STARS & THEIR "GOOD" VIBRATIONS

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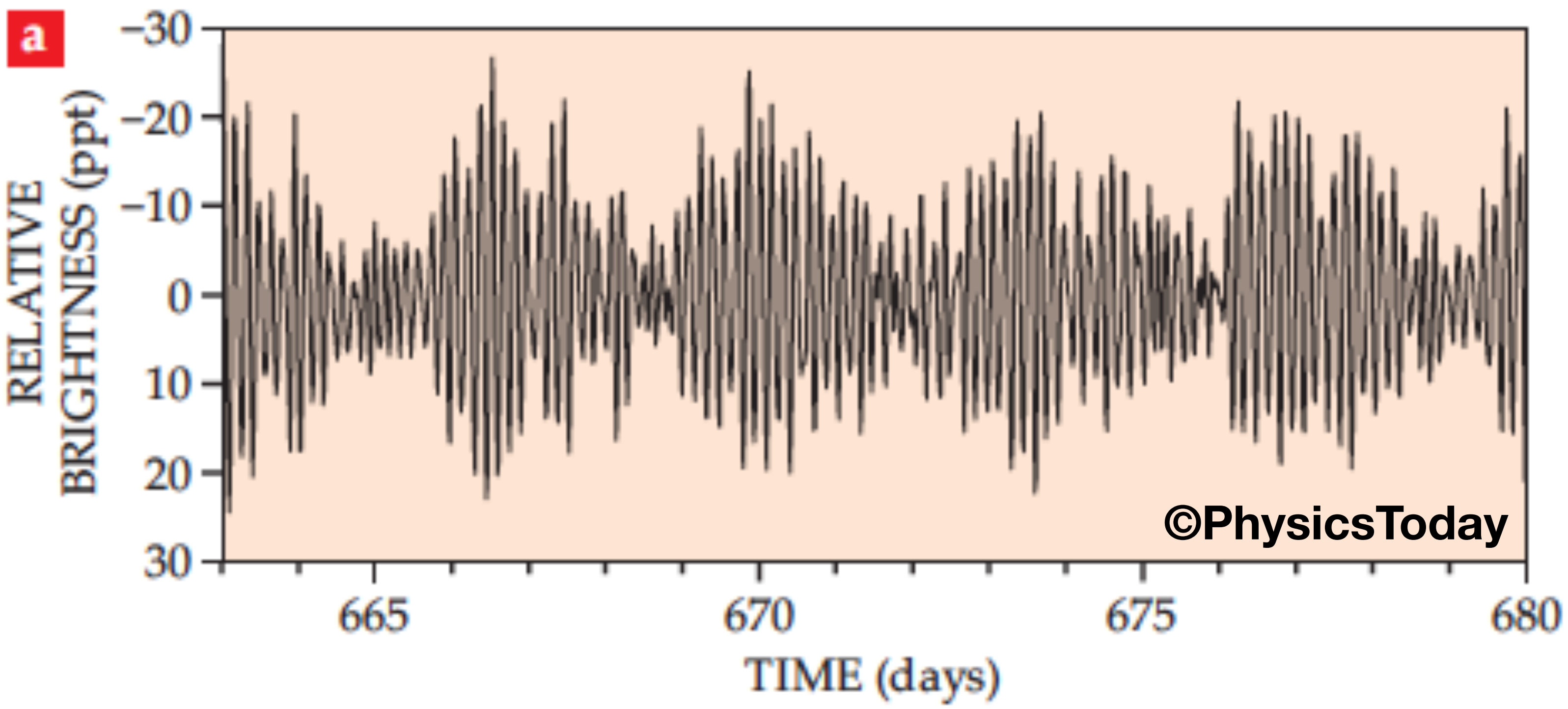
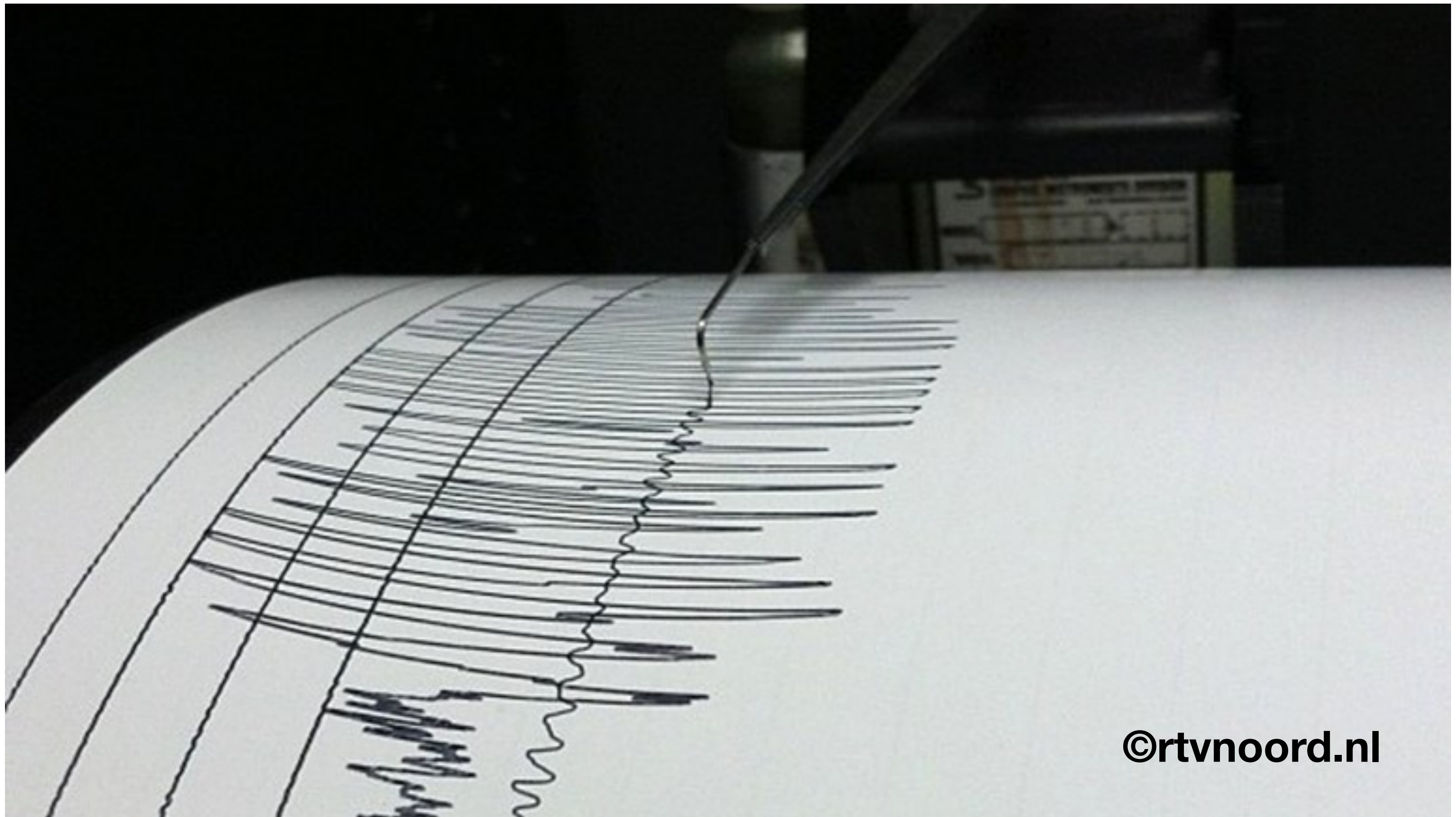
Konkoly, 18 May 2021

MAMSIE erc KU LEUVEN

Take-home message

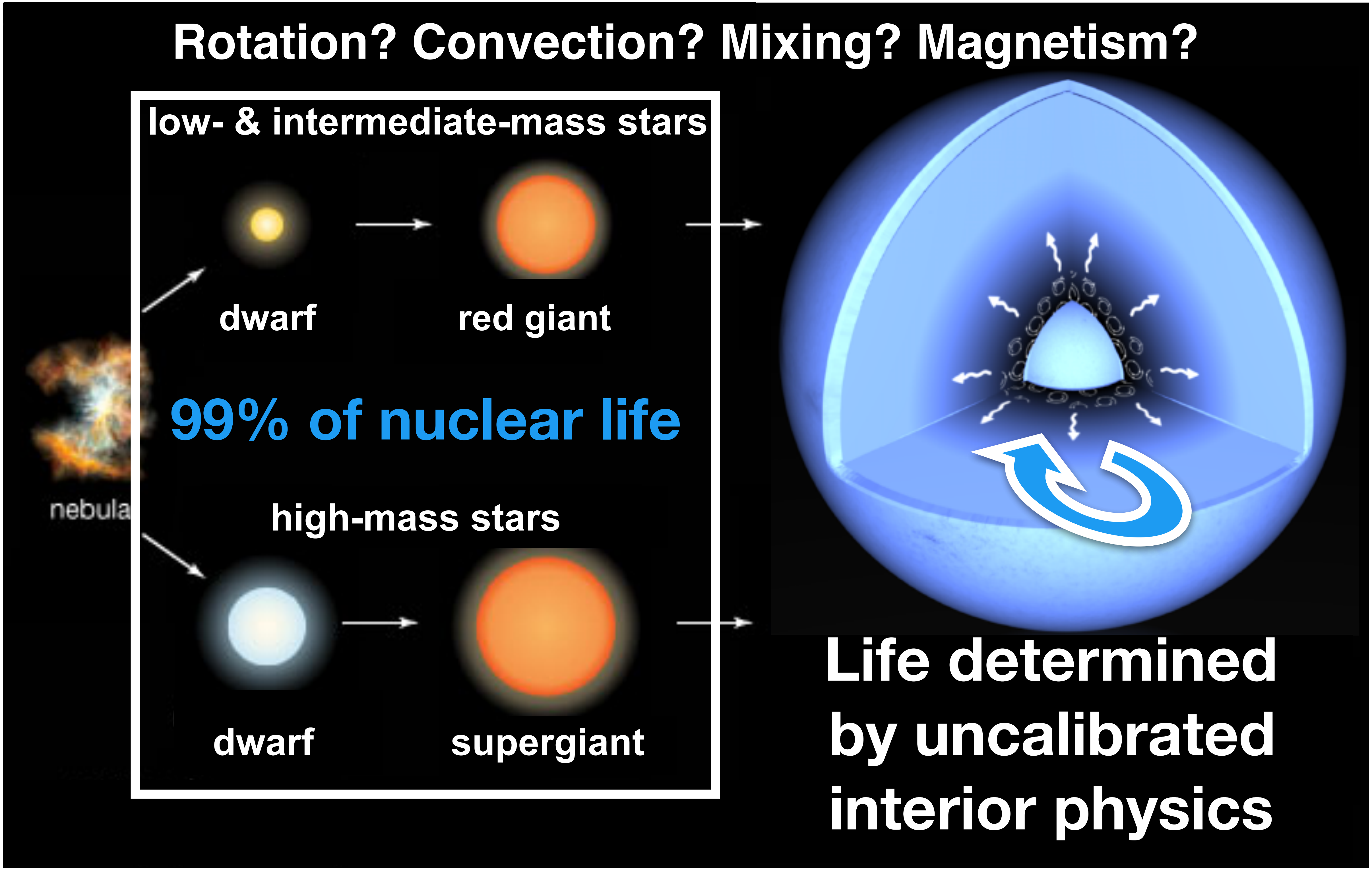




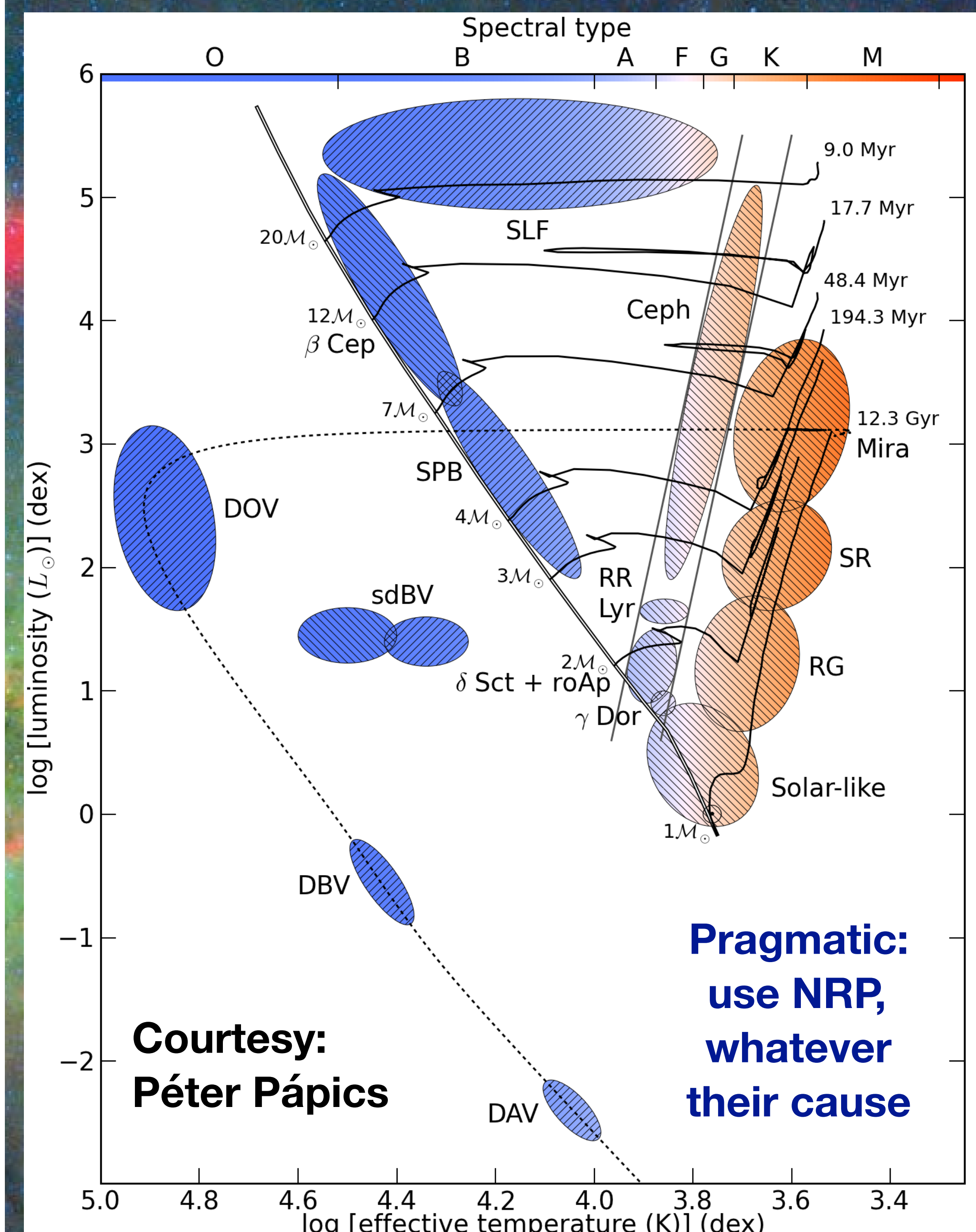
Seismic waves offer *localised* measurements of internal stellar physics: new look@SSE

