Mean flow and fluctuations in a modified Taylor-state MHD flow: recent results of the DTS experiment

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outline

- *DTS* set-up
- Super-rotation !
- Modified Taylor state *(mean flow)*
- Waves *(fluctuations)*
- Conclusions

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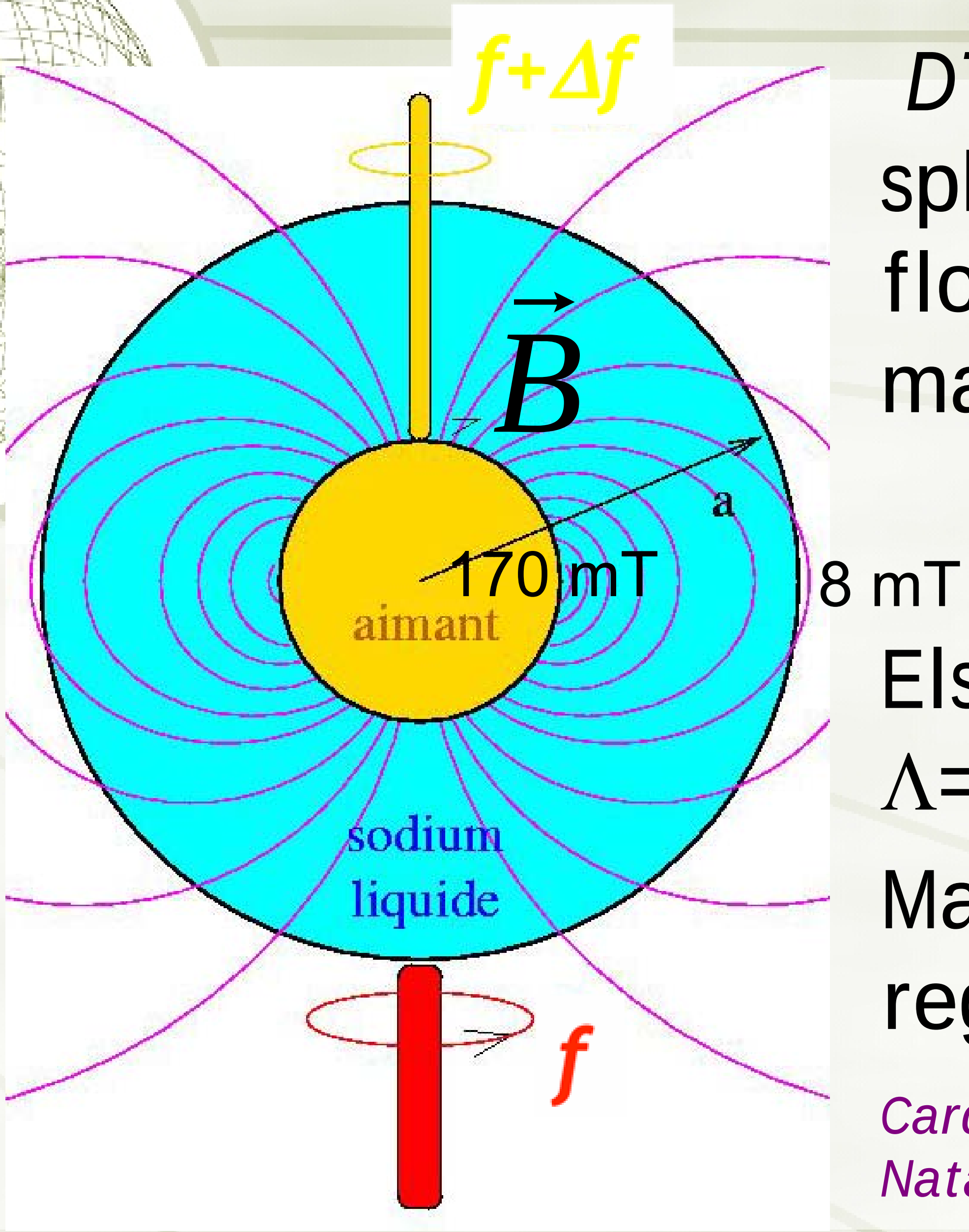
DTS experiment

- 50 litres of liquid sodium
- Outer sphere radius a=21cm
- Global rotation (f < 15 Hz)
- Differential rotation ($|\Delta f|$ < 45 Hz)



DTS = Rotating spherical Couette flow in a dipolar magnetic field

Elsasser number $\Lambda=\sigma B^2/\rho 2\pi f\approx 1$

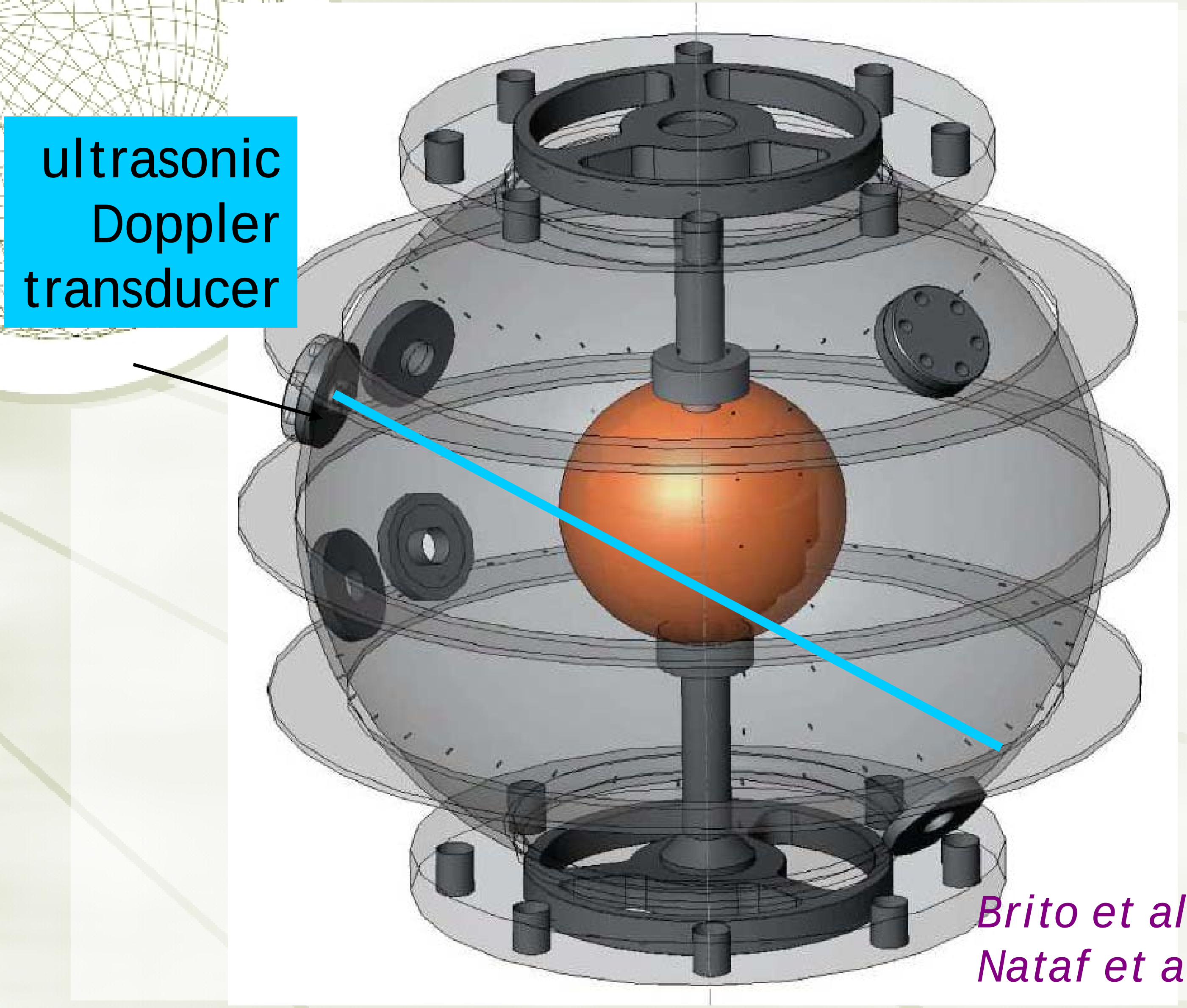
Magnetostrophic regime

Cardin et al, MHD, 2002
Nataf et al, GAFD, 2006

The DTS experiment is NOT a dynamo BUT:

- The flow modifies the magnetic field (Rm up to 40)
- The magnetic field modifies the flow (N of order 10)

- Global rotation can be present
- Numerical modelling is tractable



ultrasonic Doppler transducer

Brito et al, Exp. Fluids, 2001
Nataf et al, 2006, 2008

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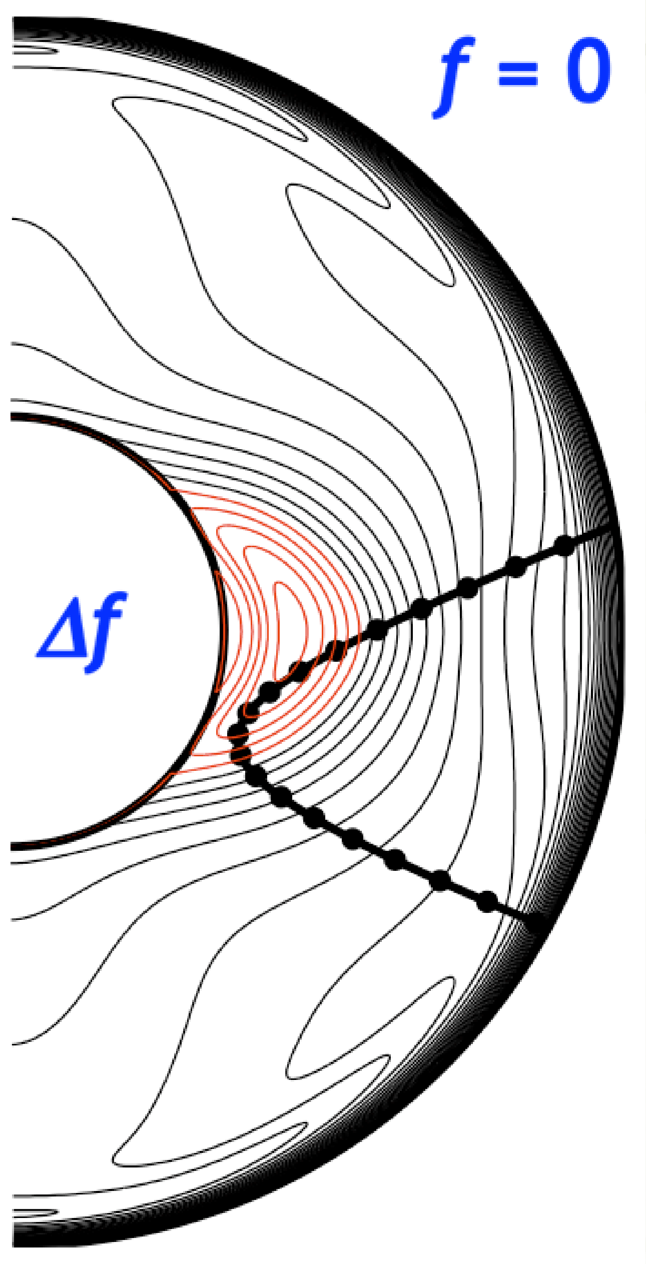
Outer sphere at rest



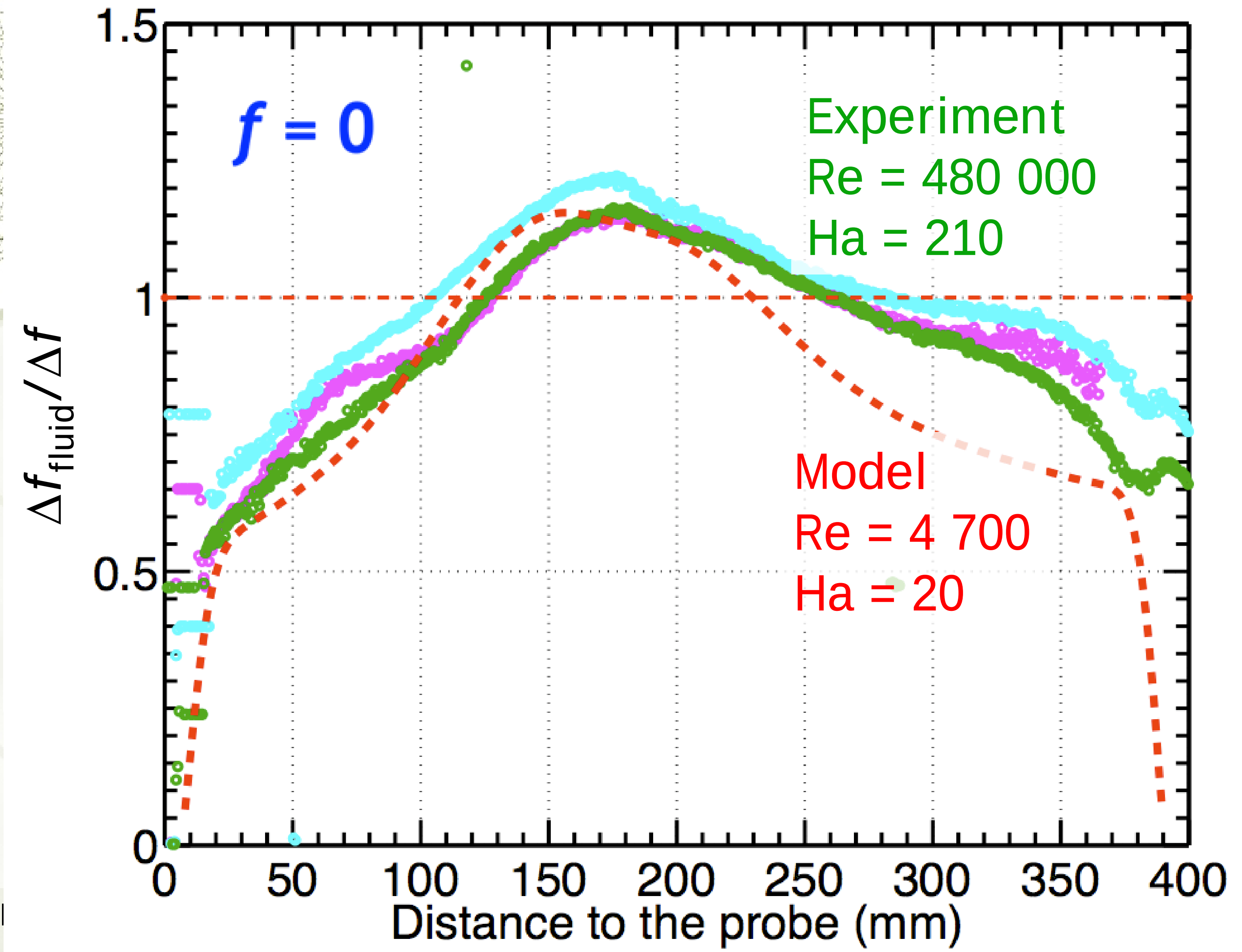
Axisymmetric non-linear model (D. Jault)

