The role of the Swarm mission in advancing our understanding of Earth's core dynamics

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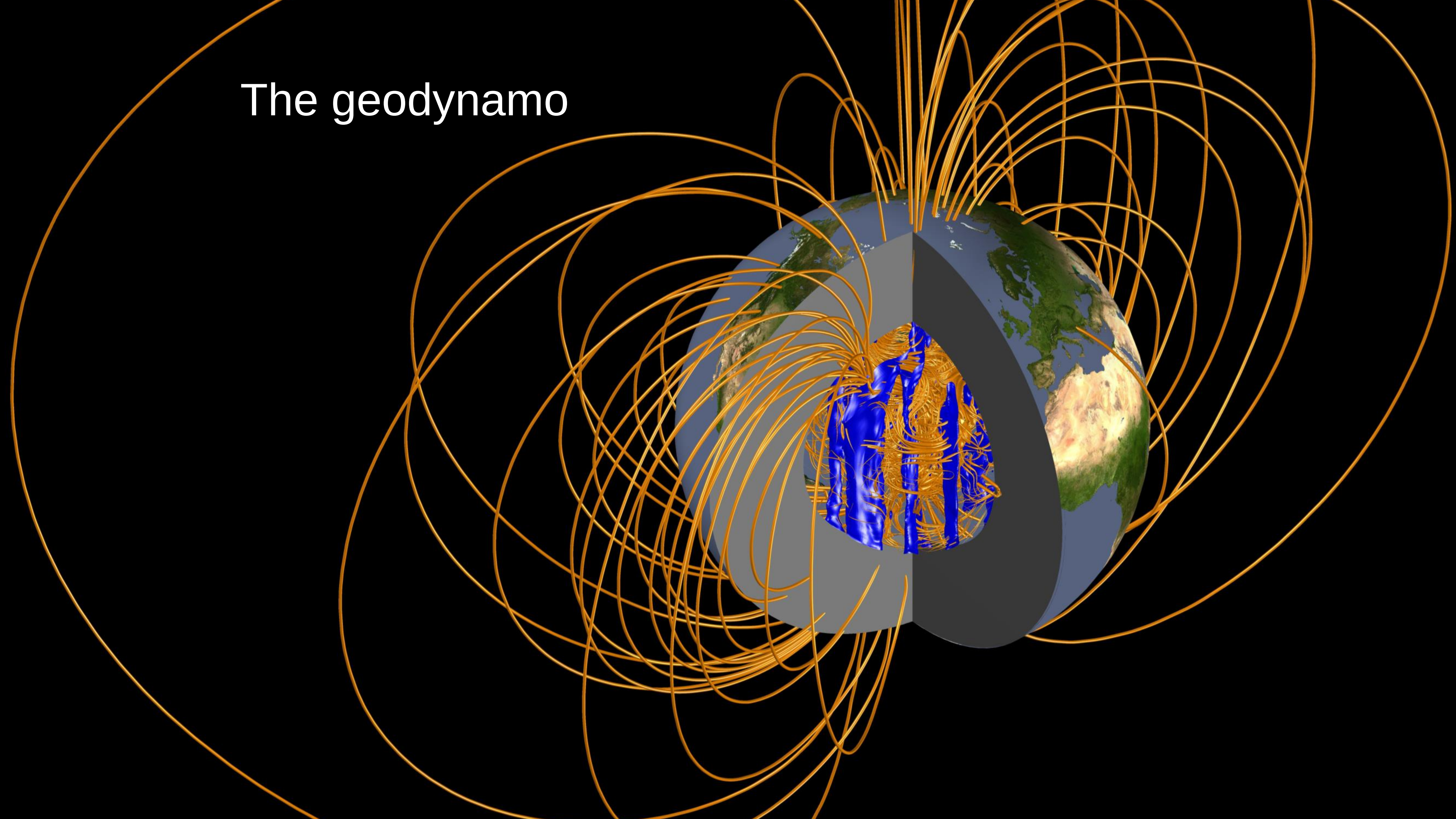
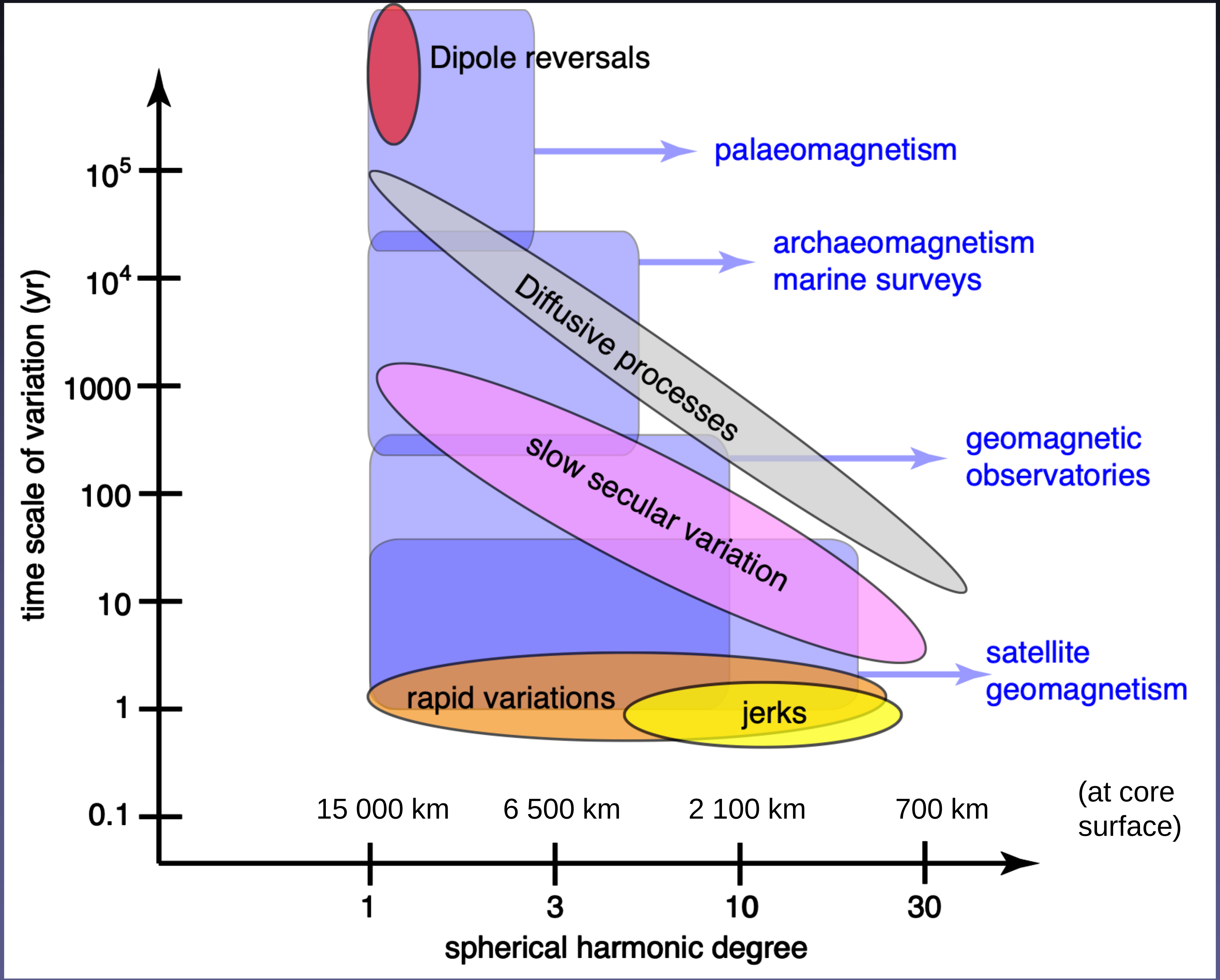
Swarm 10 Year Anniversary & Science Conference 2024

