

# Exploring the physics of the Earth's core with numerical simulations

Nathanaël Schaeffer

ISTerre / CNRS / Université Grenoble Alpes

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# Collaborators

This presentation covers some aspects of my research at ISTERre since 2008. It involves several collaborators at ISTERre:

- PhD student Simon Cabanes (2011 – 2014)
- PhD student Jérémie Vidal (2014 –)
- Post-doc Aldo Figueroa (2011)
- Post-doc Elliot Kaplan (2015 –)
- 6 Master students,
- The whole Geodynamo team,
- Ludovic Métivier (also at LJK);

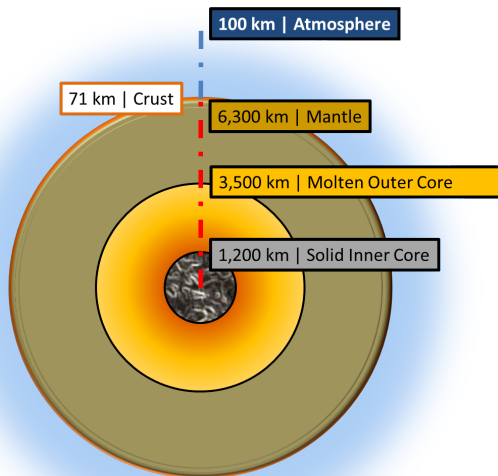
and outside:

- Alexandra Pais (Coimbra, Portugal),
- Julien Monteux & Hagay Amit (Nantes),
- Alexandre Fournier & Julien Aubert (Paris)

# Outline

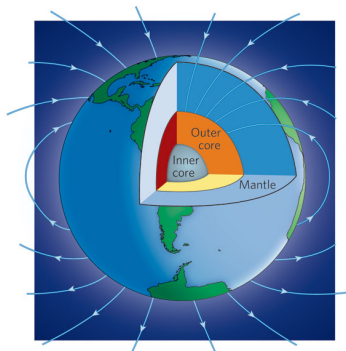
- 1 Introduction
- 2 Columnar flow in the core
- 3 Torsional Alfvén wave reflection
- 4 Turbulence in geodynamo simulations
- 5 Turbulence in DTS
- 6 Summary & Future directions

# Structure of the Earth

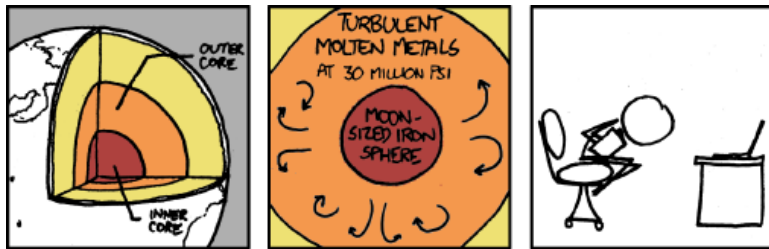


# Geophysical introduction

- The Earth is losing heat since its formation.
- Plate tectonics linked to mantle convection
- Seismology and geodesy require a liquid iron core
- Earth's dynamic magnetic field requires conducting fluid motion.
- A self-sustained dynamo is at work, as in many planets and stars.



# Cool facts about the Earth's core



I FREAK OUT ABOUT FIFTEEN MINUTES INTO  
READING ANYTHING ABOUT THE EARTH'S CORE  
WHEN I SUDDENLY REALIZE IT'S *RIGHT UNDER ME*.

<http://www.xkcd.com/913/>

# Cool facts about the Earth's core

- A broad range of time-scales
  - ▶ from months (SV) to million years (reversals)
- Viscosity of water
  - ▶ very low Ekman number  $E \sim 10^{-15}$
- Large scale motions at the top of the core have speeds around **10 km/year** (0.3 mm/sec, turnover time is about 200 years)
  - ▶ Turbulent motion (very high Reynolds number  $Re \gtrsim 10^8$ ).
  - ▶ Magnetic Reynolds number  $Rm \gtrsim 1000$  ( $Pm \sim 10^{-5}$ )
  - ▶ Very low Rossby number  $Ro \sim 3 \times 10^{-6}$ .
- Magnetic field is dominated by a **tilted dipole**.
- Magnetic energy dominates kinetic energy by a factor  $10^4$  (4 mT estimated in the core, 0.5 mT or 5 gauss at the surface).
  - ▶ Very low Lehnert number (Rossby based on Alfvén speed)  $Le \sim 10^{-4}$ .
- Heat flux extracted by the mantle ( $\sim 10$  TW,  $< 100$  mW/m<sup>2</sup>).
  - ▶ Strong convection (very high Rayleigh number  $Ra \gg 10^{20}$  ? Probably many times critical).

# Broad questions

- Broad picture: how do planetary dynamos actually work?
  - ▶ Magnetic field reversals?
  - ▶ Is convection strong enough?
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- Can the magnetic field be used to probe the Earth's deep interior?
  - ▶ link to geochemistry and Earth's evolution
  - ▶ link to seismology

# Basic rotating MHD in planetary cores

## Navier-Stokes equation

$$\partial_t \mathbf{u} + (2\Omega \mathbf{e}_z + \nabla \times \mathbf{u}) \times \mathbf{u} = -\nabla p + \nu \Delta \mathbf{u} + (\nabla \times \mathbf{b}) \times \mathbf{b} - \alpha g T \vec{r}$$

## Induction equation

$$\partial_t \mathbf{b} = \nabla \times (\mathbf{u} \times \mathbf{b}) + \eta \Delta \mathbf{b}$$

## Temperature equation

$$\partial_t T + \mathbf{u} \cdot \nabla T = \kappa \Delta T$$

$$E = \nu / D^2 \Omega \sim 10^{-15}$$

$$Pm = \nu \mu_0 \sigma \sim 10^{-5}$$

$$Ra = \Delta T \alpha g D^3 / \kappa \nu \gg 1 \quad (?)$$

$$Pr = \nu / \kappa \sim 1$$

# Basic rotating MHD in planetary cores

## Navier-Stokes equation

$$\text{acceleration} = \text{advection}$$

**Pressure gradient + Coriolis force**

+ Magnetic force + Archimedes force + viscous drag

## Induction equation

$$\text{magnetic field variations} = \text{Induction} + \text{ohmic losses}$$

## Temperature equation

$$\text{temperature variations} = \text{Advection} + \text{thermal conduction}$$

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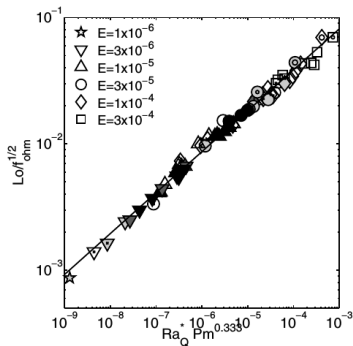
# 20 years of geodynamo simulations

