Collisionless plasma dynamo

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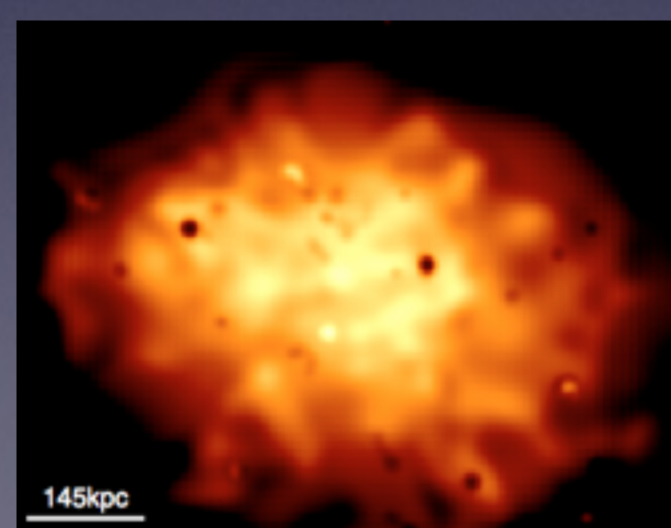
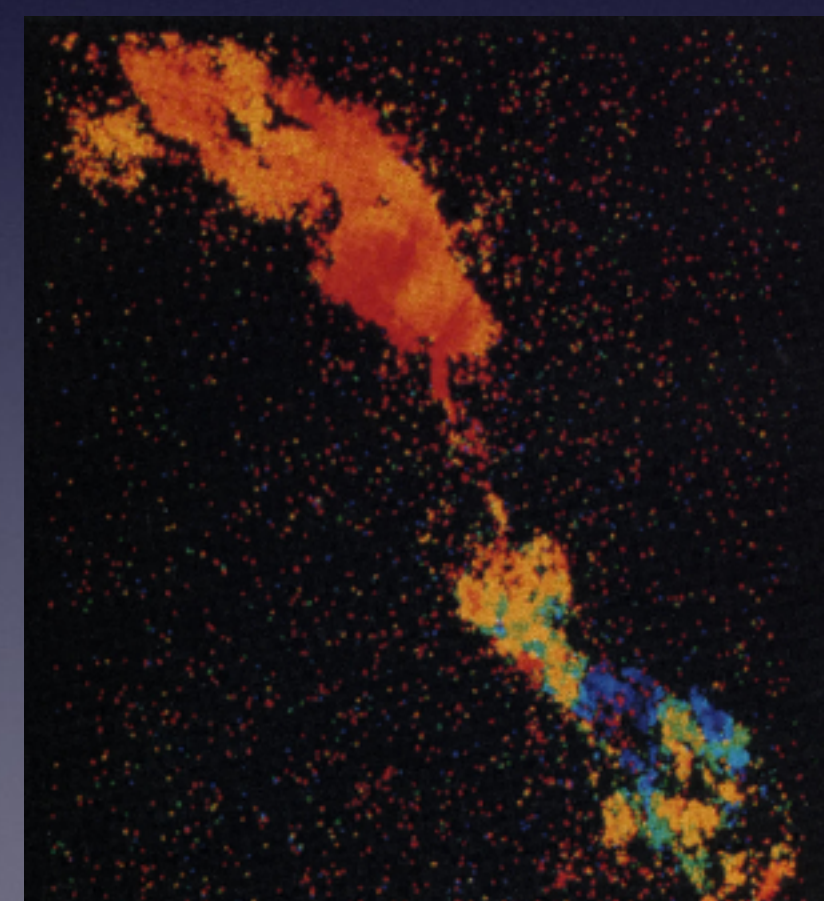
Acknowledgements:
S. Cowley, M. Kunz, C. Cavazzoni



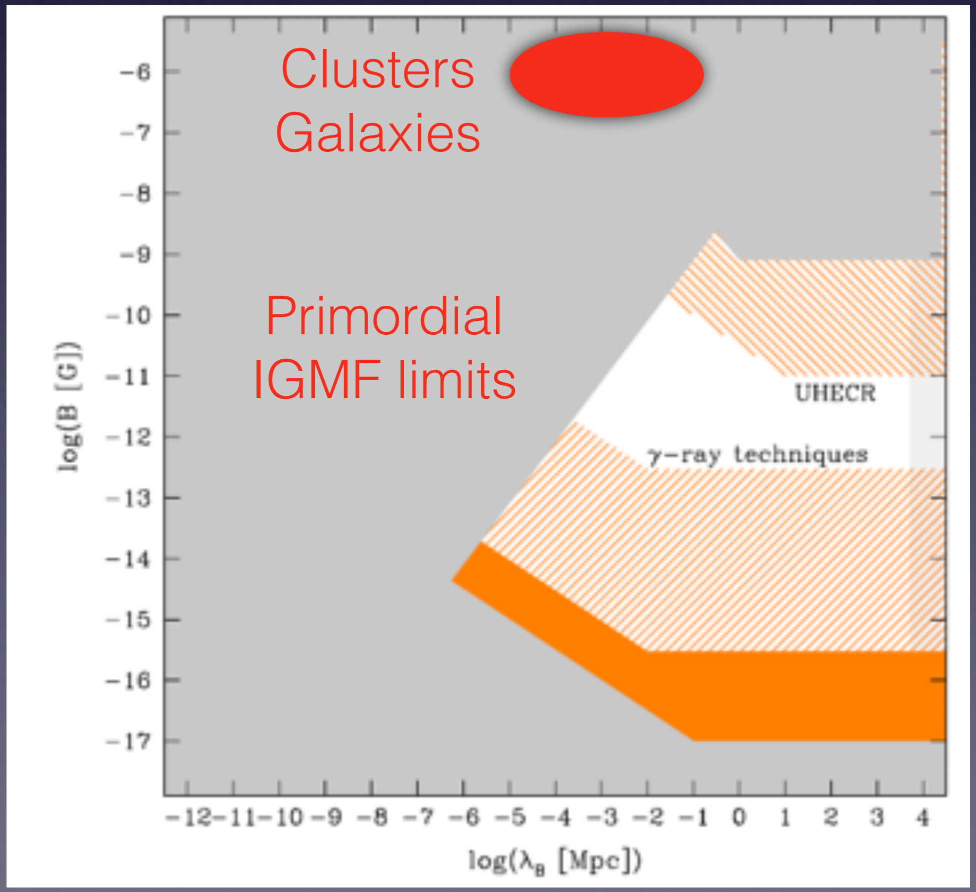


[PNAS, 113, 3950 (2016)]

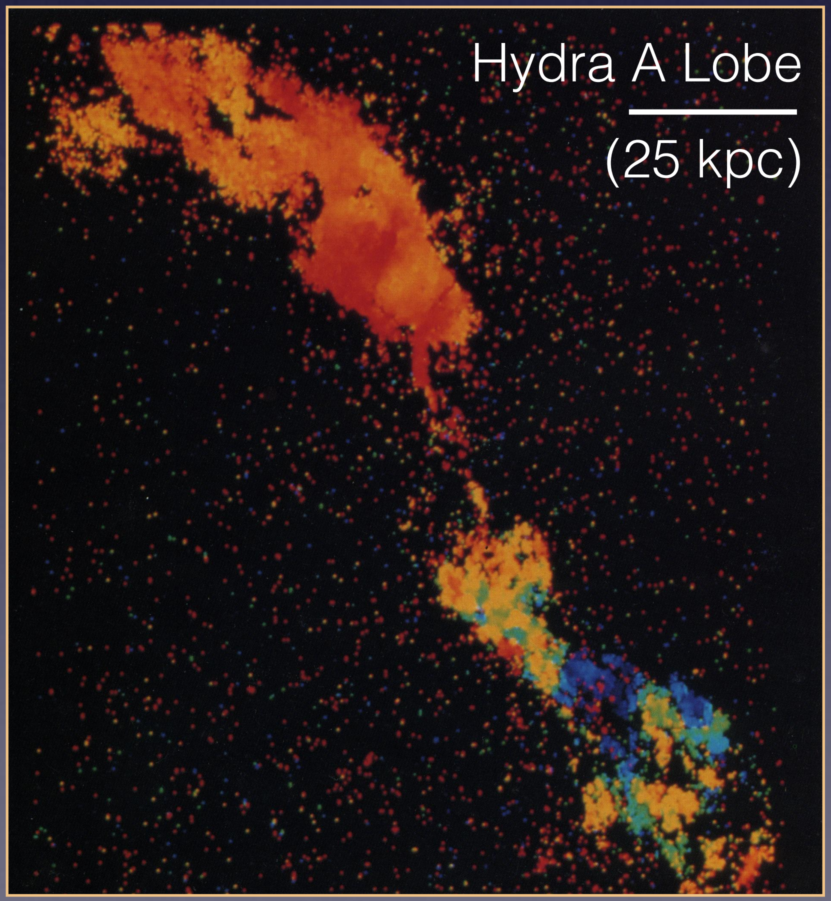
SF2A, June 2016

Cosmic magnetogenesis

- How are magnetic fields generated on cosmic scales ?
  - Magnetic seeds in the early Universe: $10^{-21}(-10^{-9}\ ?)$ G
  - ICM fields: 1-40 μG at fairly large (~ 1-10 kpc) scales
  - Constraint: 5-15 fold increase on a few Gyr



Durrer & Neronov, A&A Rev. 2013



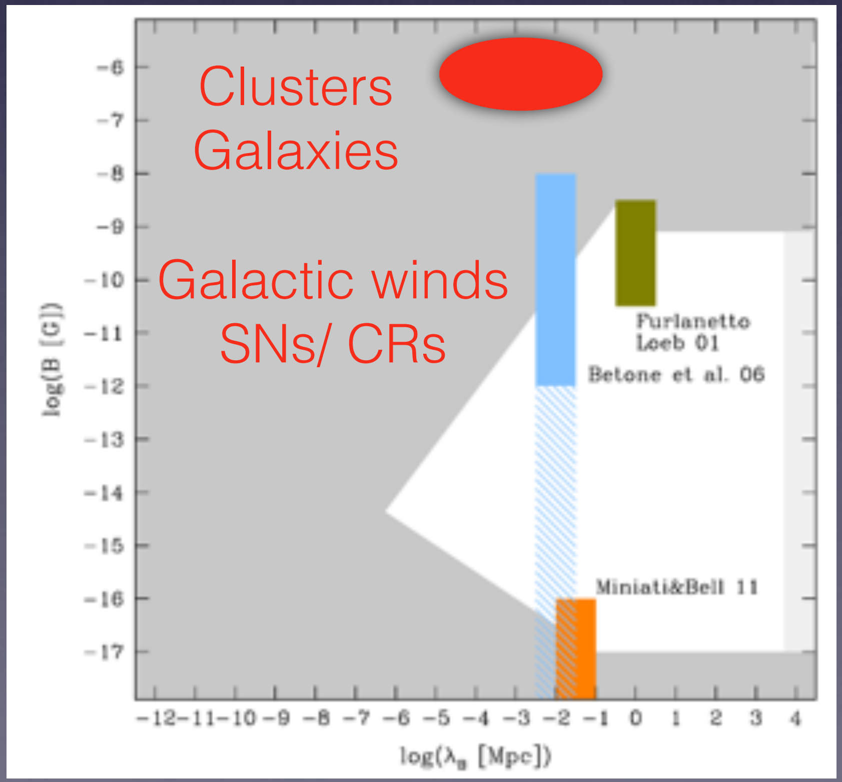
Taylor & Perley, ApJ 1993

ICM magnetic fields

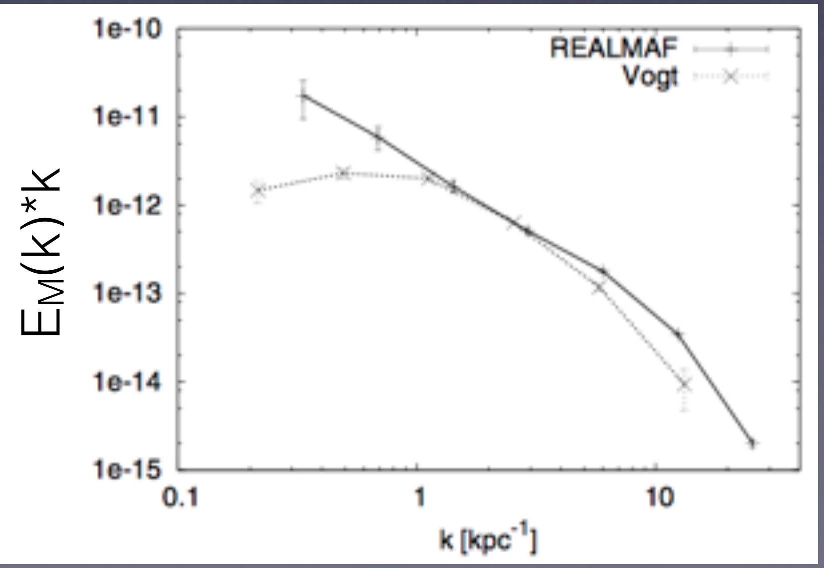
- How do you make microGauss fields at 1-100 kpc scales ?

- Different processes invoked
  - Magnetization via galactic outflows and jets
  - Collisionless shocks in ICM / filaments
  - Dynamo effect throughout cosmic times

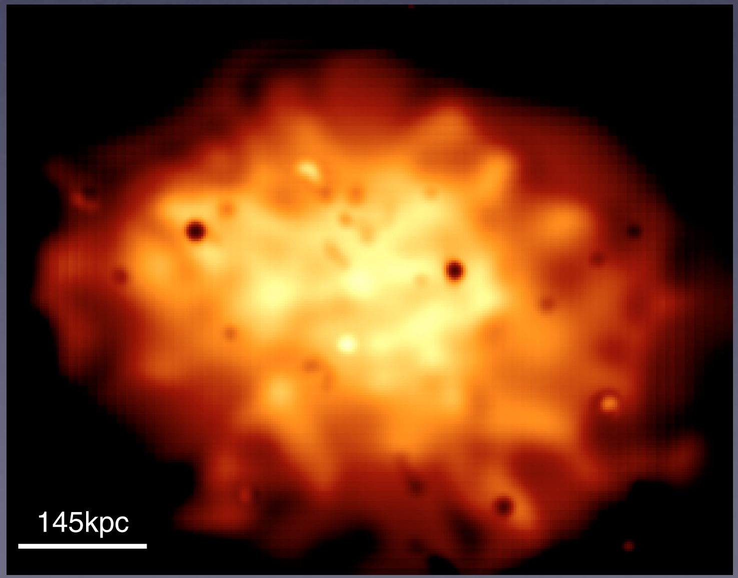
- Is turbulence (T~10-100 Myr) in the ICM or filaments a good dynamo ?



