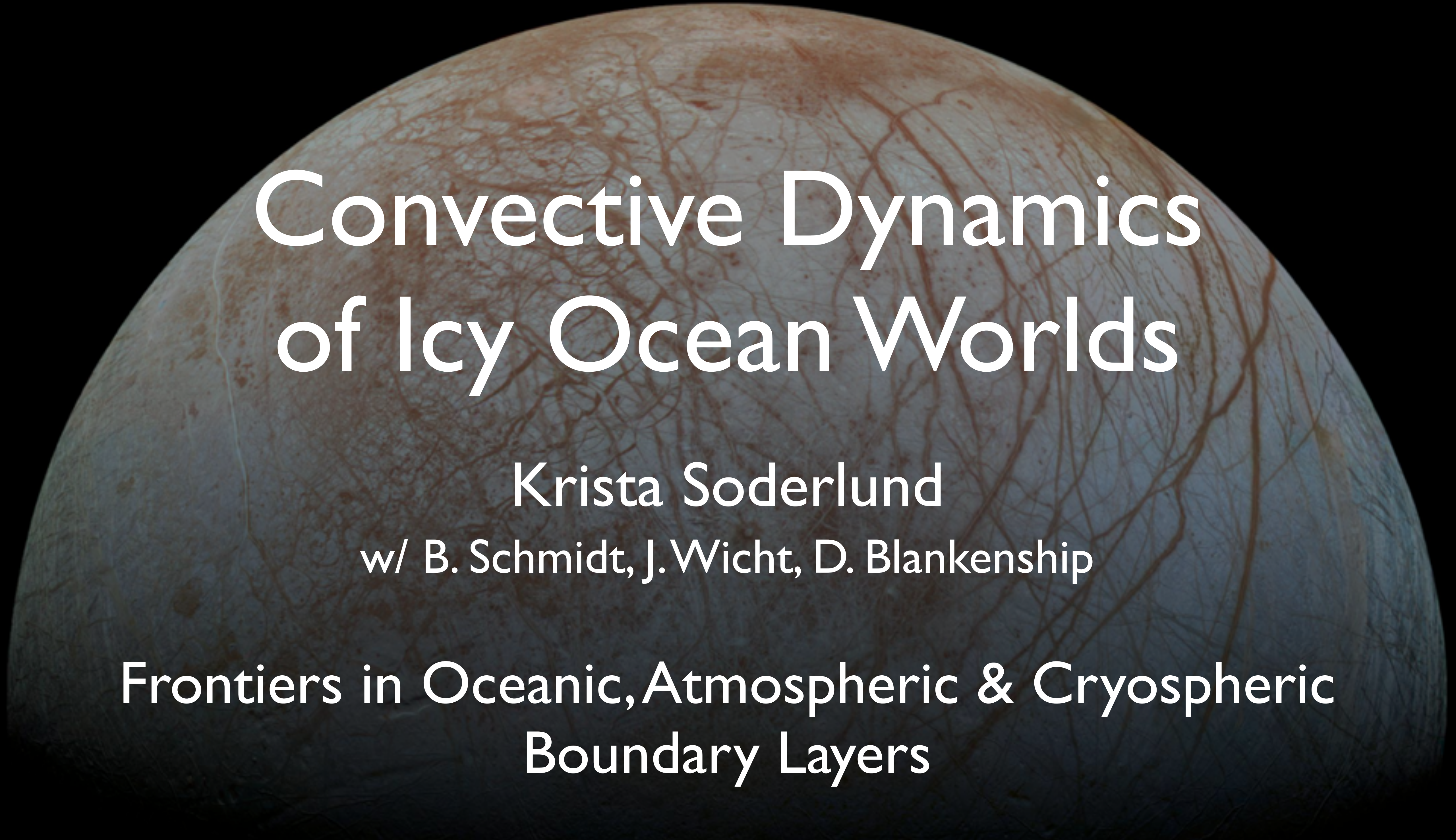


Convective Dynamics of Icy Ocean Worlds

Krista Soderlund
w/ B. Schmidt, J. Wicht, D. Blankenship

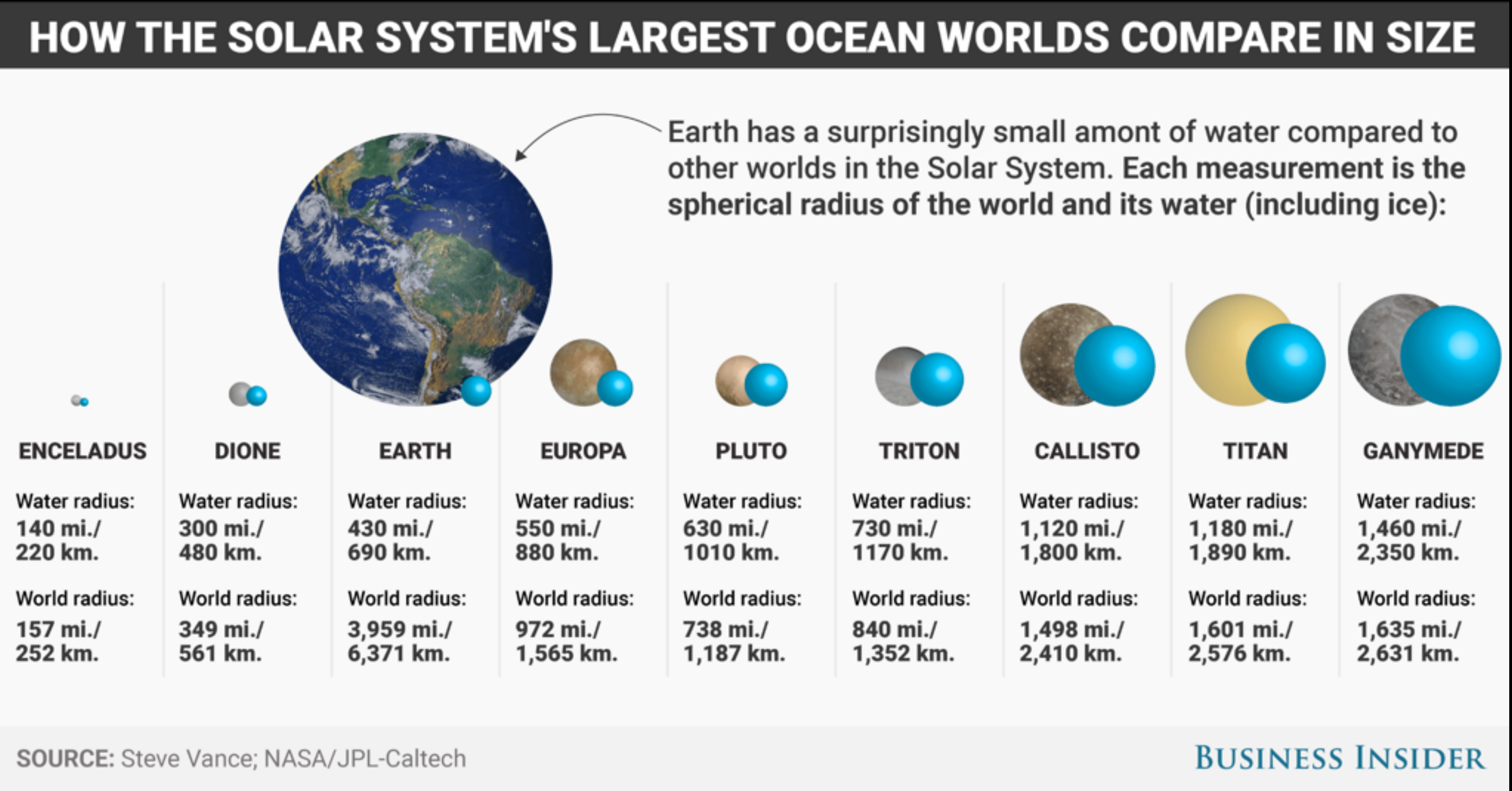
Frontiers in Oceanic, Atmospheric & Cryospheric Boundary Layers

21 May 2018

INSTITUTE FOR GEOPHYSICS
THE UNIVERSITY OF TEXAS AT AUSTIN

Habitability of Ocean Worlds

- Ocean worlds are exciting prospects for habitability



HOW THE SOLAR SYSTEM'S LARGEST OCEAN WORLDS COMPARE IN SIZE

Earth has a surprisingly small amont of water compared to other worlds in the Solar System. **Each measurement is the spherical radius of the world and its water (including ice):**

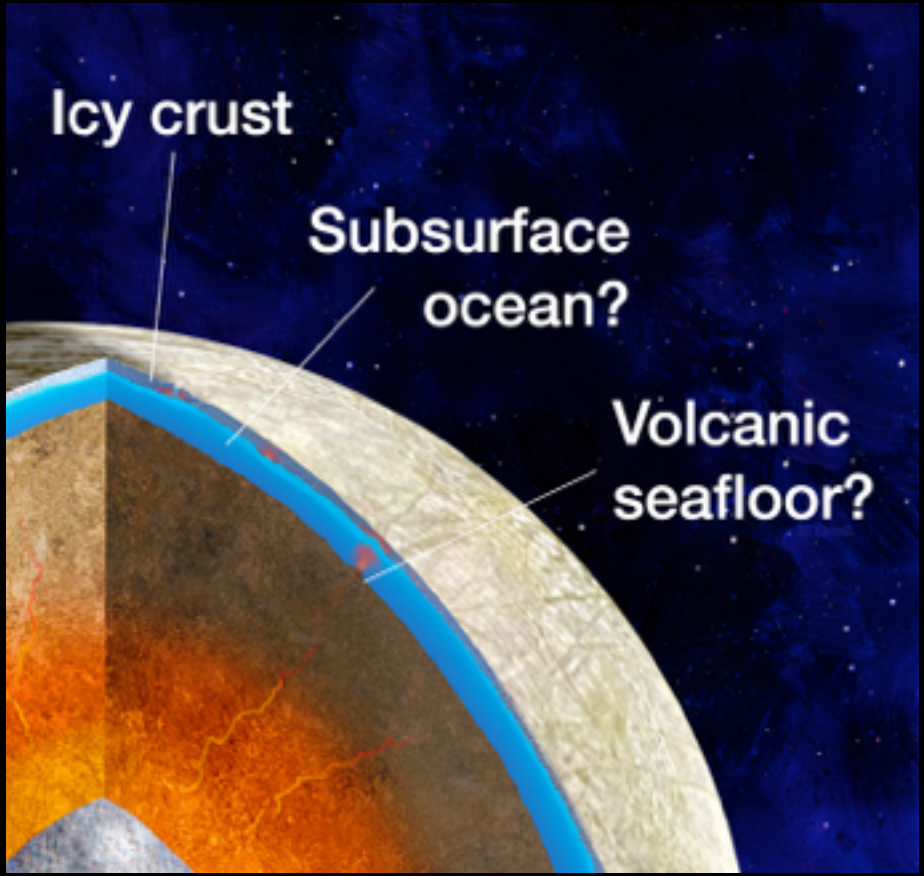
	Water radius:	World radius:
ENCELADUS	**140 mi./ 220 km.**	**157 mi./ 252 km.**
DIONE	**300 mi./ 480 km.**	**349 mi./ 561 km.**
EARTH	**430 mi./ 690 km.**	**3,959 mi./ 6,371 km.**
EUROPA	**550 mi./ 880 km.**	**972 mi./ 1,565 km.**
PLUTO	**630 mi./ 1010 km.**	**738 mi./ 1,187 km.**
TRITON	**730 mi./ 1170 km.**	**840 mi./ 1,352 km.**
CALLISTO	**1,120 mi./ 1,800 km.**	**1,498 mi./ 2,410 km.**
TITAN	**1,180 mi./ 1,890 km.**	**1,601 mi./ 2,576 km.**
GANYMEDE	**1,460 mi./ 2,350 km.**	**1,635 mi./ 2,631 km.**

SOURCE: Steve Vance; NASA/JPL-Caltech

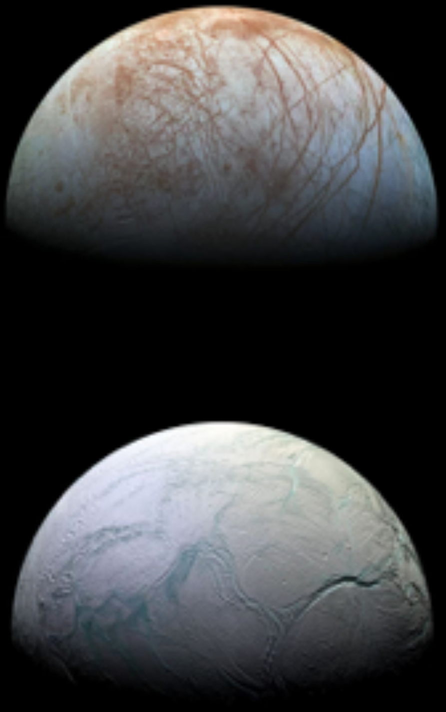
BUSINESS INSIDER

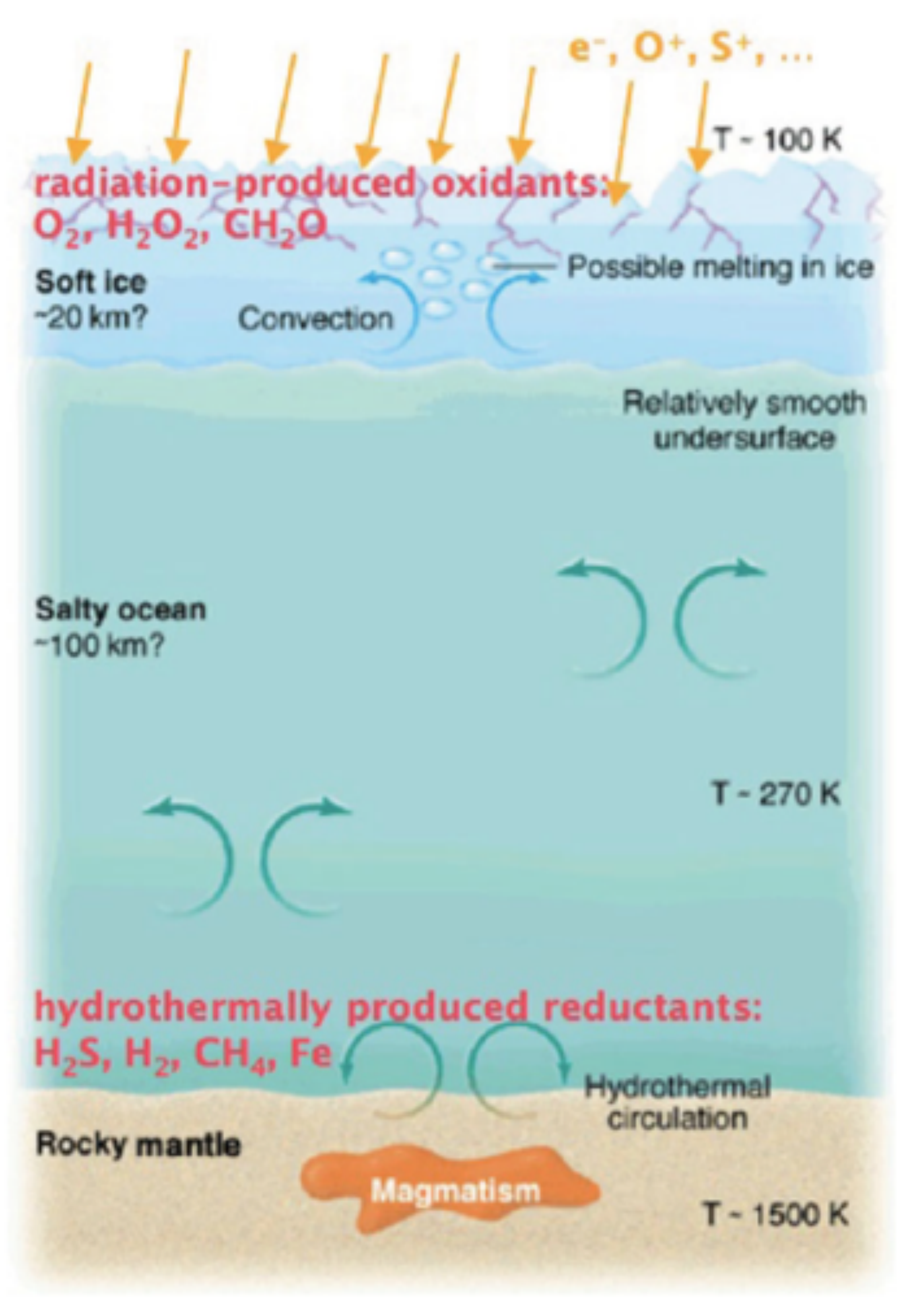
Habitability of Ocean Worlds

- Oxidants are produced on the surface by ion irradiation
- Reductants might be produced at the seafloor if hydrothermal circulation is present



Credit: NASA

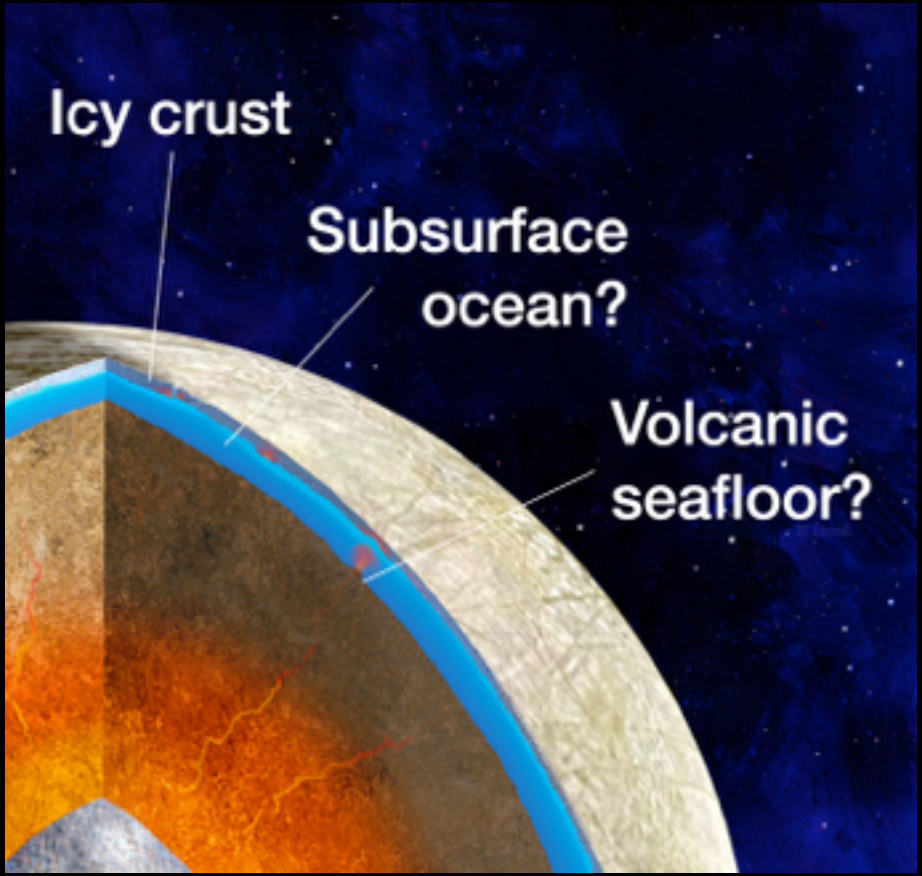




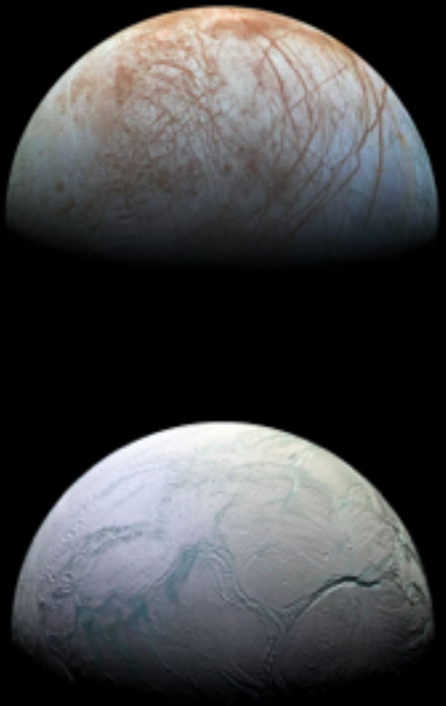
Credit: Pappalardo (2010), after Stevenson (2000)

