Physics of Fluids

POLAR HEAT TRANSPOT ENHANCEMENT IN SUB-GLACIAL OCEANS ON ICY MOONS

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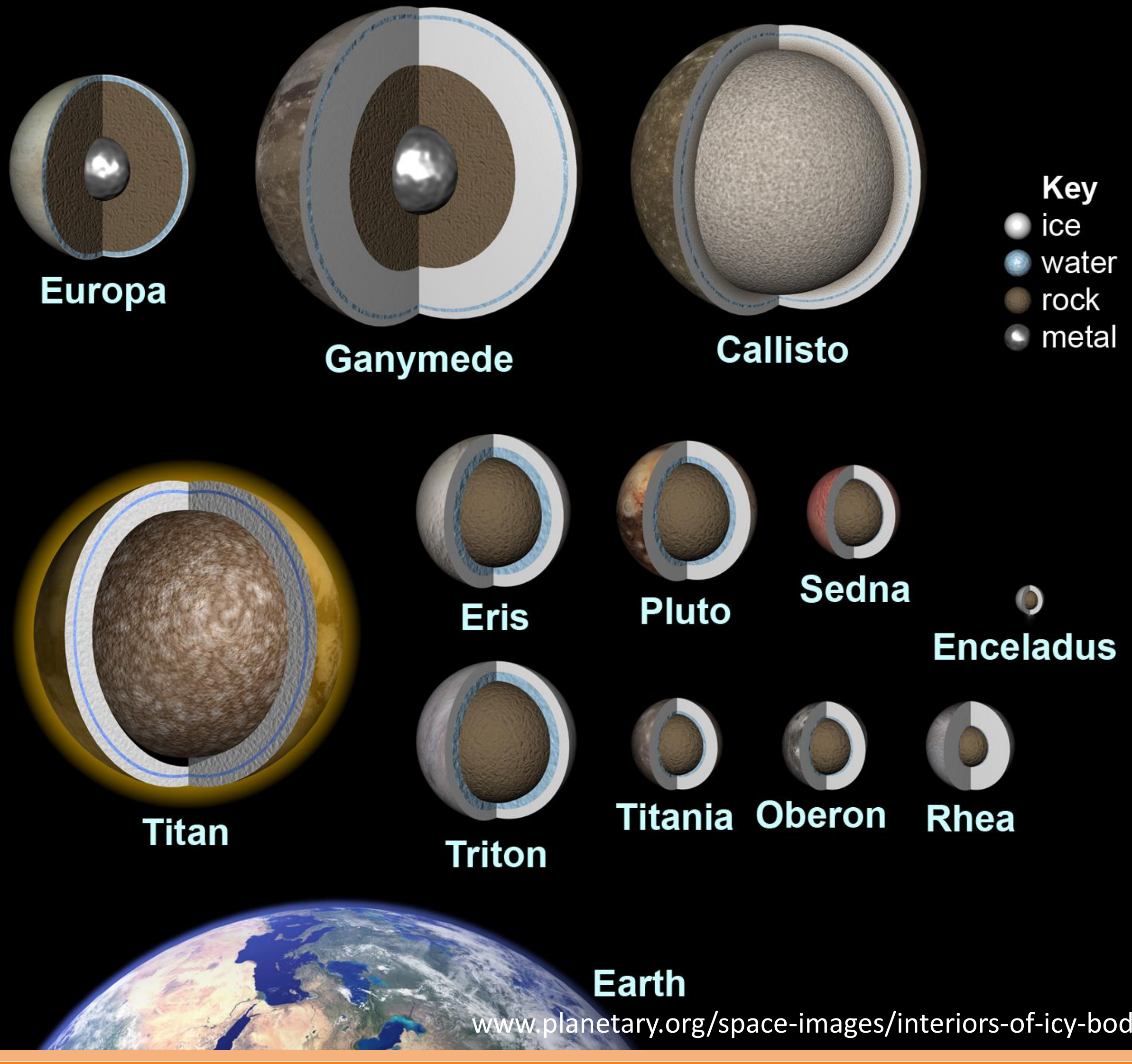
EGU General Assembly 2023

Motivation: Dynamics in sub-glacial oceans on icy moons



www.planetary.org/space-images/interiors-of-icy-bodies

www.universetoday.com/wp-content/uploads/2011/10/enceladus_geysers.jpg

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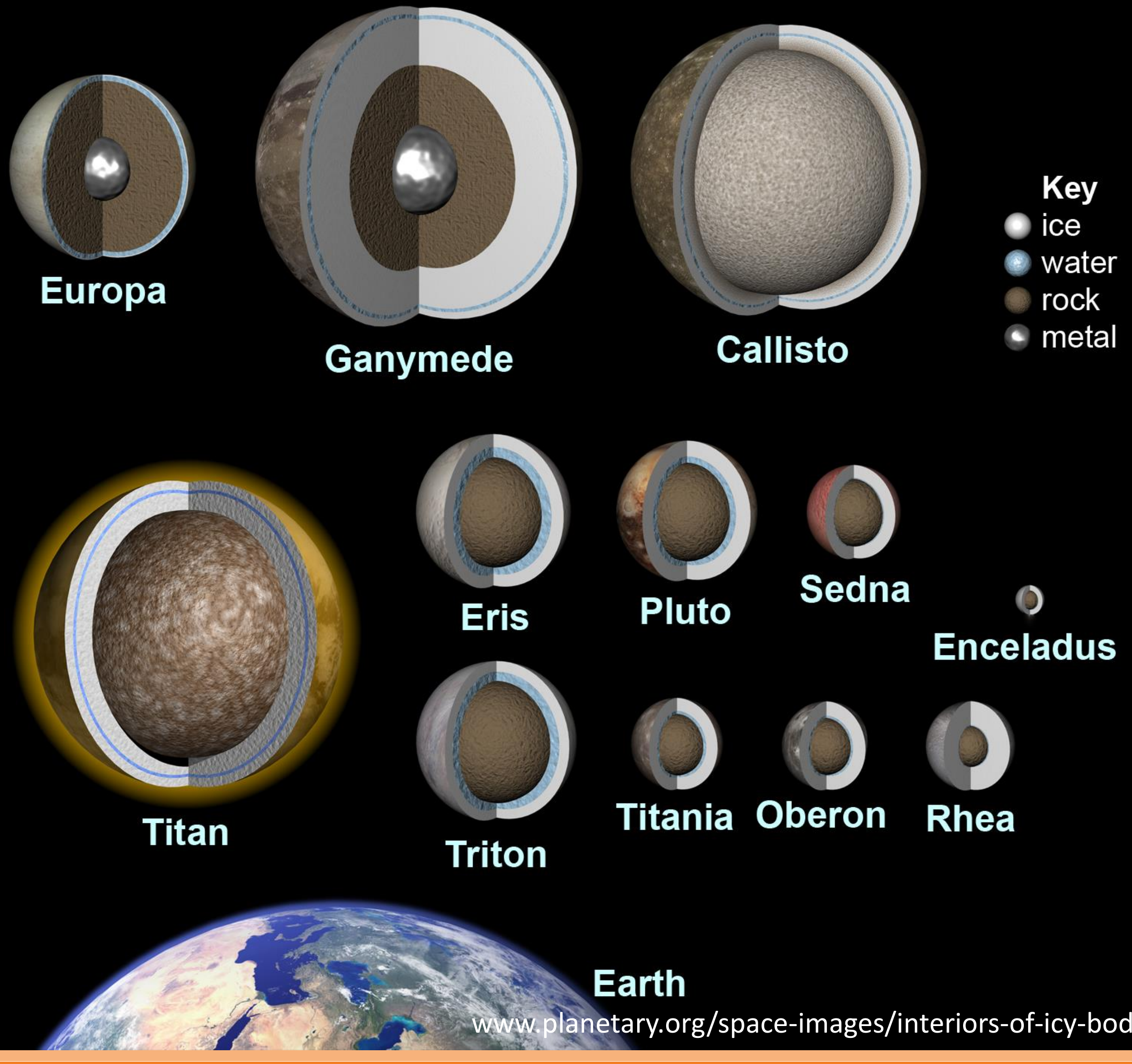

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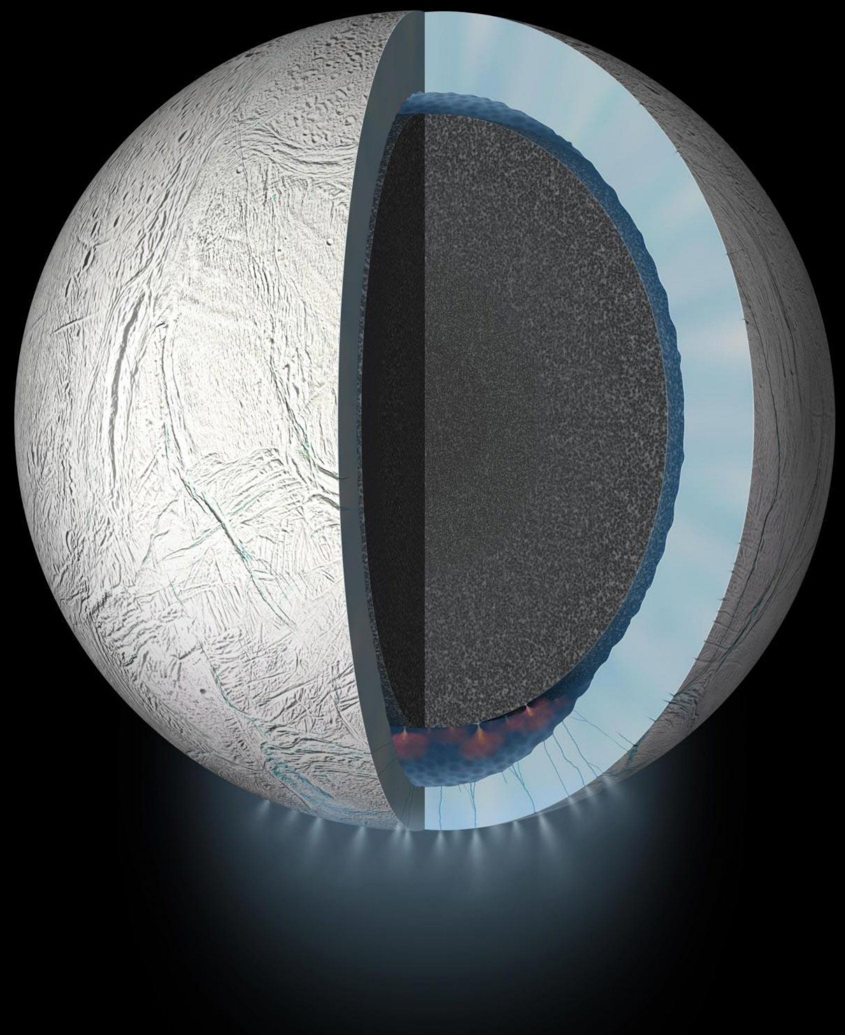
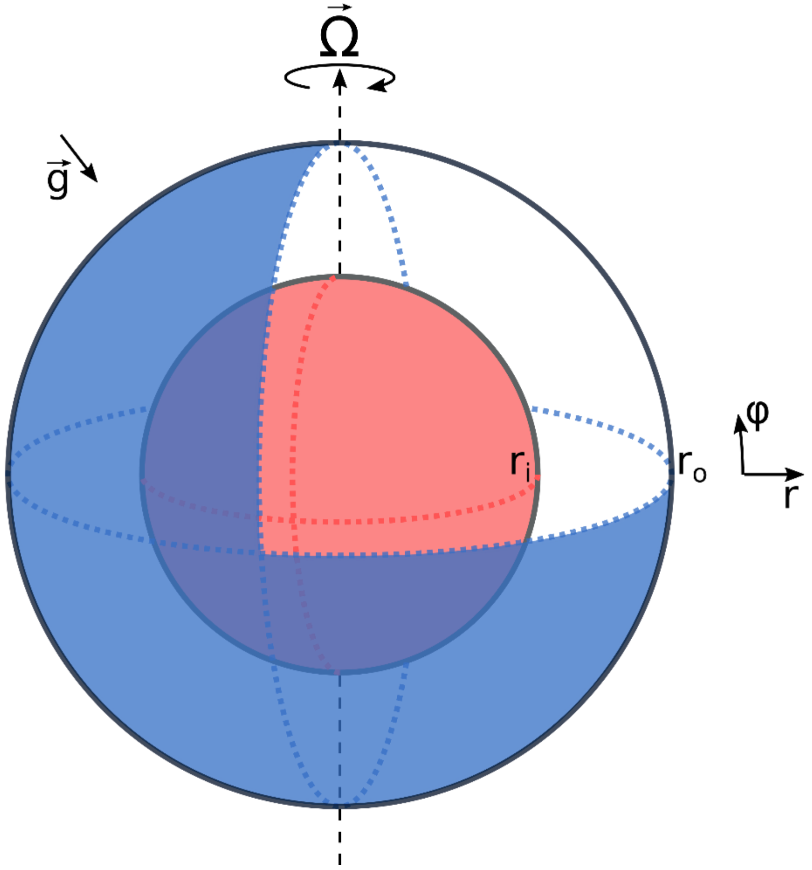


www.scitechdaily.com/images/Enceladus-Plume-768x614.jpg

Setup: Spherical rotating Rayleigh-Bénard convection (RRBC)



- **Direct numerical simulations** (DNS) of spherical rotating Rayleigh-Bénard convection (RRBC)

- **<u>Control parameters:</u>**
  - Fluid properties: $\mathrm{Pr} = \frac{\nu}{\kappa} = 4.38$
  - Thermal driving: $\mathrm{Ra} = \frac{\alpha g \Delta T H^3}{\nu\kappa} = 10^6$
  - Radius ratio: $\eta = r_i/r_o = \{0.6, 0.8\}$
  - Rotation rate: $\mathrm{Ro}^{-1} = \frac{2\Omega H}{\sqrt{\alpha g \Delta T H}}$

    $(\mathrm{Ek}^{-1} = \frac{2\Omega H^2}{\nu})$

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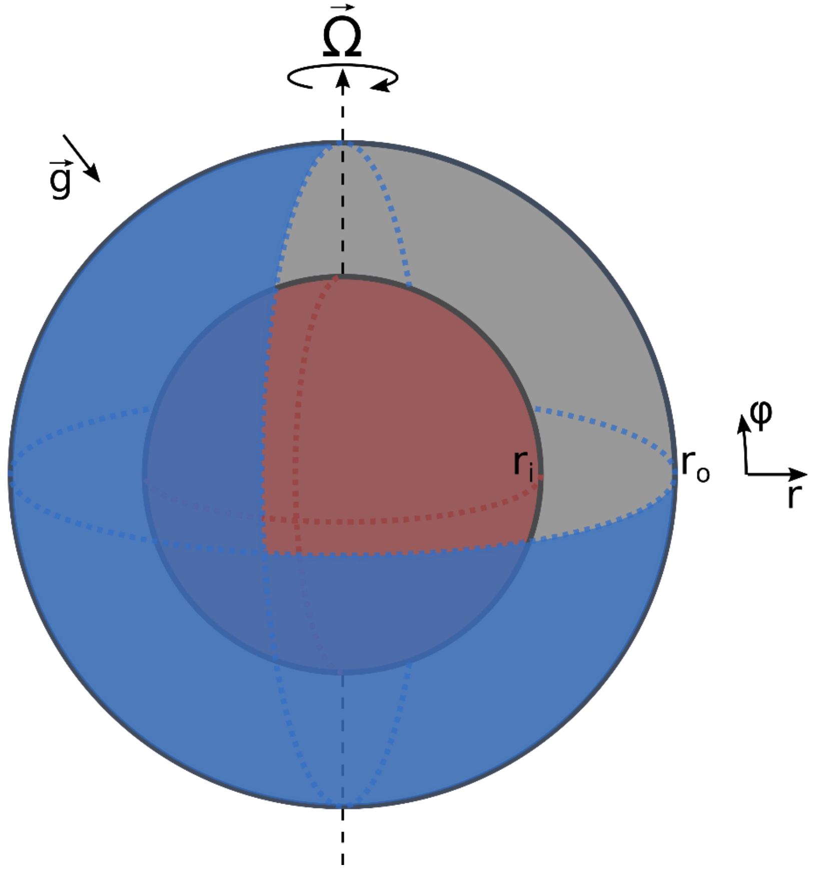

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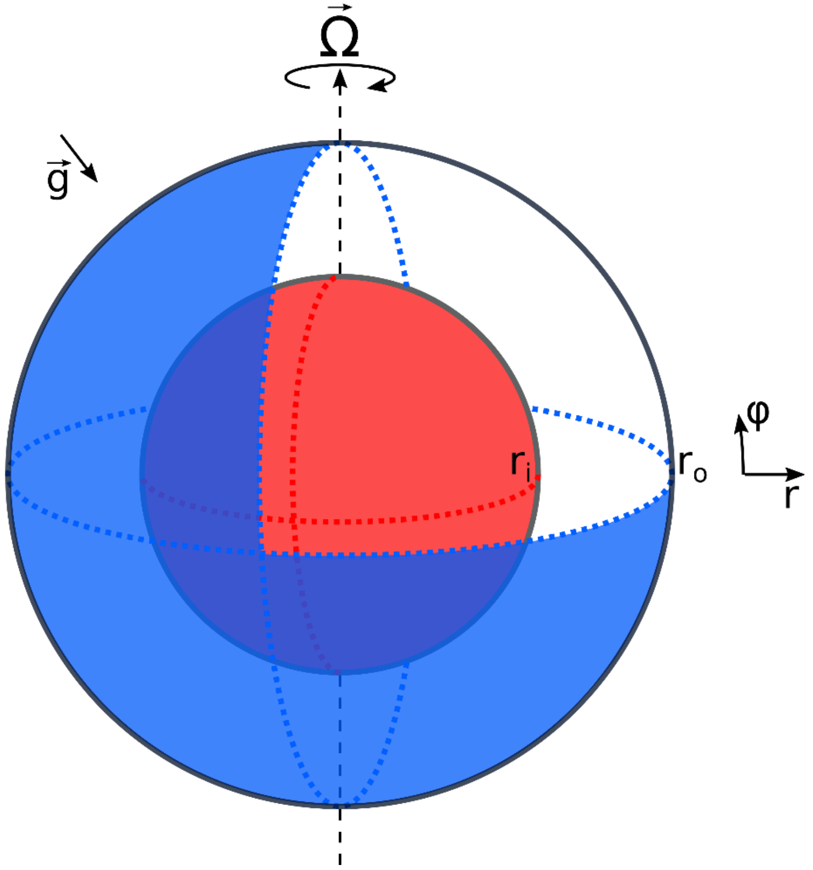

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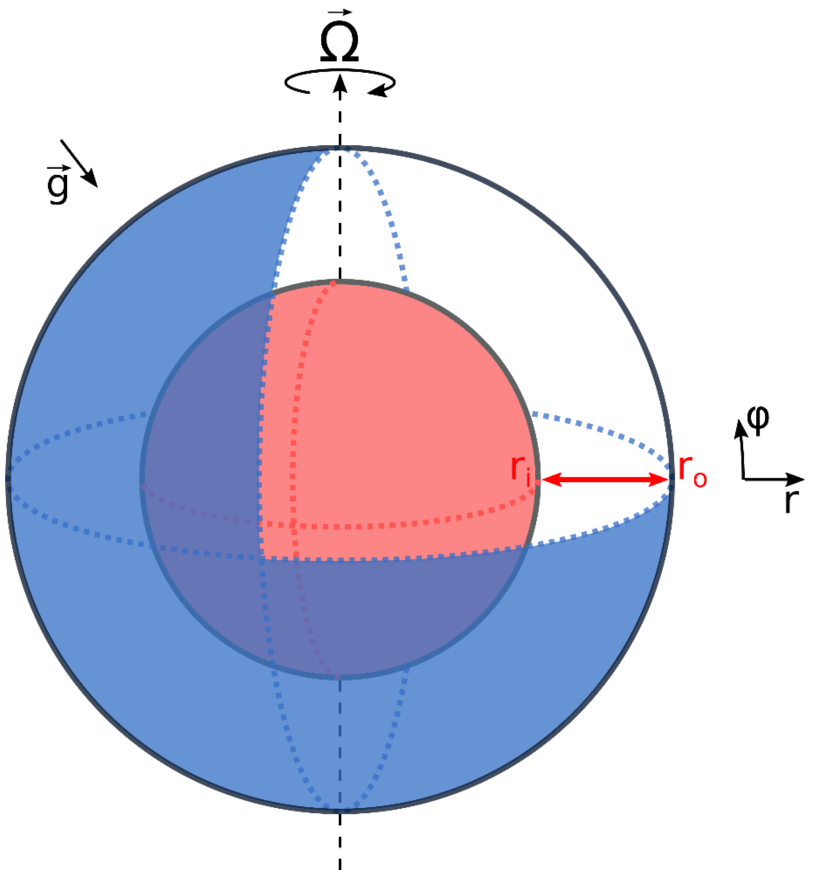

