Towards Turbulent, Liquid Metal Dynamos

IPAM, 10/30/14

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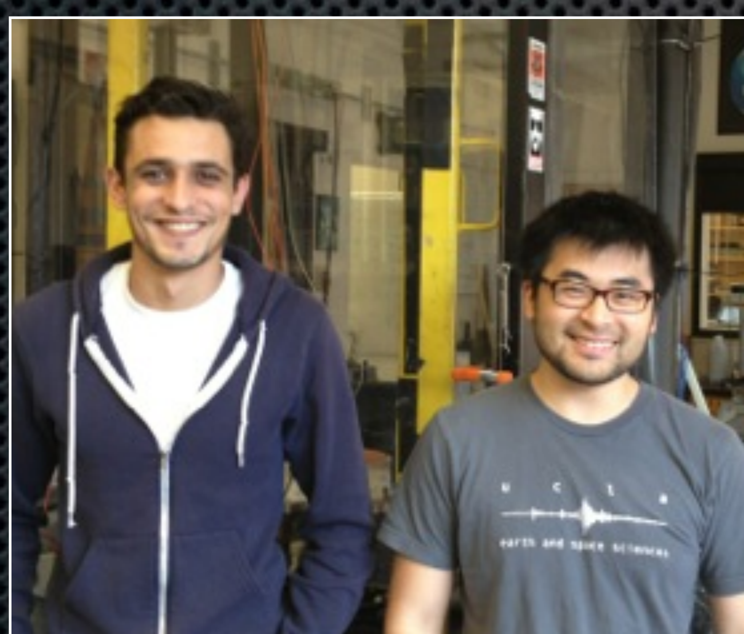

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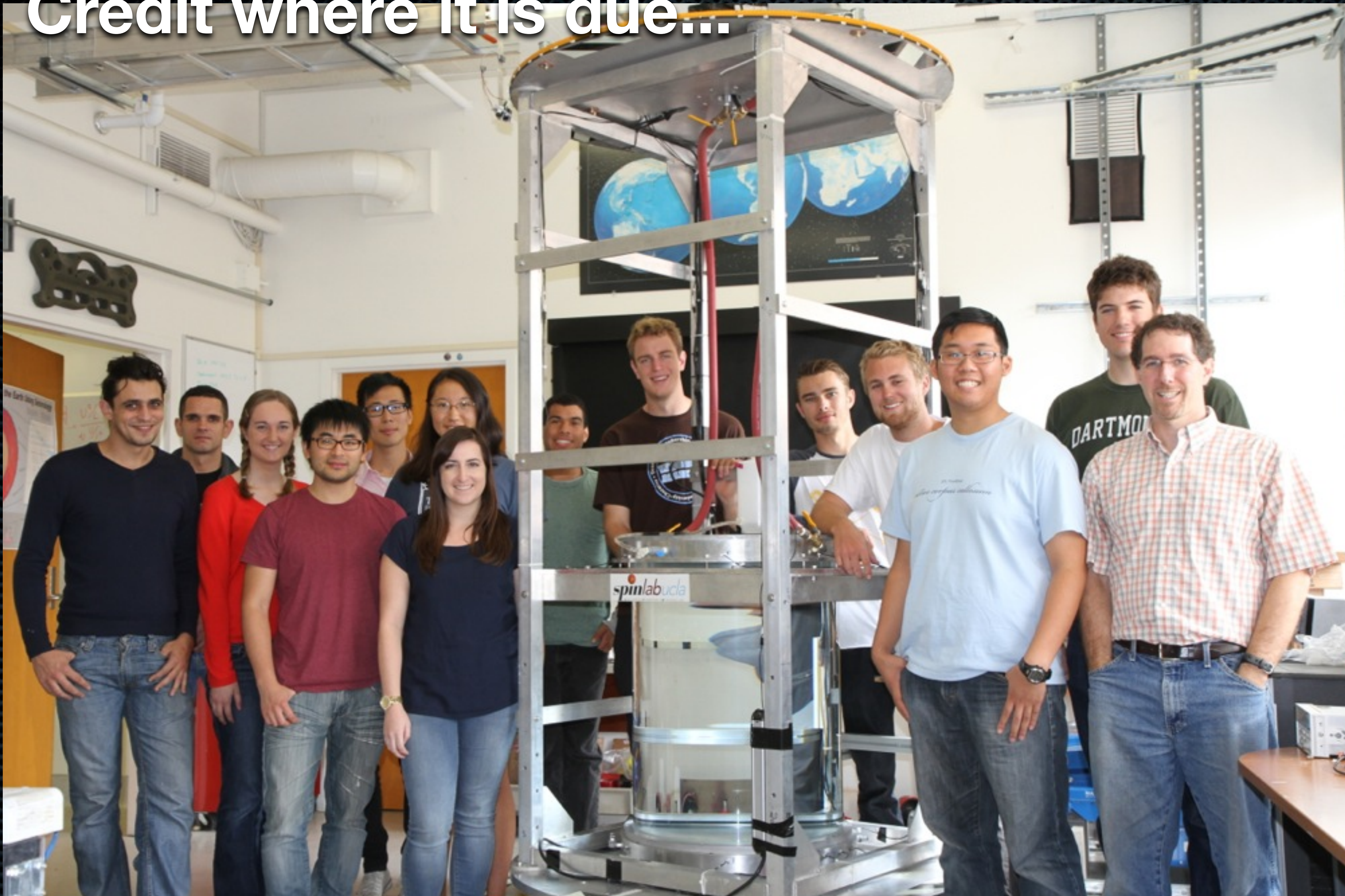
Credit where it is due...



Talk Outline

- Natural dynamos
- State of the Science
- Problems with Present Framework
- Towards Liquid Metal Dynamos

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Dynamos

- Generate magnetic fields and then continual regeneration
- Galactic, stellar, planetary, asteroidal
- Magneto-hydrodynamic processes:
    - Convert kinetic energy of flowing metals/plasmas into magnetic energy

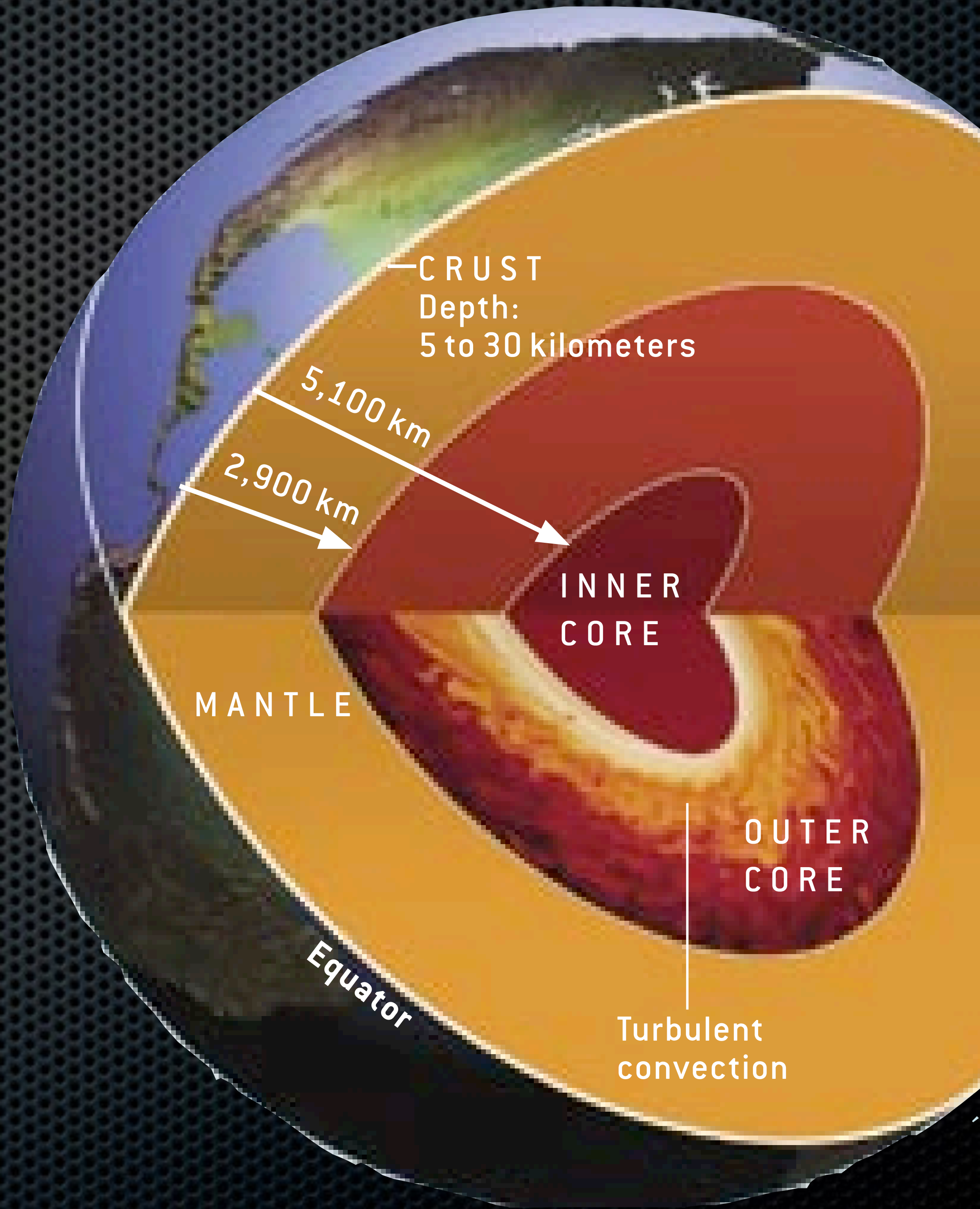
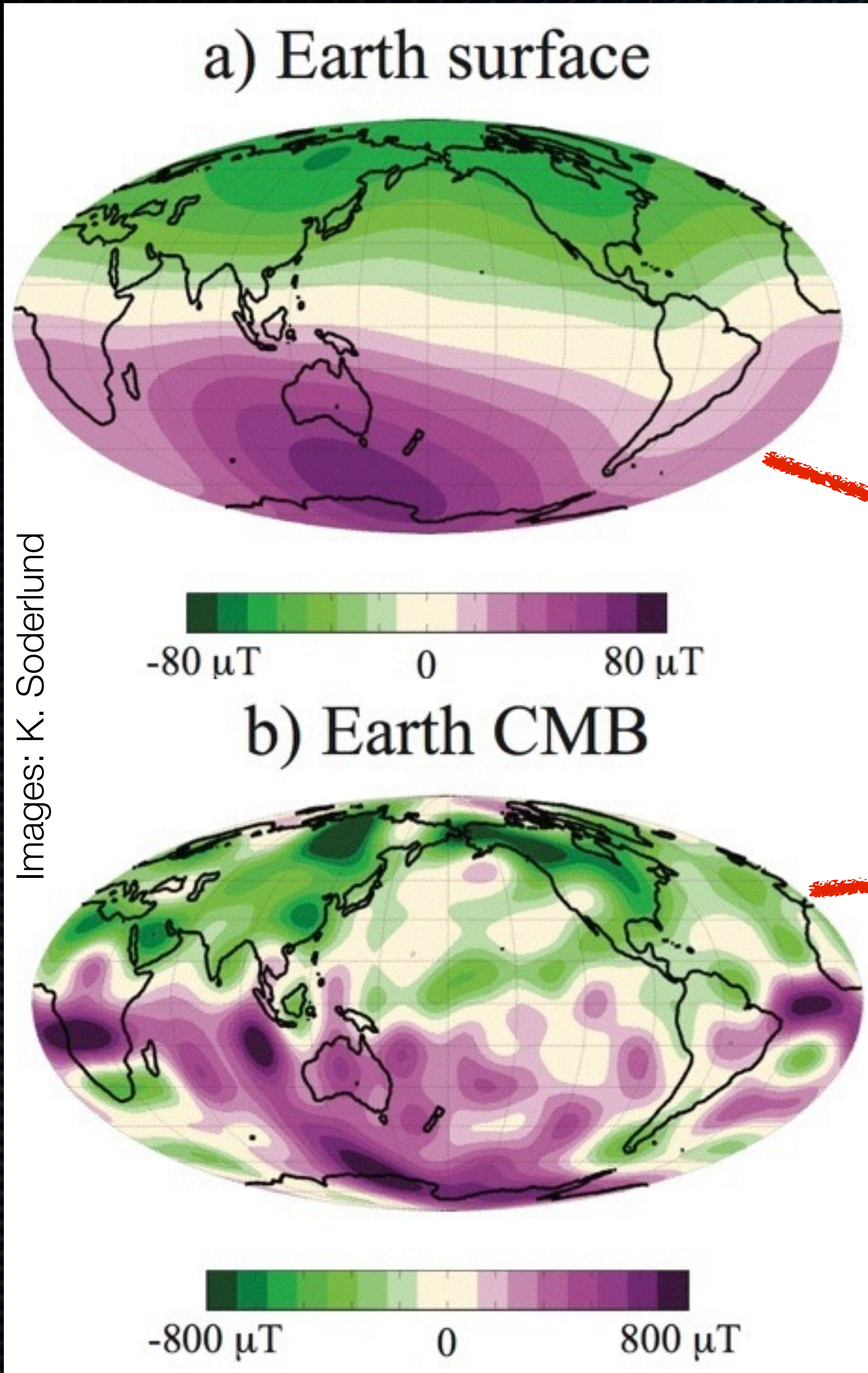


Image: Glatzmaier & Olson, SciAm 05



Images: K. Soderlund

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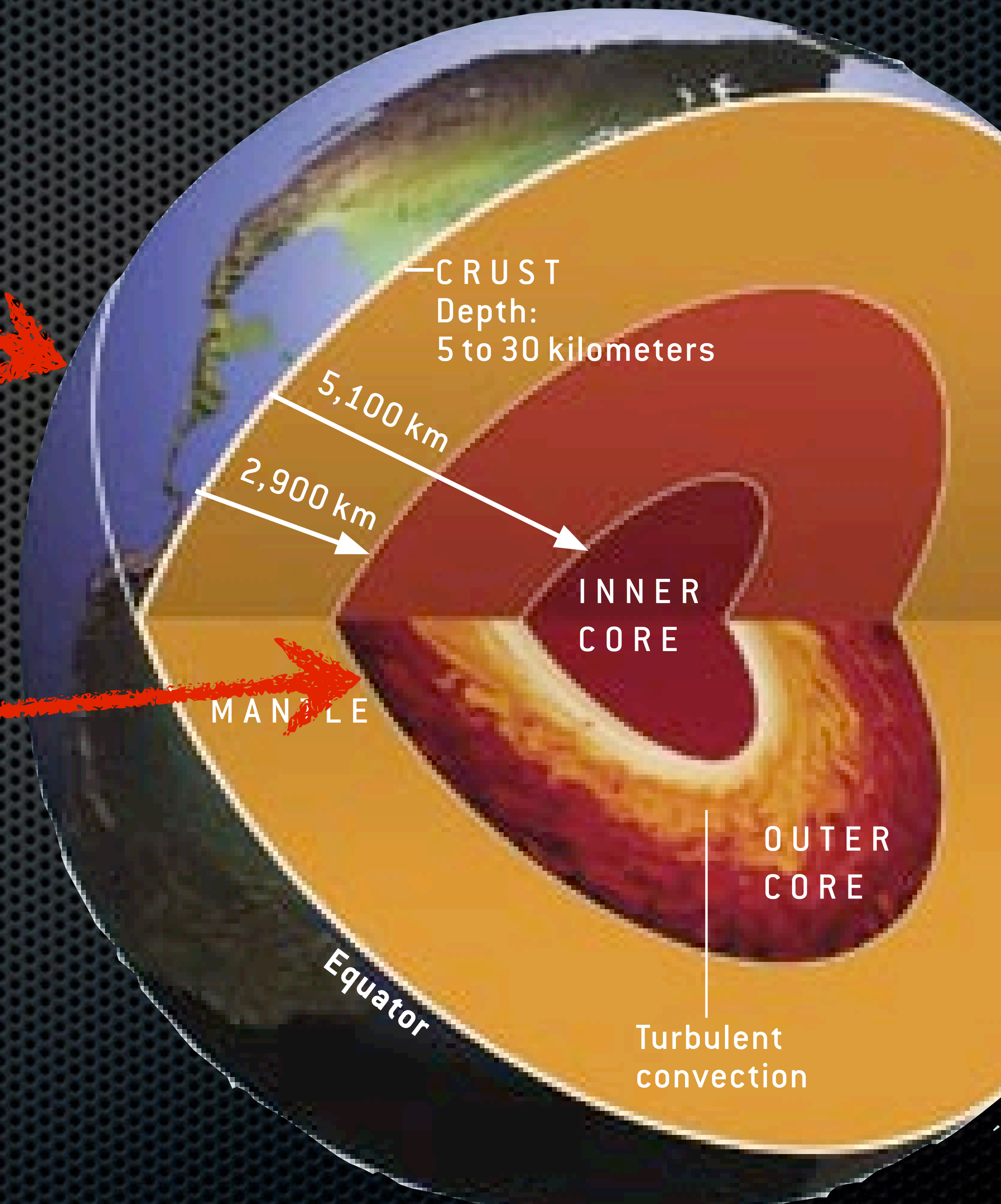

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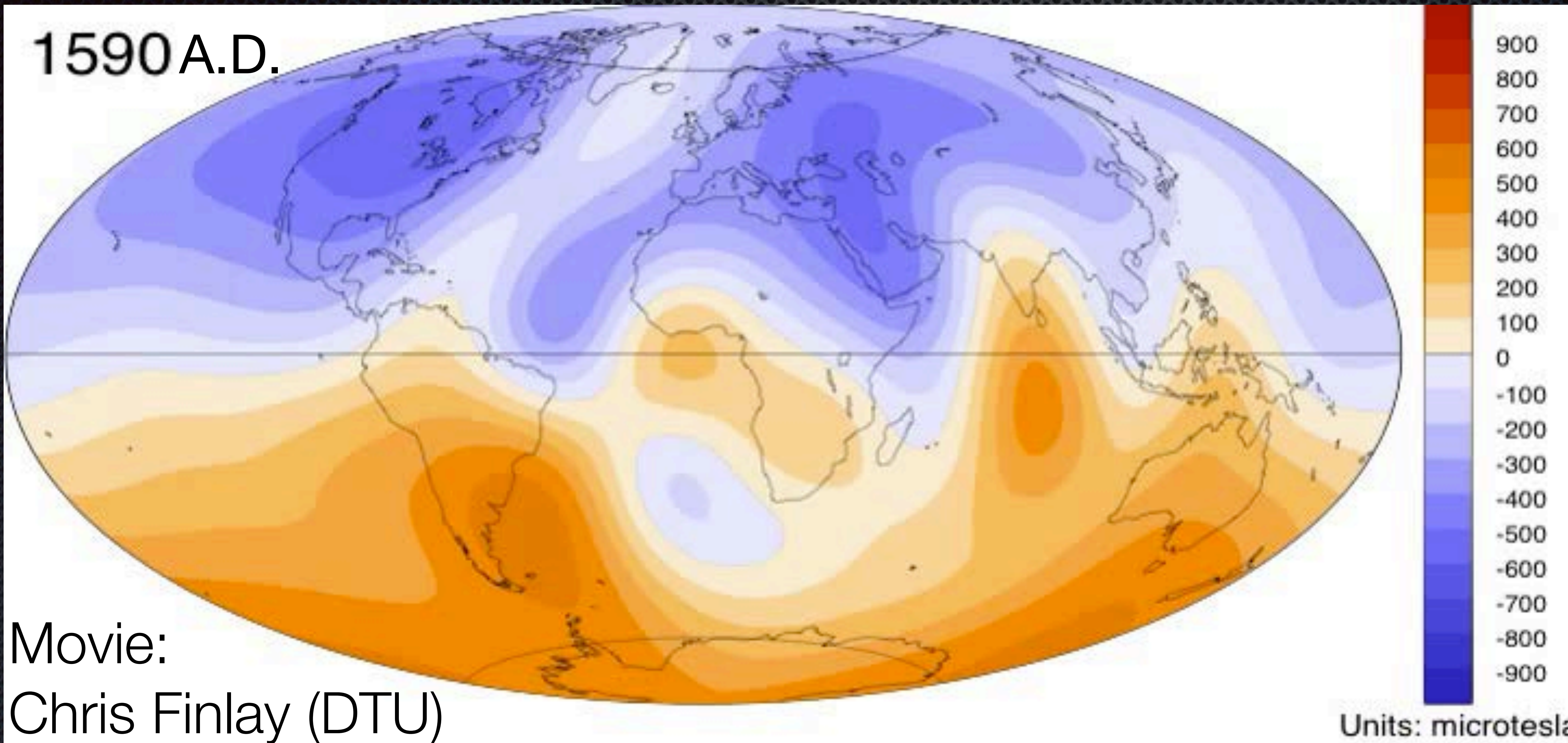
Core-Mantle Boundary B_r



- Geomagnetic field changes over relatively short times
  - Only present explanation: MHD process in fluid core

Governing Equations

- Navier-Stokes Equation

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + 2\mathbf{\Omega} \times \mathbf{u} = -\frac{1}{\rho_o} \nabla p + \alpha T \mathbf{g} + \nu \nabla^2 \mathbf{u} + \frac{1}{\rho_o} \mathbf{J} \times \mathbf{B}$$

- Induction Equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

- Energy Equation

$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \kappa \nabla^2 T + S$$

- Current Density

Ampere's Law: $\mathbf{J} = \frac{1}{\mu_o} \nabla \times \mathbf{B}$

- Continuity

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

Dynamo Action: Inherently Turbulent

- Magnetic induction equation:

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \vec{u} \times \vec{B} + \left(\frac{1}{Rm} \right) \nabla^2 \vec{B}$$

$$Rm = \frac{\text{induction}}{\text{diffusion}} = \frac{UL}{\eta} \sim 10^3$$

$$Rm = \frac{UL}{\nu} \frac{\nu}{\eta} = Re\, Pm$$

Dynamo Action: Inherently Turbulent

- Magnetic Prandtl Pm ~ 10^–6 in liquid metals
- Requires Reynolds number Re ~ 10^8 - 10^9 in Earth's core

$$Rm = \frac{UL}{\nu}\frac{\nu}{\eta} = Re\,Pm$$

Dynamo Action: Inherently Turbulent

- So $Re >> 1$ in natural dynamo settings
  - But constrained by rotational and magnetic effects
    - Rossby number:

$$Ro = \frac{\text{inertia}}{\text{Coriolis}} = \frac{U}{2\Omega L} \sim 10^{-6}$$

    - Interaction Parameter:

$$N = \frac{\text{Lorentz}}{\text{inertia}} = \frac{\sigma B^2 L}{\rho U^2} \sim 10^{6}$$

