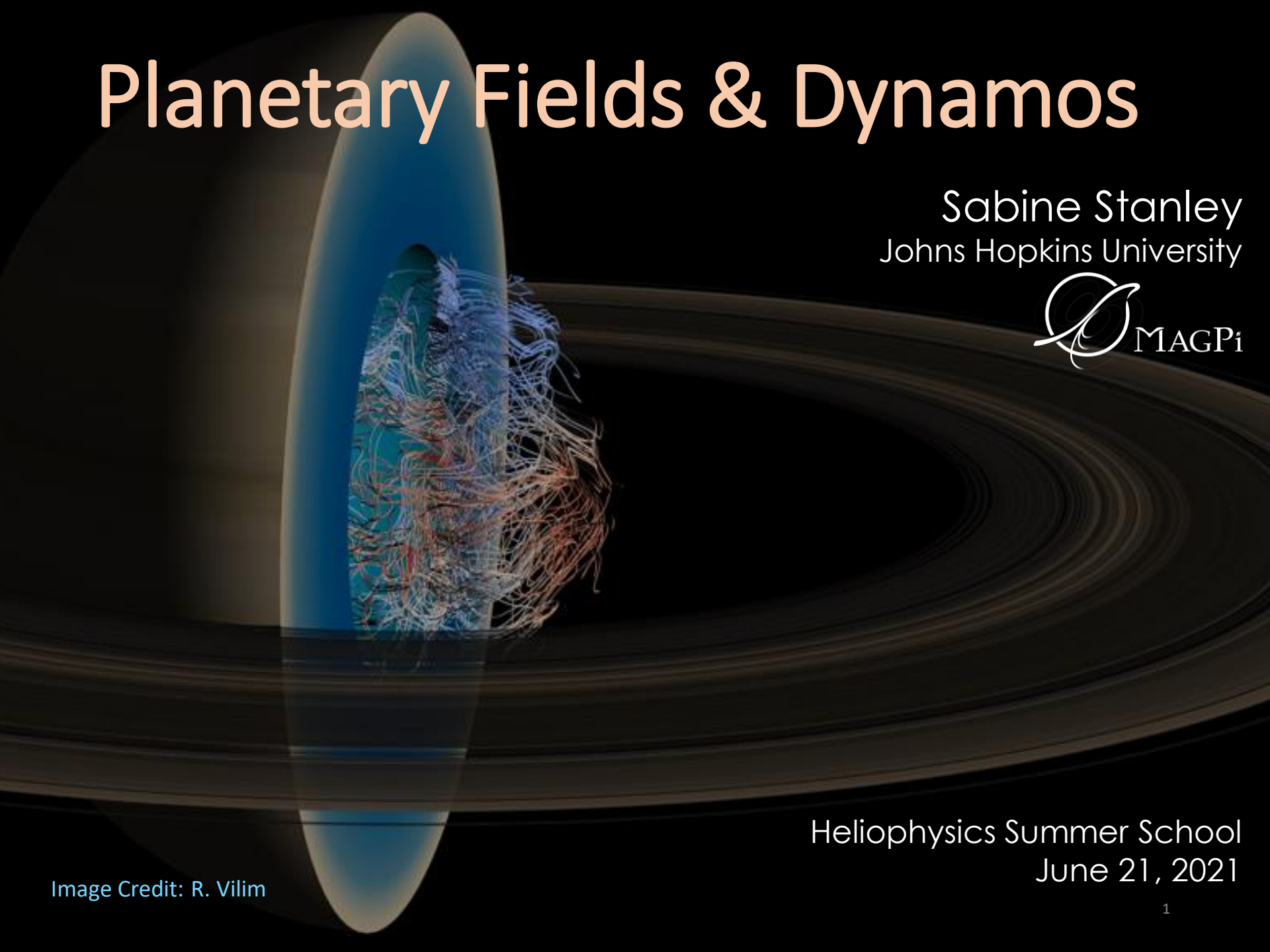
Planetary Fields & Dynamos

Sabine Stanley
Johns Hopkins University

MAGPi

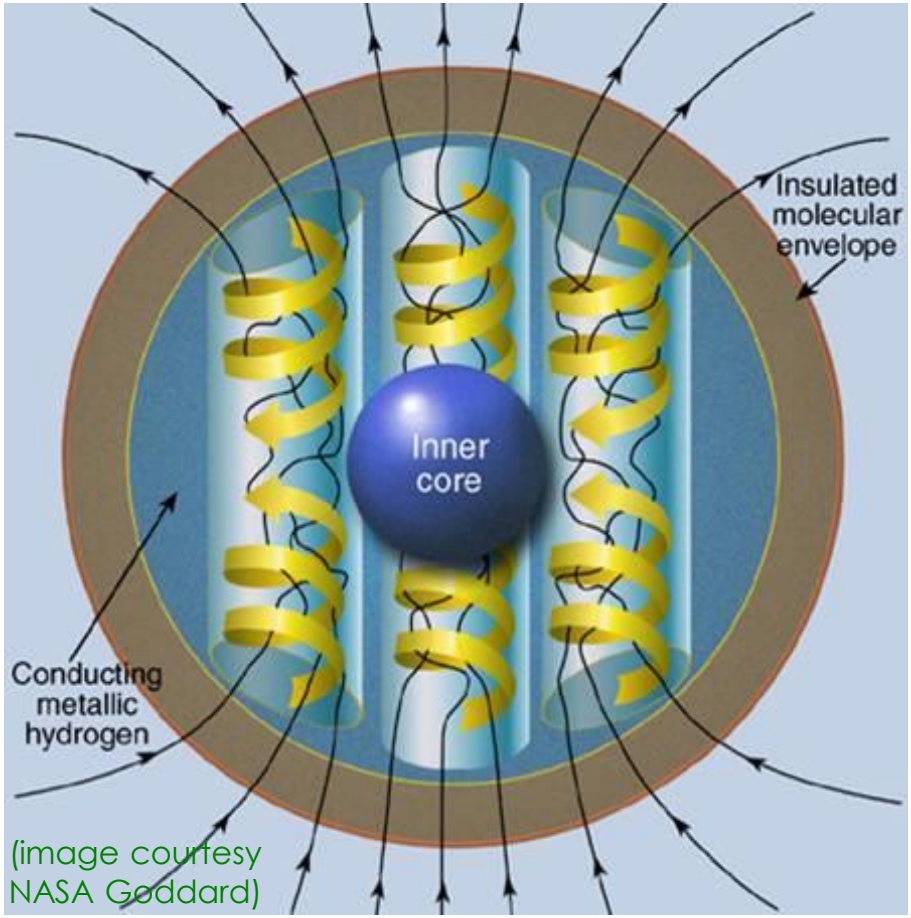


Heliophysics Summer School
June 21, 2021

Image Credit: R. Vilim

REVIEW: PLANETARY DYNAMOS 101

Mechanical Energy → Electromagnetic Energy



complex motions

+

electrically conducting fluid

+

presence of a magnetic field

⇓

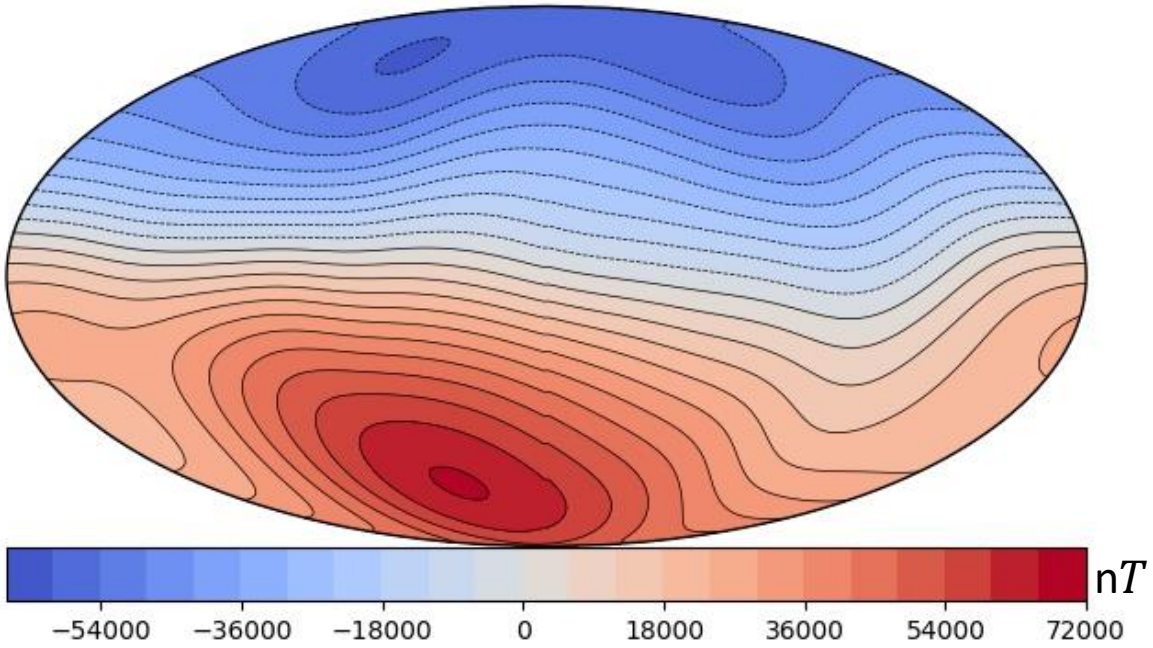
maintain field against Ohmic decay

WARM UP QUESTIONS

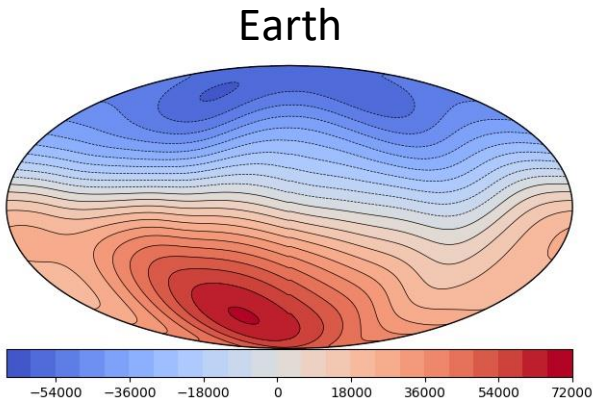
(1) What are some differences between planetary magnetic fields and stellar magnetic fields?

(2) NAME THAT PLANET!

