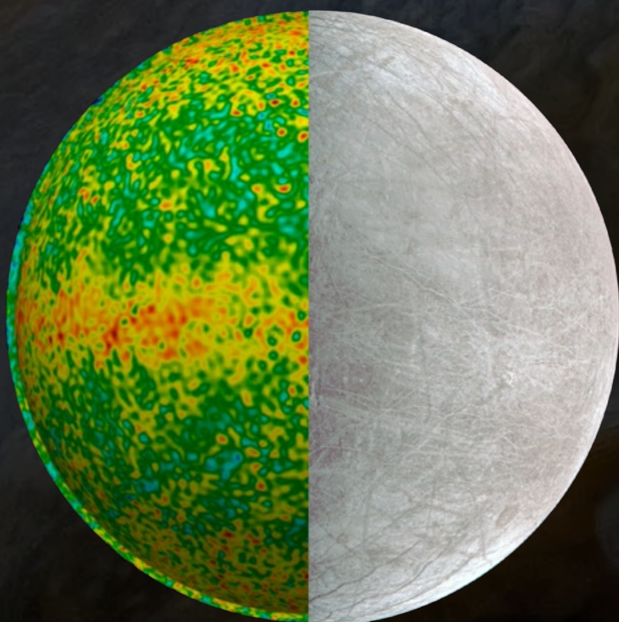
Rotating Convection in Ocean Worlds of the Outer Solar System



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UCLA Institute for Pure & Applied Mathematics
Workshop on Rotating Turbulence: Interplay and Separability of Bulk and Boundary Dynamics

27 January 2025

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INSTITUTE FOR GEOPHYSICS
THE UNIVERSITY OF TEXAS AT AUSTIN

Outline

1) Introduction to Icy Ocean Worlds
2) Drivers of Fluid Motions in Icy Ocean Worlds
3) Governing Equations and Common Approximations
4) Rotating Convection in Icy Ocean Worlds
5) Testing Oceanographic Hypotheses
6) Conclusions

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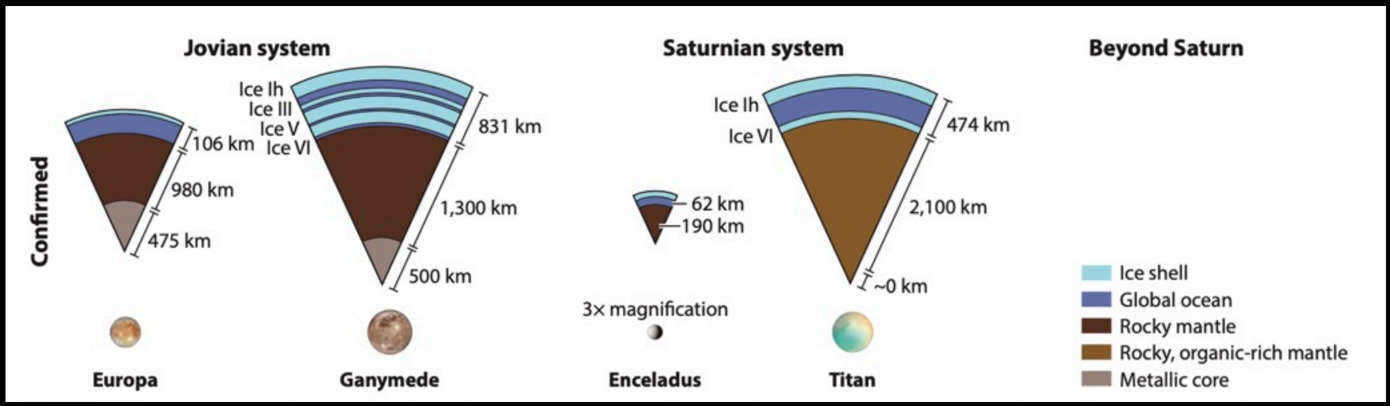
Icy ocean worlds may be common in the outer solar system.



Credit: Soderlund et al. (2024)

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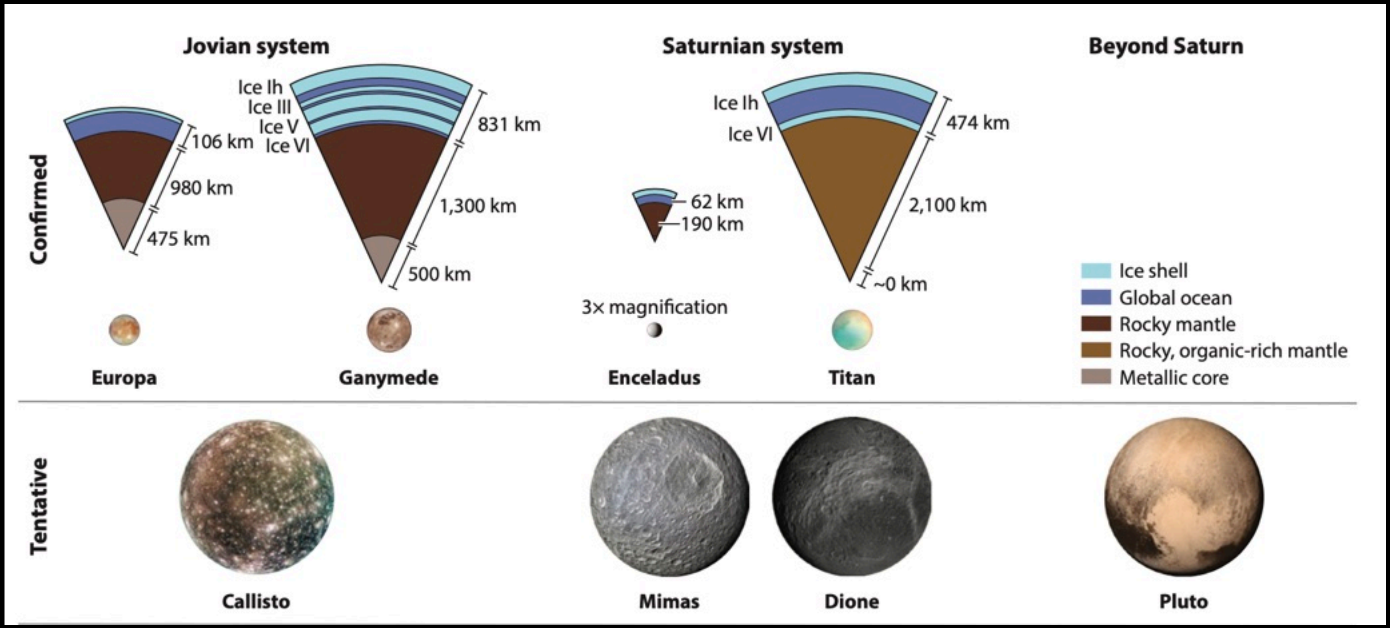
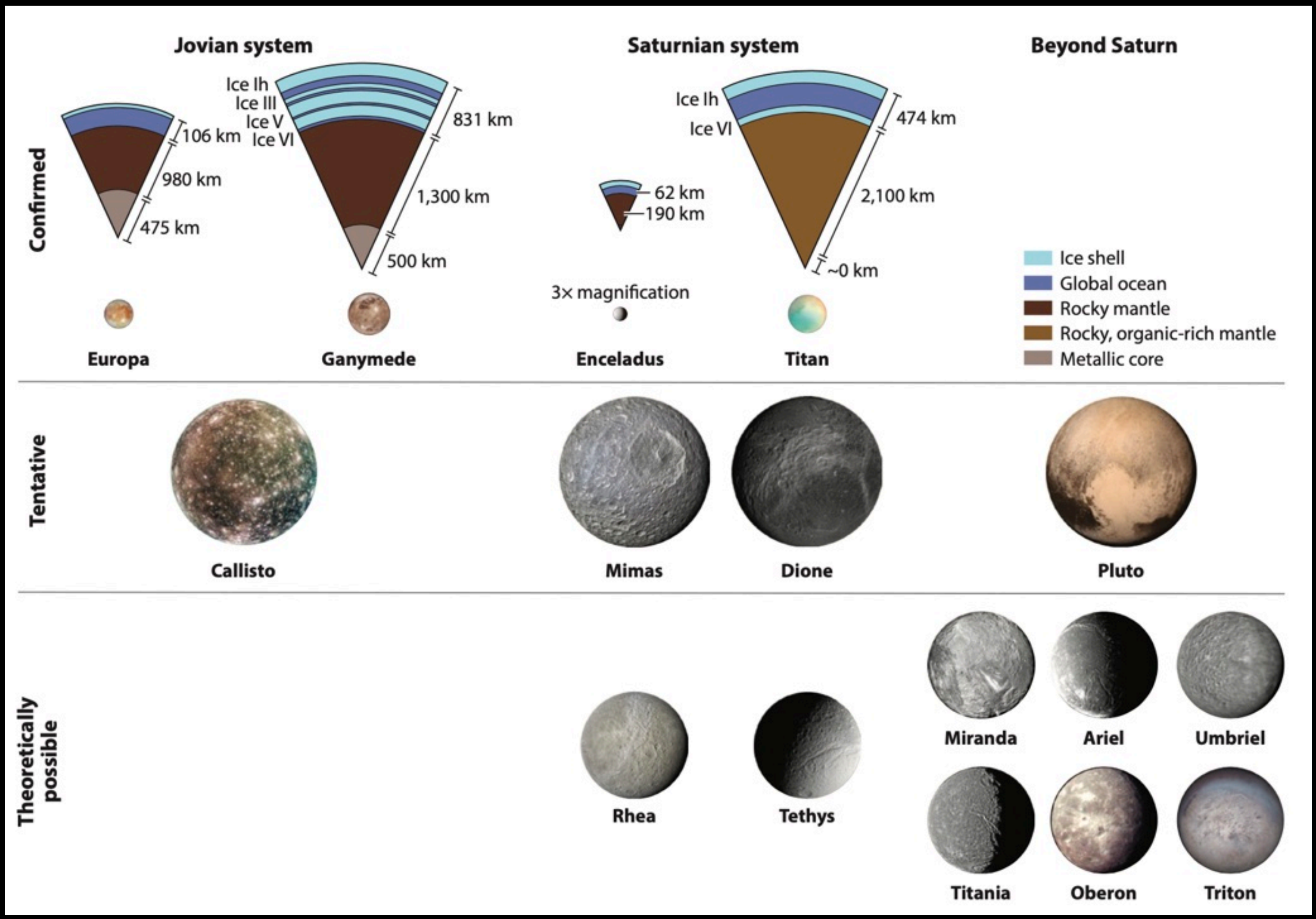


Credit: Soderlund et al. (2024)

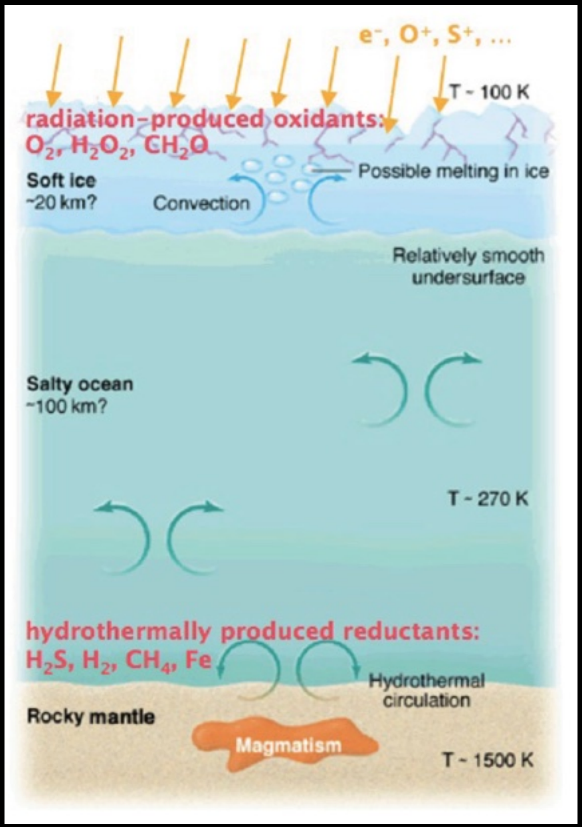
For ice-covered ocean worlds, we are in a data-poor, possibility-rich universe.



Credit: Soderlund et al. (2024)

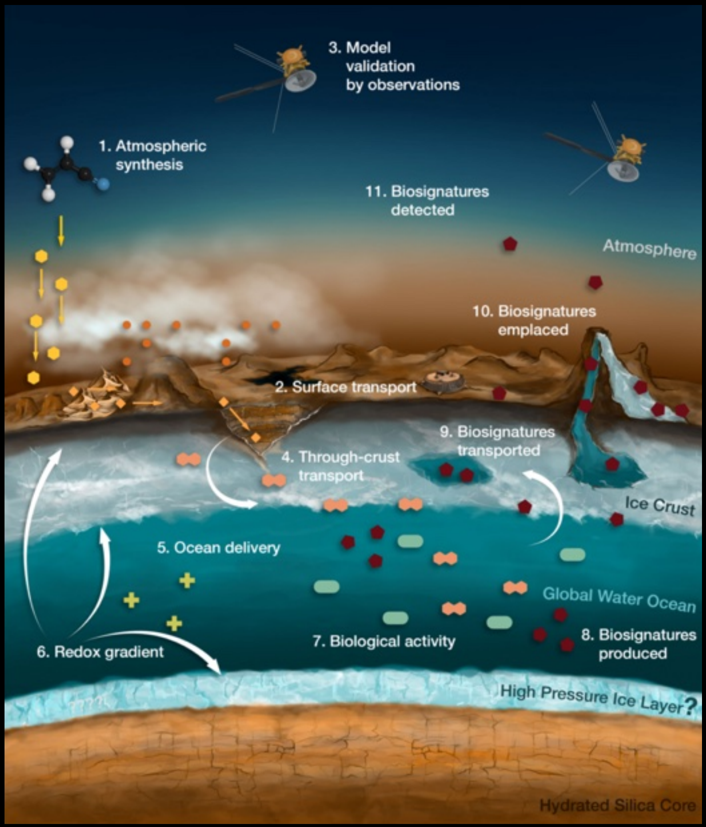
Ocean worlds are exciting prospects for habitability.

Europa and Enceladus



Credit: Pappalardo (2010), after Stevenson (2000)

Titan and Ganymede



Credit: NASA/JPL-Caltech/Titan NAI team

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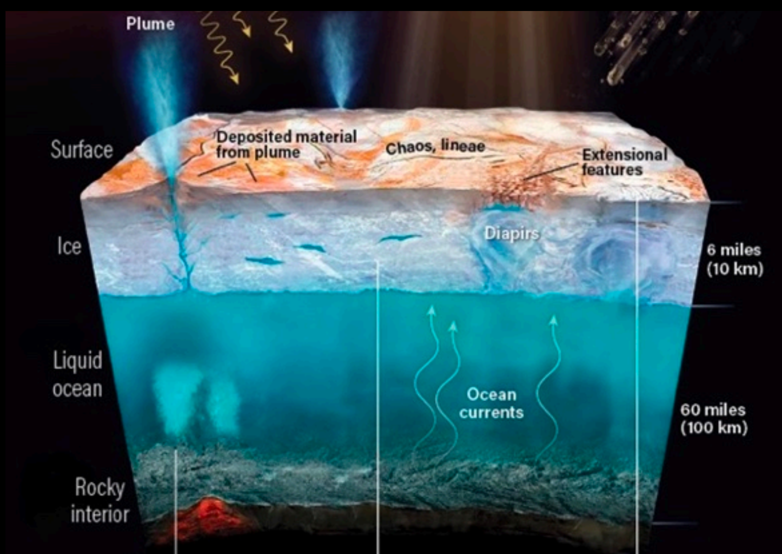
Planetary oceans are a natural laboratory for studying oceanographic processes in settings that challenge traditional assumptions made for Earth.

- Some driving mechanisms are common to both Earth and exo-oceans, such as buoyancy-driven flows and tides
- Other mechanisms, such as libration, precession, and electromagnetic pumping, are likely more significant for moons in orbit around a host planet

Buoyancy-driven flows are caused by the exchange of heat and salt between the ocean and the underlying mantle/core and overlying ice shell.

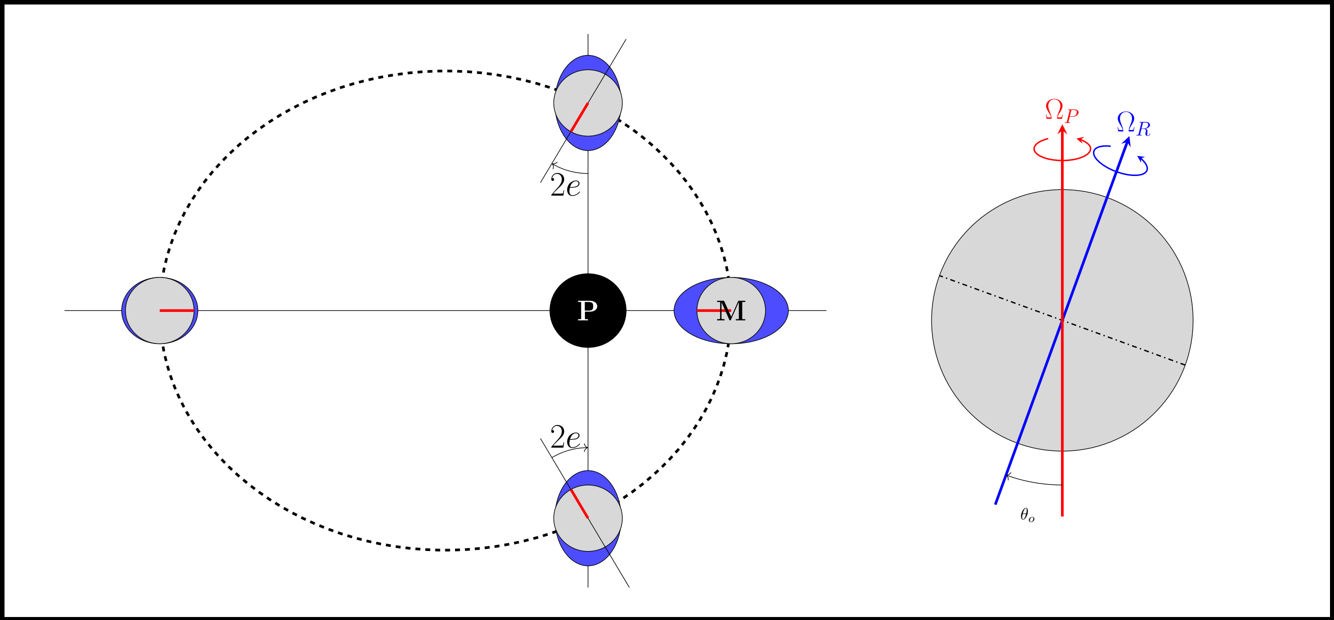
- Radiogenic and tidal heating within the mantle result in a basal heat flux
- Water–rock reactions and melting/freezing of the ice shell modify ocean salinity
- Tidal heating and ice shell thickness variations may drive horizontal convection



Credit: NASA/JPL-Caltech

Mechanically driven flows are the consequence of the moons' orbits and rotation.

