Asteroseismology: diving deep into stars

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21 May 2024, N3AS Online Seminar

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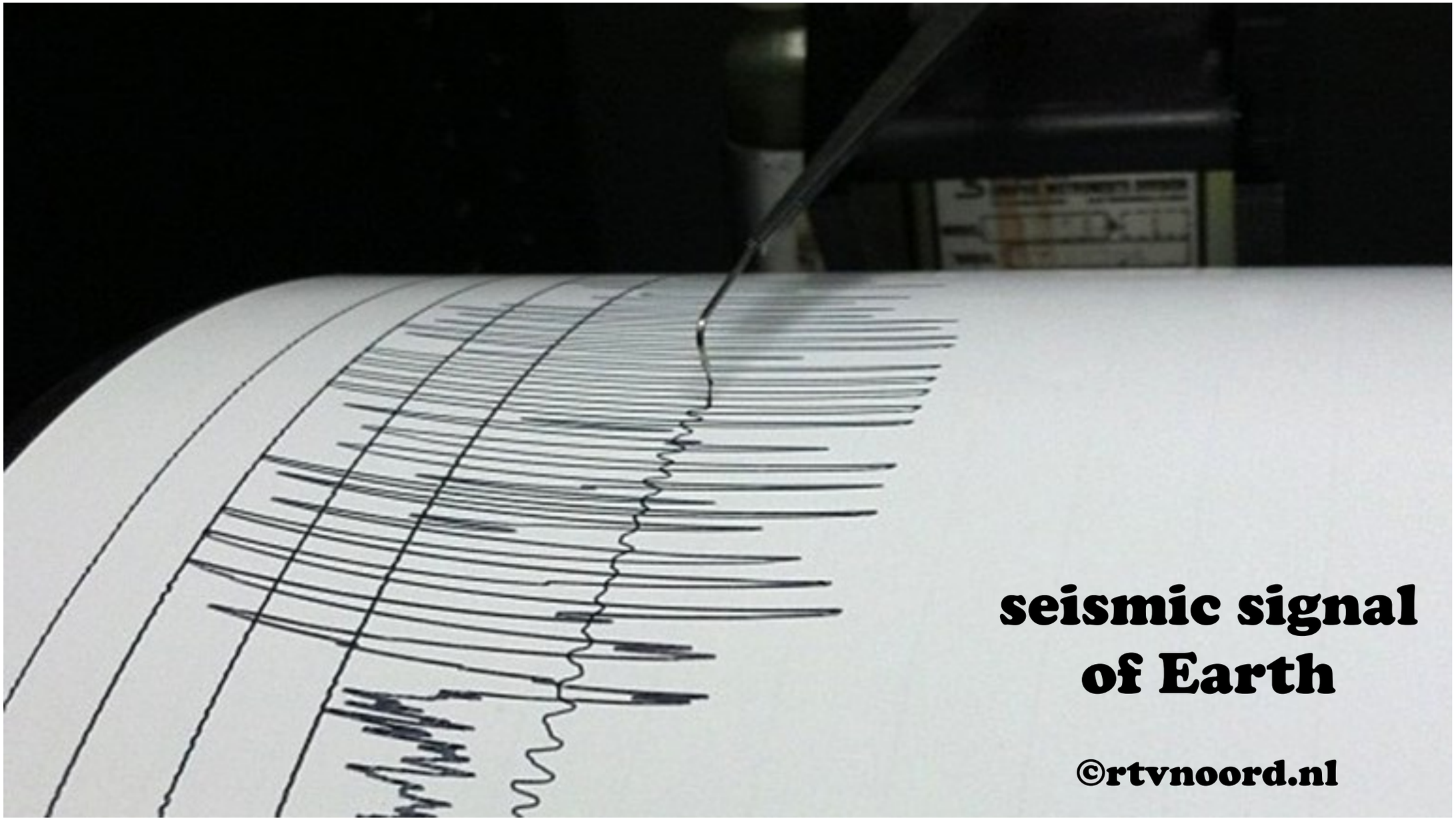
Waves allow us to “see” the invisible



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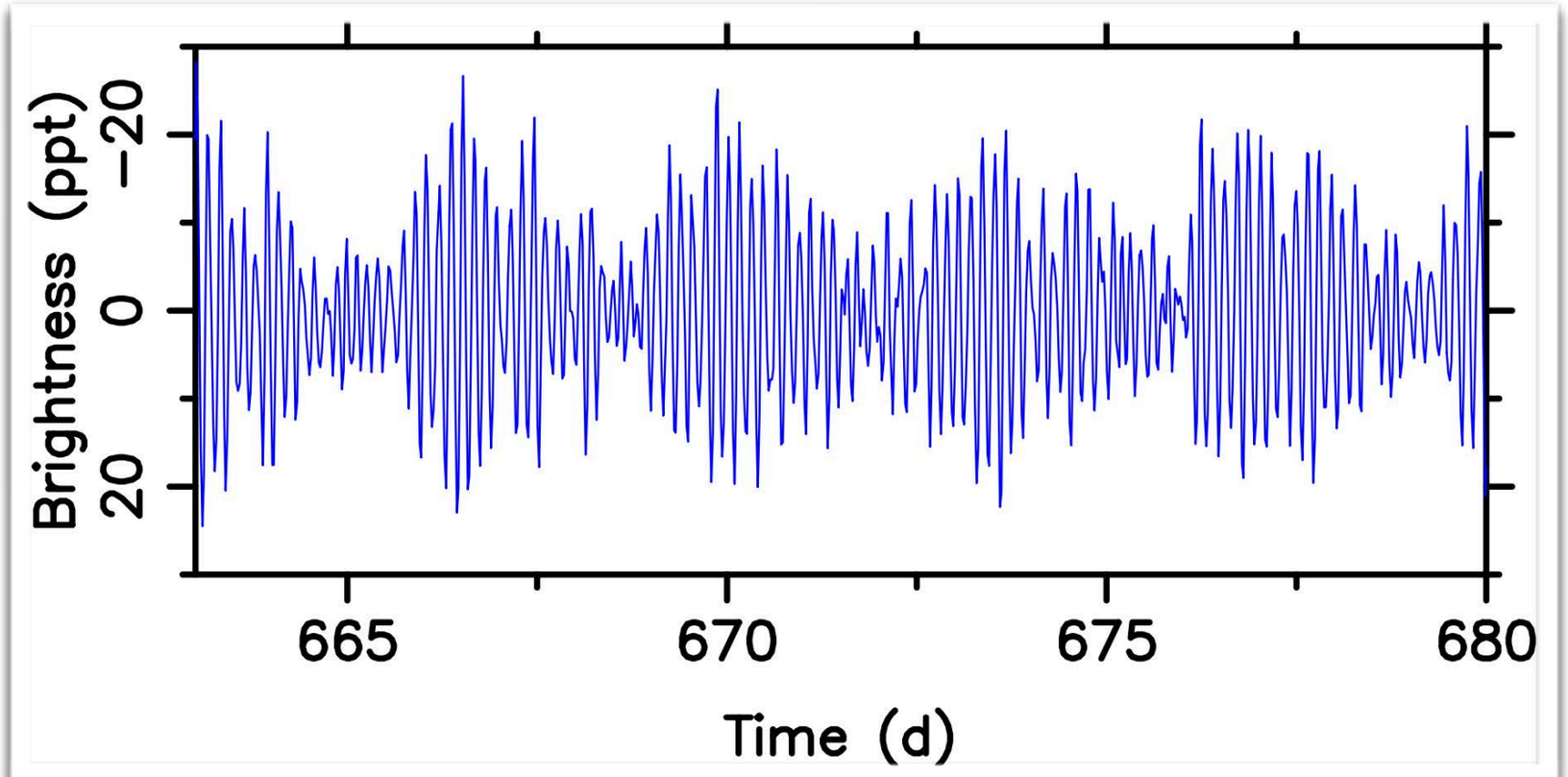
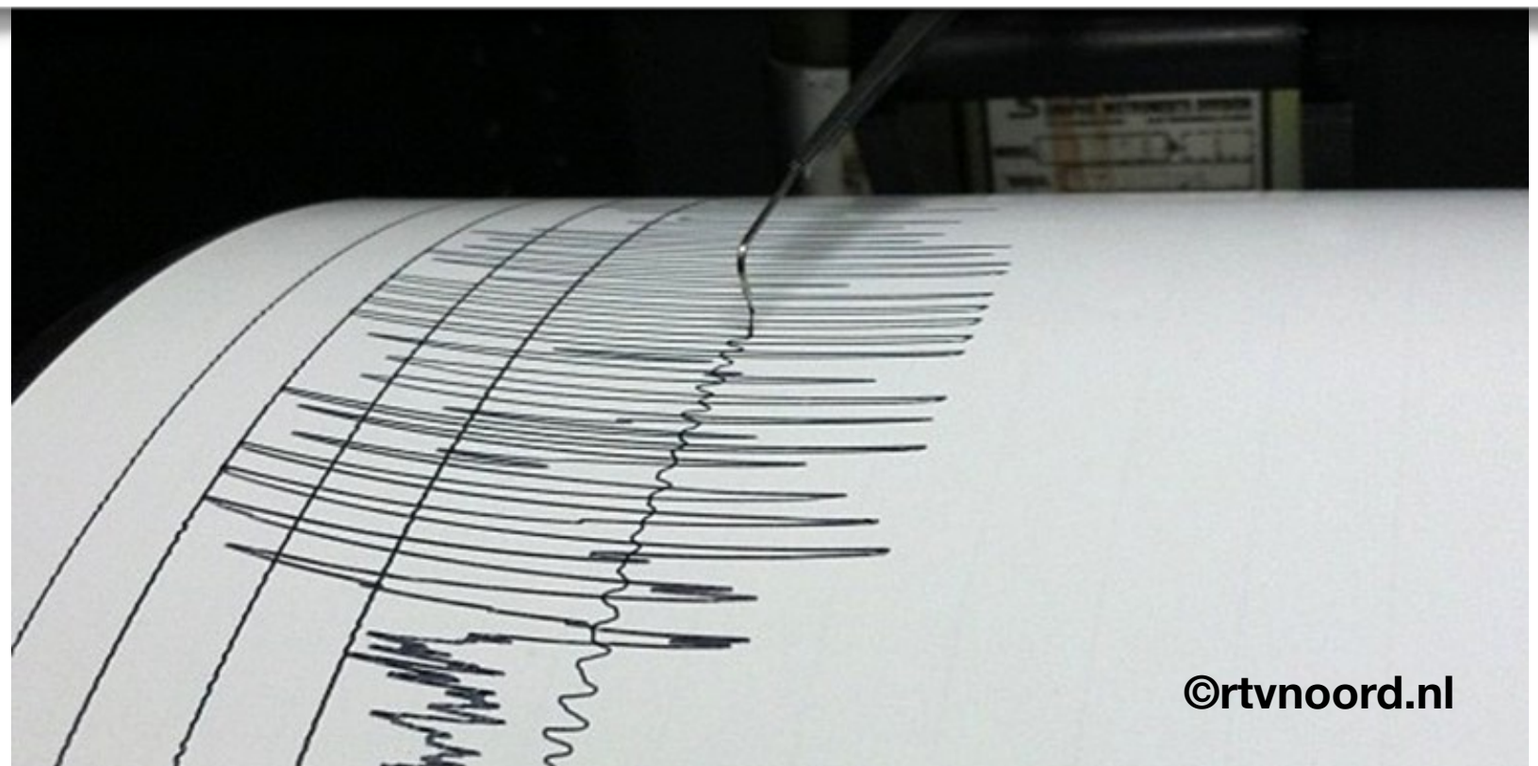
Can we detect waves inside stars?





Yes we can!... seismic waves offer localised measurements of internal physics & chemistry from observations of stellar surface

seeing "inside" the stars brings surprises...

