New constraint on Europa's ice shell: Magnetic signature from the ocean

F. Daniel

Joint work with: C. Gissinger, L. Petitdemange

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Northwestern University

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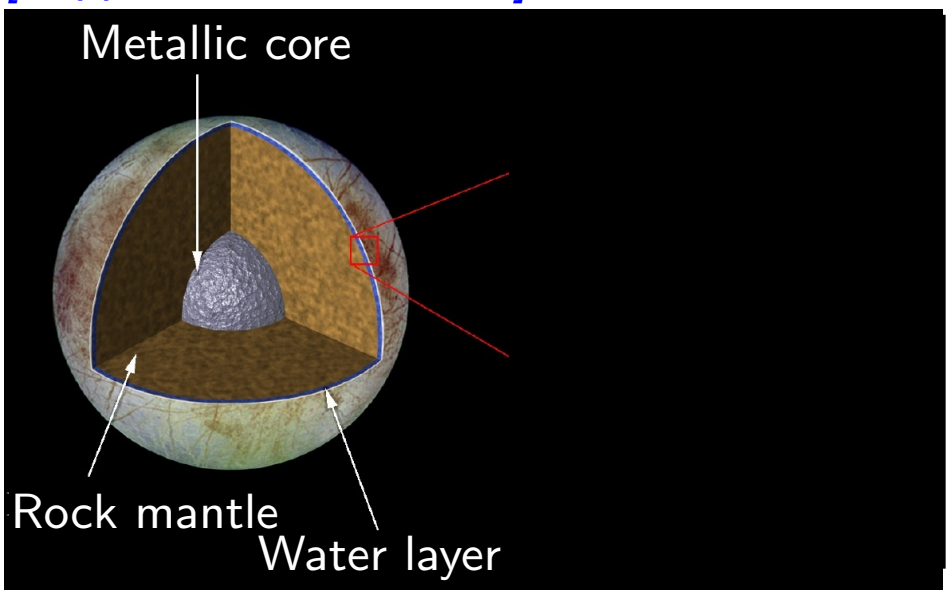
Europa

©*Galileo* space mission

Europa: some figures

[Pappalardo et al., 1999]



[Vance et al. 2018, Soderlund et al. 2020]

- Radius $\sim 1560\,km$

Europa: some figures

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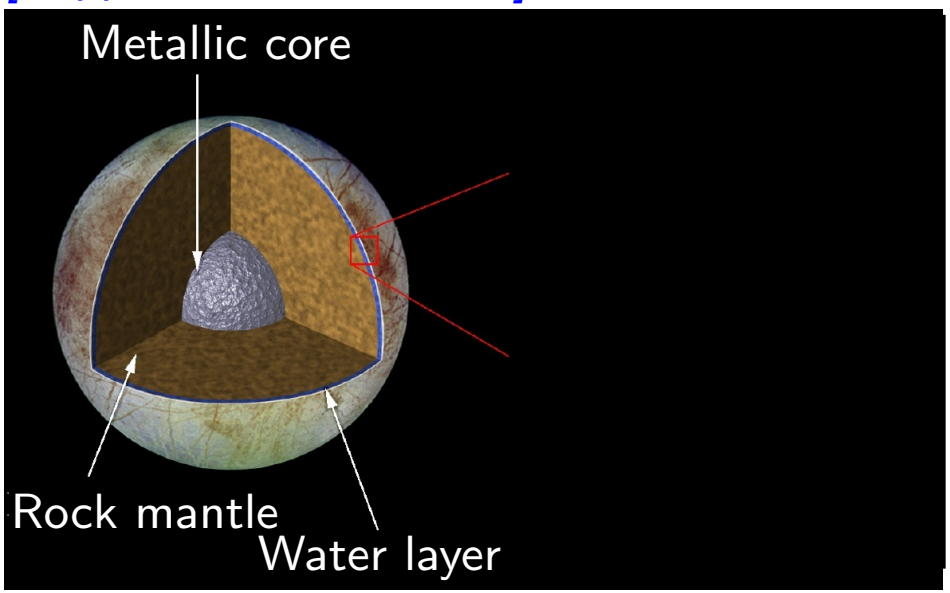

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  - Metallic core $\sim 500\,km$

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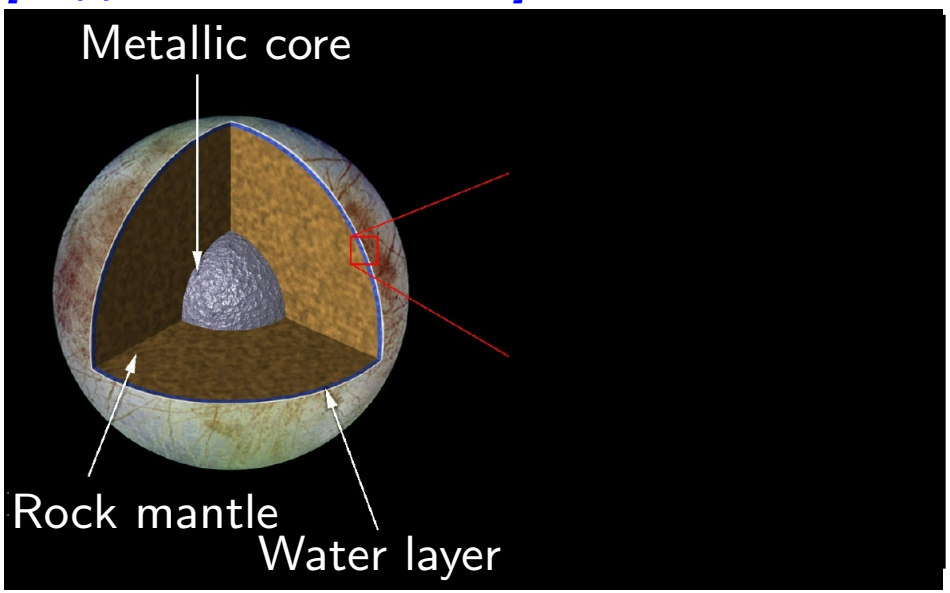

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  - Rock mantle $\sim 1000\,km$

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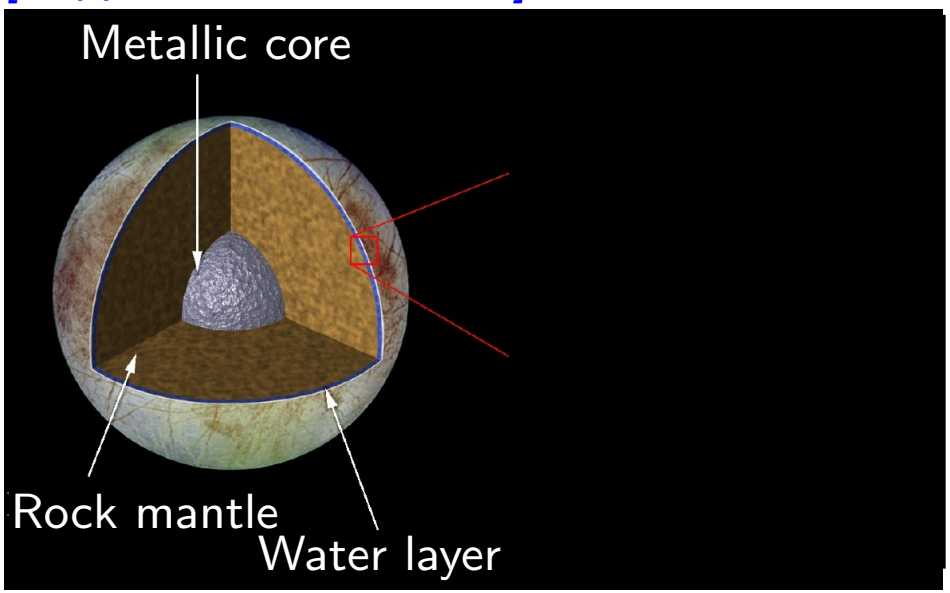

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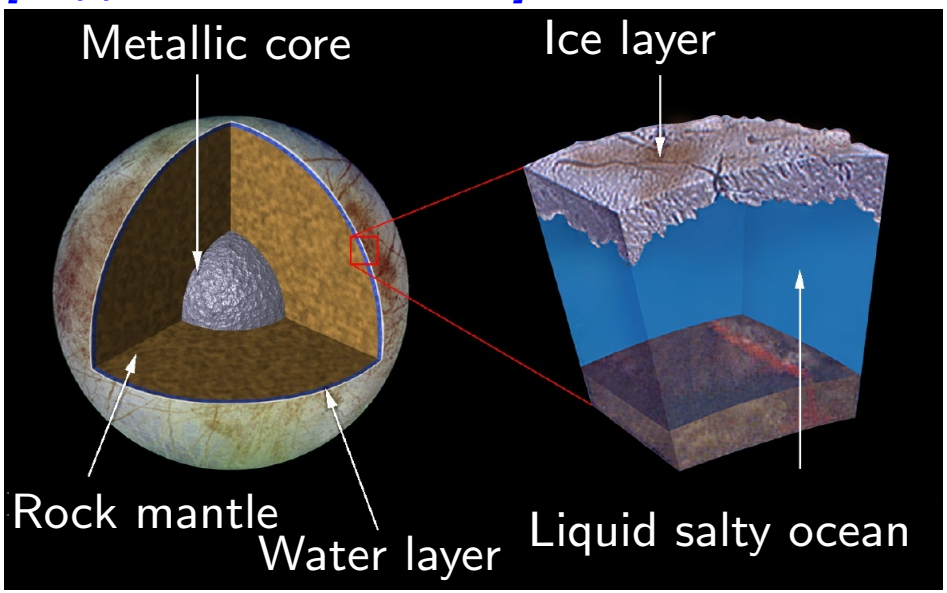

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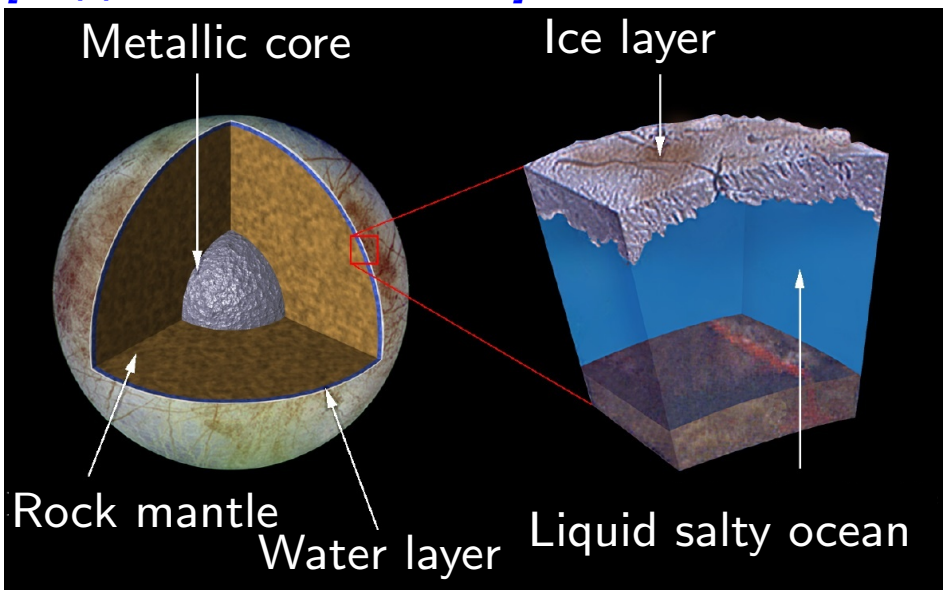
- Radius $\sim 1560\,km$
  - Metallic core $\sim 500\,km$
  - Rock mantle $\sim 1000\,km$
  - Water layer $\sim 100\,km$
- Ice $\sim 5 - 30km$
- Liquid ocean $\sim 80 - 130km$

Europa: Fluid Dynamics

[Pappalardo et al., 1999]



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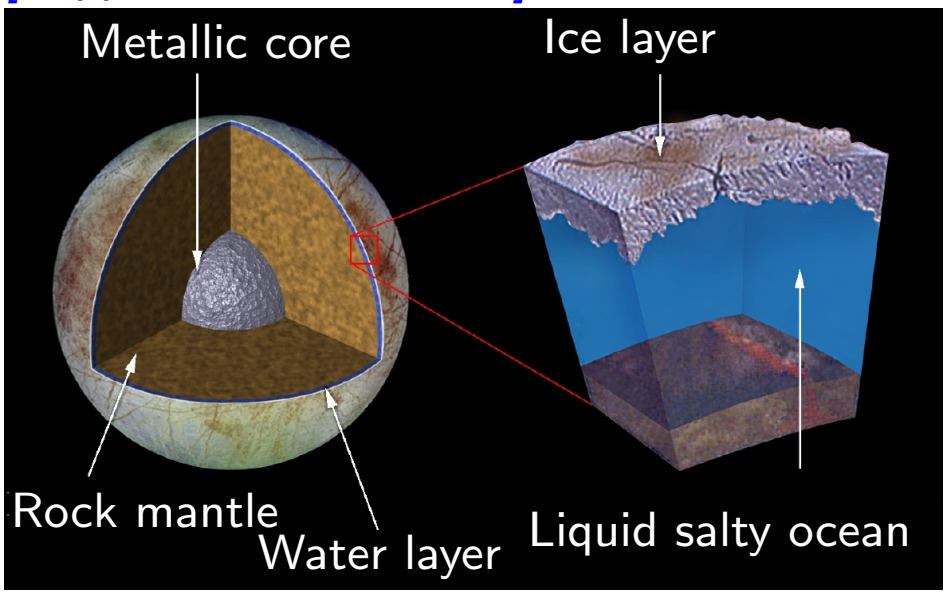

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Model Europa's subsurface ocean to predict the thickness of the ice

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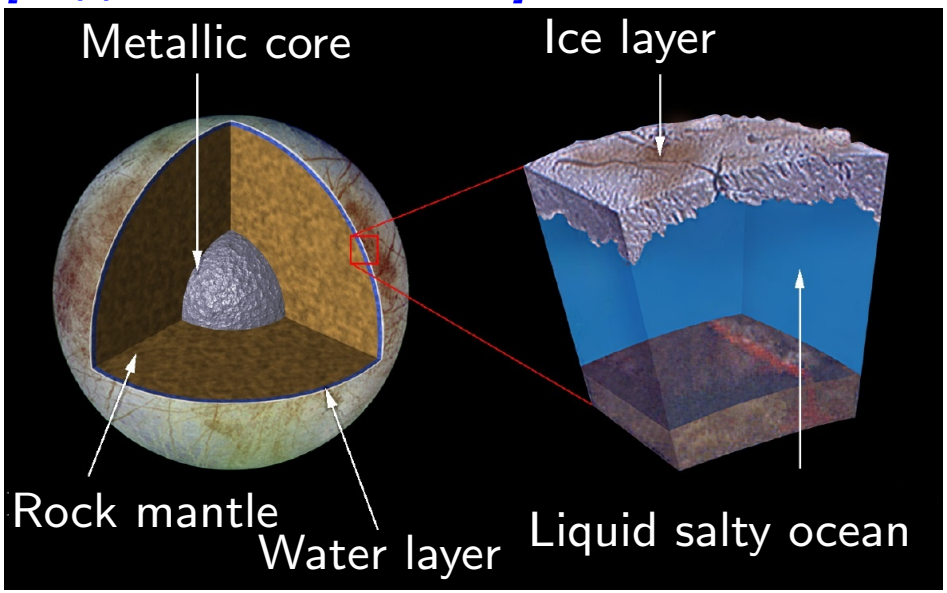

Possible forcing

- Convection *[Soderlund et al., 2014, Gastine et al., 2016]*
- Tides *[Tyler 2008, Lemasquerier et al. 2023]*
- Magnetic field of Jupiter *[Gissinger and Petitdemange 2019, Daniel et al. 2025]*
- Inertial waves *[Rovira-Navarro 2018]*
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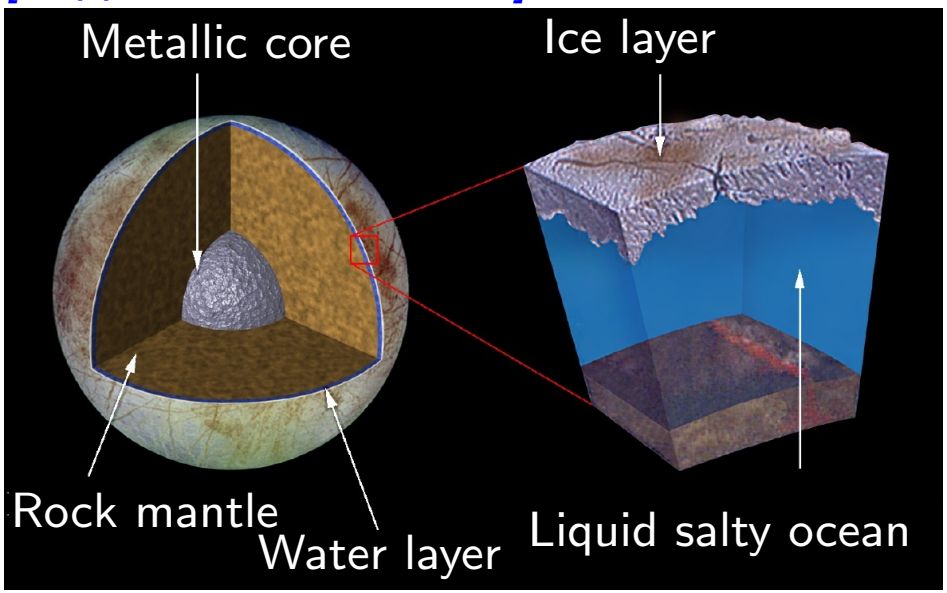

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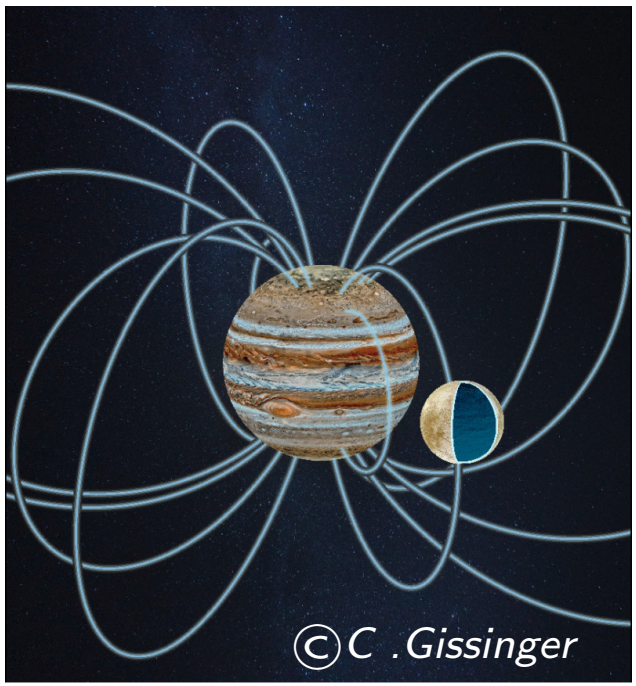

