Core Dynamics and Energetics

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SOUTHERN UNIVERSITY OF SCIENCE AND TECHNOLOGY

地球与空间科学系
DEPARTMENT OF EARTH AND SPACE SCIENCES

Earth’s core

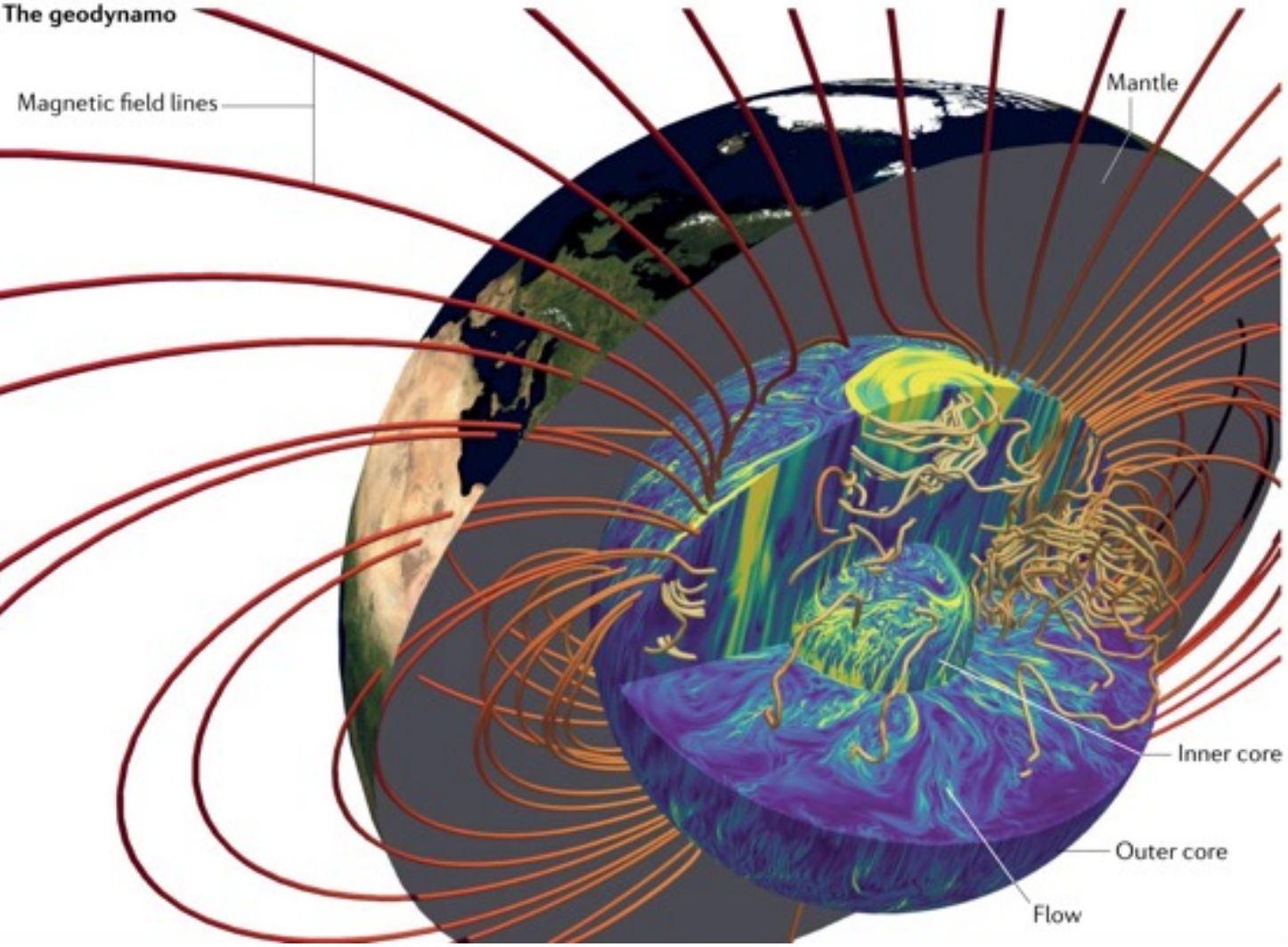


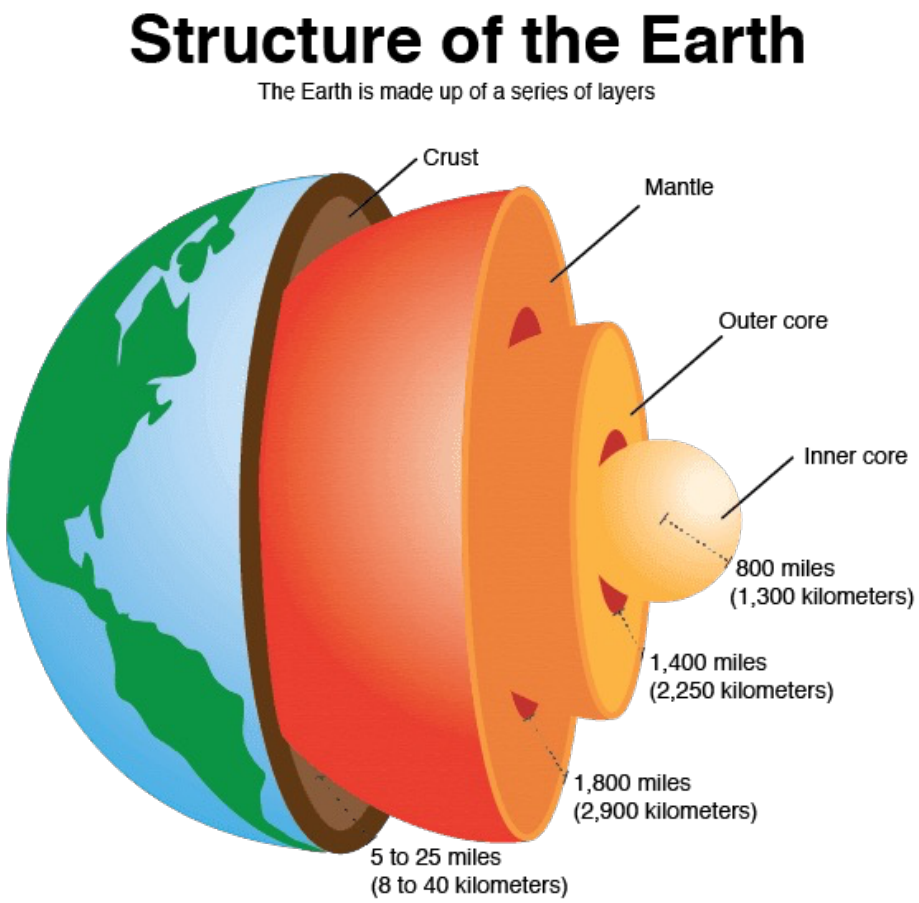
Image credit: N. Schaeffer

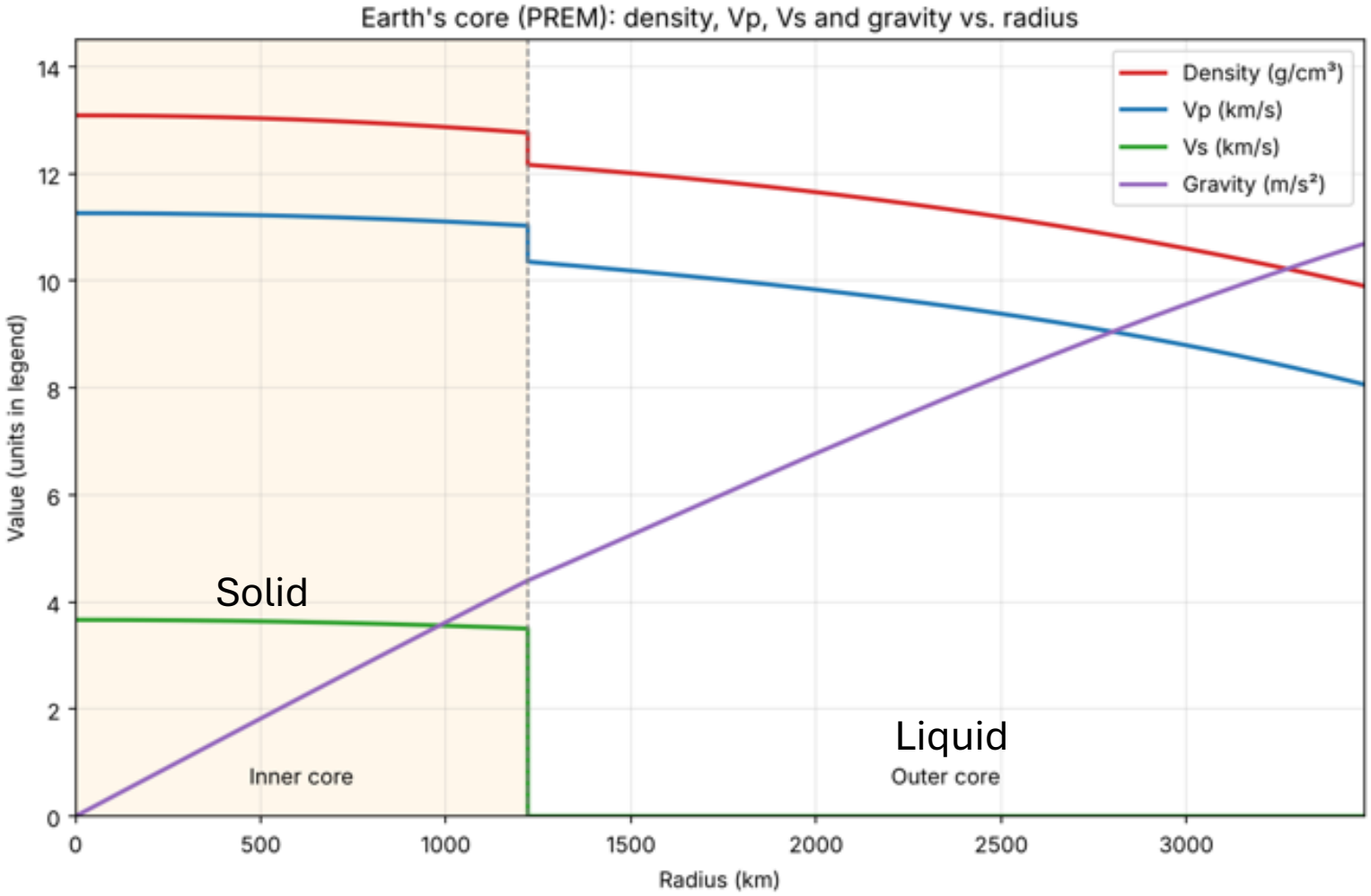
- The heart of the planet
- Dynamical and energetic
- Origin of Earth’s magnetic field
- Heat sources

Outline

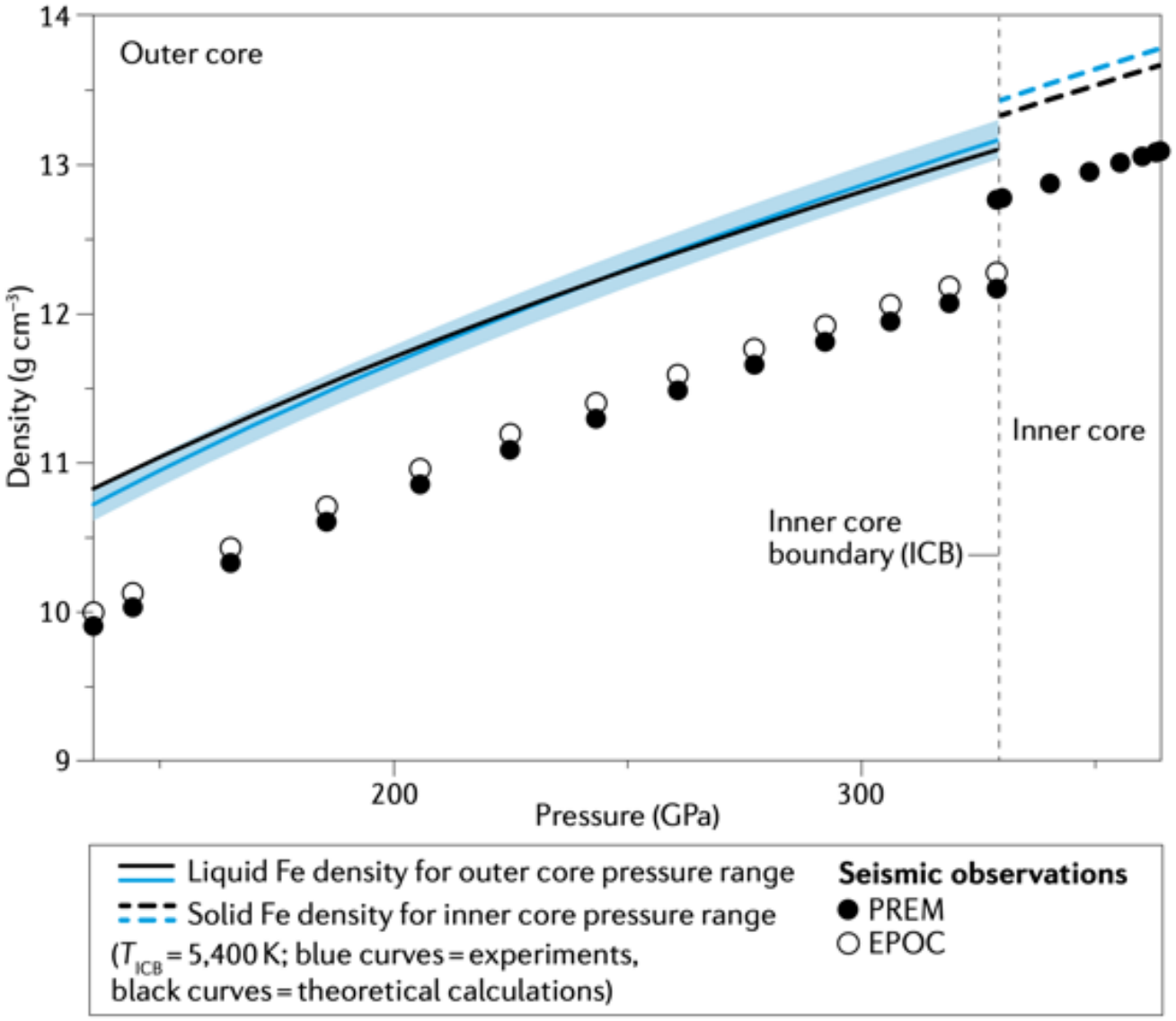
- Structure and composition of the core
- Core dynamics: Earth’s magnetic field generation
- Energy budget and thermal evolution of the core

Structure


Structure of the Earth
The Earth is made up of a series of layers
Crust
Mantle
Outer core
Inner core
800 miles
(1,300 kilometers)
1,400 miles
(2,250 kilometers)
1,800 miles
(2,900 kilometers)
5 to 25 miles
(8 to 40 kilometers)


Earth's core (PREM): density, Vp, Vs and gravity vs. radius
Density (g/cm³)
Vp (km/s)
Vs (km/s)
Gravity (m/s²)
Value (units in legend)
Radius (km)
Solid
Liquid
Inner core
Outer core
0
2
4
6
8
10
12
14
0
500
1000
1500
2000
2500
3000

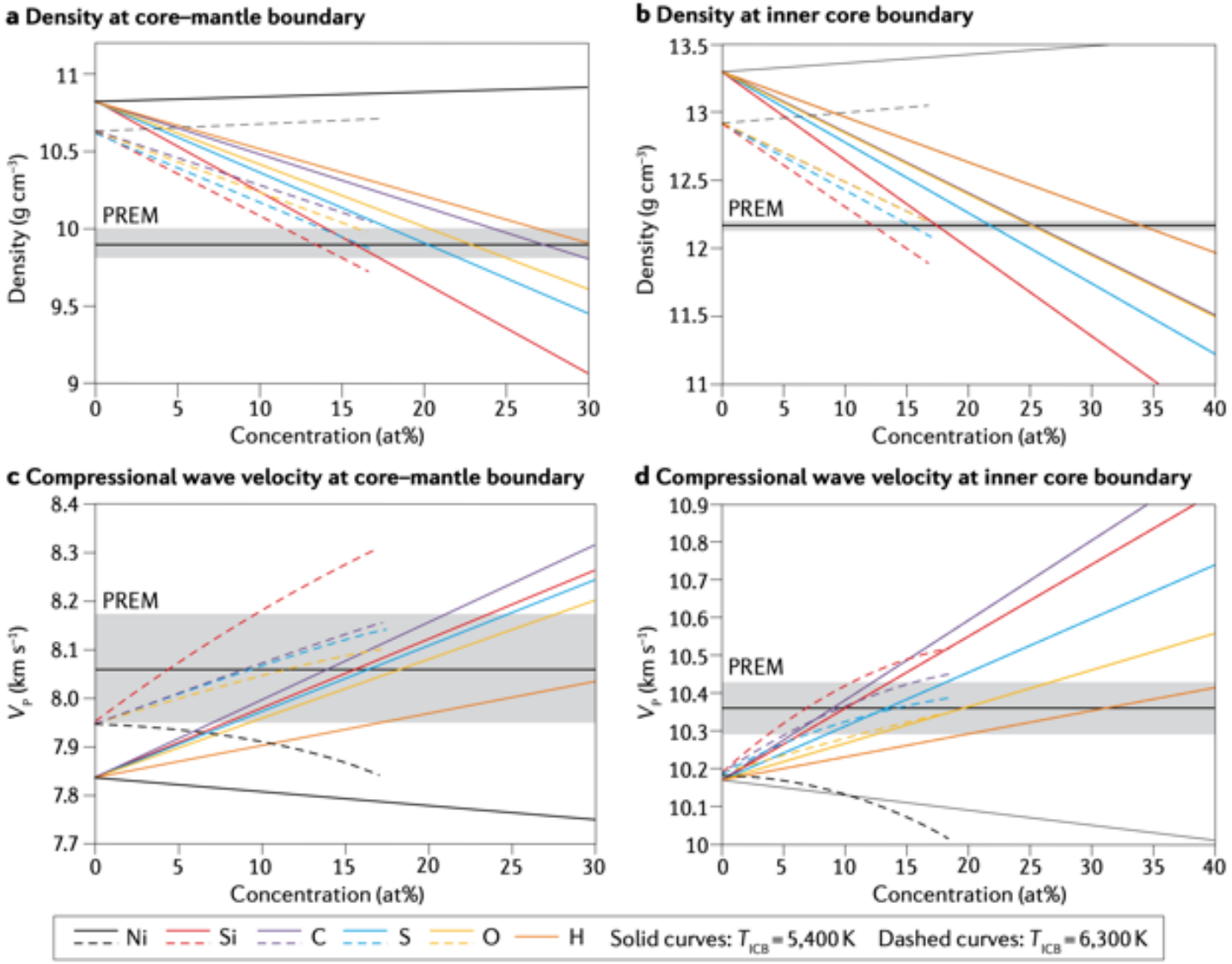
Composition



- **High density reveals that Earth's core has to be primarily made of iron.**
- **The density deficit relative to pure iron is attributed to the presence of substantial amounts of 'light' elements** (e.g. sulfur, silicon, oxygen, carbon and hydrogen)

Hirose et al., 2021, Nat. Rev. E. E.

Composition



Hirose et al., 2021, Nat. Rev. E. E.