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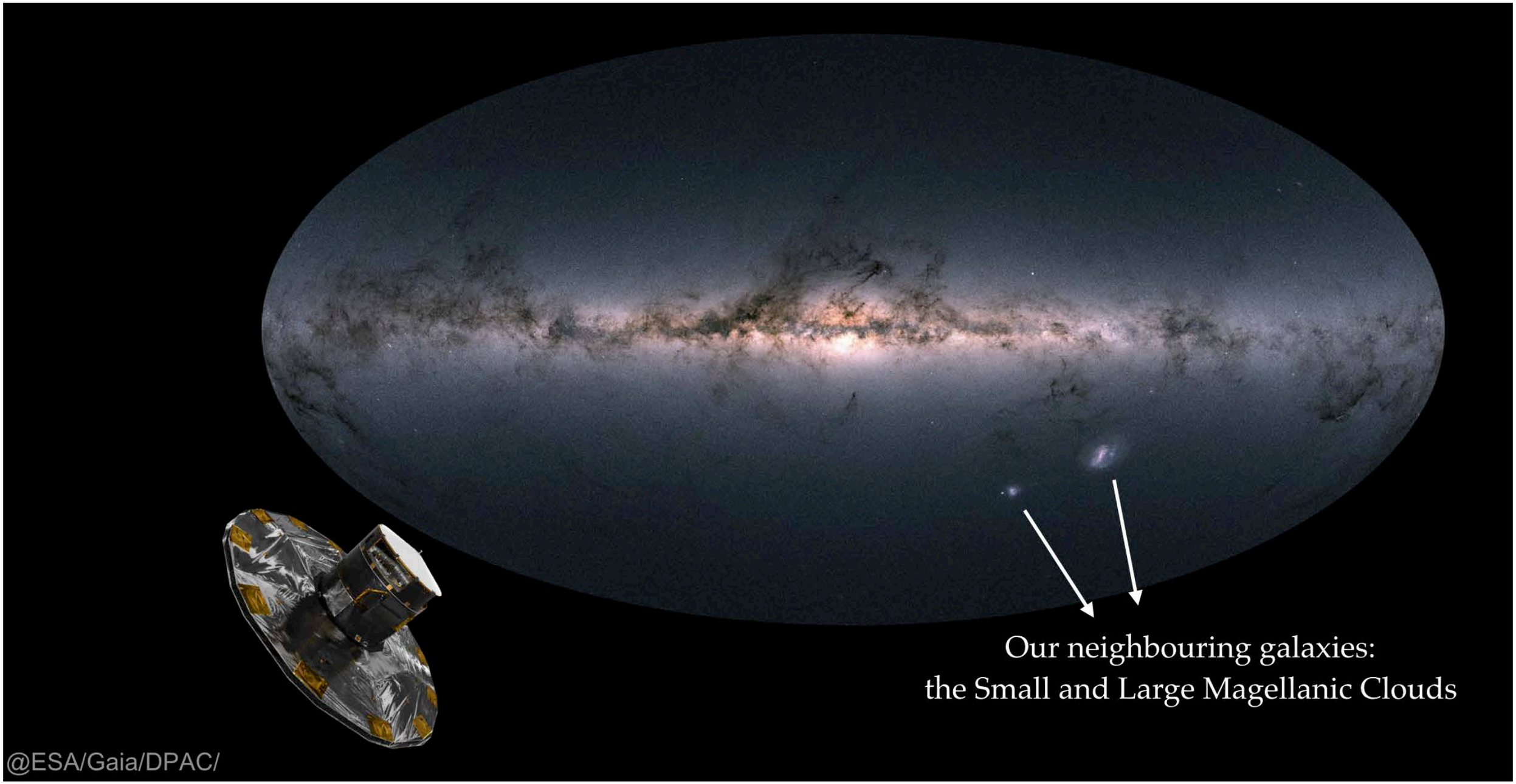
Where? in Milky Way



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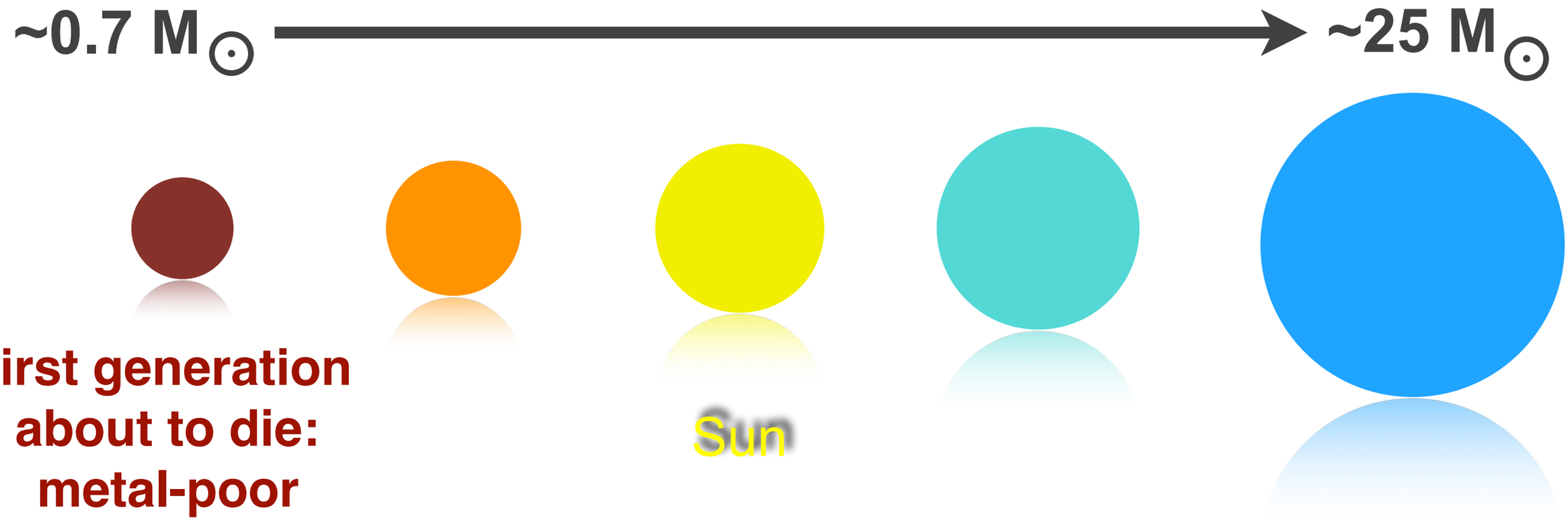
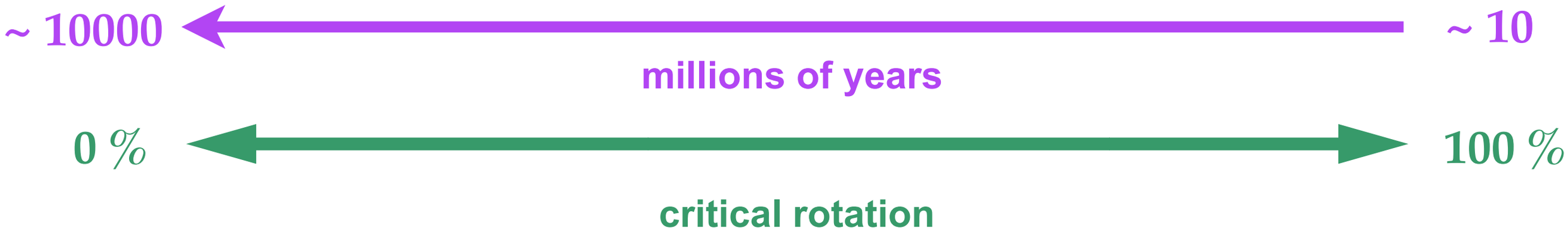
Playground: masses, ages, rotation rates





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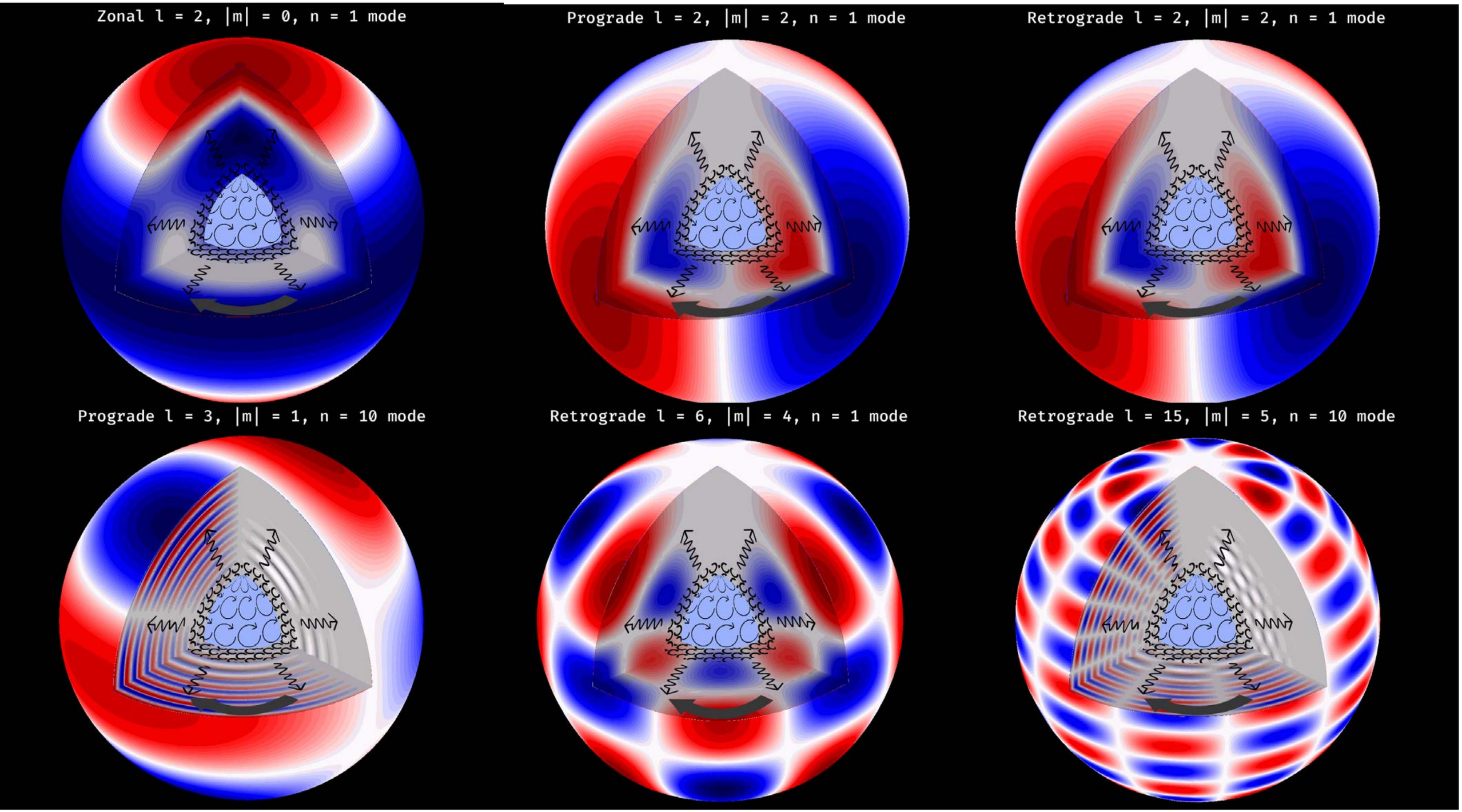
Nonradial oscillations



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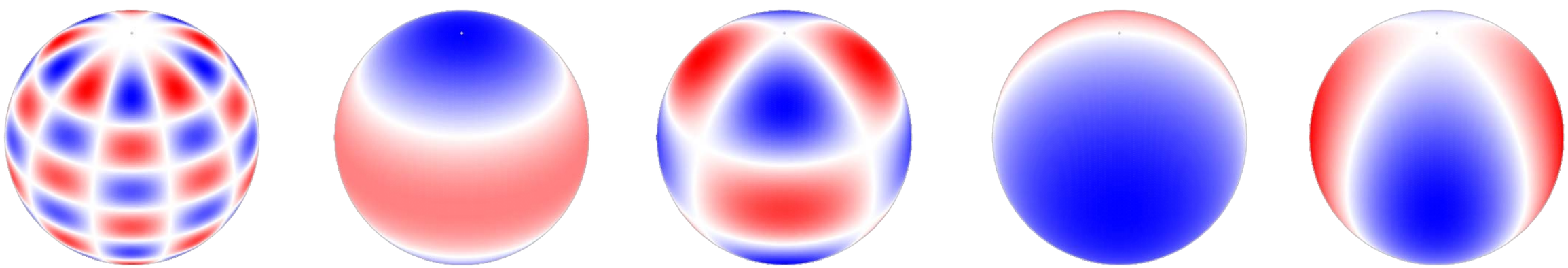
Mathematically speaking

- **Wave equation:** $\omega^2 \boldsymbol{\xi} + i\omega \mathcal{B}(\boldsymbol{\xi}) + \boldsymbol{C}(\boldsymbol{\xi}) = 0$

- **Simplest case: displacement due to oscillation mode described by spherical harmonic & frequency:**

$$\boldsymbol{\delta r} = \xi_r \boldsymbol{a}_r + \boldsymbol{\xi}_{\mathrm{h}} \ , \quad \boldsymbol{\xi}(r, \theta, \phi, t) \ =$$