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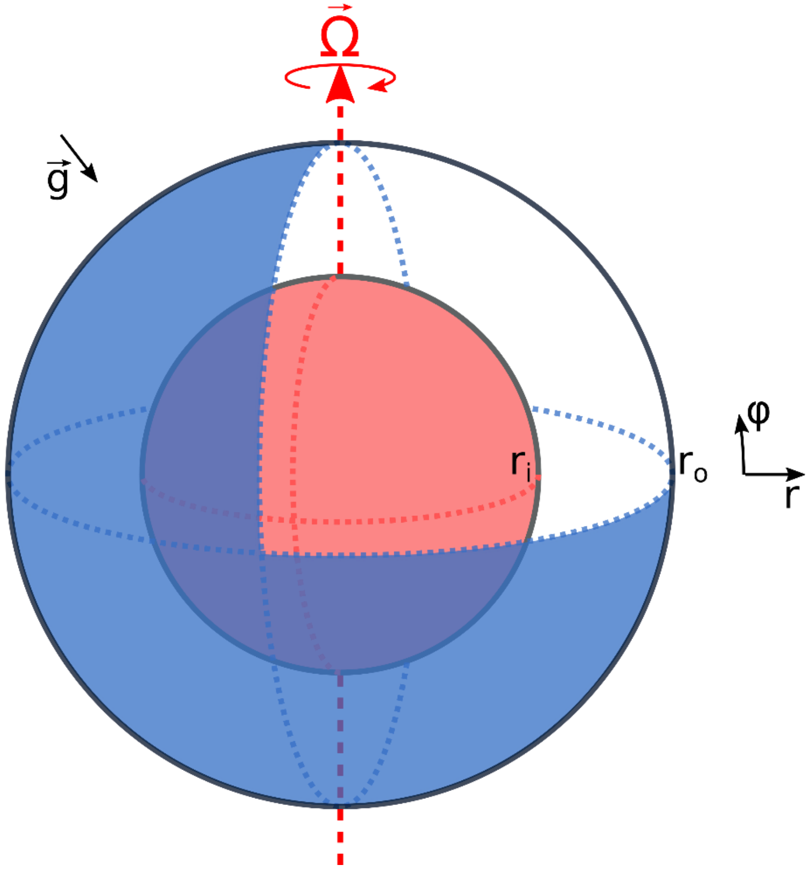

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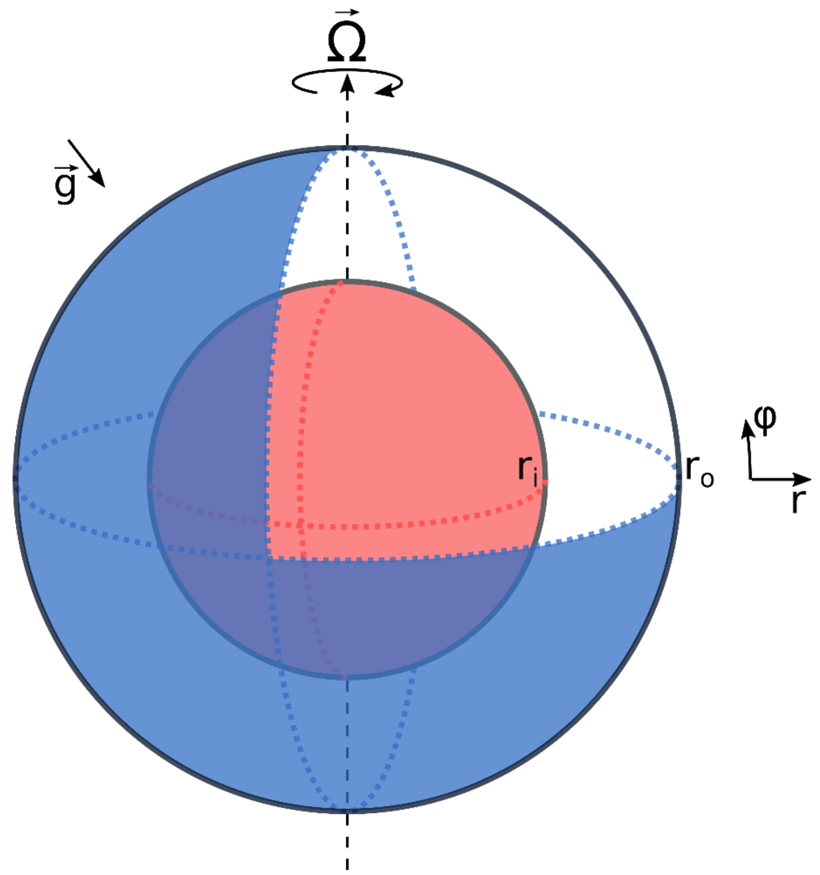

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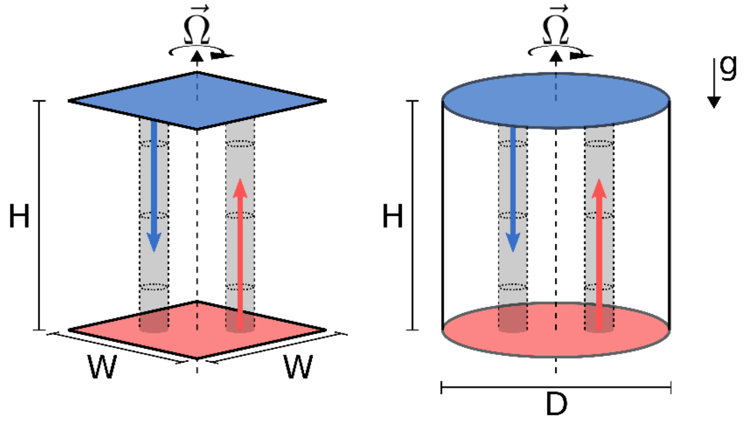
- **Response parameters:**
  - Heat transport: $\mathrm{Nu} = \frac{qH}{\kappa \Delta T}$
  - (Momentum transport: $\mathrm{Re} = \frac{UH}{\upsilon}$)

Planar vs. spherical RRBC

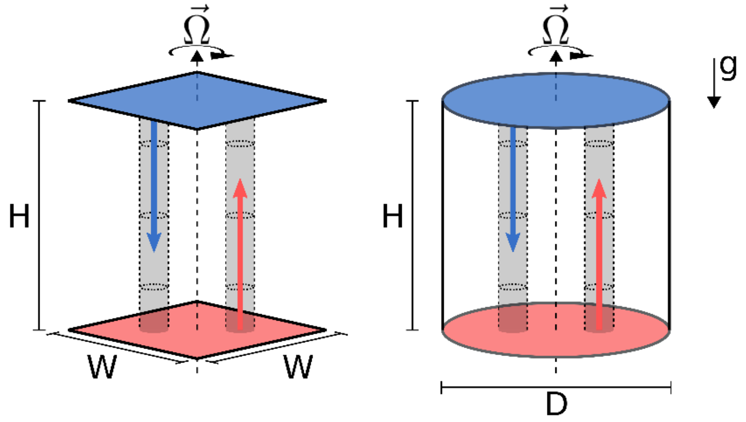
In planar RRBC:



- **Ekman pumping** through **vertically coherent vortices**

Planar vs. spherical RRBC

In planar RRBC:
(with $\mathrm{Pr} > 1$)



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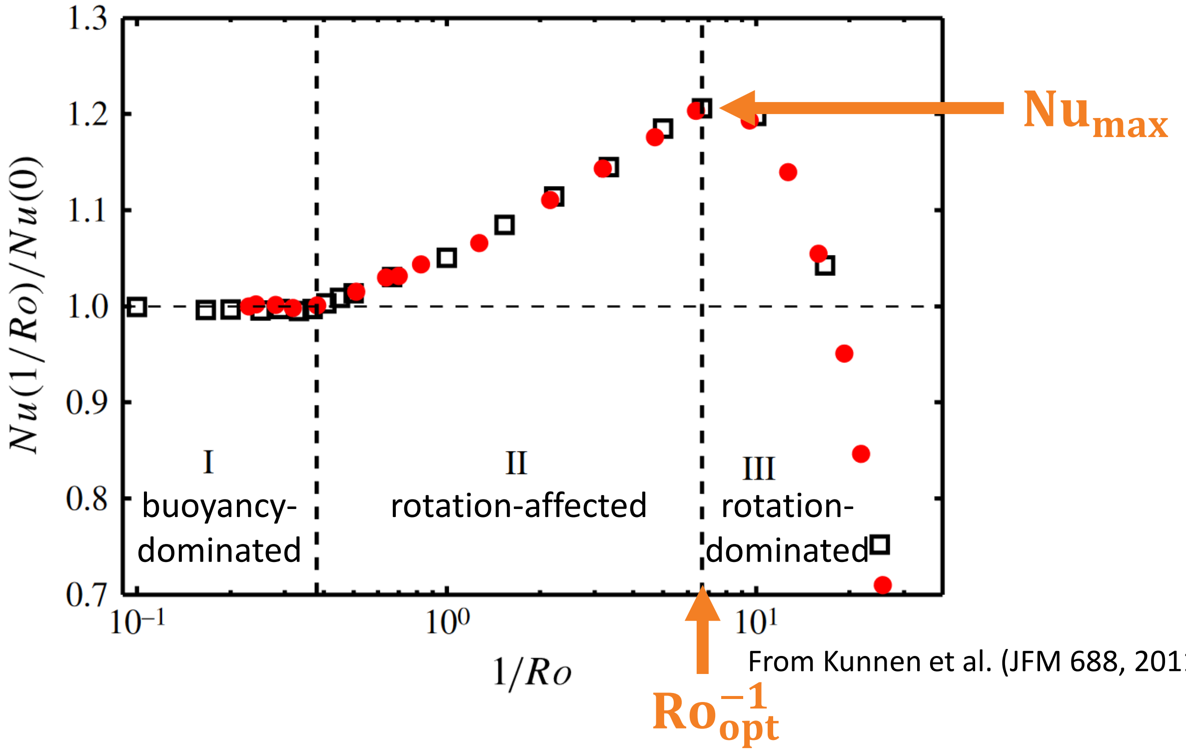

From Kunnen et al. (JFM 688, 2011)

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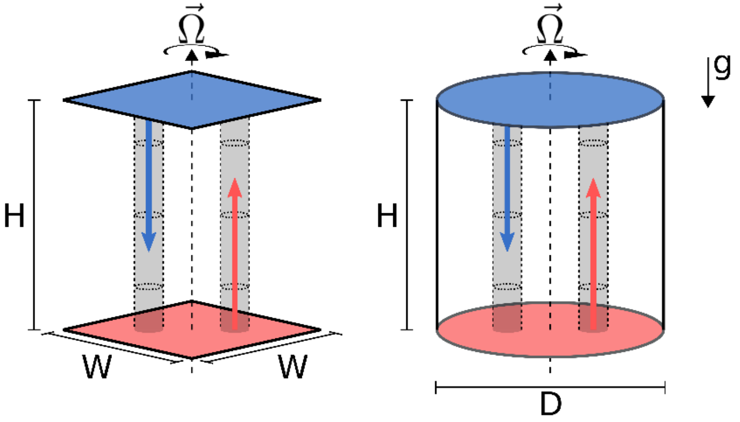

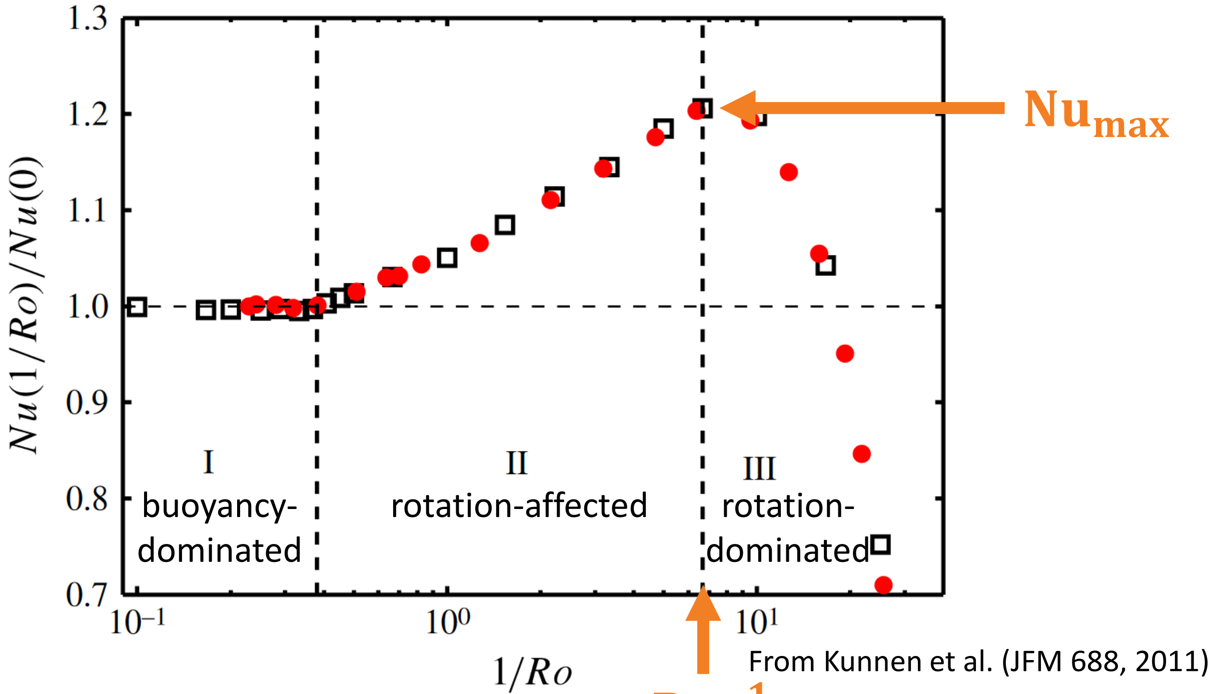

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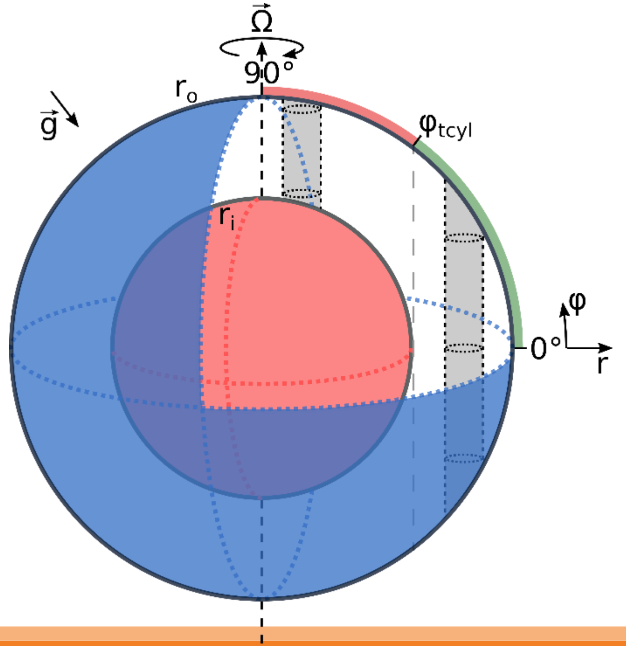
In spherical RRBC:

- Formation of **axially aligned Taylor columns**



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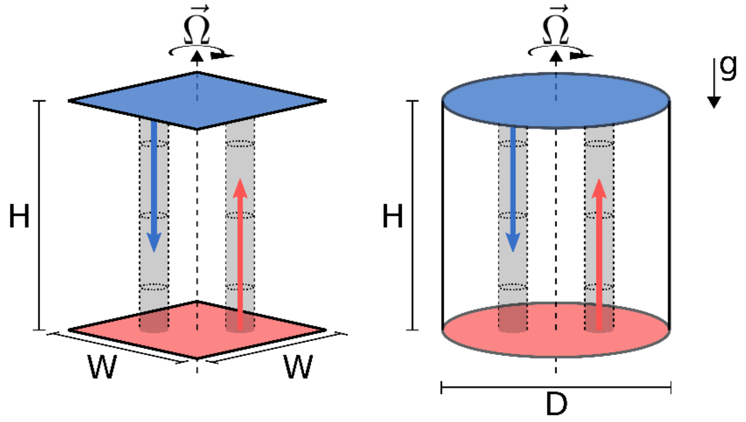

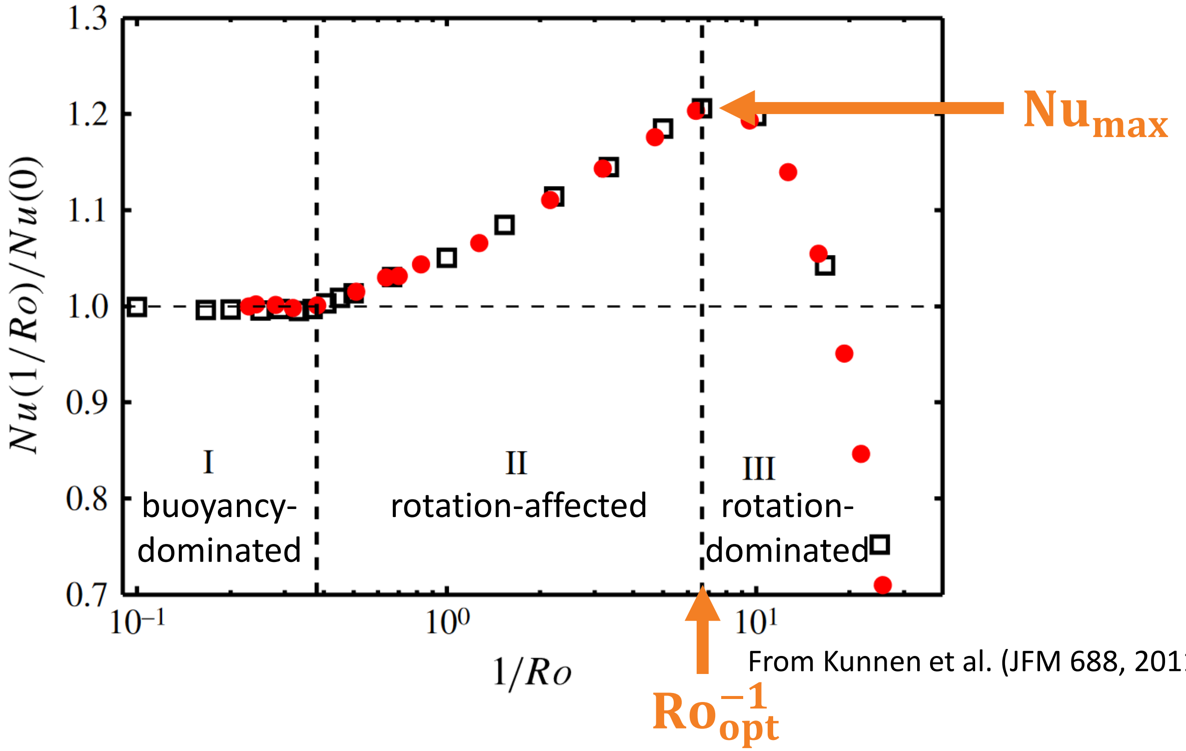

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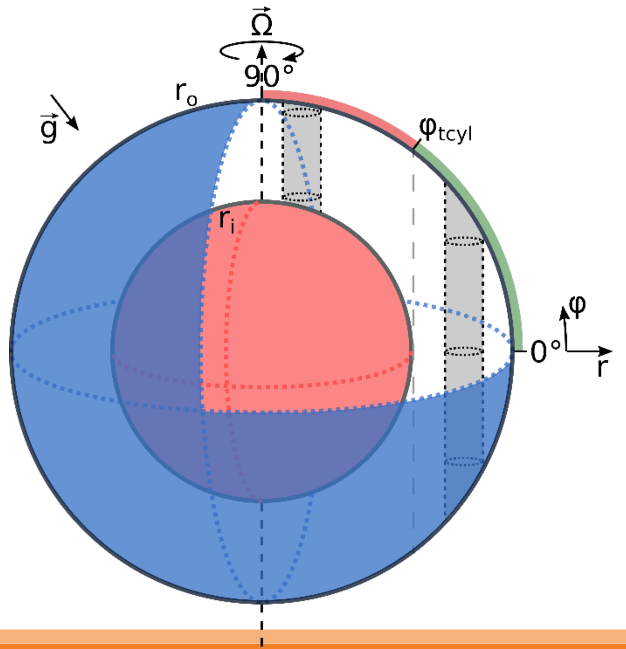
In spherical RRBC:
(with $\mathrm{Pr} > 1$)

- Formation of **axially aligned Taylor columns**
- Ekman pumpig through these columnar vortices?
- Heat transport enhancement in the polar tangent cylinder?



