Atmospheric and oceanic tidal dissipation on rocky planets

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LTE | Observatoire de Paris | PSL

Tides and motions in planetary systems (in honour of Prof. Ferraz-Mello), Paris (April 2026)

A collaborative work

AstroGeo ERC

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(AstroGeo PI)

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(Research engineer)

Pierre Auclair-Desrotour
(Associate astronomer)

Tidal theory of Ocean planets

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(Postdoc researcher)

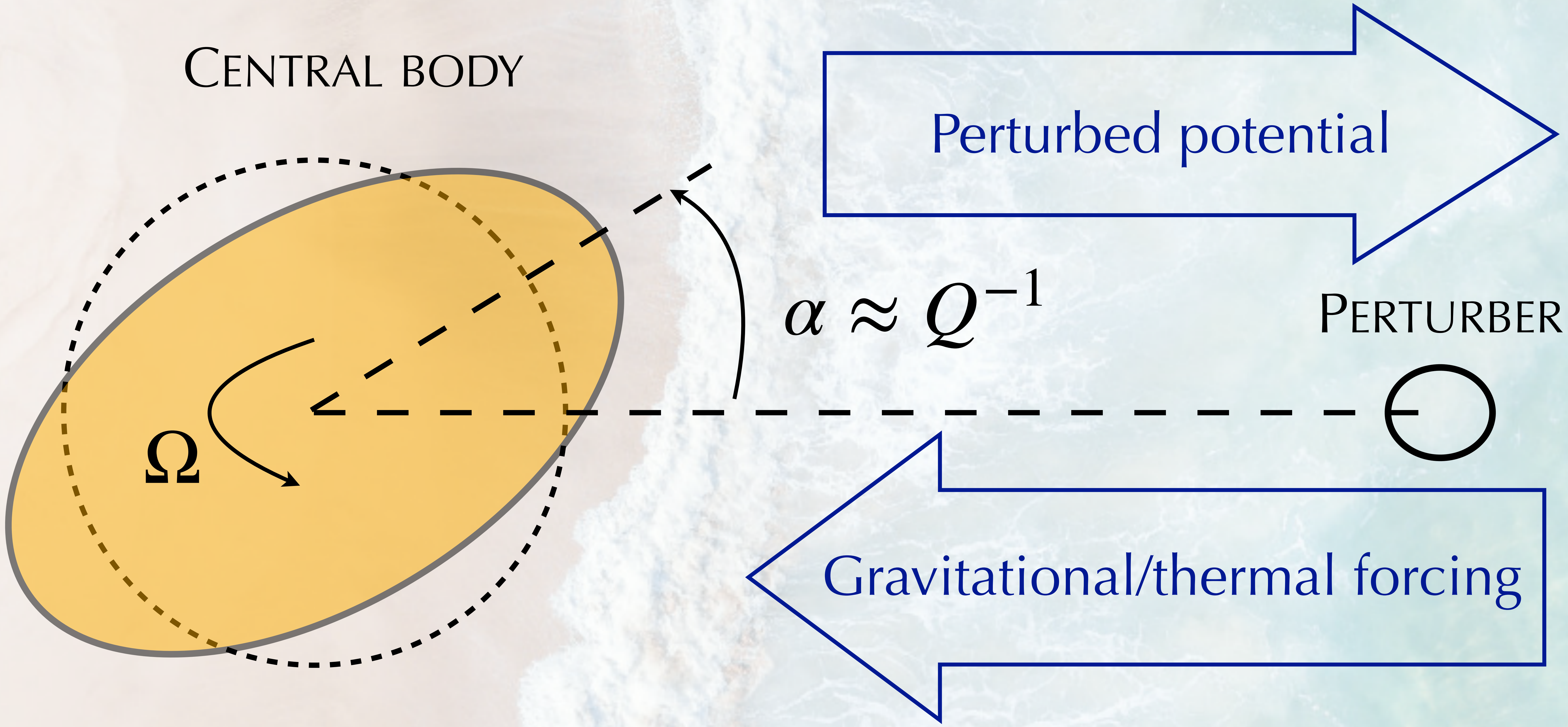
Gwenaël Boué
(Associate professor)

Baptiste Loire
(PhD student)

Radiative forcing
Gravitational potential
Radiative forcing
Solid tides
Oceanic tides
Thermal tides
rheology
bare rock / ocean
tidal heating, volcanism
slow down
slow down
spin up
Migration / alignment
tidal heating
thermal structure, absorbers
Radiative forcing
Life
Climate
carbon cycle, O_2
Surface conditions
Rotation
general circulation
core-mantle coupling
True Polar Wander
flattening
Orbit
Milankovitch cycles
tidal heating
carbon cycle
glaciation cycles
Internal structure
weathering
Ellipticity
mantle convection plate tectonics
Internal dynamics
Milankovitch cycles

The complex tidal Love number

Tidal interaction = gravitational coupling between two celestial bodies causing deformation and energy dissipation.

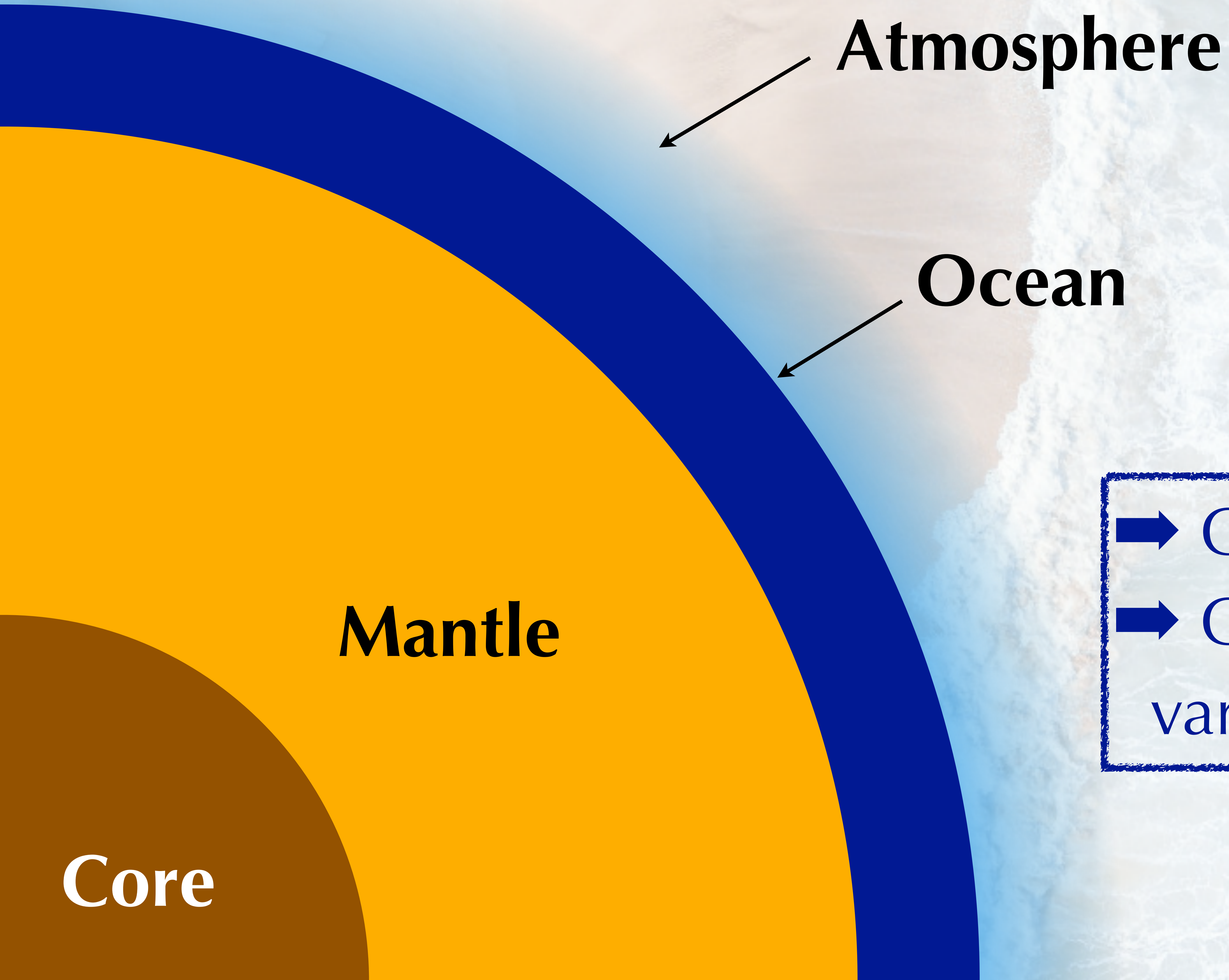


Tidal response :

- ➡ delayed by **dissipative processes**
- ➡ quantified by the complex-valued tidal **Love number k_2**

See Alexandre's talk

Rocky planets are <u>not</u> homogeneous bodies



Tidal Love number = intrinsic quantity determined by the planet's internal structure and rheology

➡ Complex tidal response

➡ Coupling between layers due to variations in **self-attraction** and **loading**

The prominent role of fluid tides

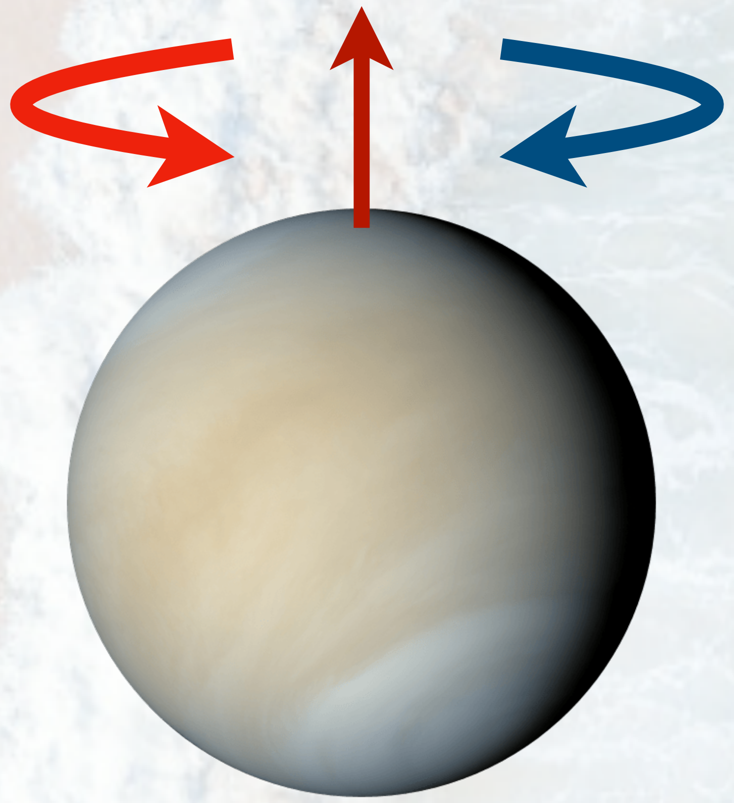
On Venus

Atmos. 0.01 %

Mass — Solid part 99.99 %

Torque

Relative contributions of the solid part and atmosphere to Venus' spin evolution?



