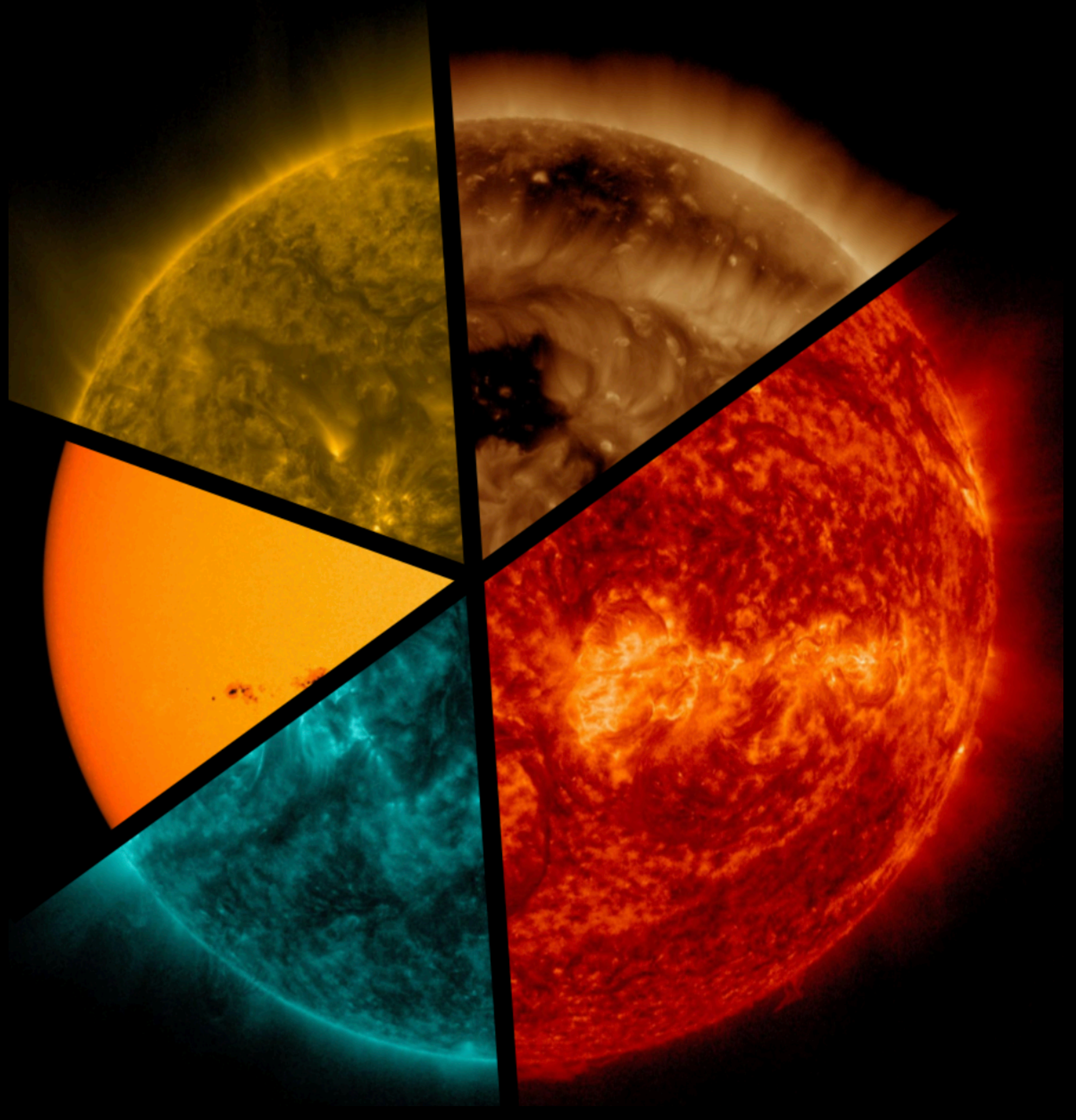


Sharpening our view on the inner workings of stars with star quakes: the current and future role of space-based observations

Andrea Miglio

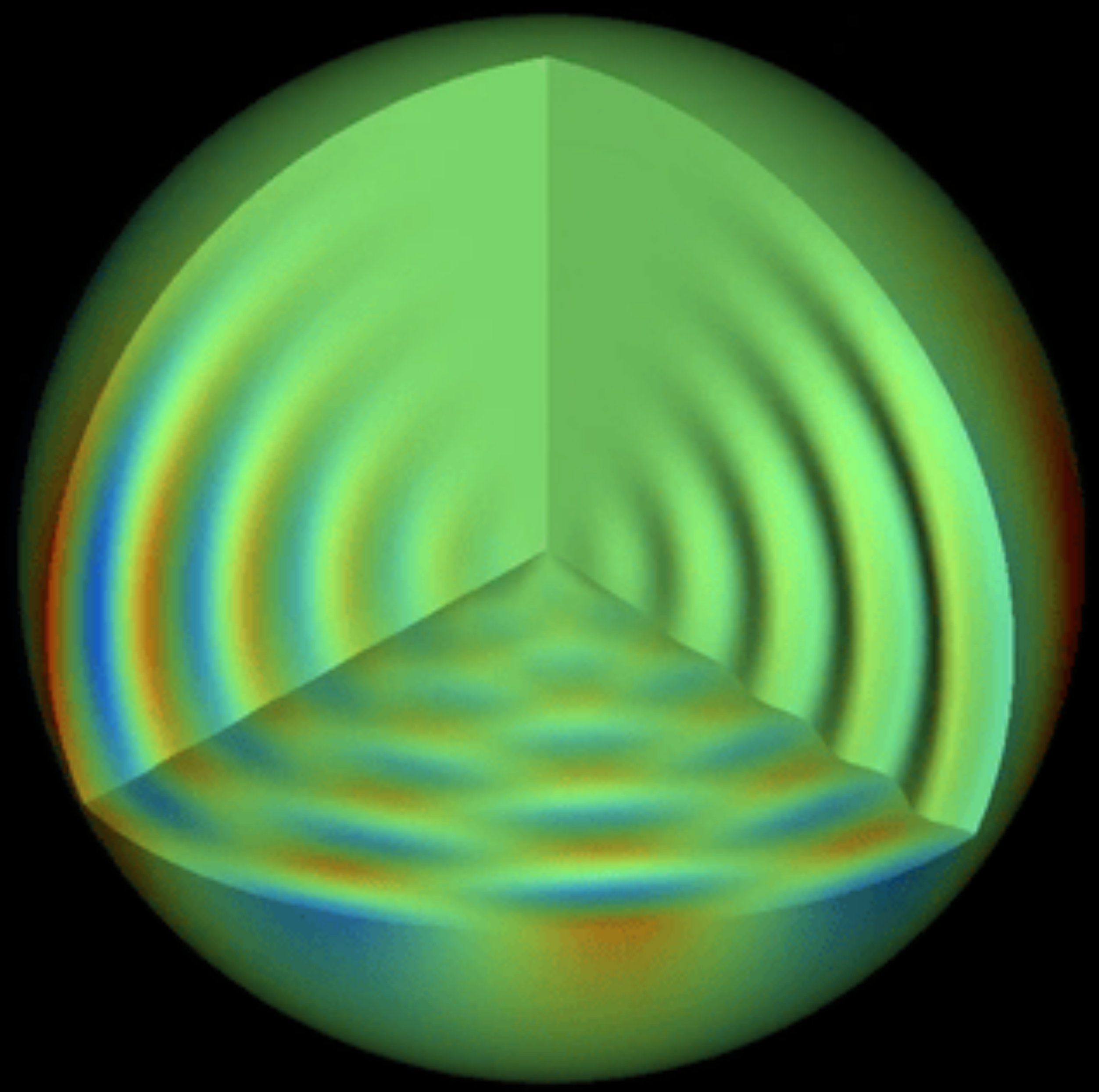
Alma Mater Università di Bologna
Istituto Nazionale di Astrofisica
University of Birmingham

Funded by the European Union

European Research Council
Established by the European Commission

STARS II
Bologna 16-20 June 2025

credits: S. Charpinet, IRAP, Toulouse



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THANKS PAOLA

STELLAR STRUCTURE AND EVOLUTION: WHY DO WE CARE

- our understanding of stellar structure and evolution underpins most of astrophysics

STARS II: A CLEAR SUCCESS FROM THE START

a cosmologist noted: “stellar structure and evolution is a cornerstone of astrophysics”

STELLAR STRUCTURE AND EVOLUTION: WHY DO WE CARE

- our understanding of stellar structure and evolution underpins most of astrophysics
- stars are formidable physics laboratories

however

"The internal constitution of stars" (Eddington, 1926)

"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. Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is hidden behind substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within ?"

“Stars and atoms” (Eddington, 1927)

Ordinary stars must be viewed respectfully like objects in glass cases in museums; our fingers are itching to pinch them and test their resilience.

Pulsating stars are like those fascinating models in the Science Museum provided with a button which can be pressed to set the machinery in motion. To be able to see the machinery of a star throbbing with activity is most instructive for the development of our knowledge.

Oxford: Clarendon Press, 1927

ACOUSTIC MODES IN STARS

- Eddington 1918

Cepheid Variables and the Age of the Stars.

GENTLEMEN,—

There seems to be little doubt that Cepheid variation must be attributed to some kind of pulsation having the period of the light-variation. If we have two similar globes of fluid executing oscillations under their own gravitation, their periods will be inversely proportional to the square-root of the density. This relation can be inferred at once from the theory of dimensions, since in gravitational units density is of dimensions $(\text{time})^{-2}$. We need not consider either the type of pulsation or the law of distribution of density and temperature in the interior, provided the two stars are homologous. This relation is found to be nearly fulfilled by the known Cepheids, although they differ in mass and the conditions cannot be perfectly homologous. If, then, we consider a particular star whose density slowly varies in the course of evolution, the theoretical conditions should be very closely fulfilled, and the changes of density could be deduced from the change of period.