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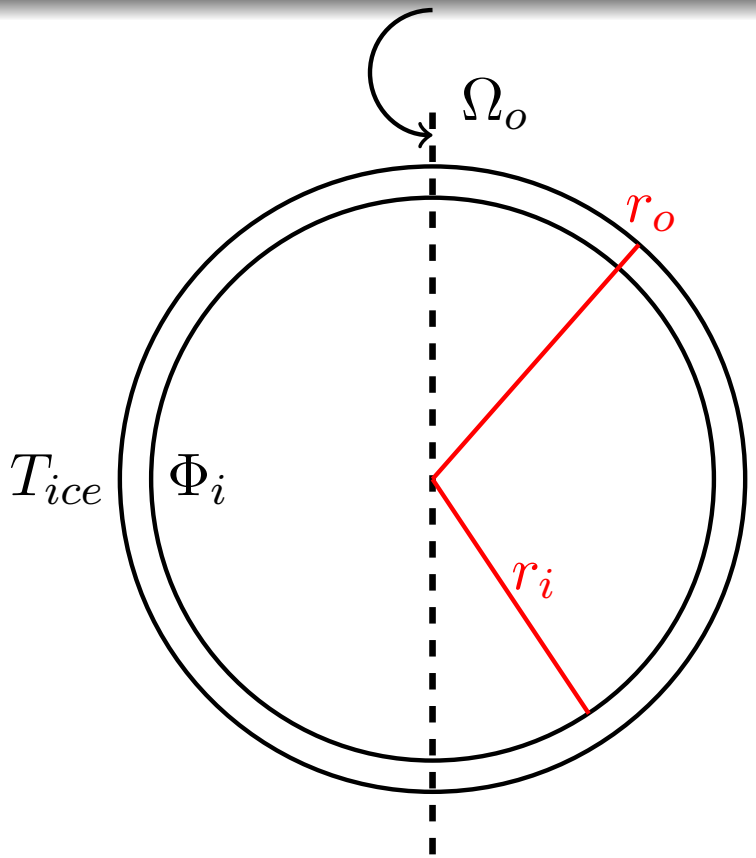
Model Europa's subsurface ocean to predict the thickness of the ice

Simulations



- Solve for $\mathbf{u}, \mathbf{B}, T$
- $r_i/r_o = 0.9$ (Europa $0.92 - 0.94$)
- Boussinesq
- constant ν, κ, η
- $d = r_o - r_i$

- BC for u: no slip
- BC for B: insulating
- BC for T: imposed flux at r_i and temperature at r_o
- Oscillating magnetic field $B_0(t)$
- PaRoDy code *[Dormy 1998, Aubert 2008, Schaeffer 2013]*

Dimensionless parameters

$$Ra^Q = \frac{\alpha_T \Phi_i g_o r_o^2 r_i^2}{\nu \kappa k},\ Ek = \frac{\nu}{r_o^2 \Omega_o},\ \widetilde{\Lambda} = \frac{B_o^2}{\rho \mu_0 \nu \Omega_o},\ Pr = \frac{\nu}{\kappa},\ Ek_\eta = \frac{\eta}{r_o^2 \Omega_o}$$

	Ra^Q	Ek	$\widetilde{\Lambda}$	Pr	Ek_η
DNS	$10^5 - 10^{12}$	$10^{-5} - 10^{-4}$	$1 - 3.10^3$	12	10^{-2}
Europa	$10^{31} - 10^{32}$	$10^{-14} - 10^{-13}$	10	12	$10^{-3} - 10^{-2}$

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- thermal Ra^Q
- magnetic $\widetilde{\Lambda}$

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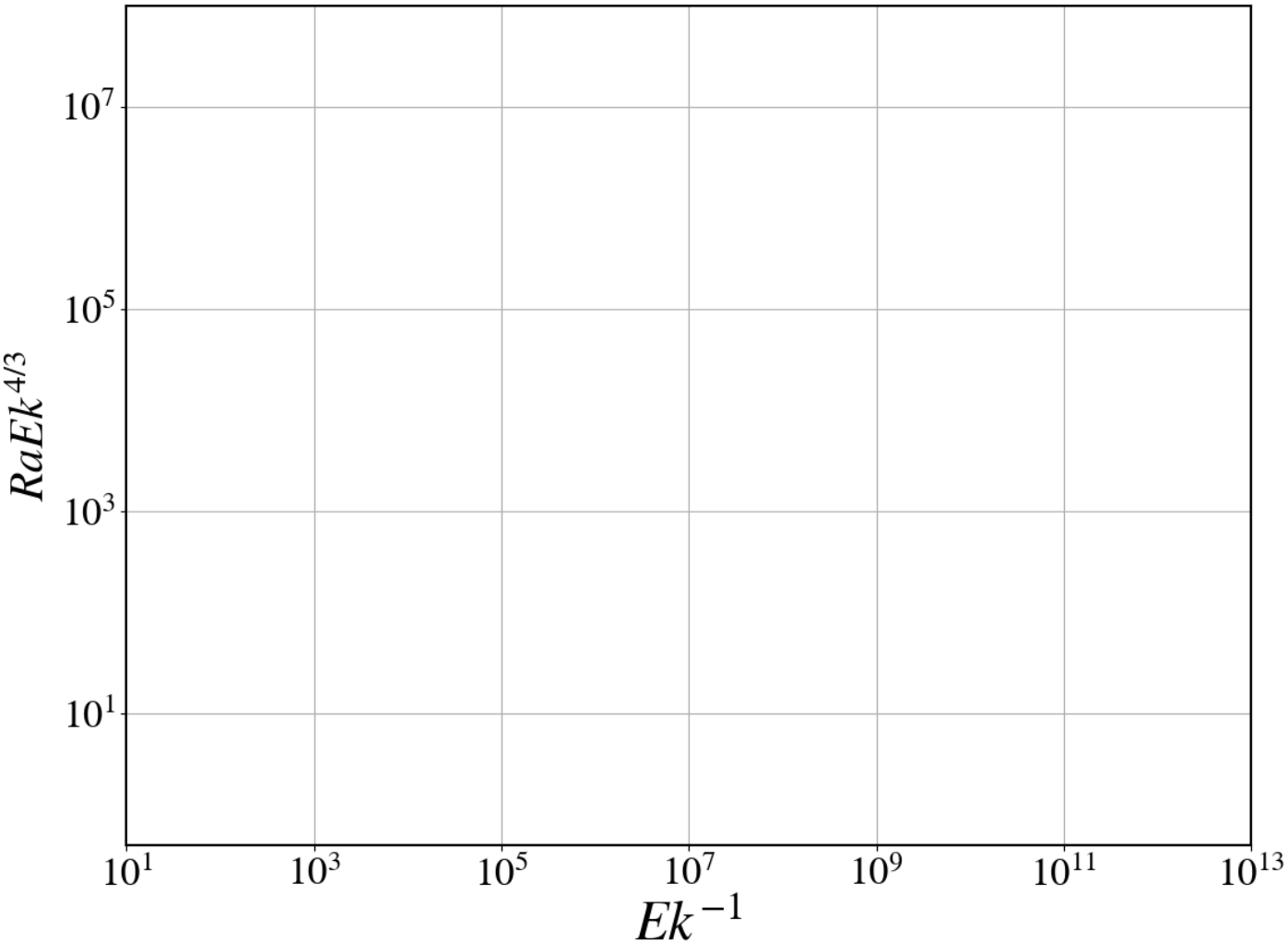
Ouputs:

- e.g. $Nu = \dfrac{\Phi}{k \Delta T / d}$

Limit $\Lambda = 0$: Rotating Rayleigh-Bénard convection



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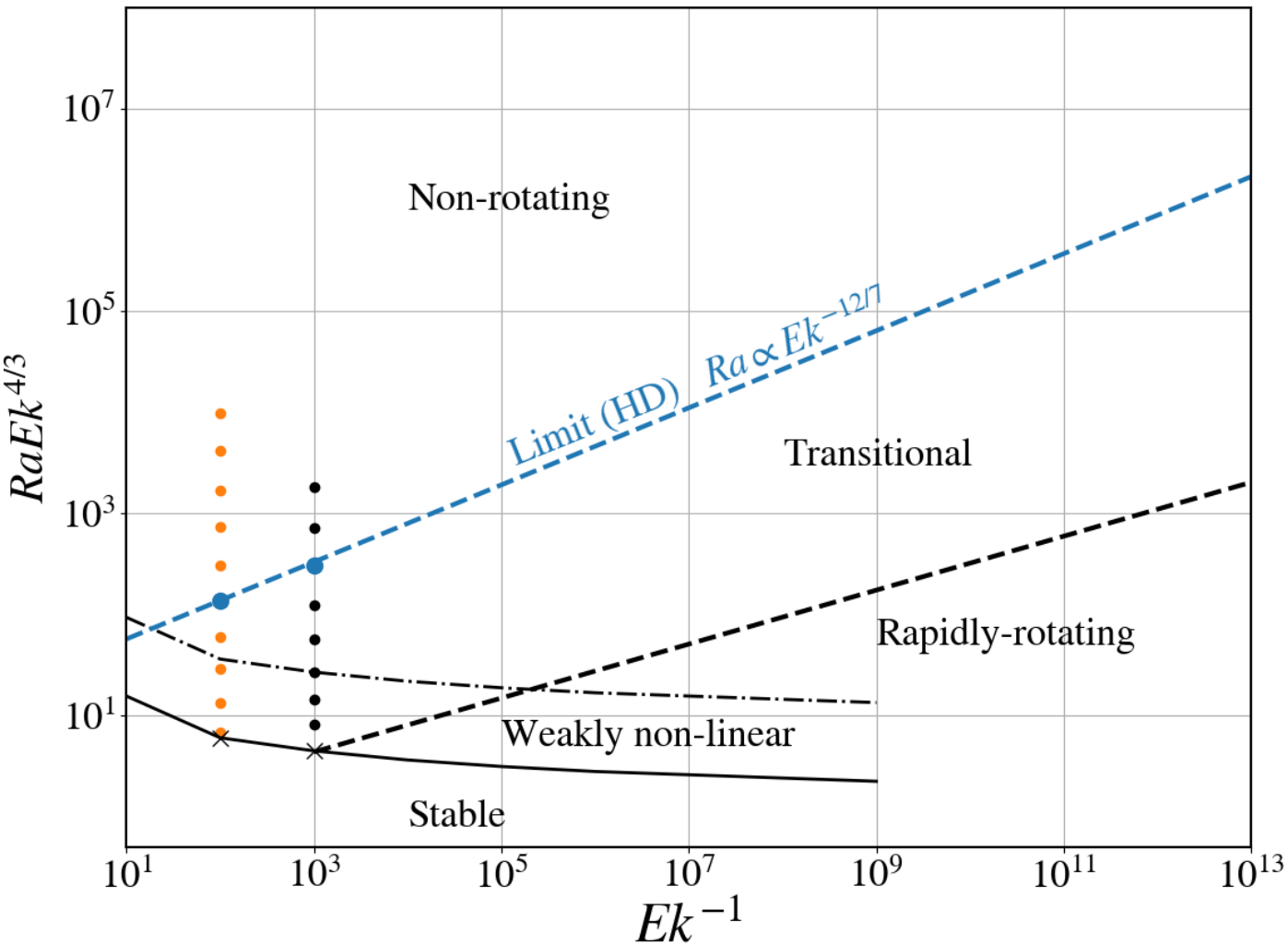

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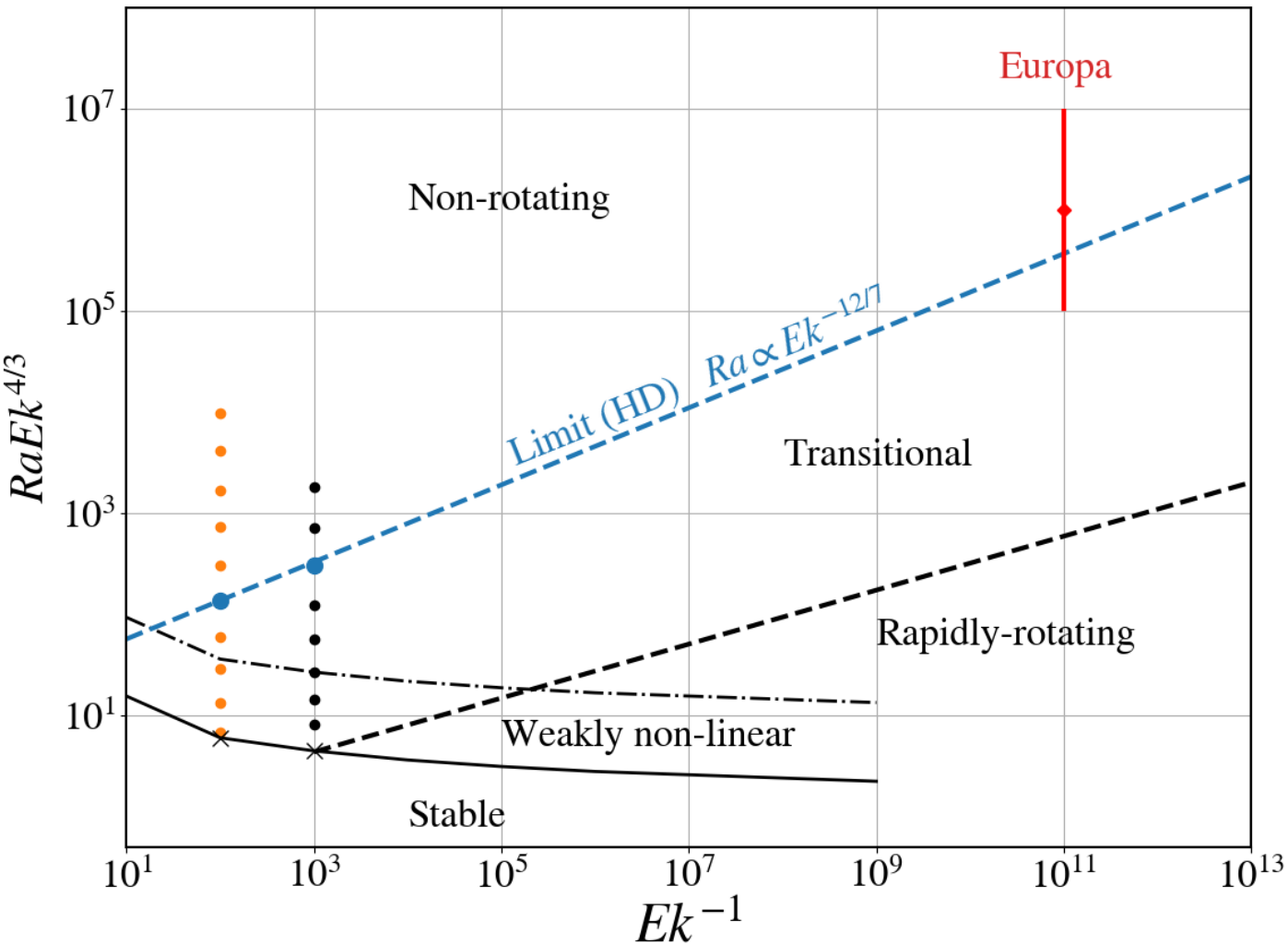

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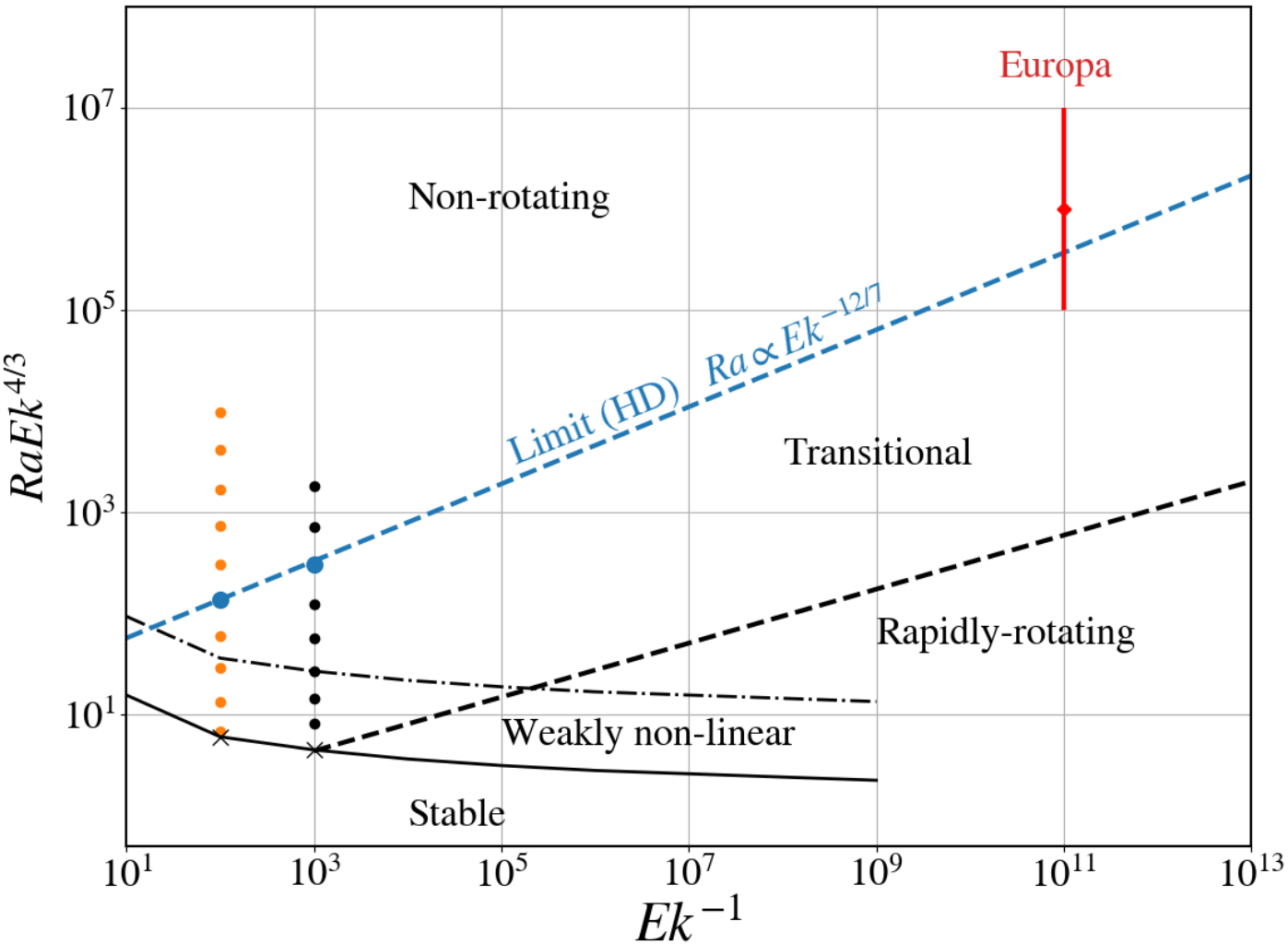

Figure: Regime diagram adapted from *[Lemasquerier et al., 2023]* and *[Gastine et al., 2016]* for RRBC.

