# Le Noyau liquide de la Lune: Bretagne ou Bahamas?

Jérôme Noir

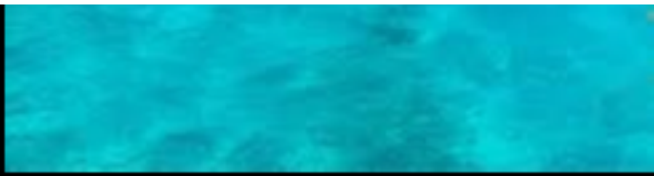
Collaborators: D. Cébron, M. Calkins, Y. Charles, J. Aurnou, M. Le Bars, F. Hemmerlin, M. Lasbleis



# Why the Earth's moon ?

**The only extraterrestrial body for which we have:**

- **Samples**
- **Seismic data**
- **Rock magnetic data**
- **LLR (k2/dissipation/rotational dynamics)**



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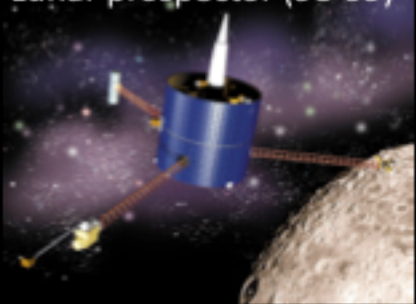
- **Gravity**
- **Surface composition**


Apollo (61-72)


Lunar prospector (98-99)

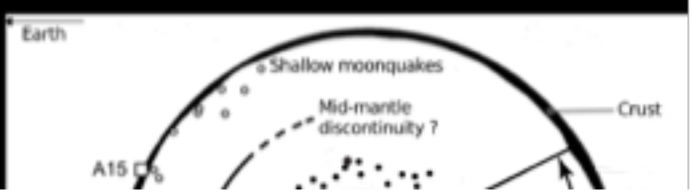




# Does the Moon posses a liquid core ?

Evidence of  a liquid layer in the deep moon structure:
Partialy molten mantle versus Liquid core…

- Absence of farside deep moonquakes. (Melt/Core)
- Tidal dissipation from LLR(Melt/







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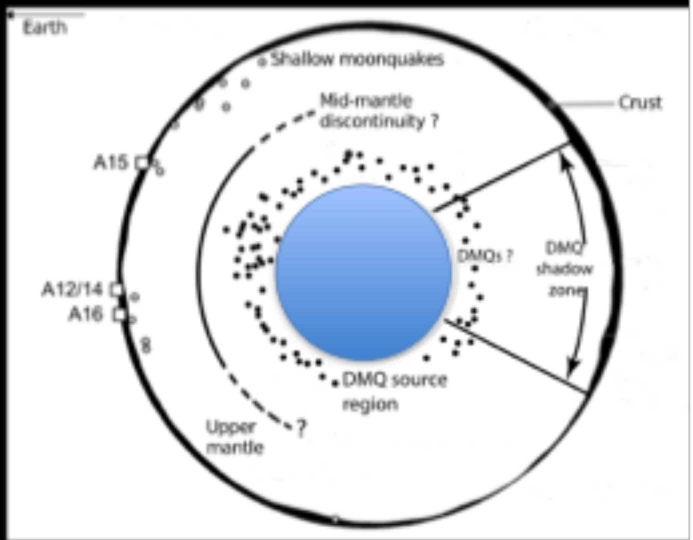
- Remanent rock magnetism. (Early moon dynamo->Core)
- Moment of Inertia (Core)






# The two models of internal structure:

Williams et al 2001, Nimo et al. 2012

Khan et al. 2004, 2013,
J. de Viries et al. 2010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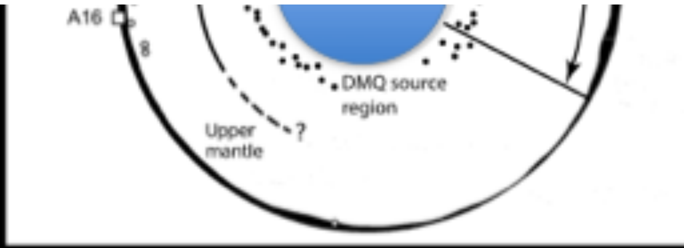




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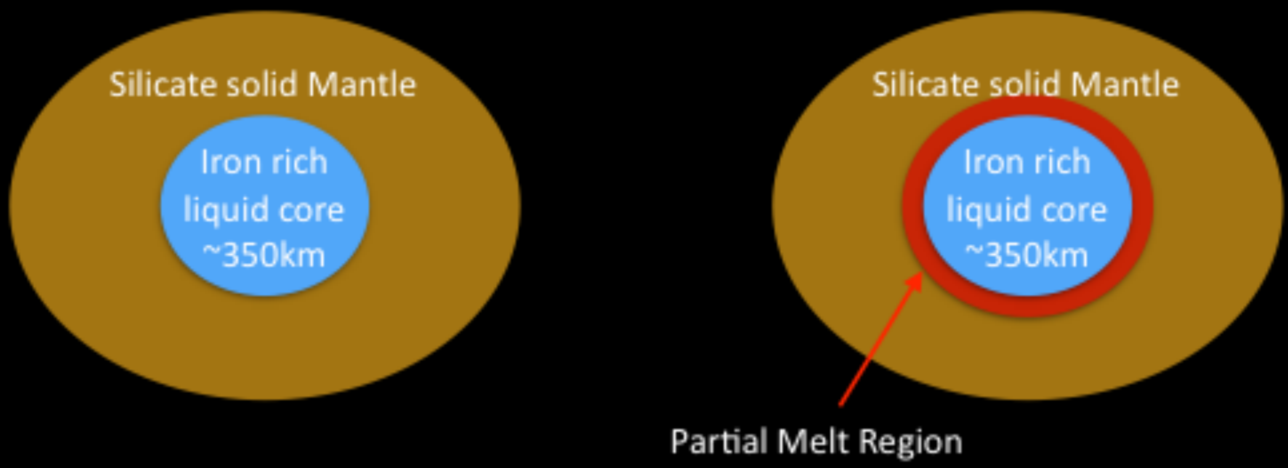




# The LLR observations.




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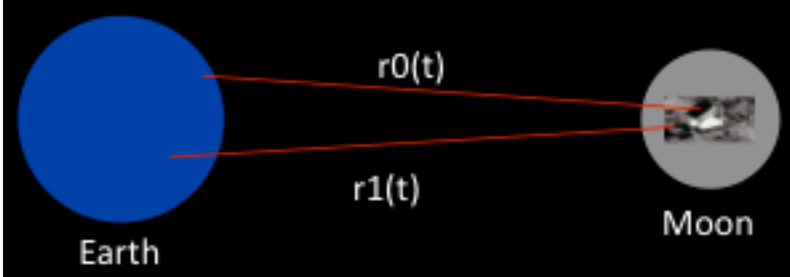
# The dissipation from LLR observations

Lunar Laser Ranging (LLR)




A gravitational torque acting on the moon will deform the planet and change its rotation. Both effects combine into time dependent r0,r1,.. measured by LLR.

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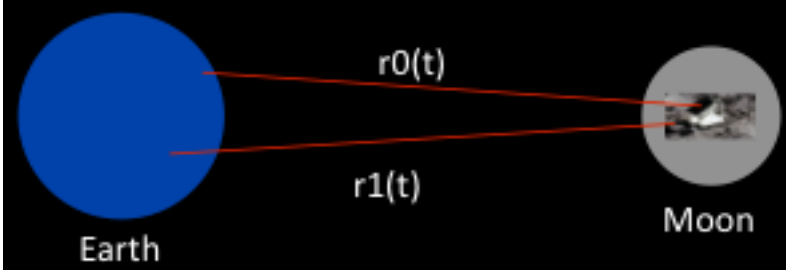


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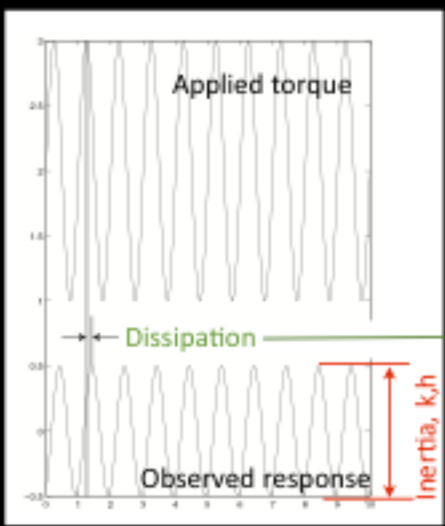



Dissipation from LLR

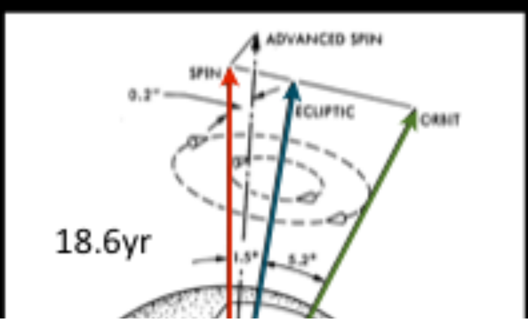
$$1/Q=1/Q_{tidal} + 1/Q_{core}$$

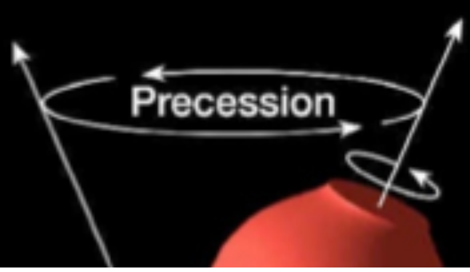
Anelasticity of the mantle

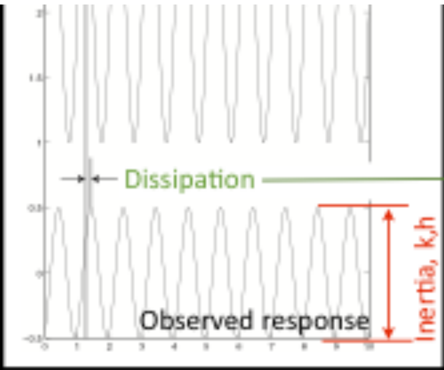
Viscous friction at the CMB



In the absence of dissipation, the spin vector of the moon would remain in the Cassini plane.