The period of a Cepheid variable can be determined with great accuracy; in many cases it is given in the ephemerides to seven significant figures. Some of these stars have been observed for more than a century. We can thus discover very small changes of density, and so determine (or at least set a limit to) the rate of progress of stellar evolution.

$$P \propto \langle \rho \rangle^{-1/2} \propto (R^3/M)^{1/2}$$

Ritter 1879

ACOUSTIC MODES IN STARS

- different pulsators and non homologous stars have different proportionality factors (pulsation constants) $P = Q\,\langle\rho\rangle^{-1/2}$

RADIAL PULSATIONS OF STARS

P. LEDOUX[1] AND C. L. PEKERIS[2]

ABSTRACT

It is shown that the period τ of the fundamental mode of radial pulsation of a star is given to a good approximation by the expression

$$\tau = 2\pi\sqrt{\frac{I}{-(3\bar{\Gamma}_1 - 4)\Omega}}$$

where I denotes the moment of inertia of the star about its center, Ω its gravitational potential, and $\bar{\Gamma}_1$, the mean value of Γ_1 with respect to pressure. A general method of obtaining higher approximations for the period of the fundamental mode as well as for the periods of the higher modes is given and is applied to the standard model. The results obtained for the standard model indicate that, in certain cases, our approximate method yields more accurate values for the periods than have been obtained by the trial-and-error method of integrating the pulsation equation.

Ledoux & Pekeris 1941, ApJ

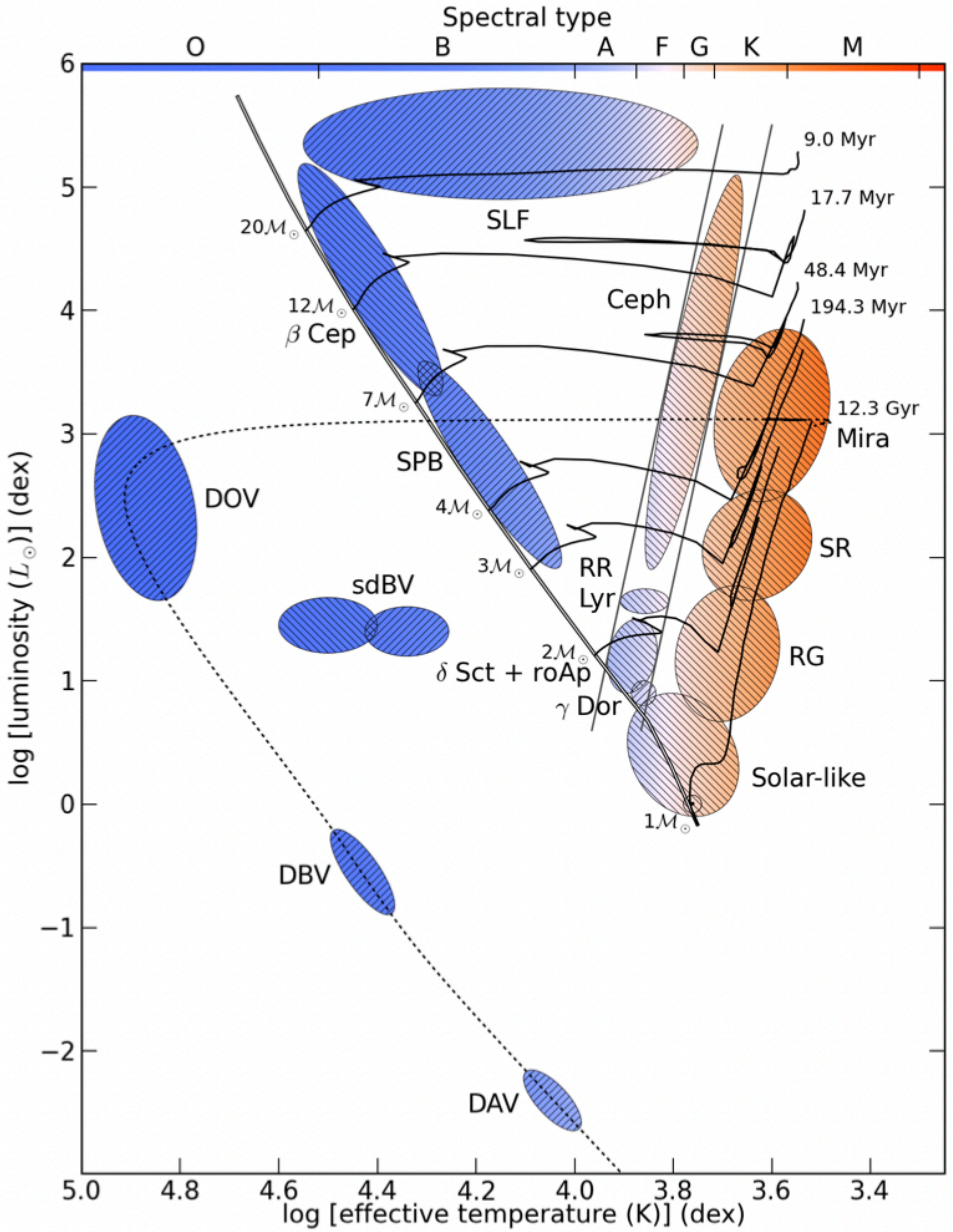
if $\frac{m_1(r)}{M_1} > \frac{m_2(r)}{M_2}$ $\quad 0 \leq r \leq R$

$$\Rightarrow \quad \sigma_1^2 > \sigma_2^2 \frac{M_1}{M_2}$$

ASTEROSEISMOLOGY

the study and interpretation of global, resonant oscillation modes in stars

- variety of physical structures
  - mass
  - evolutionary state
  - physical processes at play
- variety of pulsation modes

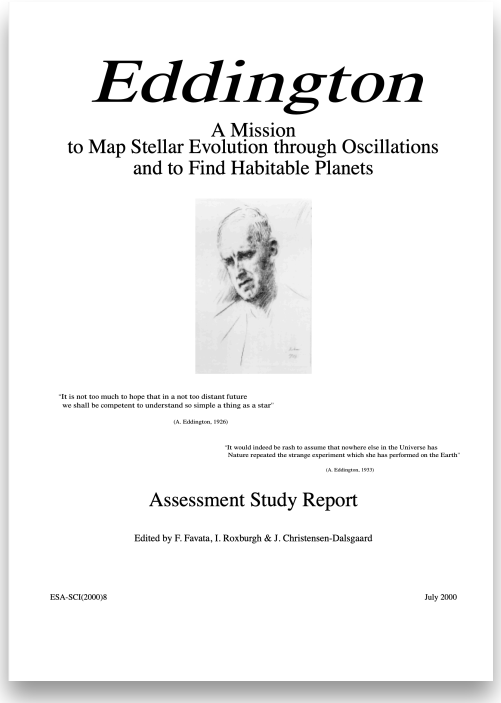


Aerts 2021

ASTEROSEISMOLOGY: DATA

field revolutionised by the advent of space-based telescopes

proposed:



Eddington

A Mission
to Map Stellar Evolution through Oscillations
and to Find Habitable Planets

"It is not too much to hope that in a not too distant future
we shall be competent to understand so simple a thing as a star"

(A. Eddington, 1926)

"It would indeed be rash to assume that nowhere else in the Universe has
Nature repeated the strange experiment which she has performed on the Earth"

(A. Eddington, 1933)

Assessment Study Report

Edited by F. Favata, I. Roxburgh & J. Christensen-Dalsgaard

ESA-SCI(2000)8 July 2000

past/current:

- photometric precision → micro-mag level changes
- duration of the observations → frequency resolution resolve details of the oscillations spectrum
- number of stars with detected pulsation modes → ensemble asteroseismology

ASTEROSEISMOLOGY

oscillation modes in stars: 2 main families

pressure modes

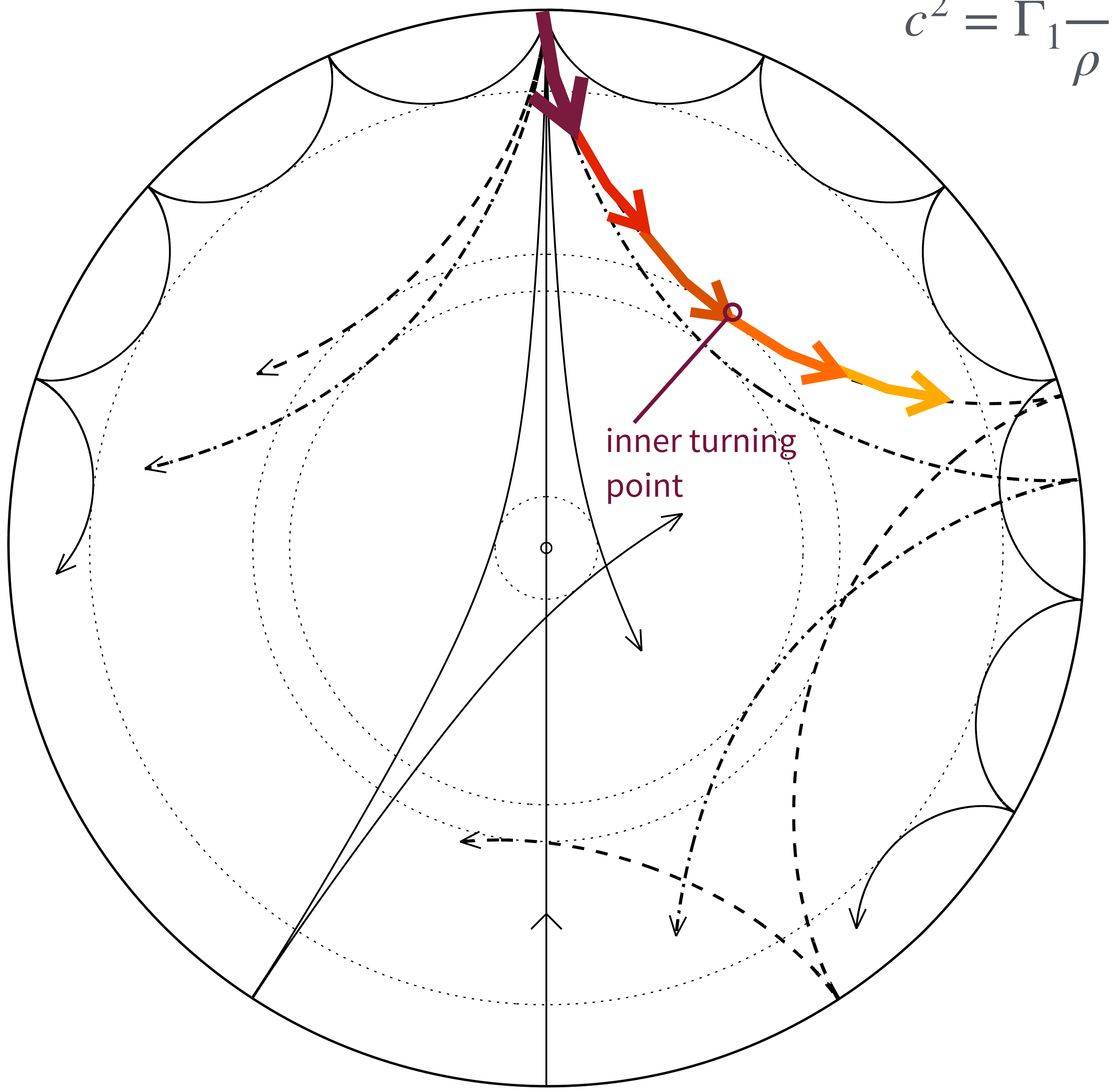
- acoustic waves
- largely determined by $c^2 = \Gamma_1 \frac{P}{\rho}$ where $\Gamma_1 = \left(\frac{\partial \ln p}{\partial \ln \rho}\right)_{\mathrm{ad}}$
- high frequencies