Re = 4700
Ha = 20
Pm = 7.5 10^{-6}

Angular velocity isocontours

Super-rotation in red

Super-rotation in DTS



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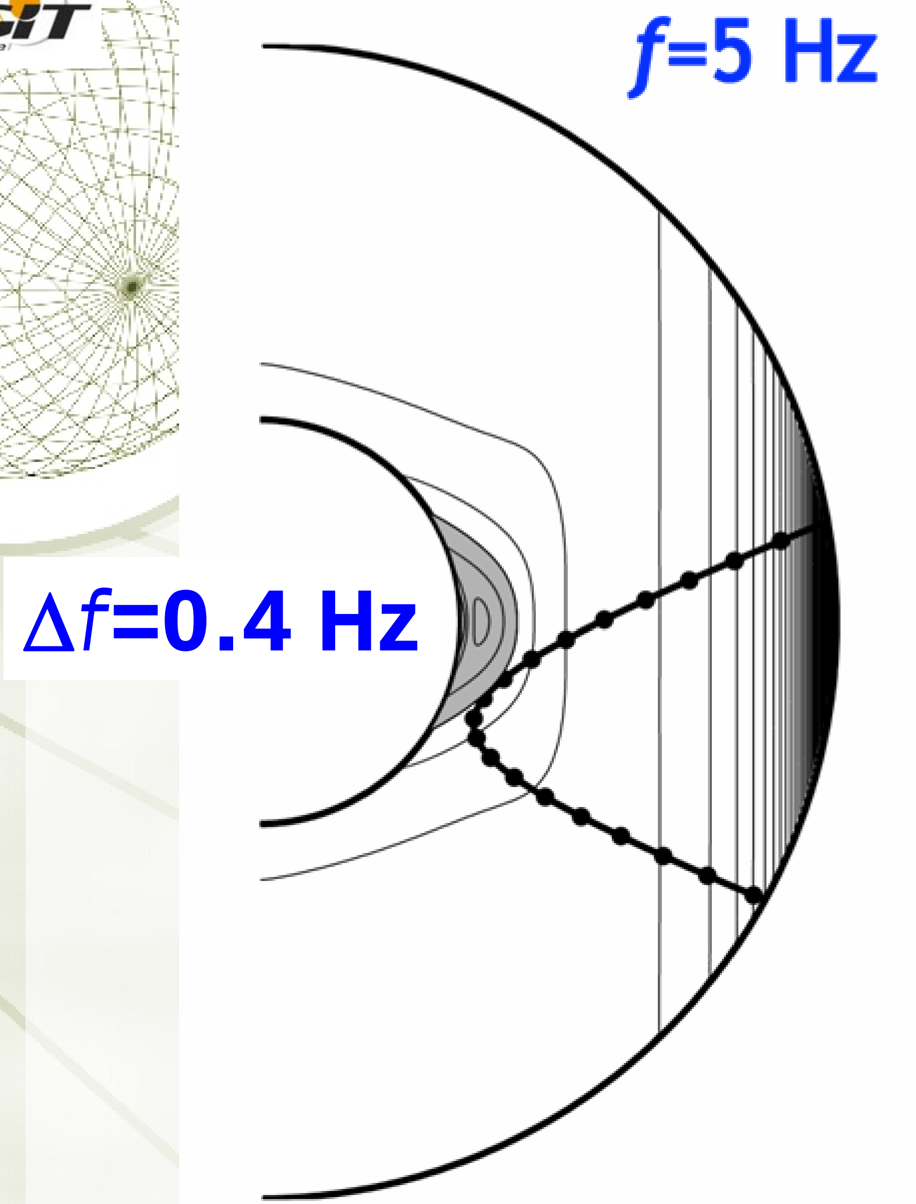
Rotating outer sphere



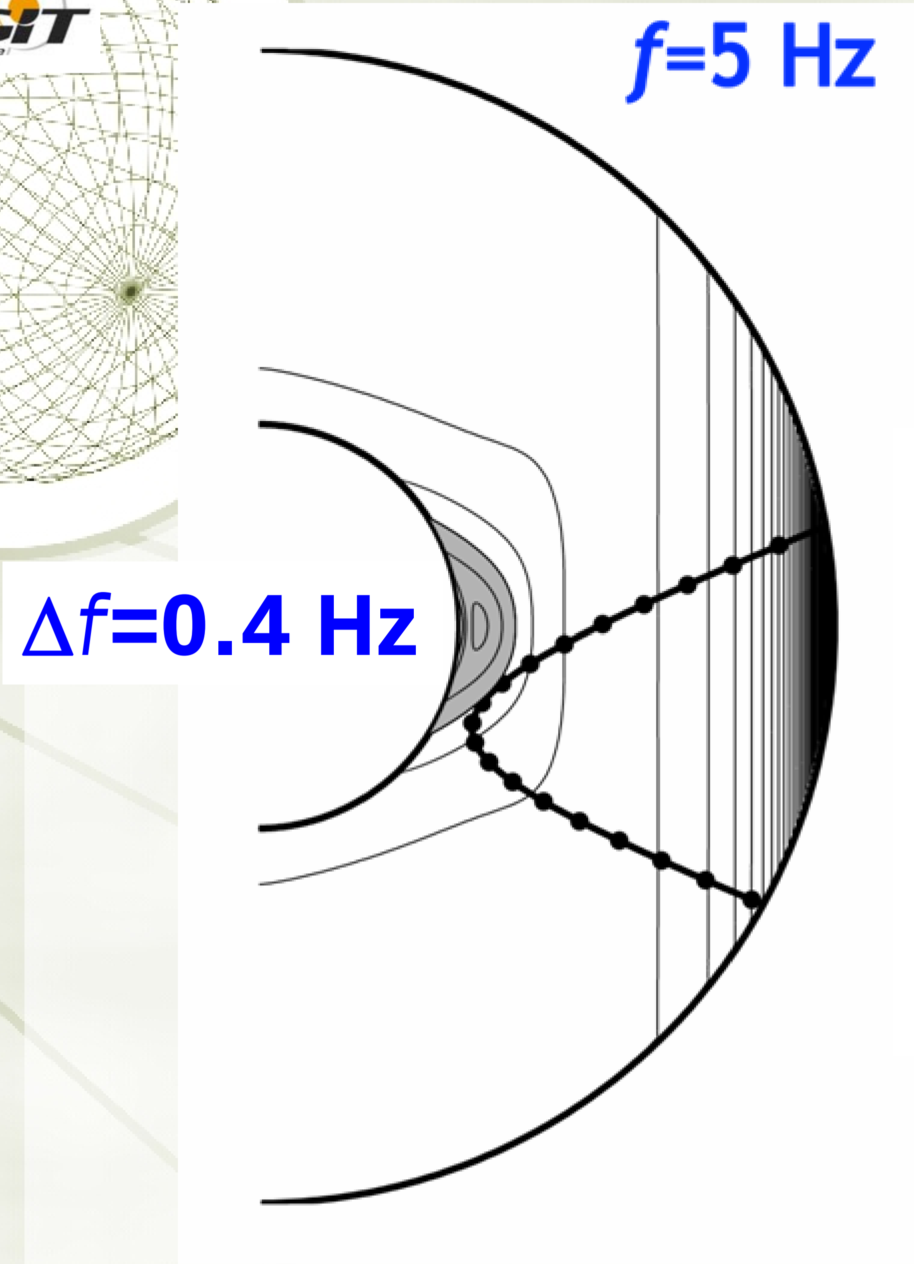
Axisymmetric
non-linear model
(D. Jault)

