Reconstruction of 3-D Core Flow from Geomagnetic Satellite Data

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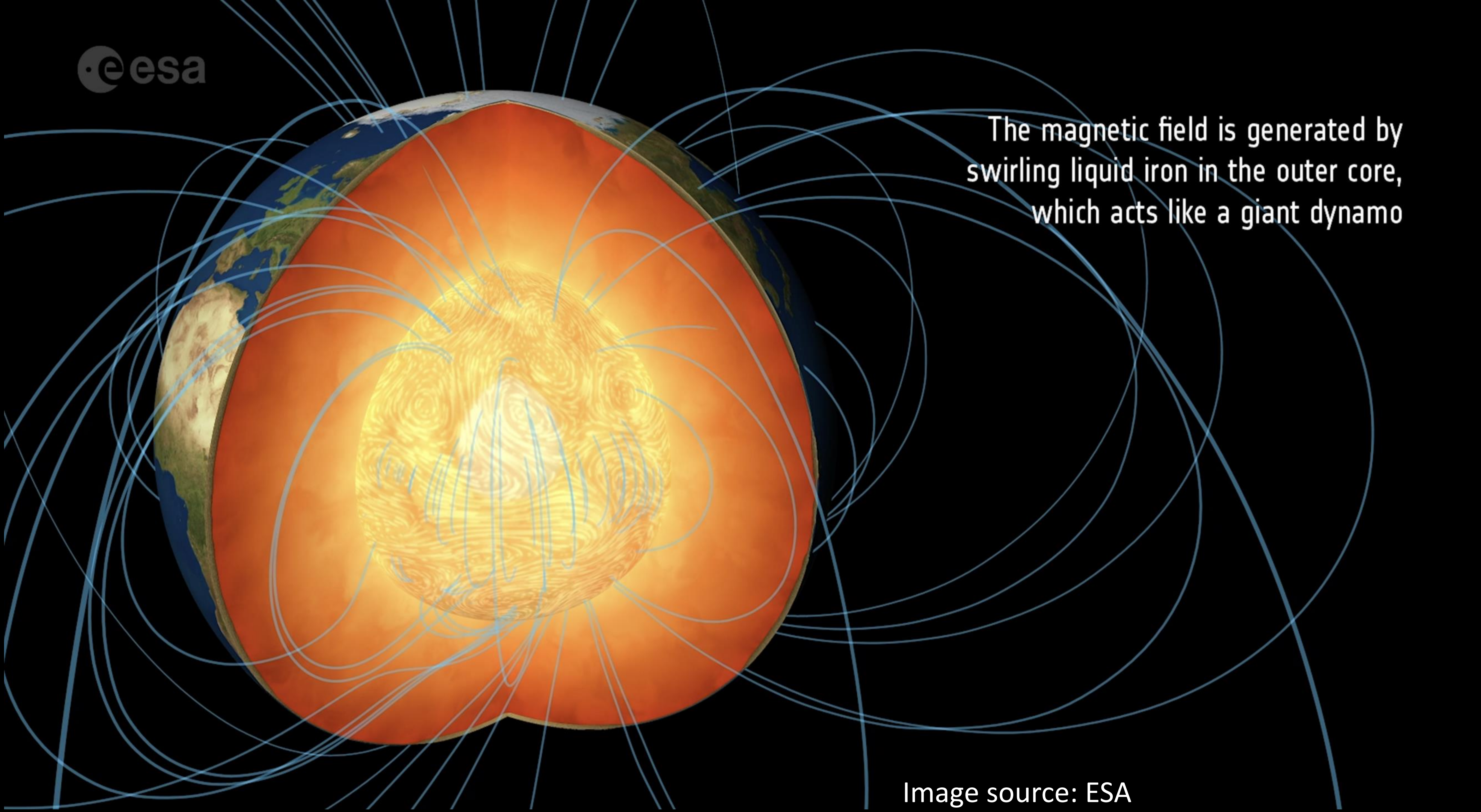
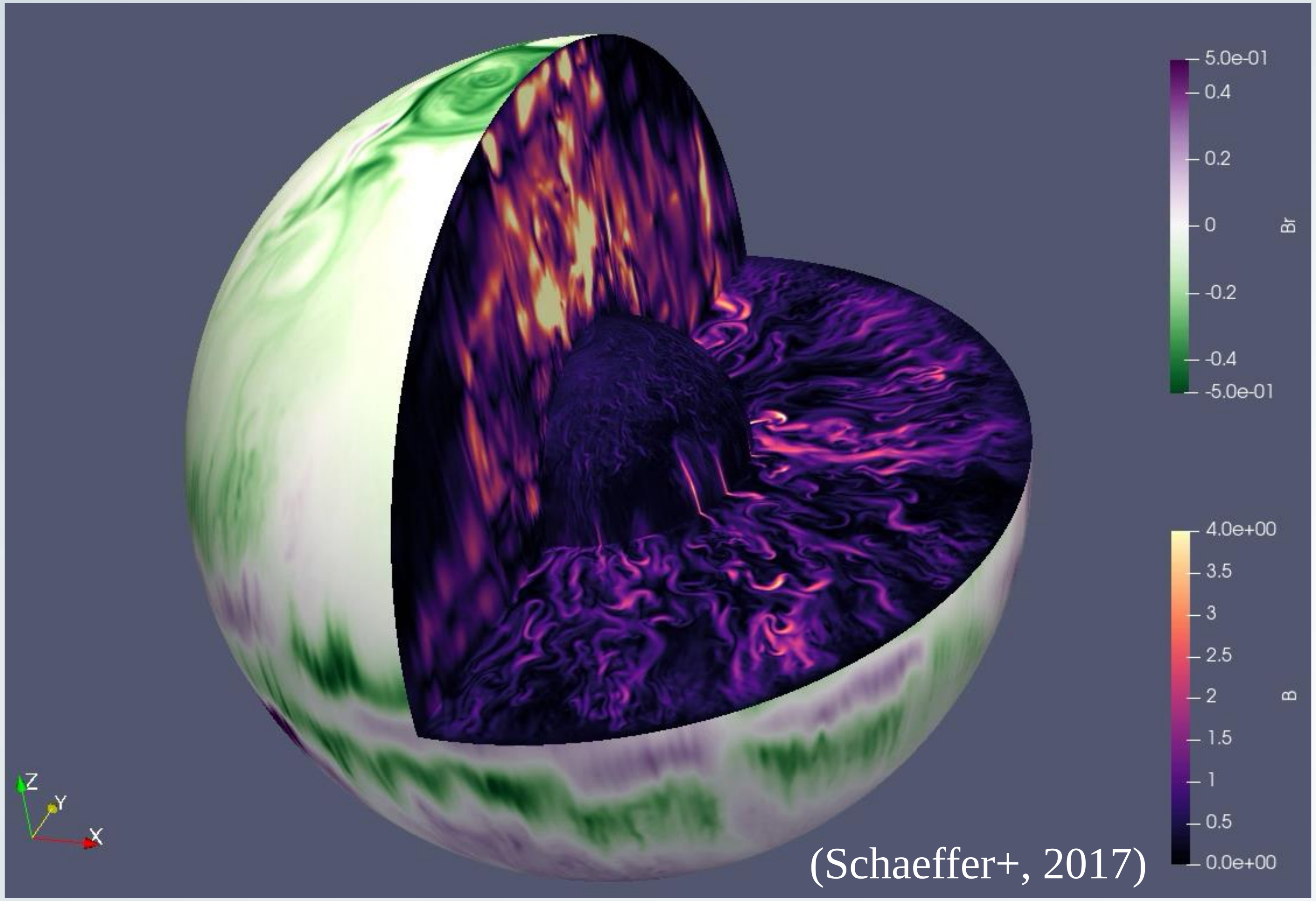
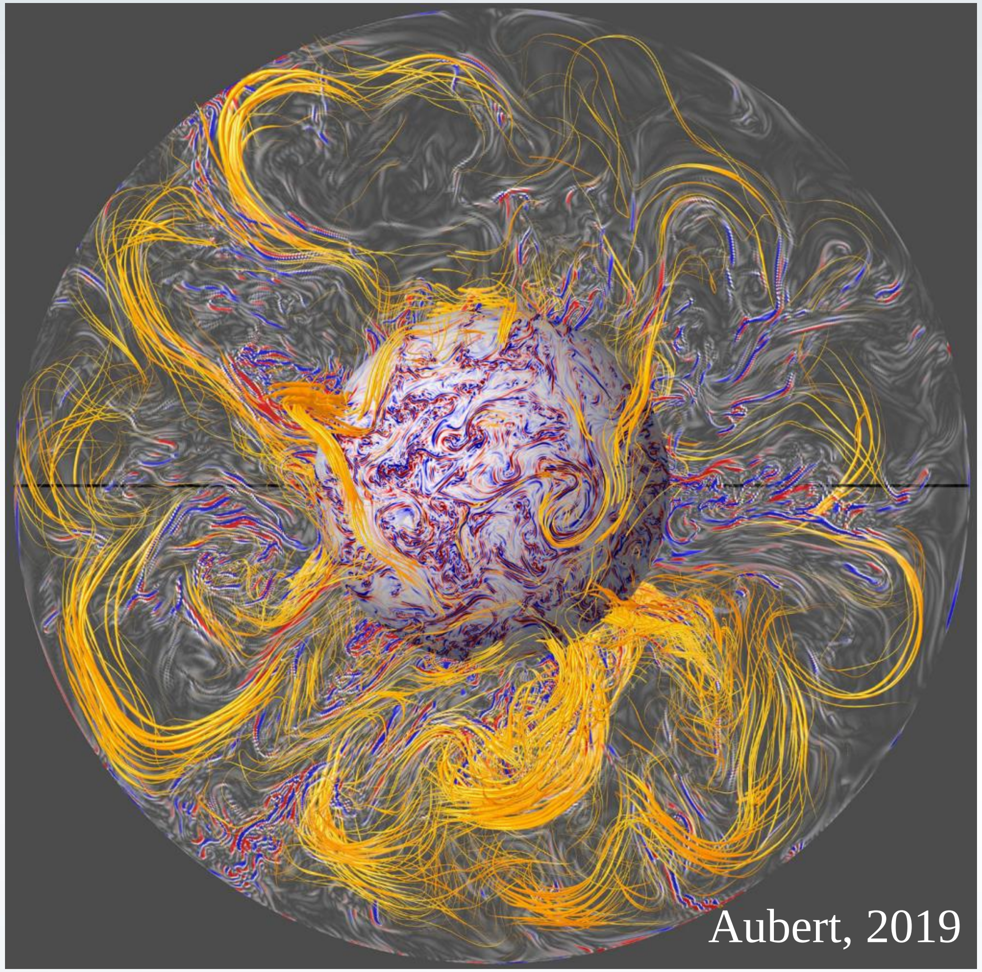


