Asteroseismology for Stellar Evolution, Exoplanets, and Galactic Structure

Image credit: NASA's Goddard Space Flight Center/S. Wiessinger

2019 Oort Graduate Lectures

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Asteroseismology for Stellar Evolution, Exoplanets, and Galactic Structure

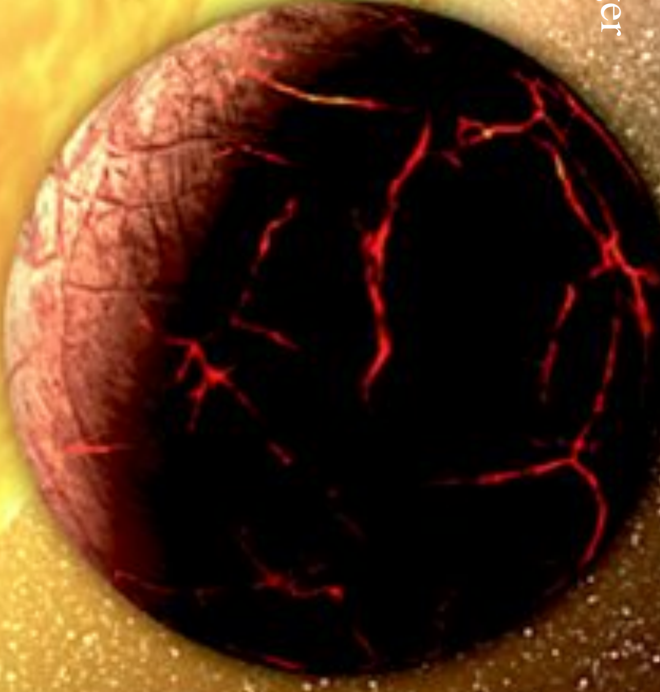


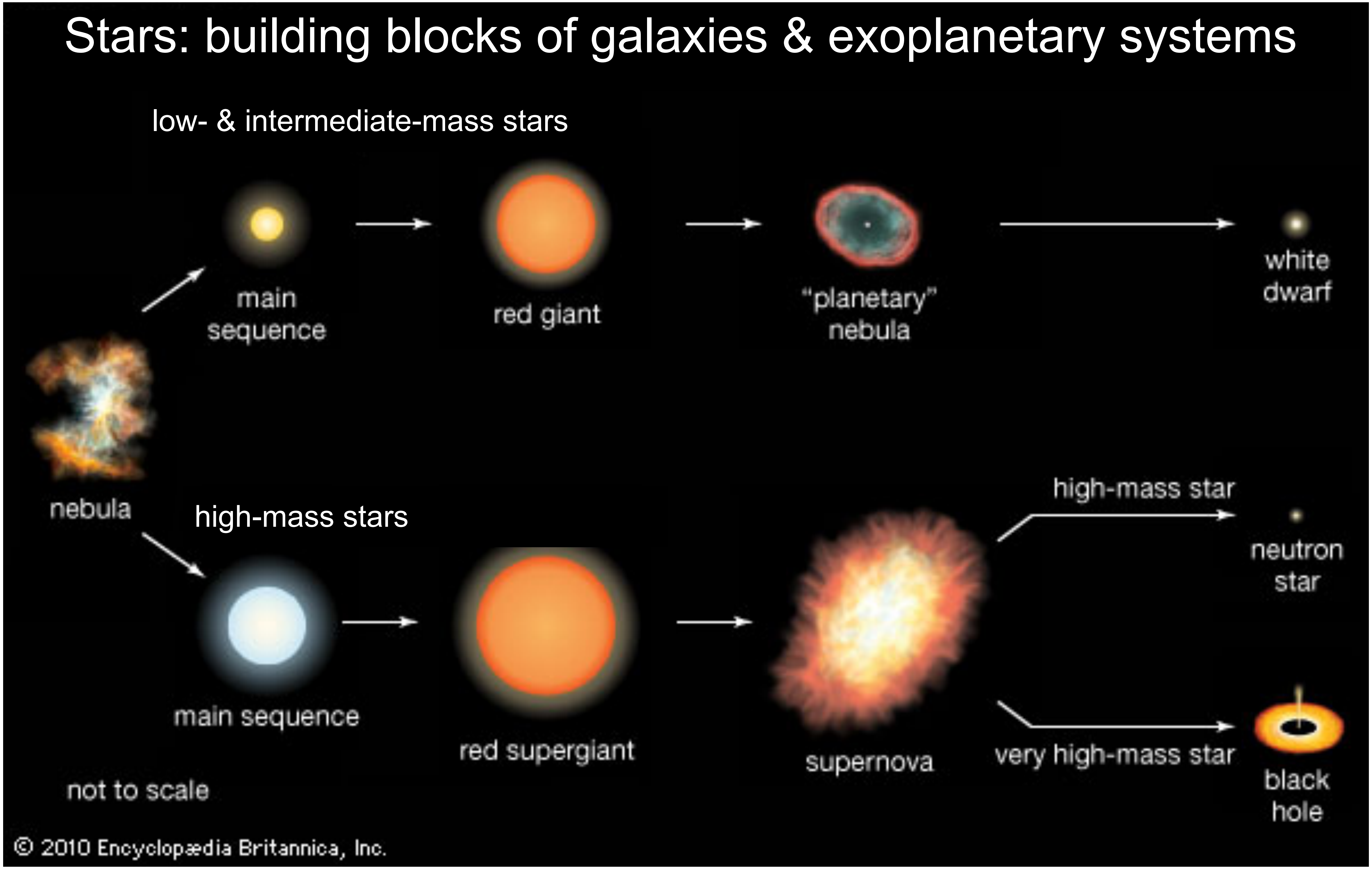
Image credit: NASA's Goddard Space Flight Center/S. Wiessinger

Class 1: Introducing starquakes

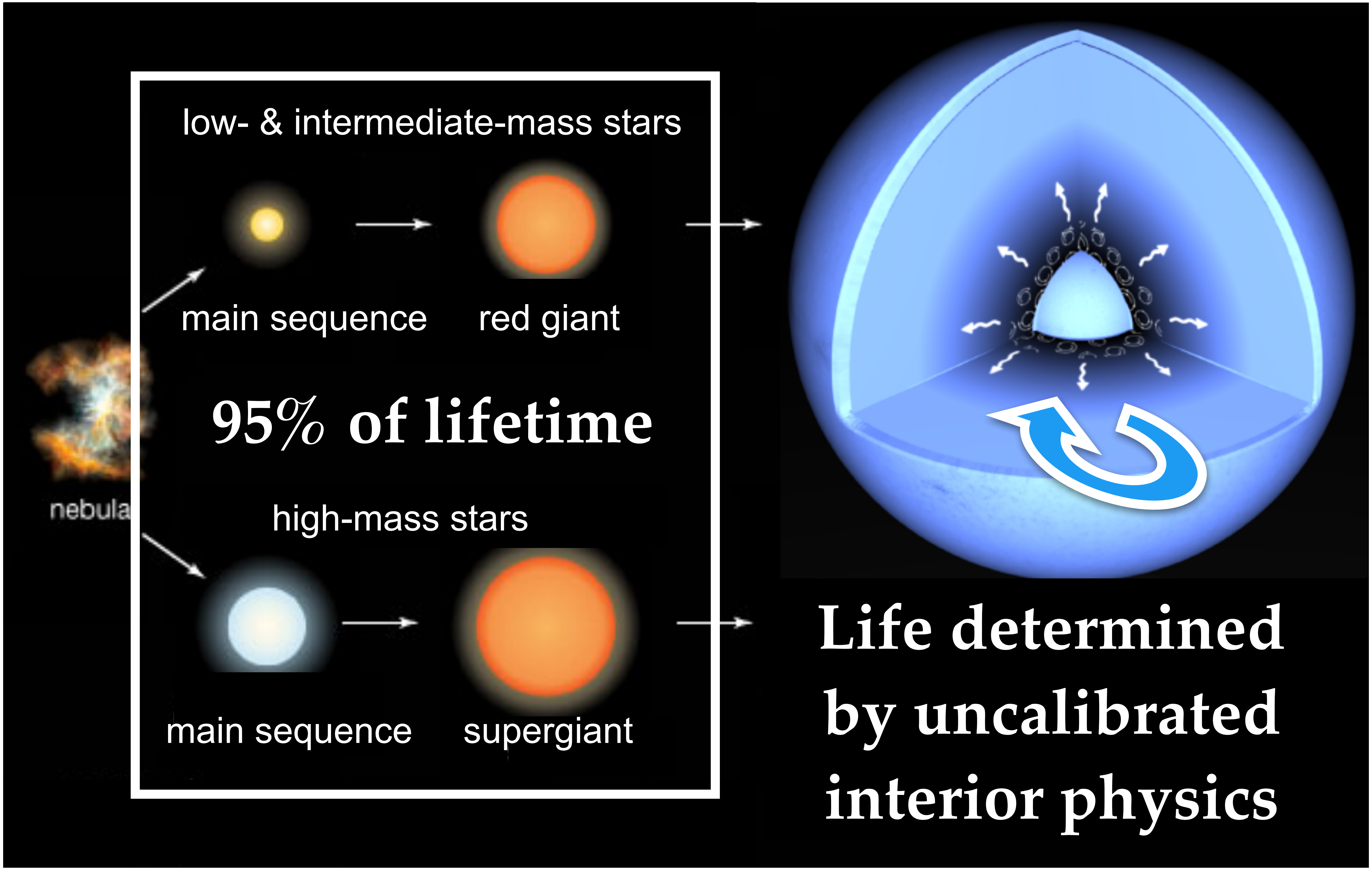
Class 2: Weighing, Sizing, Ageing

Class 3: Angular Momentum Transport

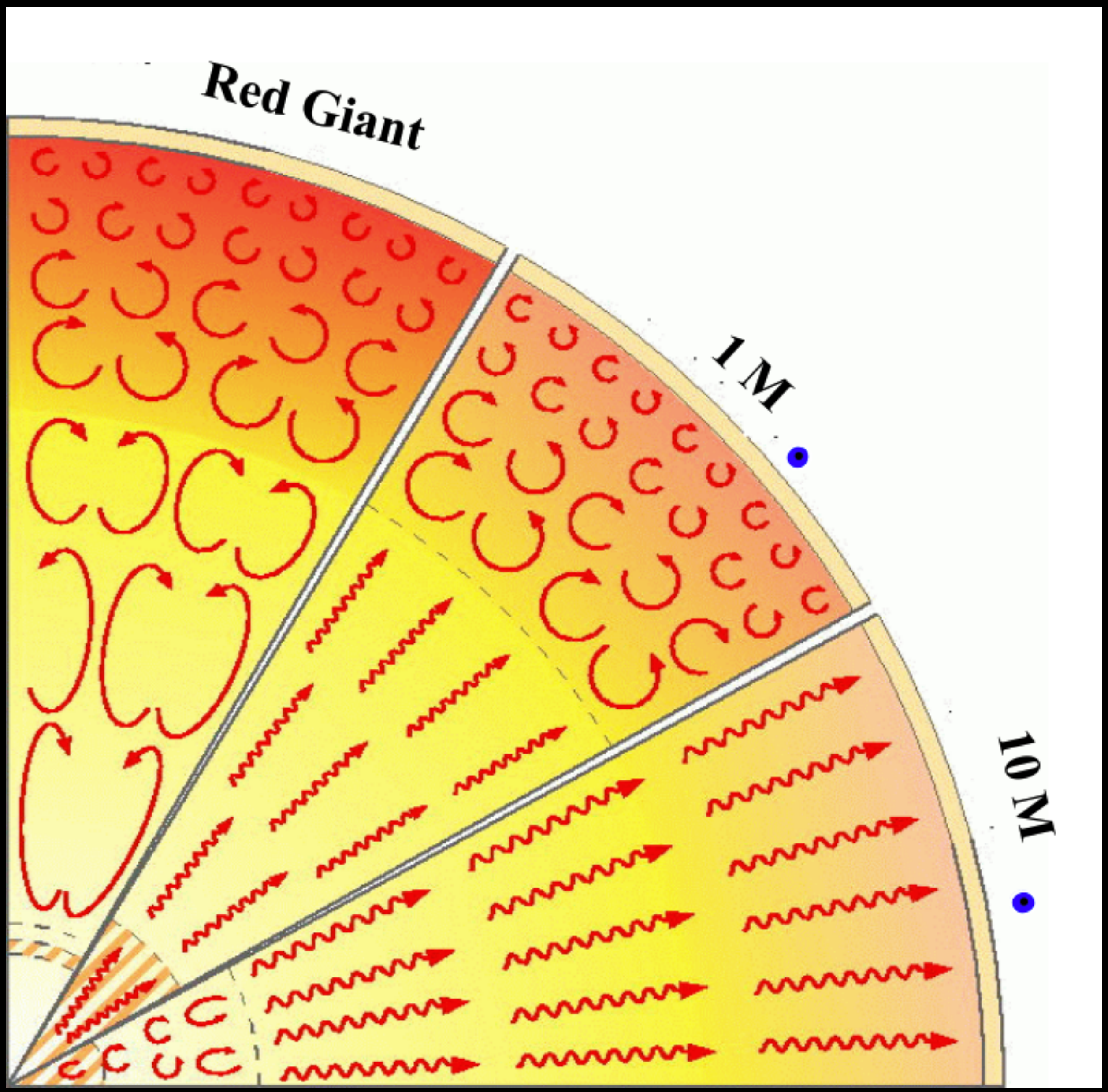
How Do Stars Live?

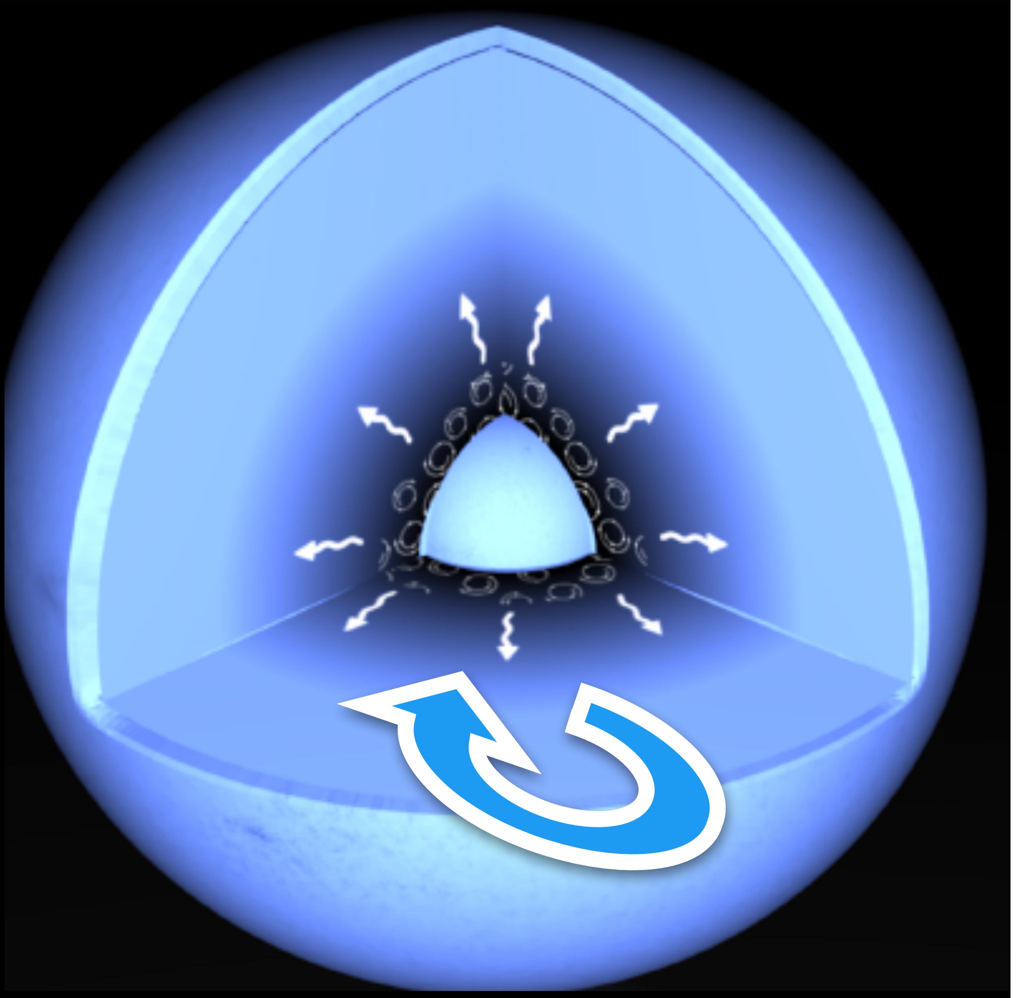


Rotation? Convection? Mixing?



Rotation? Convection? Mixing?





Life determined by uncalibrated interior physics

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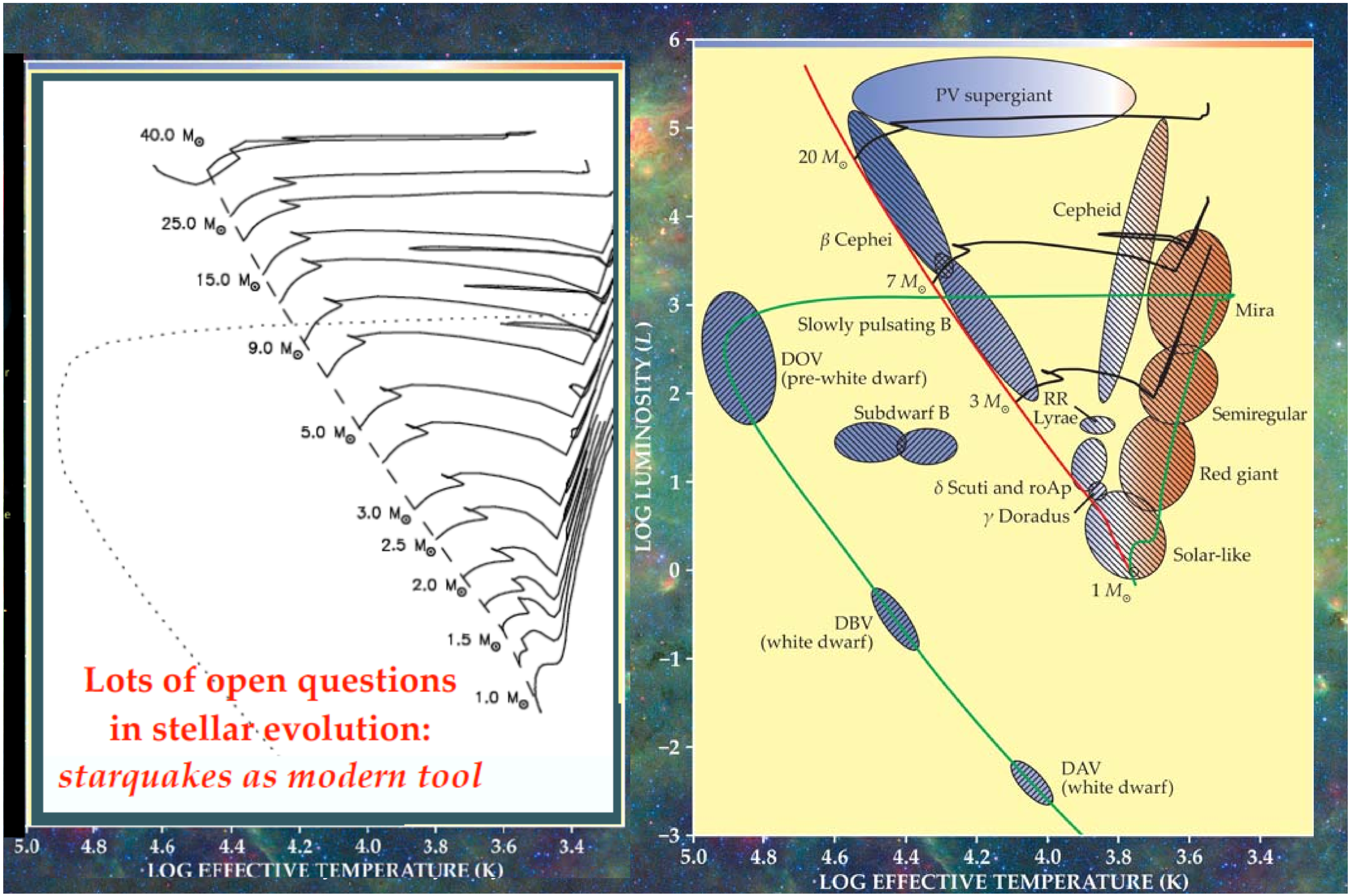
Asteroseismic HRD

