Some recent results on the Plasma Dynamo[1]

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PPPL
PRINCETON
PLASMA PHYSICS
LABORATORY

[1] St-Onge & Kunz ApJ 2018, In Review

What we're doing

- Collisionless turbulent dynamo
- Full-f Hybrid Kinetics
  - kinetic Ions,

$$\frac{\partial f_\mathrm{i}}{\partial t} + \boldsymbol{v}\cdot\boldsymbol{\nabla} f_\mathrm{i} + \left[\frac{e}{m_\mathrm{i}}\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c}\times\boldsymbol{B}\right) + \frac{\boldsymbol{F}}{m_\mathrm{i}}\right]\cdot\boldsymbol{\nabla}_{\boldsymbol{v}} f_\mathrm{i} = 0.$$

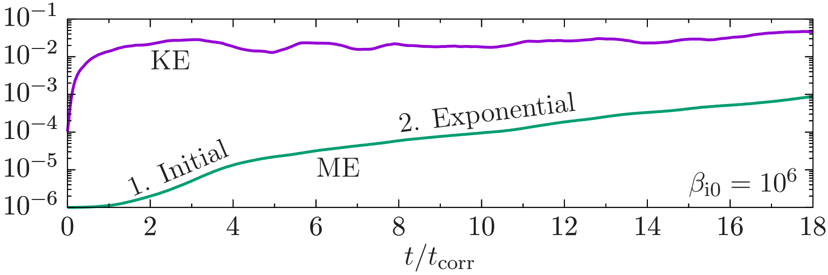
  - isothermal fluid electrons,

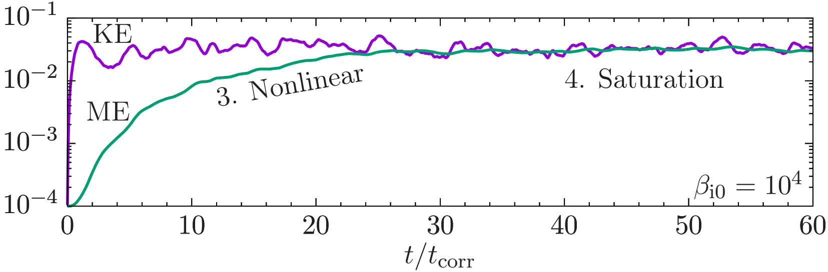
$$\boldsymbol{E} + \frac{1}{c}\boldsymbol{u}_\mathrm{i}\times\boldsymbol{B} - \frac{\eta}{c}\boldsymbol{\nabla}\times\boldsymbol{B} + \frac{\eta^\mathrm{hyper}}{c}\boldsymbol{\nabla}\times\nabla^2\boldsymbol{B} = -\frac{T_\mathrm{e}\boldsymbol{\nabla} n}{en} + \frac{(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B}}{4\pi en}.$$

- Non-helical, incompressible, time-correlated ($\sim L/u_\mathrm{rms}$) forcing
- Focus on two specific runs:

$$\begin{array}{lllll}
(1) & L = 16\rho_\mathrm{i0} & \beta_\mathrm{i0} = 10^6 & N = 504^3 & \mathrm{PPC} = 216 \\
(2) & L = 10\rho_\mathrm{i0} & \beta_\mathrm{i0} = 10^4 & N = 252^3 & \mathrm{PPC} = 216
\end{array}$$