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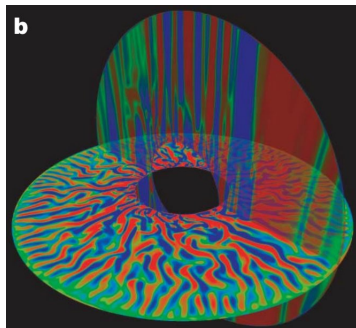
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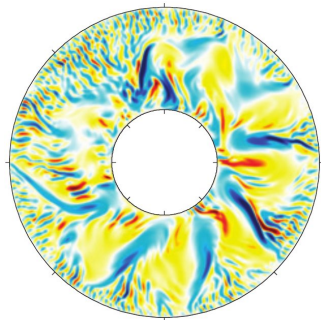
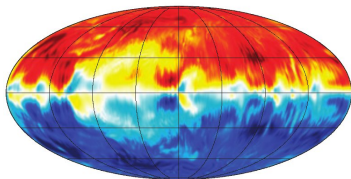
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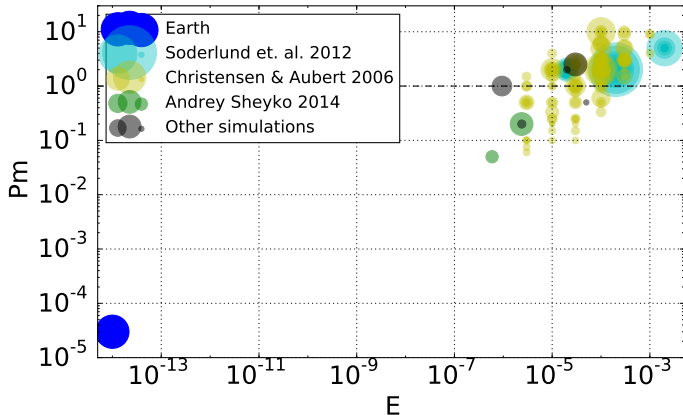
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- Many others

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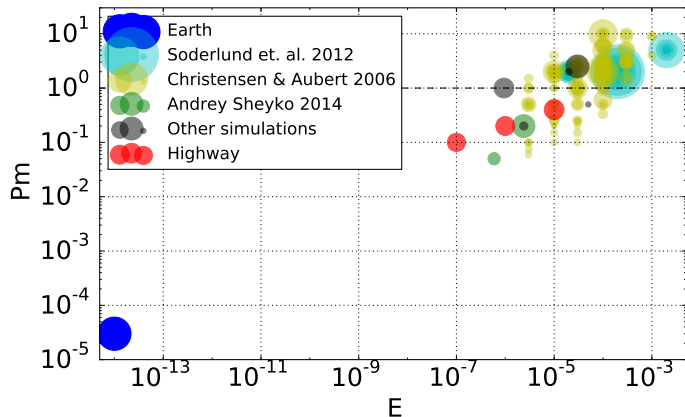


$$E = \frac{\nu}{\Omega D^2}$$

$$Pm = \frac{\nu}{\eta}$$

$$Rm = \frac{UD}{\eta}$$

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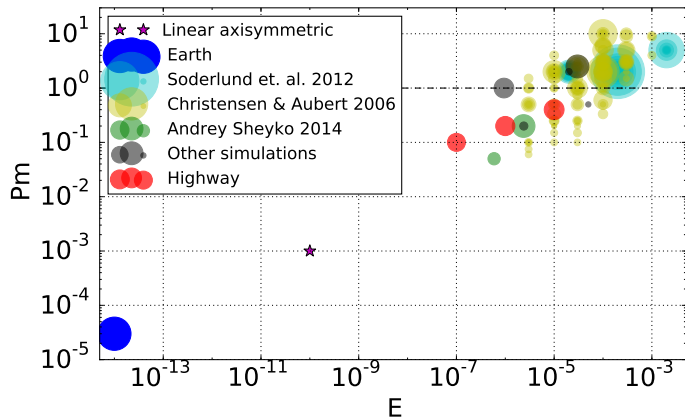


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# Spherical MHD simulations with XSHELLS

- Spherical harmonics,
- finite differences (radial),
- versatile,
- very efficient even on your laptop,
- OpenMP and/or MPI parallelization with good scaling,
- about three times faster than the second best,
- open source.

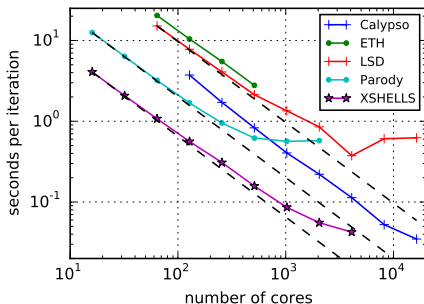


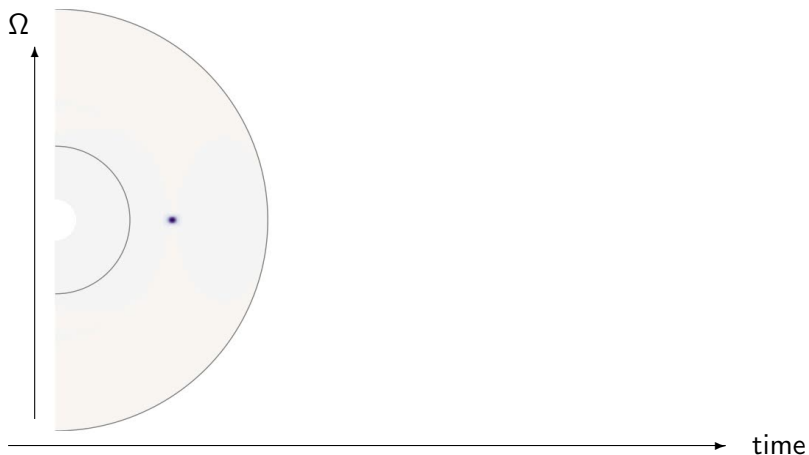
Figure 1: Performance of the 5 finite difference + spherical harmonics geodynamo codes in the CIG strong scaling test (Matsui *et al* in prep.) with spatial resolution  $N_r = 512$ ,  $L_{max} = 255$ .

<https://bitbucket.org/nschaeff/xshells>

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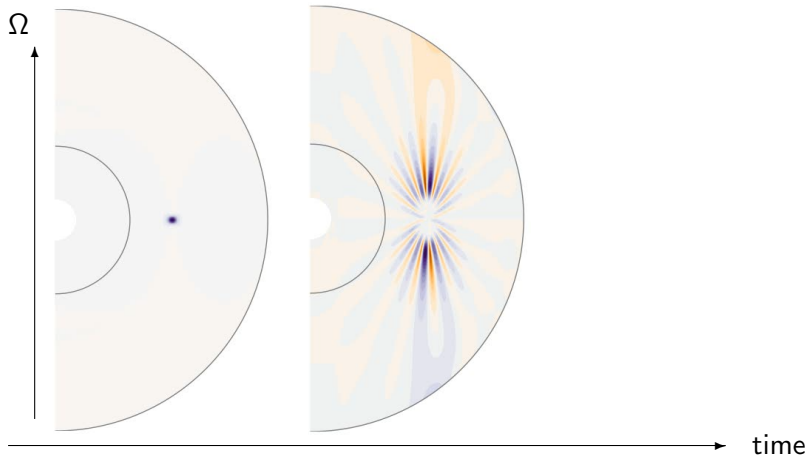
# Taylor columns and Inertial waves