See Sylvio's talk

The prominent role of fluid tides

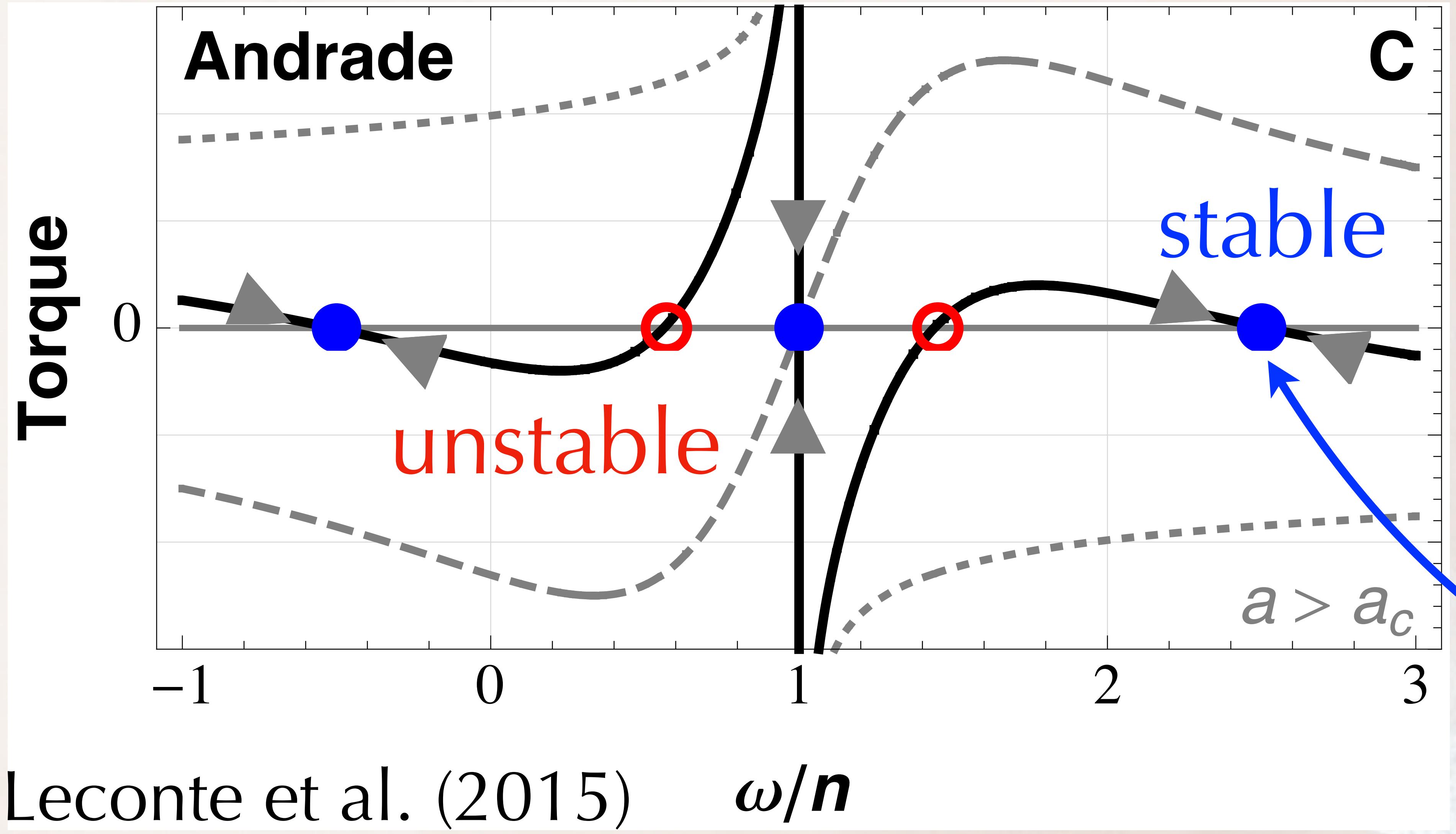
On Venus

Atmos. 0.01 %

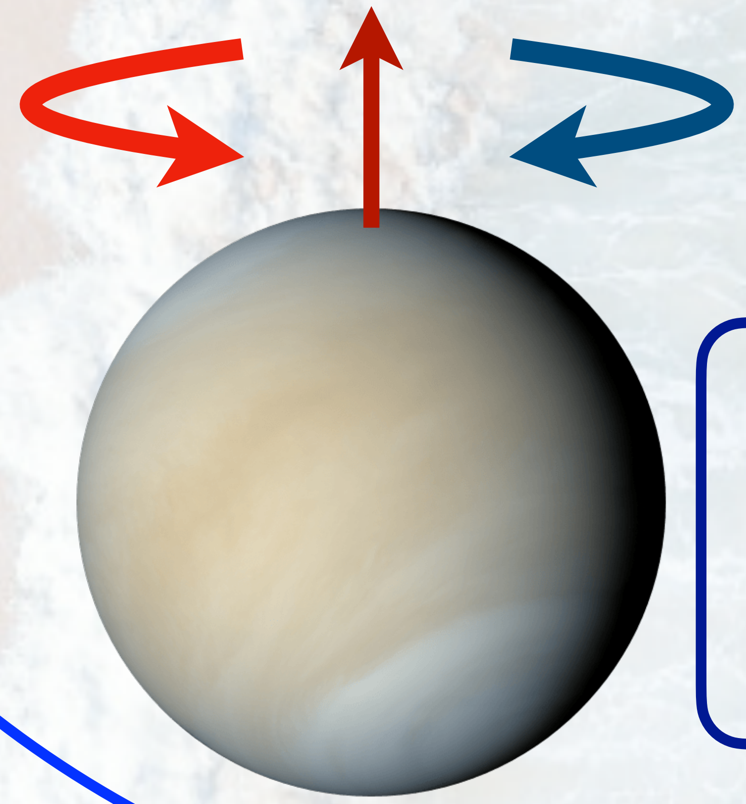
Mass — Solid part 99.99 %

Torque — ~ 50 % | ~ 50 %

Decelerating torque | *Accelerating* torque



Leconte et al. (2015)



Gold & Soter (1969), Ingersoll & Dobrovolskis (1978), Dobrovolskis & Ingersoll (1980), Correia & Laskar (2001,2003), Revol et al. (2023), Musseau et al. (2024)

Venus is driven towards an asynchronous state of equilibrium

Tidal locking!

See Sylvio's talk

The prominent role of fluid tides

On Earth

Mass

Atmosphere 8.6×10^{-5} %

Ocean 0.023 %

Solid part 99.98 %

Torque

Solid, oceanic, and atmospheric contributions?

The prominent role of fluid tides

On Earth

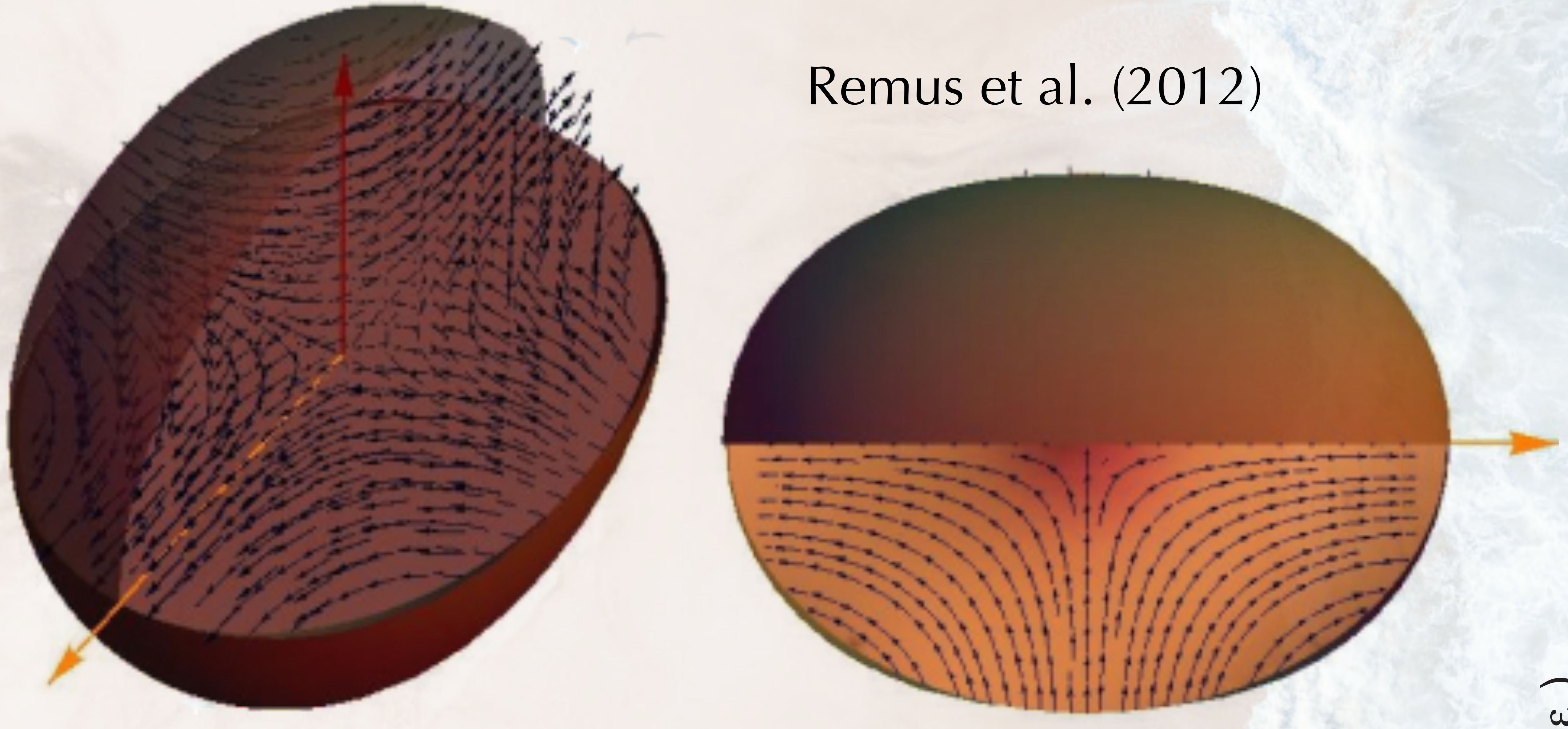
	Tidal potentials	Angular acceleration $''/cy^2$	LOD rate ms/cy
Solid Earth	Sectorial	−65	0.12
–	Tesseral	−15	0.03
–	Total	−80	0.15
Ocean	Sectorial	−1084	1.98
–	Tesseral	−205	0.37
–	Total	−1369	2.35
Total Solid Earth + Ocean		−1449	2.50

Decelerating torque | *Accelerating* torque

Kelvin (1882), Chapman & Lindzen (1970), Zahnle & Walker (1987), Ray (2001), Schindelegger & Ray (2014)