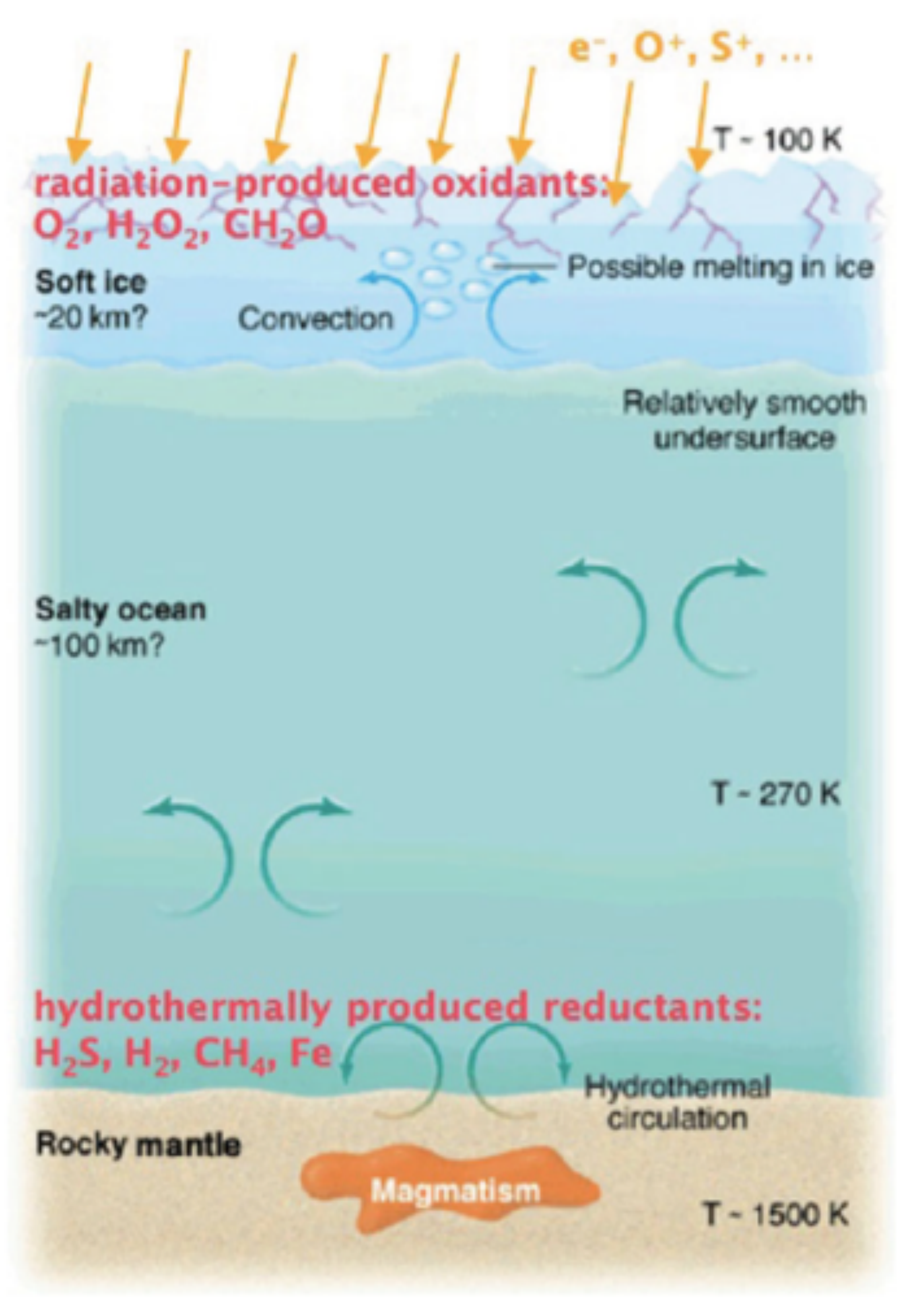
Habitability of Ocean Worlds

- ➡ How are heat and materials transported across the oceans of icy satellites?



Credit: NASA





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

Outline

1) Theoretical Predictions for Convection
2) Numerical Convection Models
3) Boundary Layer Implications
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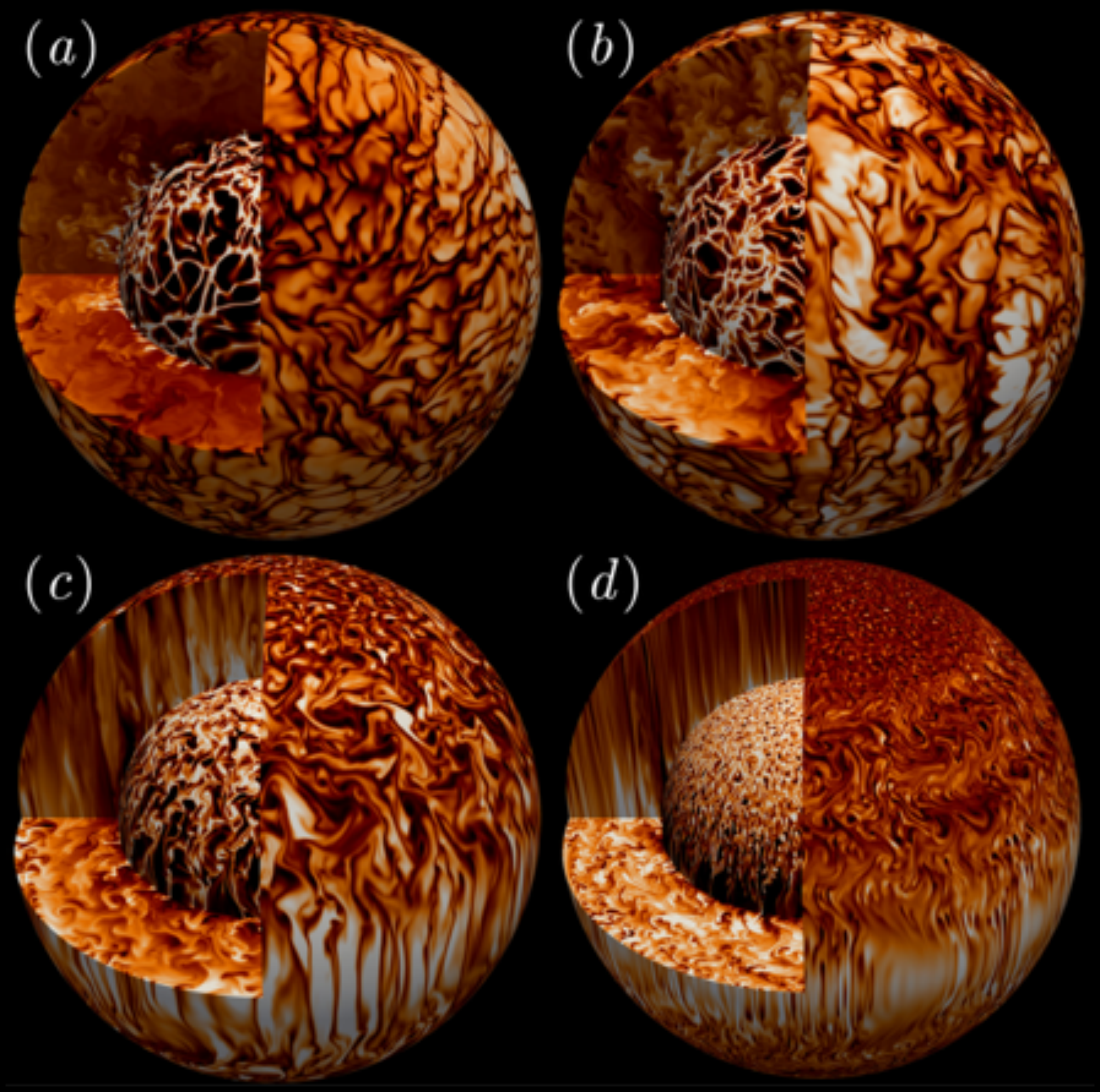
Influence of Rotation

- Diversity of dynamical regimes in rotating spherical shell Rayleigh-Bénard convection



- Temperature fluctuations (Gastine et al. 2016)

  (a) Non-rotating

  (b) Weak rotational influence

  (c) Moderate rotational influence

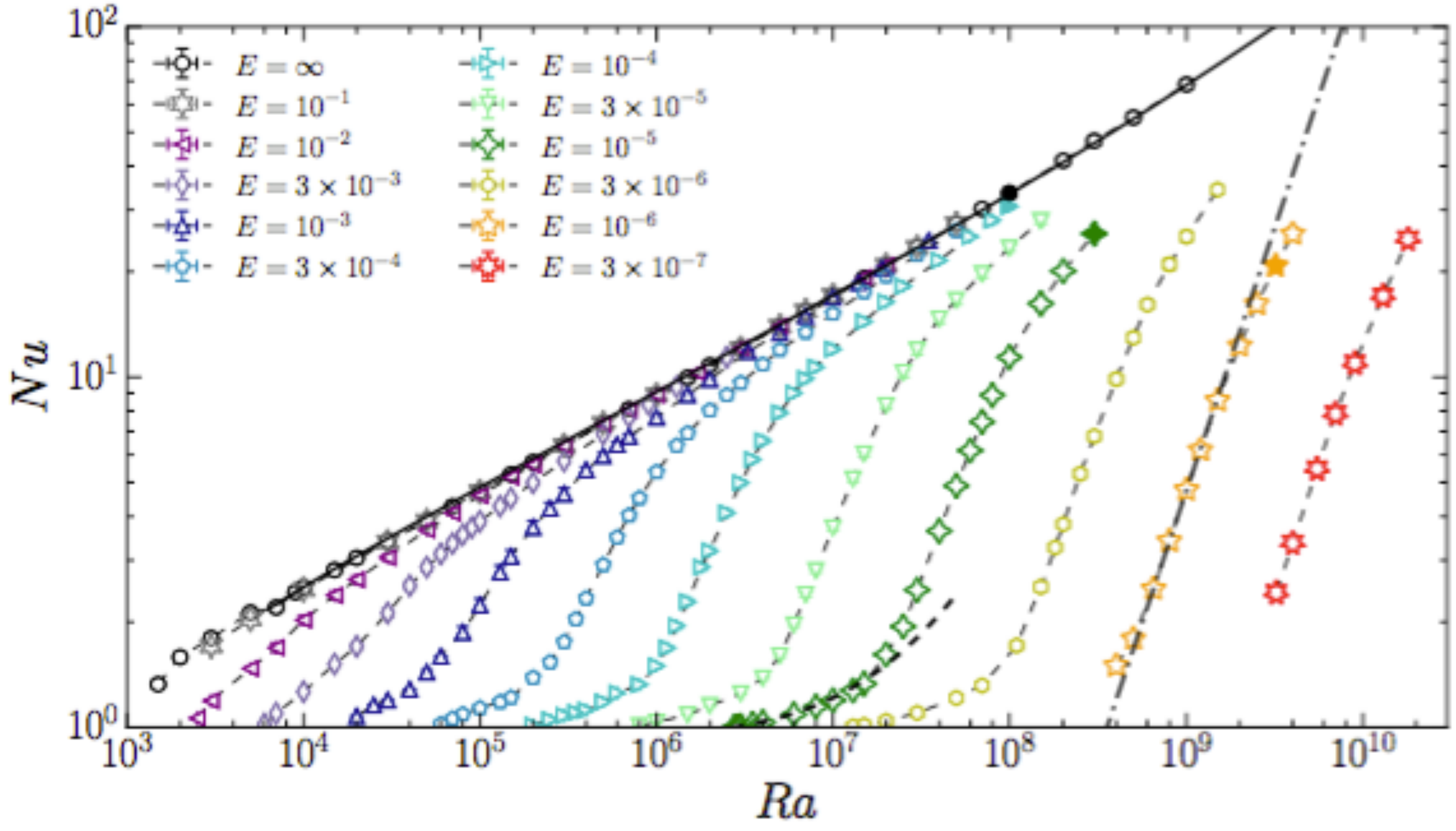
  (d) Stronger rotational influence

Convective Regimes

- Gastine et al. (2016): Extensive suite of rotating spherical shell RBC models to study scaling behaviors

Convective Regimes

- Gastine et al. (2016): Extensive suite of rotating spherical shell RBC models to study scaling behaviors
    - Heat transfer efficiency (*Nu*) as a function of thermal forcing (*Ra*) and rotation rate (*E*)



$$Nu = \frac{\text{Total heat flux}}{\text{Conductive heat flux}} = \frac{QD}{\rho C_p \kappa \Delta T}$$

$$Ra = \frac{\text{Buoyancy}}{\text{Diffusion}} = \frac{\alpha g_o \Delta T D^3}{\nu \kappa}$$

$$E = \frac{\text{Viscous force}}{\text{Coriolis force}} = \frac{\nu}{\Omega D^2}$$

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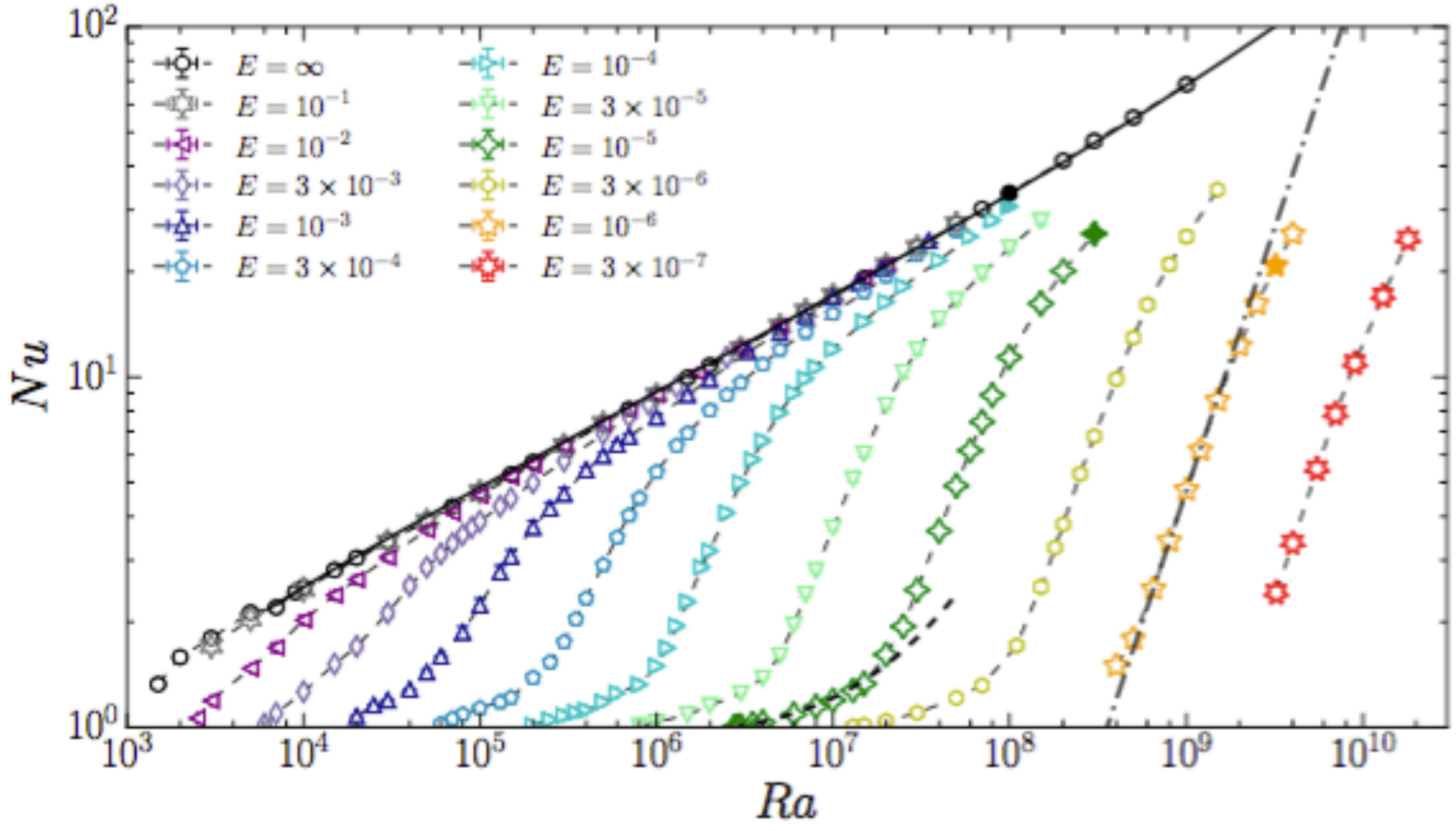

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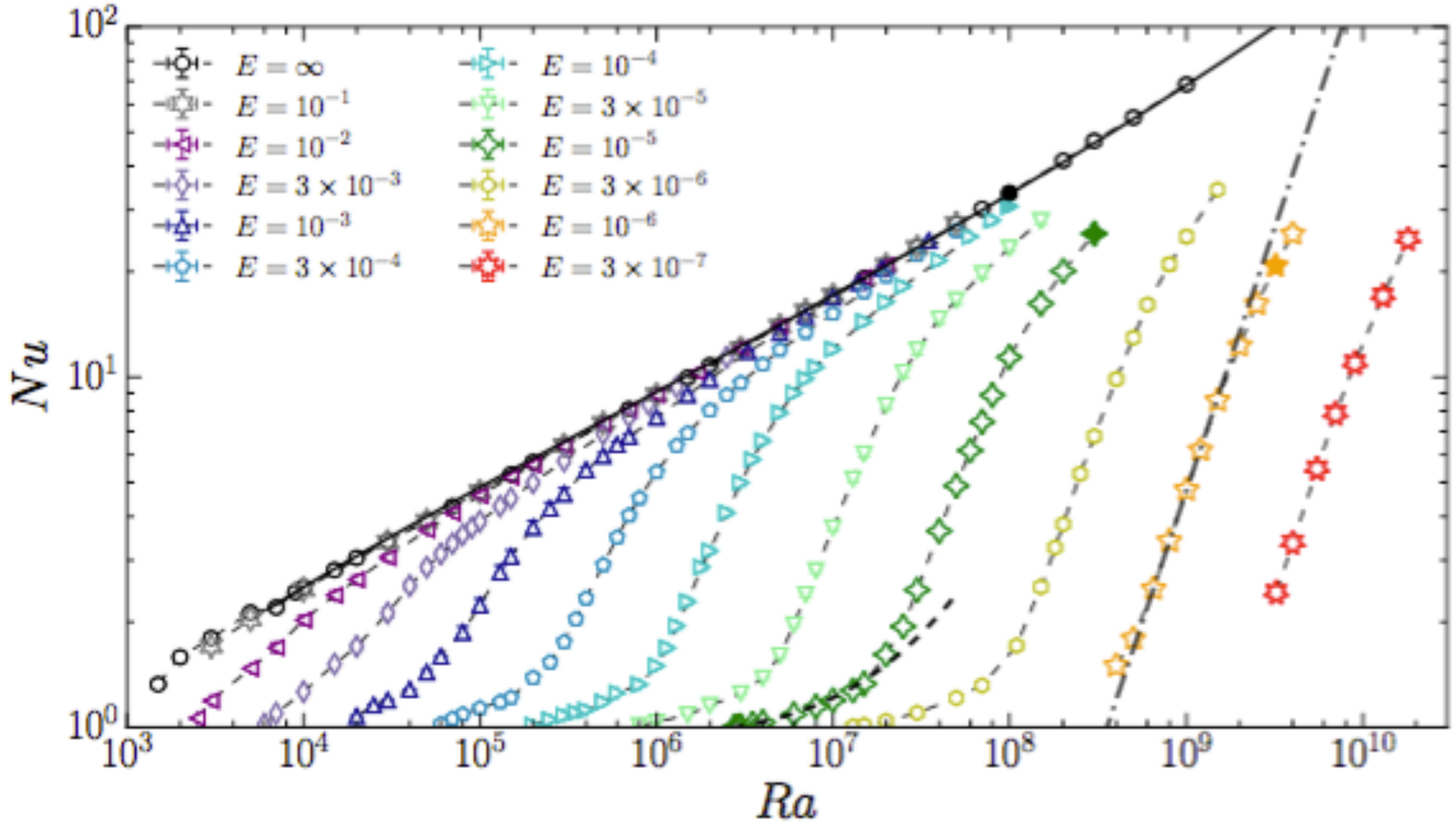