Re = 60 000
Ha = 210
Pm = $7.5\ 10^{-6}$
E = $4.7\ 10^{-7}$

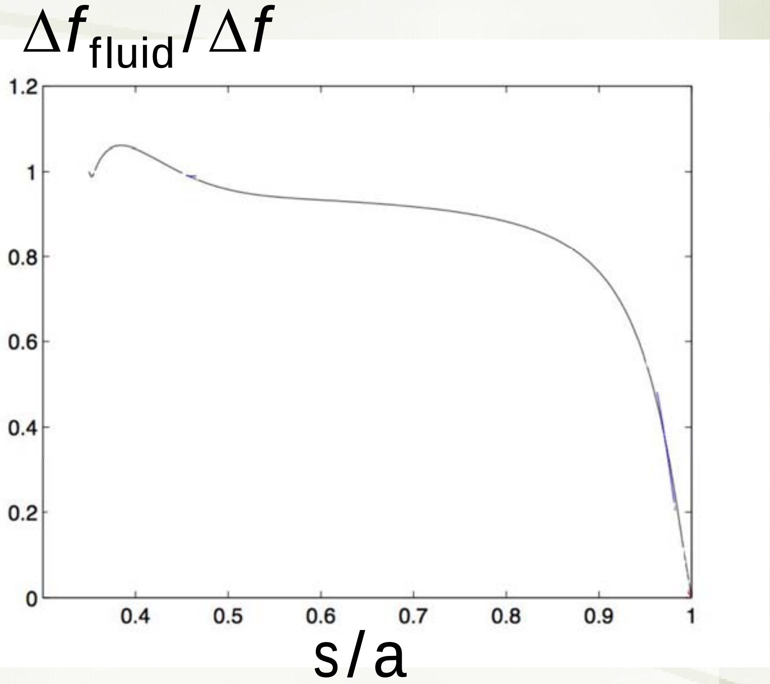
Angular velocity
isocontours

Super-rotation shaded

Nataf et al, PEPI, 2008



Angular velocity in the equatorial plane

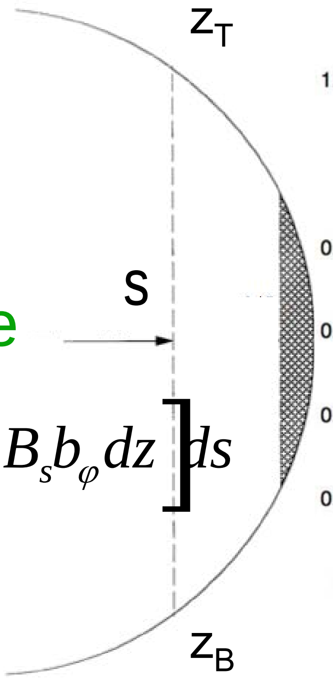


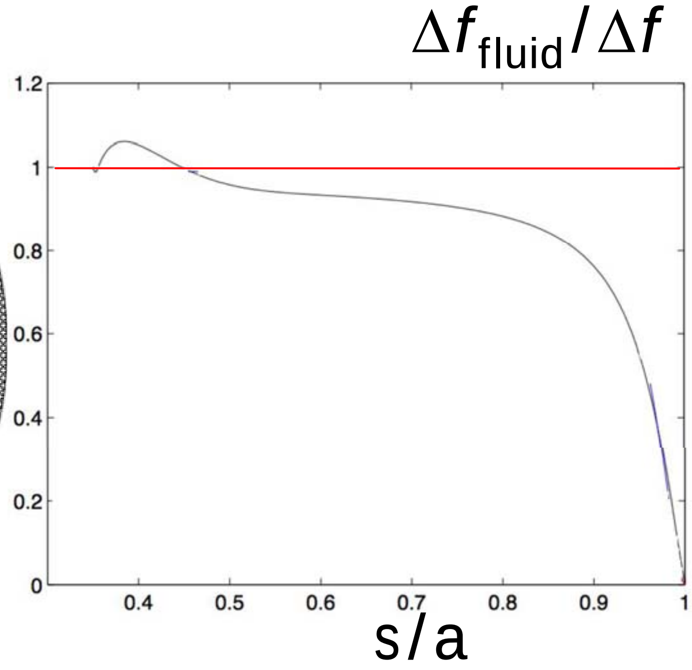
Taylor state (Taylor, 1963)

$$0 = \eta \Delta_H b_\varphi + s B_s \frac{d\Delta f(s)}{ds}$$

Magnetic torque

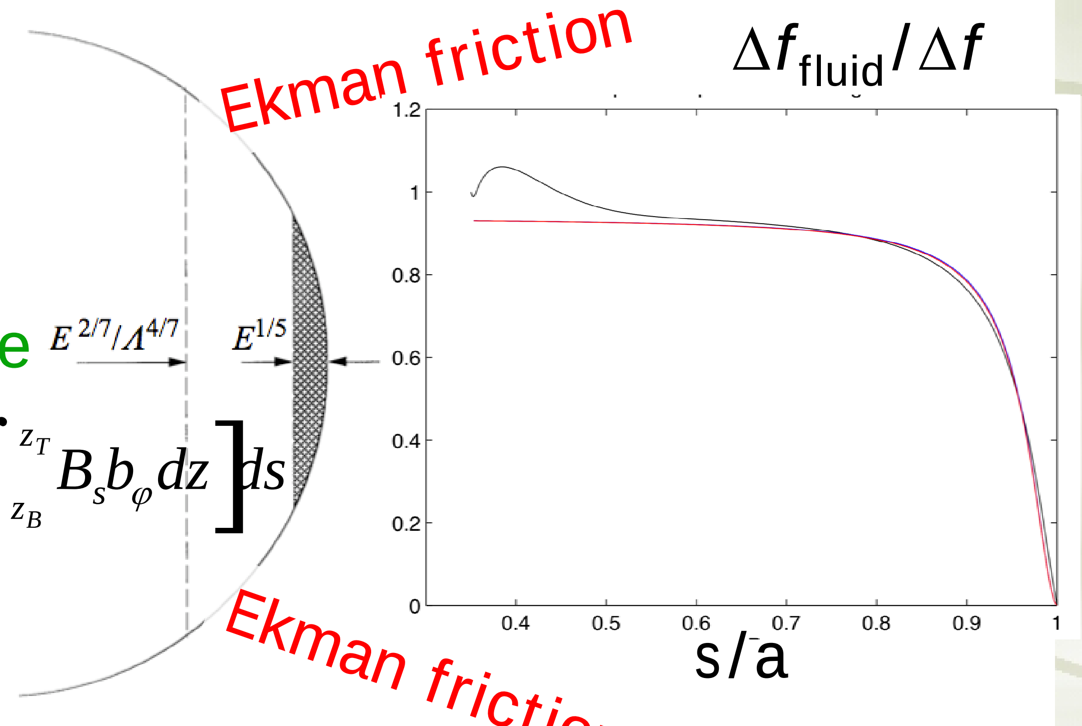
$$0 = d\Gamma_M(s) = \frac{2\pi}{\mu_0}\frac{d}{ds}\left[s^2 \int_{z_B}^{z_T} B_s b_\varphi dz\right] ds$$





Modified Taylor state (Kleeorin et al, 1997)