Likely ranges from mineral physics, cosmochemical and geochemical estimates (wt%)

Outer core:
Fe + 5% Ni + 1.7% S + 0–4.0% Si + 0.8–5.3% O + 0.2% C + 0–0.26% H

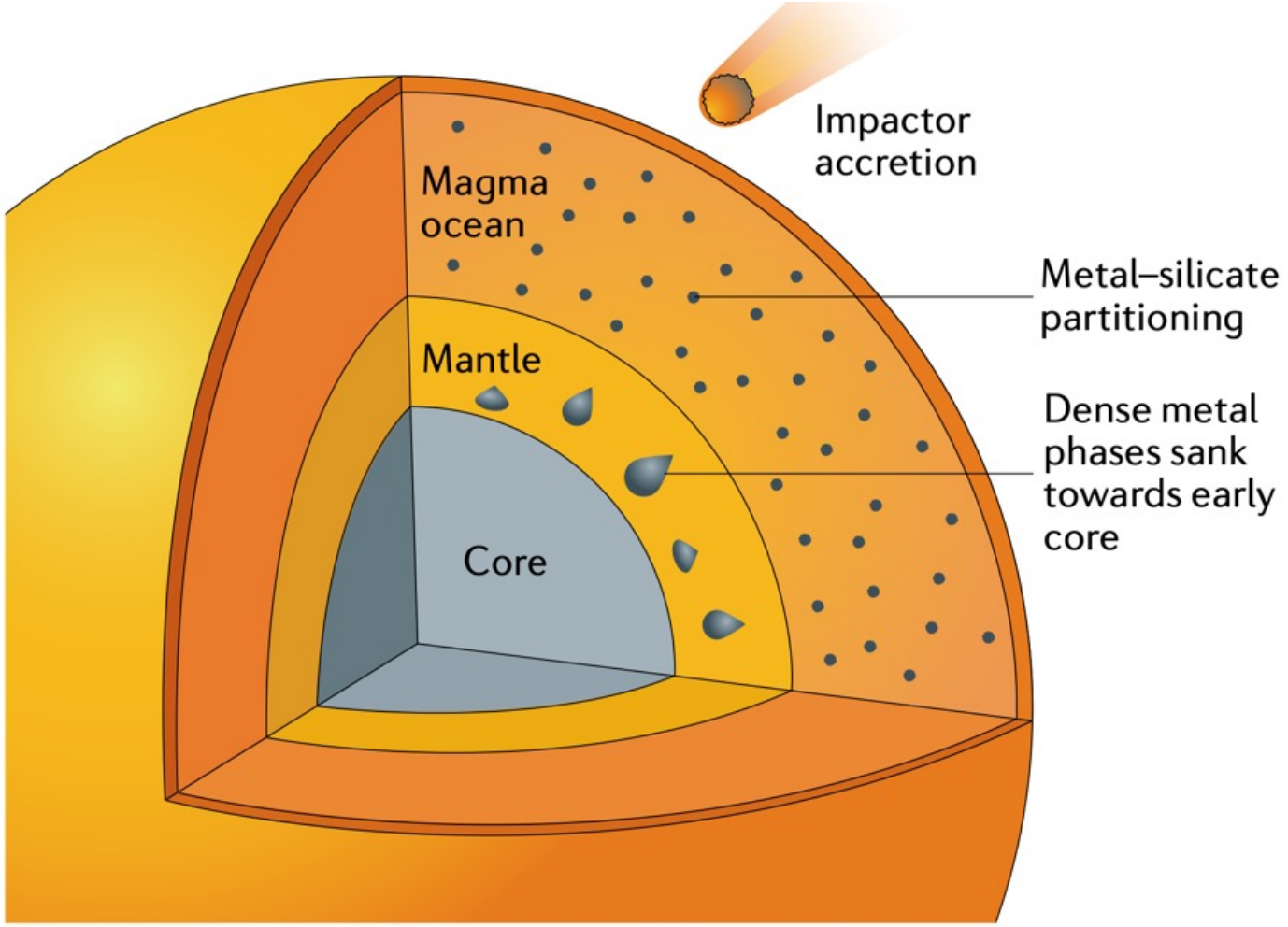
Inner core :
Fe + 5% Ni + 0–1.1% S + 0–2.3% Si + 0–0.1% O + 0–1.3% C + 0–0.23% H

Radioactive elements (e.g. potassium ^{40}K)?

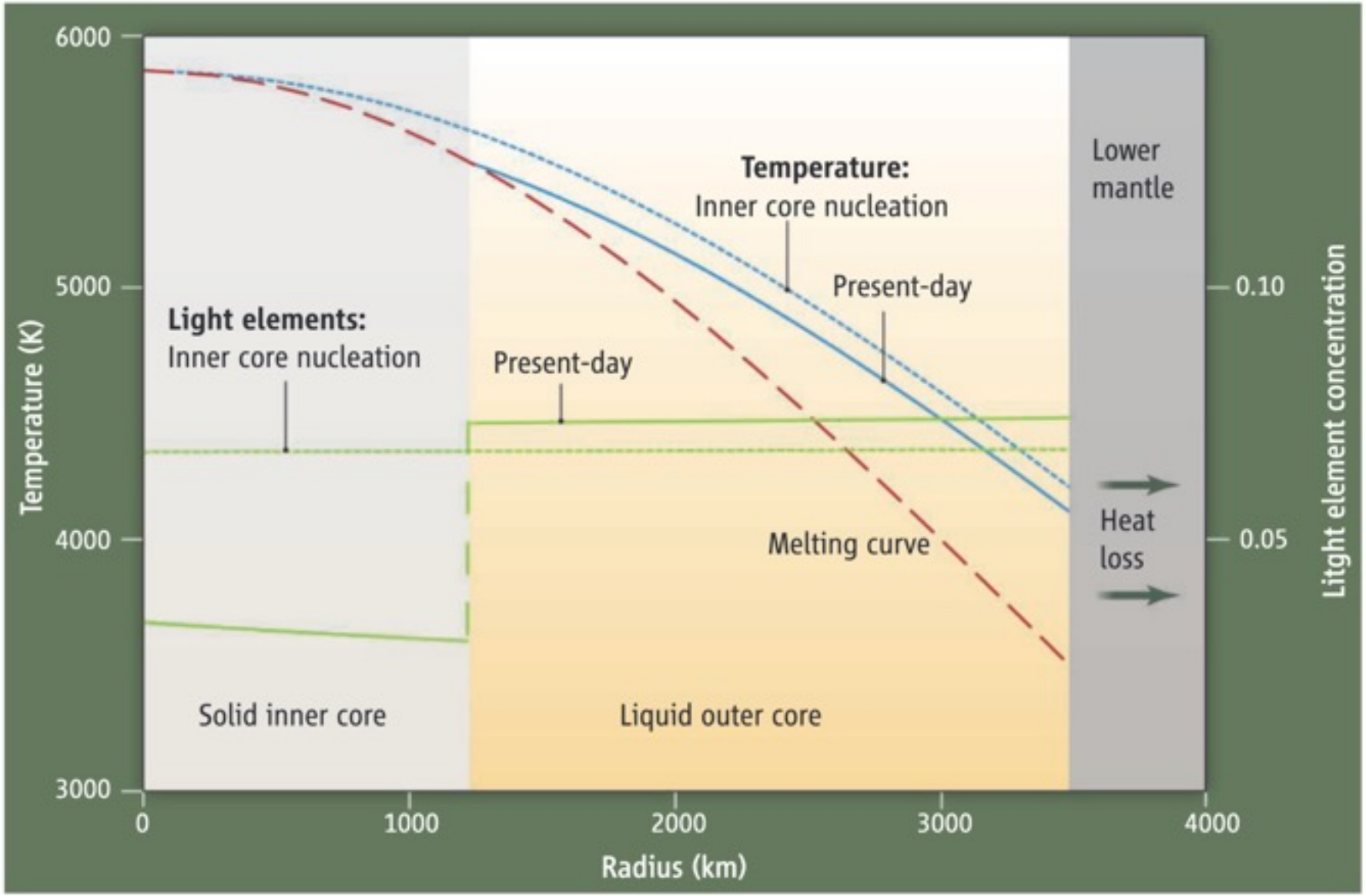
Compostion

The content of light elements in the core remains uncertain, but it is crucial for understanding:

- Earth accretion
- Core-matle differentiation
- Energy budget
- Magnetic field generation

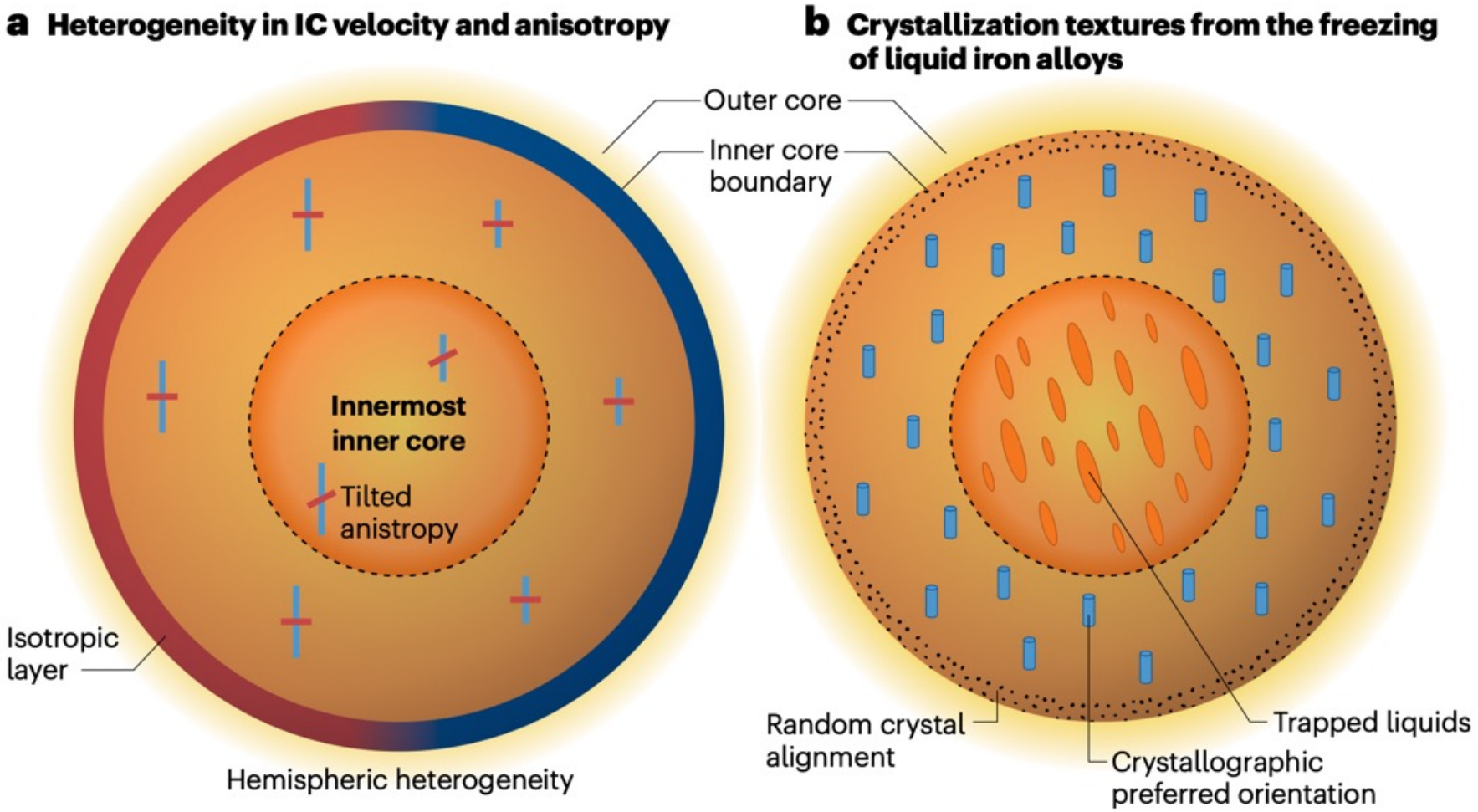


Thermal and compositional structure



Olsen, 2013, Science

Heterogeneity of inner core



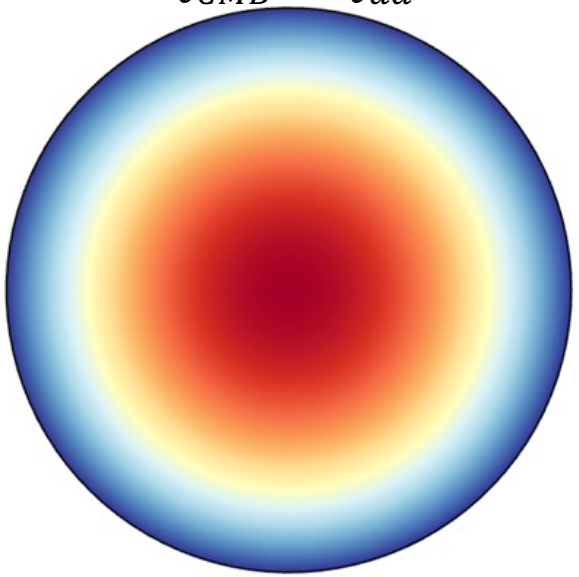
Wilson et al., 2025, Nat. Rev. E. E.

Heteogeneity and anistrophy indidate the complex crystallization of inner core.

Evolution of terrestrial planetary core

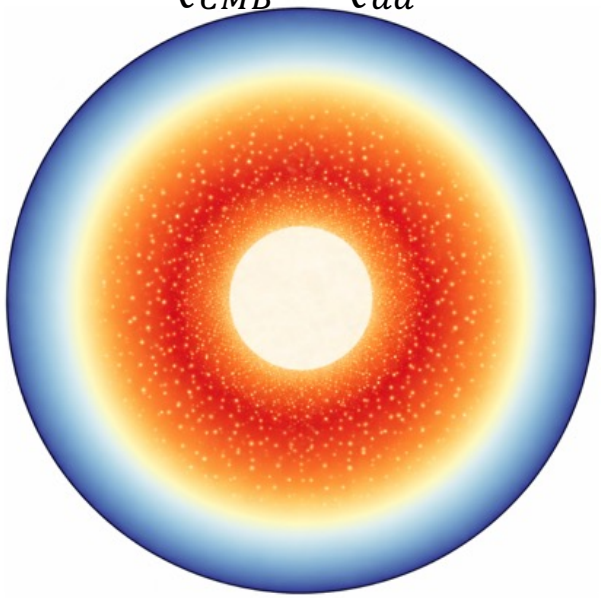
Cooling

$Q_{CMB} > Q_{ad}$



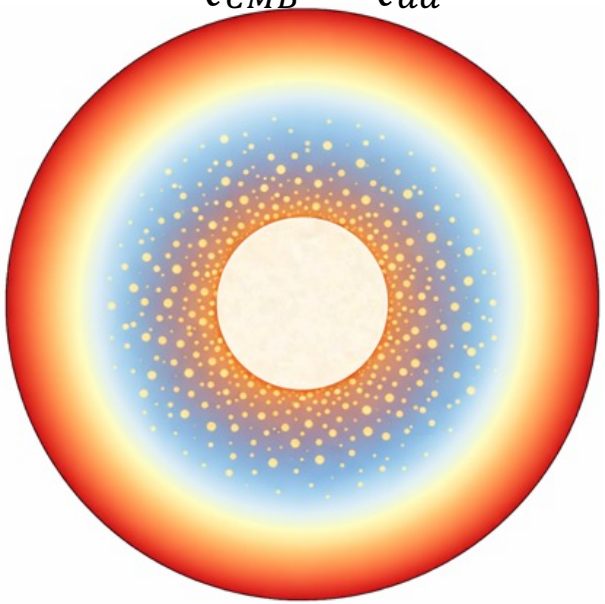
Thermal convection

$Q_{CMB} > Q_{ad}$

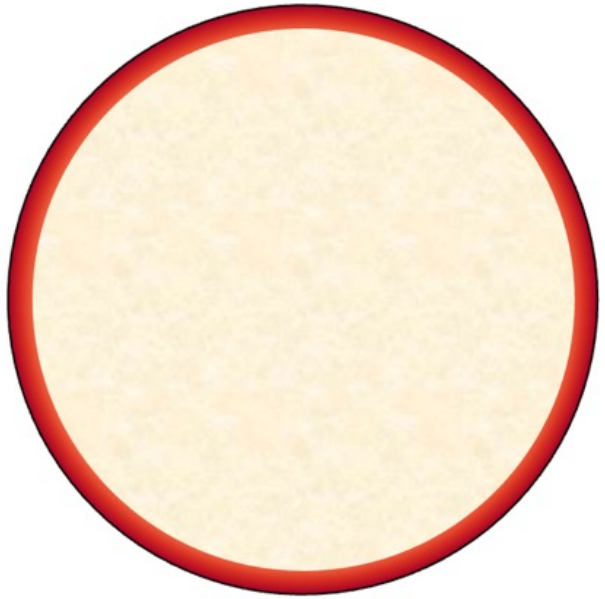


Thermal & Compositional convection (Top-heavy DDC)

$Q_{CMB} < Q_{ad}$



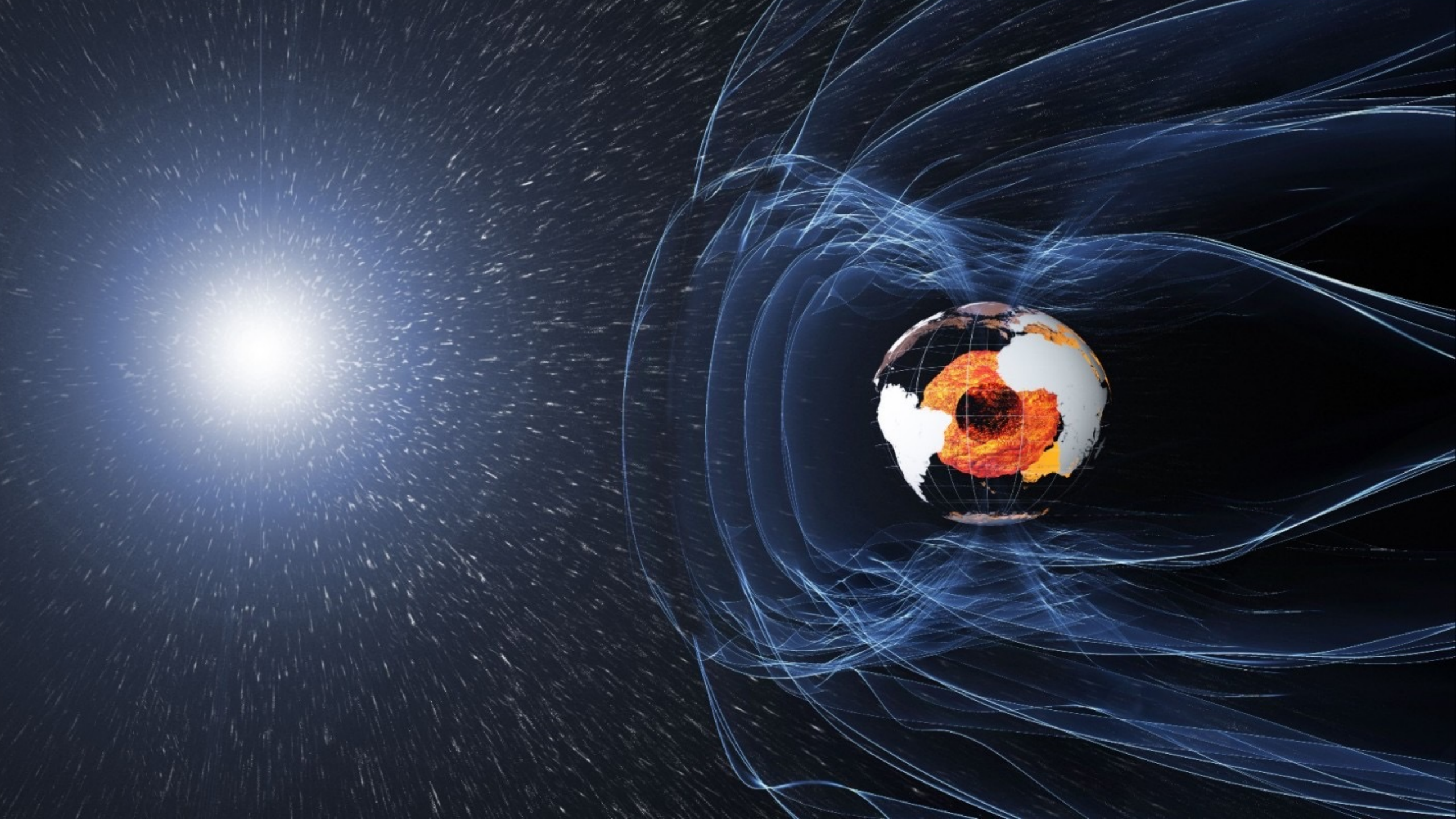
Thermal stratification & Compositional convection (Fingering convection)