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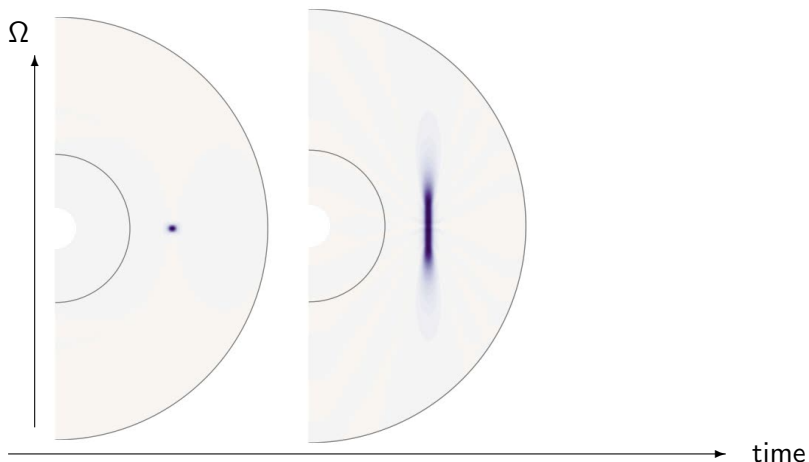


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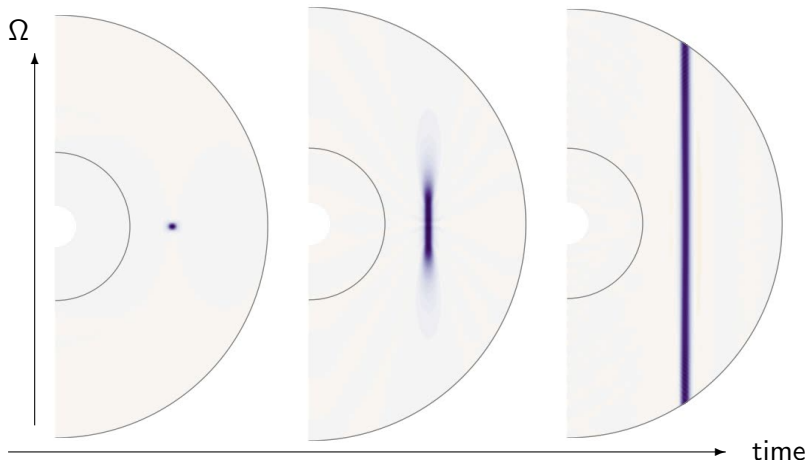
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- 2 Propagation of inertial waves at  $c = \ell\Omega$
- 3 Formation of a Taylor column in  $\tau = \Omega^{-1}L/\ell$

# Columnar flow in the Core ?

A columnar flow can be described by its equatorial plane dynamics (quasi-geostrophic model)

reduces a 3D problem to 2D

- interesting for numerical simulations
- interesting for inversion (surface flow connected to bulk flow!)

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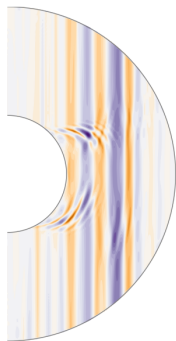
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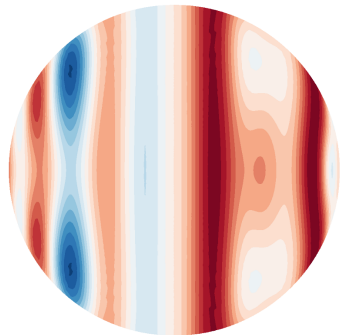
How useful is such a description ?

- valid only if Coriolis dominates...
- ... is it the case at all length scales ?
- ... at all time scales  $\tau \gg \Omega^{-1} L/\ell$  ?

# Influence of the magnetic field



Transients torsional waves within a strong magnetic field  $\Lambda = 1.5$ ,  $Le = 0.0003$  (Gillet, Schaeffer, and Jault, 2011)

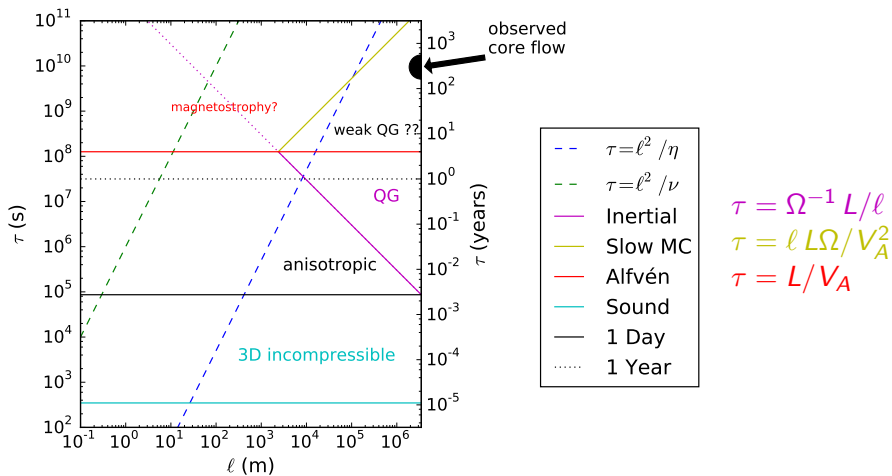


Quasi-static flow influenced by magnetic field. Parameterization at  $\Lambda = 0.9$  (Schaeffer, Lora Silva, and Pais, submitted)

## Necessary conditions for columnar flows

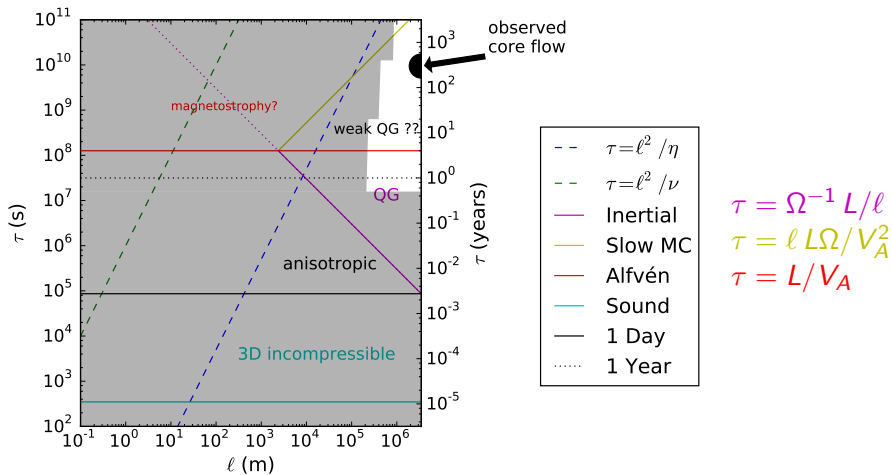
- length-scale  $l \gg \Omega^{-1} V_A$
- time-scale  $\tau \ll ?$

# Regime diagram of the Core



Nataf and Schaeffer (2015) *Turbulence in the Core*, in "Treatise on Geophysics"

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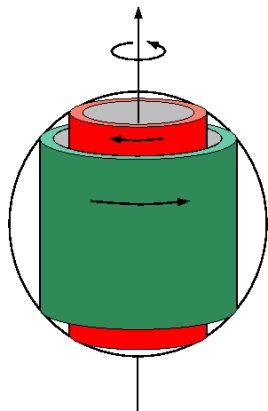


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# Torsional Alfvén Waves

- Alfvén waves constrained by rotation can only propagate as geostrophic cylinders.
- Their speed is related to the integral over  $z$  and  $\phi$  of  $B_s^2$ .
- Measuring their speed gives information about the magnetic field inside the core.