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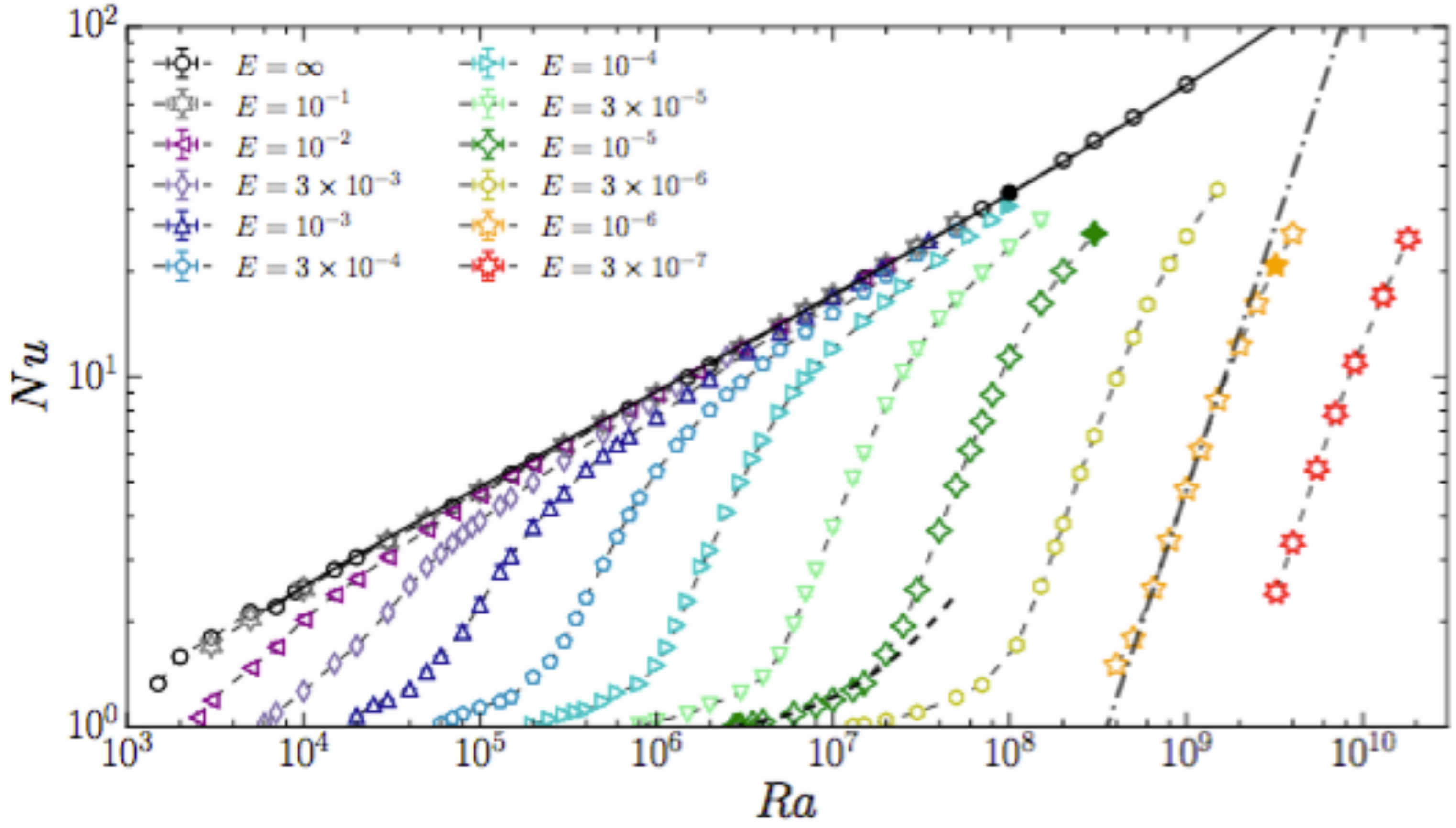

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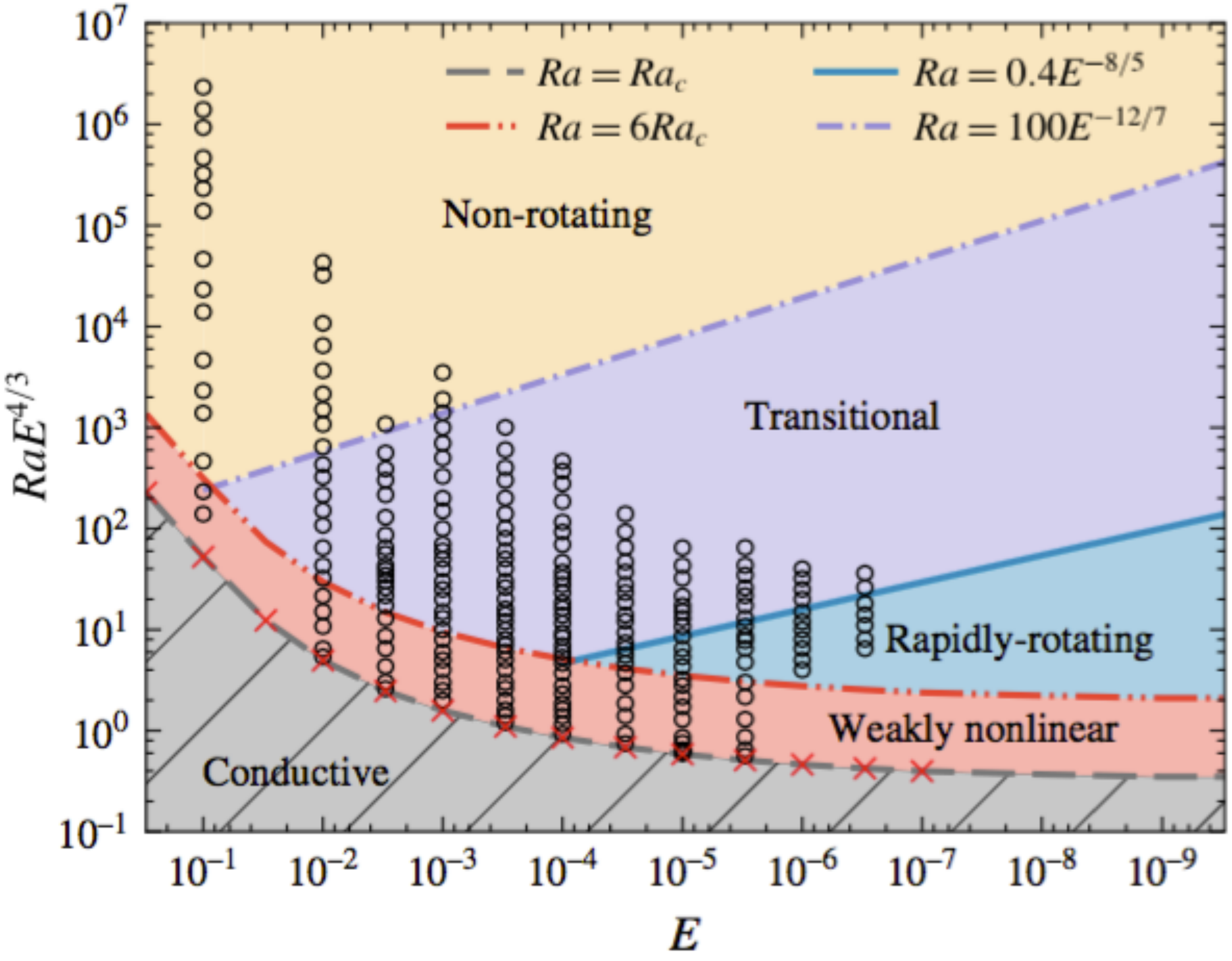
$$Nu = 0.15 Ra^{3/2} E^2$$

$$Nu = 0.07 Ra^{1/3}$$

Convective Regime Transitions

- Convective regimes and their predicted boundaries



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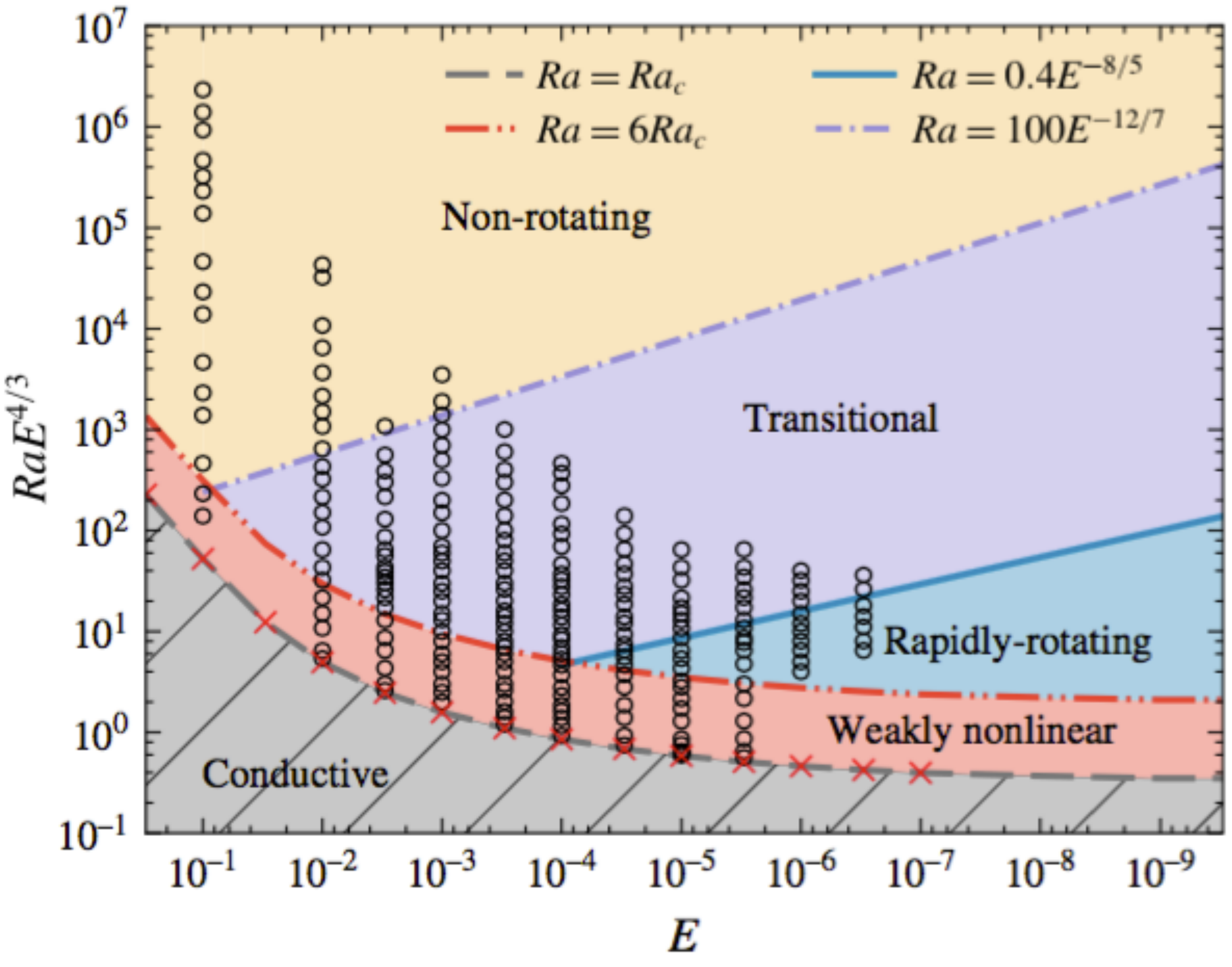

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Intersection between shallow and steep *Nu-Ra* scalings

Convective Rossby number of the thermal BL is less than unity (Julien et al. 2012)

Credit: Gastine et al. (2016)

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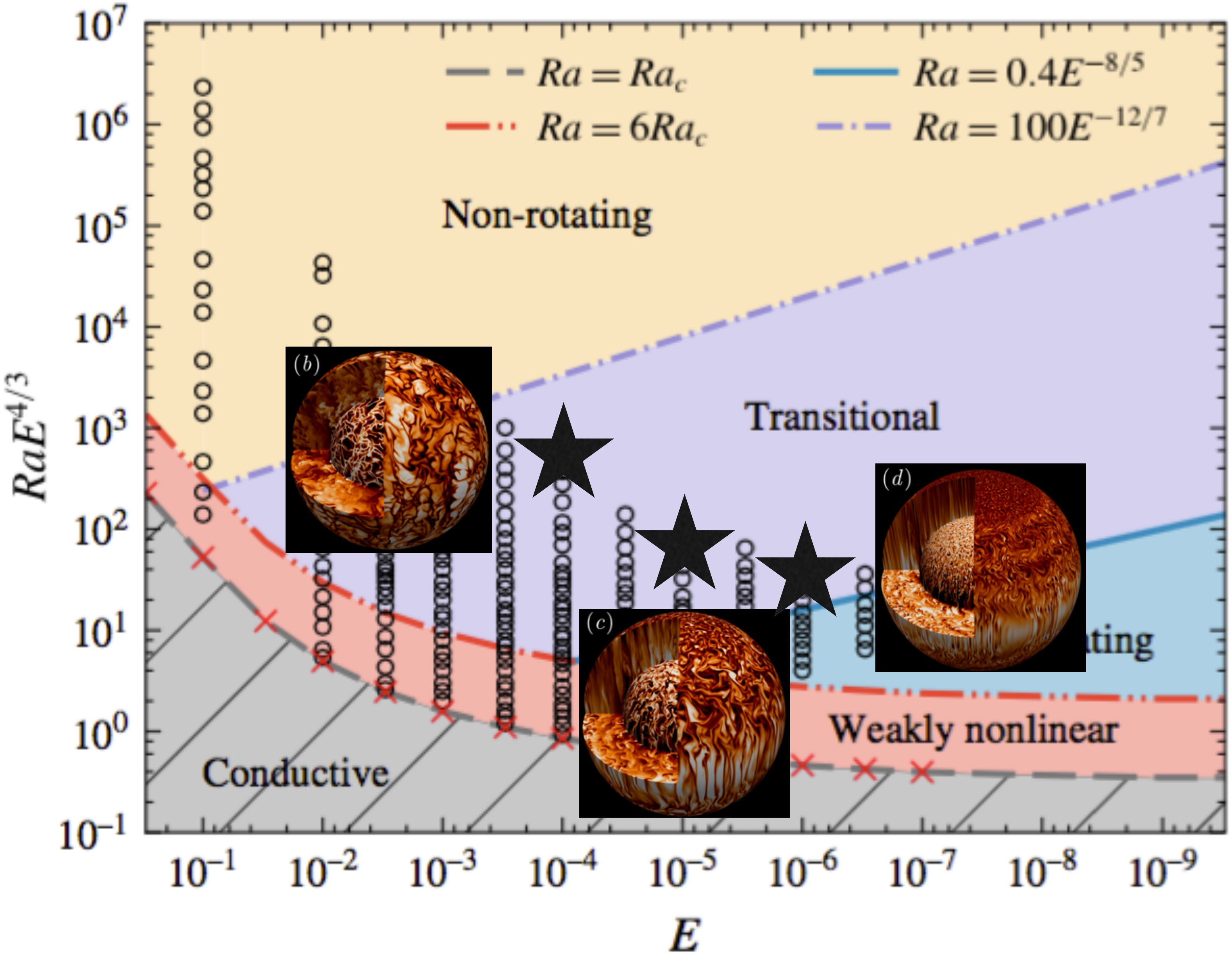

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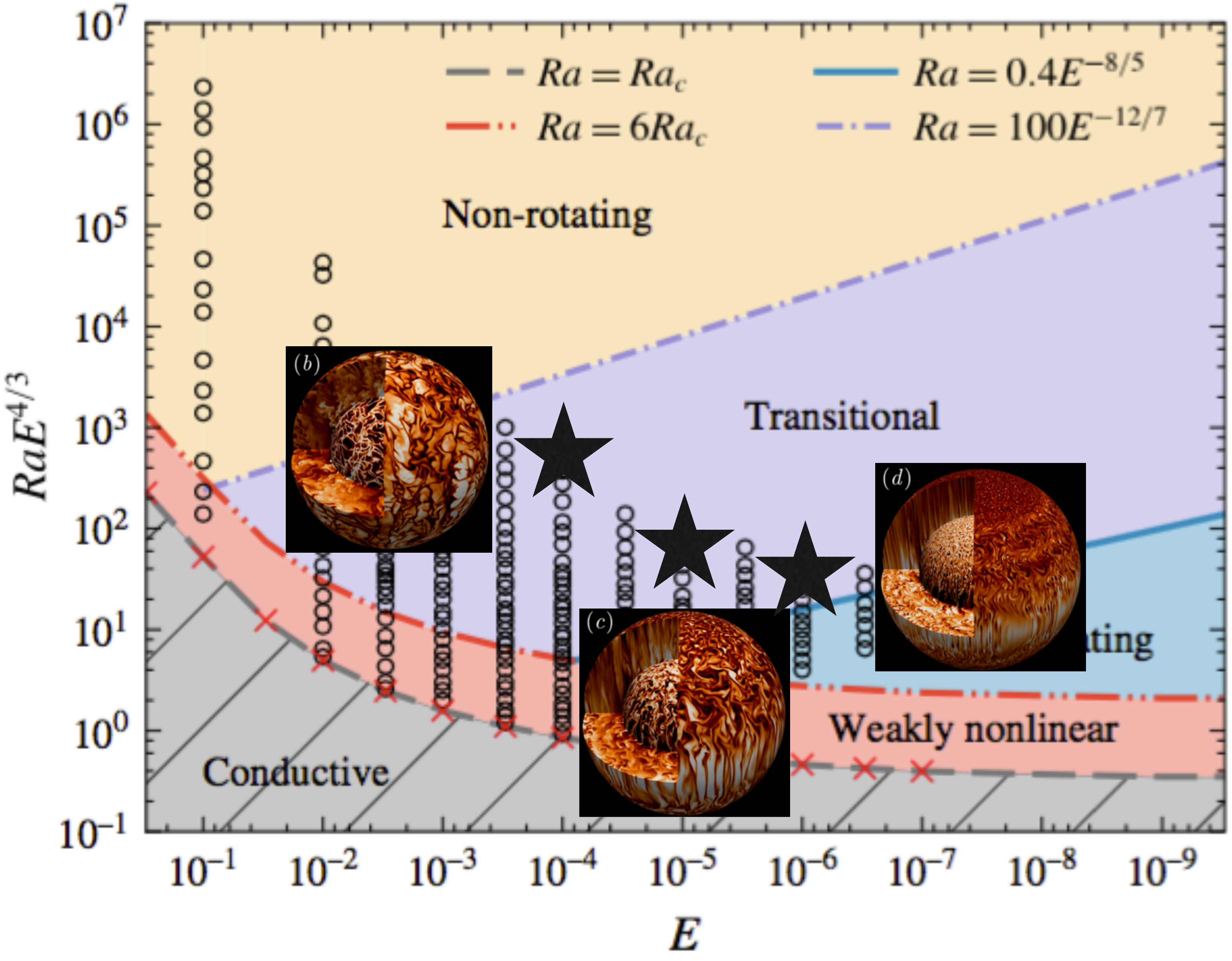
Convective Regime Predictions

- Application to icy ocean worlds



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Ekman number is easy to estimate

Credit: Gastine et al. (2016)

Convective Regime Predictions

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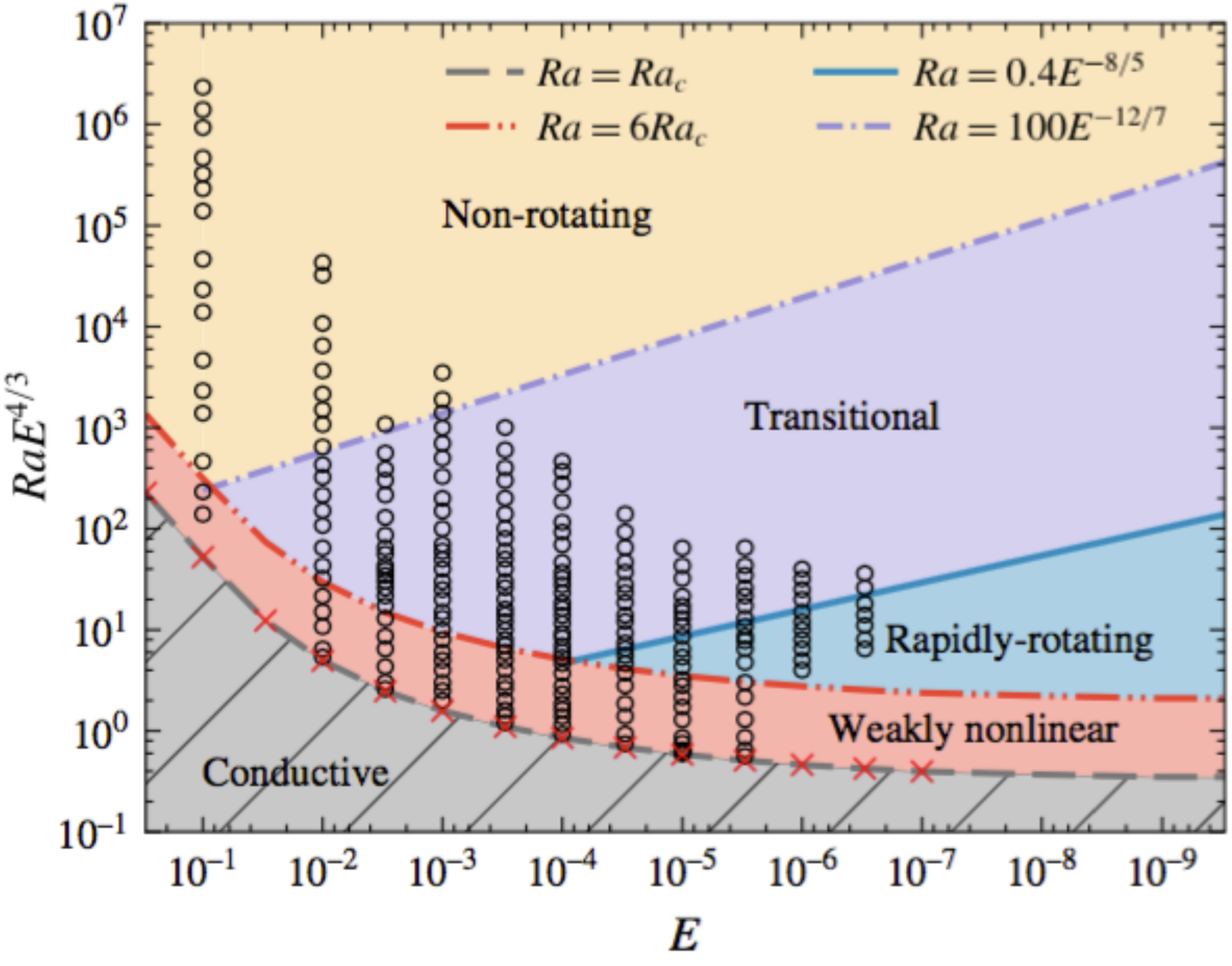


$$E = \frac{\text{Viscous force}}{\text{Coriolis force}} = \frac{\nu}{\Omega D^2}$$