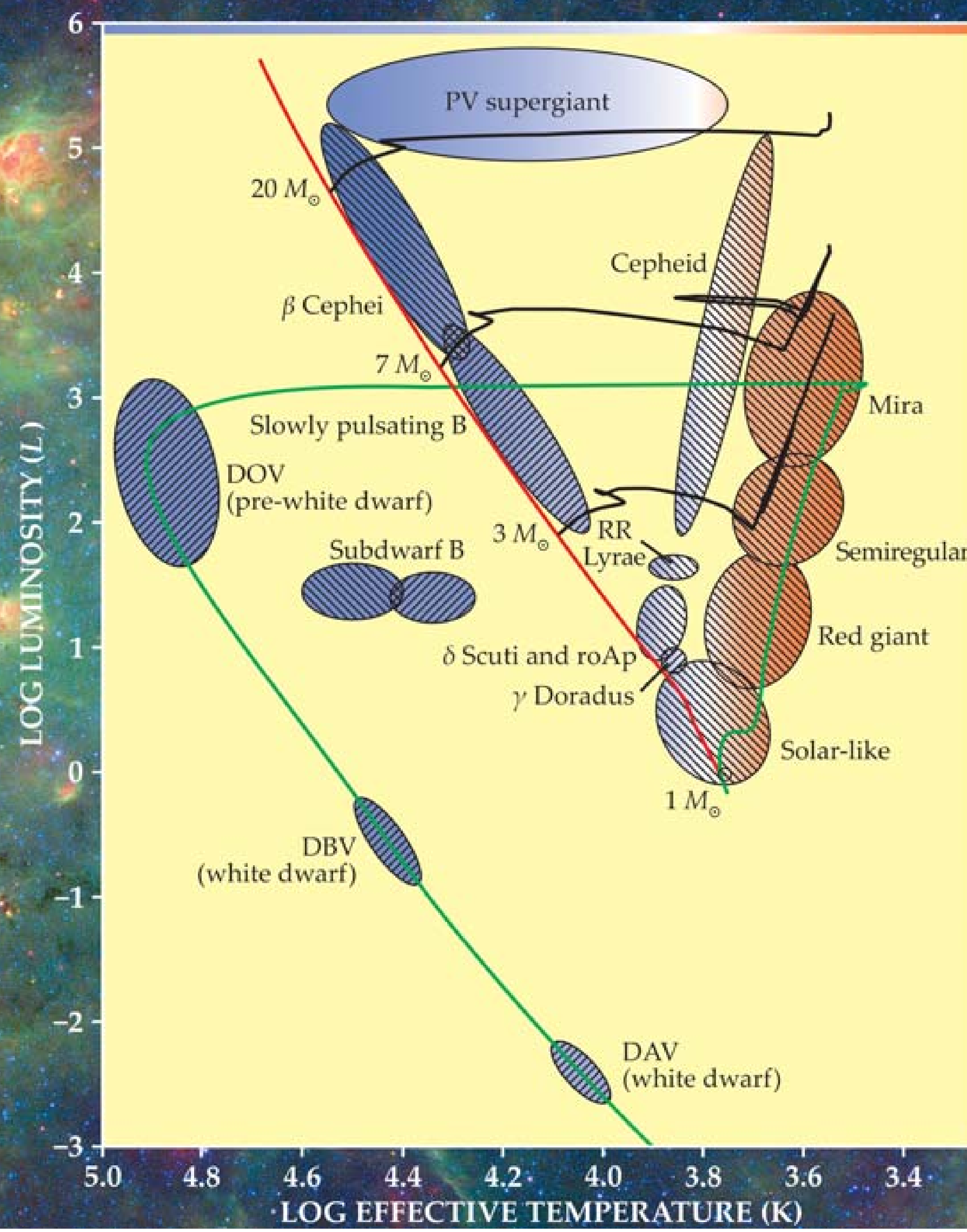


Lots of open ? in stellar physics

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

***Connection* between life of host star and its exoplanets?**

***Stellar versus dynamical* evolution of our Milky Way?**

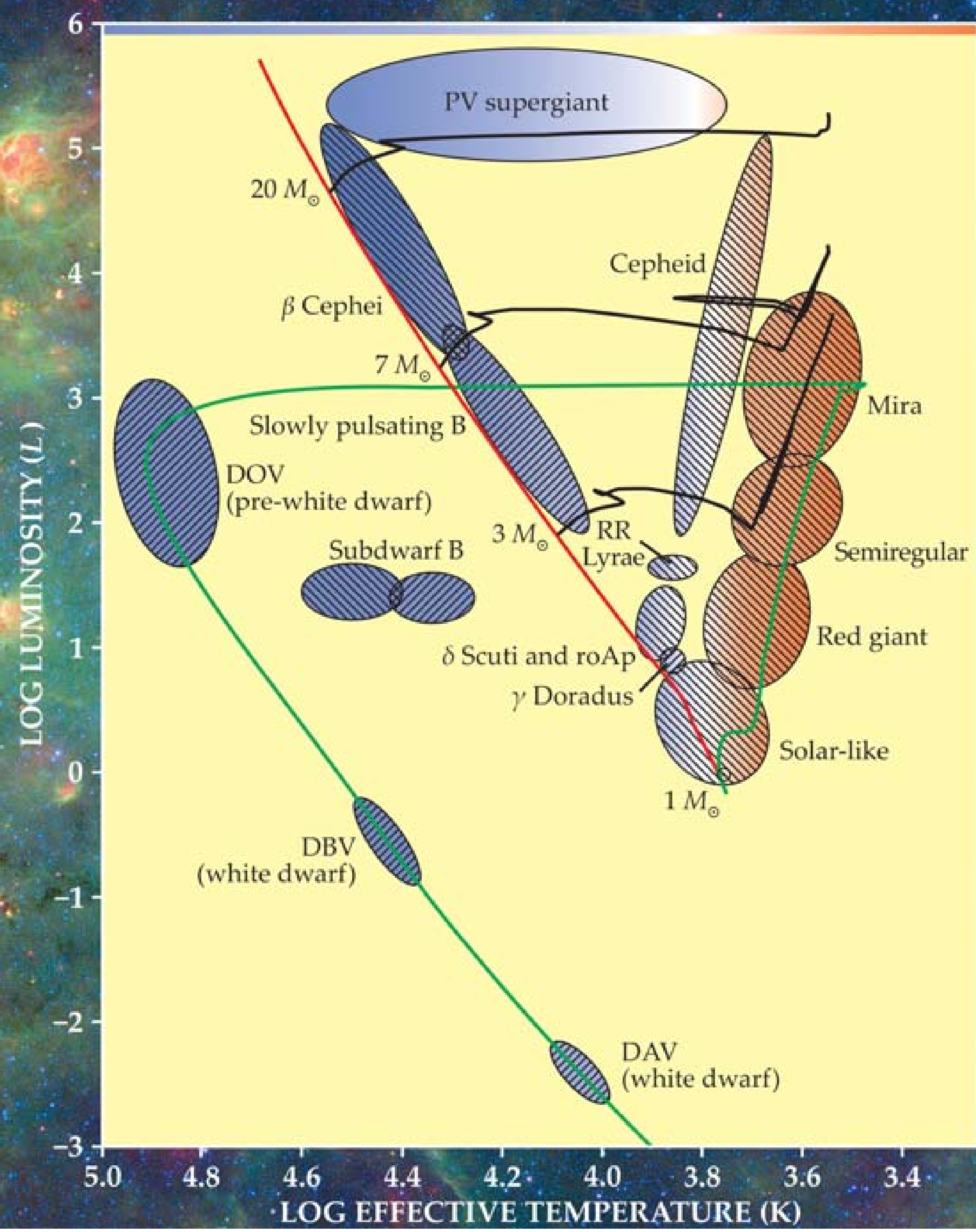


From C. Aerts, Physics Today, May 2015

Starquakes as Modern Tool

Stellar evolution is dictated by *stellar interior*

Asteroseismology requires *long-term uninterrupted high-precision data*



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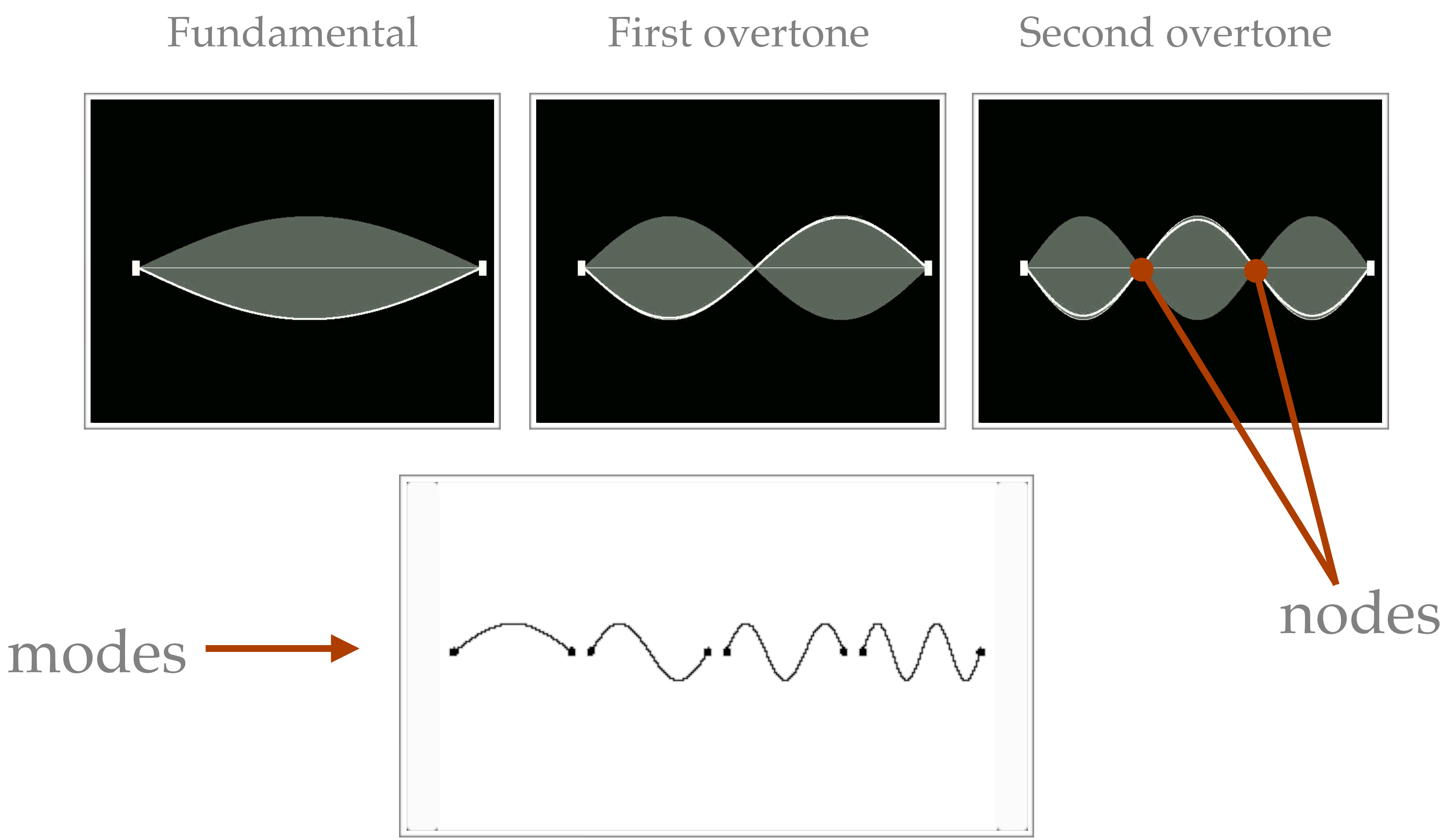
1-dimensional oscillations



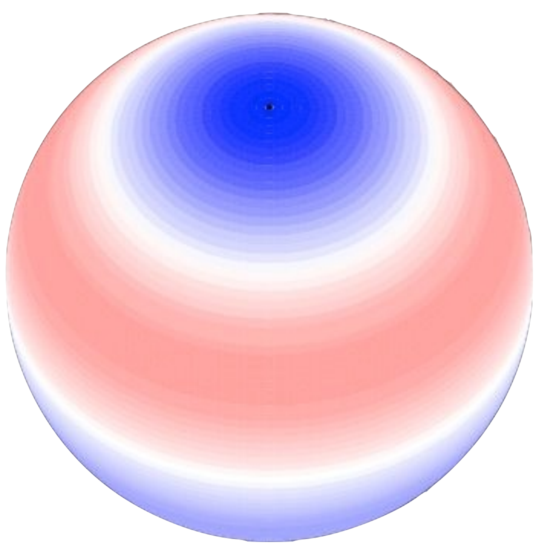
3-dimensional oscillations

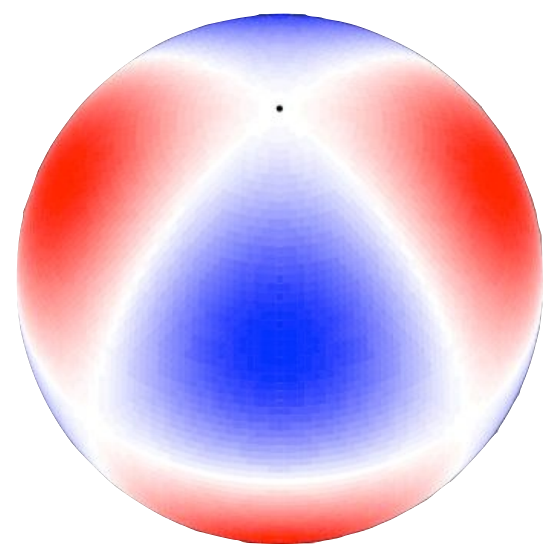
(l,m)=(3,0)
axisymmetric

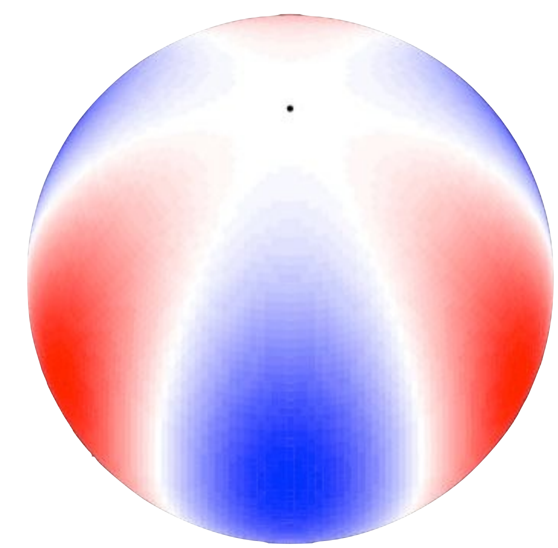
(l,m) = (3,2)
tesseral

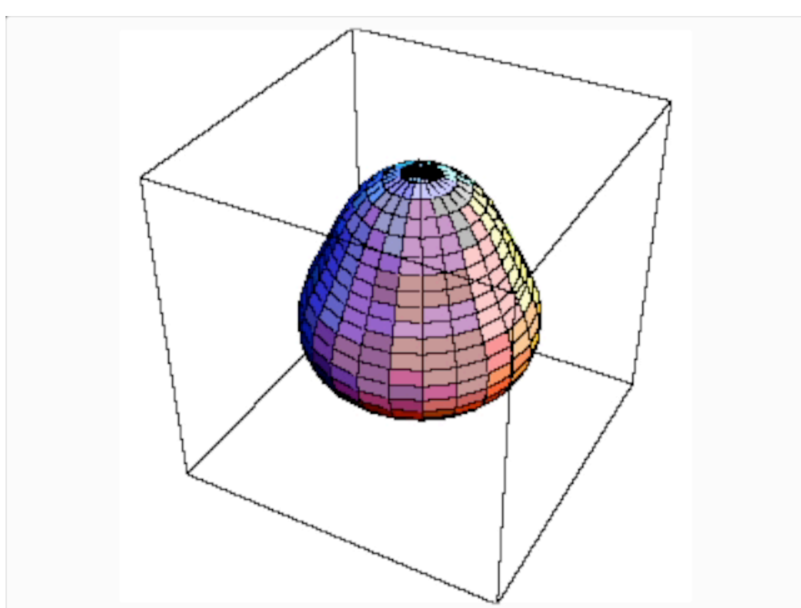
(l,m)=(3,3)
sectoral

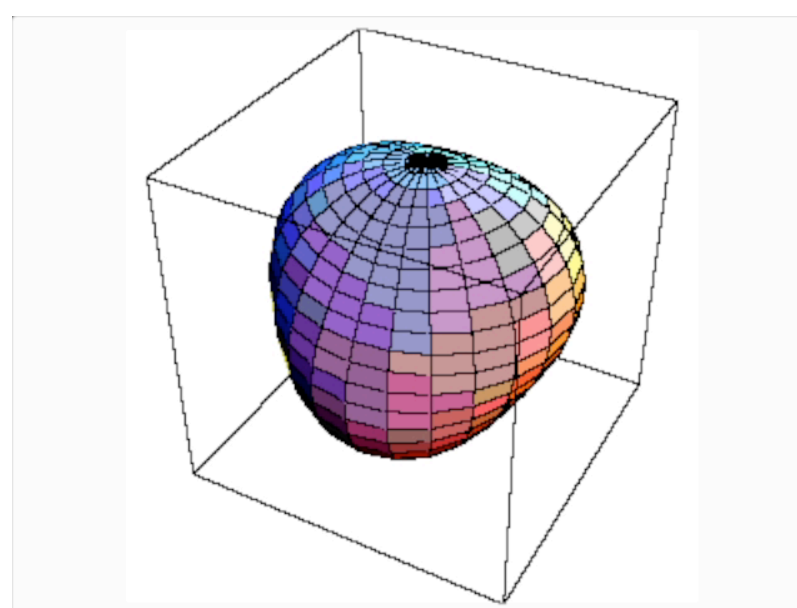
Blue: Moving towards Observer   Red: Moving away from Observer

