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Asteroseismology of Exoplanet Host Stars

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Asteroseismology: the Revolution in Stellar Physics

What is it?…Why do we (should you) care?…

How does it work in practice?…

Solar-like pulsators in Sun-like Stars (M < 1.5 $M_\odot$)

Massive Exoplanet Host Stars (M > 1.5 $M_\odot$)

Future steps

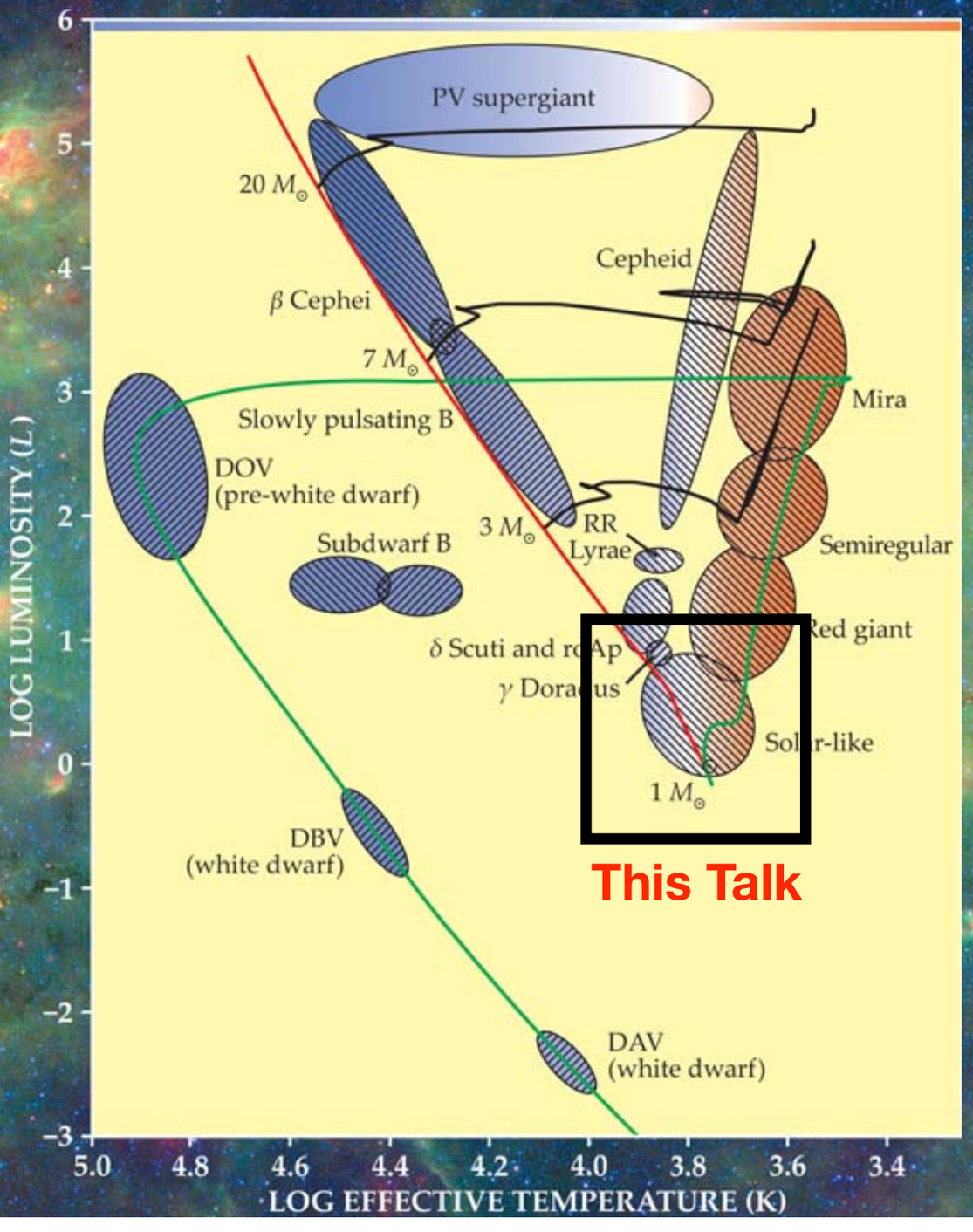
Lots of open ? on stellar structure remain

starquakes are common & useful tool

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

Connection between life of host star and its exoplanets?

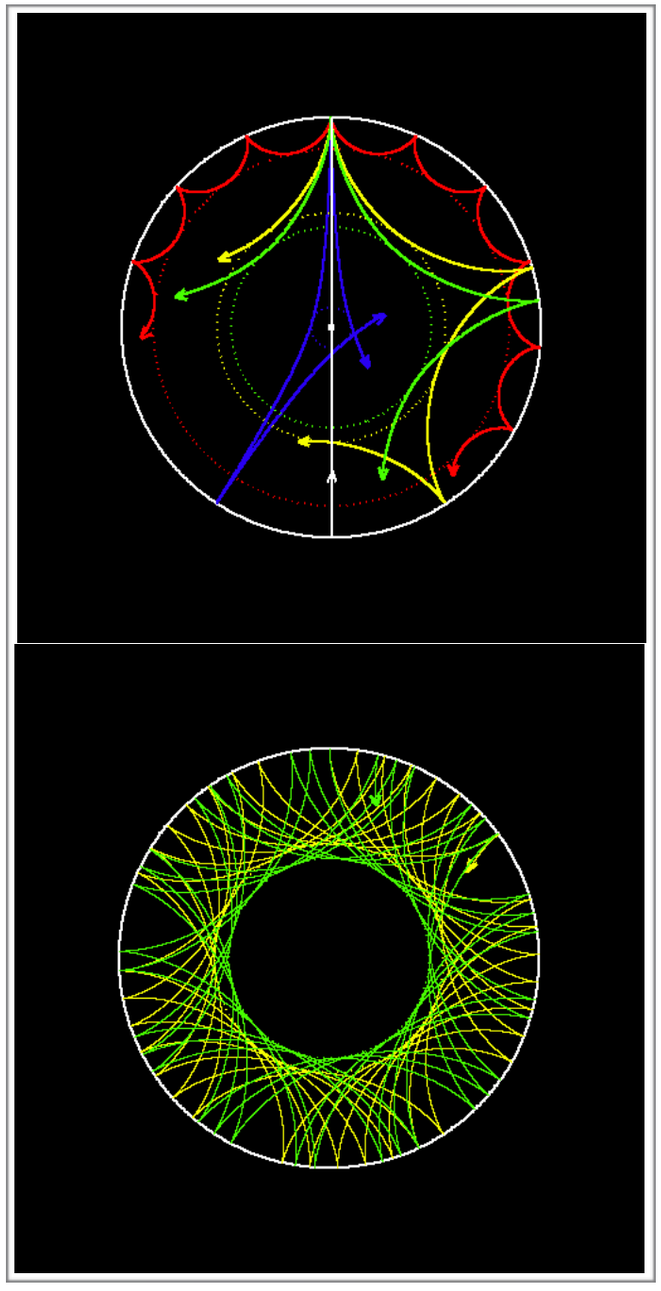
How does star *formation* happen & how is it connected to planet formation?



From C. Aerts, Physics Today, May 2015

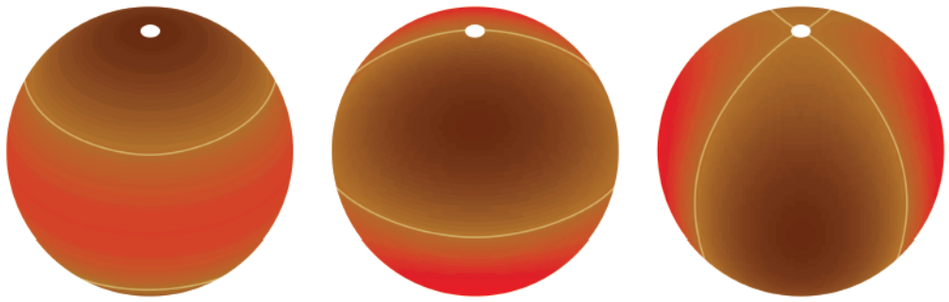
The beauty of asteroseismology

aster ⟶ star
seismos ⟶ oscillation
logos ⟶ discourse

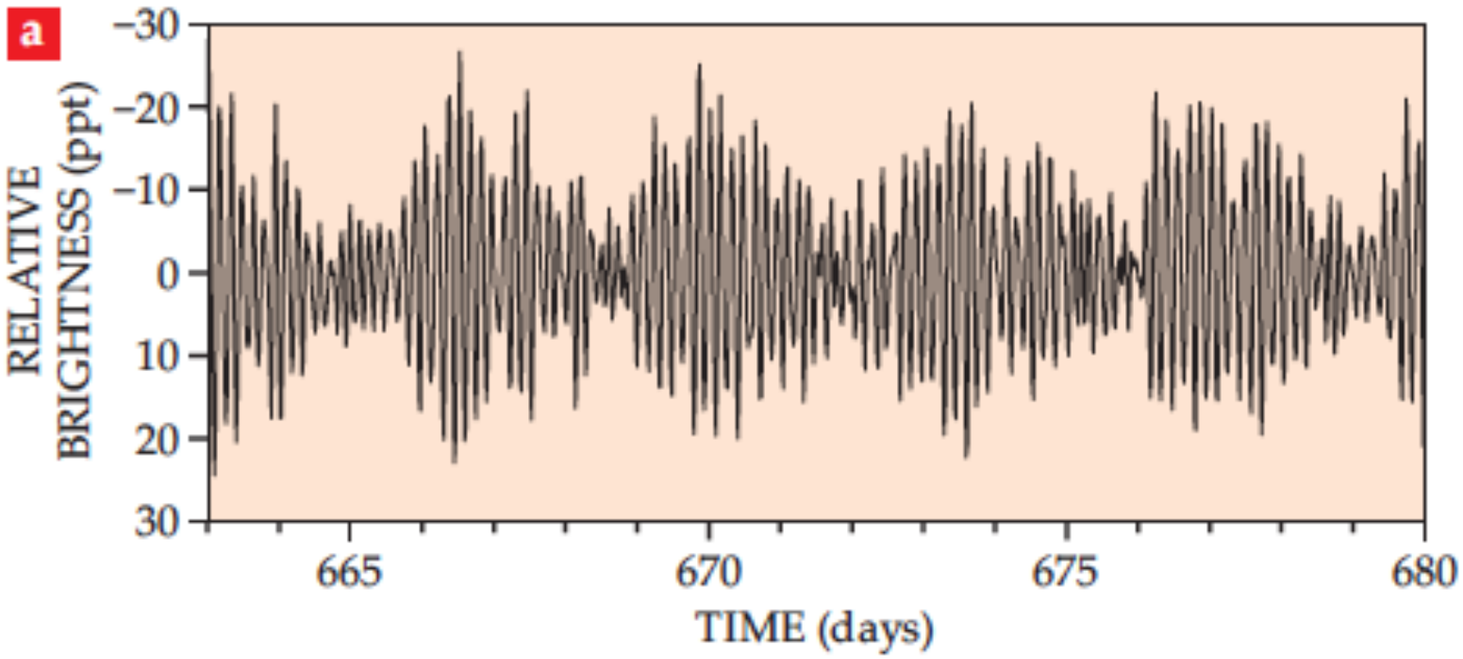


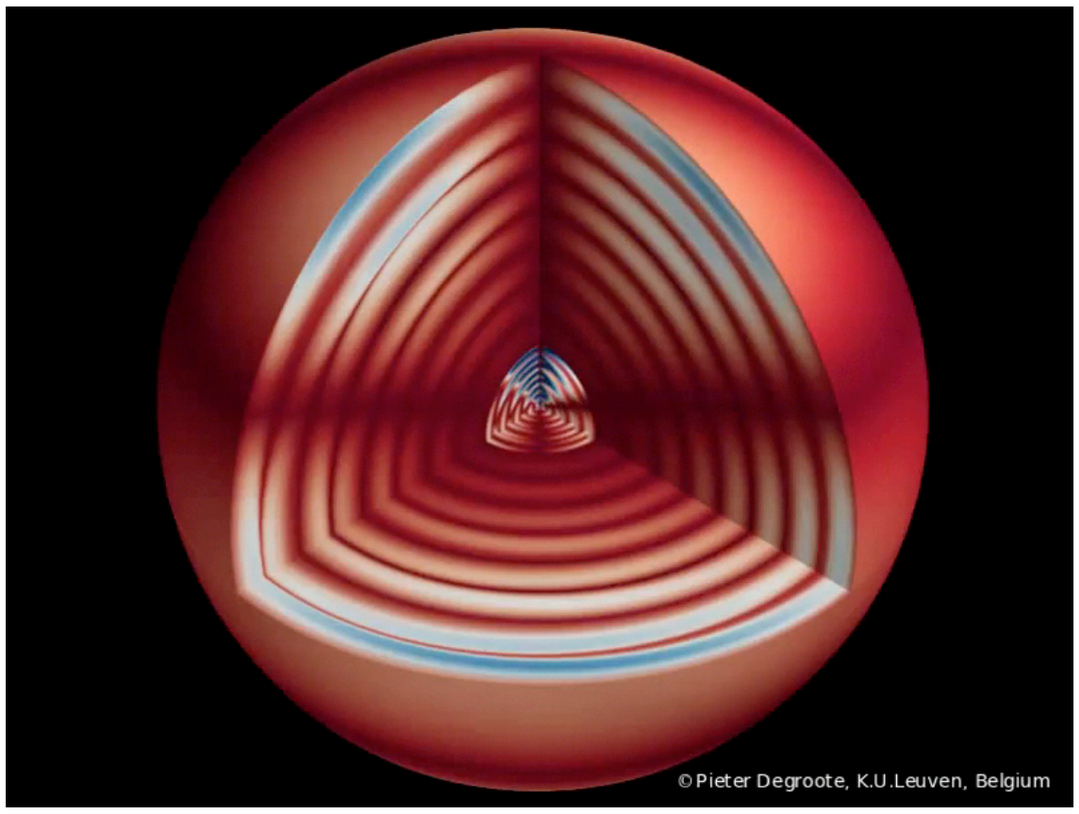
The analysis of stellar oscillations enables the **study of the stellar interior** because different modes penetrate to different depths inside the star

