Beyond the convection dynamo paradigm

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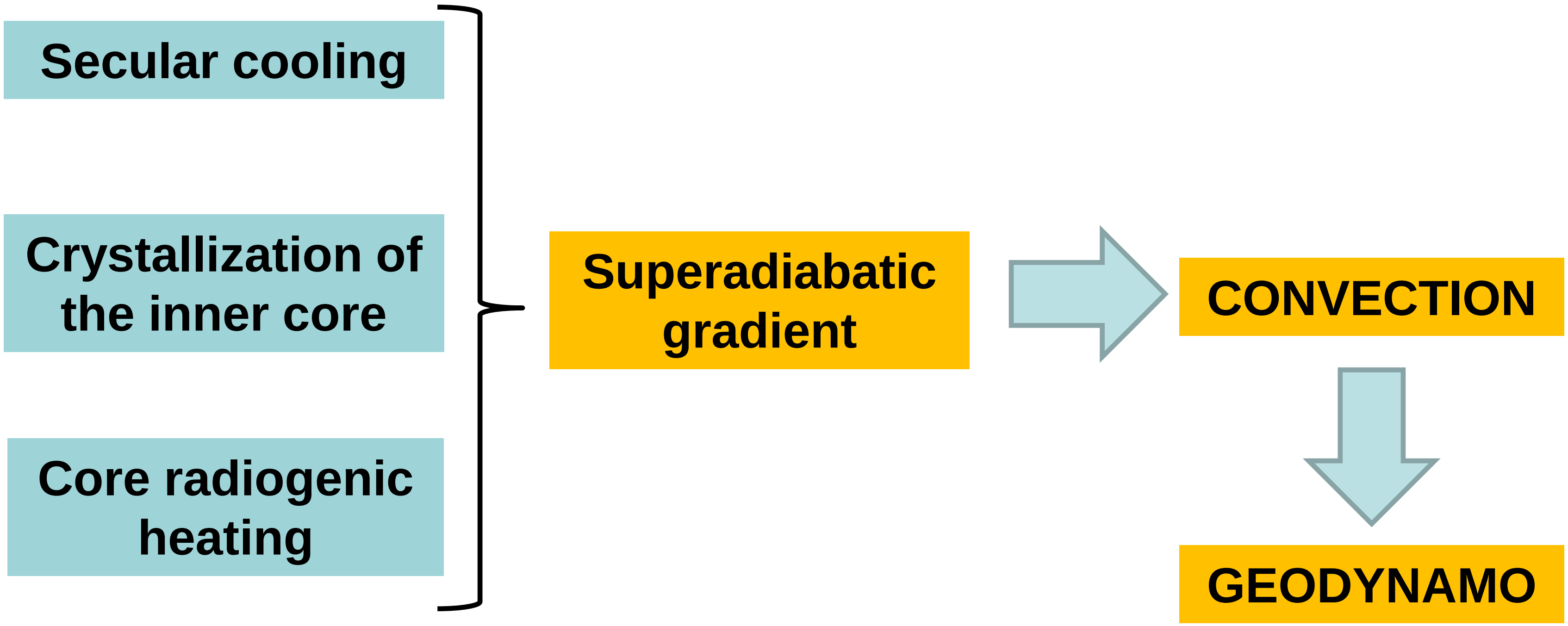
ENS Lyon, March 2019

Outline

1. Questioning the thermo-solutal dynamo paradigm for the Earth
2. Questioning the thermo-solutal dynamo paradigm for the Moon
3. Questioning the thermo-solutal dynamo paradigm beyond the Moon

The convection dynamo paradigm

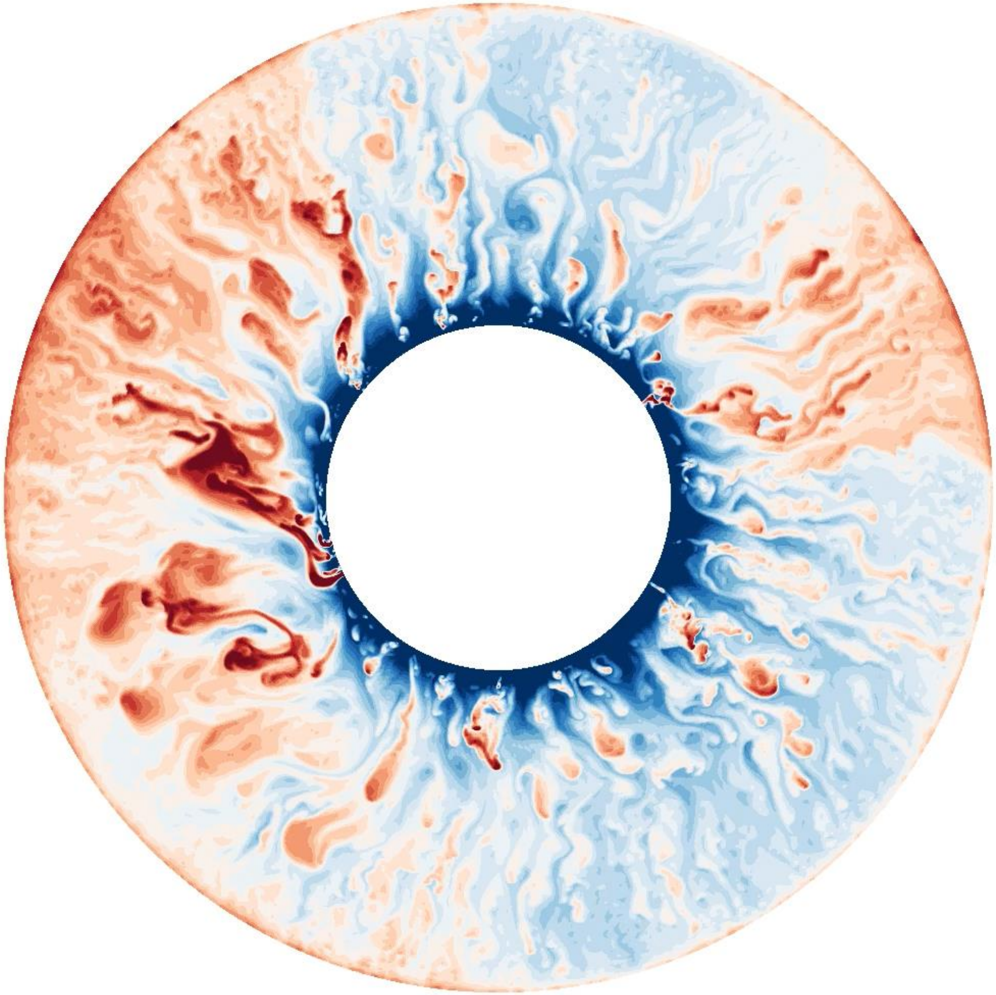
- **Currently for the Earth** : **convection**



The thermo-solutal convection paradigm

- **Currently**: **convection**

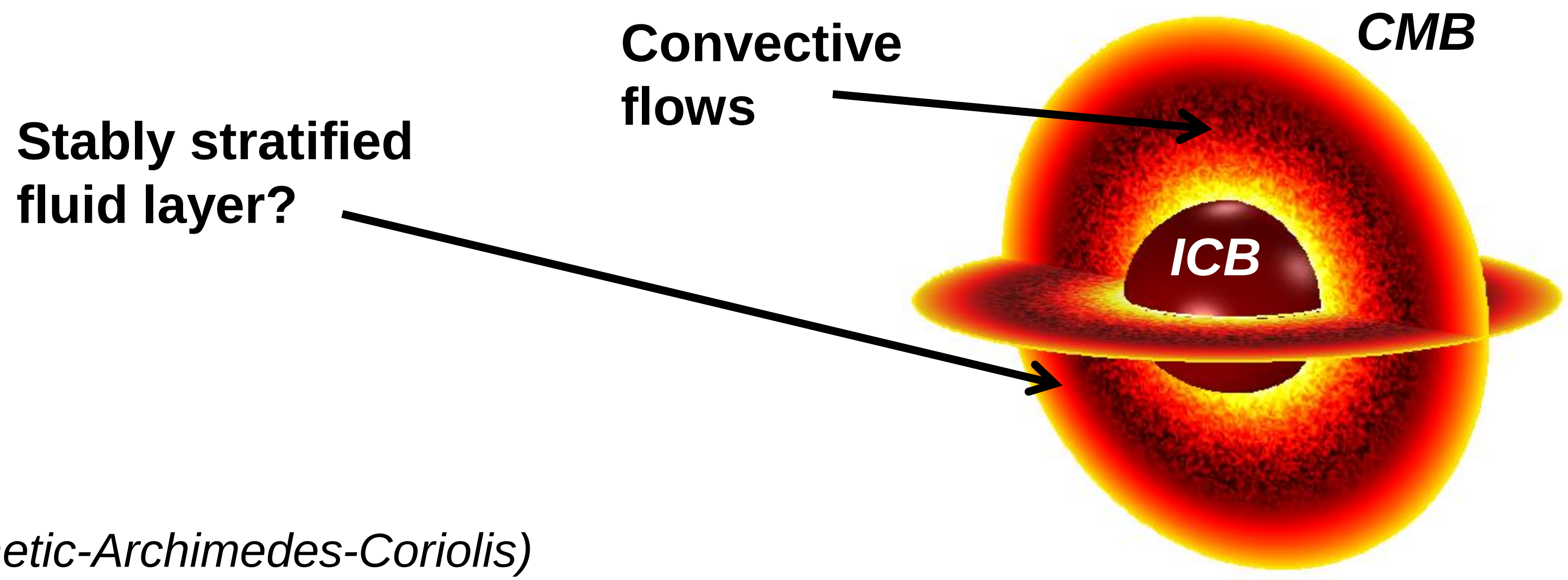
Schaeffer, HDR, 2015



Temperature in the equatorial plane

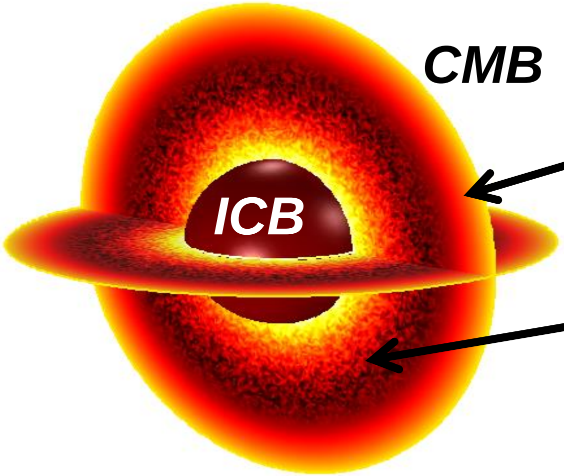
The thermo-solutal convection paradigm

- **Today, convection** probably powers the **geodynamo** …
- **But possible stratified layer! Debated presence but indirect clues** :
  - <u>Geodesy</u> : **nutations** derived dissipation? (Buffett 2010, Glane&Buffet 18)
  - <u>Geomagnetic</u>: **MAC waves** detection claimed (Buffett 2014, Buffet+16)



(MAC: Magnetic-Archimedes-Coriolis)

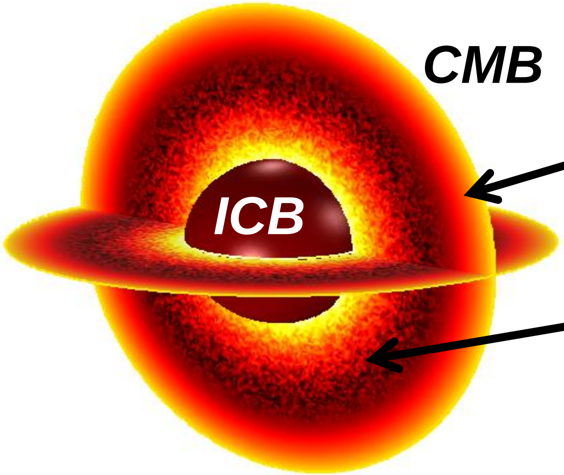
The thermo-solutal convection paradigm



No convection =>
no dynamo (?)

Reduced convection zone
=> Strongly affects geodynamo

The thermo-solutal convection paradigm



No convection => no dynamo (?)

Reduced convection zone => Strongly affects geodynamo

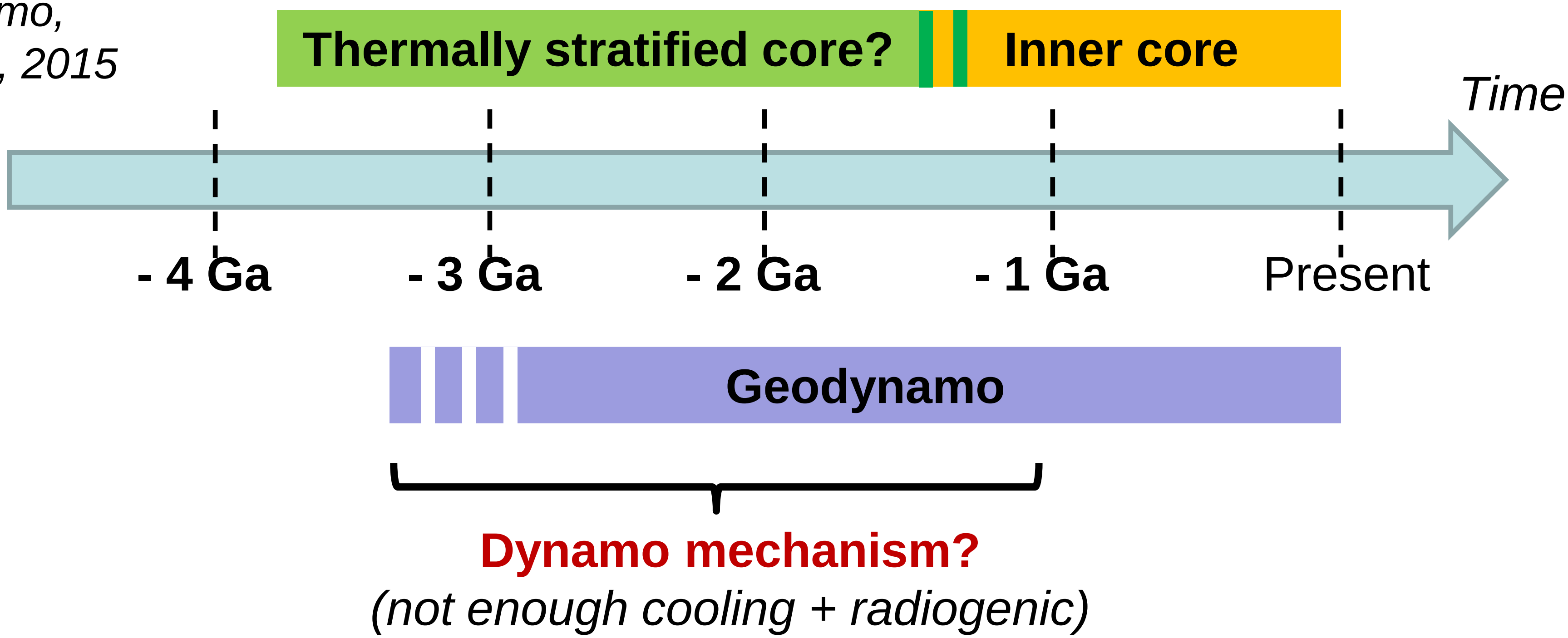
AND revised (debated) larger estimates of the **thermal conductivity question** the usual **convection model** (marginally enough power)

Nimmo, ToG, 2015

Difficulties for the current geodynamo… and in the past?

The thermo-solutal convection paradigm

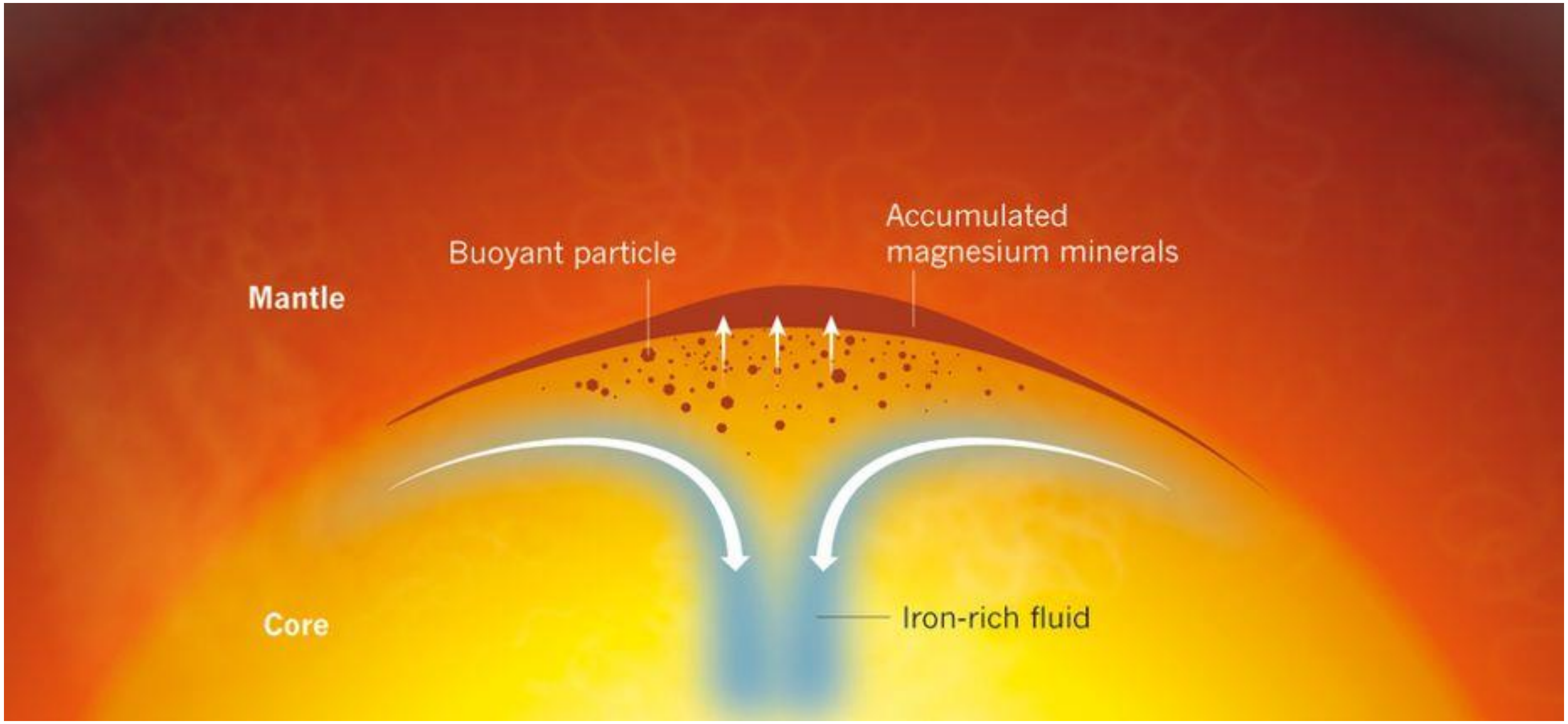
Nimmo, ToG, 2015



- **Rourke et al. (2017):** *"how to power convection in the core and thus a dynamo for the* ***vast majority of the Earth's history*** *remains one of* ***the most pressing puzzles in geophysics****"*

Precipitation in the core: a **speculative** scenario

A try to save this beloved thermo-solutal model

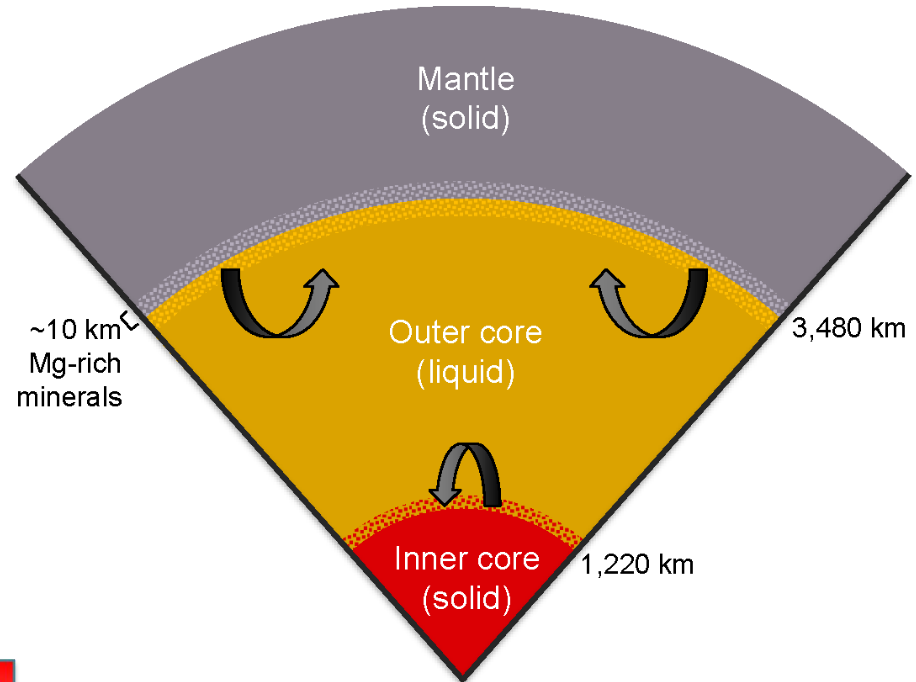


O'Rourke & Stevenson (2016)

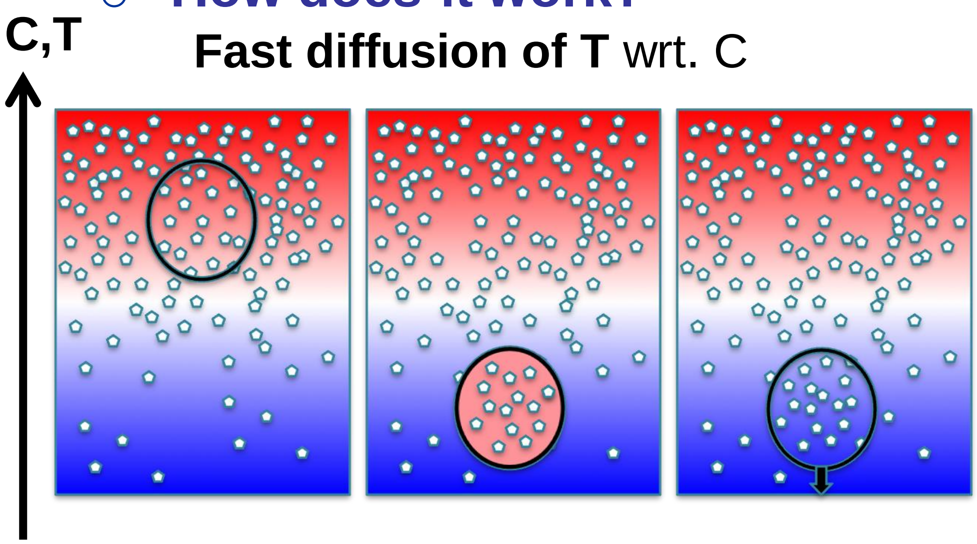
- **SiO_2** can also play (better?) this role (*Hirose et al., Nature, 2017)*
- **Speculative scenario requiring impacts**
- Other **unusual** model exist : e.g. with a **stratified BMO** ***(Laneuville+18)***

A little known double-diffusion in the Earth’s core

- **Early Earth**
  precipitation
- **Double diffusion?**
  Little known in this context but allow convection in a thermally stratified core!



- **How does-it work?**
  Fast diffusion of T wrt. C



Instability well known in ocean & stellar physics

…

But very few studies with a **rotating spherical geometry**
(Manglik+10, Net+12, Bouffard’s PhD)

Double diffusion in the Early Earth's core?

