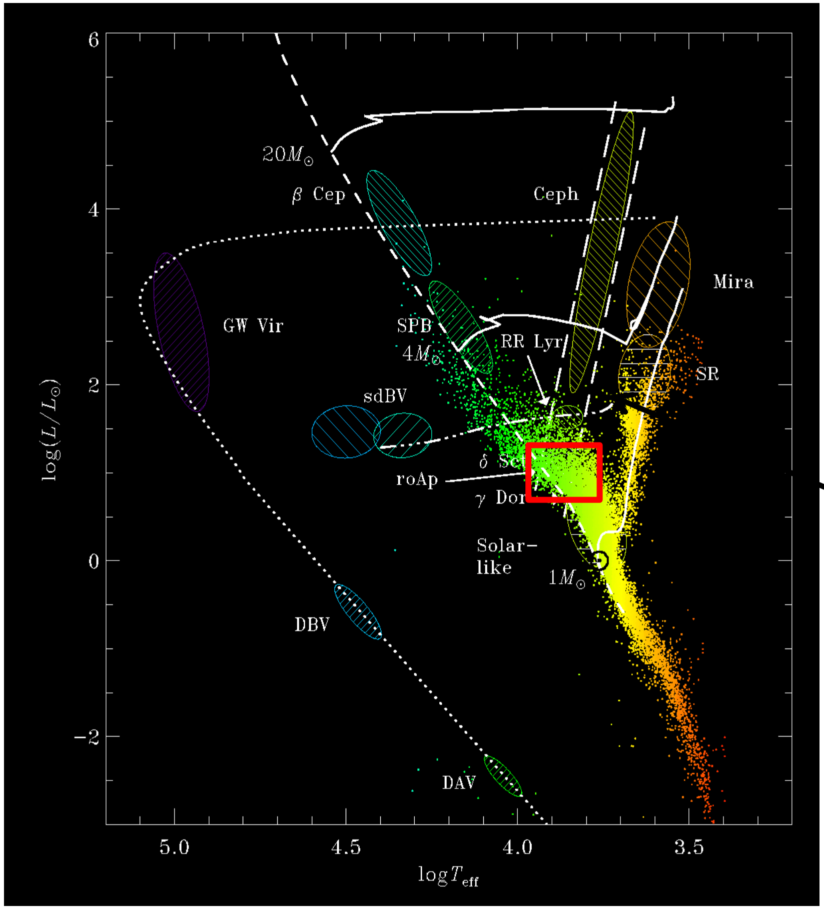
RR Lyrae



Phase

[e.g. Kolenberg et al. 2011; Szabo et al. 2014]

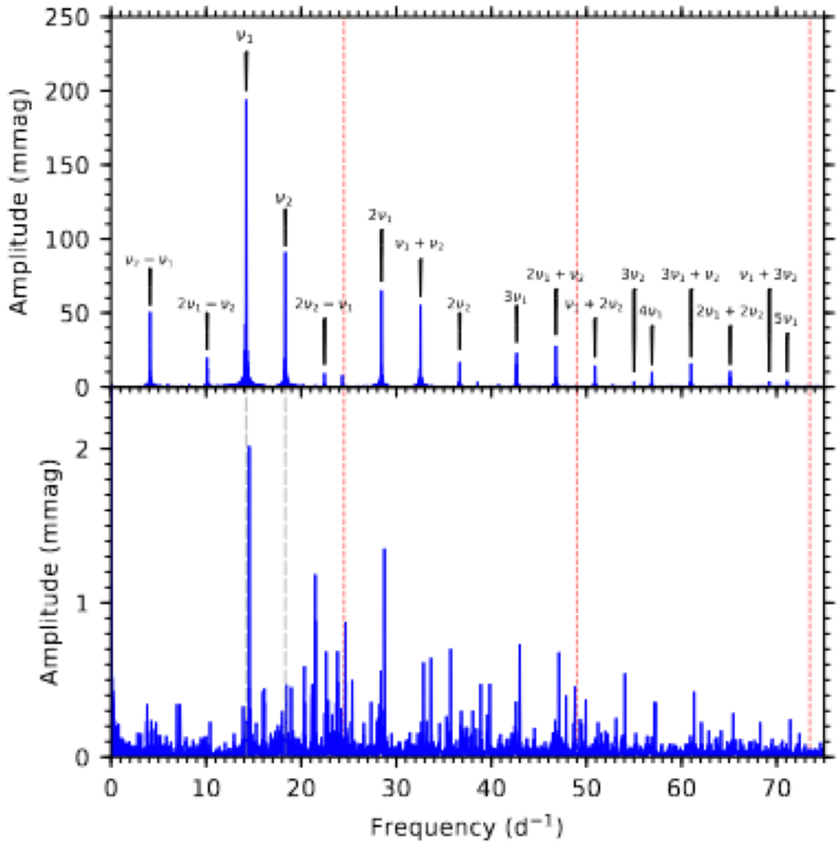
Different types of pulsations



Instability strip

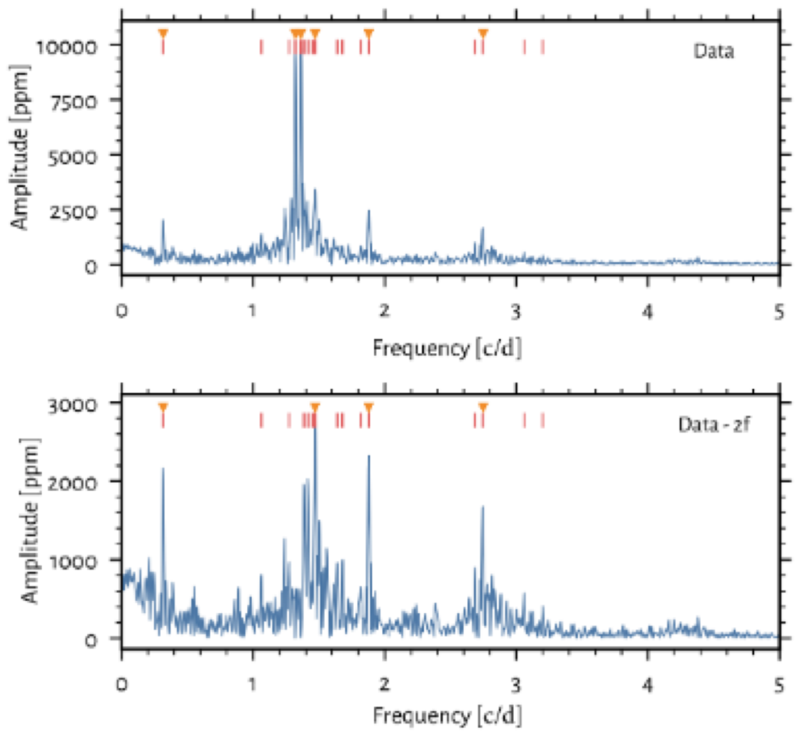
δ Scuti and γ Dor

δ Scuti



Bowman et al. 2021

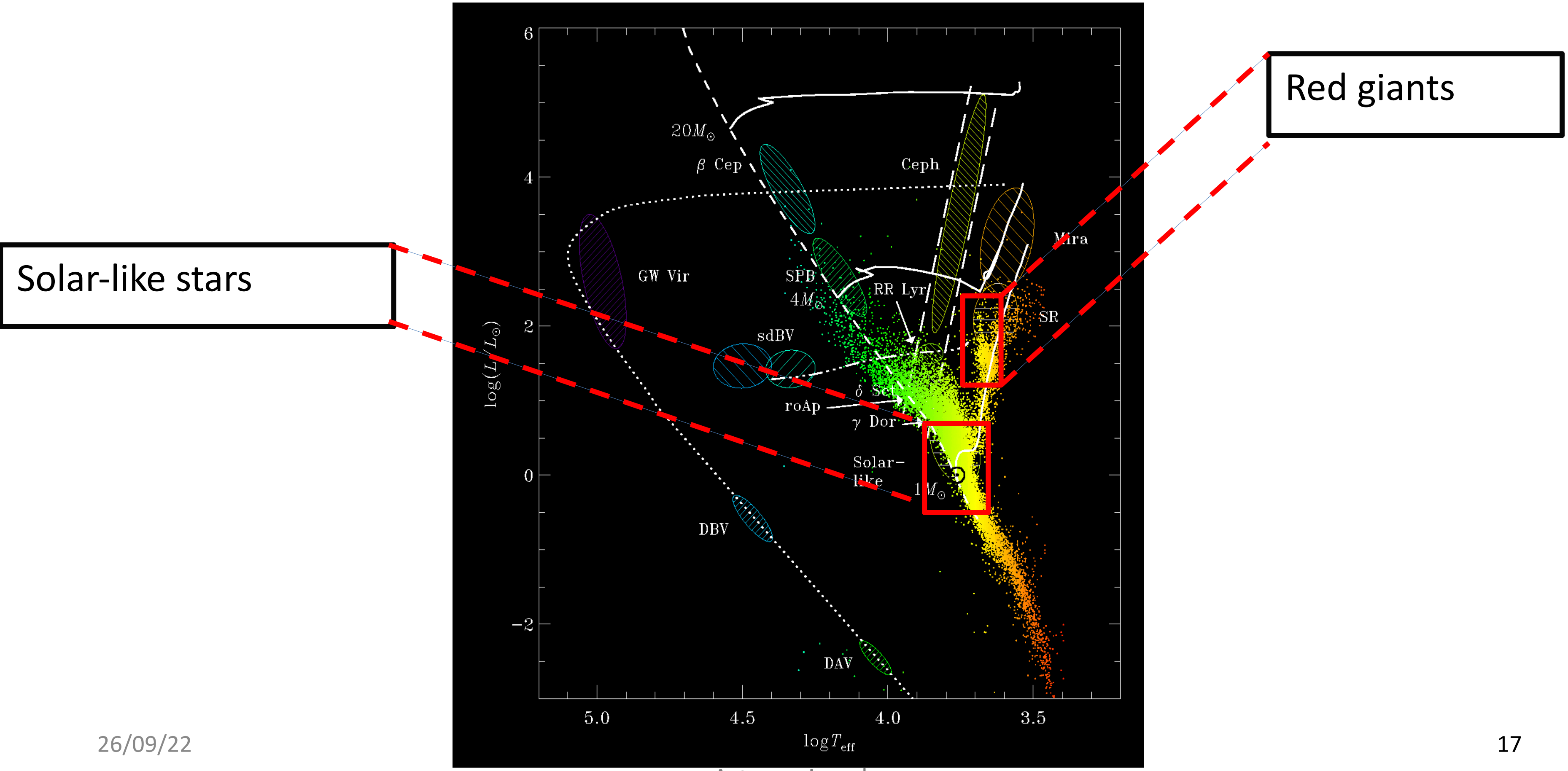
γ Dor



Antoci et al. 2021

Different types of pulsations

- Cool enough stars
  - Surface convective zone
  - E.g. Sun, red giants, lower main sequence
  - Radial and non-radial modes

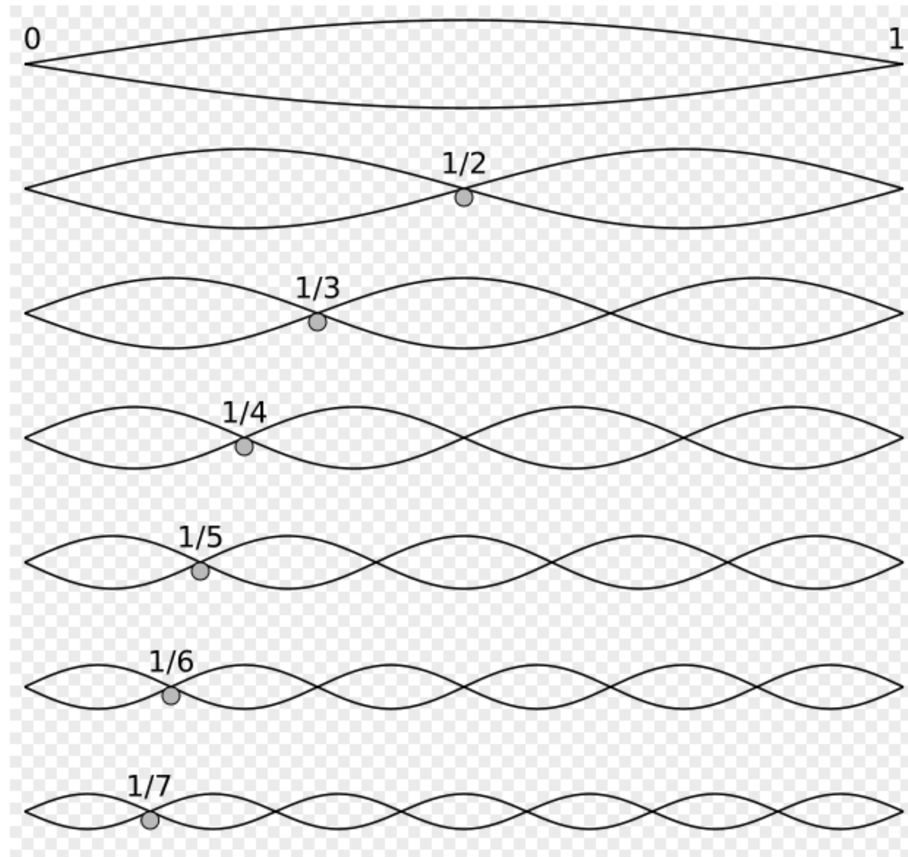


Wave propagation

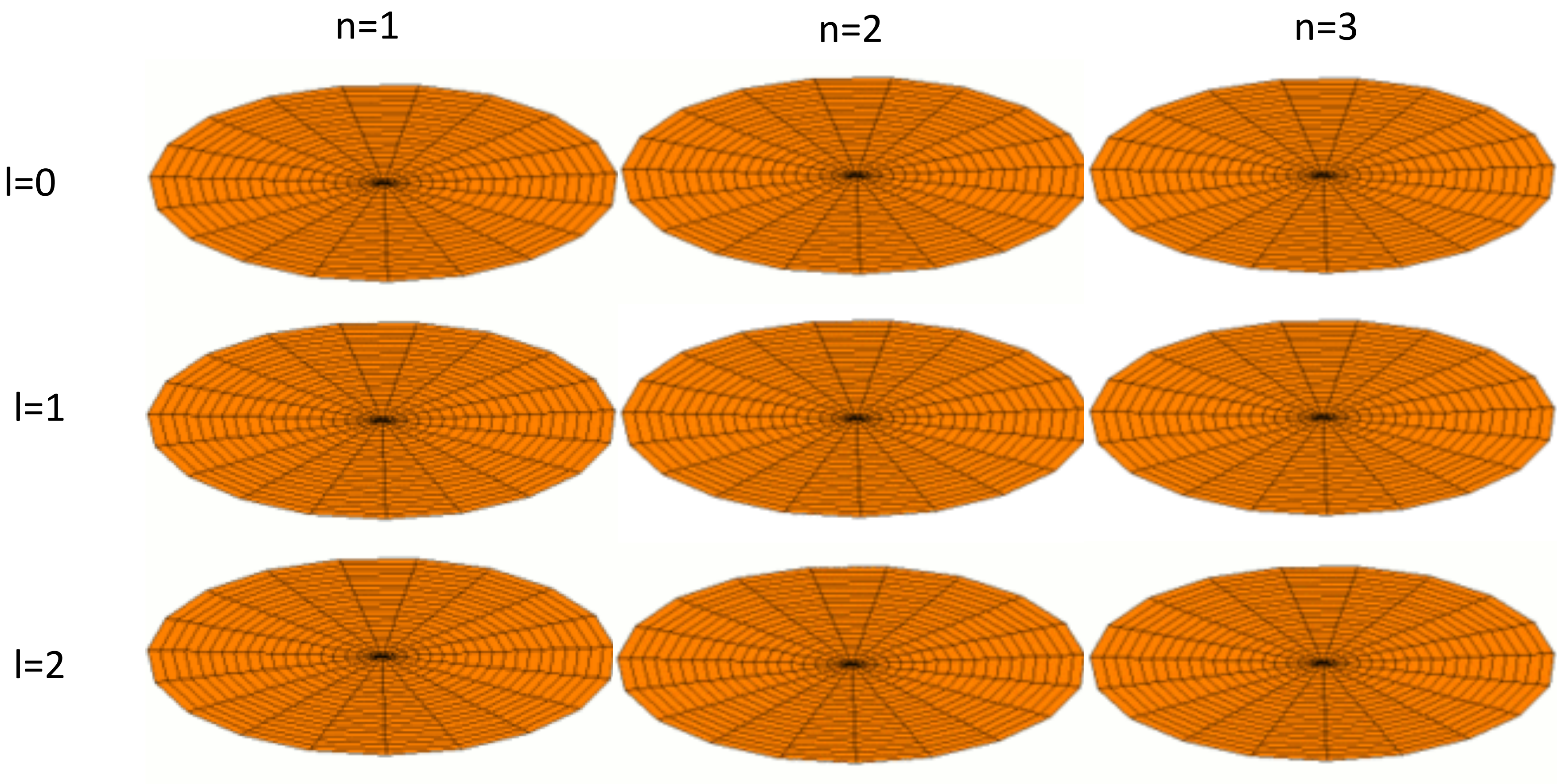
Theory of waves

In 1 D (n):

- A resonant oscillation is characterized on a string by a succession of maxima, minima, and nodes



Theory of waves



http://en.wikipedia.org/wiki/Vibrations_of_a_circular_membrane

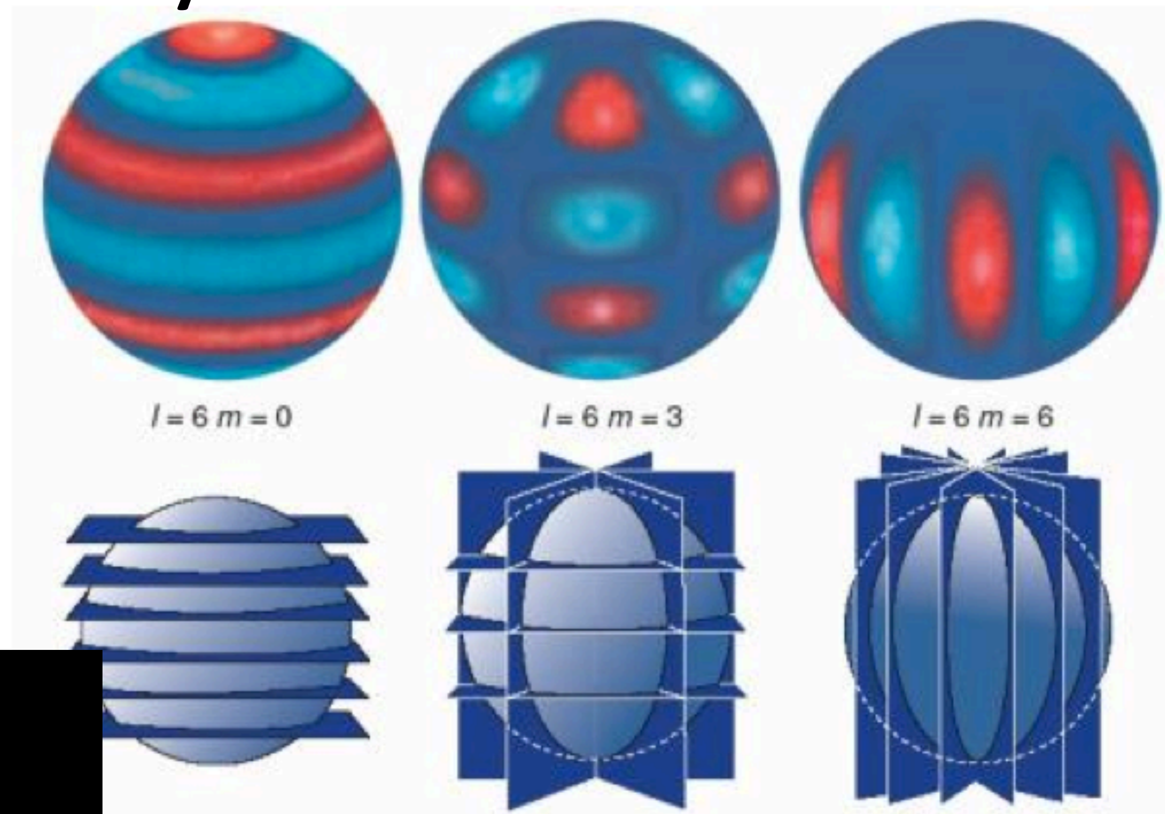
In 2 D:

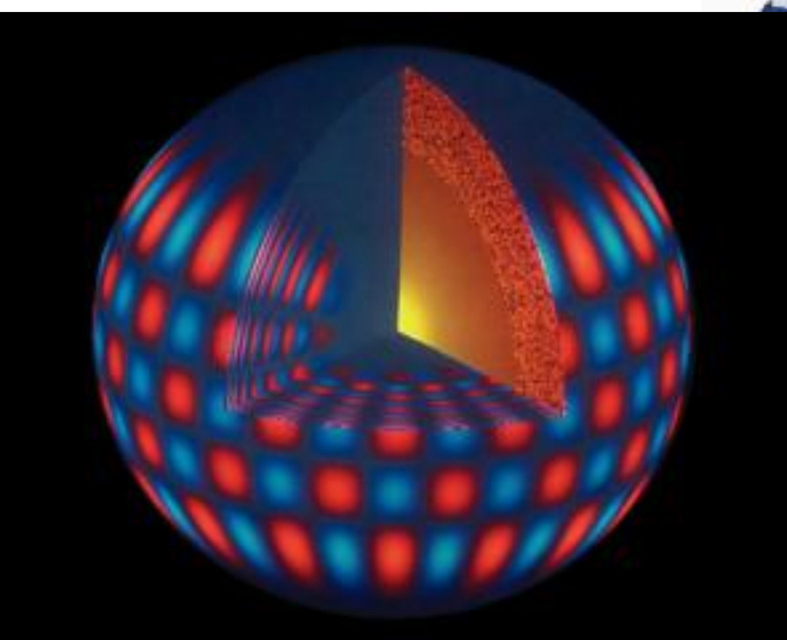
- Characterized by 2 numbers (l,n)

Theory of waves

In 3 D:

- Characterized by 3 numbers (l, n, m)





Starting from equations

- Mass conservation

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \boldsymbol{v}) = 0$$

- Momentum conservation

$$\rho \frac{d\boldsymbol{v}}{dt} = -\nabla P + \rho \boldsymbol{g}$$

- Energy equation

$$\frac{\mathrm{d}q}{\mathrm{d}t} = \frac{\mathrm{d}E}{\mathrm{d}t} + p\frac{\mathrm{d}\frac{1}{\rho}}{\mathrm{d}t},$$

- Hypotheses:
  1. Linearity: velocity of oscillating elements << sound speed
  2. Adiabaticity: conservation of entropy with time
  3. Spherical symmetry of the background state
  4. Magnetic forces and Reynold stresses negligible

Oscillations and their properties

- Small perturbations of a stationary spherically symmetric star in hydrostatic equilibrium (e.g. $p(r,t) = p_0(r) + p'(r,t)$)

- Simple waves:
  - equilibrium quantities vary slowly compared to perturbed quantities
  - gravitational acceleration negligible in momentum conservation
    - p modes: spatially homogeneous, high frequencies
    - g modes: small impact of gravity over pressure gradient, low frequencies

- Decomposition in Legendre polynomials and Spherical harmonics

Oscillations behaviour

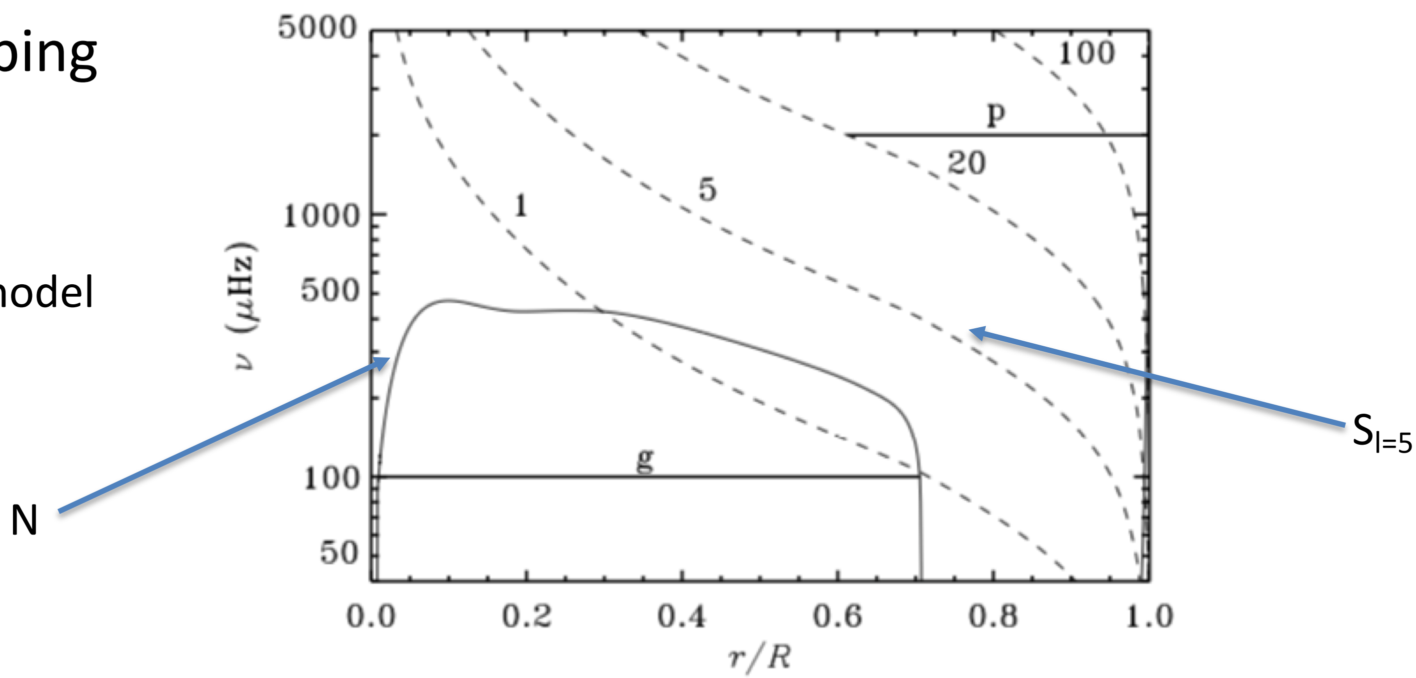
- Brunt-Väissälä $N^2 = g\left(\frac{1}{\Gamma_1 p}\frac{\mathrm{d}p}{\mathrm{d}r} - \frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}r}\right)$

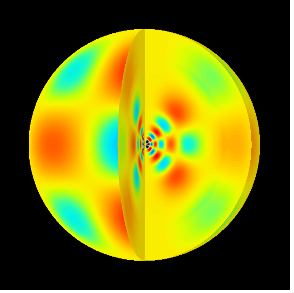
$$\frac{\mathrm{d}^2\xi_r}{\mathrm{d}r^2} = \frac{\omega^2}{c^2}\left(1 - \frac{N^2}{\omega^2}\right)\left(\frac{S_l^2}{\omega^2} - 1\right)\xi_r$$

- Lamb frequency $S_l^2 = \frac{l(l+1)c^2}{r^2}$

- Trapping

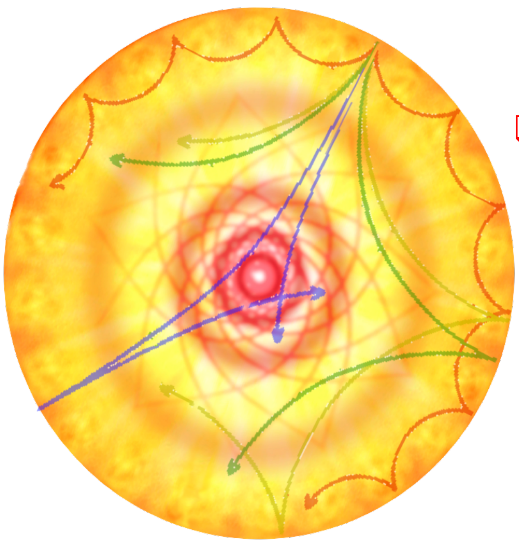
Solar model





Types of modes

- Oscillation eigenmodes characterized by:
  - ℓ : Degree
  - m : Azimuthal order
  - n : Radial Order



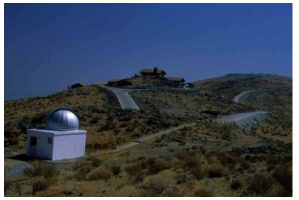
- Acoustic (p) modes:
  - Restoring force:
    - Pressure
    - Equidistant in fr
- Gravity (g)
  - R ce:
    - uoyancy
    - Evanescent in the convective zone
    - Equidistant in period
- Mixed modes
  - Coupling between p- and g-mode cavities

Directly probes the deeper layers of the Sun and the stars

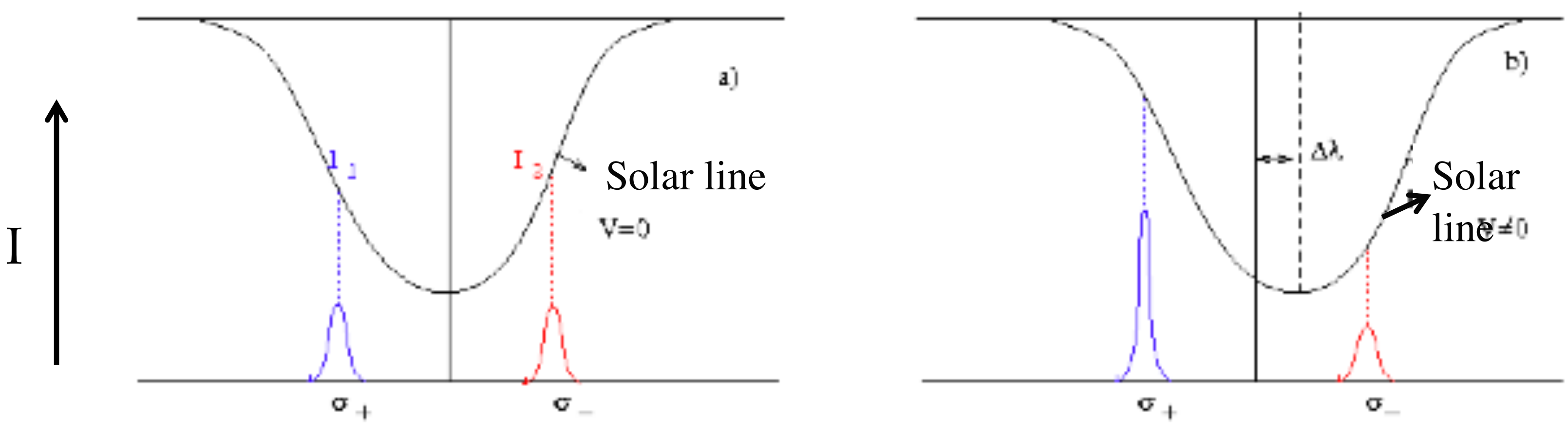
Asteroseismology

How to observe oscillations?

- Photometry: measurement of luminosity changes
  - Sun: e.g. VIRGO (Variability Irradiance Global Oscillations)
  - Stars: e.g. CoRoT, *Kepler*, K2, TESS, PLATO… → Sarah's lecture
- Doppler velocity measurement through the displacement of a spectral line (Na, Ni, K…):
  - *Zeeman effect*: B divides emission line into 2 components
  - e.g. GOLF, MDI, HMI, BiSON, GONG, SONG…



- Resolved images or integrated light

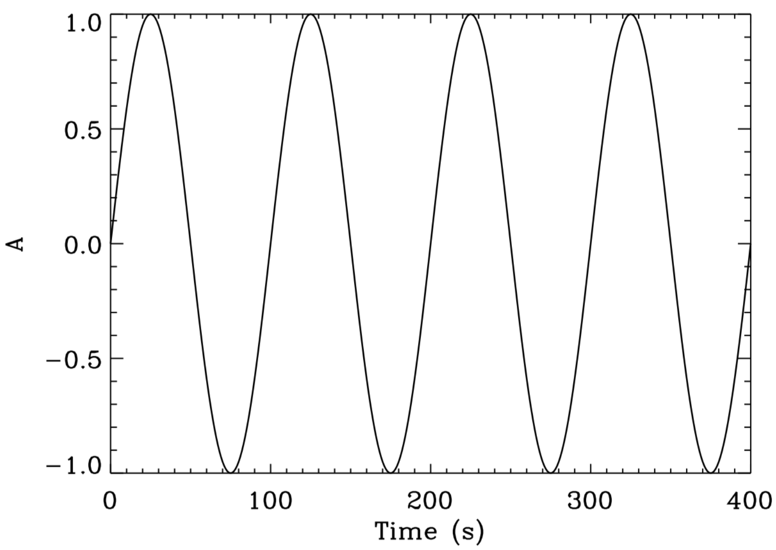


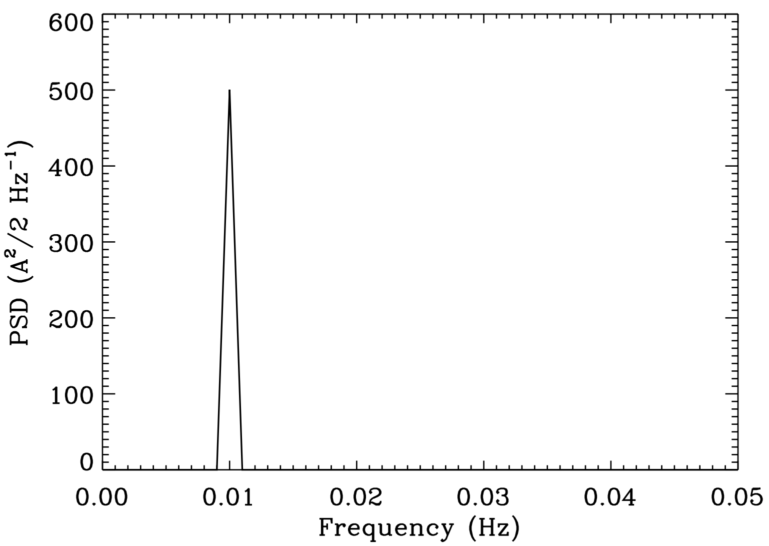
Fourier transform

1 sinusoid of period
T=100s

$$FT(A) = \int_0^T A(t)e^{2\pi i\nu t}dt$$

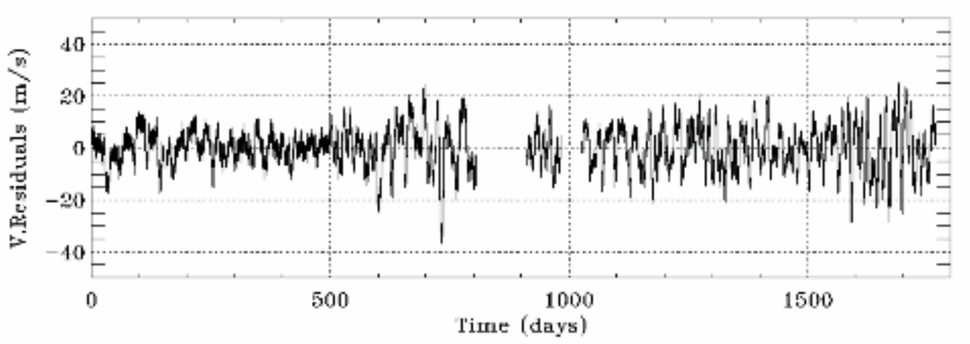
1 Dirac peak at the
frequency ν=0.01Hz

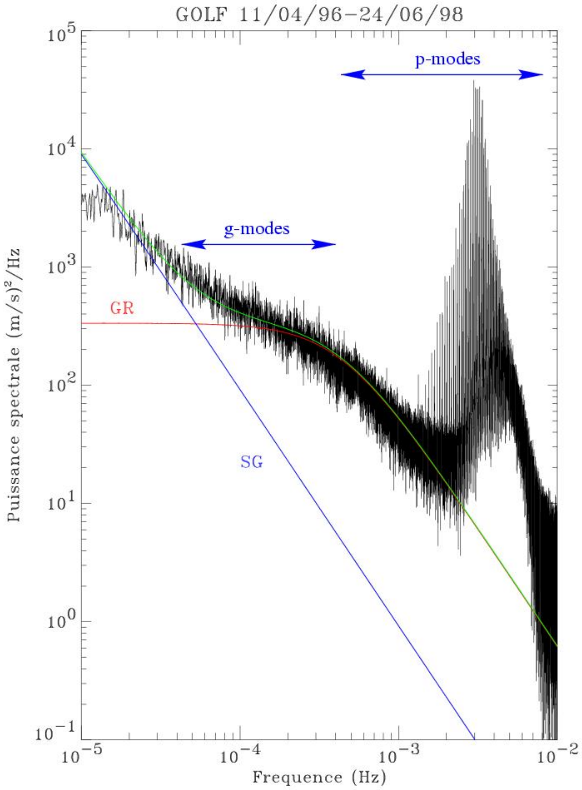




Fourier transform

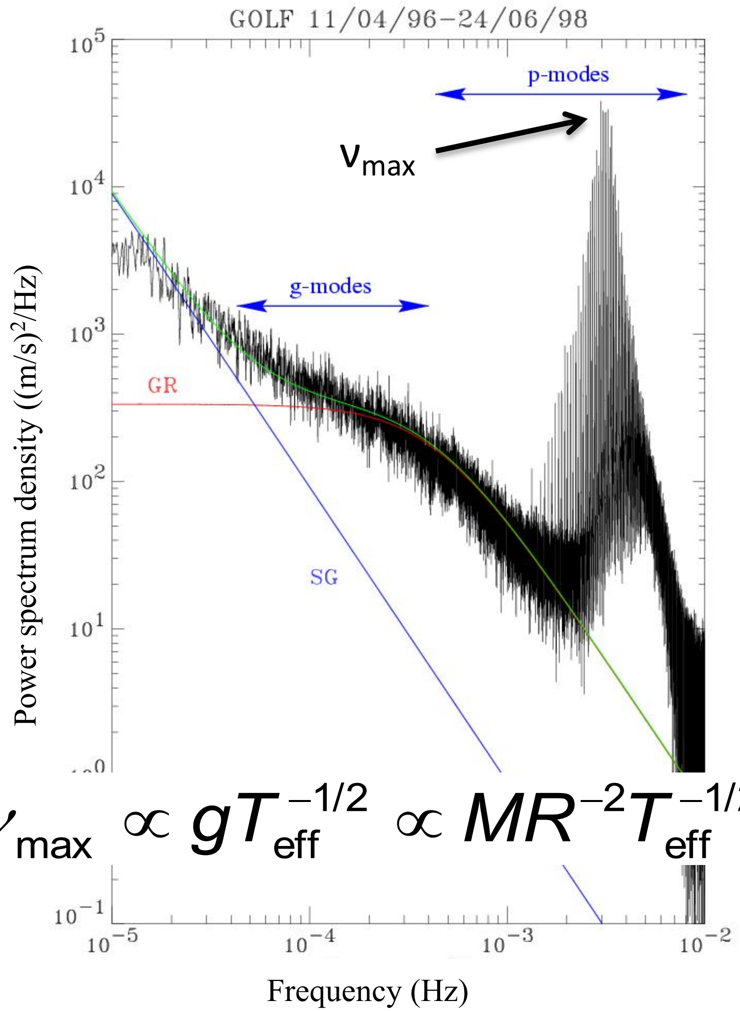
Solar oscillations $\xrightarrow{FT}$ Mode frequencies