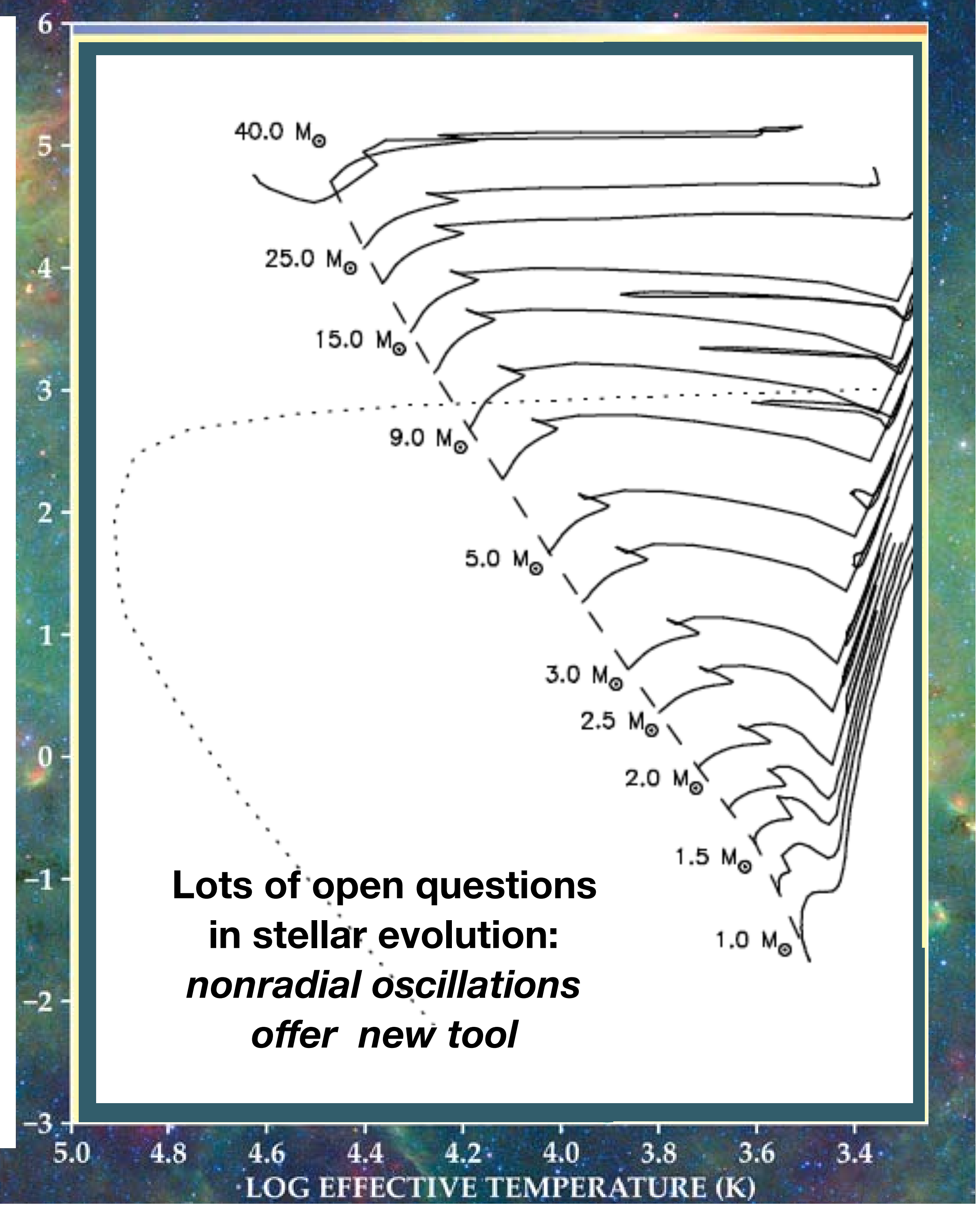
the art is to get the seismic info out of the data…

Stellar interiors: poorly known



Asteroseismology to the rescue





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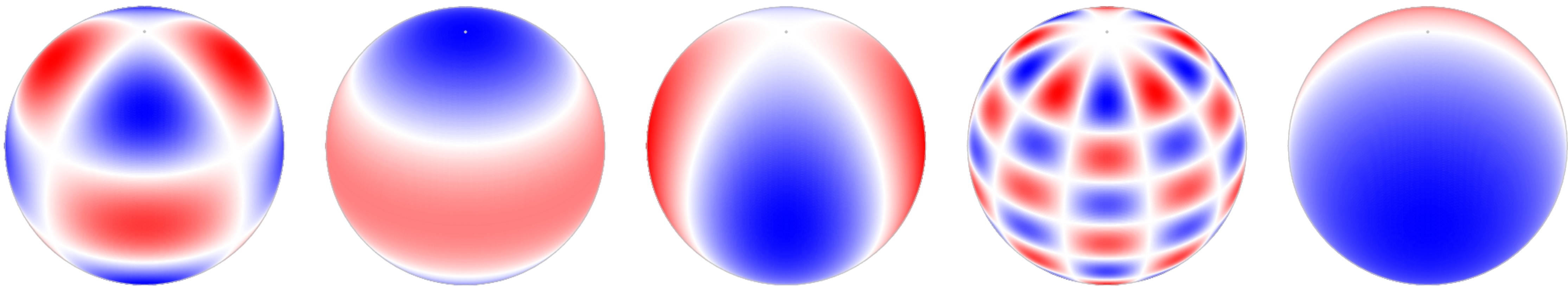
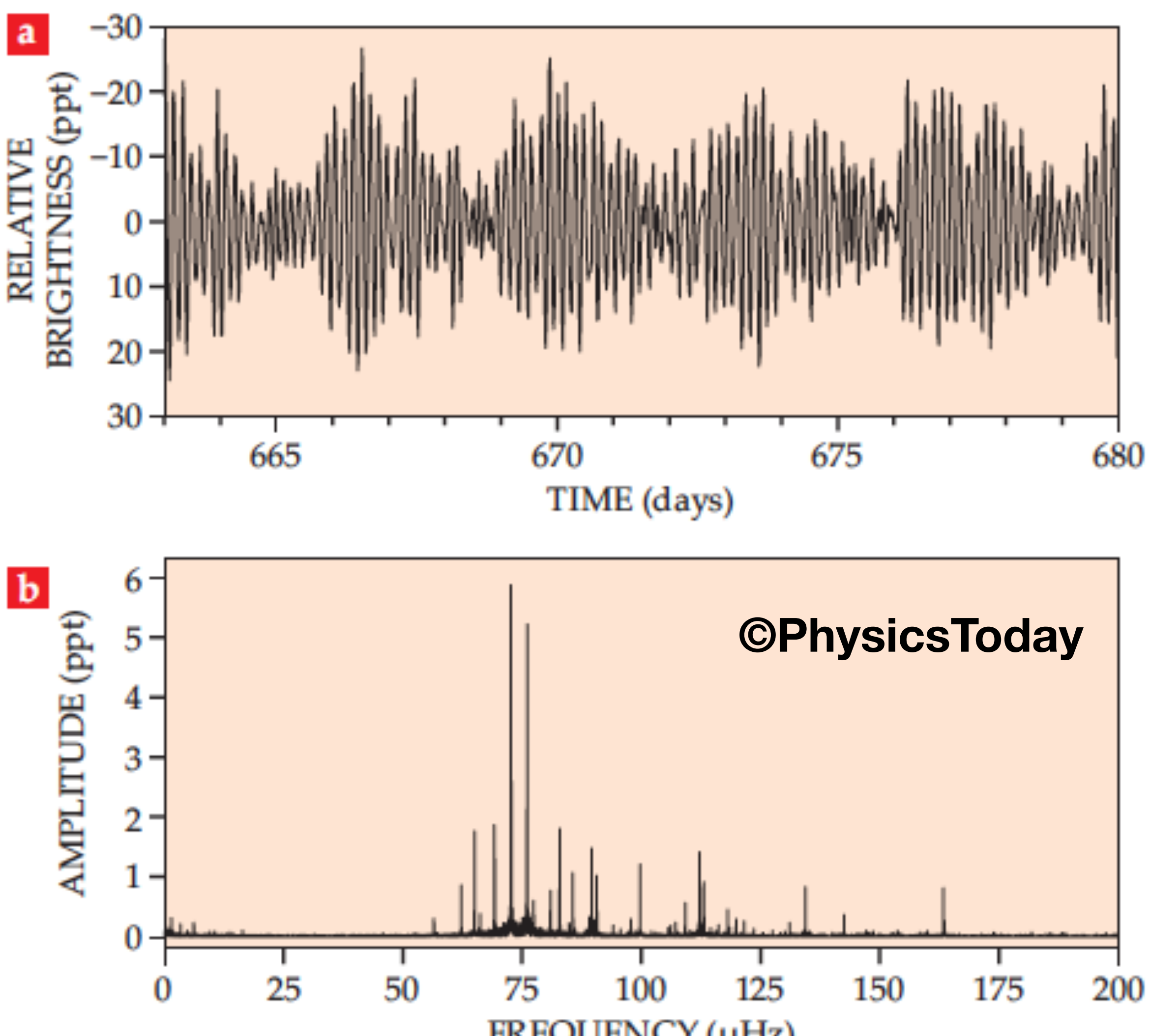
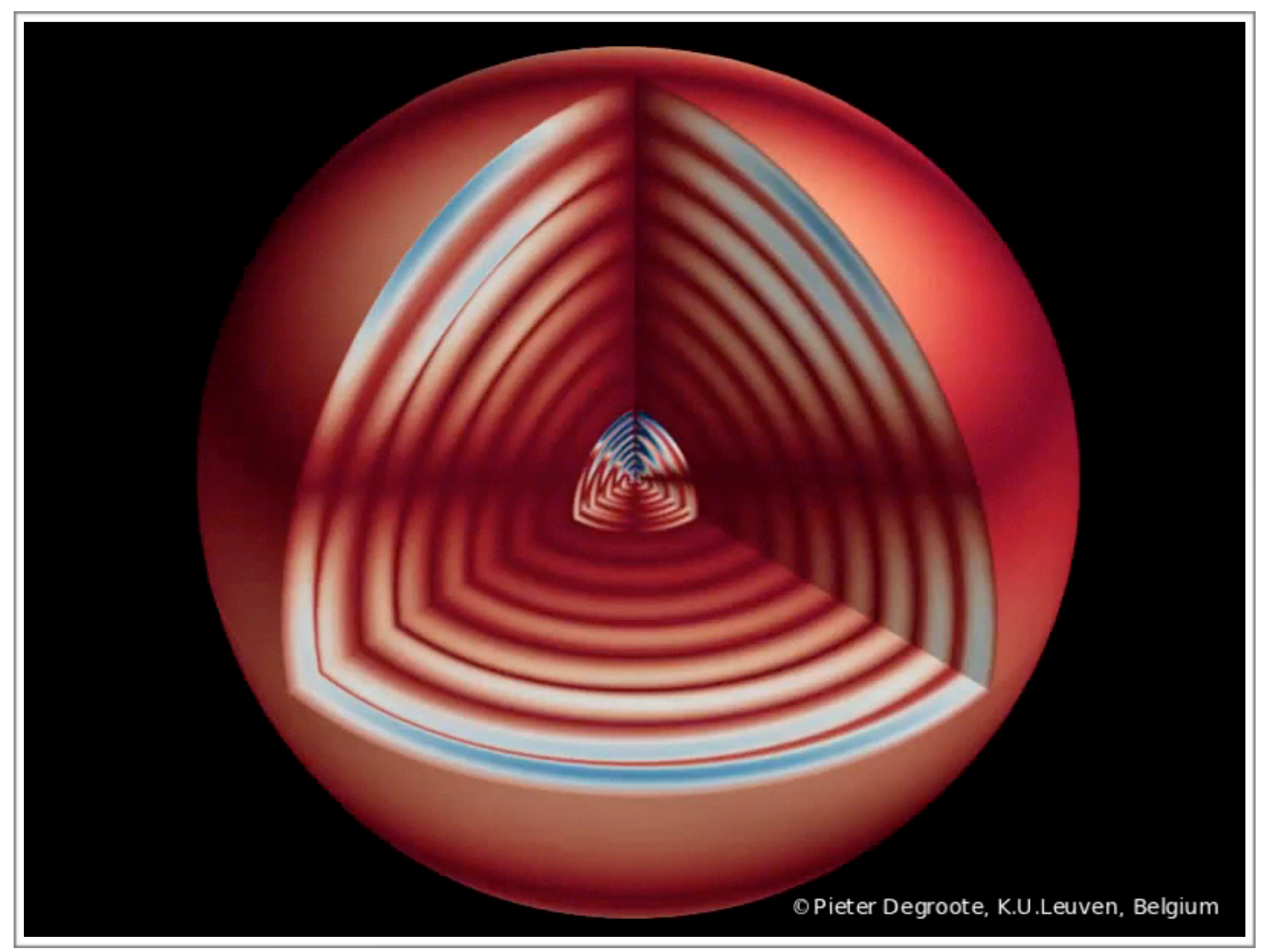
Stellar oscillations probe stellar interiors







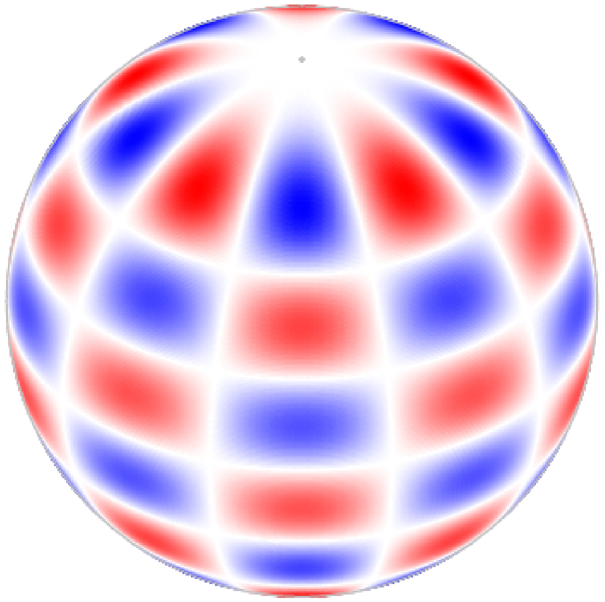
Ingredients: temporal/spatial

- **NRPs = solutions of perturbed SSE in terms of periodic eigenfunctions : eigenmodes of the star**
- **Each mode described by spherical harmonic & frequency:**

$$\boldsymbol{\delta r} = \xi_r \boldsymbol{a}_r + \boldsymbol{\xi}_{\rm h} \ , \ \ \boldsymbol{\xi}(r,\theta,\phi,t) \ = \left[\left(\xi_{r,nl} \boldsymbol{a}_r + \xi_{{\rm h},nl} \nabla_{\rm h} \right) Y_l^m(\theta,\phi) \right] \exp(-{\rm i}\, \omega_{nlm} t)$$

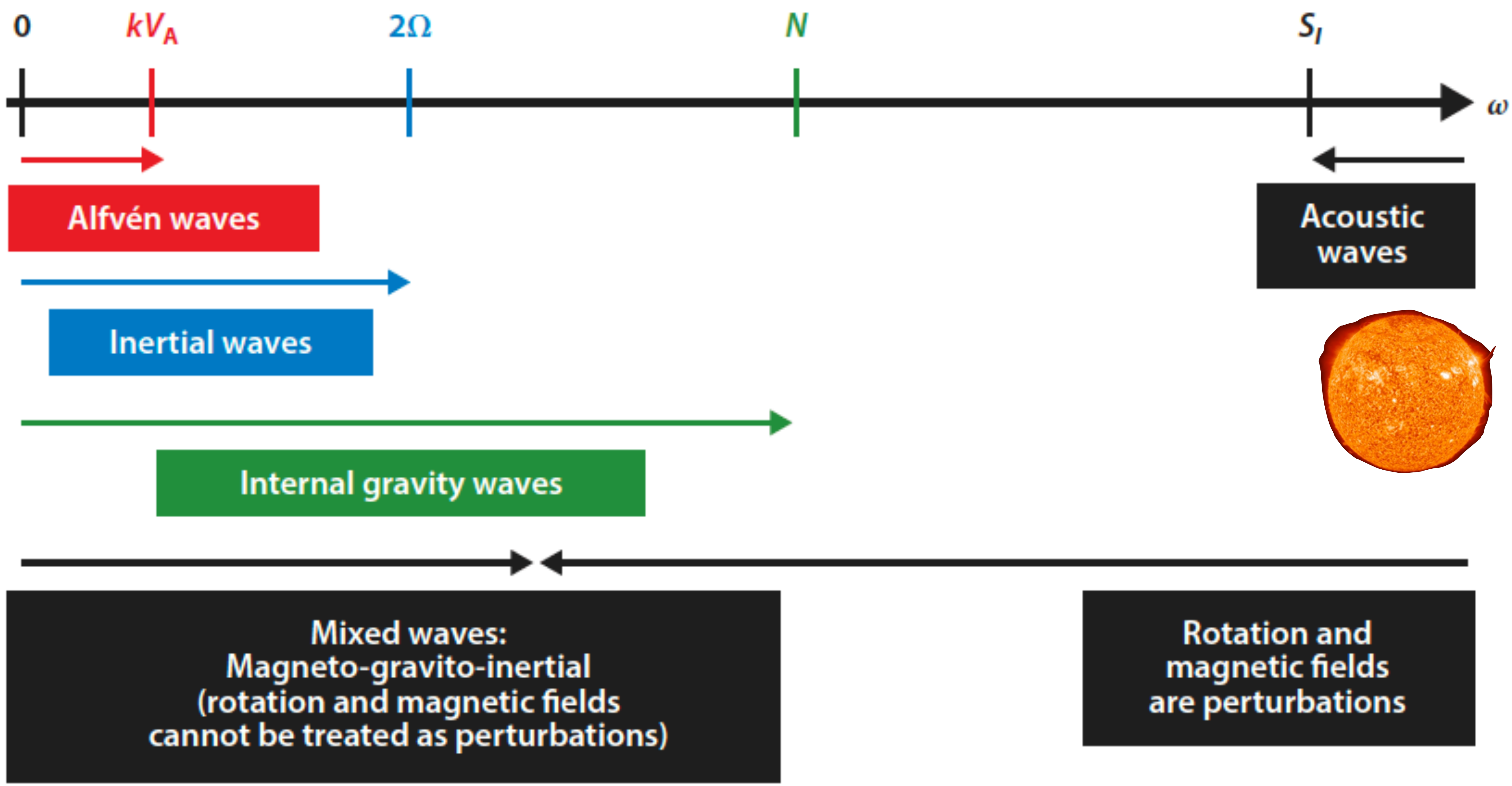
- **Dominance of restoring force?**
  1. **pressure (acoustic waves)**
  2. **buoyancy (gravity waves)**
  3. **Coriolis (inertial waves)**
  4. **Lorentz (Alfvén waves)**
  5. **tidal (tidal waves)**

Kepler!