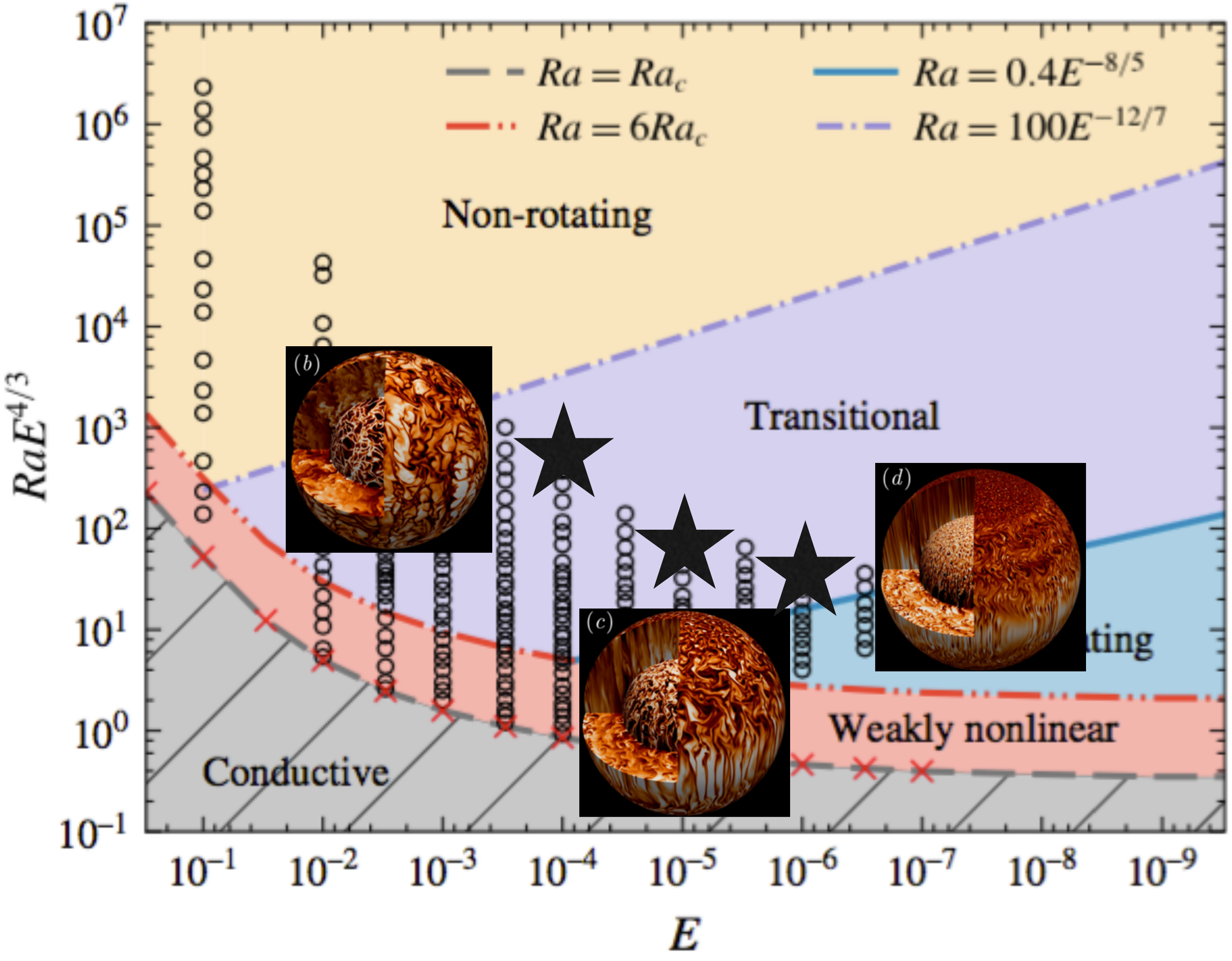
$$\boxed{Ra = \frac{\text{Buoyancy}}{\text{Diffusion}} = \frac{\alpha g_o \Delta T D^3}{\nu \kappa}}$$

Rayleigh number is harder to estimate

Credit: Gastine et al. (2016)

Convective Regime Predictions

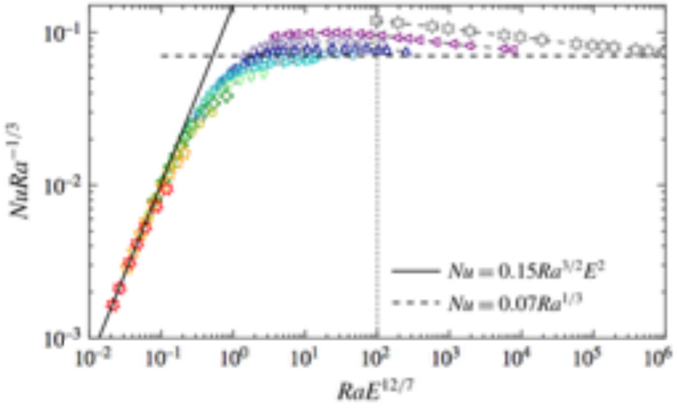
- Application to icy ocean worlds



$$E = \frac{\text{Viscous force}}{\text{Coriolis force}} = \frac{\nu}{\Omega D^2}$$

$$\boxed{\begin{aligned} Ra &= \frac{\text{Buoyancy}}{\text{Diffusion}} = \frac{\alpha g_o \Delta T D^3}{\nu\kappa} \\ Nu &= \frac{\text{Total heat flux}}{\text{Conductive heat flux}} = \frac{QD}{\rho C_p \kappa \Delta T} \end{aligned}}$$

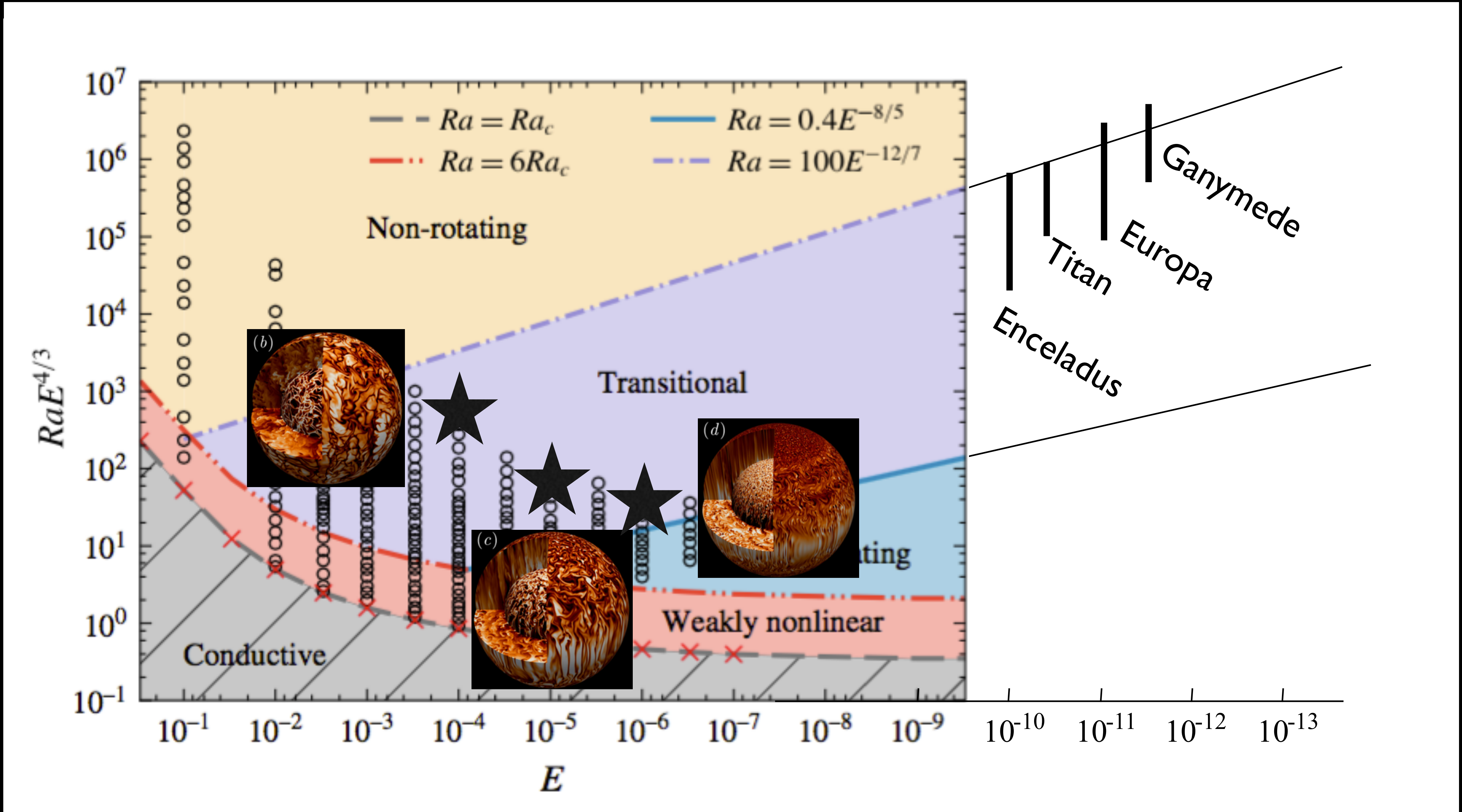
Rayleigh number is harder to estimate, use *Nu-Ra* scalings



Credit: Gastine et al. (2016)

Convective Regime Predictions

- Weak rotational influence predicted for their oceans



Credit: Gastine et al. (2016)

Outline

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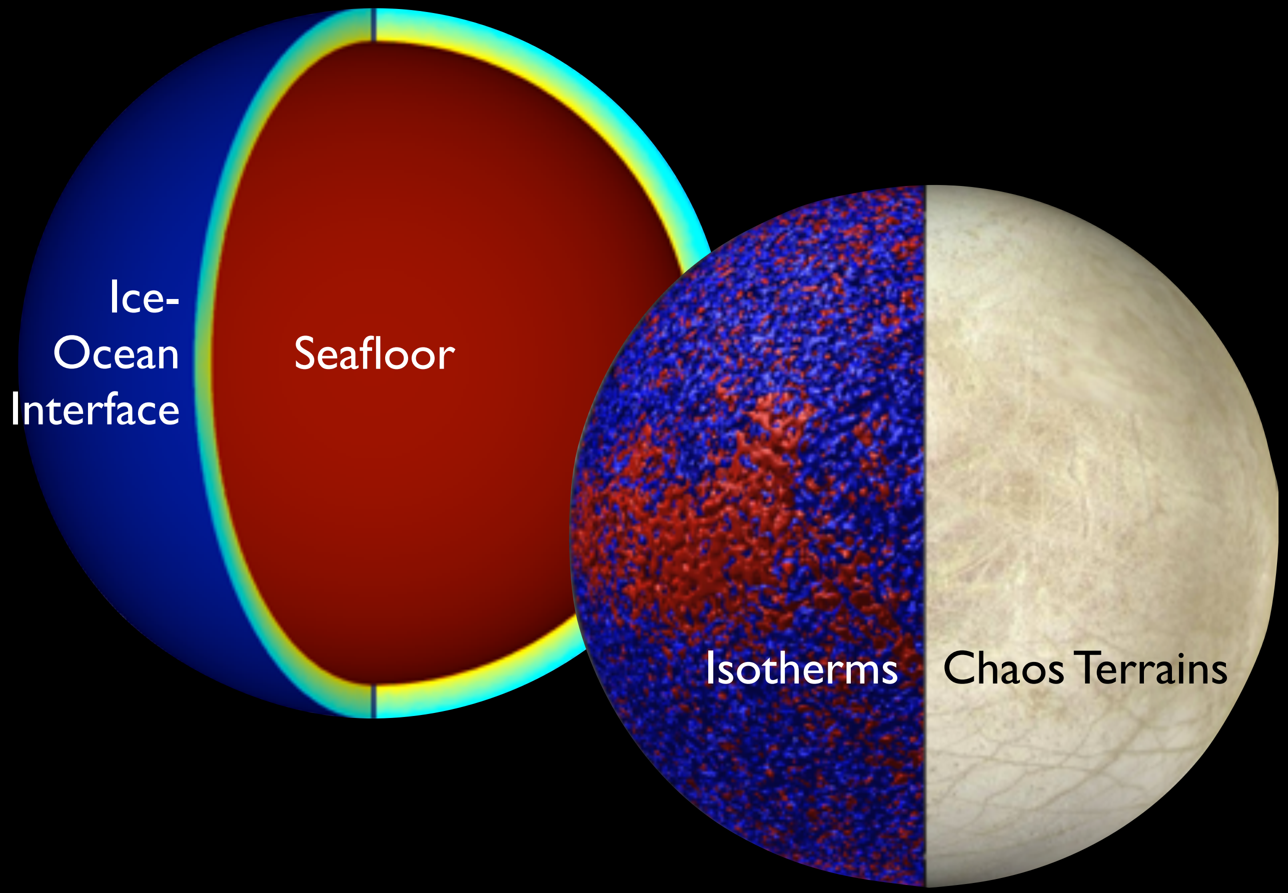
Motivation

- Numerical models of global ocean convection

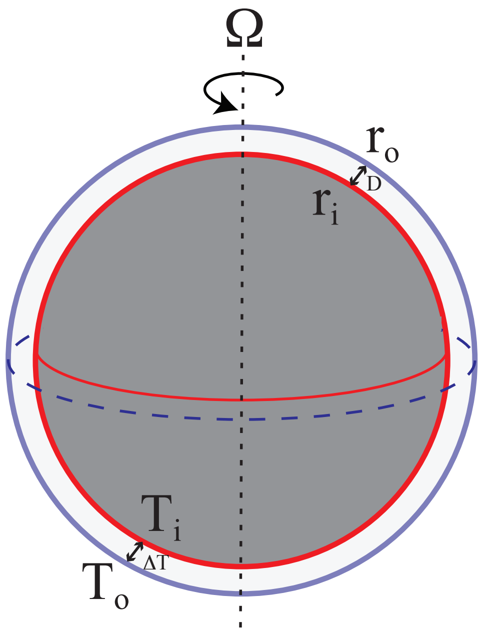


➡ How does the mantle influence the ocean?

➡ How does the ocean influence the ice shell?

Numerical Model: MagIC

- Numerical models of global ocean convection
  - Boussinesq thermal convection in a rotating spherical shell (ocean tides and salinity gradients are not considered)

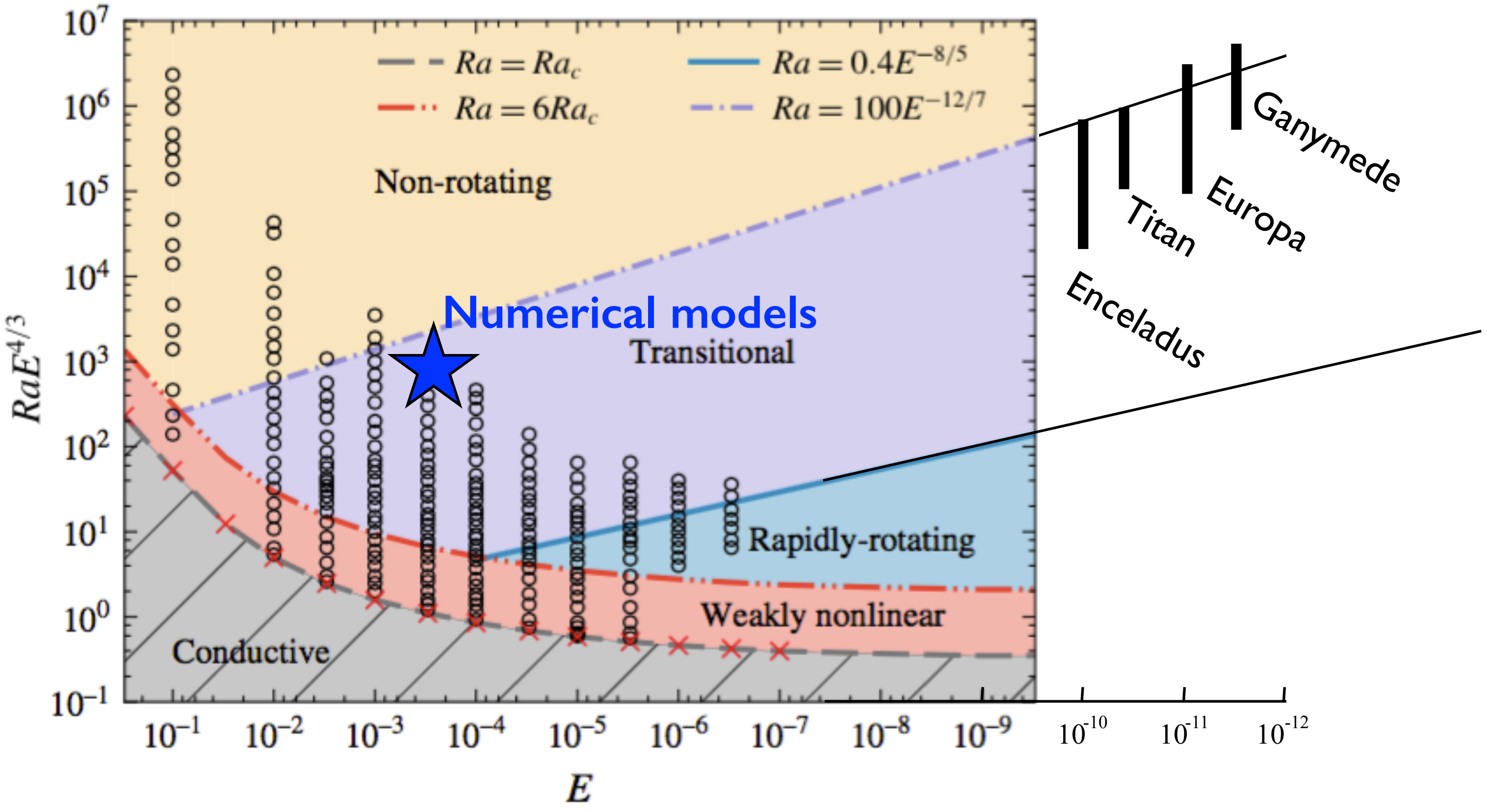


$$E\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} - \nabla^2\mathbf{u}\right) + \hat{\mathbf{z}}\times\mathbf{u} + \frac{1}{2}\nabla\Pi = \frac{RaE}{Pr}\frac{\mathbf{r}}{r_o}T$$

$$\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T = \frac{1}{Pr}\nabla^2 T \qquad \nabla\cdot\mathbf{u} = 0$$

