# Class 2: Sizing, Weighing, and Ageing Stars

Image credit: NASA's Goddard Space Flight Center/S. Wiessinger

**2019 Oort Graduate Lectures**

**Conny Aerts@Leiden University, NL**

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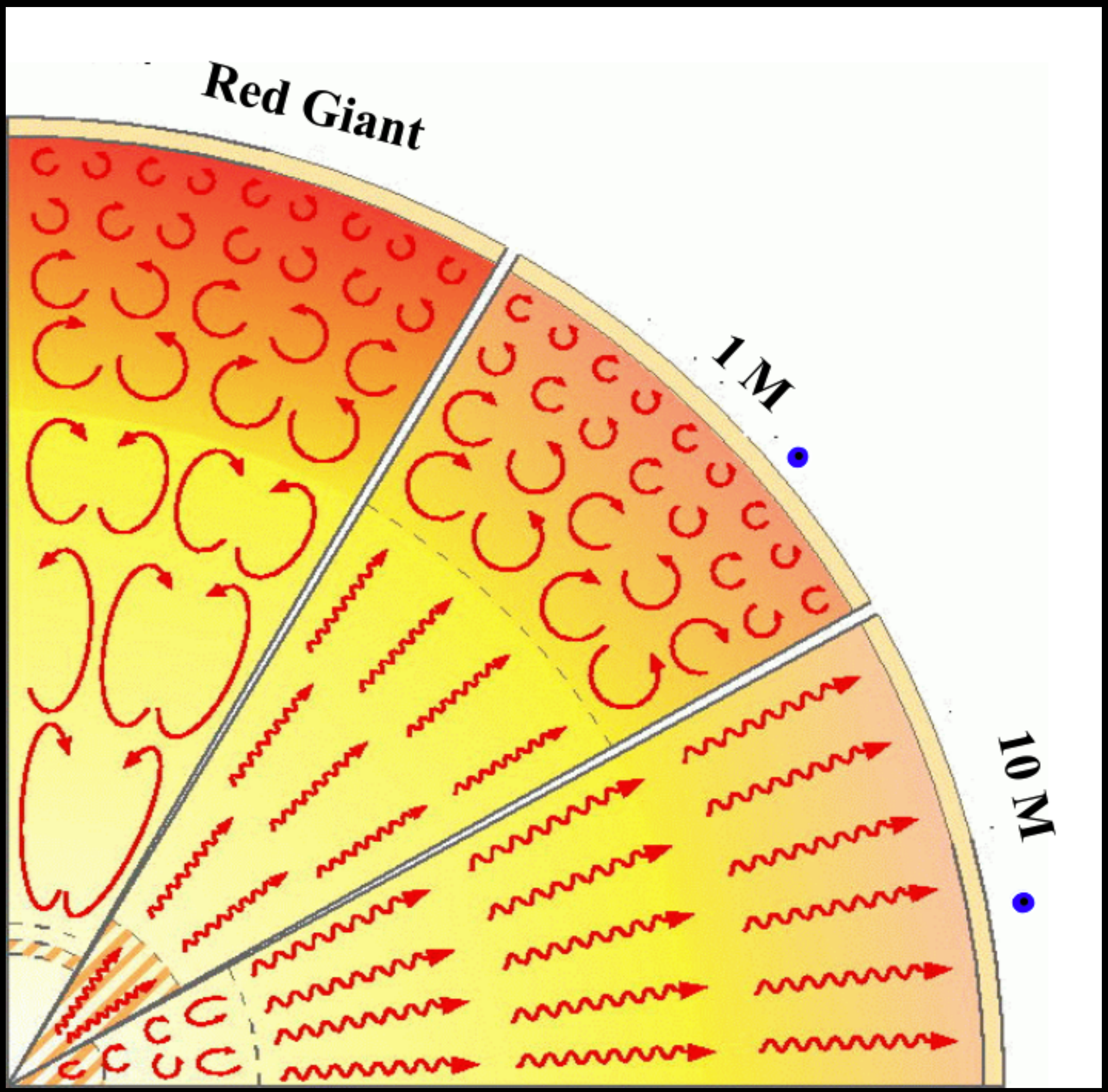
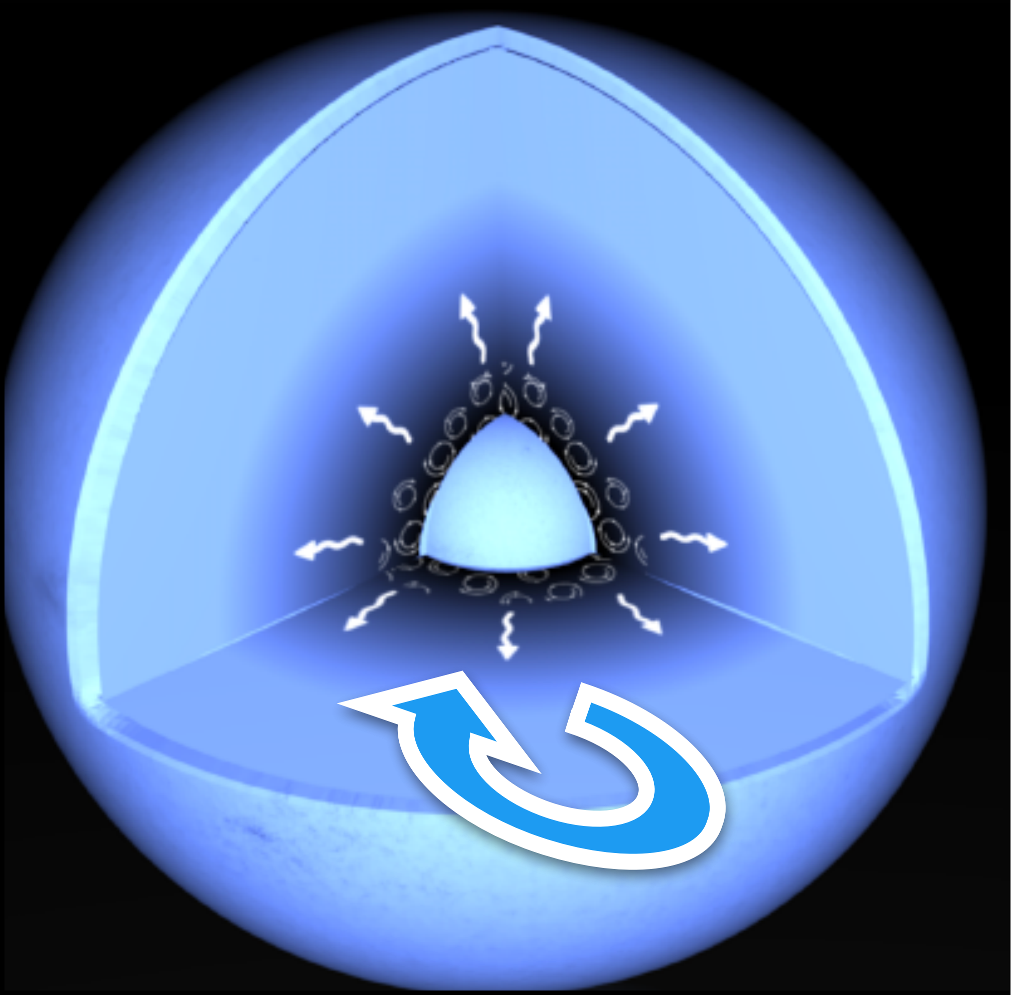
# Rotation? Convection? Mixing?



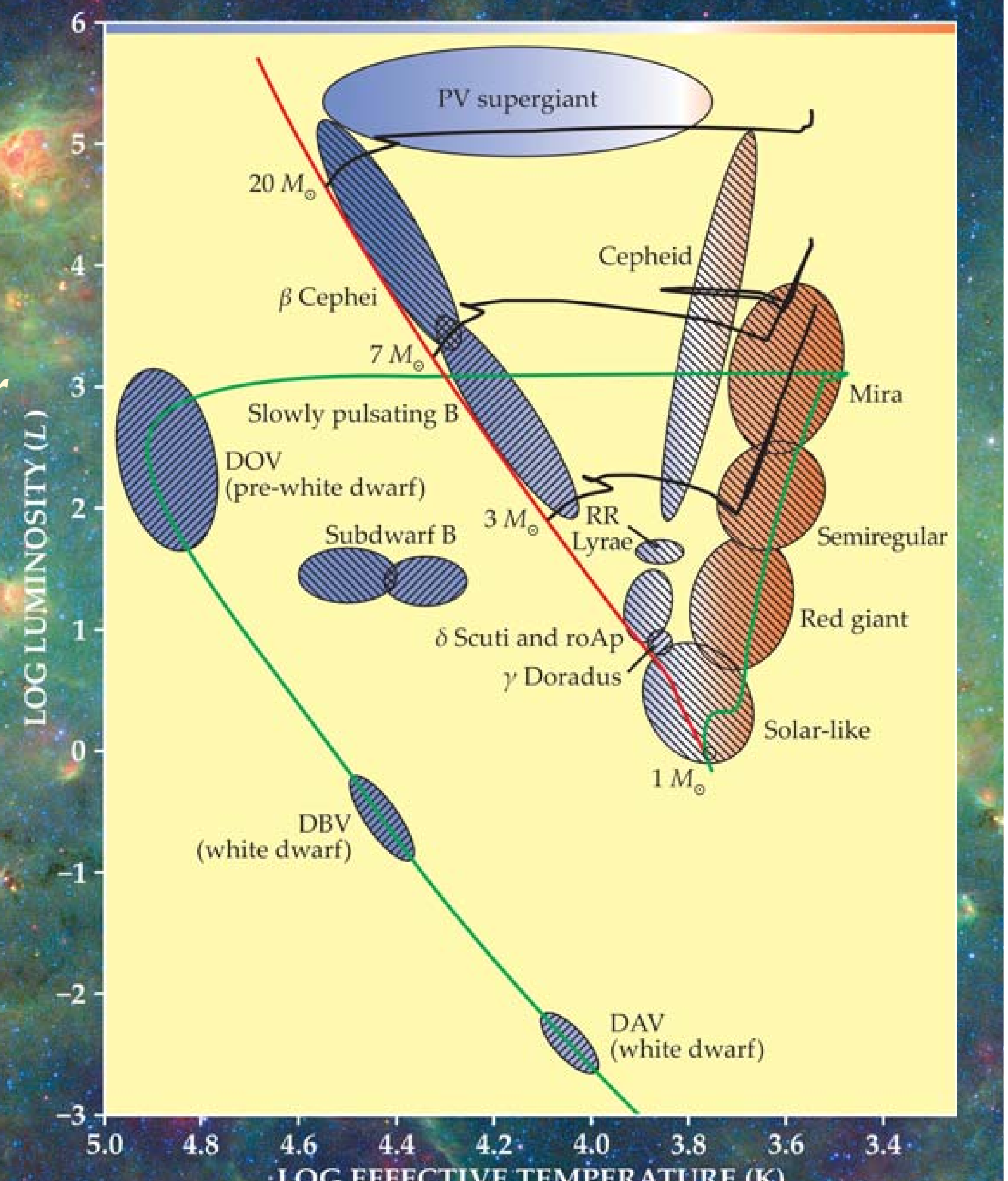
**Life determined by uncalibrated interior physics**

# Lots of open ? in stellar physics

Stellar evolution = tested from *surface properties* while life directed by *stellar interior*

*Connection* between life of host star and its exoplanets?

*Stellar versus dynamical* evolution of our Milky Way?




From C. Aerts, Physics Today, May 2015

# 3D Mode Properties

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**Perturb spherically symmetric equilibrium model**

time $\longrightarrow$ frequency (period) of mode
geometry $\longrightarrow$ spherical harmonic + radial order

$$\xi(r,\theta,\phi,t) = [(\xi_{r,nl}e_r + \xi_{\mathrm{h},nl}\nabla_{\mathrm{h}})Y_l^m(\theta,\phi)]\exp(-\mathrm{i}\omega t)$$

**Inferences of properties of stellar interiors via modes**

a) requires frequencies & identification of (l,m) of as many modes as possible from data, where the frequency precision is ~(1/total time base)

b) can only probe regions where modes are propagative

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# Asteroseismic Modelling

THEORY

mass, metallicity, age + convection? magnetism? mixing? rotation?

↓

STELLAR MODEL FOR SPECIFIED INPUT PHYSICS

↓

Theoretical predictions for oscillations

↔

OBSERVATIONS

Space photometry, high-res. spectroscopy, Gaia astrometry

↓

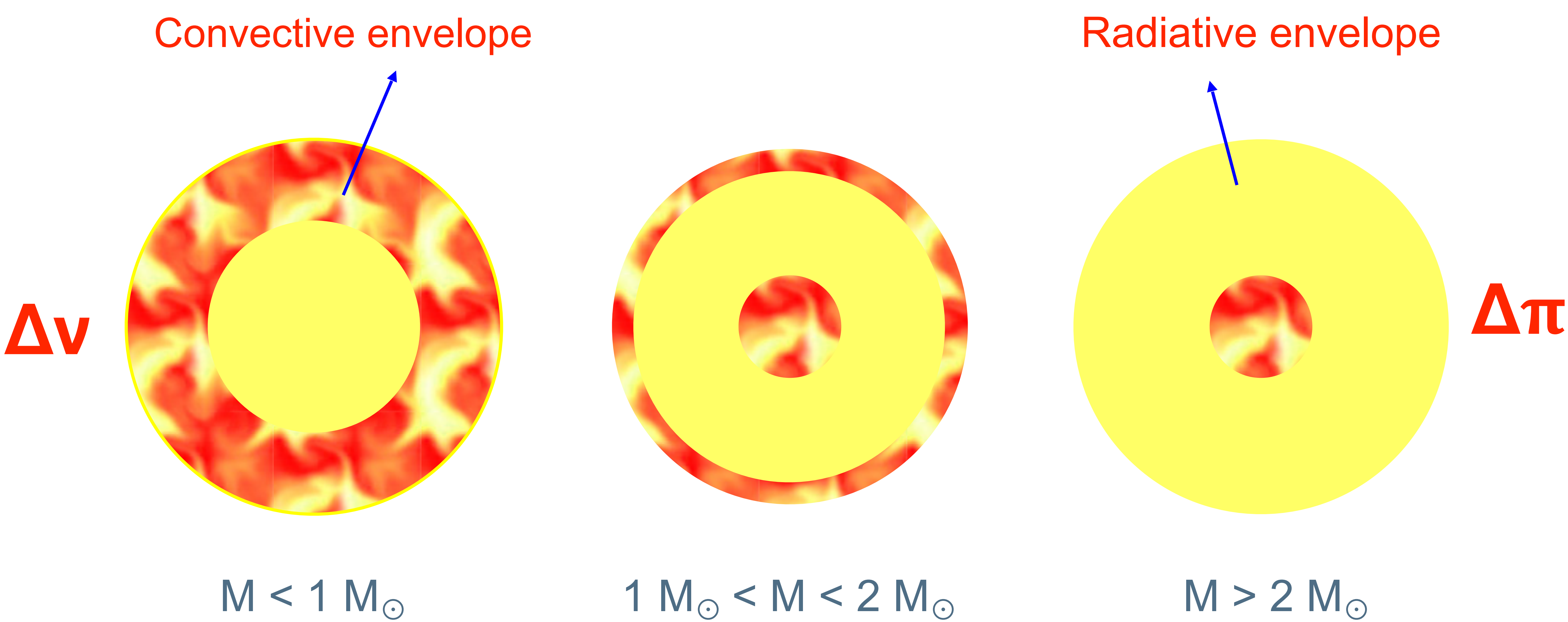
Observed properties of identified modes

**Two Major Aims (classes 2&3):**

**A) High-precision M, R, age, Z**

**B) Improve Input Physics: AM, Dmix(r)**

# Asymptotics: high/low frequencies




**Major unknowns: $M_{core}$ (r,t) & $D_{mix}$ (r,t) & $\Omega_{rot}$ (r,t)**
**extent & shape of convective boundary mixing?**
**microscopic & macroscopic envelope mixing?**

Radboud Universiteit Nijmegen

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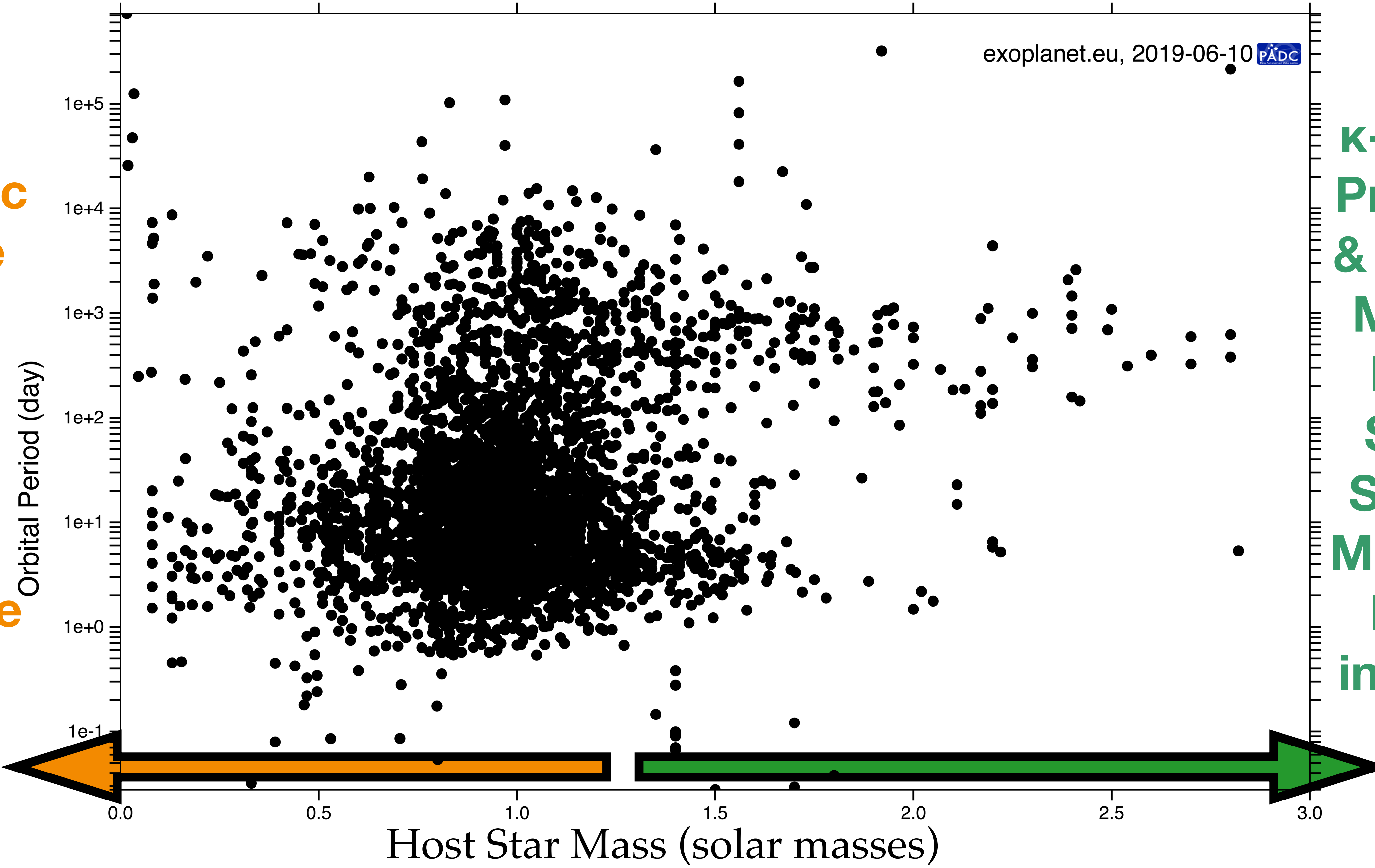
# (Exoplanet host) stars: mass & magnetism

Stochastic Pressure Modes; Highly-Variable Dynamo Fields at Surface > 50%

κ-Driven Pressure & Gravity Modes; Fossil Stable Surface Magnetic Fields in < 10%