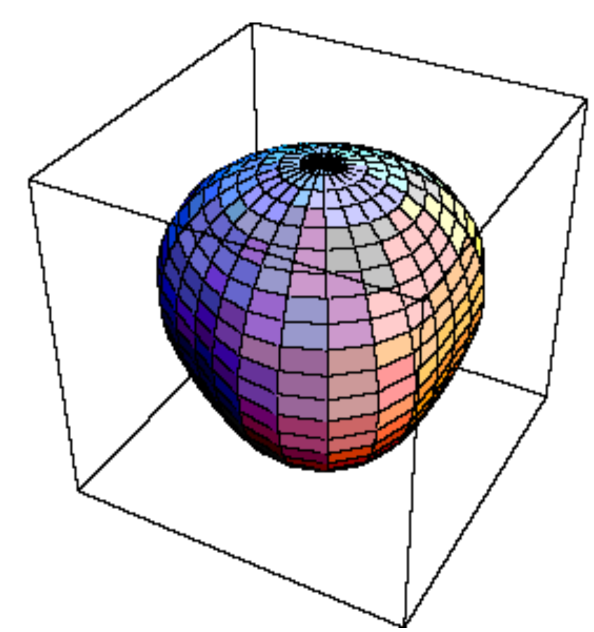




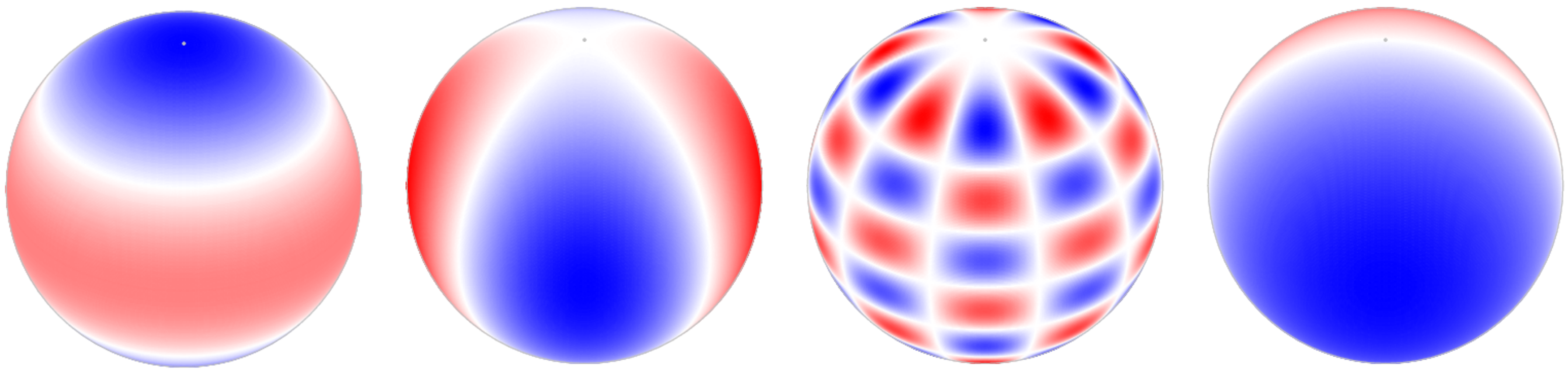


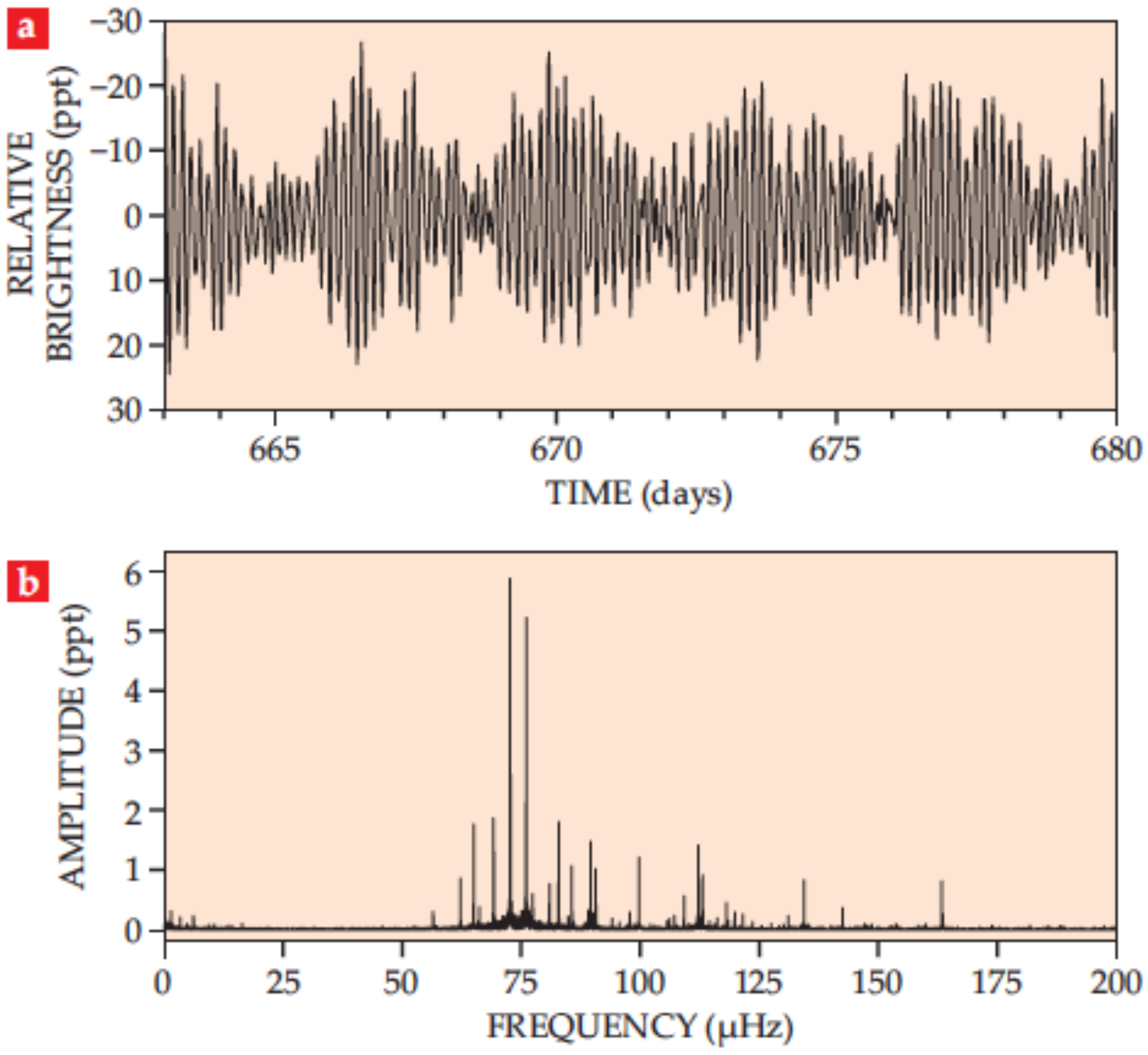


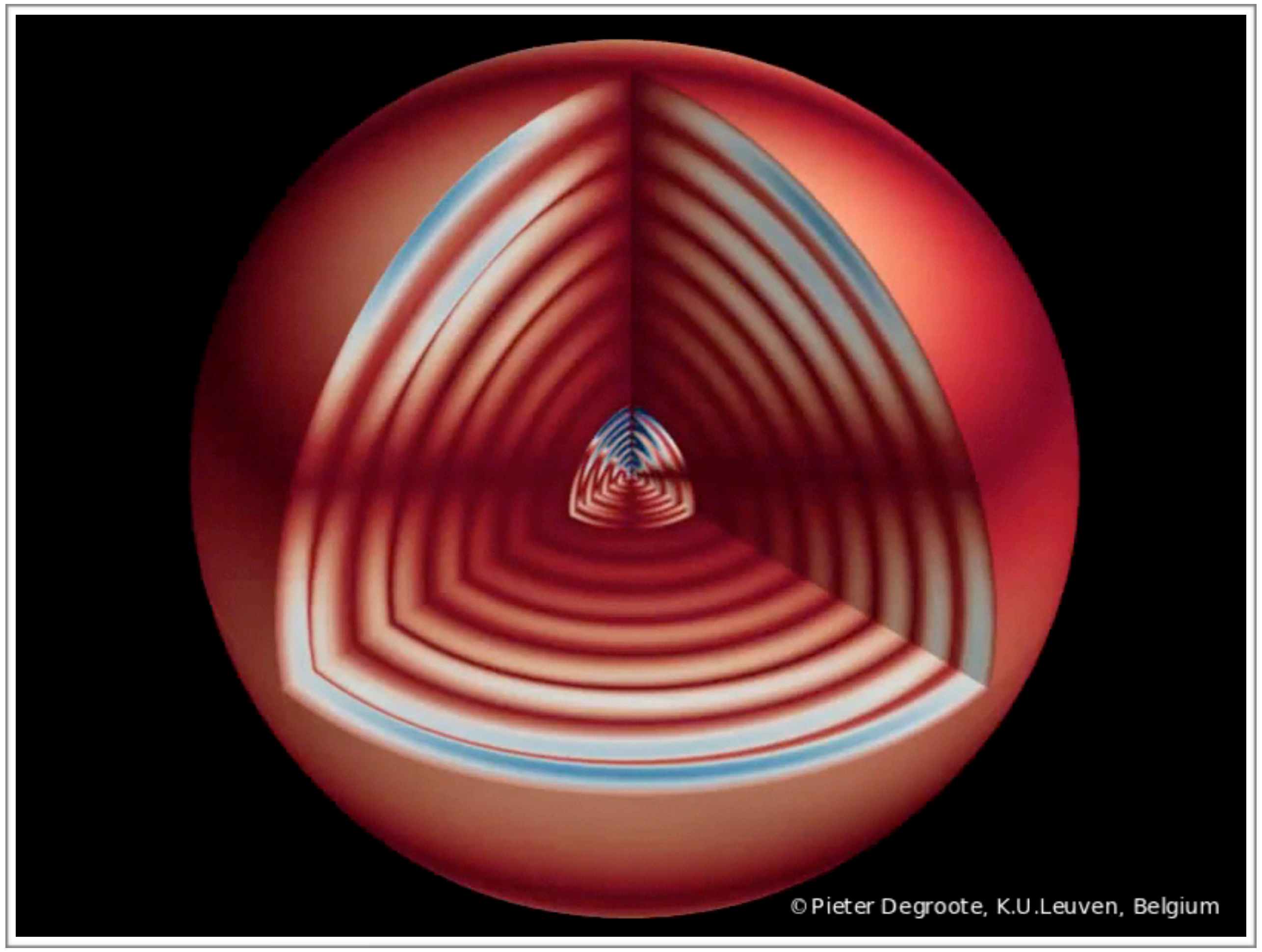




Starquakes Probe Stellar Interiors



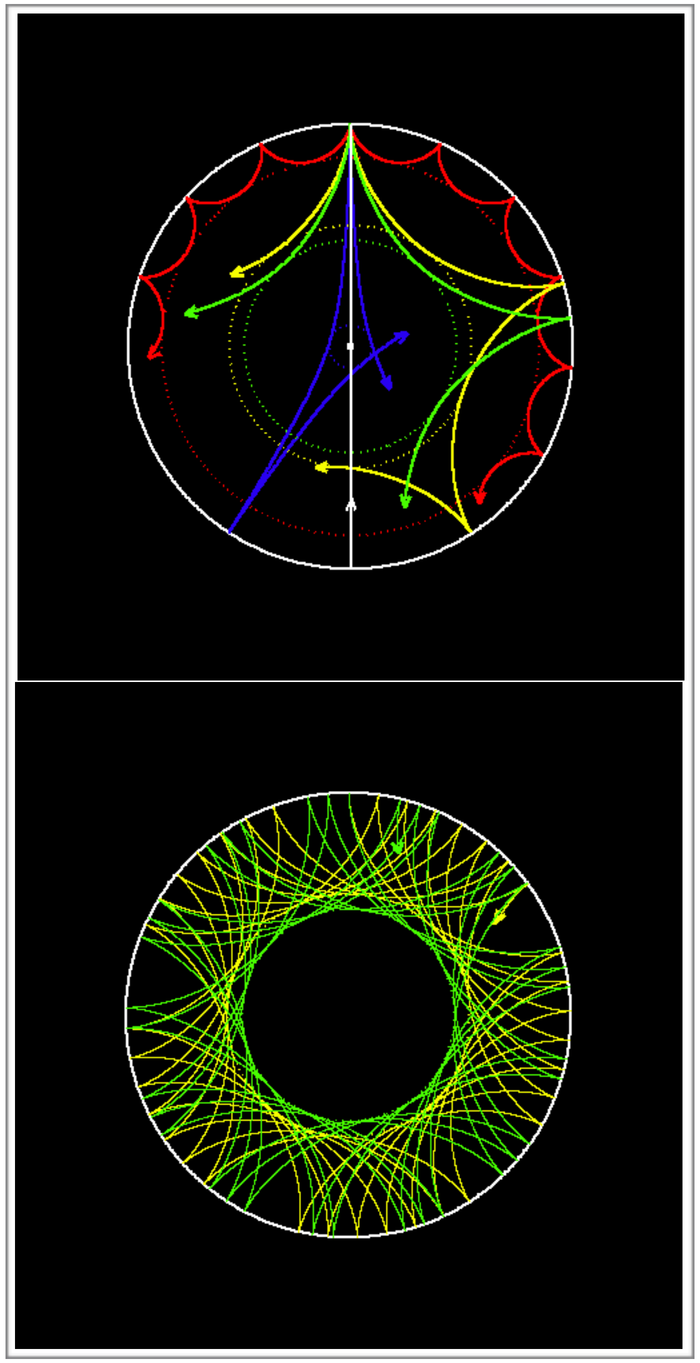




The Beauty of Asteroseismology

aster $\longrightarrow$ star
seismos $\longrightarrow$ oscillation
logos $\longrightarrow$ discourse

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



$$Y_l^m(\theta,\varphi) = (-1)^m \sqrt{\frac{2l+1}{4\pi}\frac{(l-m)!}{(l+m)!}} P_l^m(\cos\theta)\exp(im\varphi)$$

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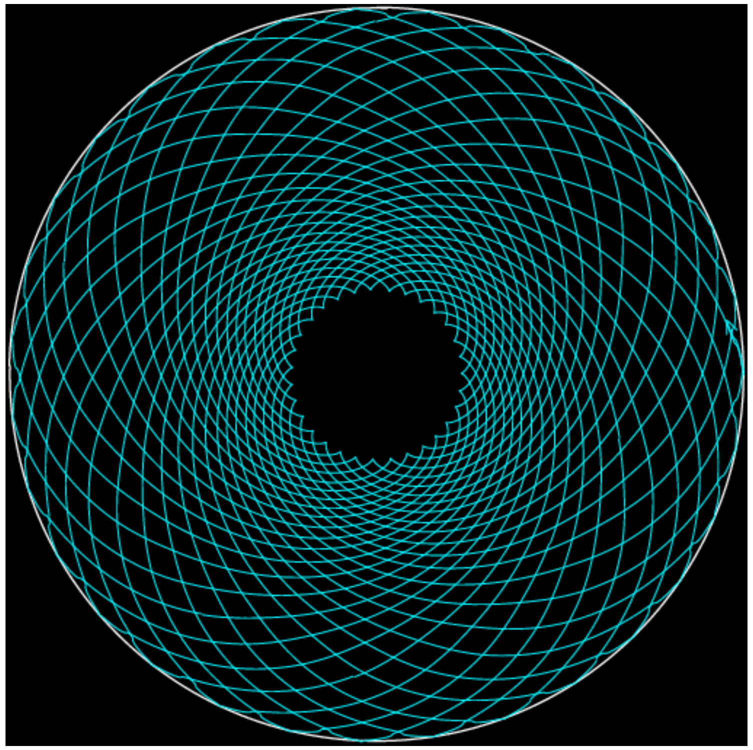
Key ingredients: wave propagation

- **Oscillations = solutions of perturbed SSE in terms of periodic eigenfunctions**
- **Each oscillation mode described as spherical harmonic & frequency:**

$$\sqrt{4\pi}\,\Re\left\{\left[\tilde{\xi}_r(r)Y_l^m(\theta,\phi)\boldsymbol{a}_r + \tilde{\xi}_{\rm h}(r)\left(\frac{\partial Y_l^m}{\partial\theta}\boldsymbol{a}_\theta + \frac{1}{\sin\theta}\frac{\partial Y_l^m}{\partial\phi}\boldsymbol{a}_\phi\right)\right]\exp(-{\rm i}\omega t)\right\}$$

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



Gravity waves propagating in radiative zone of a massive star, from surface to core

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Key ingredient: time-series analysis

- **Oscillations = solutions of perturbed SSE in terms of periodic eigenfunctions**
- **Each oscillation mode described as spherical harmonic & frequency:**

$$\sqrt{4\pi}\,\Re\left\{\left[\tilde{\xi}_r(r)Y_l^m(\theta,\phi)\boldsymbol{a}_r + \tilde{\xi}_{\mathrm{h}}(r)\left(\frac{\partial Y_l^m}{\partial\theta}\boldsymbol{a}_\theta + \frac{1}{\sin\theta}\frac{\partial Y_l^m}{\partial\phi}\boldsymbol{a}_\phi\right)\right]\exp(-\mathrm{i}\omega t)\right\}$$

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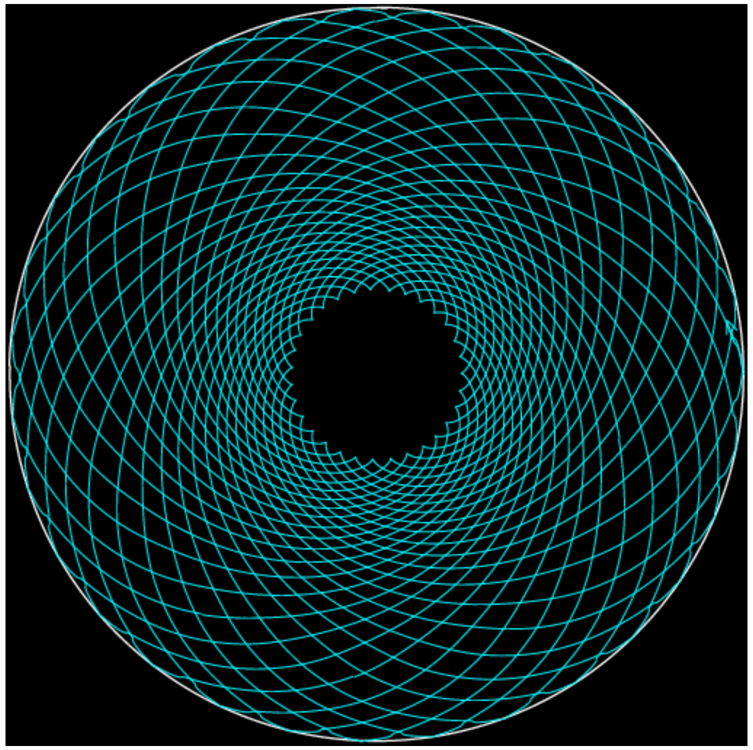
Kepler !!



Gravity waves propagating in radiative zone of a massive star, from surface to core

3D Mode Properties

Perturb spherically symmetric equilibrium model

time $\longrightarrow$ frequency (period) of mode
geometry $\longrightarrow$ spherical harmonic + radial order

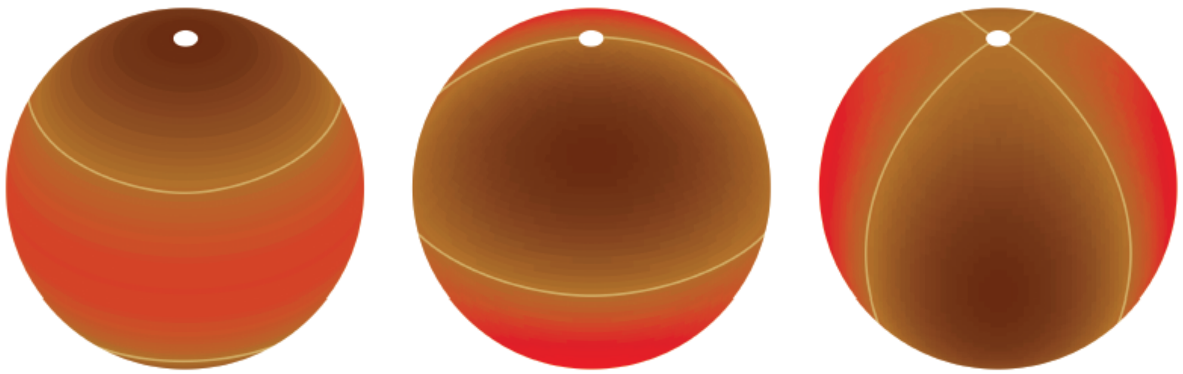
$$\xi(r,\theta,\phi,t) = [(\xi_{r,nl}e_r + \xi_{\mathrm{h},nl}\nabla_\mathrm{h})Y_l^m(\theta,\phi)]\exp(-\mathrm{i}\omega t)$$

Inferences of properties of stellar interiors via modes

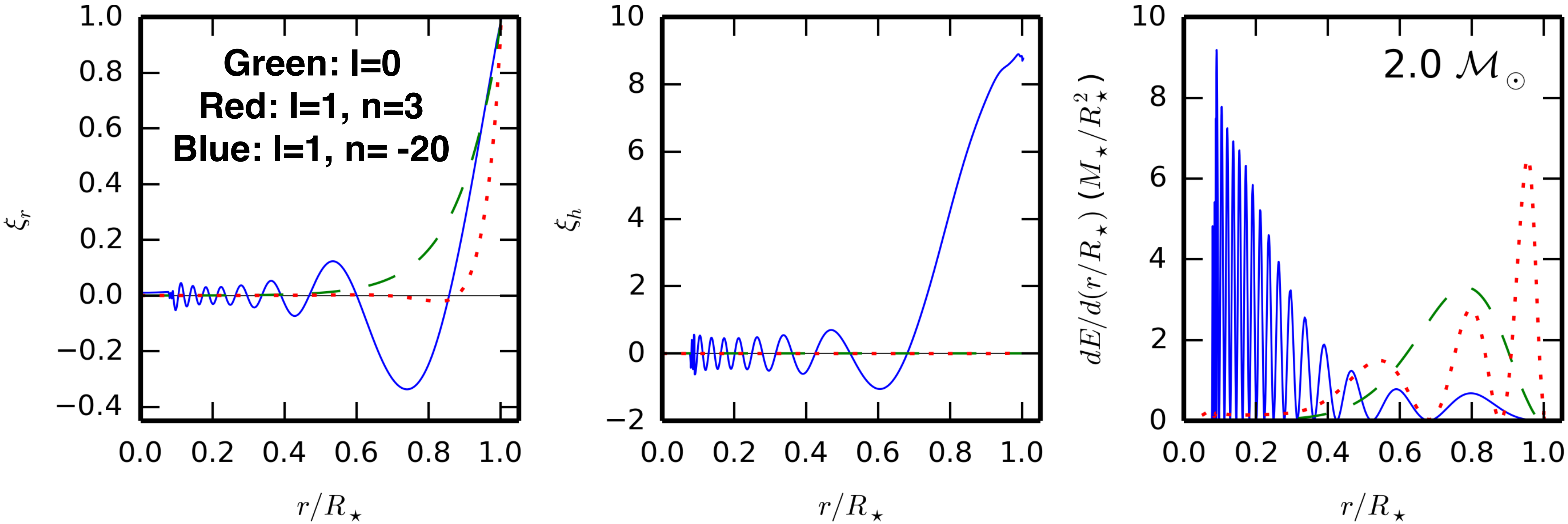
a) requires frequencies & identification of (l,m) of as many modes as possible from data (+ n from models)

b) can only probe regions where modes propagate

Probing power of p-/g-modes



p-modes: dominantly radial ξ
g-modes: dominantly tangential ξ
p-modes: probe envelope physics
g-modes: probe near-core region



Schmid & Aerts (2016)

Mode Propagation Properties (p.205/208)

Thus according to this description the solution oscillates as a function of r when

$$\text{o1)} \quad |\omega| > |N| \quad \text{and} \quad |\omega| > S_l \;, \quad \textbf{p mode} \tag{3.185}$$

or

$$\text{o2)} \quad |\omega| < |N| \quad \text{and} \quad |\omega| < S_l \;, \quad \textbf{g mode} \tag{3.186}$$

Oscillatory solutions = propagative waves

and it is exponential when

$$\text{e1)} \quad |N| < |\omega| < S_l \;, \tag{3.187}$$

or

$$\text{e2)} \quad S_l < |\omega| < |N| \;. \tag{3.188}$$

Exponentially decaying oscillations = evanescent waves

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or

$$\text{o2)} \quad |\omega| < |N| \quad \text{and} \quad |\omega| < S_l \,, \quad \textbf{g mode} \qquad (3.186)$$