- **Scales:** R, R^2/ν, T, C, such that $T_0(r) = \frac{1-r^2}{Pr}, \quad C_0(r) = \frac{1-r^2}{Sc}$

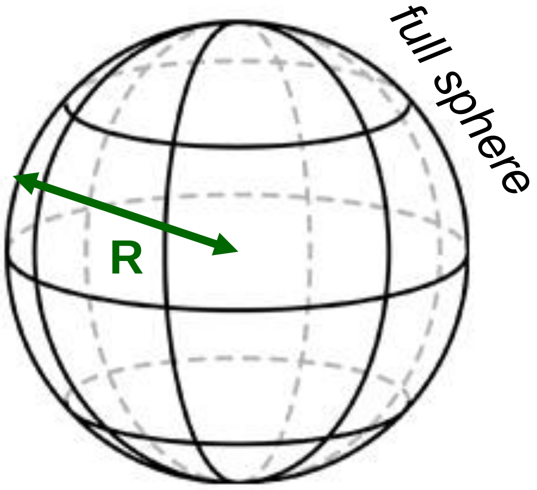
- **Equations**

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\boldsymbol{u} = -\frac{2}{Ek}\mathbf{1}_z \times \boldsymbol{u} - \nabla p + \boldsymbol{\nabla}^2\boldsymbol{u} + (Ra_T\,\Theta + Ra_C\,\xi)\; r\mathbf{1}_r,$$

$$\frac{\partial \Theta}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\Theta = \frac{1}{Pr}\left(2\,\boldsymbol{r}\cdot\boldsymbol{u} + \nabla^2\Theta\right),$$

$$\frac{\partial \xi}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\xi = \frac{1}{Sc}\left(2\,\boldsymbol{r}\cdot\boldsymbol{u} + \nabla^2\xi\right),$$

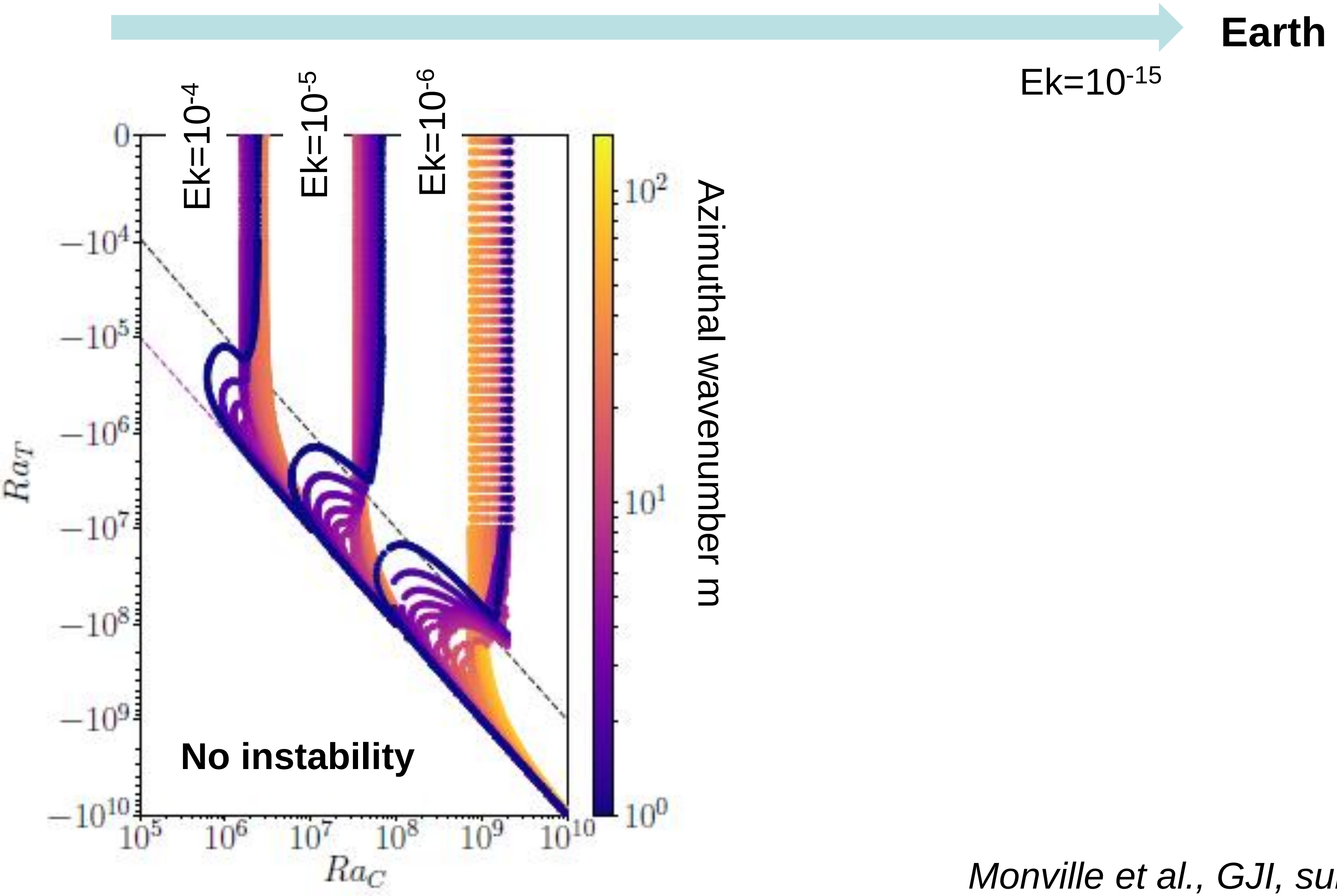
$$\boldsymbol{\nabla}\cdot\boldsymbol{u} = 0,$$



$$Ra_T = \frac{\alpha_T g_0 Q_T R^6}{6\nu{\kappa_T}^2}, \quad Ra_C = \frac{\alpha_C g_0 Q_C R^6}{6\nu{\kappa_C}^2} \qquad Ek = \frac{\nu}{\Omega_s R^2}, \quad Pr = \frac{\nu}{\kappa_T}, \quad Sc = \frac{\nu}{\kappa_C}$$

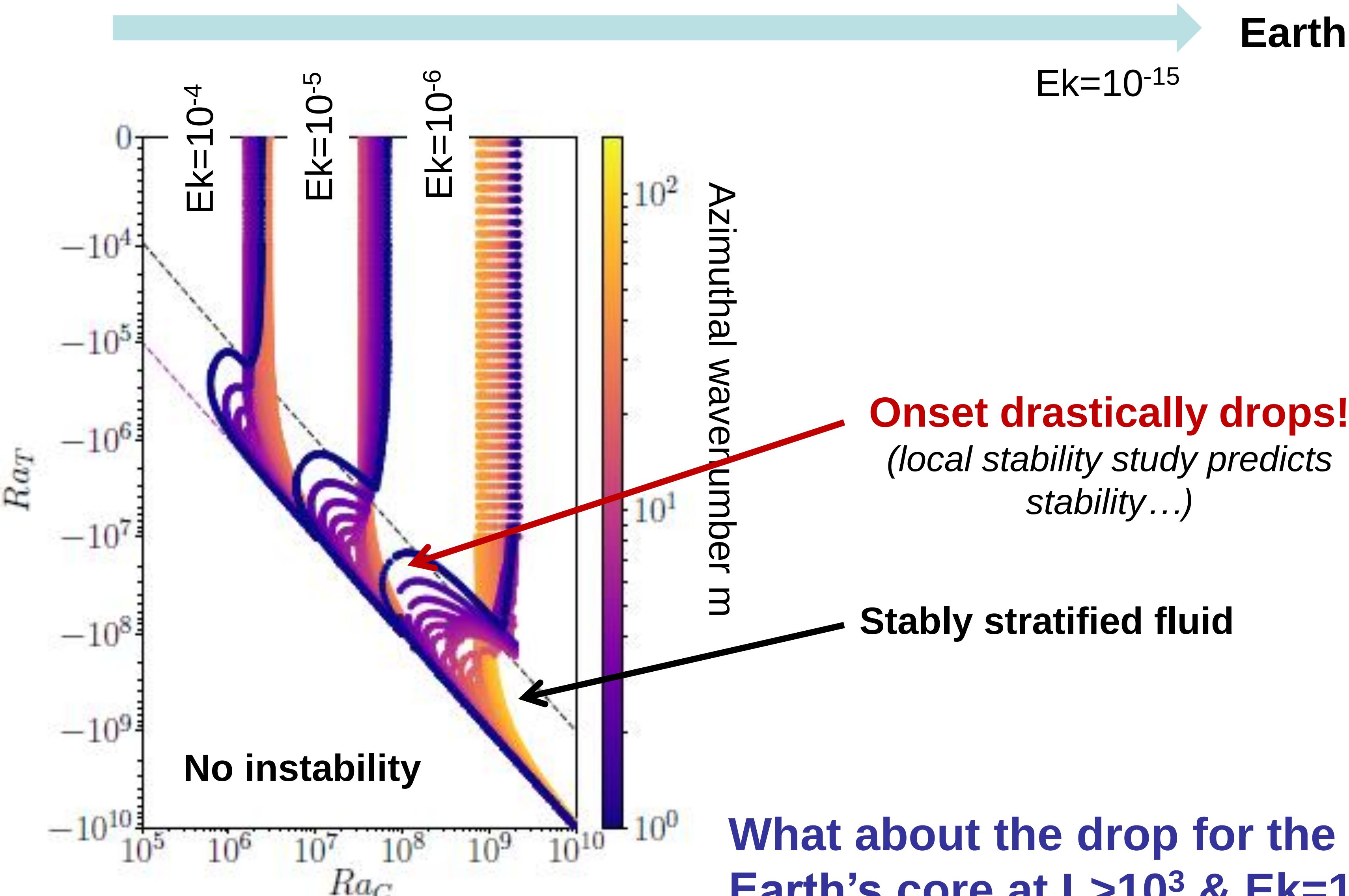
- **Codes:** open-source, pseudo-spectral => **SINGE** (linear, by J. Vidal) **& XSHELLS** (non-linear, by N. Schaeffer)

Onset in a rotating sphere at L=Sc/Pr=10



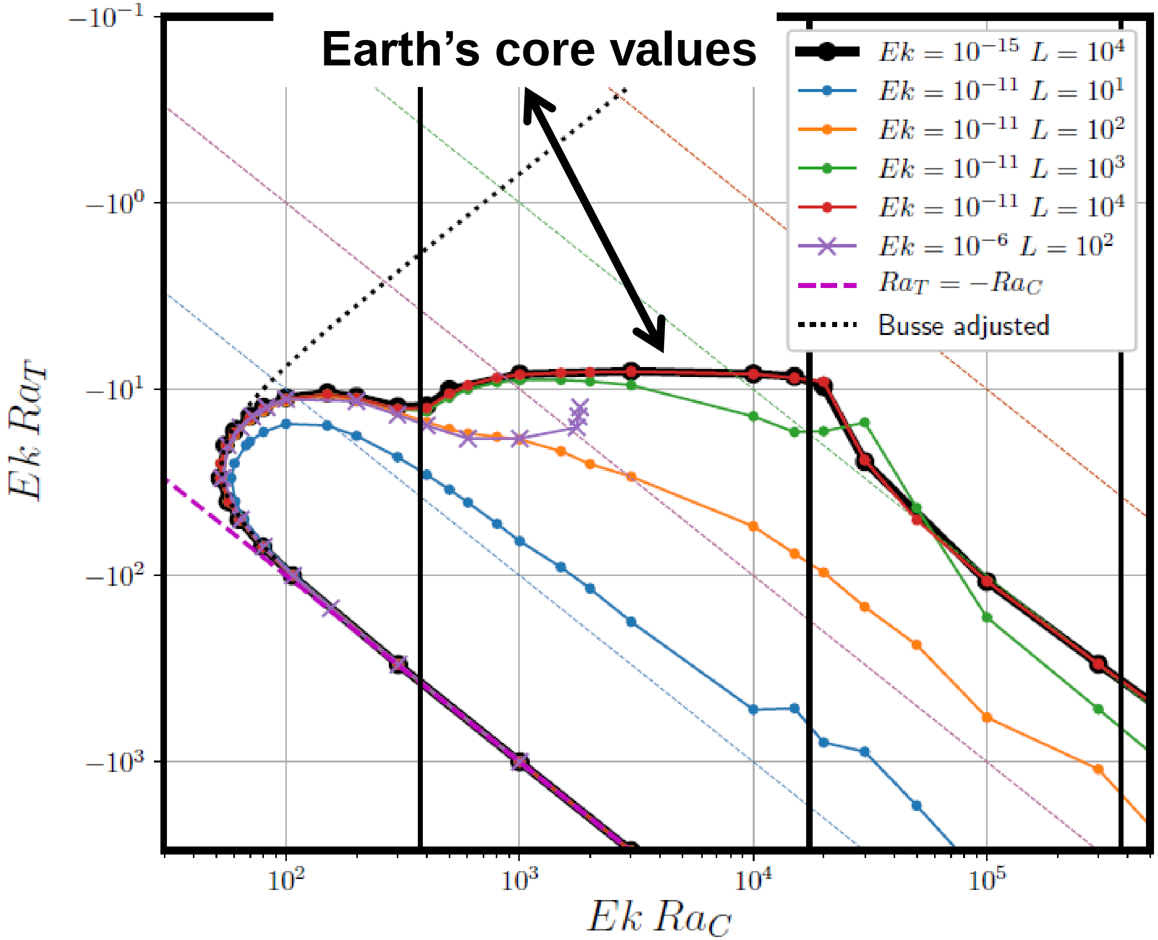
Monville et al., GJI, subm.

Onset in a rotating sphere at L=Sc/Pr=10



What about the drop for the Earth's core at $L>10^3$ & $Ek=10^{-15}$?

Onset in a rotating sphere at the Earth's core values



Inviscid double diffusive onset!

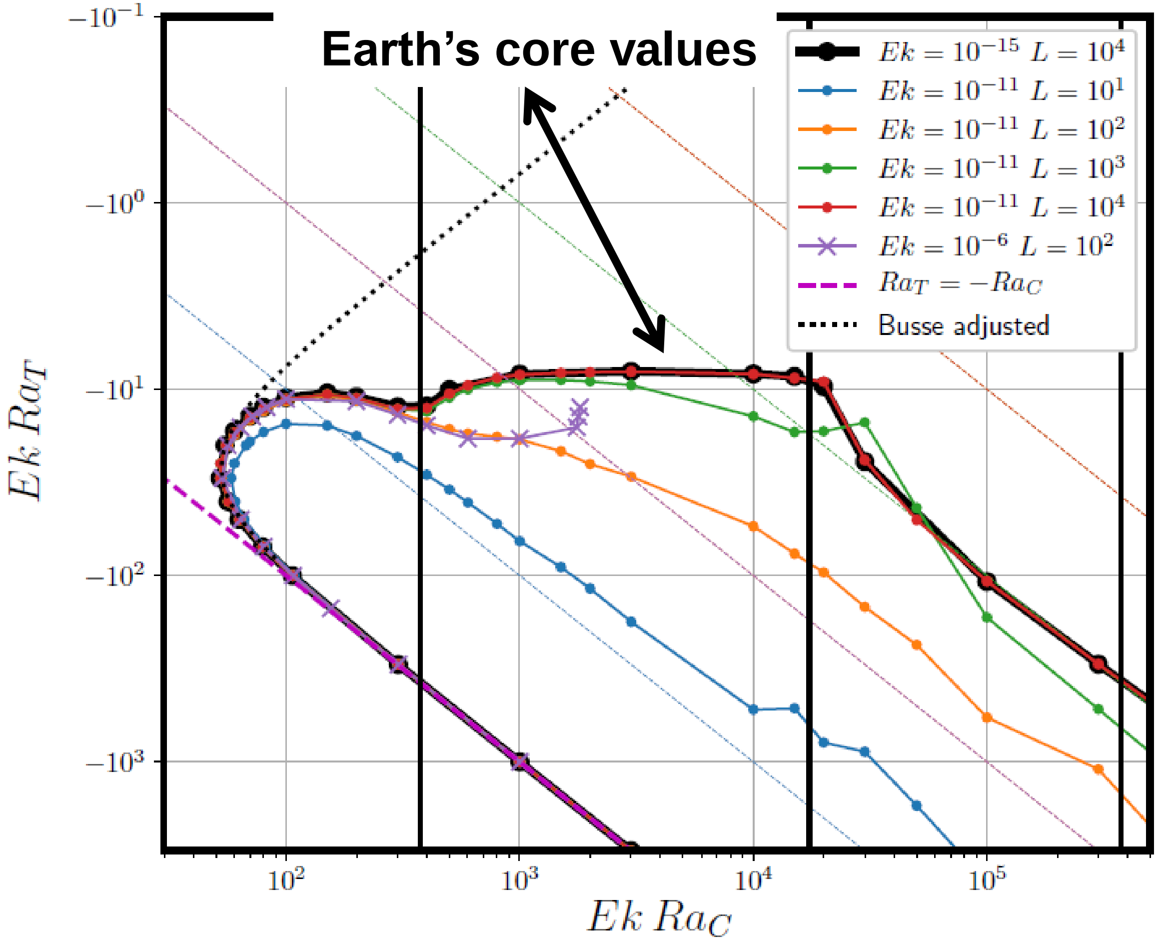
Inviscid convection domain

Thus, DDC onset varies as **Ek^{-1}**

Since usual convection onset varies as **Ek$^{-4/3}$**

⇒ Onset drop ~ Ek$^{-1/3}$

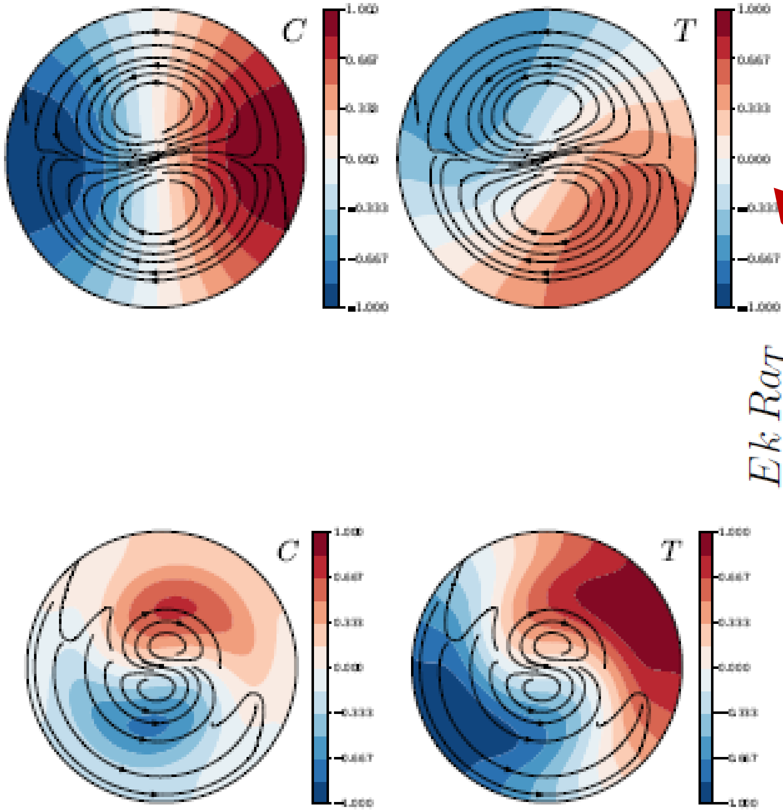
⇒ Earth: drop of 10^5

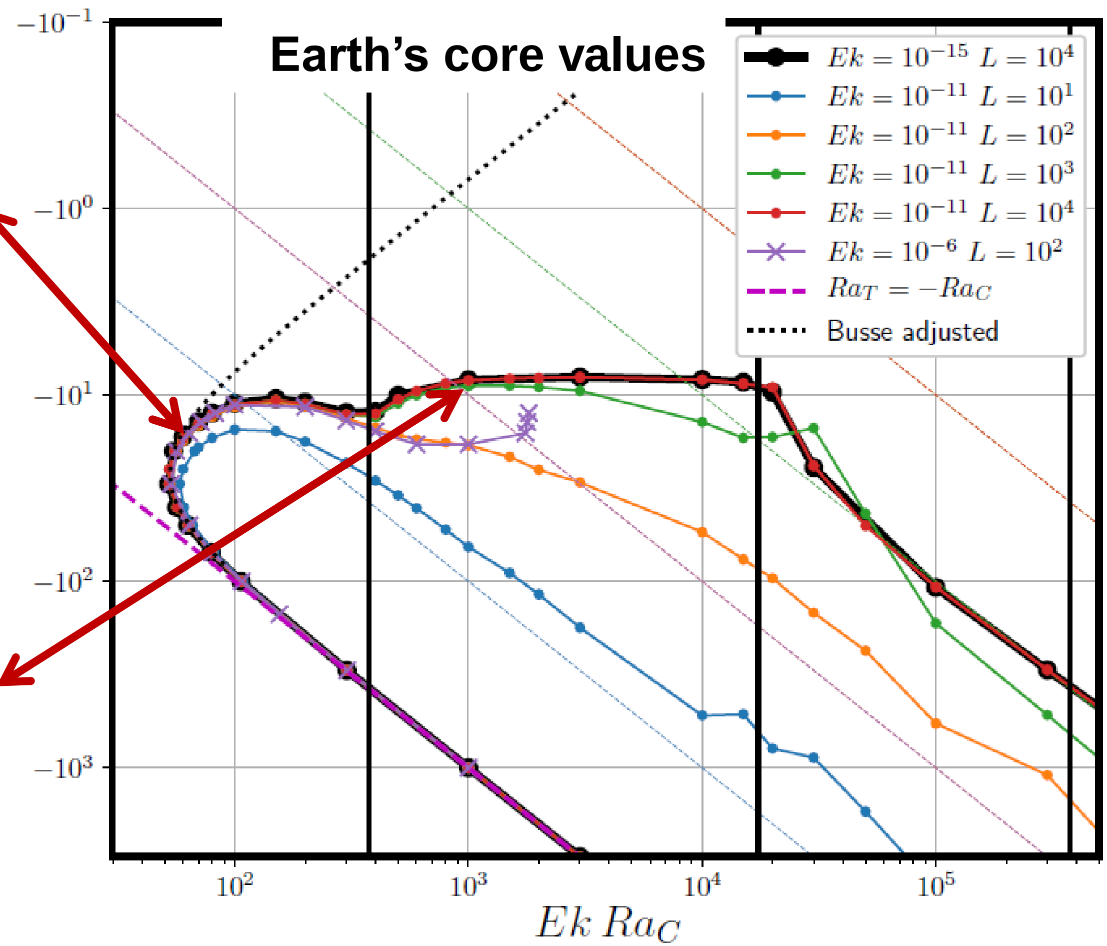


Inviscid double diffusive onset!

Monville et al., GJI, subm.

Eigenmodes at the onset



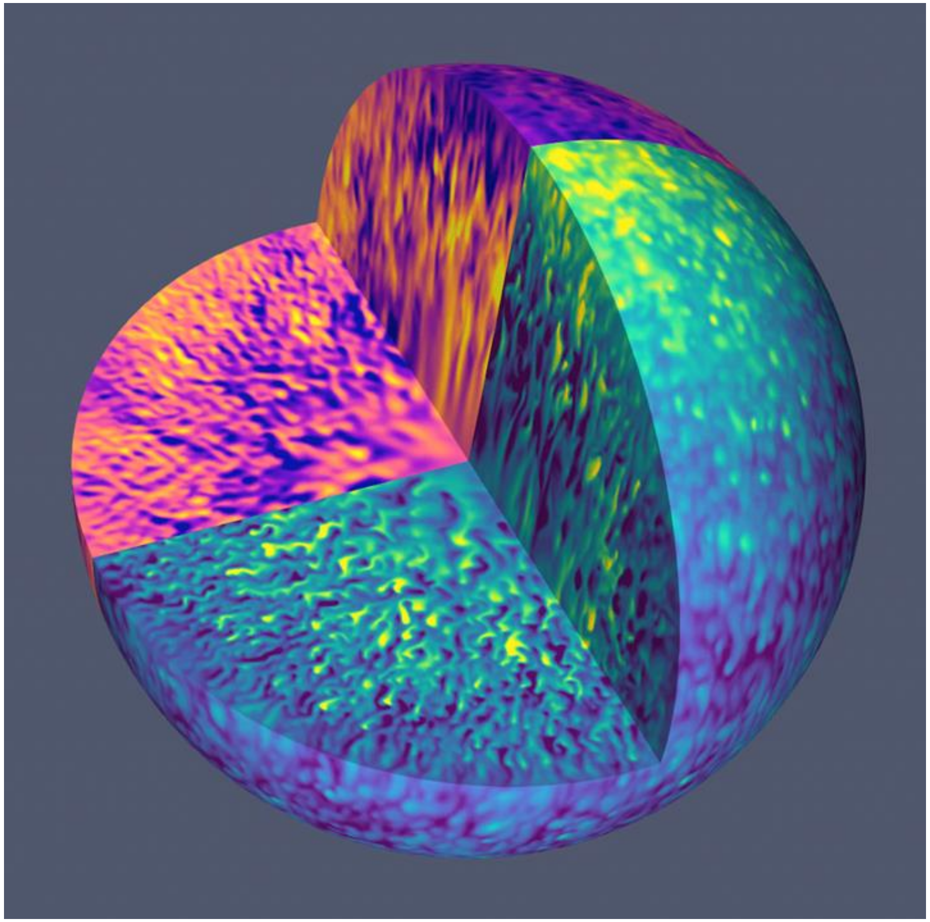


Large-scale inviscid double diffusive flow in the fingering regime

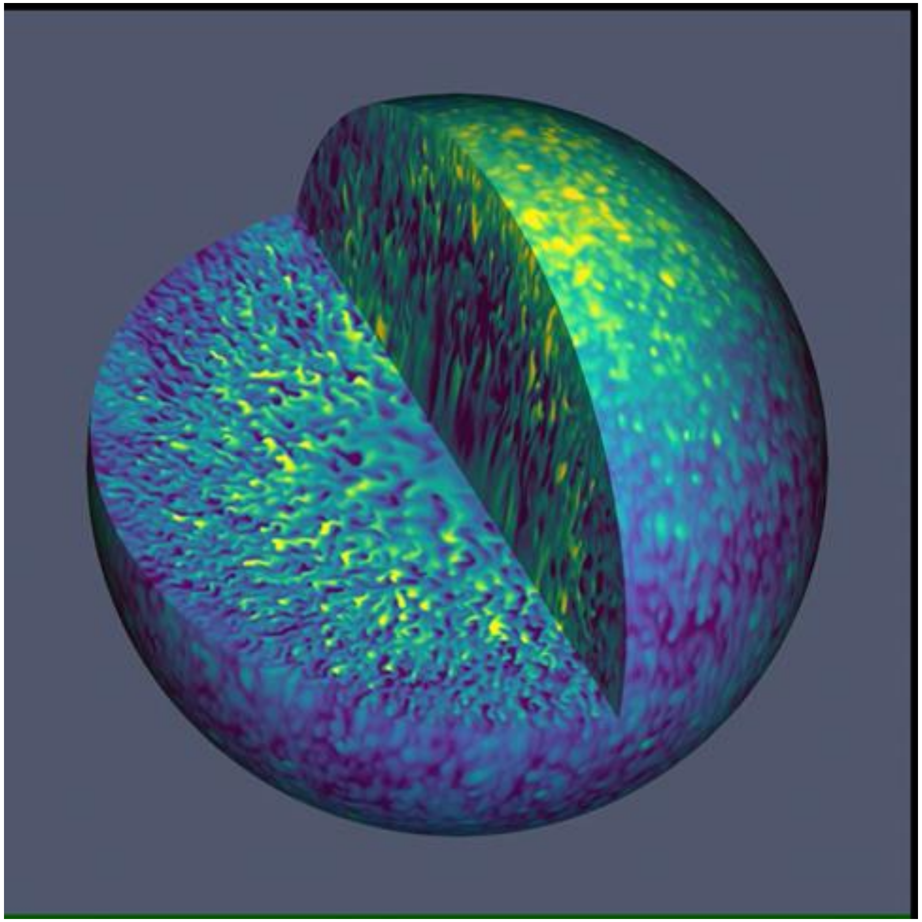
Non-linear regime?