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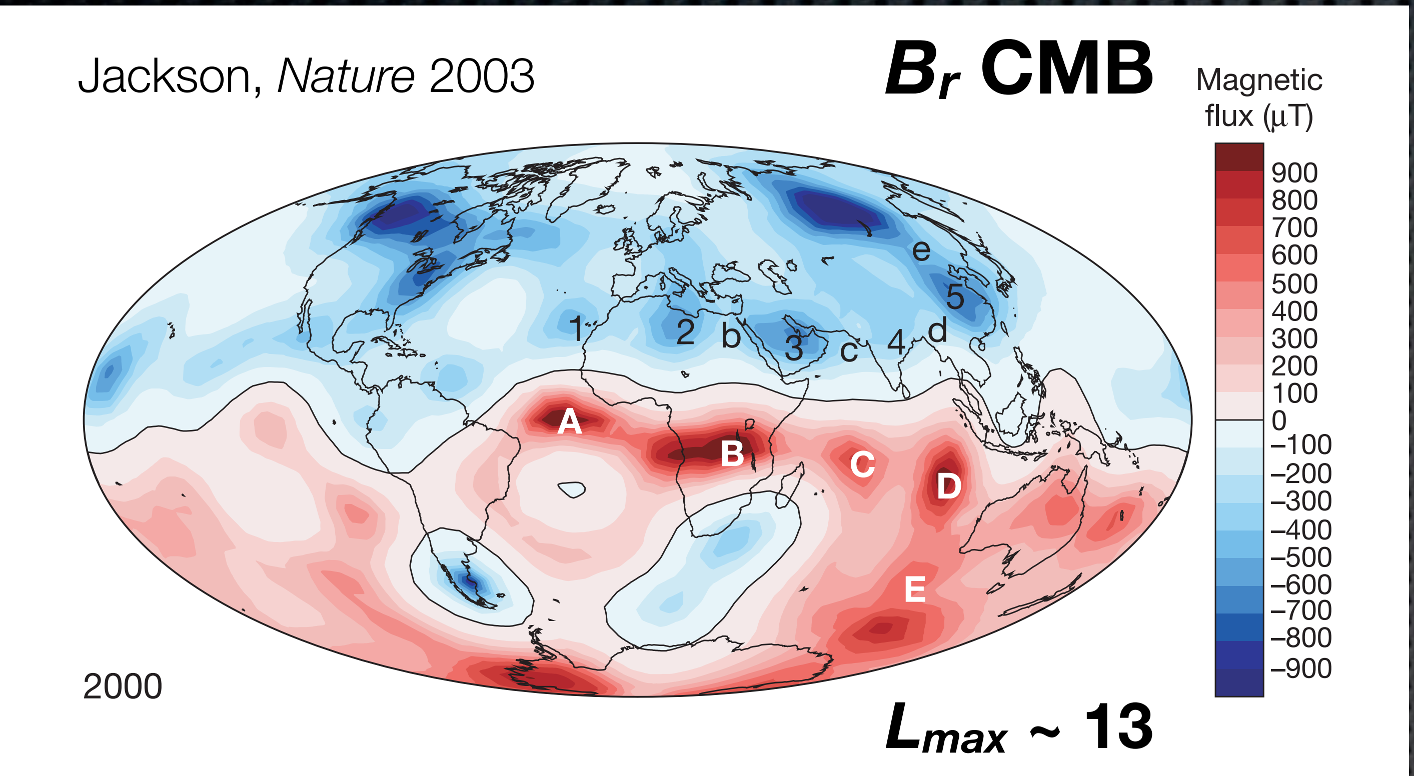
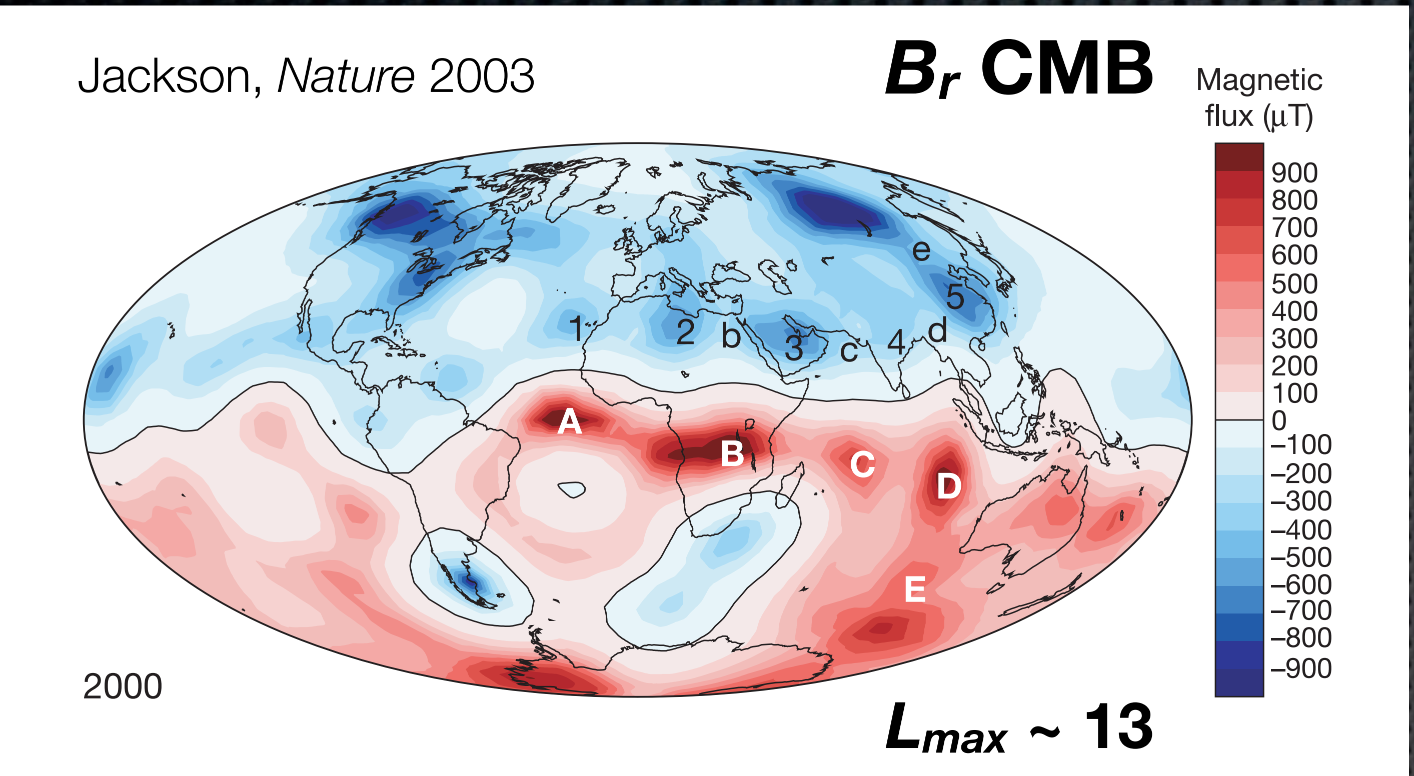
Observations



- Remote system
  - Requires accurate modeling

- Axial dipolar field
  - High and low latitude large-scale flux patches
  - Fit ~ 6 - 8 patches around TC
    - Patch scale: $L \sim 1000$ km

Observations



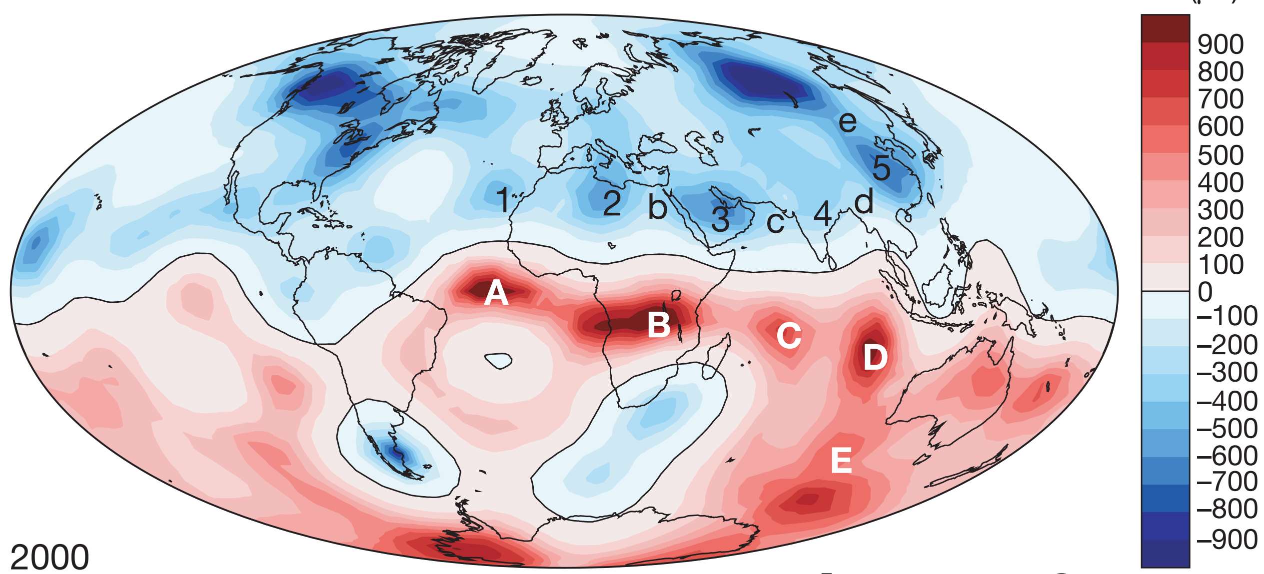
- Remote system
  - Requires accurate modeling
  - Great success in recent numerical efforts
- Axial dipolar field
  - High and low latitude large-scale flux patches
  - Fit ~ 6 - 8 patches around TC
    - Patch scale: $L \sim 1000$ km

Observations

Models

Jackson, *Nature* 2003

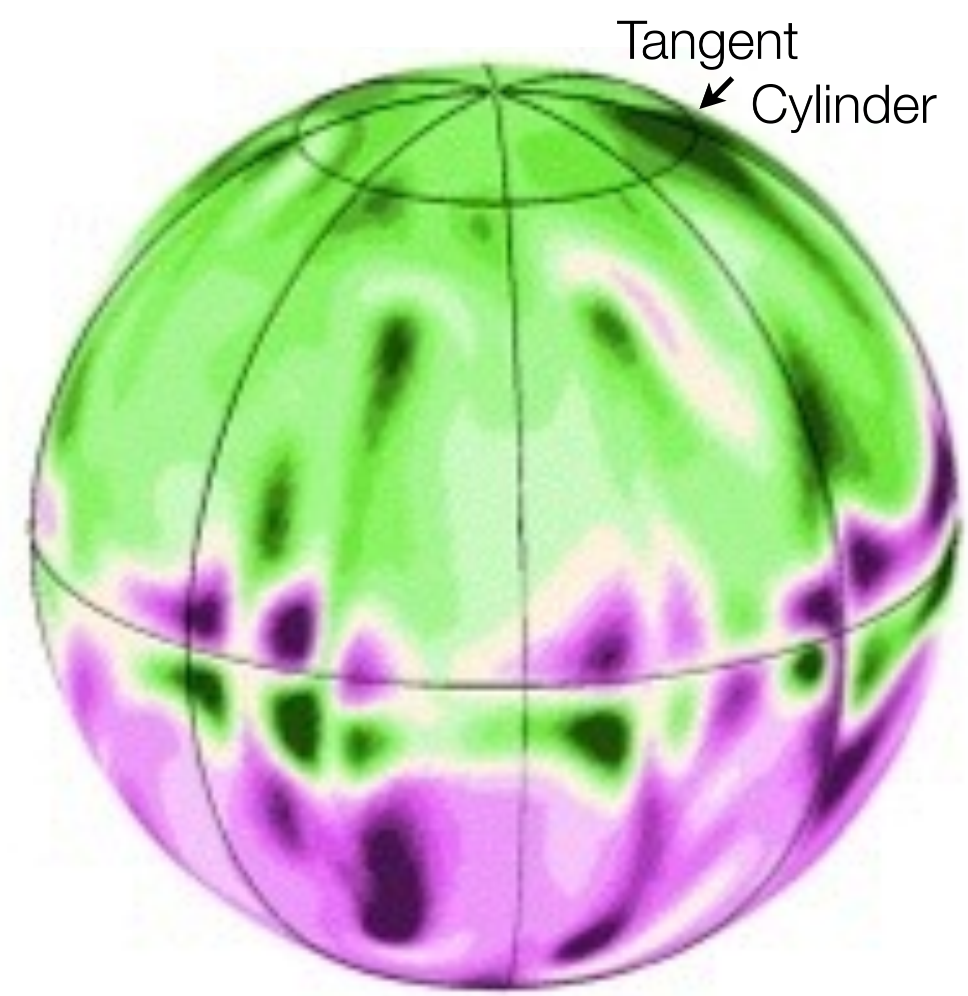
B_r CMB



L_{max} ~ 13

Soderlund et al. *EPSL* 2012

B_r CMB



Observations

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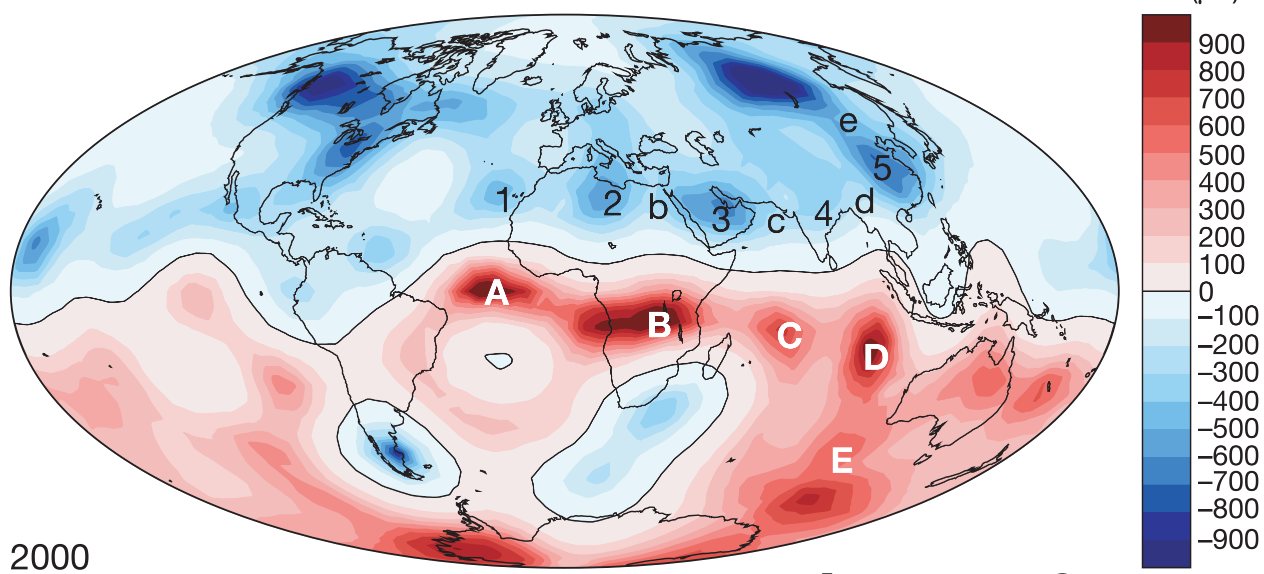
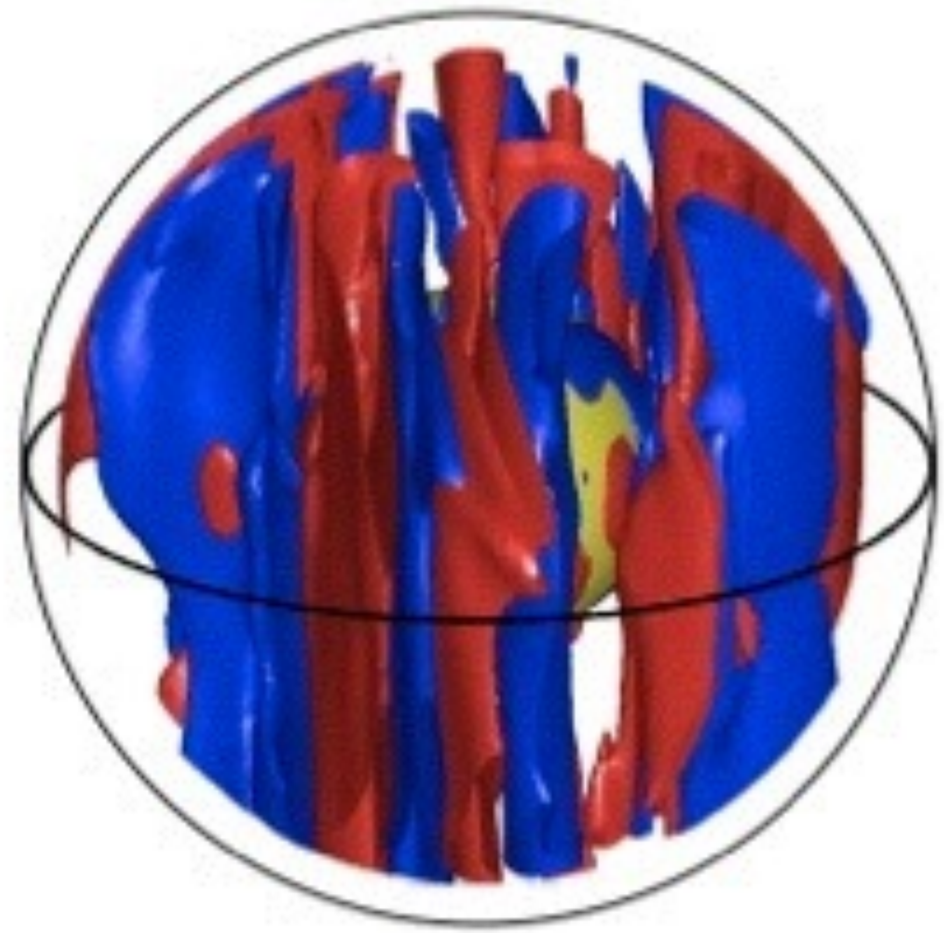


