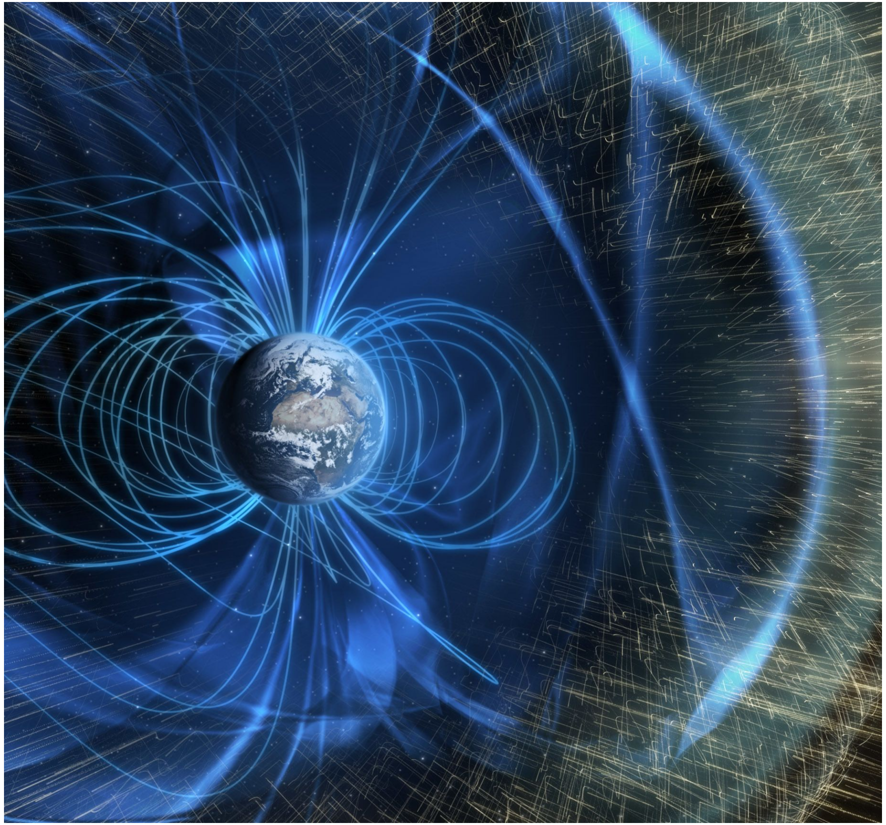
Necessary core-mantle boundary heat flux patterns for recovering the latitude of the South Atlantic Anomaly

Presented by
Dr. Filipe **TERRA-NOVA** (ANR-POSDOC)
in
ANR DYRE-COMB meeting III, Strasbourg 2025

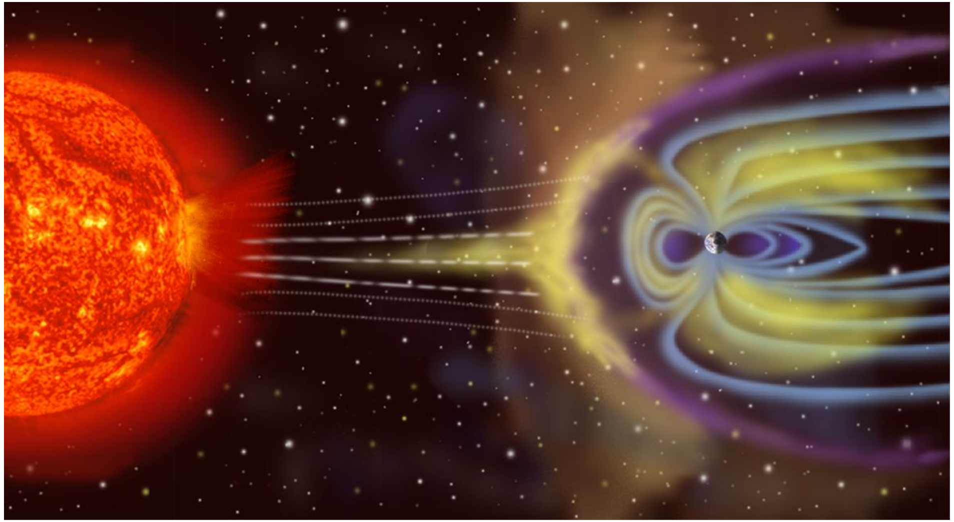


NASA/GSFC

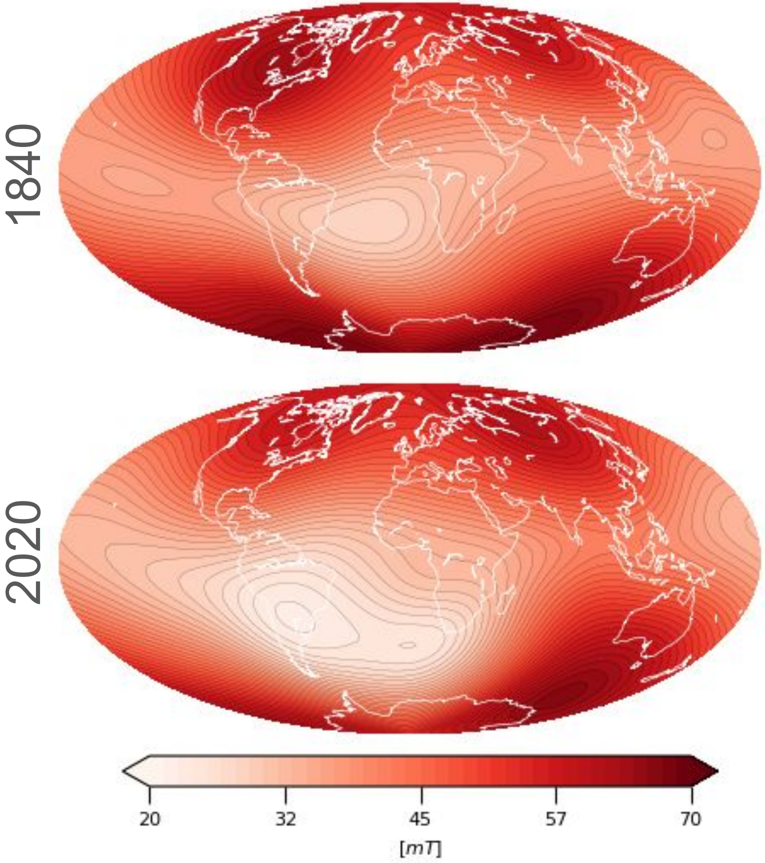
Terra-Nova, F., Amit, H., Necessary core-mantle boundary heat flux patterns for recovering the latitude of the South Atlantic Anomaly. JGR: Solid Earth, (in Review).