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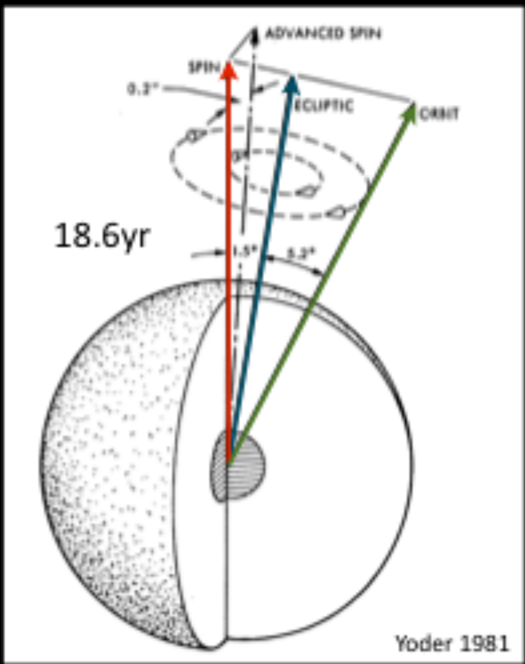
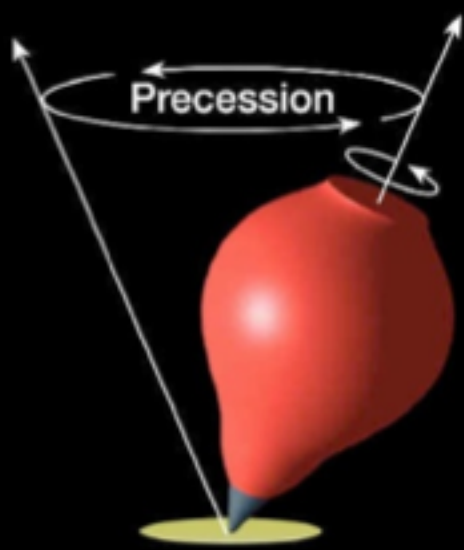
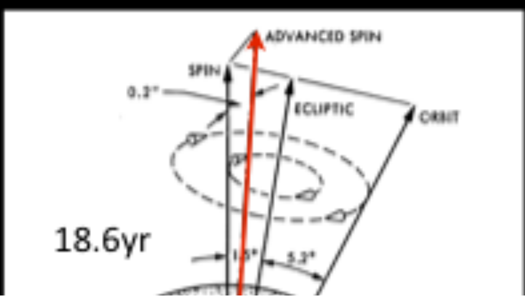




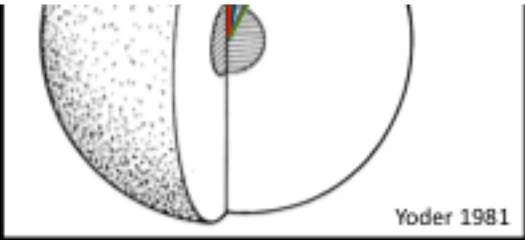

Precession of the lunar mantle exhibit -264 mas phase lag between the mantle rotation axis compare to the Cassini plane.

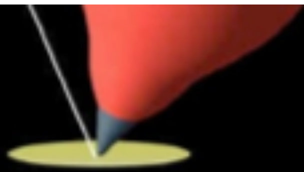



Yoder 1981:

If the dissipation is entirely due to solid friction:

$$\Delta\phi = -223\frac{k_2}{Q}$$





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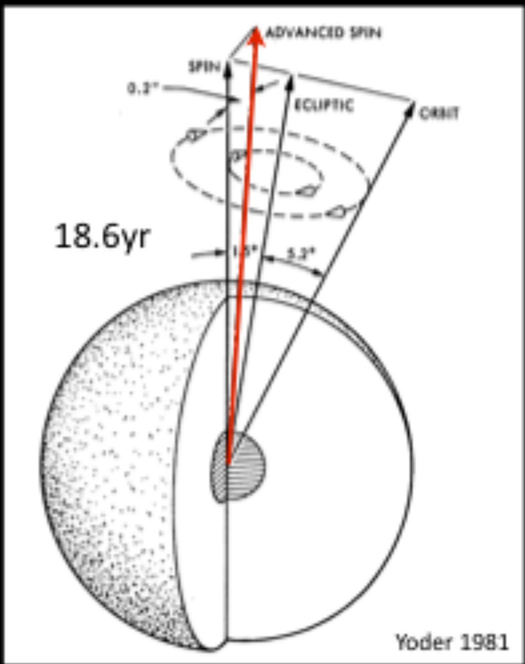


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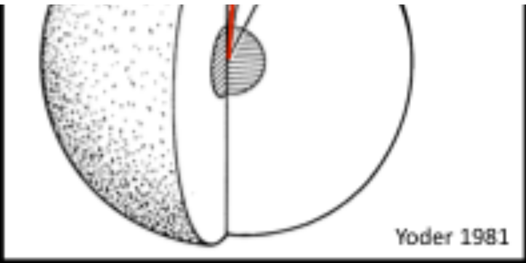
k2~0.02 - Q~35 are obtain from observations at 1month period. Assuming (k2, Q) for a silicate mantle do not vary significantly in the long period range [1month-20years]

$$Q \sim 2 << Q = 35$$



# A simple model of Lunar Core dynamics.

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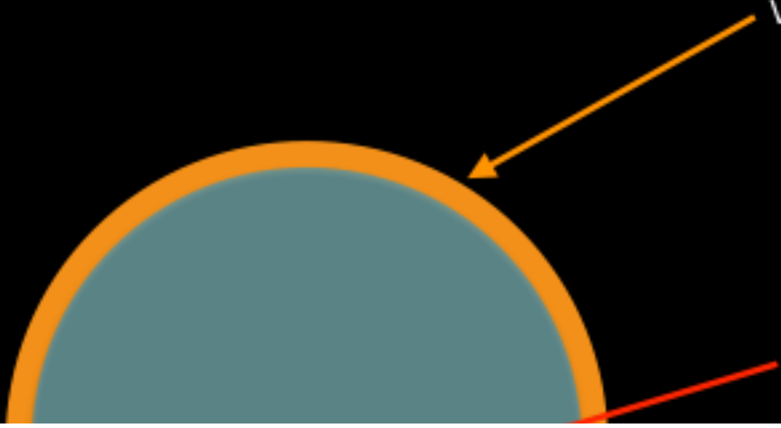
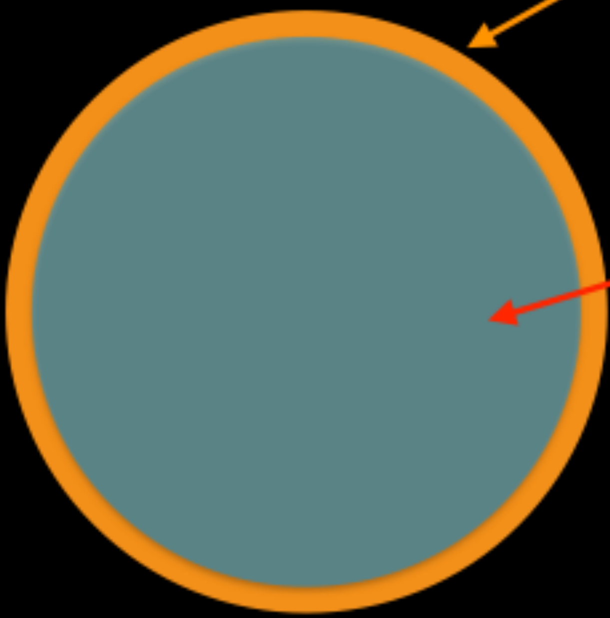



$$\delta = \sqrt{\frac{\nu}{\Omega}} \lesssim 1m$$

- Boundary layer instability
- Roughness



Viscous boundary Layer

$$\delta = \sqrt{\frac{\nu}{\Omega}} \lesssim 1m$$

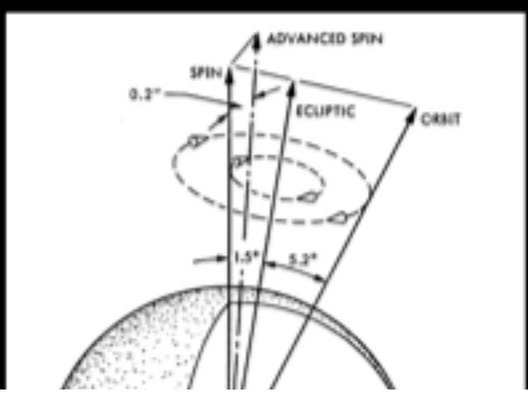
- Boundary layer instability
- Roughness

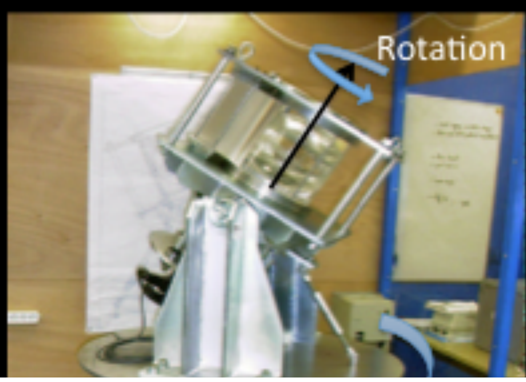
Quasi-inviscid interior

- Centrifugal instability
- Inertial parametric instability



# Precession driven flows



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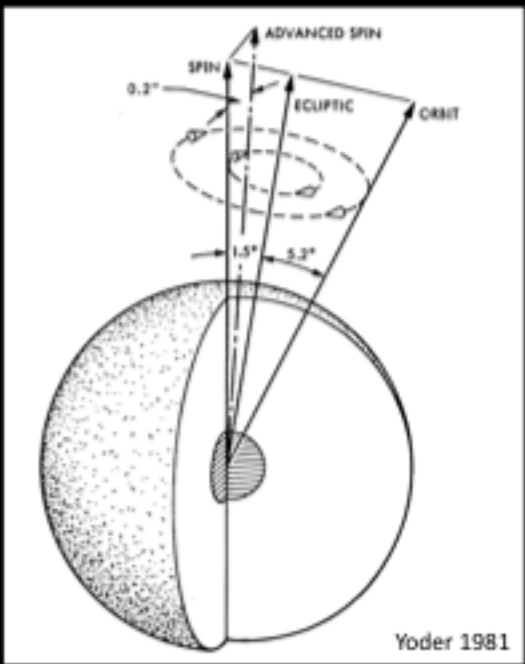