Image source: ESA

Geodynamo simulations



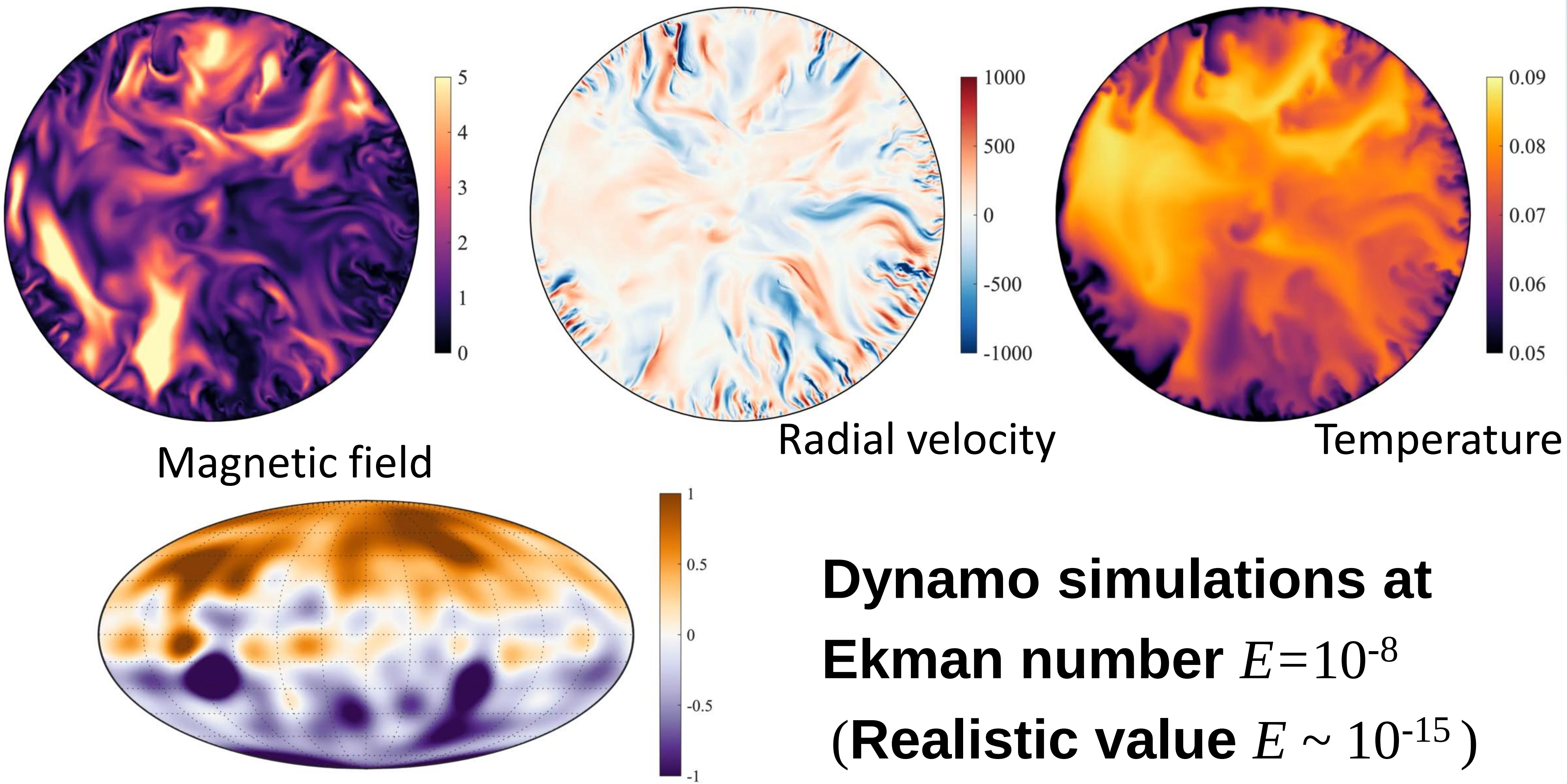
(Schaeffer+, 2017)



Aubert, 2019

Numerical simulations have significantly advanced our understanding of the geodynamo and core dynamics.

Geodynamo simulations



Dynamo simulations at Ekman number $E=10^{-8}$

(**Realistic value** $E \sim 10^{-15}$)

It remains a challenge to reach the realistic parameter regime.

Geomagnetic observations

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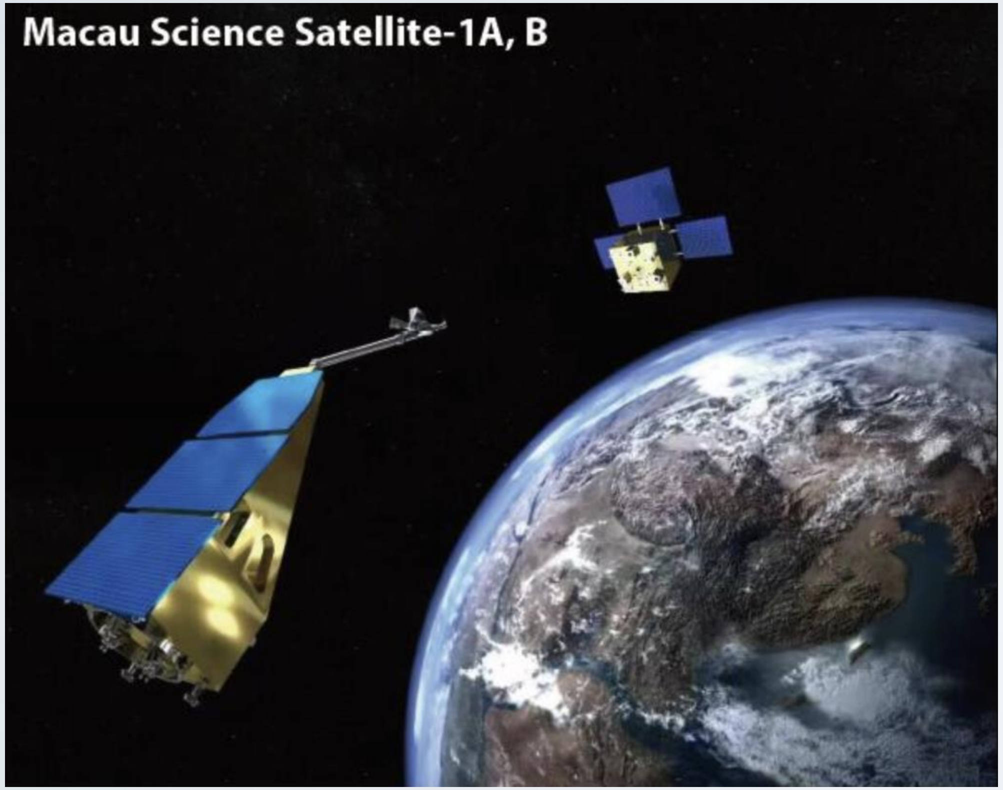
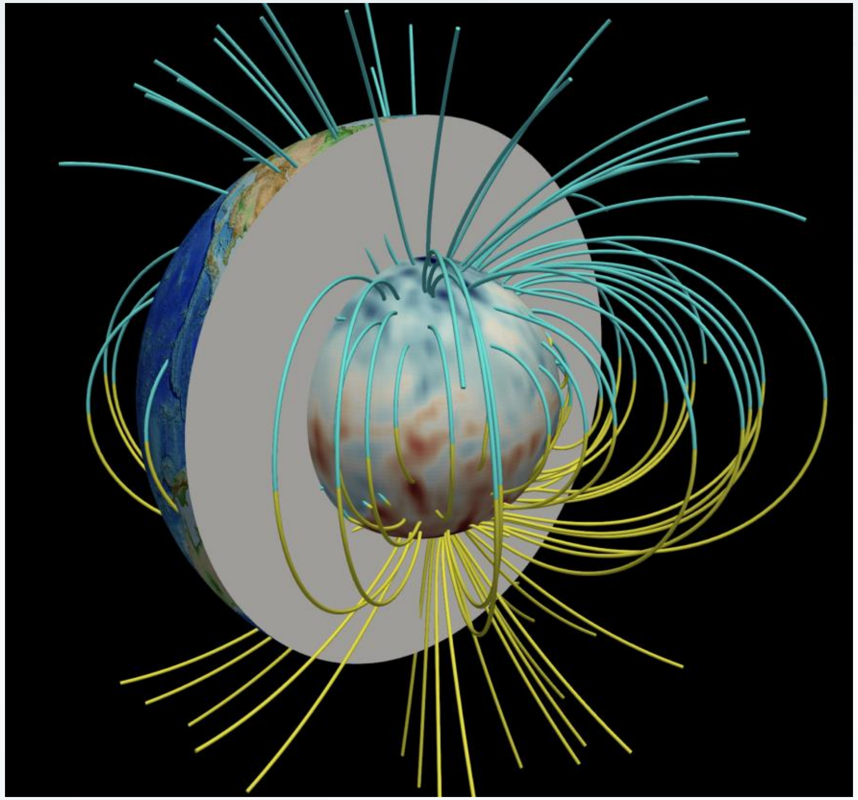
Continuous satellite measurements of the Earth's magnetic field have been available since 1999.





How to constrain the core dynamics using geomagnetic observations?

Core dynamics inversion

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❖ Kinematic inversion

(Robert & Scott, 1965; Jackson, 1997; Holme, 2015; Kloss & Finlay, 2019; Whaler et al., 2022, Li, Lin & Zhang, 2023)

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

Frozen flux approximation →

$$\frac{\partial B_r}{\partial t} = -\nabla_{\mathbf{h}} \cdot (\mathbf{u_h} B_r)$$

Can only infer large-scale 2-D core surface flow.

❖ Geomagnetic data assimilation

(Kuang+, 2009； Fournier+, 2013; Li & Jackon 2014; Sanchez et al., 2019; Li, Lin & Zhang, 2023)

Can recover 3-D core dynamics and make predictions the evolution of core field, but it requires realistic geodynamo models.