Periodic oscillation = eigenmode = standing wave

Heat-driven: coherent standing wave with long lifetime

Stochastically driven: damped + re-excited waves, short lifetime

and it is exponential when

$$\text{e1)} \quad |N| < |\omega| < S_l \,, \qquad (3.187)$$

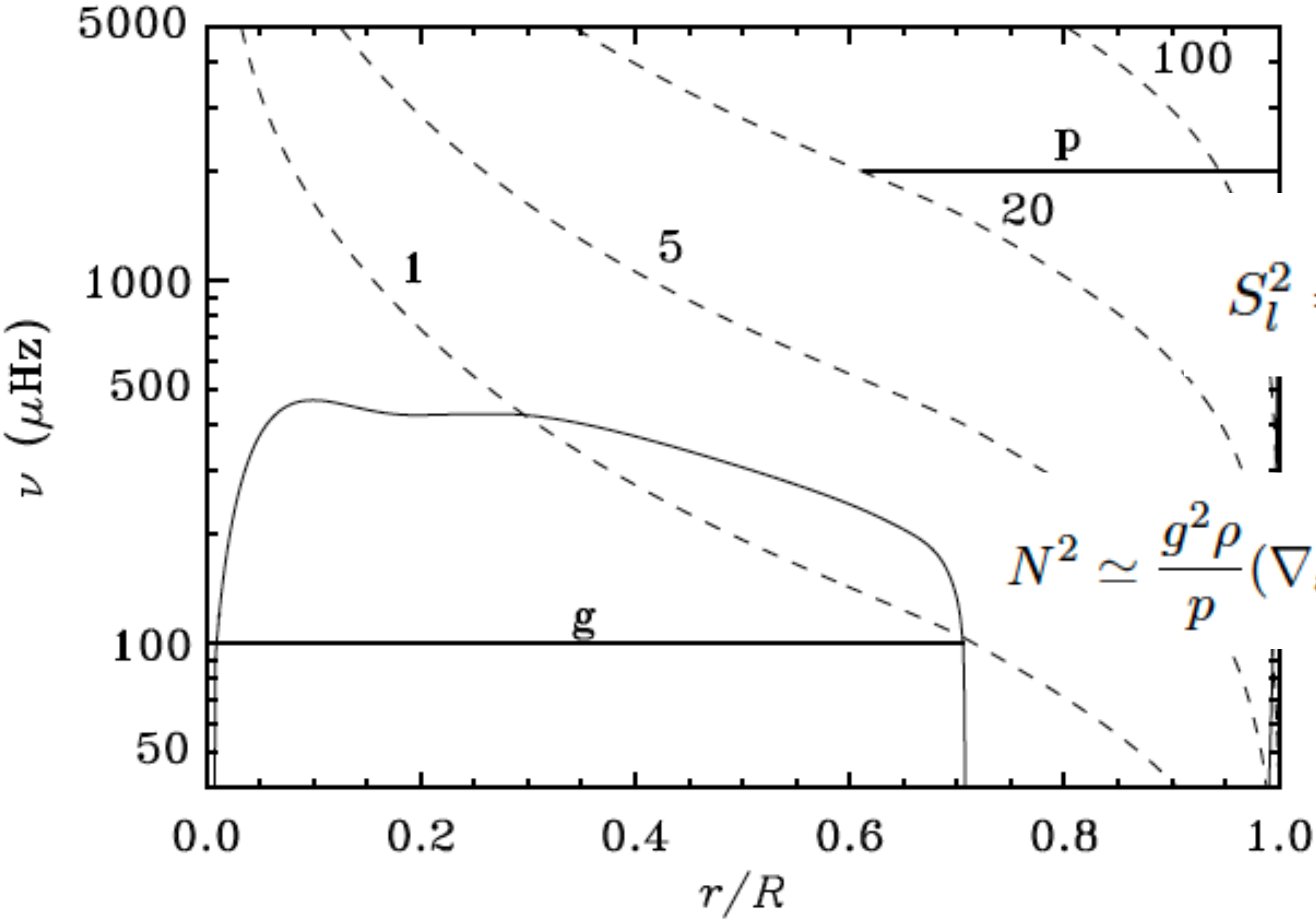
or

$$\text{e2)} \quad S_l < |\omega| < |N| \,. \qquad (3.188)$$

Exponentially decaying oscillations = evanescent waves

Propagation Cavities in Sun

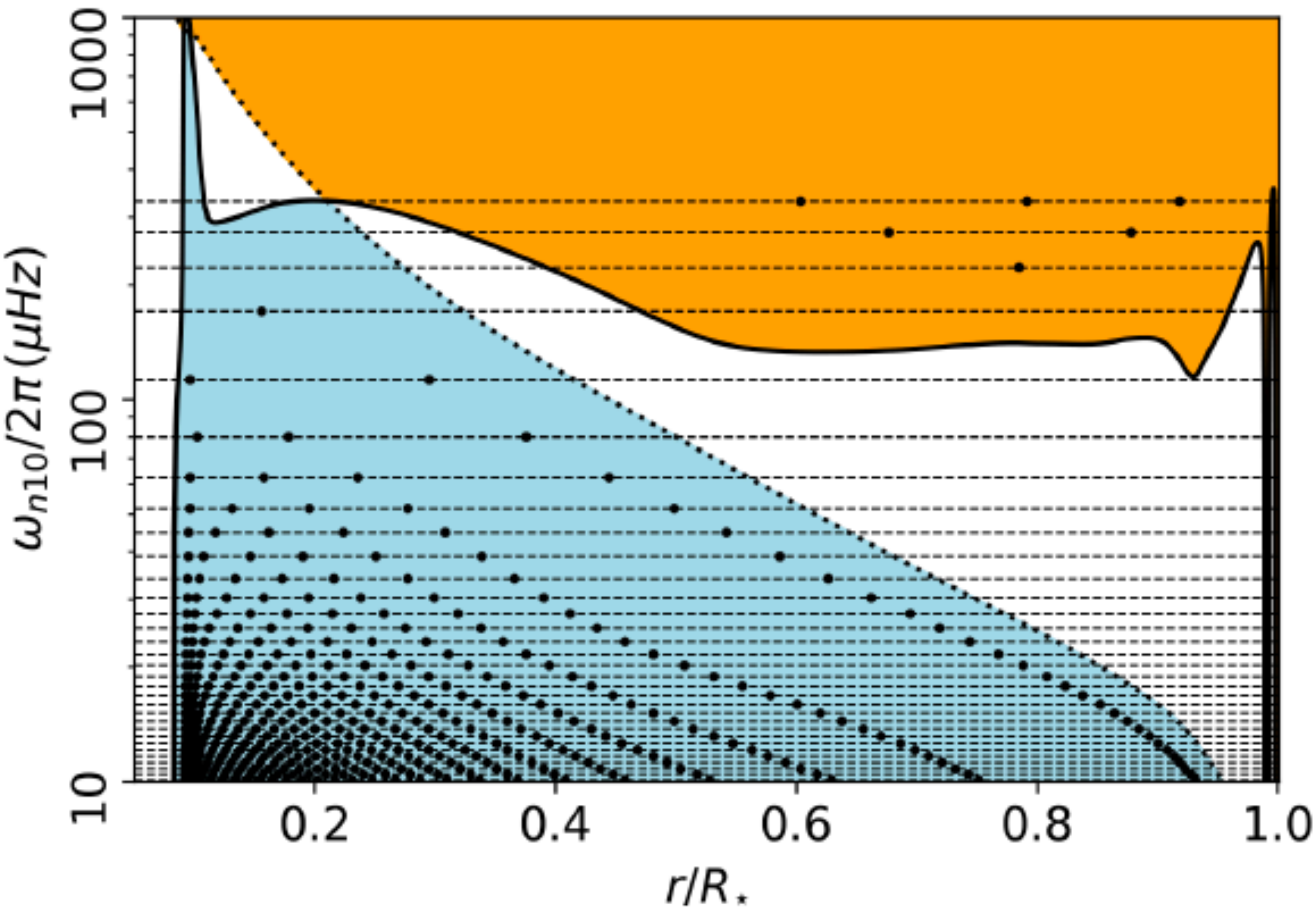
Ignoring Coriolis, centrifugal, and Lorentz forces is fine



$$S_l^2 = \frac{l(l+1)c^2}{r^2}$$

$$N^2 \simeq \frac{g^2\rho}{p}(\nabla_{\rm ad} - \nabla + \nabla_\mu)$$

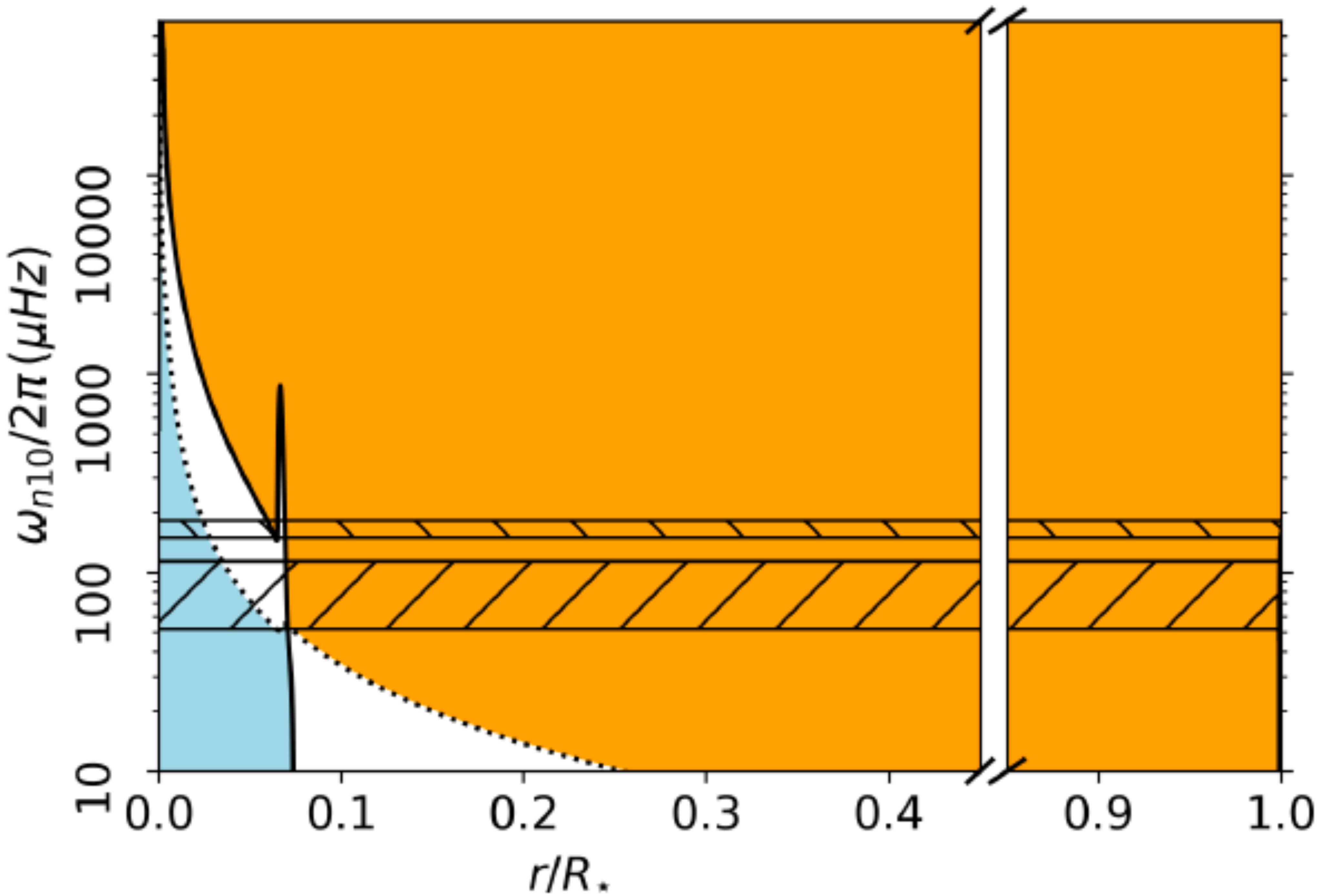
Probing power in F stars



p- and g-modes probe different regions throughout evolution

Figure courtesy of Joey Mombarg used in Aerts et al. (2019) ARAA, in press

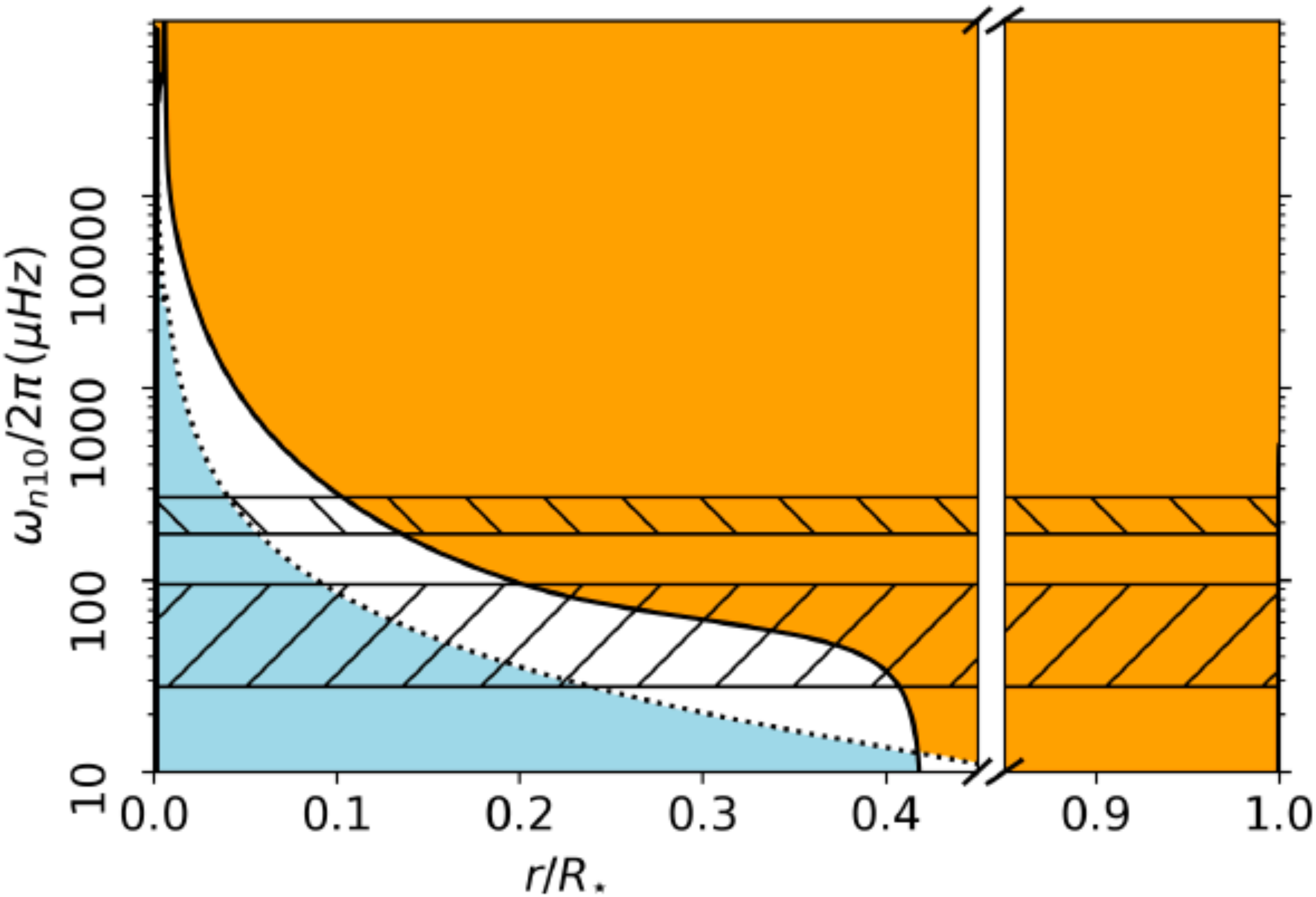
Probing power on RGB



p- and g-modes probe different regions throughout evolution

Figure courtesy of Cole Johnston used in Aerts et al. (2019) ARAA, in press

Probing power red clump



p- and g-modes probe different regions throughout evolution

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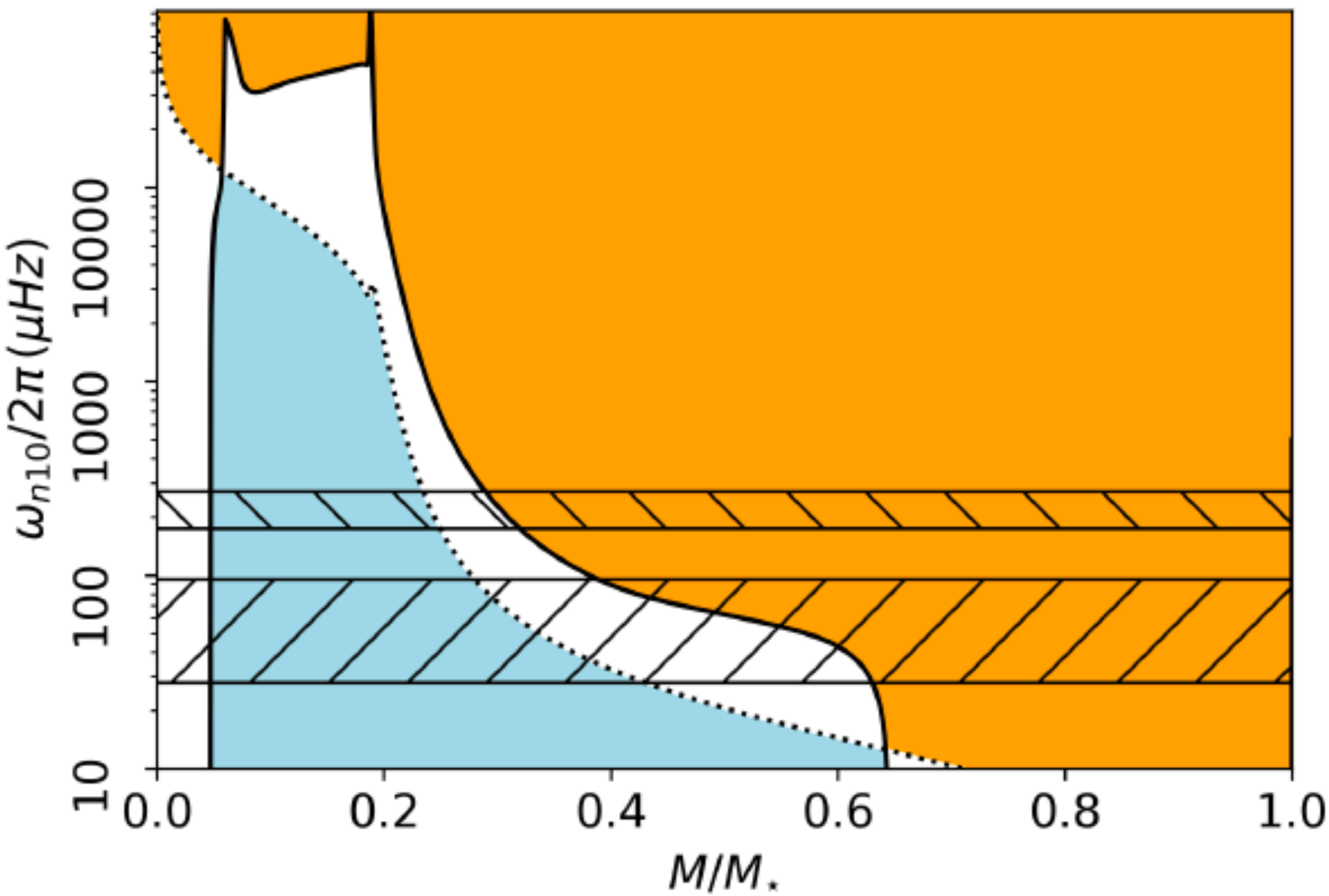

p- and g-modes probe different regions throughout evolution

Figure courtesy of Cole Johnston used in Aerts et al. (2019) ARAA, in press

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Frequency Analysis

time $\longrightarrow$ frequency (period) of mode
geometry $\longrightarrow$ spherical harmonic + radial order

$$\xi(r,\theta,\phi,t) = [(\xi_{r,nl}e_r + \xi_{\mathrm{h},nl}\nabla_{\mathrm{h}})Y_l^m(\theta,\phi)]\exp(-\mathrm{i}\omega t)$$

Inferences of properties of stellar interiors via modes

a) requires frequencies & identification of (l,m) of as many modes as possible from data (+ n from models)

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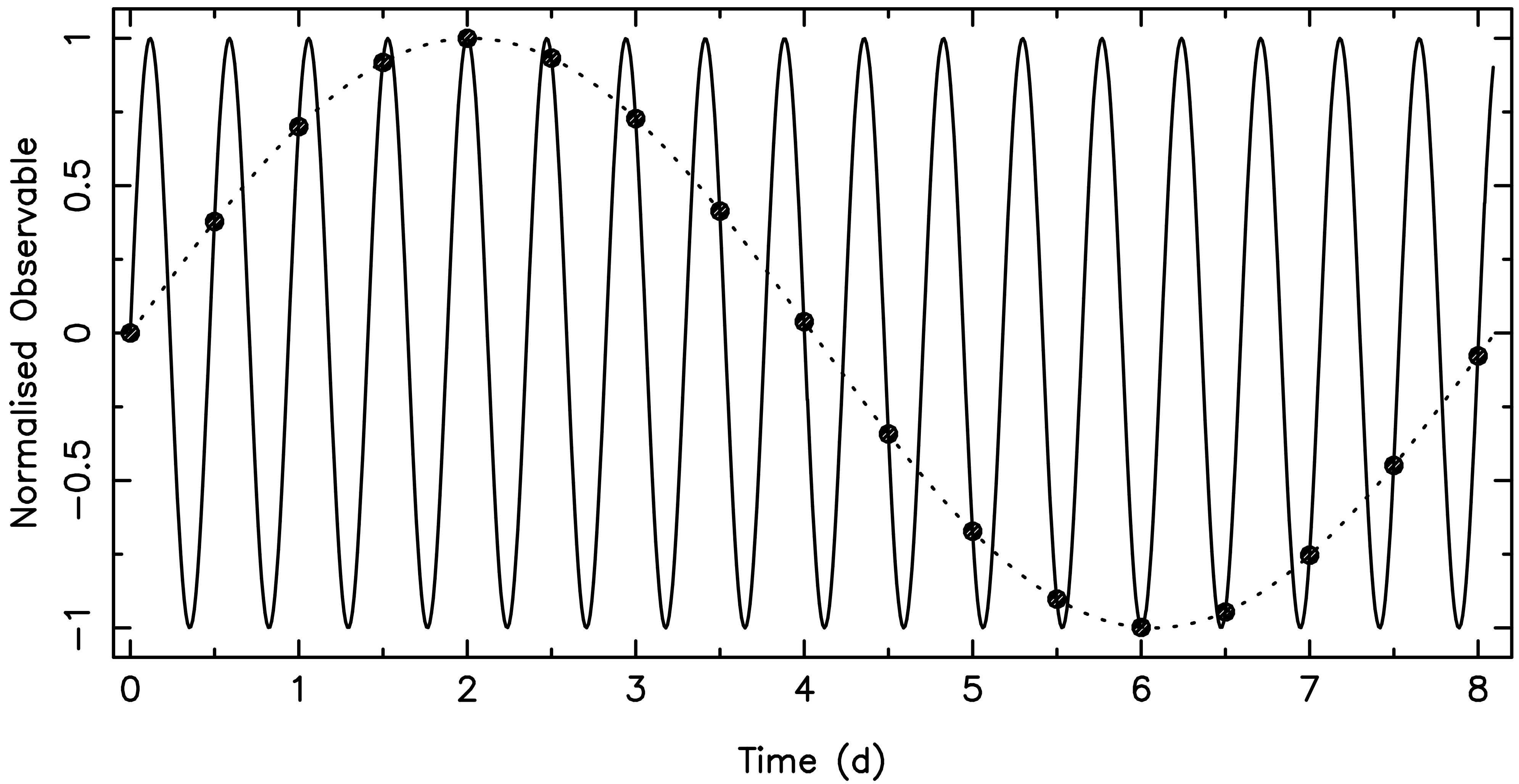
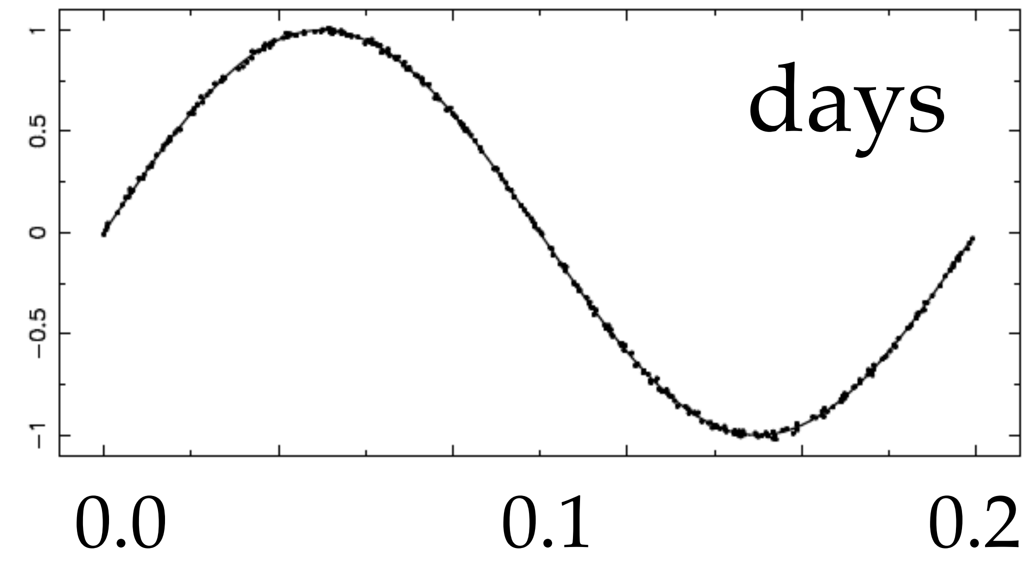
Preliminaries: the obvious…