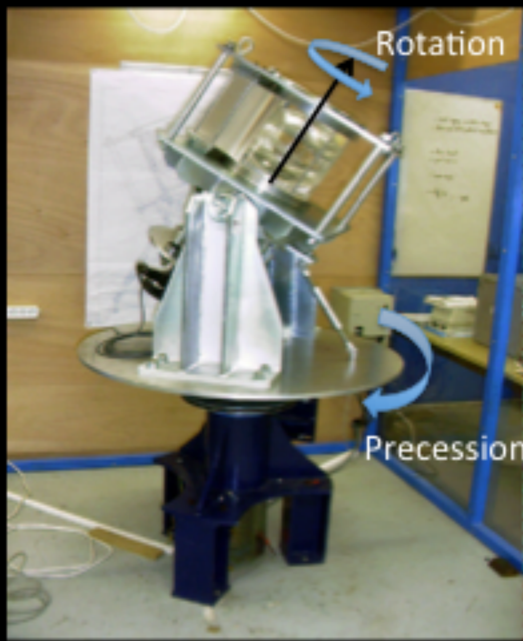




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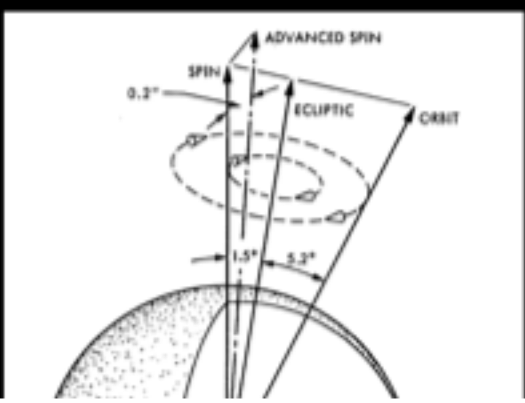


$$\Omega_c = core\ rotation\ rate$$
$$\Omega_m = mantle\ rotation\ rate$$
$$\Omega_p = precession\ rate$$
$$\Delta\Omega = \Omega_m - \Omega_c = differential\ rotation$$

$$Po = \frac{\Omega_P}{\Omega_m} \sim 4e-3$$

Yoder 1981



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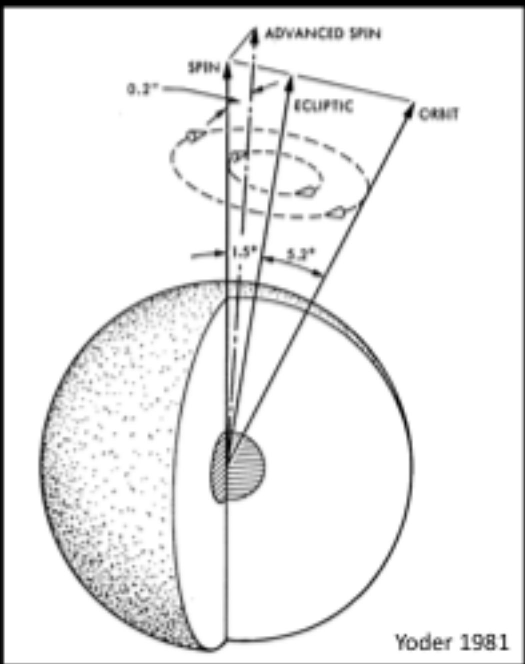



Yoder 1981

$$Po = \frac{\Omega_P}{\Omega_m} \sim 4e-3$$

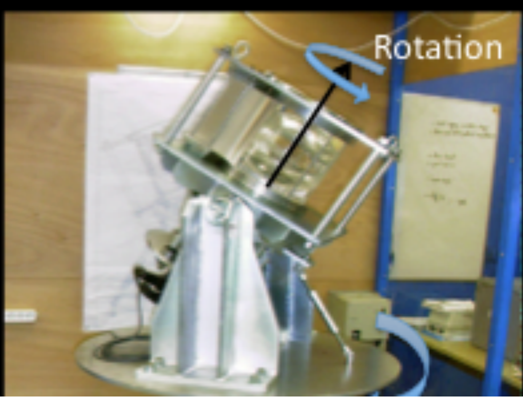
$$E = \frac{\nu}{\Omega_m R_c^2} \sim 10^{-12}$$

$$f_c = \frac{a-c}{a} \sim 10^{-5}$$

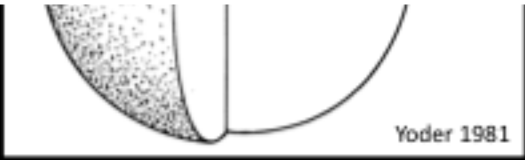


# Precession driven primary flow.

Poincaré 1910:
A first order the flow remains in quasi solid body rotation along an axis that is tilted compare to the surrounding solid shell




$$\boxed{\boldsymbol{U_c} = \boldsymbol{\Omega}_c \times \boldsymbol{r} + \boldsymbol{\nabla}\psi}$$

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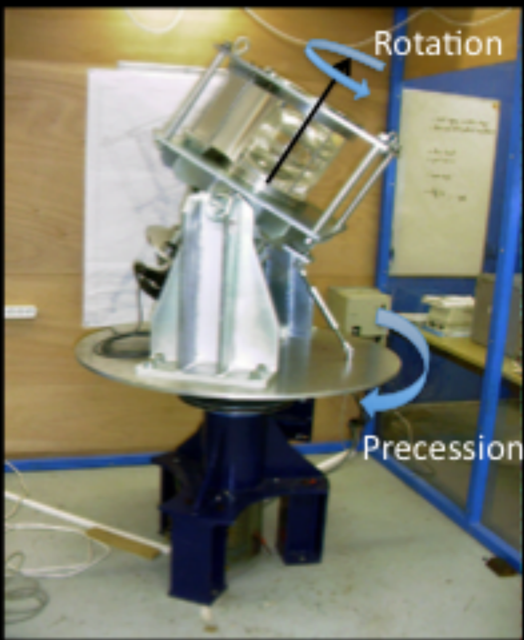


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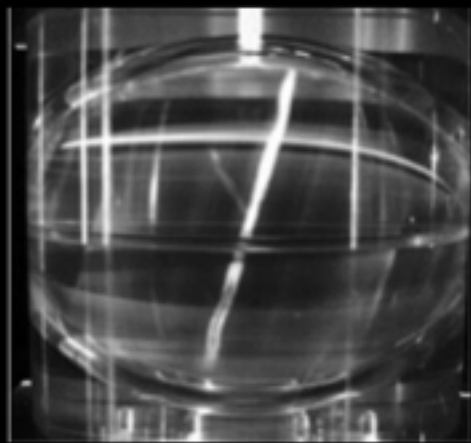
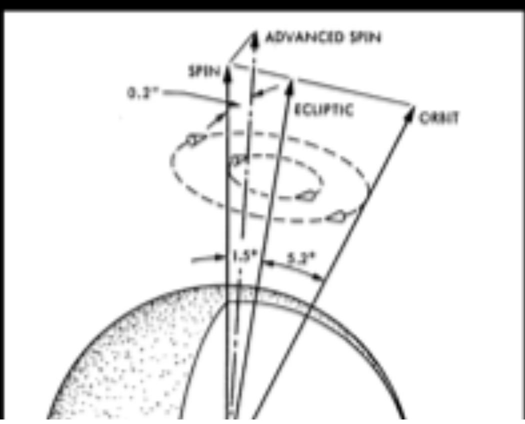




# Uniform vorticity assumption




In a steady state the direction and amplitude of the rotation vector of the liquid is fully determined by the balance between the gyroscopic, pressure and viscous torque (Busse 1968, Noir et al. 2003):

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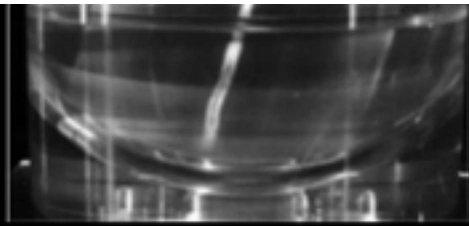
Necessary to satisfy the non penetration condition:

$$\boxed{\boldsymbol{U_c} \cdot \hat{\boldsymbol{n}} = 0}$$





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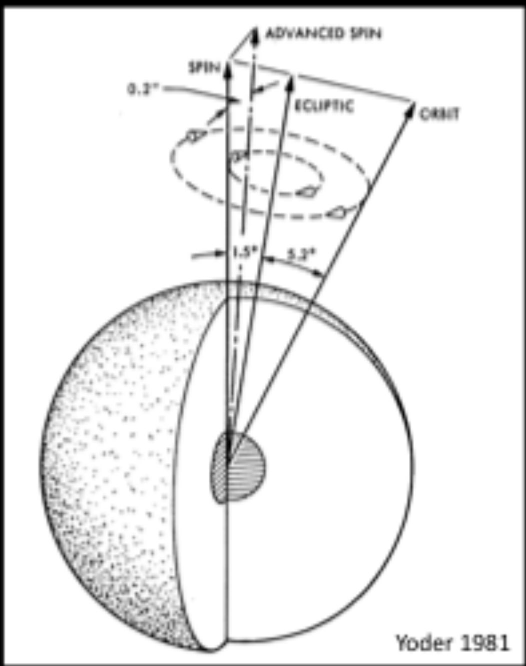


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$$\Gamma_{Prec} \propto \Omega_p \times \Omega_m$$

$$\Gamma_P \propto f_c \Delta\Omega$$

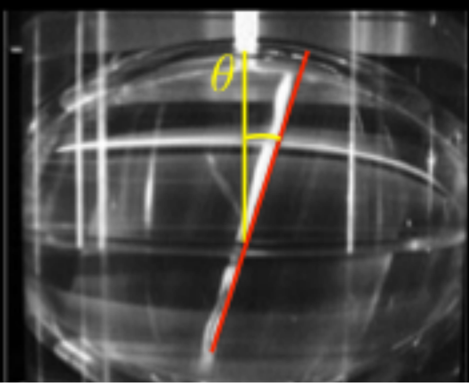
$$\Gamma_\nu \propto K \Delta\Omega$$



# Precession driven flows

At first order the fluid rotates around an axis different from the mantle spin axis

Sphere / Spheroid




The uniform vorticity theory:

- Sphere/Spheroid (Earth): Poincare 1910, Busse 1968, Noir et al. 2003.
- Triaxial ellipsoid (Moon): Noir and Cebron 2013.

$$\theta \sim 1.55°, \quad \frac{|\Omega_c - \Omega_m|}{\Omega_m} \sim 3\%$$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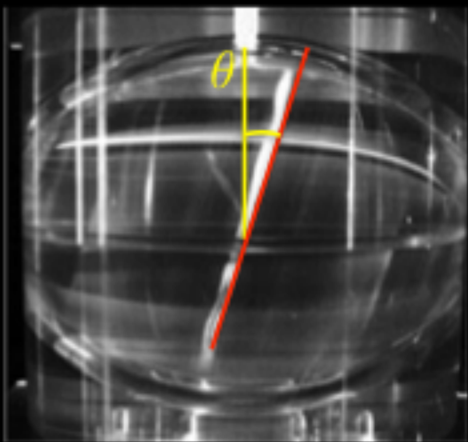


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The core mostly rotates around the normal to the ecliptic, neither the viscosity nor the ellipticity are large enough to force the core to rotate synchronously with the mantle. (Yoder 1981, Williams et al. 2001…)