L_{max} ~ 13

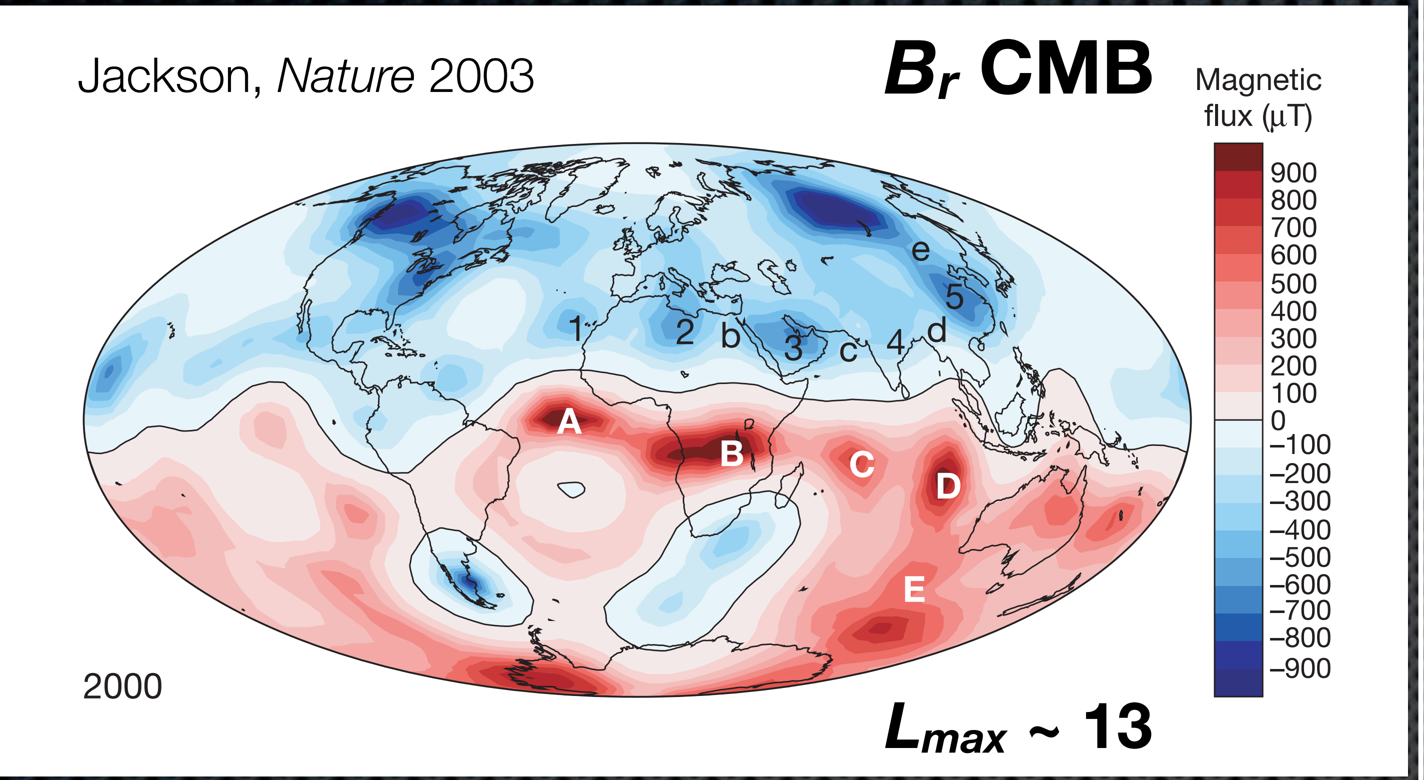
Soderlund et al. *EPSL* 2012

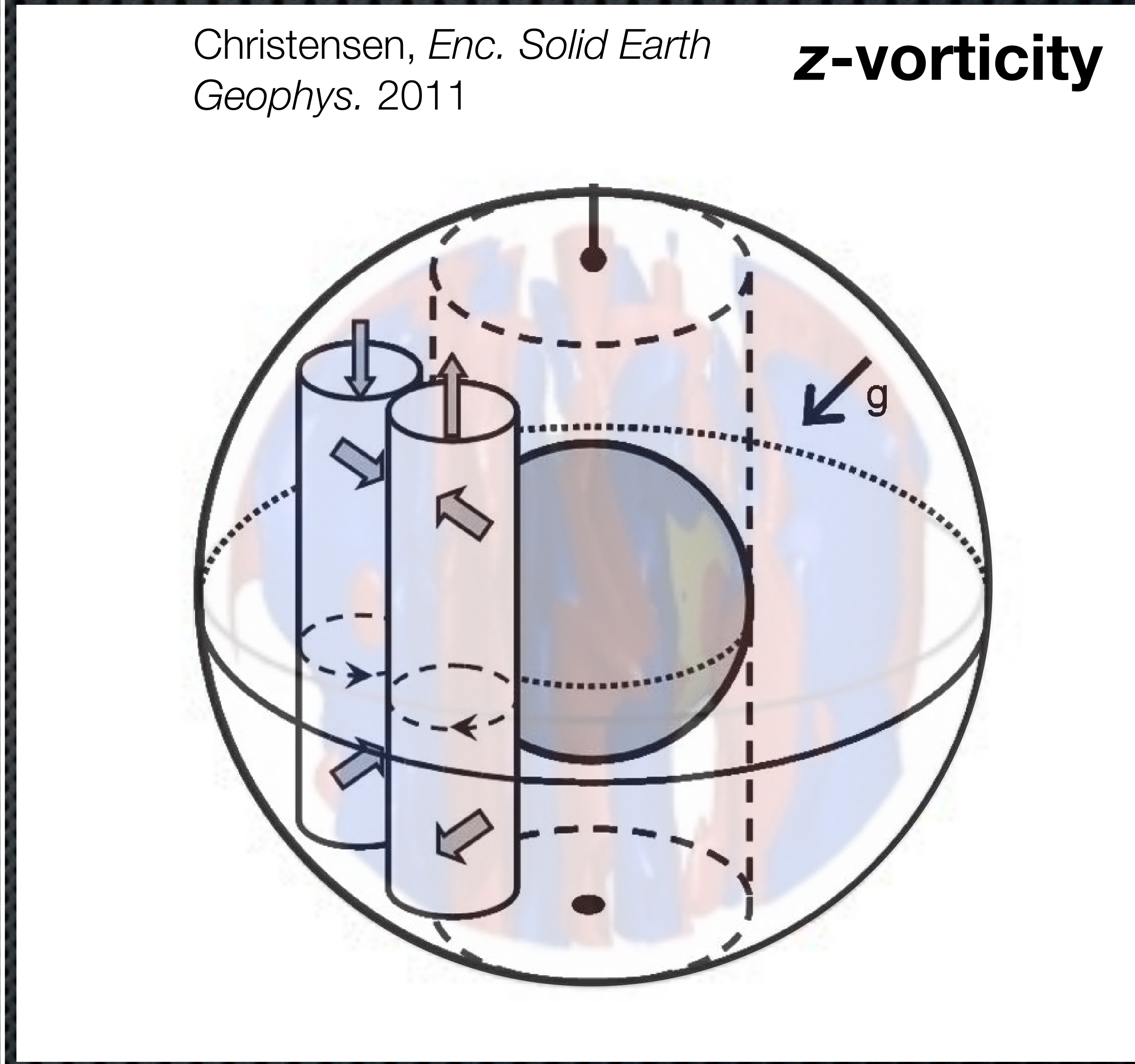
***z*-vorticity**



Observations

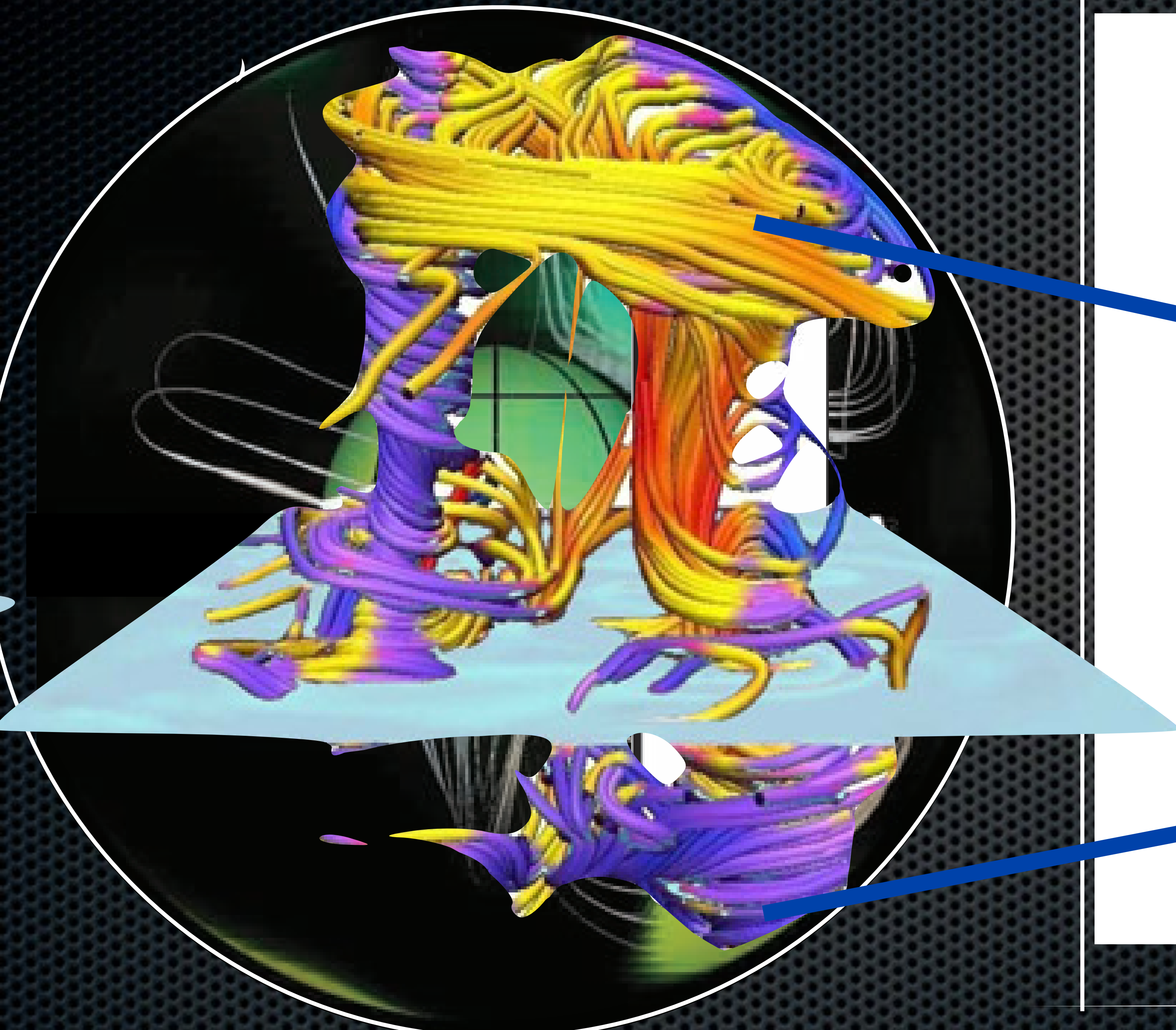
Models



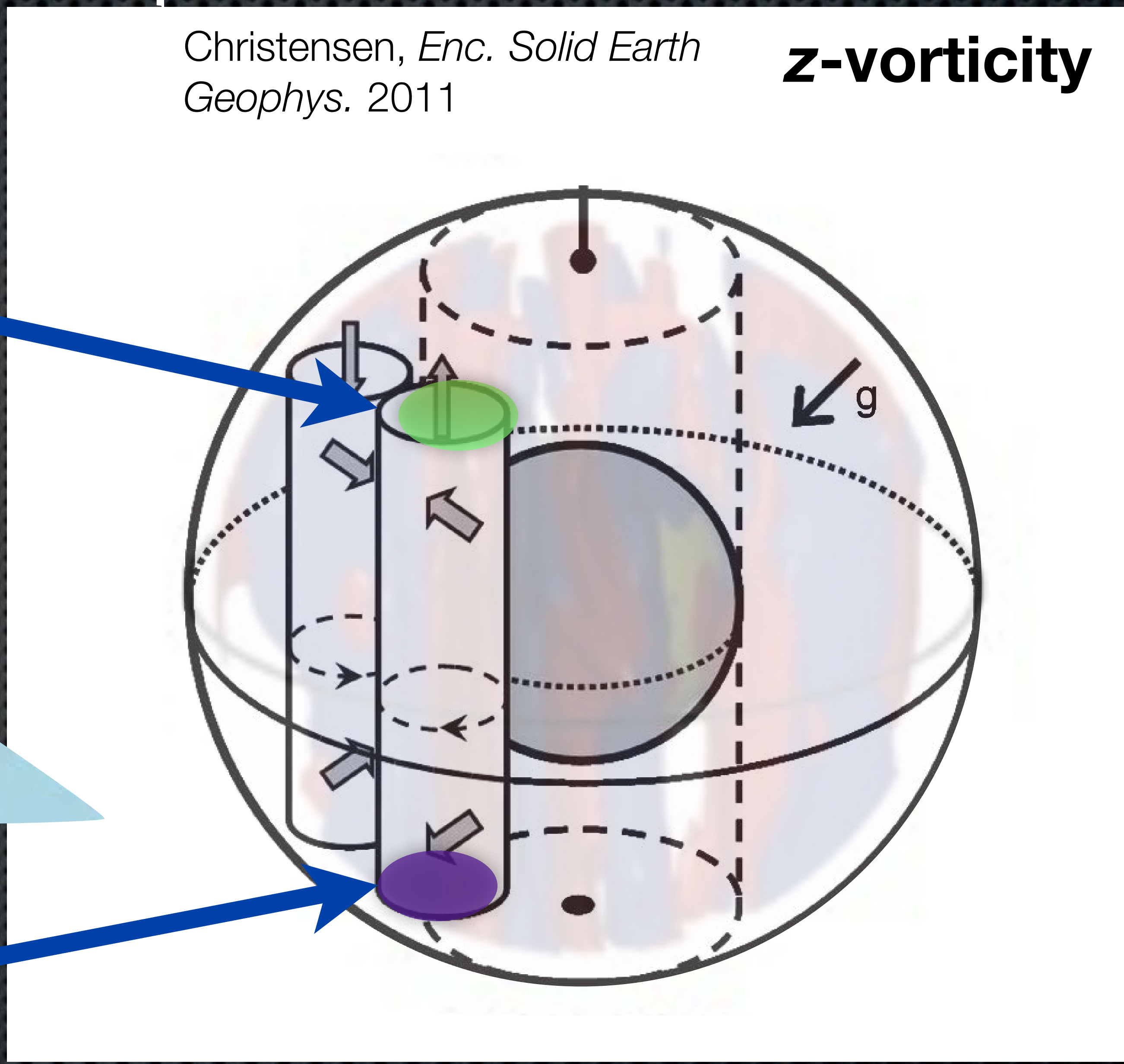


Models

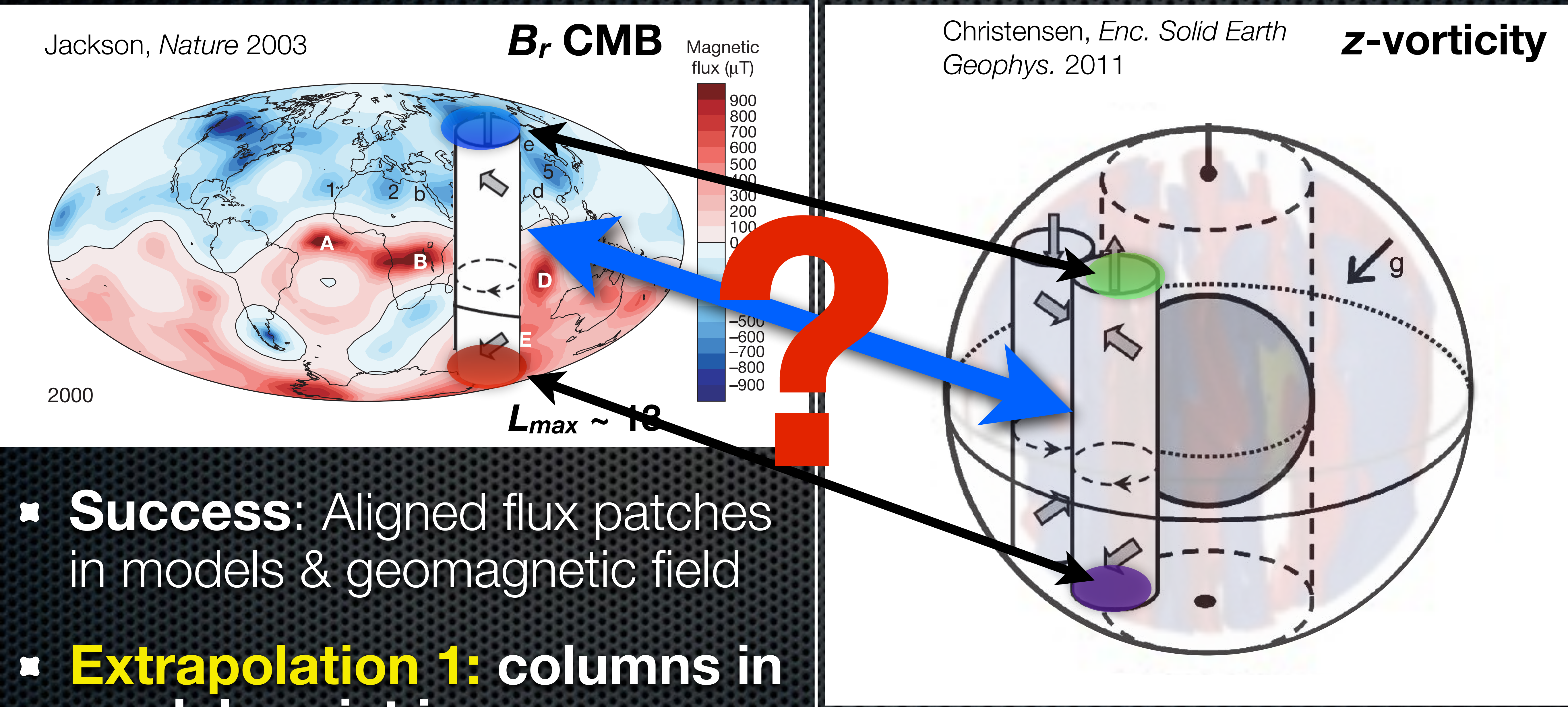
Featherstone et al. *ApJ* 2009



Aubert et al. *GJI* 2008 (*cf*. Olson et al. *JGR* 1999)



Observations Models



- **Success**: Aligned flux patches in models & geomagnetic field
- **Extrapolation 1: columns in models exist in cores**
- **Extrapolation 2: physics in models extrapolates to planetary cores**

Extrapolations valid?

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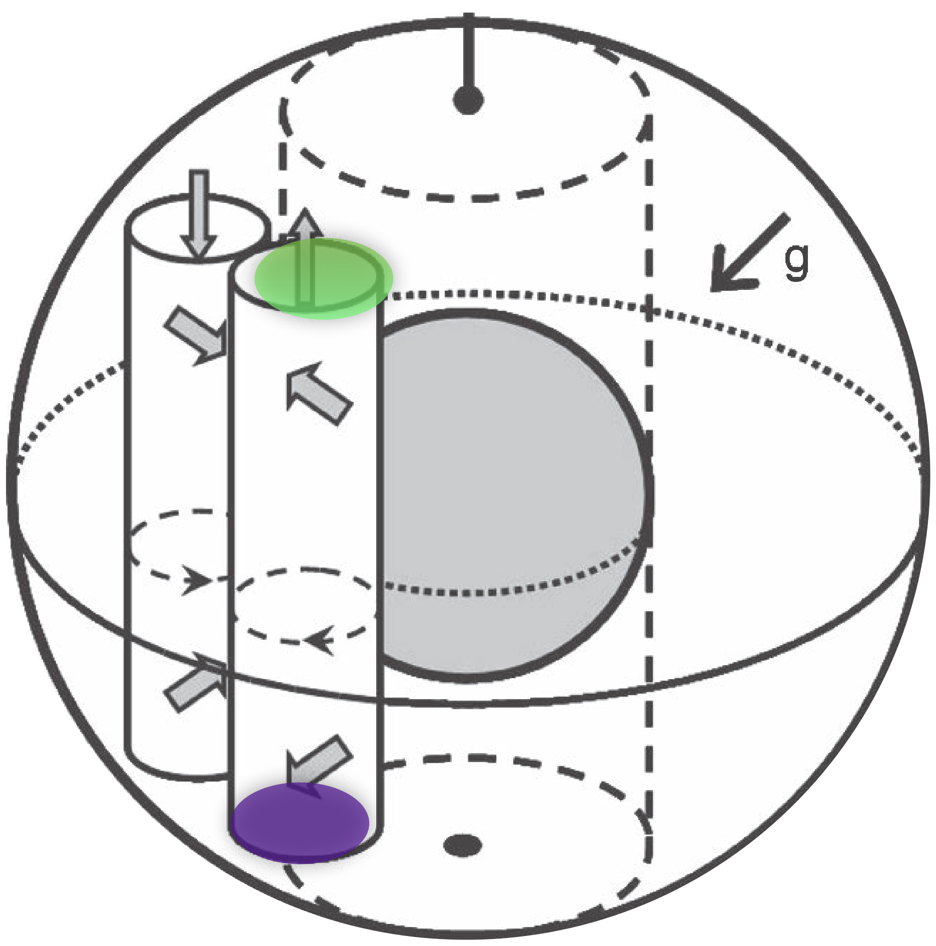
Possible Problems

- 1) Overly strong viscosity
- 2) Lack of turbulent processes
- 3) Inaccurate material properties

Christensen, *Enc. Solid Earth Geophys.* 2011



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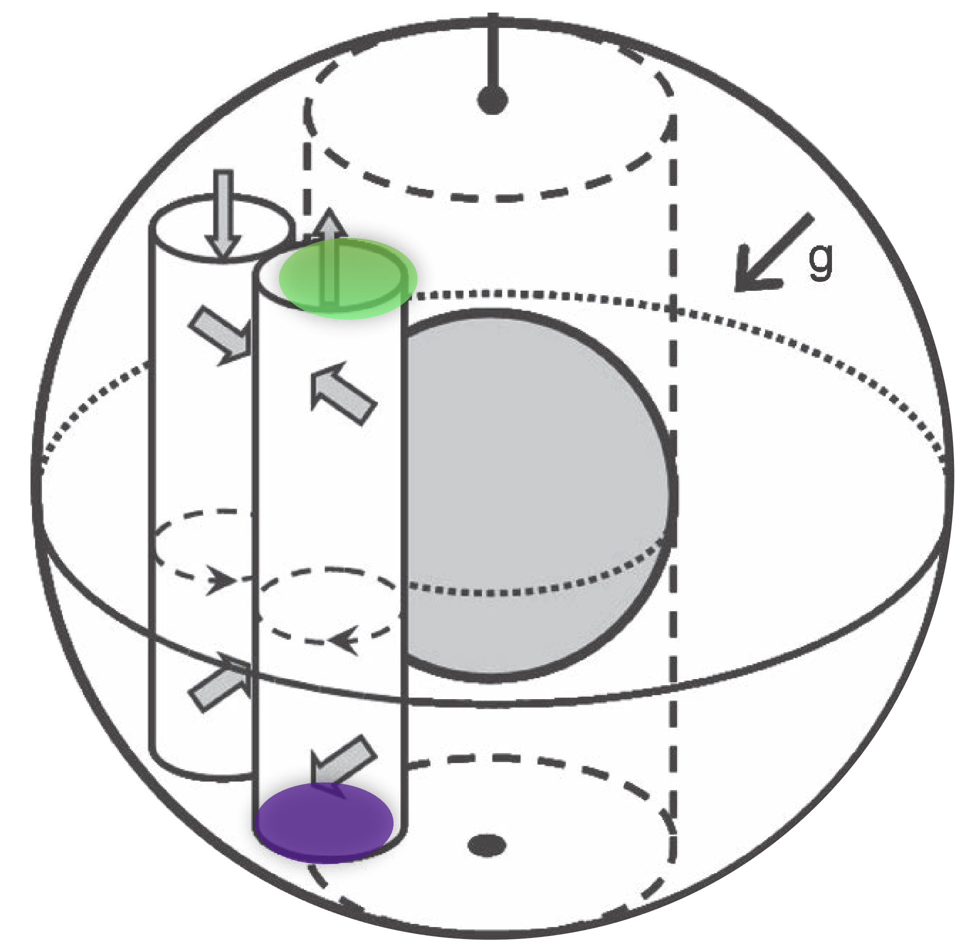

Rotating Convection Columns

- **Ekman number, E**
  - Scaled viscous force

$$E = \frac{\tau_{rot}}{\tau_{visc}} = \frac{\nu}{\Omega L^2}$$

Image: J. Cheng

Rotating Convection Columns

- **Ekman number, *E***
  - Scaled viscous force
- **Rayleigh number, *Ra***
  - Scaled buoyancy force
  - Onset Forcing:

$$Ra_C \sim E^{-4/3}$$

$$E = \frac{\tau_{rot}}{\tau_{visc}} = \frac{\nu}{\Omega L^2}$$

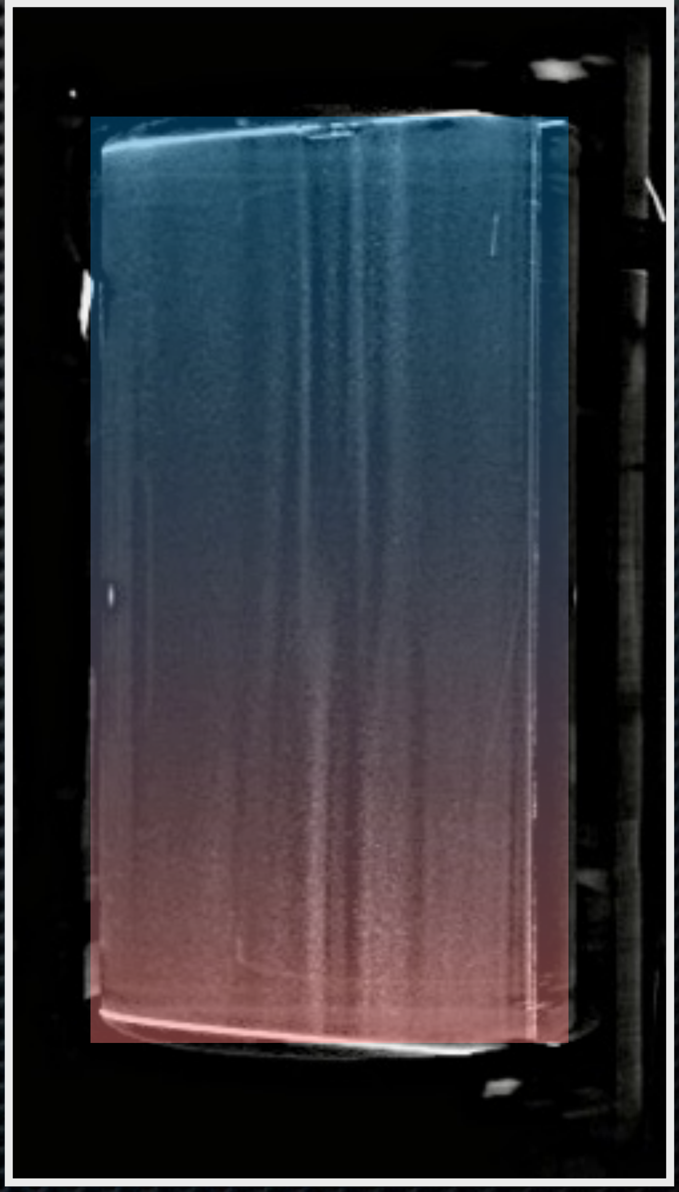

Image: J. Cheng

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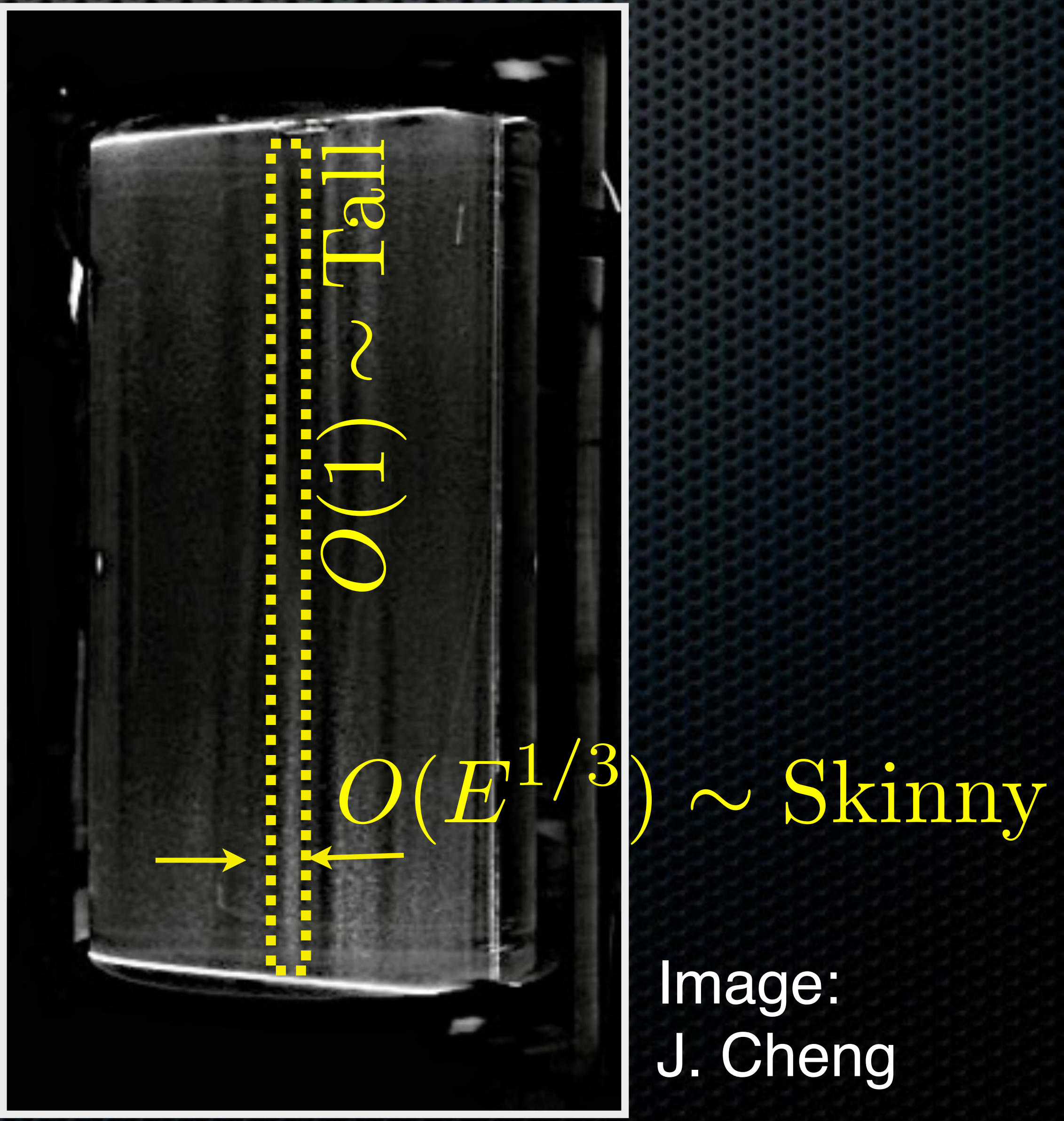
- **Rayleigh number, *Ra***
  - Scaled buoyancy force
  - Onset Forcing:

$$Ra_C \sim E^{-4/3}$$

- **Onset column *width*:**

$$\ell_C \sim E^{1/3}$$



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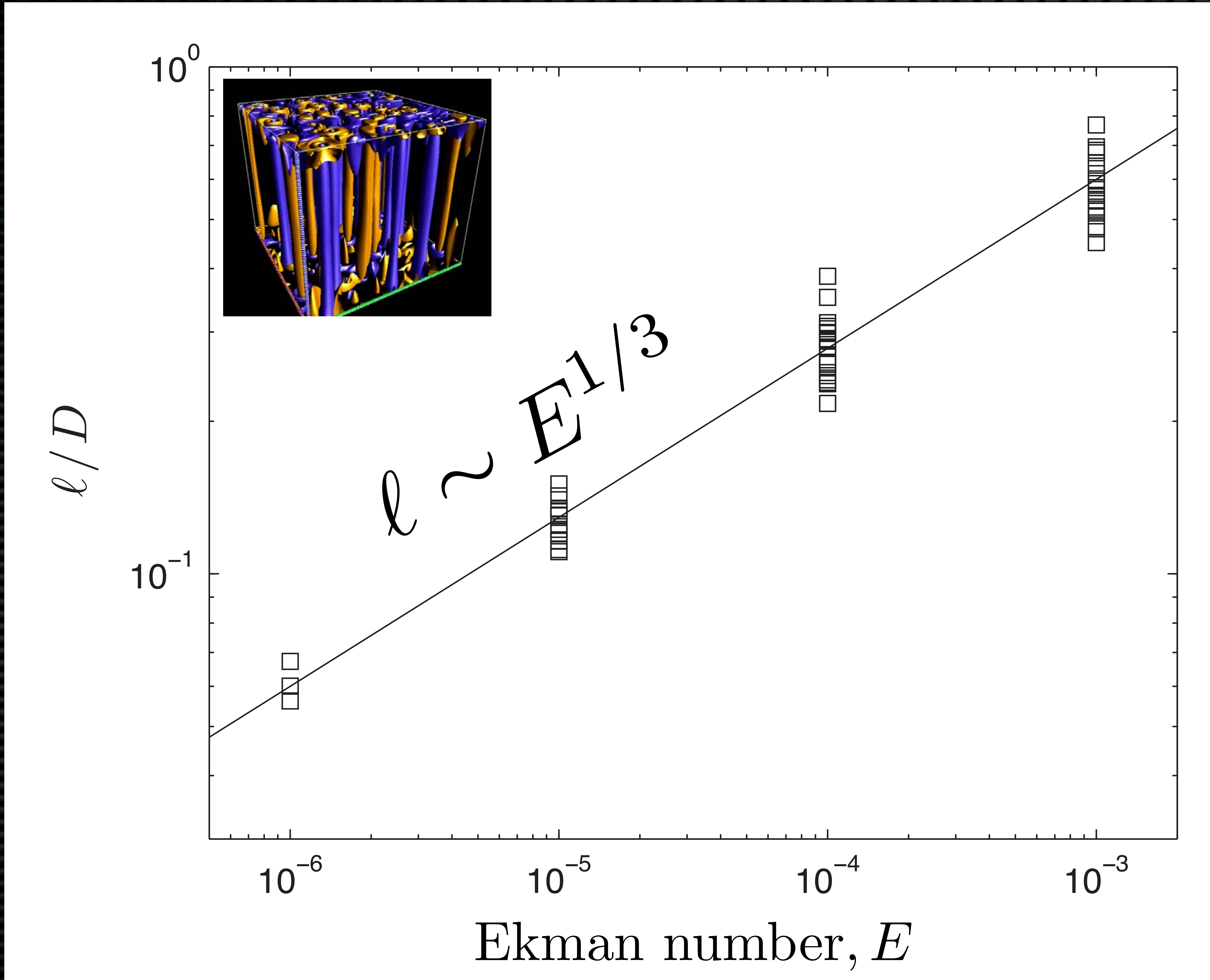
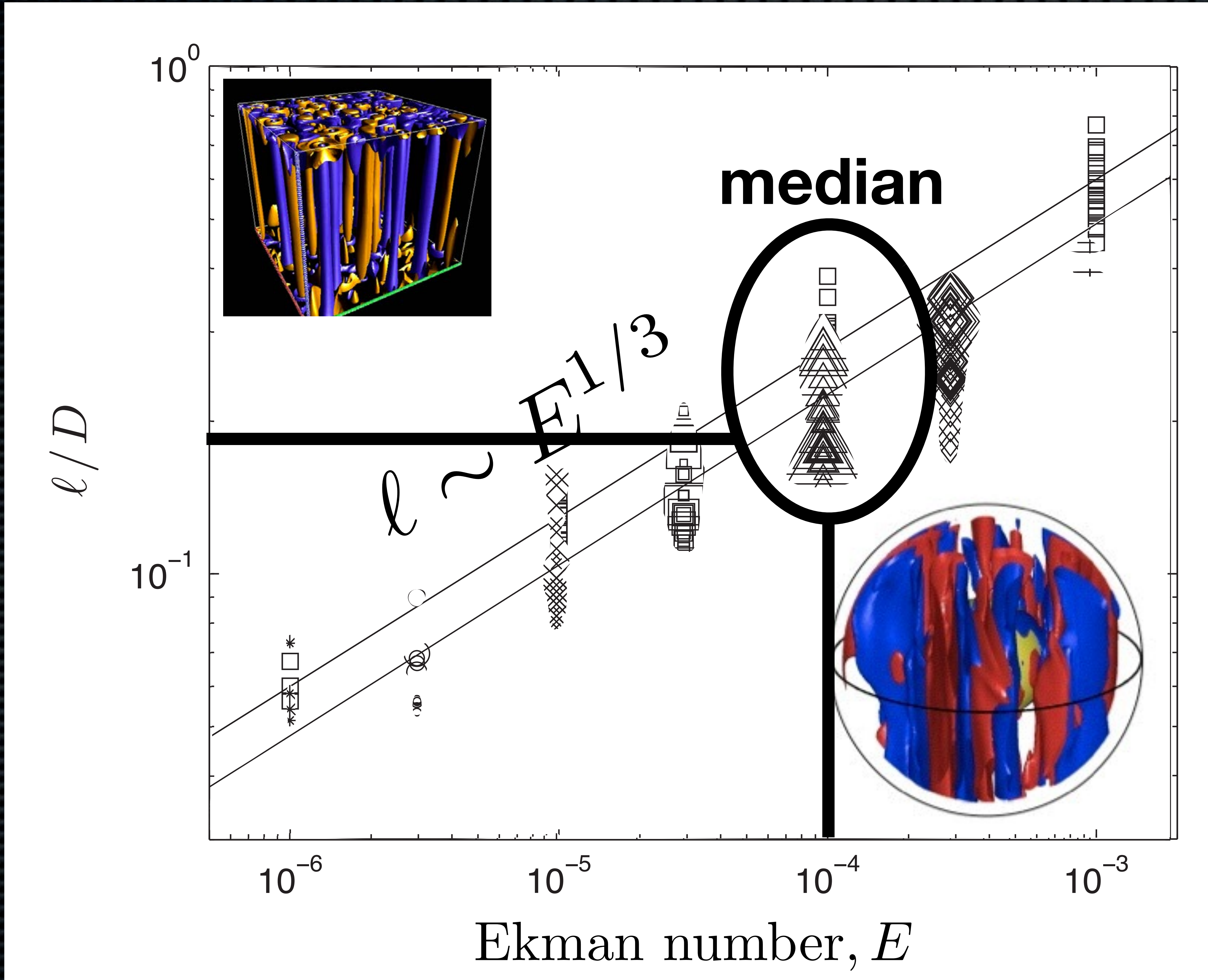


King et al. *JFM* 2013

Rotating Convection Columns



King & Buffett *EPSL* 2013

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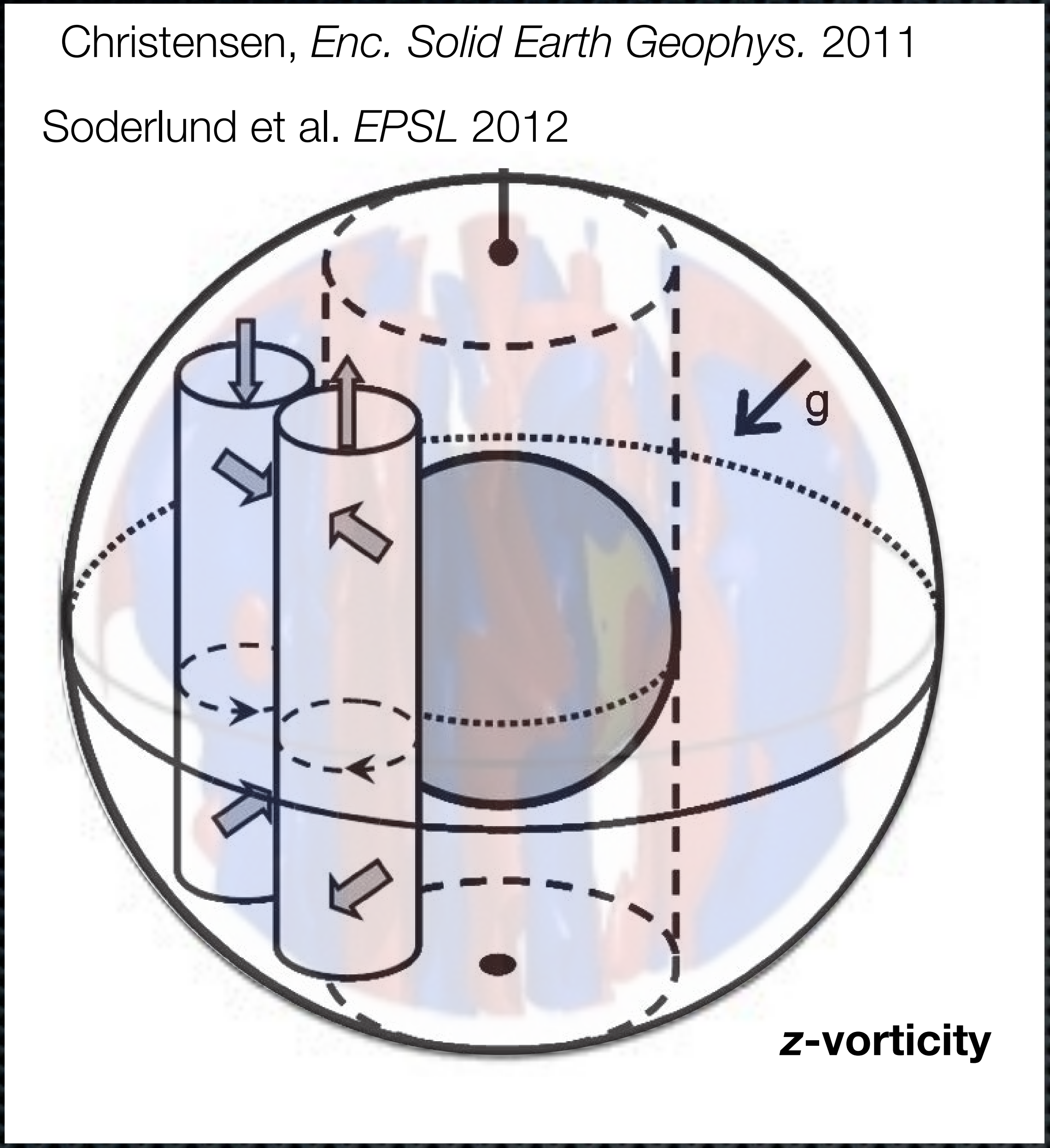


$$E = \frac{\tau_{rot}}{\tau_{visc}} = \frac{\nu}{\Omega L^2}$$

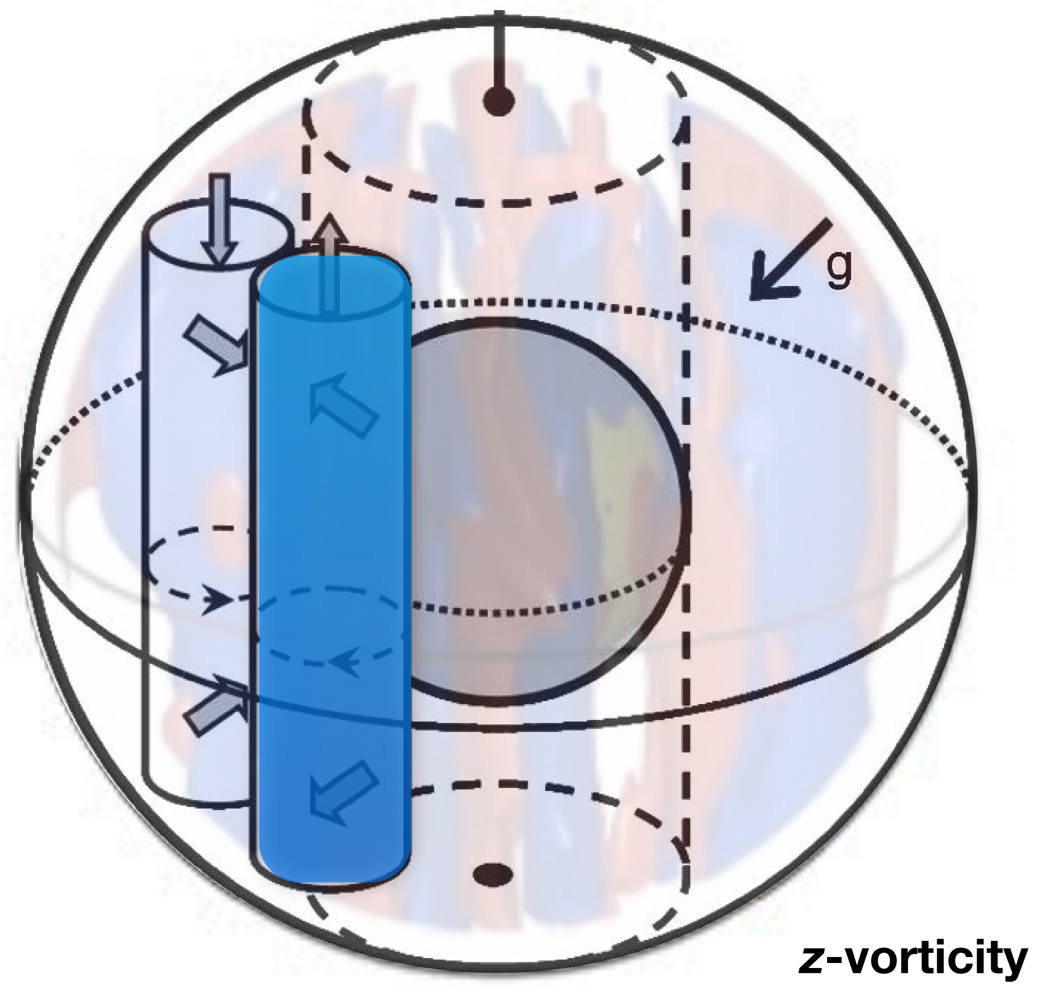
- **Models:**

E ~ 1e-4; l_c ~ 0.1

Rotating Convection Columns

Christensen, *Enc. Solid Earth Geophys.* 2011

Soderlund et al. *EPSL* 2012



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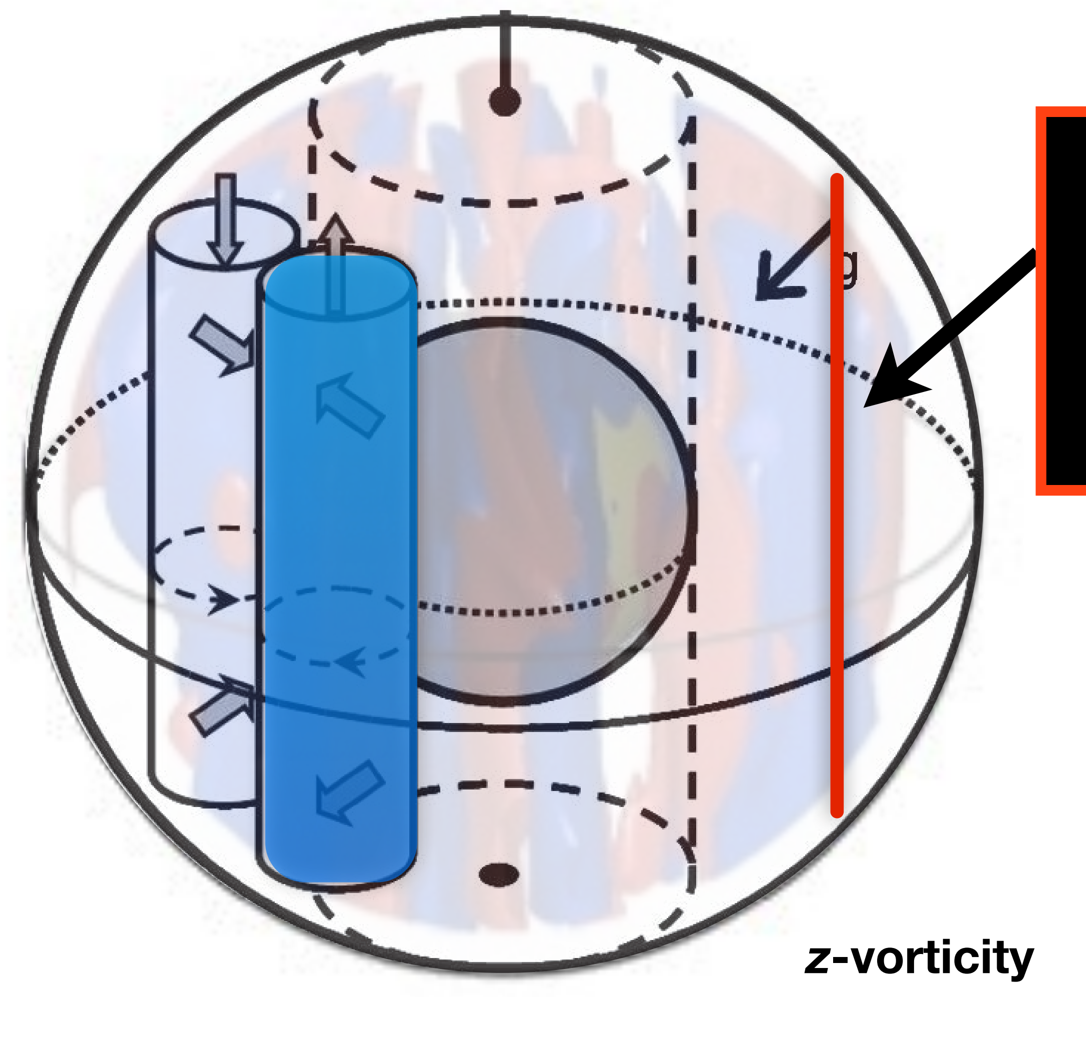


10^3 too wide

$$E = \frac{\tau_{rot}}{\tau_{visc}} = \frac{\nu}{\Omega L^2}$$

- **Models:**

E ~ 1e-4; l_c ~ 0.1

- **Earth's Core:**

E ~ 1e-15; l_c ~ 1e-5

(i.e., 10^4 x smaller than scale of flux patches)

Ineffective Columns

- *Model* $E^{1/3}$ **columns: large-scale,** $Rm_l > 1$
- *Planetary Cores* $E^{1/3}$ **columns: ~10 - 10^2 m wide; magnetically diffusive**

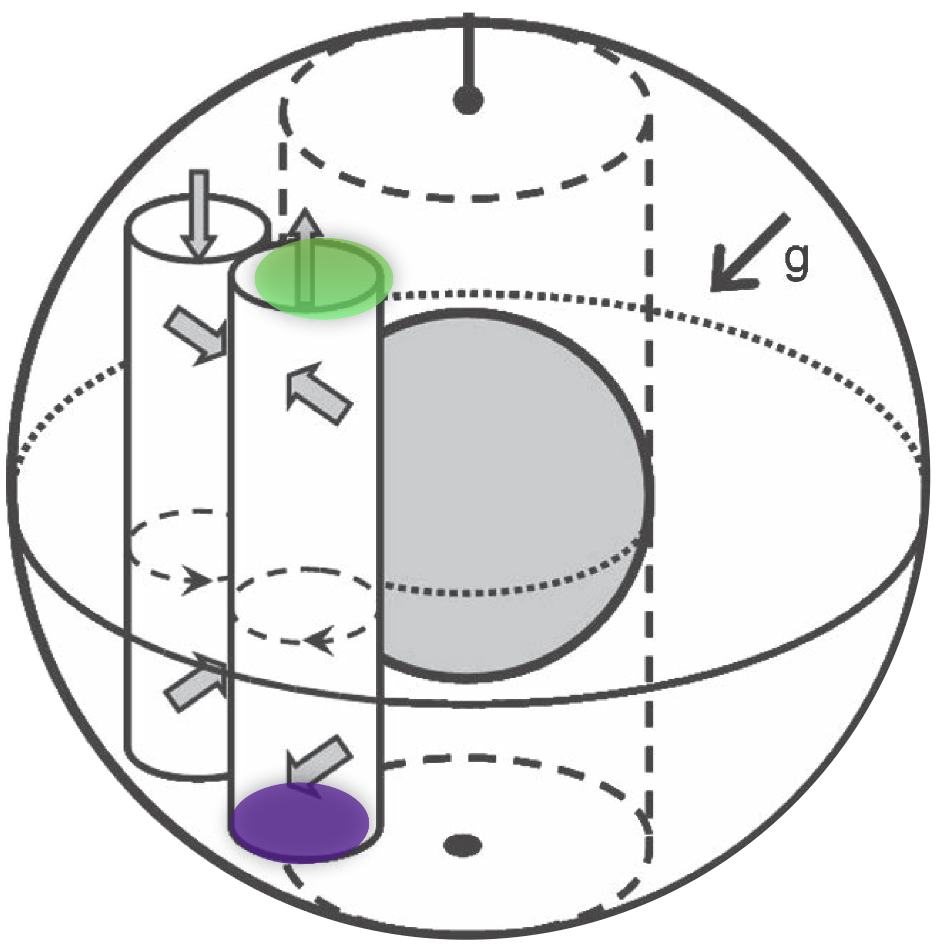
$$Rm_\ell = \frac{\tau_{diff}}{\tau_{ind}} = \frac{U_\ell \ell}{\eta} \ll 1$$

- **Thus, model-style columns will not take part in dynamo processes in planetary cores**

Possible Problems

- **1) Overly strong viscosity**
- **2) Lack of turbulent processes**
- **3) Inaccurate material properties**