The geodynamo



Observing the geodynamo across time (and space) scales



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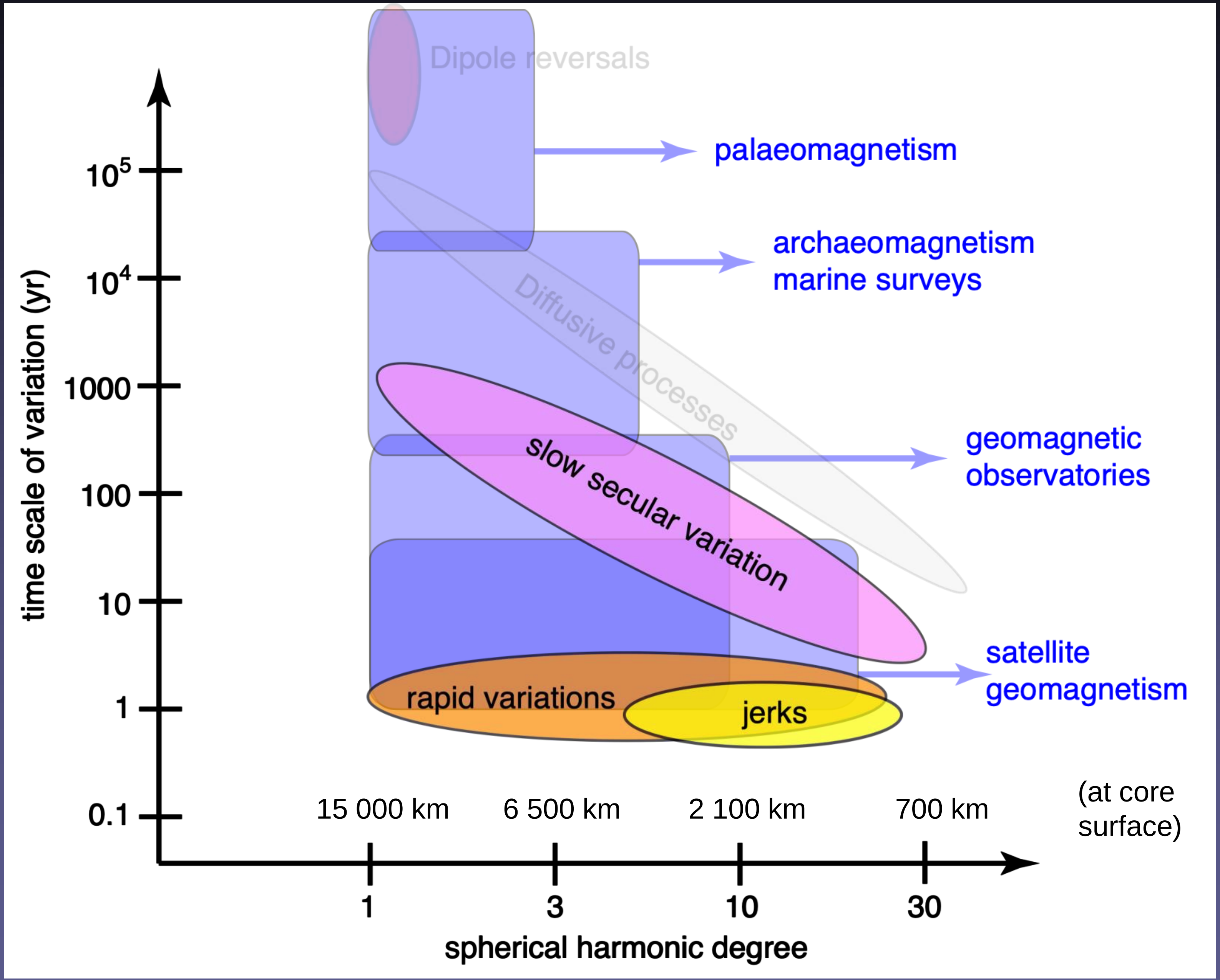


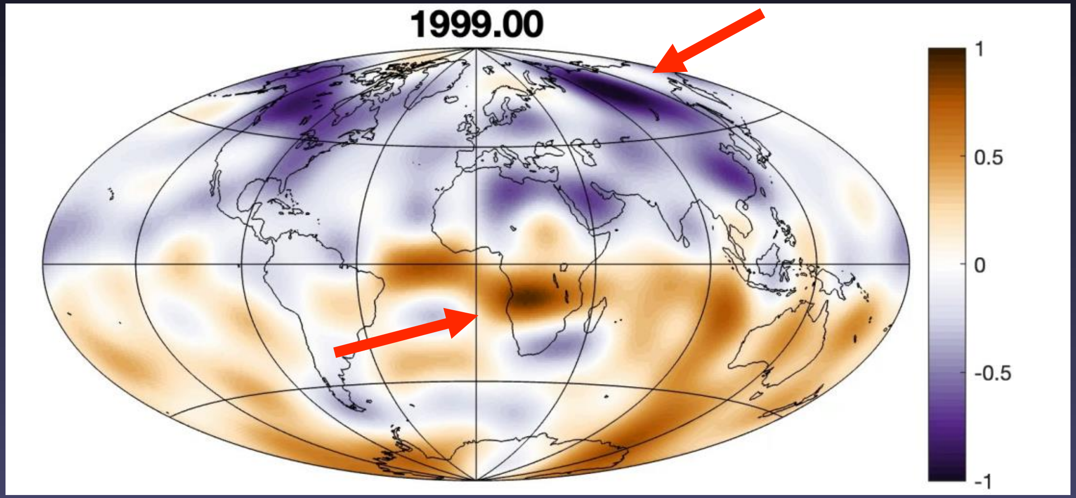
Outline

- 10 years of Swarm: vastly improved knowledge on the rapid signals co-existing with the slower secular geomagnetic variation.
- This has stimulated developments in theory and numerical geodynamo simulations, with the aim of providing a physical explanation of these signals.
- The numerical simulations solving the equations of convective fluid motion and magnetohydrodynamic induction in Earth's core have been used either as
  - direct simulations unconstrained by the data to study the rapid signals.
  - inverse models estimating the state of the geodynamo based on the data and the statistics of direct models, using data assimilation techniques. This was used to study the slow signals.
- This was done within the framework of the Swarm + 4D Deep Earth: Core project funded by ESA (2019-2024)

1- Magnetic field variations: gyres and jets

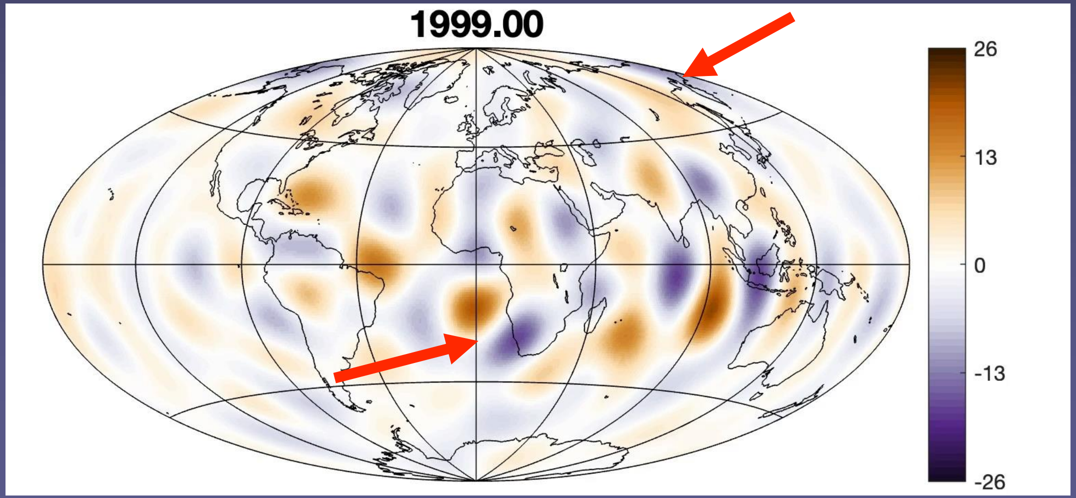
The geomagnetic field and its variations at the core-mantle boundary, as seen by satellites