3-D Core-flow inversion

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$$\frac{\partial \boldsymbol{u}}{\partial t} + \cancel{\boldsymbol{u} \cdot \nabla \boldsymbol{u}} + 2\boldsymbol{\Omega} \times \boldsymbol{u} = -\frac{1}{\rho}\nabla p + \cancel{\frac{\alpha g_o \boldsymbol{r}}{r_o}\Theta} + \cancel{v\nabla^2 \boldsymbol{u}} + \frac{1}{\rho\mu}(\cancel{\nabla \times \boldsymbol{B}}) \times \boldsymbol{B}$$

Rotation-dominated flow

$$\frac{\partial \boldsymbol{u}}{\partial t} + 2\boldsymbol{\Omega} \times \boldsymbol{u} + \frac{1}{\rho}\nabla p = 0, \quad \nabla \cdot \boldsymbol{u} = 0$$

Inertial modes

Analytical solutions
(Zhang & Liao, 2017)

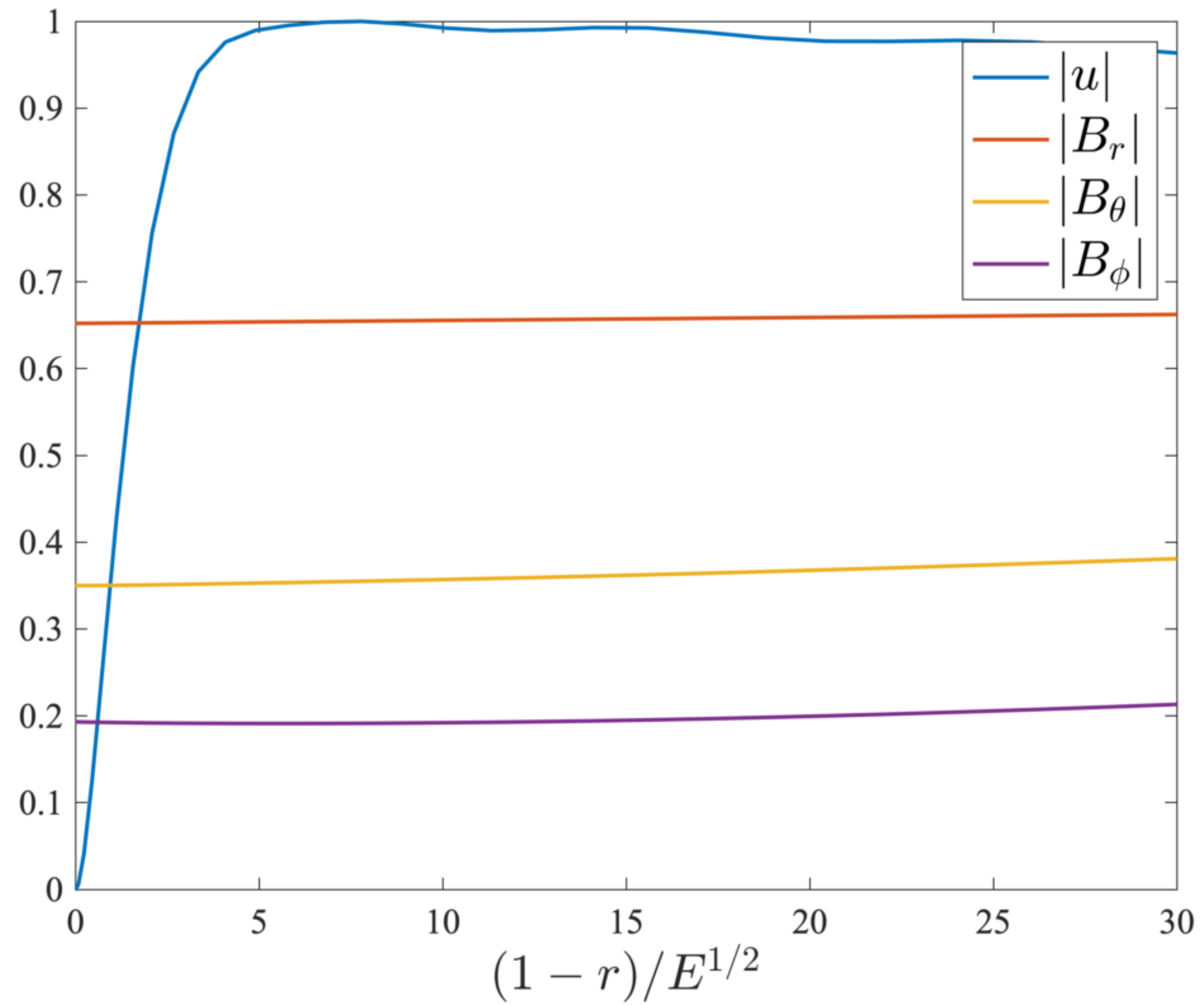
$$\boldsymbol{u}(r, \theta, \phi, t) = \sum_{mnk} C_{mnk}(t)\boldsymbol{u}_{mnk}(r, \theta, \phi)$$

Observations

$$\partial \boldsymbol{B}/\partial t = \boldsymbol{\nabla} \times (\boldsymbol{u} \times \boldsymbol{B})$$

(Kloss & Finlay, 2019)

Boundary layer



Dynamo simulations at Ekman number $E=10^{-8}$

All 3 copopnents of magnetic field show neglibible changes across the velocity boundary layer.

Therefore, we made use of three-components magnetic induction equation.

$$\partial \boldsymbol{B}/\partial t = \nabla \times (\boldsymbol{u} \times \boldsymbol{B})$$

Selection of inertial modes

$$\partial \boldsymbol{B}/\partial t = \nabla \times (\boldsymbol{u} \times \boldsymbol{B})$$

$$\boldsymbol{u}(\mathbf{r},t) = \sum_{k=1}^{K} c_k^{\mathrm{G}}(t) G_{2k-1}(\mathbf{r})\hat{\Phi} + \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n} c_{mnk}^{\mathrm{S}}(t)\Re[\mathrm{u}_{mnk}^{\mathrm{S}}(\mathbf{r})] + \sum_{k=0}^{K}\sum_{m=1}^{M}\sum_{n} c_{mnk}^{\mathrm{A}}(t)\Re[\mathrm{u}_{mnk}^{\mathrm{A}}(\mathbf{r})]$$

Axisymmetric geostrophic mode

Equatorially symmetric modes

Equatorially antisymmetric modes

- **Inertial modes are truncated at** $K = M = 10$.
- **Only the slowest** $\boldsymbol{E}^S$ **and** $\boldsymbol{E}^A$ **modes are included, i.e.** $n = 1$.
- **We use 220 inertial modes in total.** [Kloss & Finlay (2019) used 4720 inertial modes with $K = 10, M = 20, N = 60$.]

Physics-Informed Neural Networks

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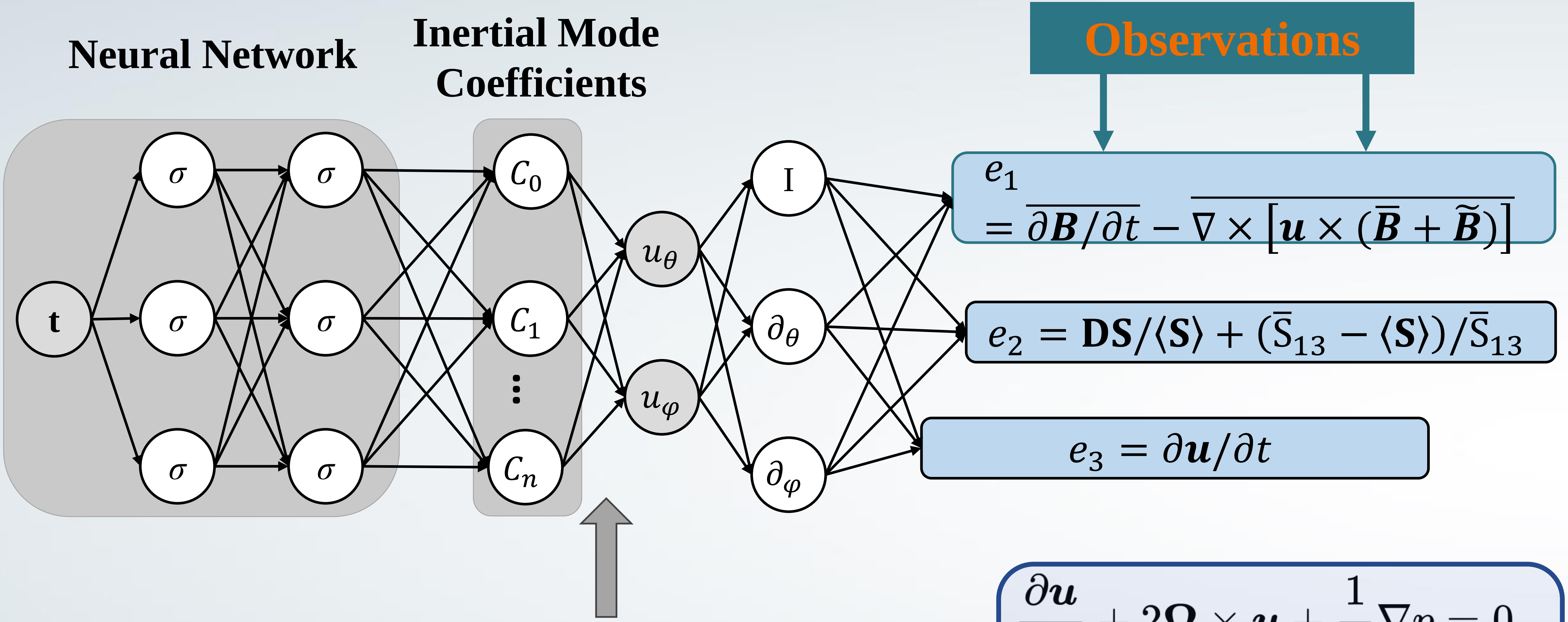


$$\boldsymbol{u}(r, \theta, \phi, t) = \sum_{mnk} C_{mnk}(t) \boldsymbol{u}_{mnk}(r, \theta, \phi)$$