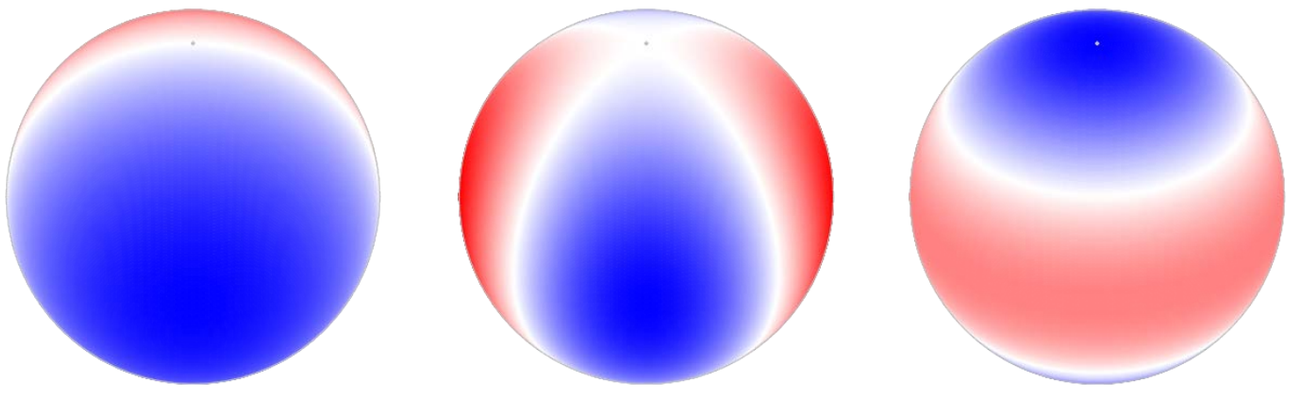
$$[(\xi_{r,nl} \boldsymbol{a}_r + \xi_{\mathrm{h},nl} \nabla_{\mathrm{h}}) Y_l^m(\theta, \phi)] \exp(-\mathrm{i}\, \omega_{nlm} t)$$

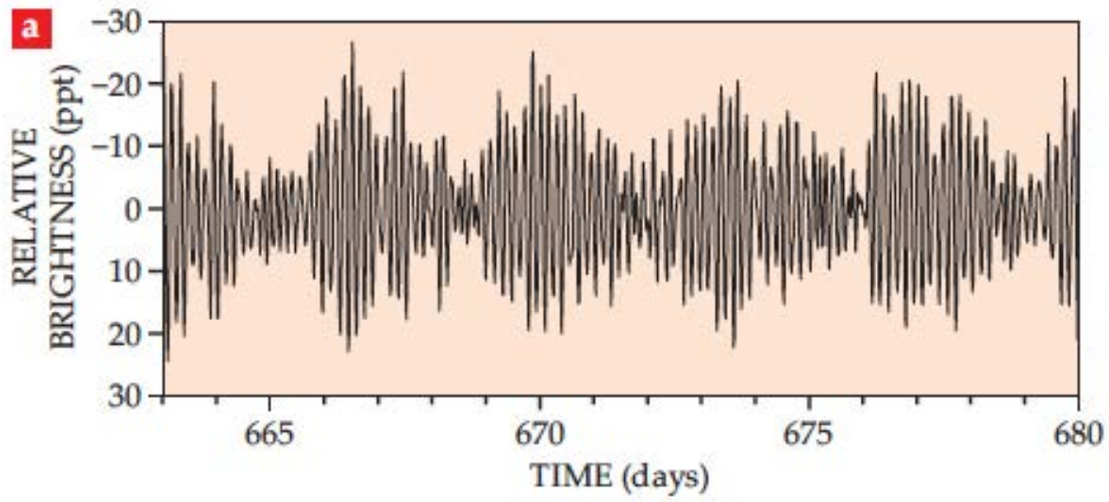


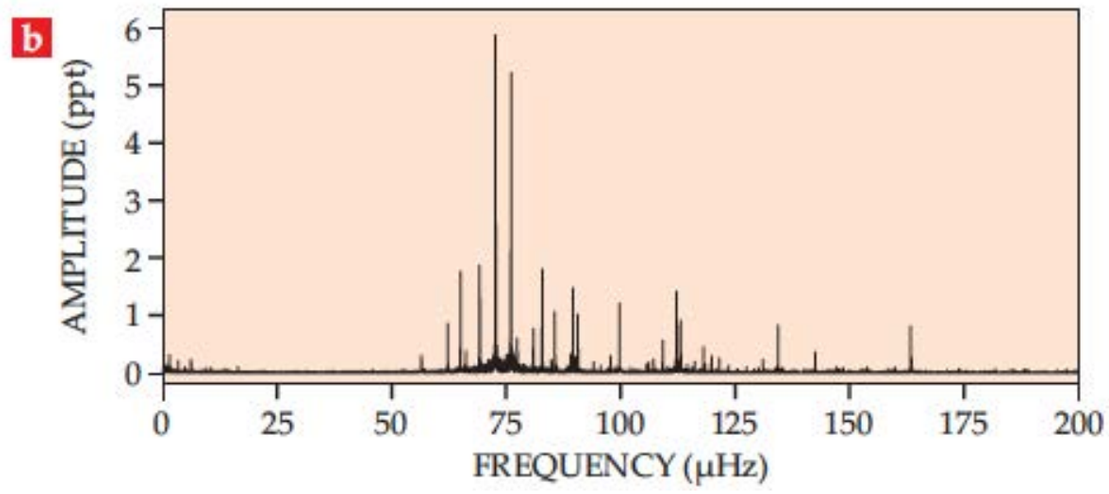
Observed oscillation modes

- **Simplest case: displacement due to each oscillation mode described by spherical harmonic & frequency**

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







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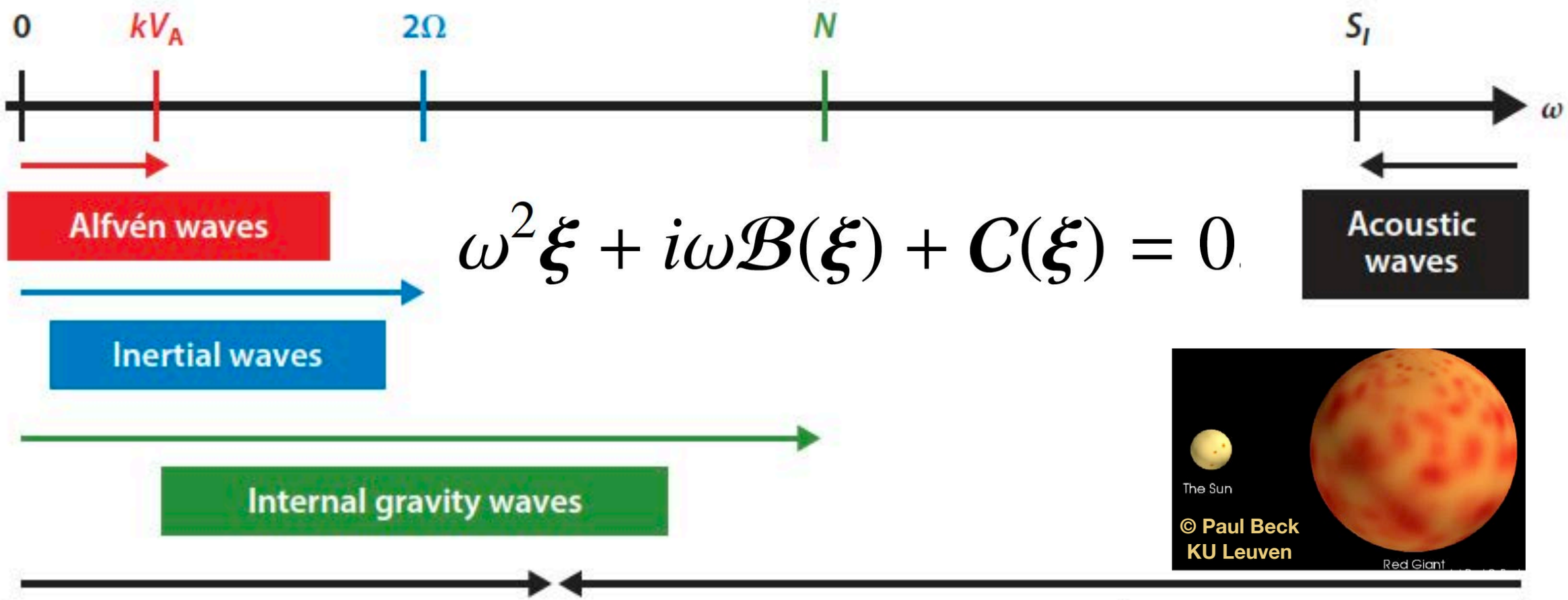
Frequency regimes



Rotation & magnetic fields
cannot be treated as small perturbations
in computations of the waves & modes

Rotation & magnetic fields
cause small perturbations

(adapted from Aerts, Mathis, Rogers, ARAA, 2019)

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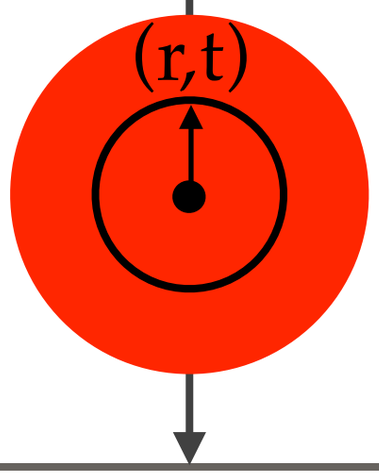
Asteroseismic modelling