radial field

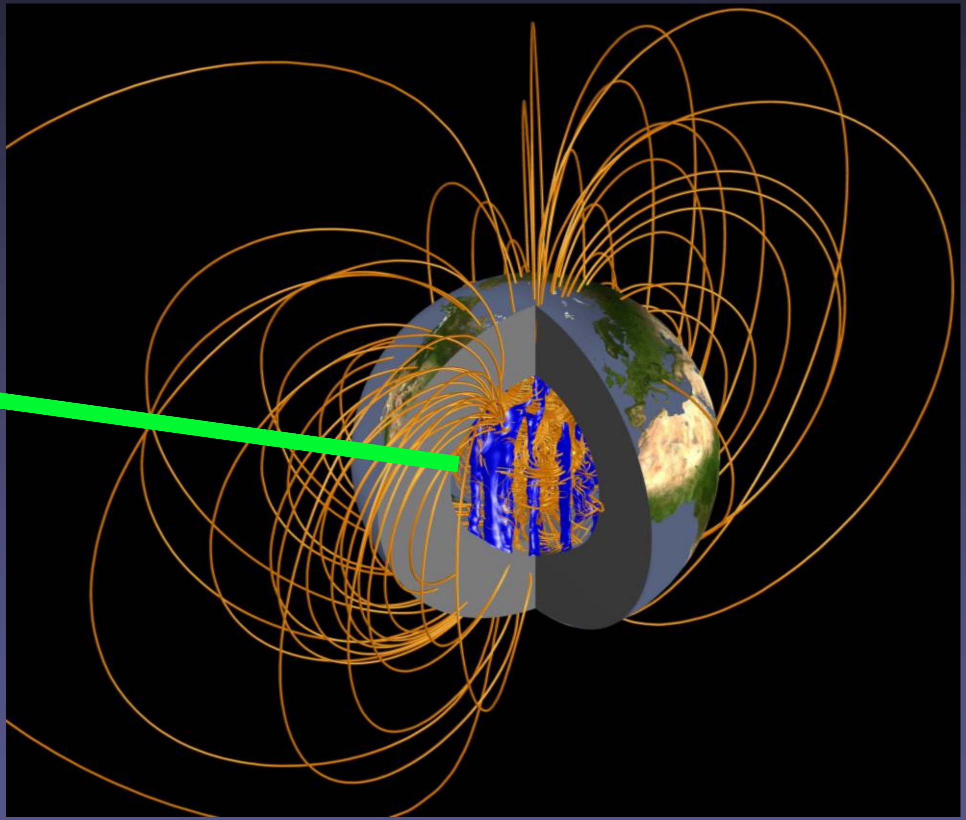


mT

rate of change



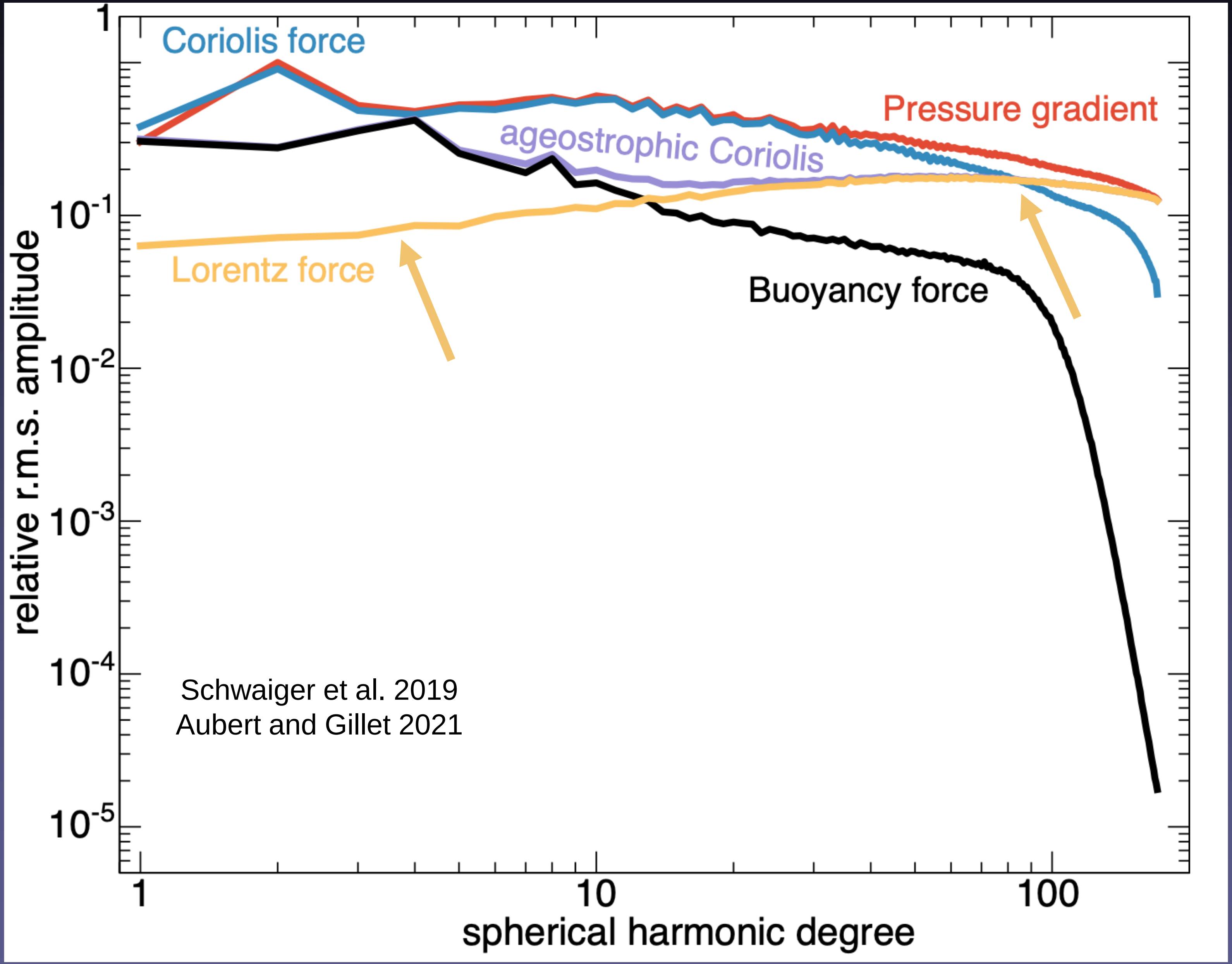
μT/yr



$$B/\dot{B} \approx 100 \text{ yr}$$

geomagnetic field model CHAOS-7 (Finlay et al. 2020)

Slow dynamics: a ‘thermal’ wind



Coriolis force ~ pressure gradient: quasi-geostrophic equilibrium

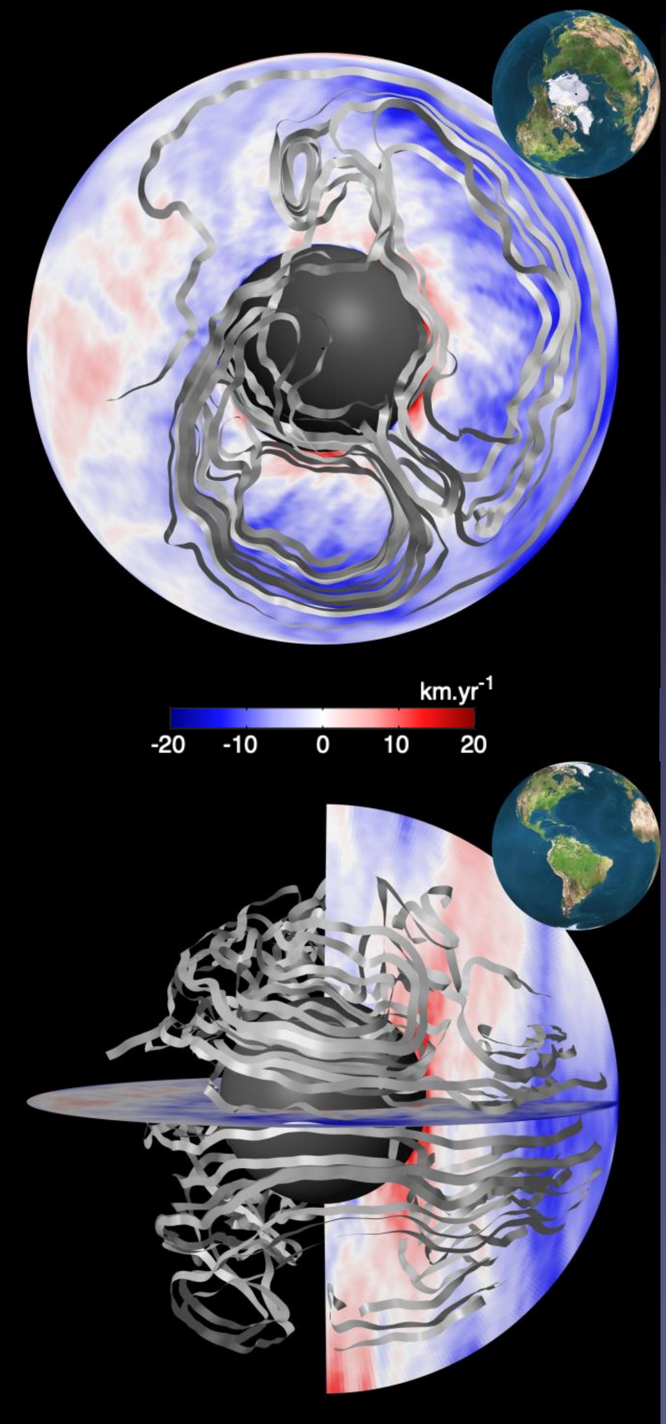
Remainder ~ Buoyancy ~ Lorentz force: MAC balance

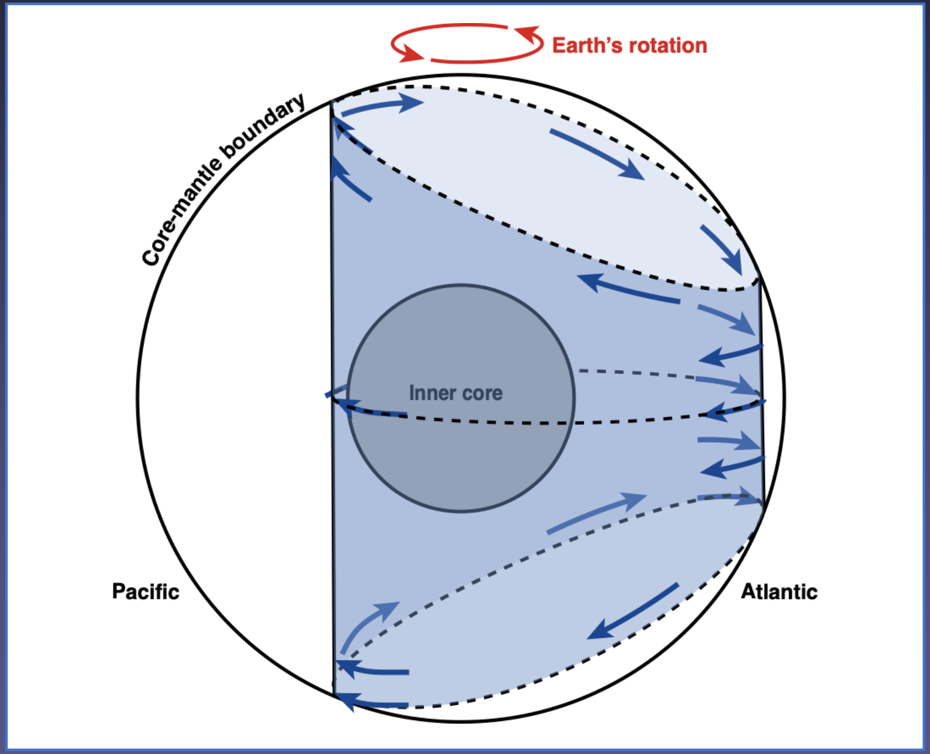
Impact of Lorentz forces mimised because of Lenz’ law

