

ASTEROSEISMOLOGY: THE ROYAL ROAD TOWARDS THE INTERNAL PHYSICS OF STARS

Conny Aerts

<https://fys.kuleuven.be/ster/staff/conny-aerts>

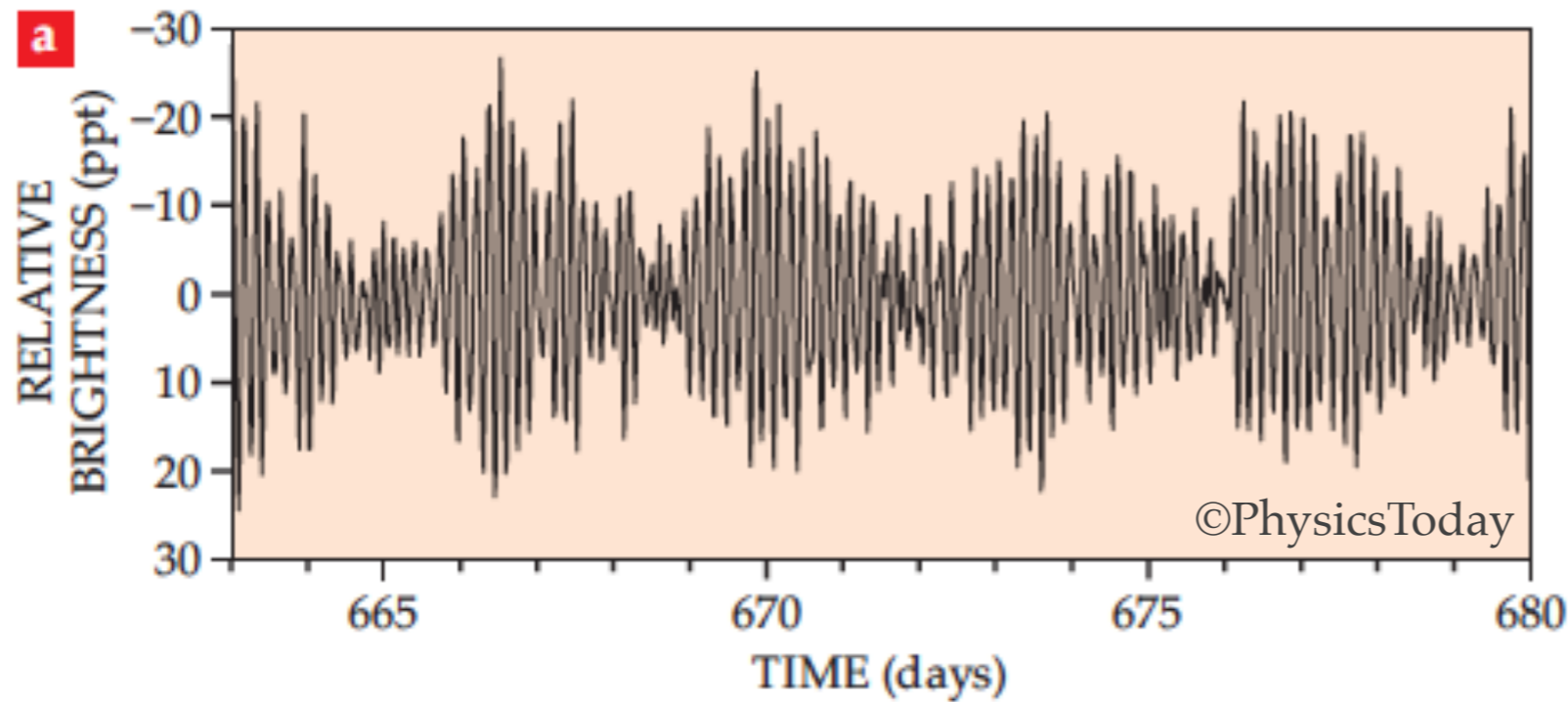
Brussels, 18 June 2021

MAMSIE
MAMSIE

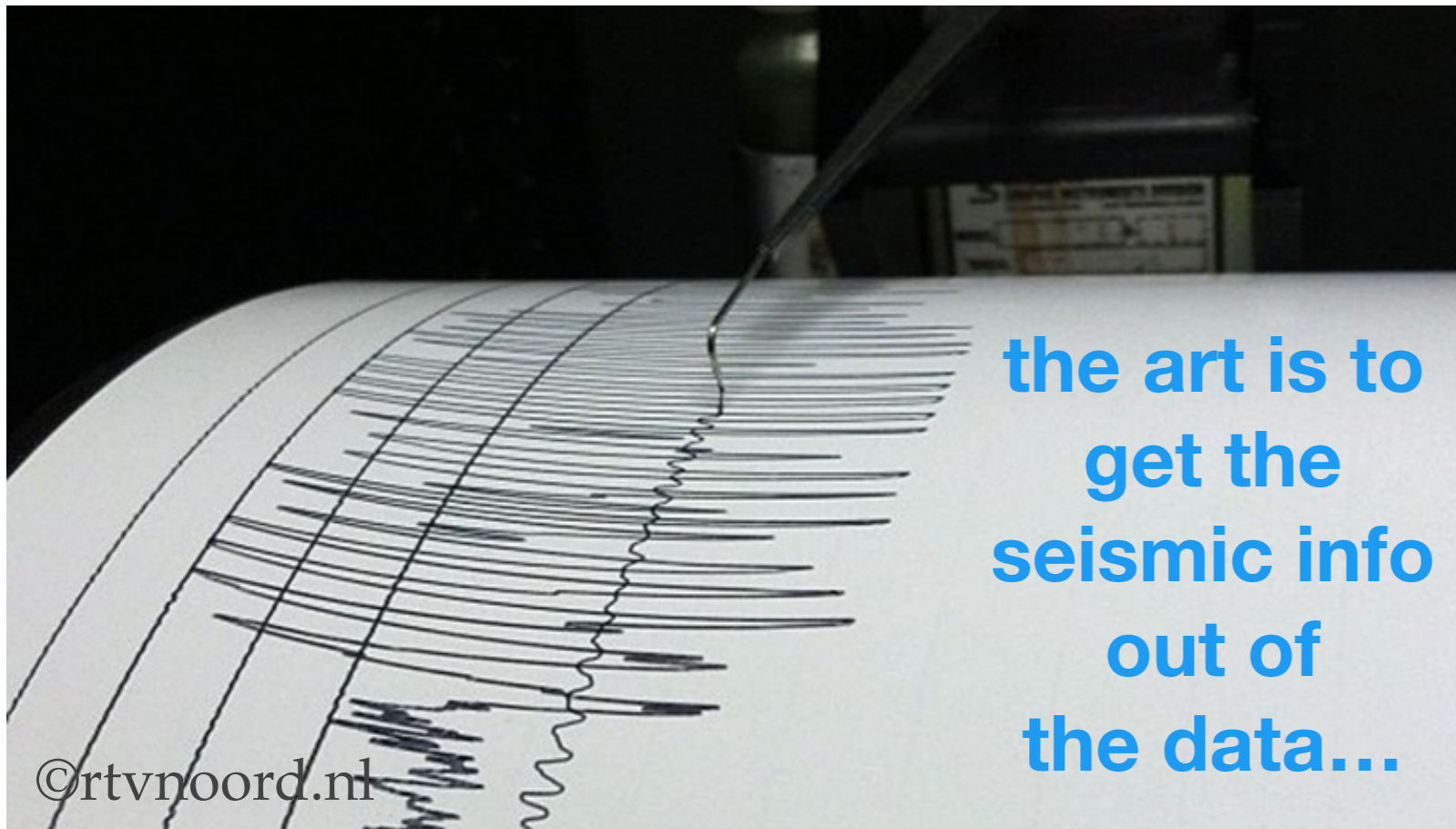


KU LEUVEN

Take-home message



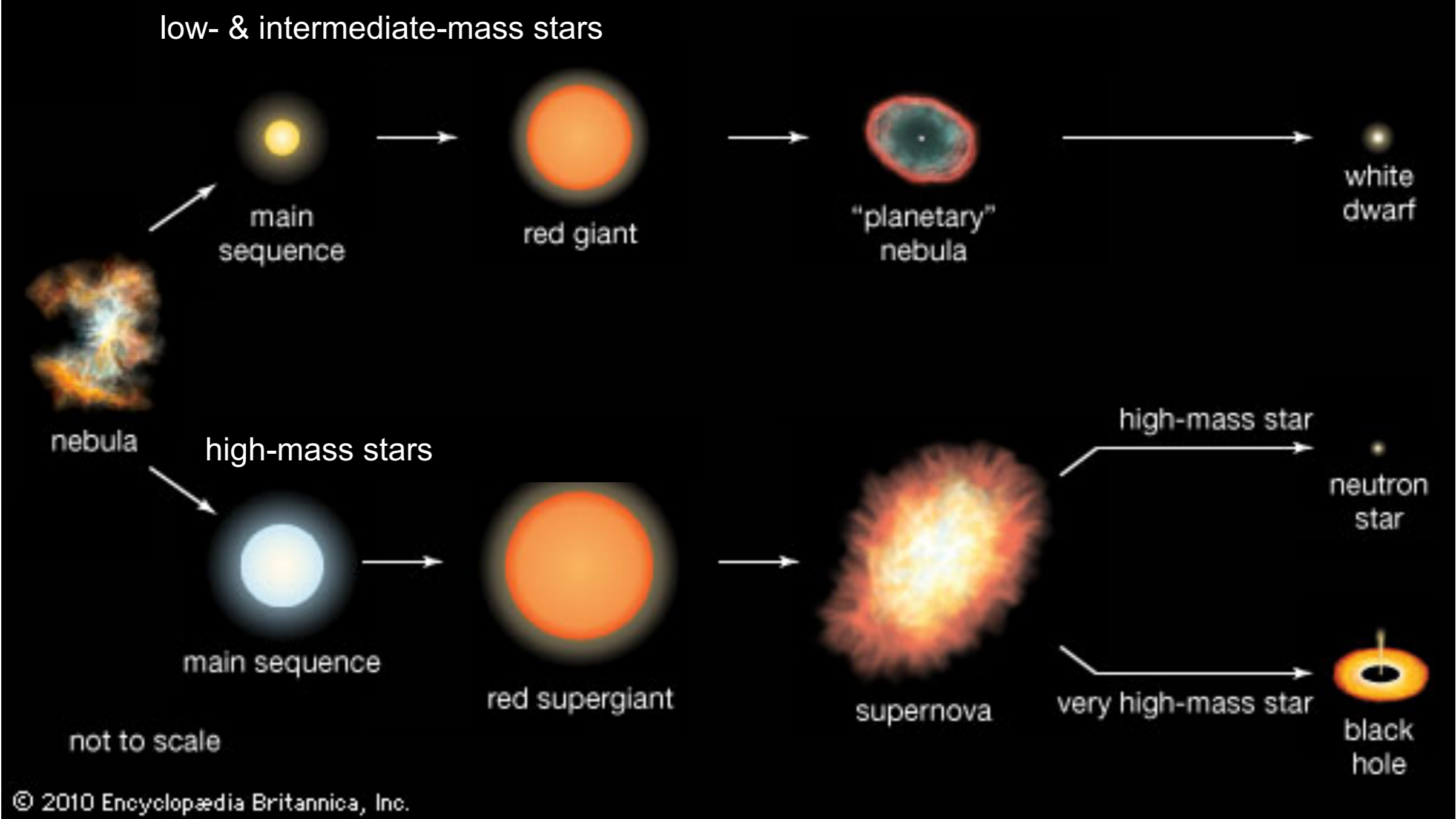
Seismic waves offer *in-situ* measurements of internal stellar physics: new look upon stars



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

How Do Stars Live?

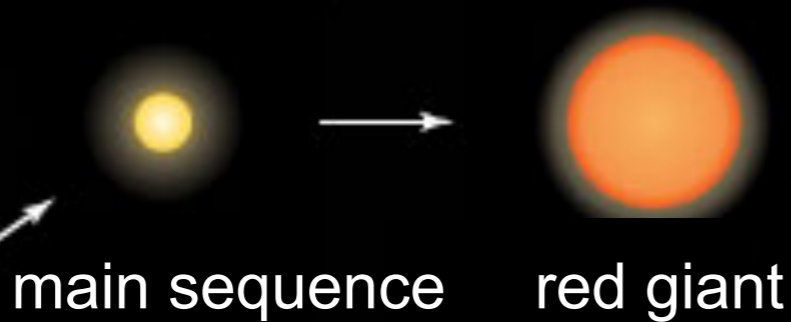
Stars: building blocks of galaxies & exoplanetary systems