Durrer & Neronov, A&A Rev. 2013



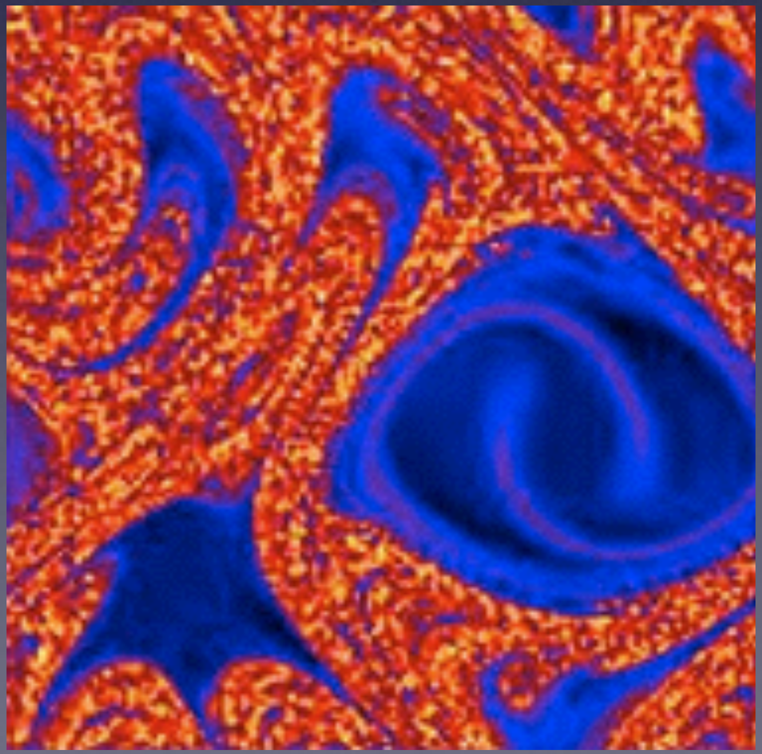
Kuchar & Ensslin, A&A 2011

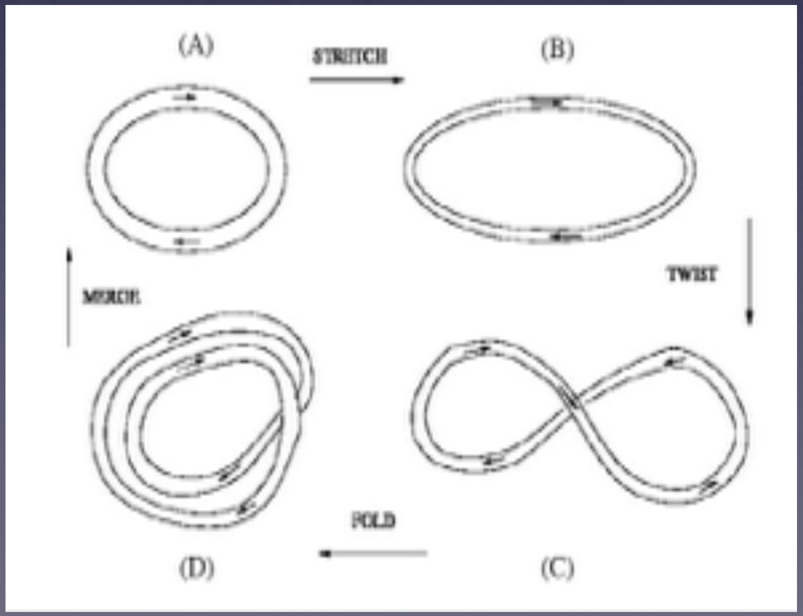


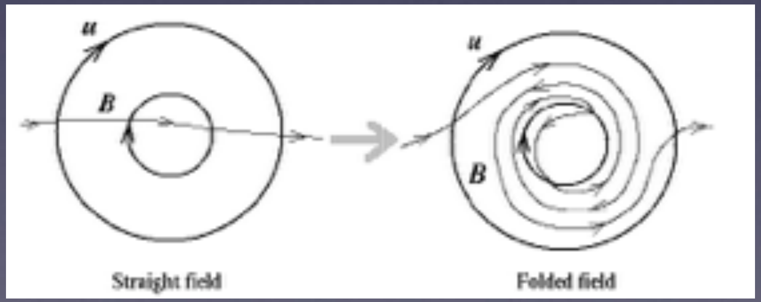
Schueker et al., A&A 2004

Turbulent “small-scale” dynamo

- Homogeneous, isotropic, non-helical, incompressible, chaotic flow of conducting fluid is a dynamo flow
  - Batchelor-Moffatt-Zeldovich’s stretch-fold mechanism
  - All you need is a smooth 3D chaotic flow, viscous flow can do the job







First evidence in 3D MHD simulations

Helical and Nonhelical Turbulent Dynamos

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(Received 13 April 1981)

Direct numerical simulations of three-dimensional magnetohydrodynamic turbulence with kinetic and magnetic Reynolds numbers up to 100 are presented. Spatially intermittent magnetic fields are observed in a flow with nonhelical driving. Small-scale helical driving produces strong large-scale nearly force-free magnetic fields.

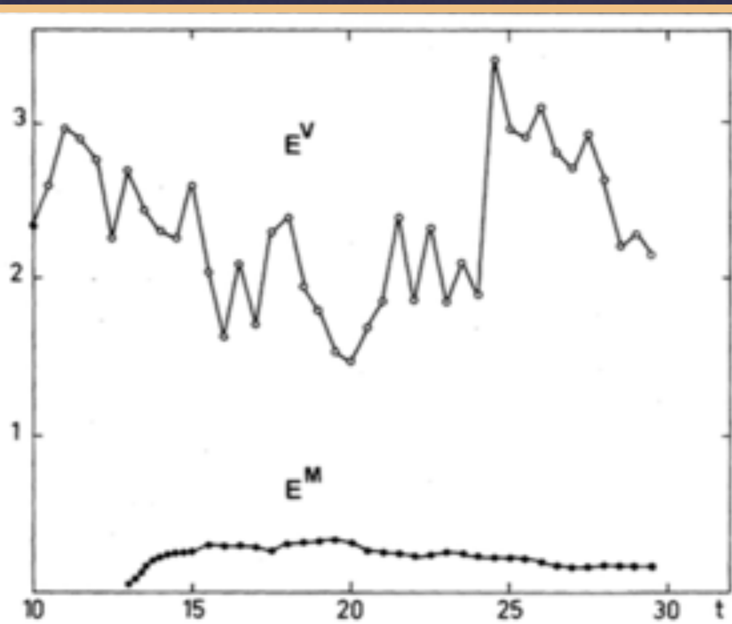


FIG. 1. Turbulent dynamo with nonhelical driving. Temporal variation of kinetic (E^V) and magnetic (E^M) energy. Reynolds numbers are $R^V = R^M \approx 100$. The time unit is the eddy-turnover time l_0/v_0.

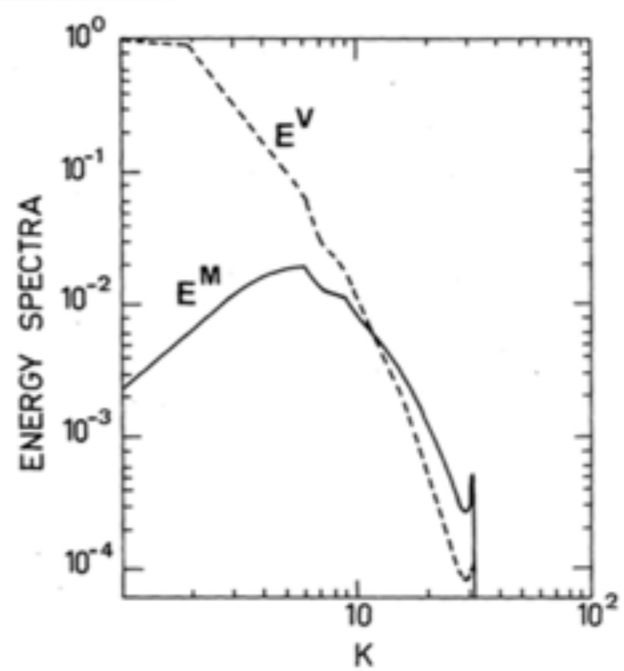
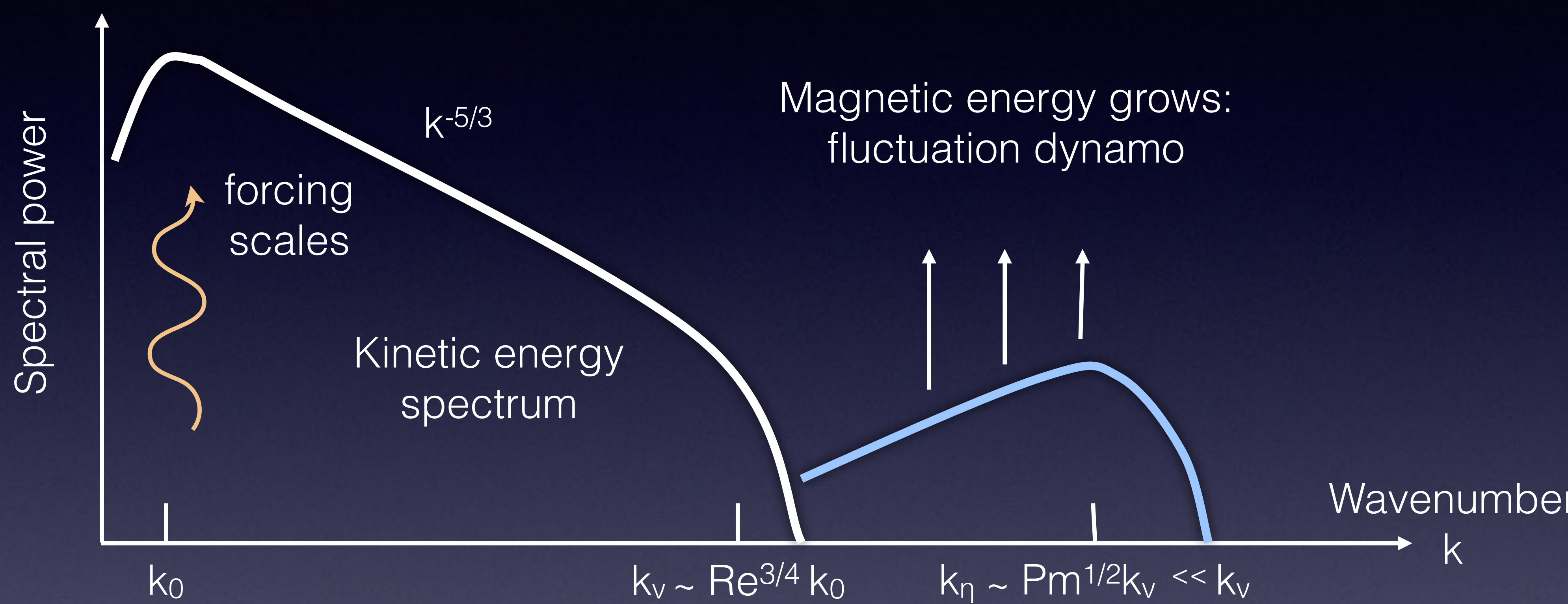


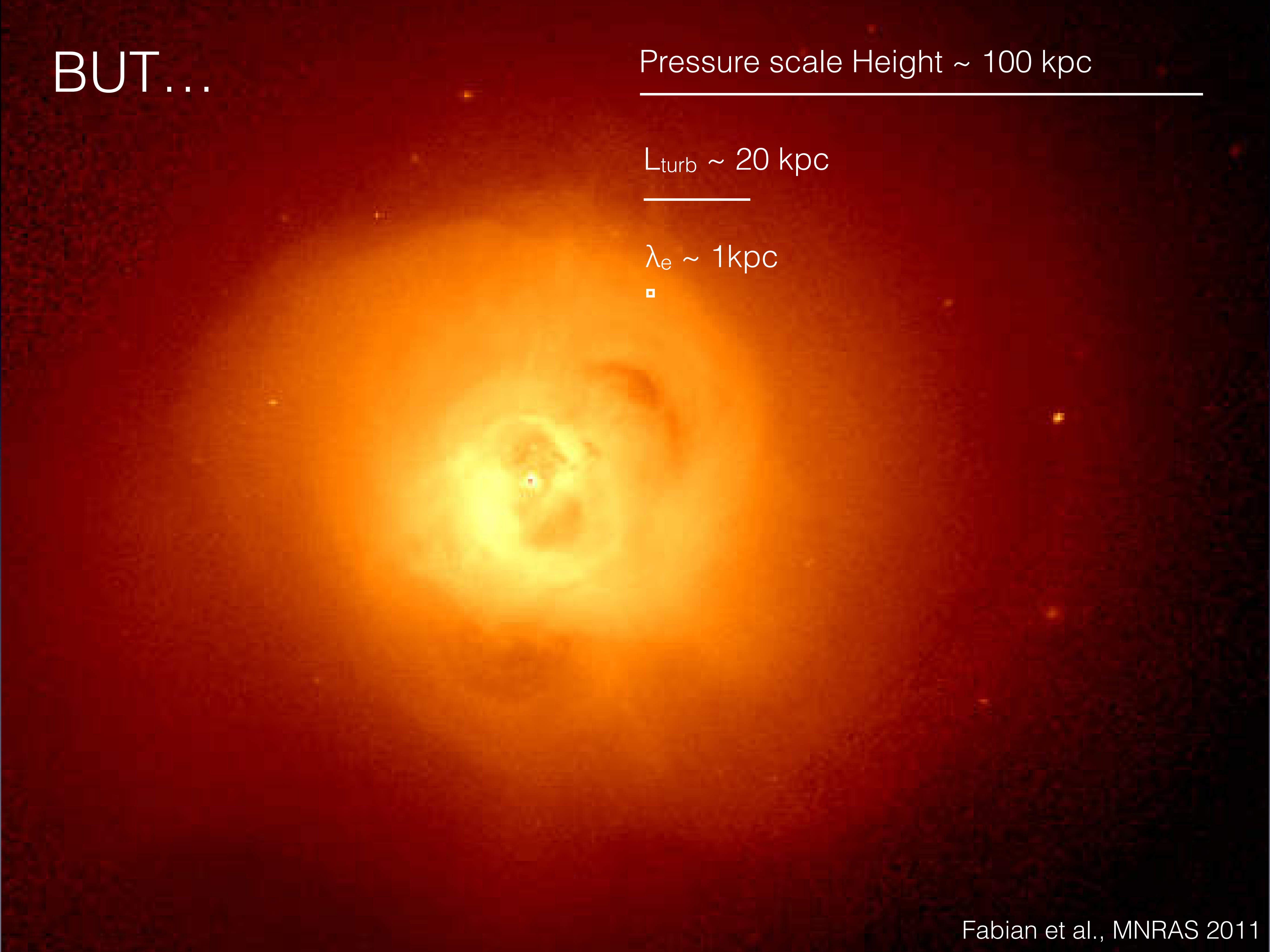
FIG. 2. Kinetic (E^V) and magnetic (E^M) energy spectra at $t = 27$. Nonhelical dynamo with $R^V = R^M \approx 100$.