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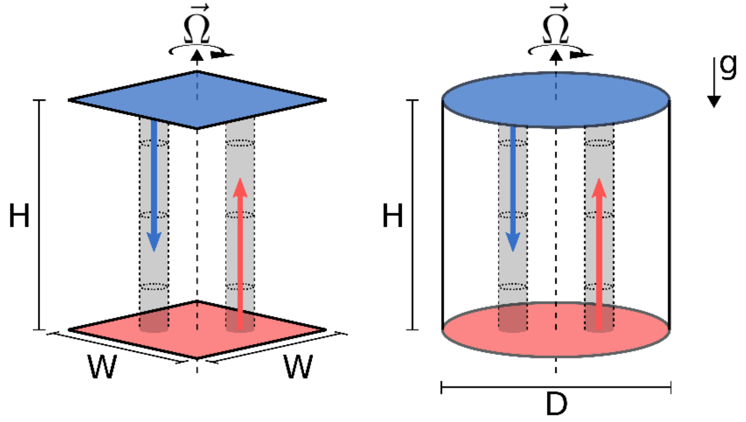

- **Ekman pumping** through **vertically coherent vortices**
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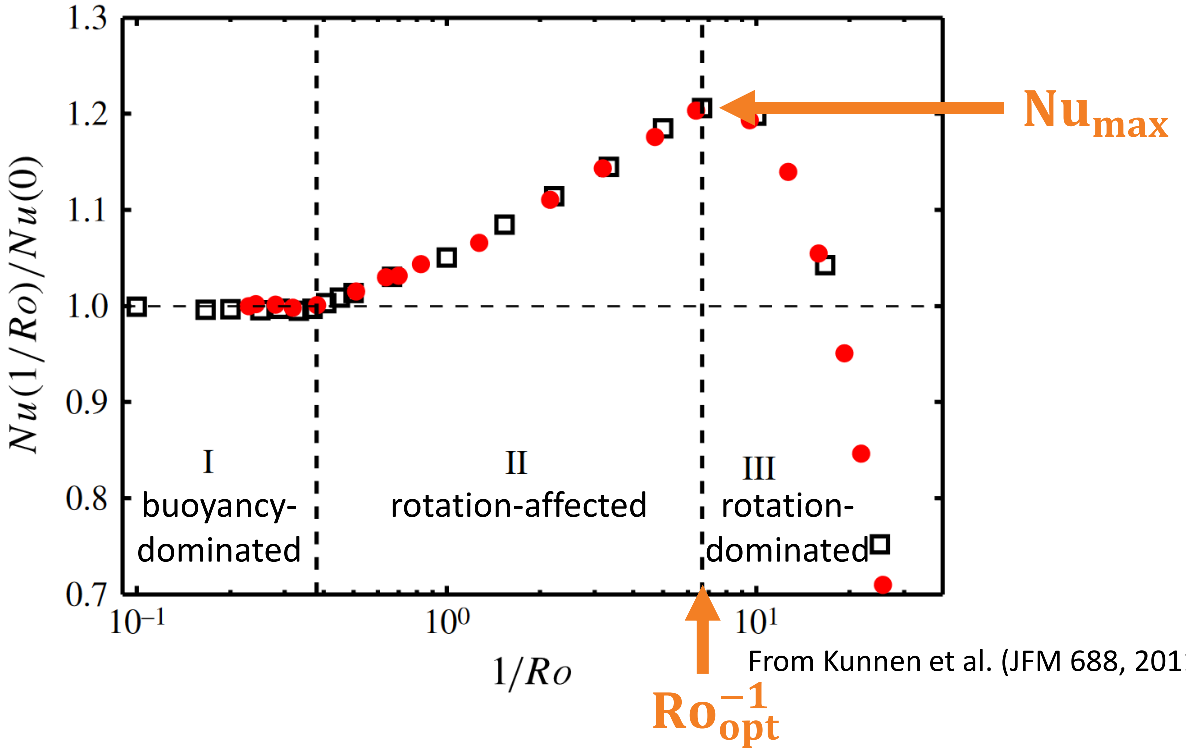

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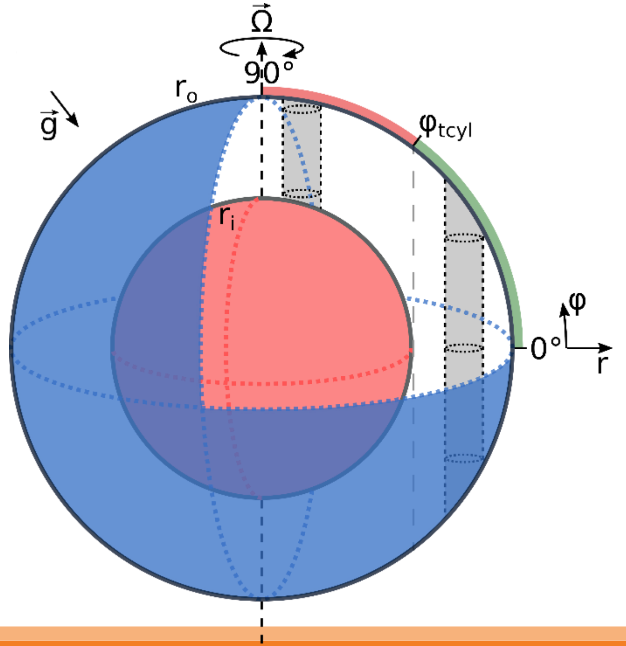


- **Does heat transport enhancement exist in spherical RRBC?**
- **Does it follow the same principles as in planar RRBC?**

?

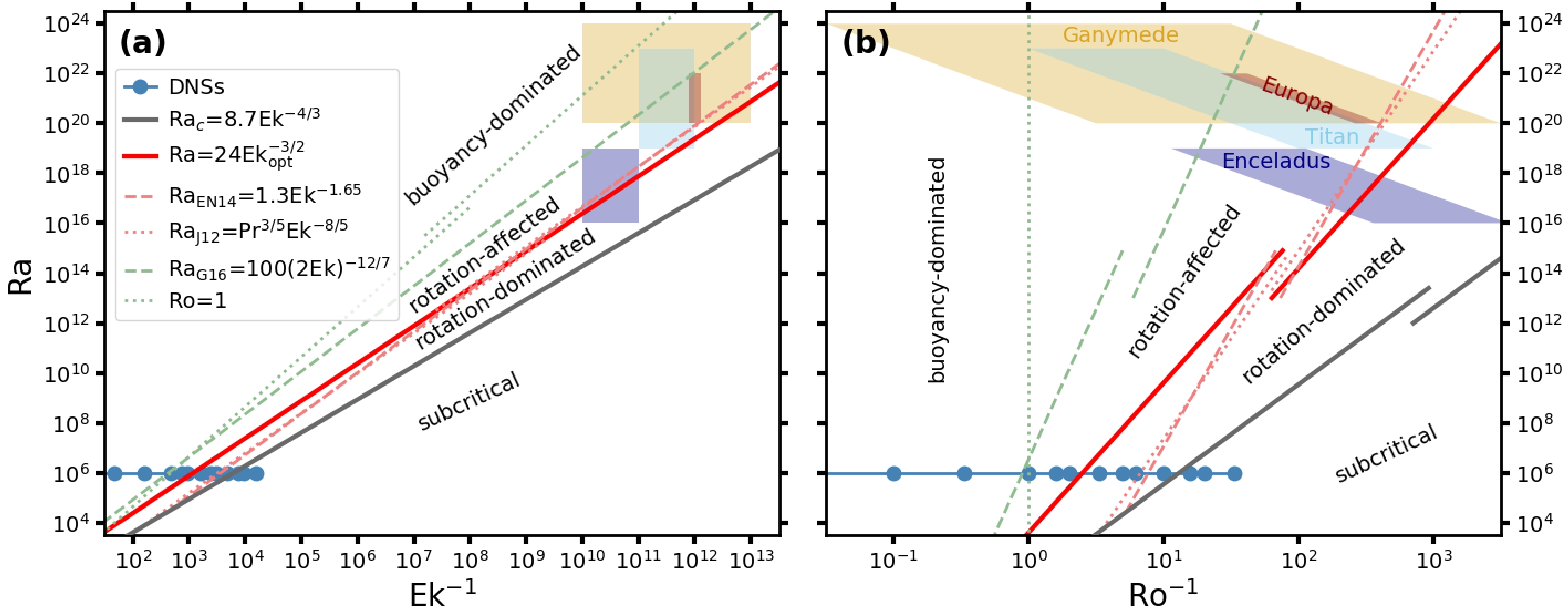
Relevance for icy moons

<u>Heat transport enhancement in **planar RRBC:**</u>

- rotation-affected regime
- $\mathrm{Pr} > 1$

<u>**Icy moon oceans:**</u>

- rotation-affected regime
- $\mathrm{Pr} \in [10,13] > 1$

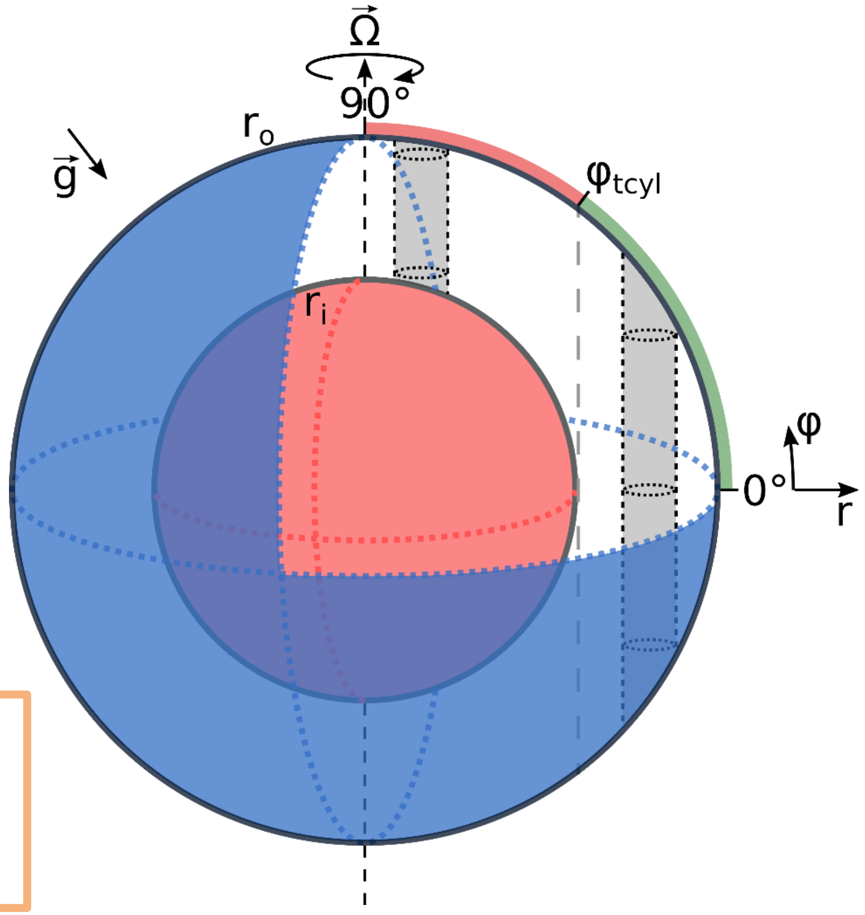


From Hartmann et al. (in prep.), based on Soderlund (GRL, 2019)

Latitudinal vs. global heat transport

Do we observe heat transport enhancement?

- Within the tangent cylinder: **Yes!**



Pr = 4.38
Ra = 10^6
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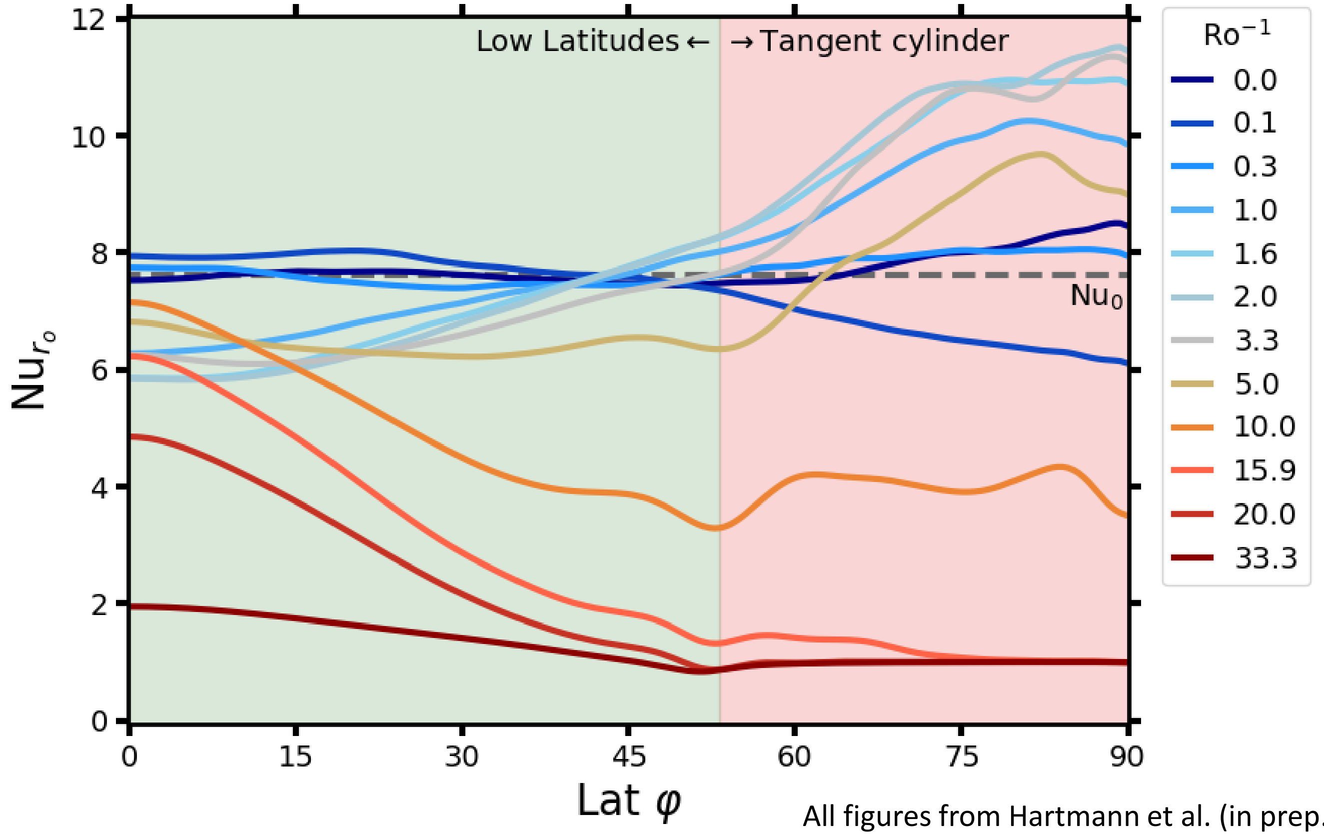

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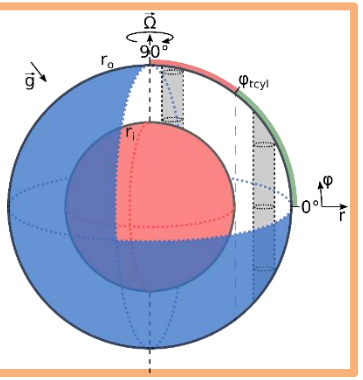

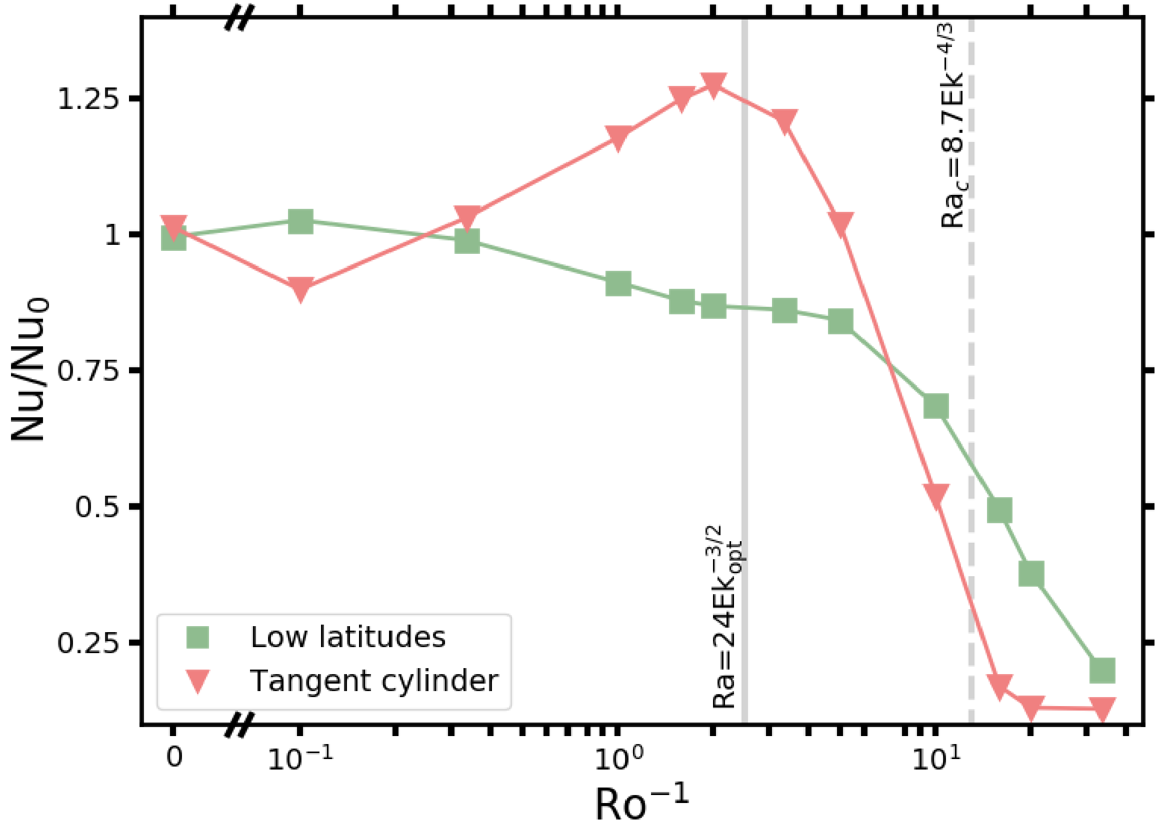

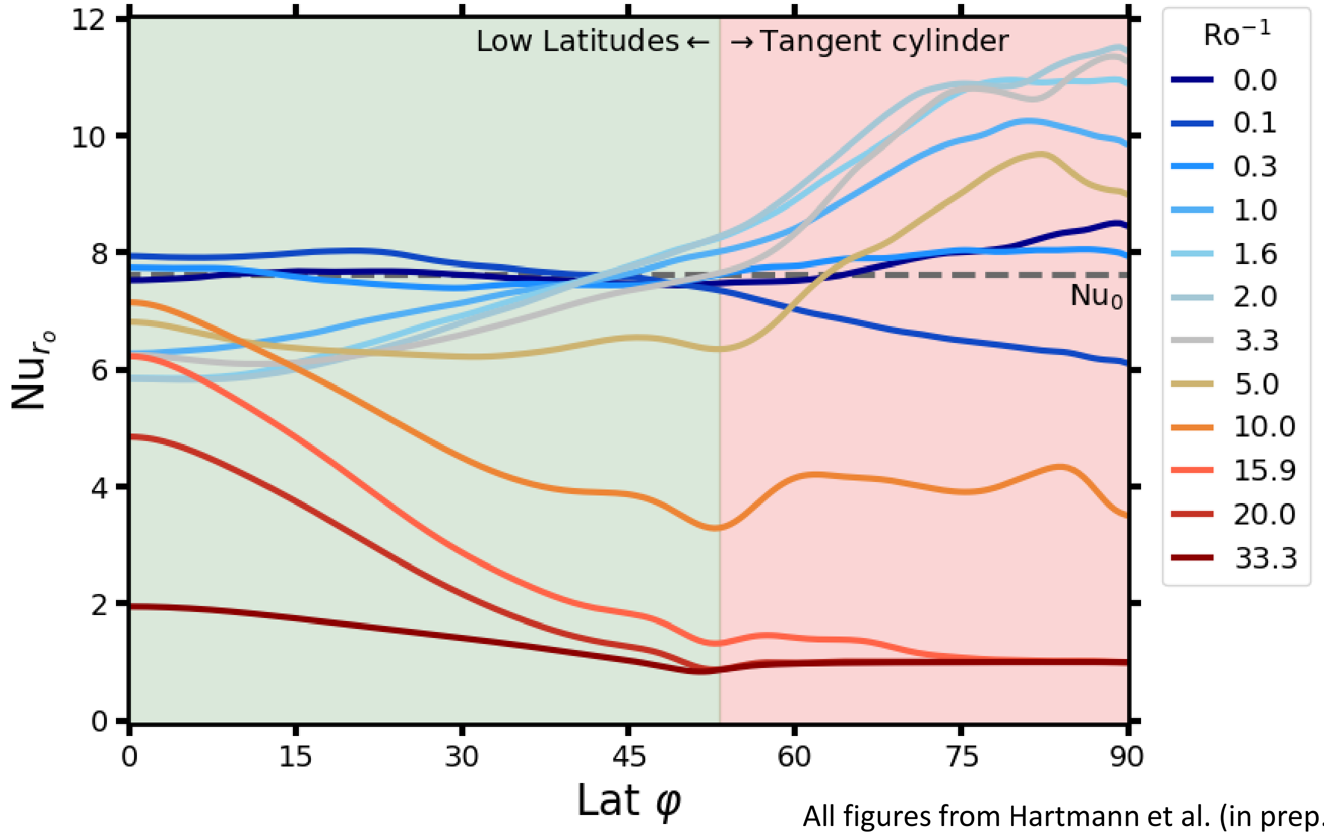

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Latitudinal vs. global heat transport

Do we observe heat transport enhancement?