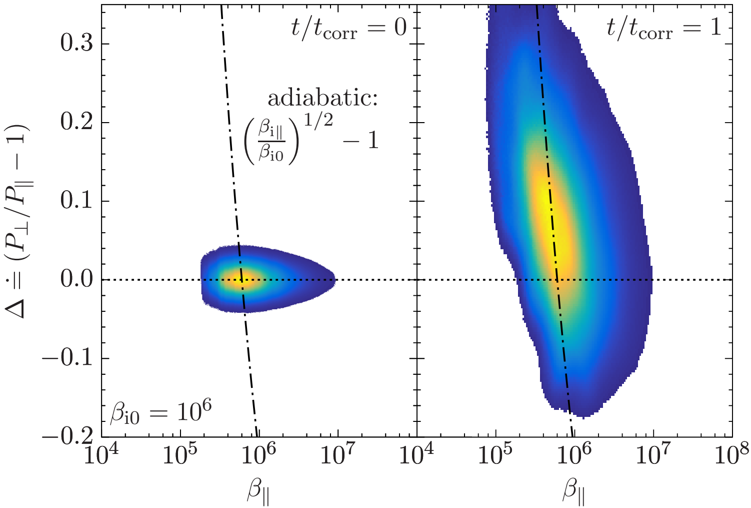
The Punchline...





`VPlayer.swf`

But what about μ conservation?



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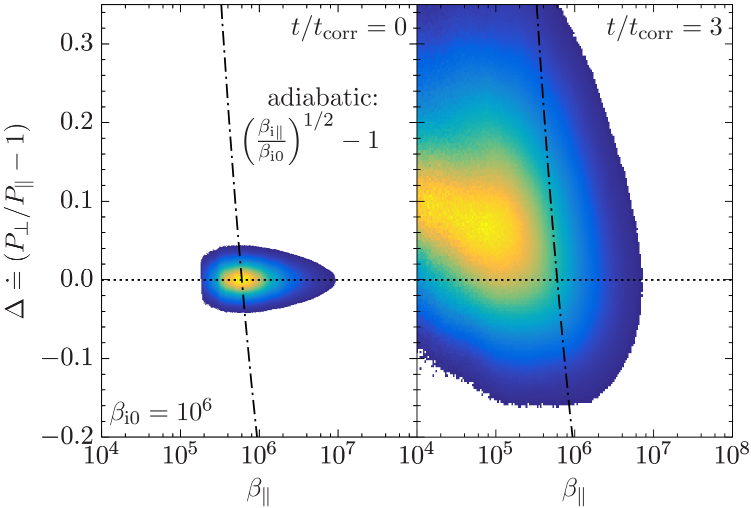


Mirrors are excited within a correlation time ($\Delta > 1/\beta$ trivially)

Mirror and firehose instabilities

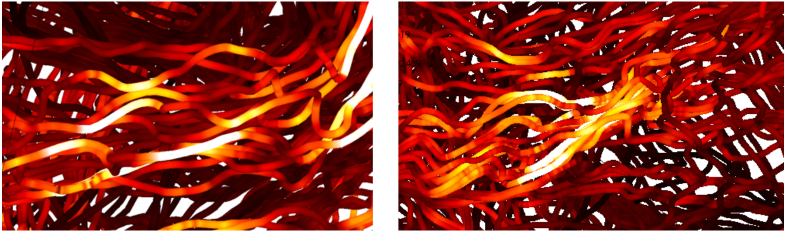
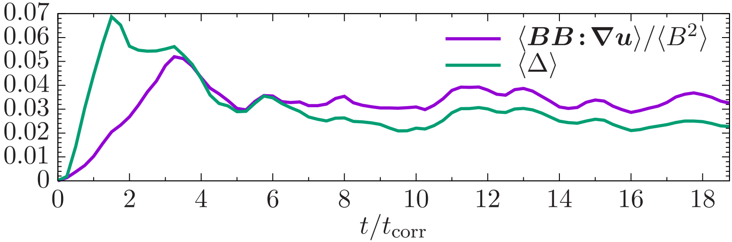
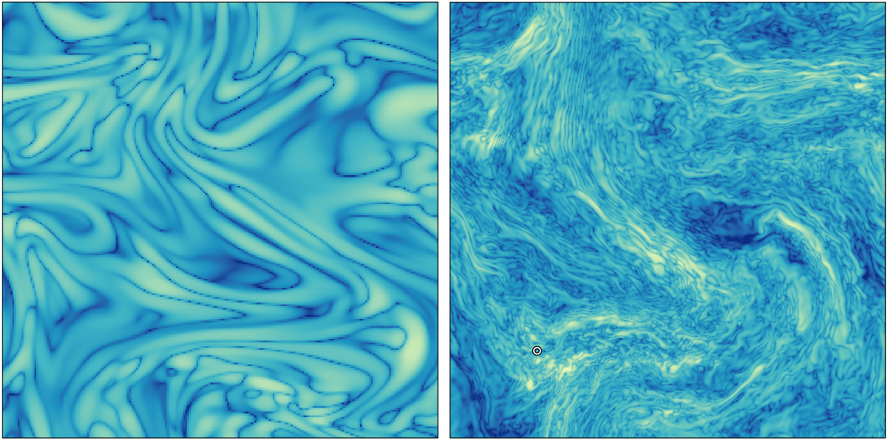