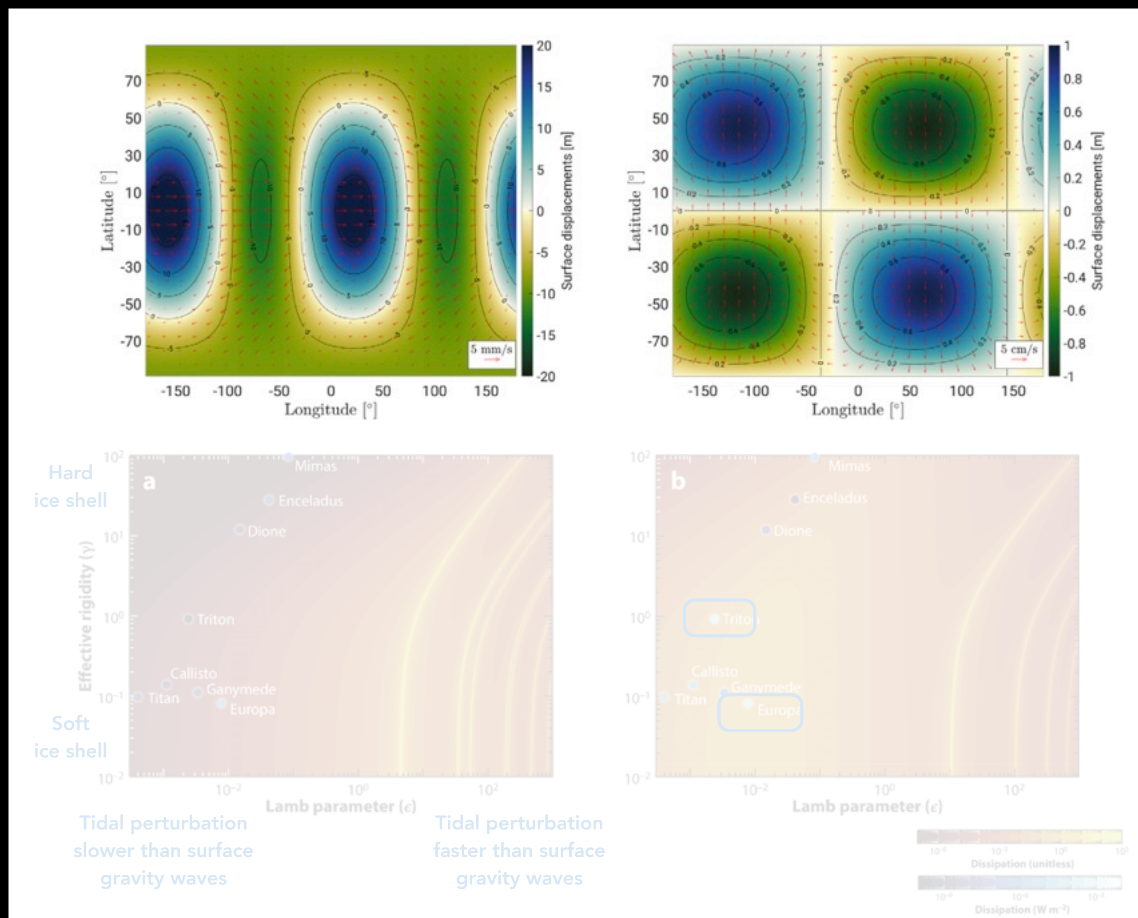
- Gravitational tides deform icy moons due to the eccentricity and obliquity of their orbits, along with moon-moon interactions
- Tidal torques cause periodic changes in the rotation of the moons (e.g., libration and precession)



Credit: Soderlund et al. (2020)

Gravitational tides deform icy moons due to the eccentricity and obliquity of their orbits, along with moon-moon interactions; can lead to strong flows and dissipation.

Eccentricity Tide
(Barotropic)



Obliquity Tide
(Barotropic)

Credit: Soderlund et al. (2020, 2024);

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Eccentricity Tide
(Barotropic)

Obliquity Tide
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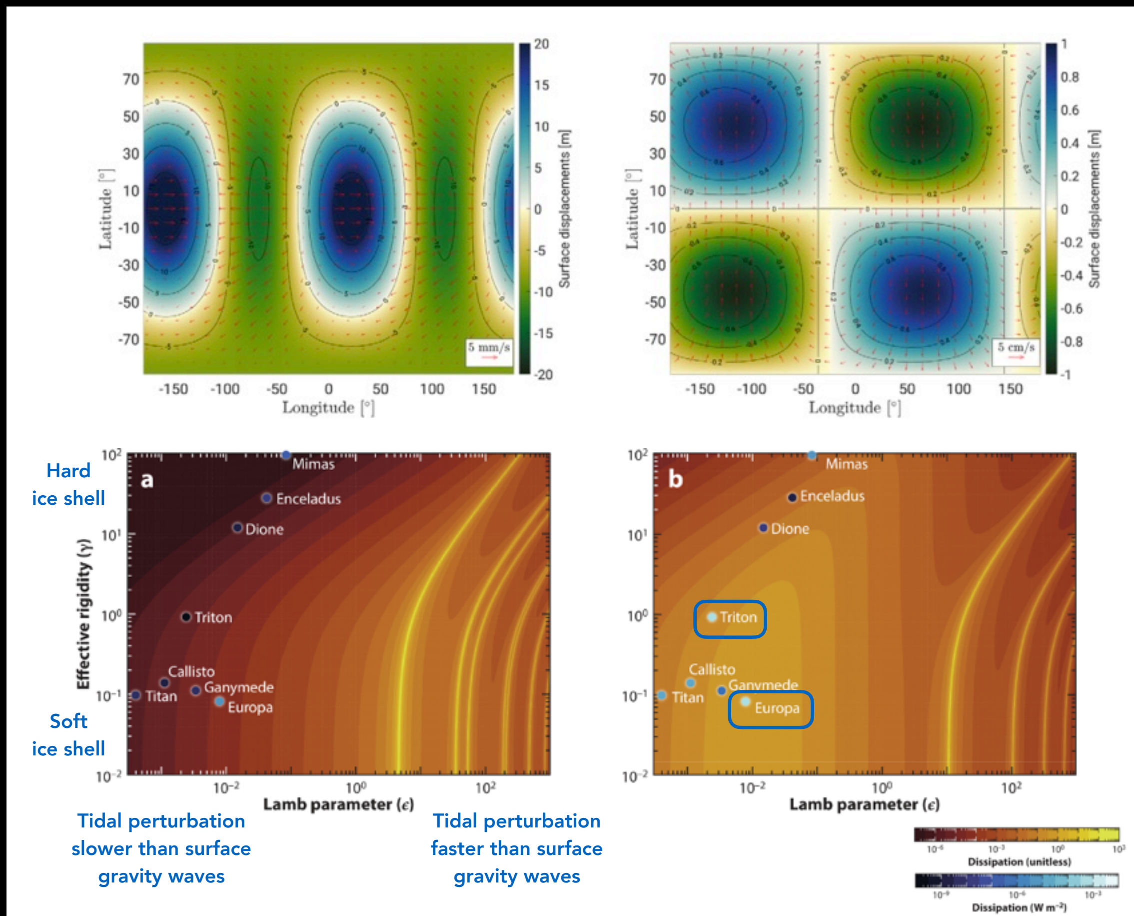
Eccentricity Tide
(Dissipation)

Obliquity Tide
(Dissipation)



Credit: Soderlund et al. (2020, 2024); adapted from Rovira-Navarro et al. (2023)

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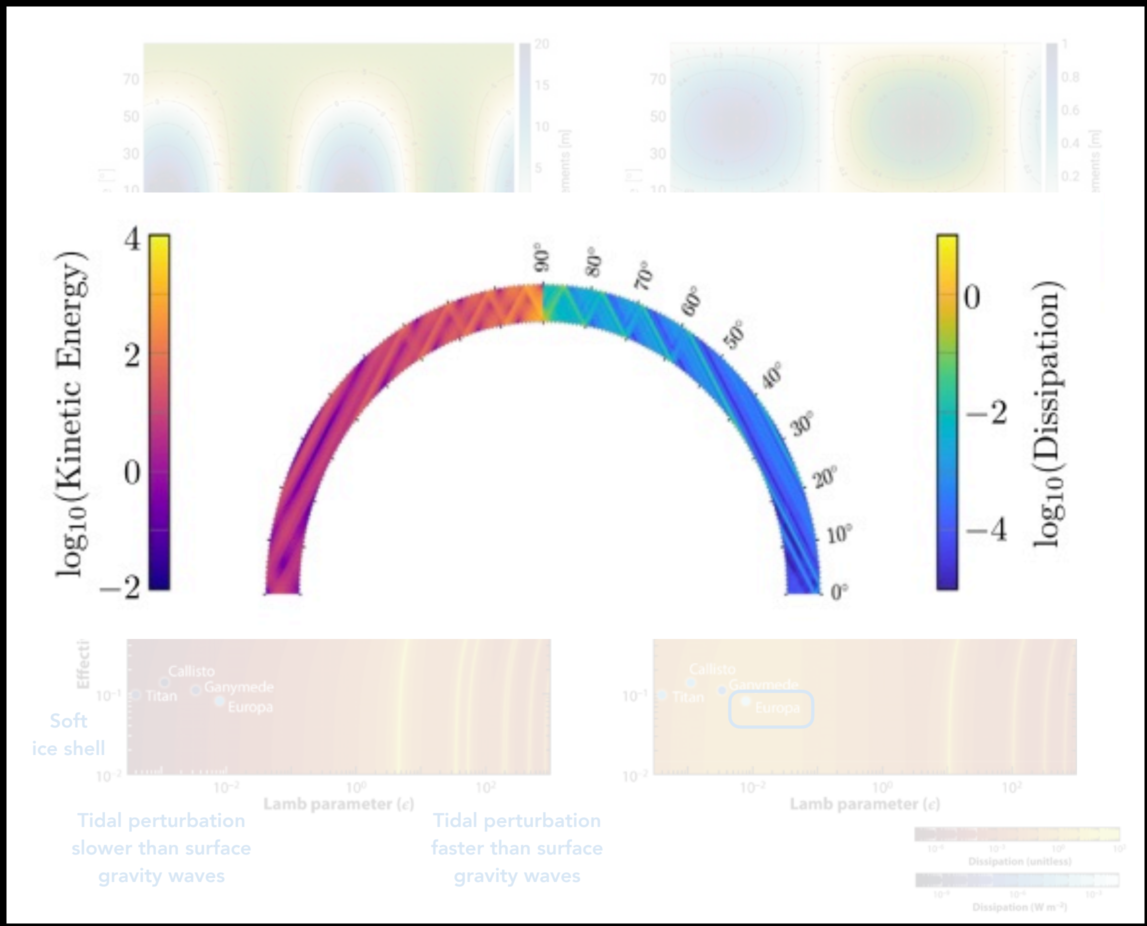
Eccentricity Tide
(with inertial waves)



Credit: Rovira-Navarro et al. (2019)

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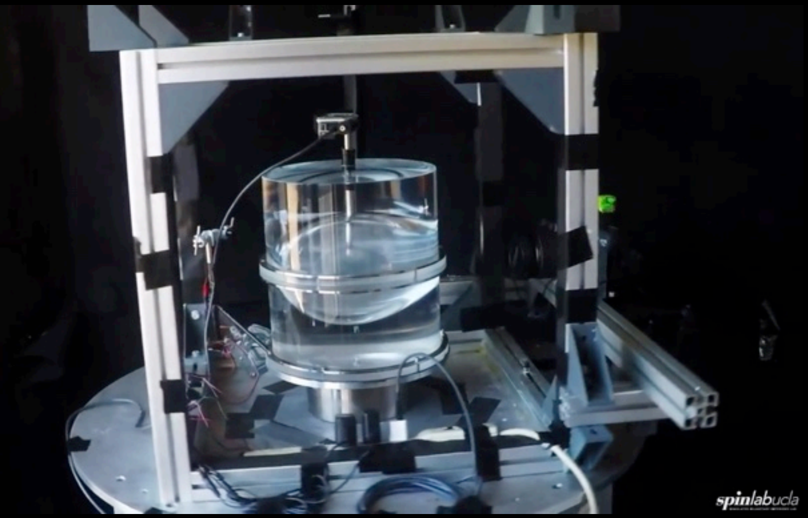
Libration-driven flows may be located in the boundary layers or in the ocean bulk, and may be quasi-steady or consist of growth-collapse cycles.



Credit: Lemasquerier et al. (2017)

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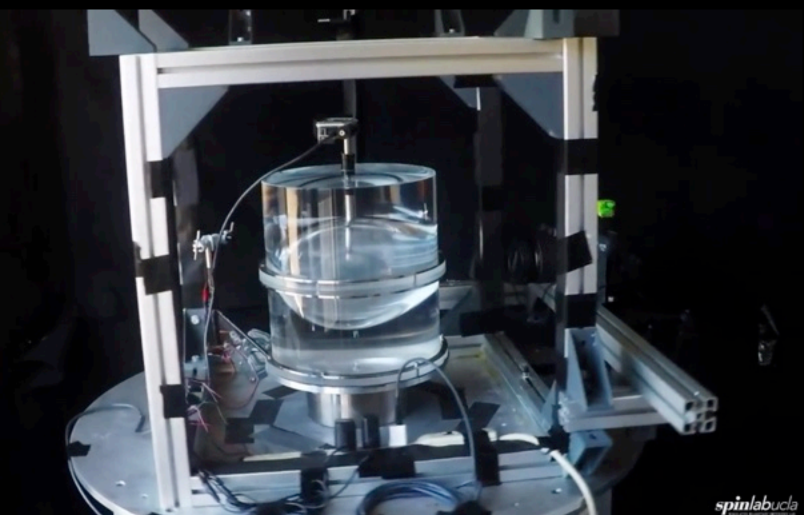
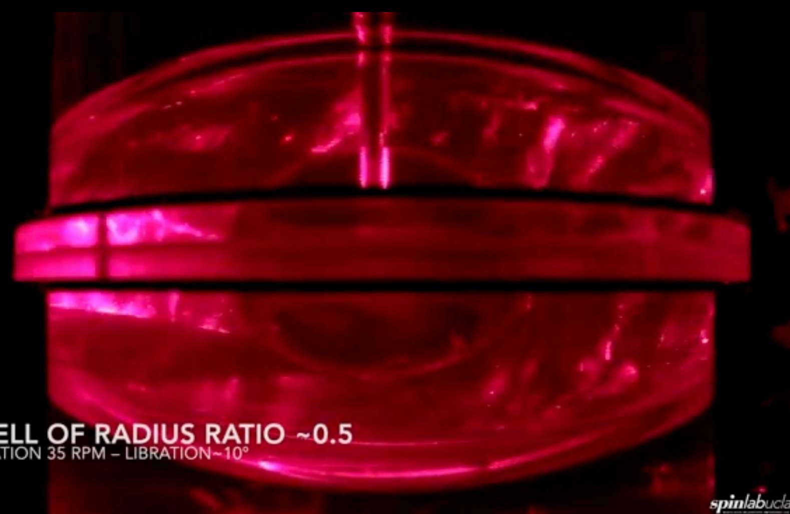
Libration-driven elliptical instabilities (LDEI) lead to space-filling turbulence





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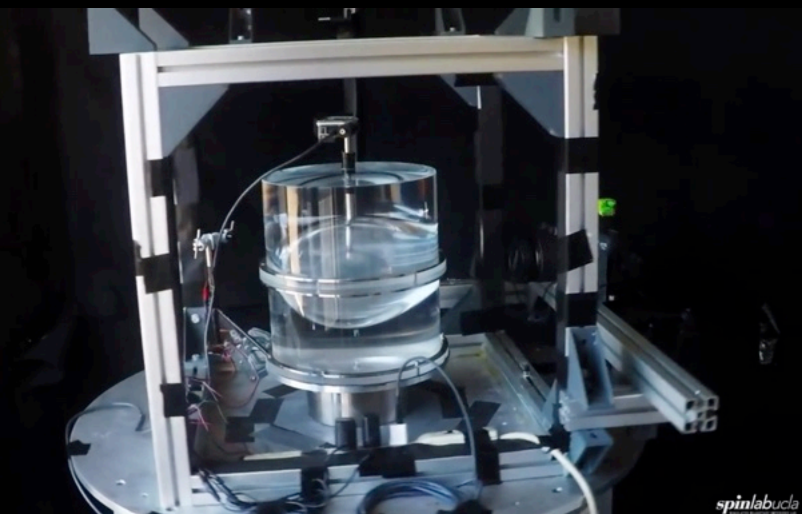
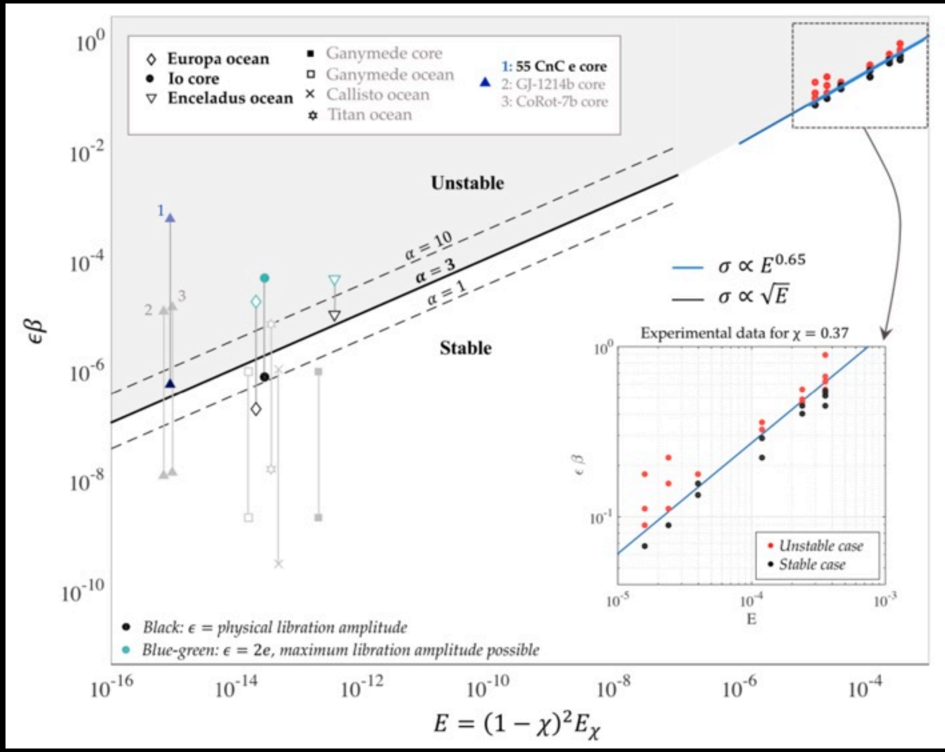
Libration-driven flows may be located in the boundary layers or in the ocean bulk, and may be quasi-steady or consist of growth-collapse cycles.