Stellar interiors: poorly known

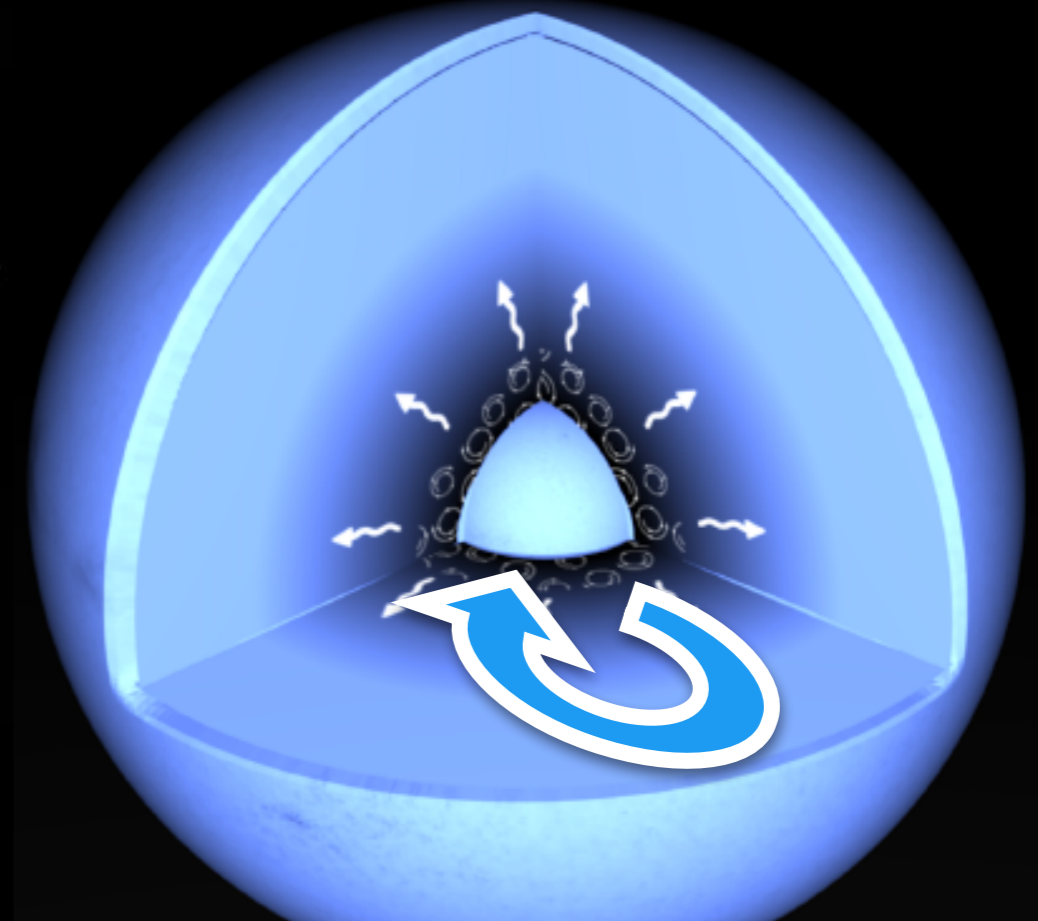
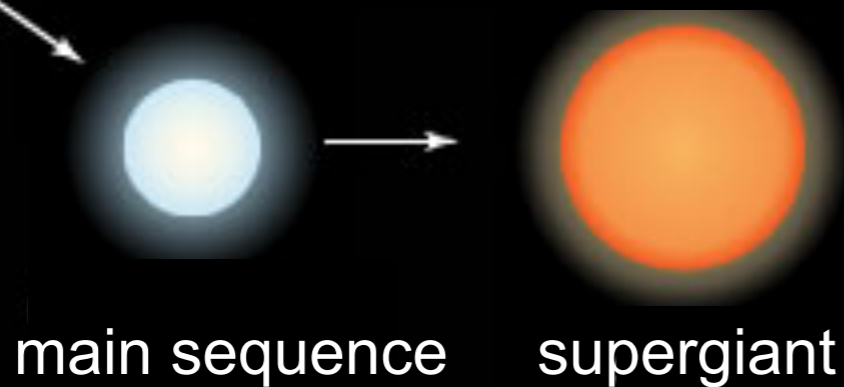
Rotation? Convection? Mixing? Magnetism?

low- & intermediate-mass stars



99% of nuclear life

high-mass stars

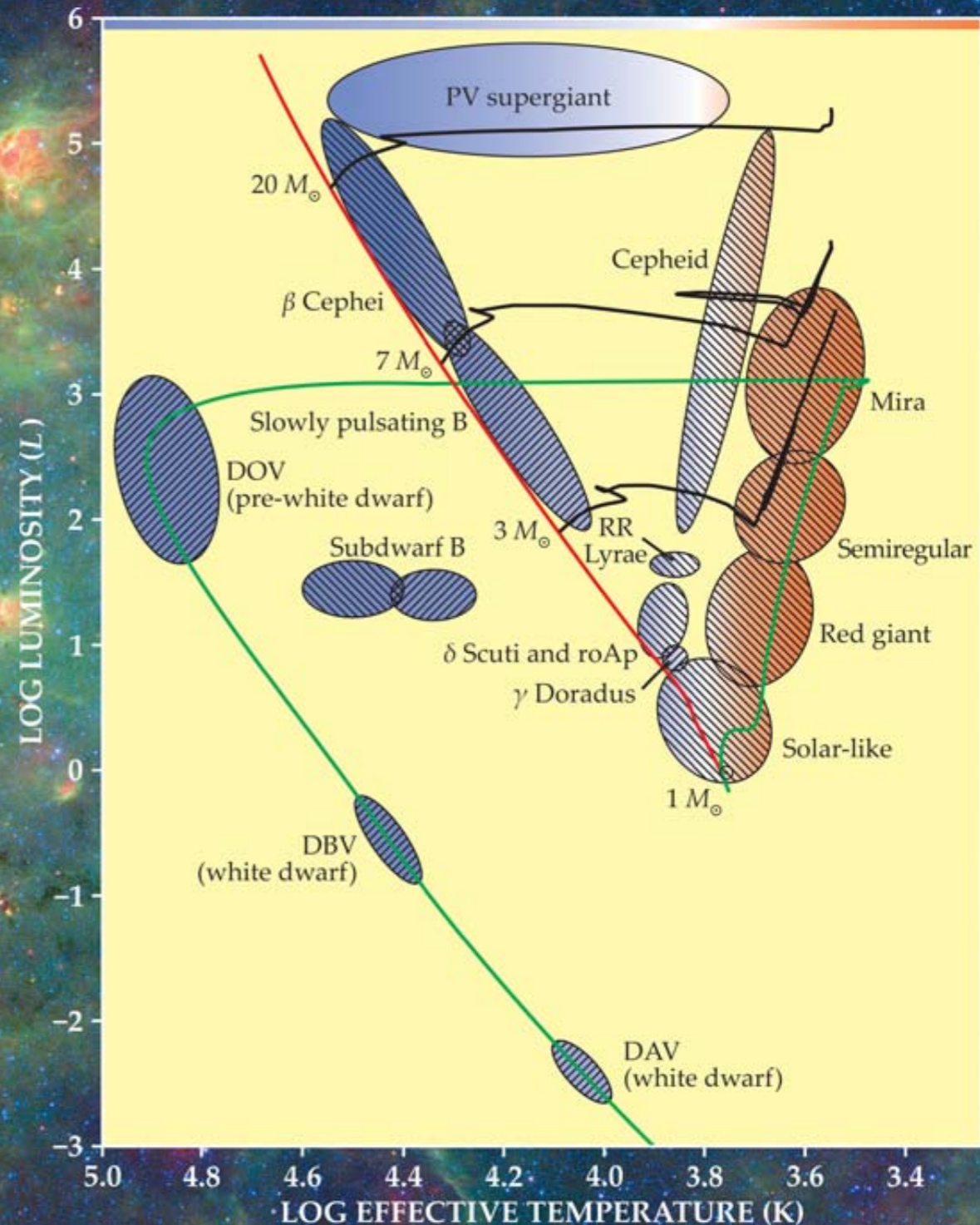


Life determined by uncalibrated interior physics

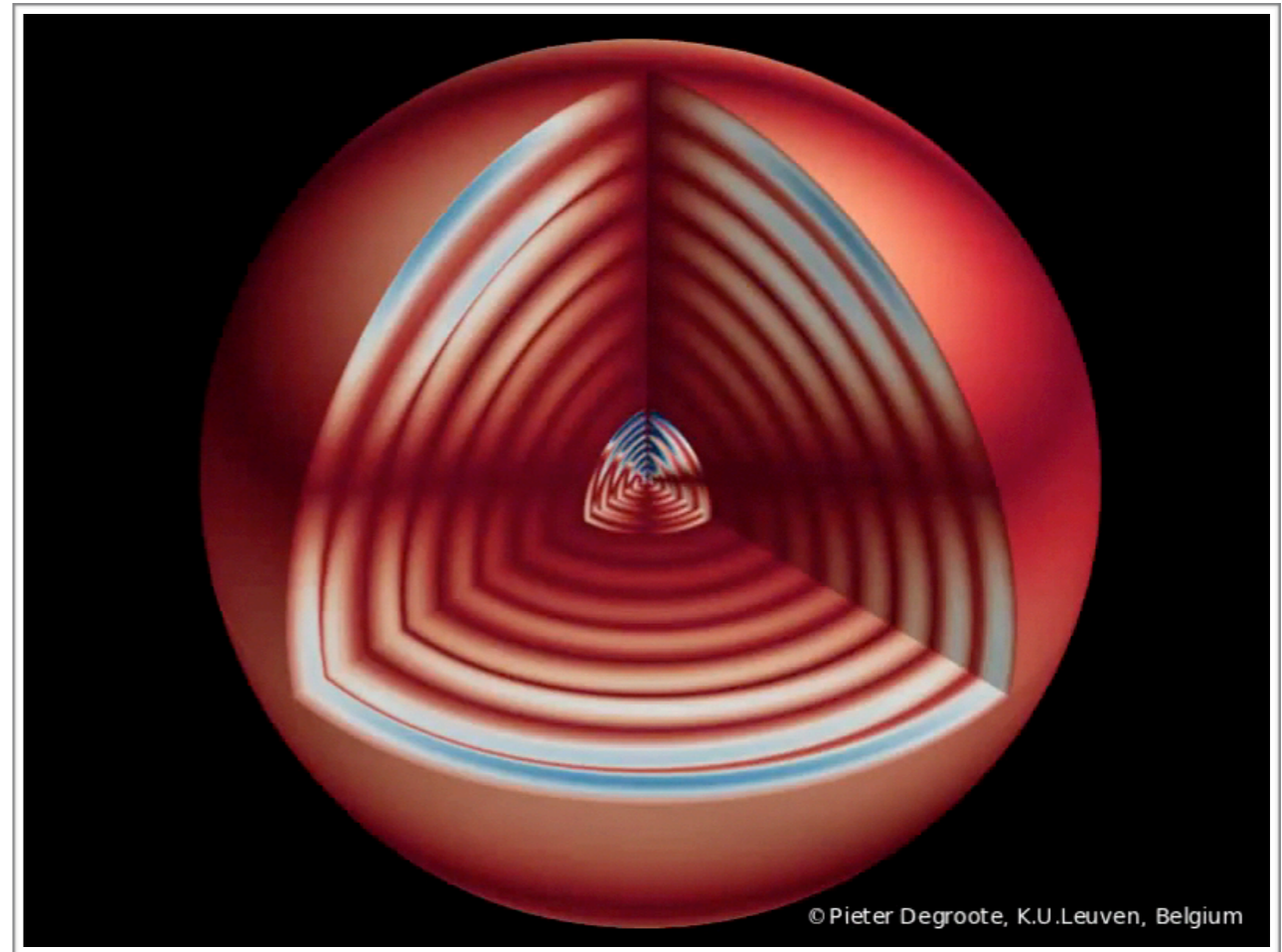
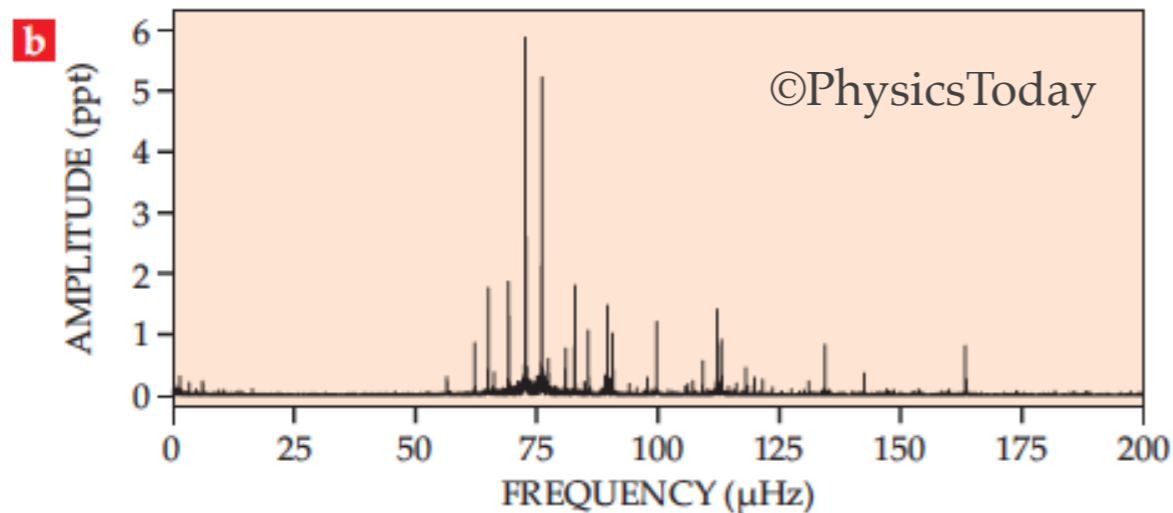
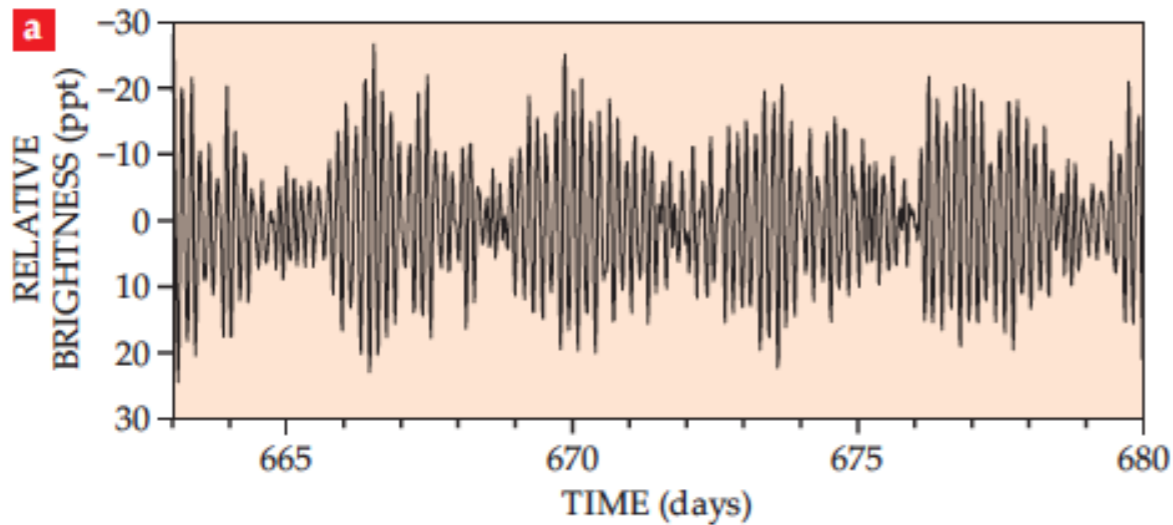
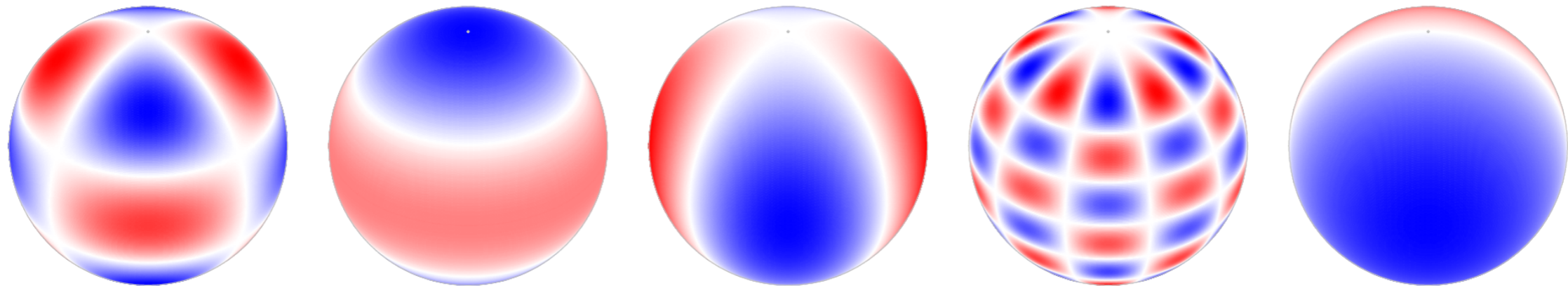
Stellar evolution is dictated by *stellar interior*