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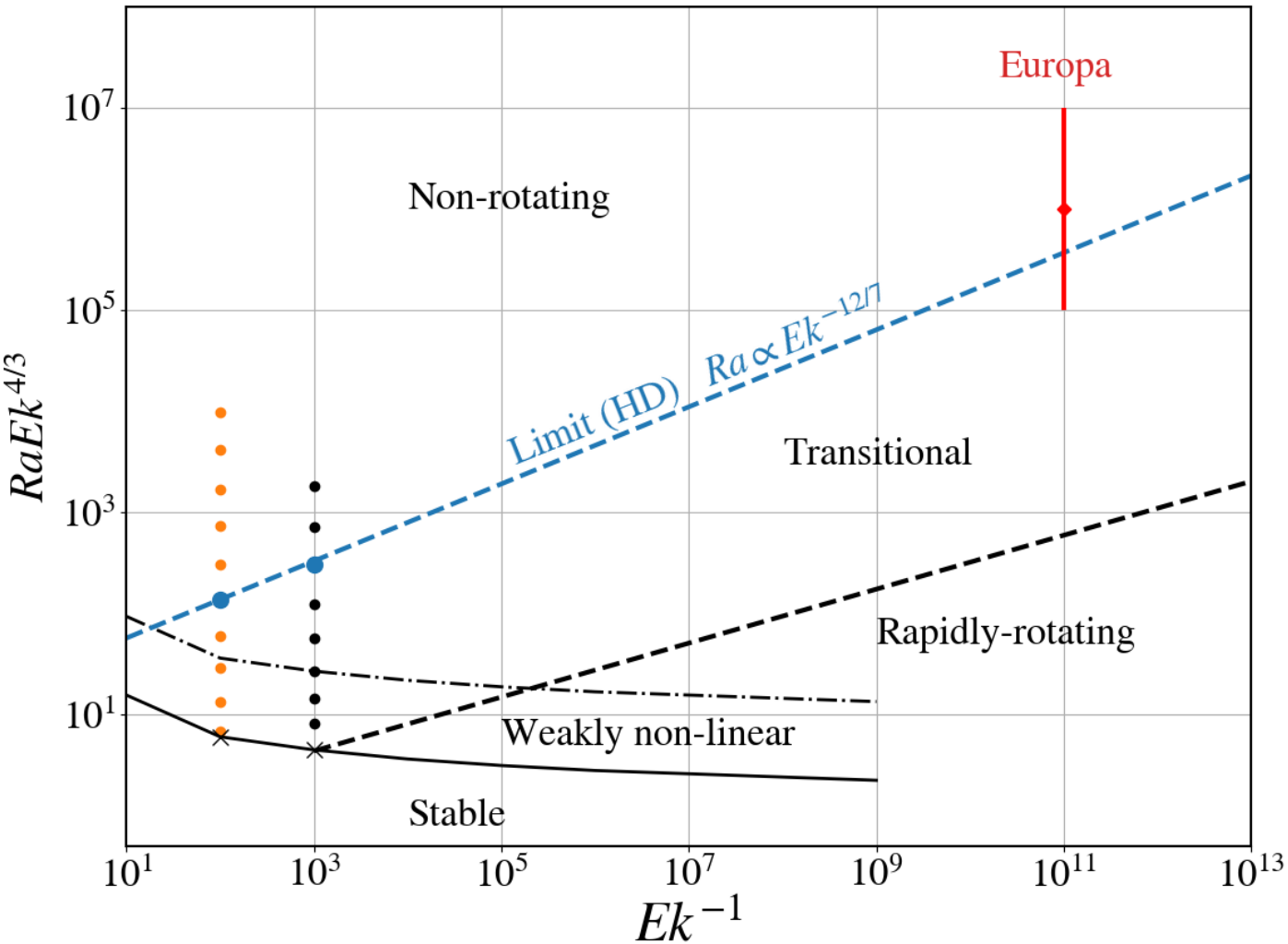

Figure: Regime diagram adapted from *[Lemasquerier et al., 2023]* and *[Gastine et al., 2016]* for RRBC. Purely hydrodynamical

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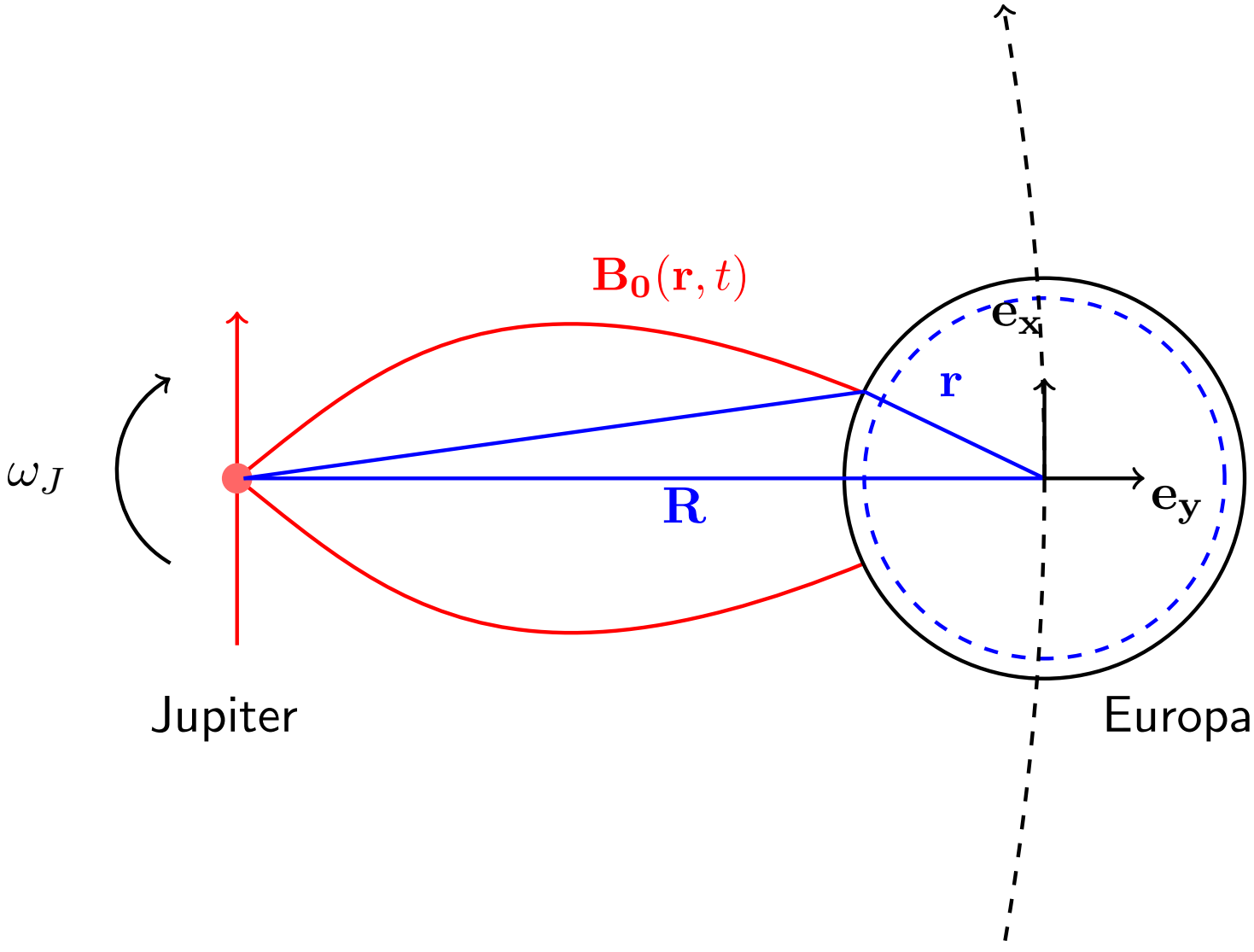

Figure: Top view sketch

Limit $Ra^Q = 0$: Geometry and amplitude of the flow *[Gissinger and Petitdemange 2019]*

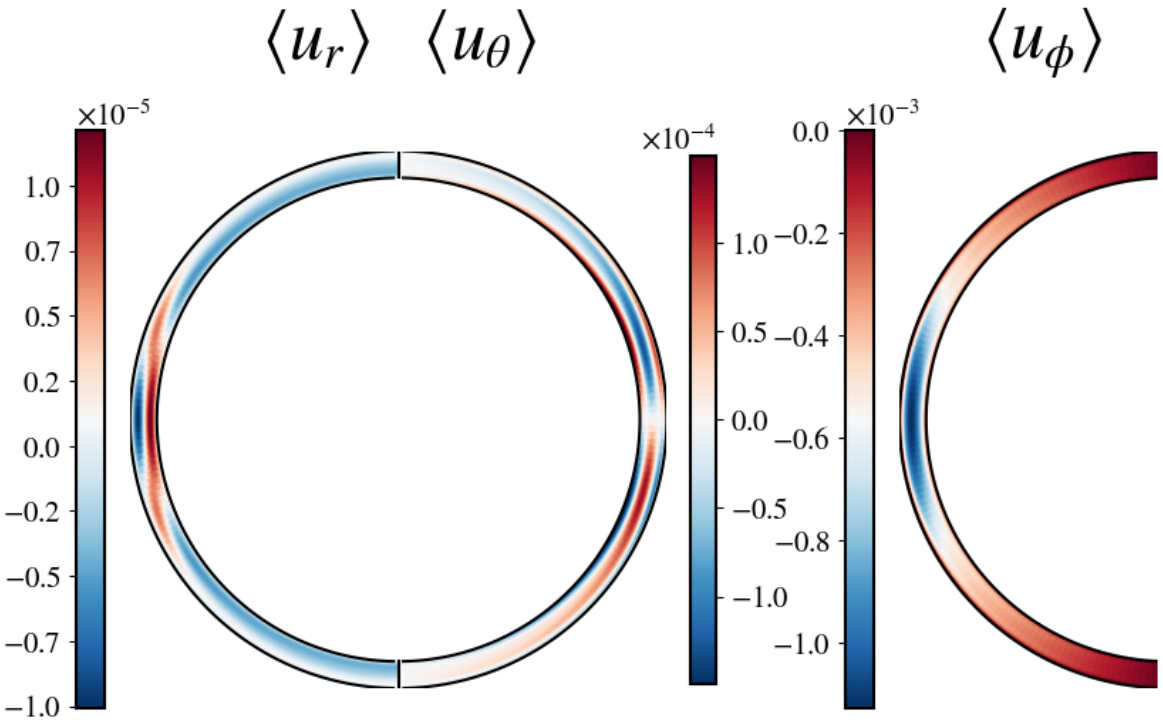

Figure: Meridional cuts of azimuthally averaged u_r, u_θ, u_ϕ for $Ek = 10^{-4}$, $\widetilde{\Lambda} = 1$.

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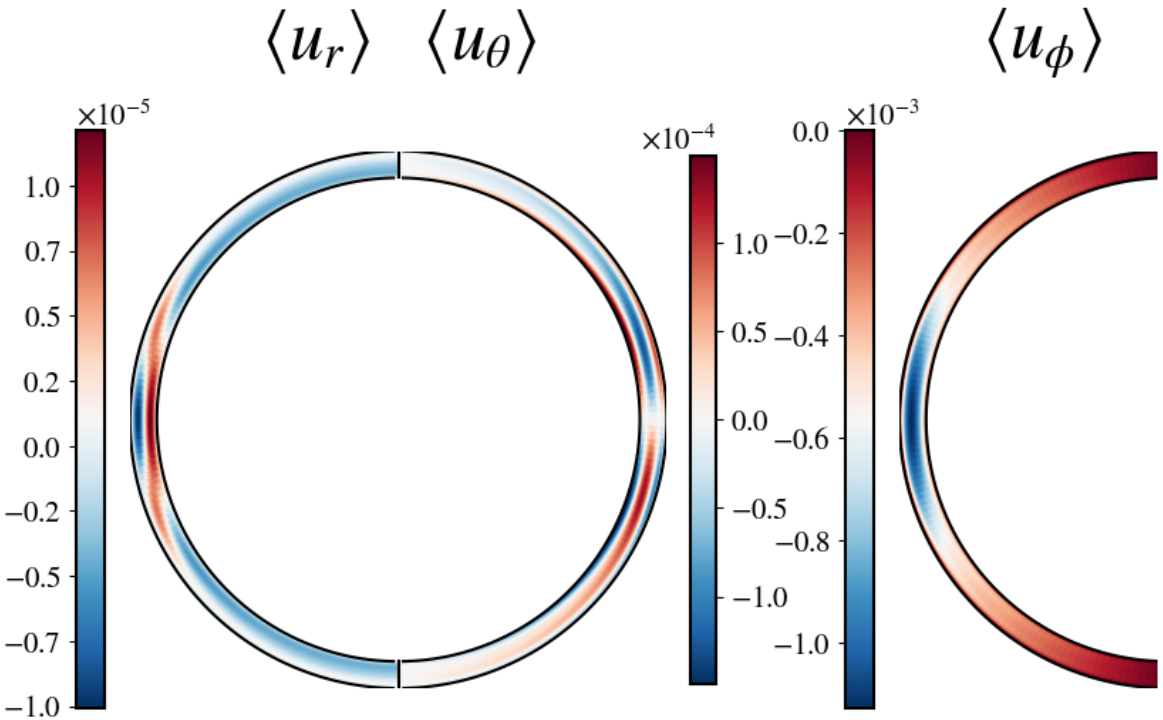


Estimate of the jet velocity for Europa:

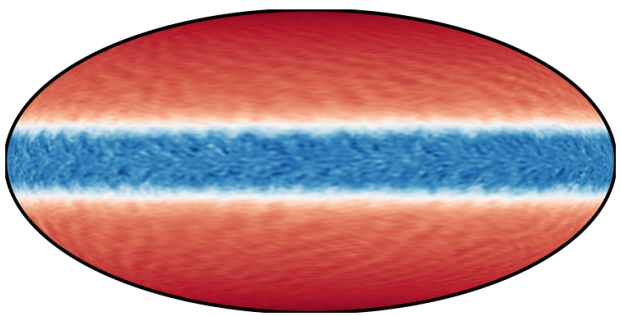
$$1 - 100\, cm/s$$

Figure: Meridional cuts of azimuthally averaged u_r, u_θ, u_ϕ for $Ek = 10^{-4}$, $\widetilde{\Lambda} = 1$.

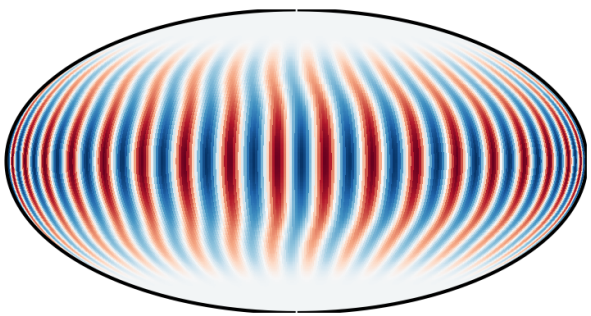
Combined forcings: $\Lambda, Ra^Q \neq 0$

- Fixed rotation $Ek = 10^{-4}$
- Four different amplitudes of the jet $\widetilde{\Lambda} \in [1, 10, 100, 3000]$
- Increase Ra^Q
- Known threshold of convection for $\widetilde{\Lambda} = 0$

$$Nu = \frac{\Phi}{k\Delta T/d} \tag{1}$$



Magnetically-driven jet



Convection

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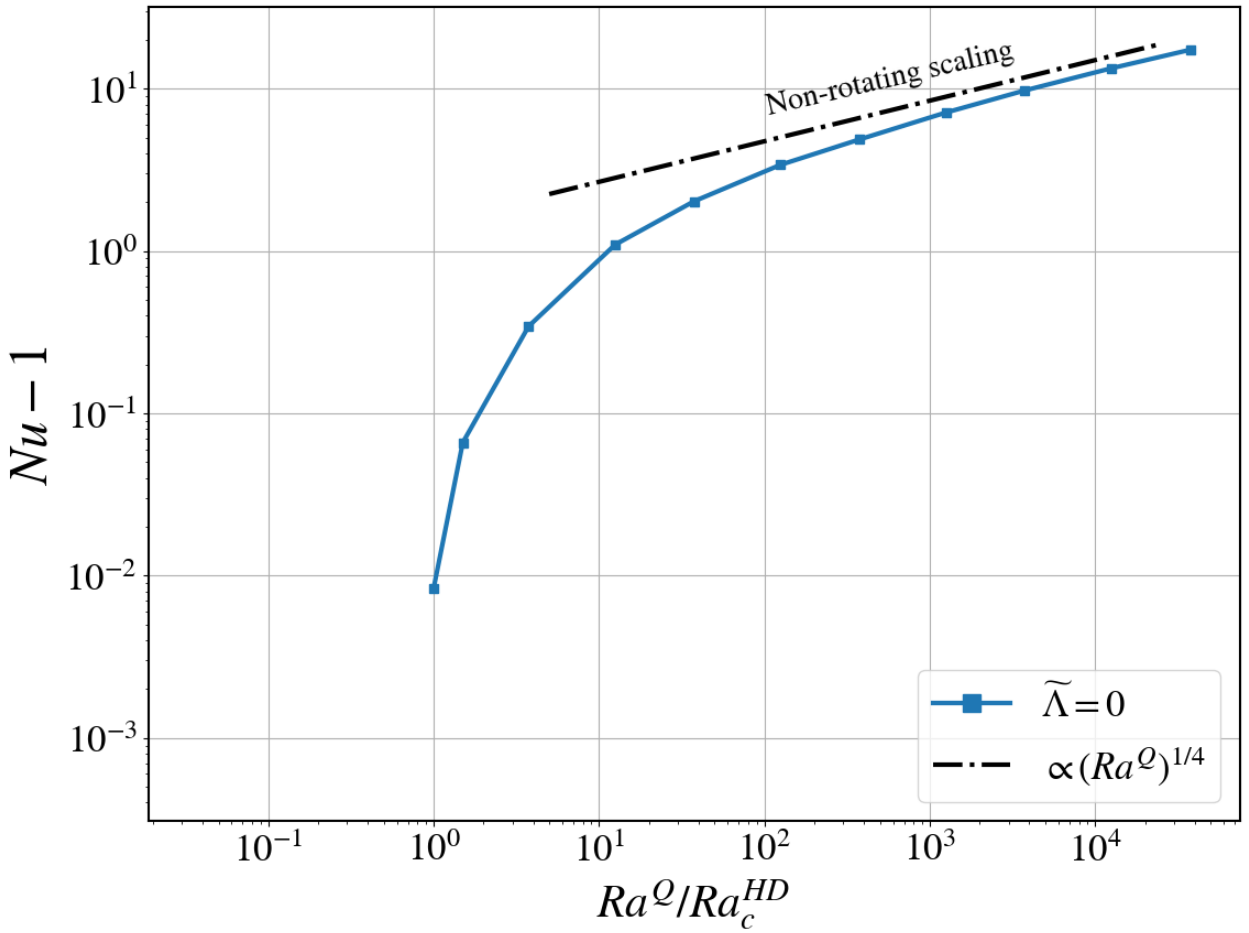

Figure: Evolution of the Nusselt number for $Ek = 10^{-4}$, $Ek_\eta = 10^{-2}$, $Pr = 12$ and different values of $\widetilde{\Lambda}$.