Libration-driven elliptical instabilities (LDEI) lead to space-filling turbulence in the oceans of Enceladus and Europa.





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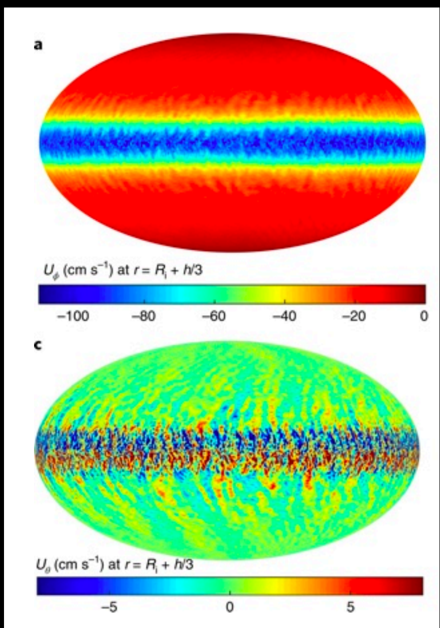
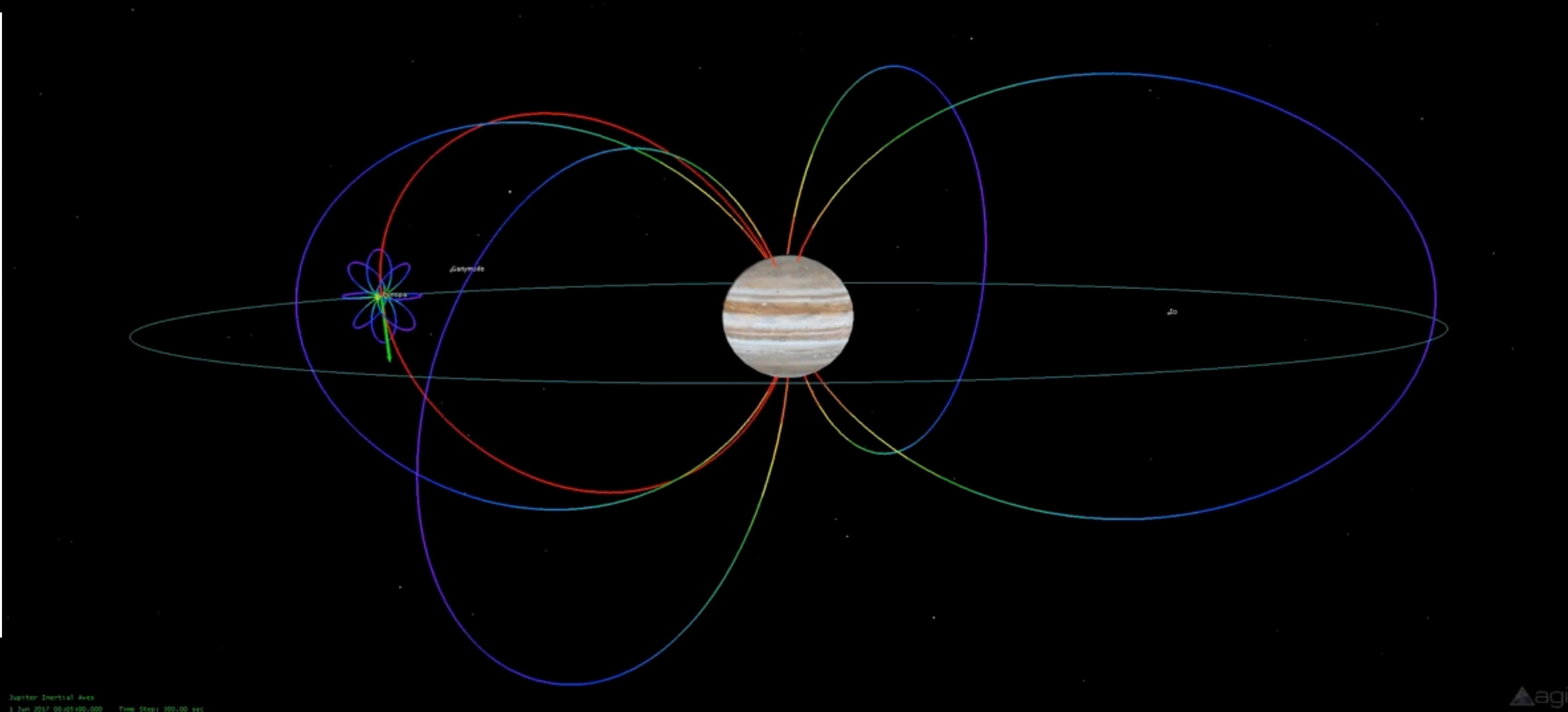
Electromagnetically pumped flows are the consequence of the interactions between a moon's induced magnetic field and the planet's intrinsic magnetic field.



Credit: Gissinger & Petitdemange (2019)



Credit: NASA/JPL-Caltech/Corey Cochrane

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Governing Equations

- Conservation of momentum

$$\underbrace{\frac{D\mathbf{u}}{Dt}}_{\text{Temporal}} + \underbrace{2\mathbf{\Omega}\times\mathbf{u}}_{\text{Coriolis}} = \underbrace{-\frac{1}{\rho_0}\nabla p'}_{\text{Pressure}} + \underbrace{\frac{\rho'}{\rho_o}\mathbf{g}}_{\text{Buoyancy}} \underbrace{-\nabla\phi'}_{\text{Grav.}} + \underbrace{\nu\nabla^2\mathbf{u}}_{\text{Viscous}} + \underbrace{\frac{1}{\mu_0\rho_o}(\nabla\times\mathbf{B})\times\mathbf{B}}_{\text{Lorentz}} \underbrace{-\frac{\mathrm{d}\mathbf{\Omega}}{\mathrm{d}t}\times\mathbf{r}}_{\text{Poincare}}$$

- Poisson's equation

$$\nabla^2\phi' = 4\pi\mathcal{G}\rho'$$

- Equation of state

$$\rho' = \rho_0(-\alpha\theta' + \beta S' + \frac{1}{\rho_0 c_s^2}p')$$

- Conservation of mass

$$\nabla\cdot\left(\rho_0\mathbf{u}\right) = 0$$

- Conservation of salinity

$$\frac{DS'}{Dt} = Q_1$$

- Heat equation

$$\frac{D\theta'}{Dt} = \frac{\theta_0}{T_0}\frac{Q_2}{c_p}$$

- Induction

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{u}\times\mathbf{B}) - \nabla\times\left(\frac{1}{\mu_0\sigma}\nabla\times\mathbf{B}\right)$$

$$\nabla\cdot\mathbf{B} = \mathbf{0}$$

Credit: Soderlund et al. (2024)

Approximation	Typically used if…	Filtered/ignored phenomena
No magnetism	Electrically insulating	Magnetic induction, Lorentz force
Anelastic approximation	$\omega L \ll c_s$	Sound waves
Boussinesq approximation	ii, ρ_0 is constant	No density variations beyond buoyancy
Linear equation of state	α, β are constant	Cabbeling, thermobaricity
Isohaline	$Q_1 \approx 0$	Variations in salinity
Isentropic	$Q_2 \approx 0$	Non-adiabatic, nonreversible processes
Thin-layer approximation	$H \ll R$	Radial gravity variations
Spherical-body approximation	$\varepsilon \ll 1$	Horizontal gravity component
Massless approximation	$\phi^{(SG)} \ll \phi_0$	Self-gravity
Rigid mantle/core	$\eta_b \ll 1$	No ocean bottom displacements
Constant rotational rate	$\Omega = \Omega_0$	Poincaré force, spin-driven flows
Linearization	Waves have small amplitudes	Turbulence, wave breaking
Traditional approximation	$H/L \ll 1$	Horizontal rotation vector component
Shallow-water approximation	$H/L \ll 1$	Internal inertial waves
Unstratified ocean	$N \approx 0$	Internal gravity waves
Nonrotating body	$\Omega/\omega \ll 1$	Rossby waves
Ocean in equilibrium	xv, xvi, $\omega L \ll c_{surf}$	All types of ocean waves

Common Approximations

- Vast majority of studies neglect magnetism and assume the Boussinesq approximation

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Common Approximations

- Vast majority of studies neglect magnetism and assume the Boussinesq approximation
- Buoyancy-driven and mechanically driven flows are generally studied separately
  - Convection → diabetic processes that determine stratification structure
  - Mechanical → diabetic processes neglected and stratification structure is assumed

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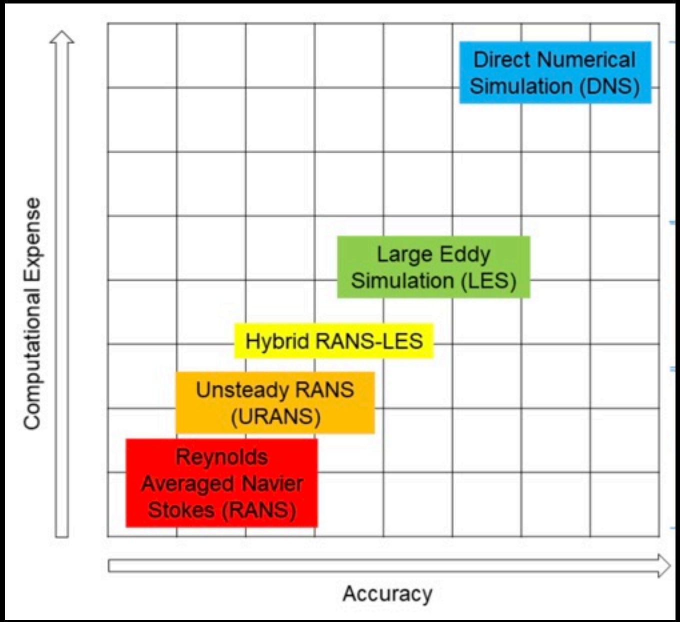
Common Approximations

- Ocean flows are turbulent! It is not possible to resolve all length and temporal scales



Credit: Hammond et al. (2022)

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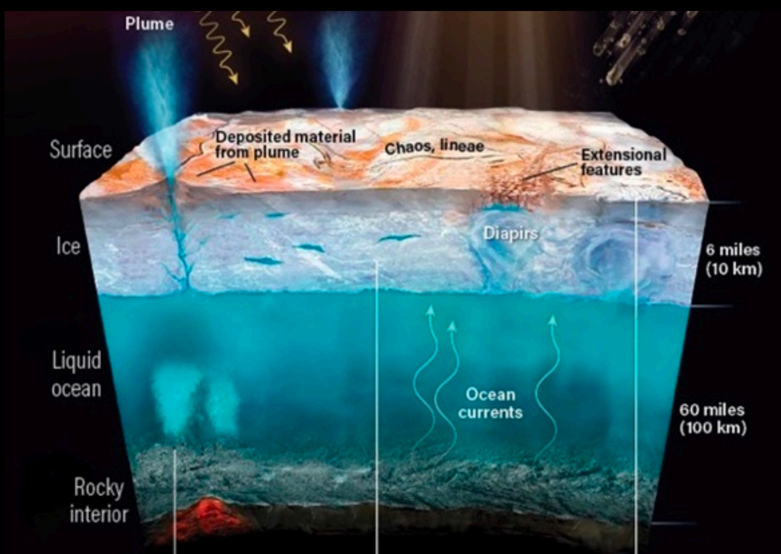
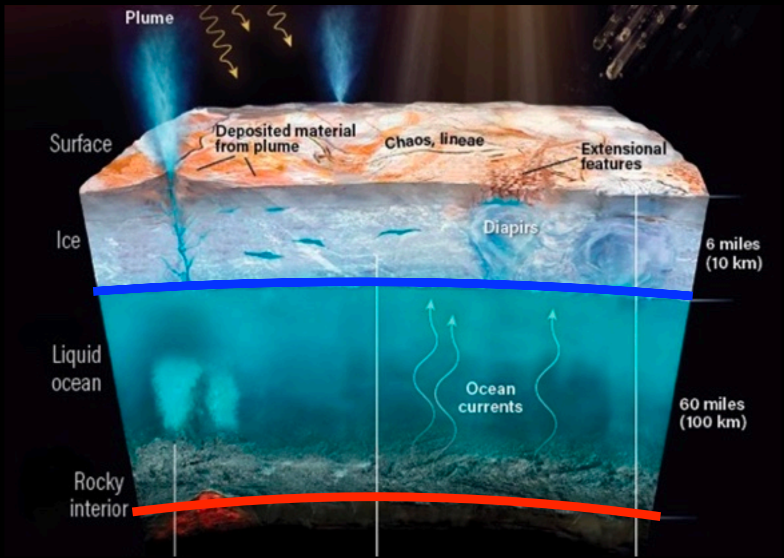


Credit: NASA/JPL-Caltech

Radiogenic and tidal heating within the mantle result in a vertical basal heat flux can generate hydrothermal plumes, turbulent convection, and global circulations.



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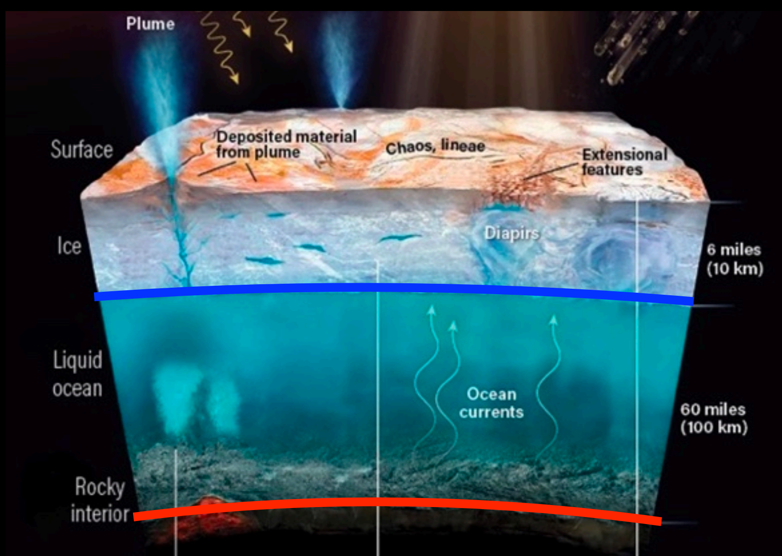
We can use scaling laws to predict the convective regimes of ocean worlds.