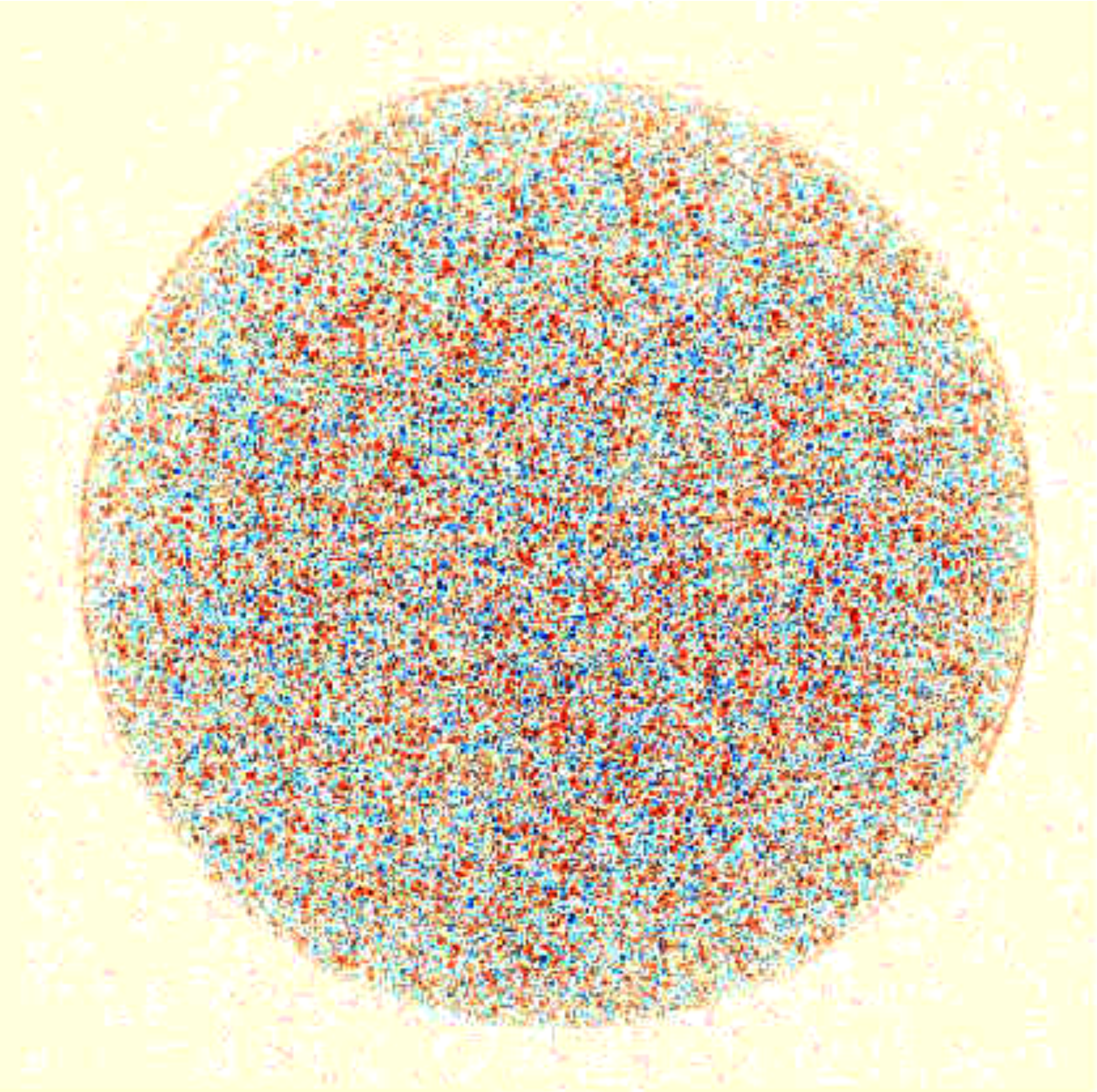

GKM

OBAF

Gyrochronology: Surface rotation & Age

Envelope rotation from split p-modes; core rotation from tilt in (Δπ, P)

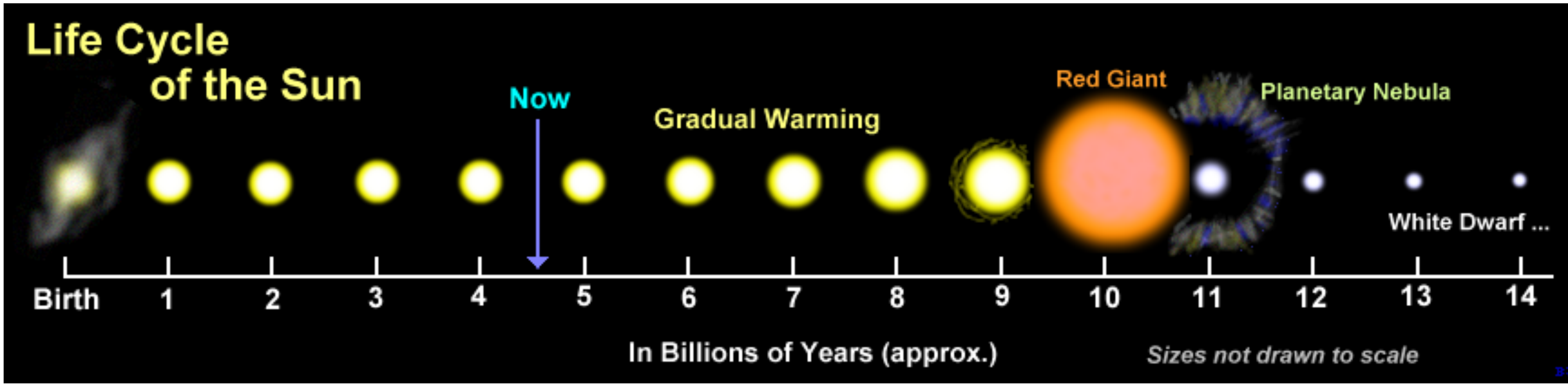
# Dopplermap of the Sun

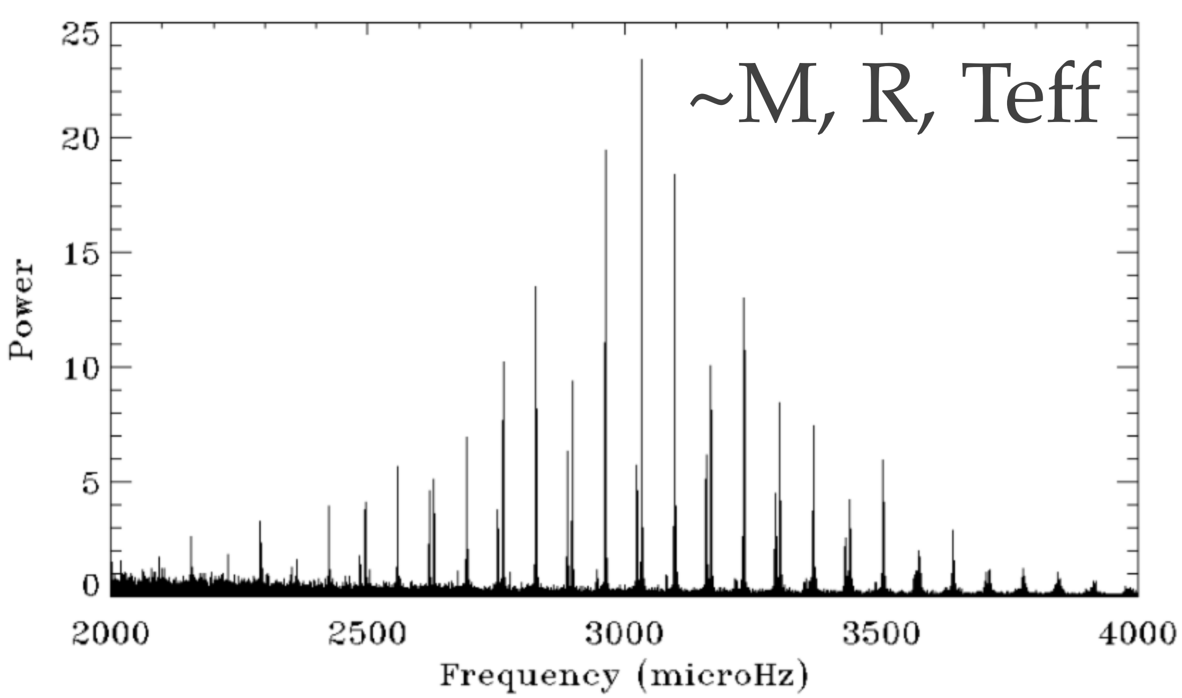


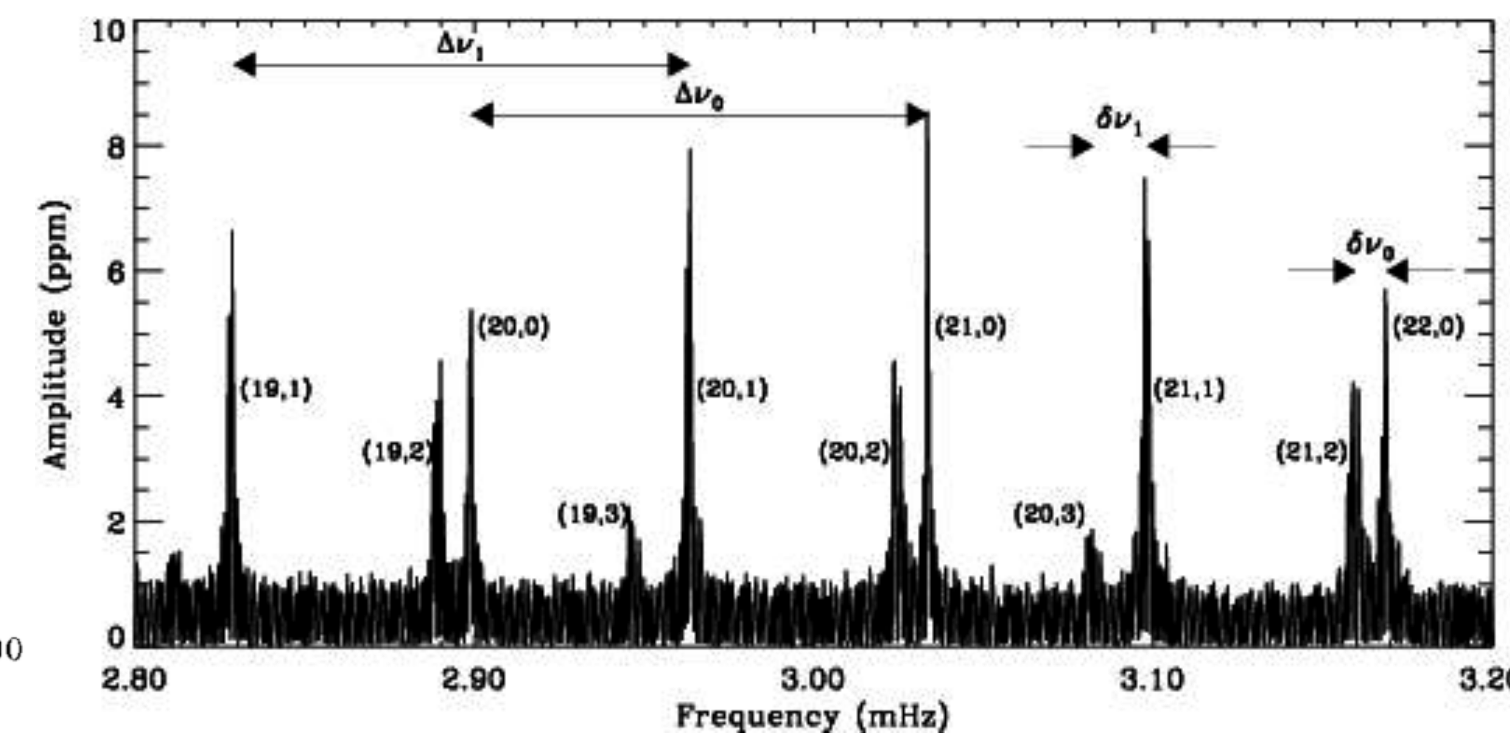
The Sun oscillates in thousands of non-radial p-modes with periods of ~5 minutes: modes visible from resolved surface

The Dopplermaps give integrated velocities of the order of some cm/s

# The Showcase of Helioseismology



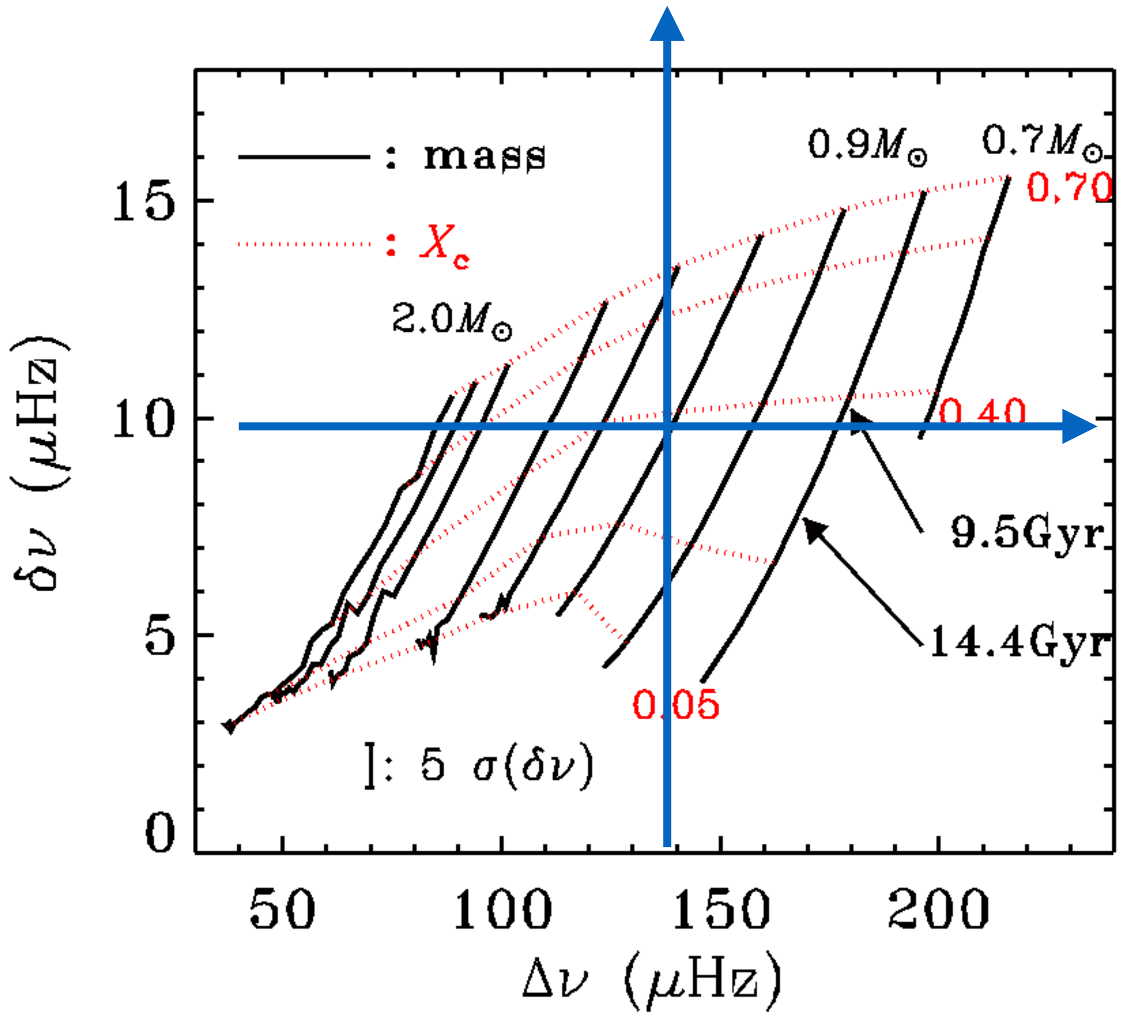




Effects of rotation and magnetism on modes can be ignored (m=0)

# Asteroseismic HRD (JCD)

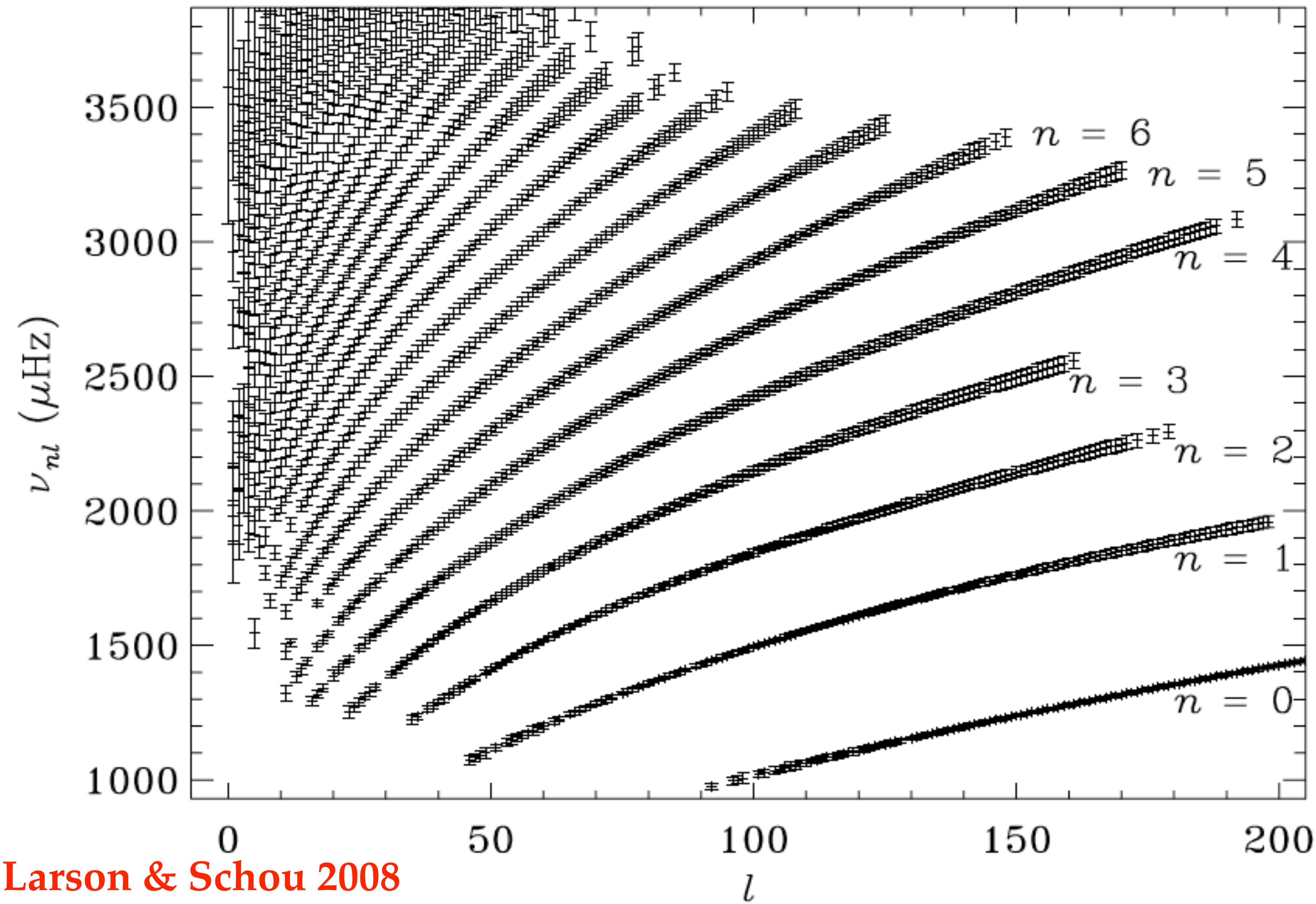
Large frequency separation: measure of sound speed
Small frequency separation: measure of discontinuities in the sound speed

Ageing from helioseismology alone is model dependent




Calibration, e.g., via meteorites, is better than 0.1% for "model S" (JCD et al.,1996)

# Rotational splitting of solar p-modes




Larson & Schou 2008

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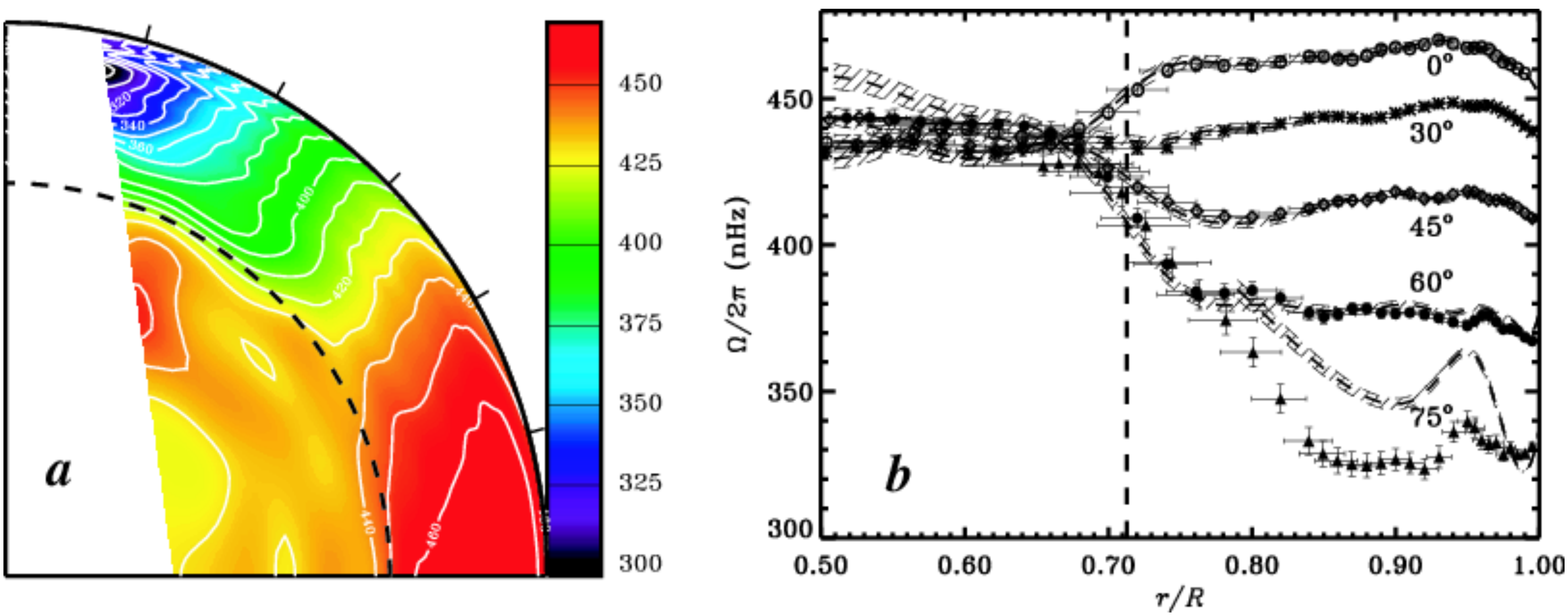
# Interior solar rotation

1st-order perturbative method: Ledoux splitting into 2l+1 components

$$\nu_{n,l,m} = \nu_{n,l} - m \int_0^R \int_0^\pi \Omega(r,\theta) K_{n,l}(r,\theta) dr + \Theta\left(\Omega^2\right)$$