Numerical Model: MagIC

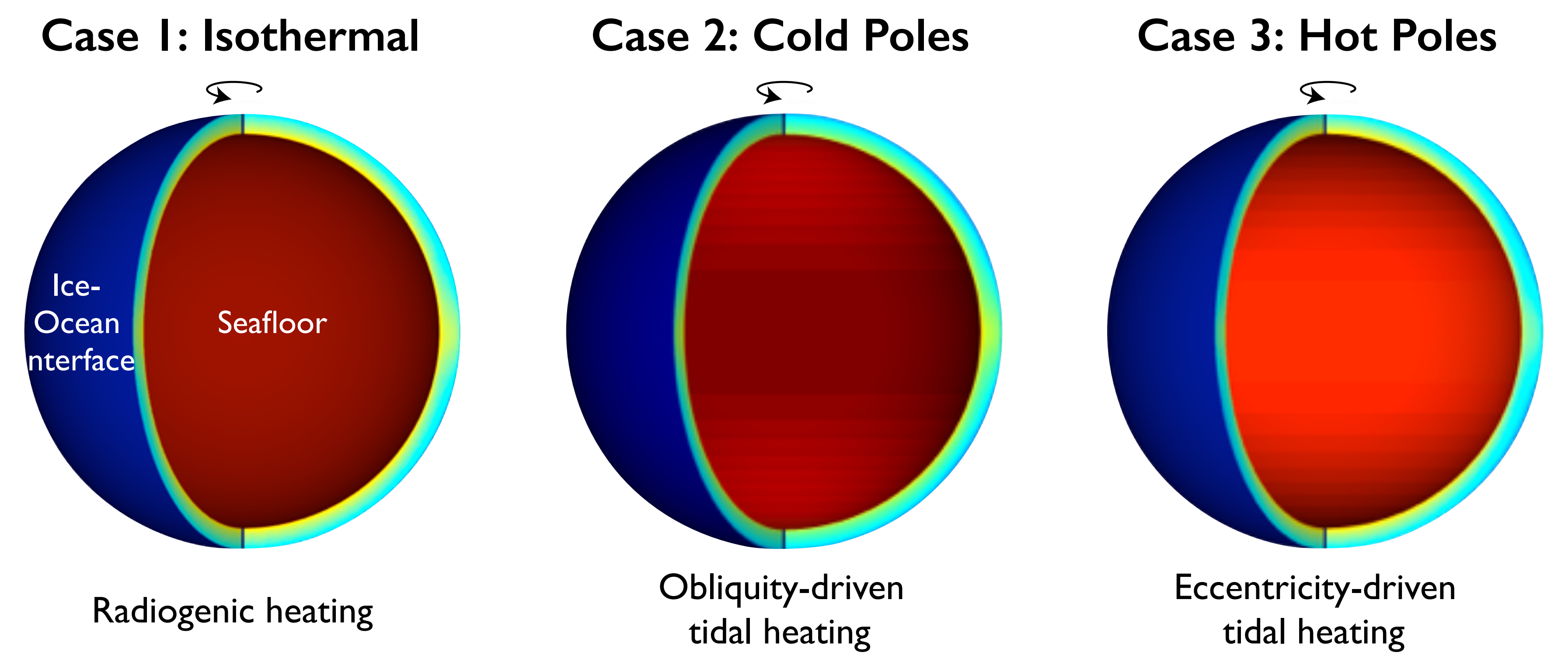
- Numerical models of global ocean convection
  - Boussinesq thermal convection in a rotating spherical shell (ocean tides and salinity gradients are not considered)
  - Transitional regime chosen a priori



Definition	Interpretation	Model
$\chi = r_i/r_o$	Shell geometry	0.9
$E = \frac{\nu}{\Omega D^2}$	$\frac{\text{Viscous force}}{\text{Coriolis force}}$	3.0×10^{-4}
$Pr = \frac{\nu}{\kappa}$	$\frac{\text{Viscous diffusivity}}{\text{Thermal diffusivity}}$	1
$Ra = \frac{\alpha g \Delta T D^3}{\nu\kappa}$	$\frac{\text{Buoyancy}}{\text{Diffusion}}$	3.4×10^{7}

Numerical Model: MagIC

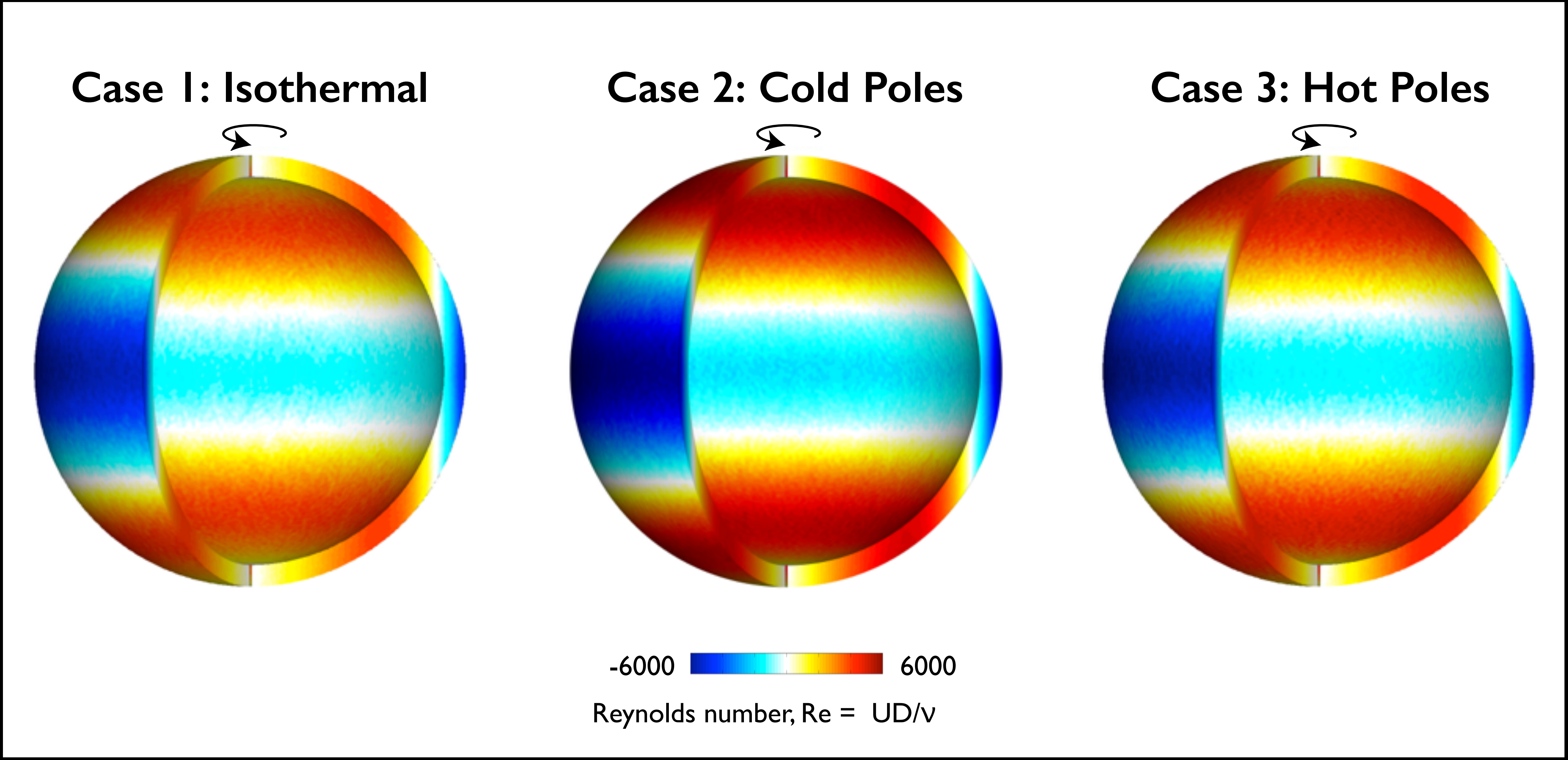
- Numerical models of global ocean convection
  - Boussinesq thermal convection in a rotating spherical shell (ocean tides and salinity gradients are not considered)
  - Transitional regime chosen a priori
  - Three mantle heat flow patterns imposed



e.g., Buethe (2013)

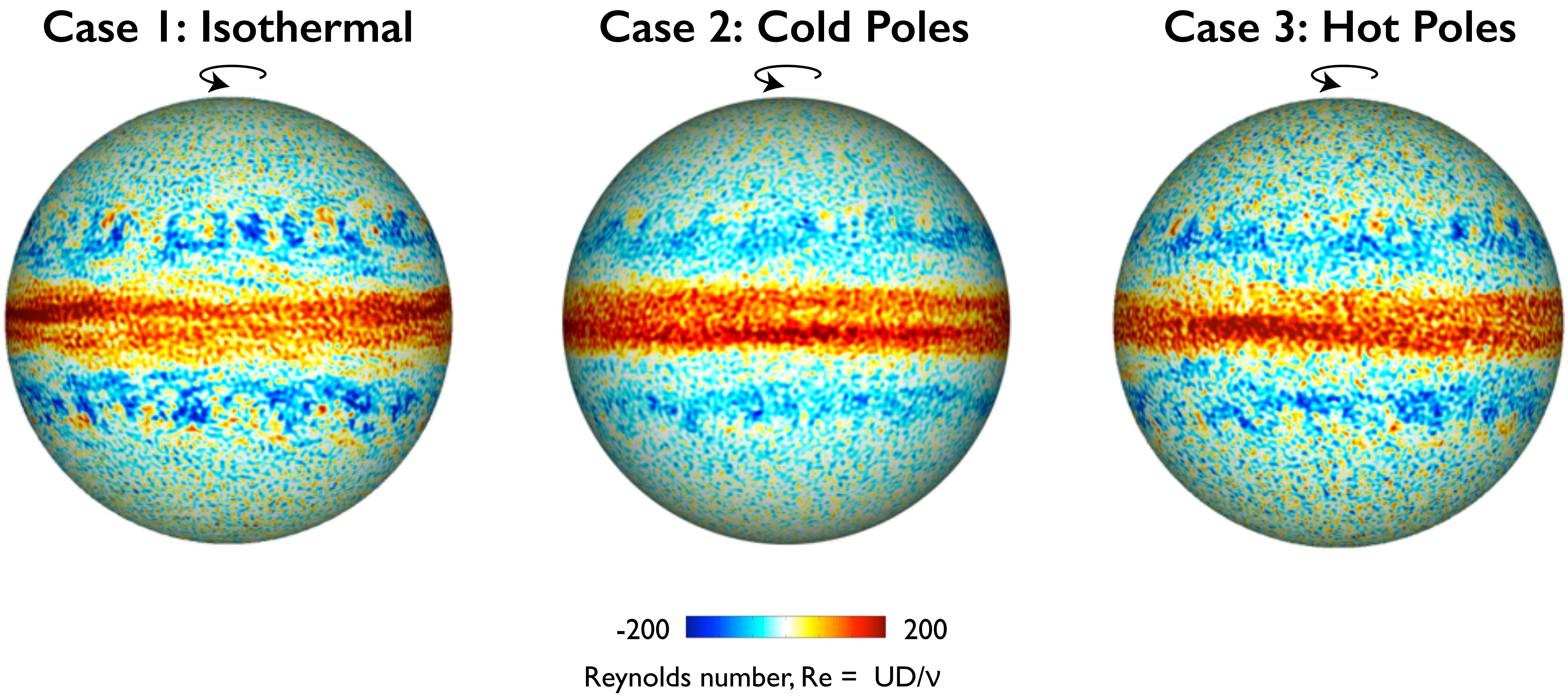
Steady Zonal Ocean Currents

- Three zonal jets develop with retrograde eqtr. flow



Steady Radial Ocean Currents

- Strong upwelling develops at low latitudes



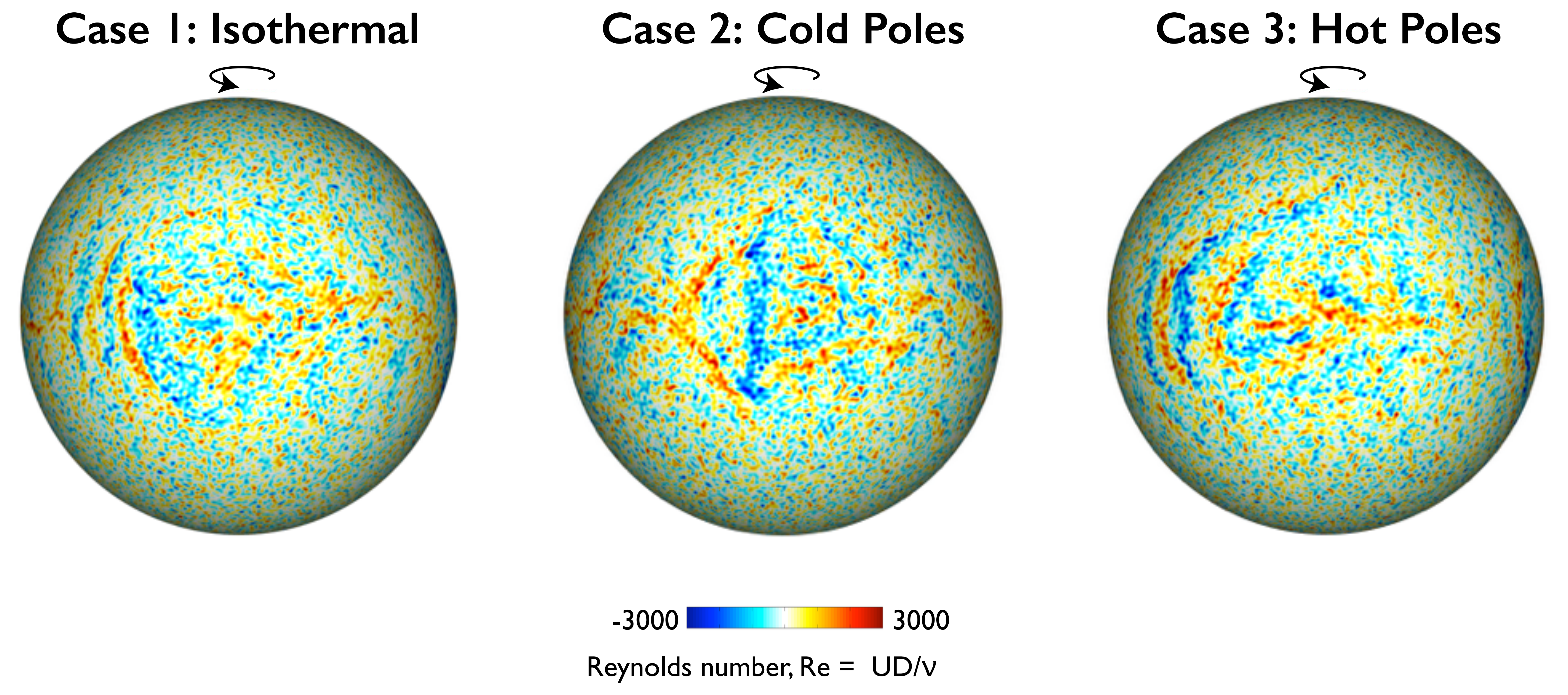
Case 1: Isothermal

Case 2: Cold Poles

Case 3: Hot Poles

Radial Ocean Currents

- Instantaneous radial velocity is faster, smaller scale



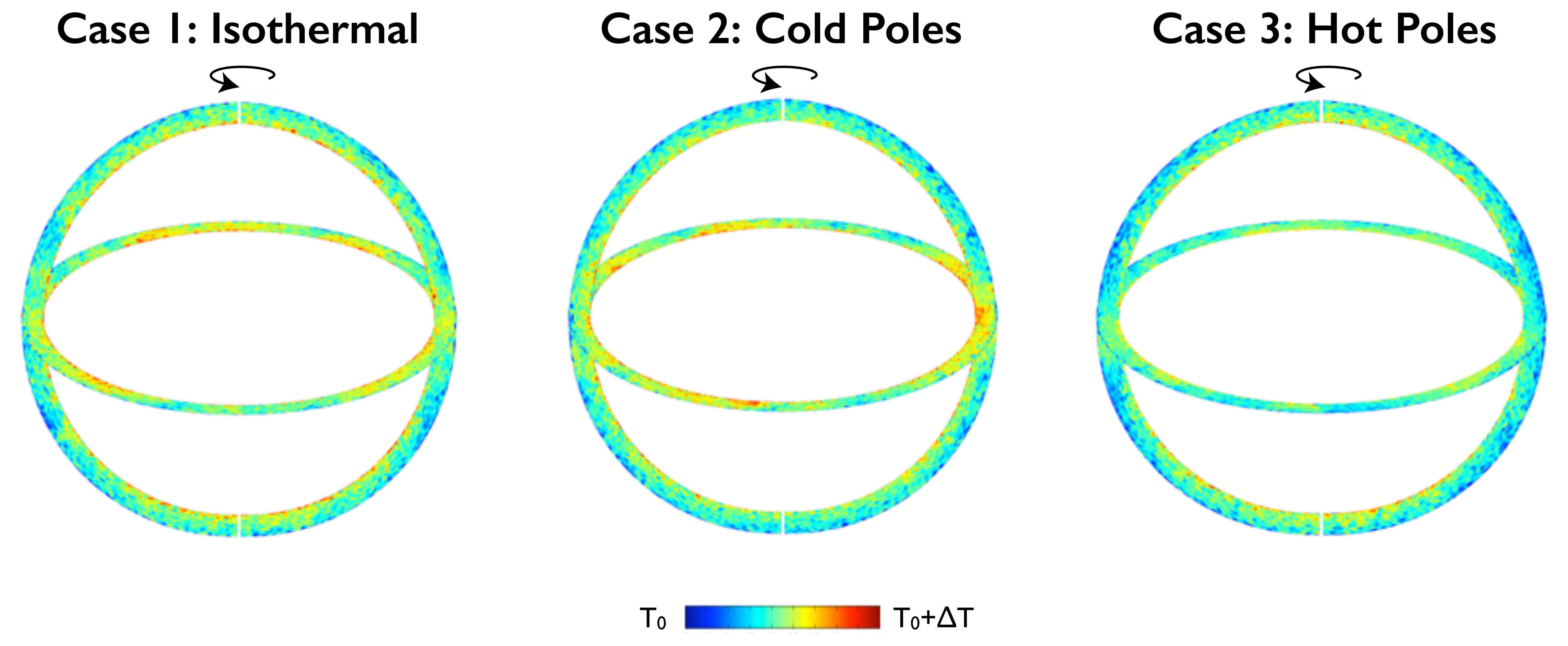
Case 1: Isothermal

Case 2: Cold Poles

Case 3: Hot Poles

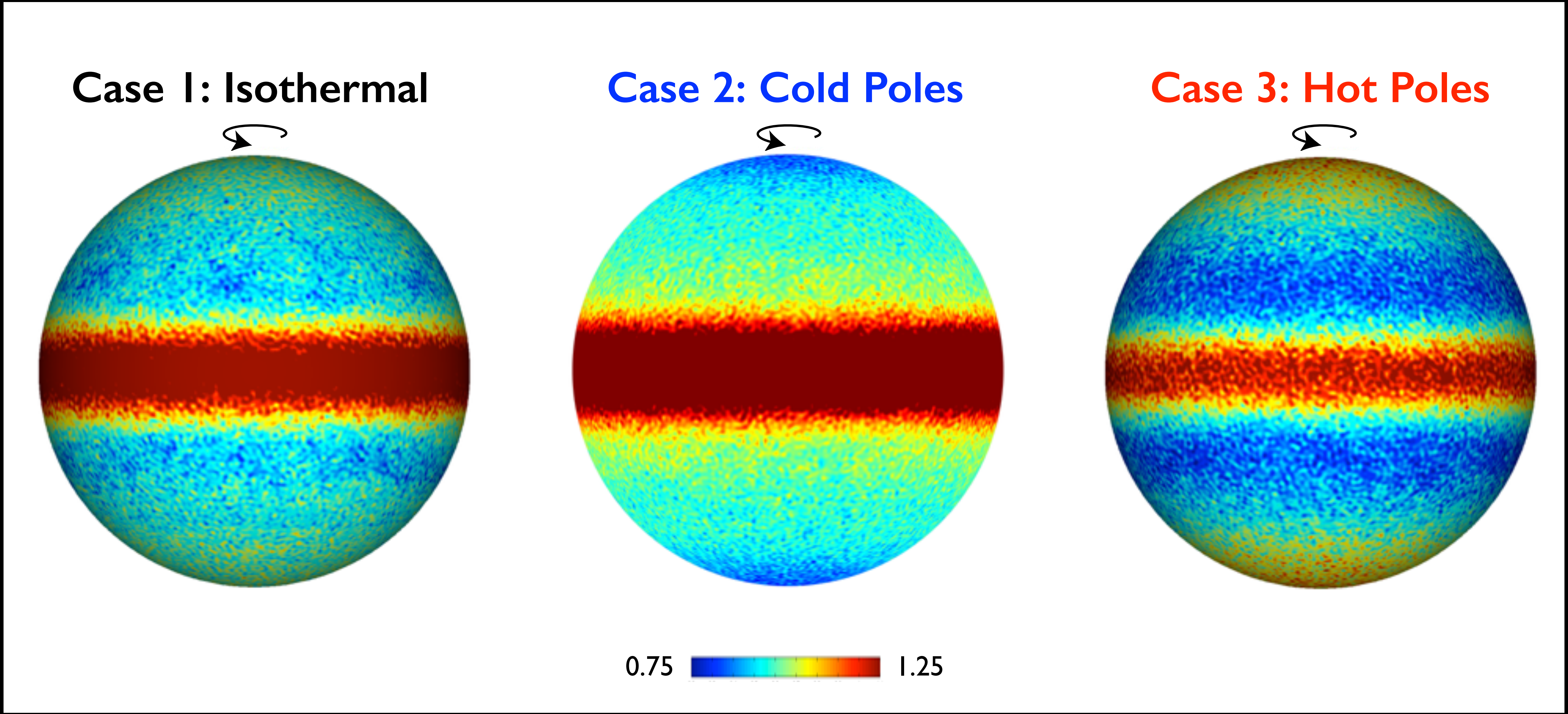
Temperature

- Thermal plumes are mixed into the bulk ocean



Convective Heat Transfer

- Ice-ocean interface heat flux peaks near equator, pattern mimics the mantle heat flow at high latitudes