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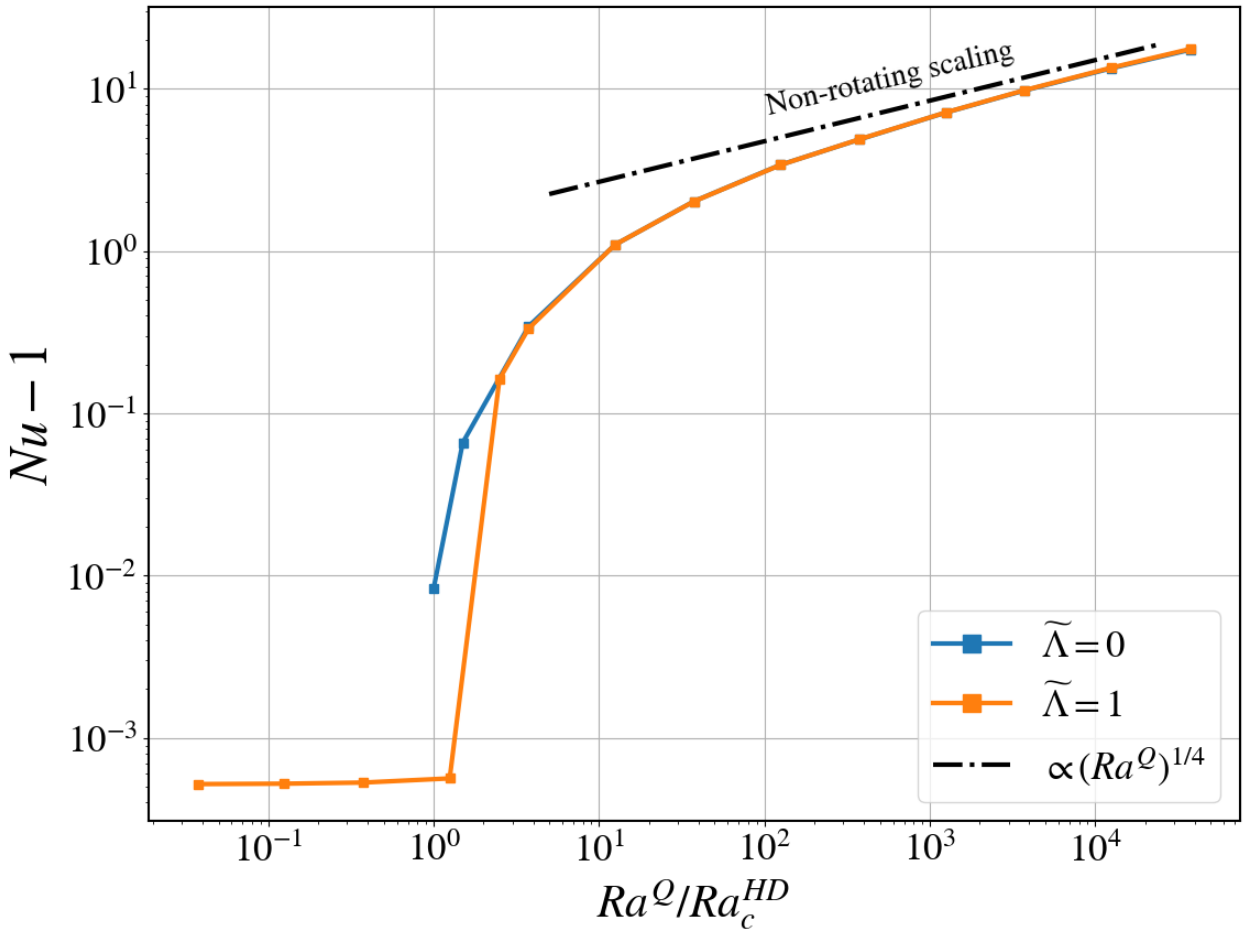

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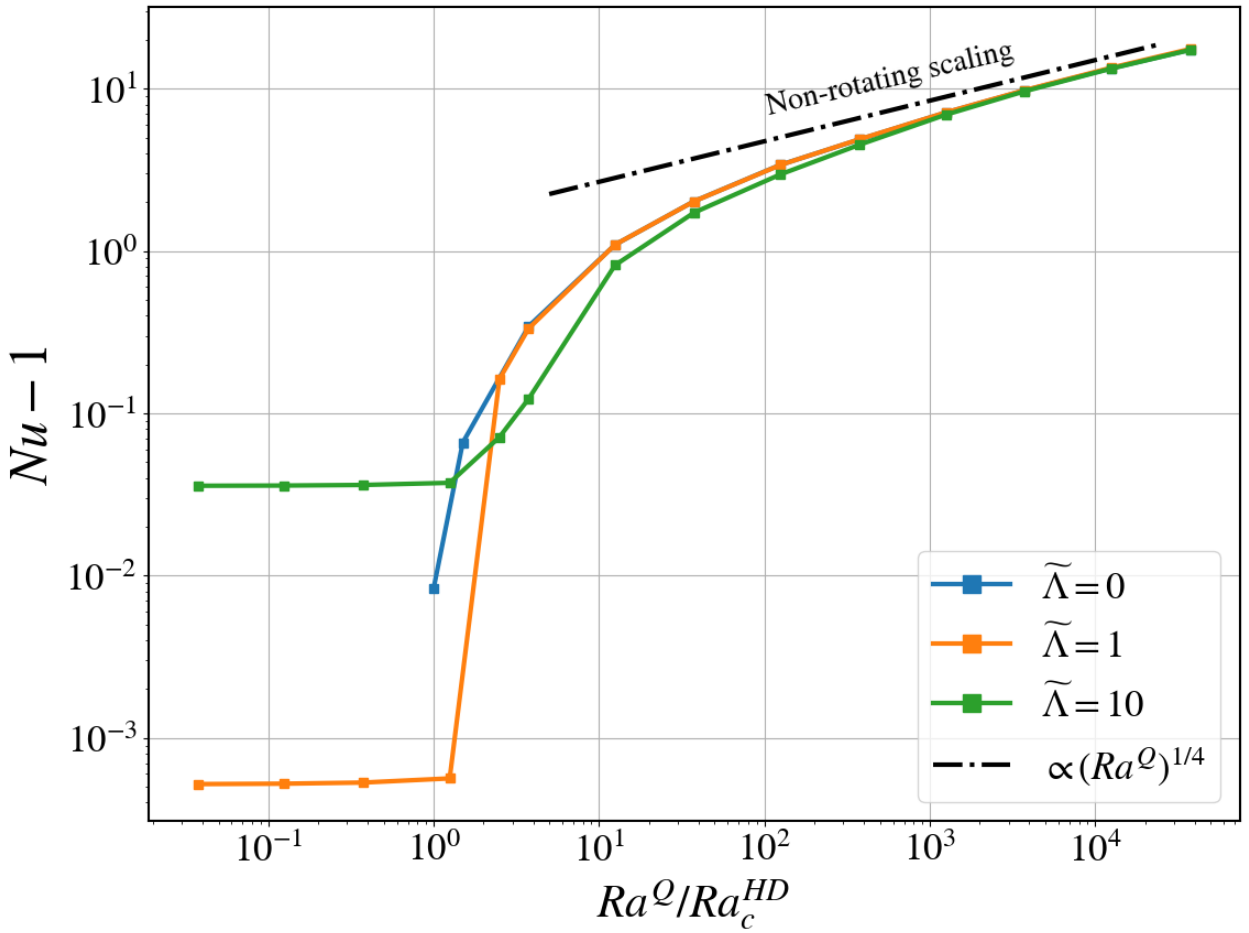

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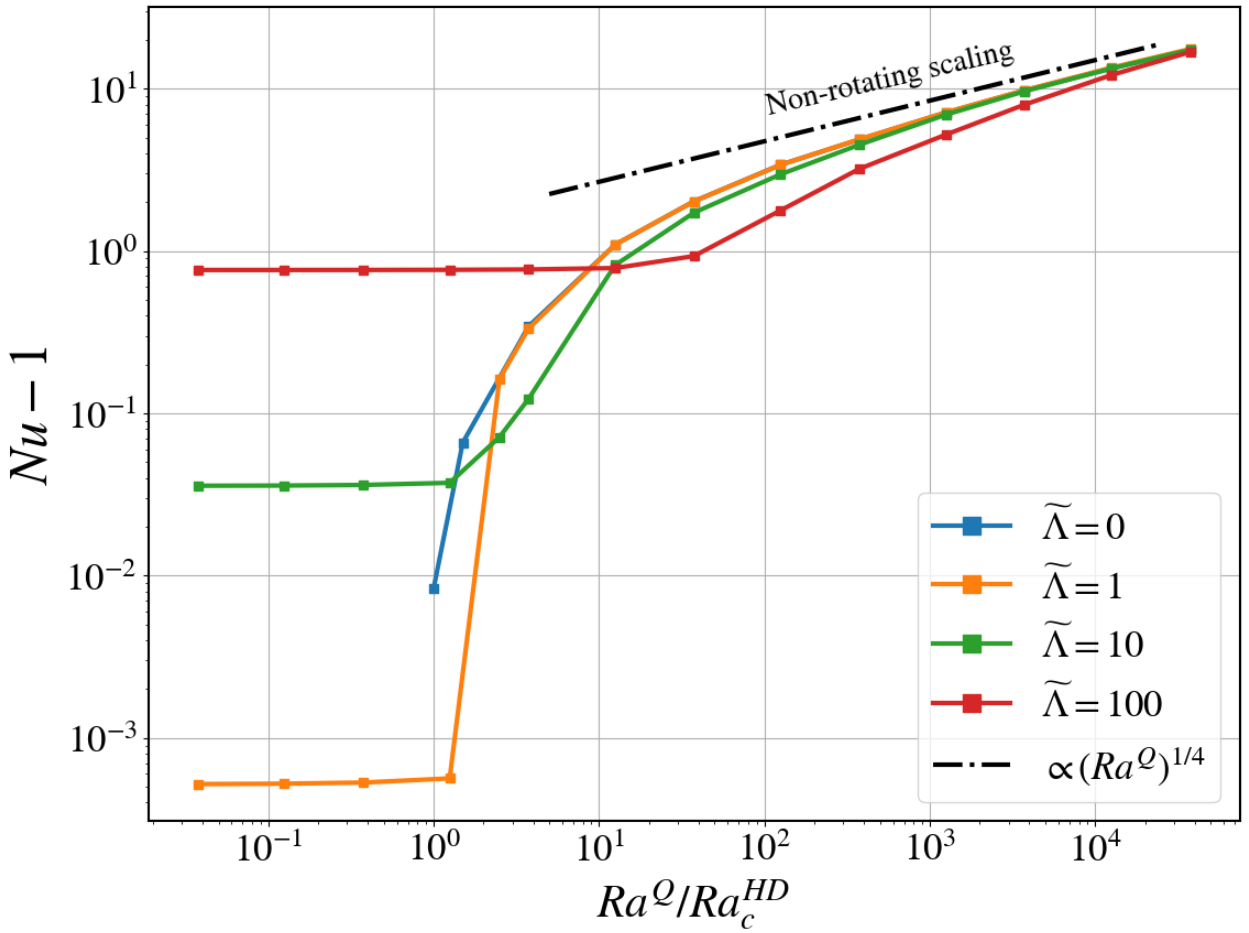

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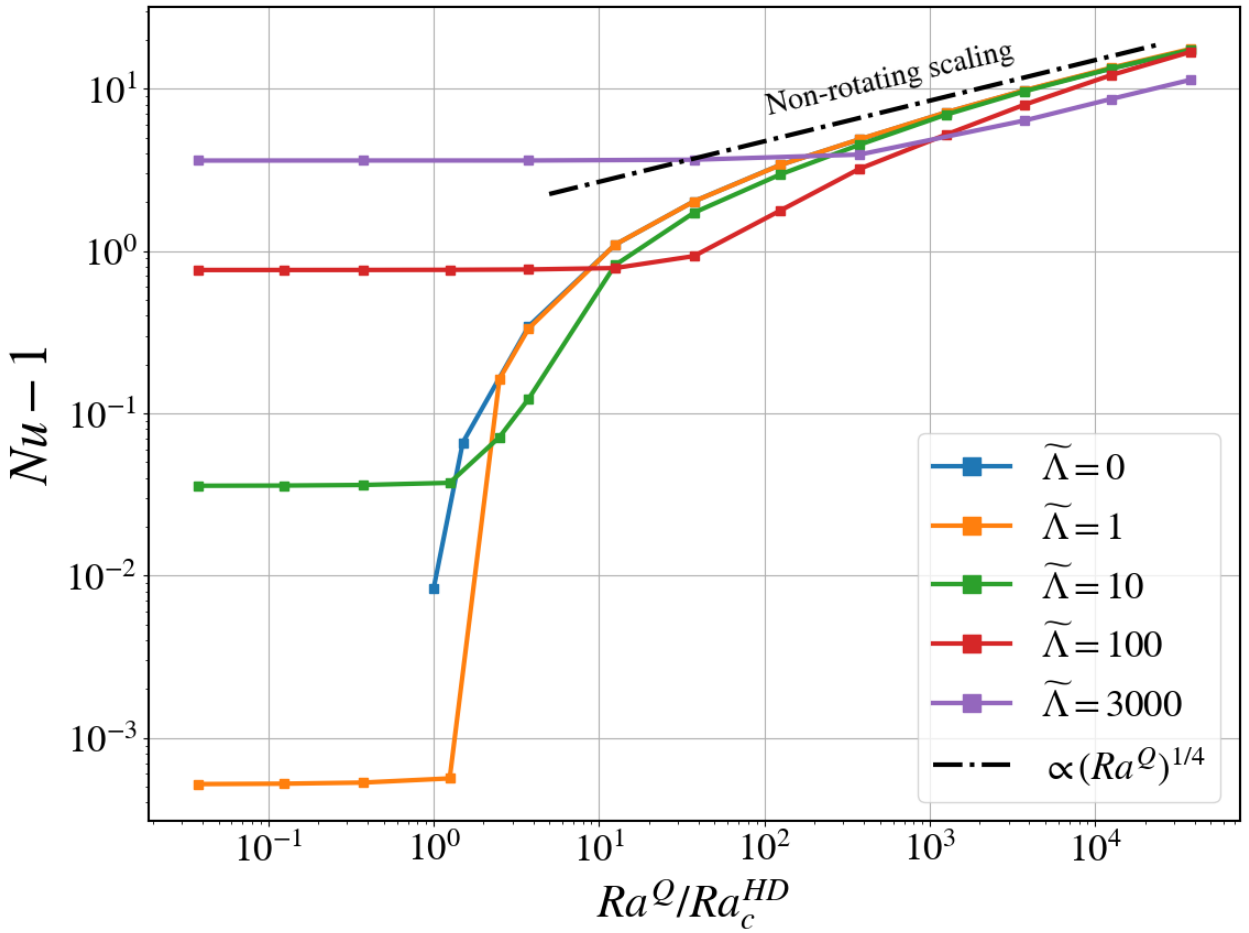

