DIVING DEEP INTO STARS VIA ASTEROSEISMOLOGY

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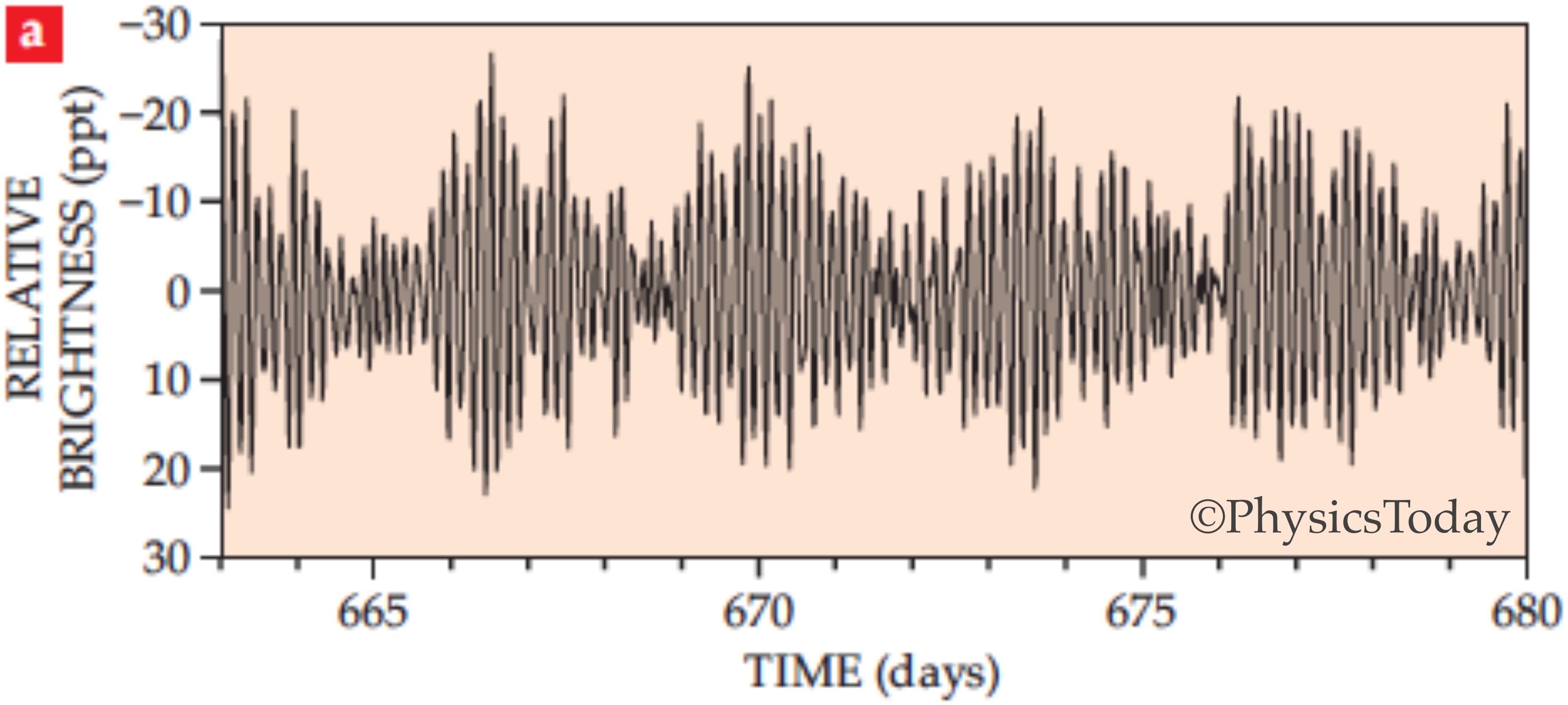
Brno, 26 April 2021

KU LEUVEN

Take-home message



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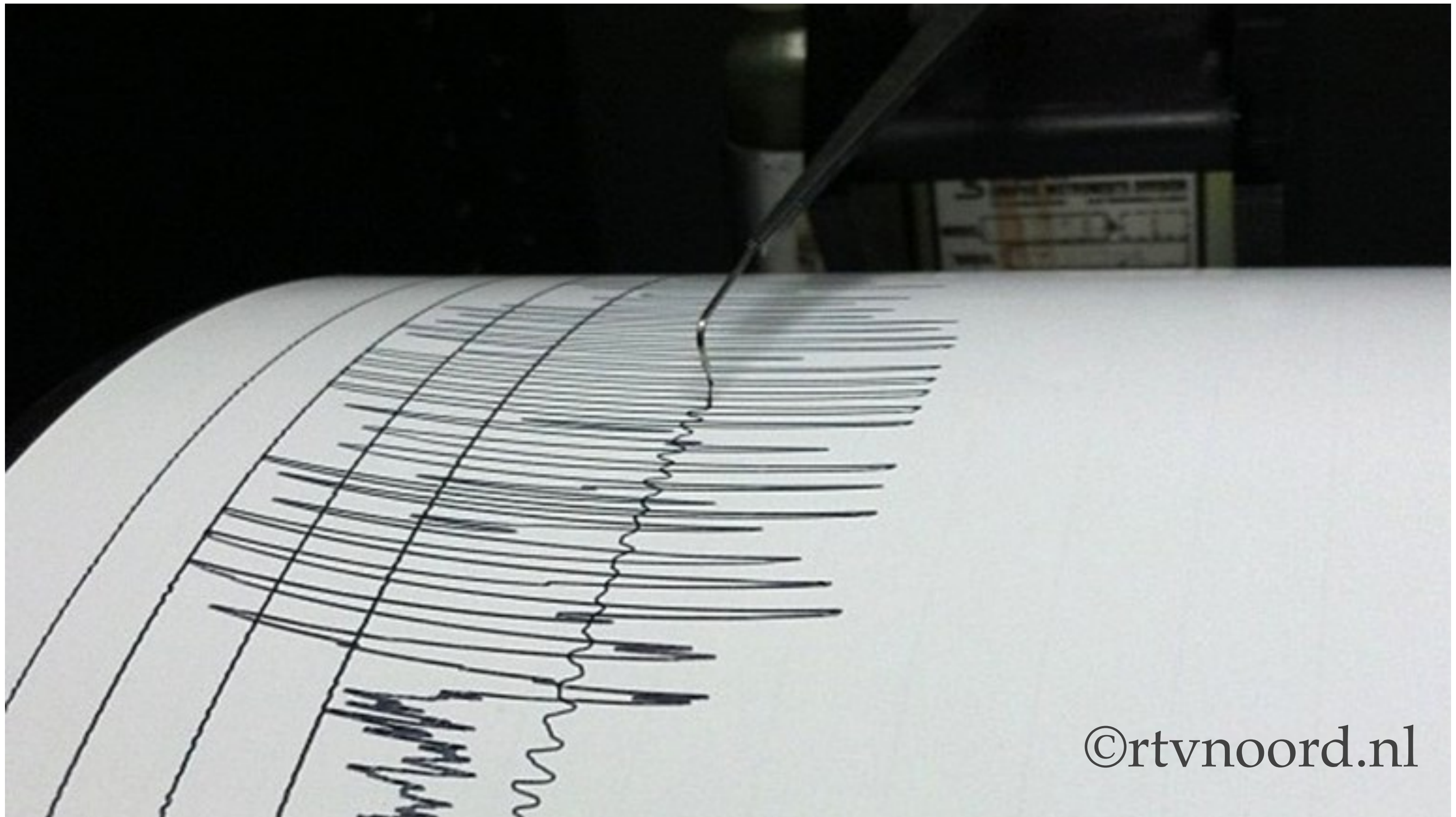

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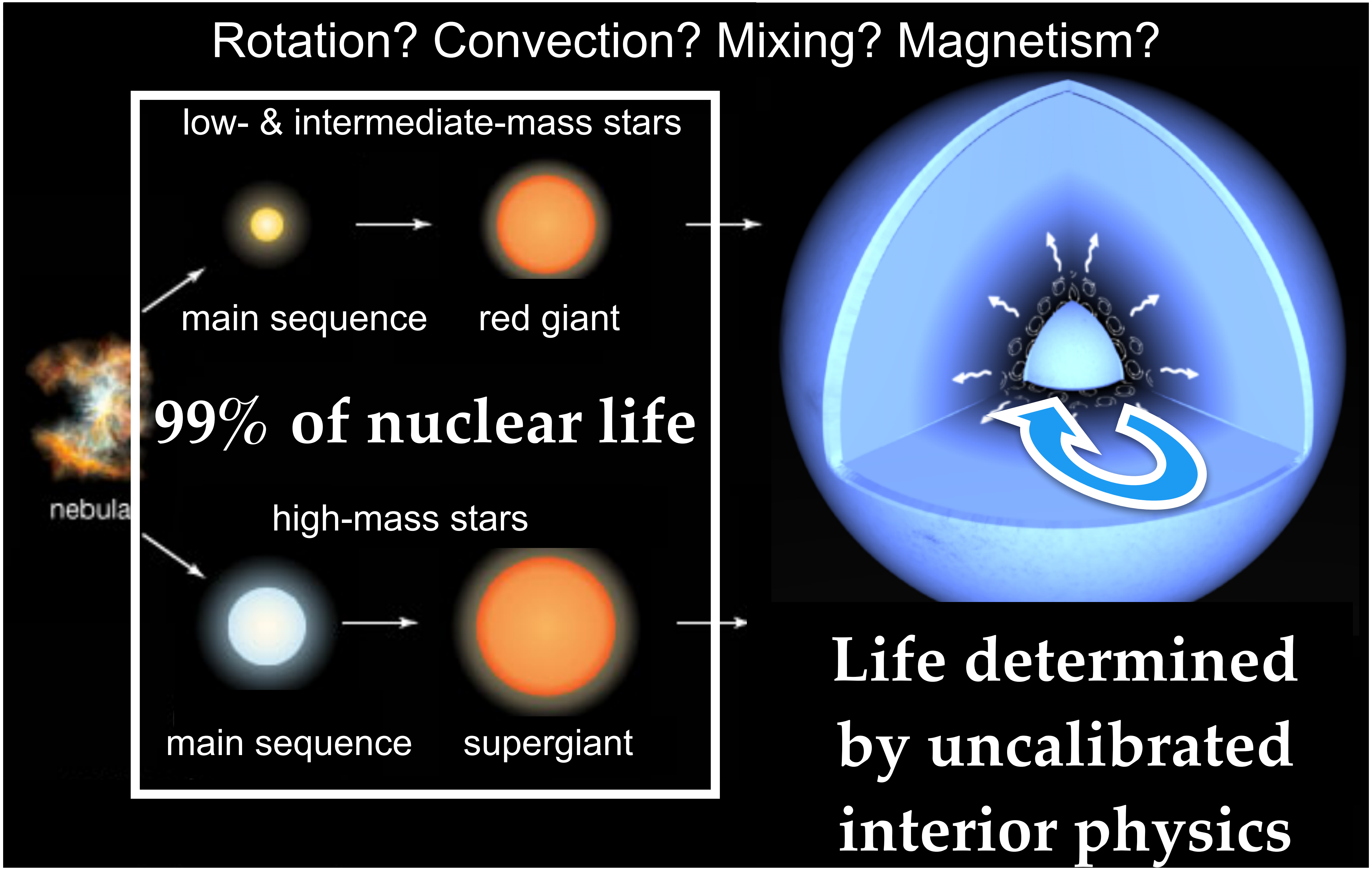
Seismic waves offer *in-situ* measurements of internal stellar physics: new look@SSE

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

Stellar interiors: poorly known

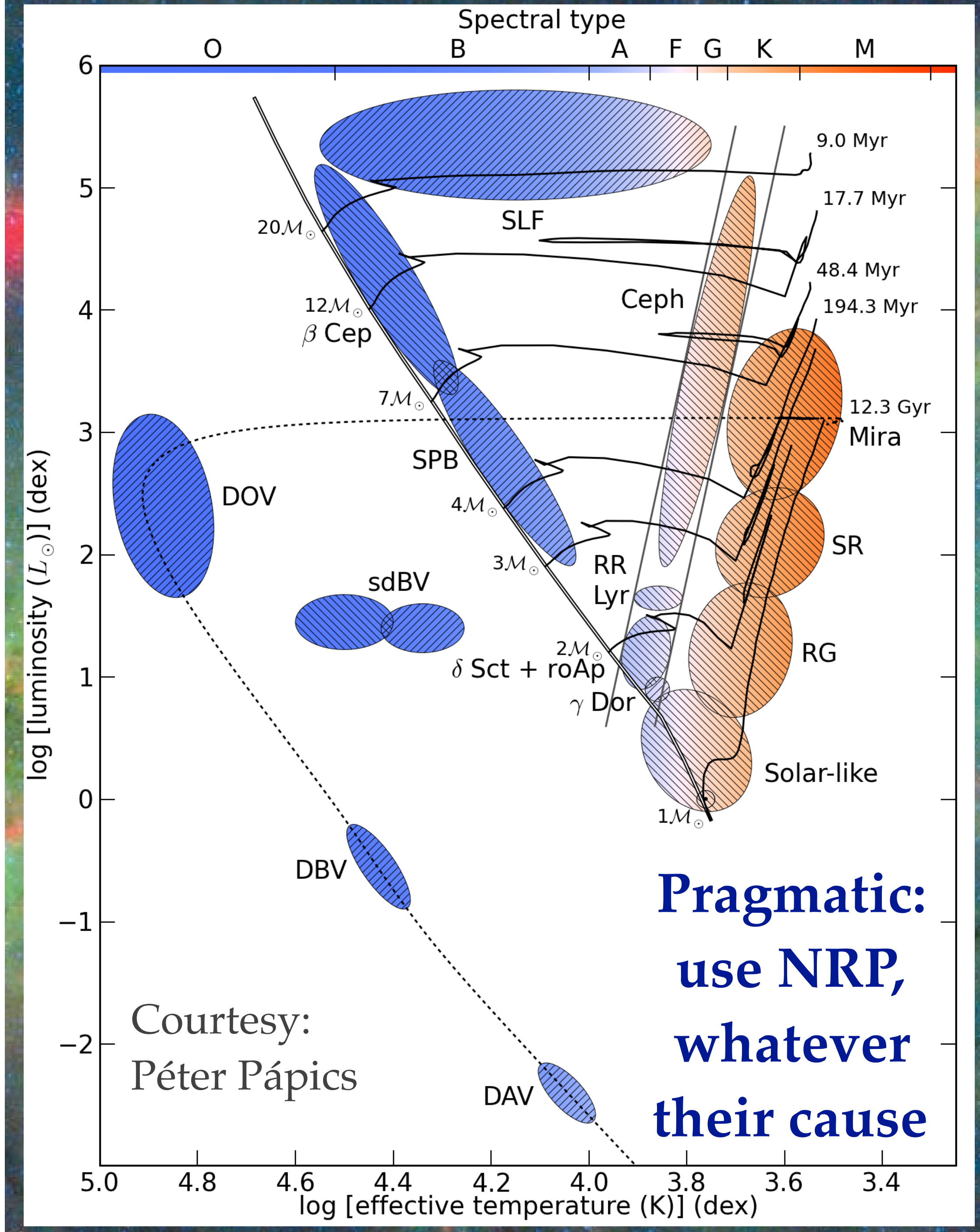


Rotation? Convection? Mixing? Magnetism?