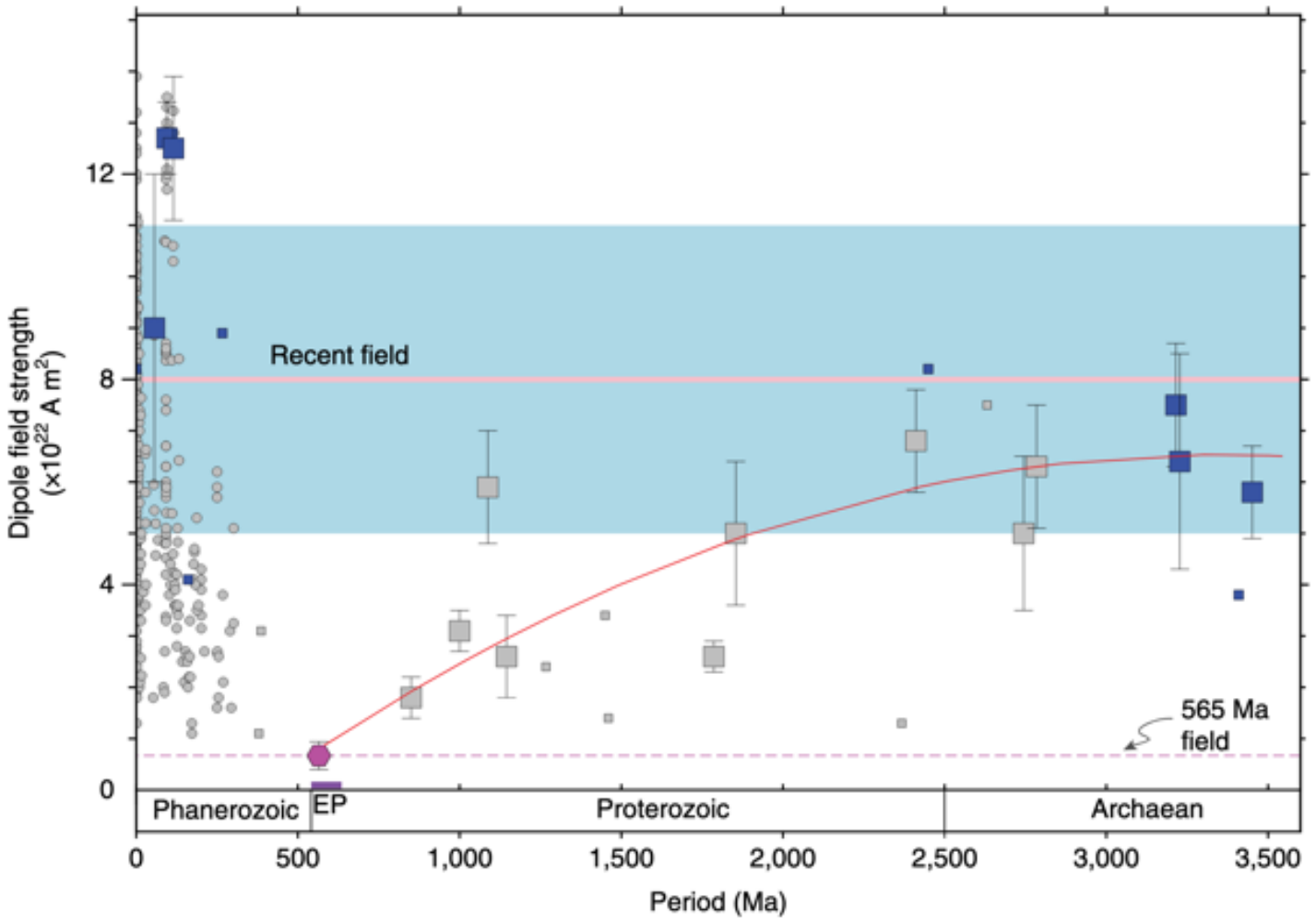
Almost fully solidified core

Outline

- Structure and composition of the core
- **Core dynamics: Earth's magnetic field generation**
- Energy budget and thermal evolution of the core



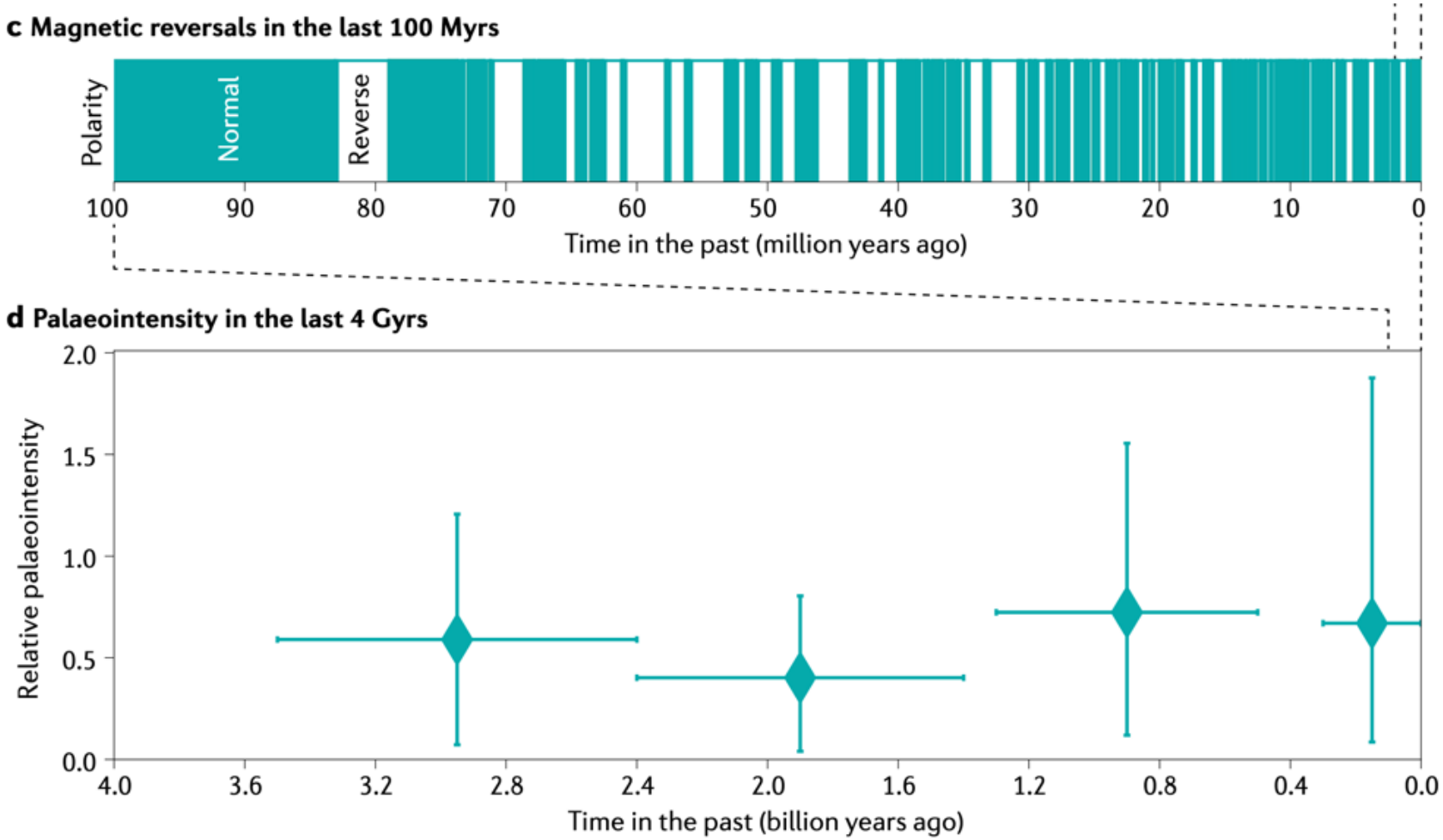
Palaeomagnetic records

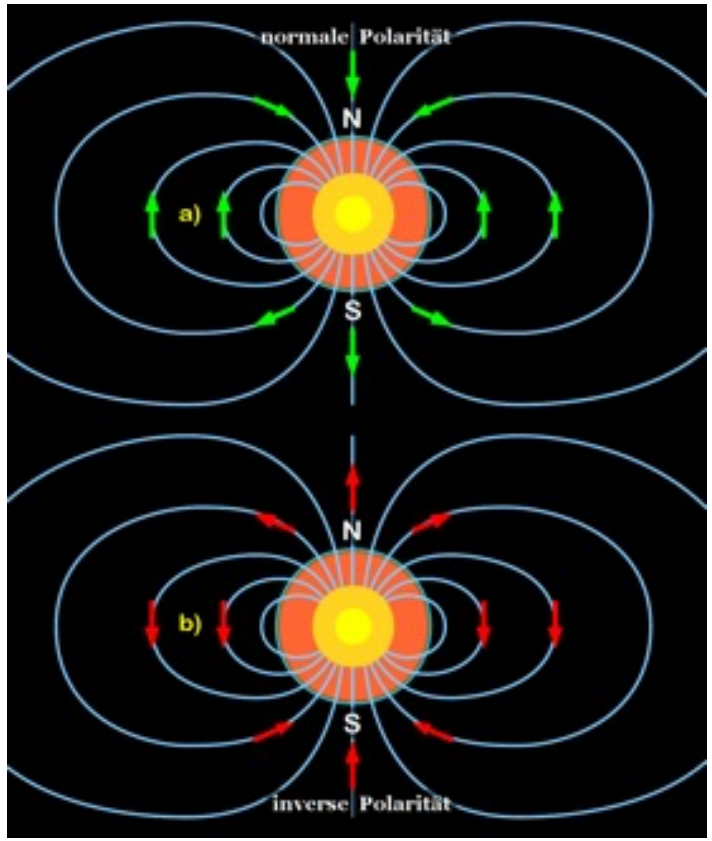


Bono et al., 2019

Magnetic field generation on Earth has persisted for at least 3.5 Gyr, long before the inner core formation.

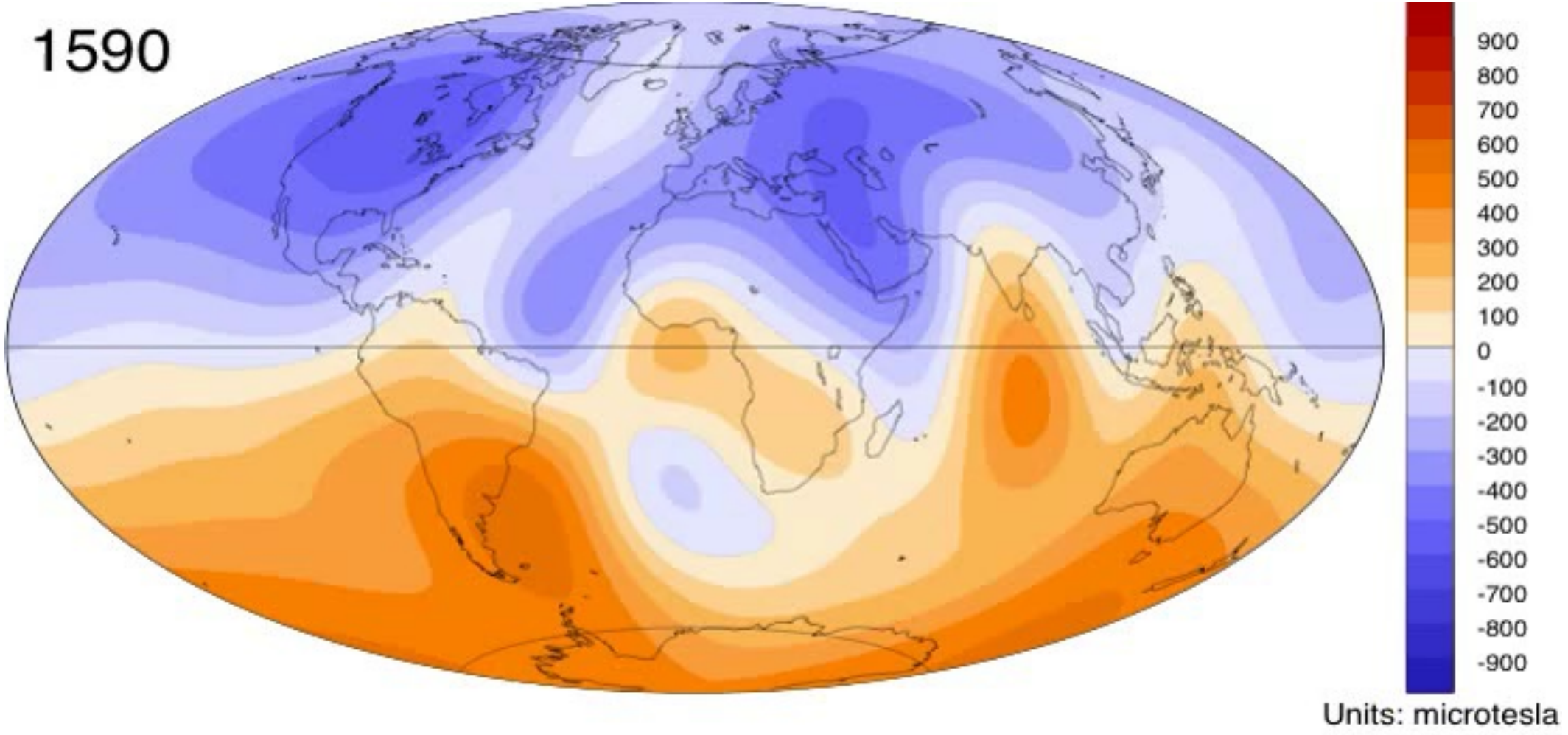
Geomagnetic reversals





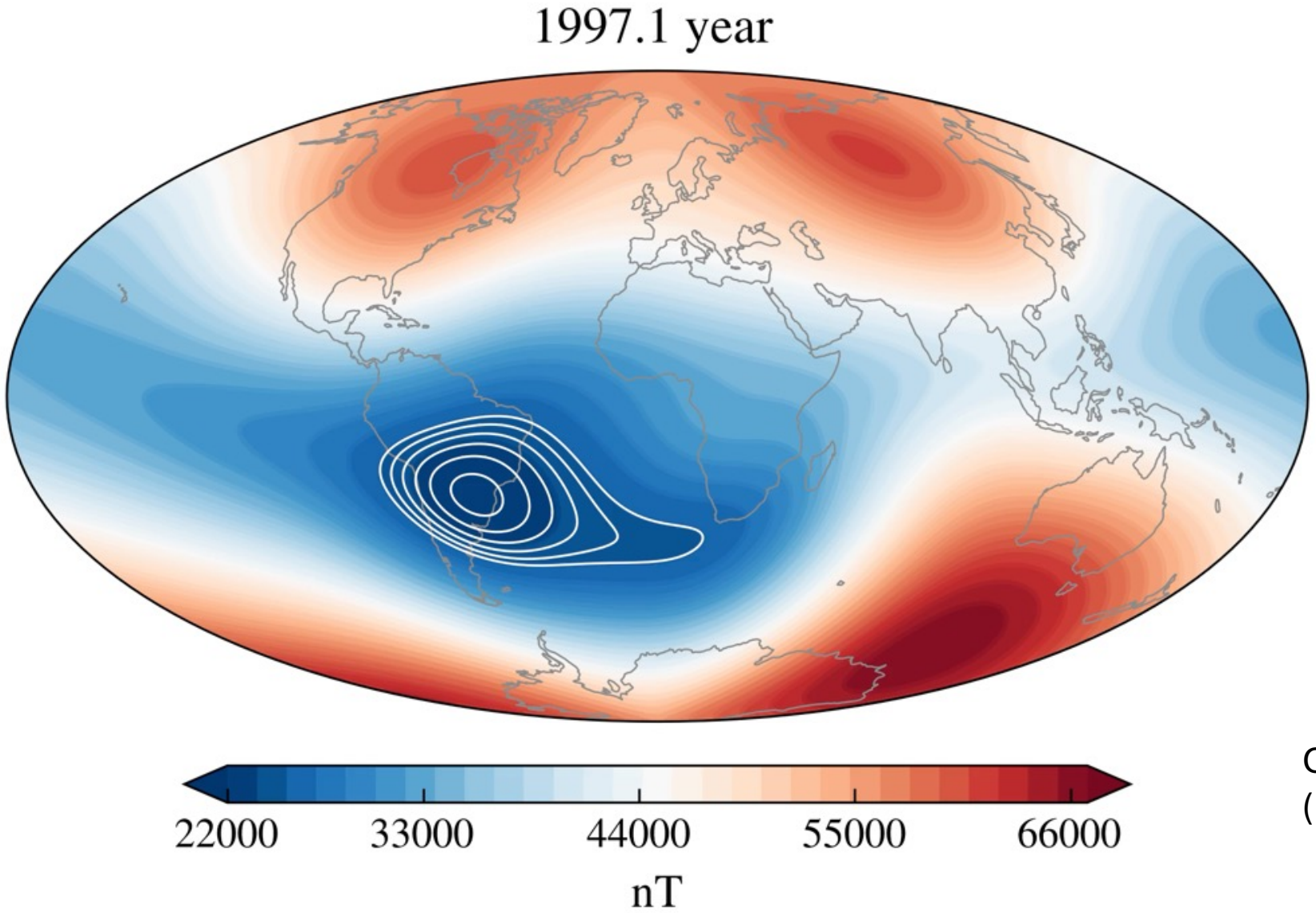
Landeau et al., 2022

Secular variations over 4 centuries



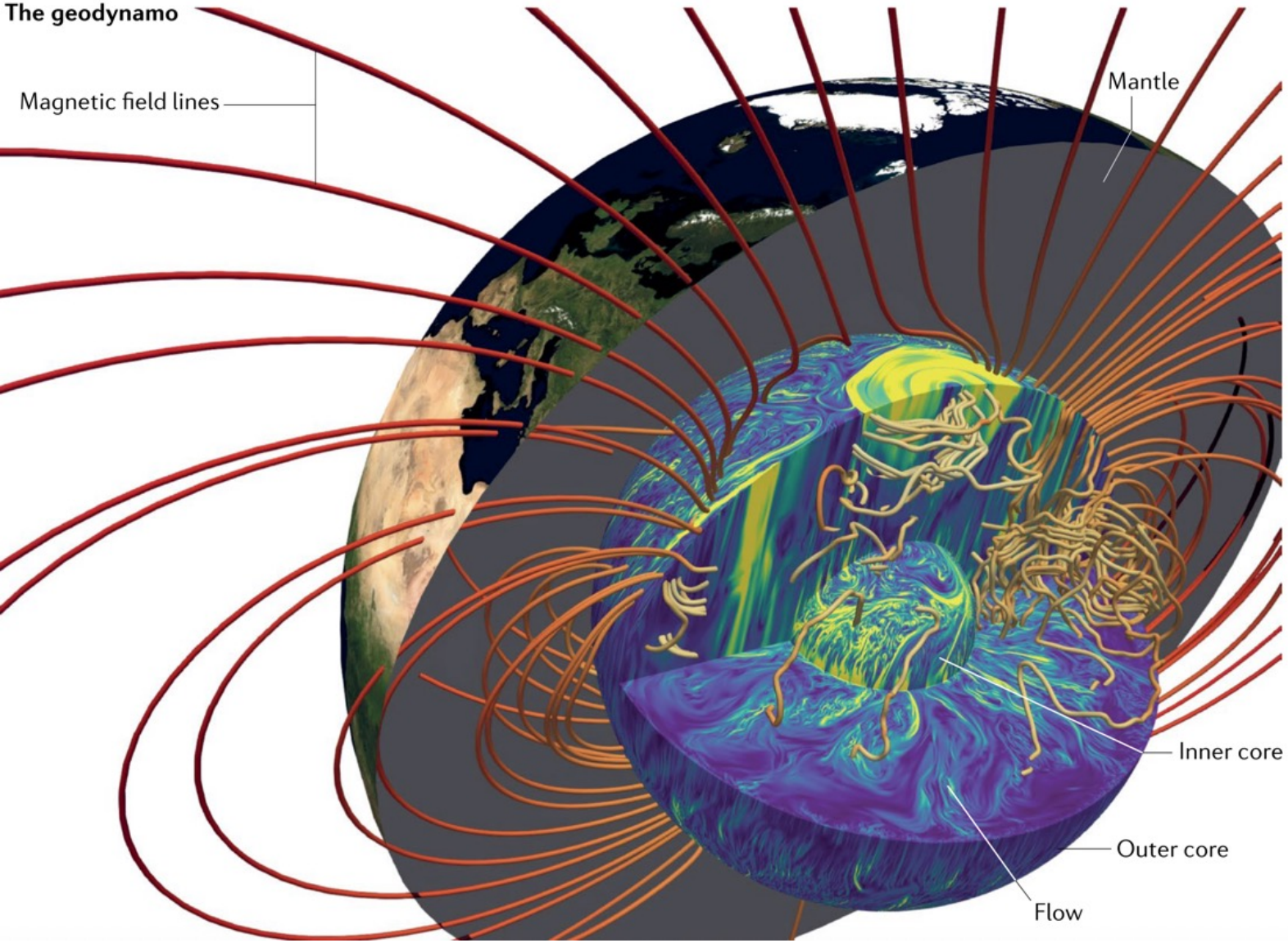
Radial magnetic field at the core-mantle boundary from gufm-1 model (Jackson et. al., 2000).