CONTEXT

The South Atlantic Anomaly

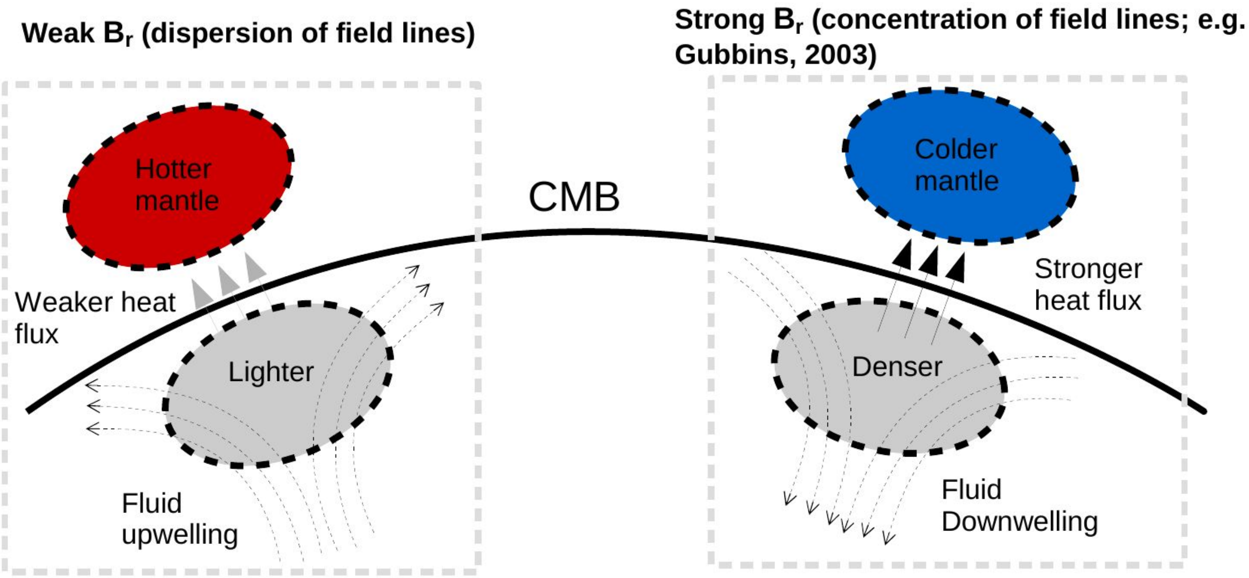


- **Today** a weak intensity field region at surface, **the South Atlantic Anomaly (SAA)**, is **observed**.
- **Also in the Past, so recurrence on the chaotic nature of geodynamo.**



The SAA gets more pronounced

Core-mantle thermal interactions



Amplitude of the **heat flux anomaly**:

$$q^* = \frac{q_{max} - q_{min}}{2q_0}$$

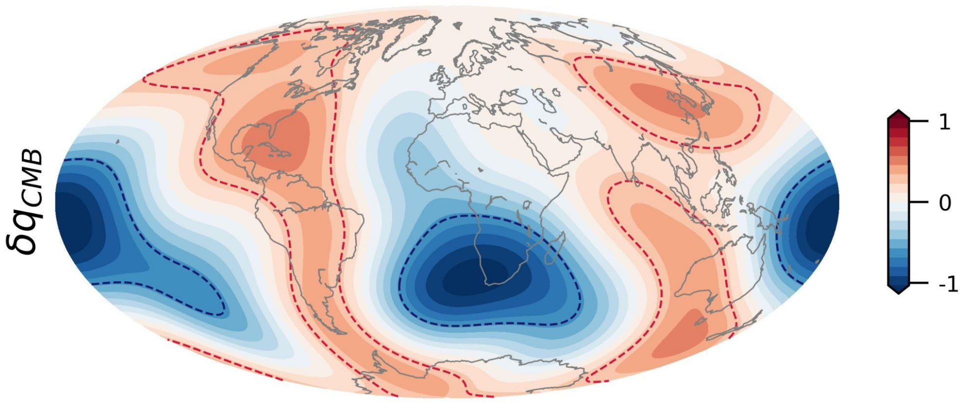
Numerical dynamos with a **tomographic CMB heat flux pattern** explain various core related **observations**, in particular the locations of intense high-latitude **geomagnetic flux patches** on the CMB (e.g. Aubert et al., 2008).

STATE-OF-ART

Characterization of the South Atlantic Anomaly

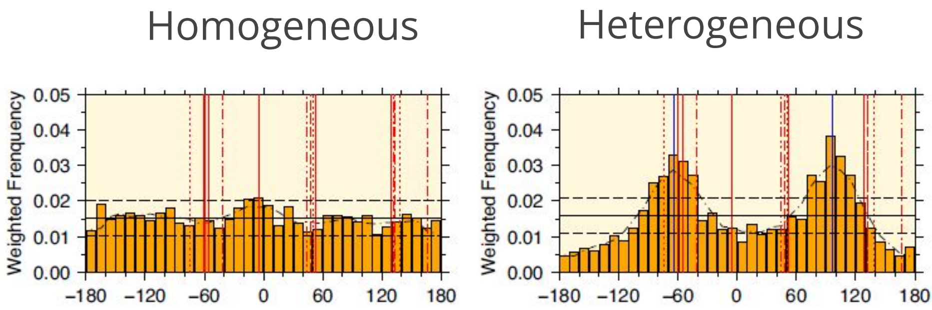
Using numerical dynamo simulations
constrained by seismic observables.

Shear waves ∝ density ∝ heat flux



Core-mantle boundary heat flux pattern based on Masters et al. (2000).

Histograms of surface intensity minima longitude



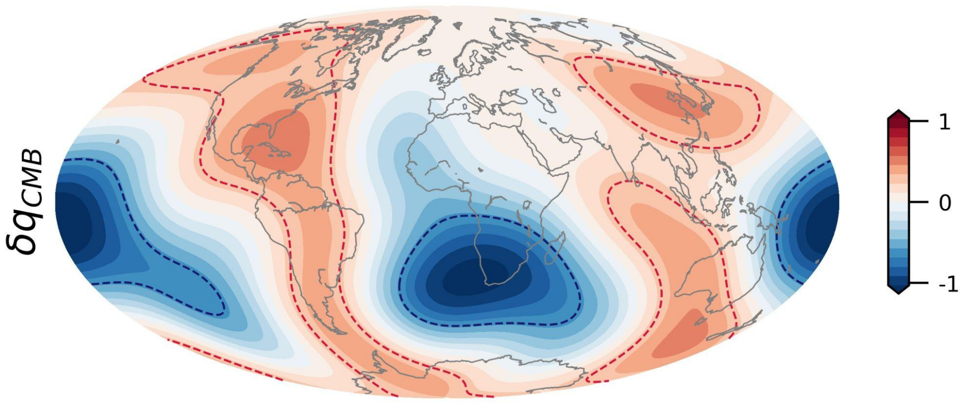
Longitude well recovered

Current **longitude consistent with mantle control** on the geodynamo **(Terra-Nova et al., 2019)**

Characterization of the South Atlantic Anomaly

Using numerical dynamo simulations
constrained by seismic observables.

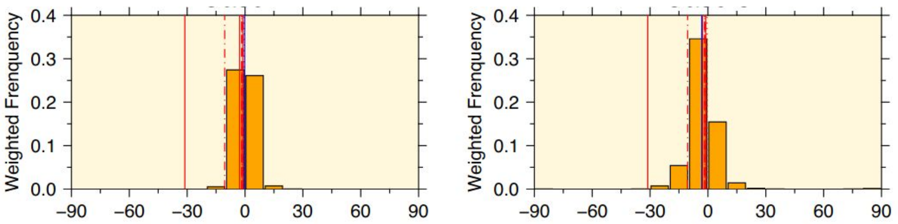
Shear waves ∝ density ∝ heat flux



Core-mantle boundary heat flux pattern based on Masters et al. (2000).