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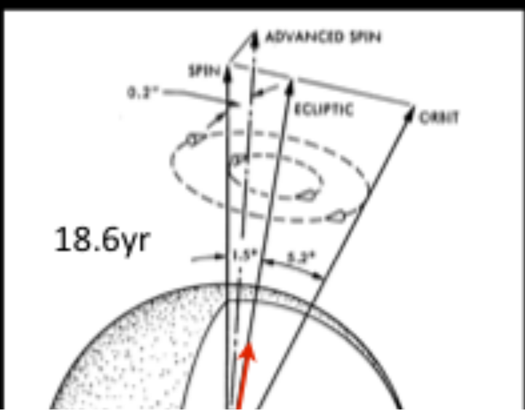


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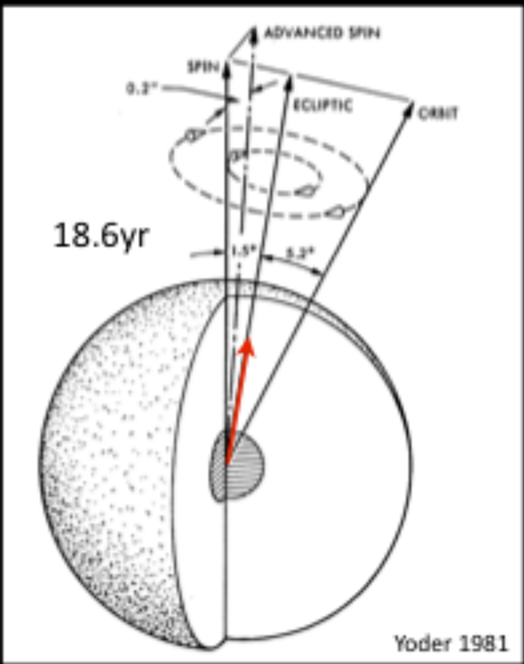


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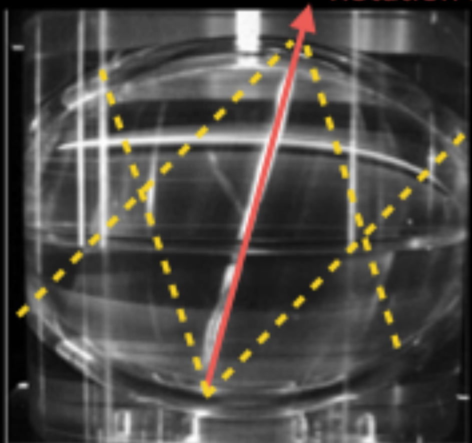
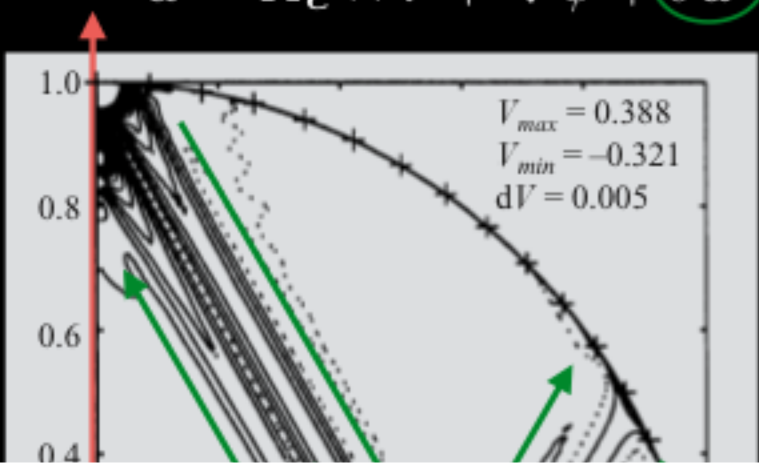
# Precession driven secondary flows

Rotation axis of the fluid



$$u = \Omega_c \times r + \nabla\psi + \delta u$$

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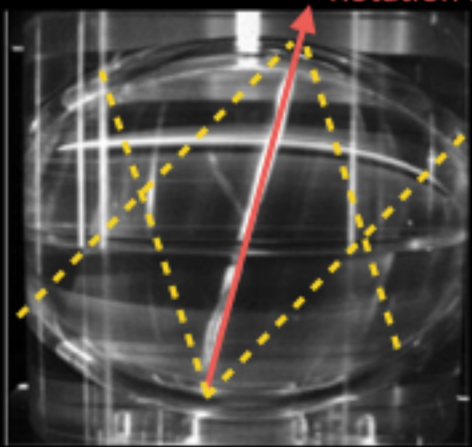
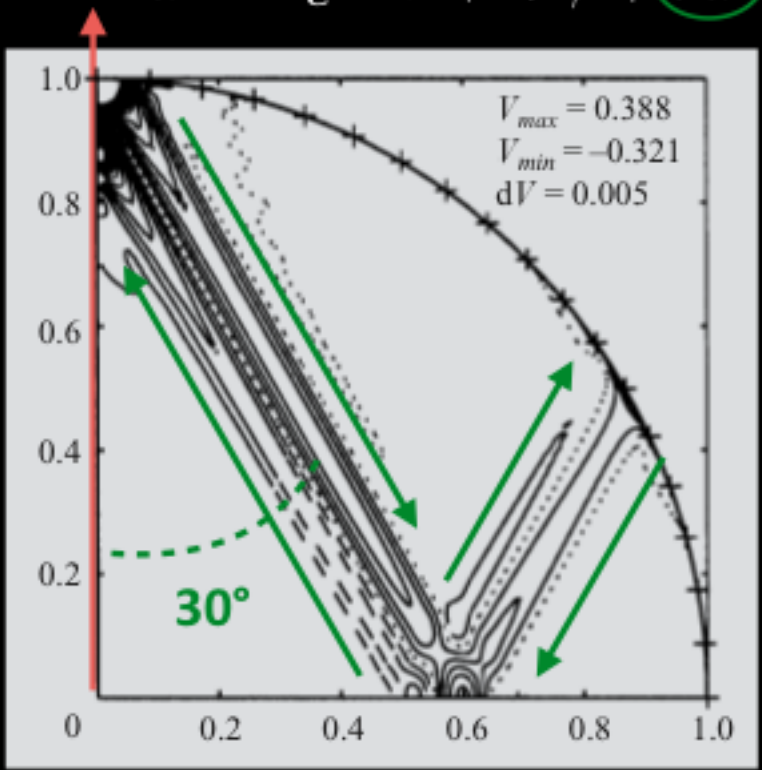


$$\boldsymbol{u} = \boldsymbol{\Omega_c} \times \boldsymbol{r} + \nabla\psi + \delta\boldsymbol{u}$$




Due to the viscosity in the boundary layer, there exists a secondary flow spawn from the critical latitudes along conical surfaces.

Roberts and Stewartson 1963

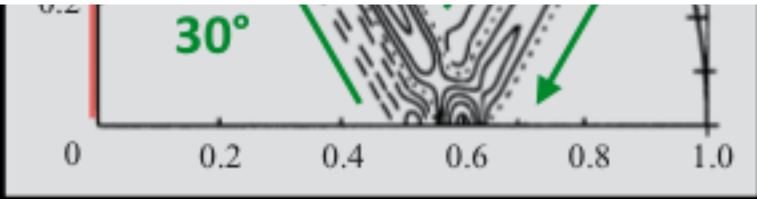
Noir et al. 2001



## Can the differential rotation account for the observed dissipation ?

critical latitudes along conical surfaces.

Roberts and Stewartson 1963




Noir et al. 2001



# Can the differential rotation account for the observed dissipation ?

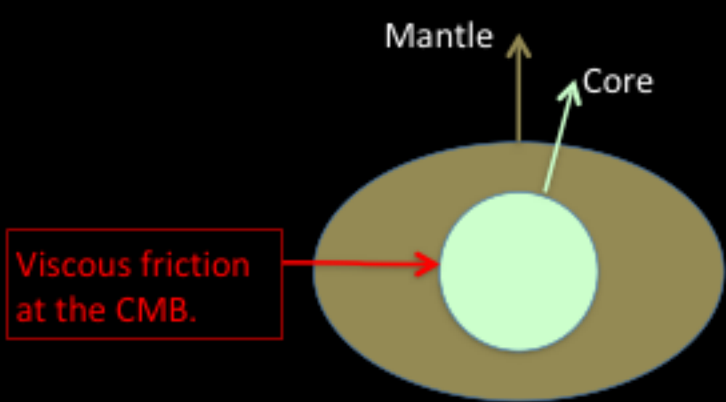


# Estimated dissipation from LLR measurements

Yoder 1981

$$0.260" = 1.3\frac{I_c}{I-m}\frac{\chi \sin 1.5°}{1+\chi^2}$$

$$\chi = \frac{\Gamma_\nu}{\Delta\Omega I_c \Omega_p}$$

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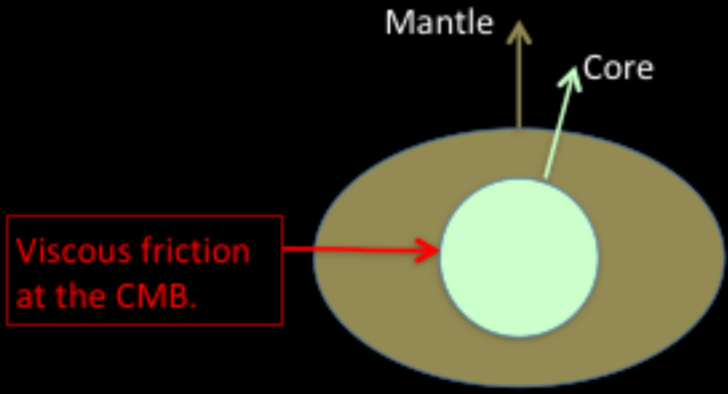


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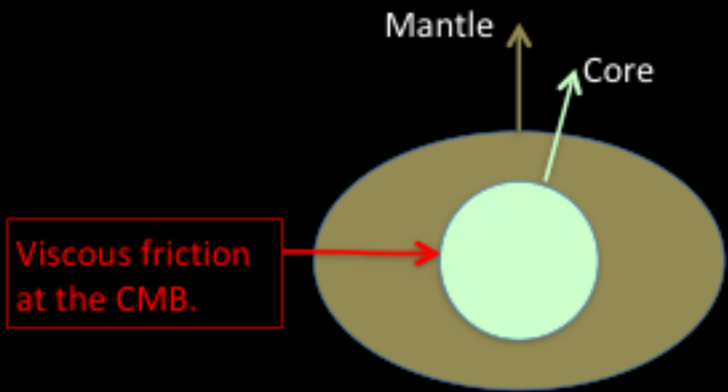
# Estimated dissipation from LLR measurements