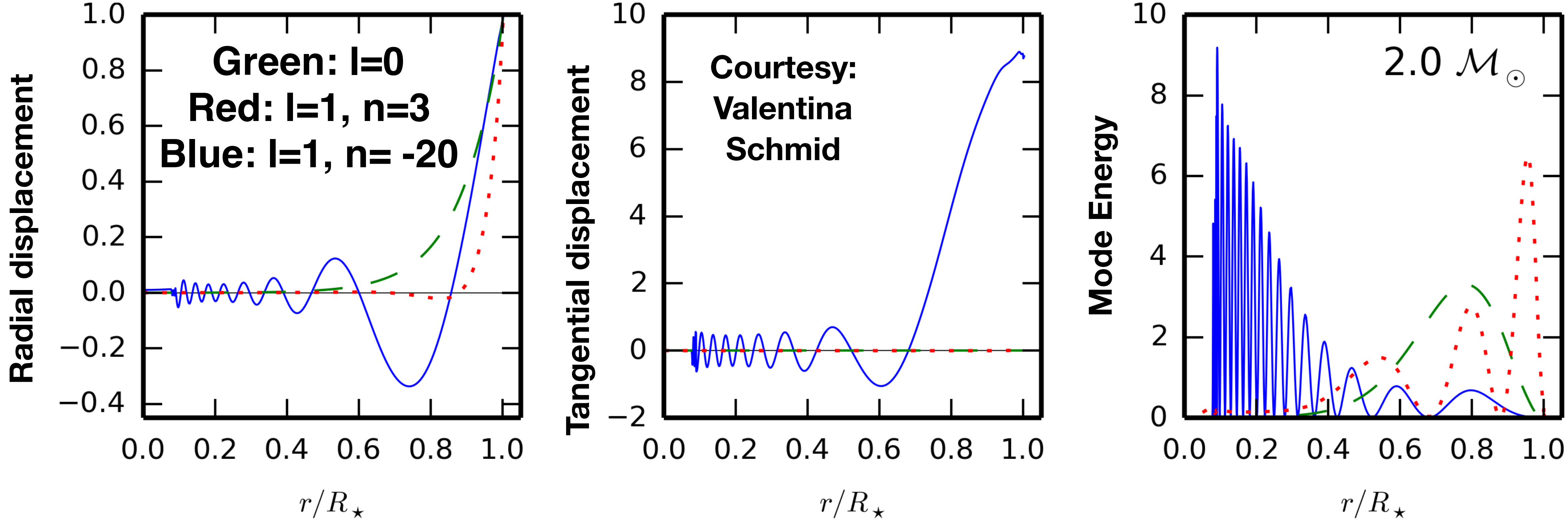
Frequency regimes

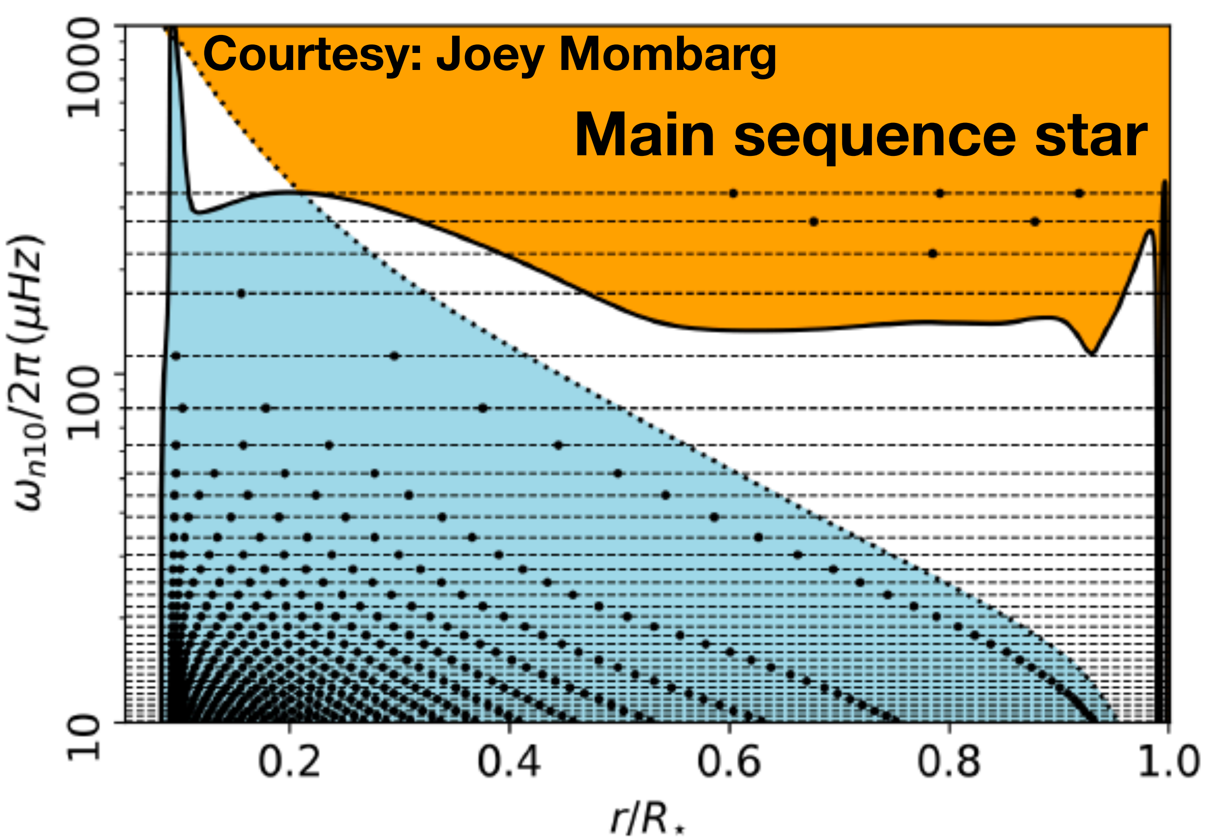
g-modes p-modes

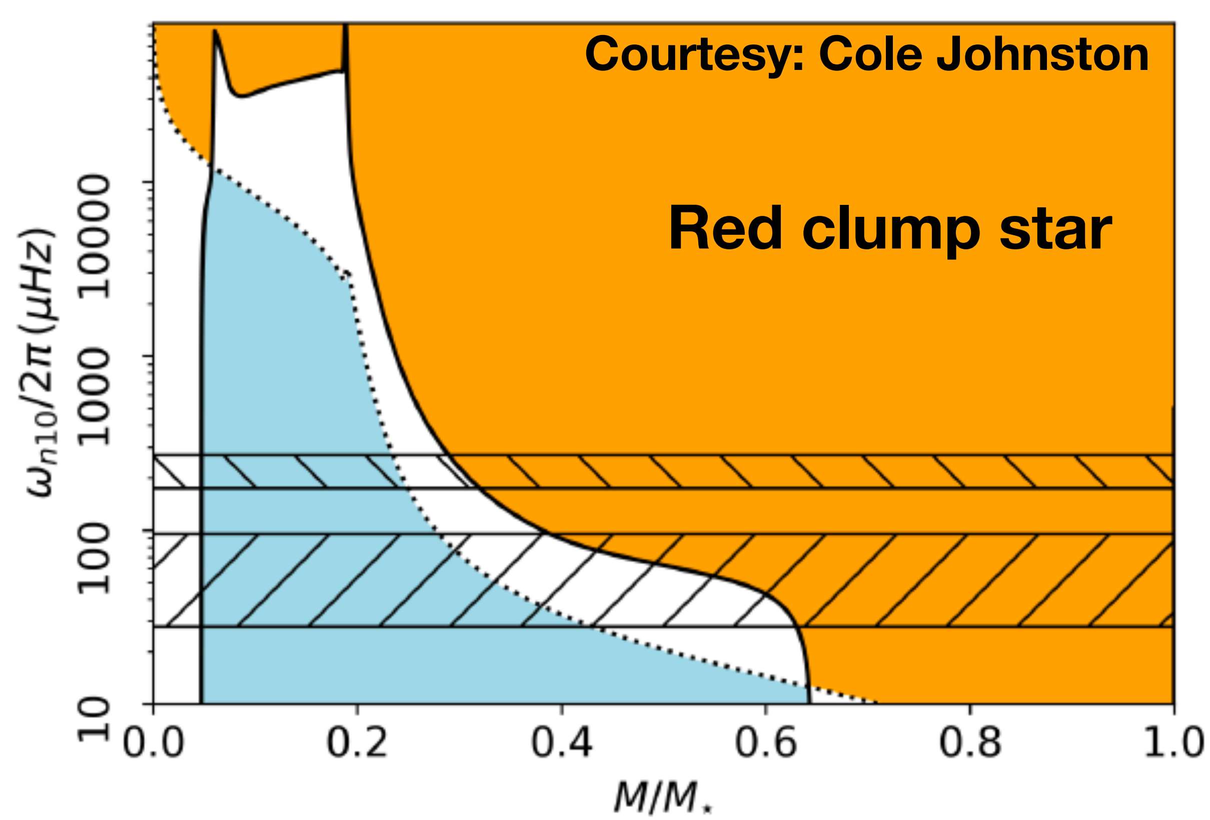


(Aerts, Mathis, Rogers, 2019, ARAA)

Probing power: p/g-modes







Data-driven modelling

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THEORY

mass, chemistry, age:
convection?
mixing? rotation?

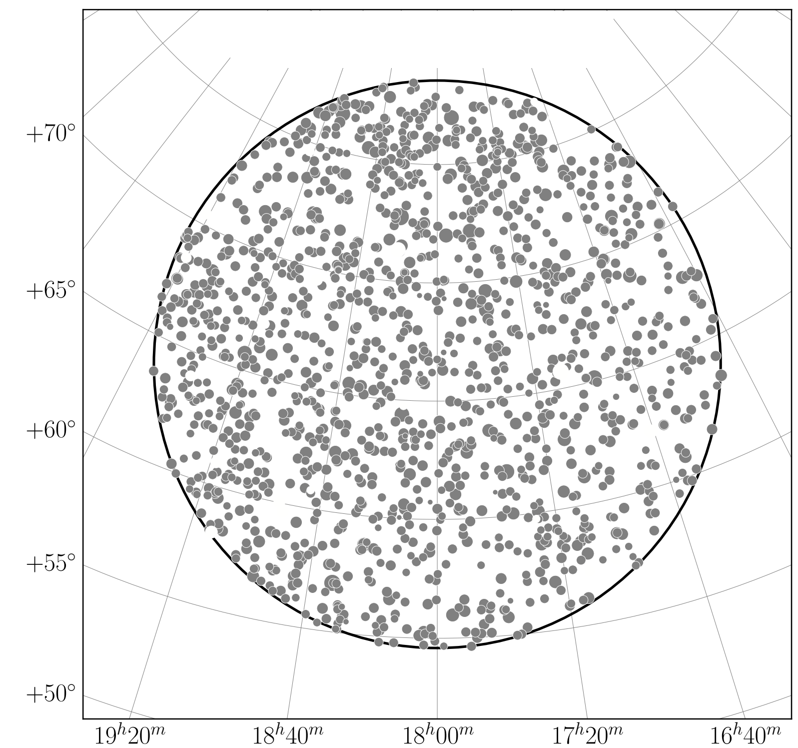
STELLAR MODEL
FOR SPECIFIED
INPUT PHYSICS

Theoretical chemistry,
luminosity, oscillations

OBSERVATIONS

Kepler/K2/TESS
high-R spectroscopy
Gaia astrometry

variability classification from ML : clustering, deep learning …



Observed chemistry,
luminosity, oscillations

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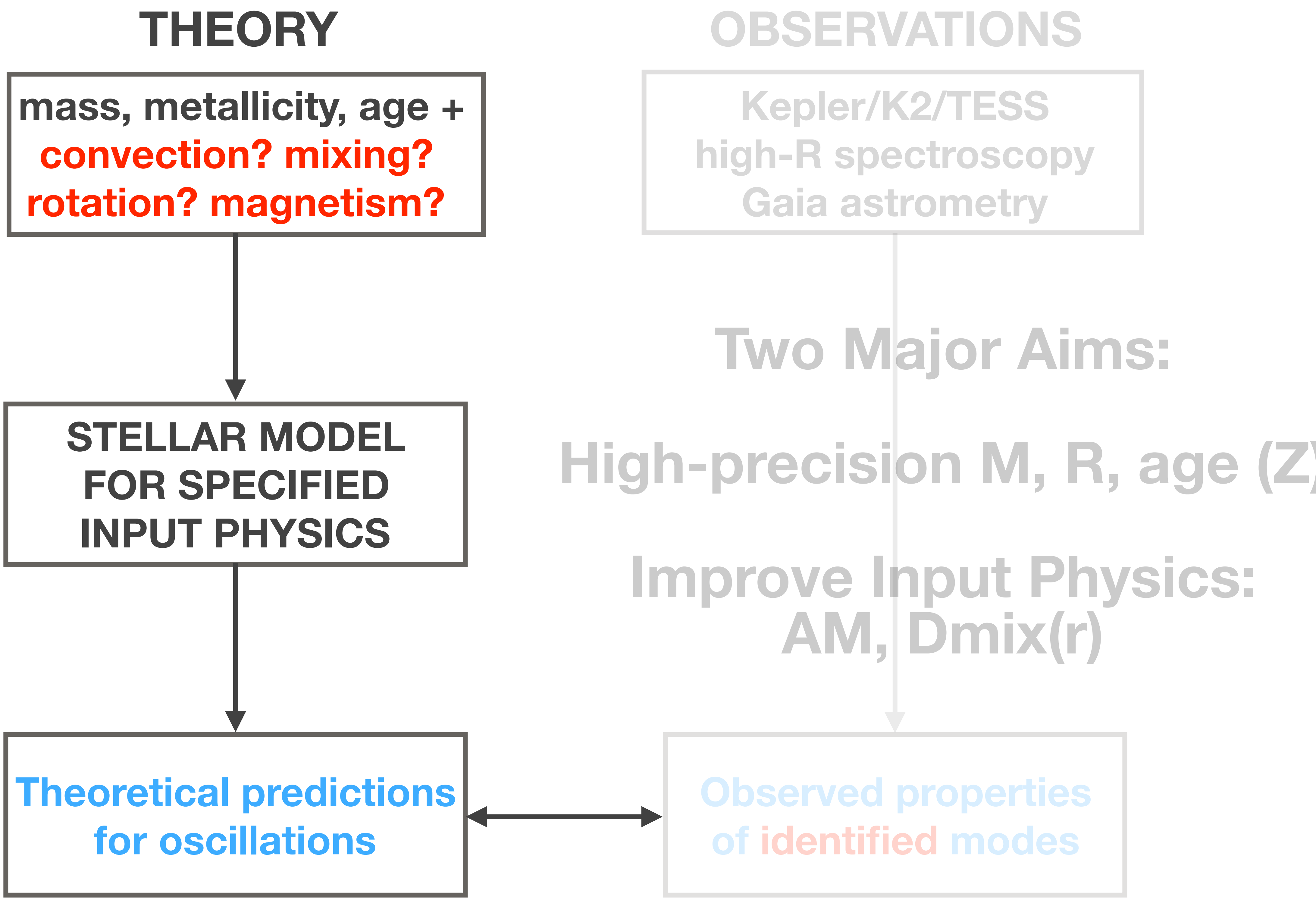
Theoretical predictions



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Aims of Asteroseismology

THEORY

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

STELLAR MODEL
FOR SPECIFIED
INPUT PHYSICS
? ? ?