Large magnetic Prandtl number regime

- In such a fluid, the dynamo field grows at small scales



- Naive ICM "MHD" parameters
  - Collisional viscosity estimate: Re ~ UL/ν ~ 10-100
  - Spitzer conductivity: Rm ~ UL/η ~ 10^{29} or more
  - Magnetic Prandtl number Pm ~ ν/η ~ $10^{28\text{-}30}$



Fabian et al., MNRAS 2011

What about weakly-collisional plasmas ?

- So far, dynamo has only been demonstrated in MHD fluids
  - Many high-energy astrophysical plasmas are not MHD fluids

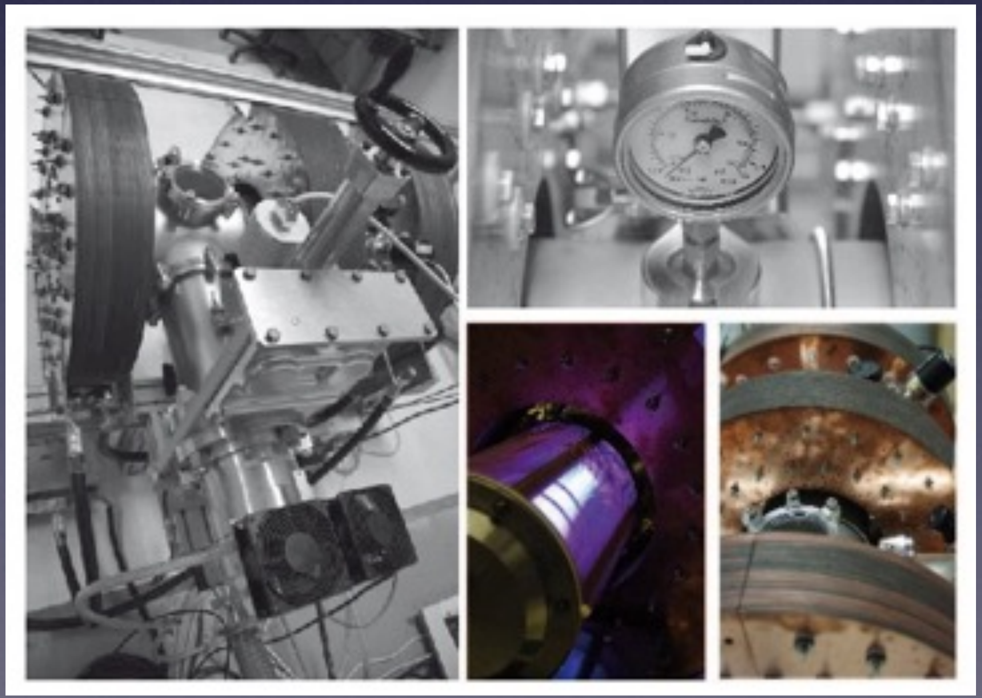
- ICM plasma regime
  - Dynamical/injection scales ~ $10^{17\text{-}18}$ km ~ 10 - 100 kpc (T~10-100 Myr)
  - Mean free path ~$10^{16\text{-}17}$ km ~ 1-10 kpc
  - Larmor radii ~ 10^4 km

- Coupled "fluid-" and "kinetic-scale" phenomena
  - Large-scale dynamics: MTI, HBI, AGN, mergers, dynamo ?
  - Collisionless damping, magnetization effects (pressure anisotropies)

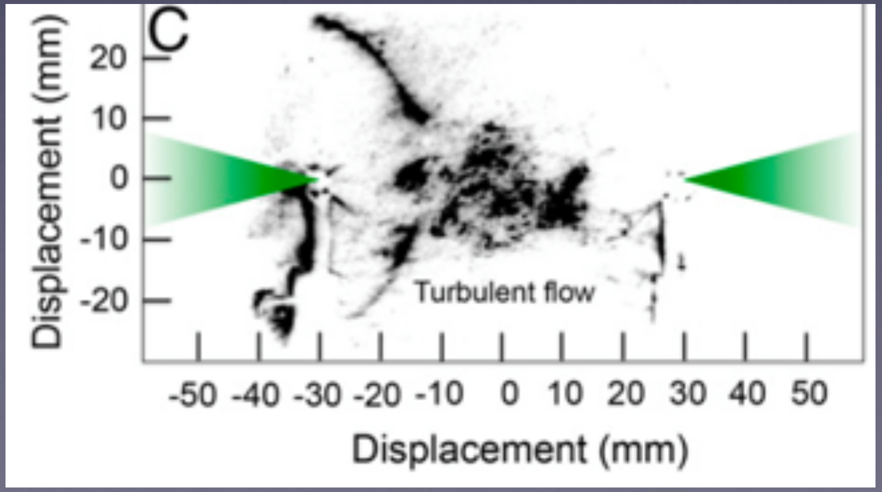
Plasma dynamo: an experimental quest in progress

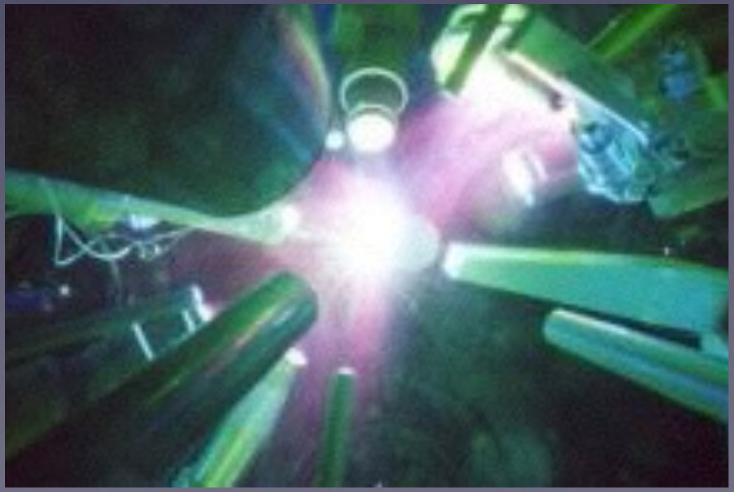
Madison Plasma Dynamo Experiment @U. Wisconsin

Turbulent Plasma experiment
@ ENS Lyon



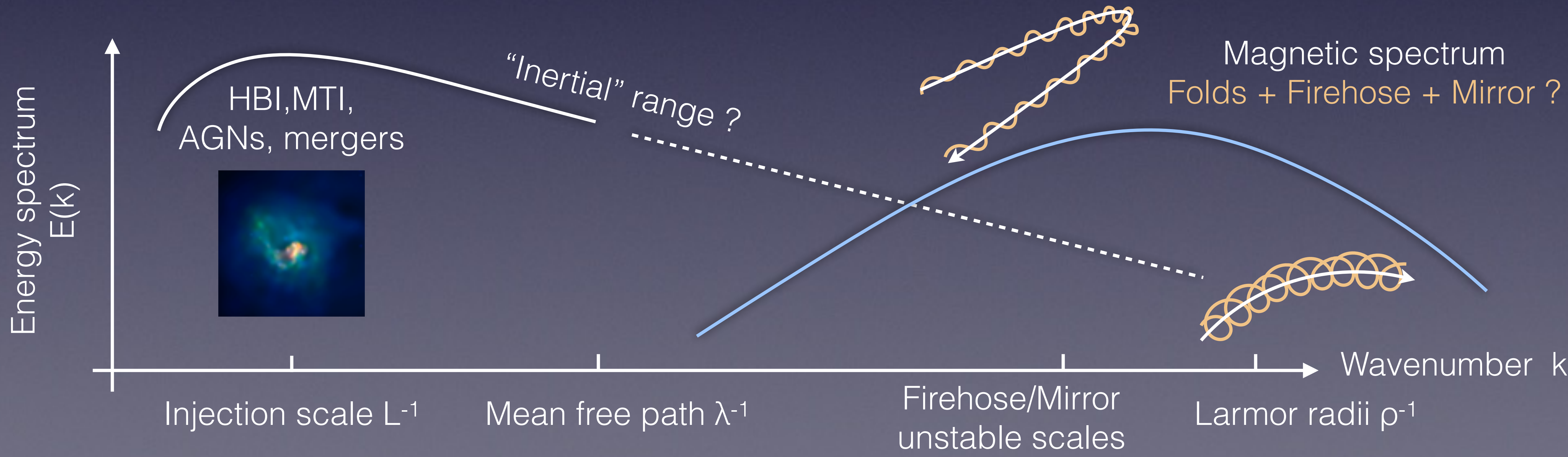
Oxford Laser Plasma group
(Gregori, Meinecke et al., PNAS 2015)





Collisionless plasma dynamo problem

- The most efficient eddies are the smallest, fastest ones
  - In the ICM, such plasma motions are weakly collisional
- Plasma is magnetised well below equipartition (ICM: 10^{-13} G)
  - Field-stretching motions (= dynamo !) generate pressure anisotropy
  - Pressure-anisotropy driven instabilities !

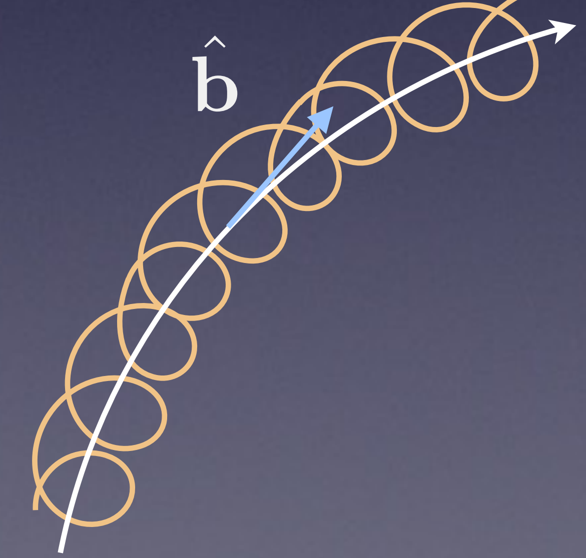


Pressure anisotropy generation

- In a magnetized, weakly collisional plasma
  - The pressure is an anisotropic tensor with respect to the direction of B
  - $\mu_s = m_s v_\perp^2 / 2B$ is almost conserved
- Large-scale, field-stretching motions generate pressure anisotropy
  - Collisions tend to relax it

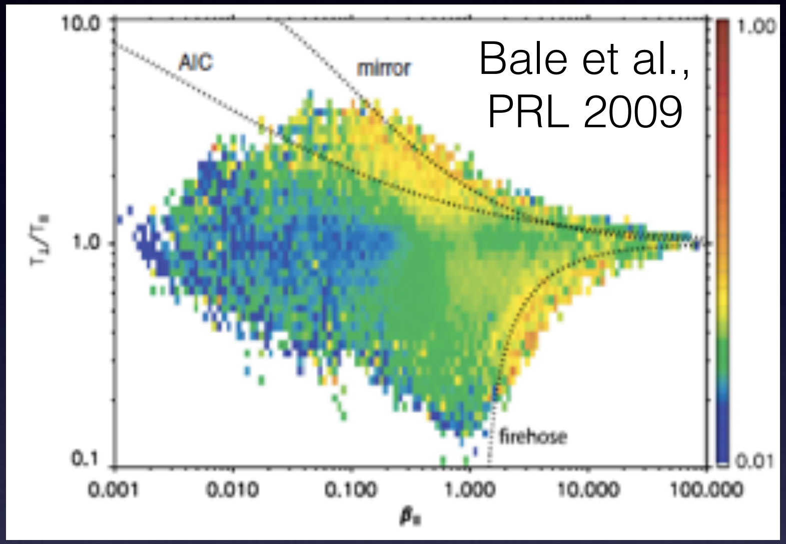
$$\frac{1}{p_\perp}\frac{\mathrm{d}p_\perp}{\mathrm{d}t} \sim \frac{1}{B}\frac{\mathrm{d}B}{\mathrm{d}t} - \nu_{ii}\frac{p_\perp - p_\parallel}{p}$$