# Torsional Alfvén waves in the Core

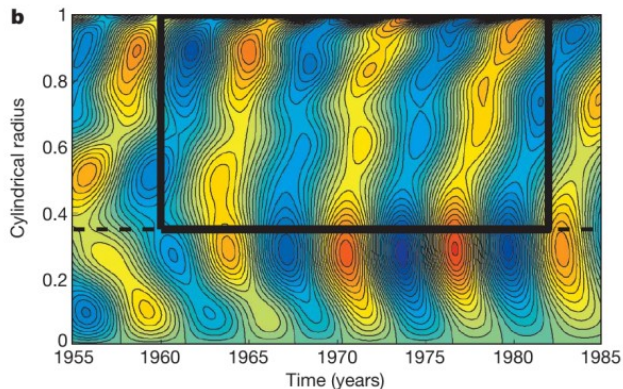
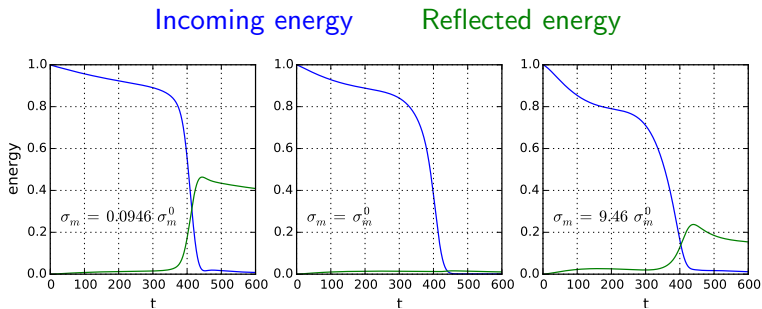


Figure 2: Time versus cylindrical radius map of angular velocity in the Earth's core, filtered around a 6 year period, as obtained by Gillet, Jault, et al. (2010).

# Influence of mantle conductivity



3D axisymmetric simulations of a torsional pulse in a sphere  
( $E = 10^{-10}$ ,  $Pm = 0.001$ ,  $Le = 10^{-3}$ )

- Slightly damps the wave along their propagation
- Strong effect when hitting the equator
- **No reflection** for a magic mantle conductivity  $\sigma_m^0(Pm)$ 
  - ▶ For  $Pm = 1$ ,  $\sigma_m^0 = 0$  (Schaeffer, Jault, et al., 2012).

# Theory for 1D Alfvén wave reflection

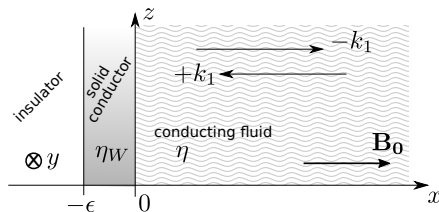
Reflection coefficient in the thin layer approximation:

$$R \simeq \frac{1 - Q - \sqrt{Pm}}{1 + Q + \sqrt{Pm}}$$

with

$$Q = \frac{V_{AE} \epsilon}{\eta_W} = GB_0 \sqrt{\frac{\mu_0}{\rho}}$$

and  $G = \sigma_m \epsilon$  the conductance of the wall.



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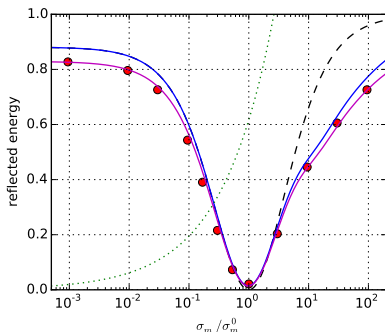
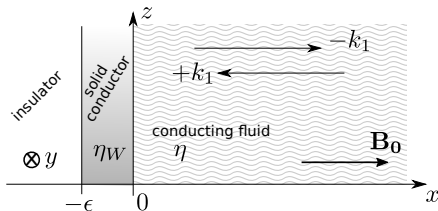
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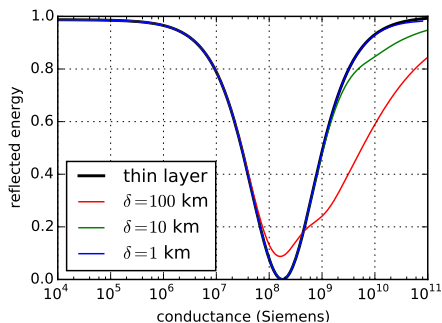
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Explains the spherical simulations:



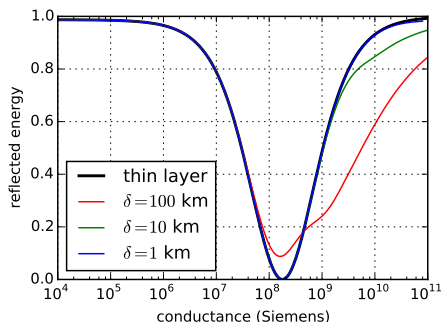
# Application to the Earth's Core



- Free propagation of torsional waves.
- Energy and momentum absorbed when hitting the equator, for  $G \sim 2 \times 10^8$  Siemens.

Free propagation of Torsional waves reconciled with strong core-mantle coupling ?

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Incidentally, numerical simulations at  $Pm \sim 1$  mimic the effect of a conducting layer at the bottom of the mantle at low  $Pm$  !

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# The model

- Earth's core geometry (Sphere)
- thermochemical convection (codensity, 75% chemical driving, Aubert *et al* 2009);
- no-slip, and fixed flux homogeneous boundary conditions
- **high rotation rate, low viscosity**
- **strong forcing** (more than 4000 times critical)

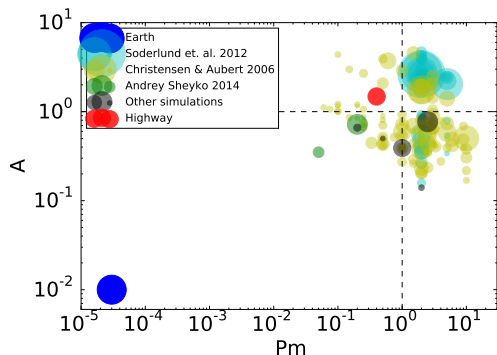
with:

- 1 Ekman number  $E = \nu / D^2 \Omega$
- 2 Rayleigh number  $Ra = \Delta T \alpha g D^3 / \kappa \nu$
- 3 Magnetic prandtl number  $Pm = \nu \mu_0 \sigma$
- 4 (Thermal) Prandtl number  $Pr = 1$ .

