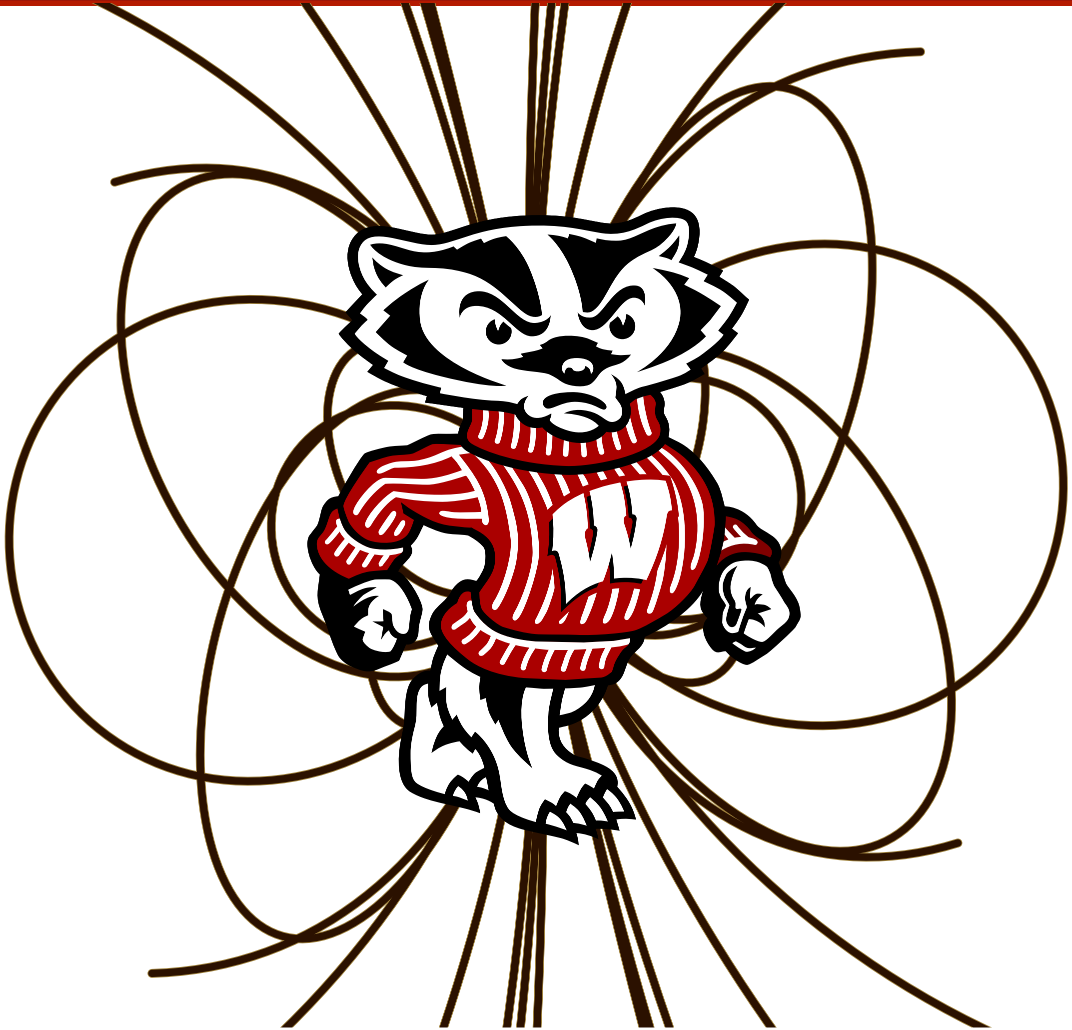
DYNAMOS: OBSERVATION, THEORY, EXPERIMENT



CARY FOREST

APS DPP MEETING
NEW ORLEANS

Acknowledgements

Colleagues Rainer Beck, Stas Boldyrev, Fausto Cattaneo, Sterling Colgate, Jan Egedal, Andrew Fletcher, Andy Jackson, Frank Jenko, Ivan Khalzov, Russel Kulsrud, Hui Li, Ann Mao, Mark Miesch, Mark Nornberg, Alex Sheckochihin, Erik Spence, Steve Tobias, and Ellen Zweibel

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Agencies NSF Astro, NSF Physics, DoE

SO MANY DYNAMOS!

Astrophysical Dynamos

Systems which Continuously convert kinetic energy of Flowing plasma into magnetic energy

OUTLINE

1. DYNAMO BASICS (THEORY)
2. ASTROPHYSICAL DYNAMOS
3. REVIEW OF EXPERIMENTS
   -LIQUID METAL
   -PLASMA DYNAMOS

Philosophy of this talk:

“What I cannot create, I do not understand”

-Feynman

DYNAMOS REGIME:

FROZEN IN FLUX: $Rm = \mu_0 \sigma UL \gg 1$

FLOW DOMINATED: $M_A = U/V_A \gg 1$

CONTINUOUS: $T \gg \mu_0 \sigma L^2$

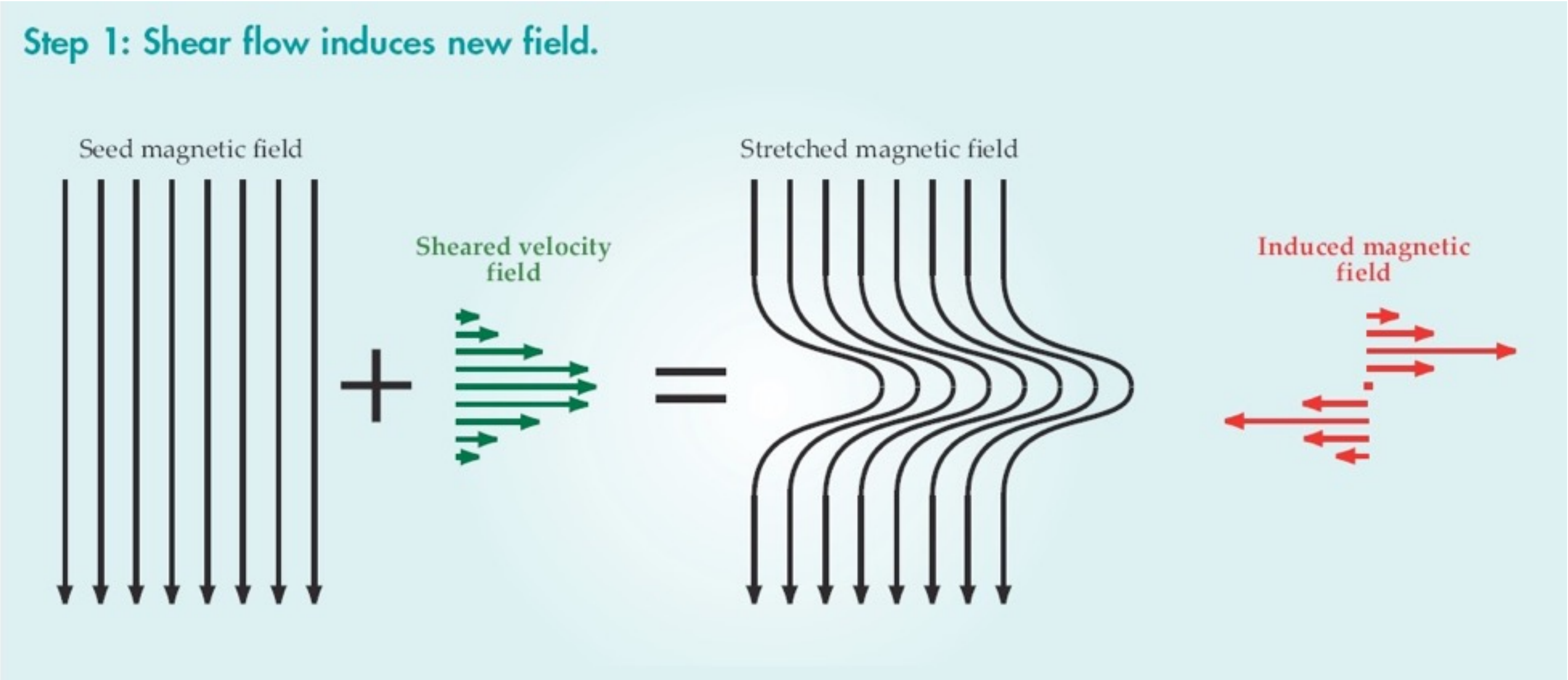
UNEXPLORED BY PLASMA EXPERIMENTS

BEHAVIOR DEPENDS UPON:

$Pm = Rm/Re, \quad Re = UL/\mu,$

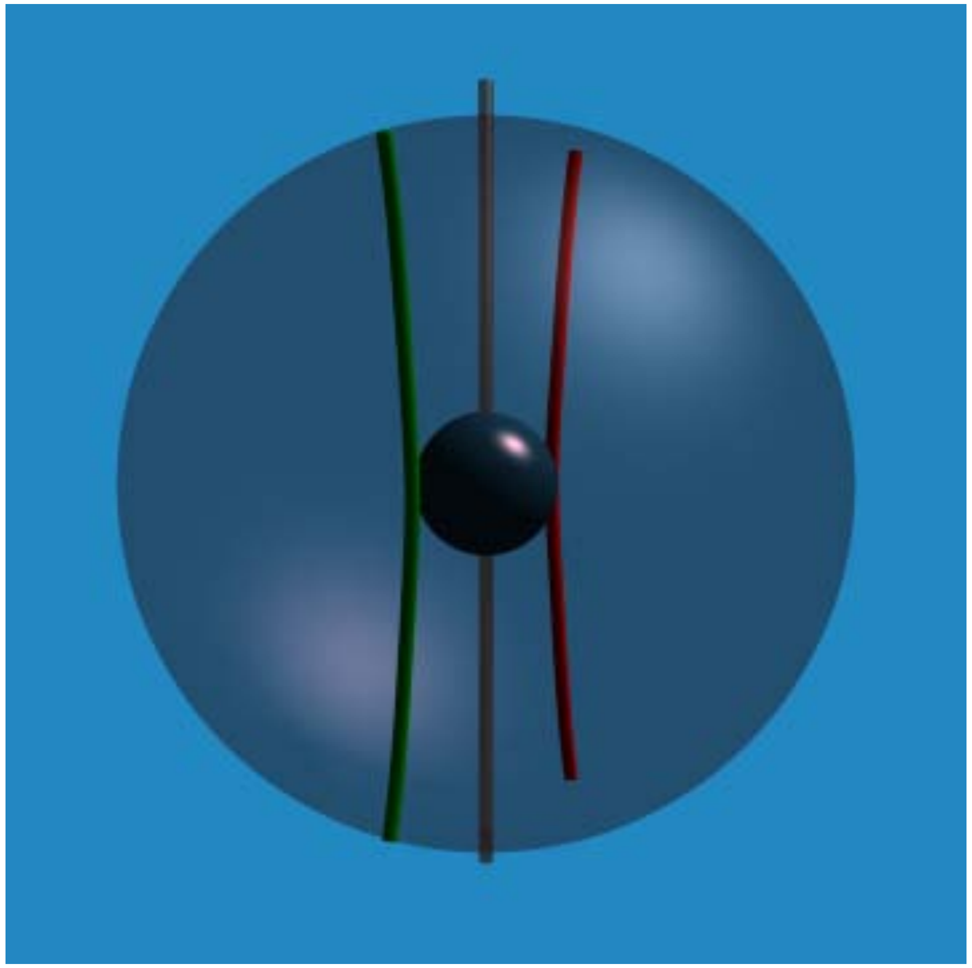
FUNDAMENTAL TENET OF PLASMA ASTROPHYSICS (WHEN $R_M \gg 1$, $M_A \gg 1$)

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{V} \times \mathbf{B} + \xcancel{\frac{1}{\mu_0 \sigma}\nabla^2 \mathbf{B}}$$



Step 1: Shear flow induces new field.

STANDARD MODEL STEP 1: STRONG TOROIDAL FIELD FROM POLOIDAL



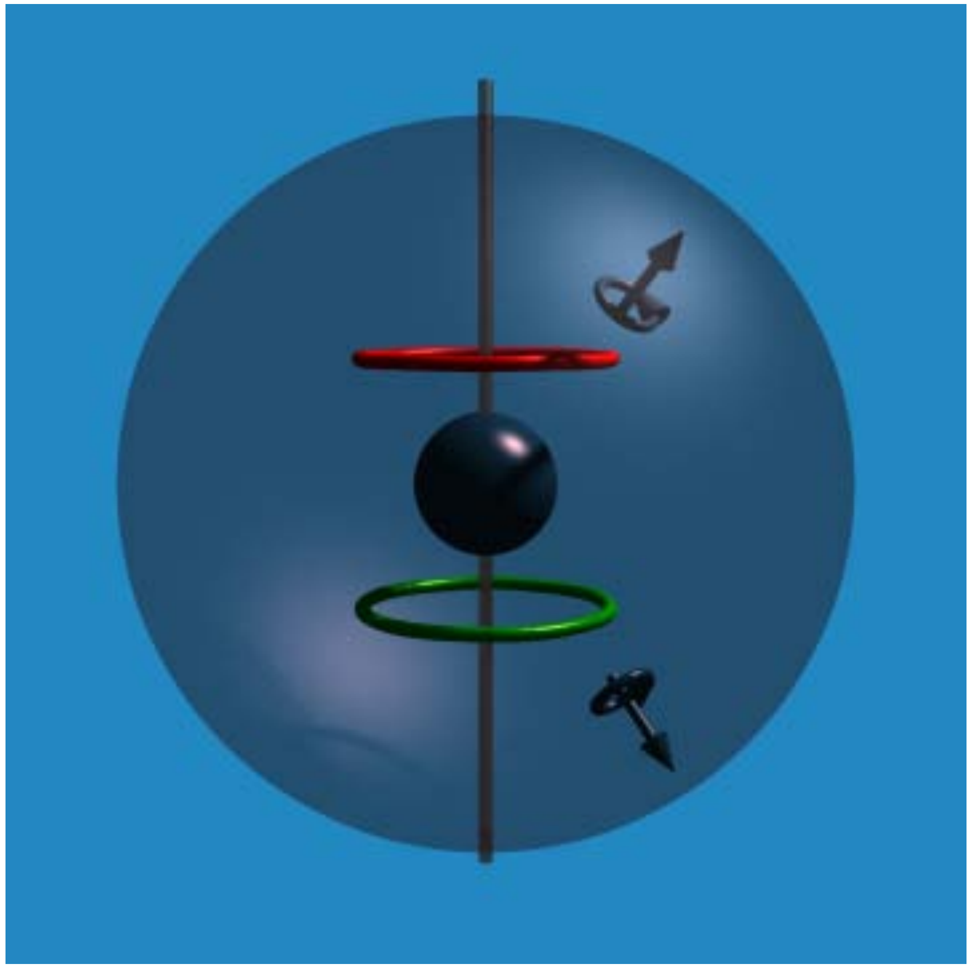
The "Ω effect"

STANDARD MODEL STEP 2: HELICAL TURBULENCE REGENERATES POLOIDAL FIELD

When the magnetic field and the fluid motions are symmetric about an axis...no stationary dynamo can exist.

T.G. Cowling(1933)

The "α effect"



$$J_\phi = \alpha B_\phi$$

E.N. Parker (1955)

TURBULENCE: FRIEND OR FOE?

- Transport of B is controlled by turbulent EMF

$$\mathcal{E} = \left\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{b}} \right\rangle$$

- Closure ansatz: $\mathcal{E} = \alpha \mathbf{B} - \beta \nabla \times \mathbf{B}$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{V} \times \mathbf{B} + \nabla \times \alpha \mathbf{B} + \eta_{turb} \nabla^2 \mathbf{B}$$

- β - effect is like resistivity (diffuses large scale B)

$$\beta = \tfrac{1}{3} \tilde{v}^2 \tau_{corr} \equiv \frac{\tilde{v}\ell}{3} \qquad \eta_{turb} = \frac{1}{\mu_0 \sigma} + \frac{\tilde{v}\ell}{3}$$

- α - effect driven by helical flow

$$\alpha = \tfrac{1}{3} \left\langle \widetilde{\boldsymbol{v}} \cdot \nabla \times \widetilde{\boldsymbol{v}} \right\rangle \tau_{corr}$$

DYNAMO CLASSIFICATION

SMALL VS LARGE SCALE

SMALL: MAGNETIC FIELD GENERATED AT (OR BELOW) SCALE OF FLOWS (RELIES ON CHAOTIC STRETCHING)

LARGE: RELIES ON LACK OF REFLEXIONAL ASYMMETRY

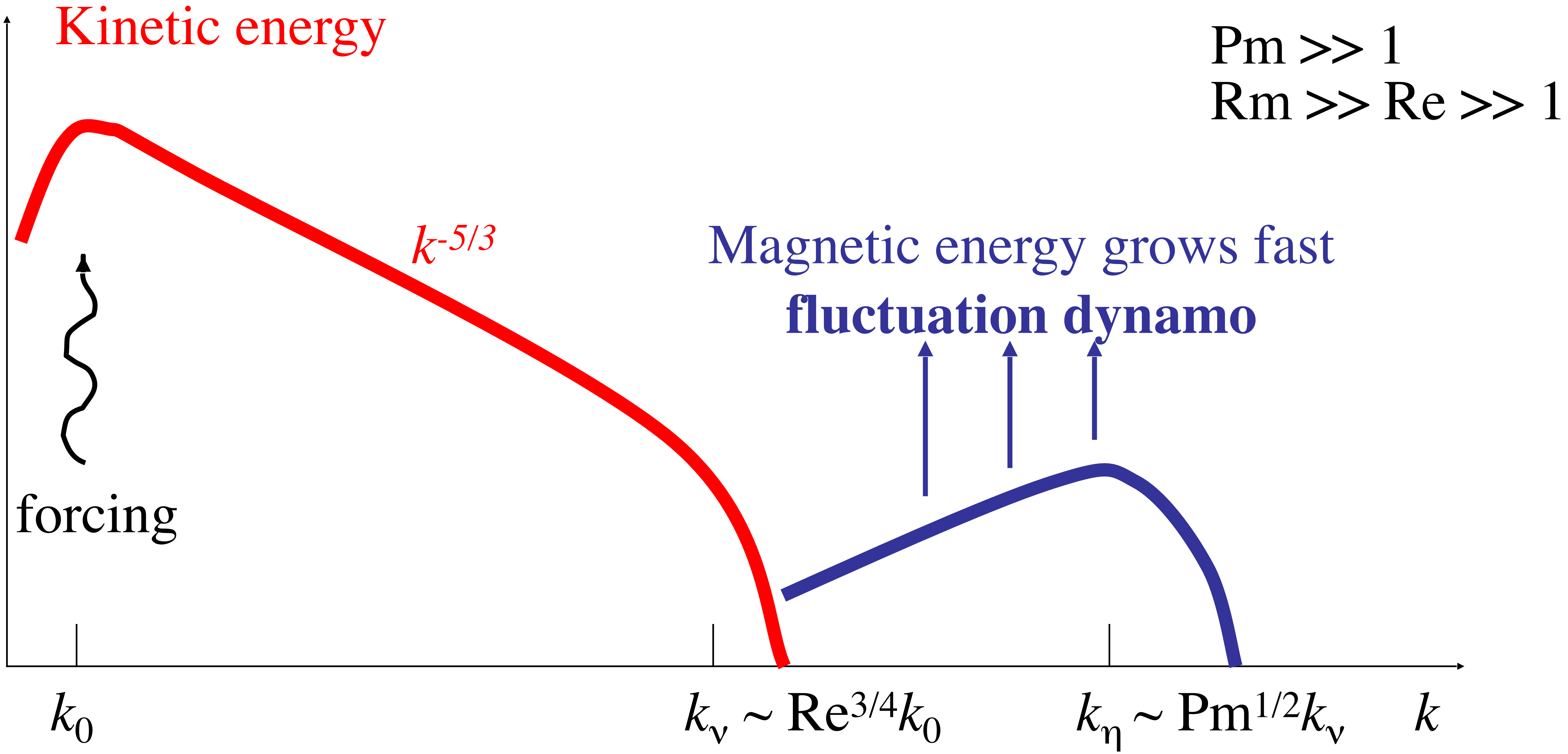
SLOW VS FAST DYNAMOS

SLOW REQUIRES RESISTIVE DIFFUSION (MODERATE RM)

FAST DYNAMOS: INDEPENDENT OF RESISTIVITY (VERY LARGE RM)

ASTROPHYSICS: LARGE-SCALE, FAST DYNAMOS (RM>>1, TURBULENT GENERATION OF NET FLUX)

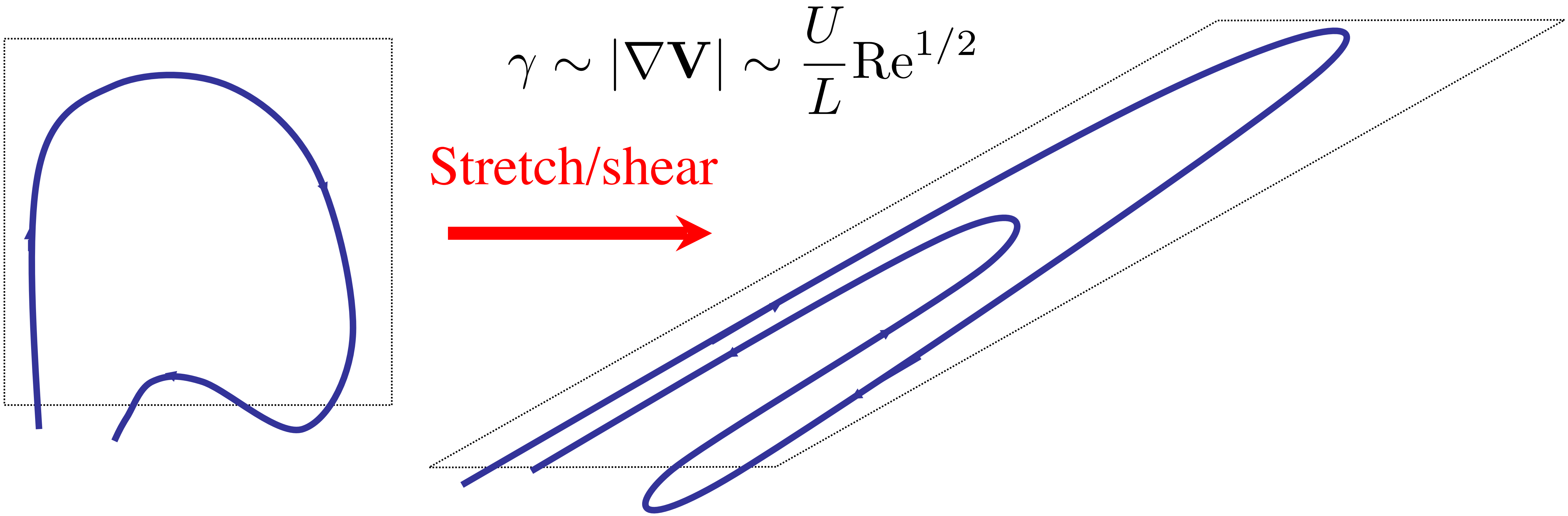
SMALL SCALE DYNAMOS EASY FOR PM >> 1; LARGE SCALE NOT SO EASY



Pm ≥ 1: it is well established numerically that non-helical fluctuation dynamo exists provided $\mathrm{Rm} > \mathrm{Rm}_c \sim 100$

[Meneguzzi, Frisch & Pouquet 1981, Kulsrud and Anderson (1992)

PM >> 1: CHAOTIC STRETCHING GIVES FAST DYNAMO

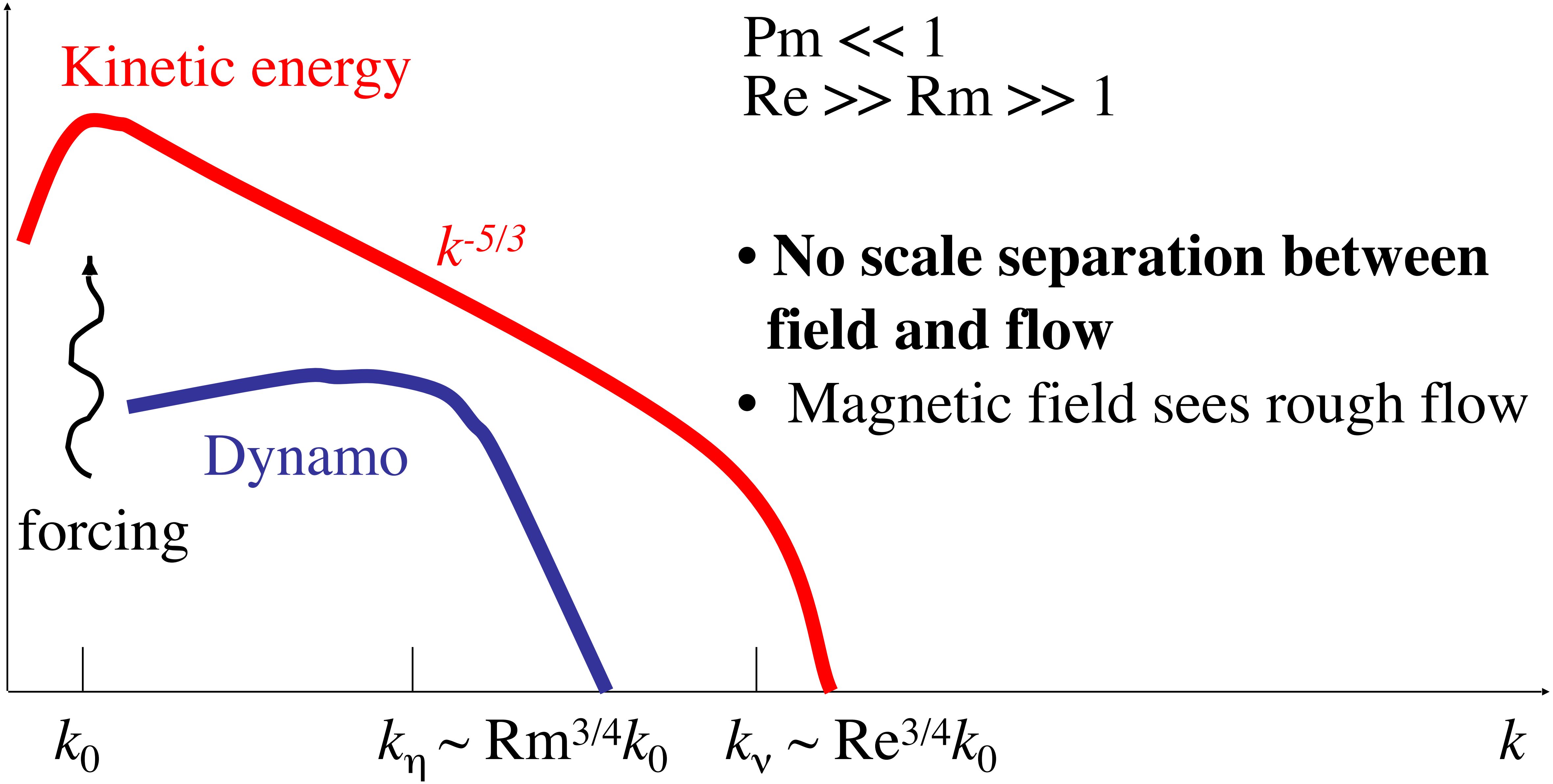


$$\gamma \sim |\nabla \mathbf{V}| \sim \frac{U}{L}\mathrm{Re}^{1/2}$$

Stretch/shear

[see Schekochihin *et al*. 2004, *ApJ* **612**, 276; Schekochihin & Cowley, astro-ph/0507686 for an account of theory and simulations]

SMALL-SCALE DYNAMOS MORE CHALLENGING FOR LOW PM



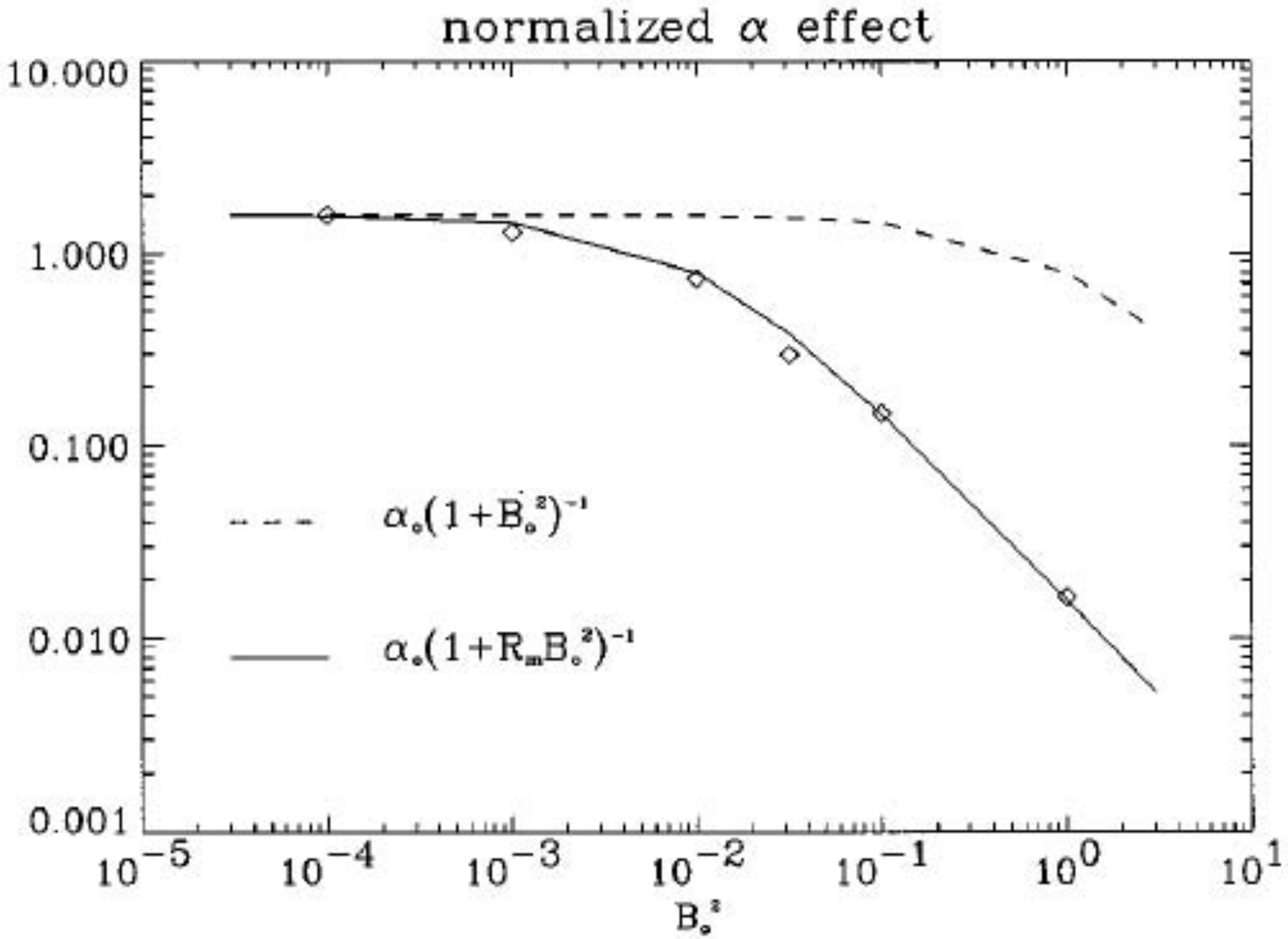
$\mathrm{Pm} \ll 1$
$\mathrm{Re} \gg \mathrm{Rm} \gg 1$