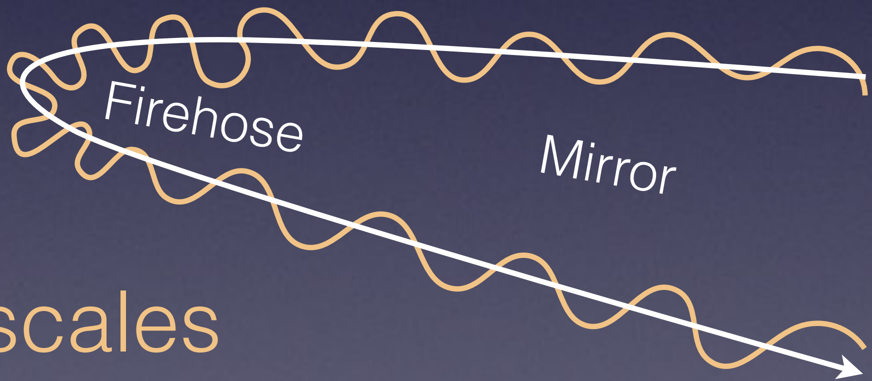
$$\frac{1}{B}\frac{\mathrm{d}B}{\mathrm{d}t} = \hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla \mathbf{u}$$



Pressure anisotropy-driven instabilities

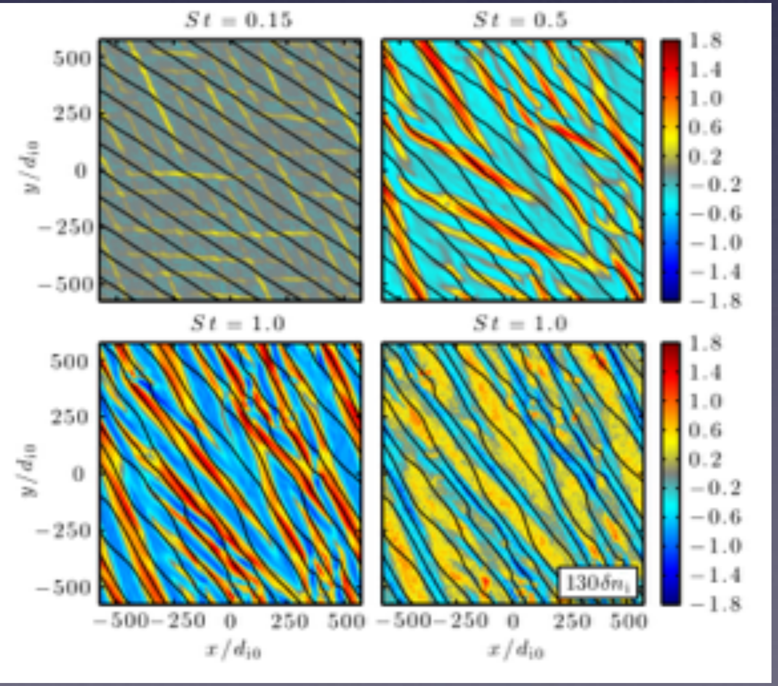
- $\mu = mv_\perp^2/2B$ conservation implies kinetic instability everywhere
  - local increase of |B| —> increase of $p_\perp$
    - mirror instable $\quad \dfrac{p_\perp - p_\parallel}{p_\perp} > 1/\beta$
  - local decrease of |B| —> decrease of $p_\perp$
    - firehose instable $\quad \dfrac{p_\perp - p_\parallel}{p_\perp} < -2/\beta$





- Small, fast scales
  - ICM: ρ_i ~ 10^4 km, Ω_i^{-1} ~ second
- Feedback non-linearly on "fluid" scales

Scheckochihin et al, ApJ 2005, Schekochihin et al., PRL 2008; Rosin et al., MNRAS 2011; Rincon et al., MNRAS 2015



Kunz et al., PRL 2014

Collisionless plasma dynamo problem(s)

- Unmagnetized problem: $\rho_i/L > 1$
  - Is a collisionless, unmagnetized 3D chaotic flow of plasma a good dynamo ?
- Magnetized problem: $\rho_i/L < 1$
  - How do pressure-anisotropy kinetic instabilities interfere with magnetic growth ?
- Annoying "details"
  - Dynamo is a fundamentally 3D process in physical space (Cowling)
  - No rigid "guide" field here: kinetic description "3V" in velocity space
- Modelling requires 3D-3V simulations (+time integration !)
  - Very costly: O(10^6-10^7 CPU hours) per simulation
  - Use simplest possible appropriate kinetic model

Forced hybrid Vlasov-Maxwell system

- Kinetic, collisionless ions (initially Maxwellian)

$$\frac{\partial f_i}{\partial t} + \mathbf{v} \cdot \nabla f_i + \left[\frac{e}{m_i} \left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c} \right) + \frac{\mathbf{F}}{m_i} \right] \cdot \frac{\partial f_i}{\partial \mathbf{v}} = 0$$

- Isothermal, fluid massless electrons

$$\mathbf{E} = -\frac{T_e \nabla n_e}{e n_e} - \frac{\mathbf{u}_e \times \mathbf{B}}{c} + \frac{4\pi\eta}{c^2}\mathbf{j}$$

$$\mathbf{u}_e = \mathbf{u}_i - \mathbf{j}/(e n_e) \qquad \mathbf{j} = (c/4\pi)\, \nabla \times \mathbf{B}$$

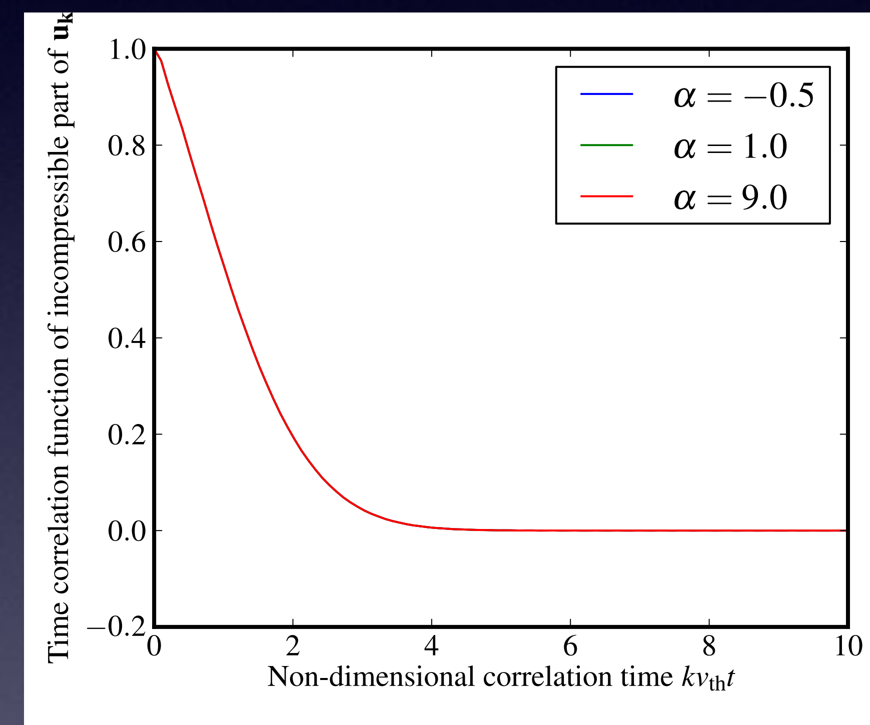
- Quasi-neutrality: $n_e = n_i$

$$\nabla \cdot \mathbf{B} = 0$$

- Maxwell-Faraday: $$\frac{\partial \mathbf{B}}{\partial t} = -c\, \nabla \times \mathbf{E}$$

Collisionless flow forcing

- δ-correlated-in-time large-scale forcing in kinetic ion equation
- In the unmagnetized regime, flow statistics controlled by phase-mixing (collisionless damping)
  - Flow correlation time is $(k_f v_{\mathrm{th}i})^{-1}$, a factor Mach number smaller than the turnover time
  - the flow is effectively highly viscous



$$\left\langle F_{\mathbf{k},i}(t)F^*_{\mathbf{k},j}(t')\right\rangle = \chi(k)\,\delta(t-t')\left(\delta_{ij} - k_i k_j/k^2\right)$$

$$\left\langle u_{\mathbf{k},i}(t)u^*_{\mathbf{k},j}(t')\right\rangle = \frac{\chi(k)}{8\pi k^2}\left(\delta_{ij} - \frac{k_i k_j}{k^2}\right)\int_{-\infty}^{\infty} d\omega\, e^{-i\omega(t-t')}\left|Z\left(\frac{\omega}{kv_{\mathrm{th}i}}\right)\right|^2$$

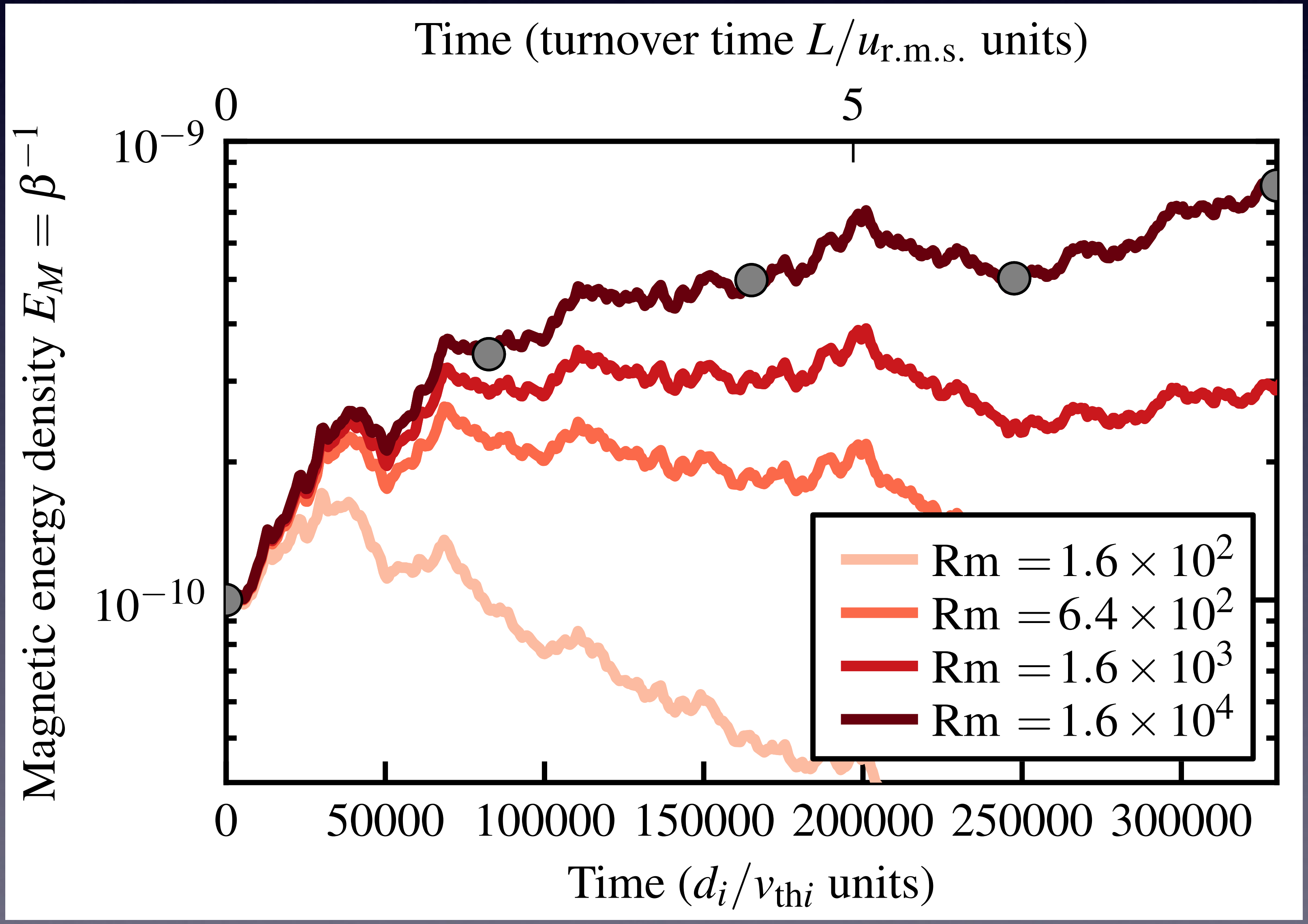
- Smooth, large-scale, chaotic, subsonic, finite-amplitude flow

Dynamo simulations setup

- Solve hybrid Vlasov-Maxwell in 3D-3V with Eulerian code
  - 3D periodic, phase-space dimensions: $L = 2000\pi d_i\,,\ \ v_{\mathrm{max}} = \pm 5 v_{\mathrm{th}i}$
  - Resolution: 64^3 (physical space) x 51^3 (velocity space) (Valentini et al., JCP 2007)
- Incompressible, isotropic, non-helical delta-correlated forcing
  - $k_f = 2\pi/L\,,$ injected power $\varepsilon = 3\times 10^{-5}\, n_{i0} m_i v_{\mathrm{th}i}^3/d_i$
  - Box-scale, collisionless chaotic flow $u_{\mathrm{r.m.s.}} \sim 0.2\, v_{\mathrm{th}i}$
- Initial conditions
  - Isotropic ion Maxwellian, $T_e=T_i$
  - Magnetic seed in wavenumber range $[2\pi/L, 4\pi/L]$
    - No guide/mean field !
    - Magnetic energy measured as inverse of plasma $\beta = 8\pi\, n_{\mathrm{i}0} T_i / B^2_{\mathrm{r.m.s.}}$

Unmagnetized regime

- Four simulations with same initial field and flow history, but different magnetic diffusivity η