99% of nuclear life

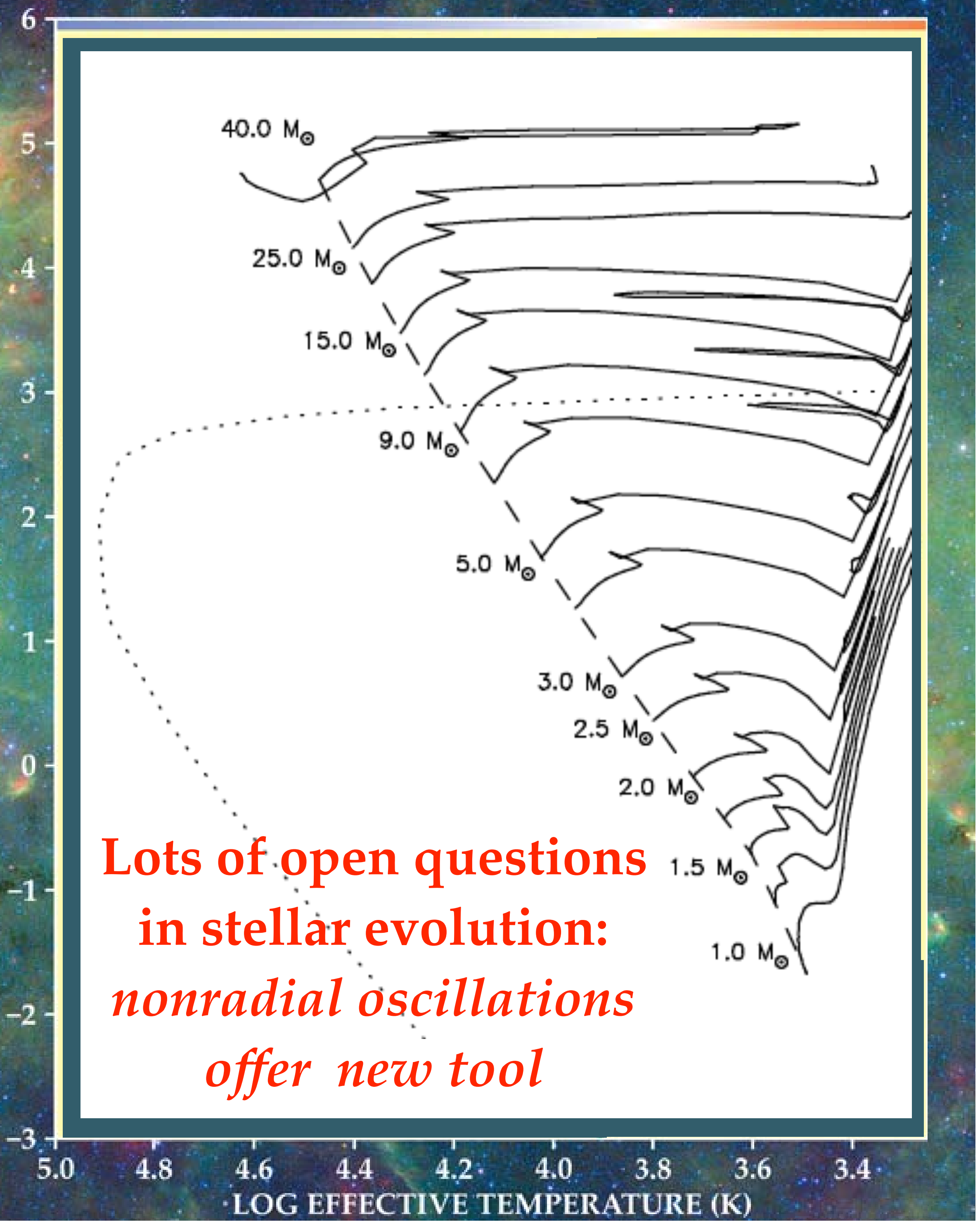
Life determined by uncalibrated interior physics

Asteroseismology to the rescue



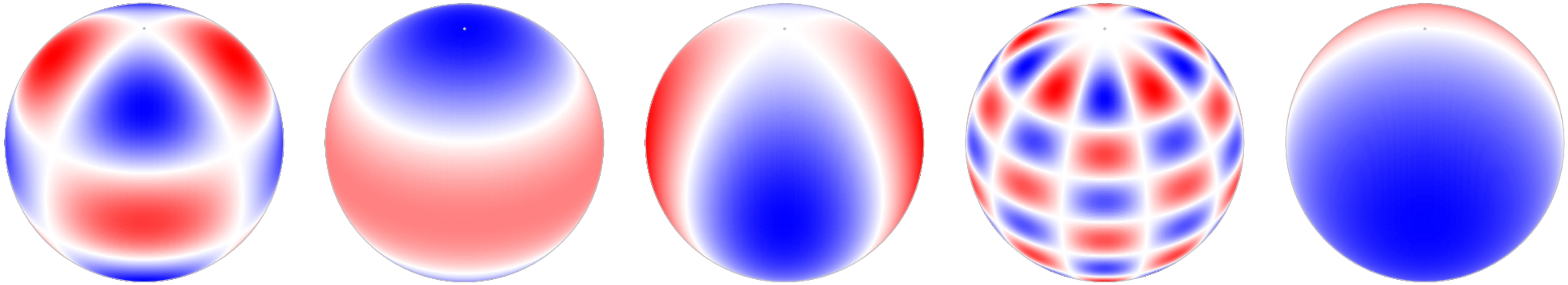
Courtesy:
Péter Pápics

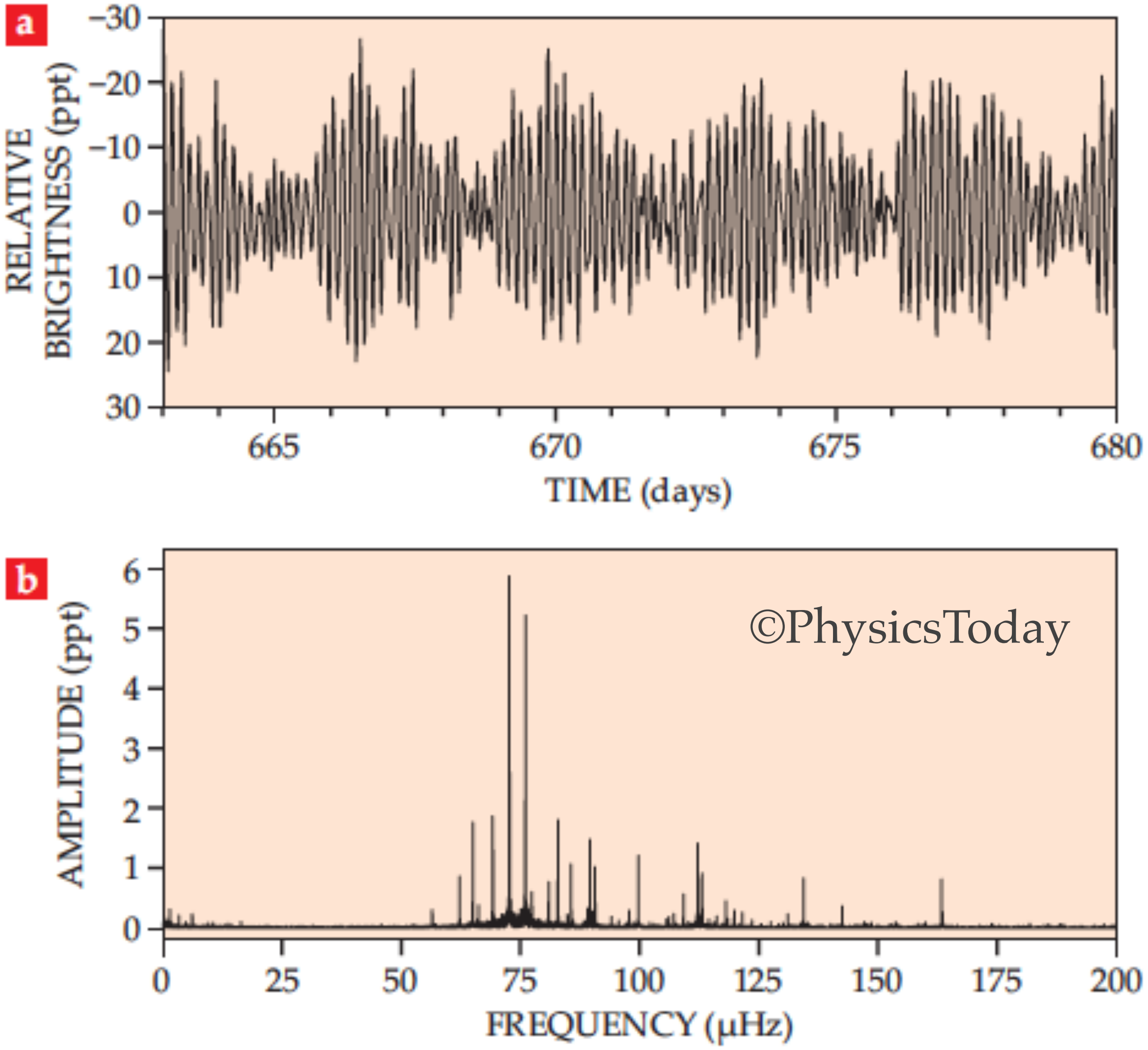
Pragmatic: use NRP, whatever their cause



Lots of open questions in stellar evolution:
nonradial oscillations offer new tool

Stellar oscillations probe stellar interiors





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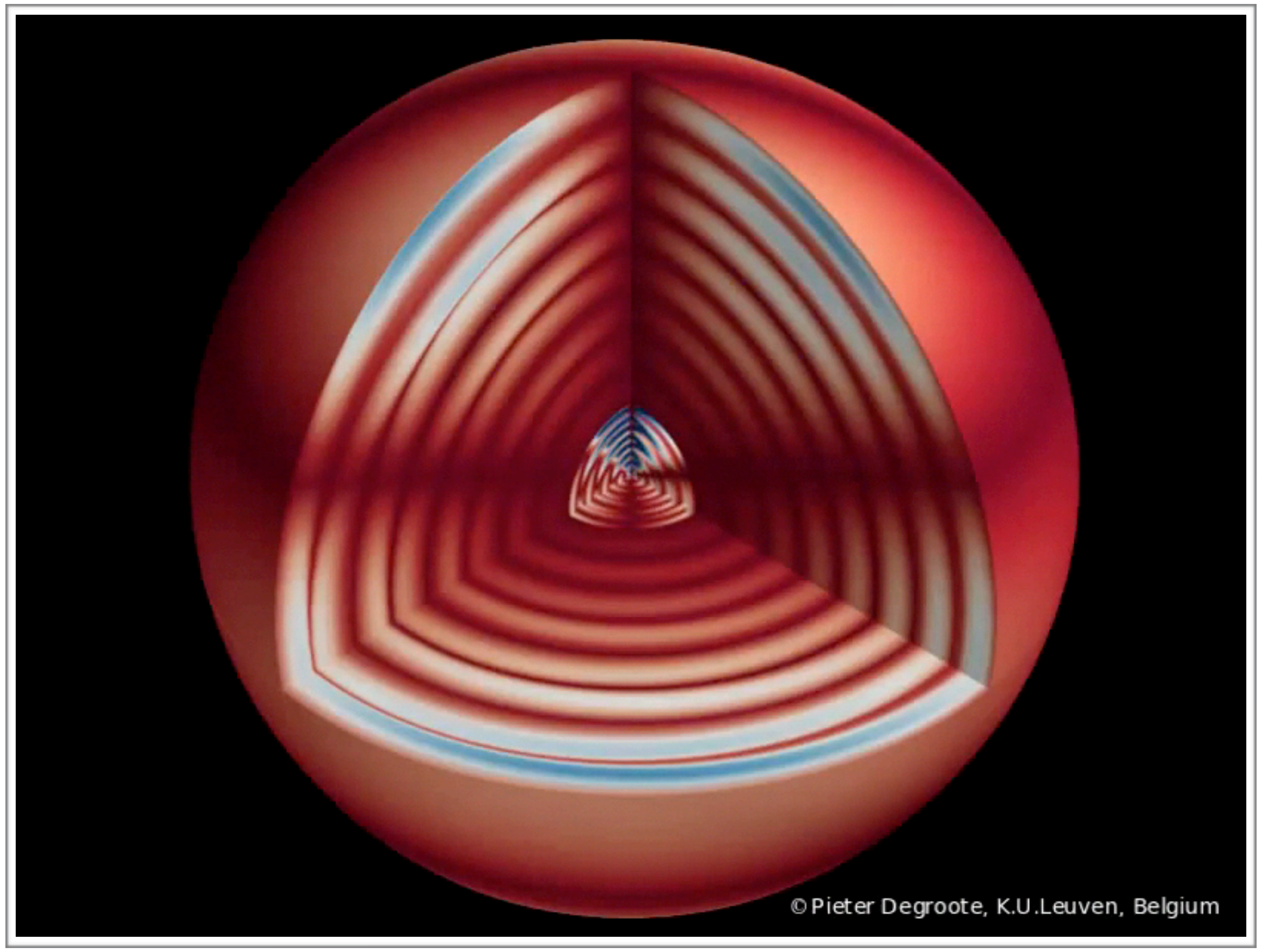

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Ingredients: temporal/spatial

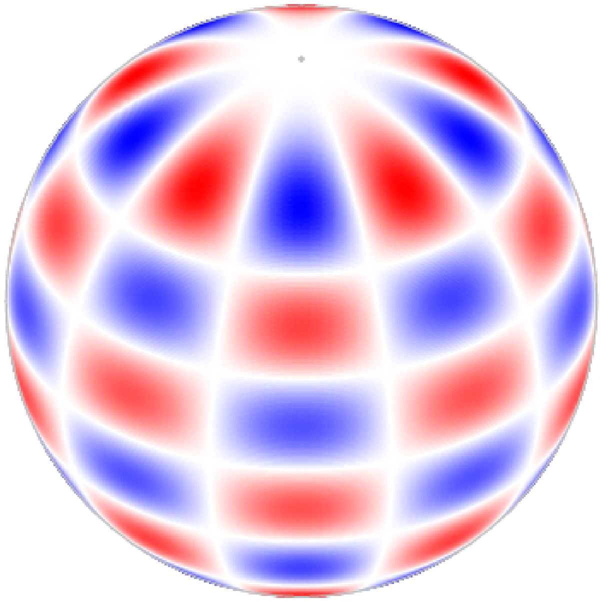
- NRPs = solutions of perturbed SSE in terms of periodic eigenfunctions : eigenmodes of the star
- Each mode described by spherical harmonic & frequency:

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

- Dominance of restoring force?

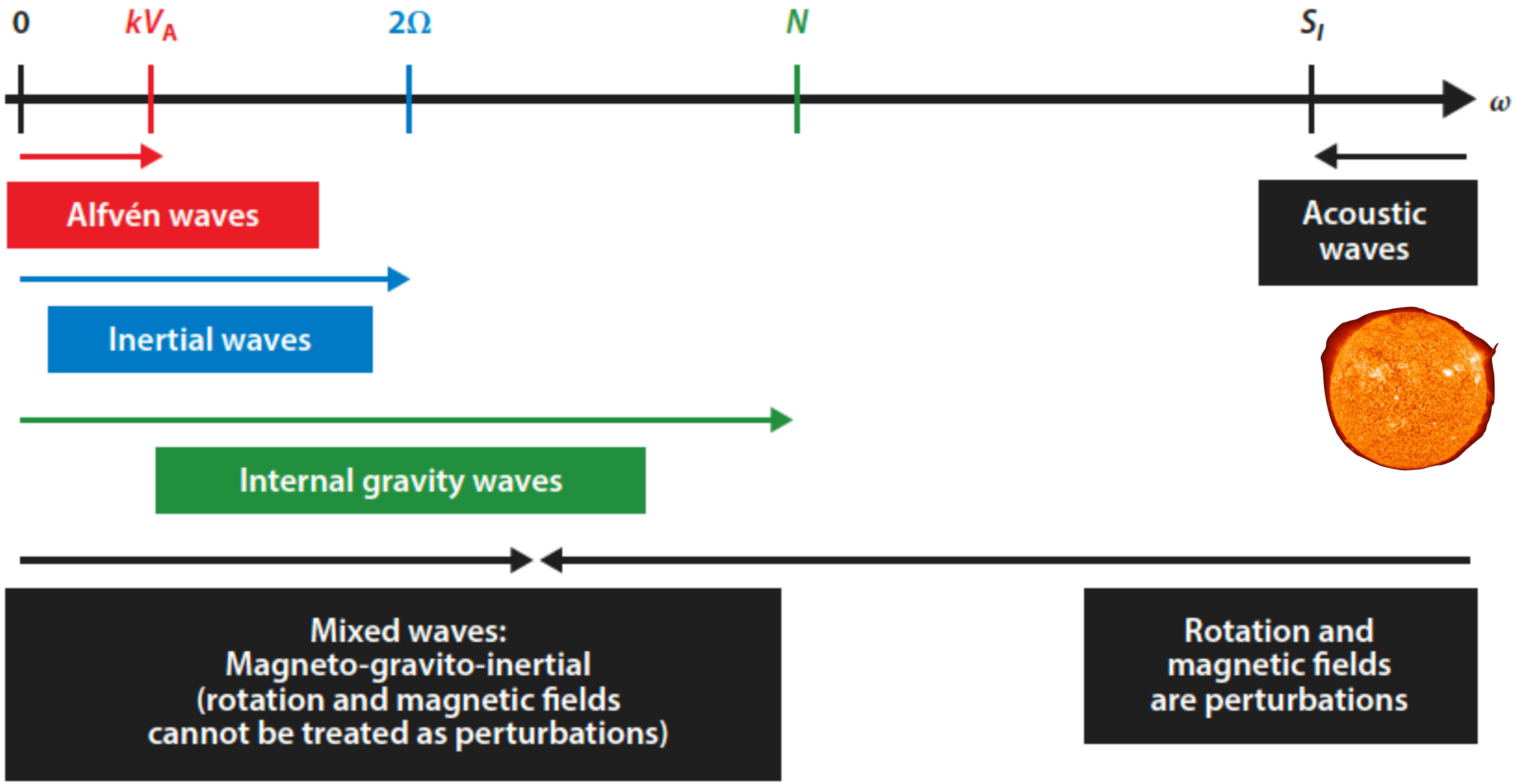
1. pressure (acoustic waves)
2. buoyancy (gravity waves)
3. Coriolis (inertial waves)
4. Lorentz (Alfvén waves)
5. tidal (tidal waves)

Kepler!