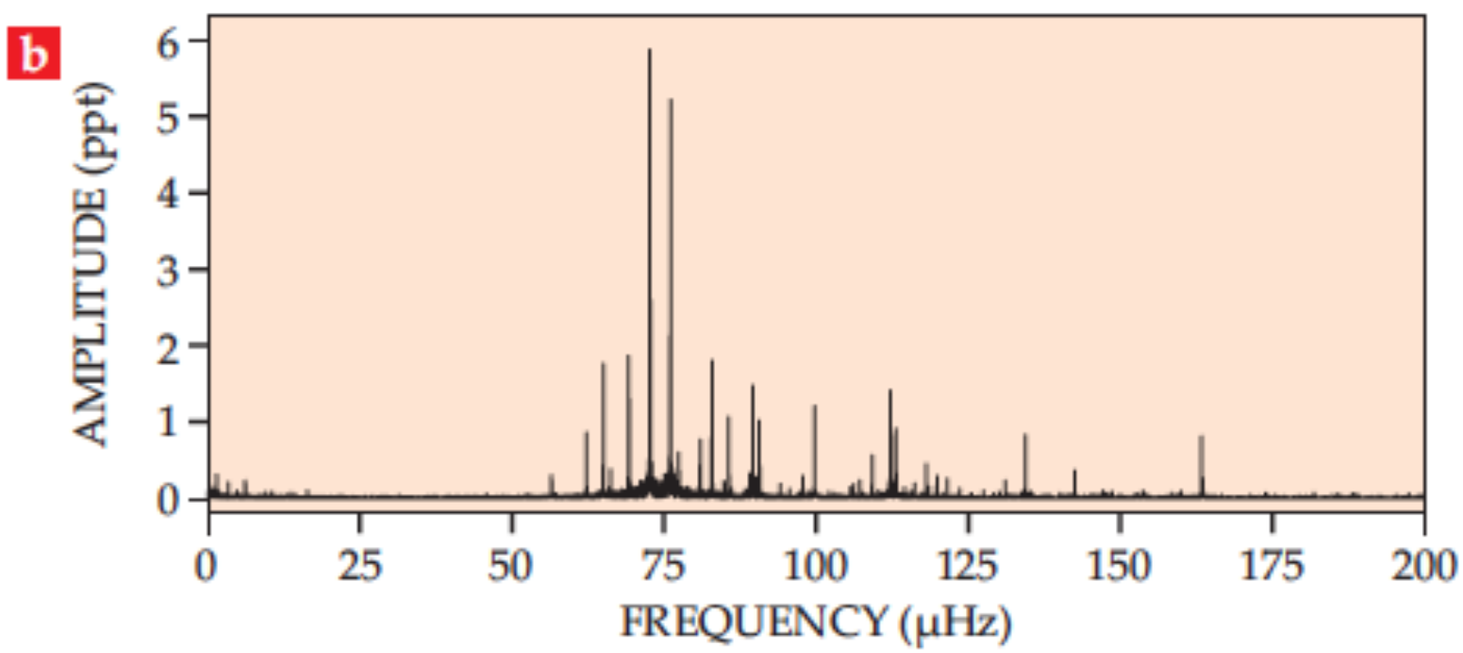
The boost from space photometry



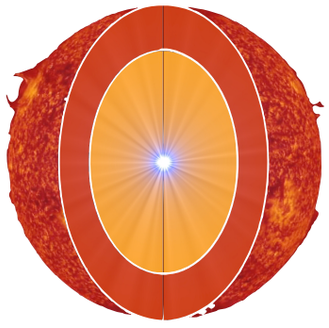
Detection of 100s of oscillation mode frequencies from **uninterrupted high-precision long-duration space photometry**

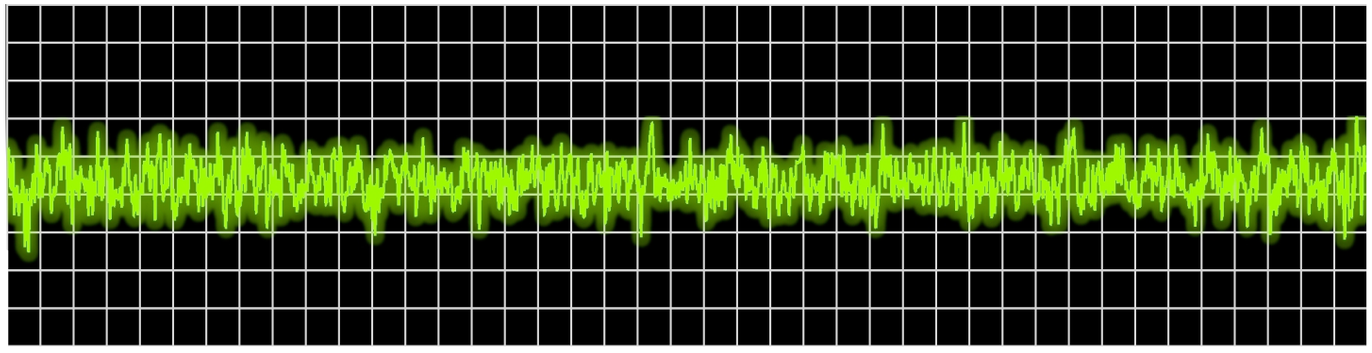






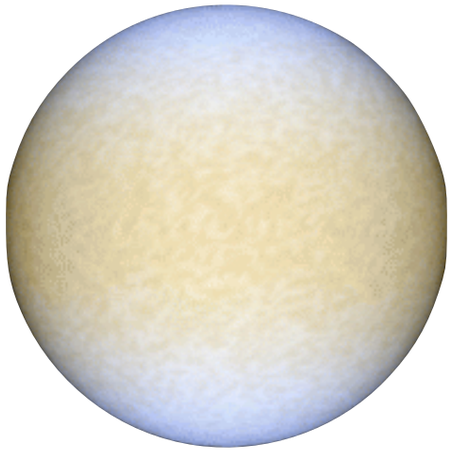
Sizes of stars from acoustic oscillations





TIME →

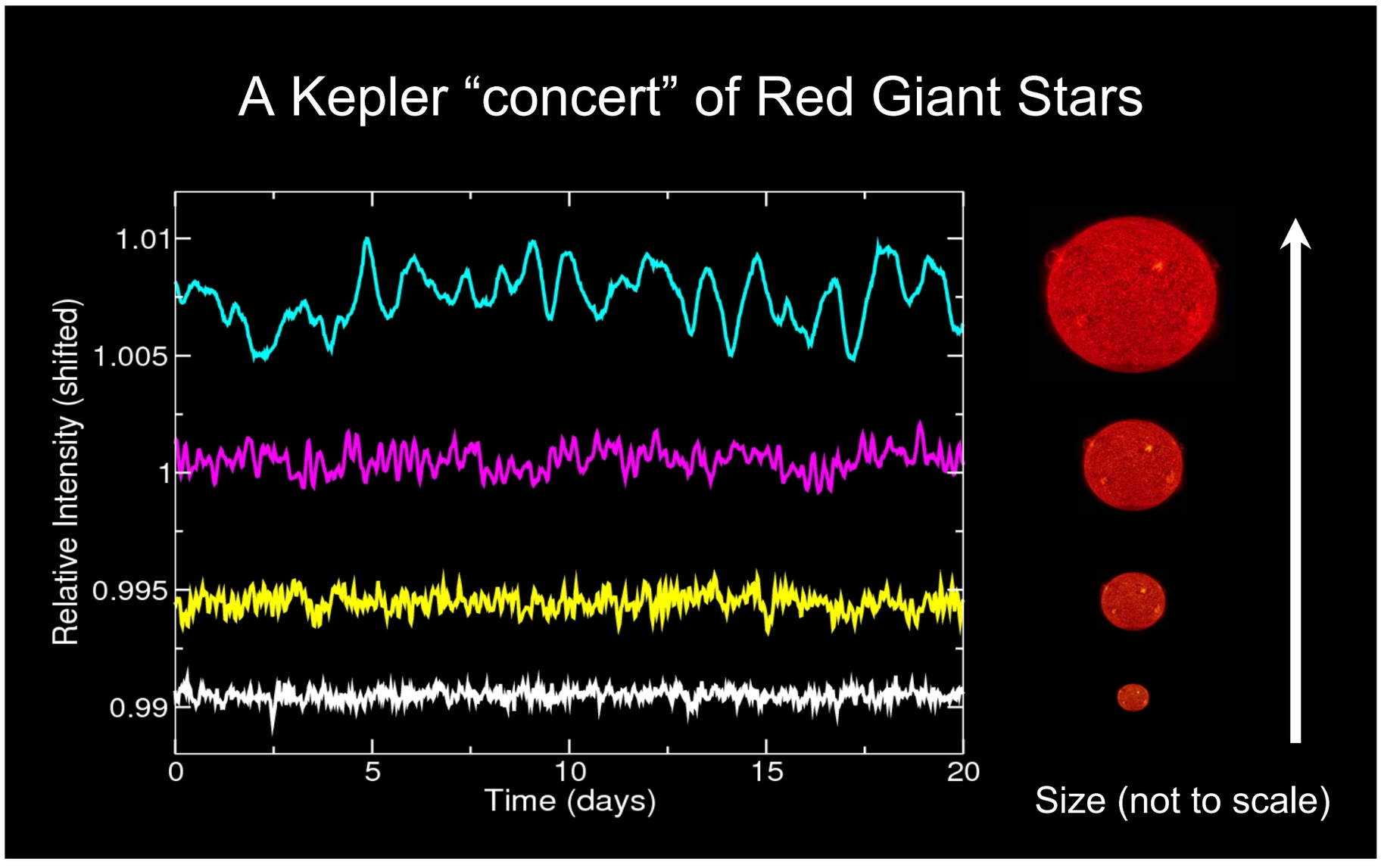
KIC 11026764



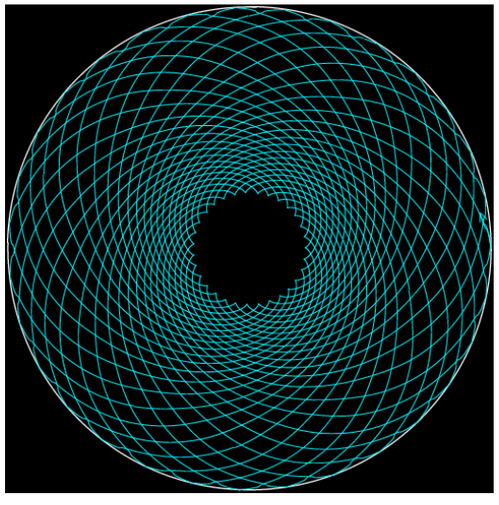
Sun

Slide Courtesy: Travis Metcalfe

Asteroseismology: how in practice?...



We observe the surface brightness and/or velocity variations due to the oscillations



Perform mathematical modelling of detected oscillation modes *v*(l,m,n)

$$\Delta_{nlm} = m \int_0^R K_{nl}(r)\Omega(r)\mathrm{d}r,$$

What are the concrete ingredients?

Time-series analysis coupled to stellar modelling

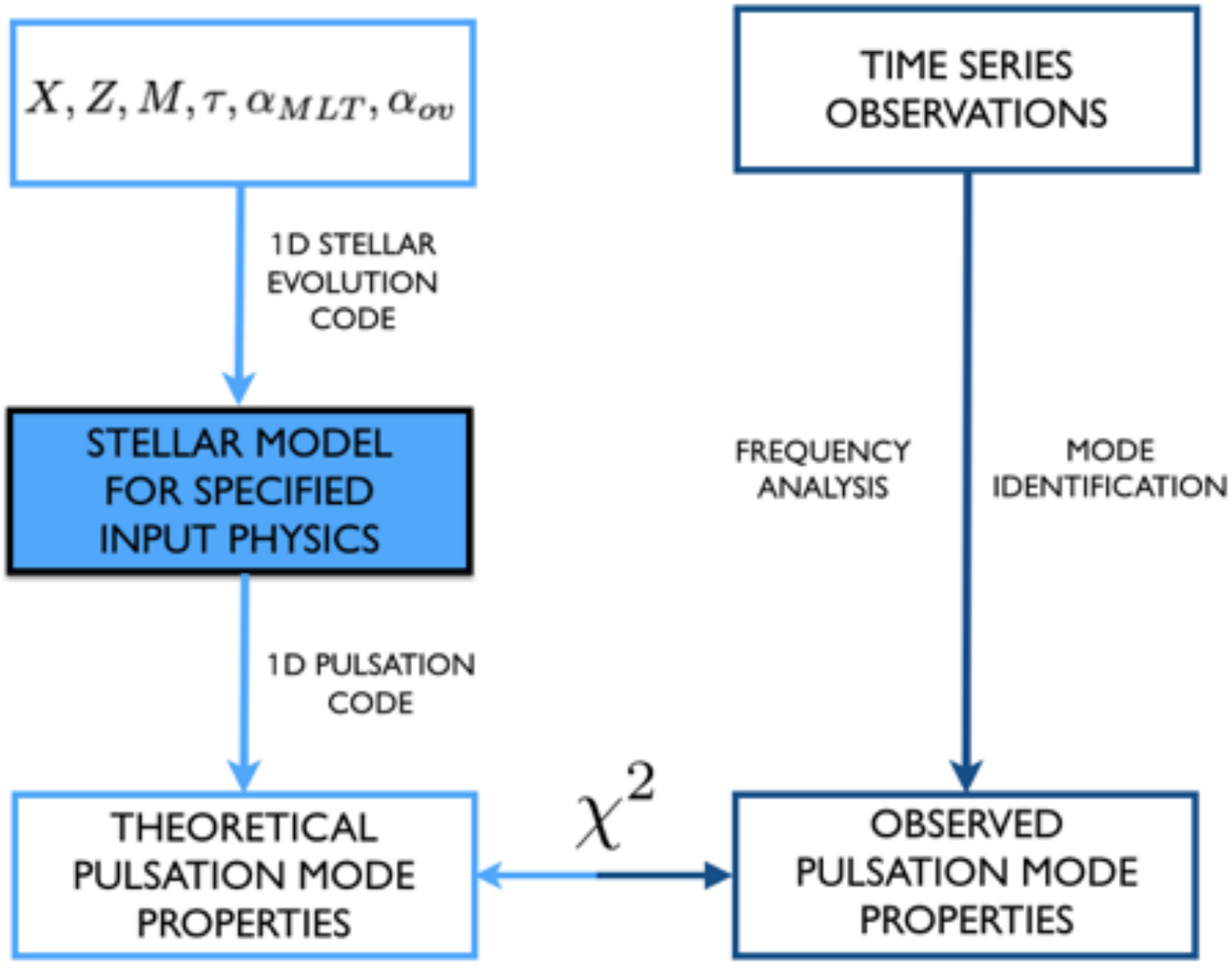
Two extremes:
pressure & gravity modes

$$\nu_{nl} = \frac{\omega_{nl}}{2\pi} \simeq (n + \frac{l}{2} + \frac{1}{4} + \alpha)\Delta\nu$$