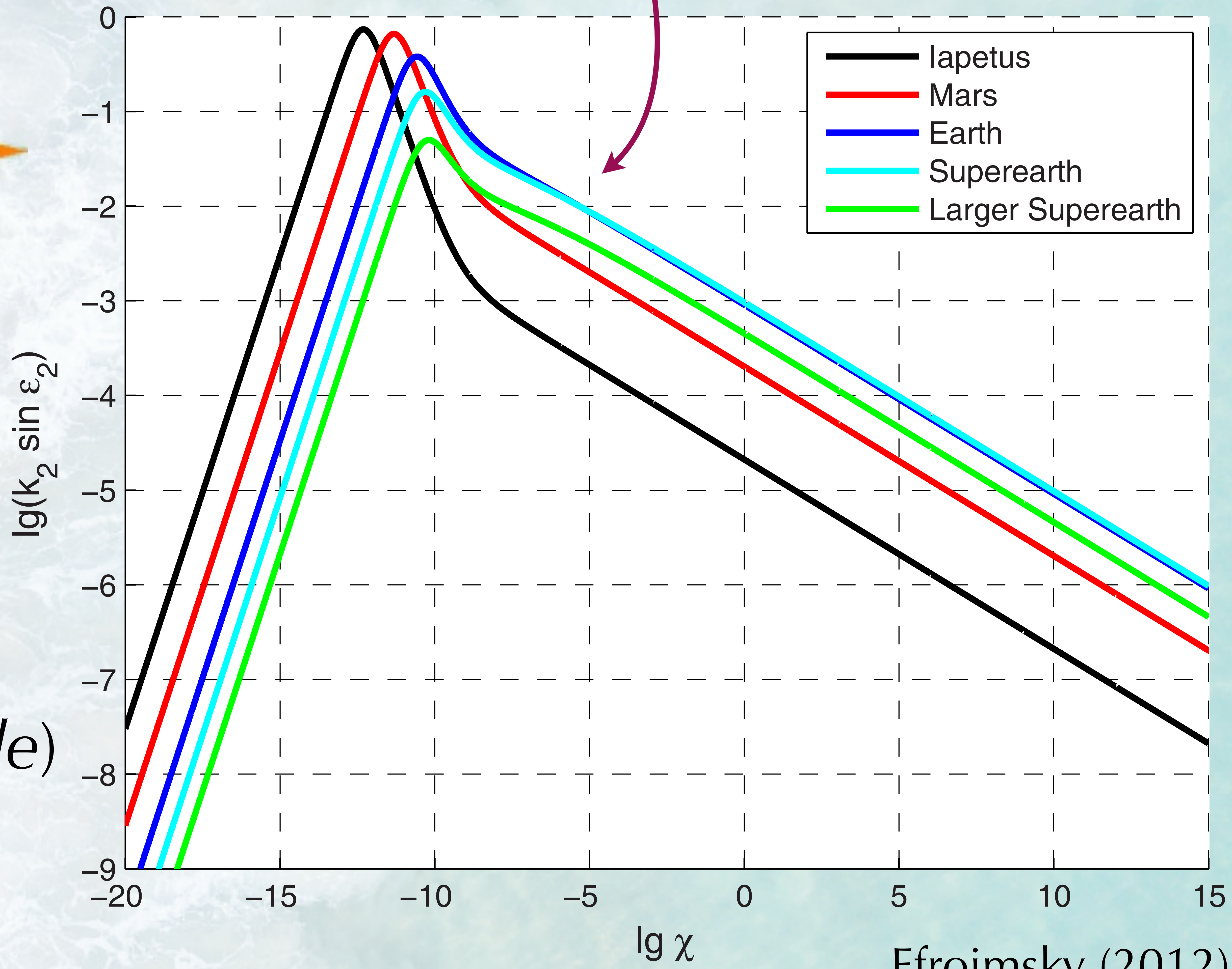
Mathews & Lambert (2009) + Lambeck (1980), Egbert & Ray (2000, 2001, 2003)

Solid tides



Remus et al. (2012)

Equilibrium tide = no resonance



Efroimsky (2012)

➡ spherically symmetric internal structure;

➡ quasi-static adjustment;

➡ no resonantly excited wave (*equilibrium tide*)

See Gwenaël's talk

Tidal wave families

Dynamical tide = tide formed by resonantly excited modes (Zahn 1975).

Auclair-Desrotour et al. (2018)

Laplace's tidal equations (LTEs)

Laplace, P. S. (1798), Traité de mécanique céleste; Longuet-Higgins (1968); Longuet-Higgins & Pond (1970)

➡ Forced wave equations on a spherical shell

drag, gravity, self-attraction + loading, forcing, Coriolis

$$\partial_t \boldsymbol{V} + \sigma_{\mathrm{R}} \boldsymbol{V} + \boldsymbol{f} \times \boldsymbol{V} + g \nabla \left(\Gamma_{\mathrm{D}} \zeta - \Gamma_{\mathrm{T}} \zeta_{\mathrm{eq}} \right) = 0$$

Horizontal momentum equation (+ Poisson's equation)

$$\partial_t \zeta + \nabla \cdot (H \boldsymbol{V}) = 0$$

Conservation of mass

$$\boldsymbol{f} = 2\Omega \cos \hat{\theta} \mathbf{e}_r$$

Coriolis parameter

$$\nabla = R^{-1} \left[\mathbf{e}_\theta \partial_\theta + \mathbf{e}_\varphi \left(\sin \theta \right)^{-1} \partial_\varphi \right]$$

Horizontal gradient operator

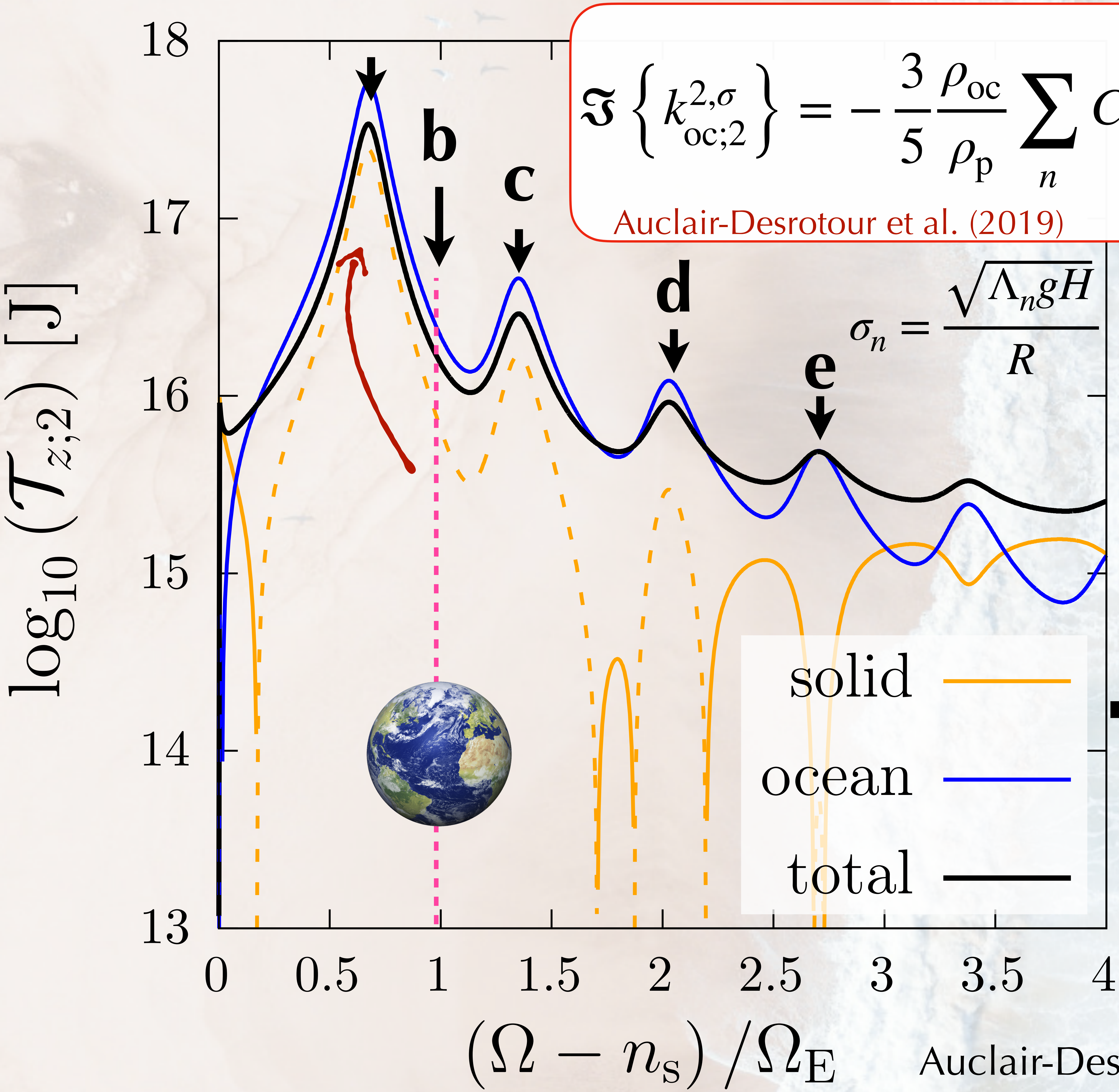
$$\nabla \cdot \boldsymbol{V} = \left(\sin \theta \right)^{-1} \left[\partial_\theta \left(\sin \theta V_\theta \right) + \partial_\varphi V_\varphi \right]$$