# The simulations

## The idea

- Keep super-criticality and  $Rm = UD/\eta \simeq 650$  fixed.
- go to more Earth-like  $A = U/B$  and  $Pm = \nu/\eta$ .

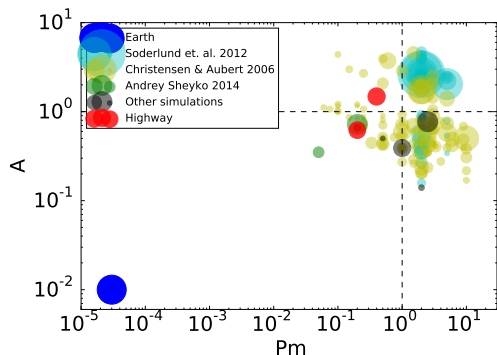


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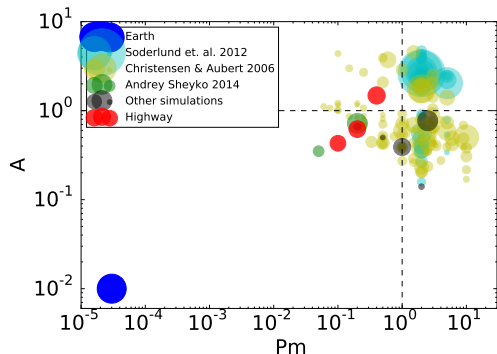


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- **jump 1:**  $E = 10^{-6}$ ,  
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 $\Rightarrow A = 0.61$   $F_\nu = 24\%$

# The simulations

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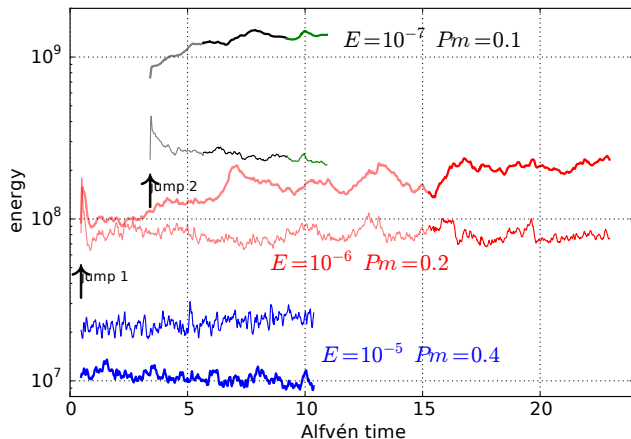
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 $\Rightarrow A = 0.61$   $F_\nu = 24\%$
- **jump 2:**  $E = 10^{-7}$ ,  
 $Pm = 0.1$ ,  $Ra = 2.4 \cdot 10^{13}$   
 $\Rightarrow A = 0.45$   $F_\nu = 17\%$

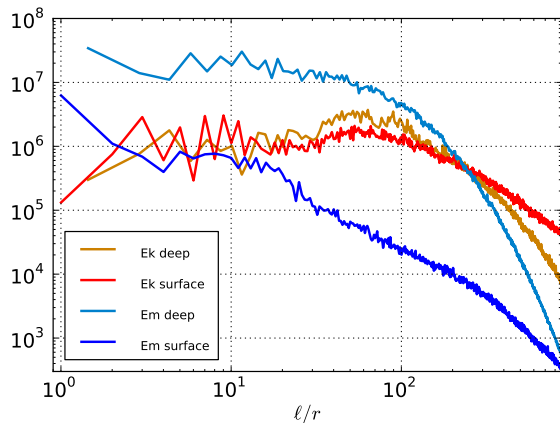
Extreme parameters, require  $2688 \times 1344 \times 1024$  points (3.7 billions)  
7 months computation on 512 cores (10.5 sec/step)

# Energy vs Time



*Jump 2* ran for 1.5% of a magnetic diffusion time, and it took about 7 months to compute on 512 cores, spending 2.5 million core hours.

## Jump 2: spectra



$$E = 10^{-7}$$

$$Pm = 0.1$$

$$Ra = 2.4 \cdot 10^{13}$$

$$Rm = 600$$

$$A = 0.45$$

$$\Lambda = 1.2$$

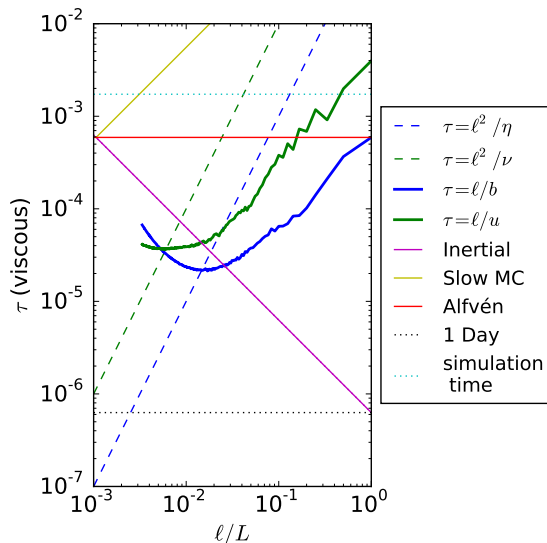
$$F_\nu = 17\%$$

$$NR = 1024$$

$$L_{max} = 893$$

- Magnetic field dominates deep in the core but not near the surface.
- Velocity spectrum nearly flat at the surface but increasing deep down.

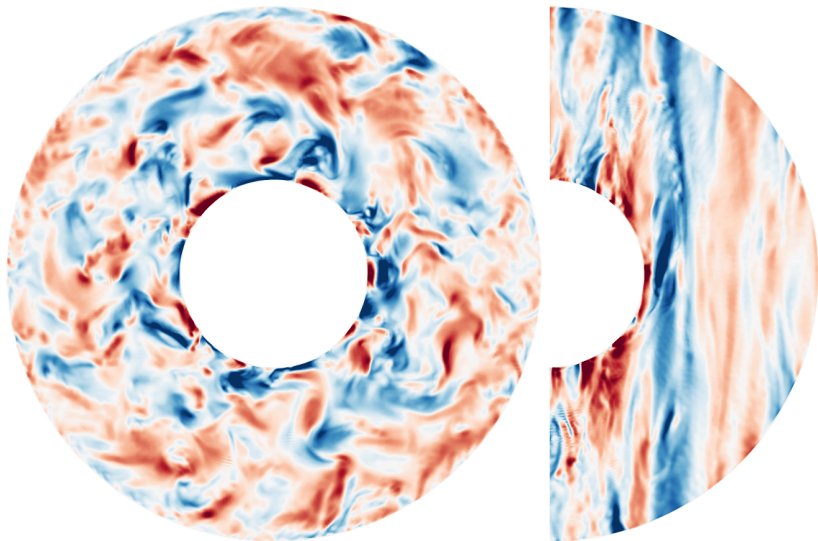
## Jump 2: regime diagram



Spectra translated into  $\tau - \ell$  space ( $E = 10^{-7}$ ,  $Pm = 0.1$ )