Non-linear rotating double diffusive convection

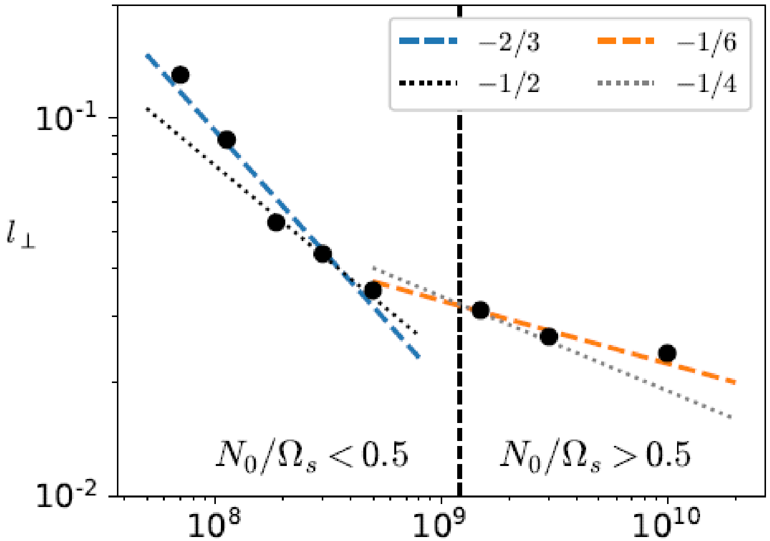
Thermal (upper) & solutal (lower) buoyancy



Vorticity magnitude



Double diffusive structures & transport at L=10



$Ra_C = - 3\ Ra_T$

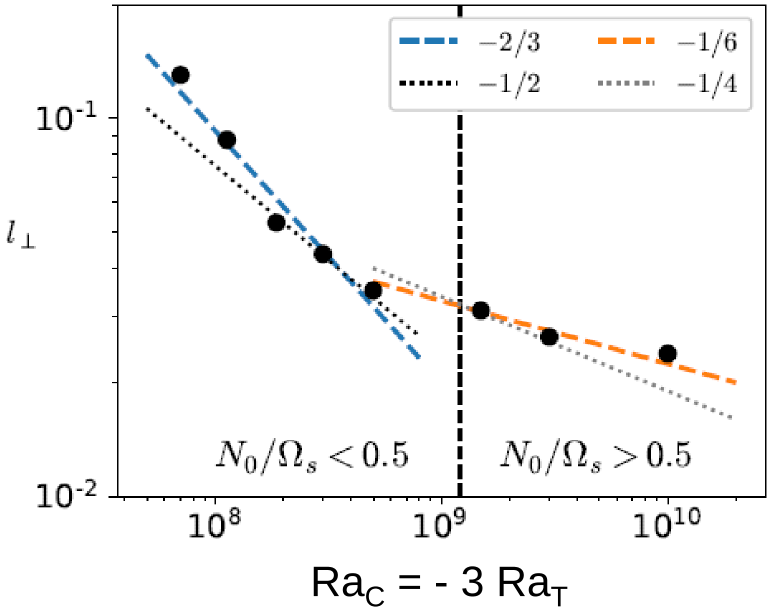
Radko, 2013, **non-rotating** : -1/4

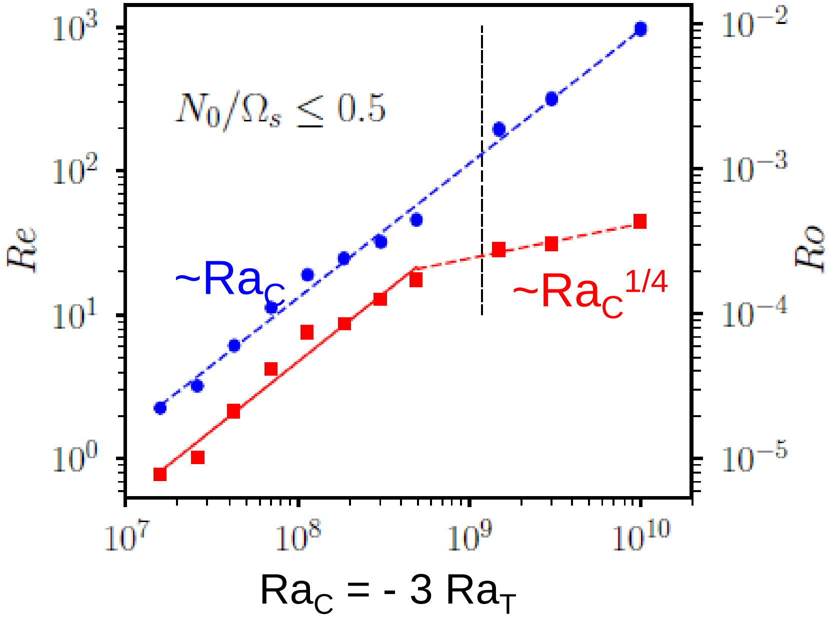
Bouffard, 2017, **rotating**: -1/2

=> Transition between 2 regimes

(weakly and strongly stratified)

Double diffusive structures & transport at L=10



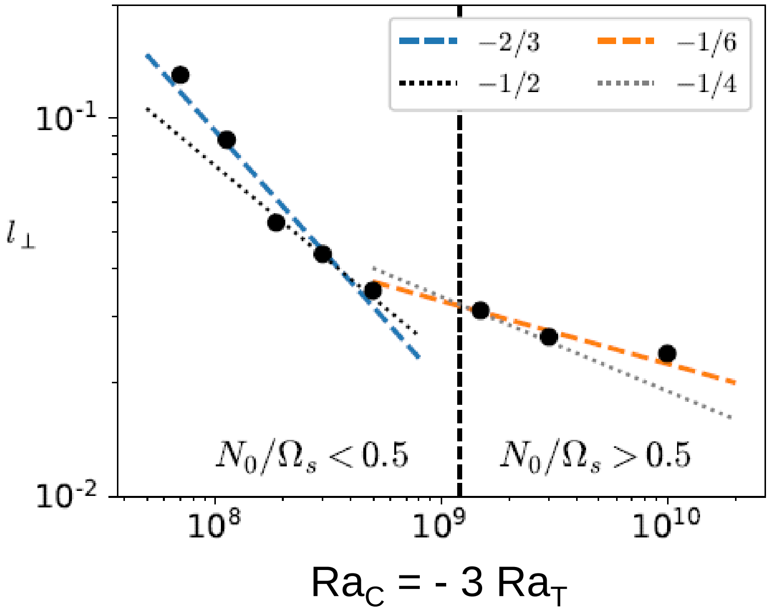


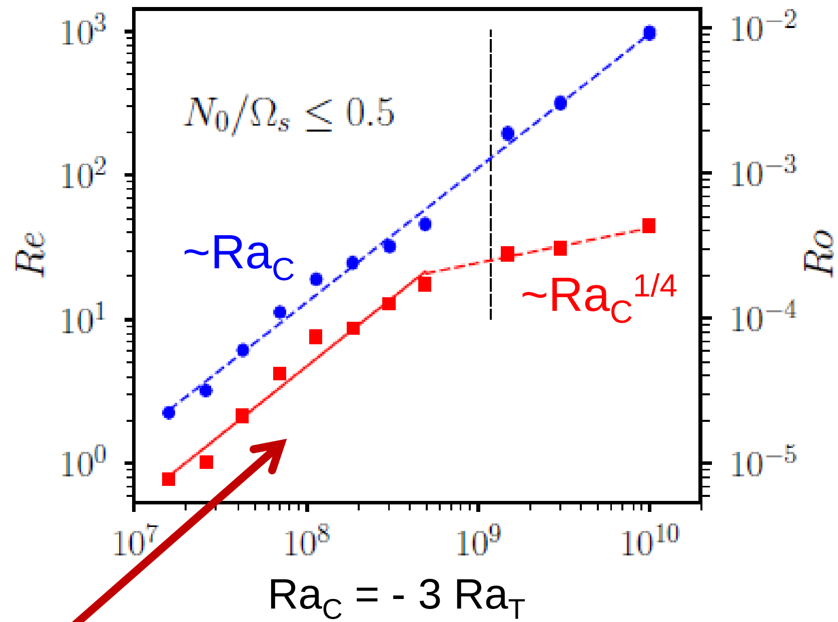
Re based on

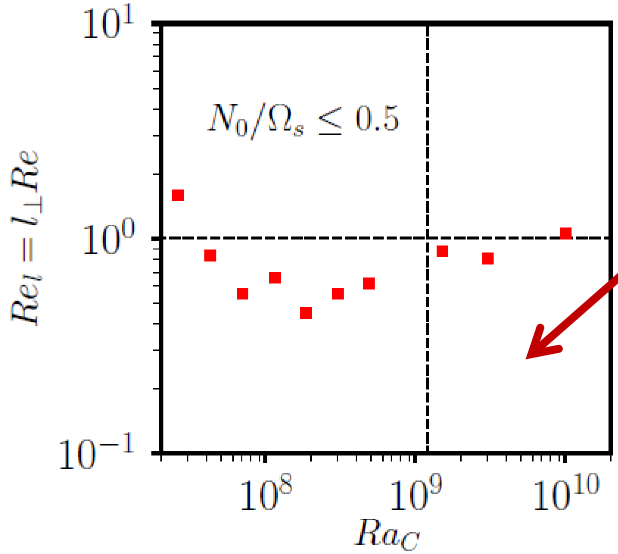
- the total NRJ (blue)
- the poloidal non-zonal NRJ (red) = proxy of the radial velocity

Monville et al., GJI, subm.

Double diffusive structures & transport at L=10







Re based on

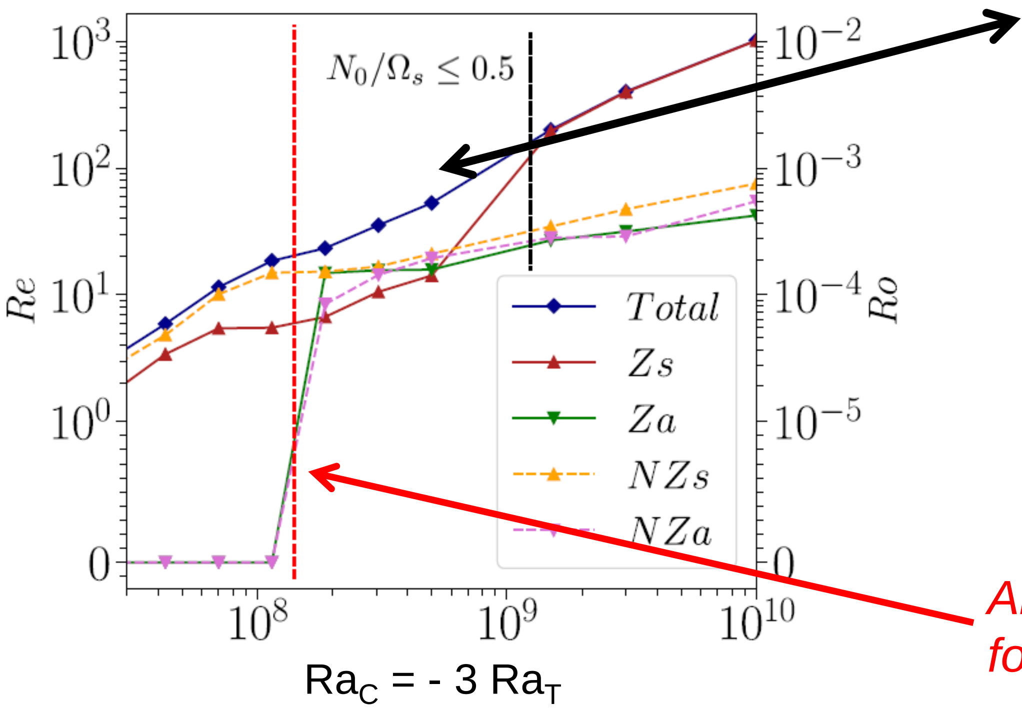
- the total NRJ (blue)
- the poloidal non-zonal NRJ (red) = proxy of the radial velocity

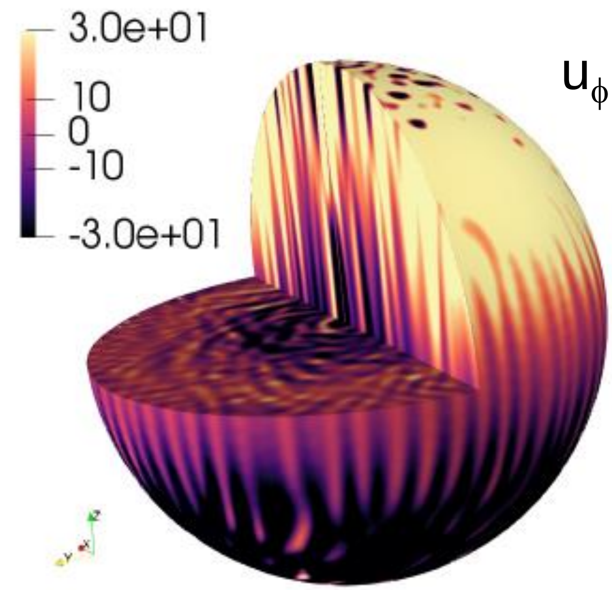
Such that $Re_l=[Pr(R_0-1)]^{-1/2} \sim 1$
(Garaud 2018)

Monville et al., GJI, subm.

Zonal flows

$$Pr = 0.3, Sc = 3, Ek = 10^{-5}$$



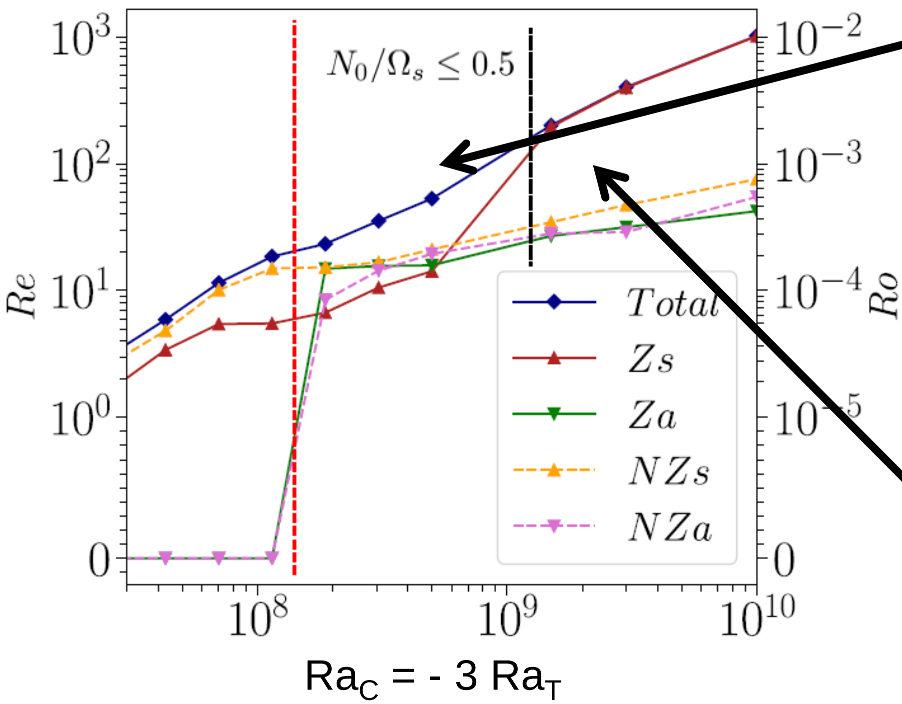


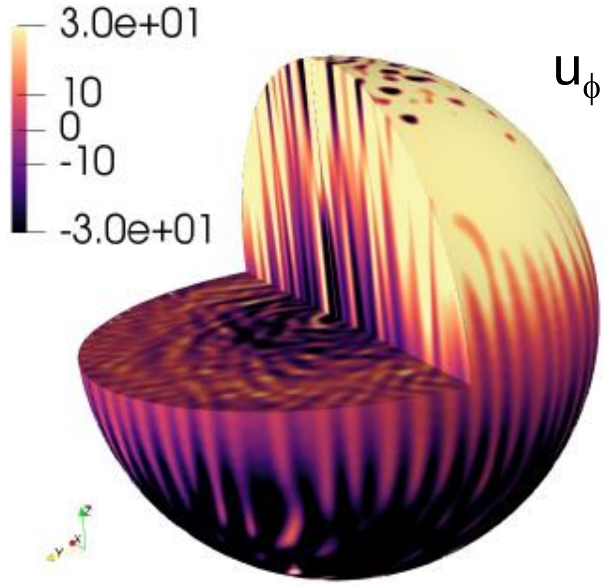
Anti-symmetric linear onset for the mode m=0

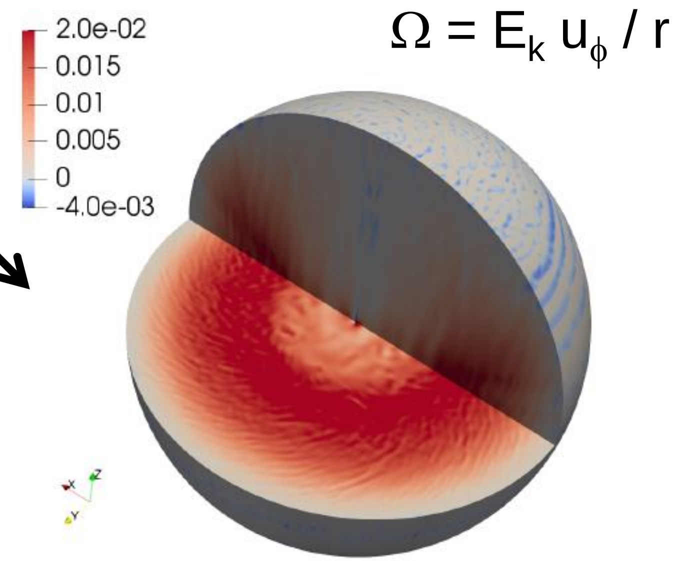
- Far from RDDC onset**, equatorially anti-symmetric zonal flow**
- Well predicted by a purely linear mechanism

Zonal flows

$Pr = 0.3, Sc = 3, Ek = 10^{-5}$



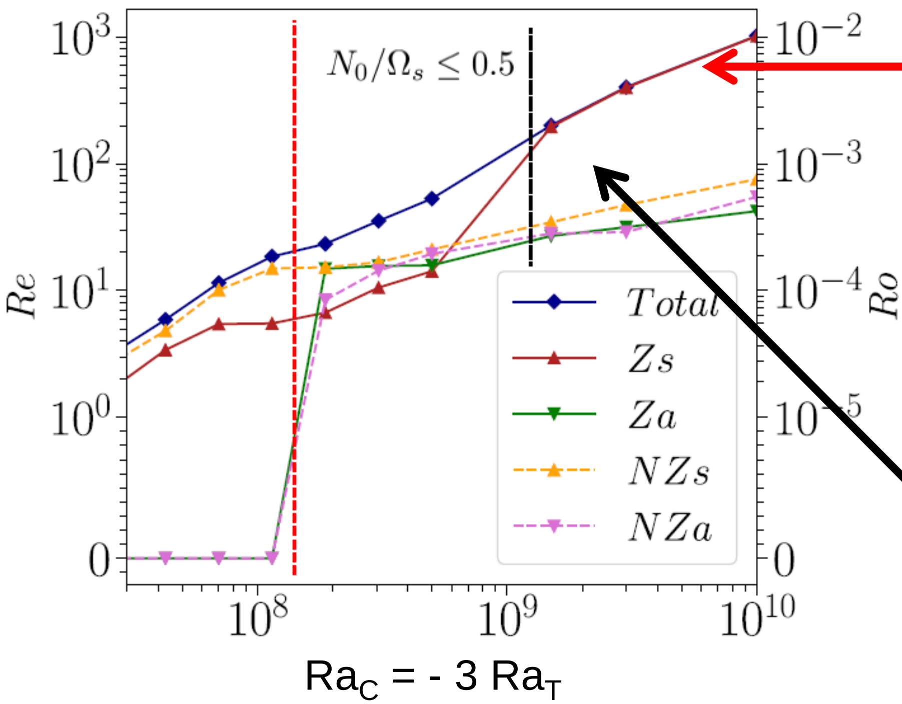




For stronger stratification, **equatorially symmetric intense zonal flows!**

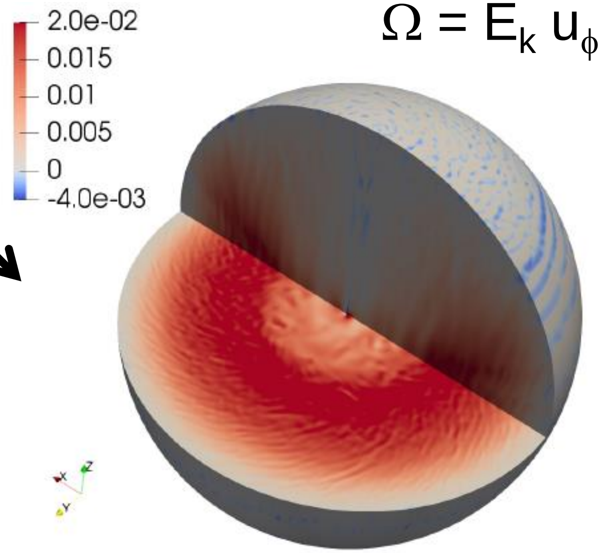
Zonal flows

$$Pr = 0.3, Sc = 3, Ek = 10^{-5}$$



Current work: double-diffusive dynamos in stably stratified fluids

$\Omega = E_k\ u_\phi / r$



For stronger stratification, **equatorially symmetric intense zonal flows!**

Outline

1. Questioning the thermo-solutal dynamo paradigm for the Earth

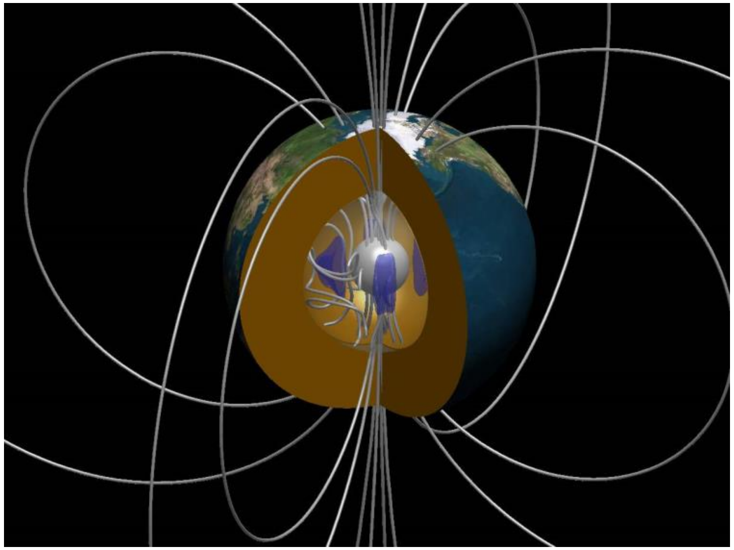
2. Questioning the thermo-solutal dynamo paradigm for the Moon