Thermal wind convective time scale

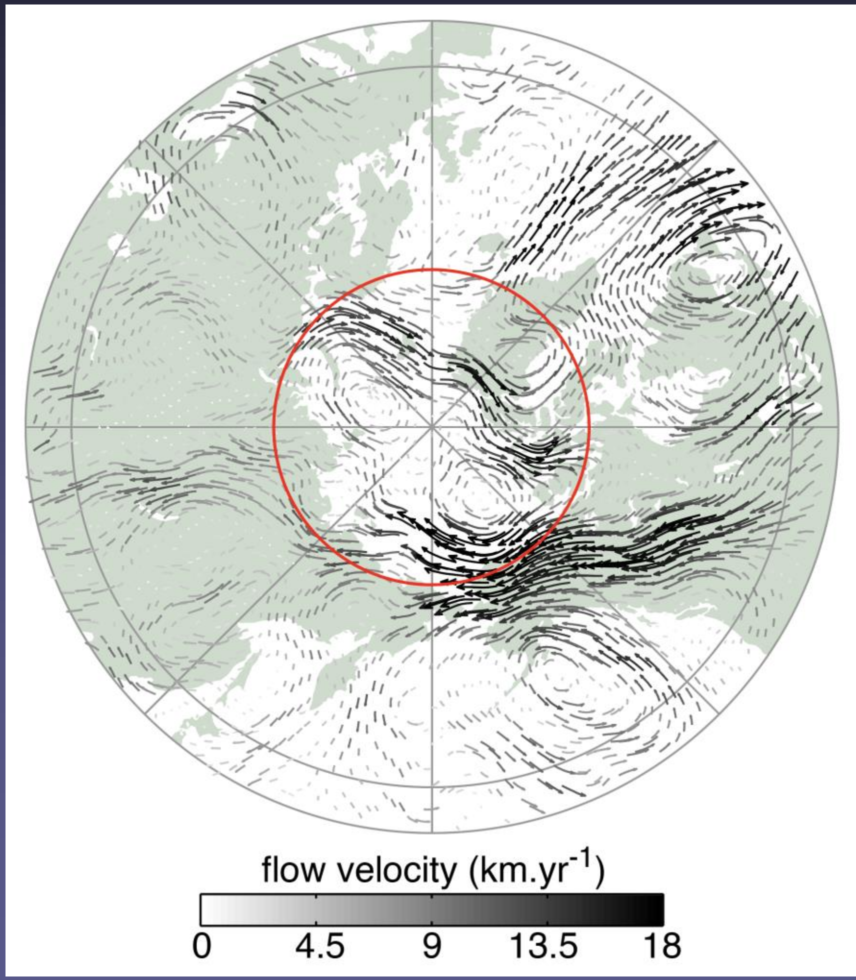
$$\tau_U \approx \frac{\rho \Omega d}{g_o C} \approx 130 \text{ yr}$$

The thermal wind in Earth's core at present: the 'gyre'… …and the 'jet'

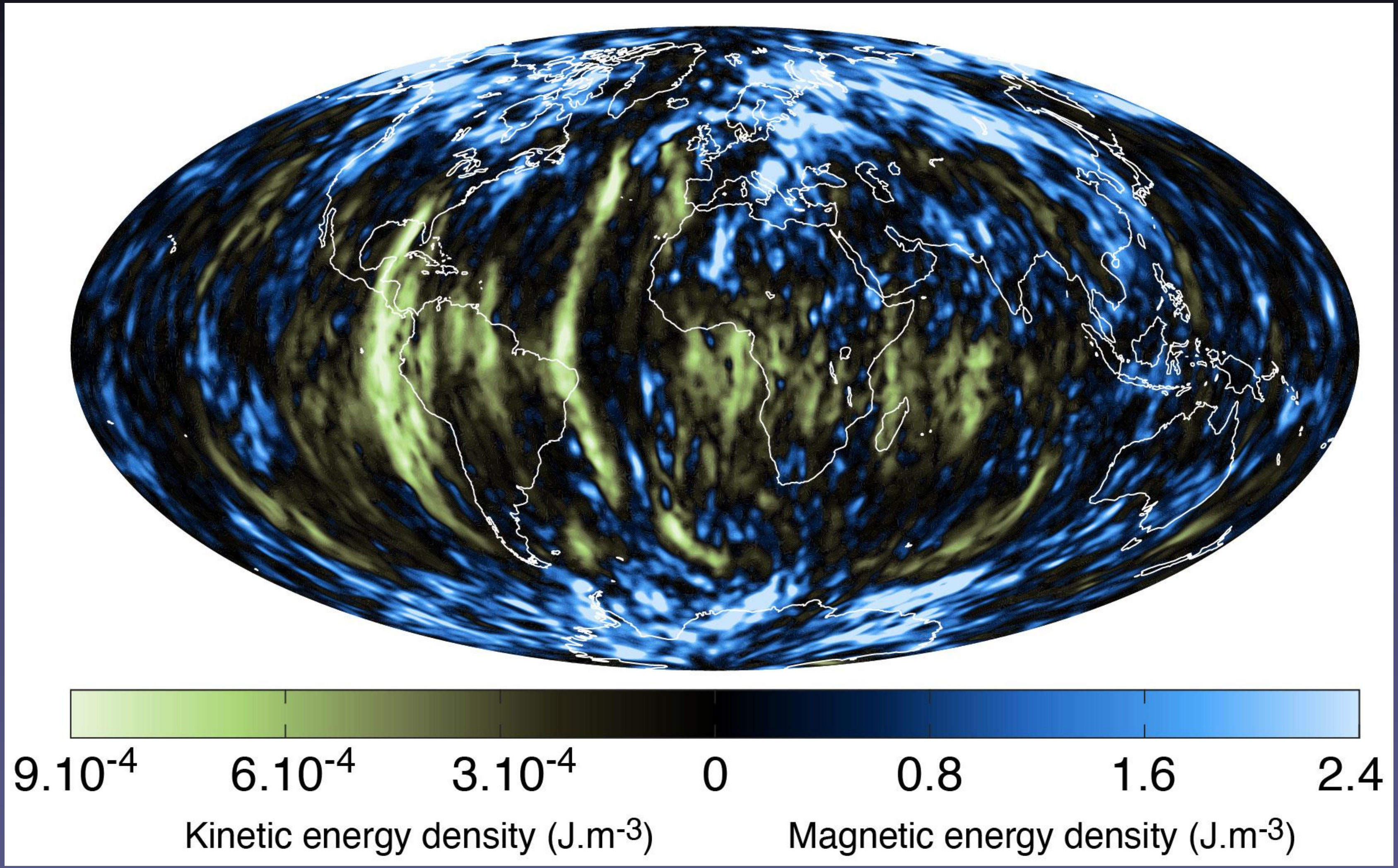




Pais and Jault 2008
Gillet et al. 2015
Livermore et al. 2017
Baerenzung et al. 2018
Aubert 2023, Finlay et al. 2023