Convective Heat Transfer

- Heat flux decomposition: total = mean + turbulent
  - *Mean* heat flux due to meridional overturning circulations
  - *Turbulent* heat flux due to fluctuating motions

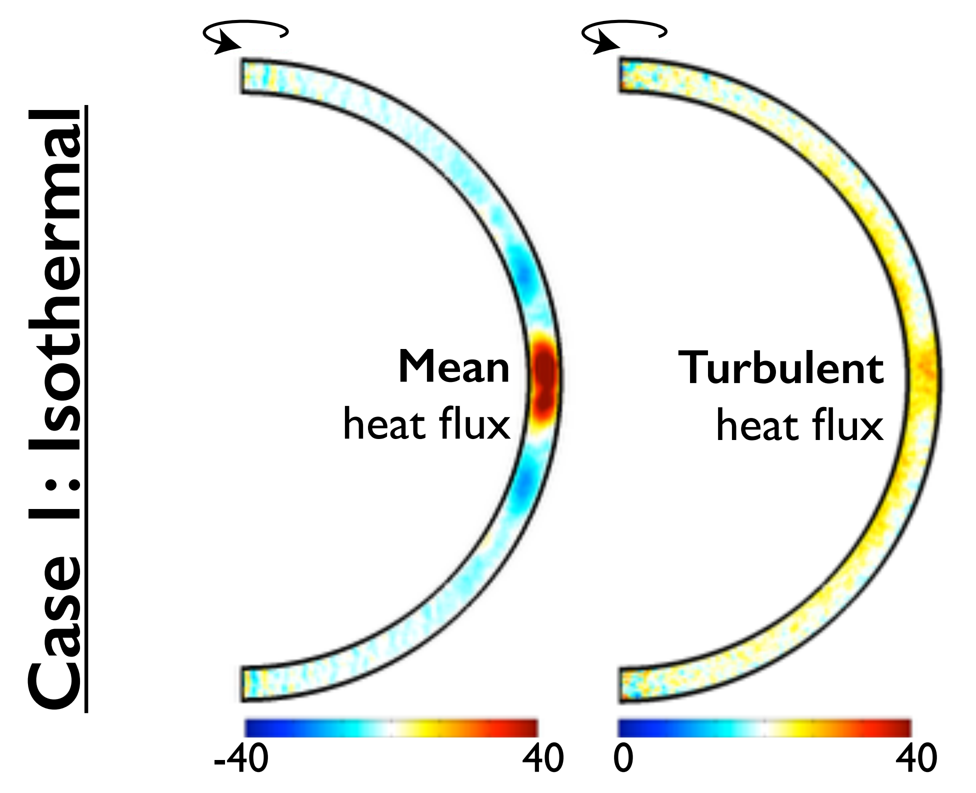
$$\underbrace{\overline{\langle V_r T \rangle}}_{\text{Total}} = \underbrace{\langle \overline{V_r}\ \overline{T} \rangle}_{\text{Mean}} + \underbrace{\overline{\langle V_r' T' \rangle}}_{\text{Turbulent}}$$

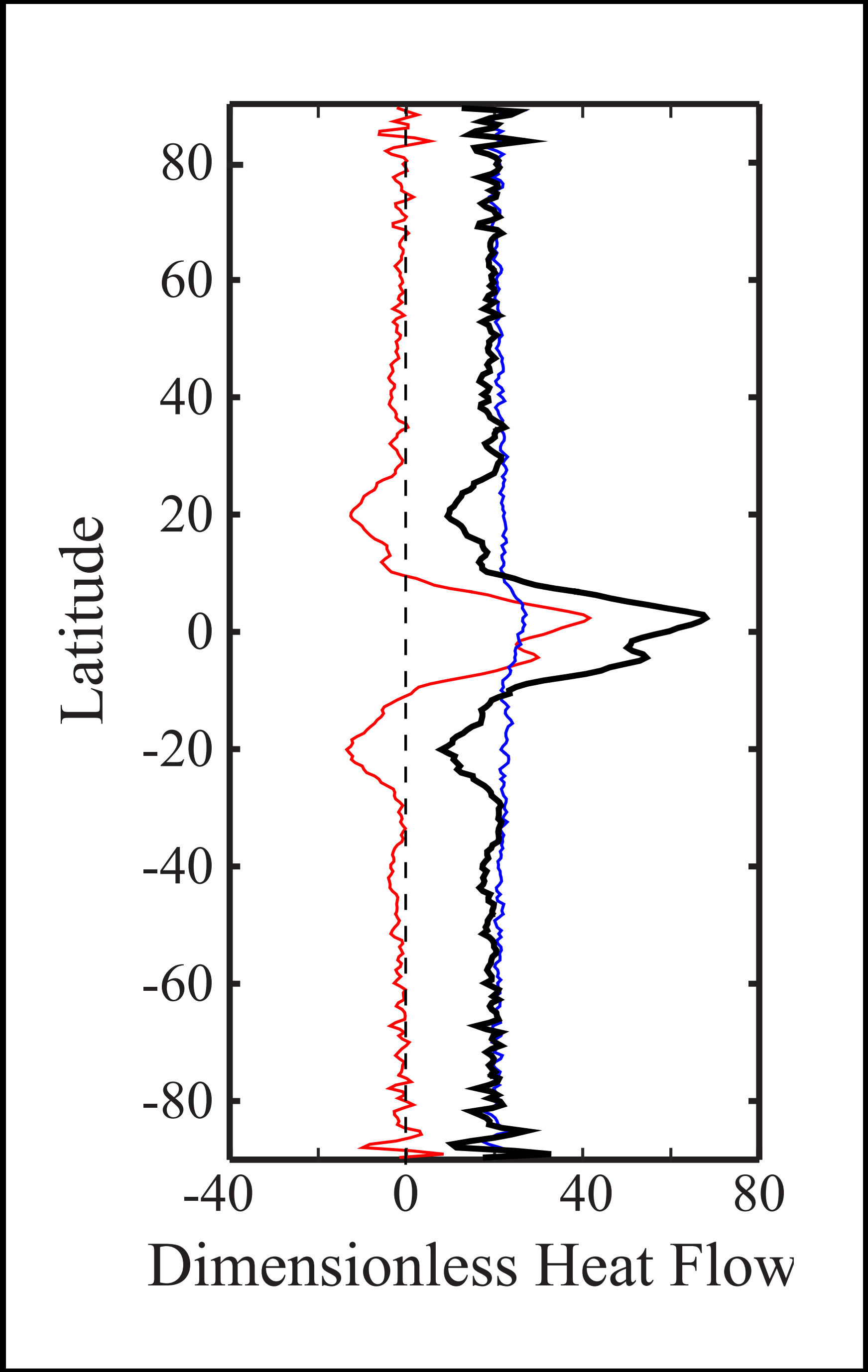
(All variables are dimensionless)

(Overbars denote temporal averages; primes denote fluctuations from the mean; brackets denote spatial averages)

Convective Heat Transfer

- Heat flux decomposition: total = mean + turbulent
  - *Mean* heat flux due to meridional overturning circulations (red)
  - *Turbulent* heat flux due to fluctuating motions (blue)





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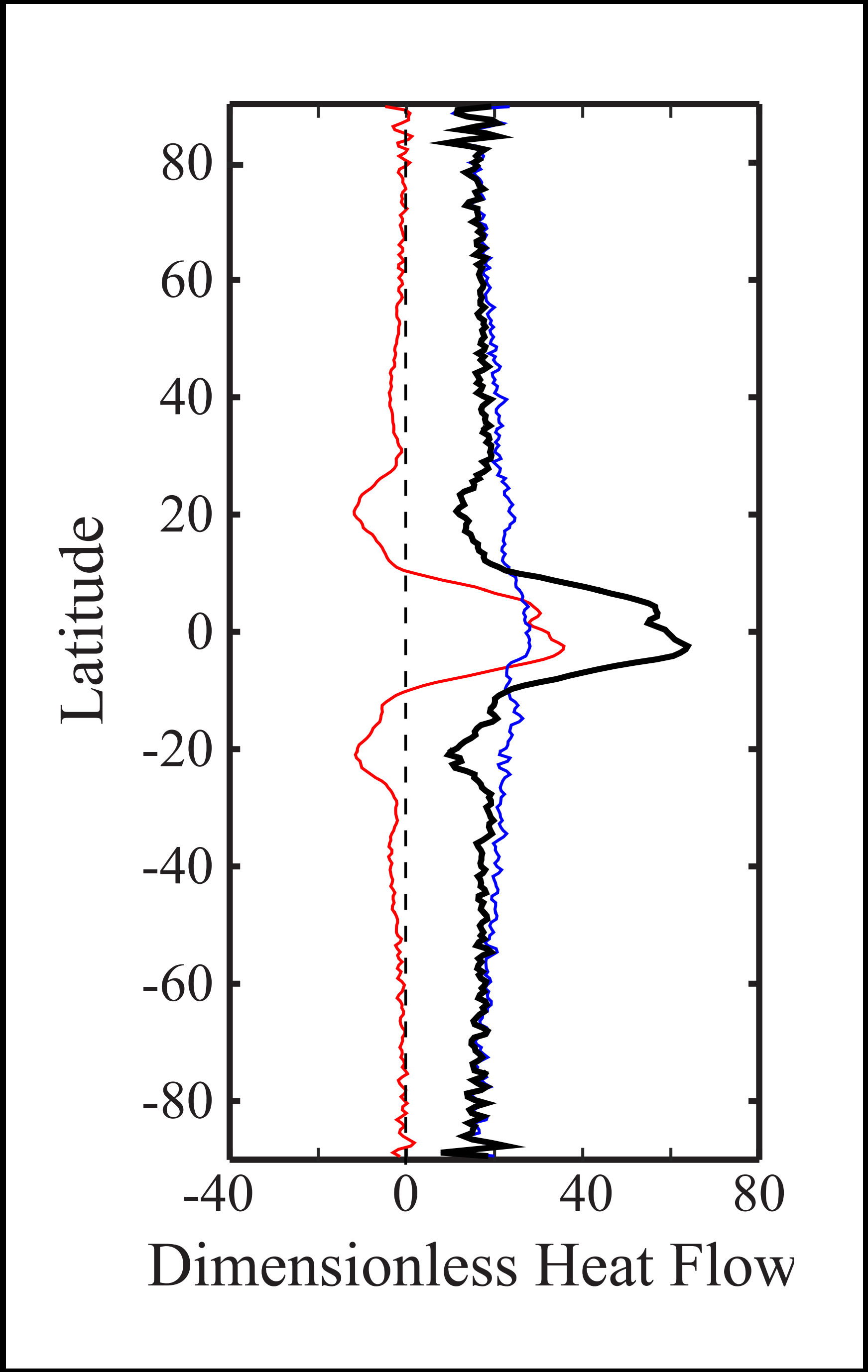

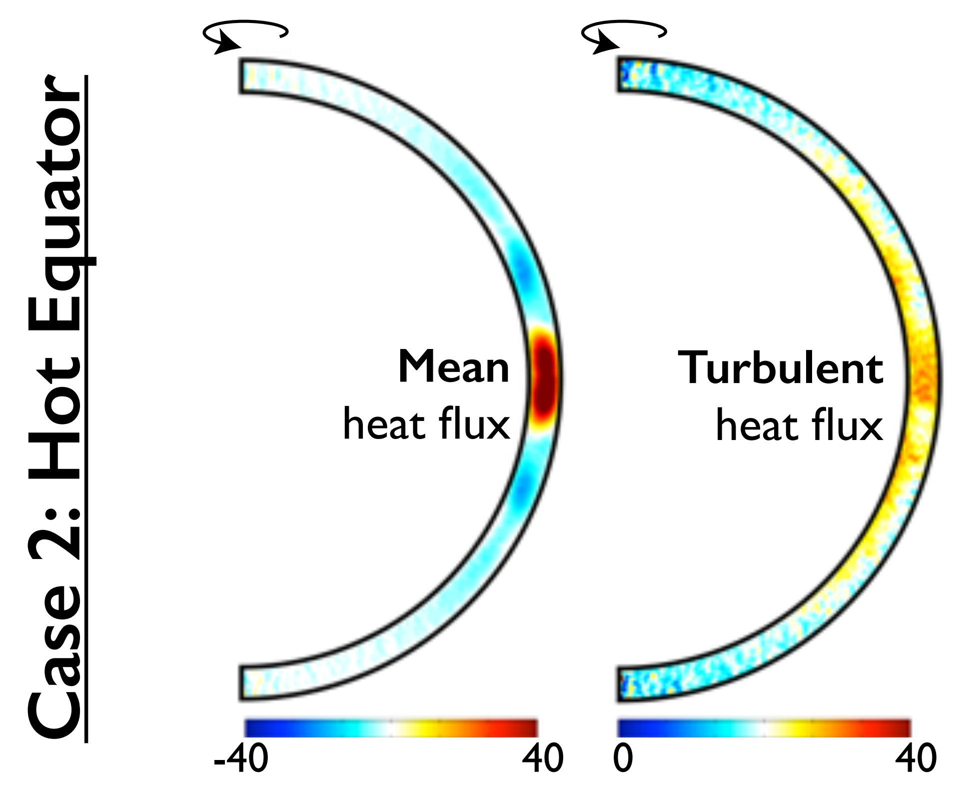

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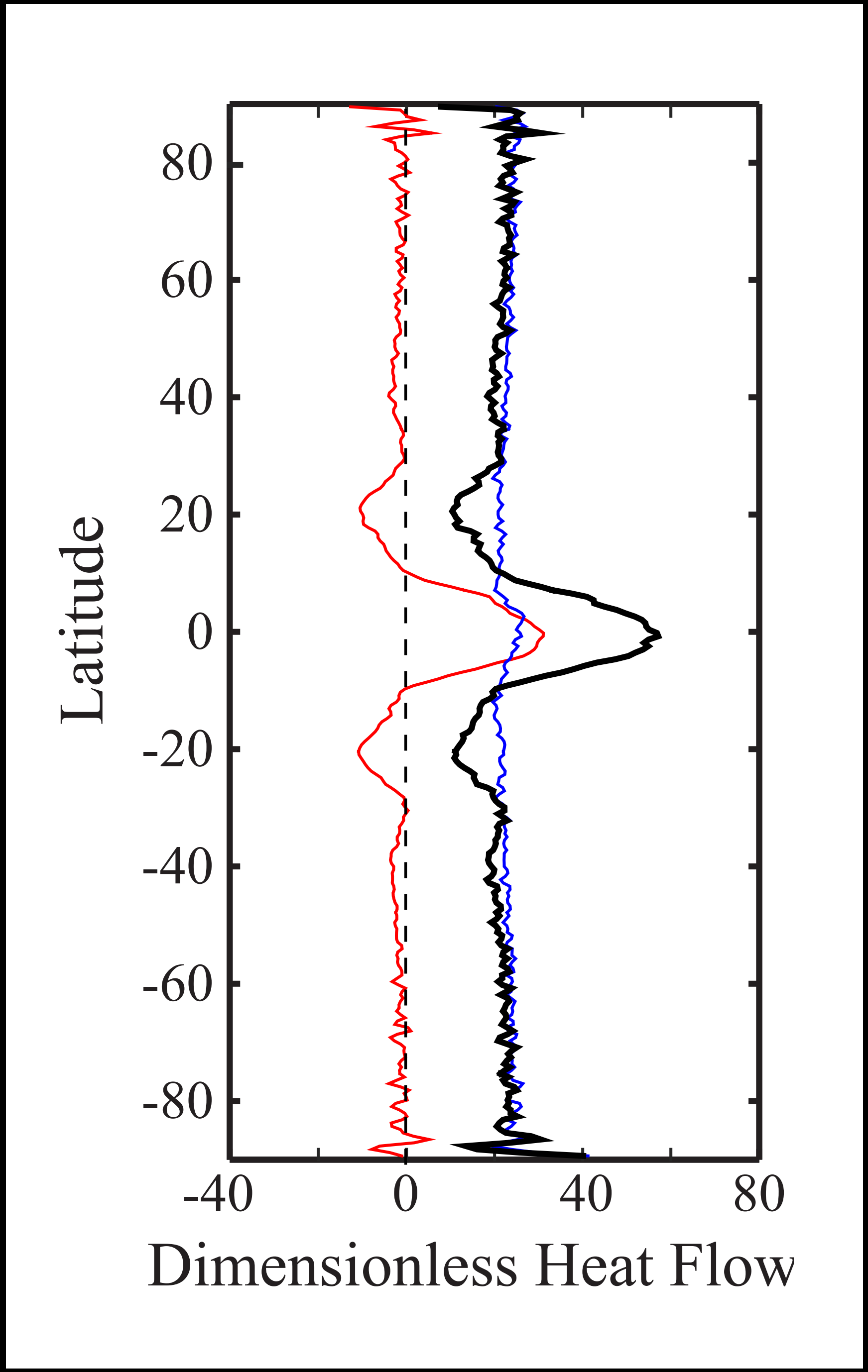

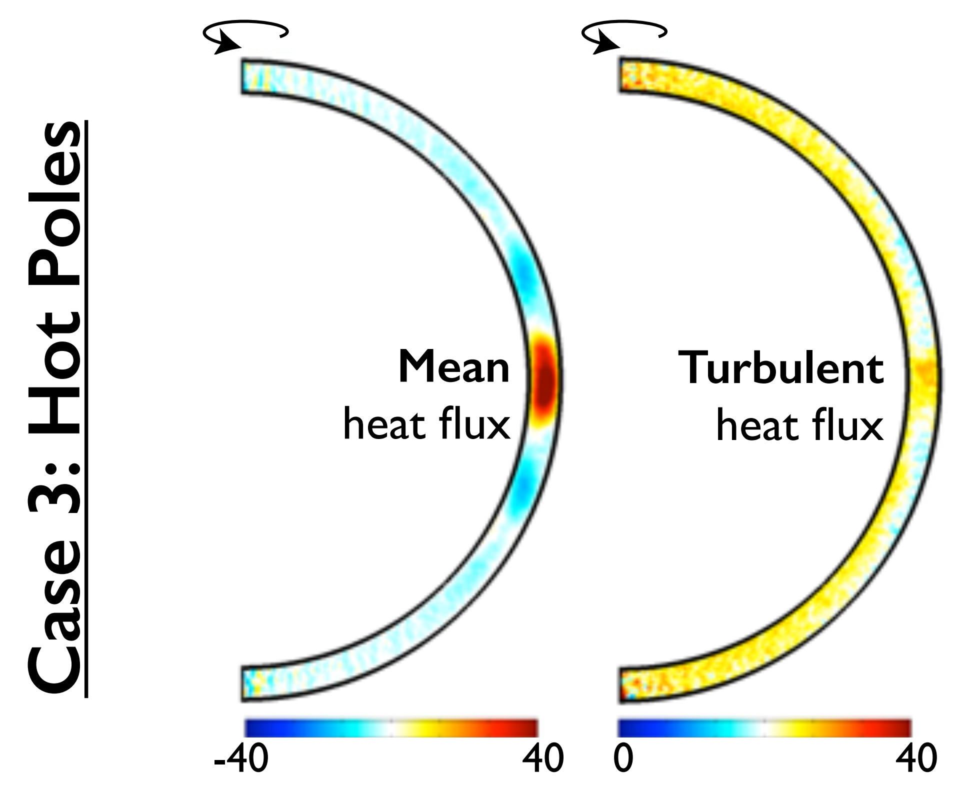

Global Oceanographic Models

- **Zonal Flows**
  - Zonal jets with westward flow near equator, eastward flow at high latitudes are not sensitive to mantle heat flow variations
- **Radial Velocity**
  - Mean equatorial upwelling and mid-latitude downwelling are not strongly dependent on mantle heating
- **Convective Heat Transfer**
  - Heat flux peak at low latitudes is robust to mantle heating heterogeneities
  - Polar heat flux behavior depends on mantle heat flow pattern

