VKS experiment :

turbulent dynamos in the laboratory

F. Daviaud

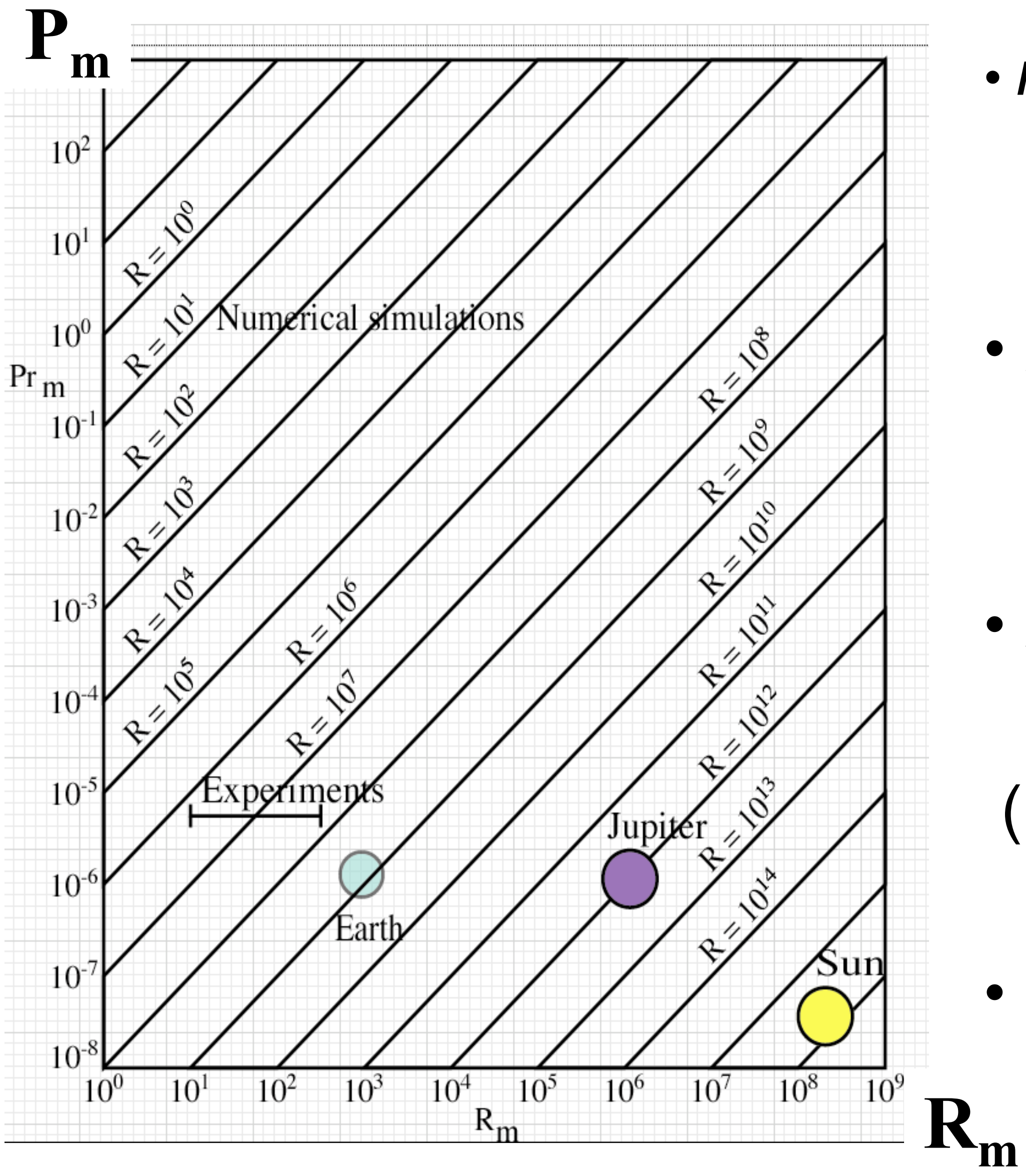
VKS collaboration: CEA – CNRS - ENS Paris - ENS Lyon

F. Daviaud, A. Chiffaudel, B. Dubrulle, S. Aumaitre,
C. Gasquet, V. Padilla, L. Marié, F. Ravelet, R. Monchaux
CEA, DSM/DRECAM/SPEC
in collaboration with DEN/DTN/STPA, CEA Cadarache

S. Fauve, F. Pétrélis, N. Mordant, M. Berhanu
ENS-Paris, Laboratoire de Physique Statistique

J.-F. Pinton, P. Odier, M. Bourgoin, R. Volk, M. Moulin,
N. Plihon
ENS-Lyon, Laboratoire de Physique

Simulations, Experiments and Nature



- *magnetic Reynolds number:*

  $R_m = \mu_0 \sigma U L$

- *kinetic Reynolds number:*

  $R_e = U L / \nu$

- *magnetic Prandtl number:*

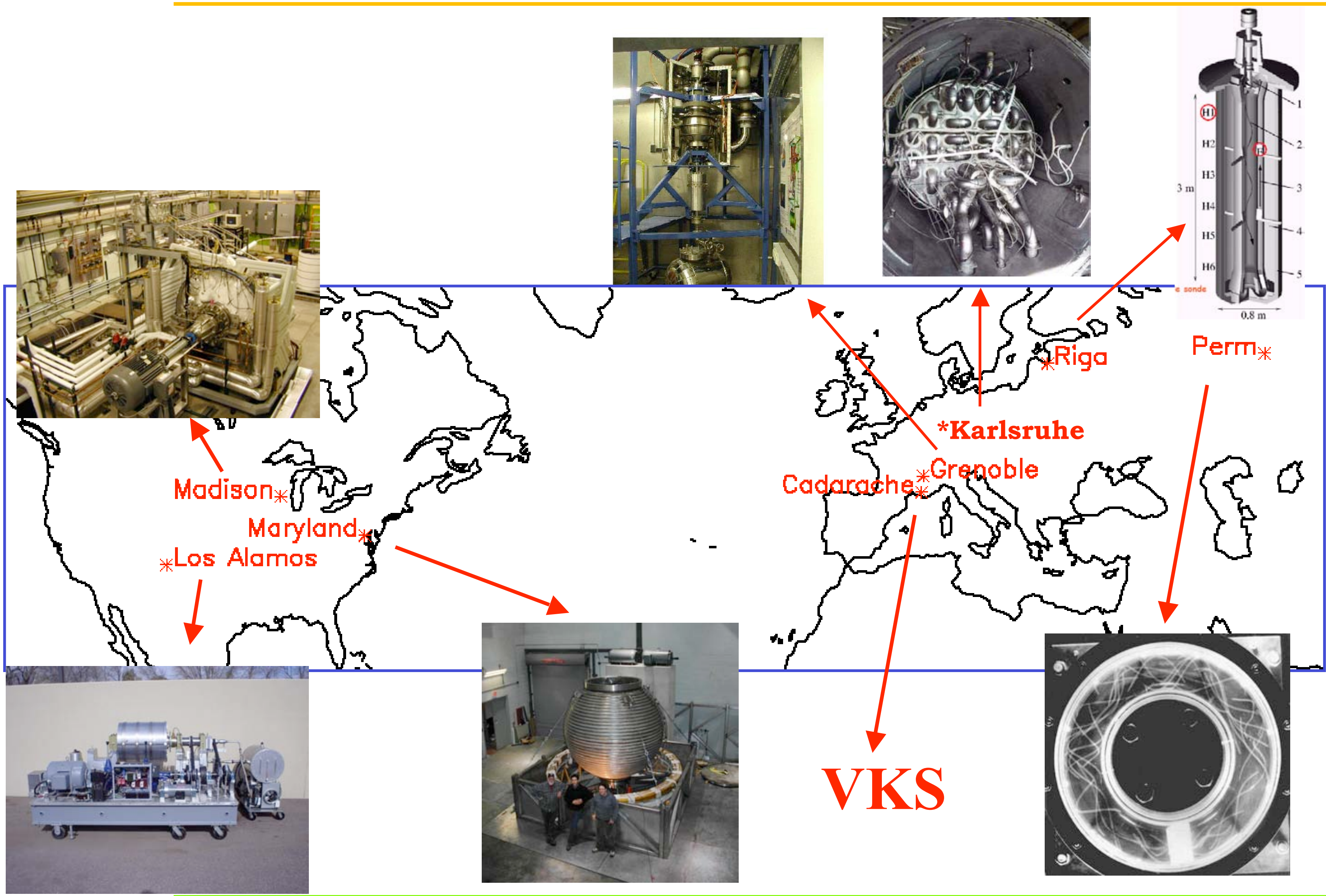
  $P_m = \mu_0 \sigma \nu$

  ($P_m = R_m / R_e < 10^{-5}$ liquid metals)

- *Rotation number:*

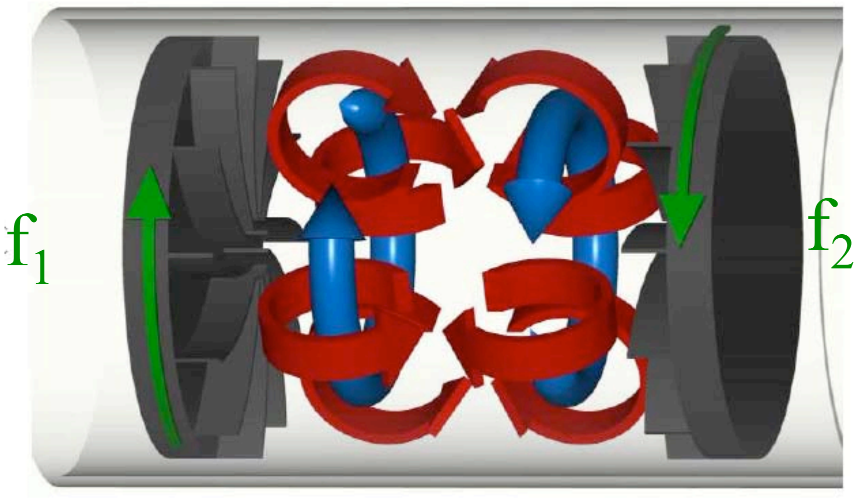
  $\Theta = L \Omega / U$

Dynamo experiments



VKS2 experiment

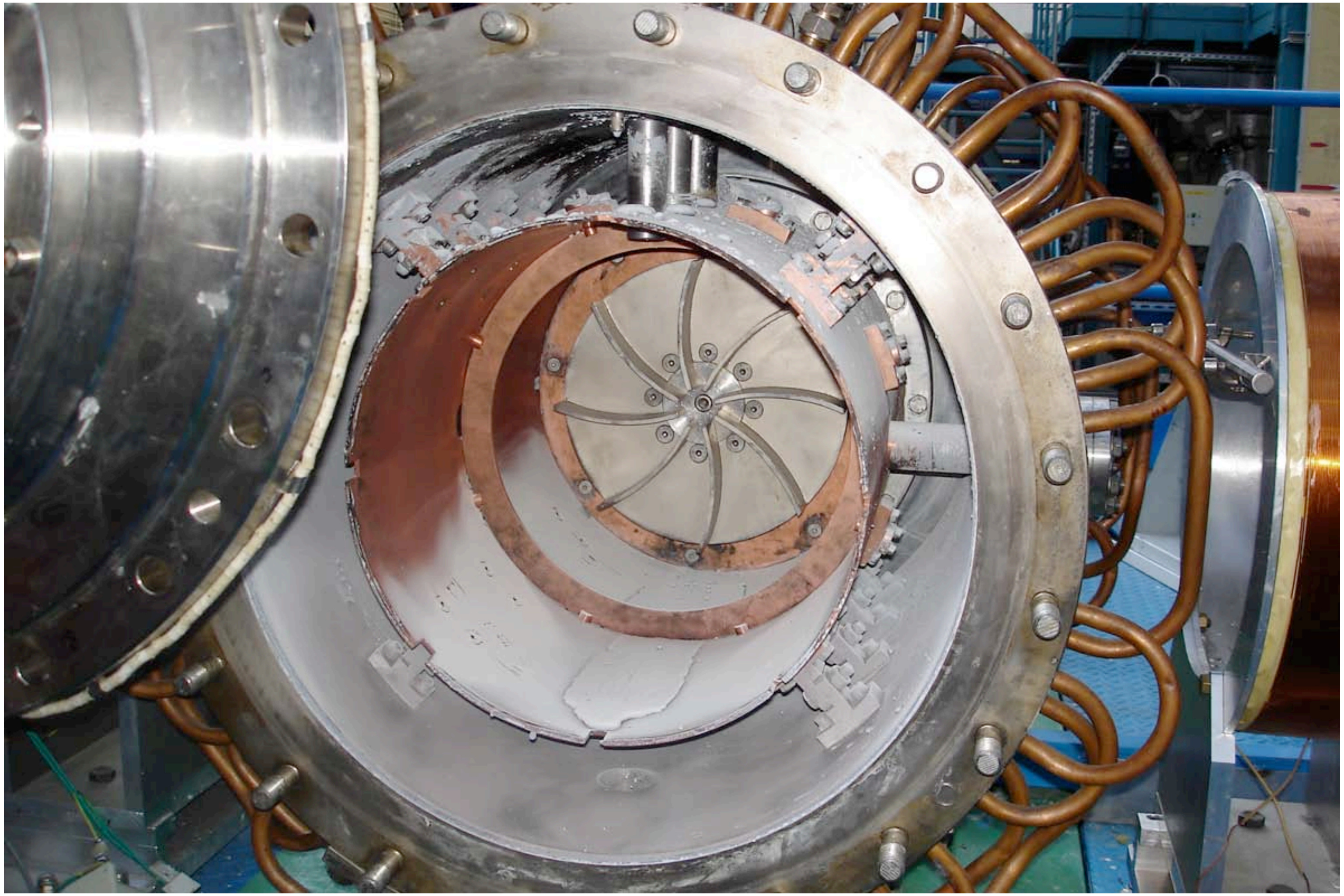
- von Karman flow in a cylinder filled with liquid sodium between 2 counter rotative propellers