For small precession rate, as for the moon, the differential rotation vector lies in the equatorial plane




$$P = \boldsymbol{\Gamma_\nu} \cdot (\boldsymbol{\Omega_m} + \boldsymbol{\Delta\Omega}) \sim \boldsymbol{\Gamma_\nu} \cdot \boldsymbol{\Delta\Omega}$$

$$\boldsymbol{U_c} = \boldsymbol{\Omega}_c \times \boldsymbol{r}$$

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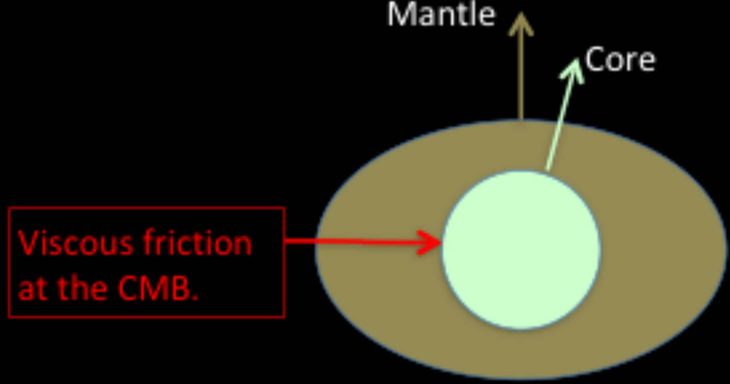


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$$\boxed{P \sim 1.4 \times 10^8 W}$$



# The classical core dissipation models

<u>Classical Core flow models for the dissipation:</u>

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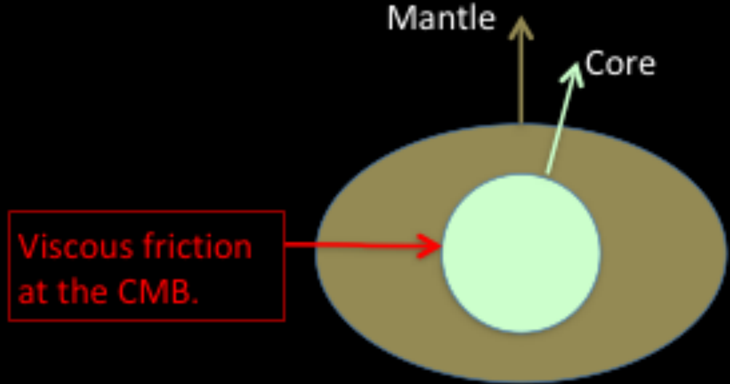


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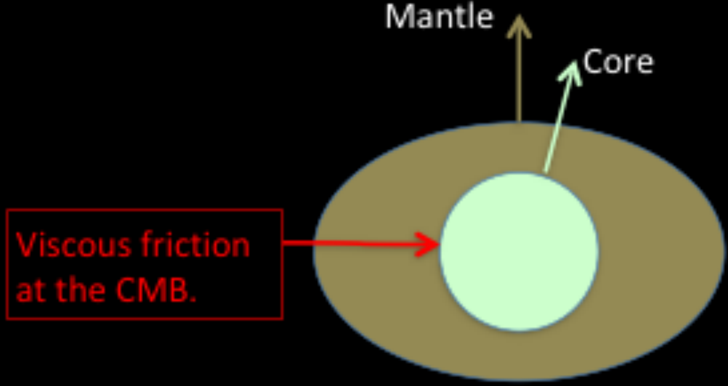


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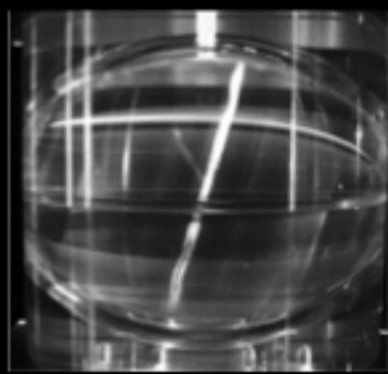
Laminar coupling

$$K \propto (I_c \Omega_c)\sqrt{E}$$

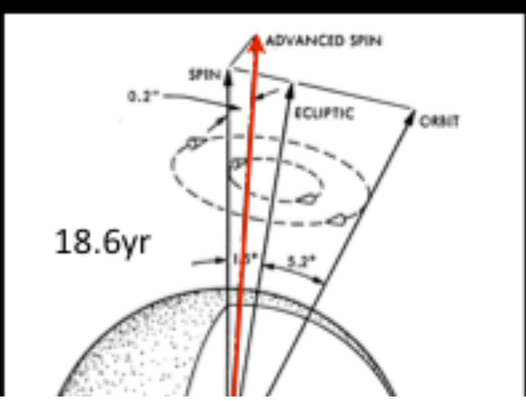


Noir 2000



# The classical core dissipation models

Precession of the lunar mantle exhibit -264 mas phase lag between the mantle rotation axis compare to the Cassini plane, which can not be explain with realistic model of mantle tidal dissipation (Williams 2001)




Assuming a large fraction of the dissipation at 18.6yr comes from the liquid core and a simple model of dissipation at the CMB with a laminar coupling:

$$10^{-7} m^2.s^{-1} \lesssim \nu \lesssim 10^{-6} m^2.s^{-1}$$

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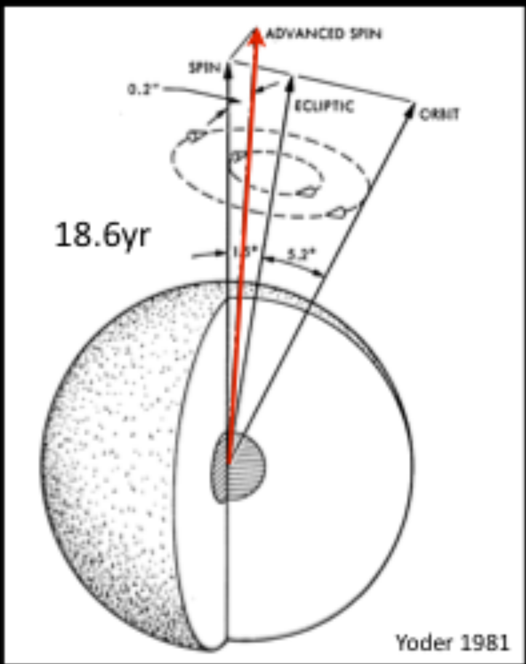


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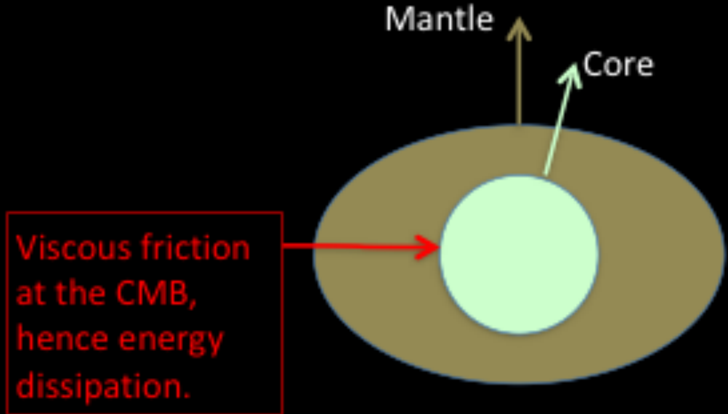


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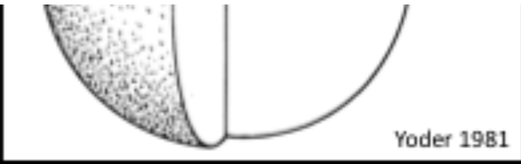


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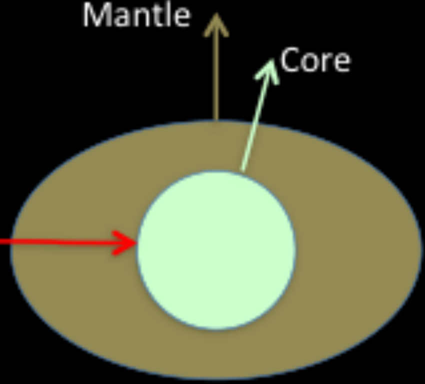
Viscous friction at the CMB, hence energy dissipation.

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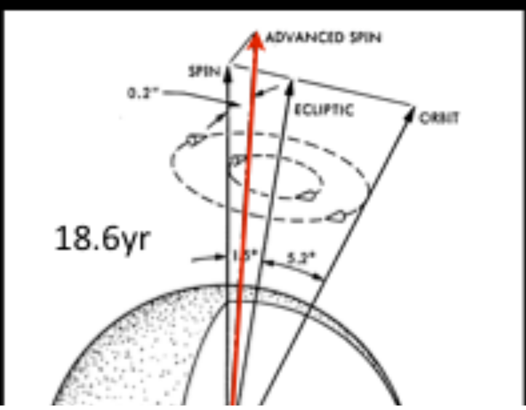


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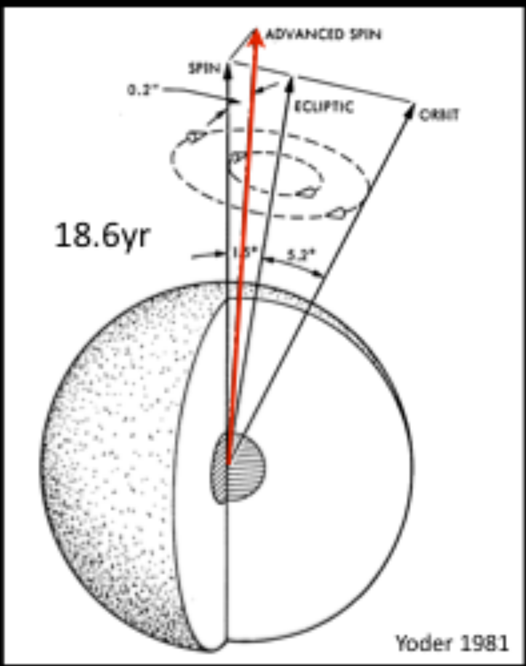


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# Can turbulence be driven in the Lunar Core ?