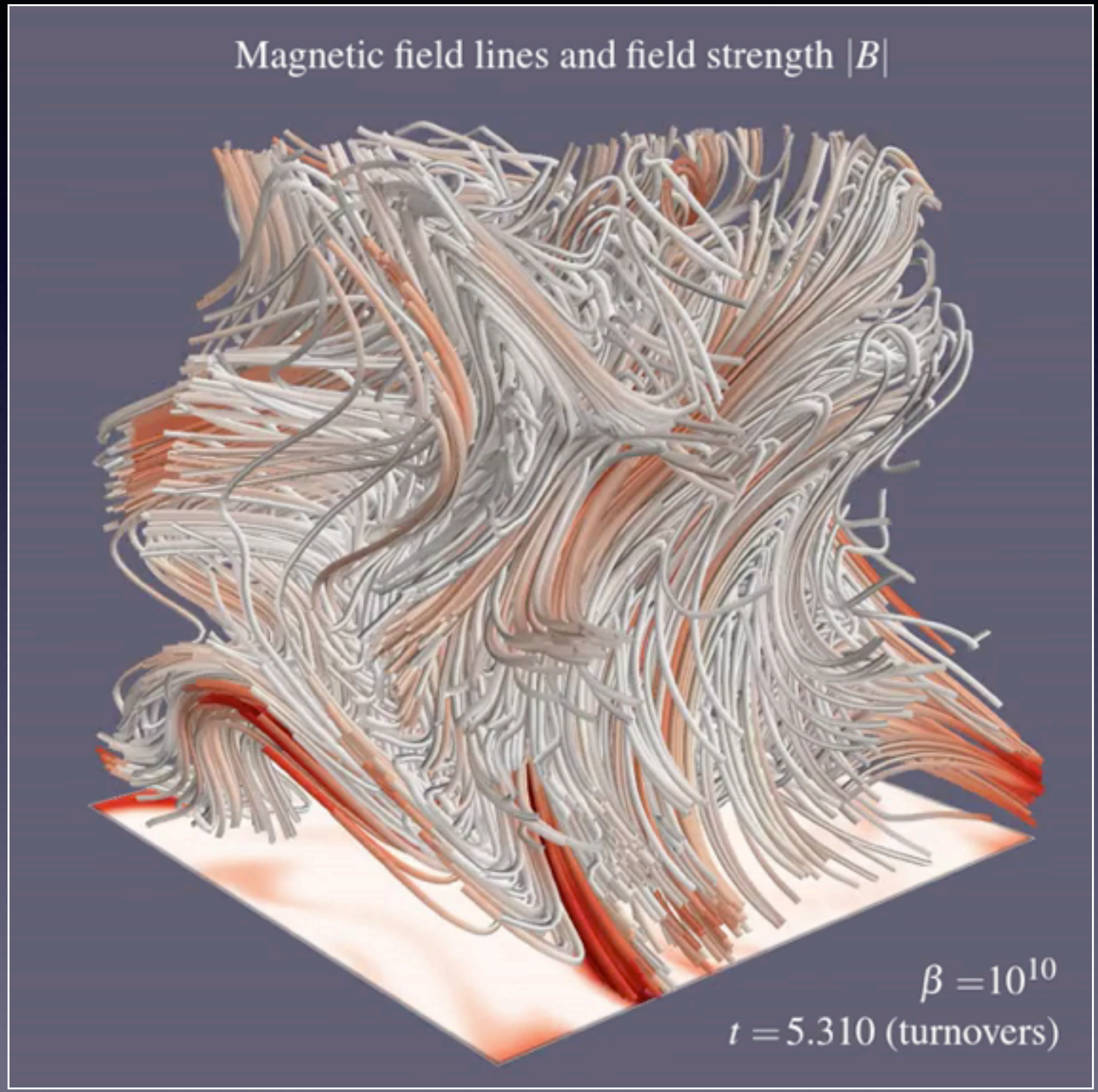


$$\beta = 10^{10}$$

$$\rho_i/L = 16$$

$$\mathrm{Rm} = \frac{u_{\mathrm{r.m.s.}}}{\eta k_f}$$

Unmagnetized regime: growing case

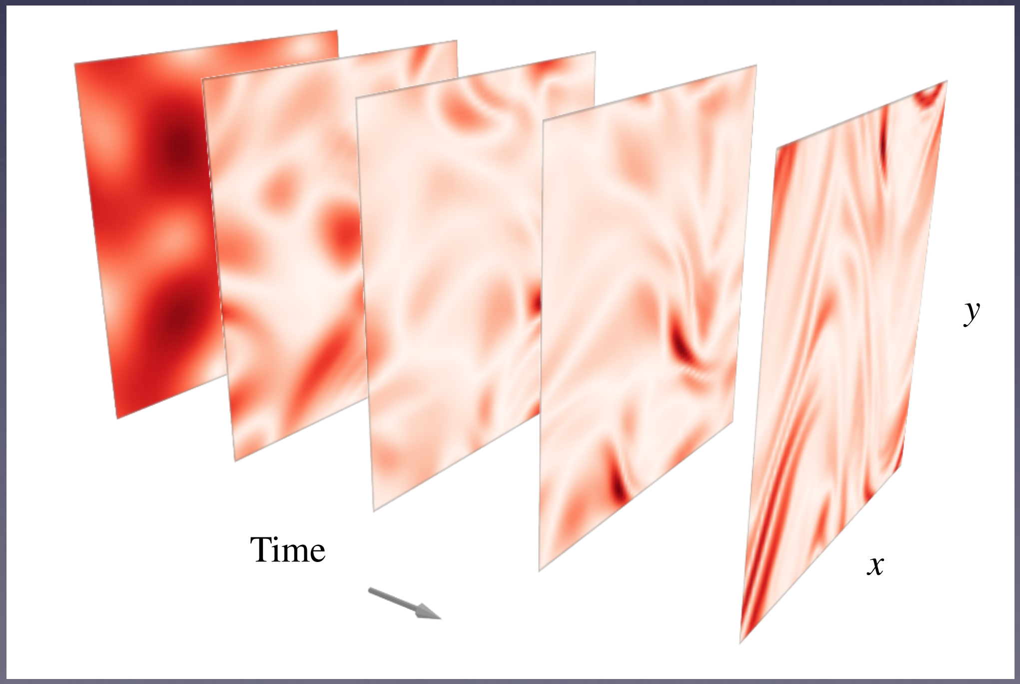


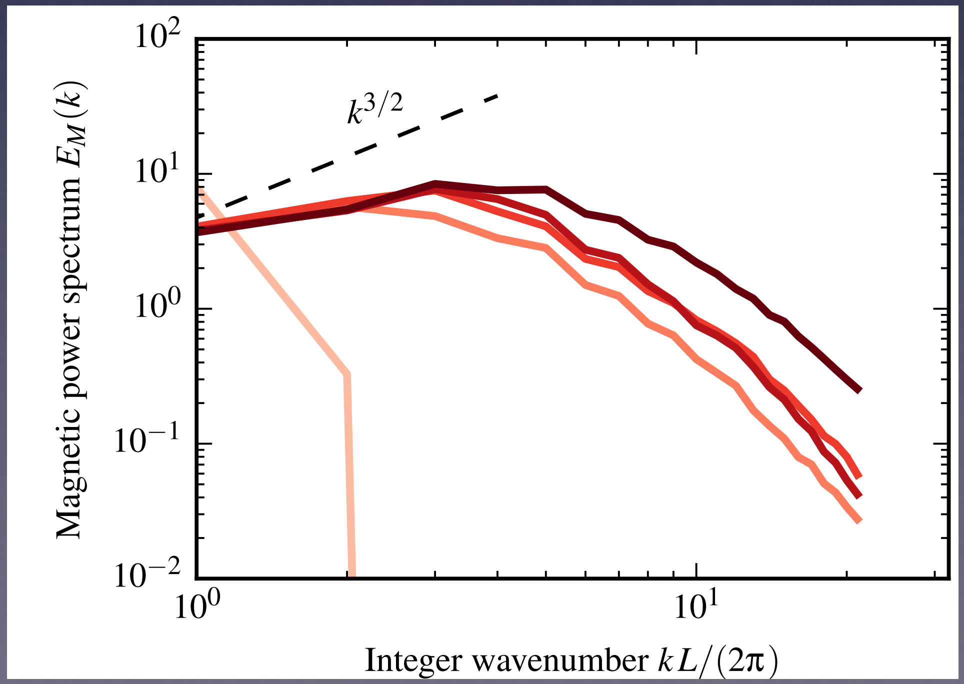
$\beta = 10^{10}$

$\rho_i / L \simeq 16$

Small-scale dynamo

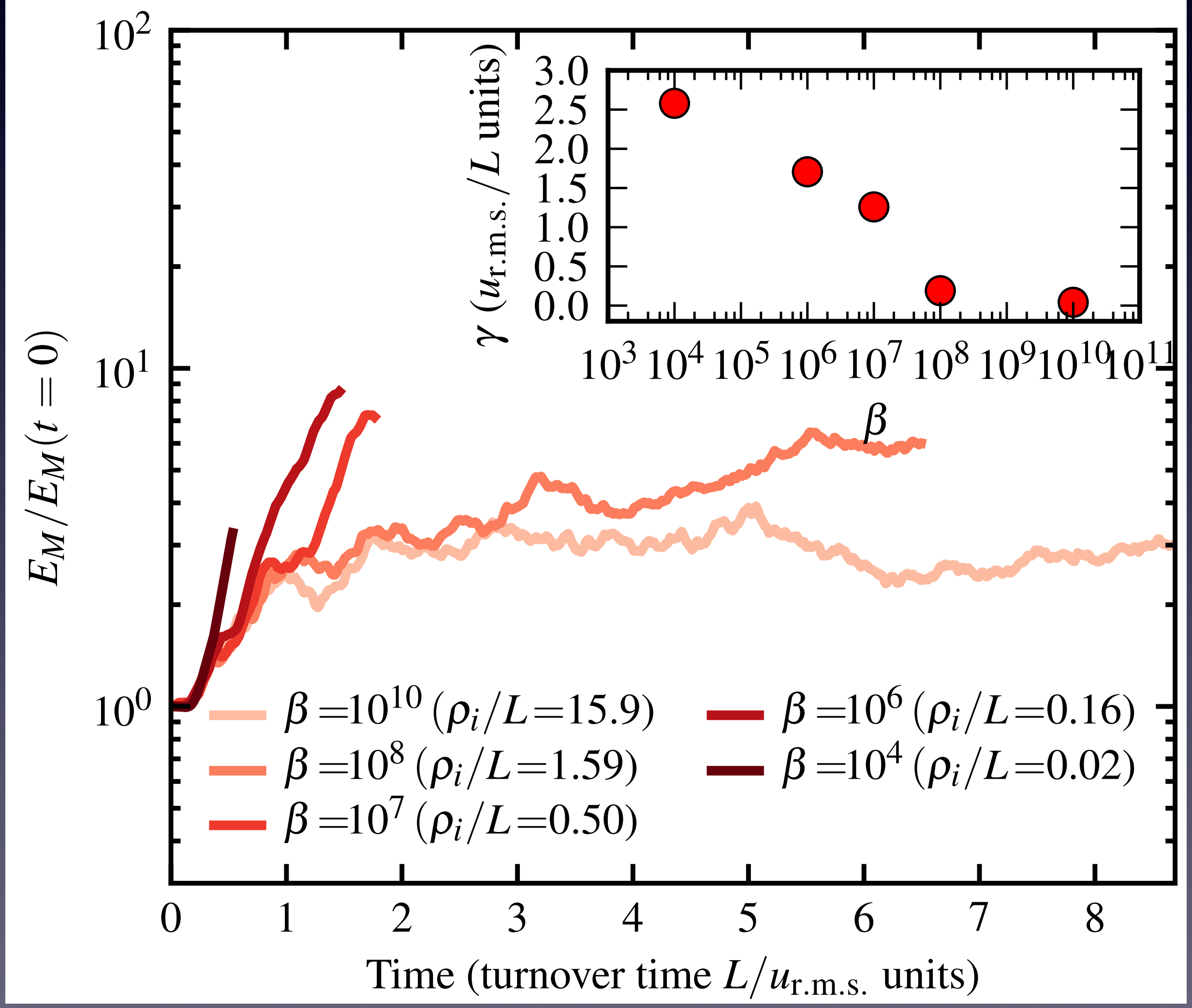
- Dynamo relies on chaotic stretching and folding of field lines
  - Folded field structure
  - Spectral evolution consistent with the formation of a Kasantsev spectrum
- Critical Rm larger than in MHD
  - Interpreted as a small flow correlation time effect
  - Energy growth rate ~ 0.15 turnover rate for Rm ~ 15000