Theoretical predictions
for oscillations

OBSERVATIONS

Kepler/K2/TESS
high-R spectroscopy
Gaia astrometry

Observed properties
of identified modes

Two Major Aims:

High-precision M, R, age (Z)

Improve Input Physics:
AM, Dmix(r)

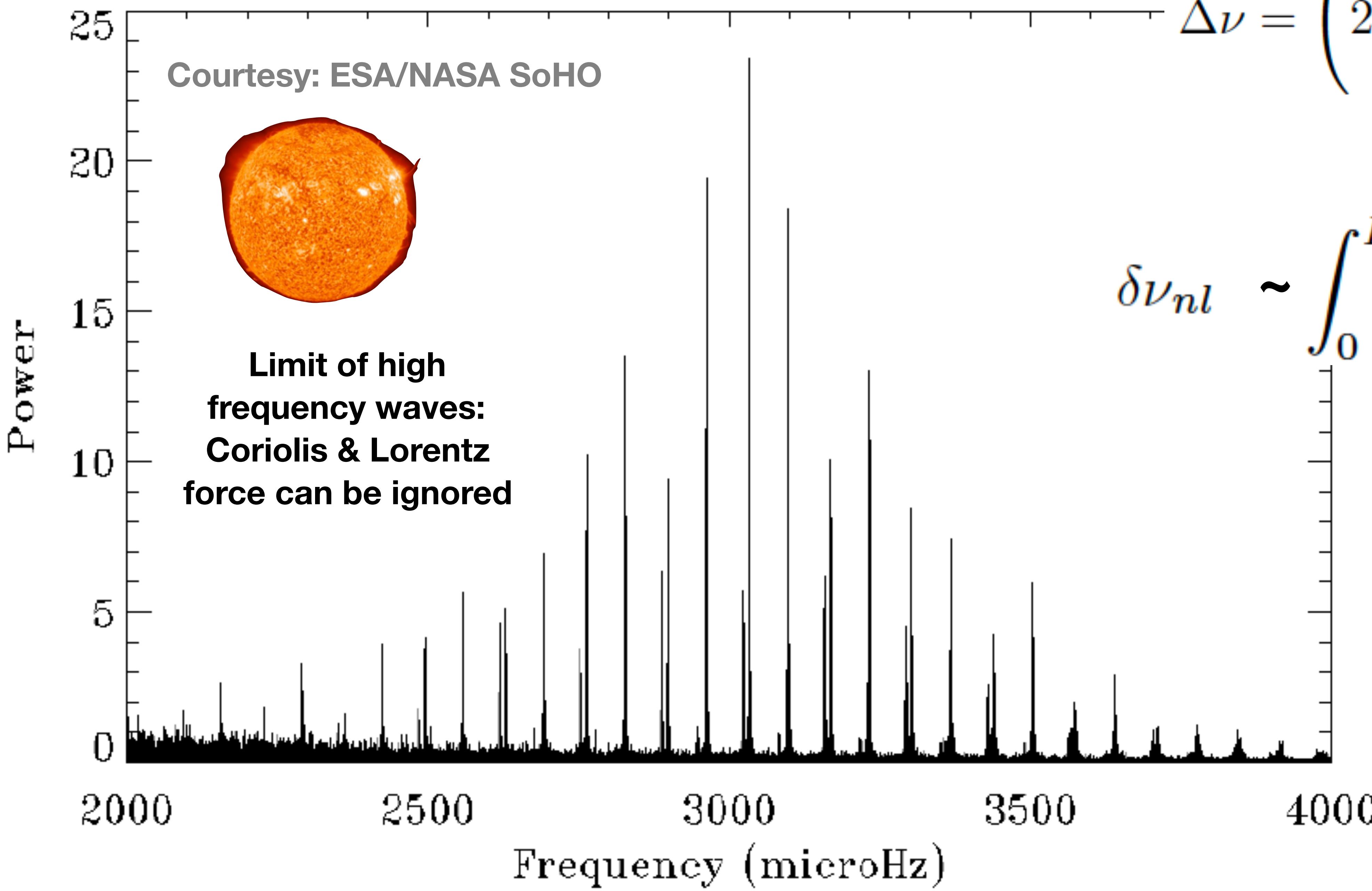
Some Applications:

1) weighing, sizing, ageing low-mass stars ("service")

2) Internal rotation

3) Internal chemical mixing

Helioseismology paved the way



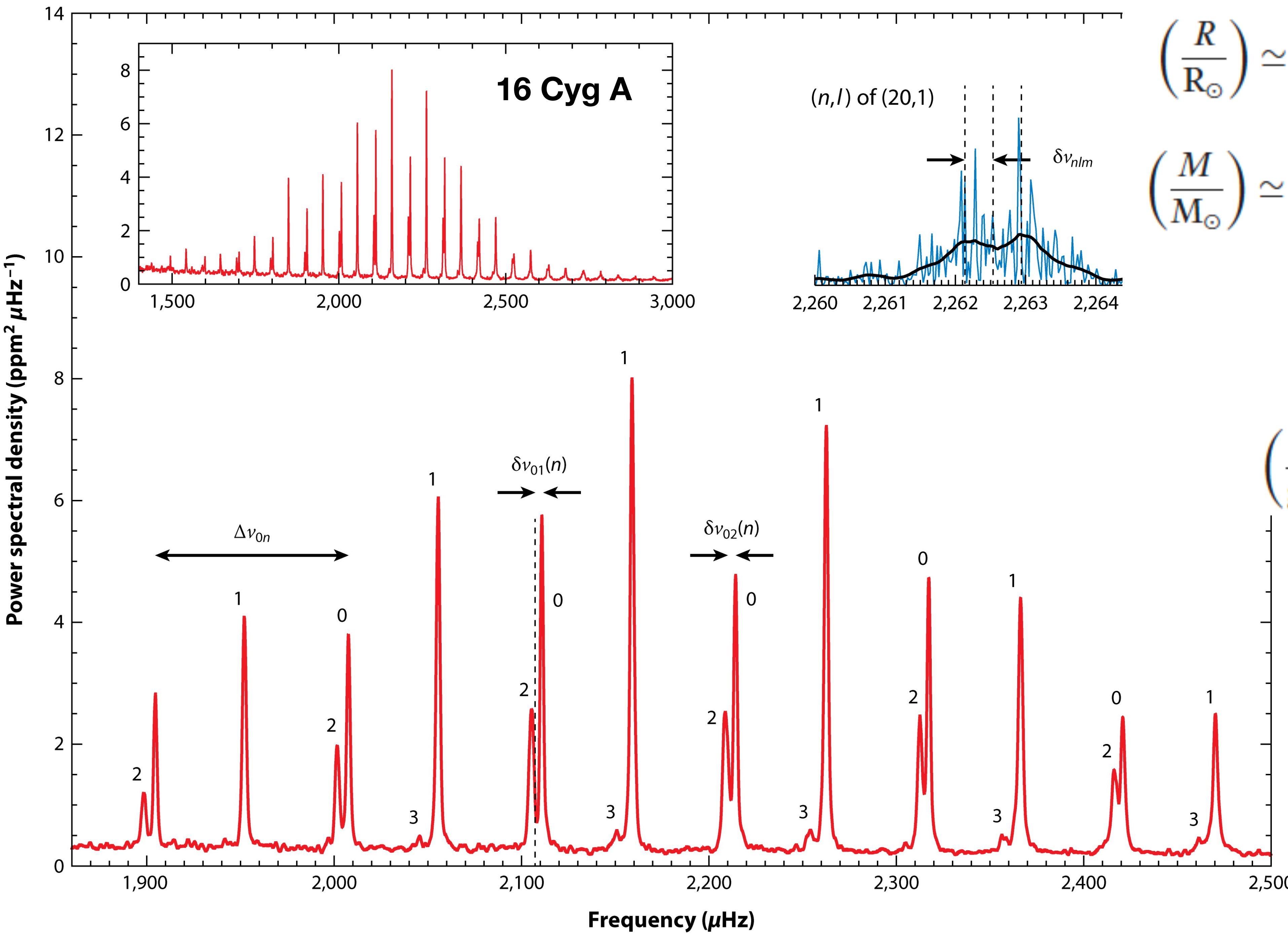
Limit of high frequency waves: Coriolis & Lorentz force can be ignored

$$\Delta\nu = \left(2\int_0^R \frac{dr}{c_s}\right)^{-1}$$

$$\delta\nu_{nl} \sim \int_0^R \frac{dc_s}{dr}\frac{dr}{r}$$

(Christensen-Dalsgaard, 2002, RMP)

Low-mass stars: R, M, age



Chaplin WJ, Miglio A. 2013. Annu. Rev. Astron. Astrophys. 51:353–92

$$\left(\frac{R}{R_\odot}\right) \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)\left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^{-2}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{0.5},$$

$$\left(\frac{M}{M_\odot}\right) \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^{3}\left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^{-4}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1.5},$$

$$\left(\frac{\rho}{\rho_\odot}\right) \simeq \left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^{2},$$

$$\left(\frac{g}{g_\odot}\right) \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{0.5}.$$

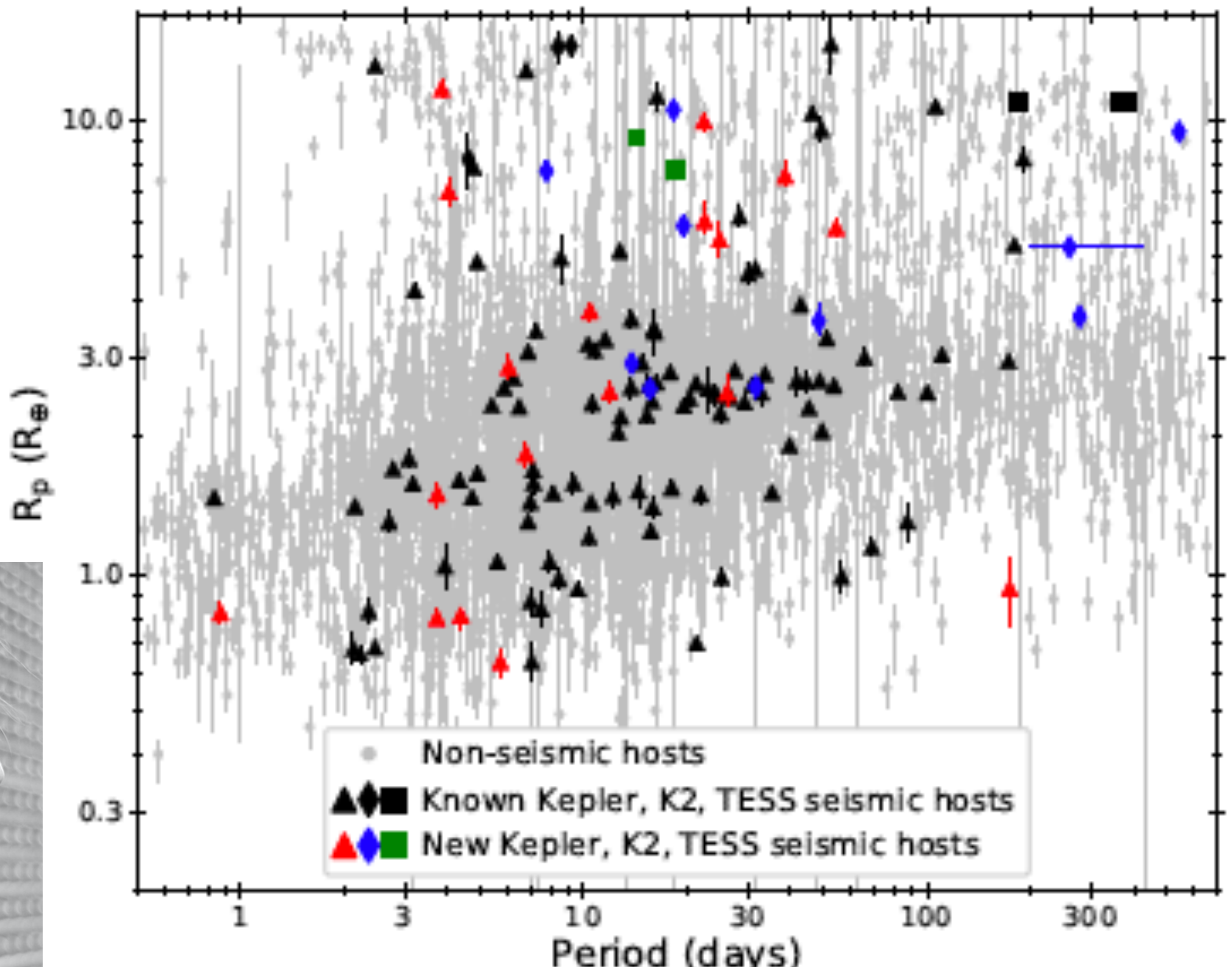
Radius ~1-2%
Mass~ 2-4%
Age ~ 20%
model dependent:
He? mixing?
atomic diffusion?

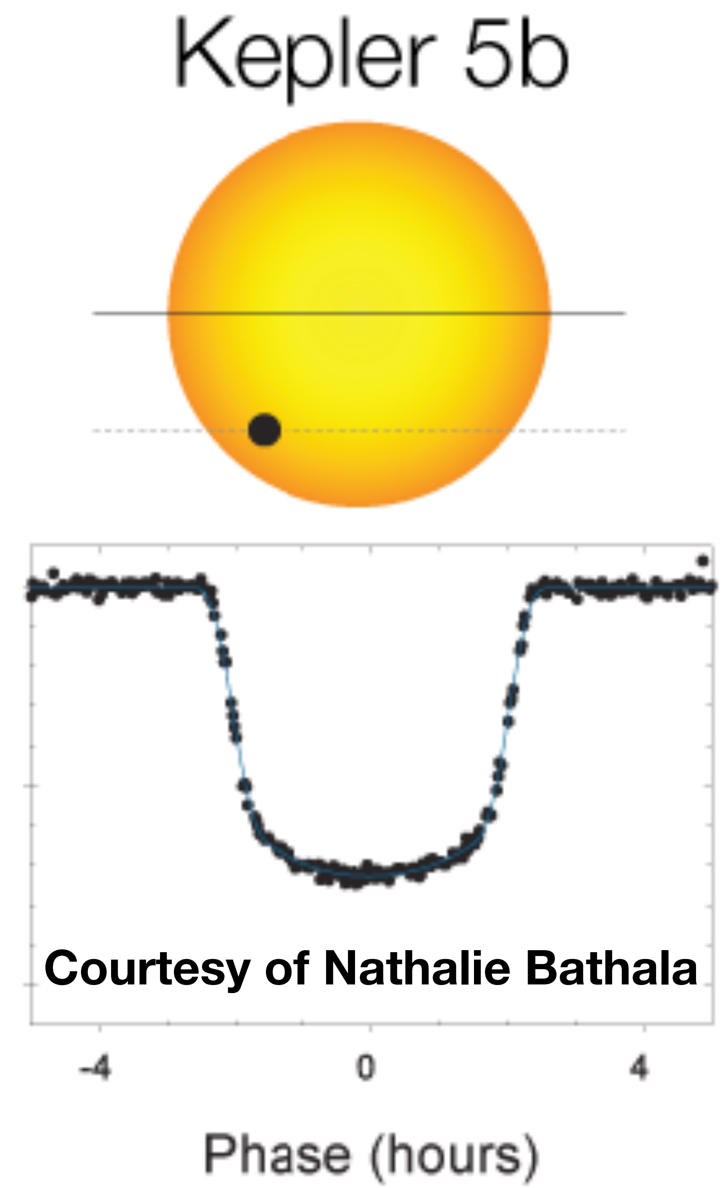
(see also Chaplin et al. 2014, Silva Aguirre et al. 2016, Verma et al. 2019, Bellinger et al. 2019, 2020…)

KU LEUVEN R, M, age for Exoplanet Research

Asteroseismology of Host Star: factor ~2 improvement for exoplanet radius + age delivery!