Histograms of surface intensity minima latitude

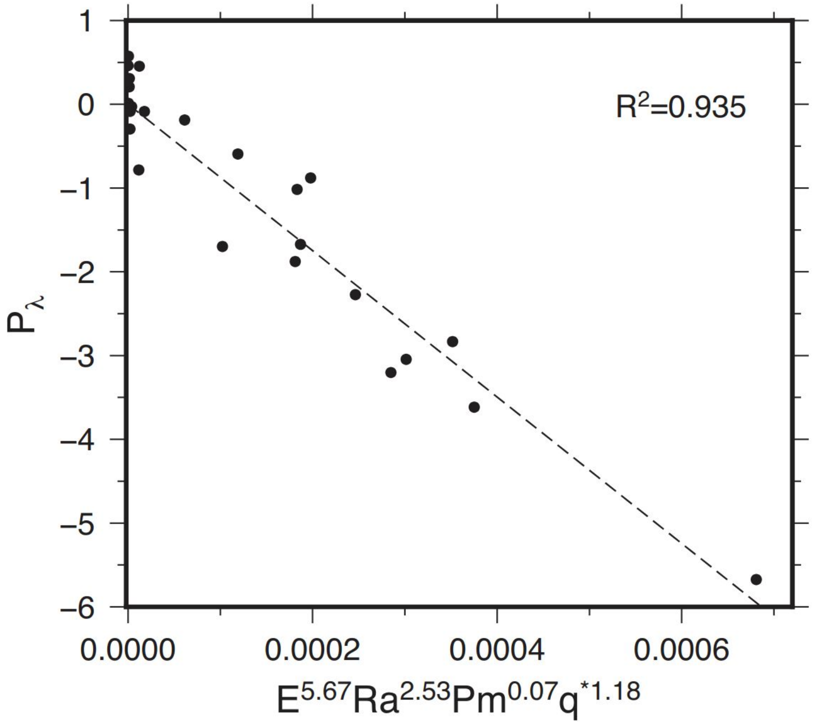
Homogeneous | Heterogeneous



Current latitude not recovered

Southern latitude but surface minima **restricted to equatorial belt**
(Terra-Nova et al., 2019)

Power law of latitudes of surface intensity minima

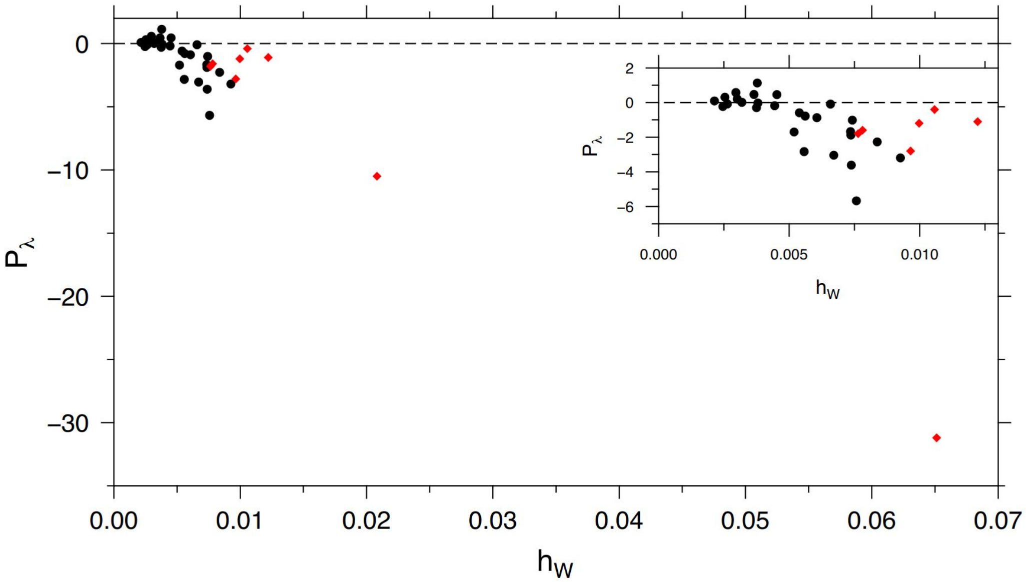


- Rotation and vigor convection domain its location.
  - Lower rotation → equatorial
  - Stronger convection → higher-latitude.

- CMB Heat flux anomaly plays a role
  - Prevail of either equatorial or southern surface minma location

Provides **vital information** for **future studies**
(Terra-Nova et al., 2019)

Longitudinal peaks vs latitude locations



- Weaker mantle control
  - Smaller peaks
  - Single or none surface minimum
  - Non-intuitively northern tendency (though weak)

- Stronger mantle control
  - Bigger peaks
  - Multiple minima
  - Southward surface minima

This same qualitative relation also holds for the geomagnetic field

Higher latitudes of surface intensity minima occur in dynamo models with **more persistent longitude peaks**

from Terra-Nova et al. (2019)

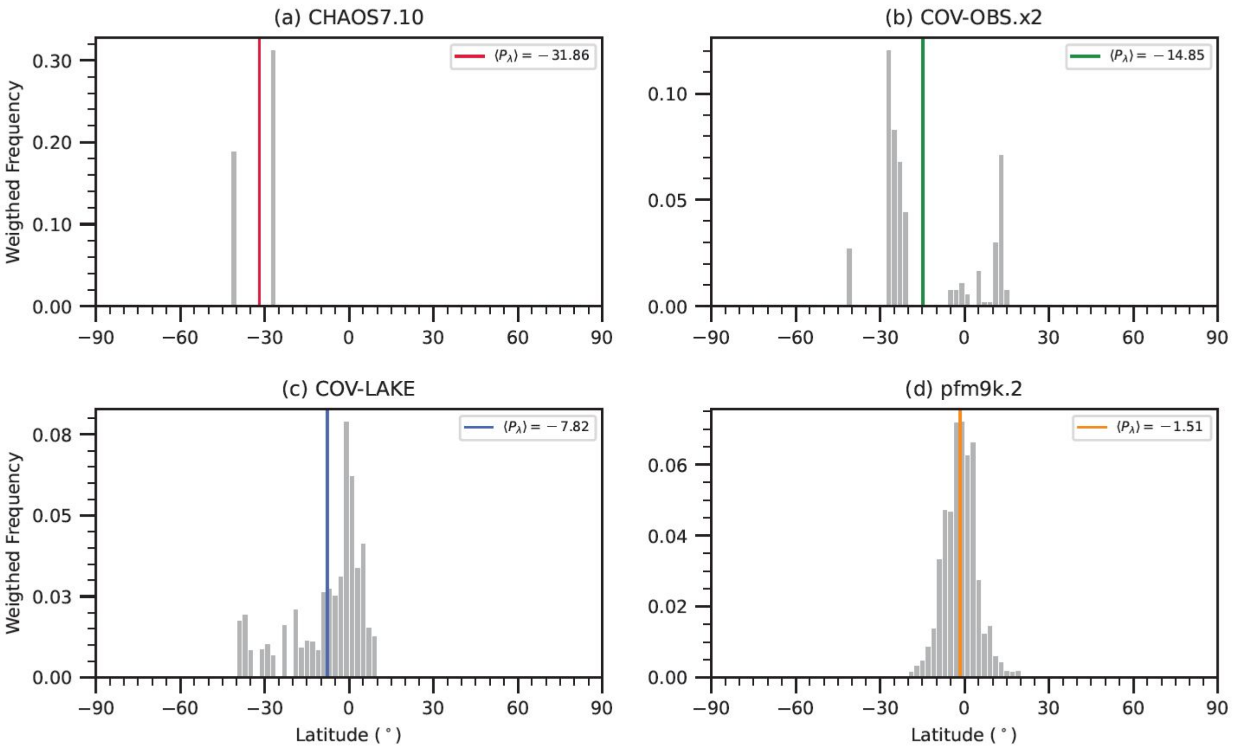
THE UNUSUAL LATITUDE OF SAA

or A FAIL OF NUMERICAL DYNAMO SIMULATIONS

Terra-Nova, F., Amit, H., Necessary core-mantle boundary heat flux patterns for recovering the latitude of the South Atlantic Anomaly. JGR: Solid Earth, (in Review).