- Correct ordering of scales
- Fair scale separation

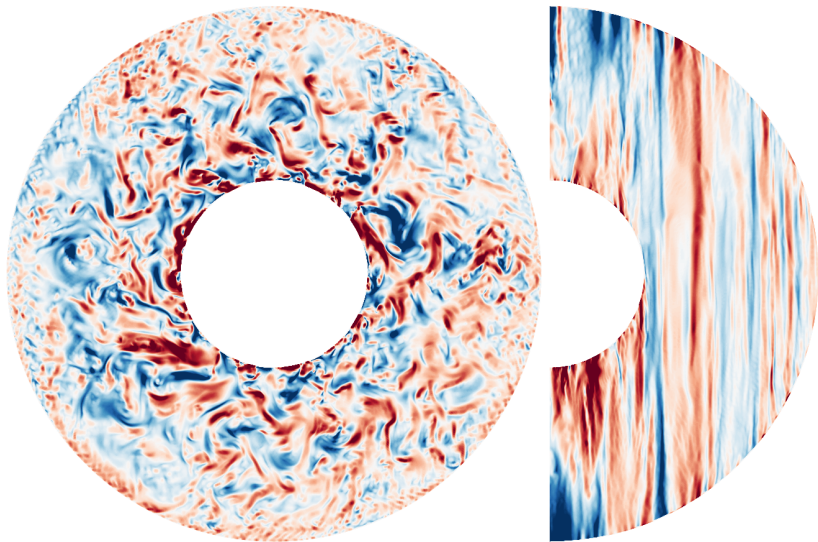
Snapshot: initial  $U_\phi$  ( $E = 10^{-5}$ ,  $Pm = 0.4$ ,  $A = 1.5$ )



$NR = 224$ ,  $L_{max} = 191$



Snapshot: jump 1  $U_\phi$  ( $E = 10^{-6}$ ,  $Pm = 0.2$ ,  $A = 0.62$ )



$NR = 512$ ,  $L_{max} = 479$

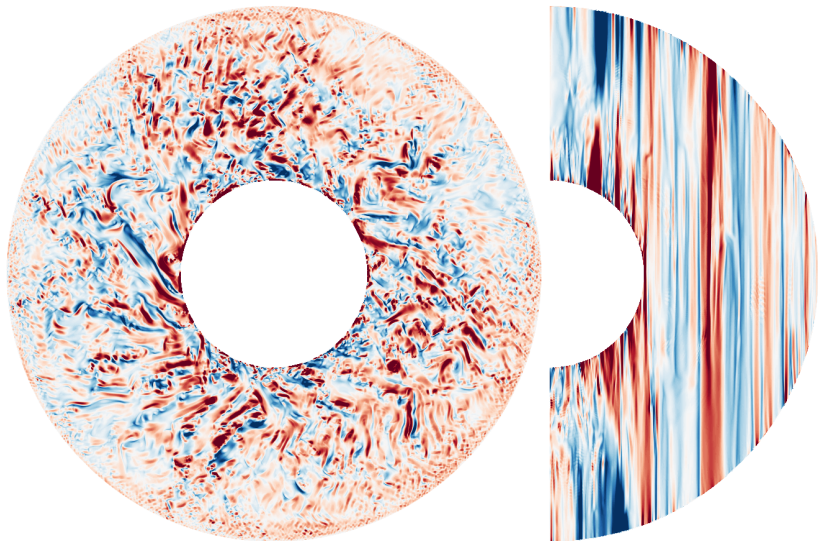
HDR N. Schaeffer (ISTerre)

Earth's core simulations

30 September 2015

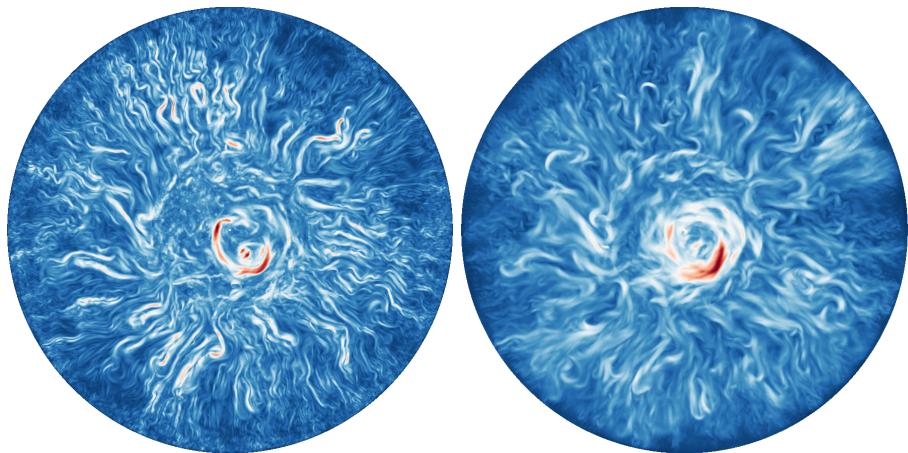
30 / 46

Snapshot: jump  $2 U_\phi$  ( $E = 10^{-7}$ ,  $Pm = 0.1$ ,  $A = 0.43$ )



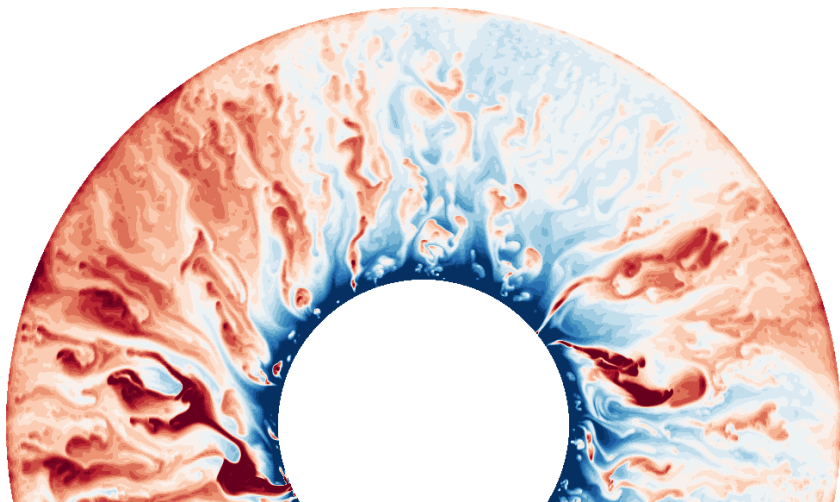
$NR = 1024$ ,  $L_{max} = 893$

## Jump 2: z-averaged energy densities



z-averaged equatorial energy densities, left:  $\langle U_{eq}^2 \rangle$ , right:  $\langle B_{eq}^2 \rangle$ .  
 $E = 10^{-7}$ ,  $Pm = 0.1$ ,  $Rm = 600$ ,  $A \sim 0.45$ .