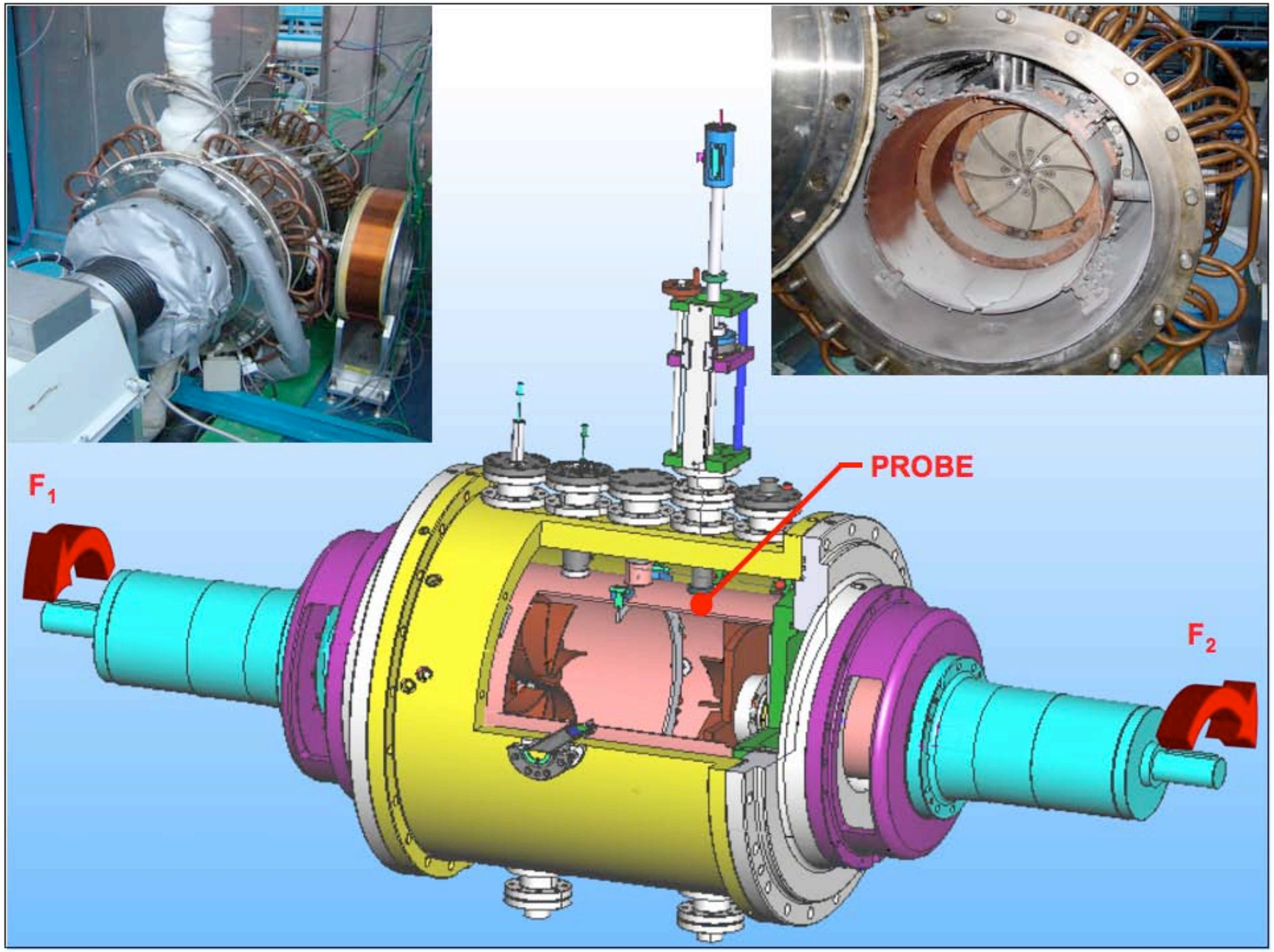
- cylinder L = Ø = 0,6 m
  → 160 l sodium
- power P = 300 kW
- 2 propellers f: 0 à 30 Hz
- cooling system 120°-160° C
- mechanical seals special Na

VKS2 experiment

- iron propellers
- annulus in shear layer
- copper shell with Na at rest



VKS2 experiment



Measurements: B, pression, temperature, torque

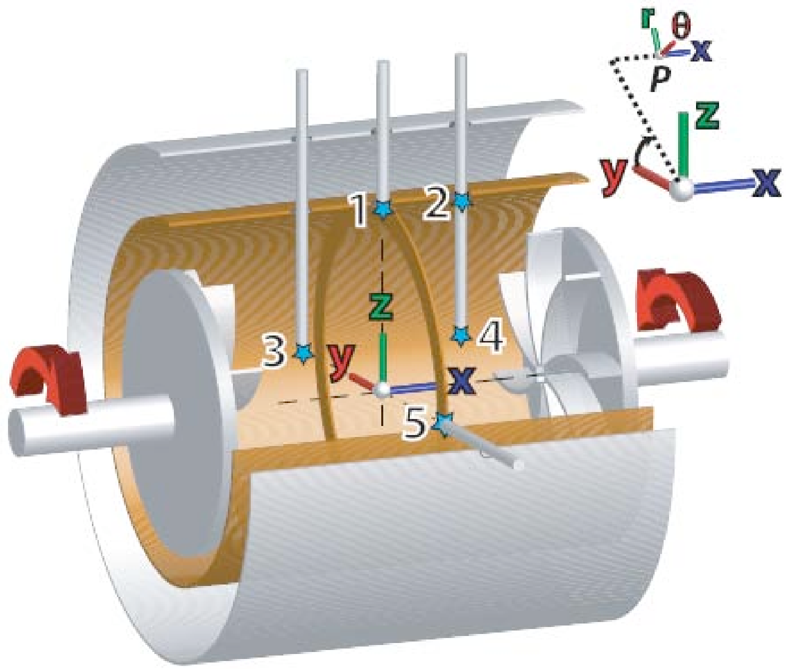
VKS2 experiment

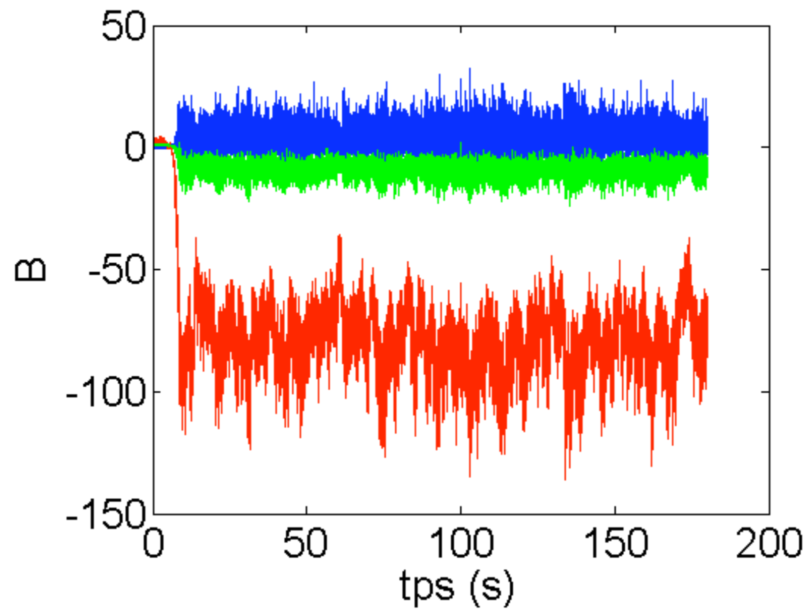
Experimental platform CEA Cadarache (DEN/DTN/STPA)

VKS2 experiment

Stationary dynamo

with symmetric driving $f_1=f_2$

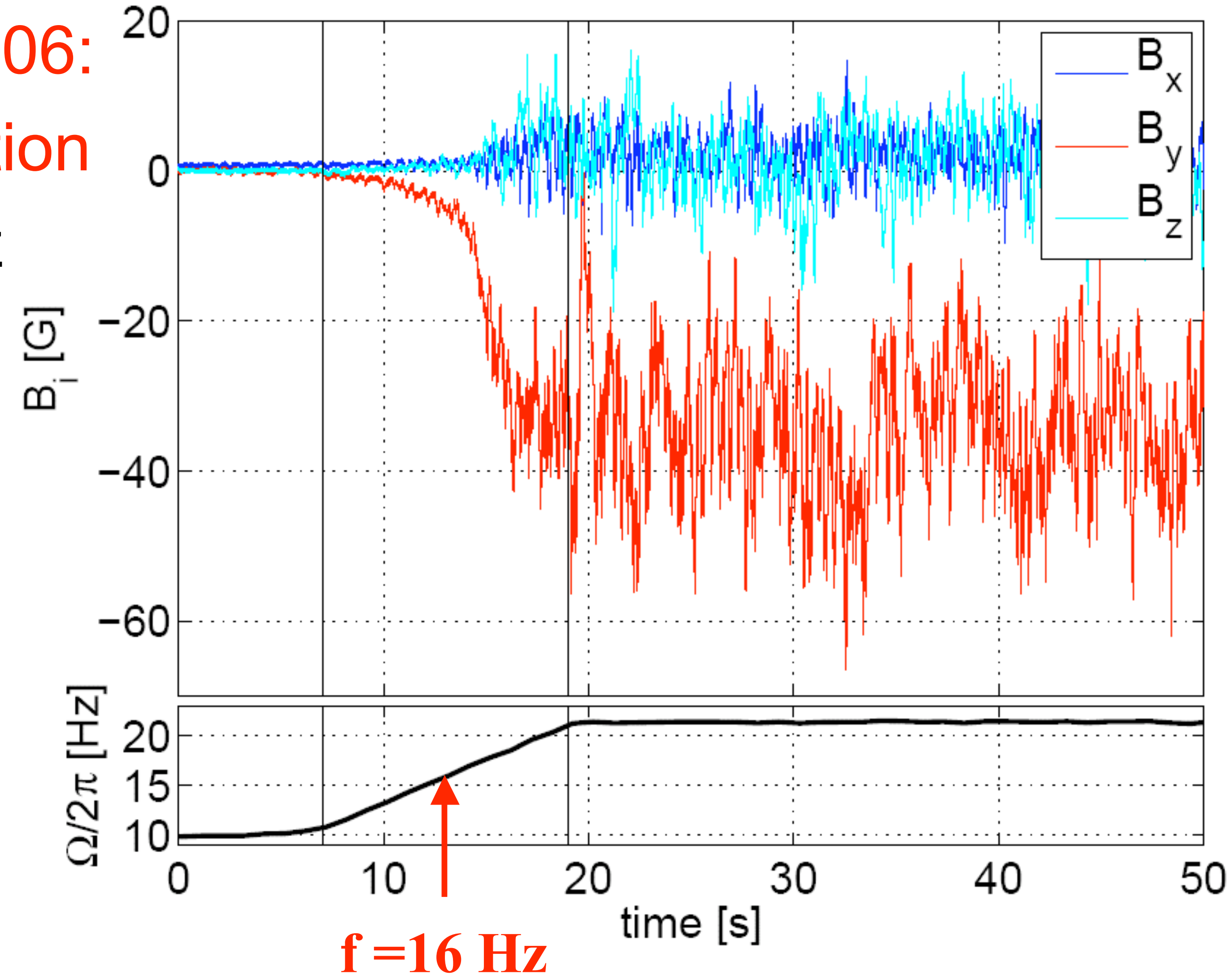




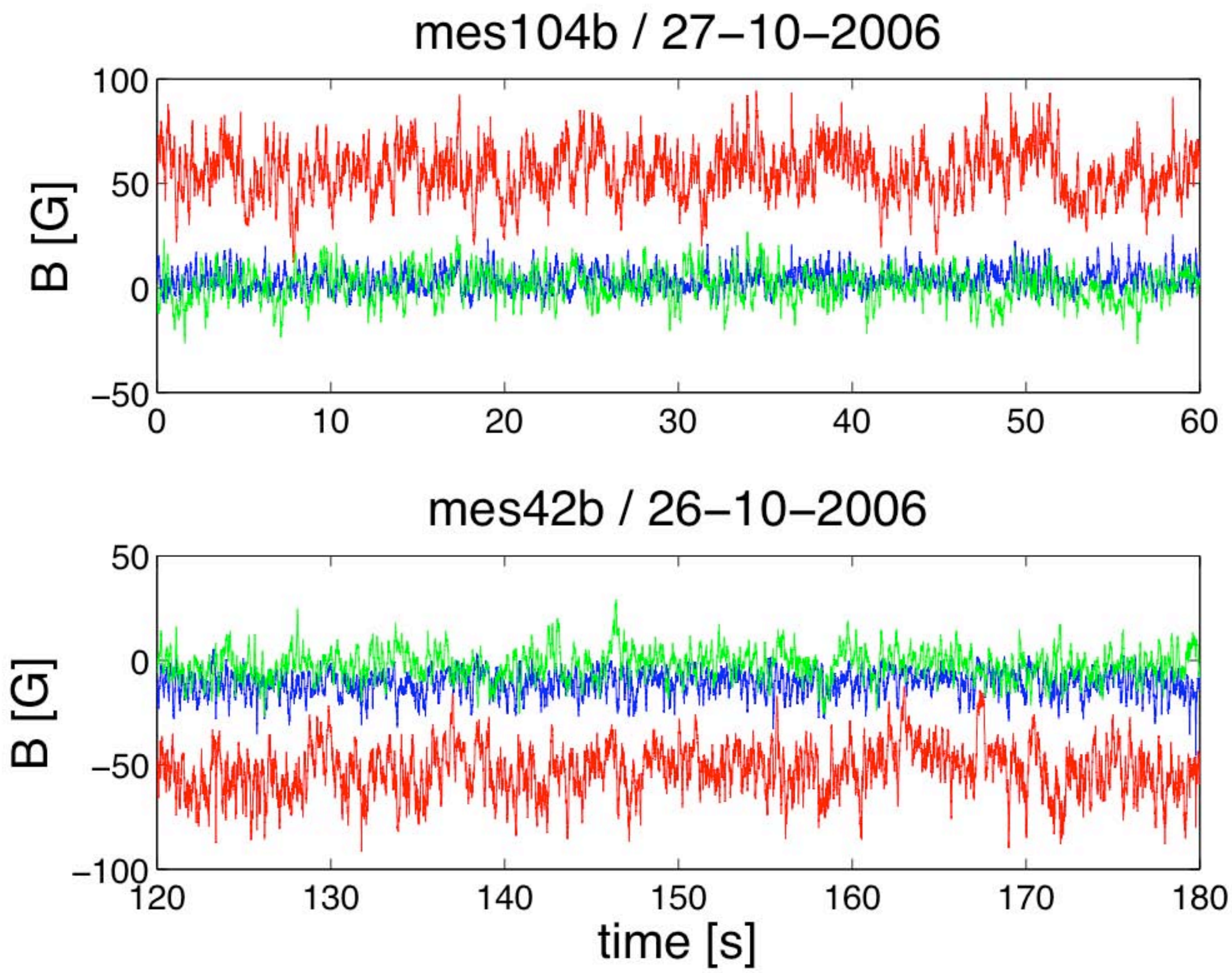
Observation of a turbulent dynamo

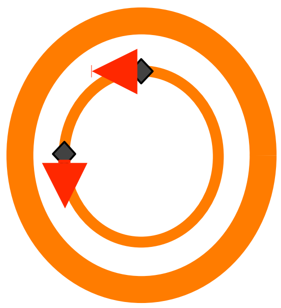
September 06:
dynamo action
for f >16 Hz