- **No scale separation between field and flow**
- Magnetic field sees rough flow

Pm << 1: higher threshold $\mathrm{Rm} > \mathrm{Rm}_c \sim 200$

Boldyrev 2008, Iskakov 2007, Schekochihin 2007

Numerical and Theoretical Studies show catastrophic α quenching at large Rm

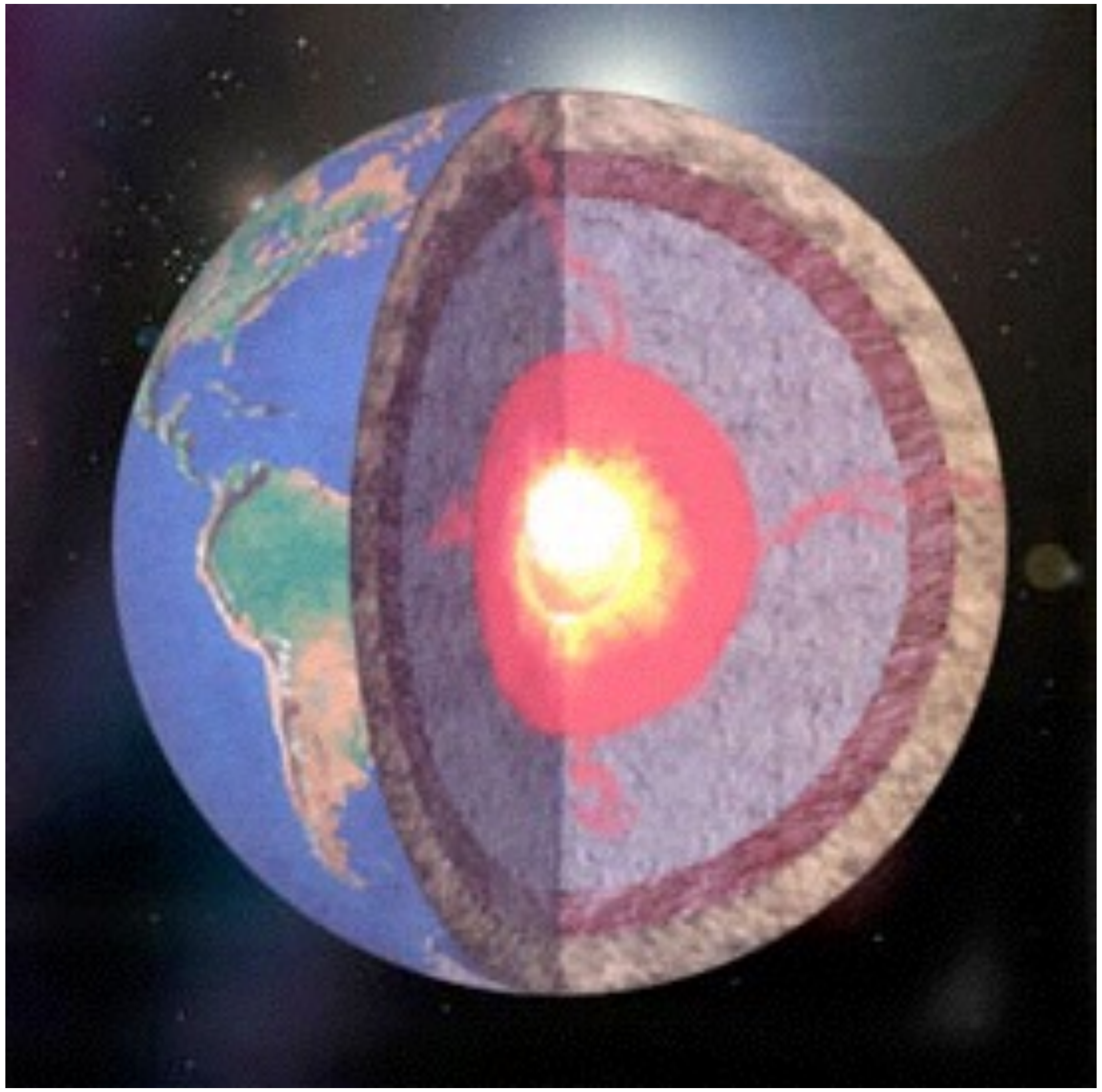


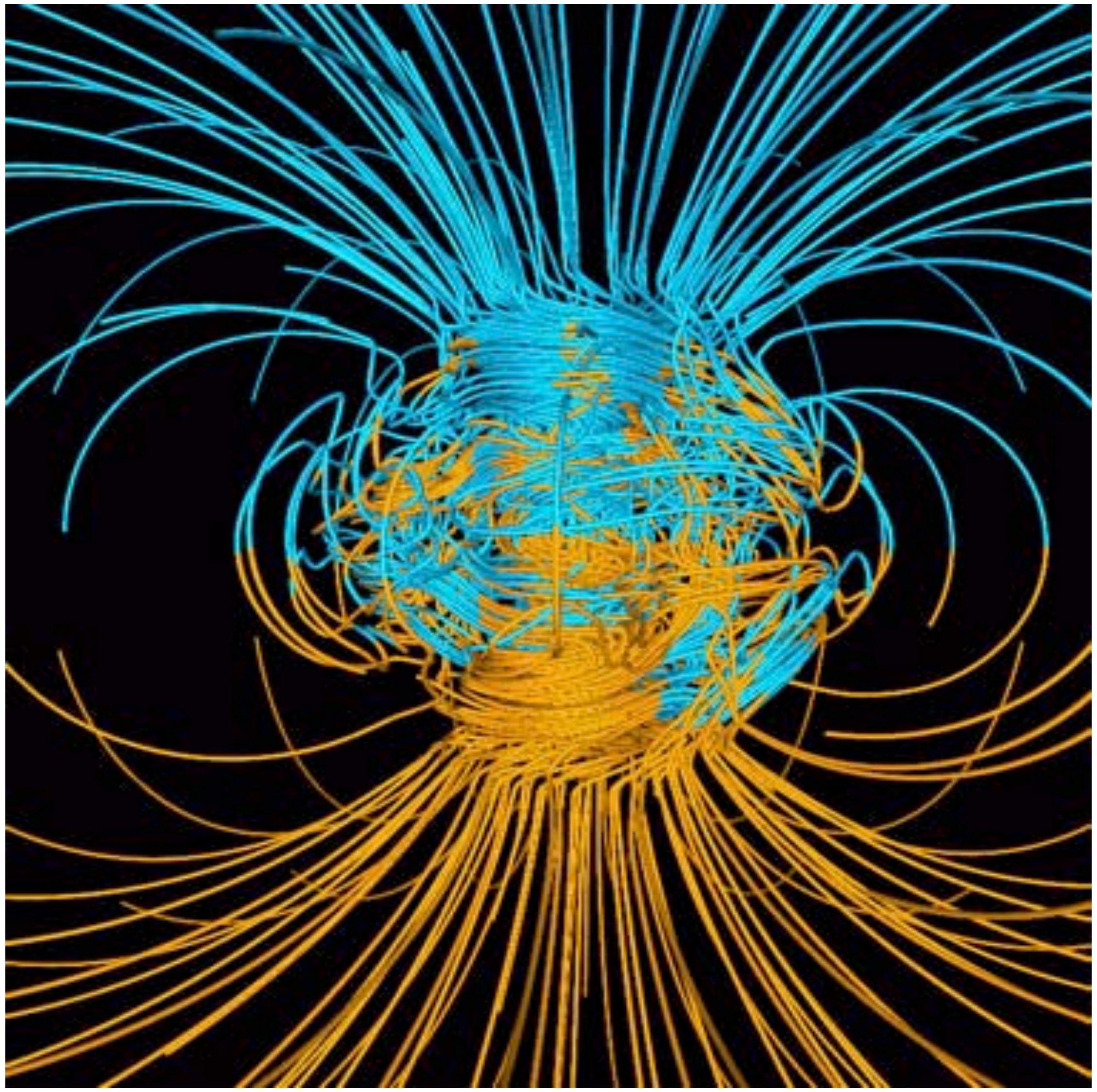
PHYSI

1996

$$\alpha = \alpha_0 (1 + R_m \langle \mathbf{B} \rangle^2 / u^2)^{-1}$$

PLANETARY DYNAMOS

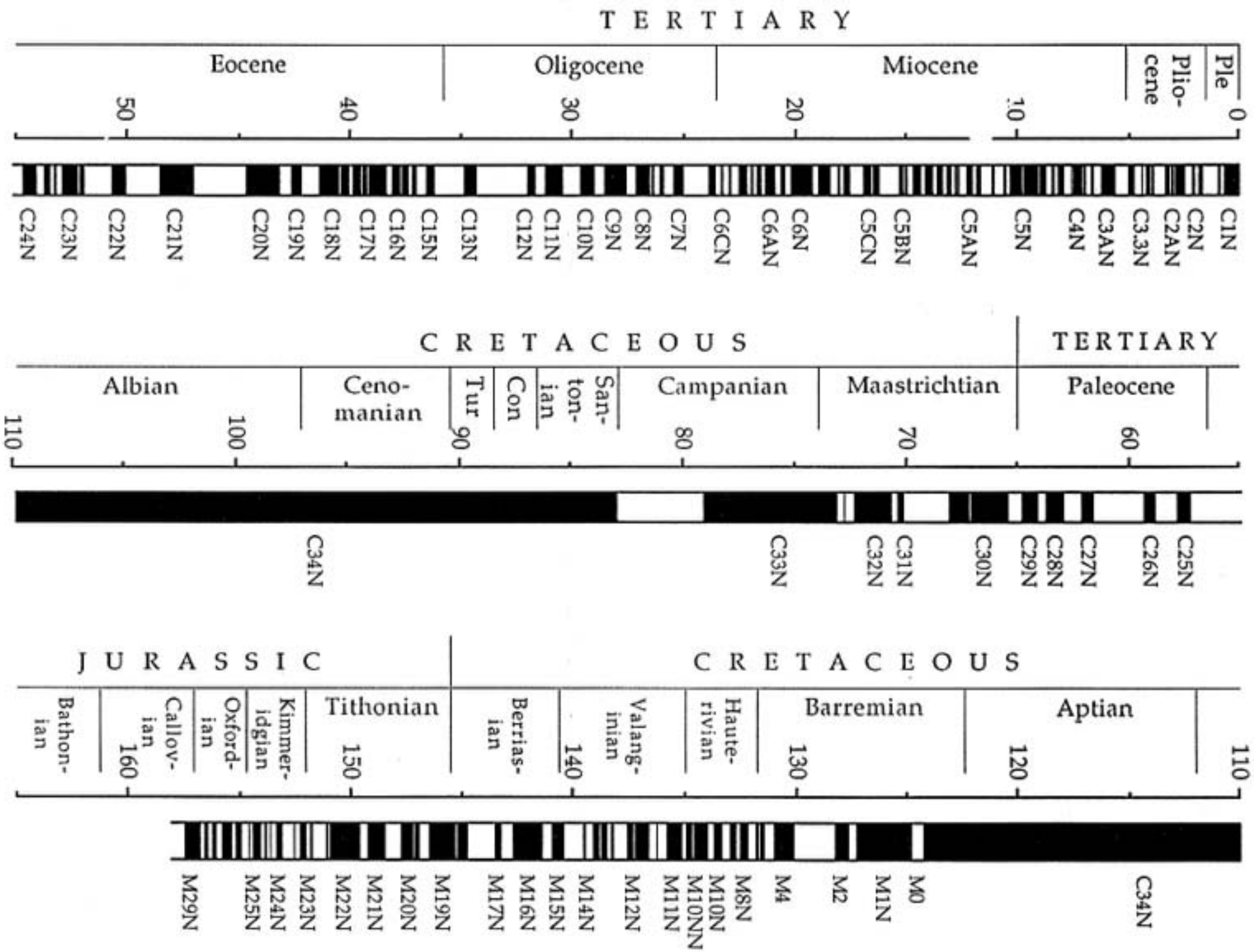




Glatzmaier and Roberts, (1995).

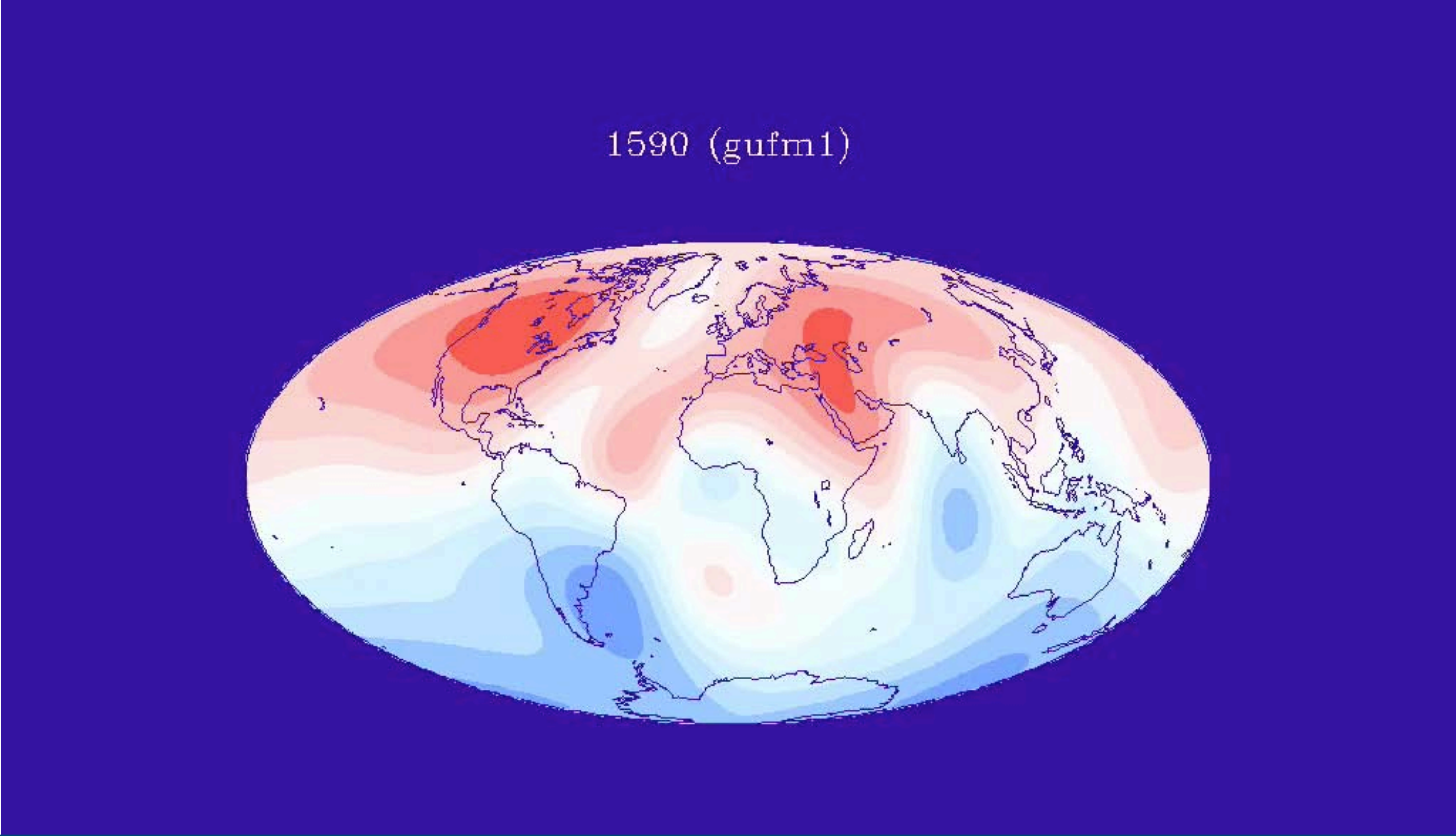
Rm~500-1000, Re=10^9, Liquid Metal

MAGNETIC REVERSALS



1

$\tau_{\sigma}=10^5$ yrs



Jackson, Jonkers and Walker, *Four centuries of geomagnetic secular variation*, Phil. Trans. R. Soc. Lond. A **358** 957 (2006).