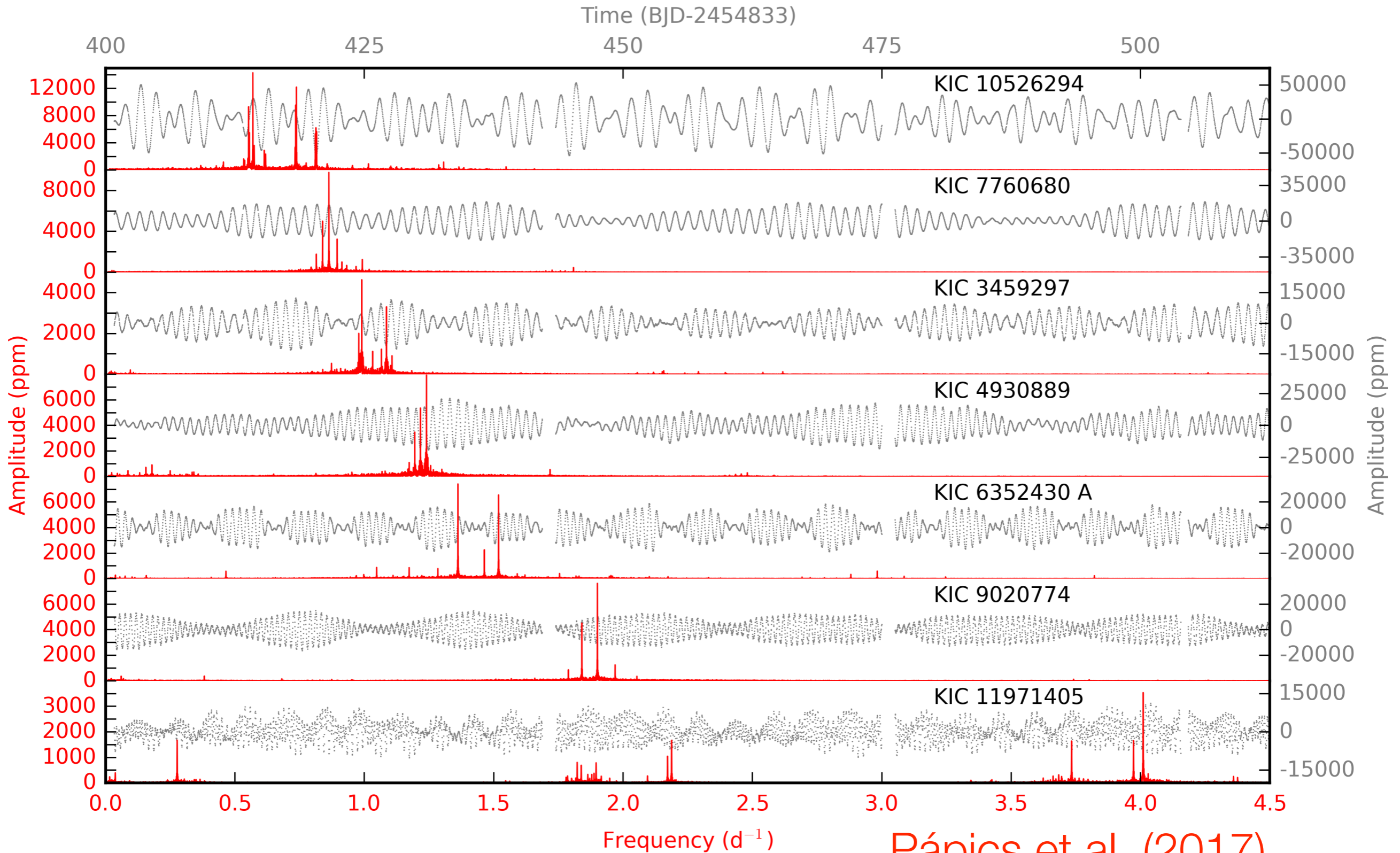
Asteroseismology to the rescue: requires *long-term uninterrupted high-precision data*

From C. Aerts, Physics Today, 2015



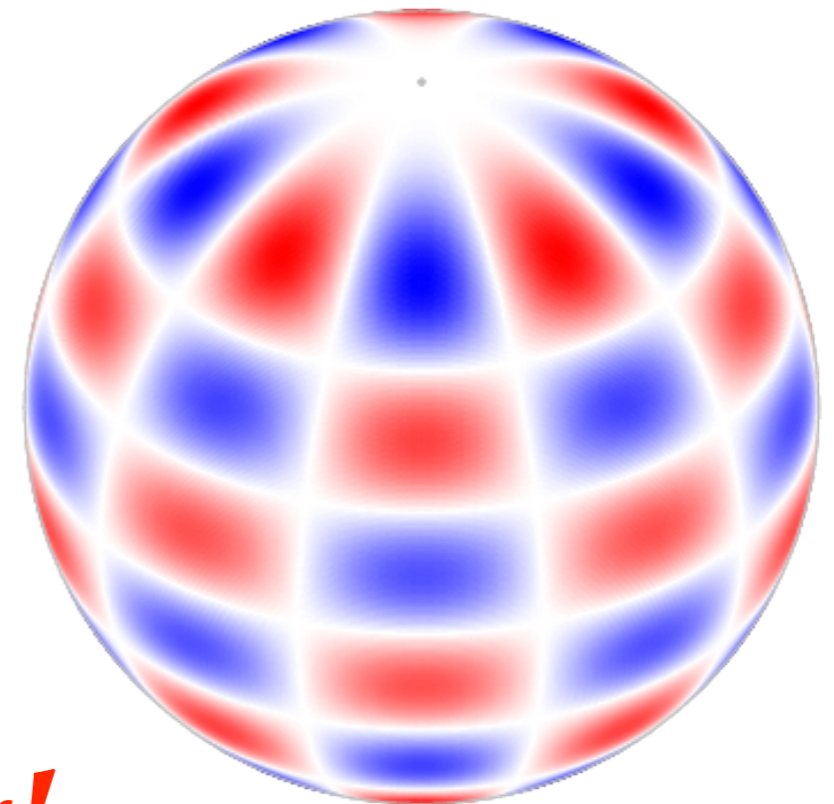
Stellar oscillations probe stellar interiors





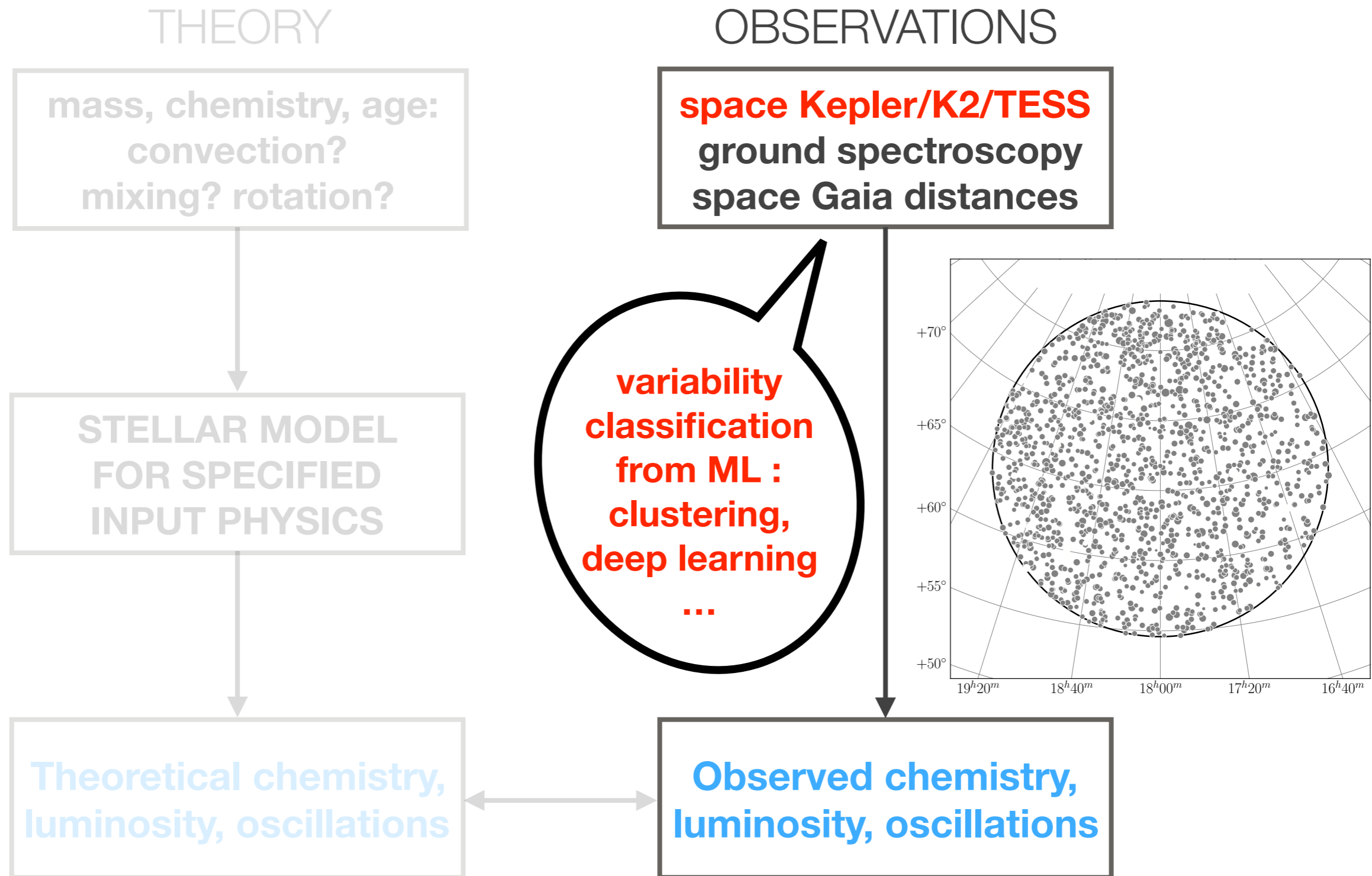
Pápics et al. (2017)

- **Periodic perturbations of equations of physics:**
oscillations are the eigenmodes of the star
- **Each mode described by spherical harmonic & frequency:**
- **Dominance of acting forces?**
 1. **pressure (acoustic waves)**
 2. **buoyancy (gravity waves)**
 3. **Coriolis (inertial waves)**
 4. **Lorentz (Alfvén waves)**
 5. **tidal (tidal waves)**

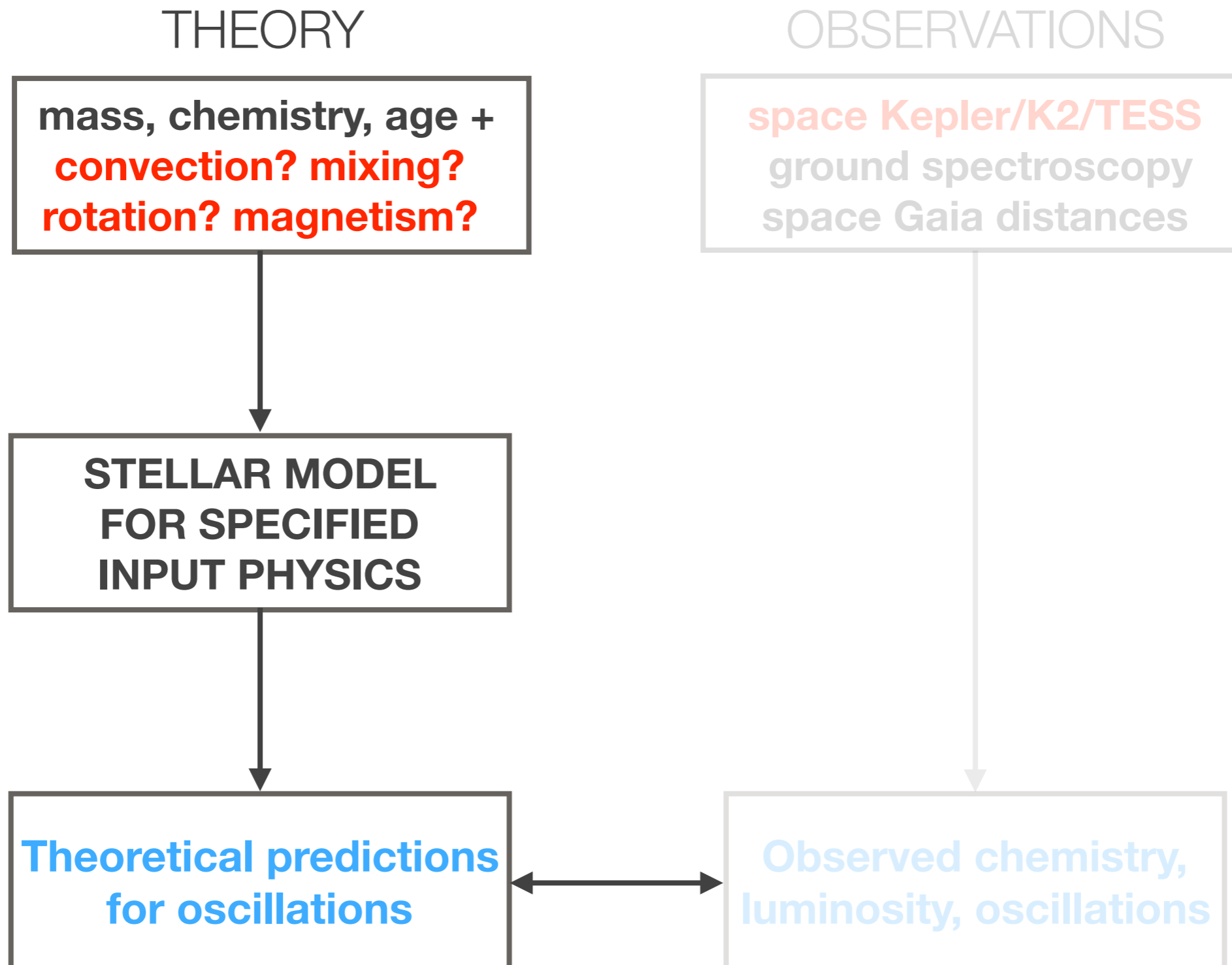


Kepler!