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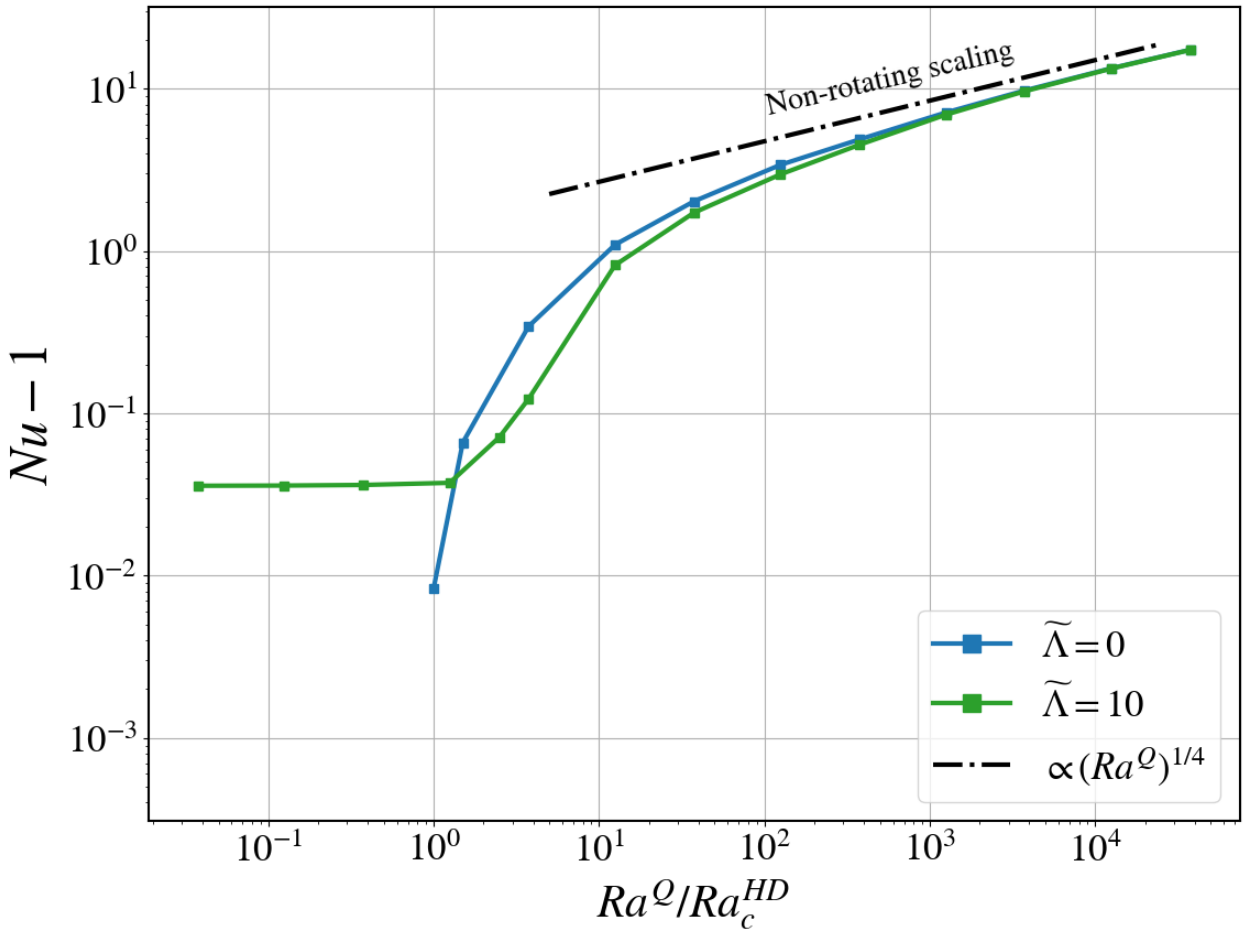
Modified thresholds: transition to NR regime



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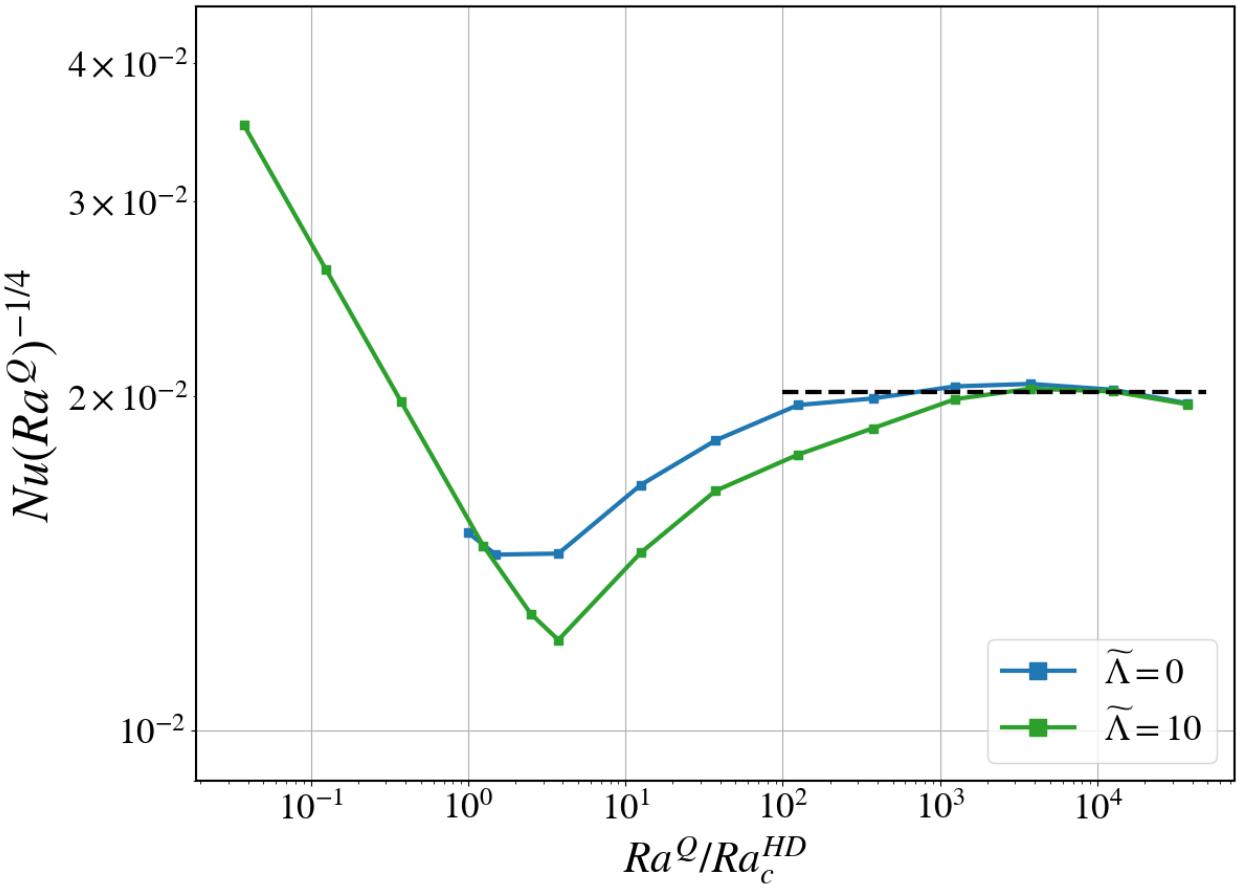

Figure: Evolution of $Nu(Ra^Q)^{-1/4}$ for $\widetilde{\Lambda} = 0$ or 10 for $Ek = 10^{-4}$, $Ek_\eta = 10^{-2}$, $Pr = 12$.

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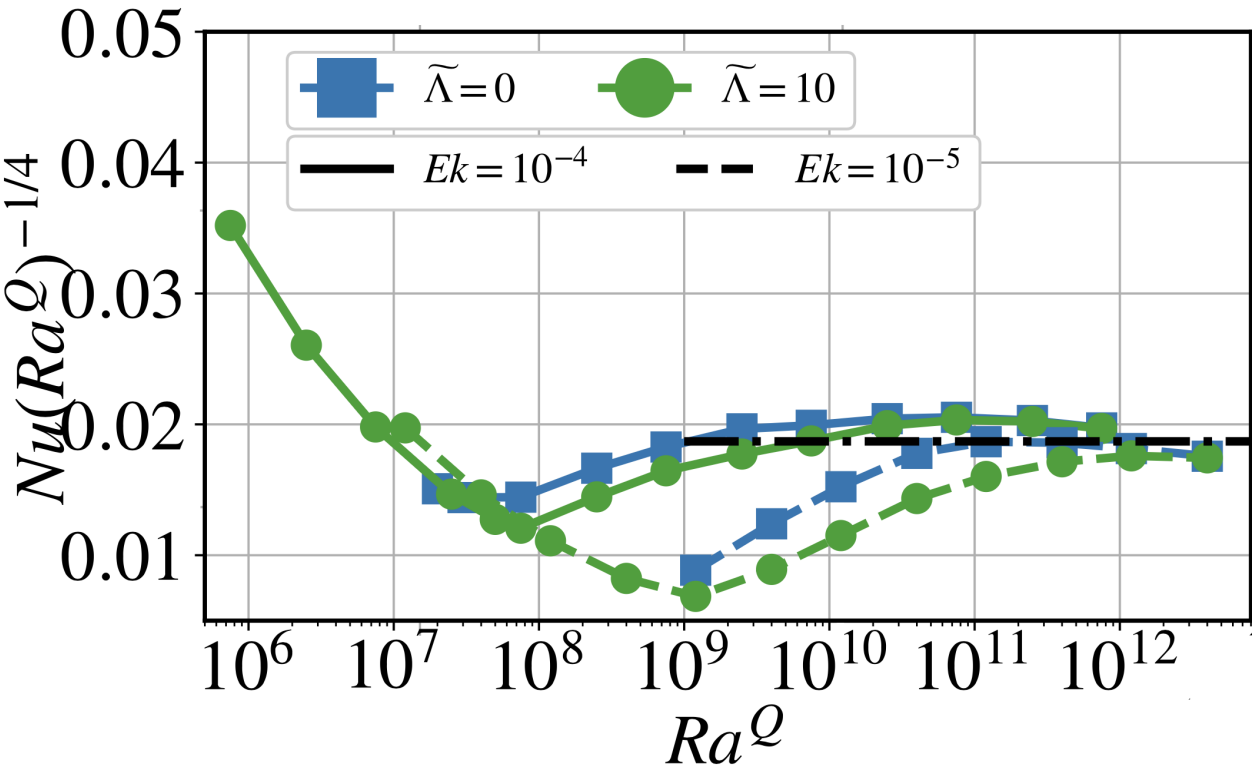

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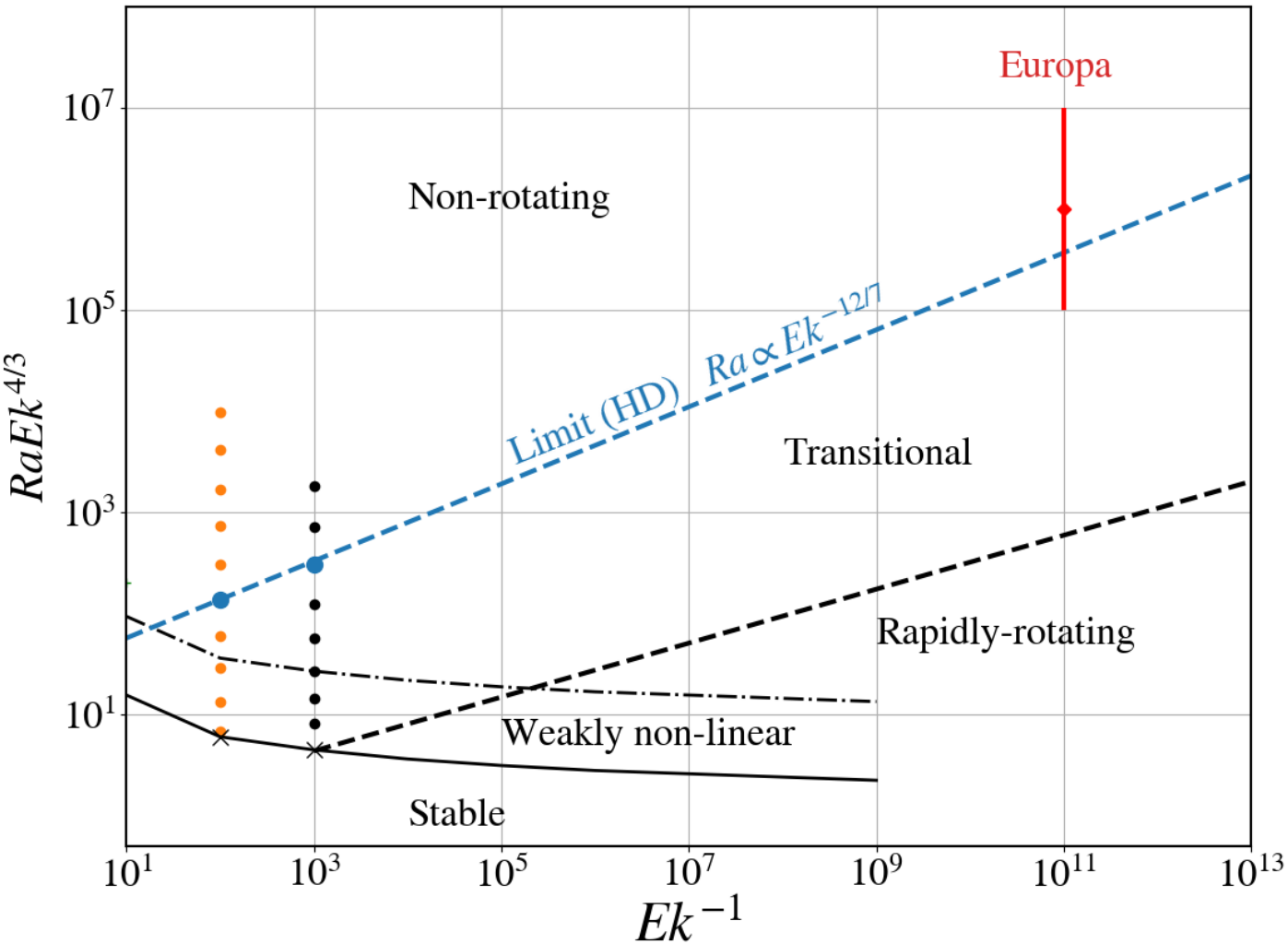
What about Europa? Importance of the thresholds



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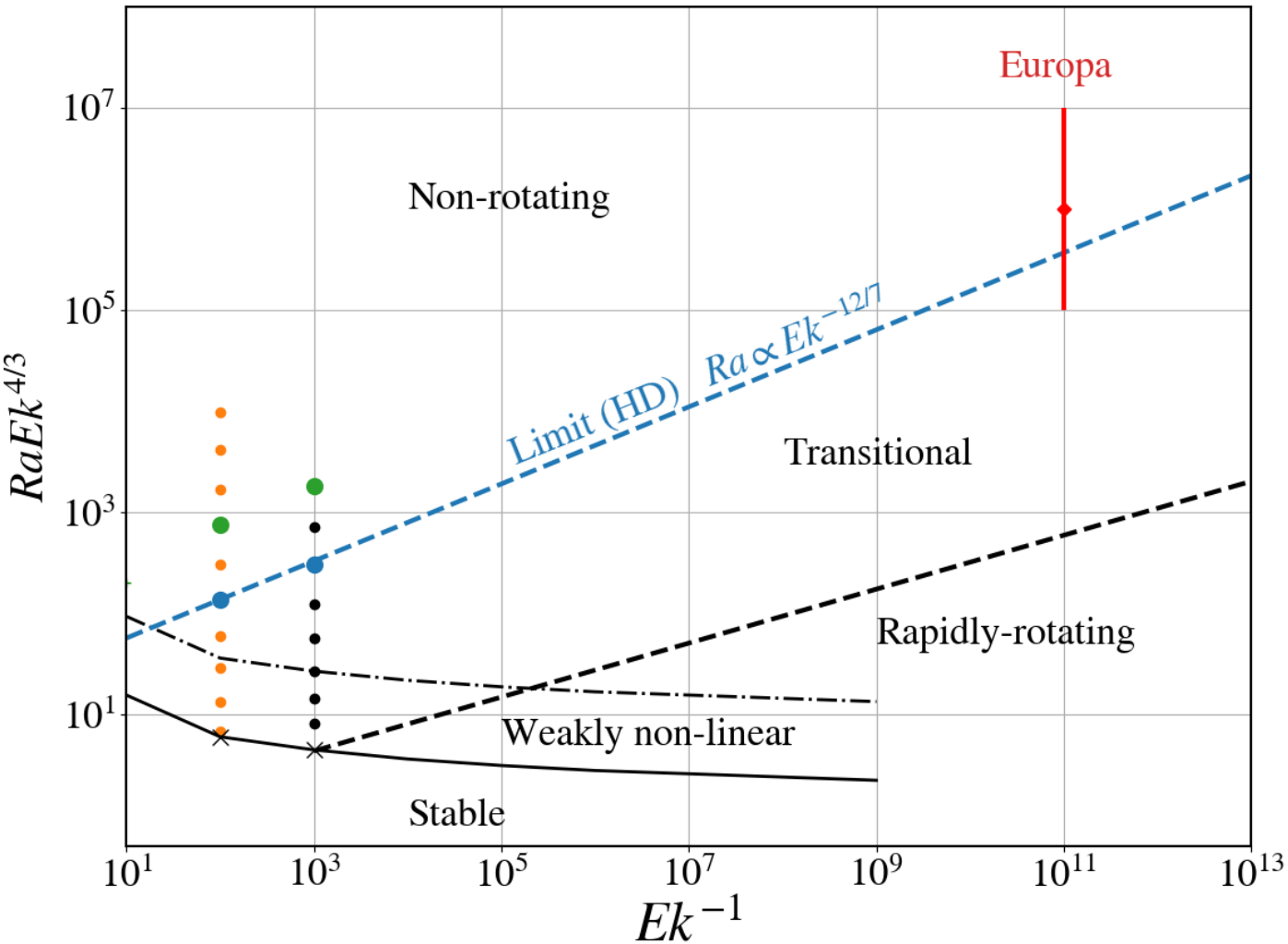

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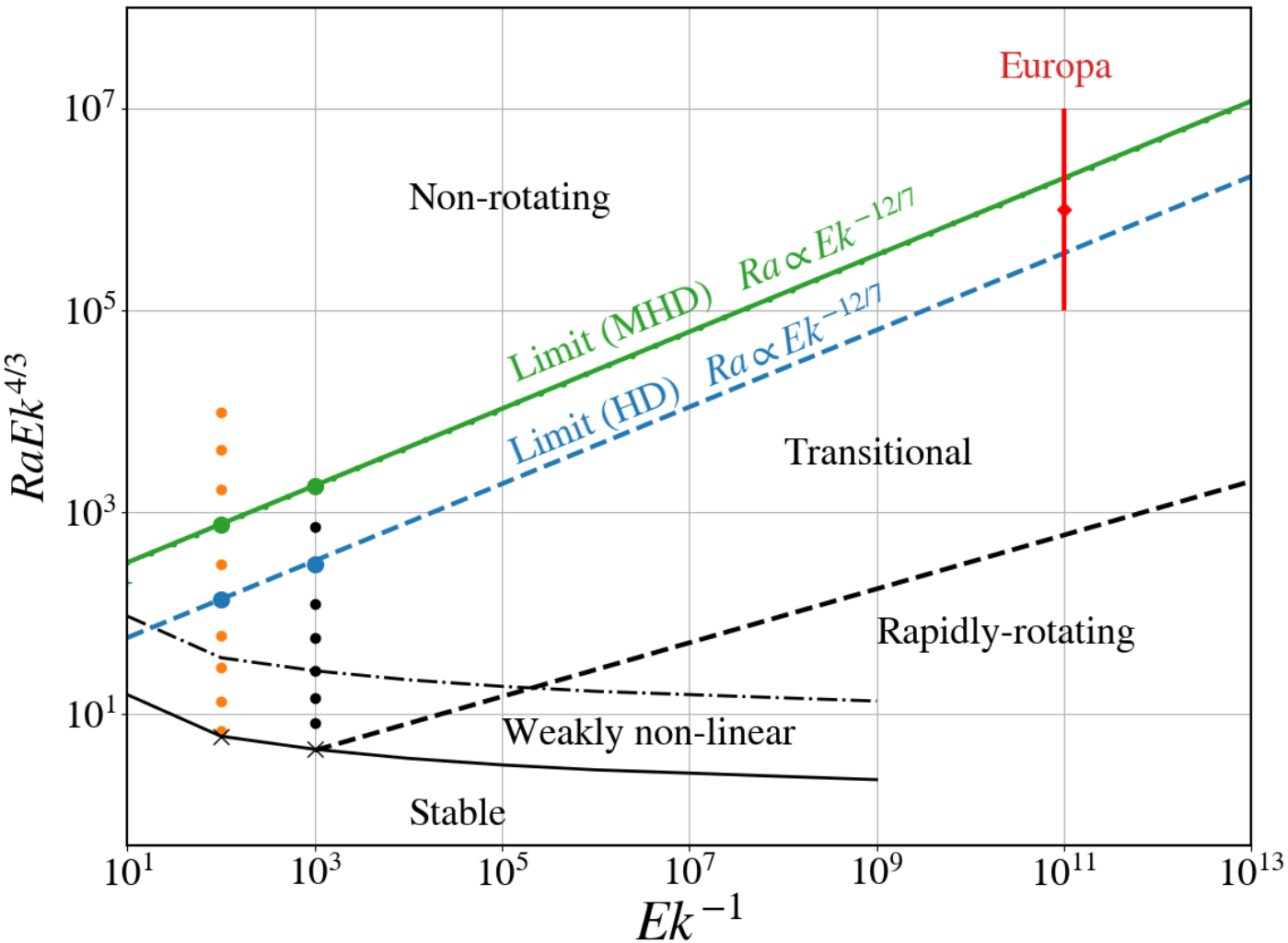