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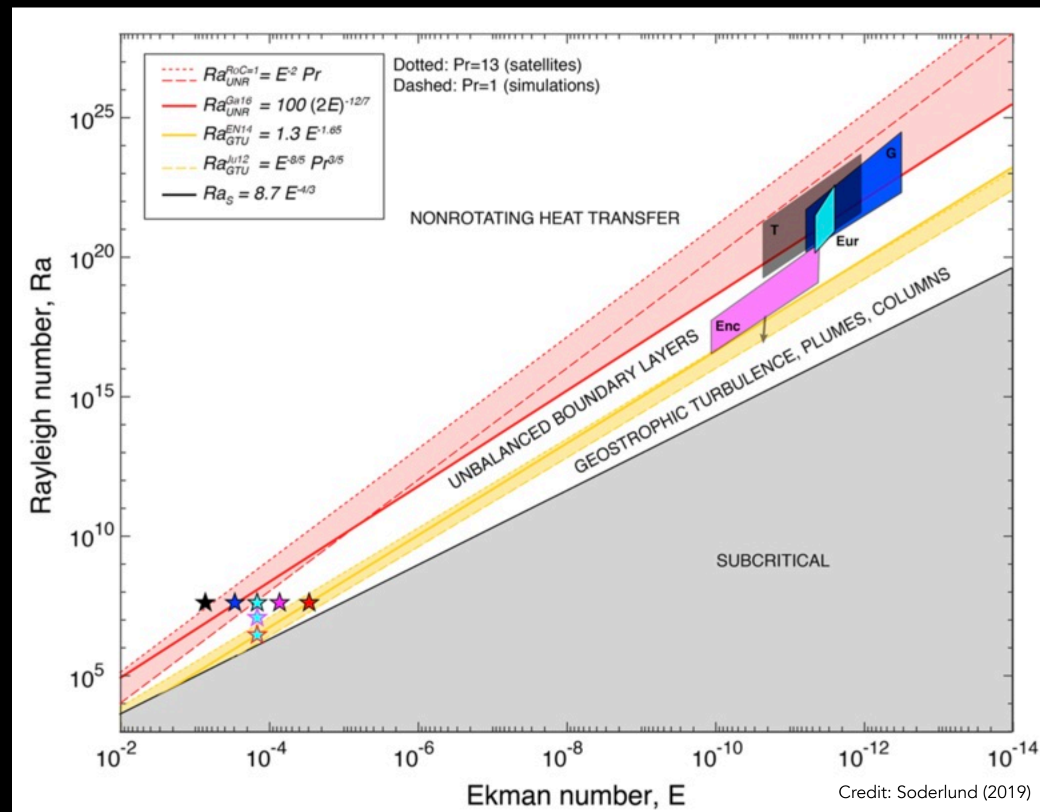

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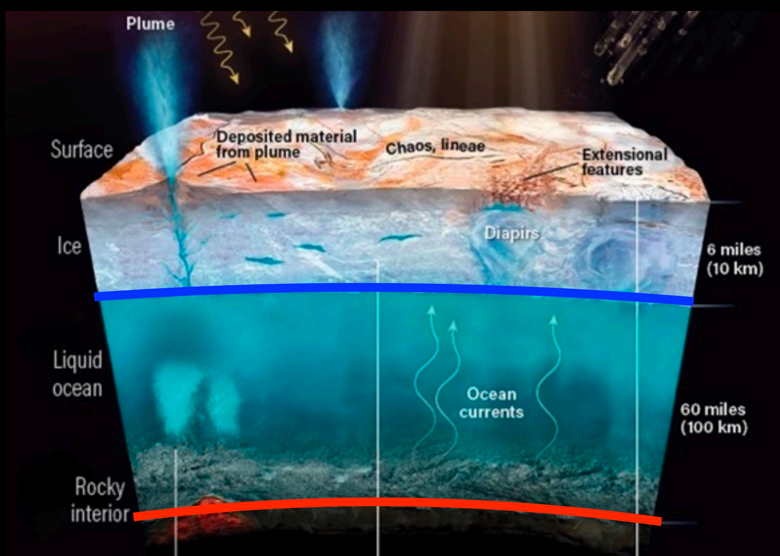
Europa, Ganymede, and Titan are weakly to moderately constrained by rotation, while Enceladus may be strongly constrained by rotation.



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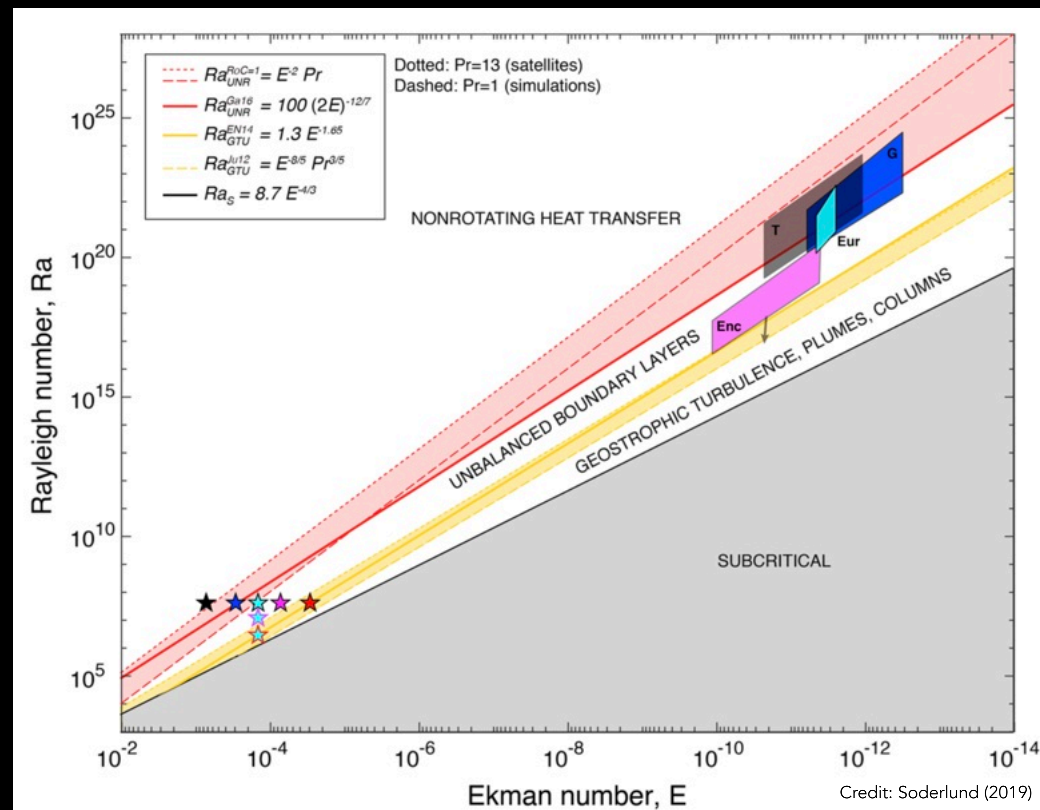

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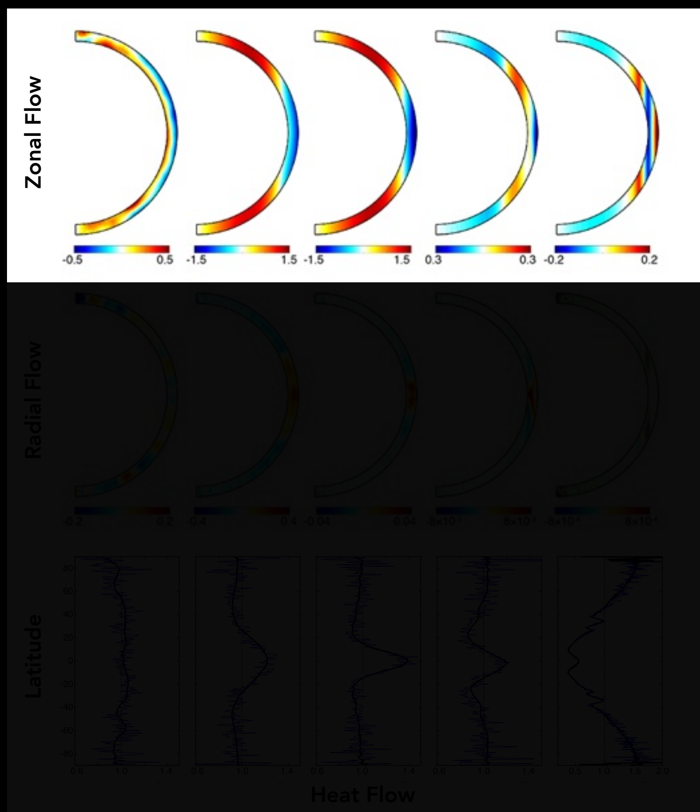
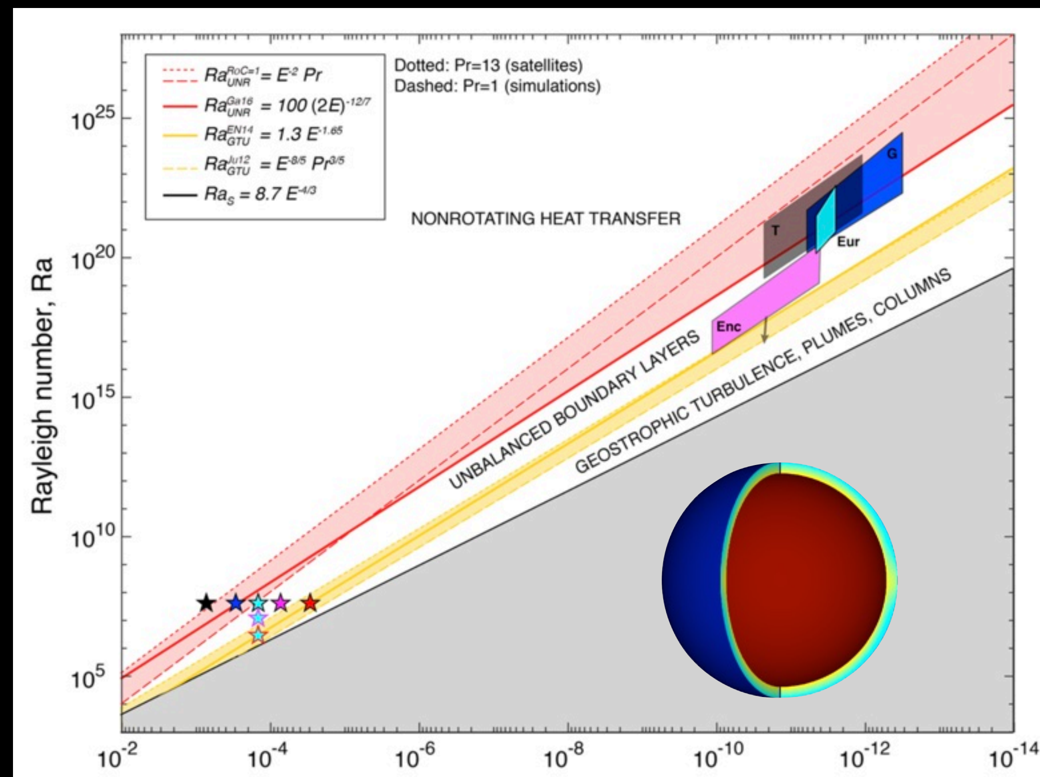
Faster Rotation





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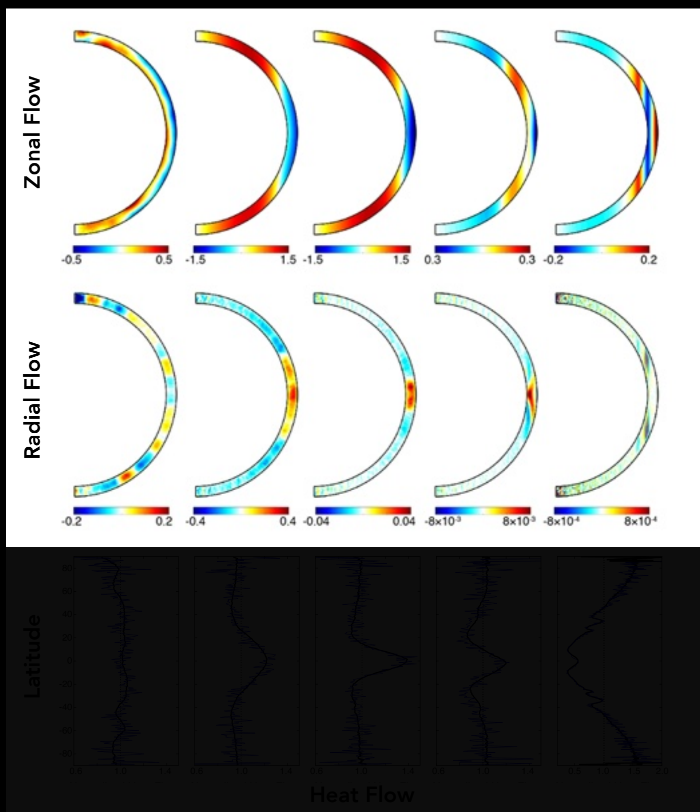

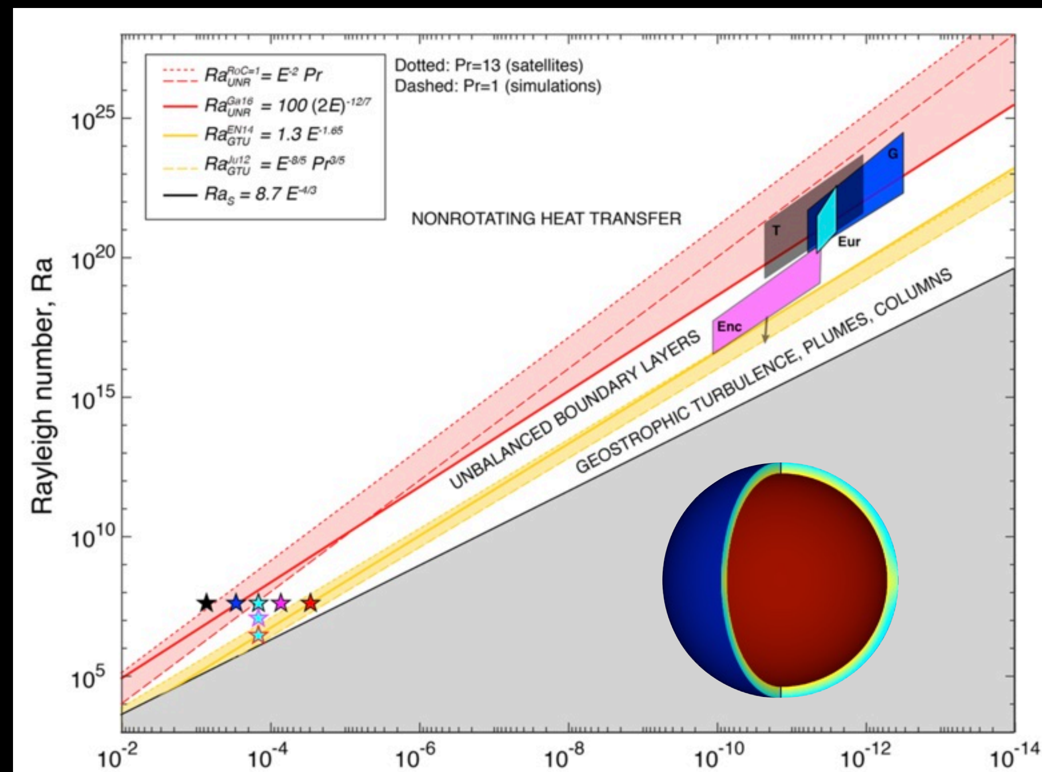

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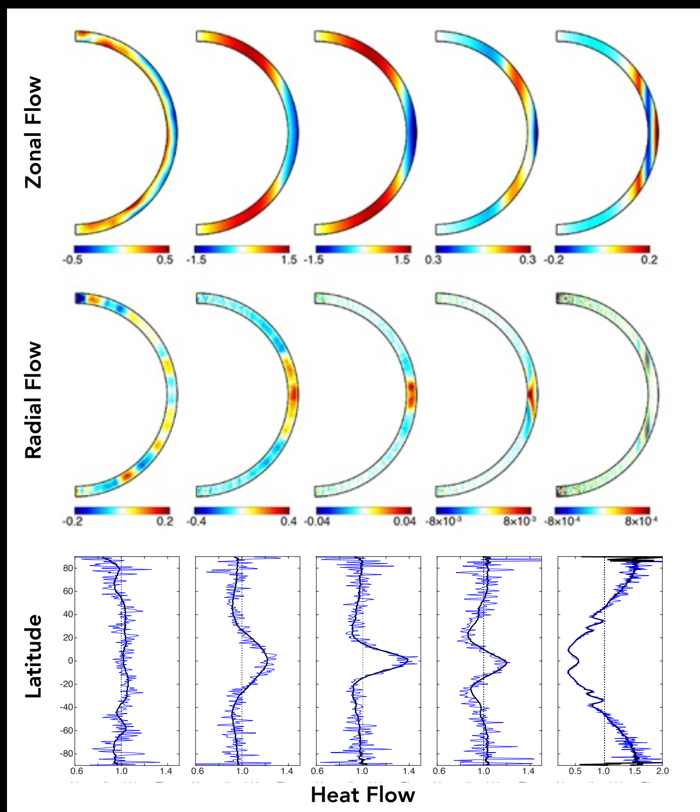