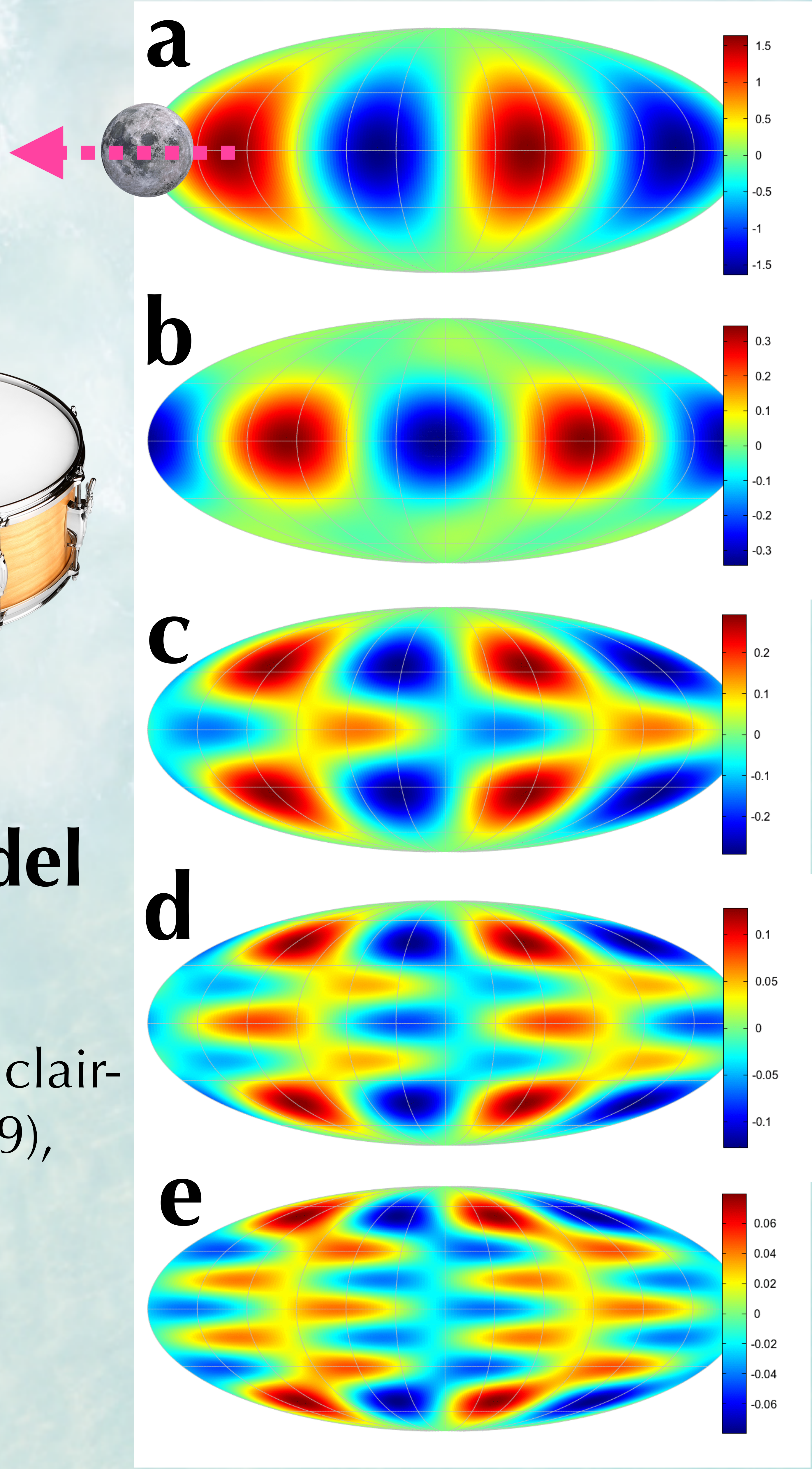
Horizontal divergence operator

Frequency dependence of the oceanic tidal torque

$$\Im\left\{k_{\mathrm{oc};2}^{2,\sigma}\right\} = -\frac{3}{5}\frac{\rho_{\mathrm{oc}}}{\rho_{\mathrm{p}}}\sum_{n} C_{2,n,2}^{2,\nu}\frac{\dfrac{\sigma_{\mathrm{R}}\sigma}{\sigma_n^2}}{\left(1-\dfrac{\sigma^2}{\sigma_n^2}\right)^2+\dfrac{\sigma_{\mathrm{R}}^2\sigma^2}{\sigma_n^4}}$$

Auclair-Desrotour et al. (2019)





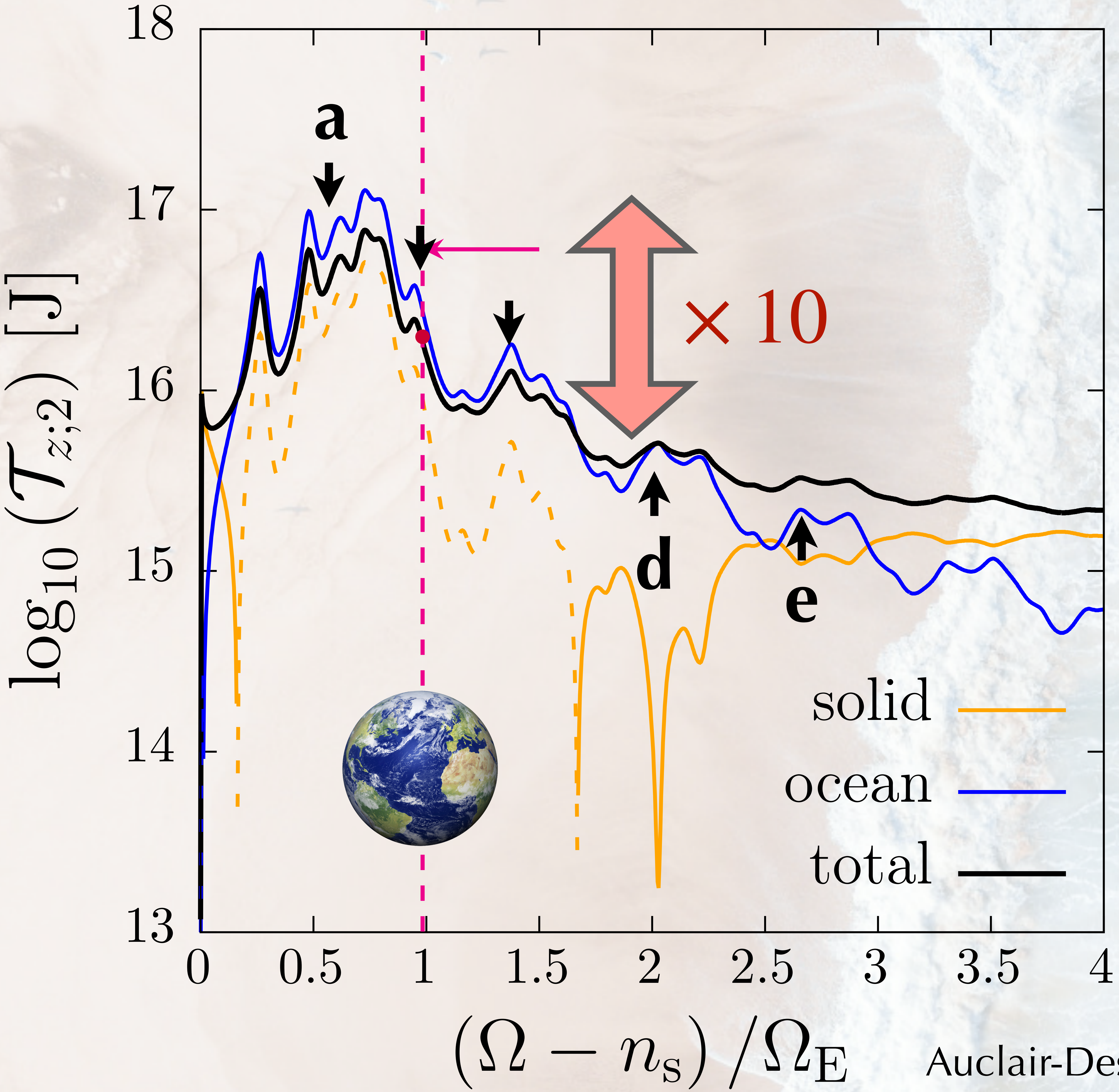
Global-ocean **model**

➡ spherical ocean

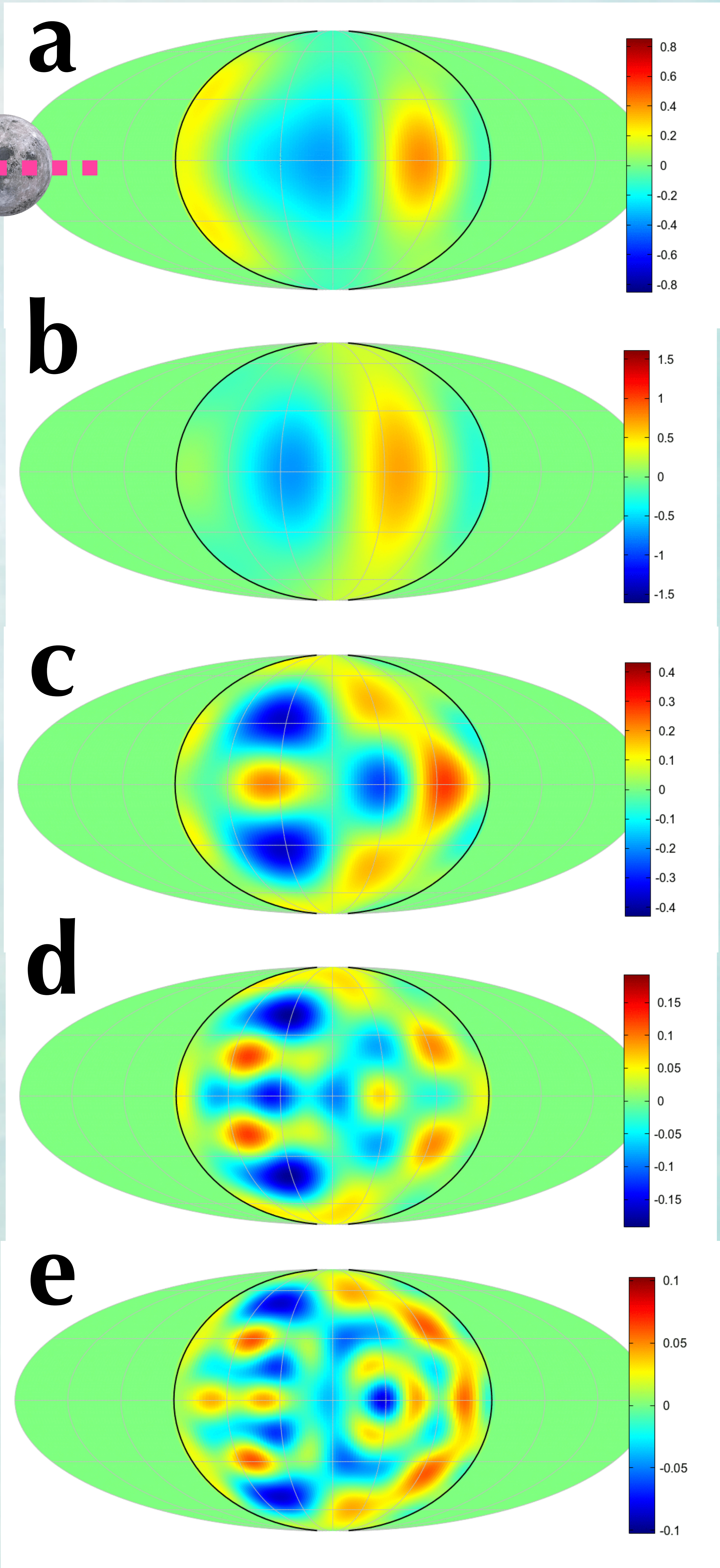
Longuet-Higgins (1968), Auclair-Desrotour et al. (2018, 2019), Tyler (2021)

Auclair-Desrotour et al. (2023)

Frequency dependence of the oceanic tidal torque



Auclair-Desrotour et al. (2023)



***Eyeball-Earth* model**

➡ hemispherical ocean

Webb (1980, 1982), Farhat et al. (2022, 2024), Auclair-Desrotour et al. (2023)

+ Loire et al. (2026), in prep.