228 *N. Kleeorin, I. Rogachevskii, A. Ruzmaikin, A. M. Soward and S. Starchenko*

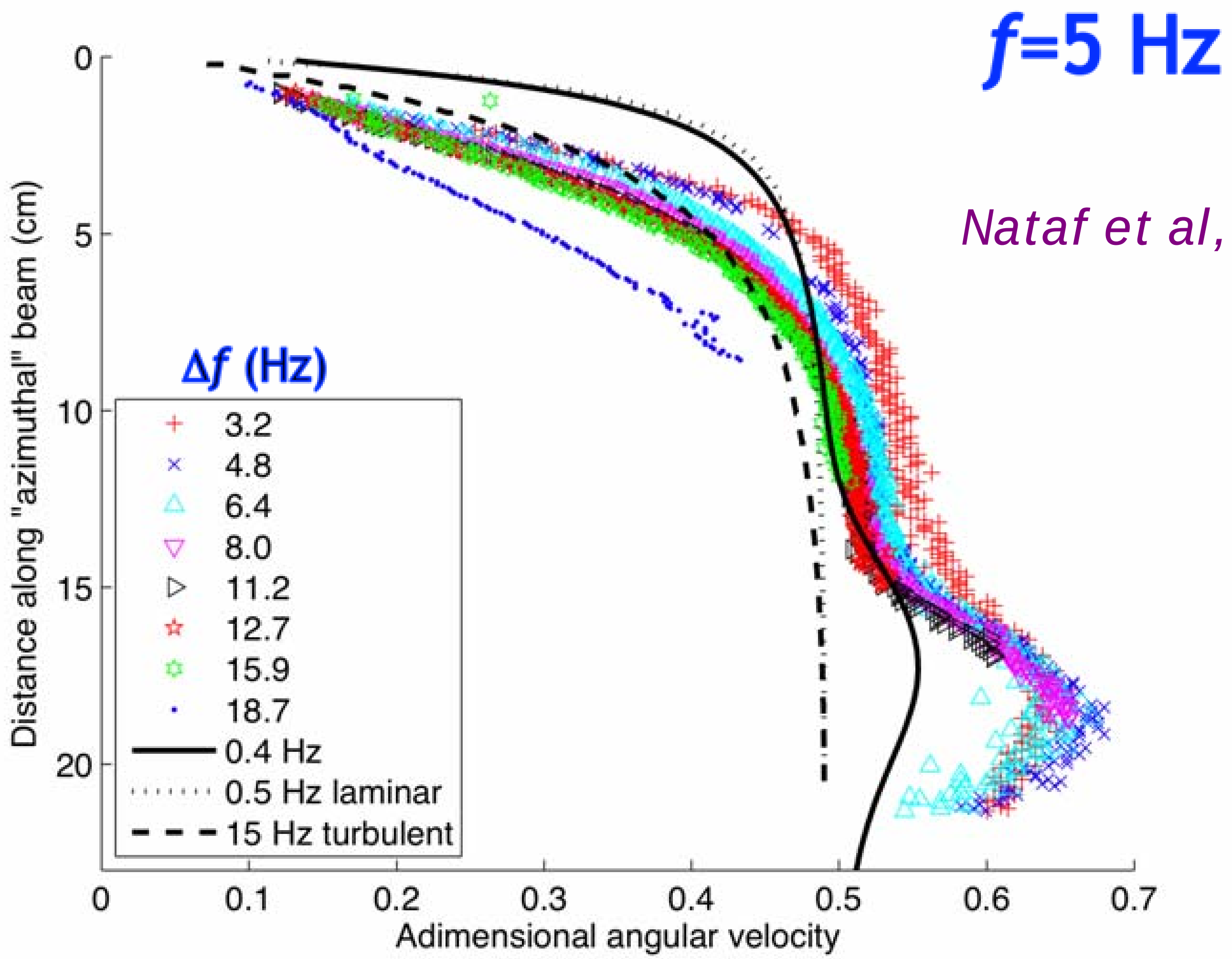


Magnetic torque

$$2d\gamma_{Ekman} = d\Gamma_M(s) = \frac{2\pi}{\mu_0}\frac{d}{ds}\left[s^2\int_{z_B}^{z_T} B_s b_\varphi dz\right]ds$$

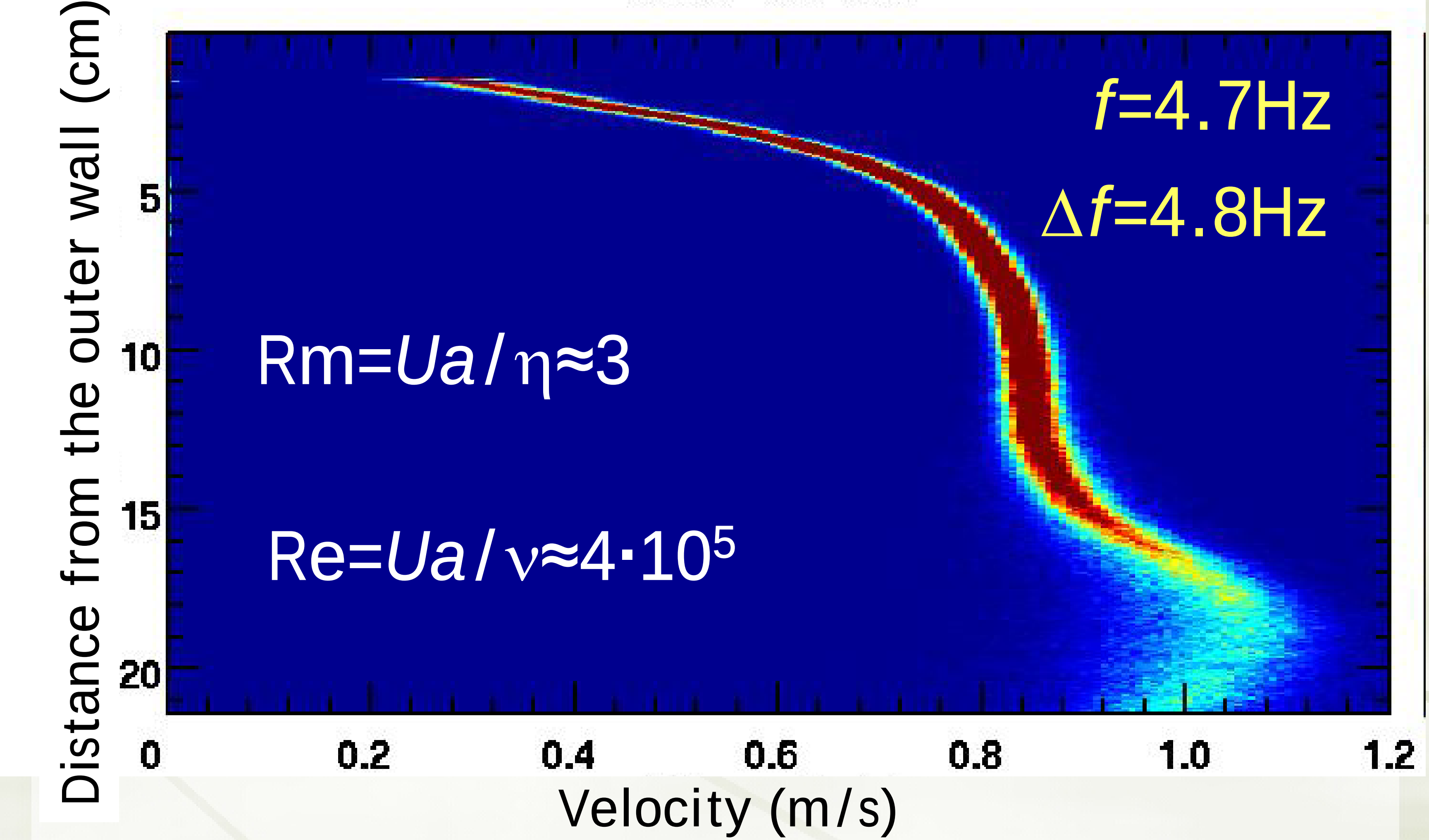
FIGURE 3. The equatorial ring in the intermediate and strong field limits $E^{1/2} \ll \Lambda \ll 1$. The outer edge of the $E^{2/7}/\Lambda^{4/7}$ magnetic–Proudman layer abuts the $E^{2/5}$ Stewartson layer shown hatched.

Experimental, numerical and theoretical velocity profiles



Nataf et al, PEPI, 2008

Angular velocity 'pdf'