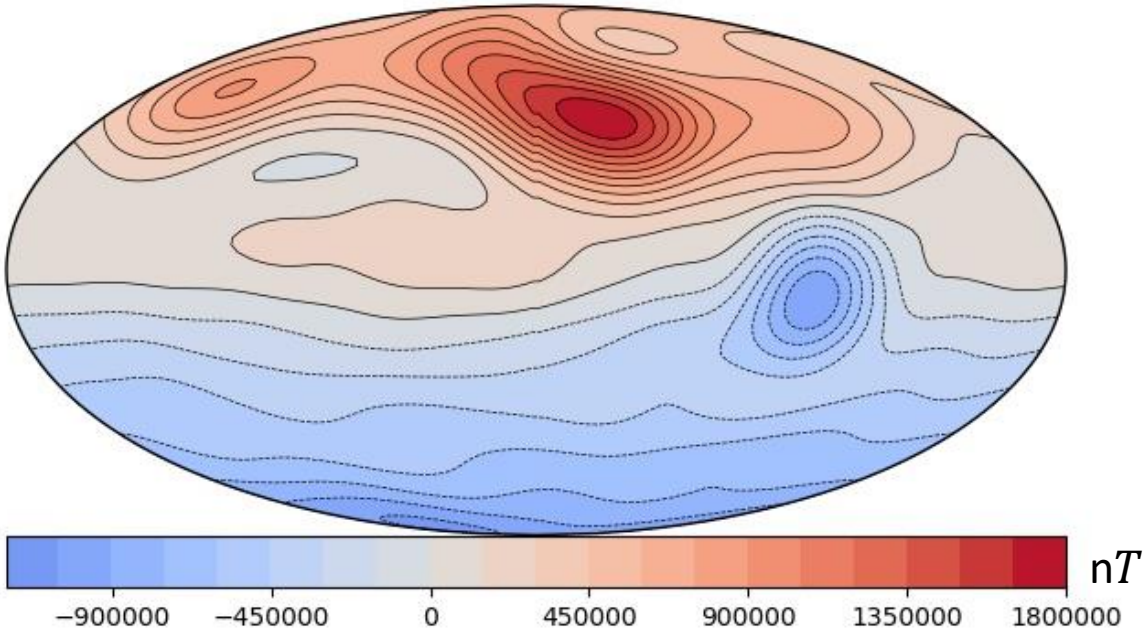
PLANETARY MAGNETIC FIELDS



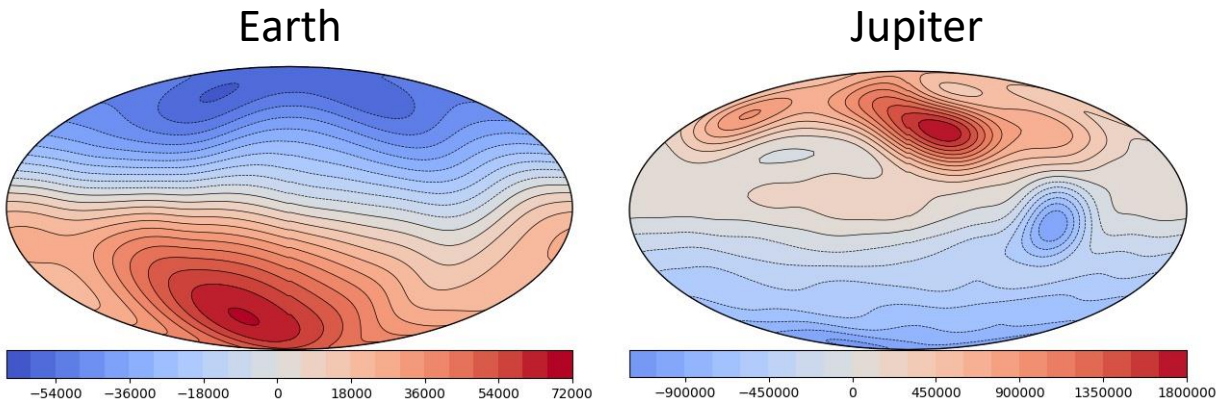
PLANETARY MAGNETIC FIELDS



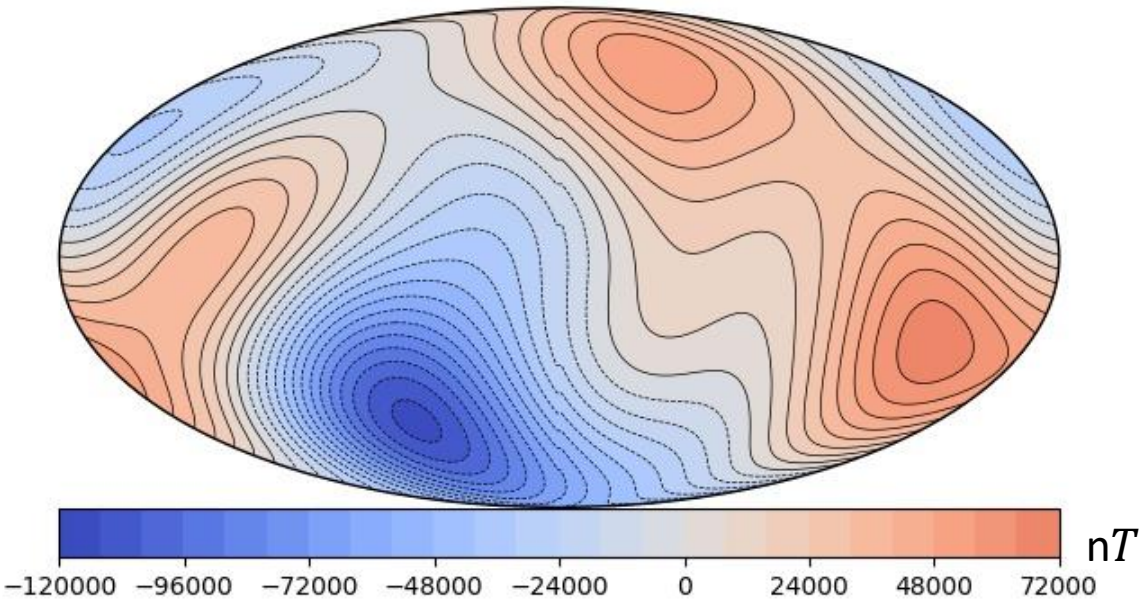
PLANETARY MAGNETIC FIELDS



PLANETARY MAGNETIC FIELDS

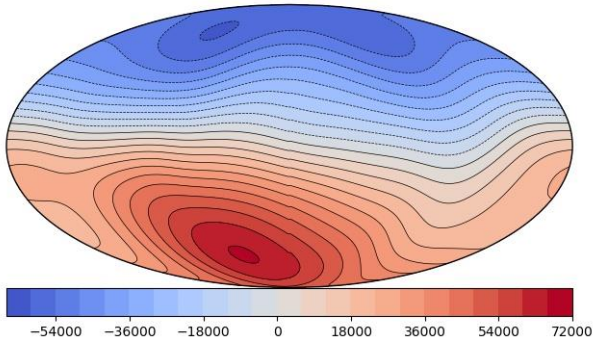


PLANETARY MAGNETIC FIELDS

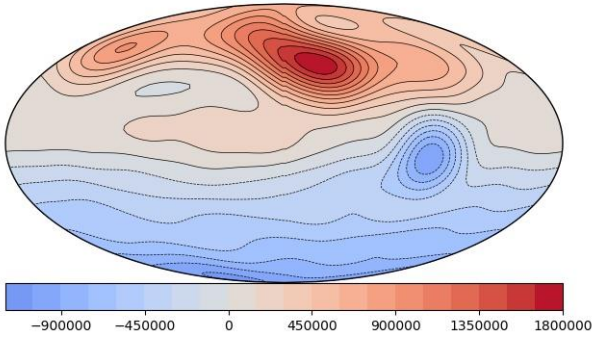


PLANETARY MAGNETIC FIELDS

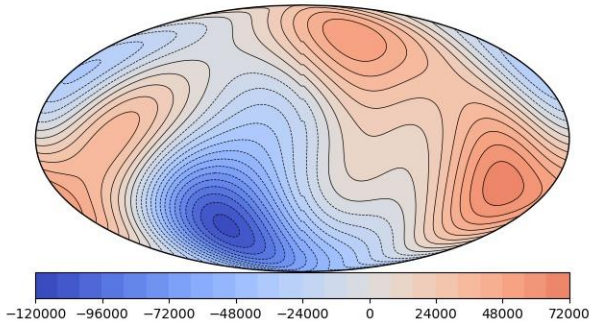
Earth



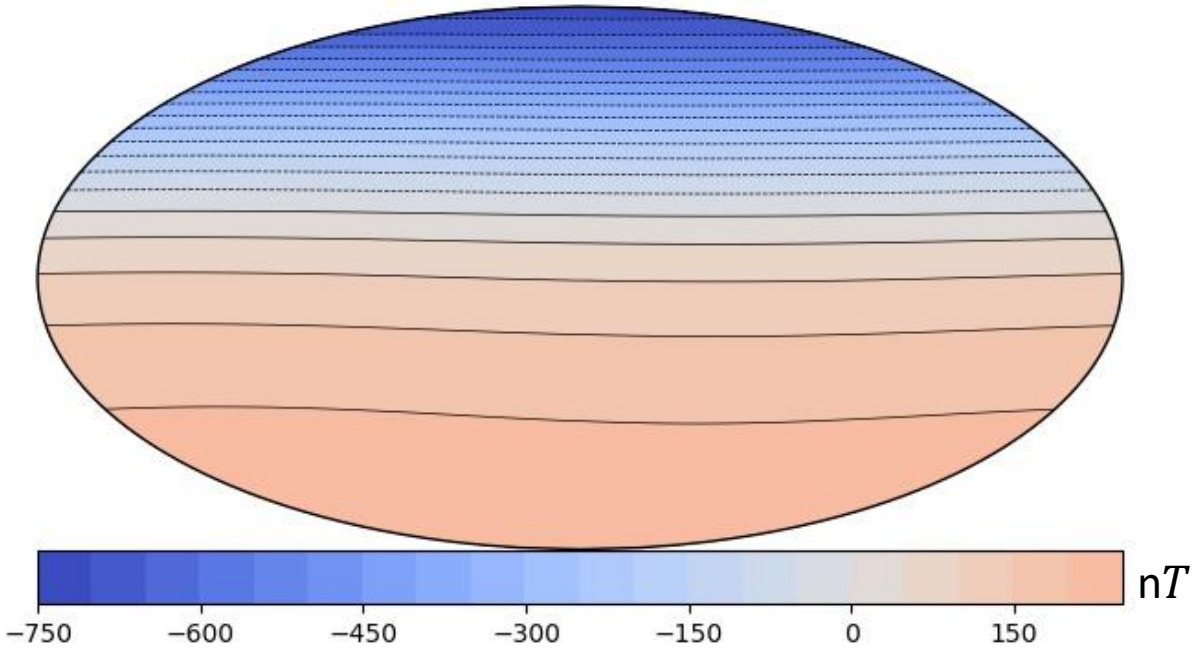
Jupiter



Uranus

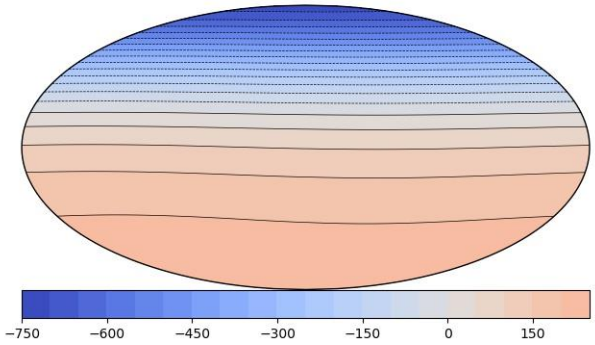


PLANETARY MAGNETIC FIELDS

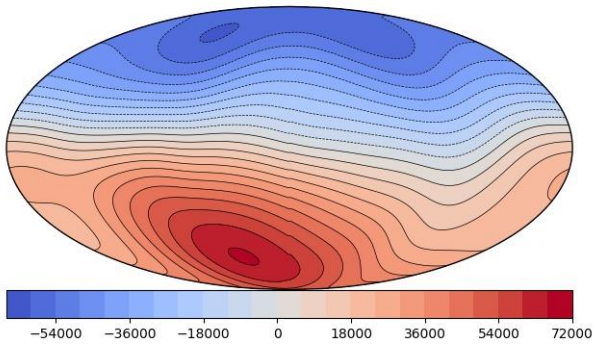


PLANETARY MAGNETIC FIELDS

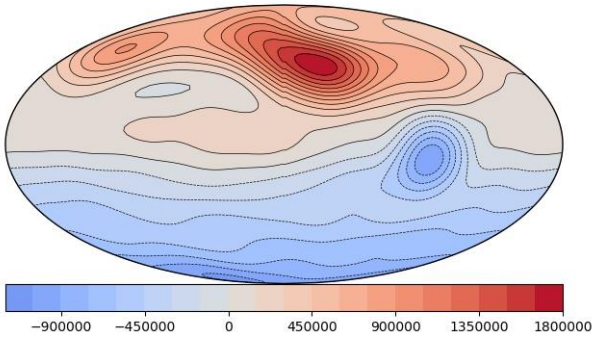
Mercury



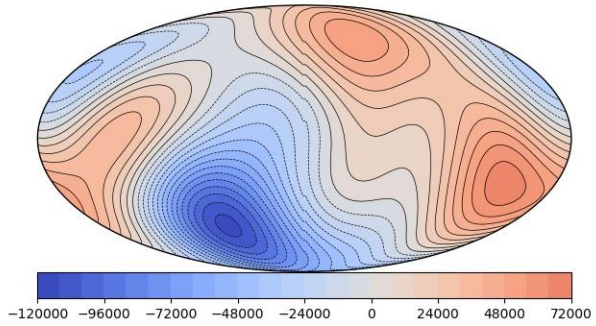
Earth



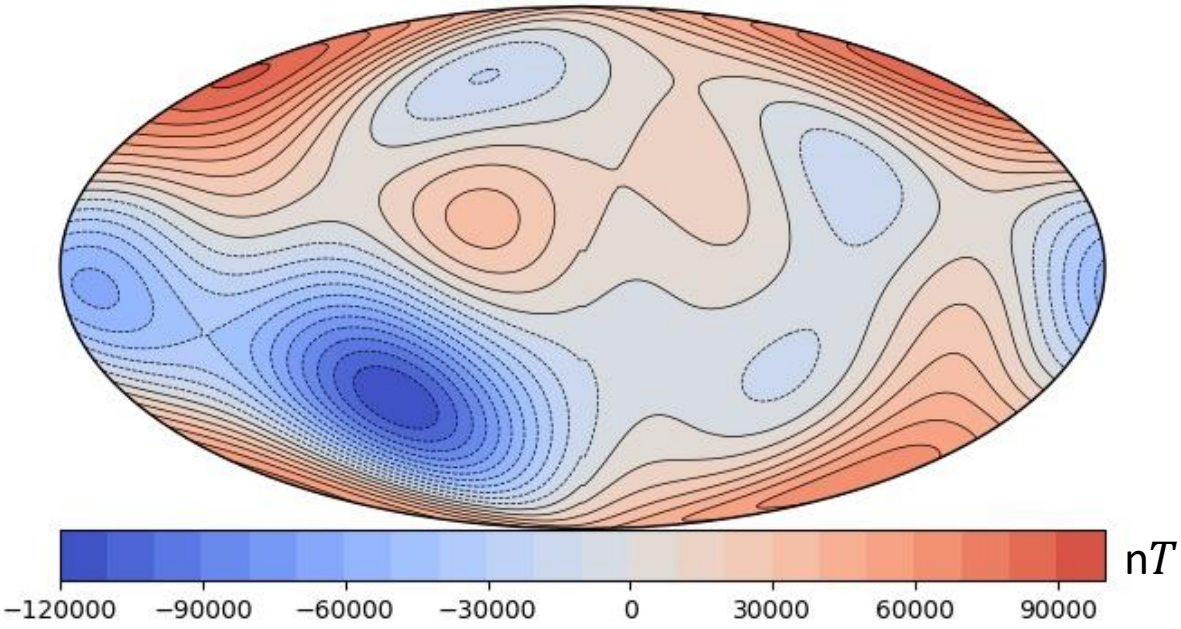
Jupiter



Uranus

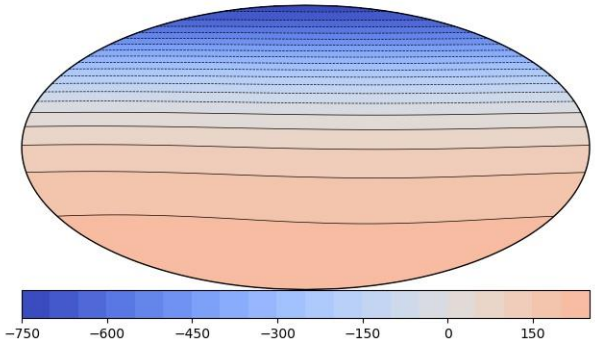


PLANETARY MAGNETIC FIELDS

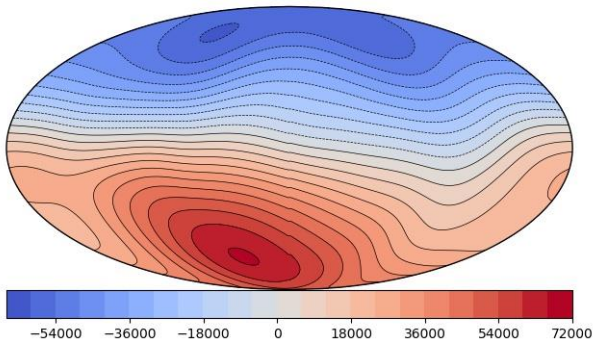


PLANETARY MAGNETIC FIELDS

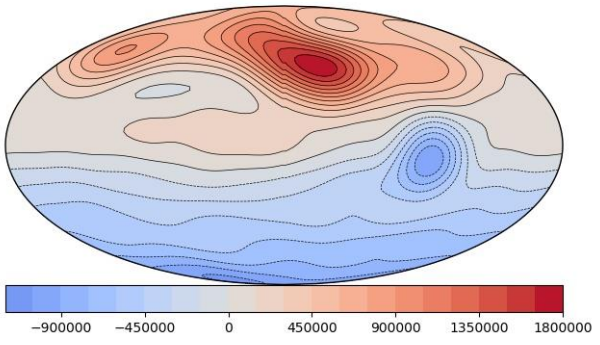
Mercury



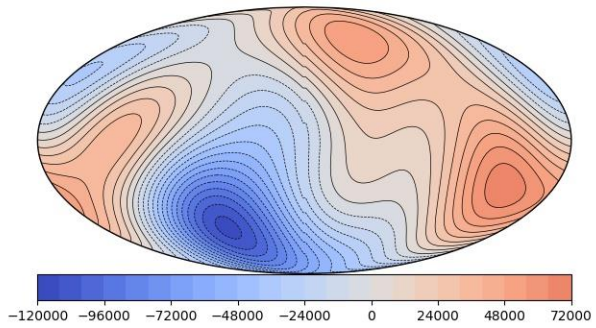
Earth



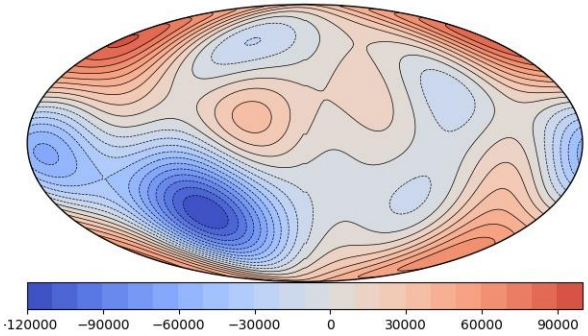
Jupiter



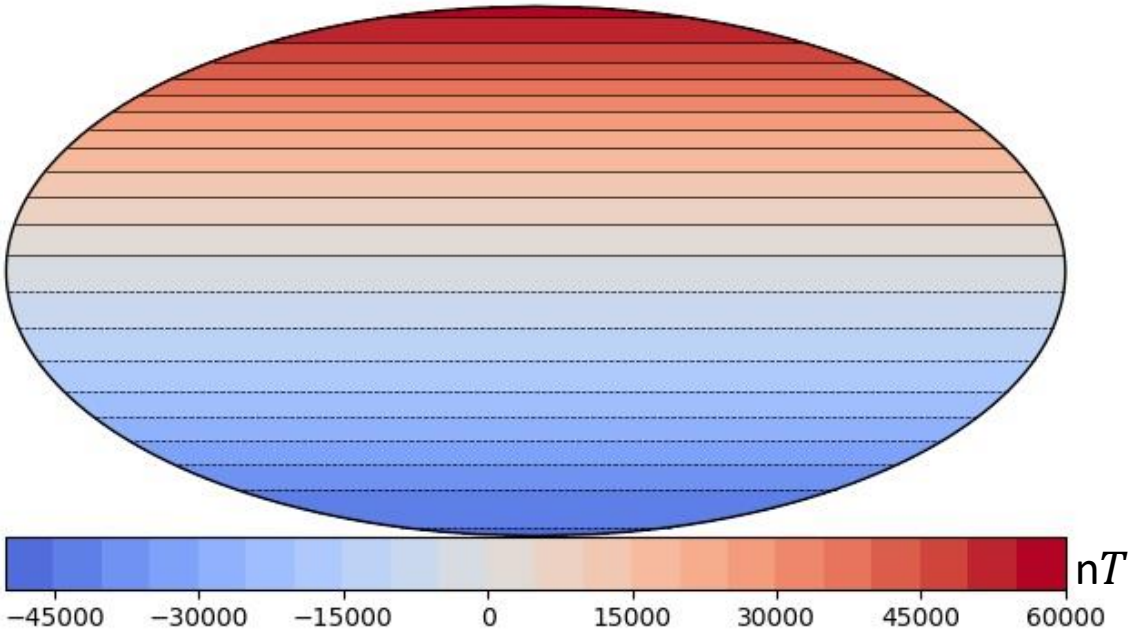
Uranus



Neptune

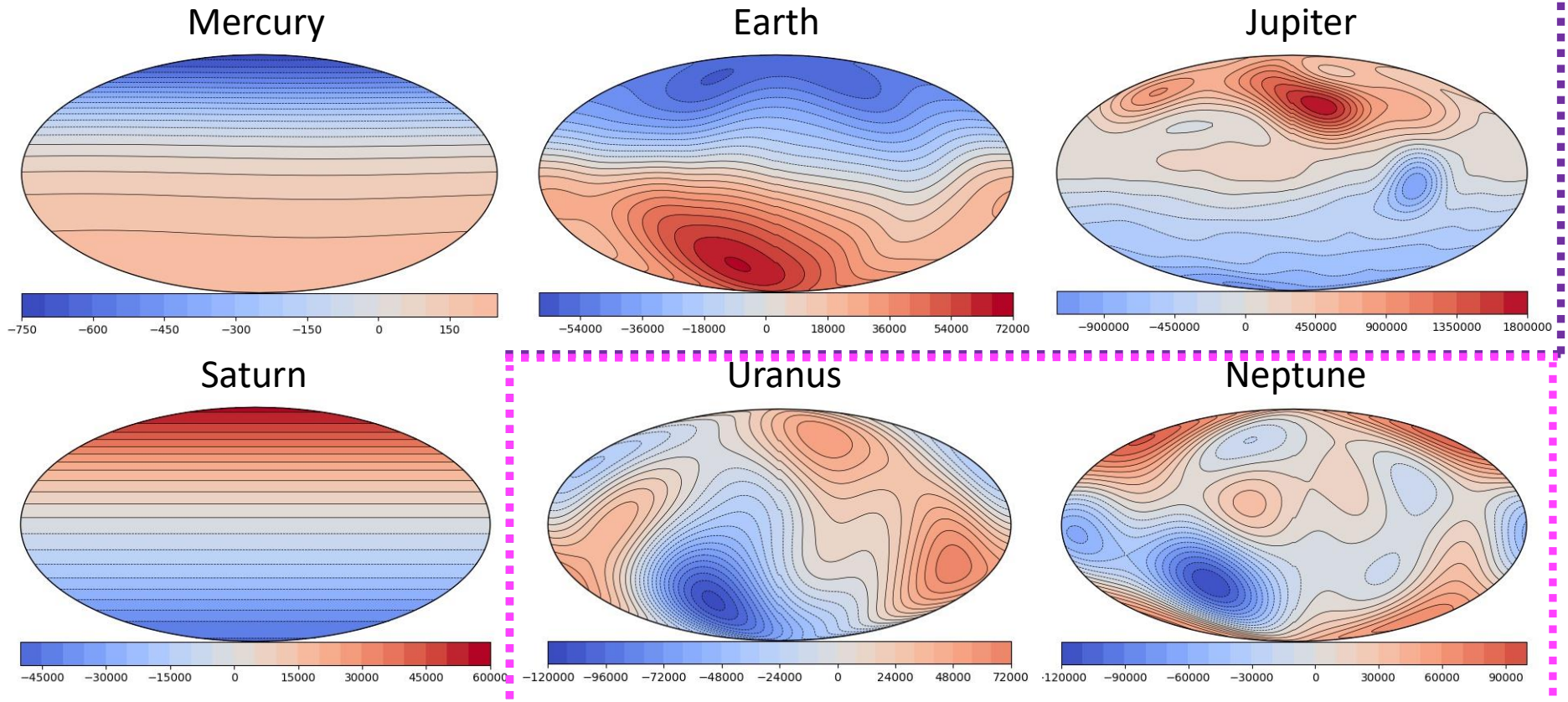


PLANETARY MAGNETIC FIELDS



PLANETARY MAGNETIC FIELDS

Planet Surface B_r



Mercury: Anderson et al. (2011), Thébault et al. (2018)
Earth: IGRF-13
Jupiter: Connerney et al. (2018)

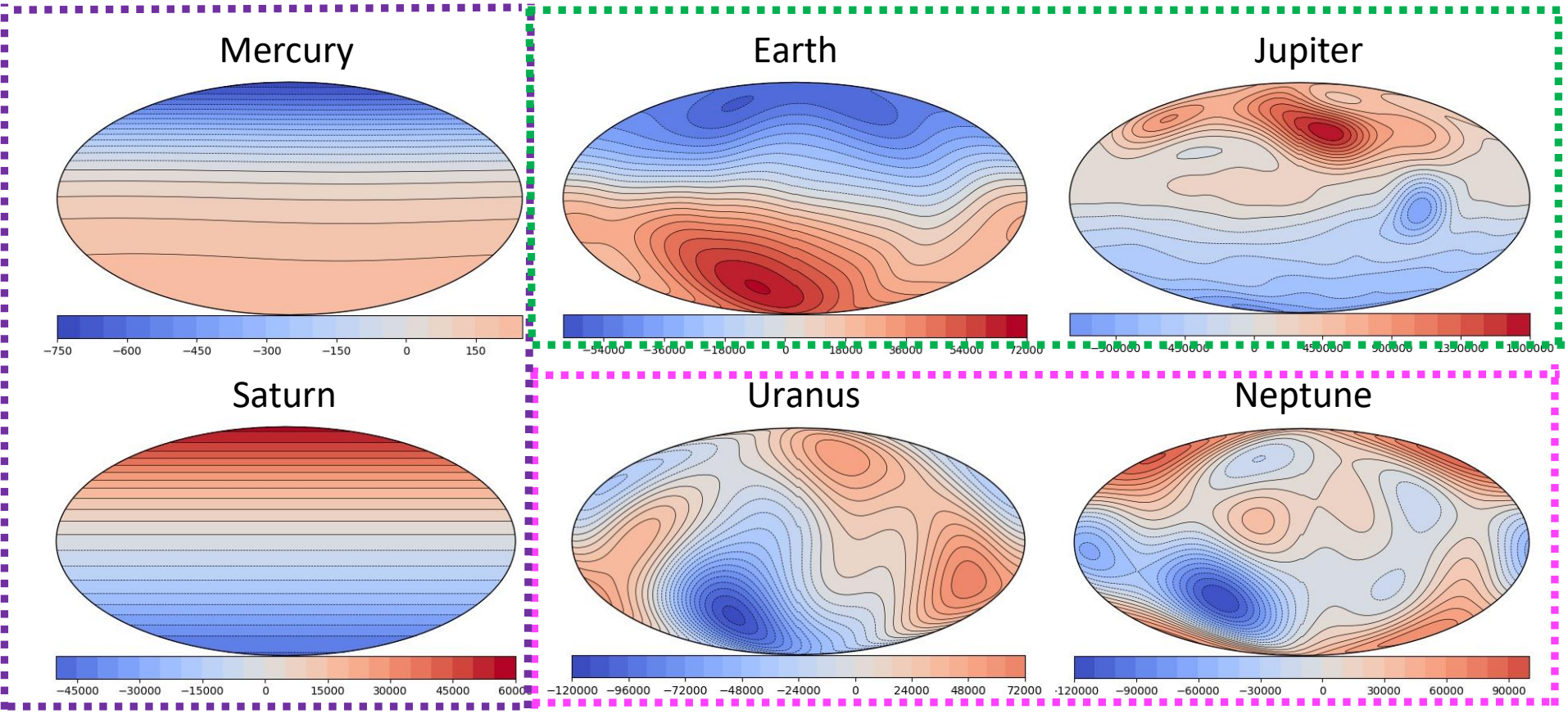
Dipole-dominated

Saturn: Dougherty et al. (2018), Cao et al. (2019)
Uranus & Neptune: Connerney et al. (1987, 1991), Holme & Bloxham (1996)

Non-dipole-dominated, multipolar

PLANETARY MAGNETIC FIELDS

Planet Surface B_r



Extreme Axisymmetry

Good Axisymmetry

Much Less Axisymmetry

& DON'T FORGET GANYMEDE!