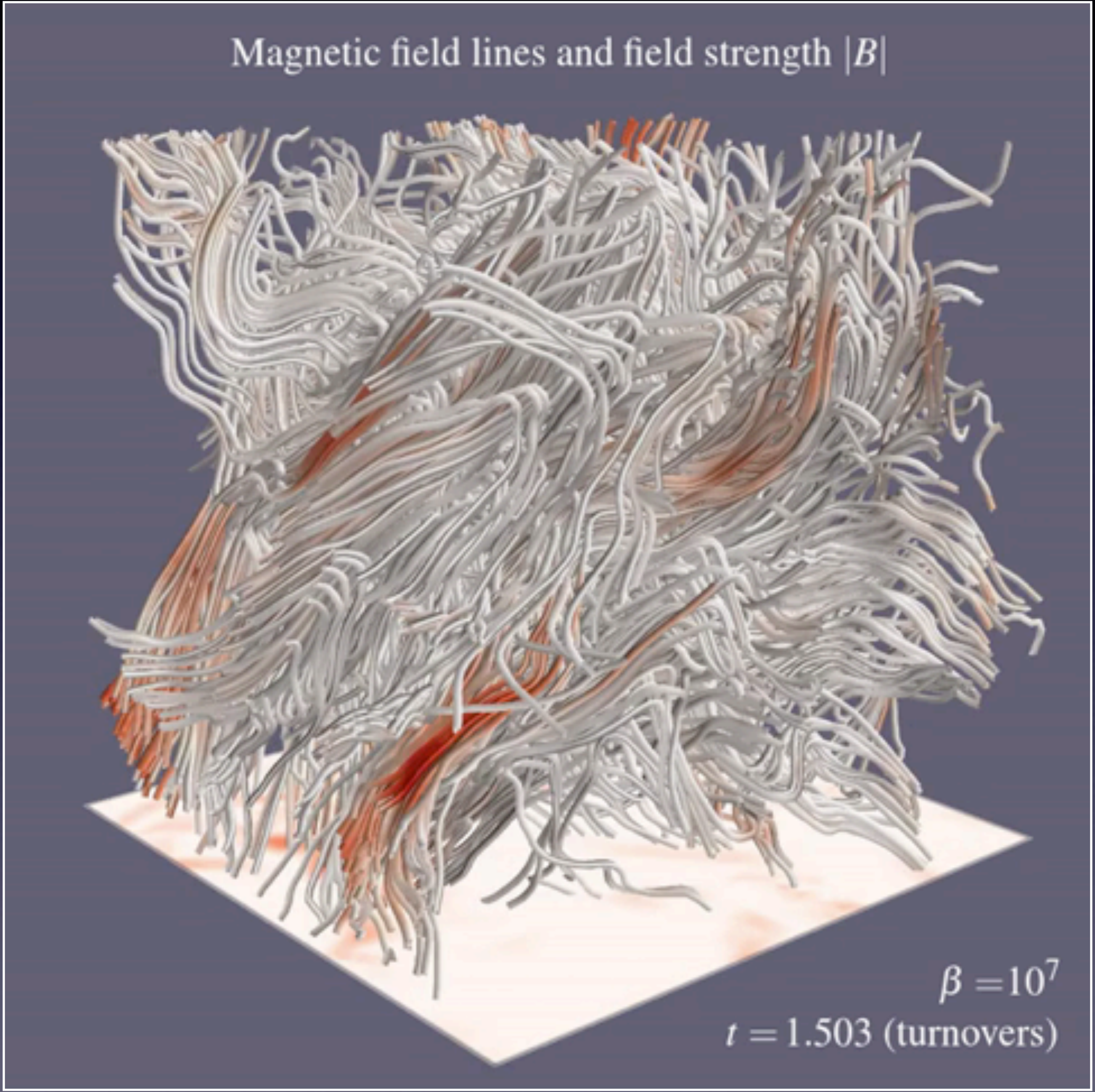
Exploring the magnetization transition

- Four simulations with same resistivity and input power, but different initial values of β



- Magnetic growth appears to self-accelerate

Magnetization transition

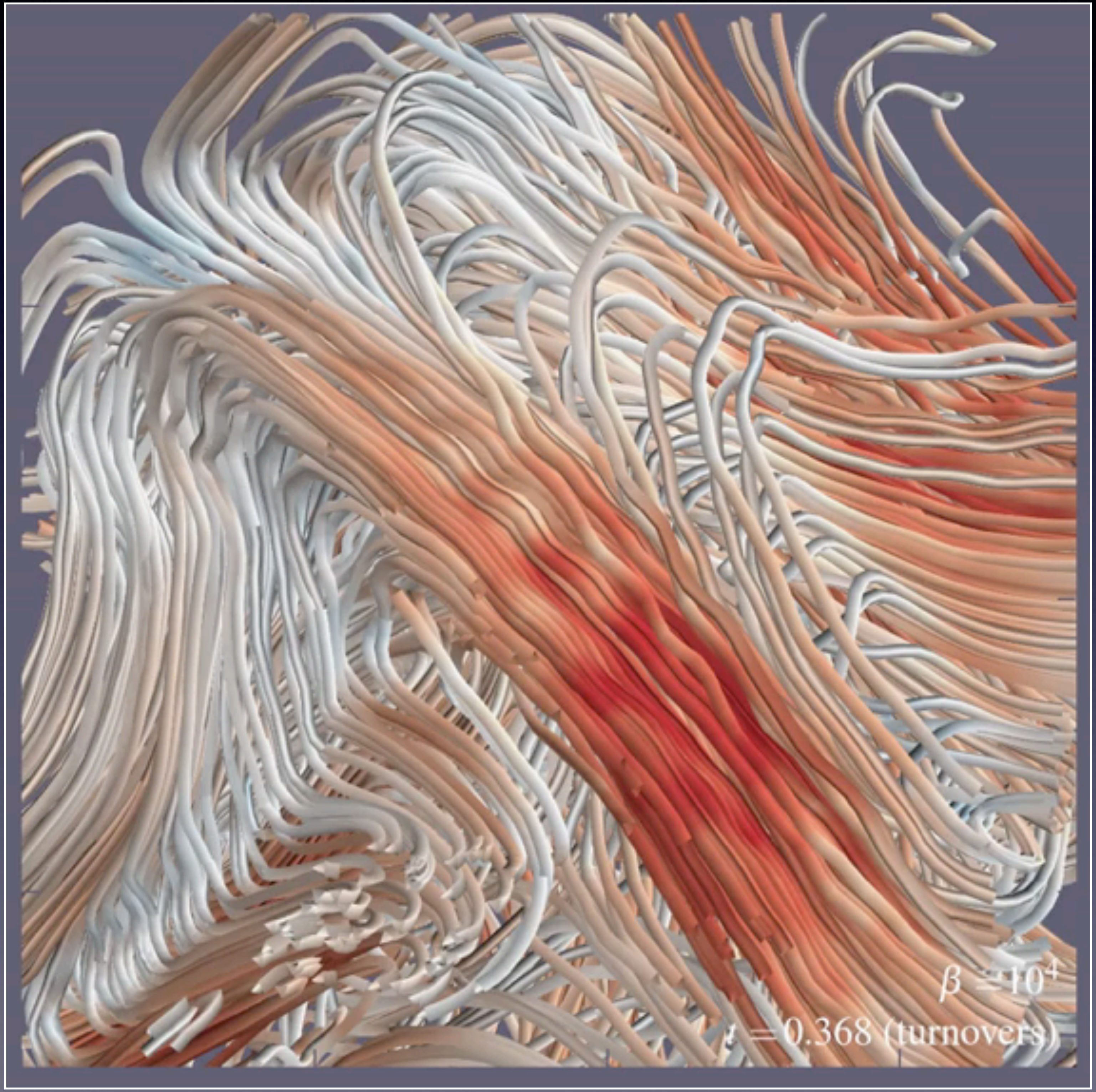


$$\beta = 10^7$$

$$\rho_i/L \simeq 0.5$$

- No scale-separation between stirring and kinetic scales !