$$\Delta\nu = \left[2\int_0^R \frac{\mathrm{d}r}{c}\right]^{-1}$$

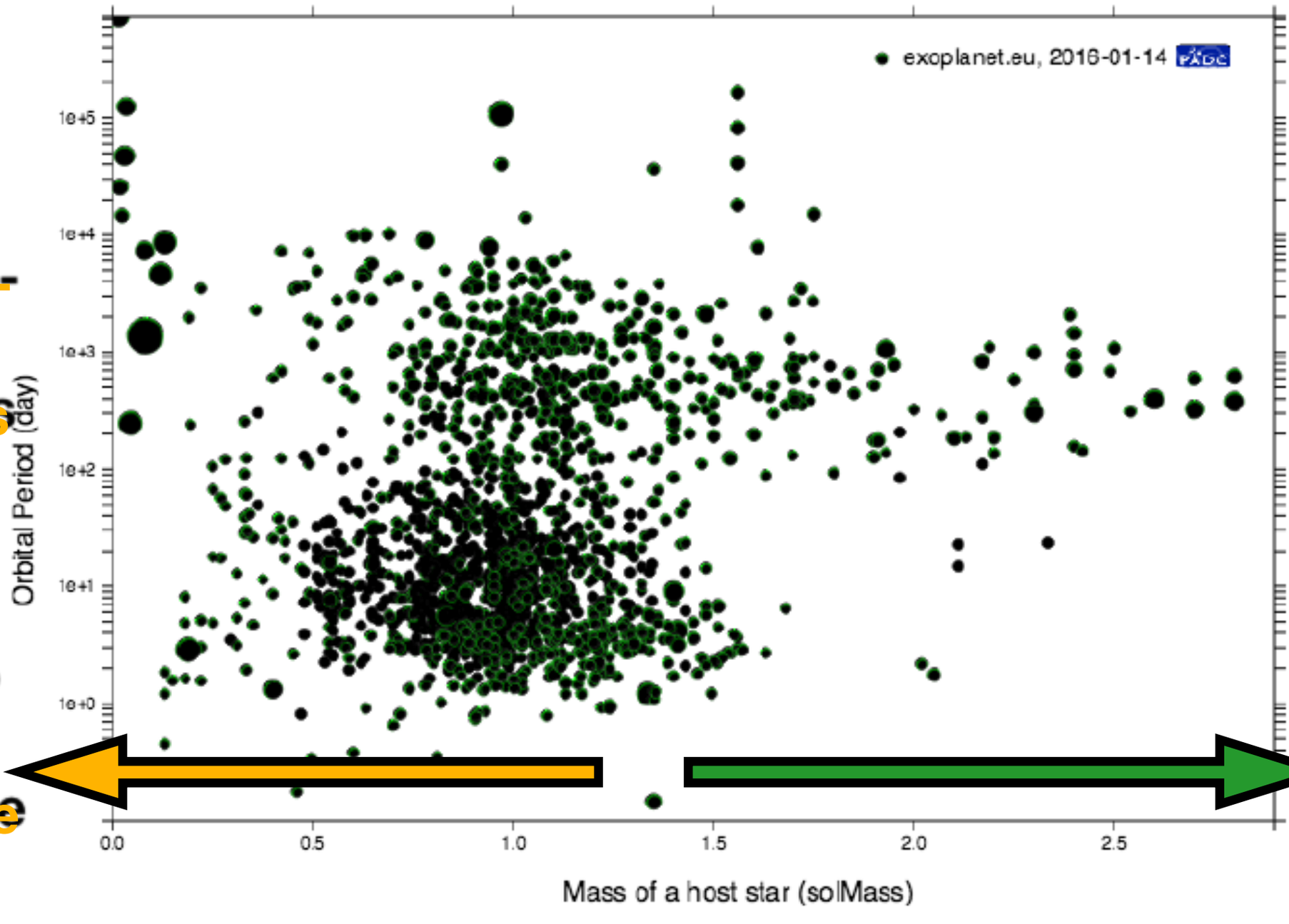
$$\Pi = \frac{\Pi_0}{L}(n + l/2 + \alpha_g)$$

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



The exoplanet host stars: mass

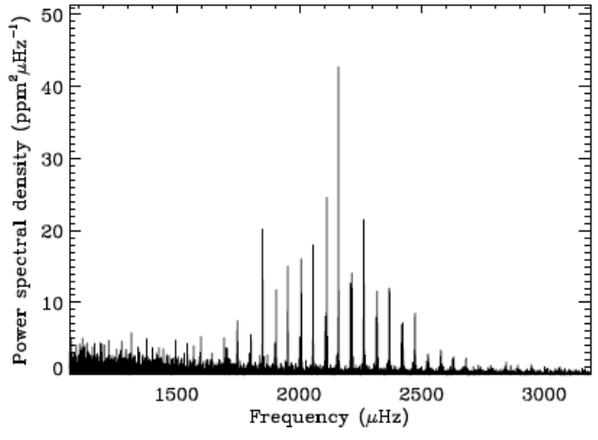
Pressure-Mode Pulsators & Highly-Variable Dynamo Fields at Surface

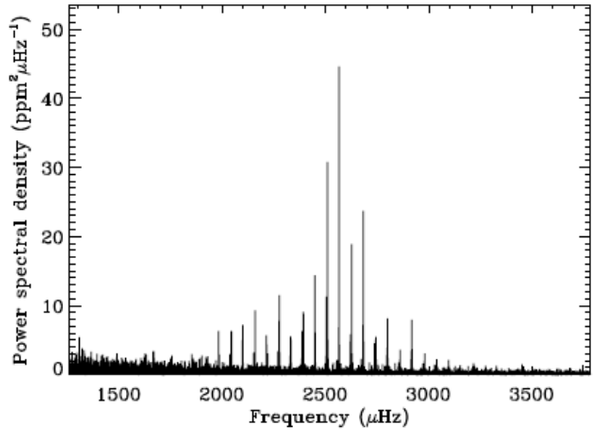


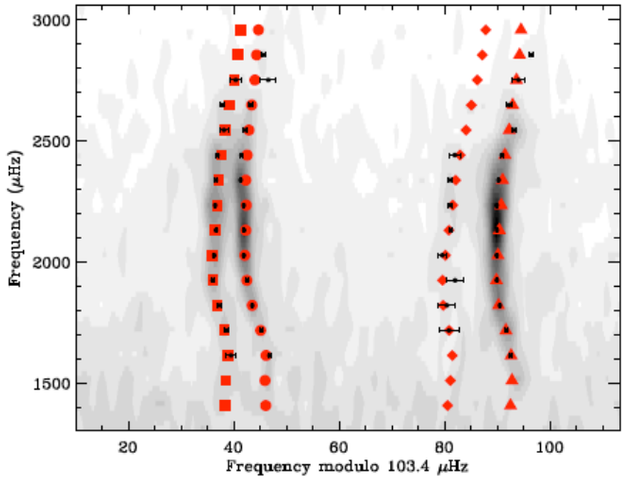
Gravity-Mode Pulsators & Fossil Stable Surface Magnetic Fields in 10%

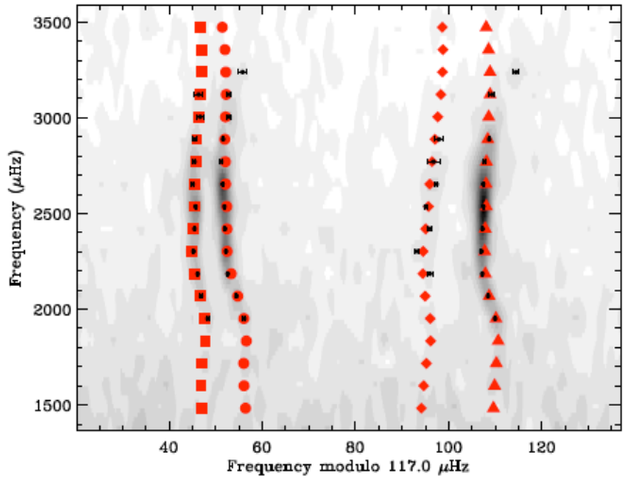
"Easy cases": solar-like pressure modes

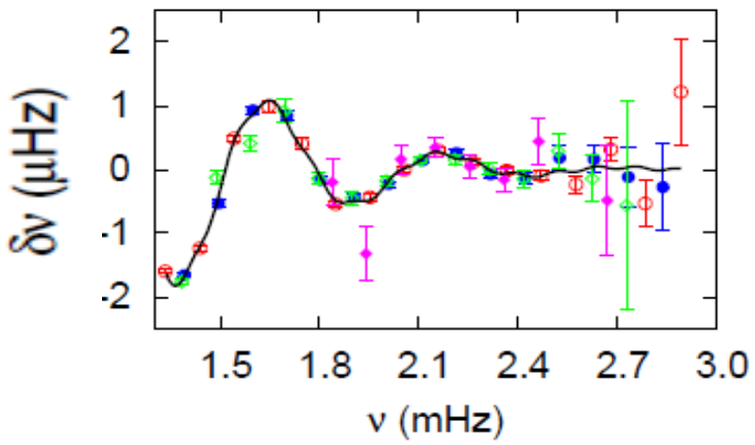
in-depth seismic probing à-la Helioseismology

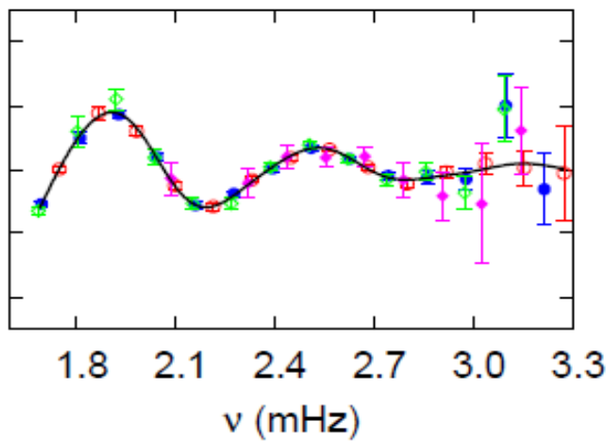












The exoplanetary system 16 Cyg A&B, *Kepler*, Metcalfe et al. (2012); Davies et al. (2015)

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)

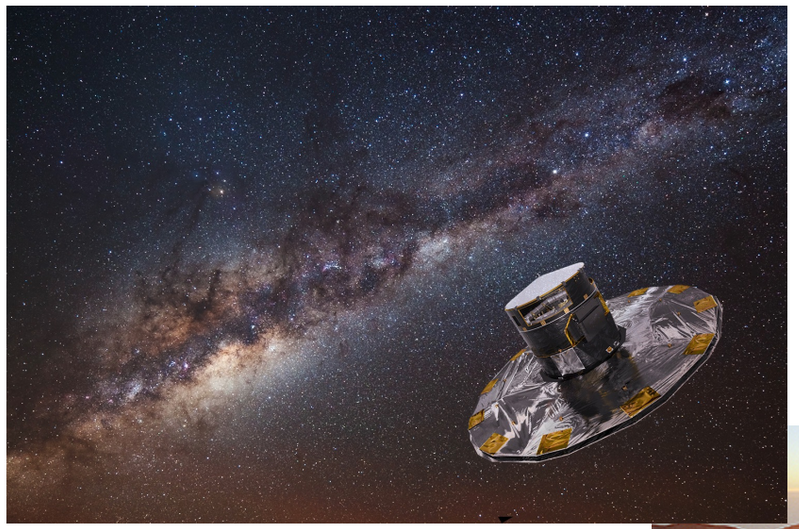
Large samples: use scaling relations

- **Scaling relations for solar input physics & p modes:**

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

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

deliver **seismic mass, radius, age:** 10x better precision for 100s of solar-like stars observed with Kepler