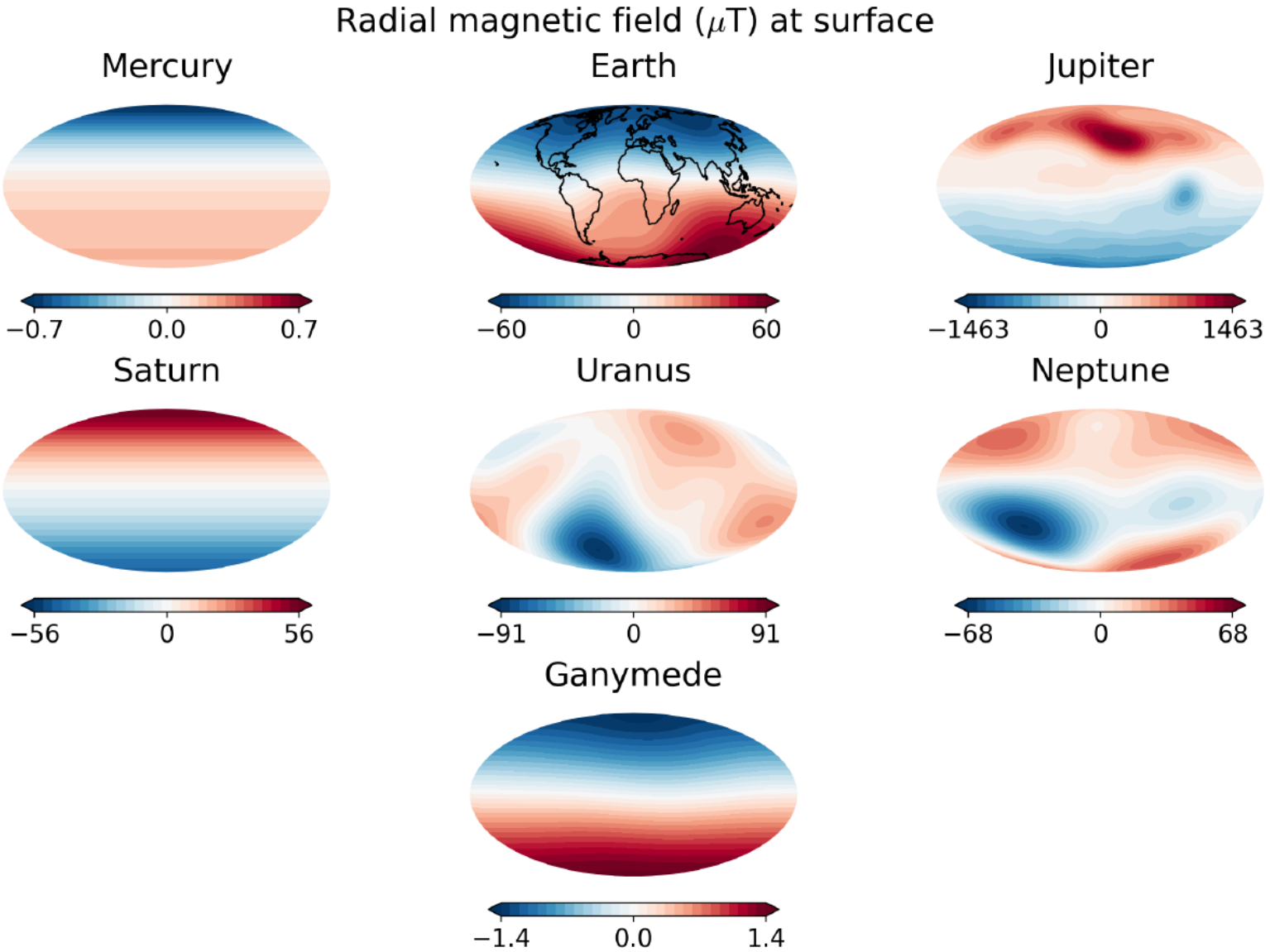


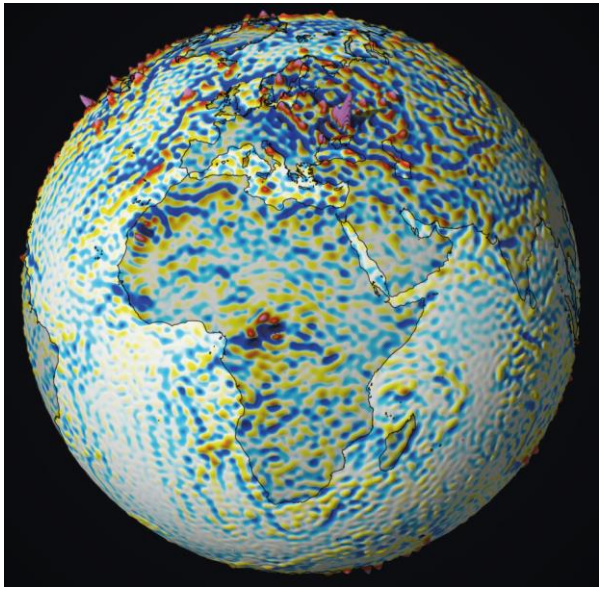
Image credit: Ankit Barik

& CRUSTAL MAGNETIC FIELDS

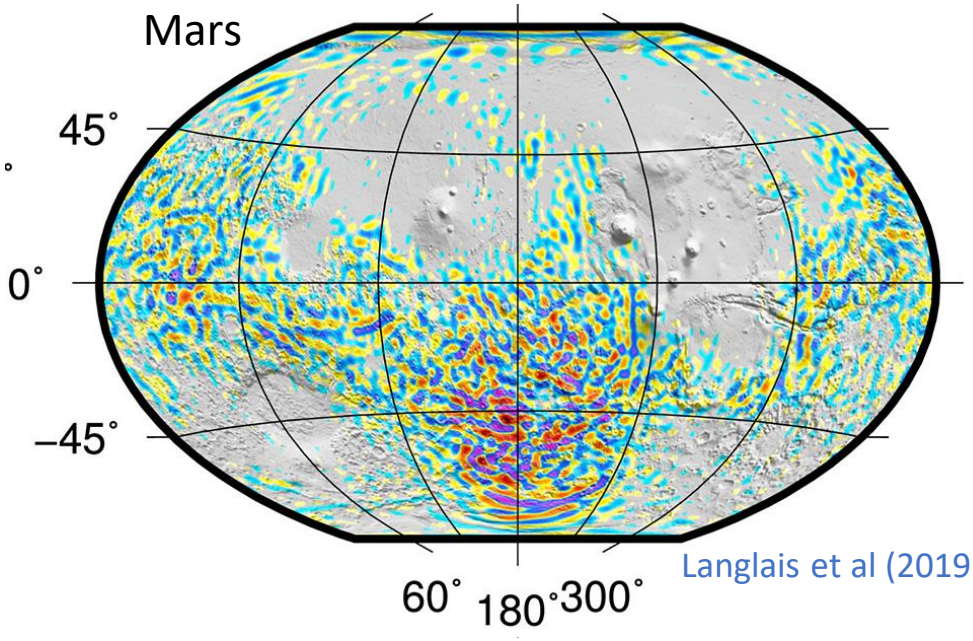
Dynamos of days gone past…

Earth

© ESA-DTU Space DLR



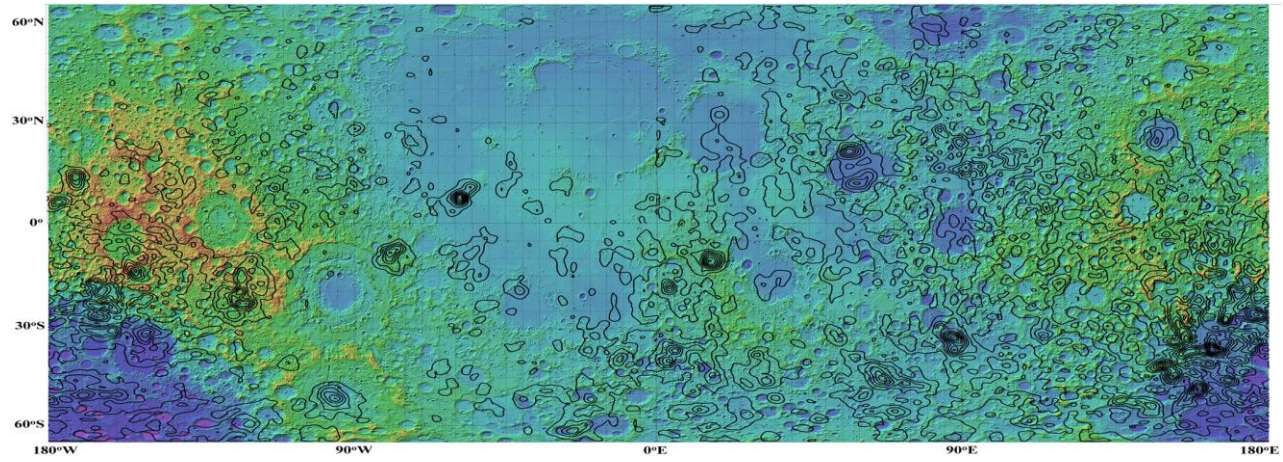
Mars



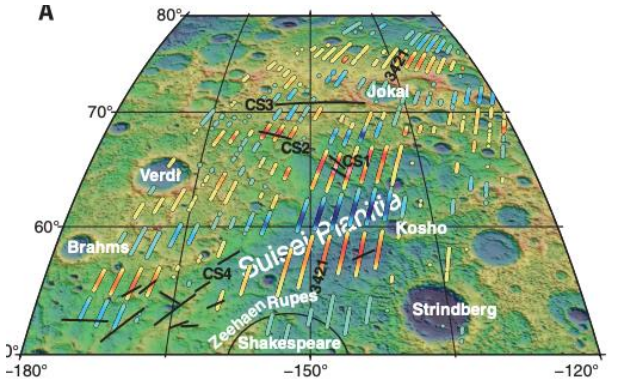
Langlais et al (2019)

Moon

Hood et al (2021)



Mercury

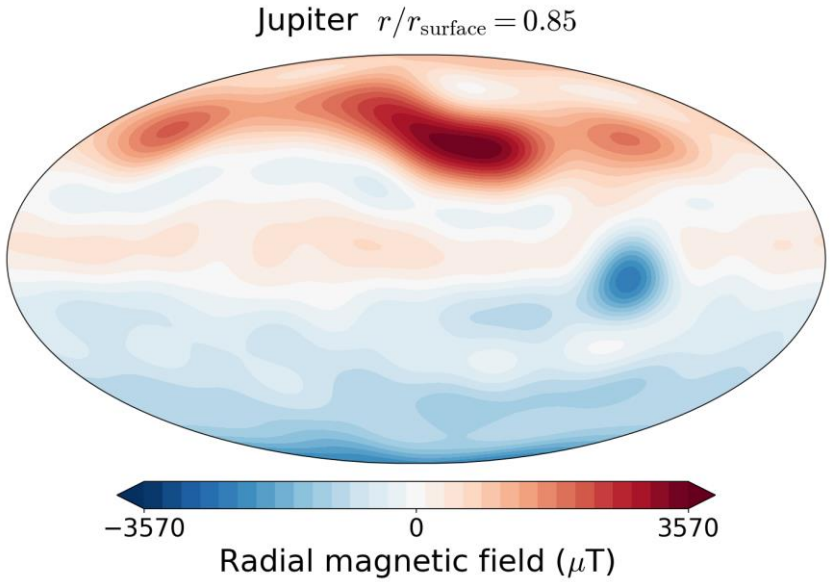


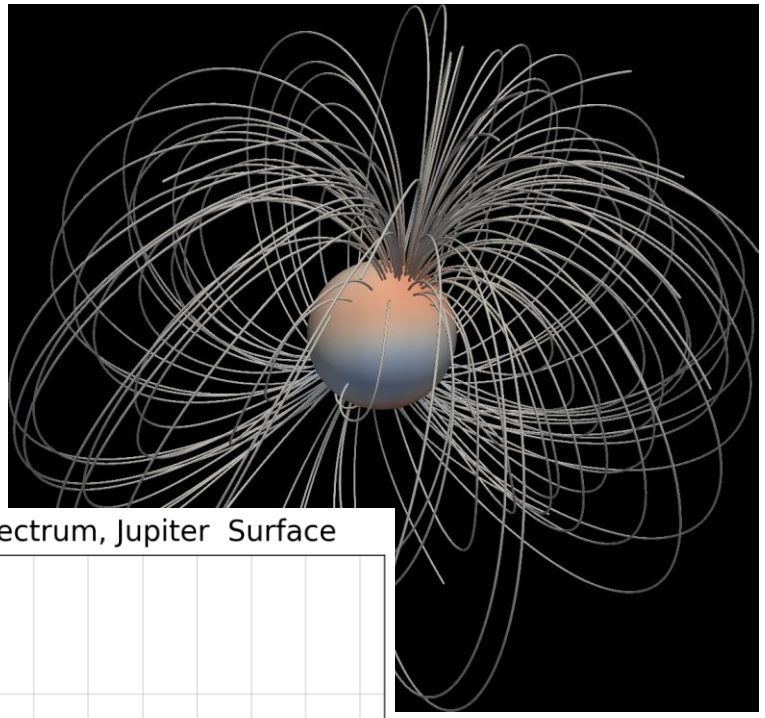
Johnson et al (2015)

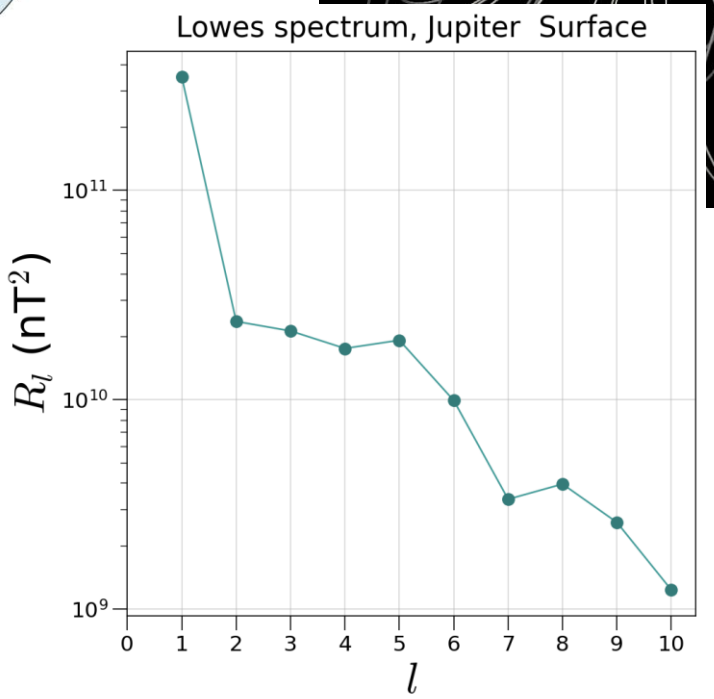
WANT TO MAKE YOUR OWN FIGURES?

Ankit Barik created ….

https://github.com/AnkitBarik/planetMagFields







QUANTIFYING FIELD STRUCTURE

Using a spherical harmonic representation of the field:

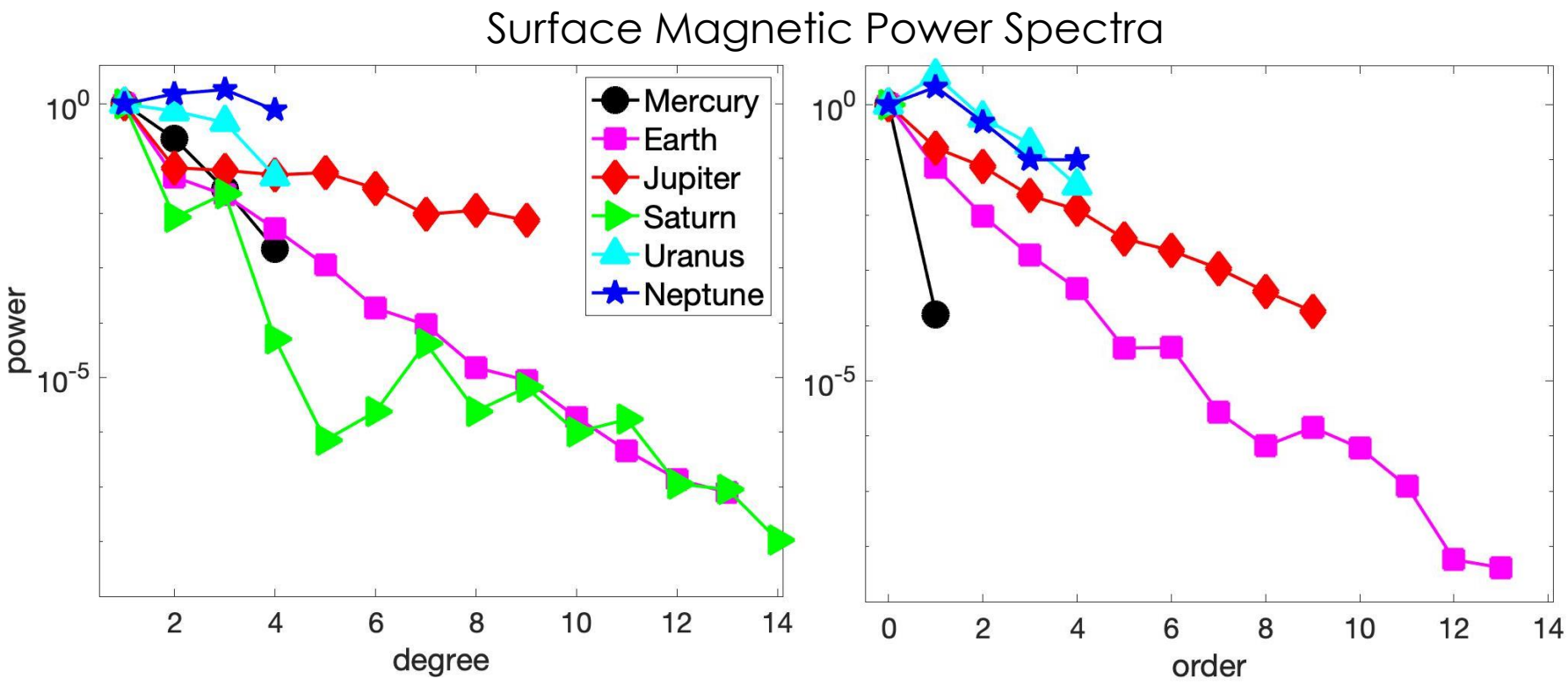
$$V(r,\theta,\phi) = a\sum_{l=1}^{\infty}\left(\frac{a}{r}\right)^{l+1}\sum_{m=0}^{l}\left[g_l^m(r)\cos(m\phi) + h_l^m(r)\sin(m\phi)\right]P_l^m(\cos\theta)$$

Calculate the magnetic power spectrum:

$$p(l,m,r) = (l+1)\left(\frac{a}{r}\right)^{(2l+4)}\left[\left(g_l^m\right)^2 + \left(h_l^m\right)^2\right]$$

Pick a radius r, sum over all m's or sum over all l's, make graphs….

LENGTHSCALES & RESOLUTION

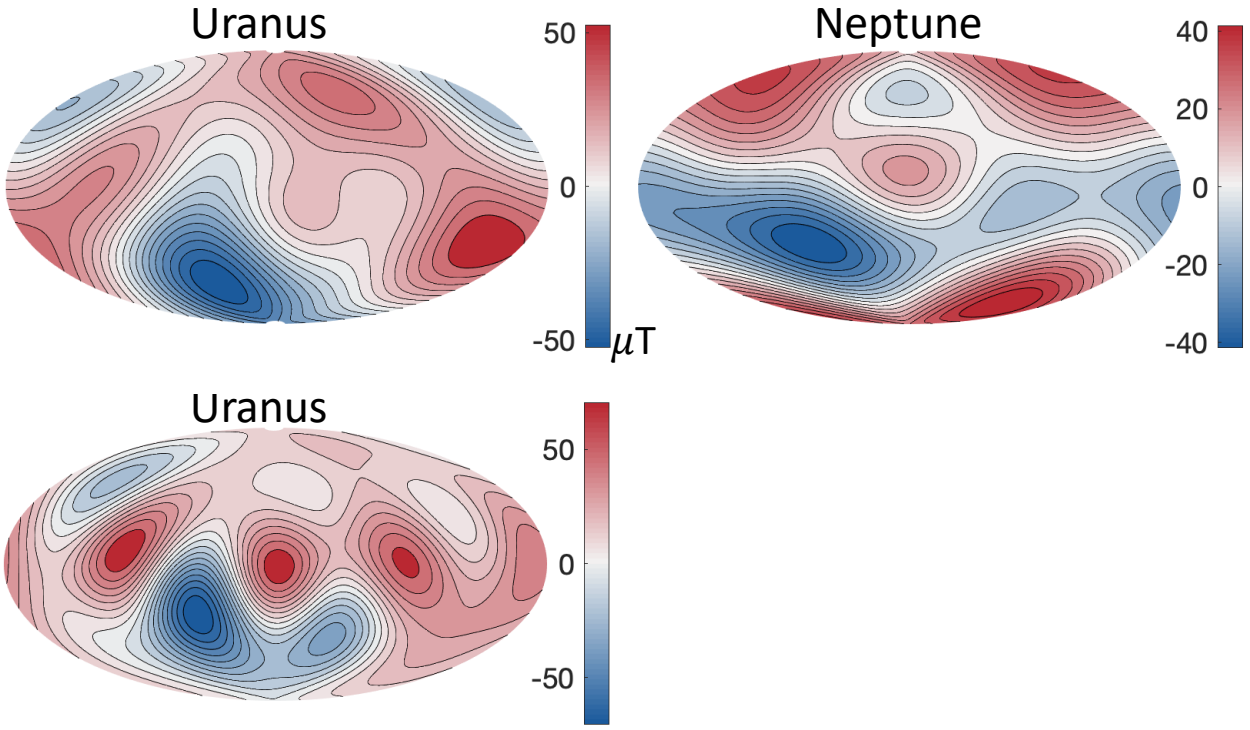


Quite a variety in distribution of length scales

Also a variety in resolution

RESOLUTION EXAMPLE

Single Flyby data

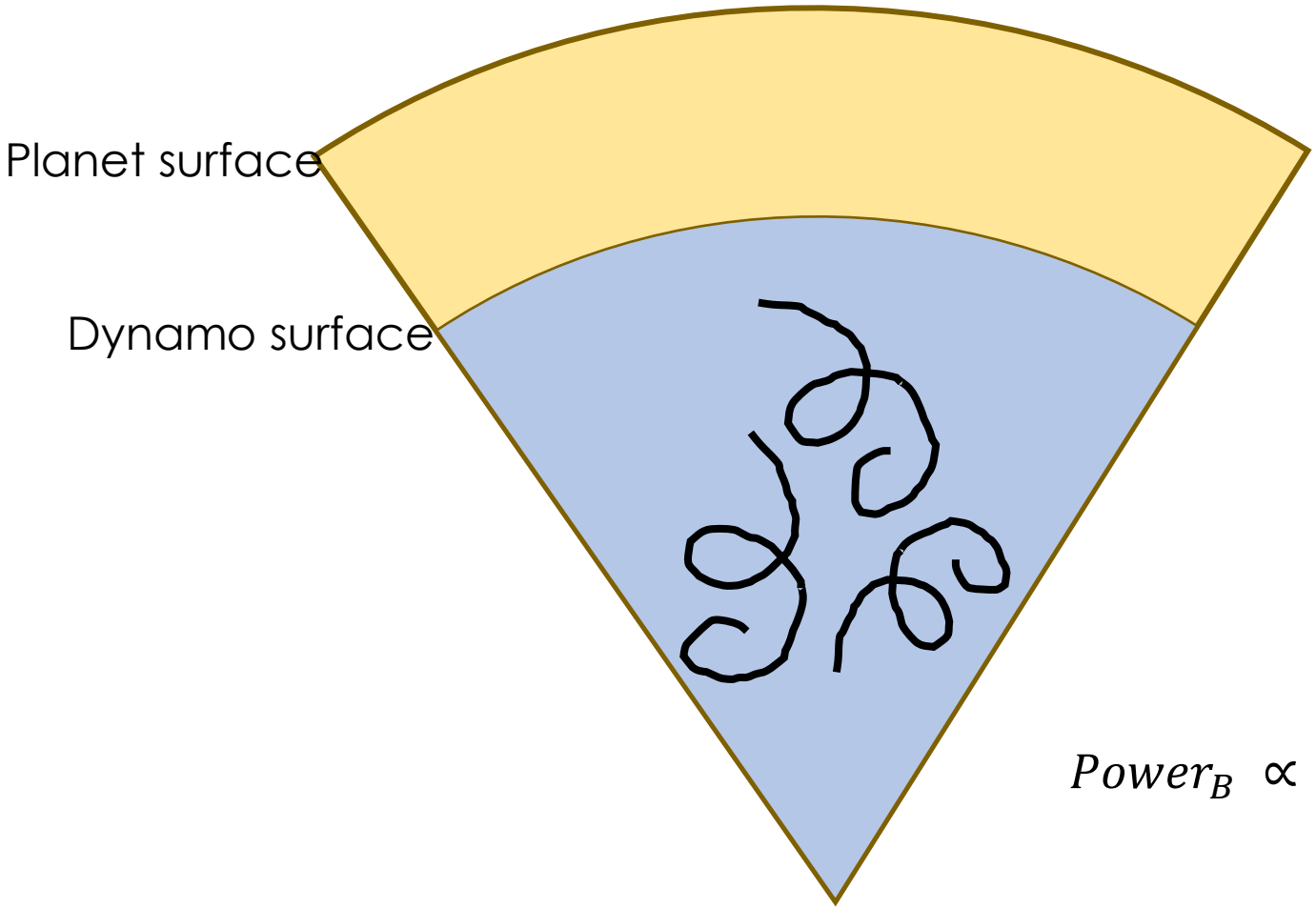


Voyager 2 flybys (Connerney et al. 1987, 1991, Holme & Bloxham, 1996)

Voyager 2 flyby + auroral footprints (Herbert, 2009)

(Please send another mission, much appreciated, thank you)