Staircase patterns in the history of Earth's rotation

Farhat et al. (2022)

Anisotropic tidal response

Coriolis → Rotational scattering

Continents → Coastal scattering

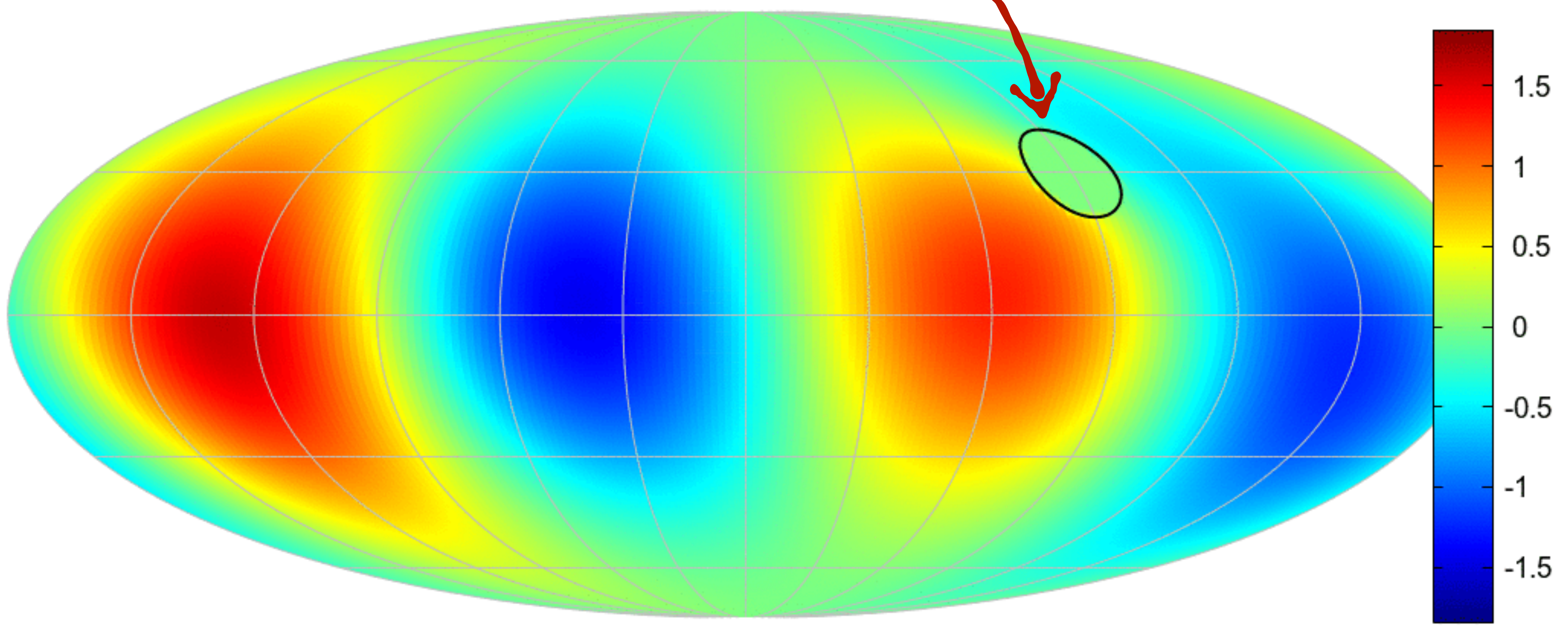
➡ Multiple resonantly excited modes
➡ The tidal response depends on the planet's obliquity

➡ **Semi-analytical theory generalised to continents of arbitrary sizes**

➡ **The isotropic approximation results in significant errors for ocean planets**

See posters 1 & 2

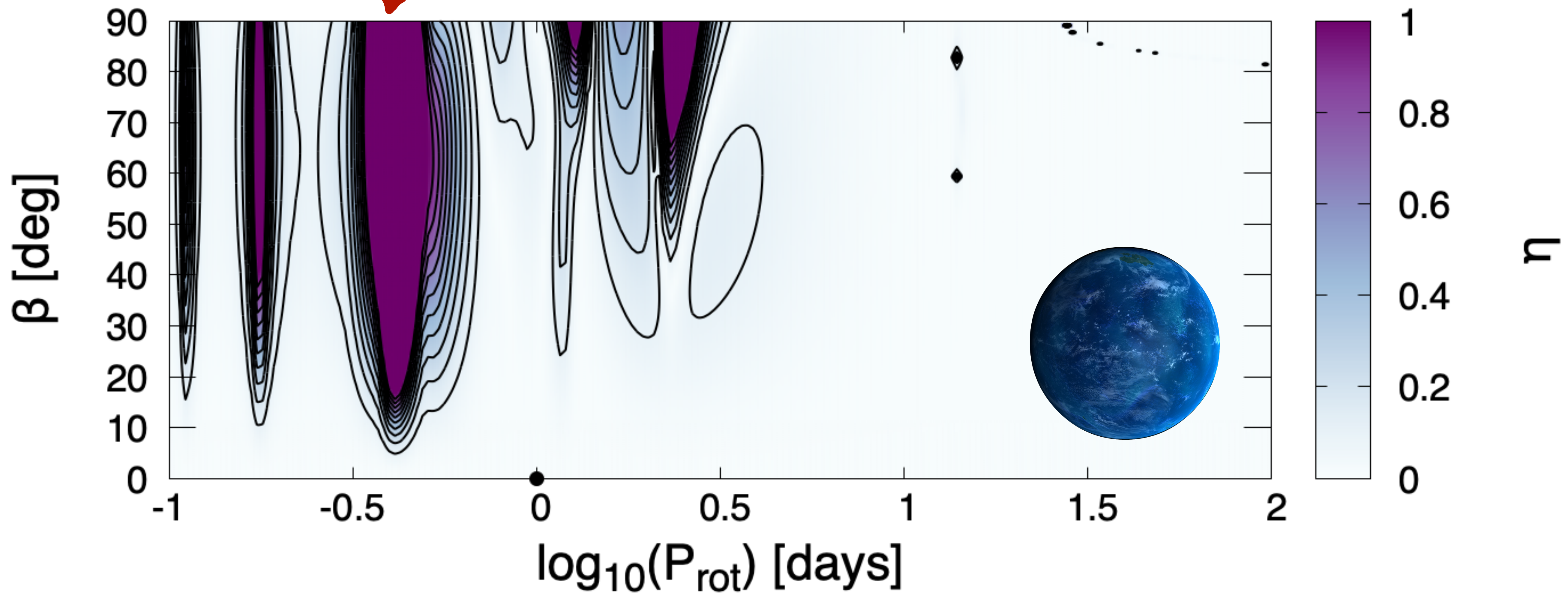
Greenland



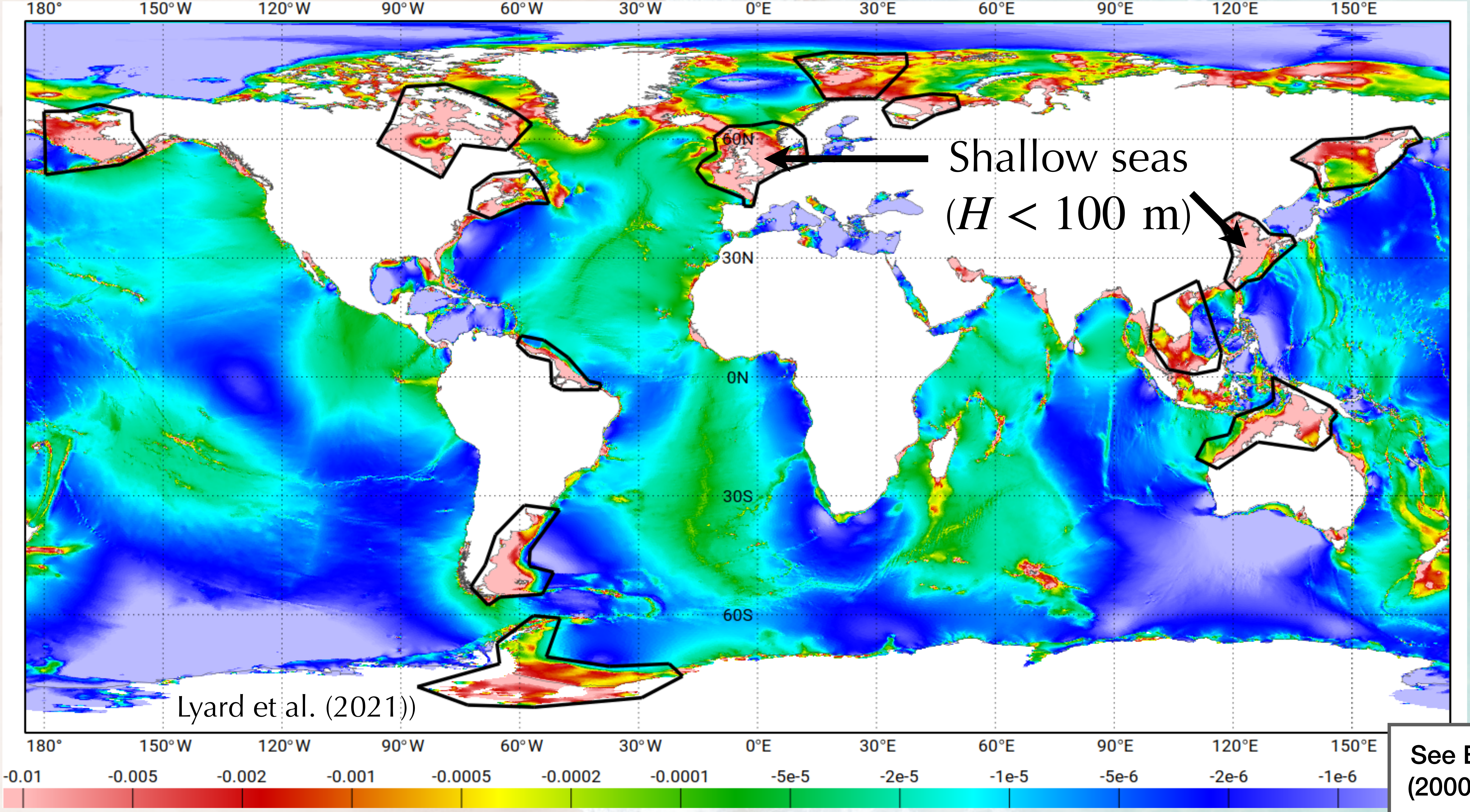
Auclair-Desrotour, Farhat, Boué, Gastineau, Laskar (2023)

Spurious resonances

Auclair-Desrotour, Boué, Loire (2025)