3. Questioning the thermo-solutal dynamo paradigm beyond the Moon

Beyond the Earth, the Moon is the only body for which we have data constraining the planetary magnetic field evolution over a long timescale

A lunar magnetic field

Current Earth

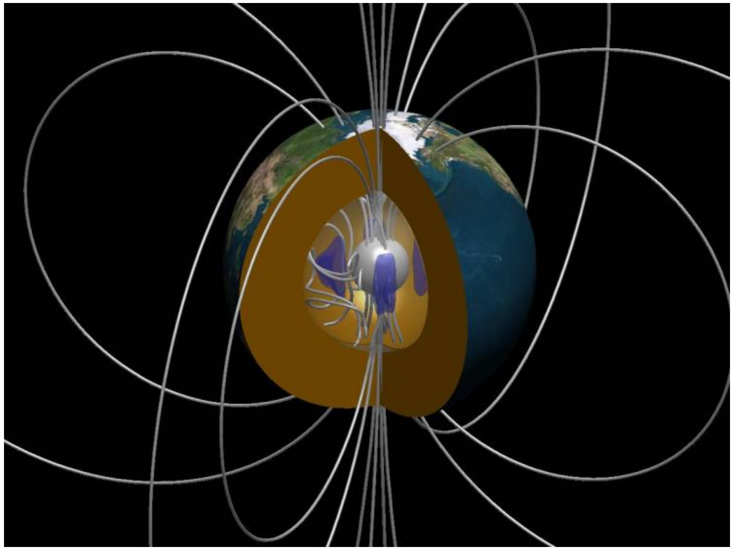


Aubert, IPGP

- **Global** magnetic field
- **Dynamical (internal)** origin

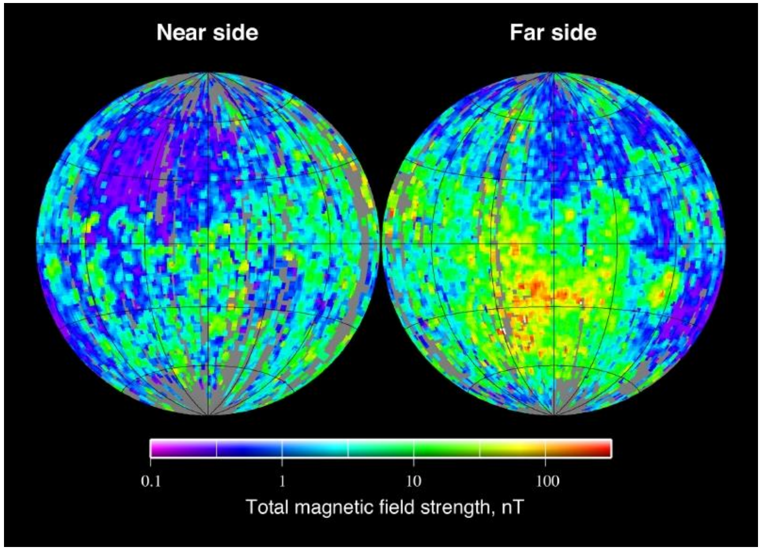
A lunar magnetic field

Current Earth



Aubert, IPGP

Current Moon



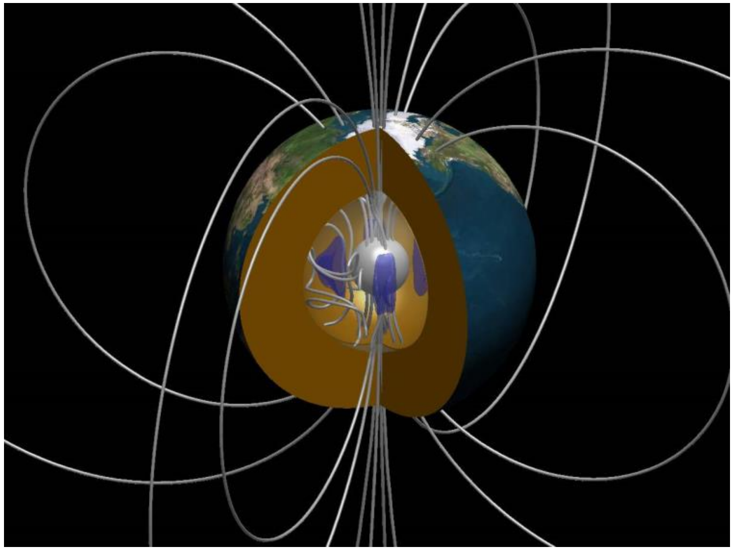
Spatial data, Wieczorek, IPGP

- **Global** magnetic field
- **Dynamical (internal)** origin

- **Local** magnetic field
- **Static (crustal)** origin

A lunar magnetic field

Current Earth



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- **Global** magnetic field
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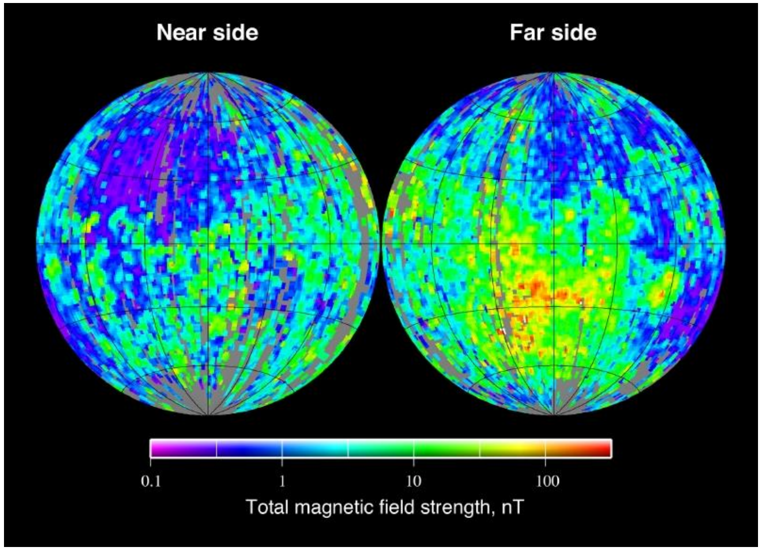
Current Moon



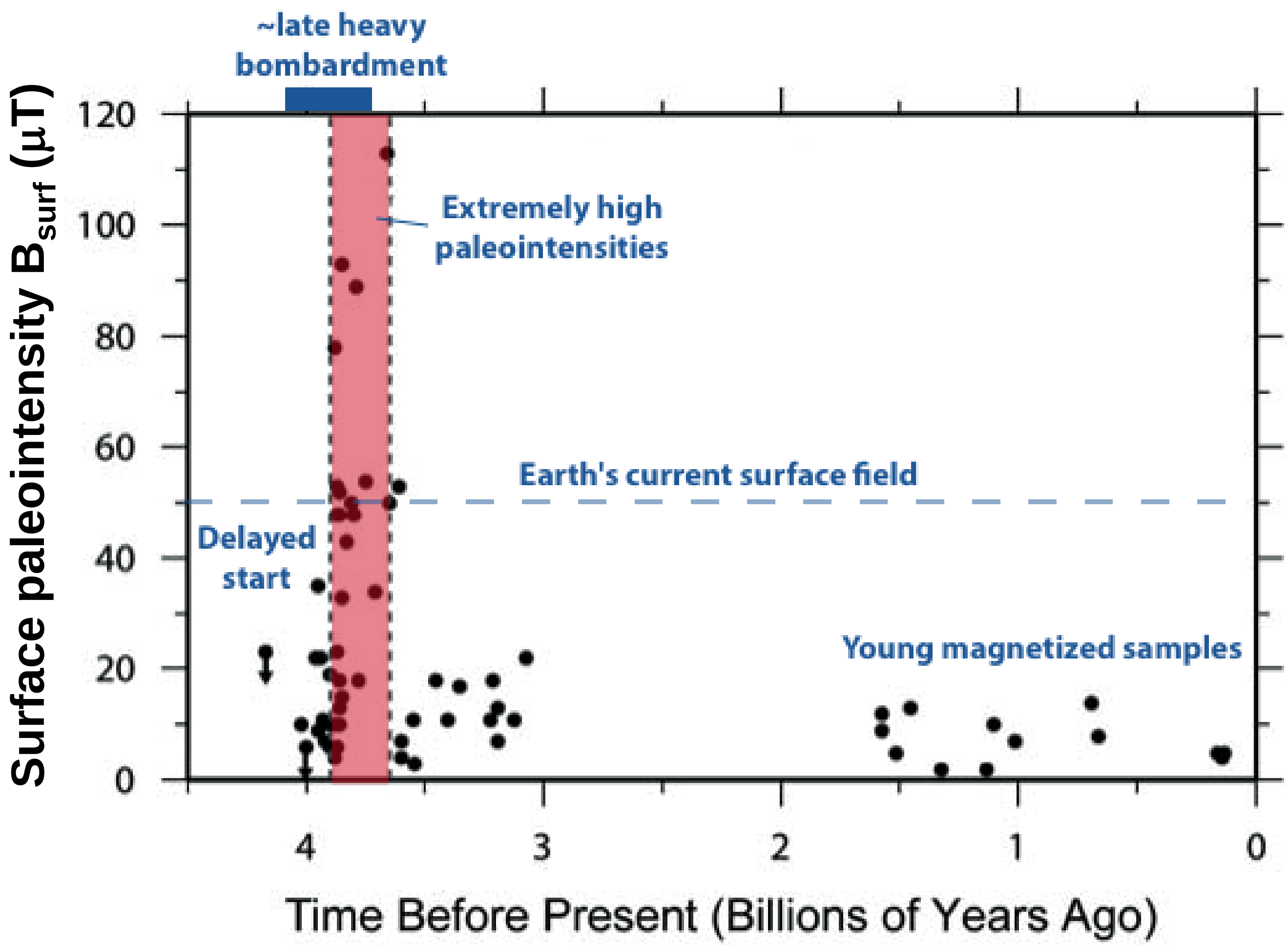
Spatial data, Wieczorek, IPGP

- **Local** magnetic field
- **Static (crustal)** origin

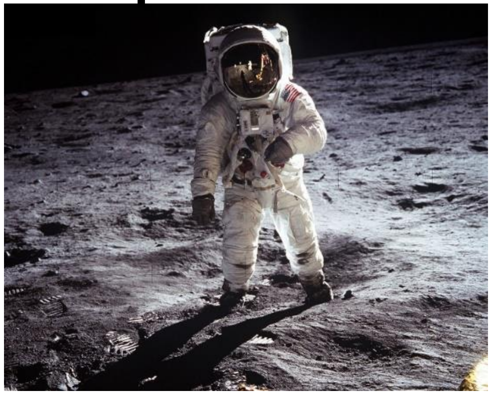
Time evolution of the lunar magnetic field, recorded in the lunar rocks?

Paleomagnetic analyses of lunar rocks

Fuller & Cisowski, Geomagnetism (1987)
Wieczorek et al., Rev. Miner. Geochem. (2006)



Data from Apollo rocks



Apollo 11

Paleomagnetic analyses of lunar rocks

Fuller & Cisowski, Geomagnetism (1987)
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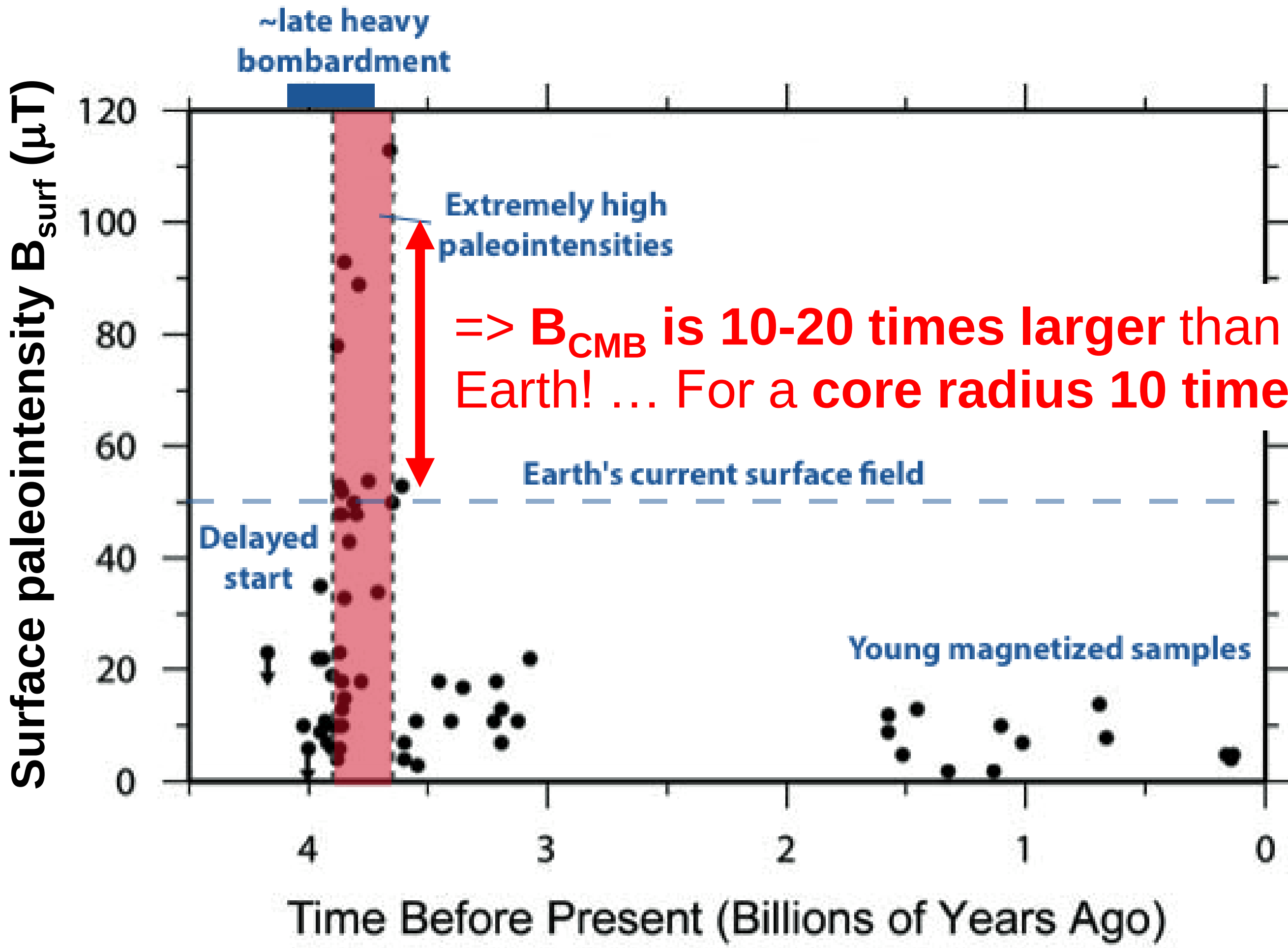
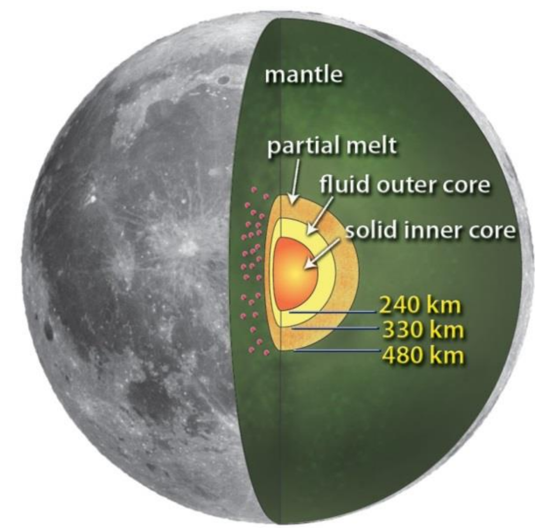
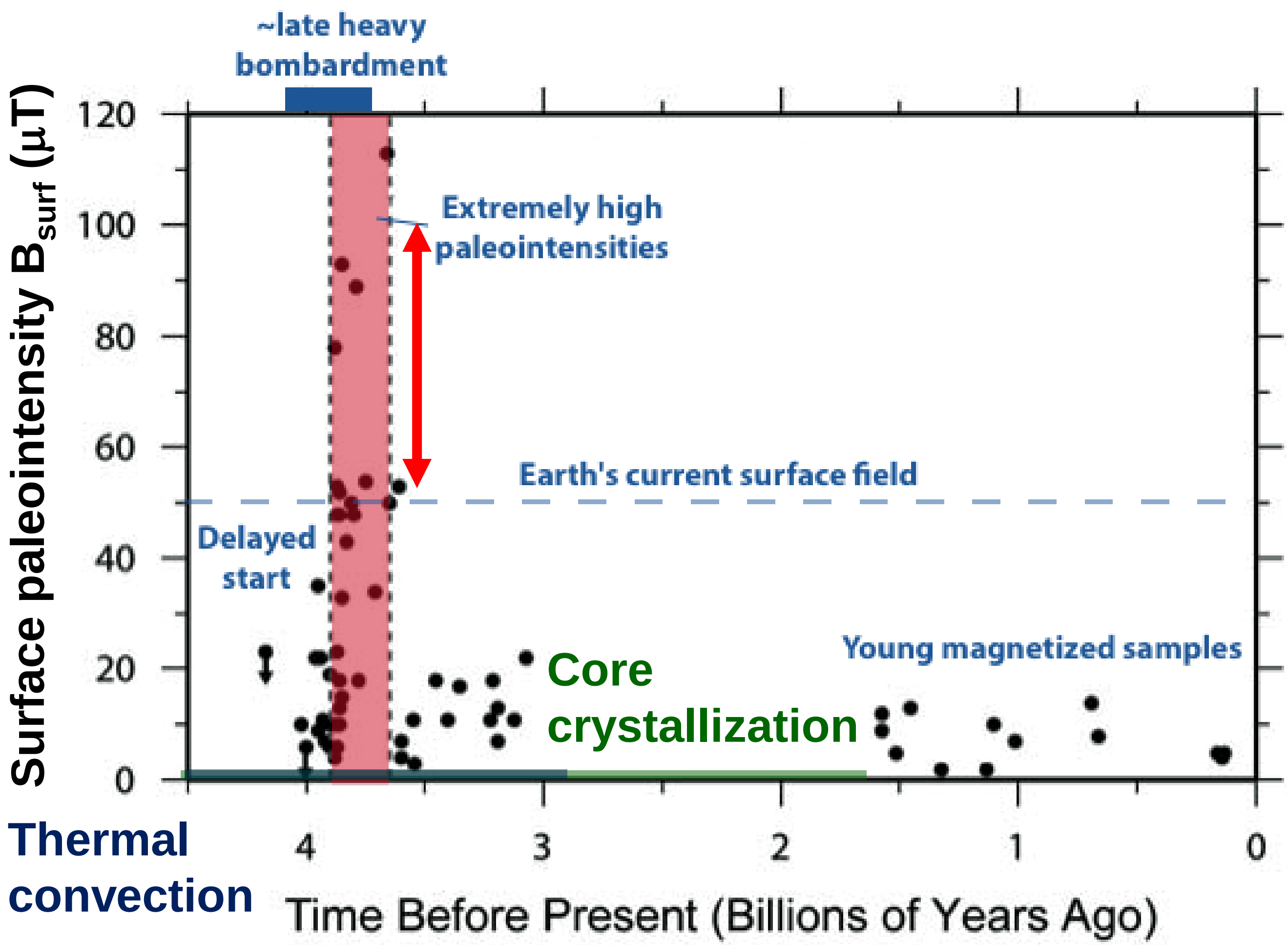


=> **B_{CMB} is 10-20 times larger** than B_{CMB} of the current Earth! … For a **core radius 10 times smaller**?!



Convective dynamo models

Models : B_{surf} < 2 μT

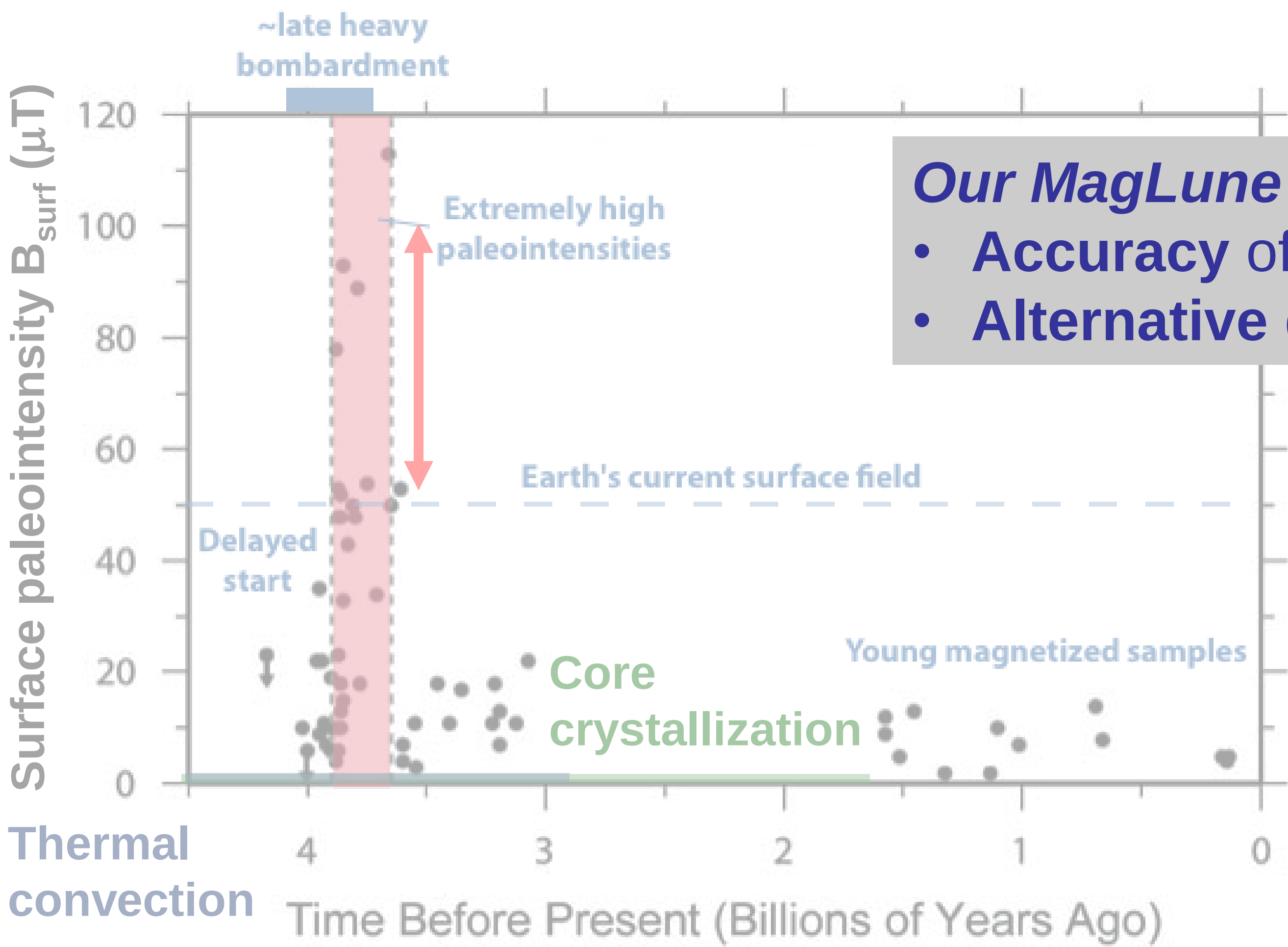


Thermal convection

Laneuville et al. (2014)
Evans et al. (2014)

Scheinberg et al. (2015)
Evans et al. (2017)