Frequency regimes

g-modes p-modes



Alfvén waves

Inertial waves

Internal gravity waves

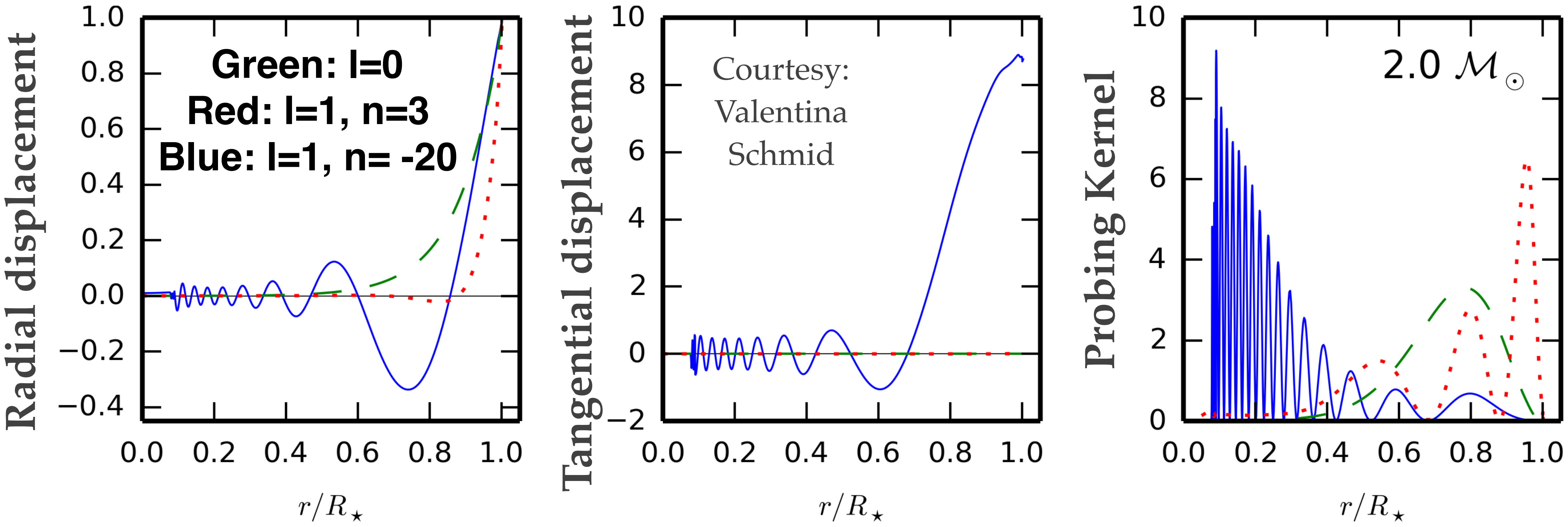
Acoustic waves

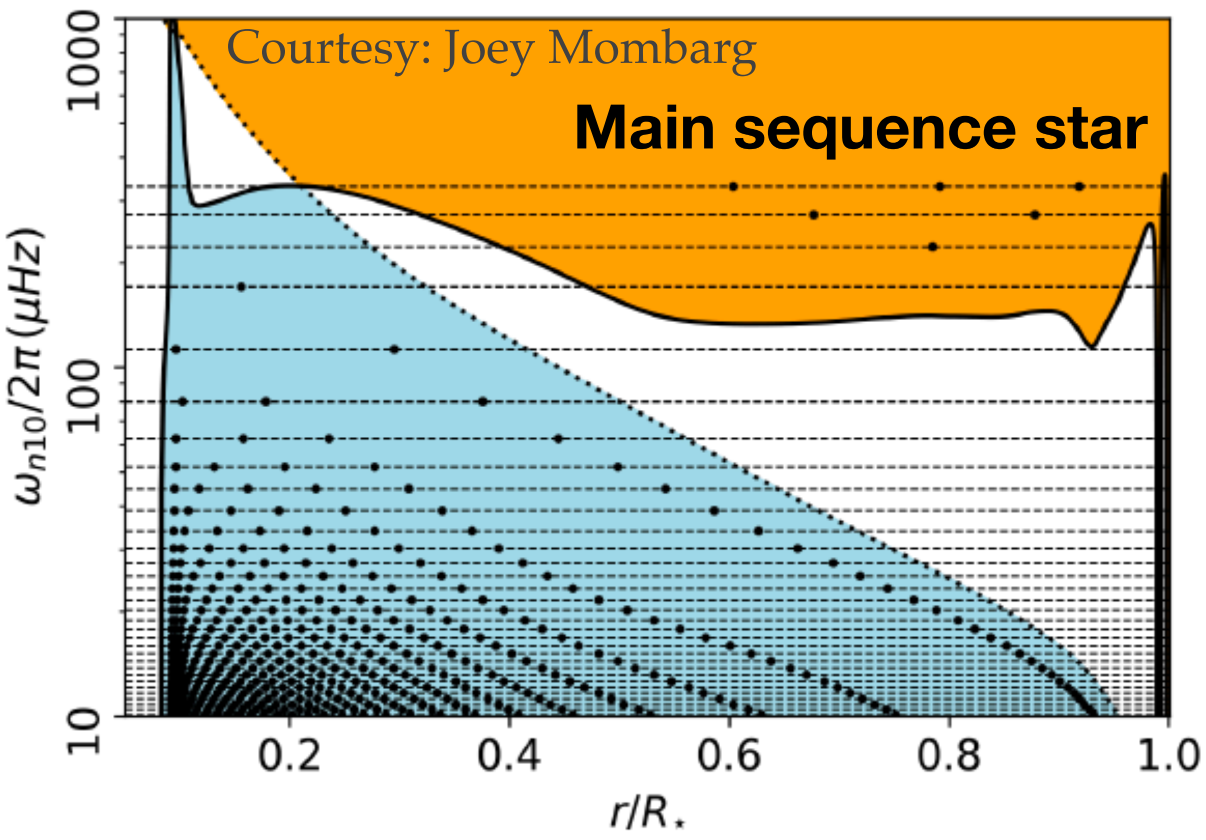
Mixed waves:
Magneto-gravito-inertial
(rotation and magnetic fields
cannot be treated as perturbations)

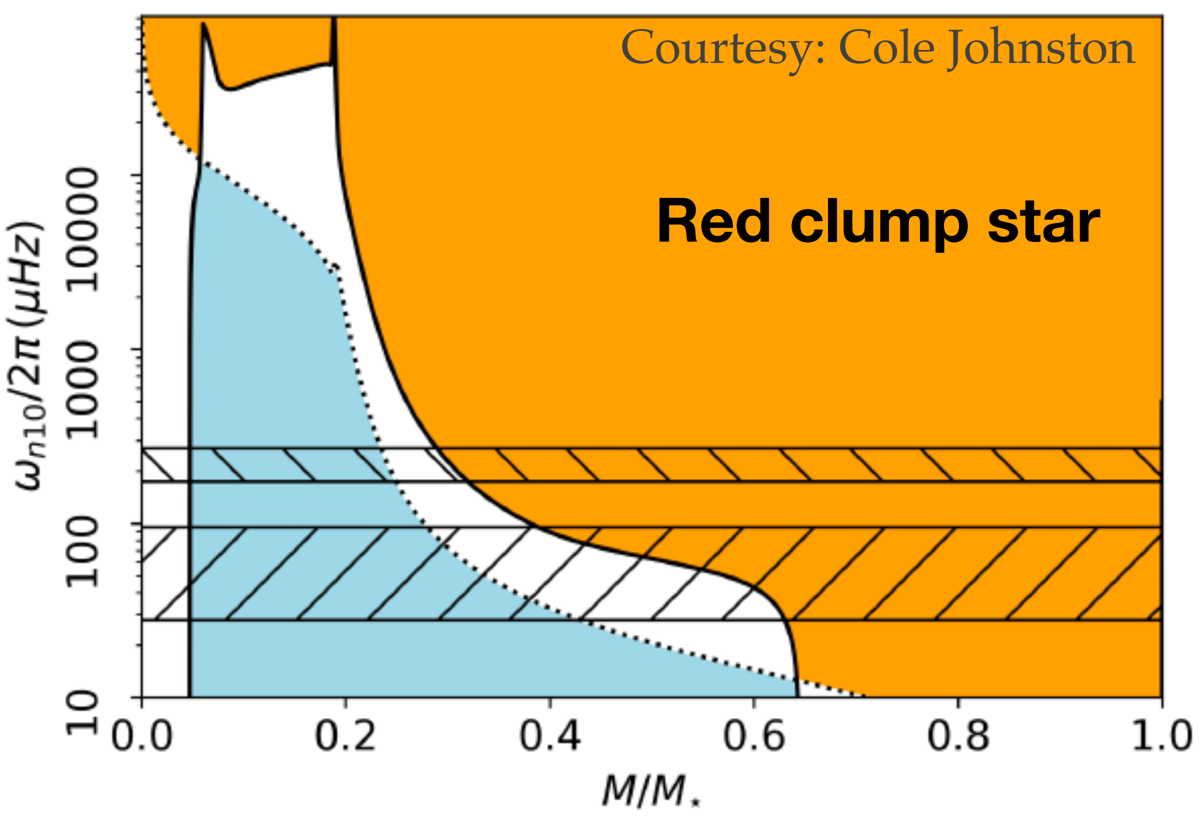
Rotation and
magnetic fields
are perturbations

(Aerts, Mathis, Rogers, 2019, ARAA)

Probing power: p/g-modes


Courtesy: Valentina Schmid


Courtesy: Joey Mombarg


Courtesy: Cole Johnston

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Data-driven modelling

THEORY

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

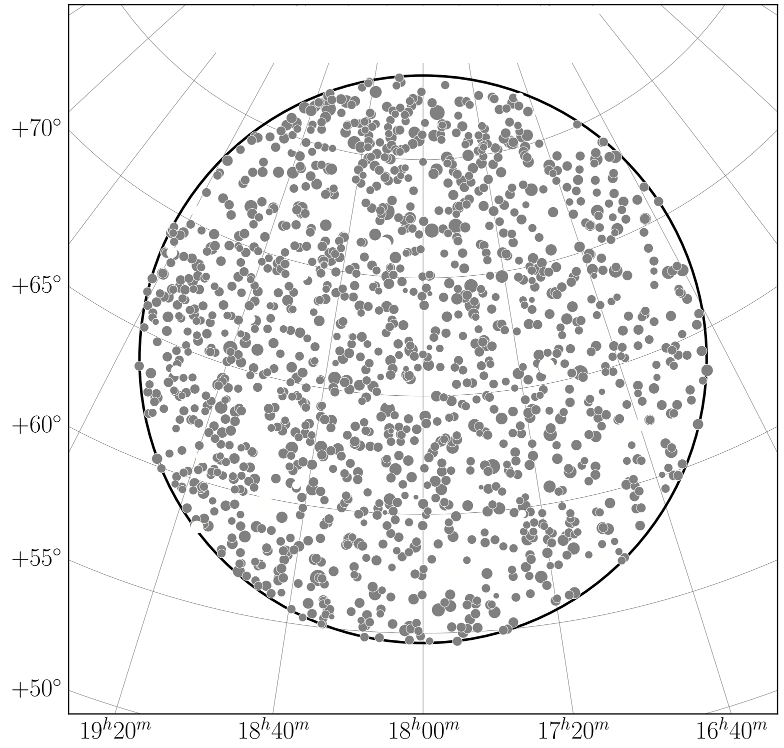
STELLAR MODEL
FOR SPECIFIED
INPUT PHYSICS

Theoretical chemistry,
luminosity, oscillations

OBSERVATIONS

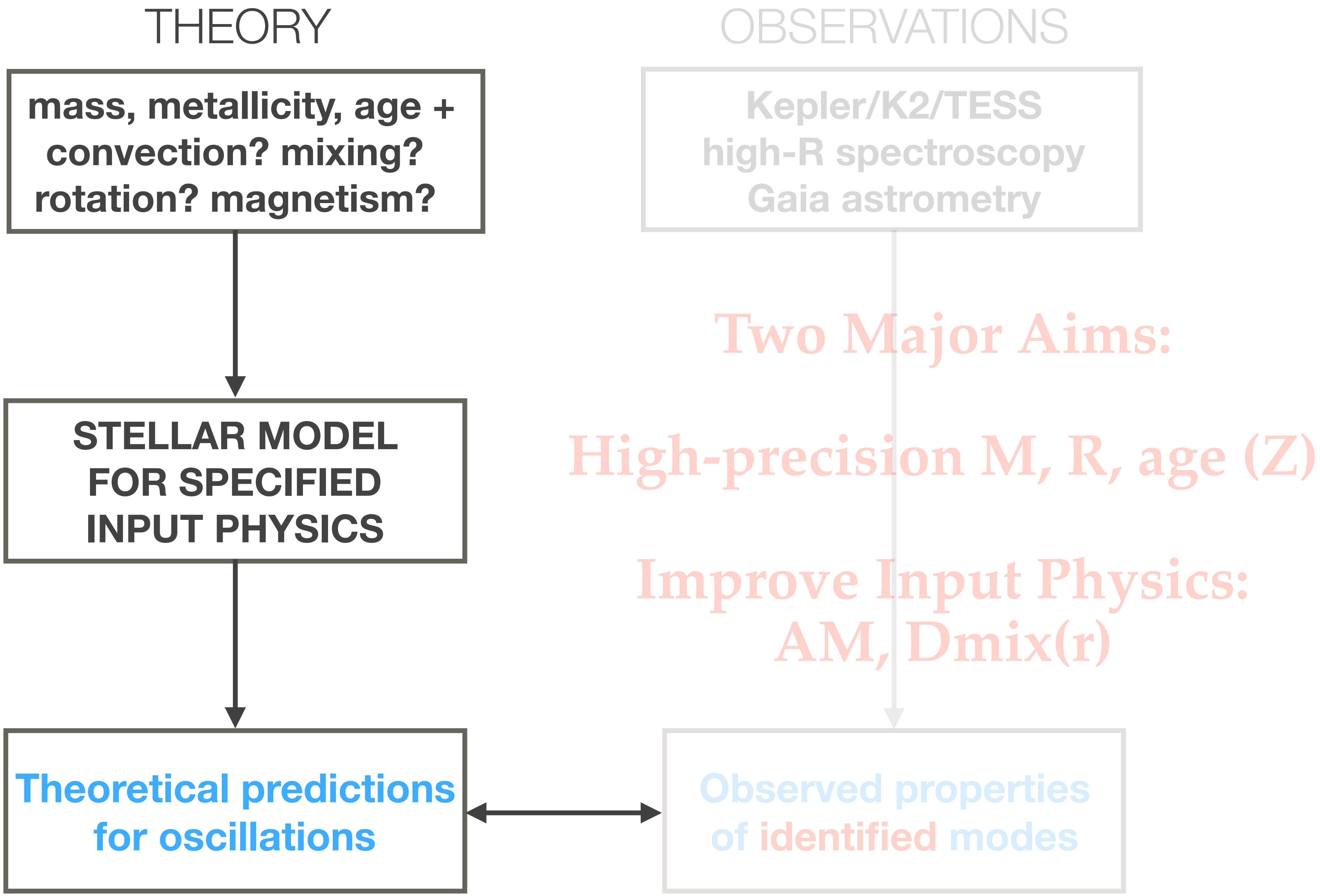
Kepler/K2/TESS
high-R spectroscopy
Gaia astrometry

variability classification from ML : clustering, deep learning …



**Observed chemistry,
luminosity, oscillations**

Theoretical predictions



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

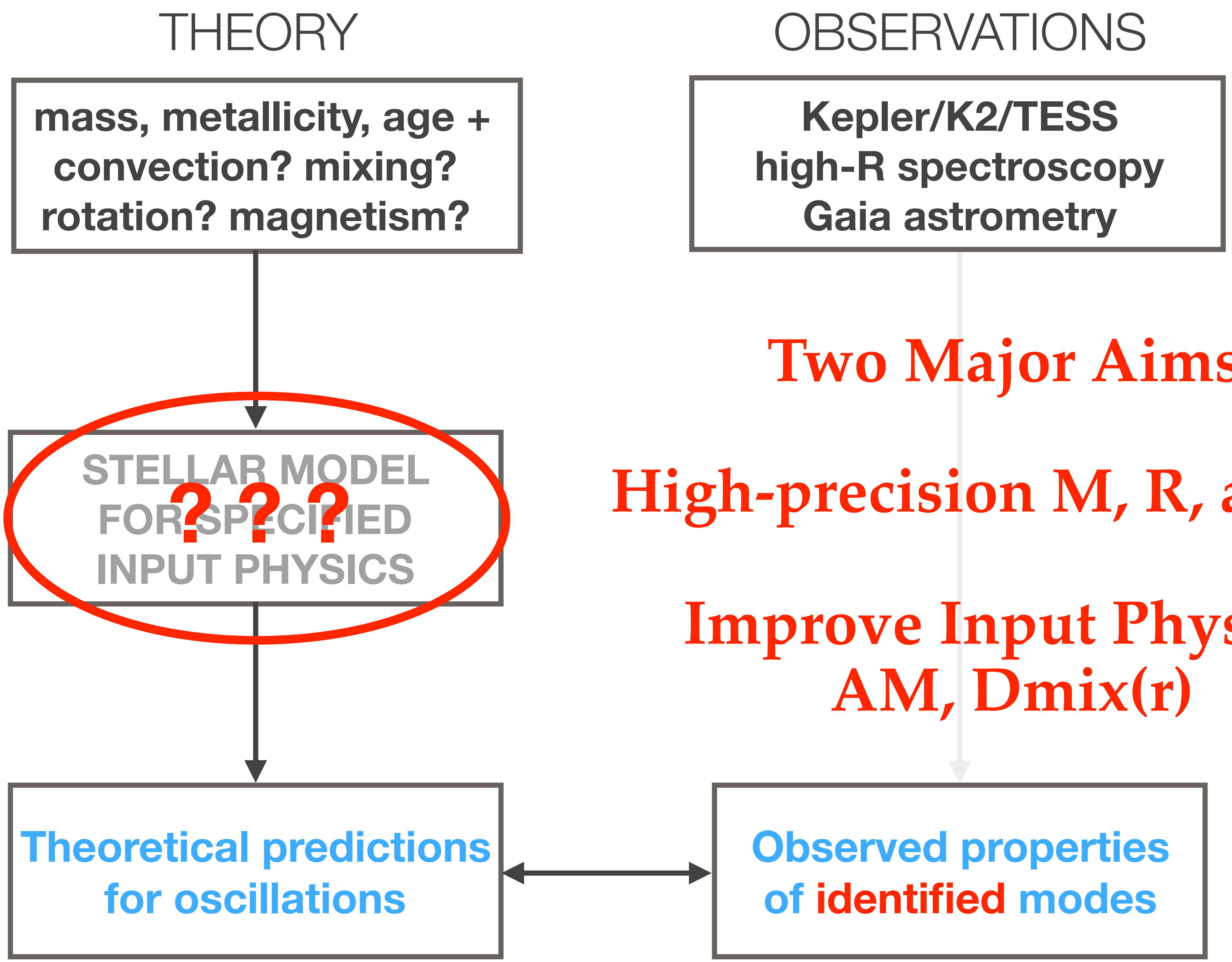
Observed properties
of identified modes

Two Major Aims:

High-precision M, R, age (Z)

Improve Input Physics:
AM, Dmix(r)

Aims of Asteroseismology



THEORY

mass, metallicity, age +
convection? mixing?
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STELLAR MODEL
FOR SPECIFIED
INPUT PHYSICS

? ? ?