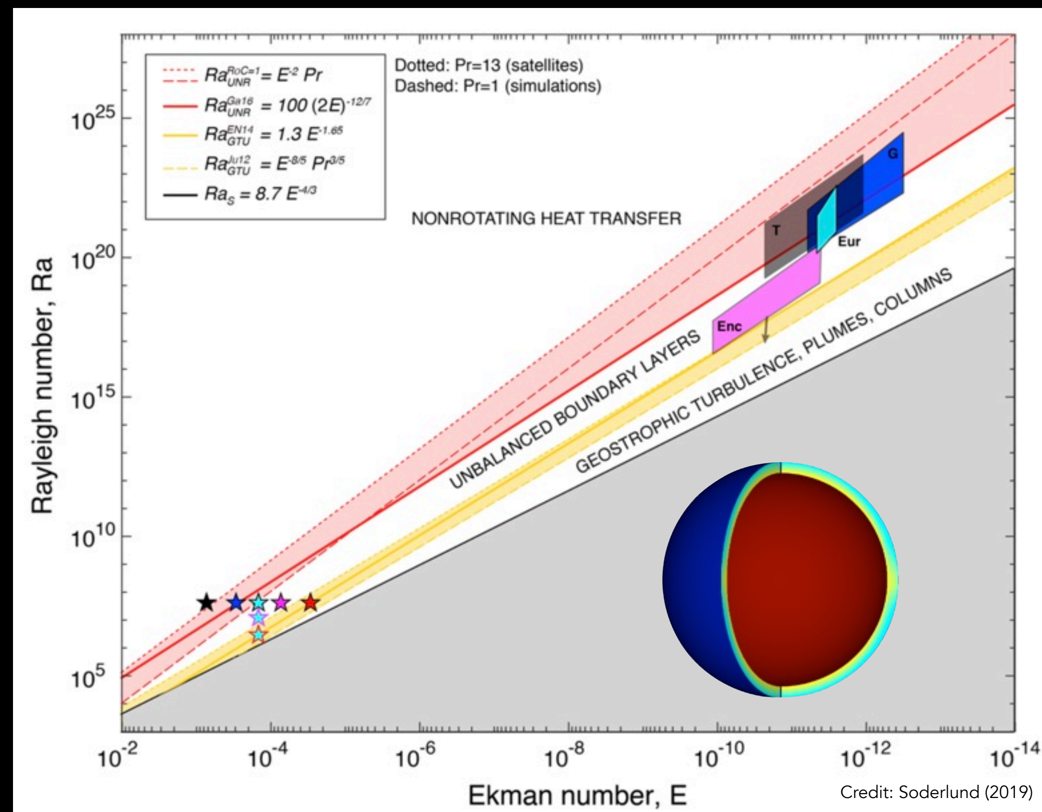

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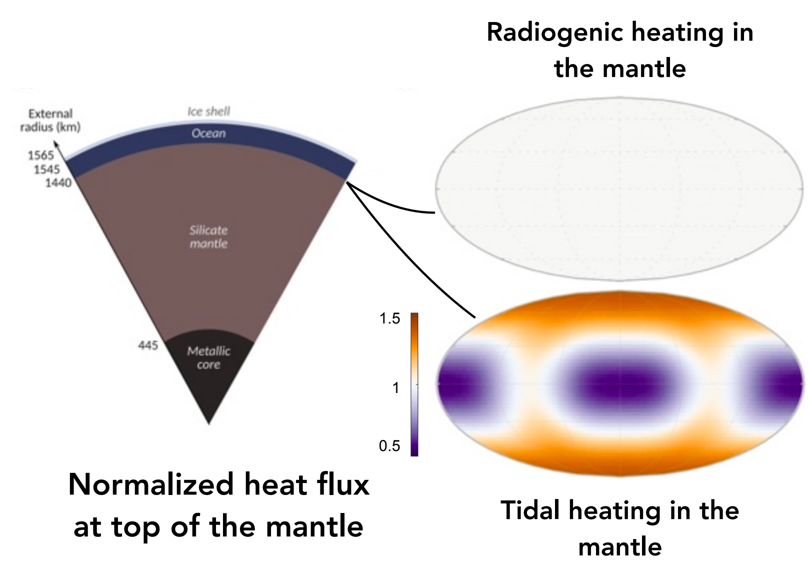
Mantle heating may be uniform (radiogenic) or spatially heterogenous (tidal).



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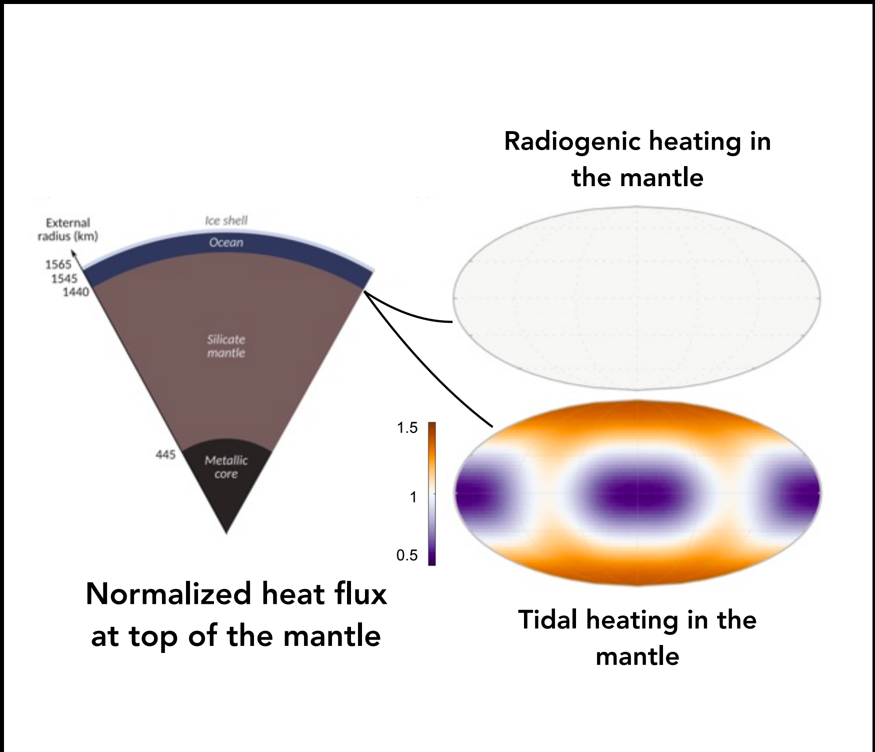

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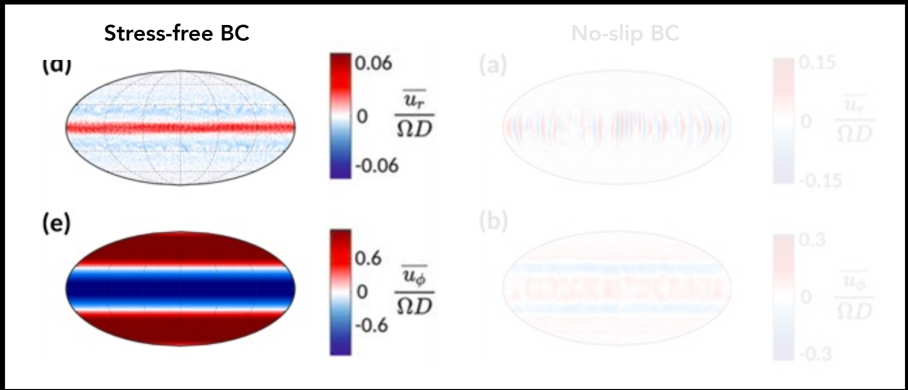
RADIOGENIC (Uniform heat flux)



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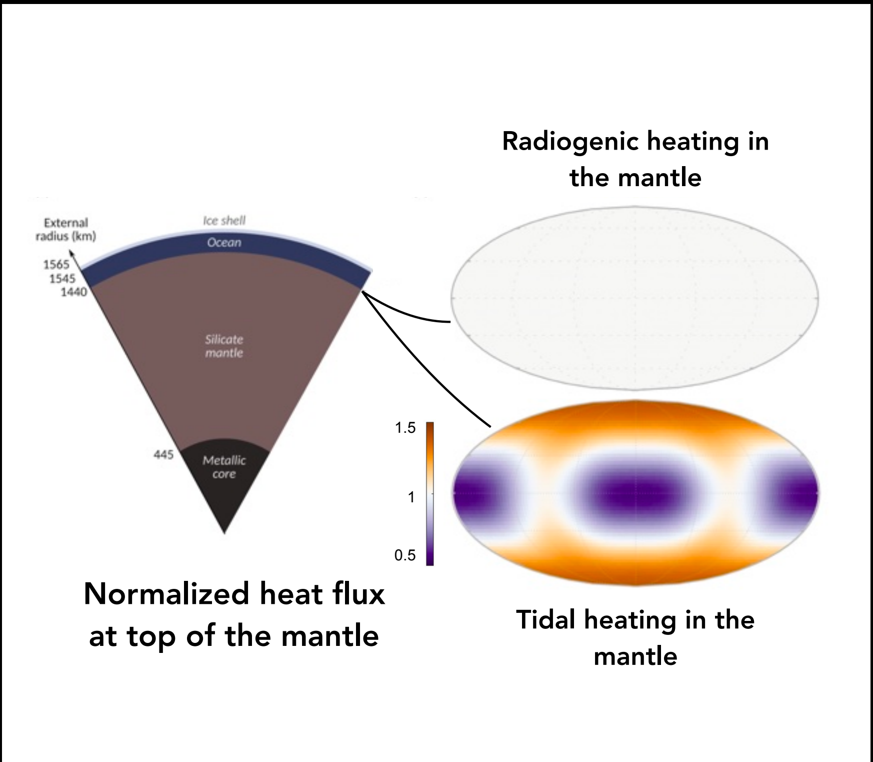

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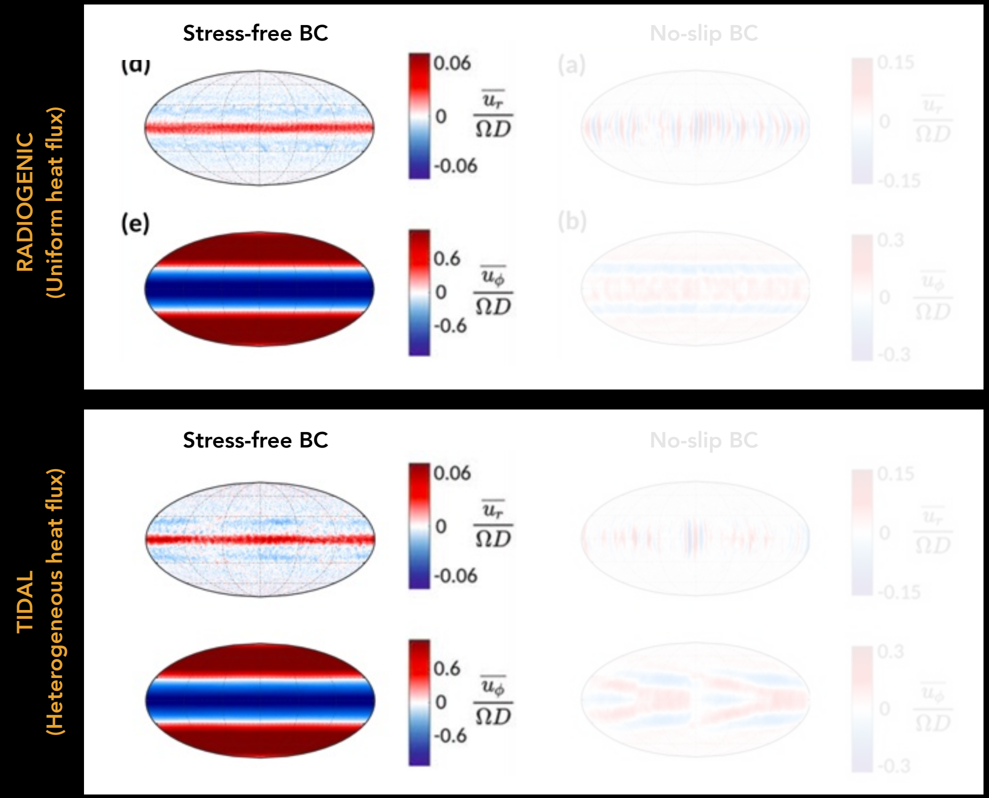

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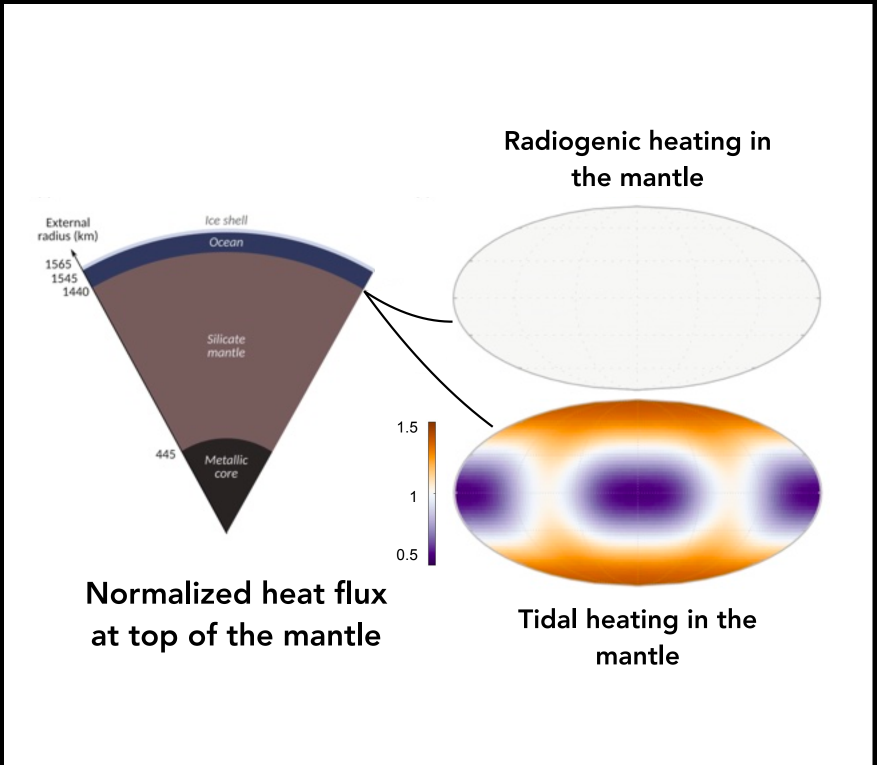

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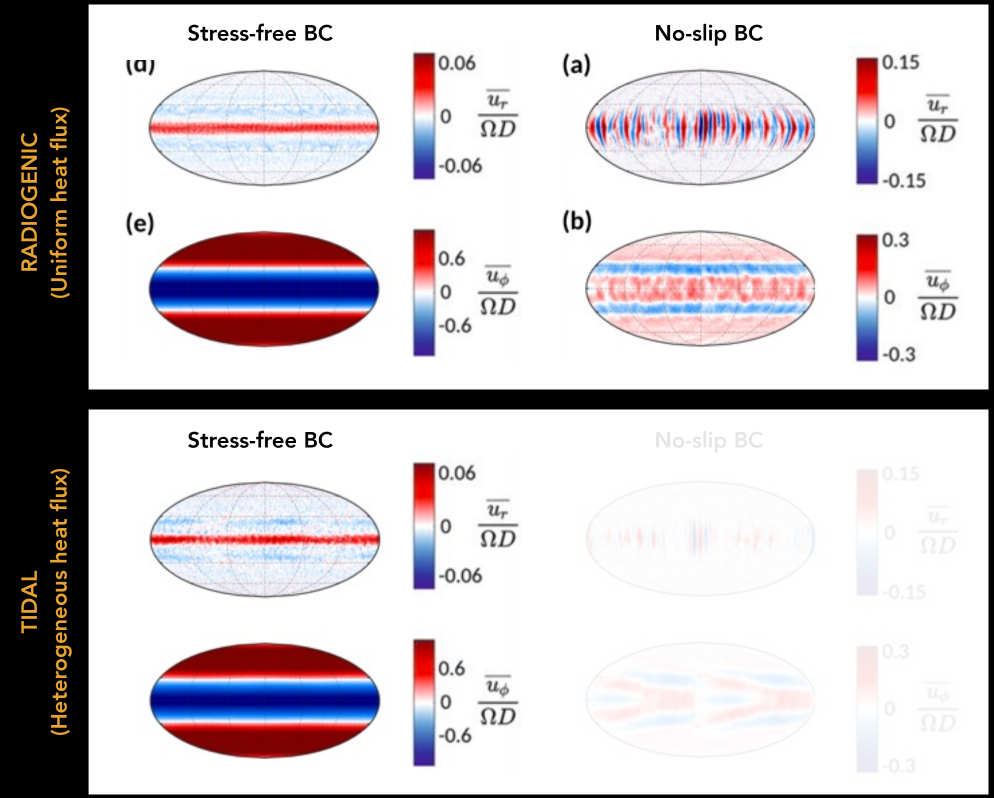

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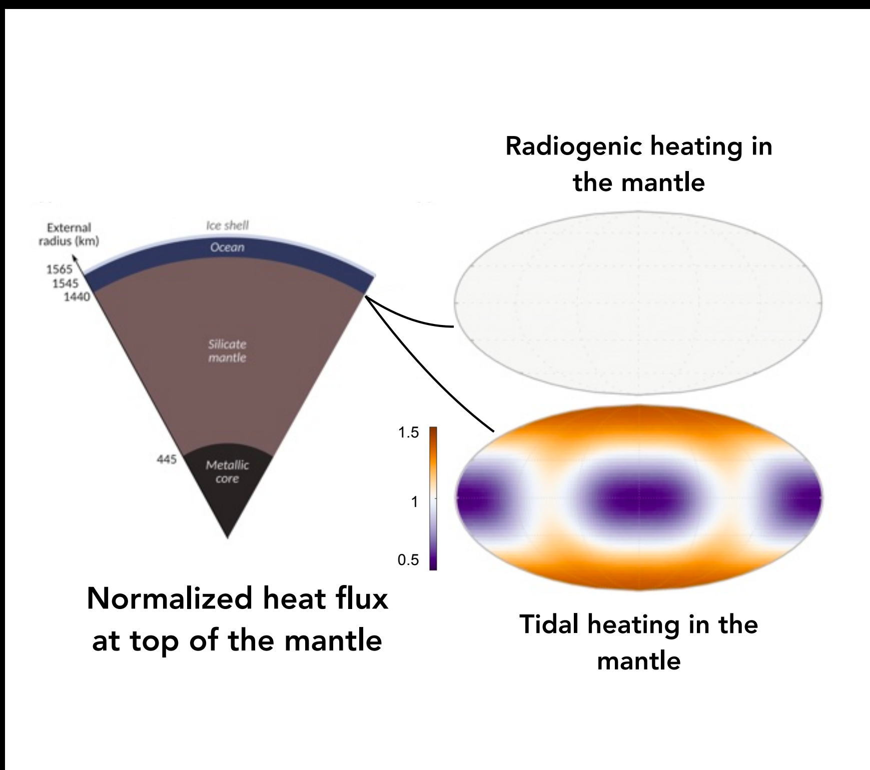
Heterogeneous tidal heating in the mantle could drive large-scale thermal winds.