MagLune project

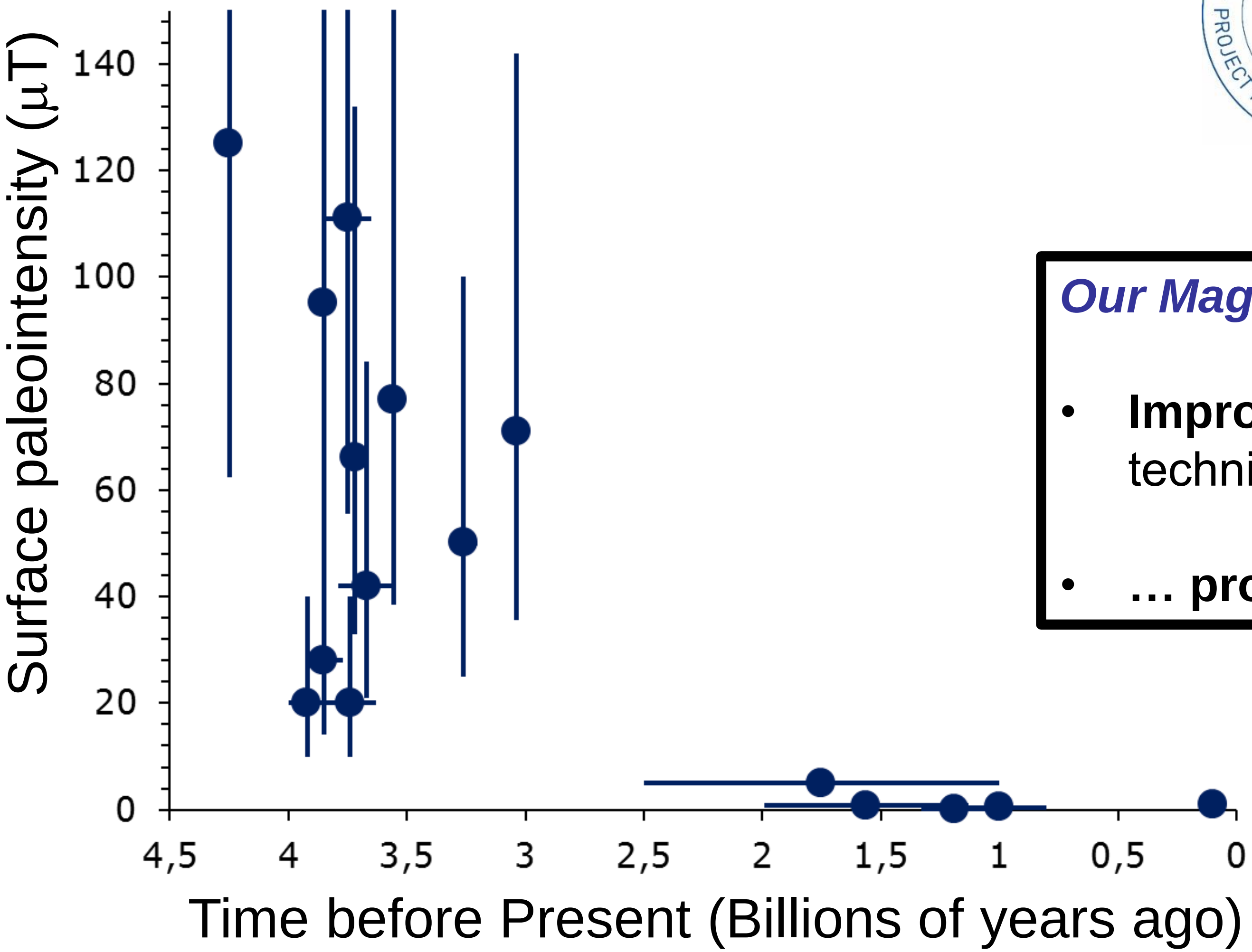


Our MagLune ANR Project

- **Accuracy** of data? **Error bars?**
- **Alternative** dynamo **models?**

Improved paleomagnetic data

Courtesy of C. Lepaulard & J. Gattacceca (CEREGE)

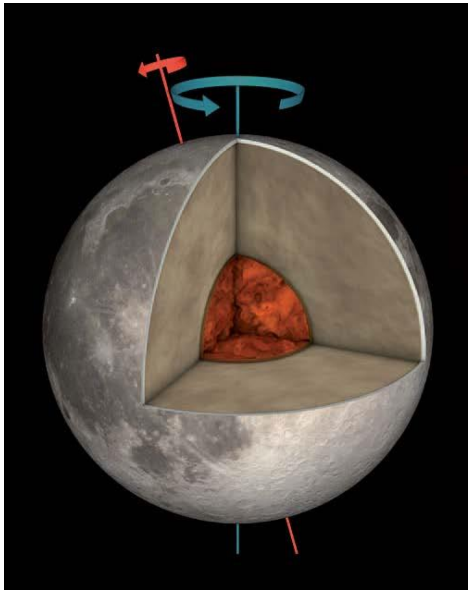


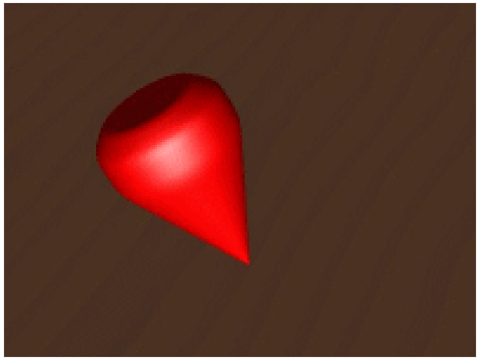
Our MagLune ANR Project

- **Improved** data with **modern** techniques…
- **… providing error bars!**

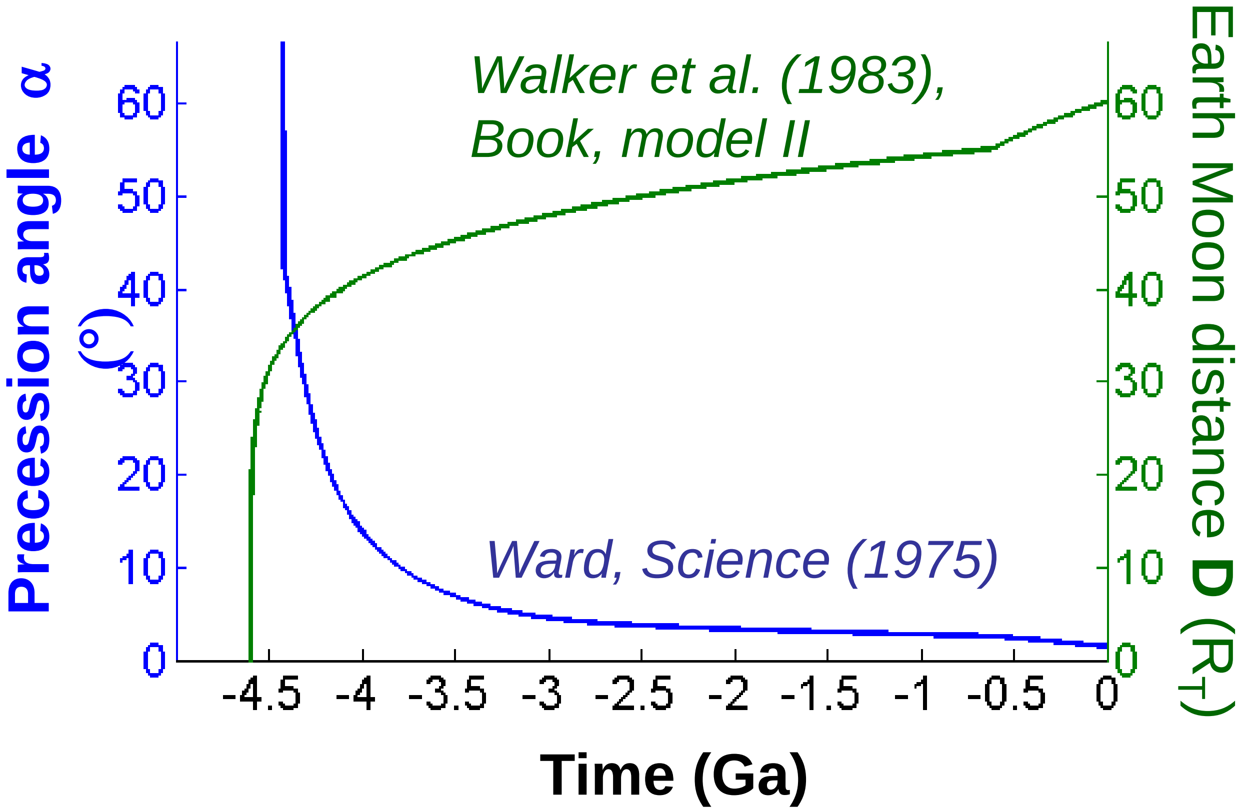
Lunar precession history

Precession
(angle α, rate P_o)



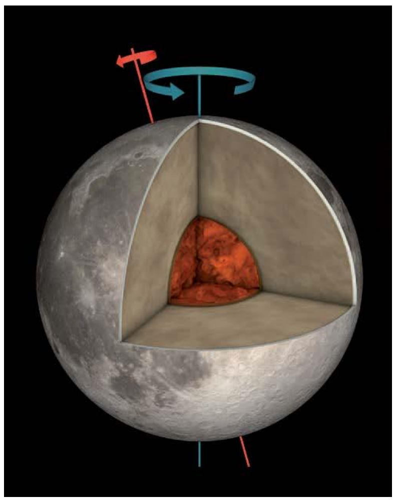


Dynamo model proposed by Dwyer et al. *Nature* 2011



Precession driven flows

Precession (angle α, rate P_o)



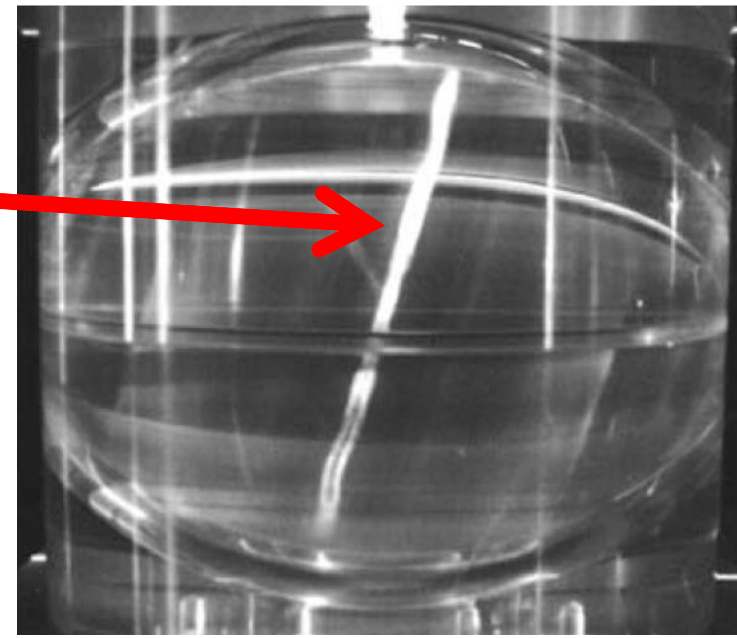
Precession forced flow

1) Inviscid bulk (Poincaré flow)

+

2) Viscous layers

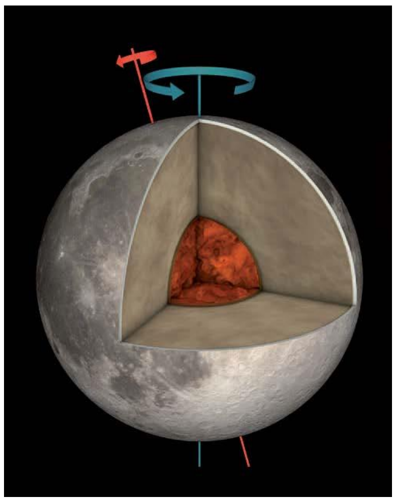
Tilted rotational flow



Noir (2003)

Precession driven flows

Precession
(angle α, rate P_o)



Precession forced flow

1) Inviscid bulk (Poincaré flow)
+
2) Viscous layers

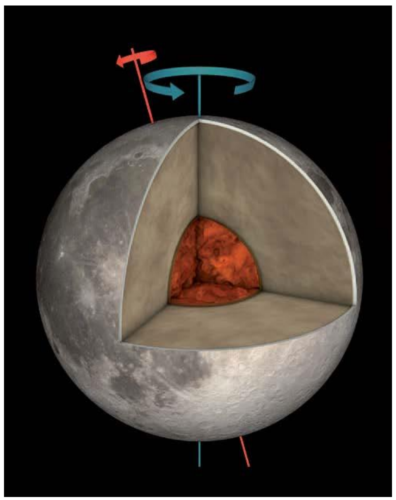
X

Dynamo magnetic field

For planetary regimes

Precession driven flows

Precession
(angle α, rate P_o)



Precession forced flow

1) Inviscid bulk (Poincaré flow)

2) Viscous layers

Instability due to **topography**

?

X

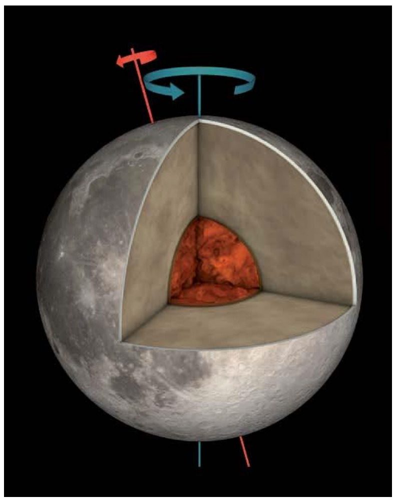
Dynamo magnetic field

?

Instability
- Of **Ekman** layer
- Of **conical** layer

Precession driven flows

Precession (angle α, rate P_o)



Precession forced flow

1) **Inviscid bulk (Poincaré flow)**

2) **Viscous layers**

Instability due to **topography** ?

Hard to simulate

Dynamo magnetic field

?

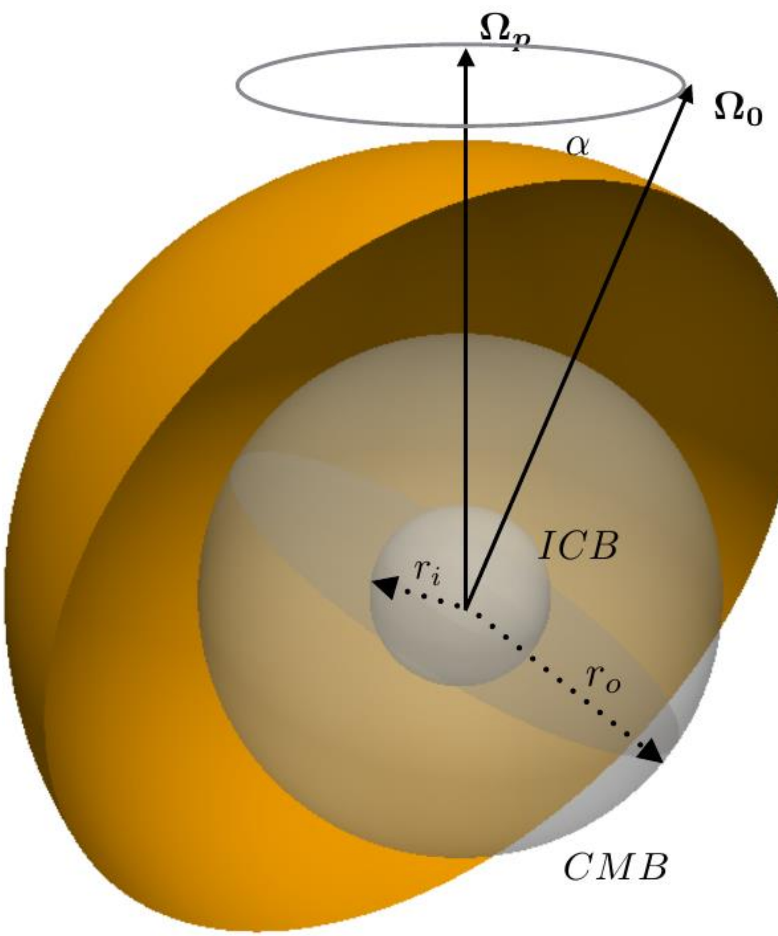
Instability

- Of **Ekman** layer
- Of **conical** layer

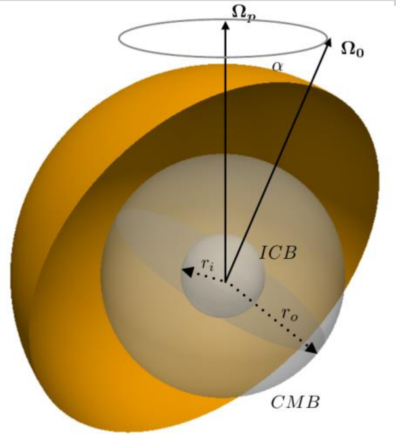
Isolated in spherical shells!

Precessing spherical shells

- **Viscous coupling only**
- **Scales:** r_o, $1/\Omega_0$, $\Omega_0\, r_o\, (\mu\rho)^{1/2}$



Precessing spherical shells



- **Viscous coupling only**
- **Scales:** r_o, $1/\Omega_0$, $\Omega_0\, r_o\, (\mu\rho)^{1/2}$
- **In the precessing frame:**

Induction $$\frac{\partial \vec{B}}{\partial t} = \frac{E}{Pm}\nabla^2 \vec{B} + \nabla \times \left(\vec{u}\times\vec{B}\right)$$

Navier-Stokes $$\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u} = -\nabla p + E\nabla^2\vec{u} + \left(\nabla\times\vec{B}\right)\times\vec{B} - 2P_o\,\vec{k}_p\times\vec{u}$$

Conservation $$\nabla\cdot\vec{u} = 0 \quad , \quad \nabla\cdot\vec{B} = 0$$

$$Pm = \sigma\mu\nu \qquad E = \frac{\nu}{\Omega R^2} \qquad P_o = \frac{\Omega_p}{\Omega_0} \qquad \eta = \frac{r_i}{r_o}$$

- **Solved with XSHELLS (open-source, spectral)** : the world **fastest spherical** dynamo **code**

*Schaeffer (2013, 2017), see the **benchmark** of **Matsui et al. (2016)***

Simulation parameters

- **Previously: no** inner **core** (η=0) ~ **20** saturated **simulations**
  Tilgner (2005, 2007), Lin et al. (2015)

- **This work : 10^3 simulations**
  Systematic study

	Lunar core	**Simulations**
flattening	$2.5.10^{-5}$	0
E	3.10^{-12}	10^{-5} – 10^{-3}
P	4.10^{-3}	3.10^{-4} – 20
α	178°	30 - 150°
η	0 – 0.7	0 – 0.7
Pm	10^{-6}–10^{-5}	0.3 – 3

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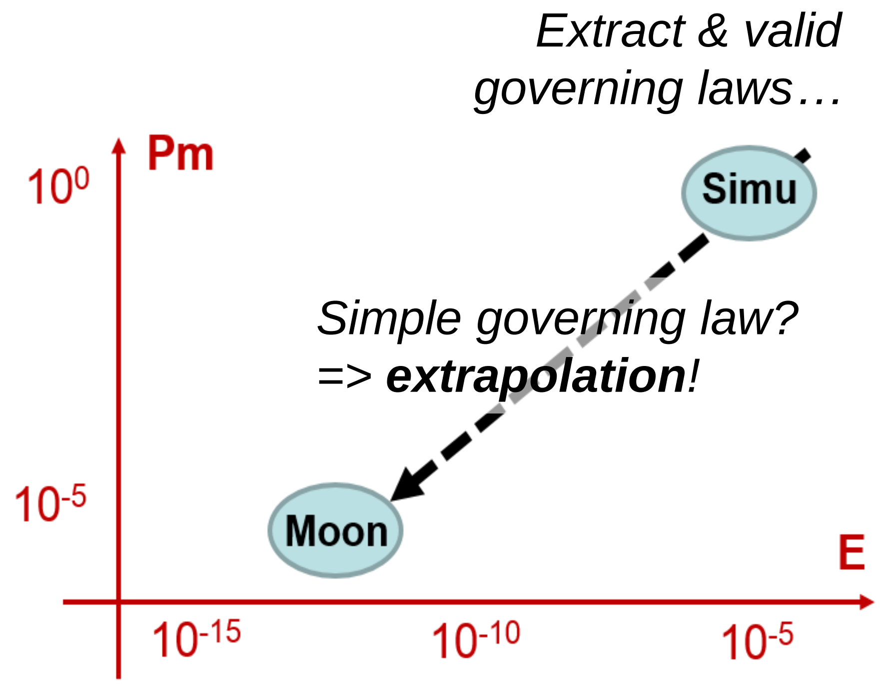
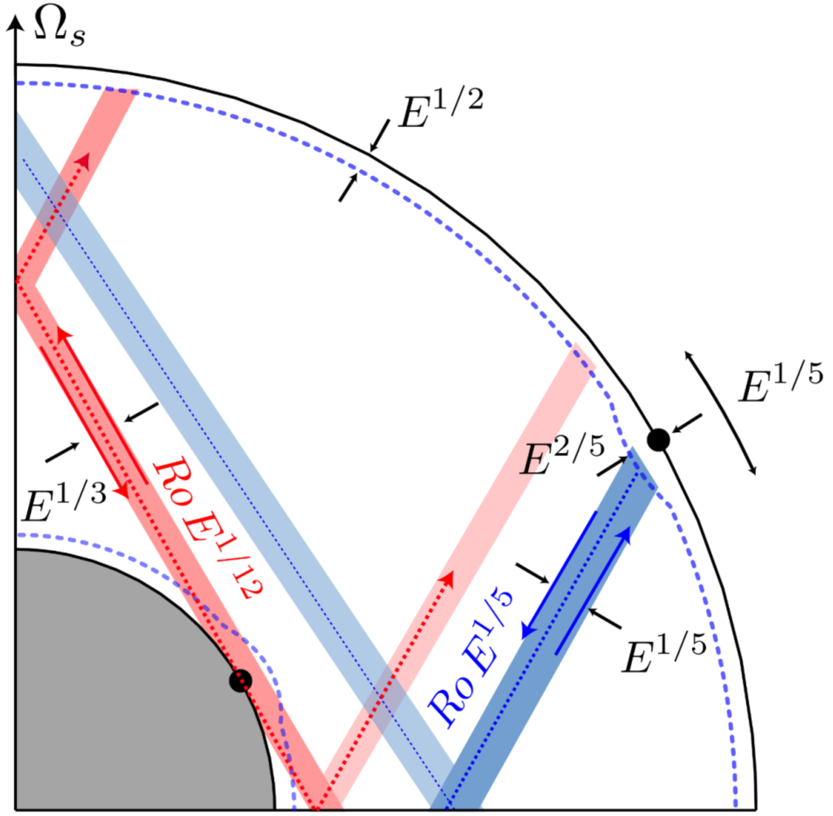
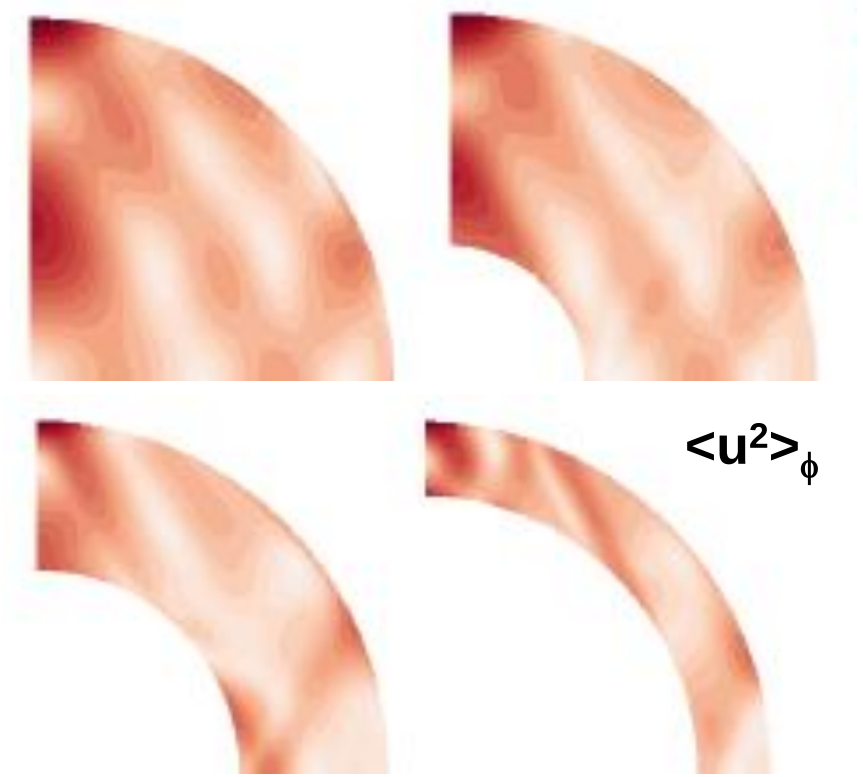


Viscous boundary & conical layers



Noir et al. (2001) ; Le Dizès & Le Bars (2017)

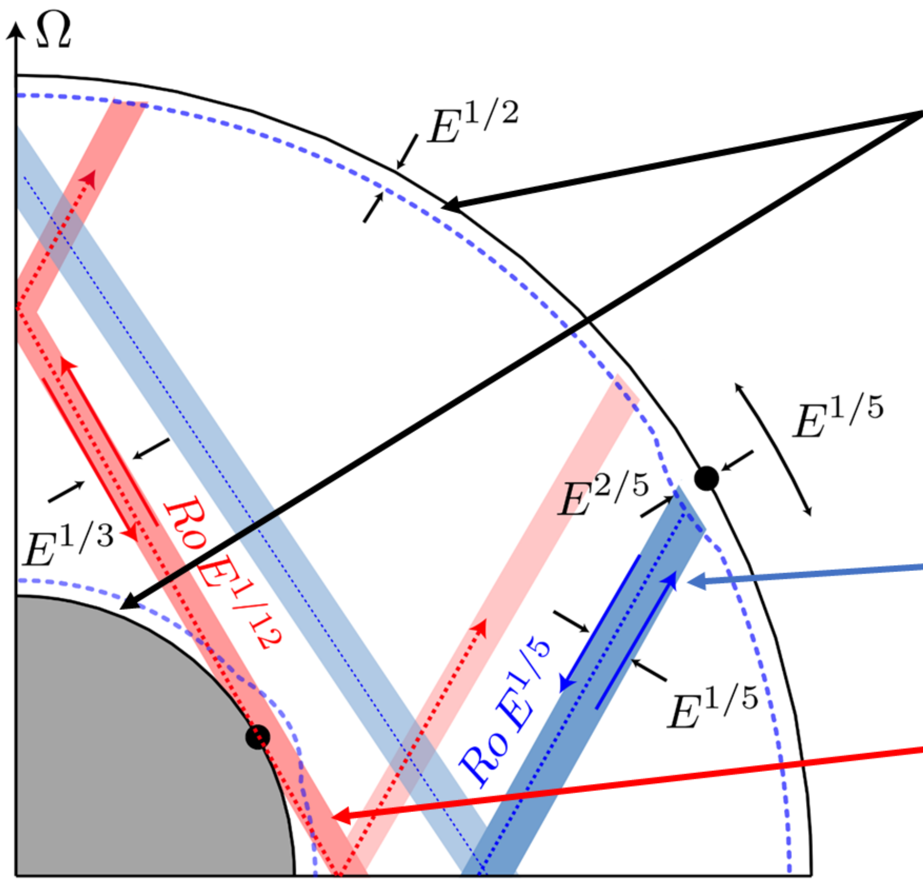
Our simulations (XSHELLS)



=> Instabilities?