The thermal wind roots the South Atlantic anomaly deep in the core

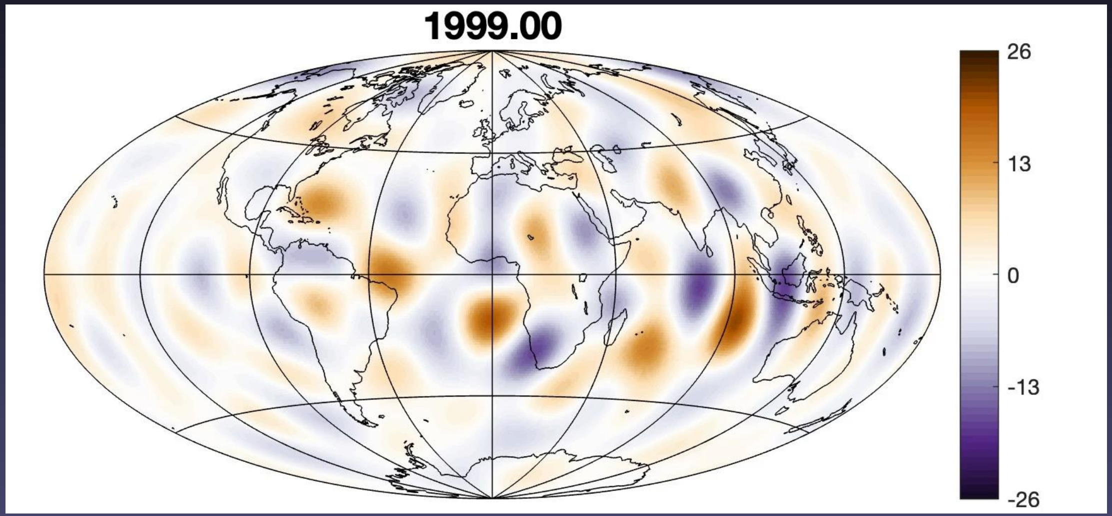


energy densities at mid-depth in the core

2- Magnetic field acceleration: waves

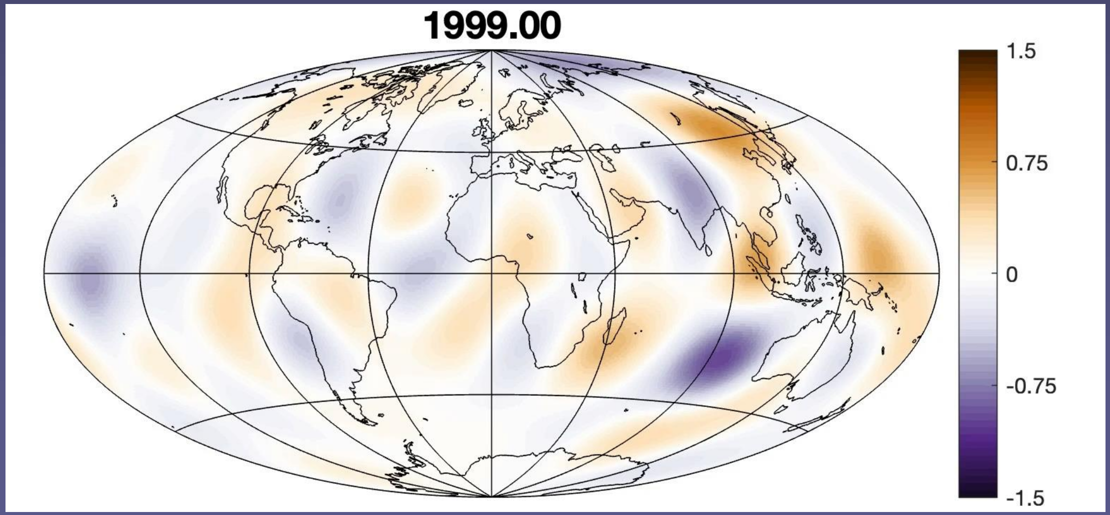
The geomagnetic field variation and acceleration at the core-mantle boundary, as seen by satellites

rate of change

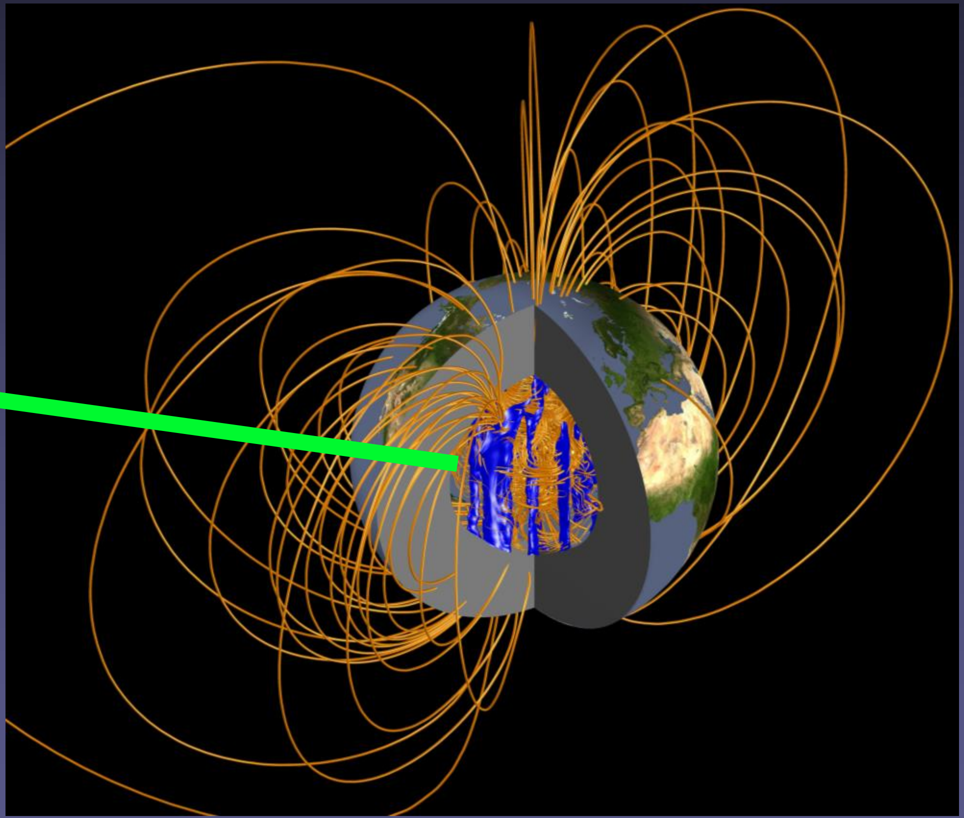


μT/yr

acceleration



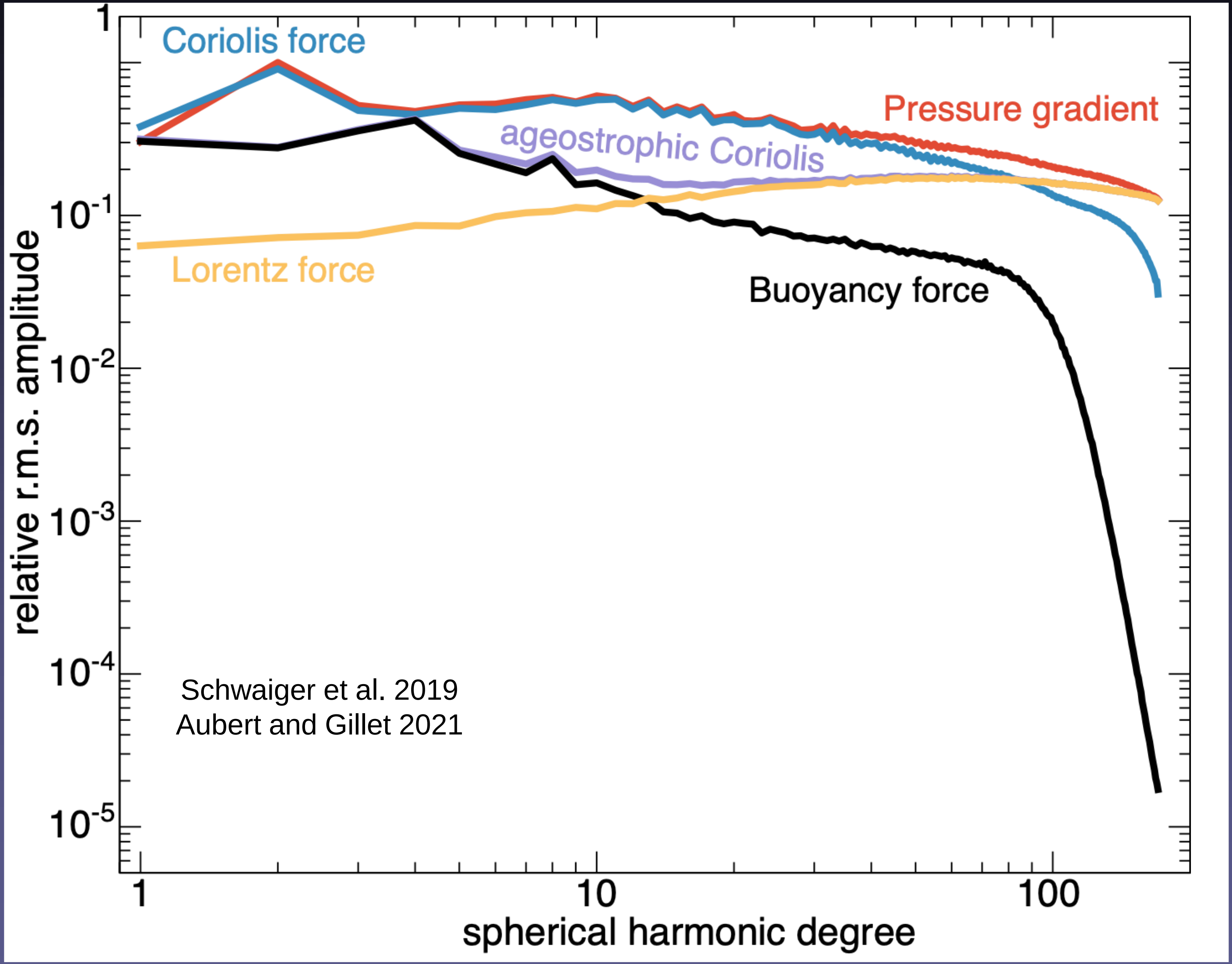
μT/yr^2



$\dot{B}/\ddot{B} \approx 10$ yr

geomagnetic field model CHAOS-7 (Finlay et al. 2020)