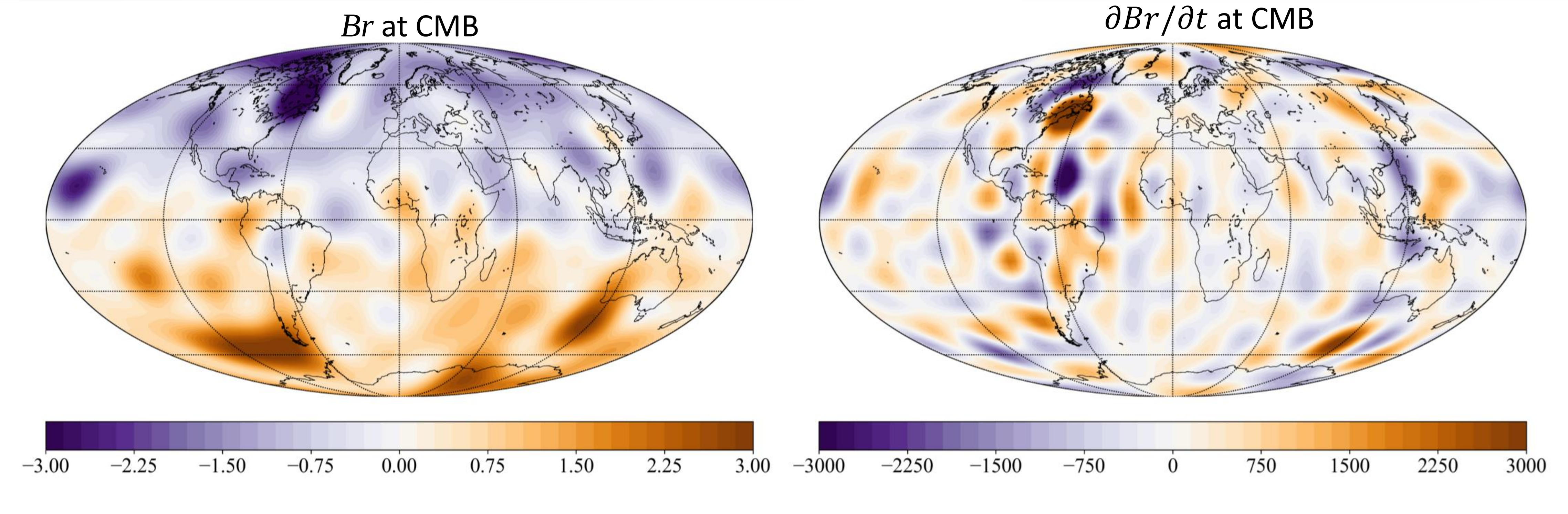
$$\frac{\partial \boldsymbol{u}}{\partial t} + 2\boldsymbol{\Omega} \times \boldsymbol{u} + \frac{1}{\rho} \nabla p = 0,$$

$$\nabla \cdot \boldsymbol{u} = 0$$

Synthetic data test

Dynamo simulation

Control Parameters				Time-averaged Output parameters		
E	Pr	Pm	Ra	Λ	Rm	χ^2
10^{-5}	1.0	3.0	2.2×10^8	36	803	1.2



Synthetic test

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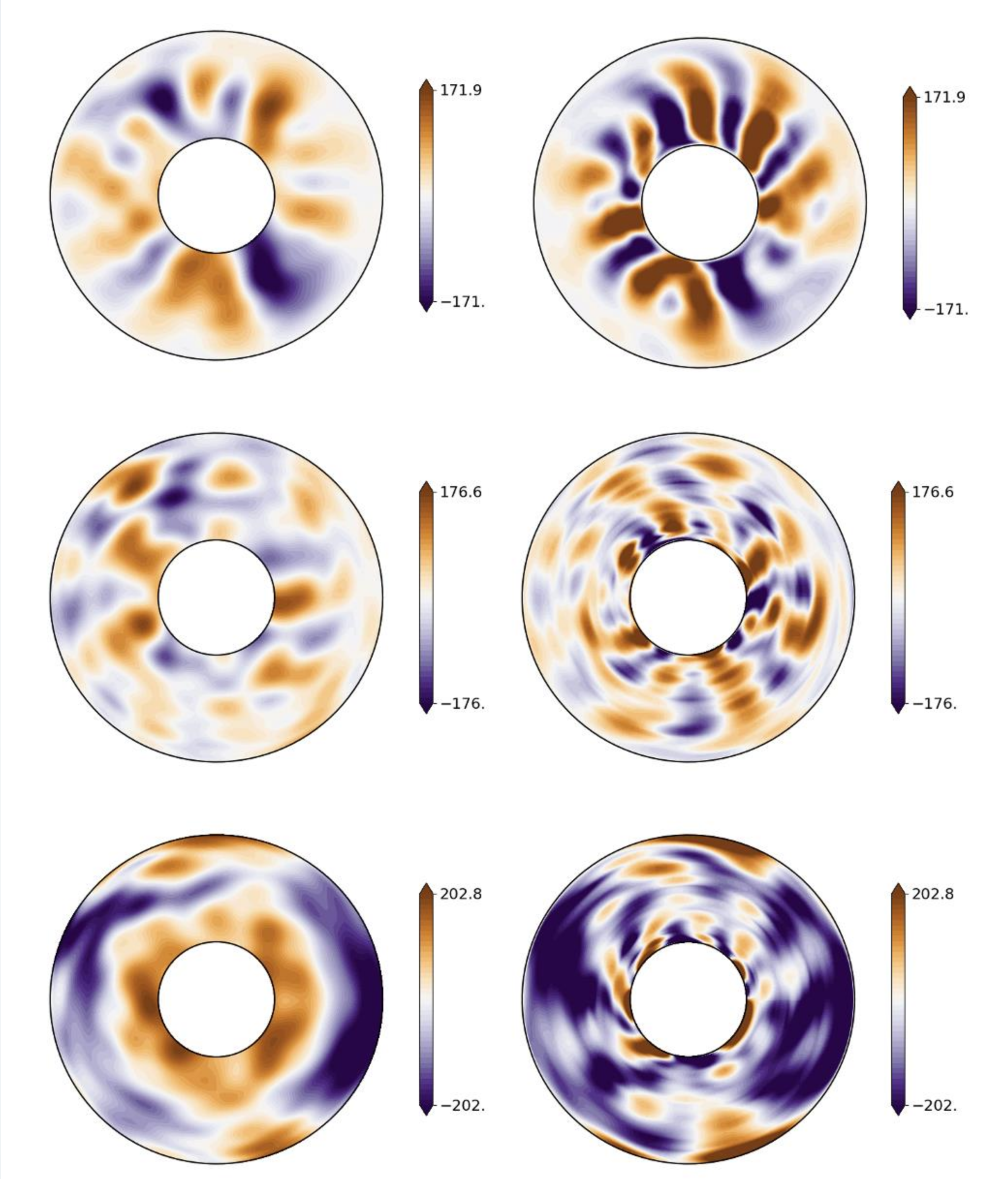
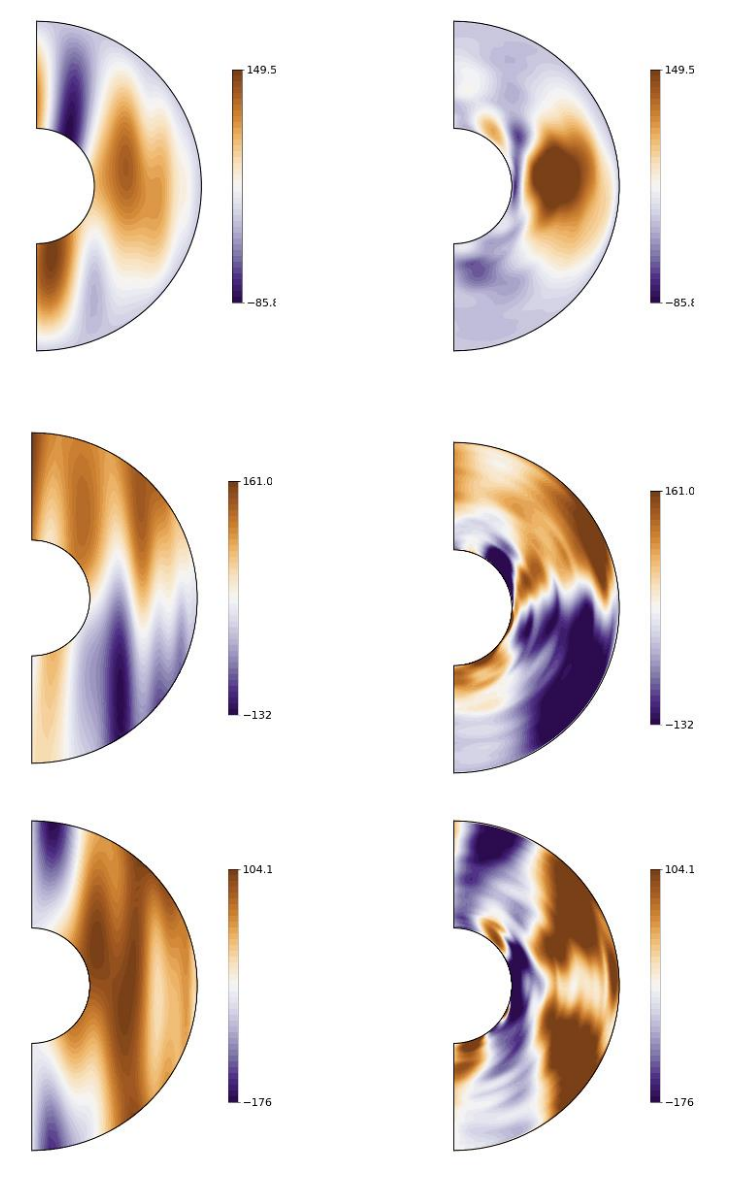
u_r