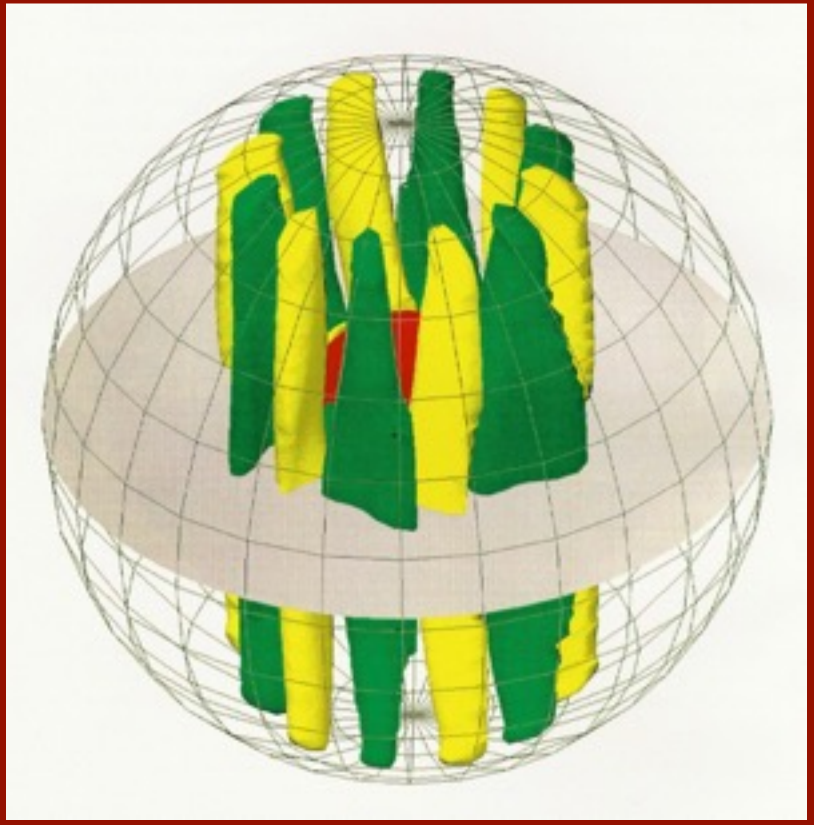
THE GEODYNAMO

MODEL

1. ROTATING CONVECTION GIVES HELICAL VORTICES

α^2 DYNAMO

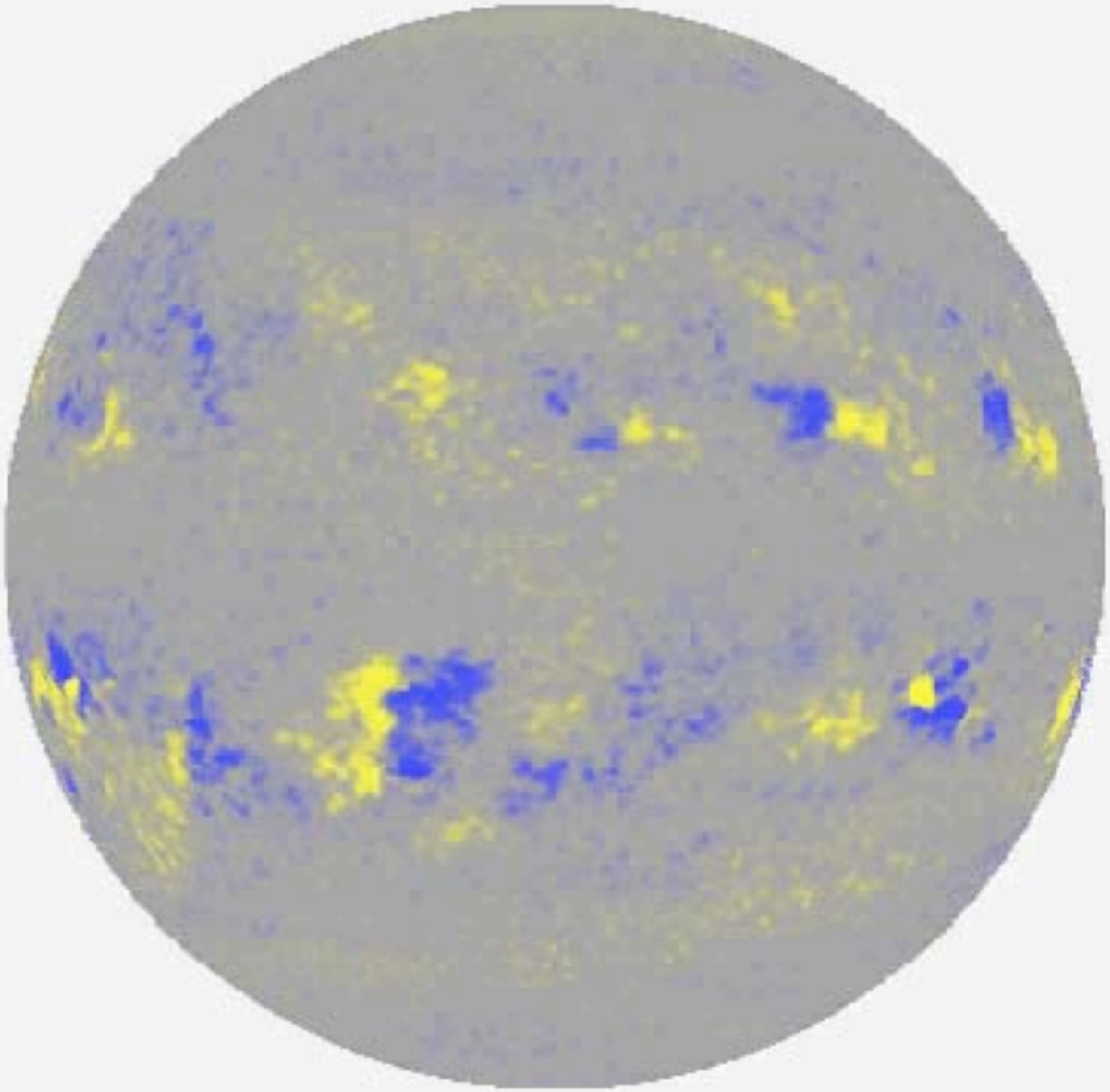
2. SIMULATIONS CAPTURE SELF-EXCITATION



PROBLEMS

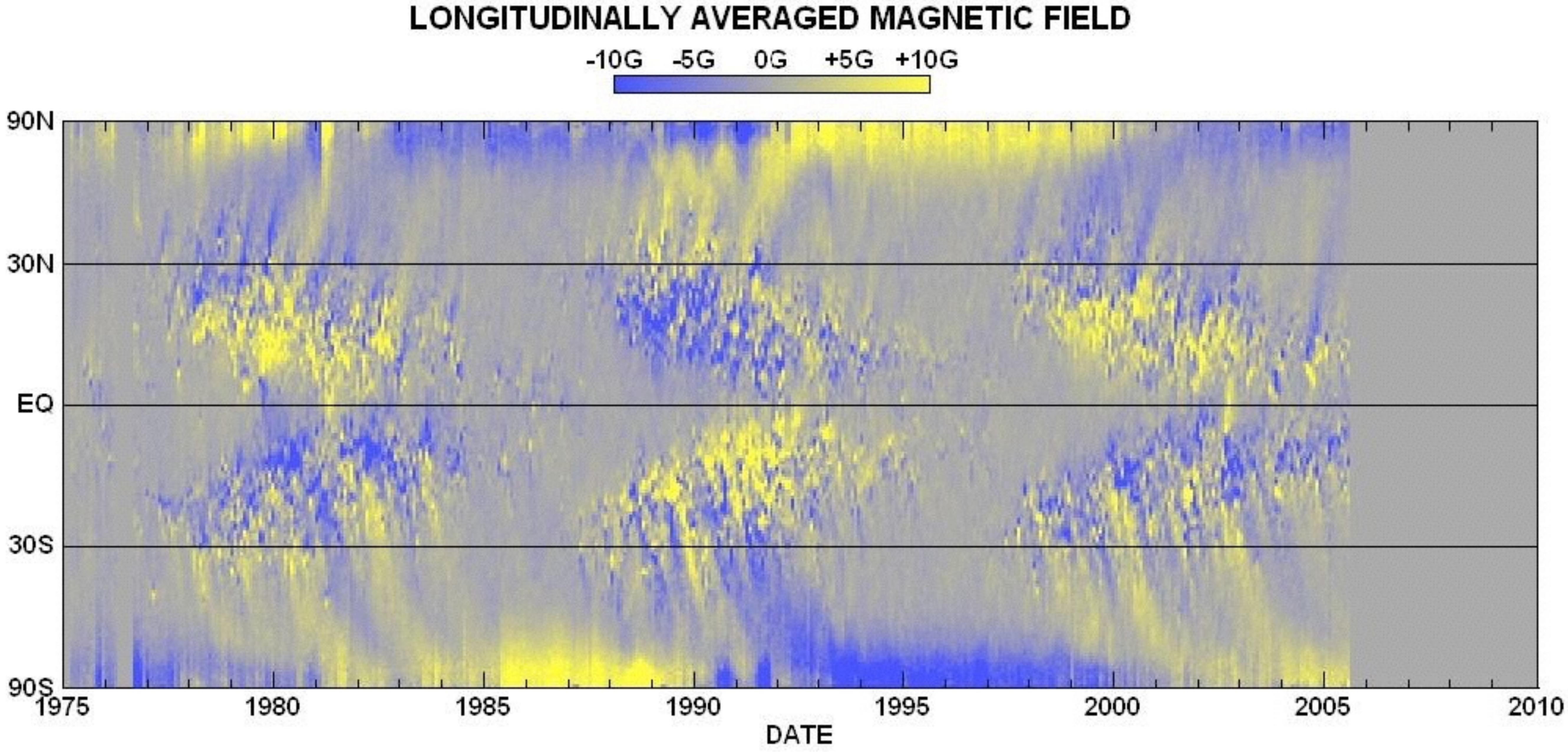
1. NOT YET RESOLVING VISCOUS SCALES
2. FEW OBSERVABLES

THE SUN'S DYNAMO



Rm~10^8, Re=10^{11}, τ_σ=10^{11} yrs

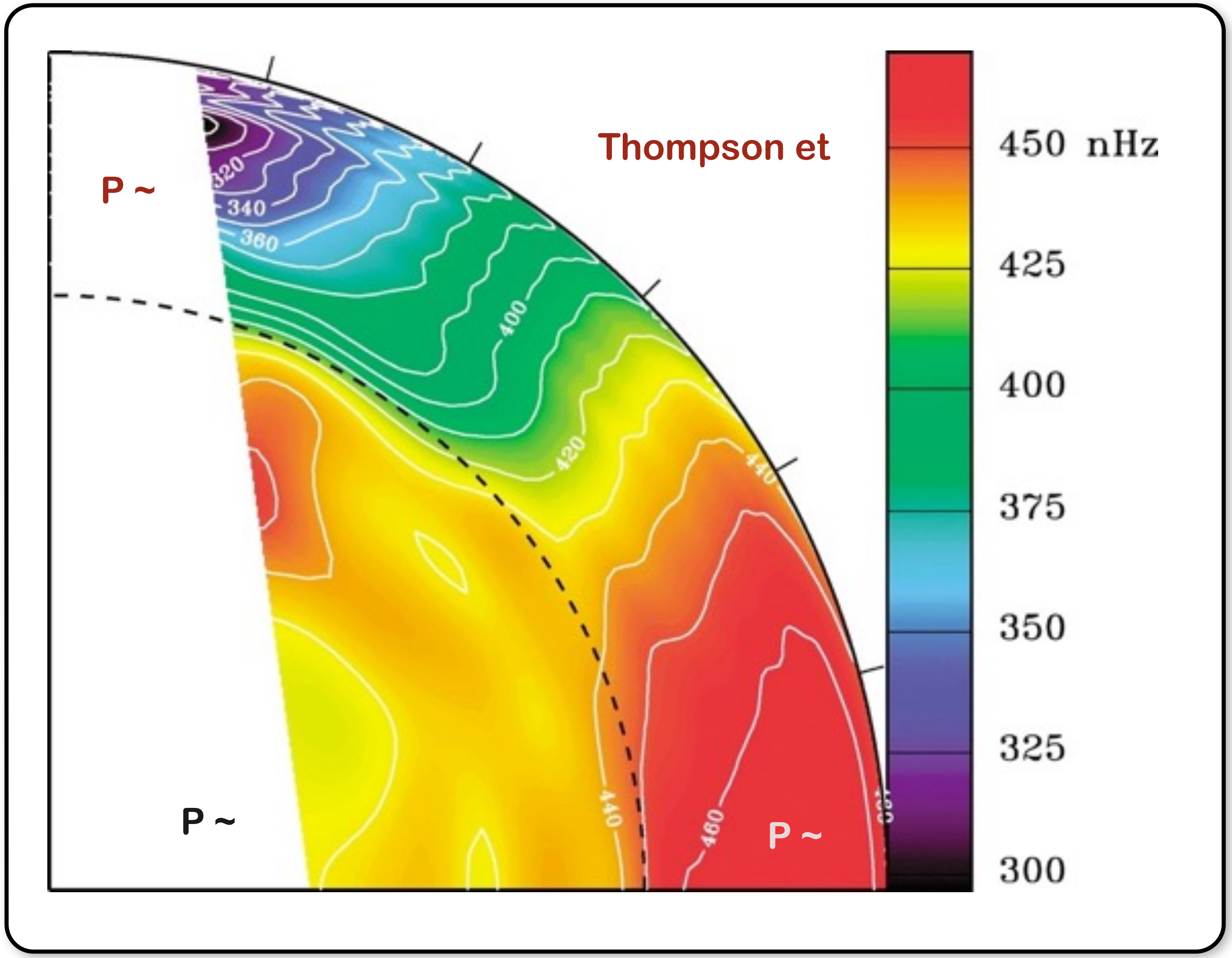
+ weak large scale field

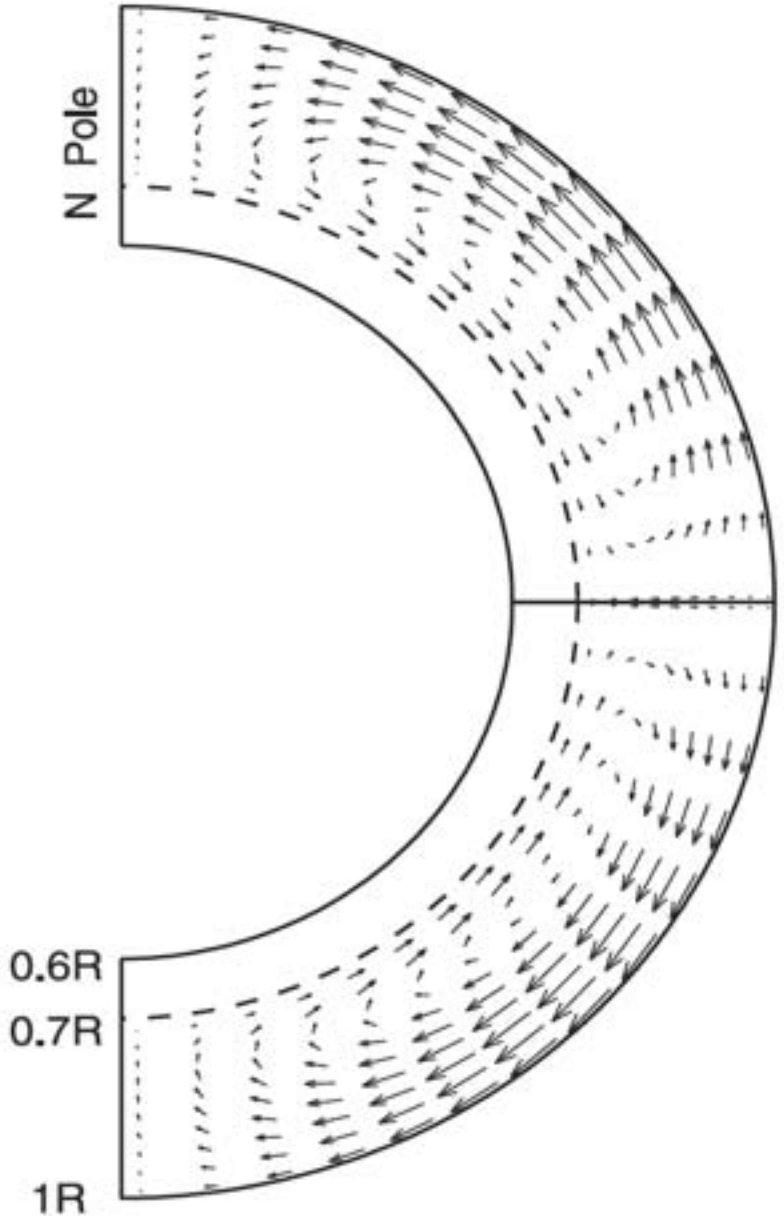


NASA/NSSTC/Hathaway 2005/10

DIFFERENTIAL ROTATION

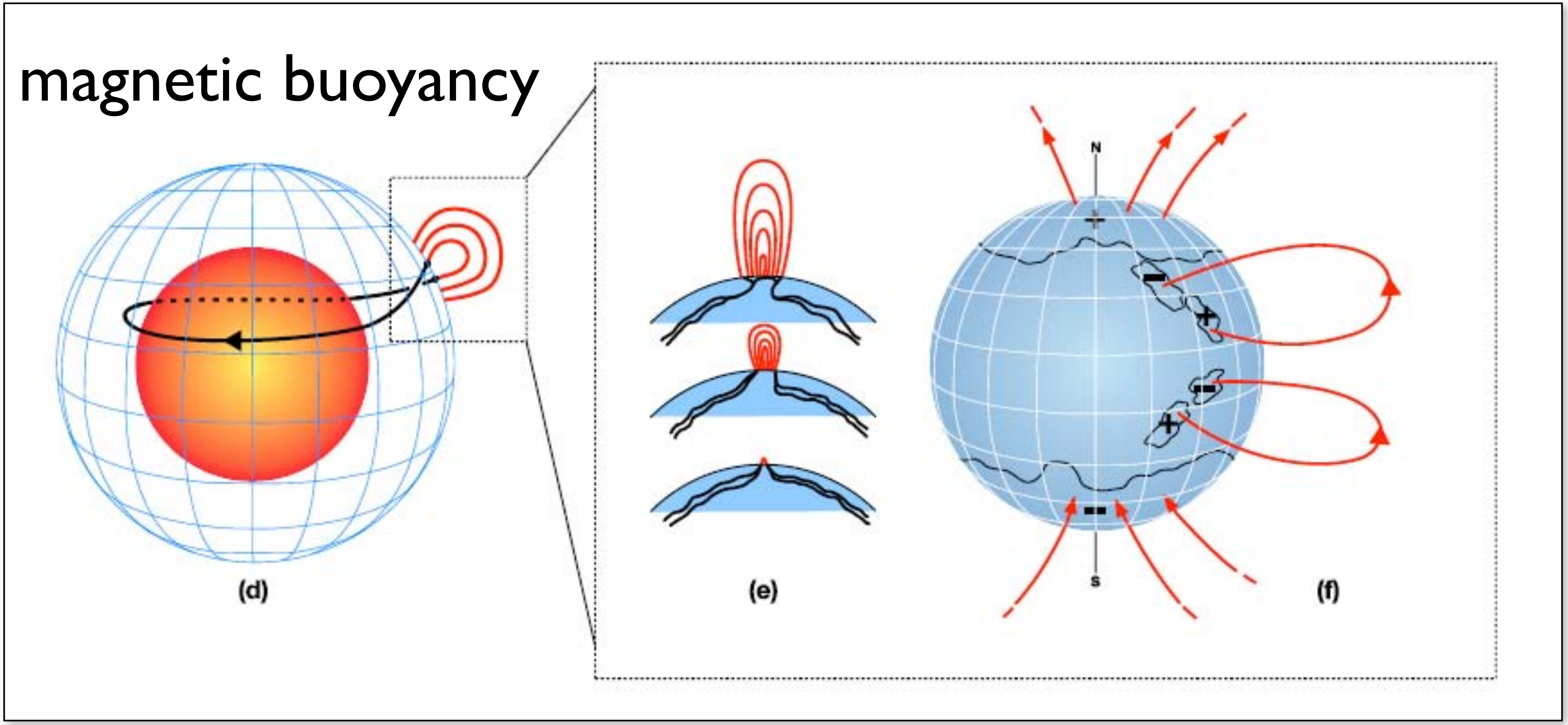
POLOIDAL FLOW





angular momentum transport open issue

INTERFACE OR FLUX TRANSPORT MODELS OF SOLAR CYCLE


magnetic buoyancy

Dikpati & Gilman 2006

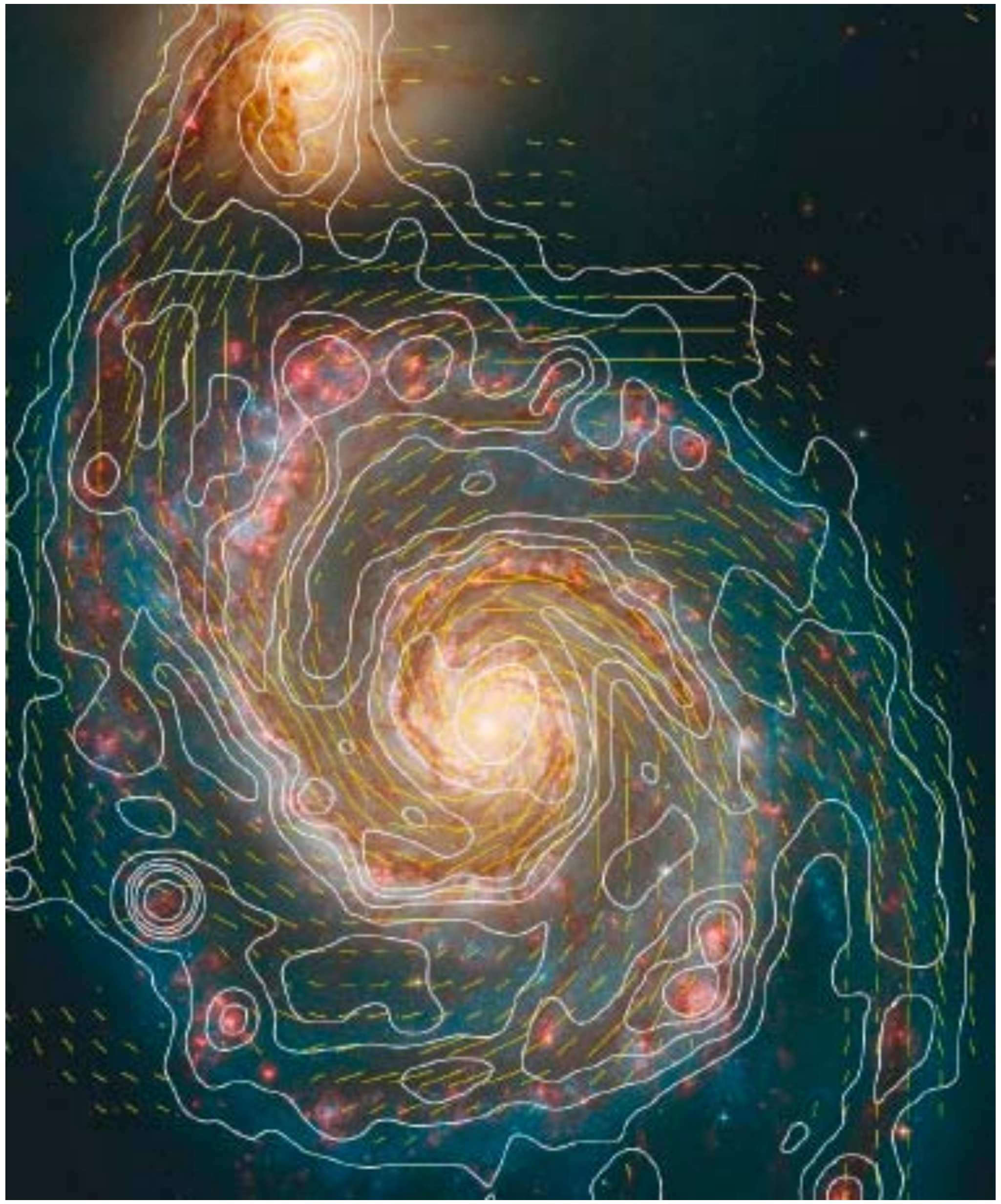
THE SOLAR DYNAMO

SOME ISSUES

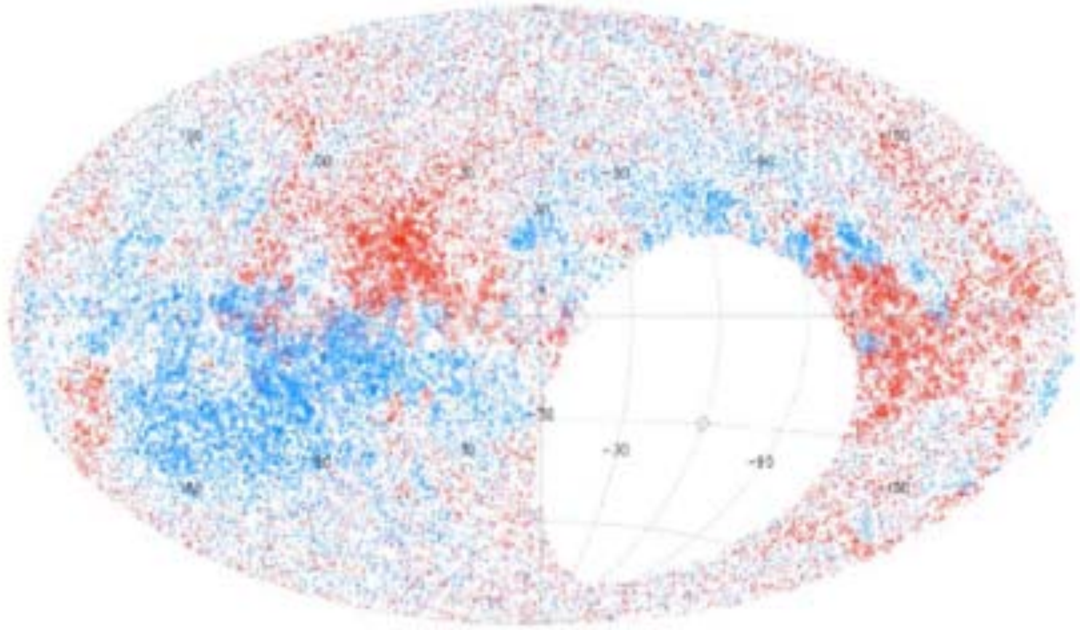
1. 22 YR CYCLE SET BY
   - (A) POLOIDAL ADVECTION OF FLUX OR
   - (B) DYNAMO WAVES OR
   - (C) TURBULENT TRANSPORT OF MAGNETIC FIELD (RESISTIVITY, MAGNETIC PUMPING, MAGNETIC BUOYANCY
2. . α QUENCHING AND DOMINANCE OF SMALL-SCALE DYNAMO
3. IMPOSSIBLE TO RESOLVE WITH GLOBAL MODELS

Galactic Magnetic Fields: large-scale field + small-scale Dynamo

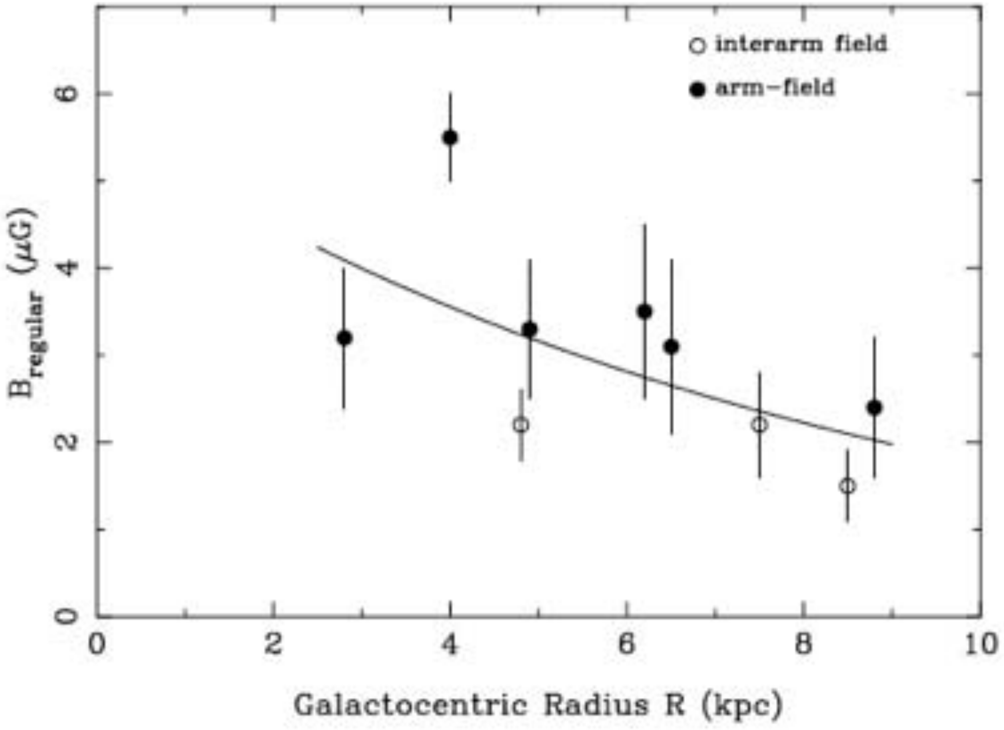
$B_{PHI} \sim 3 B_R \sim 30 B_Z$



M51

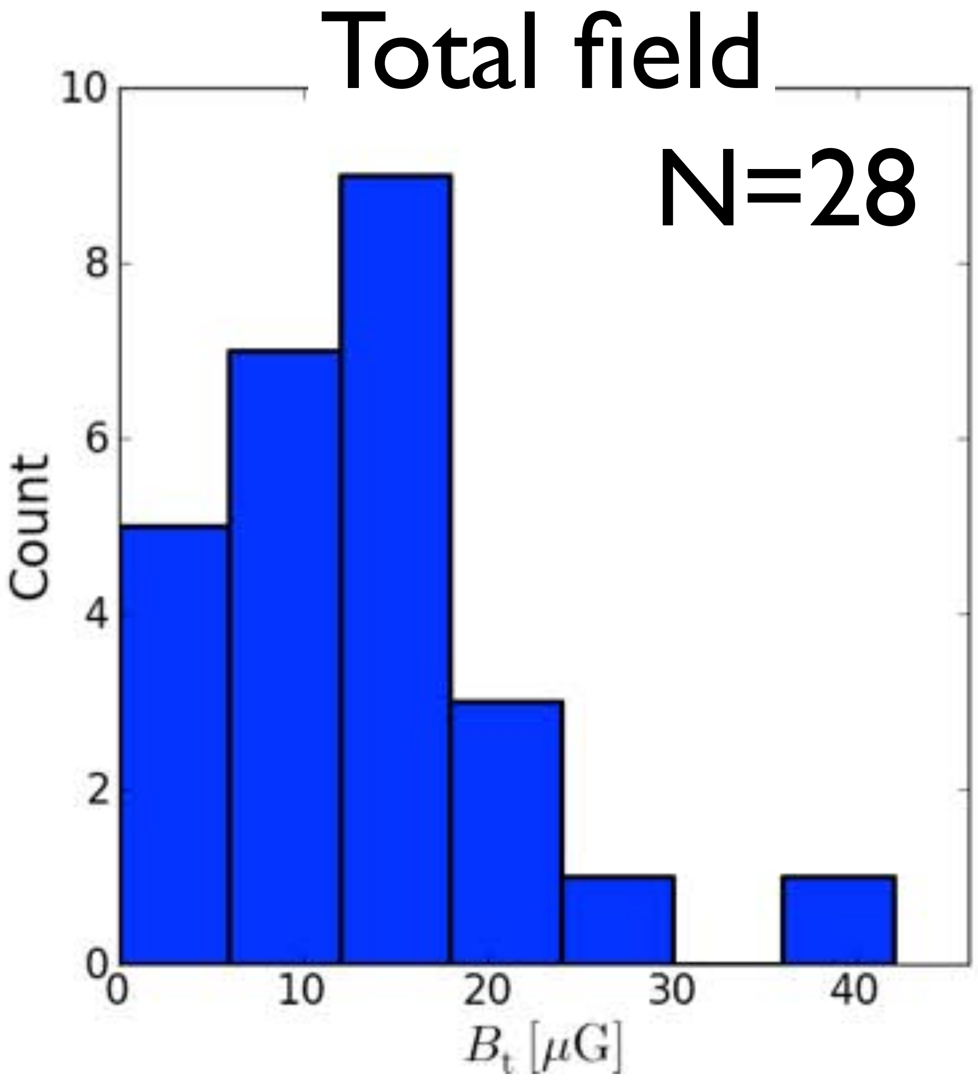


Faraday rotation along 38000 lines of sight
In the Milky Way (NVSS survey)



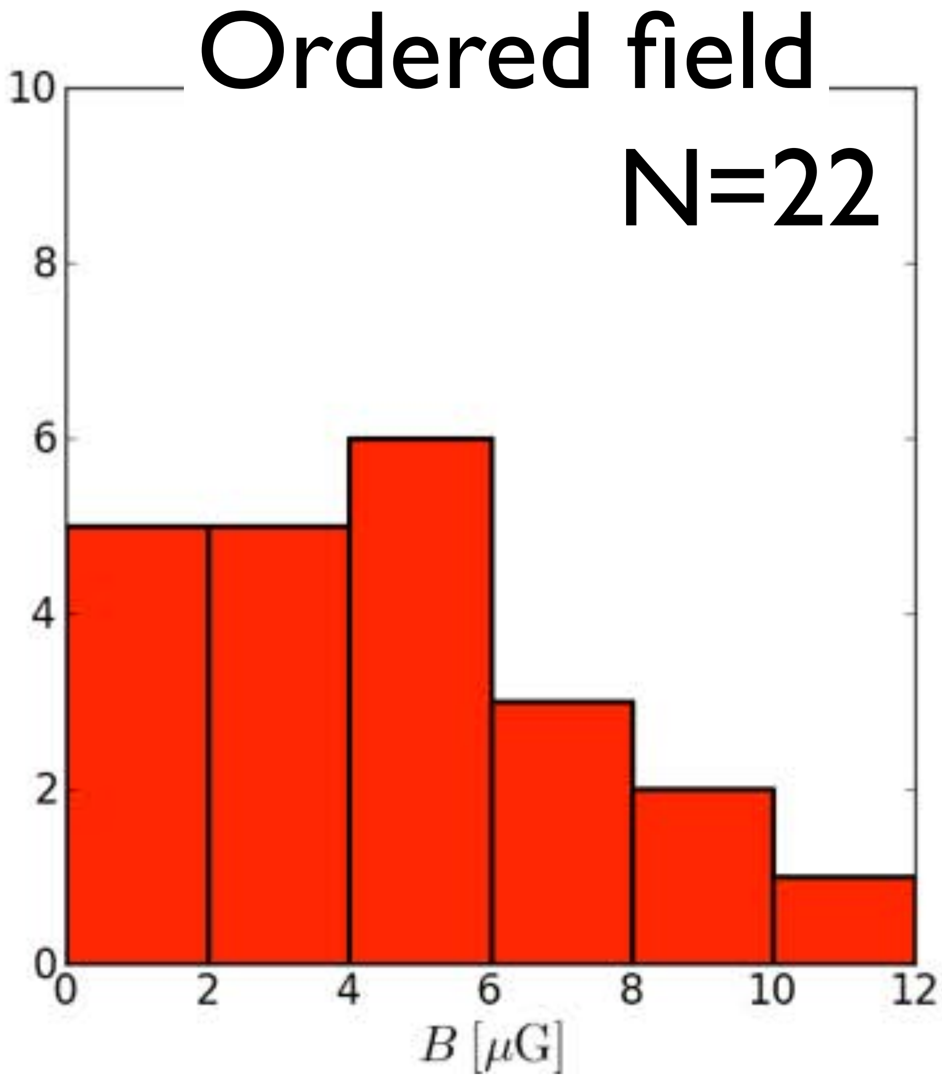
$Rm \sim 10^{14}$, $Re = 10^{9}$, Plasma

SMALL SCALE DYNAMO TWICE AS STRONG AS LARGE SCALE DYNAMO IN SPIRAL GALAXIES


Total field

N=28

Average: 16 ±15 μG


Ordered field

N=22

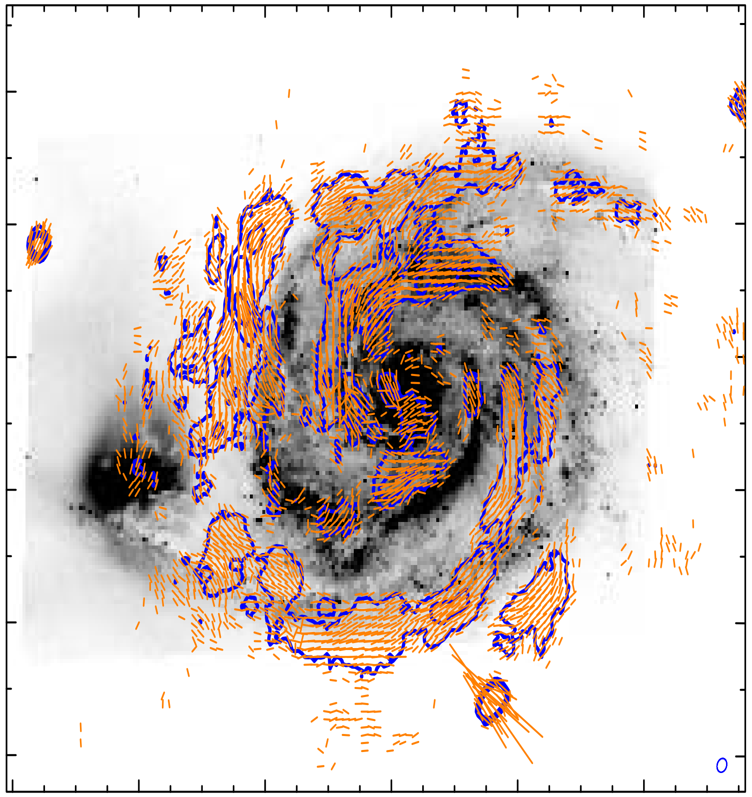
Average: 4 ±3 μG

B_{ord}/B_{ran} 0.4 ±0.2

Compilation: Fletcher 2010

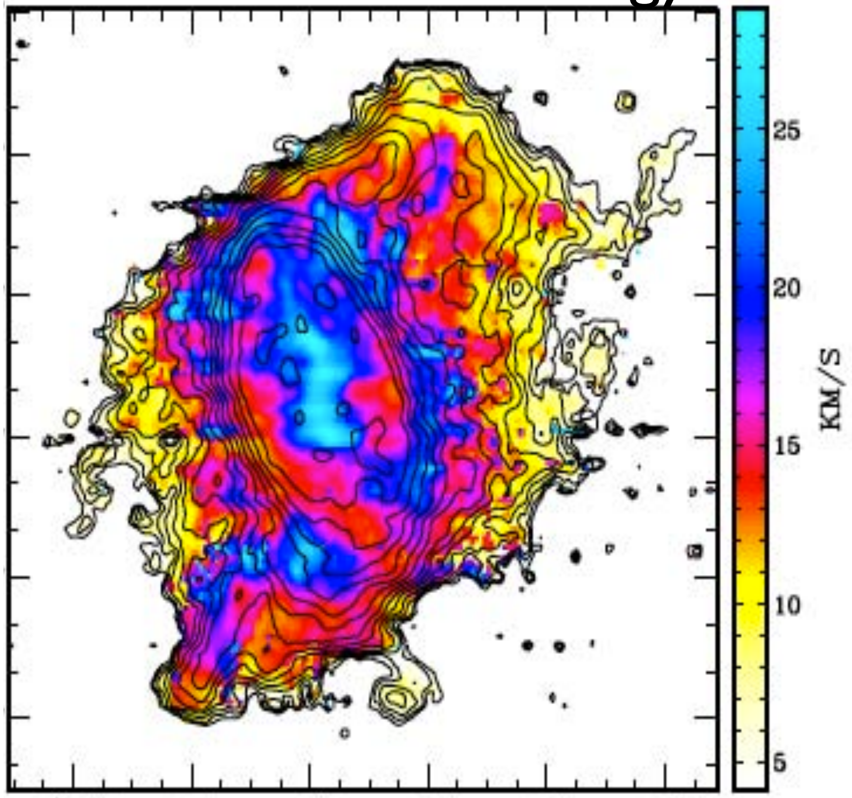
THERE IS SELF-REGULATION OF MAGNETIC, INTERNAL, TURBULENT FLOW, AND COSMIC RAY ENERGY DENSITY

Magnetic Field and Pressure



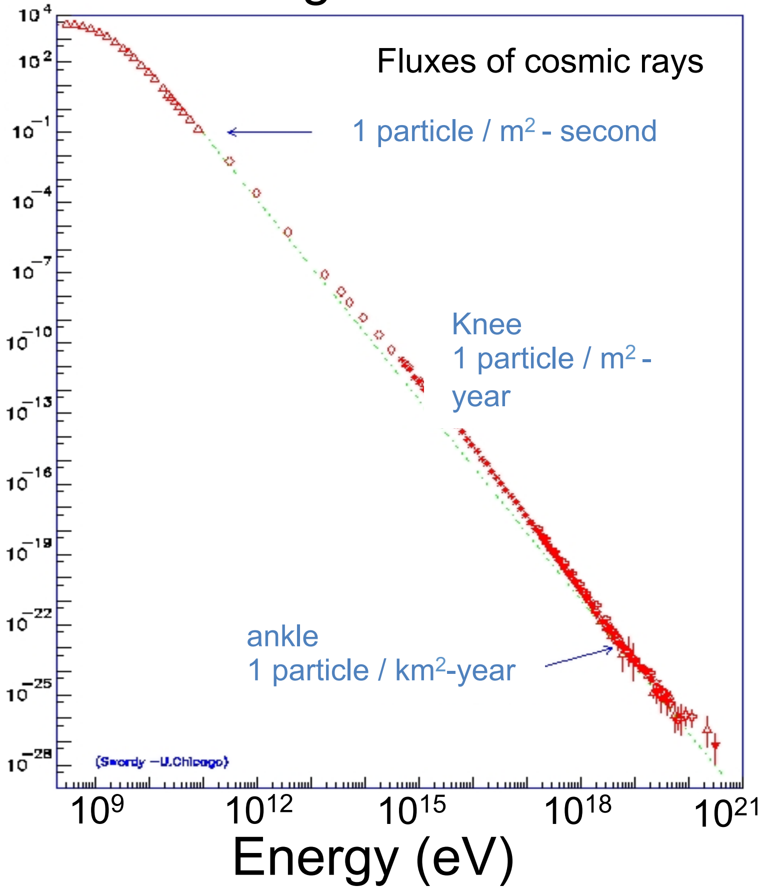
$$\frac{B^2}{2\mu_0}, \quad P$$

turbulent flow energy



$$\frac{\rho\tilde{V}^2}{2}$$

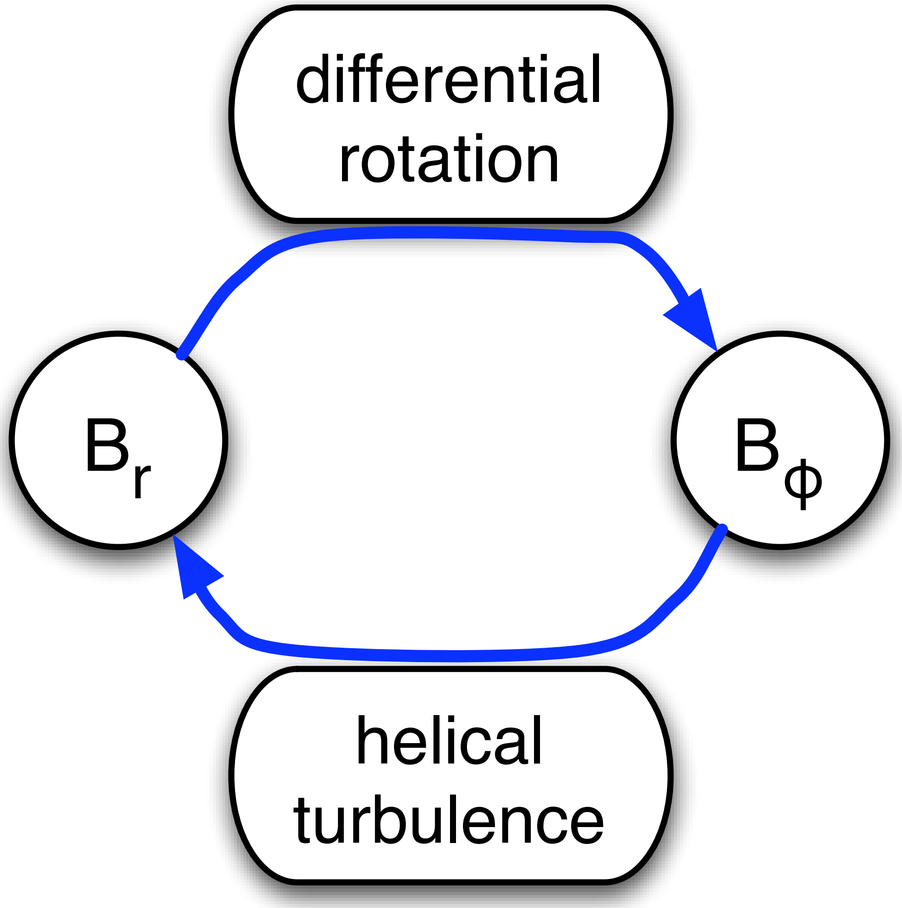
Energetic Particles



Cosmic Rays

Ann Mao

α Ω MODEL FOR THE GALACTIC MAGNETIC FIELD WITH SUPERNOVAE DRIVEN TURBULENCE



differential rotation

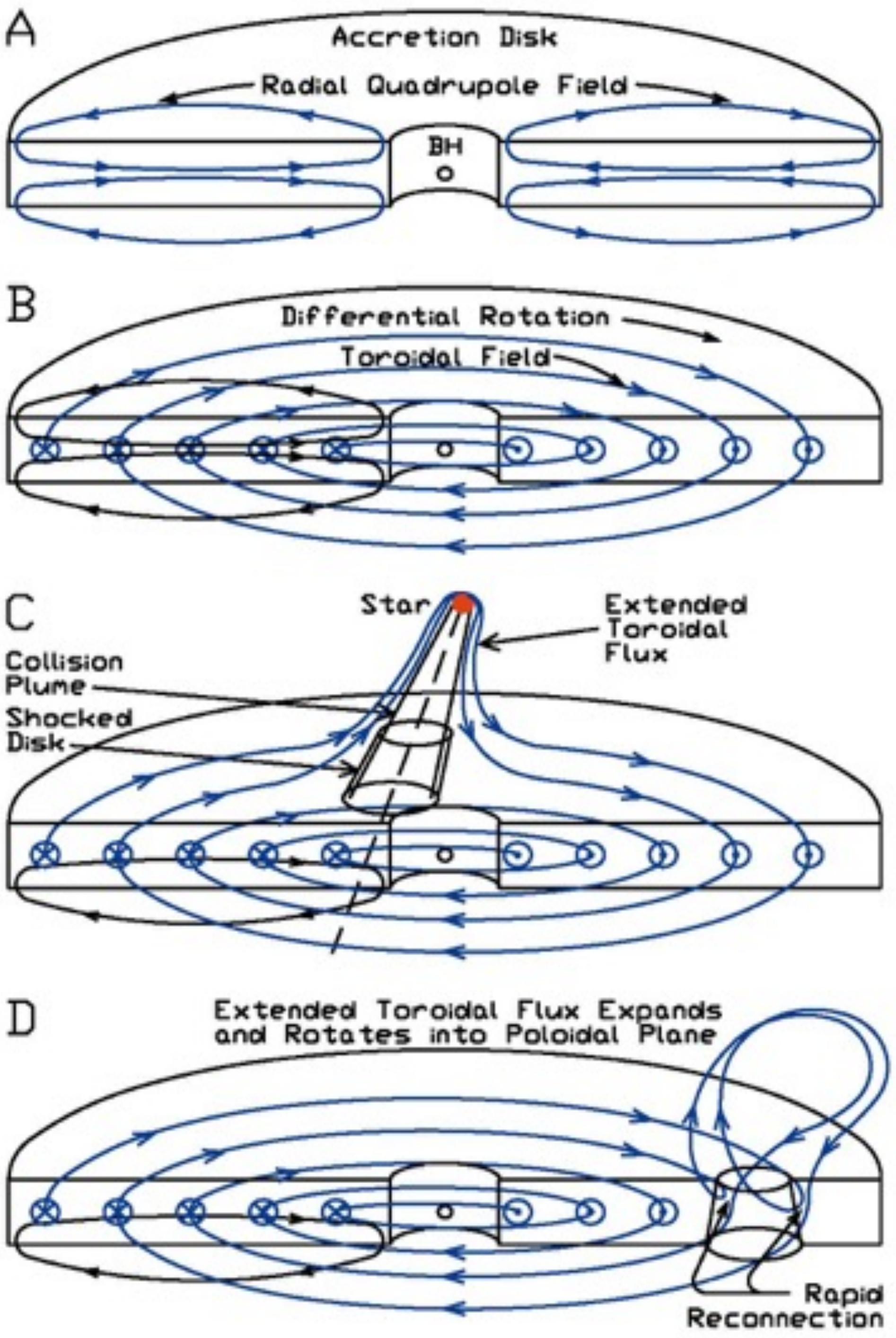
B_r

B_ϕ

helical turbulence

$$\frac{\partial B_\phi}{\partial t} = r\frac{d\Omega}{dr}B_r + \eta_T\frac{\partial^2 B_\phi}{\partial z^2}$$

$$\frac{\partial B_r}{\partial t} = -\frac{\partial}{\partial z}\alpha B_\phi + \eta_T\frac{\partial^2 B_z}{\partial z^2}$$