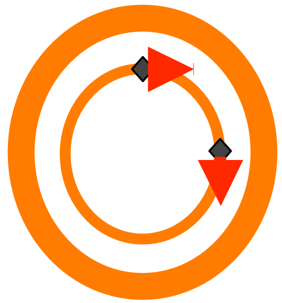
$f_1 = f_2$



Dynamo field orientation





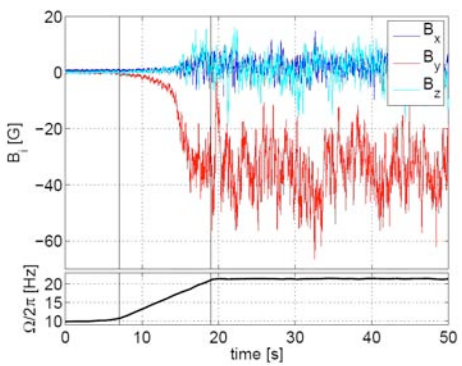


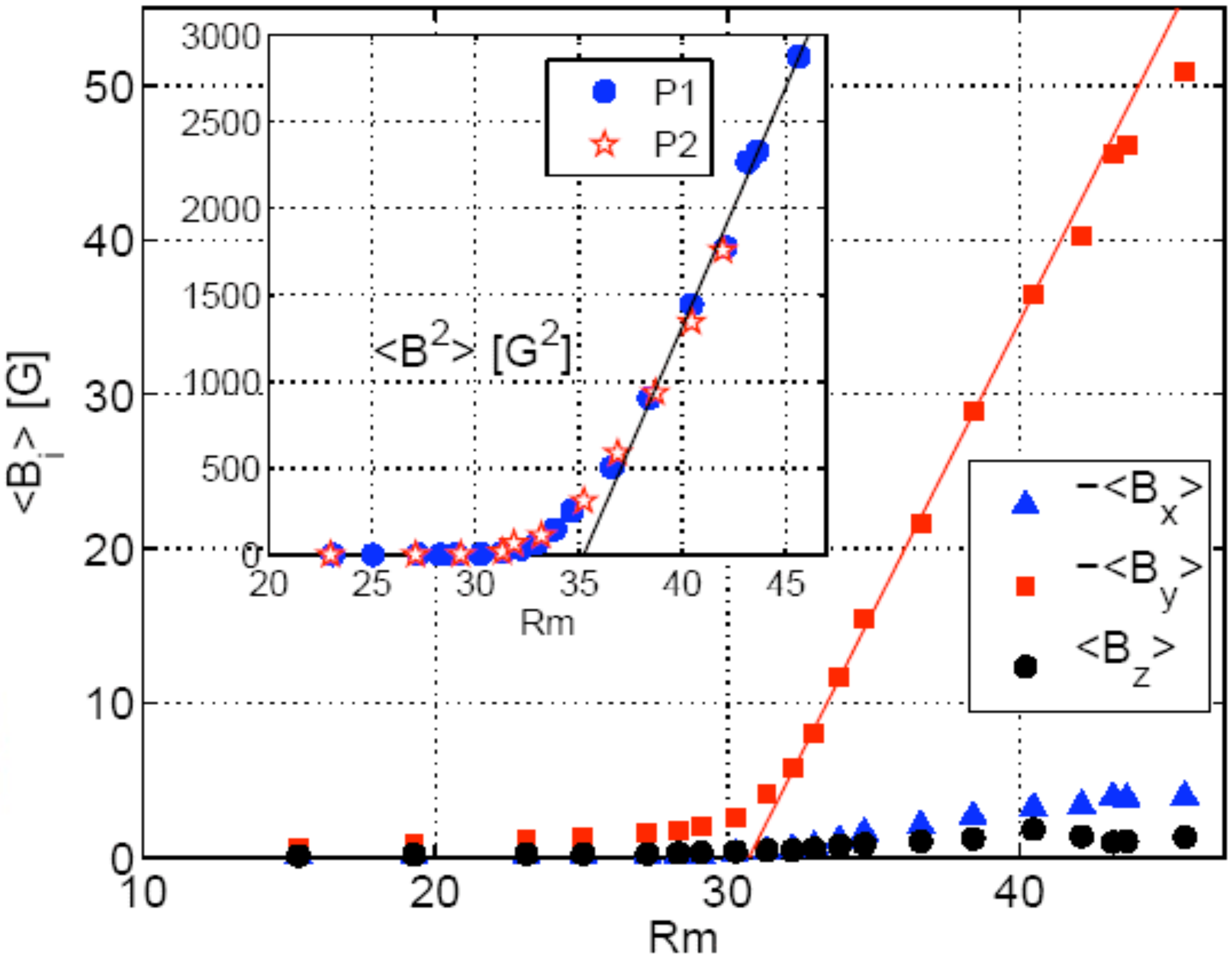
Dynamo bifurcation: evolution of <B>

$B \sim (R_m - R_m^c)^\alpha$

scaling

$\frac{1}{2} < \alpha < 1$?

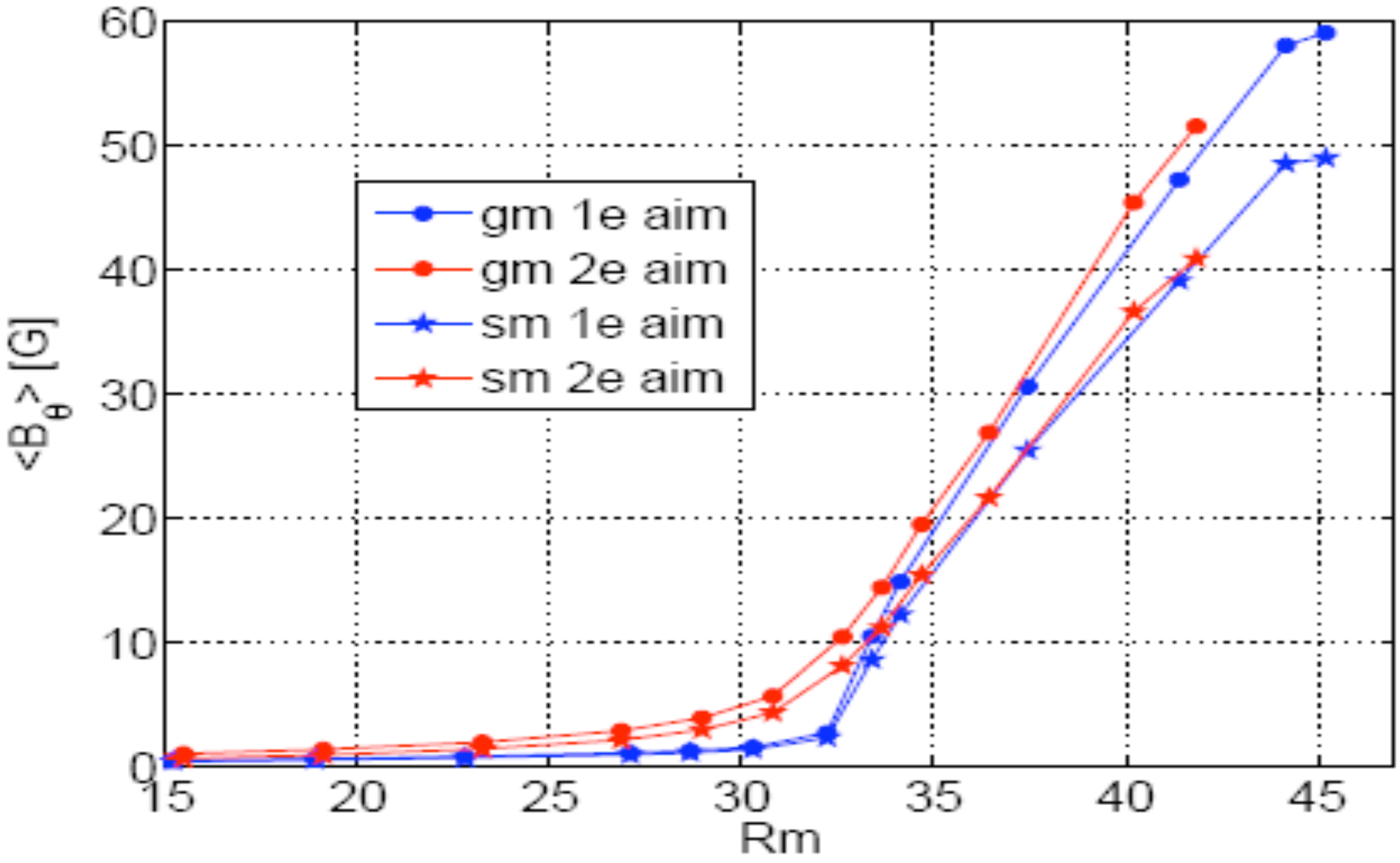




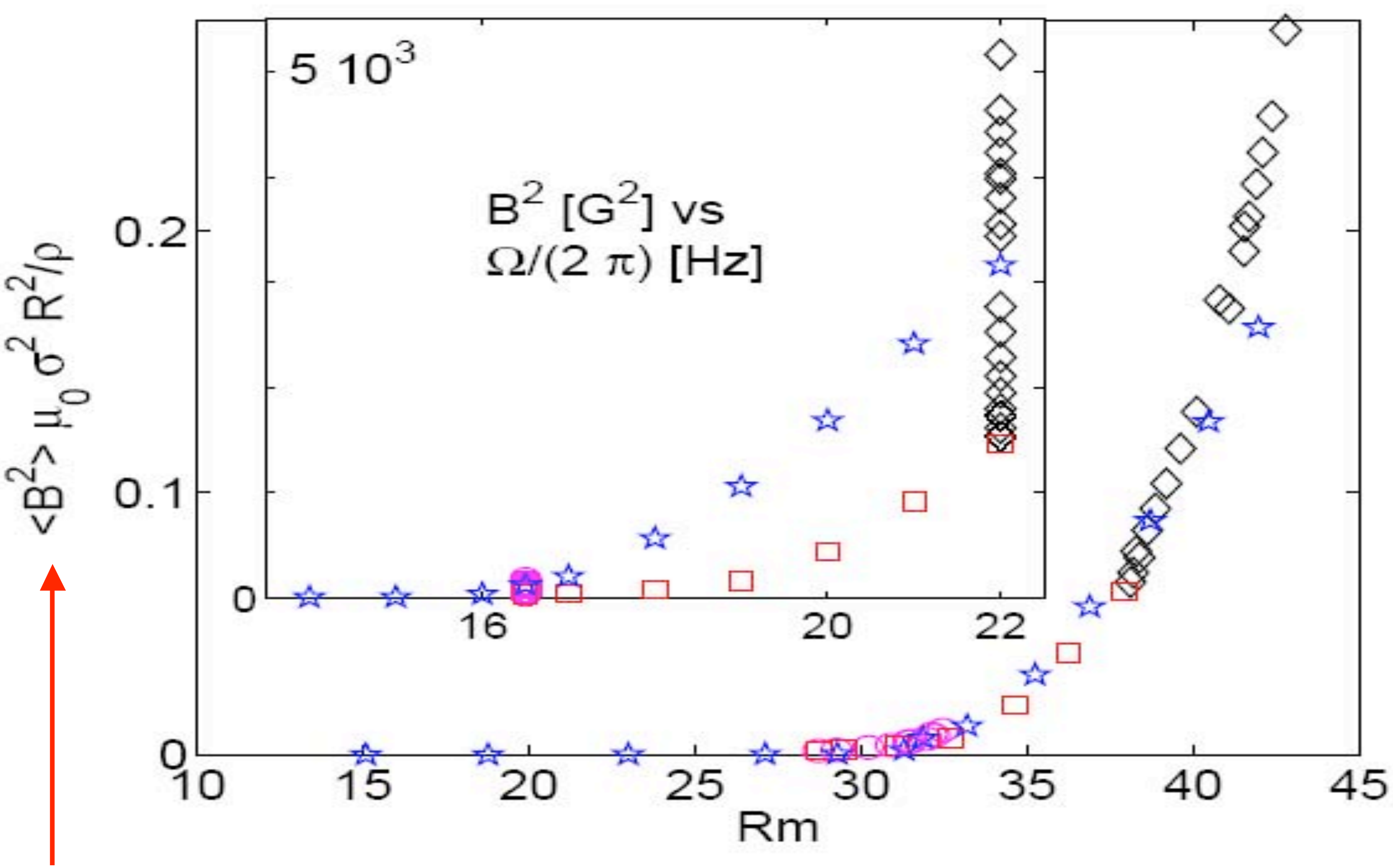
Monchaux et al. Phys.Rev.Lett. 2007

Bifurcation: evolution of <B>

Imperfect bifurcation



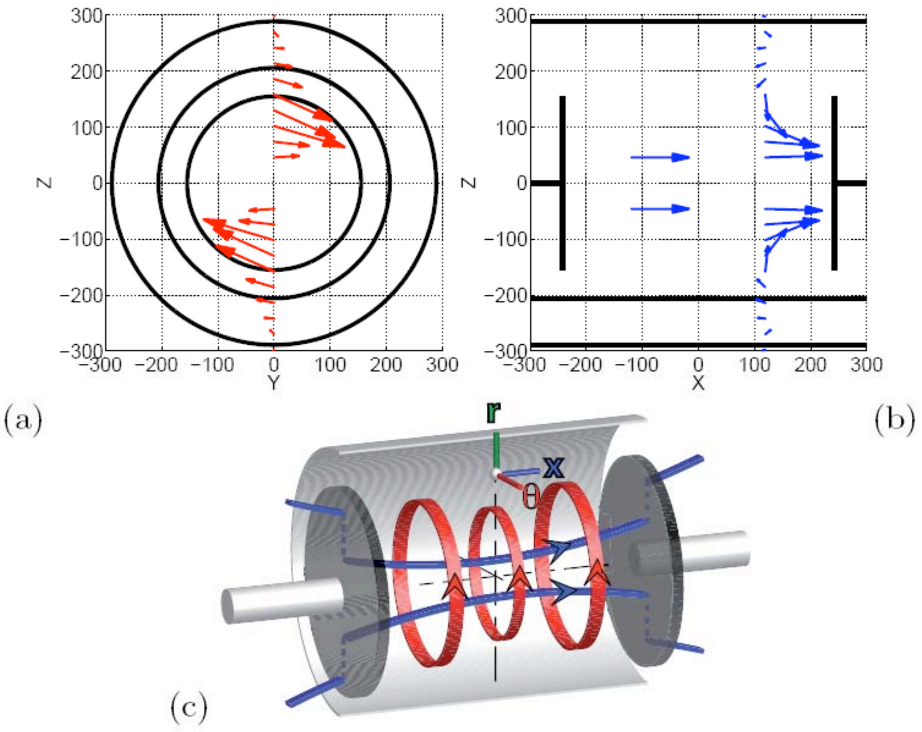
Bifurcation: scaling law of saturated <B>