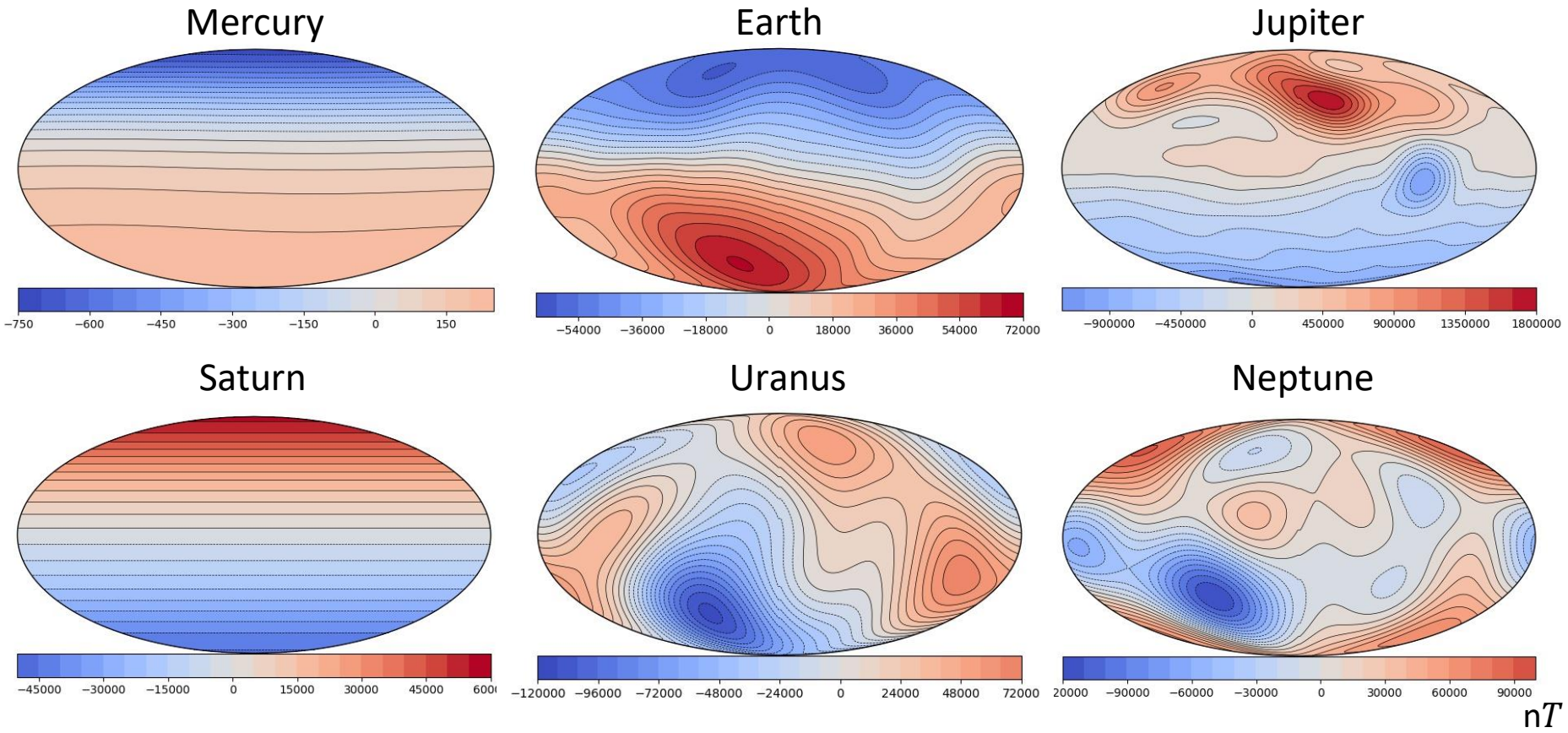
DYNAMO SURFACE



$$Power_B \propto \left(\frac{R_{Planet}}{R_{Dynamo}}\right)^{2l+4}$$

PLANETARY MAGNETIC FIELDS

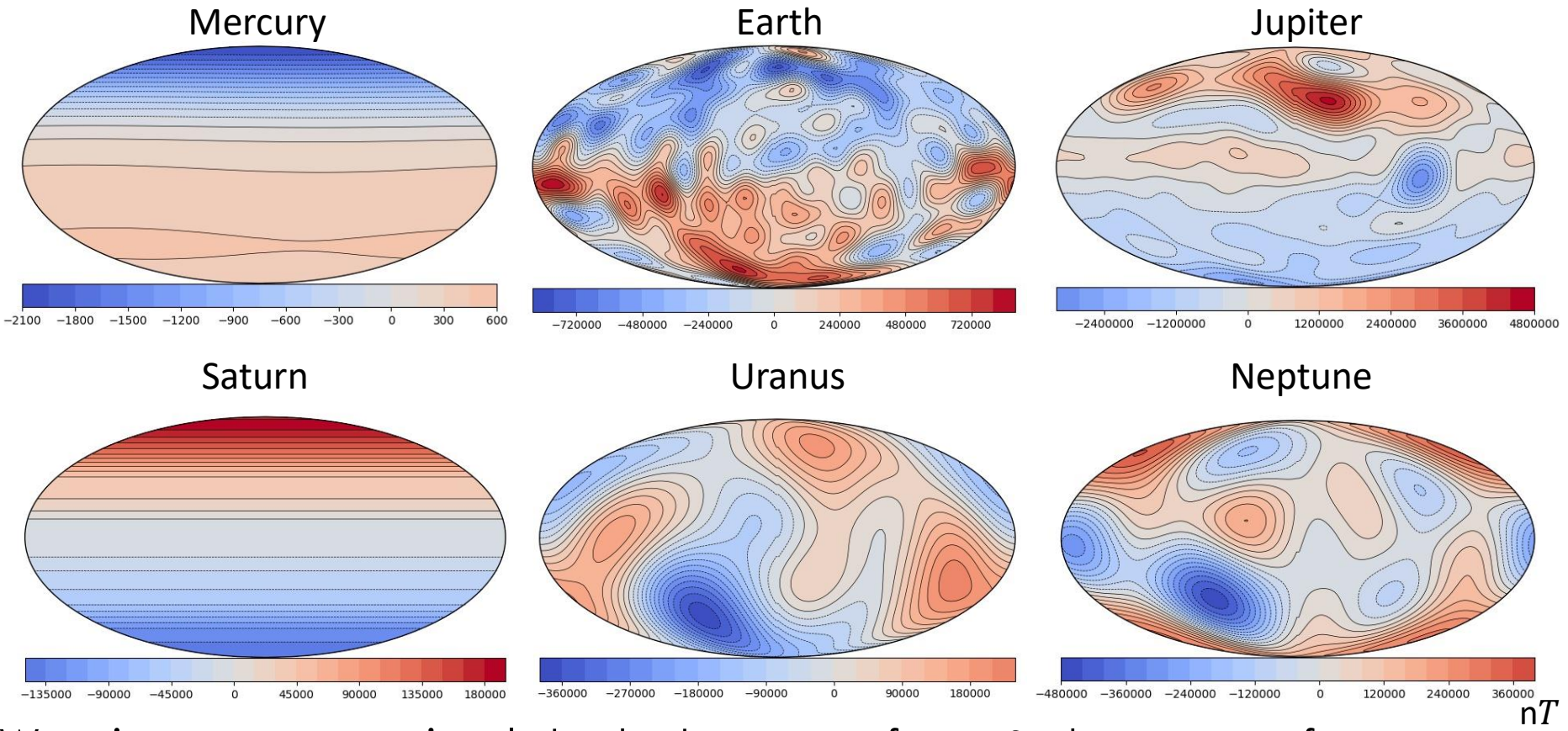
Planet Surface B_r



PLANETARY MAGNETIC FIELDS

Q: Which one changes the most?

Dynamo Surface B_r

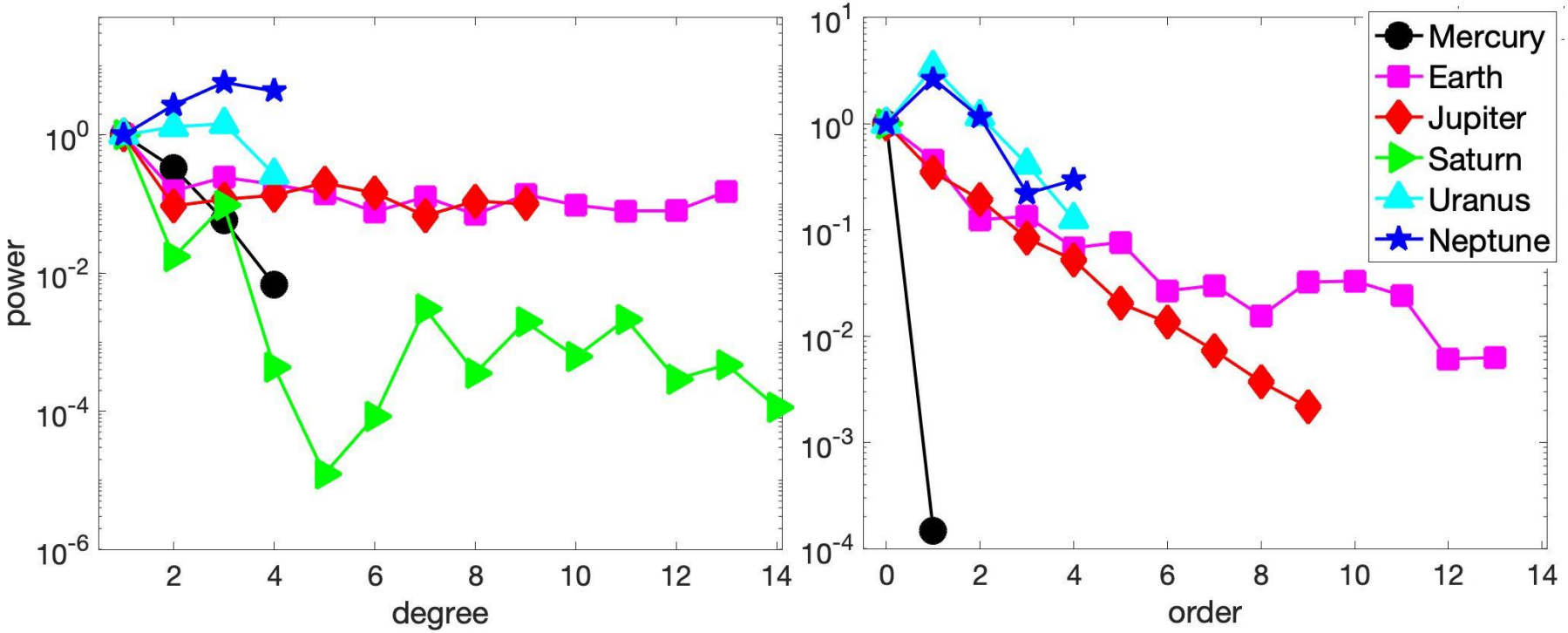


Warnings : assumes insulator between surface & dynamo surface

: assumes knowledge of depth to dynamo surface

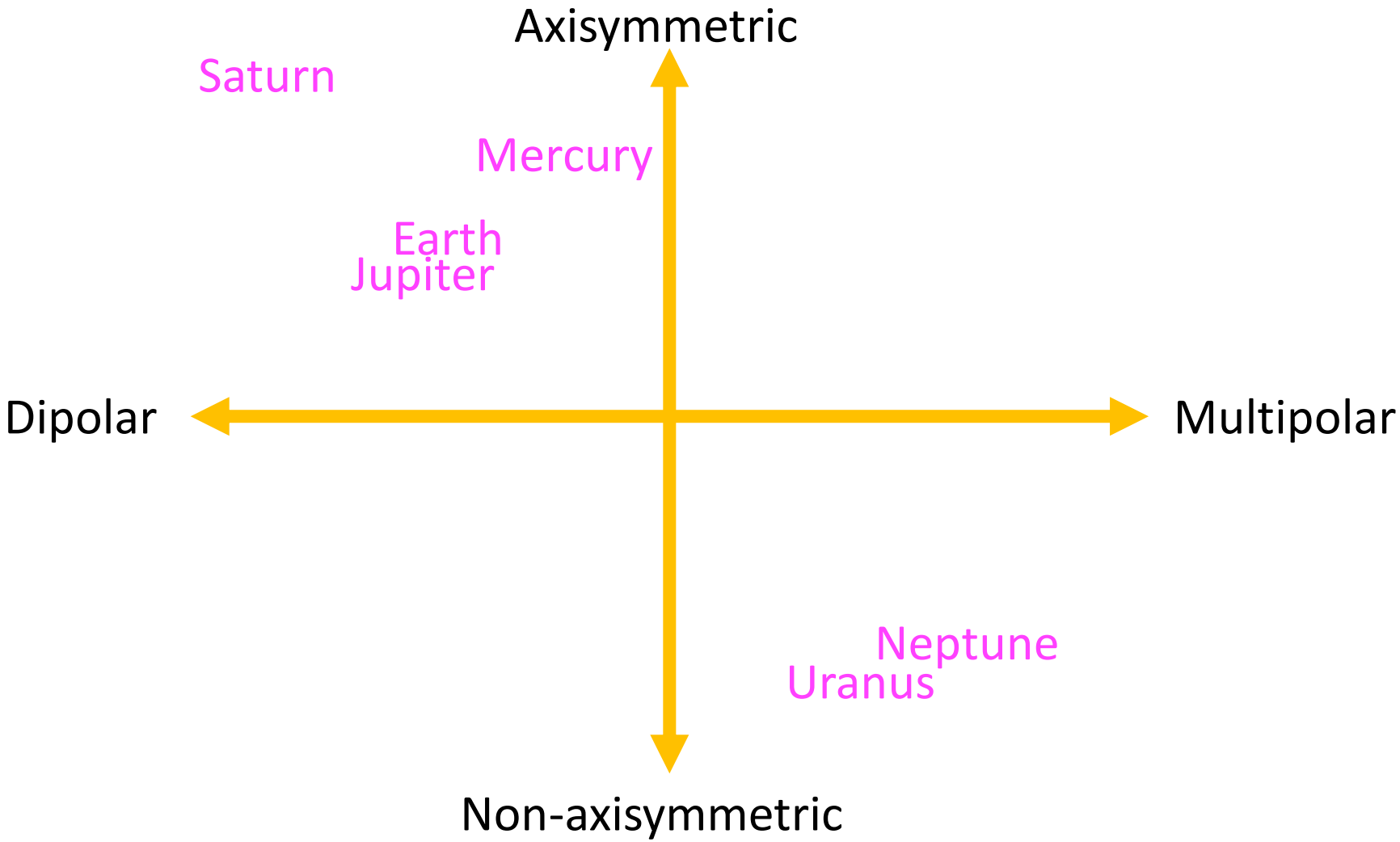
LENGTHSCALES

Dynamo Surface Magnetic Power Spectra

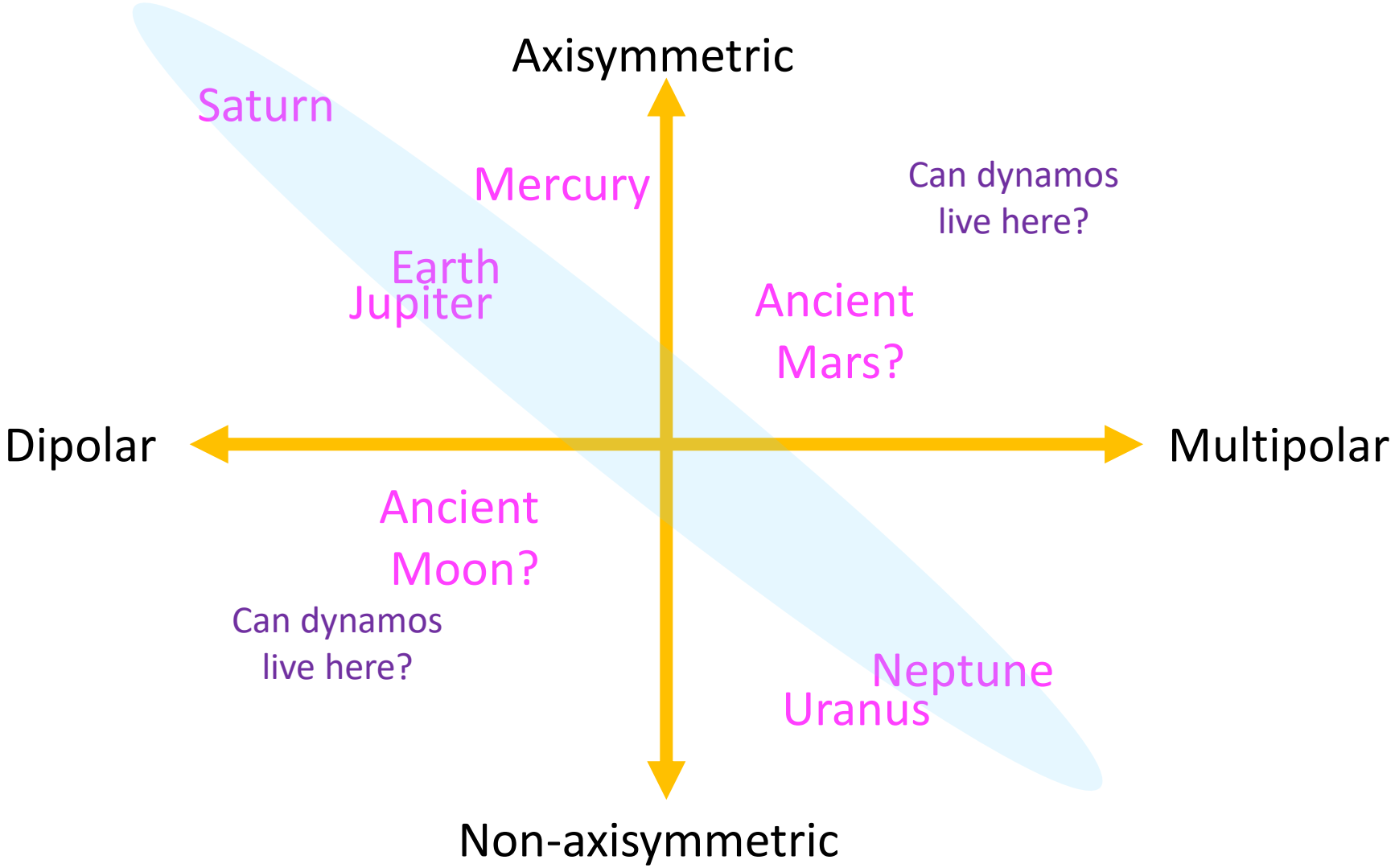


Still quite a variety in distribution of length scales at dynamo surface

MORPHOLOGY CLASSIFICATION ATTEMPT

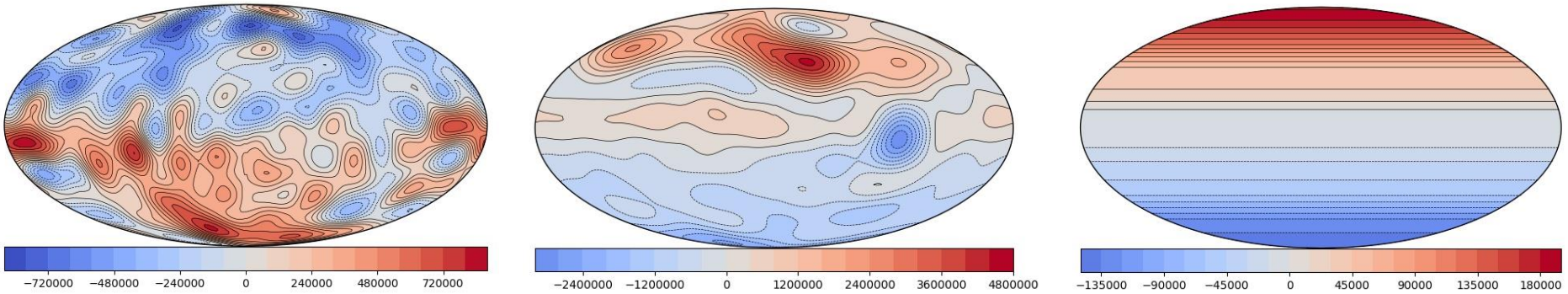


MORPHOLOGY CLASSIFICATION ATTEMPT



MAGNETICALLY INTERESTING TIMES

Dynamo Surface Br



We now know Jupiter's & Saturn's dynamo fields to similar spatial resolution as Earth's field

The fields are fundamentally different!

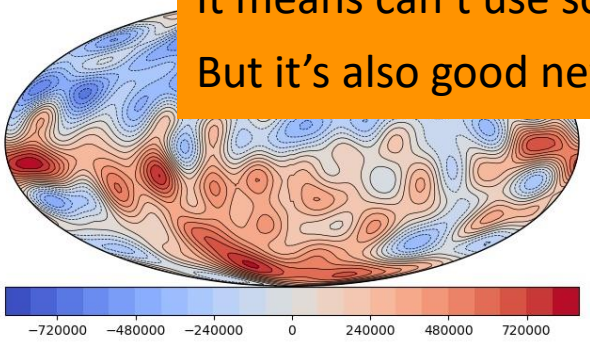
MAGNETICALLY INTERESTING TIMES

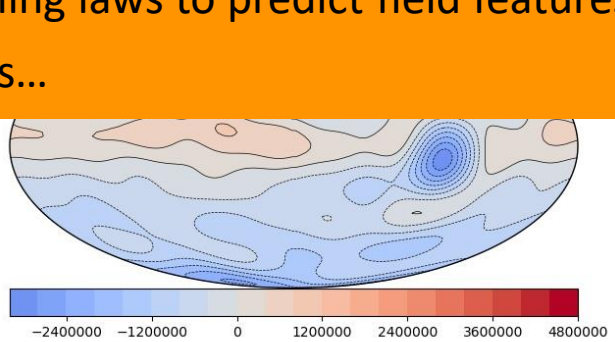
Scary claim: Differences NOT due to different parameter regimes.

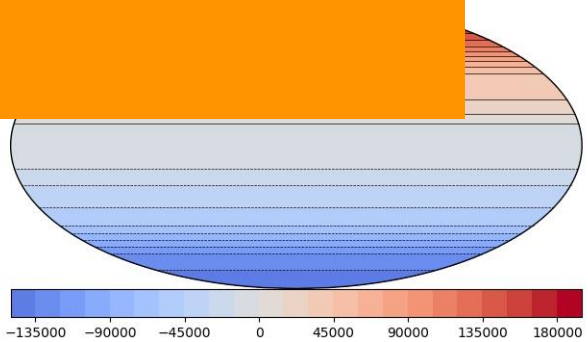
Why is that scary?

It means can't use scaling laws to predict field features.

