Torsional Alfvén waves in a dipolar magnetic field: *experiments and simulations*

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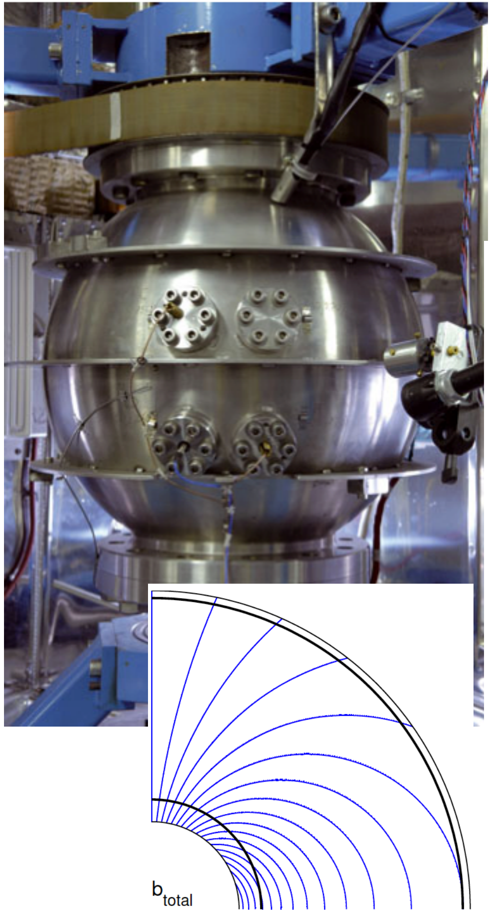
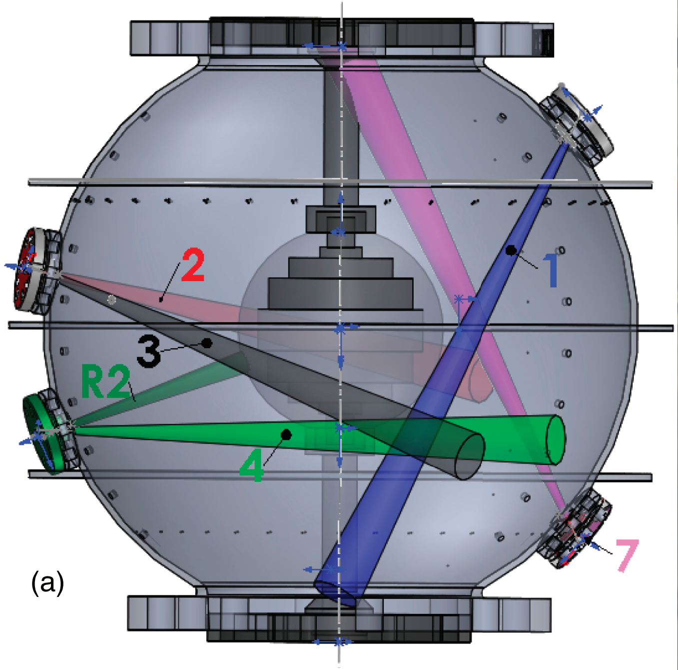
FDEPS Research Seminar, Kyoto

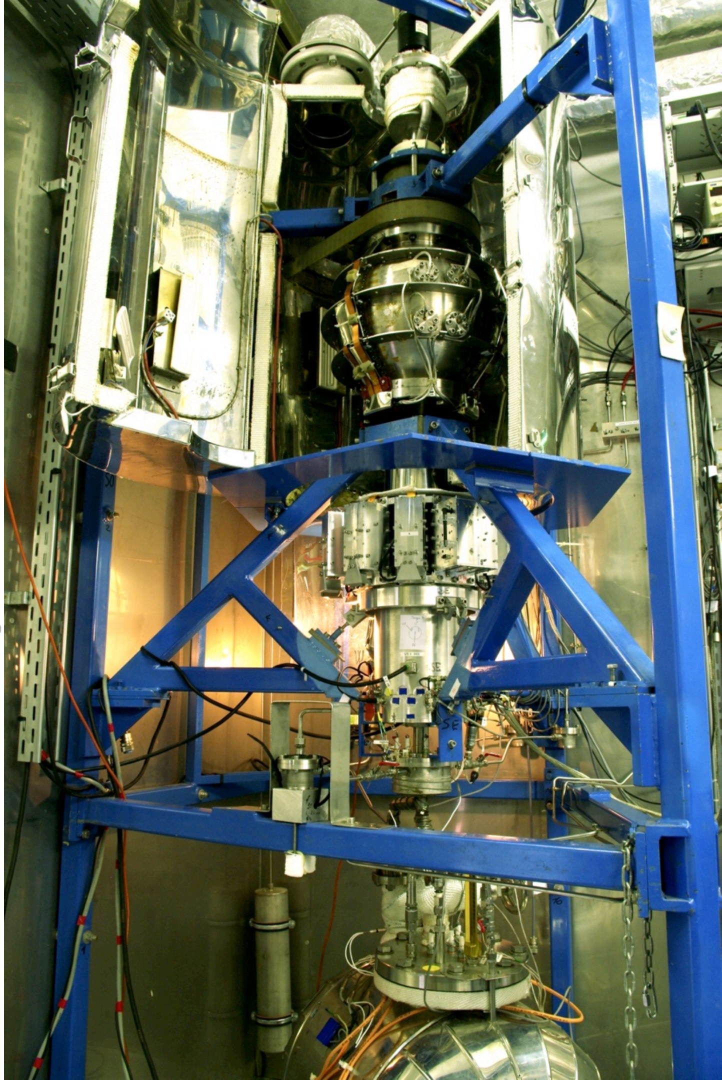
The liquid sodium DTS experiment

- The goals of DTS:
  - explore the *magnetostrophic* regime, in which the Coriolis force and the Lorentz force are comparable.
  - Pave the way for a spherical Couette dynamo experiment.
- First measurements in 2005.
- DTS-Ω version in 2015.

The DTS set-up







Physical properties of liquid sodium

Property	symbol	Value	Unit
Density	ρ	930	$kg.m^{-3}$
Electrical conductivity	σ	9.10^6	$\Omega^{-1}\ m^{-1}$
Kinematic viscosity	ν	$6.5.\ 10^{-7}$	m^2/s
Magnetic Diffusivity	η	$8.84.10^{-2}$	m^2/s
Temperature	T	130	°C

Physical parameters of DTS

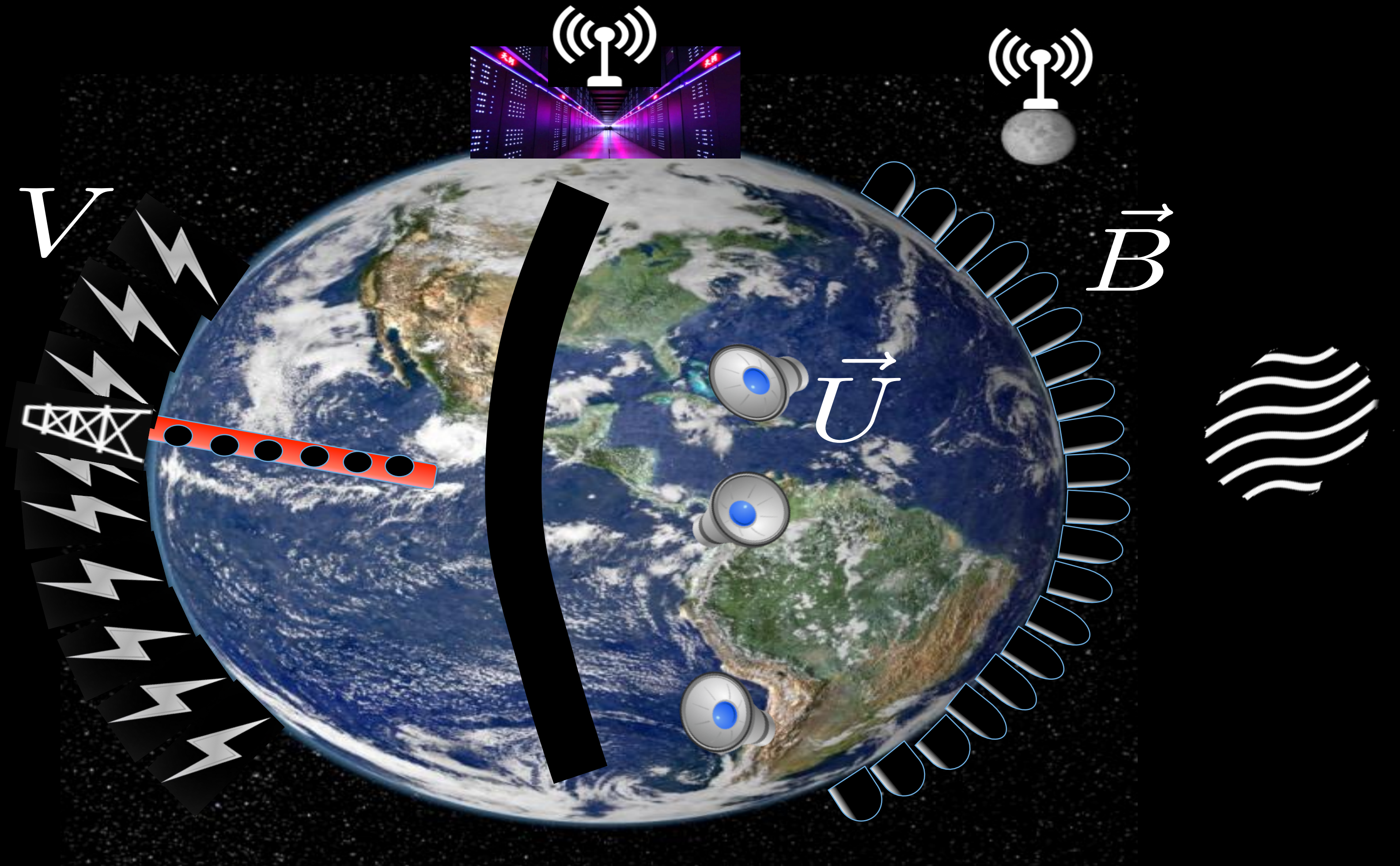
Property	symbol	Value	Unit
Outer sphere radius	r_o	210	mm
Inner sphere radius	r_i	74	mm
Outer sphere maximum rotation rate	f_o	15	Hz
Inner sphere maximum rotation rate	f_i	30	Hz
$B(r=r_o, \theta=\pi/2)$	B_o	8	mT
$B(r=r_i, \theta=\pi/2)$	B_i	173	mT

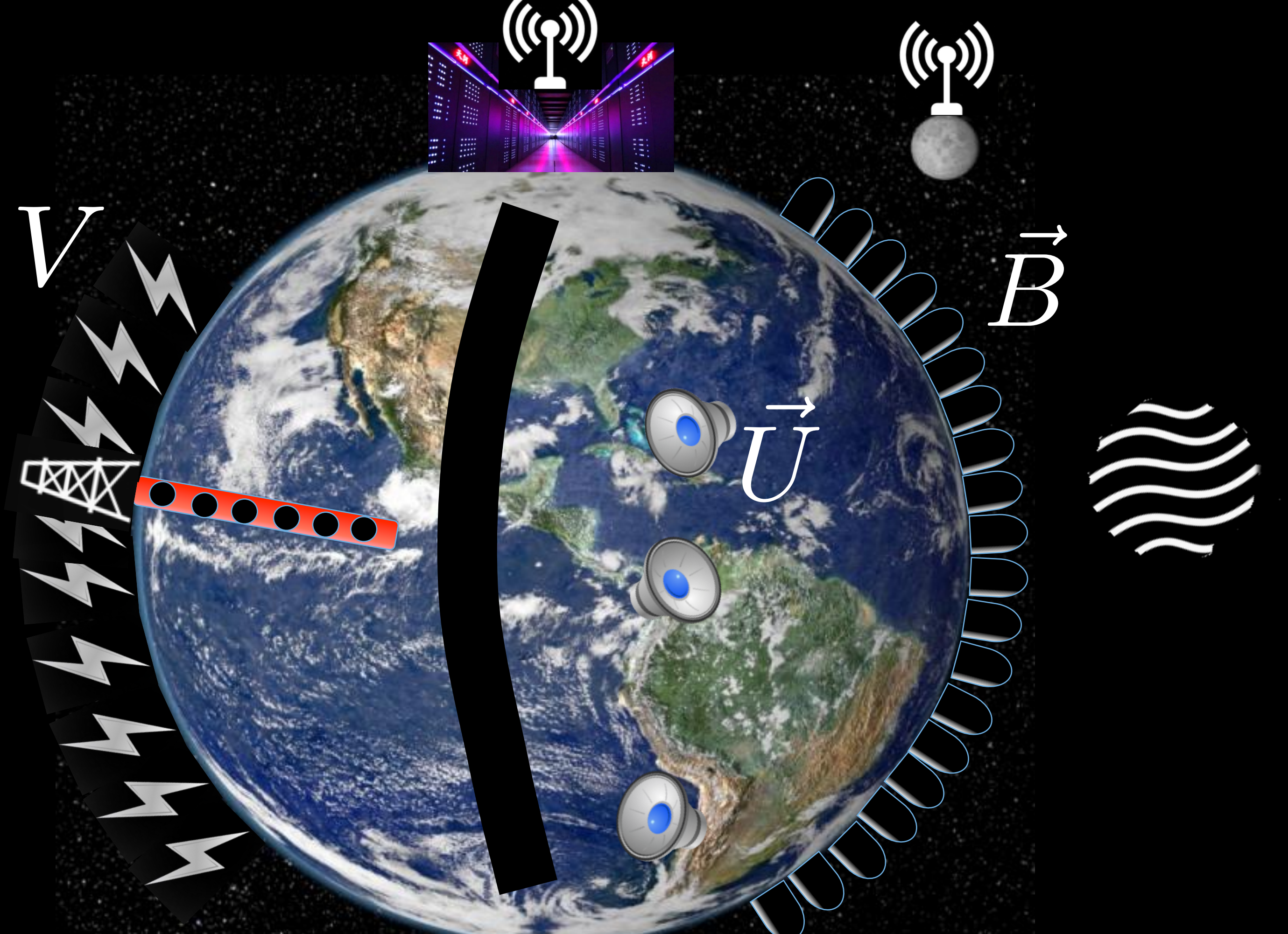
Dimensionless numbers for f_o = 15 Hz, Δf = 30 Hz

Number	expression	value		*Earth core*
Magnetic Prandtl	ν / η	**7.4 x 10^{-6}**		*~10^{-5}*
Ekman	$\nu / \Omega r_o^2$	**1.6 x 10^{-7}**		*~10^{-15}*
Reynolds	$\Delta\Omega\, r_o^2 / \nu$	**1.3 x 10^{7}**		
Magnetic Reynolds	$\Delta\Omega\, r_o^2 / \eta$	**94**		*~10^{3}*

Measurement techniques

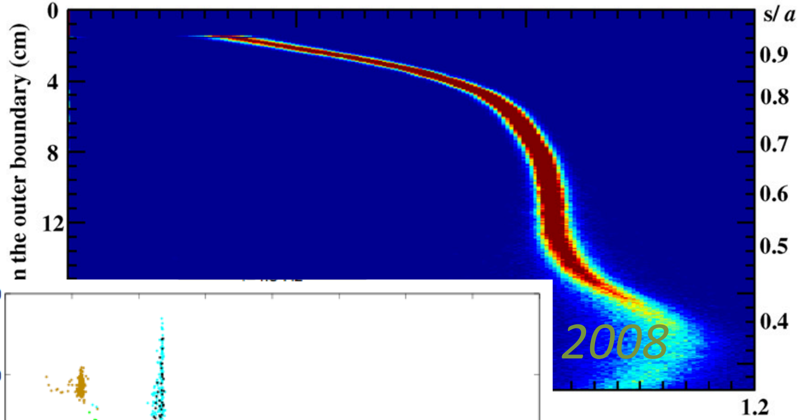
- Magnetic field at the surface
- Magnetic field in a sleeve inside the fluid
- Electric potentials at the surface
- Ultrasound Doppler Velocimetry