Magnetic splitting (l+1) is negligible for Sun's magnetic field

# Weighing & Sizing Stars

THEORY

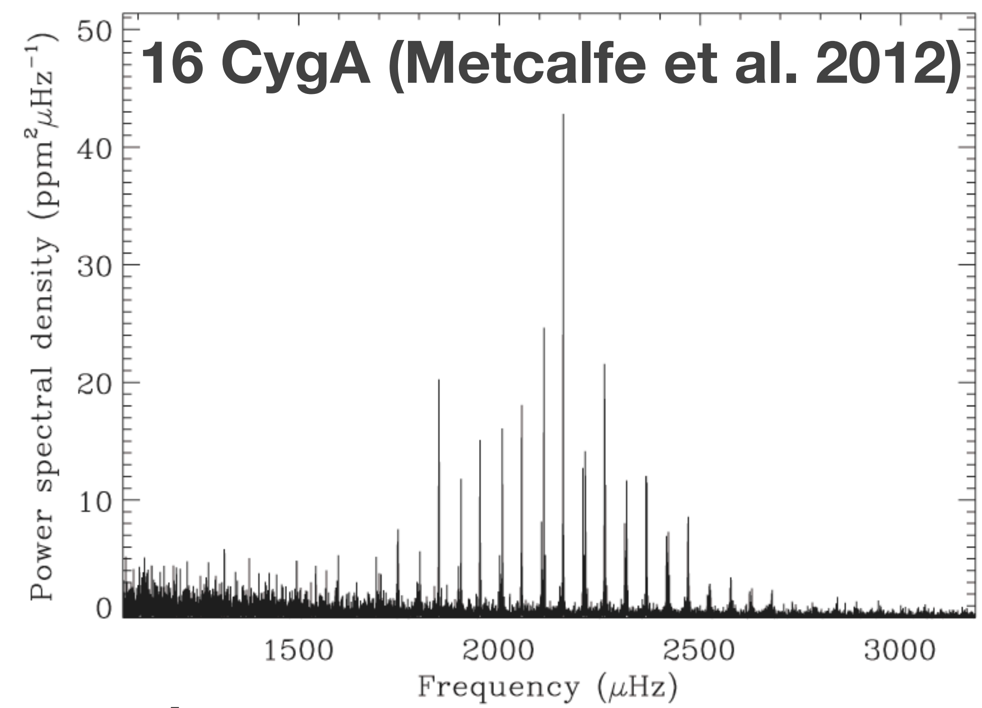
**mass, metallicity, age**

**STELLAR MODEL FOR SOLAR-LIKE INPUT PHYSICS**

**Theoretical predictions for oscillations**

OBSERVATIONS

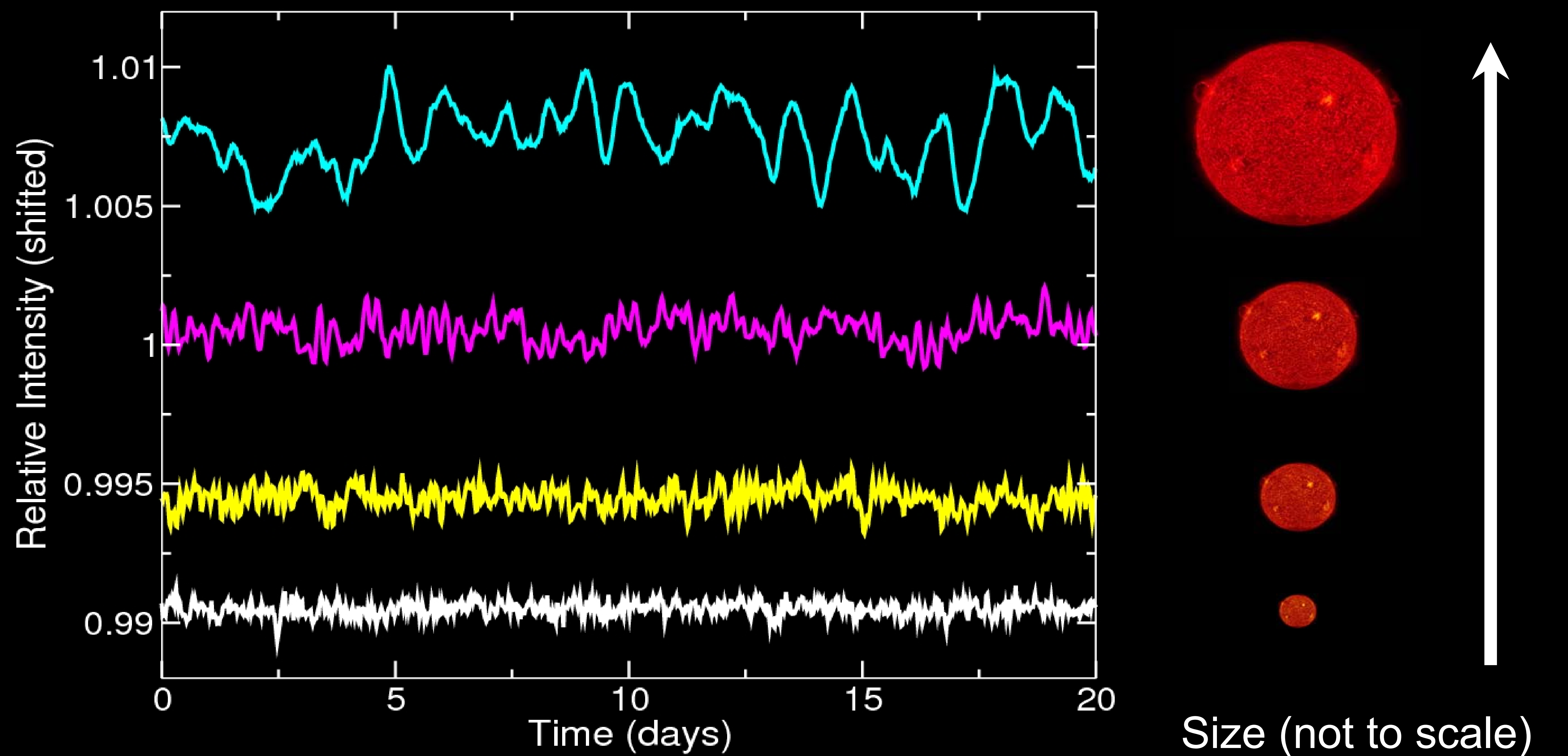
**Kepler photometry**
**Teff from spectroscopy**




**Observed properties of oscillations**

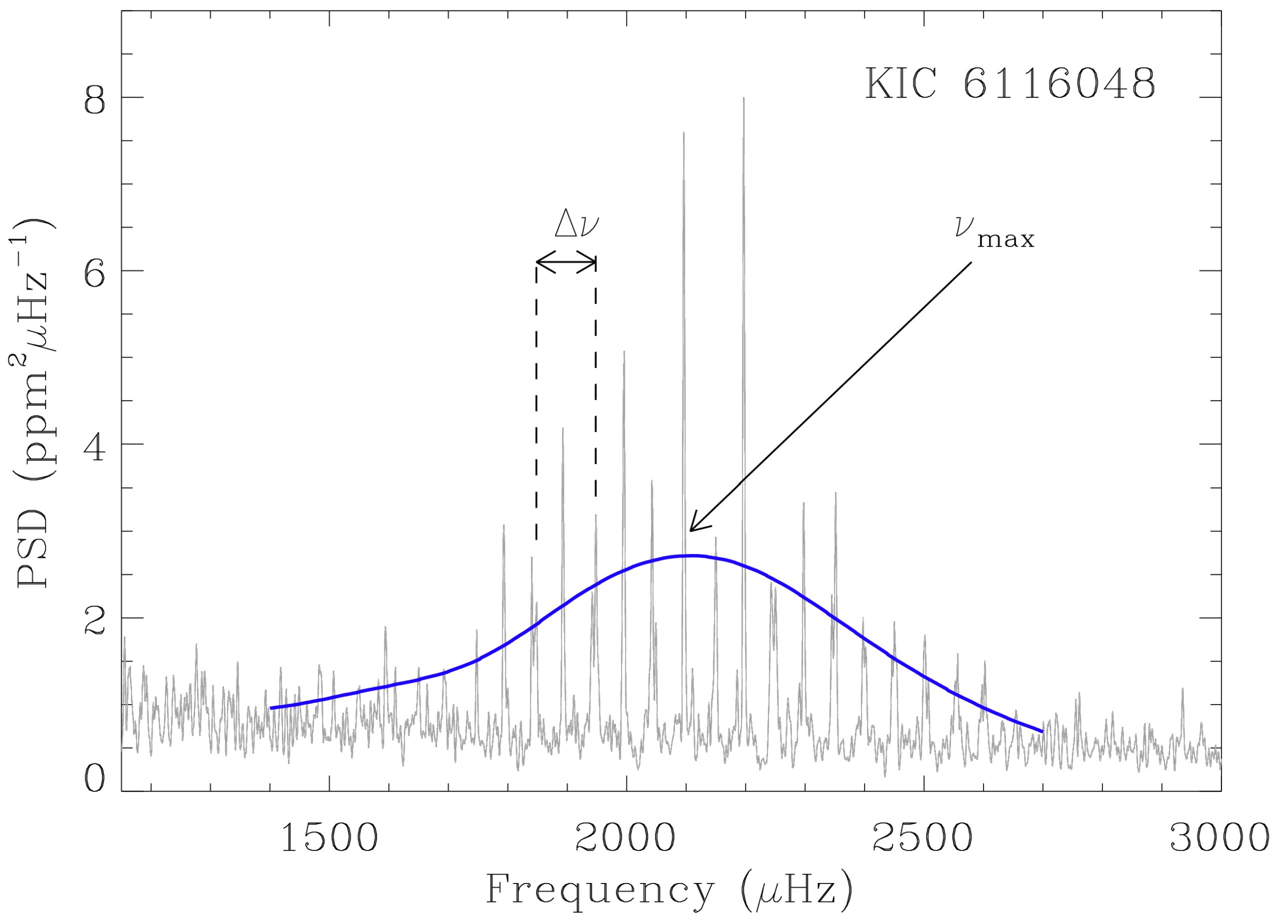
# Size Does Matter!

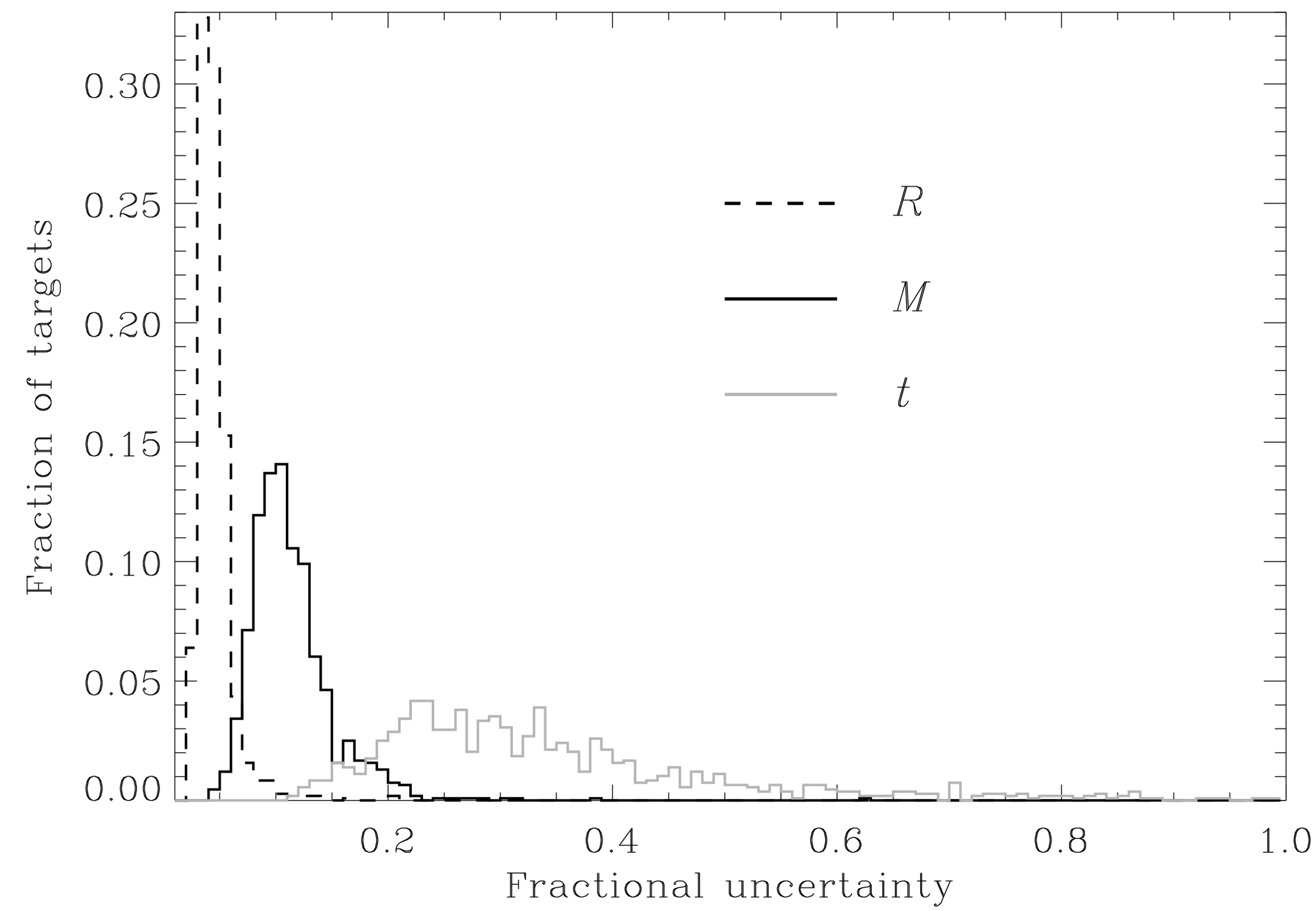
$$\frac{\Delta\nu}{\Delta\nu_\odot} = \left(\frac{M}{M_\odot}\right)^{\frac{1}{2}} \left(\frac{R}{R_\odot}\right)^{-\frac{3}{2}} \qquad \frac{\nu_{\rm max}}{\nu_{\rm max,\odot}} = \frac{M}{M_\odot} \left(\frac{R}{R_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{-\frac{1}{2}}$$




Slide courtesy of Daniel Huber

# Kepler data: SLO in 500+ dwarfs

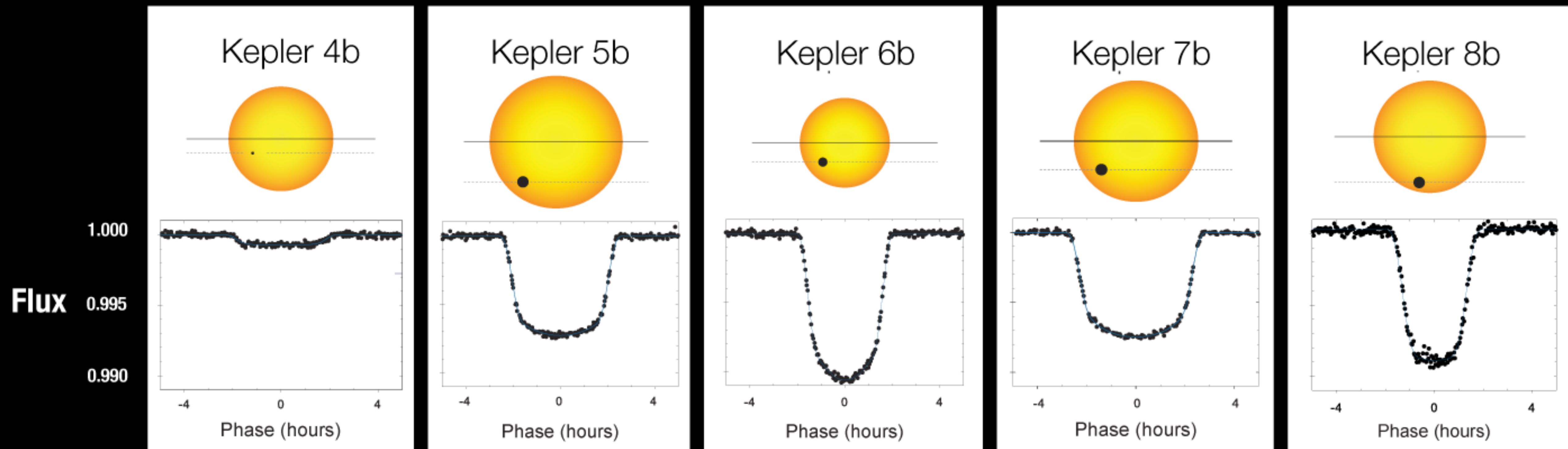



$$\frac{\nu_{max}}{\nu_{max,\odot}} = \frac{M}{M_\odot}\left(\frac{R}{R_\odot}\right)^{-2}\left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{-\frac{1}{2}} \qquad \frac{\Delta\nu}{\Delta\nu_\odot} = \left(\frac{M}{M_\odot}\right)^{\frac{1}{2}}\left(\frac{R}{R_\odot}\right)^{-\frac{3}{2}}$$

**No asteroseismic modelling of frequencies, but “scaling of solar physics” (Chaplin et al. 2014)**

# Transit Light Curves




| | Kepler 4b | Kepler 5b | Kepler 6b | Kepler 7b | Kepler 8b |
|---|---|---|---|---|---|
| **Orbital Period (days)** | *3.2 days* | *3.5 days* | *3.2 days* | *4.9 days* | *3.5 days* |
| **Size ($R_E$)** | *4.31* | *18.8* | *15.0* | *16.9* | *18.3* |

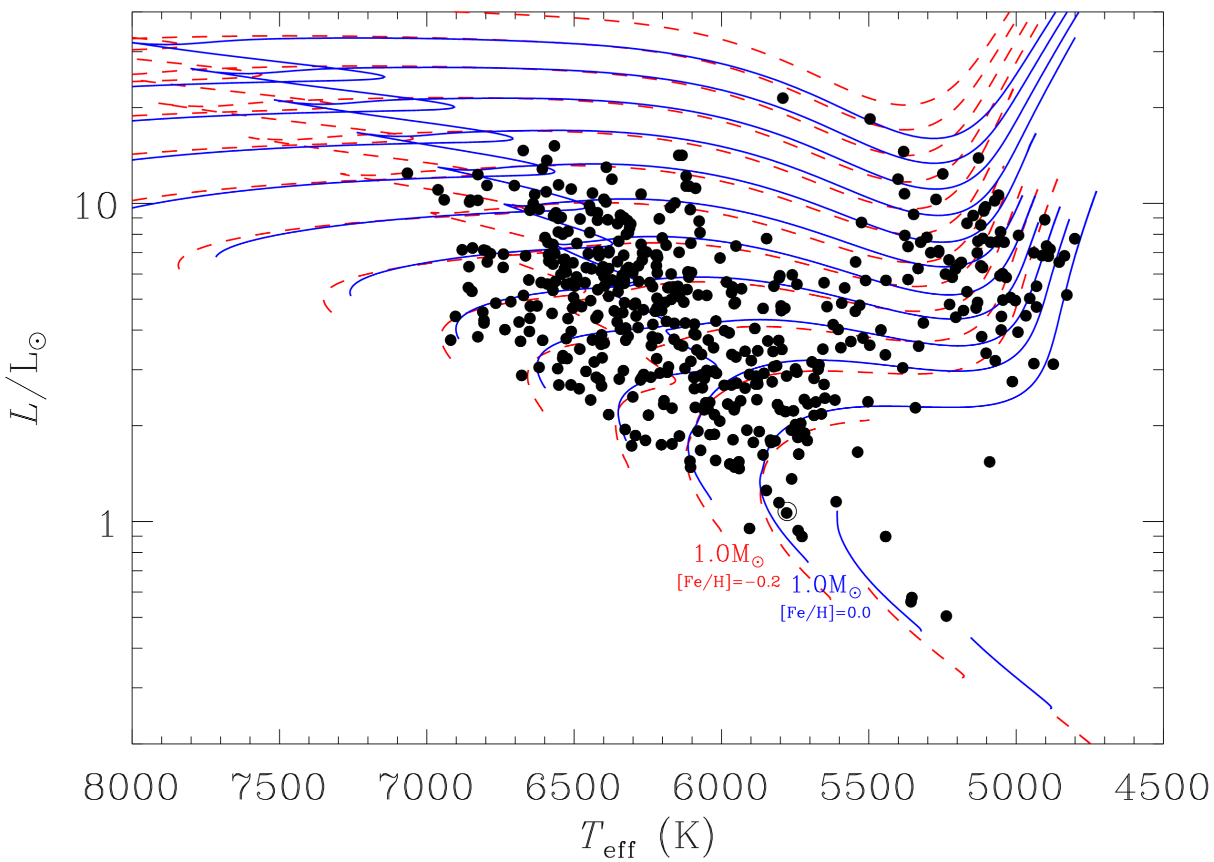
**Radius of exoplanet requires radius of host star!**

**Asteroseismology to the rescue** 😉

Slide courtesy of W. Borucki, NASA

# Asteroseismology & Exoplanets

- Delivery of **seismic mass, radius, age** for **exoplanet host stars** for understanding of exoplanetary systems