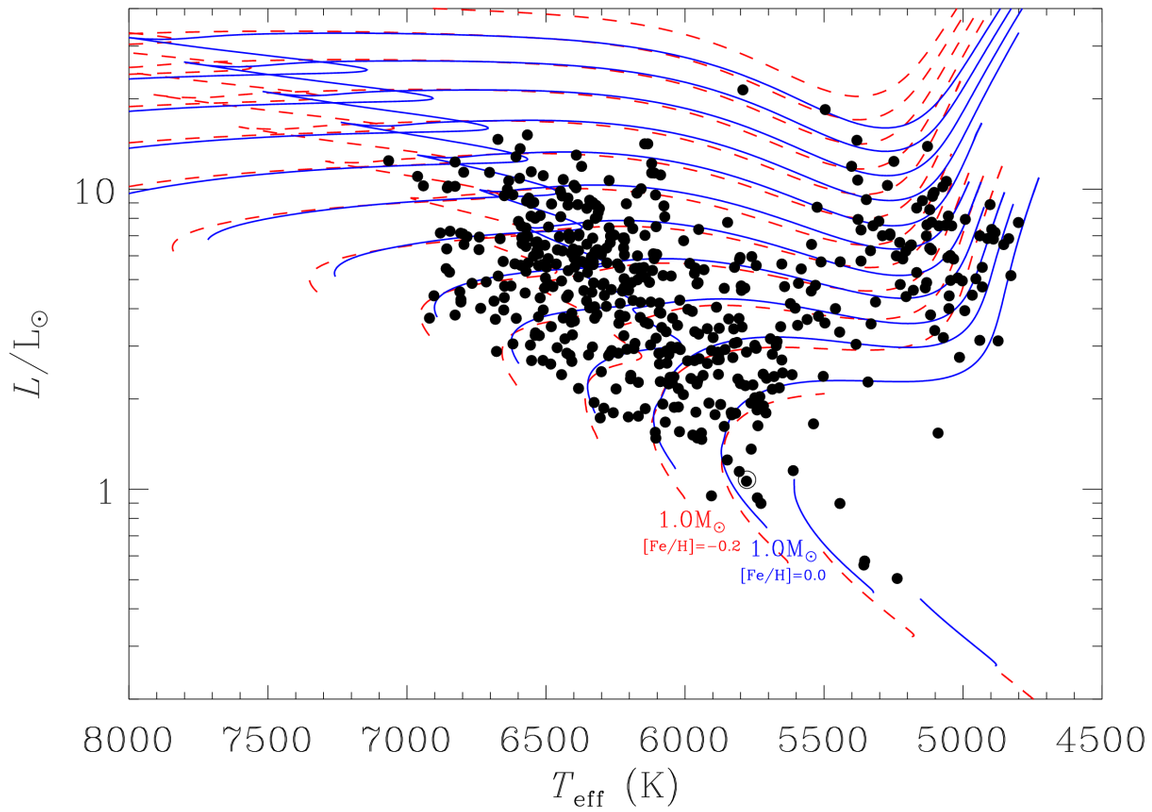
VLT at Paranal

ESO PR Photo 45a/99 (8 December 1999) © European Southern Observatory

A distance from Gaia and/or a radius from interferometry can take away the model dependency!

Asteroseismology of Exoplanet Hosts

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

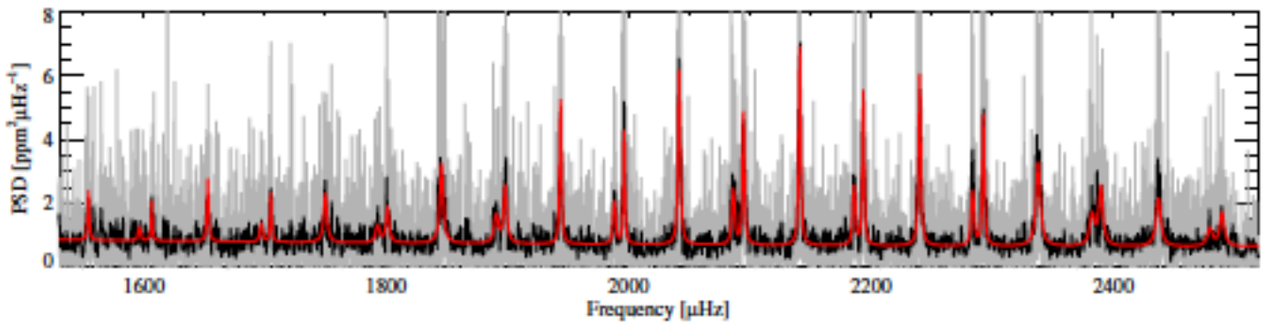


Ballot et al. (2011), Lebreton & Goupil (2014):

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

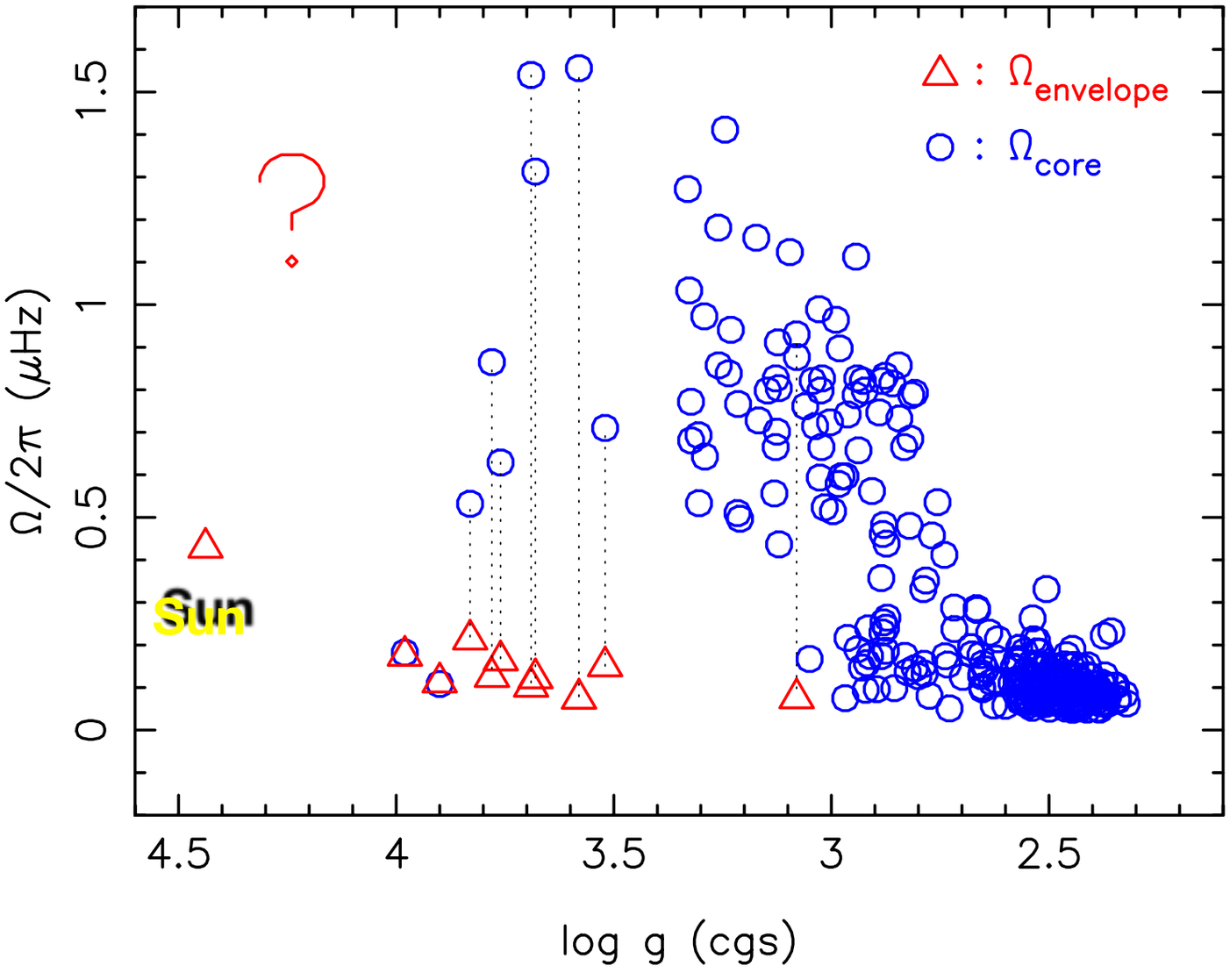
Improves planet parameters!



Ensemble asteroseismology +spectroscopy:
M:3.7%, R:1.3%, age:12%
Huber et al. (2013), Chaplin et al. (2014)

Rotational splitting of mixed modes in SG & RG

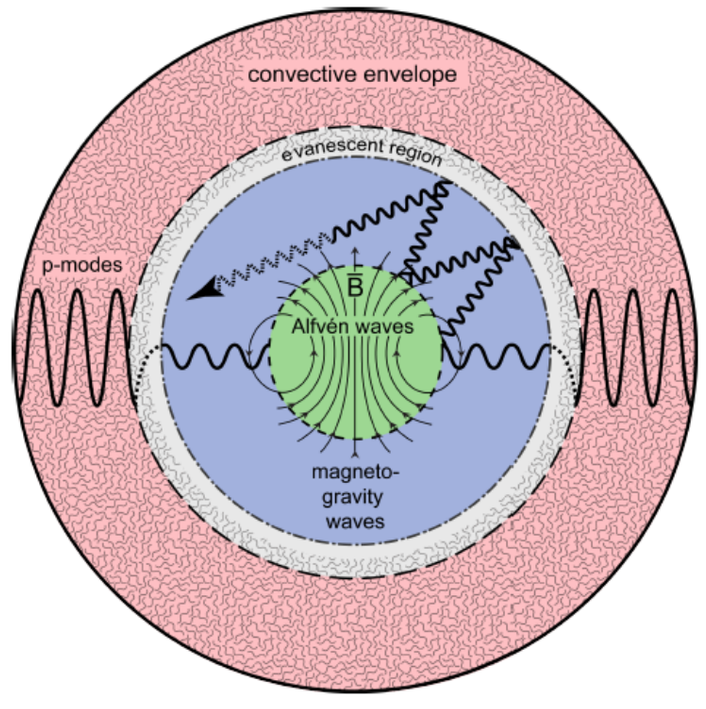
unravels core rotation… cannot be done for Sun!



from ≠ splittings of dipole mixed modes:

$$\Delta_{nlm} = m \int_0^R K_{nl}(r)\Omega(r)\mathrm{d}r,$$

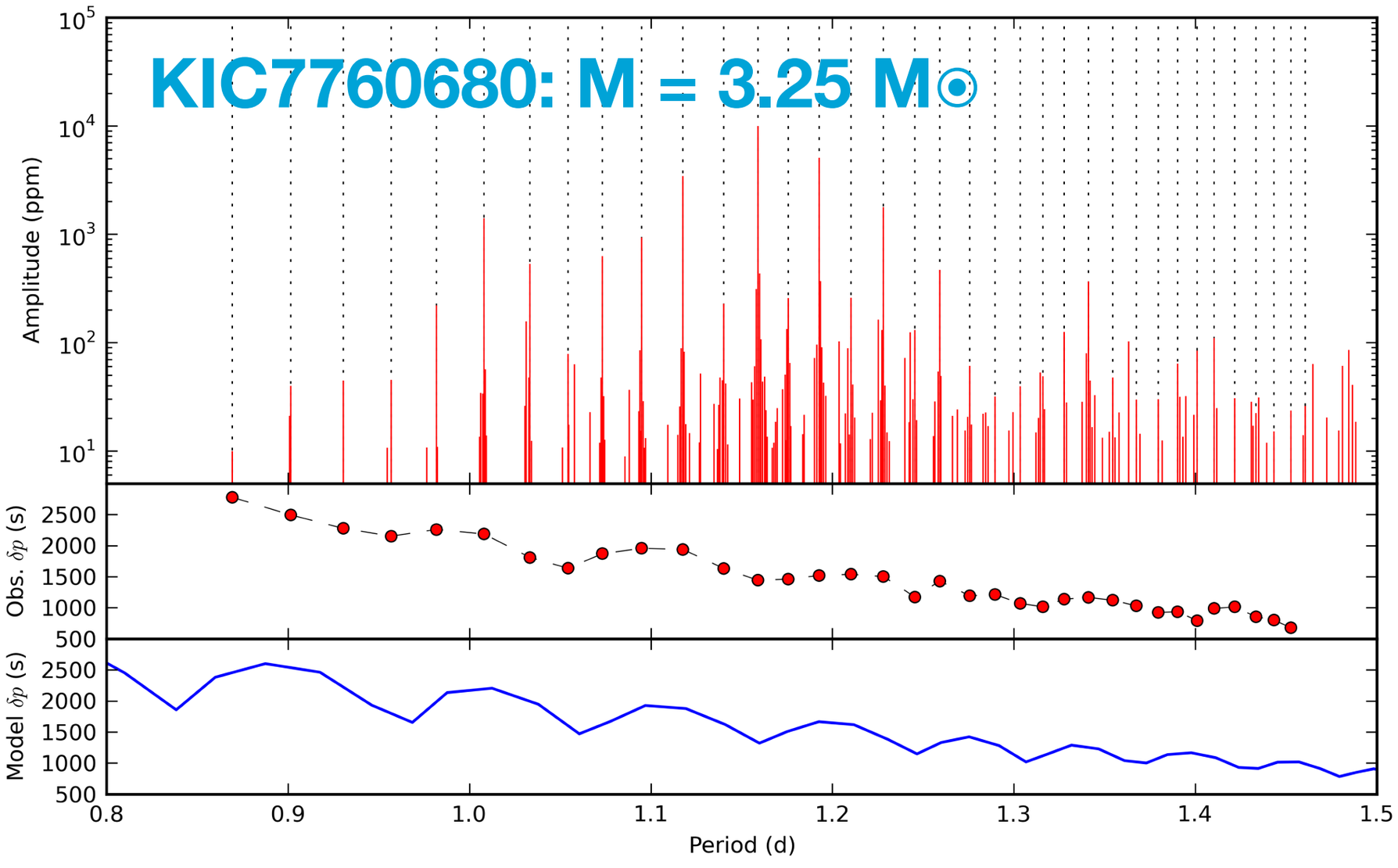
Beck et al. (2012), Mosser et al. (2012), Deheuvels et al. (2014,2015):
only factor 5 to 20 faster core-than-envelope rotation in RG
strong core/envelope coupling



standard models 100x wrong: strong internal magnetic fields? (Fuller et al. 2015; Stello et al. 2016)