South Atlantic Anomaly vs. data type

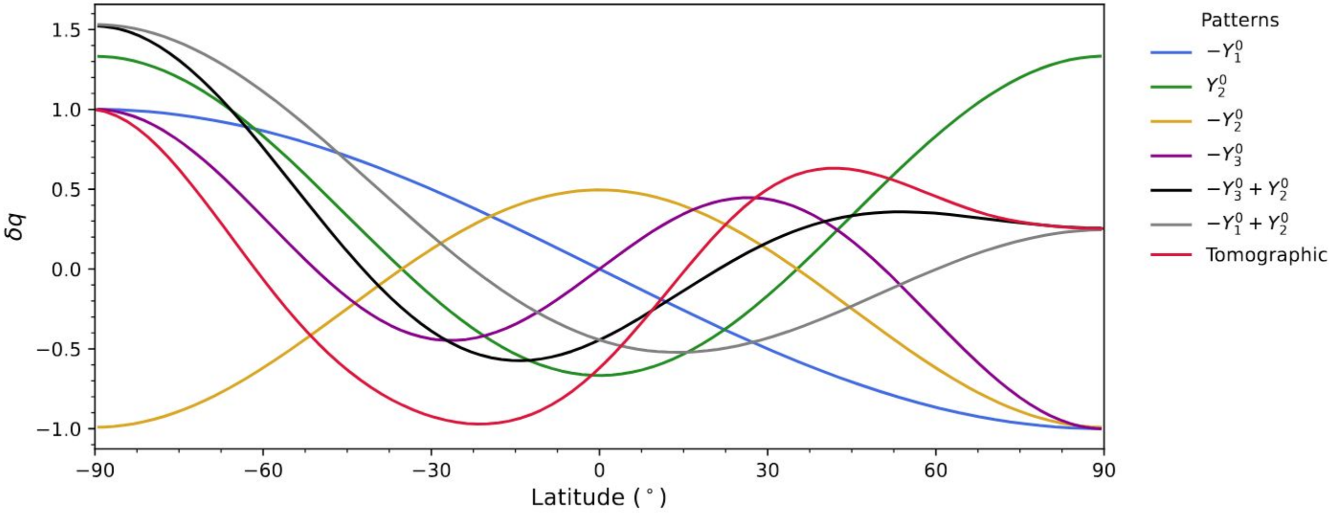
Using geomagnetic field models constrained by data from different data sources



Distinct locations of surface intensity minima between **archeological** and **historical/modern** geomagnetic **field models**

South Atlantic Anomaly vs. CMB heat flux patterns

Using numerical dynamo simulations
constrained by fundamental patterns



Can the **SAA** current latitude help to **constrain** the **lowermost mantle heat flux**?

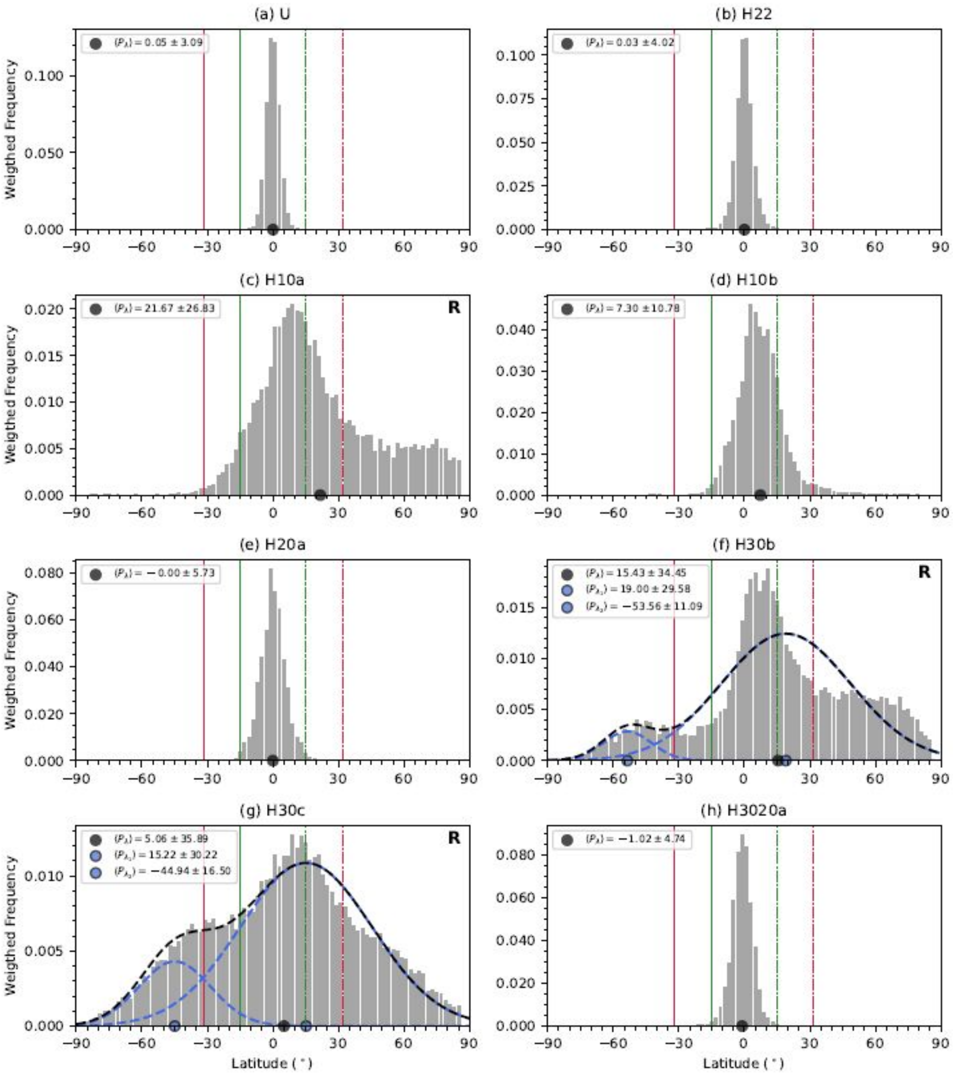
Distribution in latitude

Results for different convection vigor (Ra number) and distinctive fundamental patterns.

- Dipole dominated simulations produce restricted minima at the equatorial belt.

- Reversing simulations reach larger latitudes.

Best simulation has latitude = -7.3±10.8º (-26º present day)