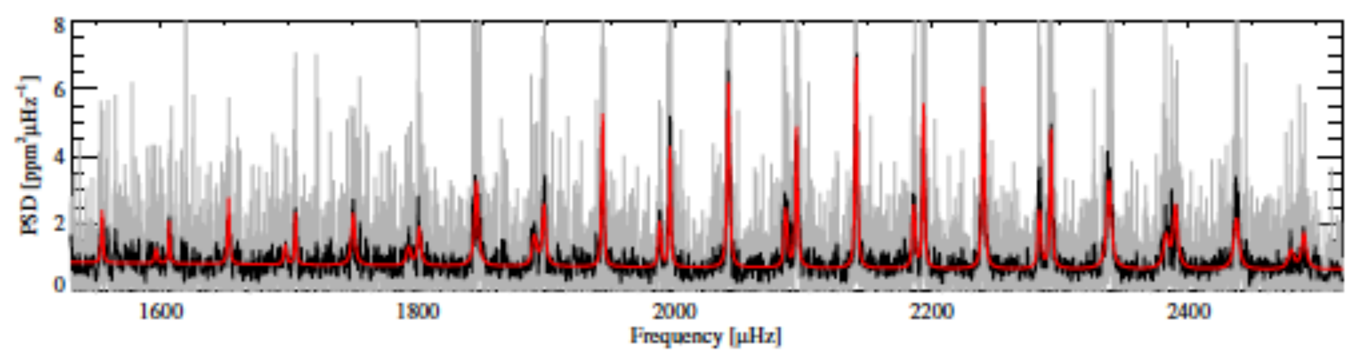



**Ballot et al. (2011), Lebreton & Goupil (2014):**

**HD 52265 (CoRoT), a G0V type, planet-hosting star modelled for various choices of input physics**

**Radius: 1.32 ± 0.02 $R_{sun}$,**
**Mass: 1.23 ± 0.09 $M_{sun}$,**
**Age: 2.32 ± 0.22 Gyr**

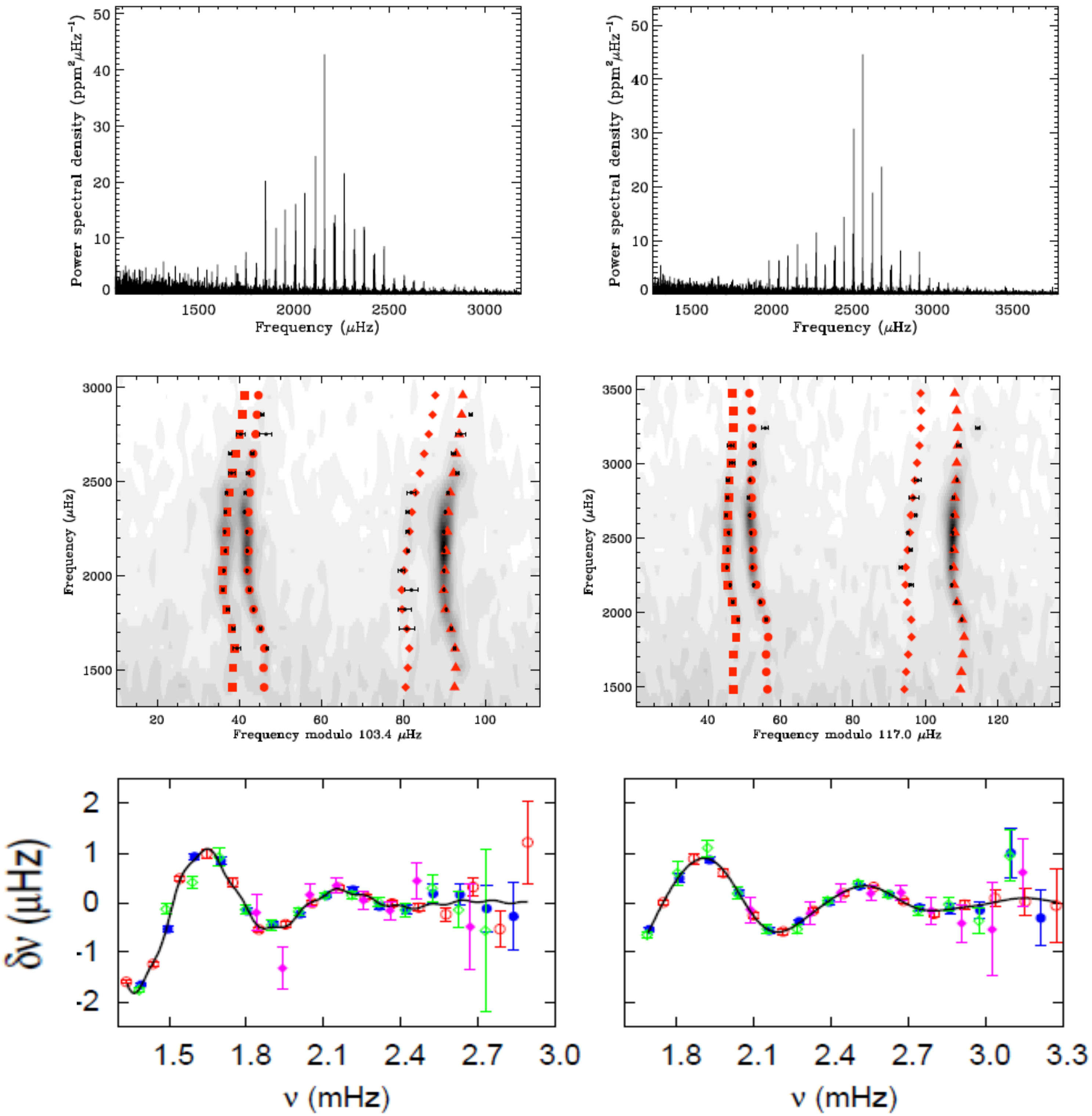
**Improves planet parameters!**




**Ensemble asteroseismology + spectroscopy for Kepler legacy sample (66 stars): M: 4%, R: 2%, age: 10%**

**(Chaplin et al. 2014; Silva Aguirre et al. 2017)**

# Asteroseismic modelling for SLO



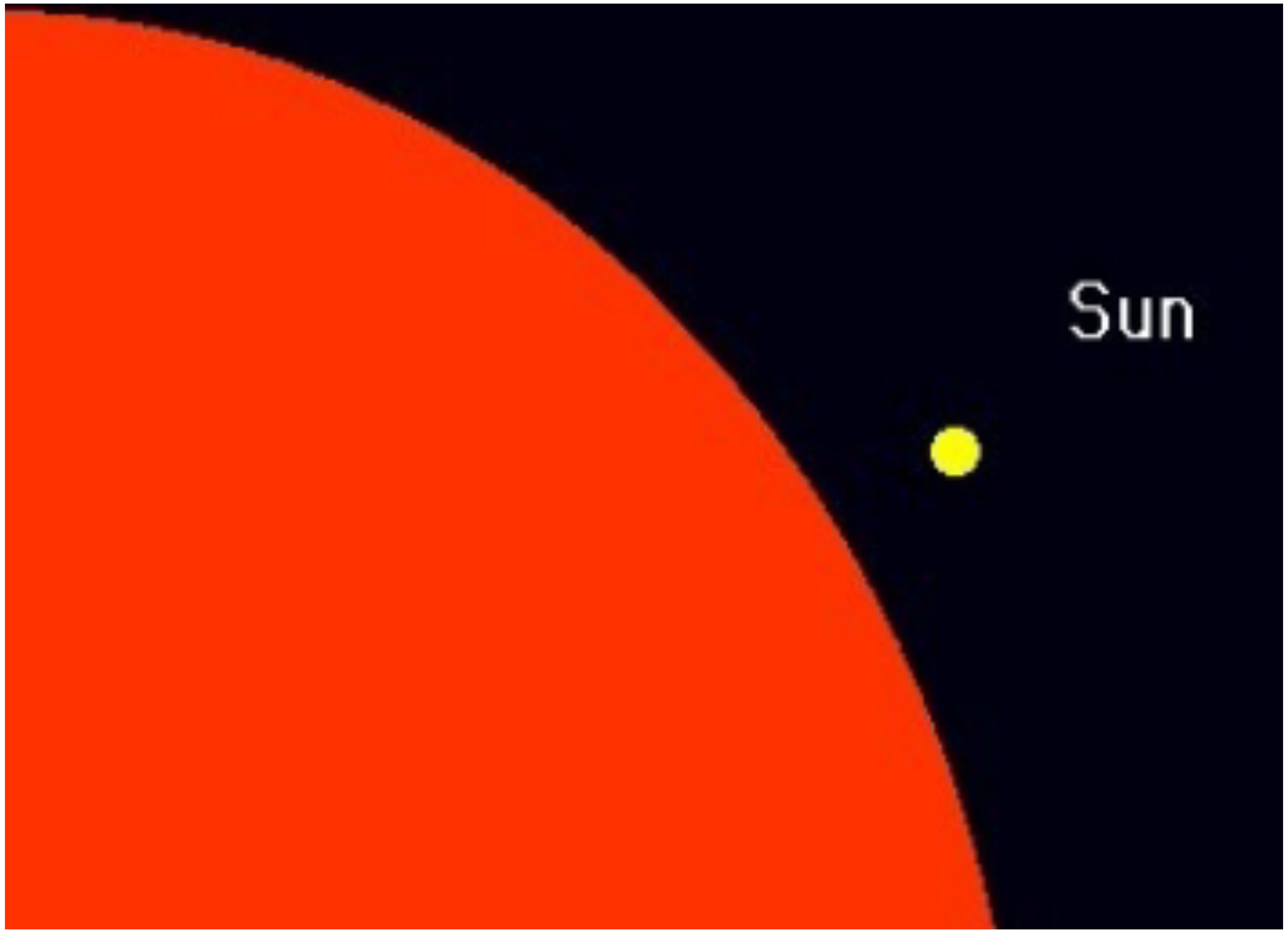

**16 Cyg A&B, *Kepler*, Metcalfe et al. (2012)**

**Seismic Helium abundances of 0.24±0.01(2) for A(B) Verma et al. (2014)**

**Analysis of acoustic glitches (sharp features): gives depth of convective envelope & extent of He ionisation zone (Mazumdar et al. 2014)**

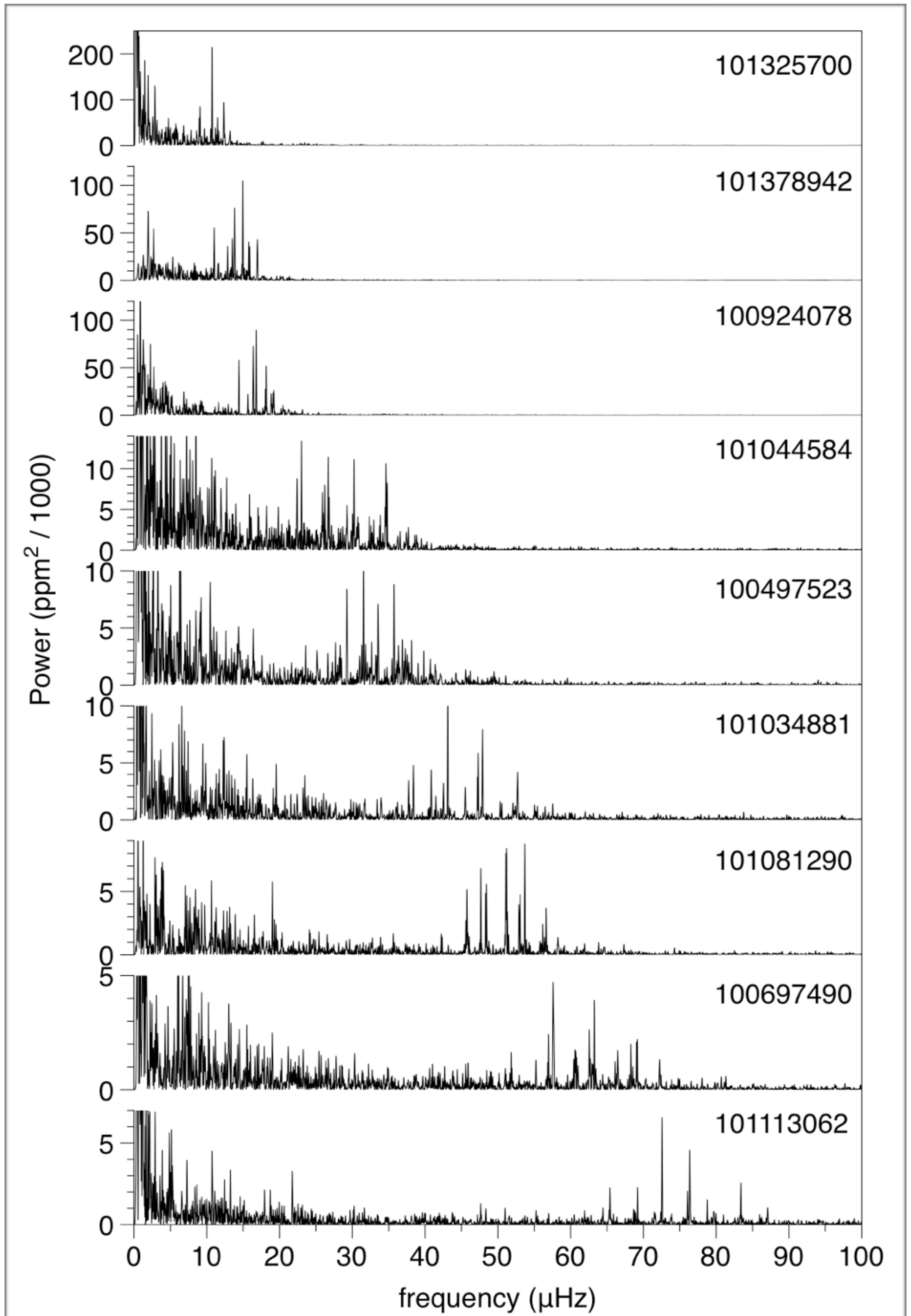
# Red Giant Asteroseismology

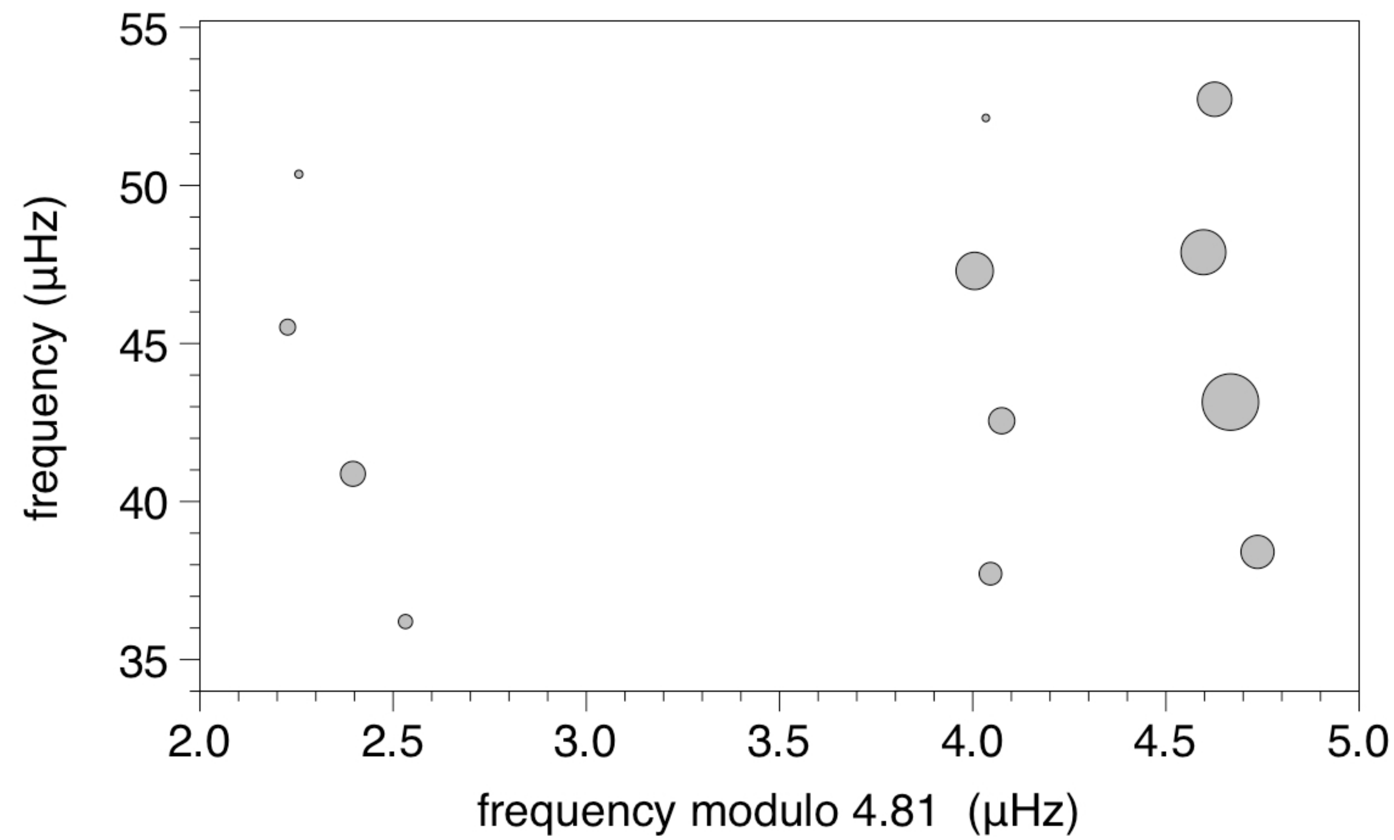
**$0.8\ M_{\odot} < M < 3.0\ M_{\odot}$**