u_θ

u_ϕ



Inverted Reference



u_r

u_θ

u_ϕ

Inverted Reference

Synthetic test

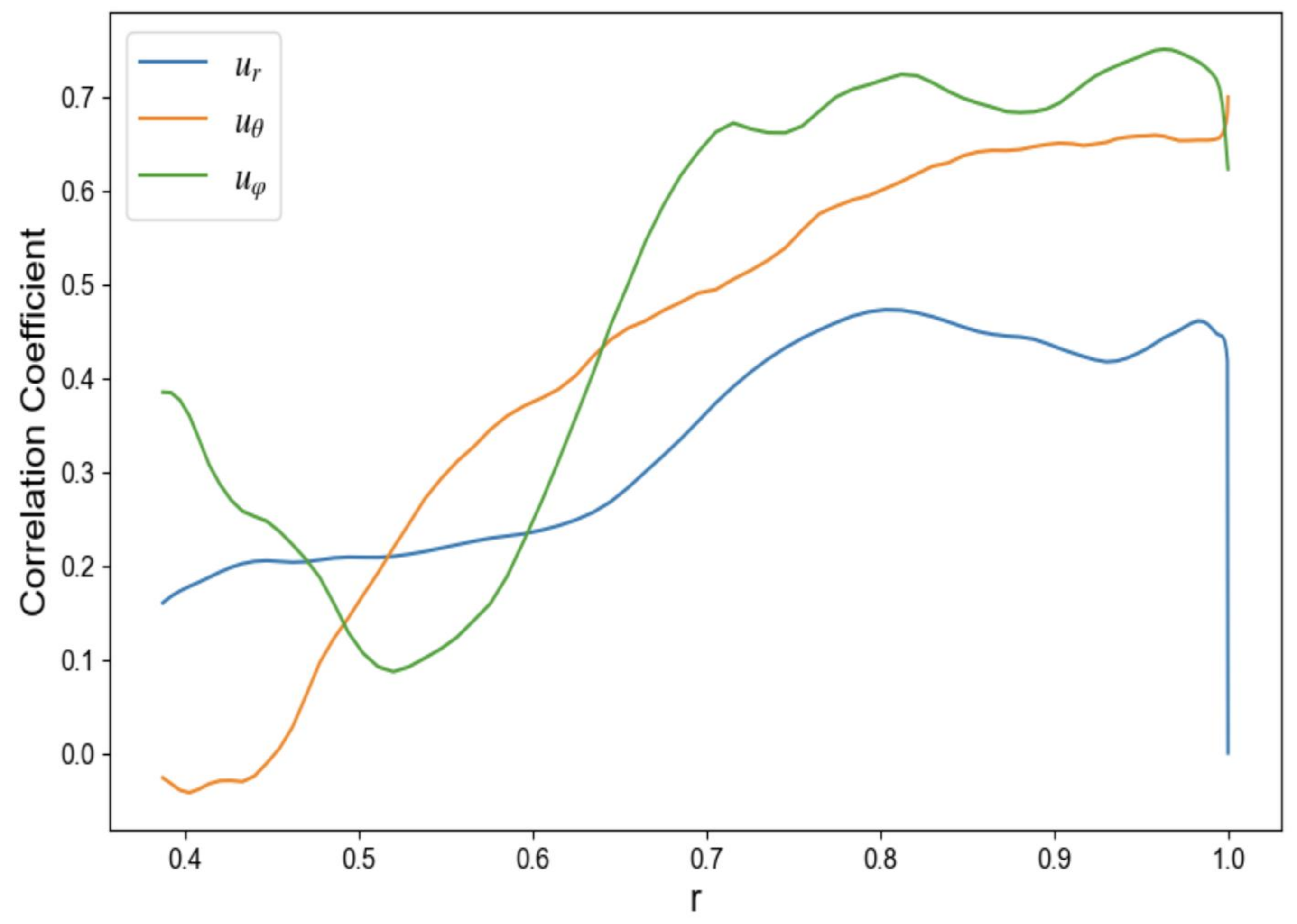
Correlation coefficients

$$C_r(r) = \frac{\sum_{N_s} u_r(r,\theta,\varphi)u_r^{\mathrm{ref}}(r,\theta,\varphi)}{\sqrt{(\sum_{N_s} u_r(r,\theta,\varphi)u_r(r,\theta,\varphi))(\sum_{N_s} u_r^{\mathrm{ref}}(r,\theta,\varphi)u_r^{\mathrm{ref}}(r,\theta,\varphi))}},$$

$$C_\theta(r) = \frac{\sum_{N_s} u_\theta(r,\theta,\varphi)u_\theta^{\mathrm{ref}}(r,\theta,\varphi)}{\sqrt{(\sum_{N_s} u_\theta(r,\theta,\varphi)u_\theta(r,\theta,\varphi))(\sum_{N_s} u_\theta^{\mathrm{ref}}(r,\theta,\varphi)u_\theta^{\mathrm{ref}}(r,\theta,\varphi))}},$$

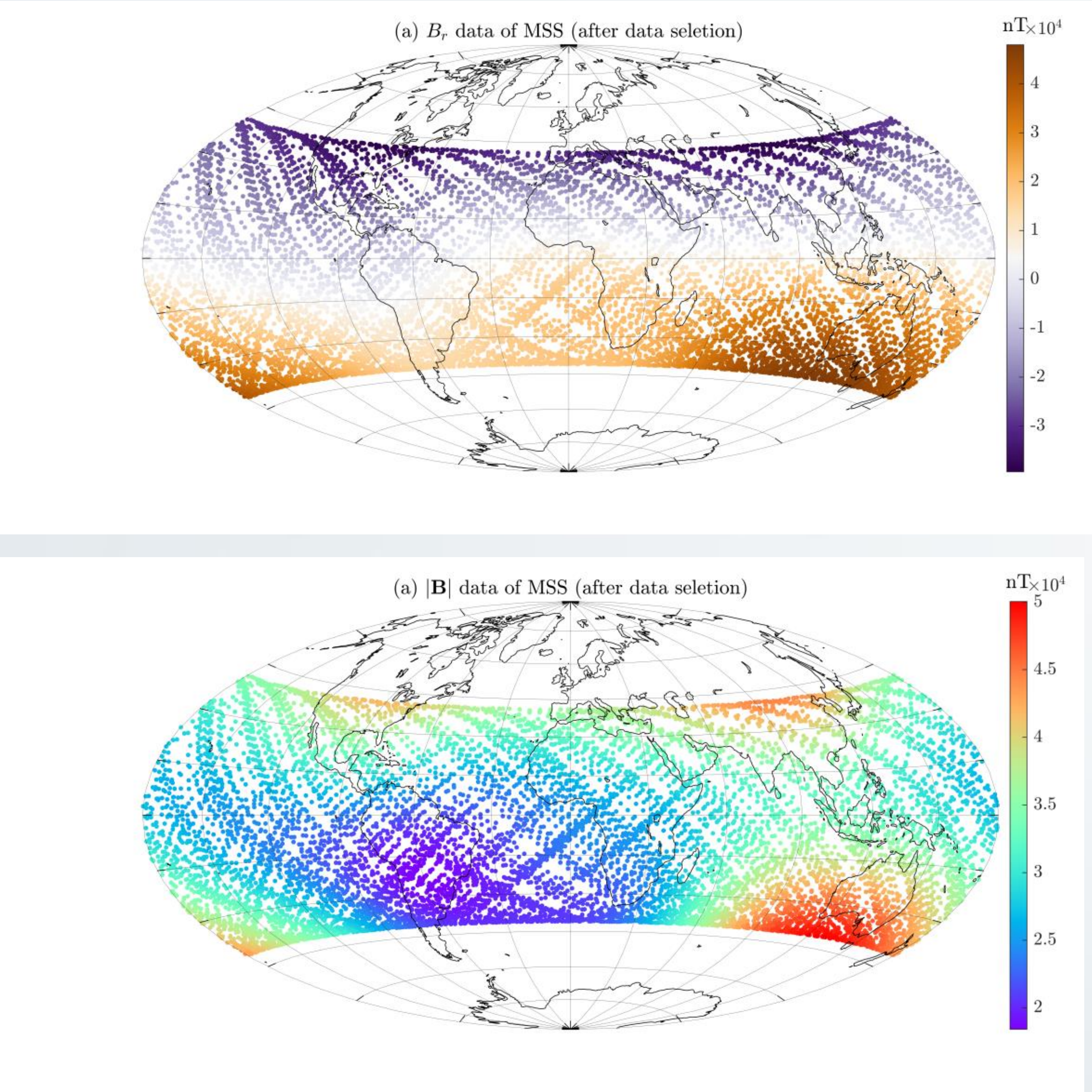
$$C_\varphi(r) = \frac{\sum_{N_s} u_\varphi(r,\theta,\varphi)u_\varphi^{\mathrm{ref}}(r,\theta,\varphi)}{\sqrt{(\sum_{N_s} u_\varphi(r,\theta,\varphi)u_\varphi(r,\theta,\varphi))(\sum_{N_s} u_\varphi^{\mathrm{ref}}(r,\theta,\varphi)u_\varphi^{\mathrm{ref}}(r,\theta,\varphi))}}$$