Figure: Visual evidence of mirror instabilties.

- Kinetic instabilities generate magnetic energy above ρ_{i}.
- Evidence of firehose visually and in magnetic curvature PDFs.
- Plasma becomes Braginskii-like ($3\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}\,\boldsymbol{:}\,\boldsymbol{\nabla u} \sim \nu_{\mathrm{eff}}\Delta$):



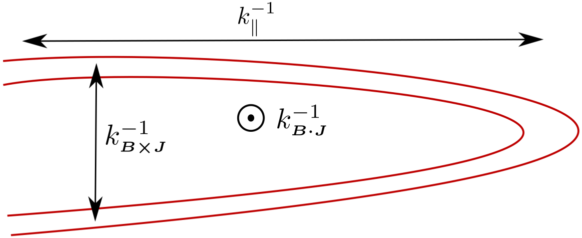
Does it look like MHD?



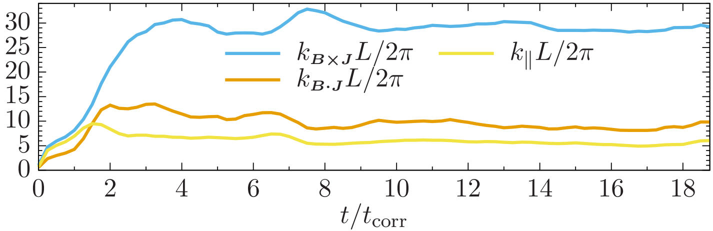
MHD $(\mathrm{Pm} = 500)$ | Kinetic

Similarities to a collisional plasma

It will be useful to define characteristic wavenumbers (Schekochihin *et al.* 2004):



Even in the collisionless regime, magnetic field develops sheet-like folded structures.



Spectra

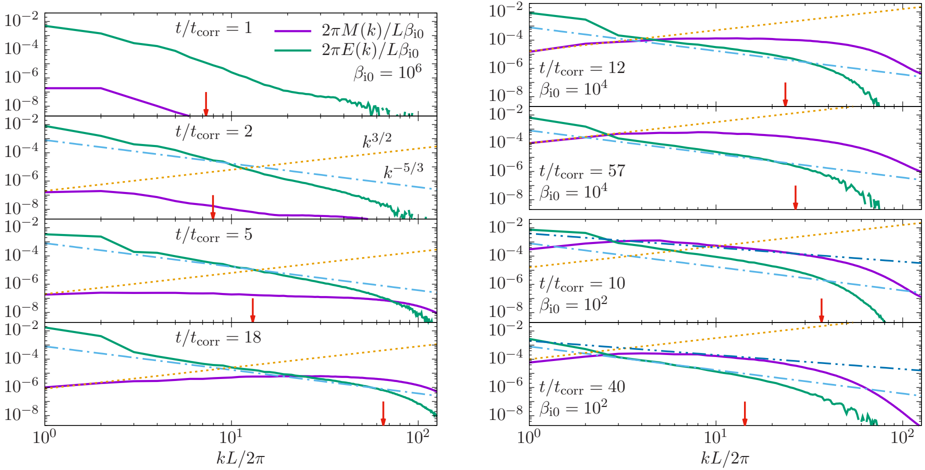


Figure: Kinetic and magnetic energy spectra. Red arrow denotes position of mean Larmor radius.