**Solar-like p-mode oscillations & mixed p/g modes;**
**Slow rotators: ignore Coriolis and Lorentz forces is fine!**

# Discovery of NRP in RG

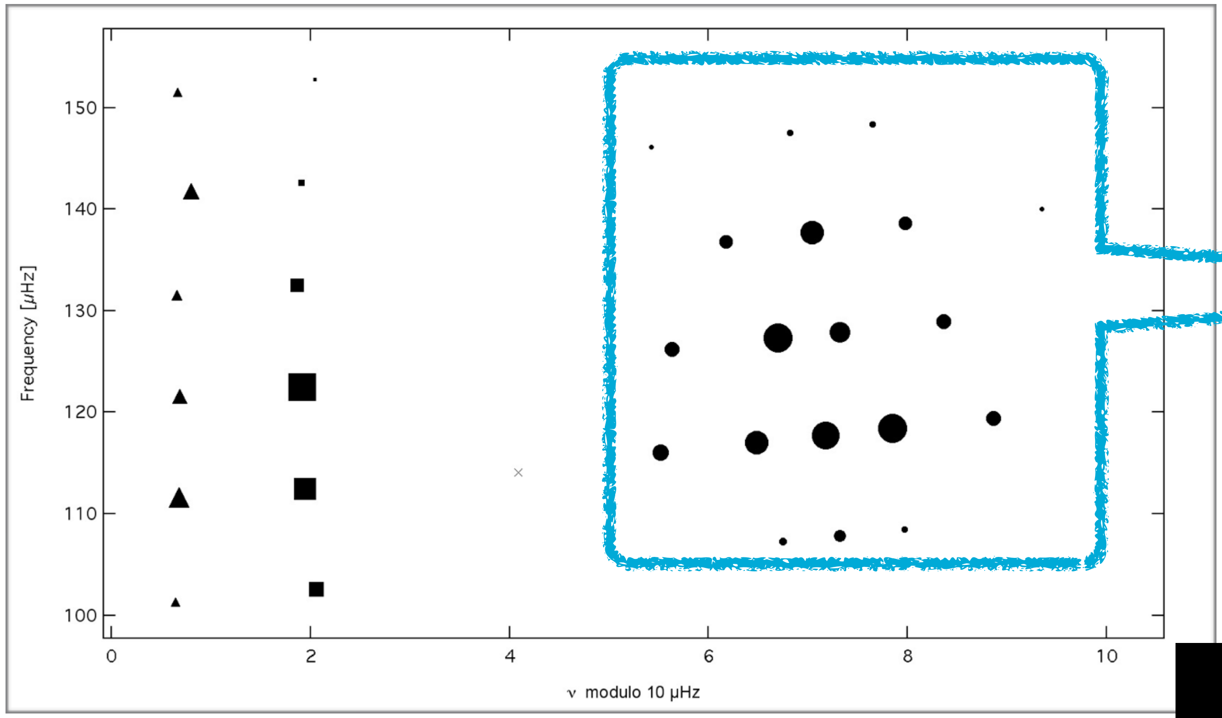


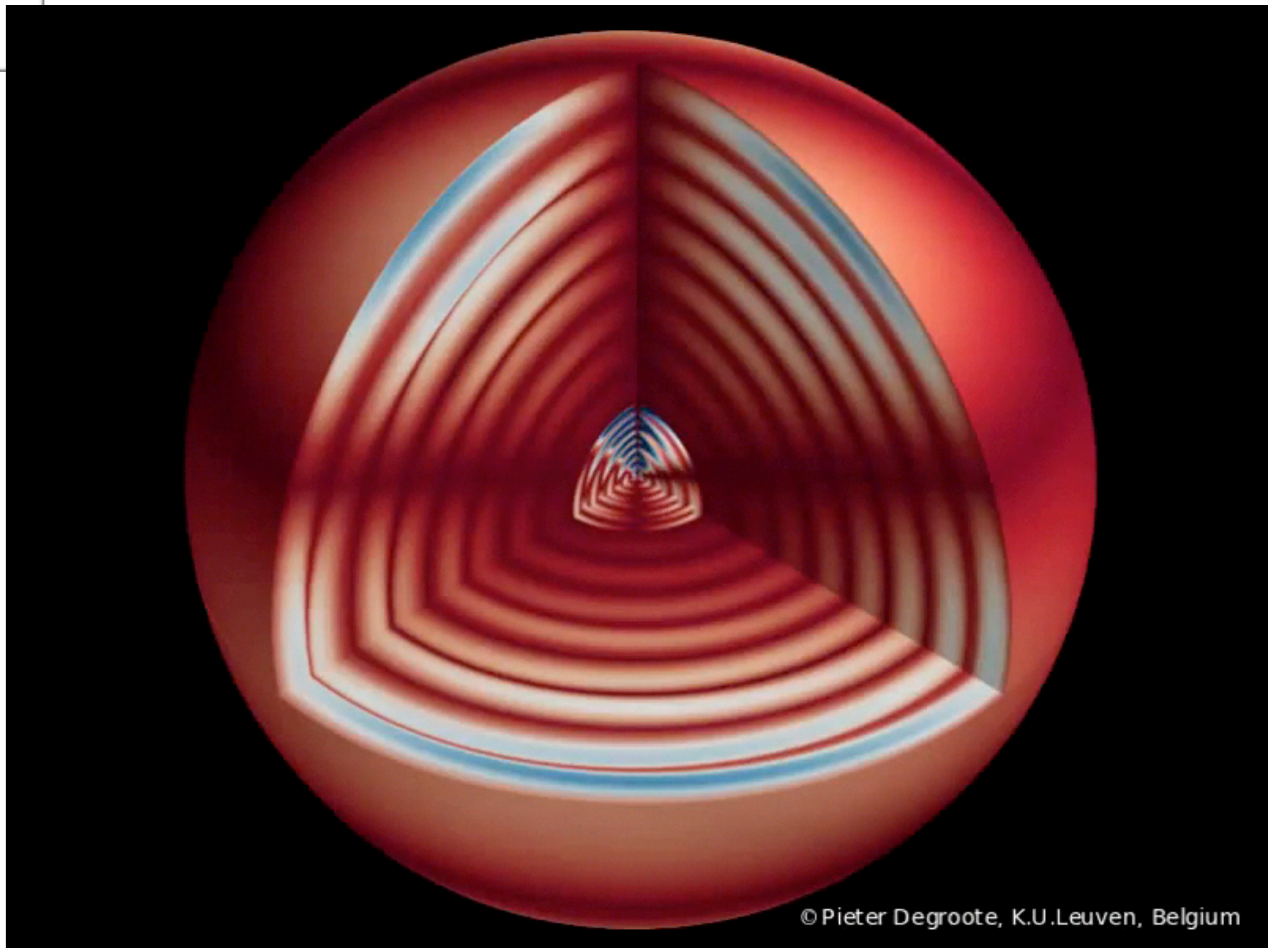

**De Ridder et al. (2009, Nature)**

**Acoustic modes with periods of several hours; frequency of maximum power scales with radius**

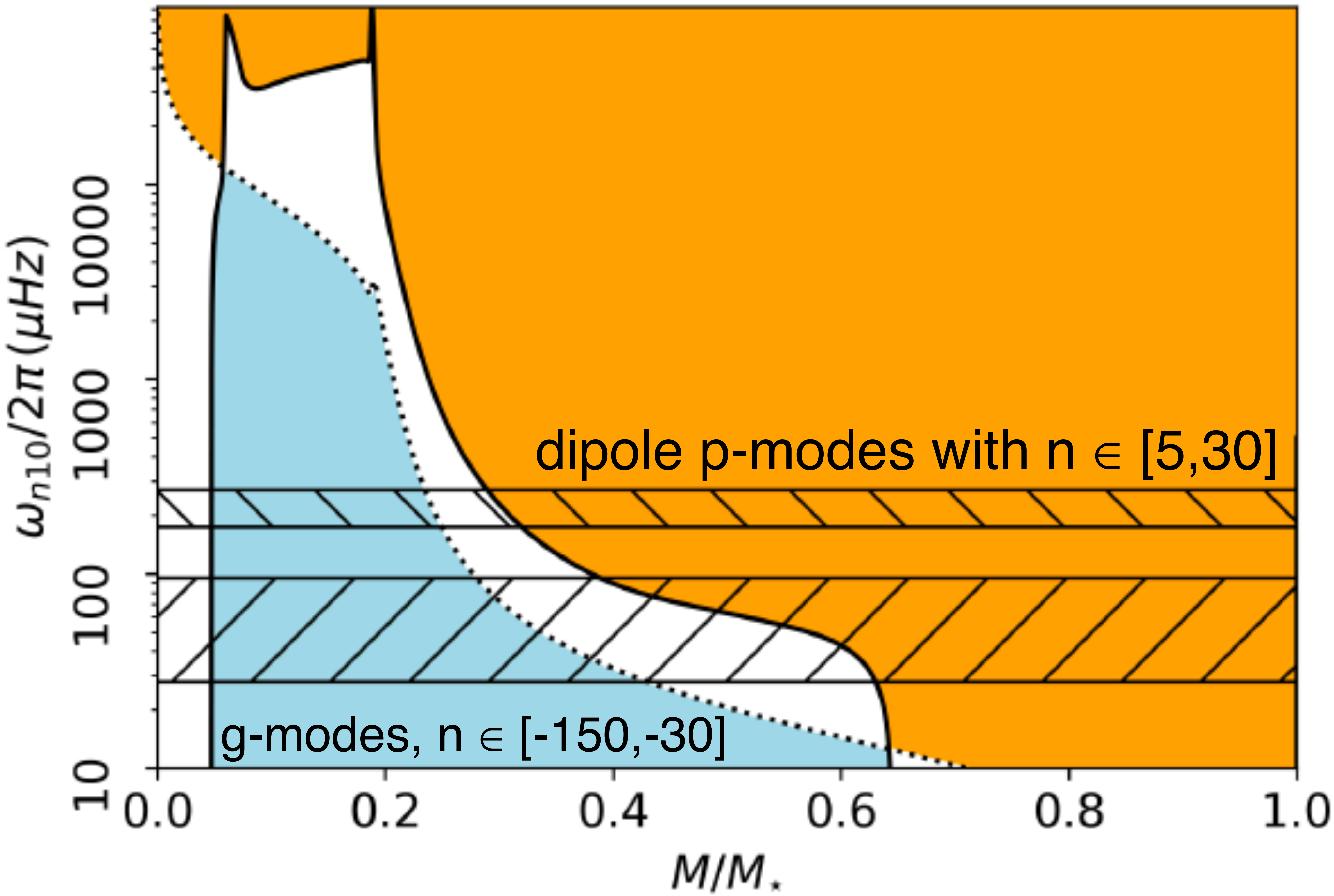
# Discovery of mixed modes in RG




**Beck et al. (2011, Science) &**
**Bedding et al. (2011, Nature):**
**dipole mode forrest**
**behave as acoustic modes in envelope & gravity modes near core**



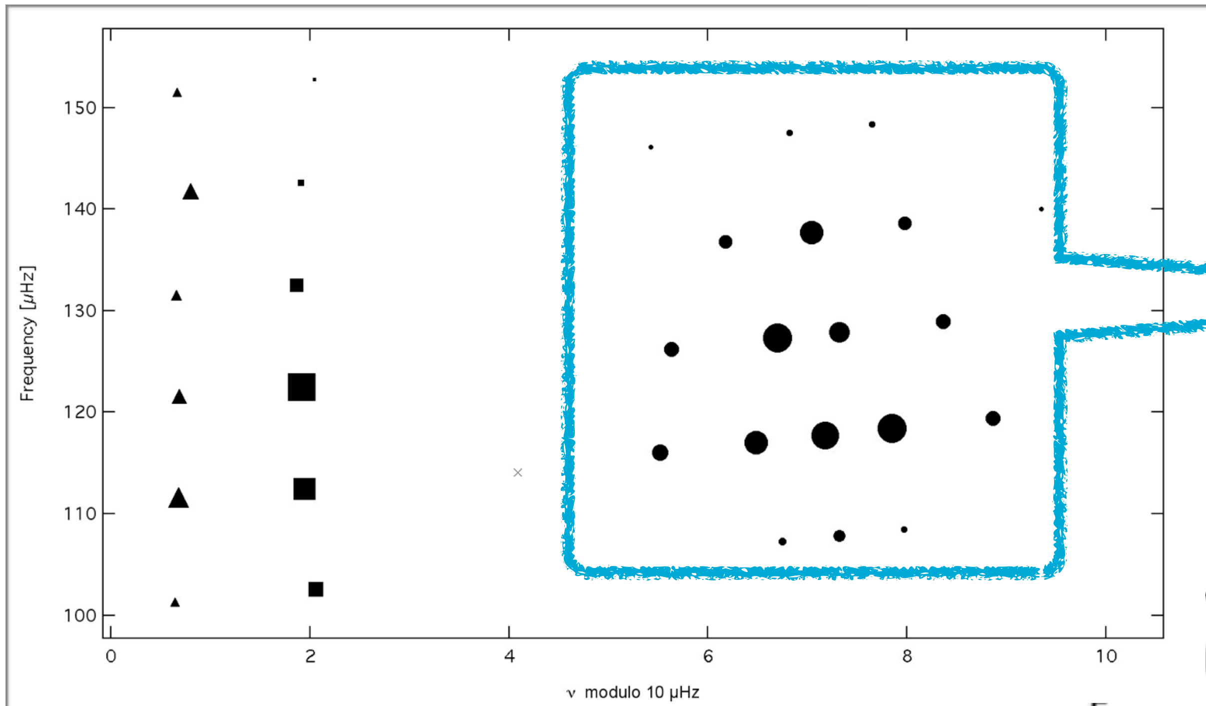
# Probing power red clump



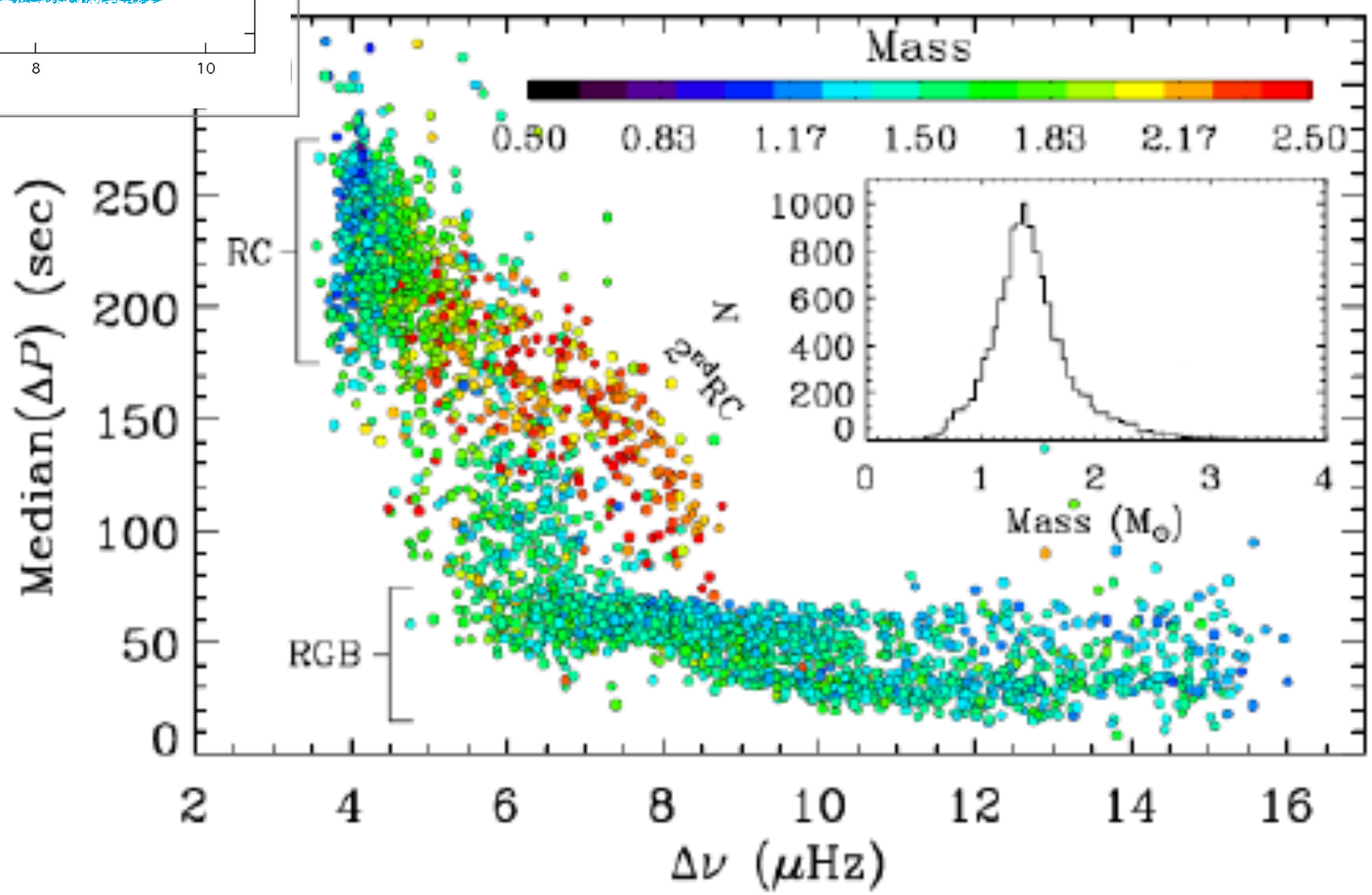

**p- and g-modes probe different regions throughout evolution**

**Figure courtesy of Cole Johnston used in Aerts et al. (2019) ARAA, in press**

# Mixed modes probe core




**Beck et al. (2011, Science) & Bedding et al. (2011, Nature): dipole mode forrest behave as acoustic modes in envelope & gravity modes near core**




**These red giants look entirely similar at their surface!…**

**Stello et al. (2013)**

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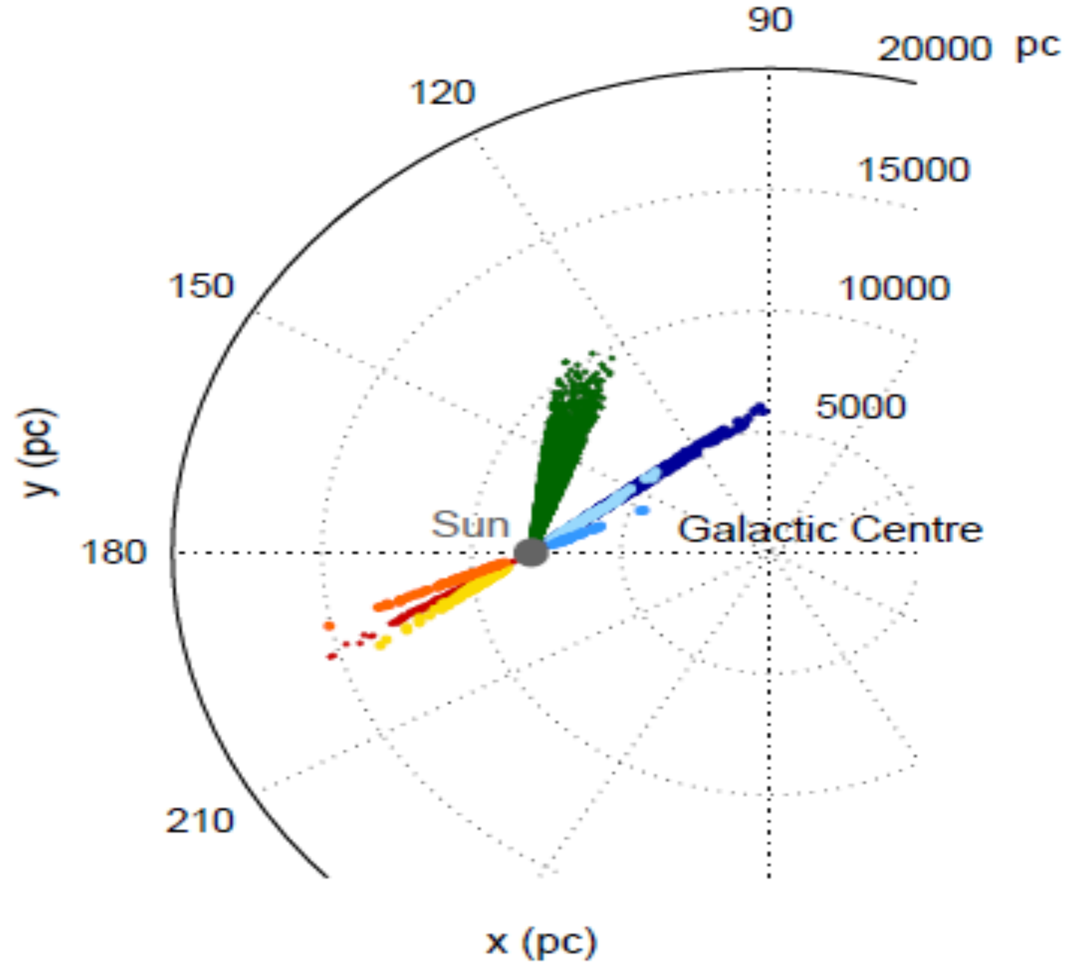
# Asteroseismology & Galactic Archeology

- **Scaling relations for sun-like input physics:**

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

$$\frac{\Delta\nu}{\Delta\nu_\odot} = \left(\frac{M}{M_\odot}\right)^{\frac{1}{2}}\left(\frac{R}{R_\odot}\right)^{-\frac{3}{2}}$$

deliver **seismic mass, radius, age:** **relative precisions of 8, 4, 20% for 1000s of stars (RG) observed with Kepler (4 yrs)**

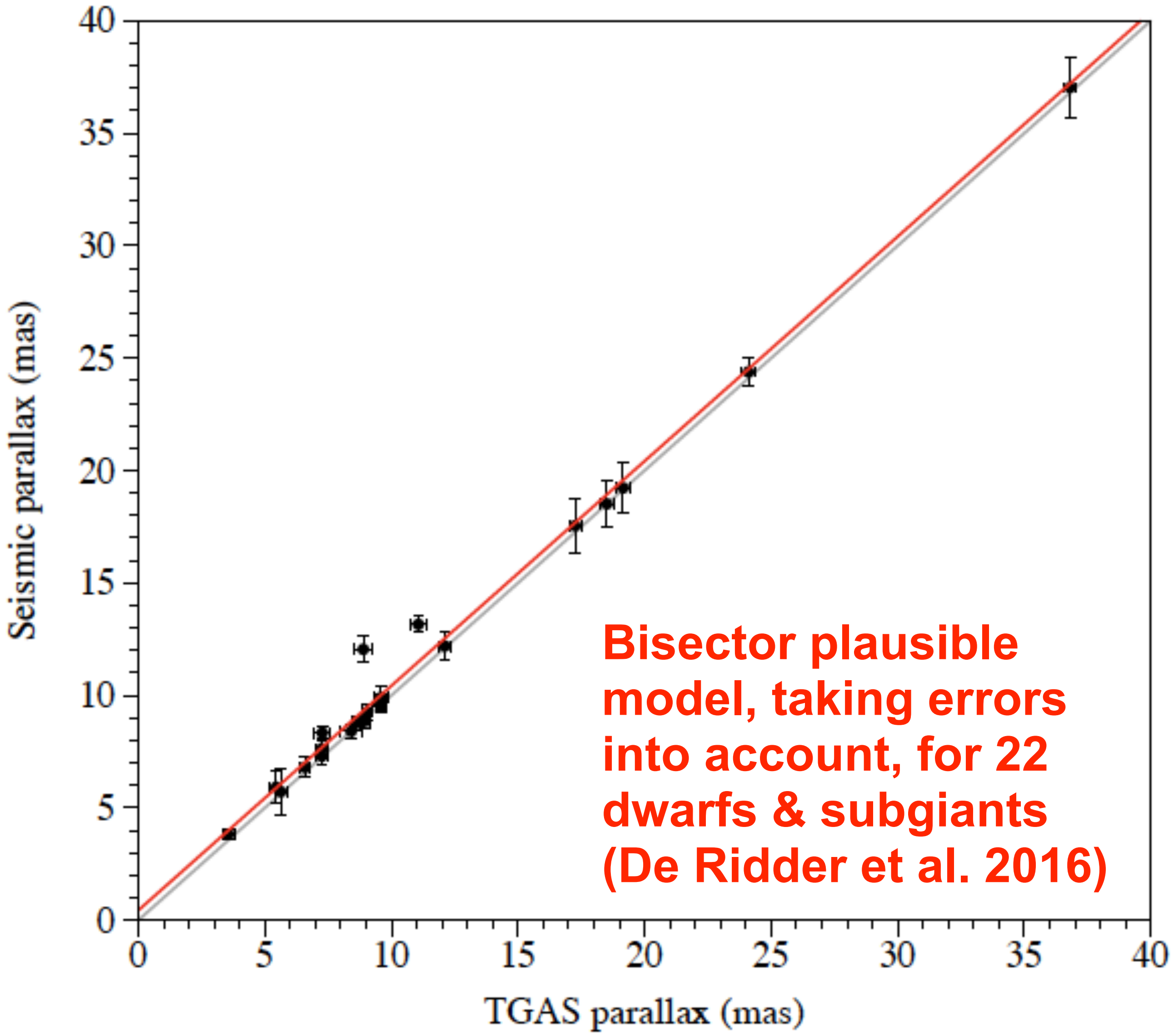



**Transform into seismic luminosities & distances, relative precision of few %**

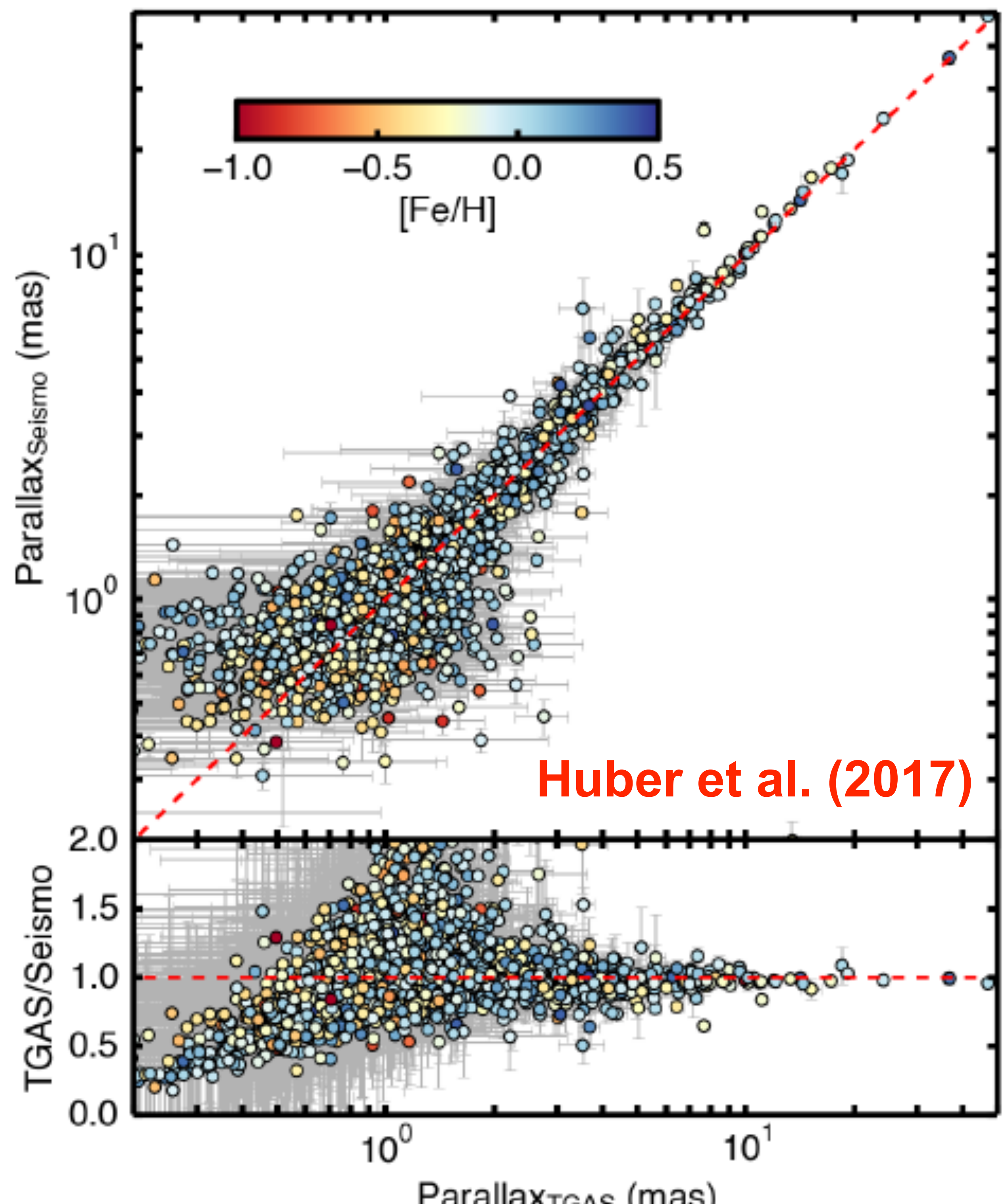
**(Silva Aguirre et al. 2012, Miglio et al. 2013, Rodrigues et al. 2014, Anders et al. 2016)**