Christensen, *Enc. Solid Earth Geophys.* 2011



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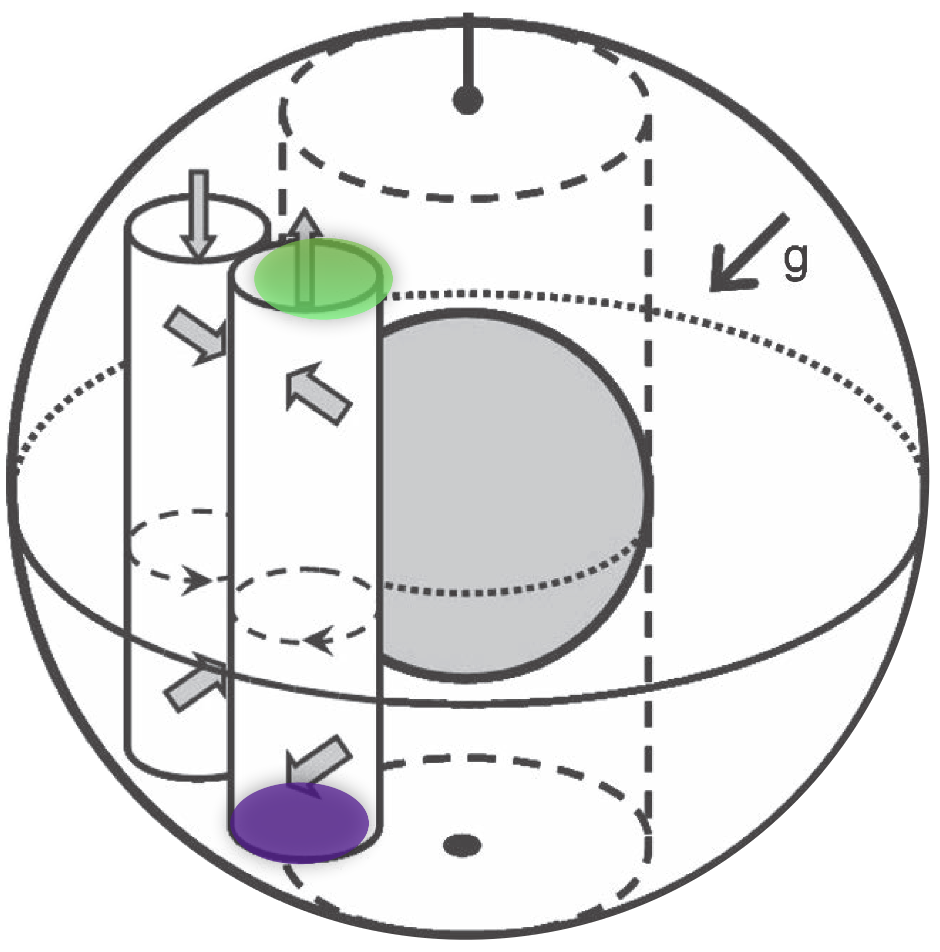
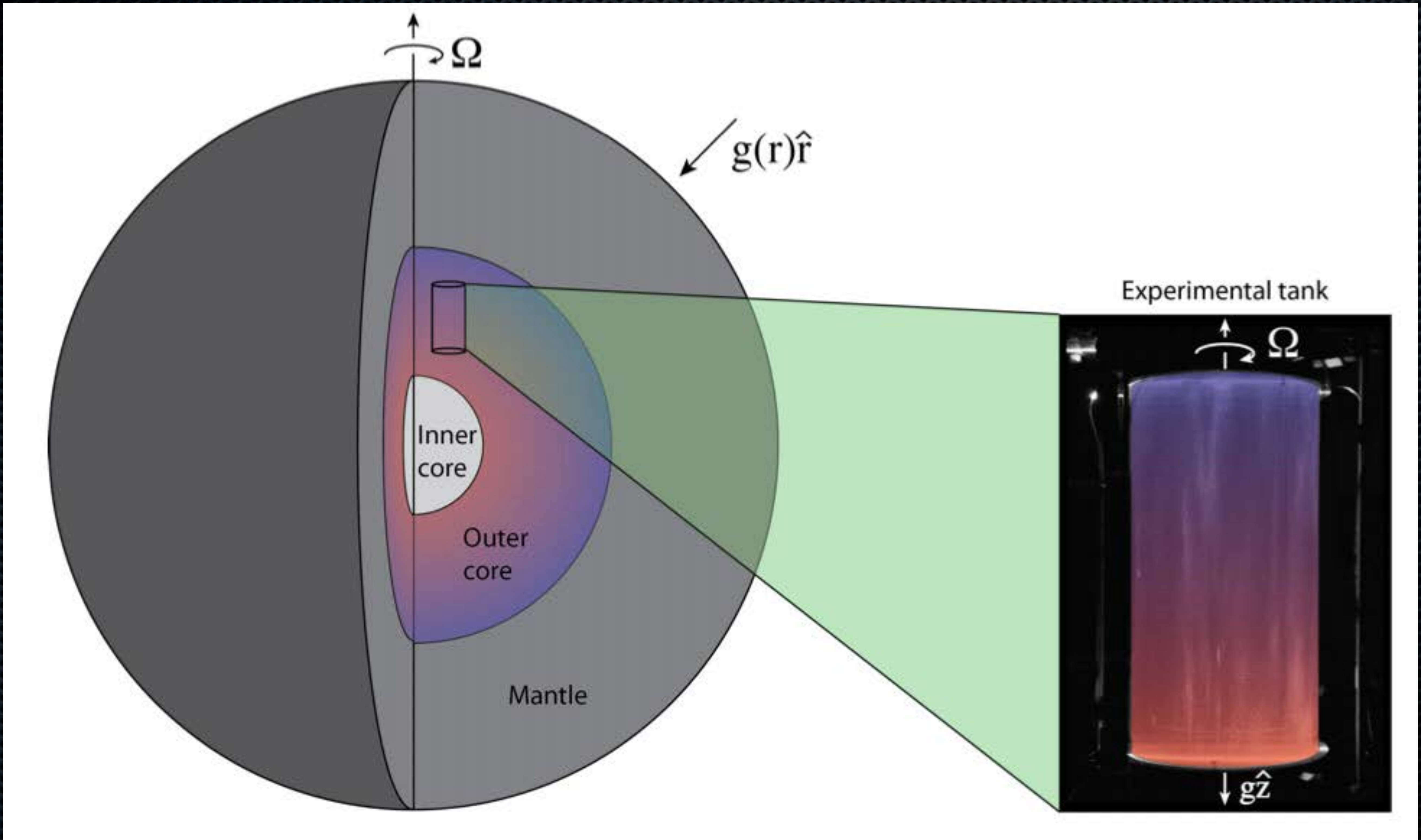
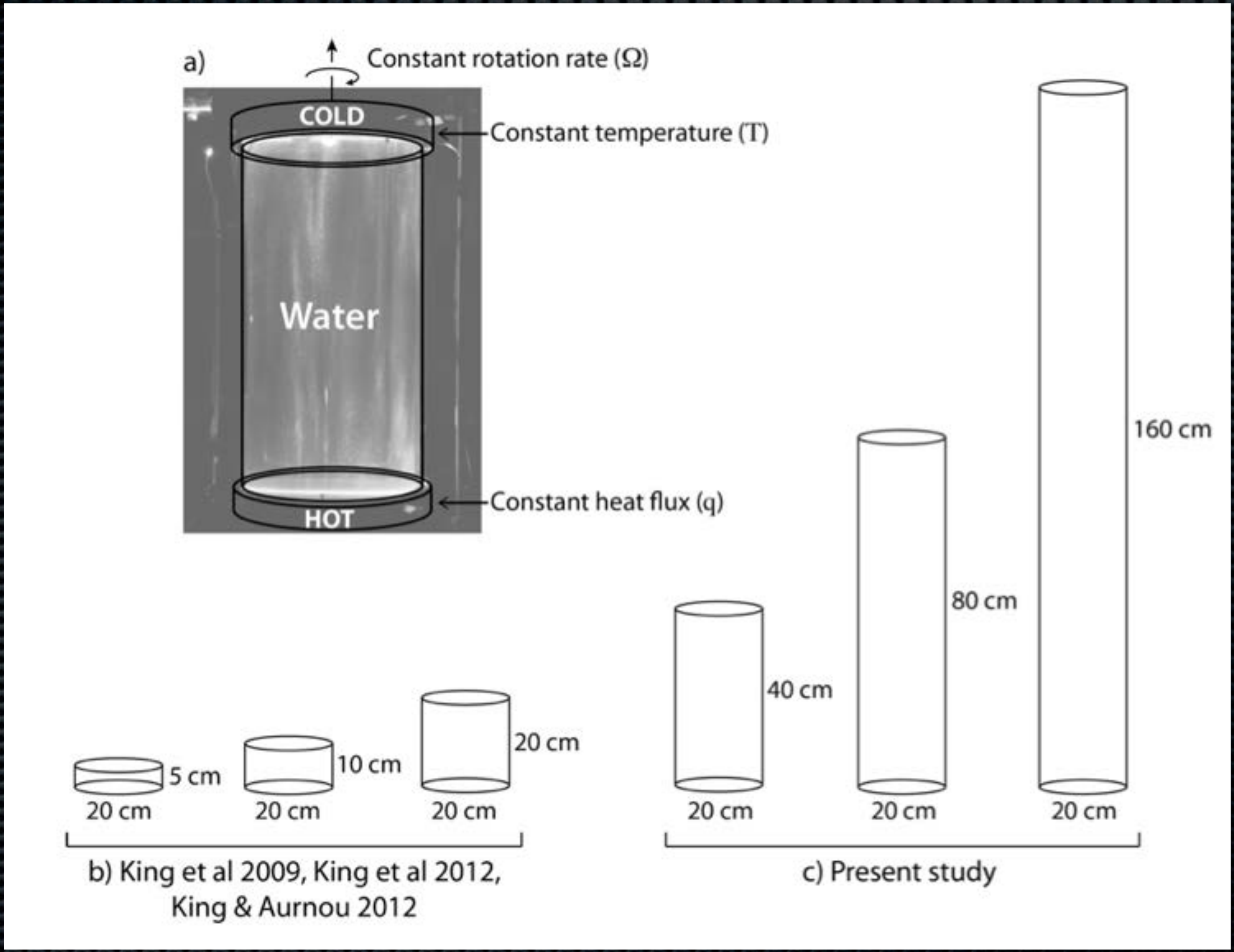


Rotating Convection in Water



Cheng et al. *GJI* 2014

Rotating Convection in Water



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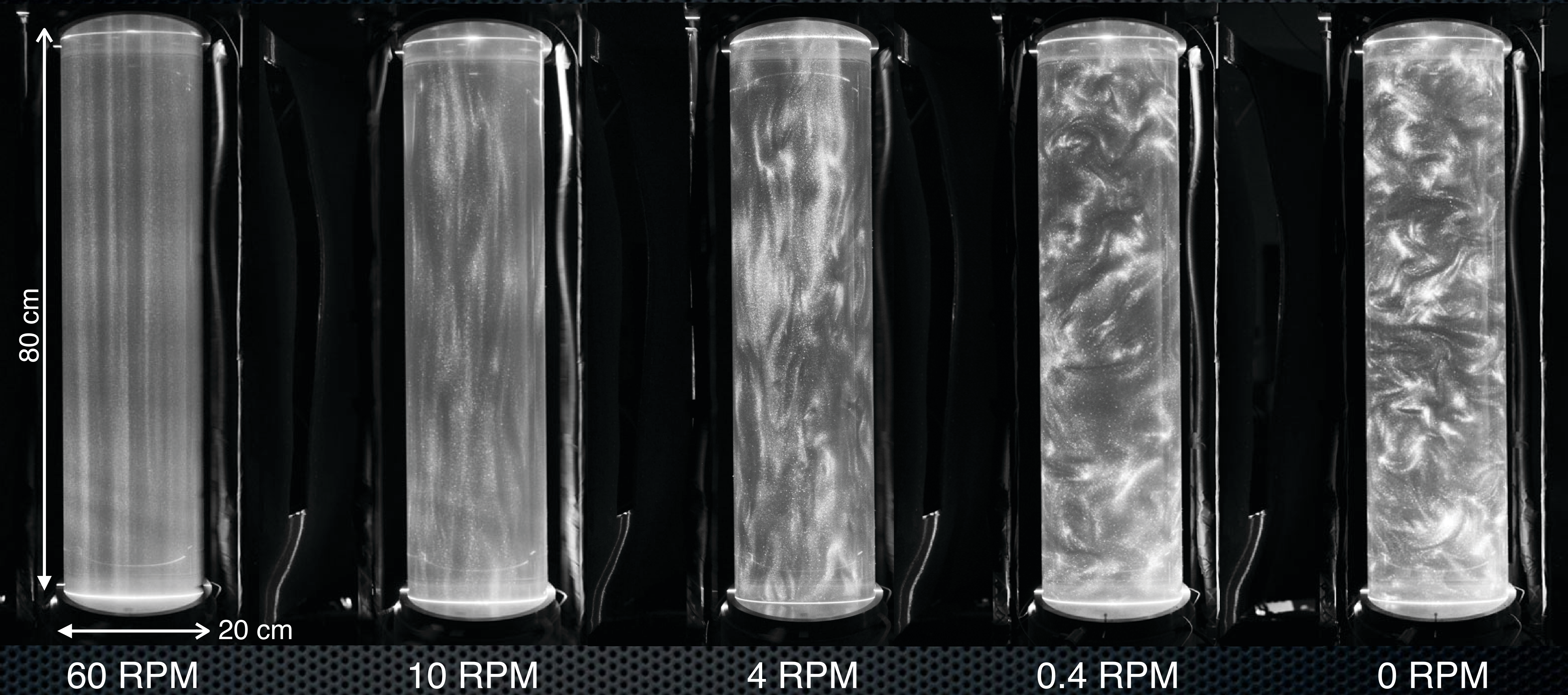
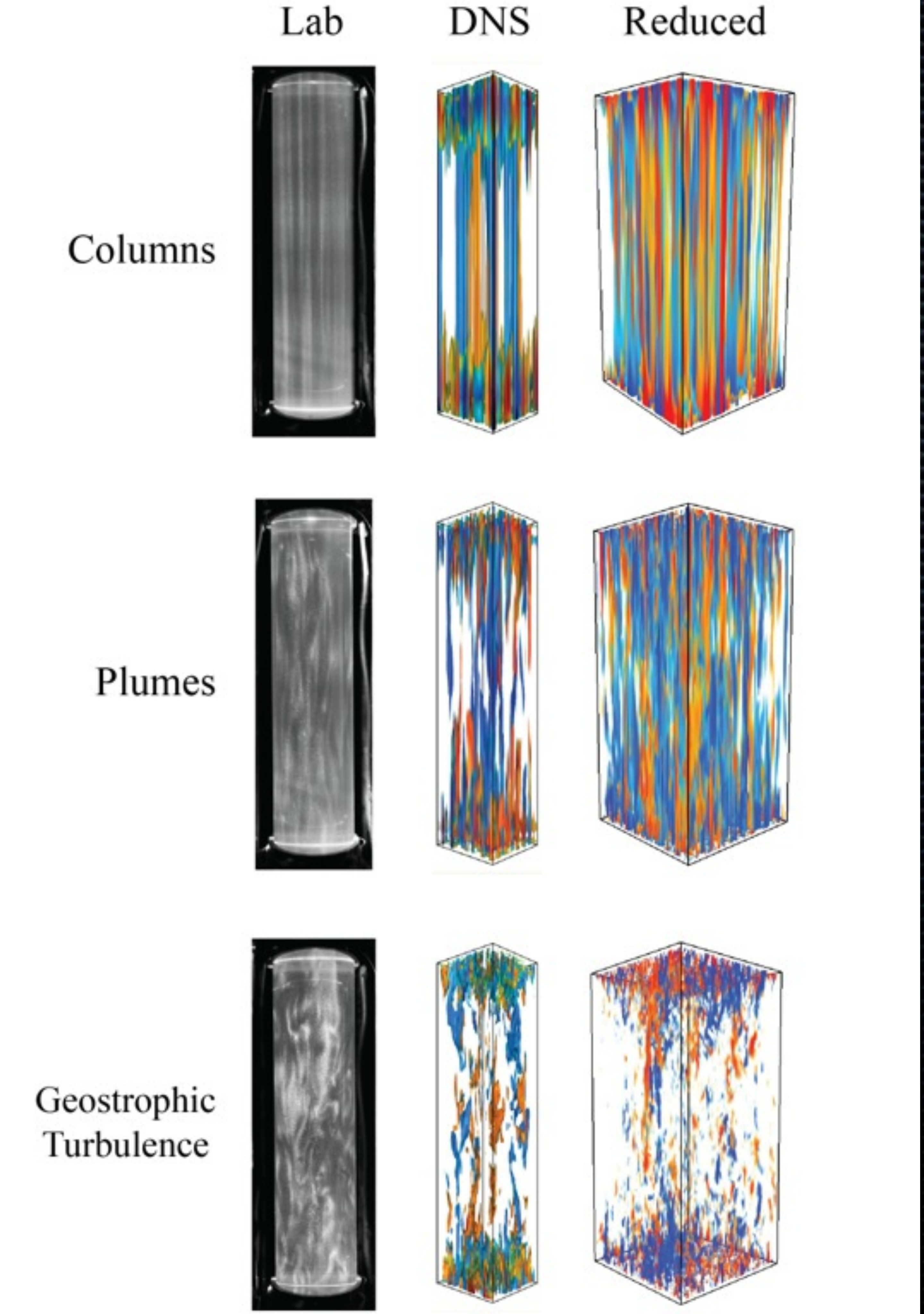


- Convection columns are (relatively) easily destabilized

Cheng et al. *GJI* 2014

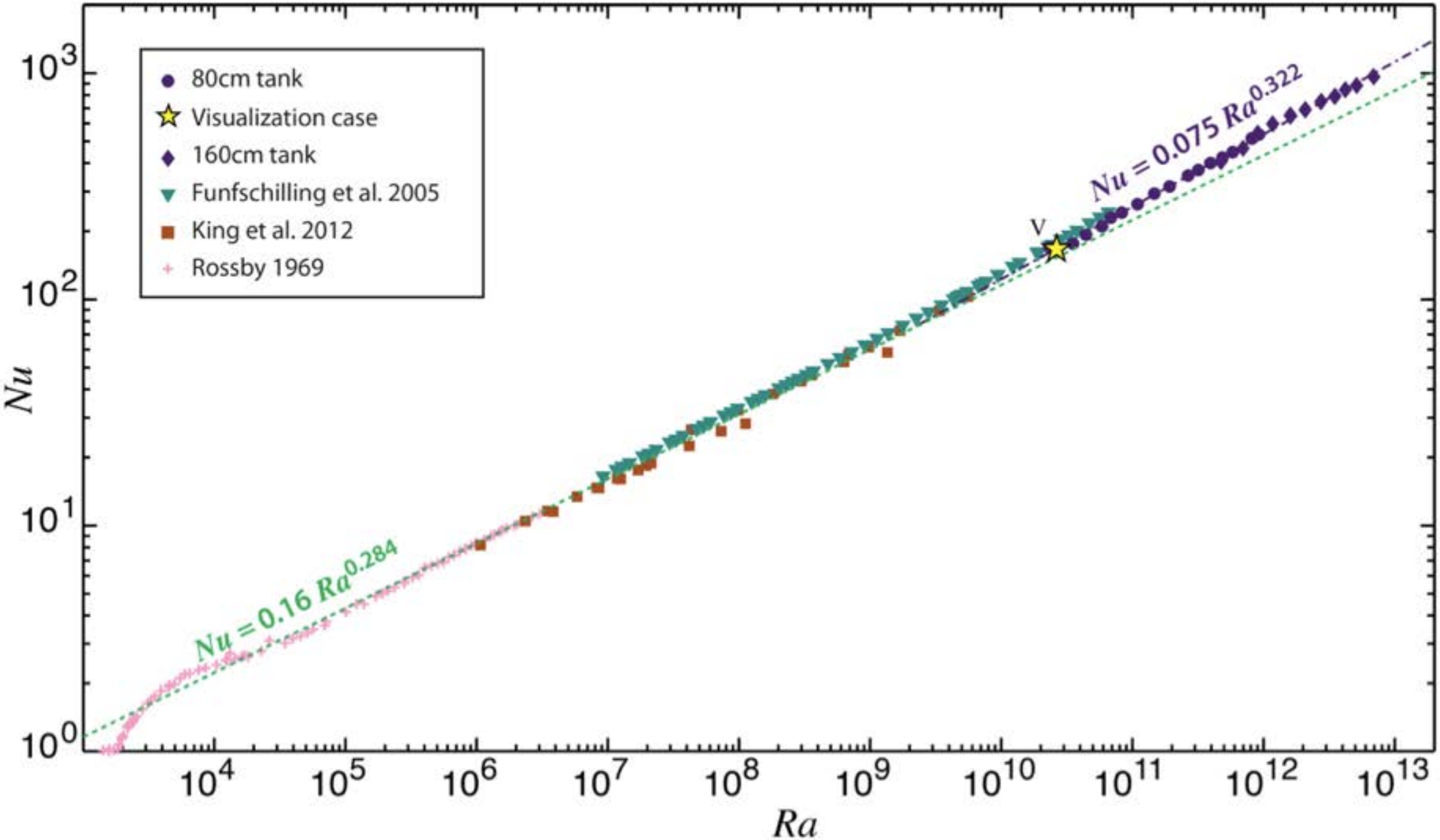
Rotating Cor

Lab versus Theory
(for water)



Aurnou et al., in prep 2014

Rotating Convection in Water



Cheng et al. *GJI* 2014

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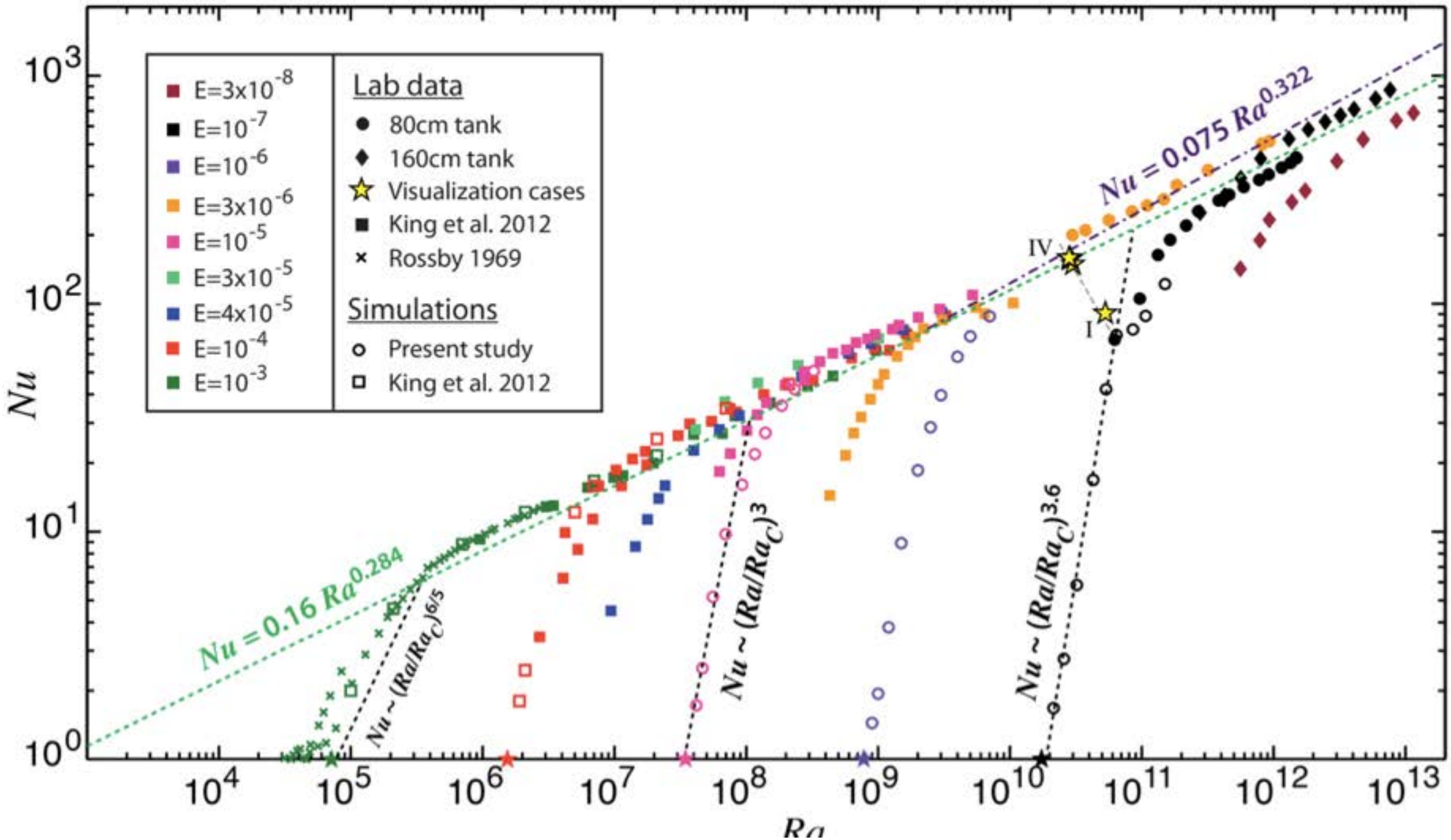

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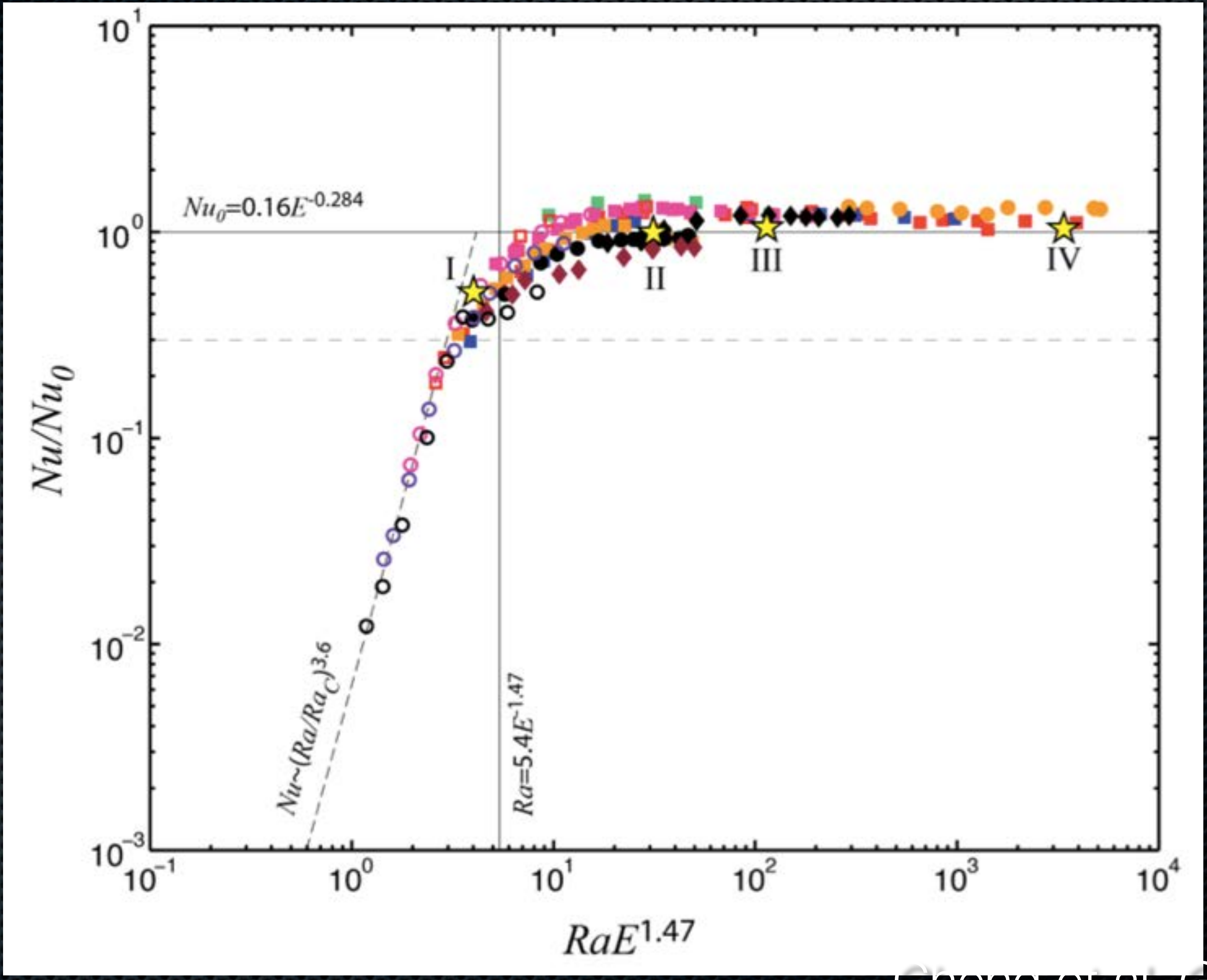