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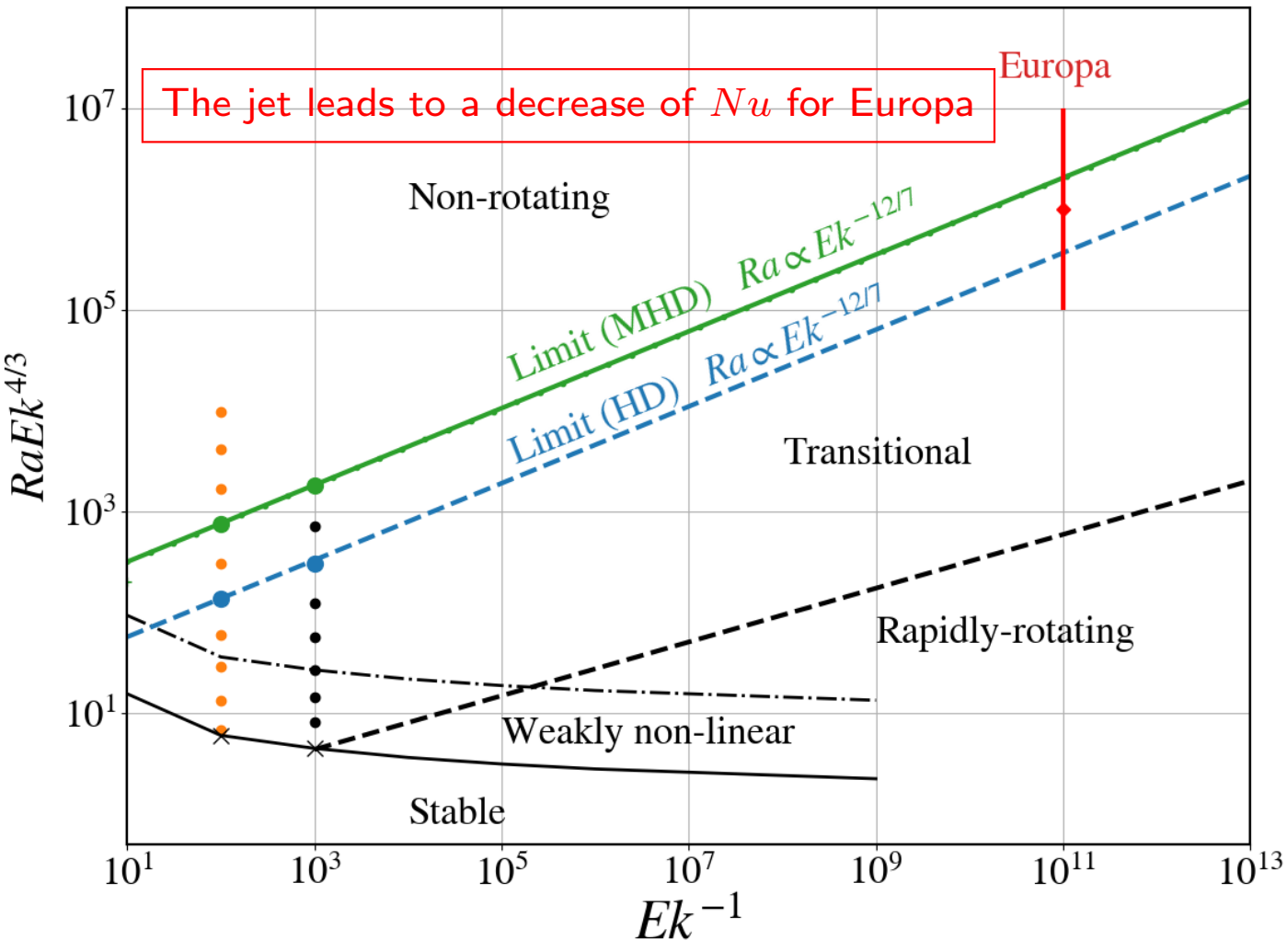
CCL1



[Daniel et al.2025]

Heat flux and ice thickness

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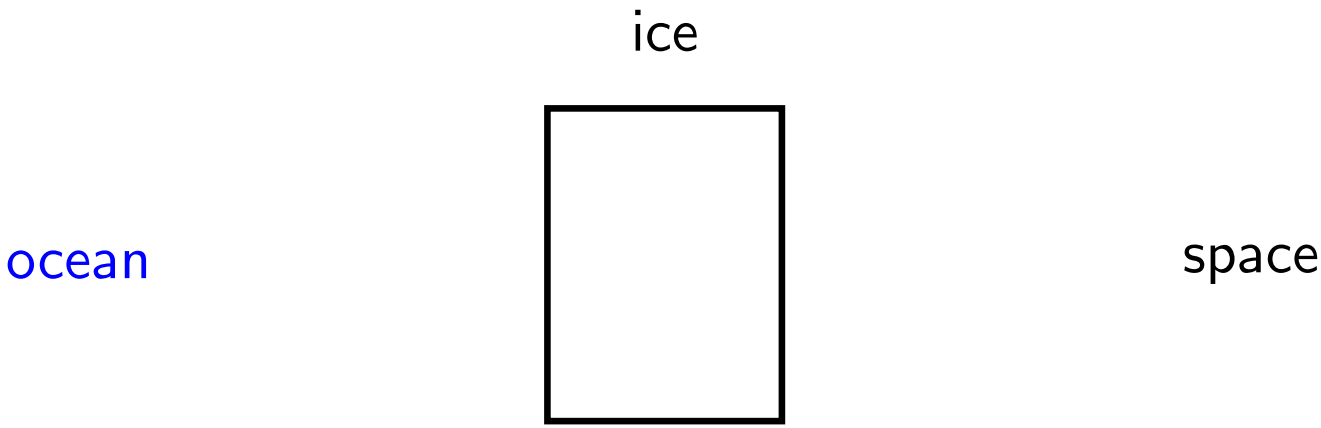

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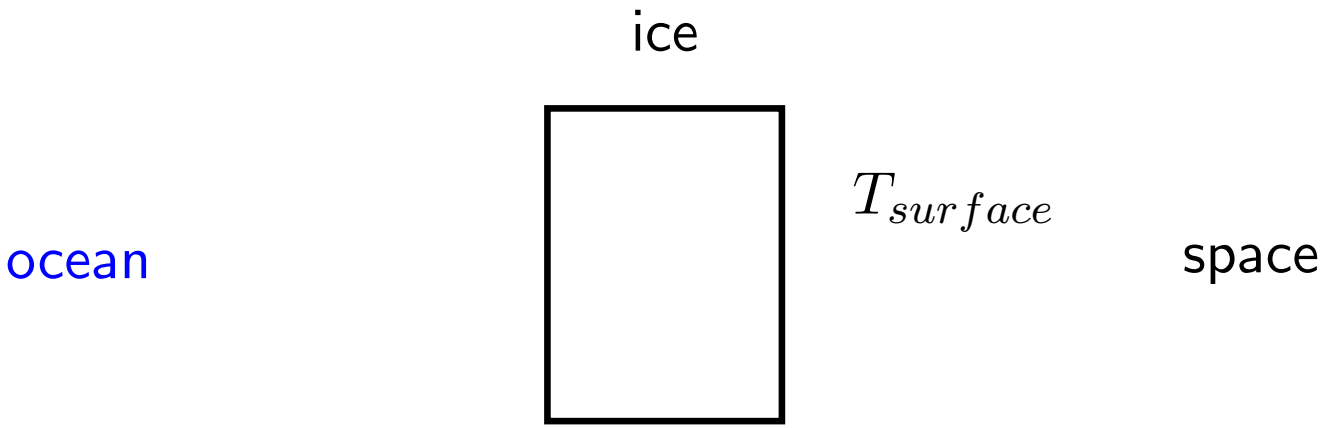

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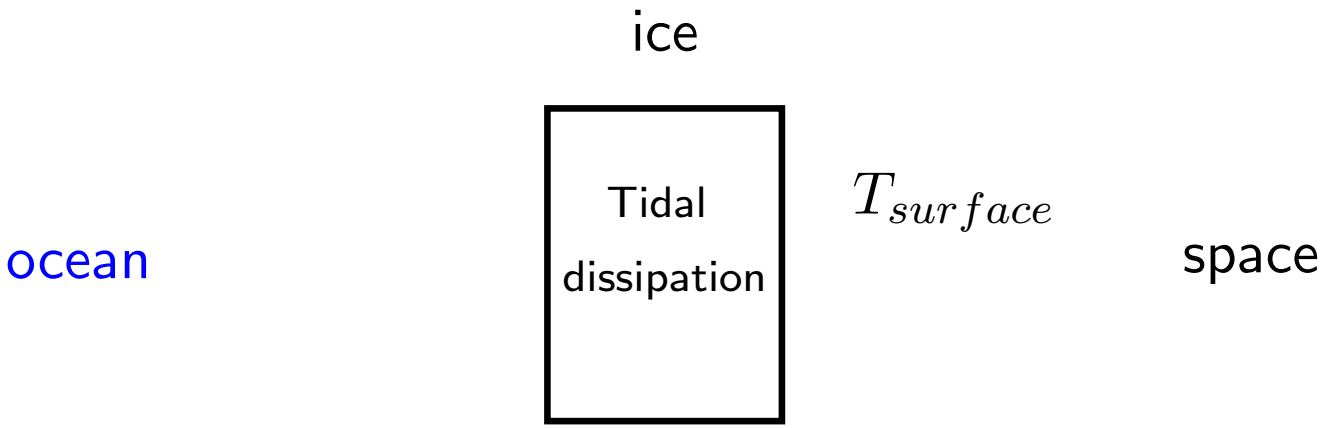

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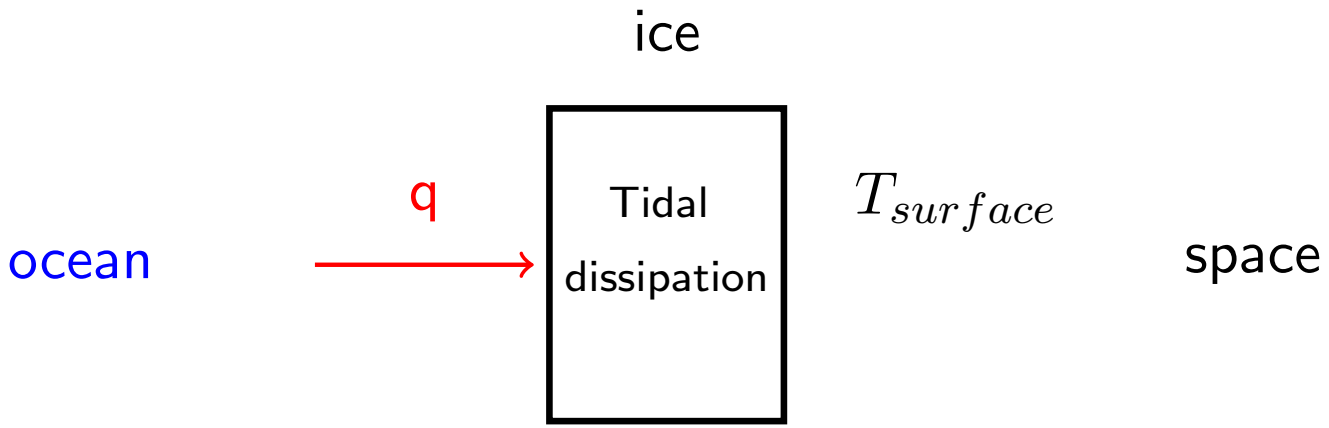
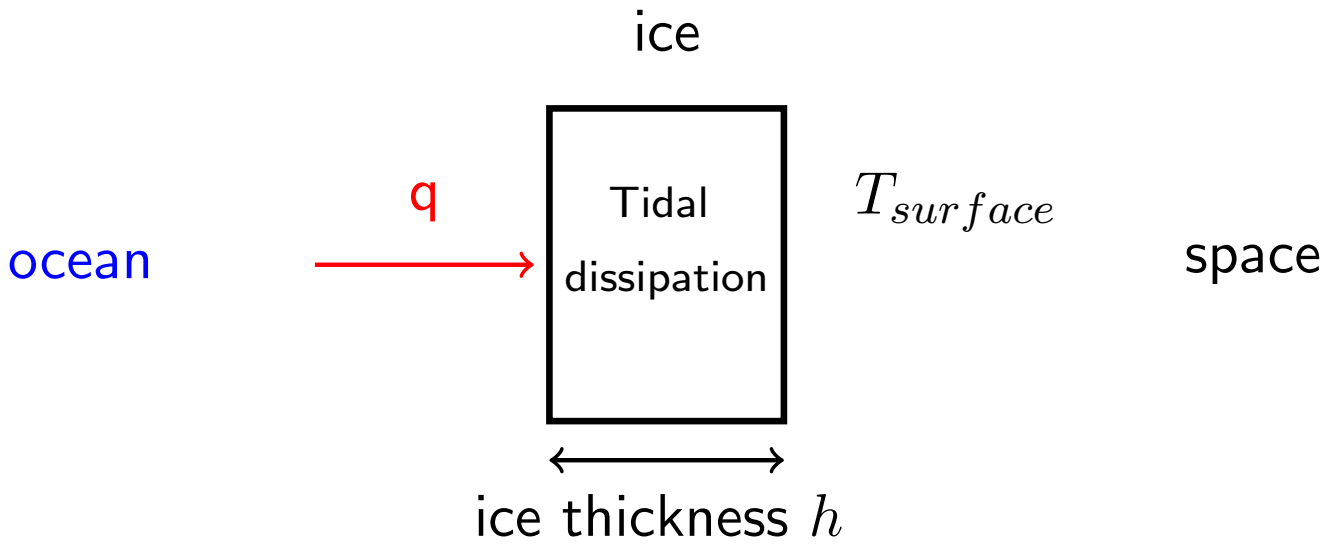
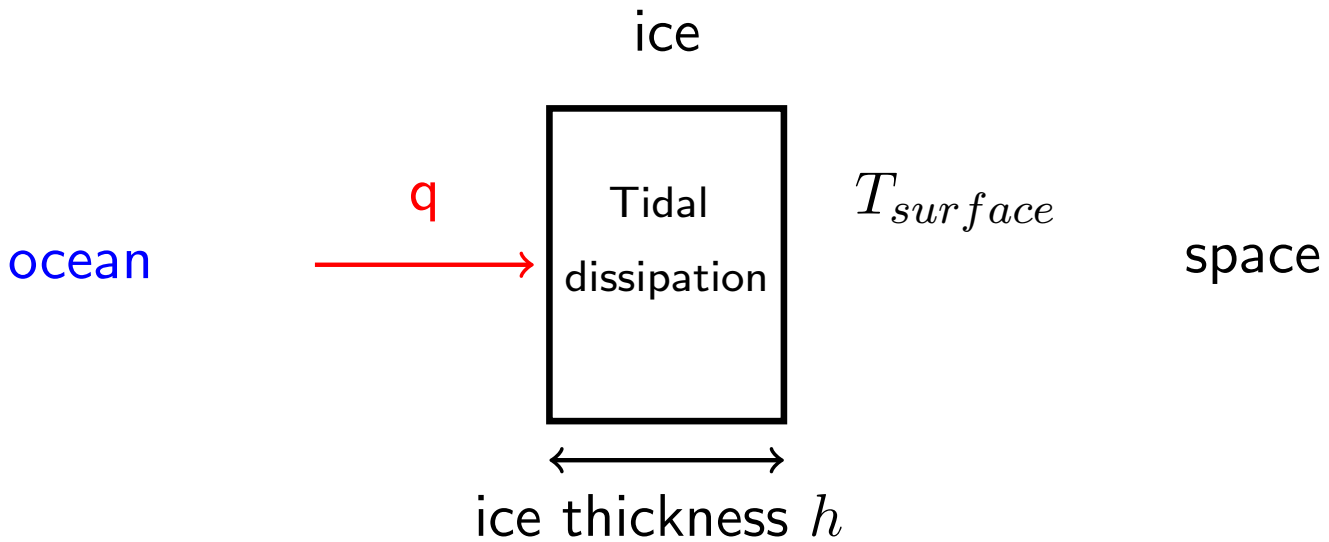


Heat flux and ice thickness



Heat flux and ice thickness

Heat flux at the ice/ocean interface $q = -k\frac{\partial T}{\partial r}|_{r=r_o}$: constraint on the ice thickness h *[Nimmo et al. 2007]*.