THEORY

numerical stellar models

Major assumption:
stars are spherical

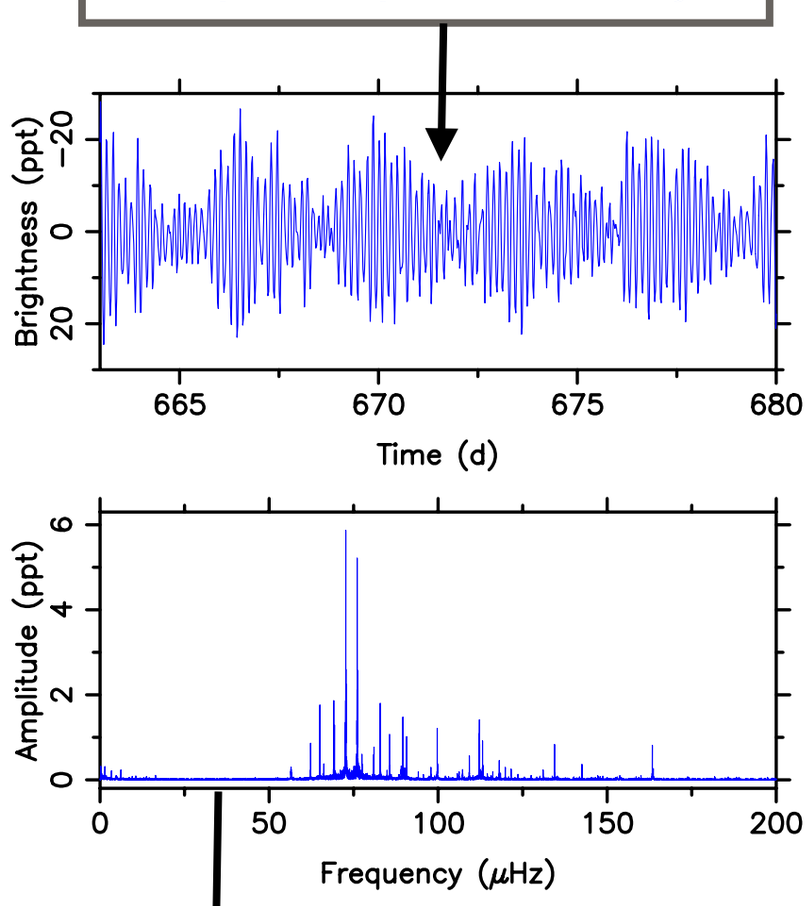


stellar pulsation code

Theoretical frequencies

OBSERVATIONS

space photometry



Observed frequencies

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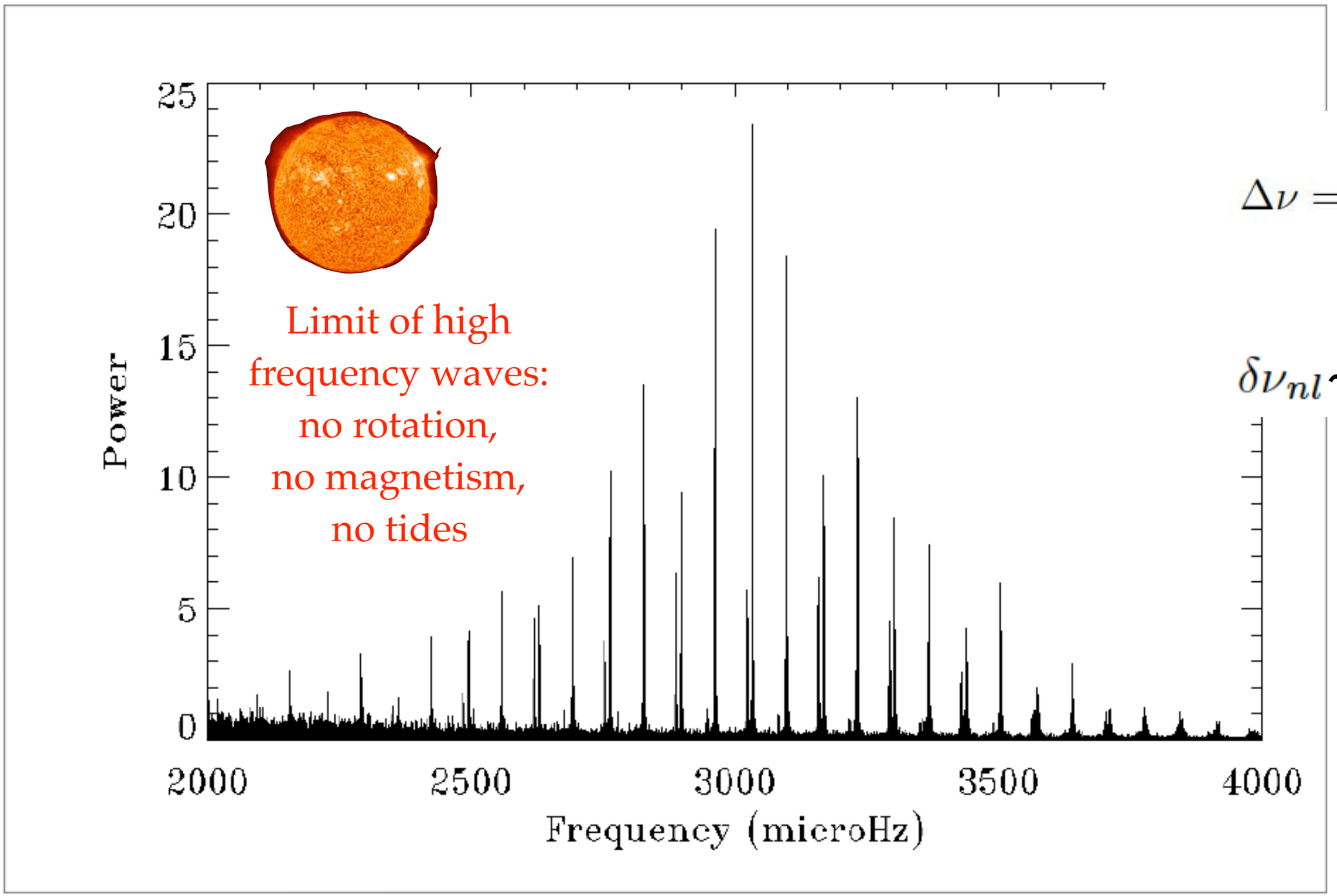
Helioseismology paved the way



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

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

(Christensen-Dalsgaard, 2002, RMP)

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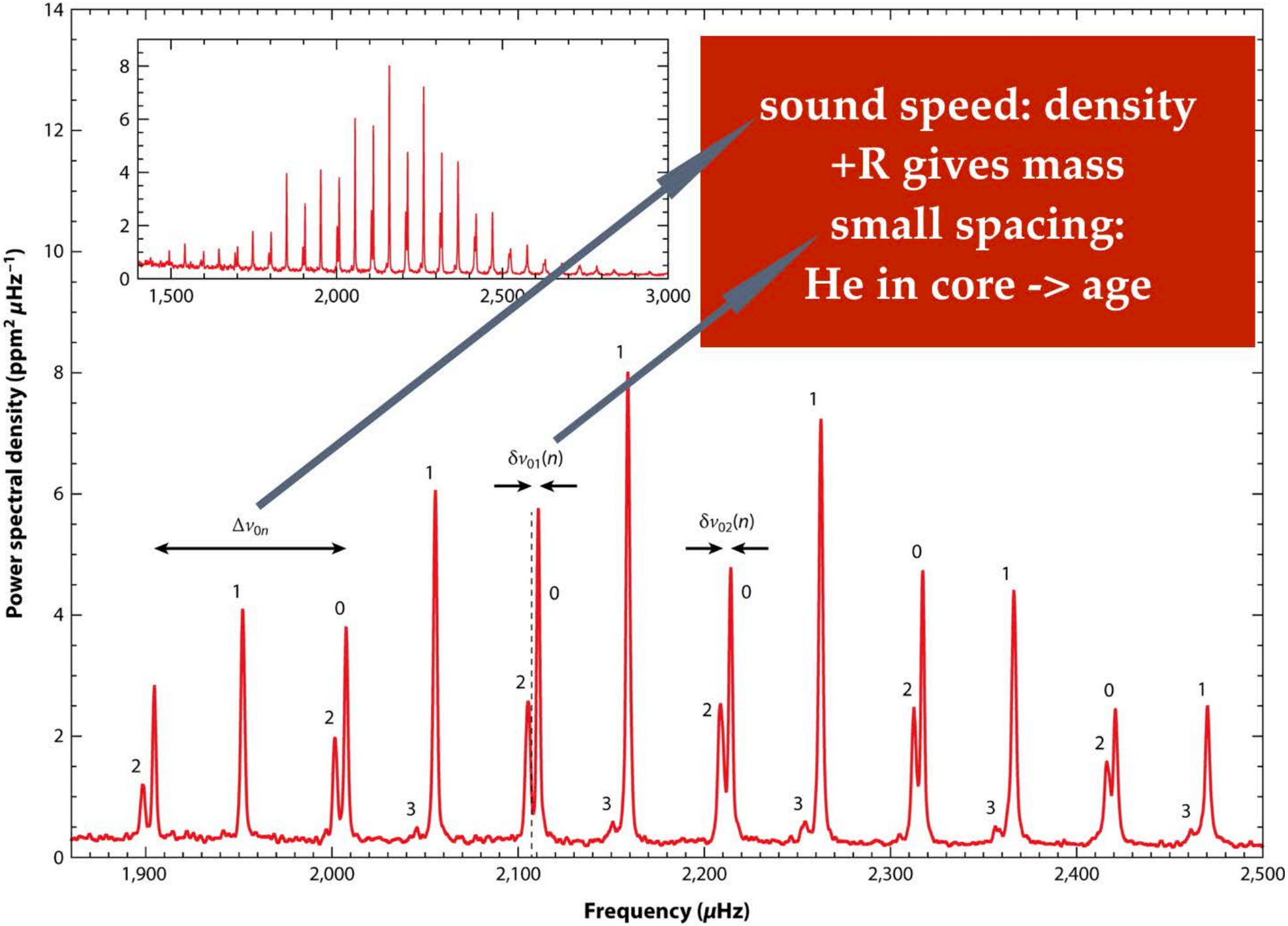
Sizing & Weighing Stars



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

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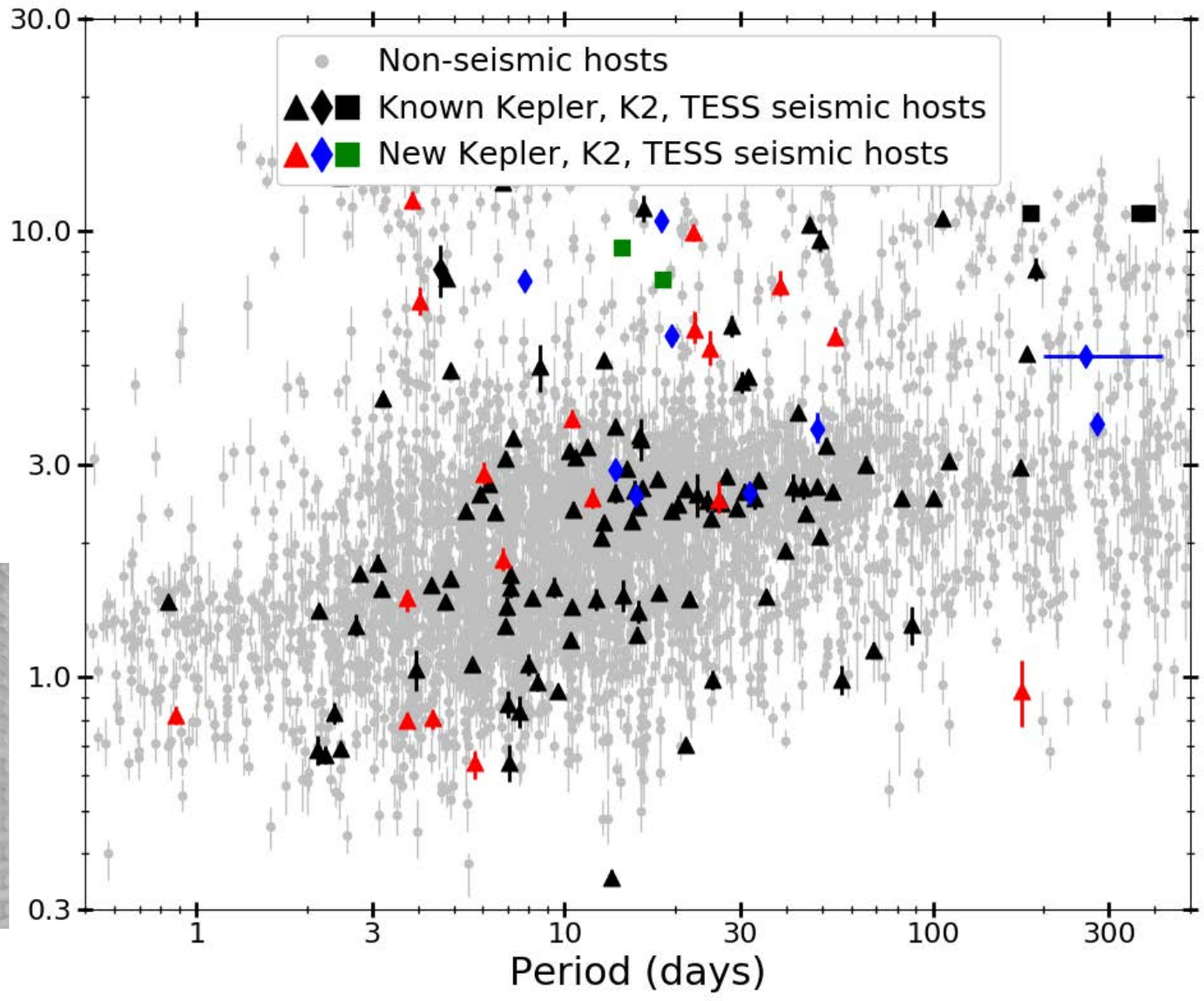
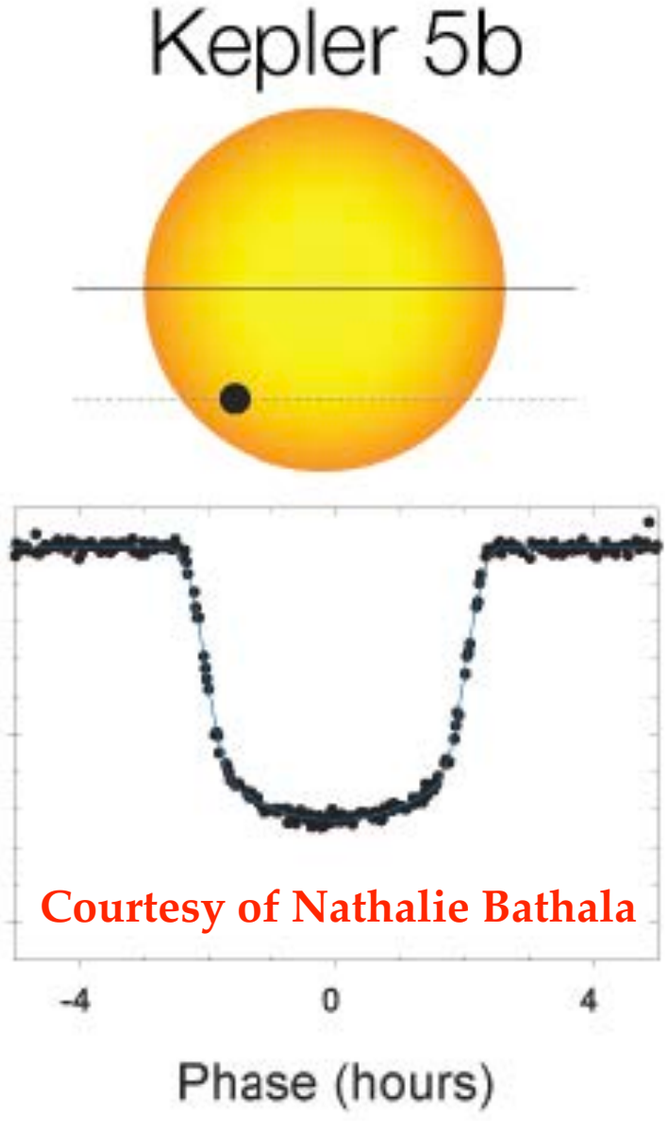
Radius, Mass, Age of Exoplanet hosts