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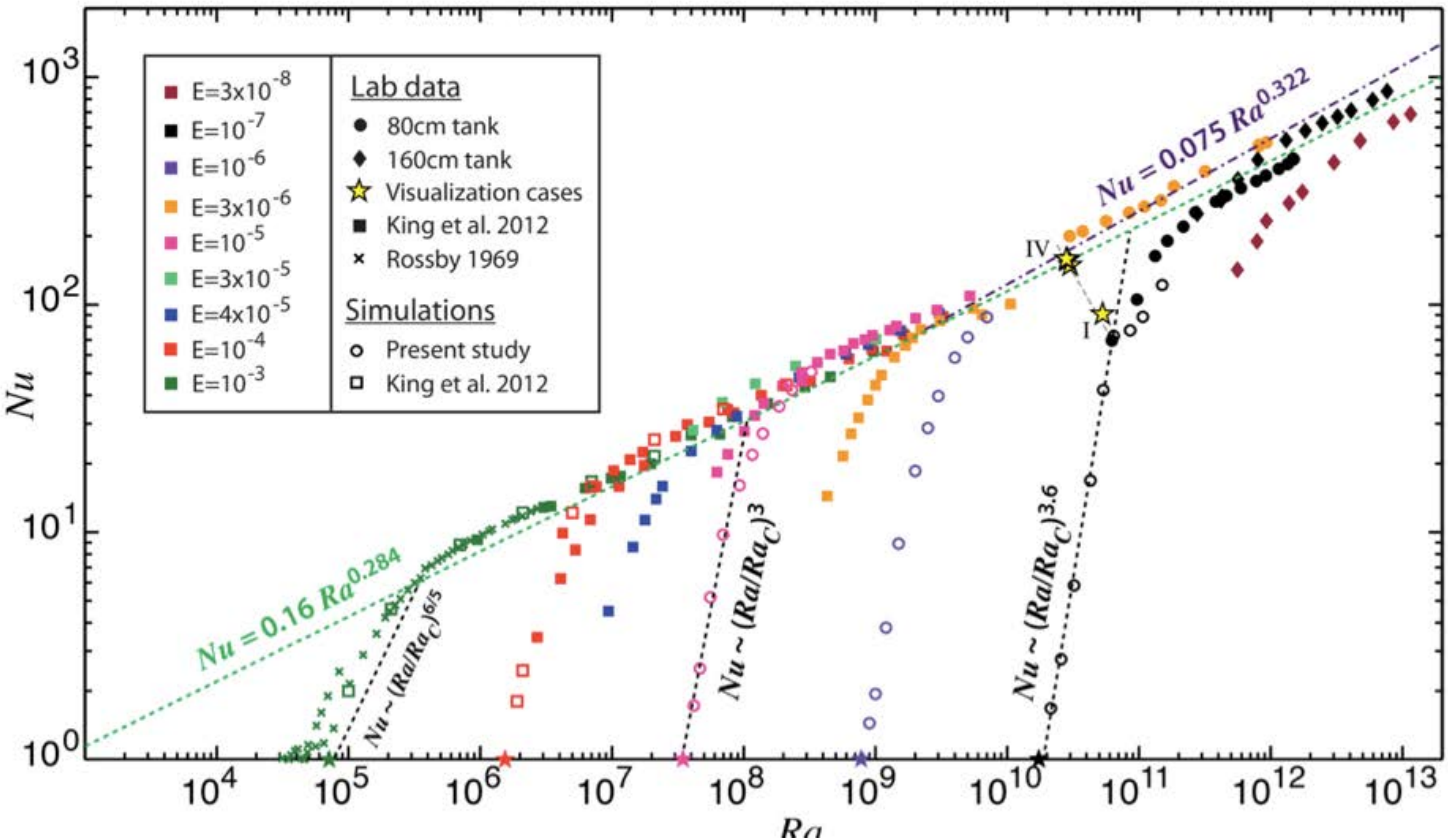

Cheng et al. *GJI* 2014

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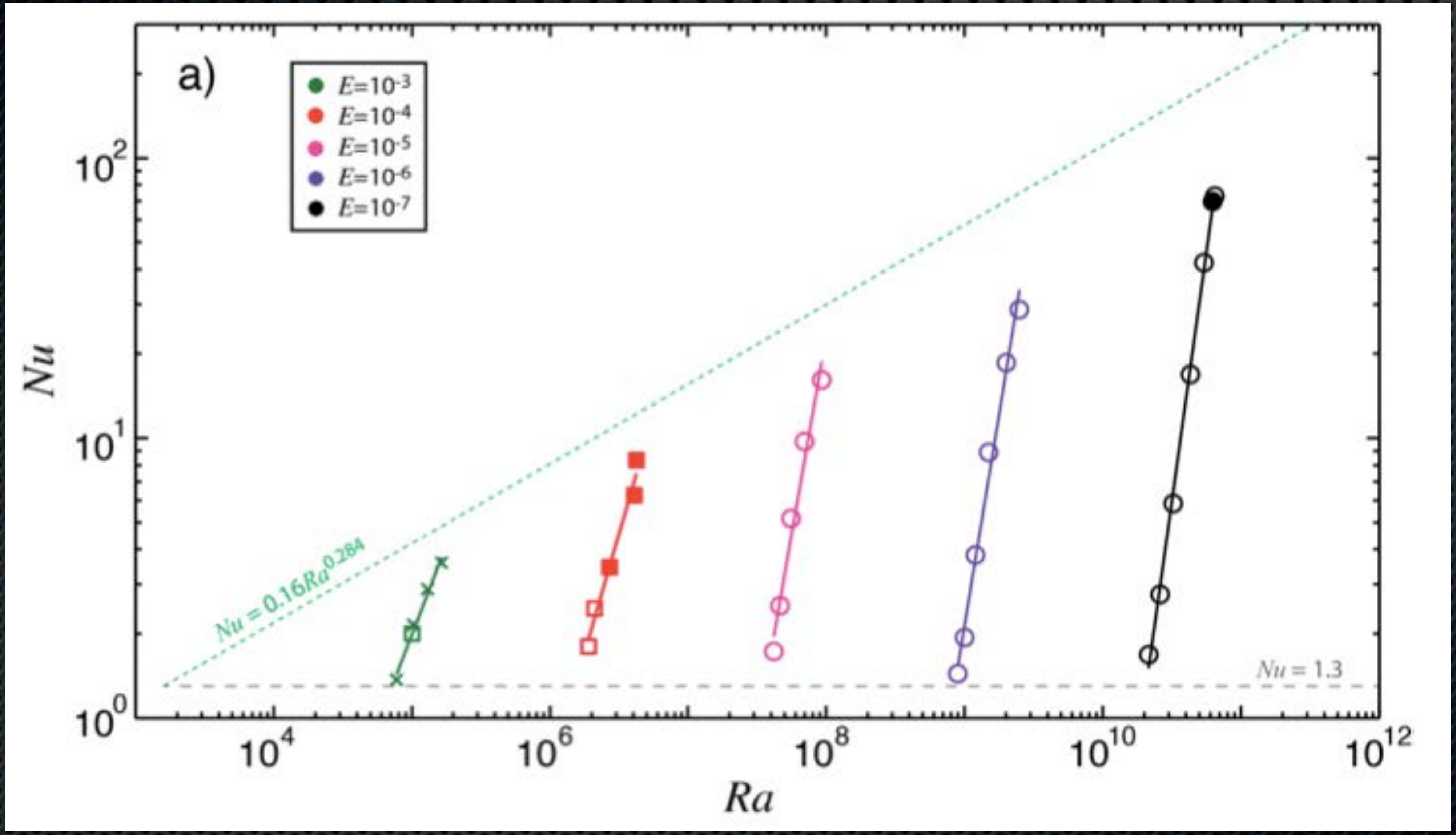

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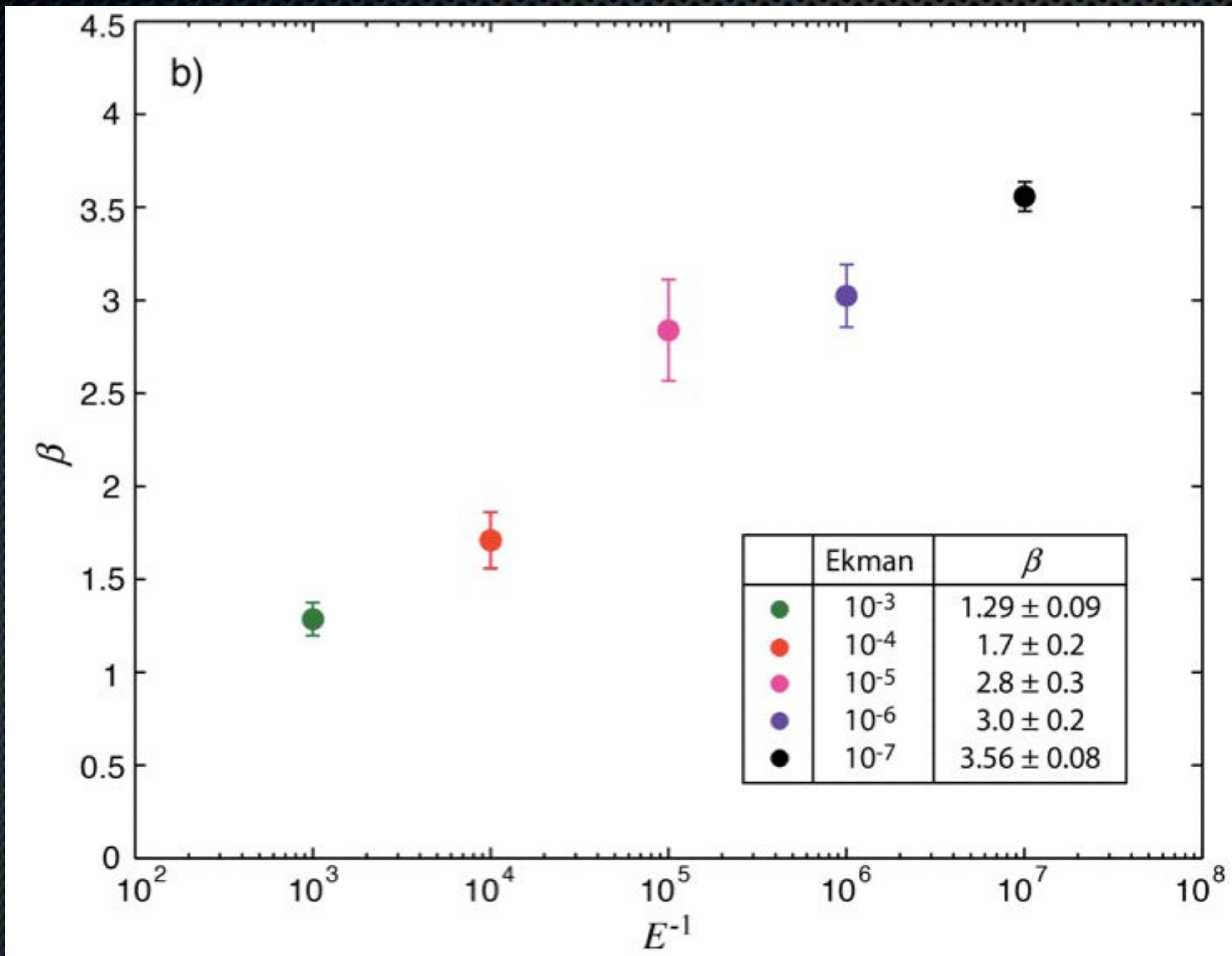

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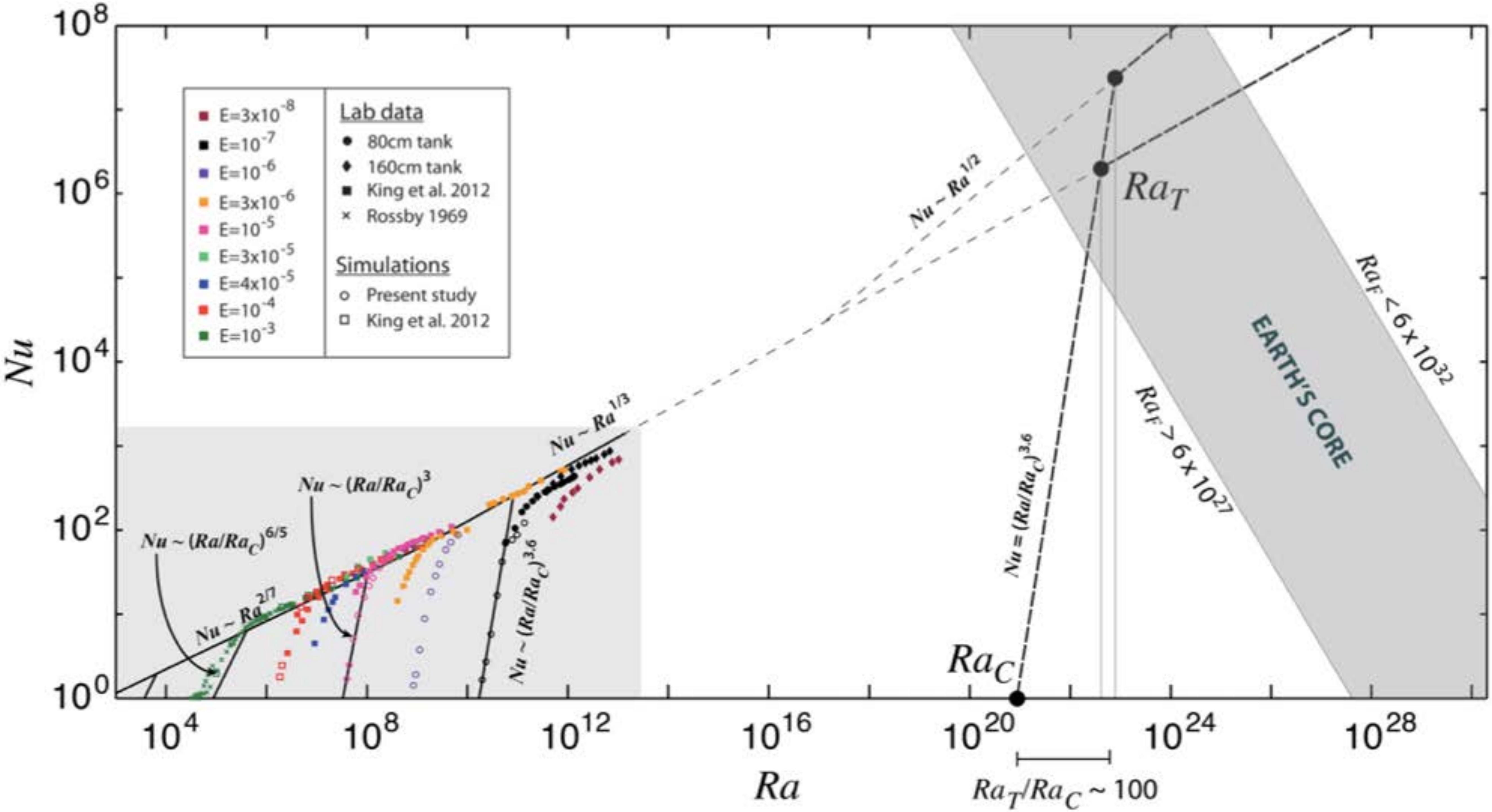


Cheng et al. *GJI* 2014

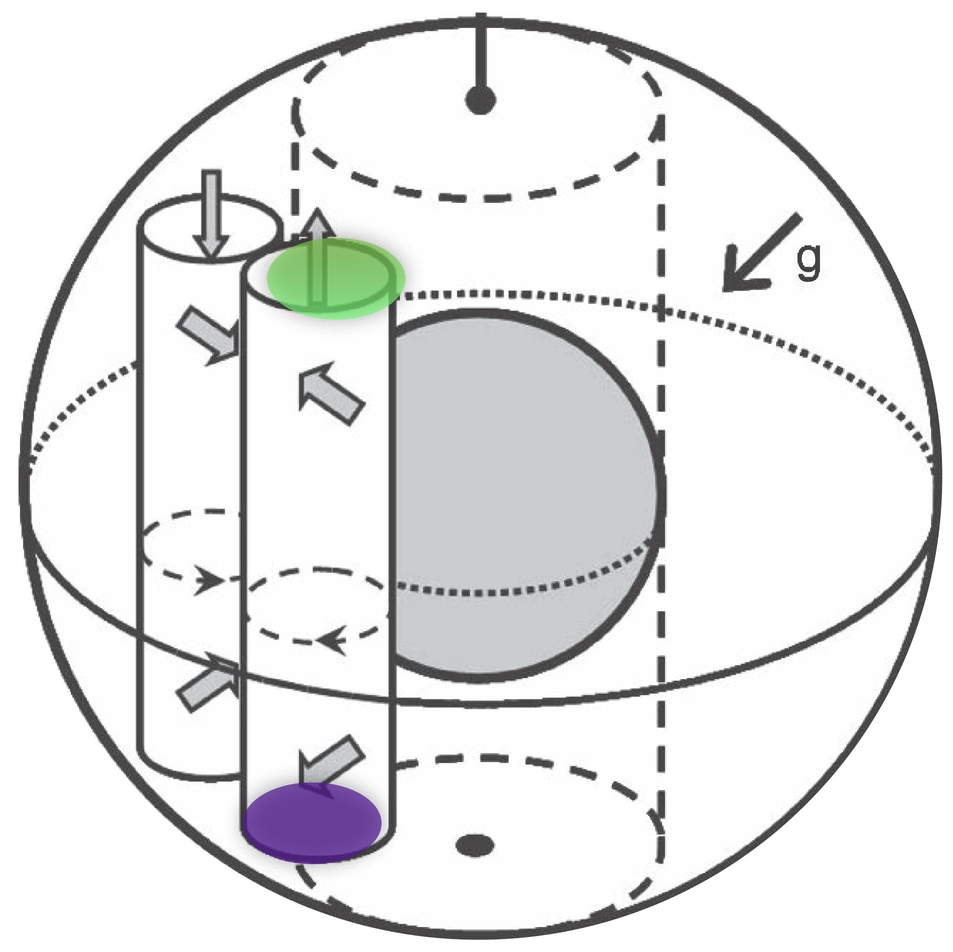
Rotating Convection in Water

- Unlikely that convection is columnar in planetary cores
  - Geostrophic convective turbulence makes more sense

Possible Problems

- 1) Overly strong viscosity
- **2) Lack of turbulent processes**
- 3) Inaccurate material properties

Christensen, *Enc. Solid Earth Geophys.* 2011



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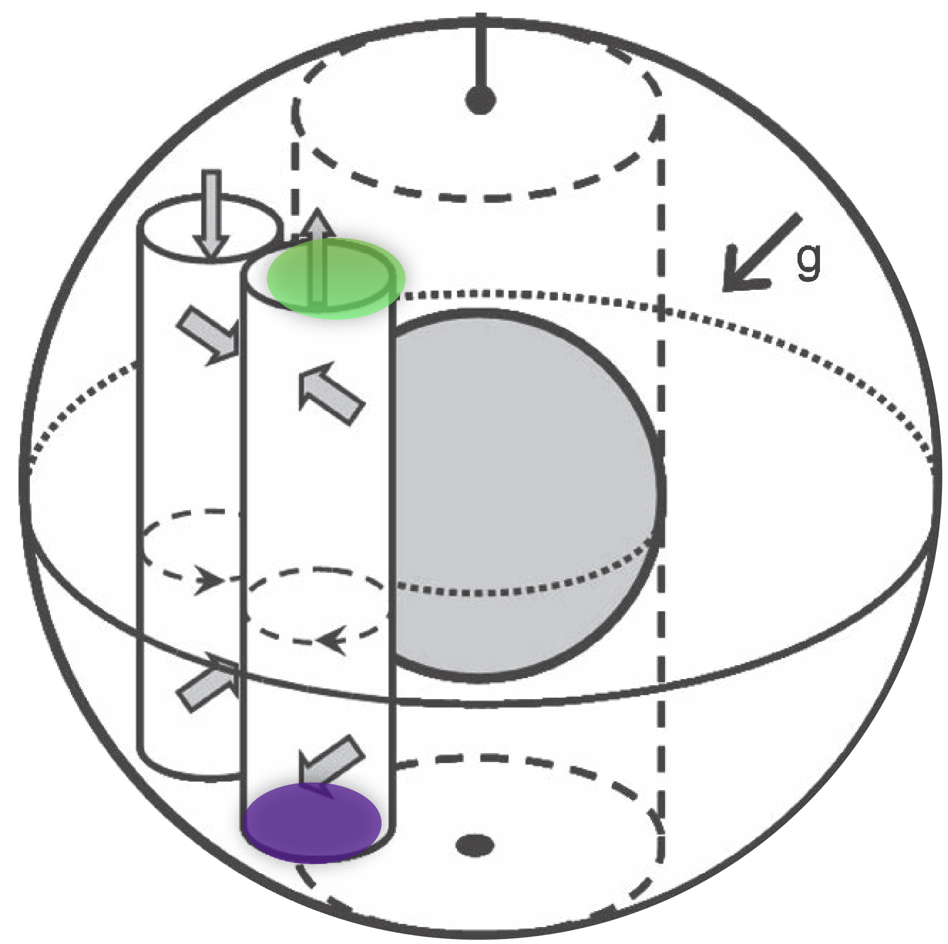
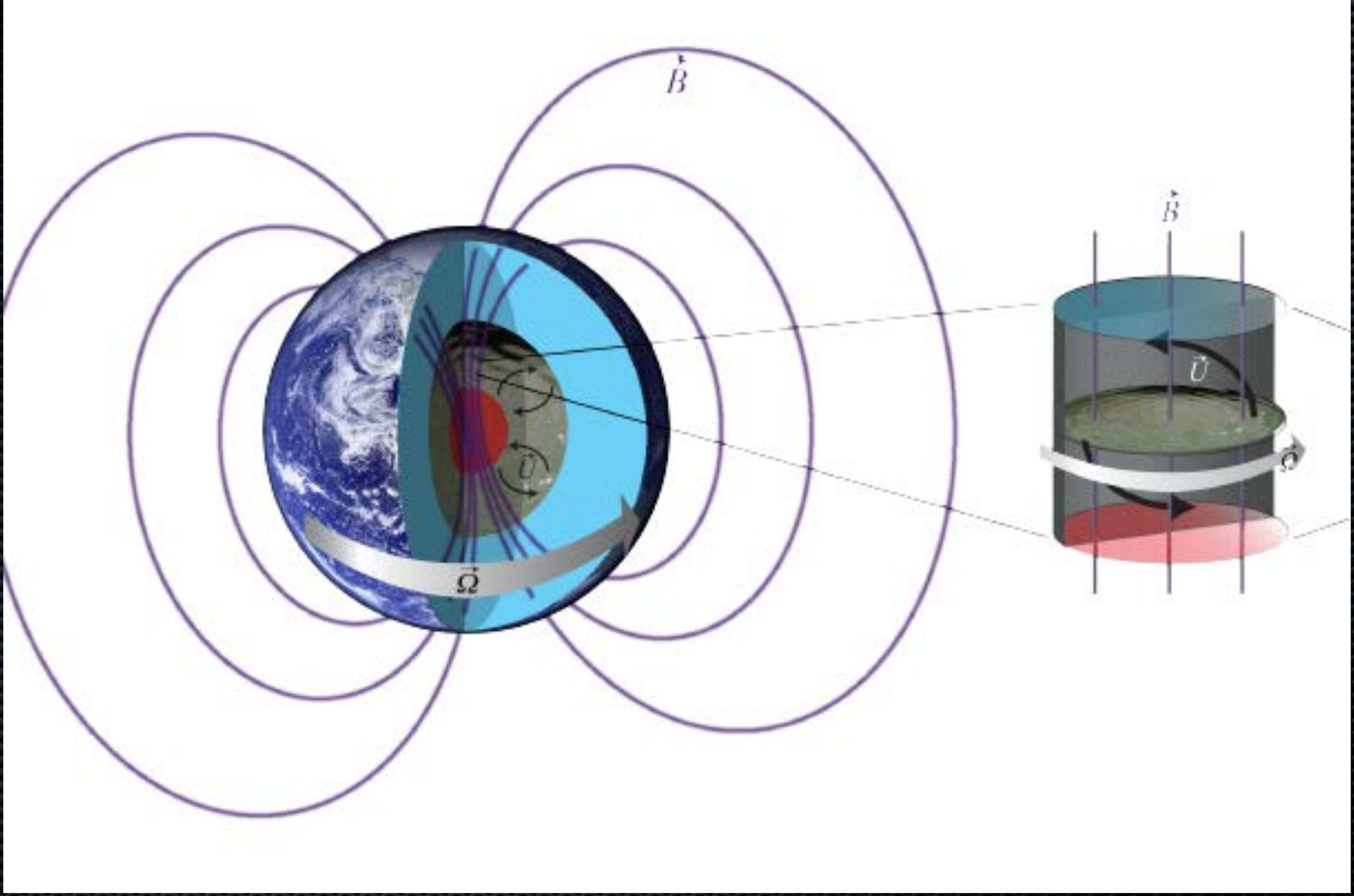
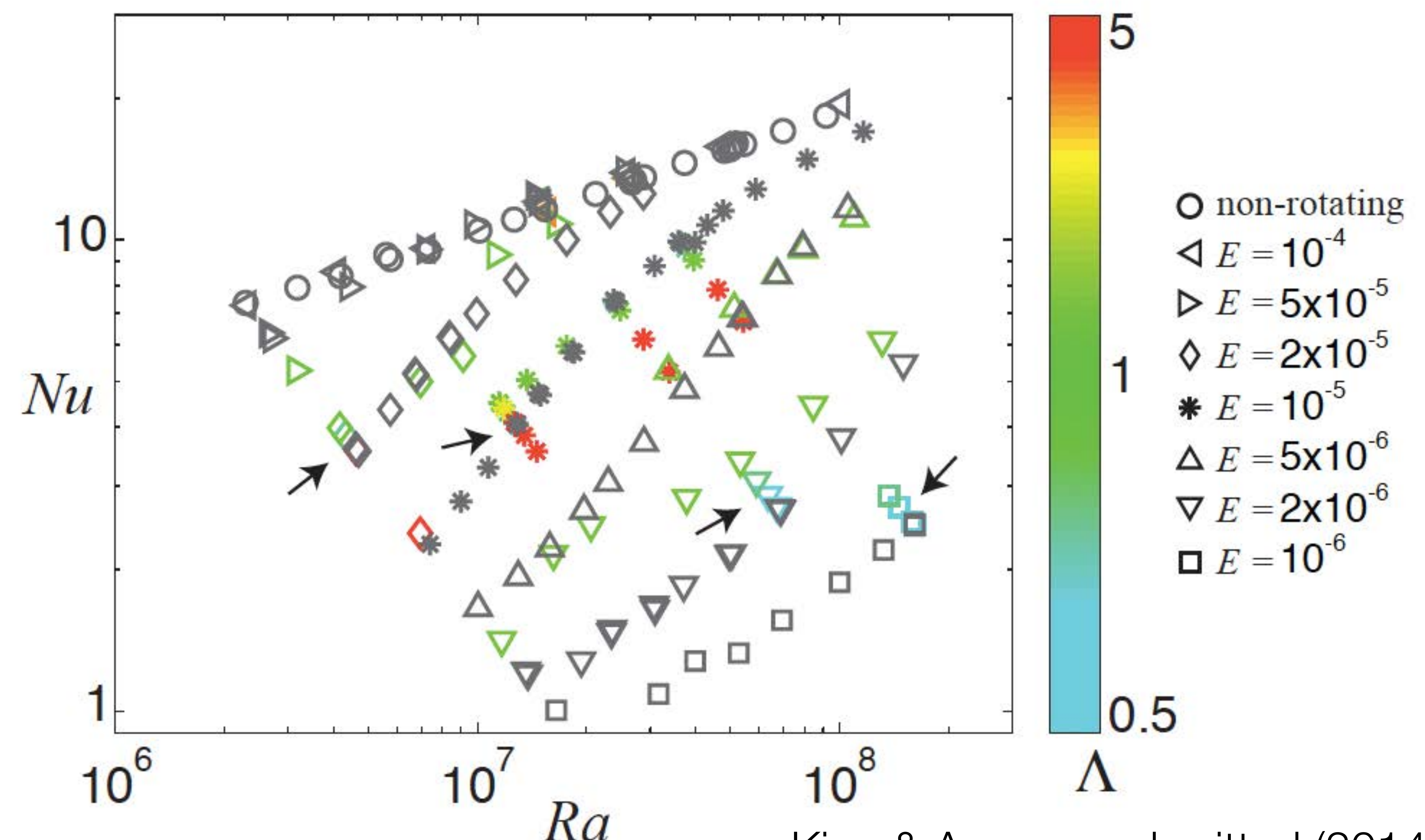