ASTEROSEISMOLOGY

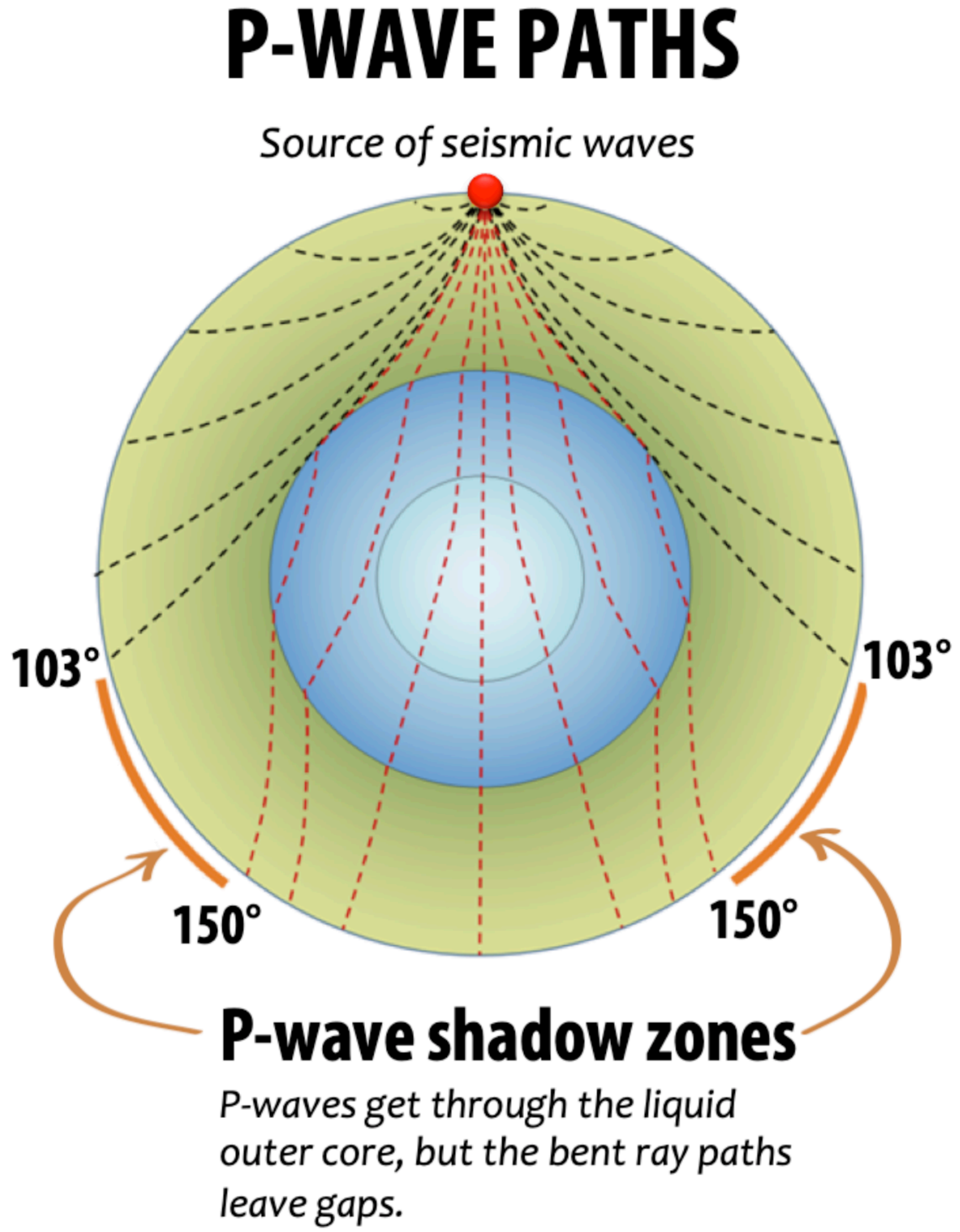
propagation of modes: low mass star

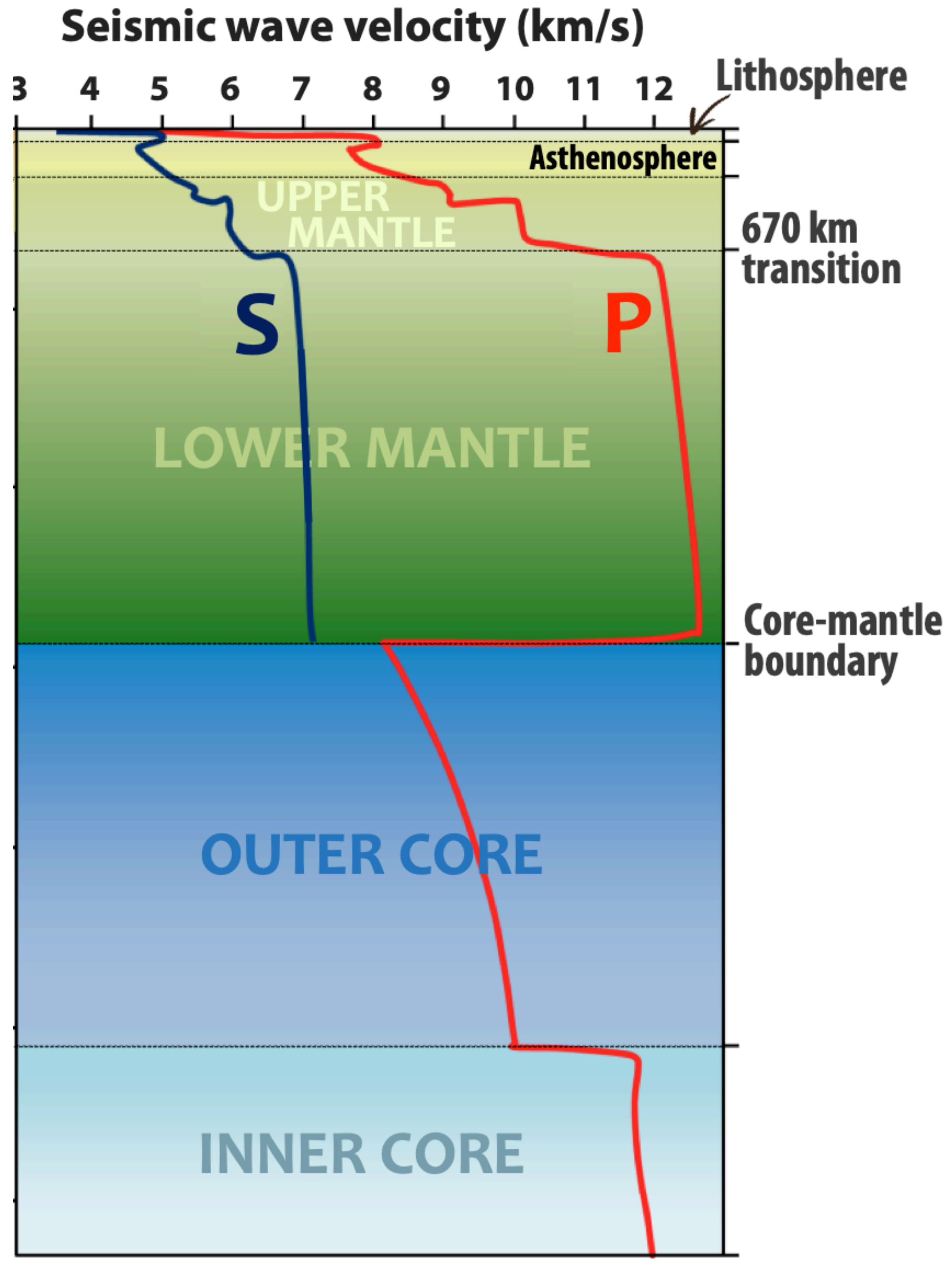
pressure modes

$$c^2 = \Gamma_1 \frac{P}{\rho} \propto \frac{T}{\mu}$$



propagation of primary waves: the Earth





source: wikipedia

ASTEROSEISMOLOGY

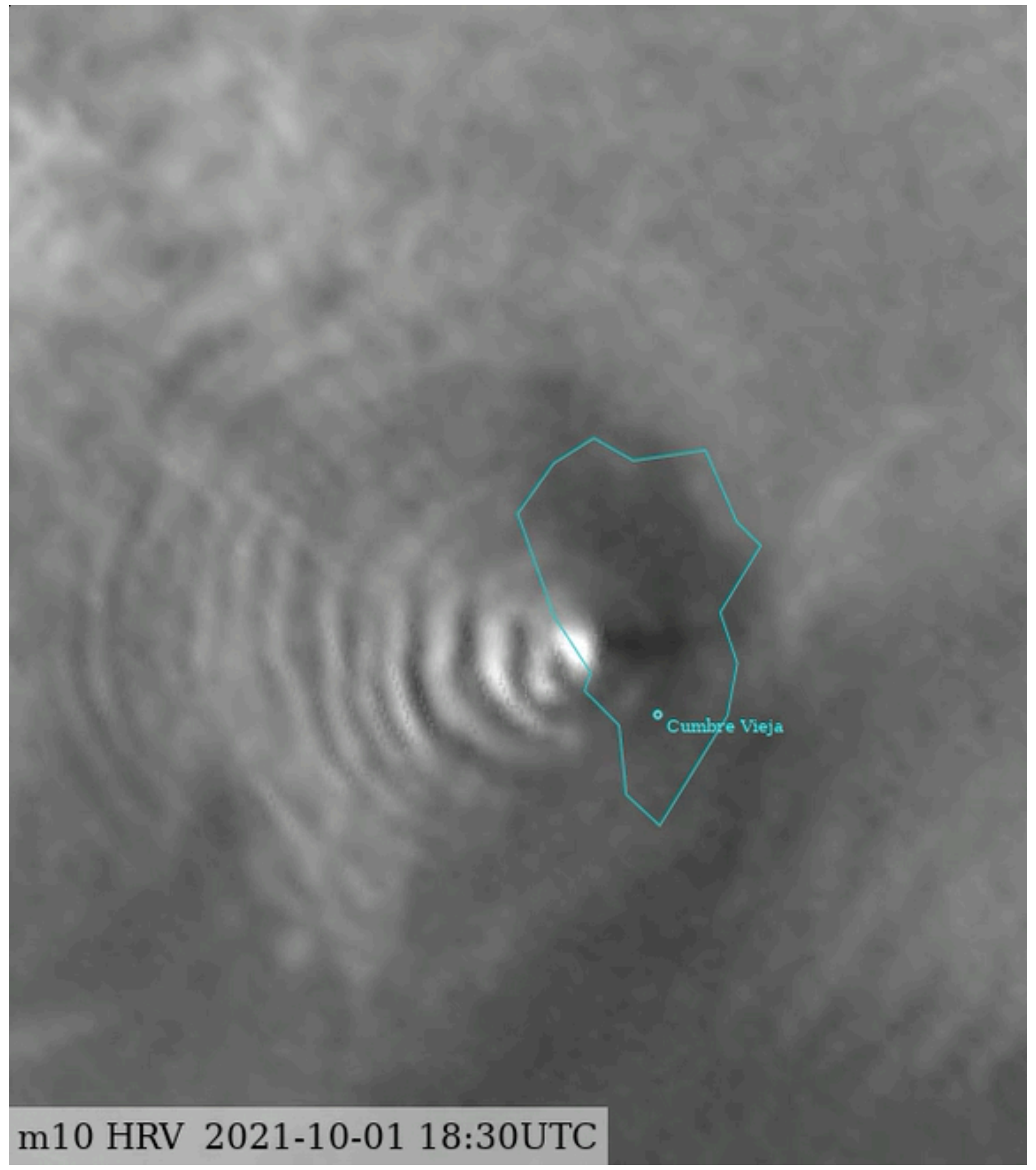
oscillation modes in stars: 2 main families

gravity modes

- restoring force: buoyancy
- propagate in radiative regions
- sensitive to near-core conditions

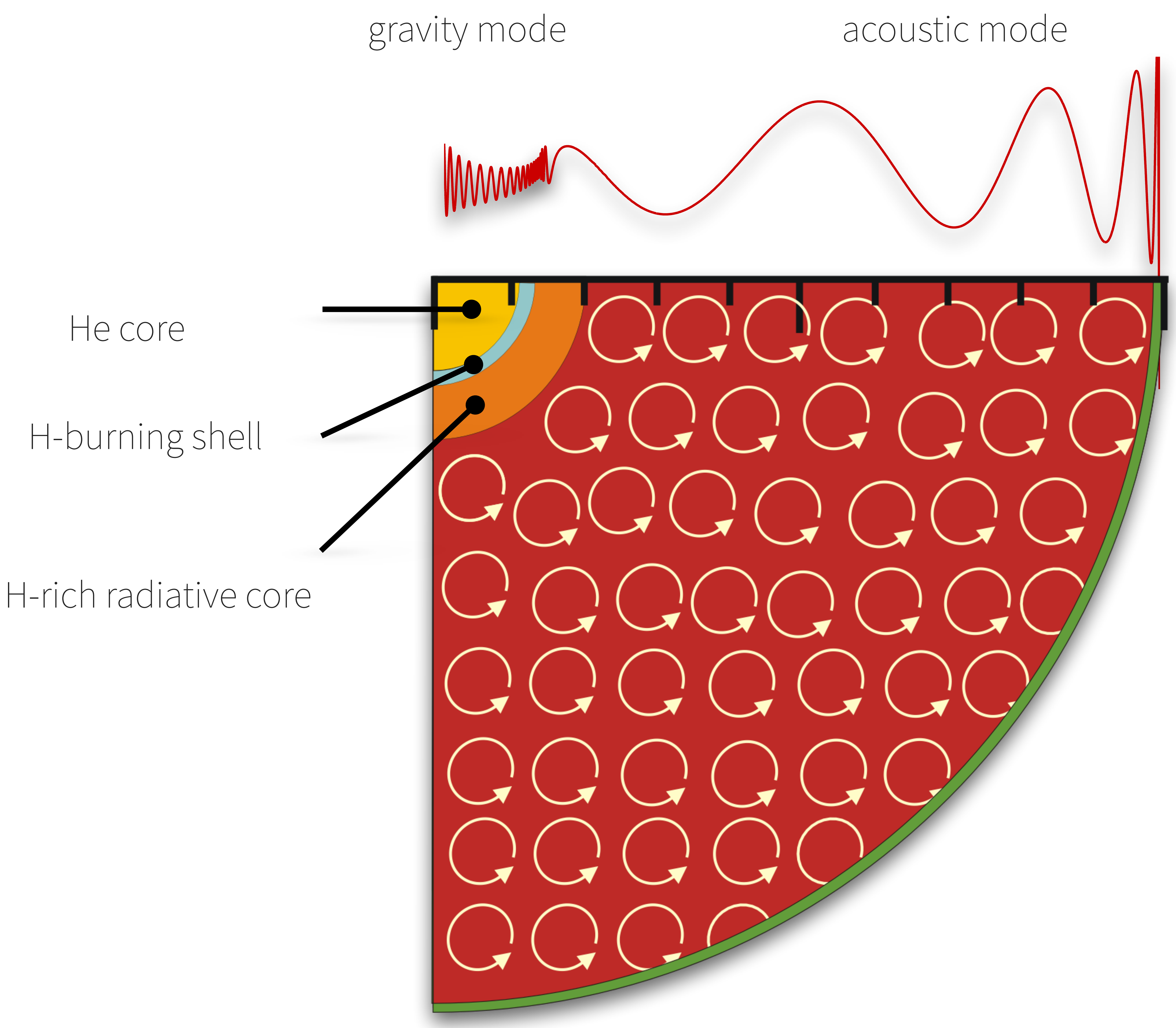
