The Future of Plasma Astrophysics: 5 Questions I would like to Answer

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Cosmic rays: Fermi telescope settles mystery of origin

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Science correspondent, BBC News, Boston

14 February 2013 Last updated at 19:14 GMT

Solved?

The IC 433 supernova was a rich source of gamma rays

5 Questions

1. When and how did the universe become magnetised? ✔
   “Magnetogenesis”
2. How do microscopic collisionless plasma instabilities affect the macroscopic plasma behaviour? ✔
   “Anomalous transport properties – viscosity, resistivity”
3. How are particles accelerated to high energies?
   “Cosmic rays”
4. How and why do plasmas explode?
   “Solar/stellar flares, disc flares, substorms”
5. How do we turn magnetic energy rapidly into heat?
   “Coronal heating, three dimensional reconnection”

Magnetogenesis.

Top down or bottom up.

Is field made/amplified at small scale then cascaded to large scale or does it just grow at large scale?

Magnetogenesis.

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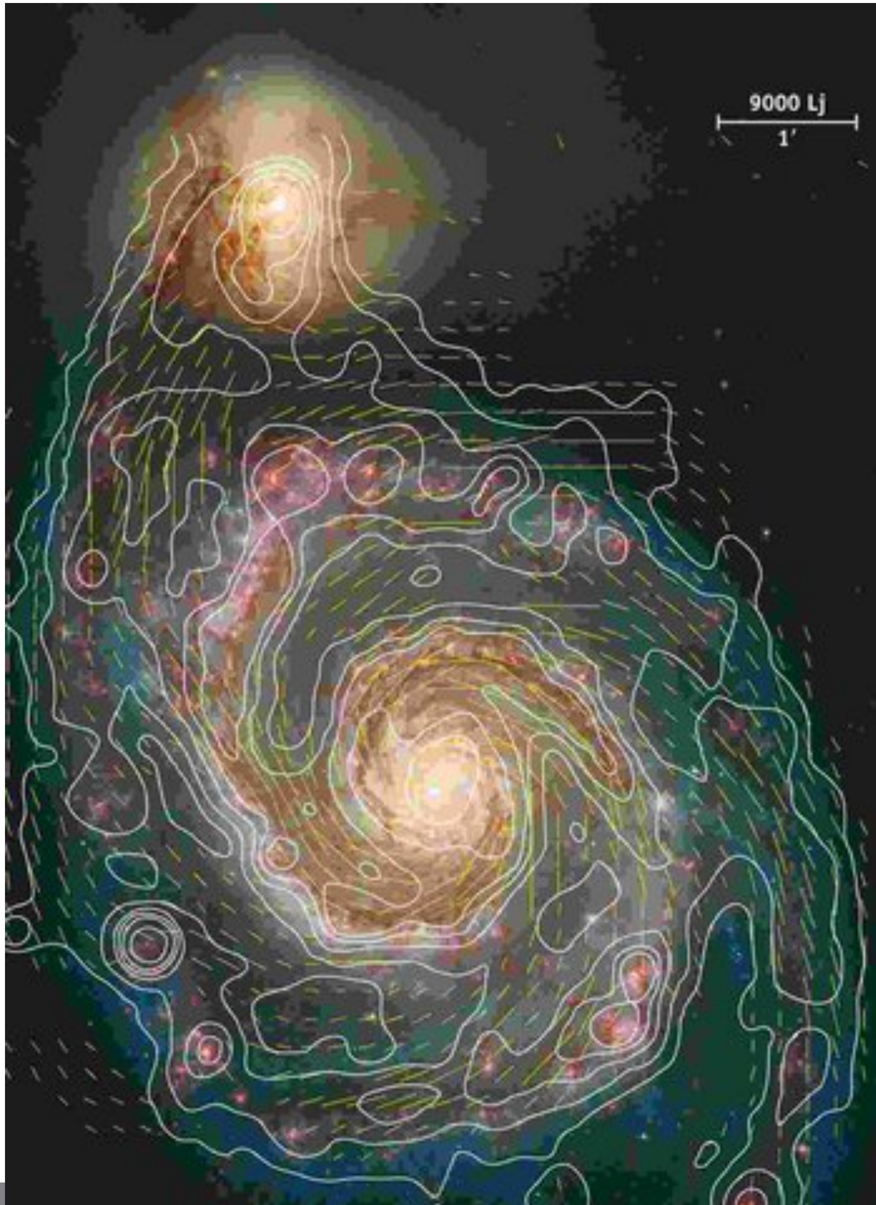
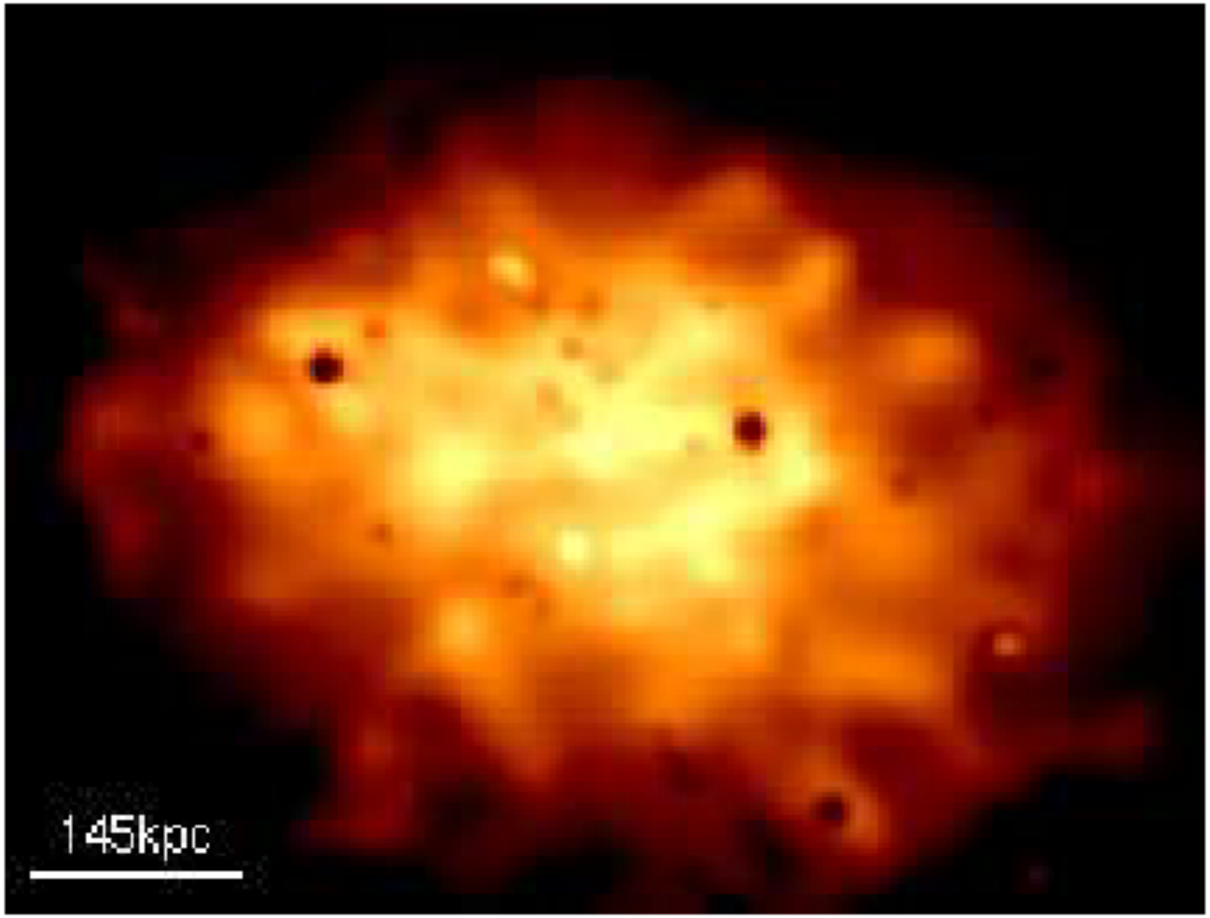
M51