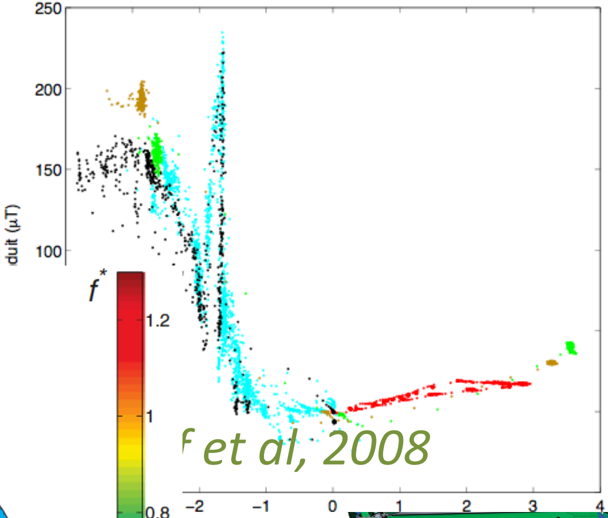

V
$\vec{U}$
$\vec{B}$

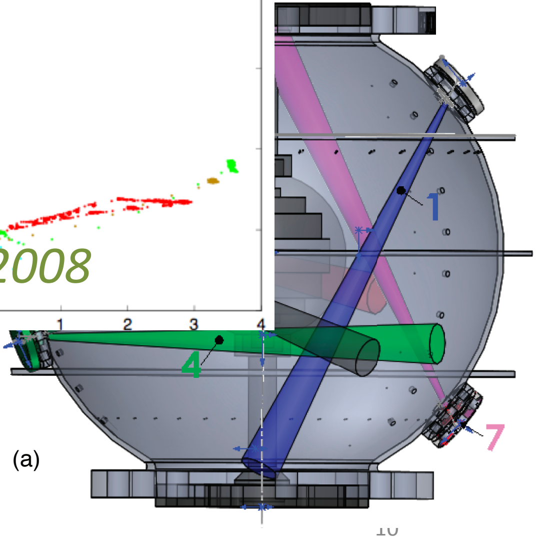

V
$\vec{B}$
$\vec{U}$

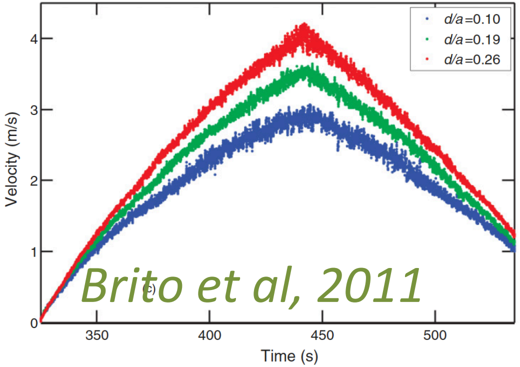
Main results

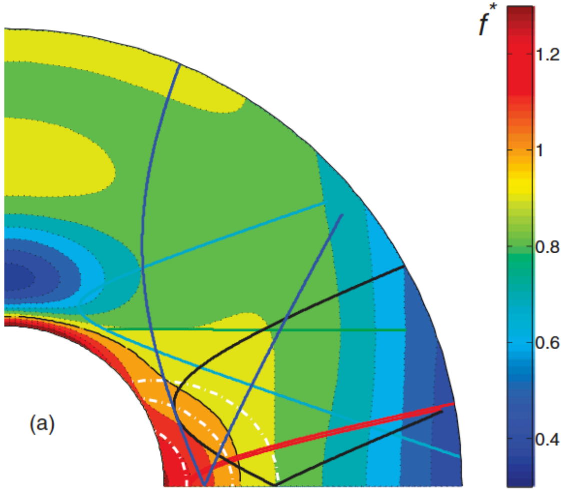
- Mean state:
  - ➢ Modified Taylor state
  - ➢ Induction peak at $Ro_{eff} \sim -1$
  - ➢ Super-rotation
  - ➢ $\Lambda \sim 1$ frontier





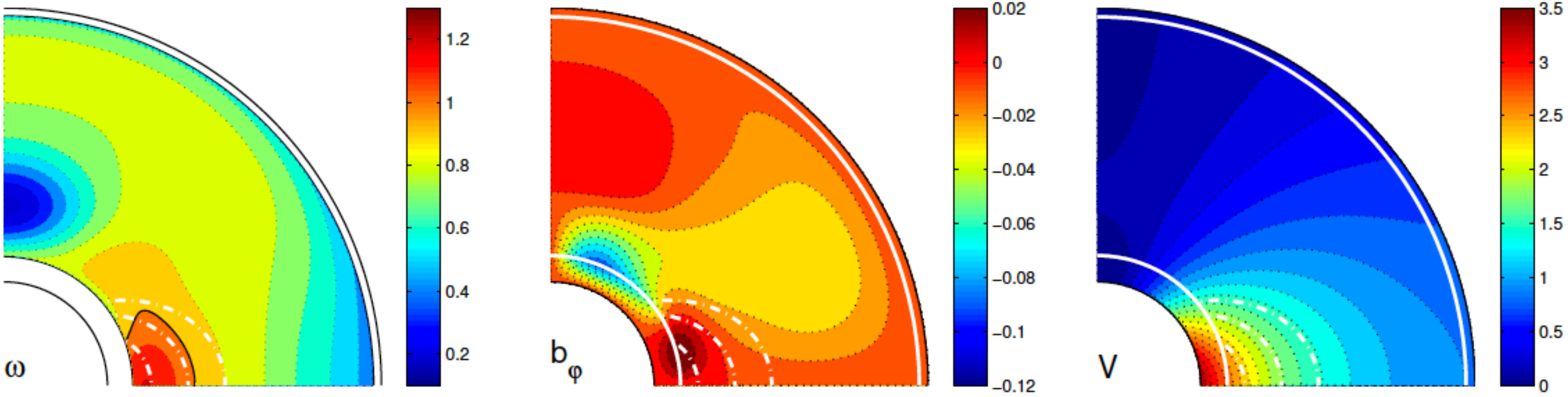






Main results

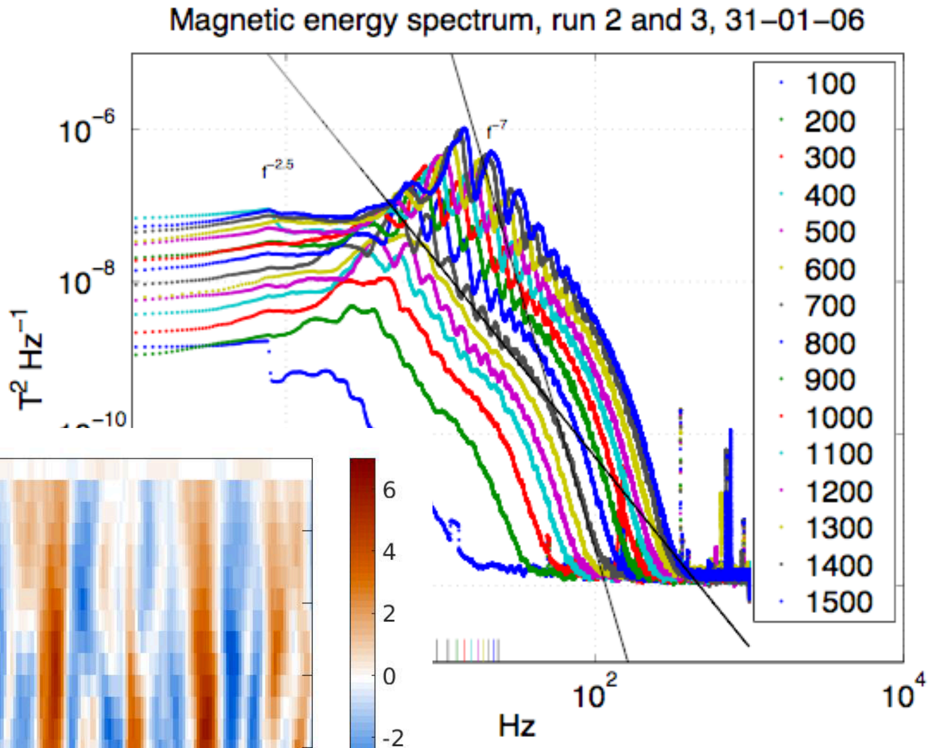
- Mean state:
  - ➢ Induction and diffusion: using the DTS experiment as a Navier-Stokes solver!



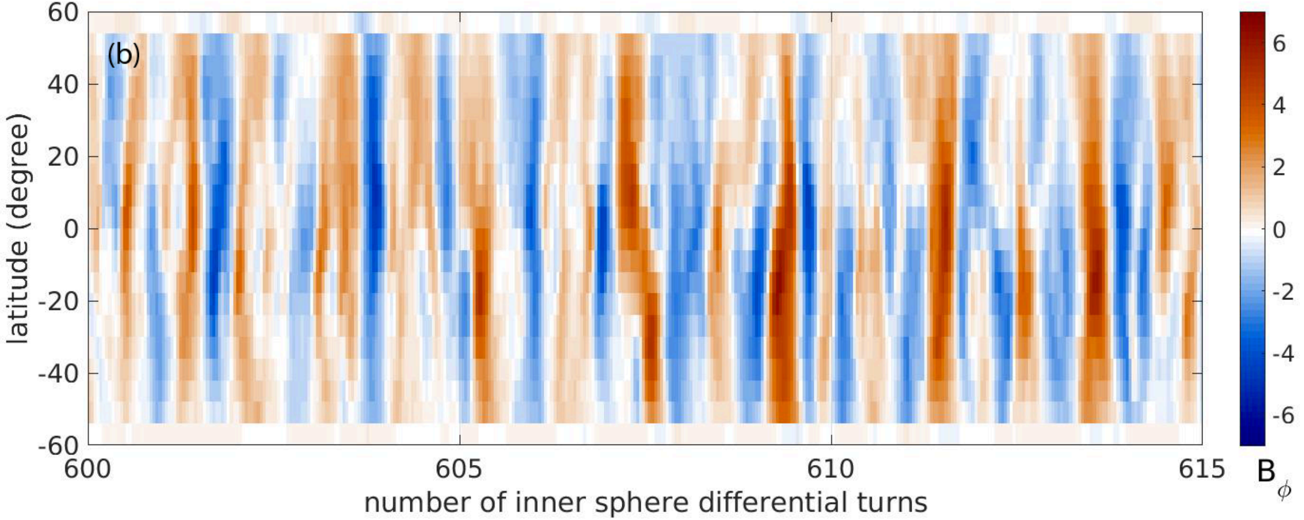
Nataf, 2013

Main results

- Fluctuations:
  - Modes and filaments



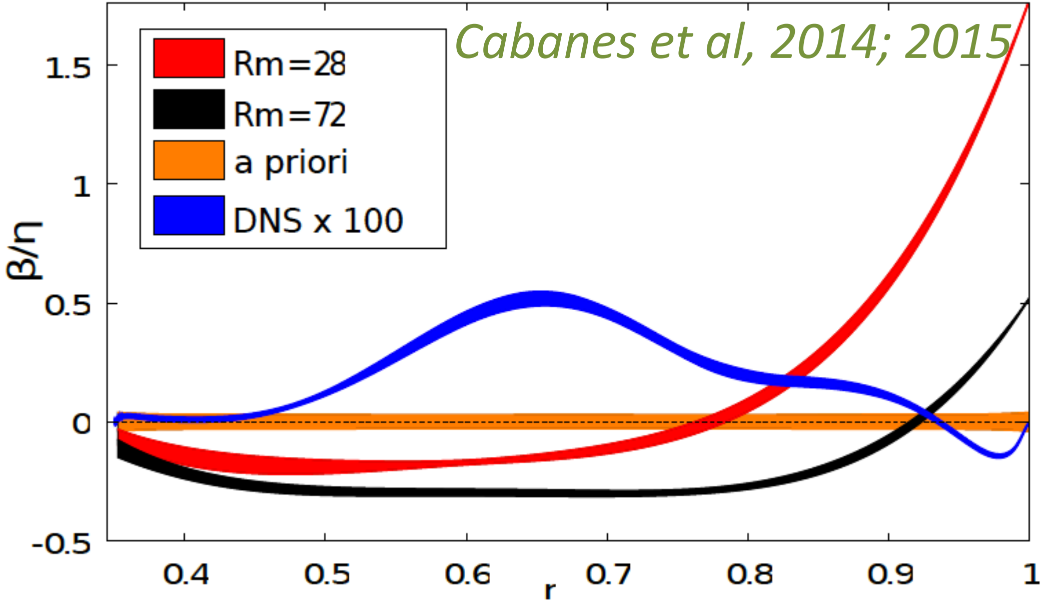
Schmitt et al, 2008; 2013



Kaplan et al, 2018

Main results

- Fluctuations, diffusion, and mean flow:
  - ➢ Turbulence *reduces* magnetic diffusivity



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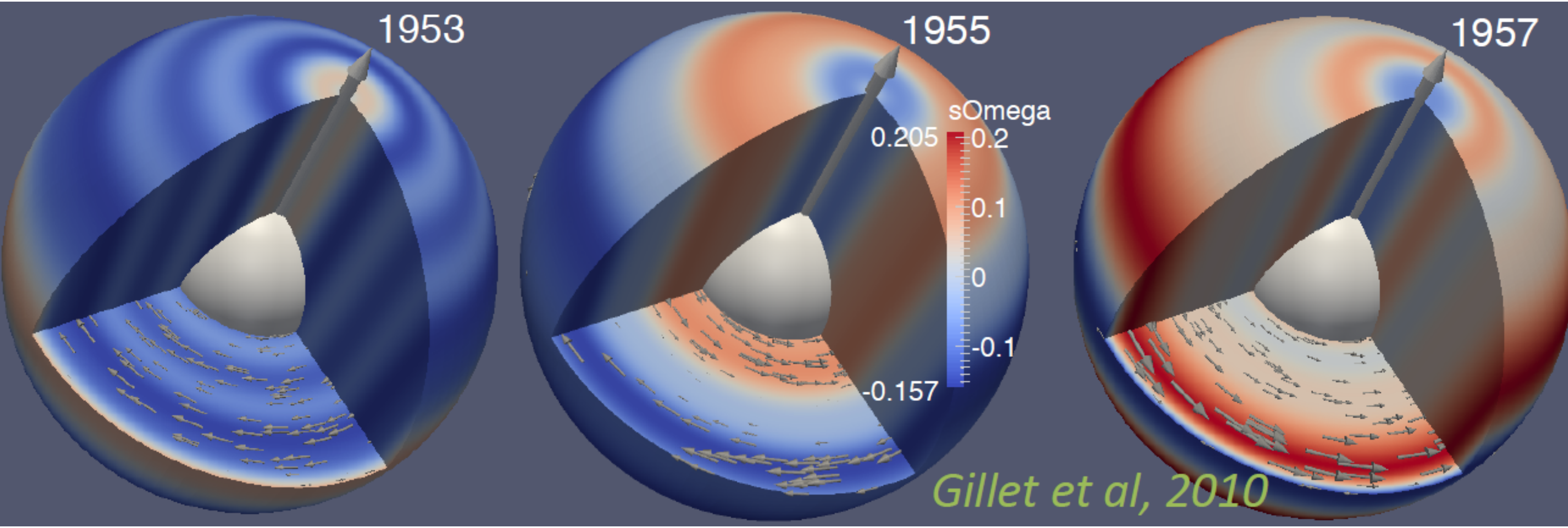
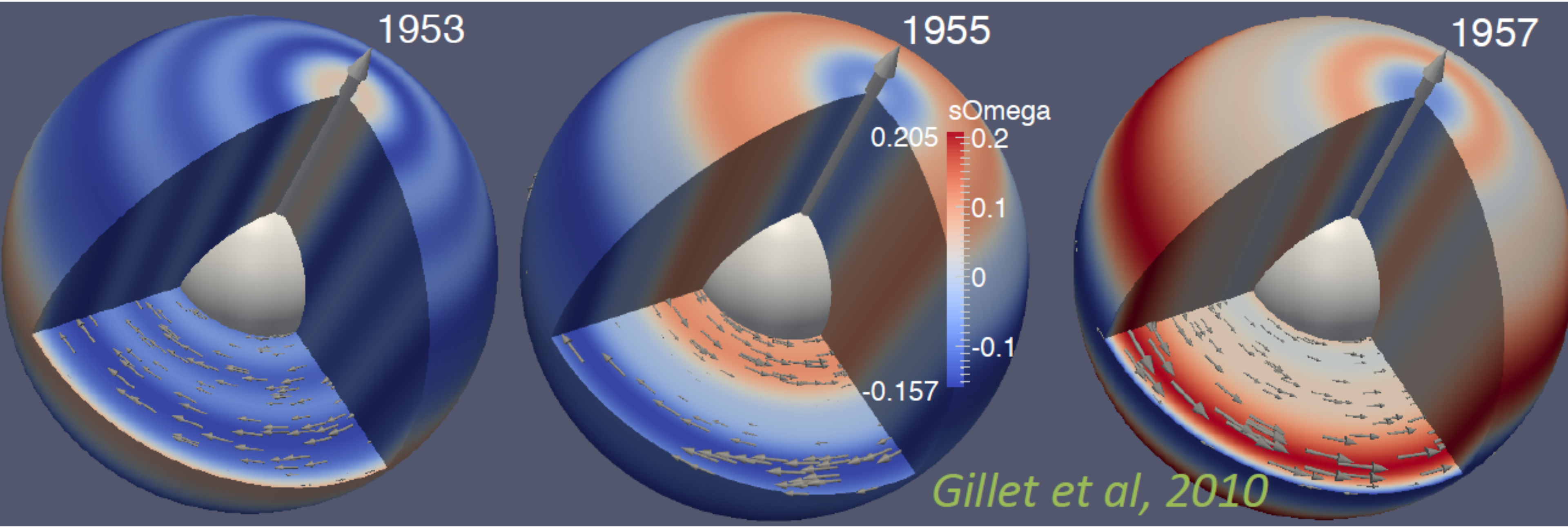
Torsional Alfvén waves in the Earth's core