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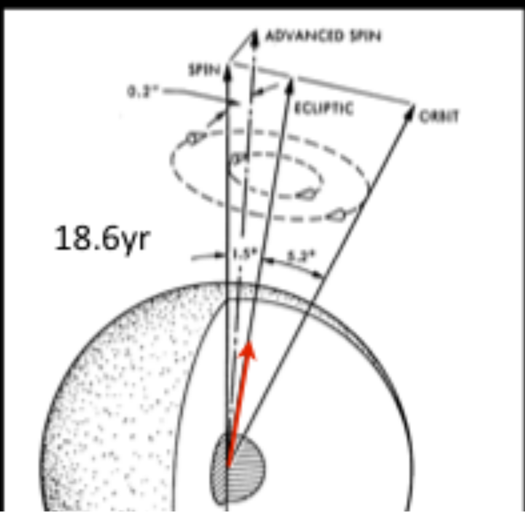
# Ekman Layer stability

At first order the fluid rotates around an axis different from the mantle spin axis




$$\theta \sim 1.55°, \ \frac{|\Omega_c - \Omega_m|}{\Omega_m} \sim 3\%$$

Is the Ekman boundary layer stable ?

$$Re = \frac{|\Omega_c - \Omega_m| R \sqrt{\frac{\nu}{\Omega}}}{\nu} \sim 10^4$$

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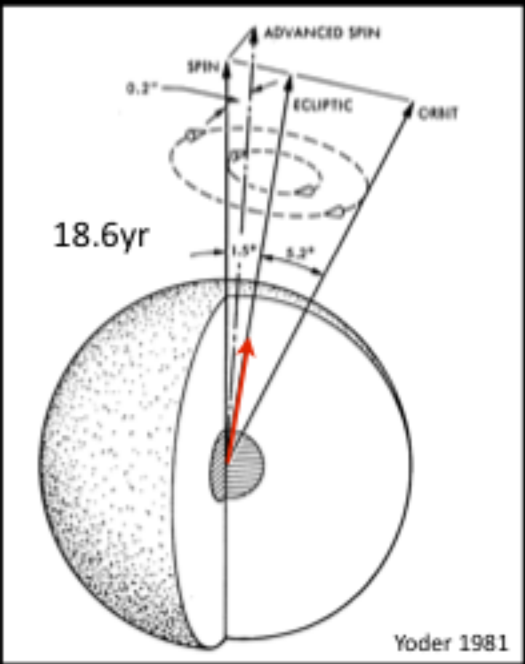


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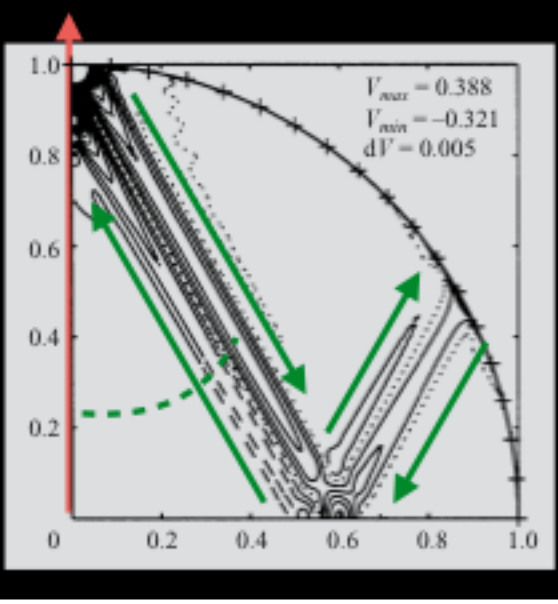
The large Re-value suggests that the thin viscous boundary layer could be unstable. There is no theory at the moment that let us predict how much dissipation it can generate. One may expect the small volume of the Ekman layer to limit this effect.





# Conical shear layer stability




$$\boldsymbol{u} = \boldsymbol{\Omega_c} \times \boldsymbol{r} + \boldsymbol{\nabla}\psi + \delta \boldsymbol{u}$$

Roberts and Stewartson 1963

$$\delta u \propto \Delta\Omega E^{1/5}$$

$$\delta u \sim 1.5m/13.5days$$

$$\delta \sim 1.5km$$

$$Re \sim 2 \times 10^7$$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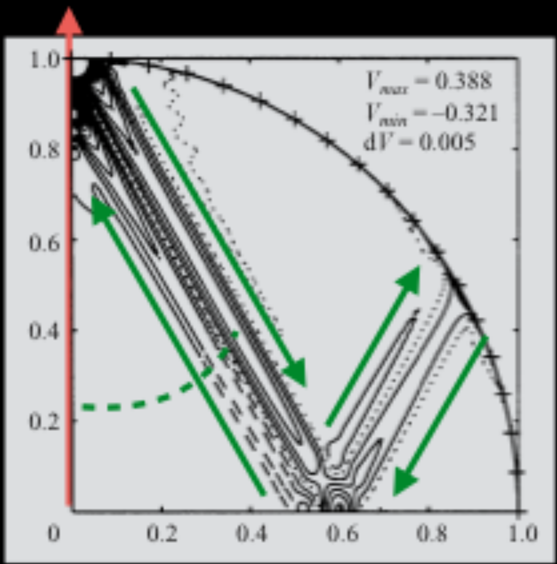


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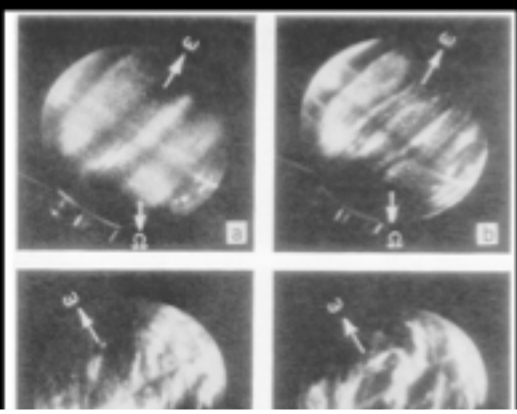
# Bulk instabilities in precessing cavities.



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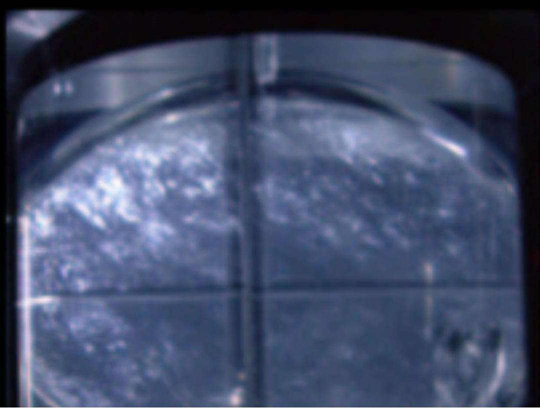

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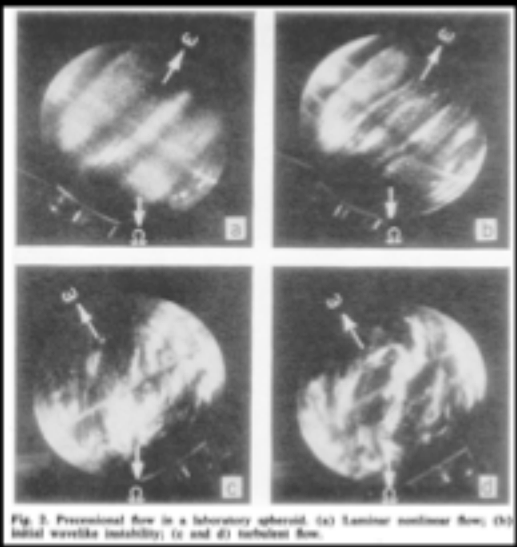
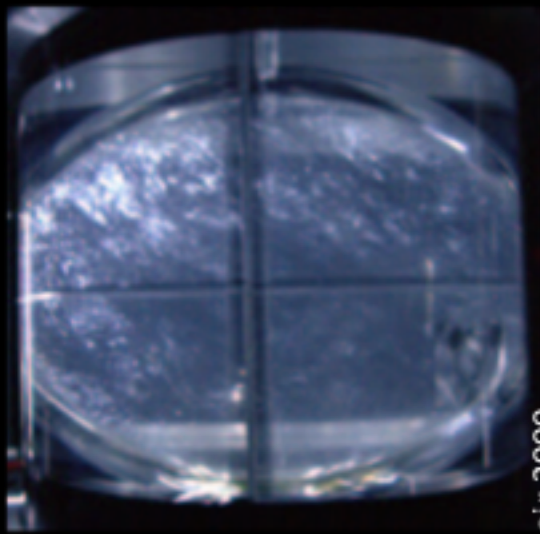


Fig. 2. Precessional flow in a laboratory spheroid. (a) Laminar nonlinear flow; (b) initial wavelike instability; (c and d) turbulent flow.

Malkus 1968



Noir 2000



# Stability of Precession driven flows

- Inertial modes = Resonant modes of a rotating fluid cavity (Greenspan 1968)
- The solid body rotation induced by precession is certainly the simplest inertial mode, also know as the Poincaré mode.

Background flow

$$\omega_I \pm \omega_{II} = \Omega_f$$

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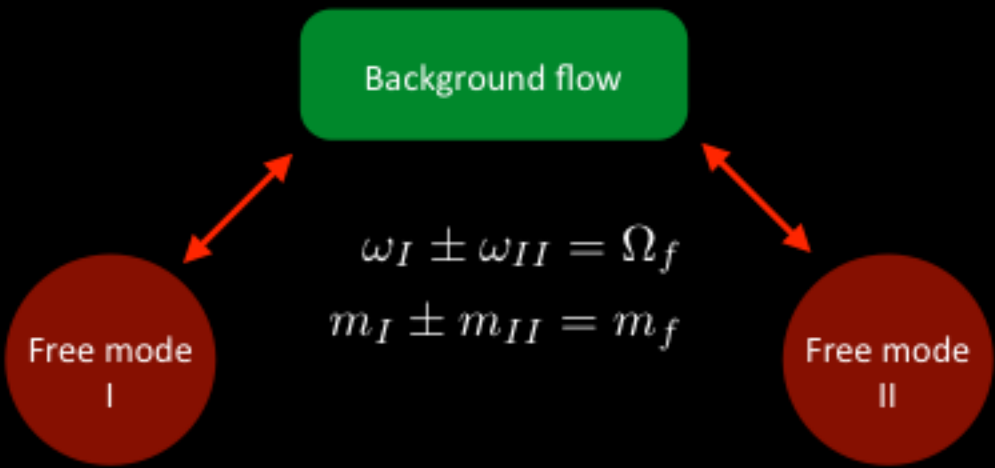


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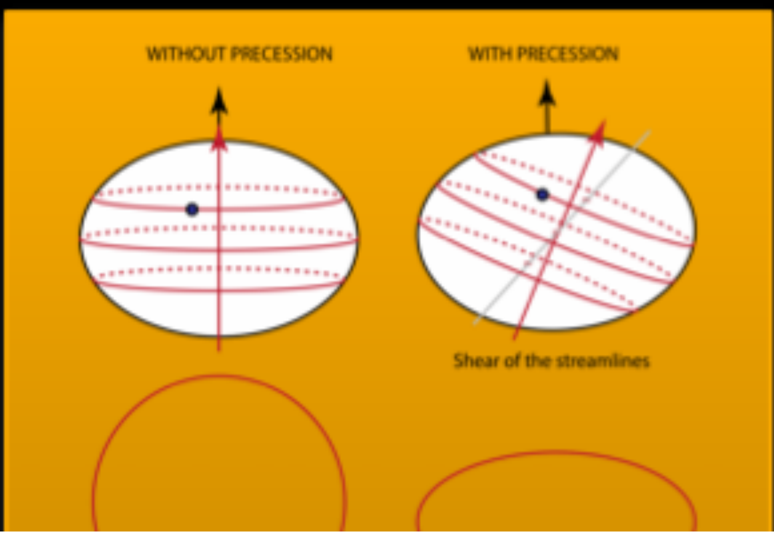
The mechanisms underlying the instability of the Poincaré flow has been derived by Kerswell in 1993.