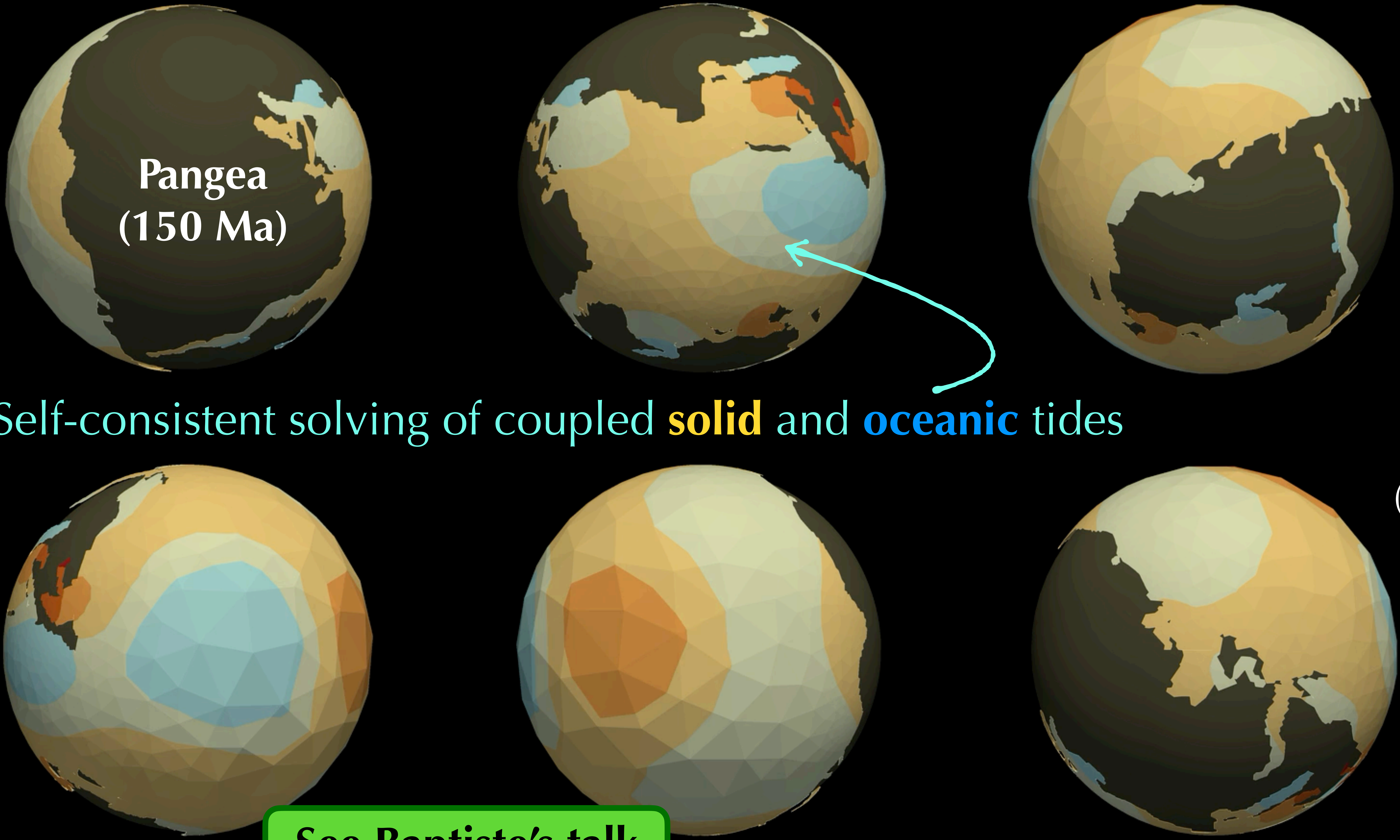


Tidal energy dissipation in Earth's oceans



See Egbert & Ray (2000, 2001, 2003)

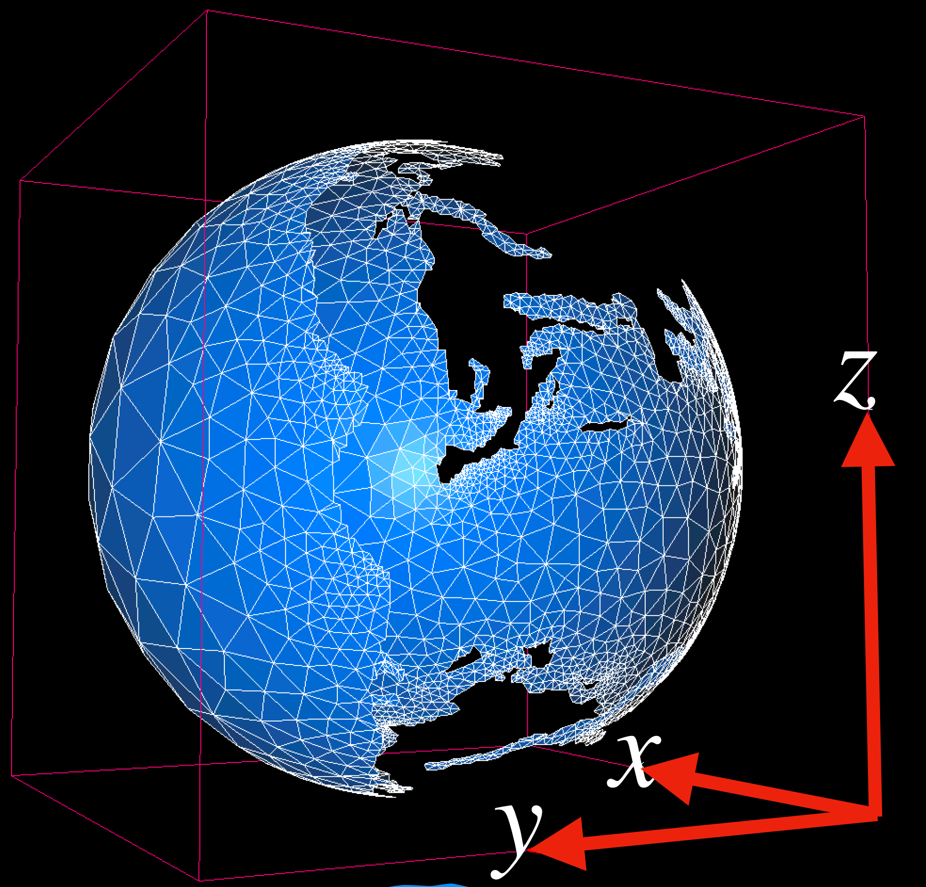
New fast FEM-solver for ocean planets



➡ Self-consistent solving of coupled **solid** and **oceanic** tides

See Baptiste's talk

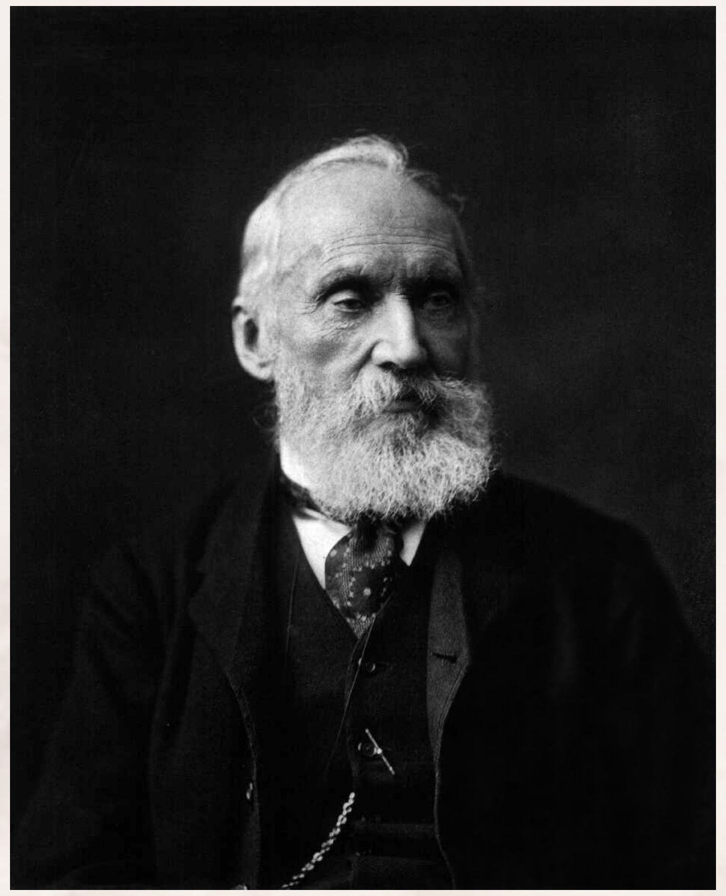
= 1 minute with 1 CPU



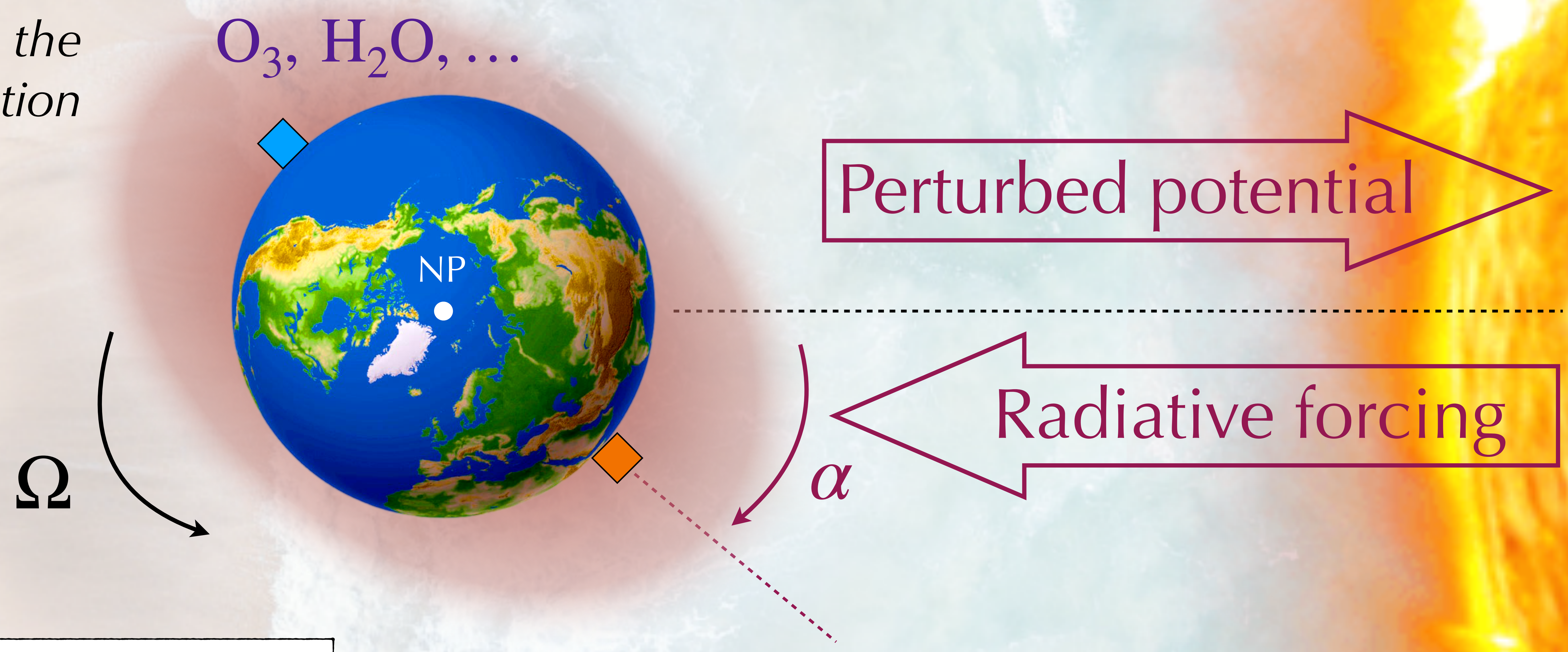
Baptiste Loire
(3rd yr PhD student)