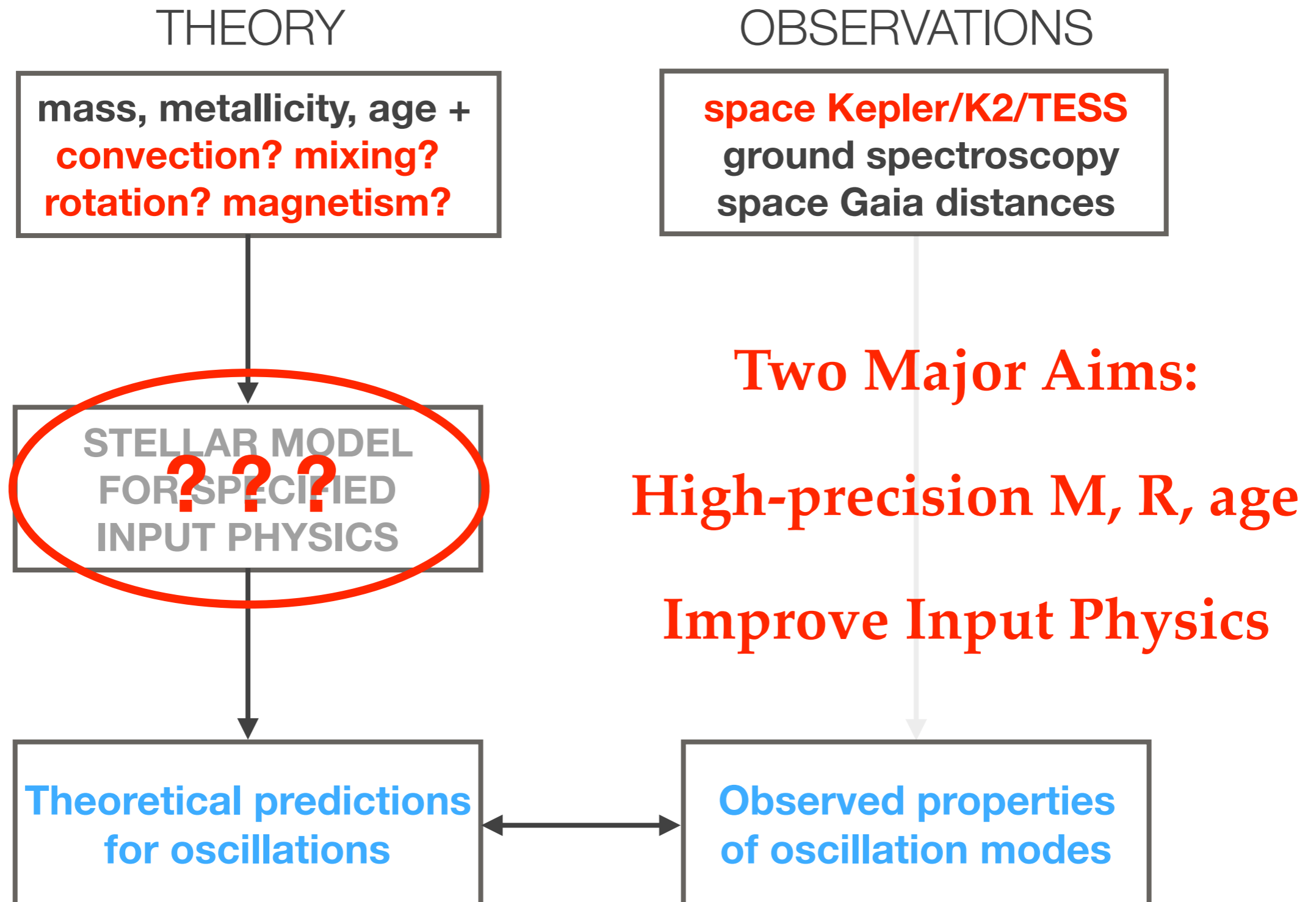
Data-driven modelling



Theoretical predictions



Aims of Asteroseismology

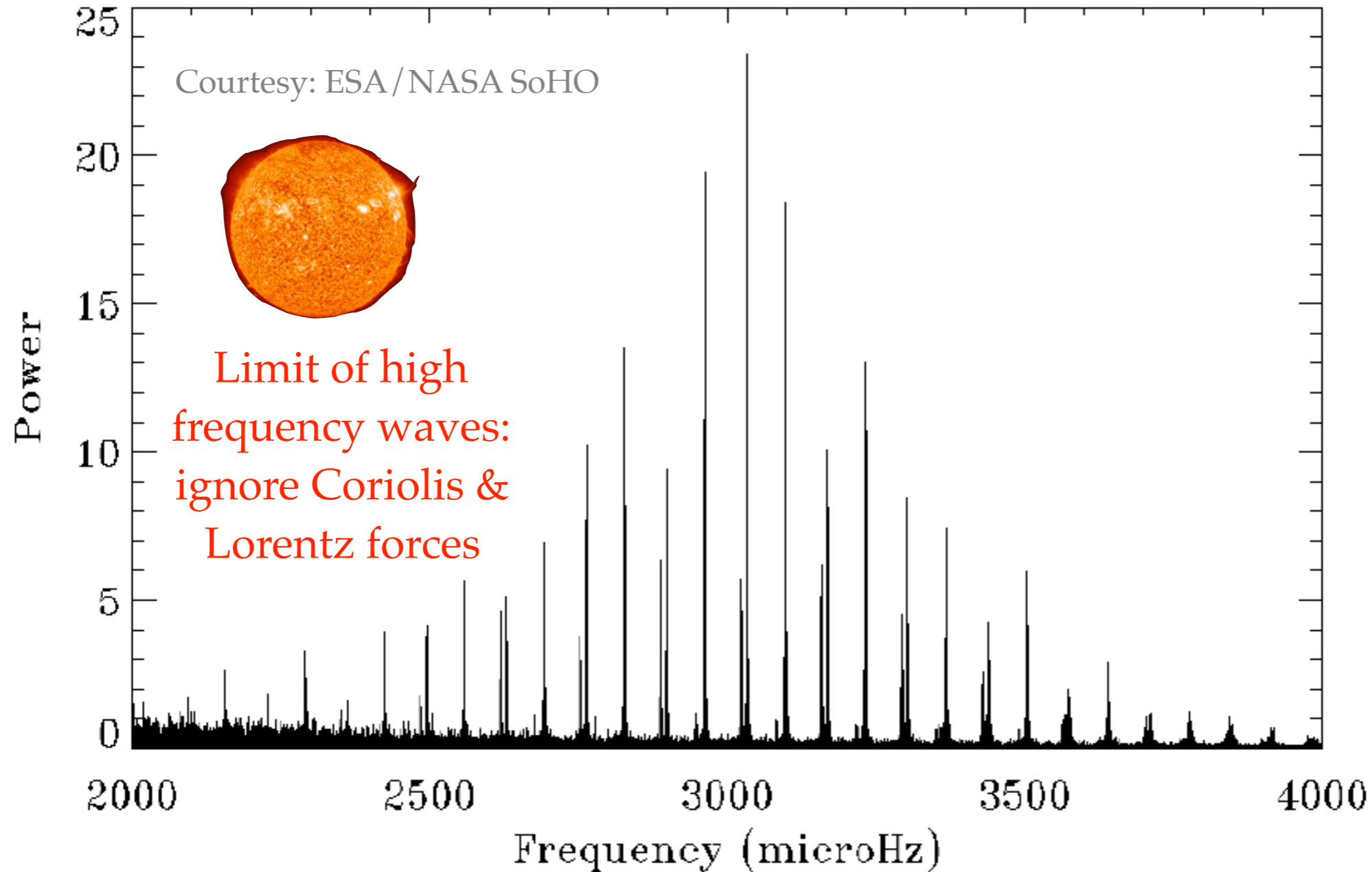


SOME APPLICATIONS:

**1) WEIGHING, SIZING, AGEING
OF STARS**

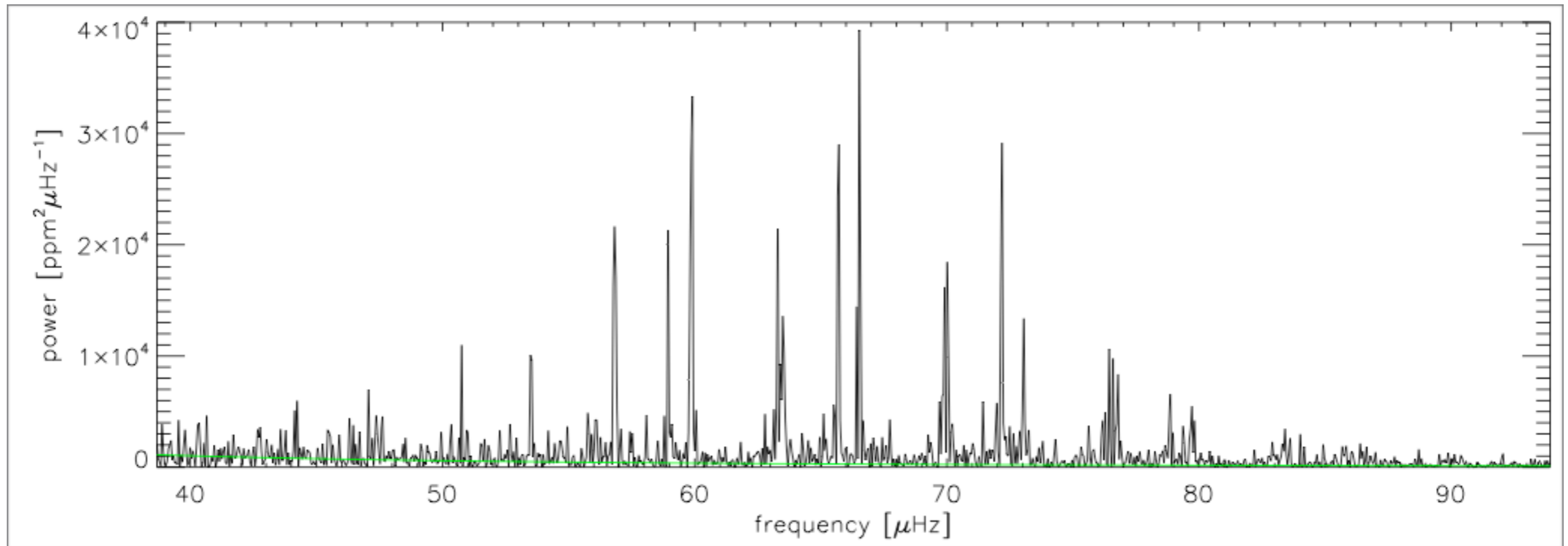
**2) INTERNAL ROTATION
OF STARS**

Helioseismology paved the way



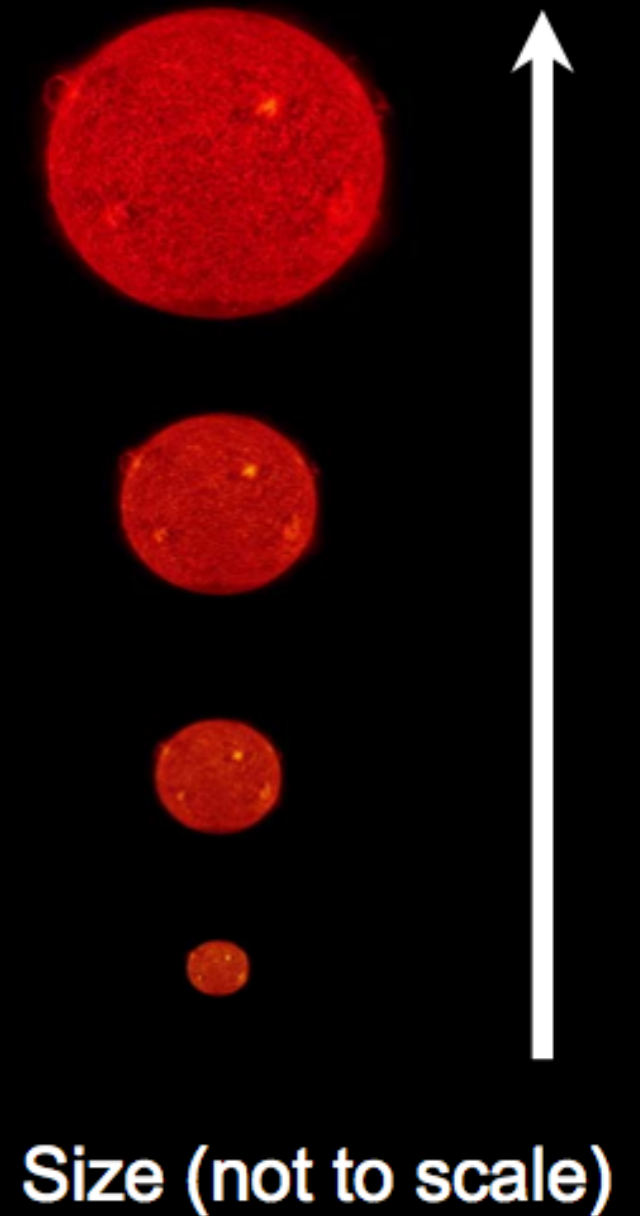
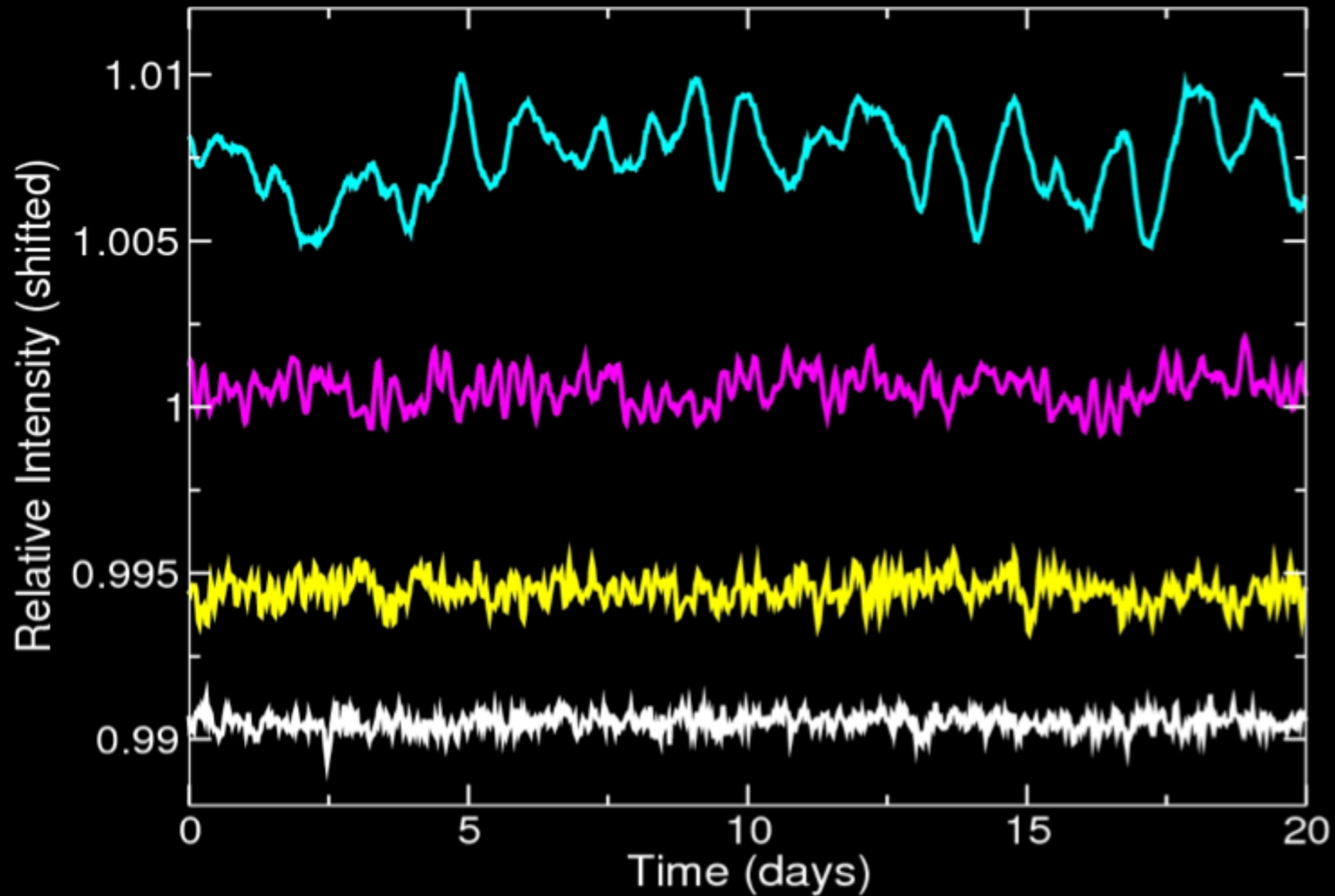
(Christensen-Dalsgaard, 2002, Reviews of Modern Physics)

Courtesy: NASA Kepler

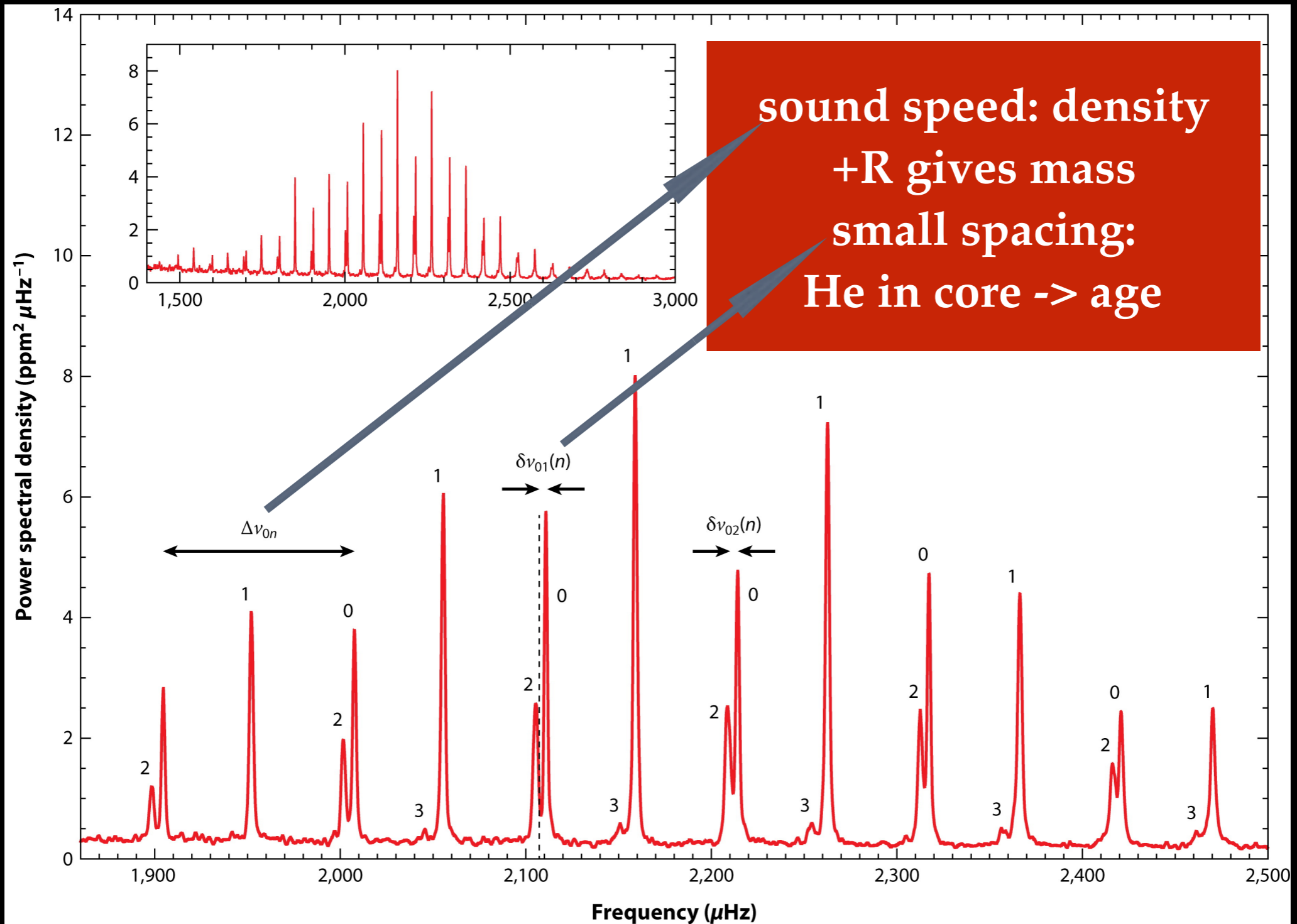


(Hekker & Christensen-Dalsgaard, 2017, *Astronomy & Astrophysics Review*)

Sizing stars to 1% precision



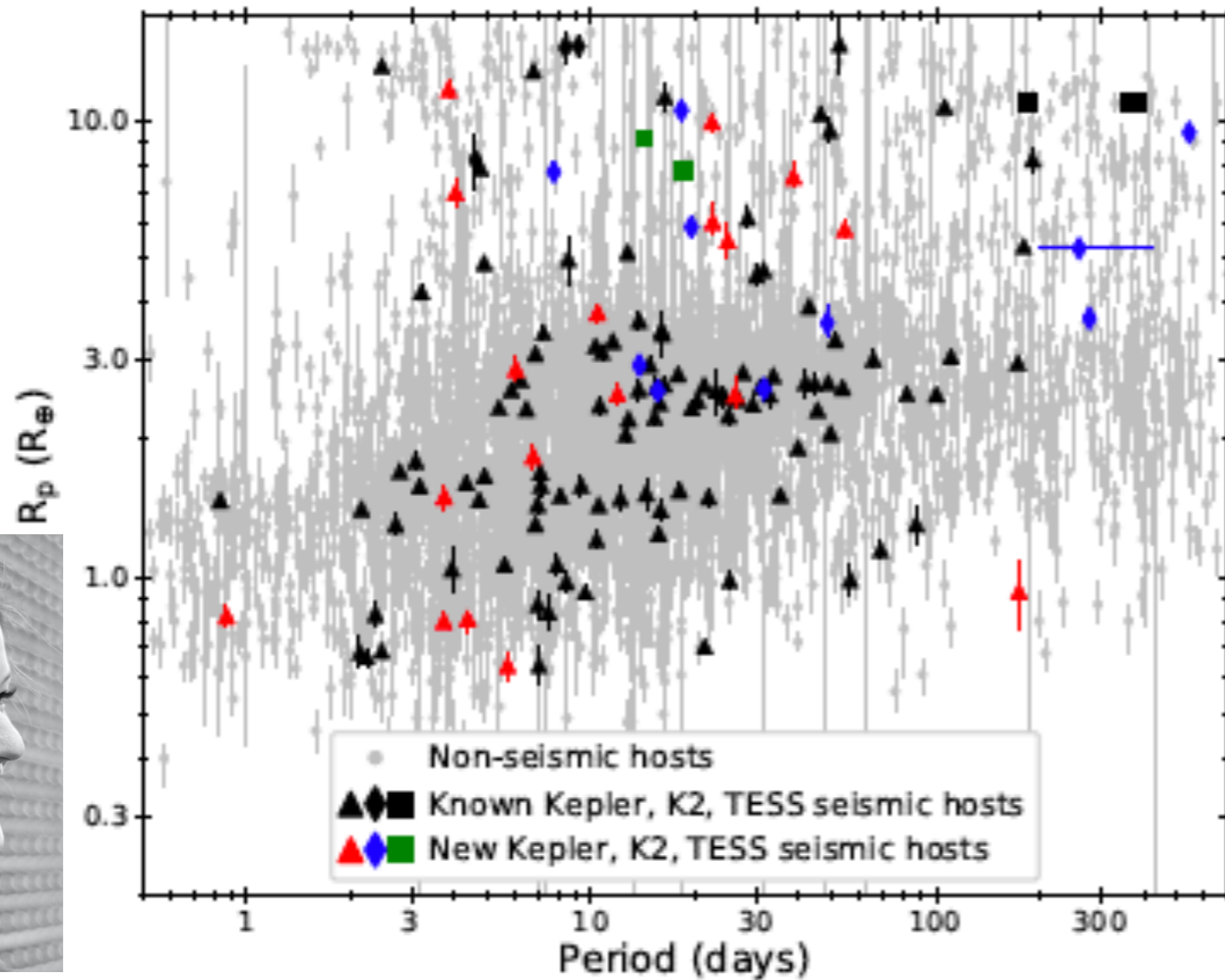
Weighing/ageing stars to 2/10% precision



Chaplin WJ, Miglio A. 2013.

Annu. Rev. Astron. Astrophys. 51:353–92

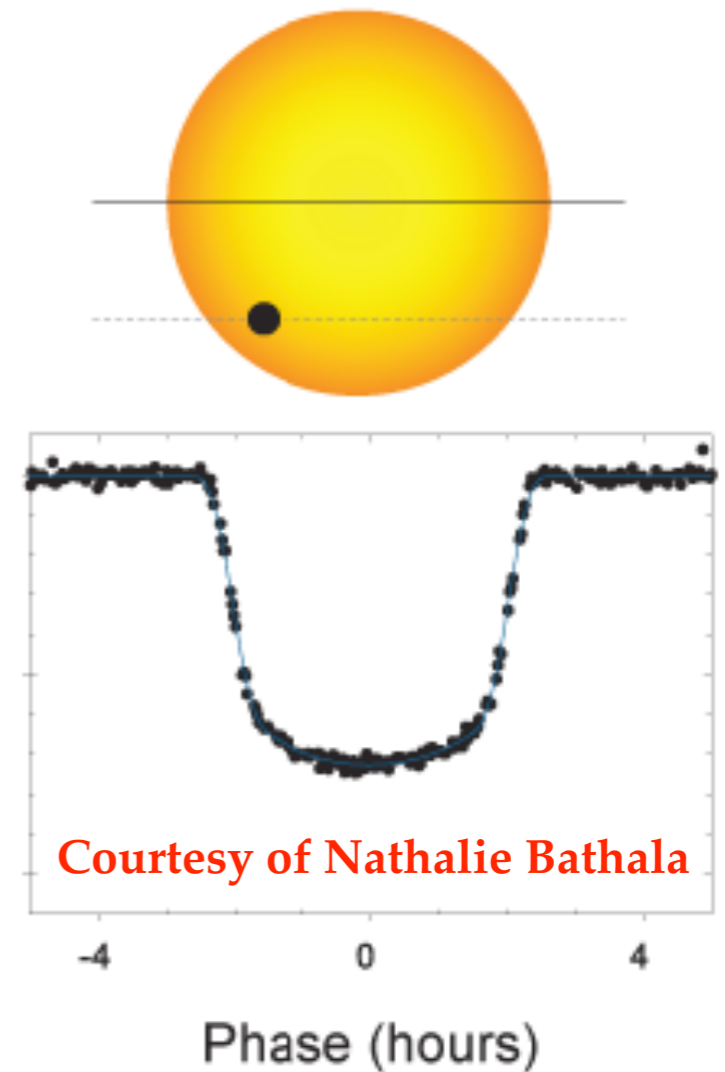
Asteroseismology of Host Star: factor ~2 improvement for exoplanet radius + **age delivery!**