- Within the tangent cylinder: **Yes!**
- Globally: **No!** Polar enhancement balanced by equatorial reduction

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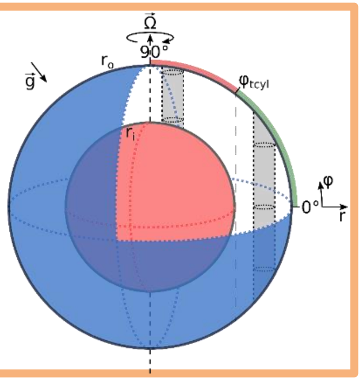
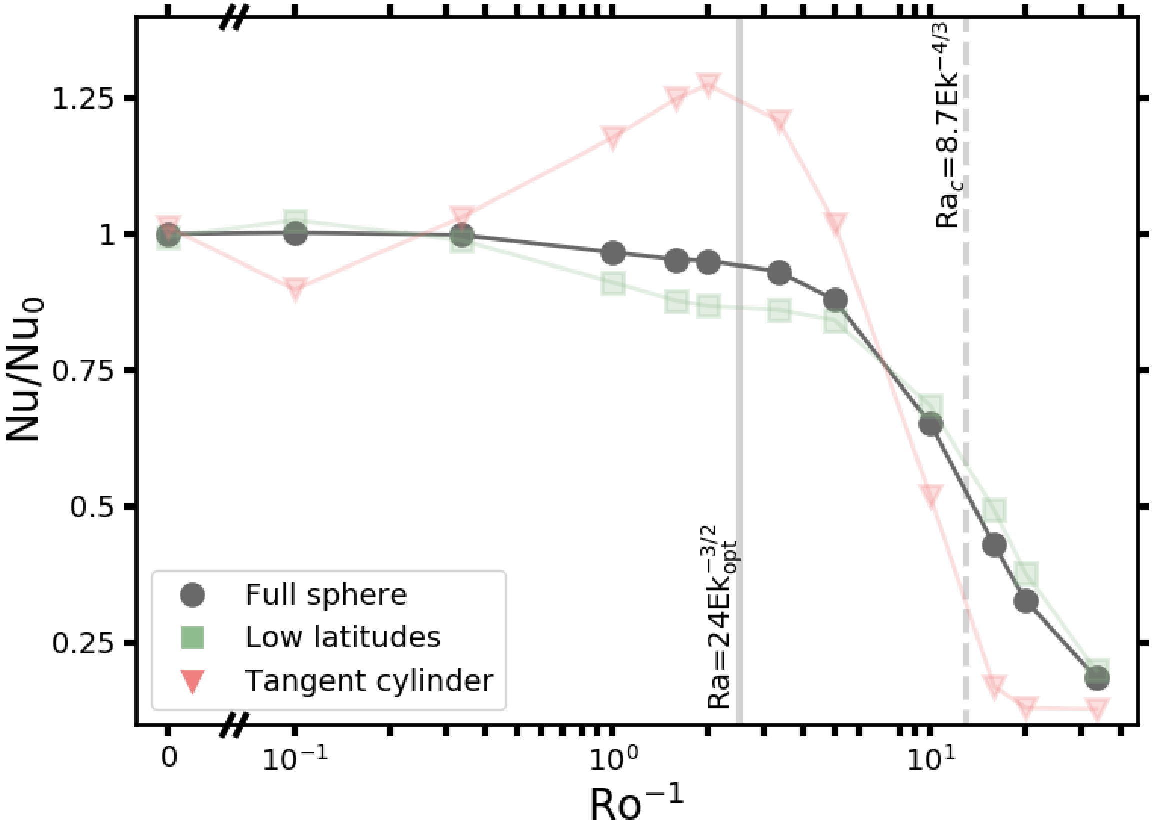
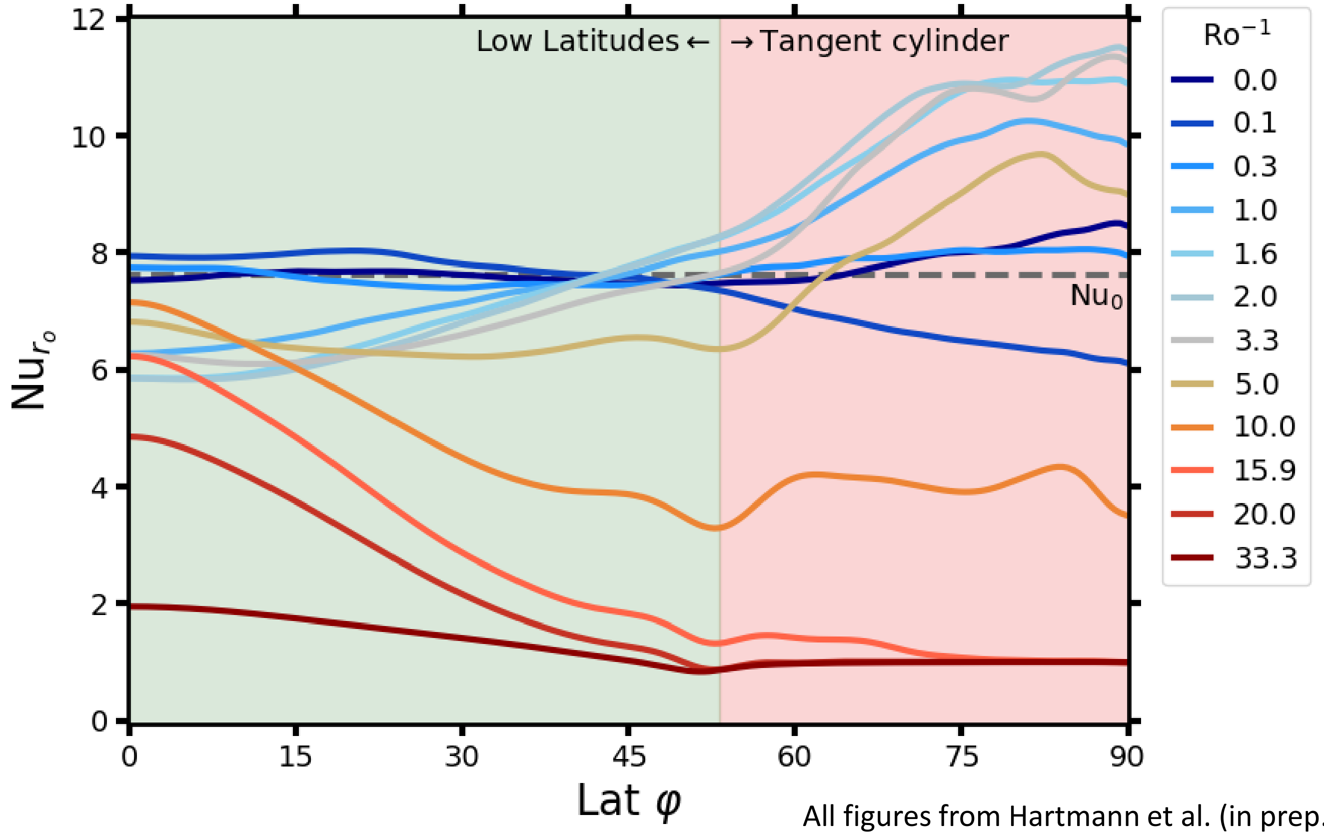
$Ra = 10^6$
$\eta = 0.6$





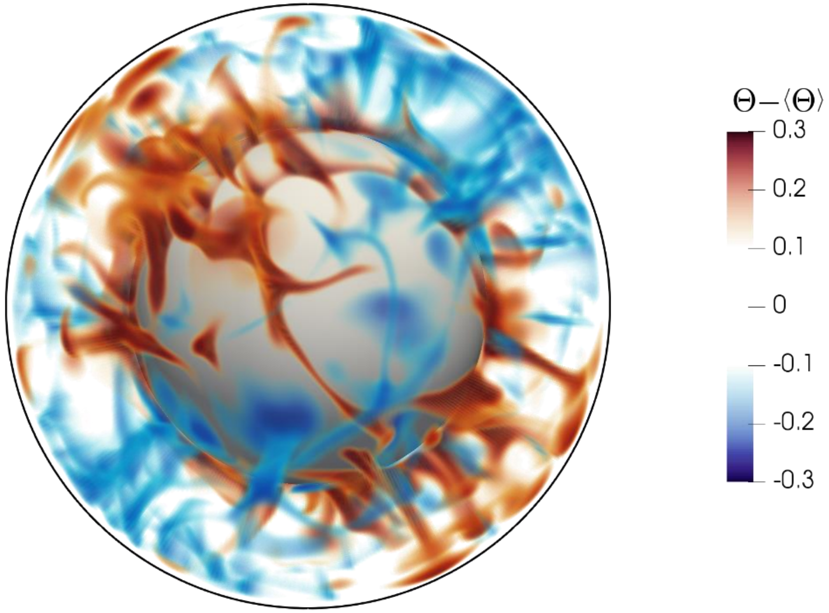


All figures from Hartmann et al. (in prep.)

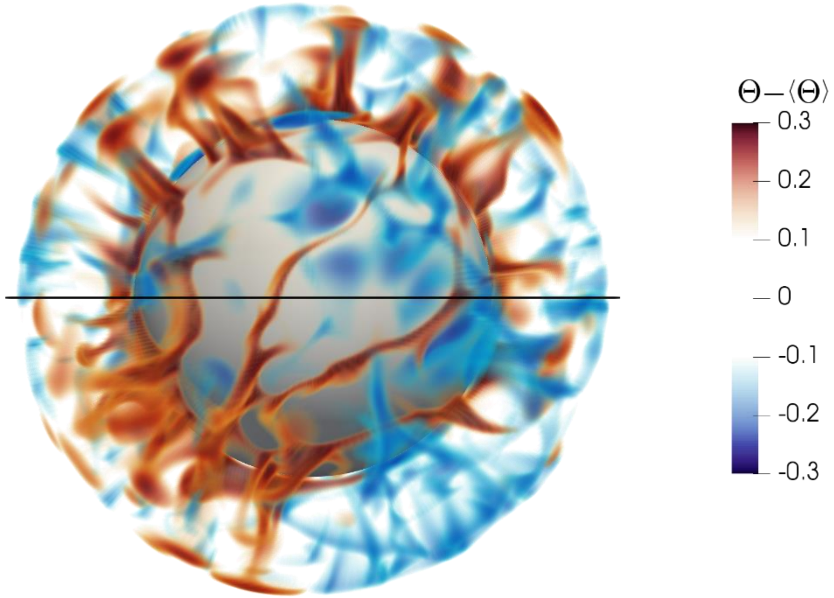
Flow snapshots: Temperature field

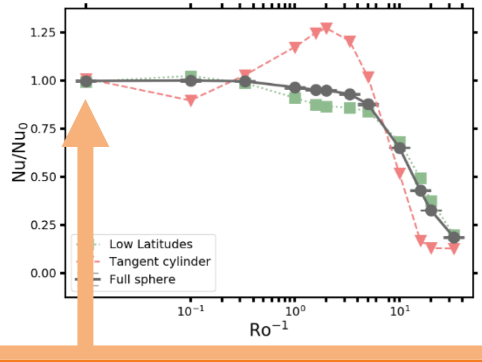
- **Non-rotating, pure RB** $(\mathrm{Ro}^{-1} = 0)$
  - Radial, buoyant plumes
  - Persistent „large-scale circulation“

Polar view (South):



Equatorial view:





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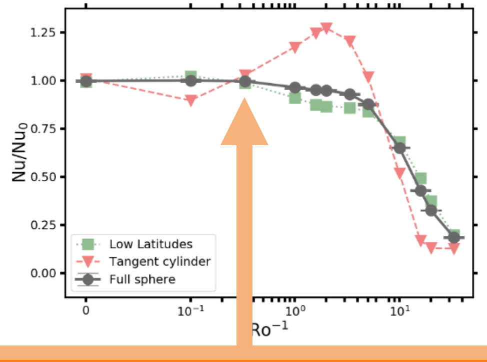
- **Weak rotation** $(\mathrm{Ro}^{-1} = 0.3)$
  - Radial, buoyant plumes
  - Homogeneous distribution



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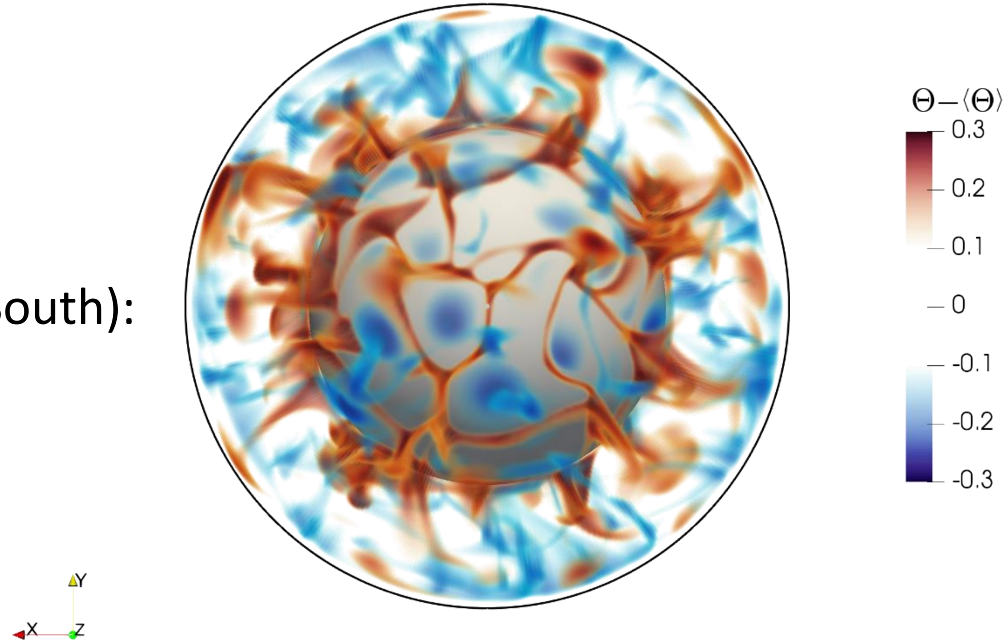

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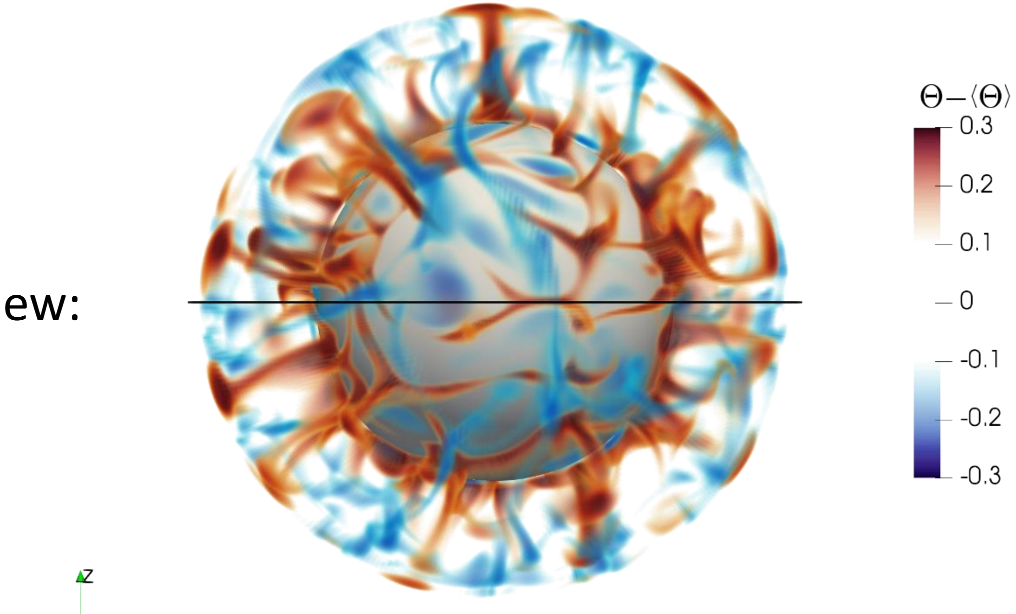

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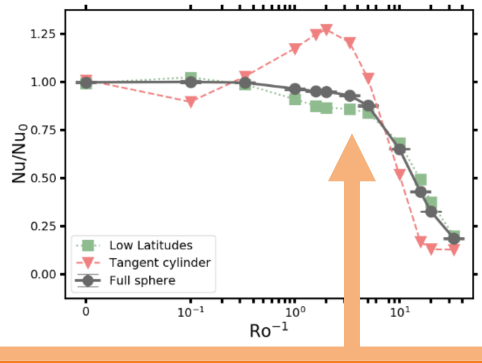
  - Radial, buoyant plumes
  - Persistent „large-scale circulation“
- Weak rotation $(\mathrm{Ro}^{-1} = 0.3)$
  - Radial, buoyant plumes
  - Homogeneous distribution
- **Moderate rotation** $(\mathrm{Ro}^{-1} = 3)$
  - Taylor-Columns, sheet-like plumes
  - Polar heat transport enhancement



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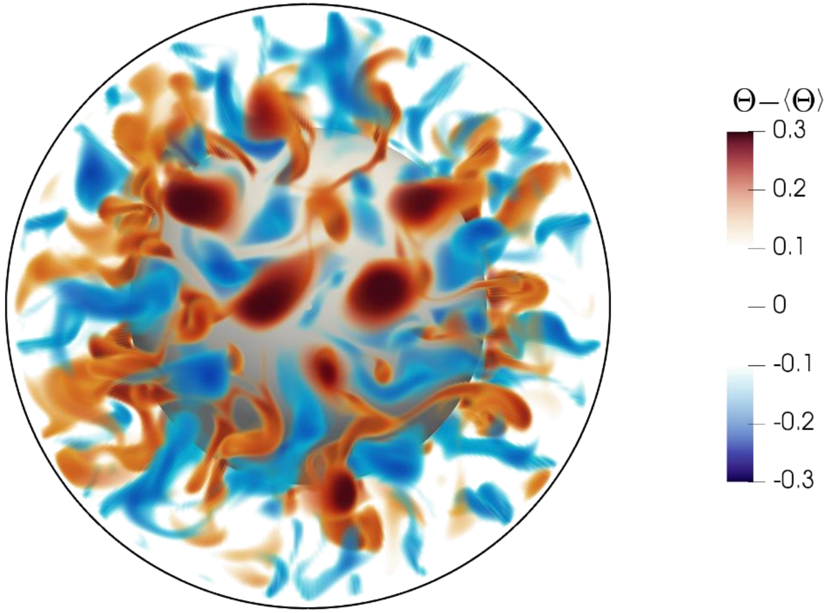

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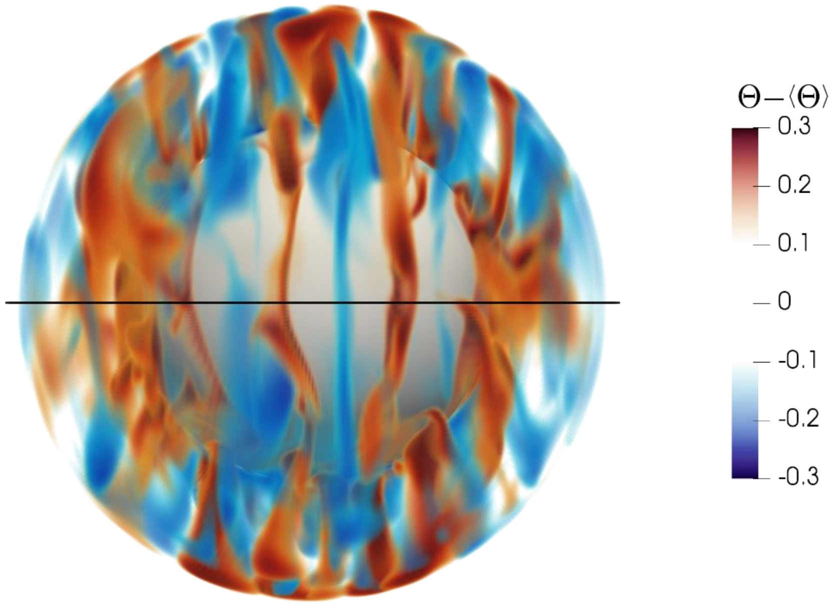

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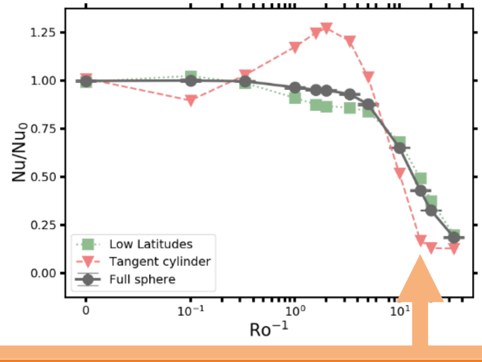
- <u>Weak rotation</u> $(\mathrm{Ro}^{-1} = 0.3)$
  - Radial, buoyant plumes
  - Homogeneous distribution
- <u>Moderate rotation</u> $(\mathrm{Ro}^{-1} = 3)$
  - Taylor-Columns, sheet-like plumes
  - Polar heat transport enhancement
- **<u>Strong rotation</u>** $(\mathrm{Ro}^{-1} = 15.9)$
  - Taylor-Columns, sheet-like plumes
  - Equatorial dominated convection
  - (Towards onset of) Diffusion-free behavior [Gastine et al. (JFM,2016) Wang et al. (GRL,2021)]



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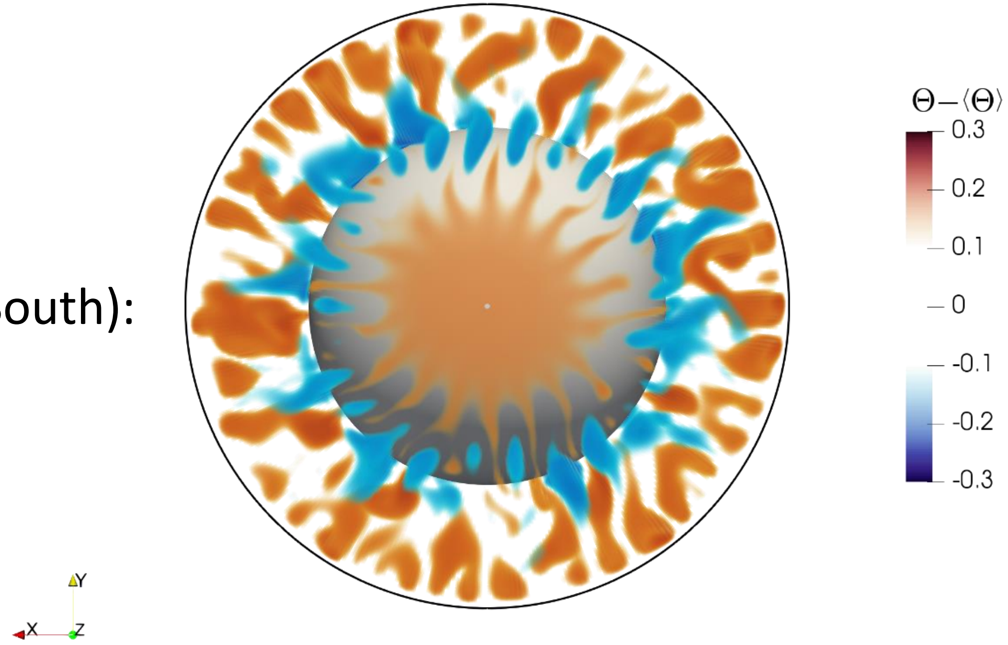