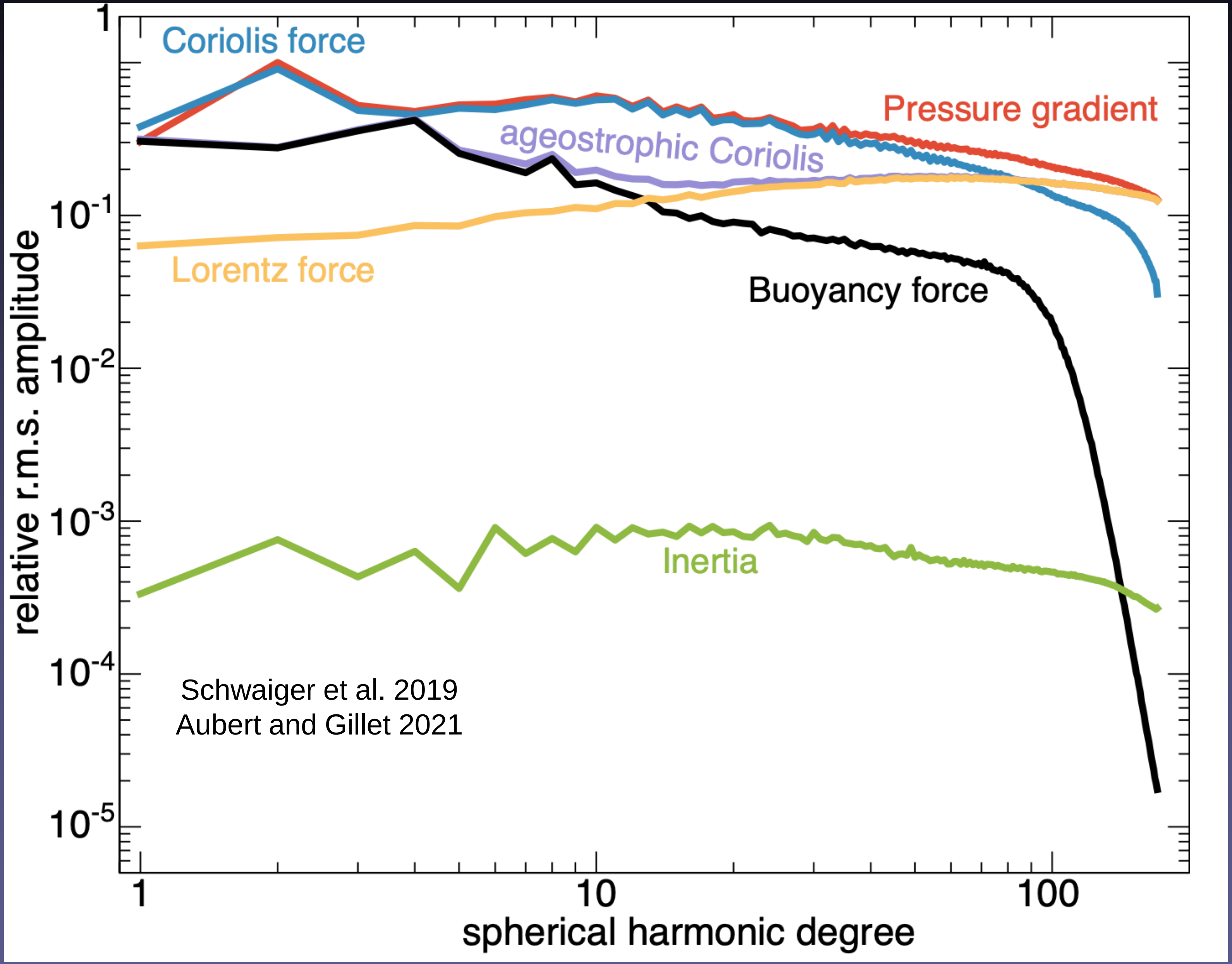
Rapid dynamics and magneto-inertial Alfvén waves



Slow, inertialess dynamics
convective overturn

$$\tau_U \approx \frac{\rho \Omega d}{g_o C} \approx 130 \text{ yr}$$

Rapid dynamics and magneto-inertial Alfvén waves



Slow, inertialess dynamics convective overturn

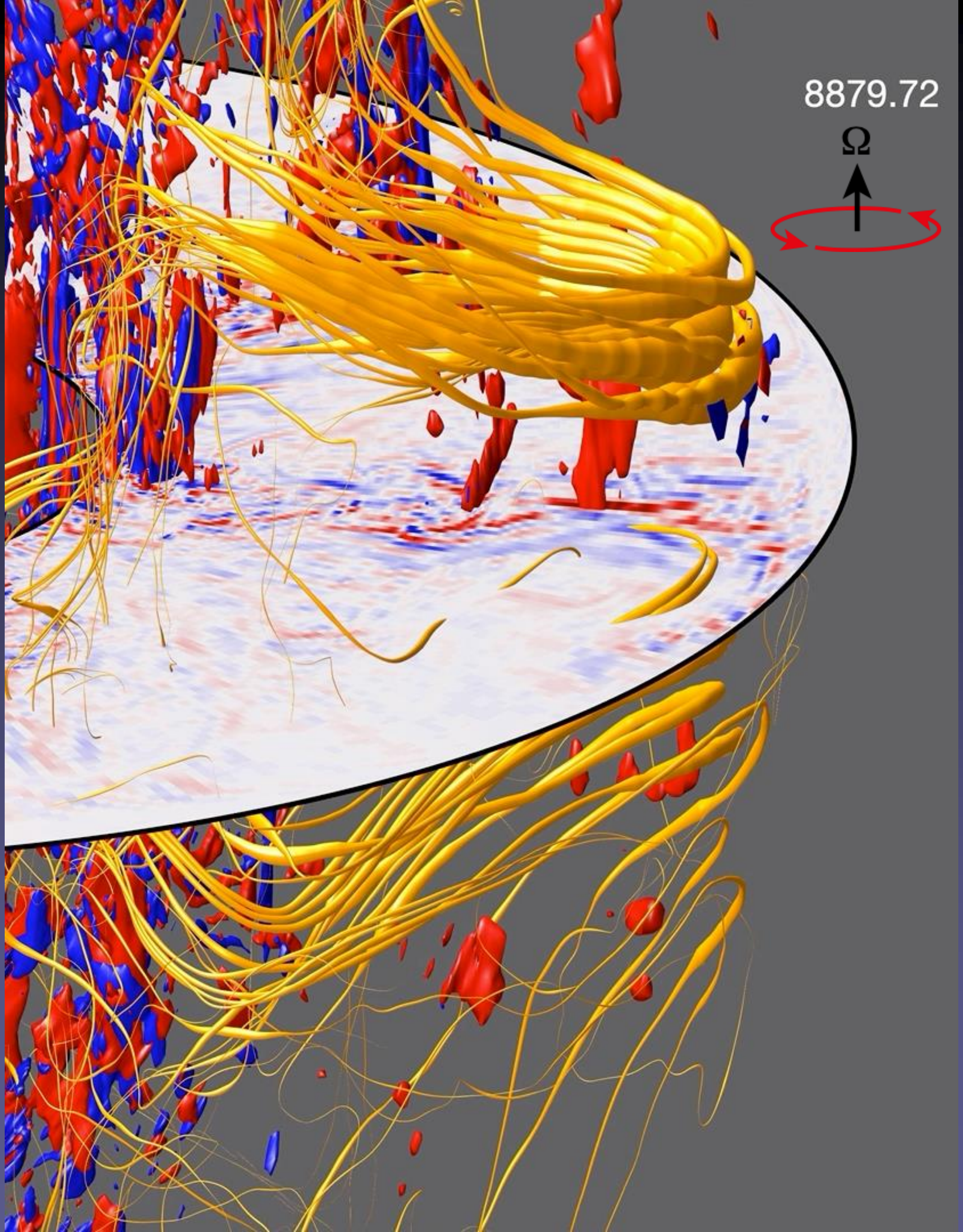
$$\tau_U \approx \frac{\rho \Omega d}{g_o C} \approx 130 \text{ yr}$$