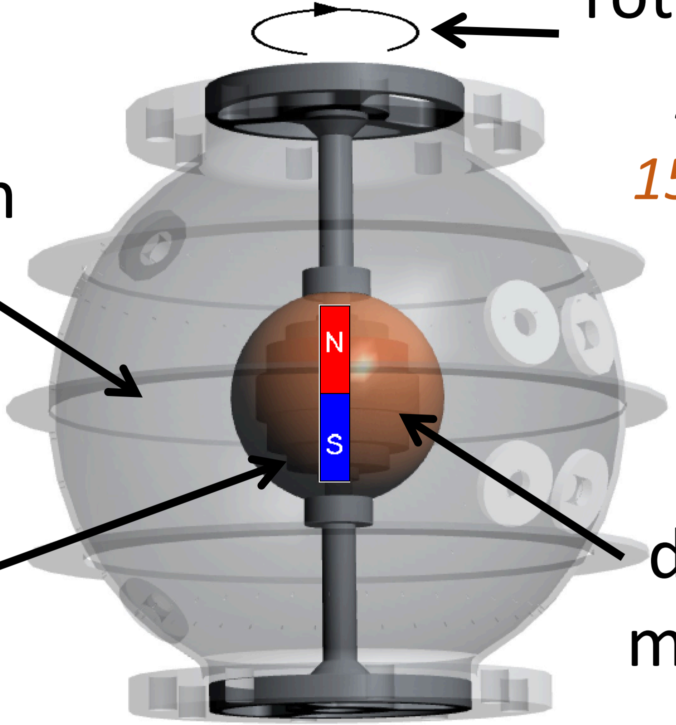
- Alfvén waves are strongly modified by the Coriolis force in planetary cores:
  - Alfvén waves that violate the Proudman-Taylor constraint are inhibited.
  - **Geostrophic Alfvén waves**, which are called torsional Alfvén waves, are favoured.

Torsional Alfvén waves in the Earth's core



Alfvén time: $\tau_A = \frac{r_o}{V_A} = \frac{r_o\sqrt{\mu_0\rho}}{B} \sim 4 \text{ years}$

Torsional Alfvén waves in the Laboratory…



rotation
f_o
15 Hz

liquid
sodium
50 L

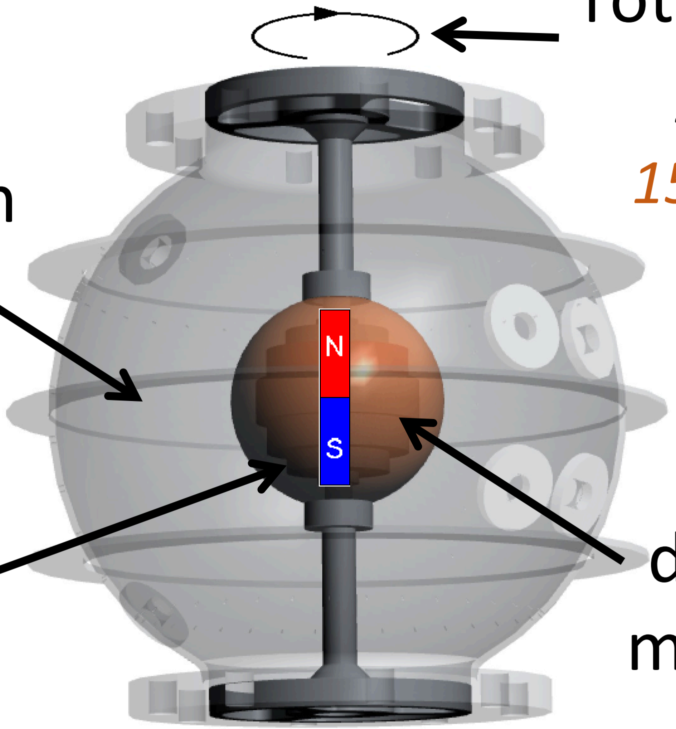
jerk
$\Delta\varphi$
90°

dipole
magnet
0.3 T

DTSΩ experiment

Nataf et al, 2008
Brito et al, 2011
Cabanes et al, 2014

Torsional Alfvén waves in the Laboratory…



…and in the computer

XSHELLS software

Schaeffer, 2013

Figueroa et al, 2013

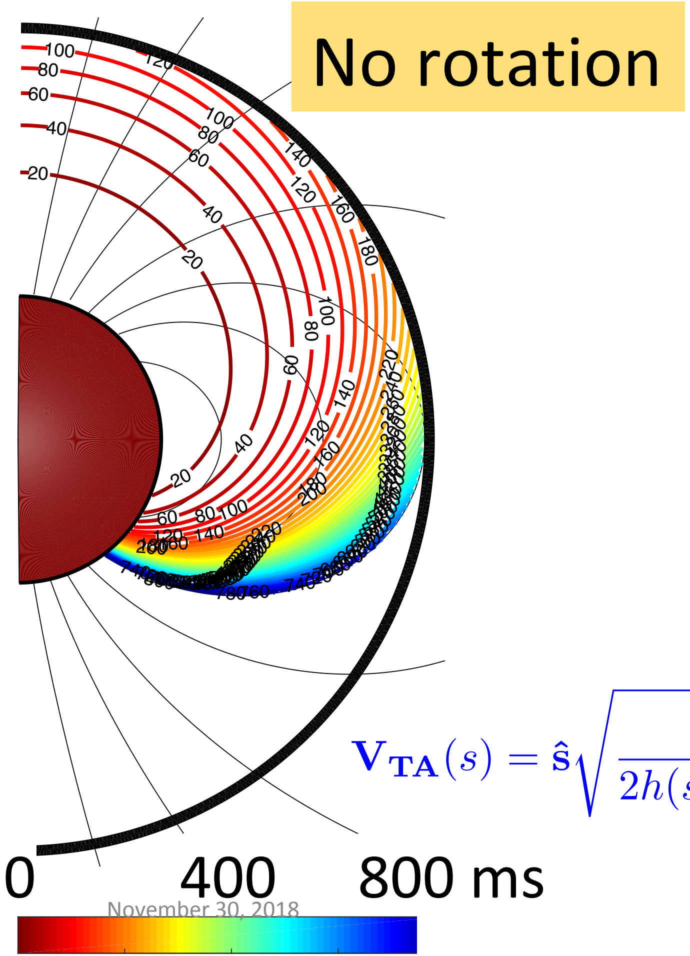
MHD axisymmetric

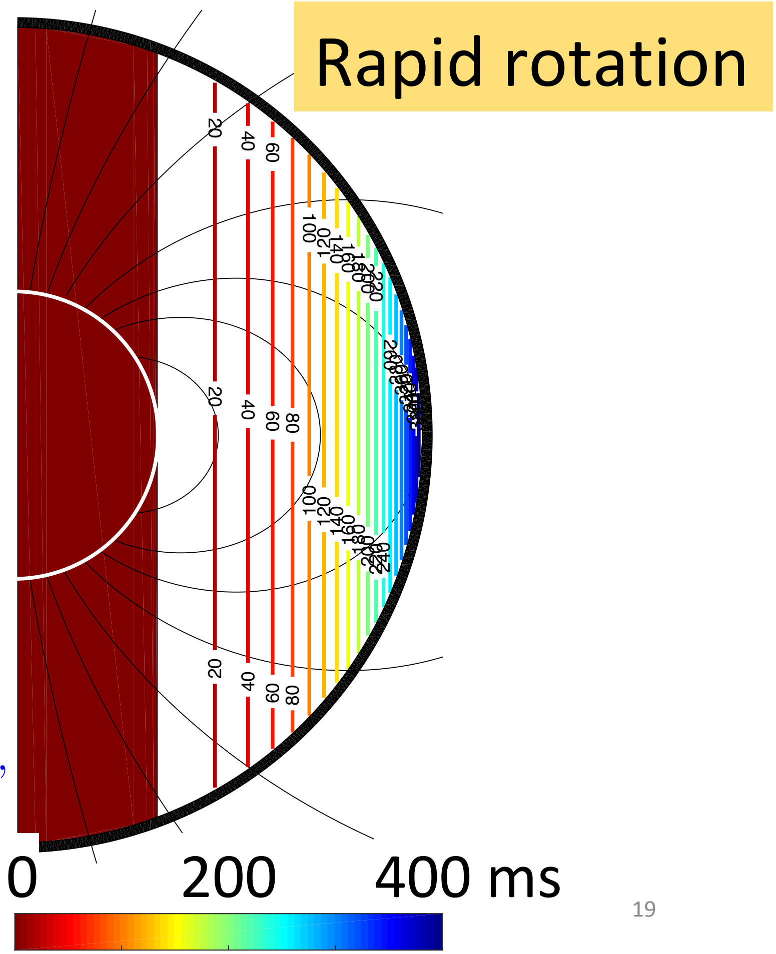
550 radial points, l_{max}=120

adaptive time-step

DTSΩ-like jerks

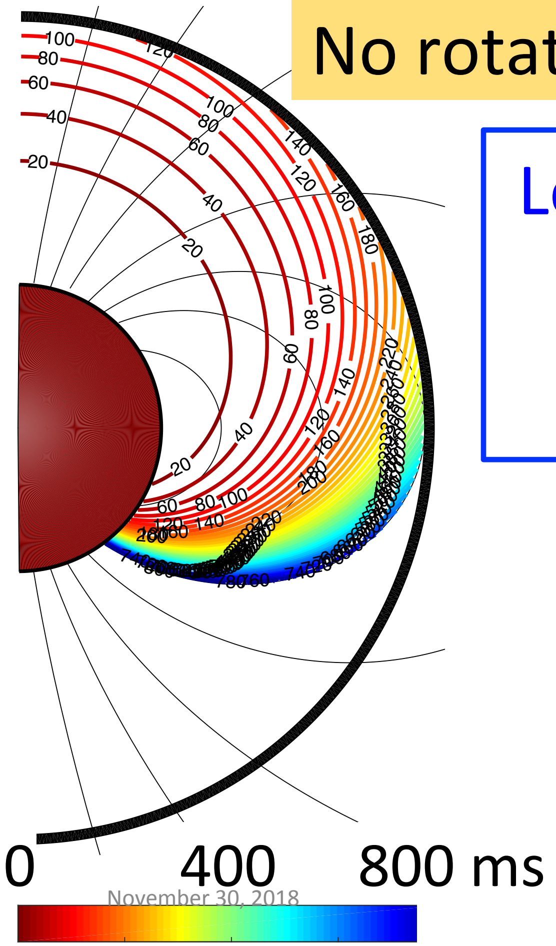
Wave fronts of *ideal* Alfvén waves in DTSΩ





$$\mathbf{V_{TA}}(s) = \hat{\mathbf{s}}\sqrt{\frac{1}{2h(s)\mu_0\rho}\int_{-h}^{h} B_s^2(s,z)dz},$$

Wave fronts of *ideal* Alfvén waves in DTSΩ



Lehnert number

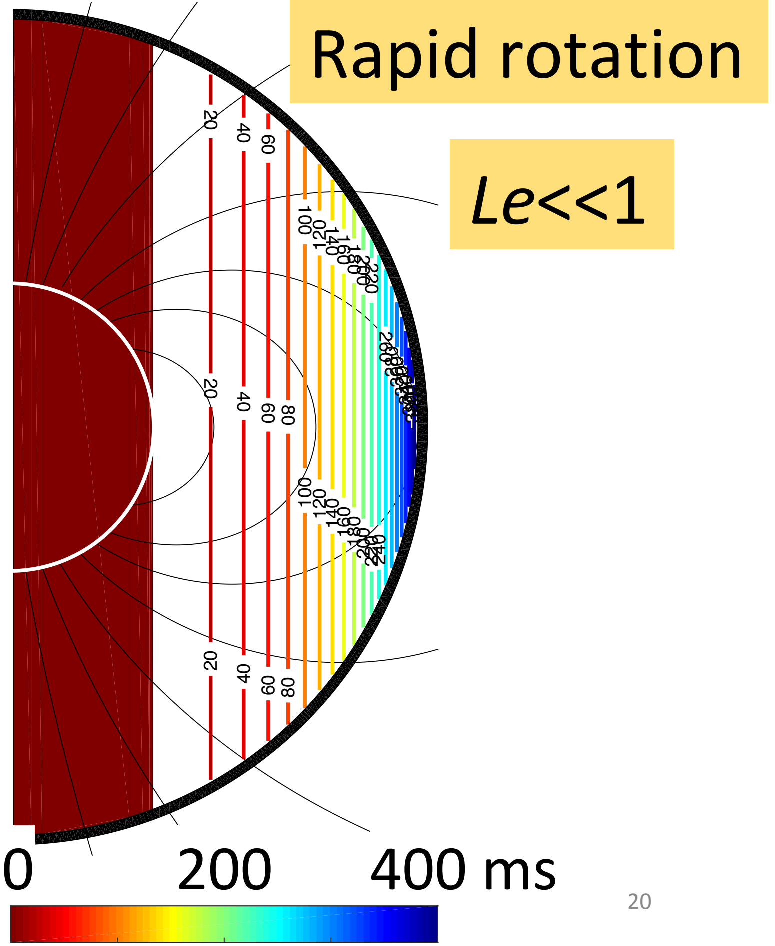
$$Le = \frac{\tau_\Omega}{\tau_A}$$

$$\tau_\Omega = \Omega^{-1}$$

$$\tau_A = \frac{r_o\sqrt{\mu_0 \rho}}{B}$$

Lehnert, 1955

Jault, 2008



Magnetic diffusion

- Alfvén waves are very difficult to study in the lab because of the **large magnetic diffusivity** of liquid metals.