Both the shear and the elliptical distortion will lead to instability in the system.

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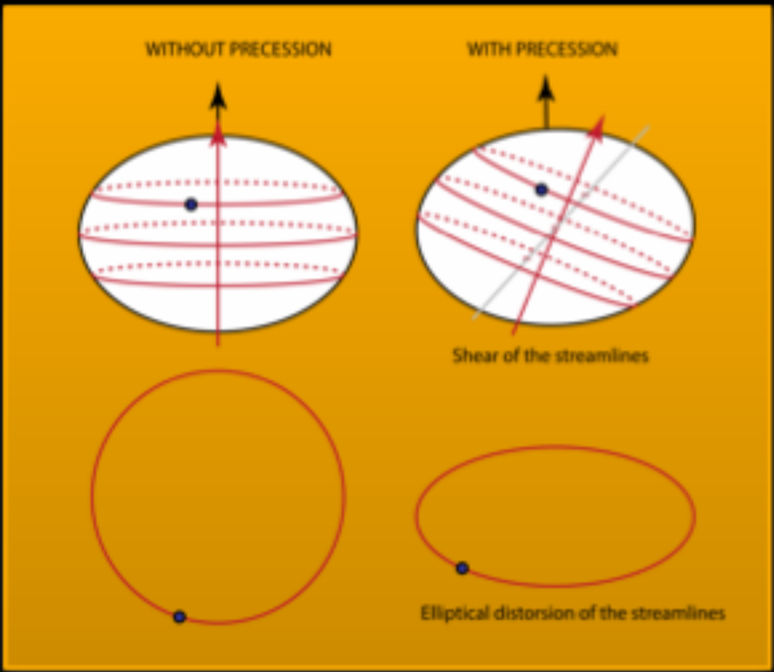


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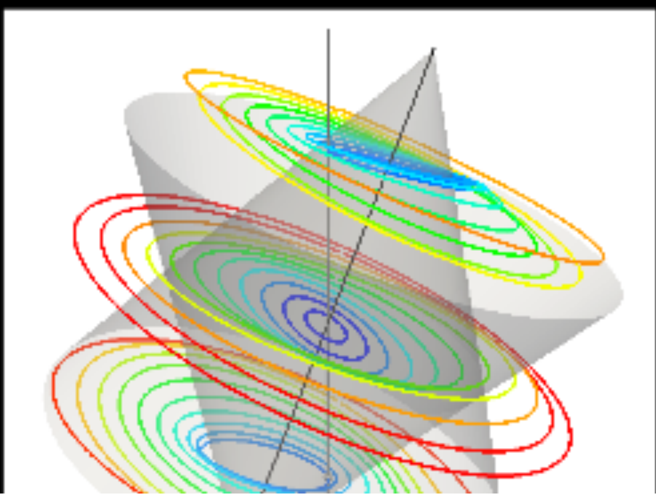

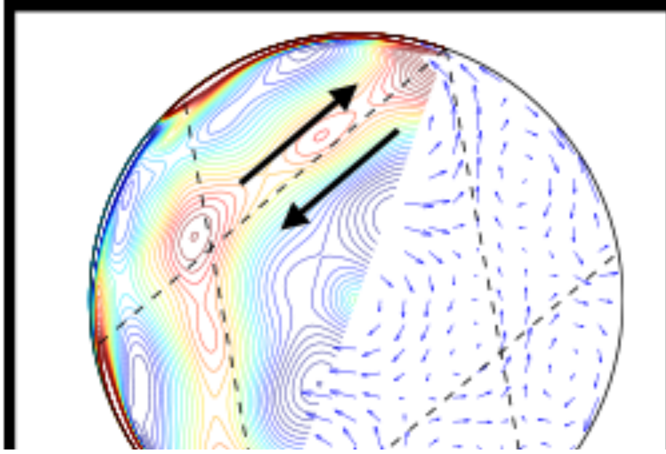

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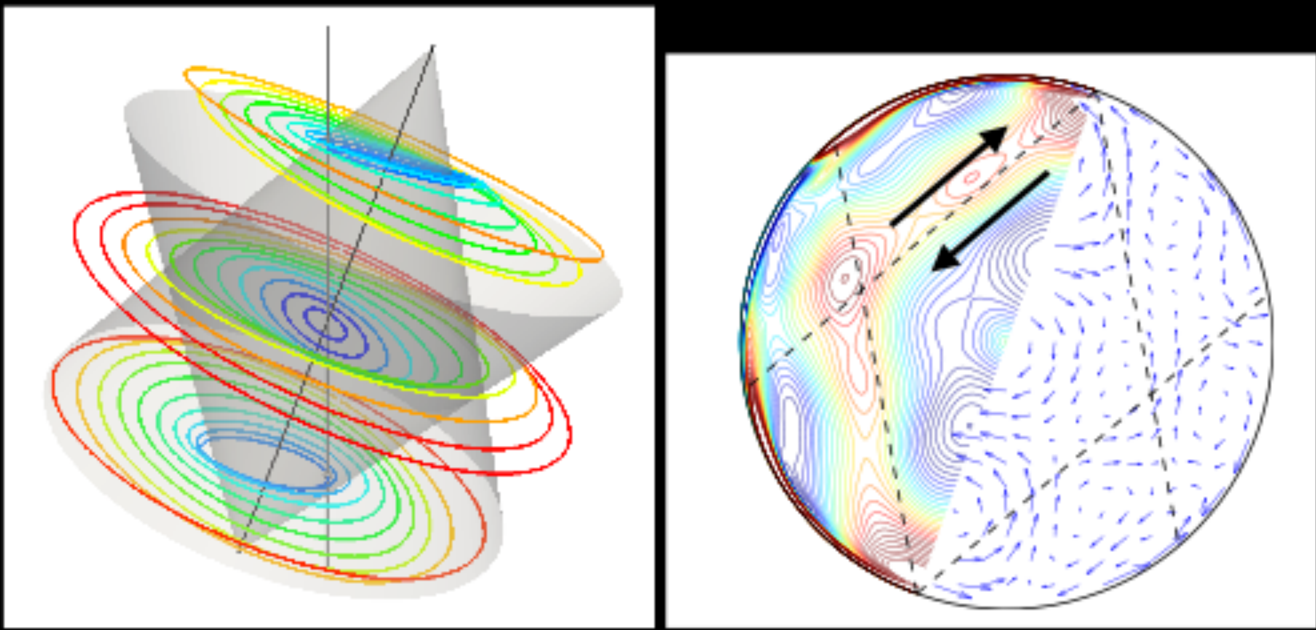



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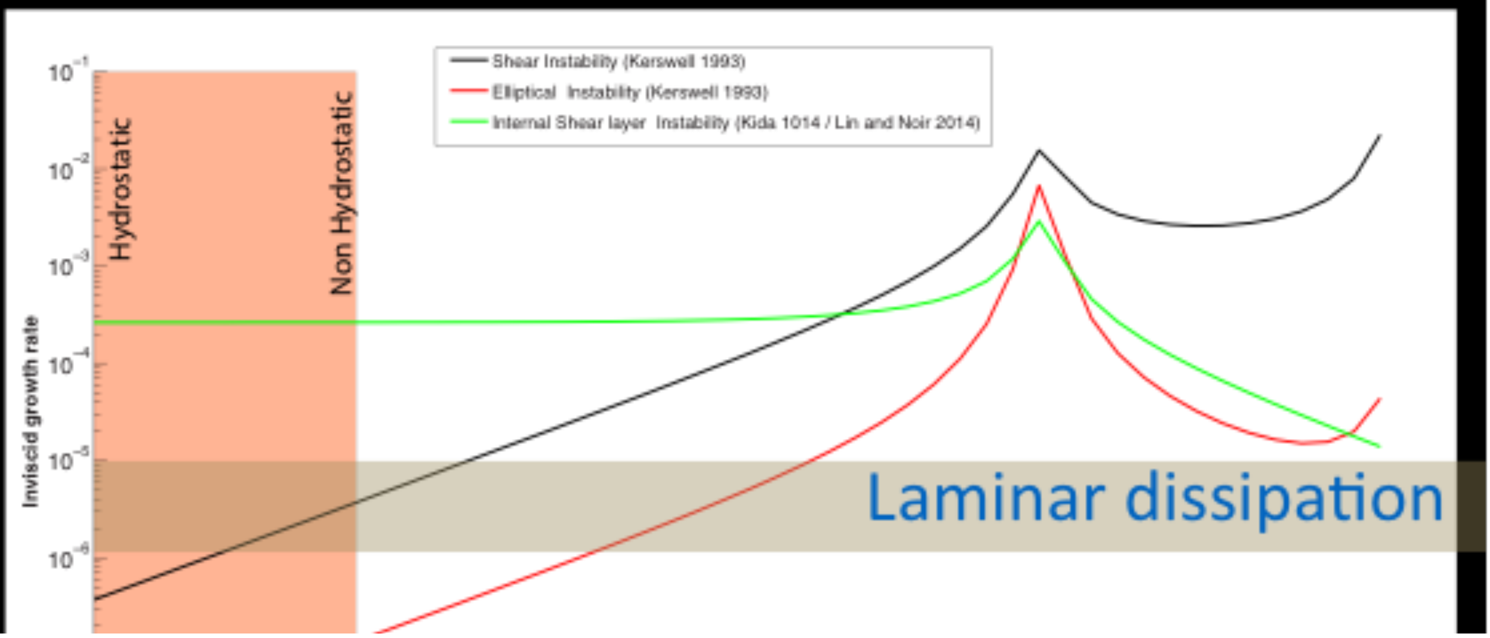
Instability criteria: Inviscid growth rate > dissipation in the boundary layer