f=4.7Hz

Δf=4.8Hz

$Rm = Ua/\eta \approx 3$

$Re = Ua/\nu \approx 4 \cdot 10^5$

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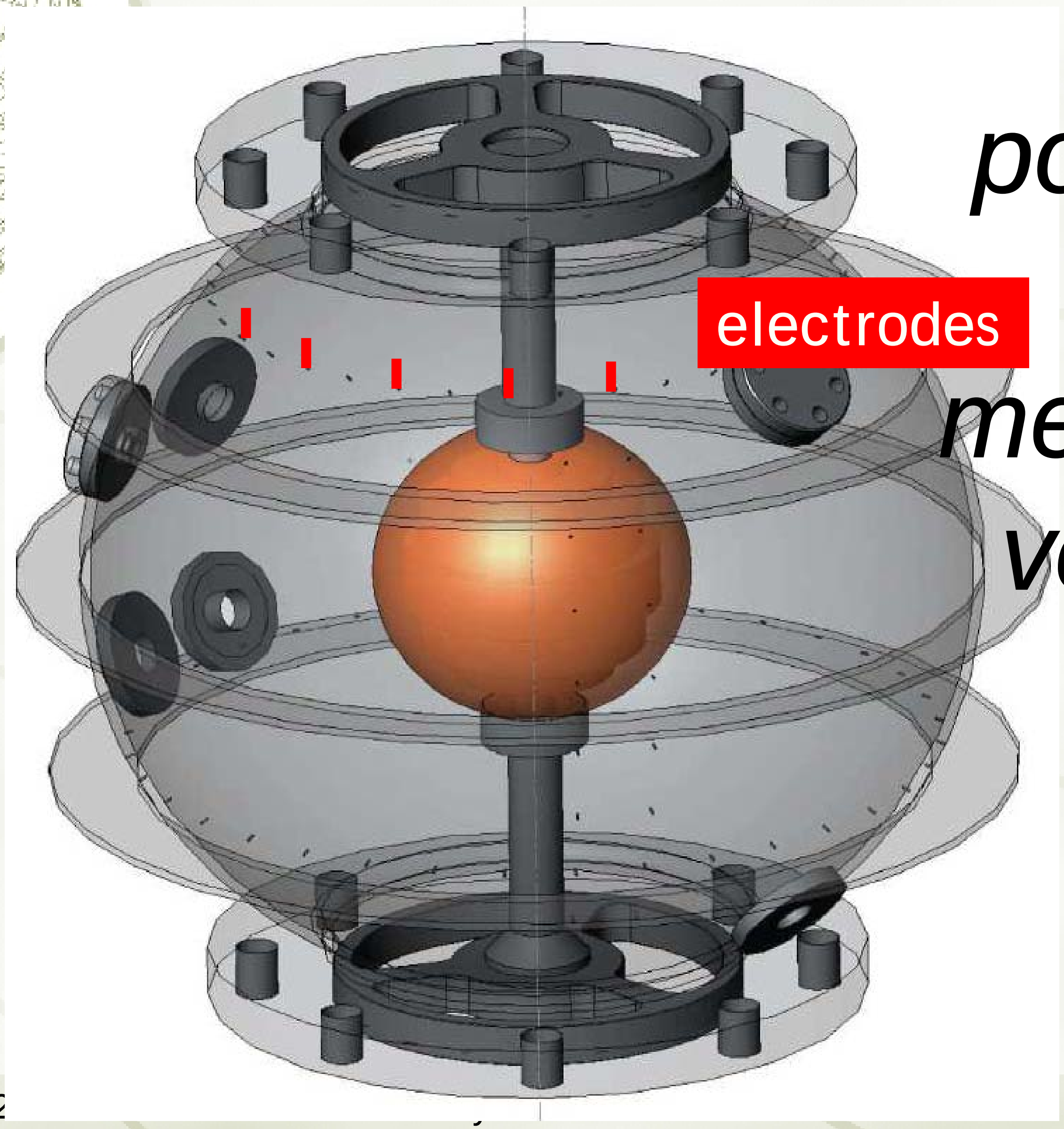
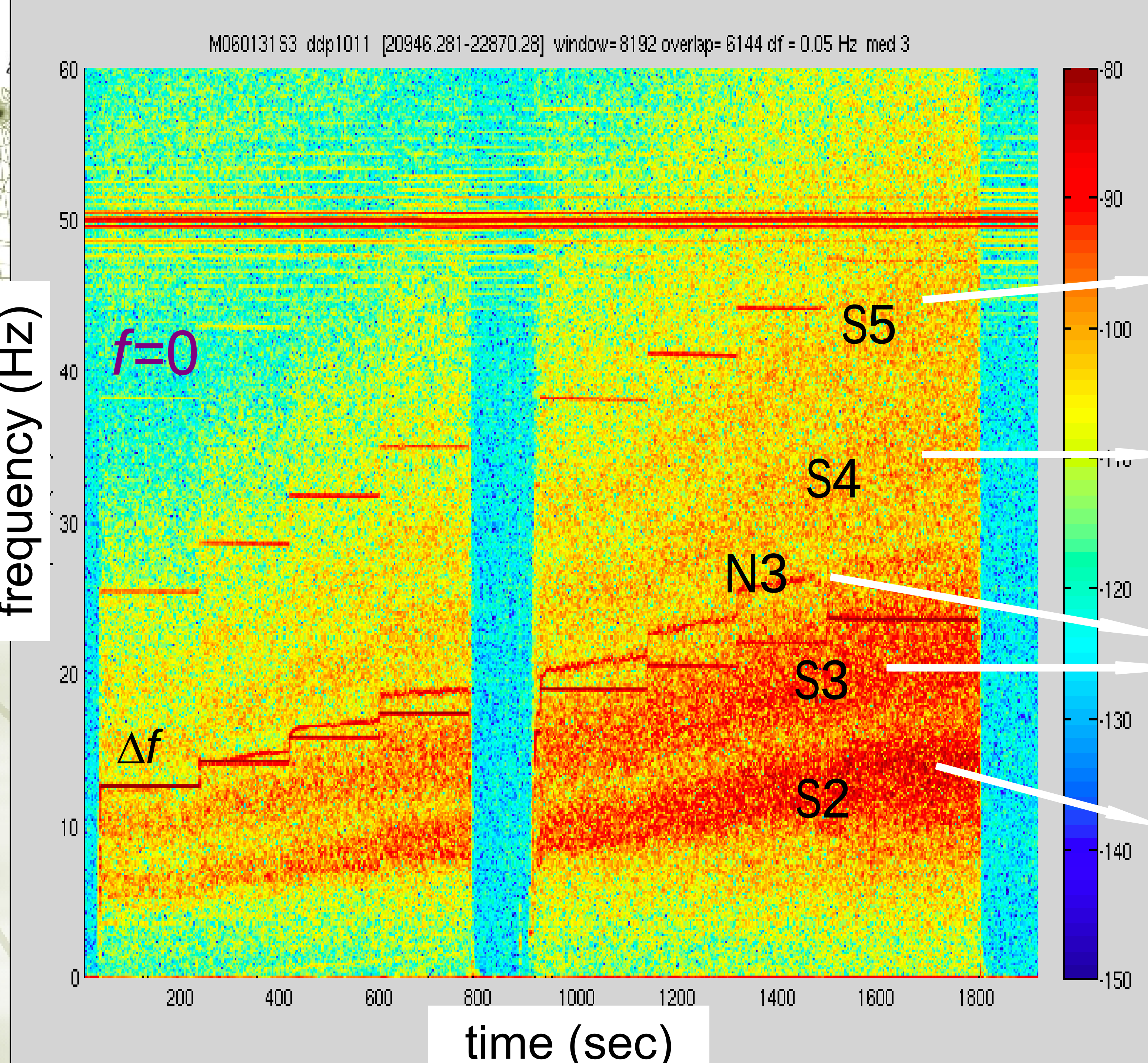
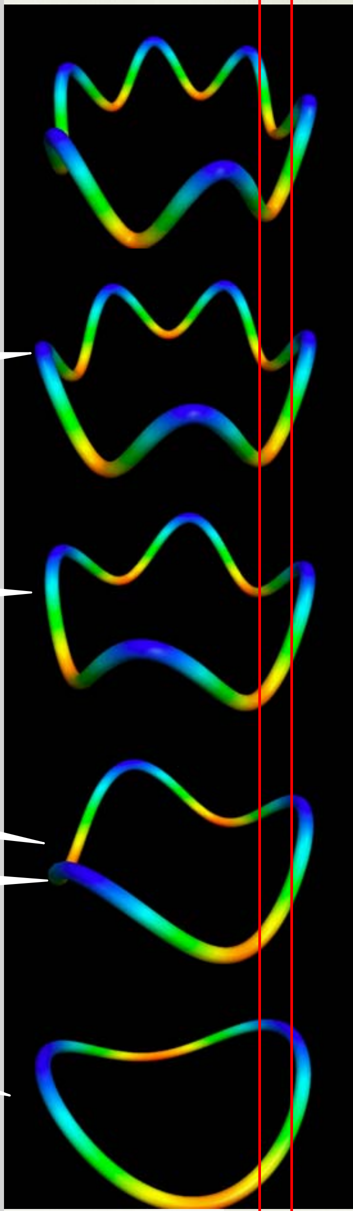
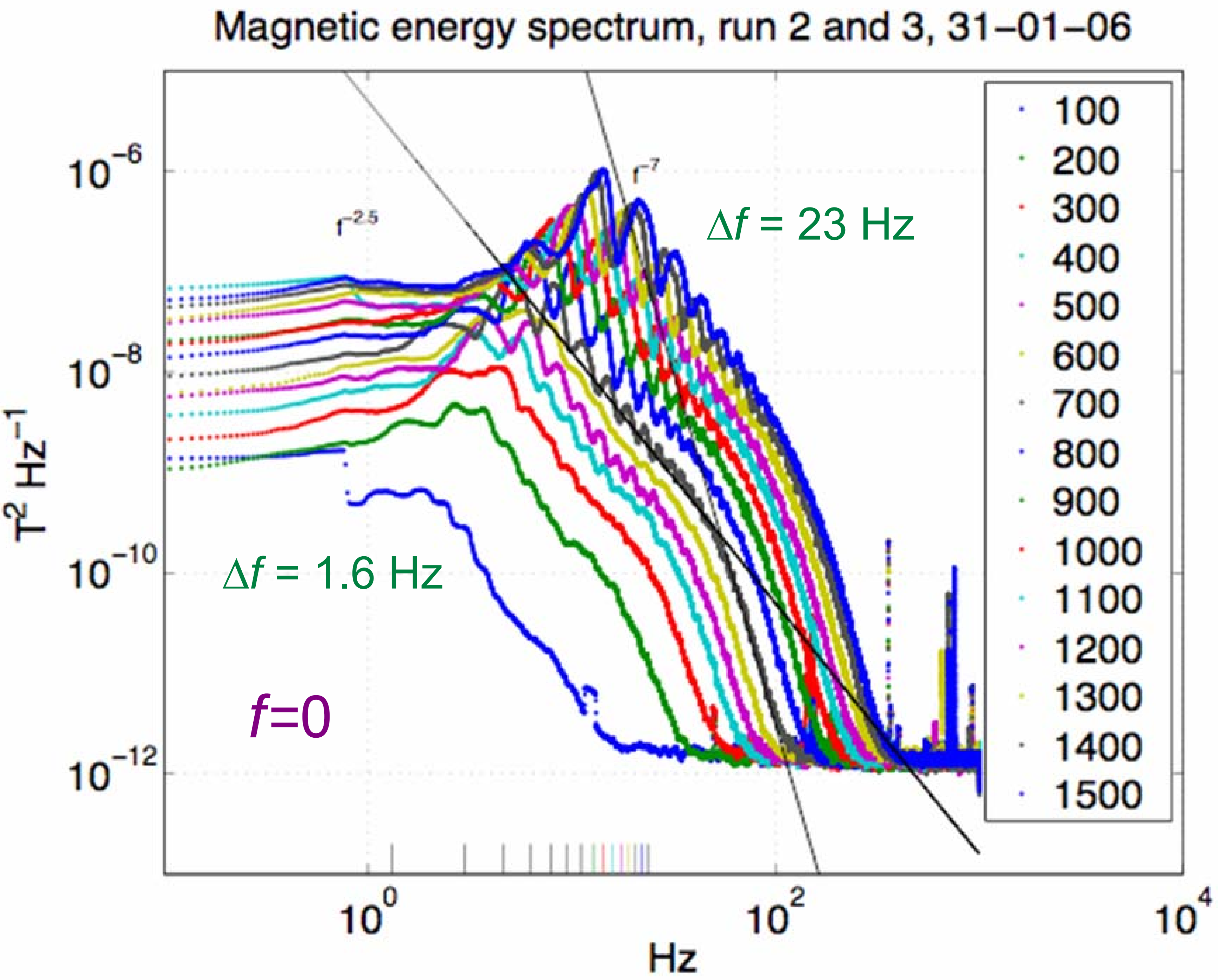
Electric potentials and meridional velocities