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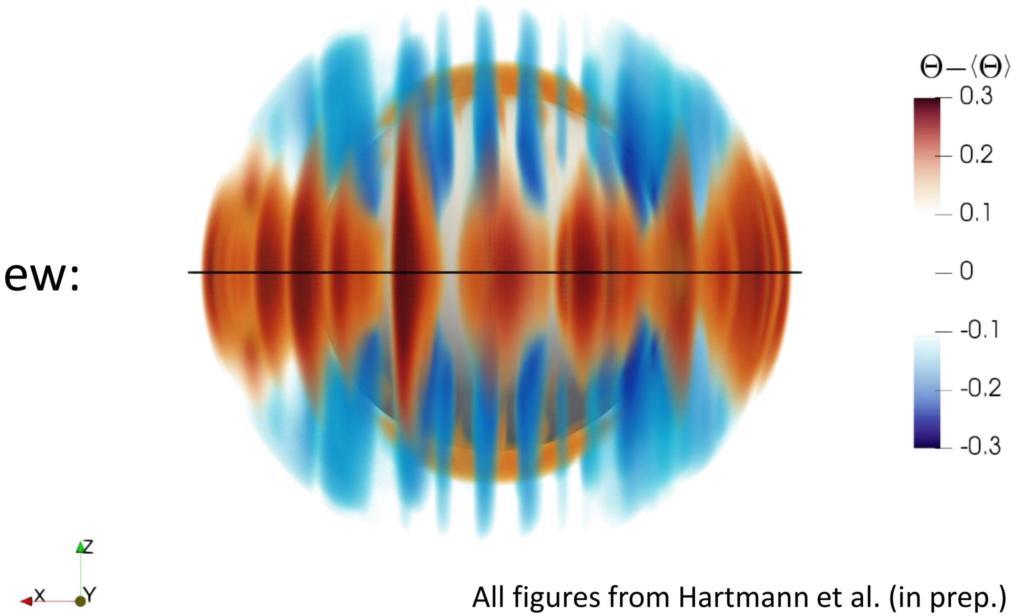


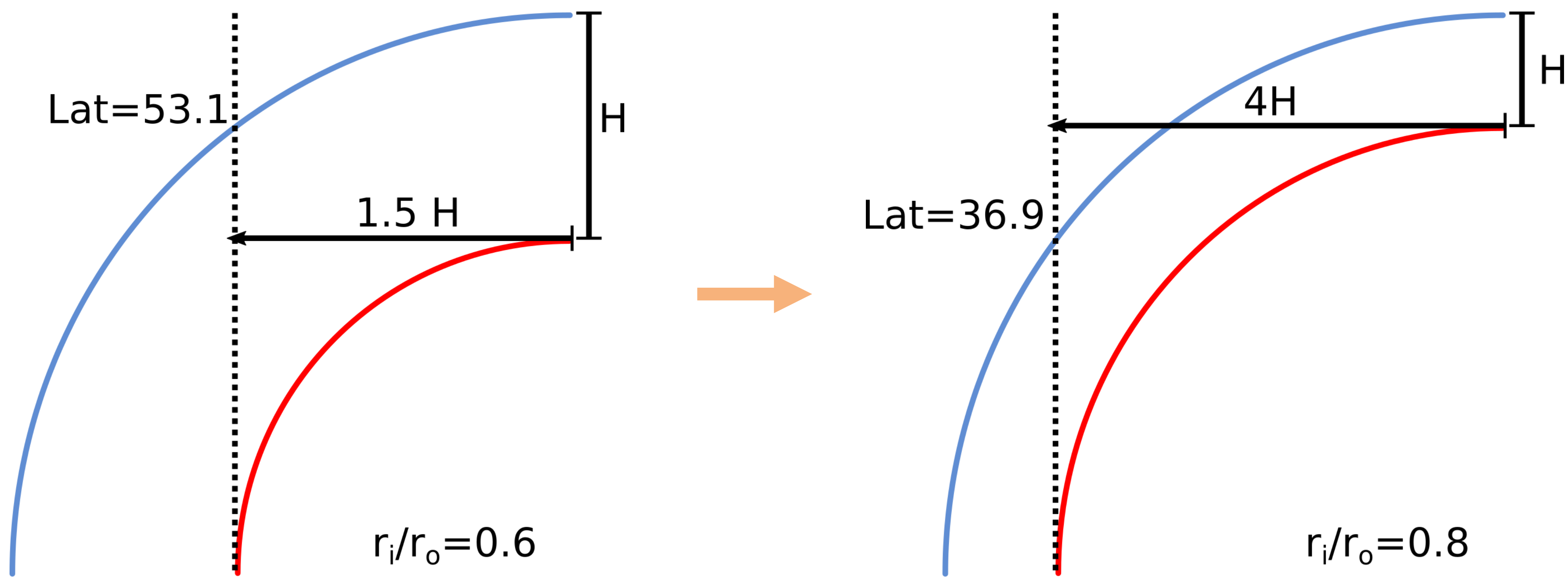
All figures from Hartmann et al. (in prep.)

Towards thinner shells...

- Radius ratio for sub-glaical oceans on icy moons:
- Increasing the radius ratio:
  $\eta = 0.6 \rightarrow \eta = 0.8$

	Enceladus	Titan	Europa	Ganymede
η	0.74 – 0.95	0.83 – 0.96	0.92 - 0.94	0.80 – 0.99

[Soderlund (GRL, 2019), Vance et al. (JGR Planets, 2018)]



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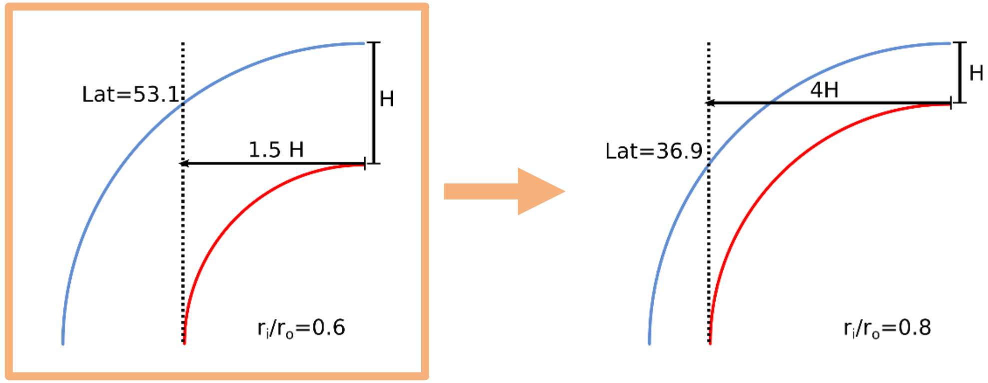

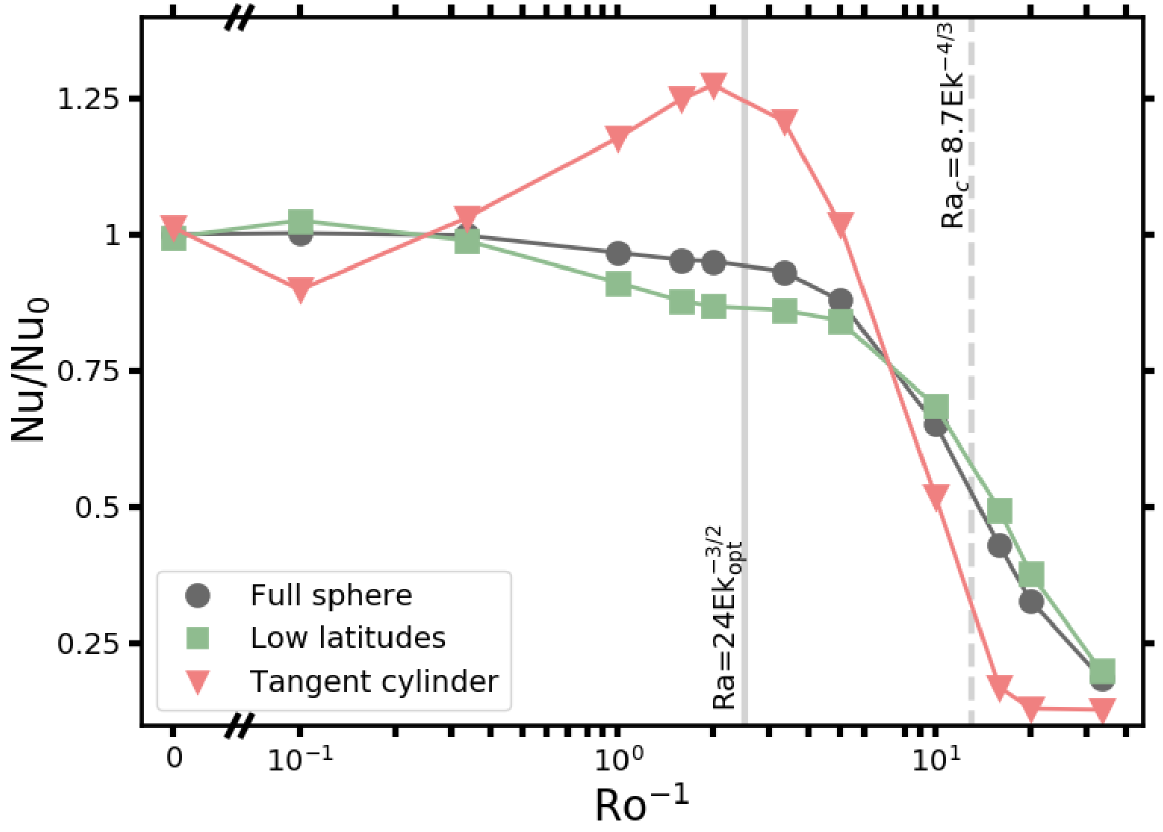

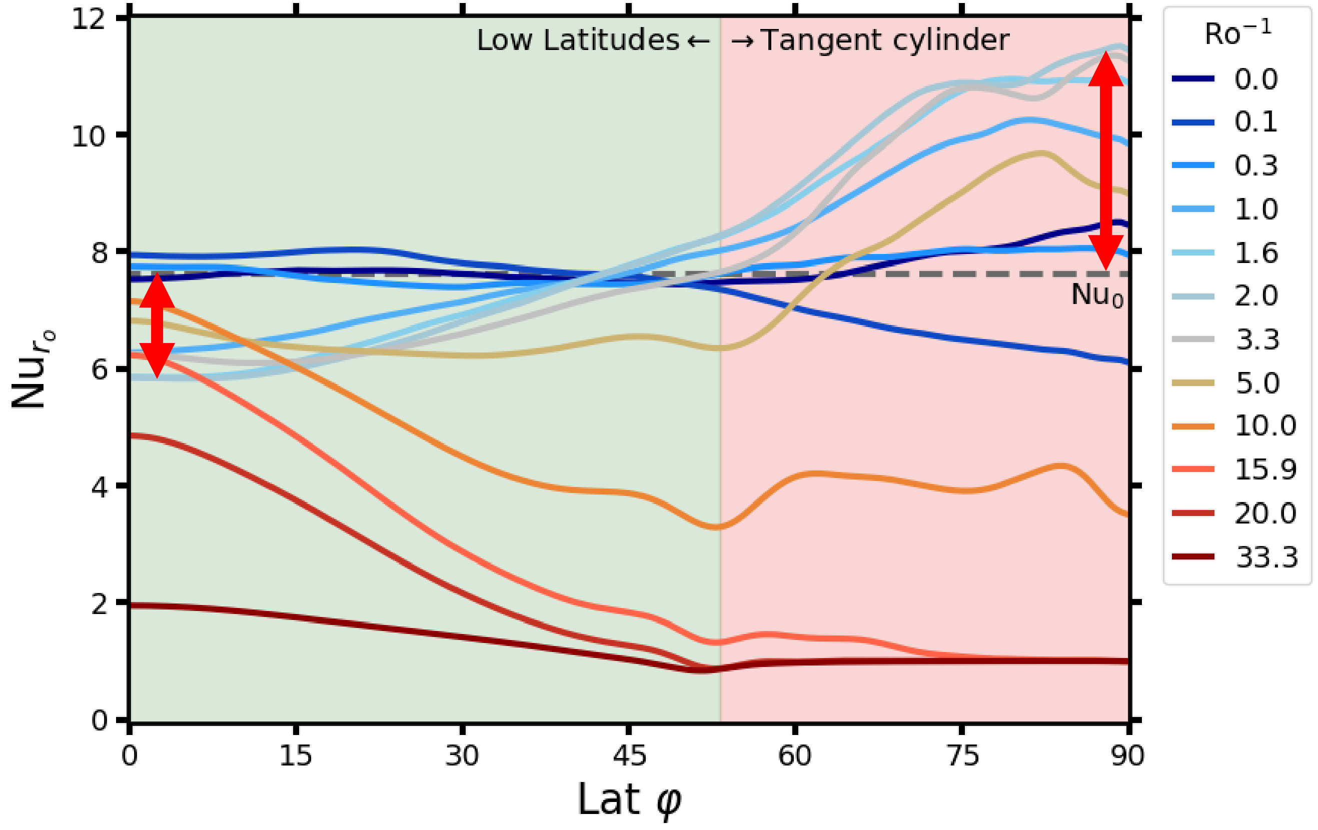

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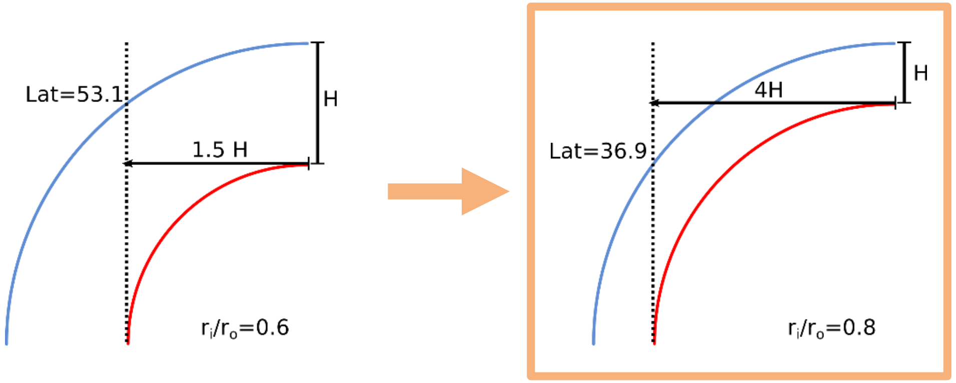

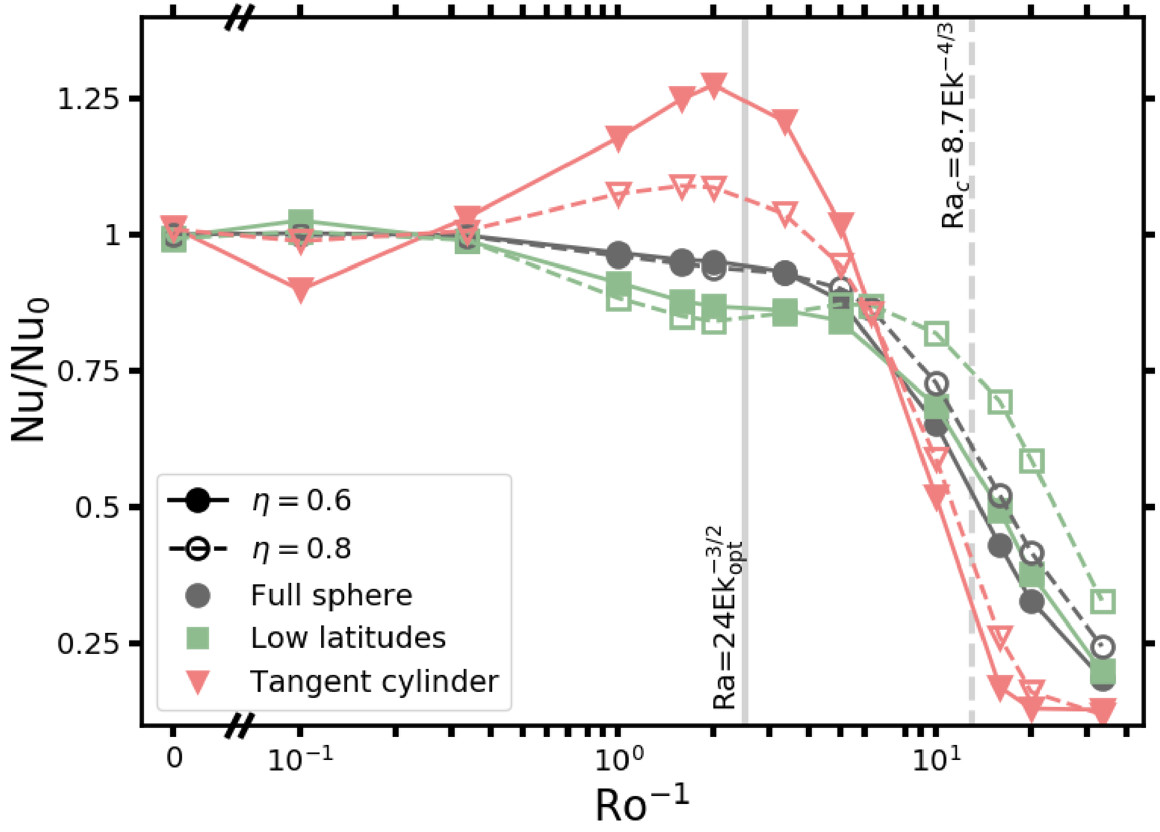

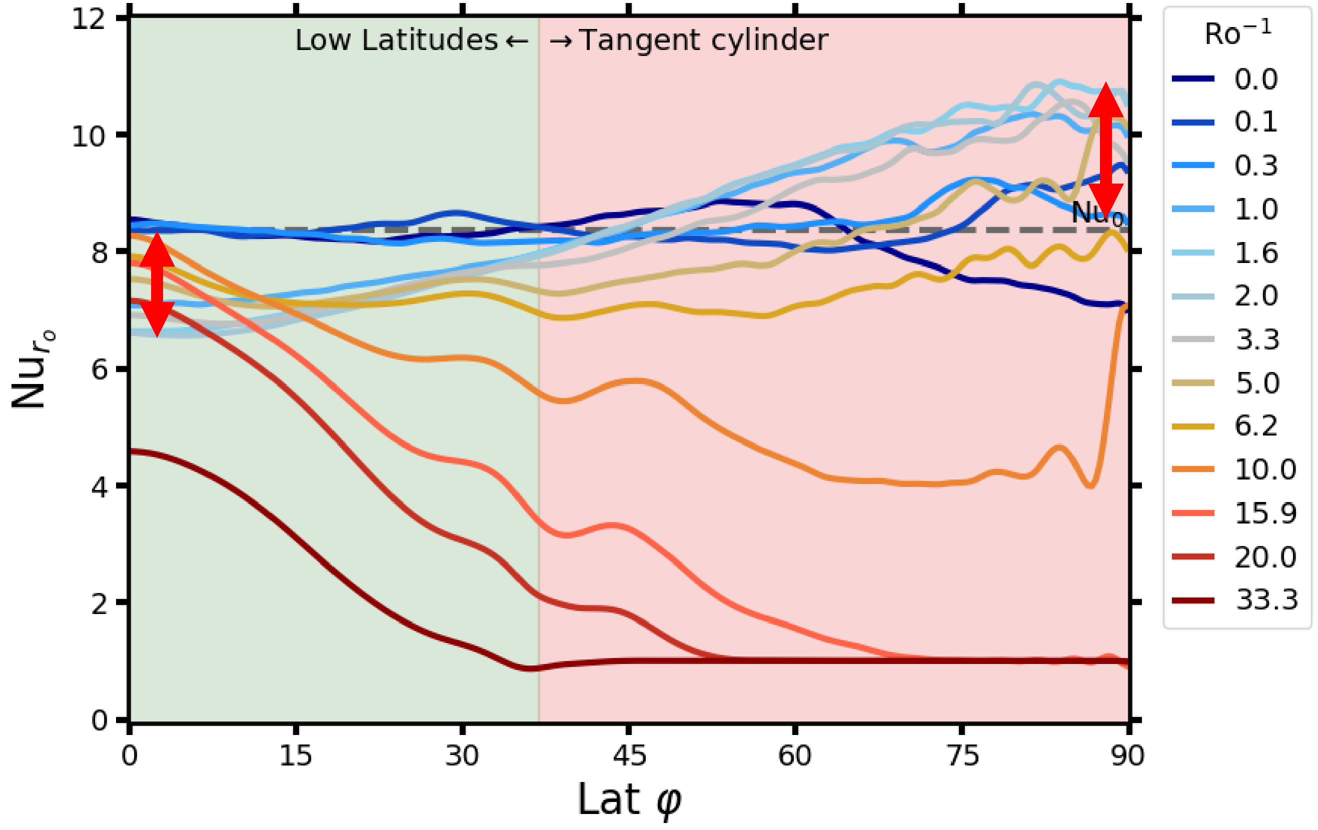

All figures from Hartmann et al. (in prep.)

Towards thinner shells...