Courtesy: Ashley Chontos

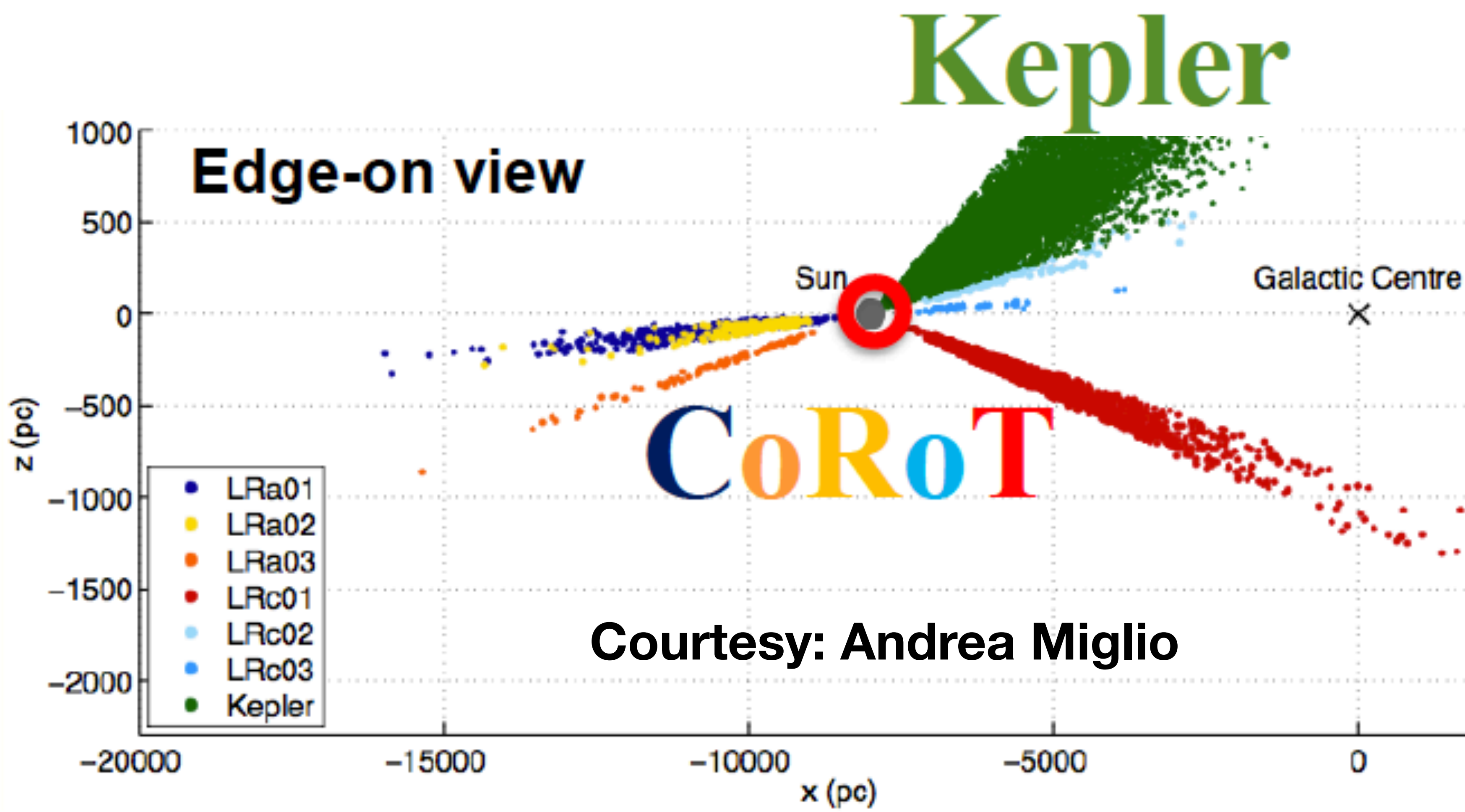


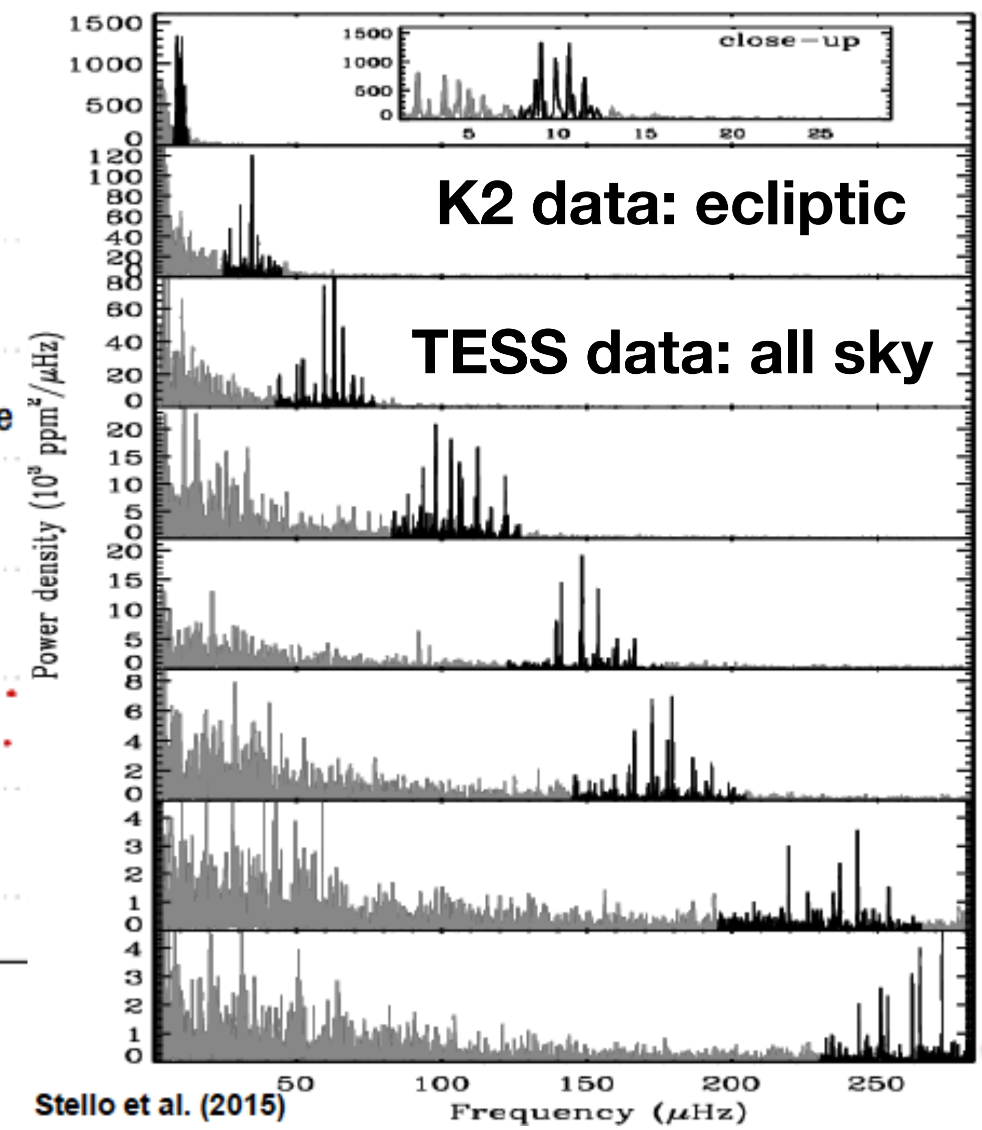


Huber et al. (2013) Van Eylen et al. (2014, 2018), Campante et al. (2016), Chontos et al. (2019, 2021)

KU LEUVEN Ages for Galactic Archaeology

Seismic mass, radius, age, log g from scaling relations
Teff from spectroscopy





Asteroseismic distances ~few%

(Silva Aguirre et al. 2012, Miglio et al. 2013 & 2021, Stello et al. 2015, Huber et al. 2017, Hon et al. 2019, Bellinger et al. 2019, Sharma et al. 2019, Jie Yu et al. 2020,…)

Some Applications:

1) weighing, sizing, ageing low-mass stars ("service")

2) Internal rotation

3) Internal chemical mixing

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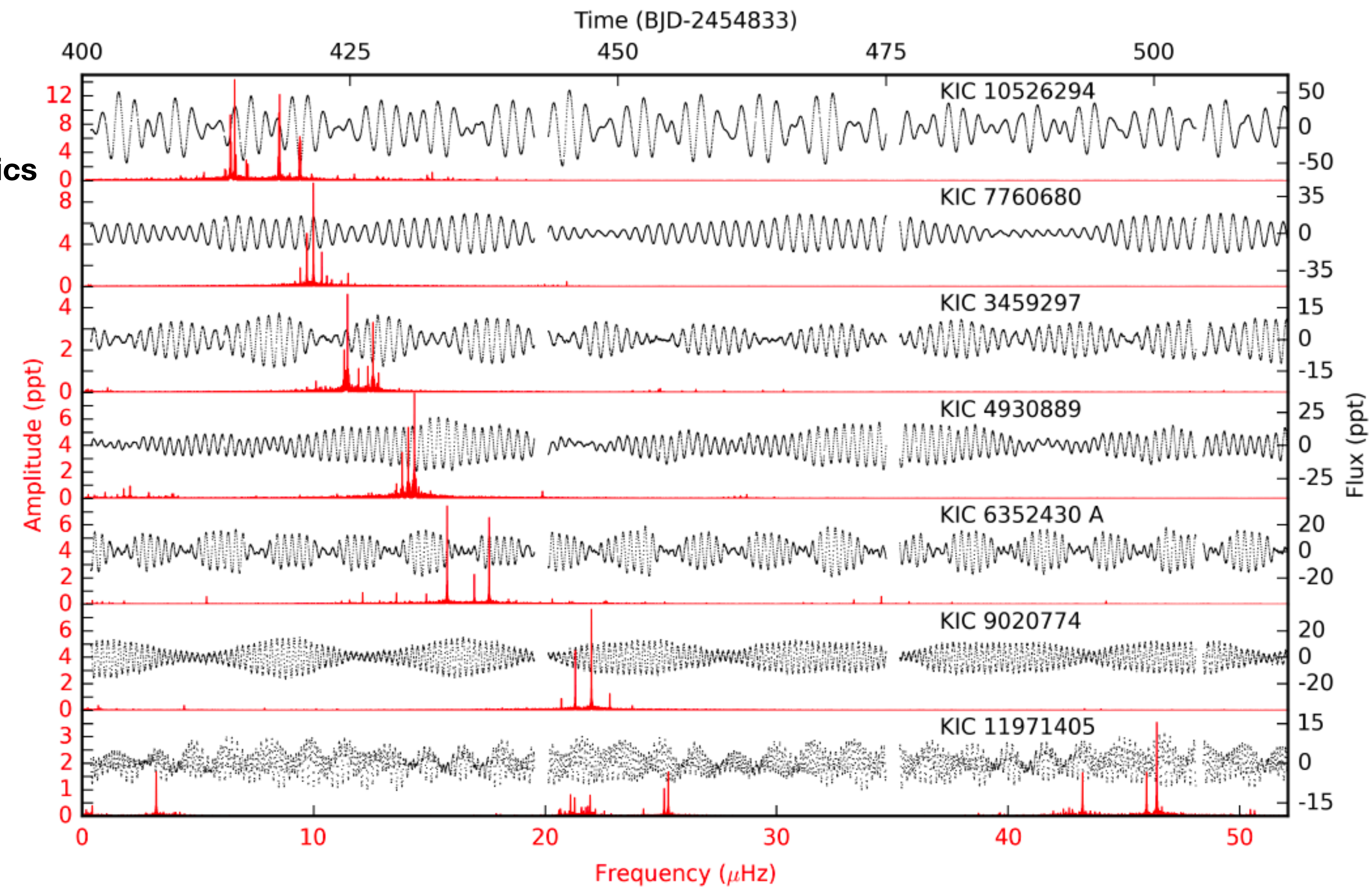
g modes in intermediate-mass stars

Courtesy:
Péter Pápics



offers new way to study core masses, Dmix(r) & Ω(r)

Pápics et al. (2017), Van Reeth et al. (2015,2016,2018), Saio et al. (2018), Gang Li et al. (2019,2020)