Magnetized regime

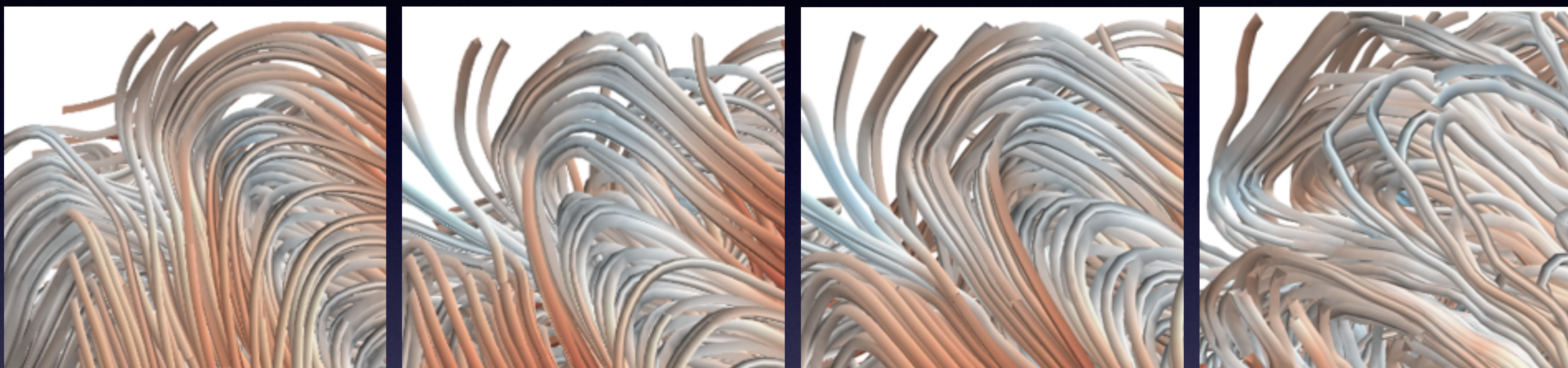


$$\beta = 10^4$$

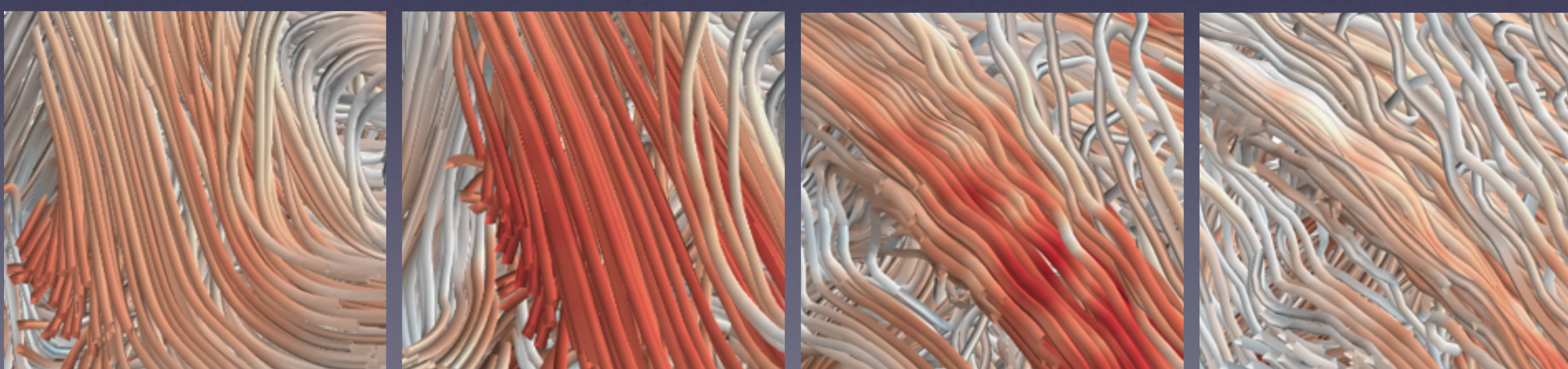
$$\rho_i/L \simeq 0.02$$

Magnetized regime

- Firehose instability in strong-field curvature regions

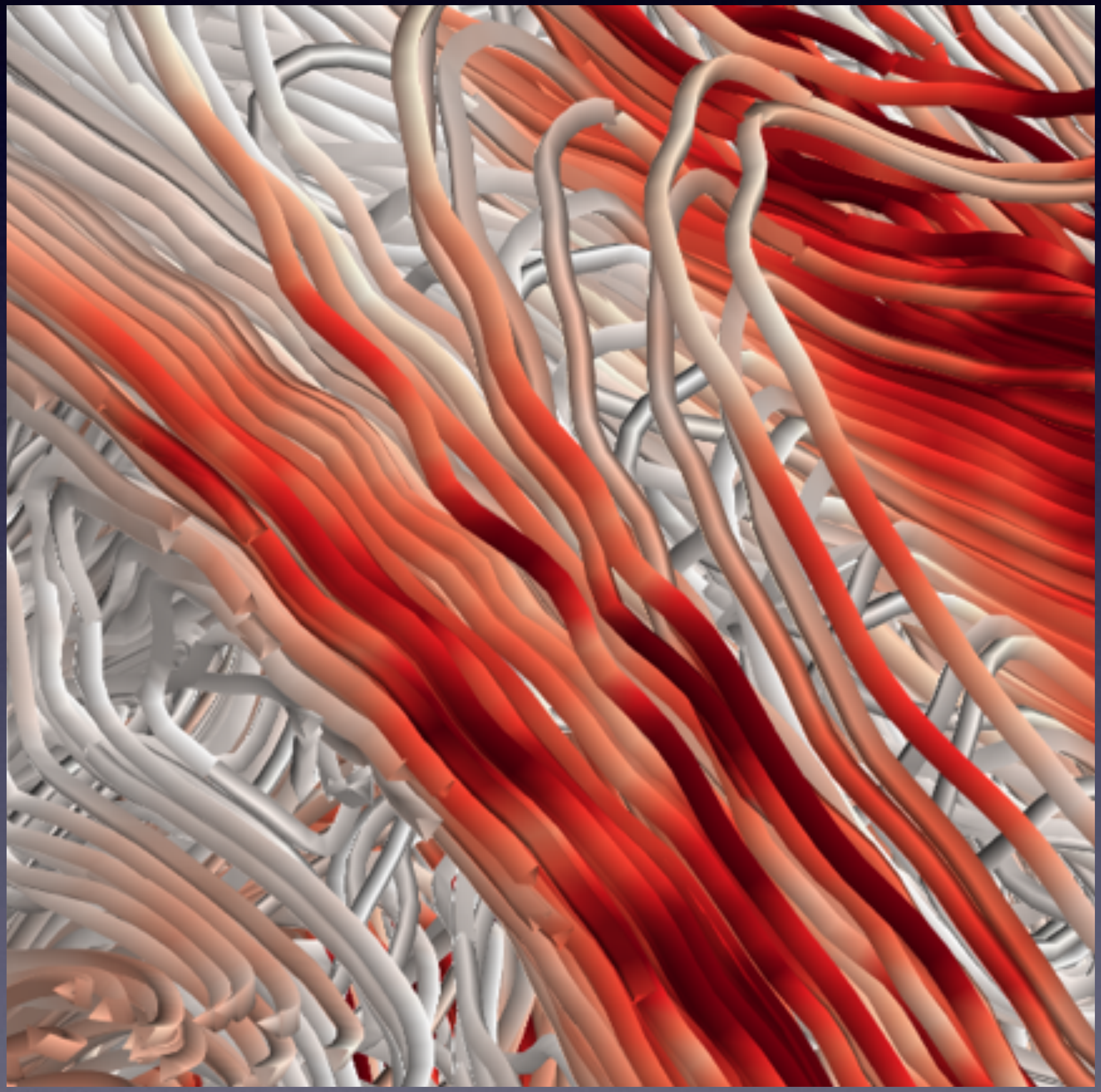


- Bubbly mirror fluctuations in field-stretching regions

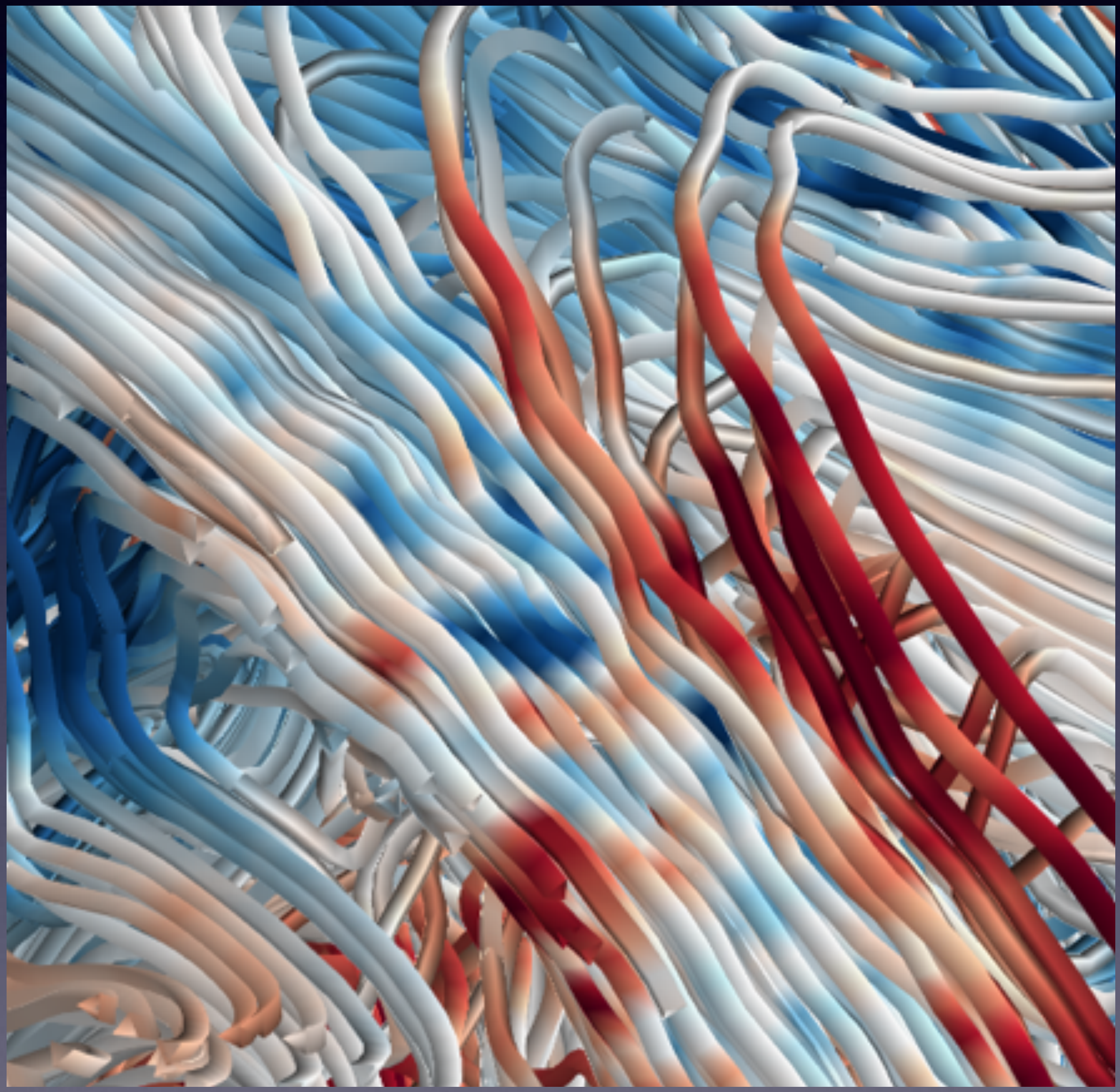


Magnetized regime

- Mirror structures: magnetic depressions and overdensities



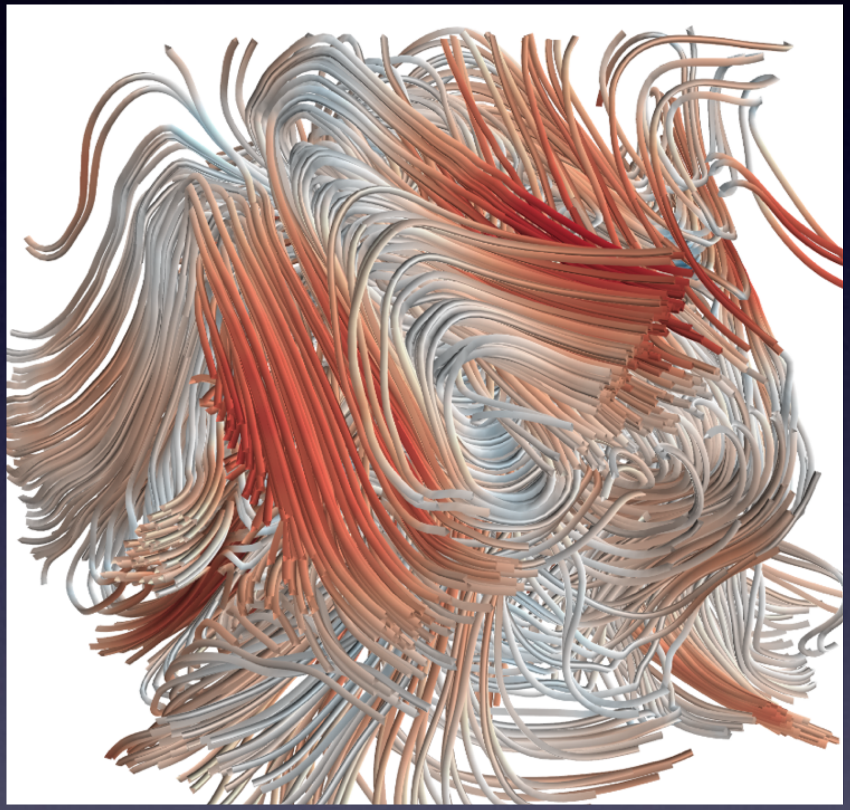
Magnetic strength

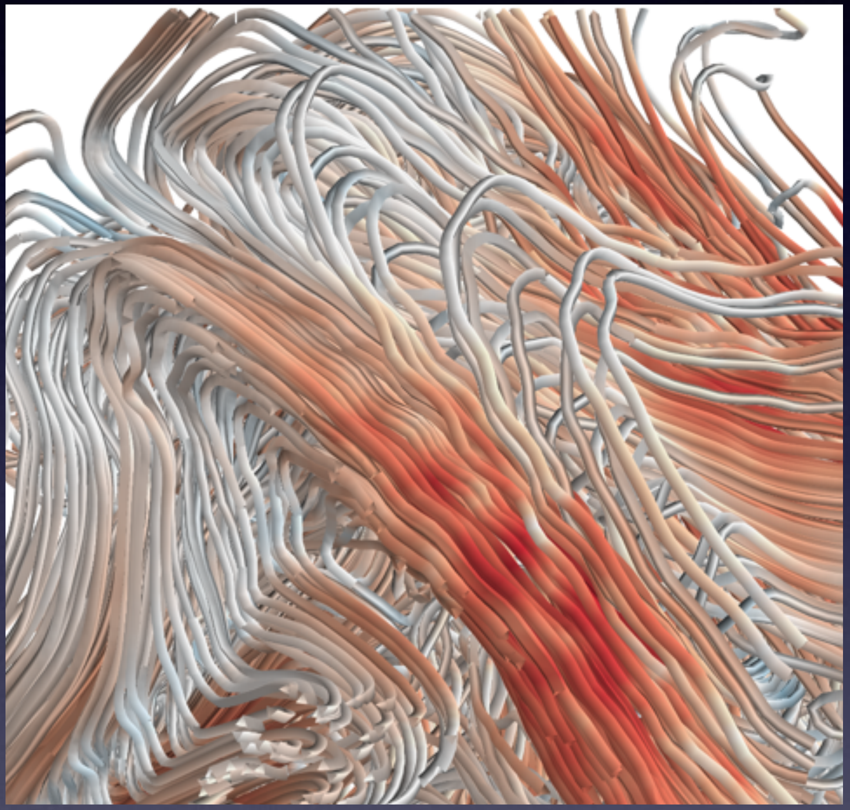


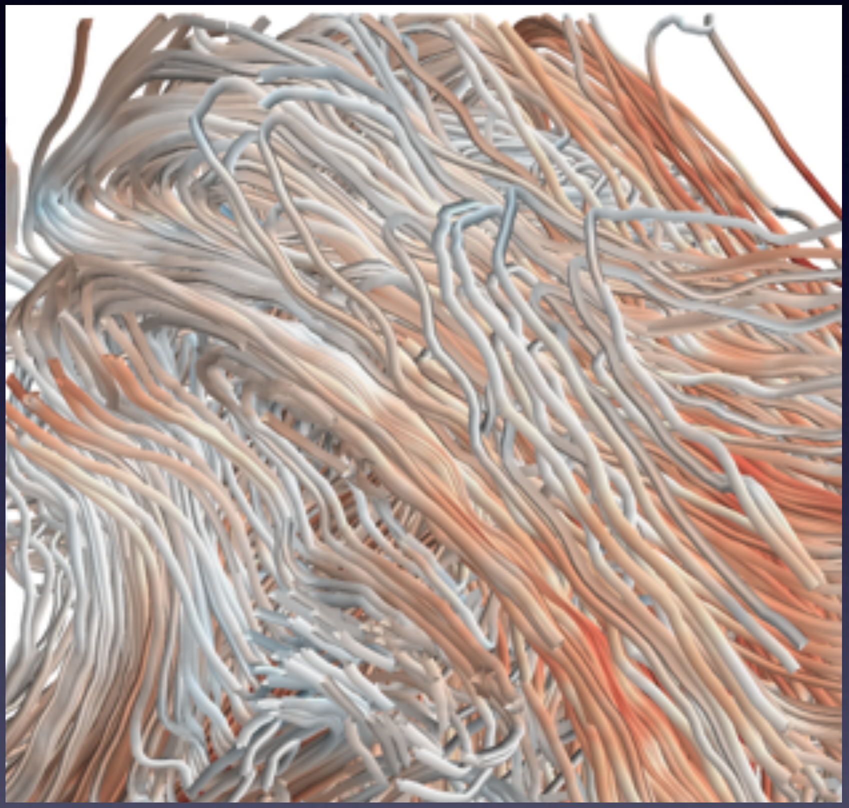
Density fluctuations

Magnetized regime

- Pressure anisotropy relaxation



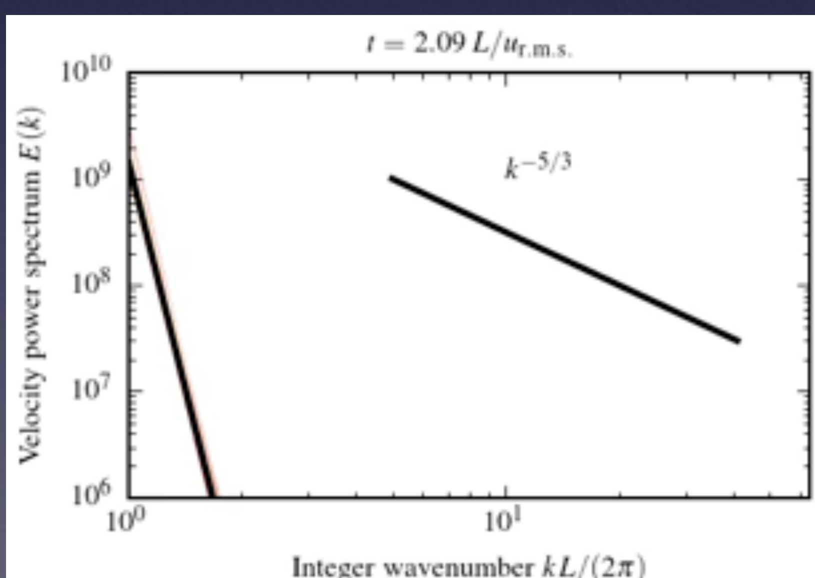




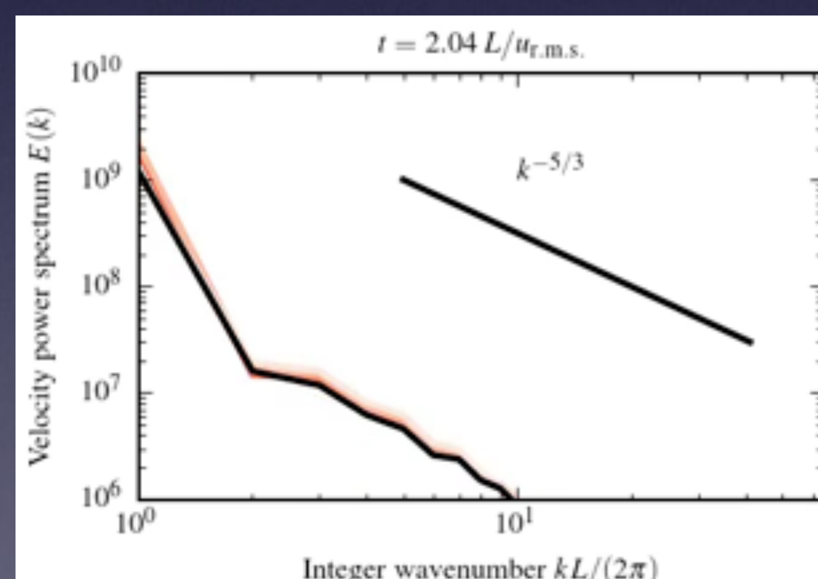
- Current limitations
  - Resolution: cannot go much further at $64^3 \times 51^3$
  - Simulations on longer timescales needed: expensive due to tiny timesteps