internal gravity waves in the Earth's atmosphere

Meteosat-10 HRV



ASTEROSEISMOLOGY

- mixed modes



ASTEROSEISMOLOGY: A NEW TOOL

what determines the pulsation spectrum of a star?

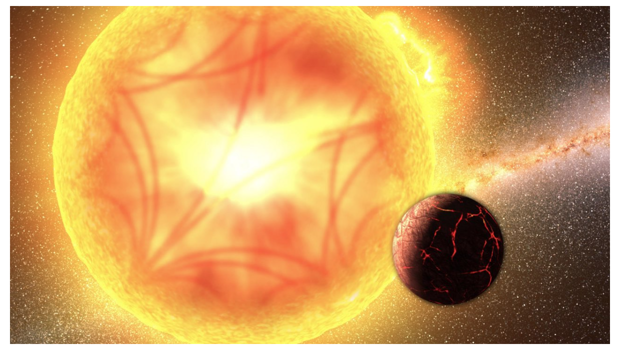
- geometry of the resonant cavity
- size, acoustic radius
- sound speed, density stratification, sharp-structure variations
- coupling between multiple resonant cavities
- structural changes due to e.g. activity cycles
- velocity fields, magnetic fields

INFERENCES ON GLOBAL STELLAR PROPERTIES

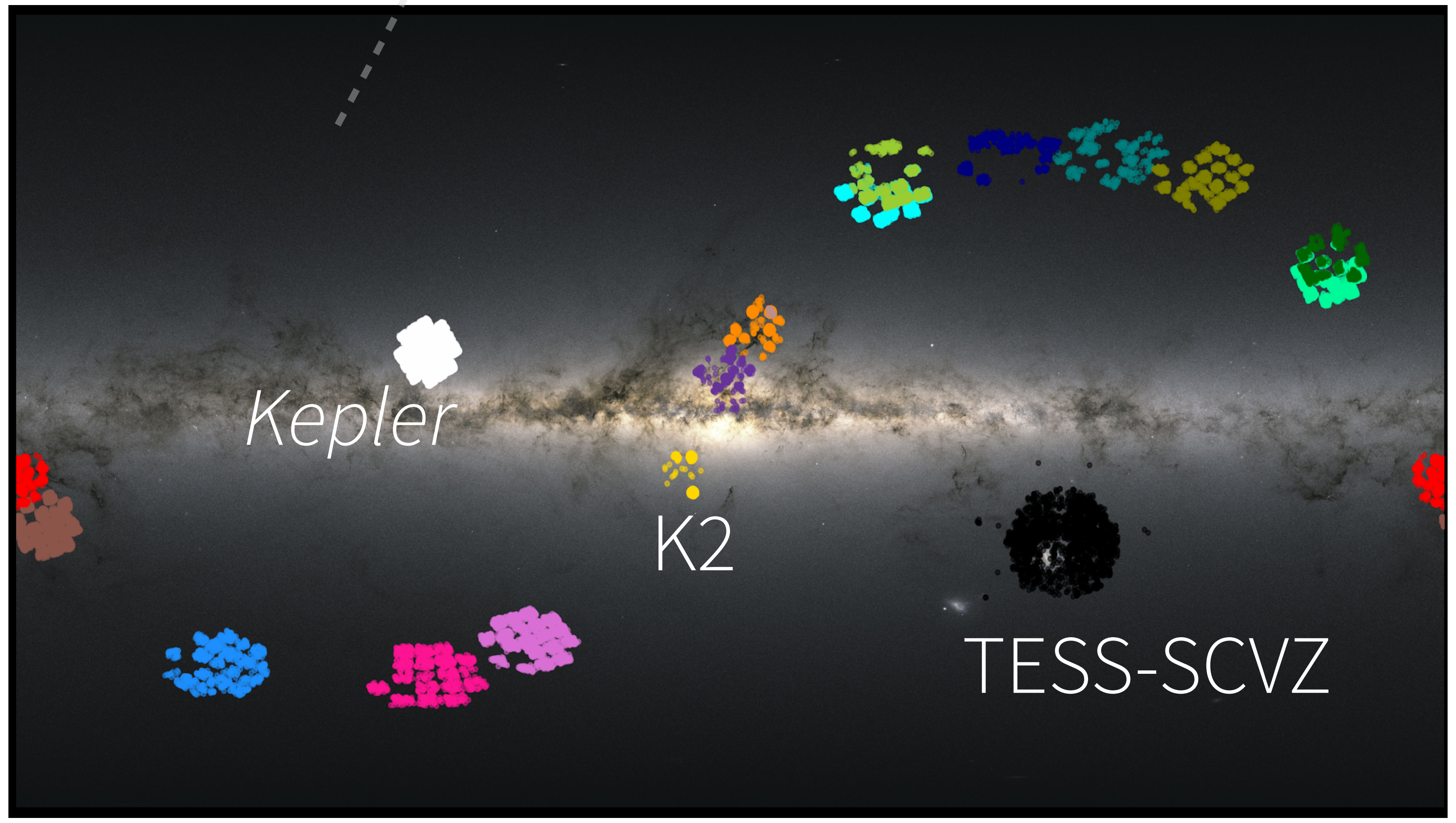
e.g.