Rotating Magnetoconvection in Metal



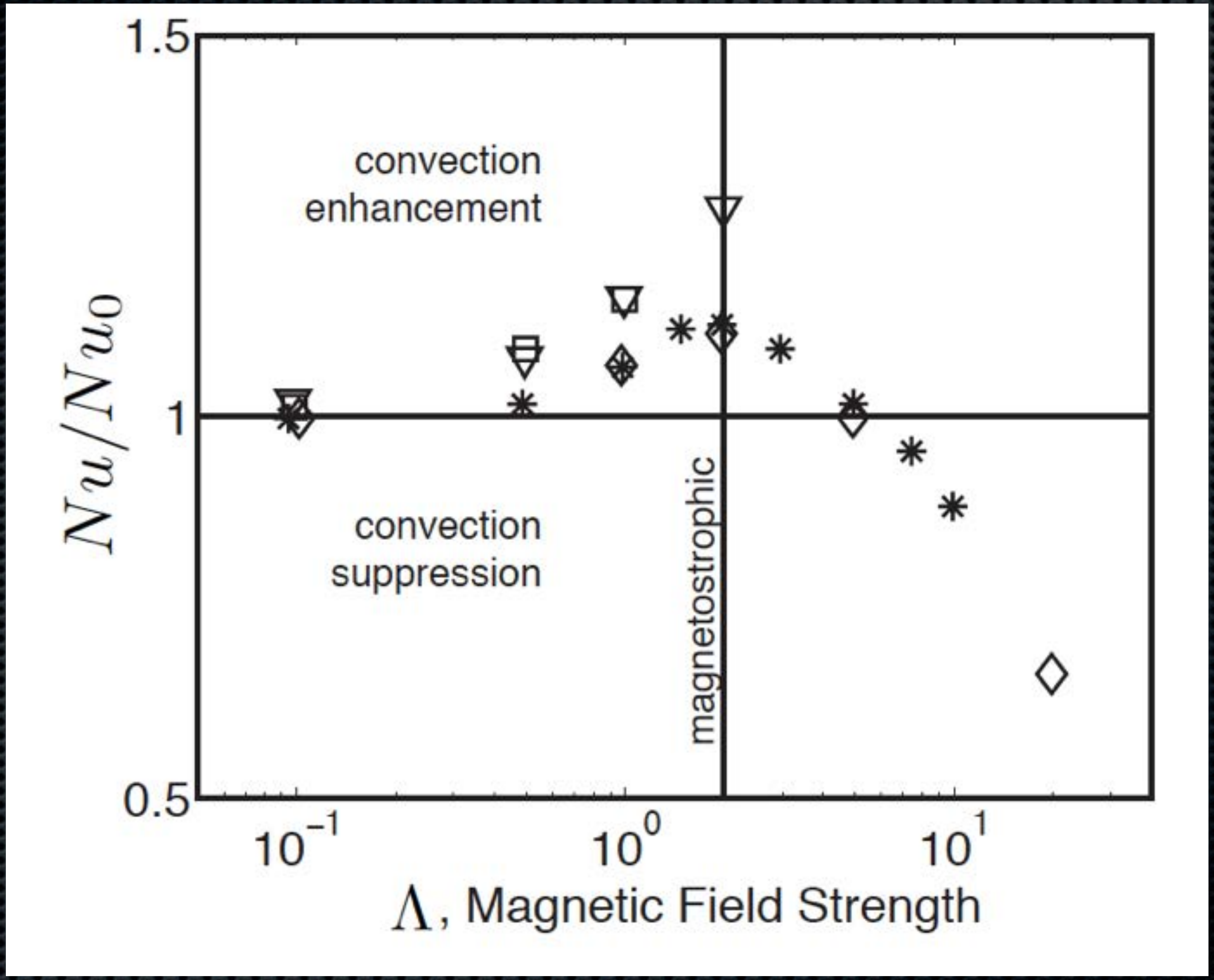
King & Aurnou, submitted (2014)

Rotating Magnetoconvection in Metal



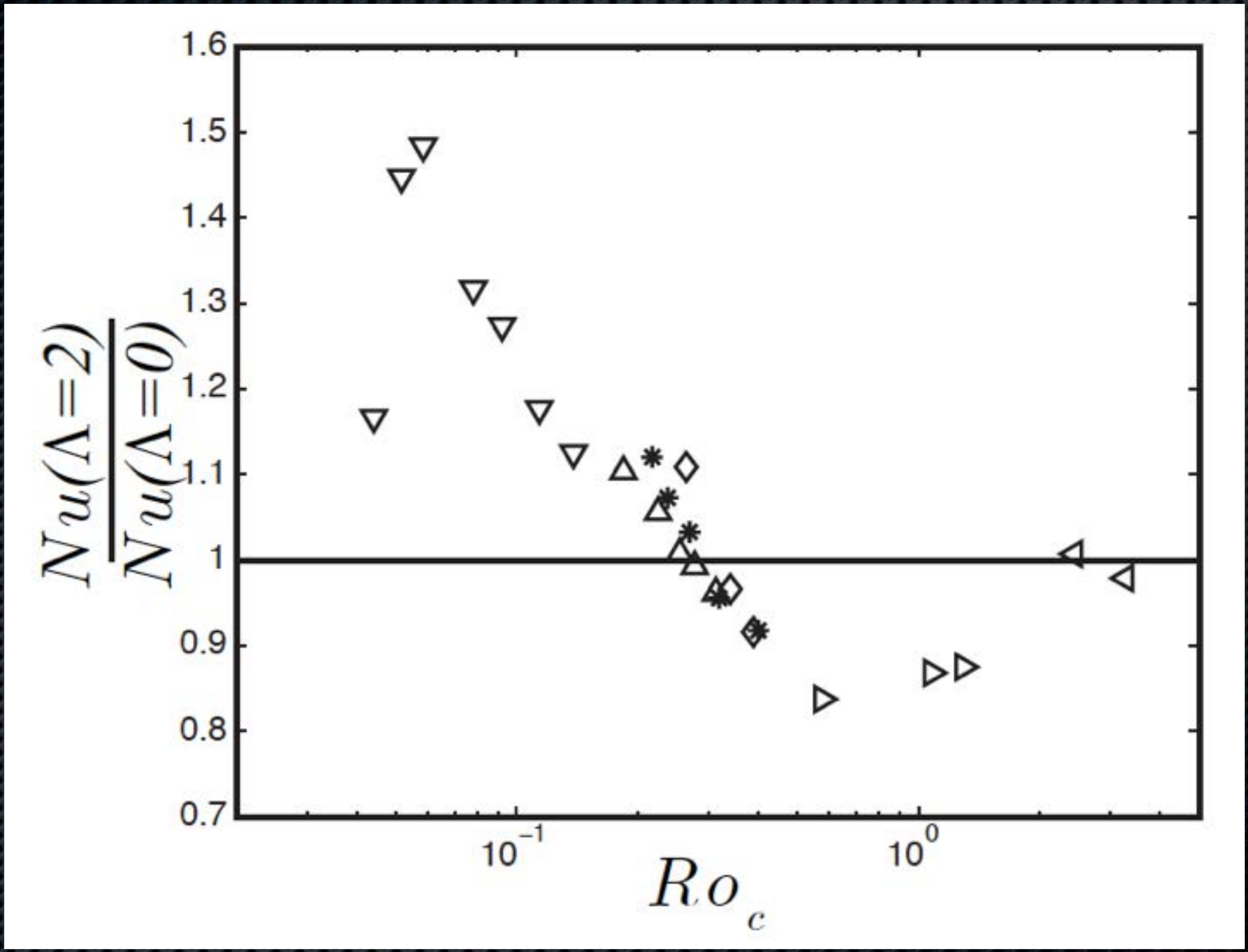
King & Aurnou, submitted (2014)

Rotating Magnetoconvection in Metal



King & Aurnou, submitted (2014)

Rotating Magnetoconvection in Metal



King & Aurnou, submitted (2014)

Rotating Magnetoconvection in Metal

- Magnetic field appears capable of further destabilizing ***injection scale*** flows in planetary core settings
  - “Magneto-relaxation” at Elsasser ~ 1 & Ro < 1
    - Need not apply at the system scale (Soderlund et al. 2012)

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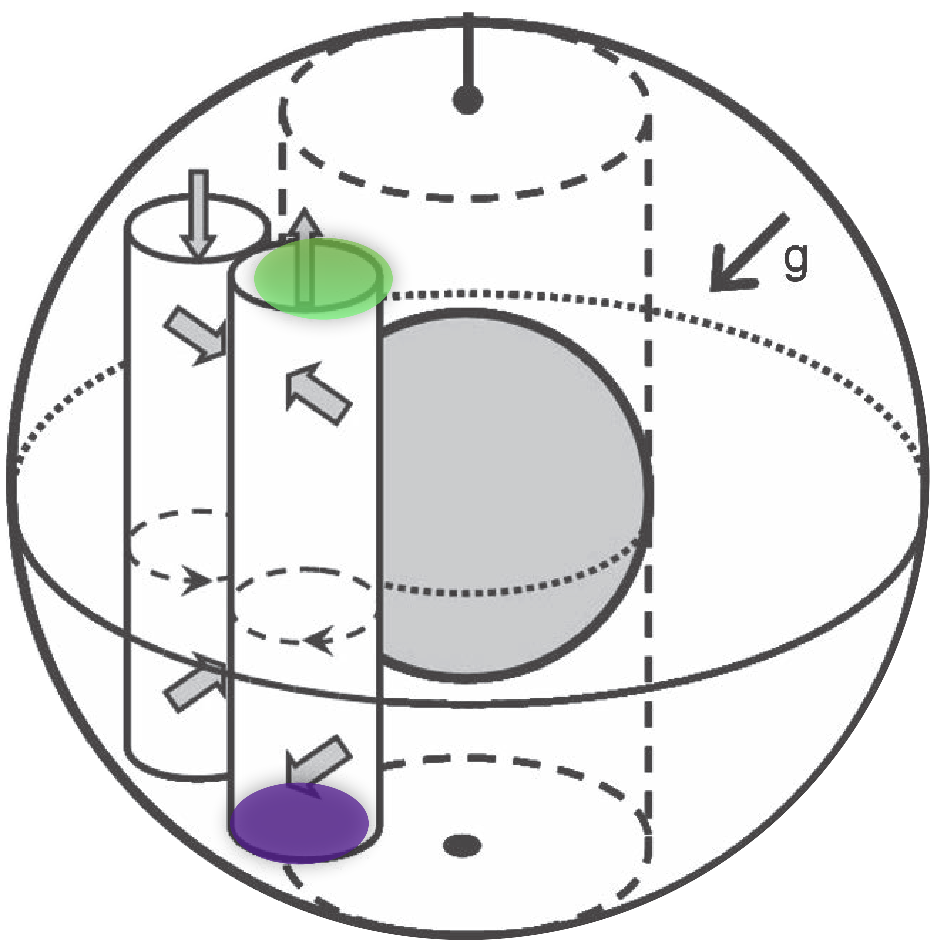
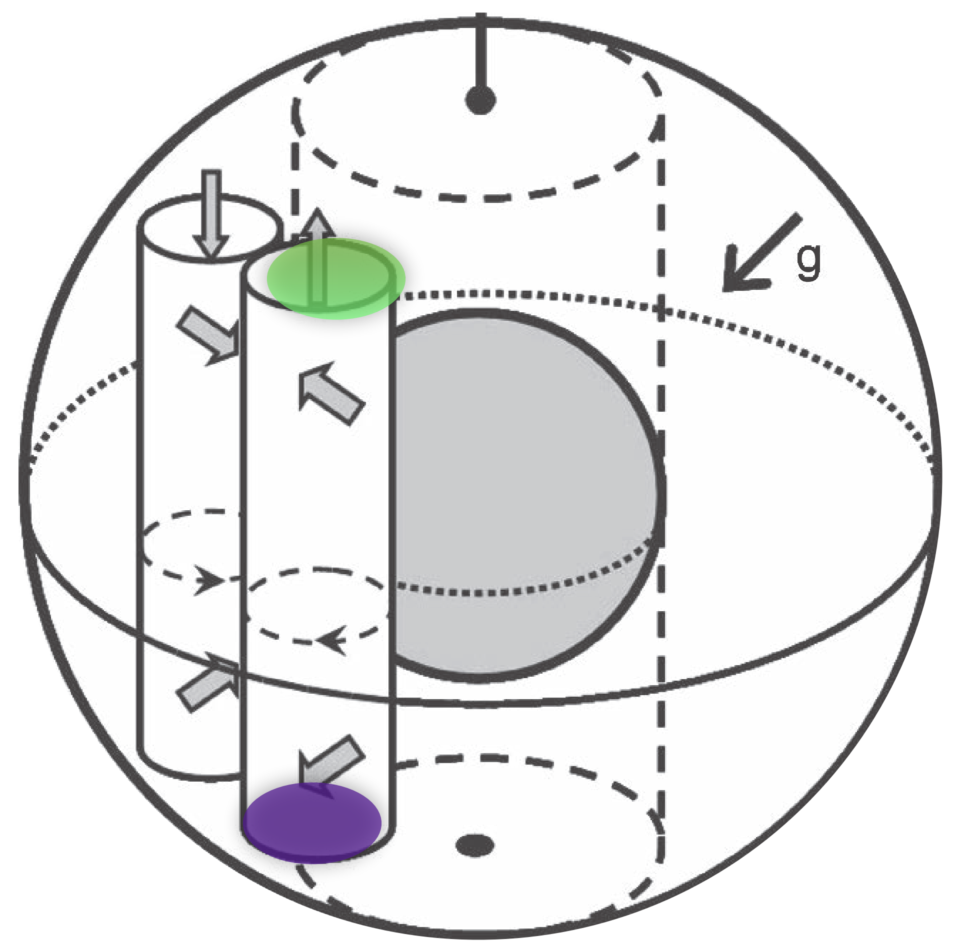


Possible Problems

- Model-style columns unlikely to exist in turbulent (**2**), liquid metal (**3**) cores
- But if they do, they're magnetically ineffective (**1**)

Christensen, *Enc. Solid Earth Geophys.* 2011



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Moving Forward

- High performance computing (HPC)
- Multi-scale asymptotic (MSA) theory
- Laboratory experiments

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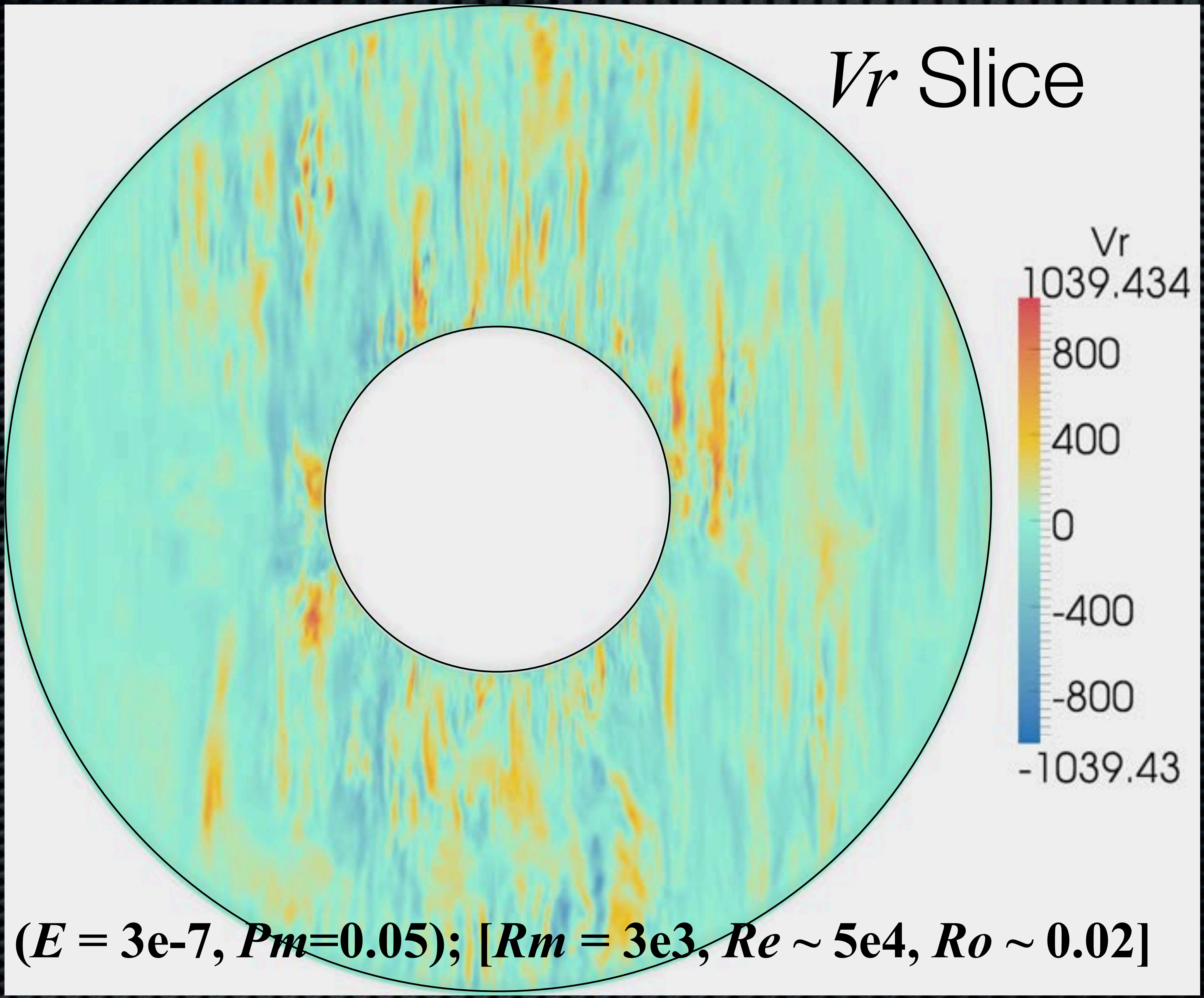
HPC Dynamo Model

(*E* = 3e-7, *Pm*=0.05); [*Rm* = 3e3, *Re* ~ 5e4, *Ro* ~ 0.02]