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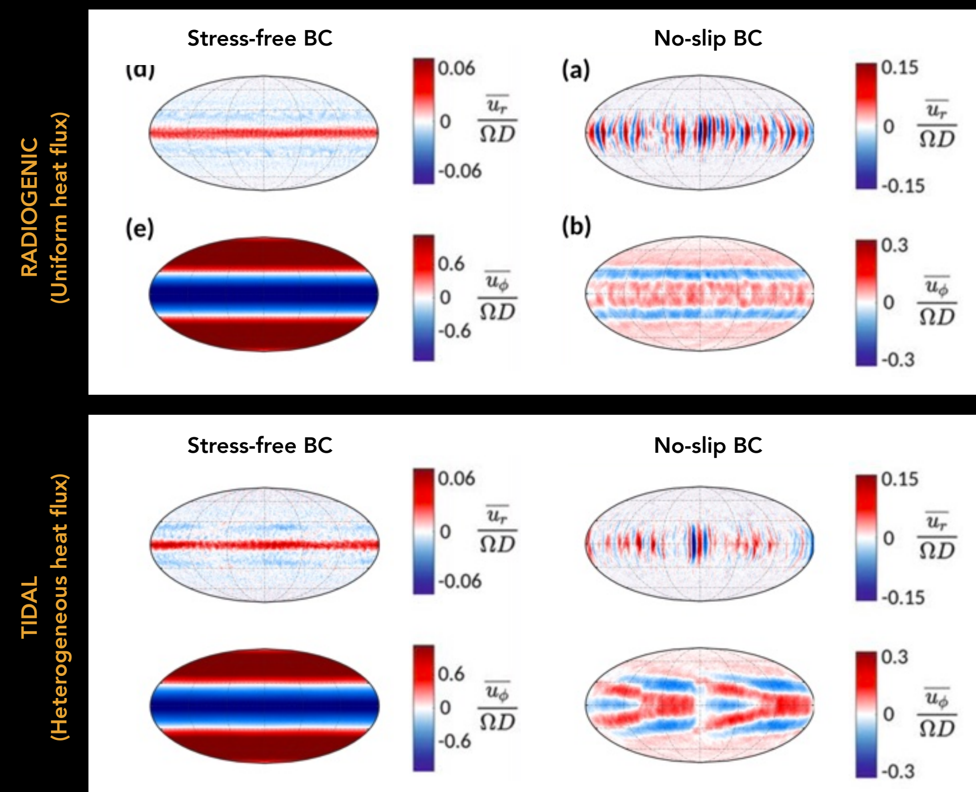
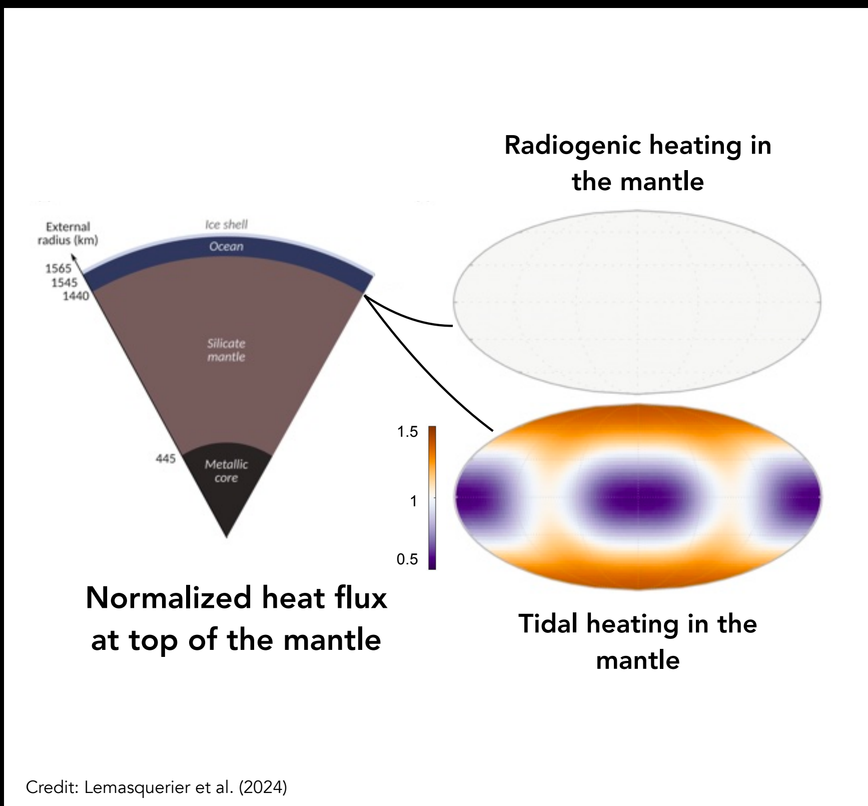
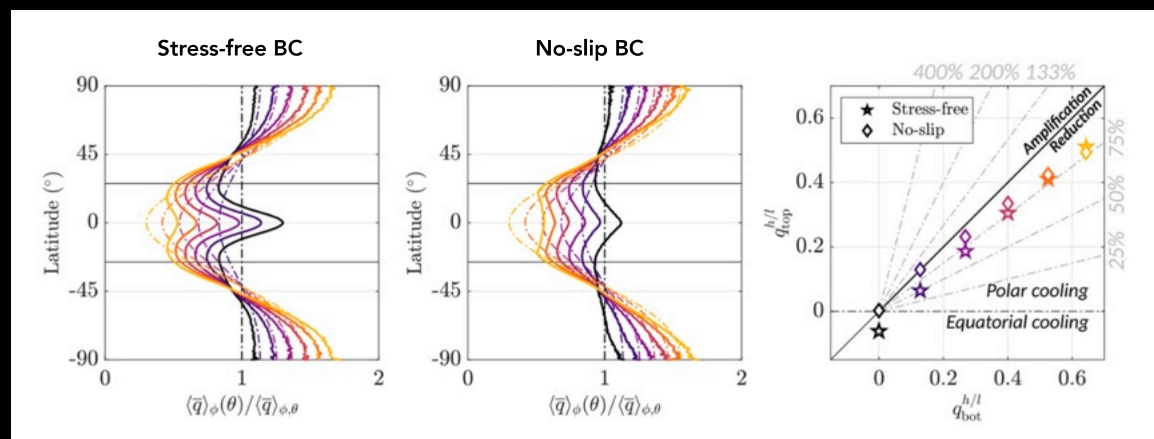


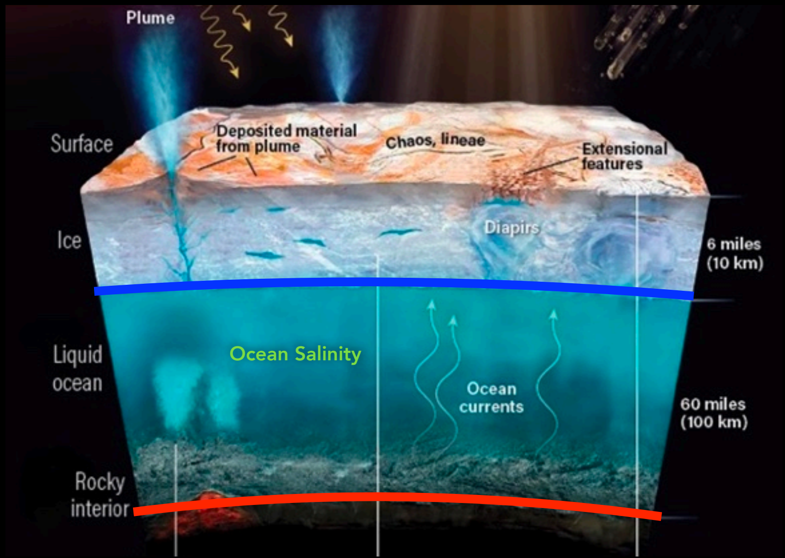
Europa, Ganymede, and Titan are weakly to moderately constrained by rotation, while Enceladus may be strongly constrained by rotation.

Latitudinal tidal heating anomaly is efficiently translated to the ice-ocean interface.

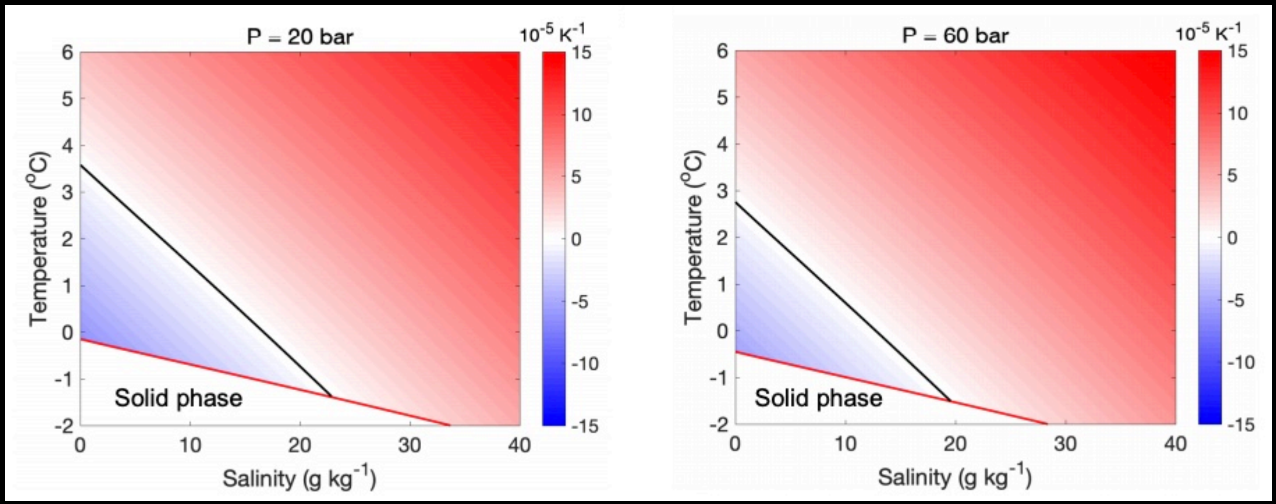




Ocean pressures and salinity can further modify convective dynamics by modifying the thermal expansivity.



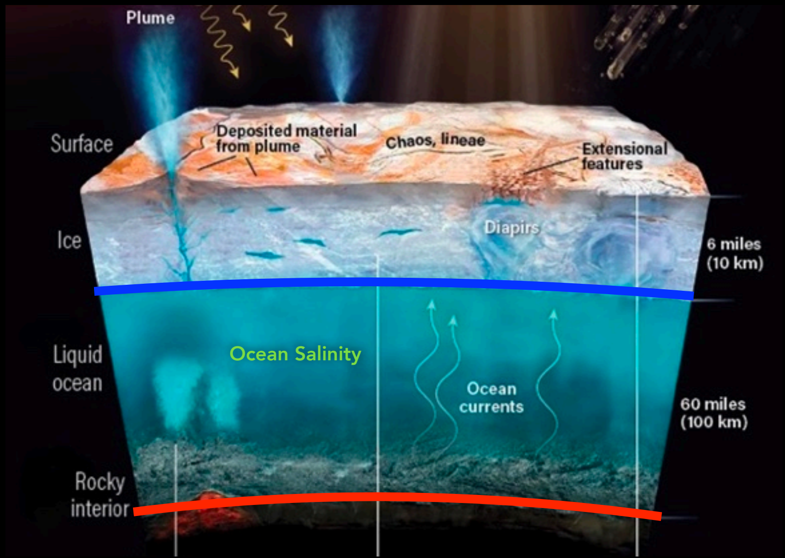
Credit: NASA/JPL-Caltech



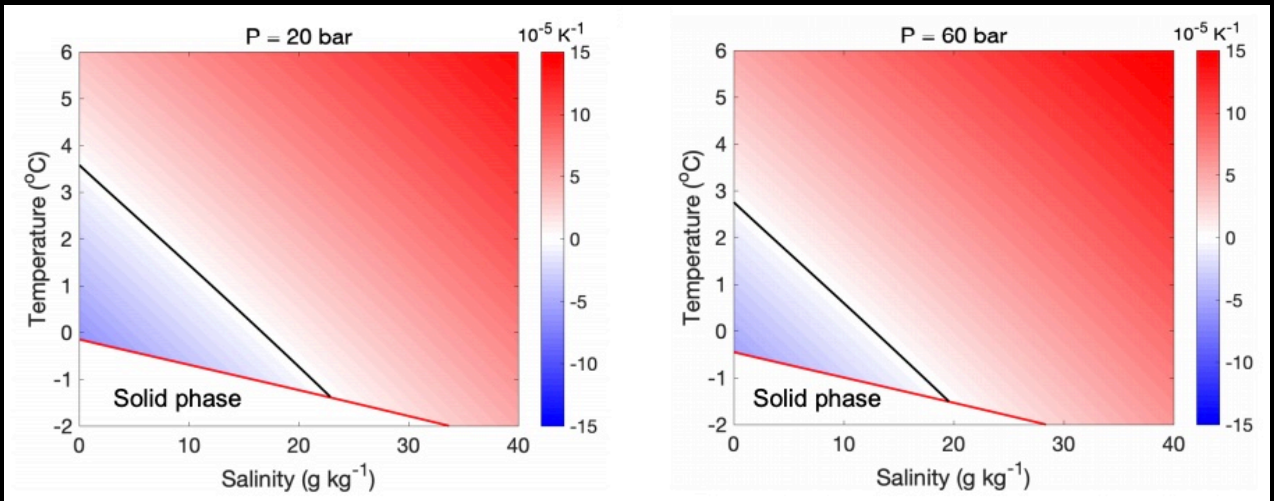
Credit: Zeng & Jansen (2021)

Ocean pressures and salinity can further modify convective dynamics by modifying the thermal expansivity.

- <u>Positive</u> thermal expansivity: water becomes <u>more</u> dense as it cools
- <u>Negative</u> thermal expansivity: water becomes <u>less</u> dense as it cools



Credit: NASA/JPL-Caltech



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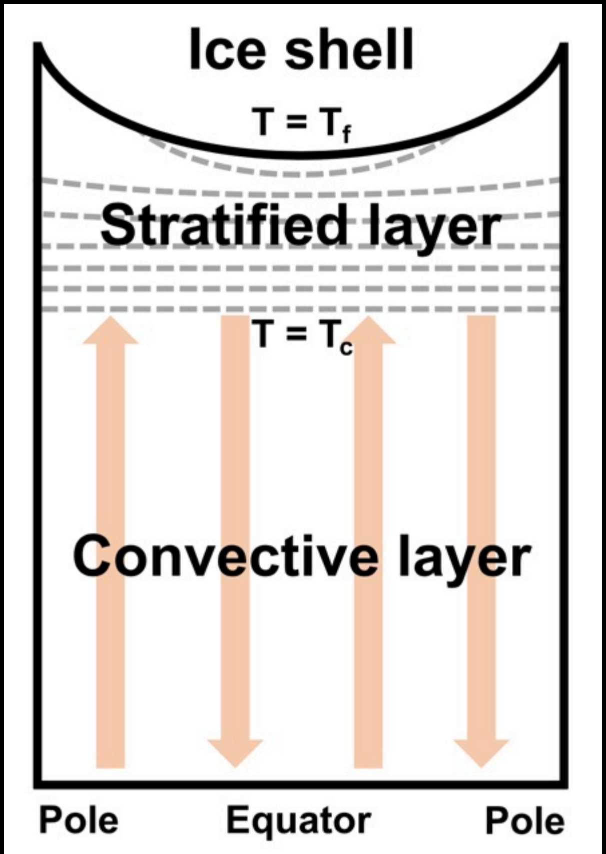

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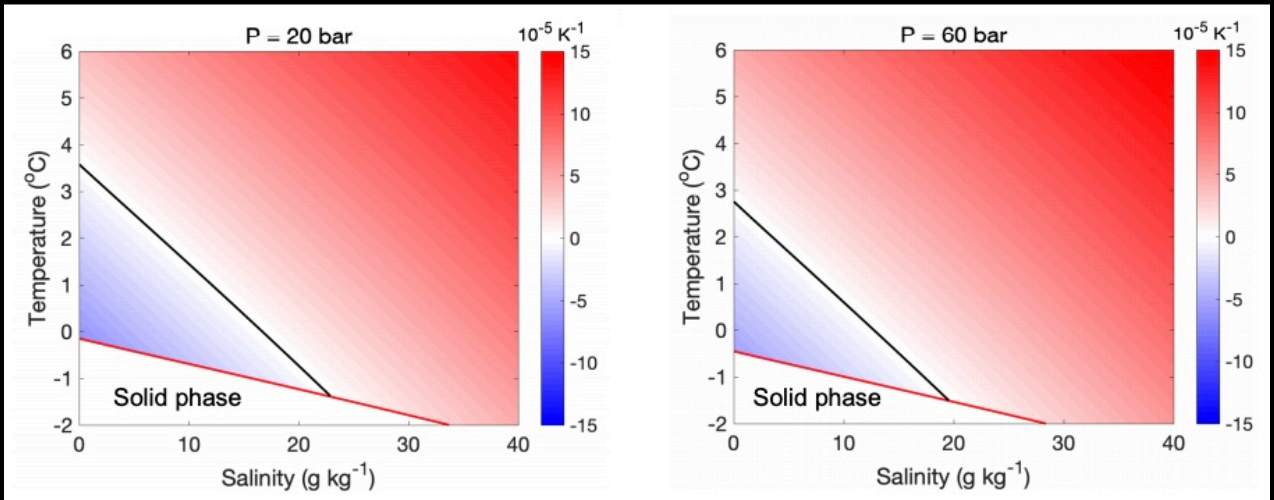