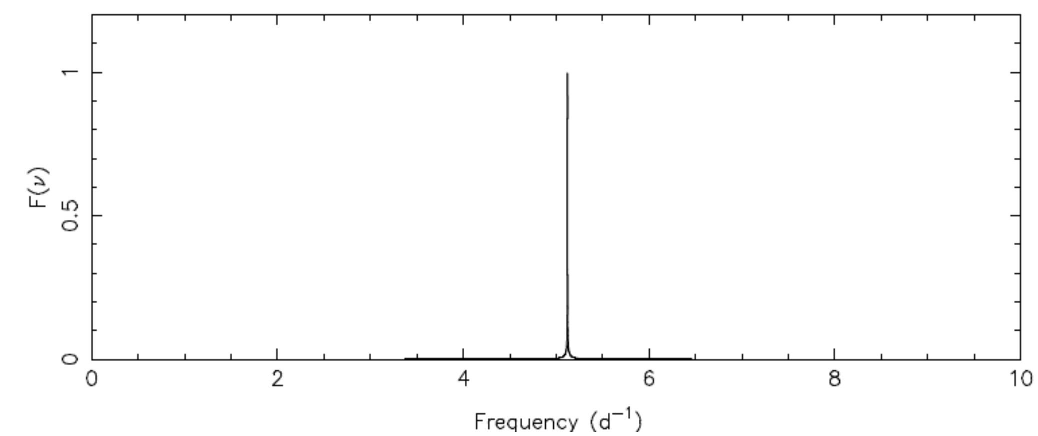


Simulated data (dots) representing a periodic signal with frequency **0.123456789 d^{-1}**. Dotted line: harmonic fit for this frequency; full line: fit with the frequency **2.123456789 d^{-1}**

Fourier Transform of sine = delta peak



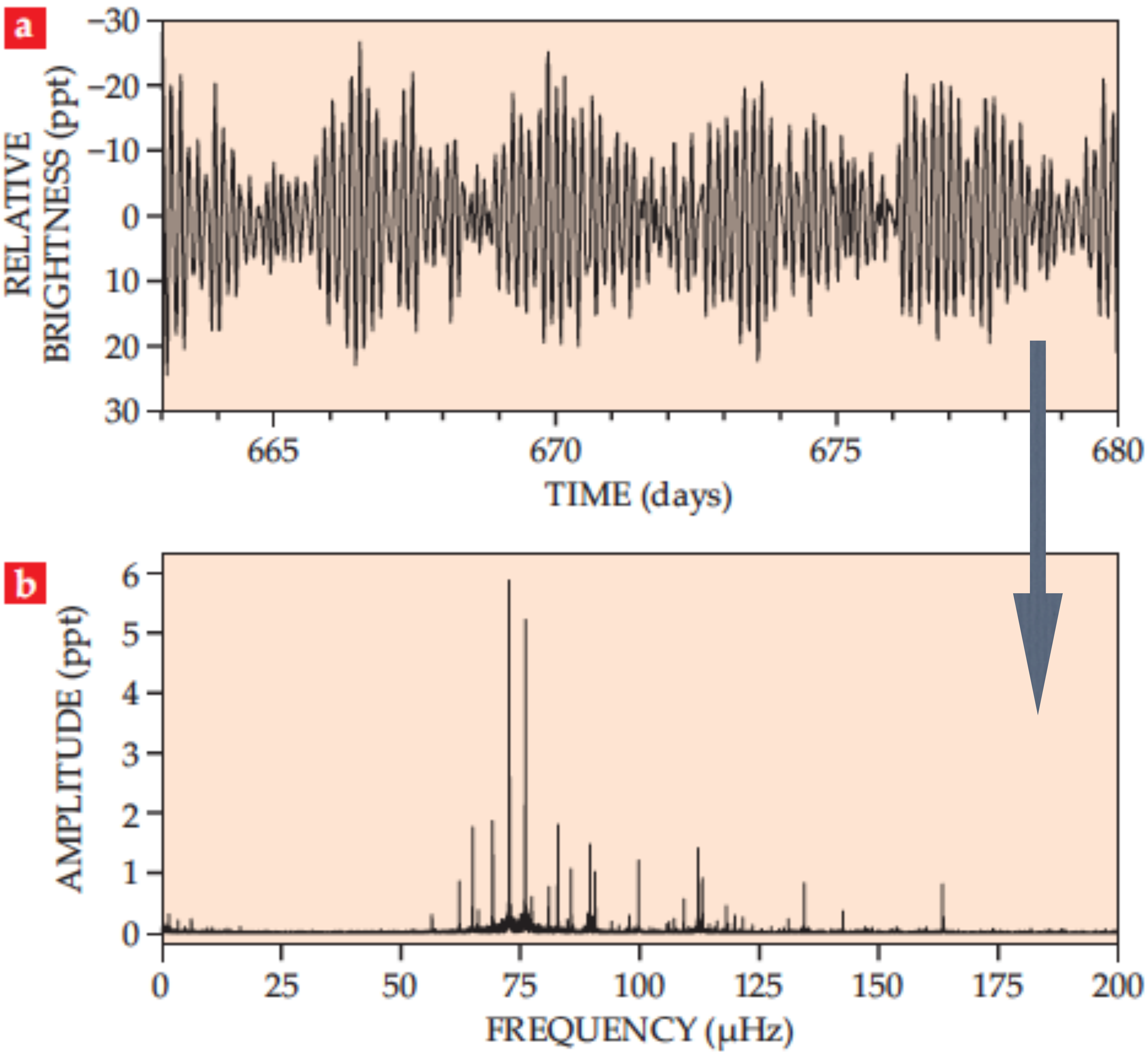
Fourier transform

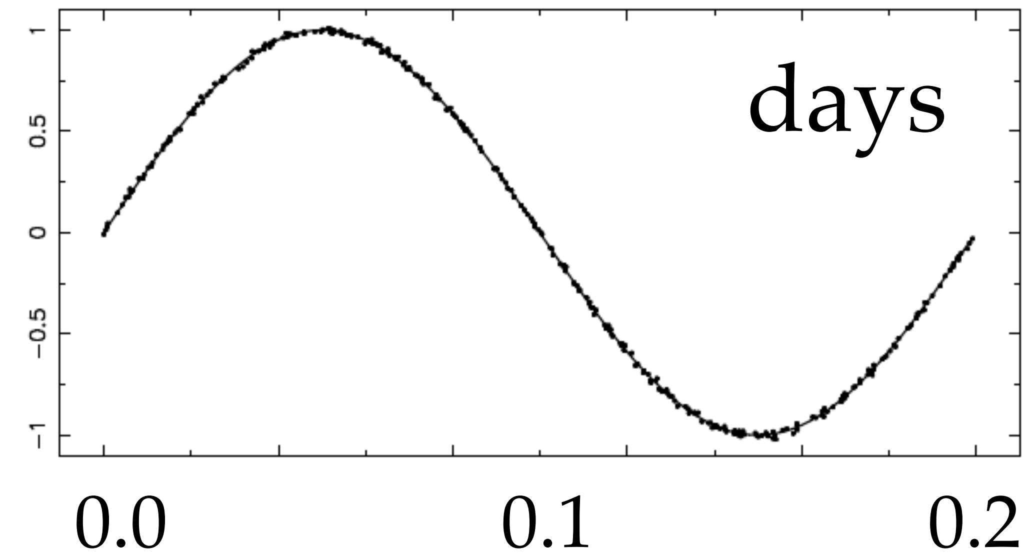


1 day = 86400 seconds

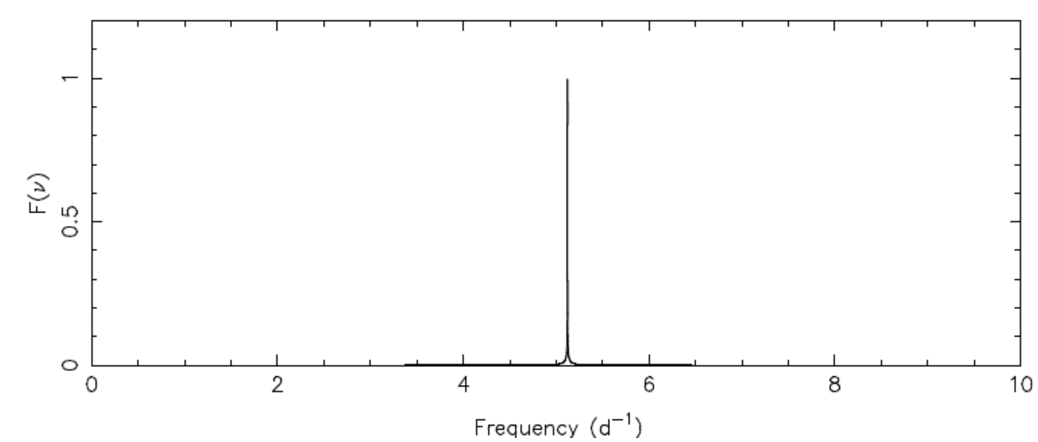
1/day = 11.57 μHz

Fourier Transform of sine = delta peak





Fourier transform



1 day = 86400 seconds

1/day = 11.57 μHz

Recap: Fourier analysis

Fourier transform of $x(t)$:

$$F(f) \equiv \int_{-\infty}^{+\infty} x(t)\exp(2\pi \mathrm{i}\, f t) dt$$

Fourier transform $F(f)$ of sum of harmonic functions with frequencies $f_1, \ldots, f_n$ and amplitudes $A_1, \ldots, A_n$:

$$\boxed{x(t) = \sum_{k=1}^{n} A_k \exp(2\pi \mathrm{i}\, f_k t) : \quad F(f) = \sum_{k=1}^{n} A_k \delta(f - f_k)}$$

For $x(t) =$ sine with frequency f_1, $F(f) \neq 0$ for $f = \pm f_1$

For $x(t) =$ sum of n harmonic functions with frequencies $f_1, \ldots, f_n$, $F(f) =$ sum of δ-functions ≠ 0 for $\pm f_1, \ldots, \pm f_n$

Real data set: $x(t)$ known for a discrete number of times t_j, $j=1, \ldots, N$

Discrete Fourier Transform

$$F_N(f) \equiv \sum_{j=1}^{N} x(t_j)\exp(2\pi \mathrm{i}\, f t_j)$$

$F_N \neq F$! but connected through window function: $w_N(t) \equiv \frac{1}{N}\sum_{j=1}^{N}\delta(t-t_j)$

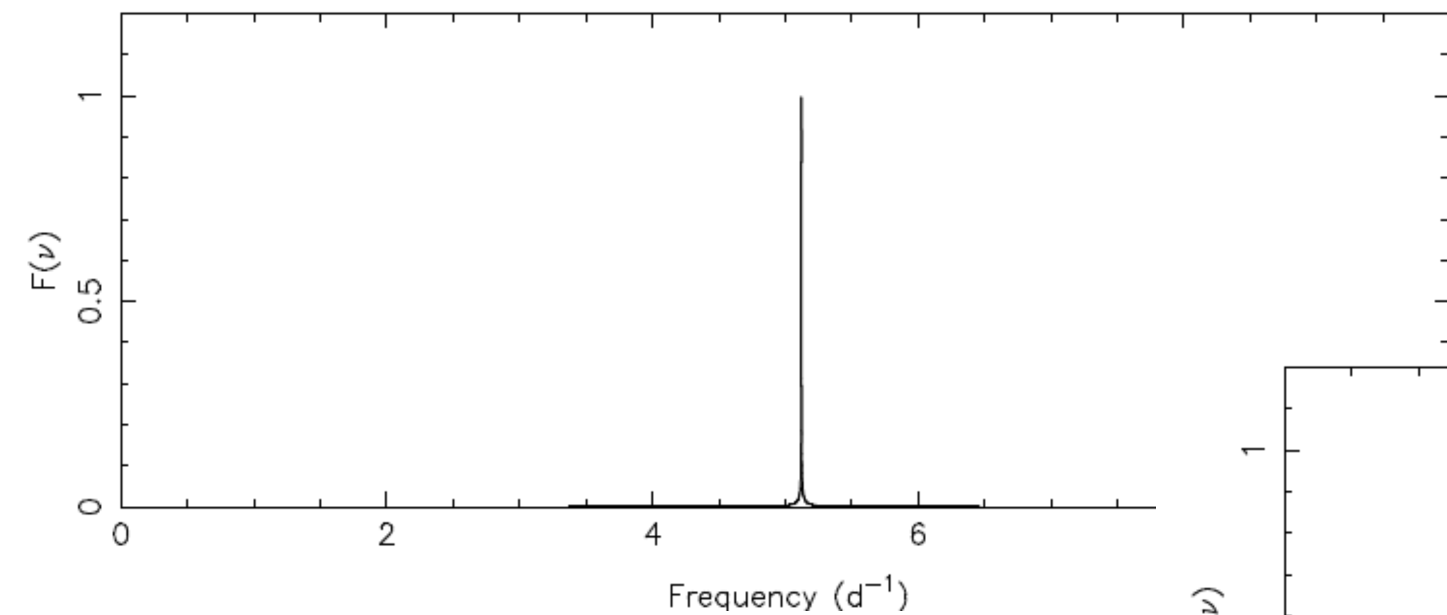
Hence: $$\frac{F_N}{N} = \int_{-\infty}^{+\infty} x(t) w_N(t)\exp(2\pi \mathrm{i}\, f t) dt$$

Discrete Fourier transform of window function = spectral window $W_N(f)$:

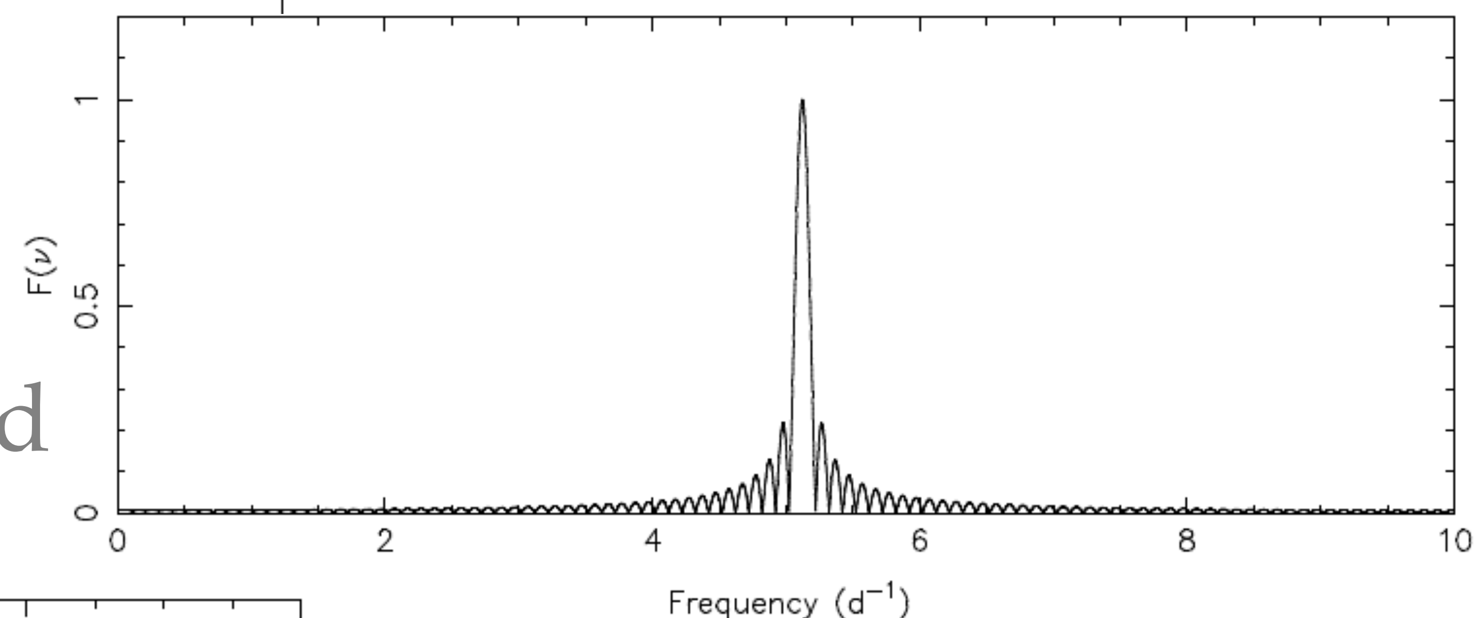
$$W_N(f) = \frac{1}{N}\sum_{j=1}^{N}\exp(2\pi \mathrm{i}\, f t_j)$$

Discrete Fourier transform = convolution of spectral window and Fourier transform: $F_N(f)/N = F(f) * W_N(f)$