(Near-)Core rotation rate

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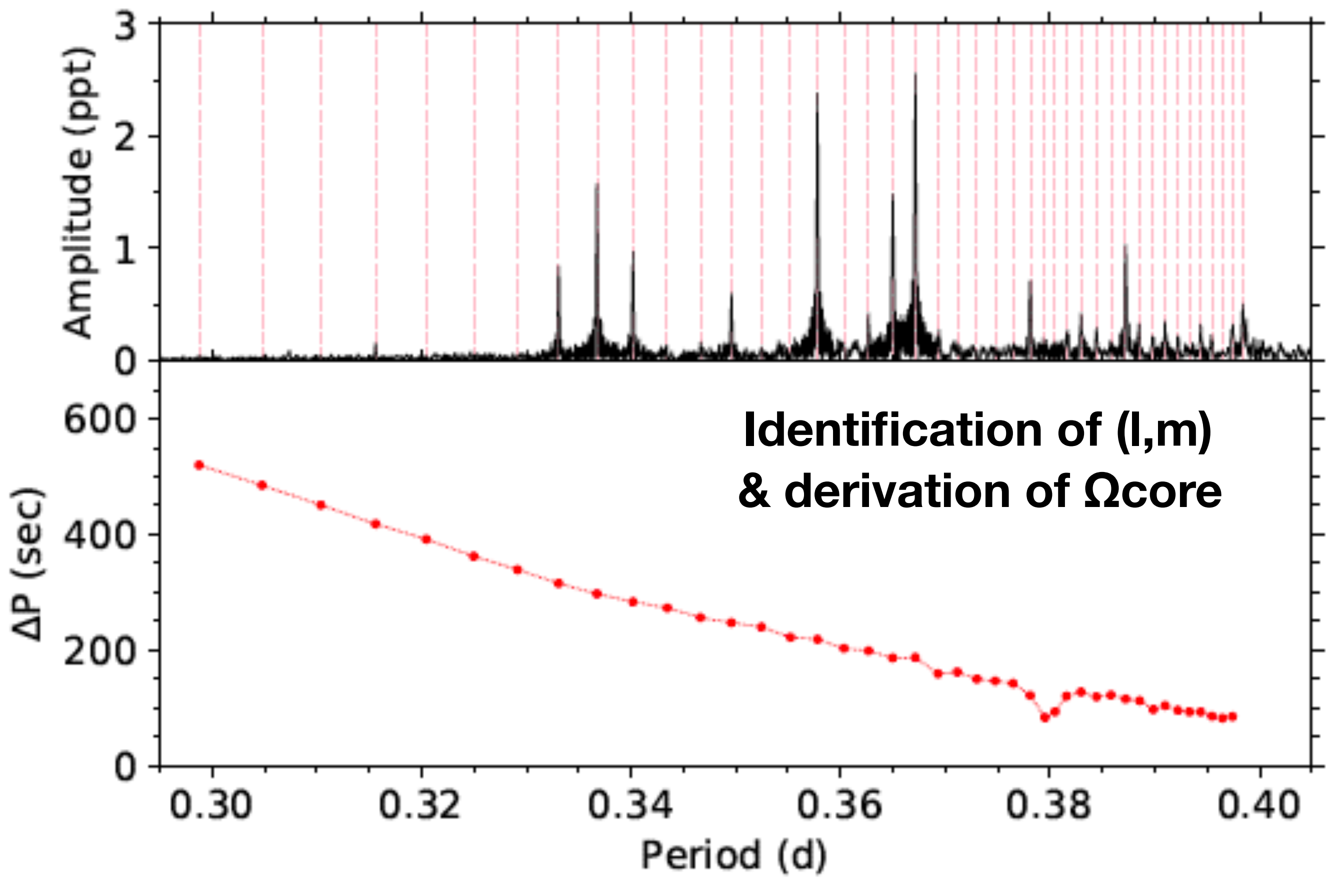
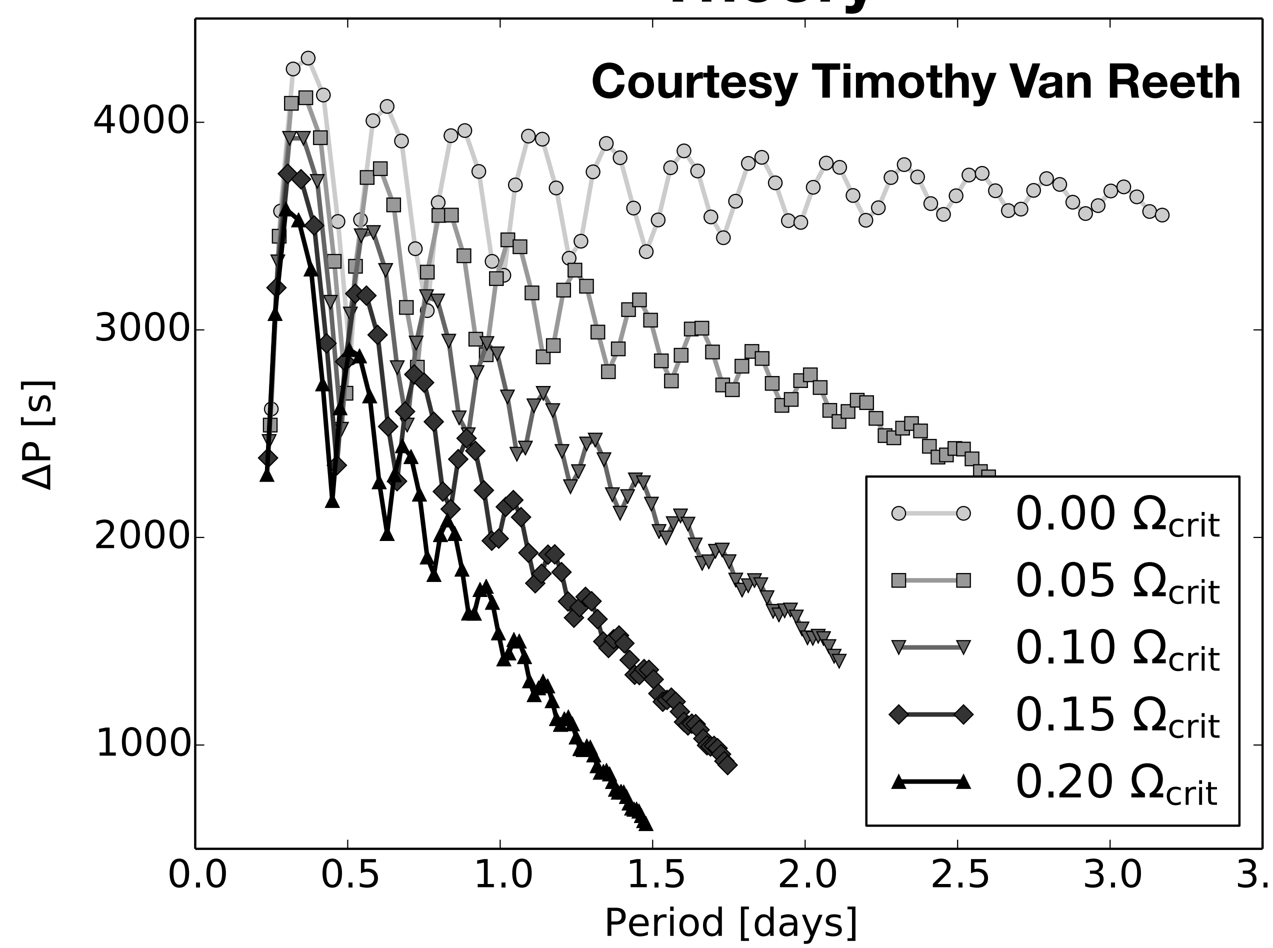
Observations



Theory



$$P_{nl} = \frac{\Pi_0}{\sqrt{l(l+1)}}(|n| + \alpha_{l,\mathrm{g}}) \ ,$$

$$\Pi_0 \equiv 2\pi^2 \left(\int_{r_1}^{r_2} N \frac{\mathrm{d}r}{r} \right)^{-1} \ .$$

With(out) Coriolis acceleration

$$\Delta P^{\mathrm{co}}_{l,m,s} = \frac{\Pi_0}{\sqrt{\lambda_{lms}}}$$

depends on Ω

(from Aerts et al. 2019 ARAA & Aerts 2021 RMP)

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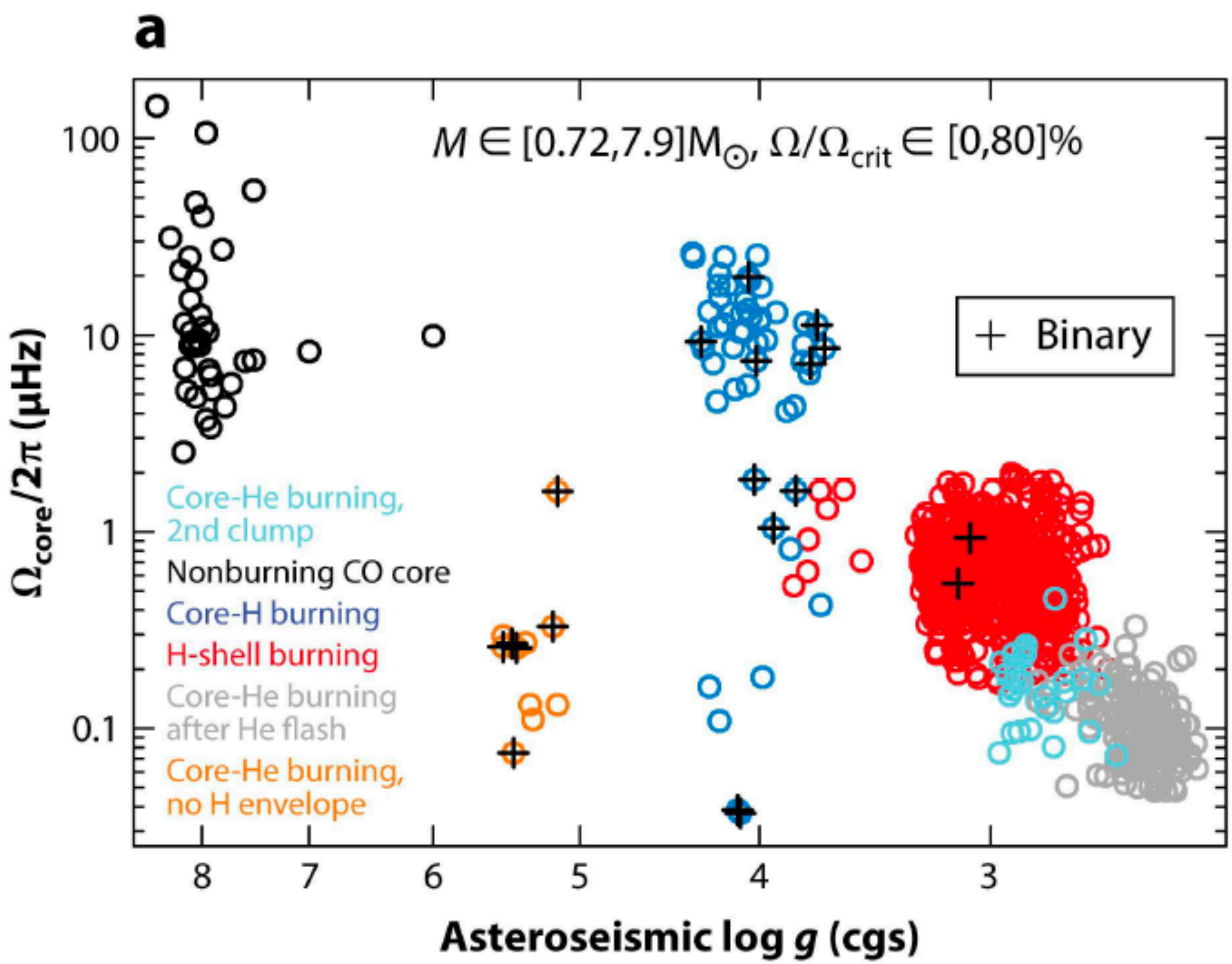
Asteroseismic estimates of Ω_{core}



1210 stars

We cannot do this for the Sun…

Aerts C, et al. 2019.
Annu. Rev. Astron. Astrophys. 57:35–78

Asteroseismic estimates of Ω_{core}

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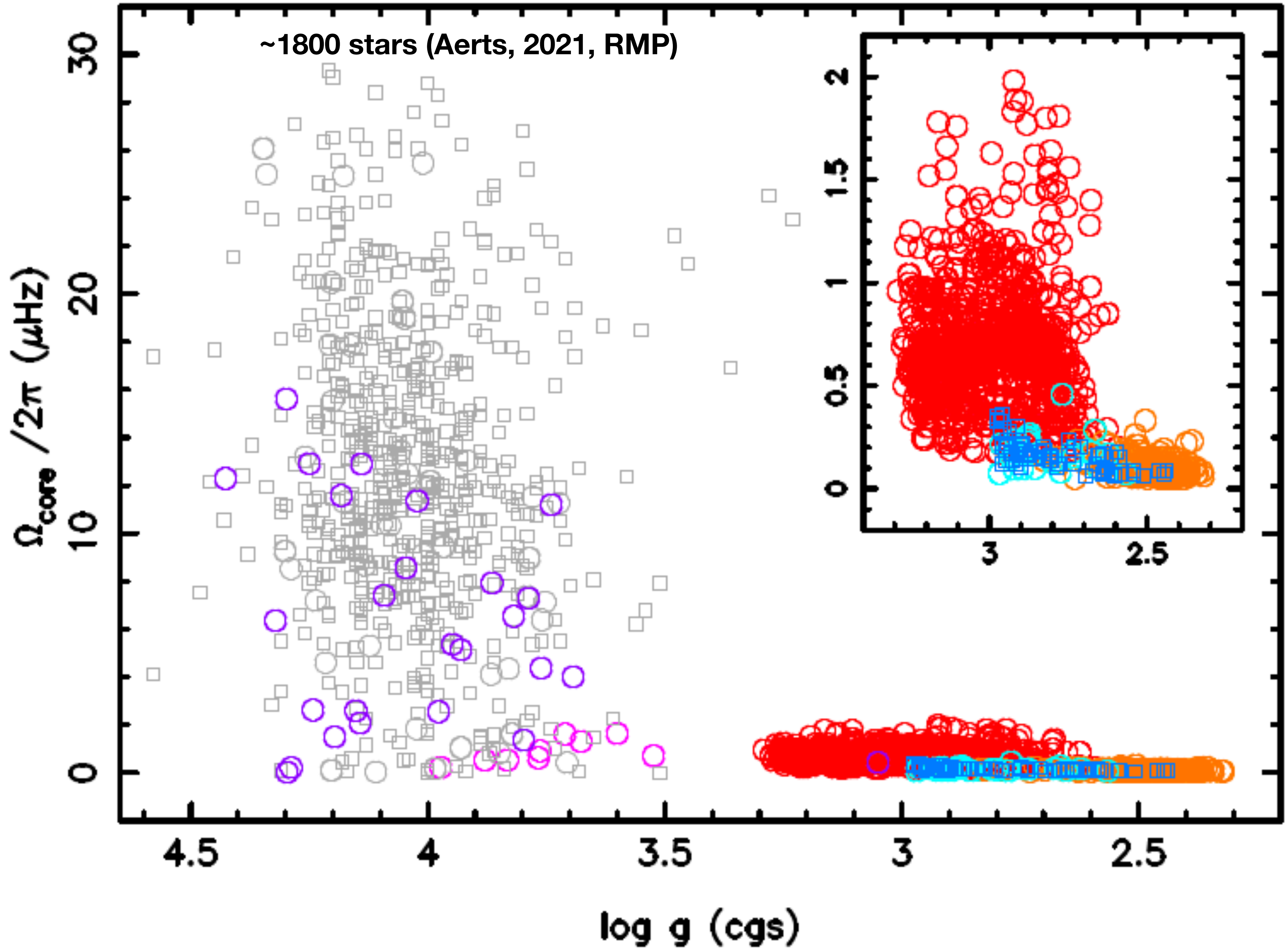

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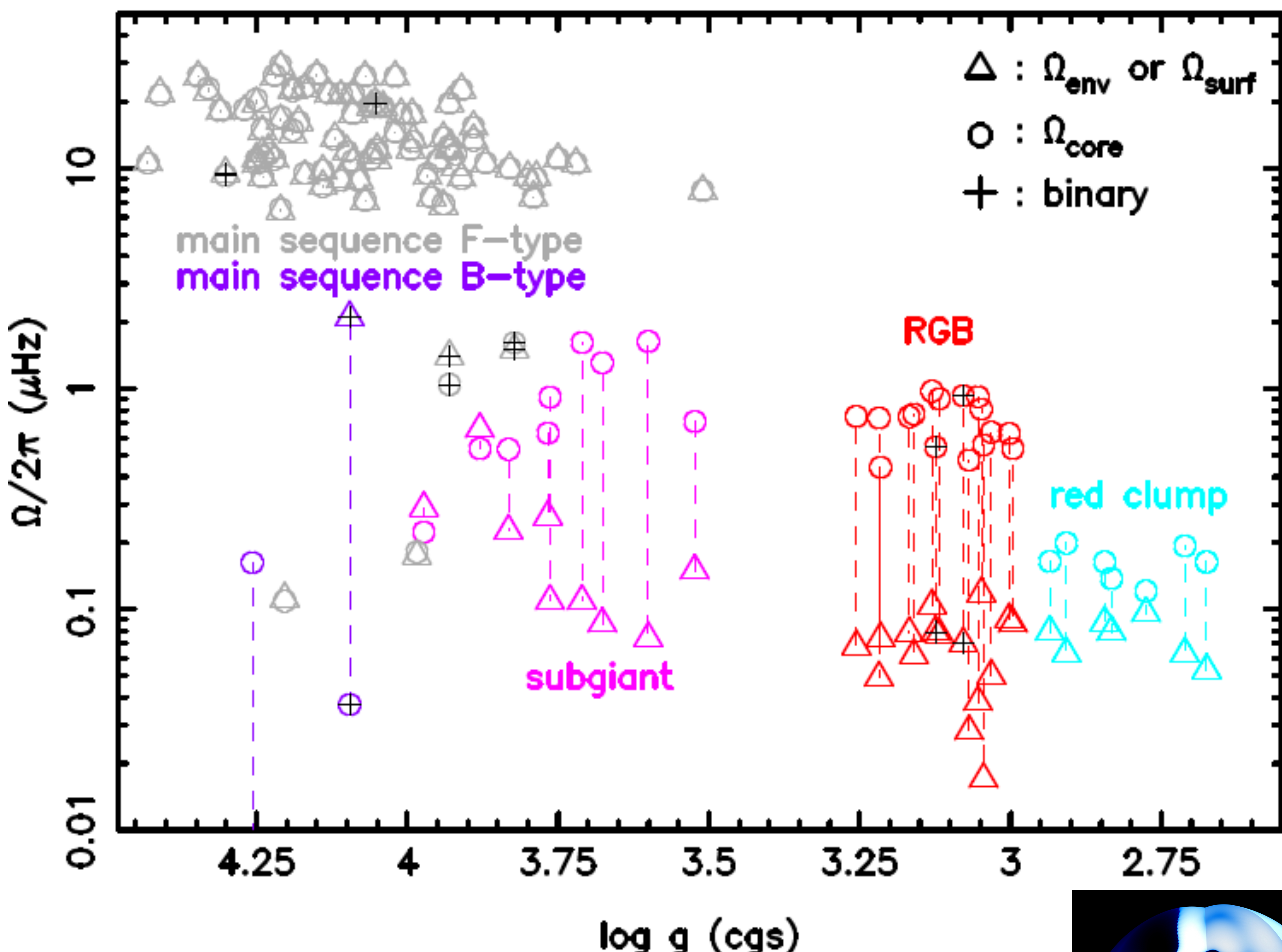
Measuring Ω_{core} versus Ω_{env}