- radius
- mass
- age

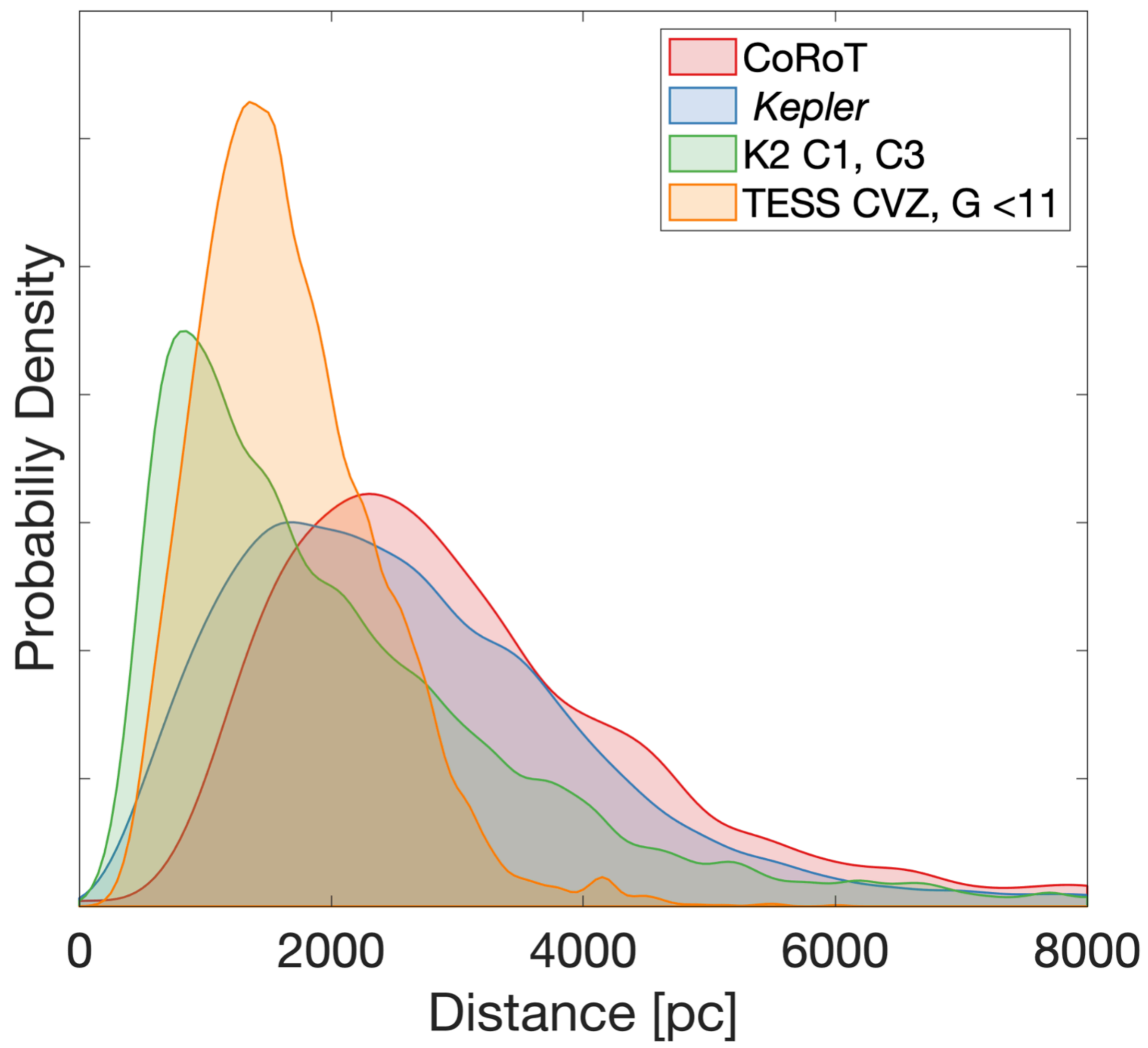
characterise exoplanetary systems

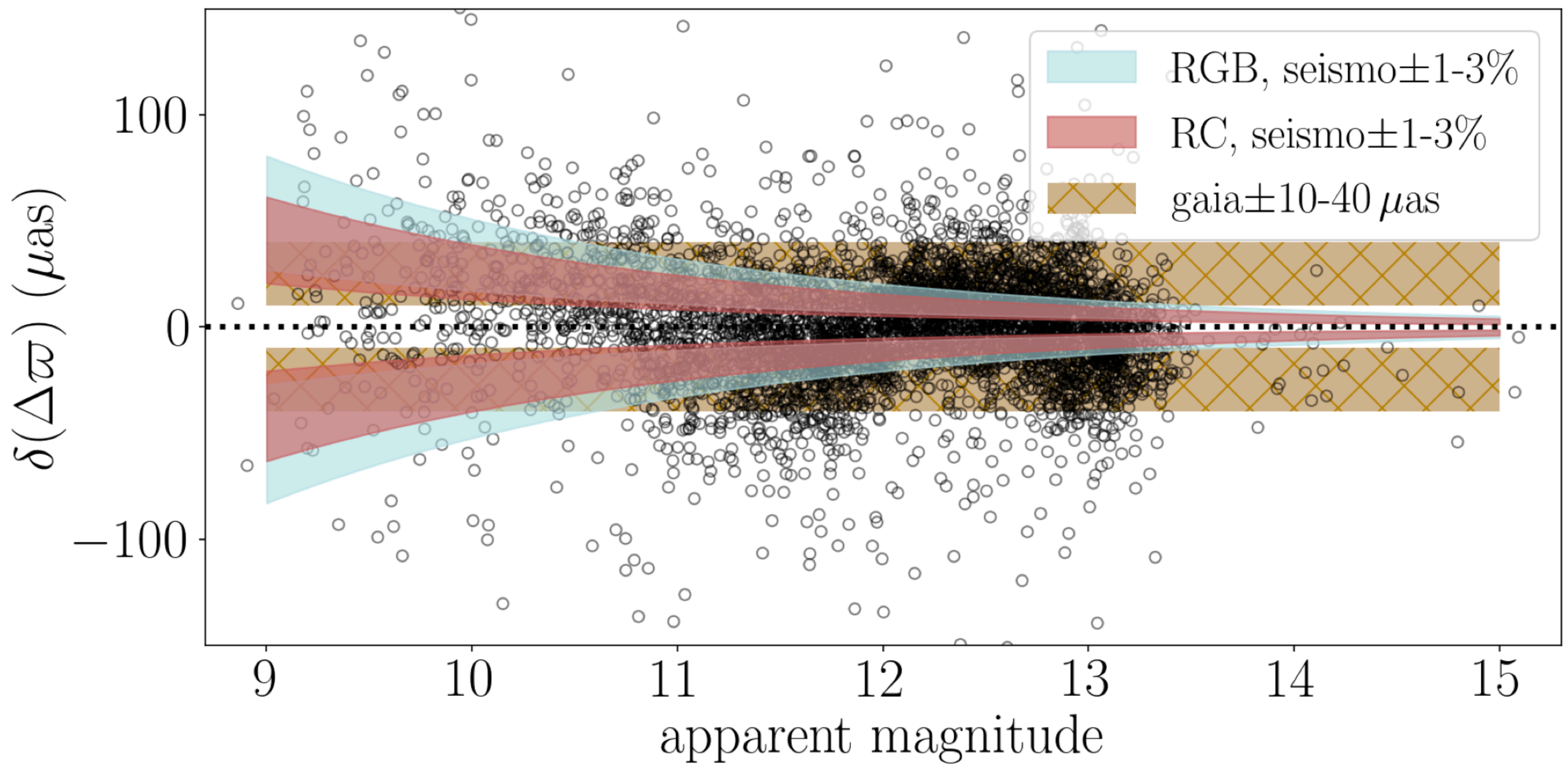


MW's assembly and evolution



% LEVEL RADIUS (DISTANCE) DETERMINATION

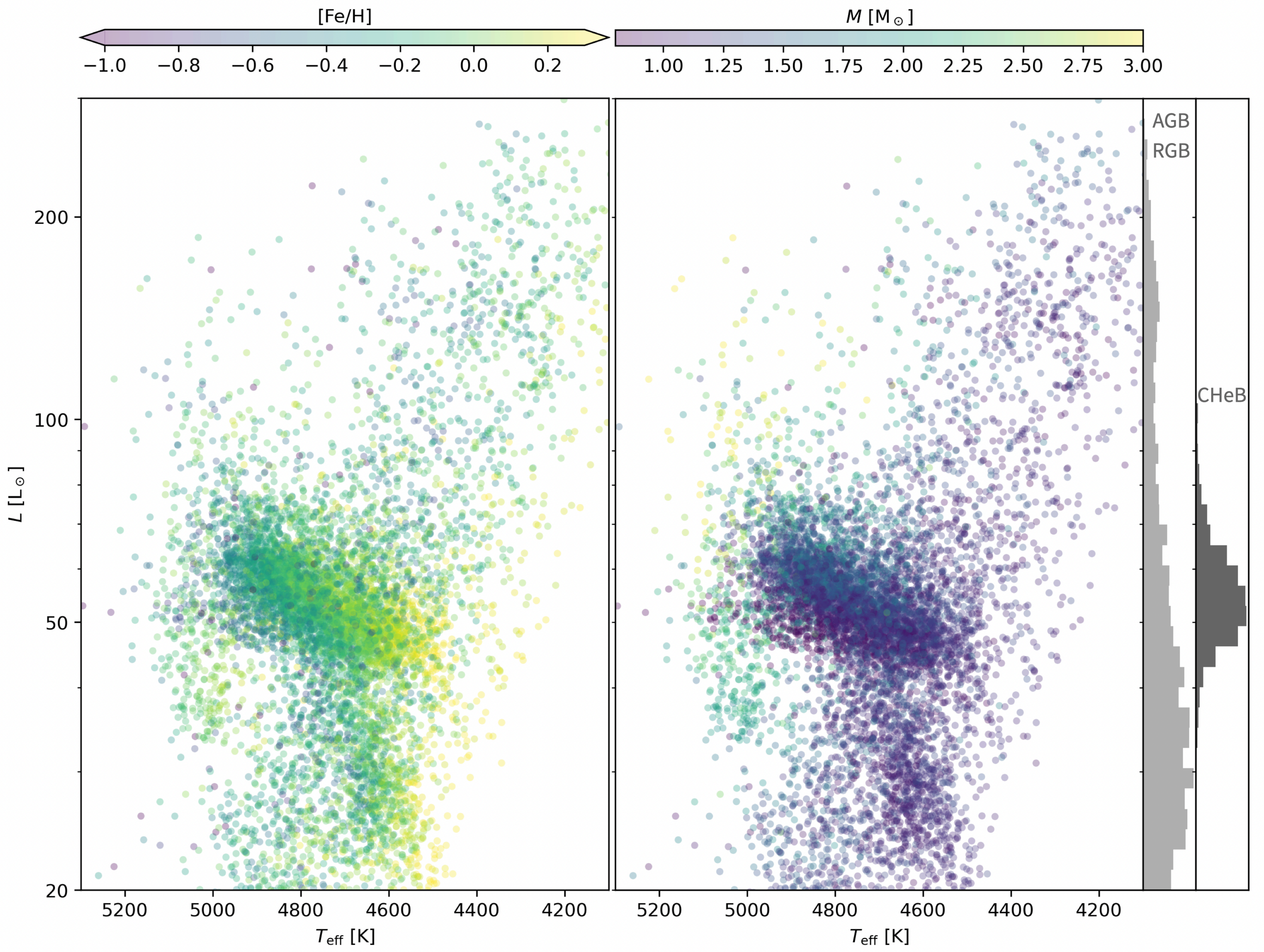




Khan et al. 2019,2023ab