**So far: stars with similar metallicity… is scaled solar physics appropriate?**

# Asteroseismology & Astrometry




**Bisector plausible model, taking errors into account, for 22 dwarfs & subgiants (De Ridder et al. 2016)**




**Huber et al. (2017)**

**Seismic parallaxes better than Gaia (DR2) parallaxes for distant red giants (up to 8 kpc for CoRoT)**

# Asteroseismic Ageing in Galaxy

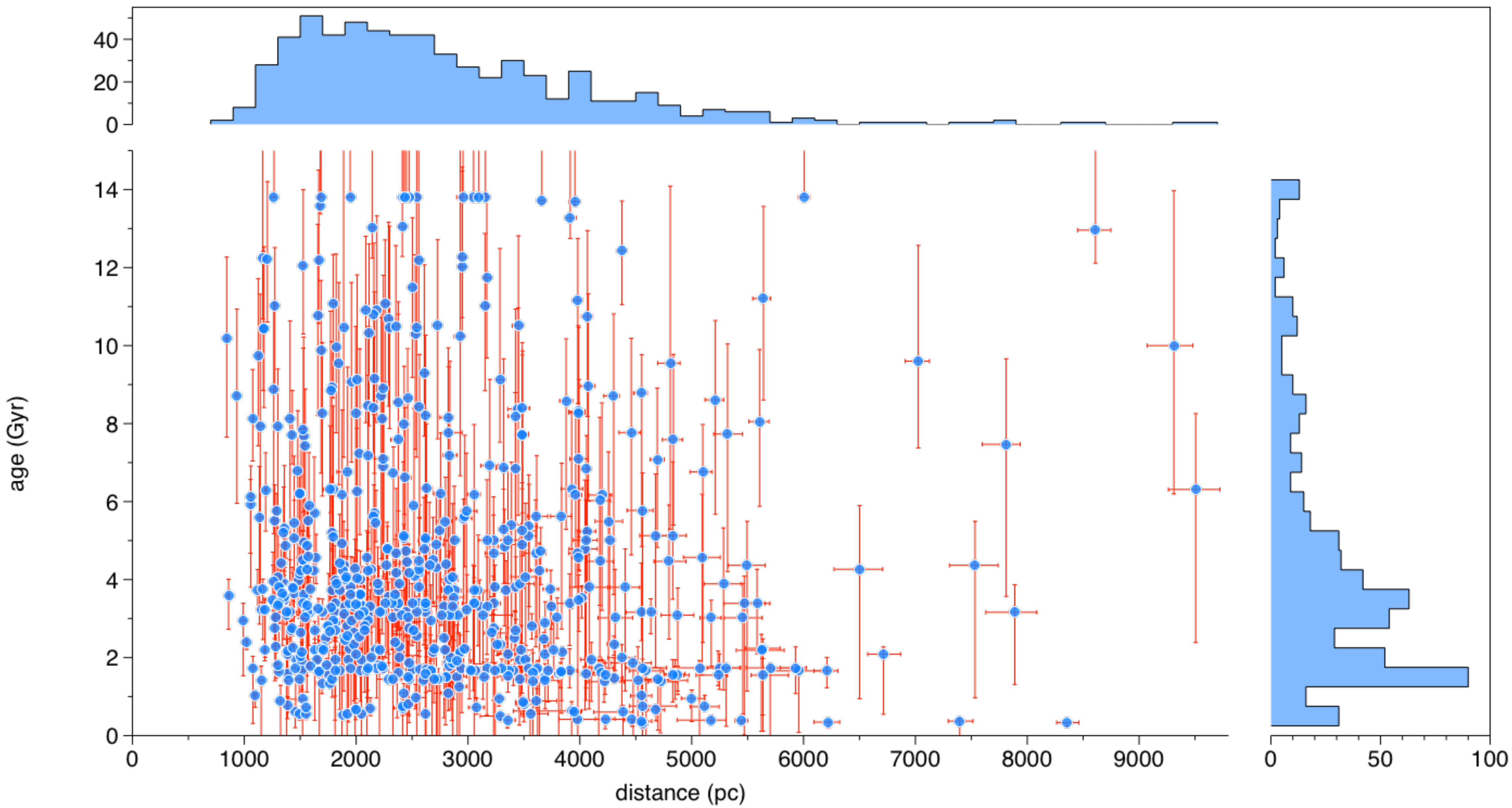
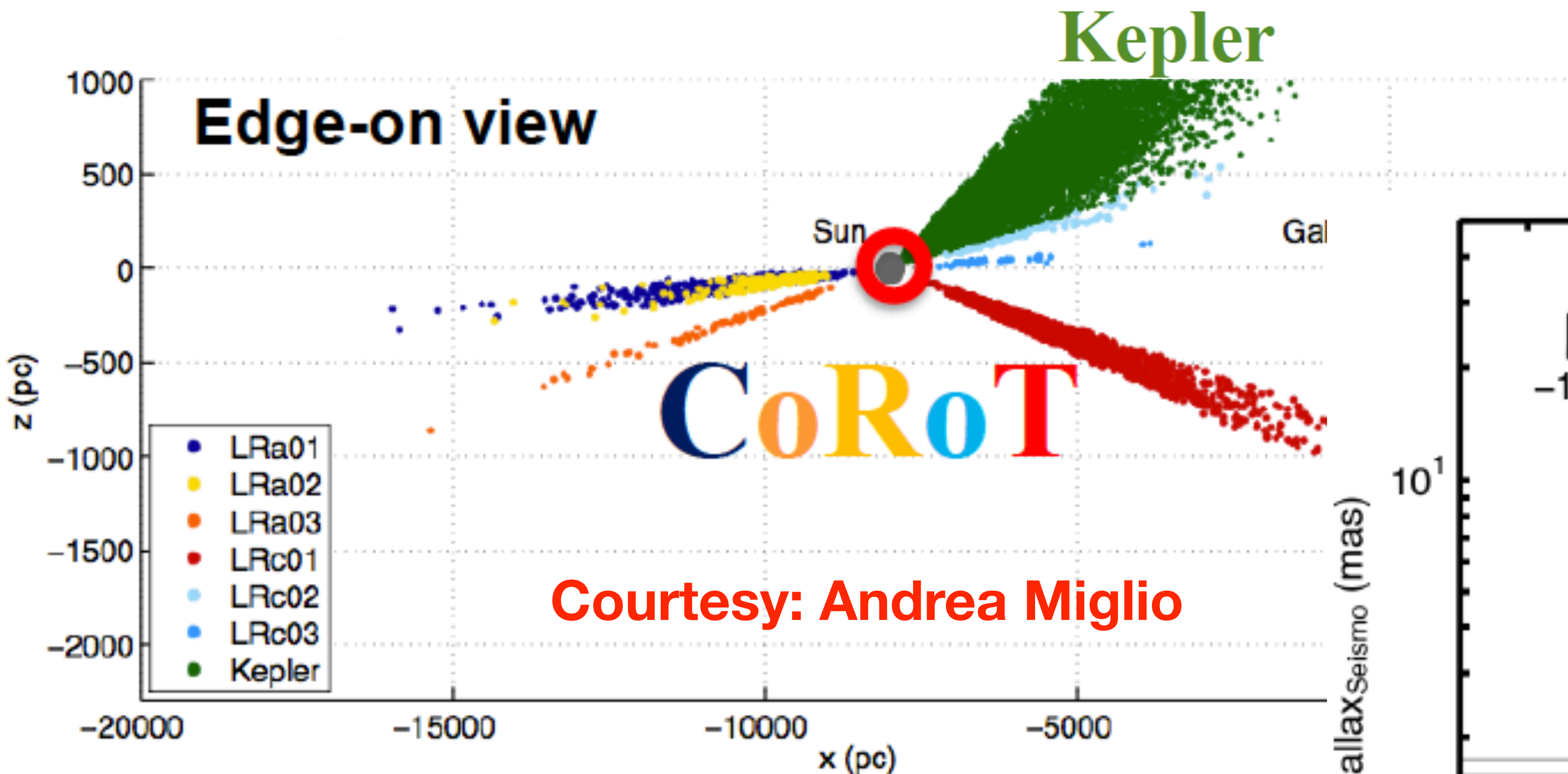
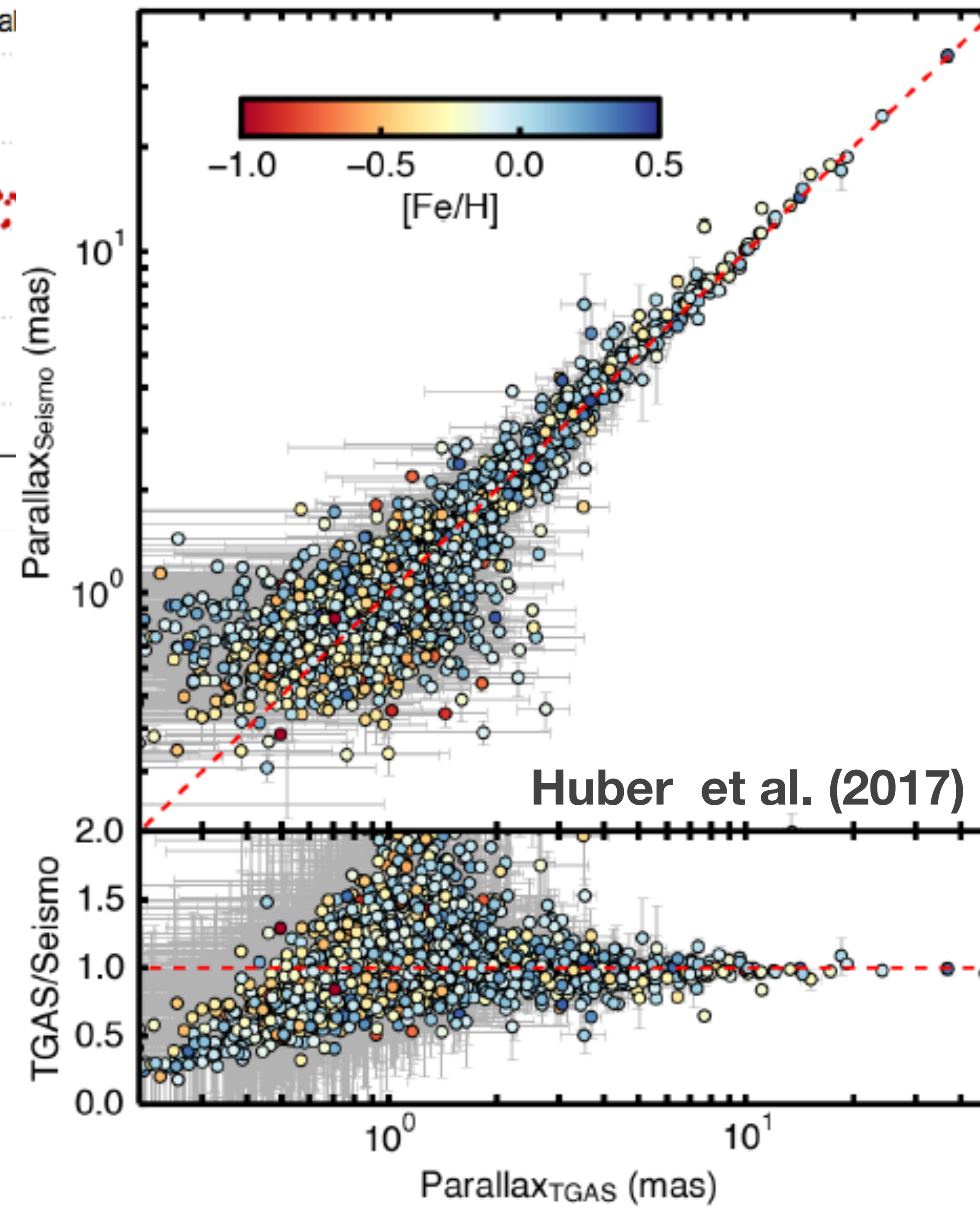



**Figure courtesy of Joris De Ridder, based on CoRoGEE (Anders et al. 2016, 2017)**

**A parallax from Gaia can (partly) take away model dependency: radius from distance & brightness (+Teff) gives mass**

# Tribute to CoRoT, Kepler & Gaia



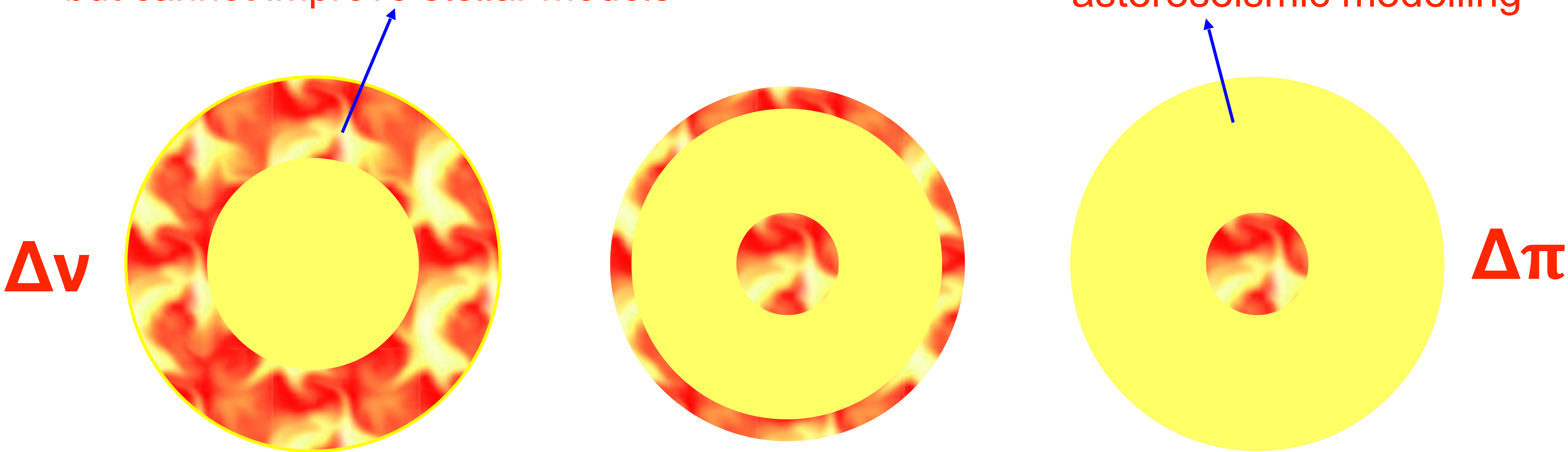




**Asteroseismic Ageing as important input for Galactic Archeology**

# Moving to stars with convective core

Scaling the Sun is OK for
4,8,20%-level R,M,age (bias?)
but cannot improve stellar models

No "Sun" to scale…
can only be done from
asteroseismic modelling




$M < 1\ M_\odot$ $1\ M_\odot < M < 2\ M_\odot$ $M > 2\ M_\odot$

**Major unknowns: $M_{core}$ (r,t) & $D_{mix}$ (r,t) & $\Omega_{rot}$ (r,t)**
**extent & shape of convective boundary mixing?**
**microscopic & macroscopic envelope mixing?**

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# “Classical” Stellar Modelling

$$\chi^2(P_1,\ldots,P_N) \equiv \sum_{j=1}^{M}\left[\frac{O_j^{\mathrm{obs}} - O_j^{\mathrm{theo}}(P_1,\ldots,P_N)}{\sigma_j}\right]^2$$

parameters $\mathcal{P} = \{P_i\}, i = 1,\ldots,N$

observables $\mathcal{O} = \{O_j\}, j = 1,\ldots,M$ errors $\sigma_j$

**Teff, log g, B-V, L, R, Z (or individual abundances), …**

$$\boxed{\text{four basic parameters} \quad (M, X, Z, \tau)}$$

# Observational Input: Precision

| Method | Type of star | Diagnostic | Precision | Model dependence |
|---|---|---|---|---|
| Spectral lines | LM | $T_{\rm eff}$, abundances | ~1% | A: medium |
| Spectral lines | IM | $T_{\rm eff}$, abundances | ~2% | A: medium |
| Spectral lines | HM | $T_{\rm eff}$, abundances | ~5% | A: medium |
| IRFM/SED[b] | LM, IM | $T_{\rm eff}$ | ~2% | A: low |
| RV & light curves[c] | EB/SB2 | $M$ | ~1% | None |
| RV & light curves[c] | EB/SB2 | $R$ | ~3% | A: low |
| Interferometry[d] | All | $R$ | ~3% | A: low |
| Typical *Gaia* DR2[e] | LM & IM | $L$ | $\lesssim$15% | A: medium |
| Typical *Gaia* DR2[e] | LM & IM | $R$ | $\lesssim$10% | A: medium |
| Cluster (E)MST[f] | All | age | ~30% | I: strong |
| Gyrochronology[g] | LM | $\Omega_{\rm surf}$ | ~10% | None |
| Gyrochronology[g] | LM | age | ~20% | I: medium |
| Coherent g modes[h] | IM | $\omega_{nlm}$ | ~0.1% | None |
| Coherent p modes[h] | IM | $\omega_{nlm}$ | ~0.01% | None |
| Damped p modes[h] | LM | $\omega_{nlm}$ | ~0.001% | None |
| Damped mixed modes[h] | RG | $\omega_{nlm}$ | ~0.01% | None |
| g-mode splittings[h] | IM | $\Omega_{\rm core}$ | ~0.1% | None |
| g-mode spacings[h] | IM | $\Omega_{\rm core}$ | ~5% | I: low |
| p-mode splittings[h] | IM | $\Omega_{\rm env}$ | ~30% | I: medium |
| p-mode splittings[h] | LM | $\Omega_{\rm env}$ | ~50% | I: medium |
| mixed-mode splittings[h] | RG | $\Omega_{\rm core}$ | ~1% | None |
| Phase modulation & RV[h,i] | PB1/PB2 | $M, R$ | as EB/SB2 | None |

**Aerts et al. (2019), ARAA, Vol. 57, in press**

**RiA via https://www.annualreviews.org/doi/pdf/10.1146/annurev-astro-091918-104359**

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# Asteroseismic Modelling

THEORY

**mass, metallicity, age + convection? magnetism? mixing? rotation?**

↓

**STELLAR MODEL FOR SPECIFIED INPUT PHYSICS**

↓

**Theoretical predictions for oscillations**

OBSERVATIONS

**Space photometry, high-res. spectroscopy, Gaia astrometry**

↓

**Observed properties of identified modes**

Theoretical predictions for oscillations ⟷ Observed properties of identified modes: **MLE**