Magnetic diffusion time:

$$\tau_\eta = \frac{r_o^2}{\eta} = 500 \text{ ms}$$

Lundquist number

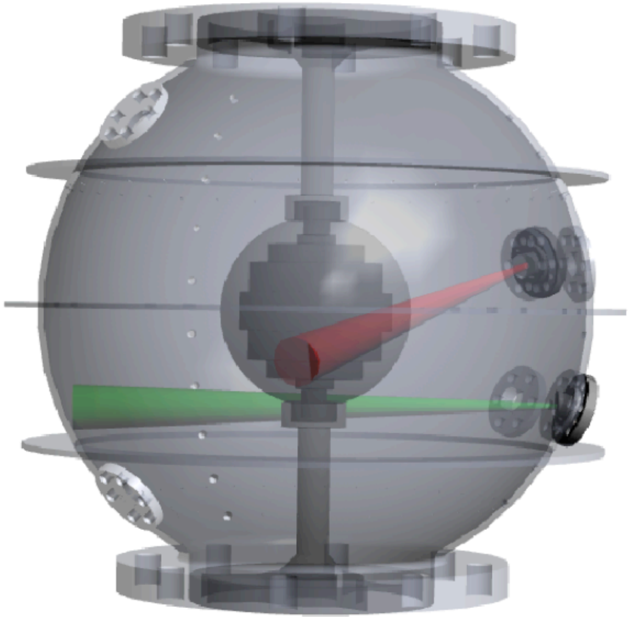
$$Lu = \frac{\tau_\eta}{\tau_A}$$

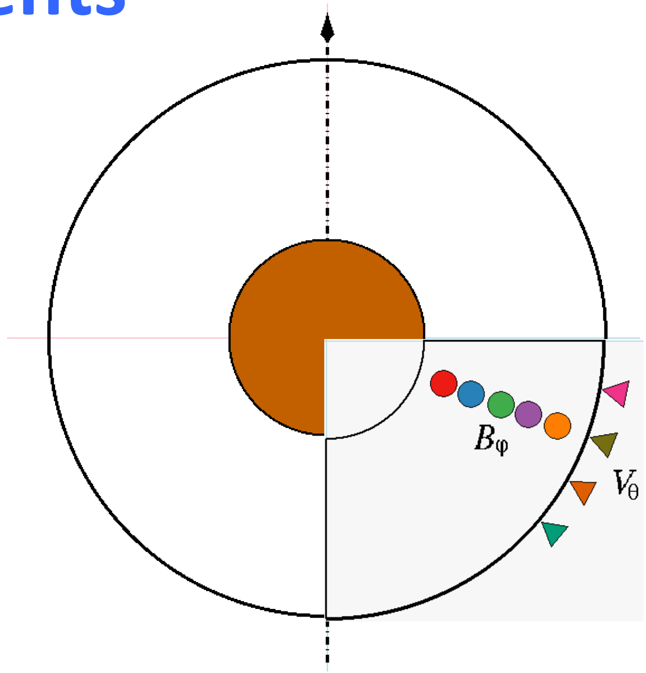
Lundquist, 1949
Lehnert, 1953
Jameson, 1961; 1964
Alboussière et al, 2011

Dimensionless numbers for f_o = 15 Hz

Number	expression	Inner sphere	Outer sphere		*Earth core*
Lehnert	τ_Ω / τ_A	**0.25**	**0.01**		~10^{-4}
Lundquist	τ_η / τ_A	**12**	**0.53**		~10^{4}

Measurements





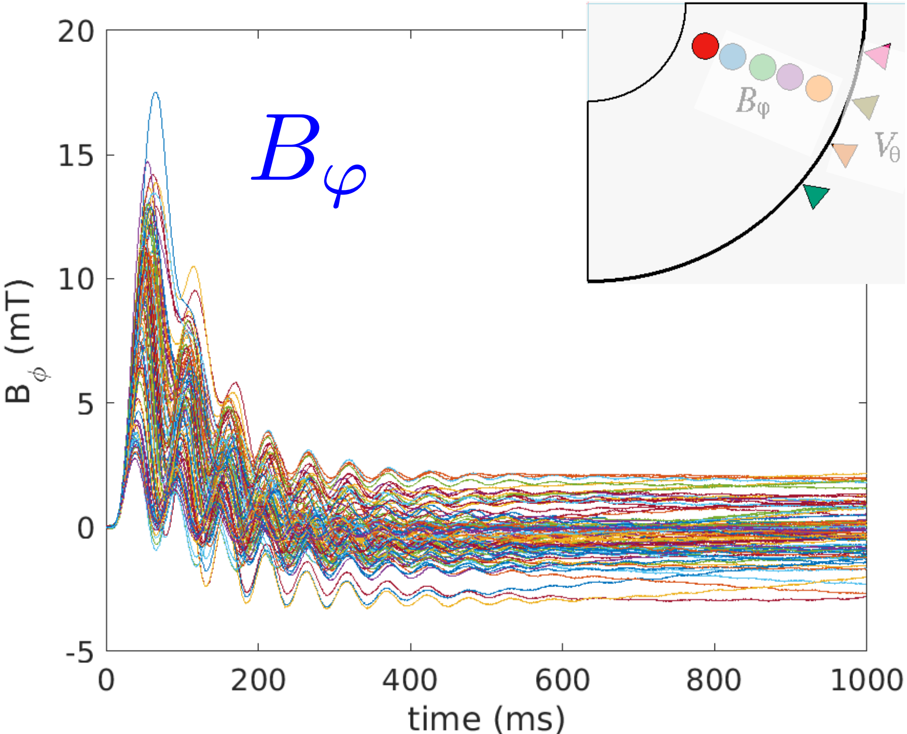
- Azimuthal magnetic field in a sleeve
- Surface electric potential
- Azimuthal fluid velocity by ultrasound Doppler

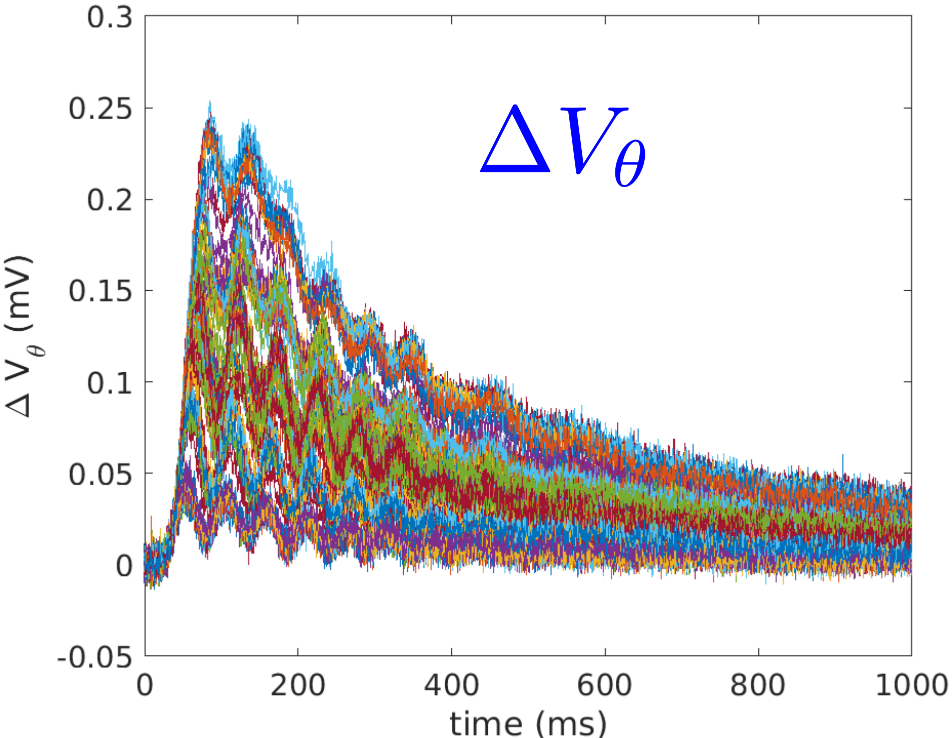
Jerks of all sizes

Azimuthal magnetic field

$f_o = 15\ Hz$

Surface electric potential





the wave comes!

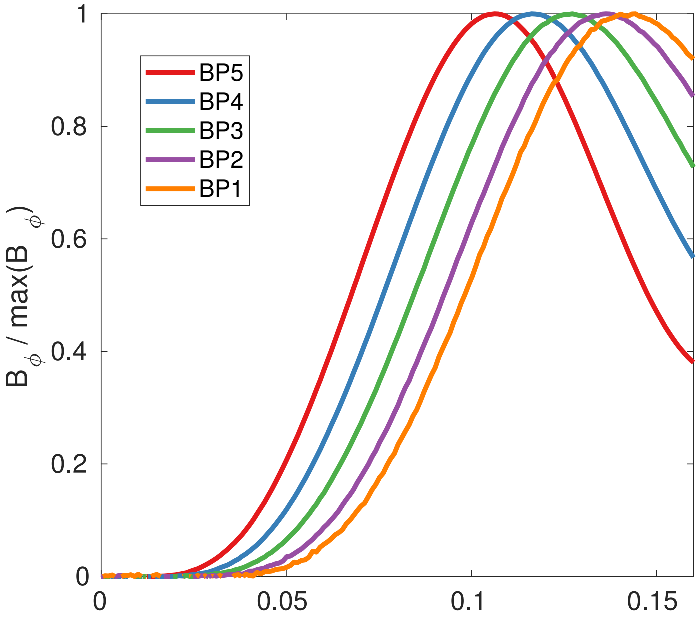
the first 80 ms

(0.16 magnetic diffusion time)

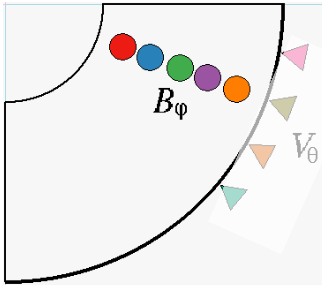
$\Delta\varphi = 90°,\ t_{rise} = 0.08\tau_\eta$