Spiral galaxy M 51 with magnetic field data. Credit: MPIfR Bonn

Rosse's M51 Sketch in 1845

Cluster Turbulence



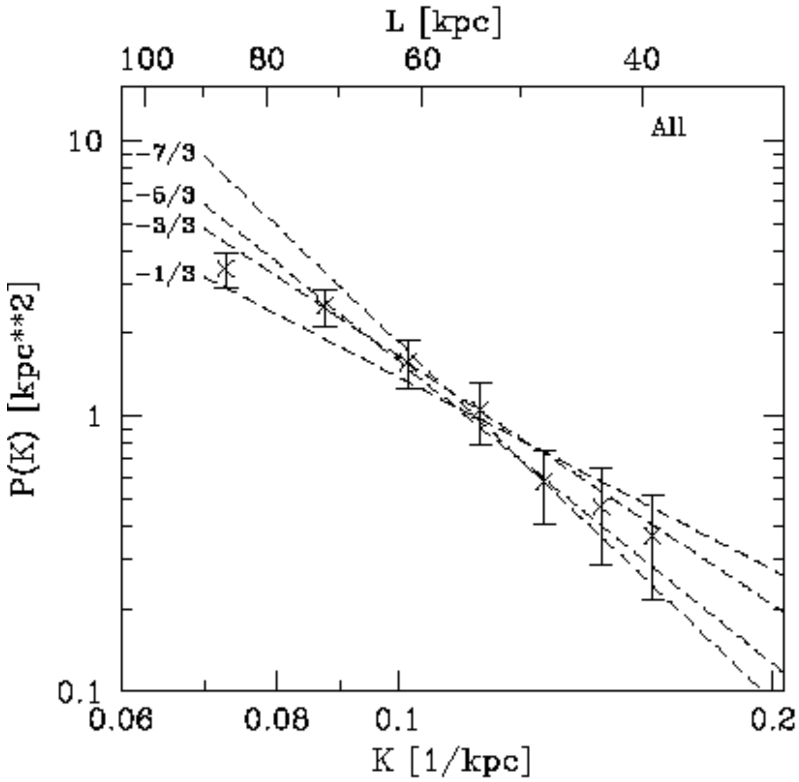
- Mergers
- AGNs
- Wakes

$L \sim 10^2 \ldots 10^3$ kpc
$U \sim 10^2 \ldots 10^3$ km/s
(subsonic)
$L/U \sim 10^8 \ldots 10^9$yr

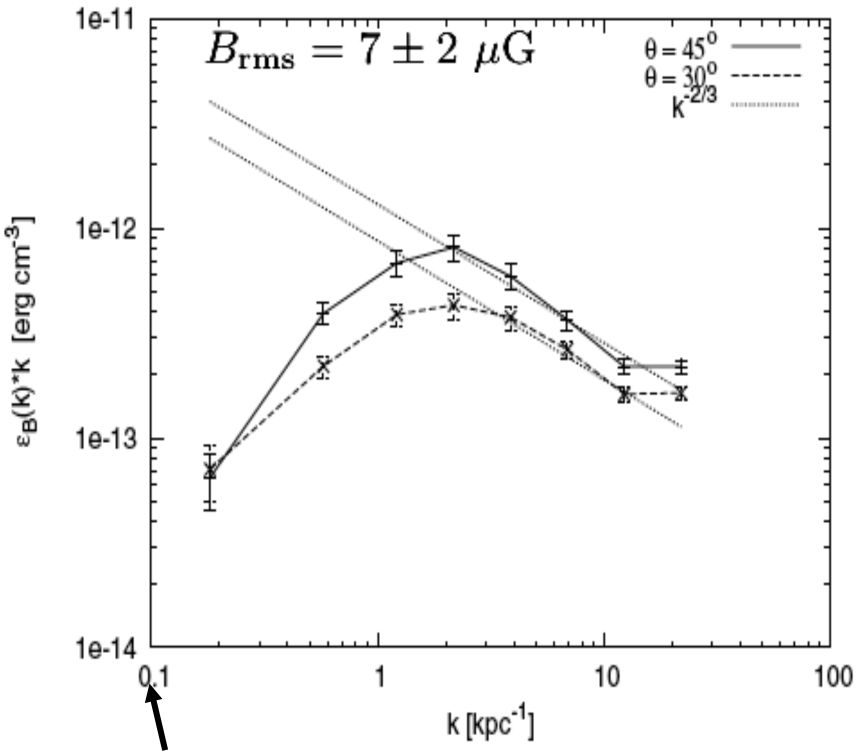
The Coma Cluster: pressure map
[Schuecker *et al.* 2004, *A&A* **426**, 387]

Cluster MHD Turbulence

TURBULENCE
Coma cluster
[Schuecker *et al.* 2004, *A&A* **426**, 387]



MAGNETIC FIELDS
Hydra A Cluster
[Vogt & Enßlin 2005, *A&A* **434**, 67]



•Magnetic Reynolds #, Rm ~ 10^{29}.

Turbulence scale is around here

CCFE CULHAM CENTRE FOR FUSION ENERGY

Many Questions

1. Seed Field: making the first field .. Particle physics, Weibel instability, stars.

-- typical assumption SEED few times 10^{-10} gauss

2. How fast can field be amplified

-- $\langle B^2 \rangle$ just magnetic energy. Small-scale-dynamo. SSD

-- mean $\langle \mathbf{B} \rangle$ -- structured flow – what structure? Helicity, sheared flow, ..?