LTE
PSL

The accelerating thermotidal torque

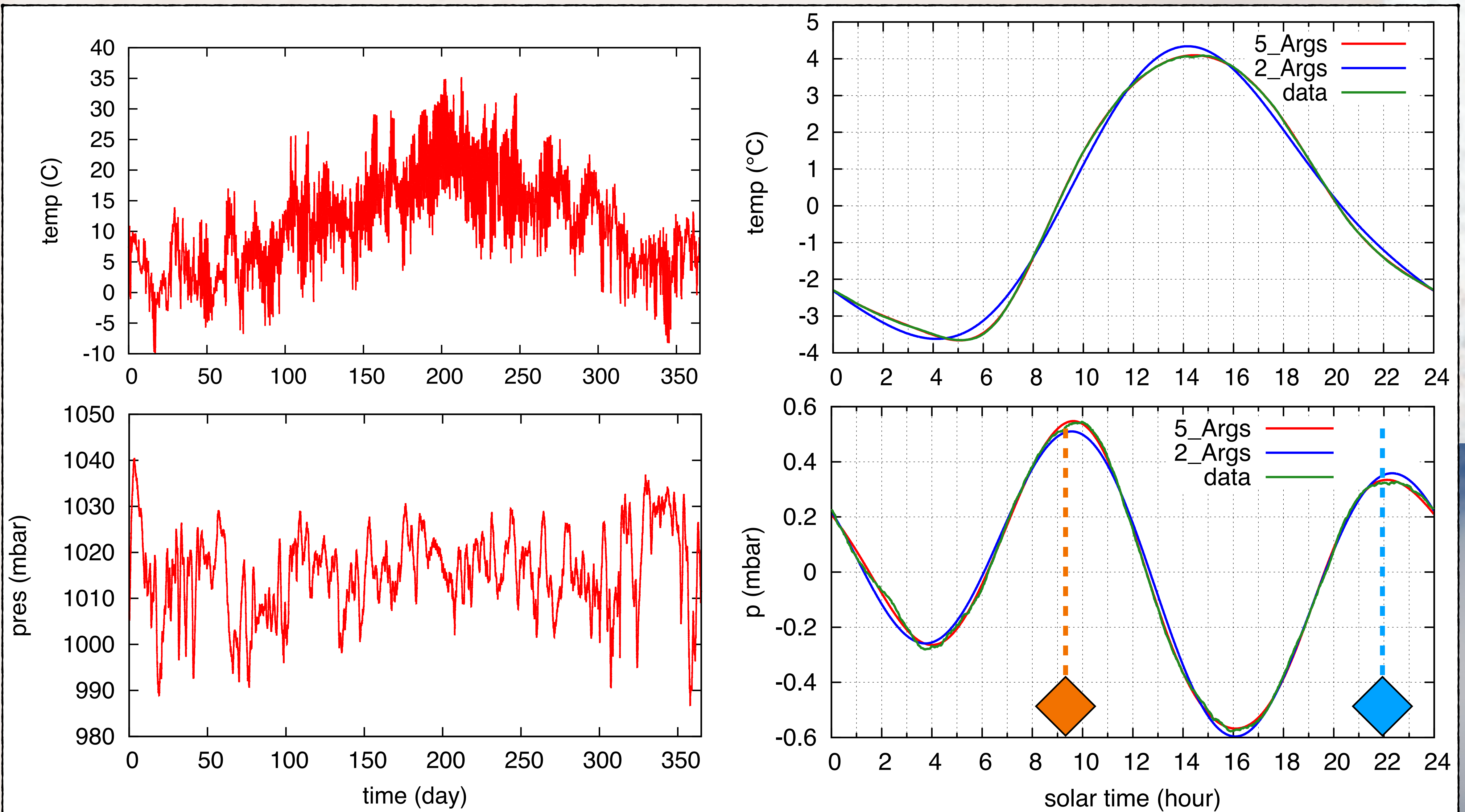


Thomson (1882), *On the thermodynamic acceleration of the Earth's rotation*



Auclair-Desrotour et al. (2017)

© J. Laskar / 48.4° N, 2.7° E



The atmosphere acts as an energy converter:

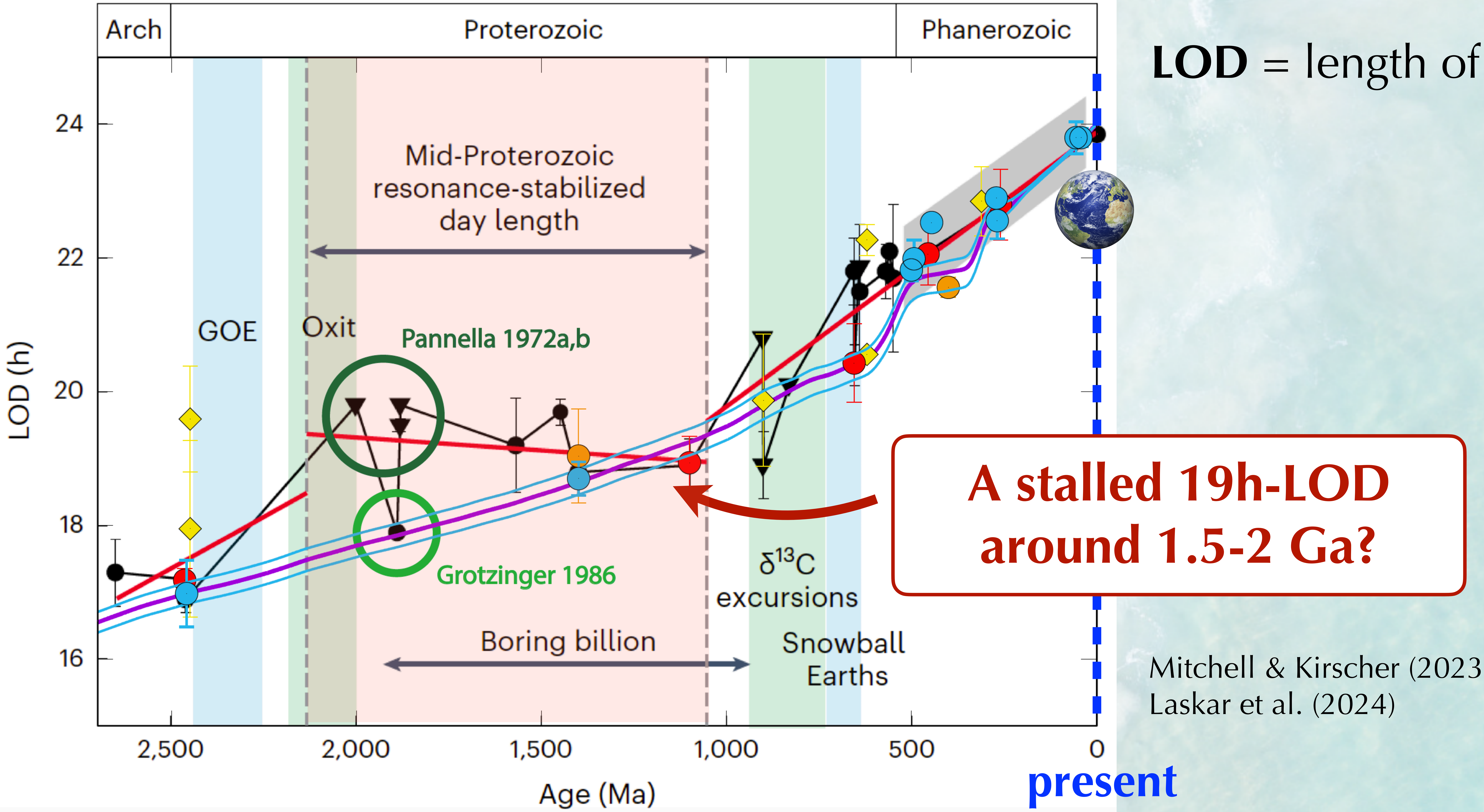
Radiative energy → Mechanical energy

Tidal bulge *in advance*

=

***Accelerating* torque**

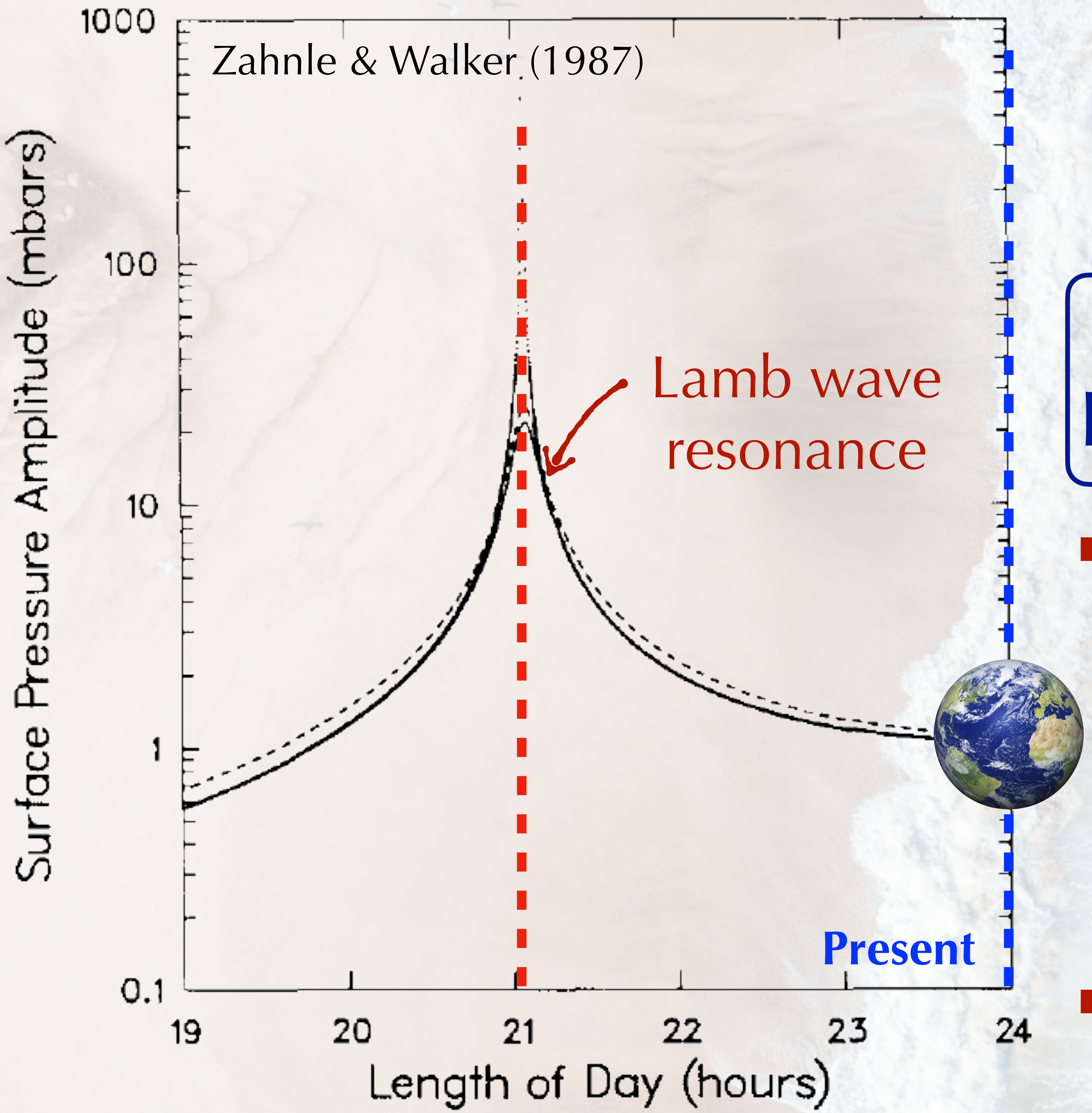
The Precambrian tide-lock hypothesis



LOD = length of the day

Mitchell & Kirscher (2023) +
Laskar et al. (2024)

The key role of resonantly excited Lamb waves



Lamb waves = planetary-scale compressibility modes similar to oceanic surface gravity modes.