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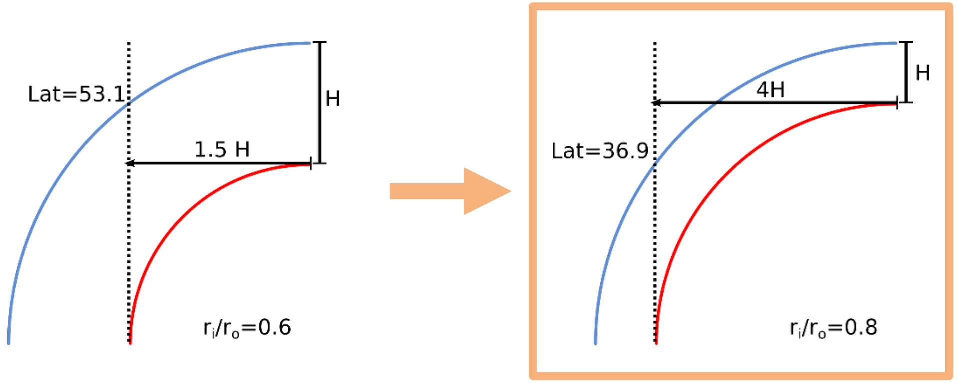

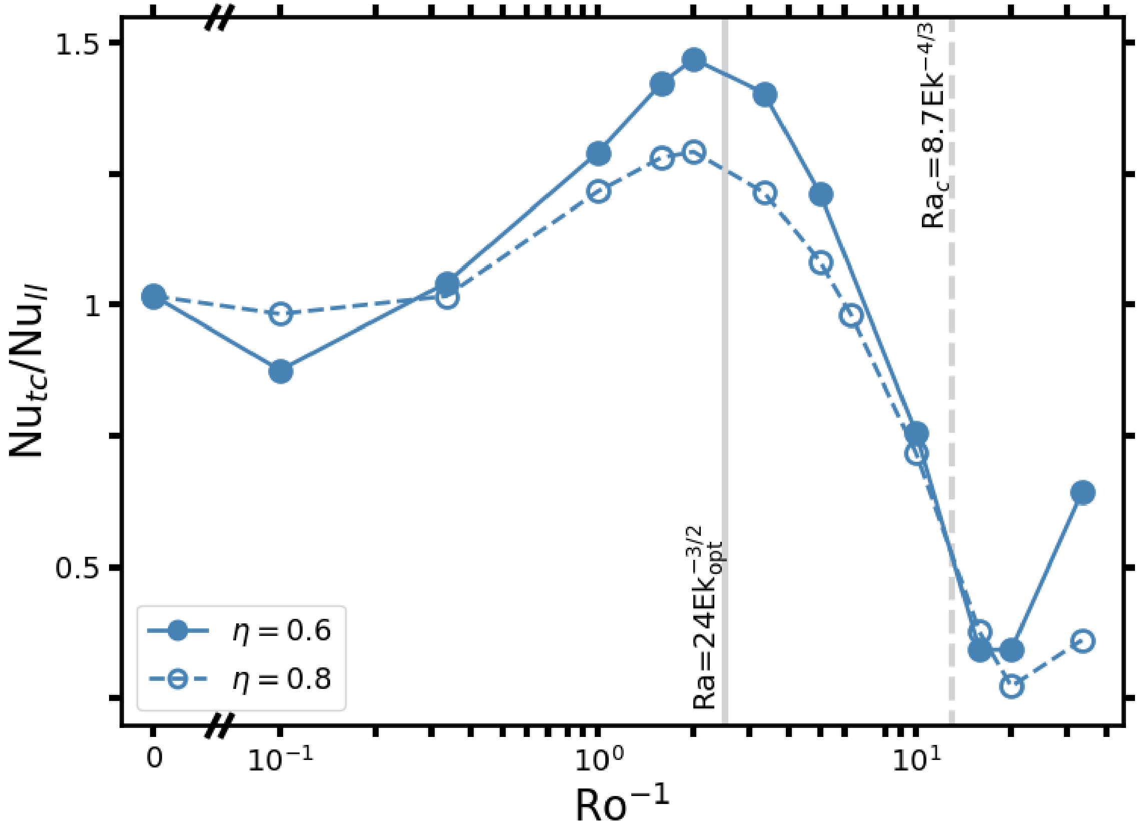

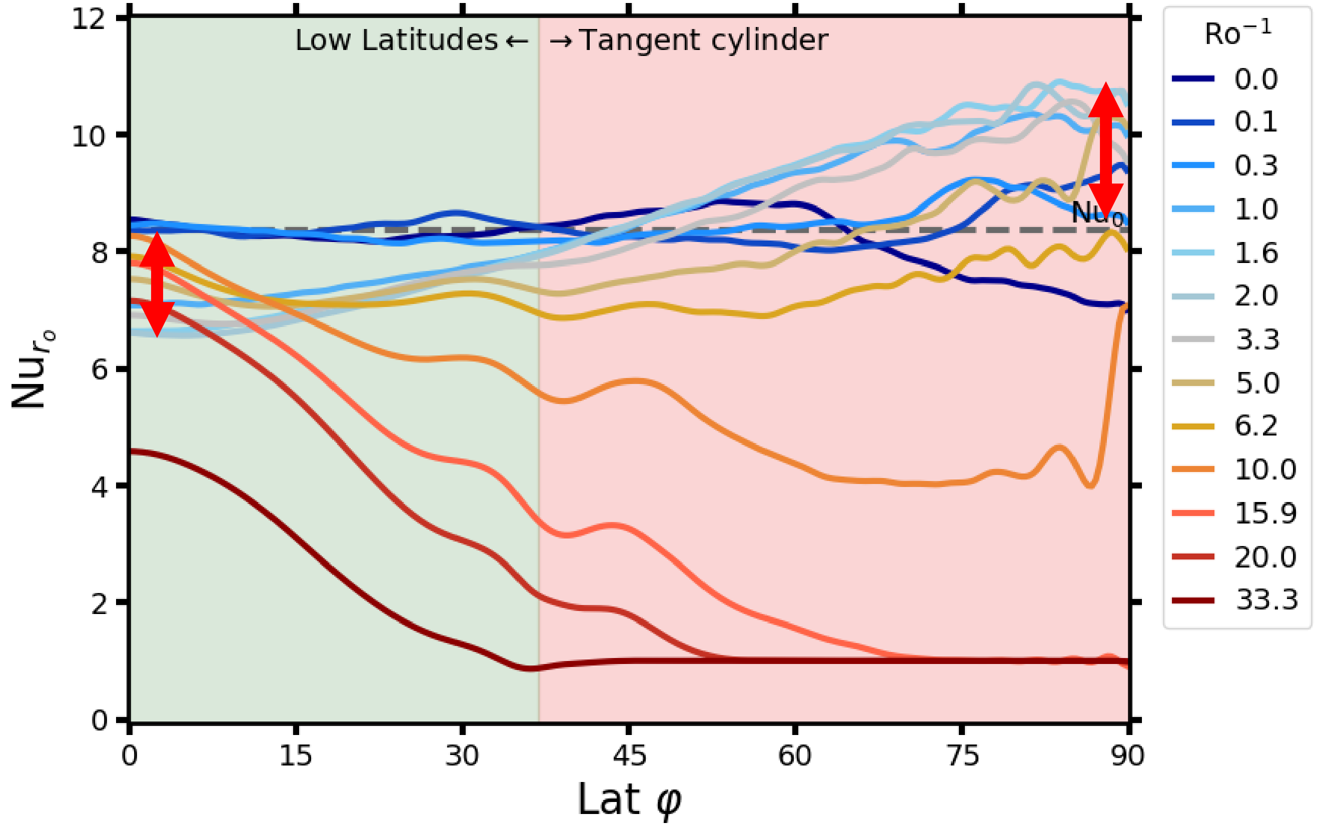

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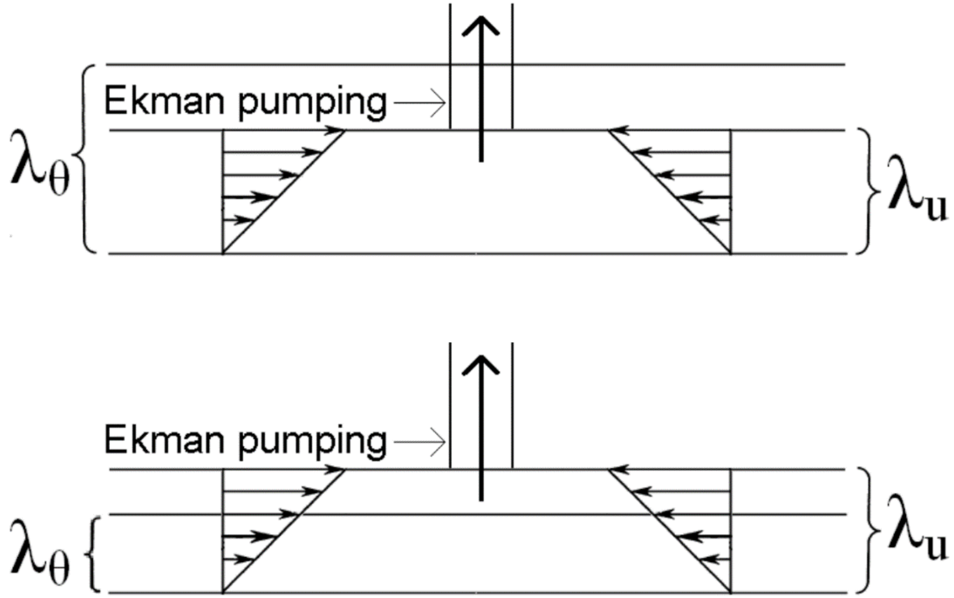
Maximal polar enhancement and boundary layer ratio

In planar RRBC:

- **Ekman pumping** to supply the vortices with cold/hot fluid **most efficient** for equal thicknesses of thermal BL λ_Θ and kinetic BL λ_u:
  $$\Rightarrow \boldsymbol{\lambda_\Theta / \lambda_u \approx 1}$$



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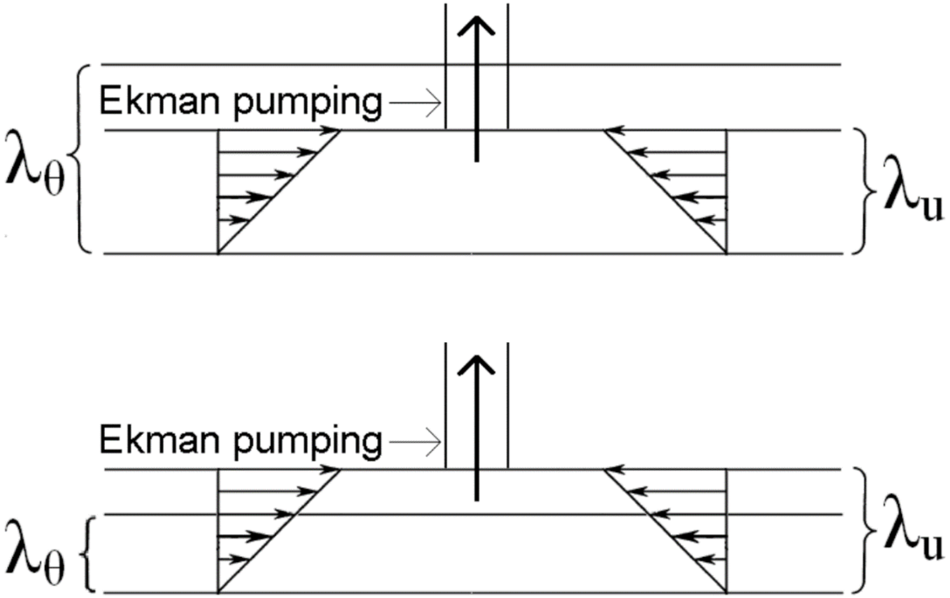

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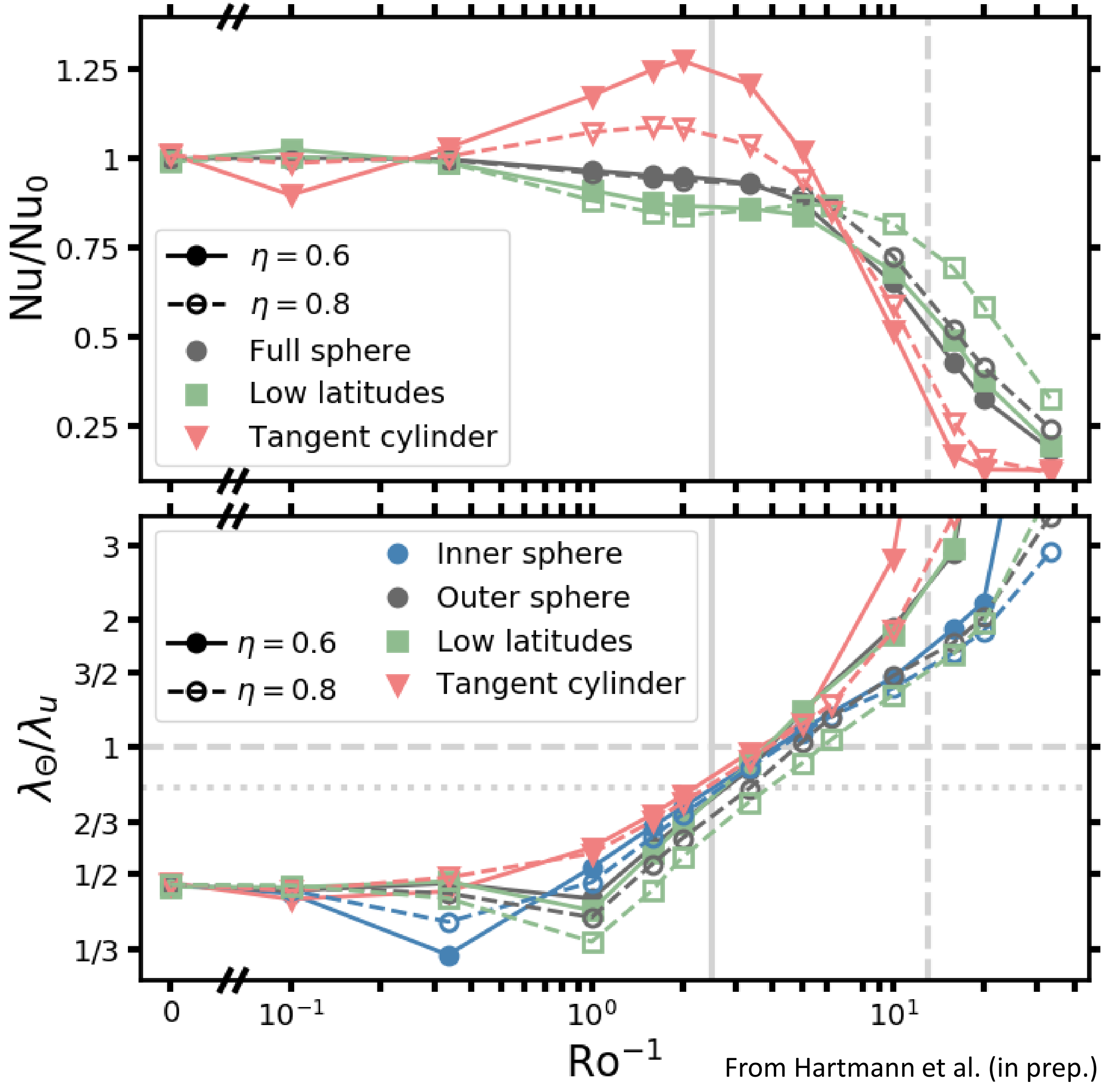

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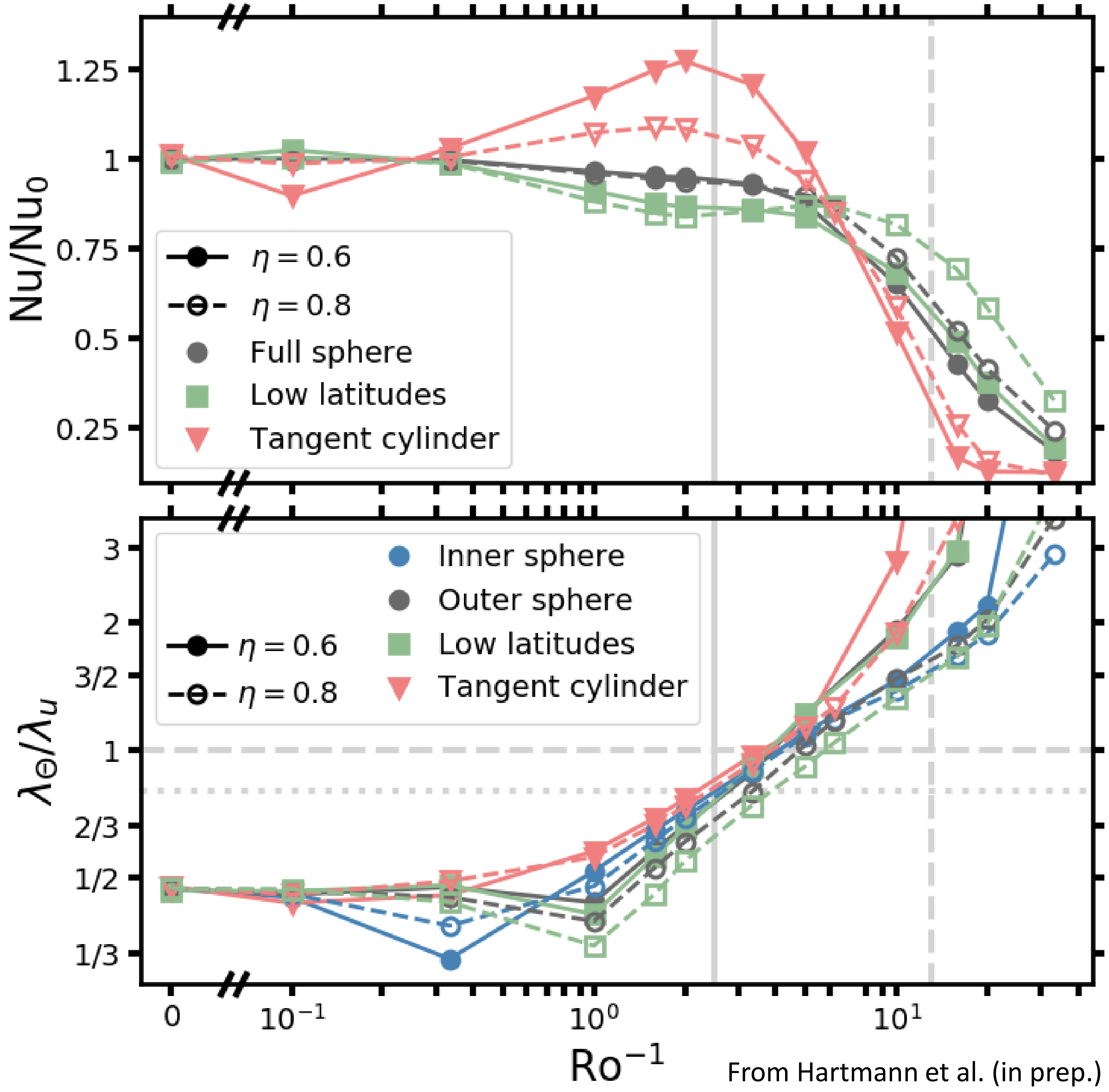

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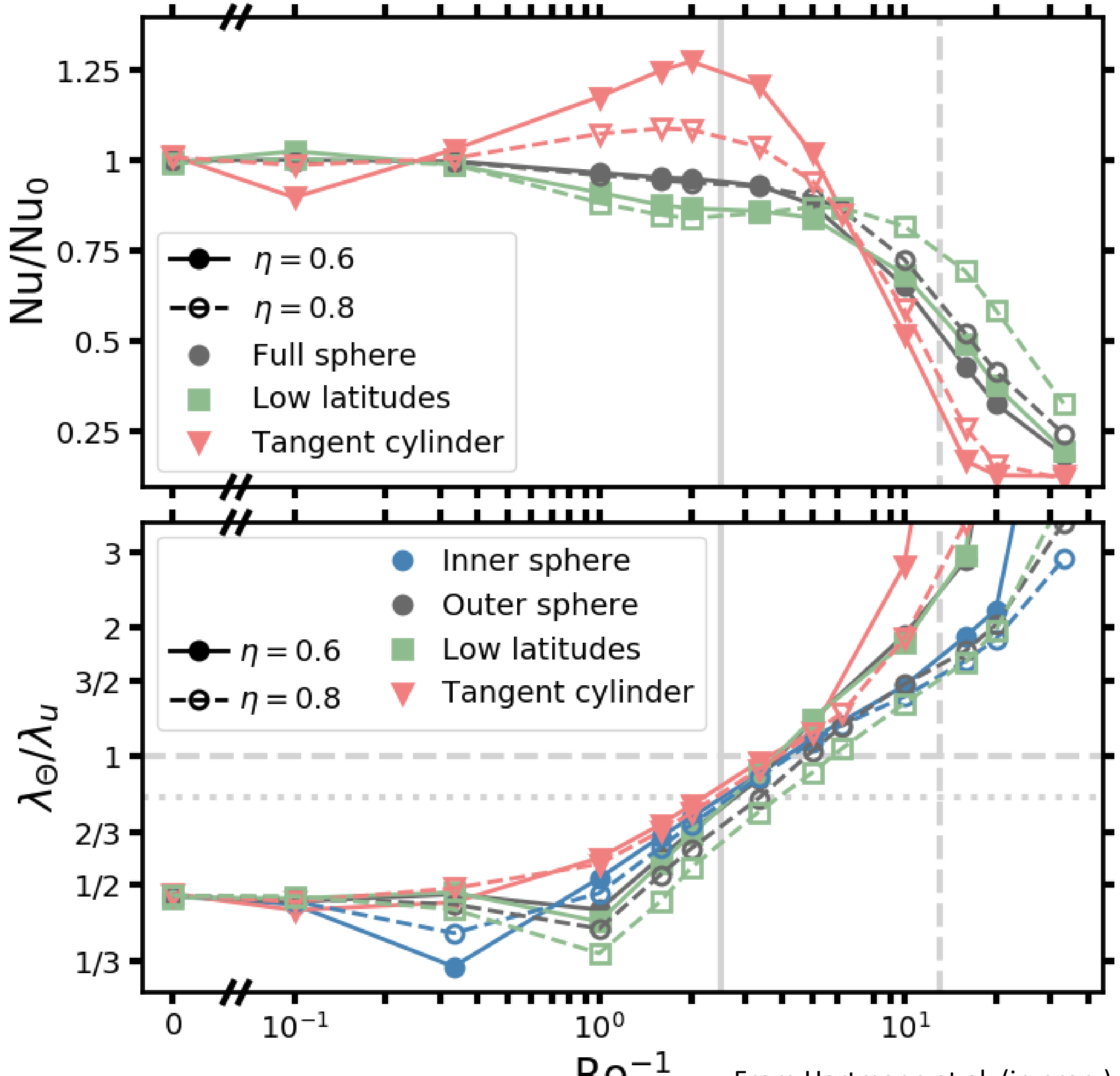
➢ **Enhancement efficiency** still controlled by the **boundary layer ratio λ_Θ/λ_u**



From Hartmann et al. (in prep.)