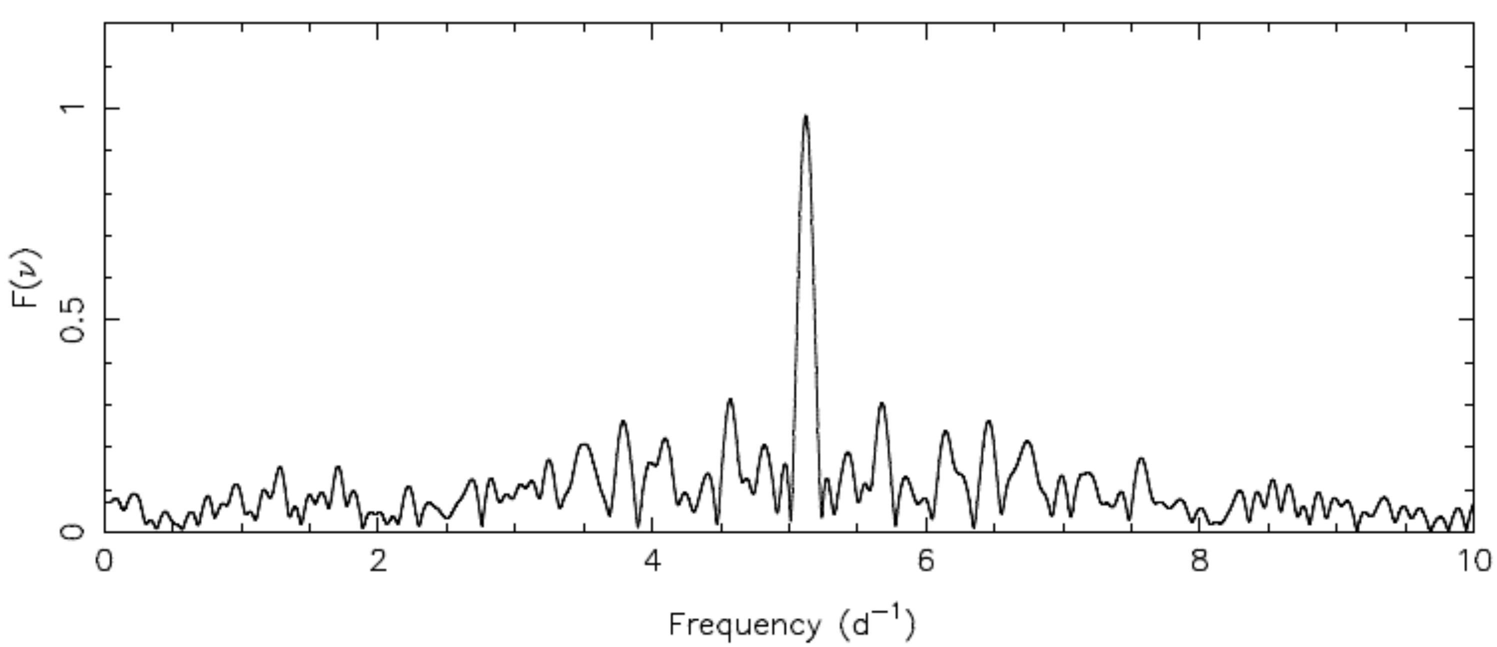
Total time base and # data points



Left: 10^6 points over 1000 d

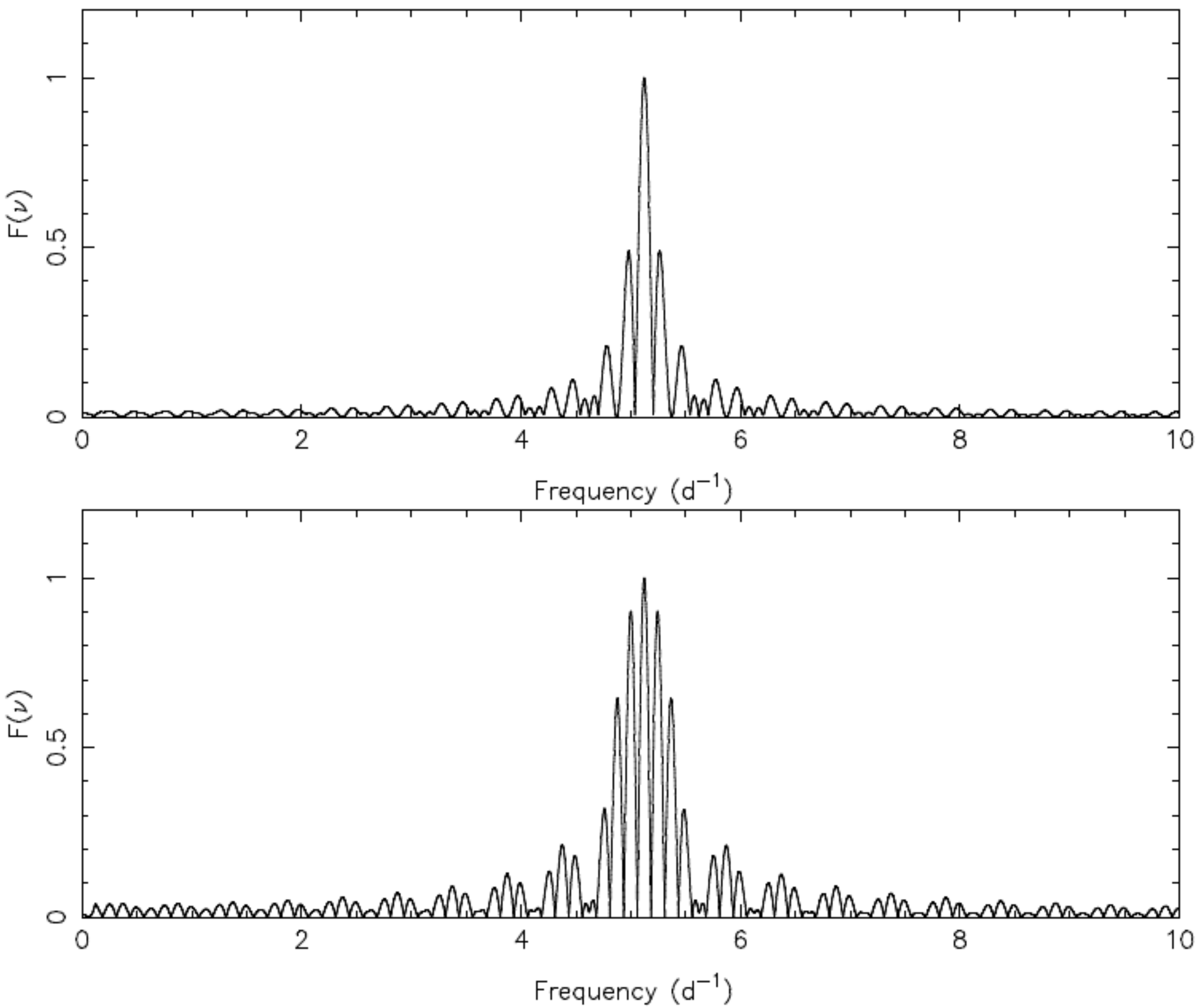


Right: 10^4 points over 10 d



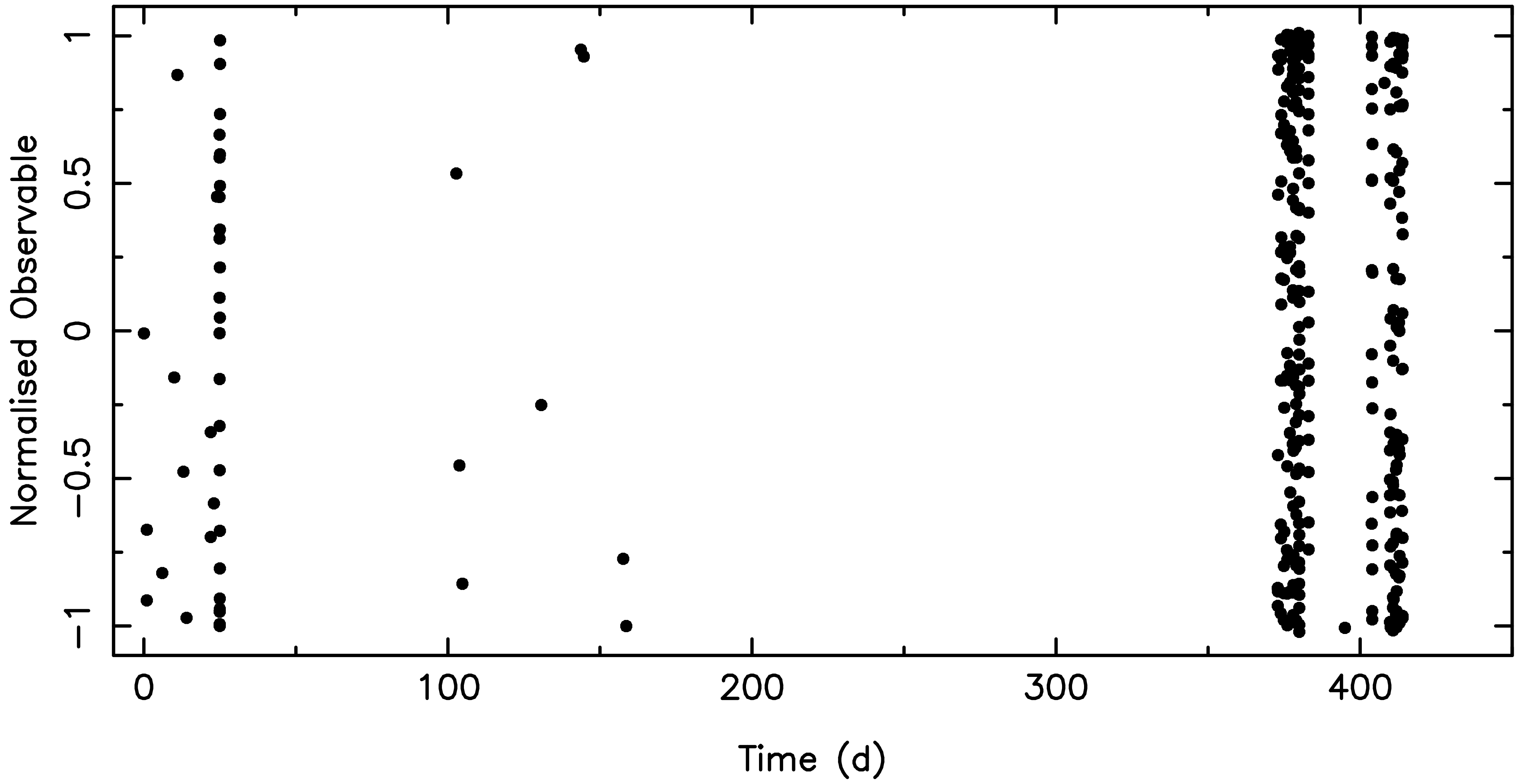
Left: 4472 points over 10 d

Influence of gaps on FT



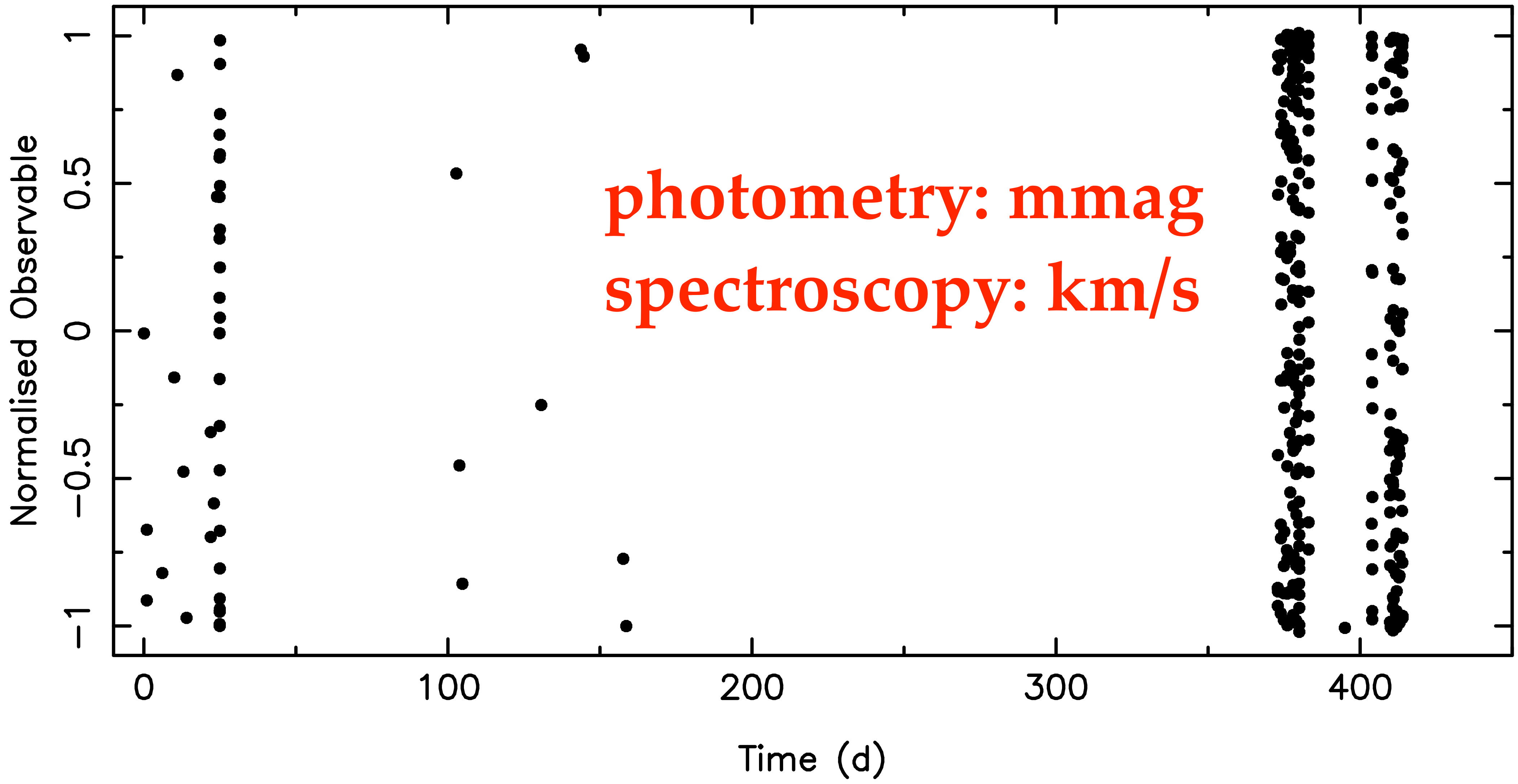
FT of noiseless time series of a sine function with $f=5.123456789d^{-1}$ generated for a finite time span of 10 days and containing one large gap from day 4 until day 6 (top) and from day 2 until day 8 (bottom).

Typical ground-based data set



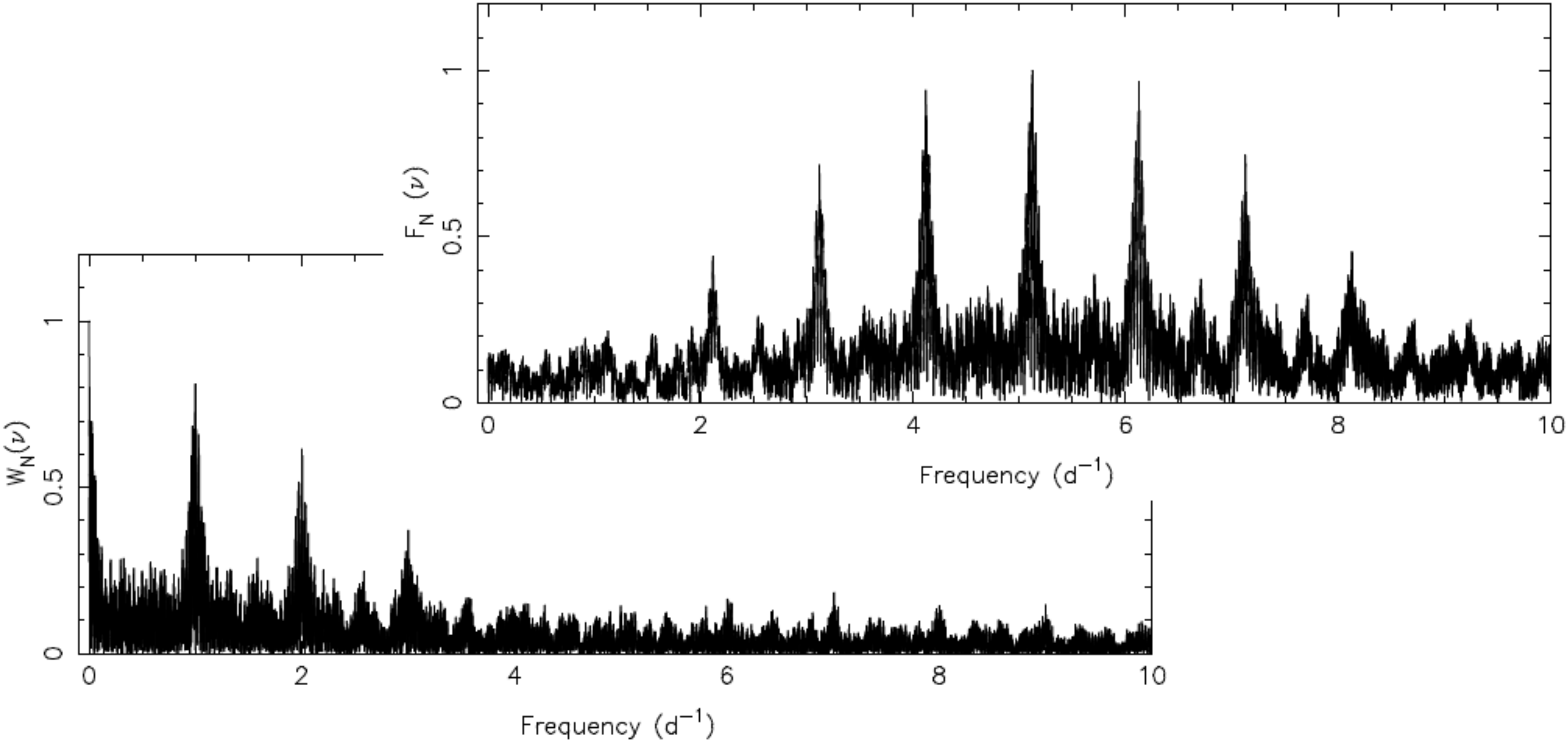
Gapped data representing a typical time series for a single-site campaign of a newly discovered pulsating star

Typical ground-based data set



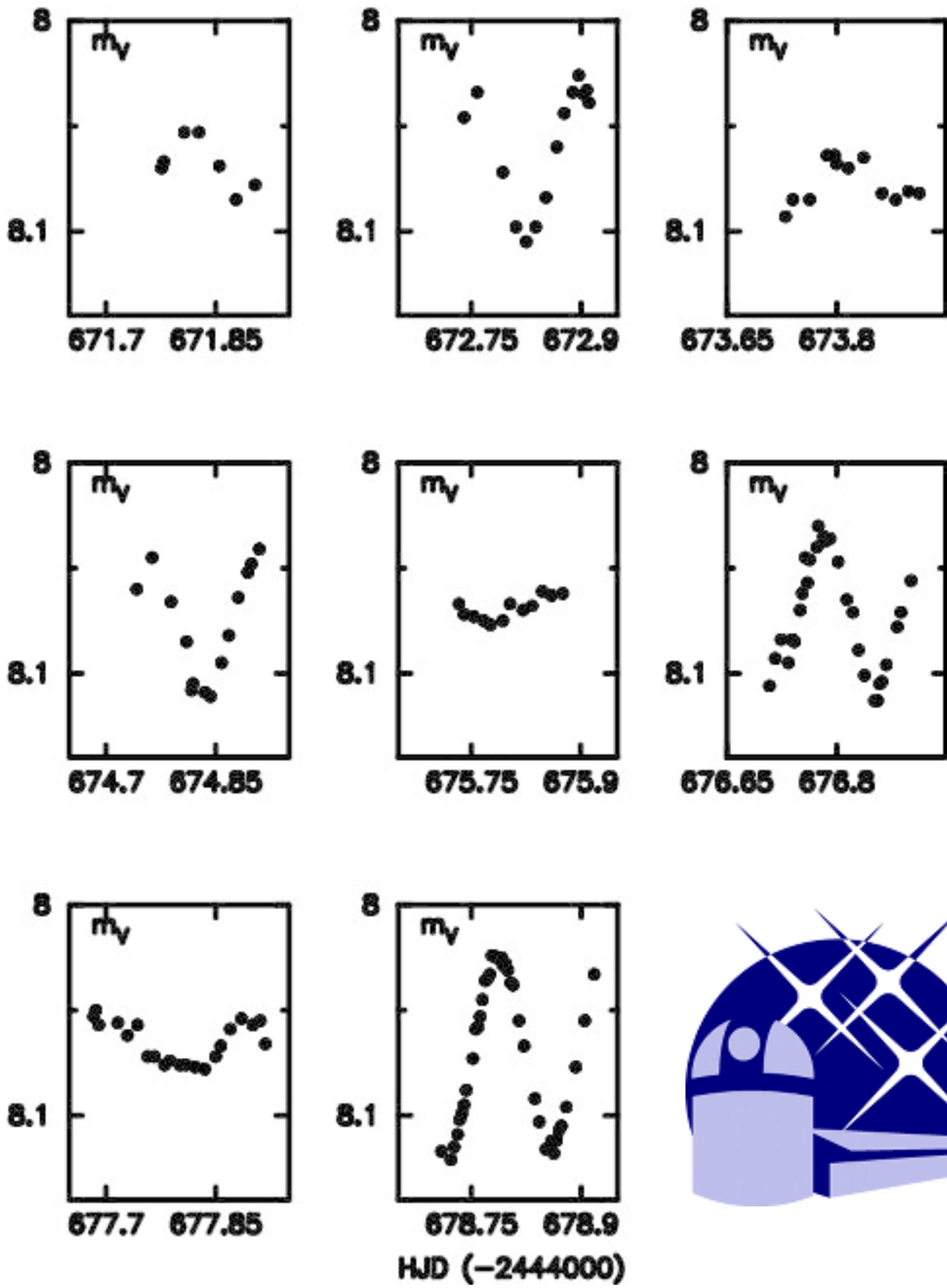
Gapped data representing a typical time series for a single-site campaign of a newly discovered pulsating star

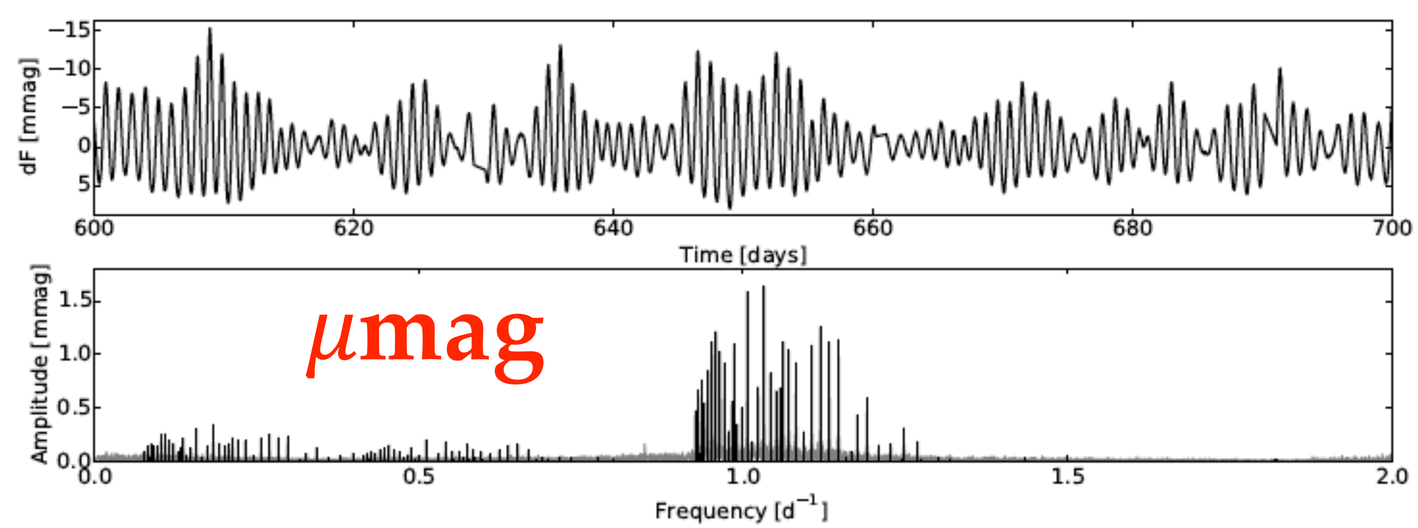
FT of these ground-based data



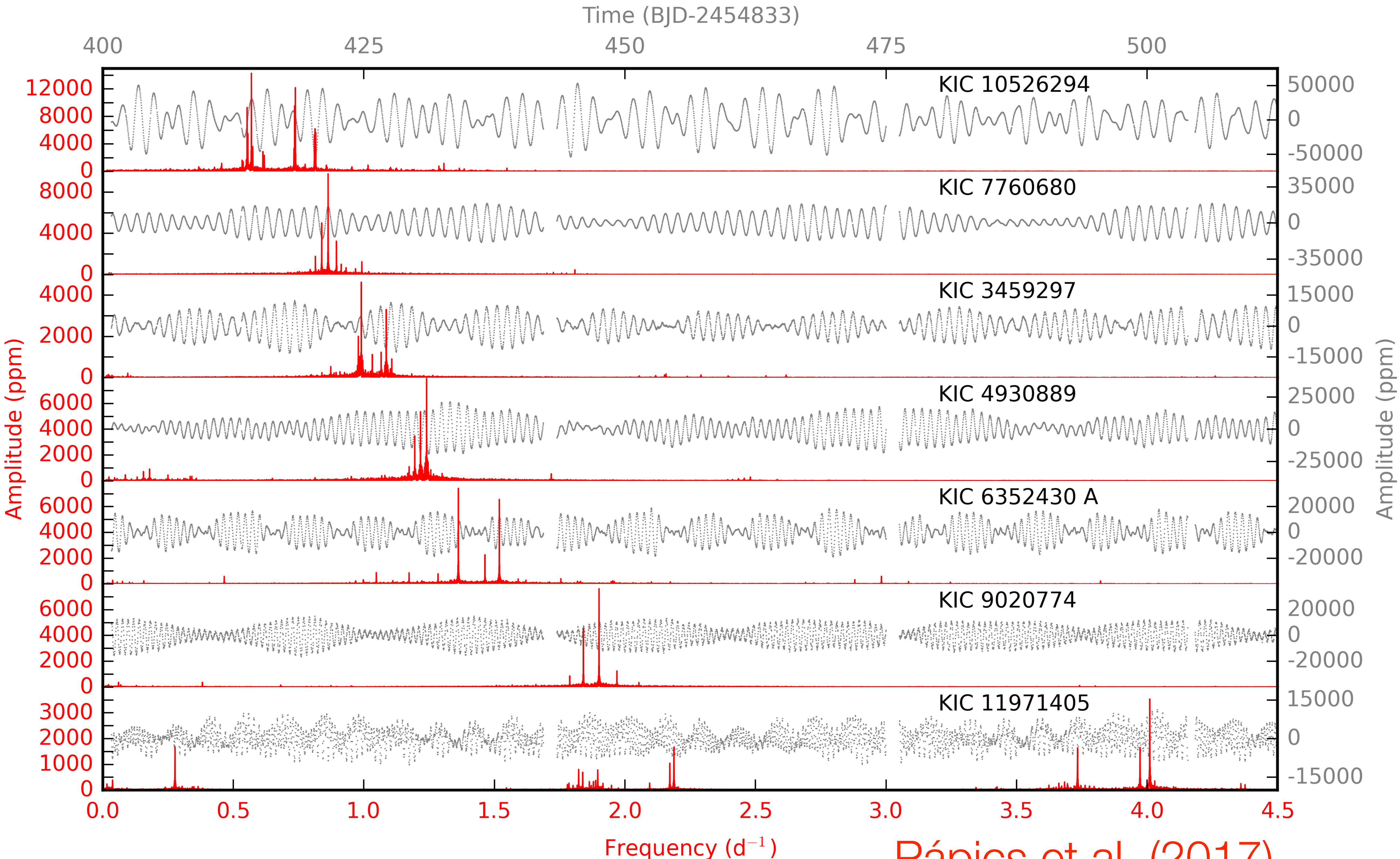
Spectral window (lower) and DFT (upper) of a noise-free sinusoid with amplitude 1 at 5.123456789 d^{-1} for the ground-based data.