Cebron et al., GJI, in press

Viscous boundary & conical layers



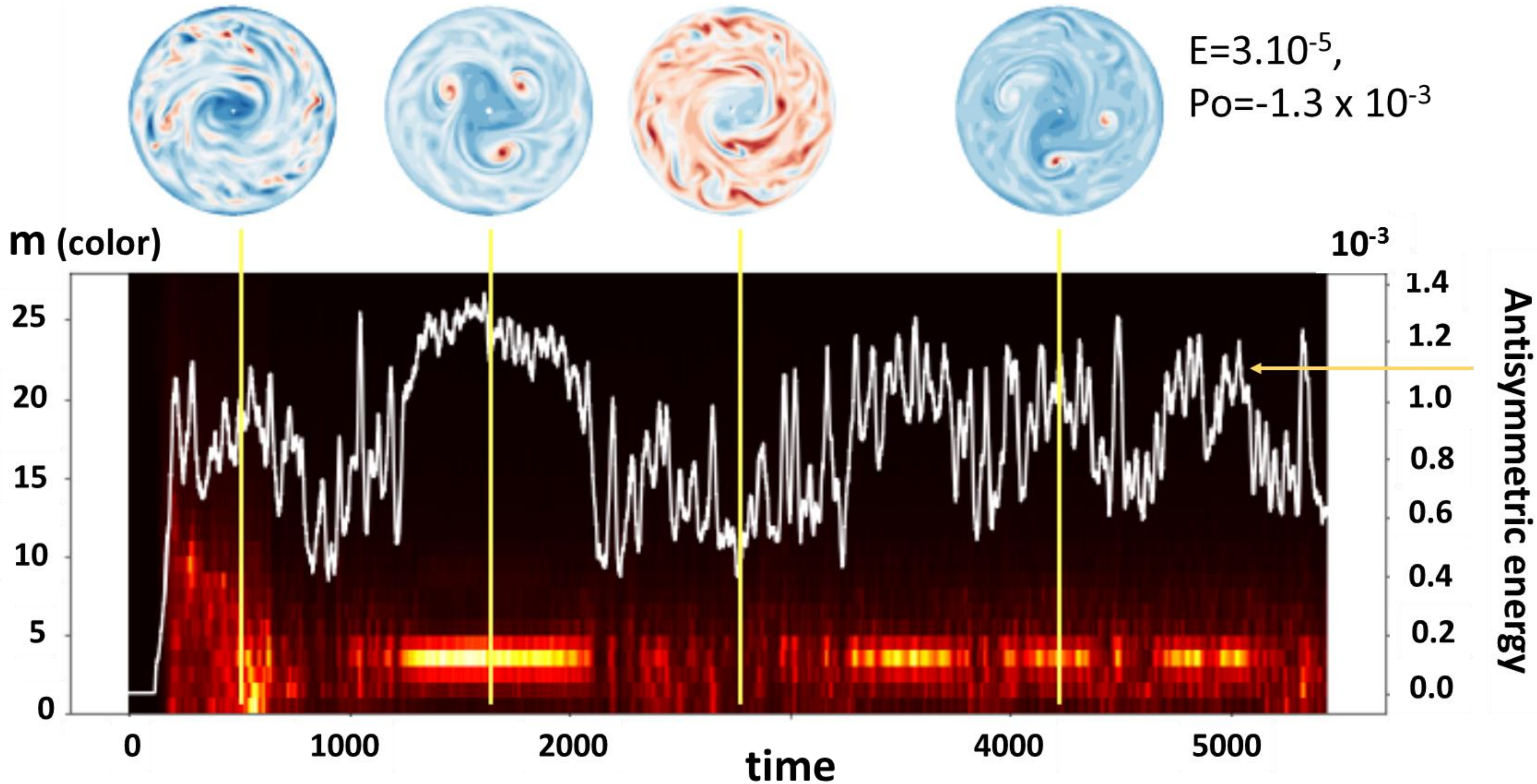
Noir et al. (2001) ; Le Dizès & Le Bars (2017)

- **Viscous Ekman** layer **instabilities**
  (Lorenzani, Tilgner, 2001, 2003)

- **Parametric instabilities**: $m_1 - m_2 = 1$
  - due to **CMB** conical layer *(Lin et al. 2015)*
  - due to **ICB** conical layer **?**

Cebron et al., GJI, in press

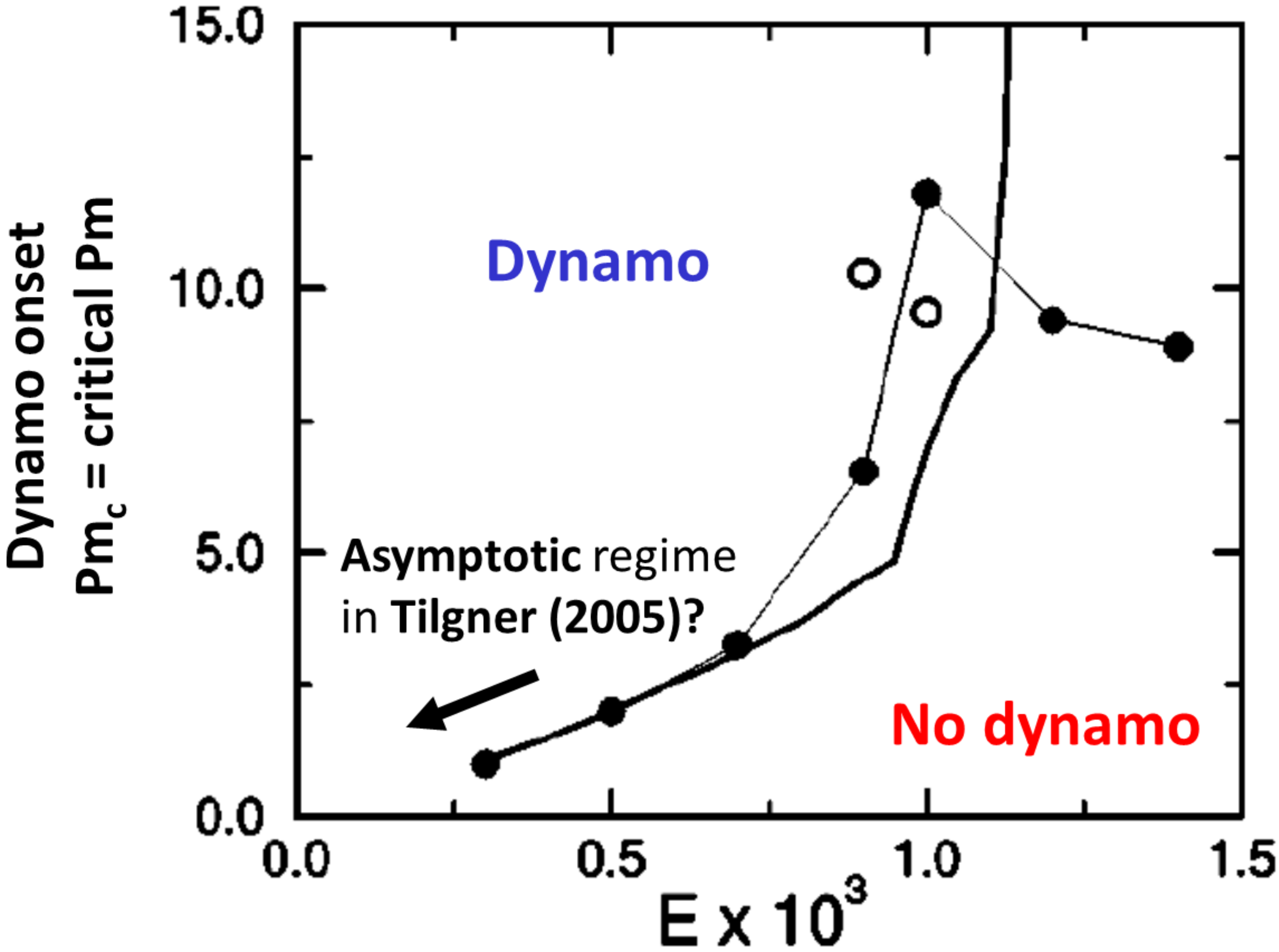
Parametric instability: large-scale vortices



Similar to Lin et al. (2015)

Cebron et al., GJI, in press

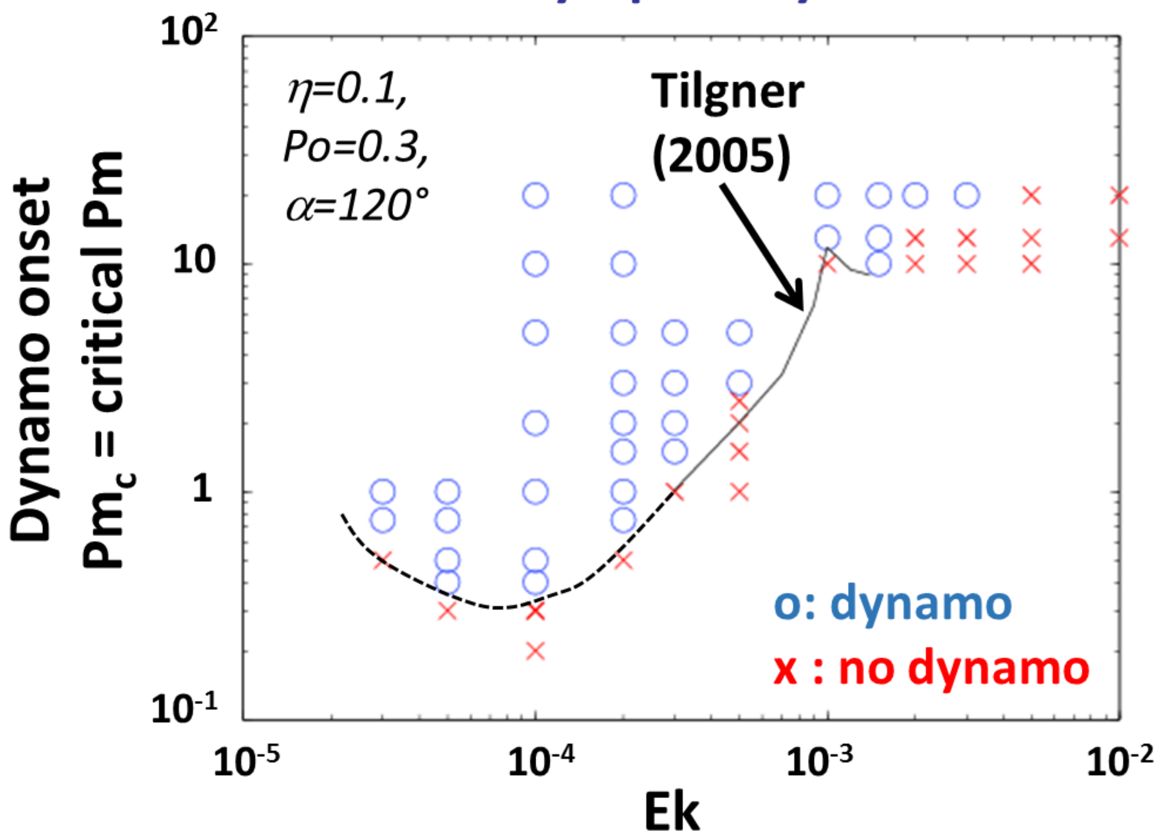
Precession driven dynamos?



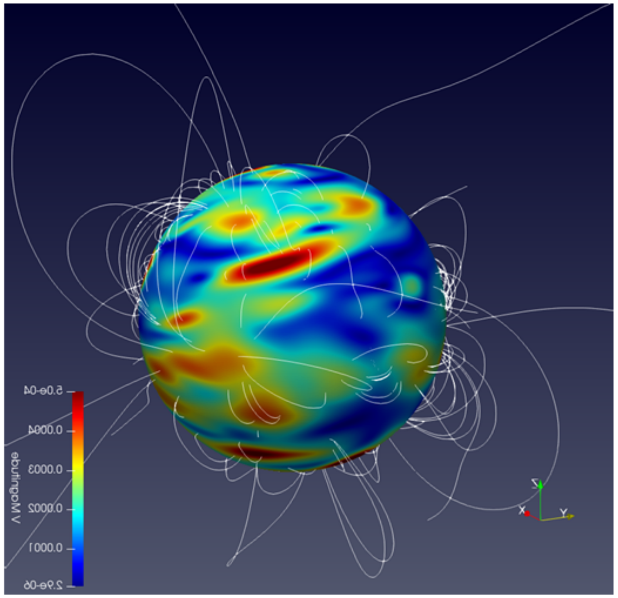
η=0.1
Po=0.3
α=120°

Dynamo capability?

Not asymptotic yet…



$E=3.10^{-4}$, Pm=2



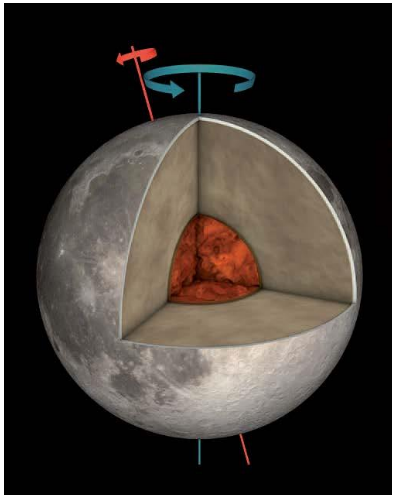
- **Small-scale** field
- **Multipolar** field
- Field **near boundaries**

=> No hope?

Cebron et al., GJI, in press

Precession driven flows

Precession (angle α, rate P_o)



Precession forced flow

1) Inviscid bulk (Poincaré flow)

2) Viscous layers

Instability due to **topography**

?

Hard to simulate

X

Dynamo magnetic field

?

Instability

- Of **Ekman** layer
- Of **conical** layer

Isolated in spherical shells!

Precessing spheroids?

- **In the precessing frame:** $\mathbf{u} \rightarrow \mathbf{u} + \mathbf{U_b}$

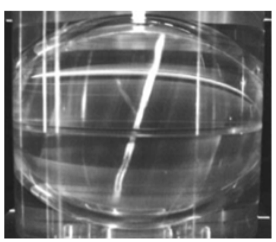
Induction
$$\frac{\partial \vec{B}}{\partial t} = \frac{E}{Pm}\nabla^2 \vec{B} + \nabla \times \left[\left(\vec{u} + \vec{U}_b \right) \times \vec{B} \right]$$

Navier-Stokes
$$\frac{\partial \vec{u}}{\partial t} + \vec{U}_b \cdot \nabla \vec{u} + \vec{u} \cdot \nabla \vec{U}_b + \vec{u} \cdot \nabla \vec{u} = -\nabla p + E\nabla^2 \vec{u} + \left(\nabla \times \vec{B} \right) \times \vec{B} - 2P_o \vec{k}_p \times \vec{u}$$

Conservation
$$\nabla \cdot \vec{u} = 0 \quad , \quad \nabla \cdot \vec{B} = 0$$

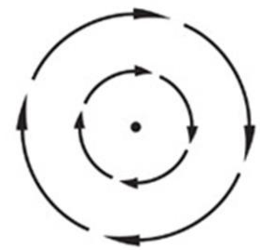
- **u : perturbated** flow in a **stress-free sphere**

- **$\mathbf{U_b}$: exact Poincaré flow** in a **stress-free spheroid**



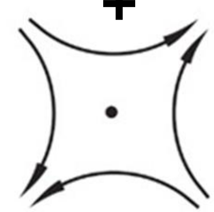
Small flattening → **sphere**

$\mathbf{U_b}$=



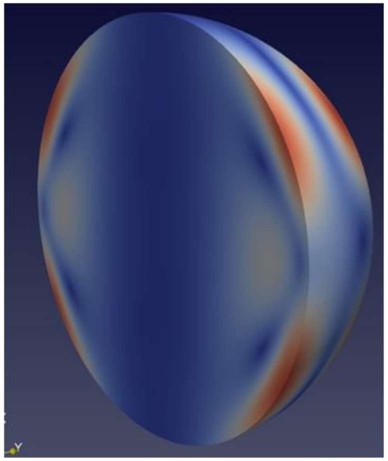
Tilted rotation

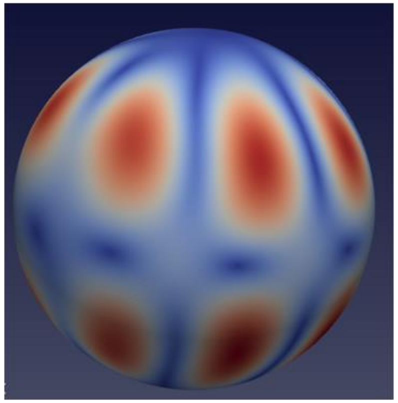
+

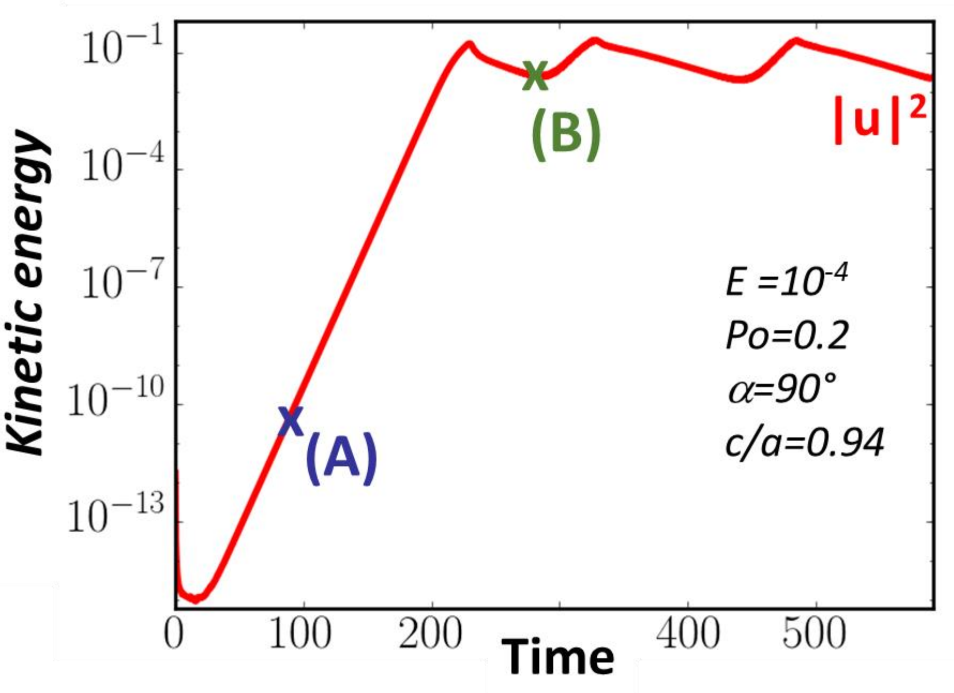


Elongational flow

Topography driven precession instability

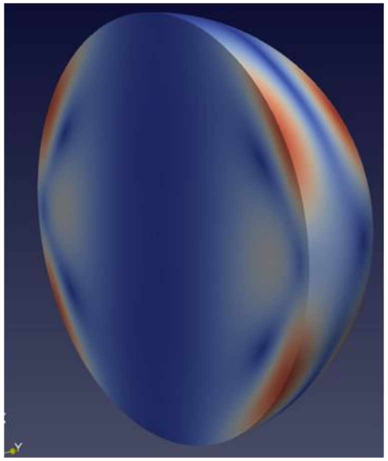




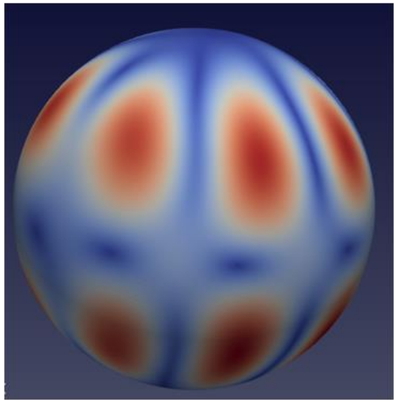


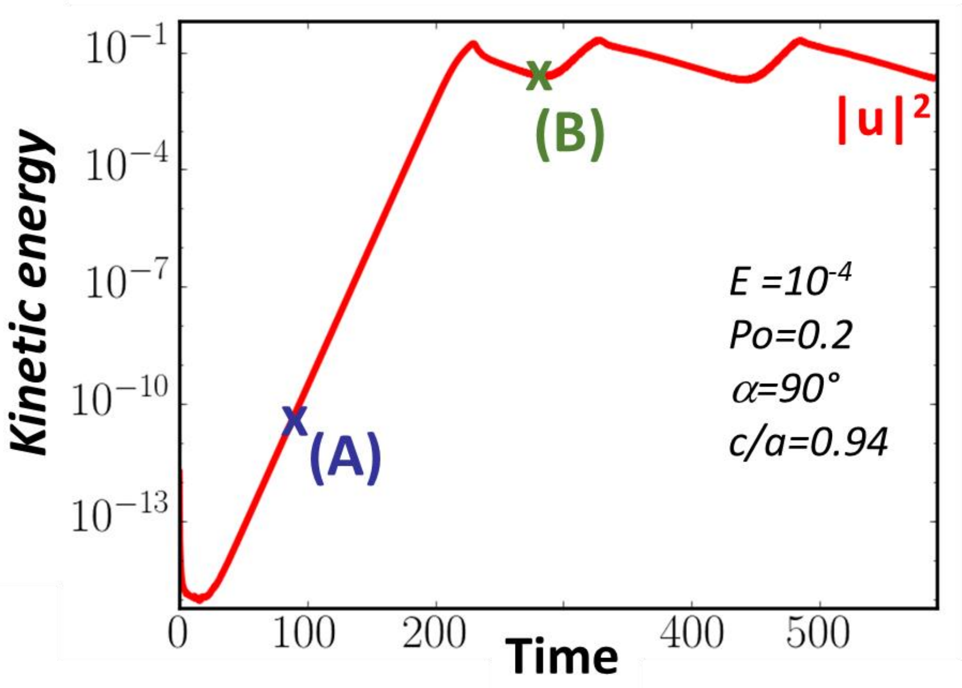
- (A) Growth m=8

Topography driven precession instability

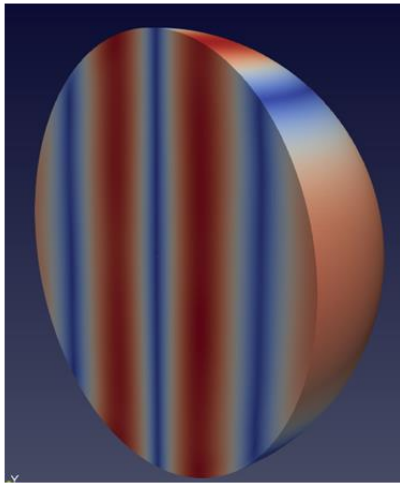


|u| (A)