Fast, magneto-inertial dynamics when slow balance is perturbed

Waves at the Alfvén time scale

$$\tau_A = \frac{D\sqrt{\rho\mu}}{B} = 2 \text{ yr in the core}$$

Rapid Alfvén waves

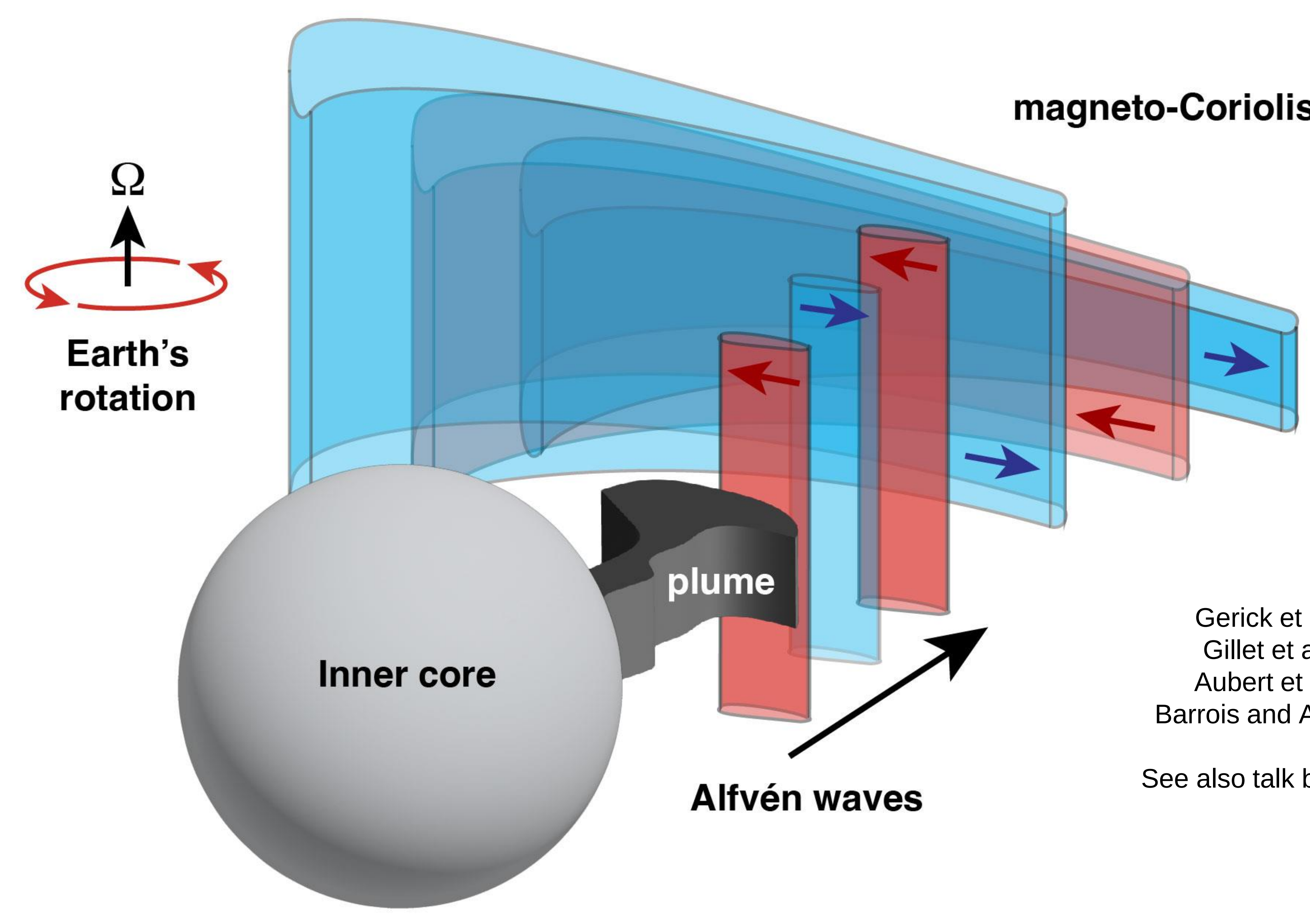


years

Direct simulation

Aubert et al. 2022

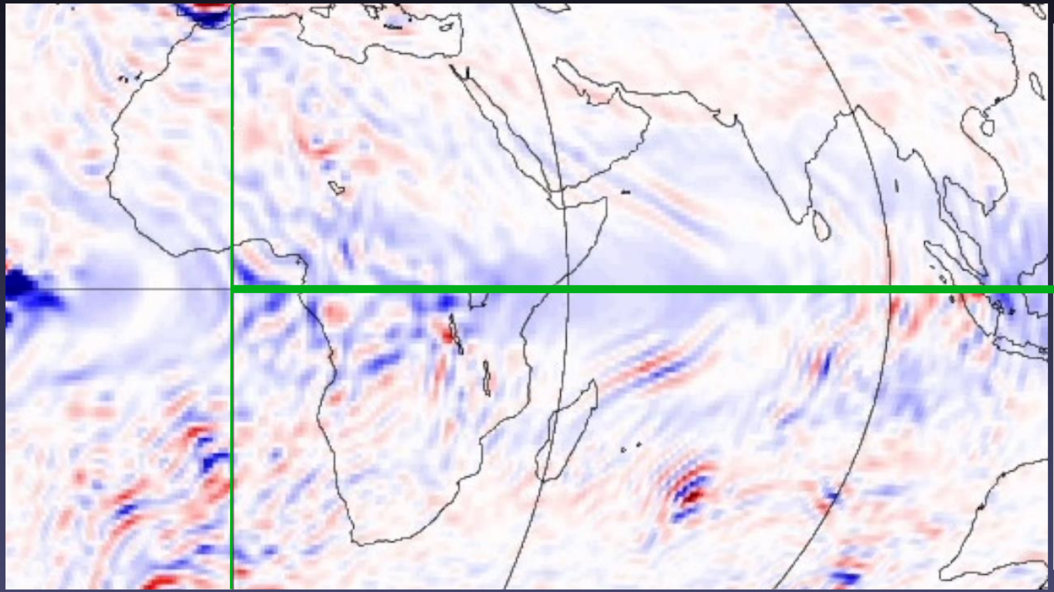
More rapid waves



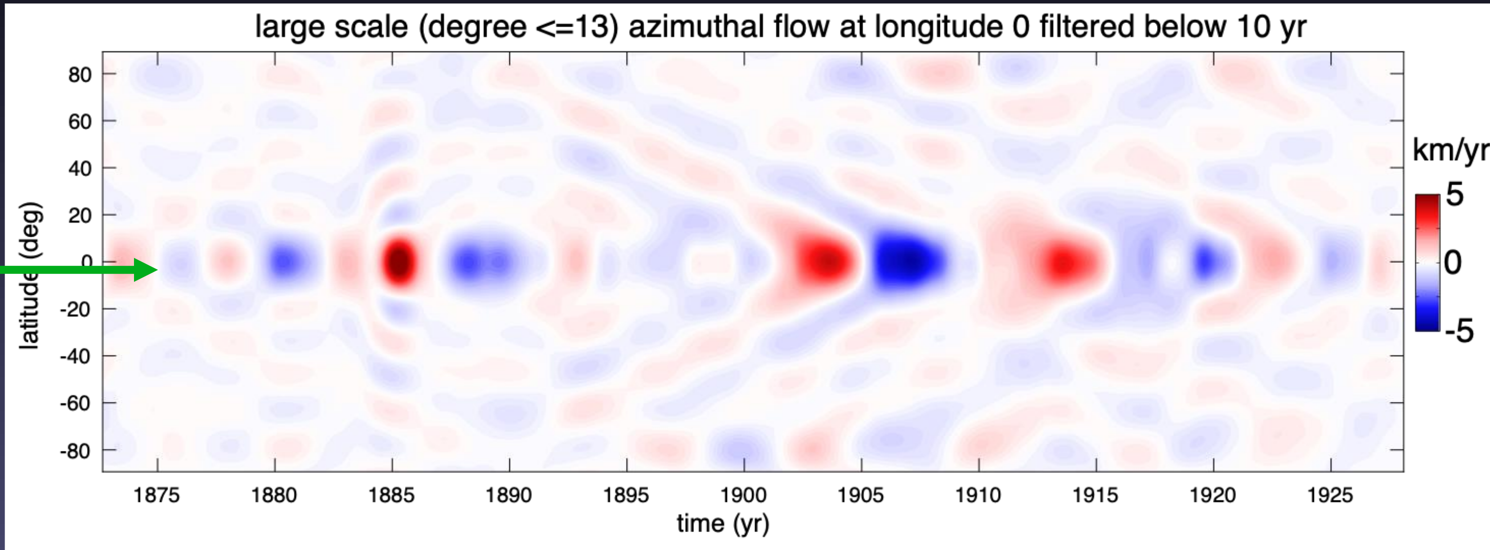
Gerick et al. 2021
Gillet et al. 2022
Aubert et al. 2022
Barrois and Aubert 2024