But it's also good news…





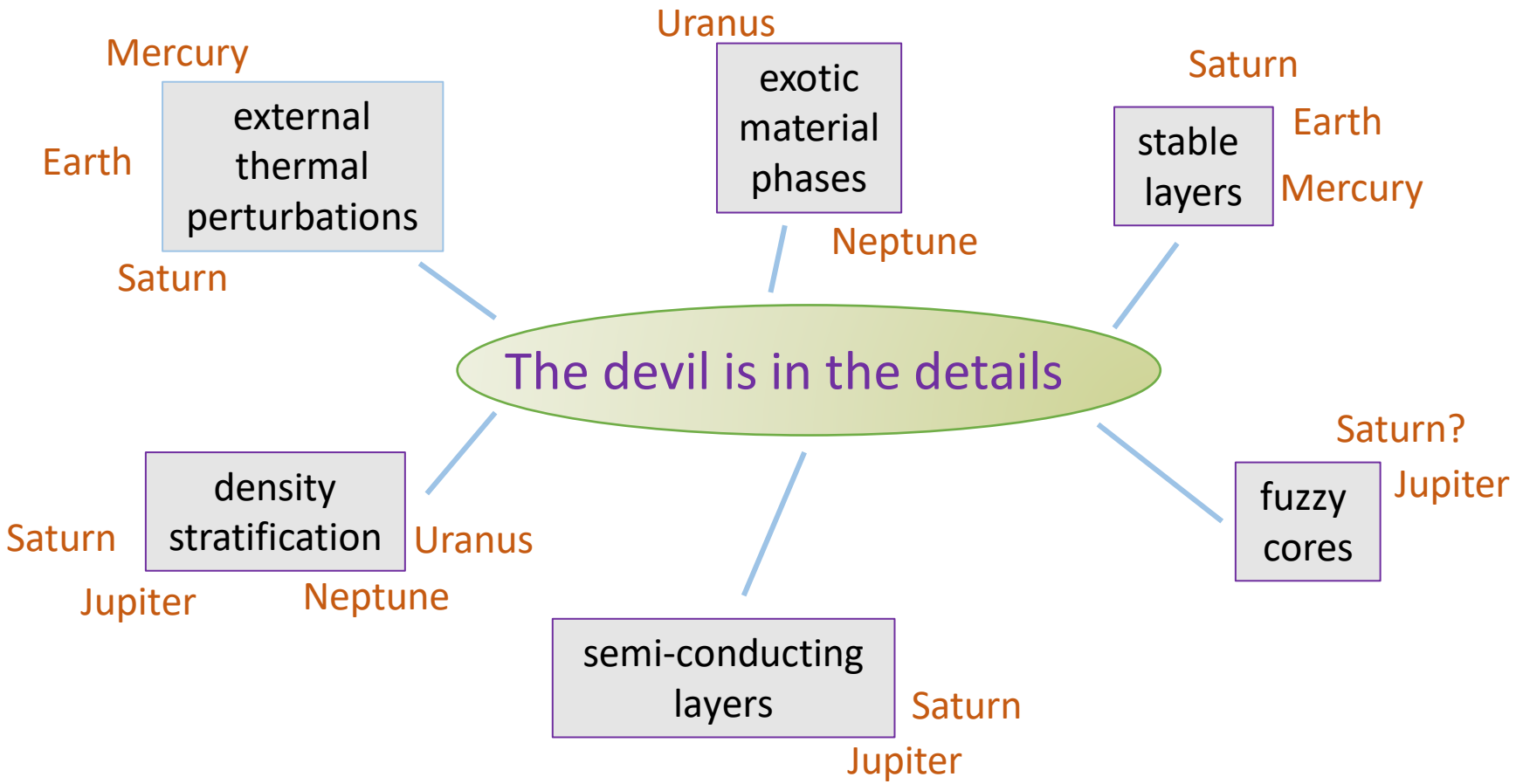


Homogeneous small-scale structure

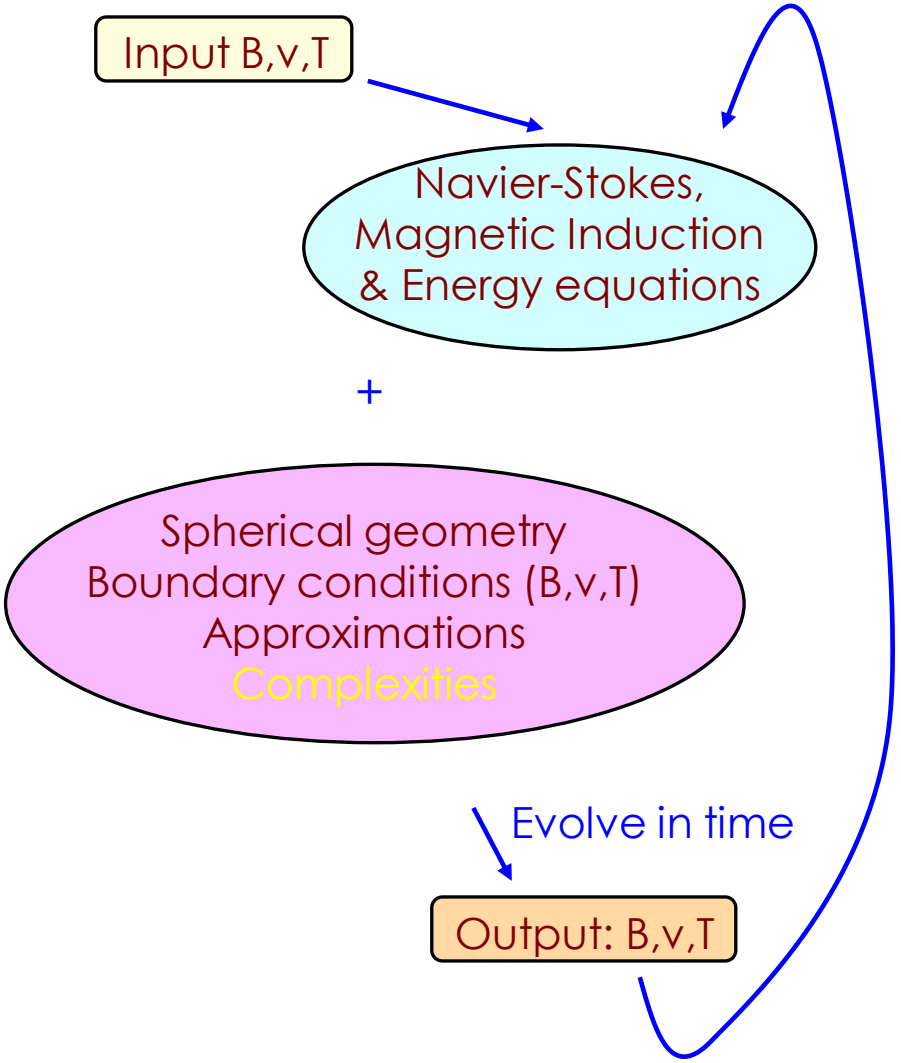
Hemispheric small-scale structure: Southern hemisphere is dipolar (Moore et al. 2018)
Zonal shearing?

Zonal small-scale structure (Cao et al. 2020)

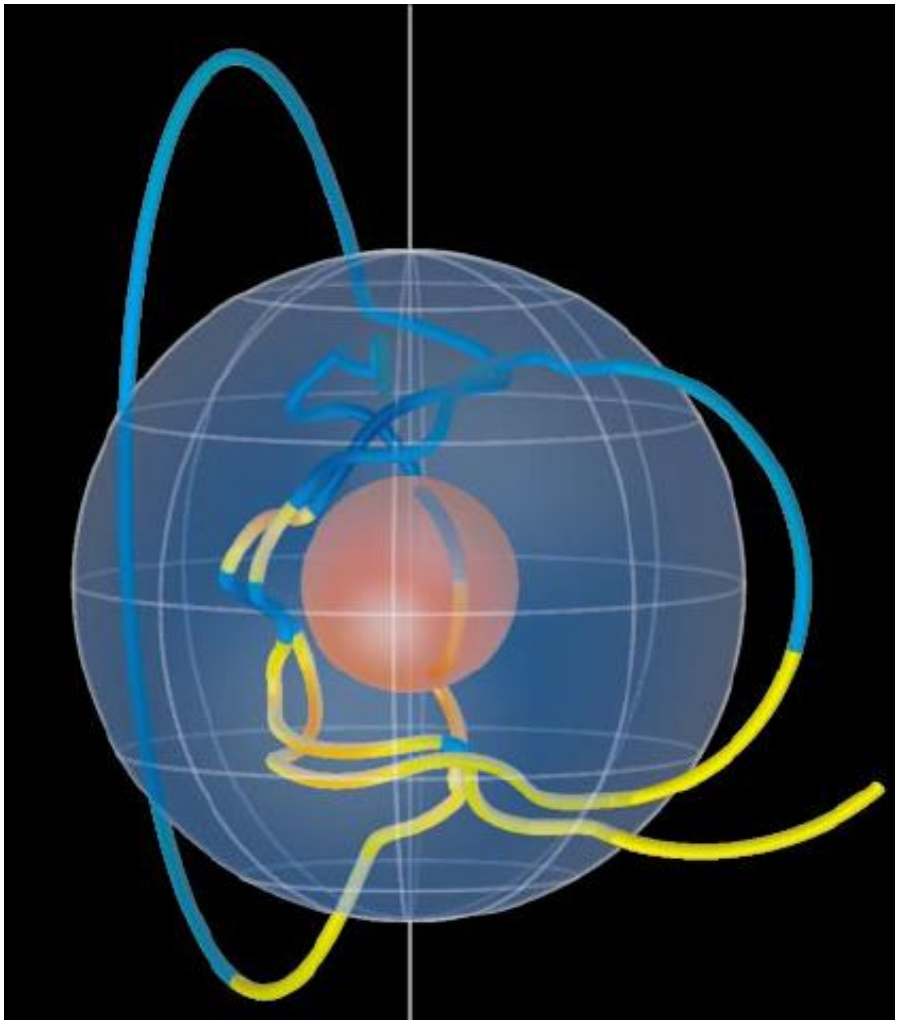
COMPLEXITIES TELL US ABOUT INTERIORS



TEST COMPLEXITIES WITH SIMULATIONS

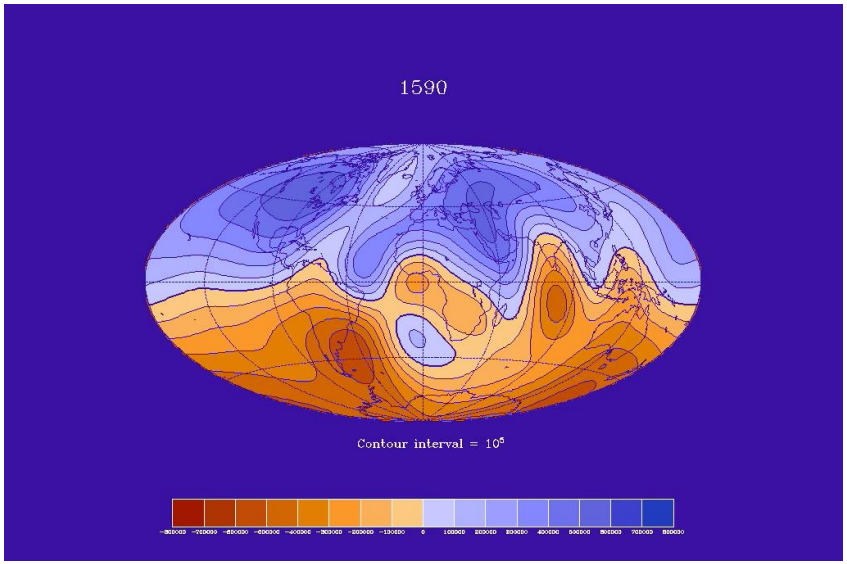


Geometry



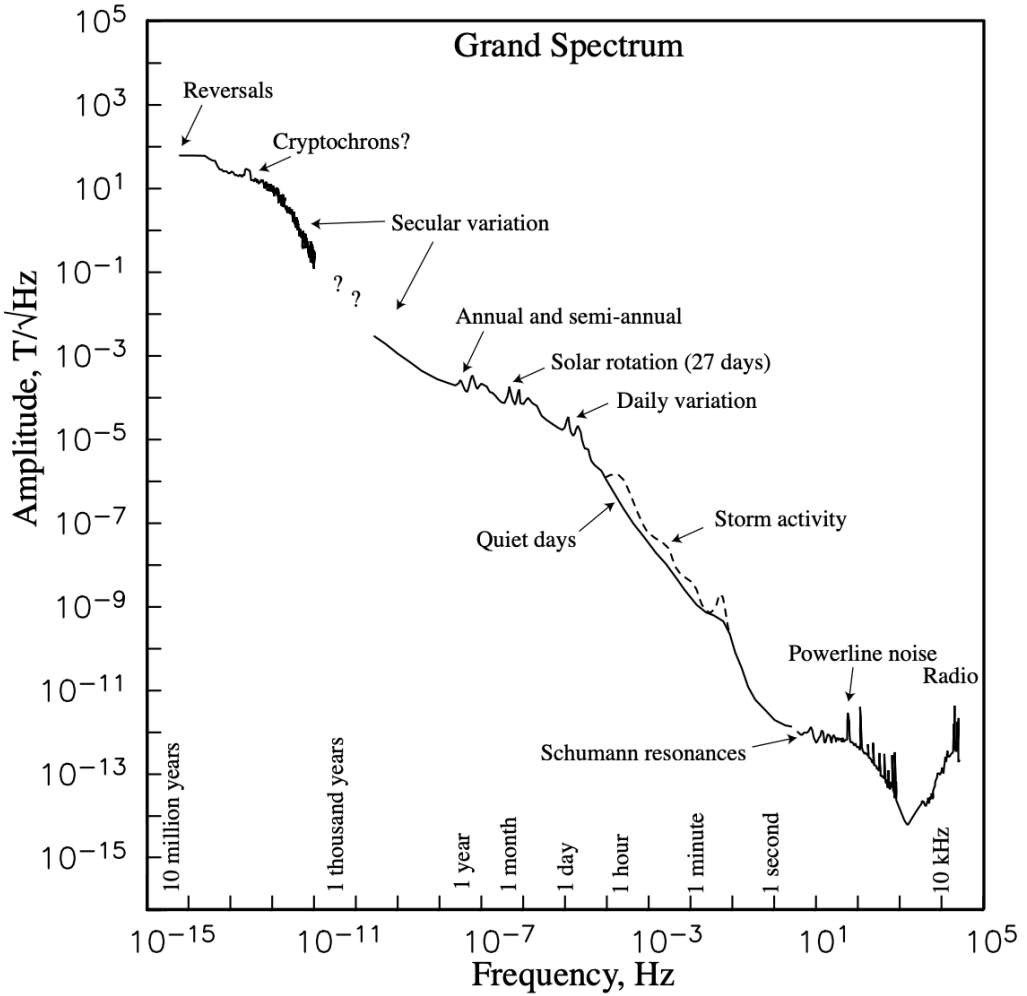
Kuang & Bloxham (1997)

GEODYNAMO



http://www.epm.geophys.ethz.ch/~cfinlay/gufm1.html

To a planetary scientist, this range & detail of information are exquisite



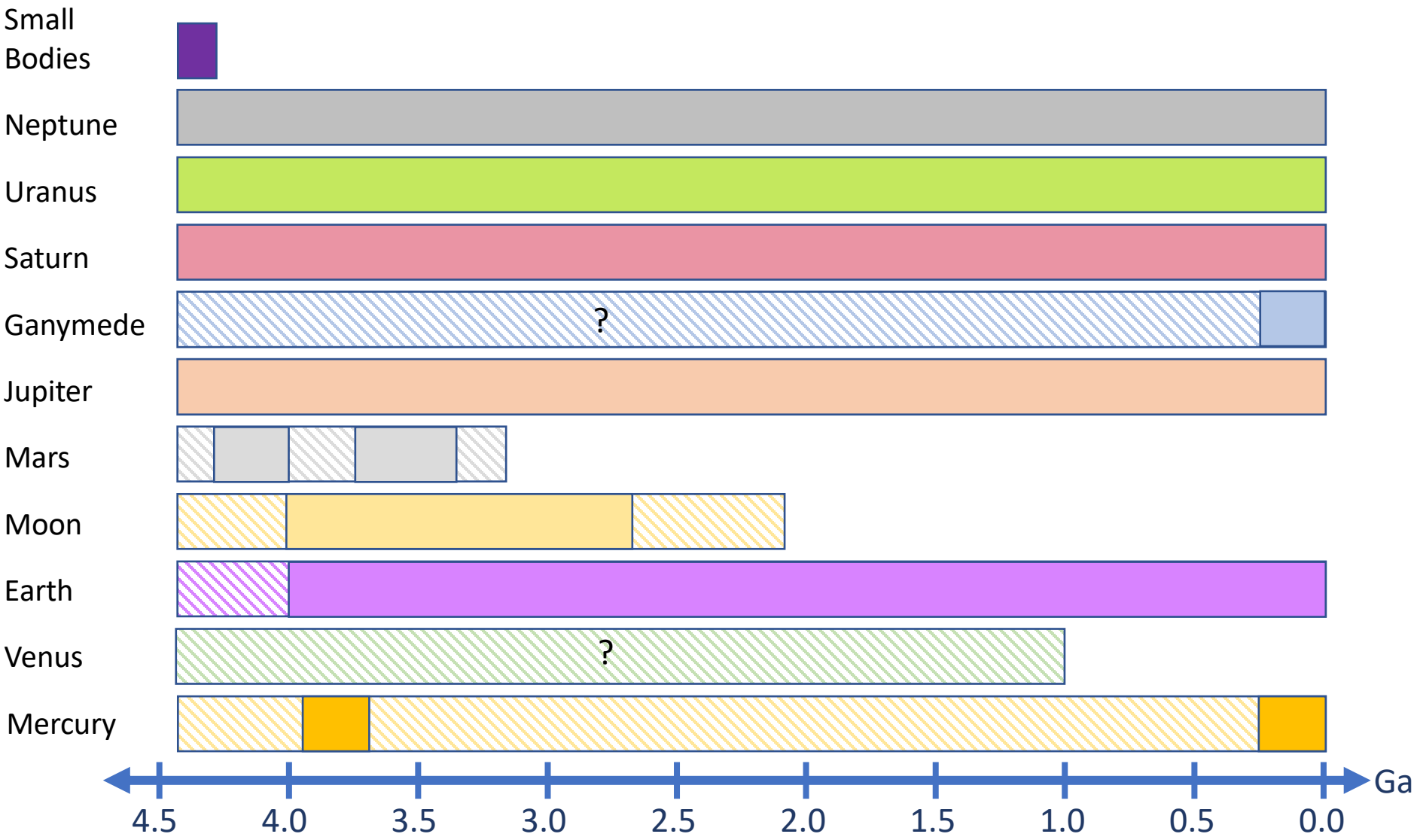
Constable & Constable (2004)

PLANETARY QUESTIONS WE CAN STUDY

- Would love to have fancy frequency spectrum plot for other planets, but not feasible in the near future. So in the meantime…

- Focus on big questions:

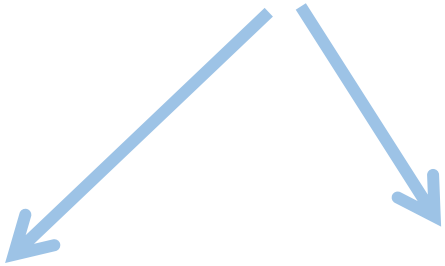
DYNAMO TIMING



REVERSALS?

Earth: 

Other planets? 



Lunar Paleopoles? ? 

Martian paleopoles?

SECULAR VARIATION

Earth:

Other planets?