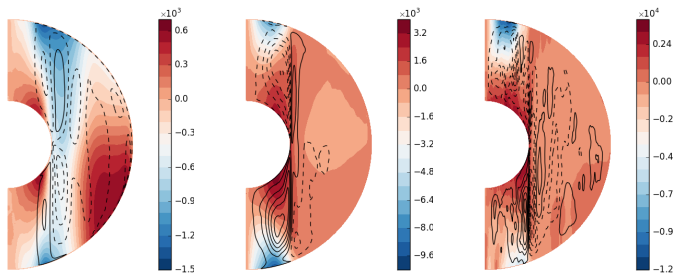
## Jump 2: Temperature field



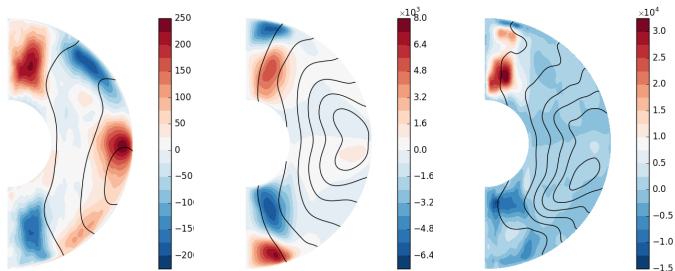
Mean temperature of each shell has been removed.

# Averages of U and B

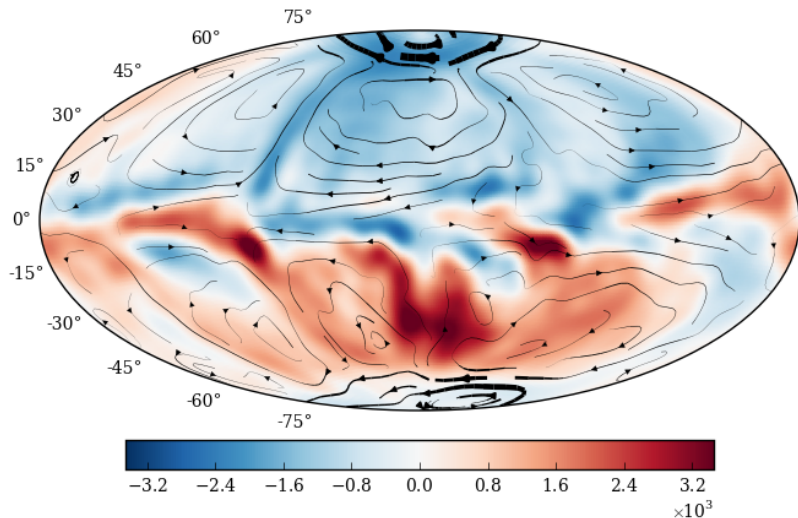
*U*



*B*



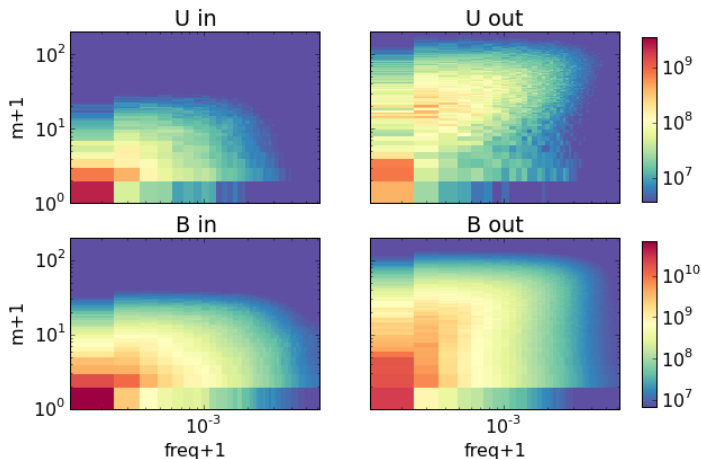
## Jump 2: Non-zonal mean flow



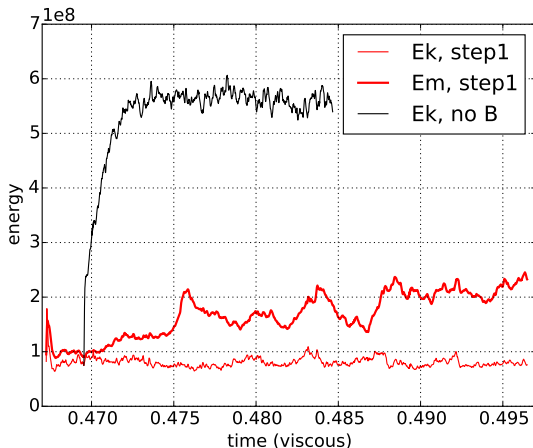
Homogeneous heat flux start to produce large scale flows at  $E = 10^{-7}$

## Jump 2: Space-time Fourier analysis

- Fourier Transform in the two homogeneous directions:  $t$  and  $\phi$ .
- Two different regions **inside** and **outside** the tangent cylinder.
- $E = 10^{-7}$ ,  $Pm = 0.1$



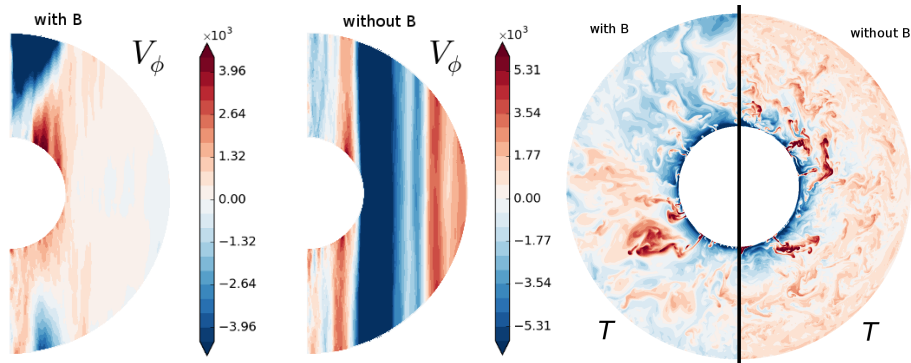
## Jump 1: Influence of the magnetic field



**Figure 3:** Energies as a function of time (normalized by the viscous diffusion time) for case jump 1 ( $E = 10^{-6}$ ) and for the same parameters as jump 1, but without magnetic field.



## Jump 1: Influence of the magnetic field



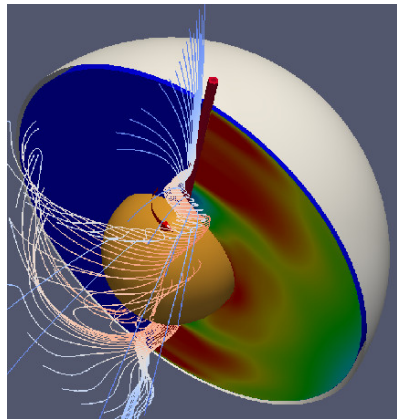
With a strong dynamo magnetic field:

- Zonal jets are suppressed, plumes extend further.
- Larger plumes...
- ... but convection still starts at small length-scale ! ( $E^{1/3}$ ).