“Standard SSE” needs fixes…
(from Aerts, 2021, RMP)

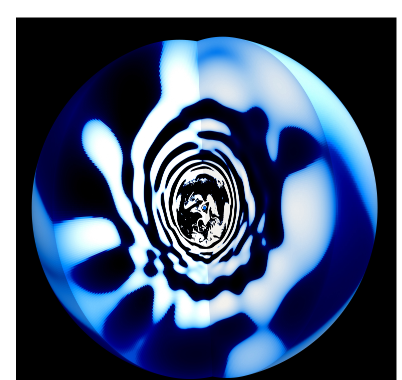
Stars rotate quasi-rigidly when having a convective core

AM transport to keep ~rigid rotation & agree with AM of WDs

Magnetism/Tayler Instability:
Fuller et al. (2019), Takahashi & Langer (2020)

and/or

IGWs:
Rogers (2015); Edelmann et al. (2019); Horst et al. (2020)



Courtesy: Philipp Edelmann

Some Applications:

1) weighing, sizing, ageing low-mass stars (“service”)

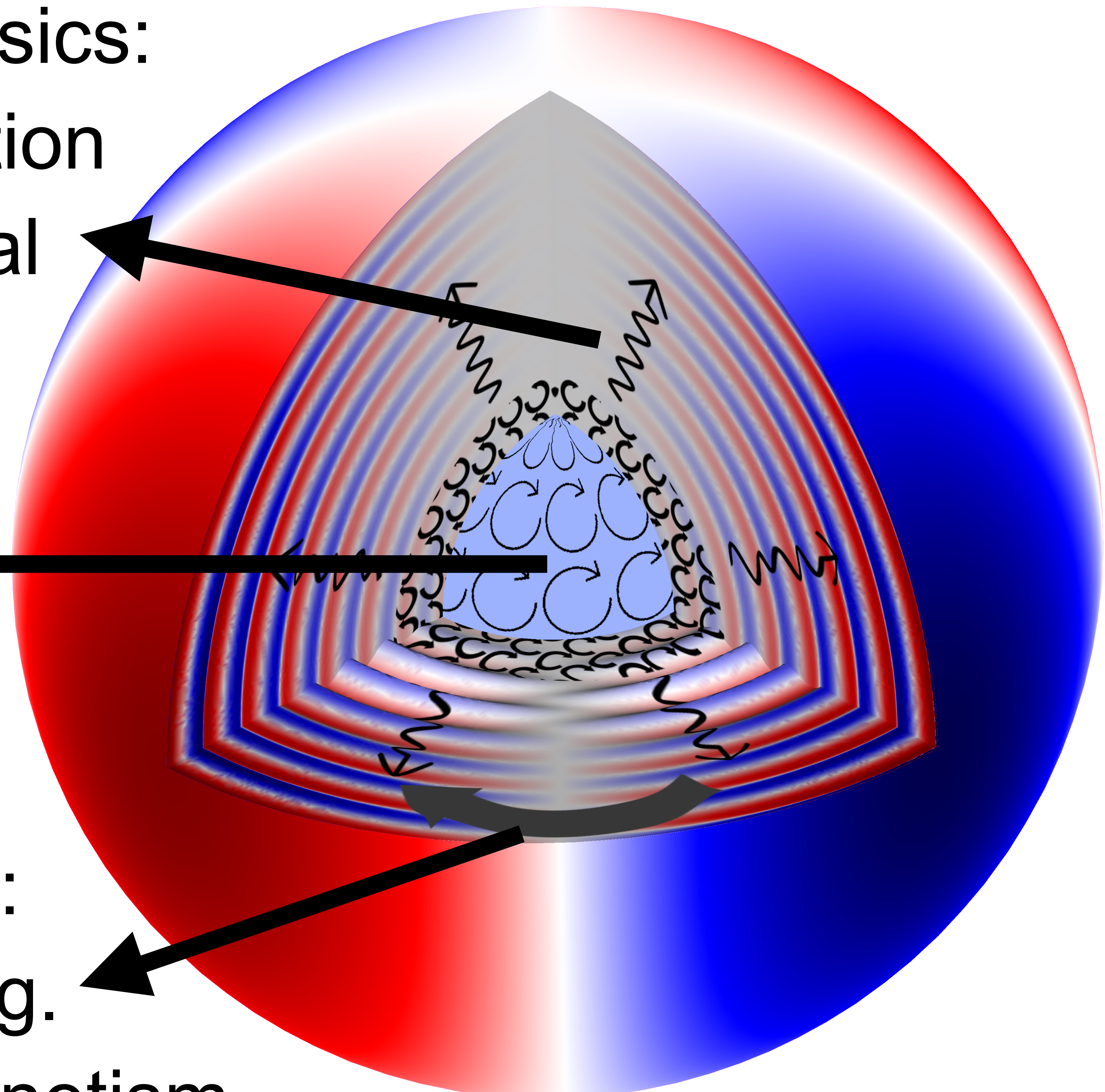
2) Internal rotation

3) Internal chemical mixing

Chemical evolution

microscopic physics:
radiative levitation
& gravitational
settling

nuclear
burning



macroscopic physics:
element transport, e.g.
rotation, waves, magnetism,…

Chemical evolution inside star

$$\frac{\partial X_i}{\partial t} = \mathcal{E}_i - \frac{\partial}{\partial m}\left(4\pi r^2 \rho X_i w_i\right) + \frac{\partial}{\partial m}\left[\left(4\pi\rho r^2\right)^2 \left(D_{\rm conv} + D_{\rm ov} + D_{\rm env}\right)\frac{\partial X_i}{\partial m}\right]$$

nuclear physics

radiative levitation from atomic physics

micro- & macroscopic element transport: efficiency and timescales? diffusive treatment…

Element mixing: largest unknown in stellar evolution; of vast importance for chemical yields in stars with convective core

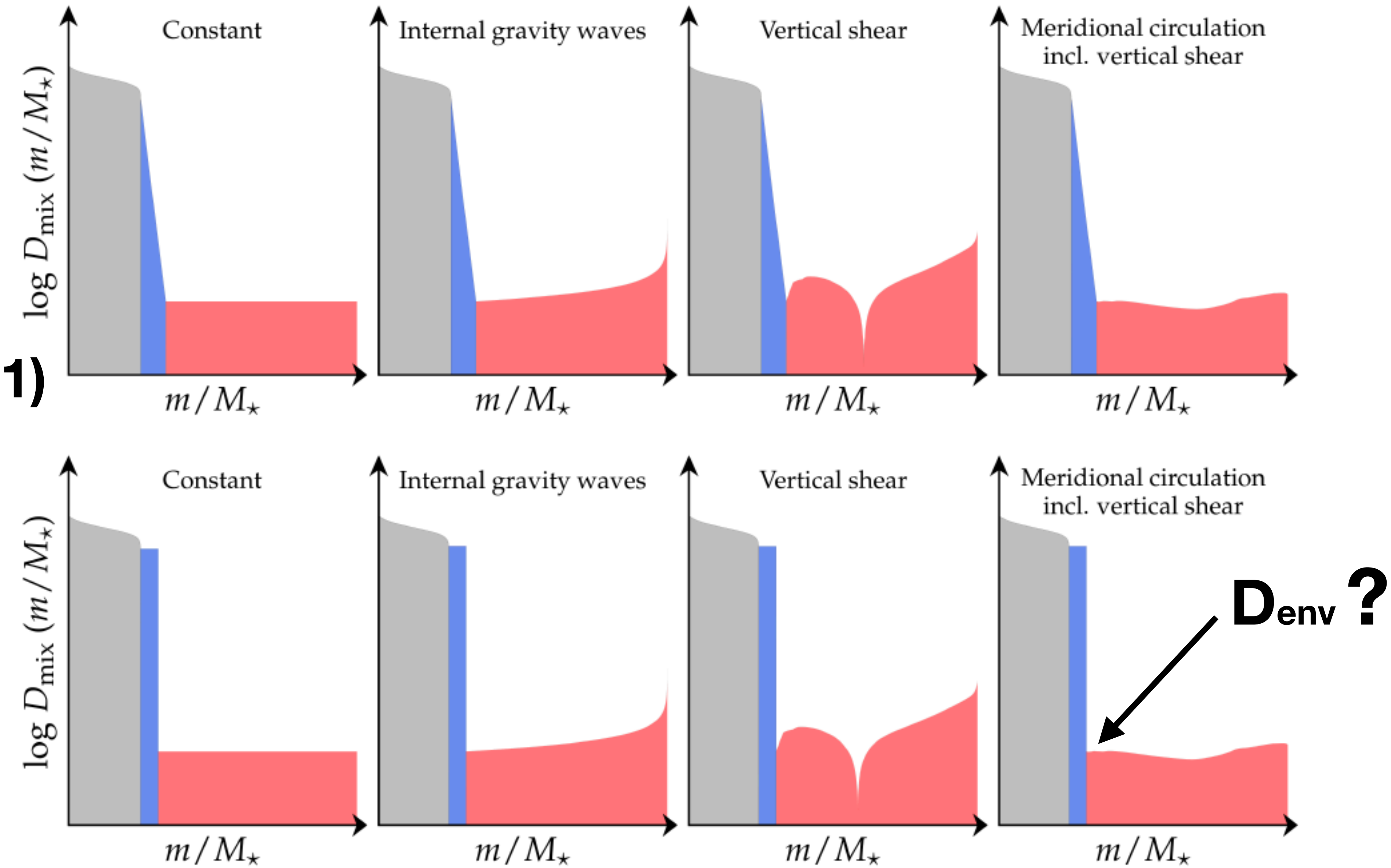
Asteroseismic estimation of $D_{mix}(r)$

Courtesy:
May Gade Pedersen

26 SPB stars by Pedersen et al. (2021)

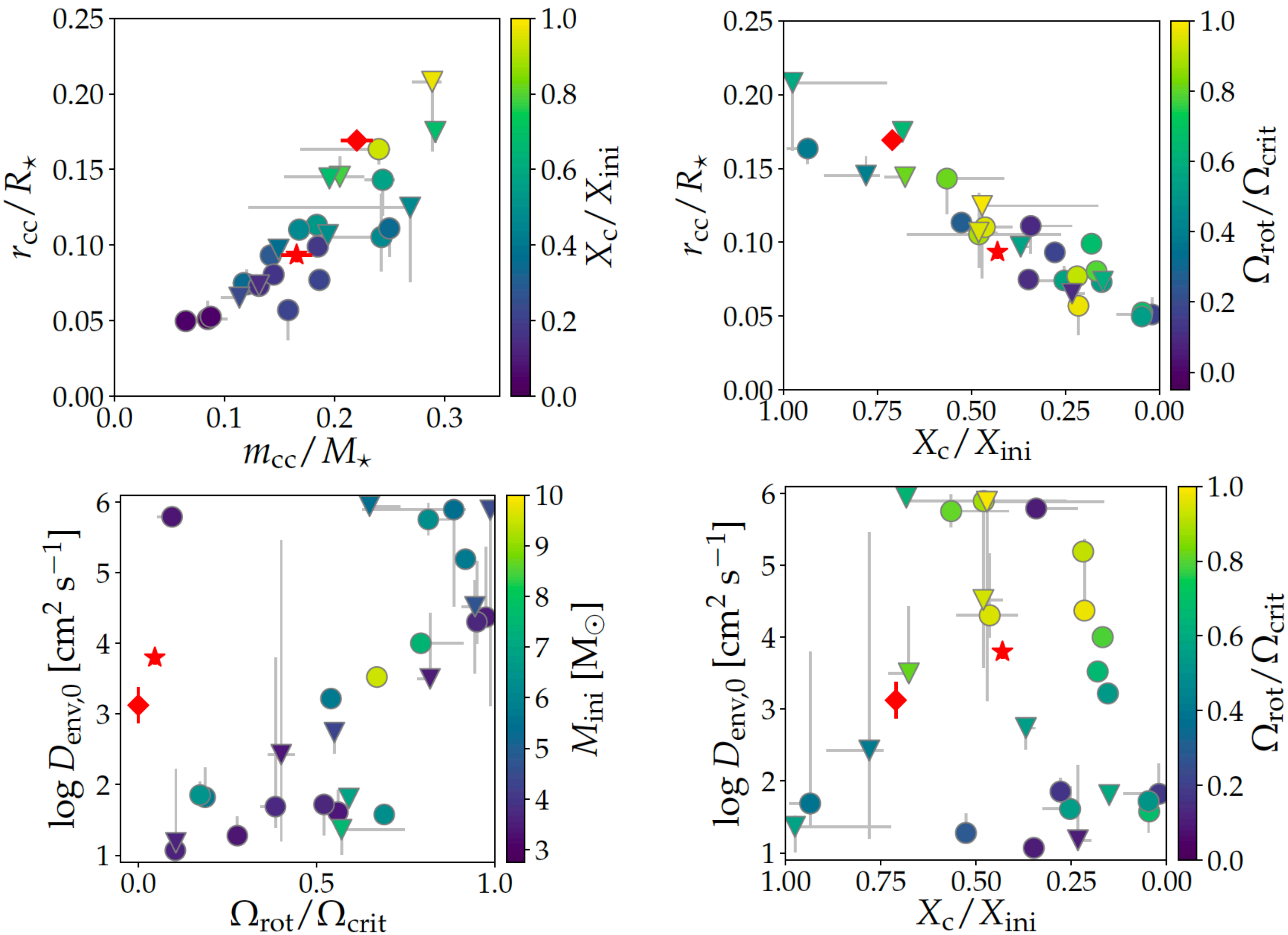
https://rdcu.be/ckjRm

Summary in Aerts (2021)



Sample	SpT	Mass range	$M_{cc}/M_\star$ range	Ω/Ω_{crit} range	D_{env} range
~20 solar-like pulsators	later than F2	$[1.1, 1.6]\,M_\odot$	$[3, 18]\,\%$	$< 10\,\%$	??
~40 g-mode pulsators	F0 – F2	$[1.3, 1.9]\,M_\odot$	$[7, 12]\,\%$	$[0, 70]\,\%$	$< 10\,\mathrm{cm^2\,s^{-1}}$
~30 g-mode pulsators	B3 – B9	$[3.3, 8.9]\,M_\odot$	$[6, 29]\,\%$	$[3, 96]\,\%$	$[12, 8.7\times10^5]\,\mathrm{cm^2\,s^{-1}}$

Stellar evolution in action



Combined asteroseismology, astrometry, and spectroscopy of a sample of 26 SPB stars (Pedersen et al. 2021)