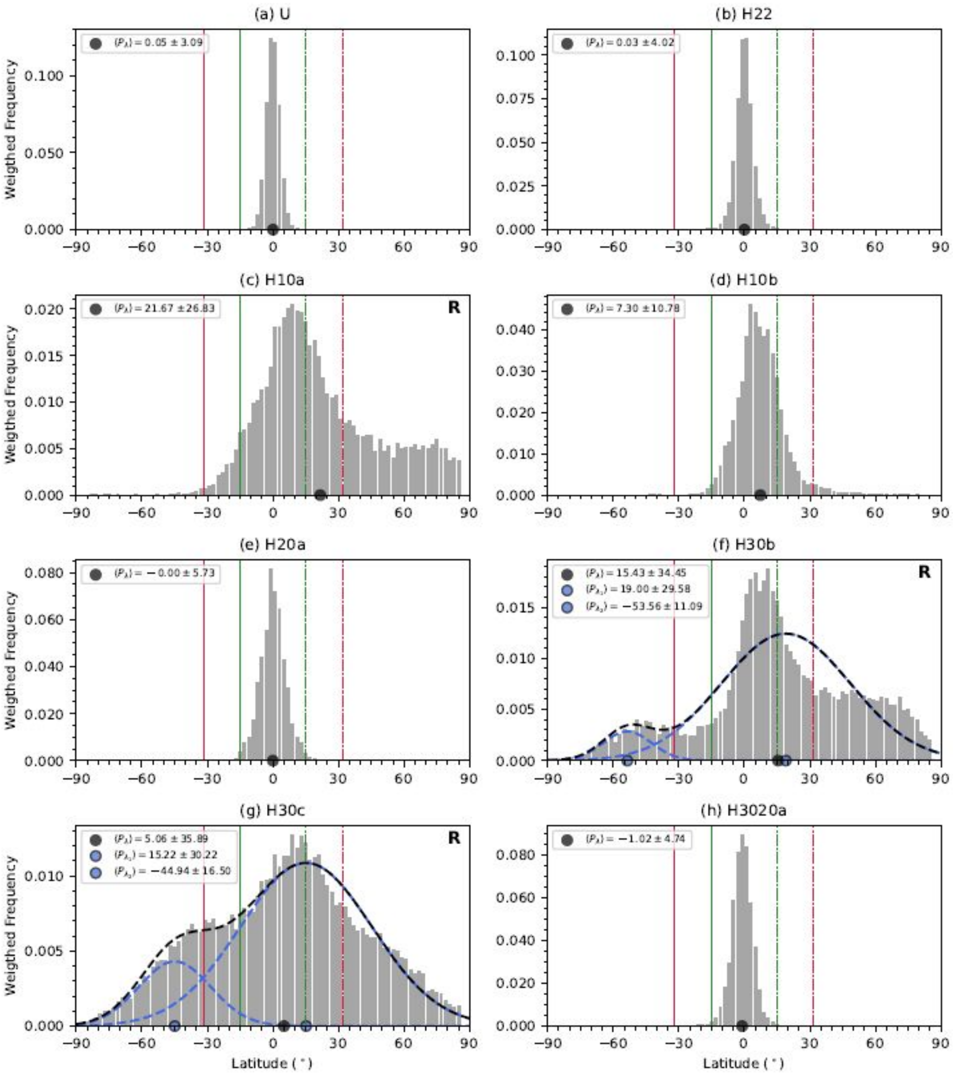


Distribution in latitude

Results for different convection vigor (Ra number) and distinctive fundamental patterns.

- Dipole dominated simulations produce restricted minima at the equatorial belt.
- Reversing simulations reach larger latitudes.

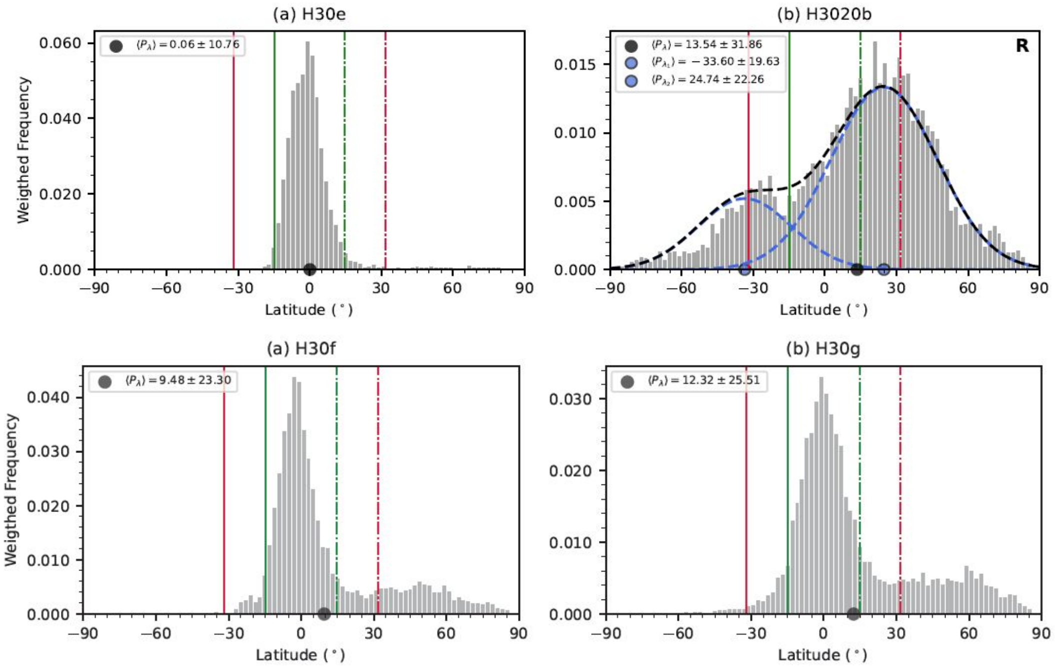
Equatorially anti-symmetric CMB heat flux is required to produce large latitudes



Characterization of the South Atlantic Anomaly

Results for different rotation rates (E number) and distinctive fluid properties (Pm number)

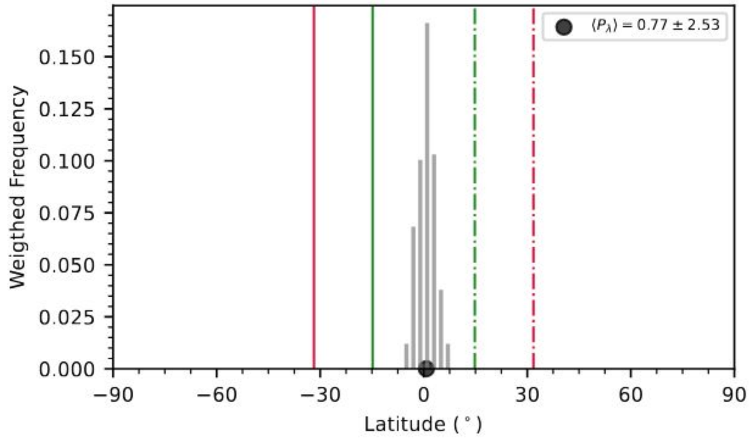
- Lower Ekman can promote larger standard deviation.
- Higher Pm can promote secondary peak without triggering reversals.



Yet equatorial surface intensity minima normal distributions

Characterization of the South Atlantic Anomaly

Using numerical dynamo simulations constrained by the morphology of present-day field



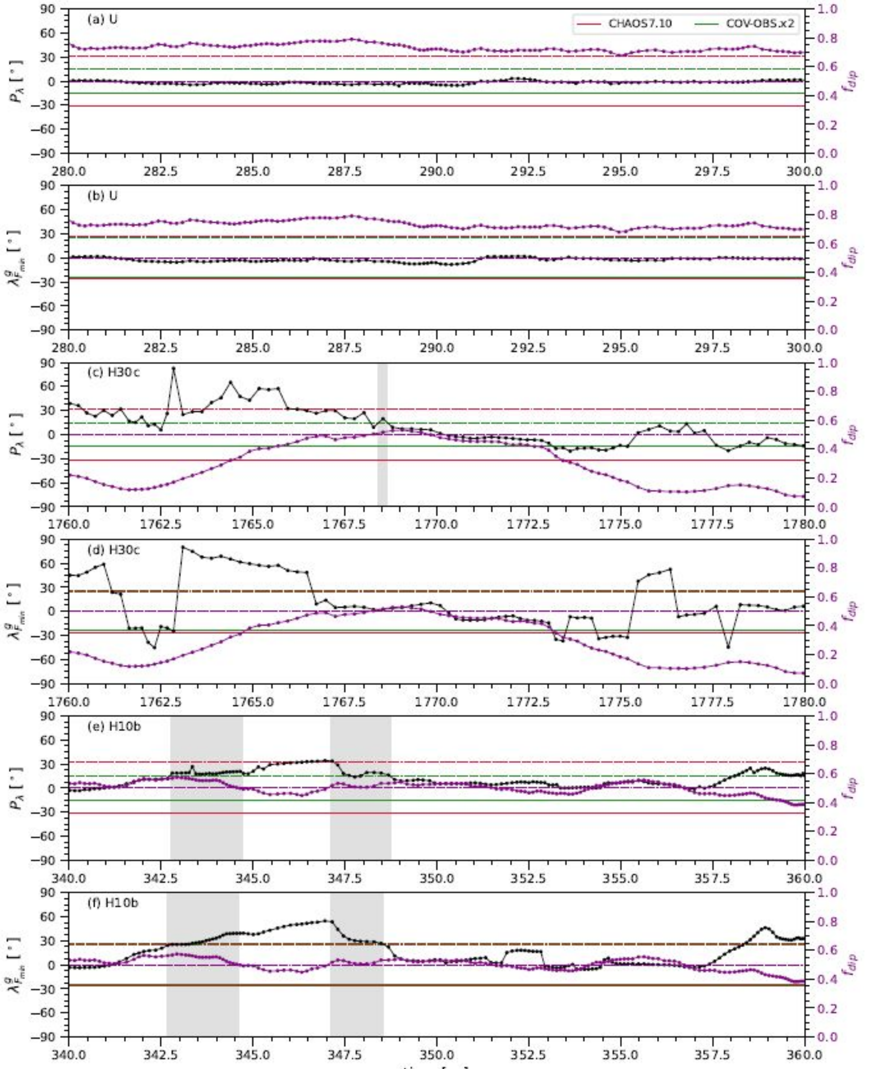
The 71% path model (Aubert and Gillet, 2021)

High-end simulations also fail in reproducing non-equatorial minima

Instataneous minima vs. dipolarity

Difficulty to **reconcile dipole dominance** and **large latitude** of surface intensity minima **in time-averages** but what about **snapshots**?