Saturn:

None detected (Cao et al. 2011)

But that might be expected (Stanley & Bloxham, 2016)

Jupiter

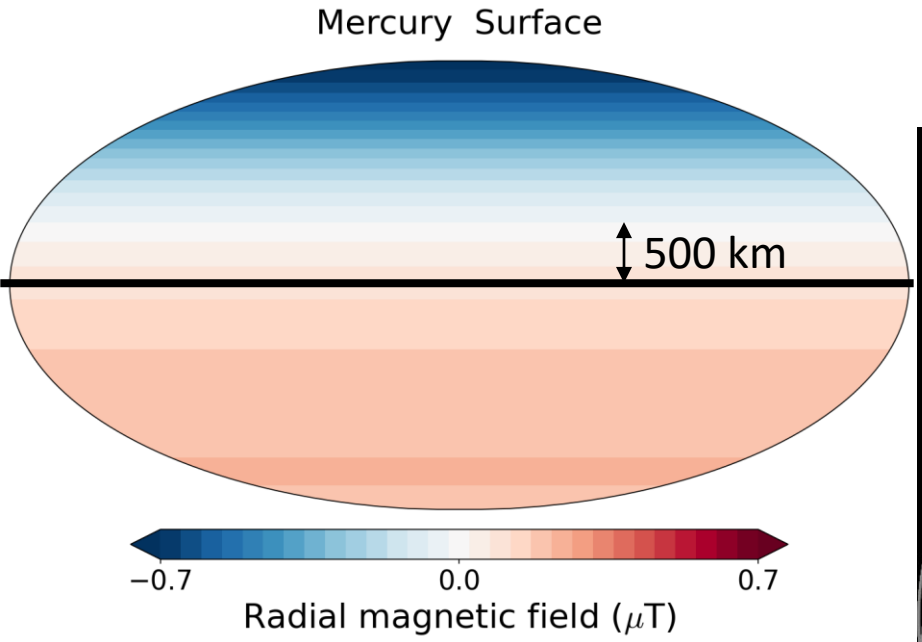
But from winds in semi-conducting layer? (Moore et al. 2019)

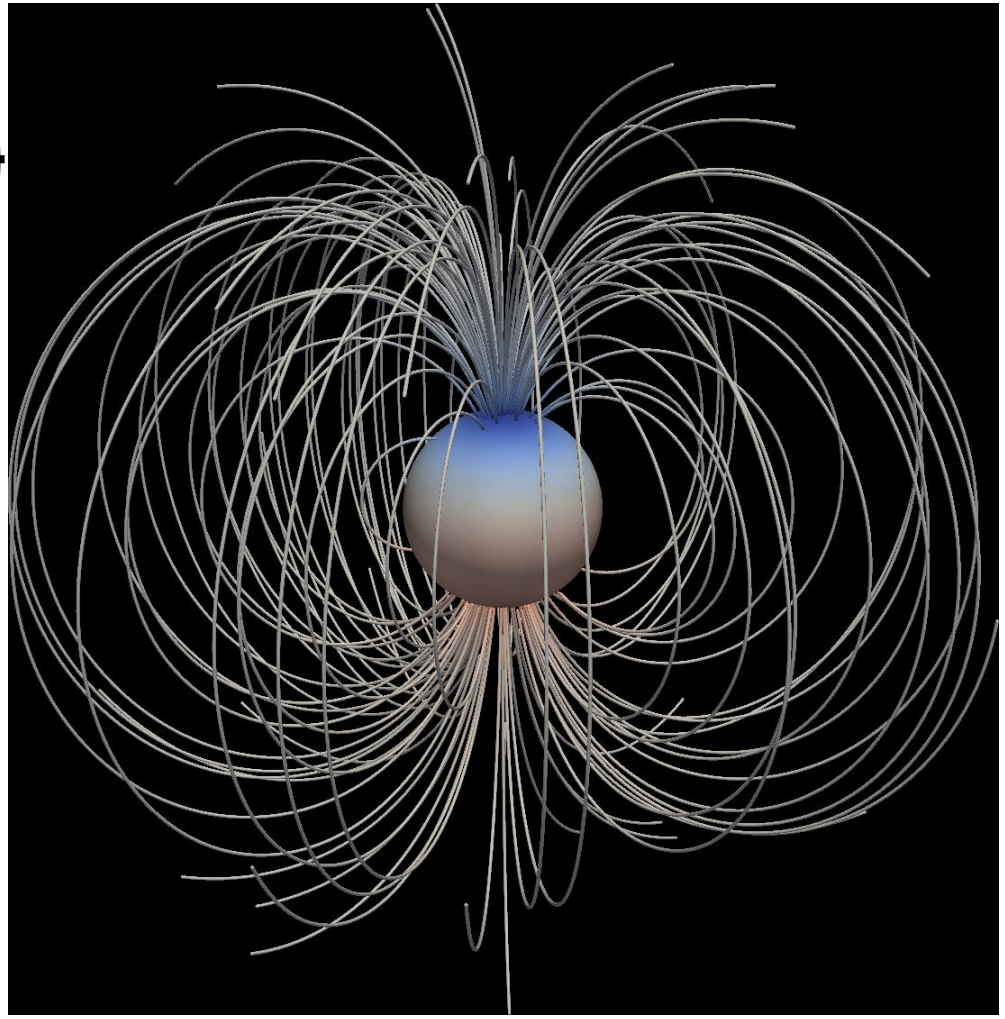
Lunar paleopoles? ?

Martian paleopoles?

A COUPLE OF CASE STUDIES

Mercury's Magnetic Field





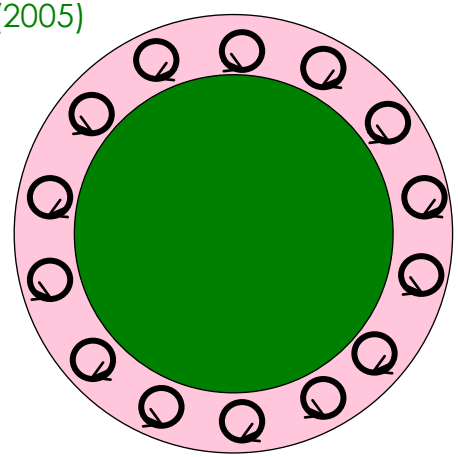
- Weak field strength
- Very axisymmetric
- Dipolar with a significant northward offset

Can a dynamo reproduce all 3 observations?

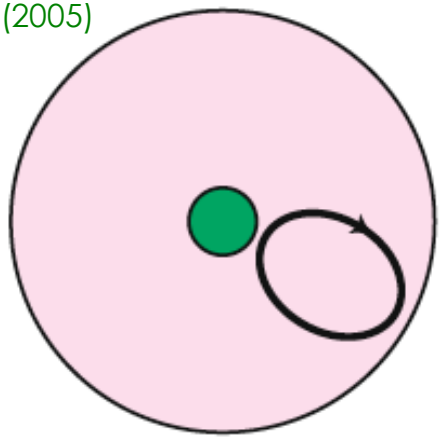
Image credit: Ankit Barik

PRE-MESSENGER CONTESTANTS

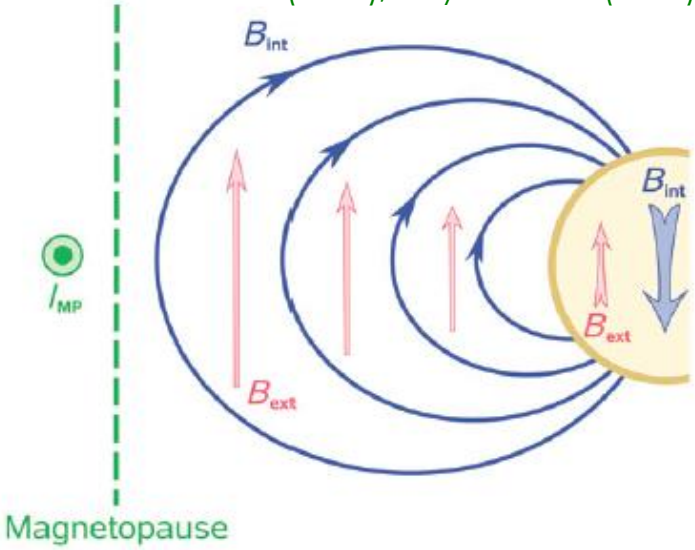
Stanley et al. (2005)

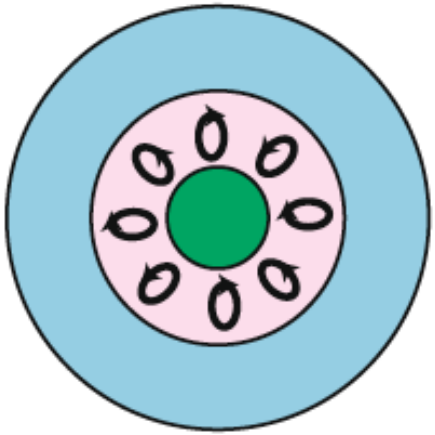


Heimpel et al. (2005)

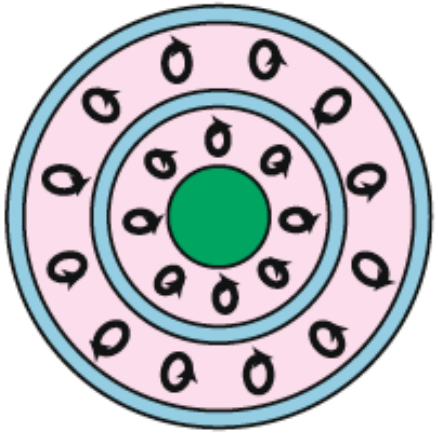


Gomez-Perez & Solomon (2010), Gomez-Perez & Wicht (2010), Heyner et al. (2011)

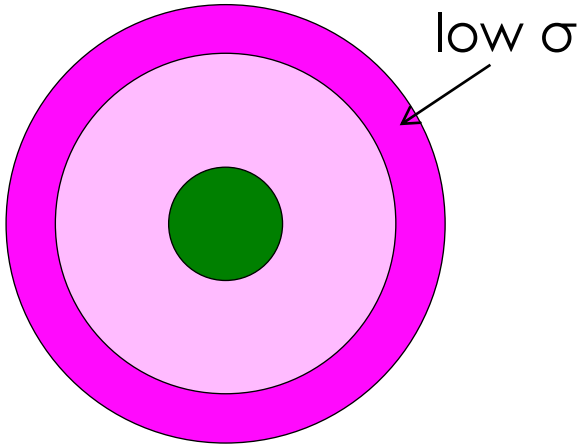




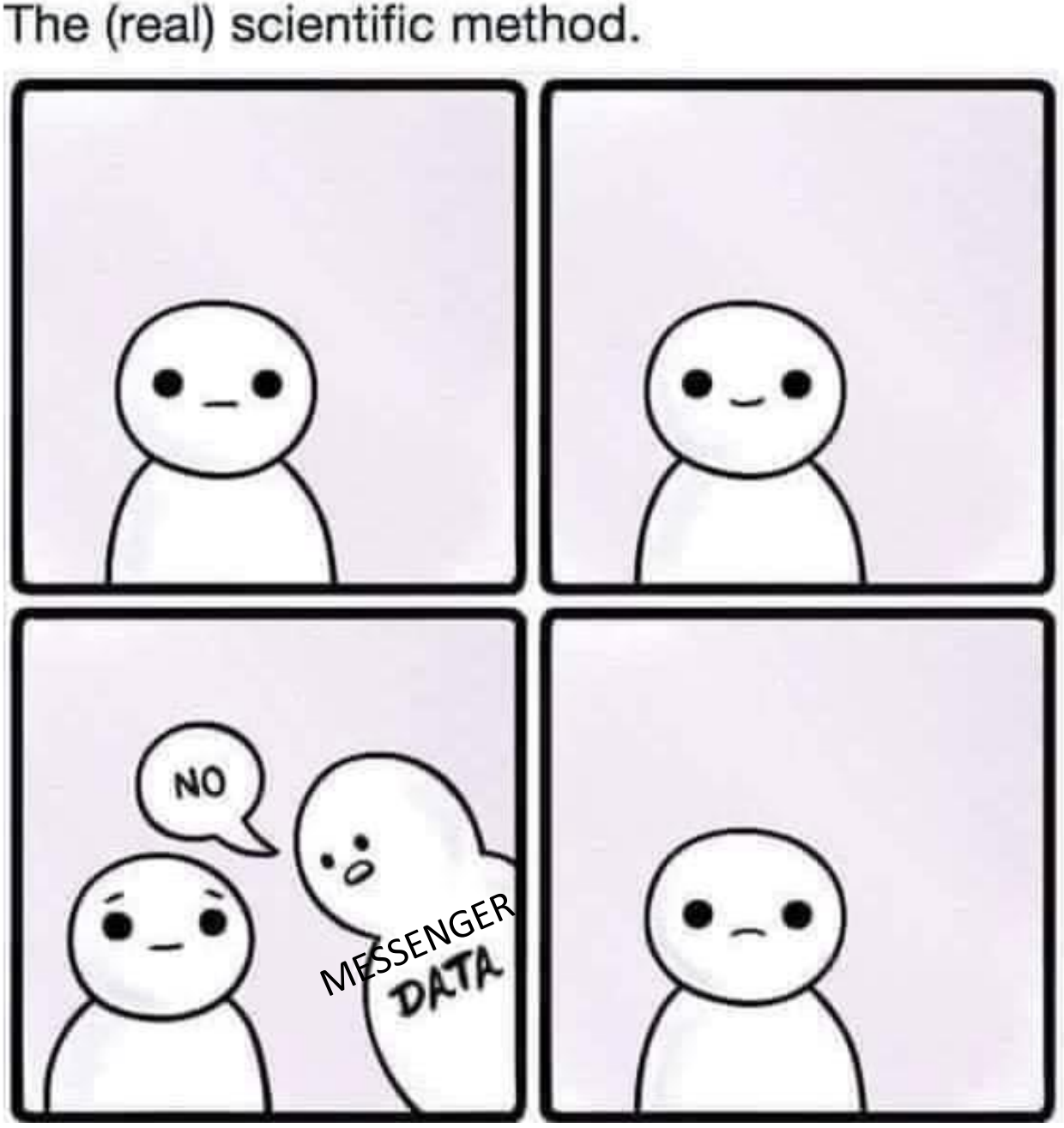
Christensen (2006), Christensen & Wicht (2008) Manglik et al. (2010)



Vilim et al. (2010)

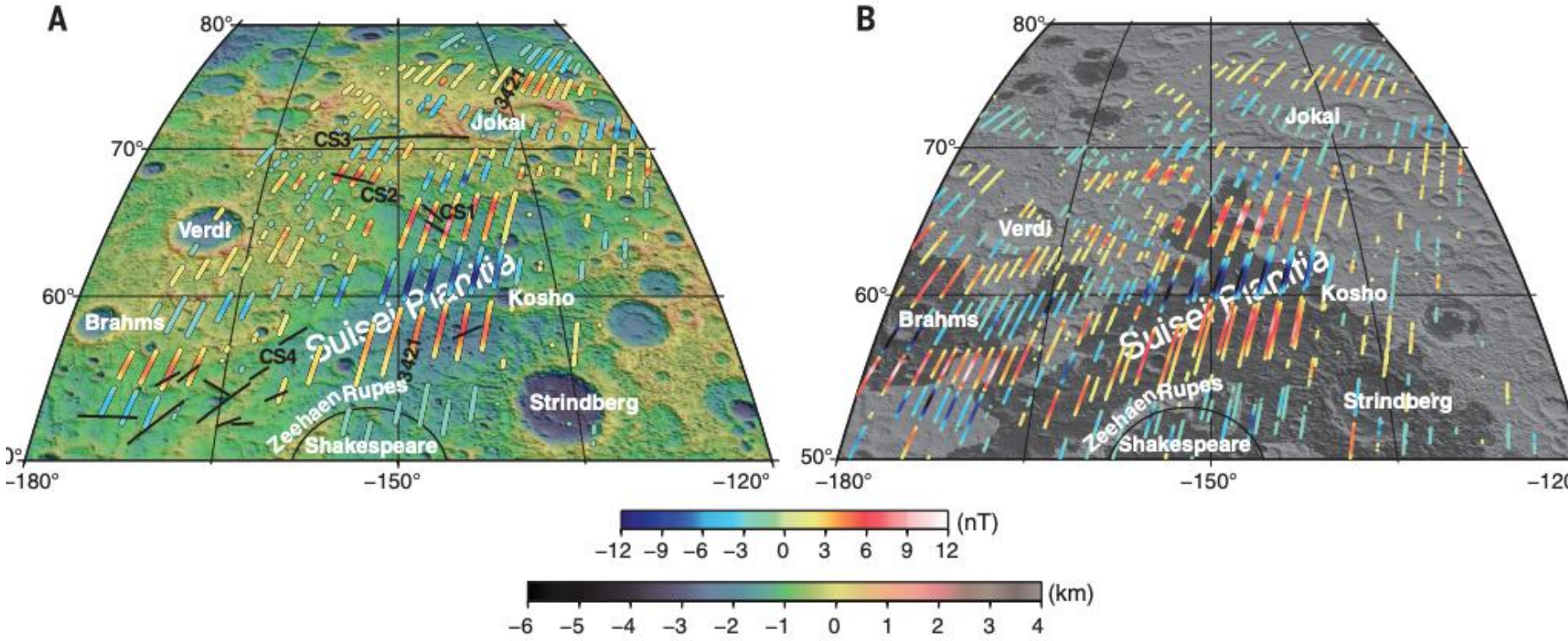


Gomez-Perez et al. (2010)



Adaptation of https://www.mrlovenstein.com/comic/769

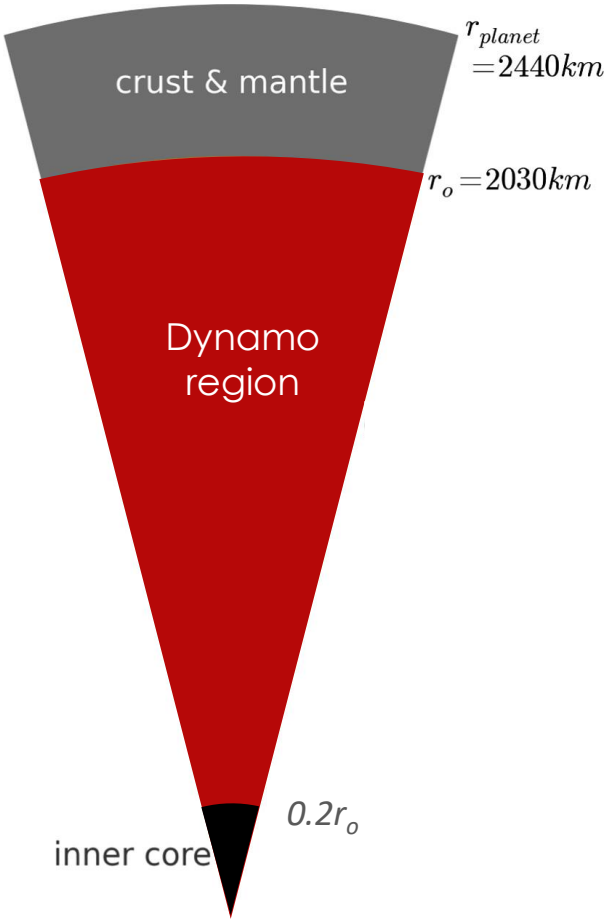
MESSENGER ALSO FOUND CRUSTAL FIELDS

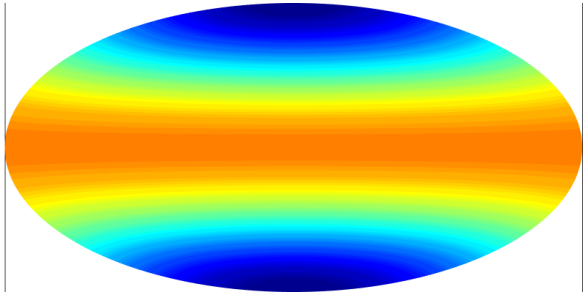


Dynamo was active ~3.7-3.9 Ga!

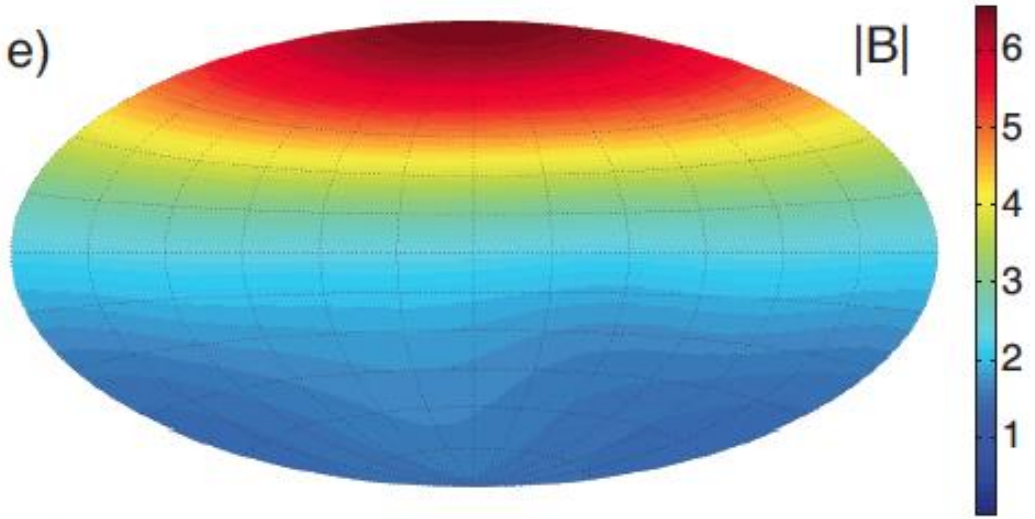
POSSIBLE CONTESTANT 1

Internal heating + degree 2 hemispheric CMB heat flux variation





= Field at CMB

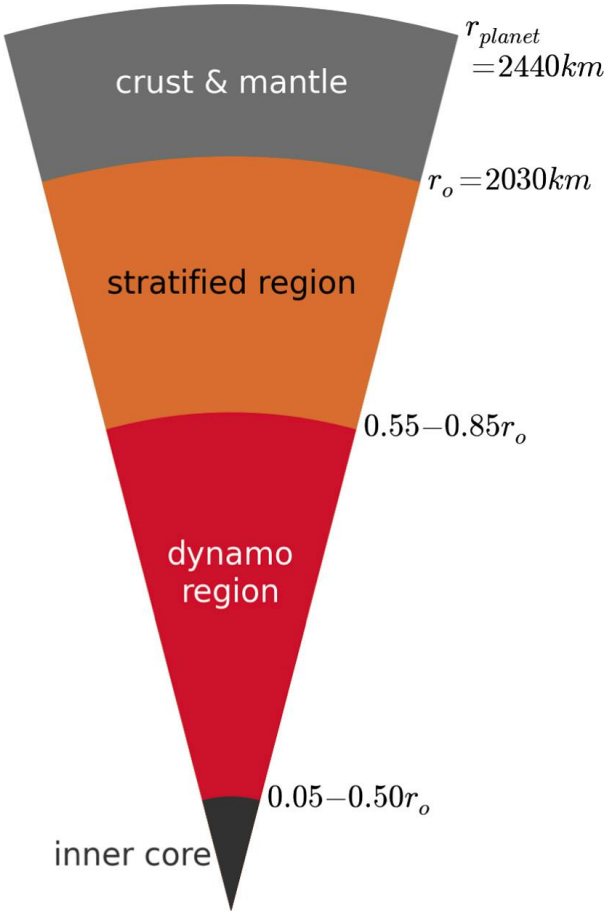


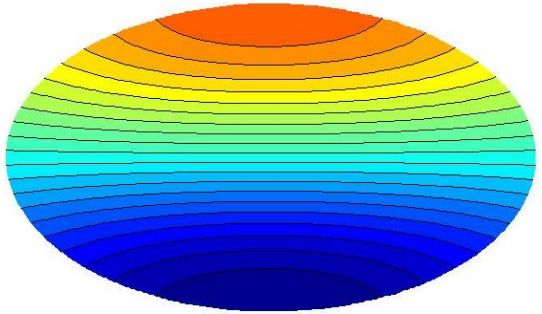
Cao et al (2014)

(field is too strong in model)