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



Courtesy:
Ashley Chontos (2021)



Courtesy of Nathalie Bathala

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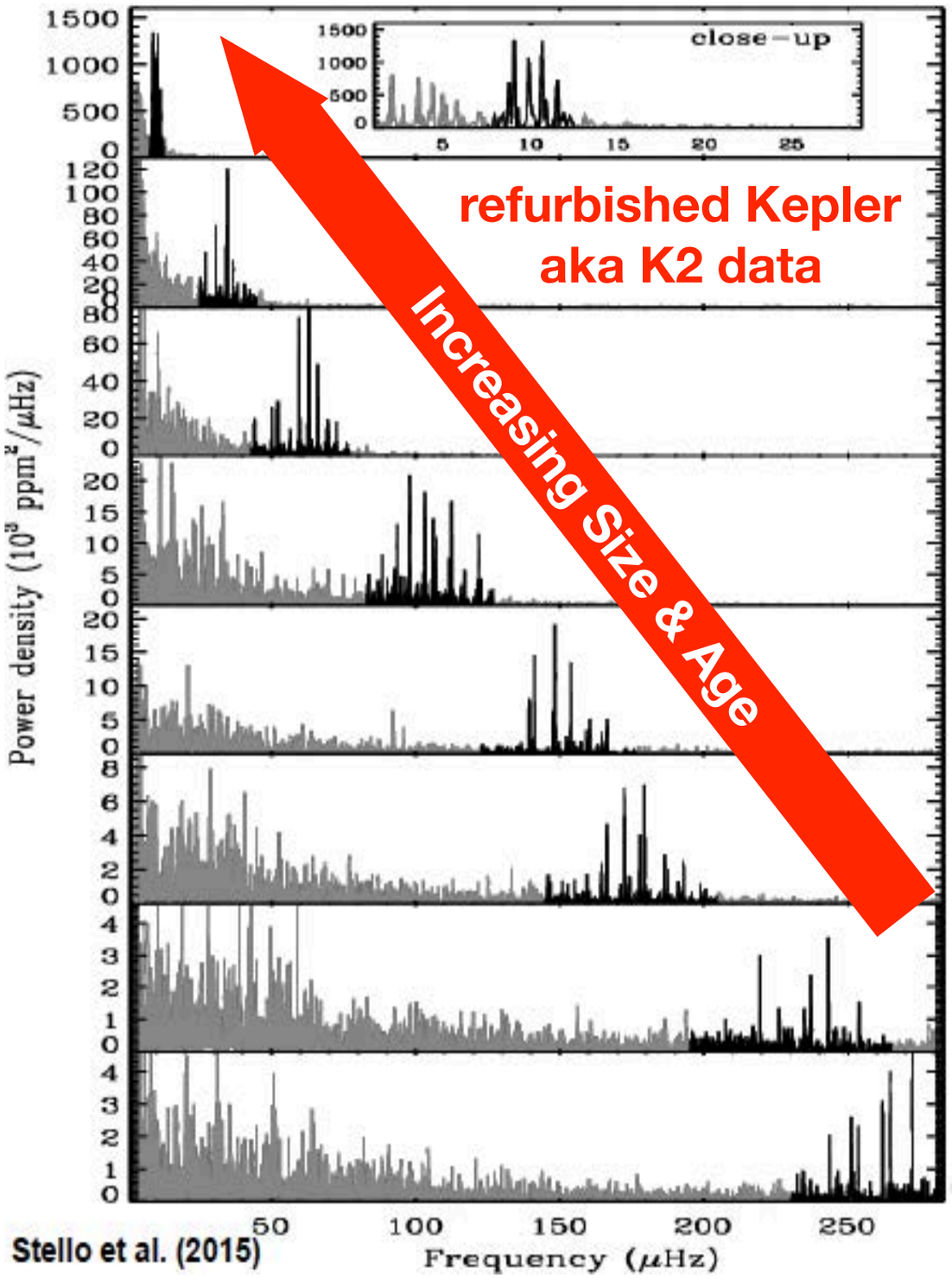
Size, Mass, Age from acoustic waves



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

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

Global parameters of 10000s of "sun-like" stars with high precision!
2, 4, 20% in radius, mass, age;
cf. red giants for galactic archaeology

Seismic distances ~few%

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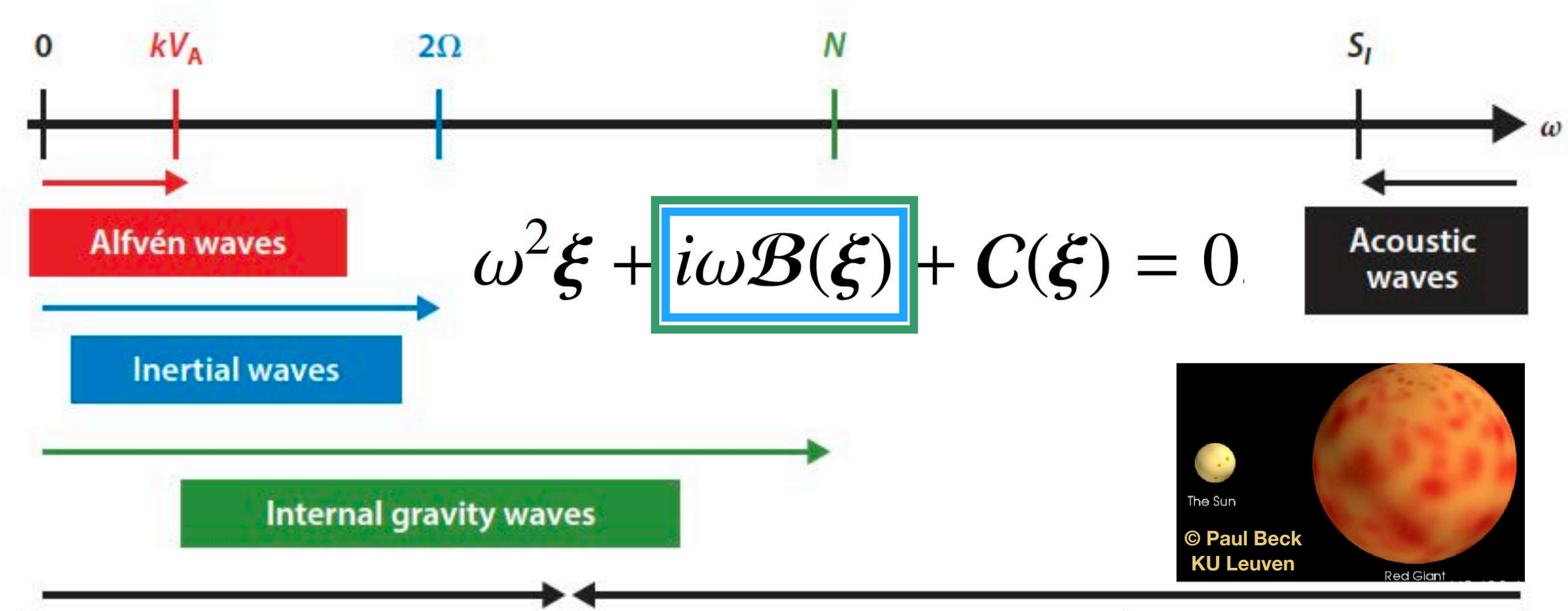
Slow waves in fast rotators



Rotation & magnetic fields
cannot be treated as small perturbations
in computations of the waves & modes

Rotation & magnetic fields
cause small perturbations

(adapted from Aerts, Mathis, Rogers, ARAA, 2019)

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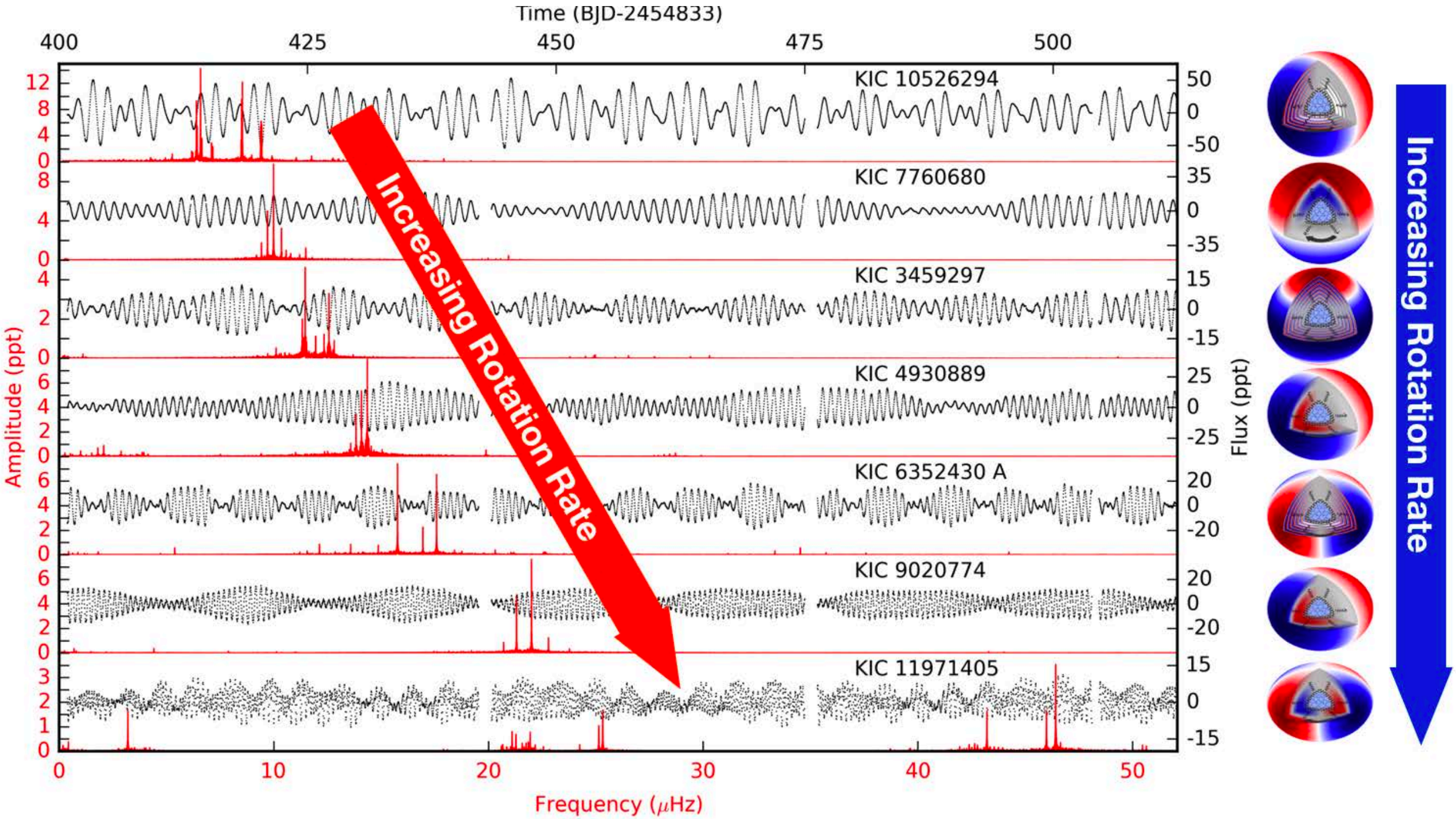
Gravito-inertial asteroseismology



opportunity to deduce He core masses & Ω(r)