Courtesy of Stirling Colgate

GALACTIC DYNAMOS

MODEL

1. TURBULENCE DRIVEN BY SUPERNOVAE

2. CONSISTENT WITH α-Ω MODEL WITH LARGE TURBULENT RESISTIVITY

CHALLENGES

1. FLUX REMOVAL ABOVE DISK

2. α QUENCHING AND DOMINANCE OF SMALL-SCALE DYNAMO

EXPERIMENTS?

...in magnetohydrodynamics one should not believe the product of a long and complicated piece of mathematics if it is unsupported by observation.

Enrico Fermi

DYNAMO EXPERIMENTS REQUIRE:

FROZEN IN FLUX: $Rm = \mu_0 \sigma UL \gg 1$

FLOW DOMINATED: $\rho U^2 \gg B^2/\mu_0$

NEW REGIME FOR PLASMA EXPERIMENTS-
ASTROPHYSICAL APPLICATIONS

HYDRODYNAMICS:

$Re = UL/\mu$, $Pm = Rm/Re$

Plasmas are Challenging

-difficult to stir

-some confinement required with weak B

Use Liquid Metals

-confinement is free

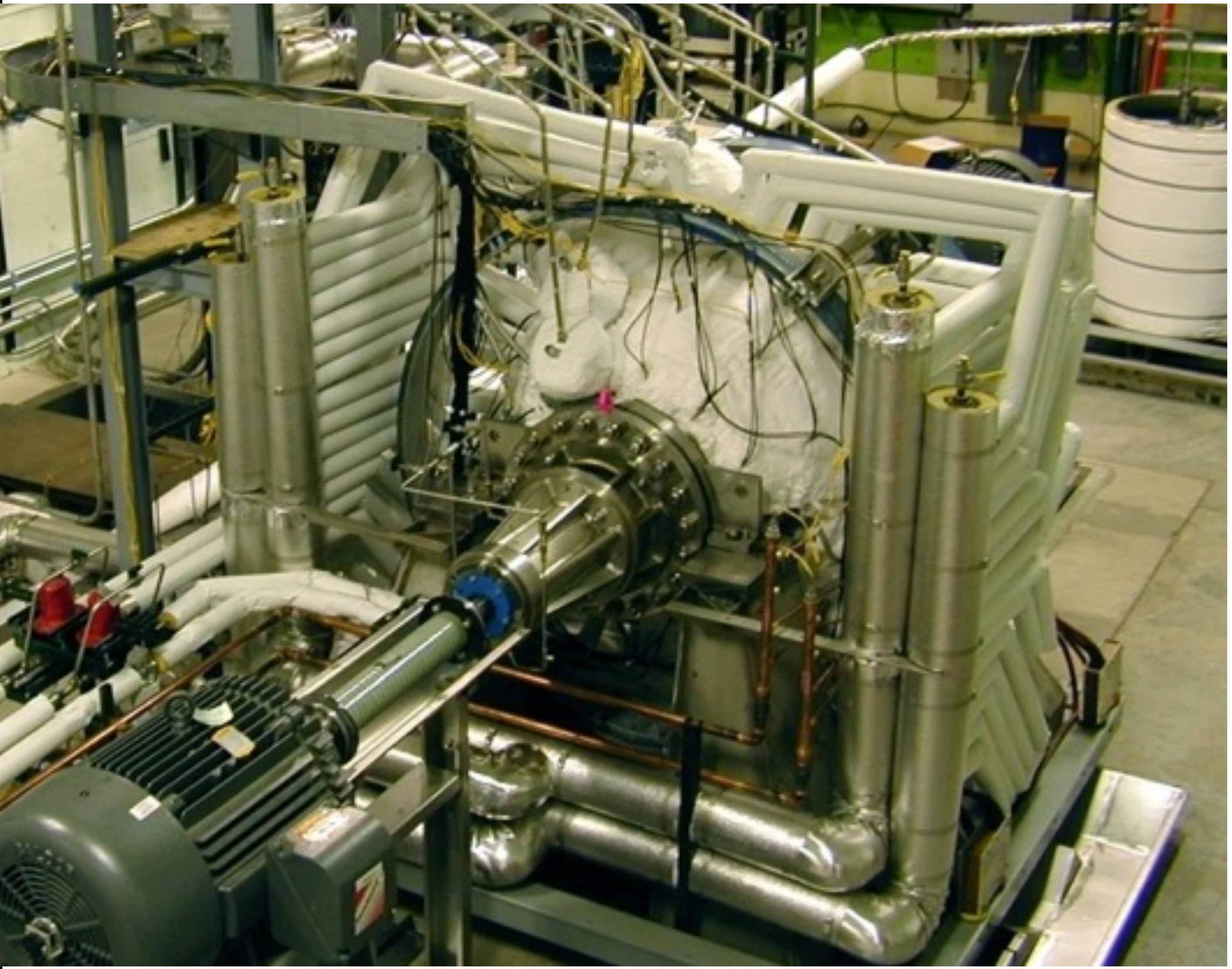
-easy to stir

-BUT power scaling is challenging: $P_{mech} \sim Rm^3 / L$

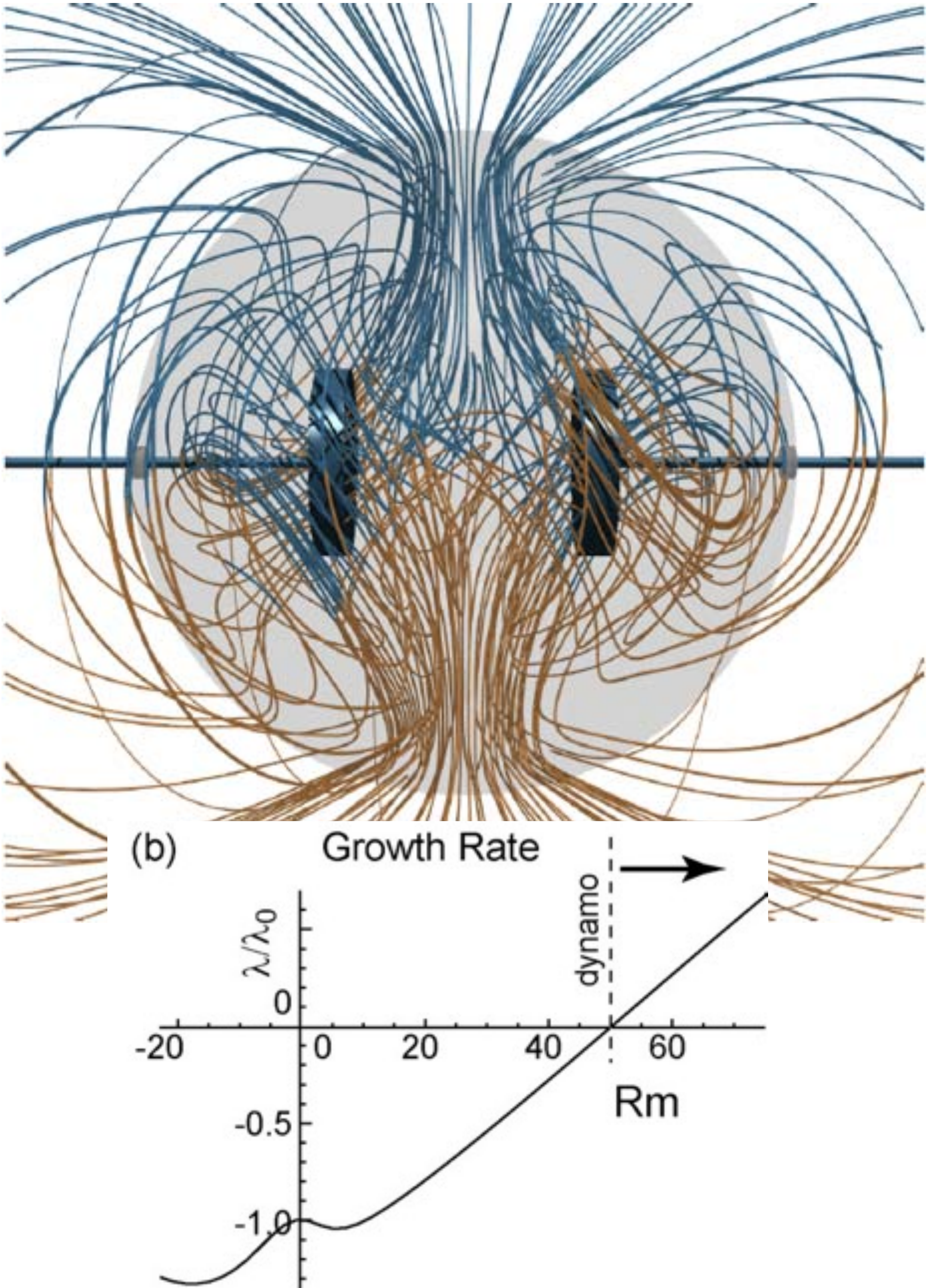
[Rm=100, P_{mech}=100 kW] — just barely at threshold

-Re = 10^7 (Pm=10^{-5}, turbulent)

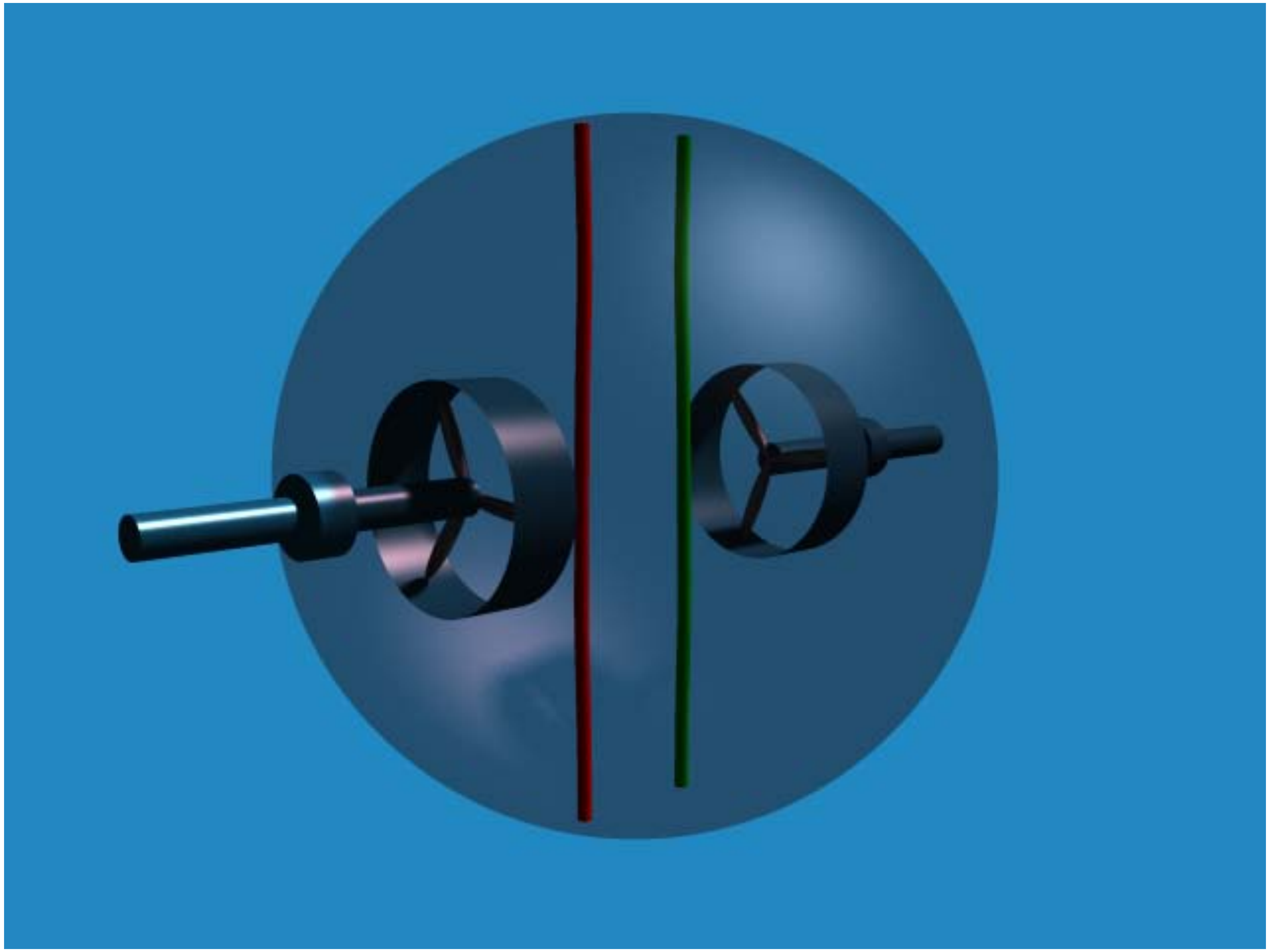
THE MADISON SODIUM DYNAMO EXPERIMENT



The Madison Dynamo
Experiment
a=0.5m, V=10 m/s
P=150kW, Rm_{max}=100



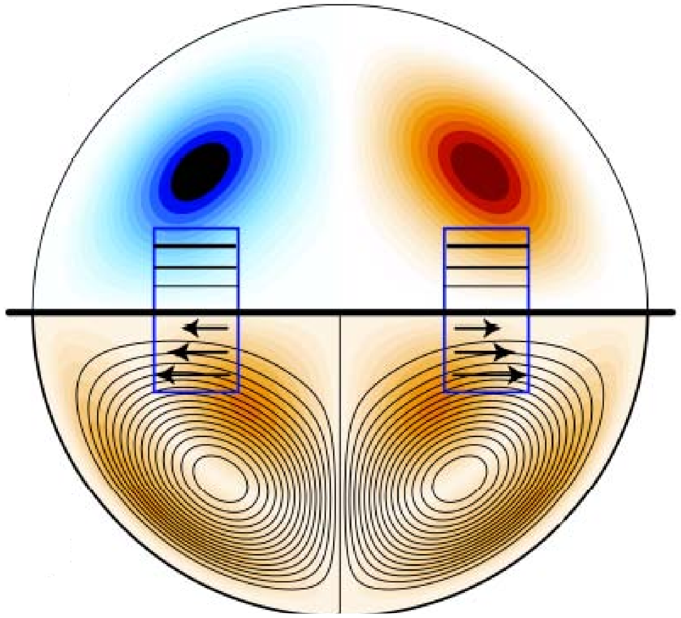
STRETCH-TWIST-FOLD DYNAMO IN SPHERE



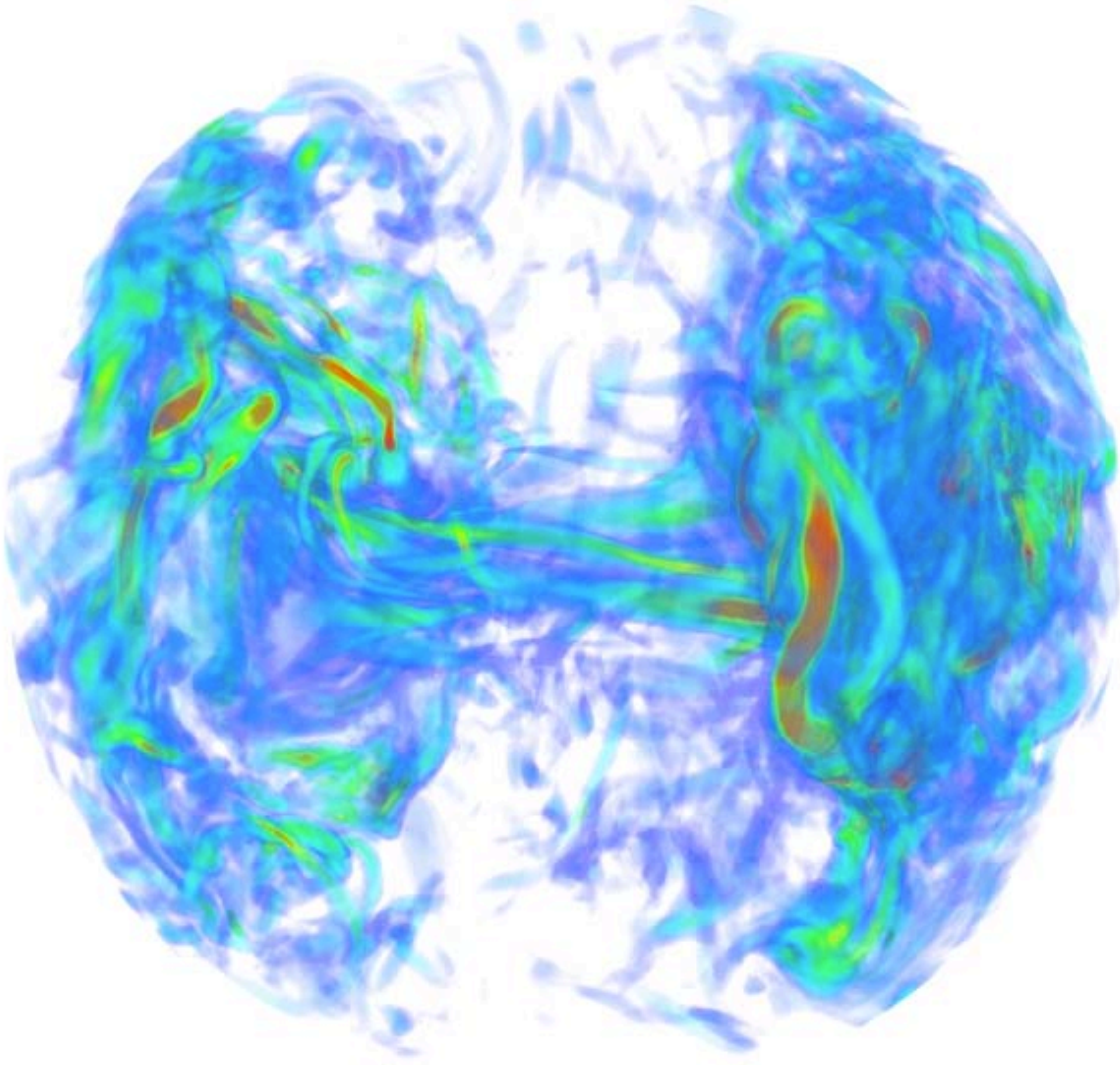
LIQUID METAL DYNAMOS ARE TURBULENT

For liquid metals

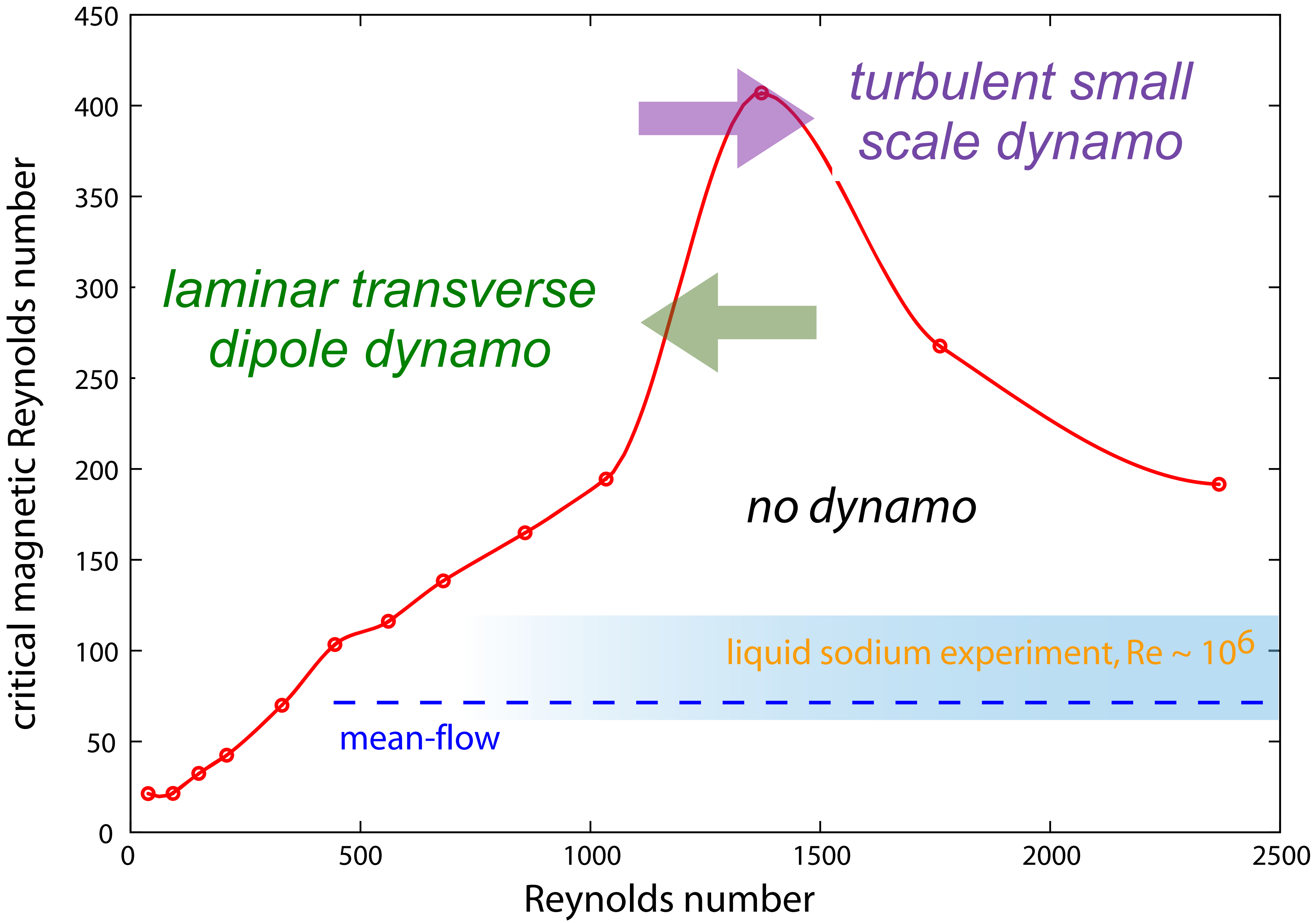
$Re \sim 10^5 Rm$



Re~2000



NUMERICAL SIMULATIONS SHOW TURBULENCE SUPPRESSES LARGE SCALE DYNAMO



Reuter, Jenko, and Forest, (2011).