Secular variations during the satellite era



CHAOS-8 model
(Kloss et al., 2026)

Dynamo theory



Motions of electrically conducting fluid in a seed magnetic field

↓ Faraday's law

Electrical currents

↓ Ampere's law

Magnetic fields

↑

Dynamo theory

- A seed magnetic field
  (magnetic fields are ubiquitous in universe)

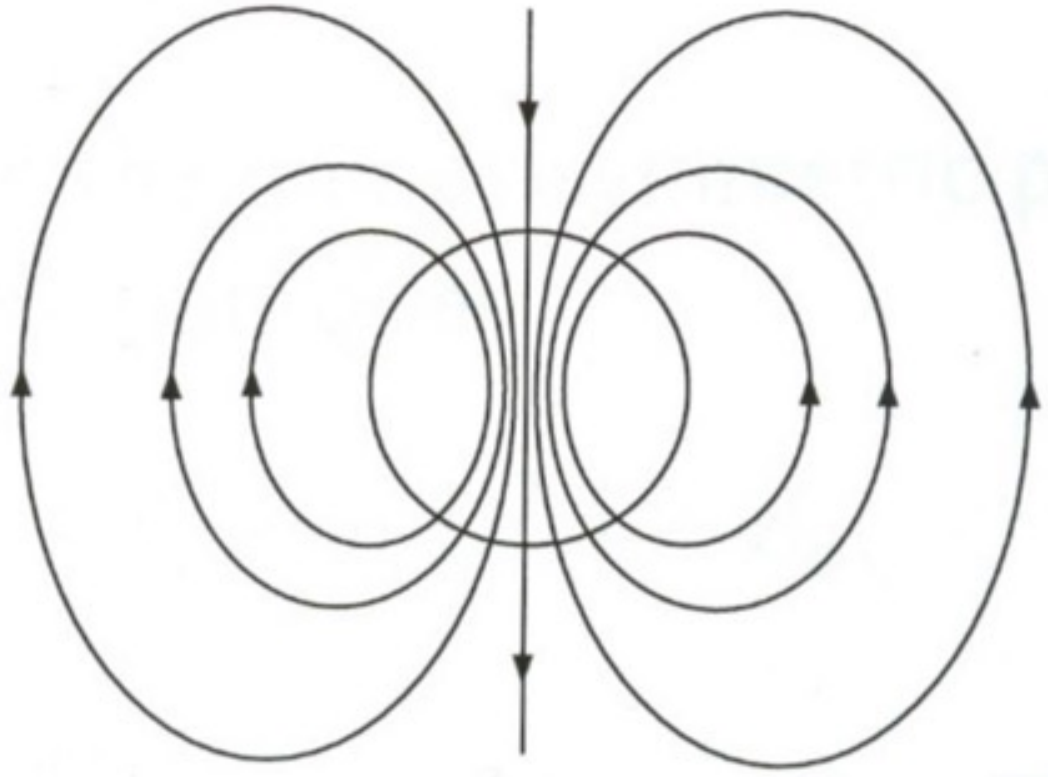
- An electrically conducting fluid layer
  (liquid iron core, metallic hydrogen)

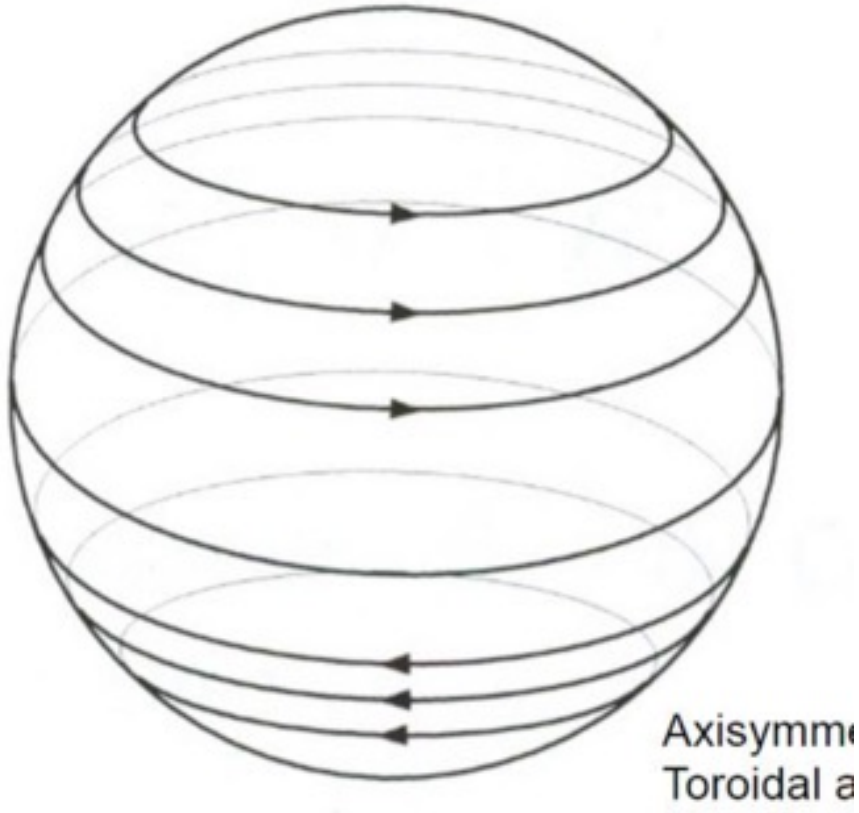
- Sufficiently vigorous fluid motions
  (energy sources)

Rotation is NOT a necessary condition!

Anti-dynamo theorem (Cowling 1937)

- There are certain types of flows which cannot maintain a dynamo.
- There are certain types of magnetic field cannot be generated by dynamo action.



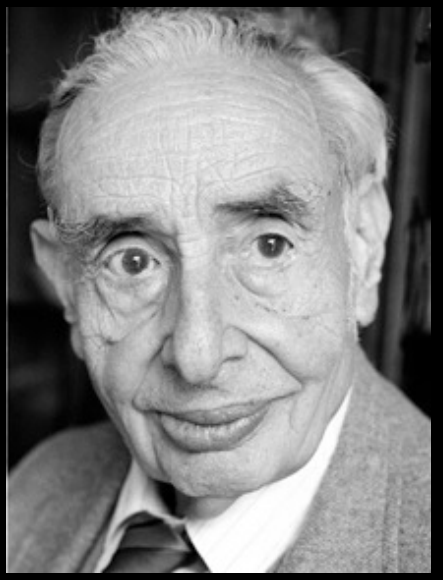


Axisymm
Toroidal a

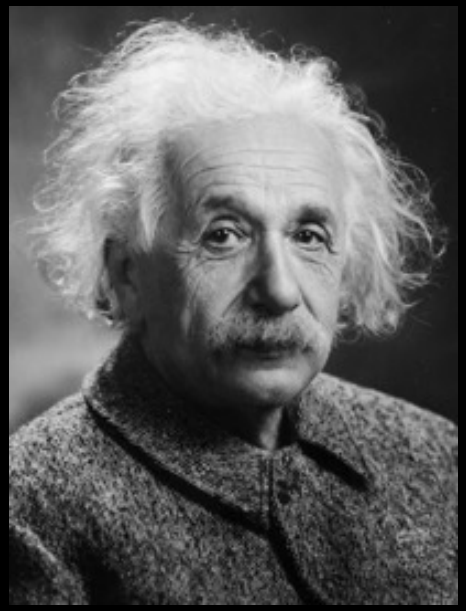
Einstein paid Elsasser a visit, and asked "What are you working on these days?". Elsasser told him, and Einstein invited him to explain dynamo theory to him. Elsasser set up the problem and then told Einstein about Cowling's theorem.

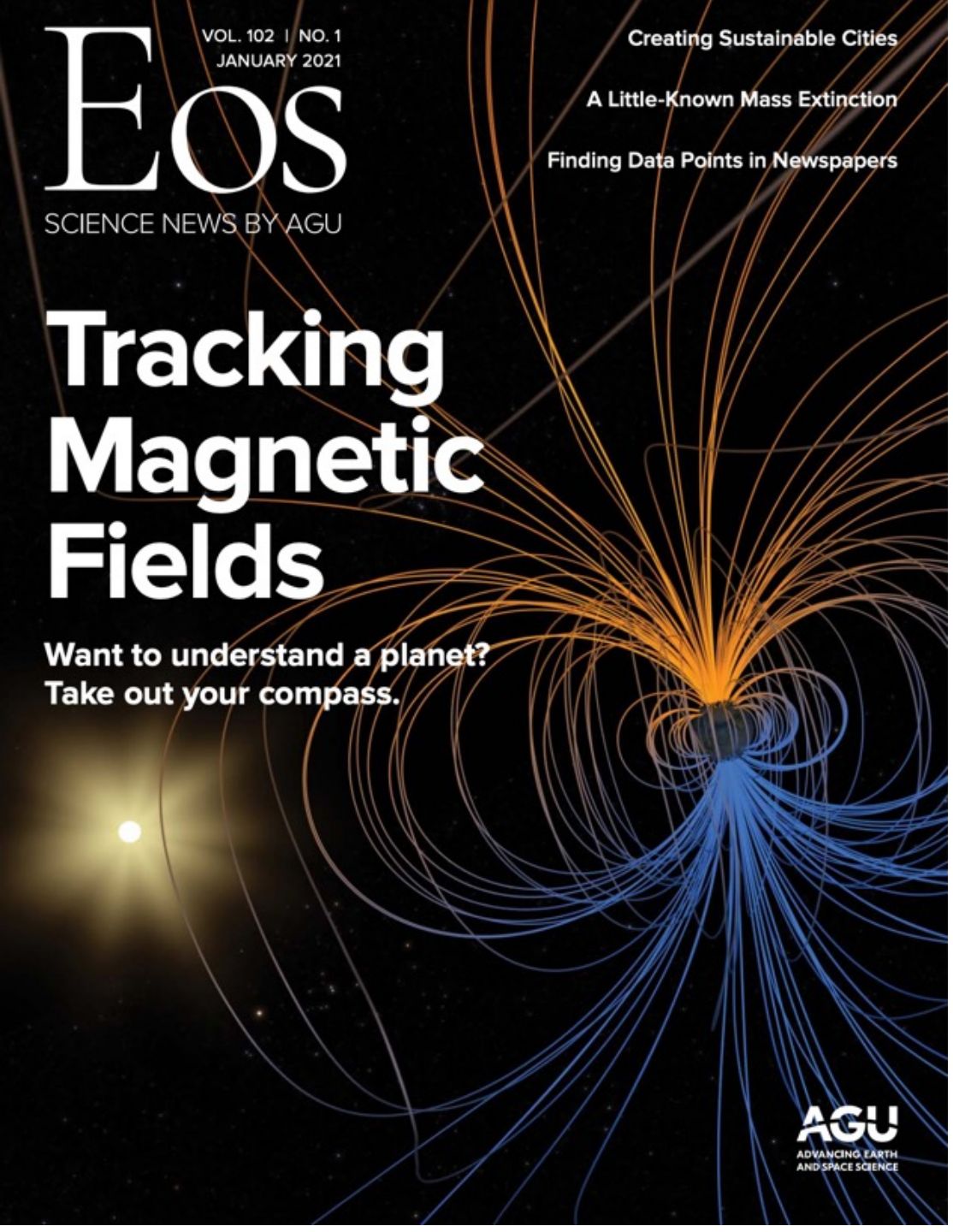
Einstein's response was, "If such simple solutions are impossible, self-excited fluid dynamos cannot exist".

(From Paul Roberts)



Walter Elsasser





The mathematics of the geodynamo are so messy that Albert Einstein did not believe it.

Dynamo equations

Navier-Stokes Eq. (流体力学) +Maxwell Eq. (电磁学) +Energy Eq. (热力学)

$$\rho_0 \frac{\partial \boldsymbol{u}}{\partial t} + \rho_0(\boldsymbol{u}\cdot\nabla)\boldsymbol{u} + 2\rho_0(\boldsymbol{\Omega}\times\boldsymbol{u}) = -\nabla P - \rho_0\alpha T\boldsymbol{g} + (\boldsymbol{J}\times\boldsymbol{B}) + \rho_0\nu\nabla^2\boldsymbol{u}$$

$$\frac{\partial T}{\partial t} + (\boldsymbol{u}\cdot\nabla)T_0 = \kappa\nabla^2 T$$

$$\mathbf{J}\times\mathbf{B} = \frac{1}{\mu_0}(\nabla\times\mathbf{B})\times\mathbf{B}$$

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

Terms representing feedback and coupling between the velocity, magnetic and temperature fields

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

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

+ Boundary Flow, Thermal and Magnetic BC on ICB & CMB.

非线性多物理场耦合方程组

Geodynamo

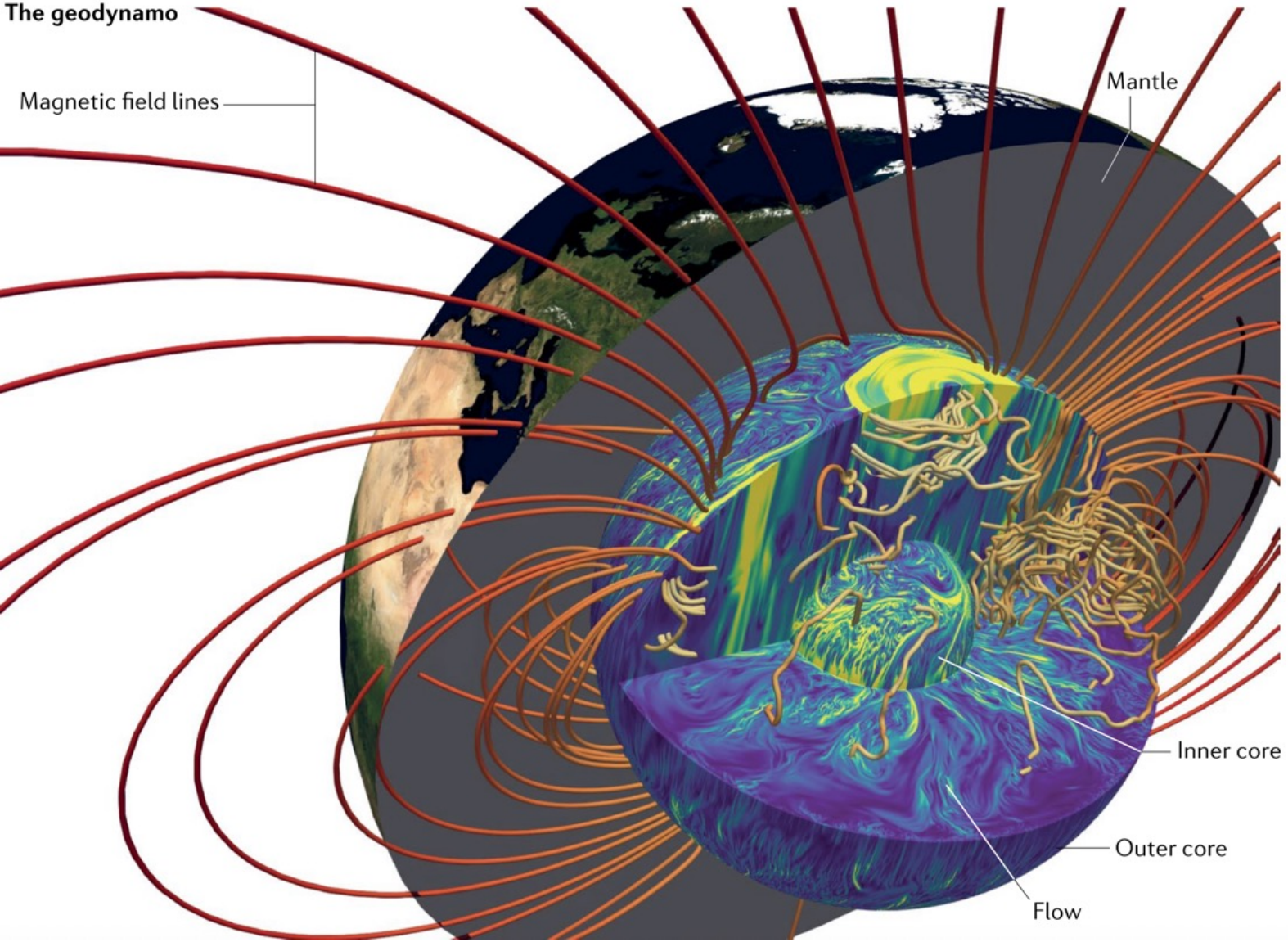
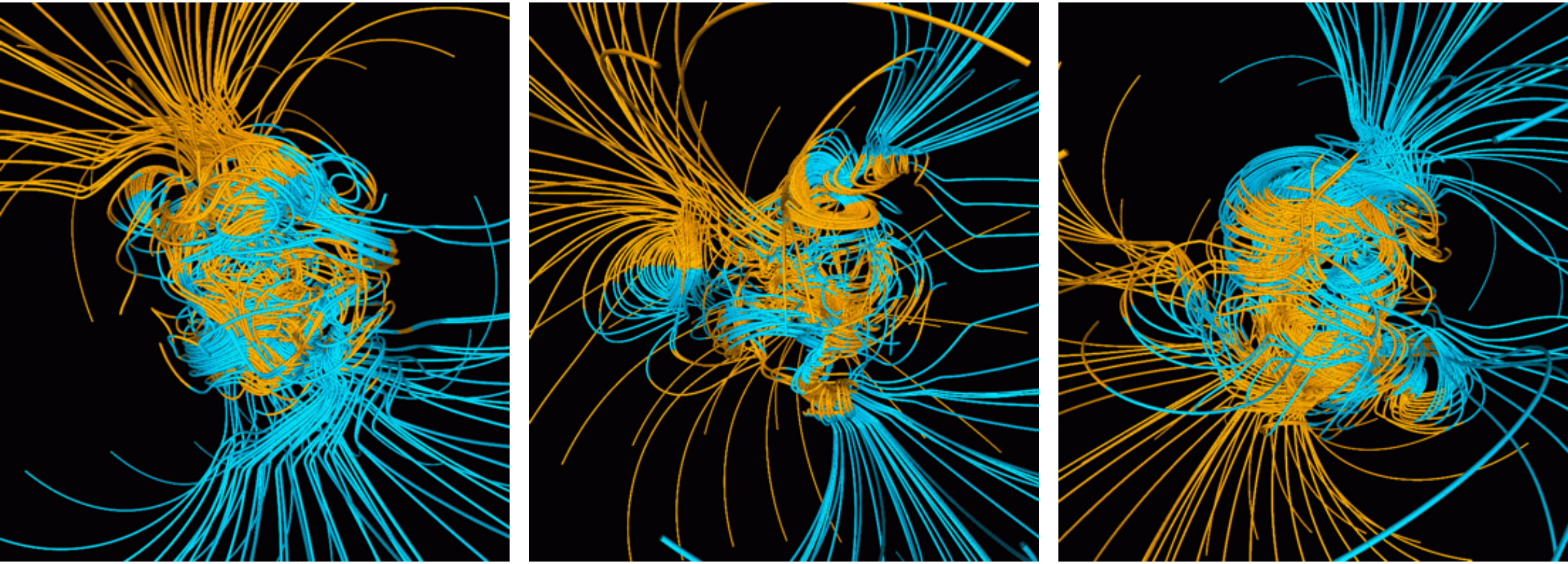


Image credit: N. Schaeffer

- Rapid rotation
- Low viscosity
- Strong magnetic field
- Turbulent convection

The dynamical system involves a very wide range of length and time scales.