azimuthal magnetic field B_φ

experiment

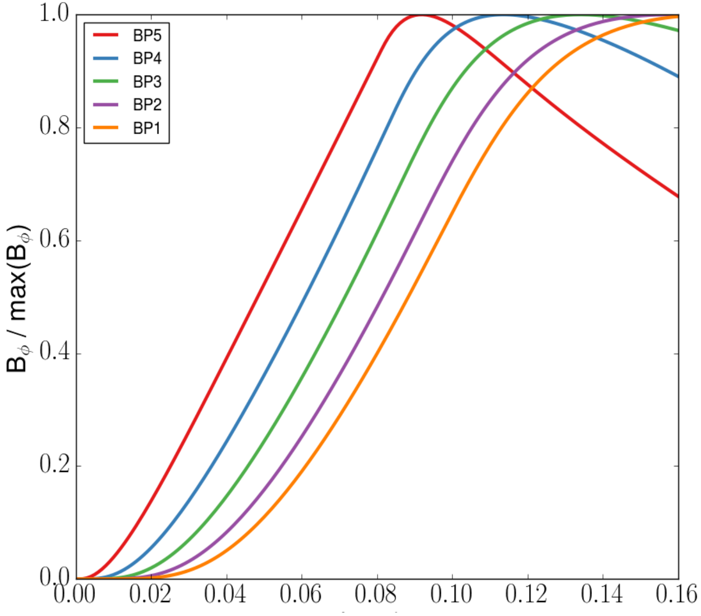


t/τ_η



$f_o = 15$ Hz

simulation



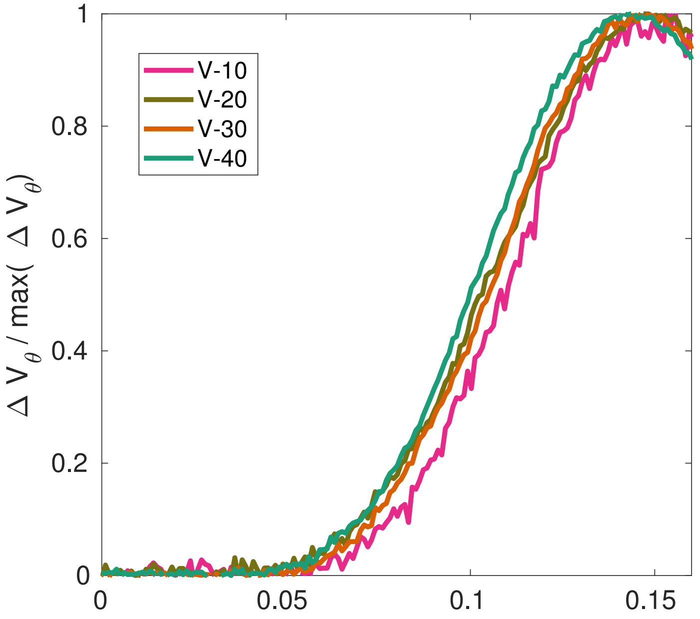
t/τ_η

surface electric potential

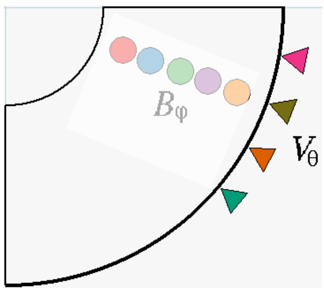
experiment

simulation

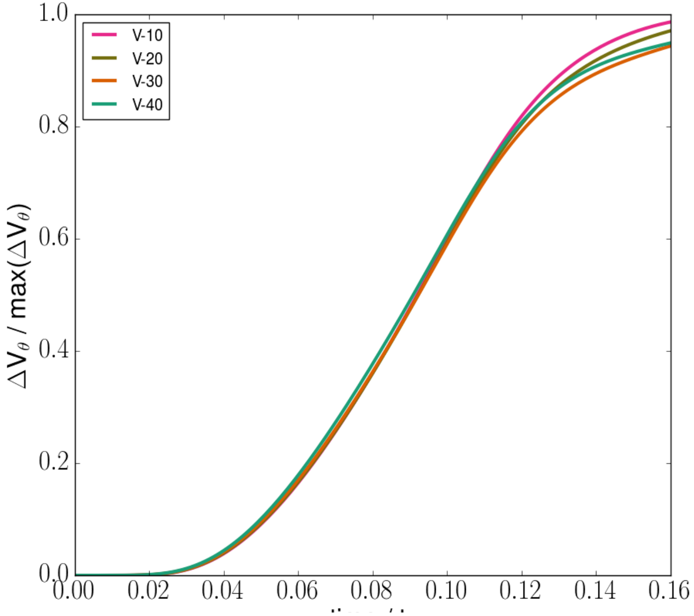
ΔV_θ



t/τ_η



f_o = 15 Hz



t/τ_η

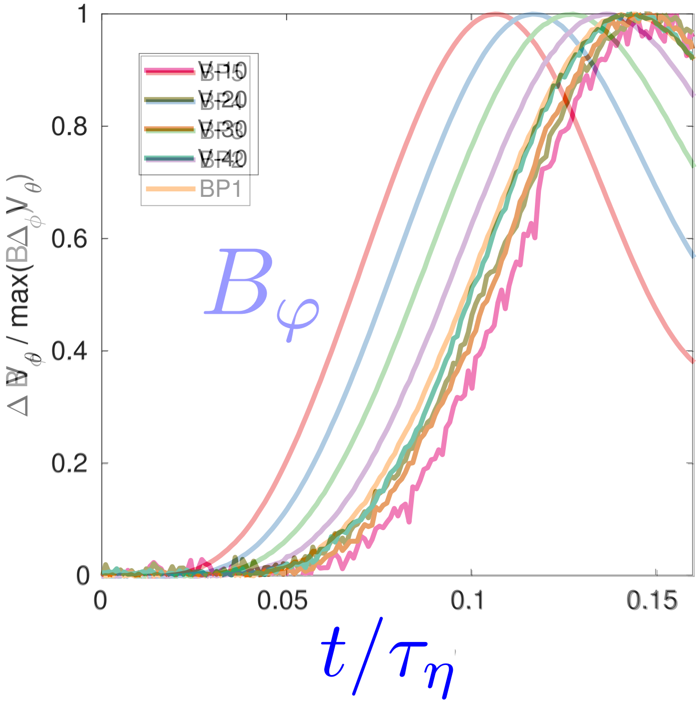
surface

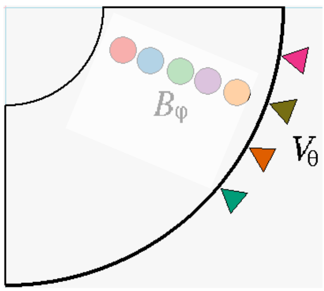
electric potential

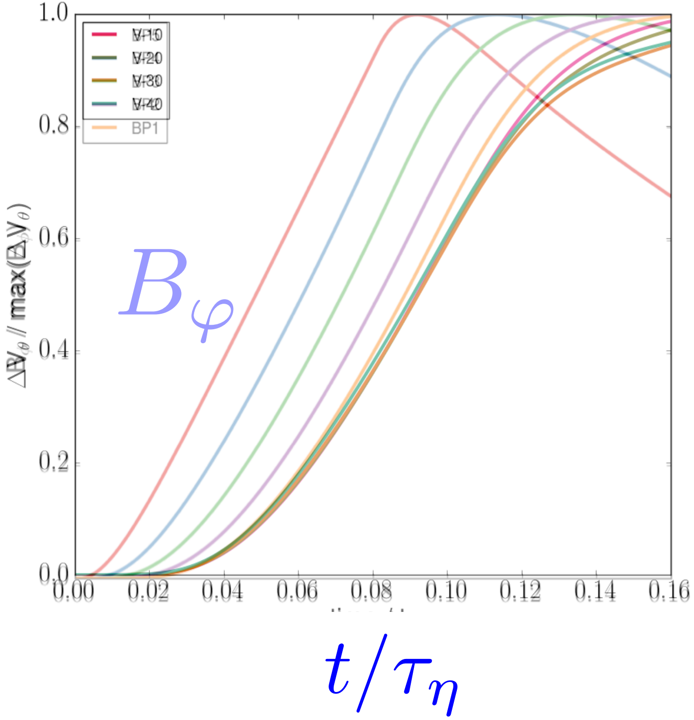
experiment

simulation

ΔV_θ







$f_o = 15\ Hz$

The signature of rotation:

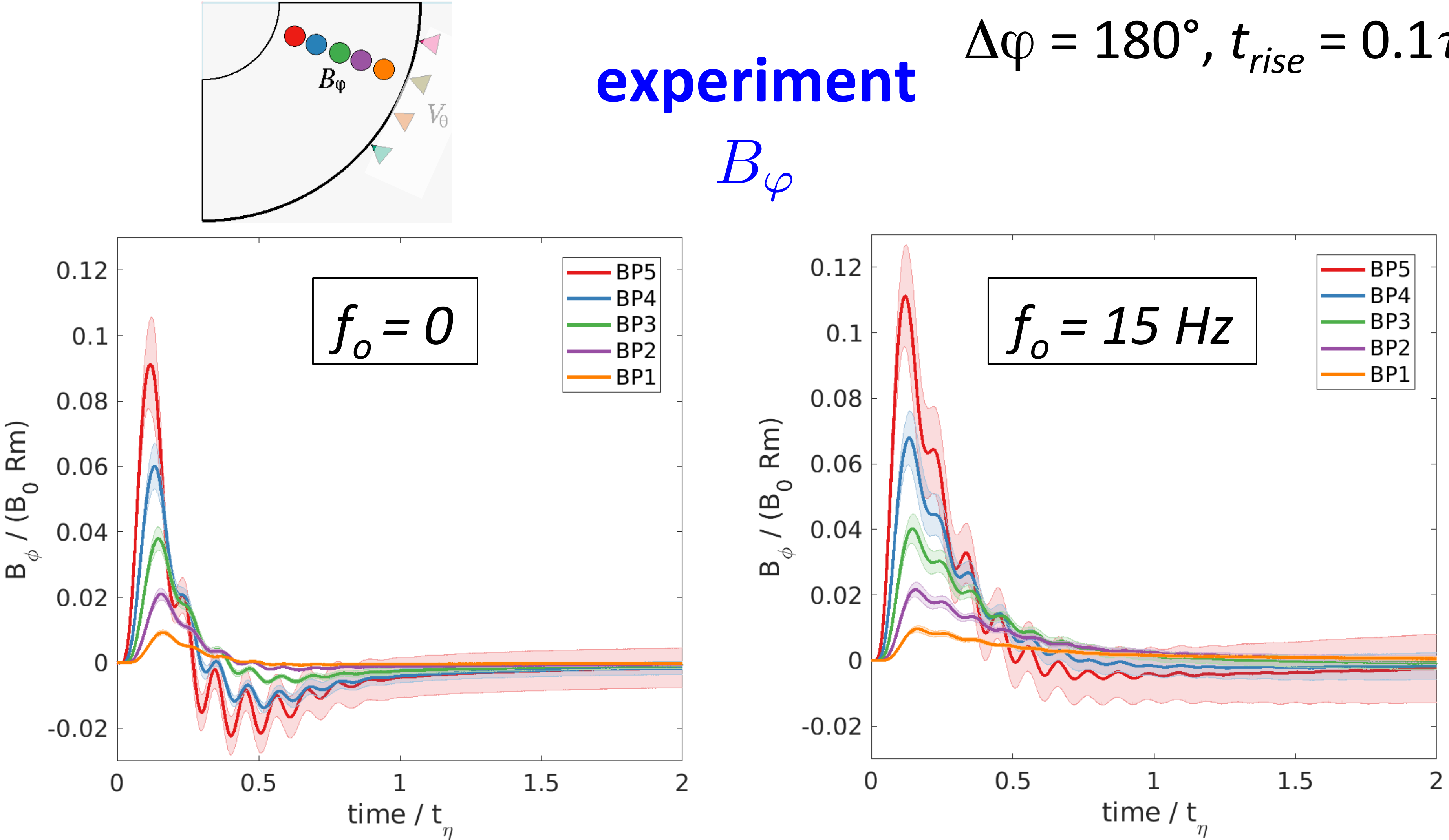
the first 500 ms

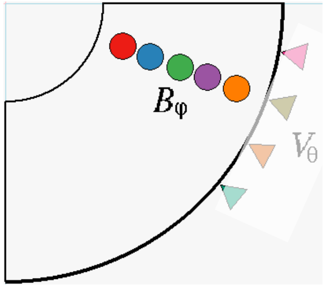
(1 magnetic diffusion time)