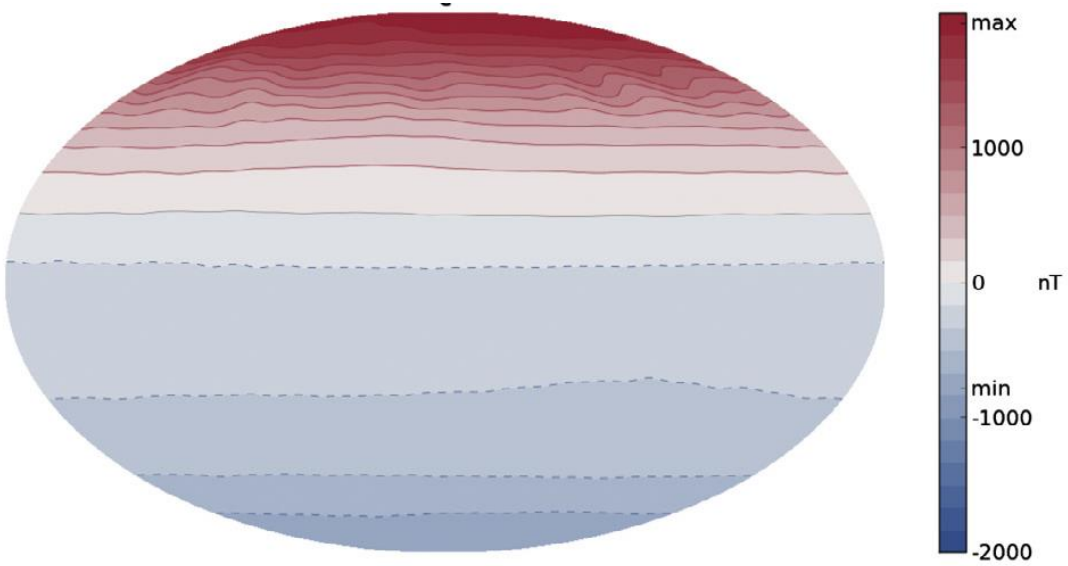
POSSIBLE CONTESTANT 2

Stable layer + degree 1 hemispheric CMB heat flux variation





= Field at CMB

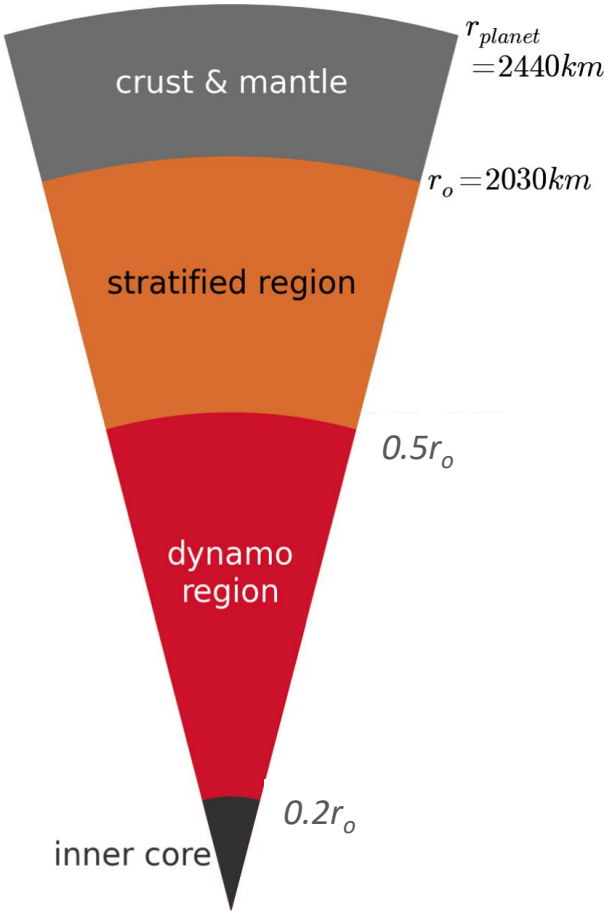


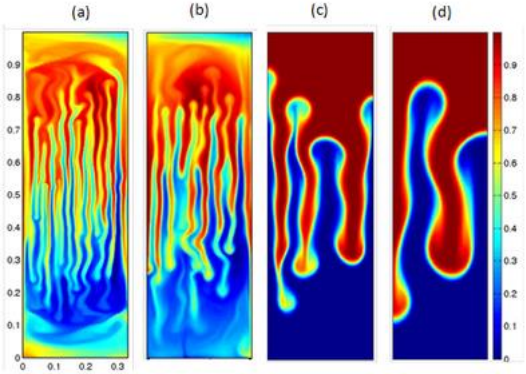
Tian et al (2015)

Why degree 1 pattern?

POSSIBLE CONTESTANT 3

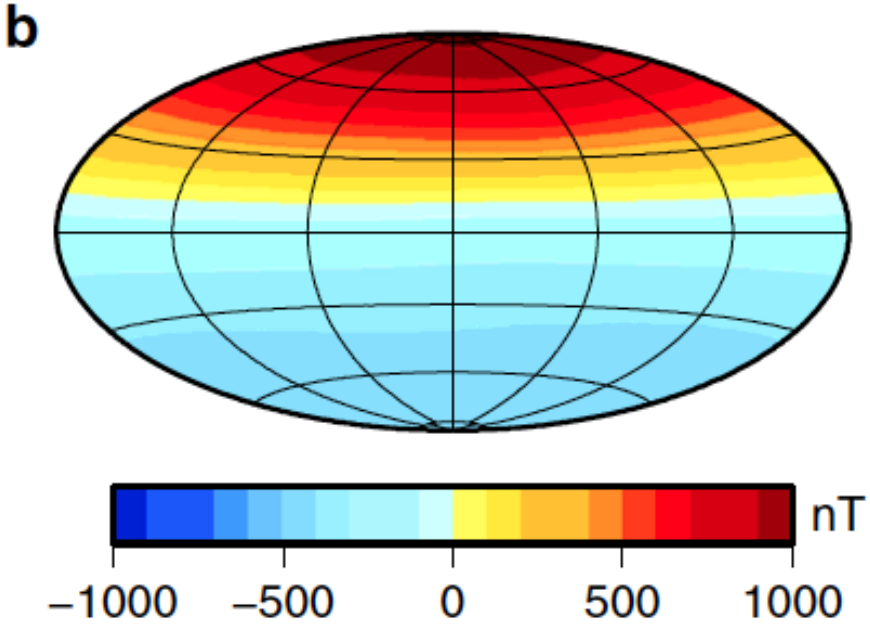
Stable layer + double diffusive convection





https://en.wikipedia.org/wiki/Double_diffusive_convection

=

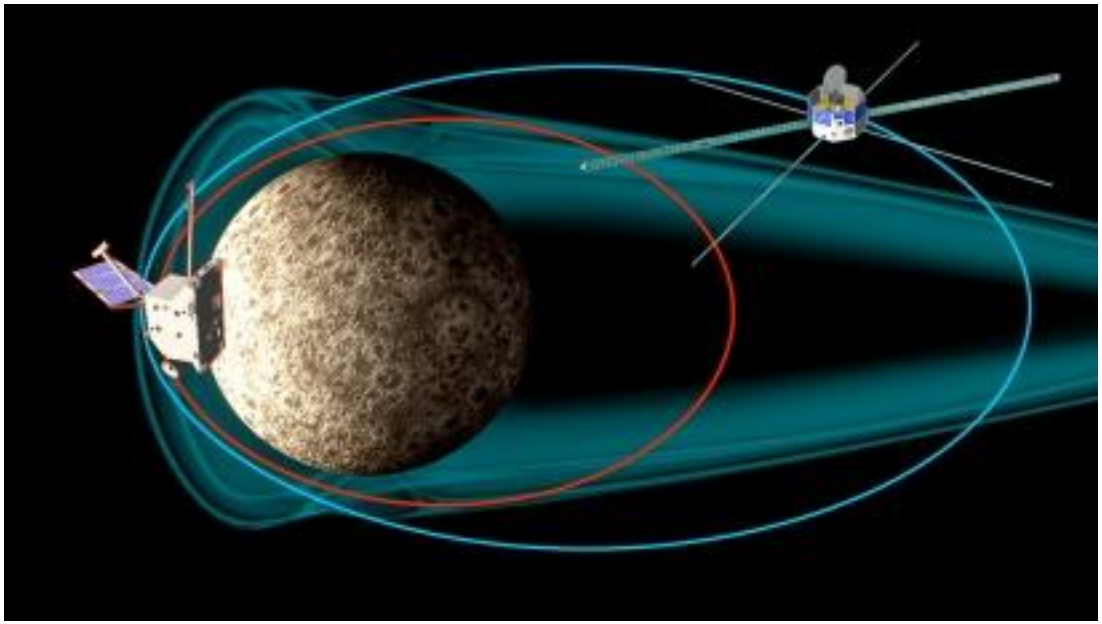


Takahashi et al (2019)

Will it work at other parameters?

FUTURE PROSPECTS

New Data: BepiColombo



Copyright: ESA

Mercury flybys:

October 1, 2021
June 23, 2022
June 20, 2023
September 5, 2024
December 2, 2024
January 9, 2025

Arriving in Mercury orbit :

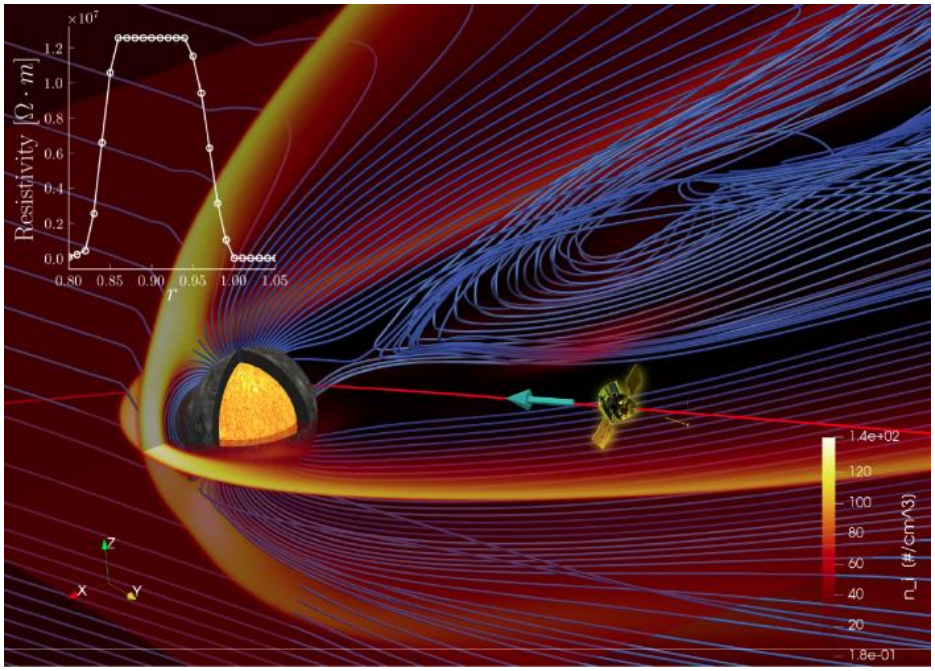
December 5, 2025

FUTURE PROSPECTS

Keep analyzing MESSENGER data!

Biggest challenge: External fields

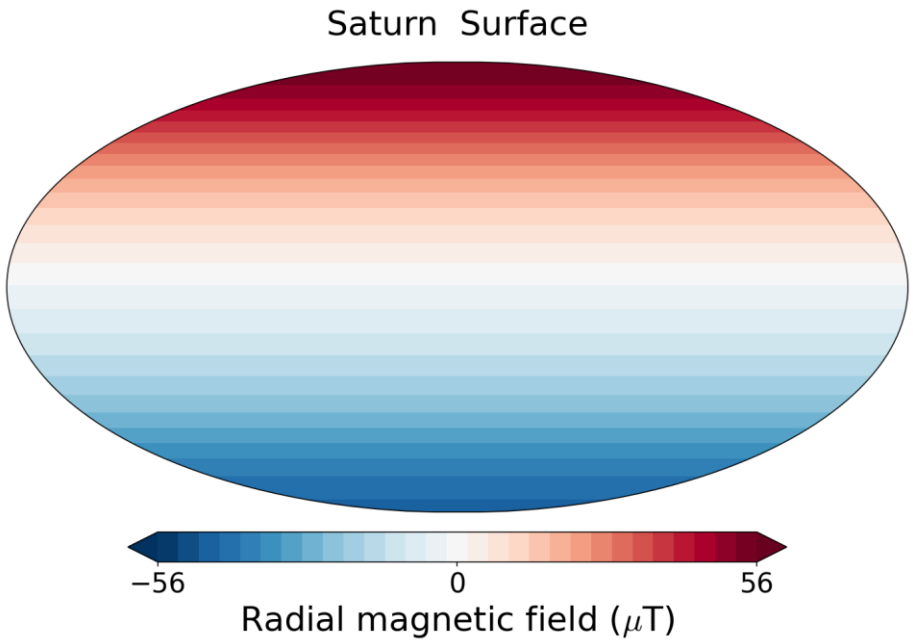
Can we model the external fields well-enough to resolve more of the dynamo field?



Dong et al (2019)

Venus Magnetic Field

Saturn's Magnetic Field



- Field strength similar to Earth's
- dipole tilt < 0.0095 degrees
- Very little secular variation
- Weird magnetic power spectrum

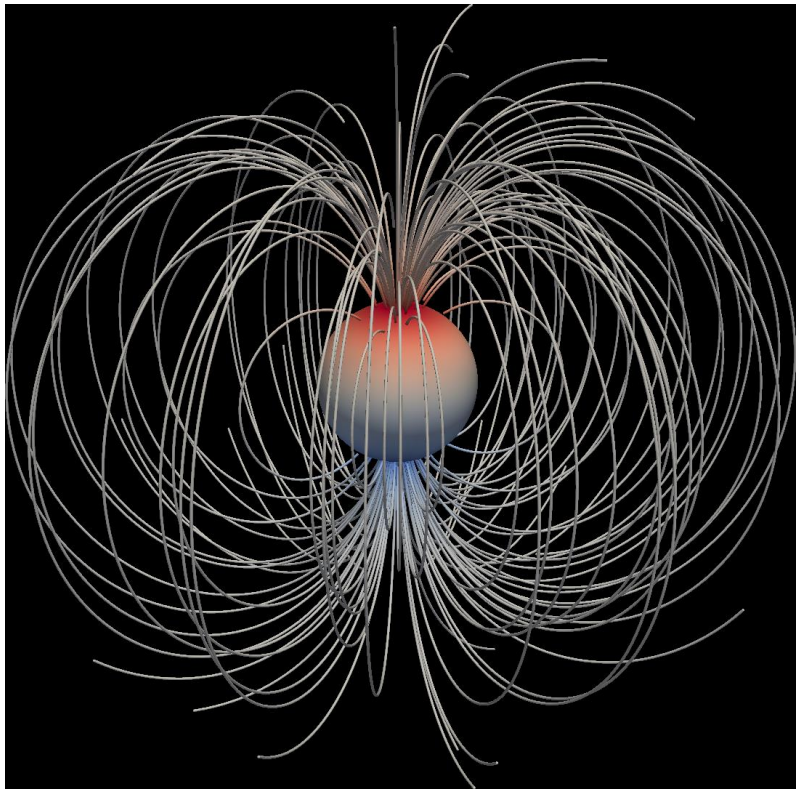
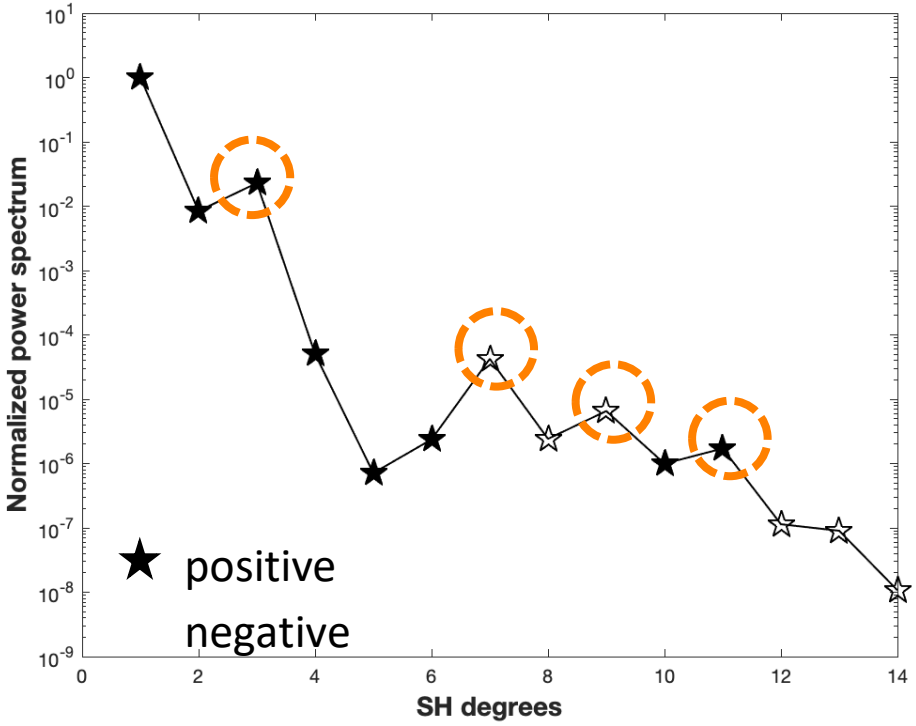


Image credit: Ankit Barik

Saturn's Magnetic Power Spectrum

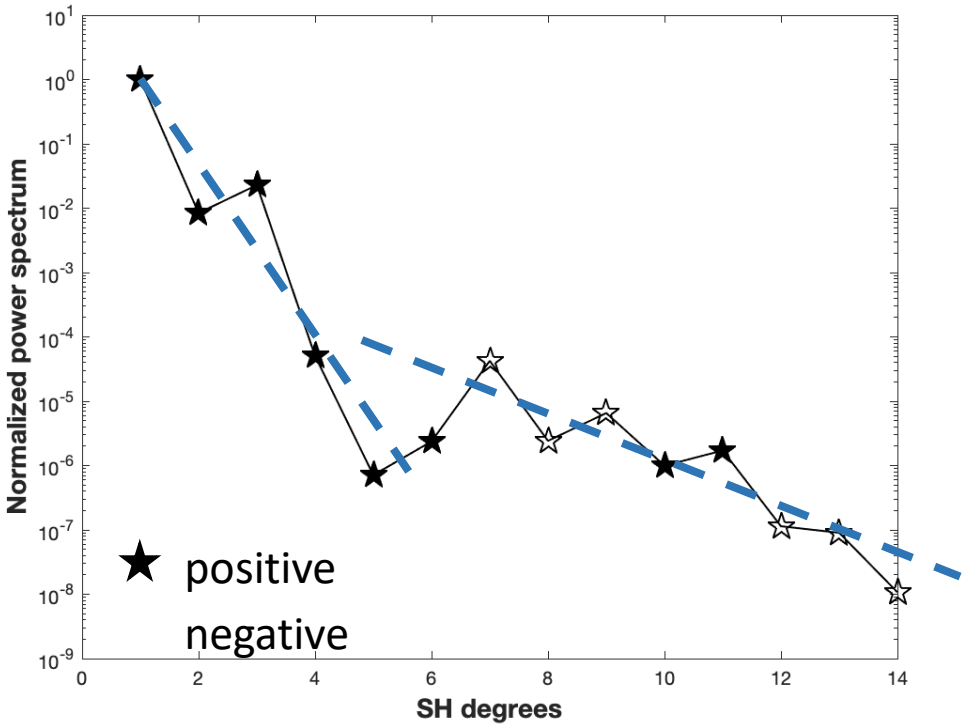
SO MUCH DETAIL! SOME IMPORTANT FEATURES:



- Excess power in odd modes

Cao et al. (2019)

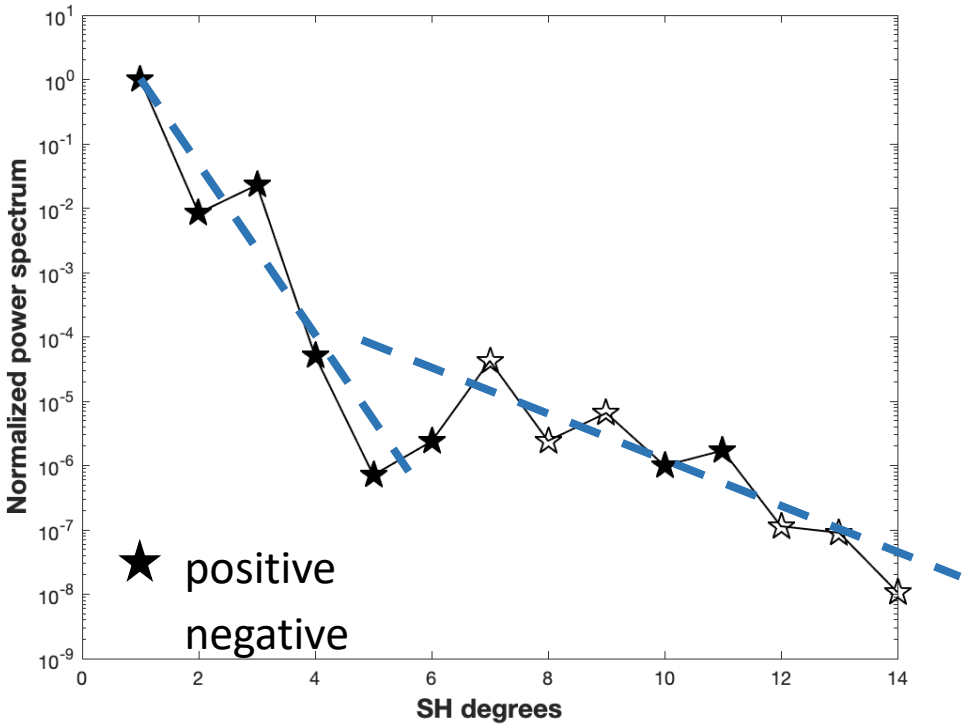
Saturn's Magnetic Power Spectrum



Cao et al. (2019)