Sun: 5 min oscillations

Power Spectrum



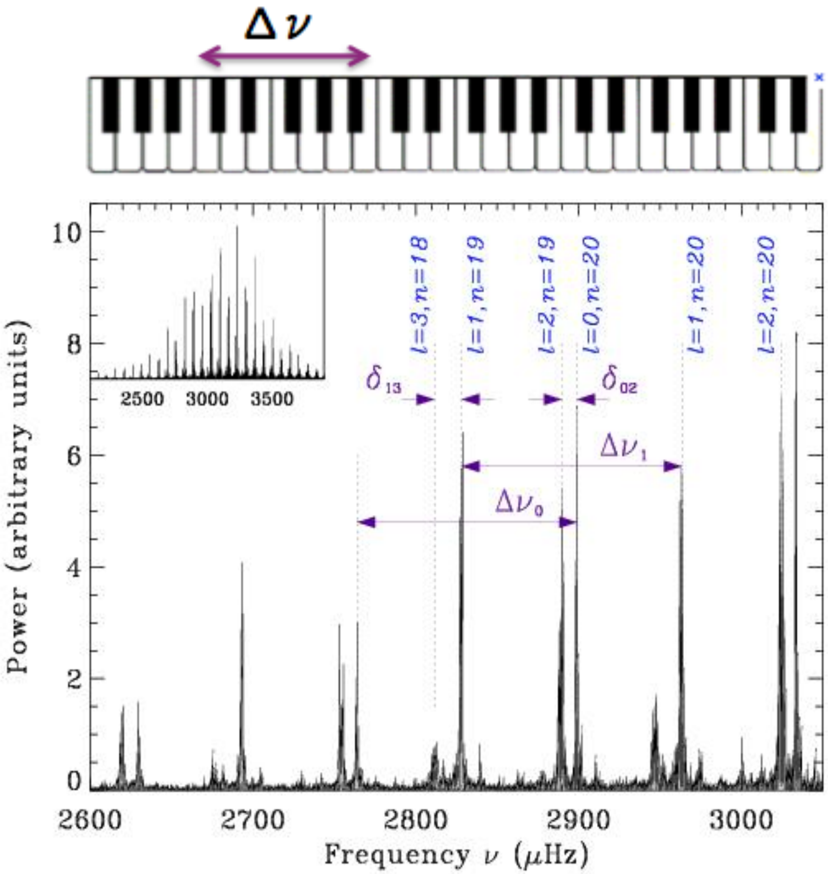
$$\nu_{max} \propto g T_{eff}^{-1/2} \propto M R^{-2} T_{eff}^{-1/2}$$

[Brown et al. 1991; Belkacem et al. 2011]

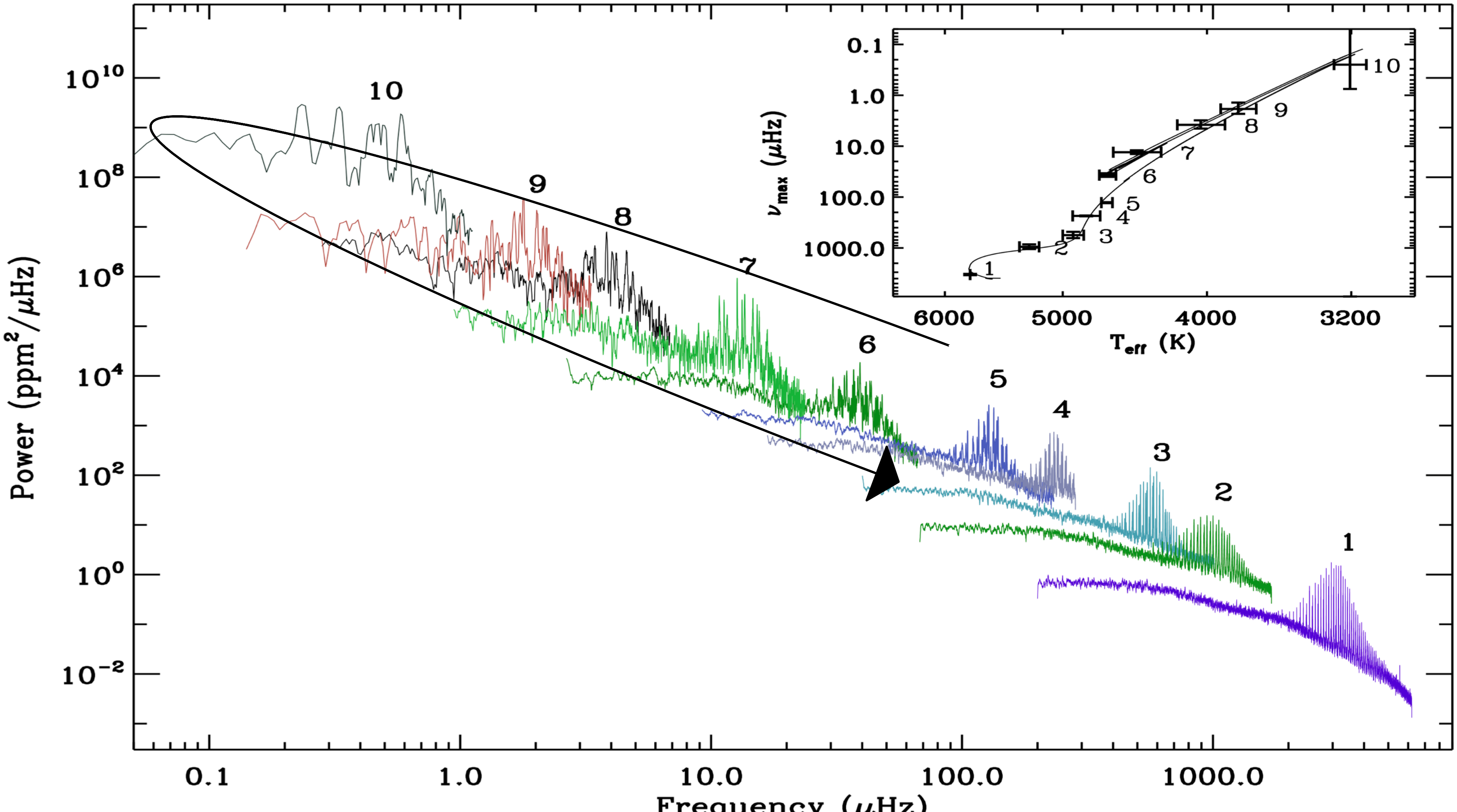
Scaling relation

- Large separation: $\Delta\nu = \nu_{n,\ell} - \nu_{n-1,\ell}$
  - Average properties of the star:
    - ✓ Acoustic diameter

$$\langle \Delta\nu \rangle \propto \langle \rho \rangle^{1/2} \propto M^{1/2} R^{-3/2}$$



Stellar evolution



García & Stello in Extraterrestrial seismology, CUP, 2015

Stellar properties: direct methods

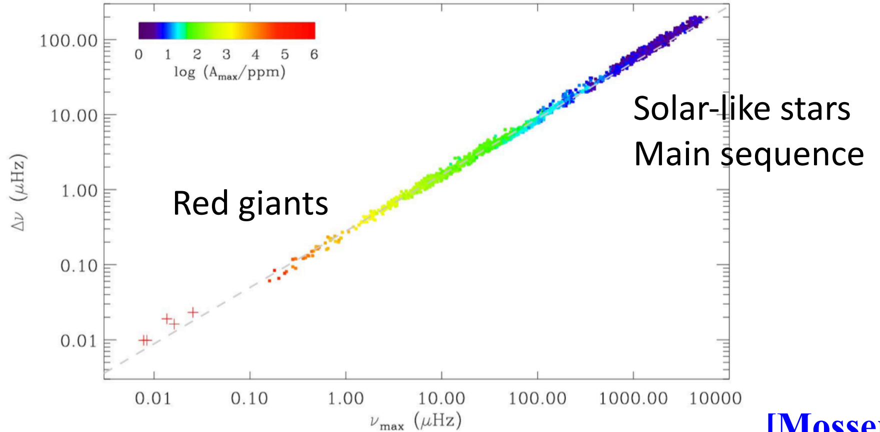
Use of scaling relations

From global asteroseismic parameters and a good estimation of T_{eff}

$$R \propto \nu_{max} \langle \Delta \nu \rangle^{-2} T_{eff}^{0.5}$$ (~5%)

$$M \propto \nu_{max}^{3} \langle \Delta \nu \rangle^{-4} T_{eff}^{1.5}$$ (~10%)

Tested both theoretically and observationally
[Kjeldsen & Bedding 1995; Huber et al. 2012; Mathur et al. 2012; Silva Aguirre et al. 2012]



[Mosser et al., 2013 SF2A]

Stellar Modeling

- Stellar models:
  - Diffusion
  - Composition
  - Equation of state
  - Opacities
  - Mixing length theory
  - Overshoot?
  - …

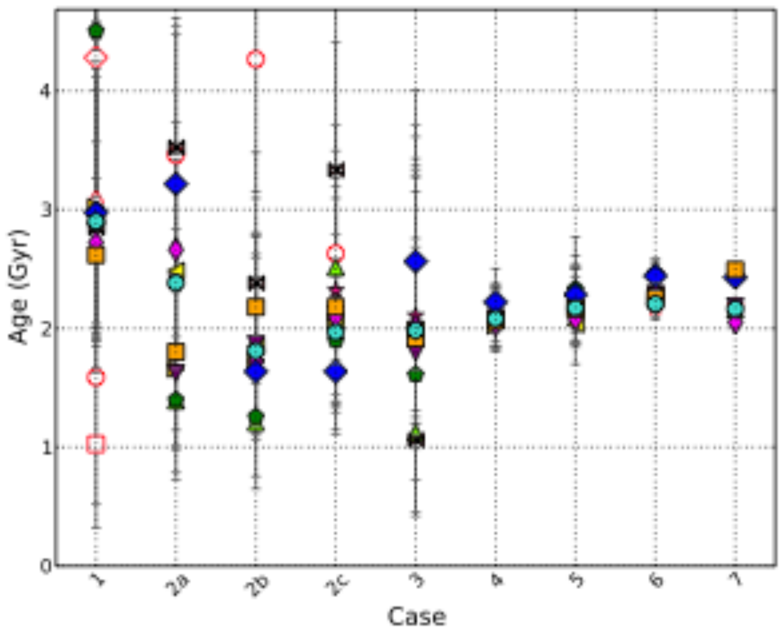
- Observables:
  - Spectroscopic: T_{eff}, Fe/H, log g, L
  - Seismic: $\Delta\nu$, ν_{max}, $\nu_{n,l}$

Find the best model that fits all the observables available

Stellar modeling

- Best fit model
  - Grid modeling [Chaplin et al. 2014]
  - E.g. Asteroseismic Modeling Portal [Metcalfe et al. 2009]

HD52265

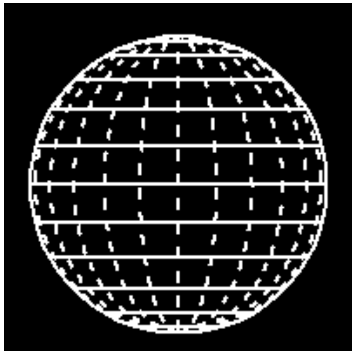


[Lebreton & Goupil 2014]

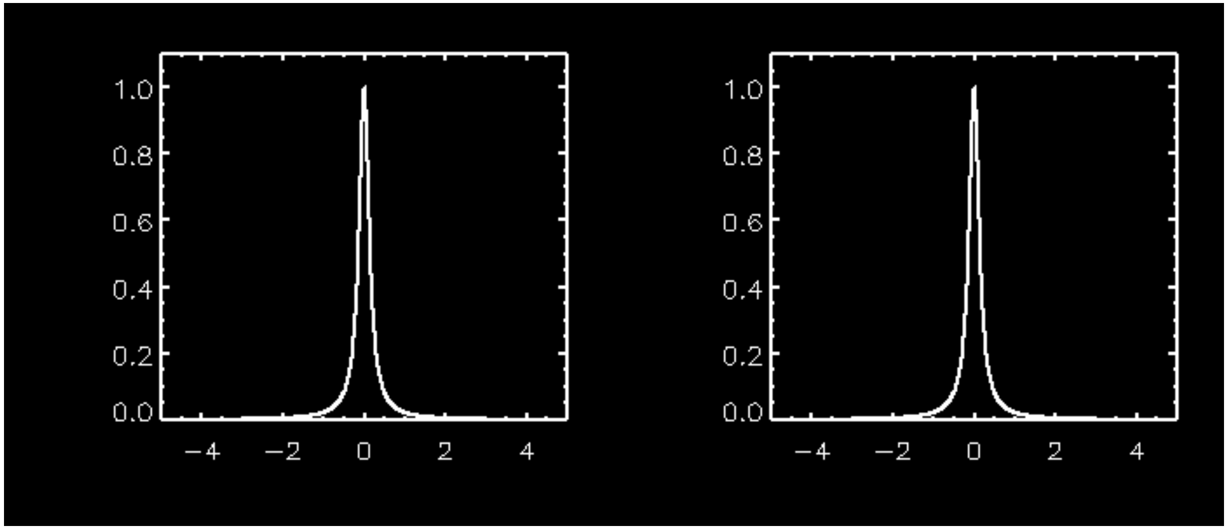
- Large sample of stars [Mathur et al., 2012; Metcalfe et al. 2014]
  - Improve precision on M, R, age
  - Structure:
    - base of convection zone

Effect of rotation on modes

Ω = 0,0

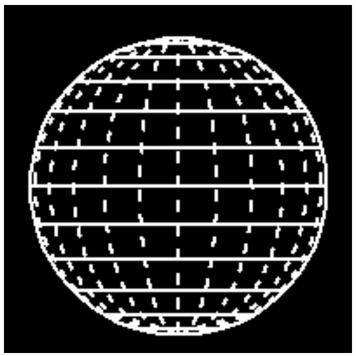


i = 90°

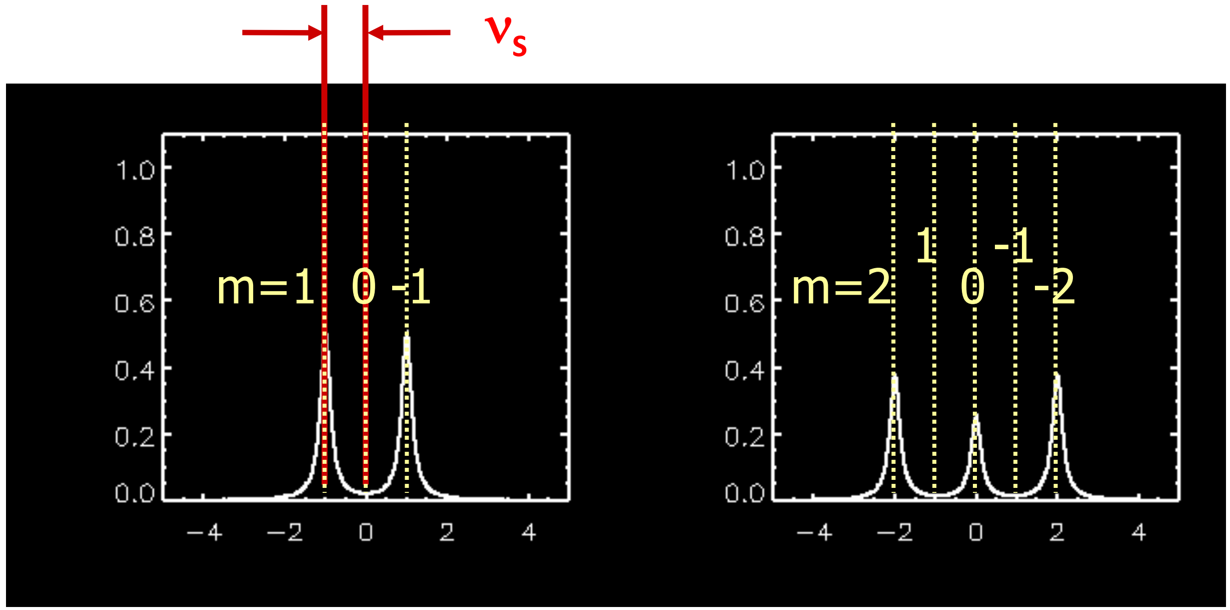


Effect of rotation on modes

Ω = 1,0



i = 90°

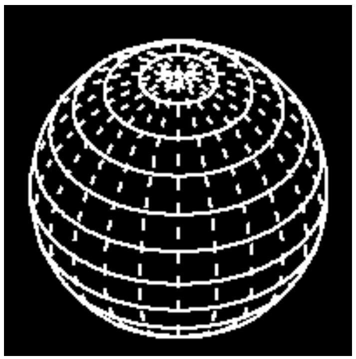


Internal rotation:

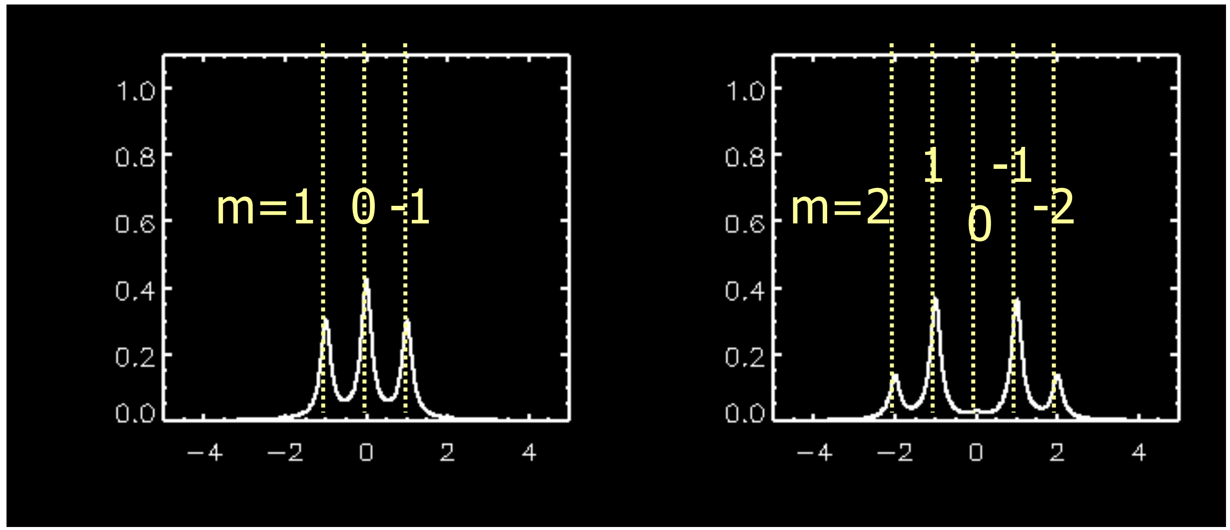
- Rotational splittings

Effect of rotation on modes

Ω = 1,0



i = 50°

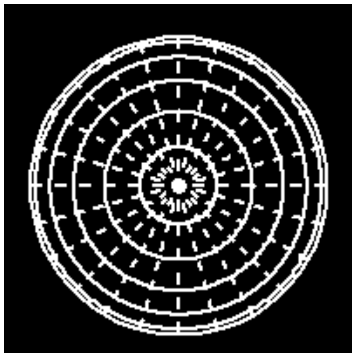


Internal rotation:

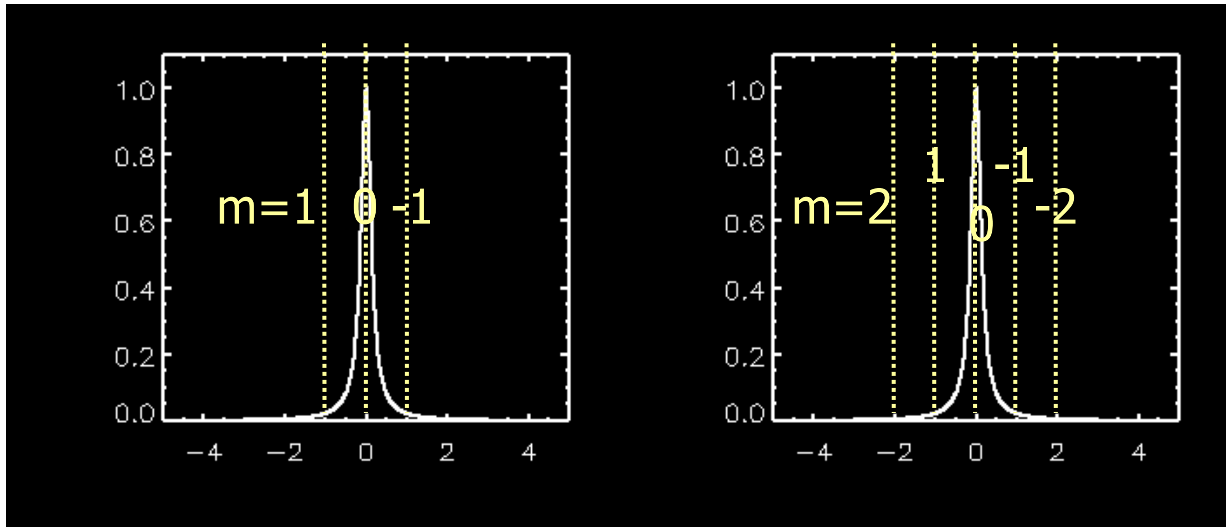
- Rotational splittings
- Complicate measurement:
  Inclination angle of the star

Effect of rotation on modes

Ω = 1,0



i = 0°



Internal rotation:

- Rotational splittings
- Complicate measurement:
  Inclination angle of the star

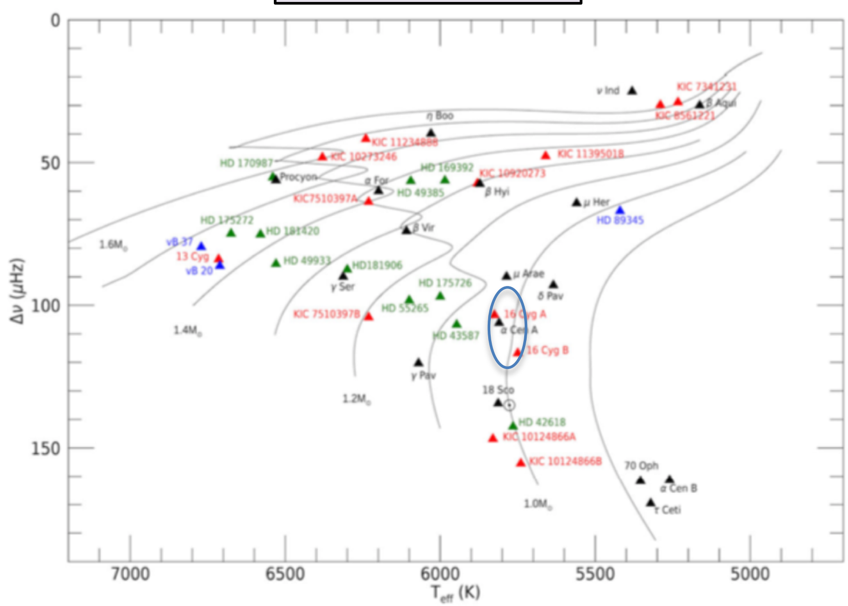
Highlights from asteroseismic studies

Space photometric missions: asteroseismic revolution

Solar-like stars

on the MS and subgiant branch

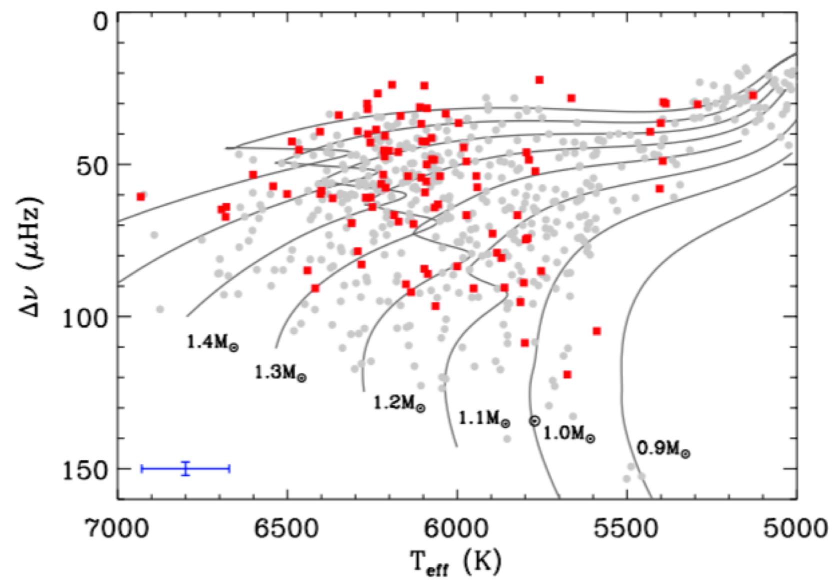
Before *Kepler*



[García & Ballot 2019, LRSP]

<50 stars

After *Kepler*



[Mathur et al. 2022]

>620 stars

Space photometric missions: asteroseismic revolution

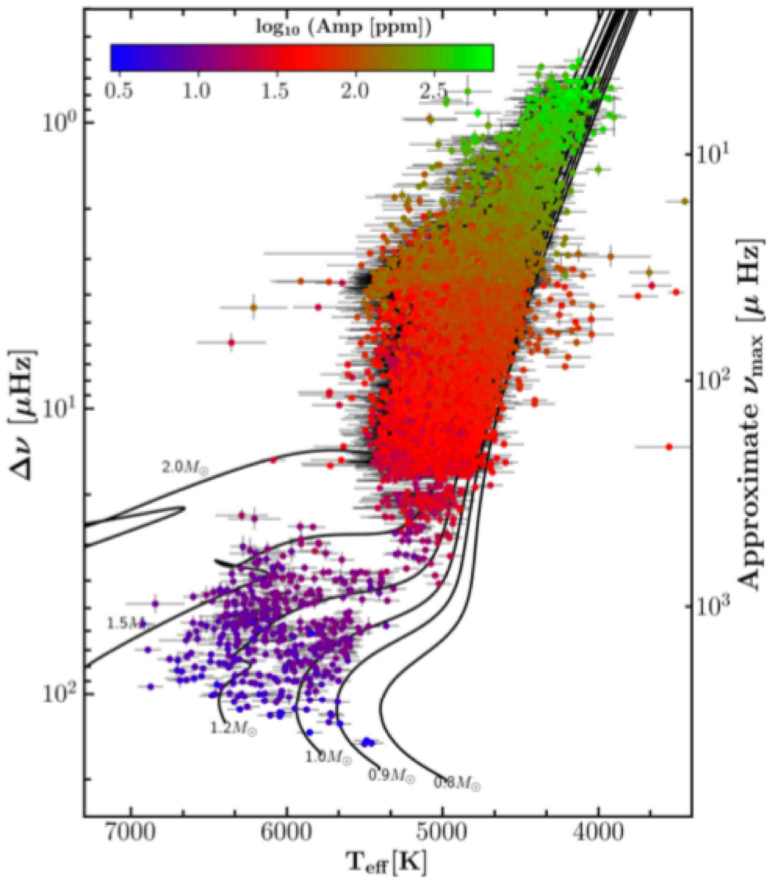
With CoRoT

[e.g. De Ridder et al. 2009]

Red Giants

With *Kepler*

>18,000 stars
[Yu et al. 2018]



With K2

>19,000 stars
[Zinn et al. 2019, 2021]

With TESS

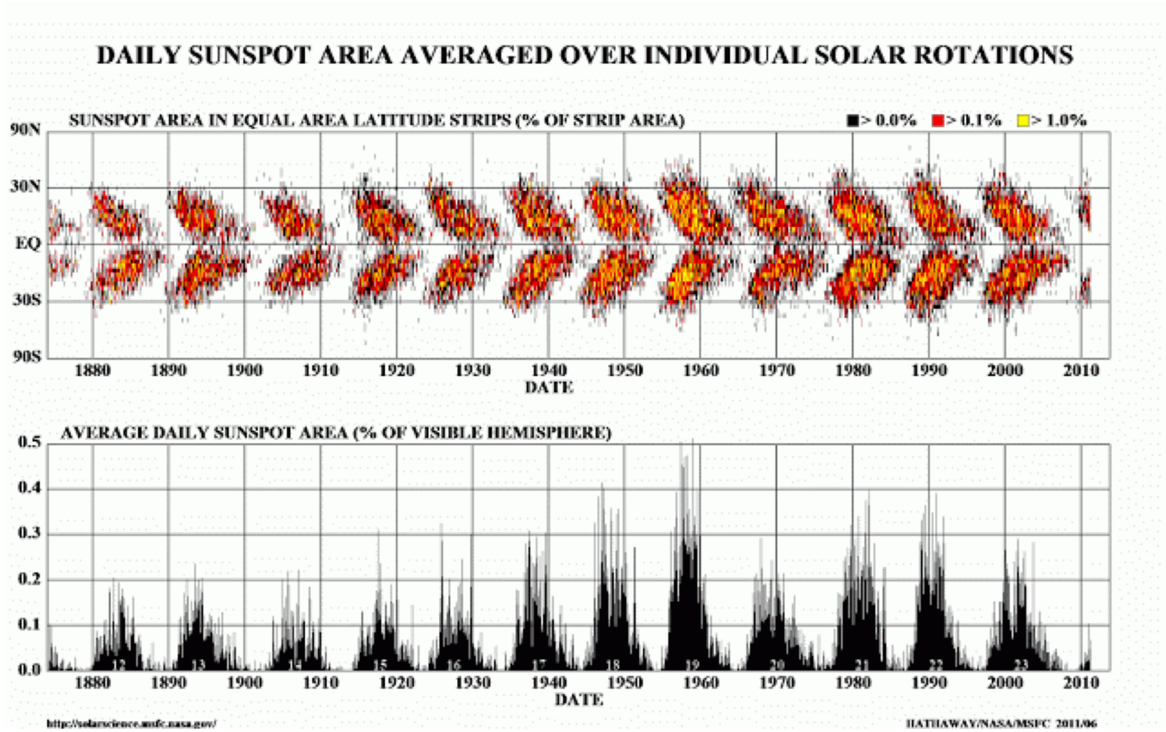
>158,000 stars
[Hon et al. 2022]

New discoveries

- Stellar physics (surface/internal rotation, magnetic field)
- Stellar evolution (from main sequence to red-giant branch)
- Binary characterization and evolution → Cole's lecture
- Exoplanetary systems characterization
- Galactic-archeology
- Clusters
- ...

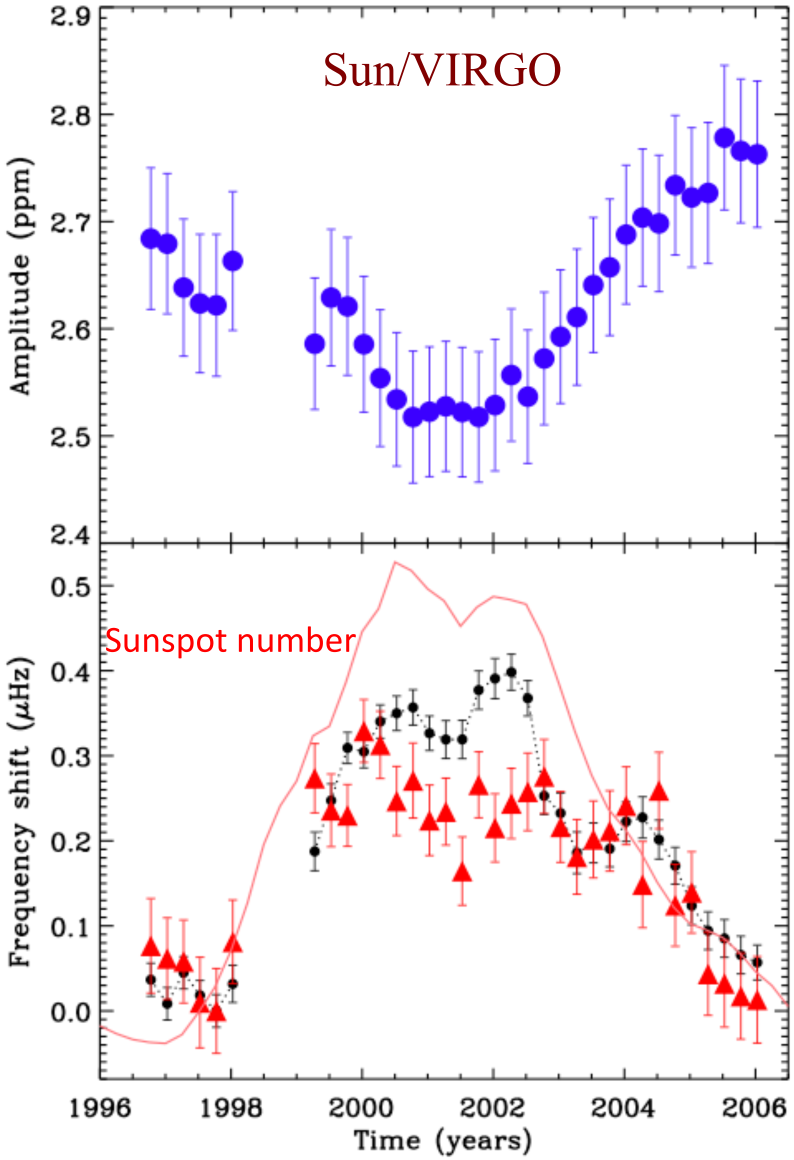
Stellar Magnetic Activity

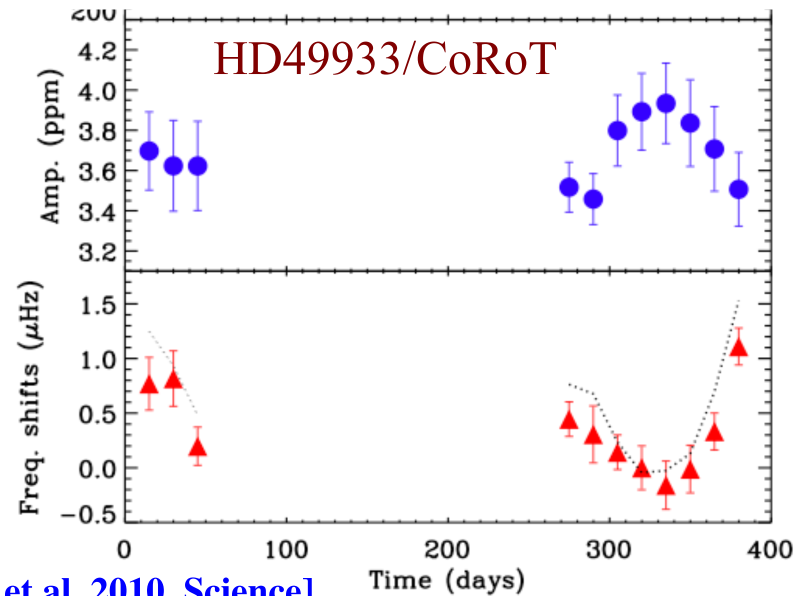
Solar magnetic activity: sunspots



- Not completely random
- Some regularity:
  - Appearance of spots
  - Spot migration: 'butterfly diagram'
  - 11-year cycle (or 22-year cycle for the magnetic polarity reversal)

Magnetic activity: photometry





[García et al. 2010, Science]

Anticorrelation between amplitude variation and frequency shifts

Pcyc>120days

- Observed in ~45 *Kepler* solar-like stars

[Salabert et al. 2016; Kiefer et al. 2017; Santos et al. 2018]