Anisotropic Turbulence

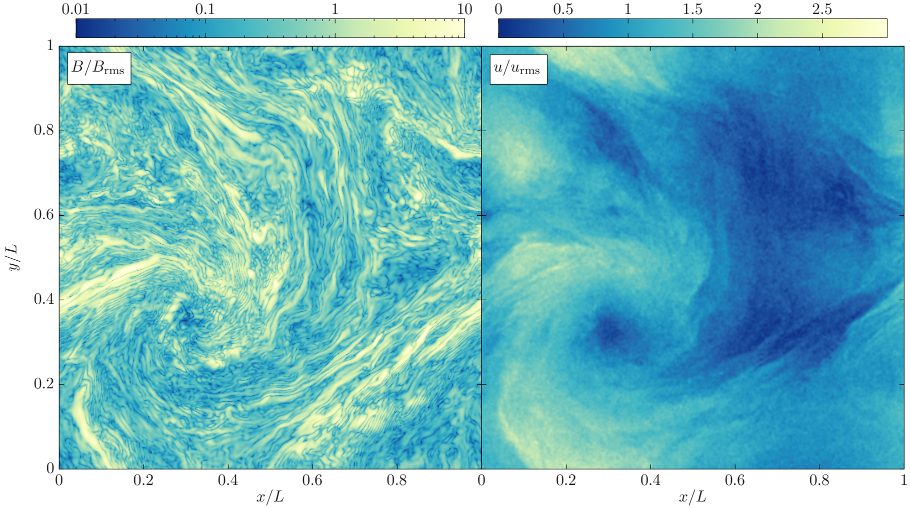


Figure: Pseudo-color images of $B/B_{\rm rms}$ and $u/u_{\rm rms}$.

Where's the gyroradius?

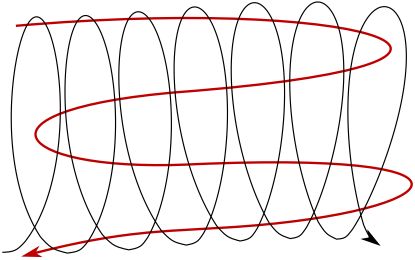


Figure: $k_{B\times J}\rho_\mathrm{i} \gg 1$

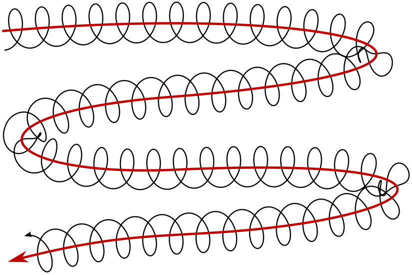


Figure: $k_{B\times J}\rho_\mathrm{i} \ll 1$

When $k_{B\times J}\rho_\mathrm{i} \gg 1$:

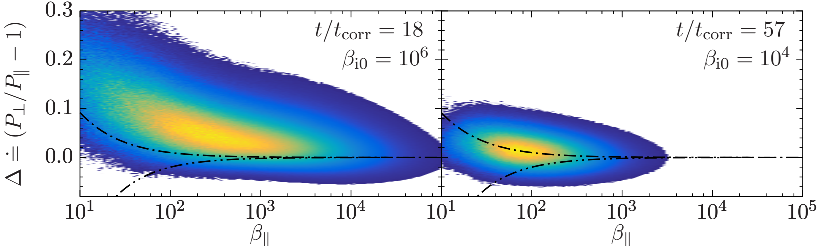
- Particles are effectively unmagnetized.
- Diffusion is Bohm-like.