Possible but only negligible fraction of snapshots show simultaneously larger dipolaty and non-equatorial minima



Instataneous minima vs. dipolarity

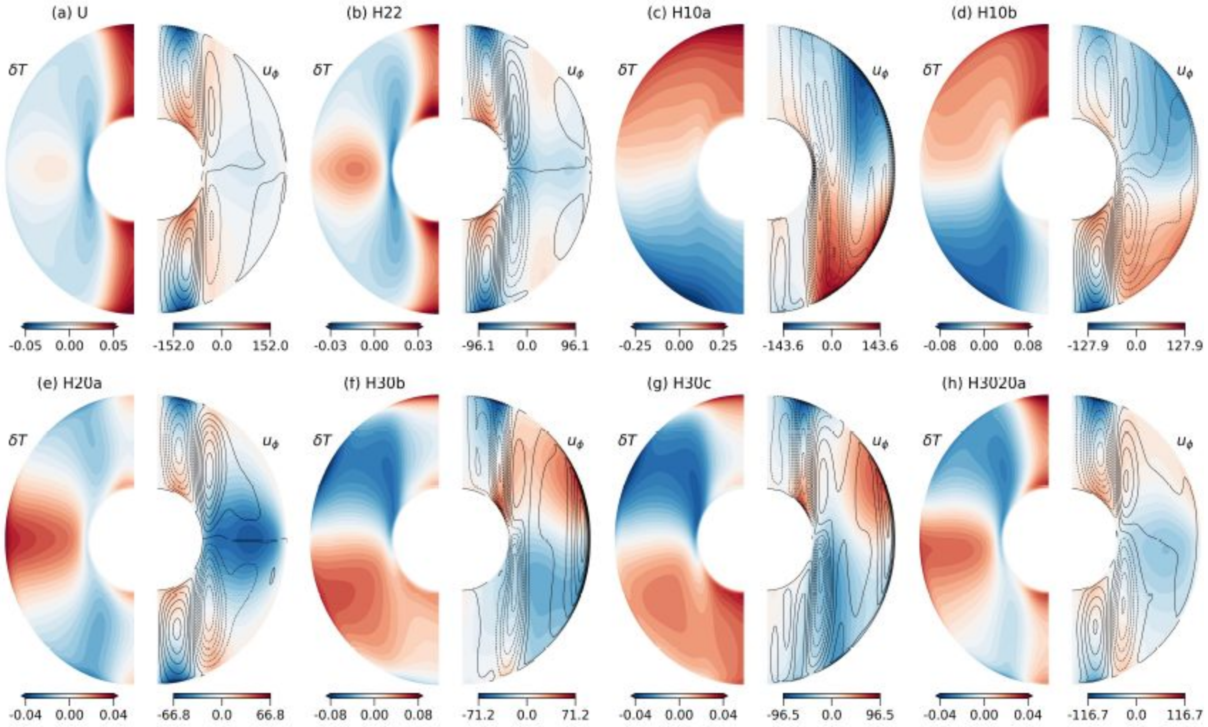
Difficulty to **reconcile dipole dominance** and **large latitude** of surface intensity minima **in time-averages** but what about **snapshots**?

Possible but only negligible fraction of snapshots show simultaneously larger dipolaty and non-equatorial minima

CASE	CHAOS7.10 $\mathcal{T}(P_\lambda, f_{dip})$	CHAOS7.10 $\mathcal{T}(\lambda^g_{F_{min}}, f_{dip})$	COV-OBS.x2 $\mathcal{T}(P_\lambda, f_{dip})$	COV-OBS.x2 $\mathcal{T}(\lambda^g_{F_{min}}, f_{dip})$
		$0.75 > f_{dip} > 0.50$		
H10b	0.11	1.52	4.57	2.16
H1020	0.00	0.00	0.29	0.00
H22	0.00	0.01	0.07	0.03
H30a	0.00	0.00	0.47	0.00
H30b	0.03	0.04	0.56	0.04
H30c	0.00	0.00	0.01	0.00
H30d	0.00	0.10	0.15	0.13
H30e	0.05	1.07	2.11	1.10
H30f	0.00	0.15	0.15	0.20
		$0.75 > f_{dip} > 0.45$		
H10b	0.22	2.97	8.61	4.04
H1020	0.00	0.00	0.29	0.00
H20a	0.00	0.00	0.06	0.00
H22	0.00	0.01	0.07	0.03
H30a	0.00	0.00	0.47	0.00
H30b	0.51	0.99	1.97	1.02
H30c	0.00	0.03	0.15	0.03
H30d	0.07	0.29	0.66	0.34
H30e	0.05	1.07	2.45	1.10
H30f	0.09	2.52	2.37	2.60
H30g	0.01	0.53	0.92	0.54
H3022b	0.00	0.01	0.01	0.01

$\mathcal{T}$ denotes the percentage of snapshots that have both large enough surface intensity minima based on the satellite or observatory era geomagnetic field models and large enough dipolarity based on the threshold value of 0.5 (top) or 0.45 (bottom). Dynamo models with all $\mathcal{T}$ values equal to zero are not shown.

Dynamical Origin: Thermal wind



The force balance between **Pressure gradient**, **Coriolis** and **Buoyancy**:

$$\frac{\partial u_\phi}{\partial z} \propto \frac{\partial T}{\partial \theta}$$

Polar upwelling of warm fluid and **downwelling of cold fluid** at the edge of the inner core tangent cylinder **(TC)** are consistent with **thermal wind**