See also talk by O. Barrois

magneto-Coriolis waves in the numerics vs. geomagnetic inference



core surface azimuthal flow, lowpass filtered below 10 yr, km/yr

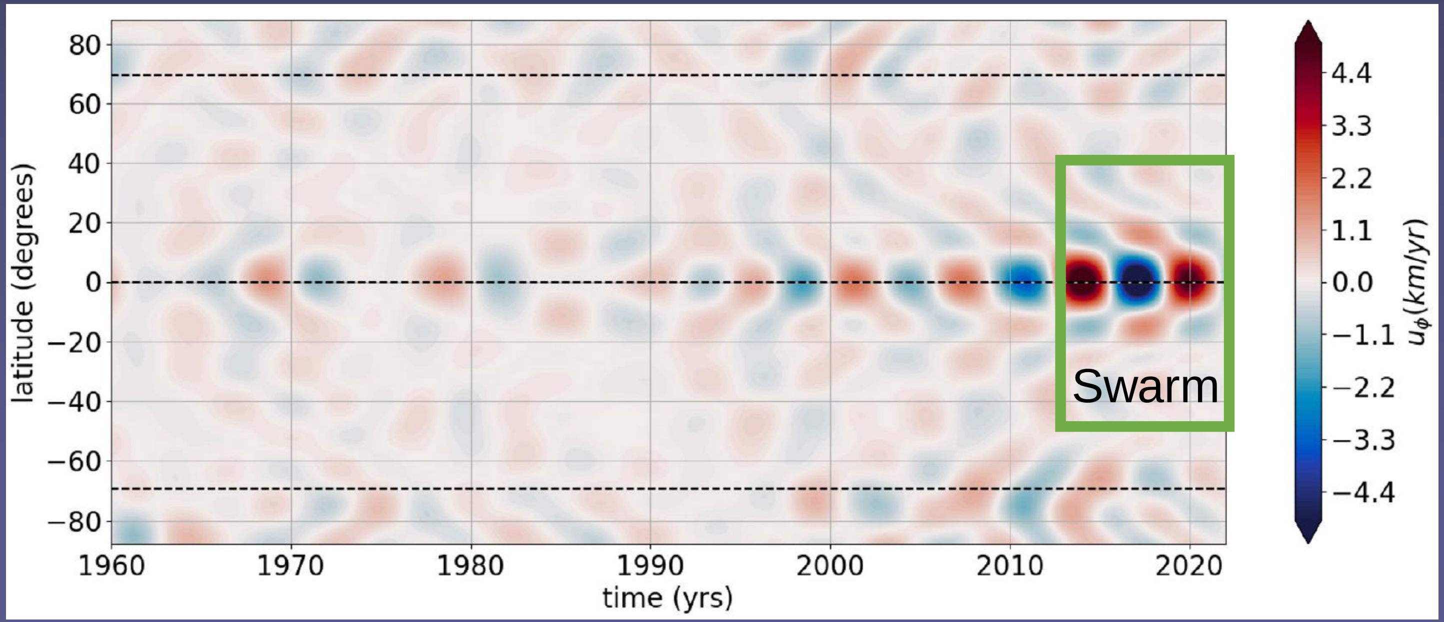


Direct simulation

Aubert et al. 2022

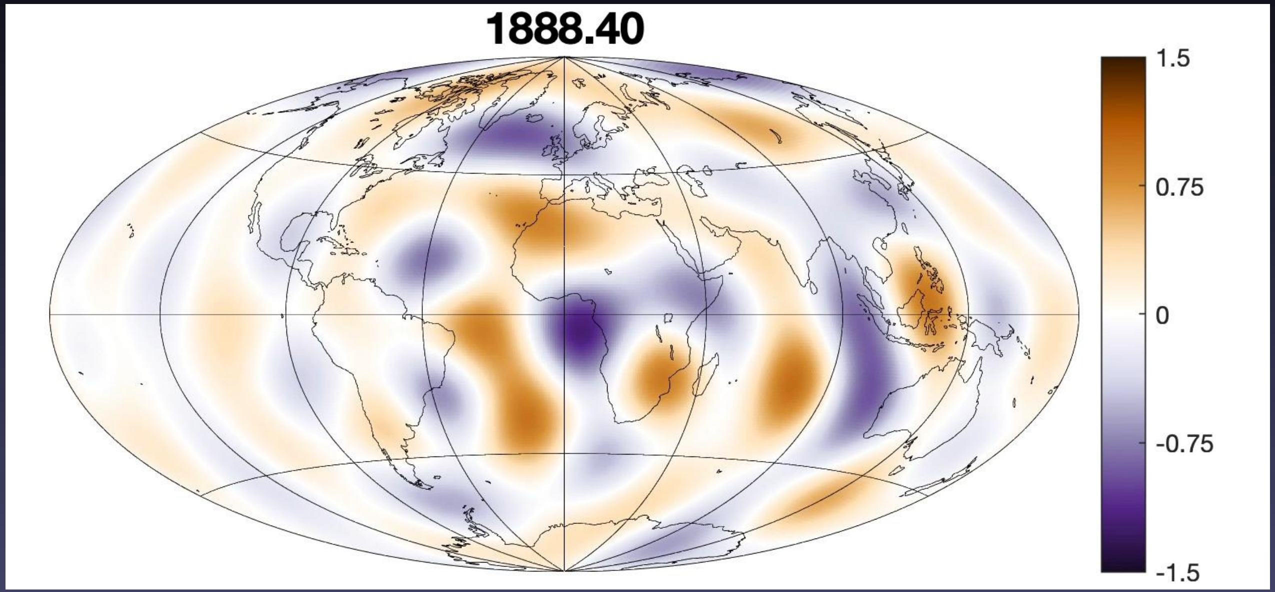
Flow inferred from geomagnetic variations
bandpass filtered btw. 4 and 9.5 yr
period ~7 years
amplitude +/- 6 km/yr

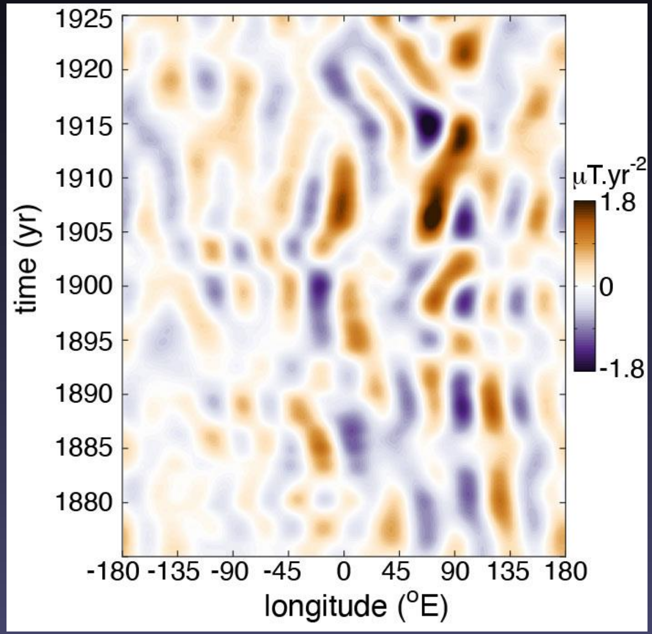
Gillet et al. 2022
Istas et al. 2023



Rapidly alternating acceleration: observation vs simulations

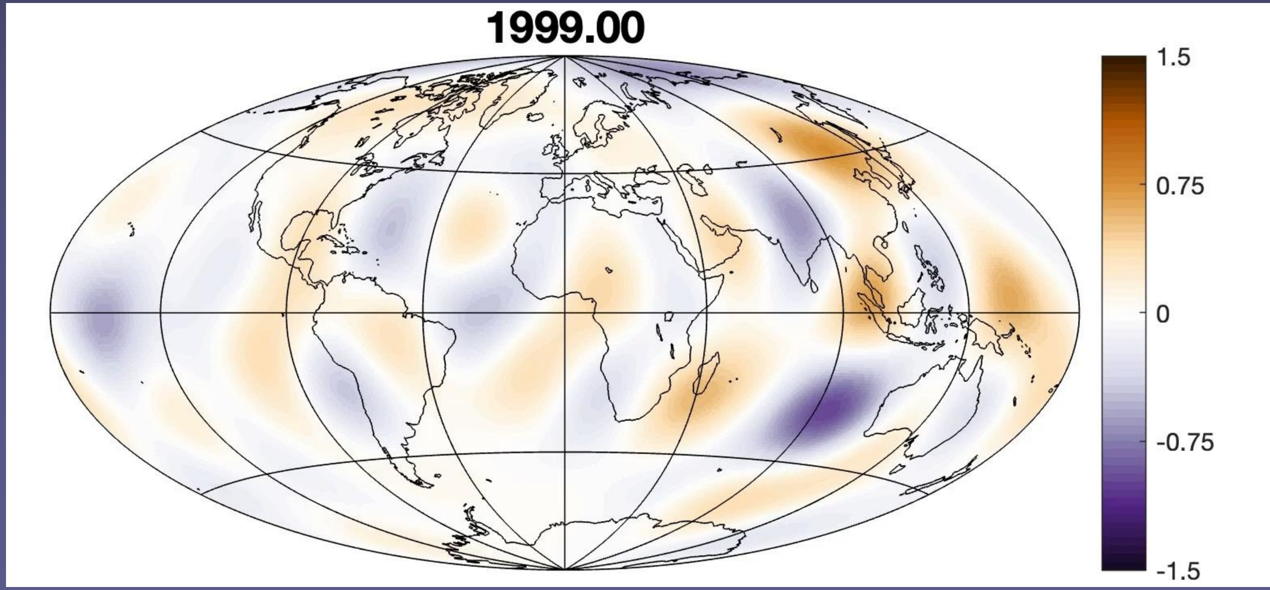
Direct Simulation
(Aubert et al. 2022)

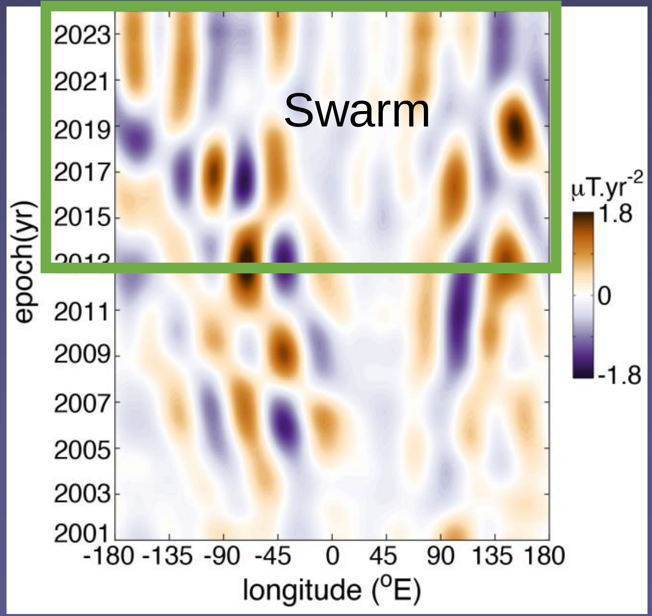




core surface radial field acceleration, muT/yr^2

CHAOS-7.9
(Finlay et al. 2020)





Take-away

- The Swarm + 4D Deep Earth: Core project funded by ESA has enabled a fruitful cross-fertilisation between data, theory and numerical simulations.

- For numerical simulations, the window opened on rapid dynamics has pushed us to elaborate models able to reproduce the regime where main forces >> inertia (aka the strong field regime)

- Magnetic variations over timescales of decades and more are explained by an eccentric westward columnar gyre in the core, the structure of which is possibly explained by Lenz' law (magnetic field avoids flow). The South Atlantic anomaly observed at present also possibly finds an explanation in this framework.

- The strong-field numerical models have been particularly useful to characterise small deviations of the main force balance, which, when balanced by inertia, give rise to hydromagnetic waves explaining the short-term accelerations seen by Swarm.

- overview paper summarising these results and more: Finlay, C.C., Gillet, N., Aubert, J., Livermore, P. and Jault, D.: Gyres, jets and waves in the Earth's core, Nature Rev. Earth. Environ. 4, 377–392, 2023, doi: 10.1038/s43017-023-00425-w