Theoretical predictions
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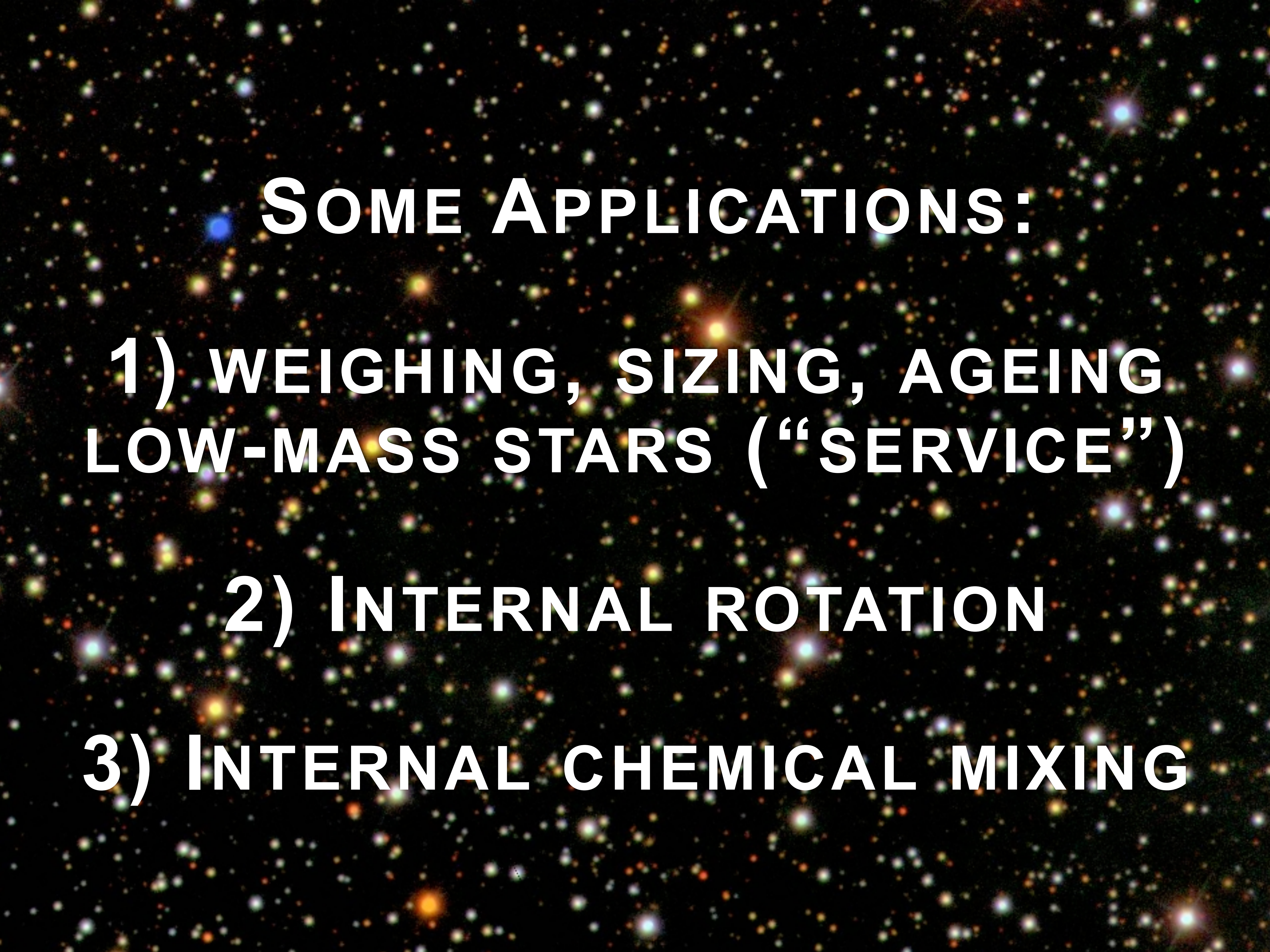


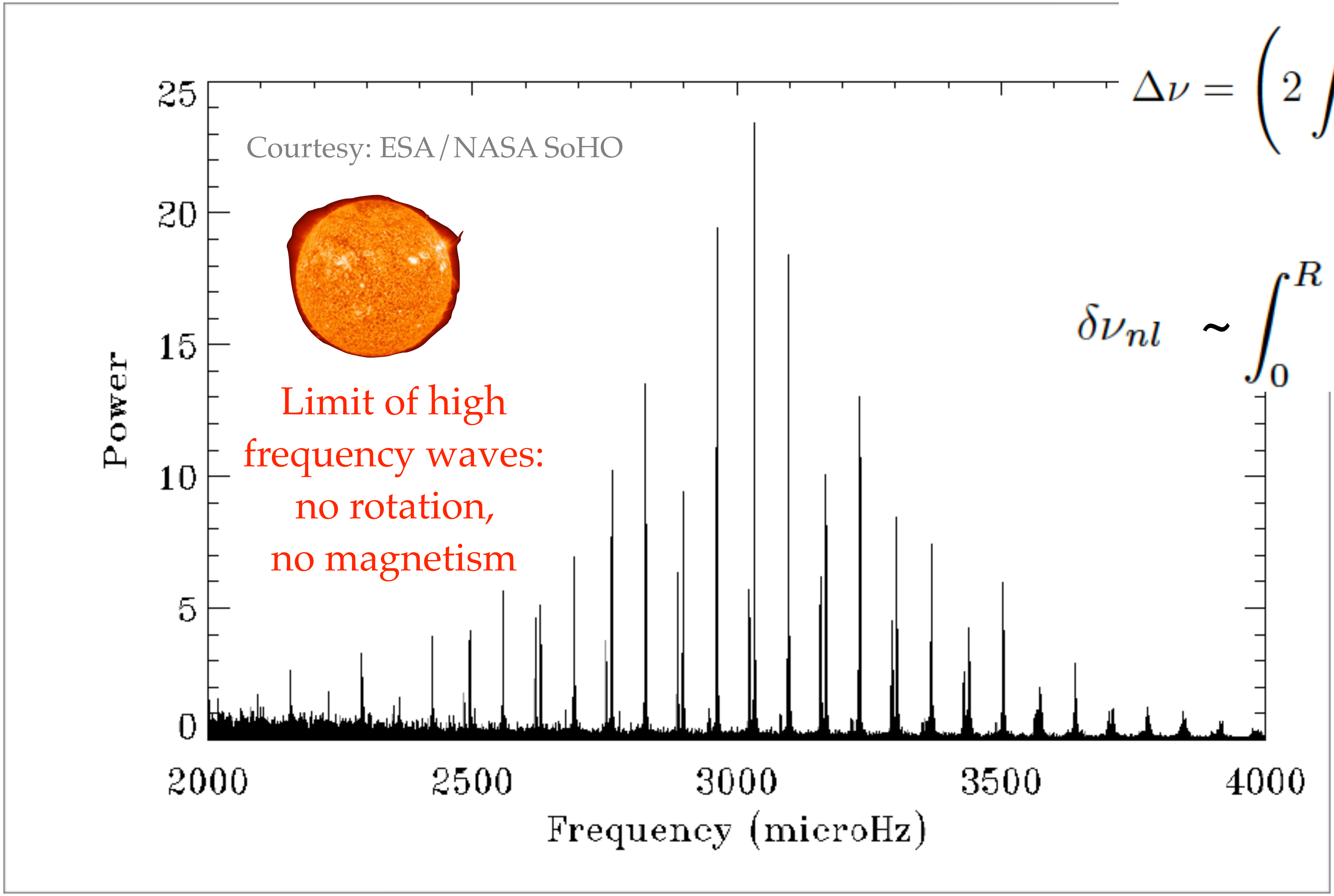
SOME APPLICATIONS:

1) WEIGHING, SIZING, AGEING LOW-MASS STARS (“SERVICE”)

2) INTERNAL ROTATION

3) INTERNAL CHEMICAL MIXING

Helioseismology paved the way



Courtesy: ESA/NASA SoHO

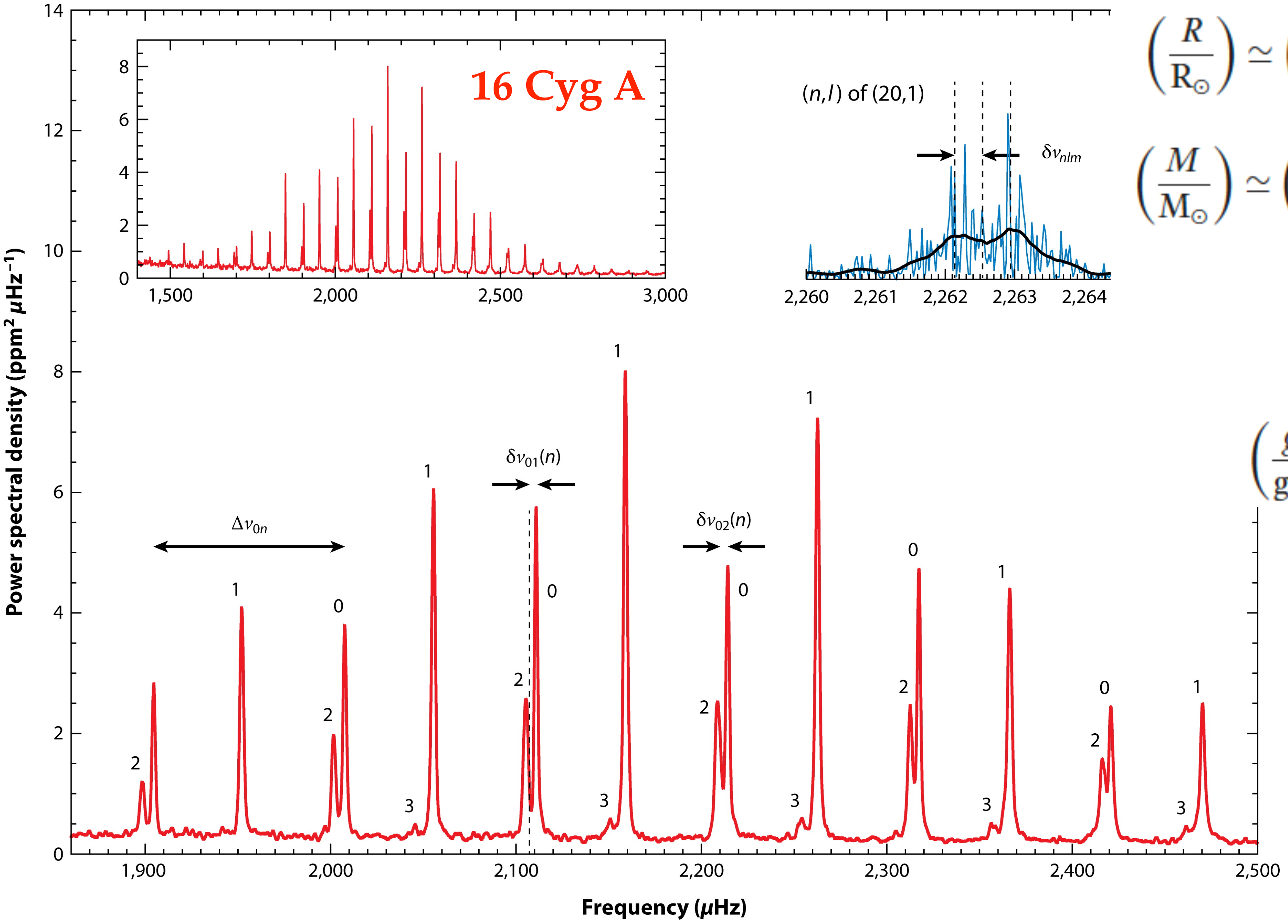
Limit of high frequency waves: no rotation, no magnetism

$$\Delta\nu = \left(2\int_0^R \frac{\mathrm{d}r}{c_\mathrm{s}}\right)^{-1}$$

$$\delta\nu_{nl} \sim \int_0^R \frac{\mathrm{d}c_\mathrm{s}}{\mathrm{d}r}\frac{\mathrm{d}r}{r}$$

(Christensen-Dalsgaard, 2002, RMP)

Low-mass stars: R, M, age



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

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

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

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

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

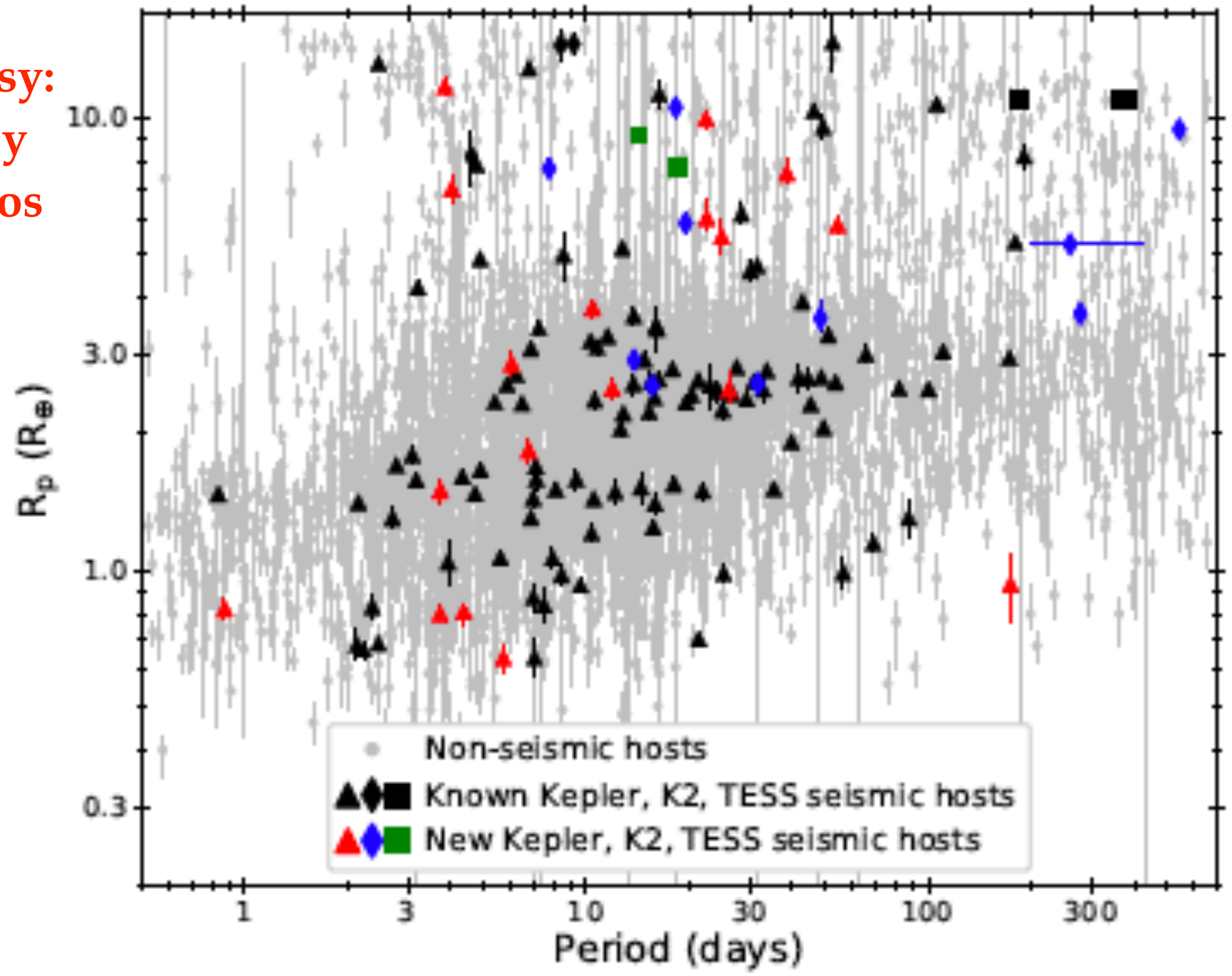
Chaplin WJ, Miglio A. 2013.
Annu. Rev. Astron. Astrophys. 51:353–92