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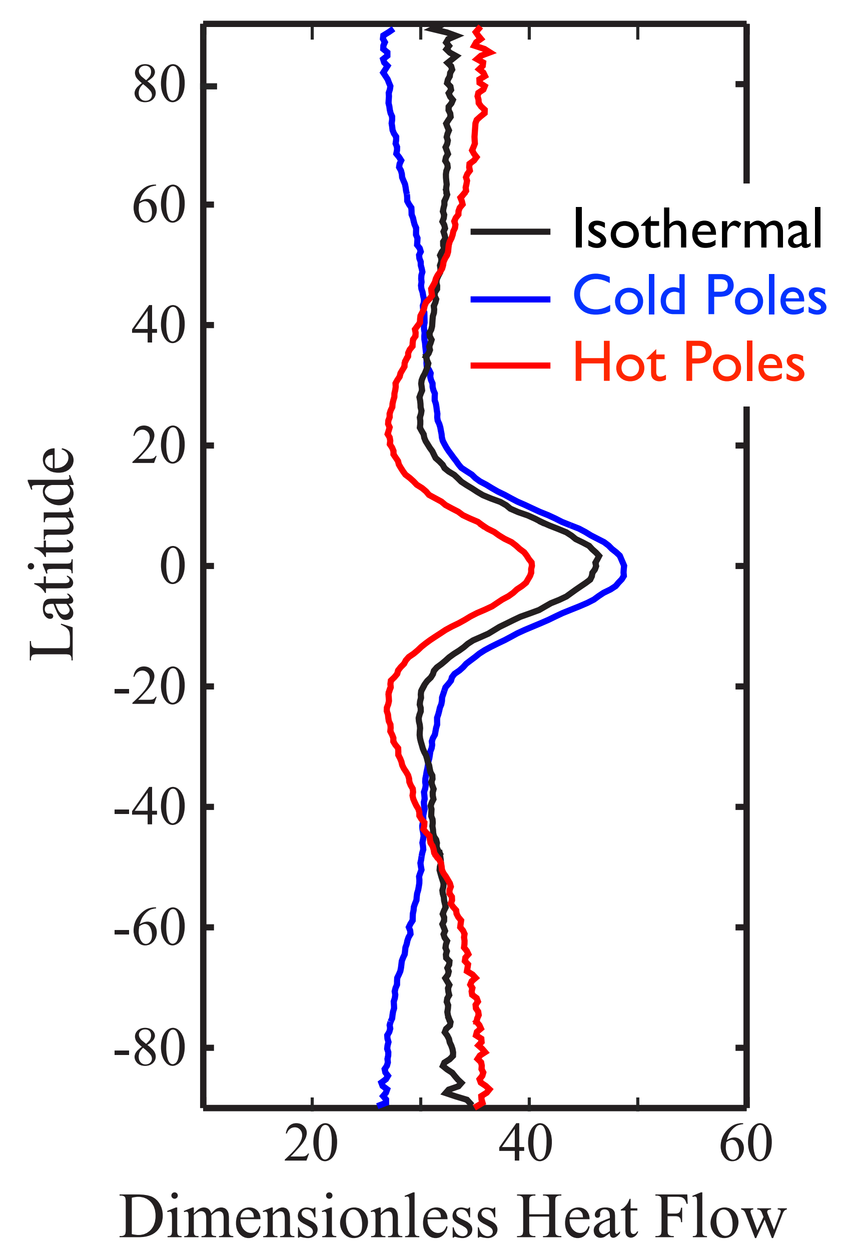
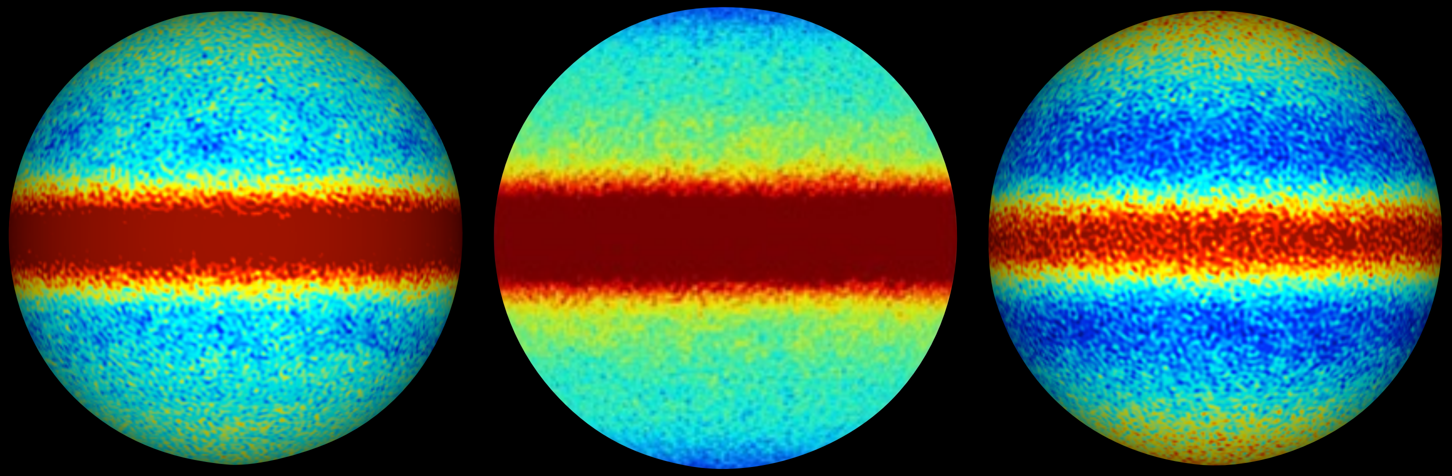
Ice Shell Implications

- Oceanic heat transfer may strongly influence any ice-ocean material exchange



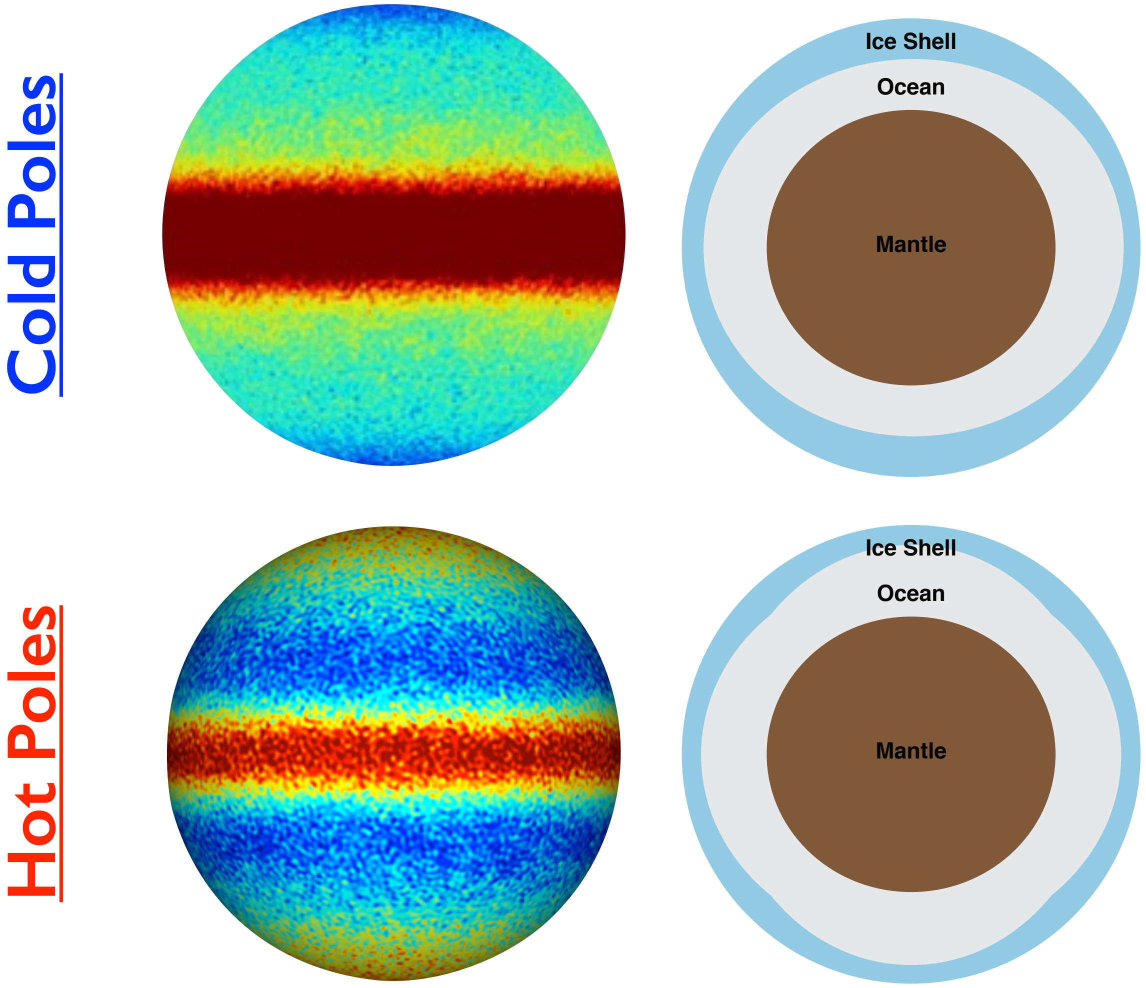
- Ice shell thickness
- Exchange mechanisms
- Geologic activity



Isothermal Cold Poles Hot Poles

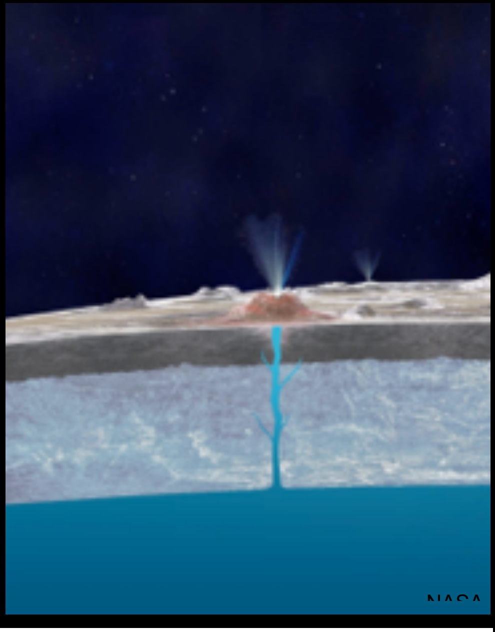
Ice Shell Thickness

- Latitudinal heterogeneity in heat flux should intensify regional melting, reducing ice thickness

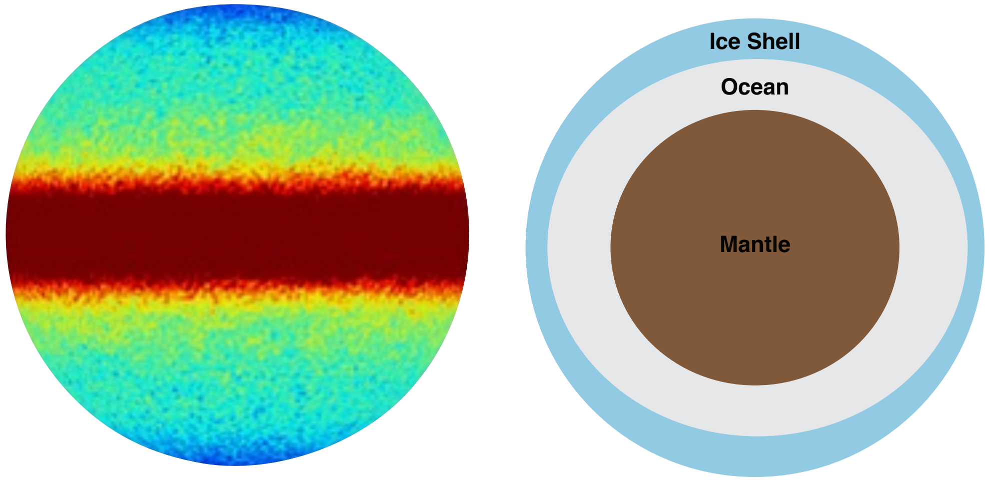


Exchange Mechanisms

- **Thin Ice Shell:** melting of the ice shell may enable direct ocean access through cracks and/or local melt-through events

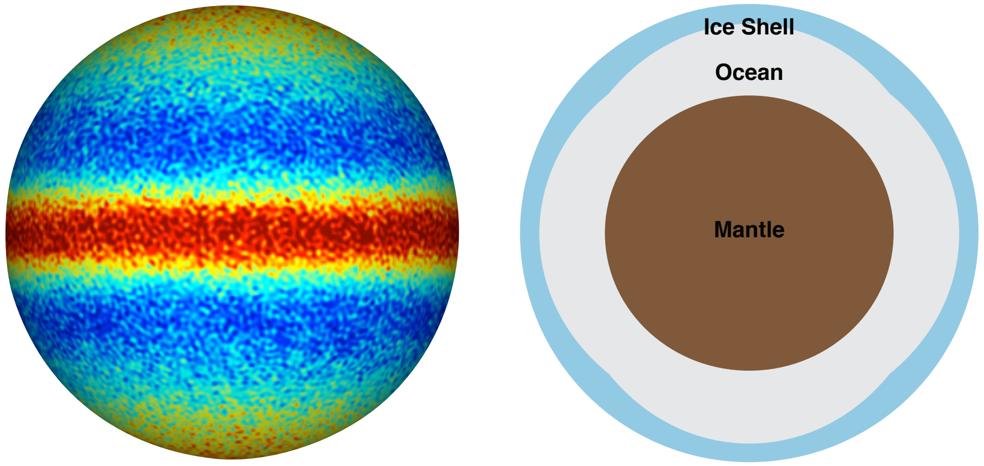


Cold Poles



Cracks / Melt-through most likely near equator

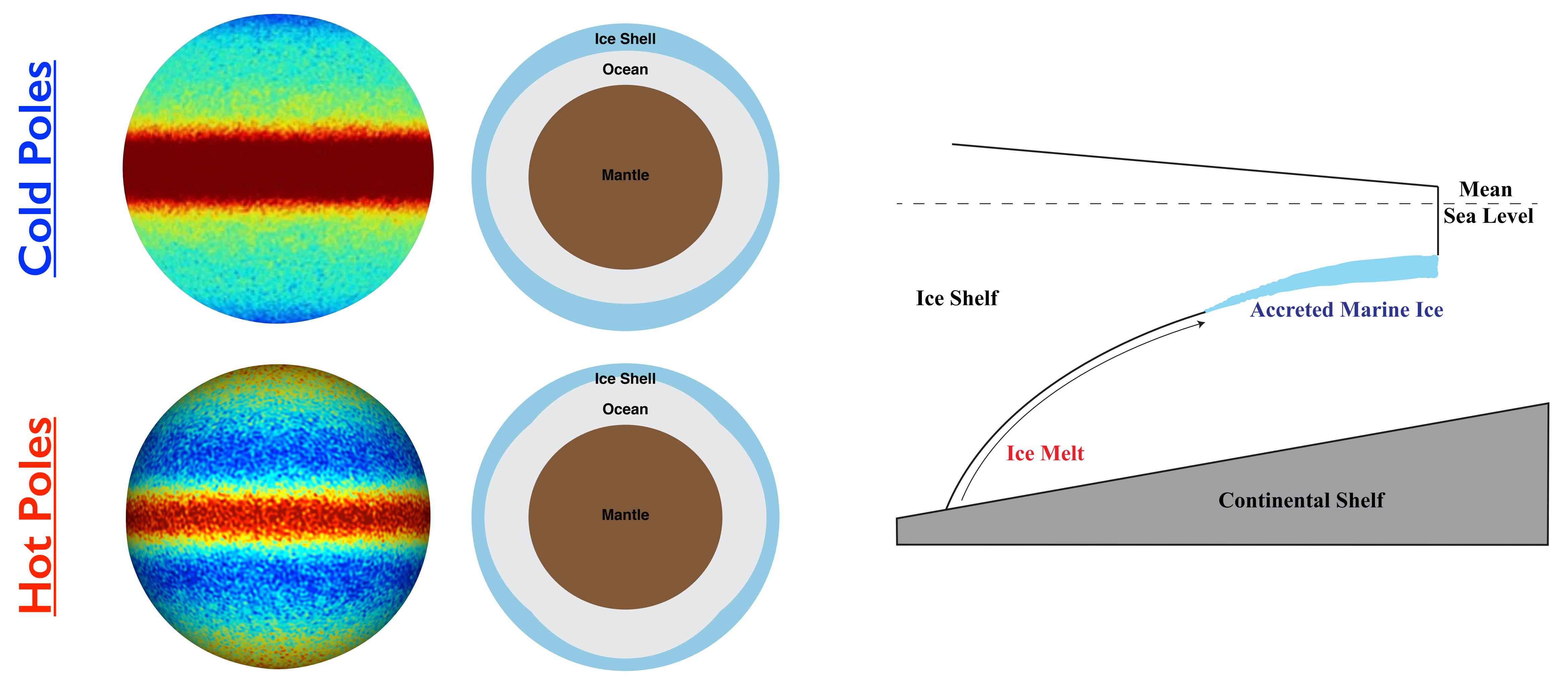
Hot Poles



Cracks / Melt-through most likely near equator and poles

Marine Ice Accretion

- Variations in ice thickness can lead to relatively pure “marine” ice accretion via an ice pump