Geodynamo simulations

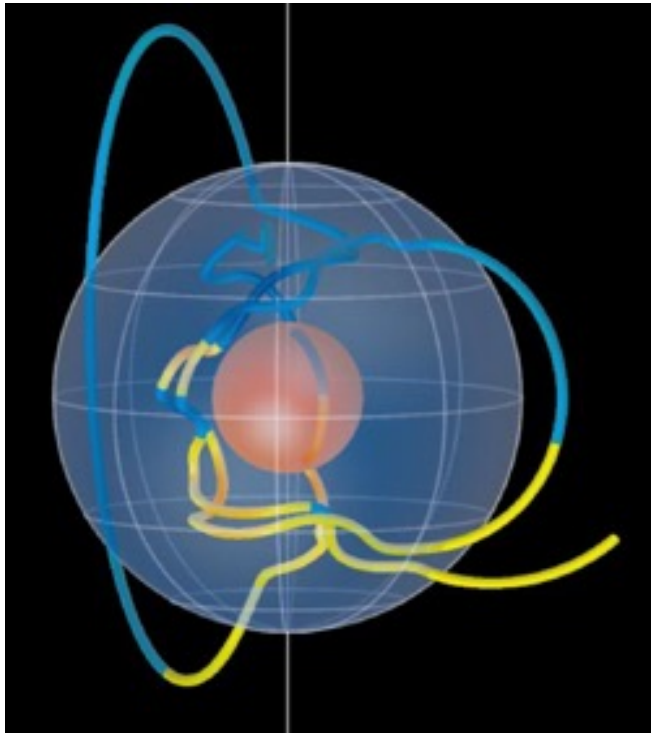


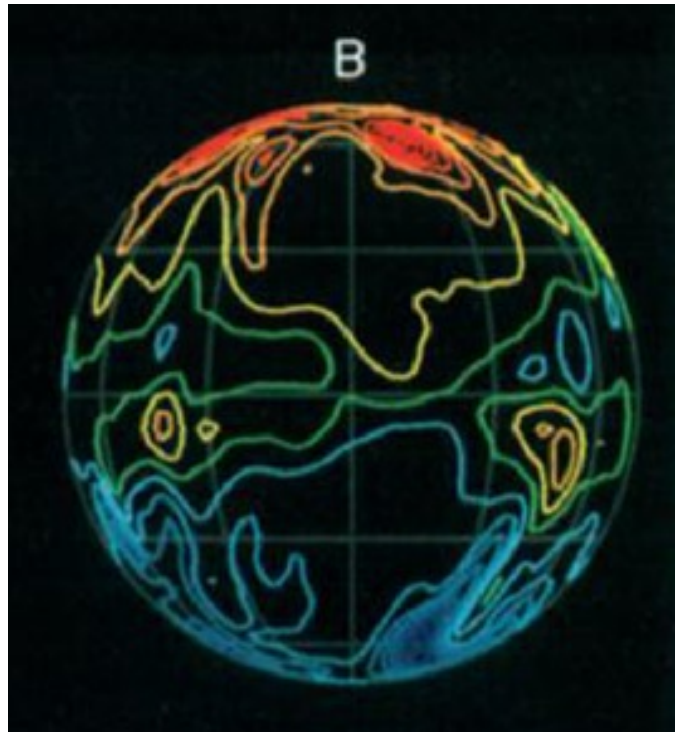
The pioneering work of Glatzmaier & Roberts (1995) opened up the field of numerical simulations of the Geodynamo.

Geodynamo simulations

The first generation of geodynamo models in spherical shell demonstrated the ability for self-consistent dynamo (e.g. Glatzmaier & Roberts, 1995; Kageyama & Sato, 1995; Kuang & Bloxham, 1996; Christensen et al., 1998).

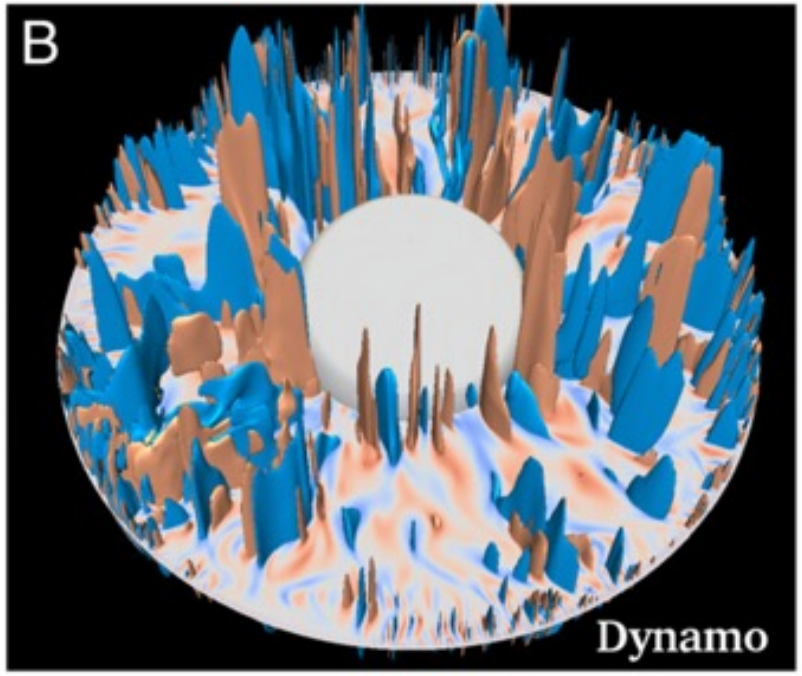




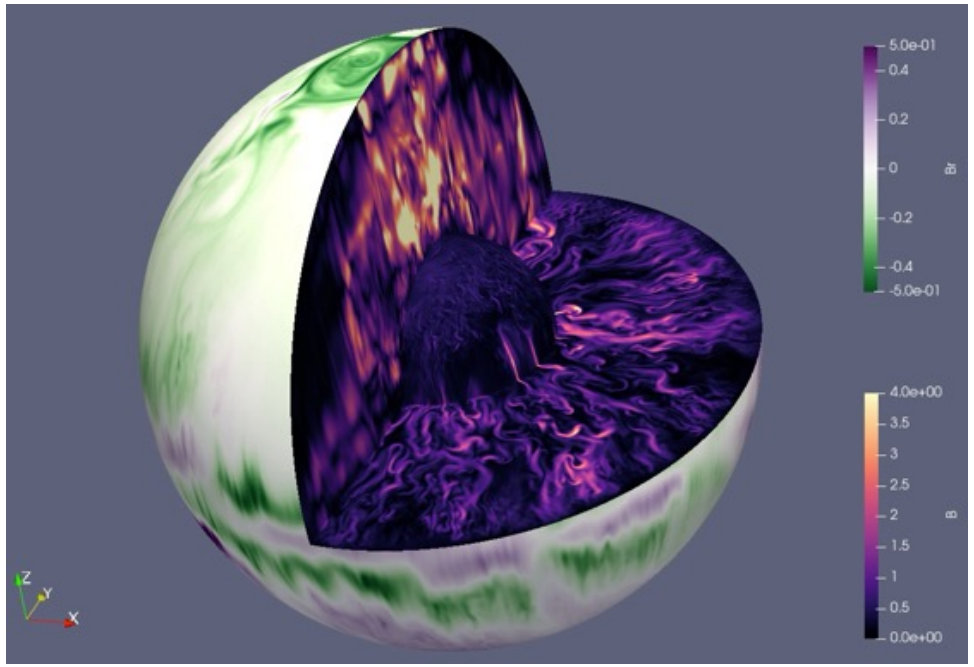


However, the first generation of geodynamo simulations operate in a regime in which the fluid viscosity plays a prominent role.

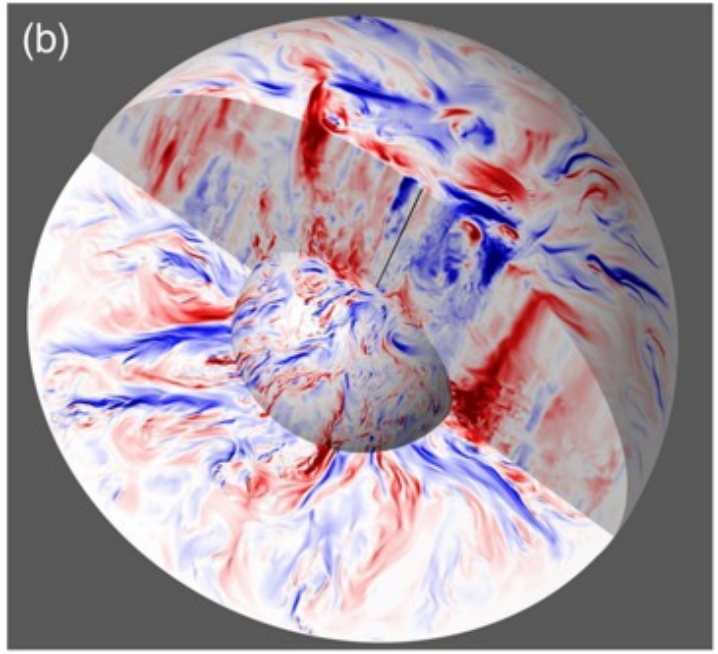
Geodynamo simulations



(Yadav+, 2015)



(Schaeffer+, 2017)

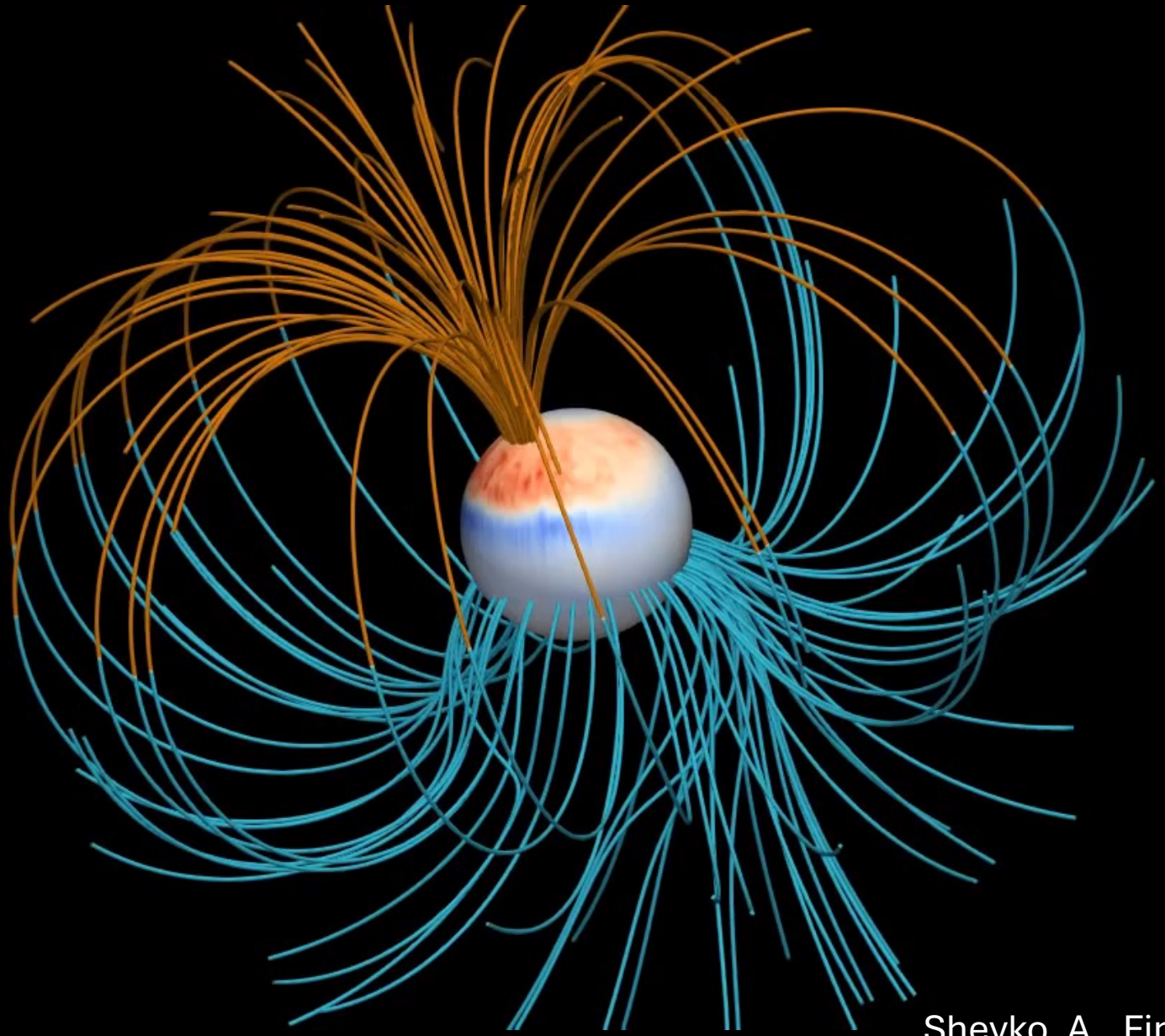


(Aubert, 2019)

The new generation of geodynamo models not only produce Earth-like magnetic fields, but also approach the realistic force balance regime.

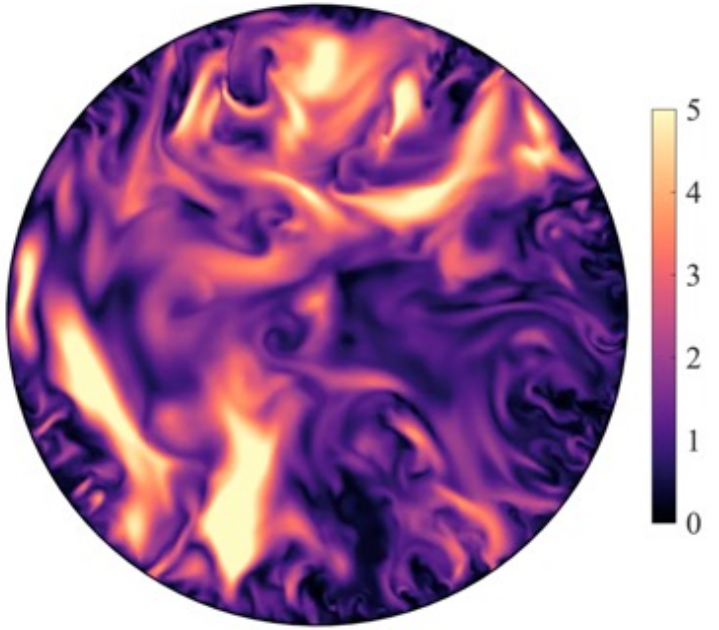
(e.g. Yadav+, 2015; Schaeffer+, 2017; Sheyko+,2017; Aubert, 2019; Schwaiger+, 2021; Dormy, 2015)