Ideas on dynamo self-acceleration

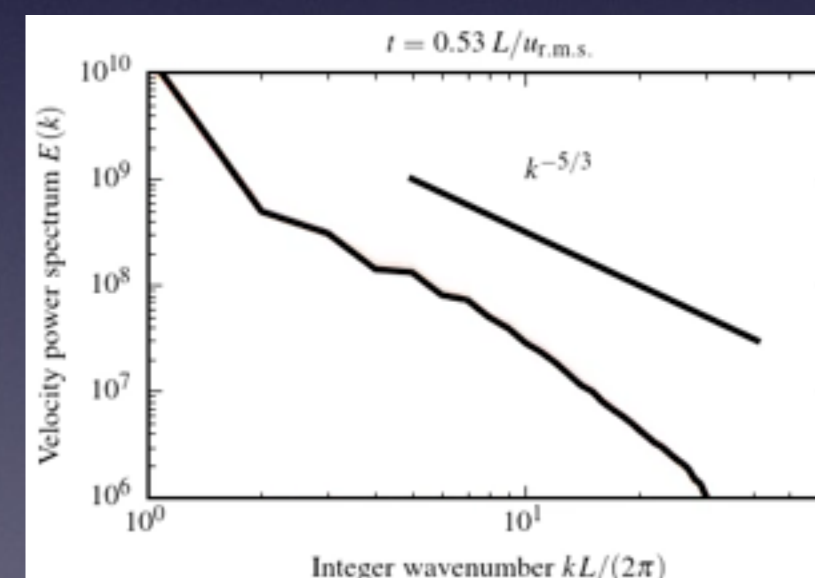
- Several “nonlinear” effects possible
  - Dynamo growth entangled with kinetic mode growth
  - Net nonlinear feedback of kinetic modes (see Matt Kunz’s talk)
  - Flow viscosity decreases at magnetisation transition, eddies with larger rates of strains are generated



$$\beta = 10^{10}$$
$$\rho_i/L \simeq 16$$

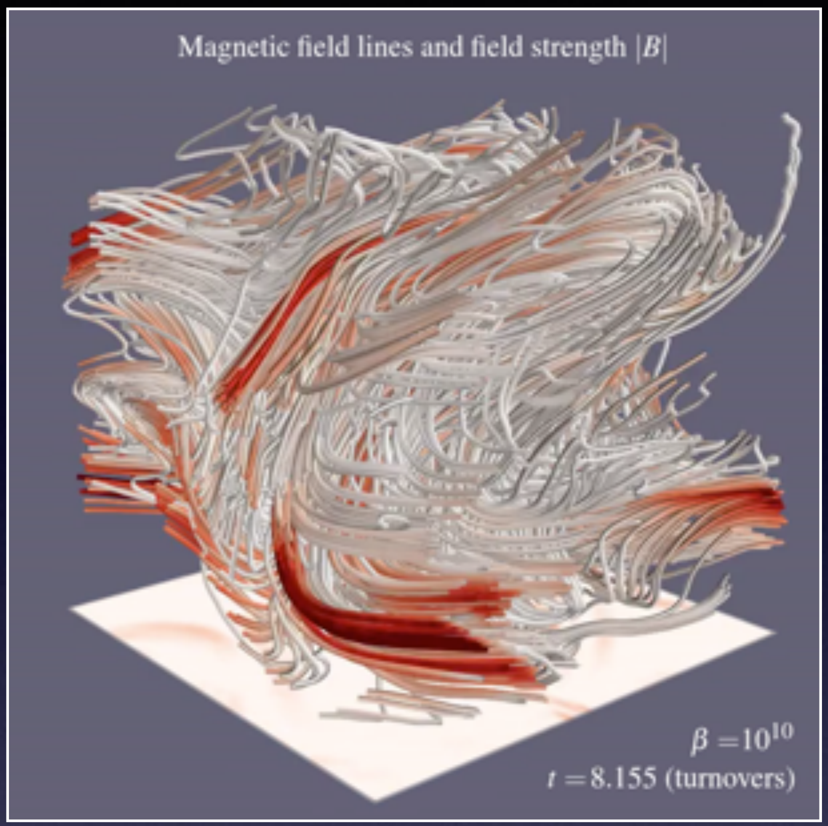


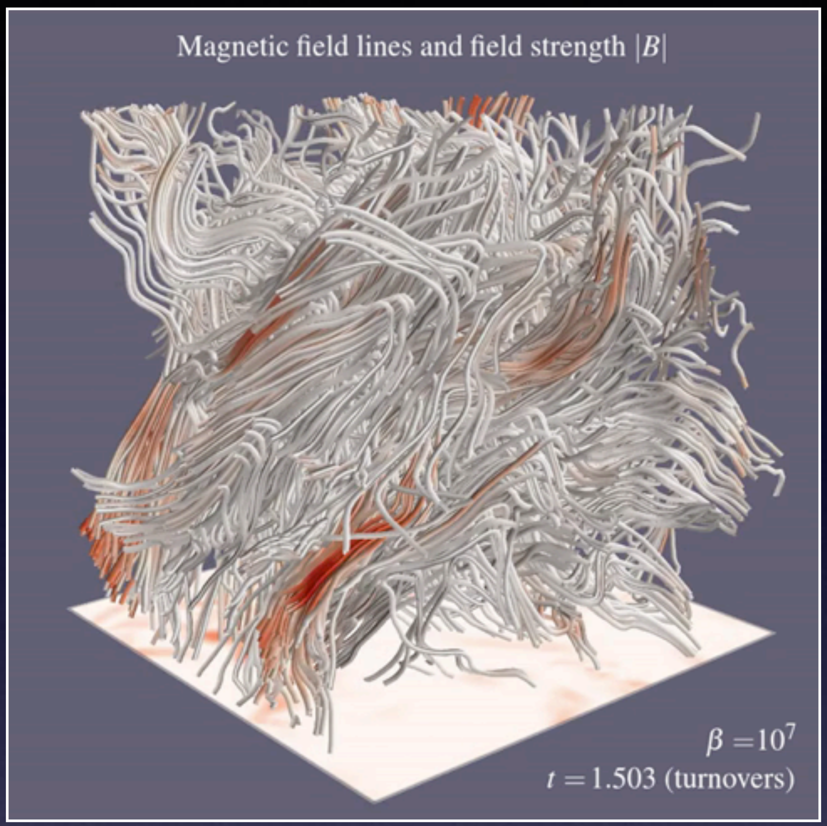
$$\beta = 10^{7}$$
$$\rho_i/L \simeq 0.5$$

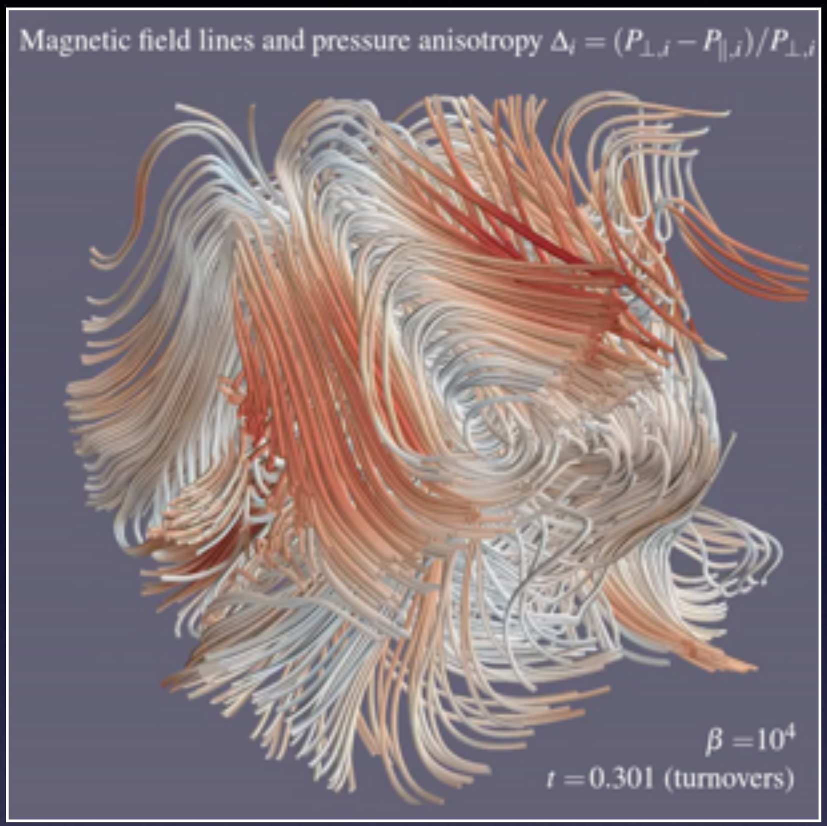


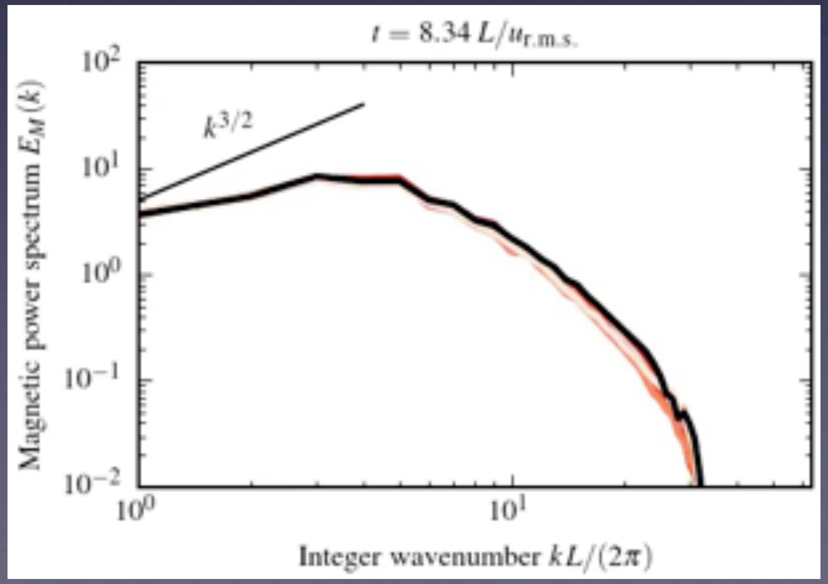
$$\beta = 10^{4}$$
$$\rho_i/L \simeq 0.02$$

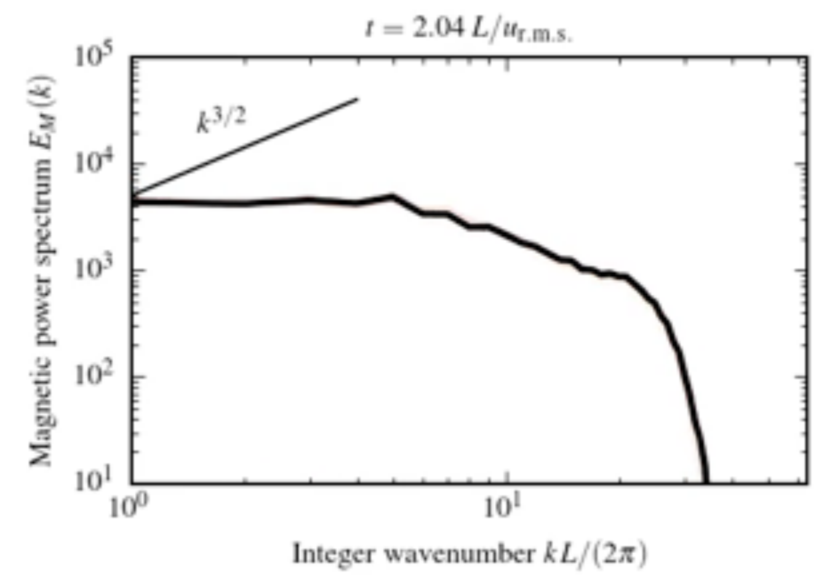
Magnetic spectra

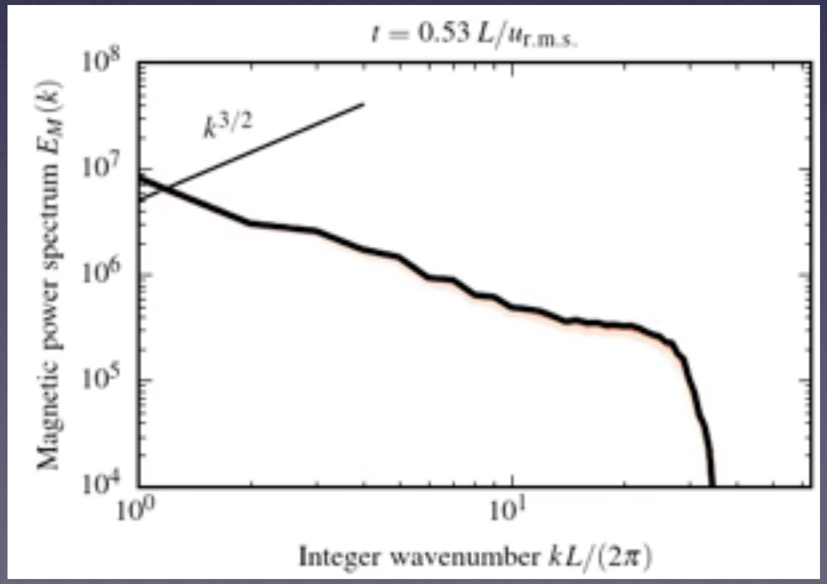












$\beta = 10^{10}$
$\rho_i/L \simeq 16$

$\beta = 10^{7}$
$\rho_i/L \simeq 0.5$

$\beta = 10^{4}$
$\rho_i/L \simeq 0.02$

Main results and conclusions

- Dynamo in an unmagnetized collisionless plasma is possible
  - Reminiscent of turbulent large Pm MHD dynamo
- Growth self-accelerates as the plasma gets magnetized
- Dynamo and kinetic instabilities become entangled in the magnetized regime
  - Firehose instability in regions of strong field-curvature (negative Δ_i)
  - Mirror instability in regions of field amplification (positive Δ_i)
  - Evolution towards pressure-anisotropy-relaxed state
- Dynamo appears to be a viable mechanism to amplify magnetic field to equipartition in weakly collisional extragalactic plasmas