ICB CMB

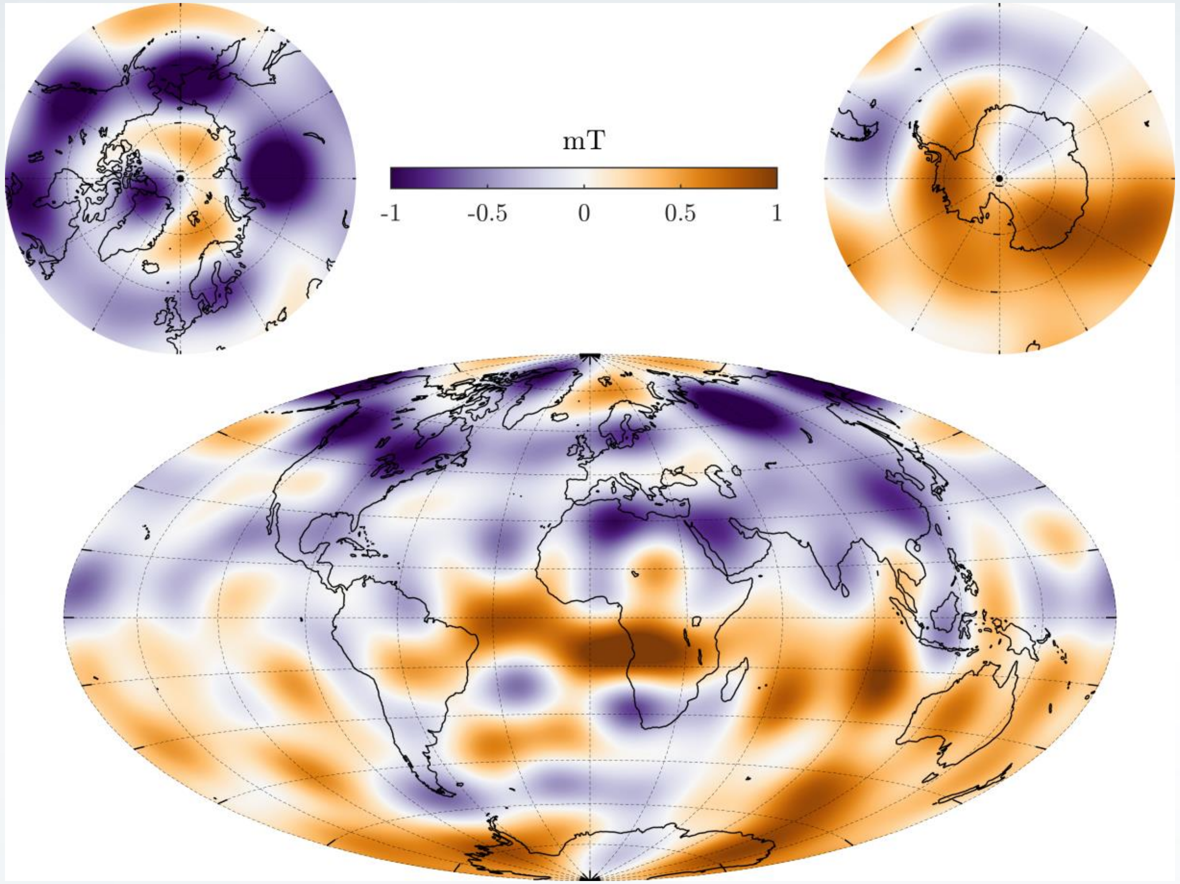


Observations

MSS-1 vector magnetic field data (2023/08/18-09/30)



Core field Br at CMB (MSS1+Swarm A)



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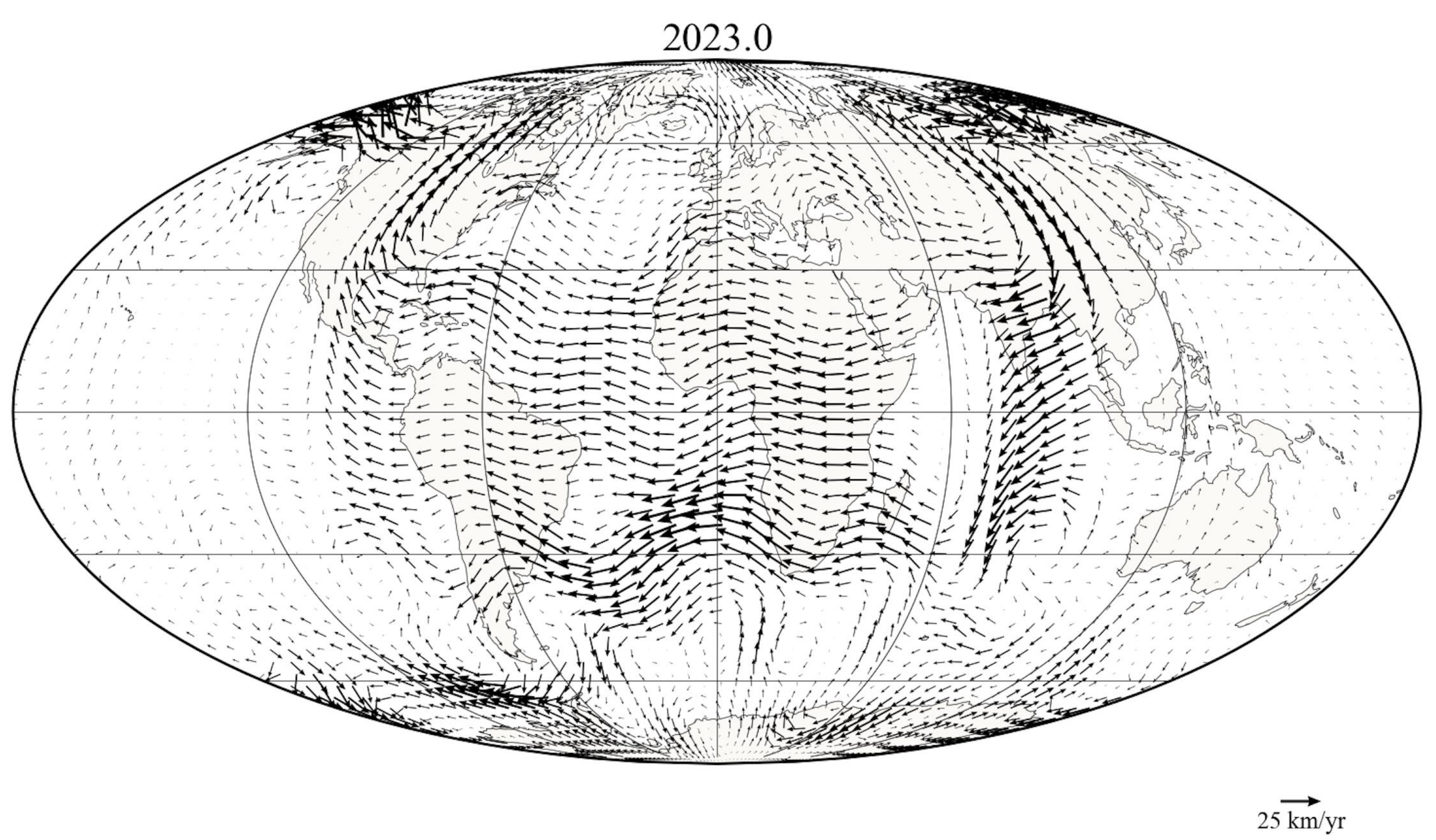
CHAOS-7 MF and SV

Core-surface flow



3-D flow visualizations

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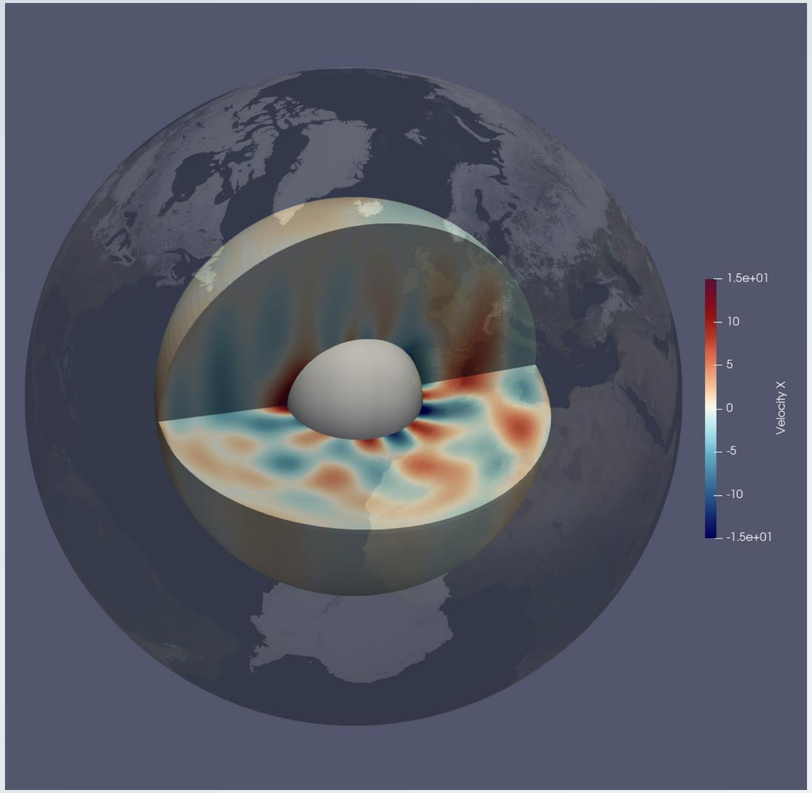
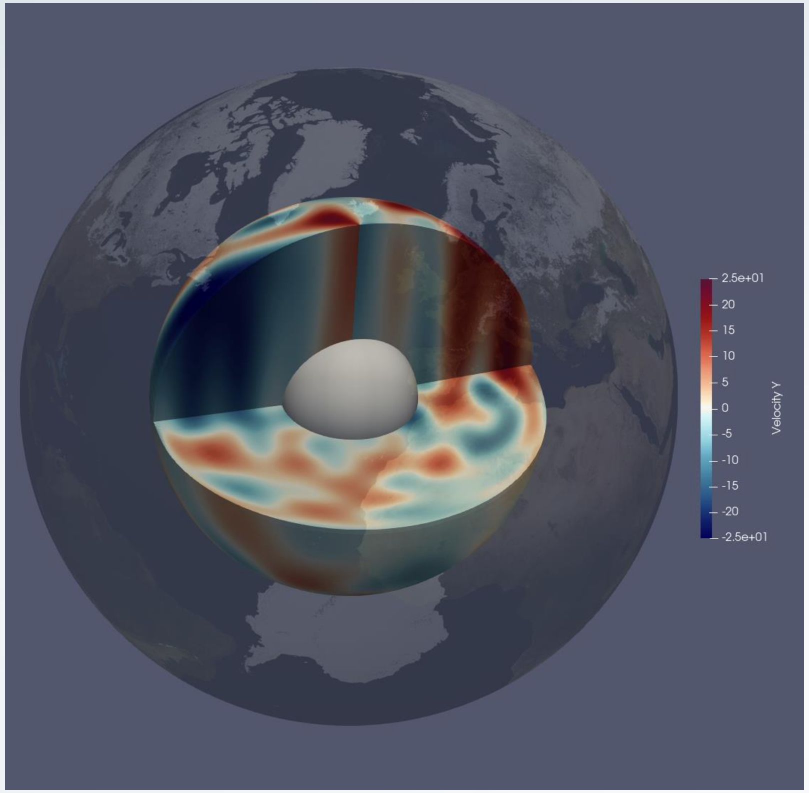
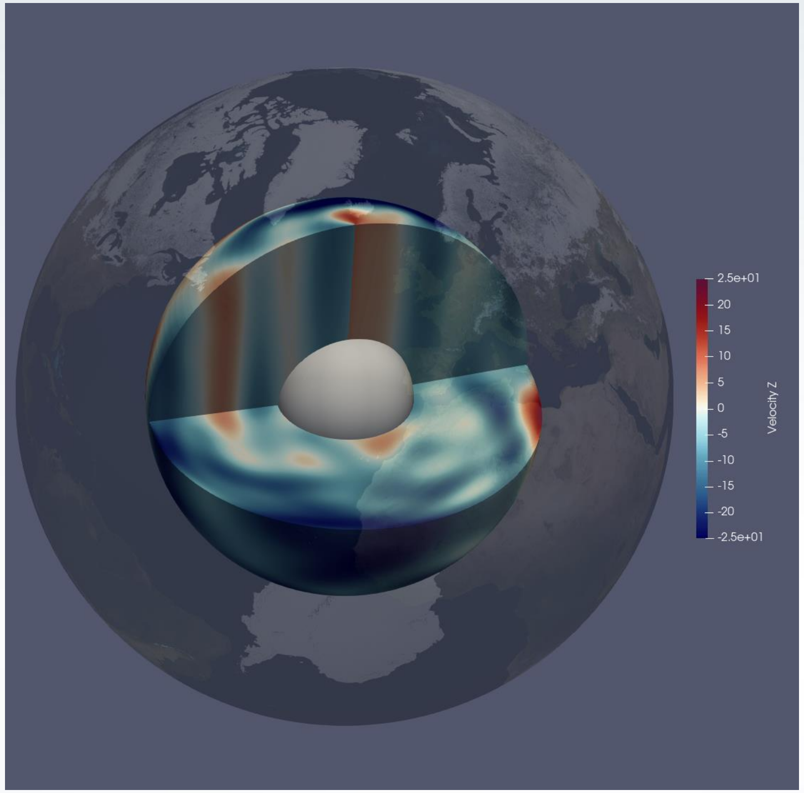