Geomagnetic reversals in simulations

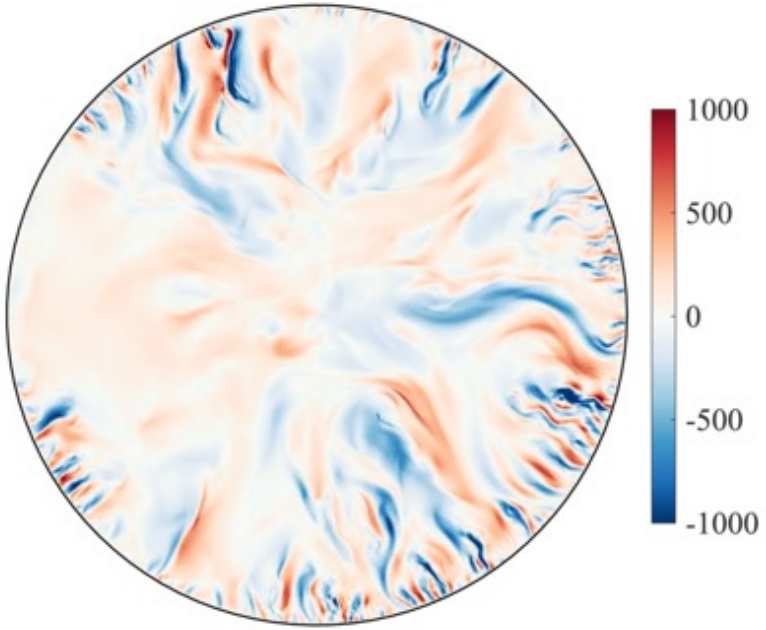


Sheyko, A., Finlay, C. C., & Jackson, A. (2016) *Nature*

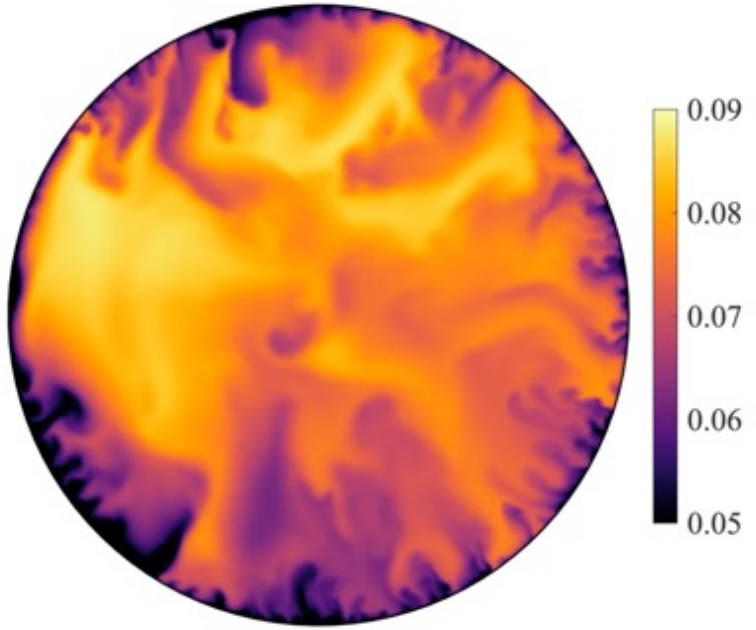
Geodynamo simulations



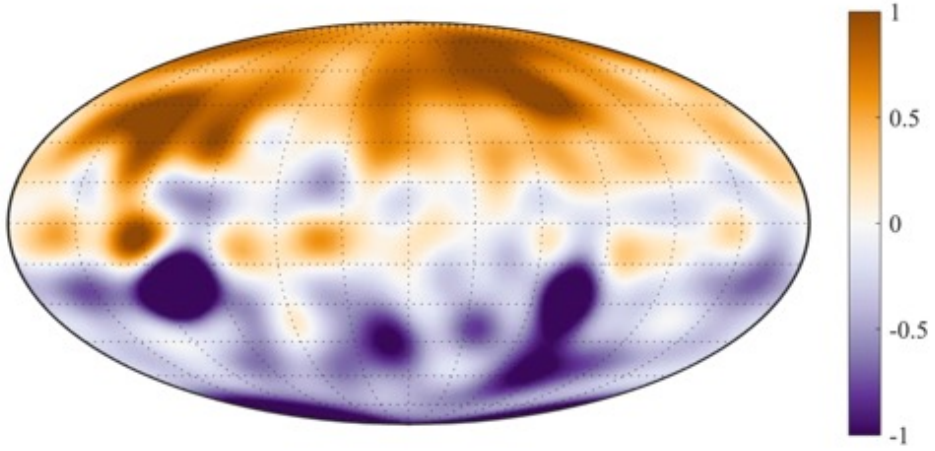
Magnetic field



Radial velocity

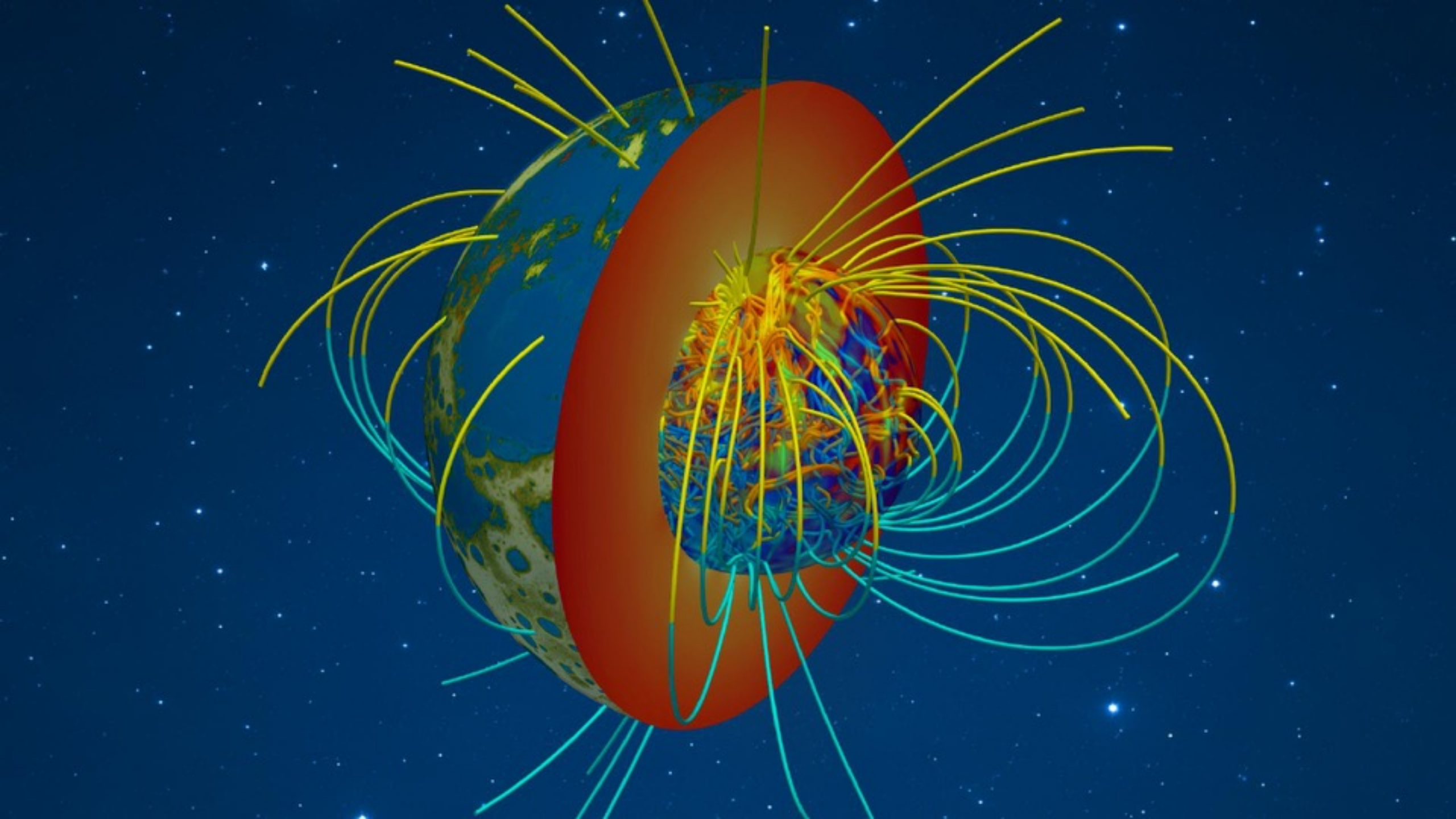


Temperature



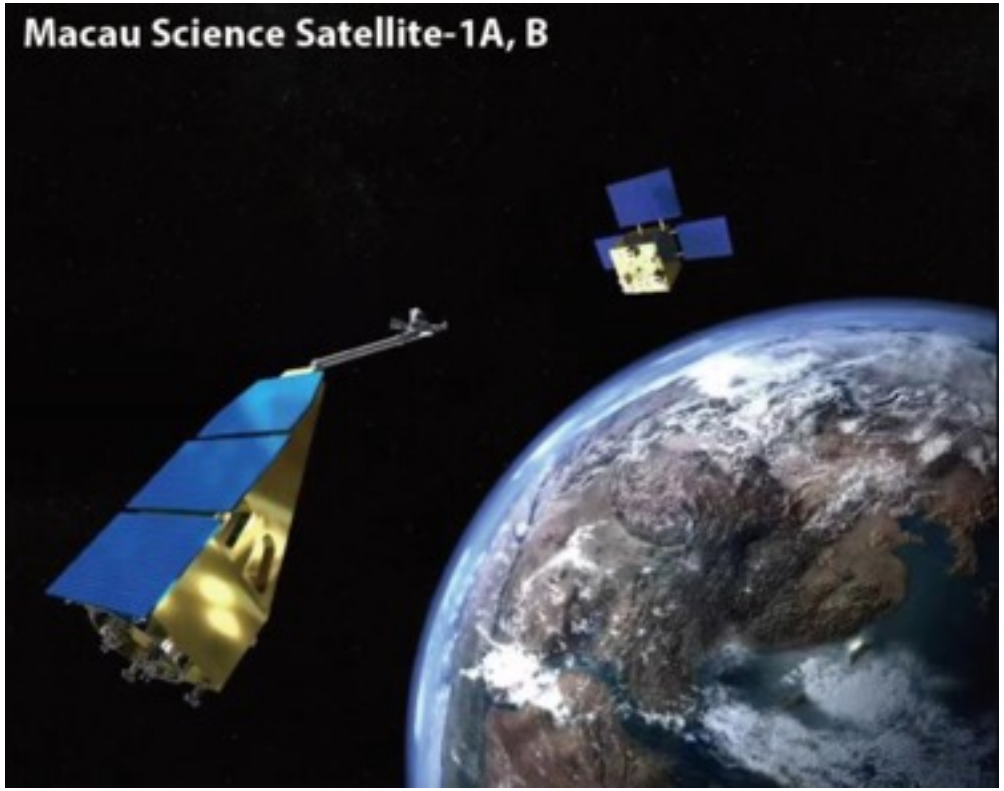
Dynamo simulation in an early-Earth model, which can produce similar magnetic field to the present-day field.

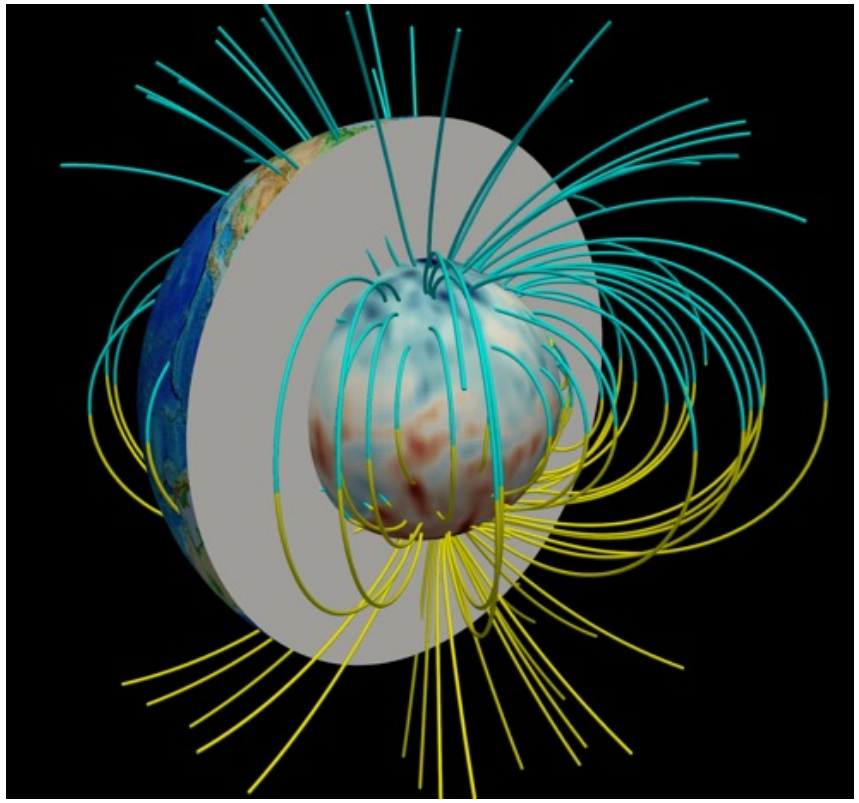
Lin, Marti, Jackson, 2025, Nature



Geomagnetic observations

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





How to constrain the core dynamics using geomagnetic observations?

Reconstruction of 3-D core flow

We developed a novel framework to reconstruct the 3-D core flow based on inertial modes expansion.

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

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

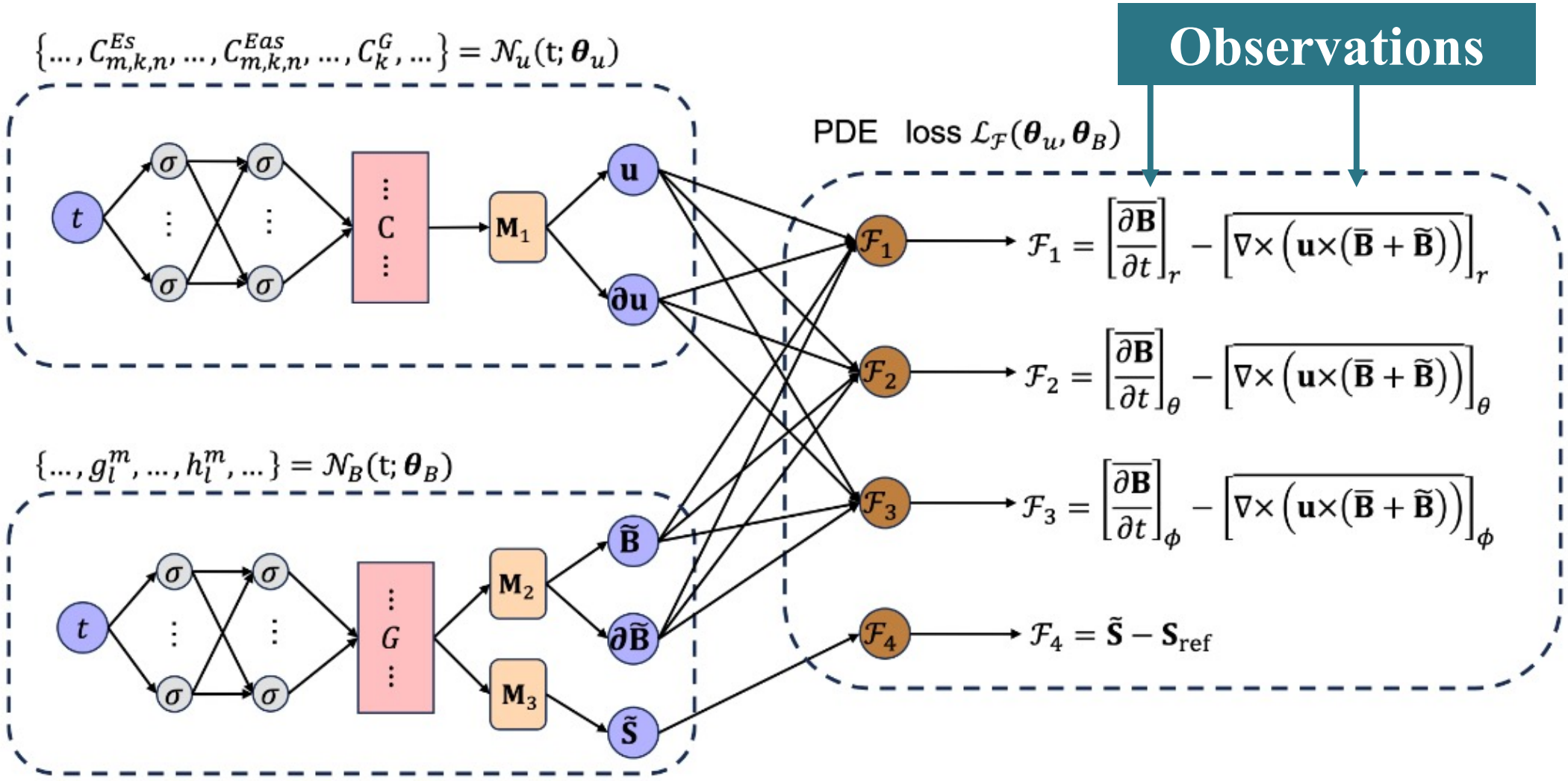
Inertial modes — Zhang & Liao, 2017

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

Kloss & Finlay, 2019

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

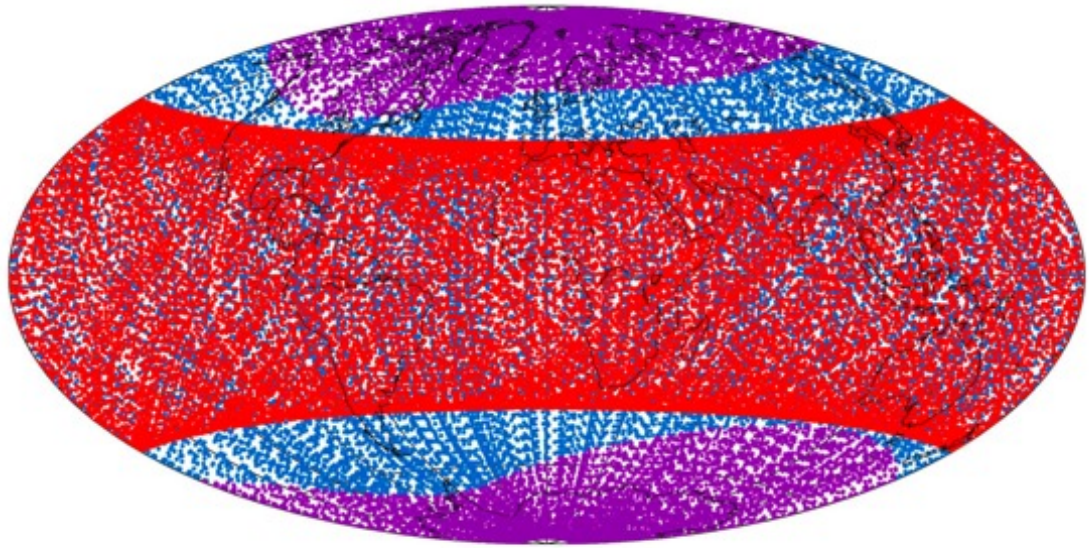
PINN-based inversion

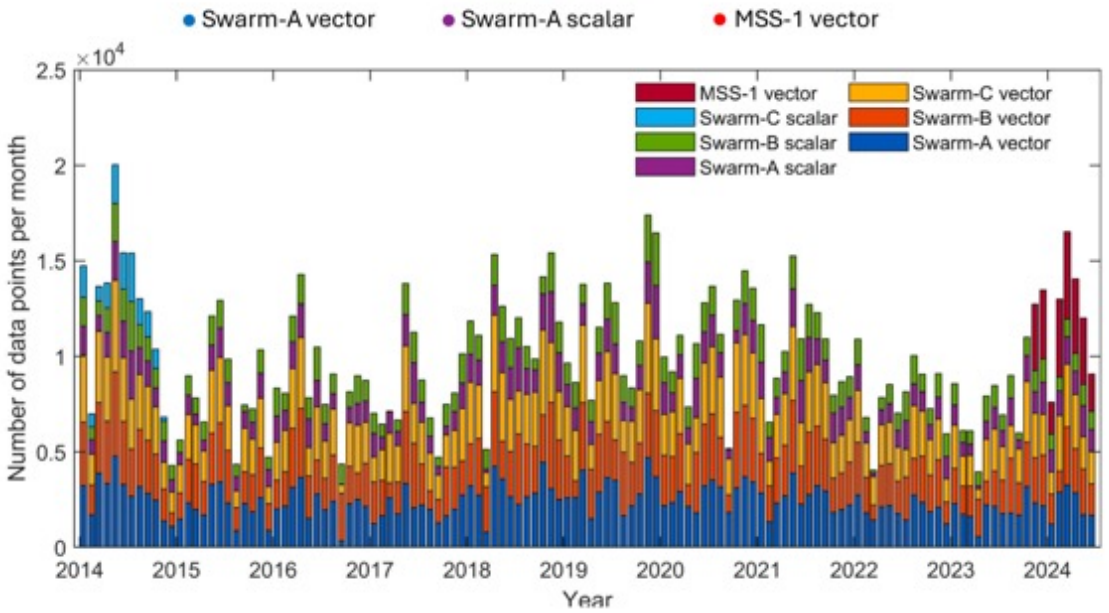


Physics-Informed Neural Networks (PINN)