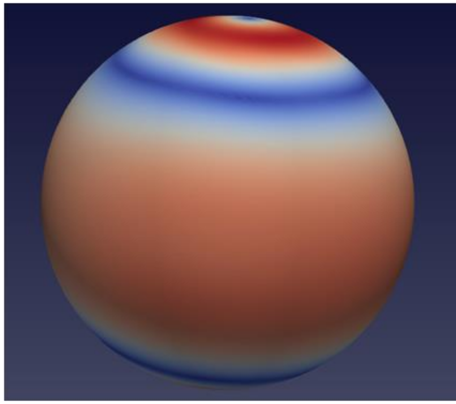




|u|



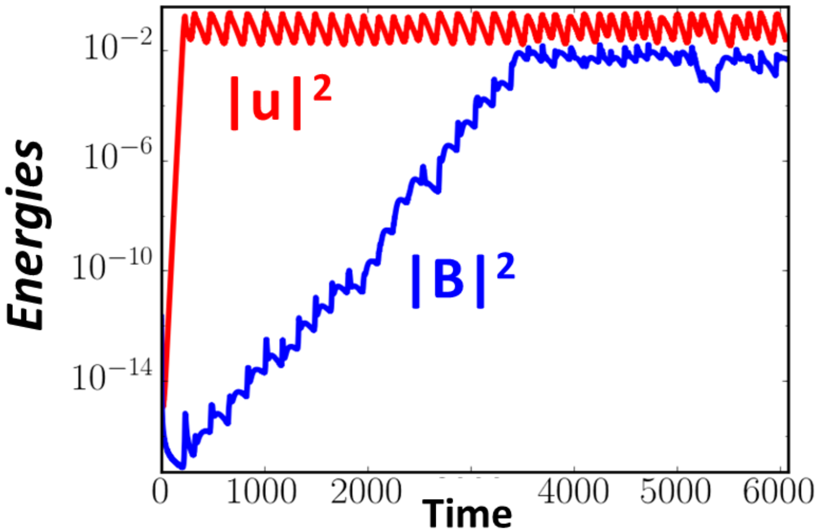
(B)



|u|

- (A) Growth m=8
- (B) Quasi-geostrophic flow
  - Similar to LSV
  - Inverse cascade *(Le Reun et al. 2017)*

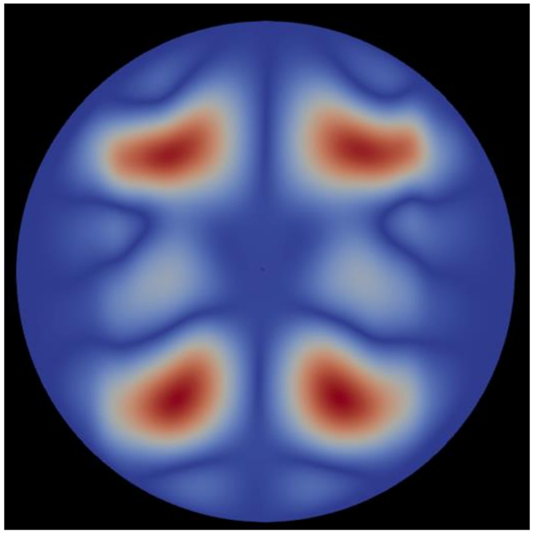
Topography driven precession dynamos

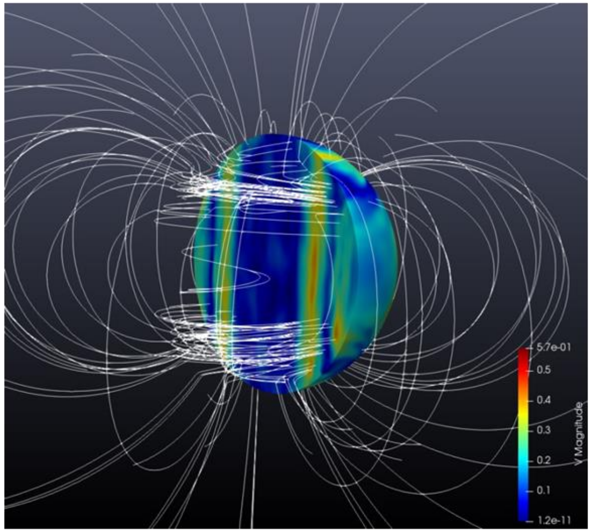


- **Large scale** magnetic field
- **Bulk** magnetic field

- **Quasi-geostrophic** flows
- Large **dipolar component**

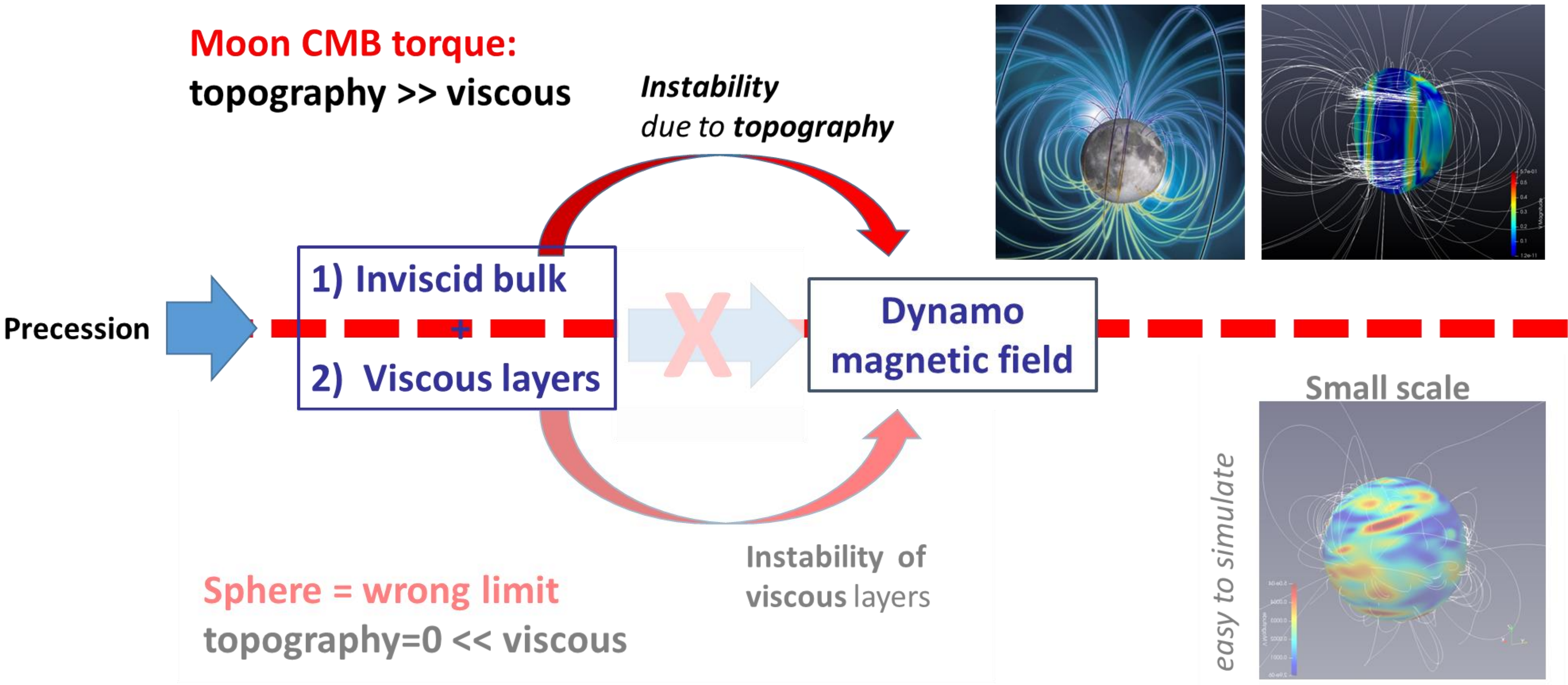
|B| $E = 10^{-4}$; $Pm = 0.5$; $Po = 0.2$; $c/a = 0.94$ |u|





=> **New family of precession dynamos**

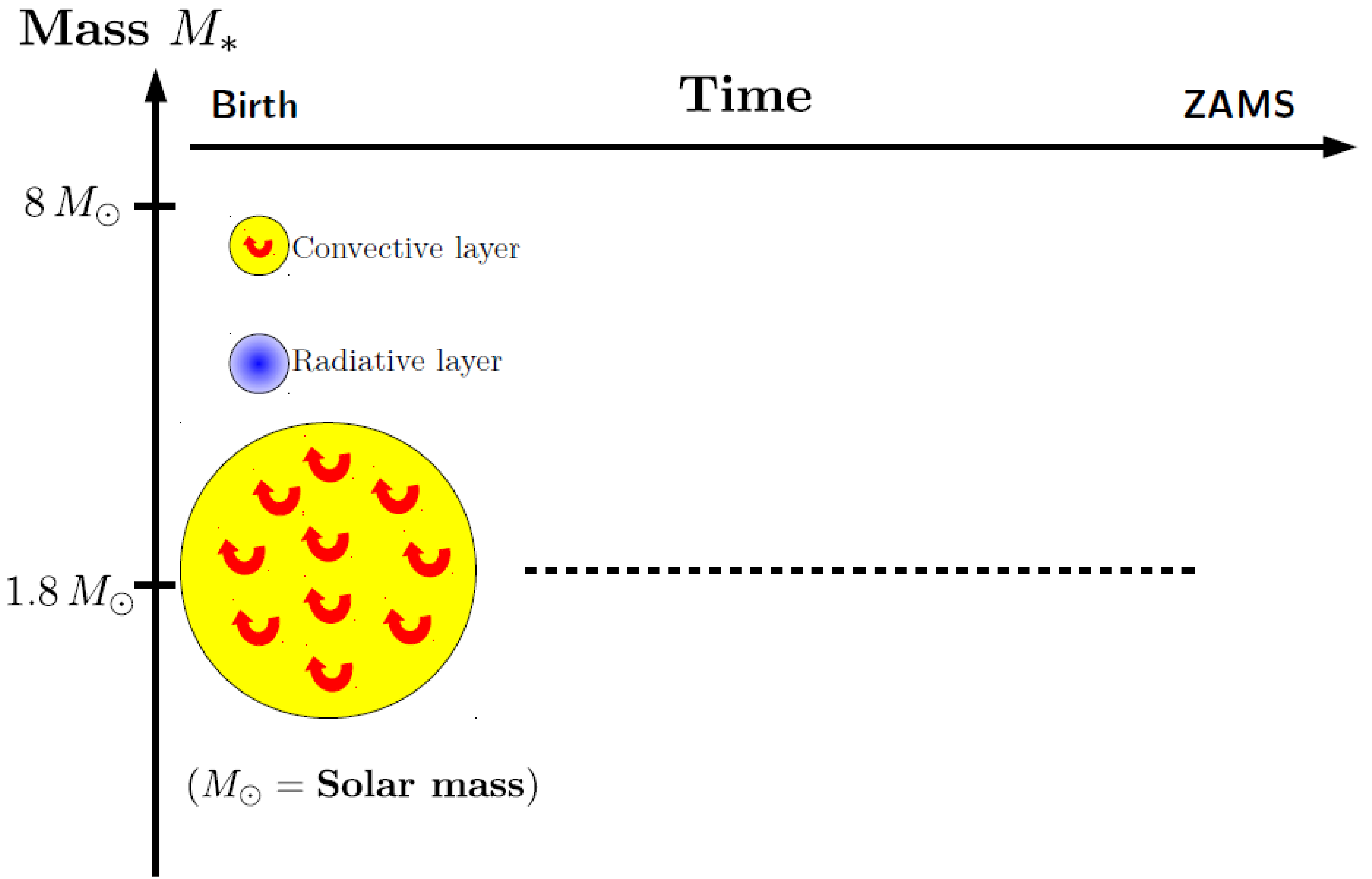
To summarize



Outline

1. Questioning the thermo-solutal dynamo paradigm for the Earth
2. Questioning the thermo-solutal dynamo paradigm for the Moon
3. Questioning the thermo-solutal dynamo paradigm beyond the Moon

Stellar context



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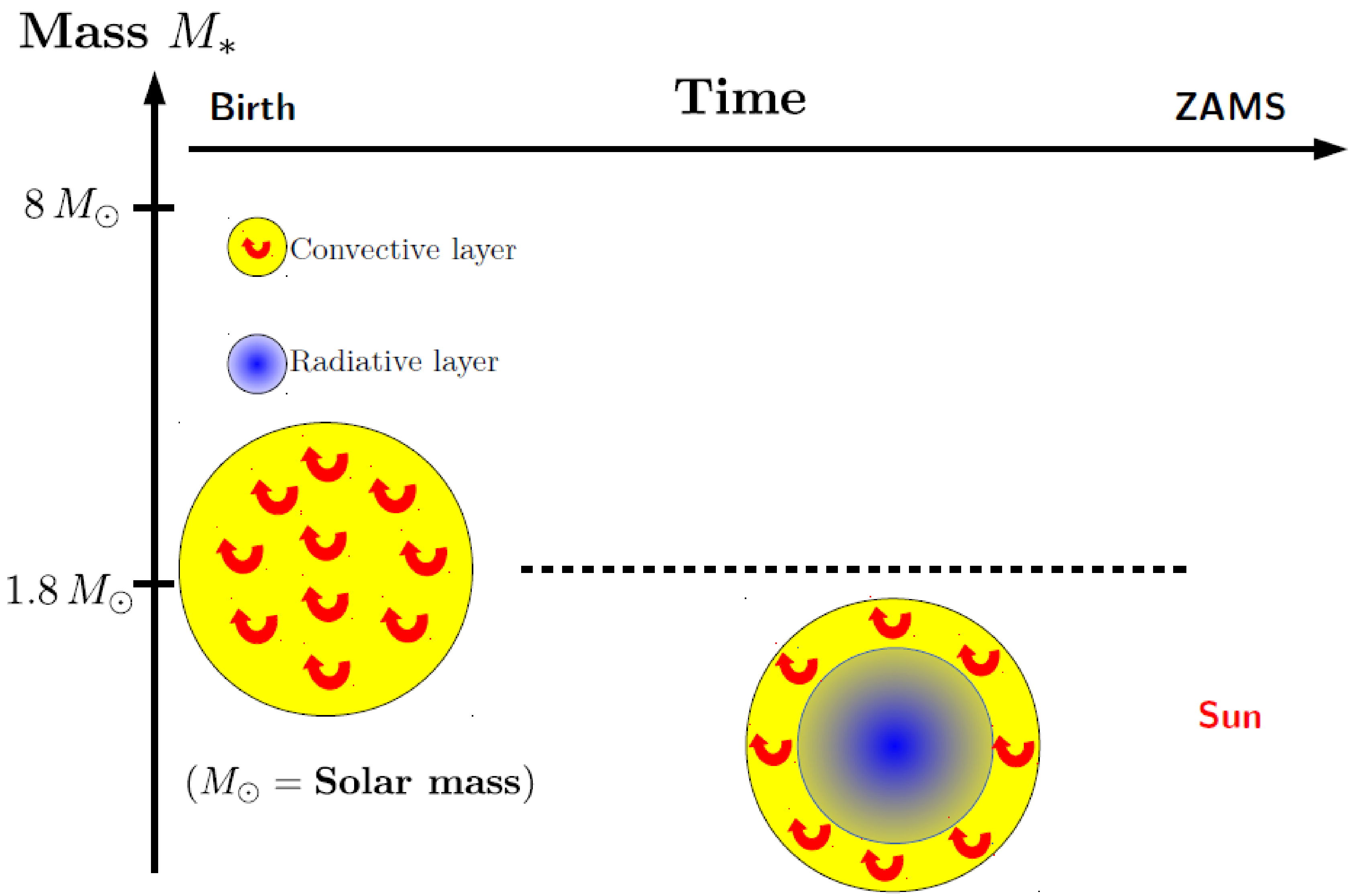
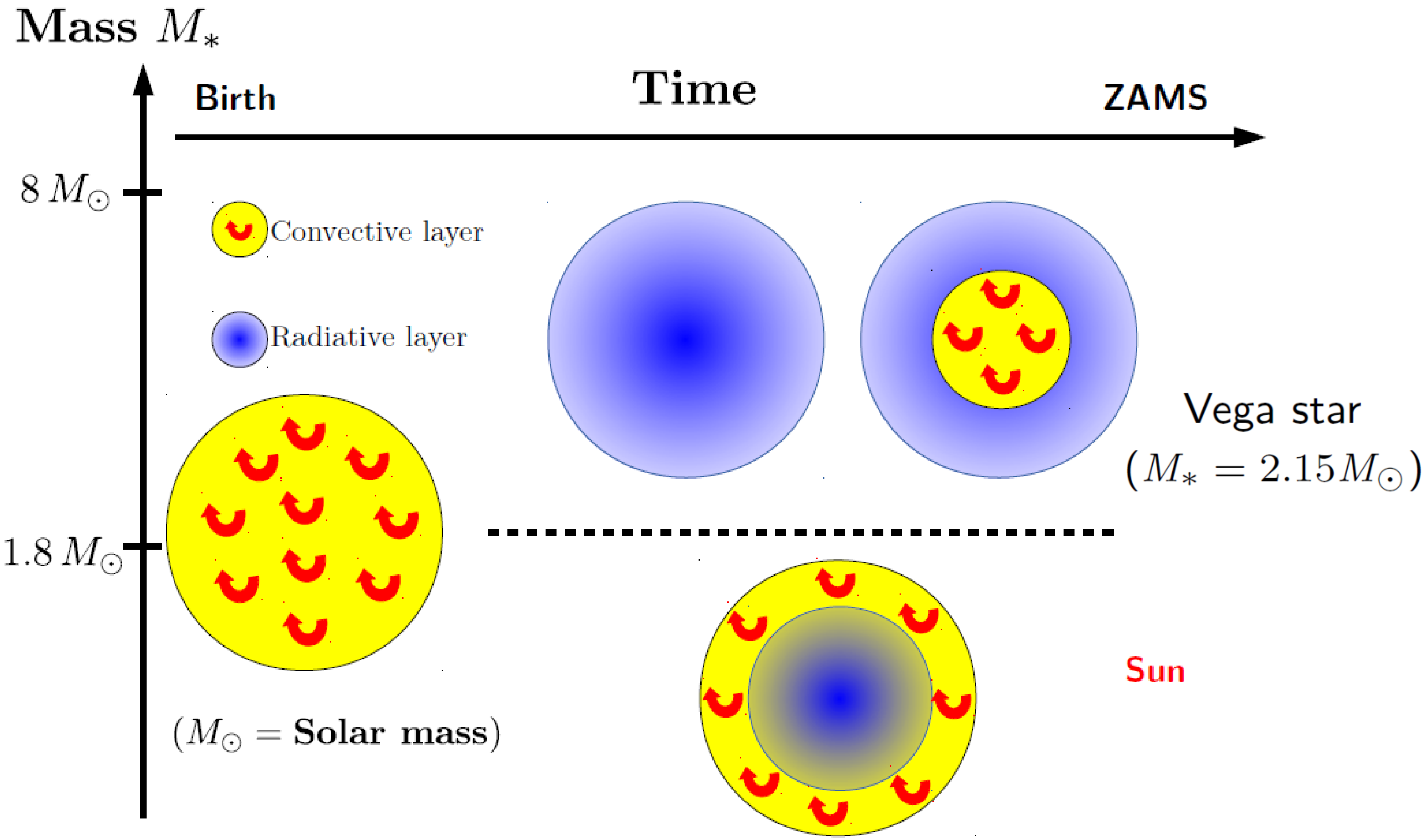



Mass M_*
Birth
Time
ZAMS
$8\,M_\odot$
$1.8\,M_\odot$
Convective layer
Radiative layer
Vega star
$(M_* = 2.15 M_\odot)$
Sun
$(M_\odot$ = Solar mass)

Magnetism of radiative stars (intermediate mass)

Lignières et al. (2008)

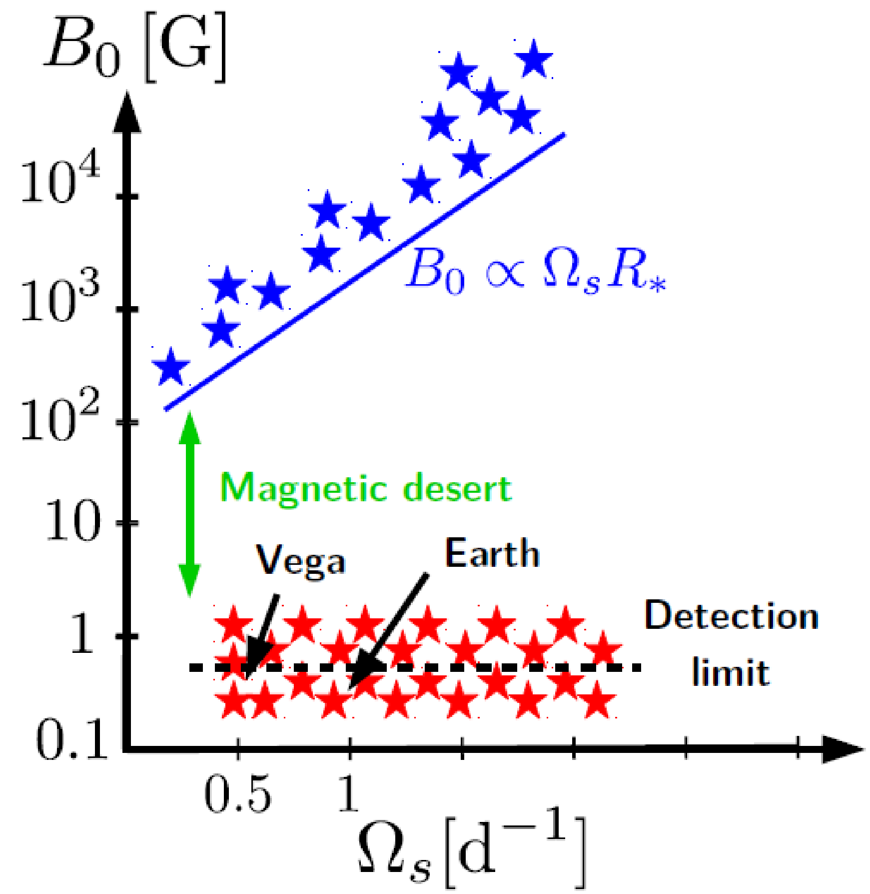
10% with surface field B_0

Strong B_0 (e.g. Ap stars)

- Typical **strength**: 10^2 - 10^4 G
- Often **static** fields
- B_0 with a **fossil** origin

Ultra-weak B_0 (e.g. Vega)

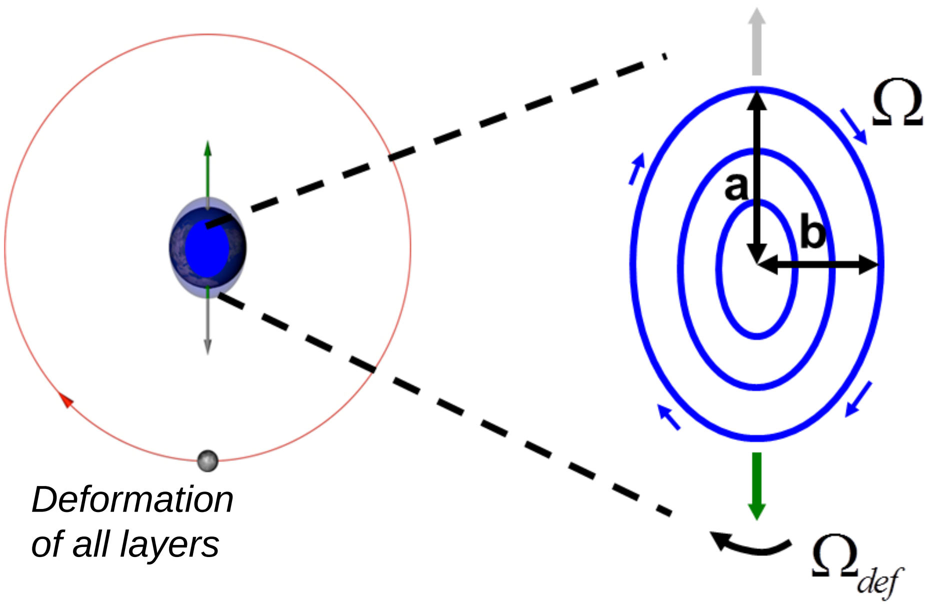
- Typical **strength**: 0.1 - 1 G
- Often **dynamical** fields
- B_0 due to **dynamos**?



Tidal dynamo in Vega?