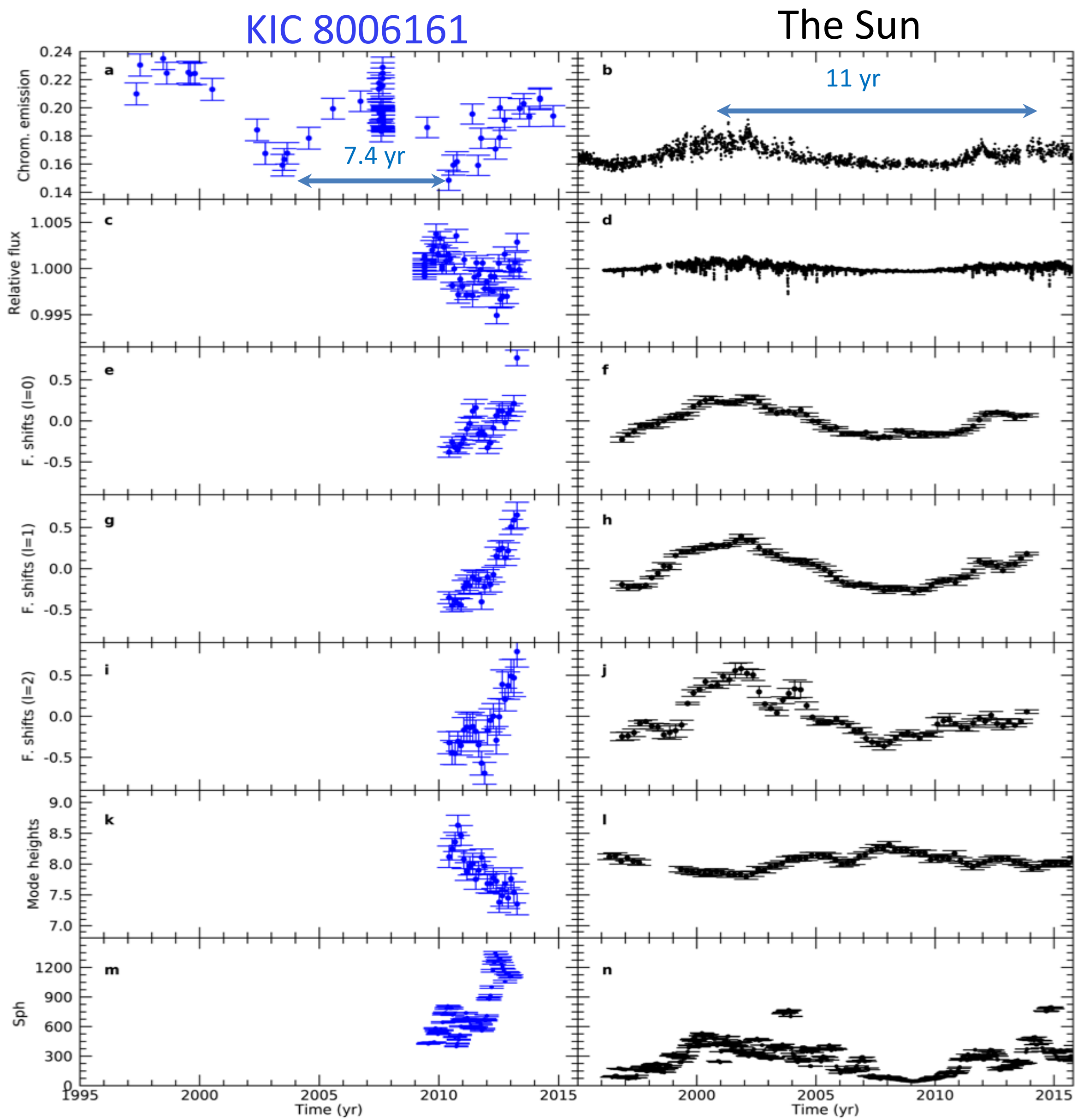
Effect of metallicity in the magnetism

KIC 8006161

Radius*	$0.930 \pm 0.009\ R_\odot$
Mass*	$1.00 \pm 0.03\ M_\odot$
Log g*	4.498 ± 0.003
Age*	4.57 ± 0.36 Gyr
Effective temperature**	5488 ± 77 K
Metallicity**	0.3 ± 0.1
Rotation period	21^{+2}_{-2} days
Inclination	38^{+3}_{-4} degrees
Cycle period	7.41 ± 1.16 years

- Stronger chromospheric emission than the Sun
- Shorter cycle period than the Sun

→ **Effect of metallicity**



[Karoff et al. 2018]

Angular momentum transport

Rotation-Age relation

Angular momentum transport

- For 2 young clusters and the Sun

- Derived a law with age:

$$\boxed{P_{rot} \sim \tau^{1/2}}$$

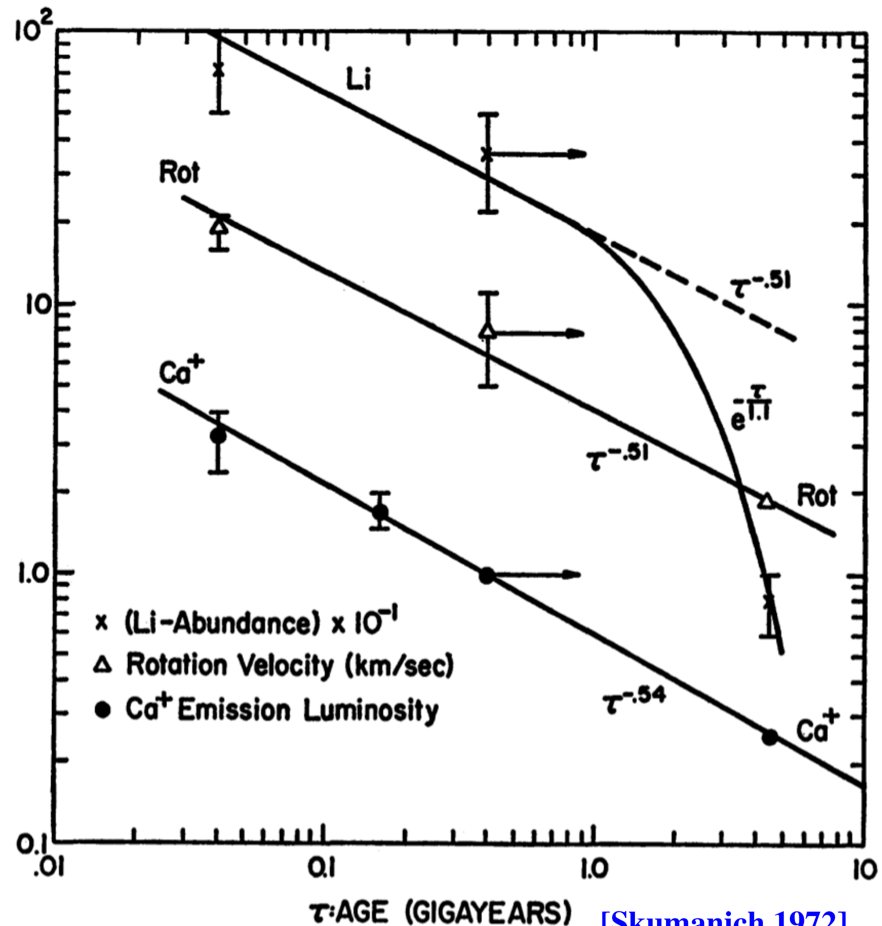
[Skumanich 1972]

Gyrochronology [Barnes 2007]

- Angular momentum loss:

$$\left(\frac{dJ}{dt}\right)_{\rm wind} = K_W \left(\frac{R_*/R_\odot}{M_*/M_\odot}\right)^{1/2} \Omega_*^3,$$

[e.g. Kawaler (1988); MacGregor & Brenner (1991)]

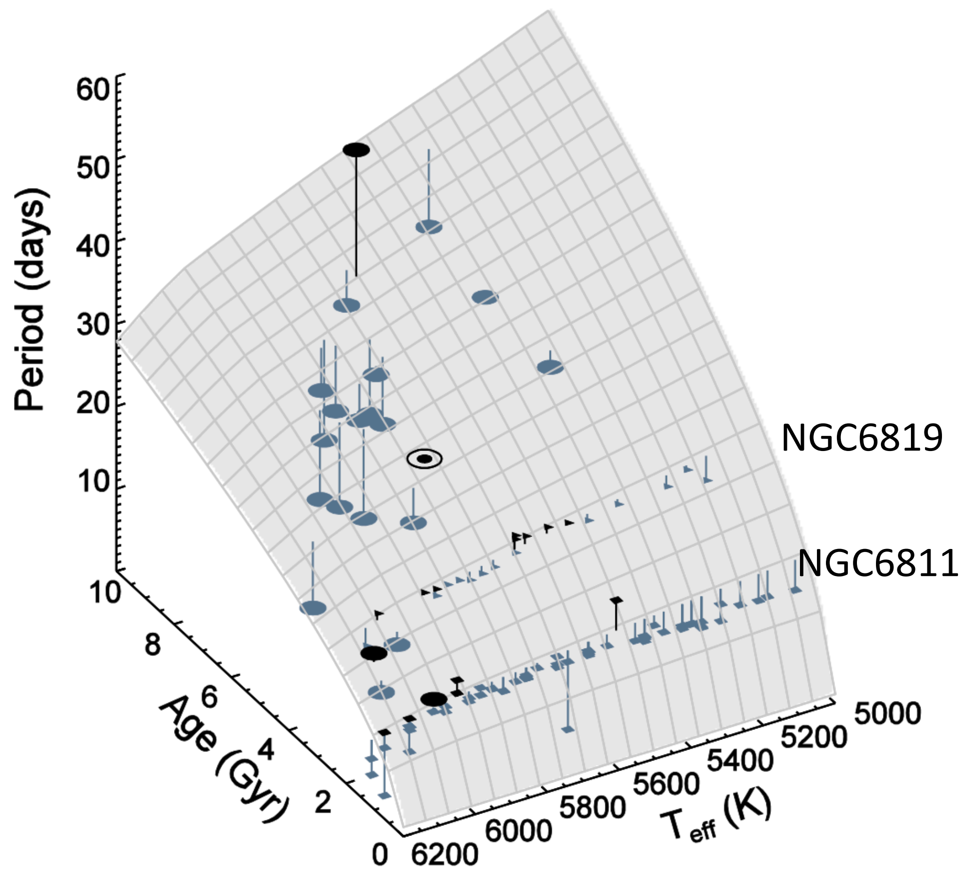


[Skumanich 1972]

Revisiting gyrochronology with *Kepler*

- Based on young clusters younger than 2.5Gyr
- Only the Sun at 4.5Gyr
- Adding 21 solar-like stars observed by *Kepler* with:
  - Rotation periods
  - High-precision ages from asteroseismic modeling
  - Precise metallicity measurement

➢ *Kepler* observations allow us to test these relationships to older stars



[van Saders et al., 2016 Nature]

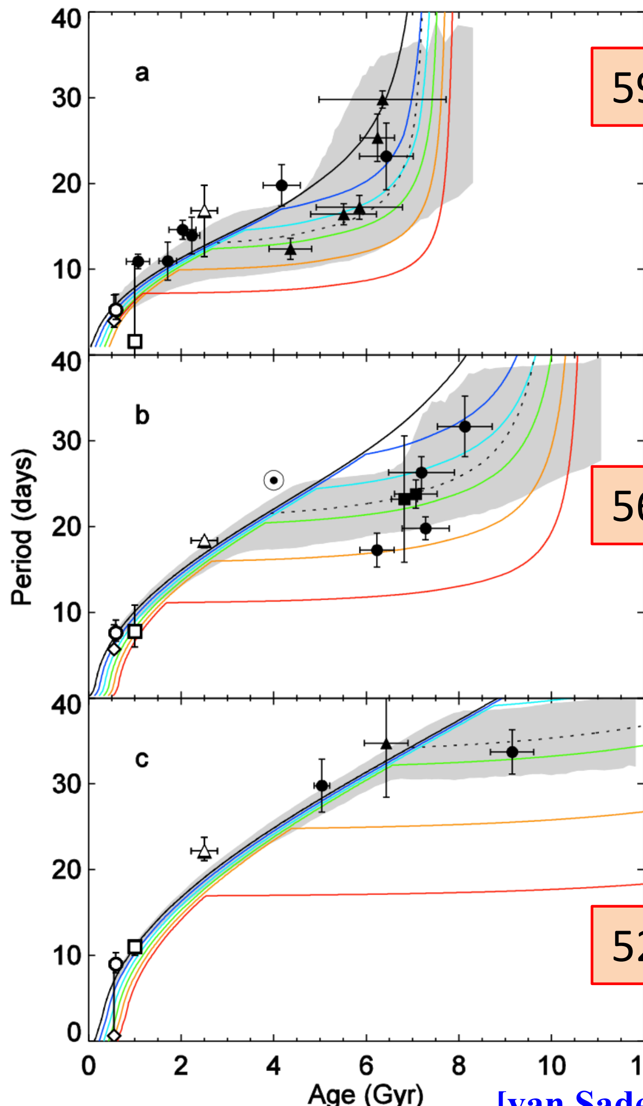
Weakened magnetic braking

- Magnetic braking prescriptions scaled on the Sun
- Stop magnetic braking at a given moment in the life of the star (with specific conditions on rotation and convection properties characterized by the Rossby number)

➢Rotation periods of the middle-aged stars that have passed this Rossby threshold represent only lower limits on the age.
➢Sun: transition phase
➢Gyrochronology applicable to certain stars

➢ Also observed with rotation periods from mode splittings

[Hall et al., 2021 Nature]



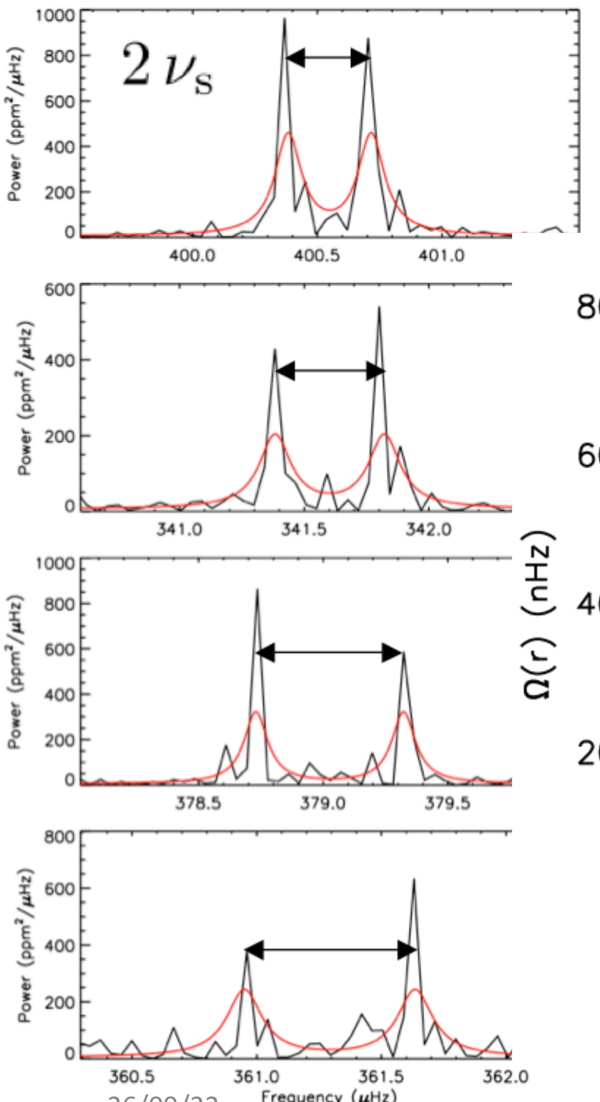
5900K<T_{eff}<6200K

5600K<T_{eff}<5900K

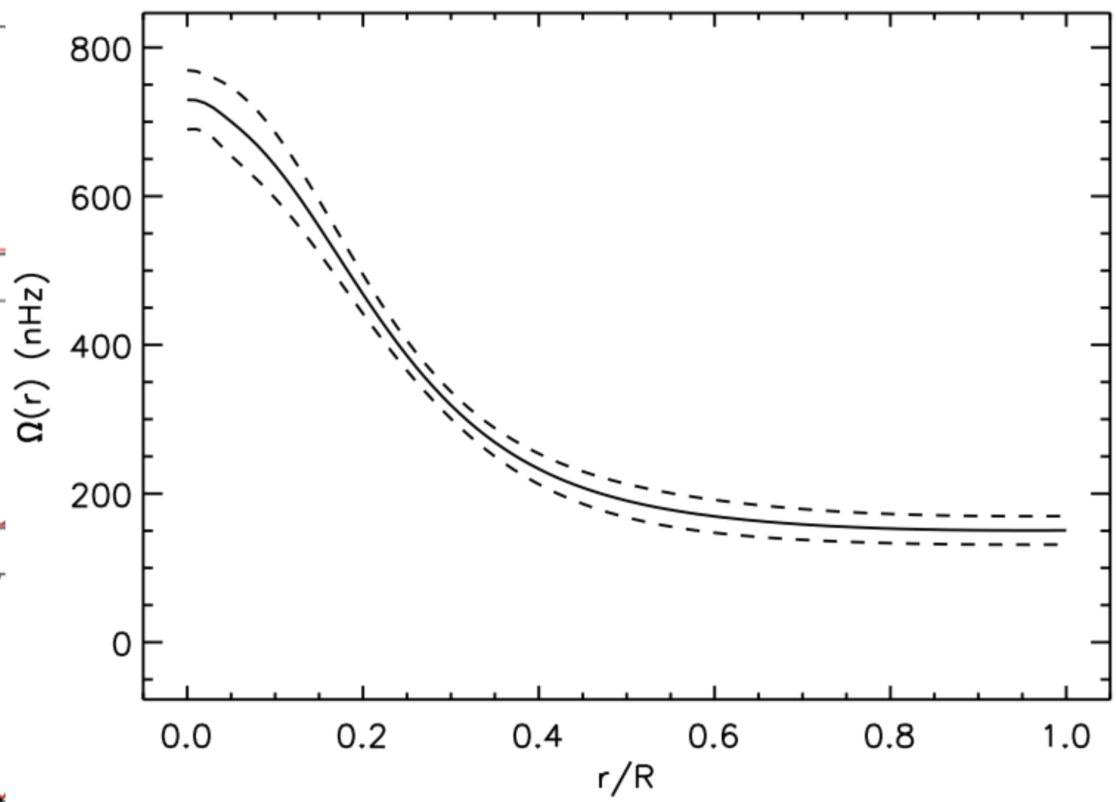
5200K<T_{eff}<5600K

[van Saders et al., 2016 Nature]

Rotation profile of a Subgiant



- Mixed modes:
  - Study the internal dynamics

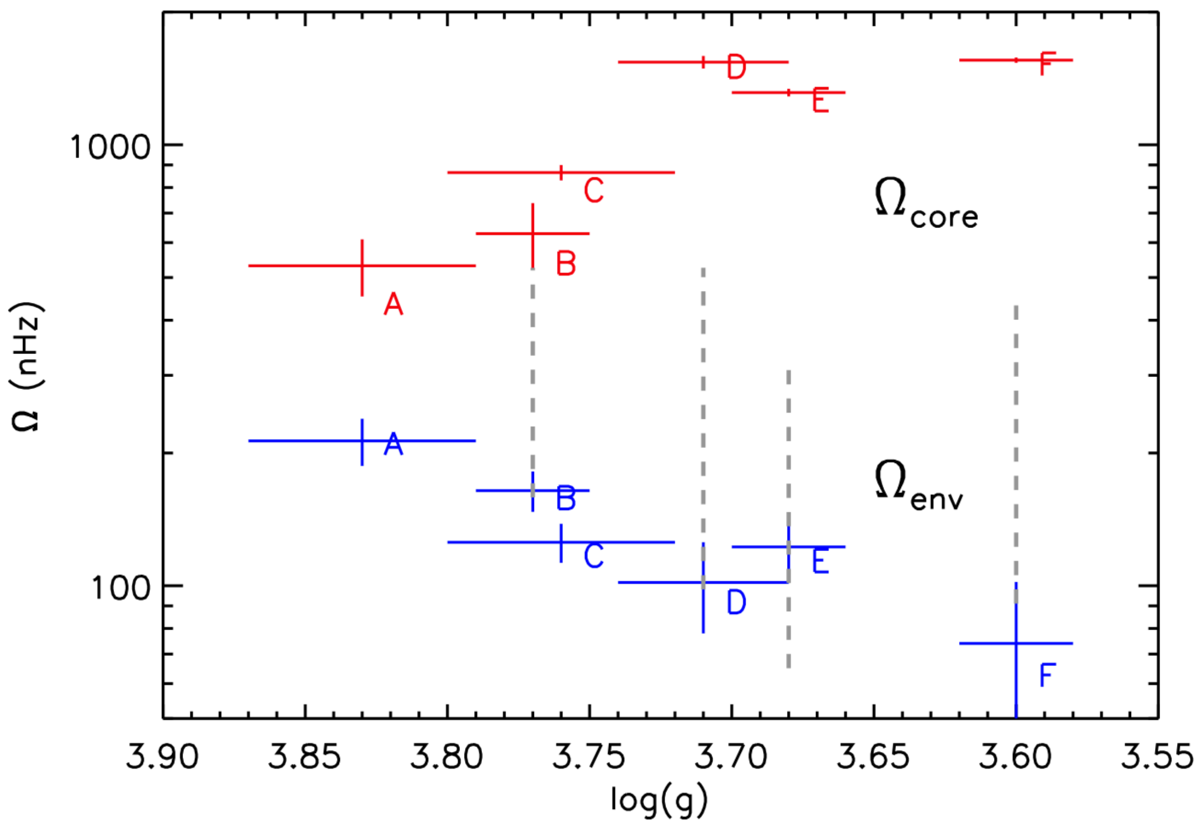


]