Li, Lin, Zhang, 2024, GRL
Li, Lin, Zhang, 2025, PEPI

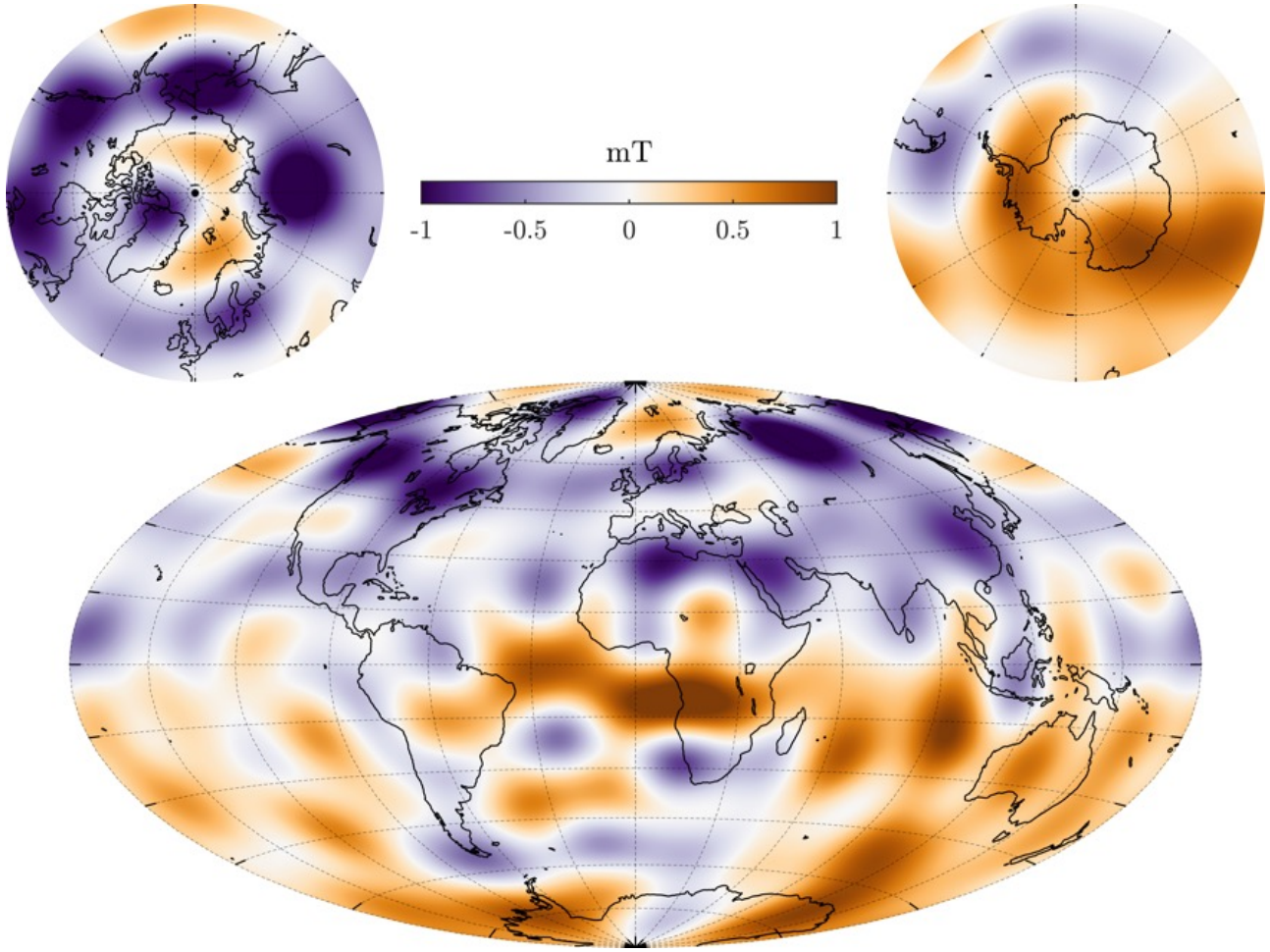
Observations and Core Field Model



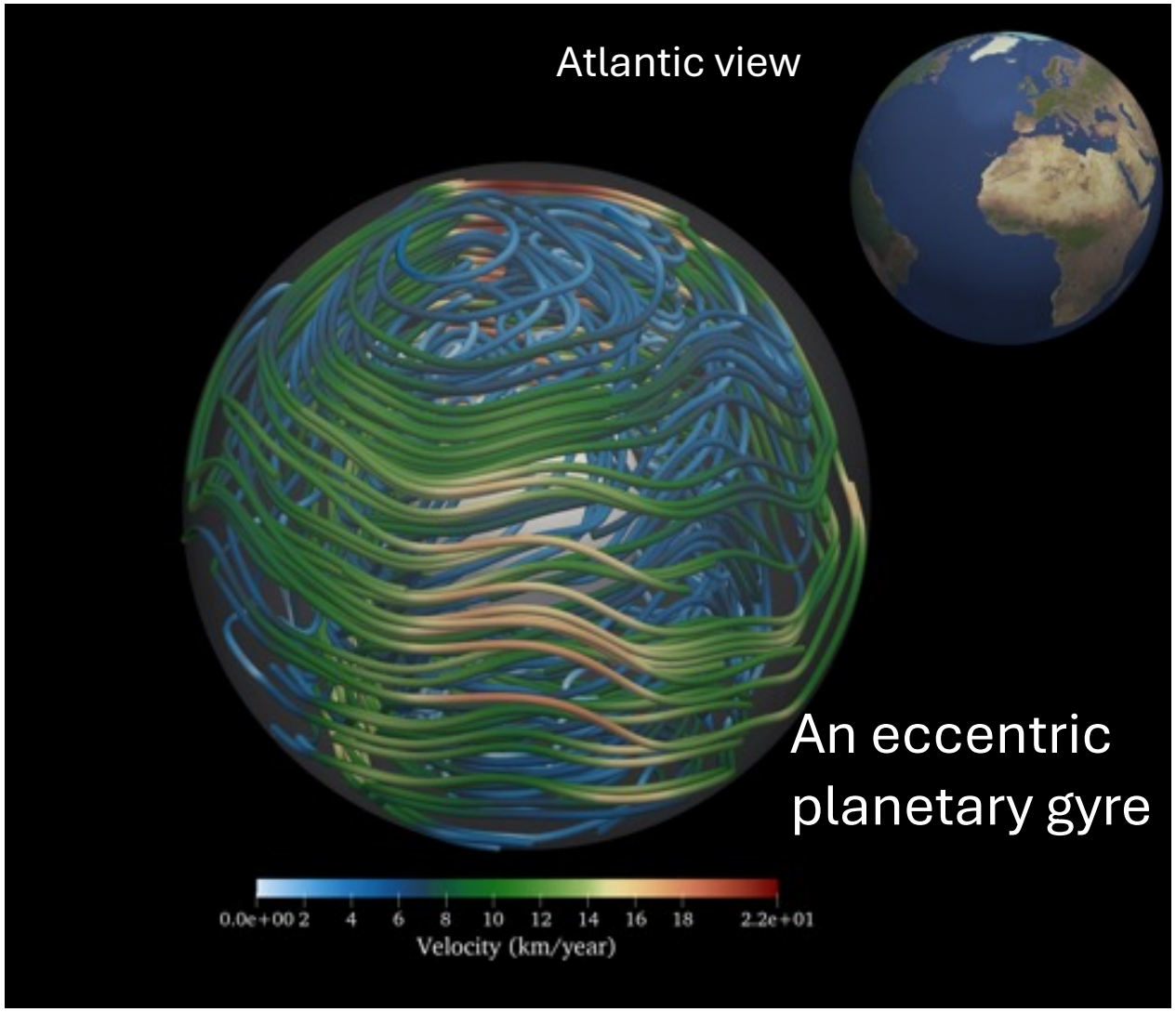


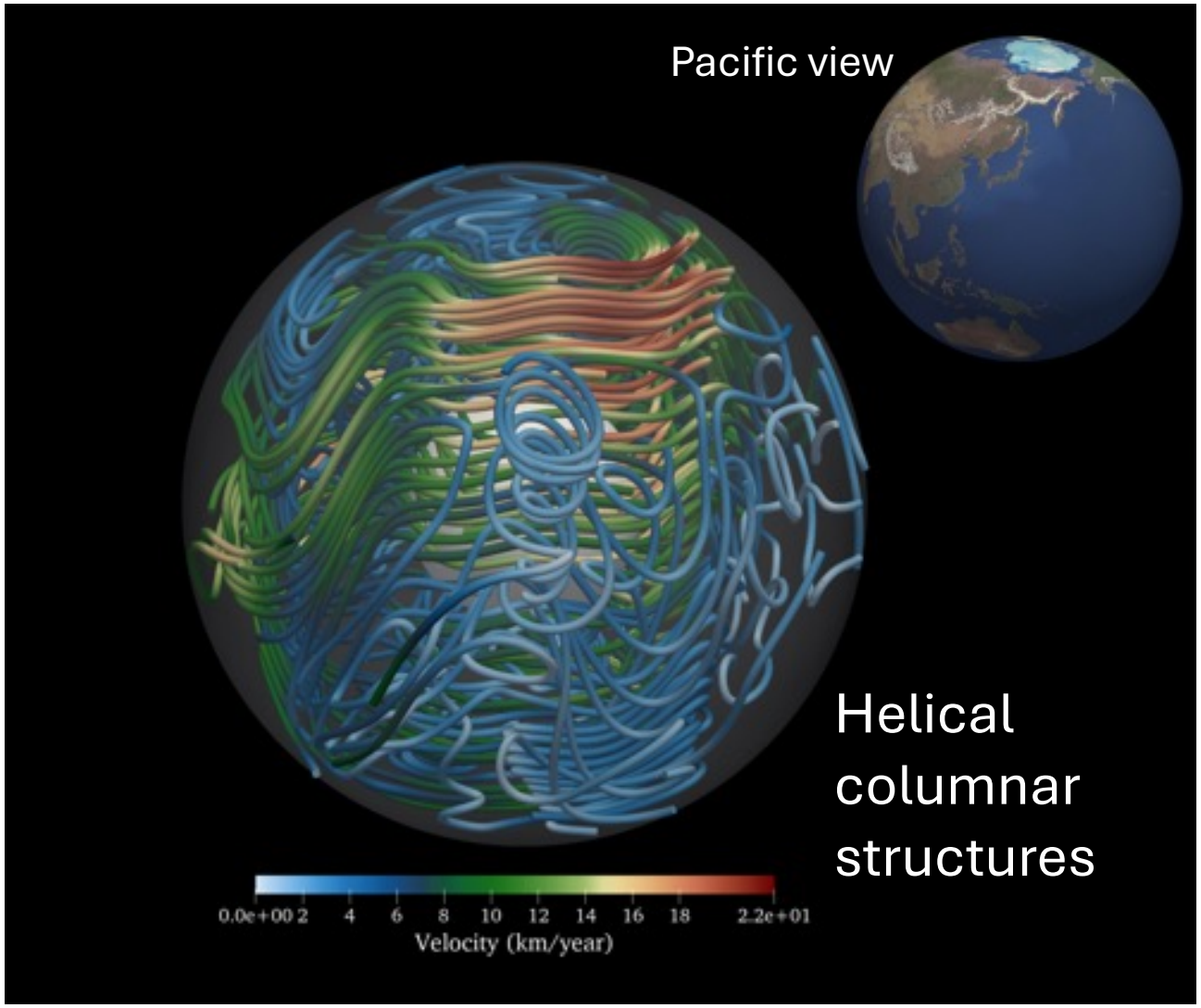
Yao et al., 2025

Core field Br at CMB (MSS1+Swarm)



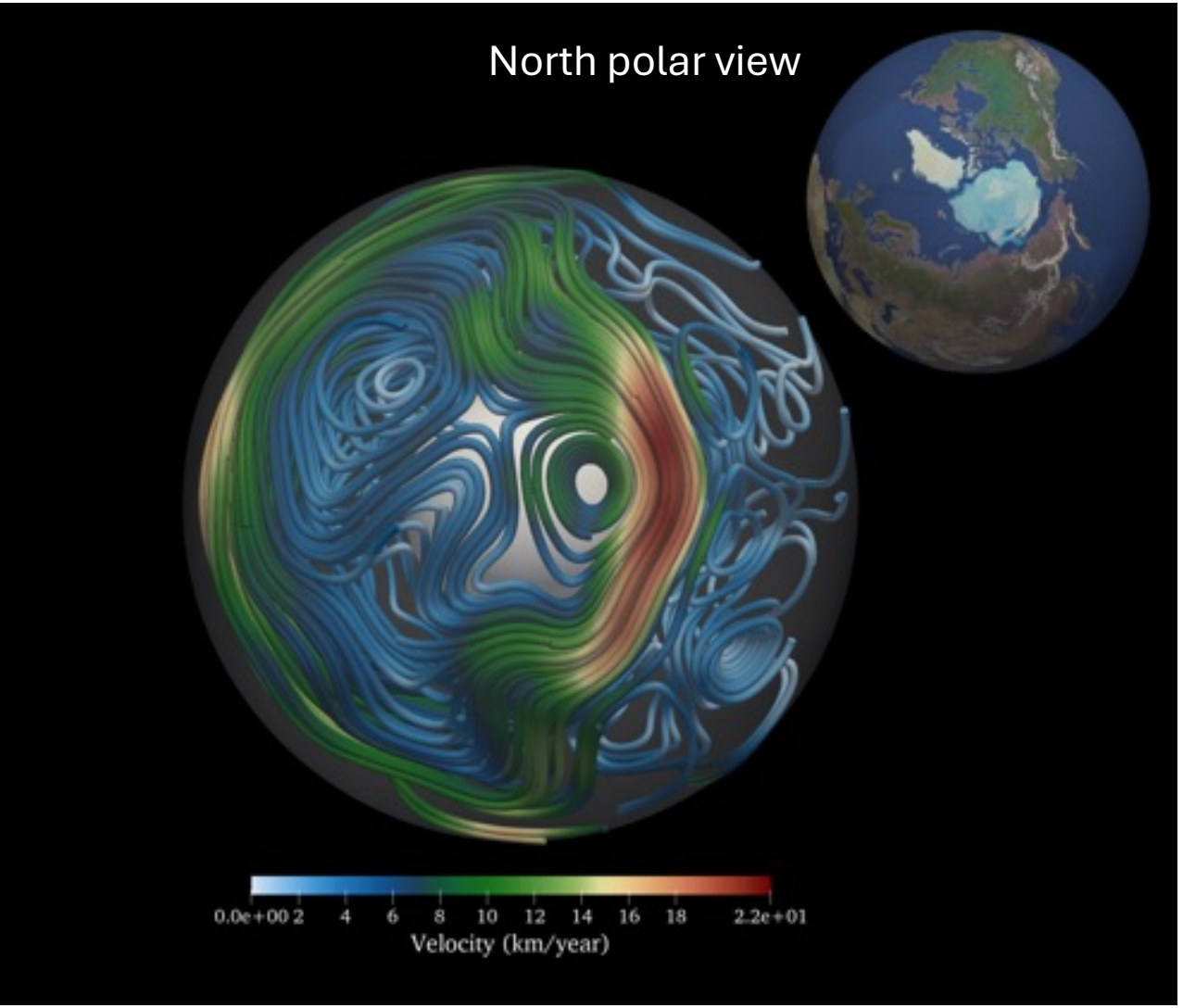
3-D streamlines

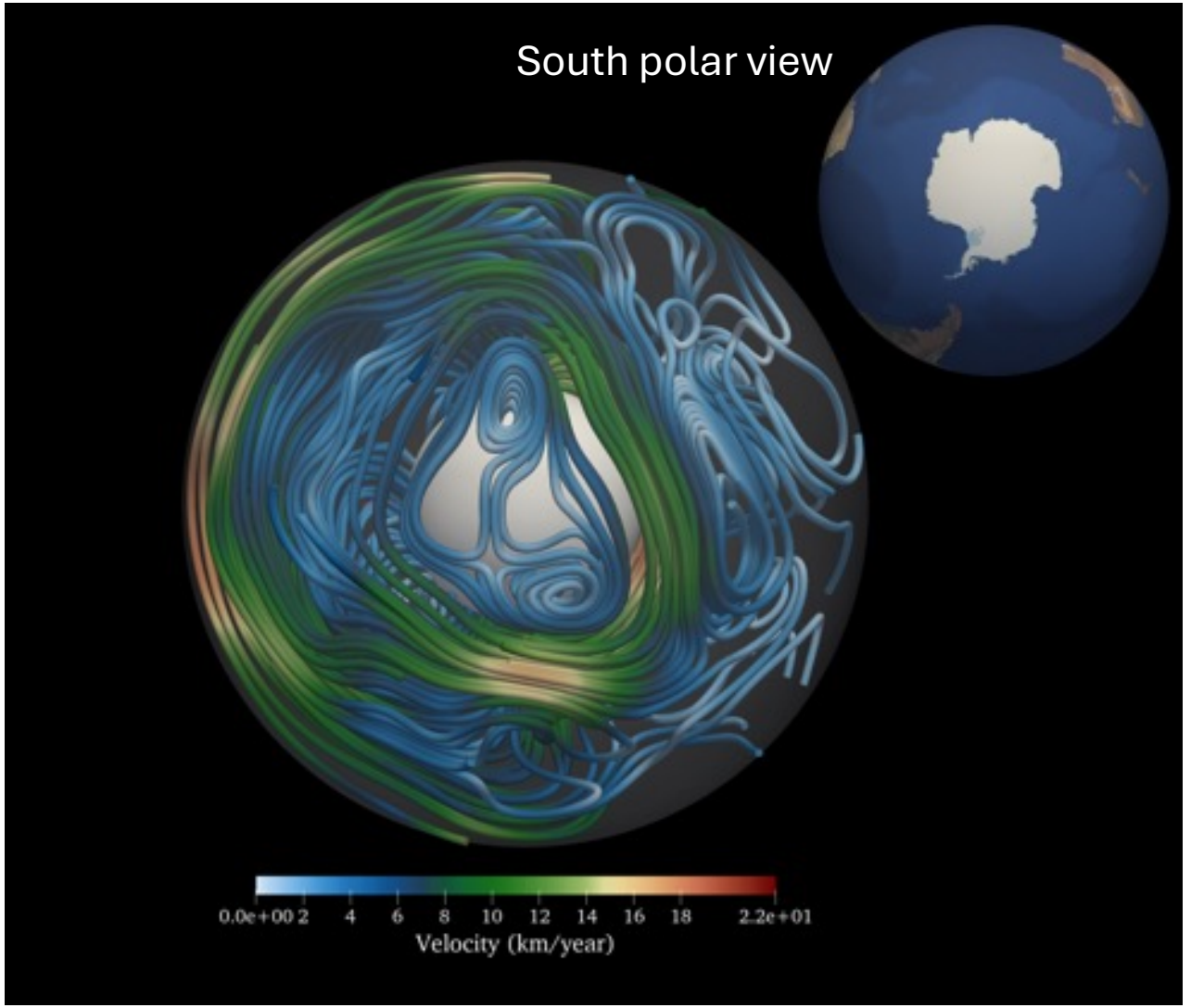




East-West Asymmetry of the Core Flow

3-D streamlines



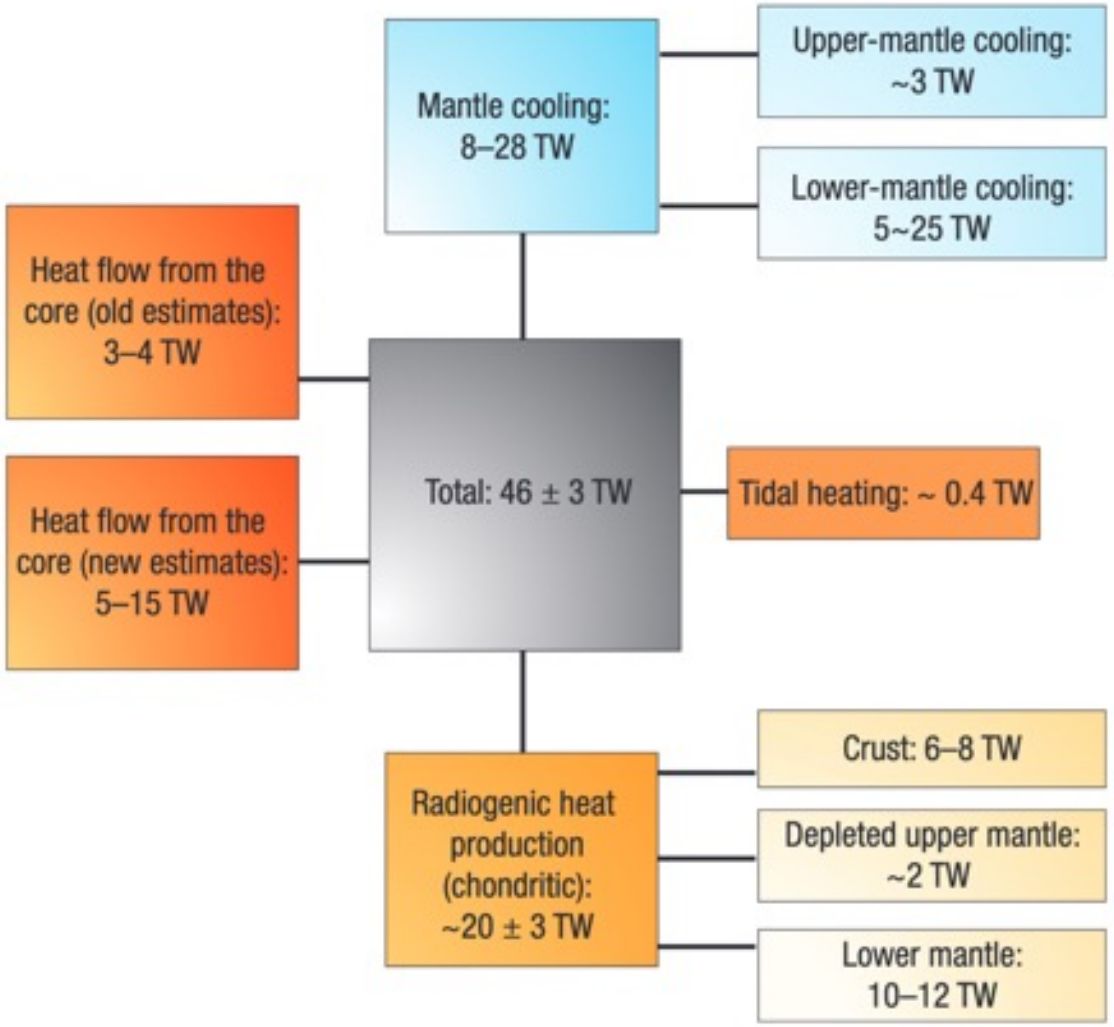


East-West Asymmetry of the Core Flow

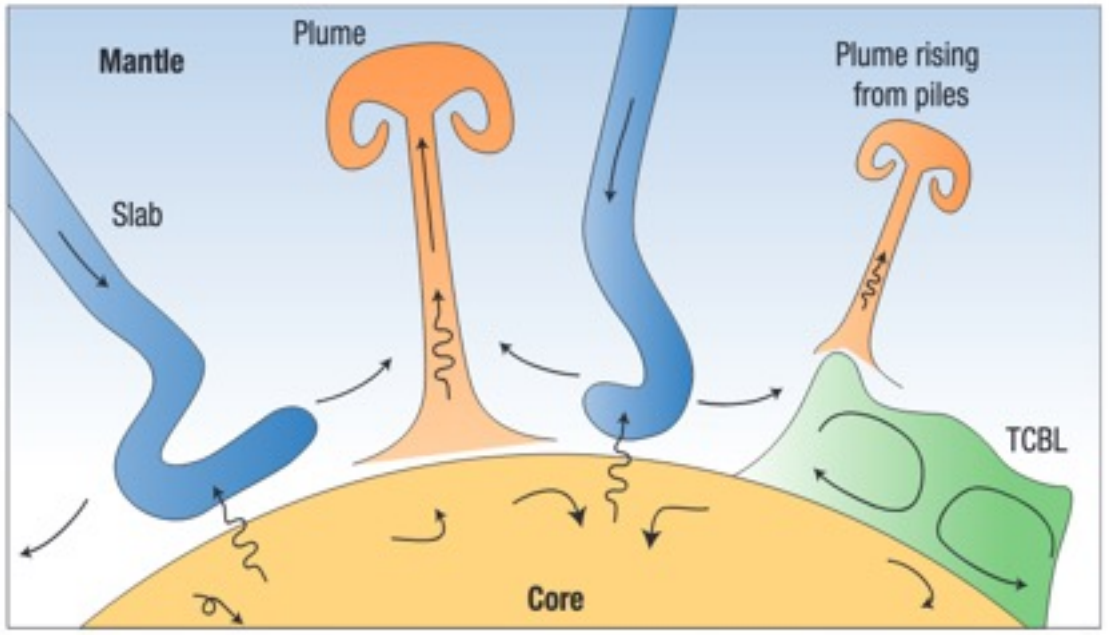
Outline

- Structure and composition of the core
- Core dynamics: Earth's magnetic field generation
- **Energy budget and thermal evolution of the core**

Global energy budget



Lay et al., 2008, Nature Geo.