Tidal instability

Tides → Elliptical streamlines



Deformation of all layers

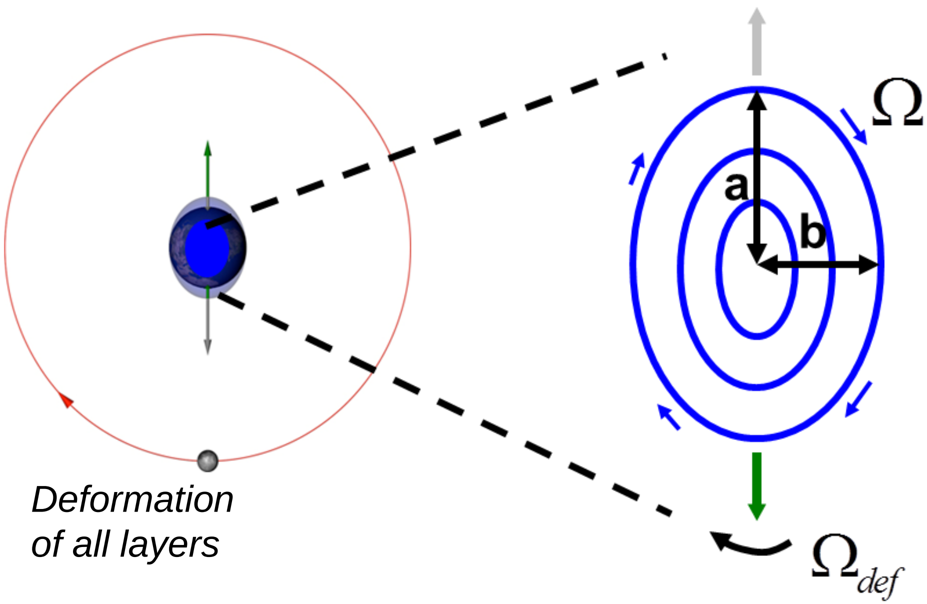
Tidal instability

Tides → **Elliptical streamlines** → **Turbulent flows**

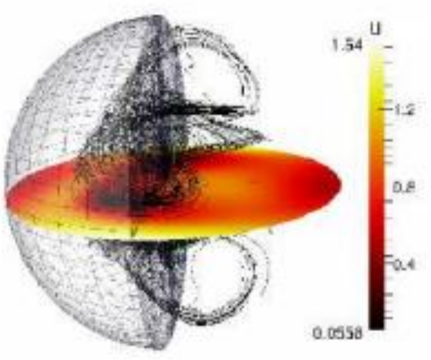
Elliptical or tidal instability!

↓ **?**

Magnetic field



Deformation of all layers



Cébron & Hollerbach (2014)

- **OK** for **neutral** or **convective** fluids
- But **tidally driven dynamos in stably stratified fluids?**

Stable stratification

- **(Dimensional) Brunt-Väisälä frequency N_0**

$$N_0^2 = -\alpha \nabla T \cdot \boldsymbol{g}$$

- $N_0^2 > 0 \Longrightarrow$ **stably stratified**,
- **Internal** gravity waves.

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$$N_0^2 = -\alpha \nabla T \cdot \boldsymbol{g}$$

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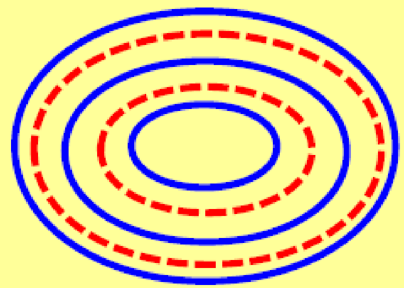
Barotropic

T



$$\nabla T \times \nabla \Phi = \mathbf{0}$$

$\Phi \ (\boldsymbol{g} = -\nabla \Phi)$

- No **baroclinic** instability,
- Growth rate **reduced** at the poles & equator.

- **Growth rate elsewhere? Dynamo?**

- **Hypothesis**: - **Boussinesq** fluid
  - **Barotropic** & **linear** gravity

Mathematical formulation

- Basic state: $\boldsymbol{U}_0, T_0, \boldsymbol{g}$,
- Scales: R_*, Ω_s^{-1}, $\Omega_s^2 R_*/(\alpha g_o)$ and $R_* \Omega_s \sqrt{\mu_0 \rho_*}$,
- **Dimensionless** numbers

$$Ek = \frac{\nu}{\Omega_s R_*^2} \leq 10^{-16}, \quad 10^{-6} \leq Pr = \frac{\nu}{\kappa} \leq 10^{-4}, \quad 10^{-8} \leq Pm = \frac{\nu}{\eta_m} \leq 10^{-4},$$

- Ellipsoidal container of equatorial ellipticity β_0.

Boussinesq equations of the perturbations $(\boldsymbol{u}, \theta, \boldsymbol{B})$ in the **inertial** frame

$$\frac{\partial \boldsymbol{u}}{\partial t} = -(\boldsymbol{u} \cdot \boldsymbol{\nabla})\, \boldsymbol{U}_0 - (\boldsymbol{U}_0 \cdot \boldsymbol{\nabla})\, \boldsymbol{u} - (\boldsymbol{u} \cdot \boldsymbol{\nabla})\, \boldsymbol{u} - \nabla p + Ek\, \nabla^2 \boldsymbol{u} - \theta\, \boldsymbol{g} + (\boldsymbol{\nabla} \times \boldsymbol{B}) \times \boldsymbol{B},$$

$$\frac{\partial \theta}{\partial t} = -(\boldsymbol{U}_0 \cdot \nabla)\, \theta - (\boldsymbol{u} \cdot \nabla)\, T_0 - (\boldsymbol{u} \cdot \nabla)\, \theta + \frac{Ek}{Pr} \nabla^2 \theta,$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times (\boldsymbol{U}_0 \times \boldsymbol{B}) + \boldsymbol{\nabla} \times (\boldsymbol{u} \times \boldsymbol{B}) + \frac{Ek}{Pm} \nabla^2 \boldsymbol{B},$$

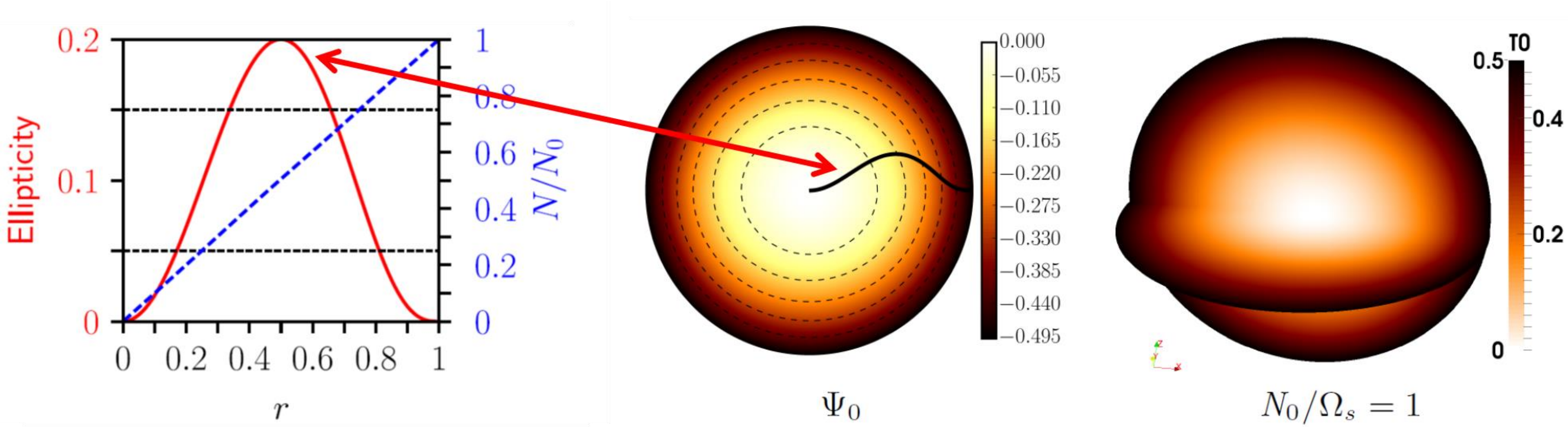
$$\boldsymbol{\nabla} \cdot \boldsymbol{u} = \boldsymbol{\nabla} \cdot \boldsymbol{B} = 0.$$

Radiative stars: idealized model (Vidal et al. MNRAS, 2018)

- Fixed $Ek = 10^{-4}$, $Pr = 1$ and $\Omega_0 = 0$,
- **Control** parameters

$$N_0/\Omega_s \text{ and max. tidal } \textbf{ellipticity } \epsilon \ll 1,$$

- **Basic** state: $\boldsymbol{U_0}(\Psi_0)$, $T_0(\Psi_0)$, $\boldsymbol{g}(\Psi_0)$,
- Barotropic state ($\boldsymbol{g} \times \nabla T_0 = \boldsymbol{0}$),
- BC: **Stress-free**, **fixed** temperature and electrically **insulating**.



Hydrodynamic instability (Vidal et al. MNRAS, 2018)

- $Ek = 10^{-4}, Pr = 1, \Omega_0 = 0,$
- **Onset** at $\epsilon_c = 0.054 \ (N_0/\Omega_s = 0)$

Hydrodynamic instability (Vidal et al. MNRAS, 2018)

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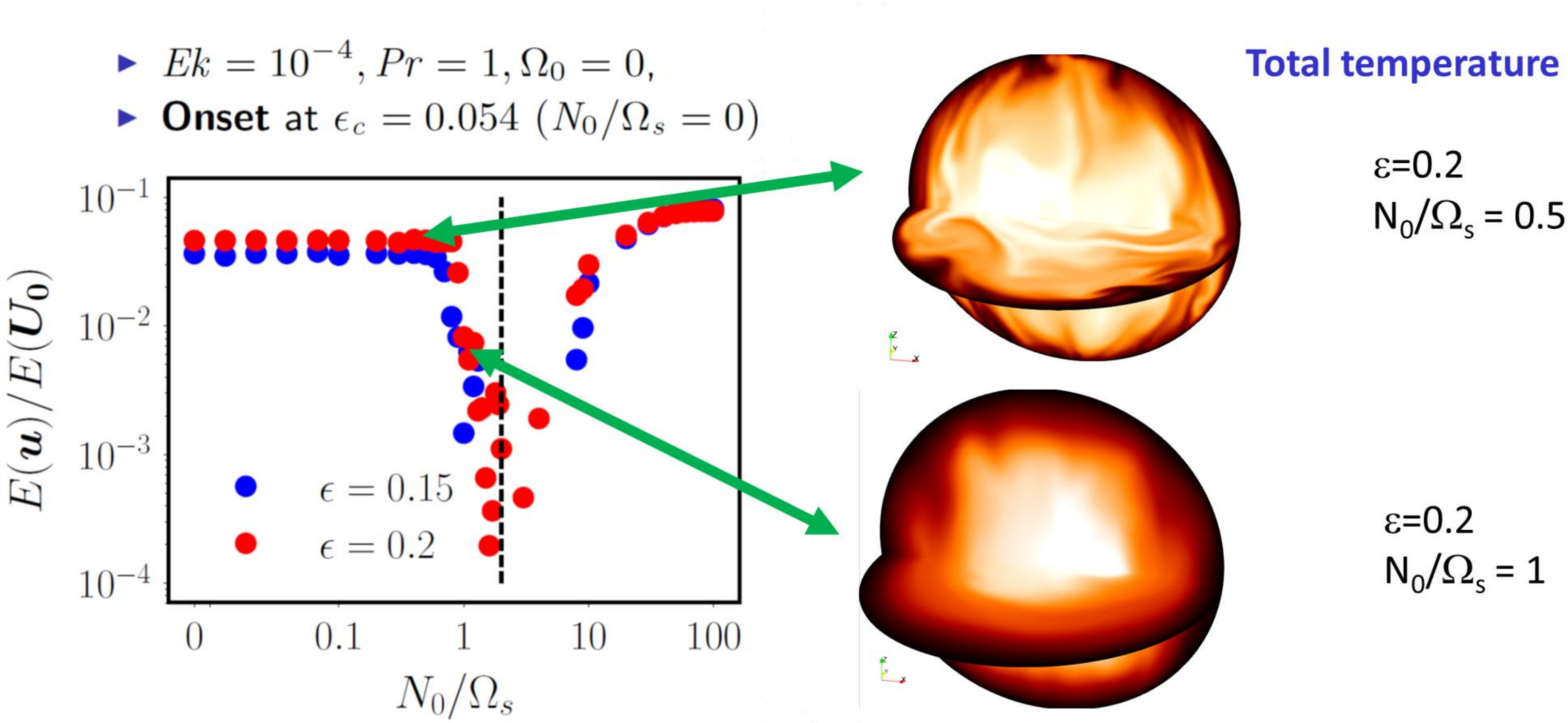
- **Onset** at $\epsilon_c = 0.054$ $(N_0/\Omega_s = 0)$



MHD simulations (Vidal et al. MNRAS, 2018)

- Basic flow $\boldsymbol{U}_0$ **not dynamo capable** (for **magnetic Prandtl** numbers $Pm \leq 5$),
- Integration over one **magnetic diffusive time**.

MHD simulations (Vidal et al. MNRAS, 2018)

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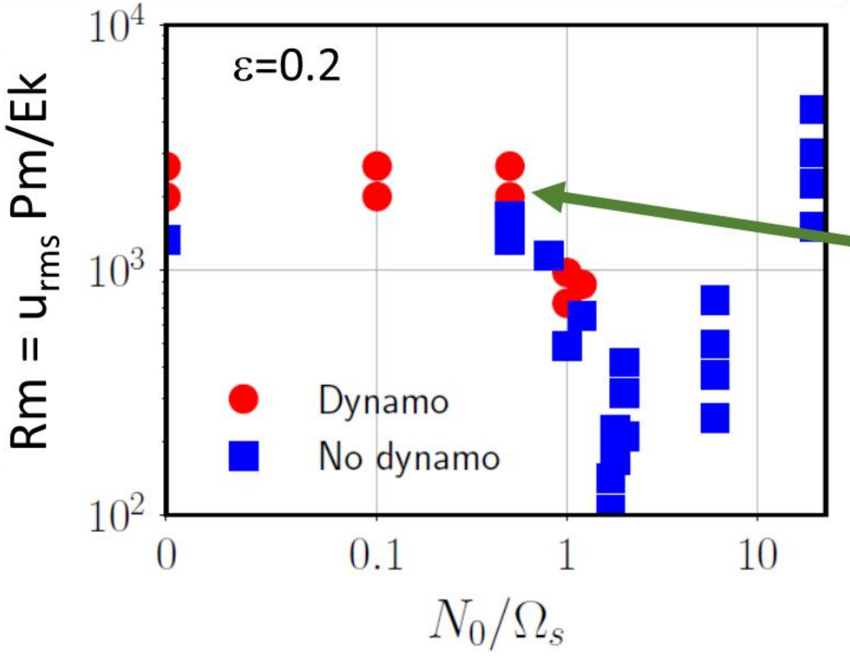
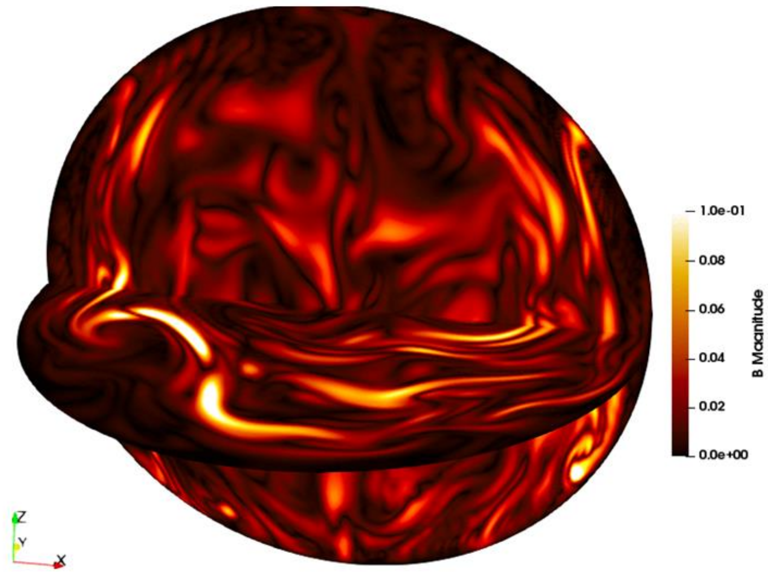
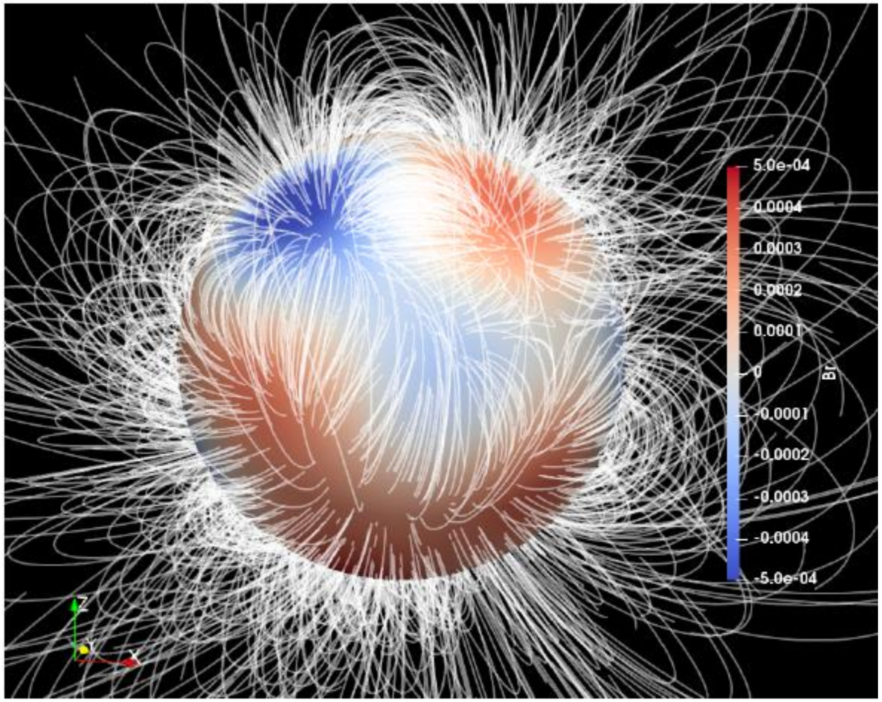




Dynamo for Rm>2000 & Pm>1

Saturated dynamo

Extrapolation (Vidal et al. MNRAS, 2018)

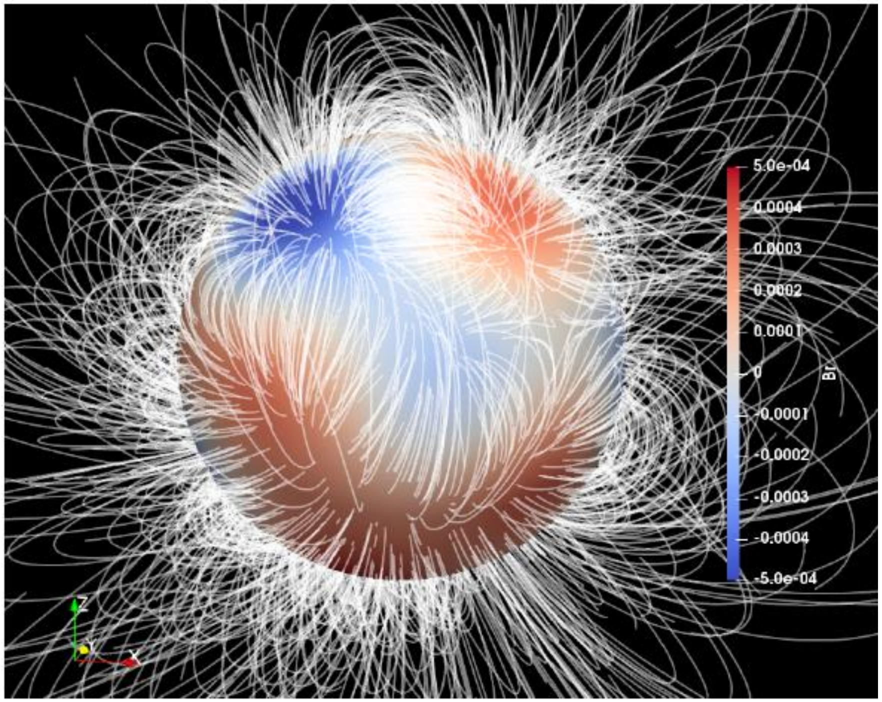


Large-scale surface field!

- Similar to convective scalings,
- Typical surface field **strength**

$$B_0 = \delta \frac{3}{2} \sqrt{\frac{3\mu_0}{4\pi}} \frac{R_*^{5/2}}{M_*^{1/2}} \Omega_s \frac{m}{D^3} \left| 1 - \Omega_0 \right| ,$$

$$10^{-3} \leq \delta \leq 10^{-2}$$



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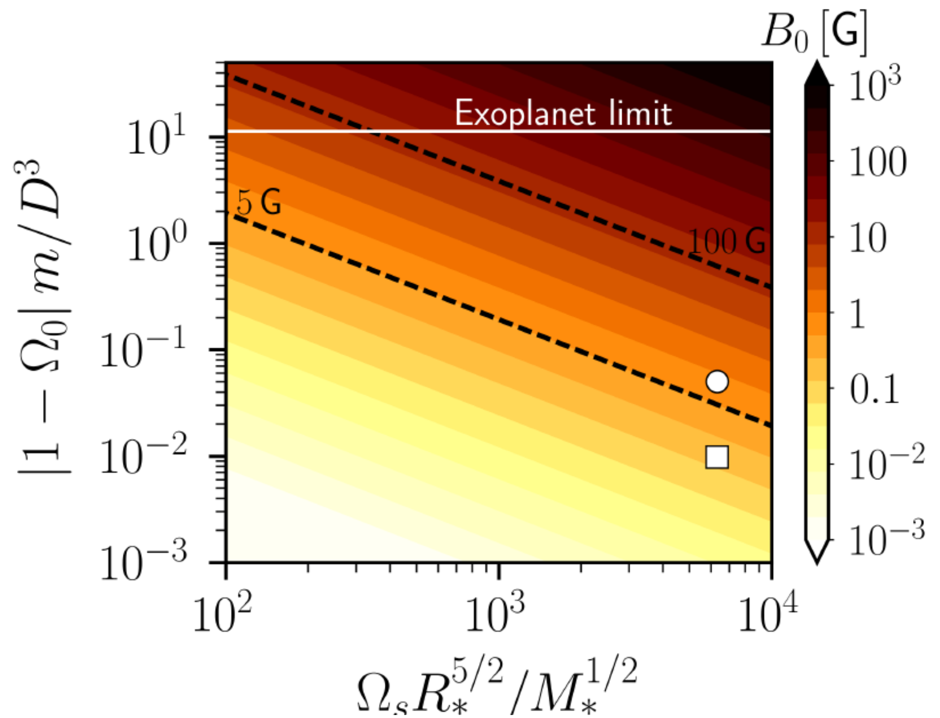
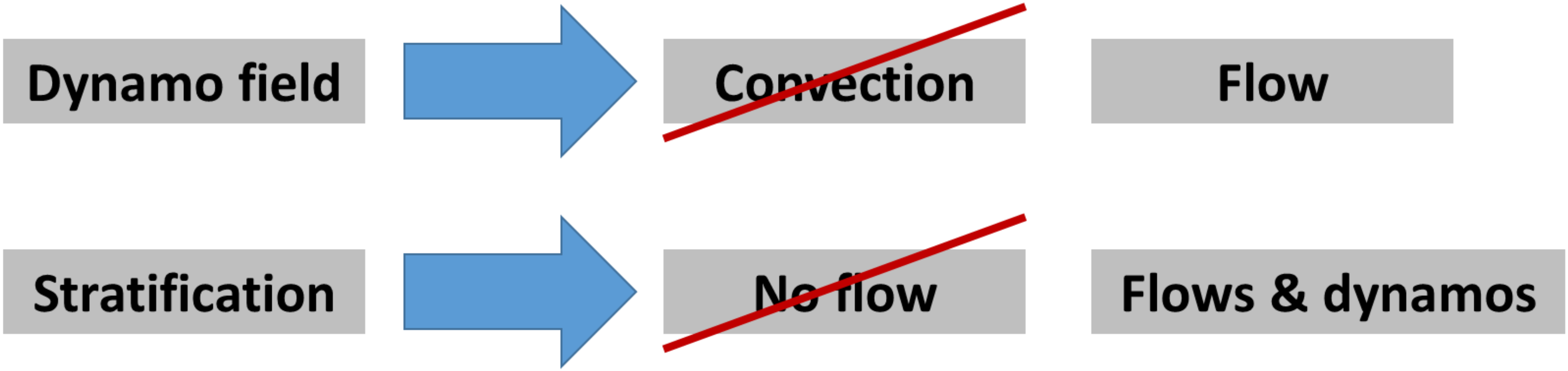


$$B_0 = \delta \frac{3}{2} \sqrt{\frac{3\mu_0}{4\pi}}\, \frac{R_*^{5/2}}{M_*^{1/2}} \Omega_s \frac{m}{D^3}\, |1-\Omega_0|$$

Vega : Measure: 0.6 ± 0.3 G
Theory: 1 - 1.5 G

Conclusions



Reading

- Tilgner 2015. Rotational Dynamics of the Core, Treatise on Geophysics, 2nd Edition
- Zhang 2017. Theory and Modelling of Rotating Fluids: Convection, Inertial Waves and Precession, Cambridge