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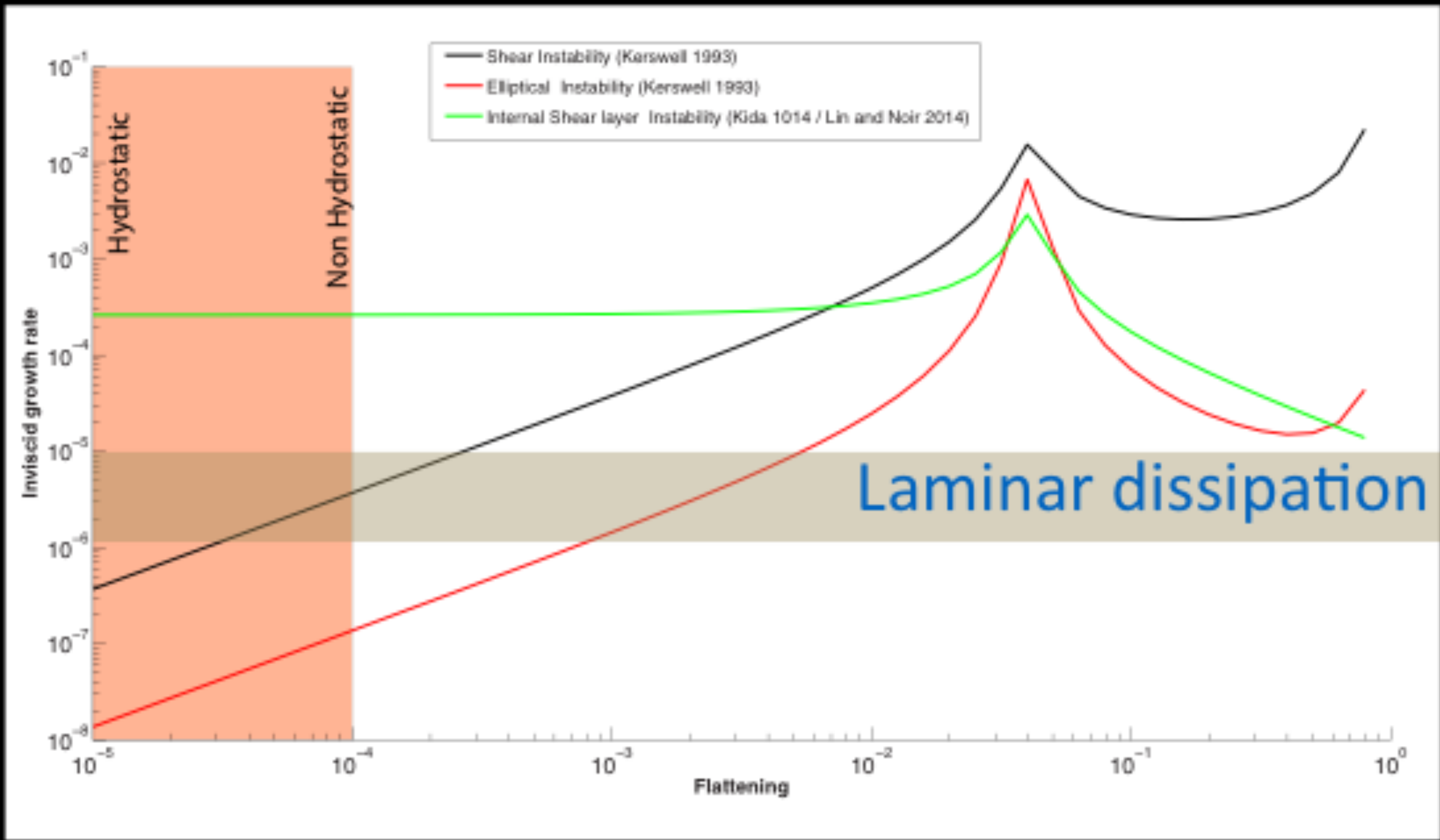




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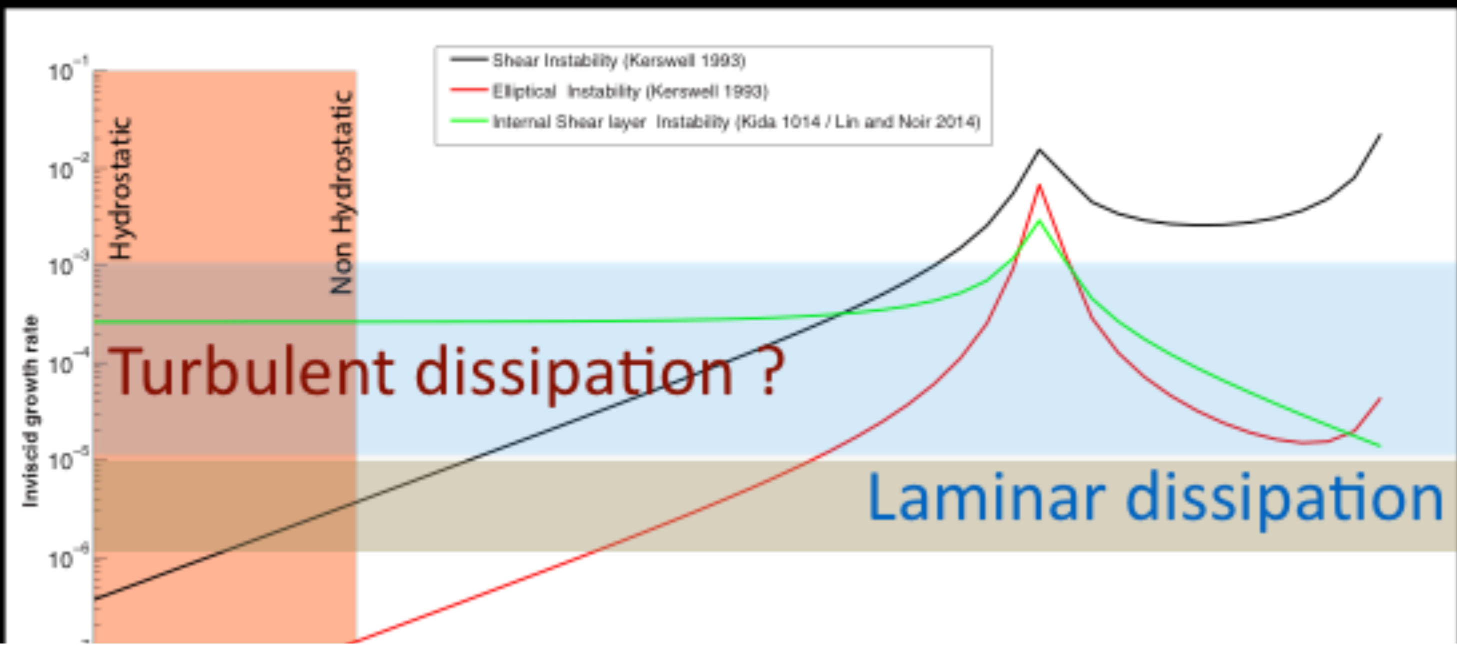




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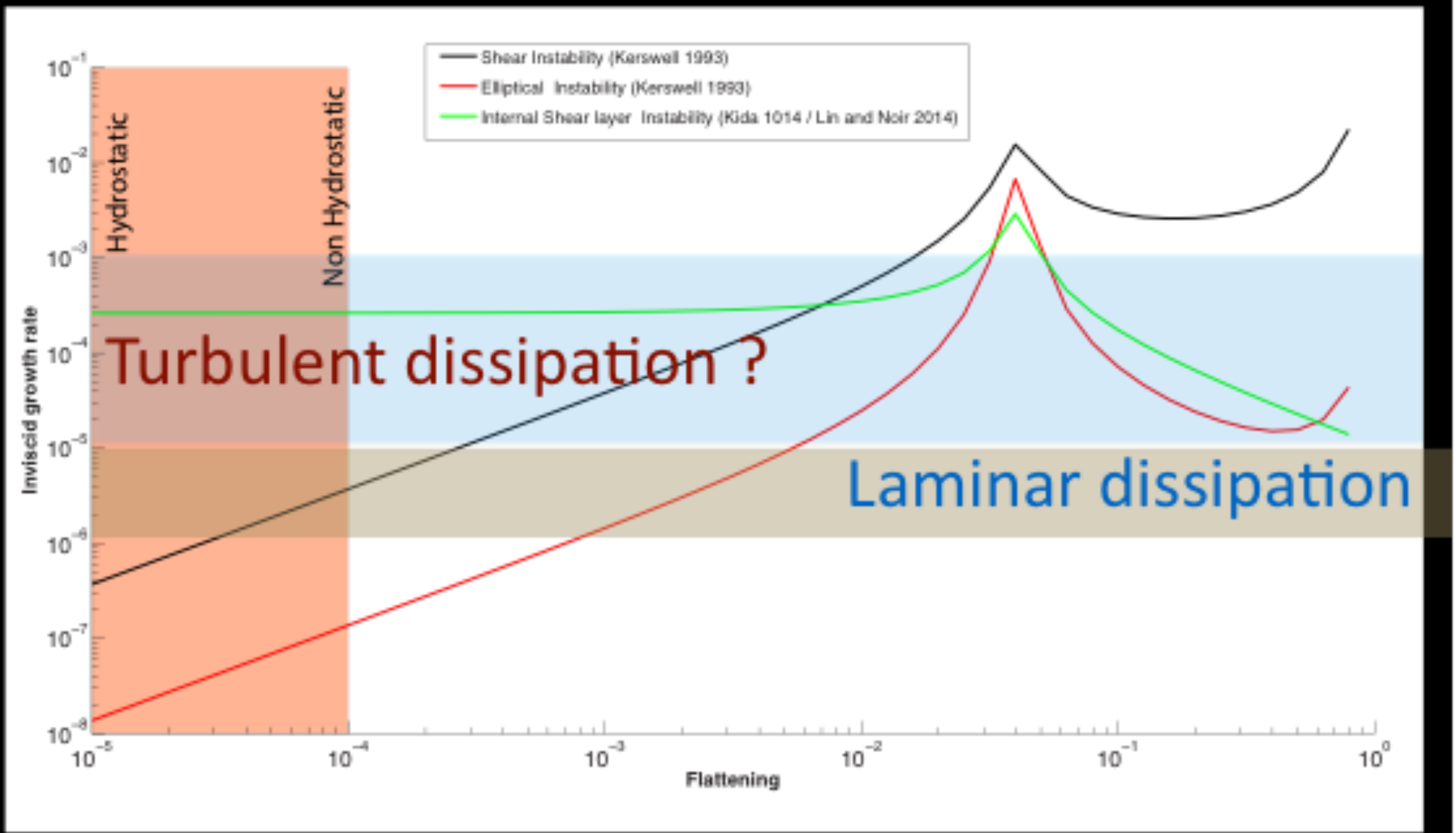




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- The boundary layer and the conical shear layers may be unstable in the Moon's liquid core.
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