LARGE SCALE DYNAMO SUPPRESSION: TURBULENT RESISTIVITY GOVERNS ONSET

Definitions

$$Rm = VL/\eta \qquad Rm_T = \tilde{v}\ell/\eta \qquad \eta = \frac{1}{\mu_0\sigma}$$

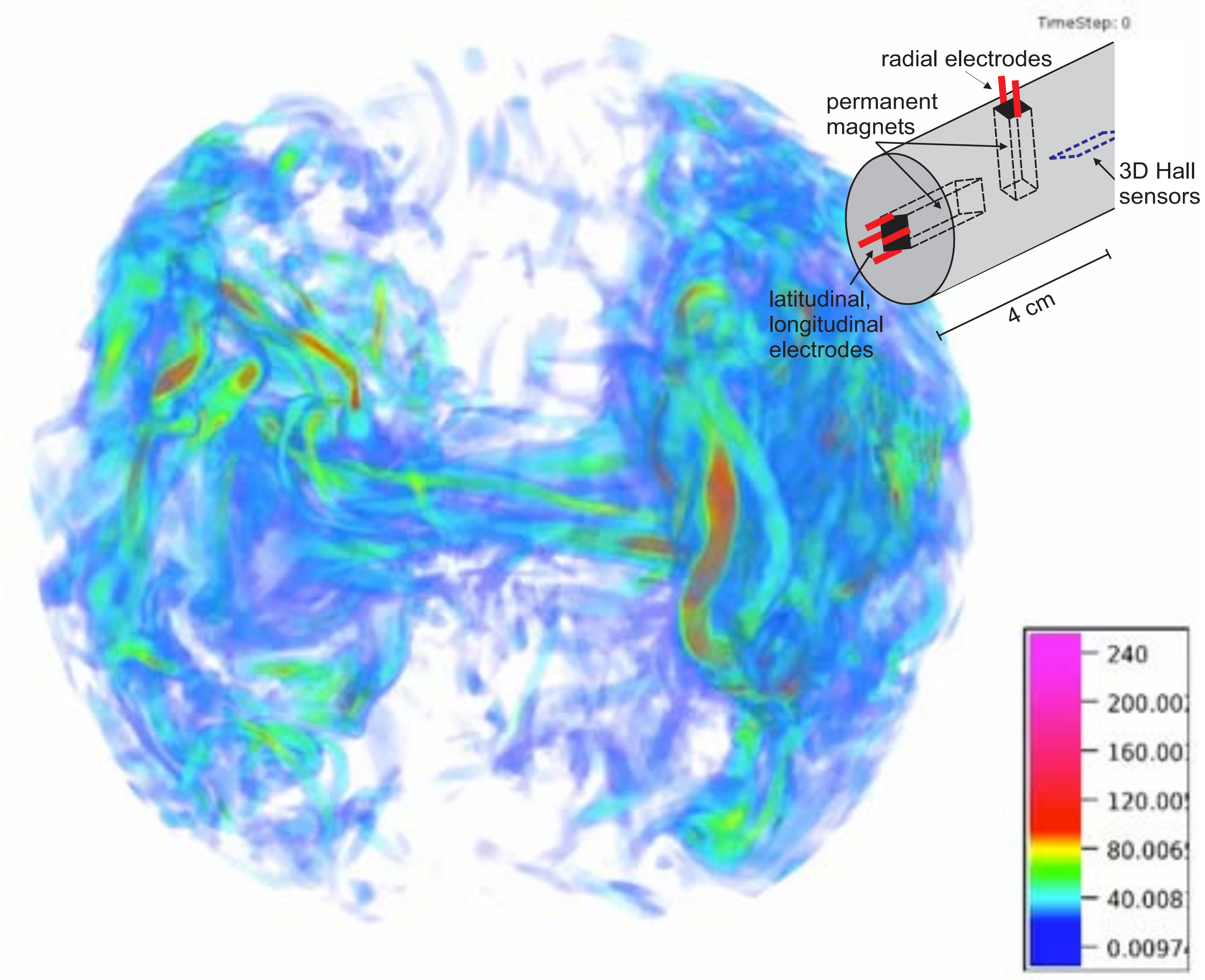
Mean-Field Electrodynamics predicts (confirmed by measurements)

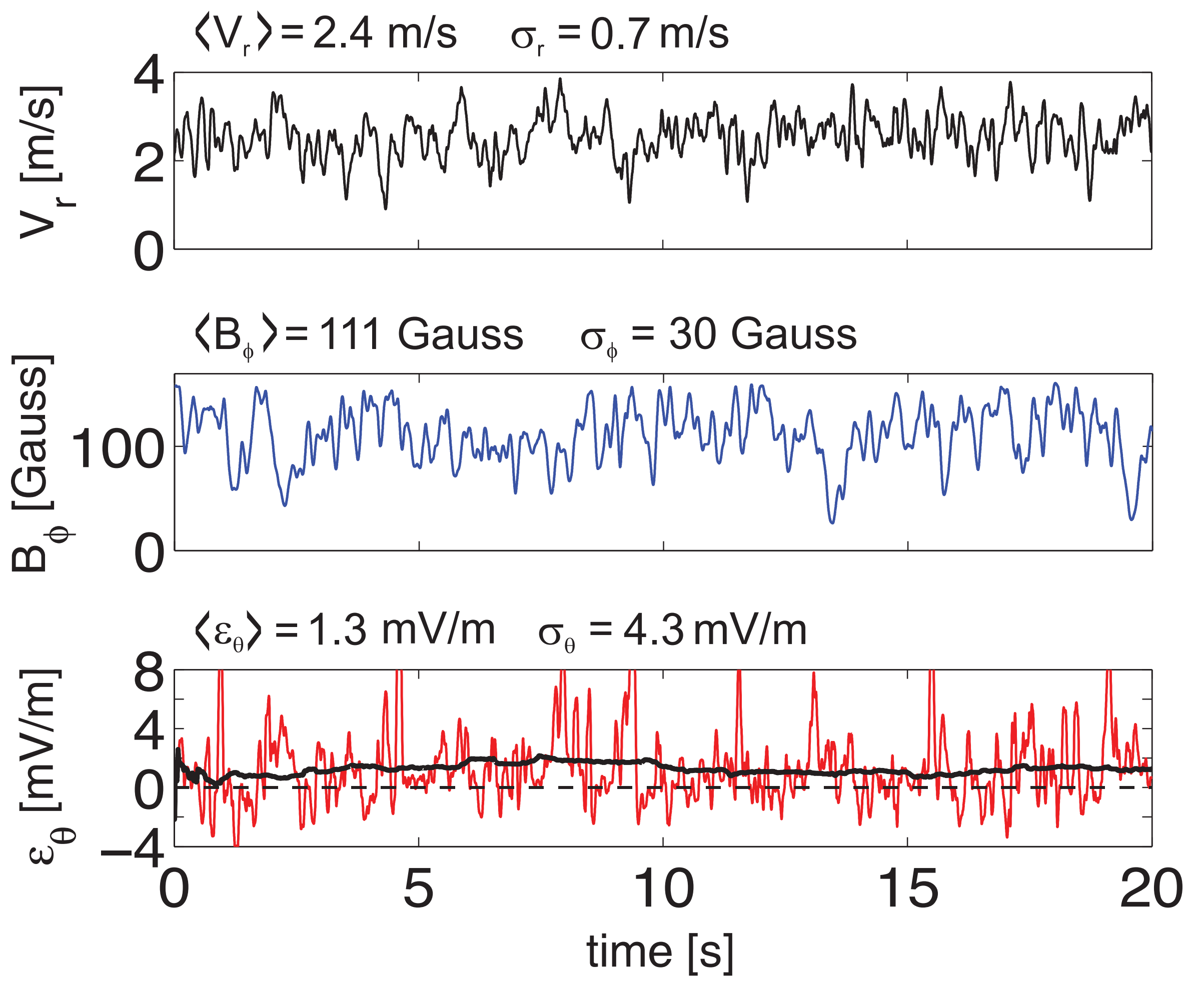
$$\eta_T = \eta\,(1 + Rm_T/3)$$

Self-Excitation Requirement

$$\boxed{Rm \geq Rm_{crit}(1 + Rm_T/3)}$$

TURBULENT EMF DIRECTLY MEASURED

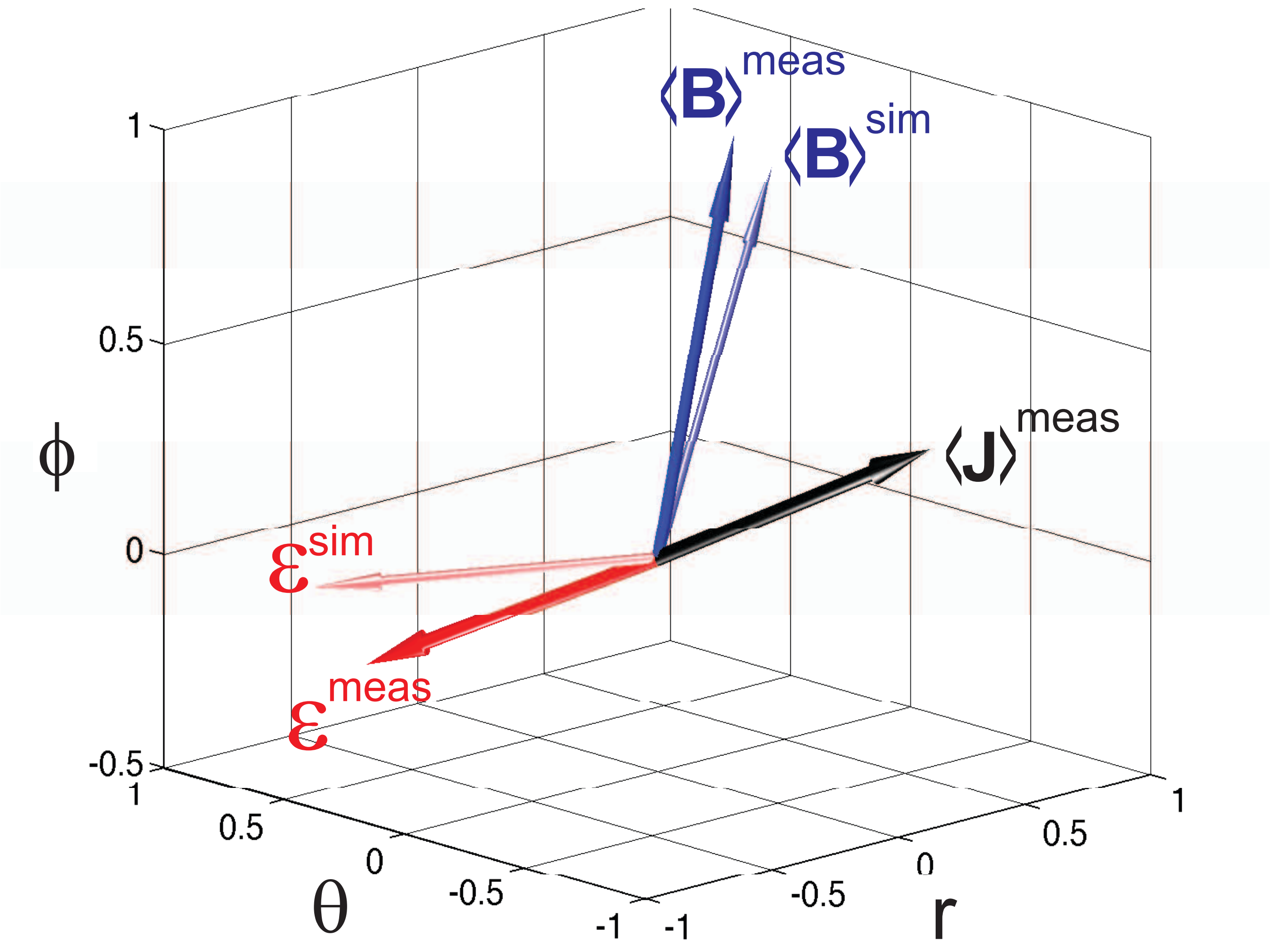


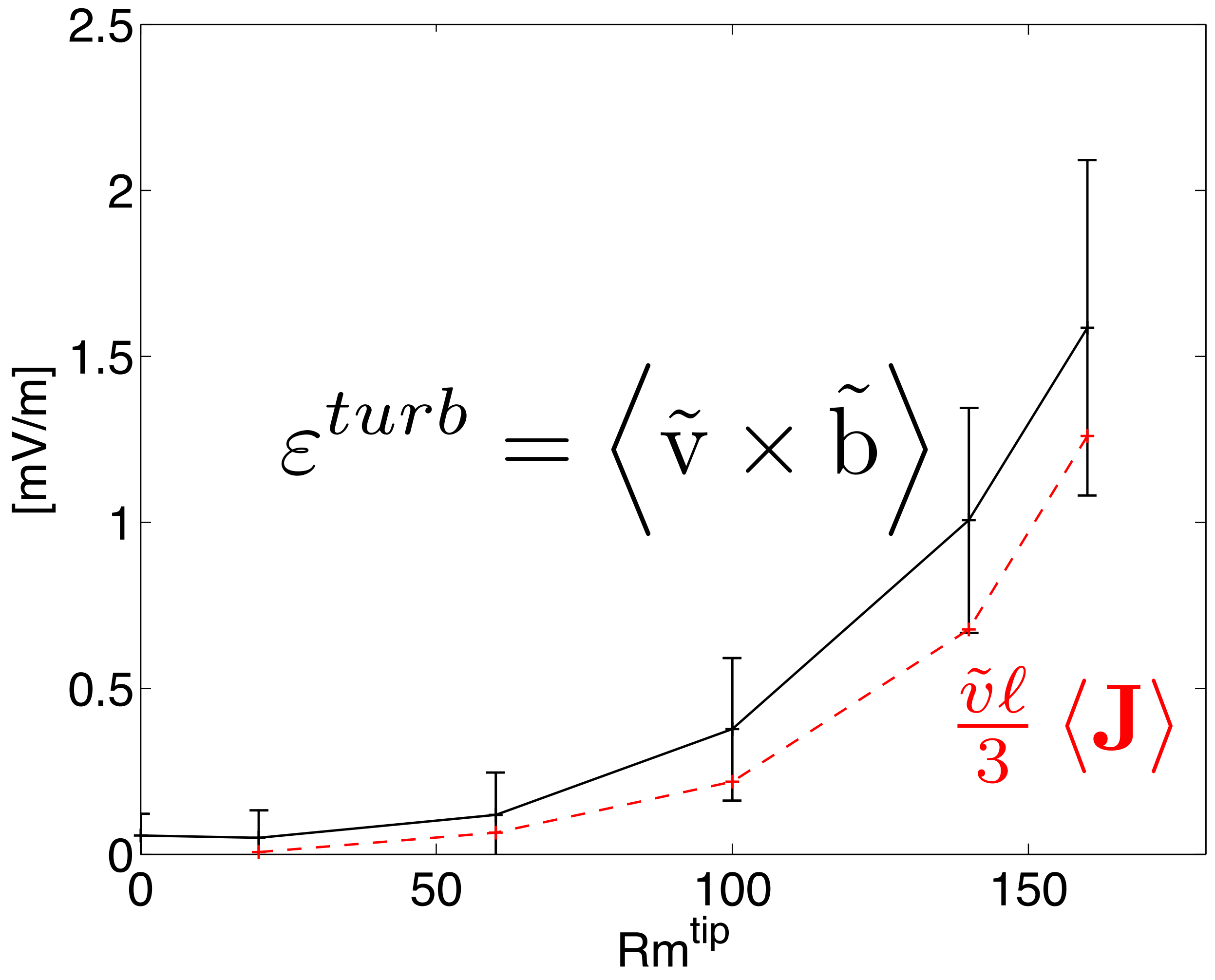


$$\varepsilon^{turb} = \left\langle \tilde{\mathrm{v}} \times \tilde{\mathrm{b}} \right\rangle$$

Rahbarnia 2012.

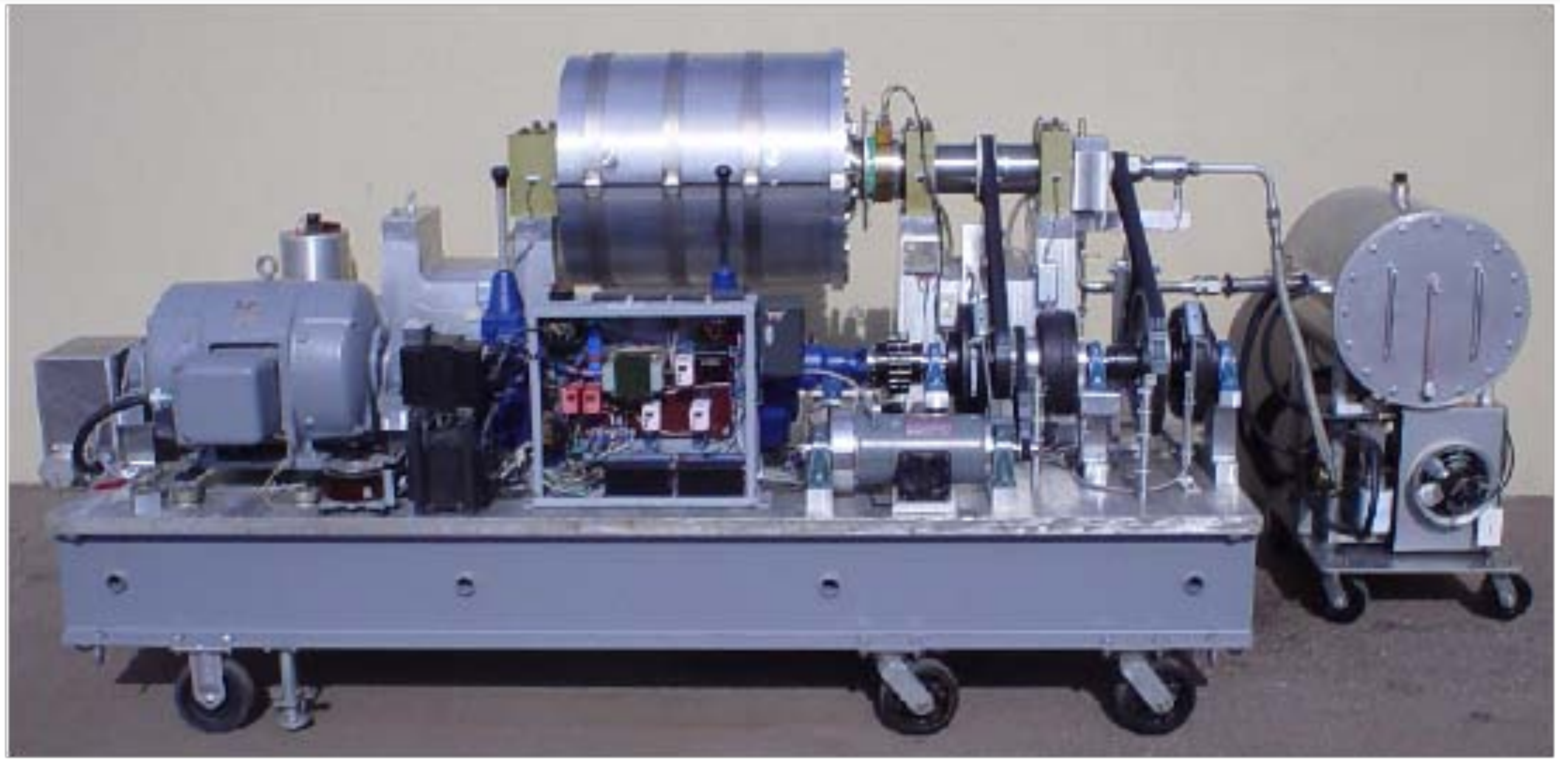
THE TURBULENT EMF OPPOSES THE LOCAL CURRENT, EQUIVALENT TO INCREASED RESISTIVITY (β EFFECT)



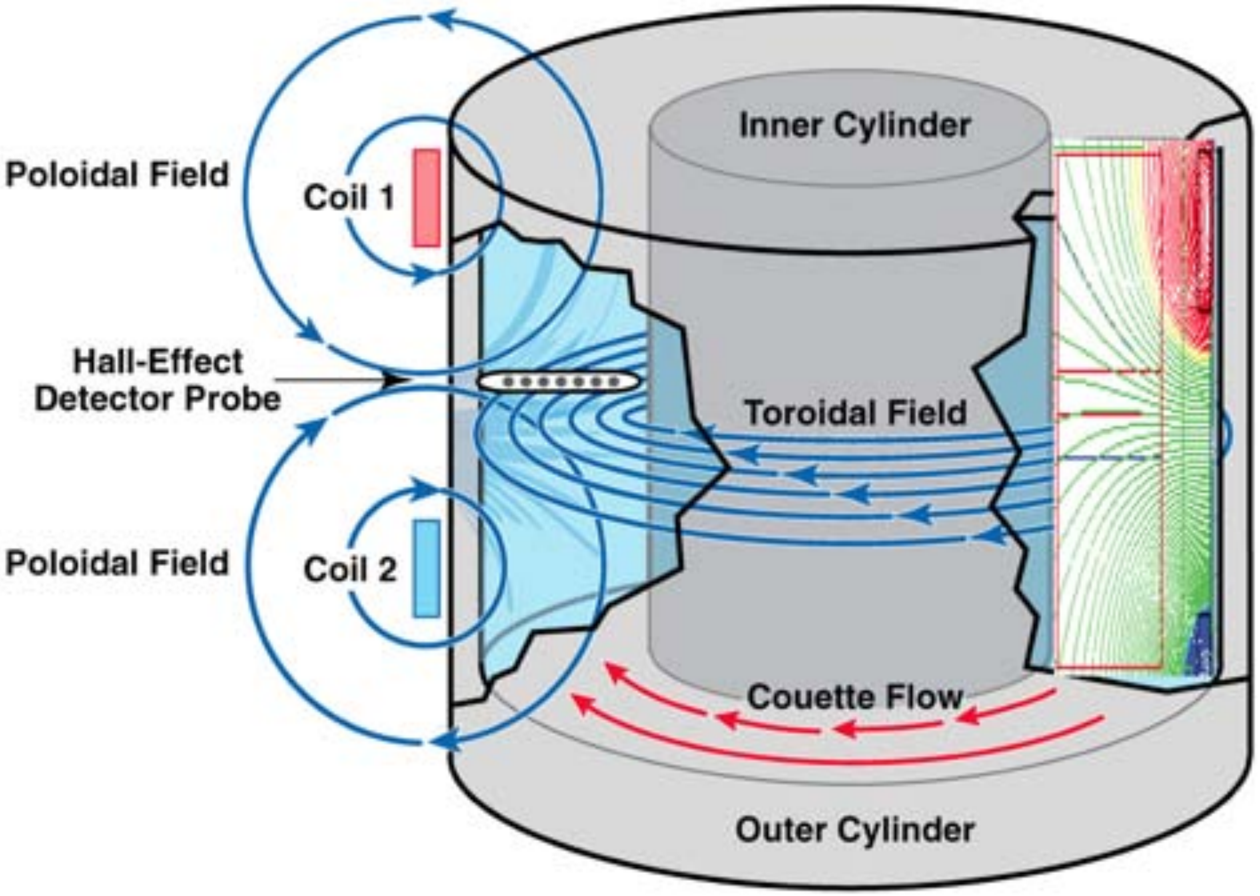


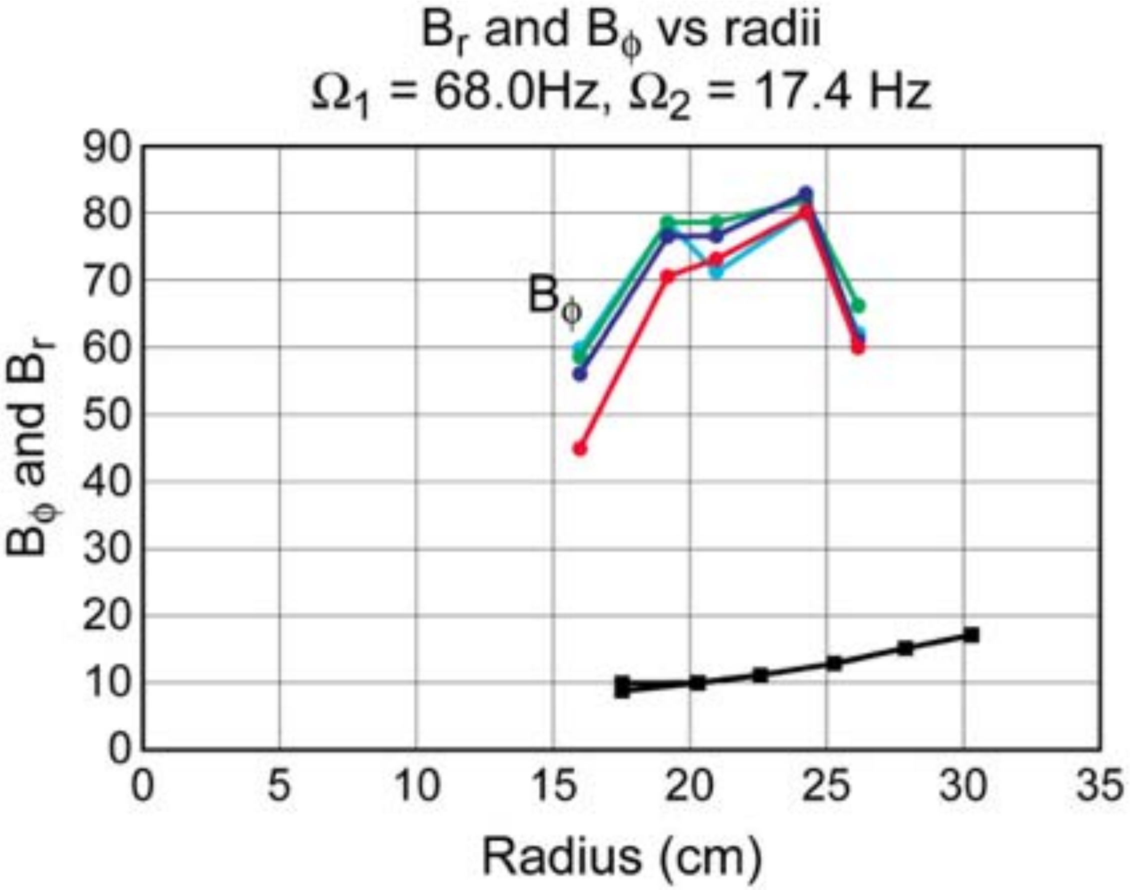
$$\eta_{eff} = \eta + \frac{\tilde{v}\ell}{3}$$

NM Tech Dynamo Exp: demonstration of Omega effect in quiet flow (no beta effect!)

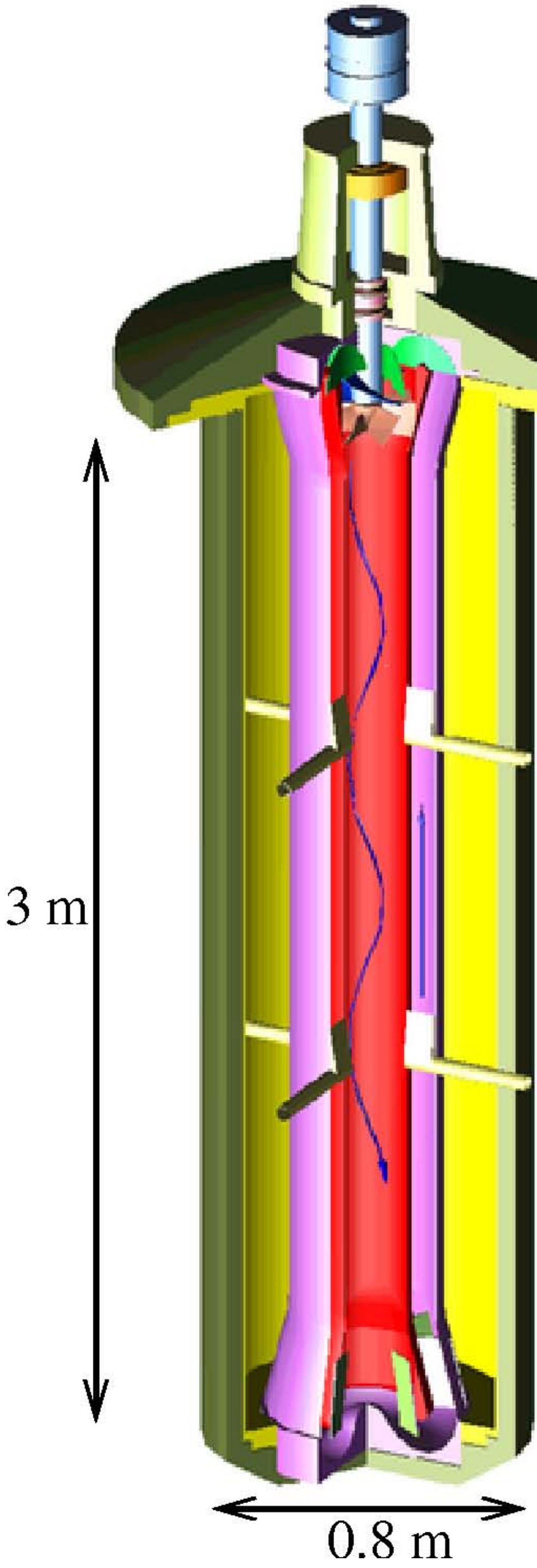


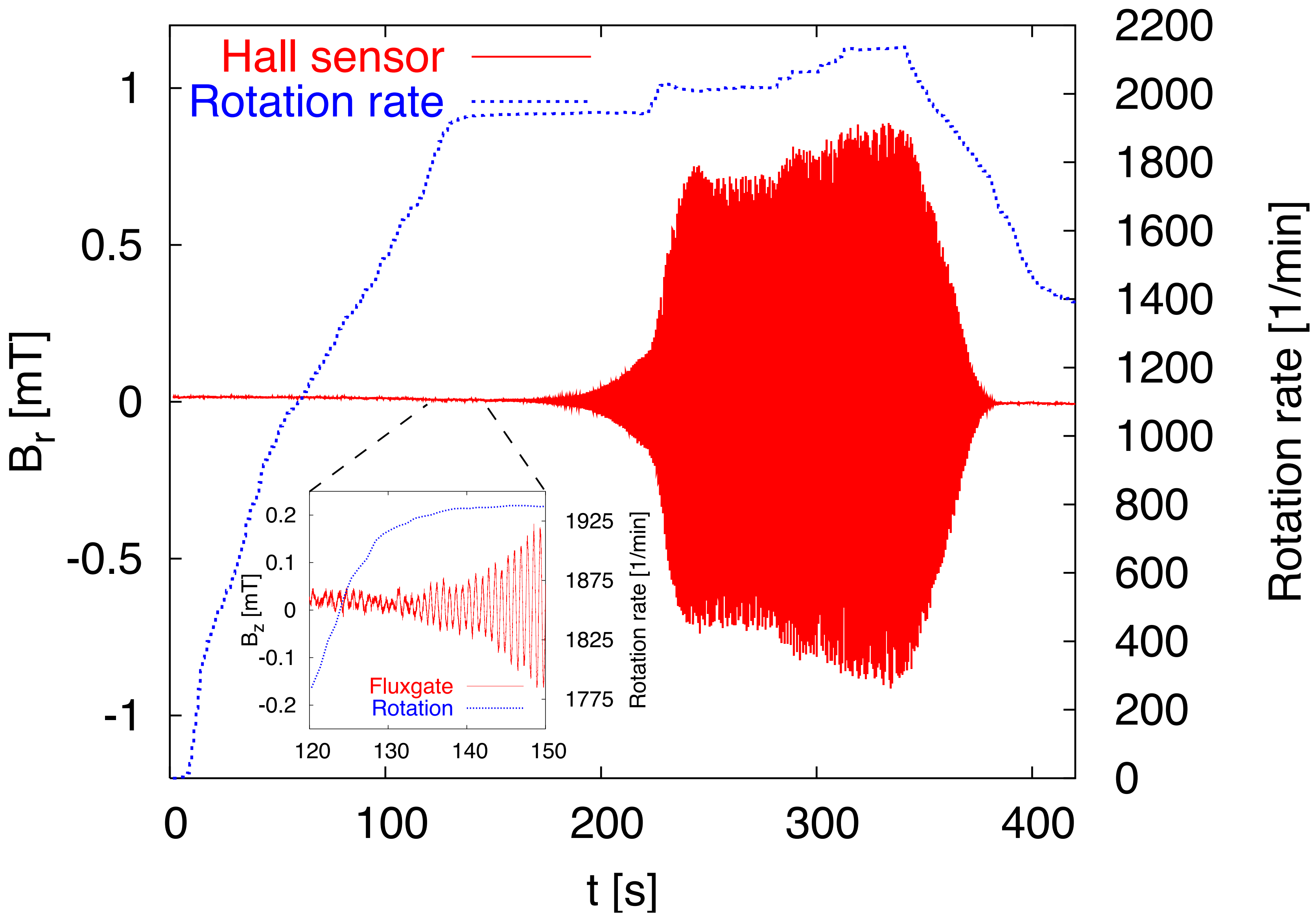
S. Colgate





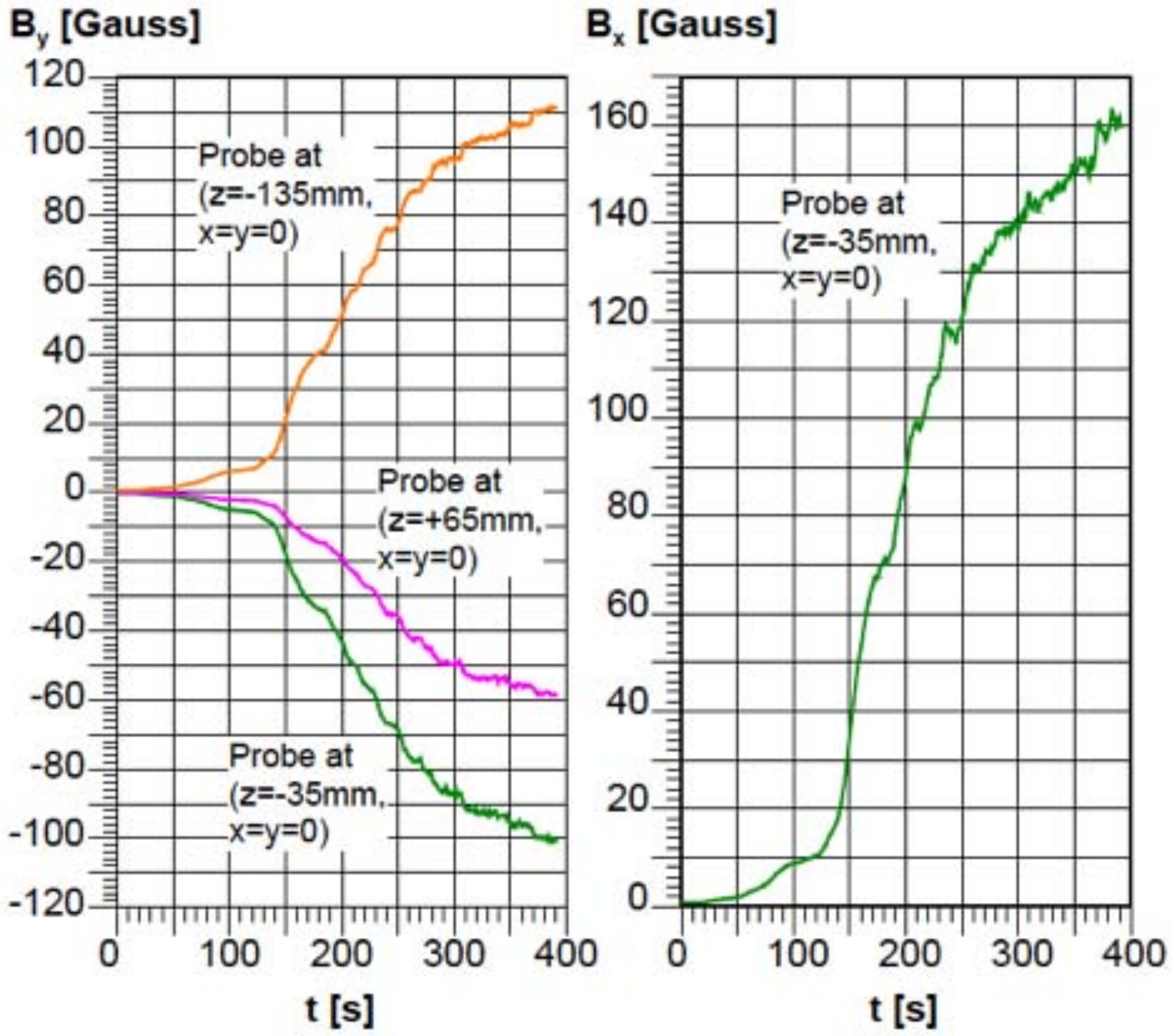
2001: RIGA SINGLE SCALE DYNAMO





- Turbulence played no role in self-excitation
- backreaction changed pitch of flow to saturate

Karlsruhe multi-scale Dynamo

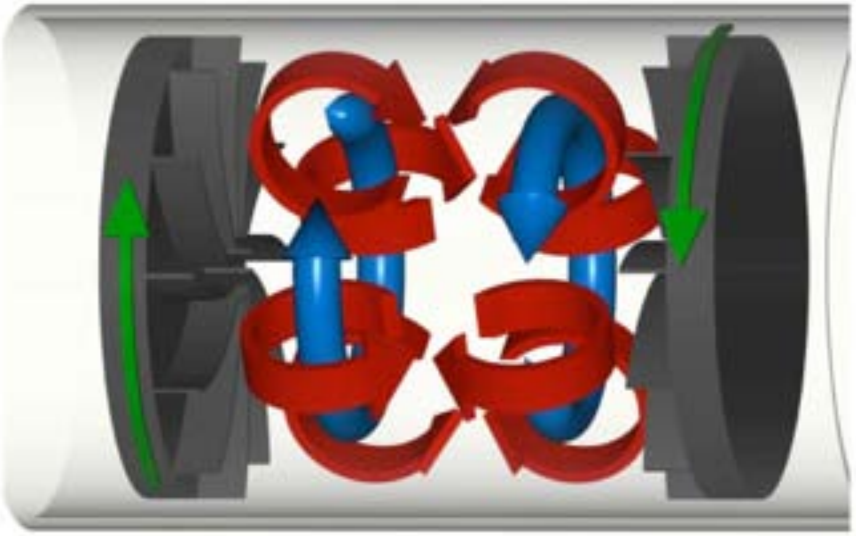


- again, turbulence played no role in self-excitation
- backreaction on flow pitch of flow to saturate

Muller and Stieglitz (2001).