Ground versus Space Photometry





The Space Photometry Revolution



Pápics et al. (2017)

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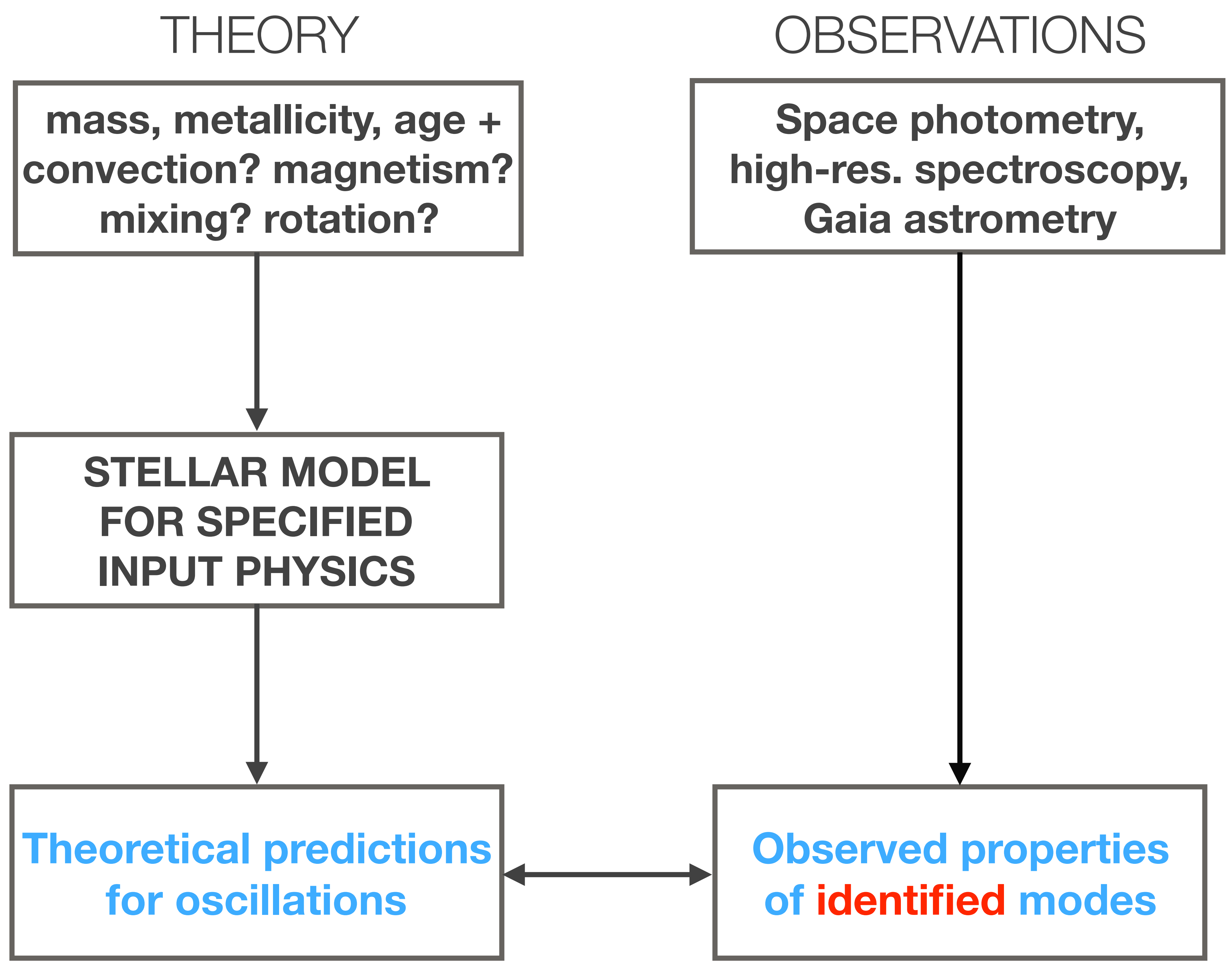
Asteroseismic Modelling



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Asteroseismic Modelling

THEORY

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

↓

STELLAR MODEL
FOR SPECIFIED
INPUT PHYSICS

↓

Theoretical predictions
for oscillations

↔

OBSERVATIONS

Space photometry,
high-res. spectroscopy,
Gaia astrometry

↓

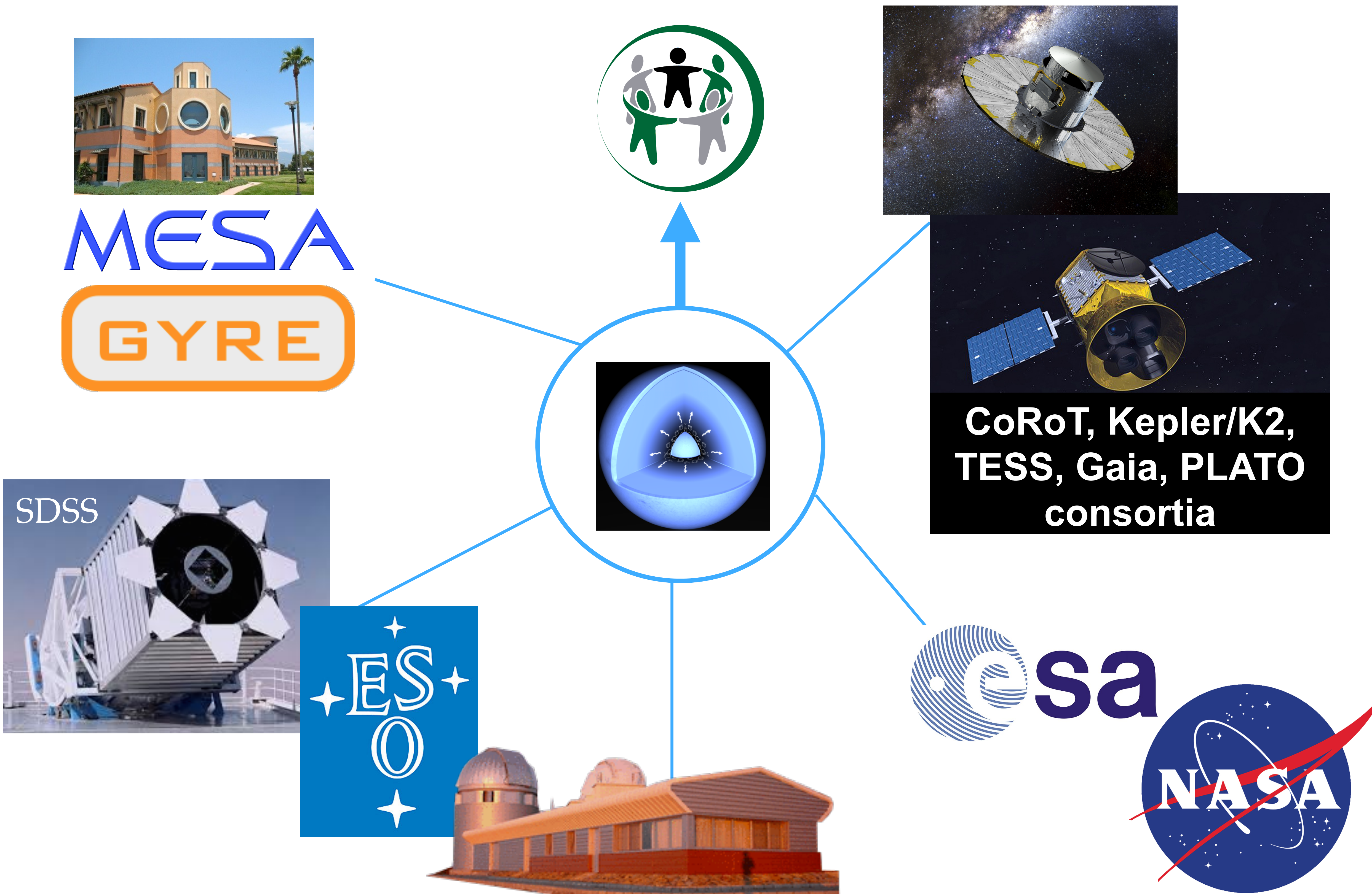
Observed properties
of identified modes

Two Major Aims (classes 2&3):

A) High-precision M, R, age, Z

B) Improve Input Physics:
AM, Dmix(r)

Worldwide Collaborations



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Open Access of Data Products & Software


Josiah Schwab


Adam Jermyn

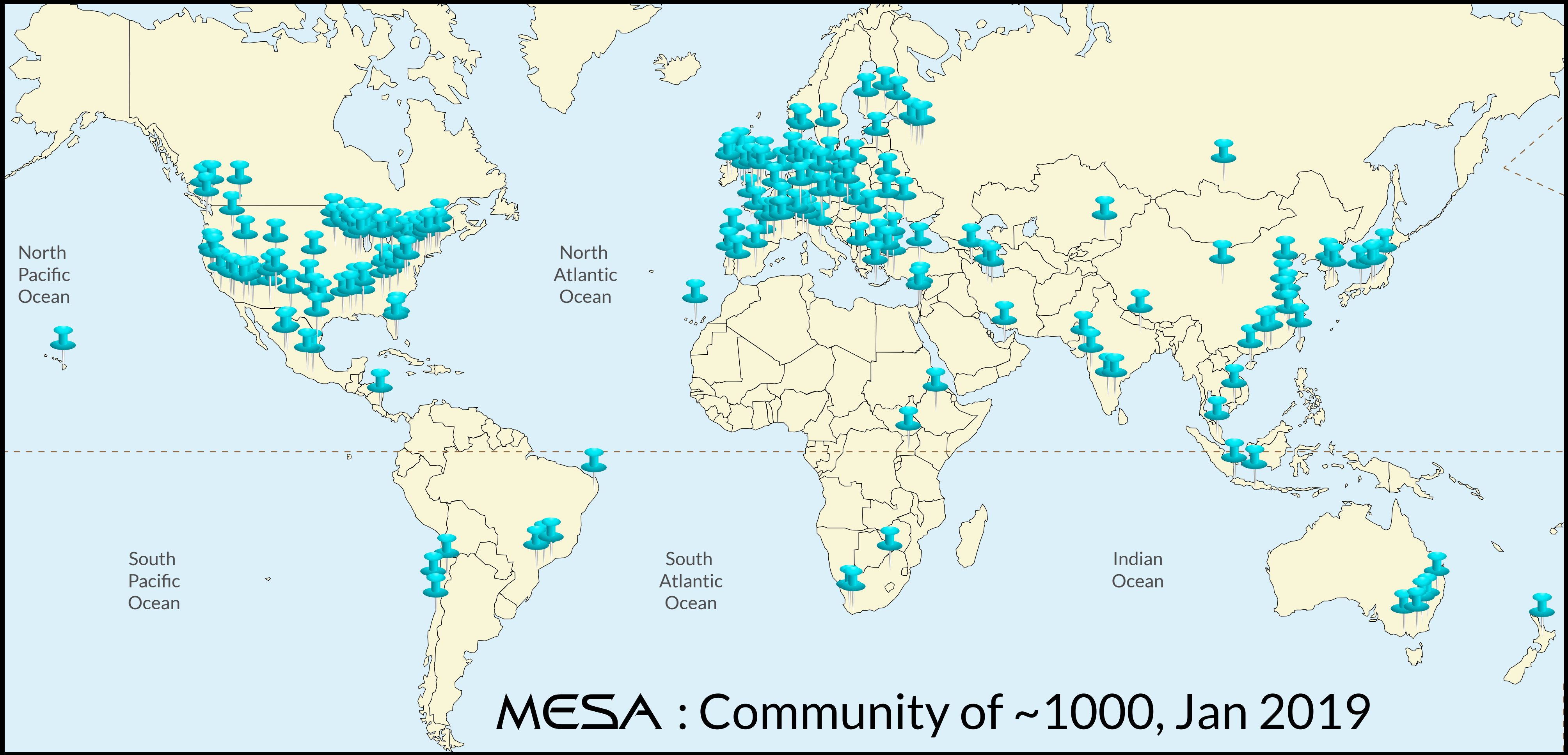
MESA

GYRE


Radek Smolec

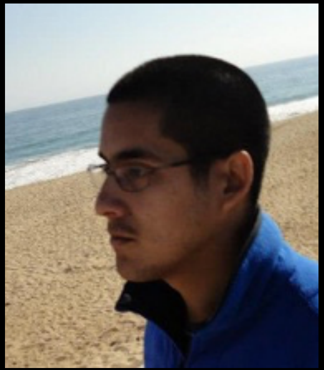

Anne Thoul


Evan Bauer




Bill Wolf


Rob Farmer


Pablo Marchant

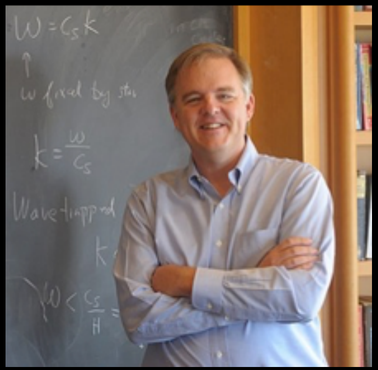

Warrick Ball


Aaron Dotter


Rich Townsend

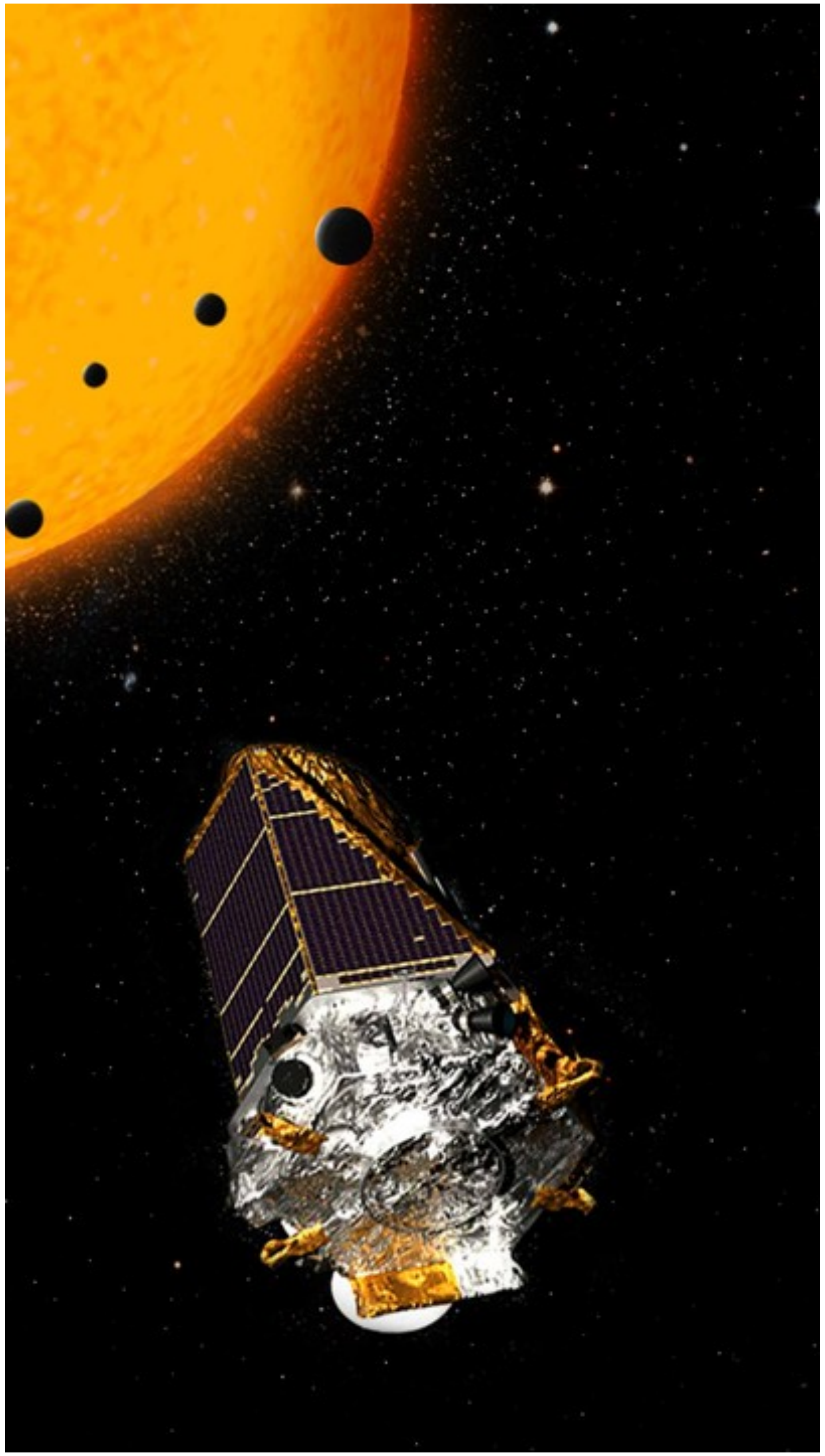

Frank Timmes


Bill Paxton


Lars Bildsten


Matteo Cantiello

1st Revolution in Asteroseismology



Precursers: WIRE & MOST;
CoRoT (2006) & Kepler (2009)/K2:

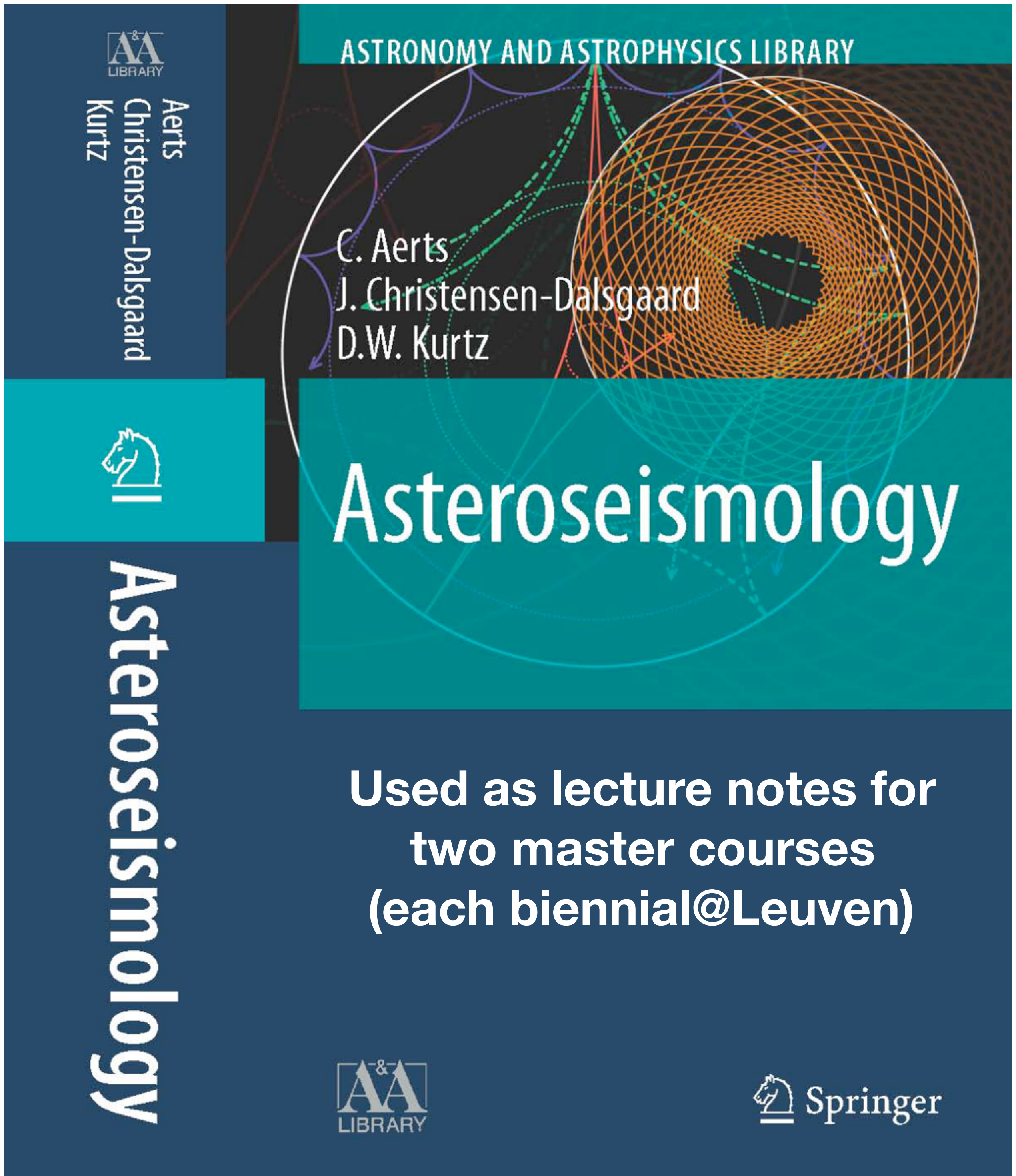
from ppt to ppm

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 + tidal asteroseismology

observational probing of internal rotation, mixing, and angular momentum

1st Revolution in Asteroseismology



Used as lecture notes for two master courses (each biennial@Leuven)