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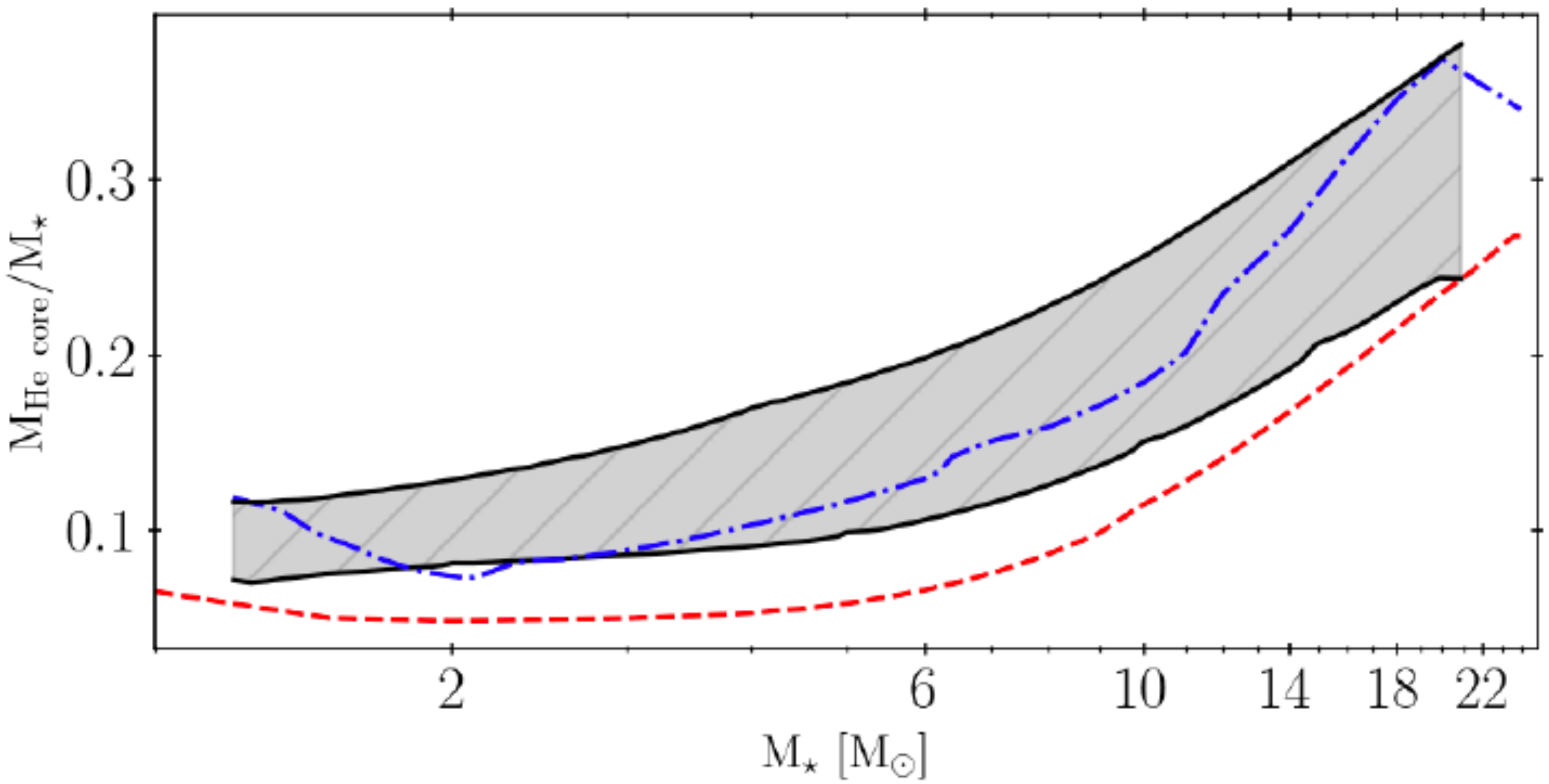
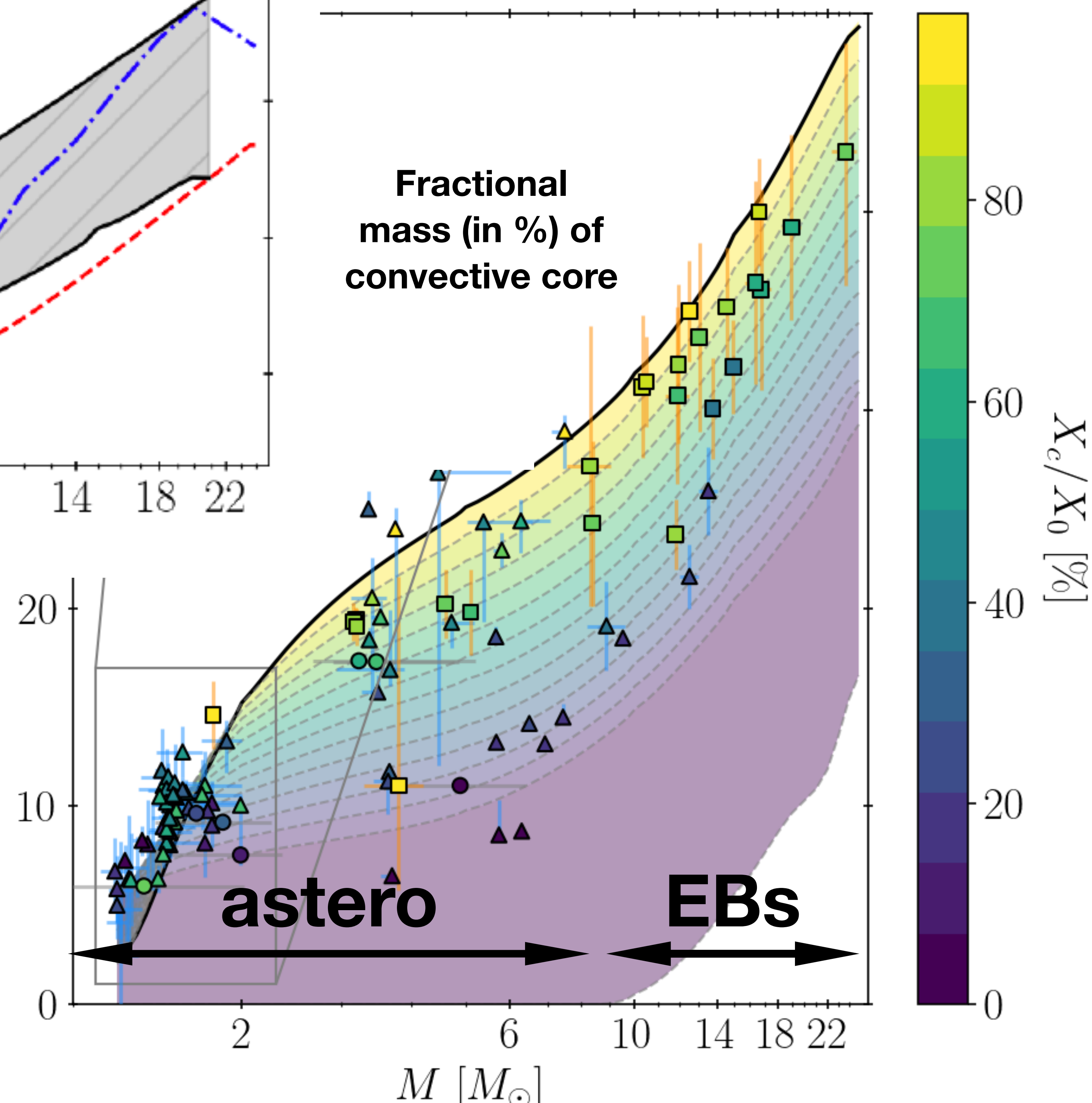
Asteroseismic & EB Core Masses

Figures Courtesy: Cole Johnston





He core at TAMS up to twice as high wrt no mixing

Cole Johnston (2021, submitted)

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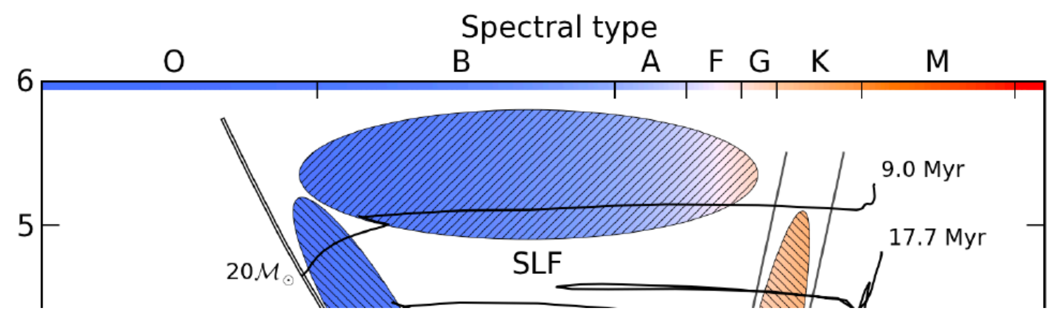
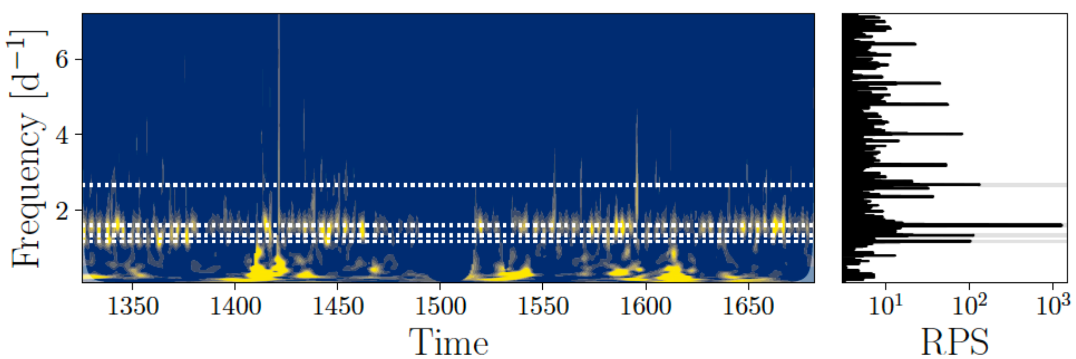
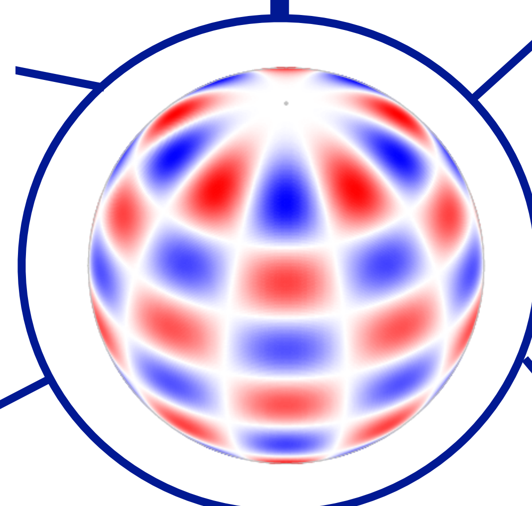
Ongoing TESS/Gaia/Spectroscopic Surveys

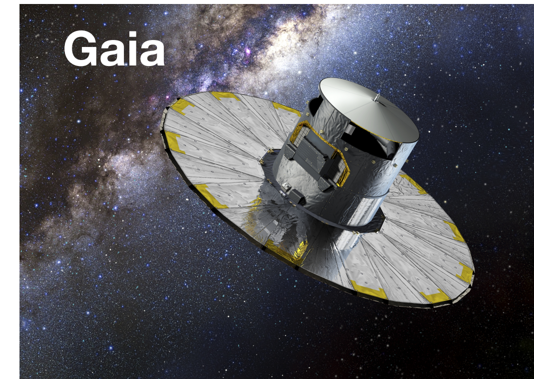
(Pedersen et al. 2019;Bowman et al. 2019, 2020; Dorn-Wallenstein et al. 2020)





Onward to high mass & evolved BSG (incl. LMC)





ESO

esa

NASA

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Onward to PLATO (2026+)

8% Data Rate is Guest Observer program via open ESA calls, incl. ToO option: welcome!

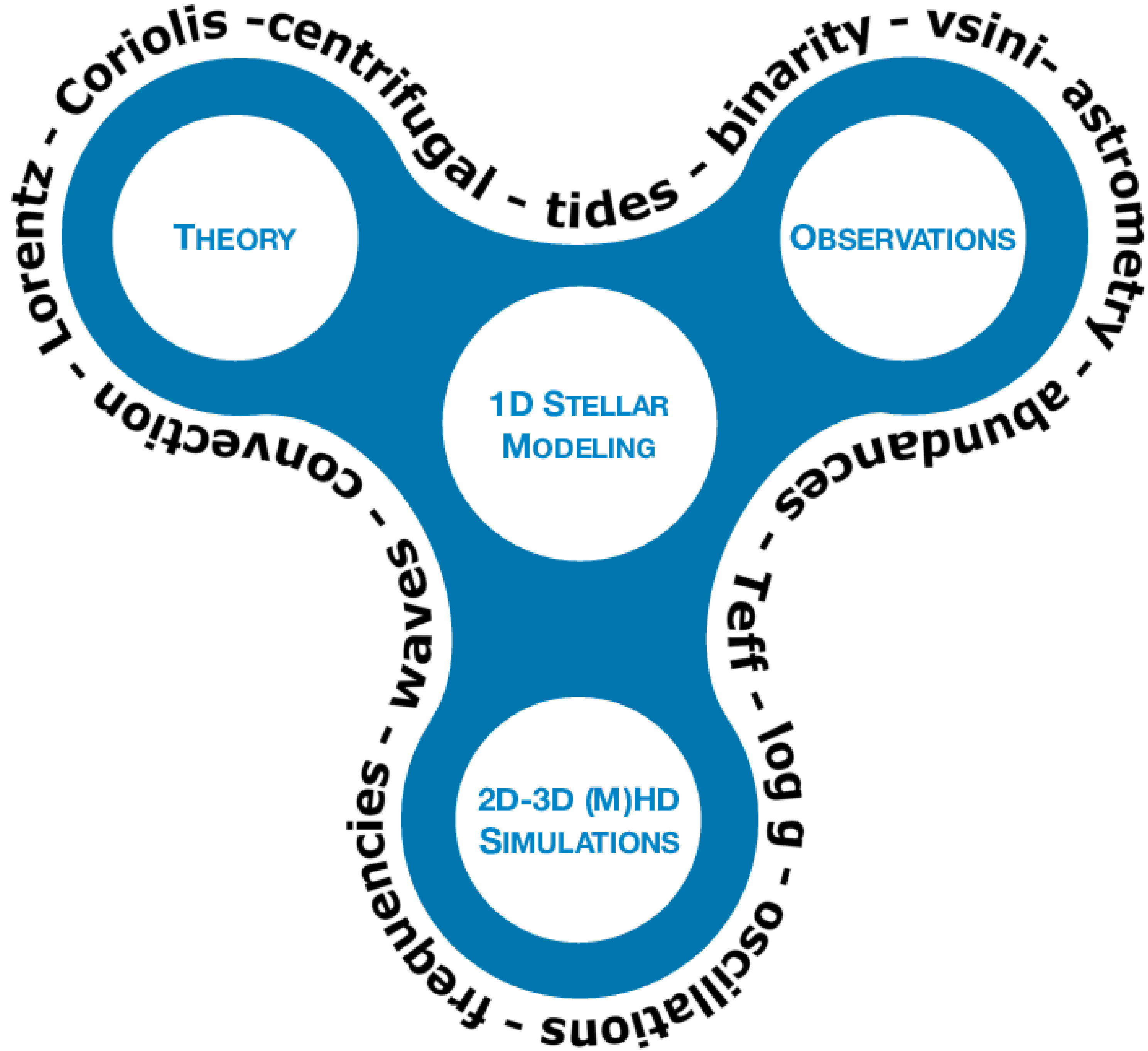

Figure courtesy:
Aerts, Mathis, Rogers, 2019: ARAA, 57, 35, https://arxiv.org/abs/1809.07779

Much more to it: tidal, magneto-, pre-MS, nonlinear,… asteroseismology
Aerts, 2021, RMP, Vol.93, 015001: https://arxiv.org/abs/1912.12300
general introduction & update for non-expert