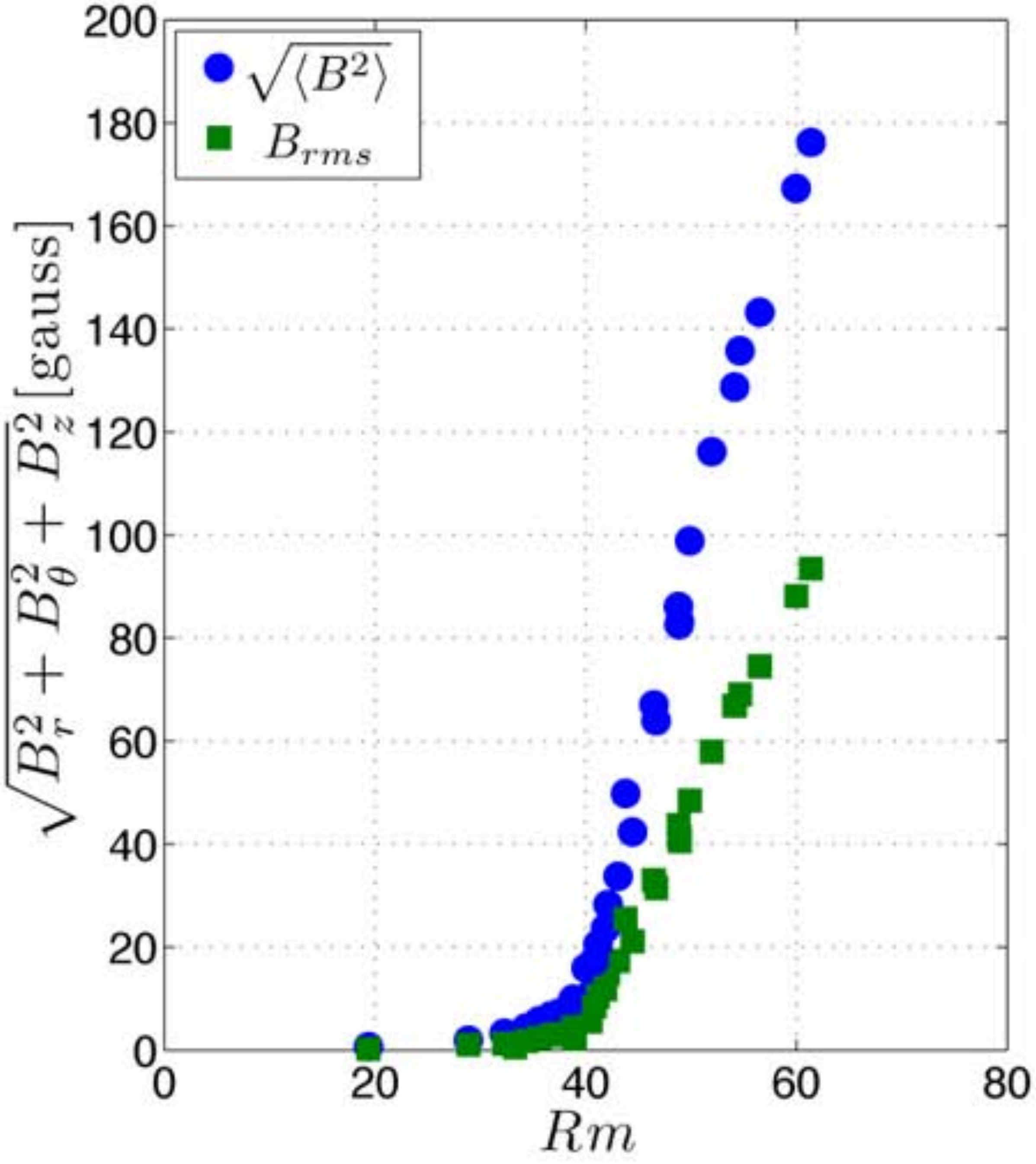
THE VON KÁRMÁN DYNAMO (CADARACHE)

Two Vortex Impeller Driven Flow



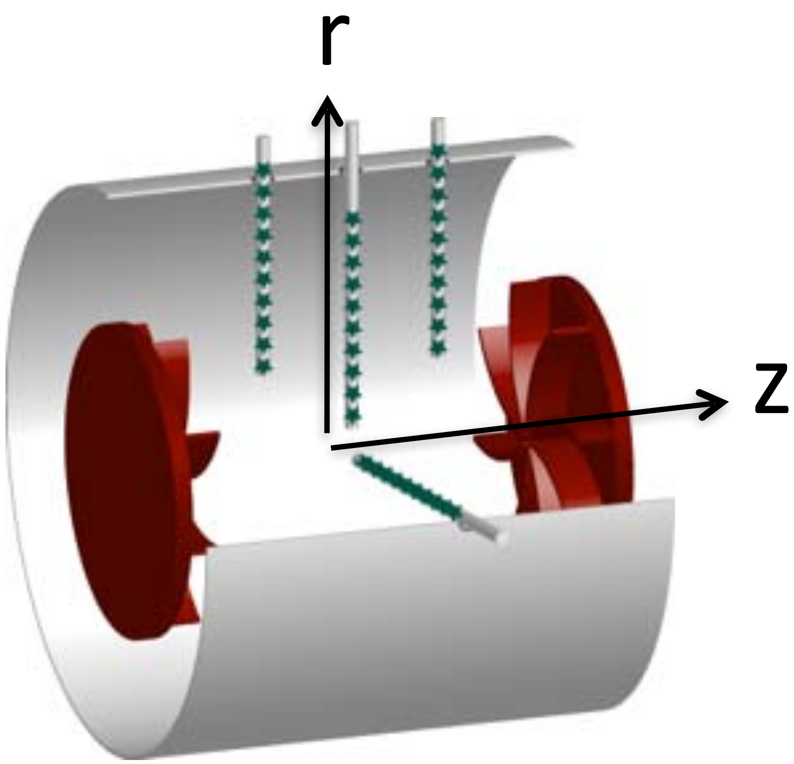
Rimpeller = 0.155 m
Rvessel = 0.289 m
160 L liquid sodium
300 kW mechanical power
T° between 120°C and 150°C (with 200kW cooling)
$Rm^{max} = 90$
$Re > 10^6$

Fe Impellers!!!

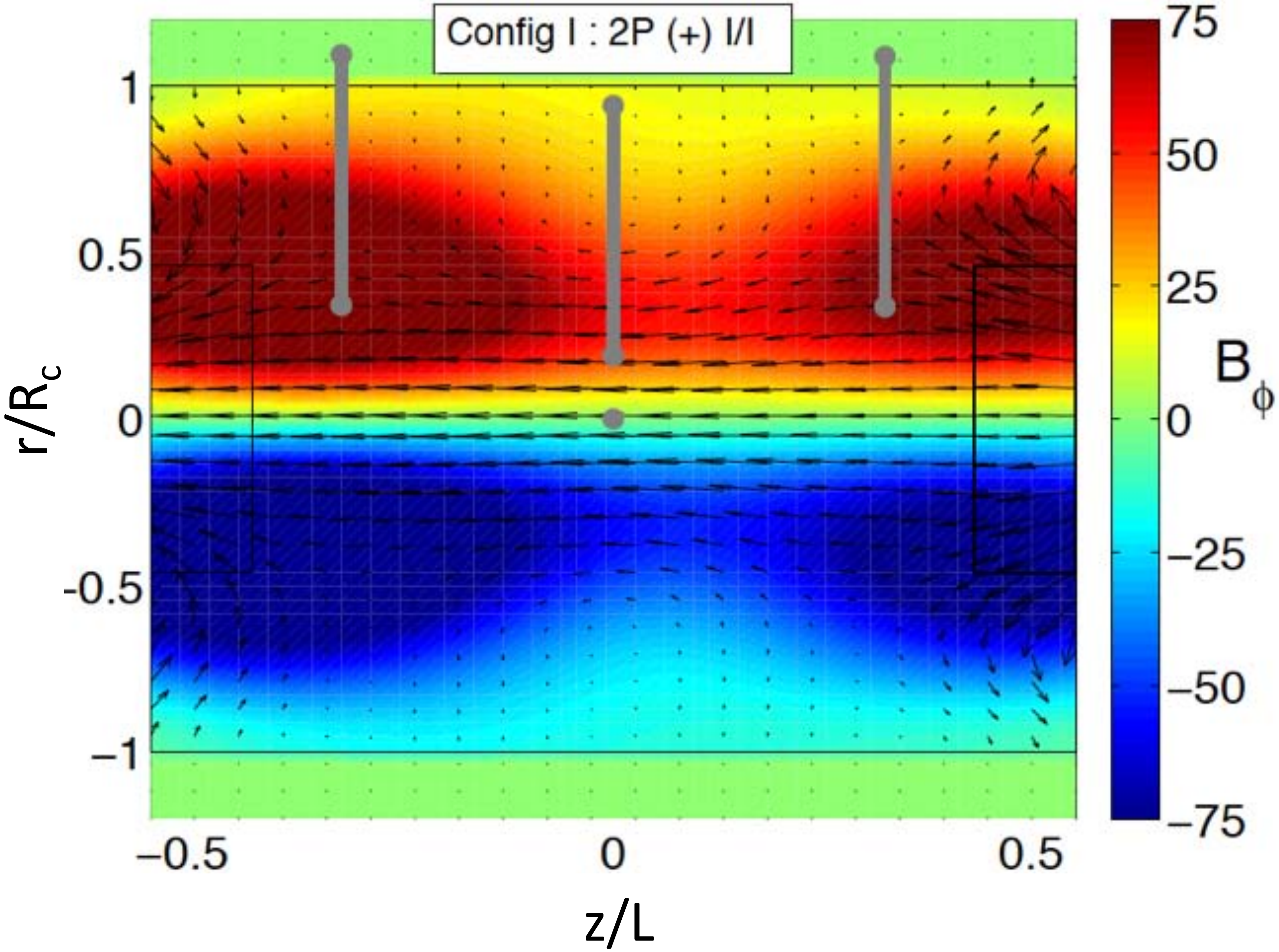


A. Monchaux et al (2007)

SYMMETRIC FIELD! NOT EXPECTED; REQUIRES ALPHA EFFECT ATTRIBUTED TO IRON BLADES

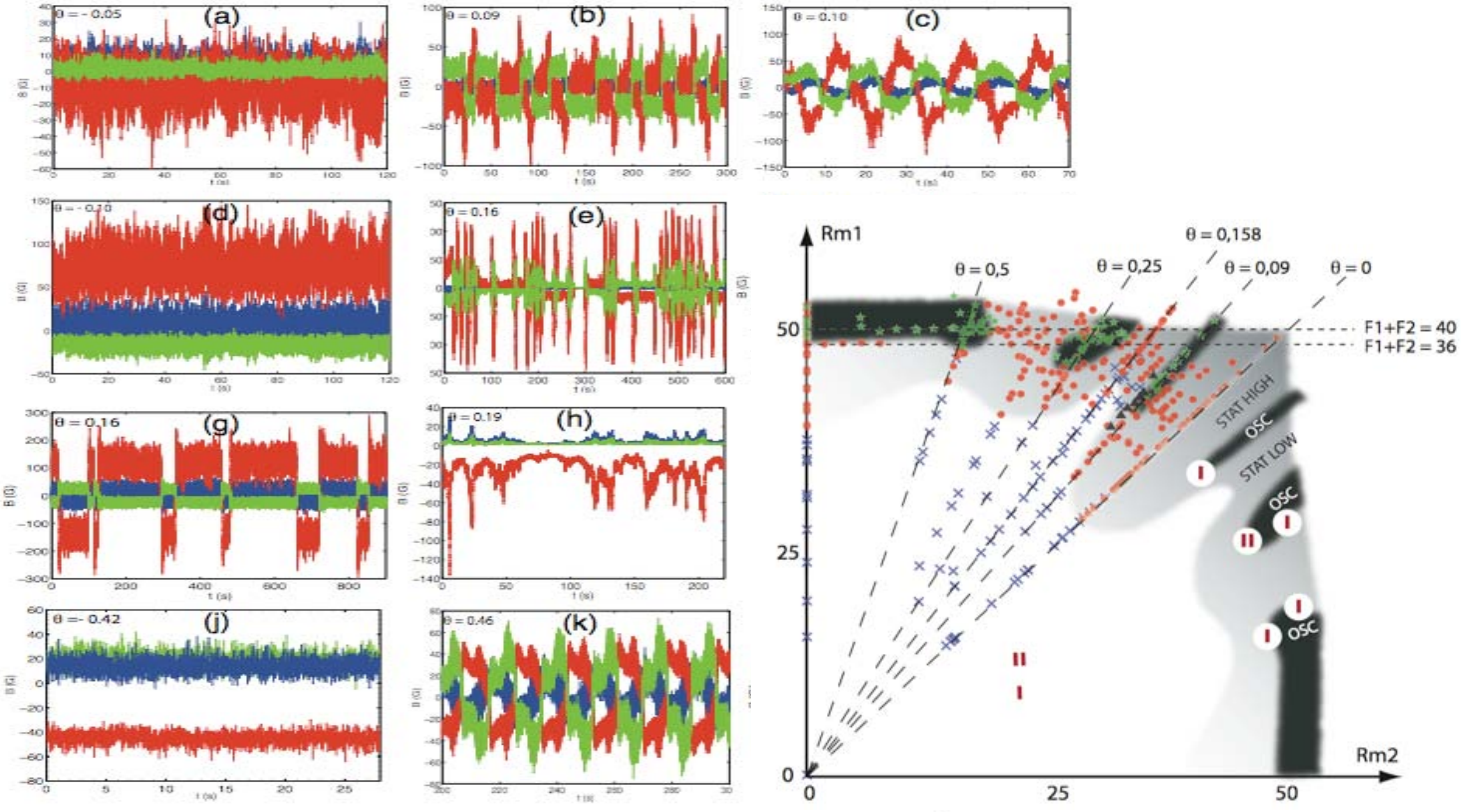


Magnetic field reconstruction



Boisson (2012)

SELF-EXCITED VKS DYNAMOS HAVE DIVERSE DYNAMICAL BEHAVIOR



Monchaux (2009).

NEXT STEP: PLASMA DYNAMO EXPERIMENTS

- Rm > 1000
- Vary Pm: laminar/turbulent, small scale
- Rapidly Rotating
- Compressibility, stratification, buoyancy
- Plasma Effects beyond MHD: neutrals, kinetic effects, Hall MHD

→Study confinement and stirring in an unmagnetized plasma

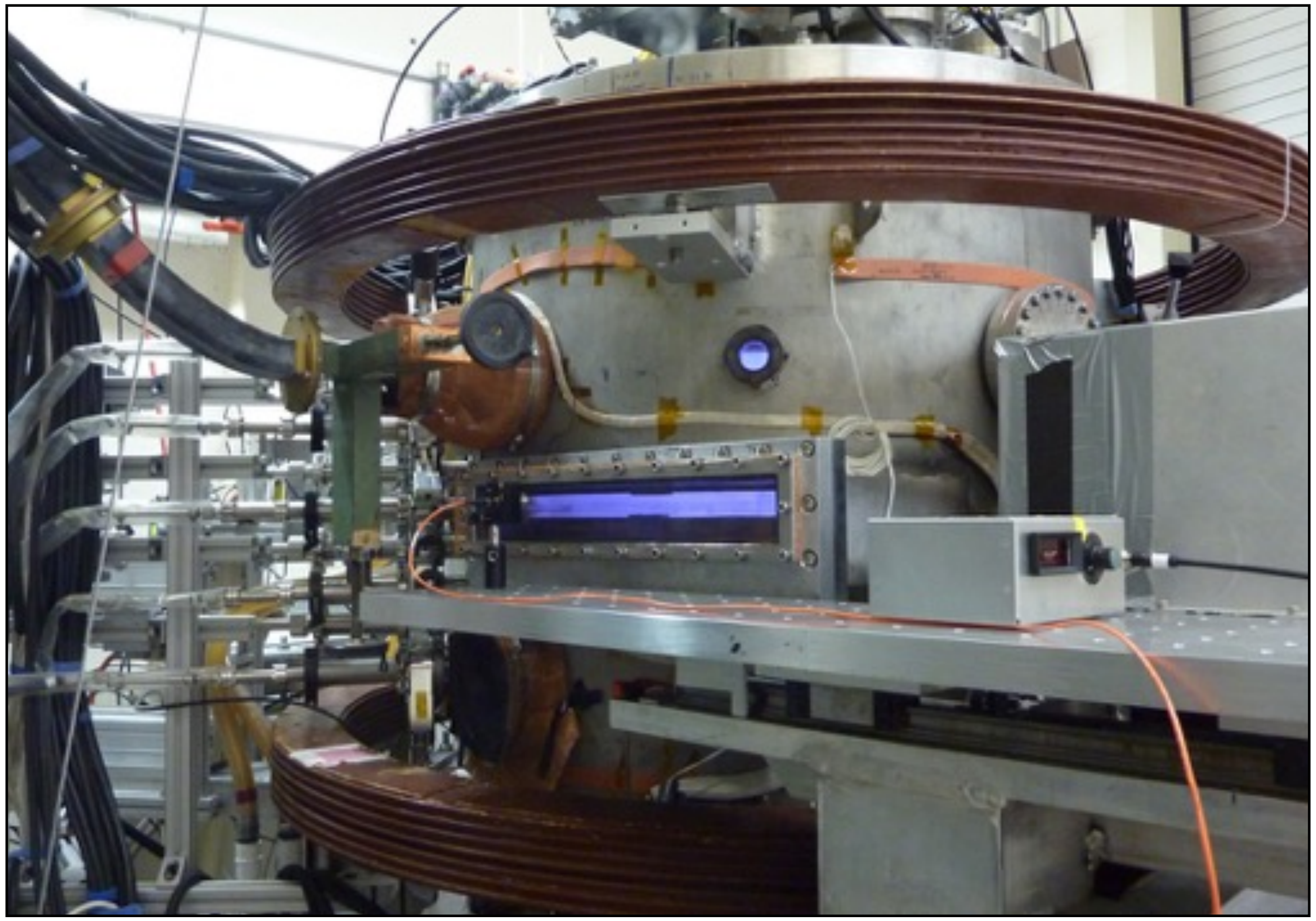
Plasma parameters determine viscosity and conductivity

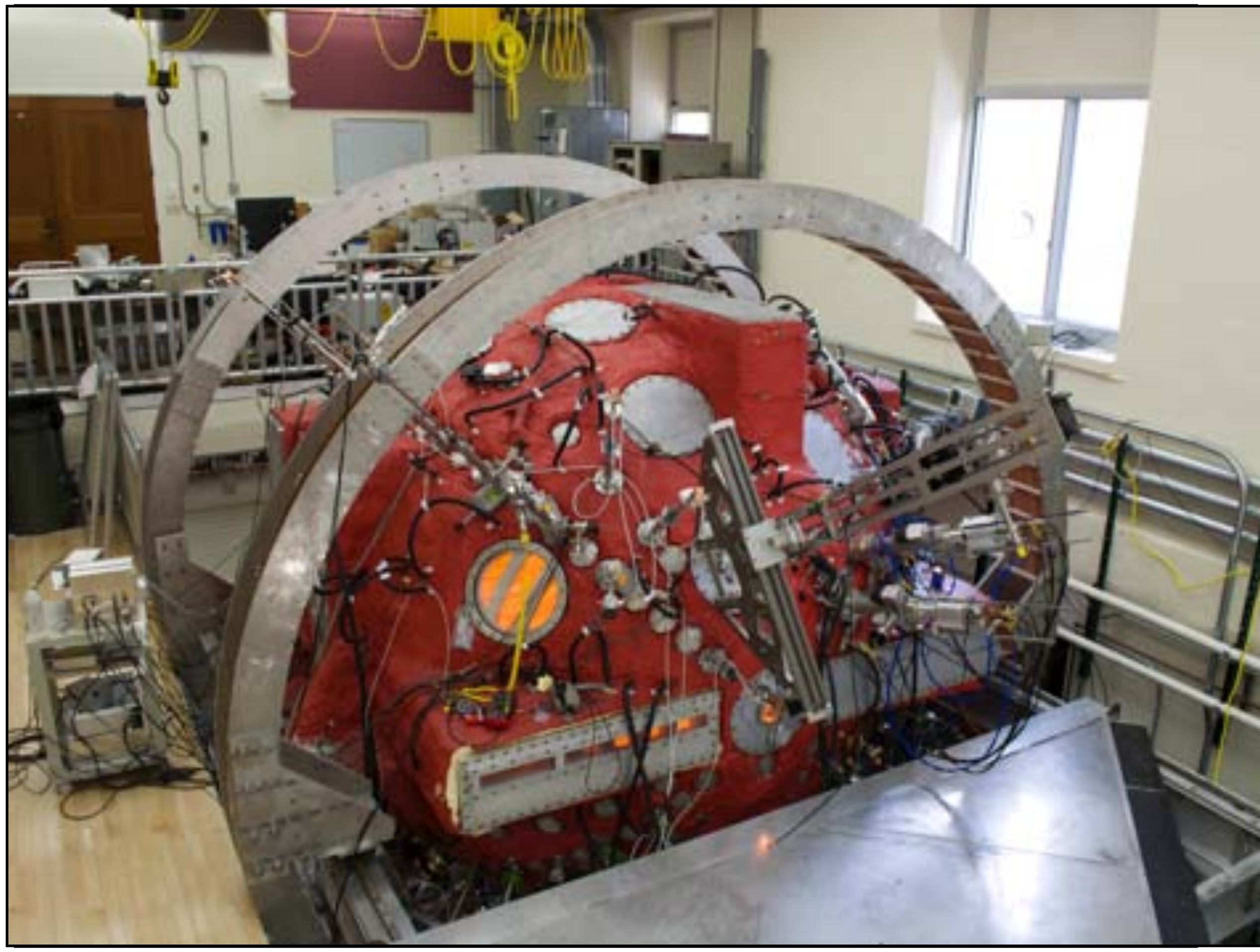
Dynamo experiments require:

$\mathrm{Re} = UL/\eta = 7.8\frac{n_{18}\sqrt{\mu}Z^4 U_{km/s} L_m}{T_{i,eV}^{5/2}}$	**>100**	Dense
$\mathrm{Rm} = \mu_0 \sigma U L = 1.6\frac{T_{e,eV}^{3/2} U_{km/s} L_m}{Z}$	**>>1**	Hot
$M_A = \sqrt{\mu_0 \rho}U/B = 0.46\frac{\sqrt{n_{18}\mu}U_{km/s}}{B_G}$	**>1**	Unmagnetized

NEXT STEP: PLASMA DYNAMO EXPERIMENTS

Plasma Couette Experiment	Madison Plasma Dynamo Experiment





	cylinder: disk systems	**spherical**
plasma:	Te = 7.5 eV, Ti=0.3 eV, L=0.4 m, n = 10^{17} m^{-3}, U_{max} = 6 (12) km/s	Te = 20 eV, Ti~1-2 eV, L=1.5 m, n = 4×10^{18} m^{-3}, U_{max} = 12 km/s
achieved:	Rm=60, Re=20	Rm=800, Re=750

Plasma Hydrodynamics

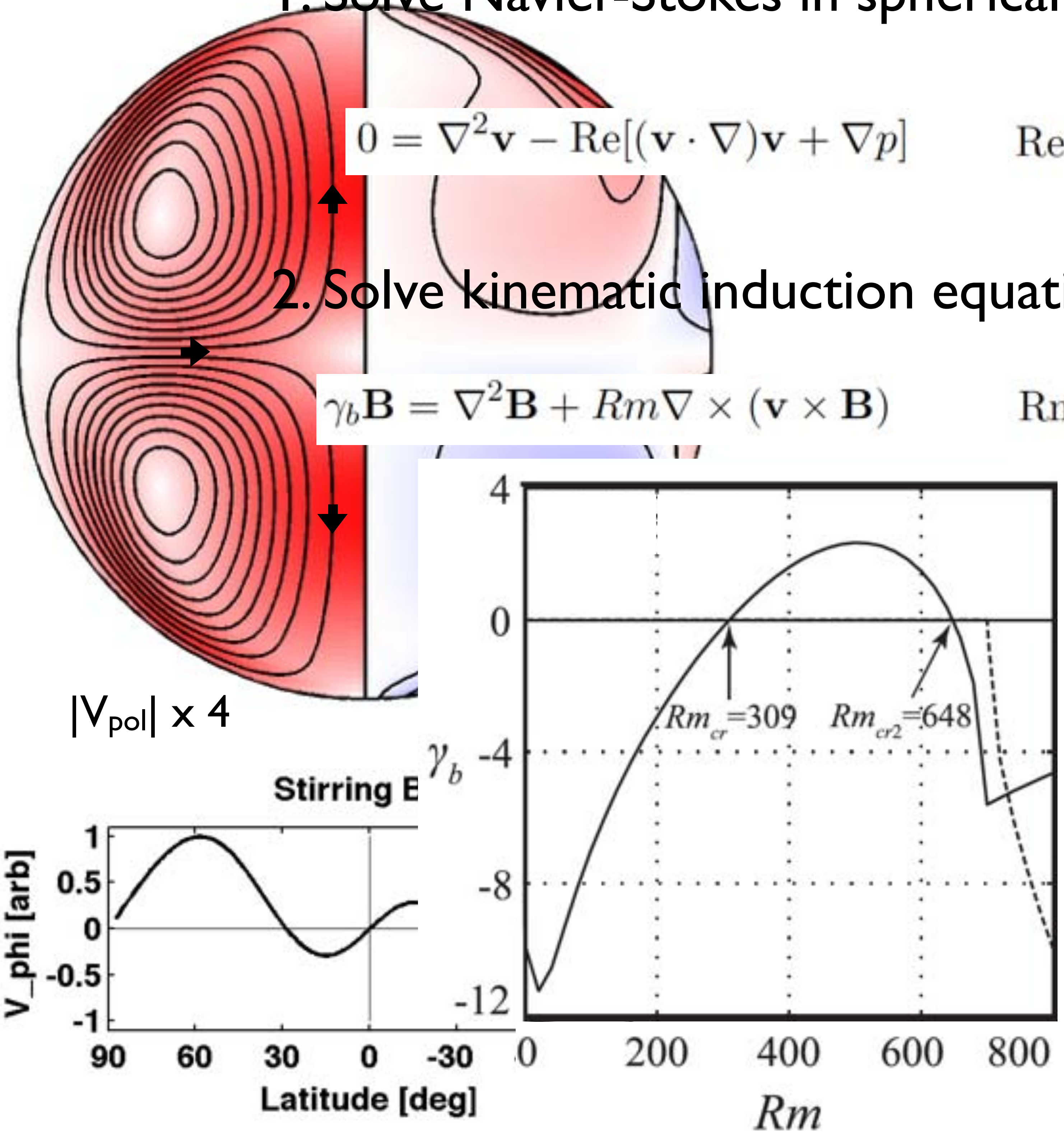
Re=300

1. Solve Navier-Stokes in spherical geometry

$$0 = \nabla^2 \mathbf{v} - \mathrm{Re}[(\mathbf{v}\cdot\nabla)\mathbf{v} + \nabla p] \qquad \mathrm{Re} = \frac{R_0 V_0}{\nu}$$

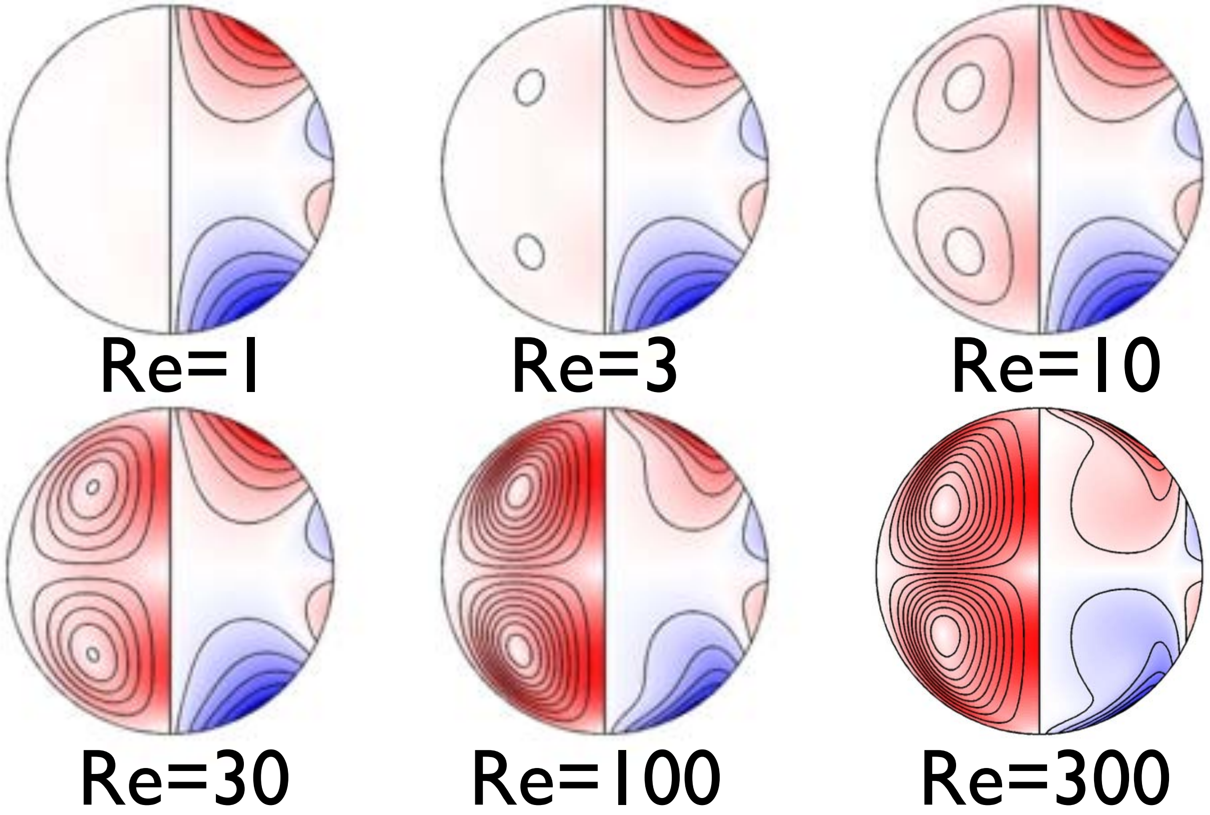
2. Solve kinematic induction equation

$$\gamma_b \mathbf{B} = \nabla^2 \mathbf{B} + Rm \nabla \times (\mathbf{v} \times \mathbf{B}) \qquad \mathrm{Rm} = \frac{R_0 V_0}{\eta}$$



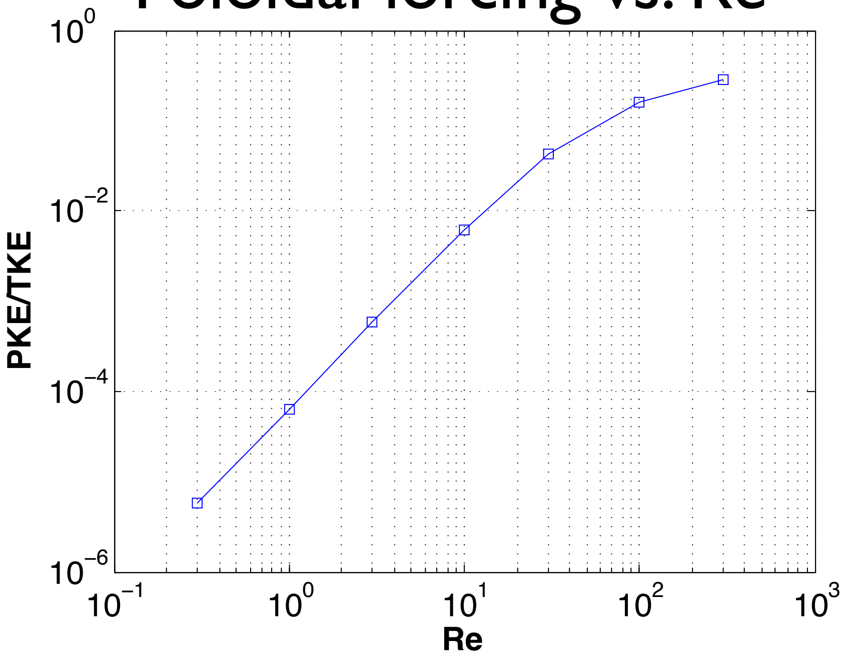
Spence, Reuter, and Forest,(2009).