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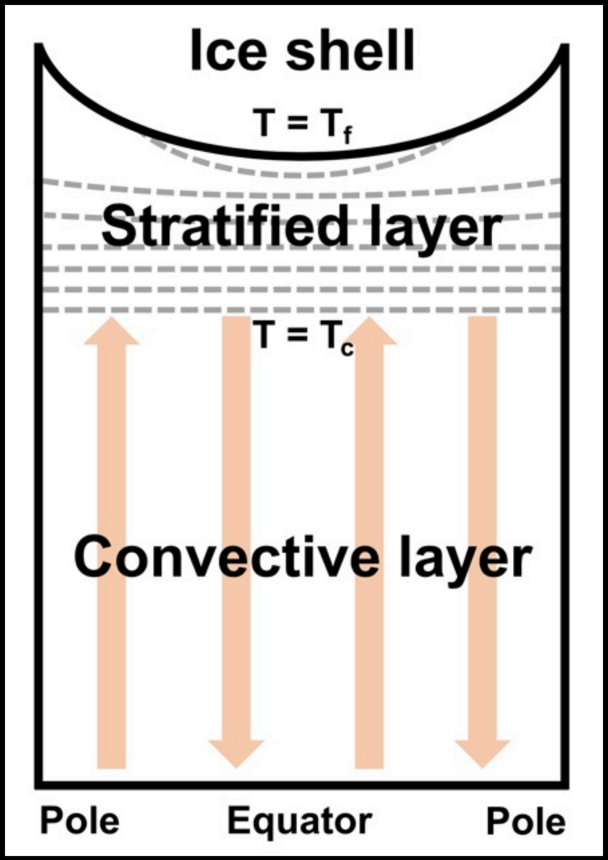

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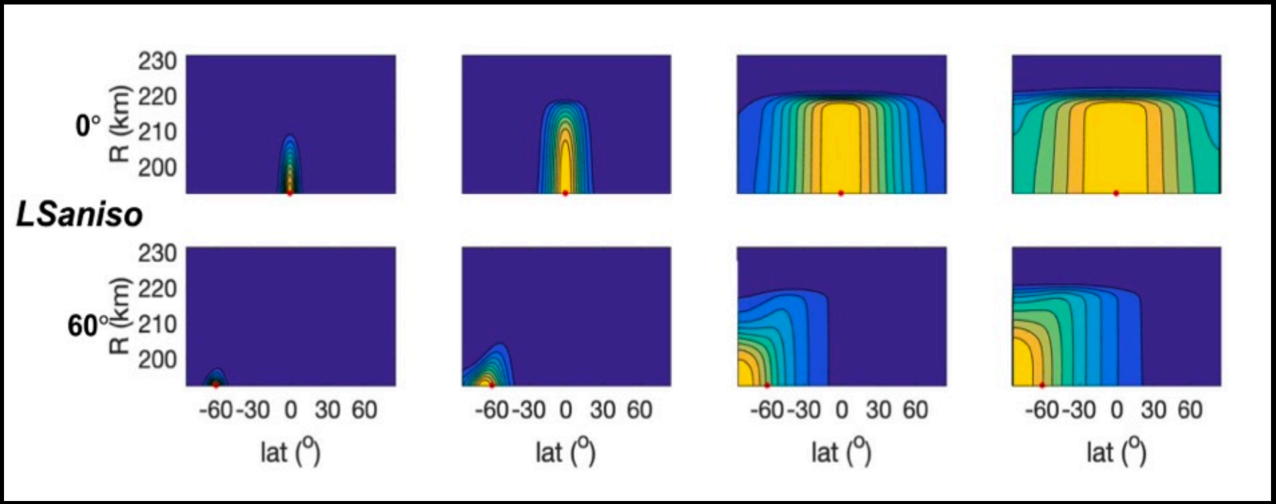
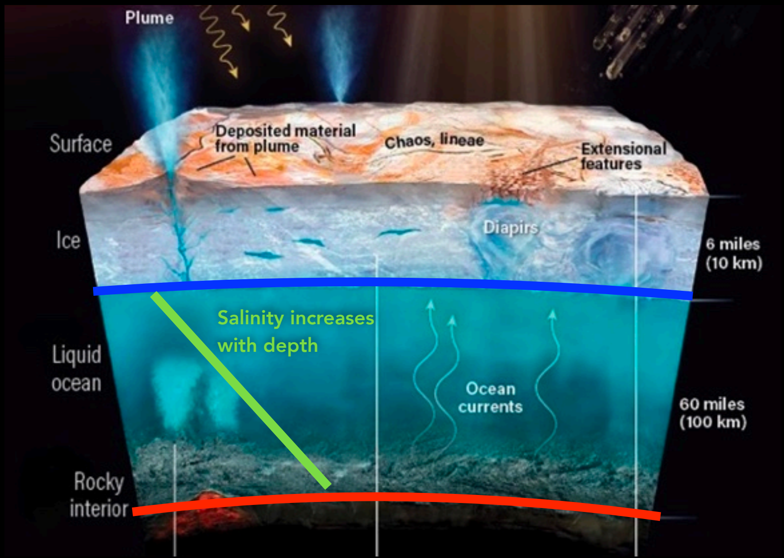


Credit: Zeng & Jansen (2021)

Temperature and salinity diffuse at different rates, which could lead to double-diffusive convection.



Credit: NASA/JPL-Caltech

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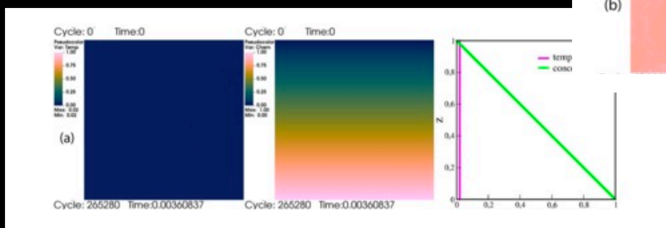
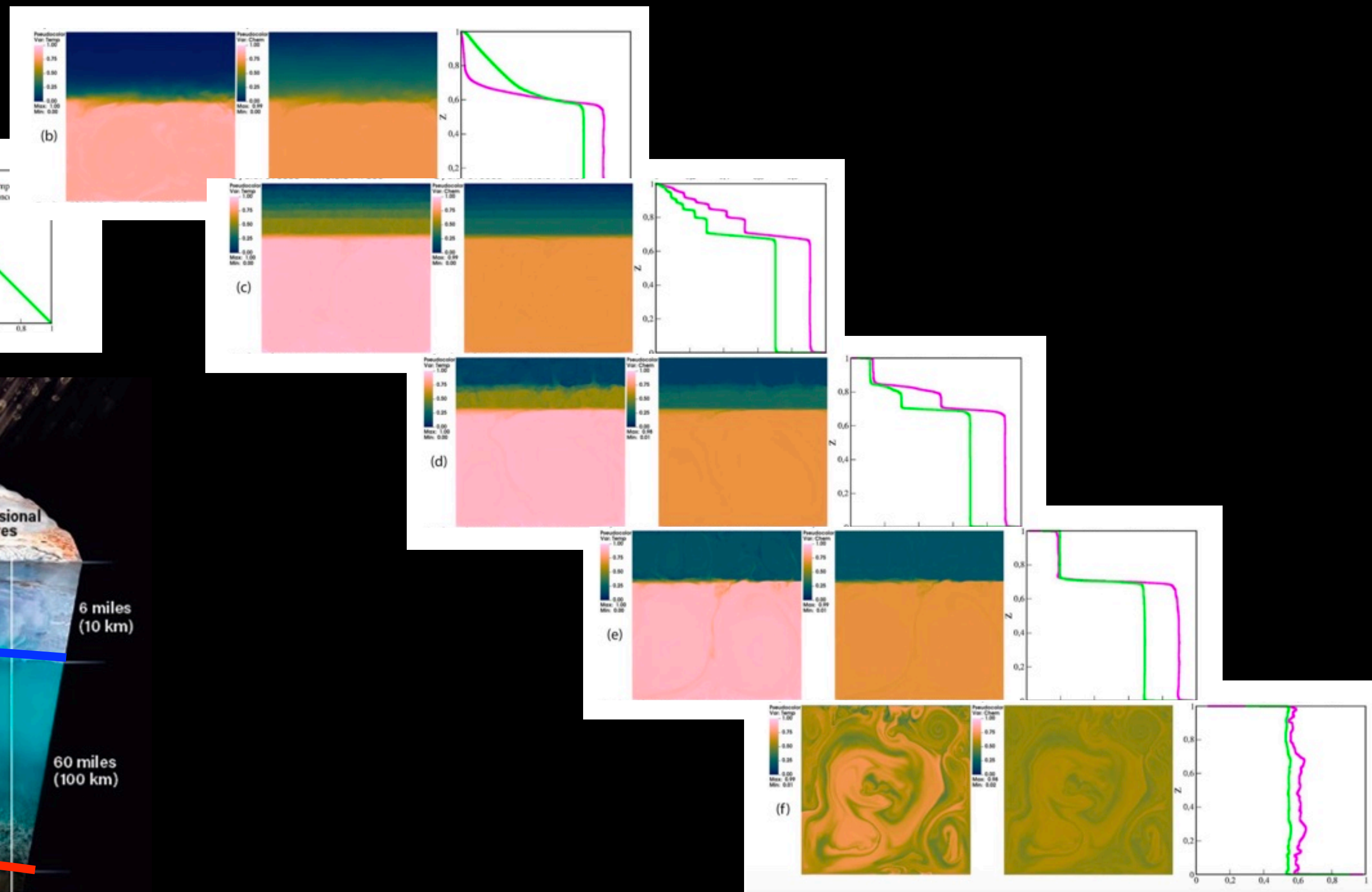
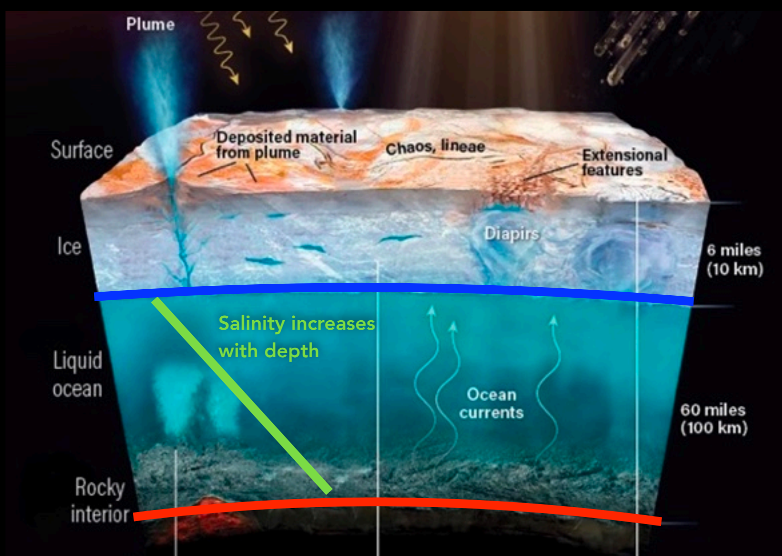


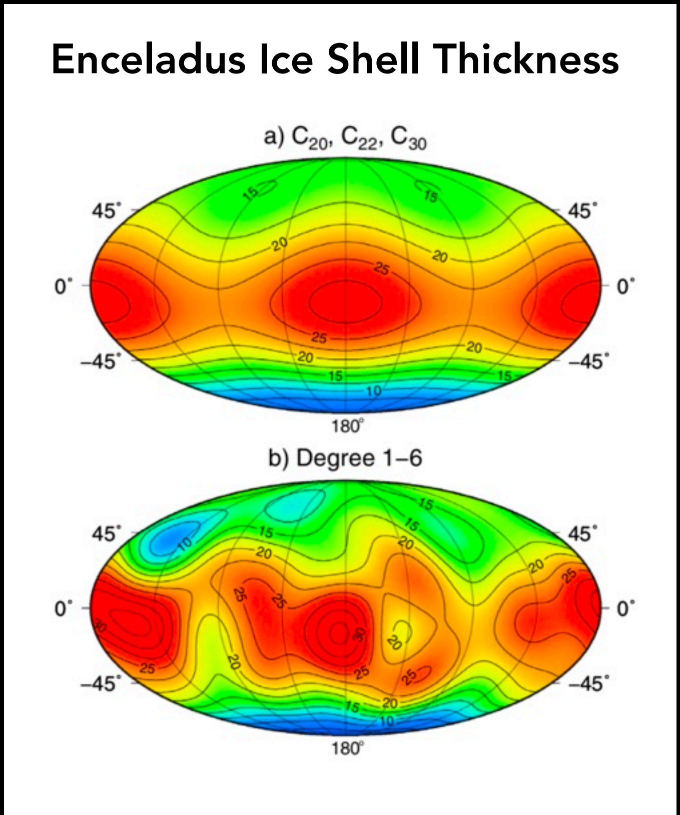




Credit: NASA/JPL-Caltech

Credit: Wong et al. (2022)

Ice shell thickness variations, and associated melting and freezing gradients assuming the ice shell is in steady-state, may drive overturning circulation.



Credit: Čadek et al. (2019)

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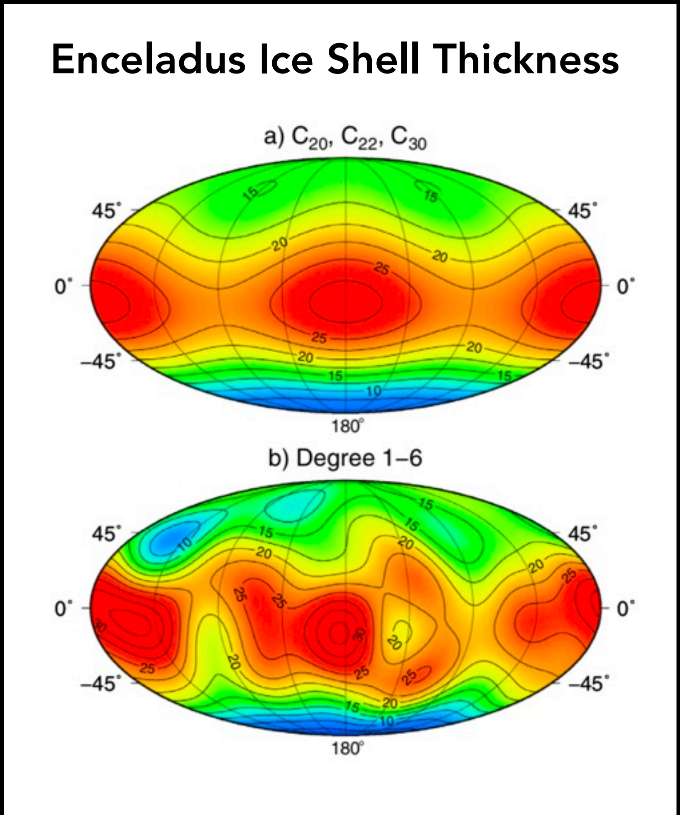
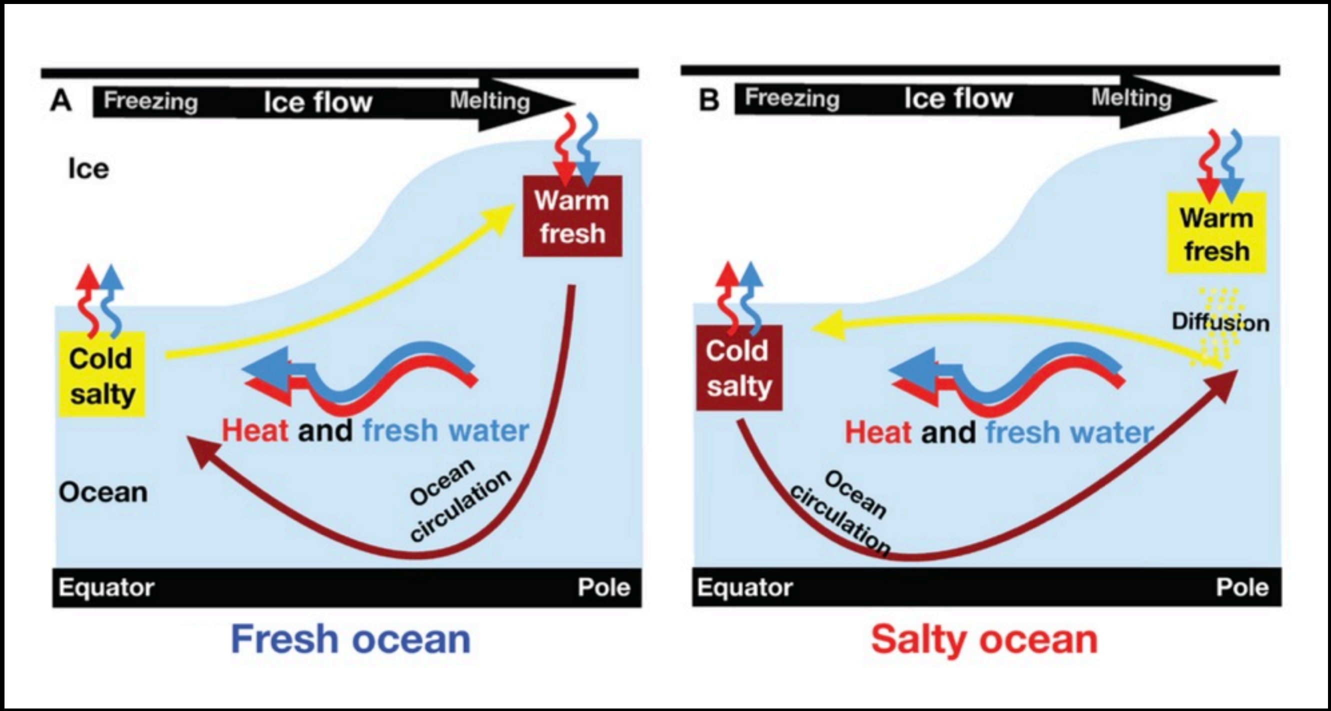
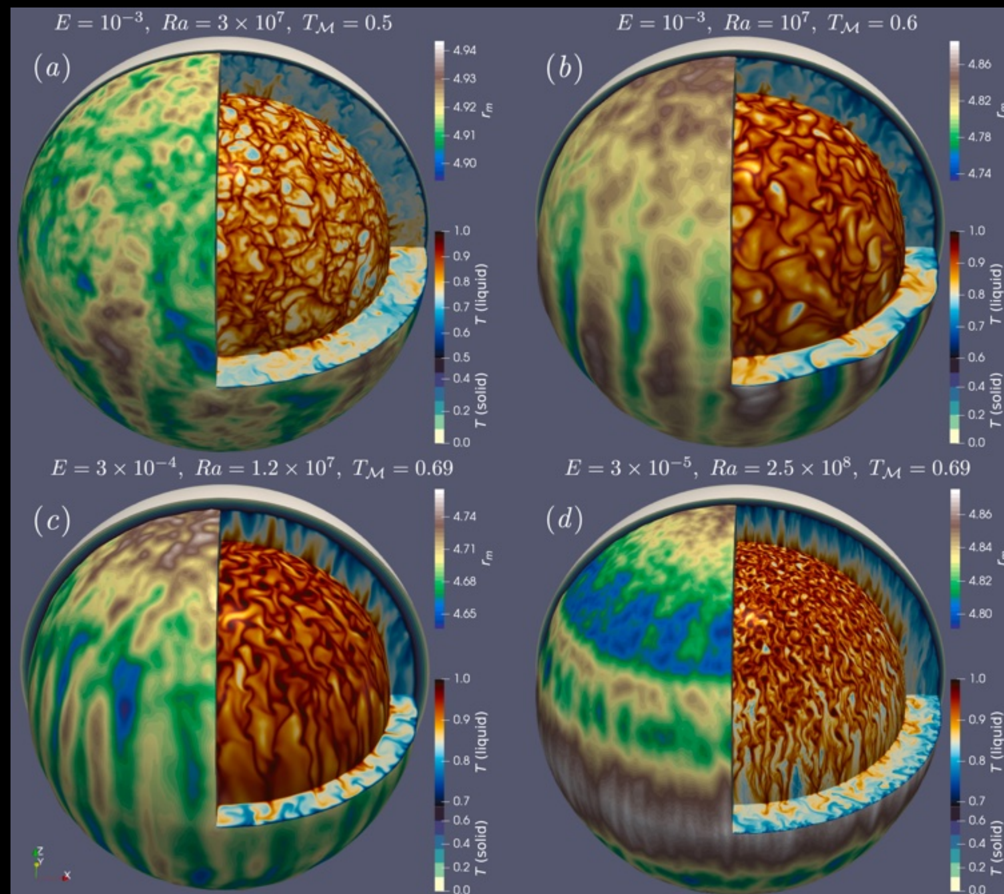