Courtesy:
Ashley
Chontos



Kepler 5b

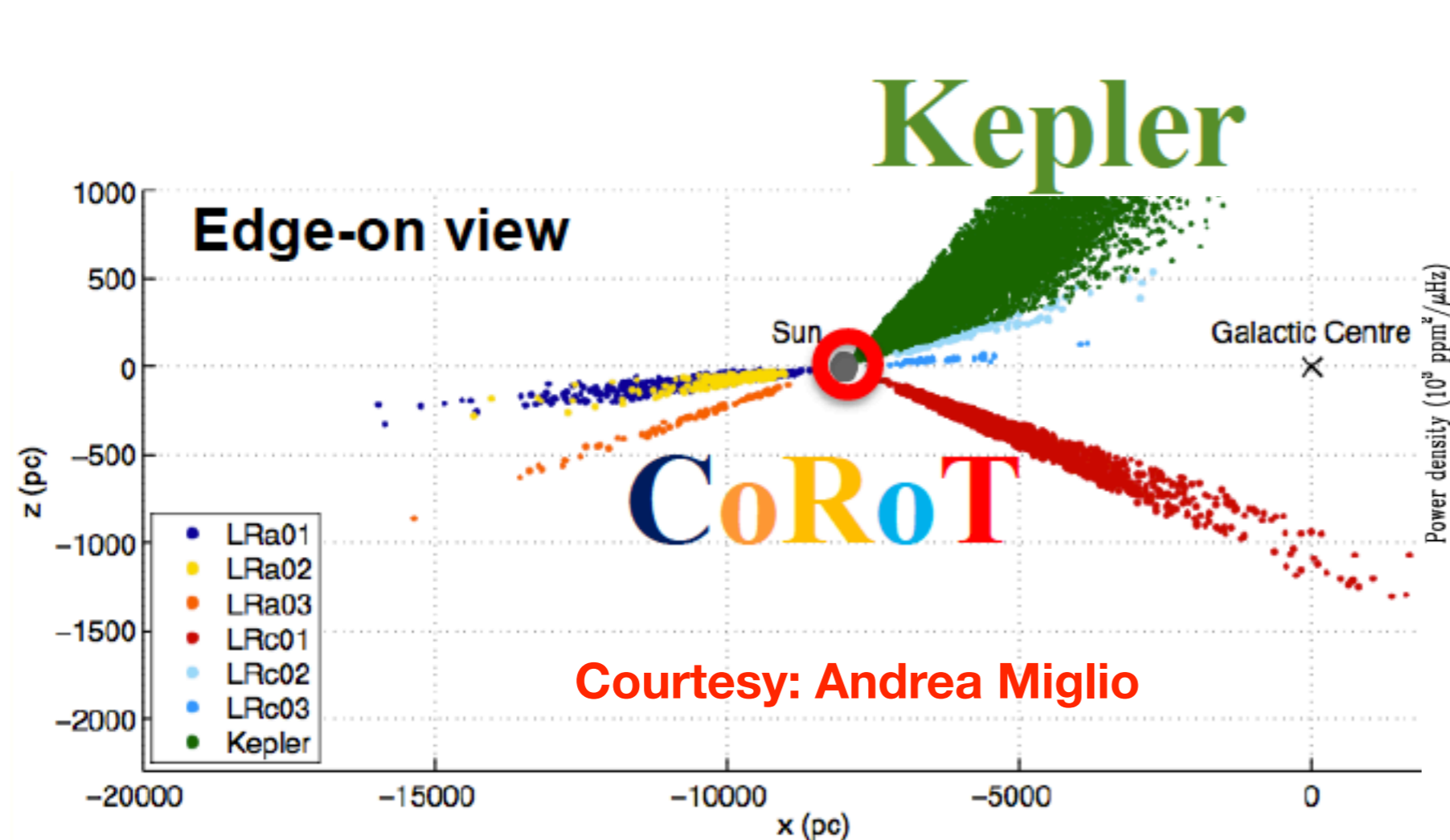


Courtesy of Nathalie Bathala

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

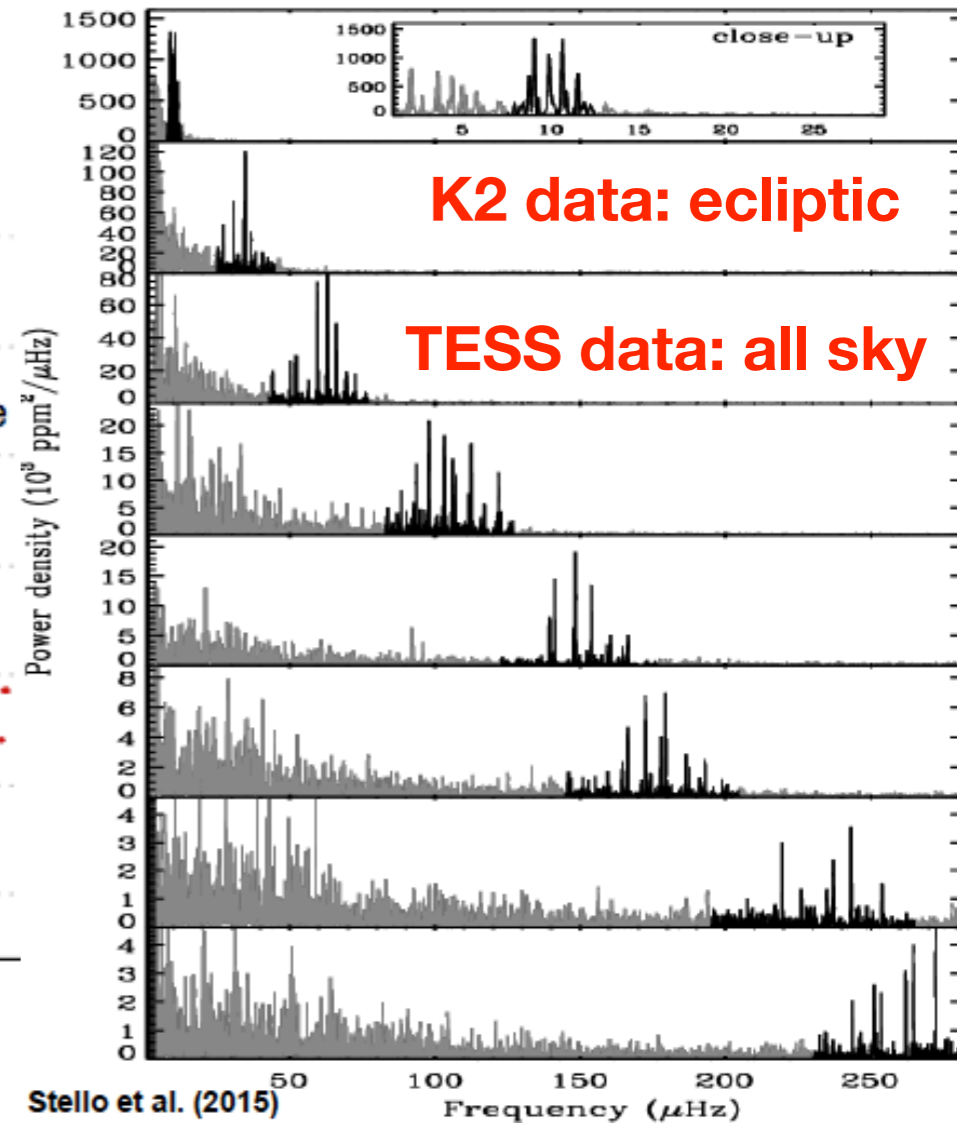
Ages for Galactic Archaeology

Seismic mass, radius, age of red giants from scaling relations



Courtesy: Andrea Miglio

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
OF STARS**

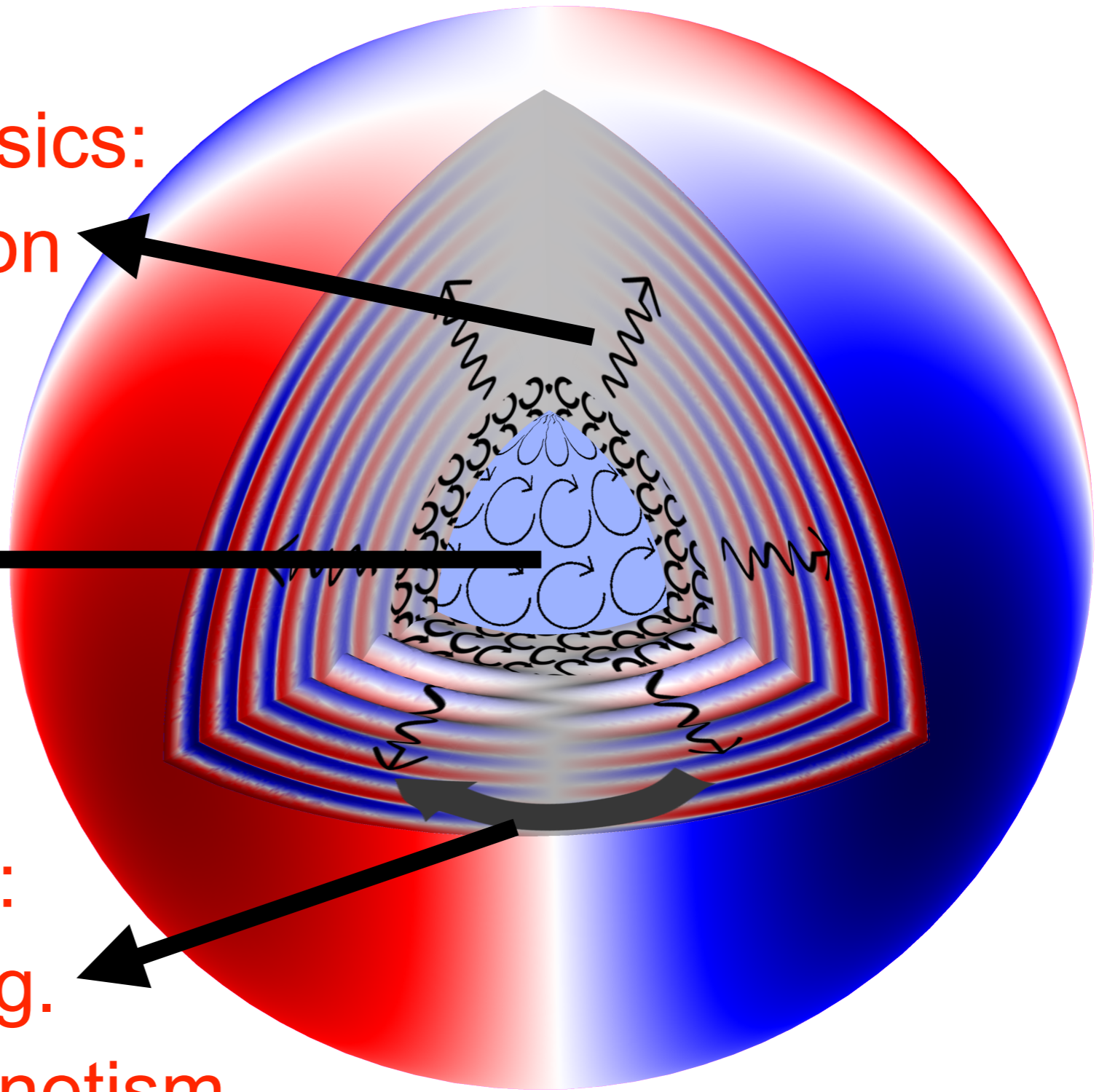
**2) INTERNAL ROTATION
OF STARS**

Chemical evolution?