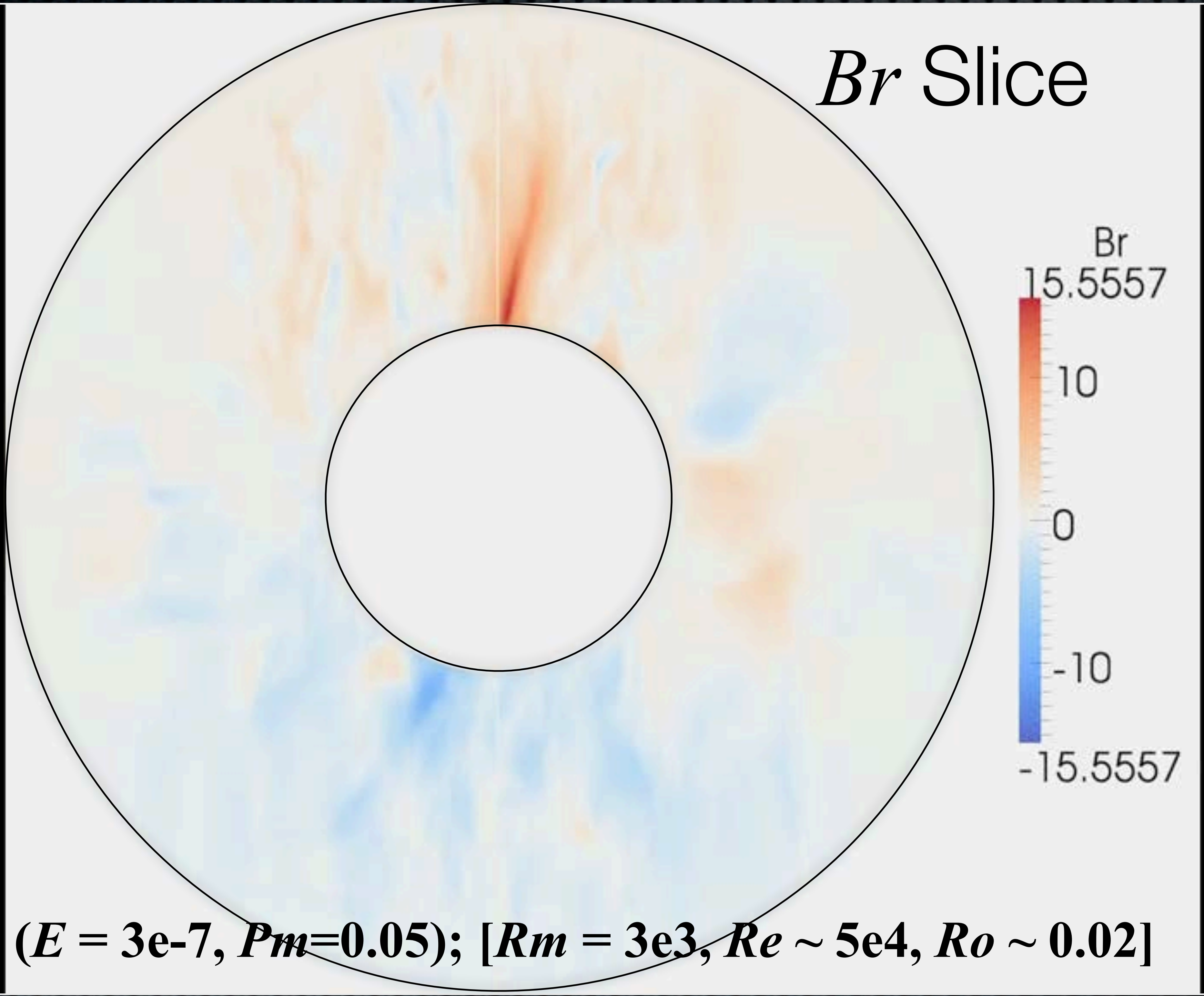
Andrey Sheyko et al., in prep. (2013)

HPC Dynamo Model



Andrey Sheyko et al., in prep. (2014)

HPC Dynamo Model



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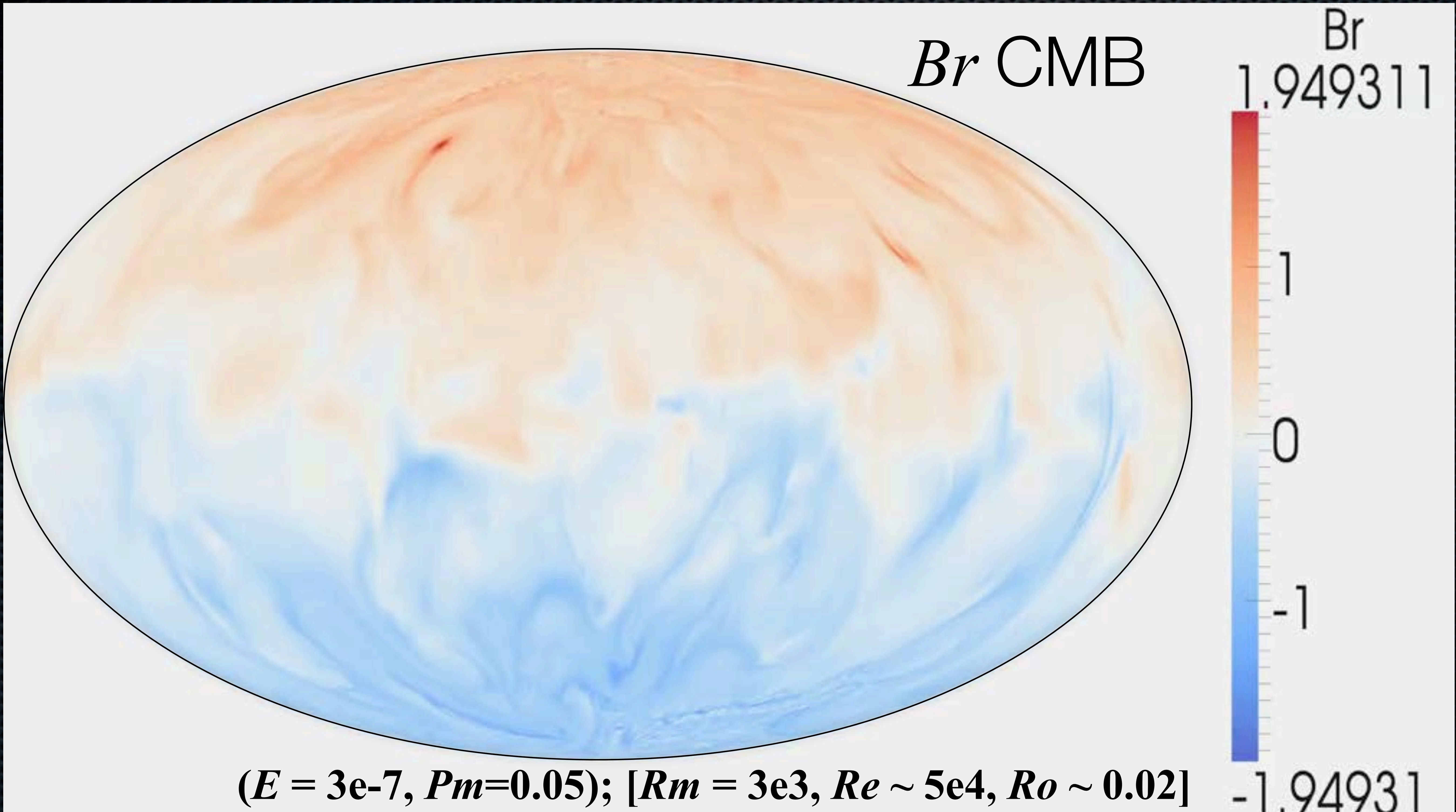


(*E* = 3e-7, *Pm*=0.05); [*Rm* = 3e3, *Re* ~ 5e4, *Ro* ~ 0.02]

Andrey Sheyko et al., in prep. (2014)

Sheyko’s HPC Dynamo

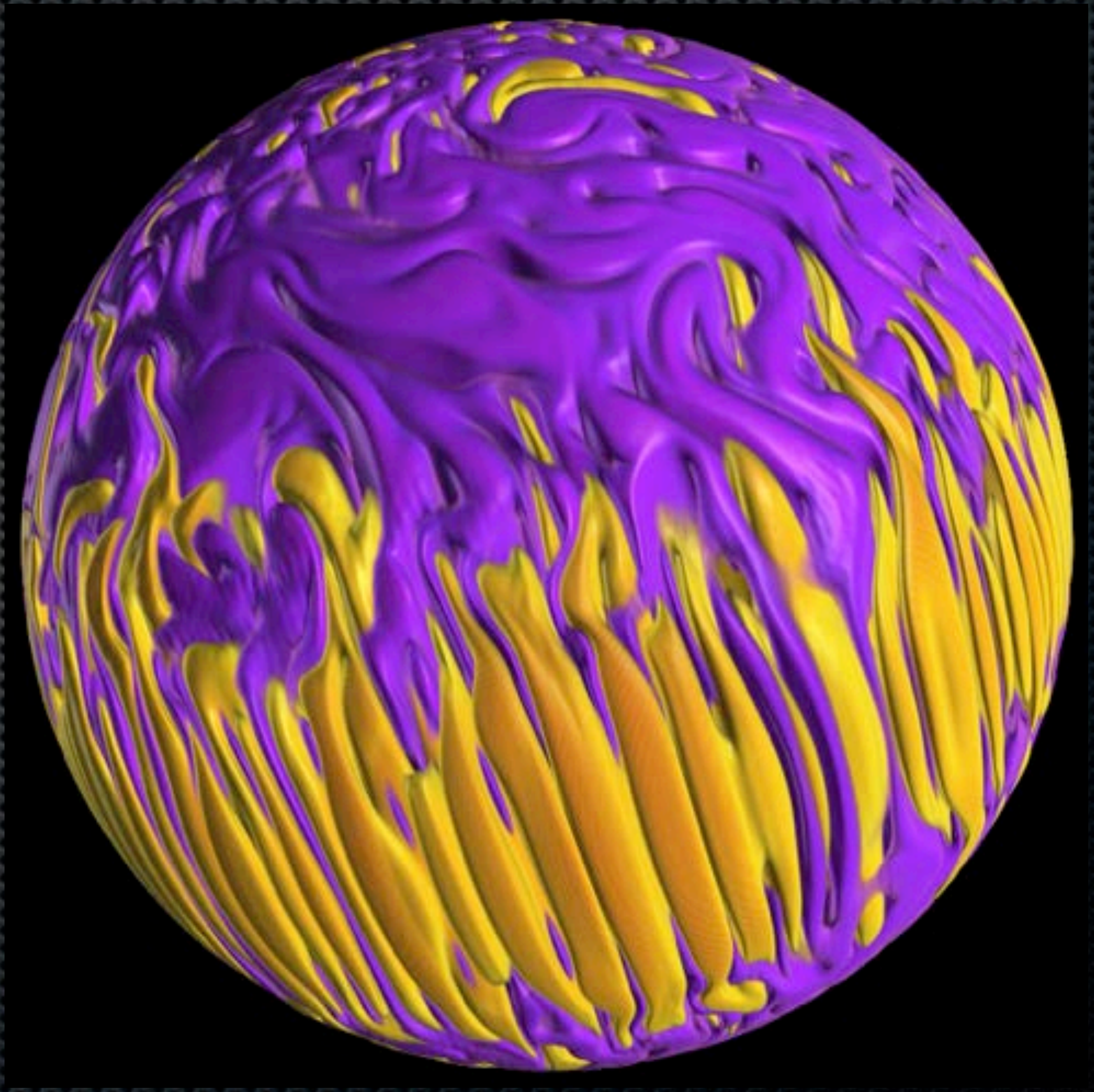
- Small-scale columns:
  - Rarely extend across outer core
  - No obvious magnetic signatures
- Large-scale turbulent flow structures inside and along TC
  - But how do *these* scale to the core?

Sheyko's HPC Dynamo

- Small-scale columns:
  - Rarely extend across outer core
  - No obvious magnetic signatures
- Large-scale turbulent flow structures inside and along TC
  - But how do *these* scale to the core?
- **Ran on 516 processors for 1.5 years...**

CIG Community Code (CCC)

- **Nick Featherstone**
- Scale to ~130,000 cores at 70%; public within next 6 months
- Flexible framework for broad usage
  - DNS & reduced modeling; planet & stellar problems
- **INCITE award (2015-2017)**



Movie: N. Featherstone

Moving Forward

- High performance computing (HPC)
- Multi-scale asymptotic (MSA) theory
- Laboratory experiments

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NoMag Device

- 1.8 m H x .6 m OD
  - $E > 3\text{e-}8$; $Ra < 5\text{e}13$
- Structures in rapidly-rotating, strongly turbulent flows
- Thermal & velocity field data
  - Velocity/vorticity/helicity scalings

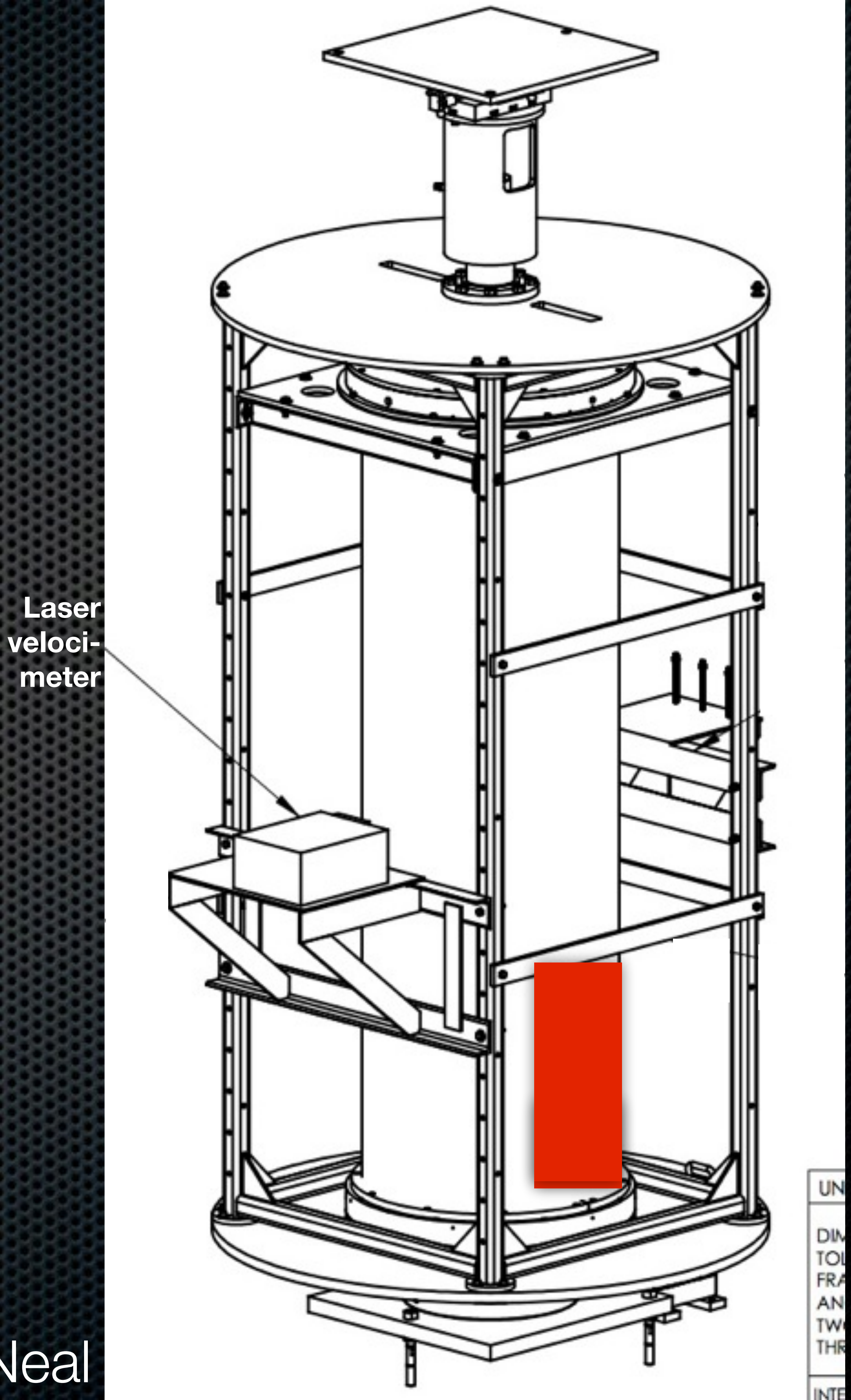


Image: J. Neal

Coupled Numerics

- DNS and asymptotically-reduced modeling (CU Boulder)
- SFEMaNS-T (UCLA-UTAM)
- Others…?

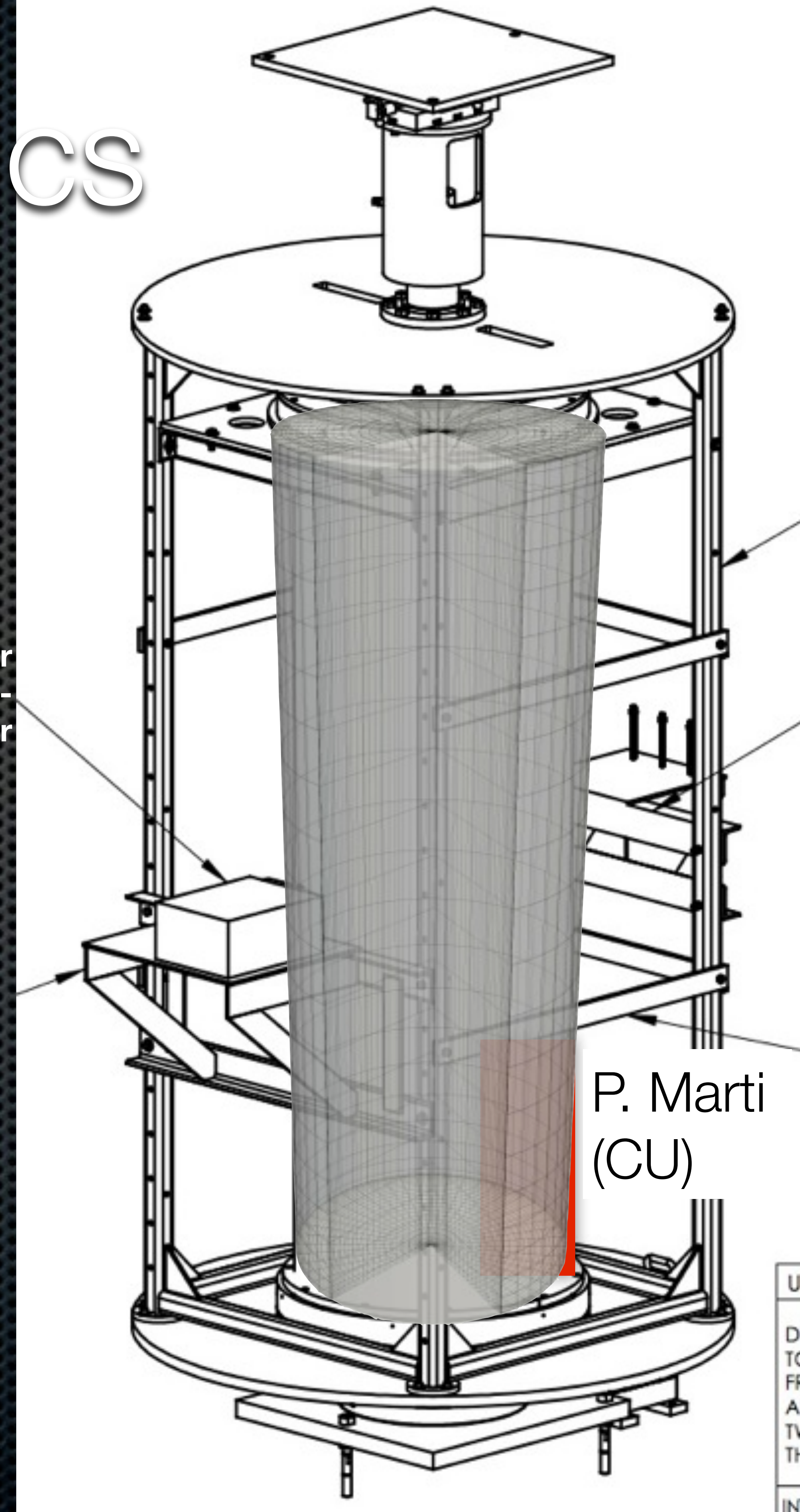
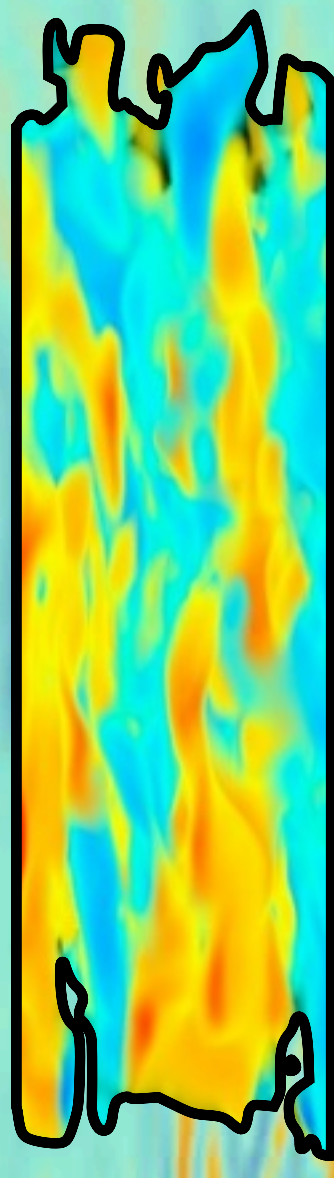
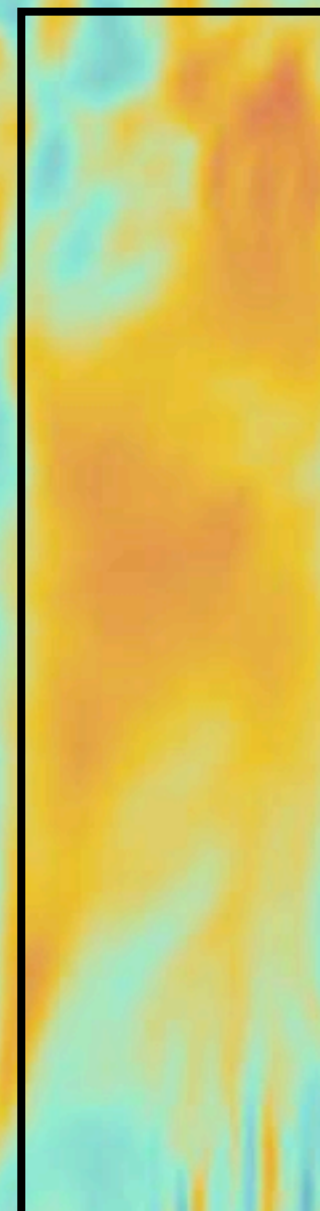


Image: J. Neal

Moving Forward

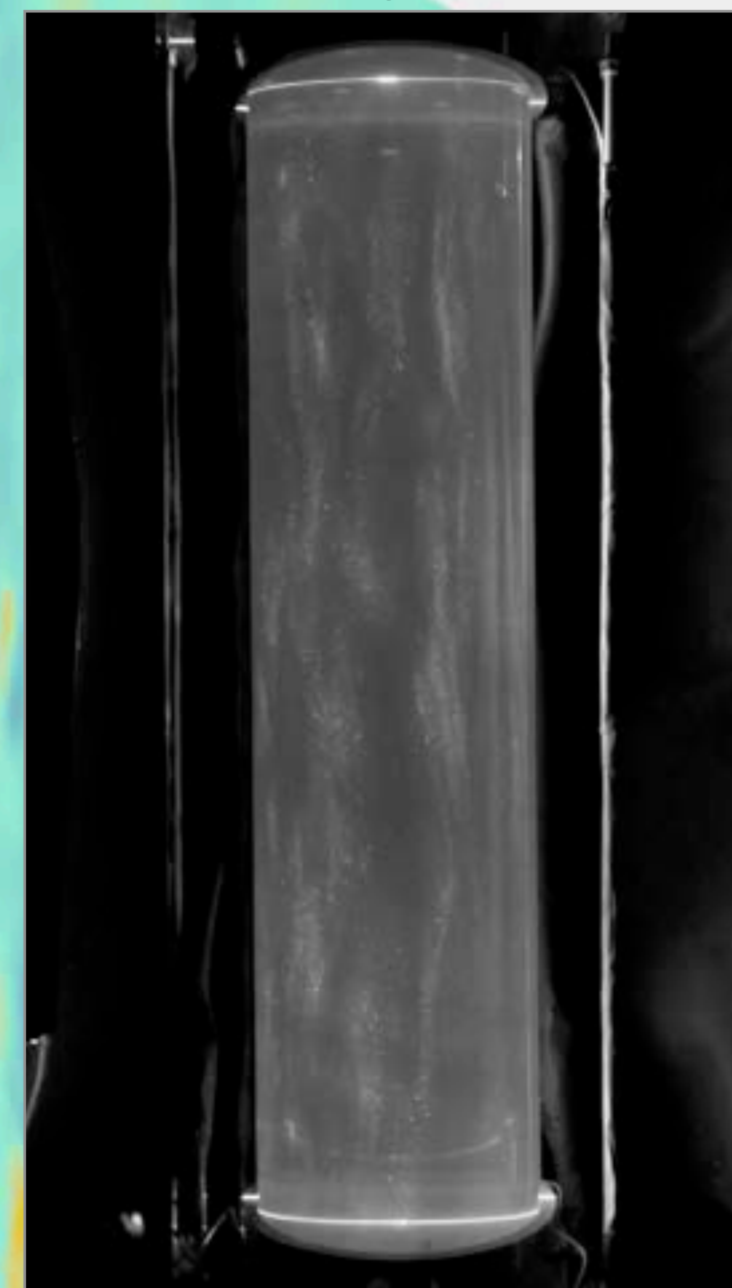
Asymp-
totics
(M. Calkins, CU)





HPC
Modeling
(A. Sheyko, ETH)

Experiments
(J. Cheng, UCLA)



Talk Outline

- Current framework of dynamo physics
- Problems with our framework
  - Present day columnar dynamos implode when scaled to planets (no induction / no columns)
- Towards liquid metal dynamos
  - Rapidly rotating, turbulent models (**E <~ 1e-7**); robust large-scale structures (large enough?)
  - Synergistic efforts will transform our understanding of planetary dynamo physics