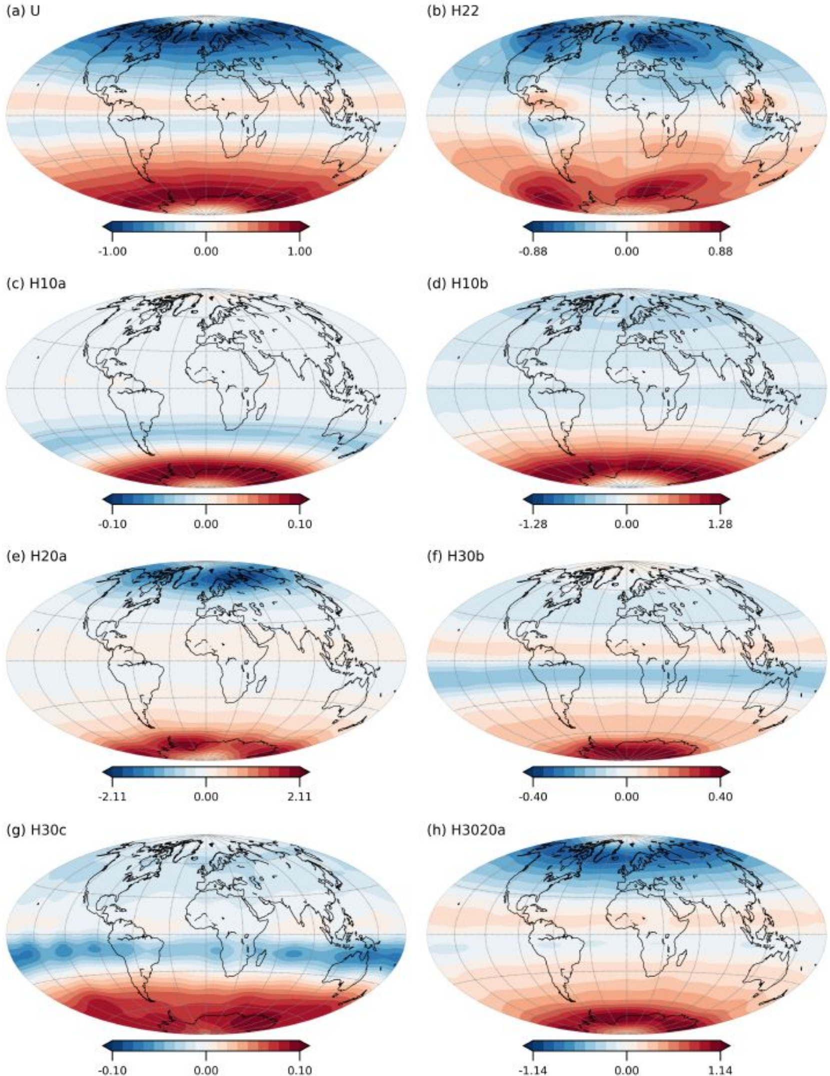
Consistent relation between temperature anomaly and azimuthal flow

Dynamical origin: Radial field

Very good temporal convergence of all simulations

- The imposed lateral outer boundary heat flux variability is well reflected in the time-average field morphologies:
    - Polar minima
    - Two pairs of high-latitude normal flux patches
    - Concentrated field at polar regions

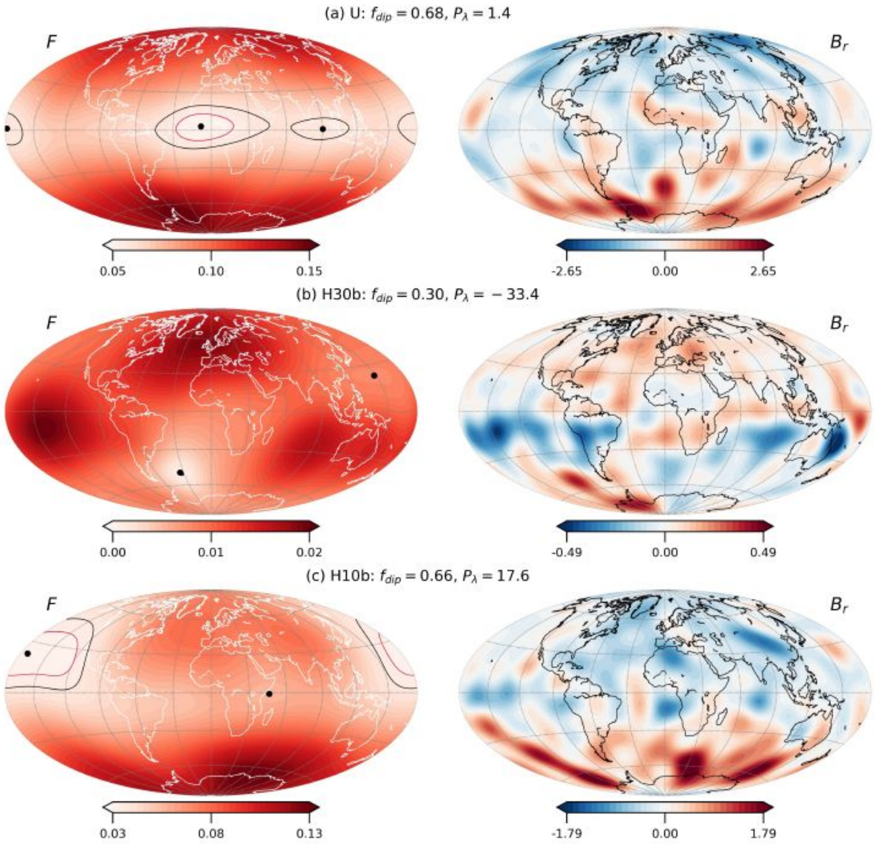
Consistent relation between azimuthal flow and radial field



Instantaneous field morphology

Amount of magnetic flux might control surface minima position

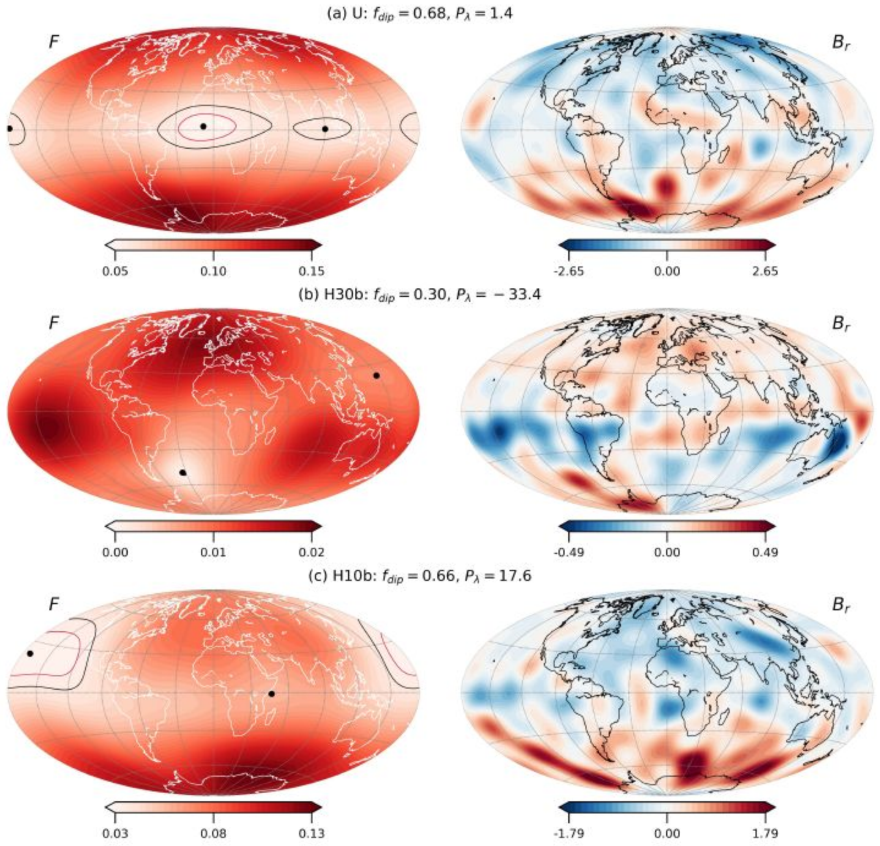
Area of minima are too sharp in reversing dynamos simulations