&A]

Internal rotation in sub giants

6 more subgiants/early RGBs

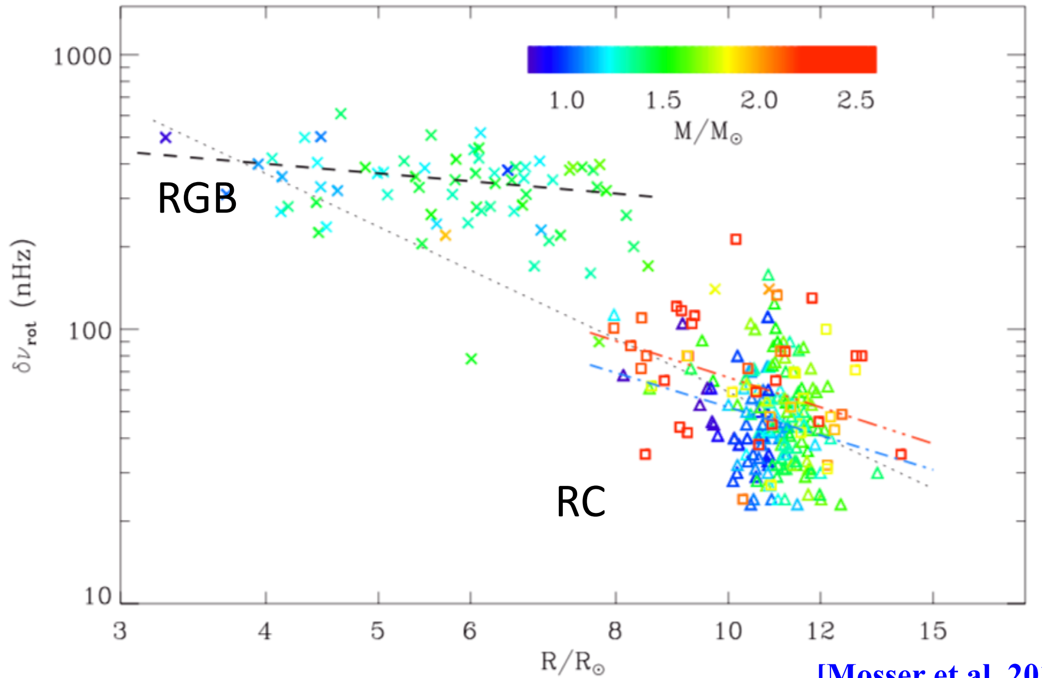


- log g as a proxy of evolution
- Vertical dashed lines are ranges of $\mathbf{\Omega}_{env}$ predicted by van Saders & Pinsonneault (2013)
- The trend with the seismic logg suggests that the core **spins up** in the subgiant phase

[Deheuvels et al. 2014, A&A]

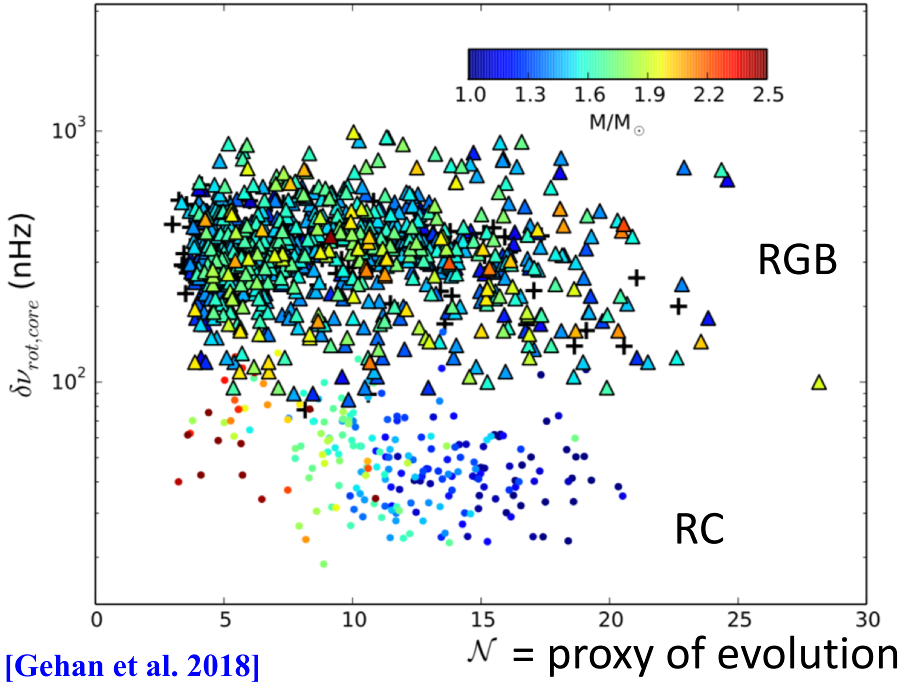
Core rotation of red giants

- From mixed modes: detection of splittings in red giants
  - Core rotates 10 times faster than the surface in average [Beck et al. 2012]
- Analysis of hundreds of stars:
  - Core spinning down on RGB and RC [Mosser et al. 2012]



[Mosser et al. 2012]

Core rotation of red giants

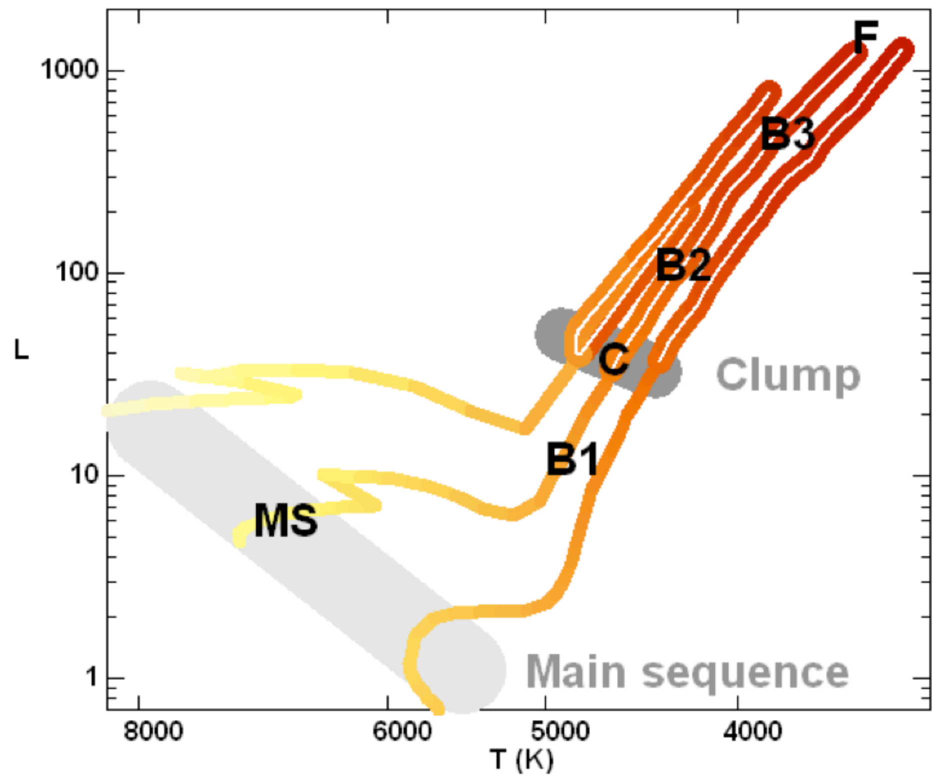


[Gehan et al. 2018]

- During RGB (triangles):
  - The core of the stars during RGB is roughly constant. No trends with Mass !!
  - Efficient AM transport to counterbalance the core contraction and not efficient during subgiant phase
- Change from RGB to the clump (circles) can be related to the expansion of the non-degenerate helium burning core.
  - It can not explain all the reduction
    - significant transfer of internal angular momentum from the inner to the outer layers.

Evolutionary stage

The RG revolution



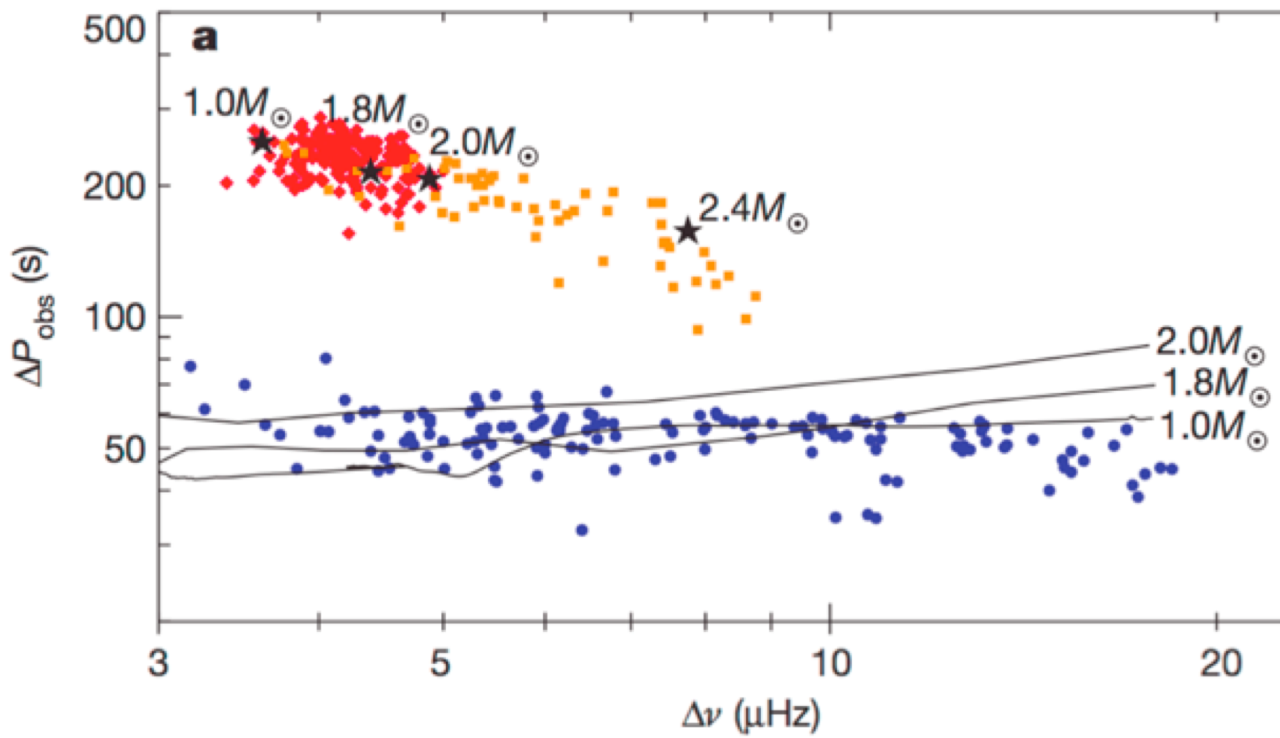
Confusion in the HR diagram:

- From their global properties a RGB star and a Red Clump giant are the same
- Same HR position, same envelopes, same large frequency spacings…
- "Just as in Hollywood, the age of a star is not always obvious if you look at the surface"

[Metcalfe, 2011]

Probing interiors of red giants

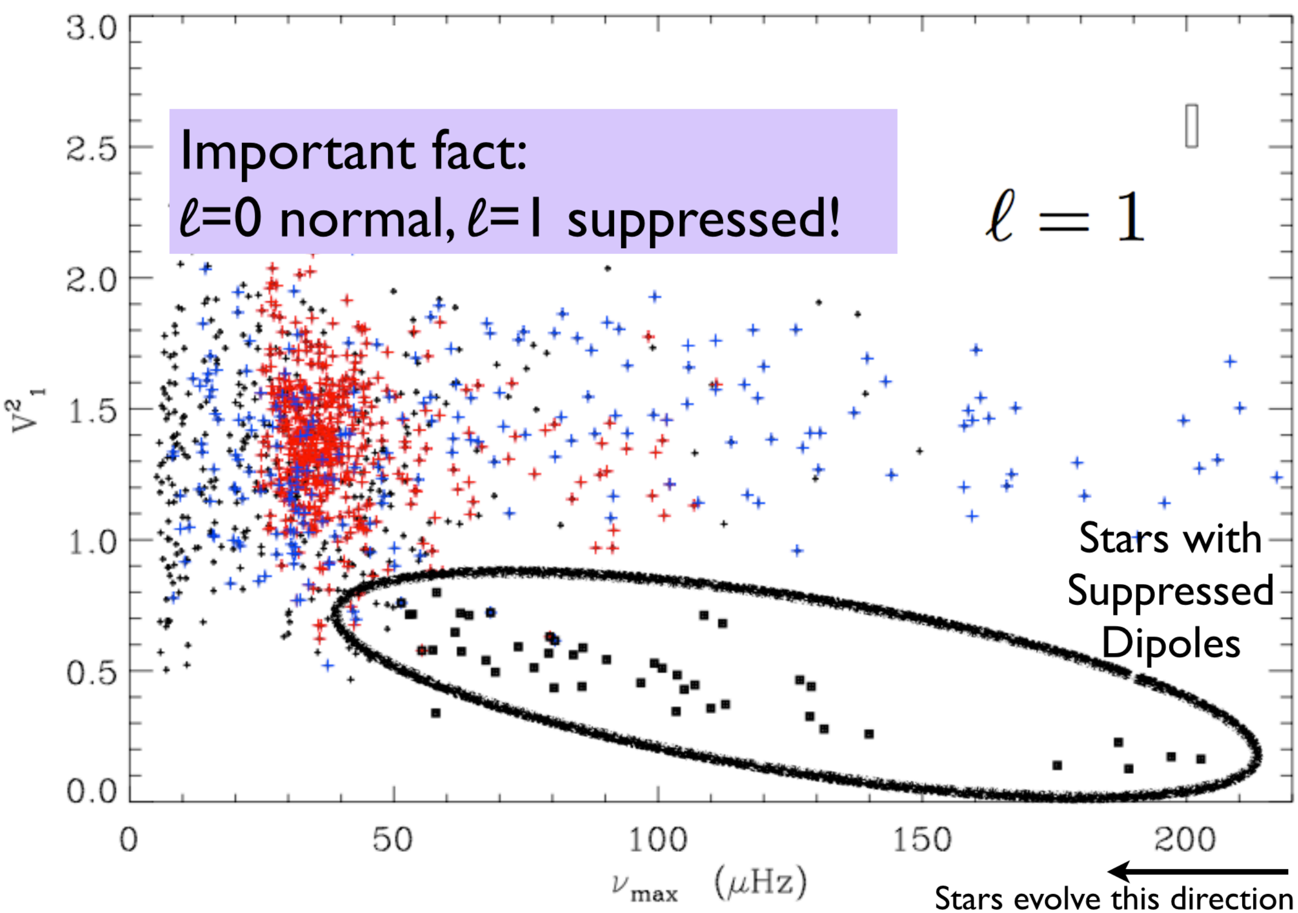
- Determination of period spacing of mixed modes ΔP
- Two regimes:
  - Large values of ΔP : burning He in their core
  - small values of ΔP : burning H in a shell



[Bedding et al. 2011, Mosser et al. 2011]

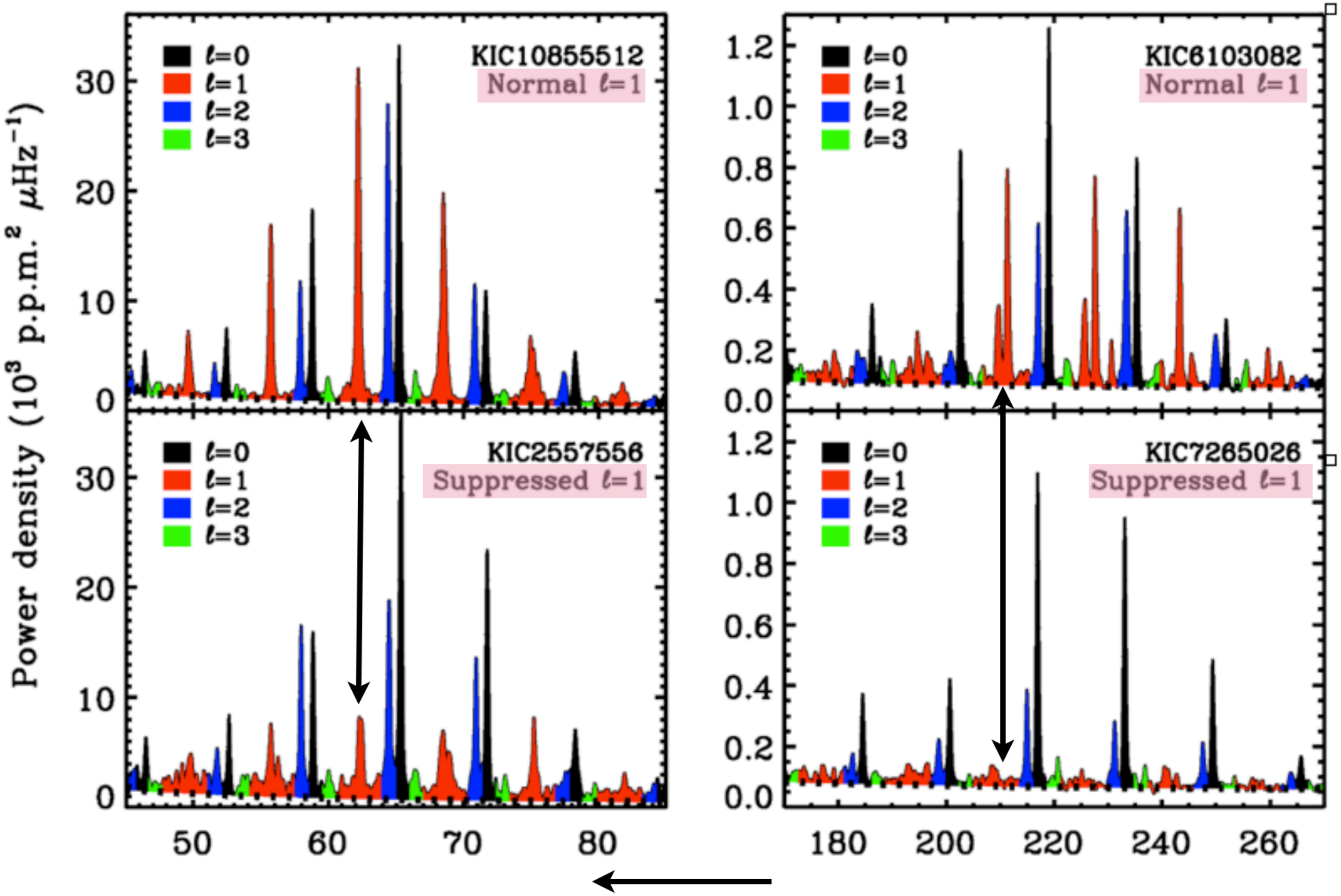
Internal magnetic field

Stars with abnormal (low) dipole modes



[Garcia et al. 2010, Mosser et al. 2012, Garcia et al. 2014]