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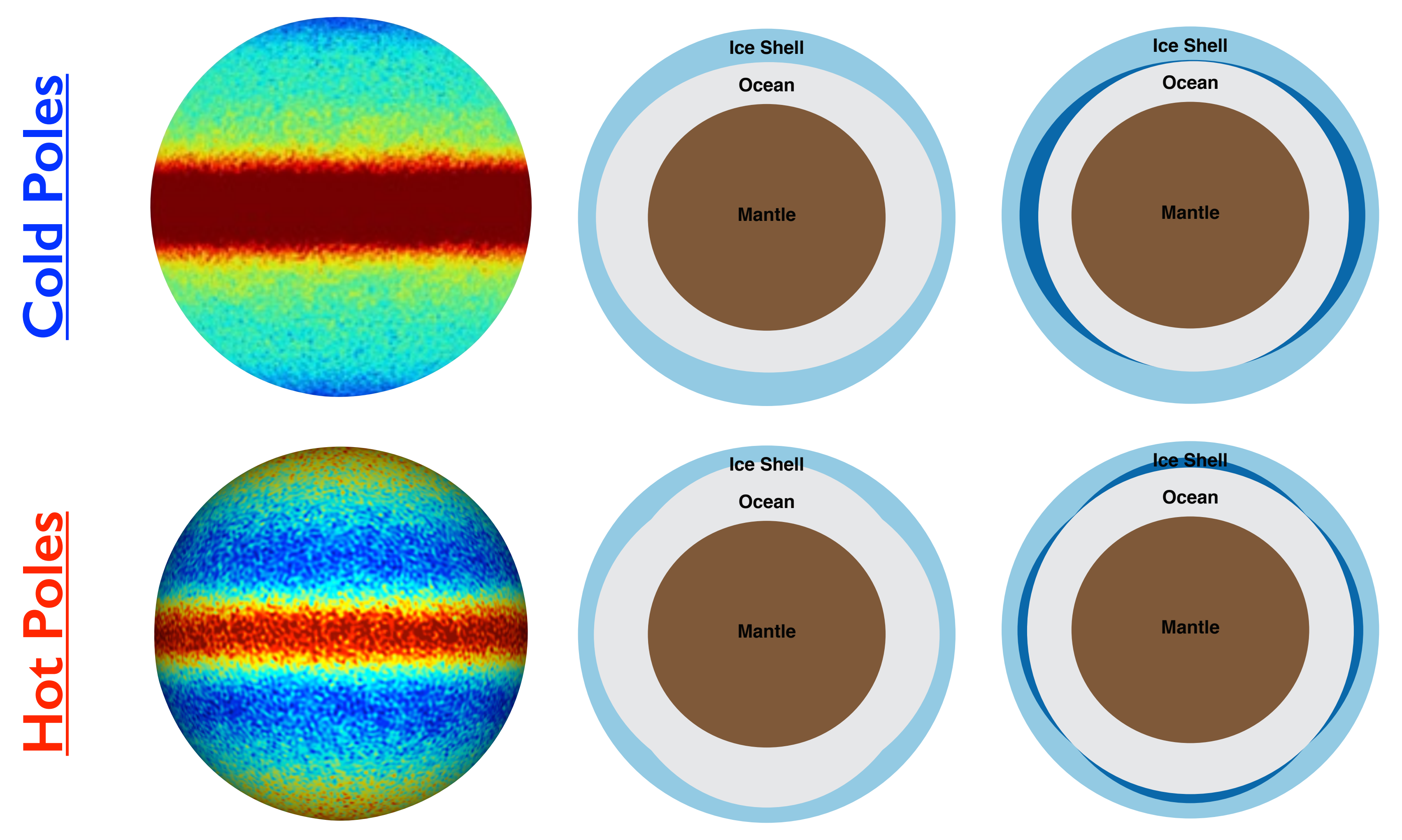
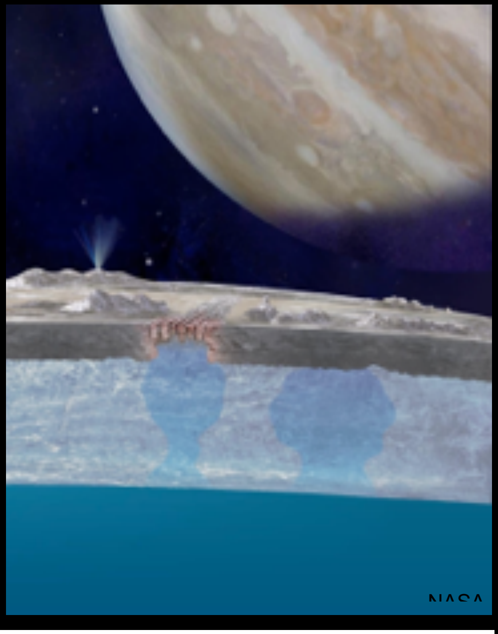
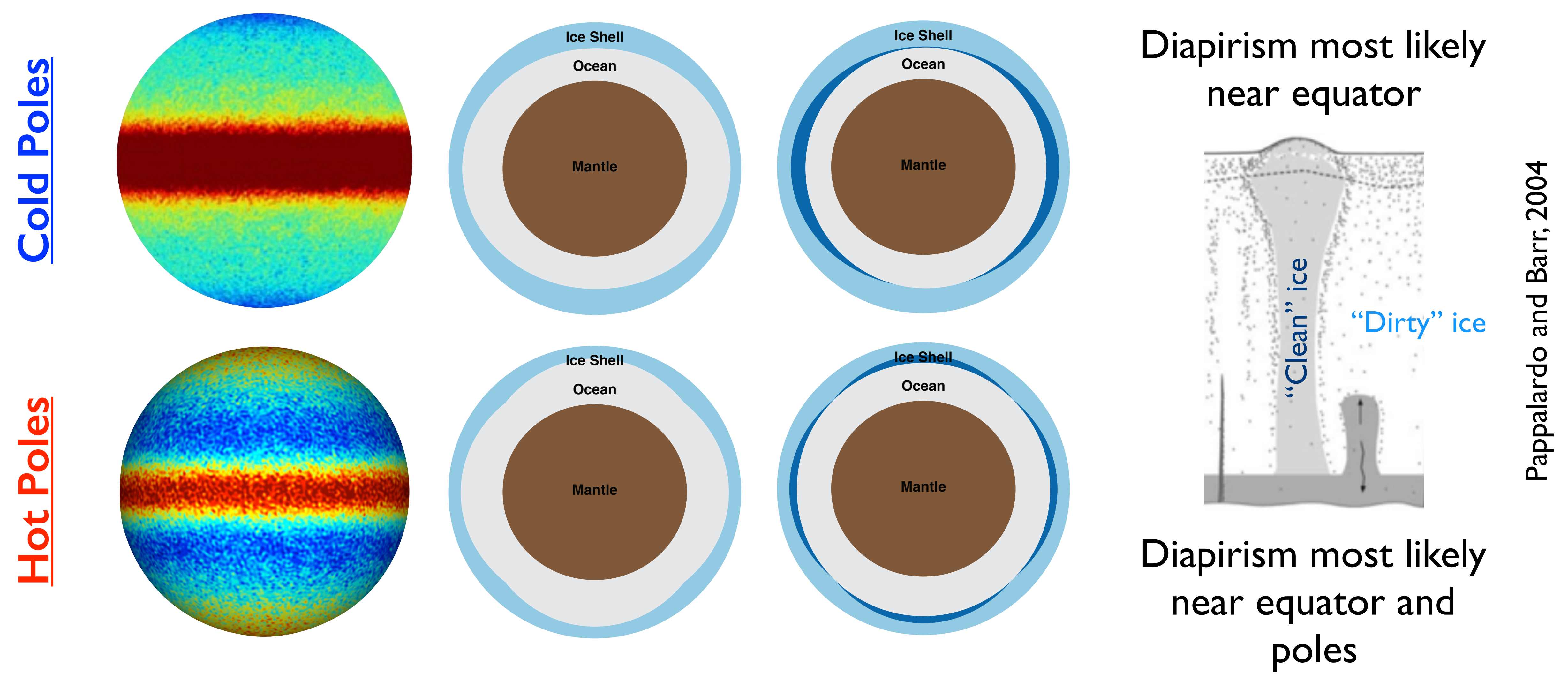


Exchange Mechanisms

- **Thick Ice Shell:** thermo-compositional diapirism may occur with any substantial thickness of relatively pure marine ice





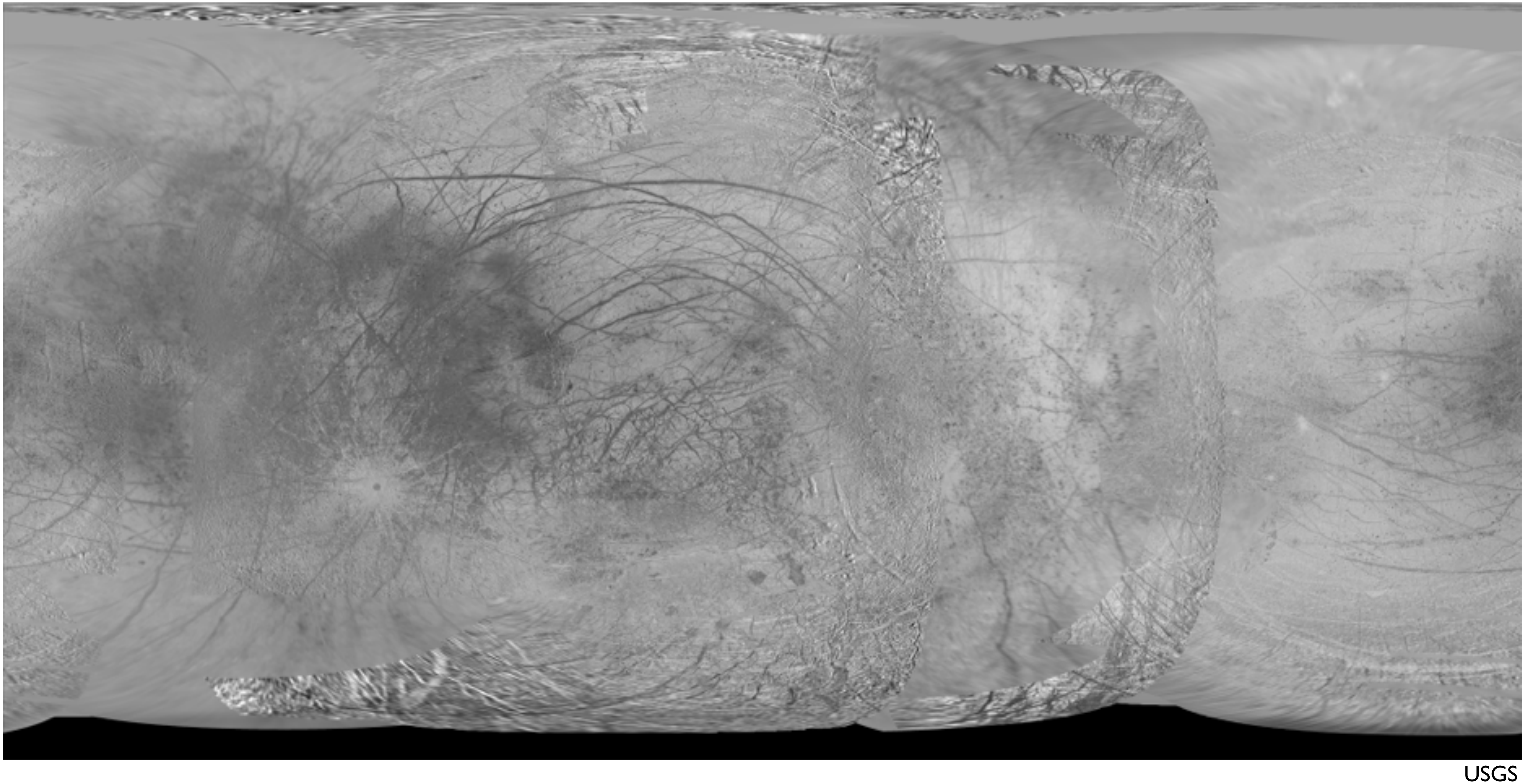
Diapirism most likely near equator

Diapirism most likely near equator and poles

Pappalardo and Barr, 2004

Geologic Activity

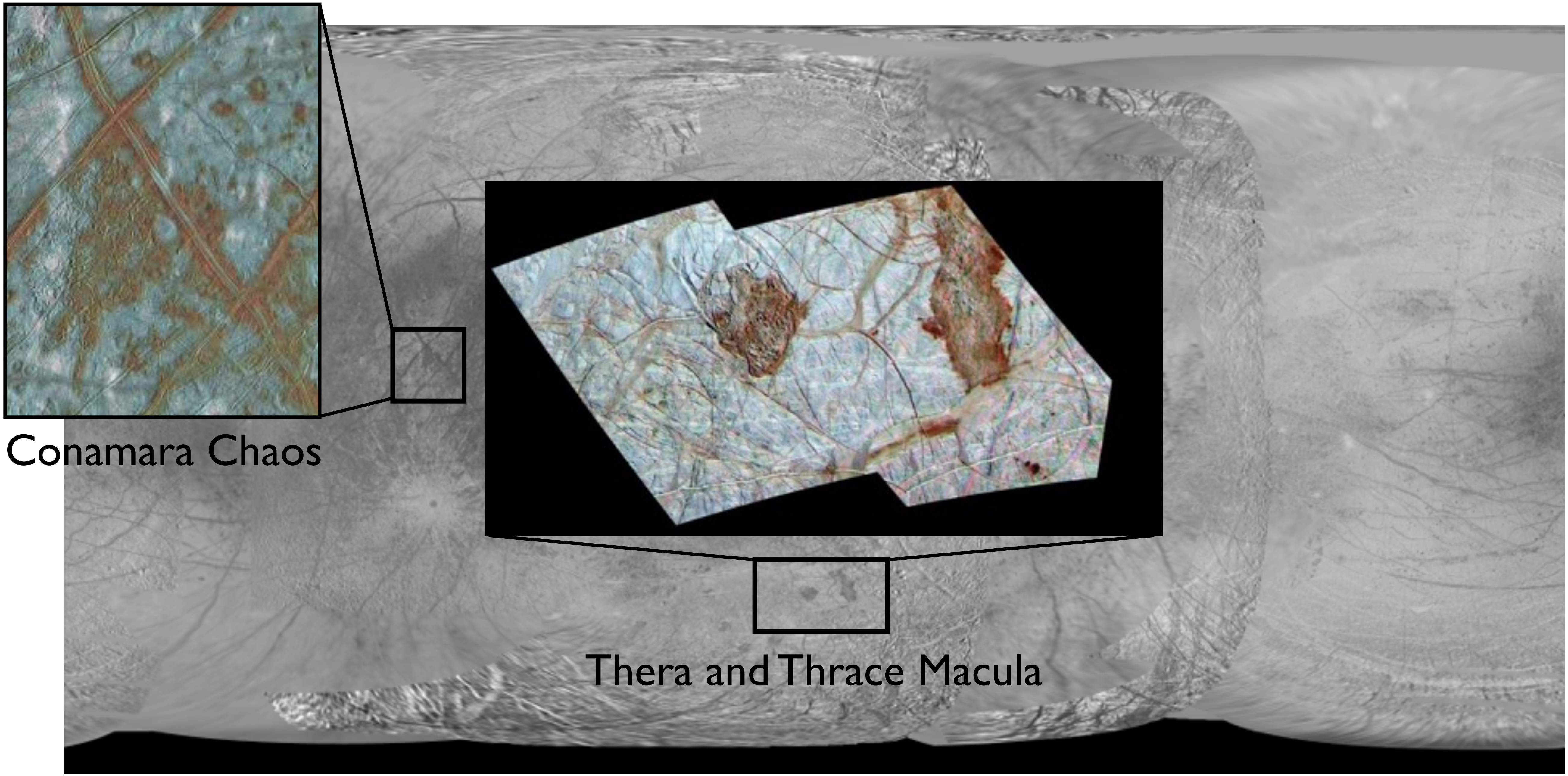
- Europa's surface is young and riddled with many unique geologic features



USGS

Geologic Activity

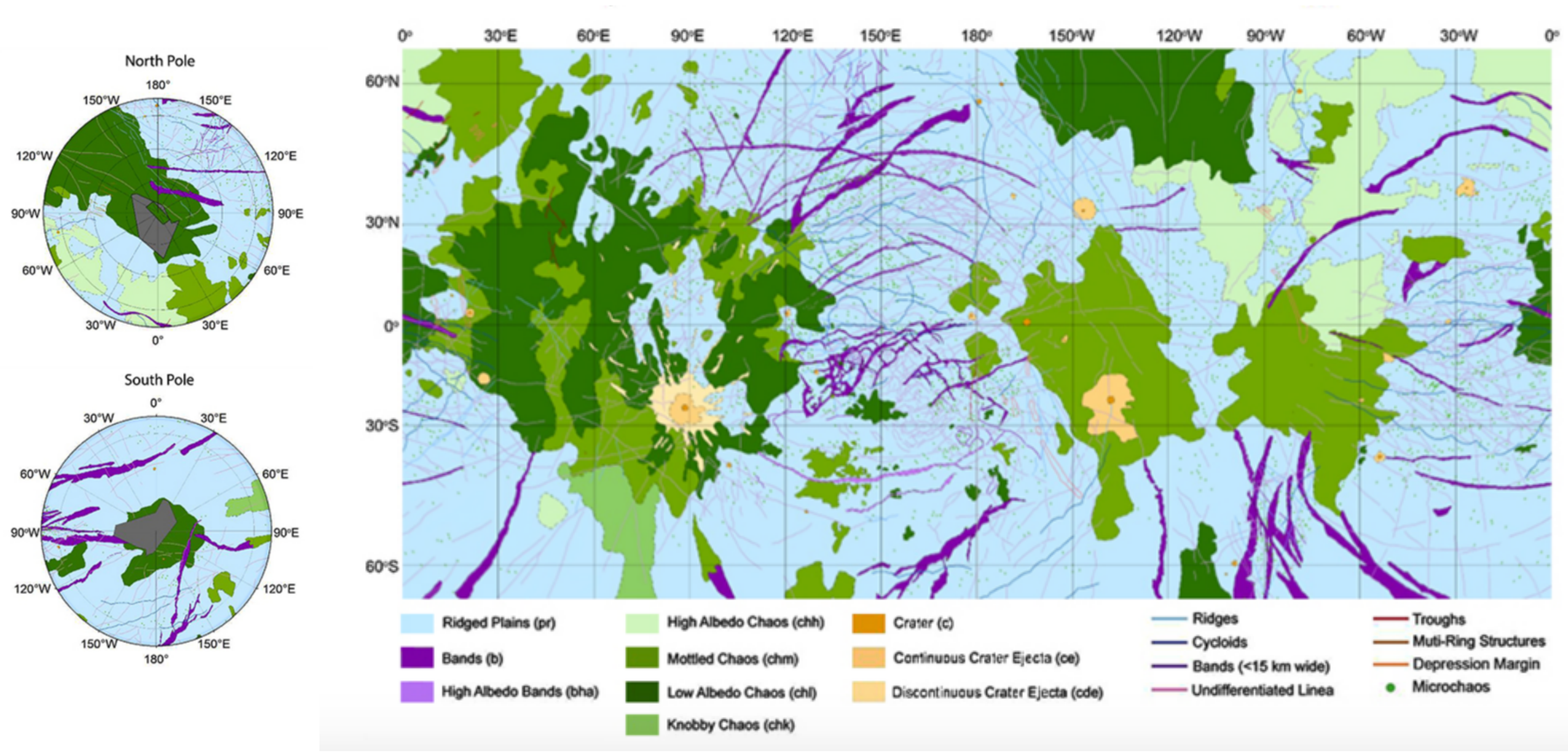
- Europa’s surface is young and riddled with many unique geologic features, such as chaos terrains



USGS

Geologic Activity

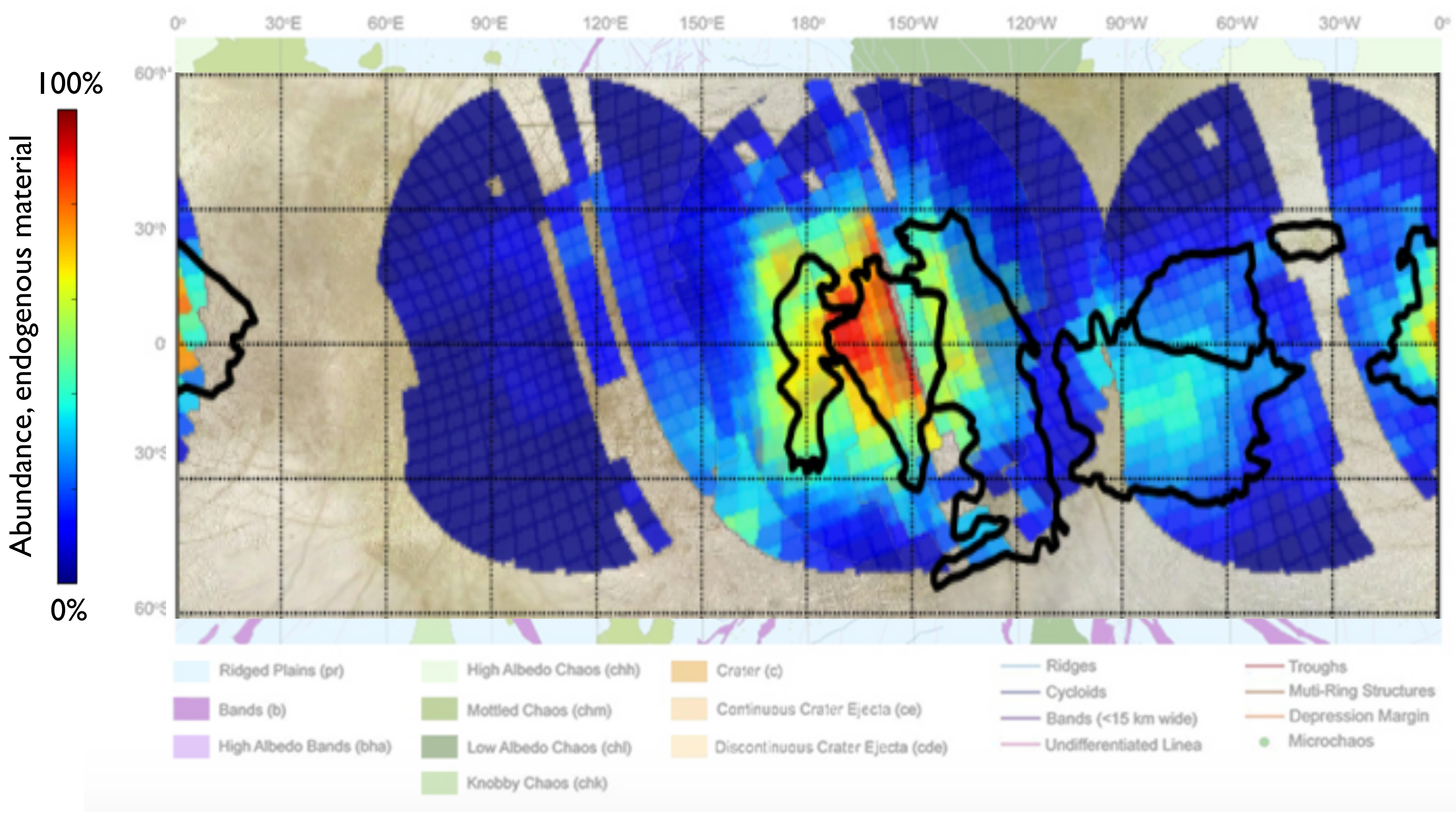
- Chaos terrains are most prevalent at low and polar latitudes



NASA/Erin Leonard, Alex Patthoff, and Dave Senske, building on work by Ron Greeley, Thomas Doggett and Melissa Bunte via EOS

Geologic Activity

- Salts with endogenic origin are coincident with leading hemisphere chaos terrains



Rischer et al. 2015

Implications for Europa

- Heterogeneous heating of the ice shell may promote exchange processes in locally thinned areas
  - Fractures and melt-through (*thin shell*)
  - Diapirism via marine ice accretion (*thick shell*)
  - Chaos terrains suggest eccentricity tidal heating of the mantle ("hot poles" case)

Outline

1) Theoretical Predictions for Convection

2) Numerical Convection Models

3) Boundary Layer Implications

4) Conclusions

Habitability of Ocean Worlds

- Oceans of Europa, Ganymede, Enceladus, and Titan predicted to be weakly influenced by rotation
    - 3D turbulence, three zonal jets, and an equatorial upwelling
    - Convective heat transfer has a maxima near the equator; high latitudes are sensitive to mantle heat flow distribution
- Oceanic heat transfer may strongly influence any ice-ocean material exchange