Heat flux and ice thickness (HD)

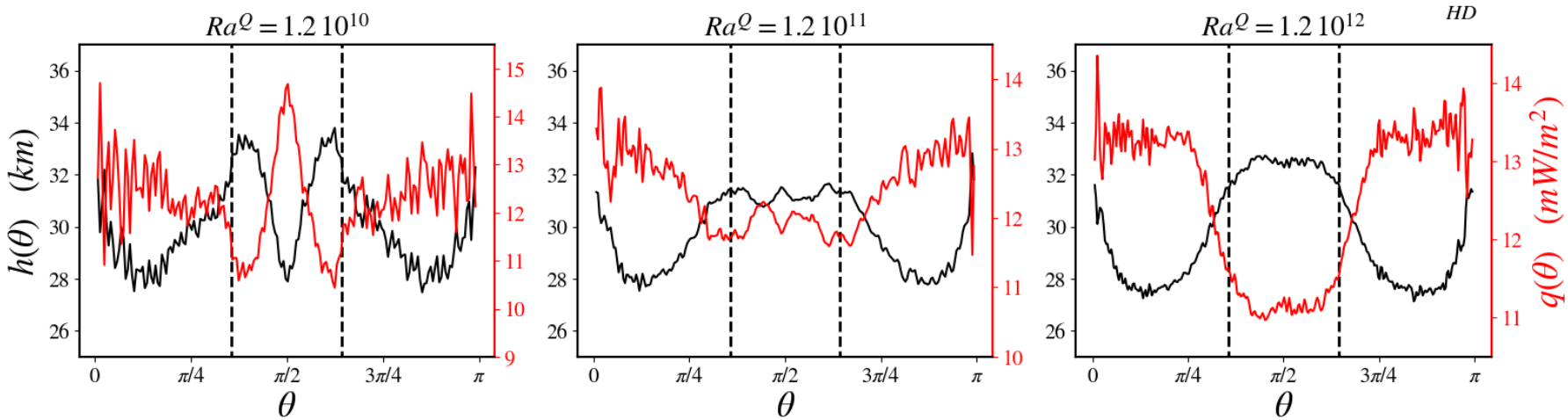


Figure: Evolution of q and h with Ra^Q for $Ek = 10^{-5}$, $Ek_\eta = 10^{-2}$, $Pr = 12$, $\widetilde{\Lambda} = 0$.

Heat flux and ice thickness (MHD)

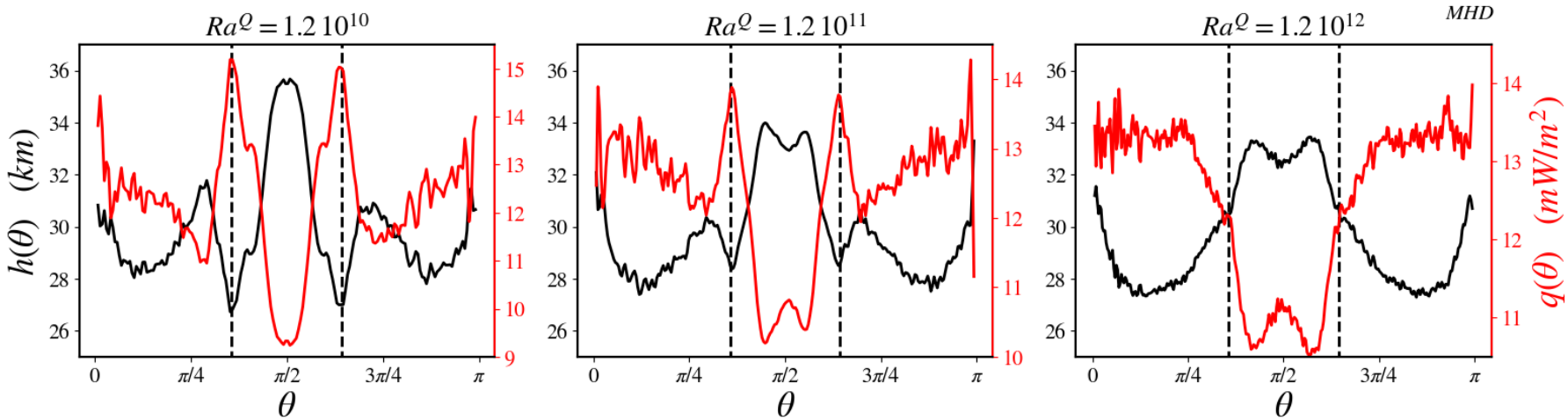


Figure: Evolution of q and h with Ra^Q for $Ek = 10^{-5}$, $Ek_\eta = 10^{-2}$, $Pr = 12$, $\widetilde{\Lambda} = 10$.

Ice thickness (MHD vs HD)

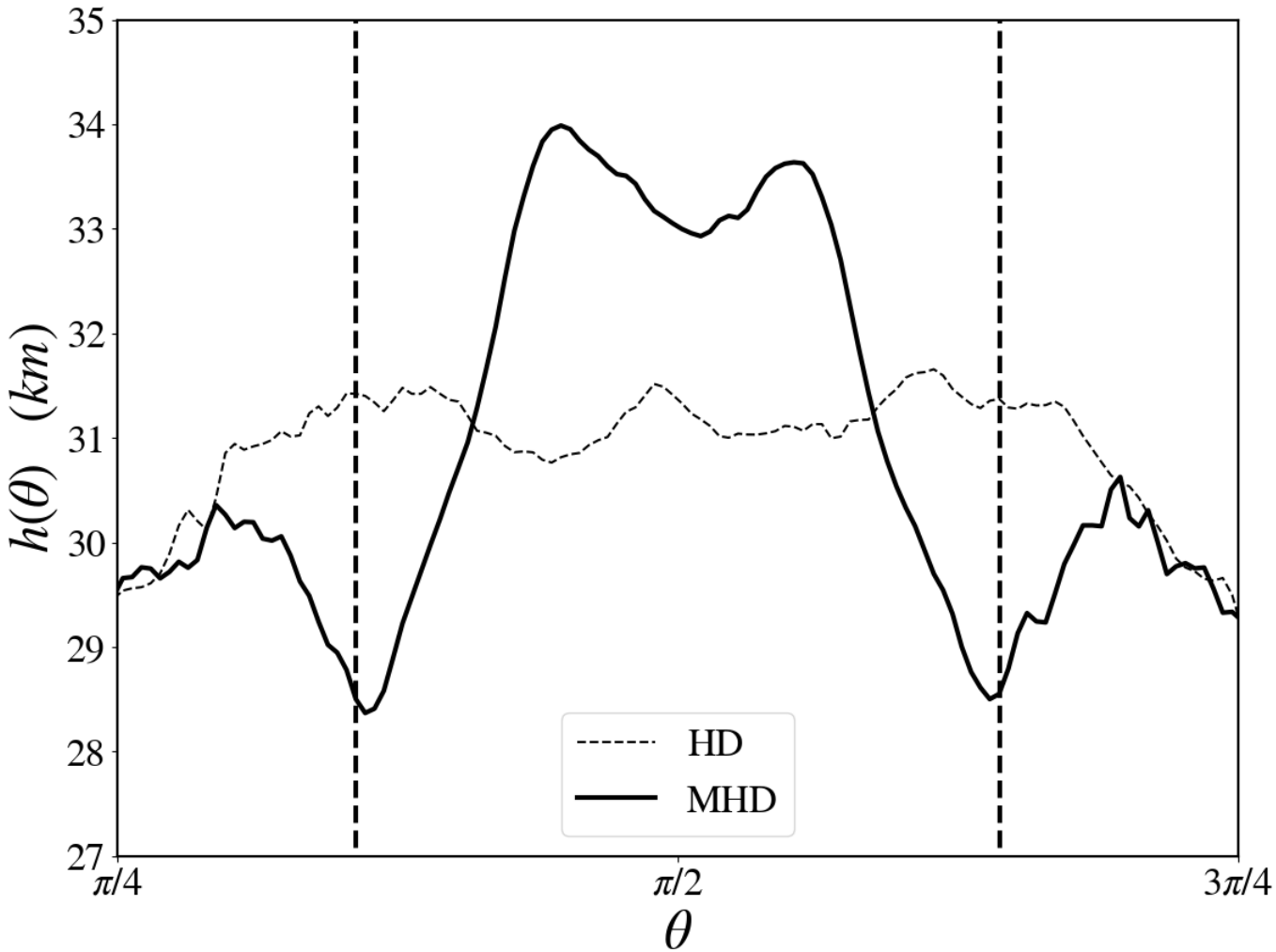
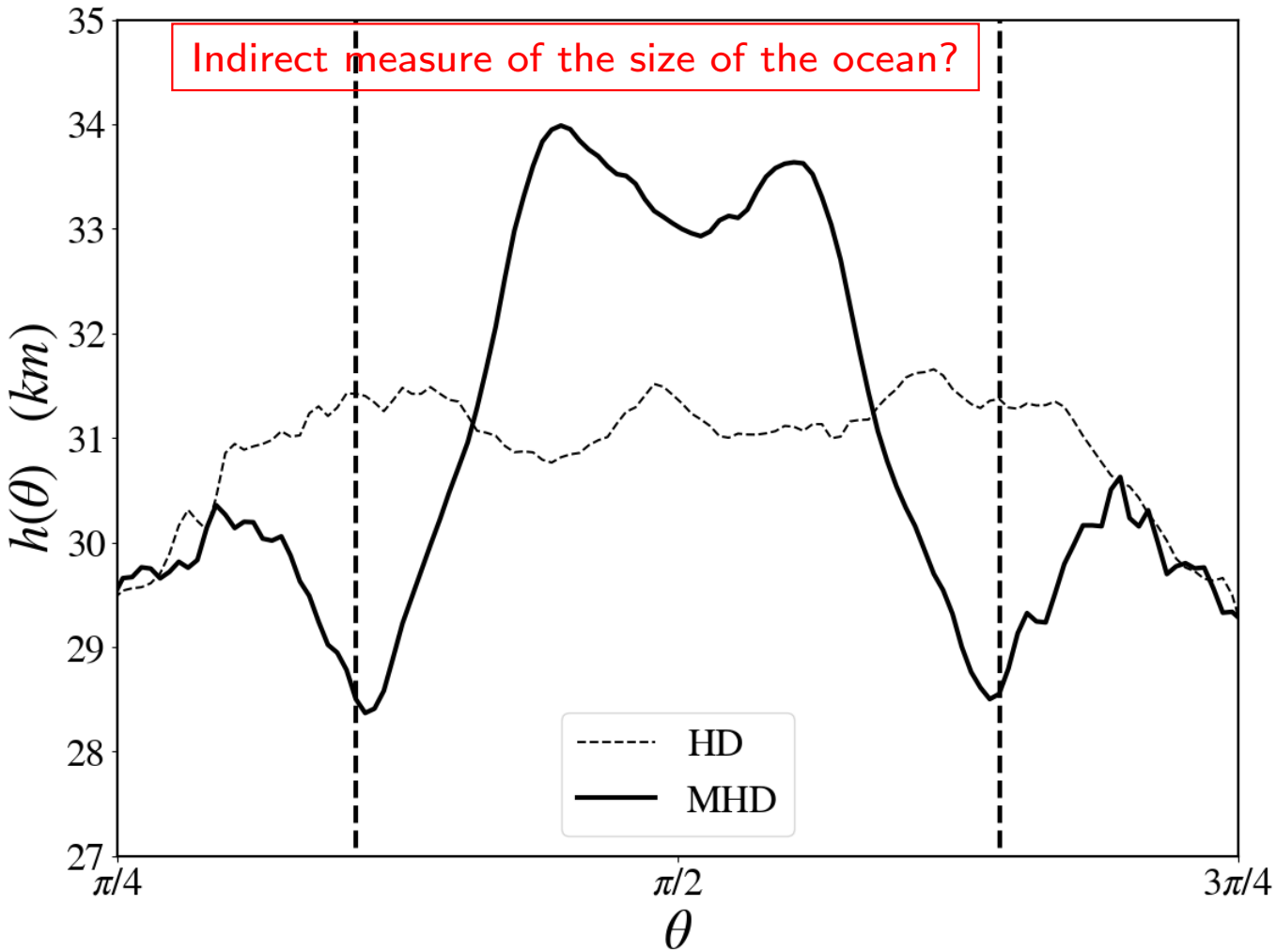


Figure: Magnified comparison for h with $Ra^Q = 1.2.10^{11}$ for $Ek = 10^{-5}$, $Ek_\eta = 10^{-2}$, $Pr = 12$, $\widetilde{\Lambda} = 10$. *[Daniel et al.2025]*

Ice thickness (MHD vs HD)

CCL2



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General conclusion

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Daniel, F., Petitdemange, L. and Gissinger, C. (2025). *New constraint on Europa's ice shell: Magnetic signature from the ocean.* Icarus, 116792.

Appendix: MHD equations for an incompressible flow using Boussinesq approximation

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} + 2\mathbf{\Omega_o}\times\mathbf{u} = -\nabla\Pi/\rho + \nu\Delta\mathbf{u} + \alpha_T g(r) T \mathbf{e_r} + (\rho\mu_0)^{-1}(\nabla\times\mathbf{B})\times\mathbf{B}, \quad (2)$$

$$\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T = \kappa\Delta T, \quad (3)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{u}\times\mathbf{B}) + \eta\Delta\mathbf{B}, \quad (4)$$

$$\nabla\cdot\mathbf{u} = 0, \quad (5)$$

$$\nabla\cdot\mathbf{B} = 0, \quad (6)$$

Pseudo-spectral code PaRoDy *[Dormy 1998, Aubert 2008]* with SHTns *[Schaeffer 2013]*

Appendix: Limit $Ra^Q = 0$: Amplitude of the recirculation

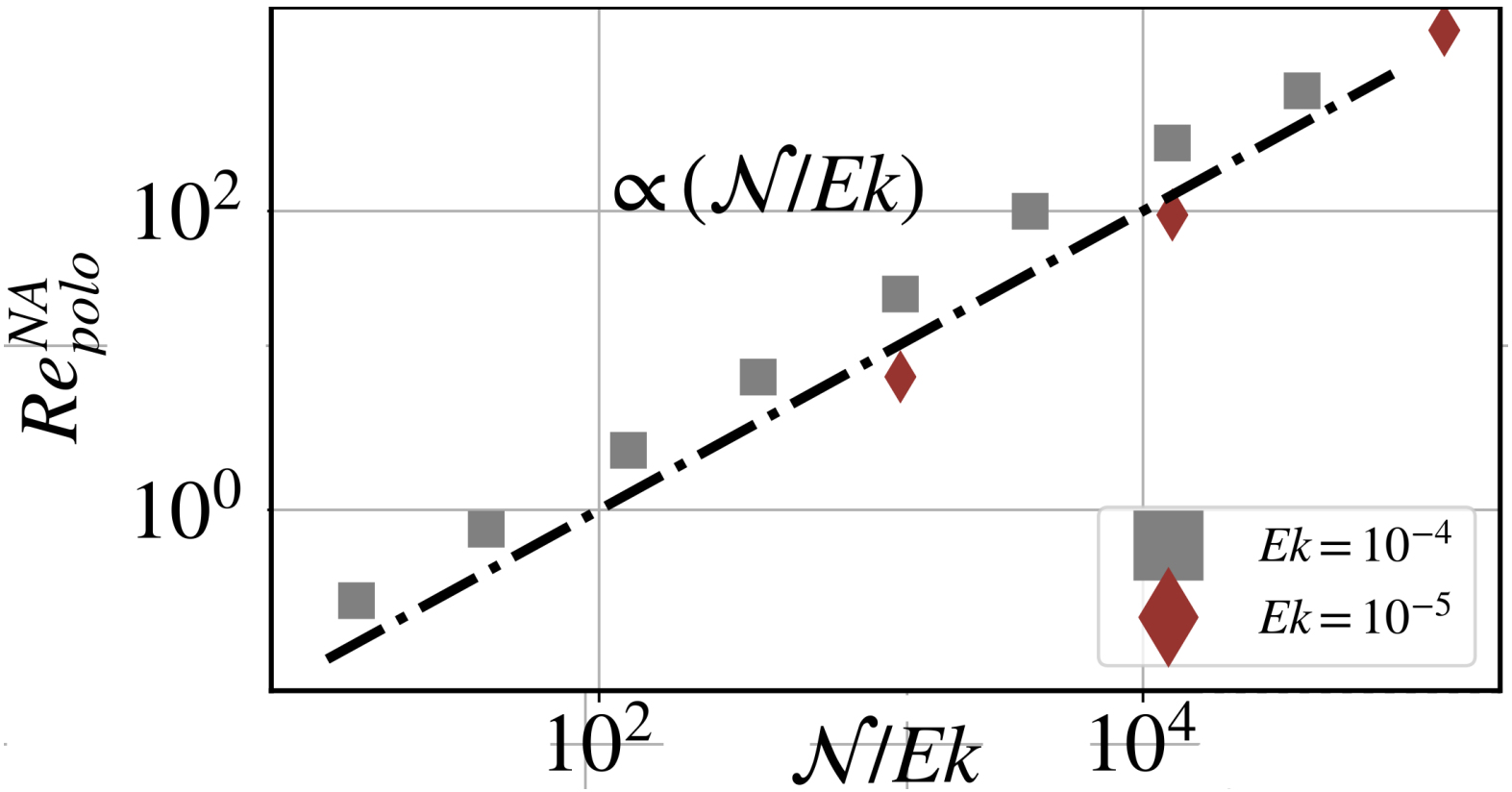

Figure: Amplitude of the velocity of the poloidal recirculation as a function of $\mathcal{N} = B_o^2 \eta / \left(\rho \mu_0 \nu c^2\right)$. *[Daniel et al. 2025]*