Credit: Čadek et al. (2019)

Credit: Kang et al. (2022)

In new phase-field thermal convection models, mean axisymmetric ice crust transits from pole-ward thinning to equator-ward thinning with the increase of the rotational constraint on the flow.

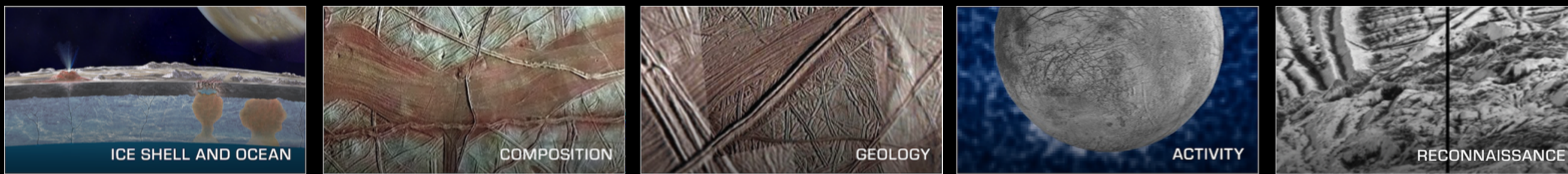


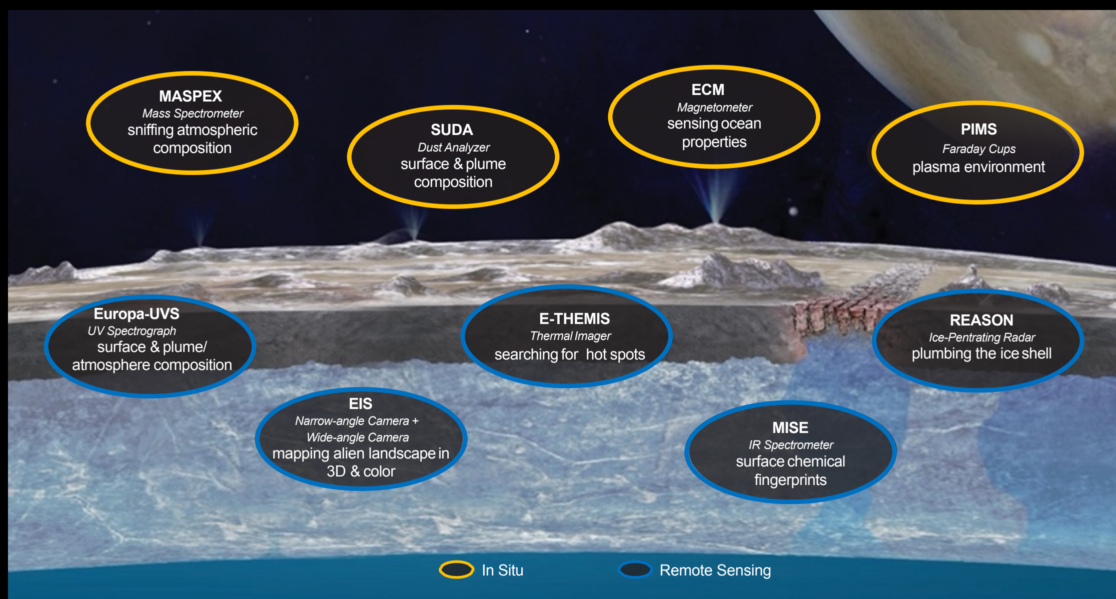
Credit: Gastine and Favier (2025)

Outline

1) Introduction to Icy Ocean Worlds
2) Drivers of Fluid Motions in Icy Ocean Worlds
3) Governing Equations and Common Approximations
4) Rotating Convection in Icy Ocean Worlds
5) Testing Oceanographic Hypotheses
6) Conclusions

NASA's *Europa Clipper* mission will explore Europa and assess its habitability

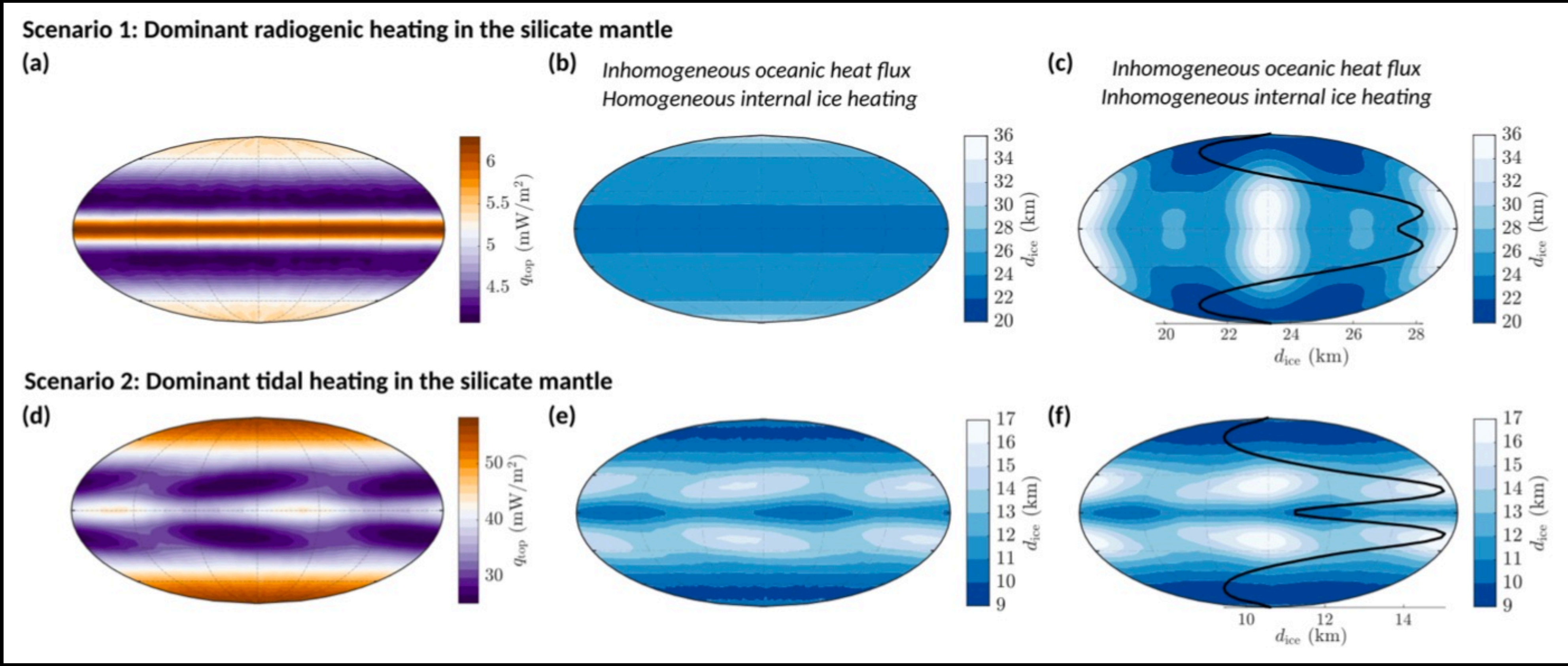




Gravity/Radio Science
internal structure

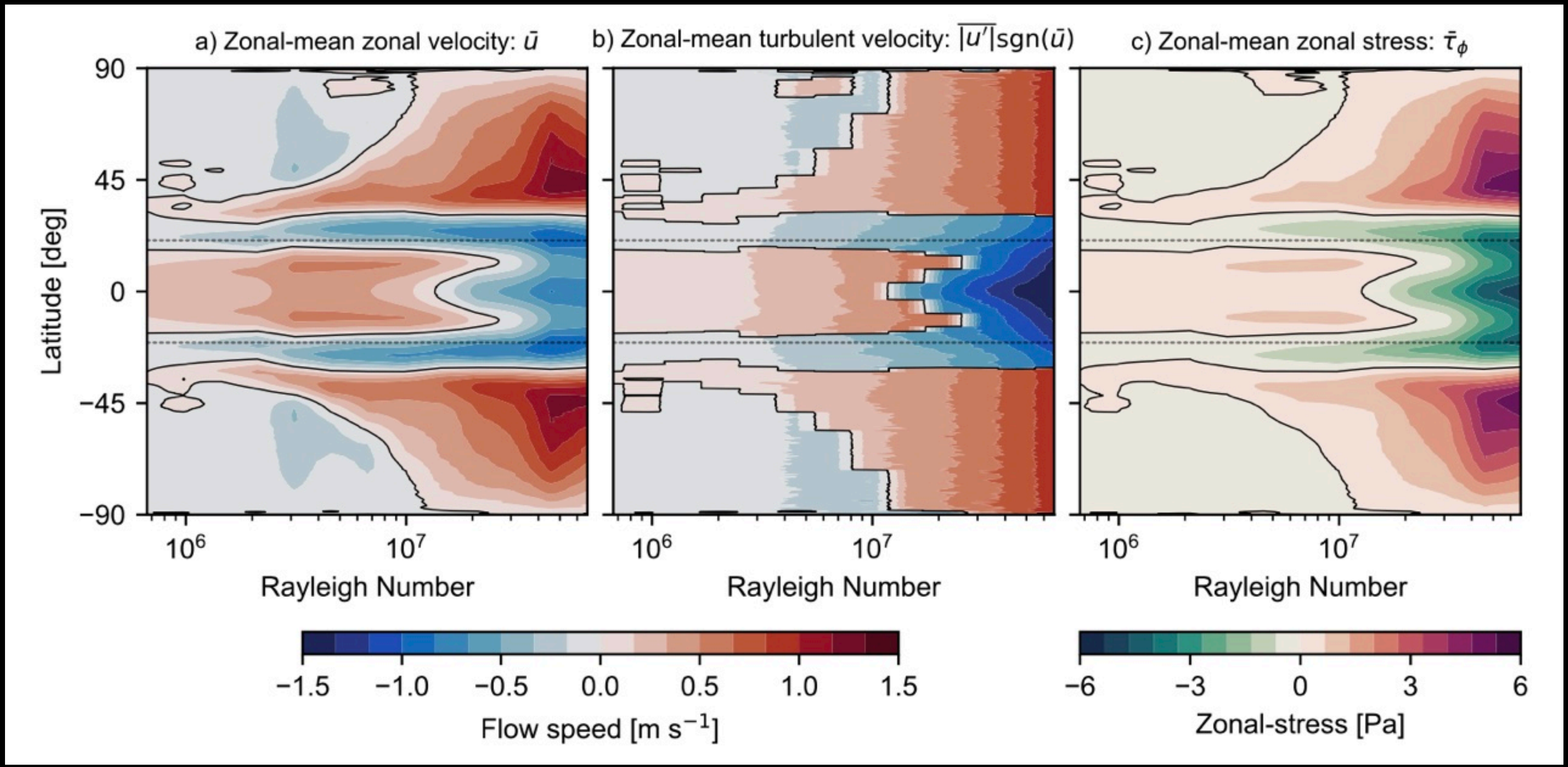
Credit: NASA/JPL-Caltech

Ice shell thickness variations may be used to constrain the pattern of mantle heating



Credit: Lemasquerier et al. (2024)

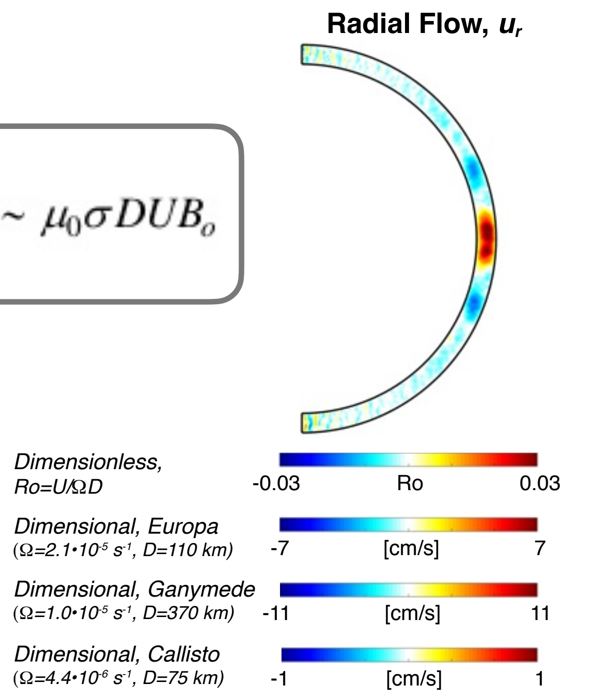
Non-synchronous rotation may be driven by torques on the ice shell due to zonal jets in the ocean



Credit: Hay et al. (2023)

Motionally-induced magnetic fields may result from circulation of salty water in presence of background magnetic field

$$b \sim \mu_0 \sigma D U B_o$$



	σ [S/m]	D [km]	b_r [nT]
Europa			
$MgSO_4$ 1 wt%, Thicker ice shell	0.4	91	1
$MgSO_4$ 1 wt%, Thinner ice shell	0.5	117	2
$MgSO_4$ 10 wt%, Thicker ice shell	3.4	96	10
$MgSO_4$ 10 wt%, Thinner ice shell	3.8	124	20
Seawater 0.35 wt%, Thicker ice shell	0.4	91	1
Seawater 0.35 wt%, Thinner ice shell	0.4	117	2
Seawater 3.5 wt%, Thicker ice shell	2.9	91	8
Seawater 3.5 wt%, Thinner ice shell	3.1	119	14
Ganymede			
$MgSO_4$ 1 wt%, Thicker ice shell	0.3	276	8
$MgSO_4$ 1 wt%, Thinner ice shell	0.5	442	36
$MgSO_4$ 10 wt%, Thicker ice shell	2.3	282	65
$MgSO_4$ 10 wt%, Thinner ice shell	4.1	458	330

Credit: Vance et al. (2021)

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Summary

- Planetary oceans are a natural laboratory for studying physical oceanographic processes in settings that challenge traditional assumptions made for Earth.

- Ice-covered oceans in the outer solar system are rich dynamical systems with flows excited and modulated by buoyancy, tides, libration, precession, and electromagnetic pumping. Each driving mechanism is inherently complex and has its own permutations, so few studies have yet crossed these artificial boundaries.

- Work aimed at understanding the interactions among these different types of flows is necessary to understand ocean dynamics and to interpret data returned by future missions (e.g., *Europa Clipper*, *Dragonfly*, *Uranus Orbiter and Probe*, *Enceladus Orbilander)*, which will reflect all driving mechanisms in aggregate.

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