Velocity field controlled by Re

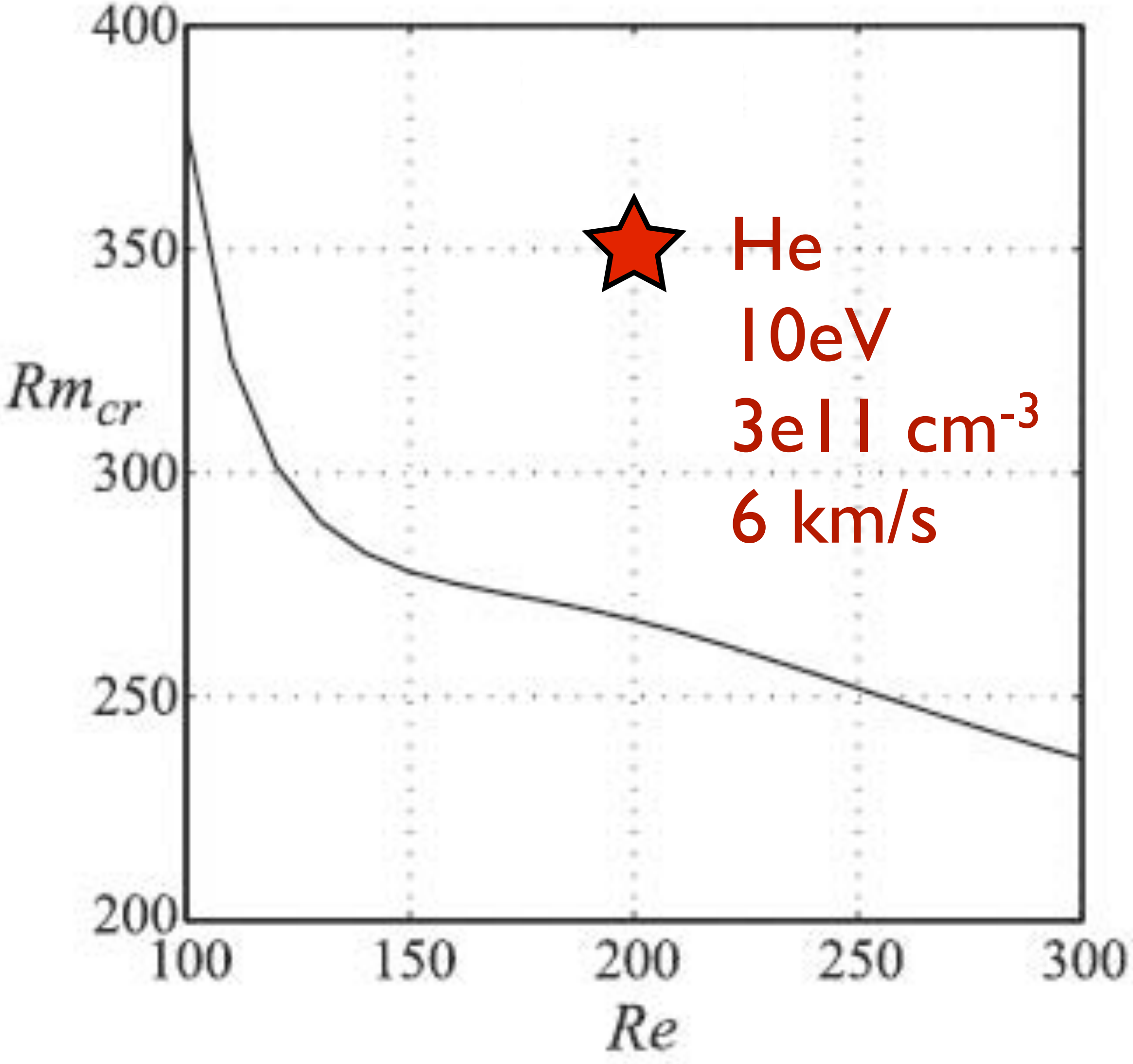

Re=1 Re=3 Re=10

Re=30 Re=100 Re=300

Poloidal forcing vs. Re



Dynamo onset vs. Re



He

10eV

3e11 cm^{-3}

6 km/s

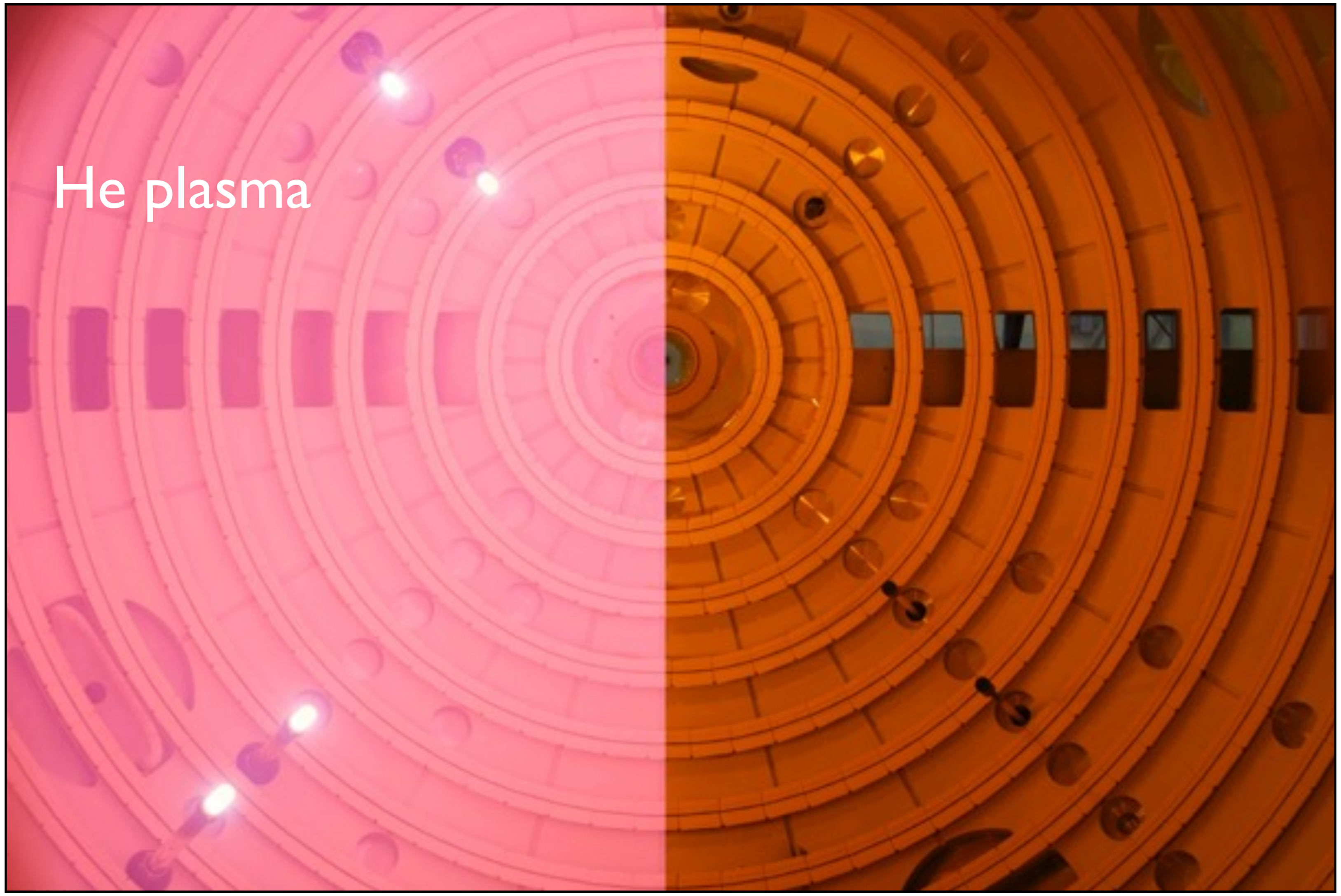
Khalzov, et al, Optimized boundary driven flows for dynamos in a sphere, PHYSICS OF PLASMAS 19, 112106 (2012)

THE MADISON PLASMA DYNAMO EXPERIMENT

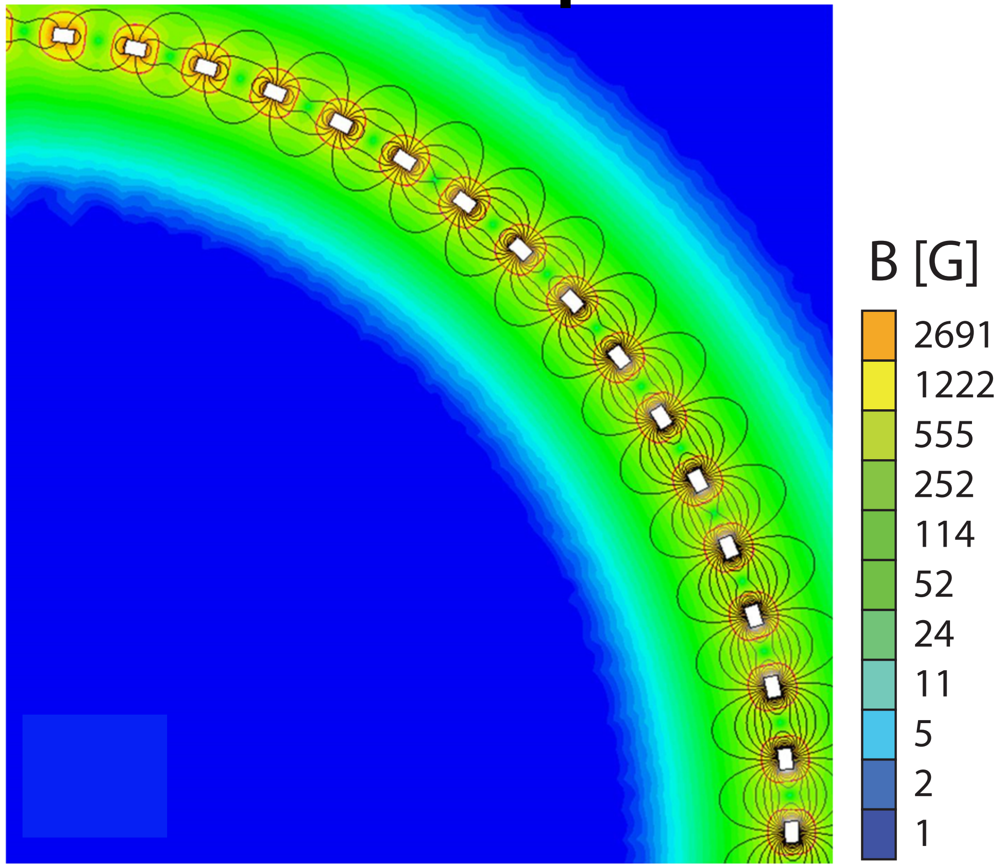
R=1.5 m
Pcath=350 kW
Pech=100 kW
pulse = 10+ sec

Cooper et al, The Madison plasma dynamo experiment: A facility for studying laboratory plasma astrophysics, Phys. Plasmas 21 013505 (2014)