$\Delta\varphi = 180°,\ t_{rise} = 0.1\tau_\eta$

experiment

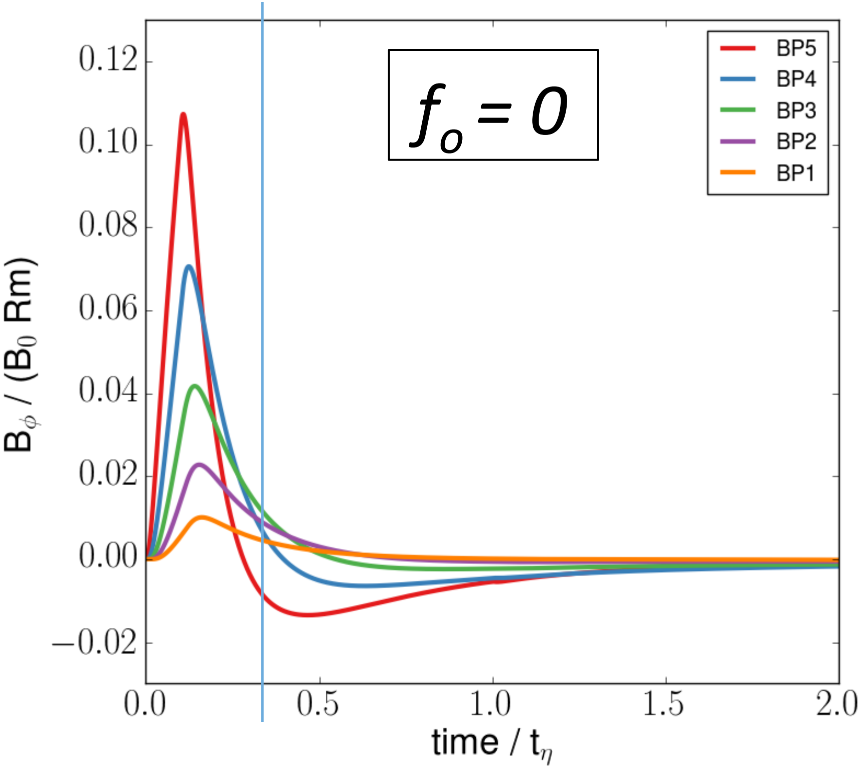
B_φ

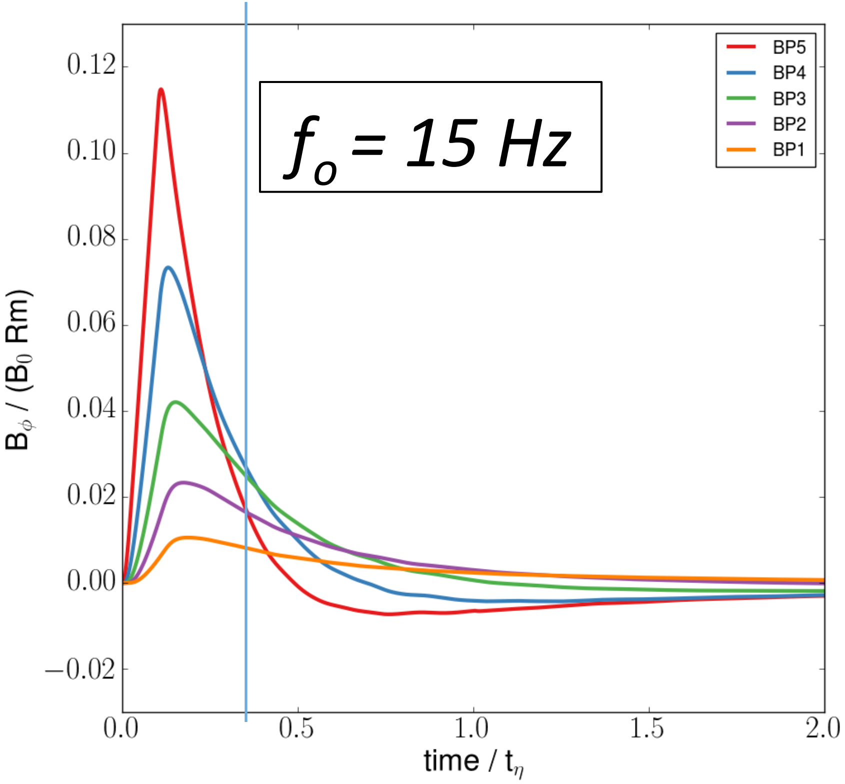




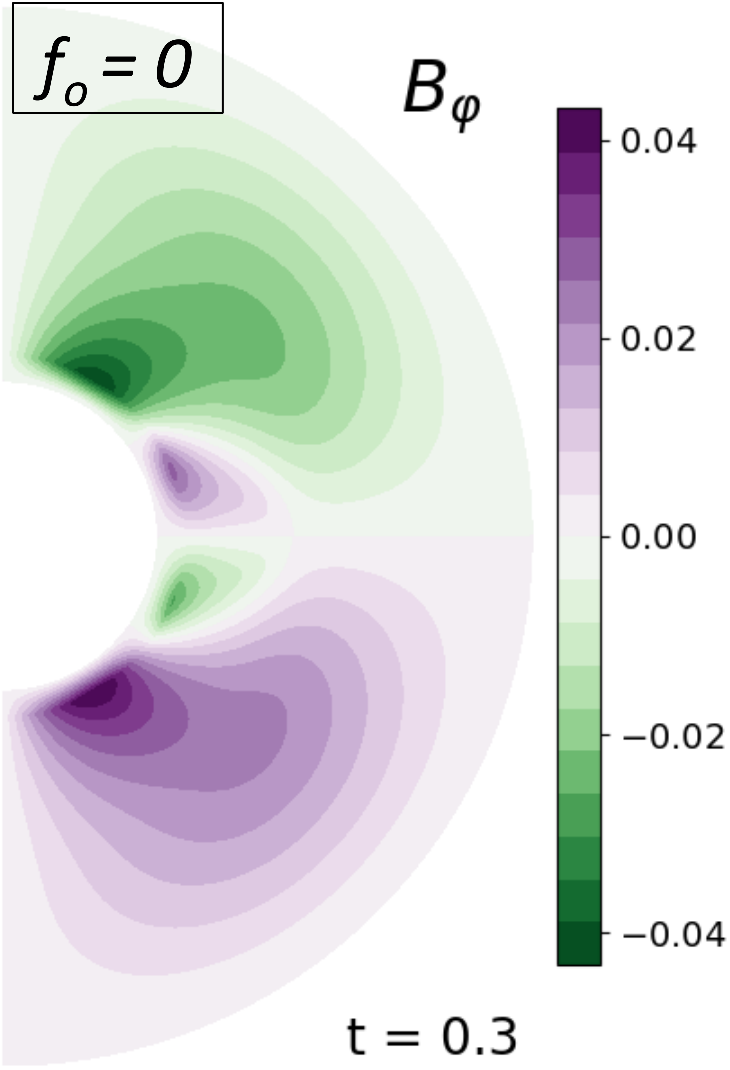
simulation

B_φ

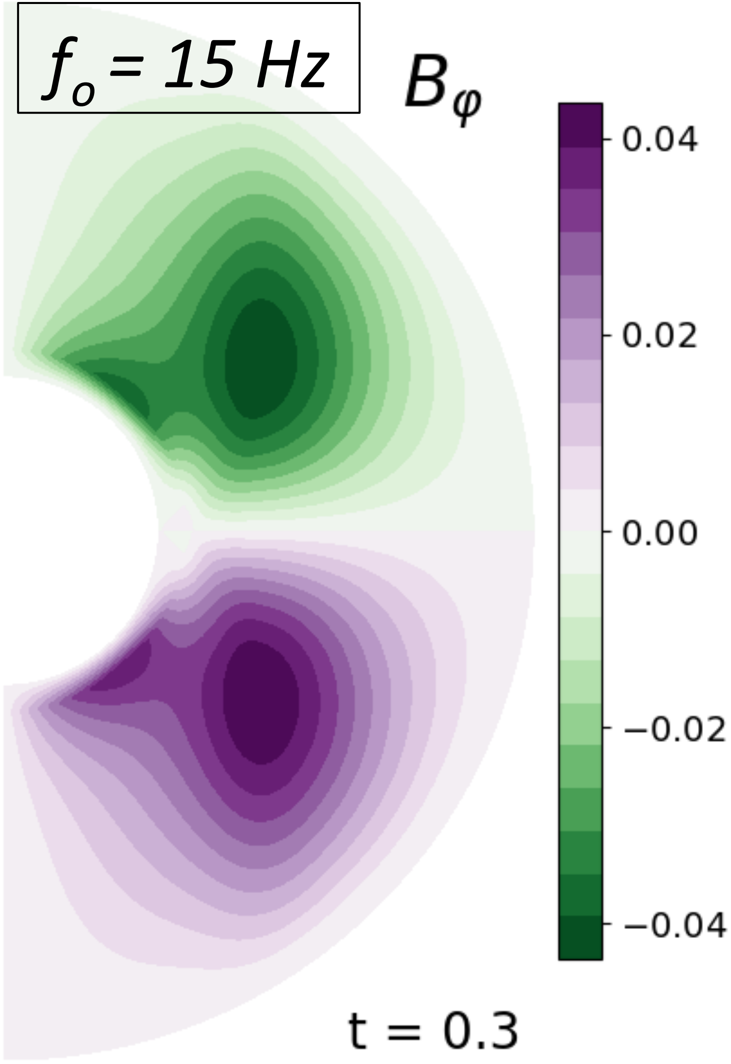




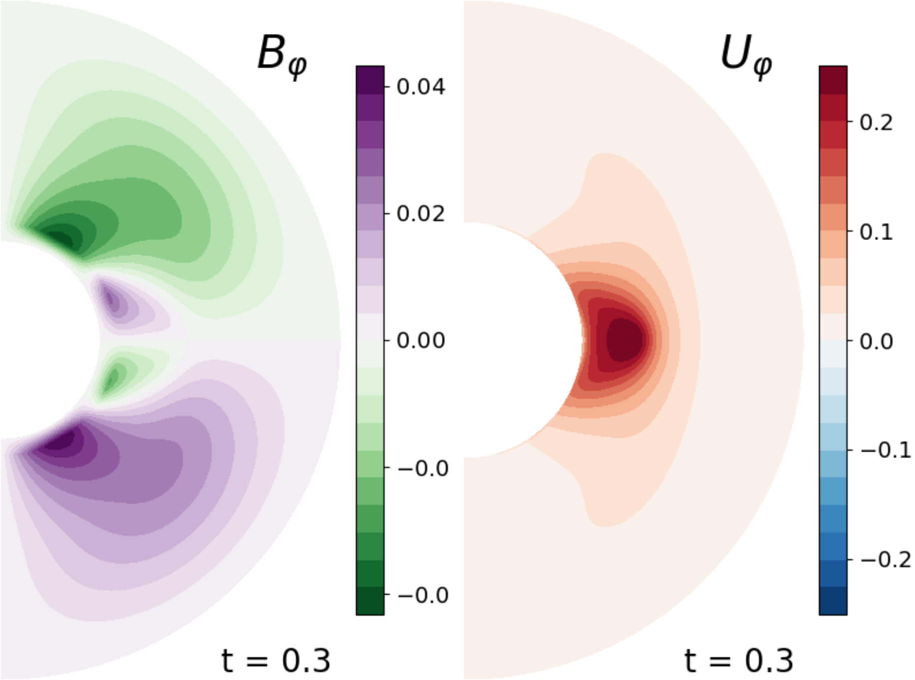
The mystery of the negative magnetic swing…



$f_o = 0$
B_φ
0.04
0.02
0.00
−0.02
−0.04
t = 0.3

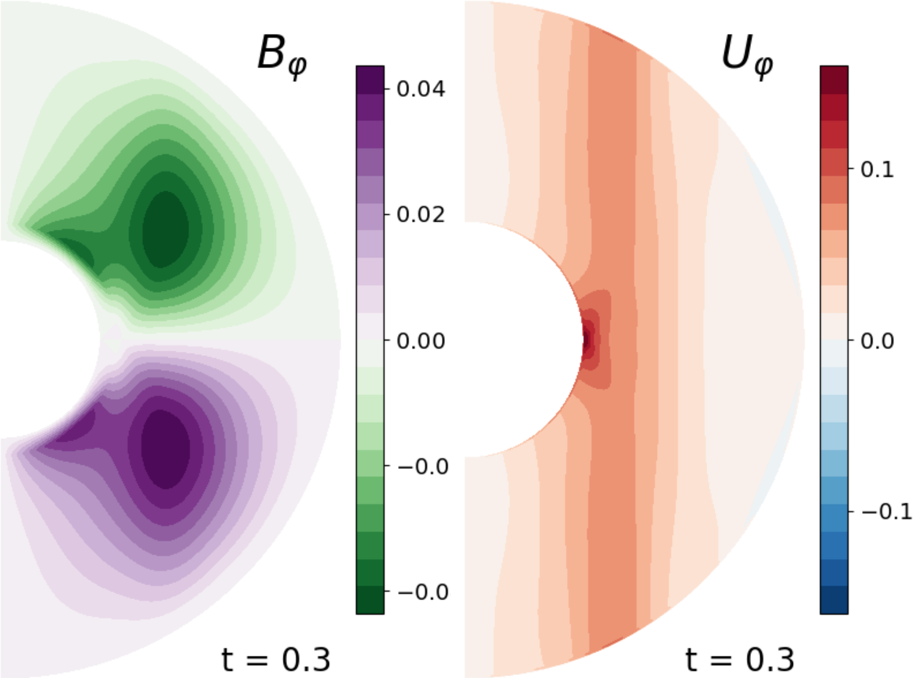


$f_o = 15$ Hz
B_φ
0.04
0.02
0.00
−0.02
−0.04
t = 0.3

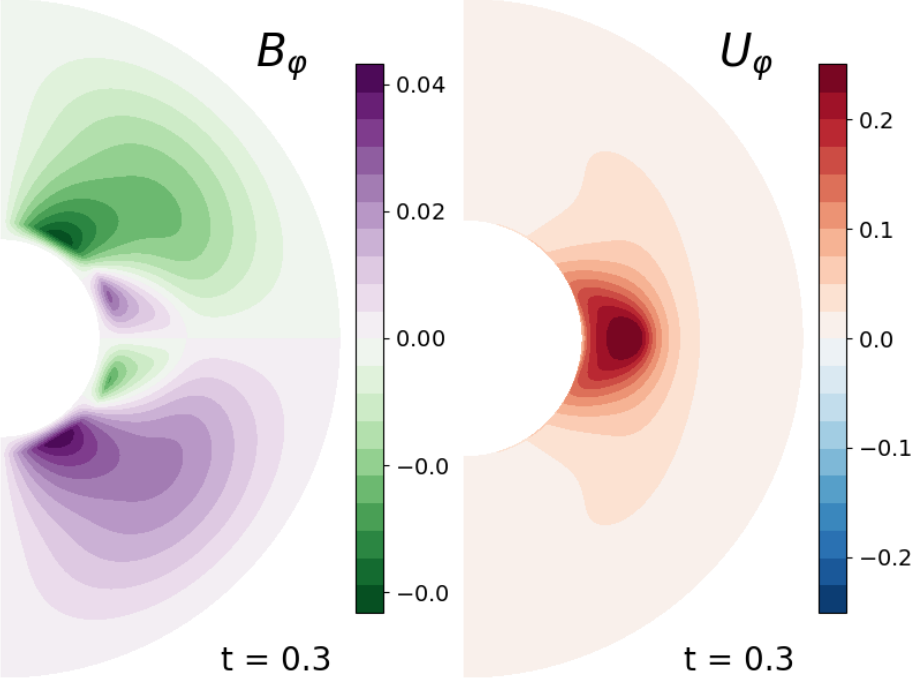

B_φ
0.04
0.02
0.00
−0.0
−0.0
t = 0.3
U_φ
0.2
0.1
0.0
−0.1
−0.2
t = 0.3

$f_o = 0$

$f_o = 15\ Hz$

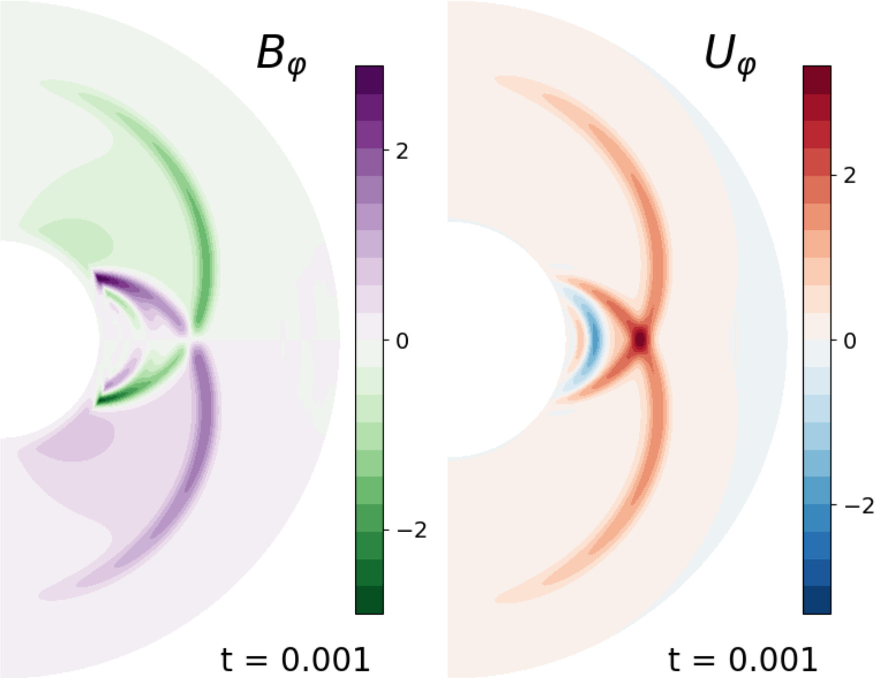

B_φ
0.04
0.02
0.00
−0.0
−0.0
t = 0.3
U_φ
0.1
0.0
−0.1
t = 0.3

The Alfvén wave from the other side…



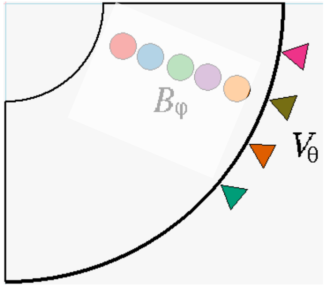
$f_o = 0$, $Lu_i = 12$

$f_o = 0$, $Lu_i = 1200$



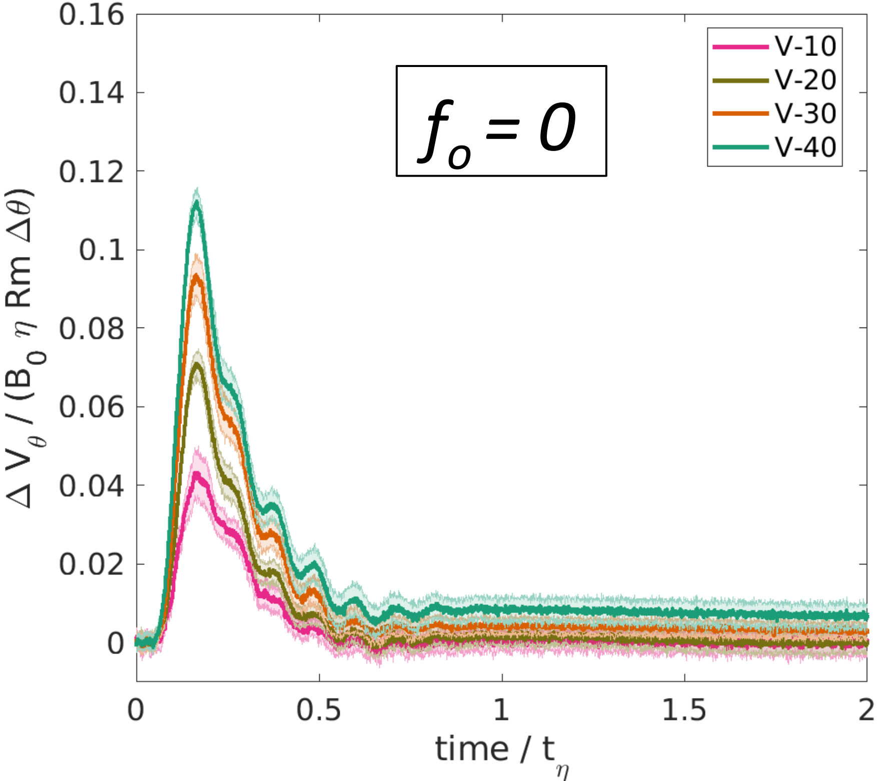
A hint on fluid velocities from surface electric potentials…

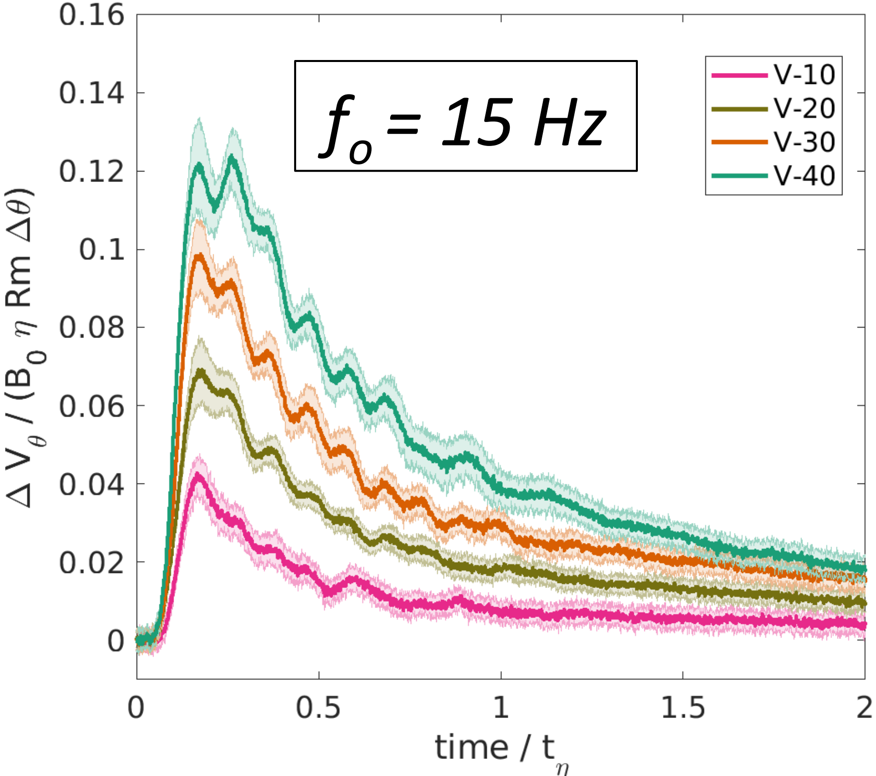
$$U_\varphi = \frac{1}{B_r}\frac{\Delta V_\theta}{r_o \Delta \theta}$$