# Outline

- 1 Introduction
- 2 Columnar flow in the core
- 3 Torsional Alfvén wave reflection
- 4 Turbulence in geodynamo simulations
- 5 Turbulence in DTS**
- 6 Summary & Future directions

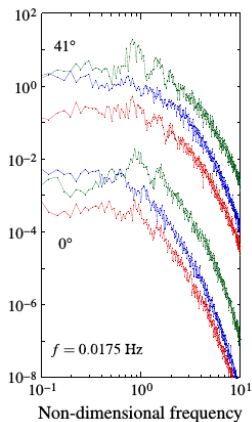
# The DTS experiment



Magnetized liquid sodium spherical Couette experiment

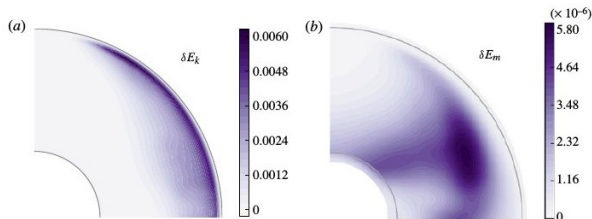
$$Rm_{rms} \sim 4 \quad Re_{rms} \sim 10^6$$

# Turbulence in non-rotating DTS



Surface magnetic probes.

Figuroa et al. (2013)



Energy density of fluctuations (kinetic and magnetic).  
 $Pm = 10^{-3}$ ,  $Re = 2611$ ,  $\Lambda = 0.034$ .

- Velocity fluctuations are stronger near the outer shell (where the imposed magnetic field is weak).
- Lorentz-Laplace force strongly damps the fluctuations deeper.
- Magnetic fluctuations are stronger in the bulk (where the imposed field is stronger).
- The turbulent fluctuations near the outer shell excite global modes (bumps in the spectra).

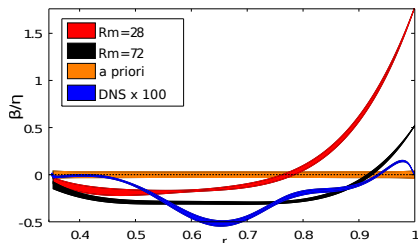
## Turbulence in non-rotating DTS: negative $\beta$

- Plenty of measurements (Ultrasound Doppler Velocimetry, Surface and bulk magnetic field, Surface electric potential).
- Use them to constrain the mean flow + turbulent EMF

$$EMF = \alpha(r)B + \beta(r) \nabla \times B$$

$\beta$  can be seen as a magnetic eddy diffusivity:  $\eta_{eff} = \eta + \beta$ .

- To explain our data, negative  $\beta$  is really needed.
- Supported by EMF computed from DNS at lower  $Re$ .



Cabanes, Schaeffer, and Nataf (2014) PRL

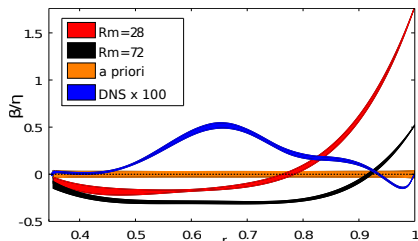
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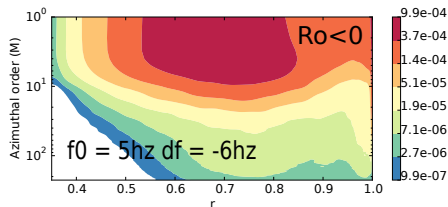
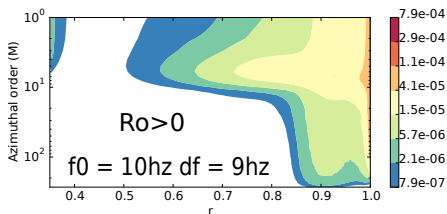
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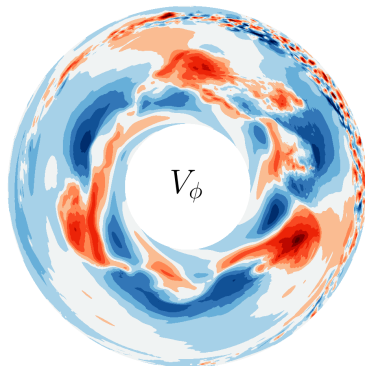
Cabanes, Schaeffer, and Nataf (2014) PRL  
[erratum submitted]

# Turbulence in rotating DTS



Elliot Kaplan: realistic DTS simulations using hyperviscosity in the last 20% of the spectrum ( $E < 10^{-6}$ ).

- Outer boundary layer turbulence.
- Large scale modes in the bulk ( $Ro < 0$ ).
- Quick decay for  $m \gtrsim 10$ , except in outer region.



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  - ▶ relevant for short time-scale,
  - ▶ length-scale limit controlled by  $Le = B/\ell\Omega$ ,
  - ▶ magnetic pumping at longer time-scale?



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- **Turbulence in DTS experiment**
  - ▶ negative eddy diffusivity spotted (why?),
  - ▶ boundary layer turbulence vs Bulk waves.

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- Back to first love: Quasi-Geostrophic models ! [many]



Thank you all for listening!



## Some numbers

	definition	initial	jump 1	jump 2	Earth's core
$N_r$		224	512	1024	
$L_{max}$		191	479	893	
$Ek$	$\nu/D^2\Omega$	$10^{-5}$	$10^{-6}$	$10^{-7}$	$3 \cdot 10^{-15}$
$Ra$	$\Delta T \alpha g D^3 / \kappa \nu$	$6 \cdot 10^{10}$	$1.2 \cdot 10^{12}$	$2.4 \cdot 10^{13}$	$10^{30} ?$
$Pm$	$\nu/\eta$	<b>0.4</b>	<b>0.2</b>	<b>0.1</b>	$3 \cdot 10^{-5}$
$Pr$	$\nu/\kappa$	1	1	1	0.1 - 10
$Rm$	$UD/\eta$	<b>710</b>	<b>660</b>	<b>585</b>	2000 ?
$A$	$\sqrt{\mu\rho}U/B$	<b>1.48</b>	<b>0.62</b>	<b>0.43</b>	0.01
$Re$	$UD/\nu$	1770	3300	5850	$2 \cdot 10^8$
$Ro$	$U/D\Omega$	0.018	$3.3 \cdot 10^{-3}$	$5.9 \cdot 10^{-4}$	$3 \cdot 10^{-6}$
$Le$	$B/\sqrt{\mu\rho}D\Omega$	0.012	$5.3 \cdot 10^{-3}$	$1.35 \cdot 10^{-3}$	$10^{-4}$
$\Lambda$	$B^2/\eta\Omega$	5.8	5.7	1.8	1 - 10
$F_\nu$	$D_\nu/(D_\eta + D_\nu)$	47%	24%	<b>17%</b>	?
$F_\eta$	$D_\eta/(D_\eta + D_\nu)$	53%	76%	<b>83%</b>	?

**Table 1:** Various input and output parameters of our simulations, where  $D$  is the shell thickness,  $U$  the rms velocity and  $B$  the rms magnetic field.