Permanent magnets confine plasma

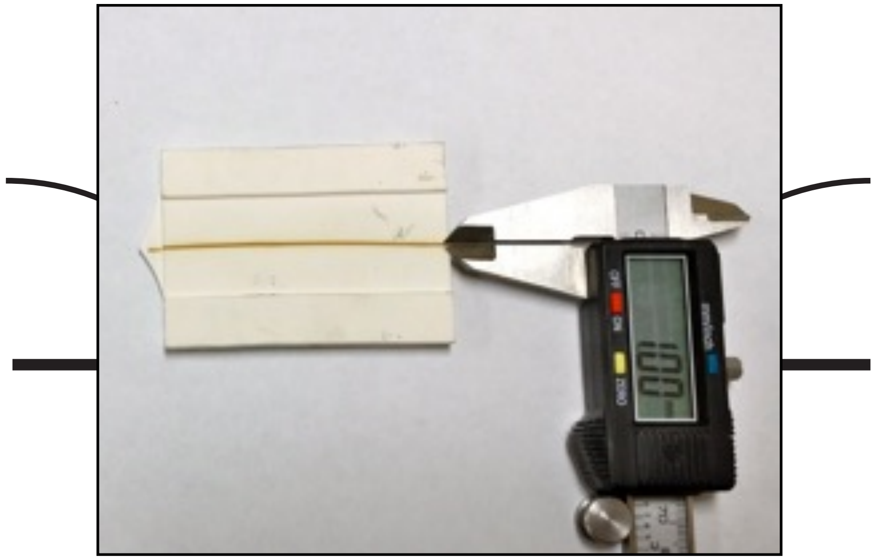


l=36 multipole



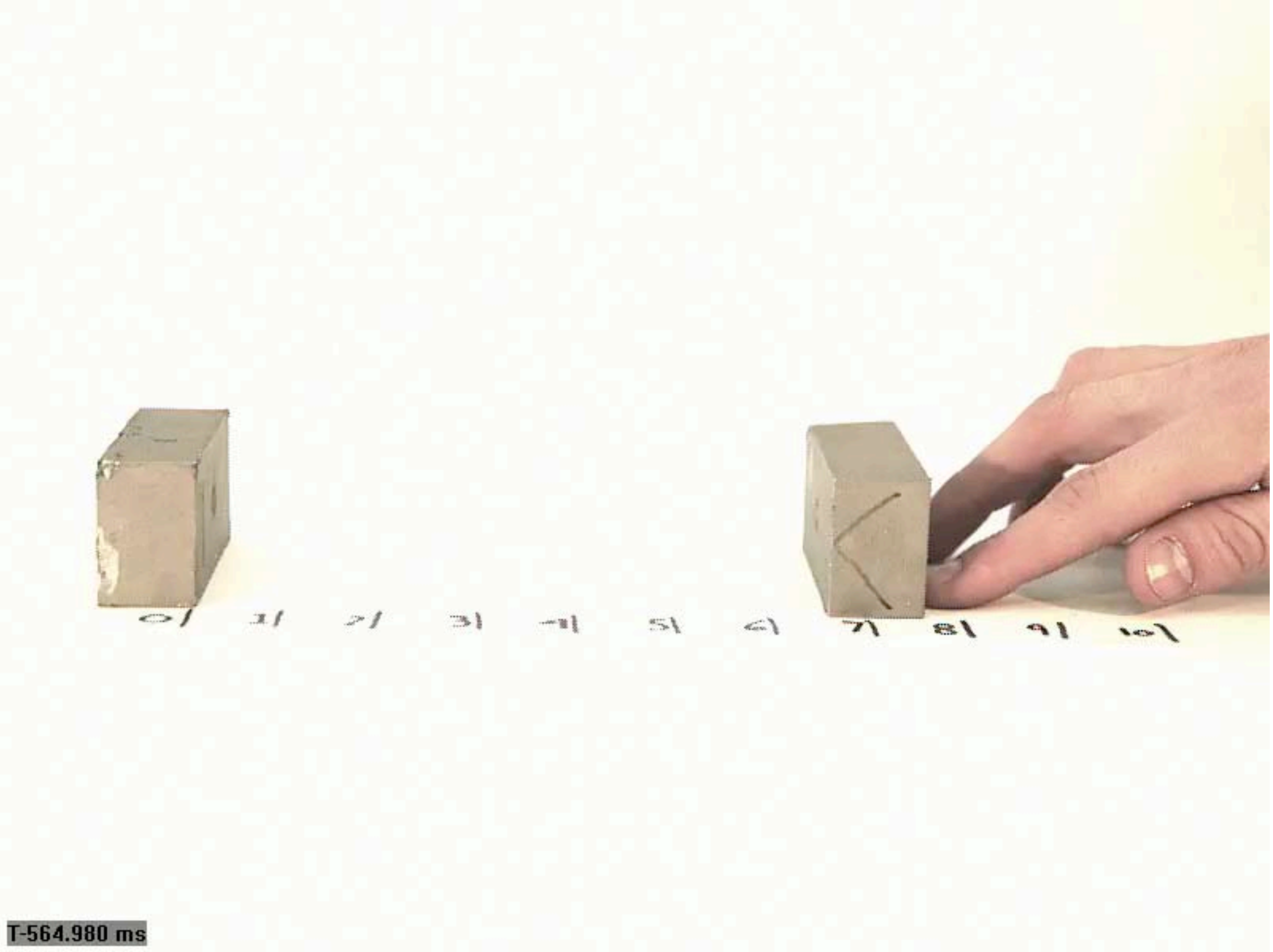
Cusp field cross-section

Cusp loss width: $w_c \approx 4\sqrt{\rho_e \rho_i} = 0.08\ \mathrm{cm}$

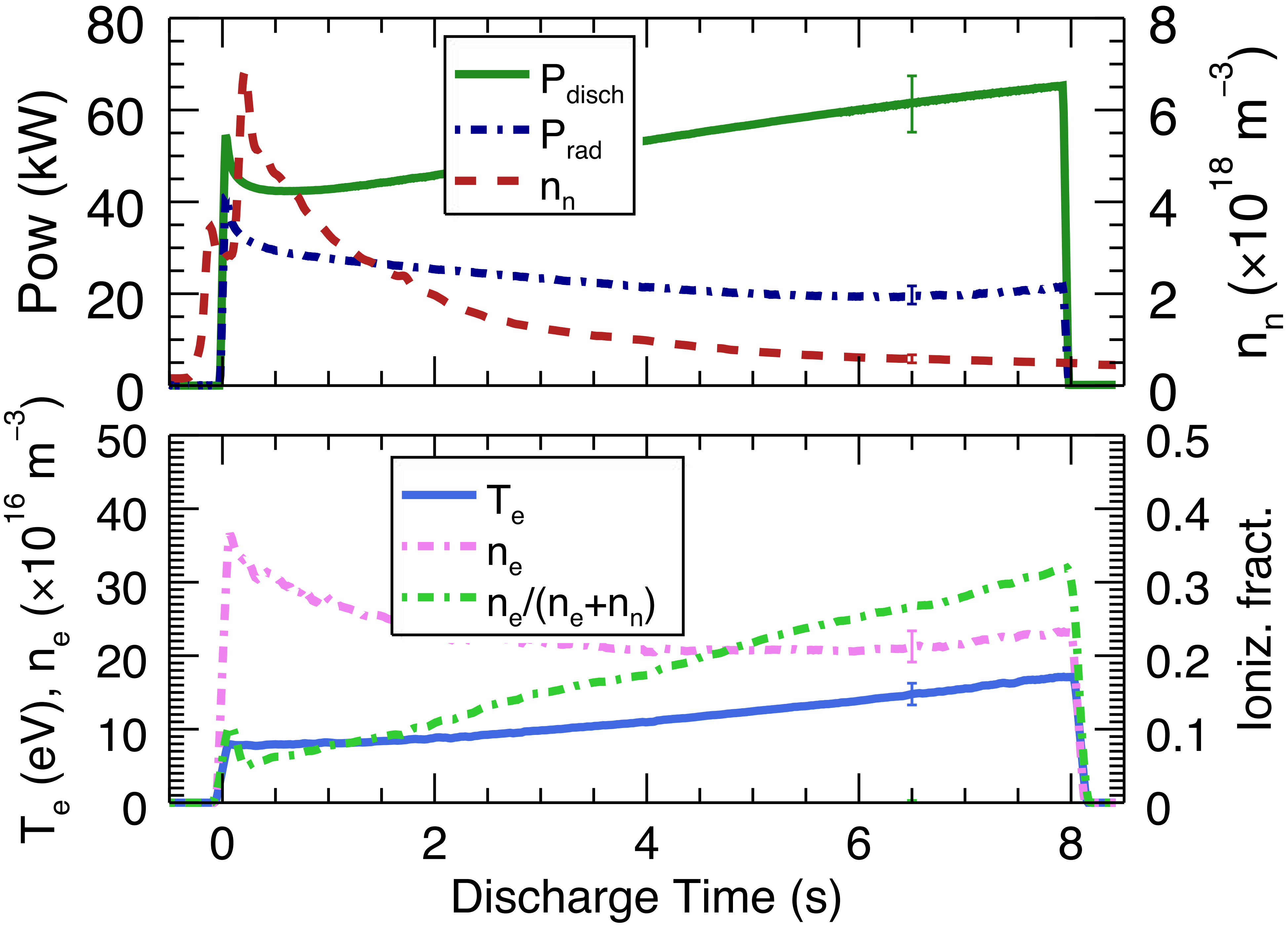


Ceramic limiter tiles show cusp width

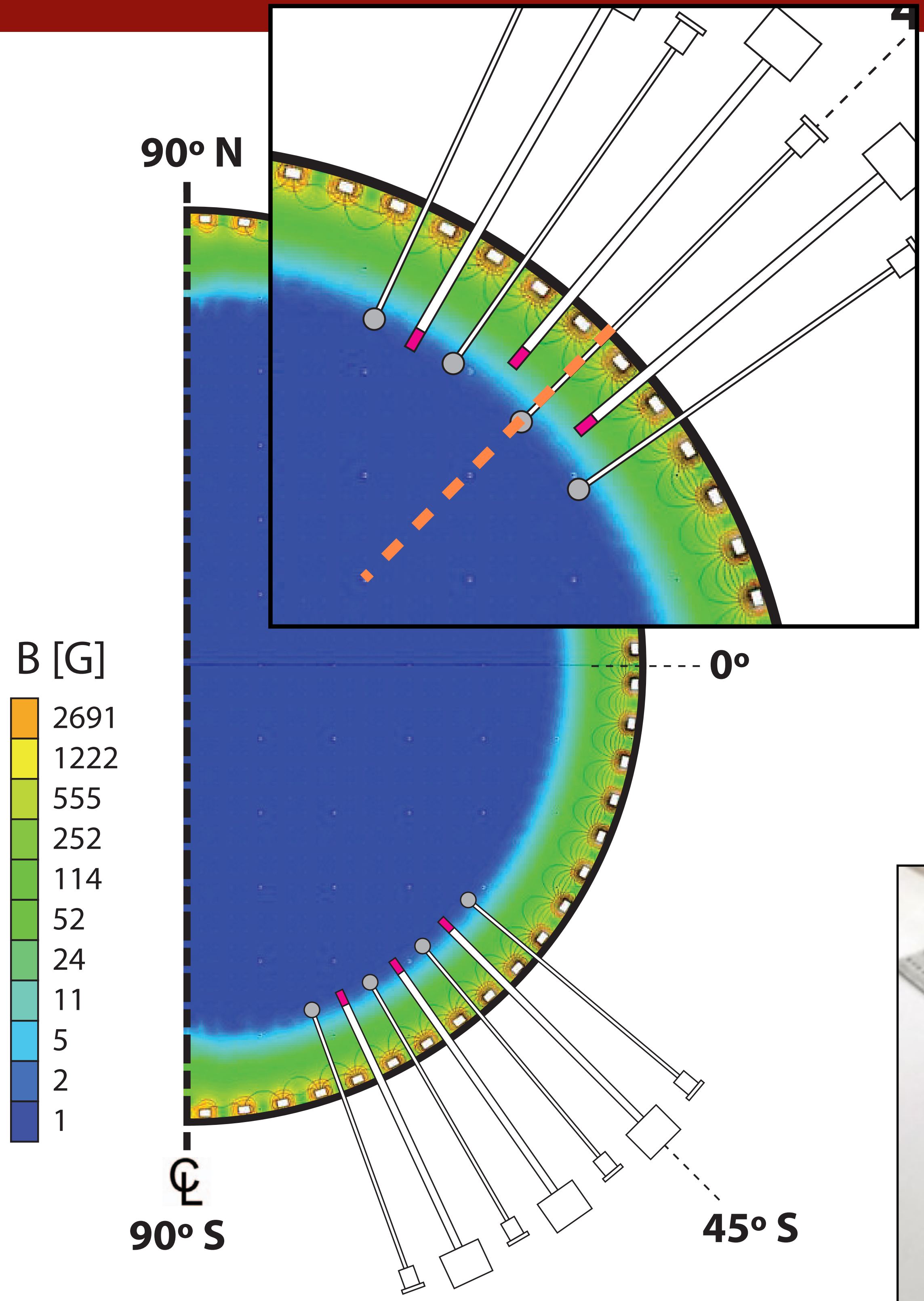
3000 4 kG SmCo magnets

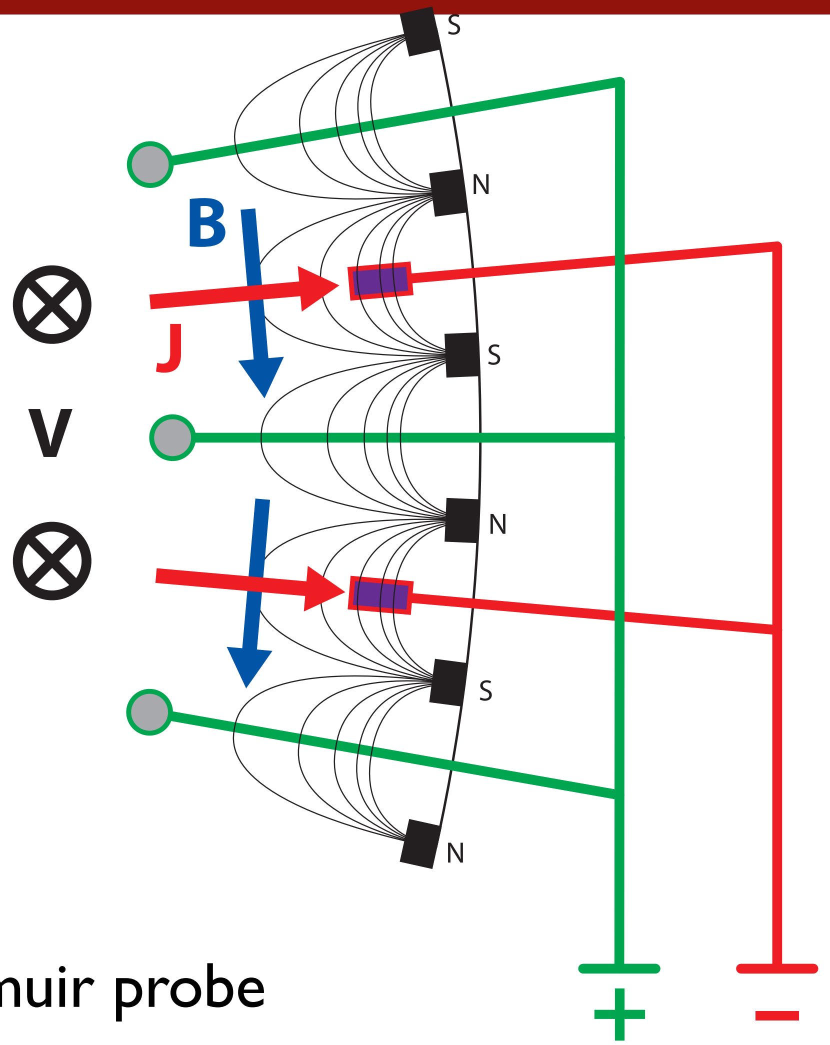

0
1
2
3
4
5
6
7
8
9
10
T-564.980 ms

LONG PULSE, HOT, DENSE, HIGH FRACTIONAL IONIZATION PLASMAS

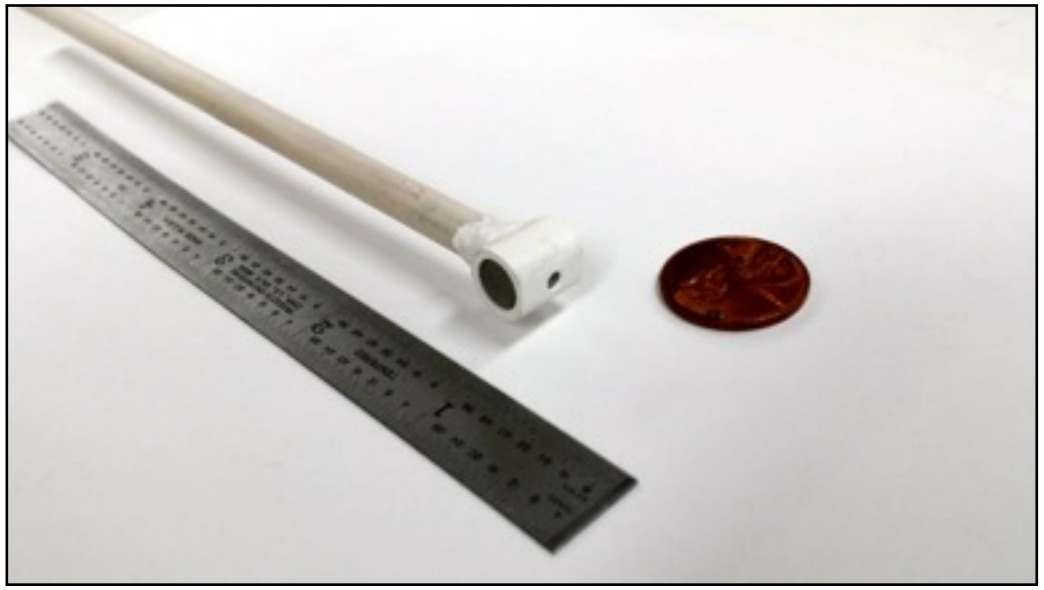


MAGNETIZED CATHODES STIR FROM PLASMA EDGE

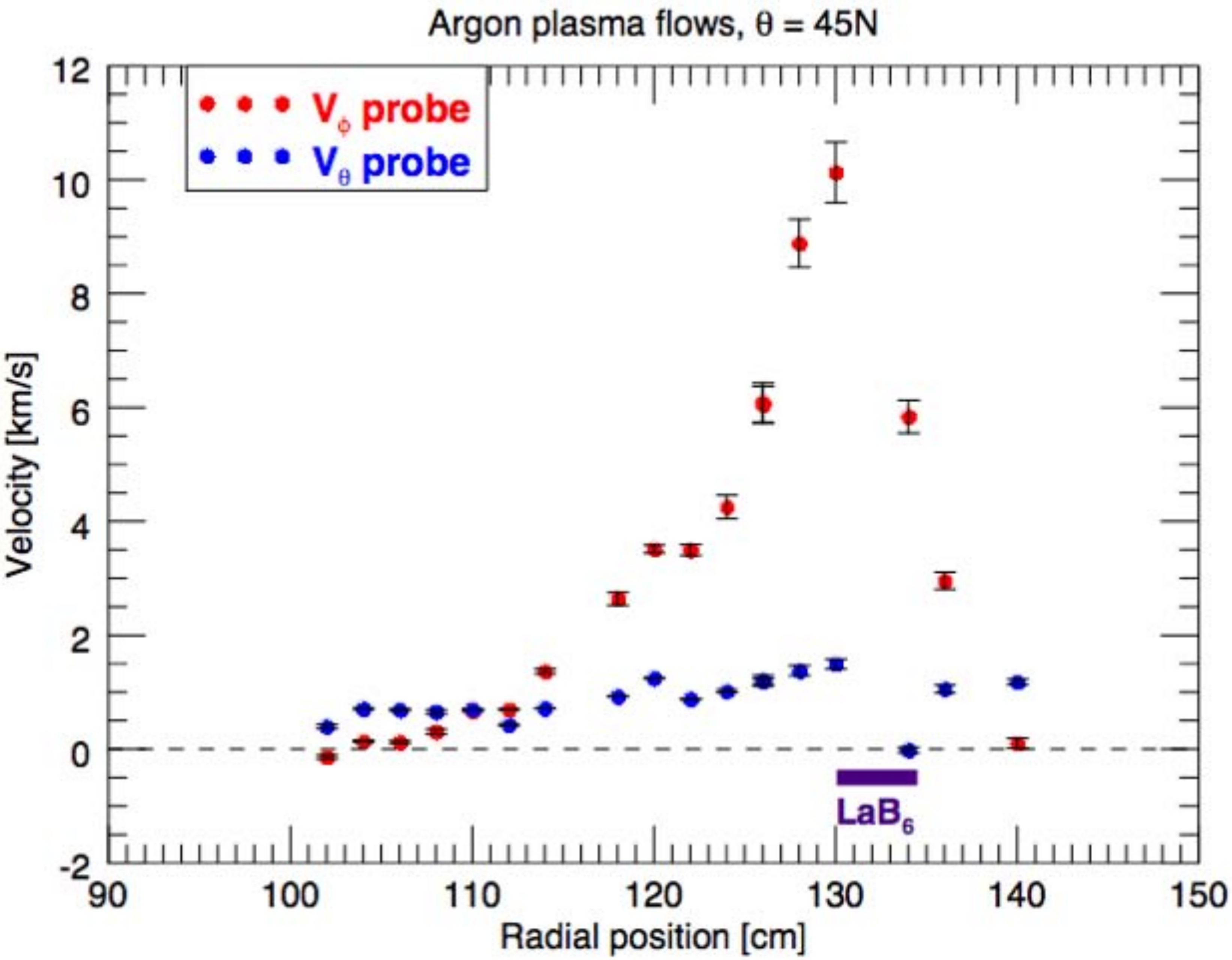


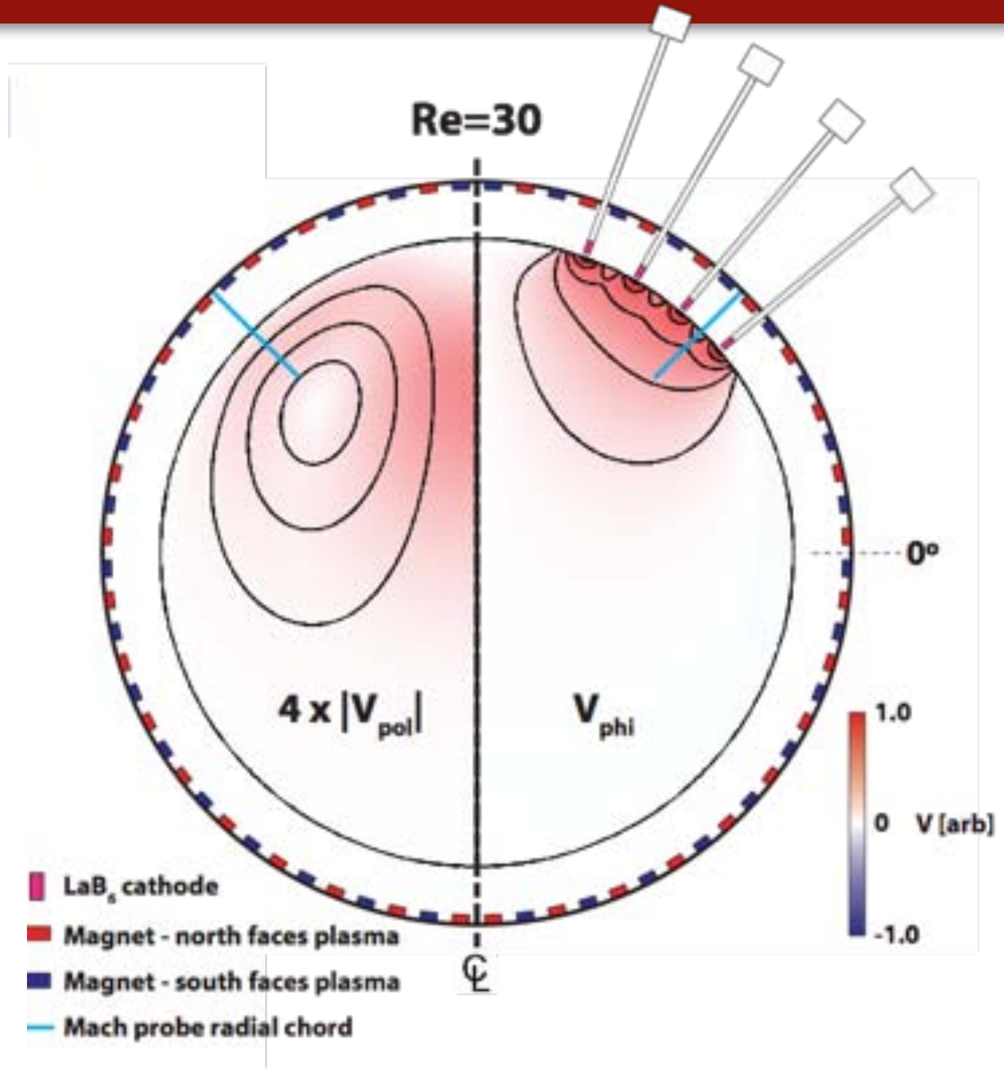


Mach/Langmuir probe

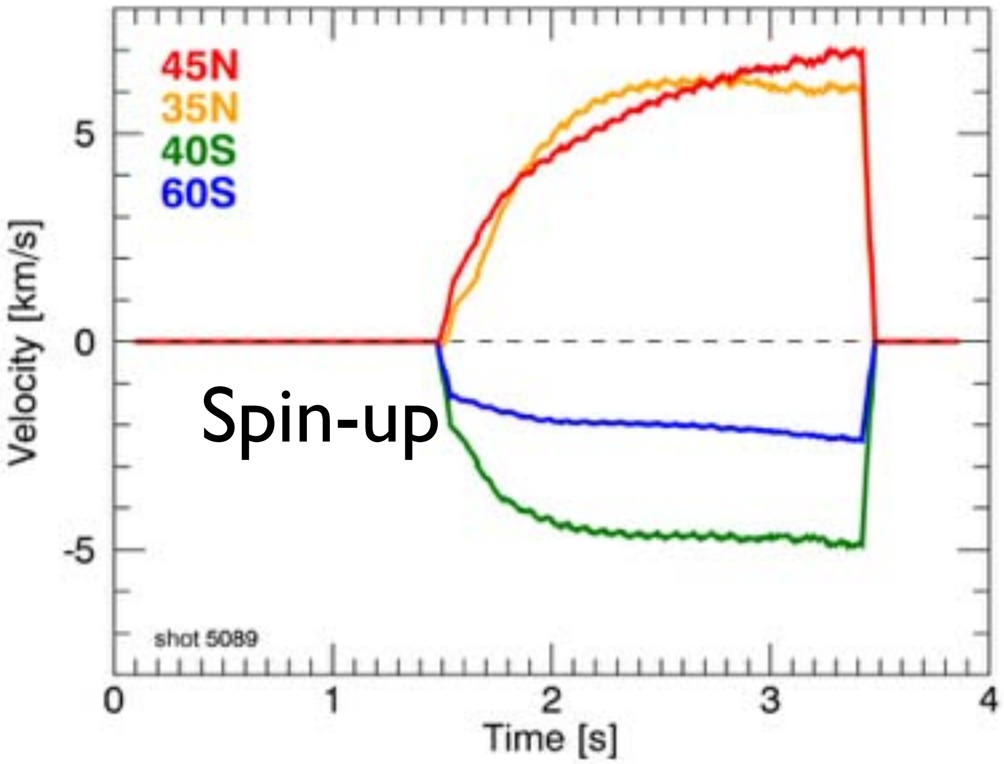


TOROIDAL AND POLOIDAL FLOWS NOW OBSERVED IN PLASMA

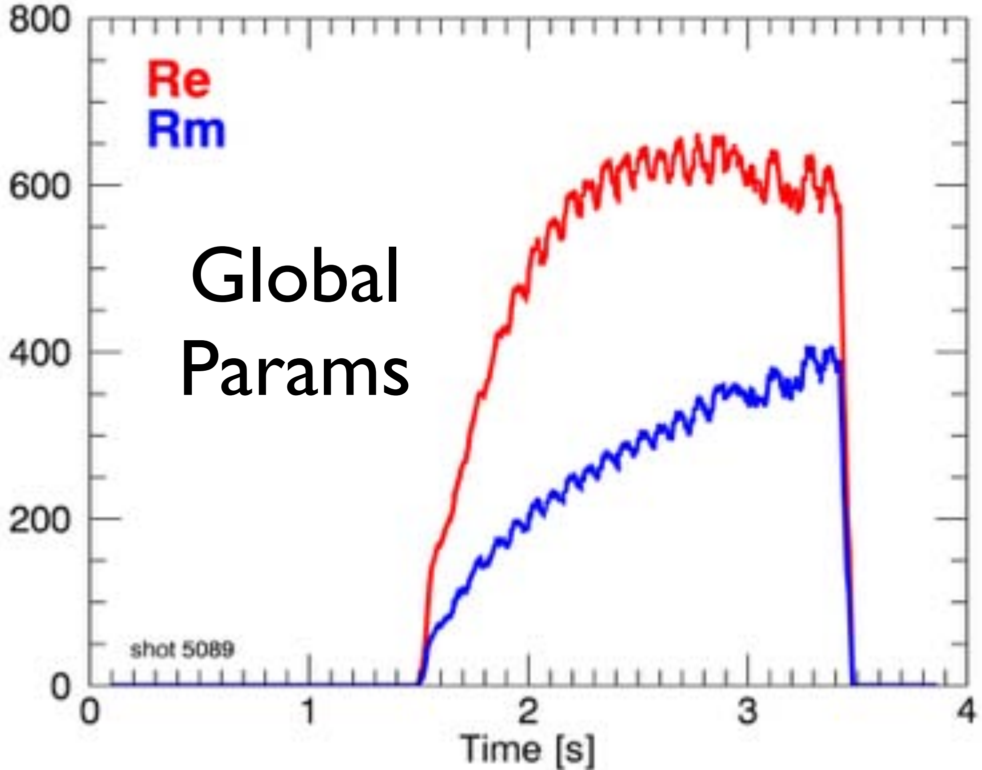




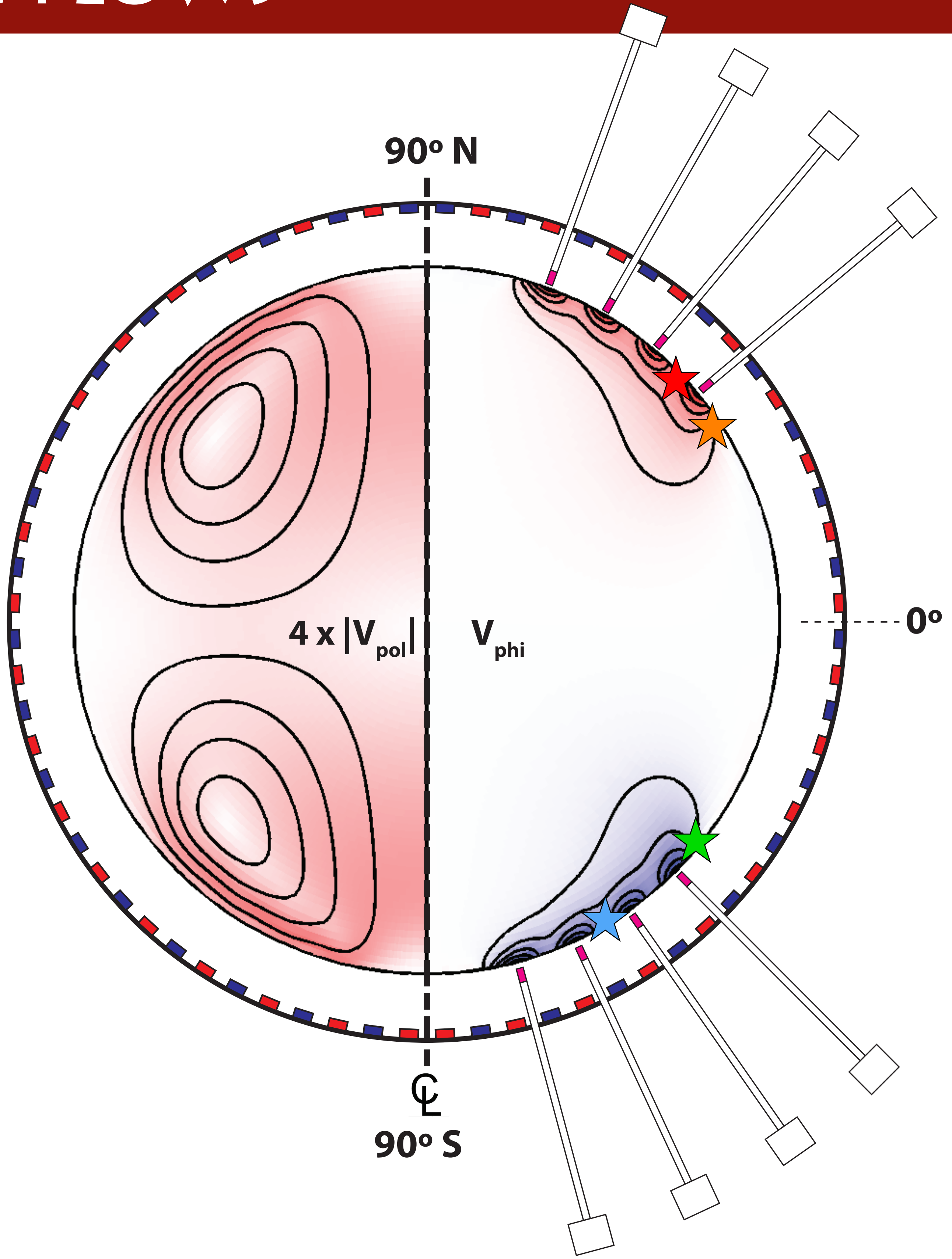
MACH PROBE ARRAY MEASURES COUNTER-ROTATING FLOWS



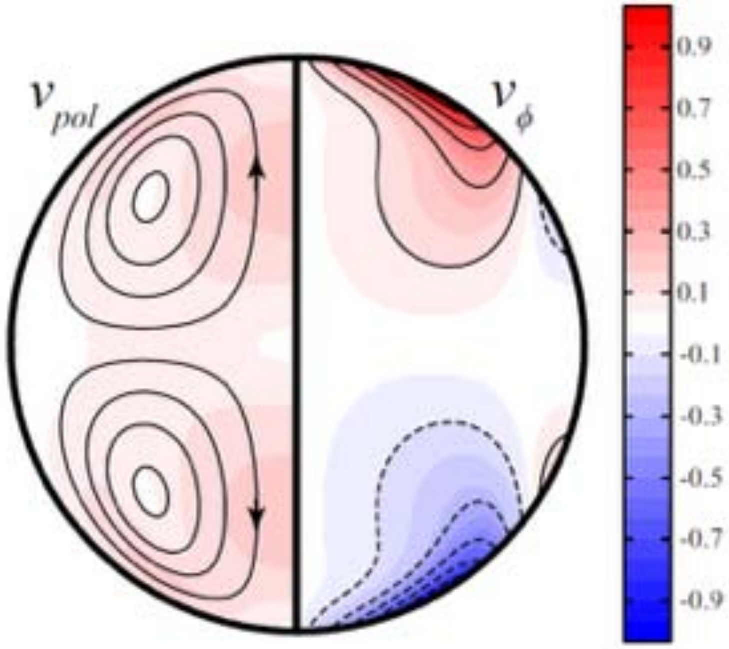
Spin-up

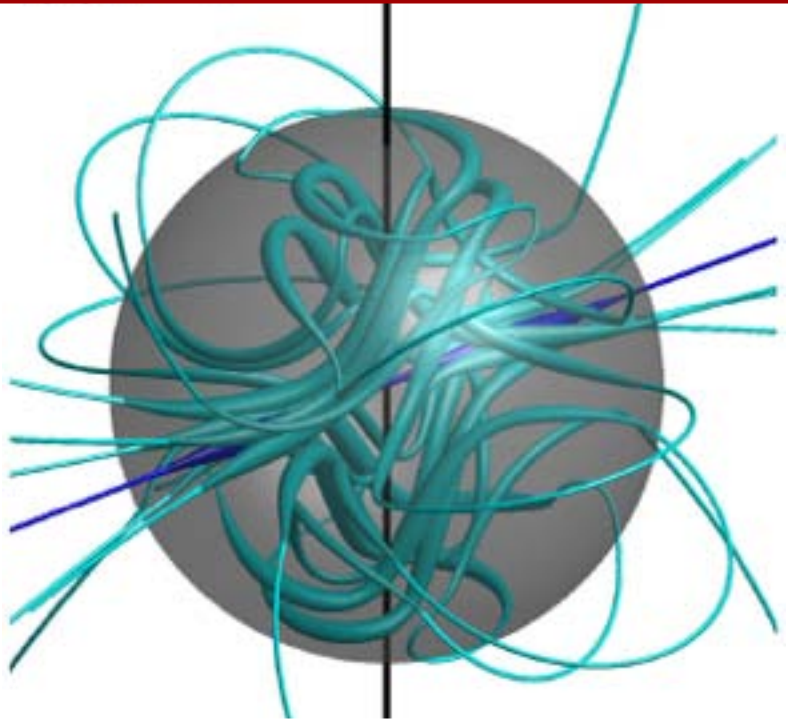


Global Params



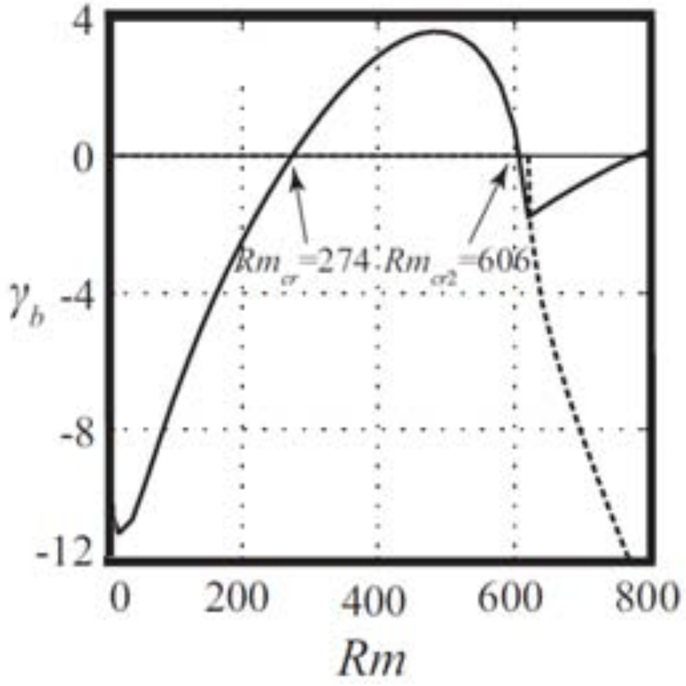
NEXT STEP: 12 CATHODES TO SEARCH FOR A DYNAMO TRANSITION

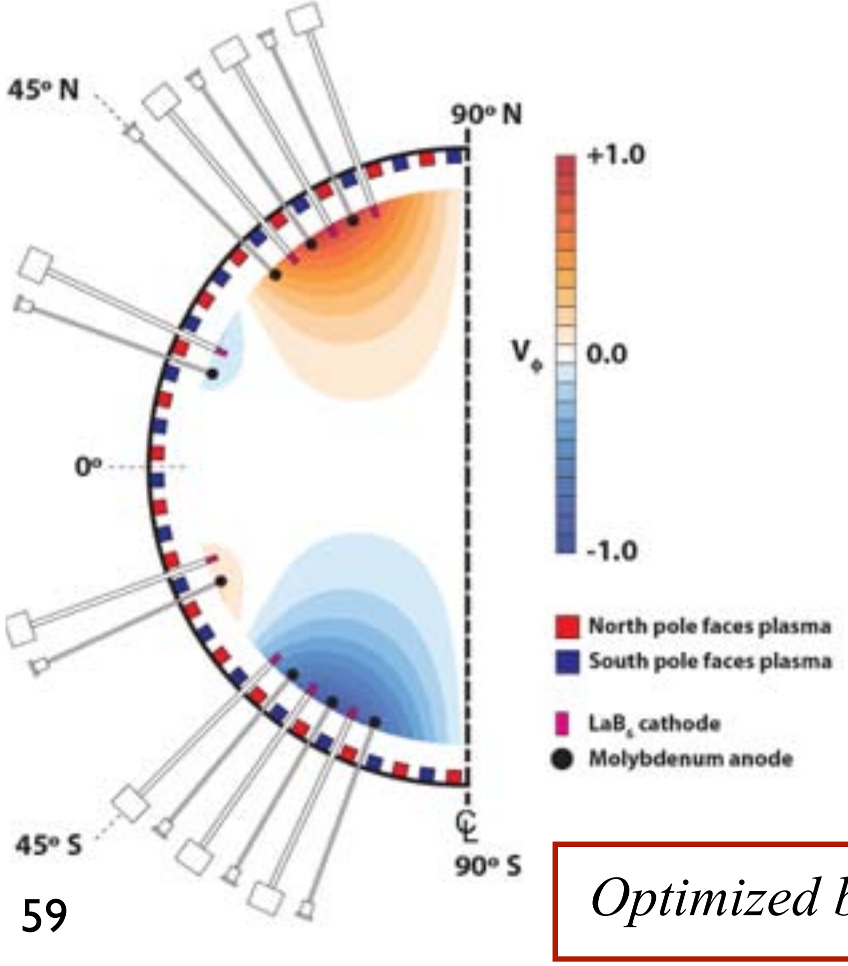




Rm=300

Dynamo growth rate





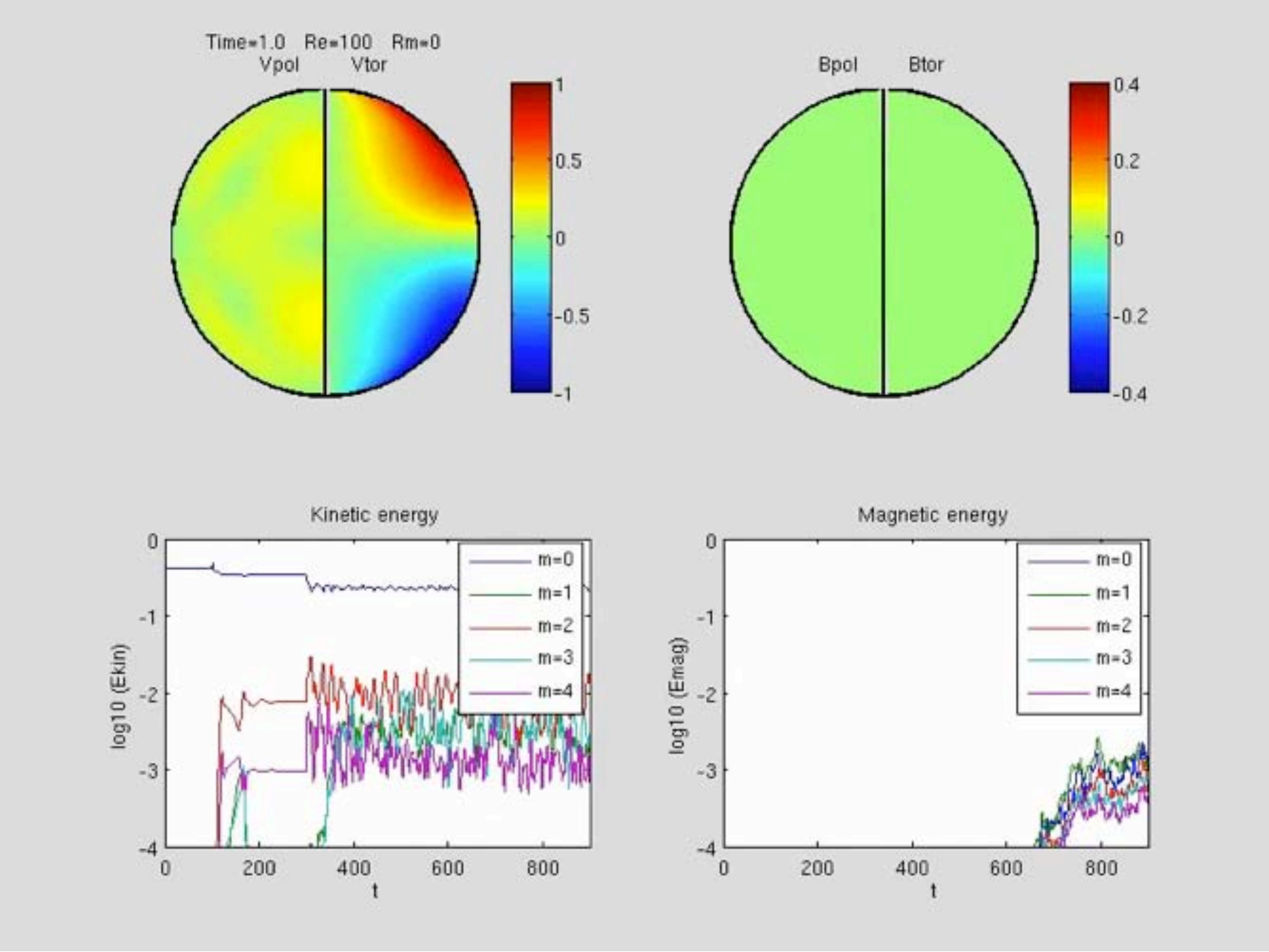
Von Karman type dynamo		
Re=150, Rm=400		
Parameter	Argon	Helium
n_e (1/cm^3)	3X10^{11}	1X10^{12}
T_e (eV)	10	10
power (kW)	100	140
v_{edge} (km/s)	5	6
B_{eqp} (G)	8	5

Steady state flows with DC LaB6 bias set v_φ (θ)

Optimized boundary driven flows for dynamos in a sphere, Phys. Plasmas **19** 112106 (2012).

SMALL SCALE, TURBULENT, FAST DYNAMO IS POSSIBLE (AT HIGH PM)

Re	**Rm**	**V** (km/sec)	**T** eV	**n** (10^{11} cm^{-3})
100	200	3	10	3
200	800	6	17	3
500	5000	10	40	5



SUMMARY

1. Fast, large scale dynamos exist in nature
    1. large scale, fast dynamo remains a theoretical challenge
2. Liquid Metal experiments self-excite under special conditions
    1. Marginally above threshold
    2. require baffles, iron blades
    3. Show Complex Nonlinear dynamics
    4. trivial saturation mechanisms
3. Liquid metal experiments exhibit turbulent resistivity
4. Plasma Dynamos Experiments now operational
    1. Operating now at high Rm, variable Pm
    2. Flow optimization underway

Thank You!