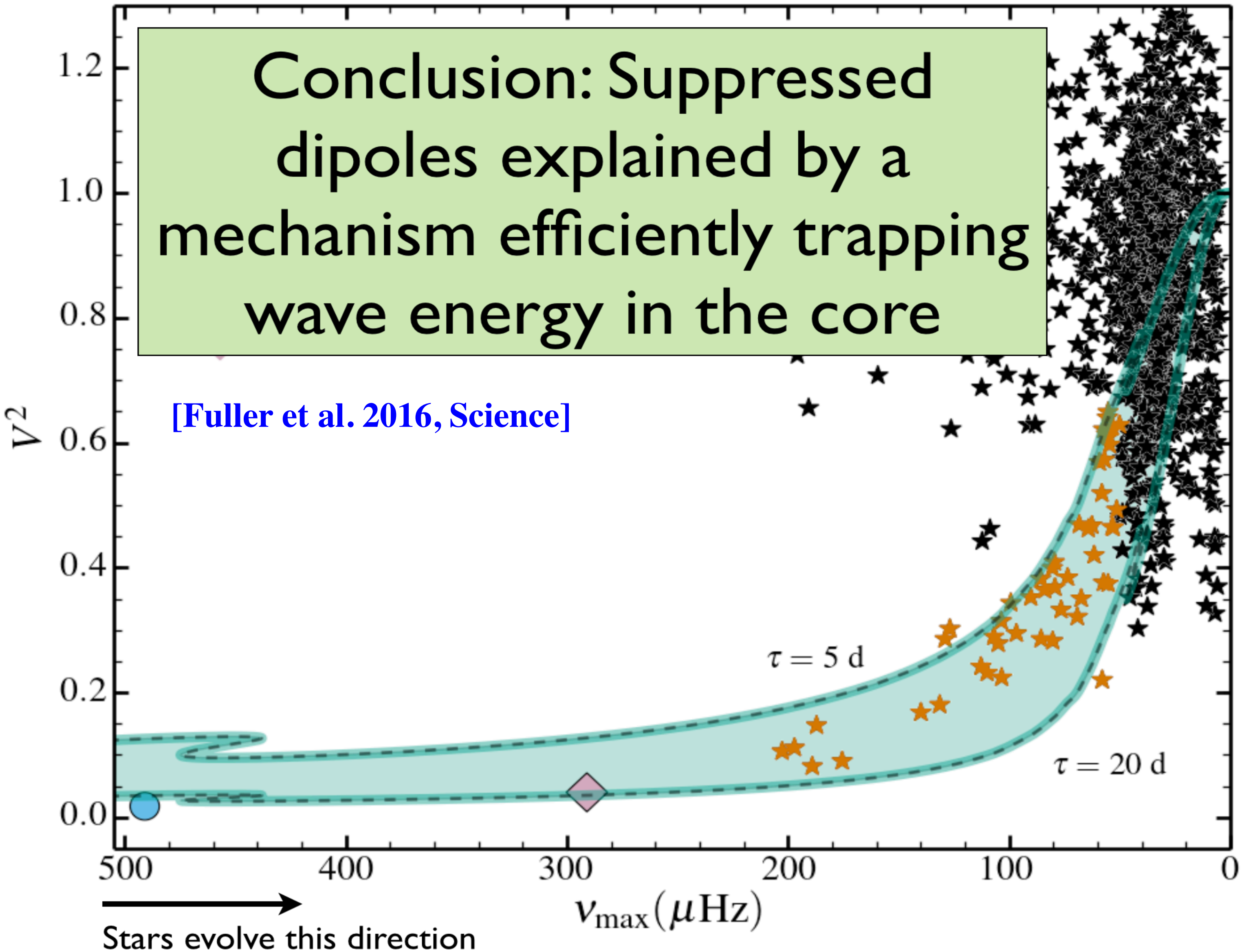
Stars with abnormal (low) dipole modes



Stars evolve this direction

[Stello et al. 2016, Nature]

Internal magnetic field



Internal Magnetic Field

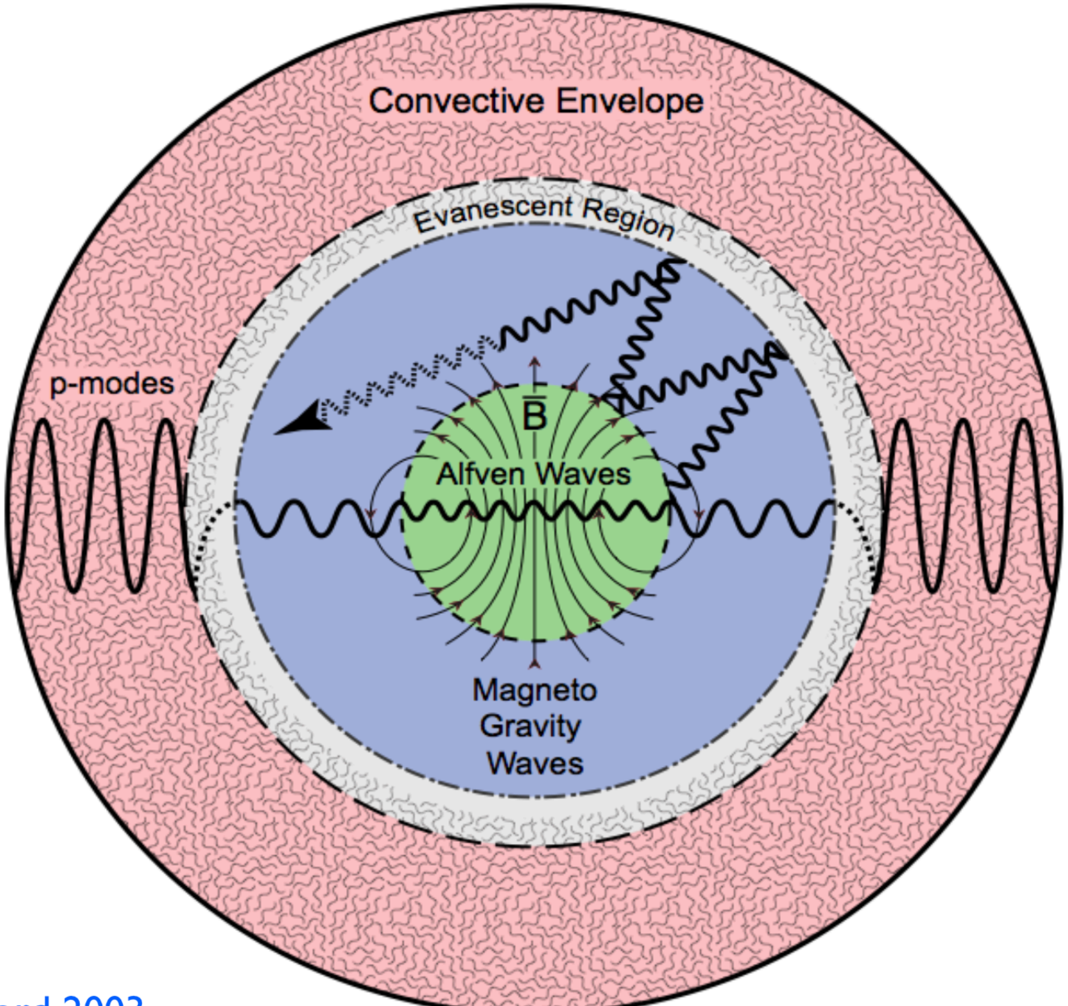
Magnetic Greenhouse Effect

Magnetic fields break spherical symmetry in the core

Dipolar waves "scattered" to high harmonic degrees ℓ

High ℓ waves trapped in the core

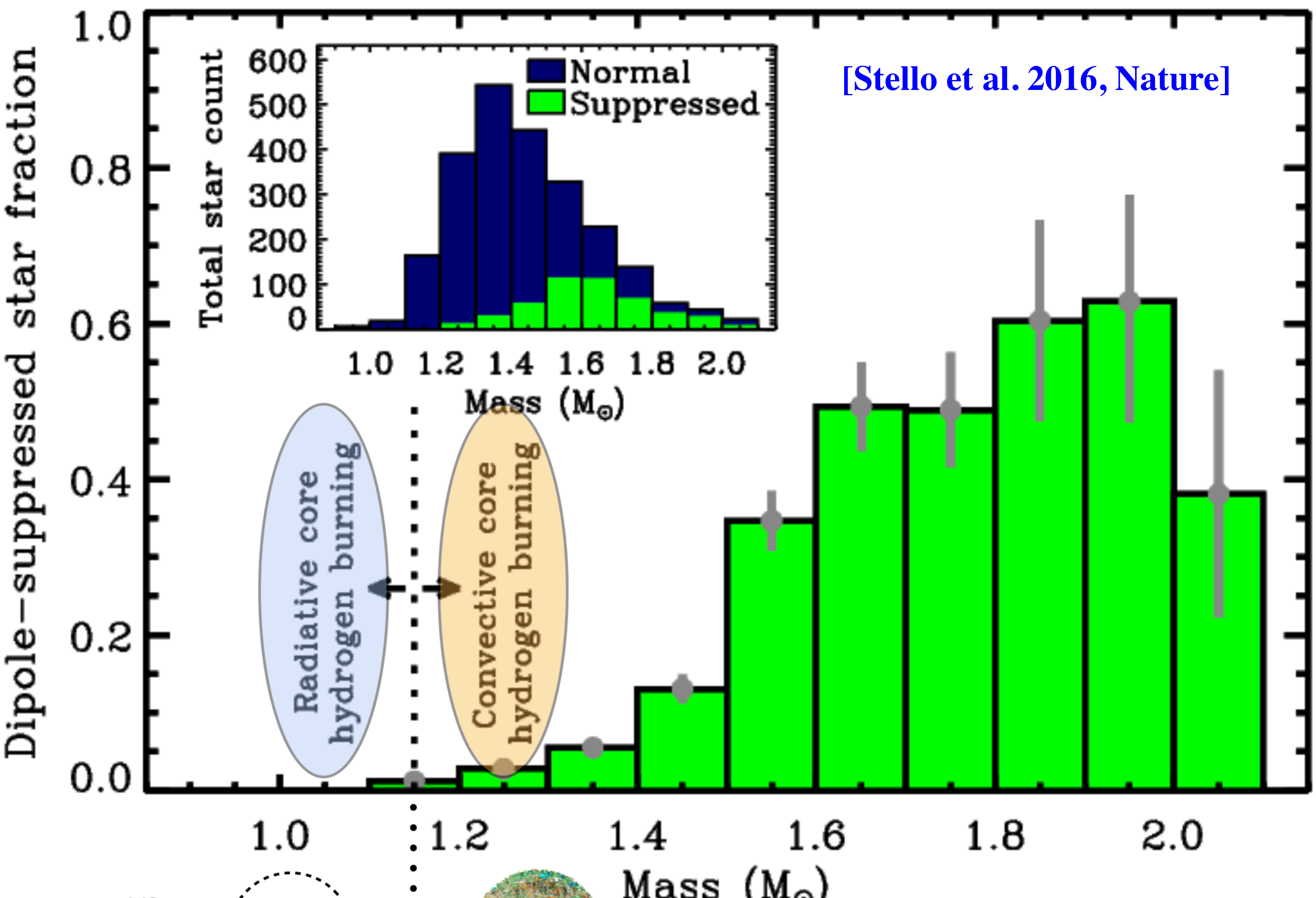
Typical Critical B-field ~ 10^5 G



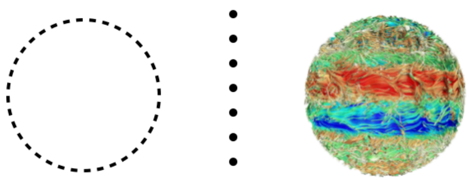
Reese et al. 2004, Rincon & Rieutord 2003, Lee 2007,2010, Mathis & De Brye 2010,2012

[Fuller et al. 2016, Science]