"Difficult cases" BAF gravity-mode pulsators

period spacings only found since space photometry



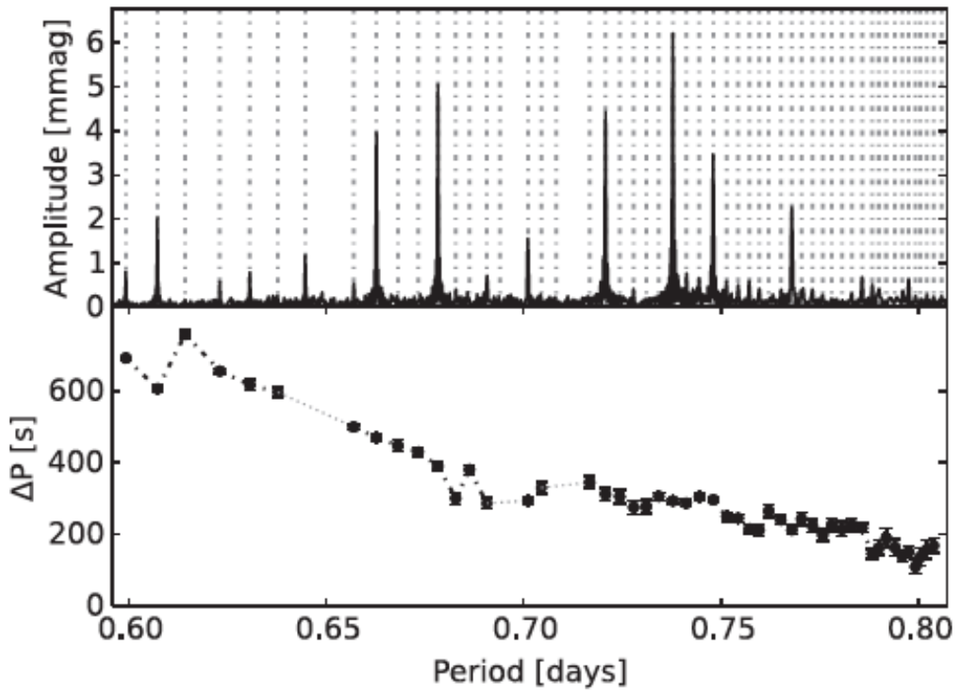
Pápics et al. (2015):
36 dipole prograde gravity modes tilted by rotation, dips due to g-mode trapping near core

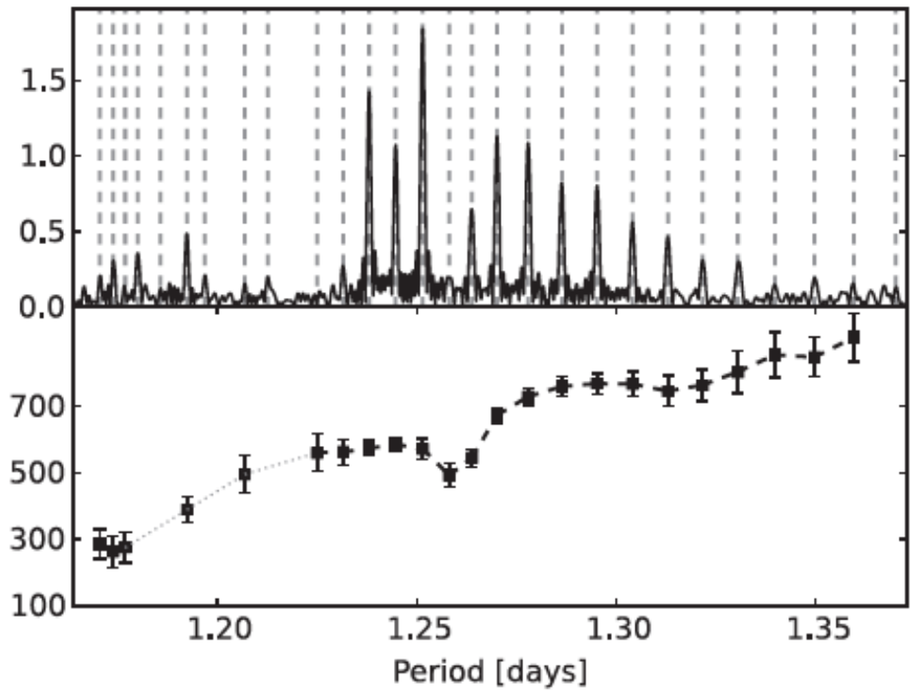
Moravveji et al. (2016):
core overshoot: 0.024
chemical envelope mixing: 6 cm^2/s
standard rotational mixing theory orders of magnitude off

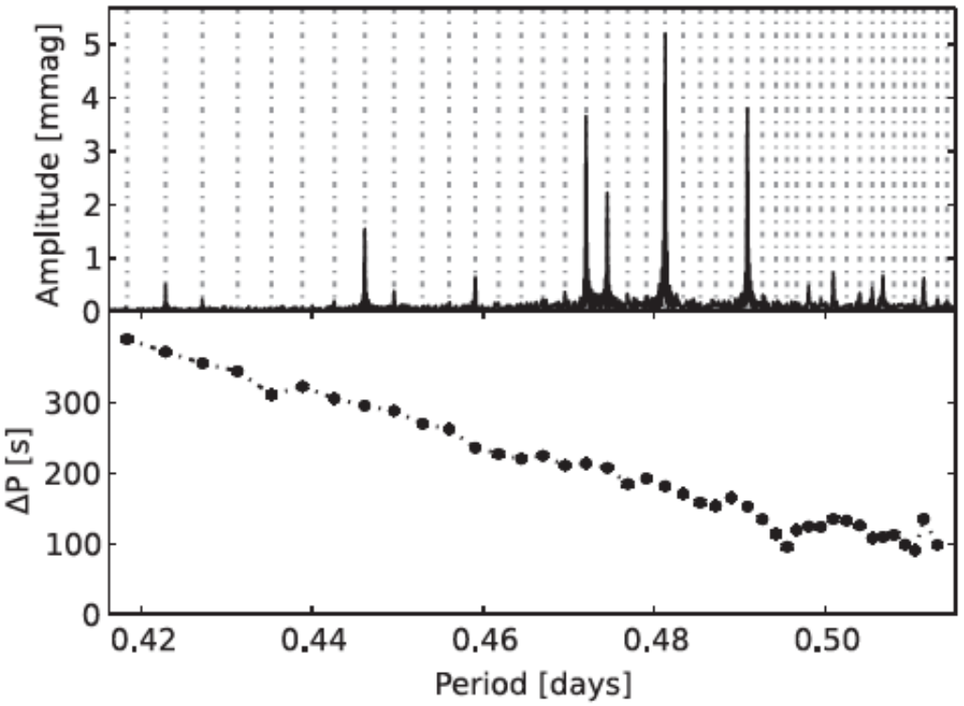
KIC 9244992 (Saio et al. 2015): <Prot> ≃ 65 days, slower envelope-than-core
KIC 11145123 (Kurtz et al. 2014): <Prot> ≃ 100 days, faster envelope-than-core
mass between 1.5 and 2.0 M⊙

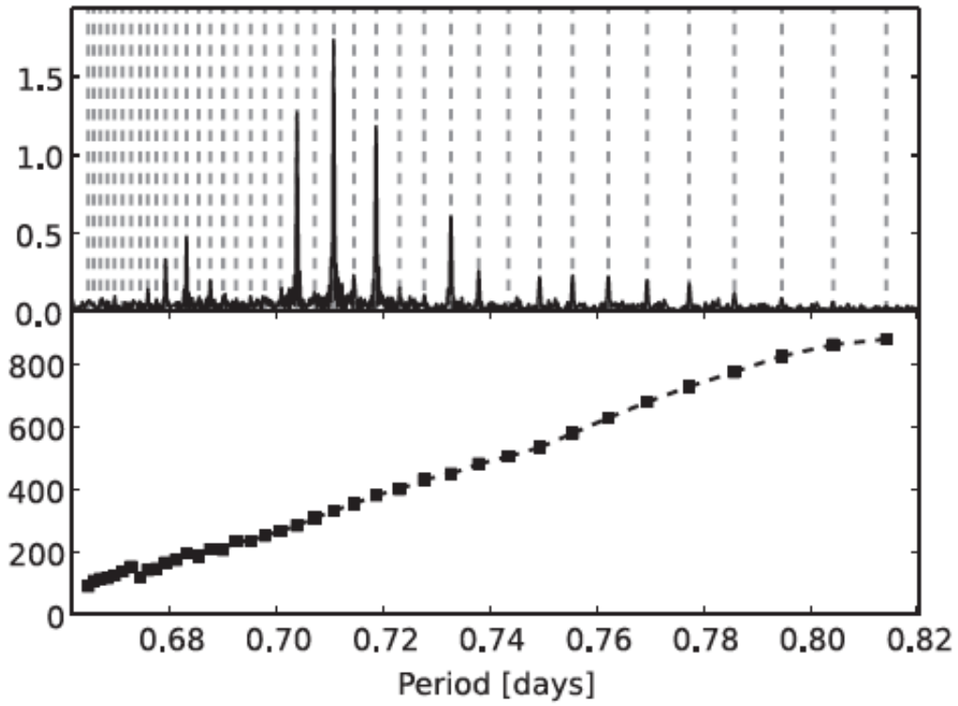
New way to probe mixing & Ω(r) in F stars:

new mathematical treatment including Coriolis force





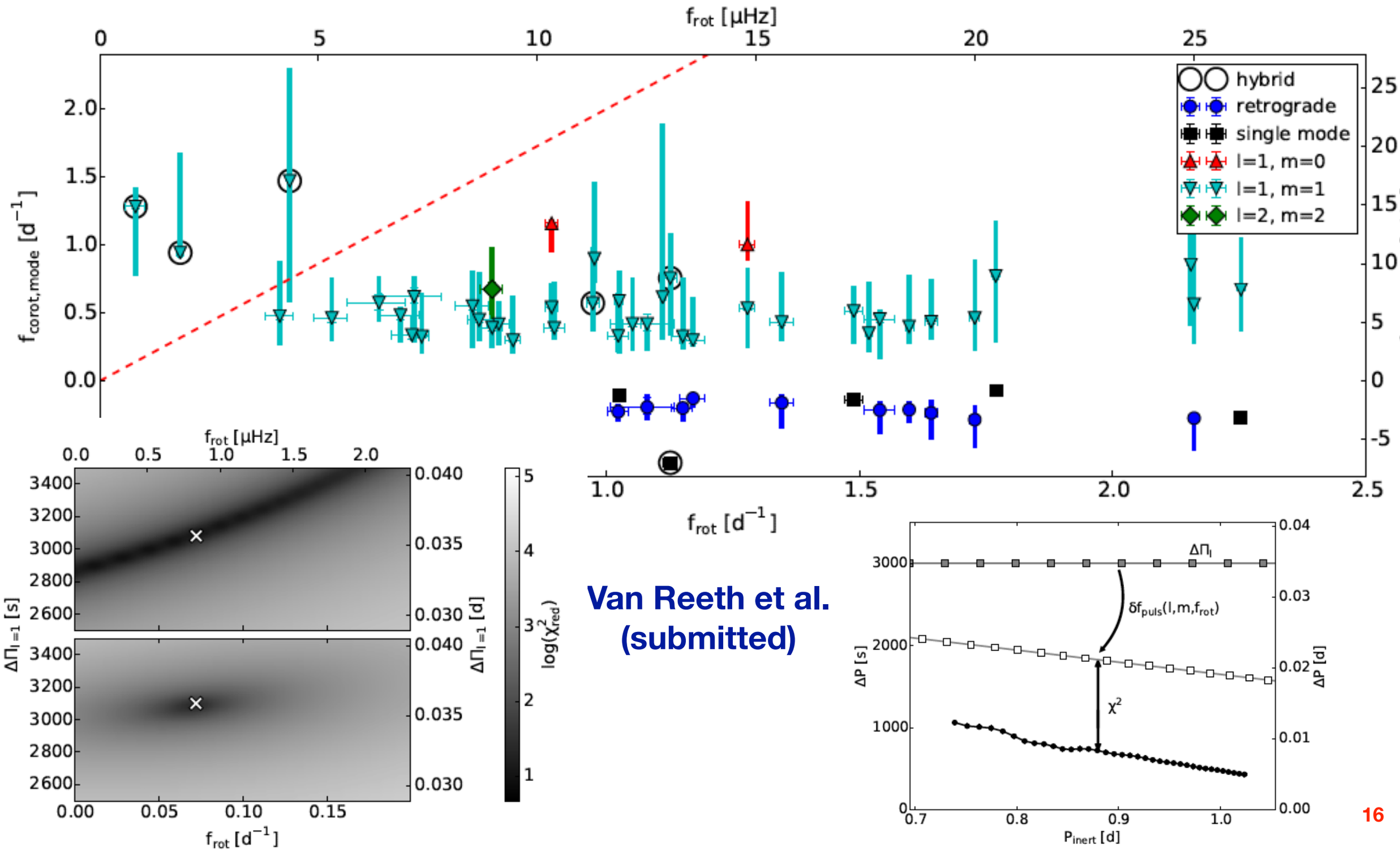




40 F-type stars with mass between 1.5 and 2 M⊙ with detected g-mode period spacings

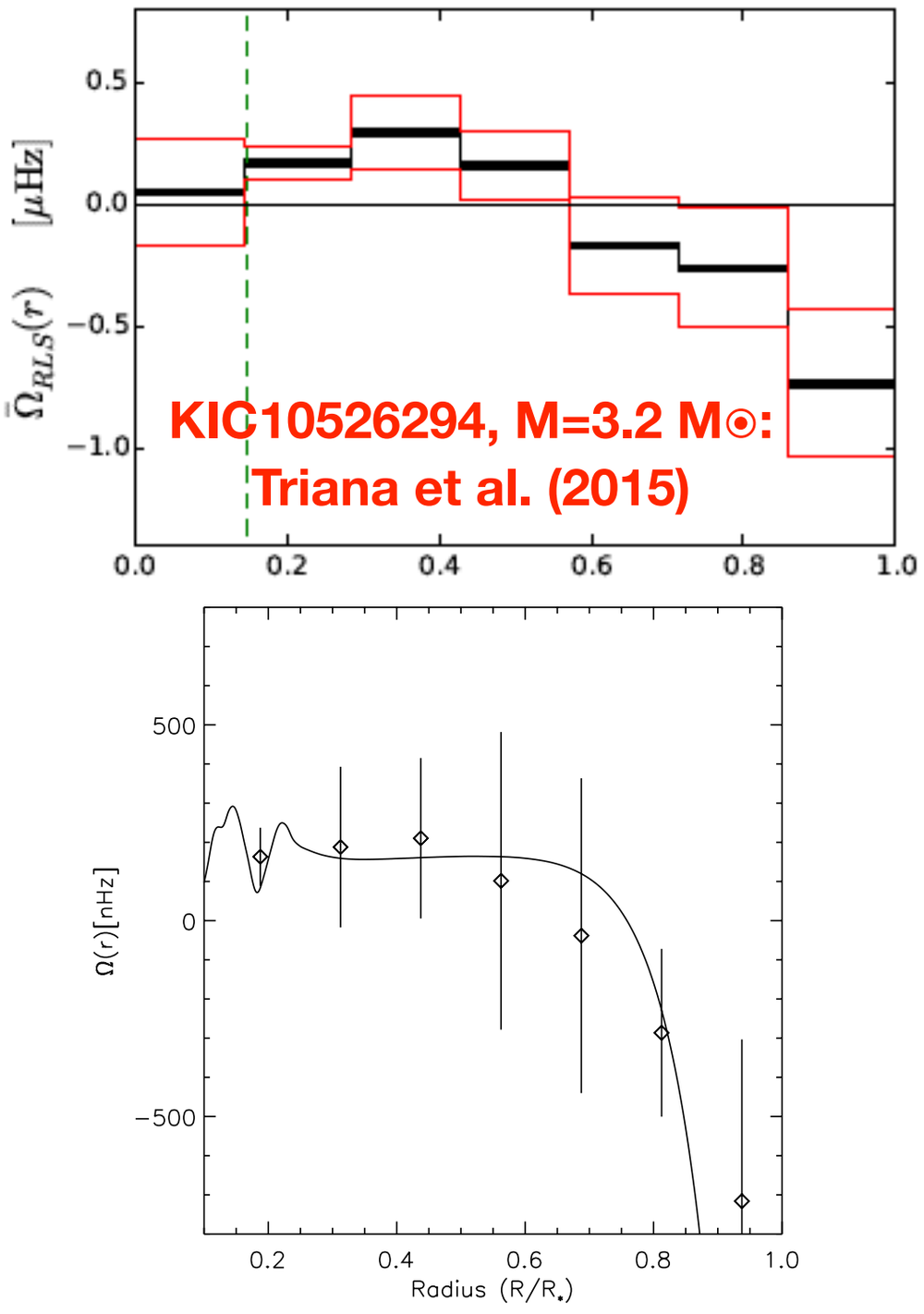
(Van Reeth et al. 2015)

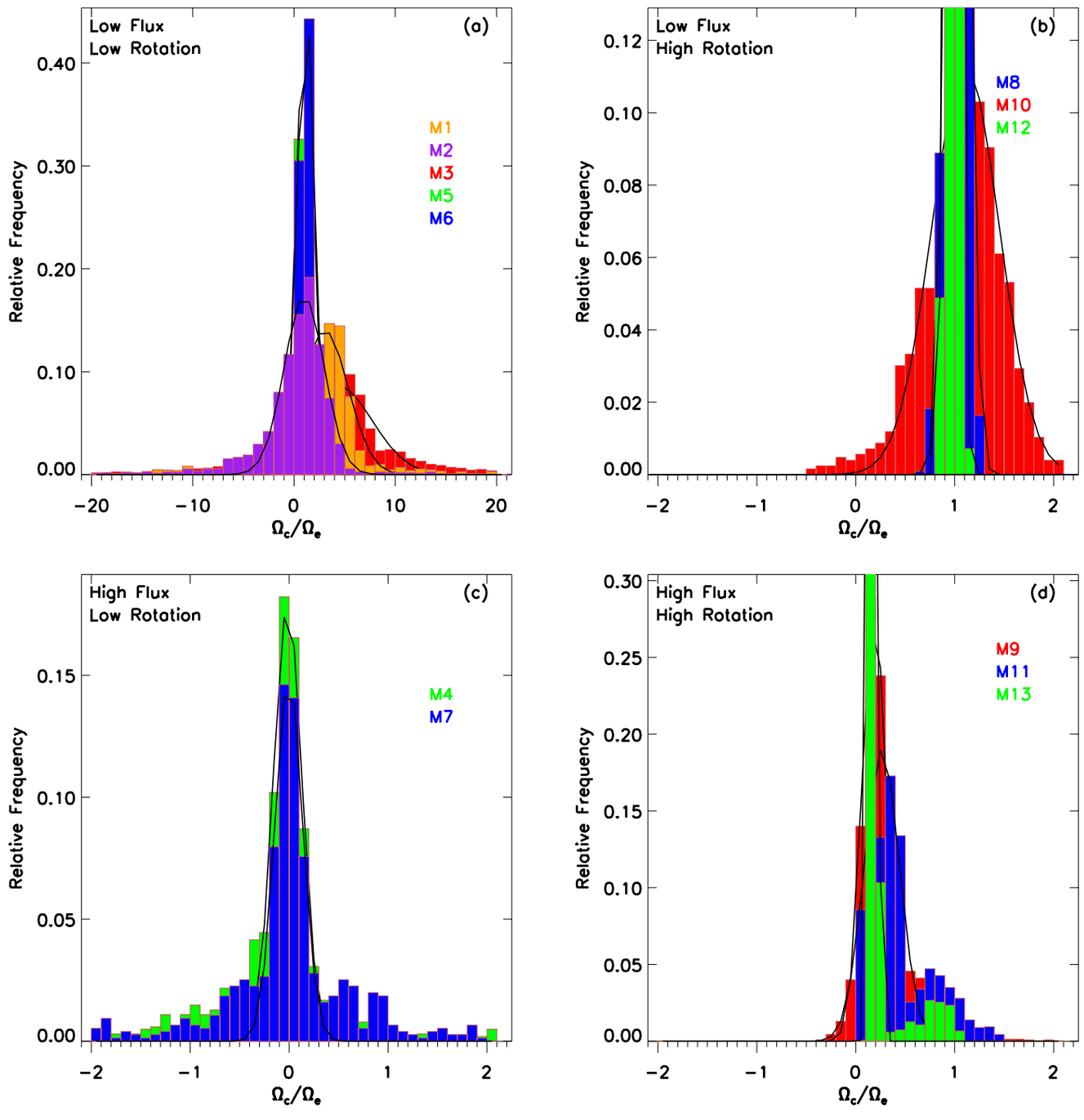
Near-core rotation of F stars with g-modes



Van Reeth et al. (submitted)

Core-to-envelope rotation: IGW in action





2/3D simulations of angular momentum transport by IGW (Rogers et al. 2013, 2015)

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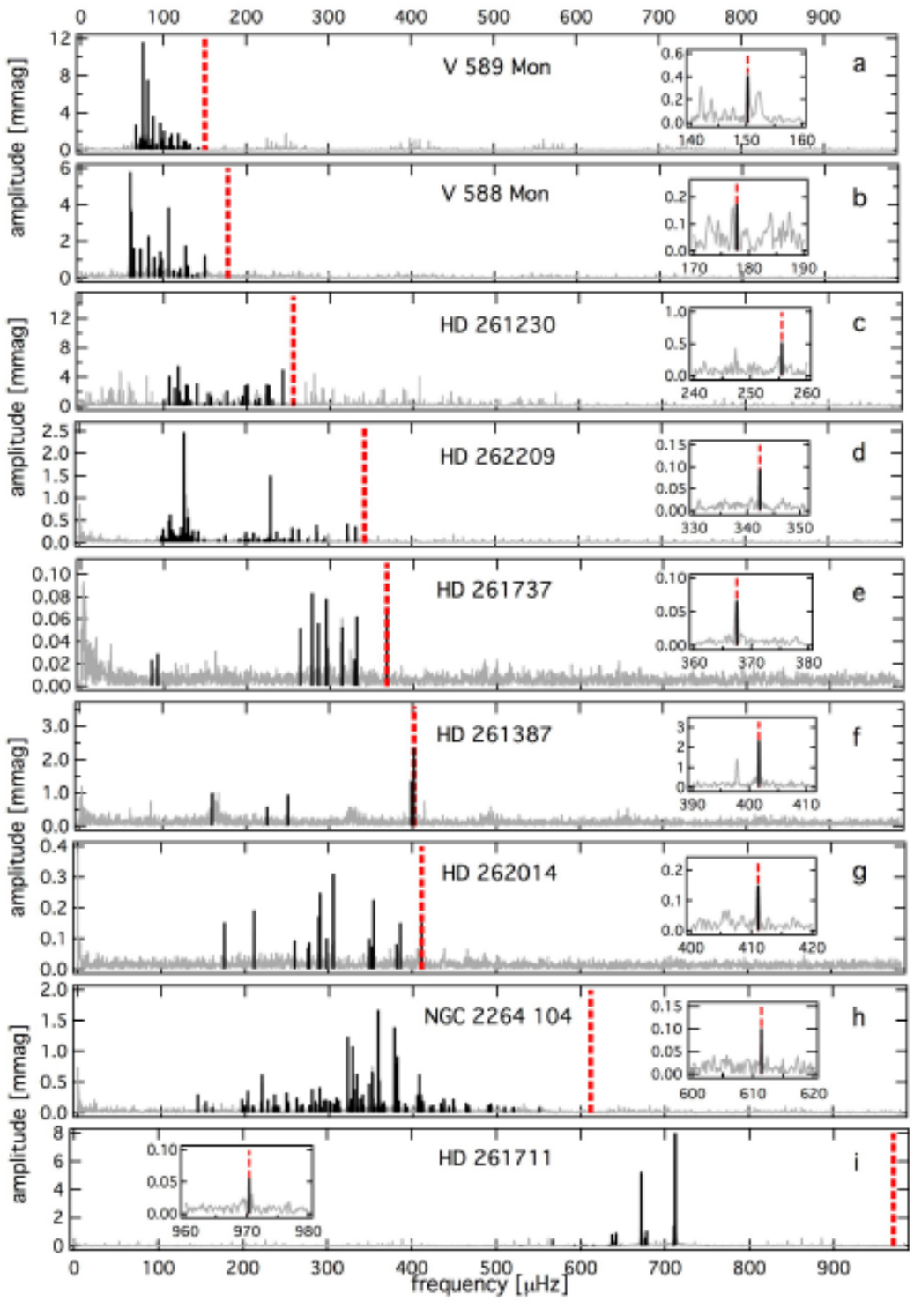
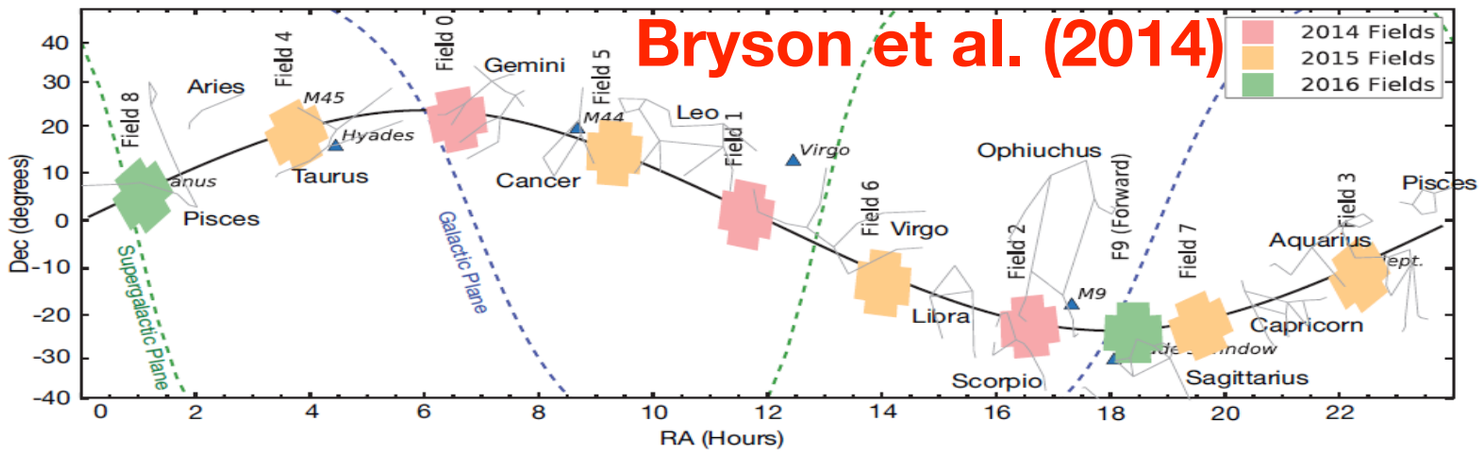
Asteroseismology in near future:

K2 potential for pre-MS pulsators & clusters



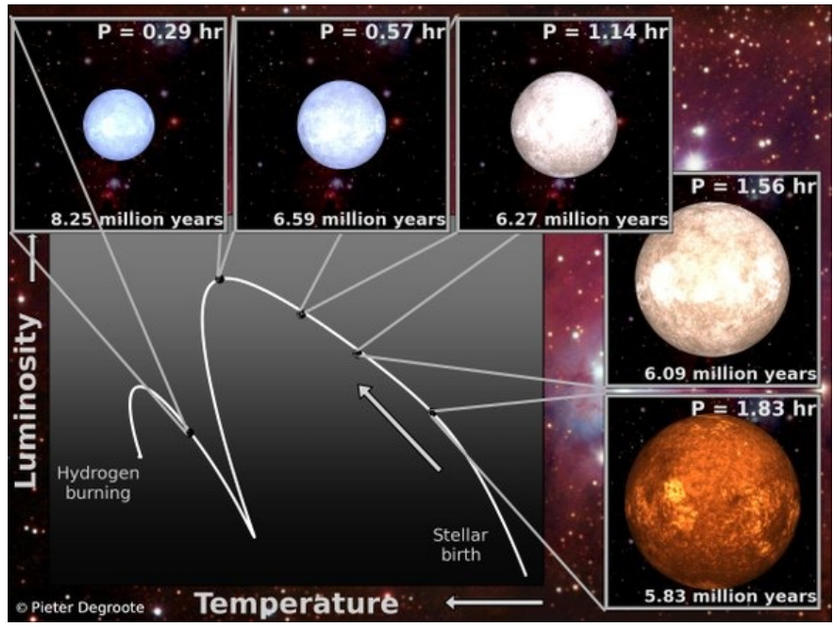


3 months/field focus on under-represented stars & clusters

Seismic evidence for multiple epochs of star formation

Rotation is slower than assumed

Zwintz et al. (2014)



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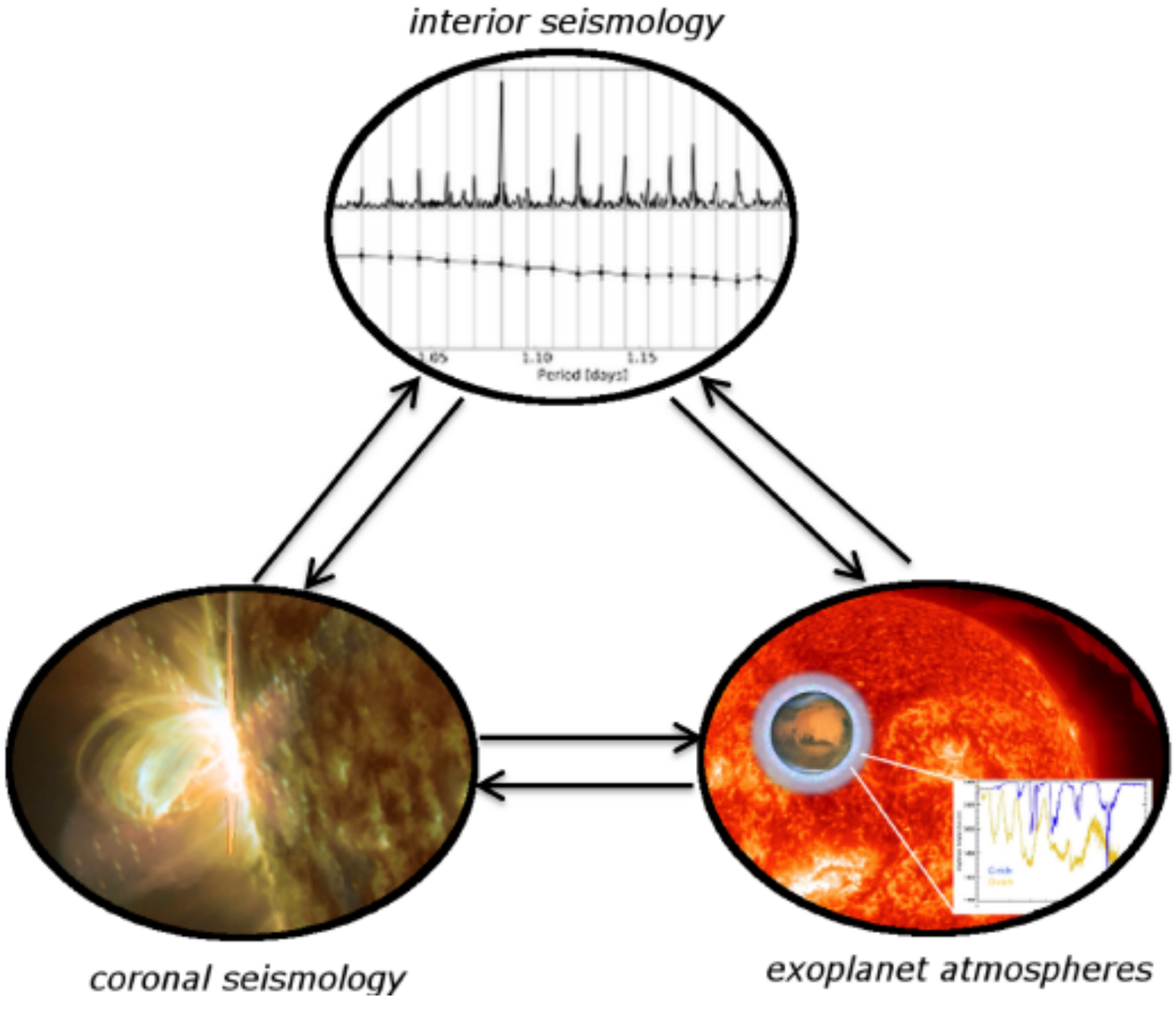
Asteroseismology & dynamical/chemical star-exoplanet interactions



Dynamical interactions and angular momentum transport/transfer?

Impact of Host Star Variability on Exoplanet Atmospheres and Climate?

Connecting stellar magnetism, flaring, rotation, pulsation and prediction of bio-markers in exoplanet atmospheres

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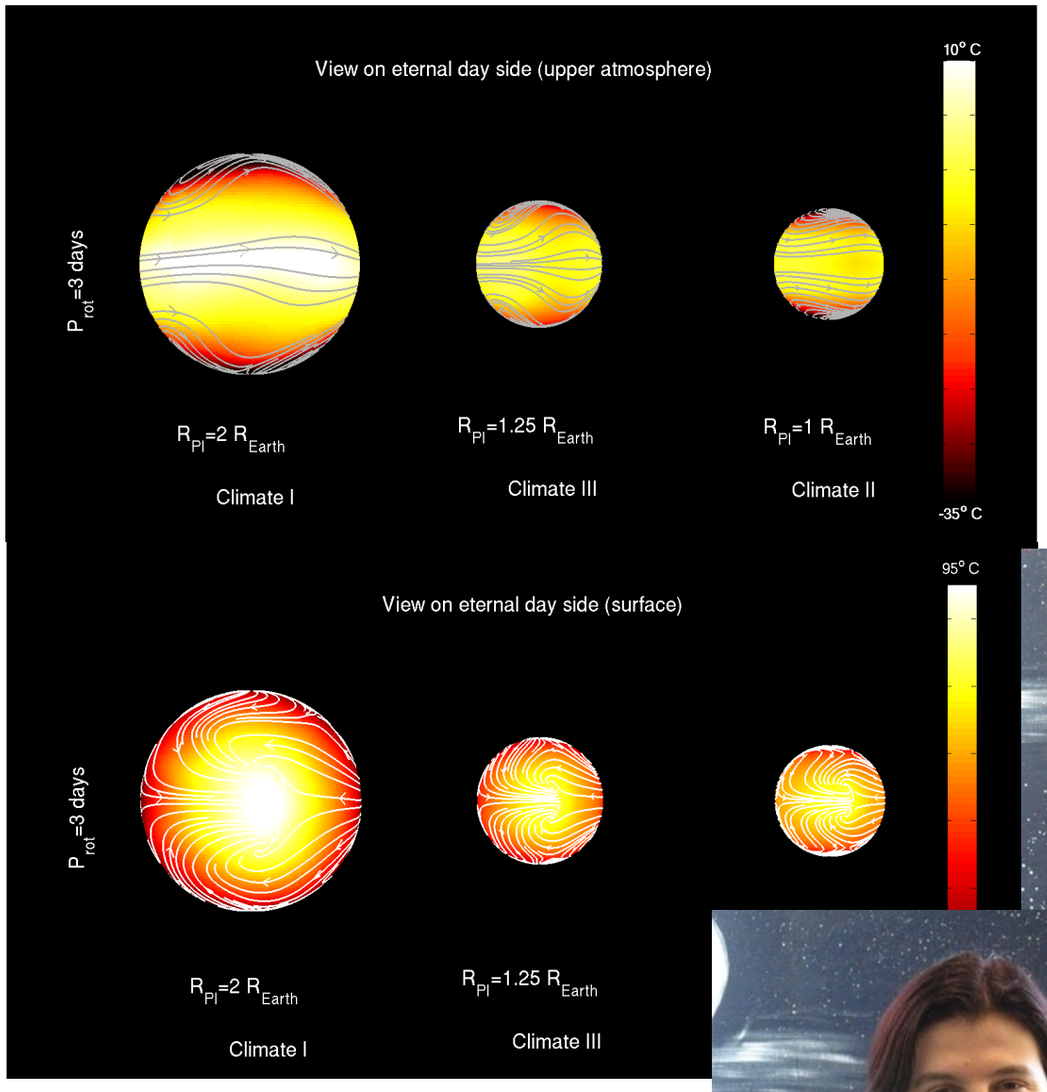
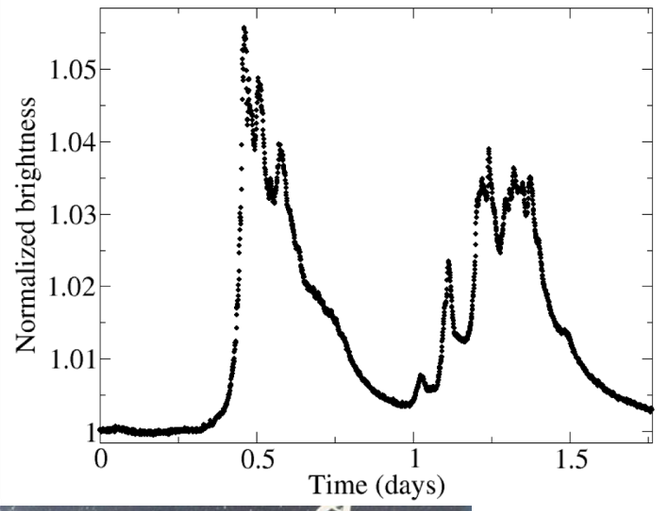
Impact host star variability on its exoplanets: modelling bio-markers in exo-atmospheres





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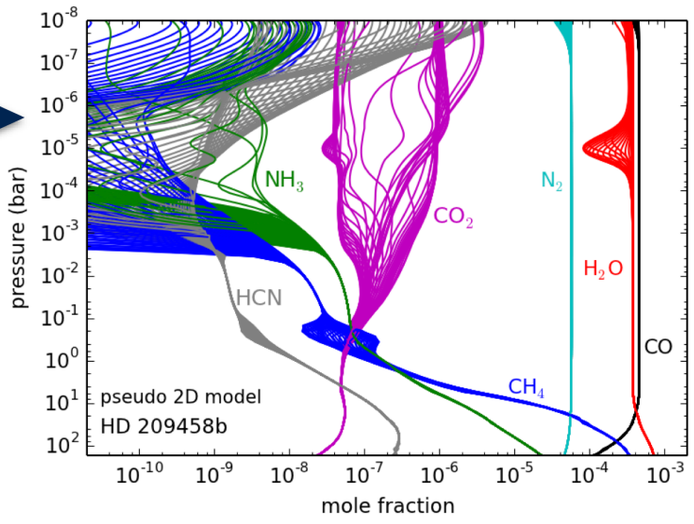
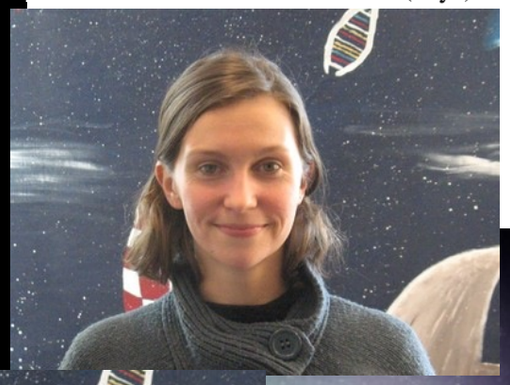
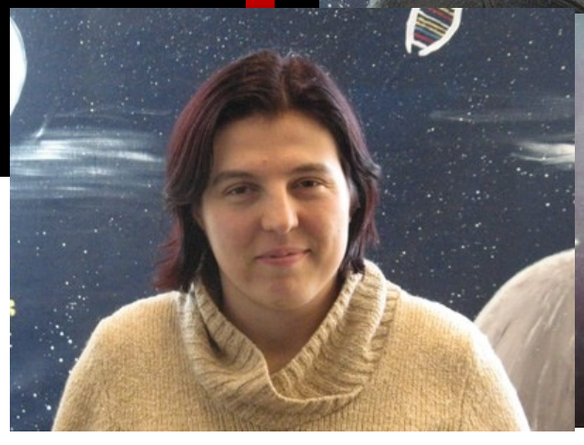
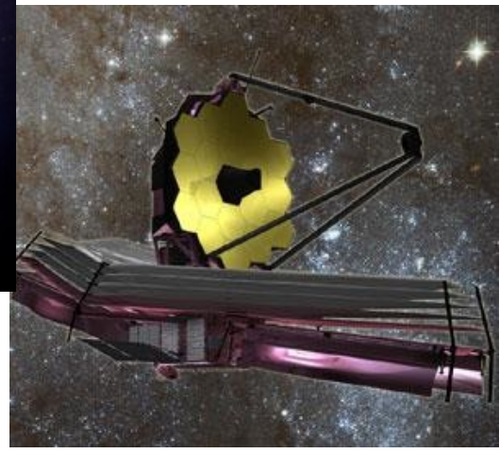