see also talk by Prada Moroni

MASSES



Kepler: Gaia DR3 + APOGEE+ asteroseismology

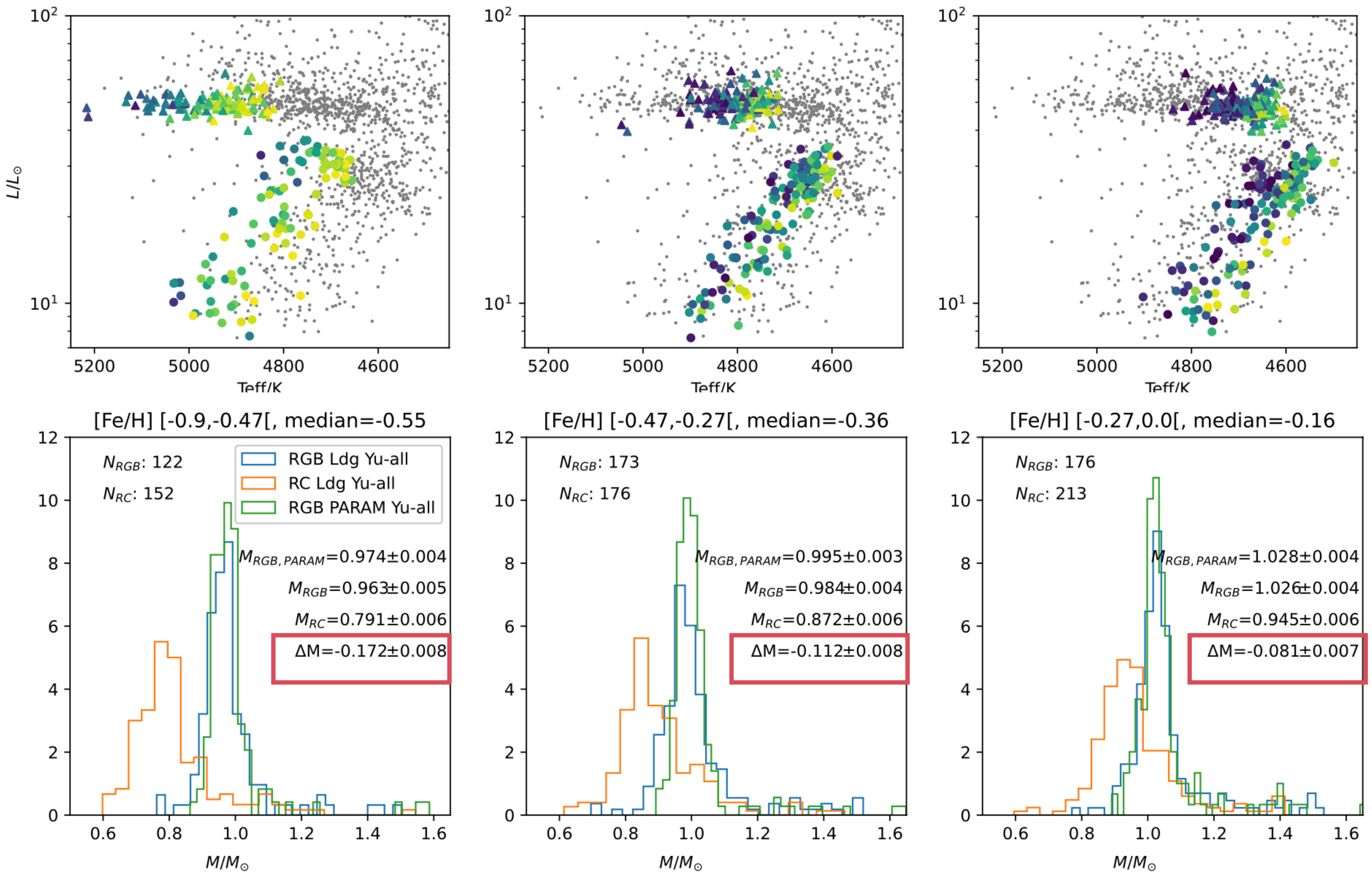
MASS LOSS

- RGB Mass loss

Brogaard et al., 2024

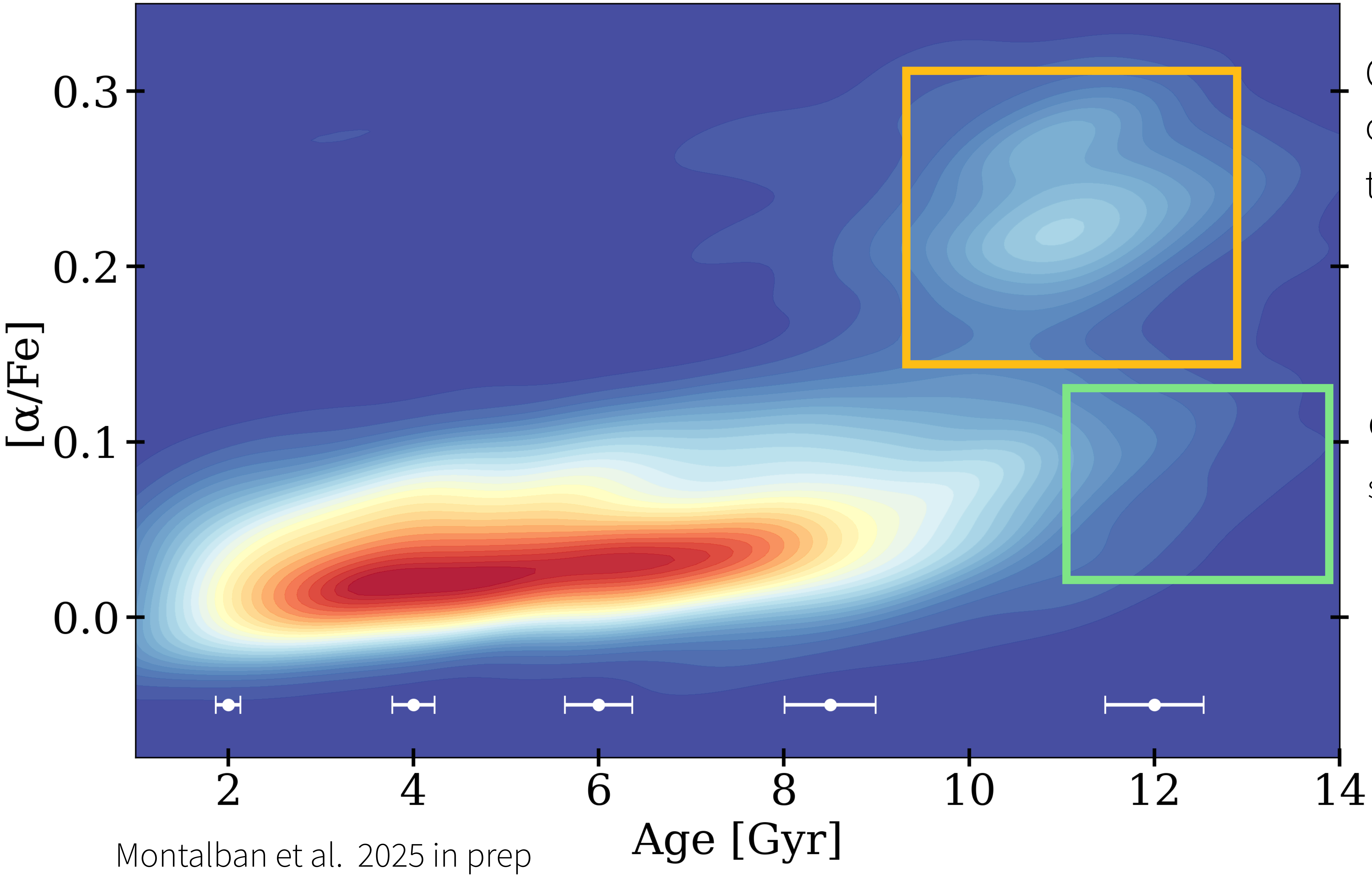
- [Fe/H] dependence
- comparison with GCs

physics behind mass loss (eventually)