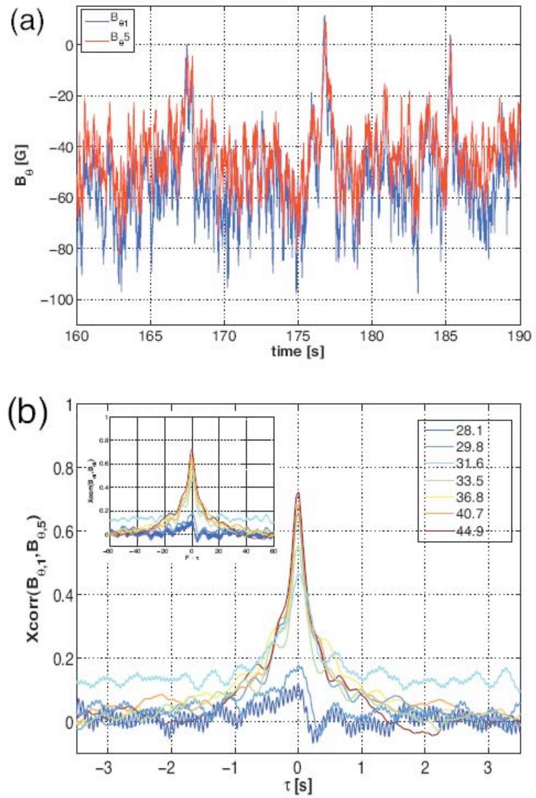


Turbulent scaling

Prediction Petrelis et Fauve EPJB 22 (2001)

Geometry of the dynamo field



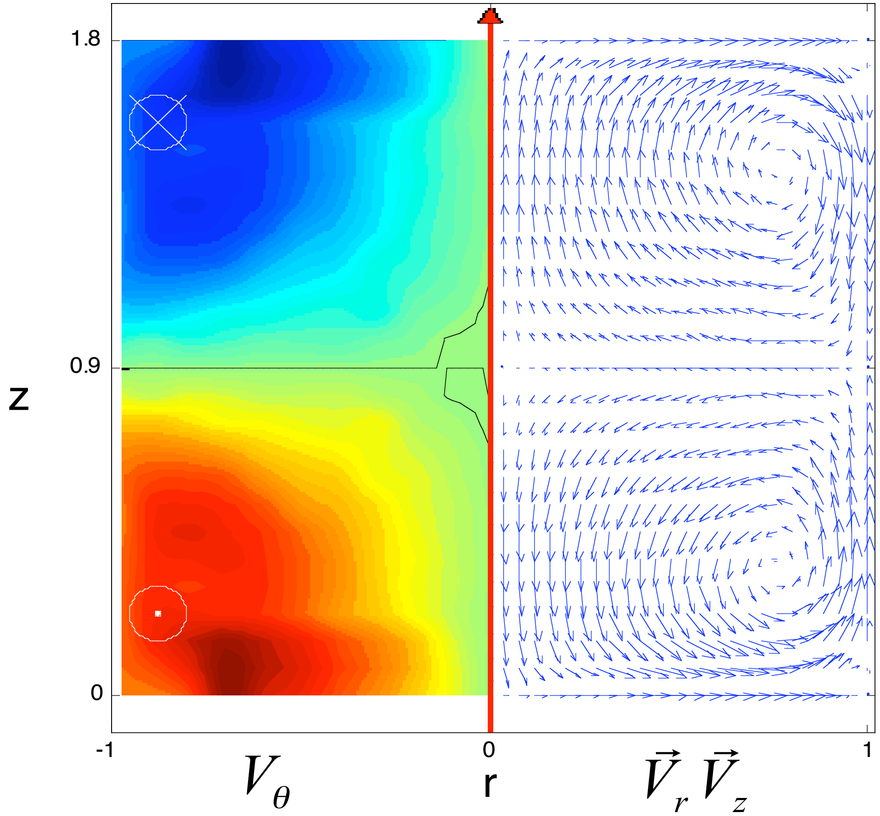


Dipolar magnetic field ~ axisymmetric (m=0 B mode)

- ≠ kinematic mode predicted with <V> (m=1 B mode)
- forbidden by Cowling theorem for <V> axisymmetric

→ created by turbulent fluctuations?

Mean flow: water experiments



Turbulent: Re ~ 5.10^5

$\delta v/v = 0.4$

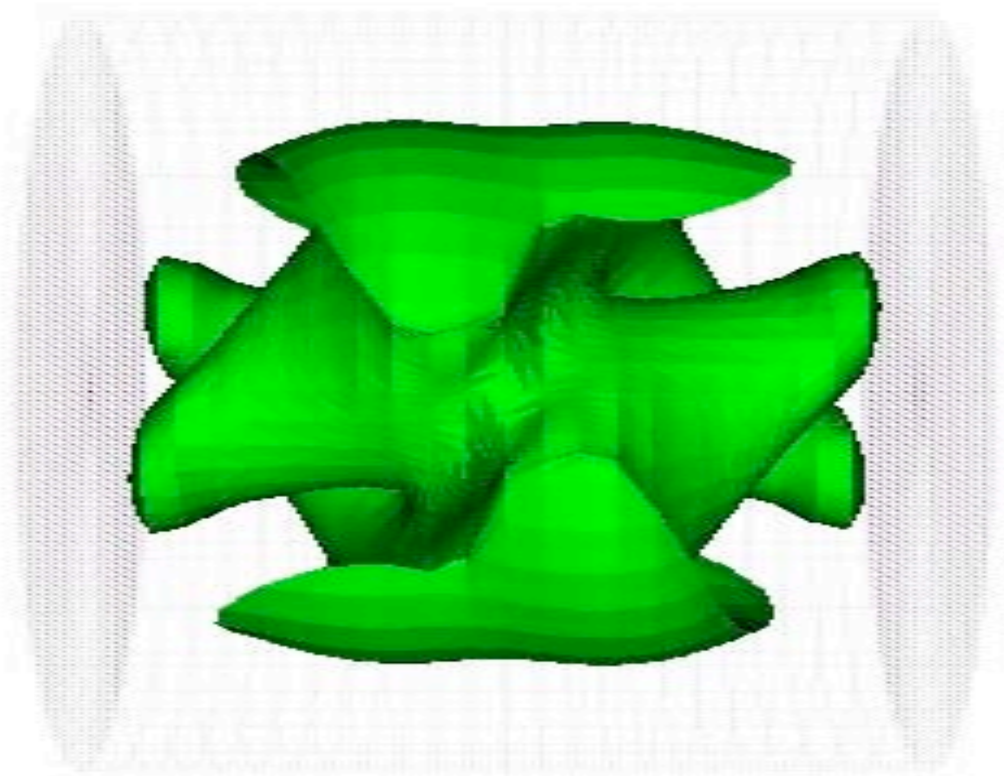
Mean velocimetry measurements (LDV-PIV)

Kinematic neutral mode

$$\frac{\partial \vec{B}}{\partial t} + R_m(\vec{v} \cdot \overrightarrow{grad})\vec{B} = R_m(\vec{B} \cdot \overrightarrow{grad})\vec{v} + \Delta\vec{B}$$

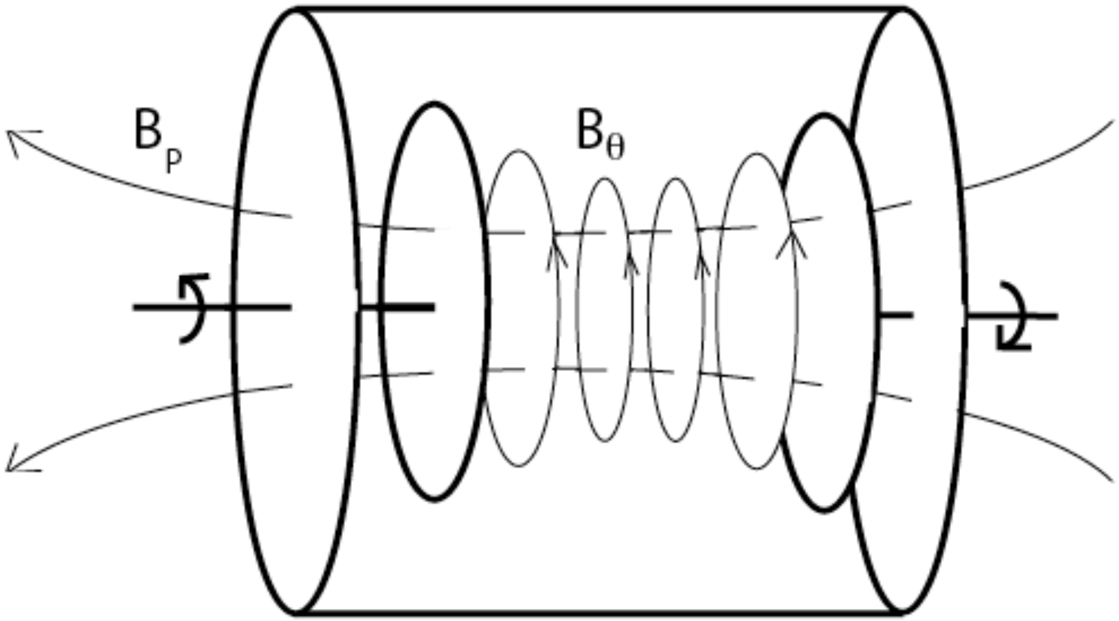
Ravelet et al.
POF 2005

Stationary
equatorial
dipole (m=1)



- equatorial dipole killed by turbulent fluctuations?
- equatorial dipole bifurcates towards axial dipole?

Turbulent α-Ω dynamo



B_θ generated from B_p because of the differential rotation (Ω effect)

B_p generated from B_θ because of helicity of the radial divergent flow between blades (α effect)

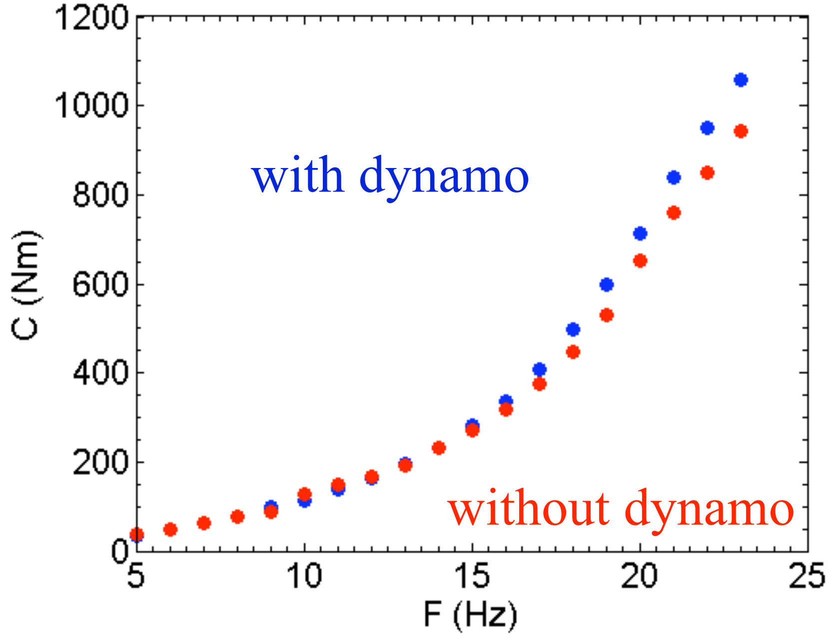
B created by turbulent non axisymetric fluctuations?