Outer sphere at rest


M060131S3 ddp1011 [20946.281-22870.28] window=8192 overlap=6144 df = 0.05 Hz med 3
frequency (Hz)
time (sec)
0
10
20
30
40
50
60
200
400
600
800
1000
1200
1400
1600
1800
-80
-90
-100
-110
-120
-130
-140
-150
f=0
Δf
S5
S4
N3
S3
S2





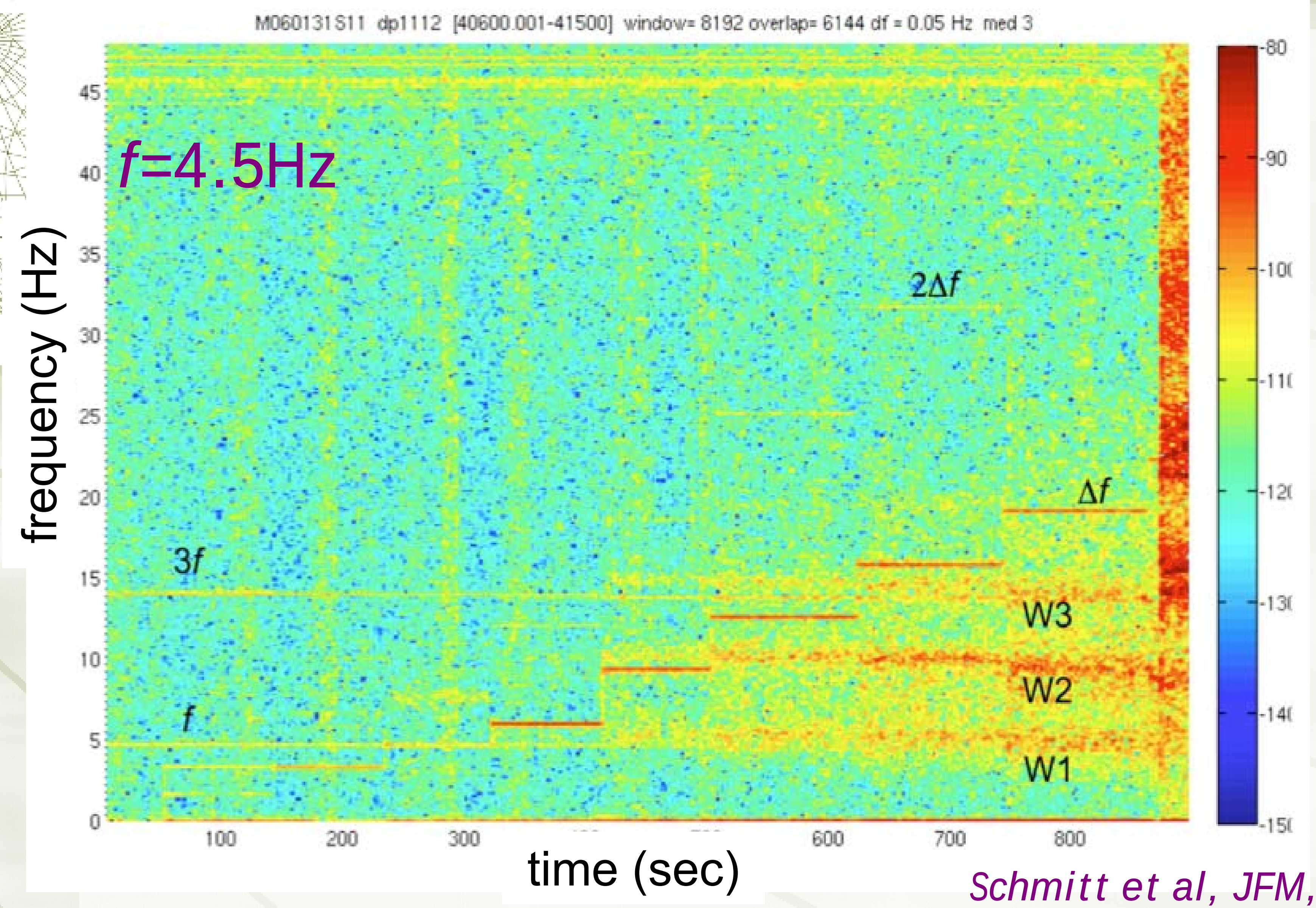
Magnetic energy spectrum, run 2 and 3, 31–01–06