experiment

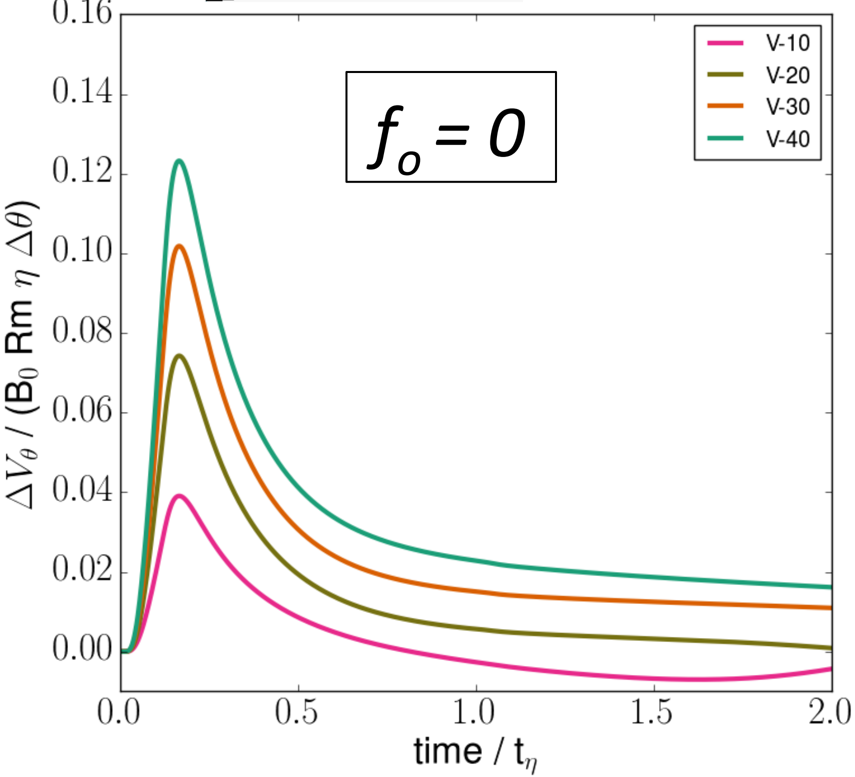
ΔV_θ

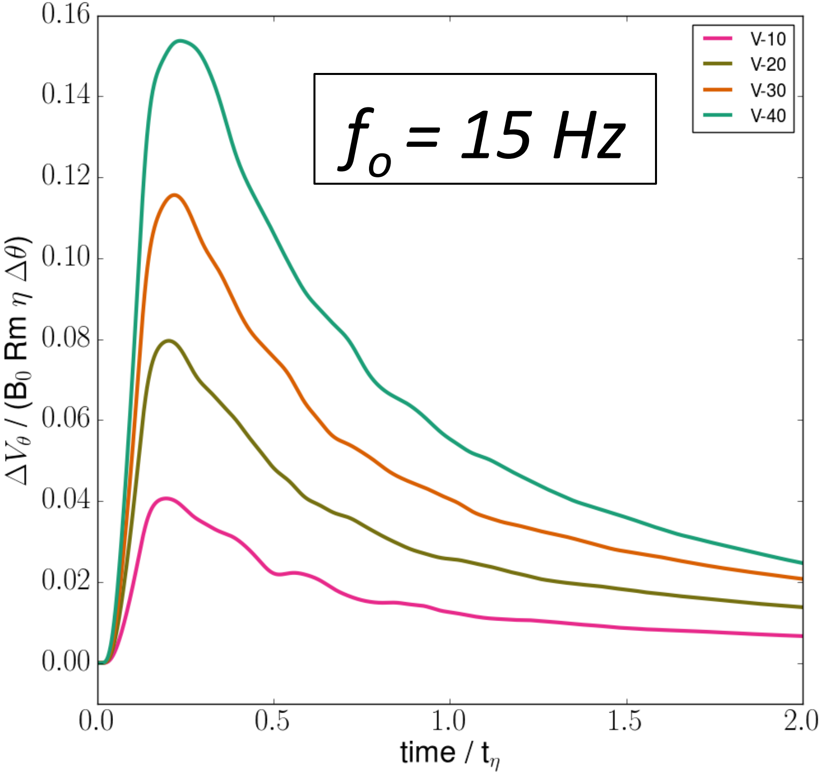


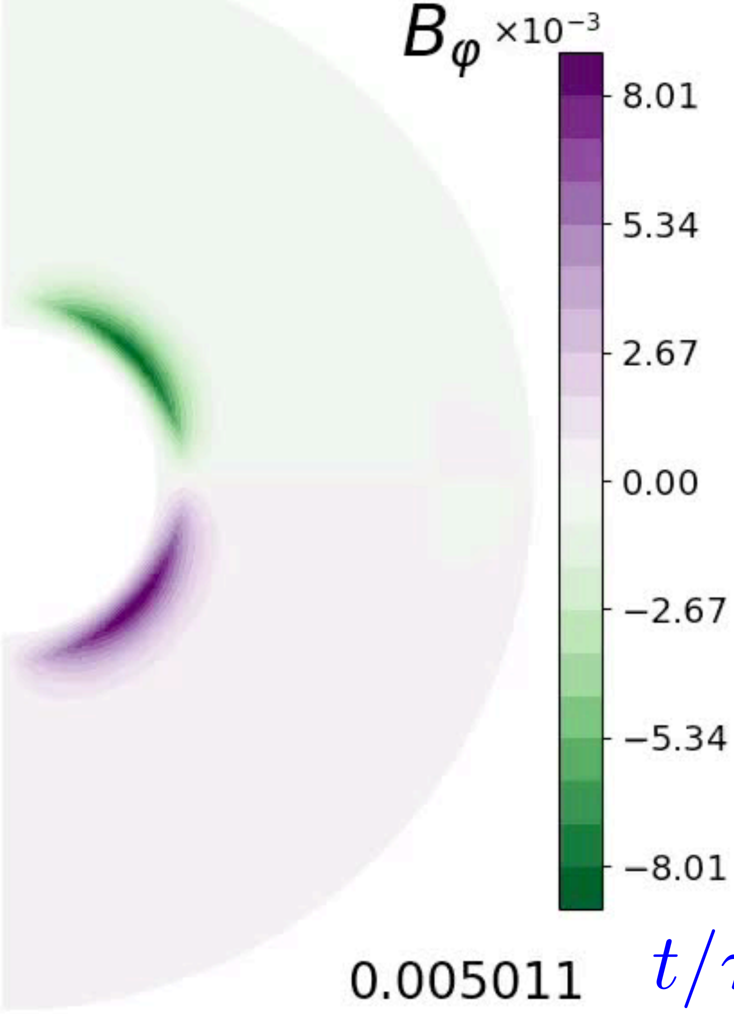


simulation

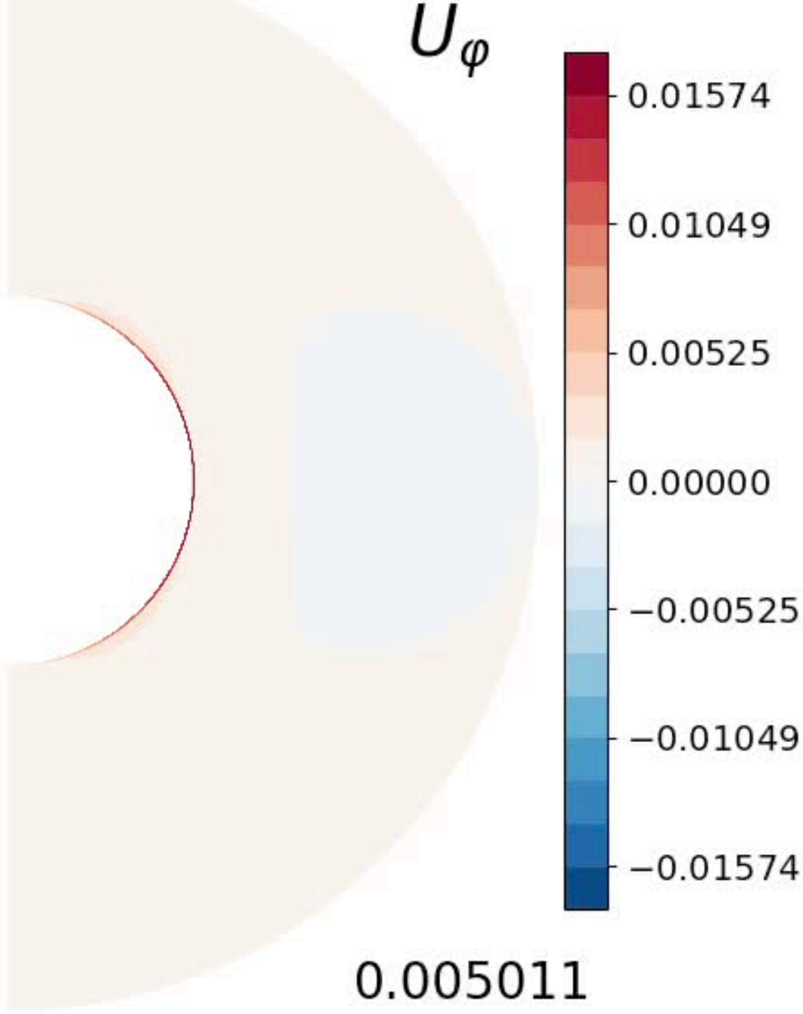
$$\Delta V_\theta$$



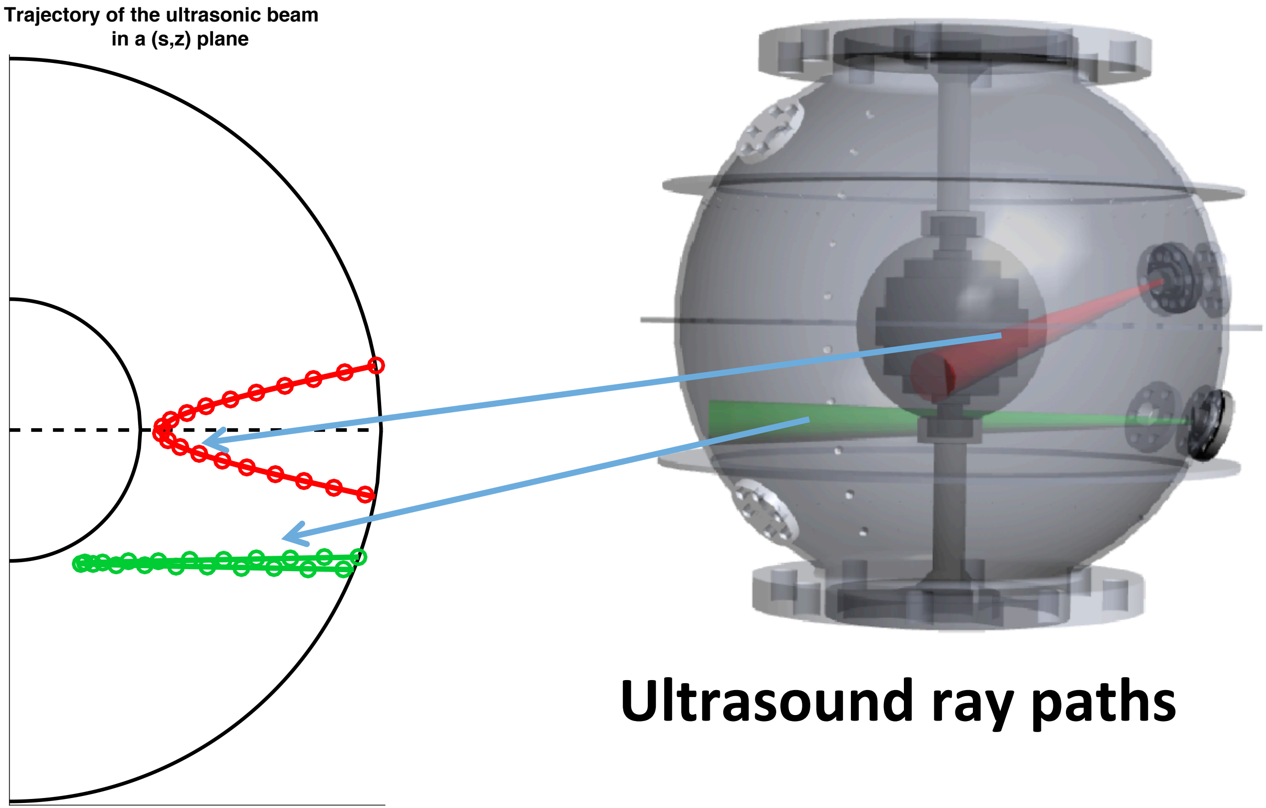



B_φ ×10⁻³
8.01
5.34
2.67
0.00
−2.67
−5.34
−8.01
0.005011

t/τ_η

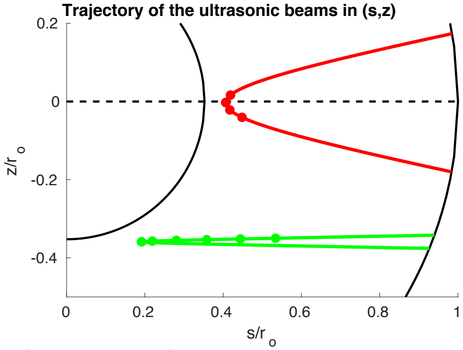

U_φ
0.01574
0.01049
0.00525
0.00000
−0.00525
−0.01049
−0.01574
0.005011

More tricky: azimuthal velocity from UDV

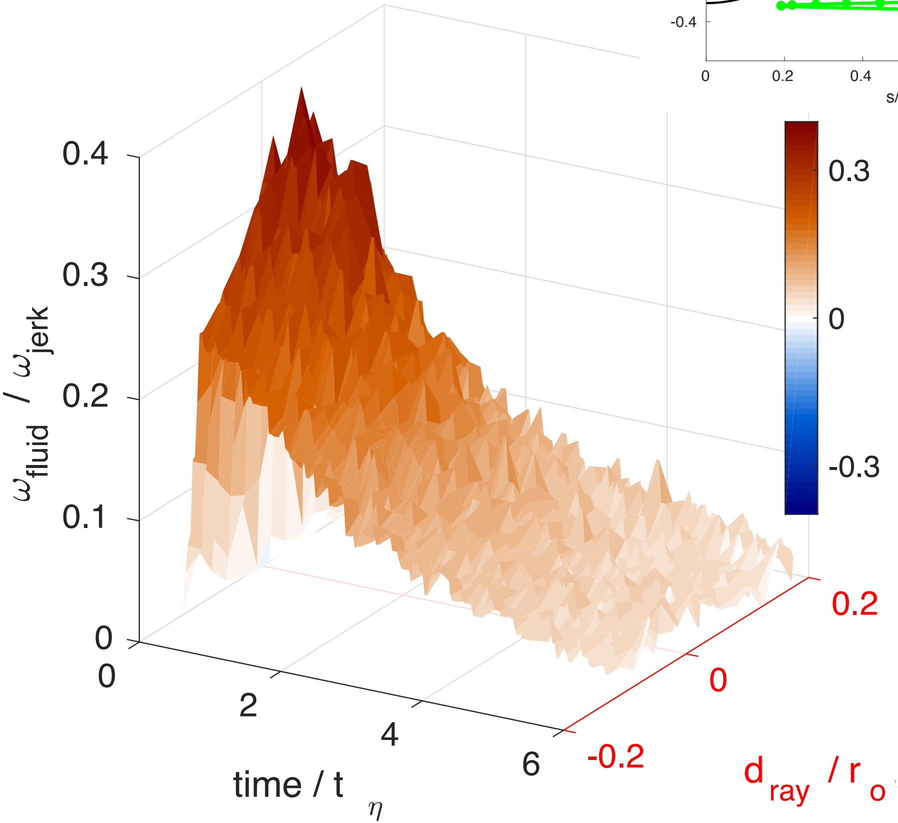


Ultrasound ray paths

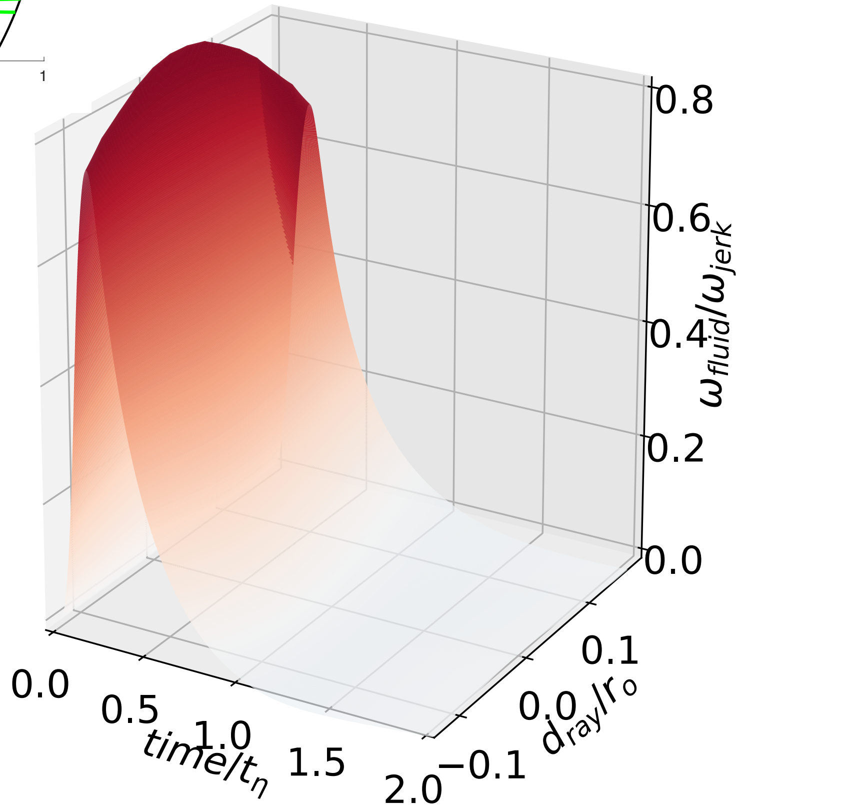
$f_o = 0$



experiment



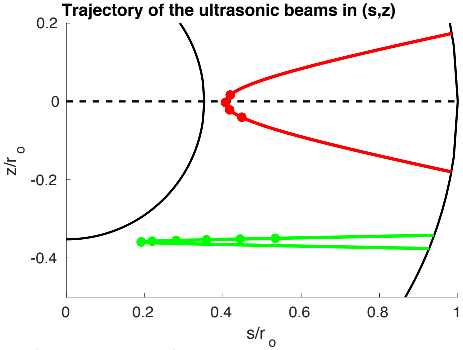
simulation

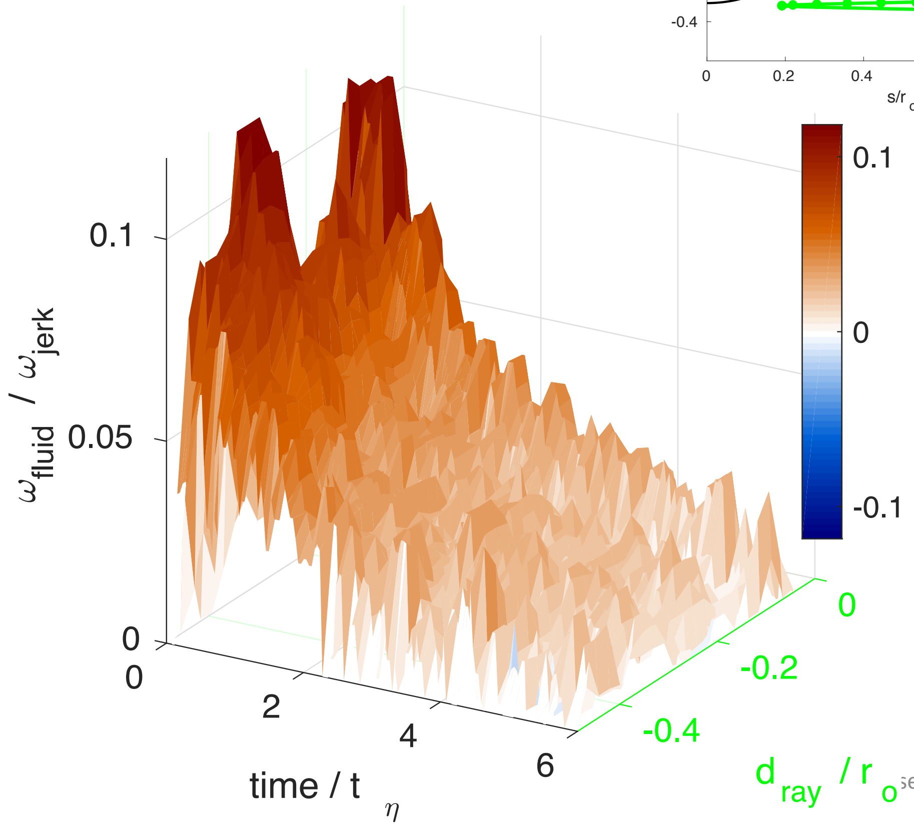


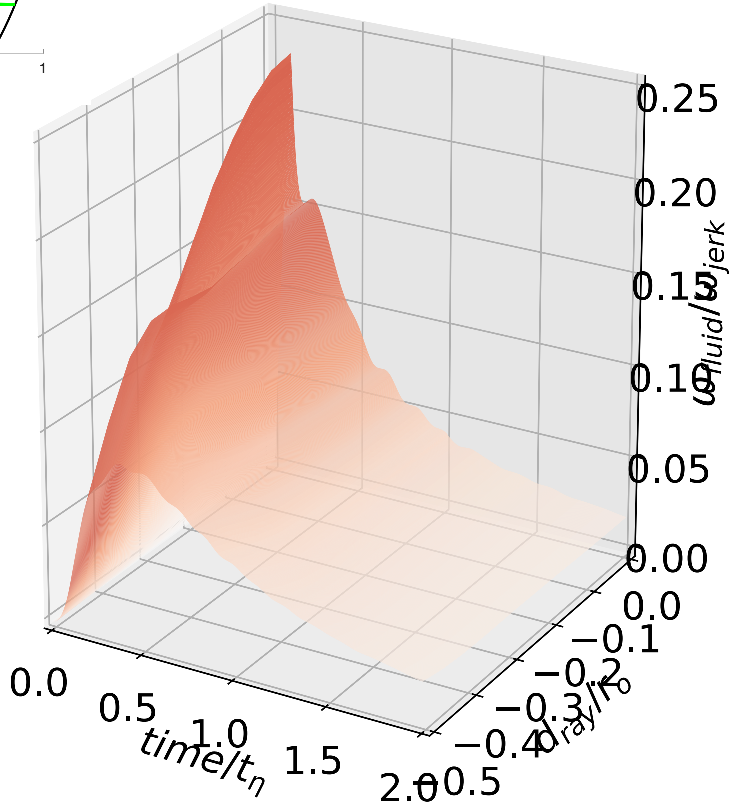
$f_o = -10\ Hz$

experiment

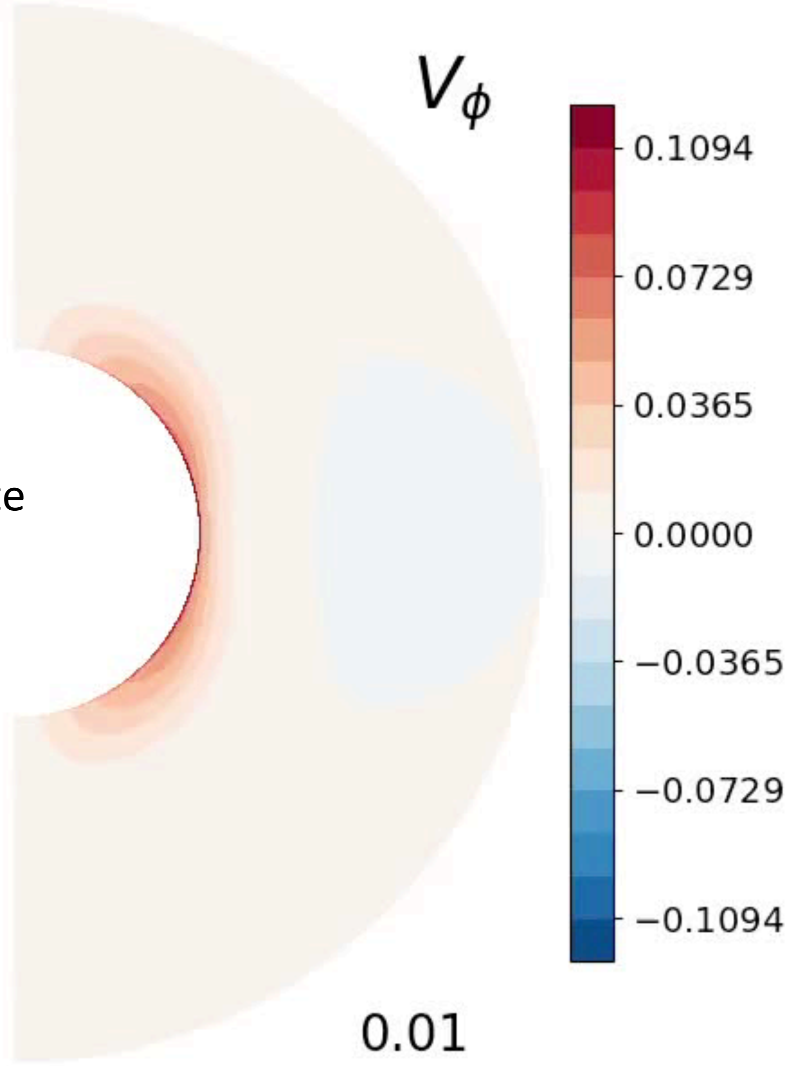
simulation







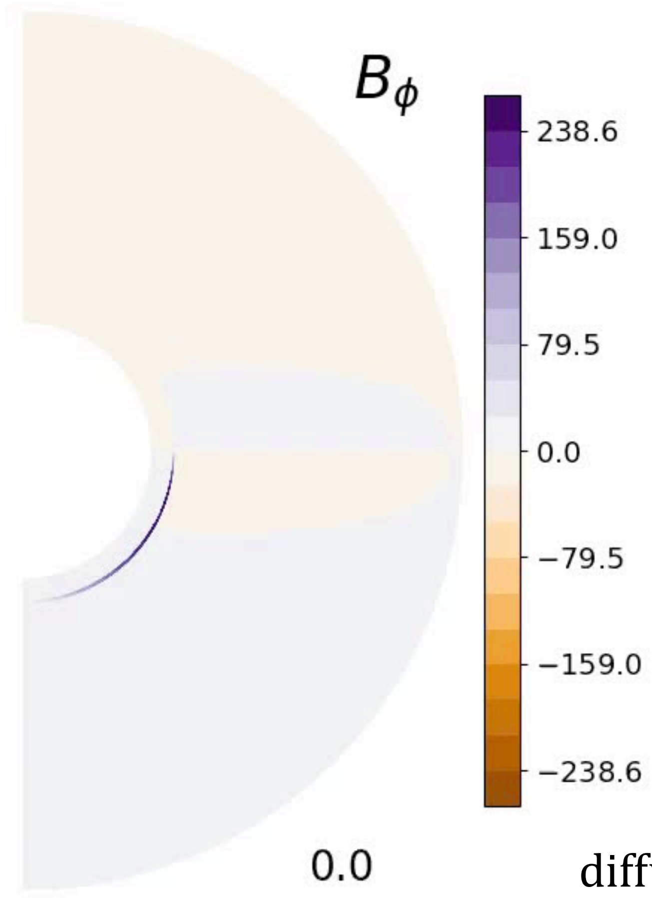