MASSES OF RGB STARS ⇨ AGES

- median age uncertainty: 10%



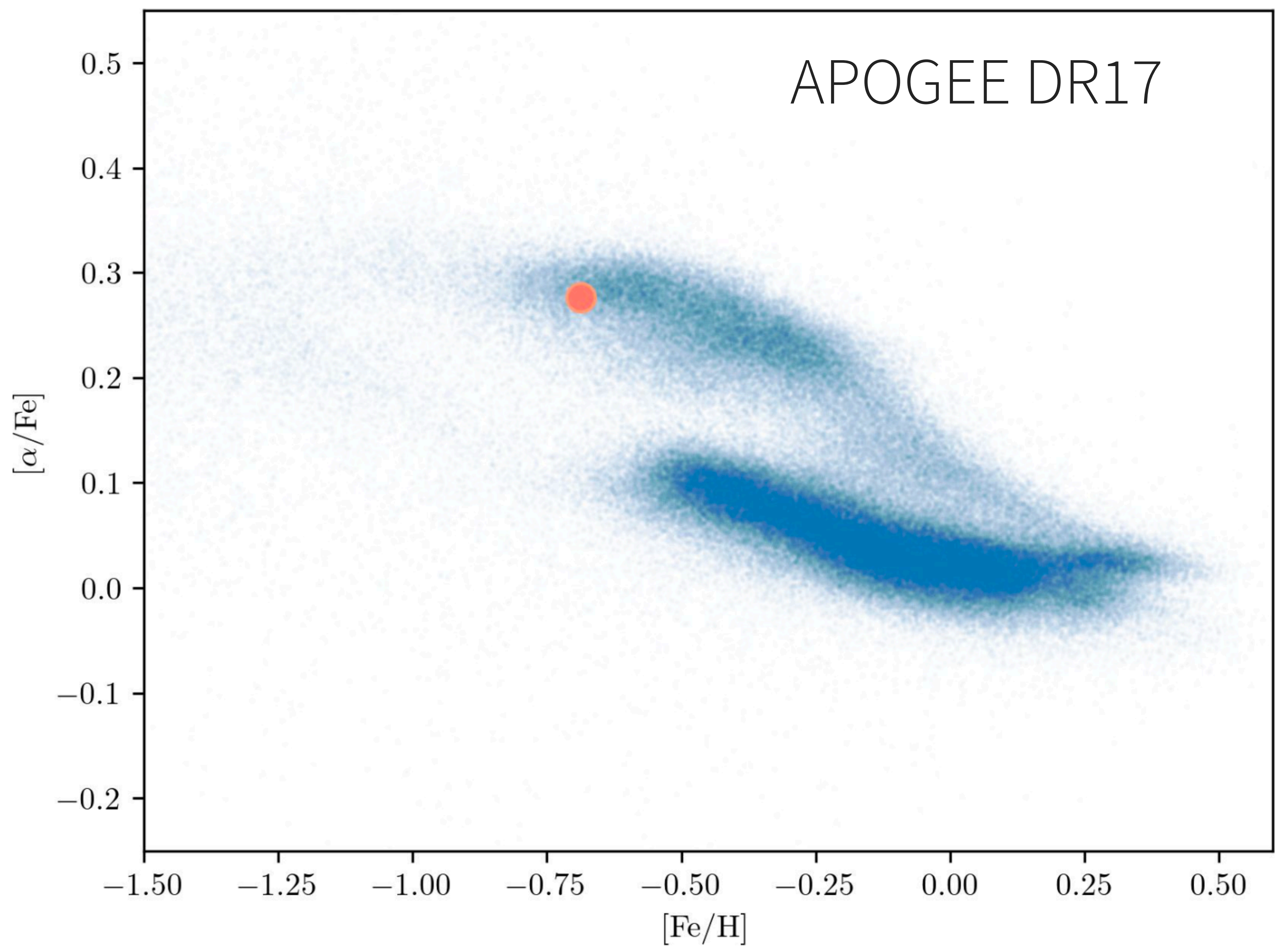
Montalban et al. 2025 in prep

Chemical thick disk ~ 11 Gyr old, chemical evolution within the high-α population

early disk?

see also Nepal et al. 2024

ACCURACY MATTERS!



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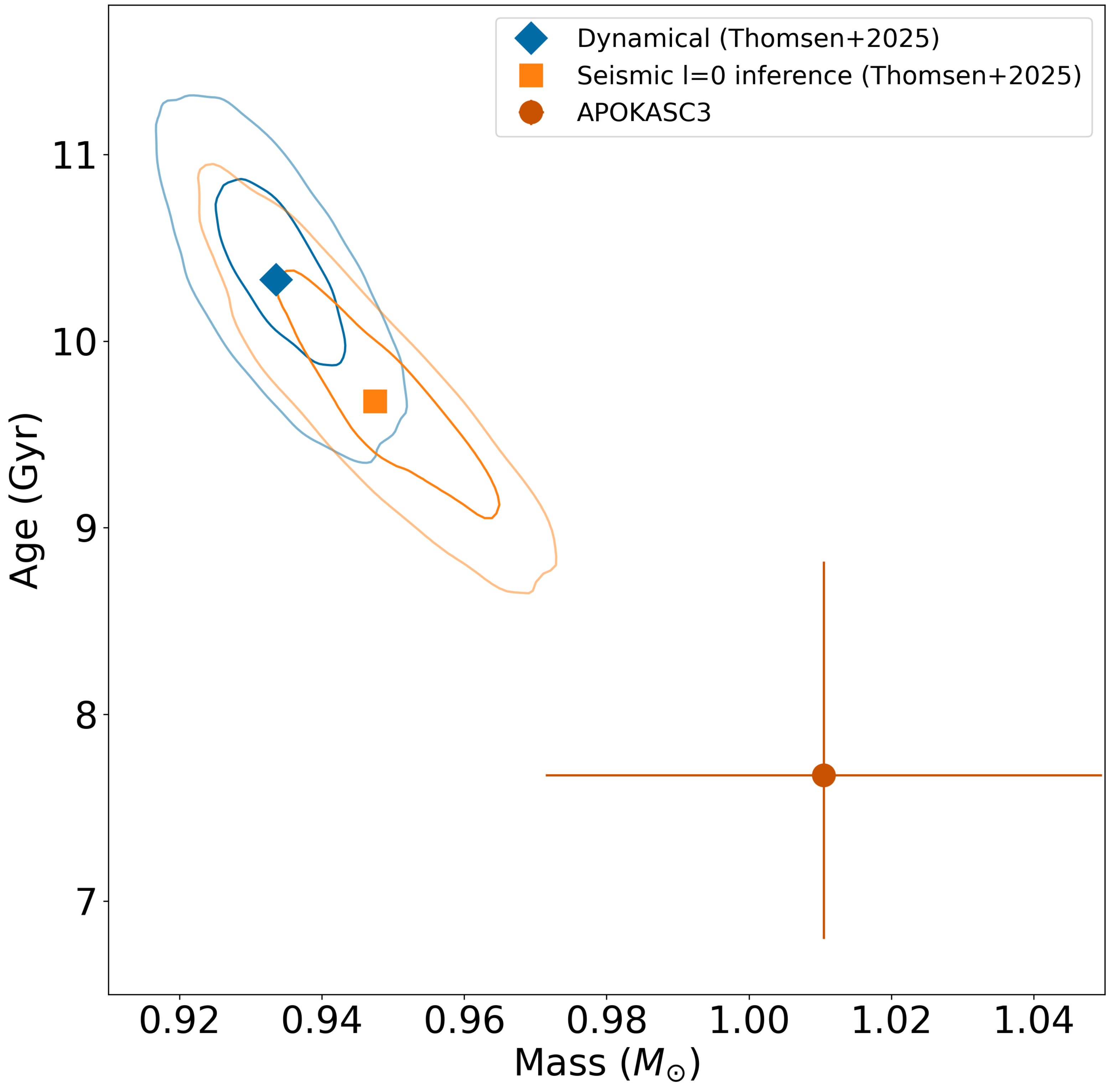


Thomsen et al. 2025, A&A, in press

seismic* and orbital masses agree to within 1.4% (~1σ)

DIRECT CONSTRAINTS ON INTERNAL STRUCTURE

a zoo of seismic diagnostics for MS stars, red giants, WDs:

- asymptotic patterns
  - $\Delta\nu \propto \sqrt{\frac{M}{R^3}}$
  - $\delta\nu_{02} \propto \int \frac{1}{r}\frac{\mathrm{dc}}{\mathrm{dr}}\mathrm{dr}$