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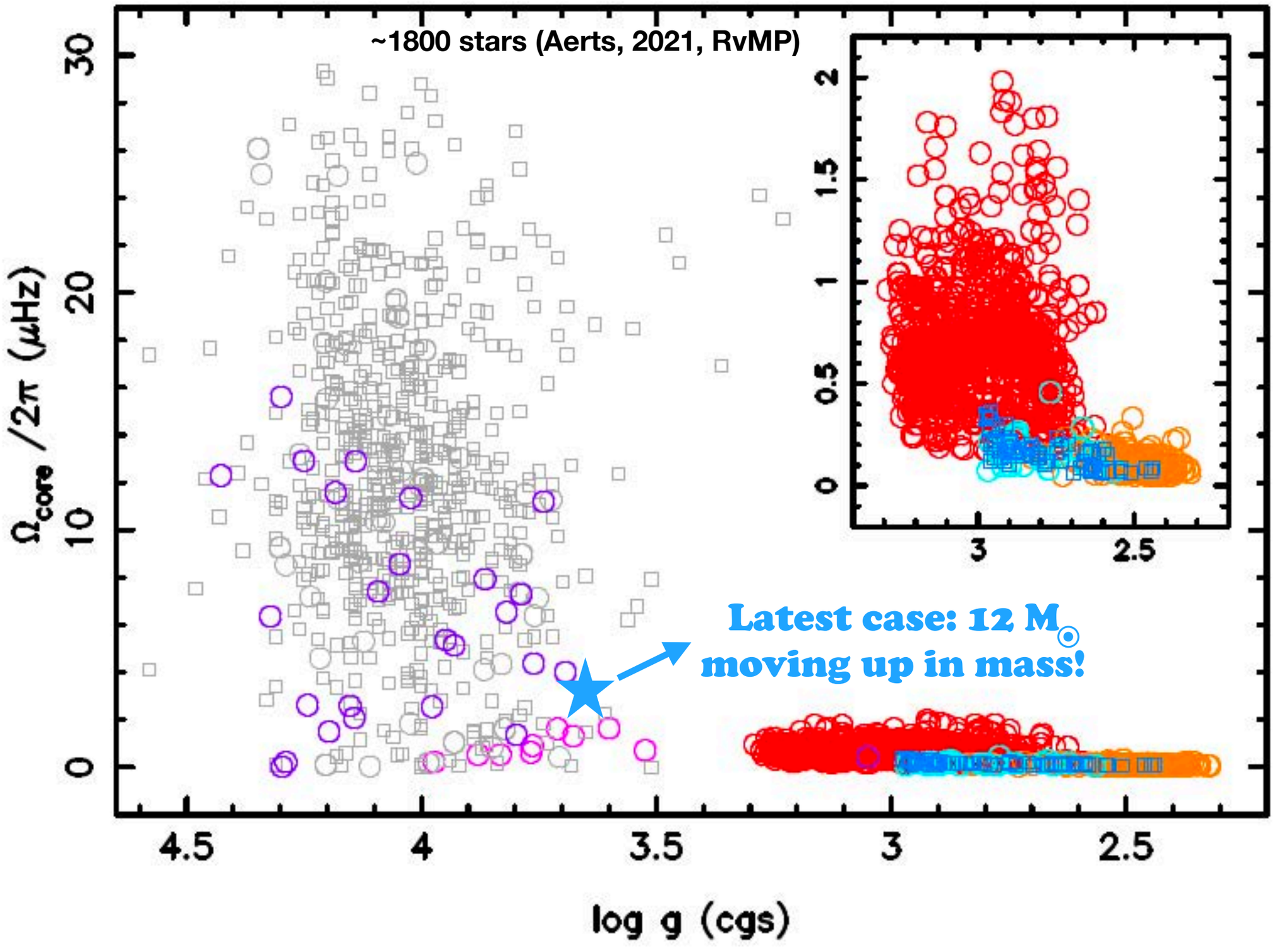
Asteroseismic estimates Ω_{core}



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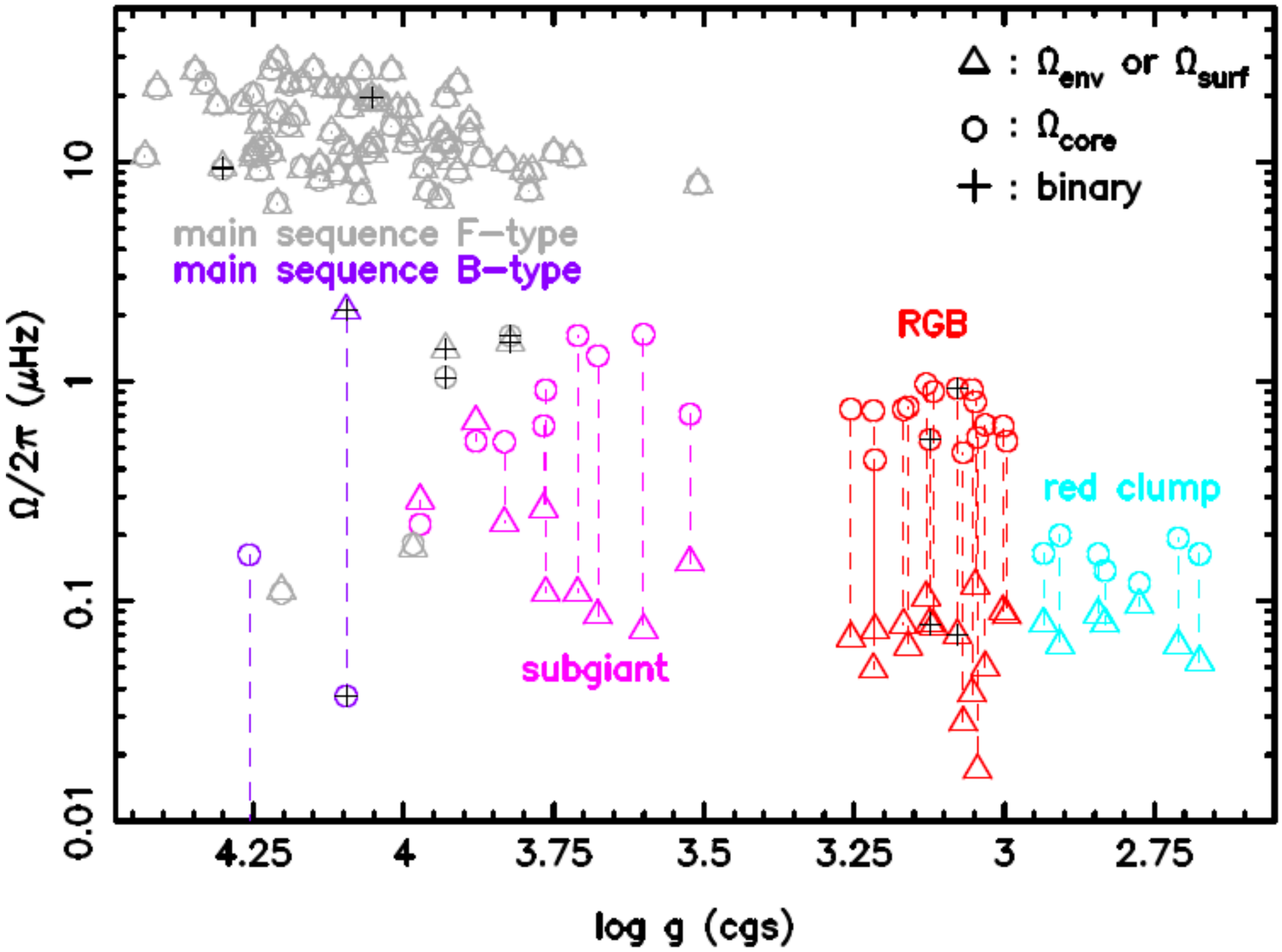
Measuring Ω_{core} versus Ω_{env}

"Standard SSE" needs fixes...

(from Aerts, 2021, RvMP)



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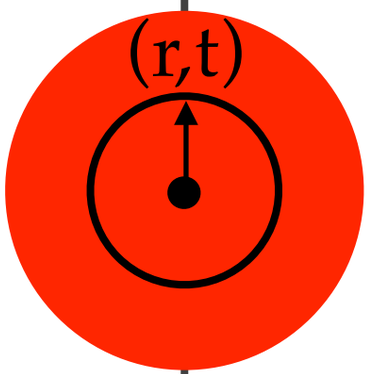
Status asteroseismic modelling

THEORY

numerical stellar models

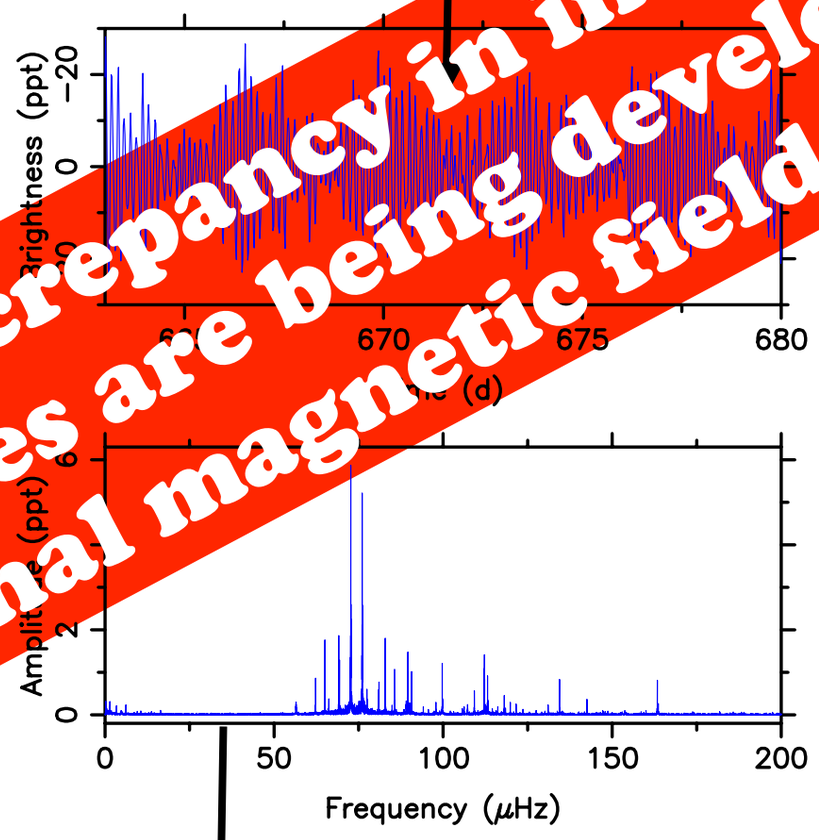


stellar pulsation code

frequencies

OBSERVATIONS

space photometry



Observed frequencies

Up to a factor 100 discrepancy in internal rotation: novel theories are being developed, including internal magnetic fields