Δf = 23 Hz

Δf = 1.6 Hz

f=0

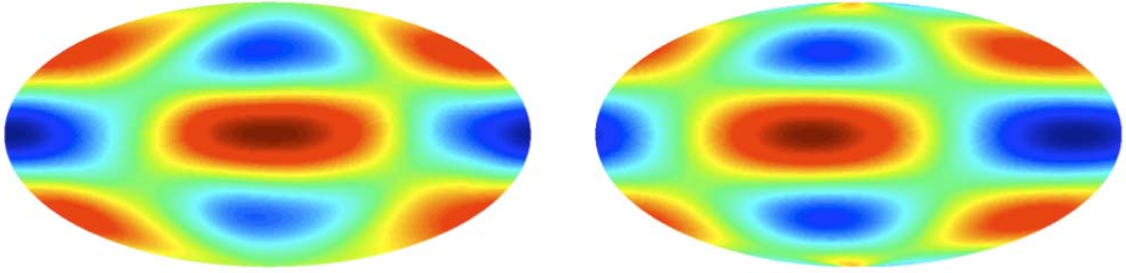
Rotating outer sphere



Schmitt et al, JFM, 2008

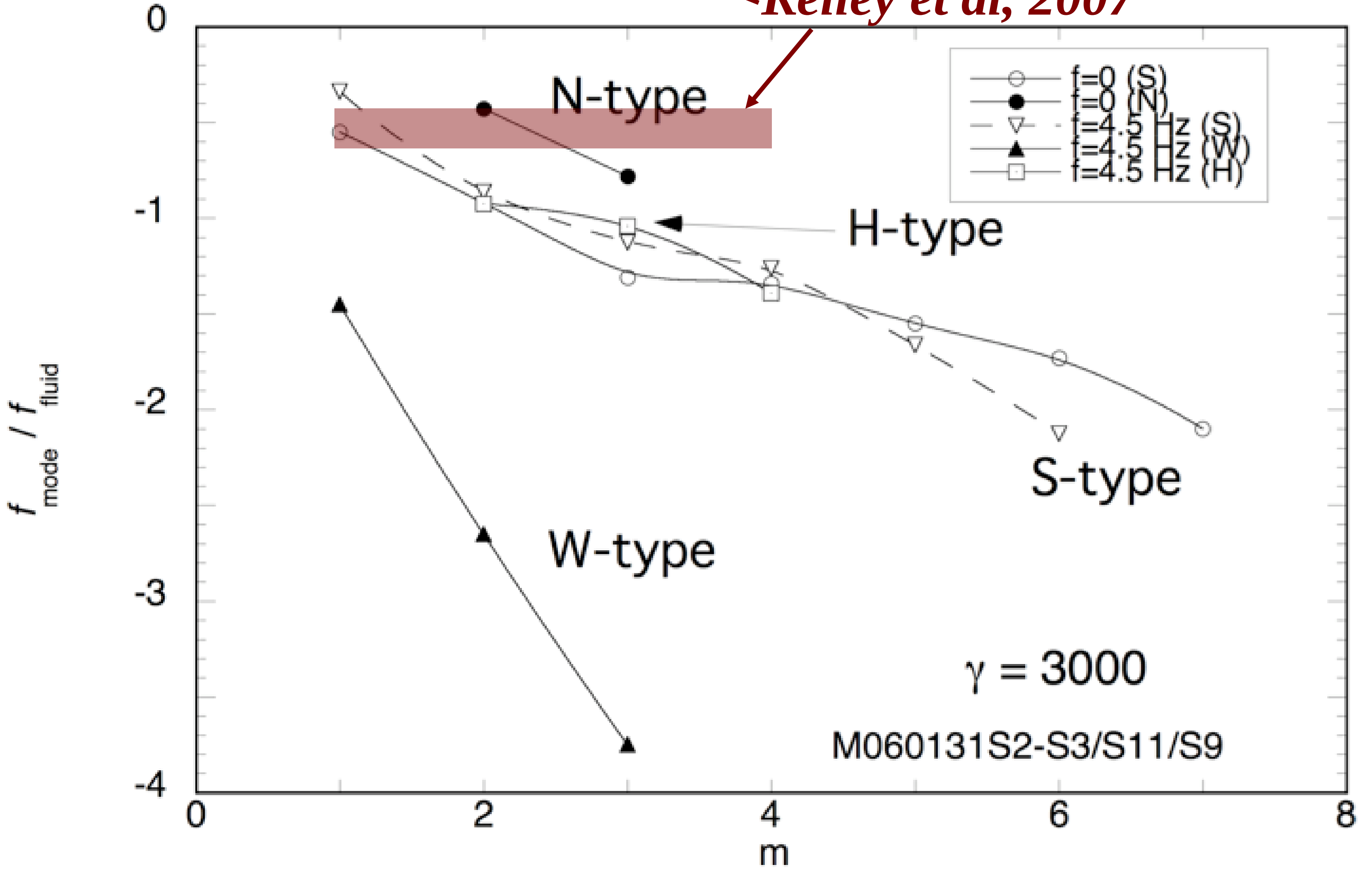
Schmitt et al, JFM, 2008

rtial waves



(a) $l_{mag} = 3,\ l = 4,\ m = 1,\ \omega/\Omega = 0.61$ (b) $l_{mag} = 3,\ l = 4,\ m = 1,\ \omega/\Omega = 0.612$

Kelley et al, 2007



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Conclusions (1/3)

- Large (25%) super-rotation observed for f=0
- Mean flow for $f \neq 0$:
  - Quasi-geostrophic (QG) domain where $\Lambda<1$: Coriolis dictates the geometry, Lorentz provides the driving.
  - Modified Taylor state : magnetic torque balances friction in the Ekman layers.
  - Experimental data well explained when turbulent layers are considered.

Nataf et al, PEPI, 2008

Conclusions (2/3)

- Fluctuations :
  - Dominated by non-axisymmetric waves/modes
  - Dispersion relations not compatible with inertial modes
- Fluctuations for *f*≠0 :
  - Almost no fluctuation/wave when Ro>0
  - The combined constraints of rotation and magnetic field kill turbulence (except in the boundary layers)

Schmitt et al, JFM, 2008

Conclusions (3/3)

- Speculations on turbulence in the Earth’s core : a very special kind :
  - For a prescribed magnetic field, and because of rotation, the flow has no freedom left to fluctuate.
  - The magnetic field can fluctuate, but only under the action of the flow.
  - There is no dynamical constraint on the density field: it can fluctuate, but only under the action of the flow.

Nataf & Gagnière, CRAS, 2008

To foster the discussion…

- Flow at Re=10^6 is highly turbulent

  not in DTS
- One can use subgrid models of turbulence

  not in DTS
- The induced magnetic field is large where the imposed field is large

  not in DTS
- Joule dissipation dominates when B is large

  perhaps not in DTS
- It is difficult to measure flow velocity in liquid sodium expts

  yes, even in DTS, but we did it…


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A few articles

- Nataf & Gagnière, On the peculiar nature of turbulence in planetary dynamos, CRAS, accepted, 2008.
- Schmitt et al., Rotating spherical Couette flow in a dipolar magnetic field: experimental study of magneto-inertial waves, *J. Fluid Mech., in press*, 2008.
- Jault D., Axial invariance of rapidly rotating diffusionless motions in the Earth's core interior, *Phys. Earth Planet. Inter.*, **166**, 67-76, 2008.
- Nataf et al., Rapidly rotating spherical Couette flow in a dipolar magnetic field: an experimental study of the mean axisymmetric flow, *Phys. Earth Planet. Inter., accepted,* 2008.
- Nataf et al., Experimental study of super-rotation in a magnetostrophic spherical Couette flow, *Geophysical and Astrophysical Fluid Dynamics*, **100**, 281-298, 2006.
- Schaeffer & Cardin, Quasi-geostrophic kinematic dynamos at low magnetic Prandtl numbers, *Earth Planet. Sci. Lett.*, **245**, 595-604, 2006.
- Schaeffer & Cardin, Rossby-wave turbulence in a rapidly rotating sphere, *Nonlinear Processes in Geophysics*, **12**, 947-953, 2005.
- Cardin et al., Towards a rapidly rotating liquid sodium dynamo experiment, *Magnetohydrodynamics*, **38**, 177-189, 2002.
- Dormy et al., A super-rotating shear layer in magnetohydrodynamic spherical Couette flow, *J. Fluid Mech.*, **452**, 263-291, 2002.