Appendix: Limit $Ra^Q = 0$: Heat transport due to the recirculation

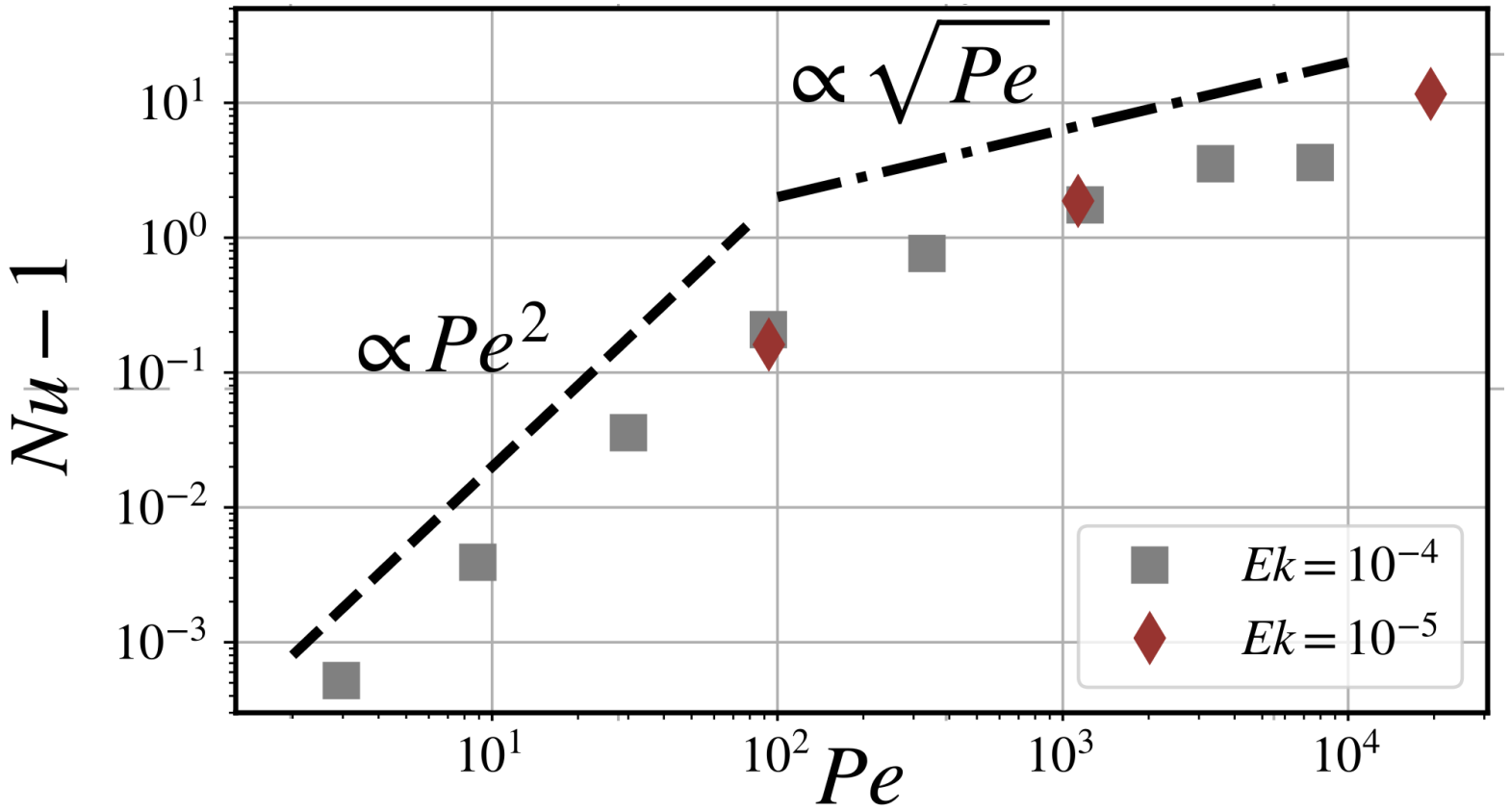

Figure: Evolution of the Nusselt number against the Péclet number $Pe = U_{jet} r_o / \kappa$ due to the Jovian field for two levels of rotation. *[Daniel et al. 2025]*

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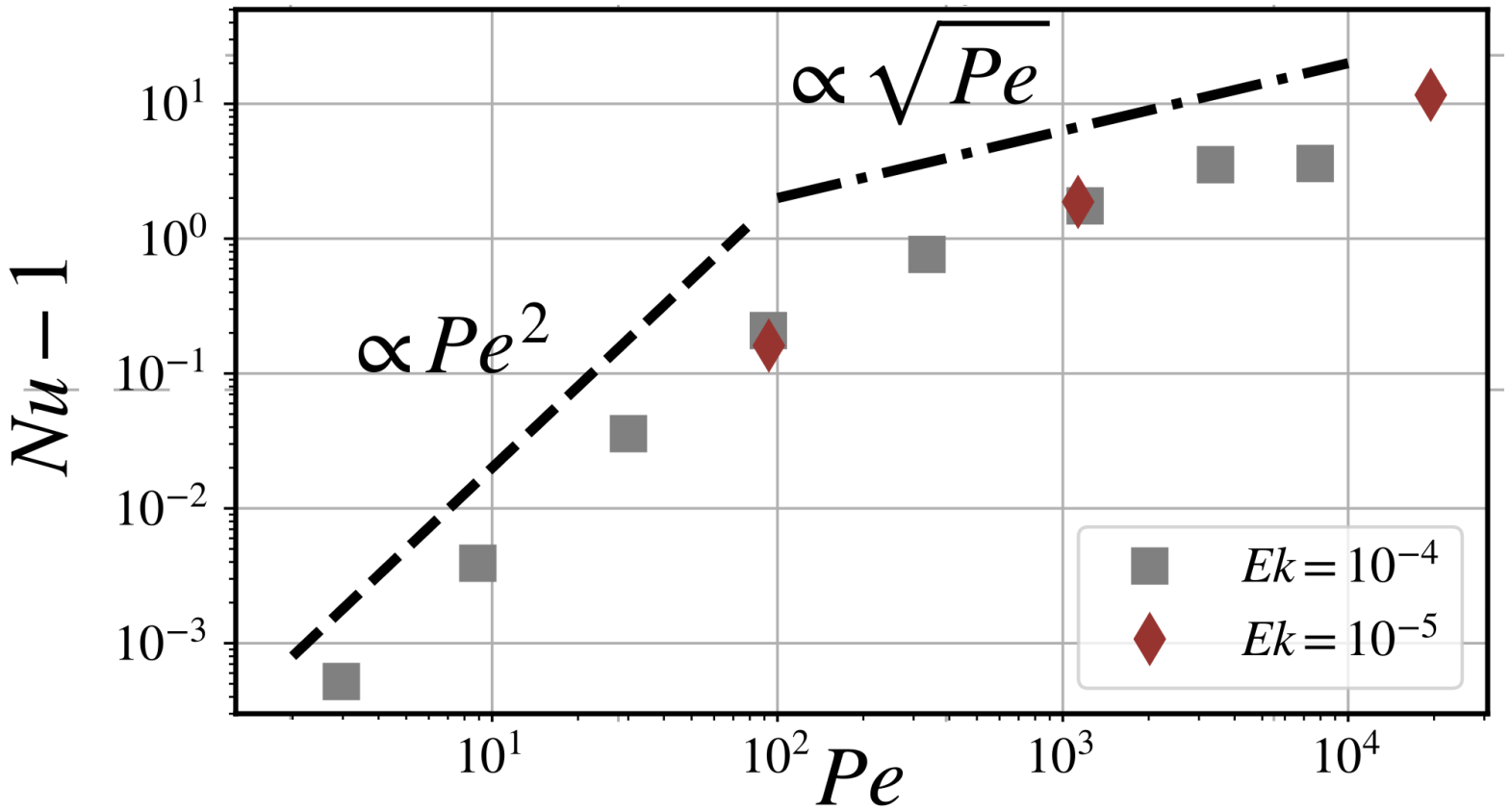

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Transport without threshold

Appendix: Can it be observed?

~~$ice \quad thickness \quad h$~~ $\rightarrow$ topography of the satellite

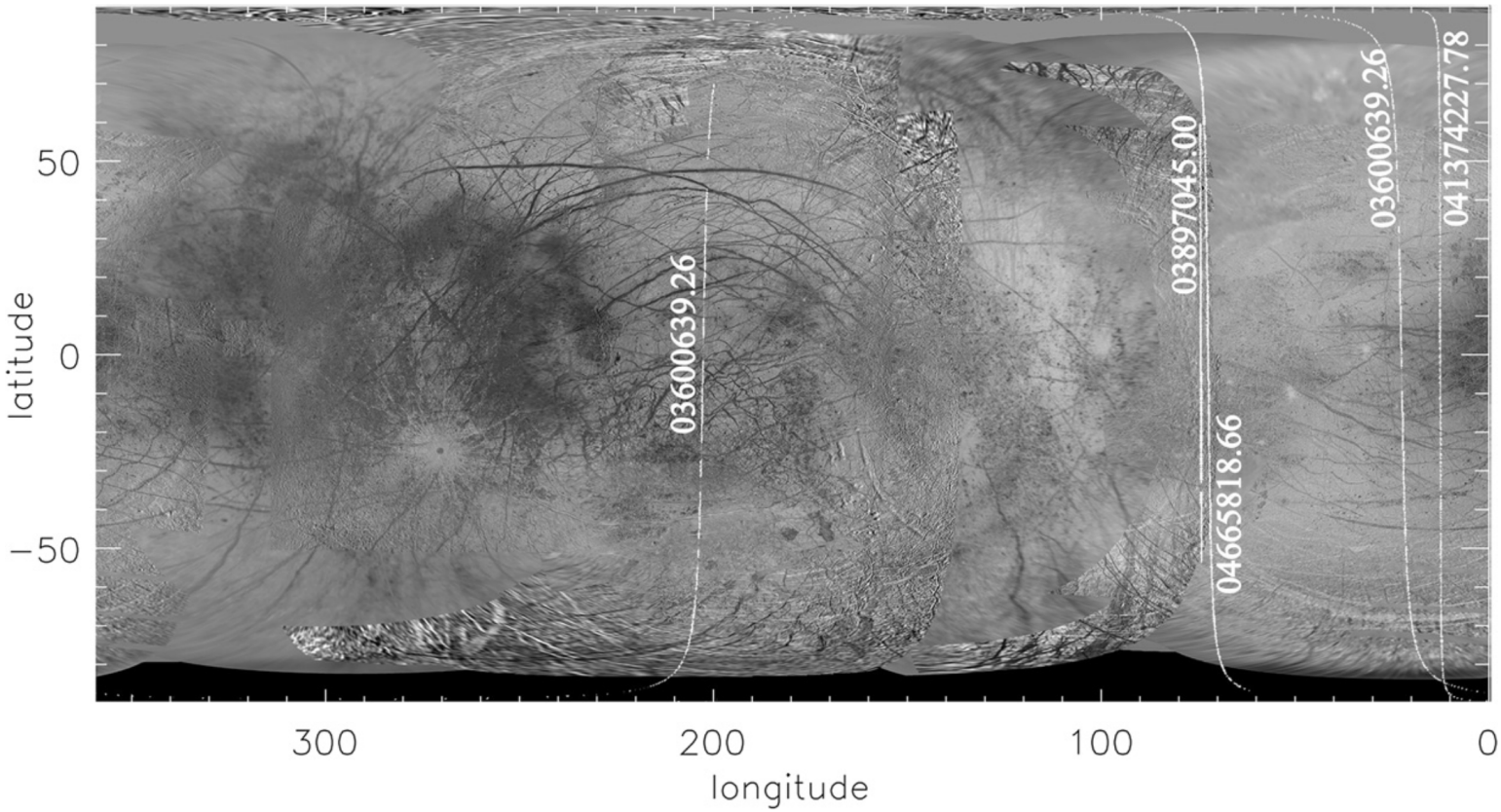

Figure: Limb profile measurements *[Nimmo et al.2007]*

Appendix: Comparisons with observations

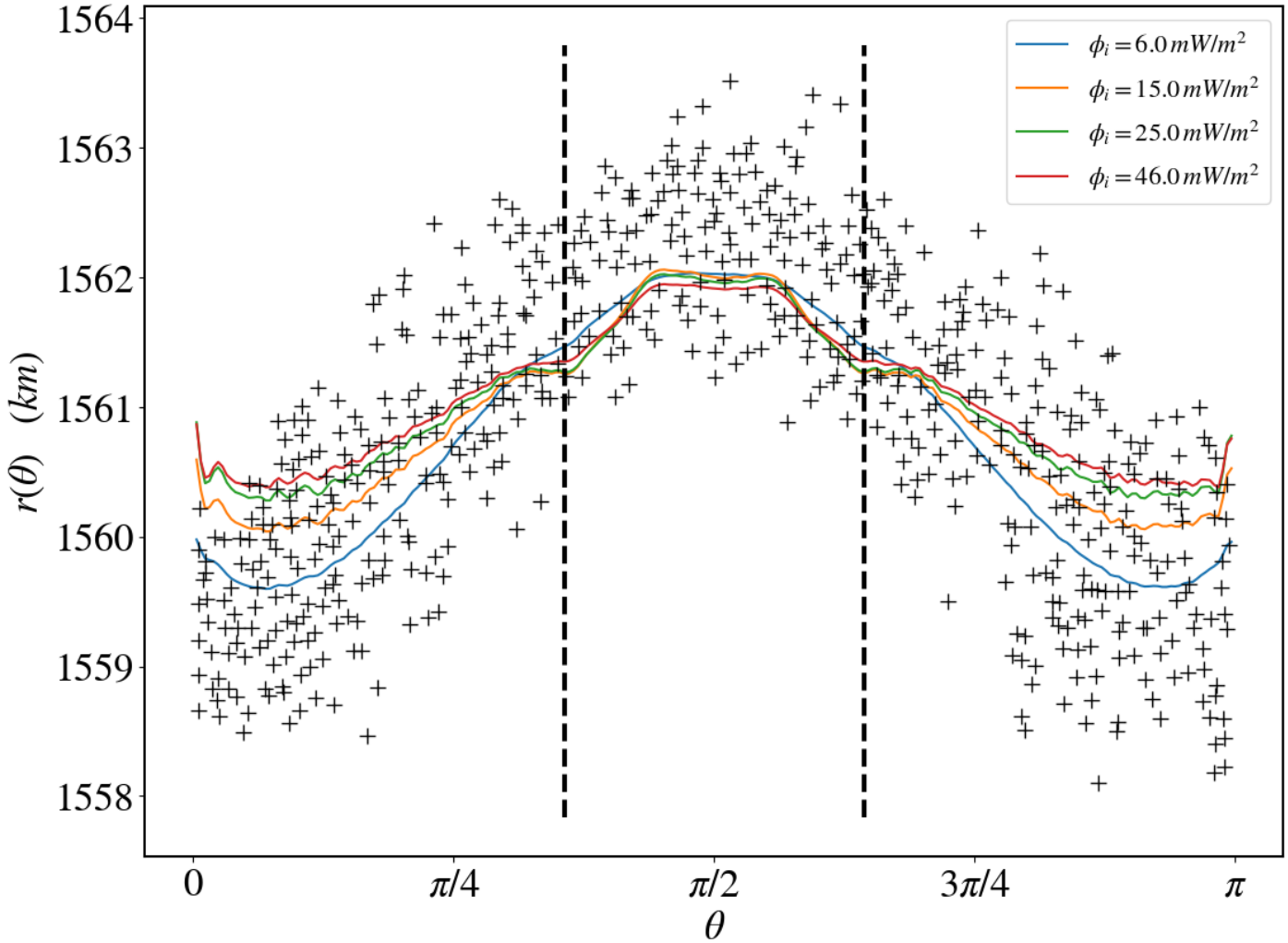

Figure: Radial profile of Europa, DNS vs observations (*[Nimmo et al.2007]*) for different ocean's floor heat flux values. *[Daniel et al.2025]*

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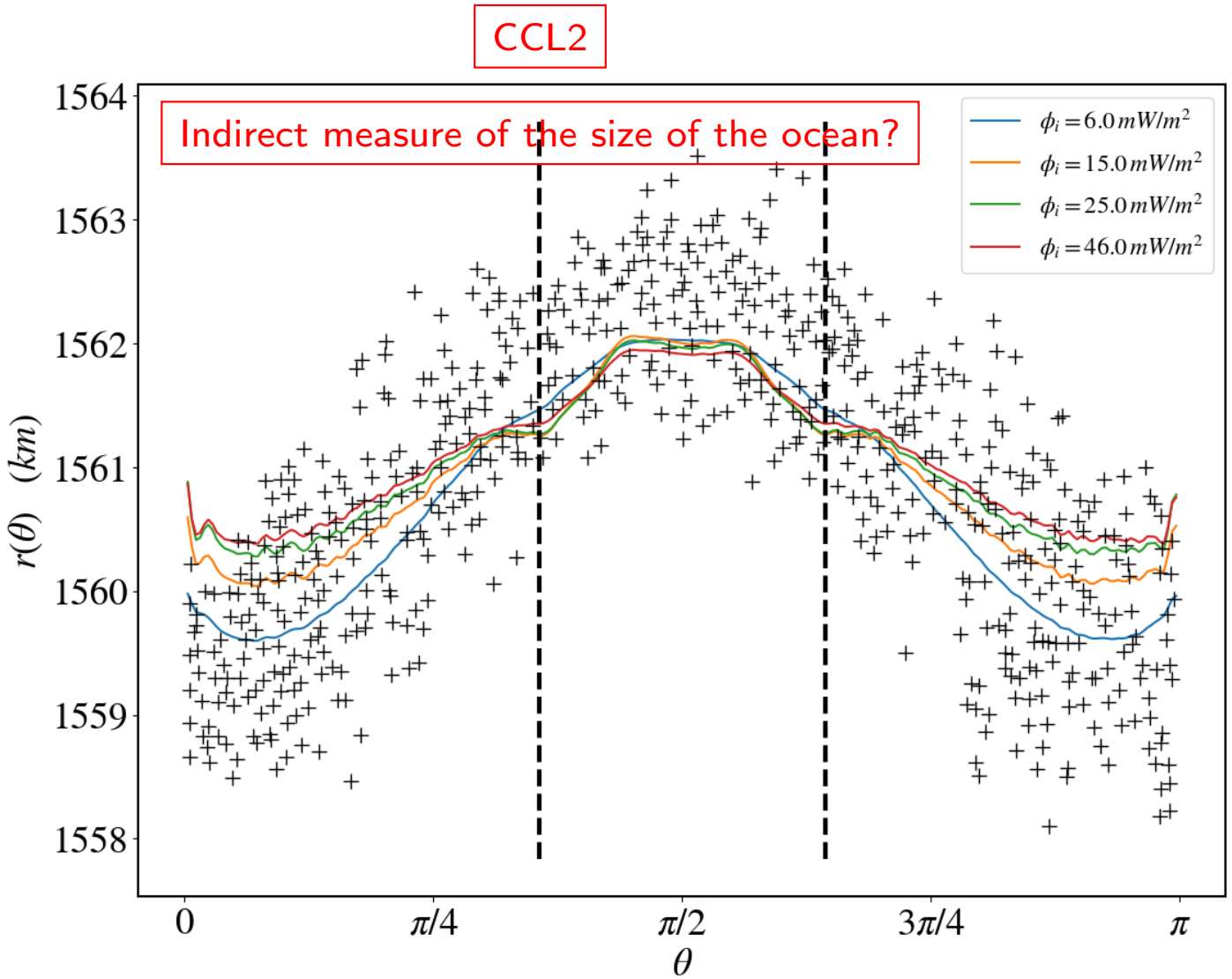

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