Precursers: WIRE & MOST; CoRoT (2006) & Kepler (2009)/K2:

from ppt to ppm

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

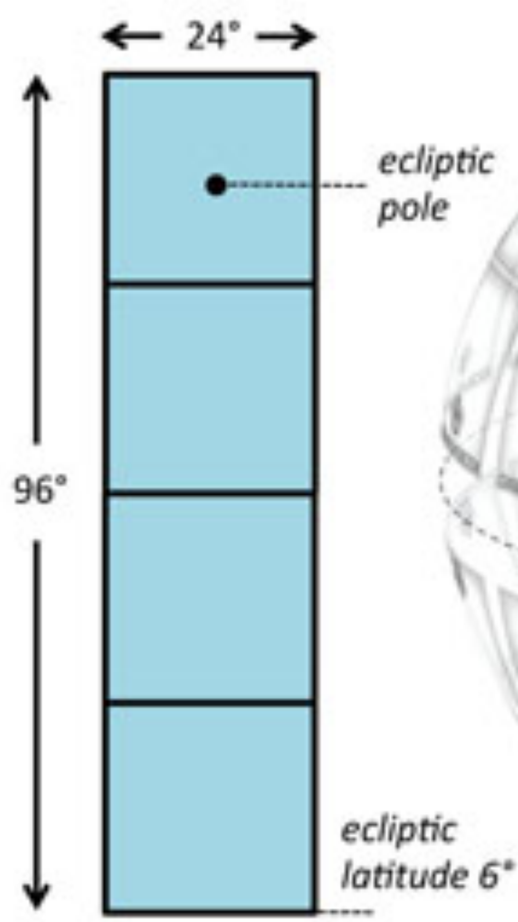
from physics in stellar envelopes to physics of stellar cores + tidal asteroseismology

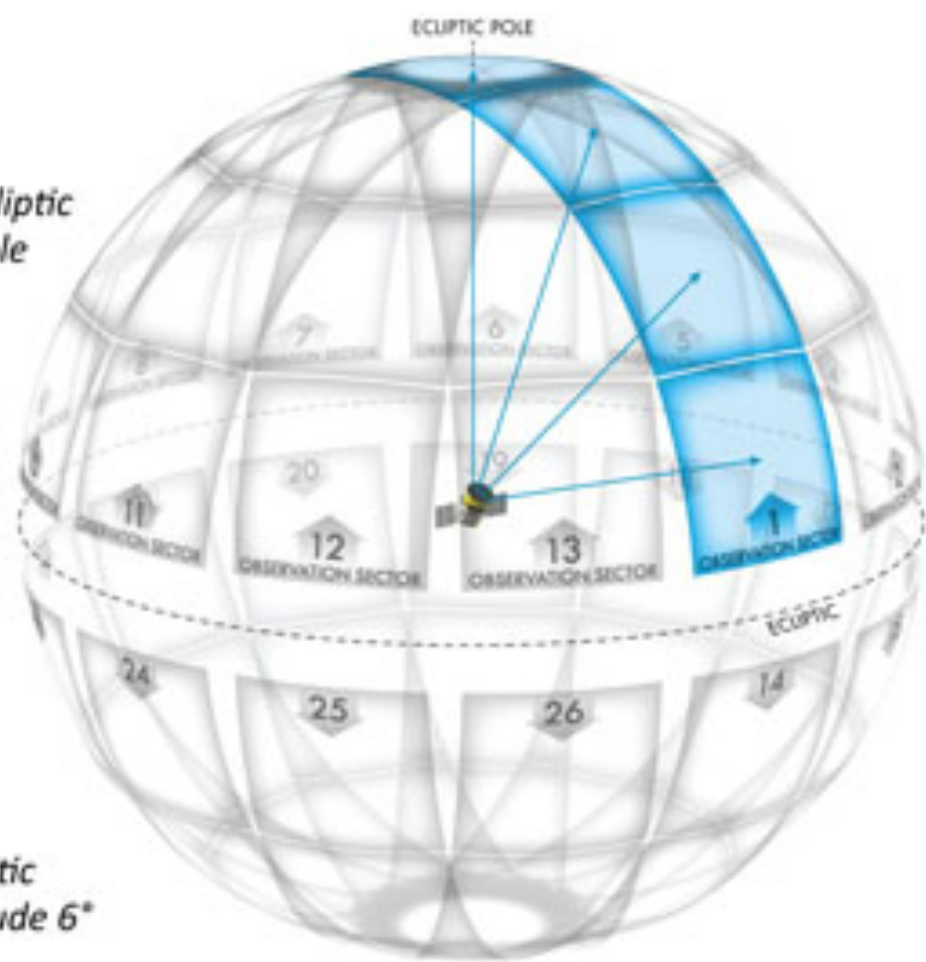
observational probing of internal rotation, mixing, and angular momentum

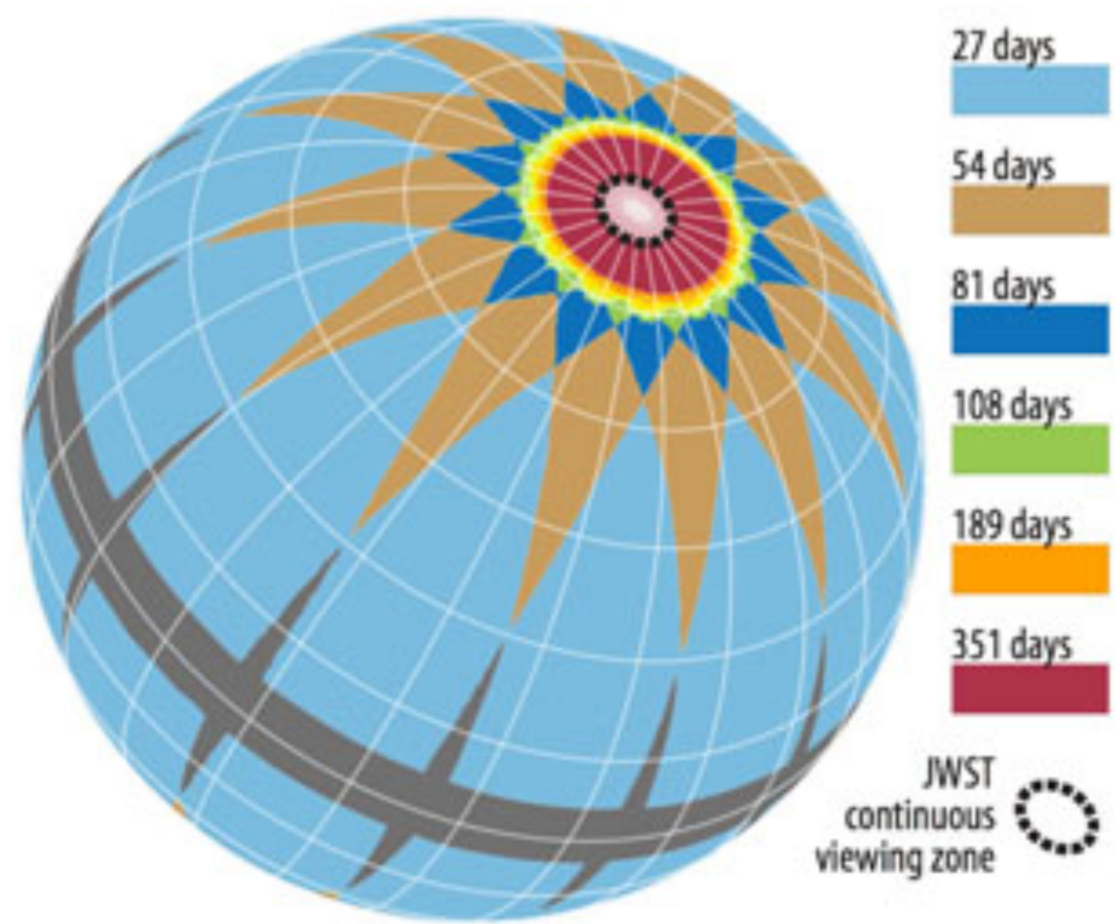
2nd Revolution in Asteroseismology

TESS, all-sky, 27d/FoV, 352d CVZ on ecliptic poles; FFI@30-min, pixel maps for 750 stars@2-min & 60 stars@20-sec

at last M >> 5 $M_\odot$







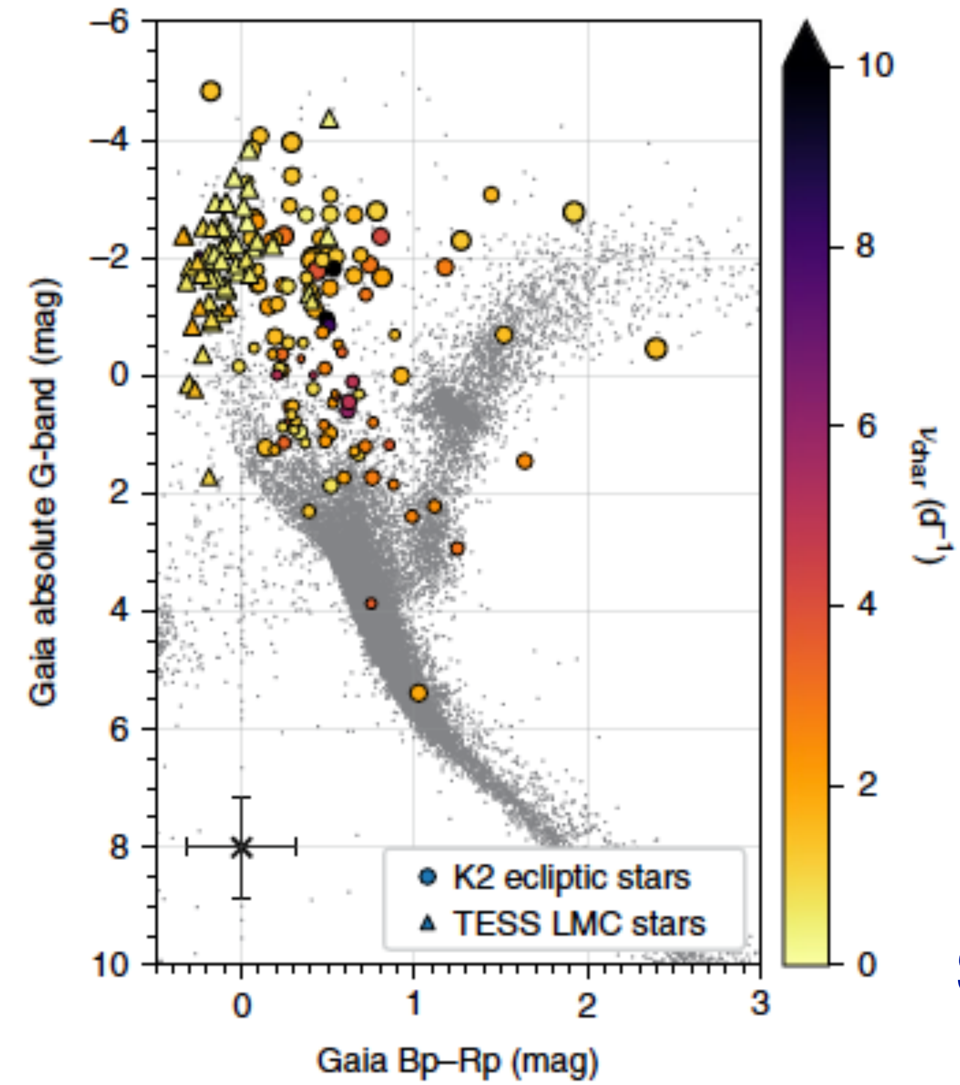
nature astronomy

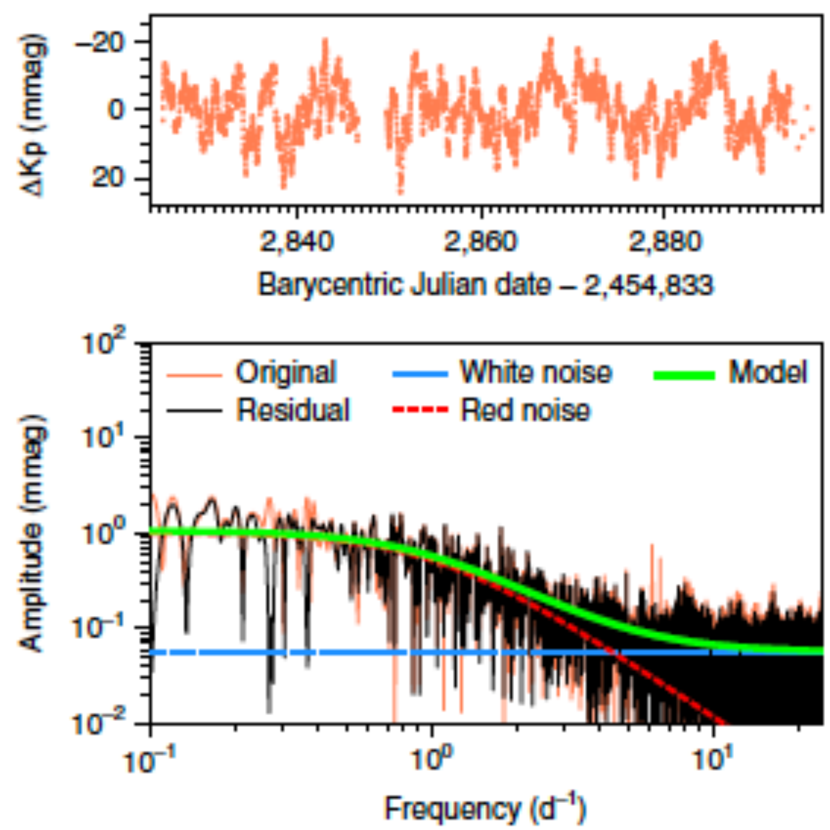
ARTICLES

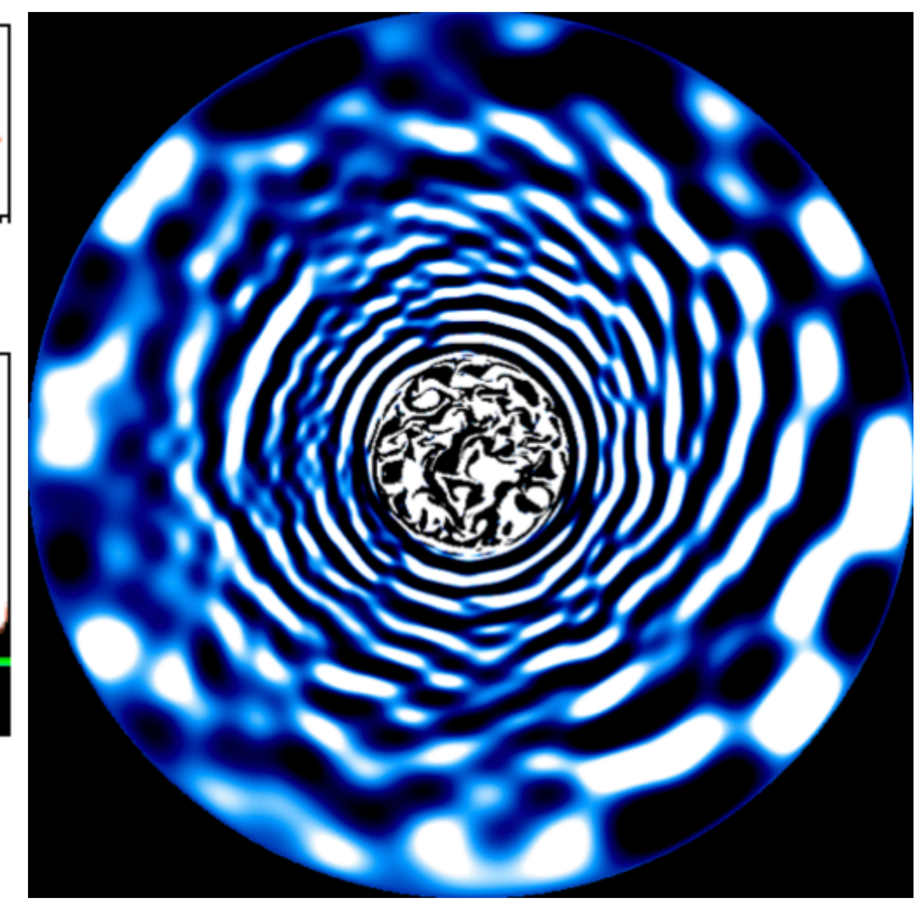
https://doi.org/10.1038/s41550-019-0768-1

Low-frequency gravity waves in blue supergiants revealed by high-precision space photometry

Dominic M. Bowman[1*], Siemen Burssens[1], May G. Pedersen[1], Cole Johnston[1], Conny Aerts[1,2], Bram Buysschaert[1,3], Mathias Michielsen[1], Andrew Tkachenko[1], Tamara M. Rogers[4,5], et al.







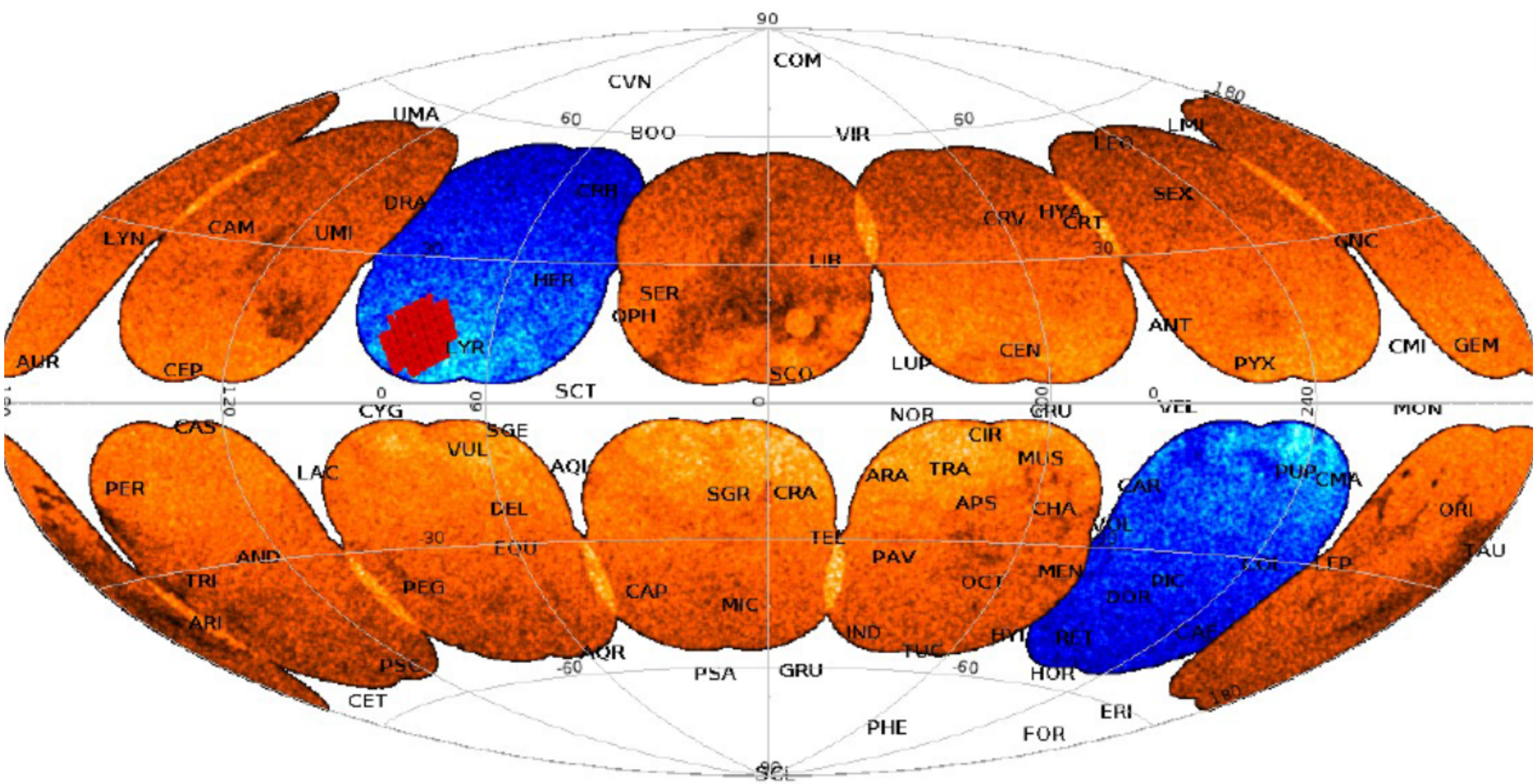
see class 3 on AM transport & mixing

KU LEUVEN 3rd Revolution: PLATO (2026-2030+)

PLATO Guest Observer Program: 8% open time (ToO)

- Galactic Archeology, Clusters, Associations, AGN?
- Asteroseismology across HRD, for large range in Z
- Binaries & tidal evolution across HRD
- Accretion, debris disks & magnetism in YSO
- Stellar winds & binary mass transfer of evolved stars

24 normal & 2 fast cameras on 1 platform, FoV 2232 sq.deg. operating from L2



Asteroseismology for Stellar Evolution, Exoplanets, and Galactic Structure

Class 1: Introducing starquakes

Class 2: Weighing, Sizing, Ageing

Class 3: Angular Momentum Transport

Image credit: NASA's Goddard Space Flight Center/S. Wiessinger