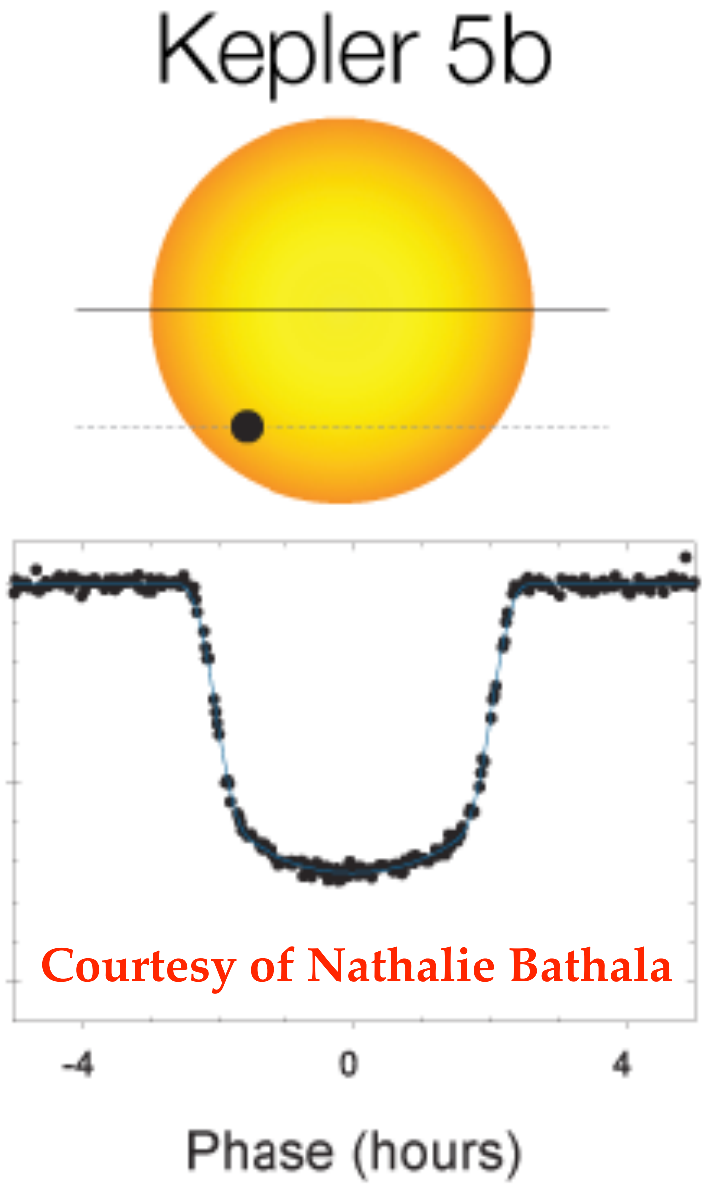
(see also Chaplin et al. 2014, Silva Aguirre et al. 2016, Verma et al. 2019, Bellinger et al. 2019, 2020…)

R, M, age for Exoplanet Research

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

Courtesy:
Ashley
Chontos





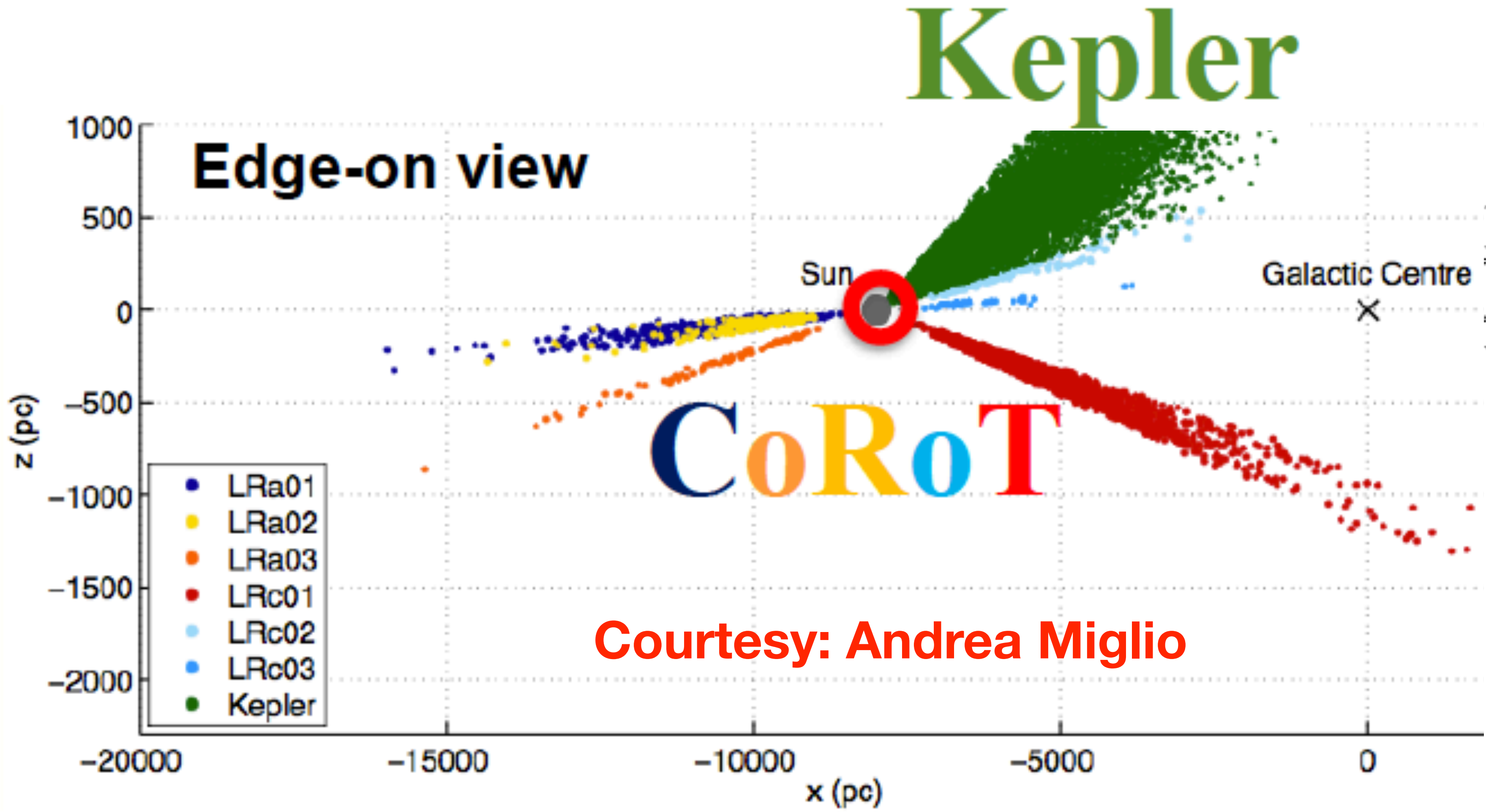
Courtesy of Nathalie Bathala

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

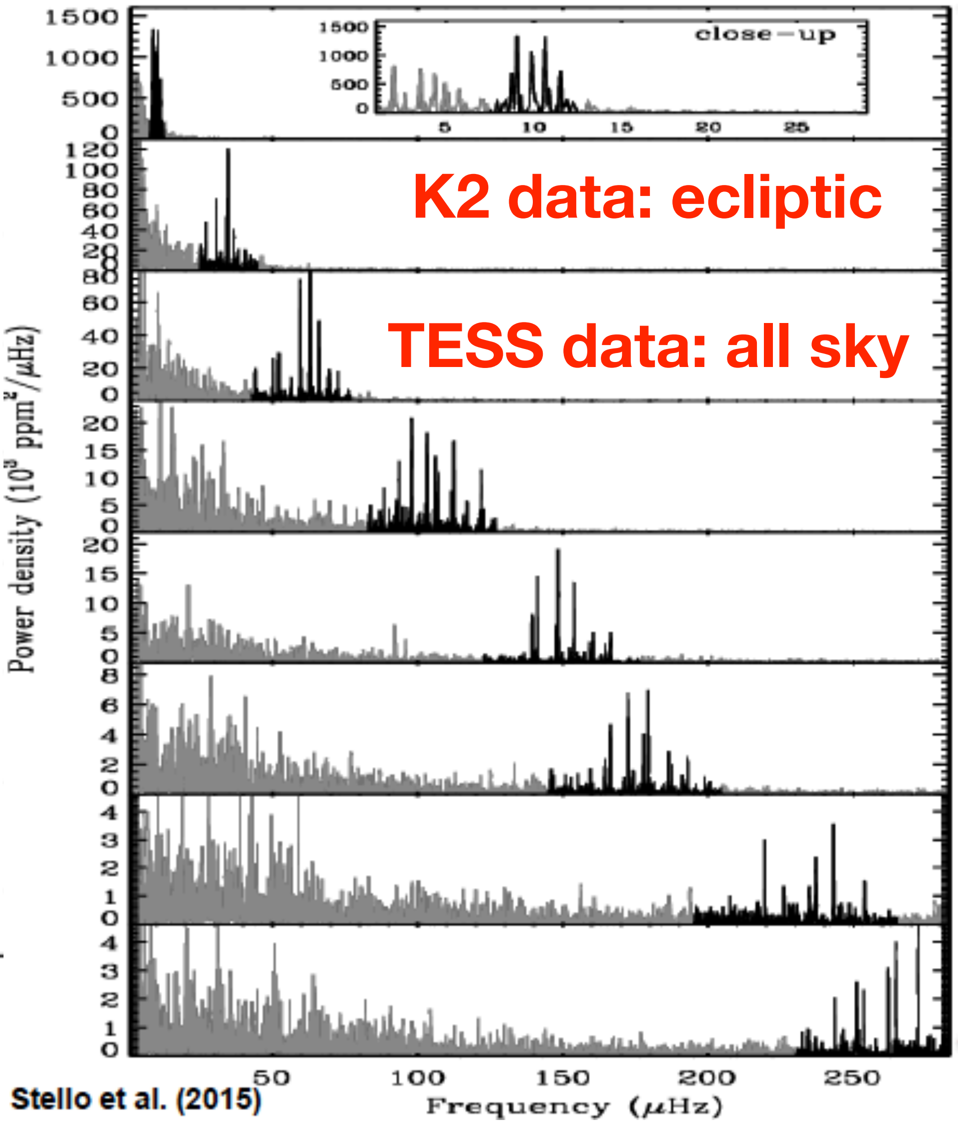
Ages for Galactic Archaeology

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

Teff from spectroscopy



Courtesy: Andrea Miglio



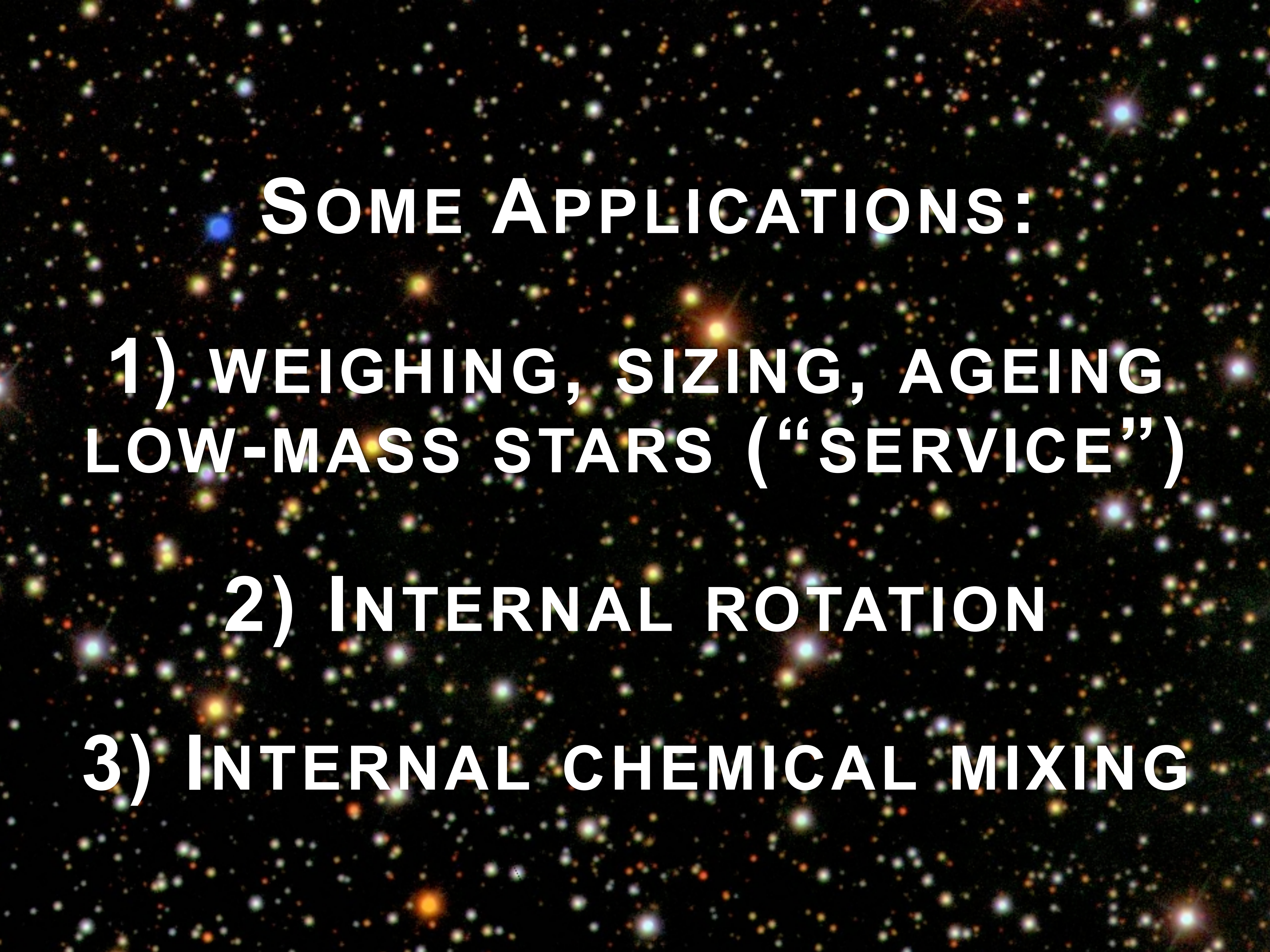
K2 data: ecliptic

TESS data: all sky

Stello et al. (2015)

Asteroseismic distances ~few%

(Silva Aguirre et al. 2012, Miglio et al. 2013, 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:

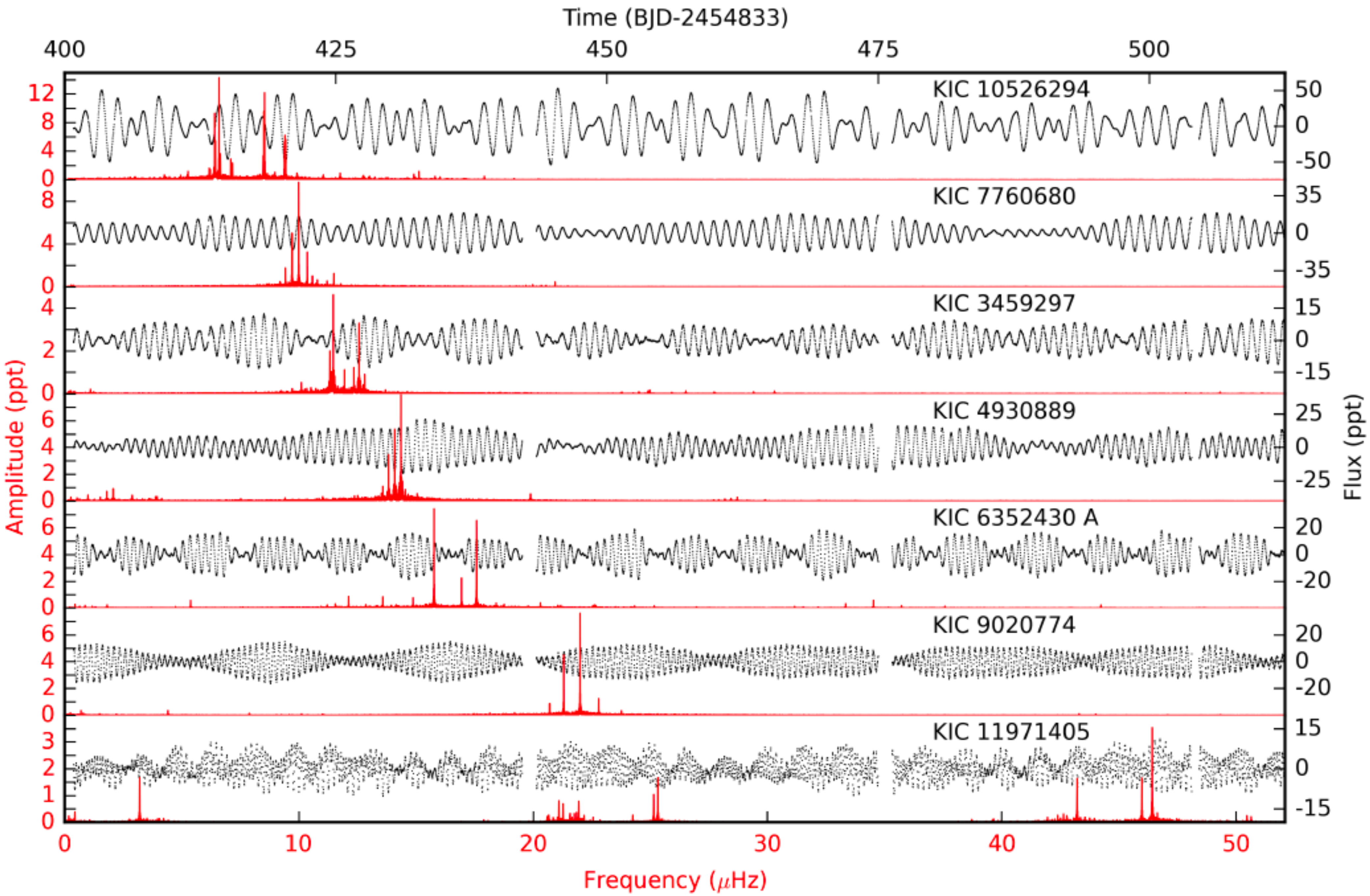
1) WEIGHING, SIZING, AGEING LOW-MASS STARS ("SERVICE")