Petrelis et al. GAFD 2007

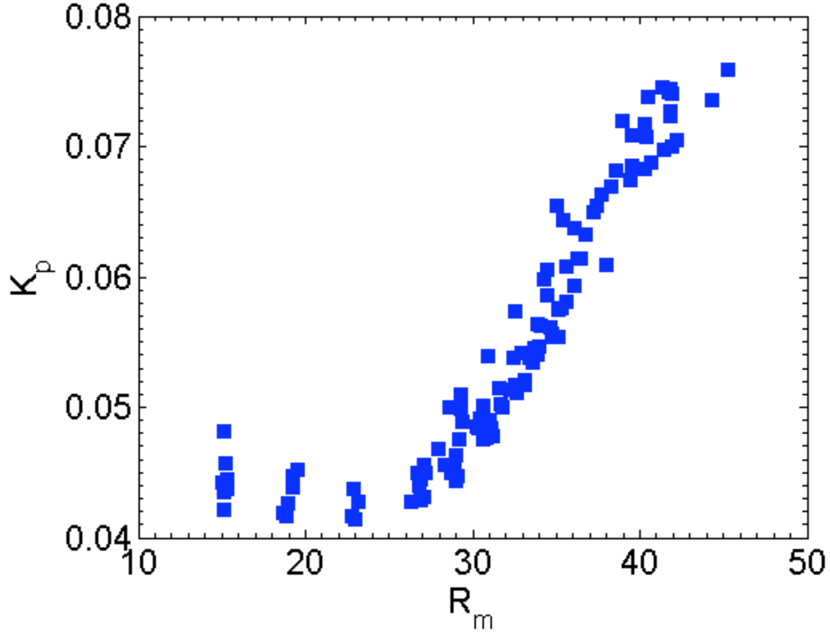
Power budget in VKS

Dynamo power: $P_T = P_{cin} + P_{mag}$

Torque



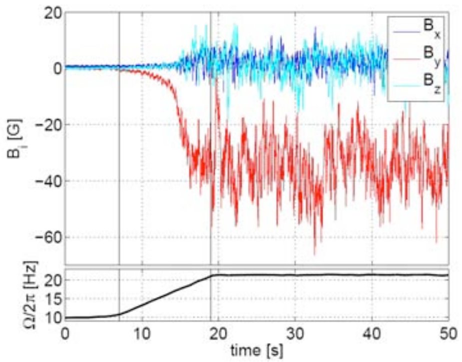
Non dimensional torque

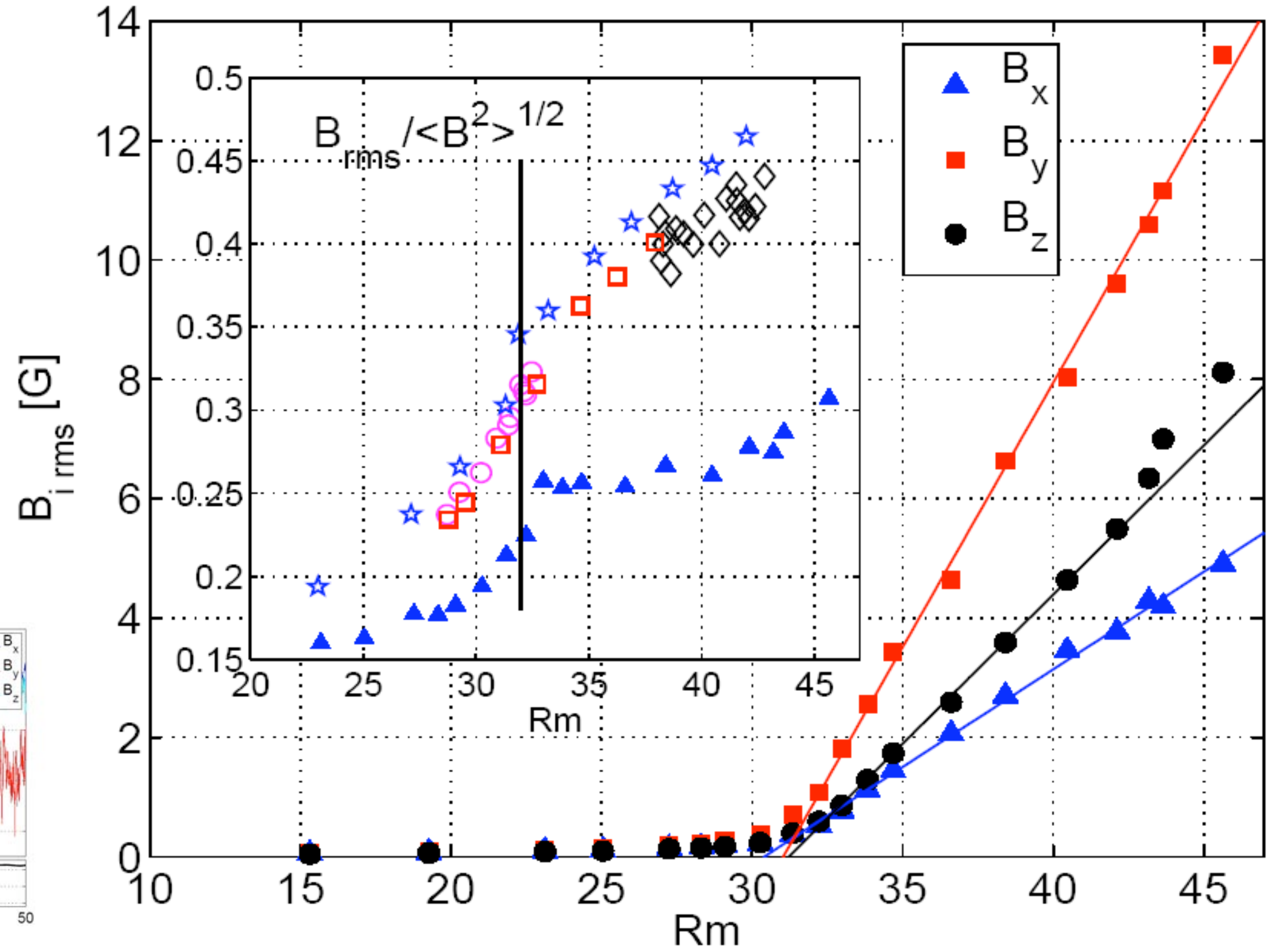


dynamo = increase of power 15%

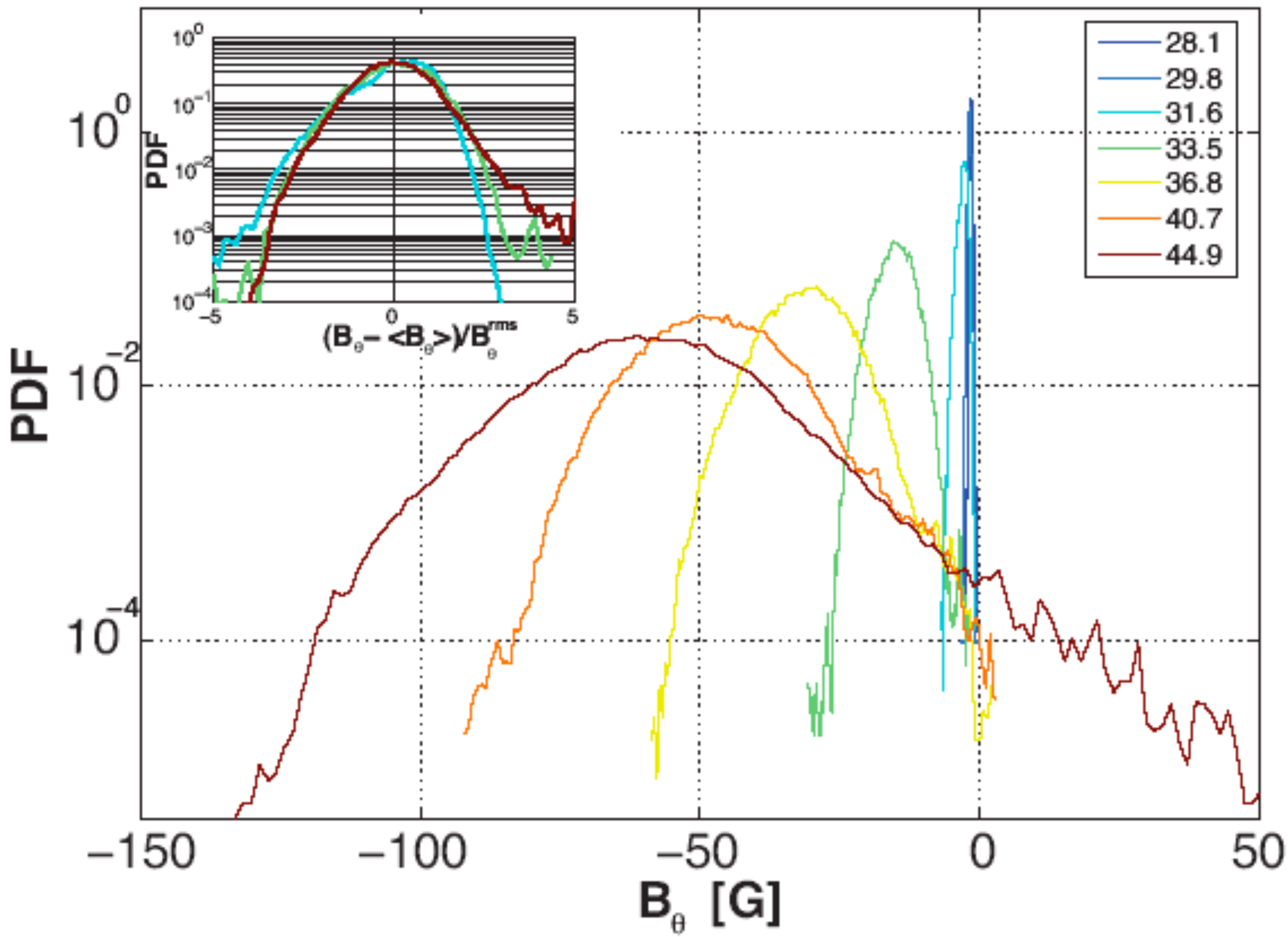
Fluctuations: evolution of B_{rms}

Bifurcation in presence of noise

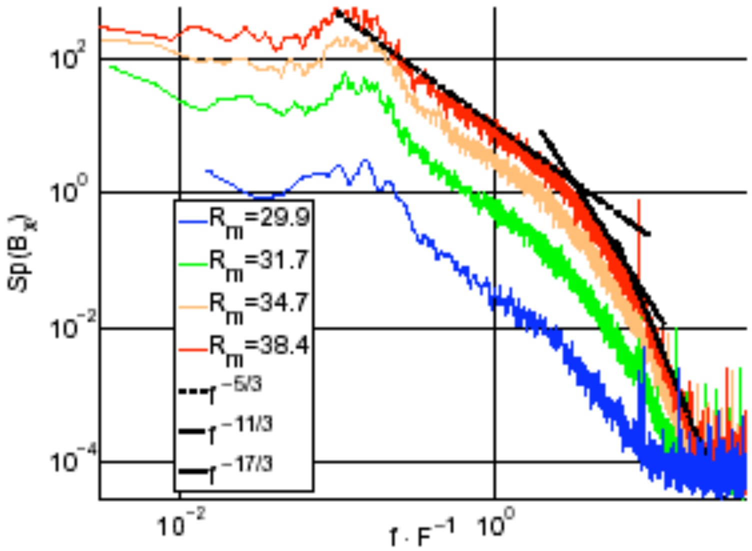




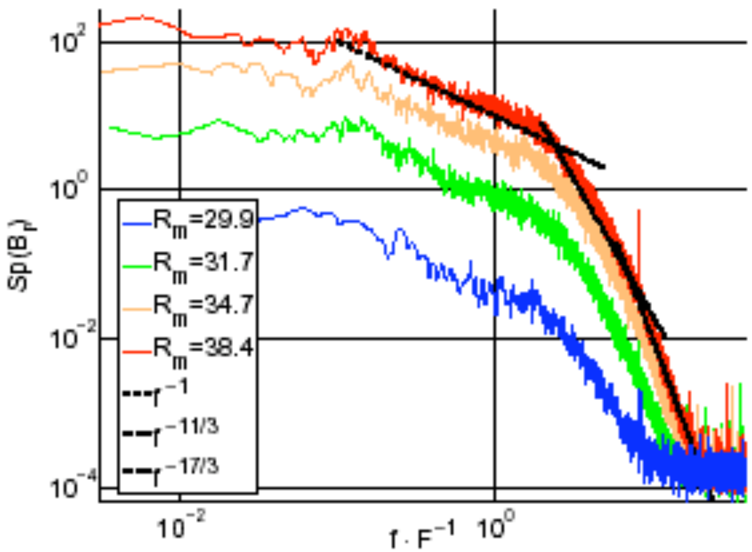
Fluctuations: PDFs



Fluctuations: time spectra



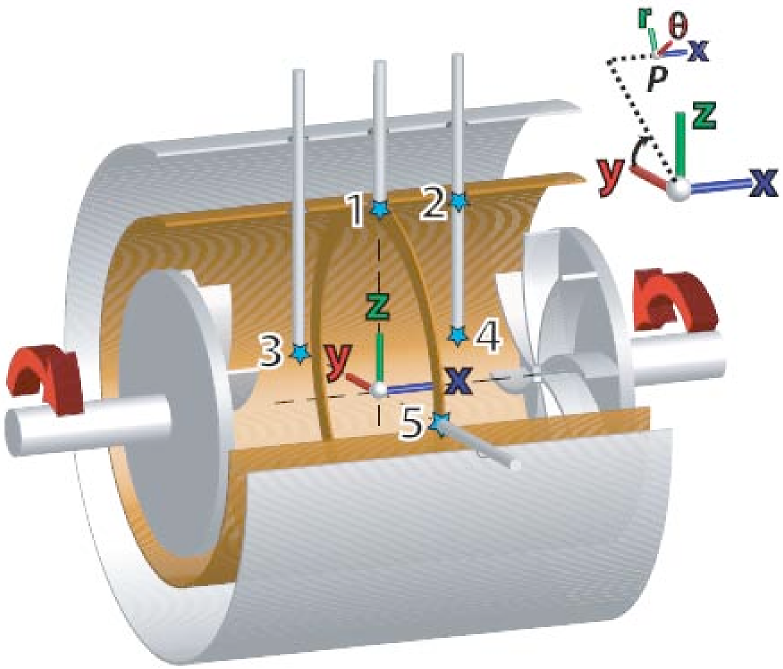
axial component

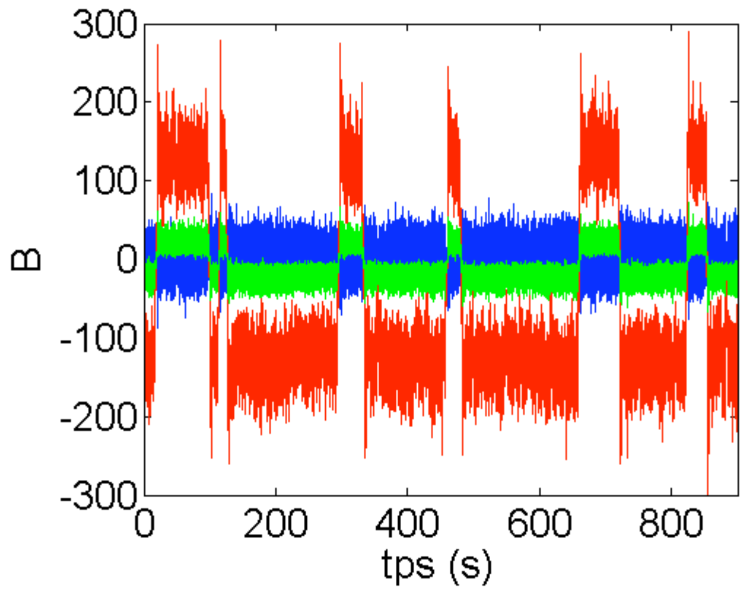


radial component

VKS2 experiment

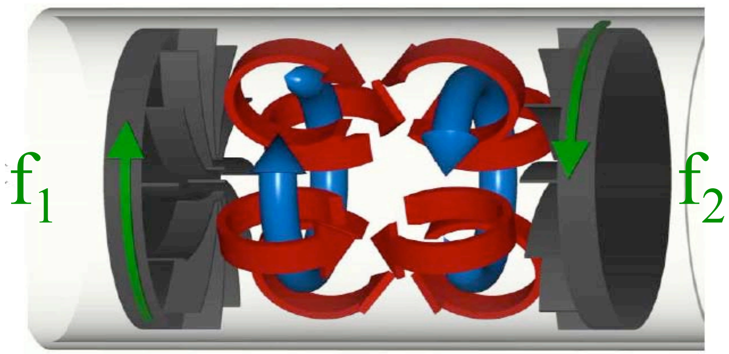
Dynamical dynamos with asymmetric forcing $f_1 \neq f_2$