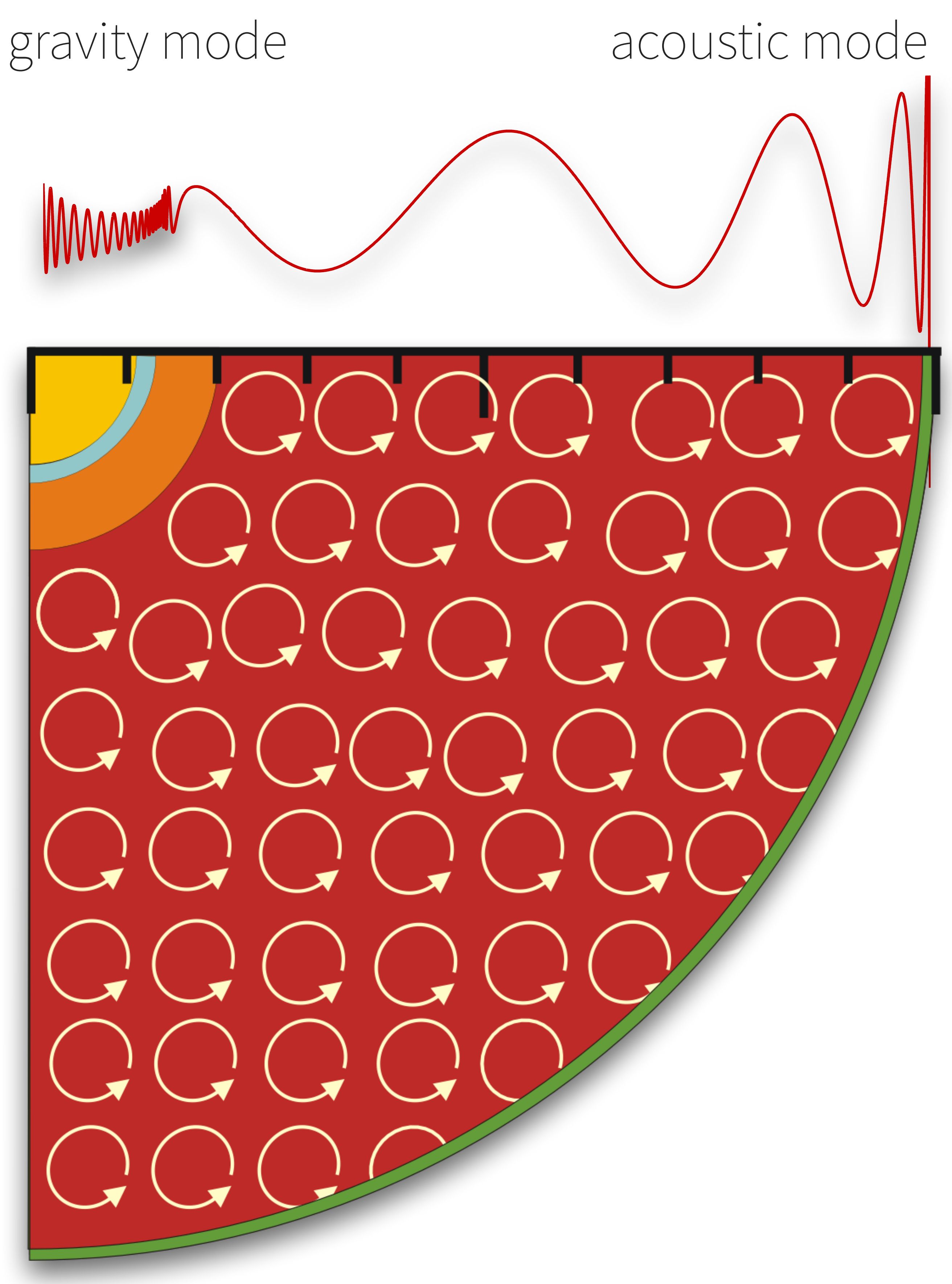
    p modes
  - average period spacing characterising g modes $\Delta\Pi_1 \propto \frac{1}{\int |N| \frac{dr}{r}}$
- departures from simple patterns
  - coupling of cavities to find partially stripped stars, non-standard core-envelope
  - structural glitches

    see Matteuzzi's talk

  ...

ROTATION

- Differential rotation



$$\delta\omega_{nlm} = m\beta_{nl} \boxed{\int_0^R K_{nl}(r)\Omega(r)\mathrm{d}r}$$

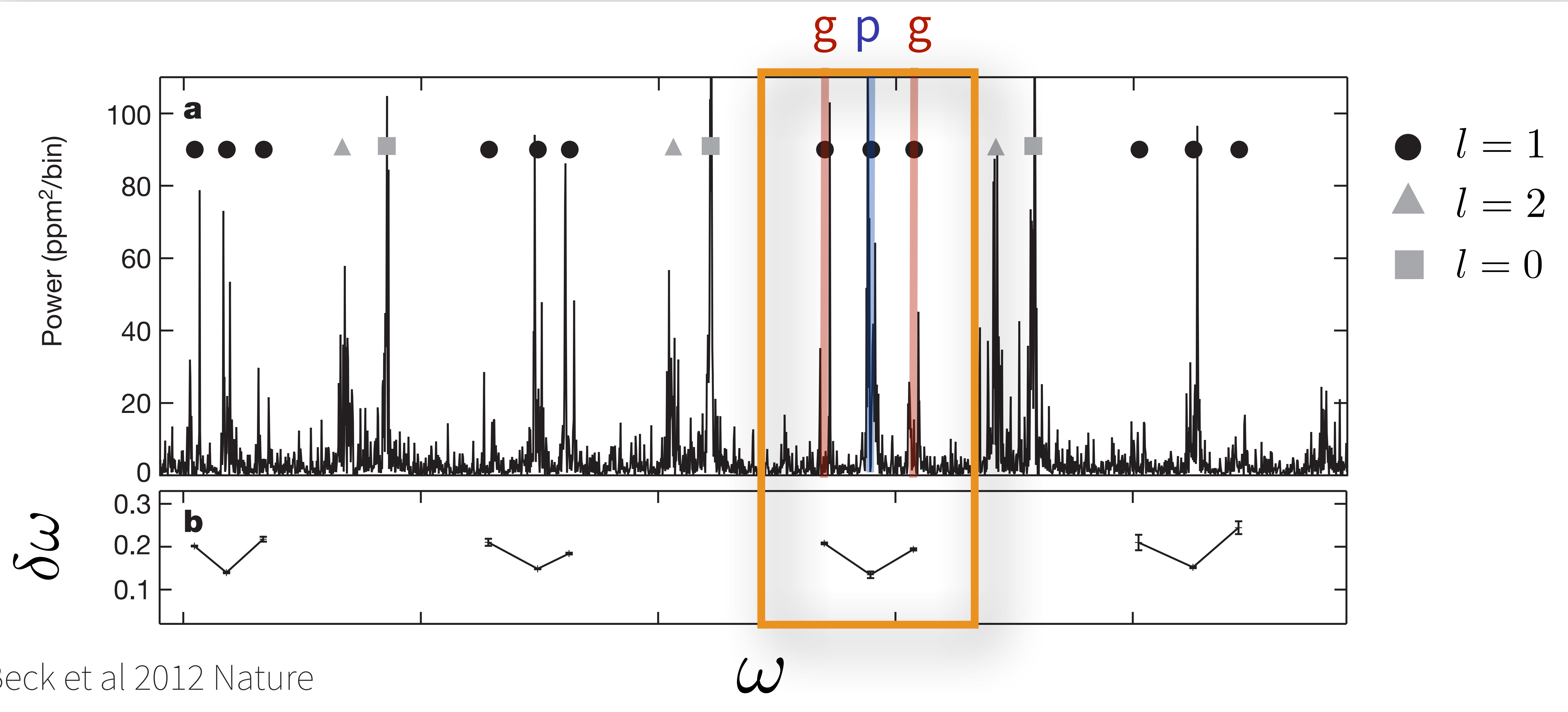
weighted mean of $\Omega(r)$

g modes K localised in the He core

p modes K significant amplitude in the envelope

H2. effects of rotation on the oscillations frequencies

- Observations of rotational splitting in a red giant



Beck et al 2012 Nature

$l = 1$
$l = 2$
$l = 0$
p
g
g

OUTLOOK ON FUTURE DATA AND EFFORTS

- *Kepler*: is that all we need, what are we missing?
    - limited harvest of planets around nearby stars, especially Earth-like planets around Sun-like stars

R-SCI-L0-12 PLATO shall determine the age of a G0V star of V= 10 (goal V = 11) with an accuracy of 10%.

R-SCI-L0-55 PLATO shall provide photometric data to determine the radius of a G0V star of V=10 (goal V=11) with a precision of 1-2%.

This requirement is directly derived from R-SCI-L0-05 and R-SCI-L0-07. In order to meet R-SCI-L0-05, and given R-SCI-L0-07, the radius of the star needs to be determined with the precision specified here.

R-SCI-L0-57 PLATO shall provide photometric data to determine the mass of a G0V star of V=10 (goal V=11) with a precision of 15%.

PLATO: BEYOND DELIVERING PIPELINES…

Predicted asteroseismic detection yield for solar-like oscillating stars with PLATO

M.J. Goupil[1], C. Catala[1], R. Samadi[1], K. Belkacem[1], R.M. Ouazzani[1], D. Reese[1], T. Appourchaux[2], S. Mathur[3,4], J. Cabrera[5], A. Börner[6], C. Paproth[6], N. Moedas[7,8], K. Verma[9], Y. Lebreton[1,10], M. Deal[11], J. Ballot[12], W. J. Chaplin[13], J. Christensen-Dalsgaard[14], M. Cunha[7], A. F. Lanza[15], A. Miglio[16,17], T. Morel[18], A. Serenelli[19,20], B. Mosser[1], O. Creevey[21], and A. Moya[22]

- The PLATO mission will produce a sample of seismically characterised MS stars 80 to 100 times larger than *Kepler,* if observing two fields for two years each .
- P1 and P2 samples: individual mode frequencies can be measured with high precision
- +24k giants in the science calibration and validation catalogue

- CoRoT, *Kepler*-K2 — have demonstrated the potential of asteroseismology (in clusters)
- TESS — observational strategy not optimised for stellar / galactic science
- PLATO

designed primarily for planet searches: **wide field**, **bright targets**, **large pixel sizes**

⇨ overcome these limitations i.e.

by measuring the frequencies of hundreds or thousands of stars that belong to **controlled environments** or key **building blocks of galaxies**

⇩

a simple mission concept strongly based on heritage from CoRoT, *Kepler*, and the knowledge being developed for PLATO

haydn

high-precision asteroseismology in dense stellar fields

radically improve our understanding of the main building blocks of cosmic structures

S

S

S

S

cale

data needed: long, high-duty-cycle, precise photometric time series of stars in dense environments

SUMMARY

- space-based observations have given us a way to access stellar interiors

- the frequencies of resonant oscillation modes may be used to
  - *infer precise stellar properties (M, R, age)*
  - *provide time-resolved picture of the Milky Way*
  - *characterise exoplanetary systems*

planet hunter with built-in capability to seismically characterise hosts

- *stress test models of stellar structure and evolution*

we need to access laboratories optimised to make full use of this tool

⇨ high-precision asteroseismology in controlled environments