u_r



u_θ



u_φ

3-D streamlines

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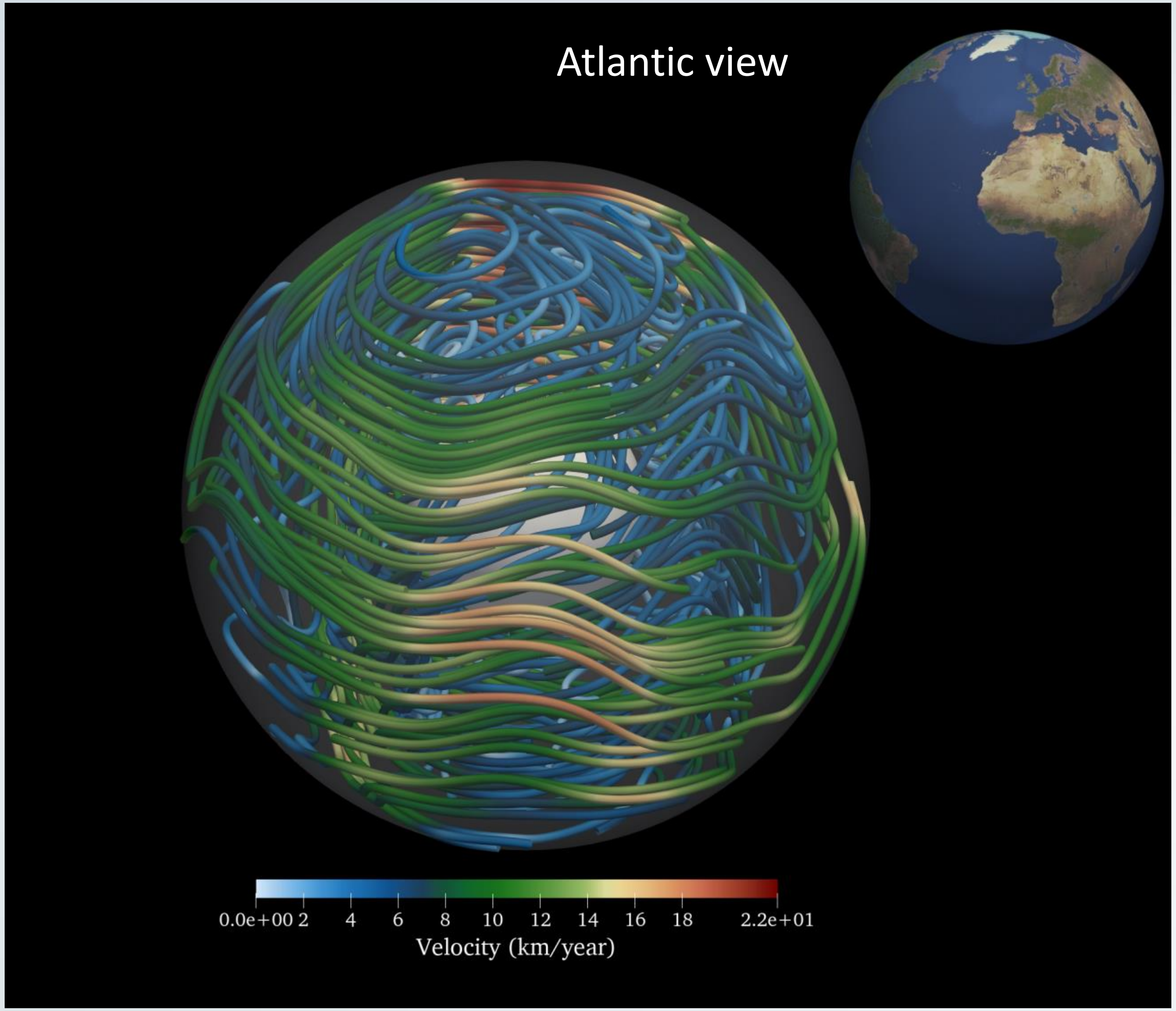
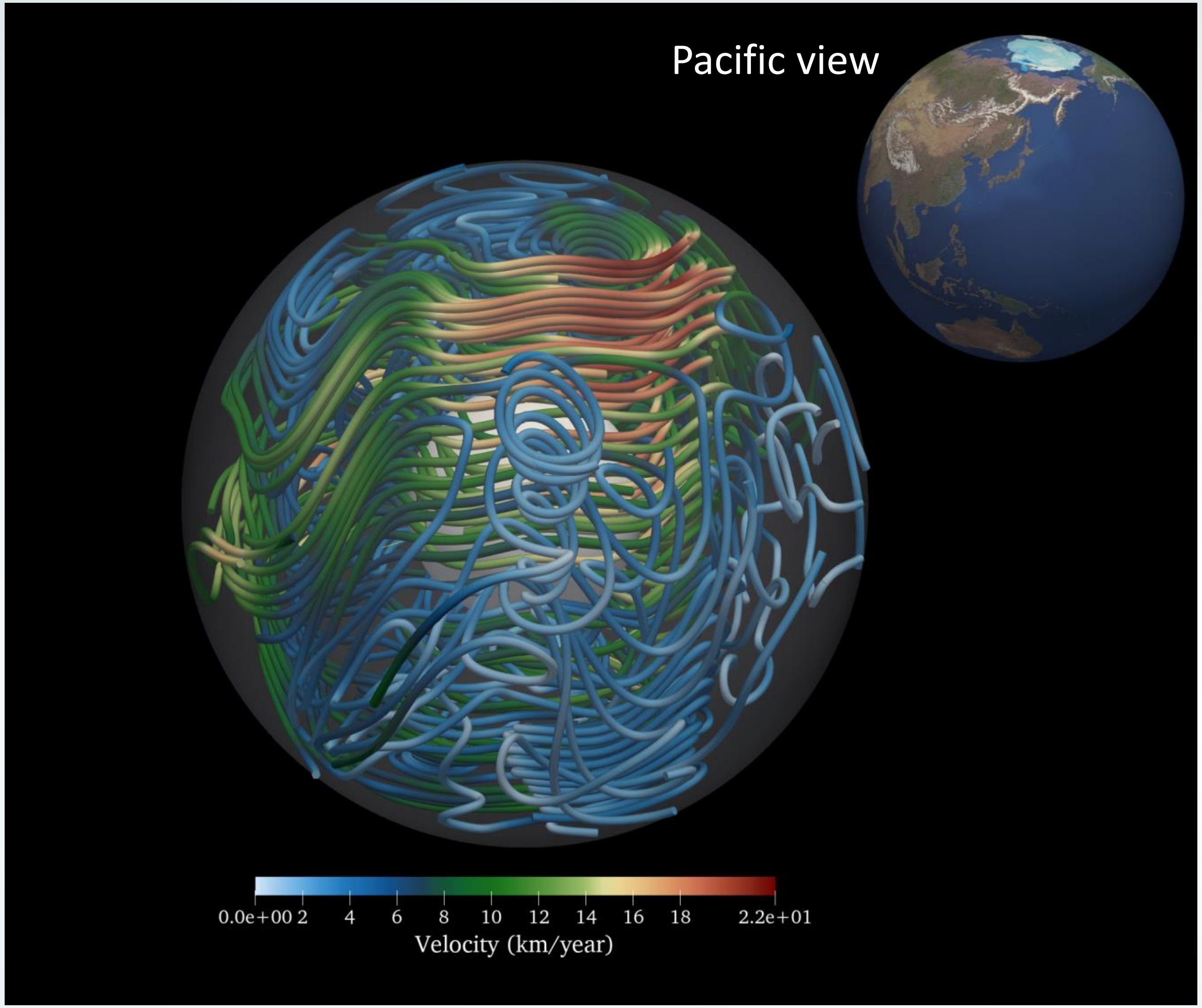
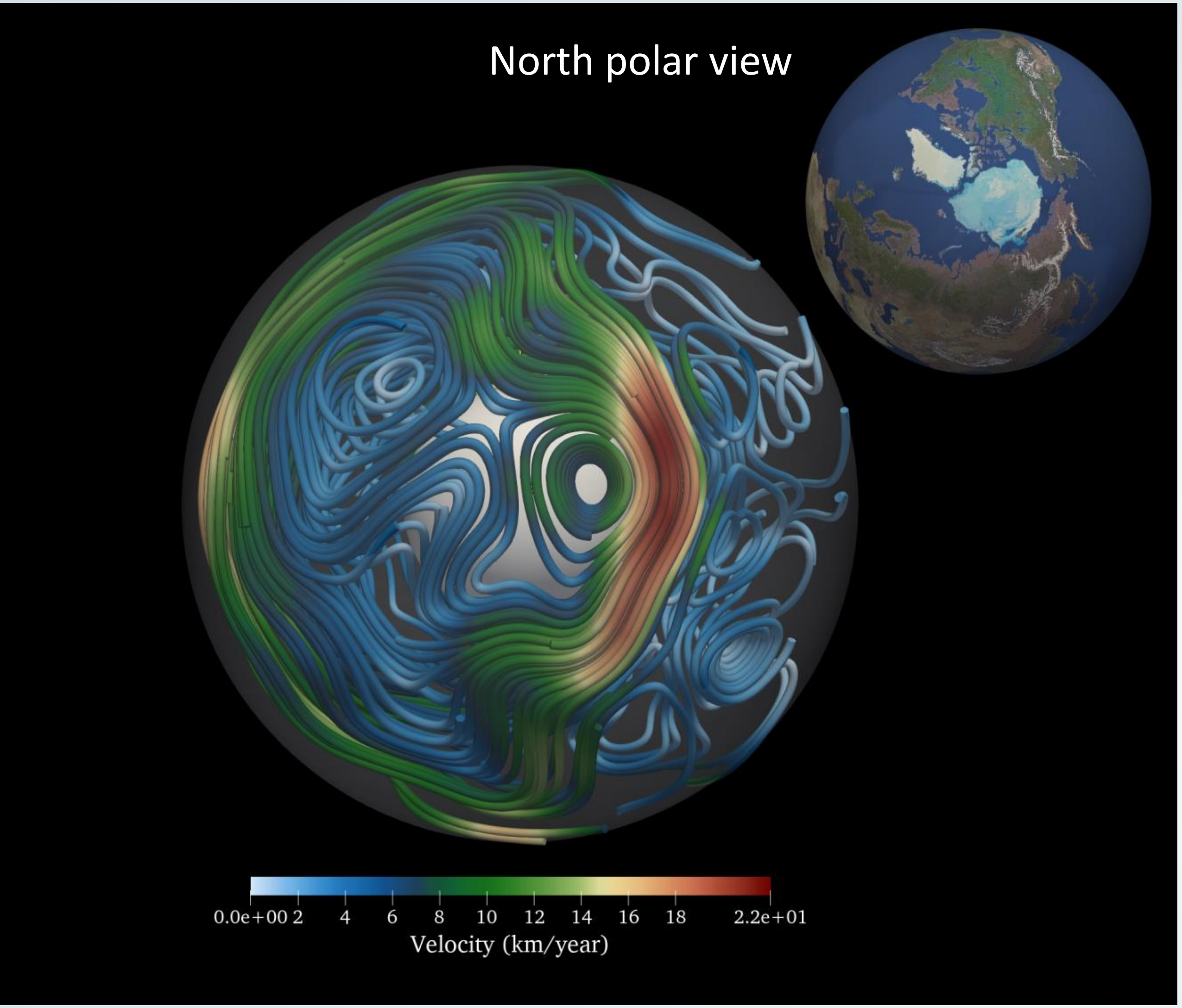
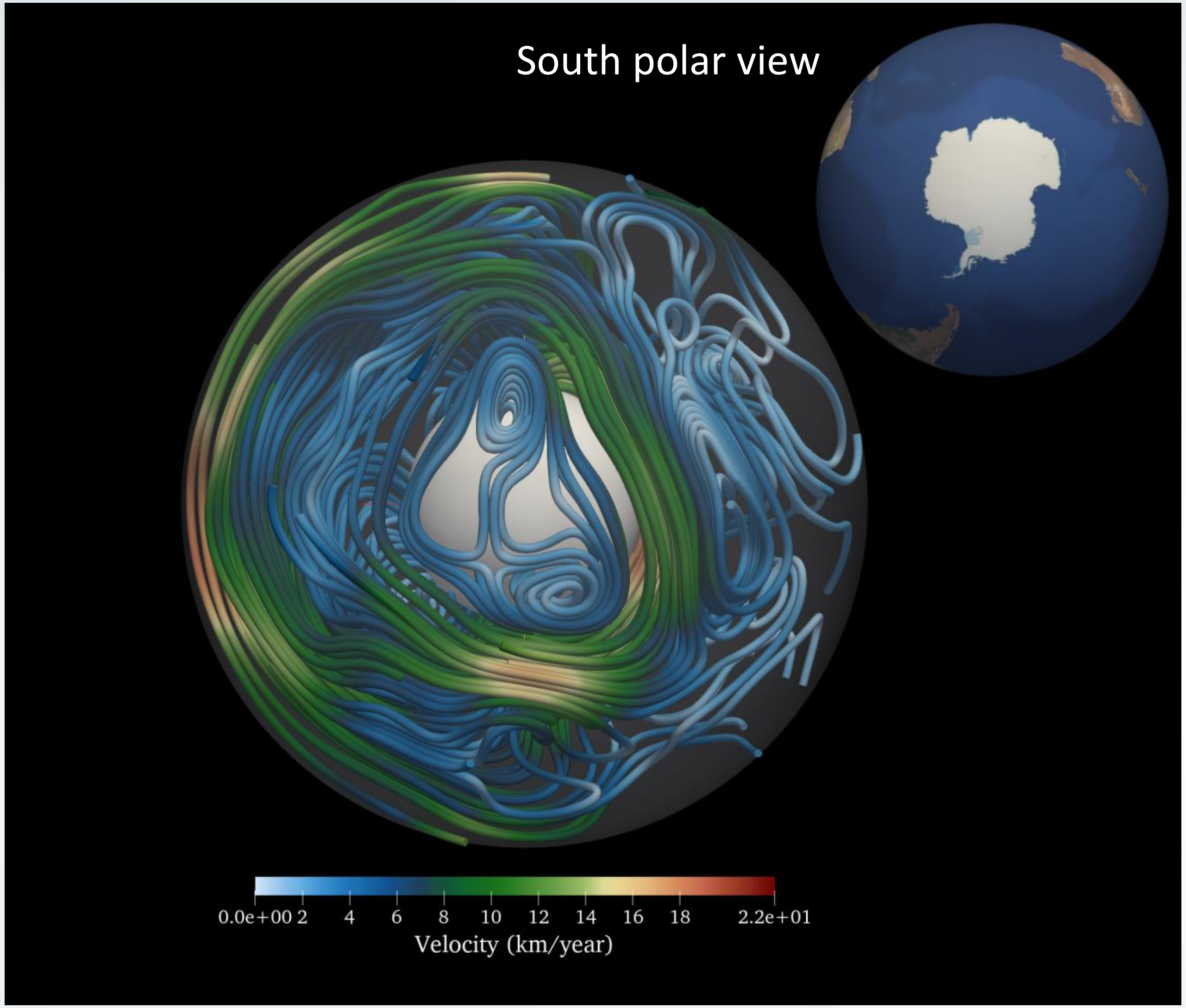