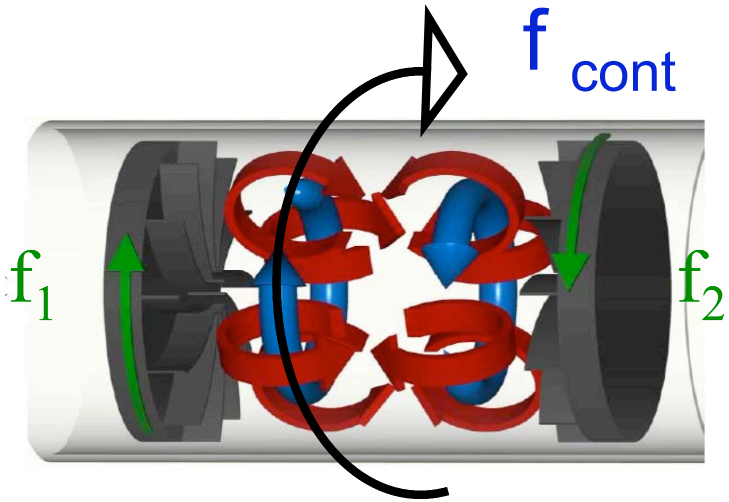


Global rotation : propellers with $f_1 \neq f_2$

$f_1 \neq f_2$ and $f_{cont} = 0$

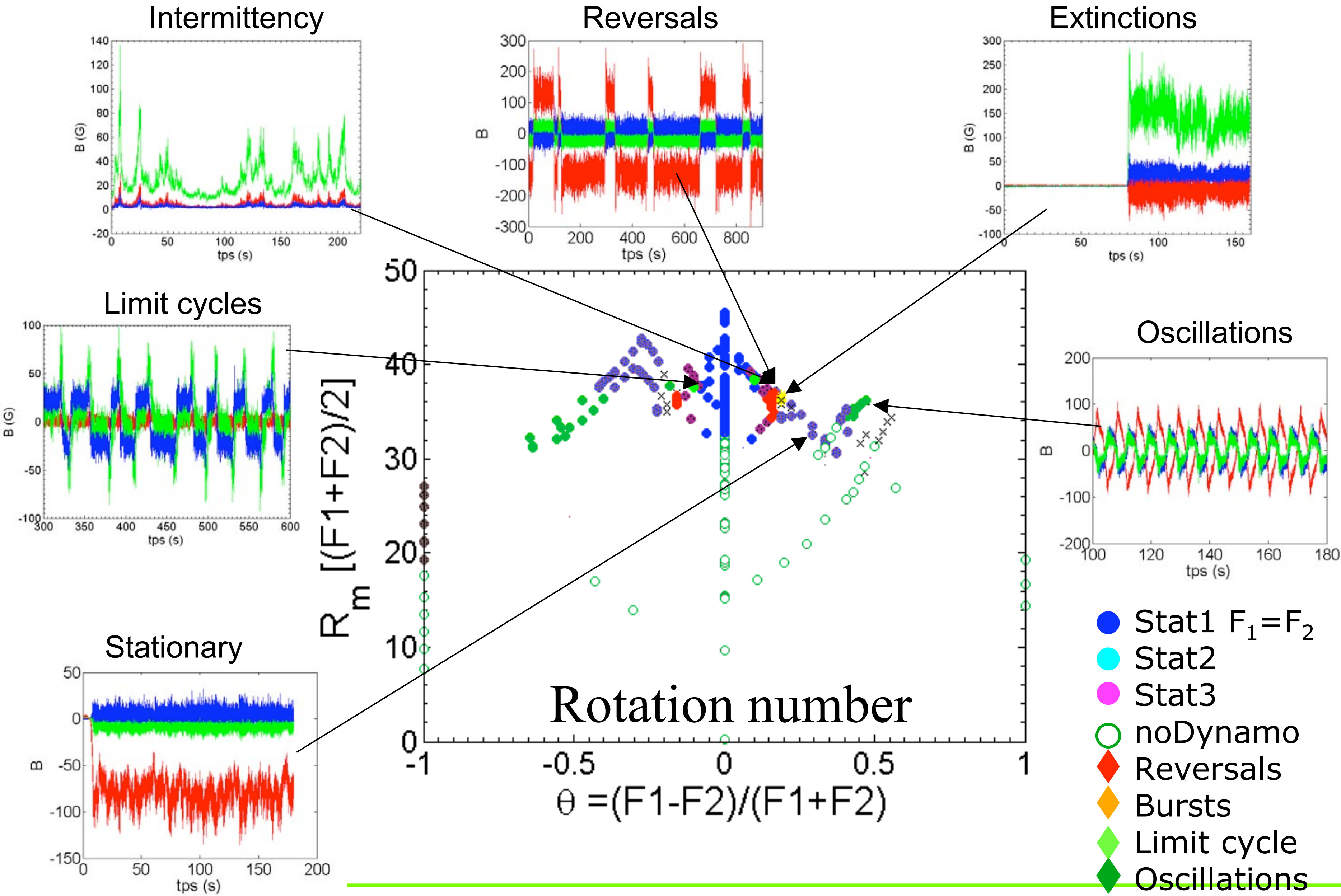


$f_1 = f_2$ and $f_{cont} = ½ (f_1 - f_2)$



L.Marié PhD

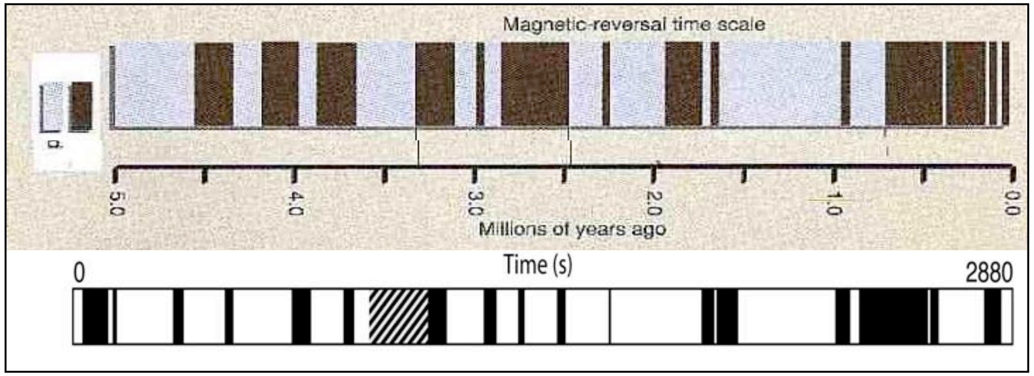
Global rotation: observed dynamics



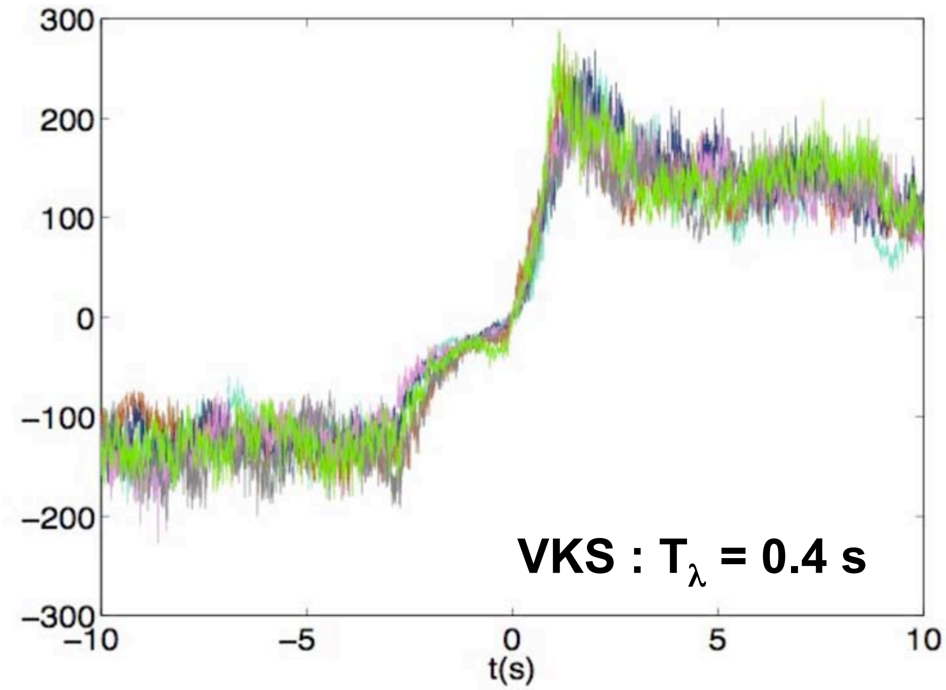
Erratic reversals of B

Berhanu et al. EPL 2007

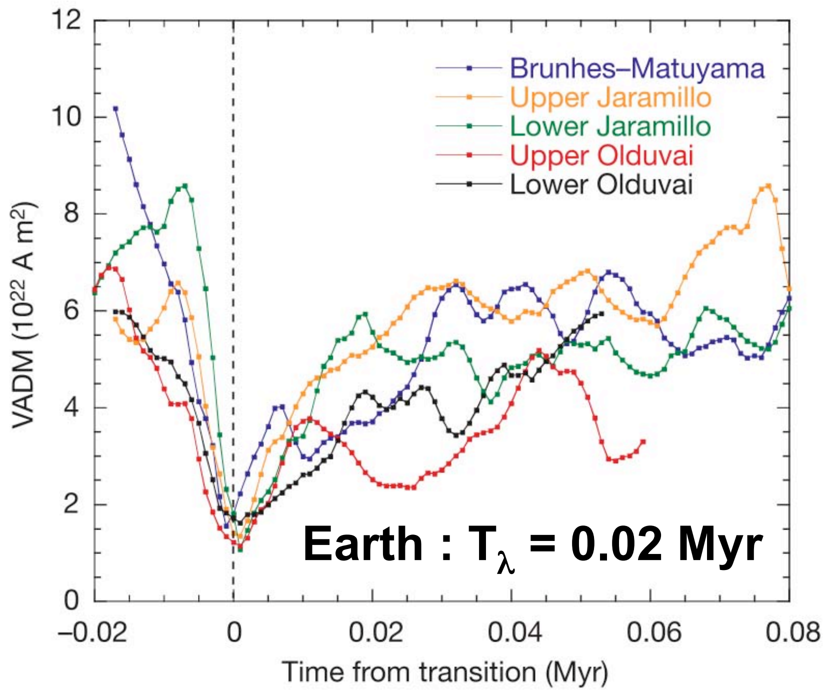
Erratic reversals of B: VKS / Earth



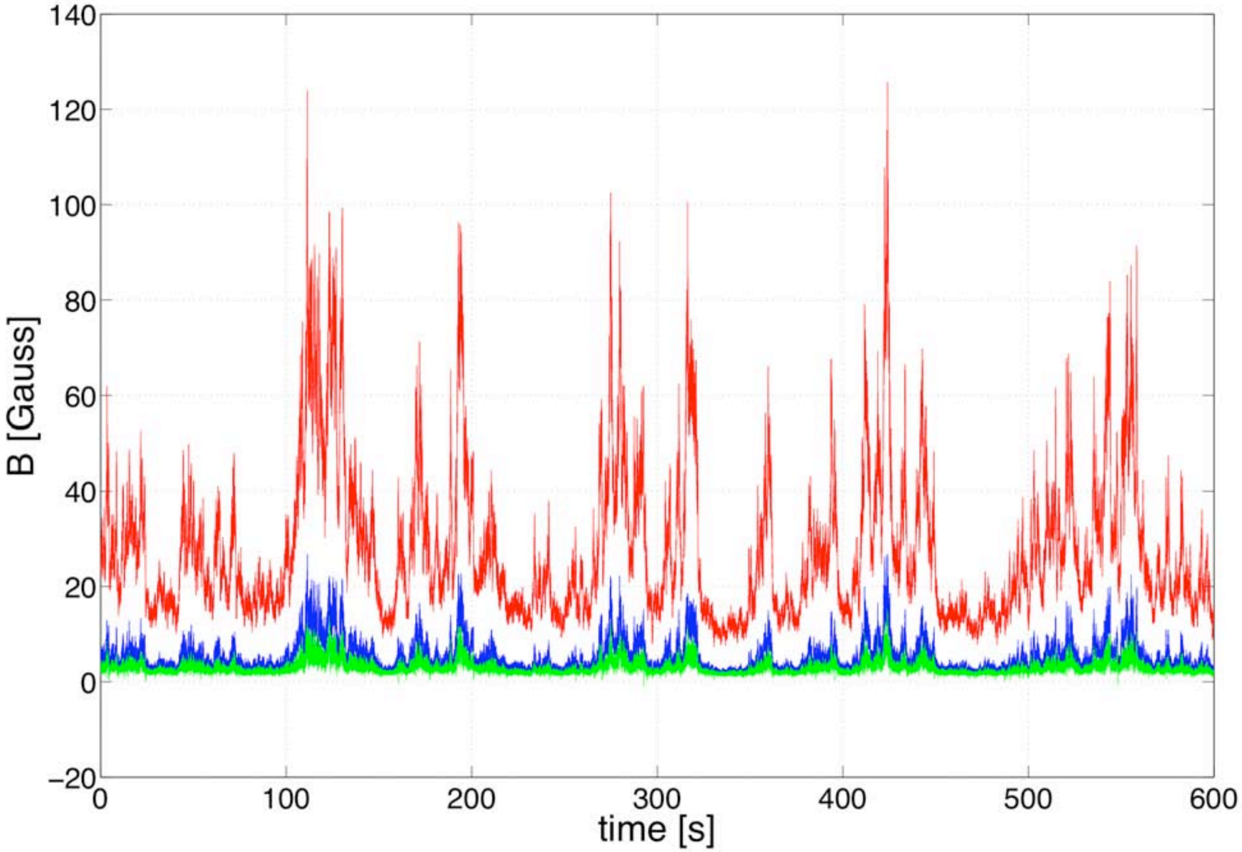
Berhanu et al. EPL 2007

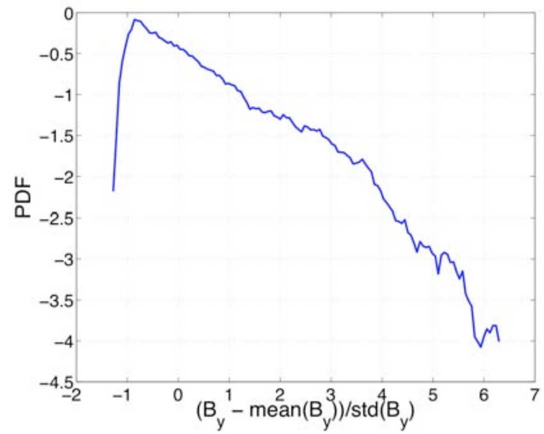