Venot et al. (2015), Tsiaris et al. (2016): modelling of photo-chemistry for ≠ C/N/O/H ratios

Effects of activity/flaring on exo-atmospheres (Venot & Decin 2015)







3D climate models of tidally-locked terrestrial exoplanets (Carone et al. 2014, 2015)

Eagerly Awaiting MIRI/JWST

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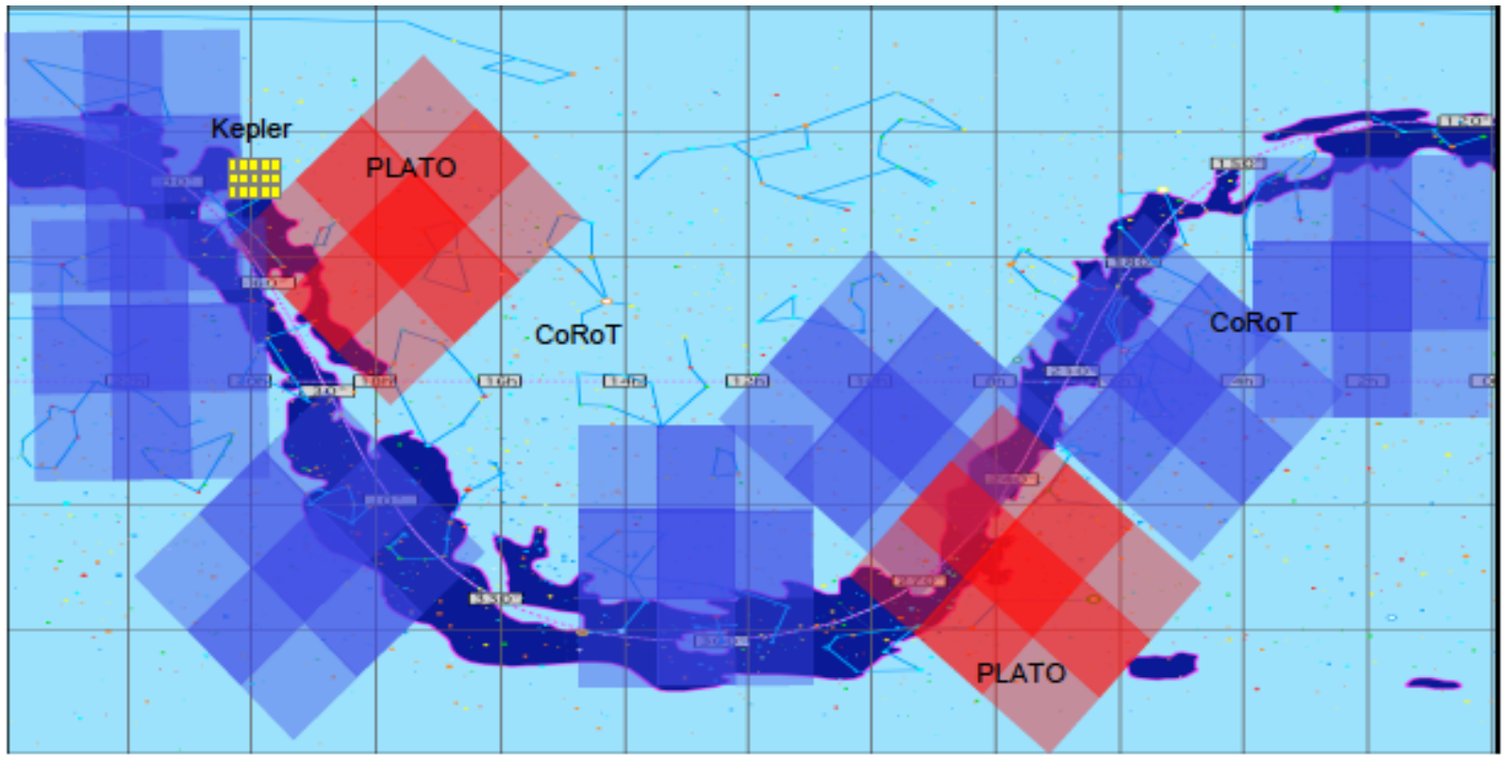
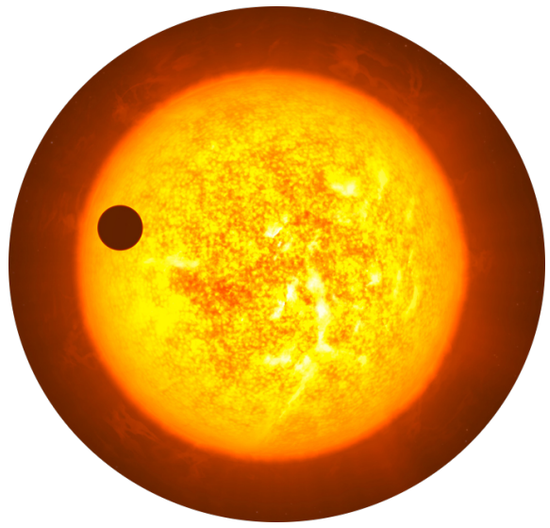
Asteroseismology & Exoplanets:
low-mass planets in HZ & wider orbits

Farther future, beyond 2024:
PLATO main mission (3 + 2 yr pointings) & its Complementary Science Programme, step-and-stare phase with targets of choice



Hopefully followed by ARIEL



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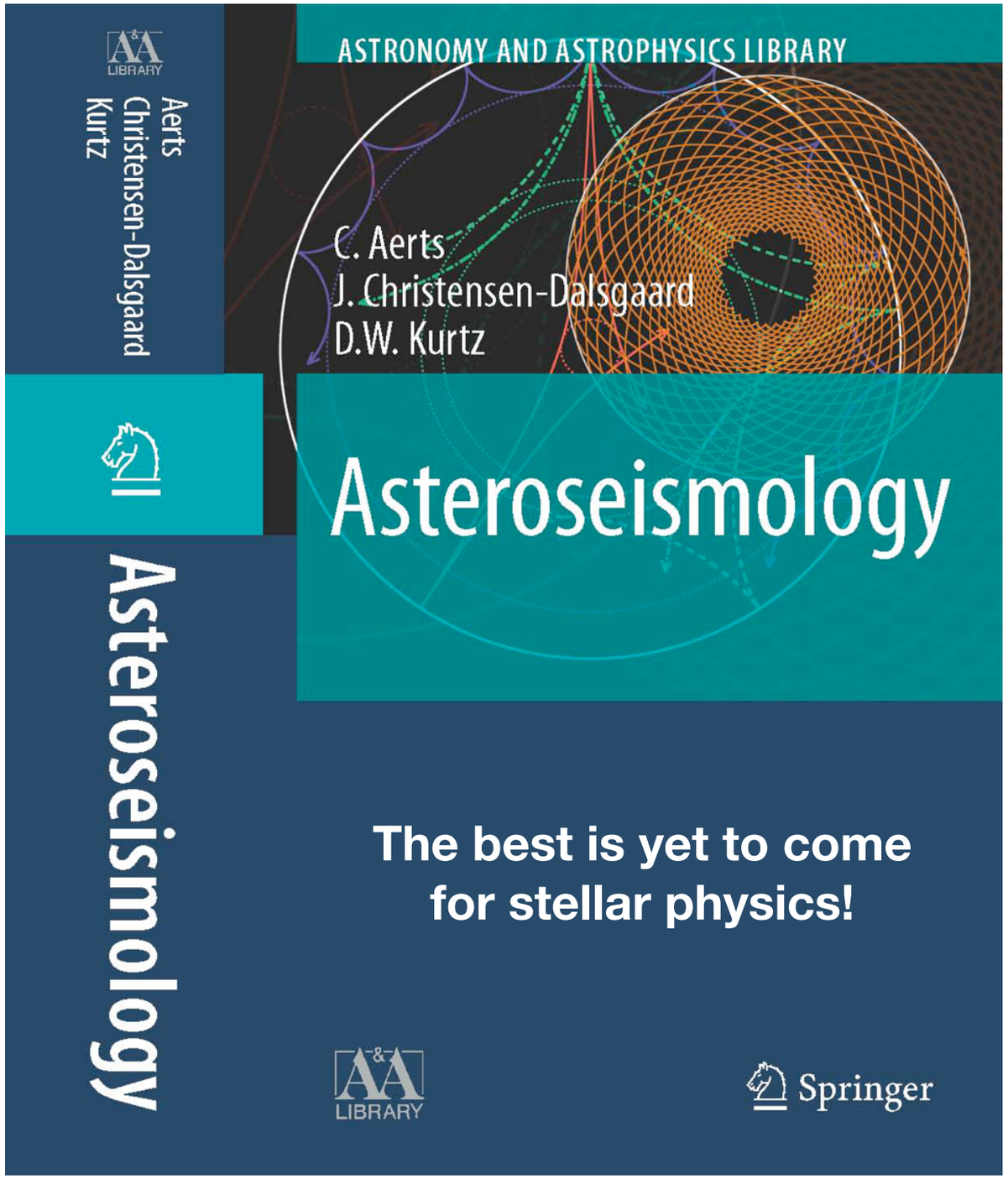
Asteroseismology: new route for stellar & exoplanetary physics



Progress made since 2009:

from ppt to ppm

from a few bright solar-like stars to thousands of stars of different types and ages

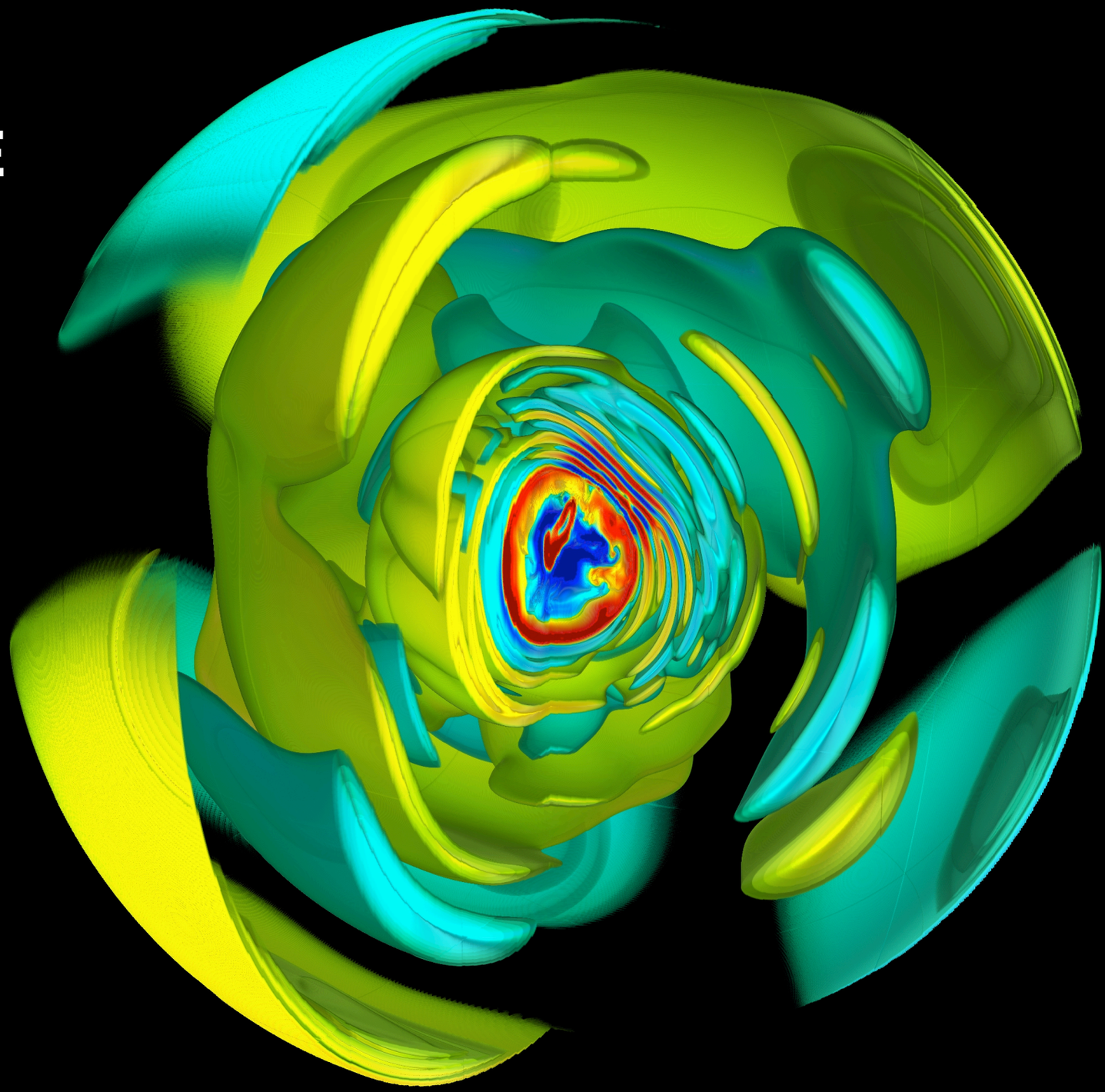
from physics in stellar envelopes to physics of stellar cores

observational probing of internal rotation, mixing, and angular momentum

STFC & ERC/AdG: MAMSIE

Coupling of 2/3D hydrodynamical simulations of massive stars to 1D stellar evolution theory to constrain angular momentum transport and mixing as a function of stellar mass and age

Direct comparisons to observations: time-series spectroscopy & Kepler data of OBAF-stars to look for IGW signature and internal differential rotation as a function of evolution



Two postdocs are advertised to work on this:

Observational/theoretical w/ C. Aerts in Leuven (conny.aerts@ster.kuleuven.be)

Numerical w/ T. Rogers in Newcastle (tamirogers@mac.com)