2) INTERNAL ROTATION

3) INTERNAL CHEMICAL MIXING

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)

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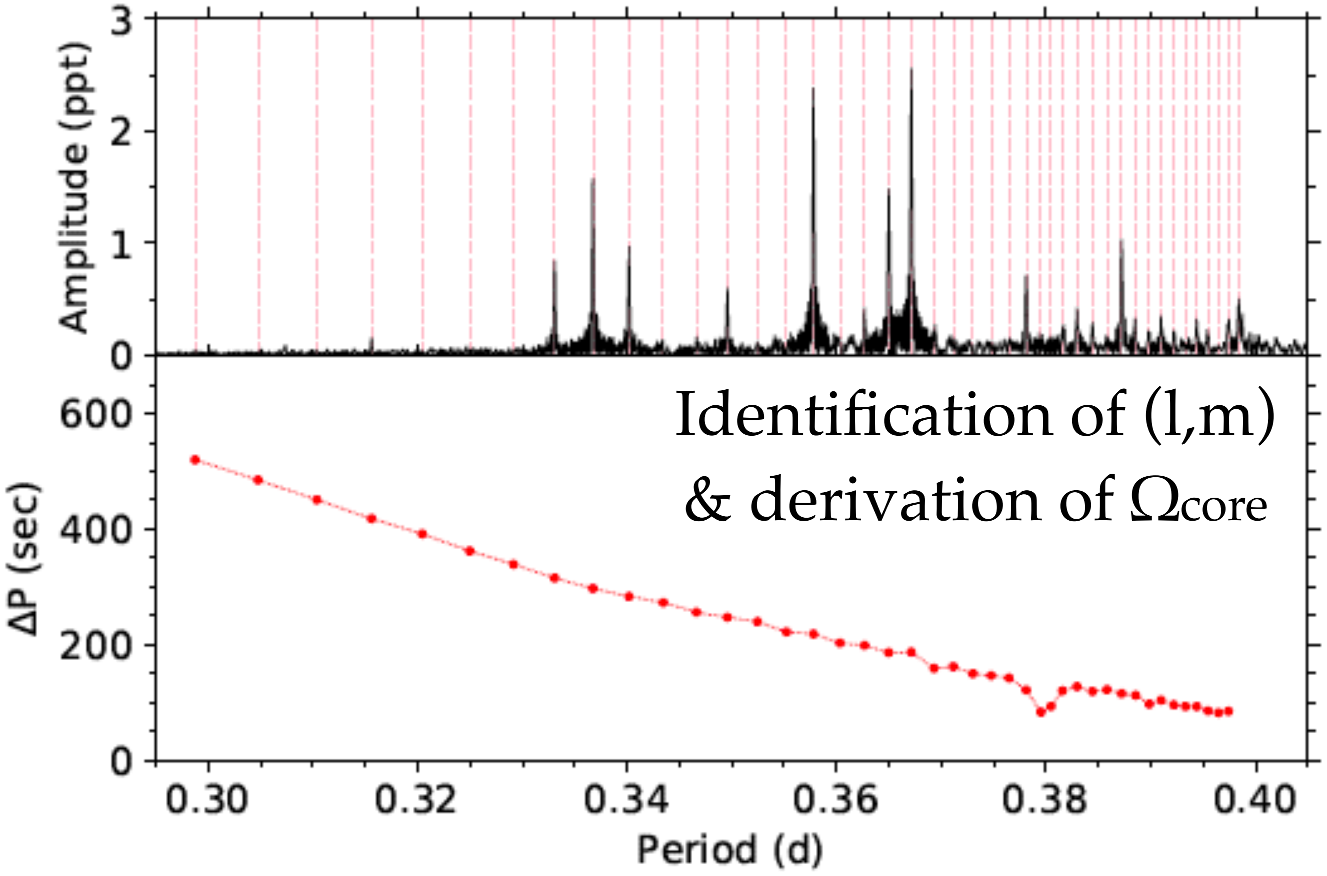
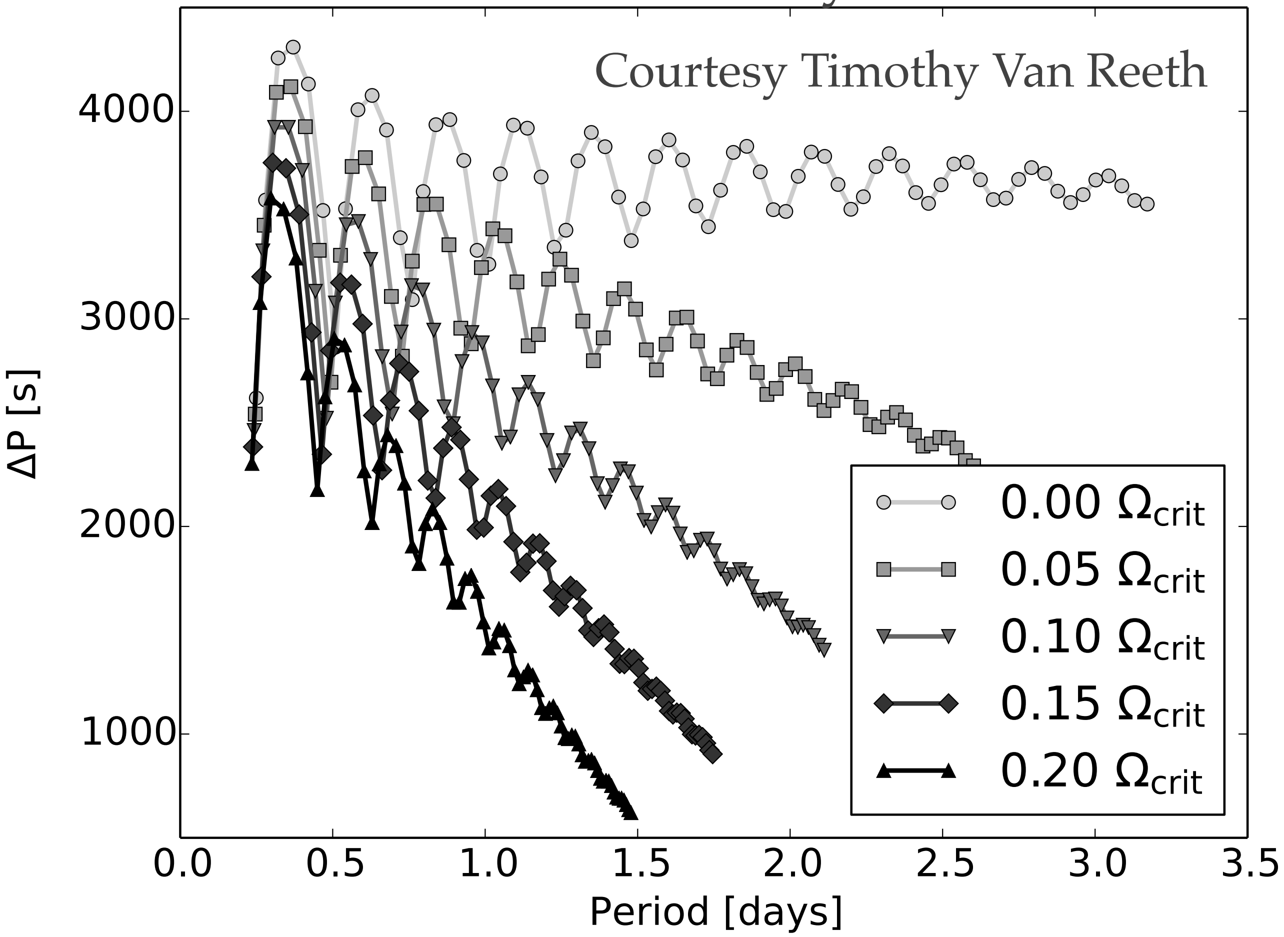
(Near-)Core rotation rate

Observations



Identification of (l,m)
& derivation of Ω_{core}

Theory



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

With(out) Coriolis acceleration

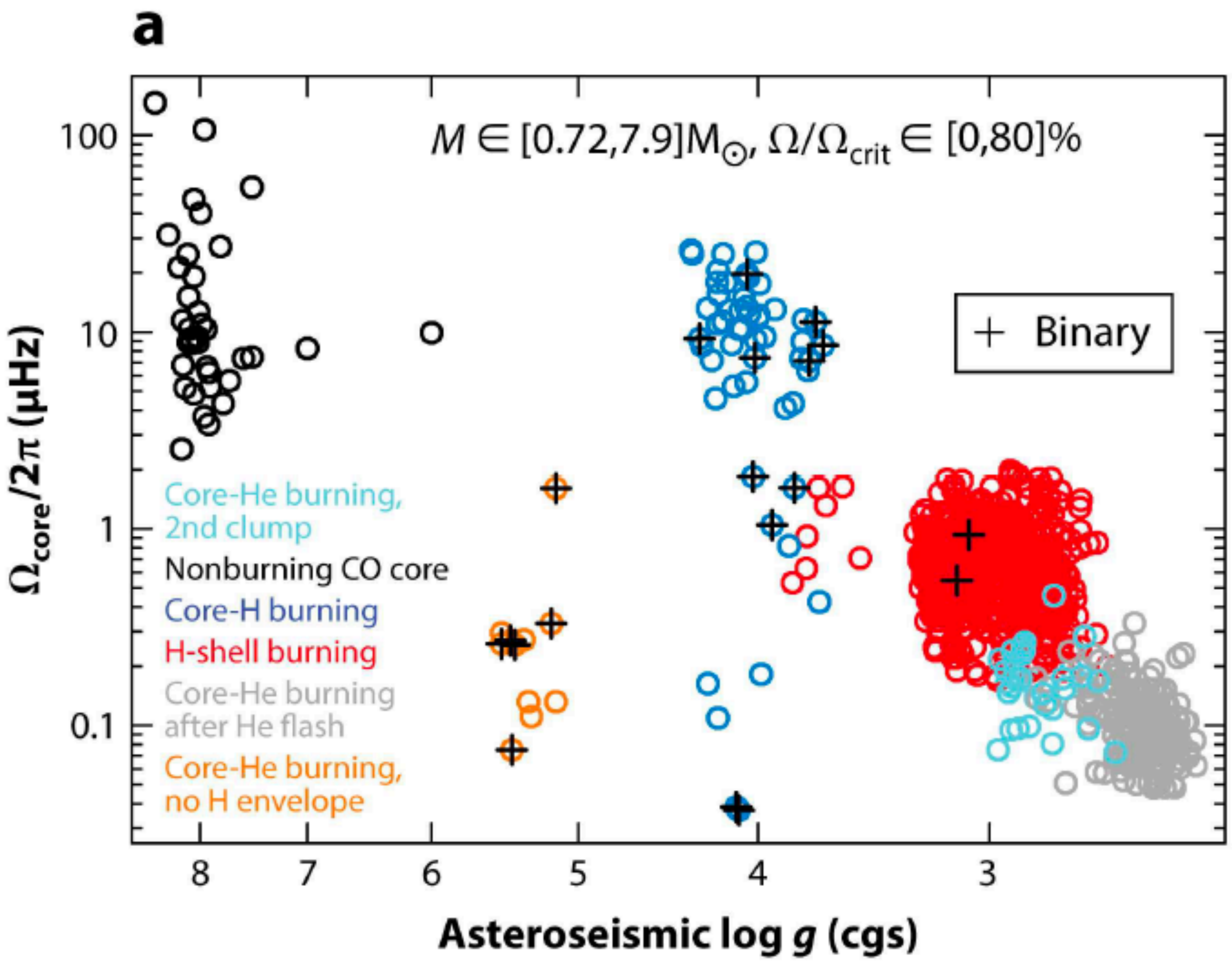
$$\Delta P^{\mathrm{co}}_{l,m,s} = \frac{\Pi_0}{\sqrt{\lambda_{lms}}}$$