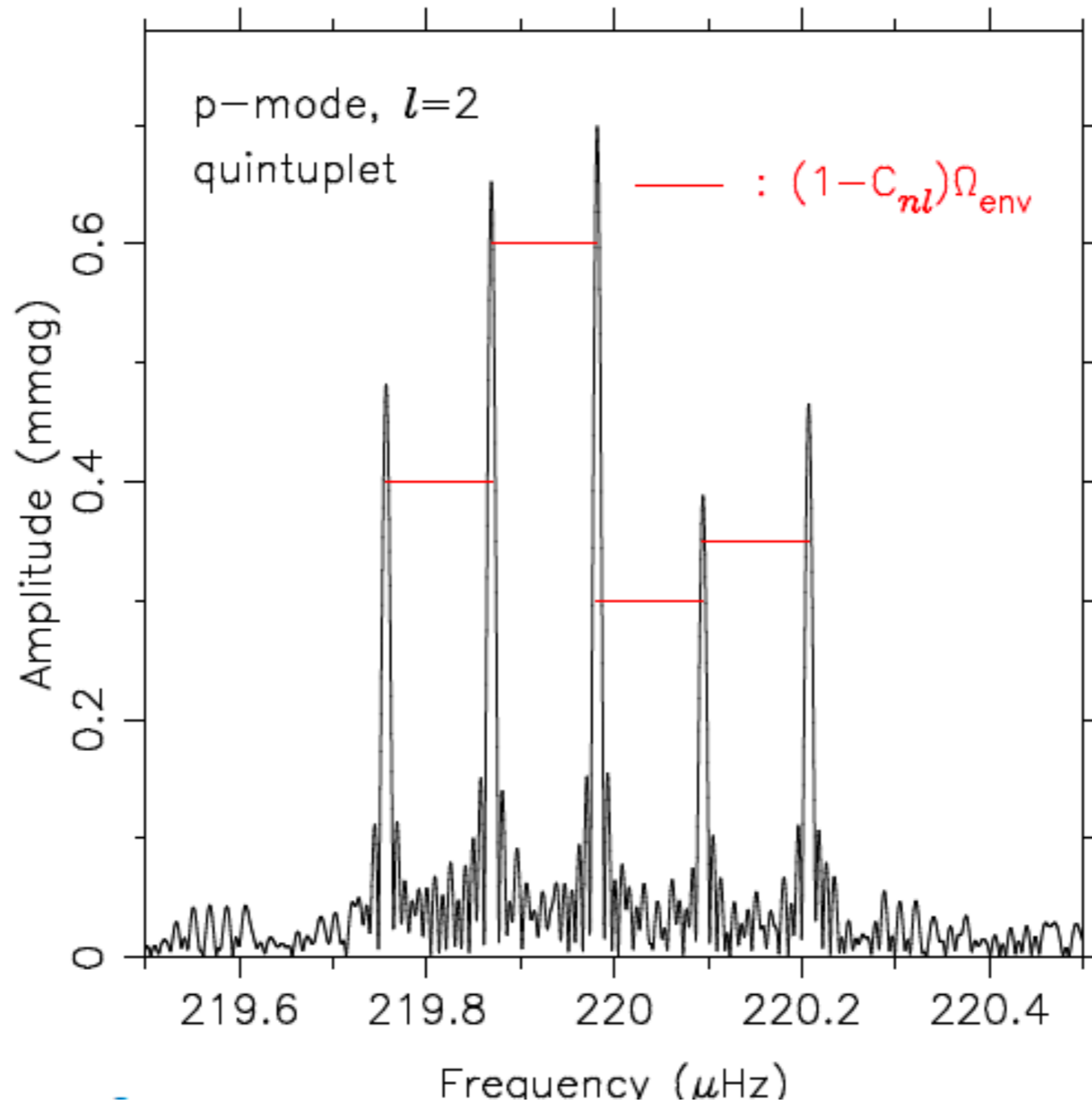
microscopic physics:
atomic diffusion

nuclear
burning

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

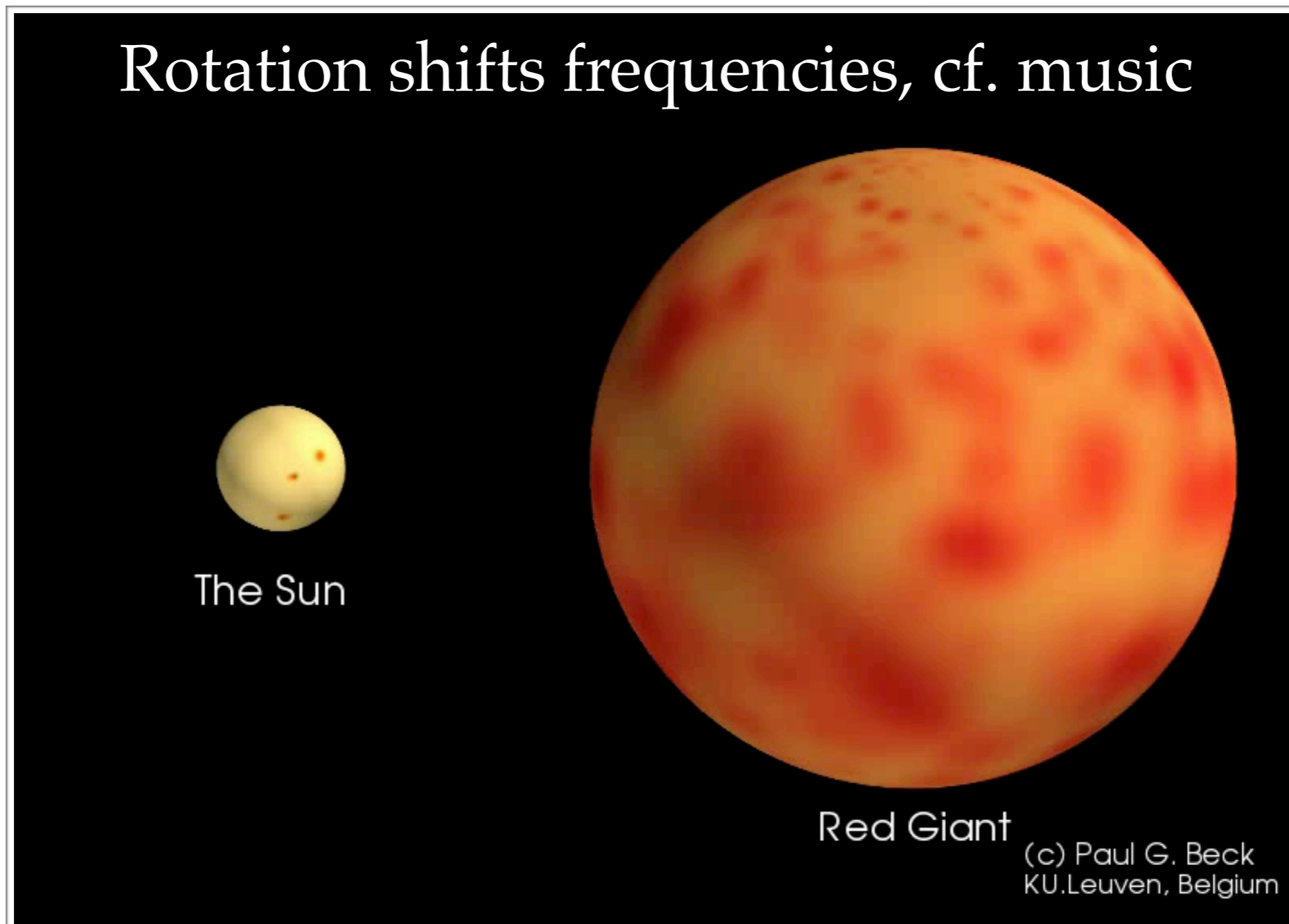


Rotational splitting of modes



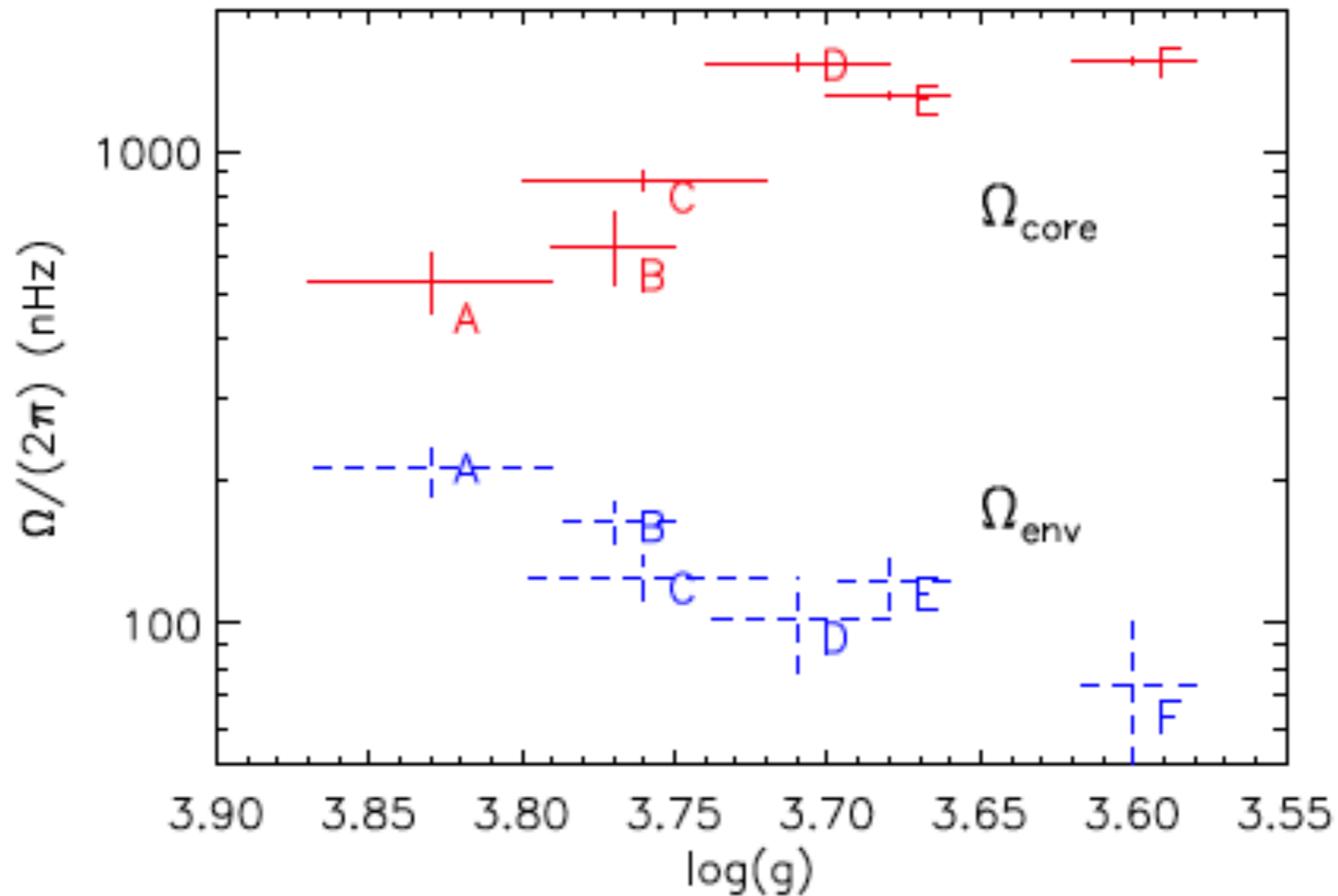
Star more massive than Sun: Kurtz et al. (2014)

Internal Stellar Rotation

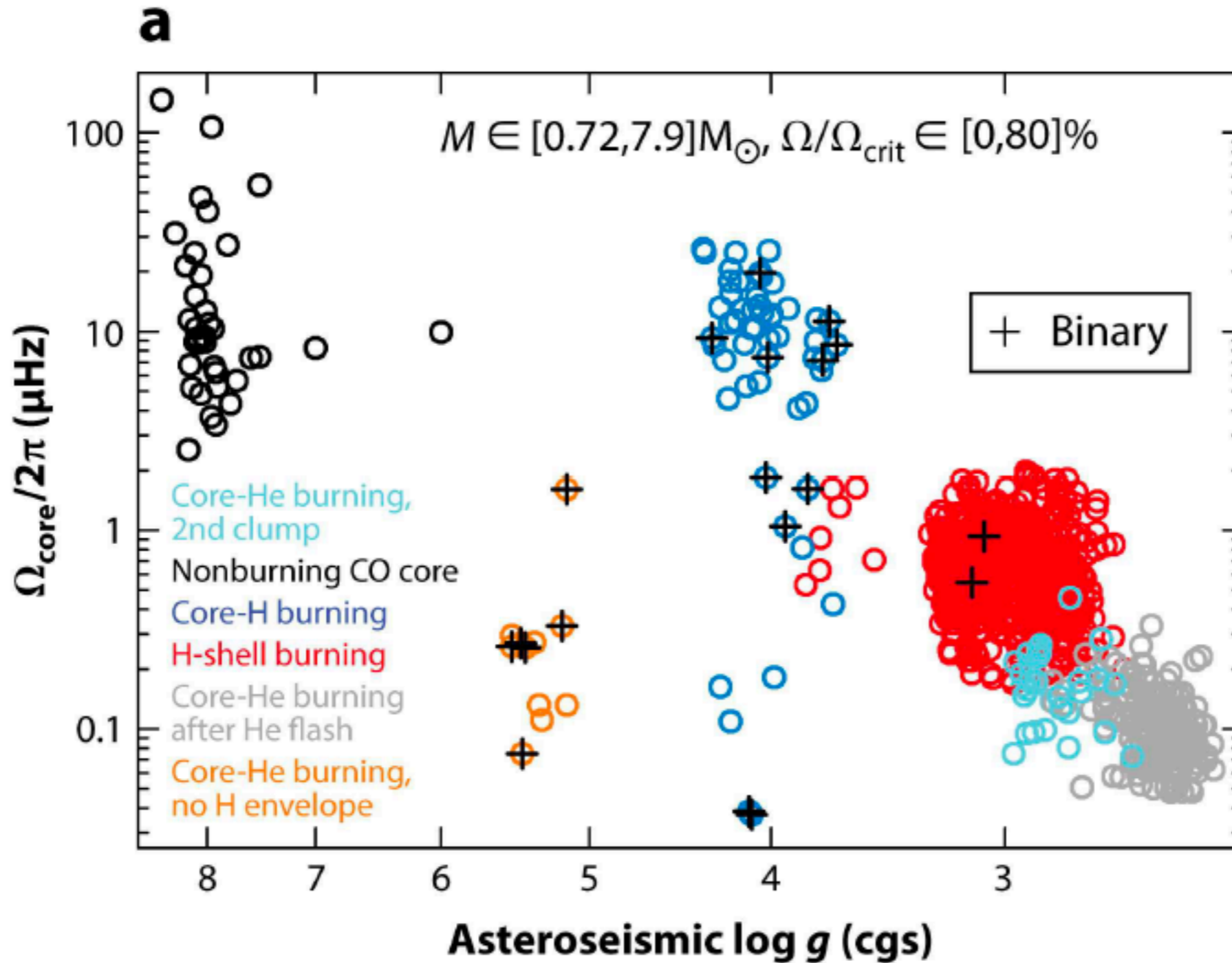


Beck et al. (2012, Nature)

“Watching” stars grow old

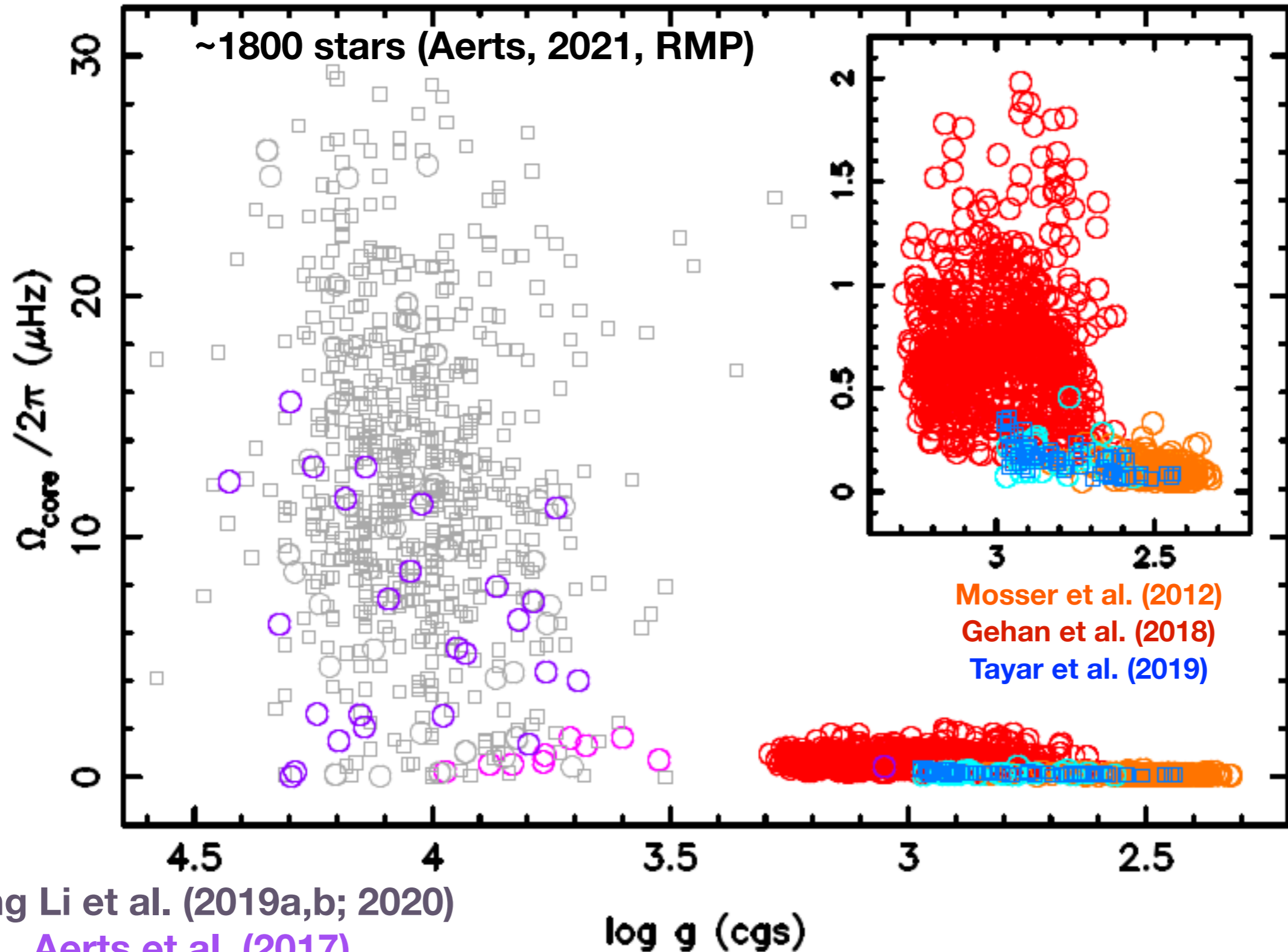


Successors of sun-like stars: Deheuvels et al. (2014)