**Two Major Aims (classes 2&3):**

**A) High-precision M, R, age, Z**

**B) Improve Input Physics: AM, Dmix(r)**

**Aerts et al. (2018): take into account that parameters are correlated**

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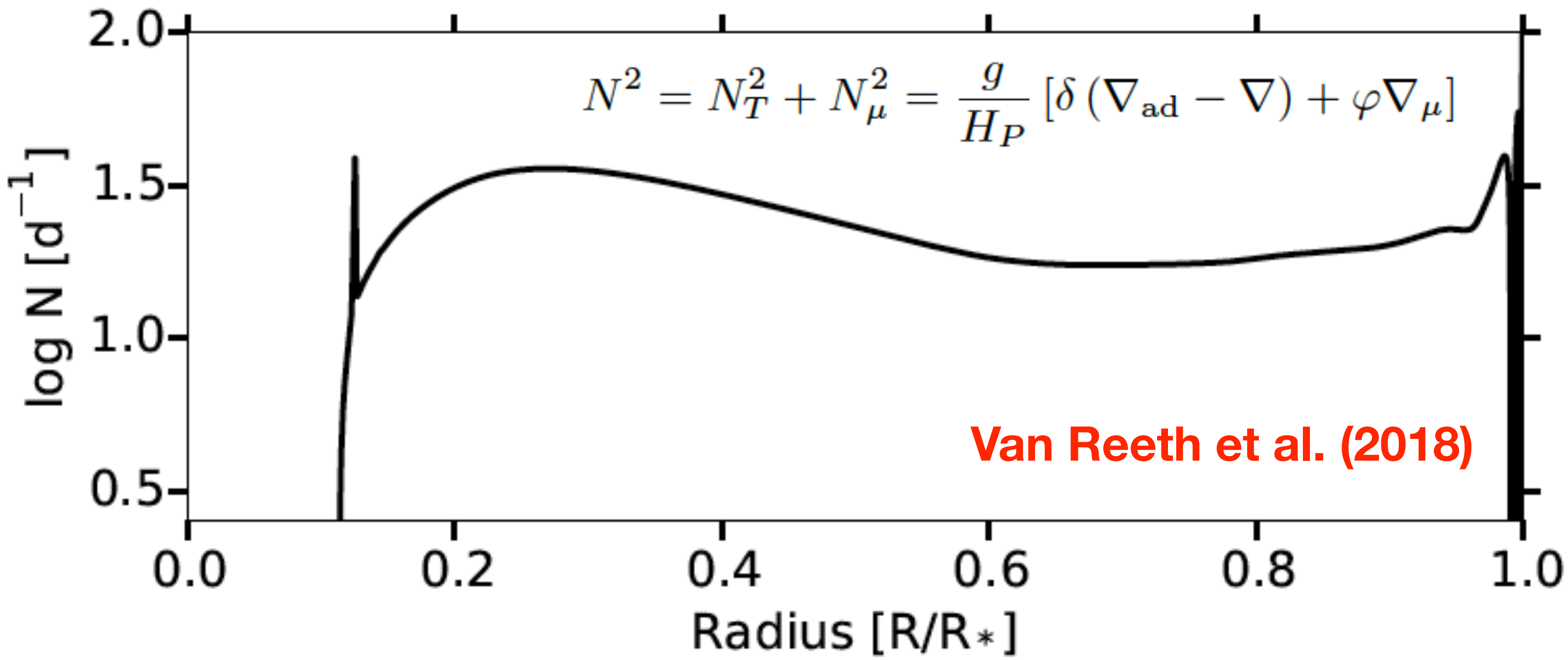
# g-mode period spacings

**In absence of rotation, expected g-mode period spacings for high-order (n), low-degree (l) NRP:**

$$\Delta\Pi_l \equiv \Pi_{l,n} - \Pi_{l,n-1} = \frac{\Pi_0}{\sqrt{l(l+1)}} \qquad \Pi_0 = 2\pi^2 \left(\int_{r_1}^{r_2} N \frac{\mathrm{d}r}{r}\right)^{-1}$$



# Discovery of g-mode period spacings

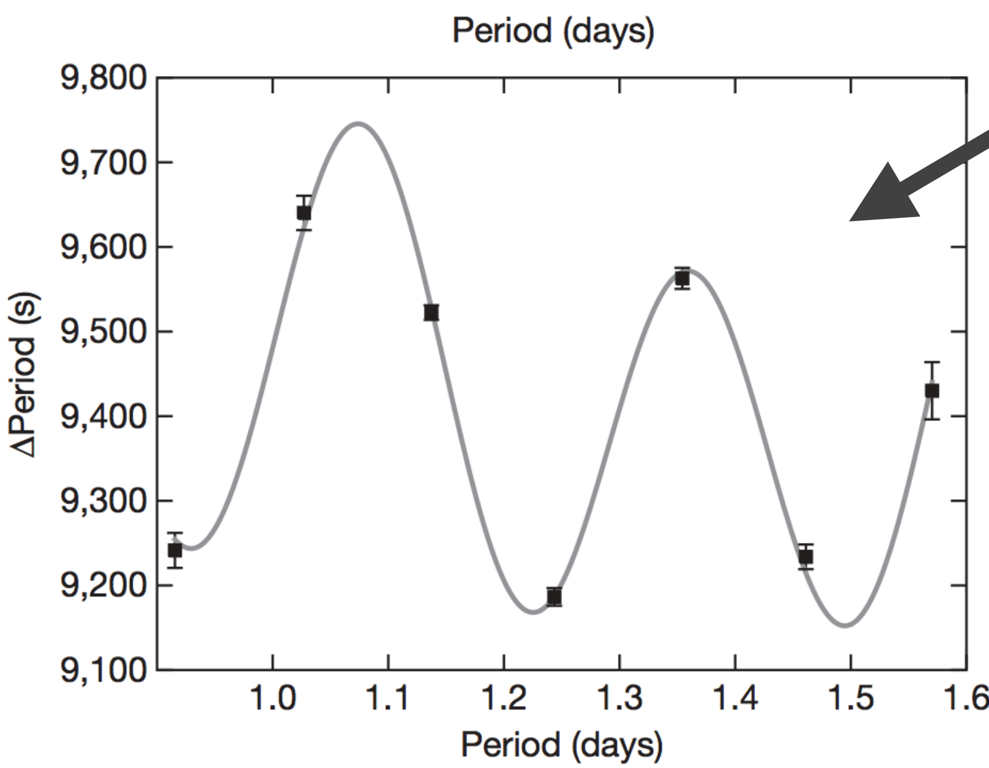
Vol 464 | 11 March 2010 | doi:10.1038/nature08864 nature

LETTERS

**From 5 months of CoRoT monitoring of the B3V star HD 50230**

## Deviations from a uniform period spacing of gravity modes in a massive star

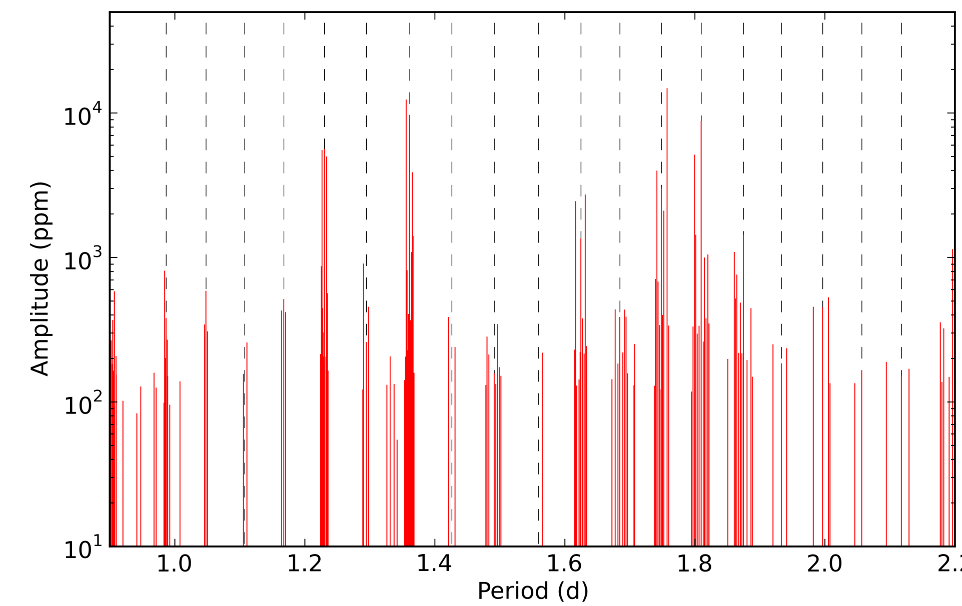
Pieter Degroote[1], Conny Aerts[1,2], Annie Baglin[3], Andrea Miglio[4], Maryline Briquet[1], Arlette Noels[4], Ewa Nien
Josefina Montalban[4], Steven Bloemen[1], Raquel Oreiro[1], Maja Vučković[1], Kristof Smolders[1], Michel Auver
Frederic Baudin[6], Claude Catala[3] & Eric Michel[3]

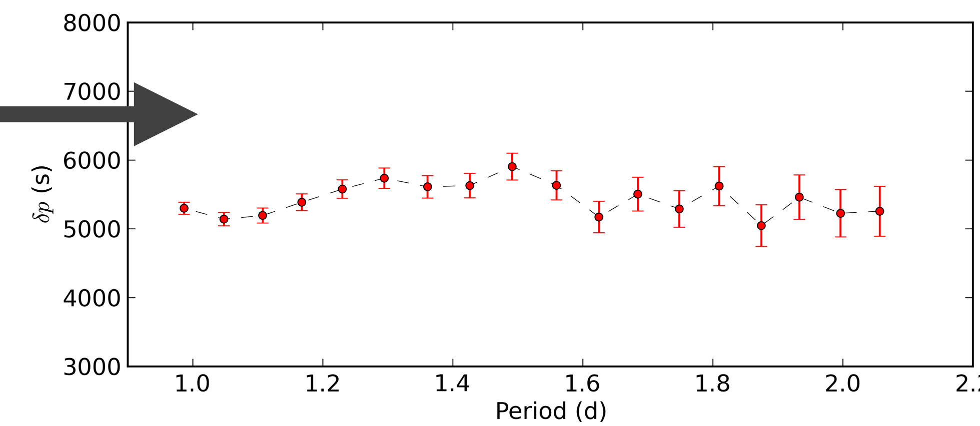



**Pápics et al. (2014)**

**4 years of Kepler data of a B9V star**

**19 zonal dipole g modes**



# Modelling of slow rotators

KU LEUVEN

**THEORY**

mass, metallicity, age + **convective overshoot? mixing?**

STELLAR MODEL FOR SPECIFIED INPUT PHYSICS

Theoretical predictions for oscillations

**OBSERVATIONS**

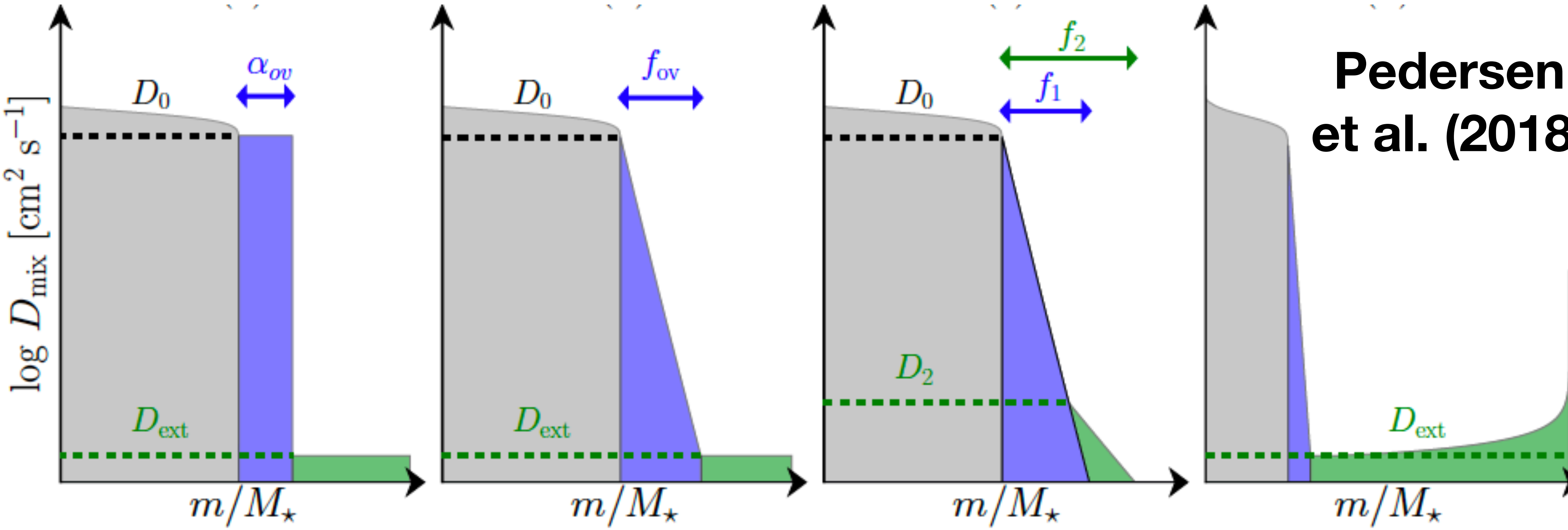
Space photometry, high-res. spectroscopy, Gaia astrometry

Observed properties of **zonal (m=0)** modes

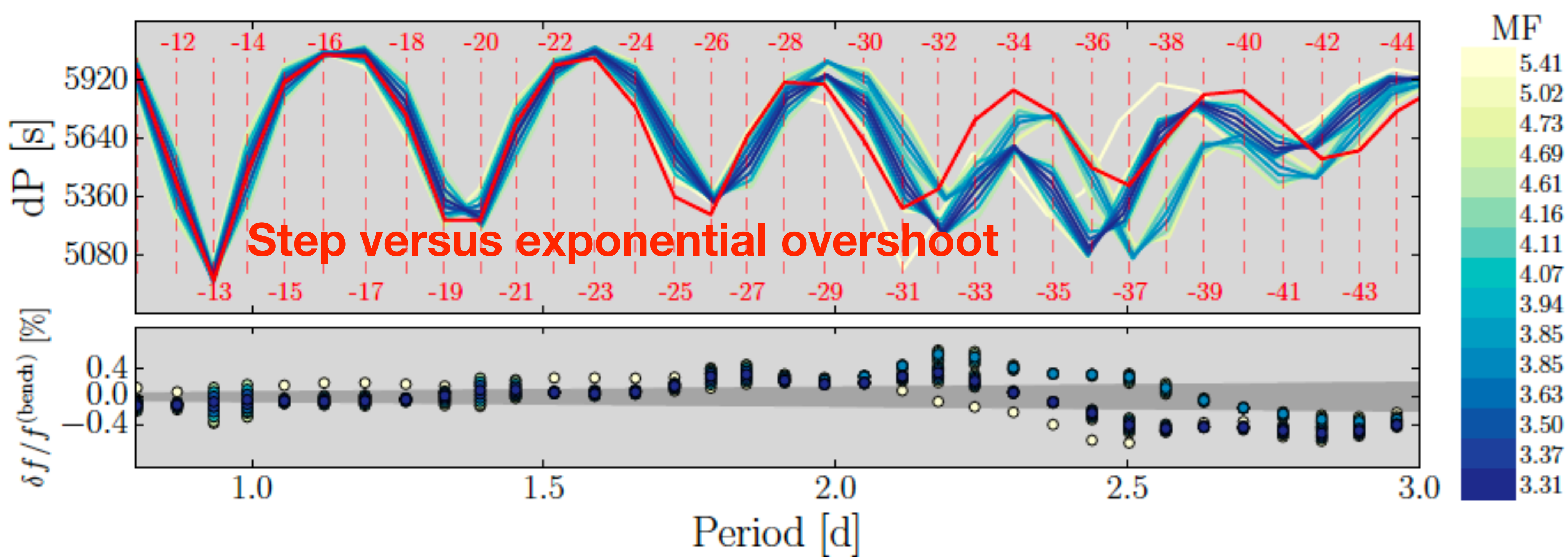
**High-precision M, R, age, Z**

**+ Estimate $D_{ov}$ & $D_{mix}$ gives core mass**

# Improving (convective boundary) mixing




**Pedersen et al. (2018)**



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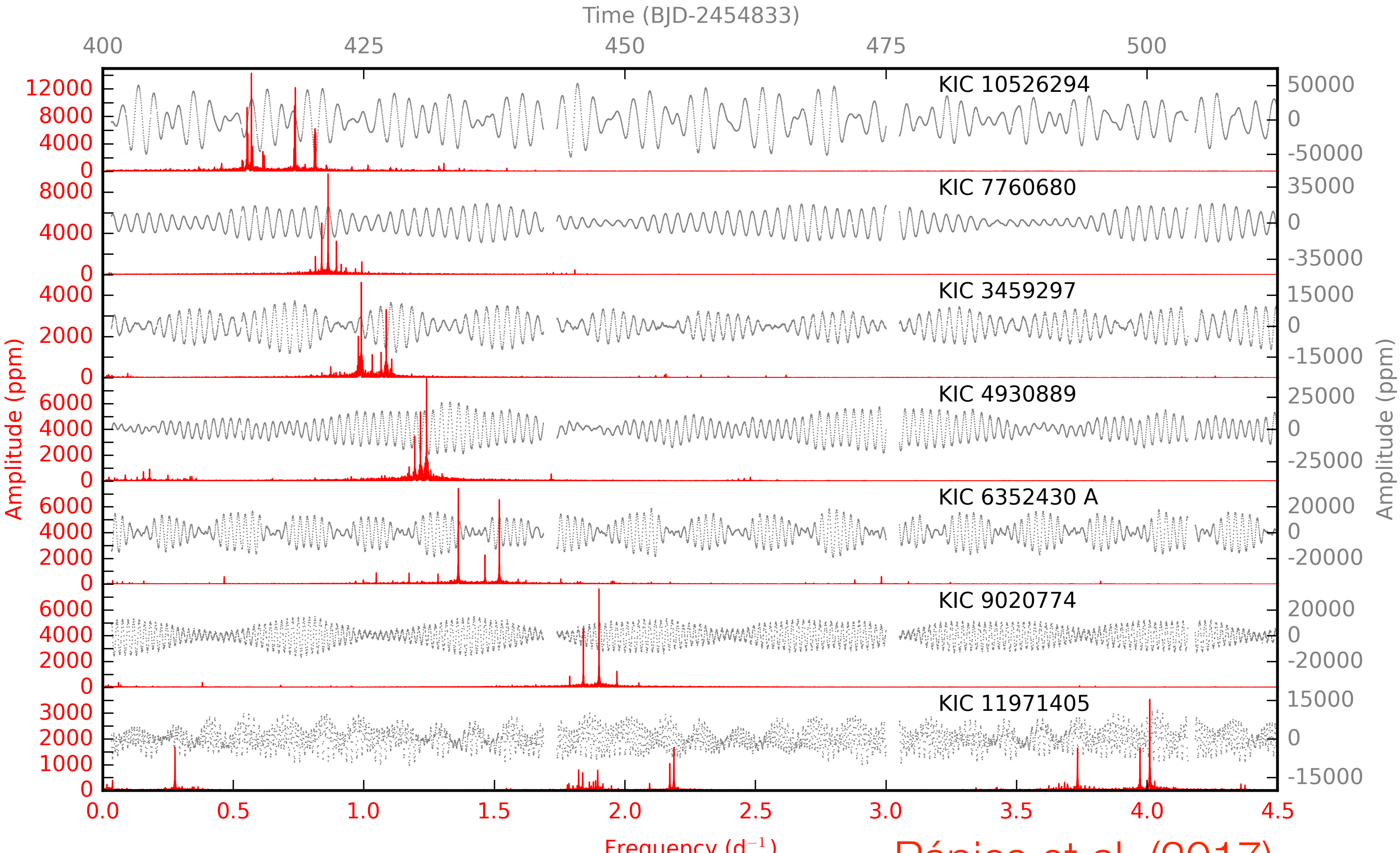
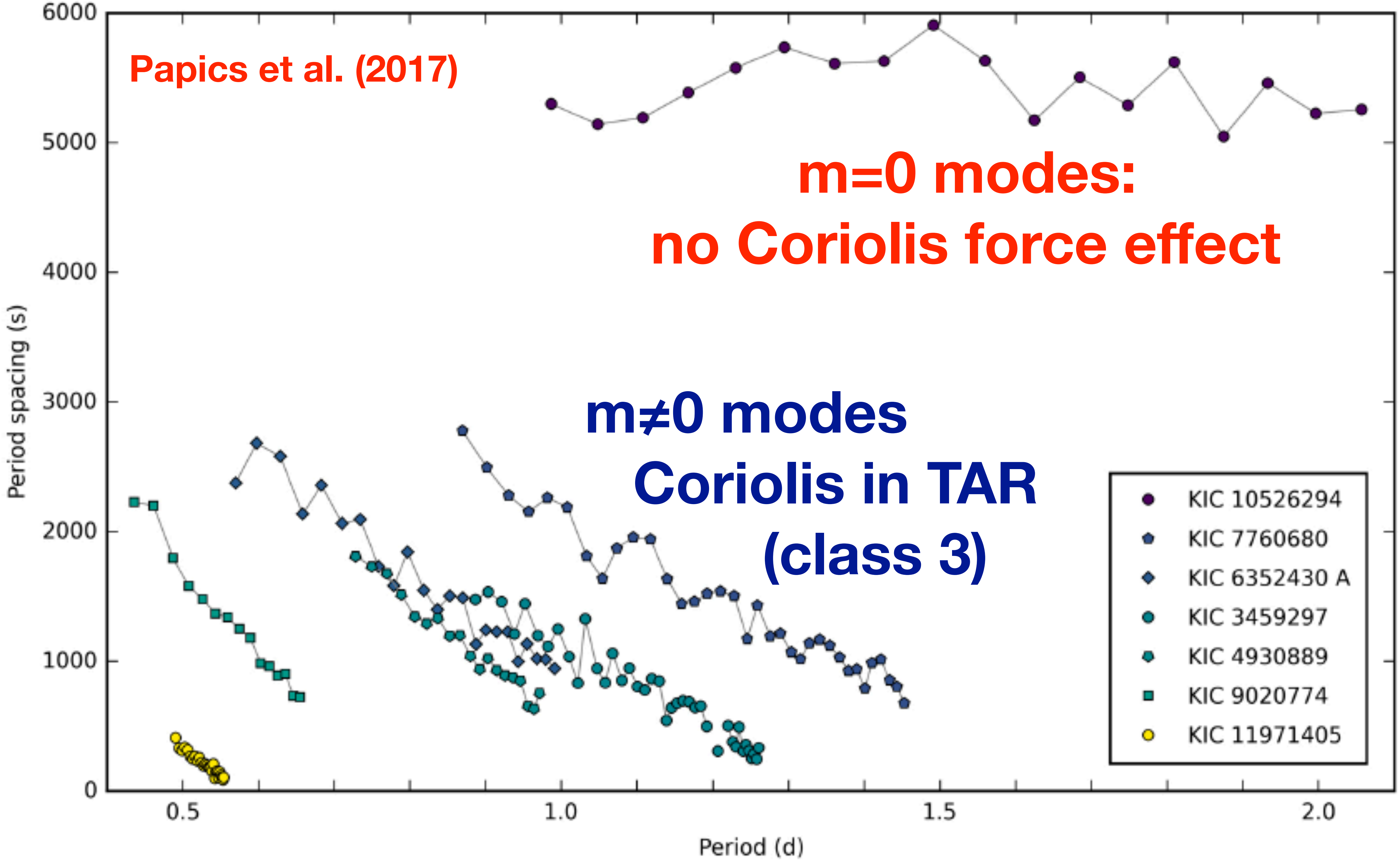
# Intermediate-mass stars from 4-yr Kepler