Sensitivity to the radial gravity profile

Radial gravity profile: $g(r) \propto r^{\gamma}$

- So far: $g(r) = const.$
- Now: $g(r) \propto r$
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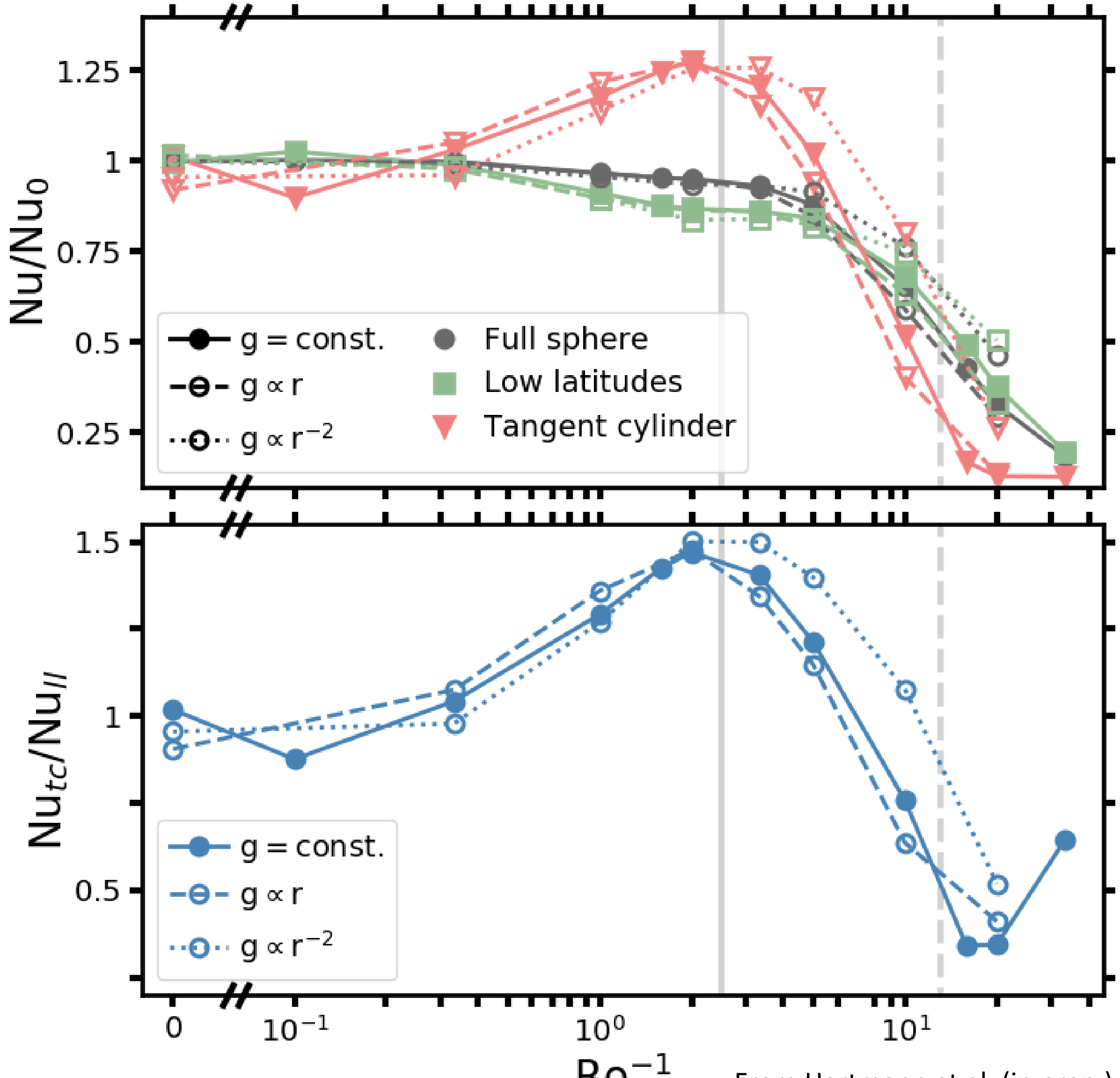

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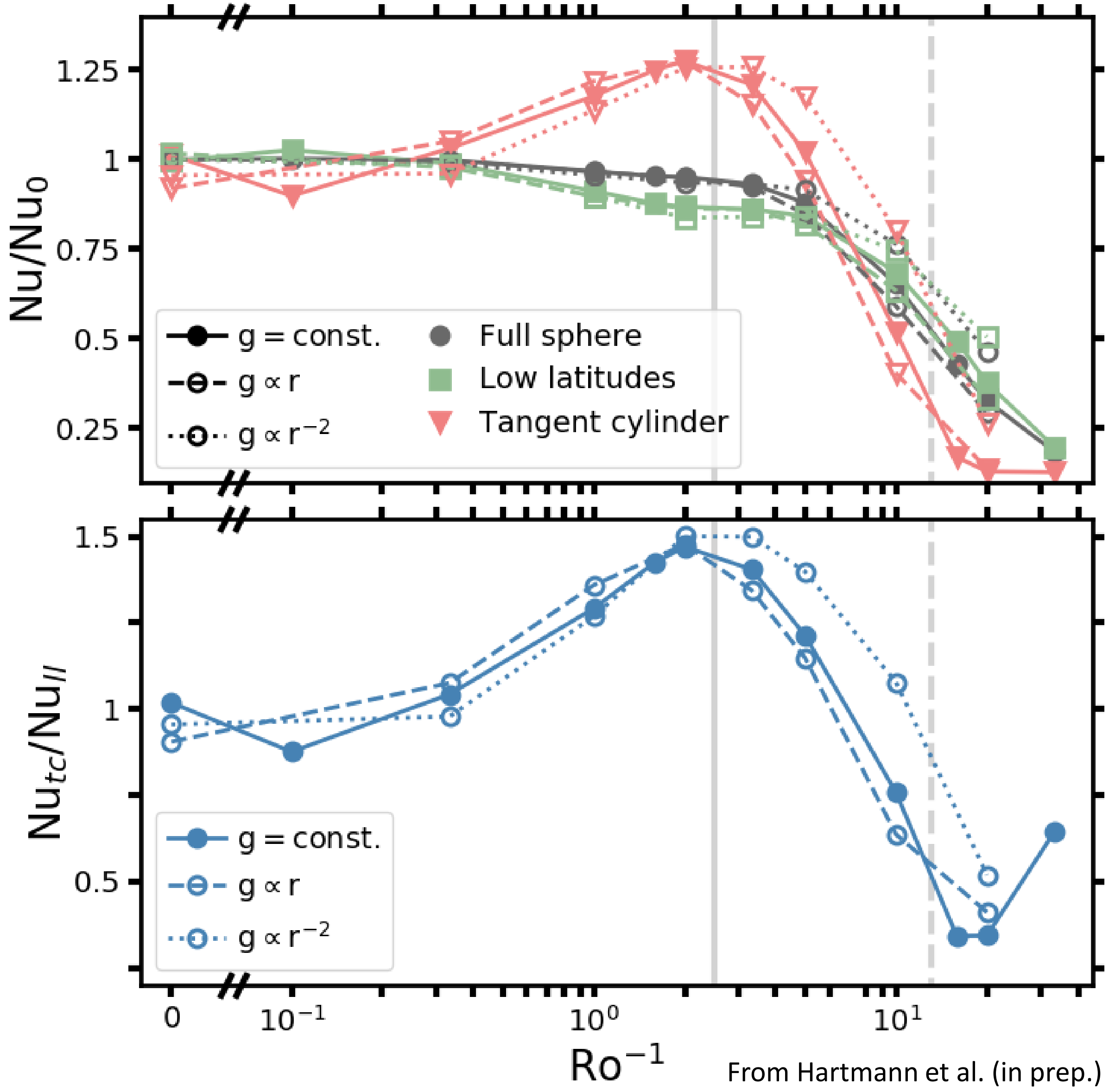

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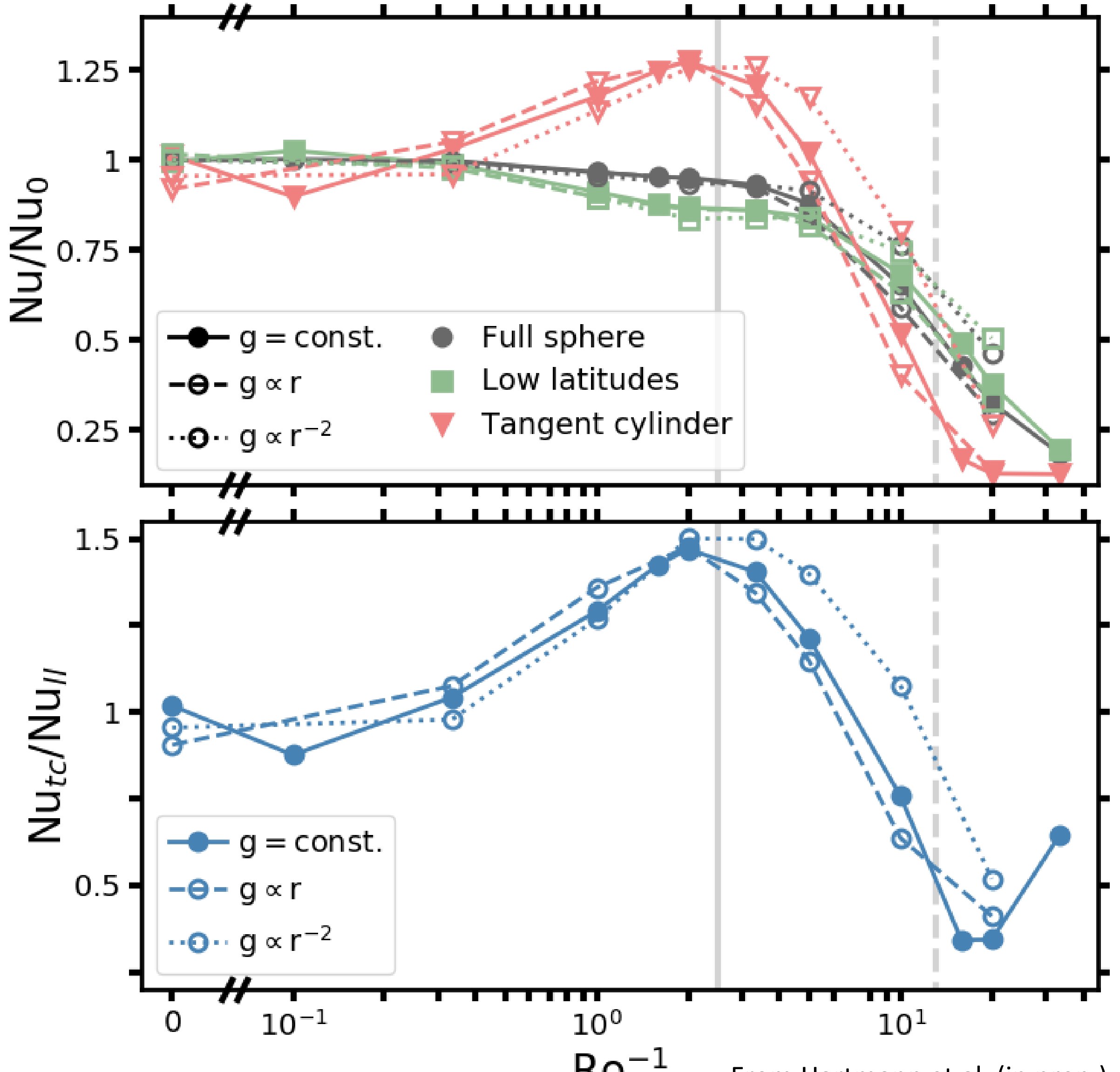

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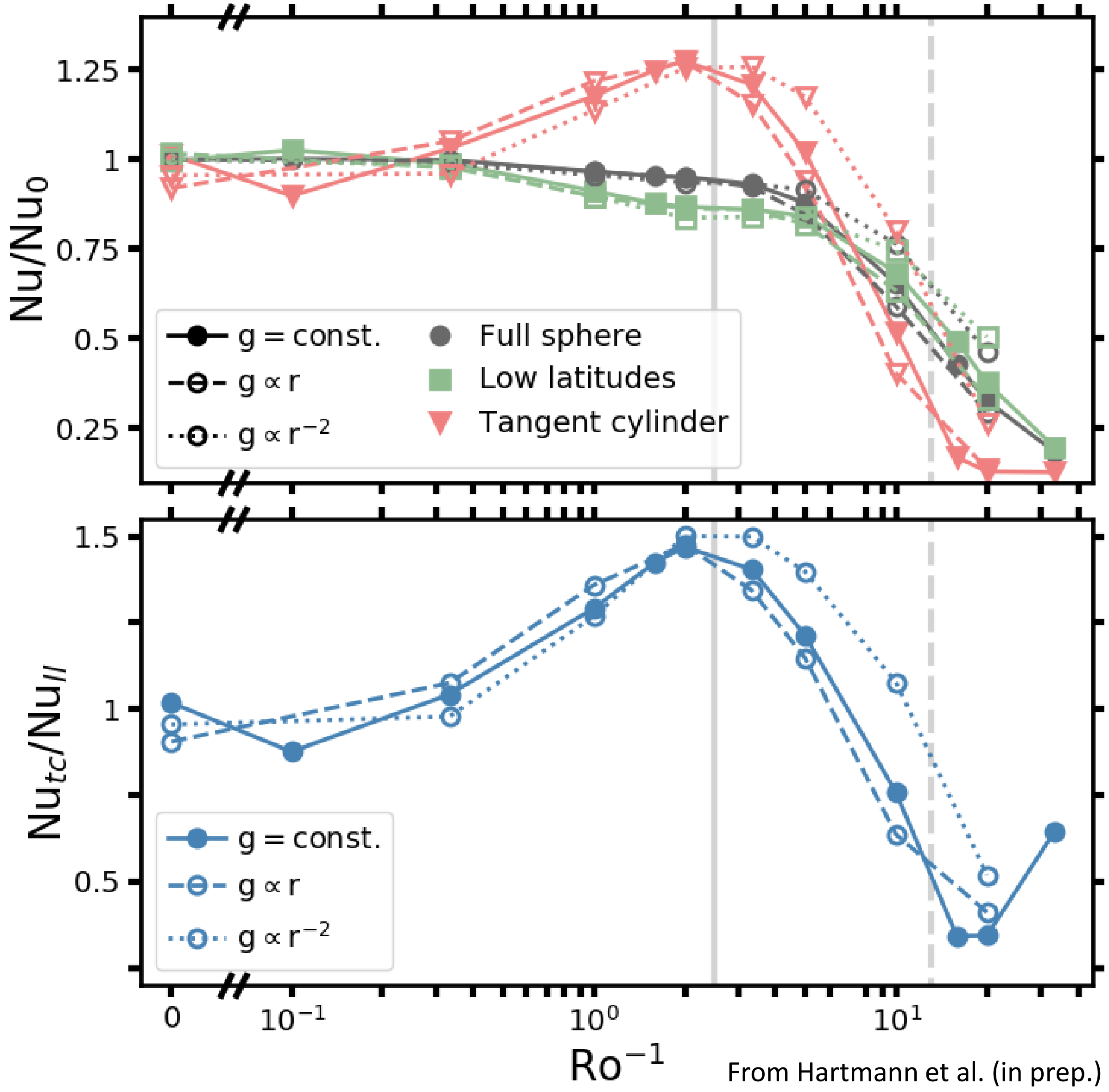

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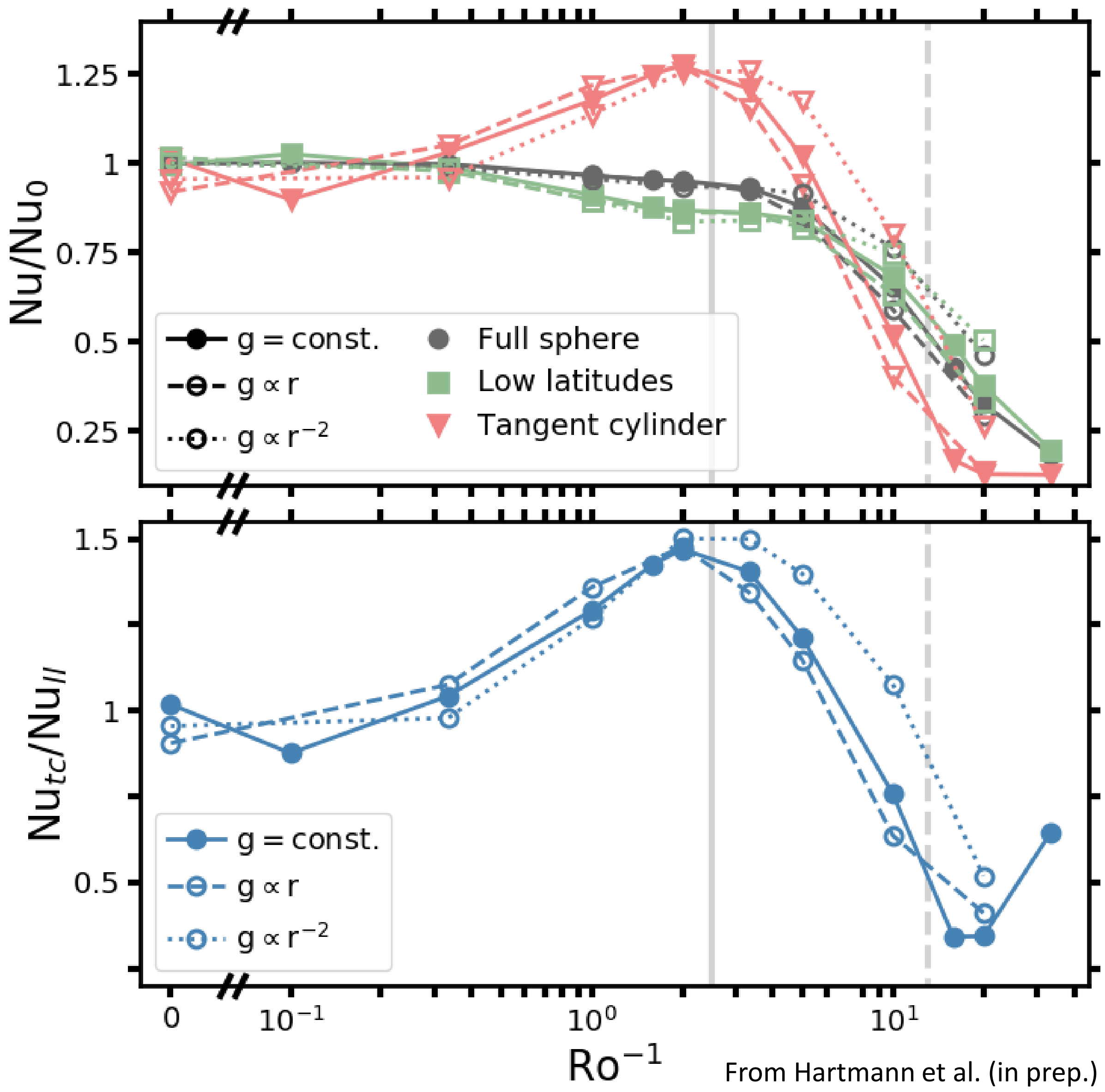