Internal magnetic field

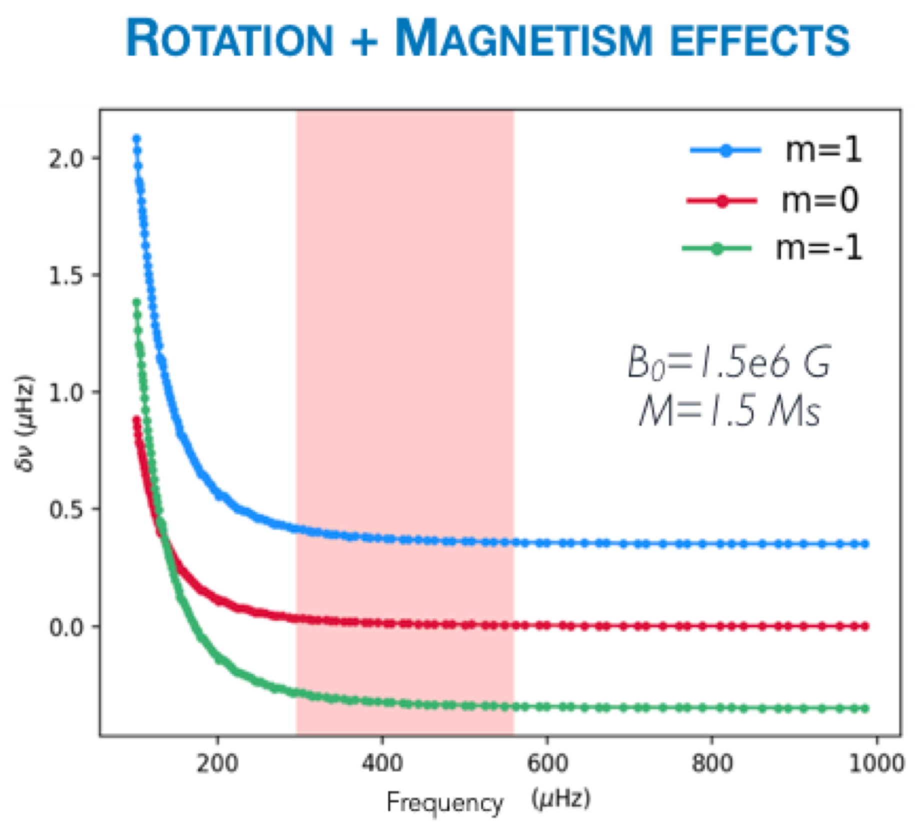


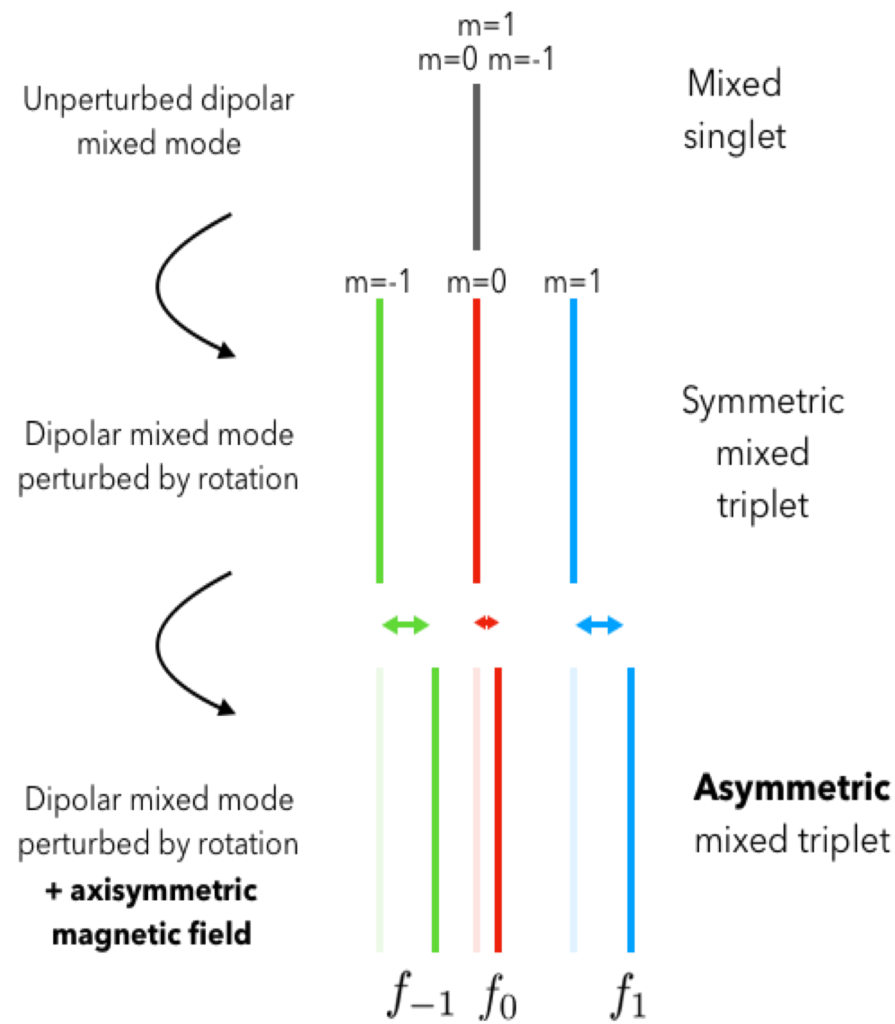
MS: Radiative Cores



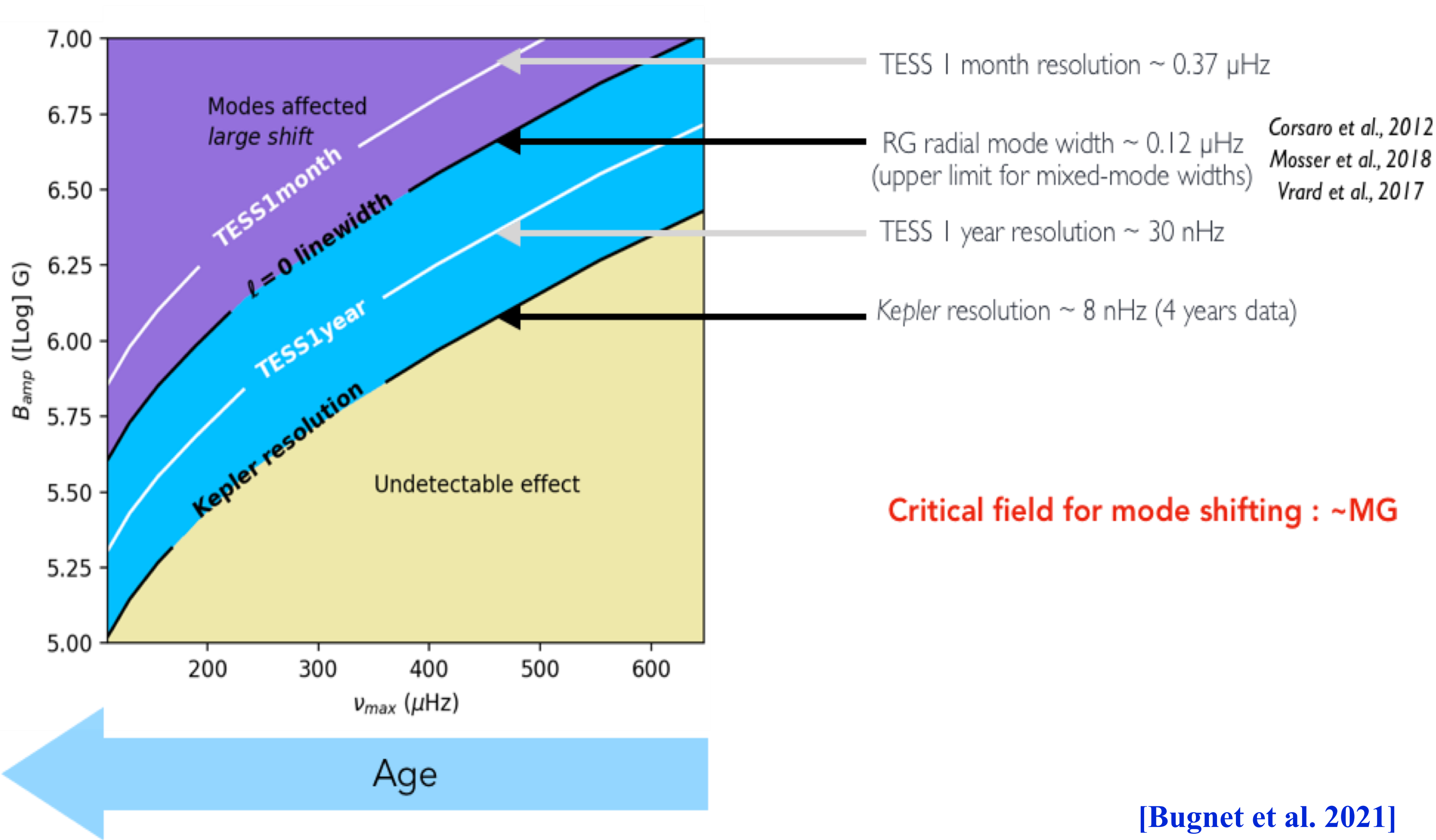
MS: Convective Cores

Effect of rotation & magnetic fields in mixed modes





Conditions for magnetic fields to be detectable



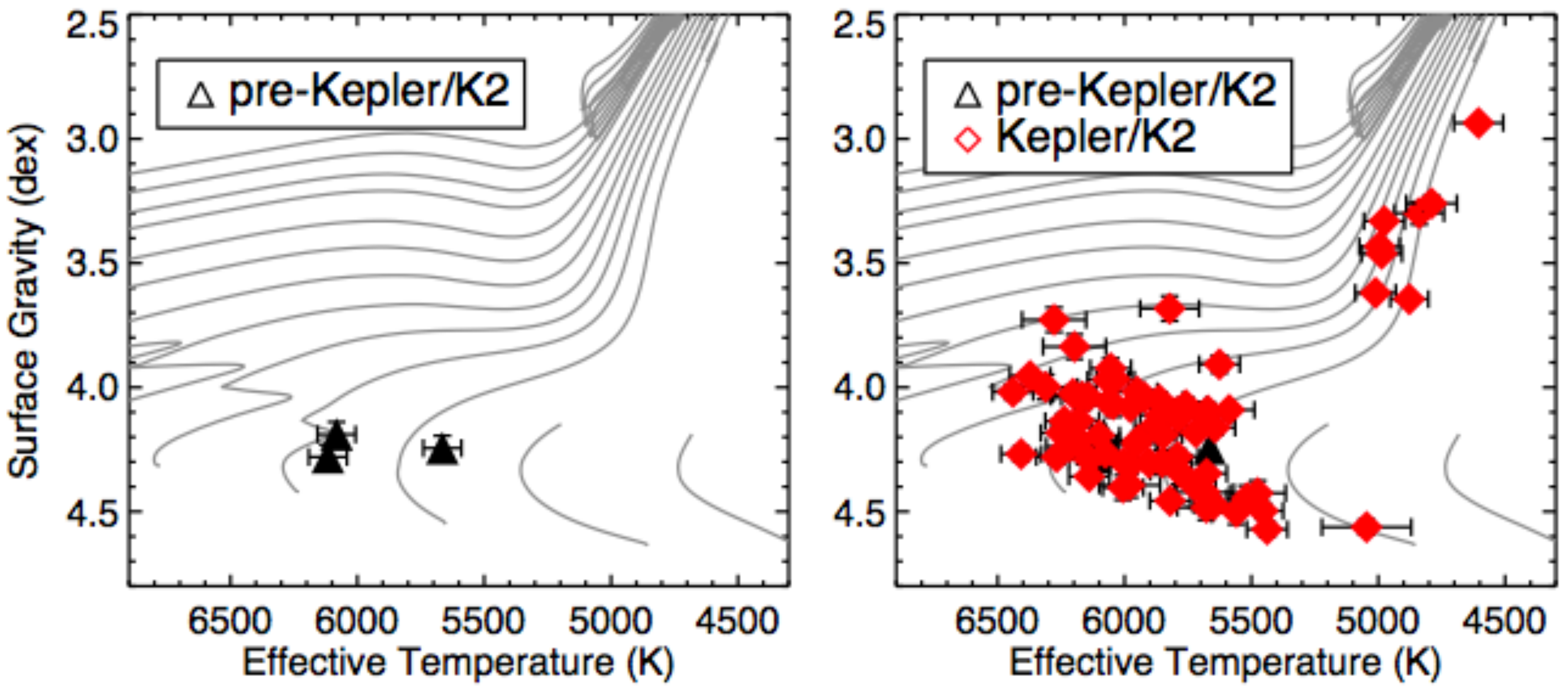
Critical field for mode shifting : ~MG

[Bugnet et al. 2021]

Detected in red giants!! [under embargo.]

Exoplanet characterization

Exoplanet characterization



[Huber 2017]

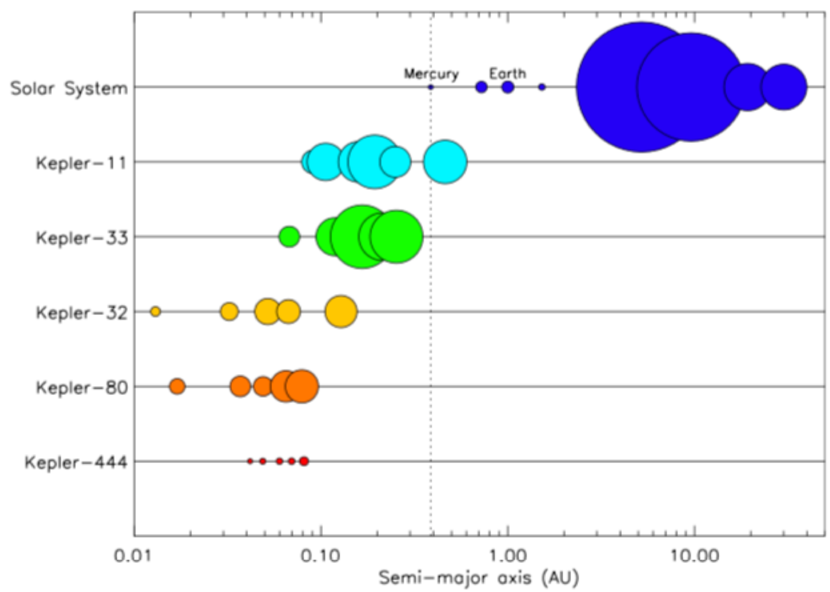
Pre-Kepler: Mu Ara; HD17156 ; HD52265

[Bazot et al. 2005; Bouchy et al. 2005] [Gililand et al. 2011] [Ballot et al. 2011]

Kepler/K2: 70 stars analyzed asteroseismically [e.g. Huber et al. 2013]

Exoplanet characterization

- Precise radii of exoplanets (for transiting planets)
- Precise ages of planetary systems:
  - Kepler-444 oldest system: ~11.2 +/-1 Gyr



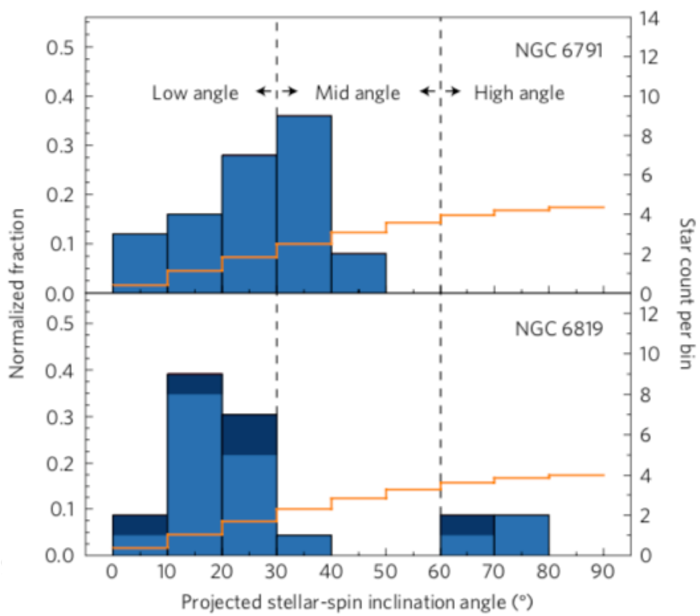
[Campante et al. 2015]

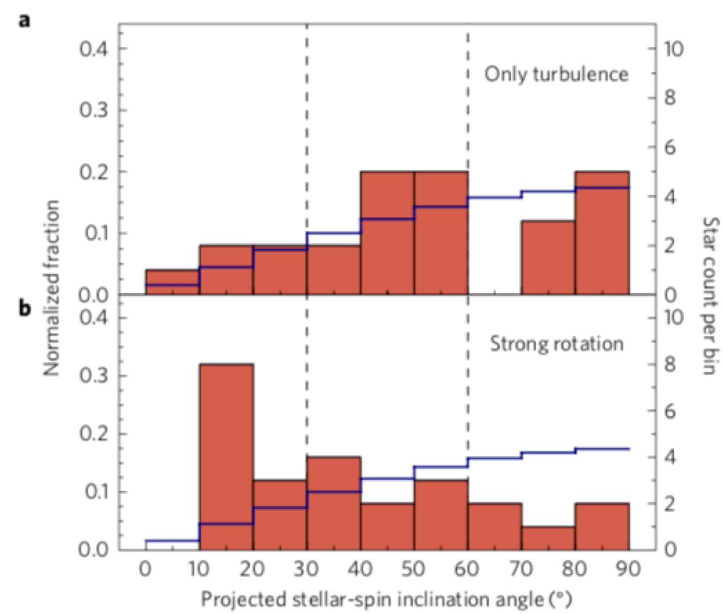
Exoplanet characterization

- Precise radii of exoplanets (for transiting planets)
- Precise ages of planetary systems:
  - Kepler-444 oldest system **[Campante et al. 2015]**
- Obliquities: **[e.g. Chaplin et al. 2013; Albrech et al. 2022]**
  - sin *i* from splittings
  - Transits → coplanarity of systems
  - Low obliquities found for 4 systems with small planets

Clusters formations

- Study of 48 red giants in clusters NGC 6791 and NGC 6819 **[Corsaro et al. 2017, Nat. Astr.]**
  - Splittings measurement: inclination angle
    - ➢ Strong spin alignment
  - Magneto-hydrodynamical simulations of proto-cluster
    - ➢ Introducing global rotation in addition to turbulent velocity
    - ➢ Reproduces better the observations
    - ➢ Cloud's rotational kinetic energy could be responsible for spin alignment

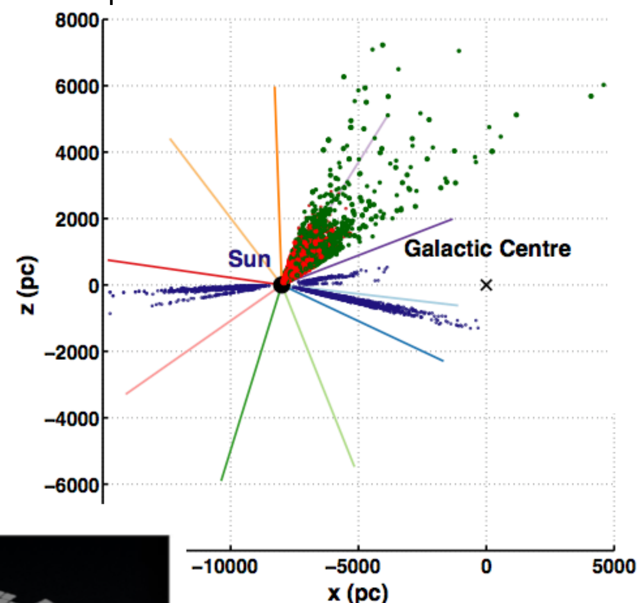


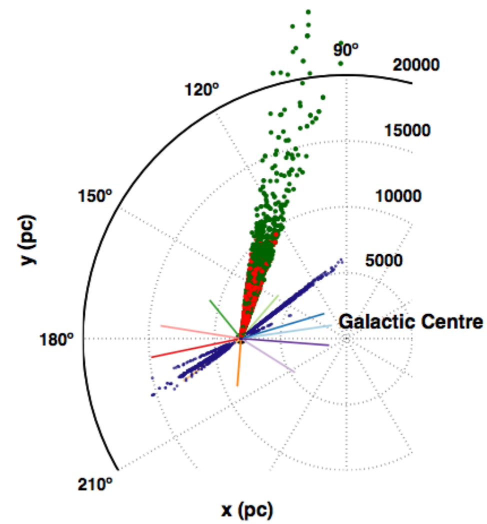


Galactic Evolution

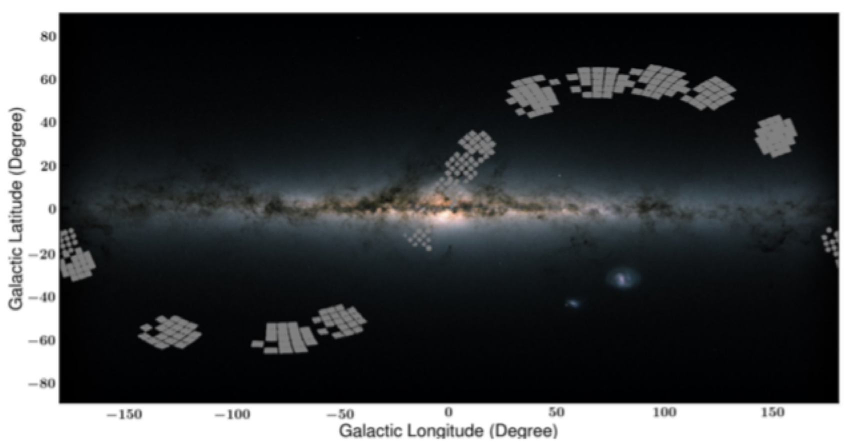
Probing the Milky Way with red giants

Asteroseismic View of the Milky Way





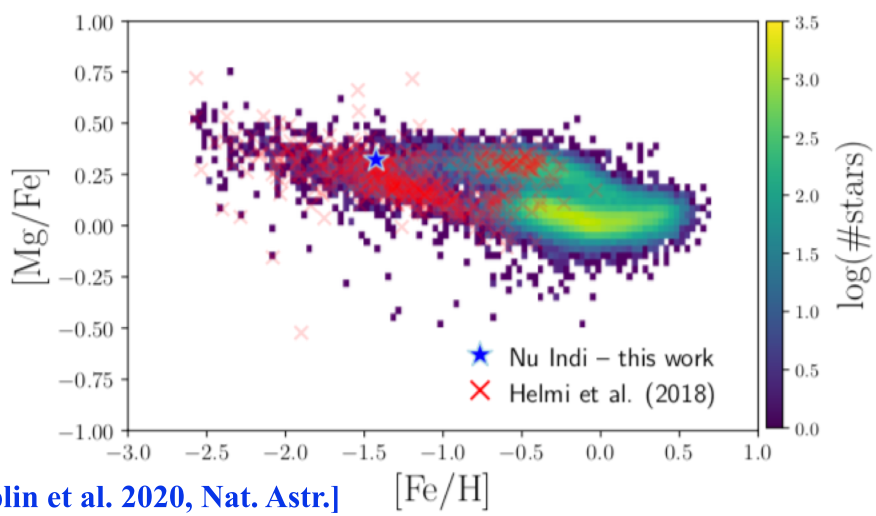
[Mathur et al. 2016]

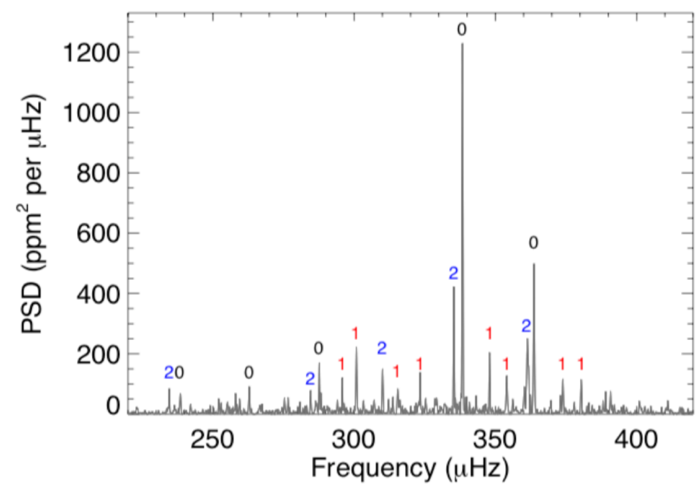


[Zinn et al. 2019;2022]

Gaia-Enceladus collision dating

- Population of stars accreted via the collision with a dwarf galaxy called *Gaia*-Enceladus
- Star ν Indi observed by TESS
  - Identified as being part of the *Gaia*-Enceladus collision of the Milky Way
  - Mode detection with TESS data
  - Seismic modeling: age = 11+/-0.7 (stat) +/- 0.8 (sys) Gyr
  - Time of the merger 11.6-13.2 Gyr ago





[Chaplin et al. 2020, Nat. Astr.]

Summary

Ideas to take home

1. Different types of pulsations.
2. Seismology is a unique tool that allows us to directly probe the solar/stellar interior: structure and dynamics.
3. Provides constraints on angular momentum transport, evolutionary states, internal rotation, magnetic fields, magnetic activity…
4. Impact on planetary systems characterization, galaxy studies, clusters formation…