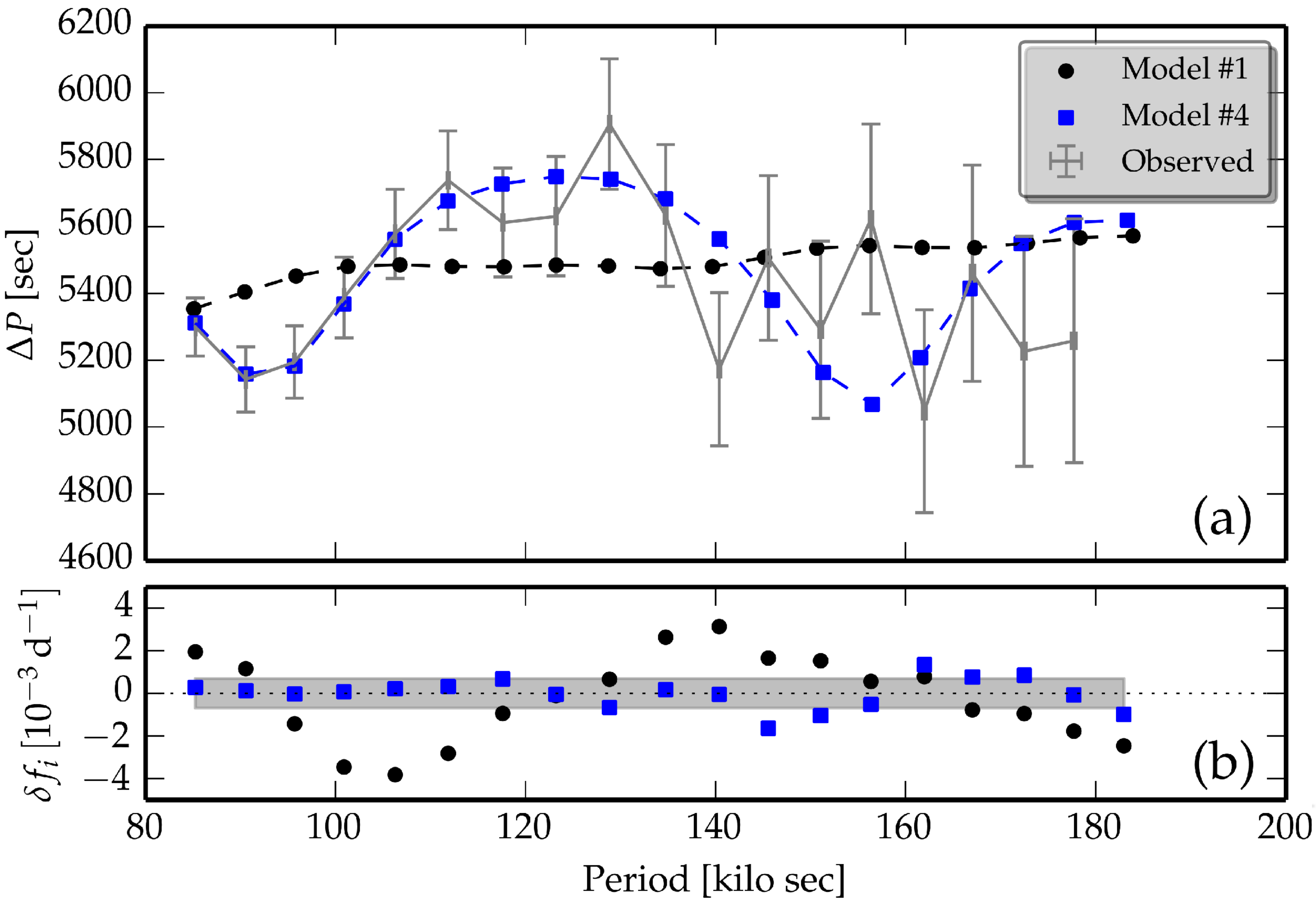


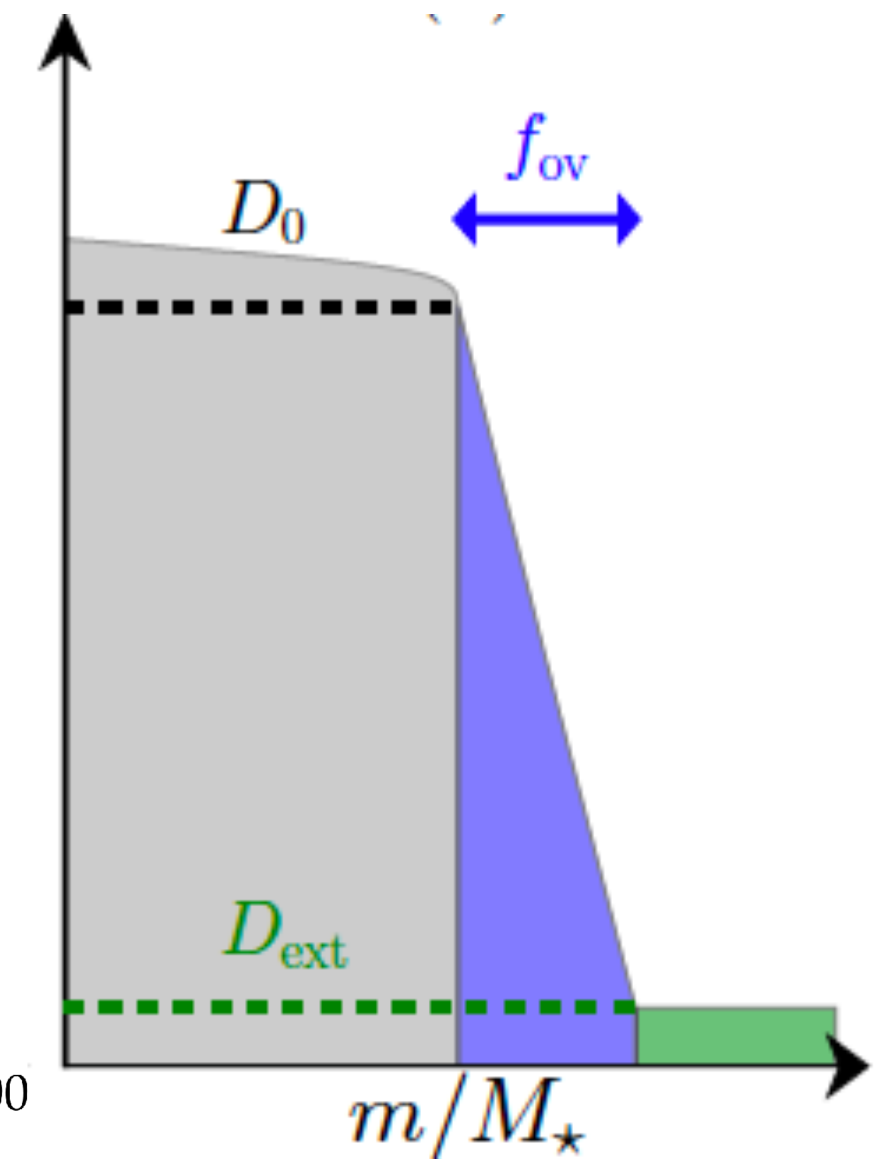

Pápics et al. (2017)

# KU LEUVEN Modelling based on zonal modes



# KIC10526294: need for envelope mixing




**Moravveji et al. (2015): zonal dipole g-mode period spacings**

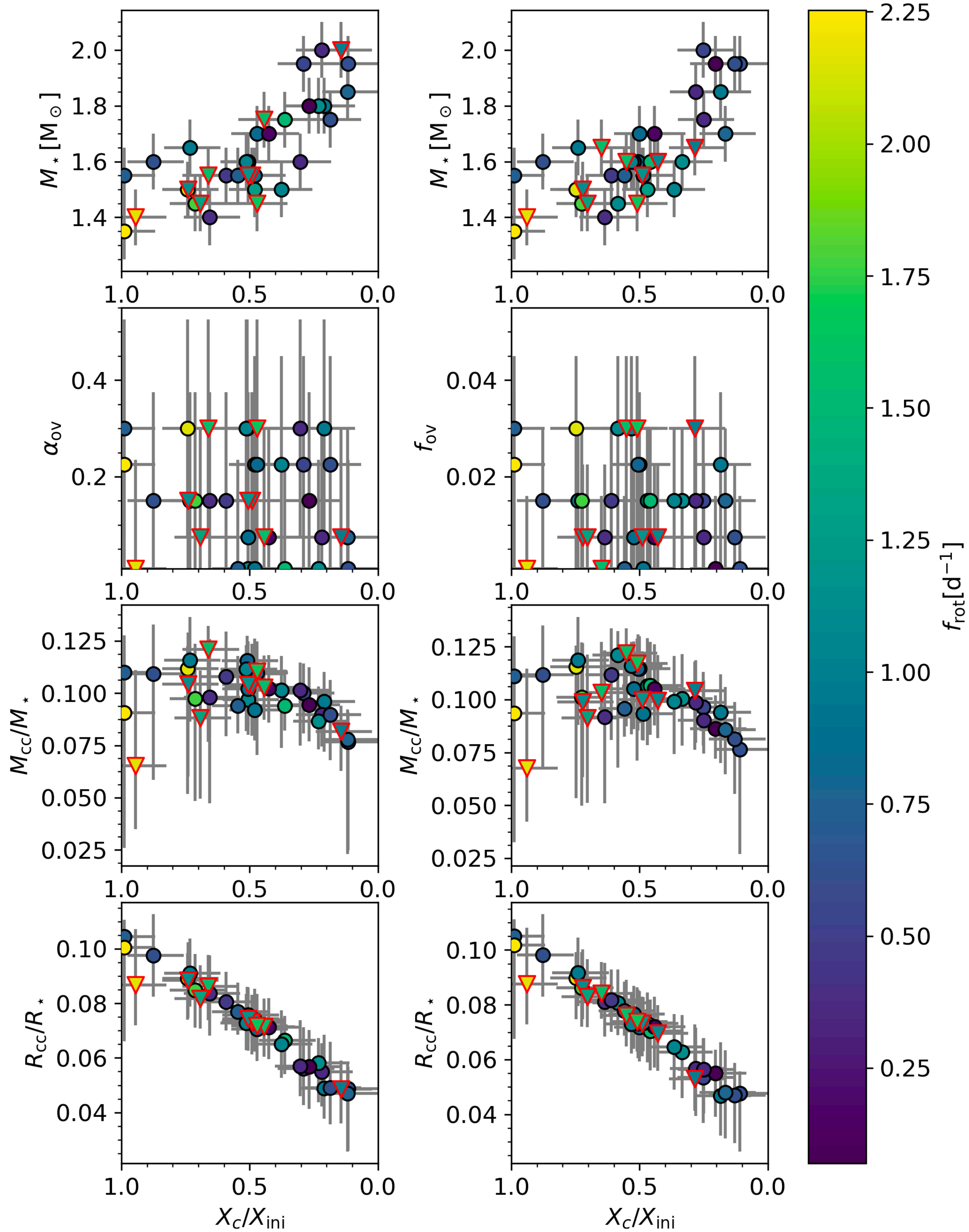
**need of envelope mixing in addition to core overshooting**

# Asteroseismic modelling of F stars

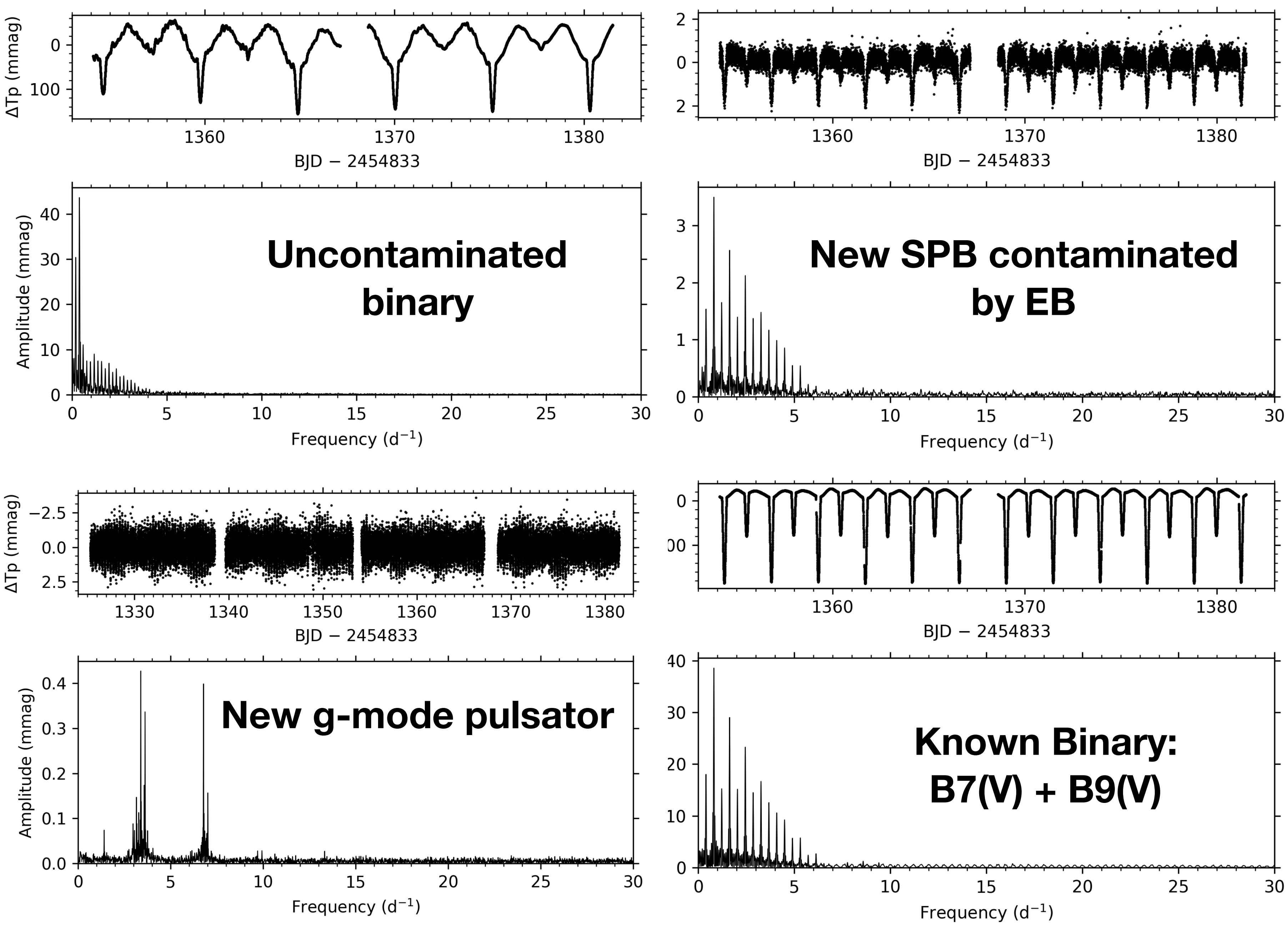
***Kepler*** **4-year LCs delivering asymptotic period spacing Δπ & Teff, log g from high-resolution spectroscopy**

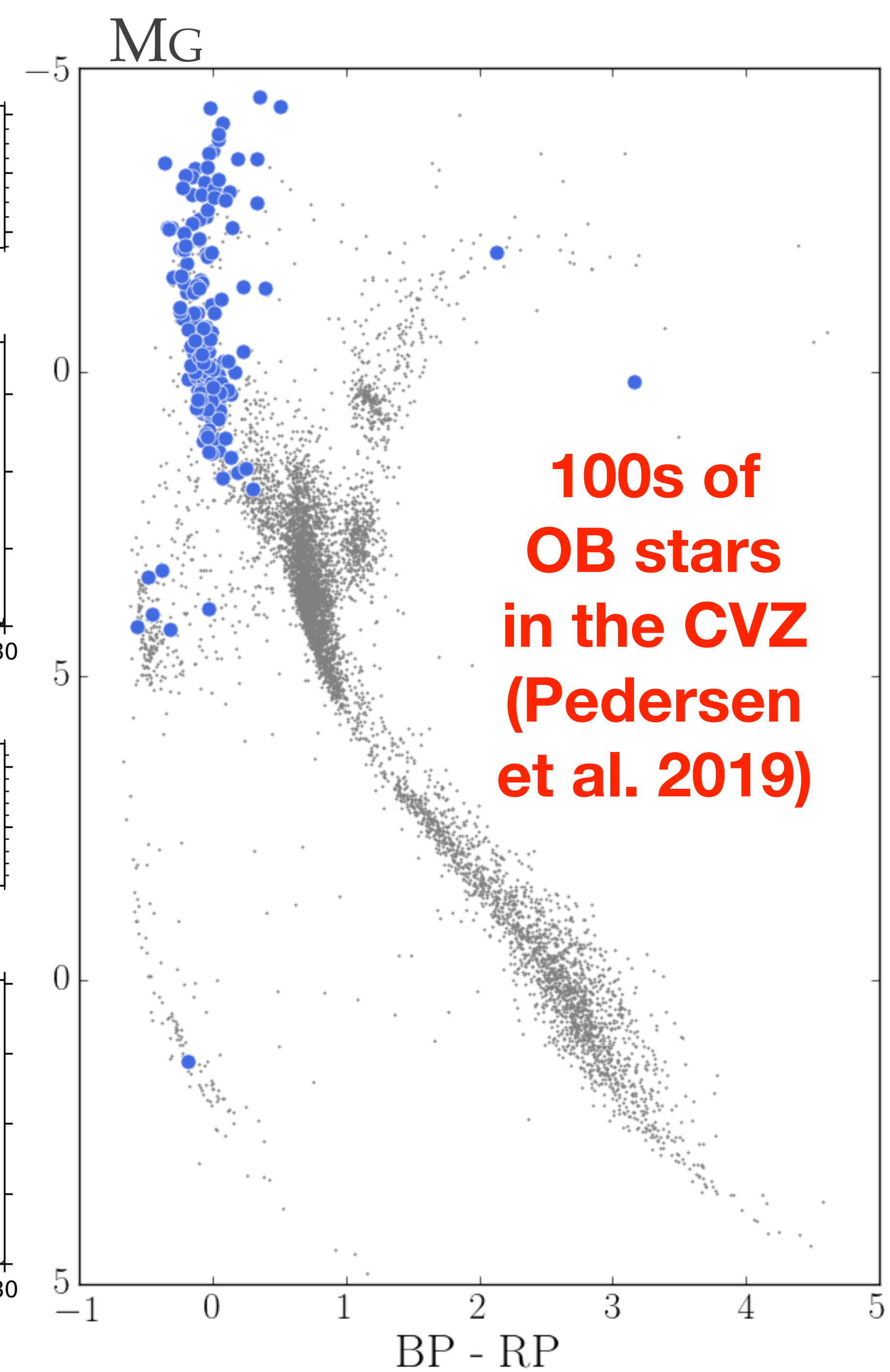
**37 F-type stars with identified gravity modes: M, Mcore, R, Rcore, age with ~10(4x), 20% precision**

**Mombarg et al. (2019): to be improved by individual g-mode period matching**



# TESS-ting teaser (Sectors 1&2)




**100s of OB stars in the CVZ (Pedersen et al. 2019)**

**Figure courtesy of Cole Johnston & Dominic Bowman, KU Leuven**

# Asteroseismology for Stellar Evolution, Exoplanets, and Galactic Structure

**Class 1: Introducing starquakes**
**Class 2: Weighing, Sizing, Ageing**
**Class 3: Angular Momentum Transport**

Image credit: NASA's Goddard Space Flight Center/S. Wiessinger