East-West Asymmetry of the Core Flow

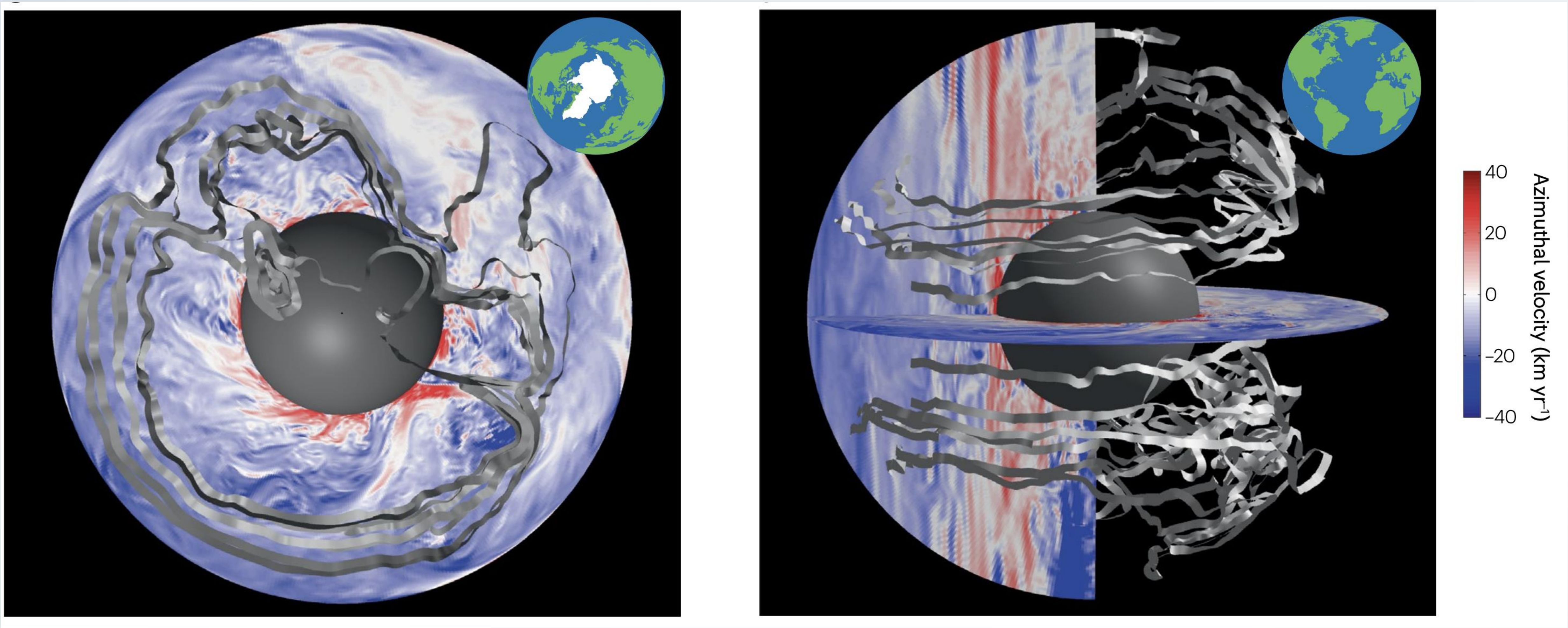
3-D streamlines





East-West Asymmetry of the Core Flow

Geodynamo simulation



Finlay et al., 2023 (geodynamo simulation of Aubert & Gillet)

Summary

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- We have developed a 3-D core flow inversion method based on the expansion of inertial modes and PINNs.
- The test experiments using the synthetic data show that it is possible to reconstruct large scale 3-D core flow.
- Preliminary 3-D core flow model derived from MSS-1 and Swarm data reveals the east-west hemispheric asymmetry in the core dynamics.
- The dynamical origin of the asymmetric core flow remains to be explored.


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