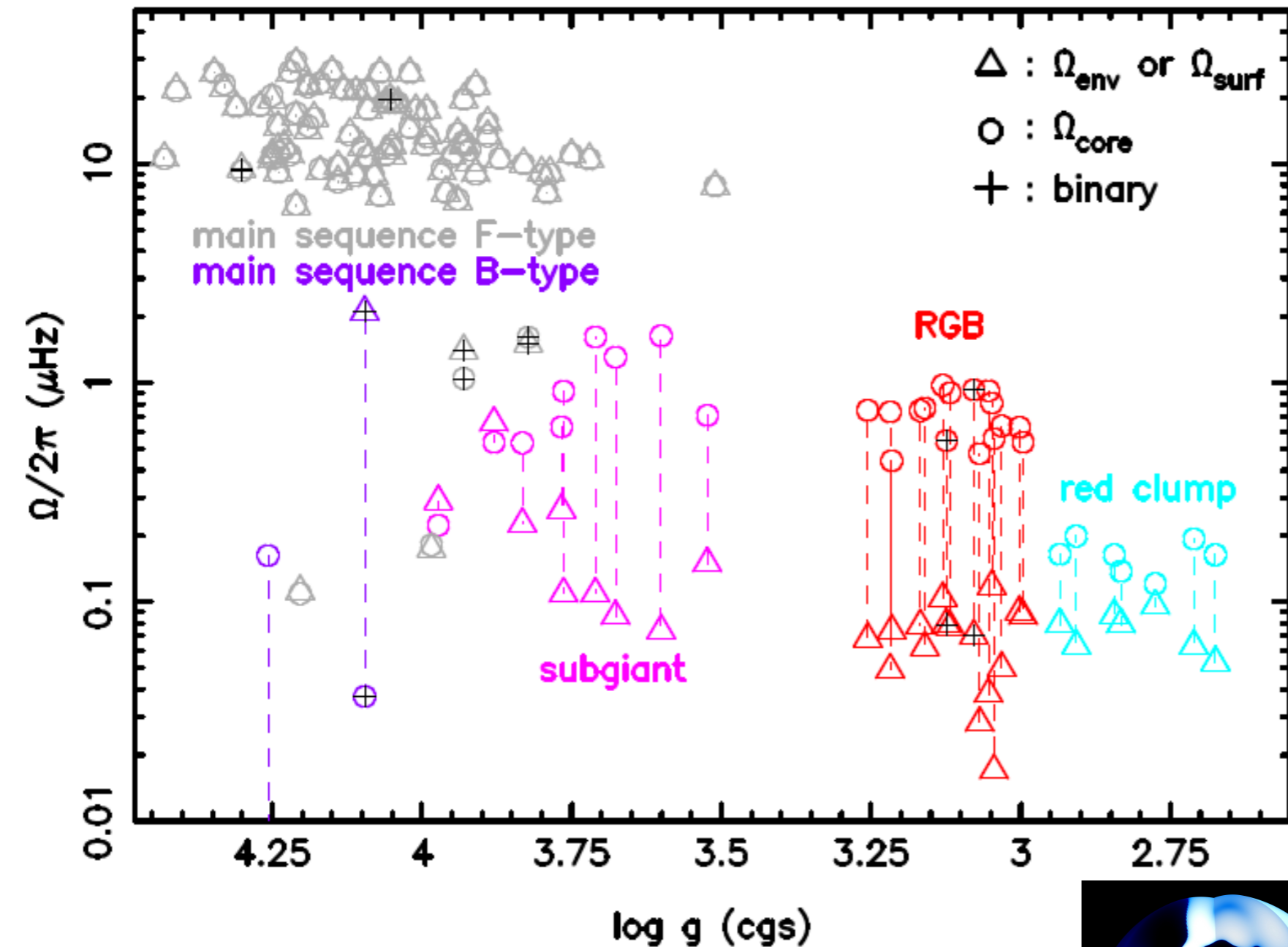


1210 stars

We cannot do this for the Sun...



Measuring Ω_{core} versus Ω_{env}



Stars with convective core rotate quasi-rigidly

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

Magnetism/Taylor Instability:

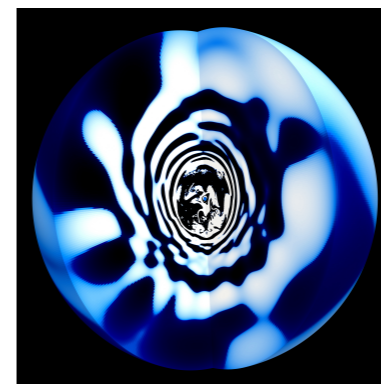
Fuller et al. (2019),
Takahashi & Langer (2020)
Loi et al. (2019, 2020),
Bugnet et al. (2021)

and/or

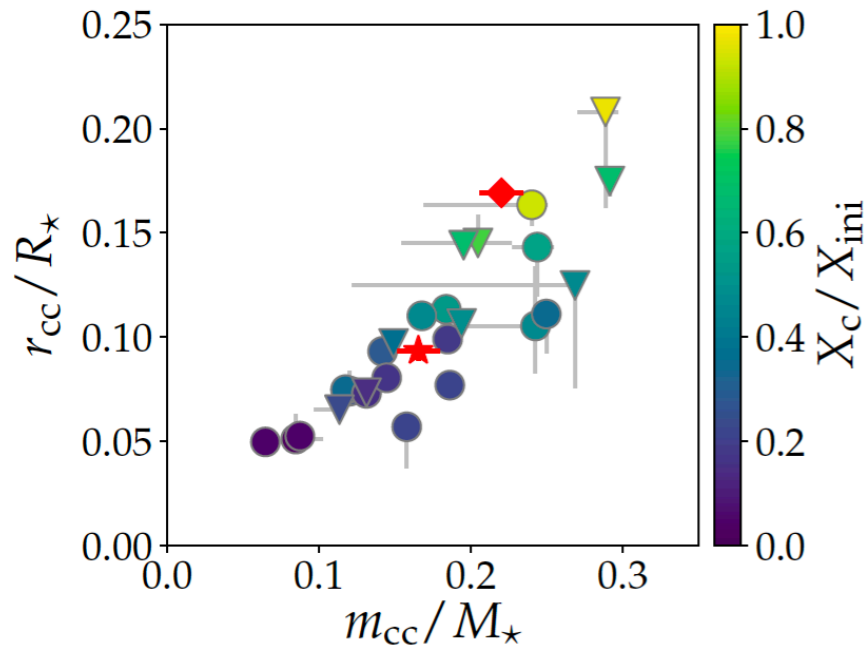
IGWs:

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

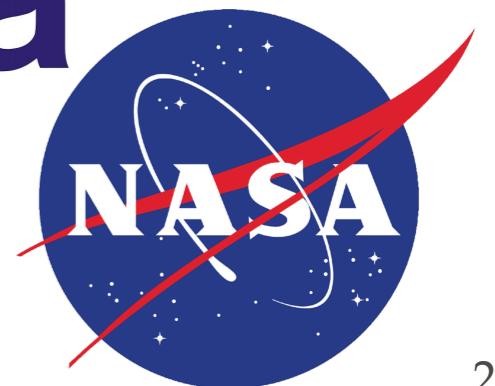
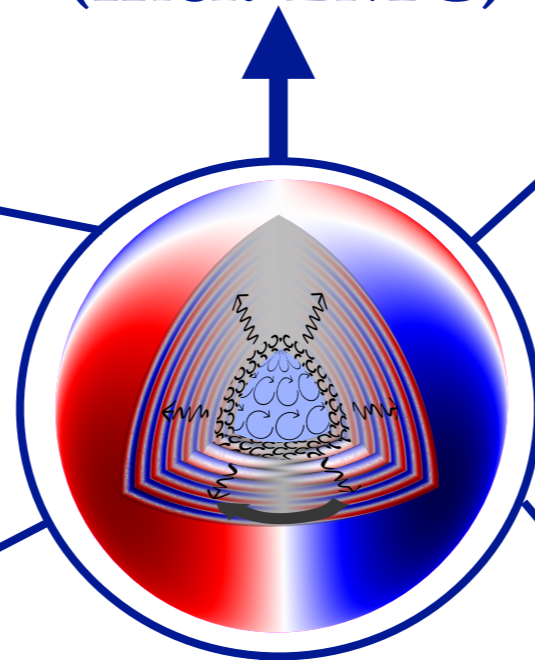
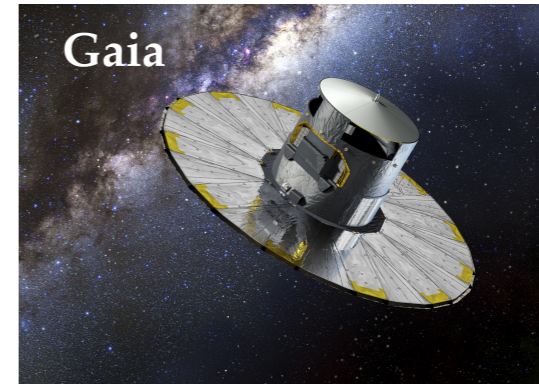
“Standard SSE” needs fixes...
(figure from Aerts, 2021, RMP, 111 stars)



Pedersen et al. (2021, Nature Astronomy)



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!



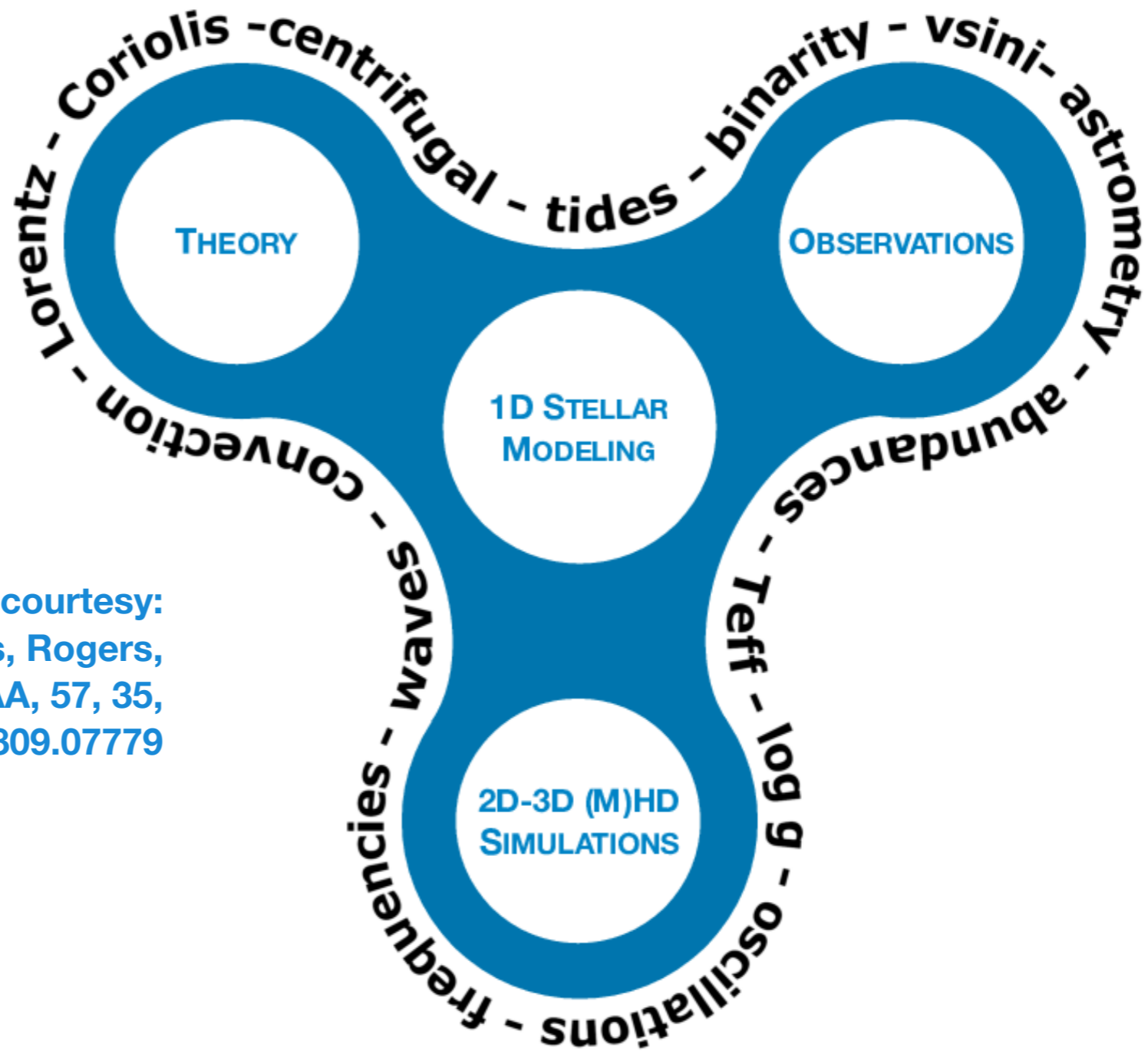


Figure courtesy:
 Aerts, Mathis, Rogers,
 2019: ARAA, 57, 35,
<https://arxiv.org/abs/1809.07779>

**Much more to it: tidal, magneto-, pre-MS,
 nonlinear, GIW, ... asteroseismology**
Aerts, 2021, RMP: <https://arxiv.org/abs/1912.12300>
general introduction & update for non-expert