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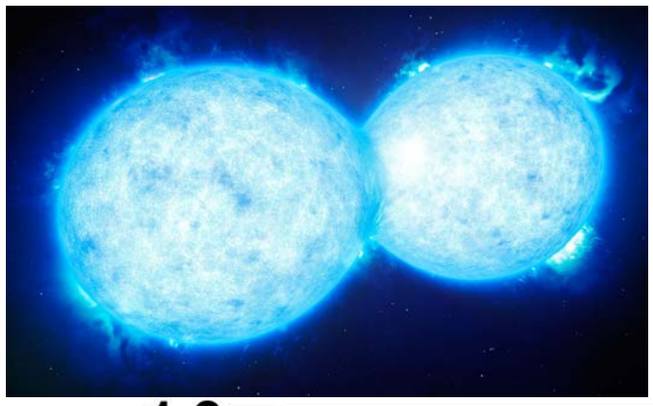
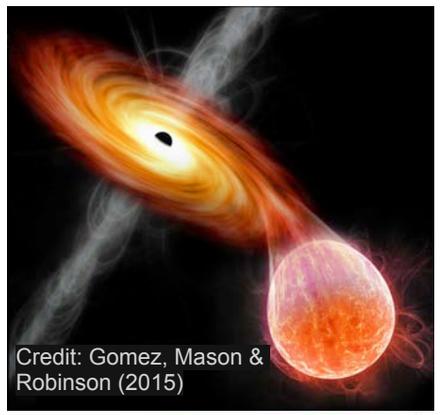
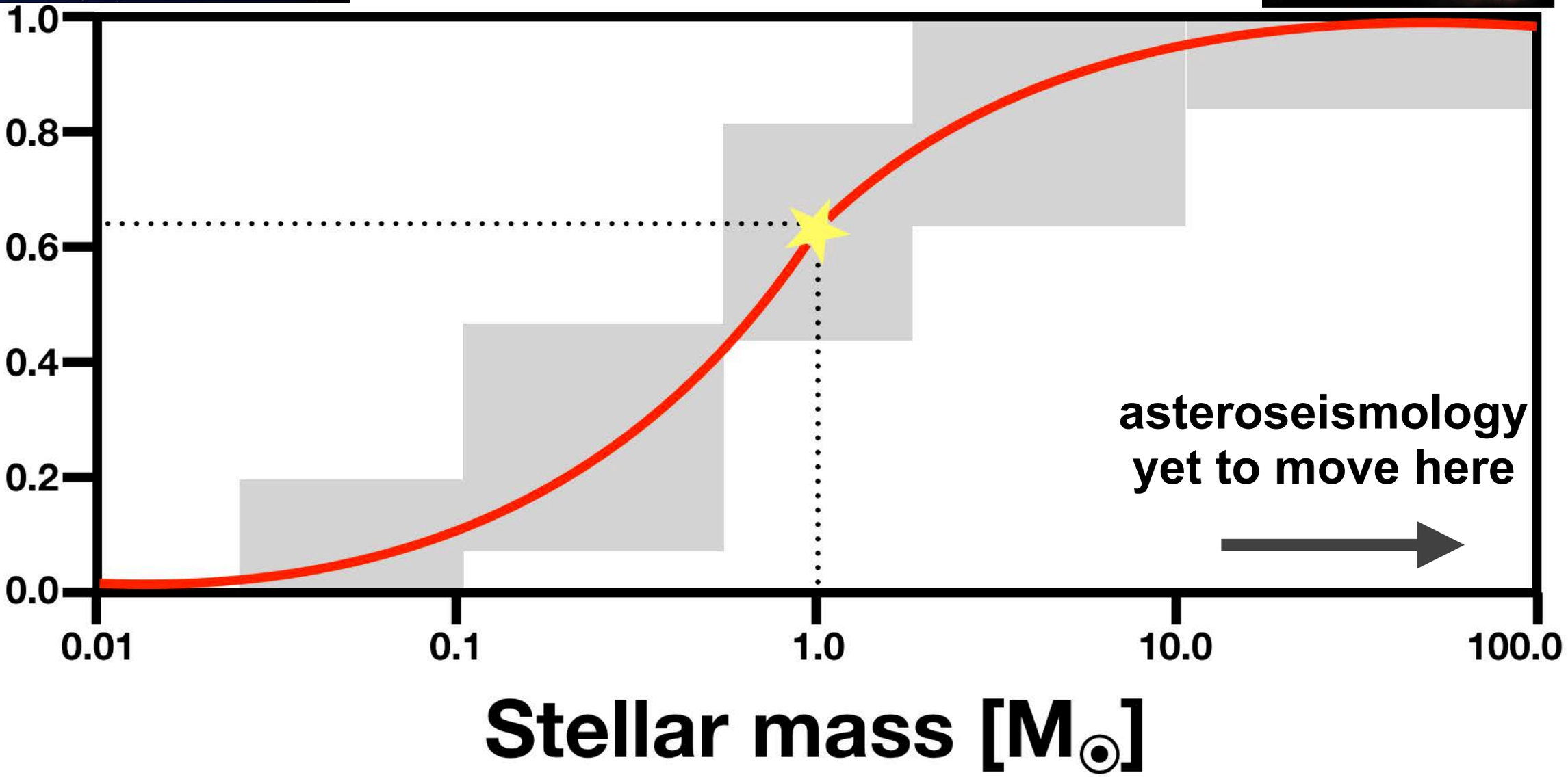
Onward to tides in close binaries







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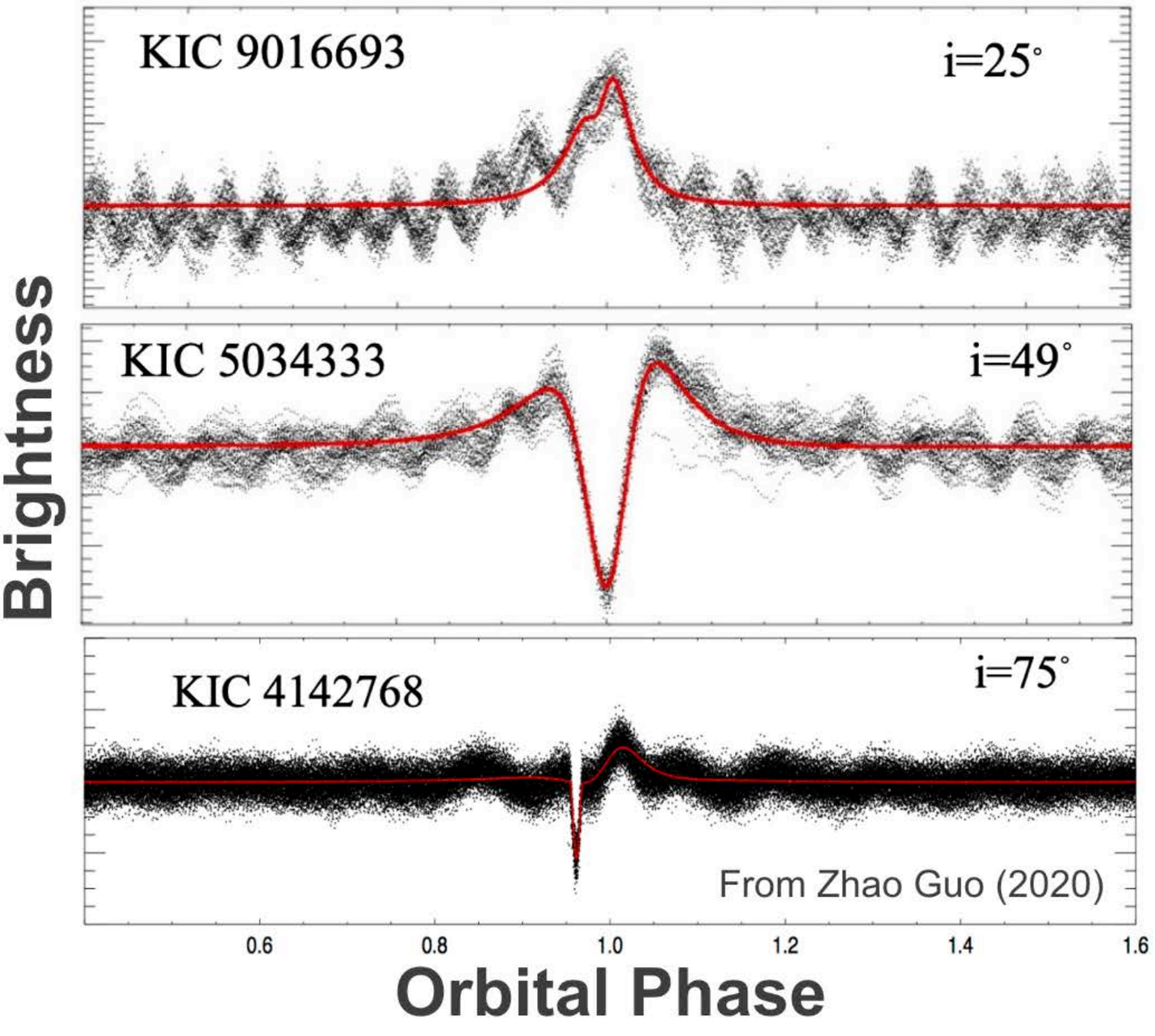
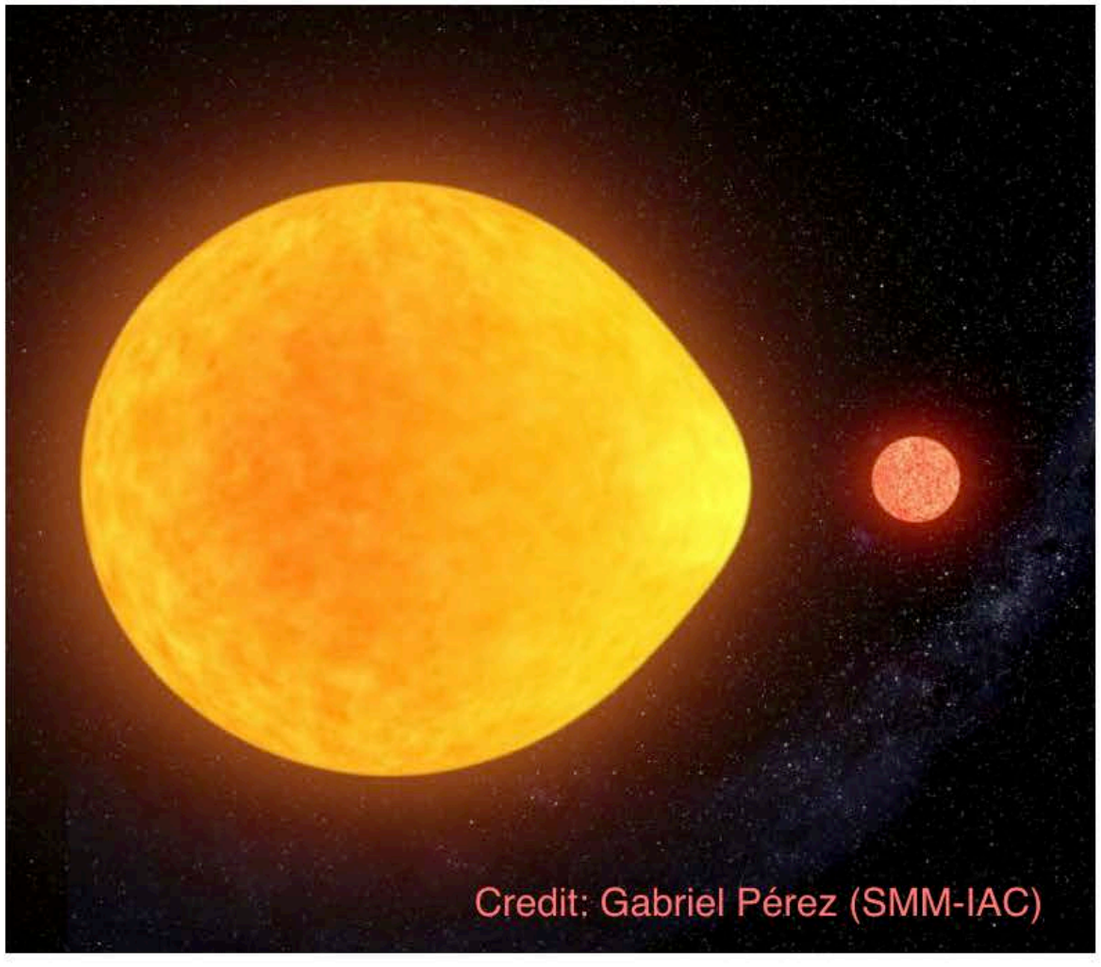
Tidal Asteroseismology