Venus-like planets can also be tide-locked in *fast* asynchronous rotation!

➡ For Earth, this question is still debated

Bartlett & Stevenson (2023); Mitchell & Kirscher (2023); Wu et al. (2023); Farhat et al. (2024); Laskar et al. (2024)

➡ Dependence on gas mixture and atmospheric structure

Farhat et al. (2024); Auclair-Desrotour et al. (2026, submitted)

➡ Coupling with the planet's interior

e.g. water cycle, carbon cycle

The atmospheric tidal theory

$$\partial_t V_\theta - 2\Omega \cos\theta V_\varphi + \frac{1}{R}\partial_\theta\left(\frac{\delta p}{\rho_0} - U\right) = 0$$

$$\partial_t V_\varphi + 2\Omega \cos\theta V_\theta + \frac{1}{R\sin\theta}\partial_\varphi\left(\frac{\delta p}{\rho_0} - U\right) = 0$$

Horizontal momentum equations

Gravitational forcing (U)

Coriolis ($2\Omega\cos\theta$ terms)

$$\partial_z \delta p + g\delta\rho - \rho_0 \partial_z U = 0$$

Hydrostatic balance

Buoyancy ($g\delta\rho$)

$$\frac{D\rho}{Dt} + \rho_0\left(\partial_z V_r + \nabla_{\mathrm{h}} \cdot \boldsymbol{V}\right) = 0$$

Conservation of mass

$$\frac{1}{\Gamma_1}\frac{Dp}{Dt} - gH\frac{D\rho}{Dt} + \rho_0 \mathscr{R}_{\mathrm{s}} \sigma_0 \delta T - \kappa\rho_0 J = 0$$

Thermodynamic equation

Thermal forcing (J)

Radiative cooling ($\rho_0 \mathscr{R}_{\mathrm{s}} \sigma_0 \delta T$)

$$\frac{\delta p}{p_0} - \frac{\delta\rho}{\rho_0} - \frac{\delta T}{T_0} = 0$$

Ideal gas law

Unified analytical solution

Isothermal atmospheres
(= uniform temperature T)

Lindzen et al. (1968); Lindzen & Blake (1972a); Auclair-Desrotour et al. (2017a)

$T = \text{cst}$

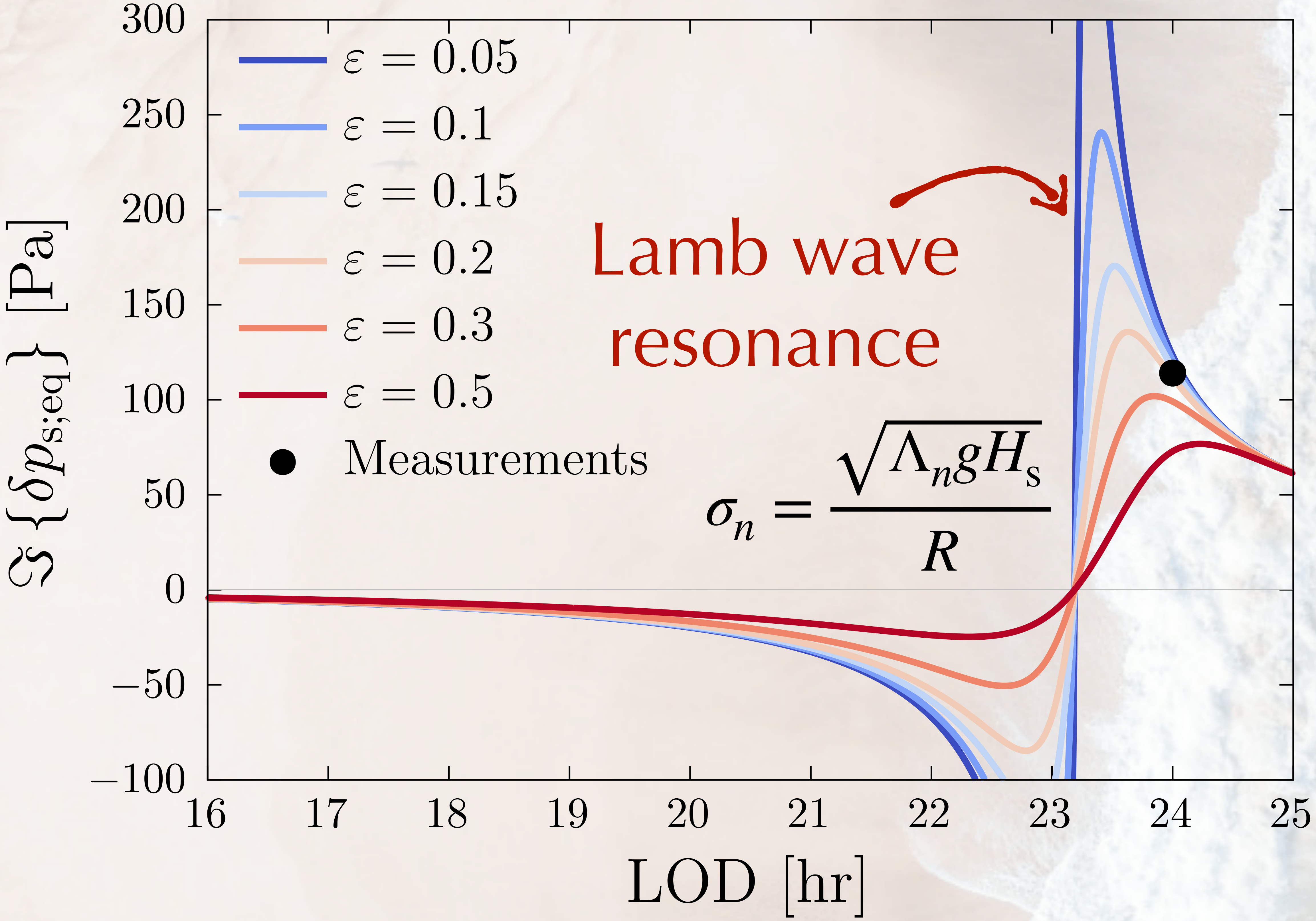
Isentropic atmospheres
(= uniform potential temperature θ)

Lindzen (1978); Farhat et al. (2024)

$$\theta = T \left(\frac{P_{\text{ref}}}{P} \right)^{\kappa} = \text{cst}$$

Unified solution

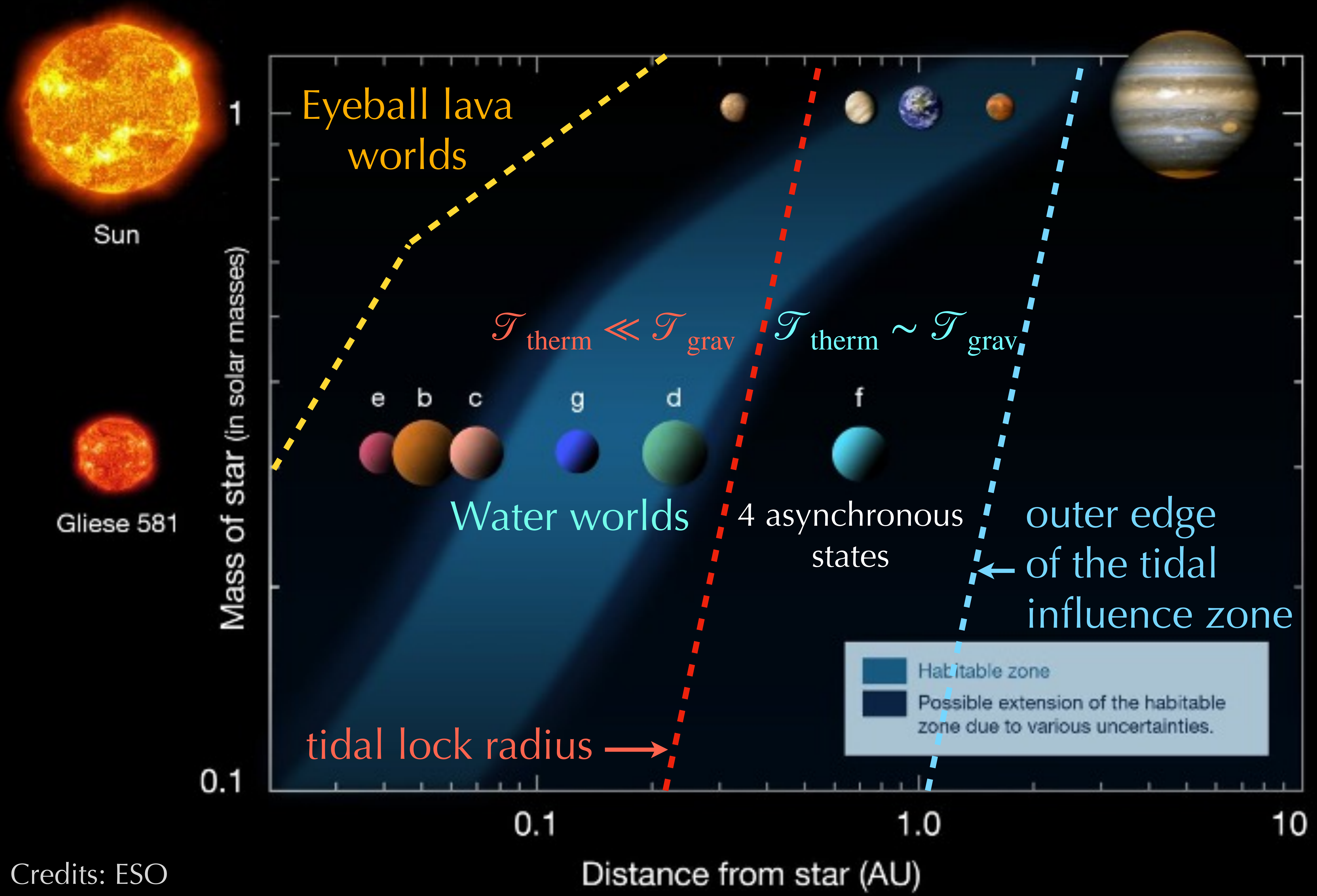
Auclair-Desrotour et al. (2026a, b), submitted



- ➡ Explicit dependence on tidal frequency and several key parameters
- ➡ Full characterisation of the resonance's properties
- ➡ Excellent agreement with barometric measurements

$$H_s = \frac{R_{\text{spec}} T_s}{g}$$

- T_s = surface temperature
- R_{spec} = specific gas constant (gas mixture)



$\mathcal{T}_{\rm grav} \propto a^{-6}$

$\mathcal{T}_{\rm therm} \propto a^{-5}$

Credits: ESO

Conclusions

➡ **Oceanic and atmospheric tidal dissipation predominate** on rocky planets due to resonances (dynamical tide)

➡ Coriolis effects and continents induce **multiple oceanic tidal modes** (scattering)

➡ **Oceanic resonances result in staircase patterns** shaping the evolution of the Earth-Moon system

➡ **Resonantly excited Lamb waves** enhance the thermotidal torque

➡ Possible **tidal locking in *fast* asynchronous rotation** (additional equilibrium states)

➡ Theory applicable to **extrasolar water and lava worlds**