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

depends on Ω

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

Asteroseismic estimates of Ω_{core}

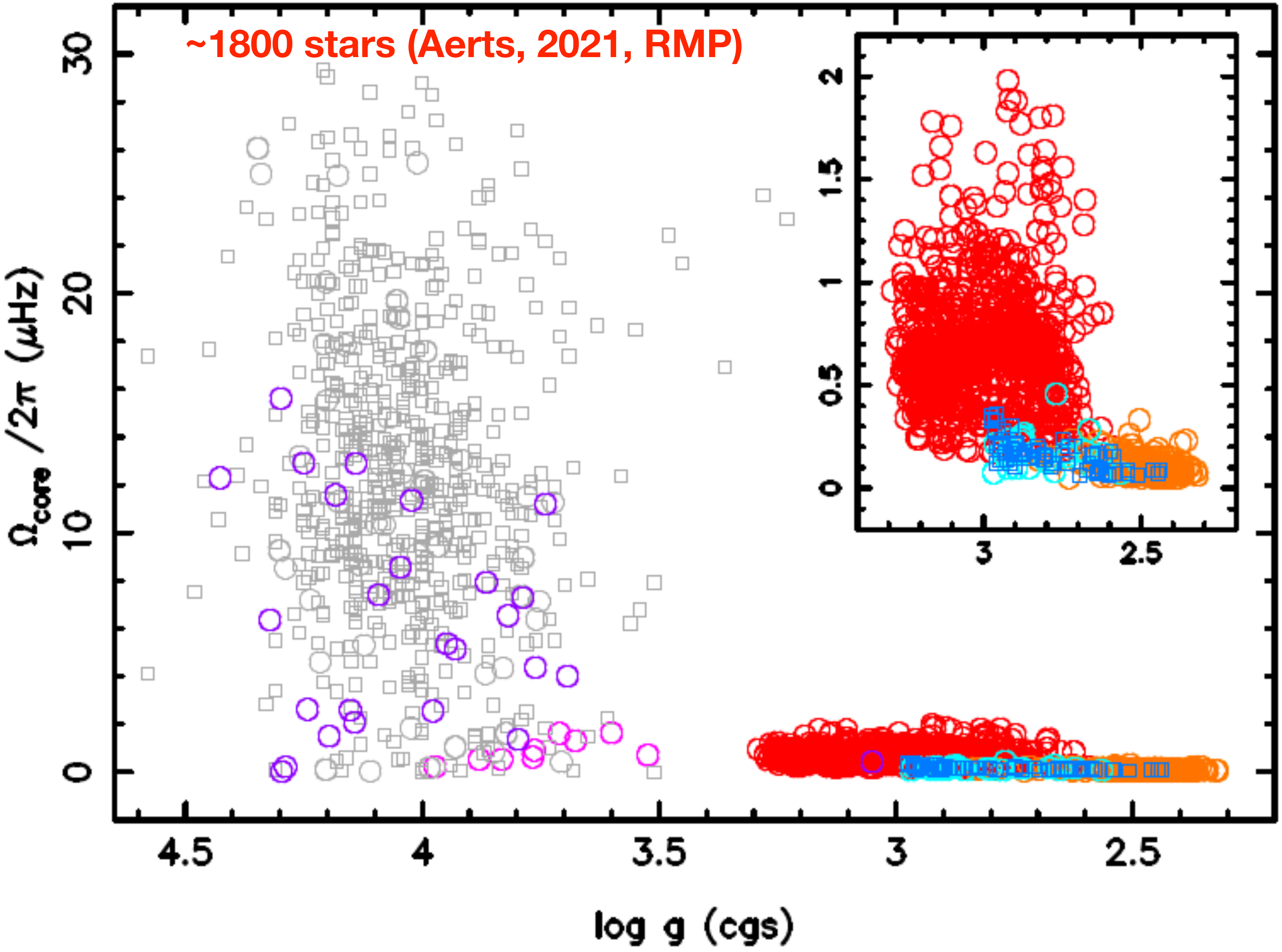


Aerts C, et al. 2019.
Annu. Rev. Astron. Astrophys. 57:35–78

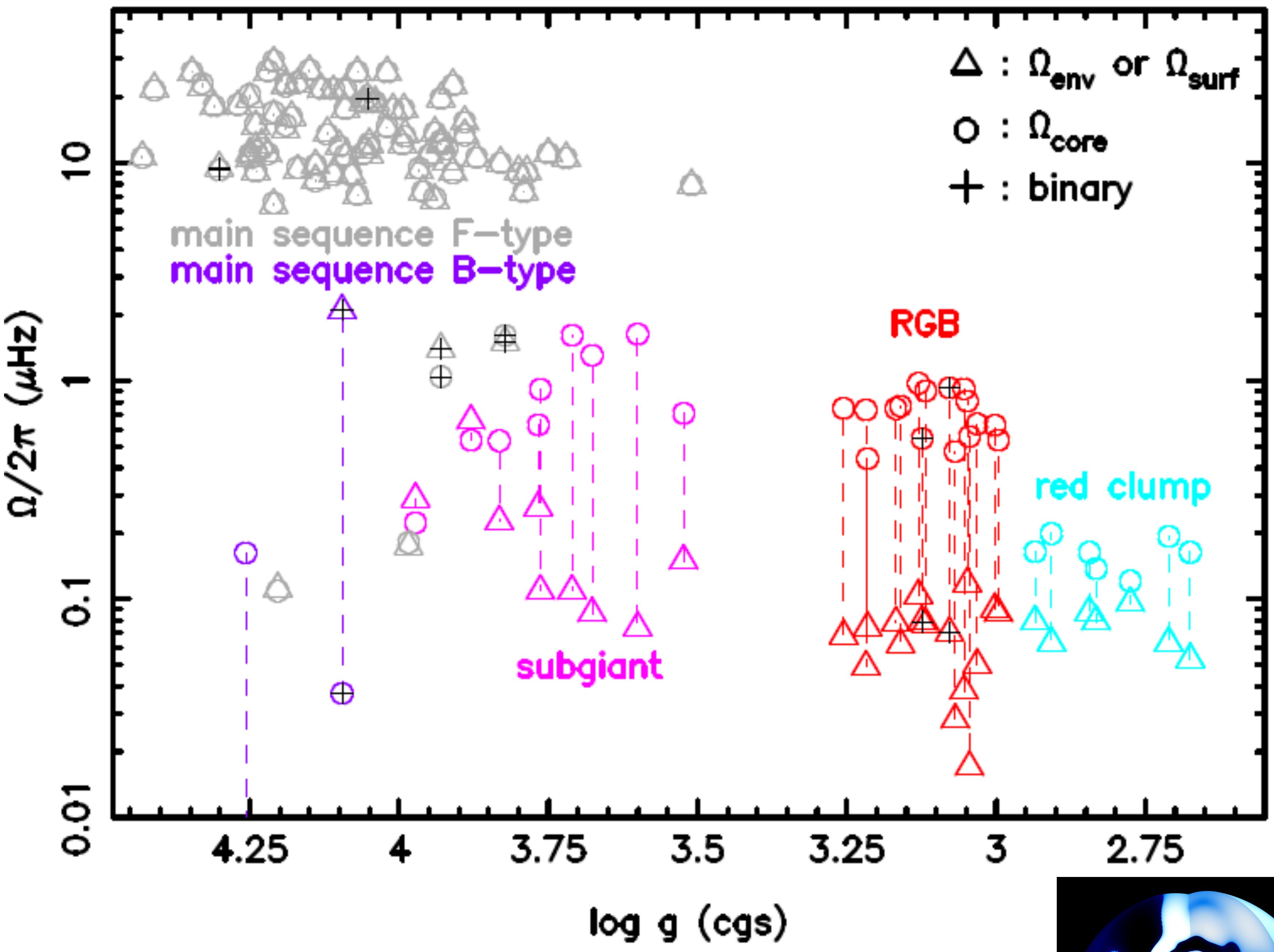
1210 stars

We cannot do this for the Sun…

Asteroseismic estimates of Ω_{core}



Measuring $\Omega_{\rm core}$ versus $\Omega_{\rm env}$



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

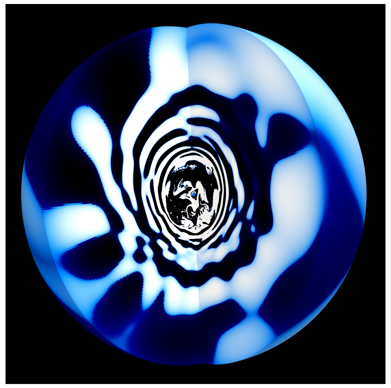
Stars rotate quasi-rigidly when having a convective core

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

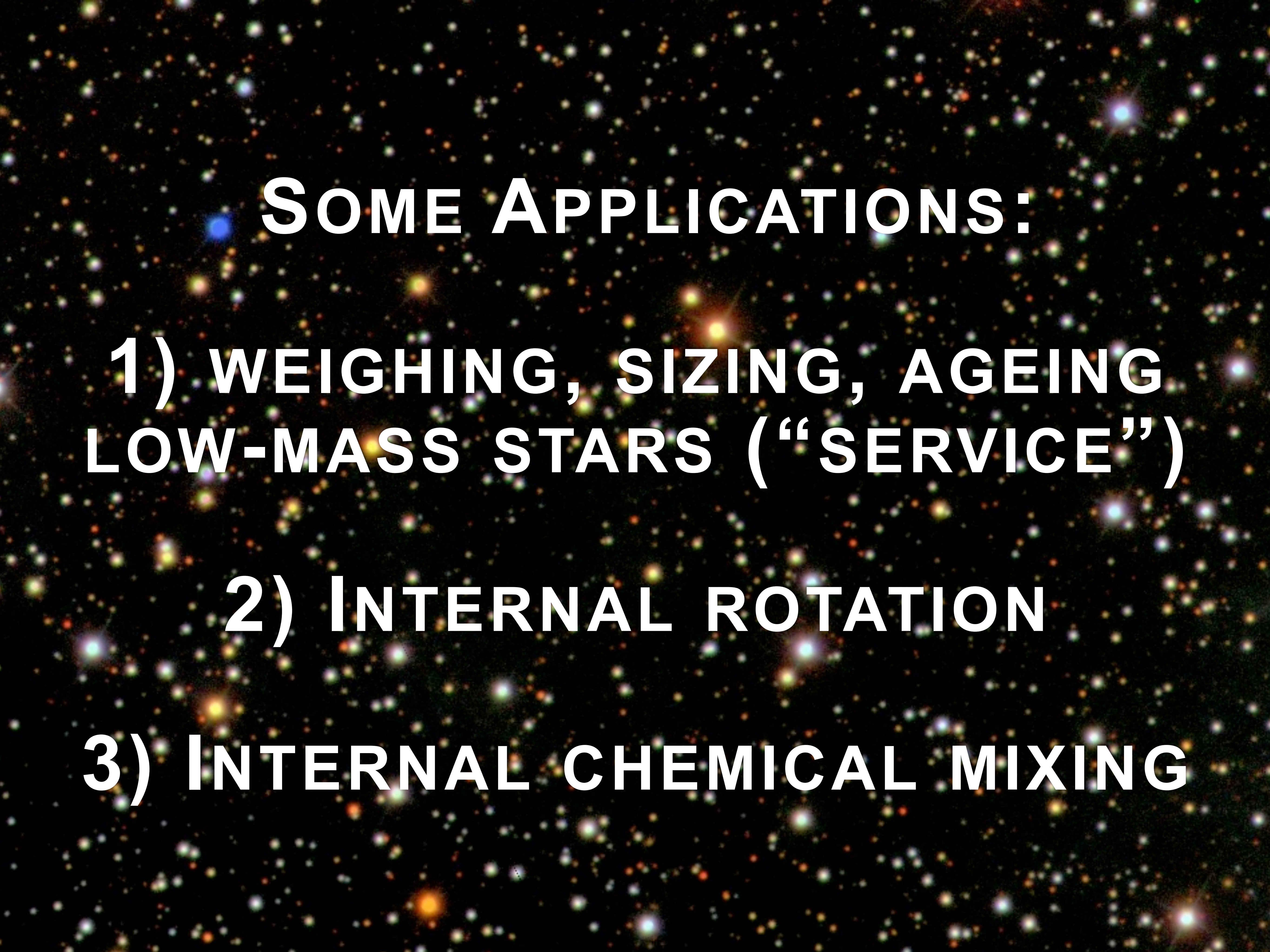
Magnetism/Tayler Instability:
Fuller et al. (2019), Takahashi & Langer (2020)

and/or

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



Courtesy: Philipp Edelmann



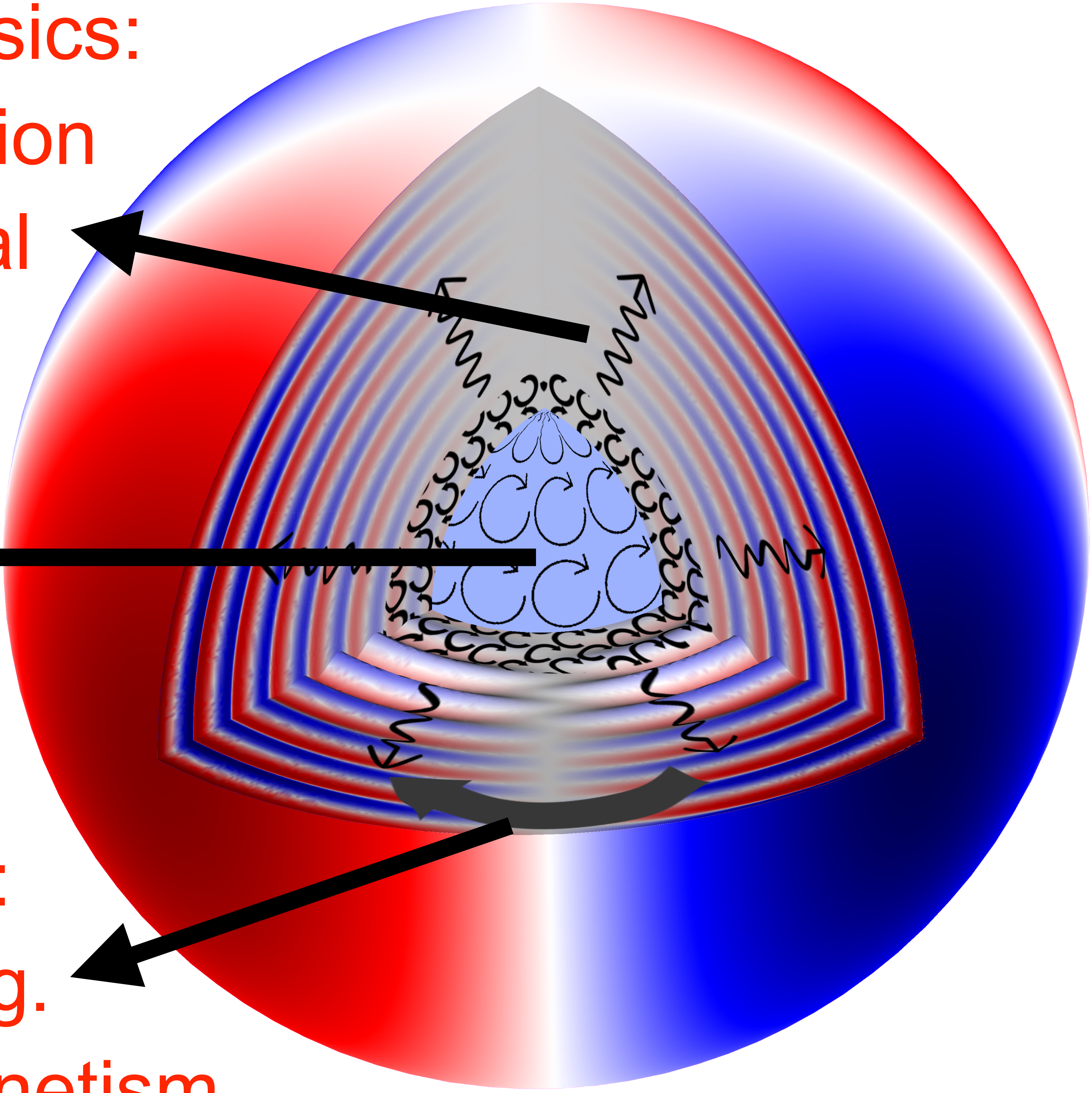
Some Applications:

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

2) Internal rotation

3) Internal chemical mixing

Chemical evolution

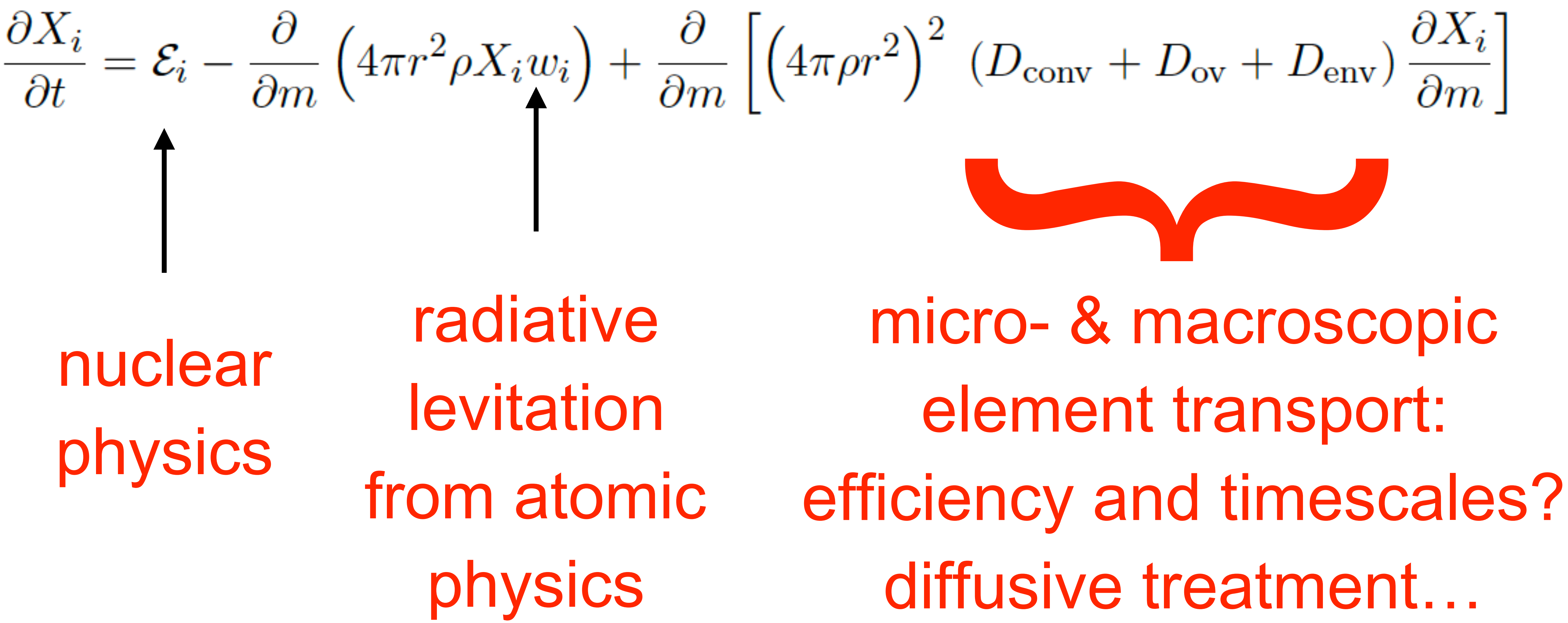


microscopic physics:
radiative levitation
& gravitational
settling

nuclear
burning

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

Chemical evolution inside star



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

nuclear physics

radiative levitation from atomic physics

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

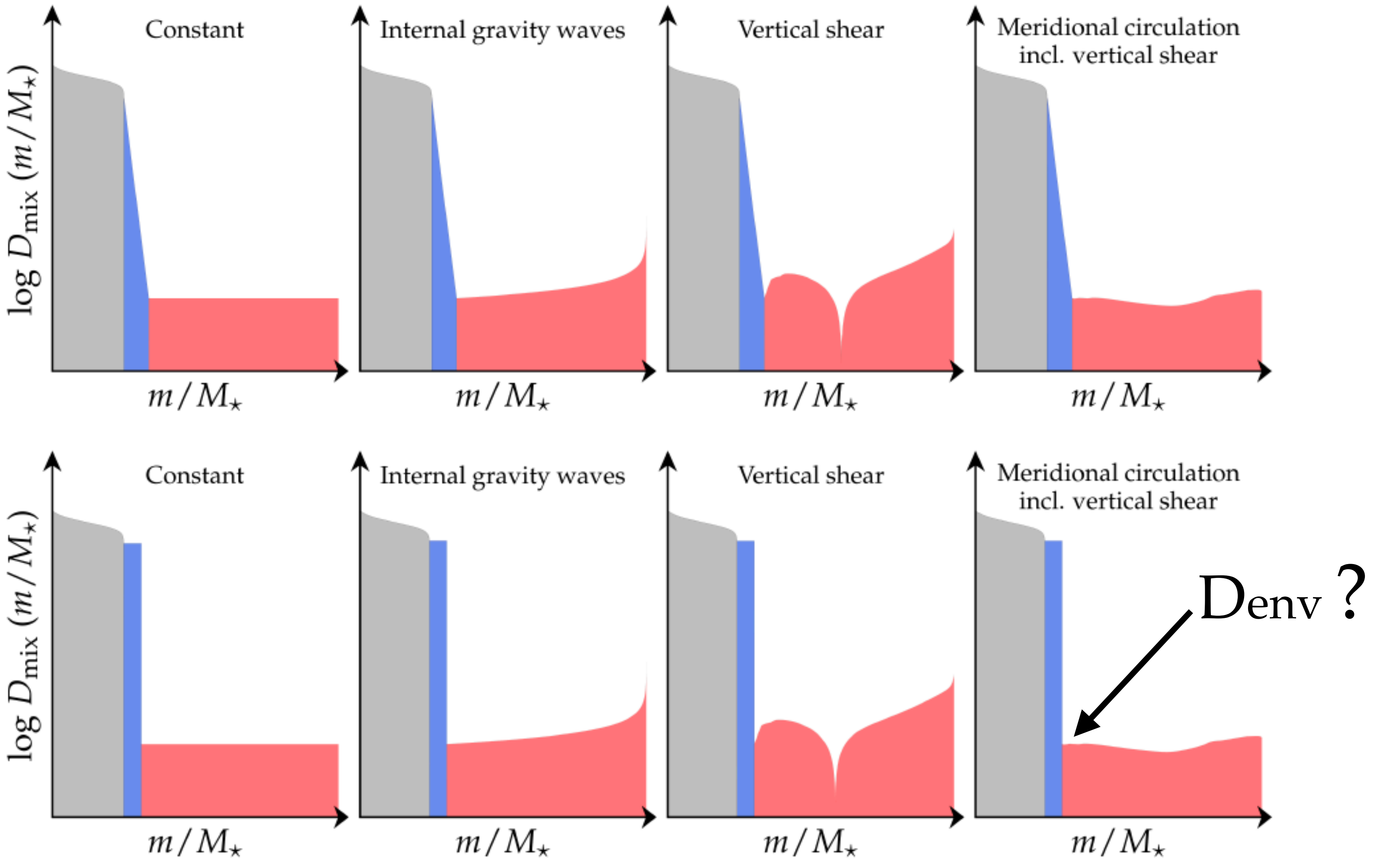
Element mixing: largest unknown in stellar evolution; of vast importance for chemical yields in stars with convective core