Instantaneous field morphology

Amount of magnetic flux might control surface minima position

Area of minima are too sharp in reversing dynamos simulations



Hemispherical ratios of magnetic flux

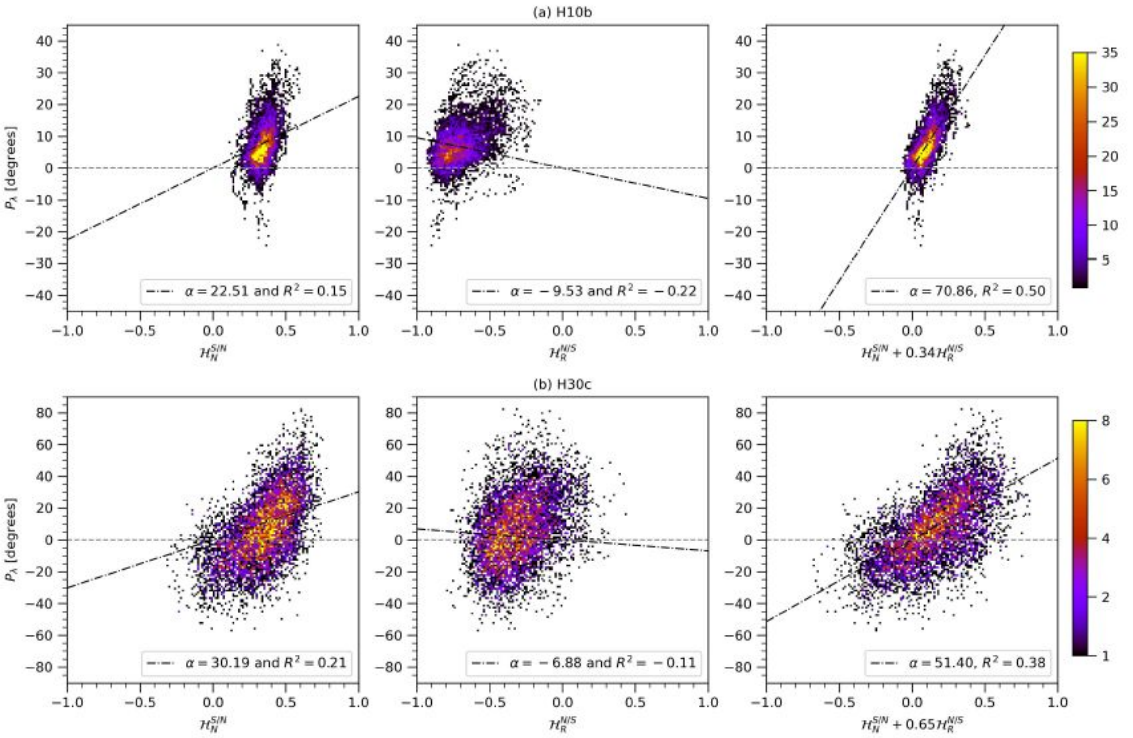
How information travel from CMB to Surface

$$\mathcal{H}_N^{S/N} = \frac{\mathcal{H}_N^S - \mathcal{H}_N^N}{\mathcal{H}_N^S + \mathcal{H}_N^N}$$

Normal flux prompt minima in the **opposite hemisphere**

$$\mathcal{H}_R^{N/S} = \frac{\mathcal{H}_R^N - \mathcal{H}_R^S}{\mathcal{H}_R^N + \mathcal{H}_R^S}$$

Reversed flux prompt minima in the **same hemisphere**



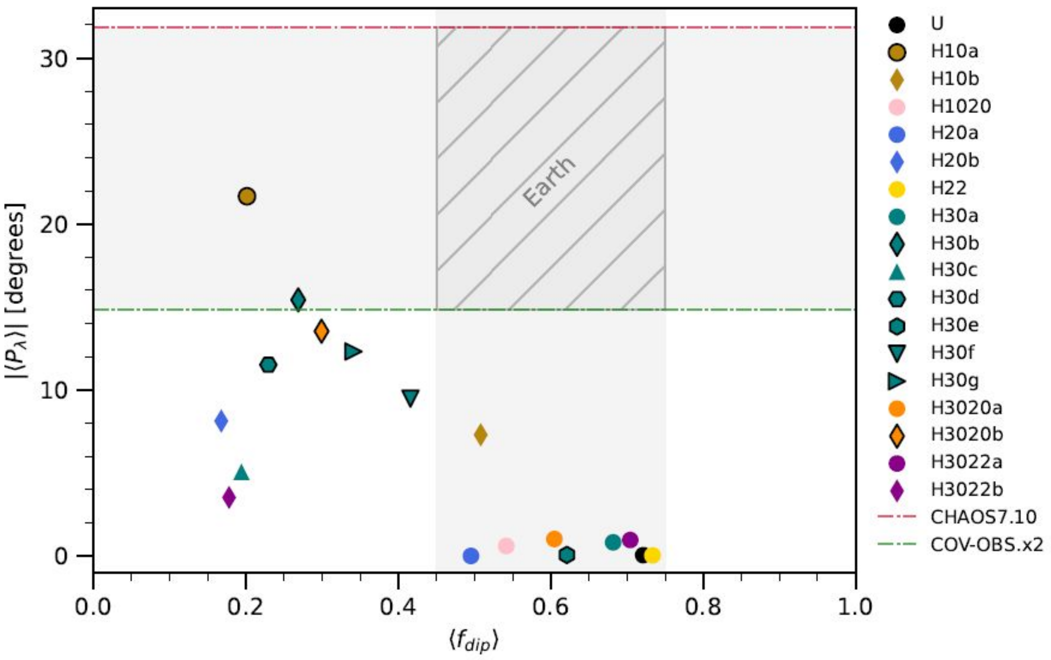
Amount of normal and reversed flux roughly controls minima latitudes
(as in Terra-Nova et al., 2017,2019)

Main Conclusions

Equatorially anti-symmetric CMB heat flux required to produce minima **large latitudes**

Current latitude is not consistently reproduced in dipole dominated simulations

Larger amplitude of anti-symmetric CMB heat flux heterogeneity may **reconcile these two observations**

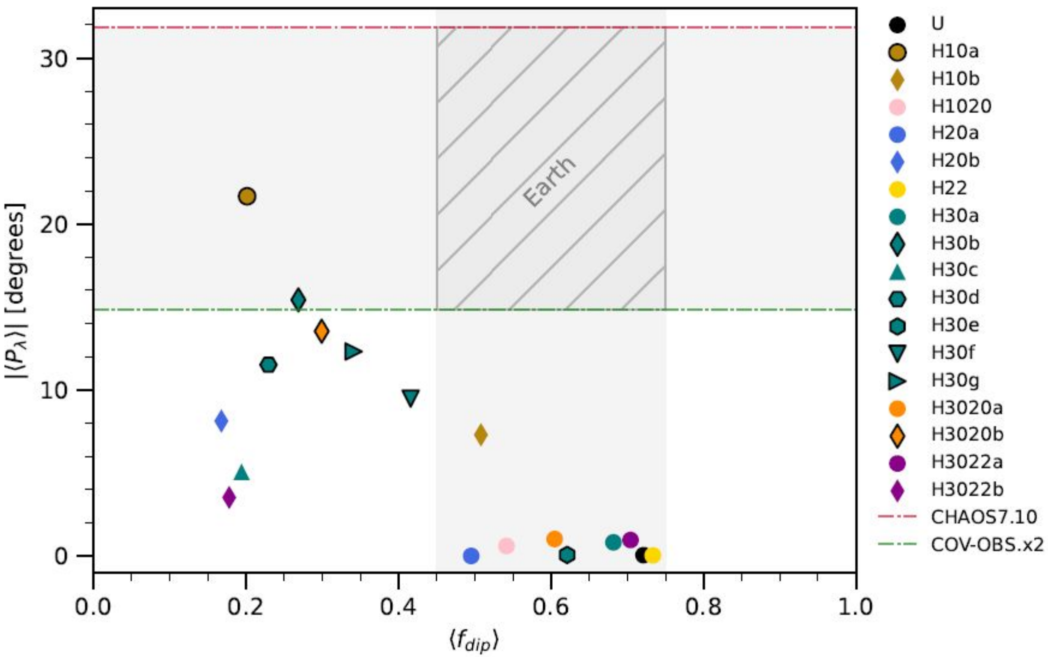


Main Conclusions

Equatorially anti-symmetric CMB heat flux required to produce minima **large latitudes**

Current latitude is not consistently reproduced in dipole dominated simulations

Larger amplitude of anti-symmetric CMB heat flux heterogeneity may **reconcile these two observations**



Thank you for the attention