- Flattening of spectral slope at higher degrees

Saturn's Magnetic Power Spectrum

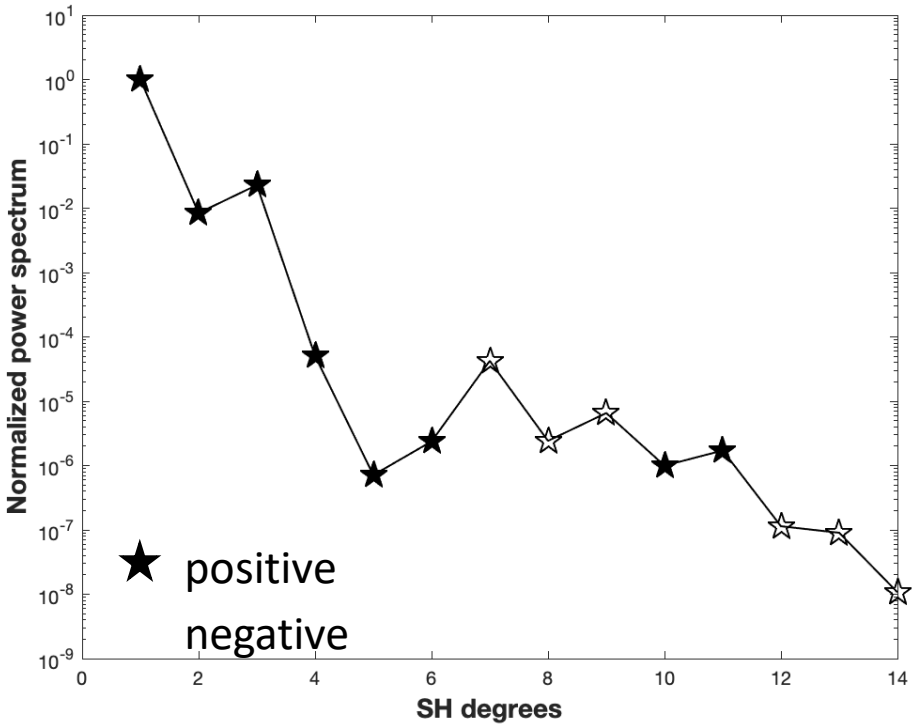


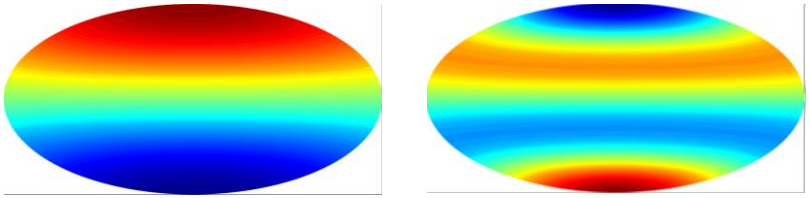
Cao et al. (2019)

$$Power \propto \left(\frac{R_S}{R_{dyn}}\right)^{2l+4}$$

Suggests different dynamo surface depths

SIGNS OF THE MODES





$l = 1$ $\quad -l = 3$

Cao et al. (2019)

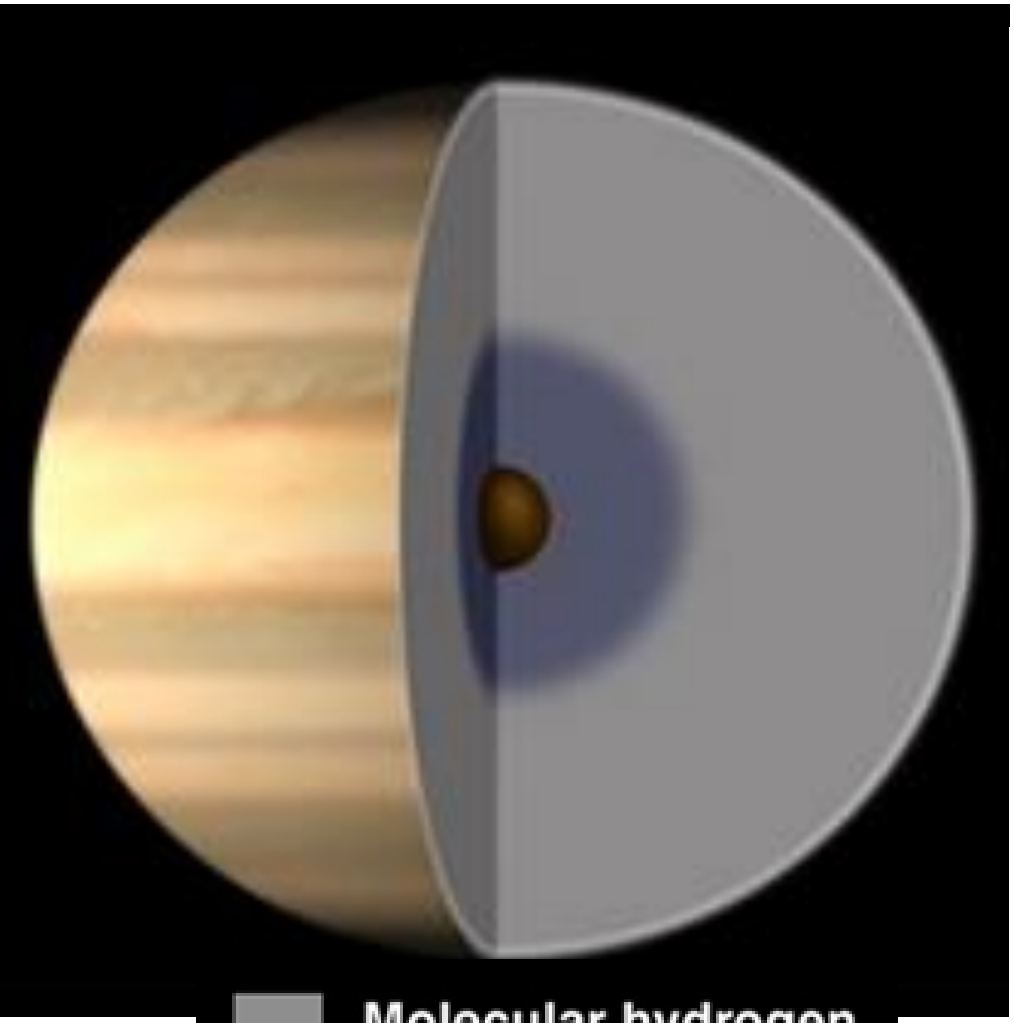
SATURN-LIKE DYNAMO MODEL

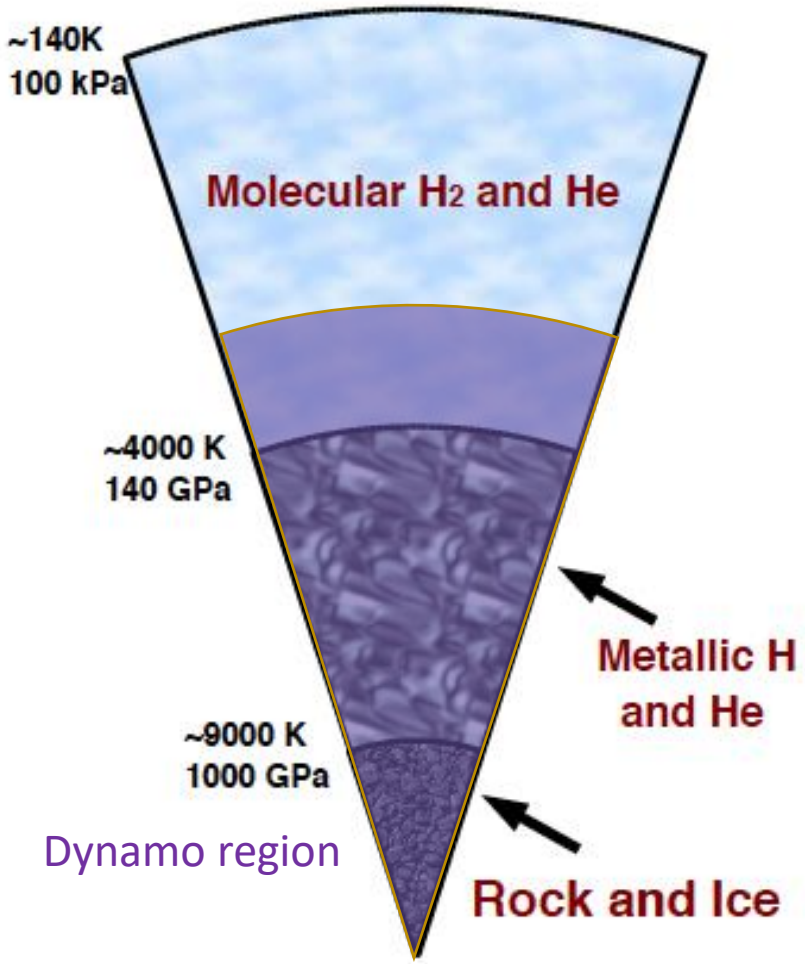
What **special** ingredients do we need in a dynamo simulation to create a Saturn-like magnetic field?

What **special** ingredients exist in Saturn?

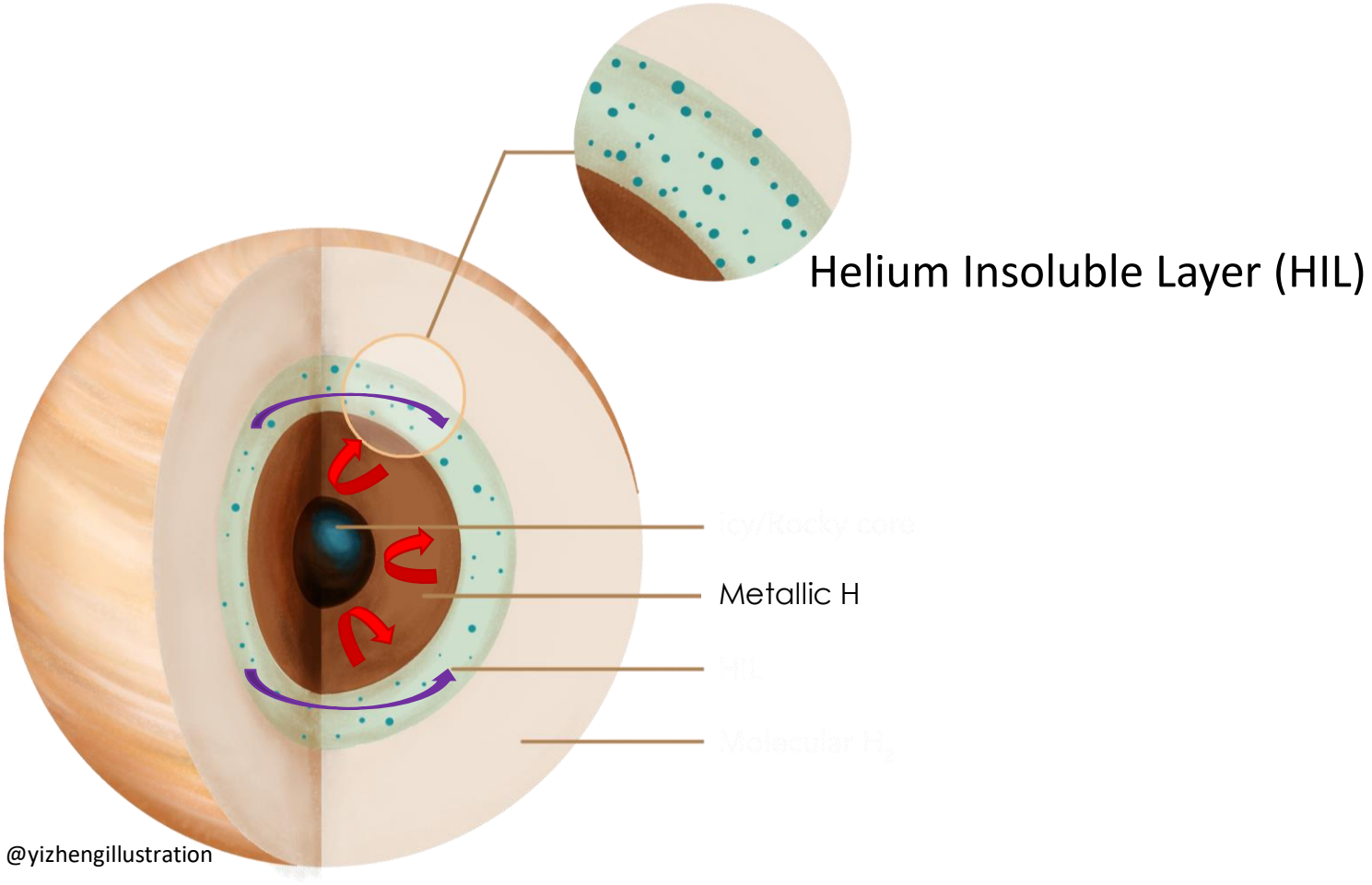
Yan & Stanley (2021)

SATURN'S INTERIOR





SPECIAL INGREDIENT !: STABLE LAYER



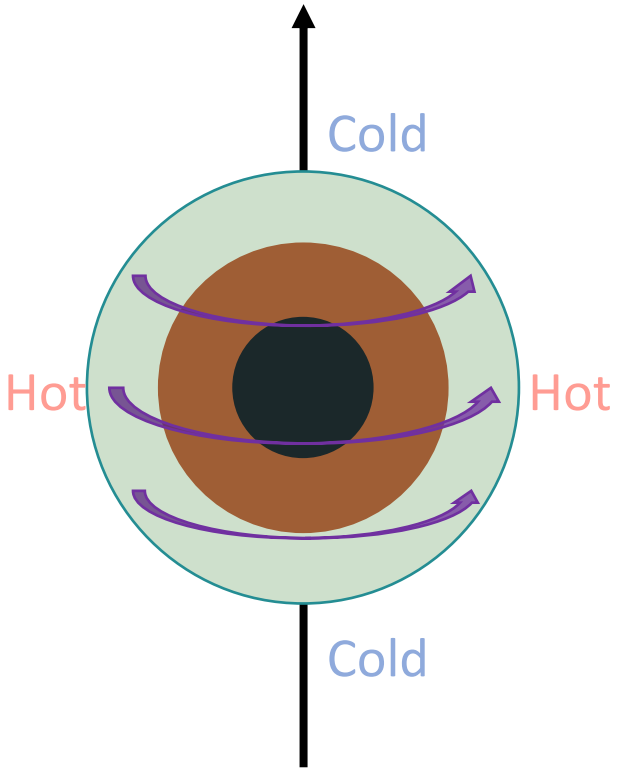
Credit: @yizhengillustration

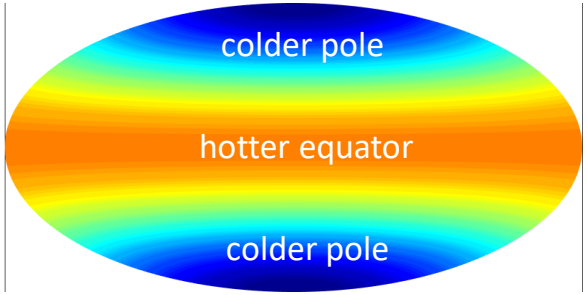
Yan & Stanley (2021)

SPECIAL INGREDIENT 2: VARIABLE HEAT FLUX

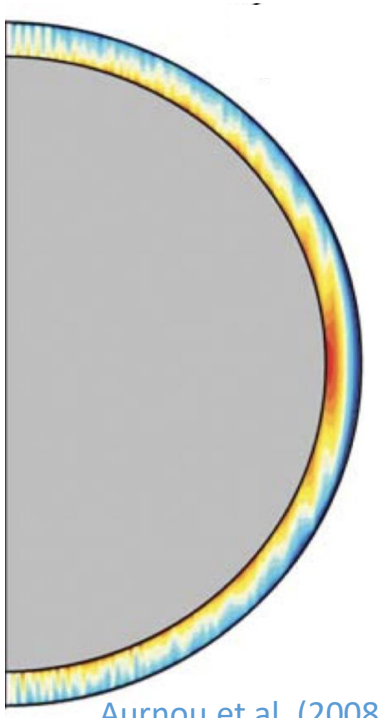
Outer boundary: heat flux depends on latitude

2) Solar Tangential Convection





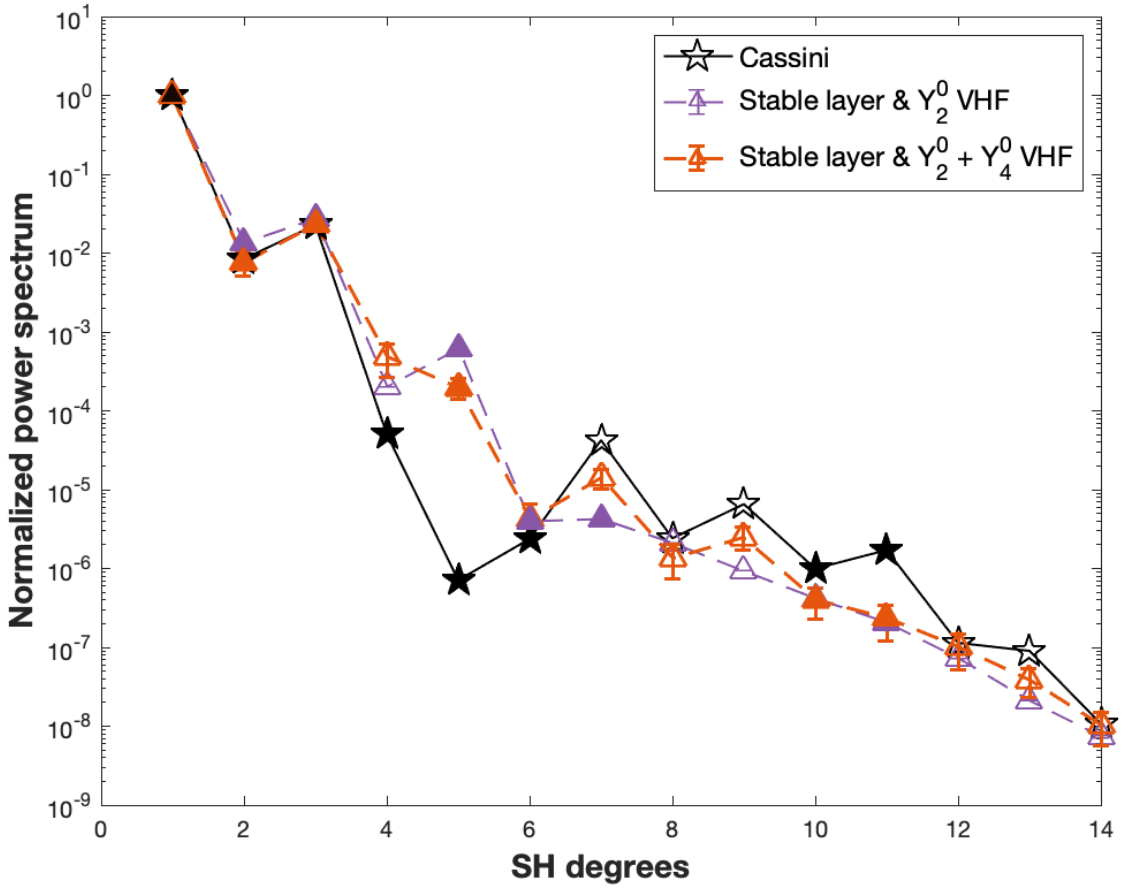
VHF drives thermal winds



Aurnou et al. (2008)

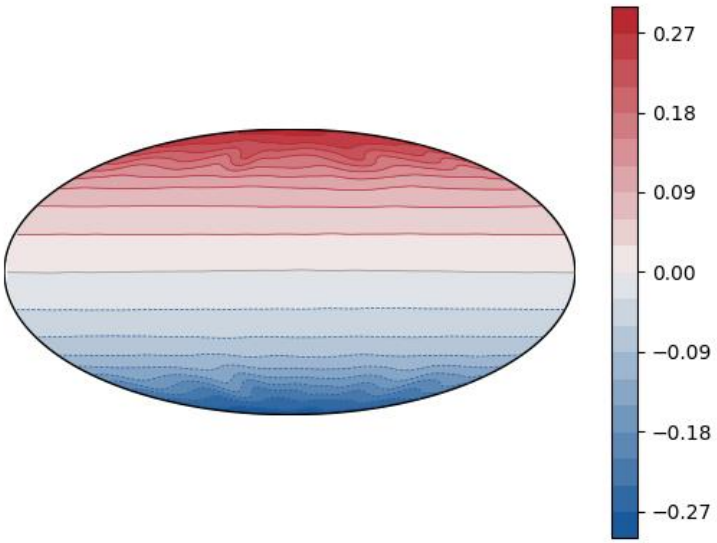
BEST MODEL SO FAR

Model with stable HIL & fancier VHF

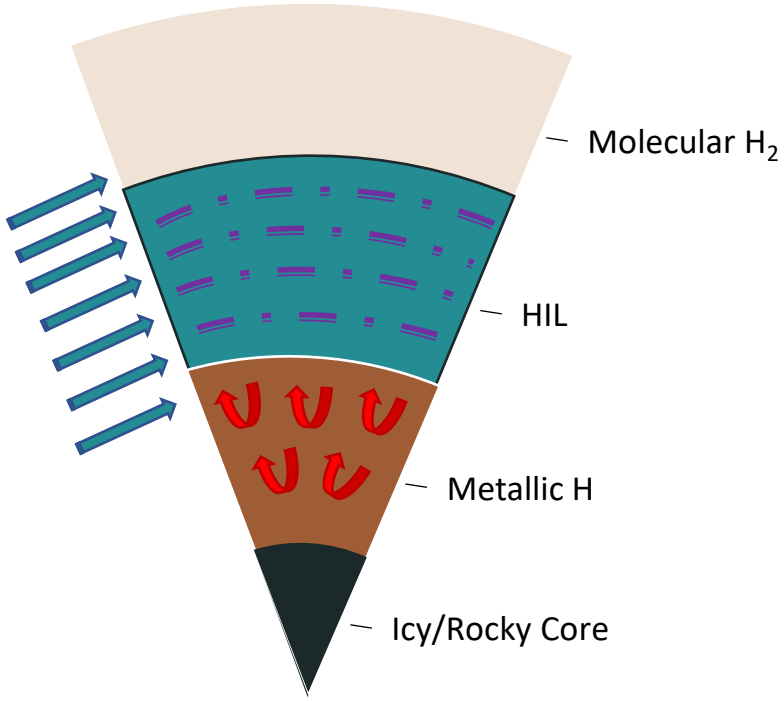


Yan & Stanley (2021)

AXISYMMETRIZATION IN ACTION



radial magnetic field



Schematic view of Saturn's interior

Yan & Stanley (2021)

SUMMARY

- Planetary magnetic fields have their own peculiarities
- Have to be careful with “simple” scaling laws
- Can use these peculiarities to learn about interior structure & dynamics →
- Magnetic fields are a powerful tool to observe a planet’s interior