When $k_{B\times J}\rho_\mathrm{i} \ll 1$:

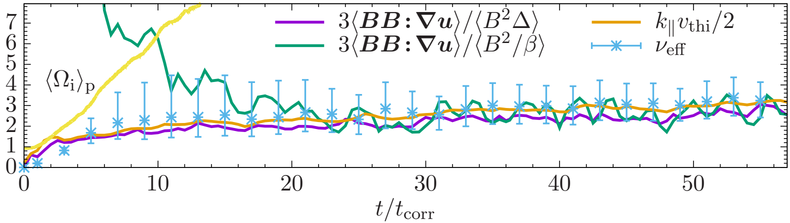
- Particles can travel along folds.
- Scattering near the sharp bends (*firehose sites!*)

Settling down

Eventually dynamo saturates with $u \sim v_{\rm A}$ ($\beta \sim M^{-2}$):



- Folds preserved (now closer to ribbons than sheets.)
- Partial suppression of $\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}:\boldsymbol{\nabla u}$, with $\nu_{\rm eff} \sim \beta\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}:\boldsymbol{\nabla u}$:



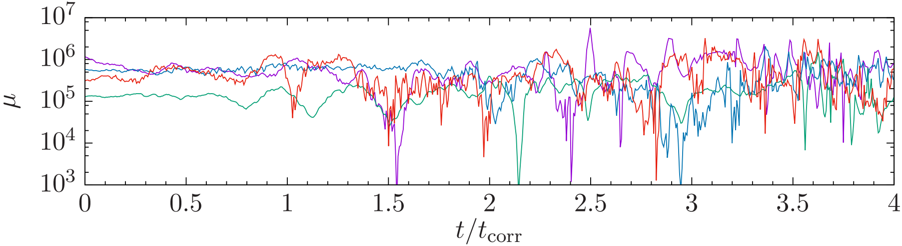
The take-away points

To summarize,

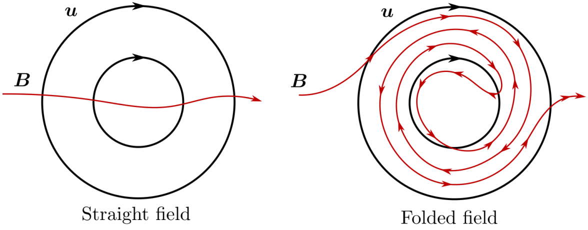
- **Dynamo exists in a collisionless magnetized plasma.** See also Rincon *et al.* 2016.
- Larmor-scale instabilities play a crucial role.
- Many features appear MHD-like (Pm $\gtrsim 1$), despite collisionless plasma.
- Saturation at $u \sim v_{\mathrm{A}}$.

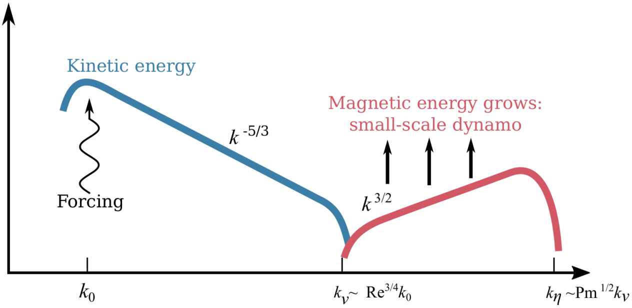
Particle Scattering

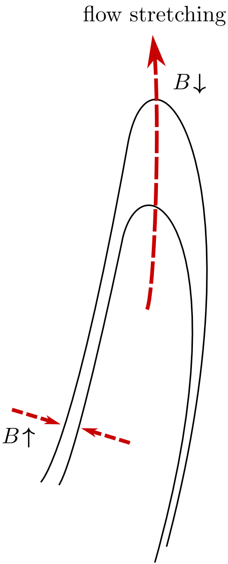
- Effective collisionality $\nu_{\rm eff}$ from pitch-angle scattering



The Kinematic $\mathrm{Pm} \gg 1$ Turbulent MHD Dynamo







From Schekochihin *et al.*, Astrophy. J. **612**, 276 (2004).