Tidally excited, tidally perturbed, tidally tilted





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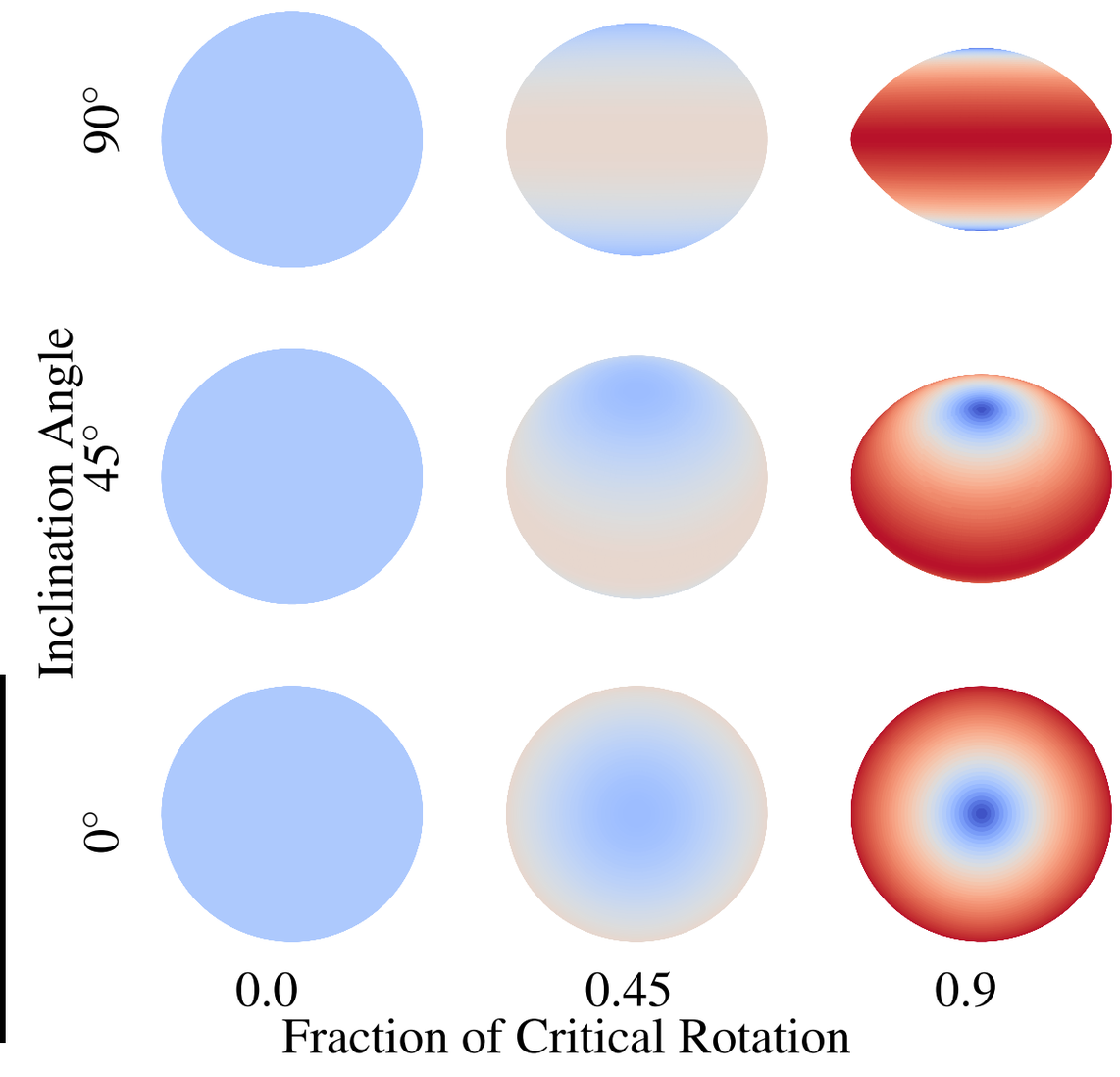
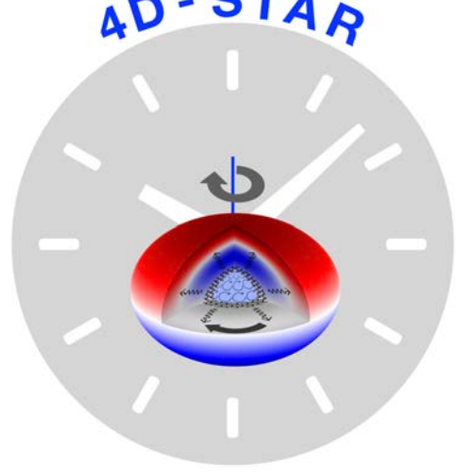
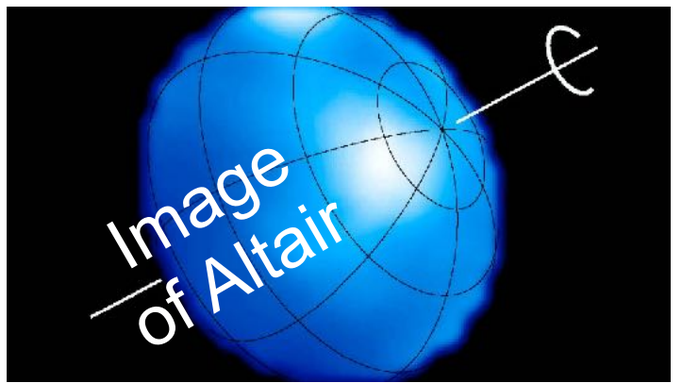
Asteroseismology of flattened stars

Stellar models with 3 spatial coordinates: distance to centre, longitude, latitude + 1 time coordinate (stellar age)



ERC SyG (2024-2029)





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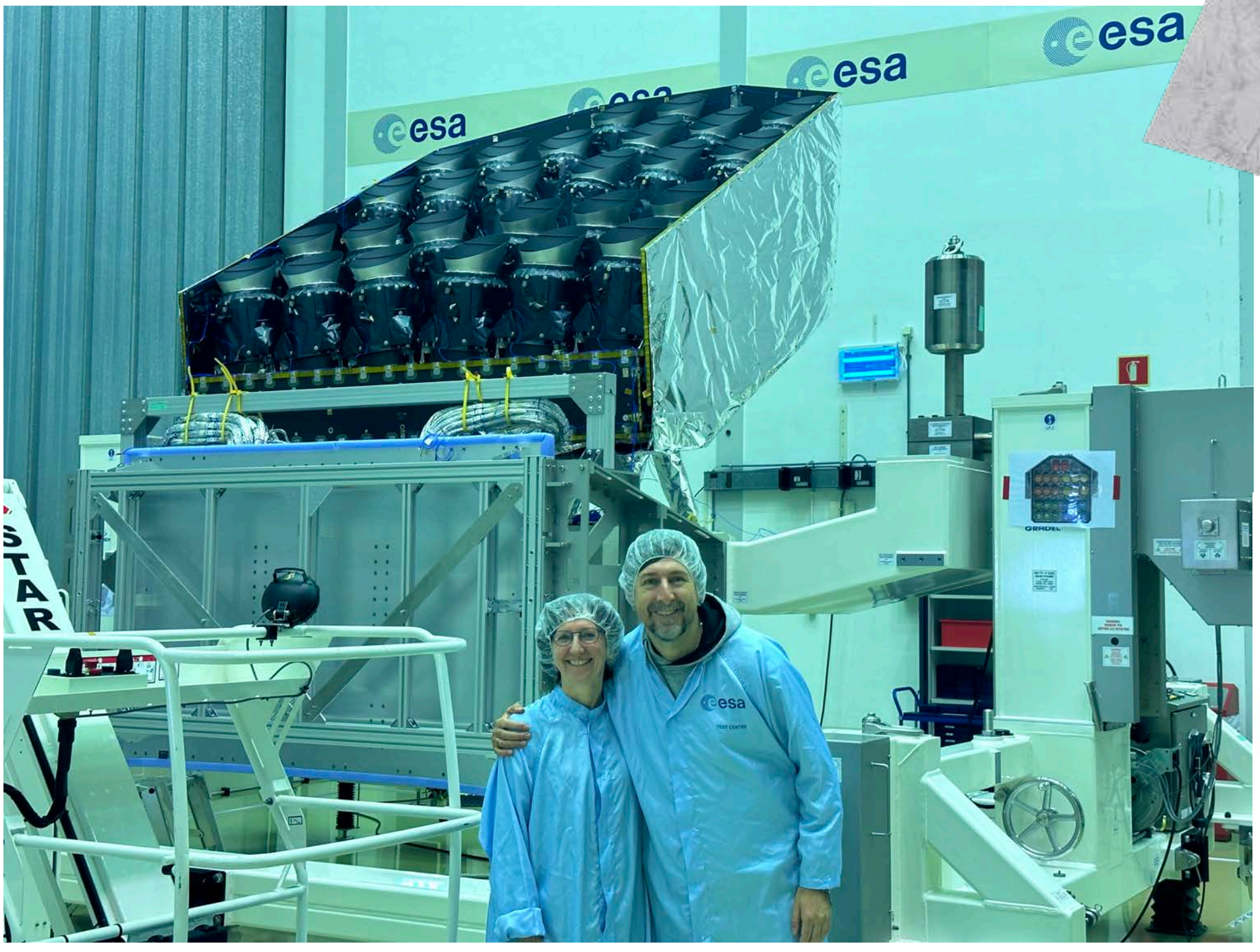
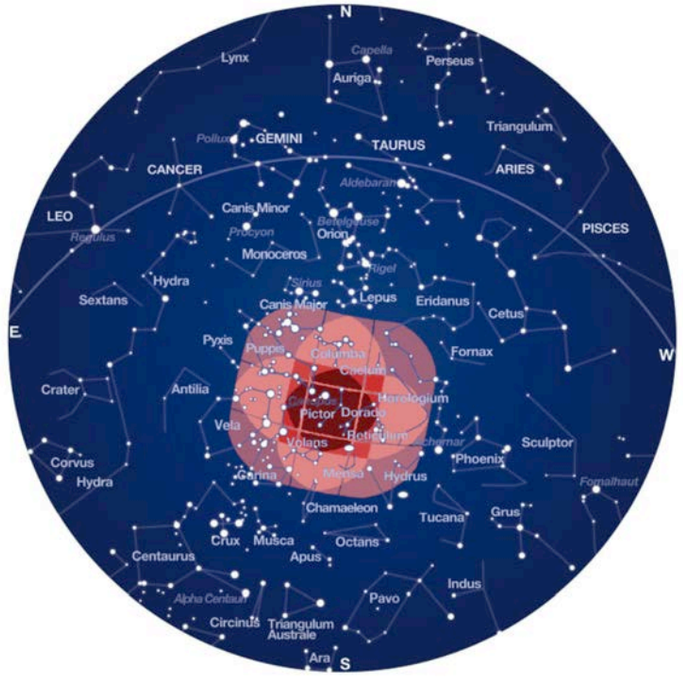
Onward to PLATO (2026+)



Rauer et al. (2024)



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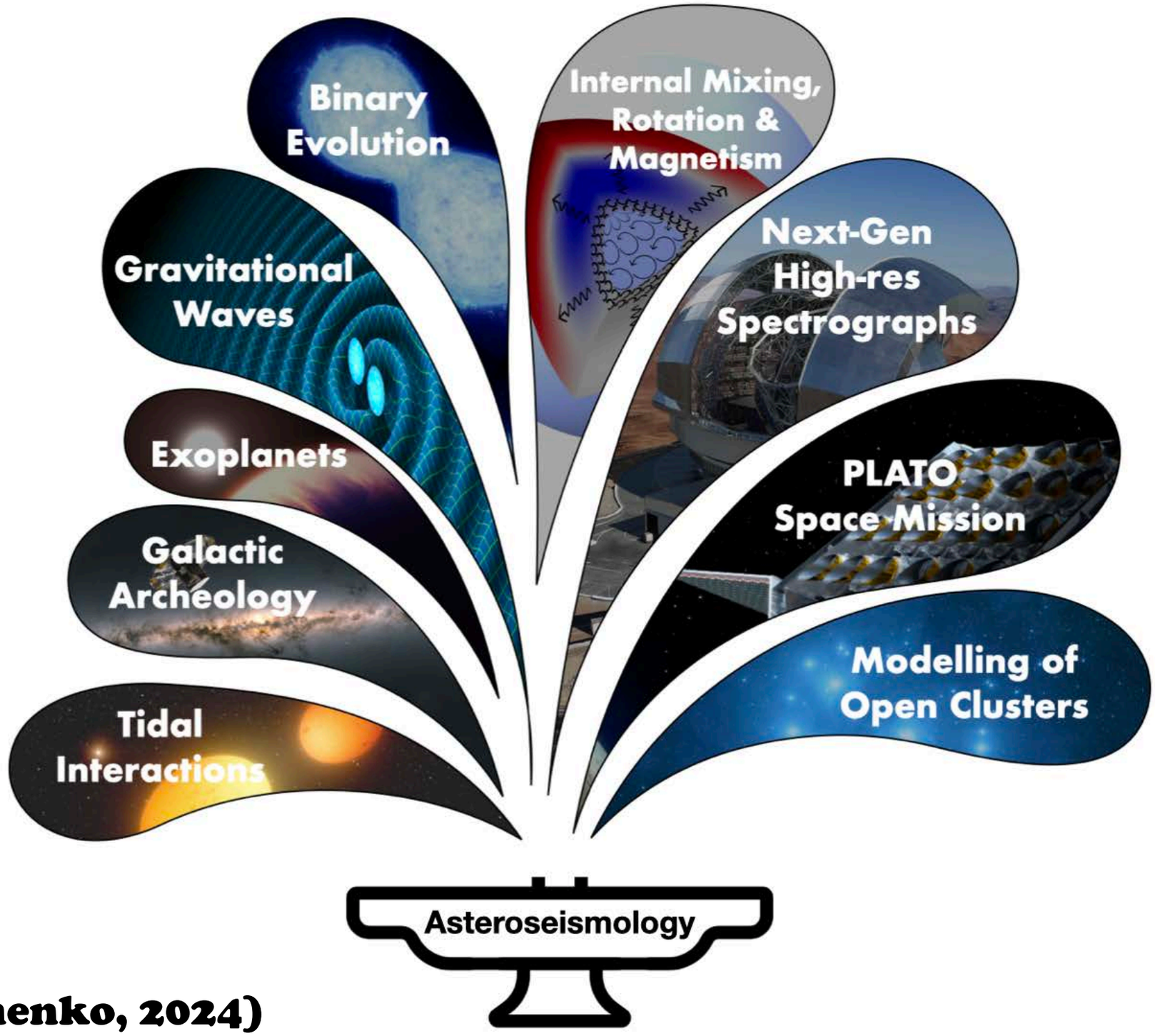
A fountain of opportunities



(from Aerts & Tkachenko, 2024)