Abrupt rapid jerks excite inertial modes



More Earth-like values:

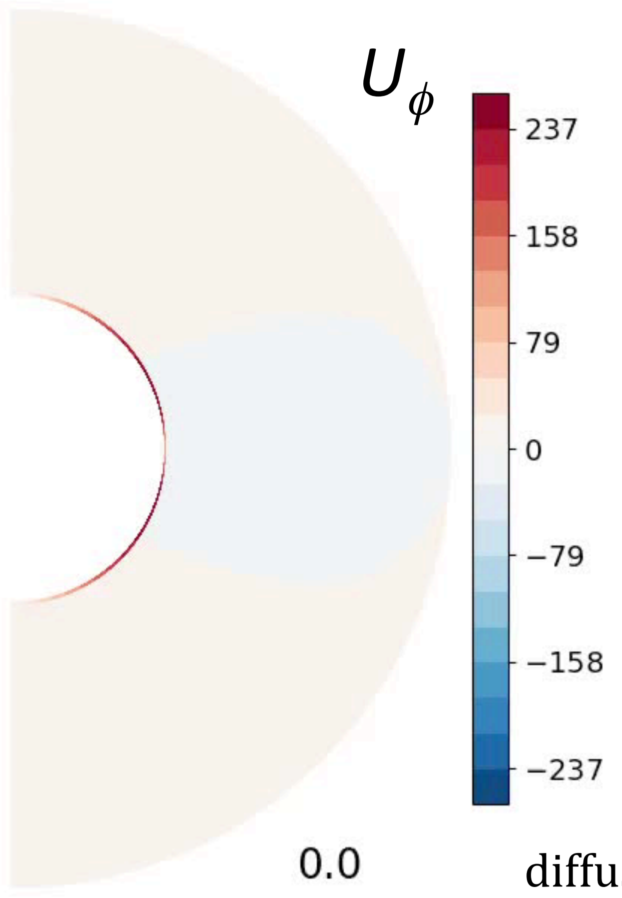
Lu_i=12 000, Le_o=10^{-3}

$E=2x10^{-7}$, $Ro=2x10^{-2}$ (but $Pm=0.1$)



diffusion time

search Seminar, Kyo



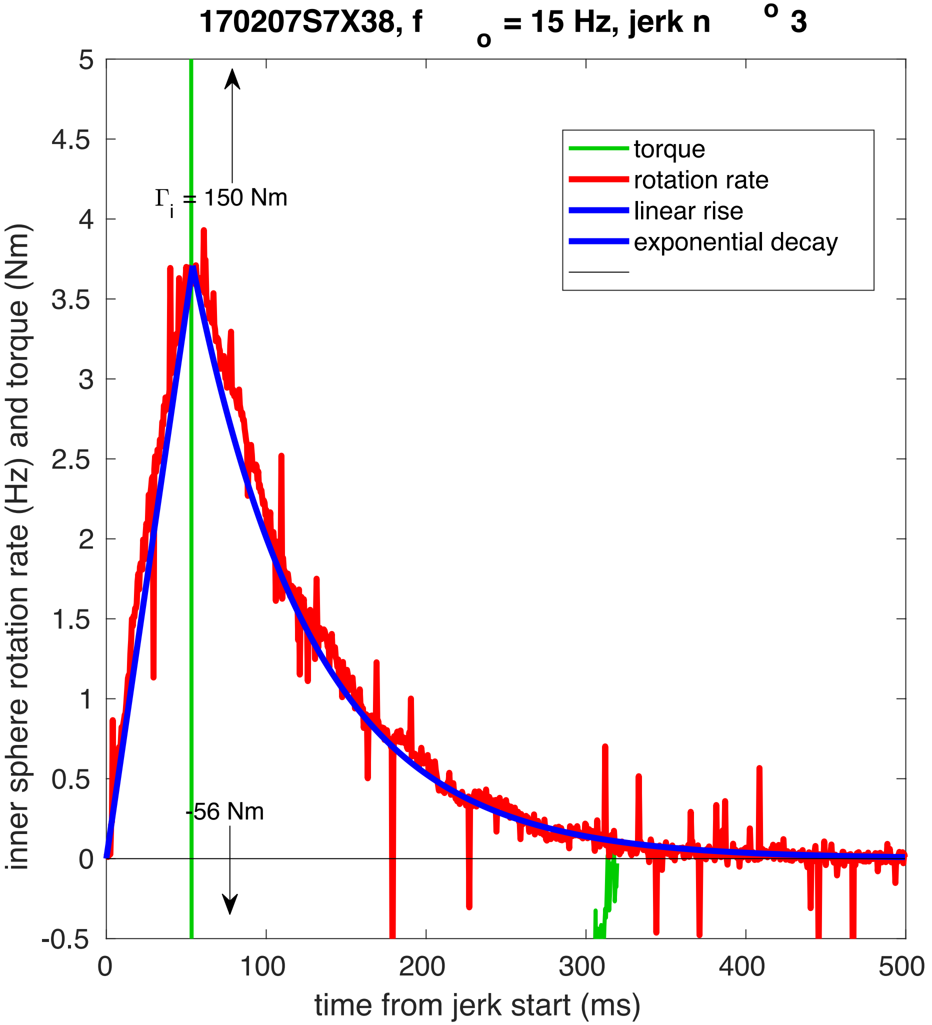
diffusion time

Take-home message

- We have triggered and observed **torsional Alfvén waves** in our DTSΩ laboratory experiment.
- Rotation, magnetic field geometry and diffusion **strongly alter** ideal Alfvén wave properties.
- XSHELLS numerical simulations help deciphering their properties, and show the triggering of **inertial waves**.
- Electric potentials and subtle differences in the magnetic signature reveal the formation of **geostrophic motions**.
- We obtained the first direct measurements of **Alfvén wave fluid velocity** from ultrasound Doppler.

Thank you

DTSΩ jerk time function



simulation

$f_o = 15\ Hz$