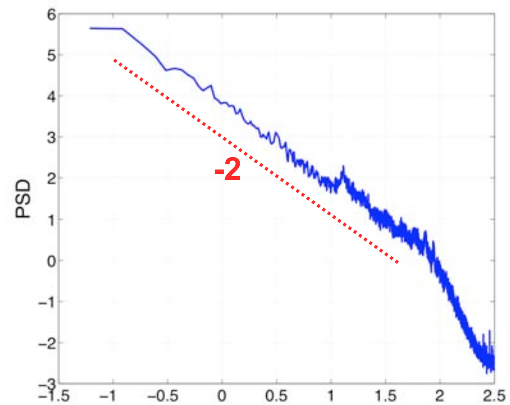
Valet et al. Nature 2005



Dynamo bursts

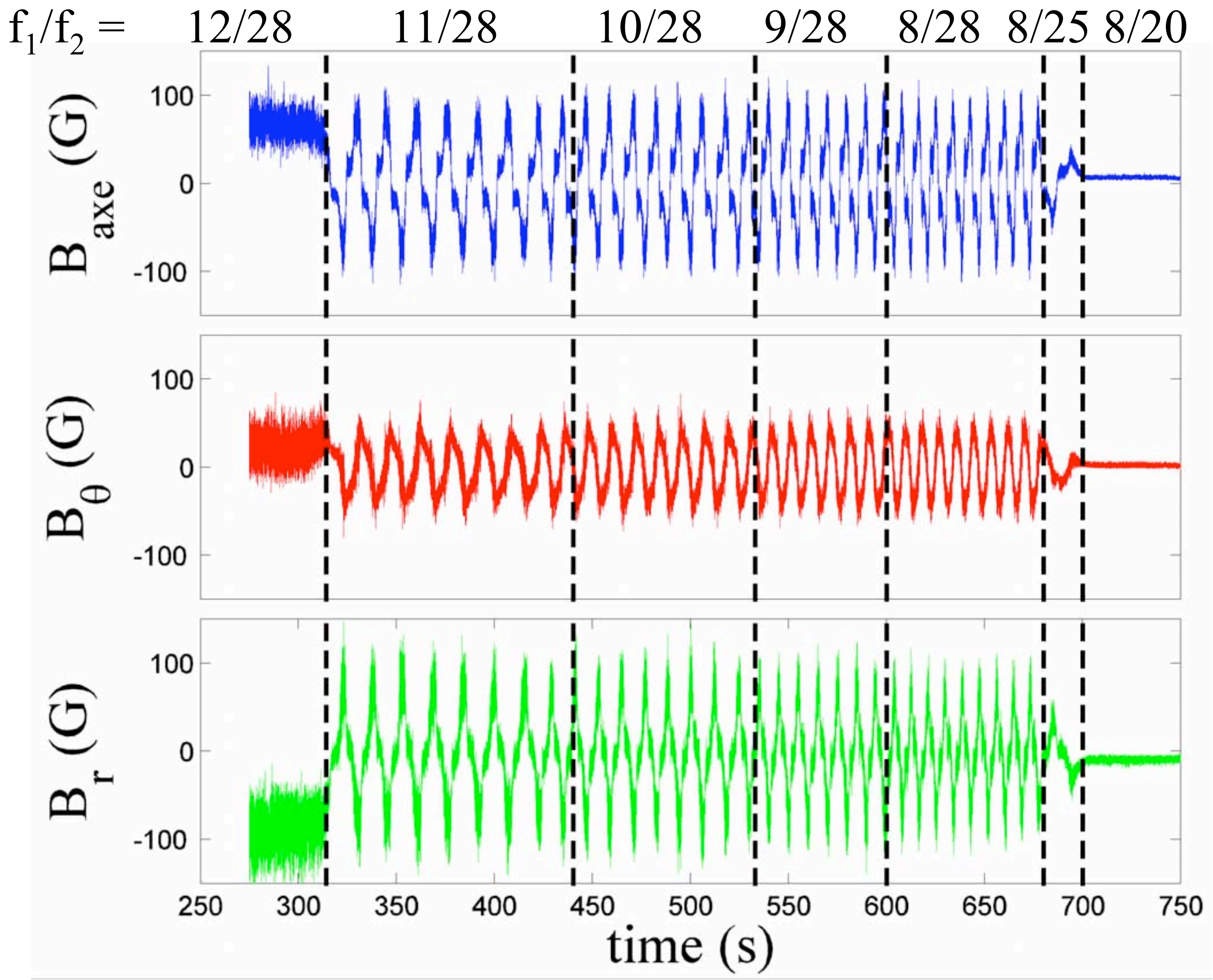




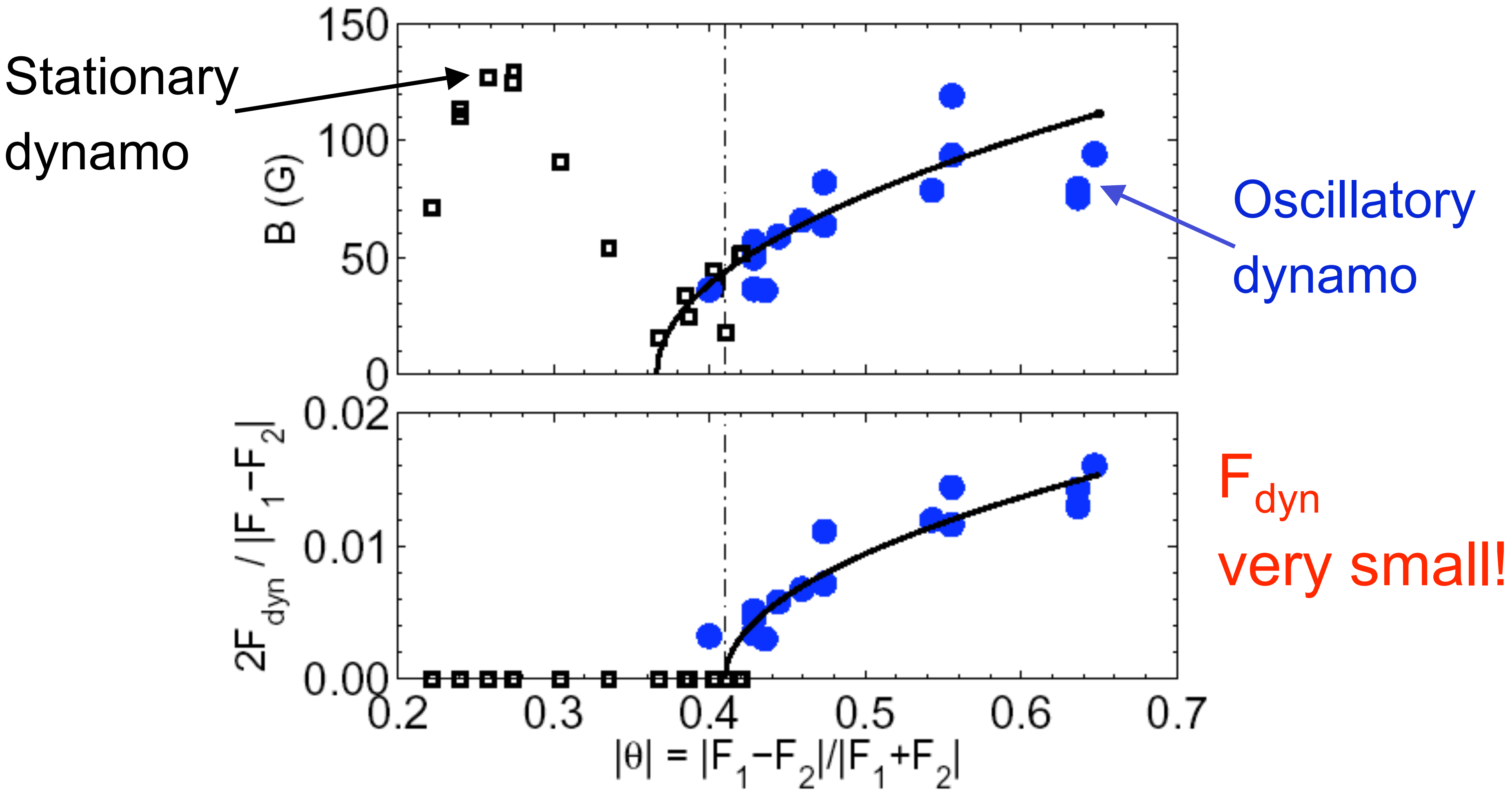


15/22, θ= 0.19

Oscillatory dynamos

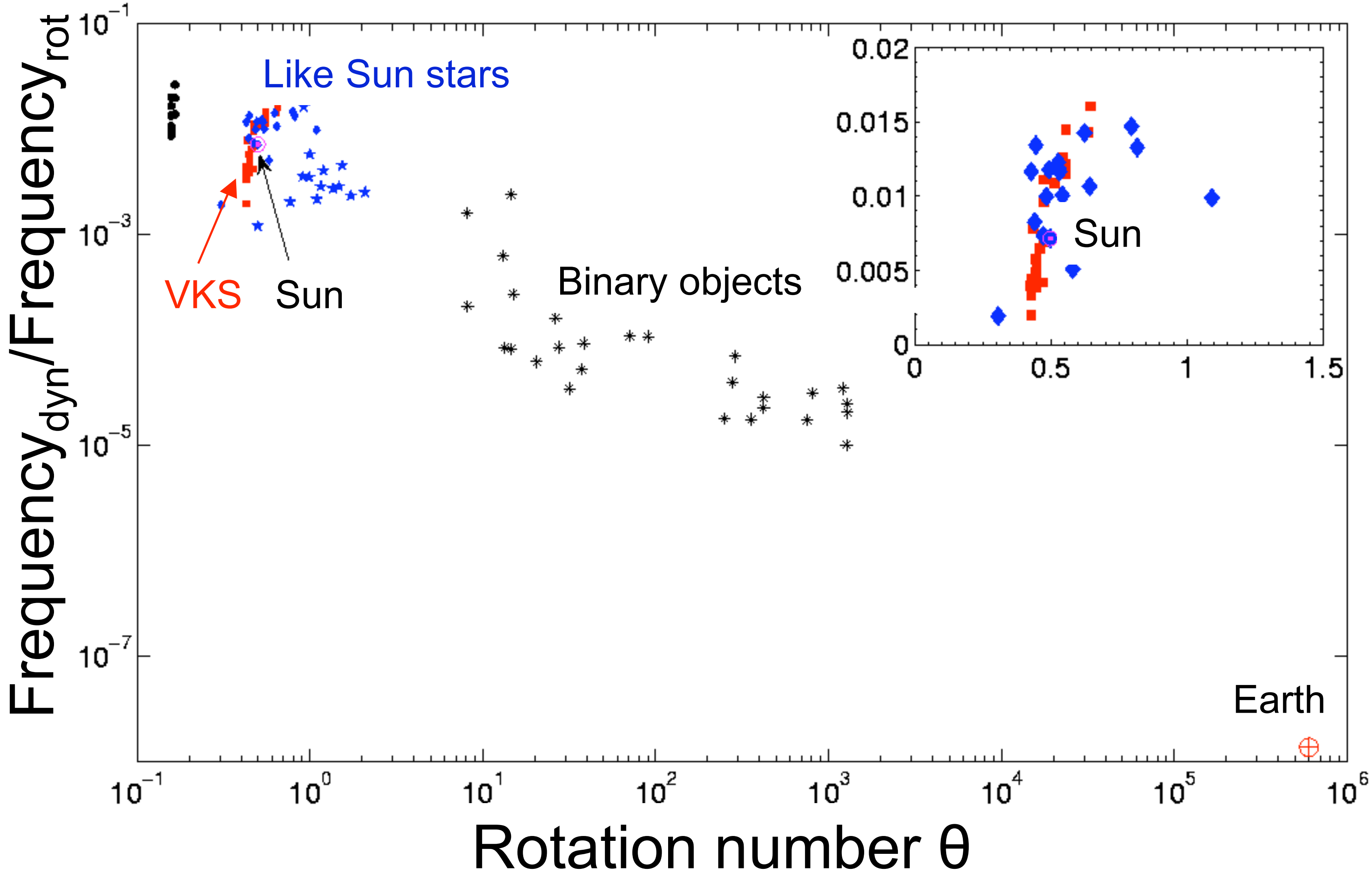


Transition to oscillatory dynamos



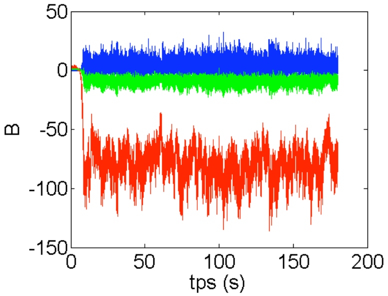
Finite amplitude and zero frequency secondary bifurcation as in low dim. systems: B and $F_{dyn} \sim (\theta - \theta_c)^{1/2}$

Oscillatory dynamos : VKS / stars

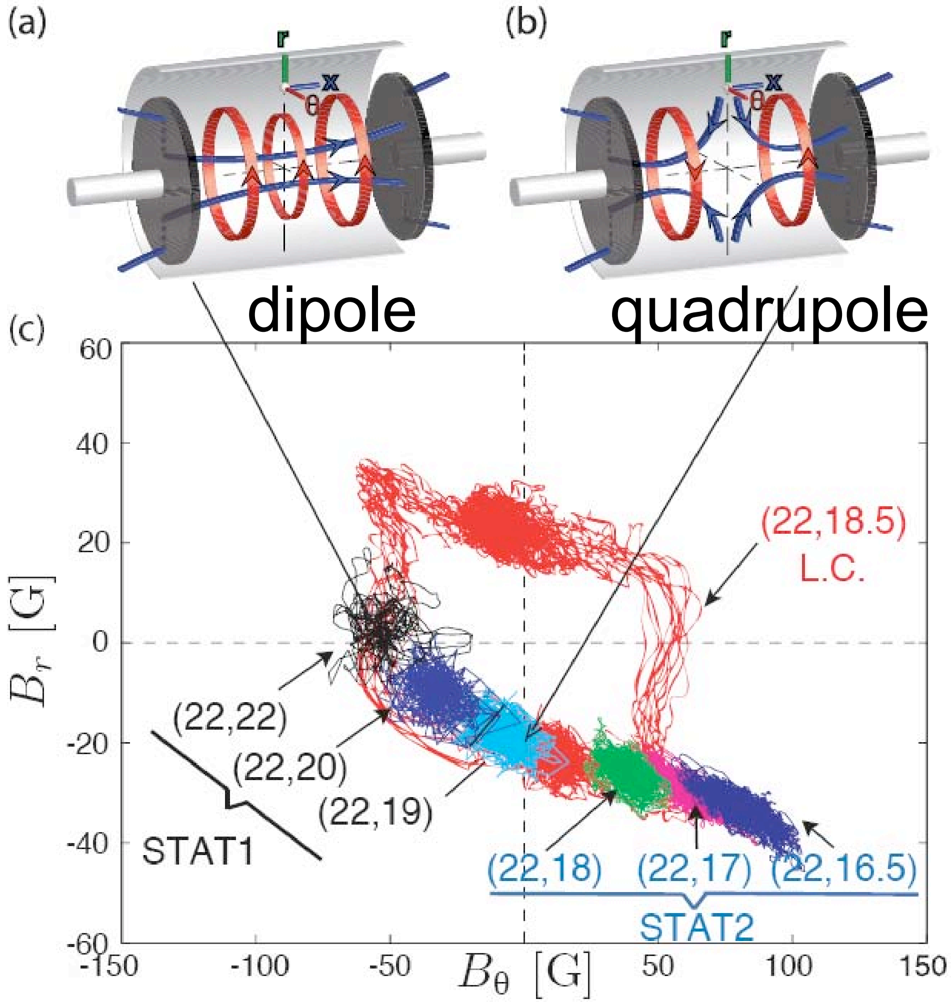


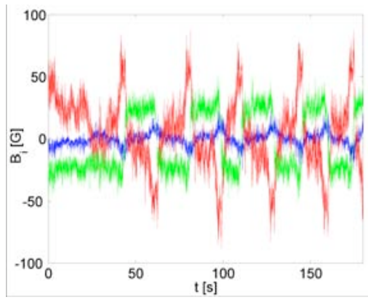
Transition stationary-limit cycle dynamos