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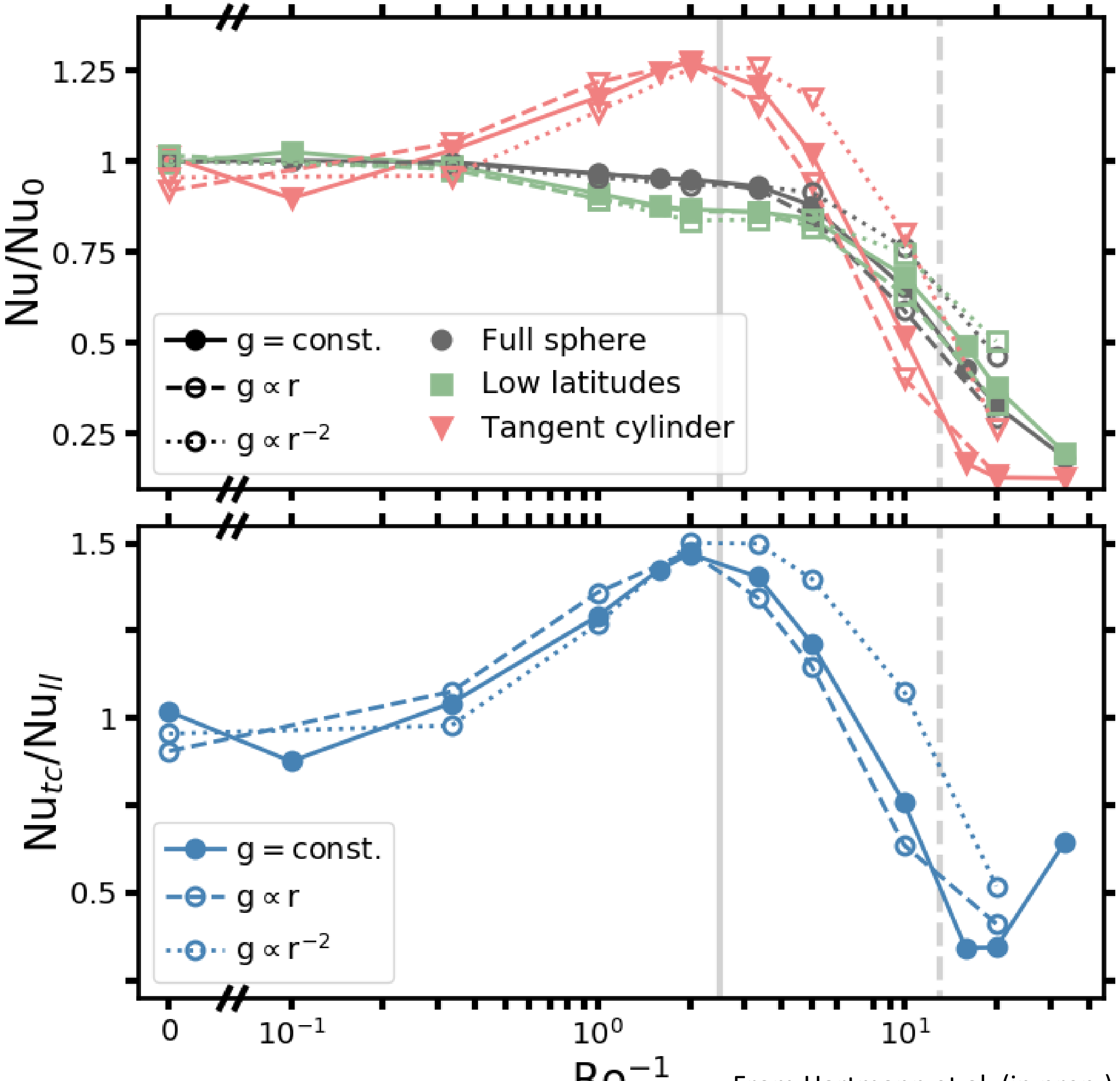

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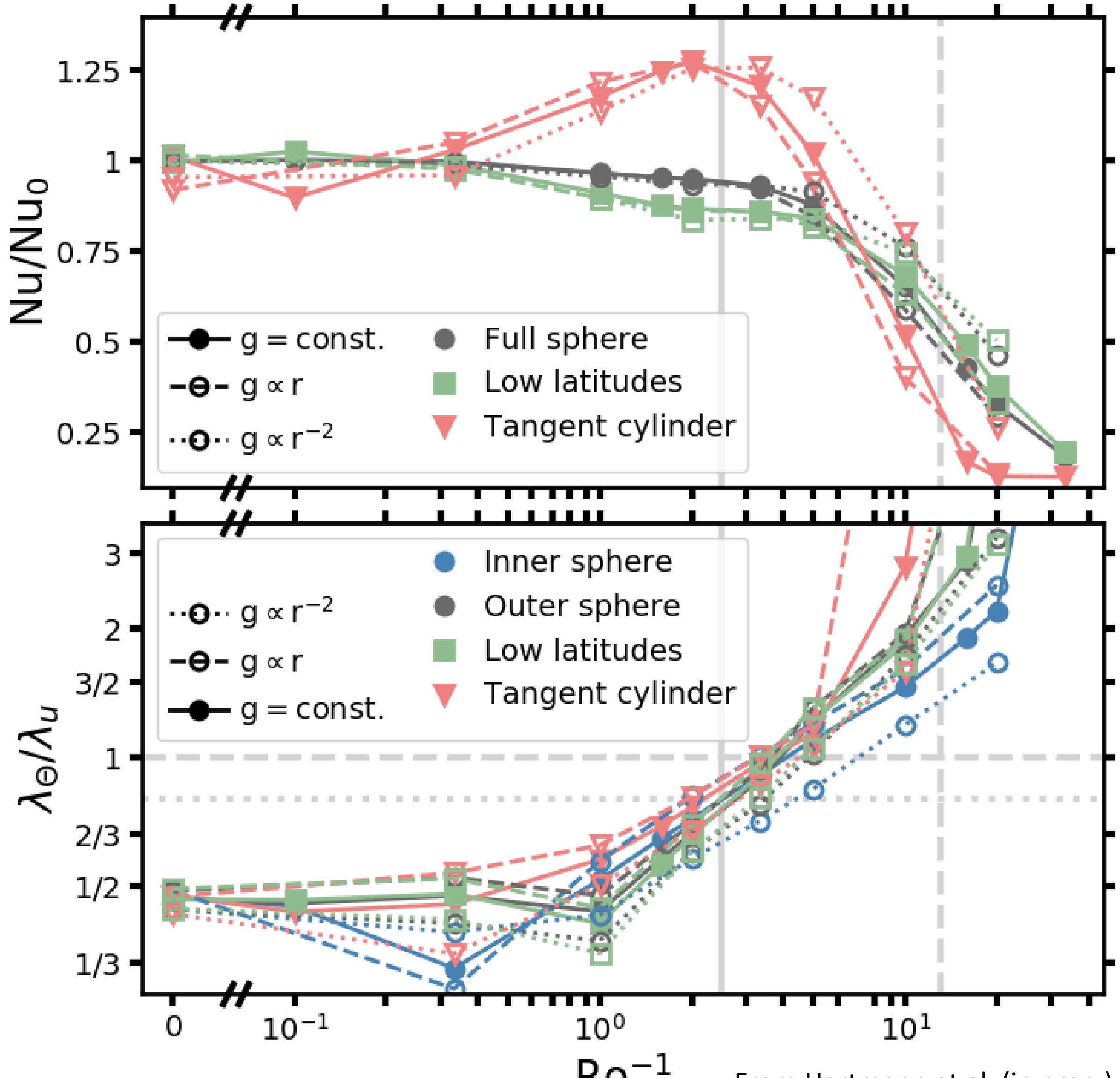

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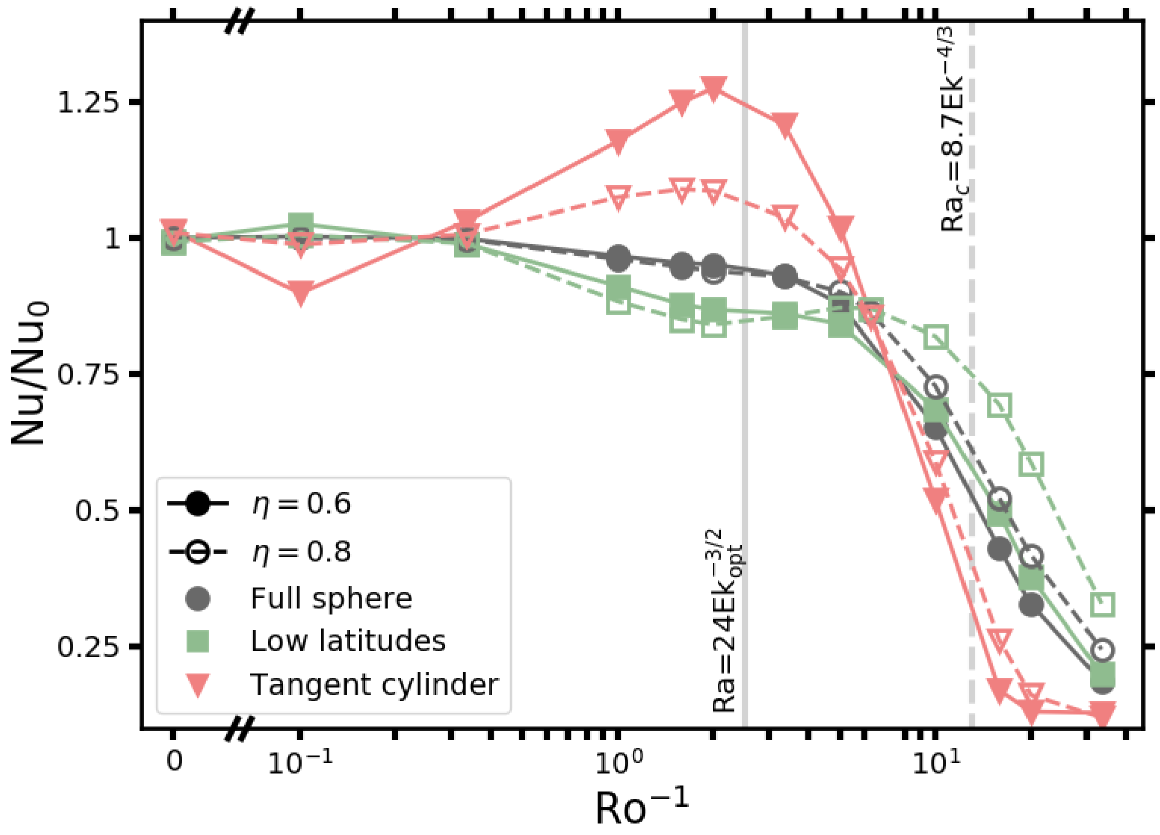

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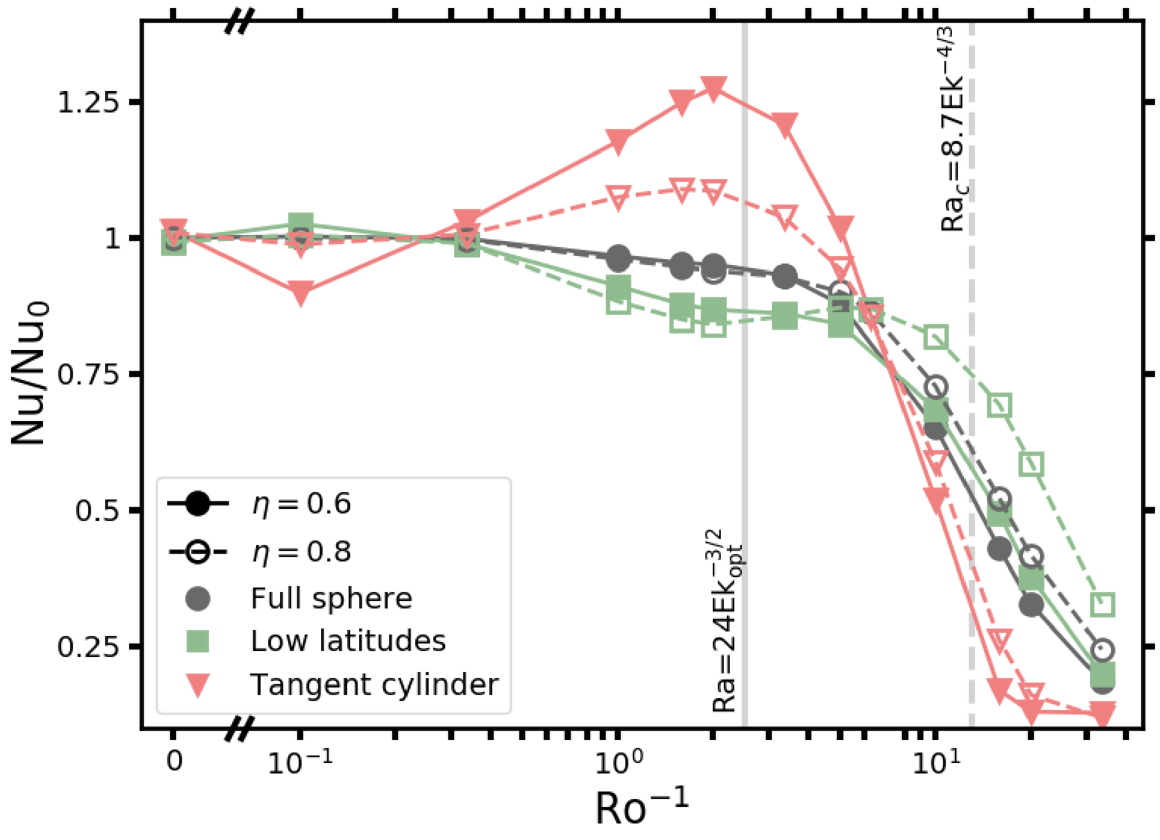

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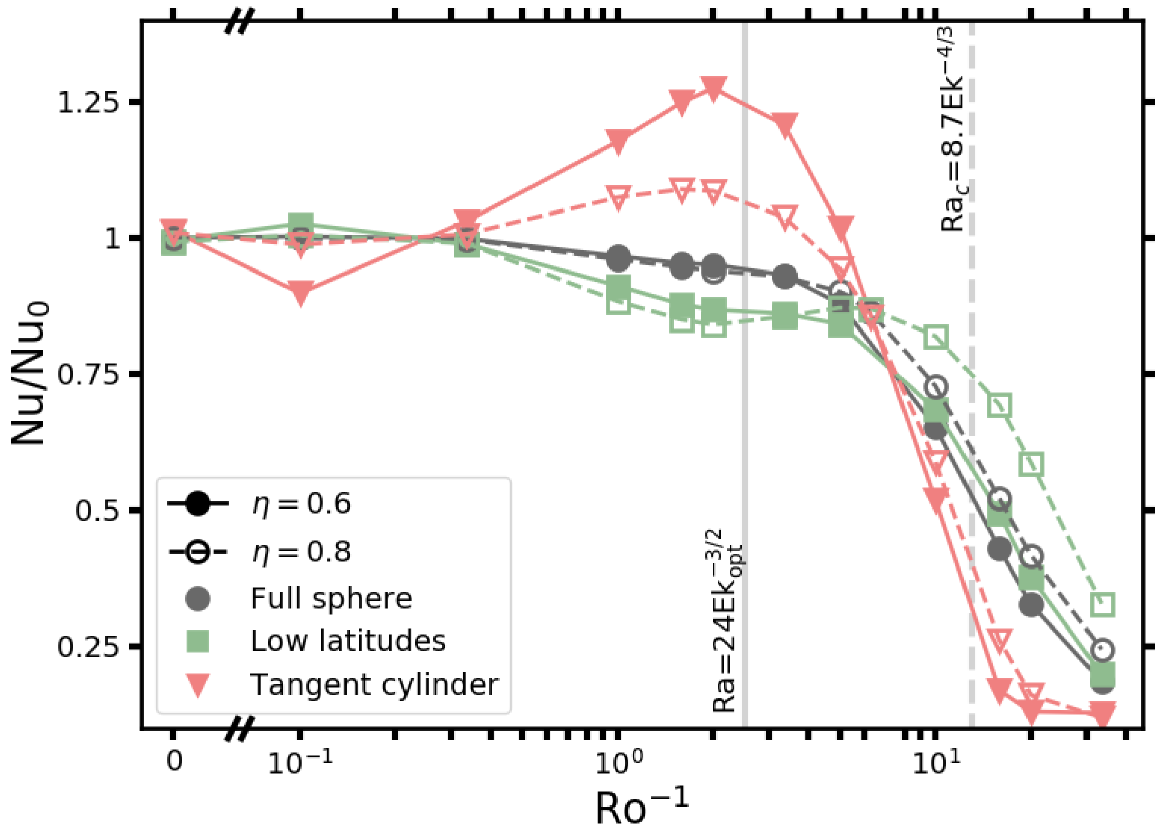

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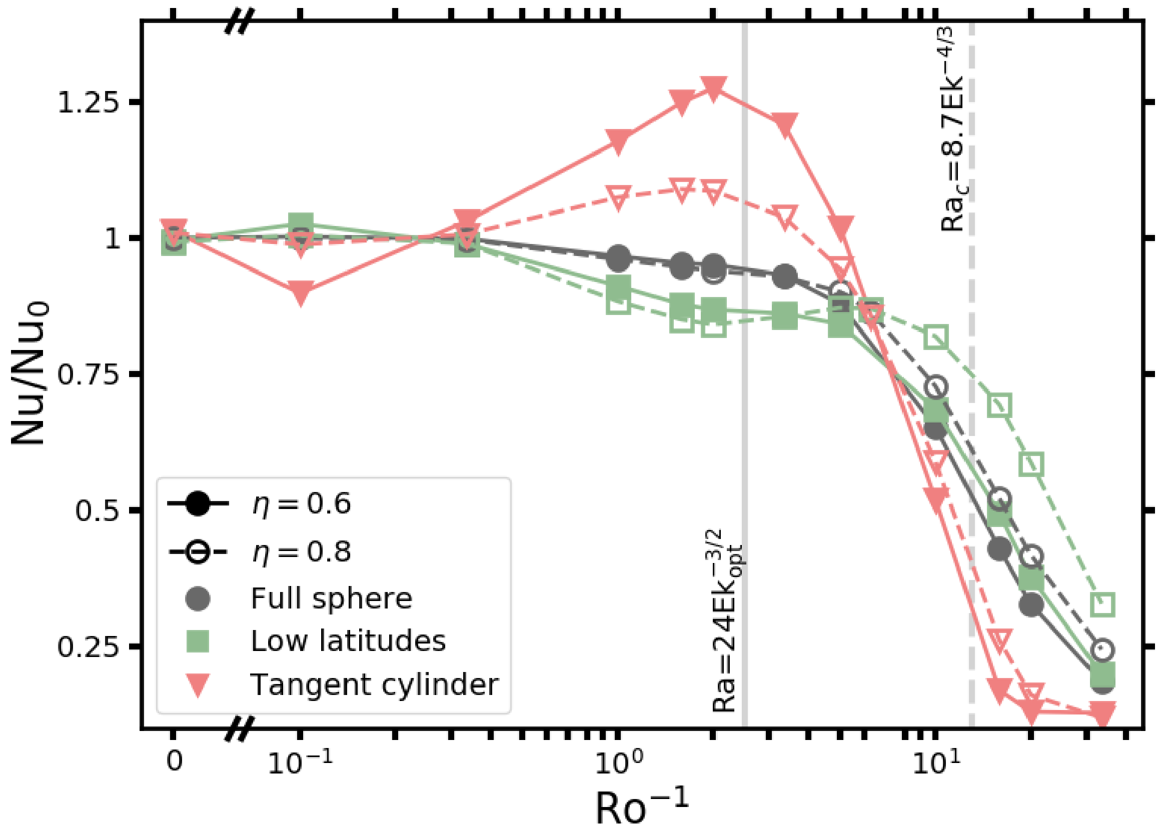

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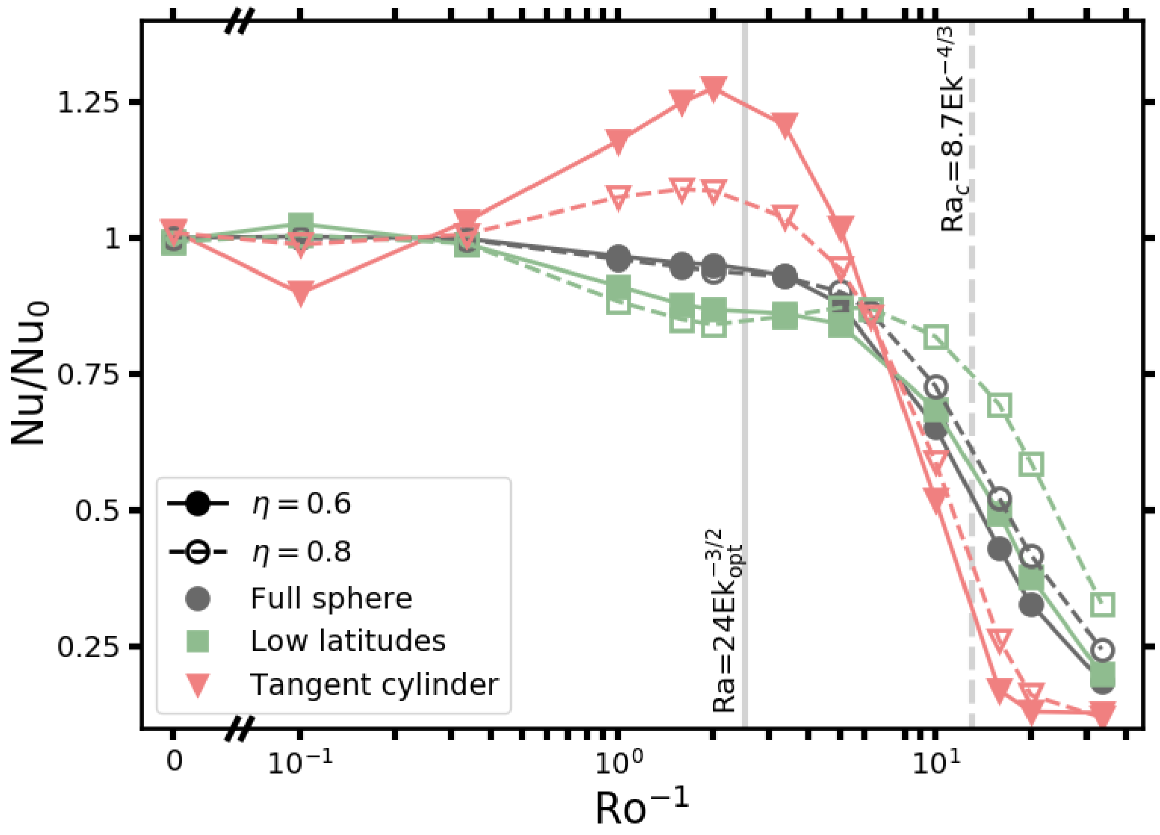

➢ Potential reason for **latitudinal variations** of the **crustal thickness** on **icy moons**

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Thank you for your interest!

Acknowledgments:

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Background: Ed Hawkins, **showyourstripes.info**