Mantle dynamics determines the CMB heat flow, with feedback from the core temperature.

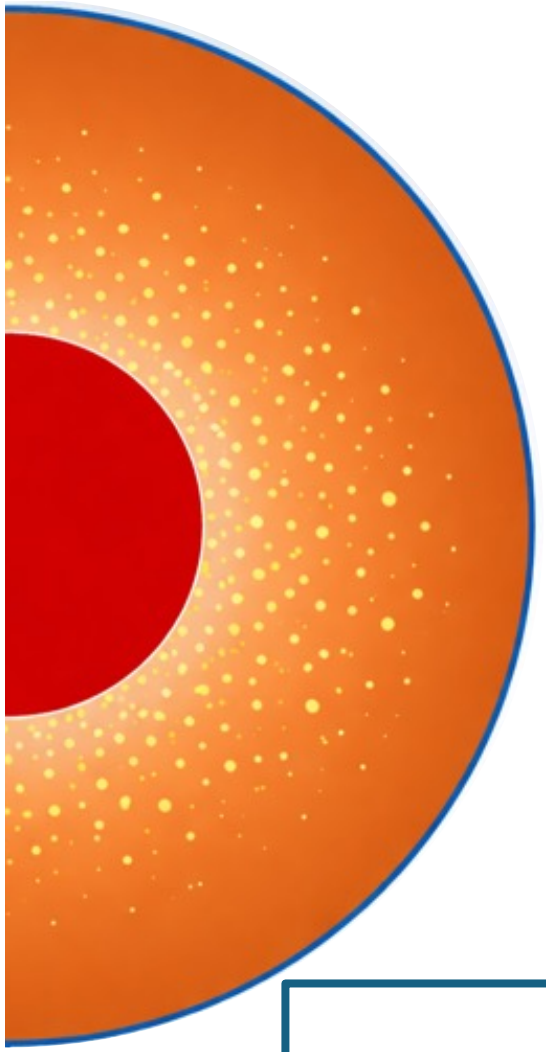
Energy budget of the core

Secular coolling $Q_s = -\int \rho C_p \frac{DT}{Dt}\, dV$

Radiogenic heat $Q_R = \int \rho h\, dV$

Gravitational energy (release of light elements) $Q_g = \int \rho \Psi \alpha_c \frac{Dc}{Dt}\, dV$

Latent heat (liquid to solid) $Q_L = 4\pi r_i^2 L_H \rho_i \frac{dr_i}{dt}$



Heat flow through CMB $Q_{cmb} = \oint \mathbf{q} \cdot d\mathbf{S}$

Determined by mantle

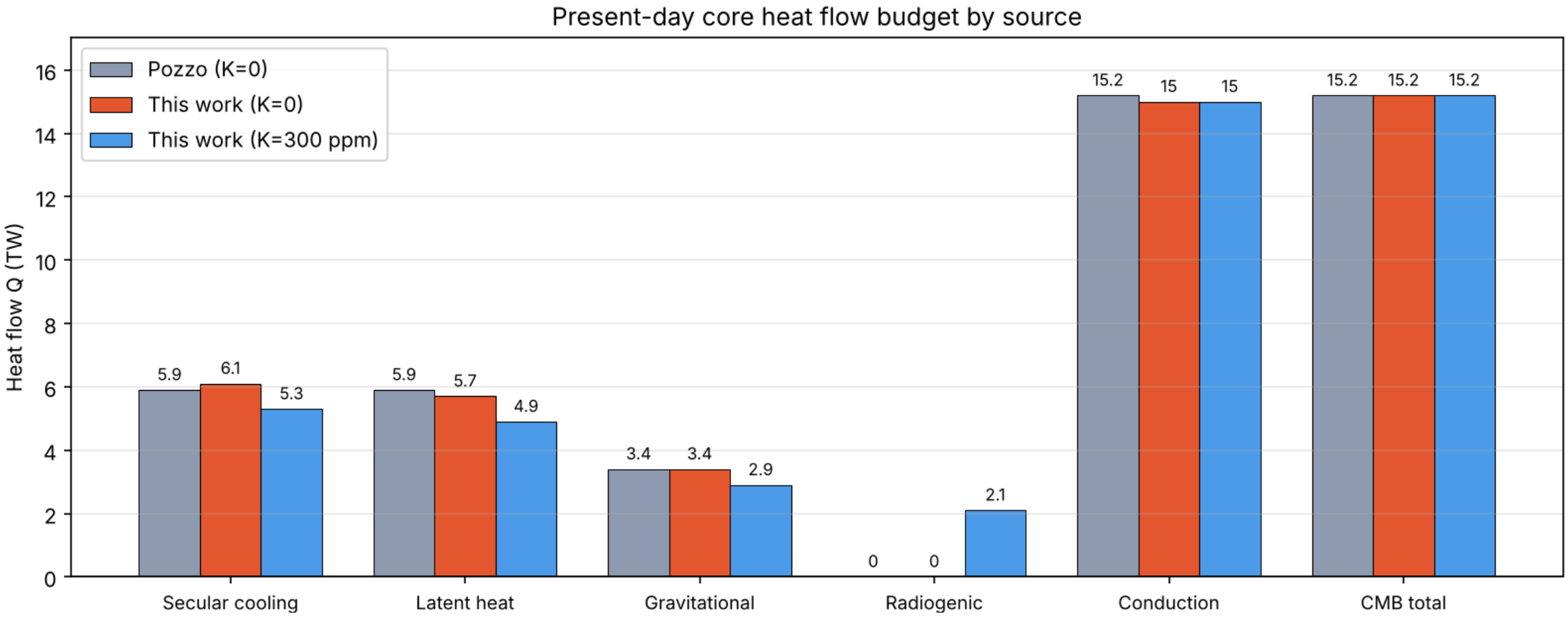
$$Q_{cmb} = Q_R + Q_s + Q_g + Q_L = Q_R + \tilde{Q}_T \frac{dT_c}{dt}$$

Present-day energy budget

	Pozzo (K=0)		*This work (K=0)*		*This work (K=300 ppm)*	
	Q *(TW)*	E *(MW K^{-1})*	Q *(TW)*	E *(MW K^{-1})*	Q *(TW)*	E *(MW K^{-1})*
Q_s, E_s	5.9	212	6.1	183	5.3	159
Q_L, E_L	5.9	389	5.7	327	4.9	284
Q_g, E_g	3.4	830	3.4	809	2.9	701
Q_R, E_R	0	0	0	0	2.1	60
Q_k, E_k	15.2	−561	15.0	−450	15.0	−450
Q_{cmb}, ΔE	15.2	870	15.2	869	15.2	753
dT_c/dt (K Gyr^{-1})	−115		−104		−90	
r_i/dt (km Gyr^{-1})	1092		1050		909	
IC age (Gyr)	0.37		0.59		0.68	

Nimmo, 2015

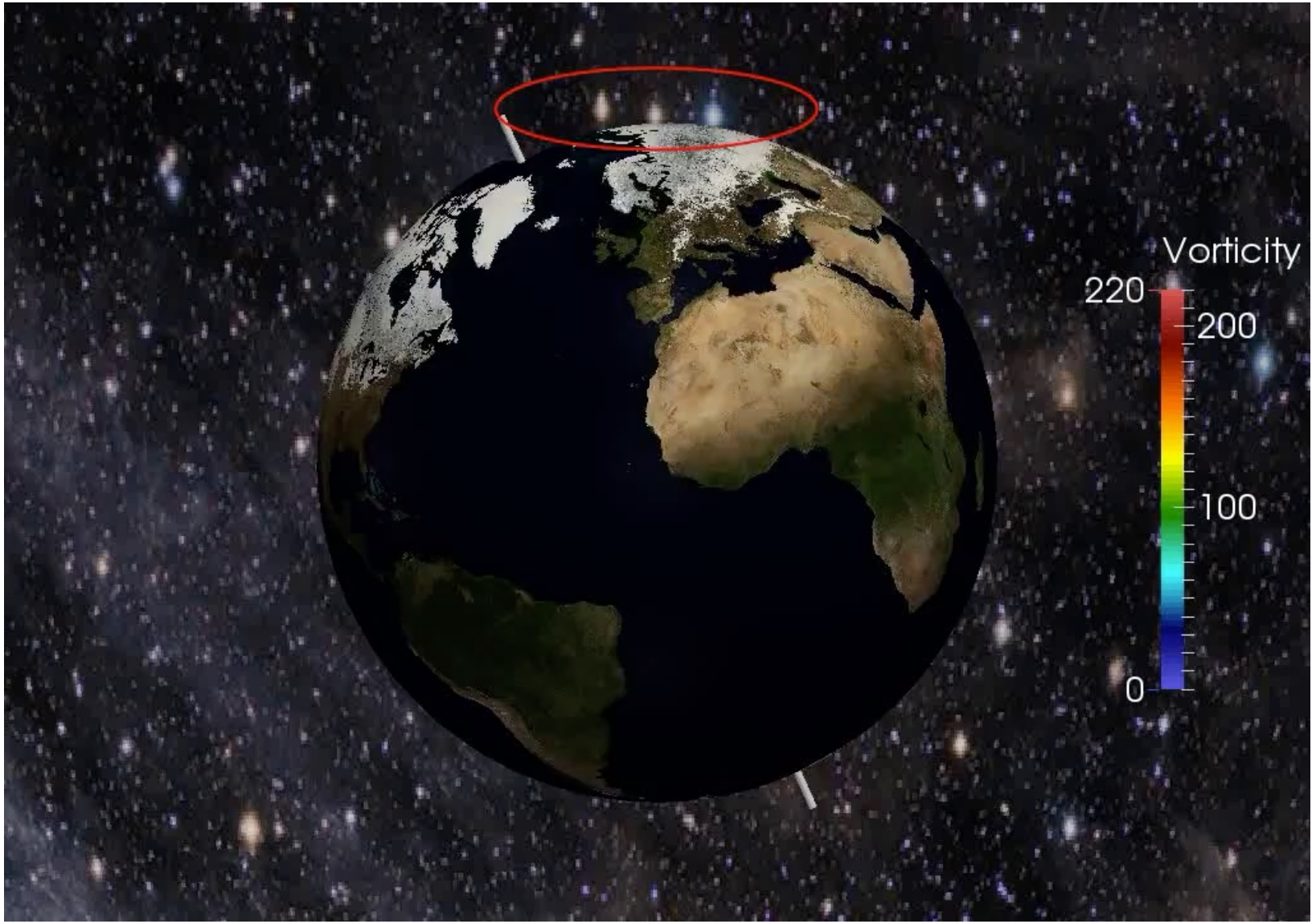
Present-day energy budget



The presence of radiogenic heat slows donw the secular cooling, and thus reduce the grow rate of the inner core.

External energy

- Tides
- Precession
- Libration
- Impact



Thermal evolution of the core

$$Q_{cmb} = Q_R + Q_s + Q_g + Q_L = Q_R + \tilde{Q}_T \frac{dT_c}{dt}$$

Core cooling history

$$\frac{dT_c}{dt} = \frac{Q_{cmb} - Q_R}{\tilde{Q}_T}$$

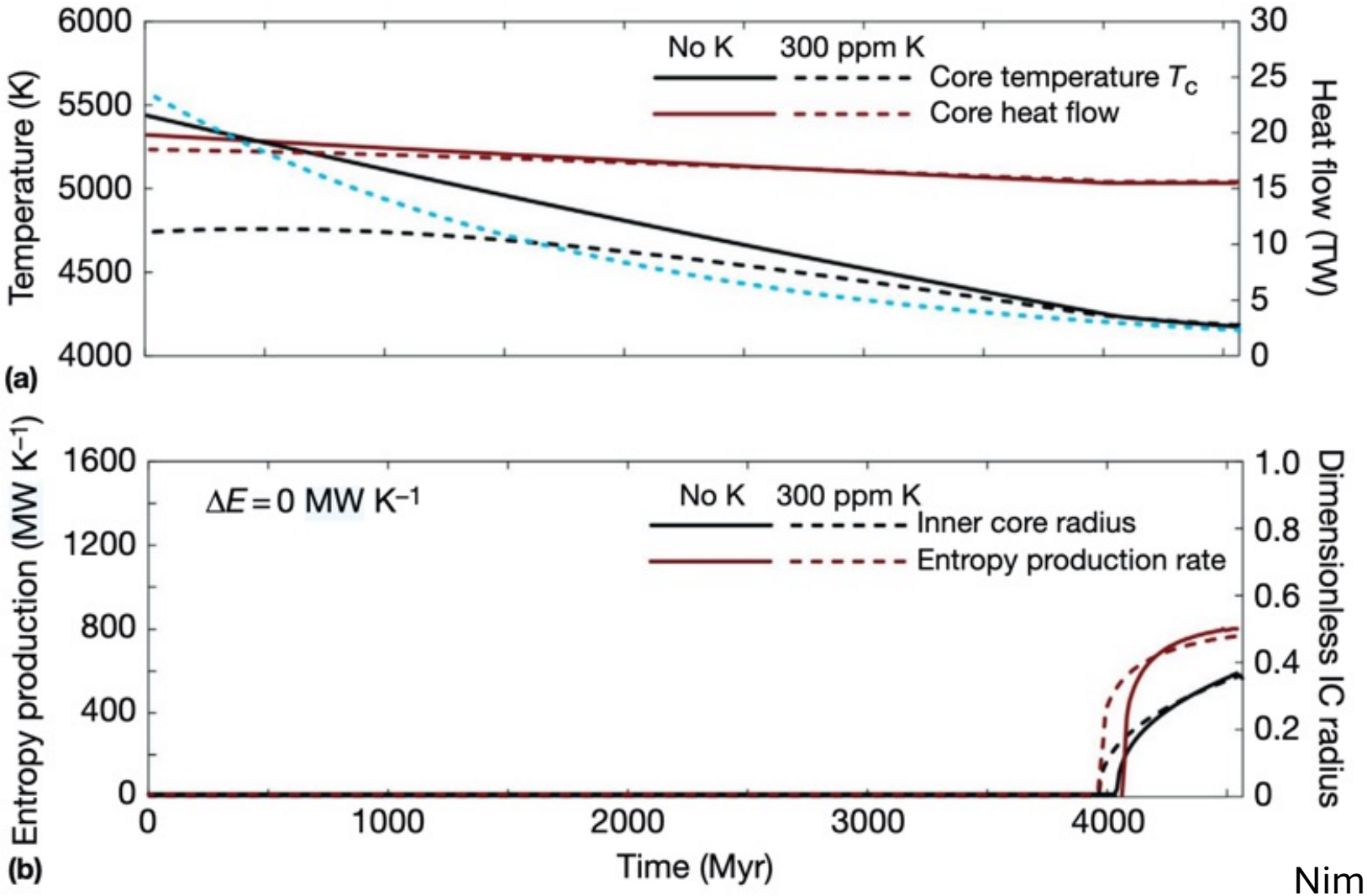
Construct the thermal history by integrating this eqaution backward from the present-day.

Large uncertainties:

- Time variation of Q_{cmb}
- Thermal and chemical properties of the core

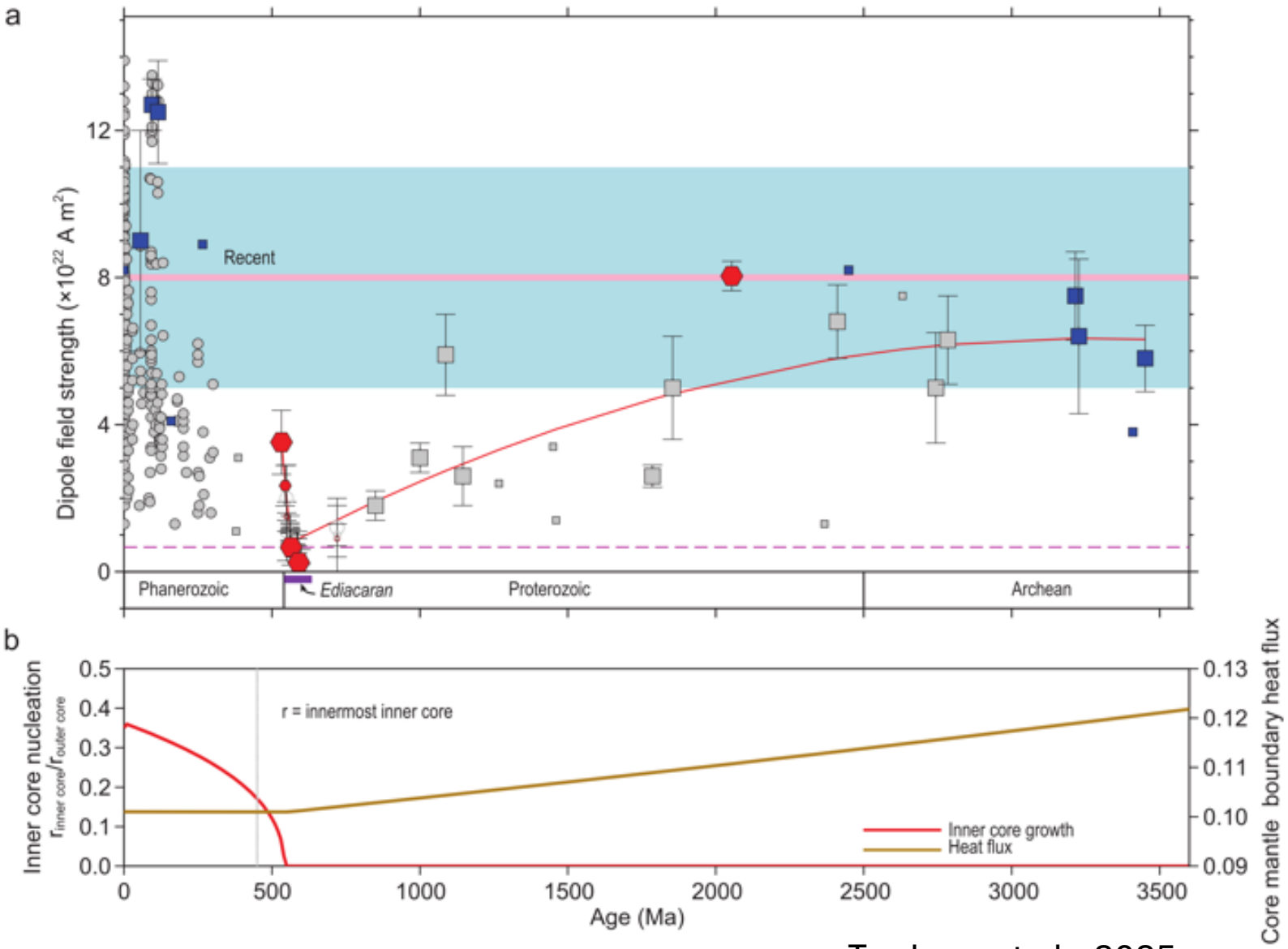
Thermal evolution of the core

An example model



Nimmo, 2015

Geomagnetic signature of ICN?



Tarduno et al., 2025

- Pacucity and uncertainties of paleomagnetic data
- Estimate the magnetic field strengthen and morphology from dyamo theory.

Summary

- Earth's core is primarily made of iron and some light elements. Its structure evolves over time. At present it consists of a solid inner core and a liquid outer core.
- Earth's magnetic field is generated in the core through dynamo action, which has been sustained for at least 3.5 billion years.
- The thermal history and present-day energy budget of the core can be constructed from first-principles thermodynamics, but with large uncertainties.
- Geoneutrino measurements may add further constraints on the radiogenic heat.