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

Courtesy:
May Gade Pedersen

Deduced for sample of 26 SPB stars by Pedersen et al., 2021, under embargo

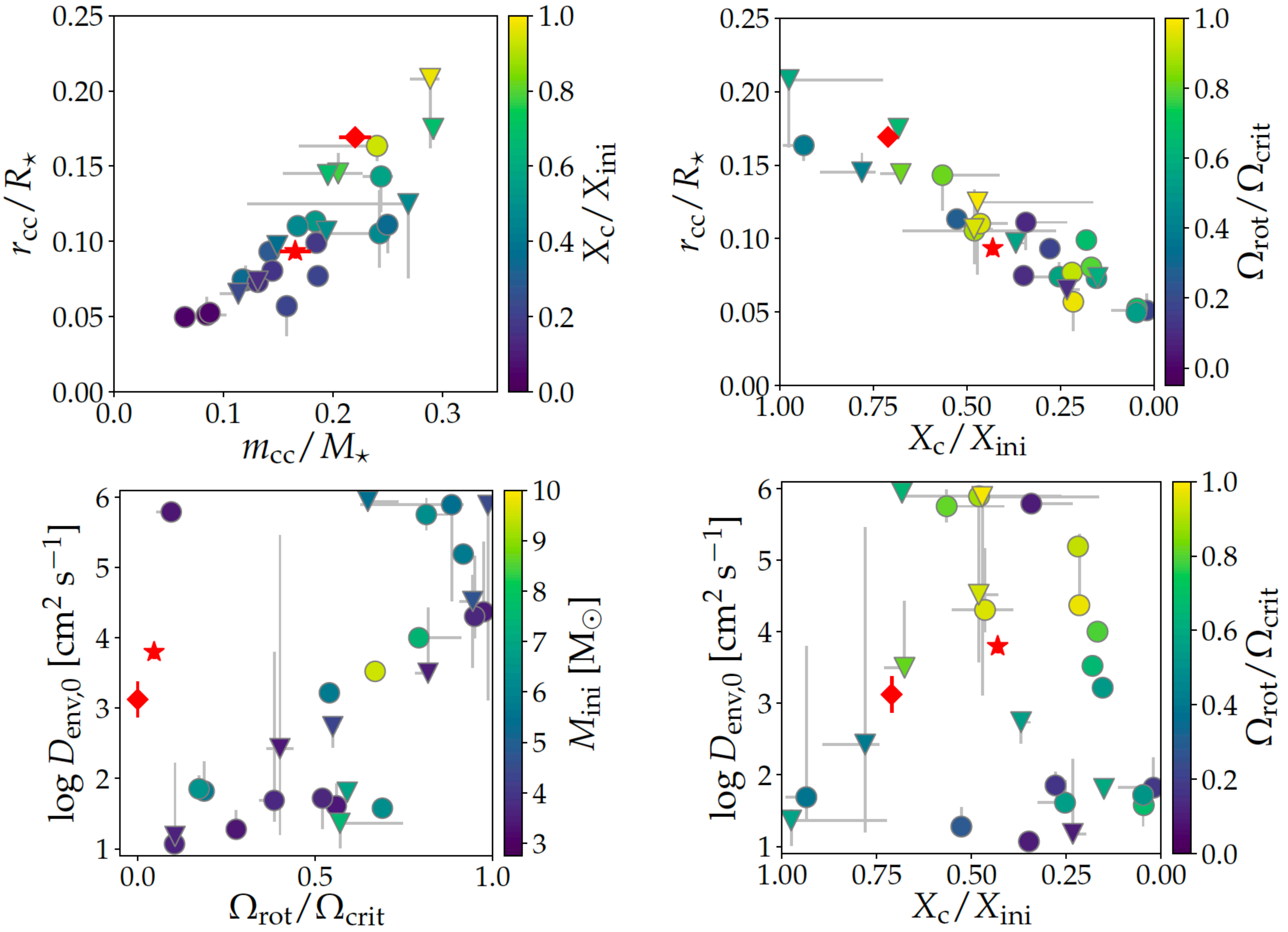
Summary in Aerts (2021)



D_{env} ?

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	$[3.3, 8.9]\,M_\odot$	$[6, 29]\,\%$	$[3, 96]\,\%$	$[12, 8.7\times10^5]\,\mathrm{cm^2\,s^{-1}}$

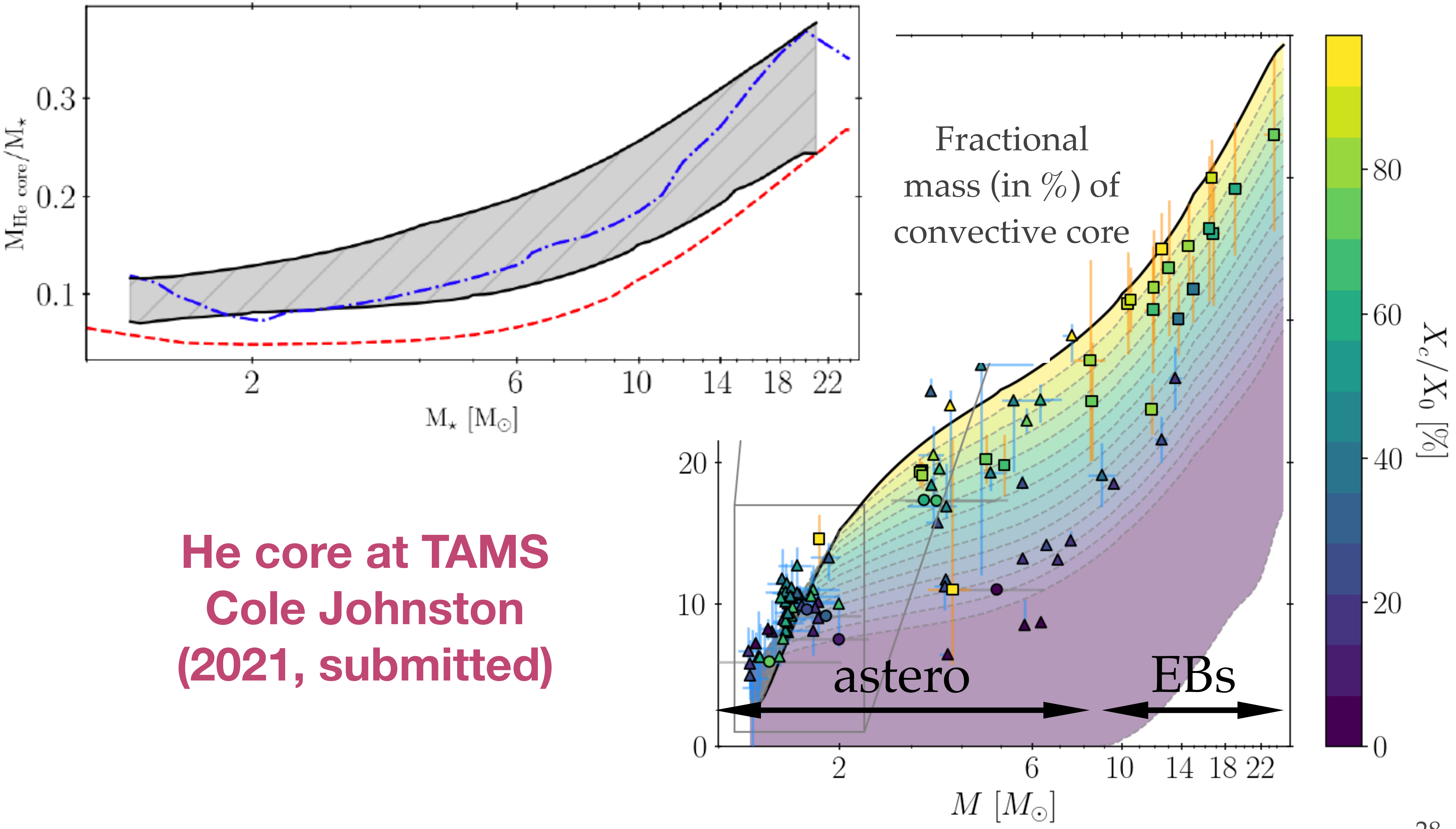
Stellar evolution in action



Combined asteroseismology, astrometry, and spectroscopy of a sample of SPB stars (Pedersen et al. 2020, 2021 under embargo)

Asteroseismic & EB Core Masses

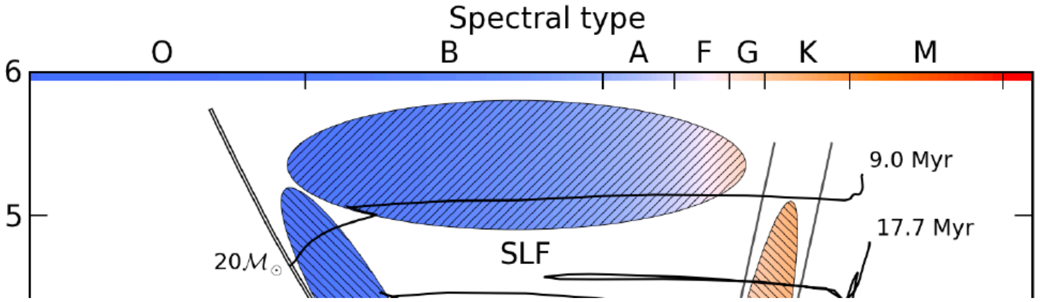
Figures Courtesy: Cole Johnston

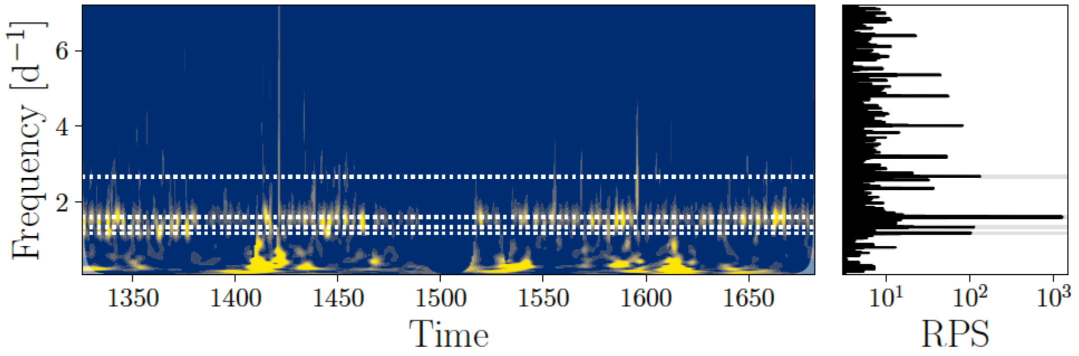


He core at TAMS
Cole Johnston
(2021, submitted)

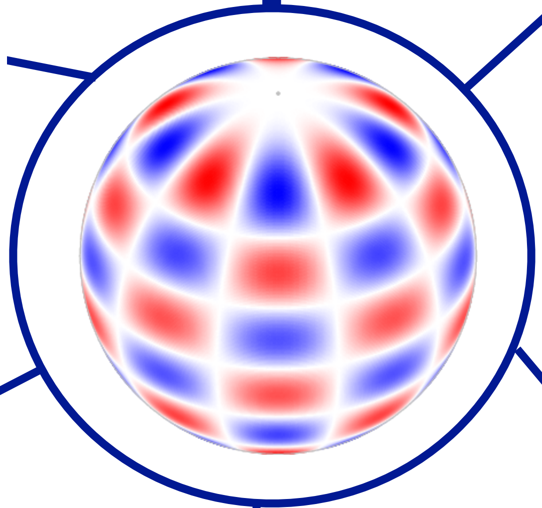
Ongoing TESS/Gaia/Spectroscopic Surveys

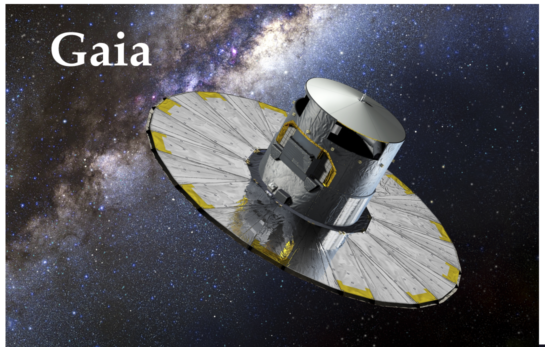
(Pedersen et al. 2019;Bowman et al. 2019, 2020; Dorn-Wallenstein et al. 2020)

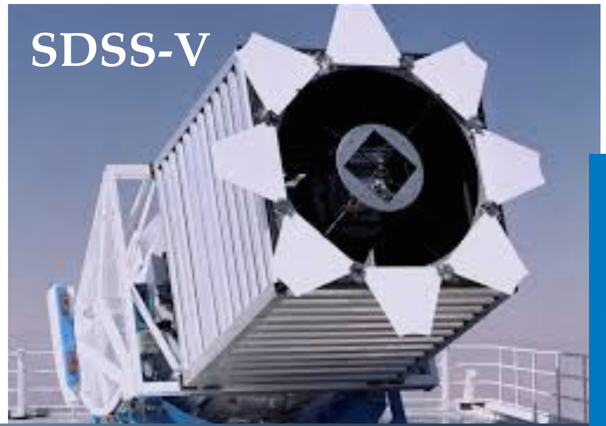




Onward to high mass & evolved BSG (incl. LMC)







Onward to PLATO (2026+)

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

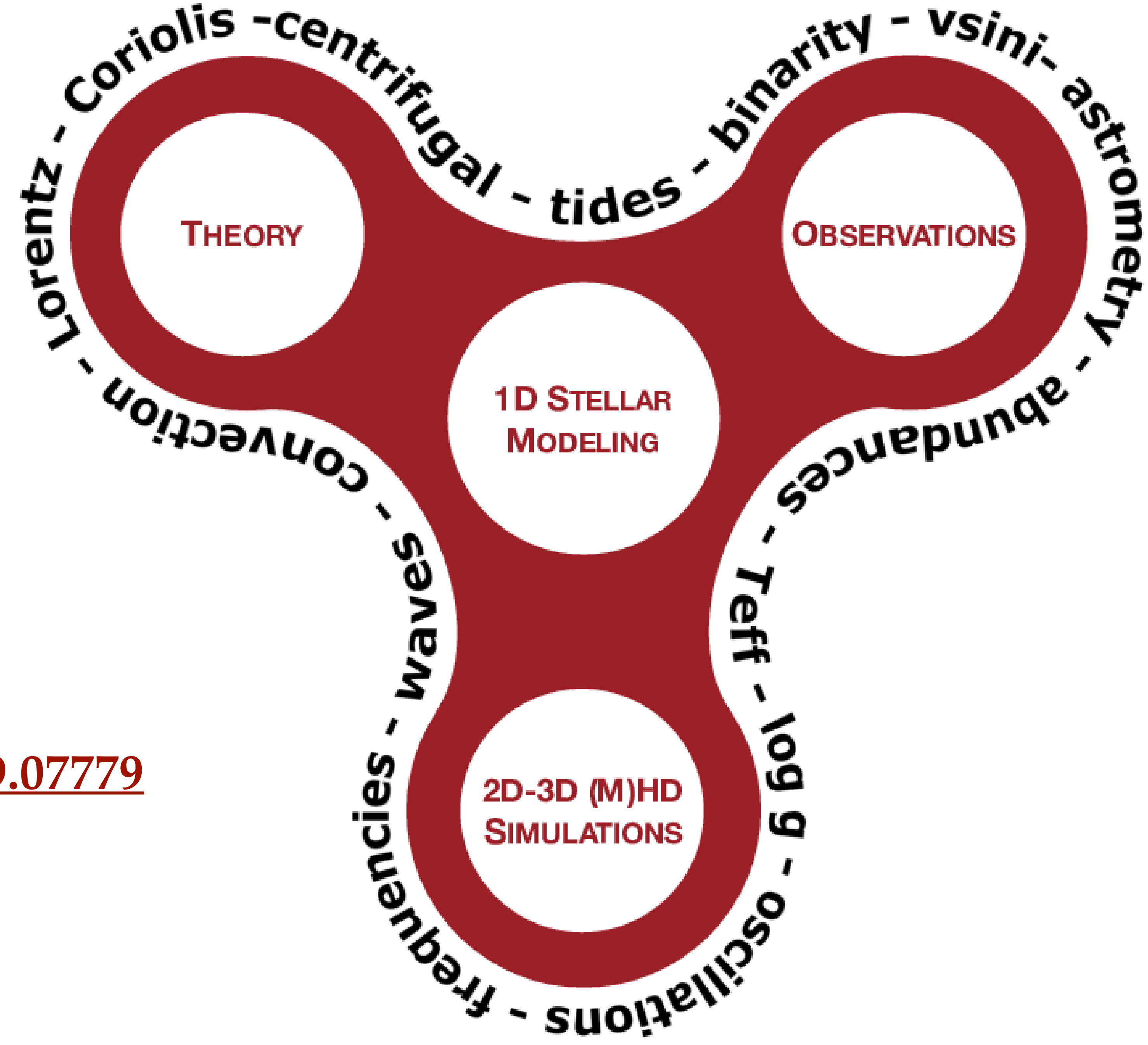


Figure courtesy:
Aerts, Mathis, Rogers,
2019: ARAA, 57, 35,
https://arxiv.org/abs/1809.07779

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