Ravelet et al.
Phys.Rev.Lett. 2008



fixed points

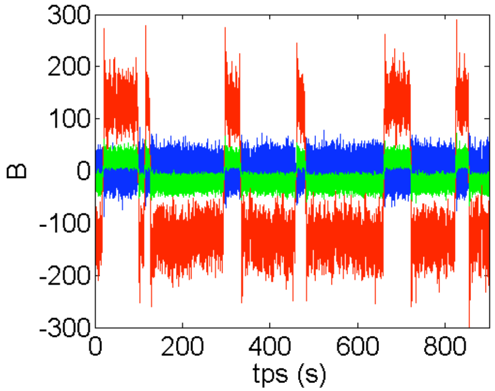


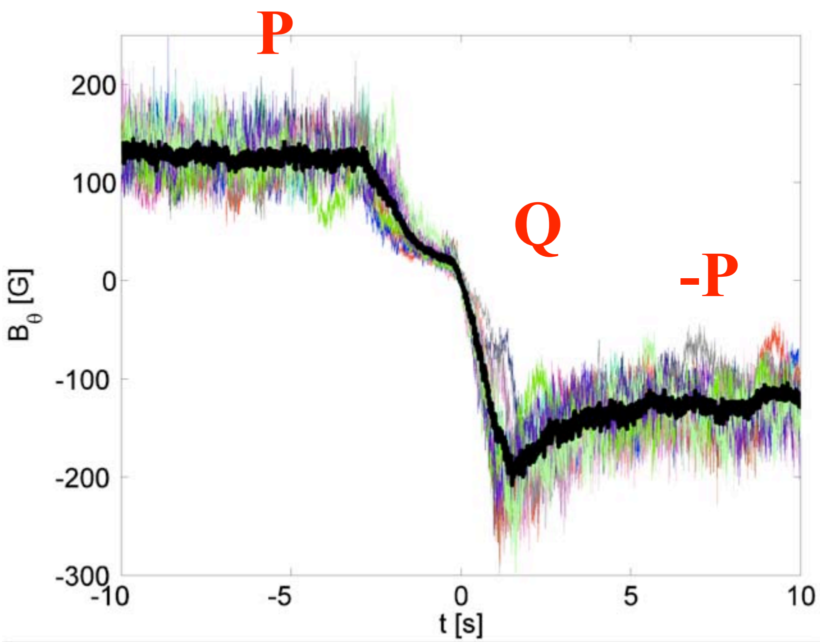


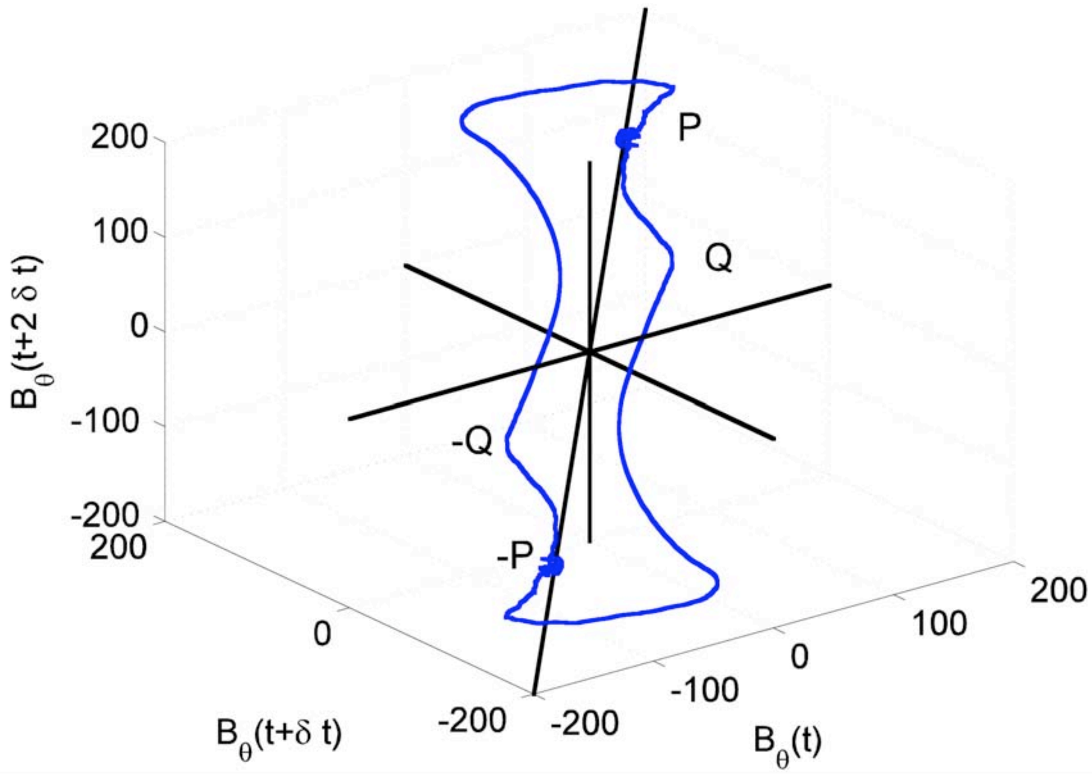
limit cycle

Saddle node-bifurcation fixed point → limit cycle
~ transition in low dimensional excitable system

Dynamo reversals





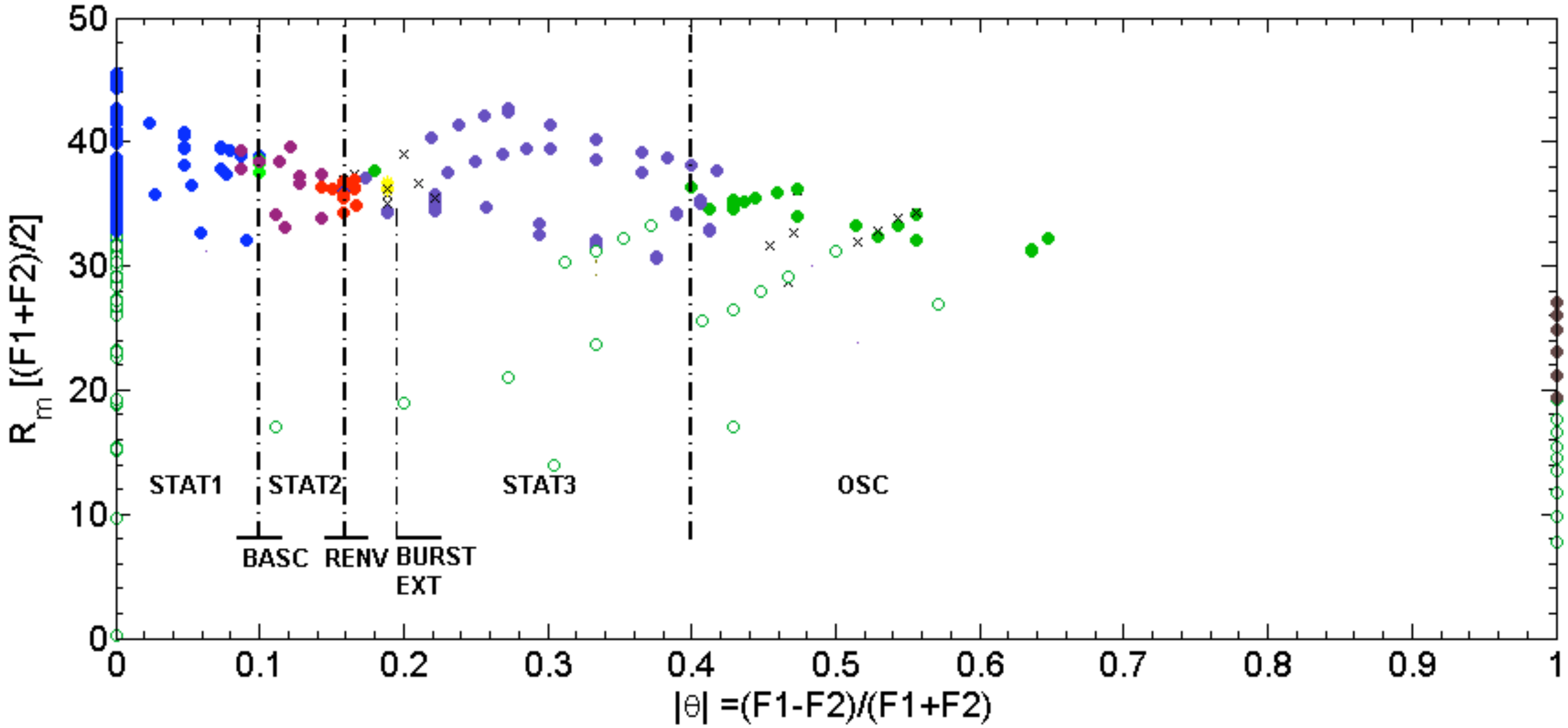


Heteroclinic orbits connecting unstable fixed points

Global rotation: states diagram

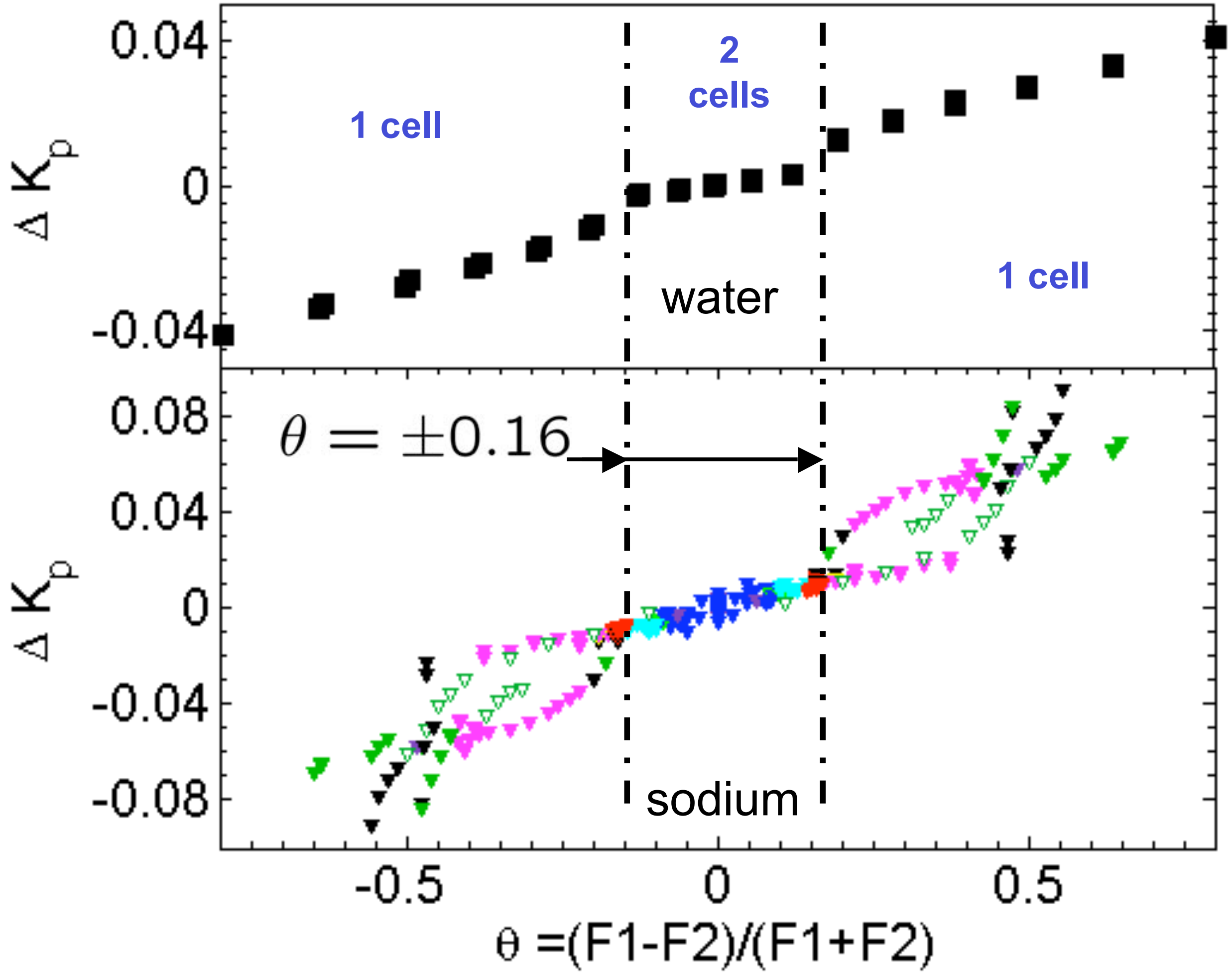
- $\theta = (f_1 - f_2) / (f_2 + f_1)$
- $R_m = 2\pi K \mu_0 \sigma R^2 (f_1 + f_2)/2$

- Stat1 $F_1 = F_2$
- Stat2
- Stat3
- noDynamo
- Reversals
- Bursts
- Basc: Limit cycle
- Oscillations



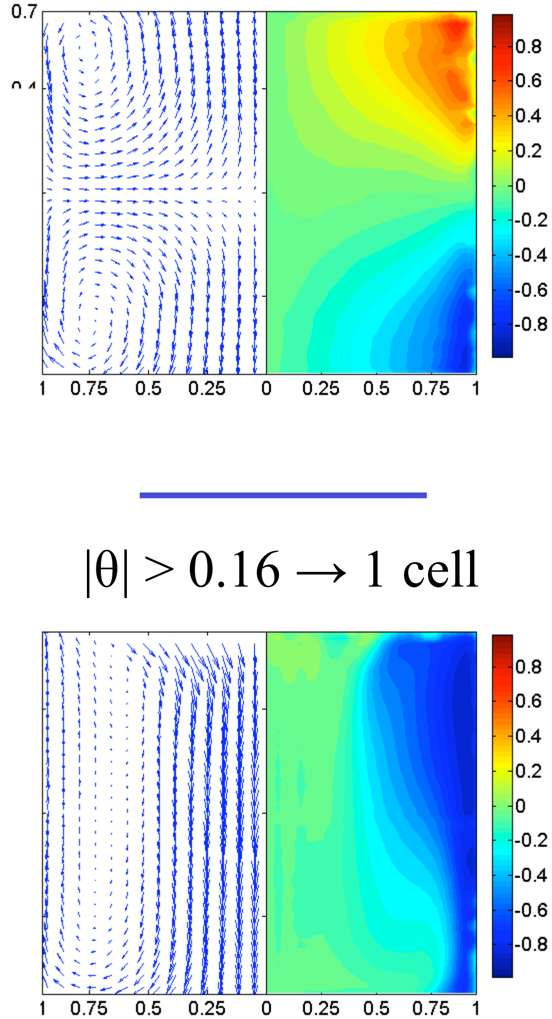
Couplings MHD - hydrodynamics

K_p= Torque/$\rho R_c^5 (2\pi f)^2$



|θ| < 0.16 → 2 cells

|θ| > 0.16 → 1 cell



Conclusion

- $f_1=f_2$: stationary turbulent dynamo

 axisymmetric neutral mode not generated by mean flow alone

- $f_1 \neq f_2$:dynamical dynamos

large scale dynamics of B

- characteristic of low – dimensional systems
- not qualitatively modified by turbulent fluctuations