2. What is the structure of the Saturated field? few times 10^{-6} gauss

-- folds, plasmoids, Alfven waves,

-- $\langle \mathbf{B} \rangle^2 / \langle B^2 \rangle$

3. Universality – do the transport properties of the medium matter.

-- P_M the magnetic Prandtl number (viscosity/resistivity)

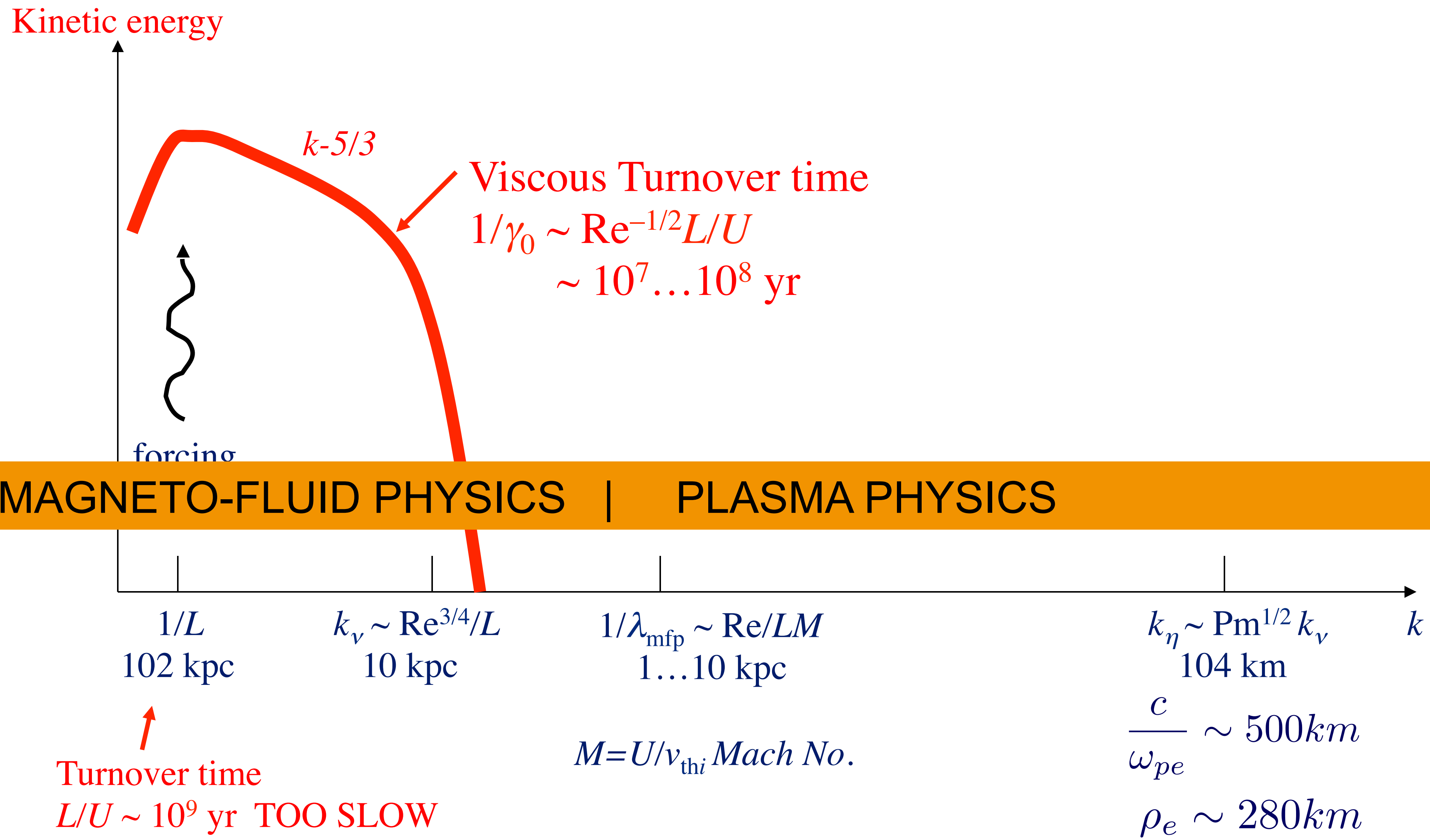
-- plasma versus rock, neutrals, cosmic rays --

4. Instability:

-- Providing the stirring flow – MRI, convection etc. Large scale?

-- Small scale instability – plasma instability – firehose, mirror, heat flow etc.

Cluster Turbulence Scales and Times

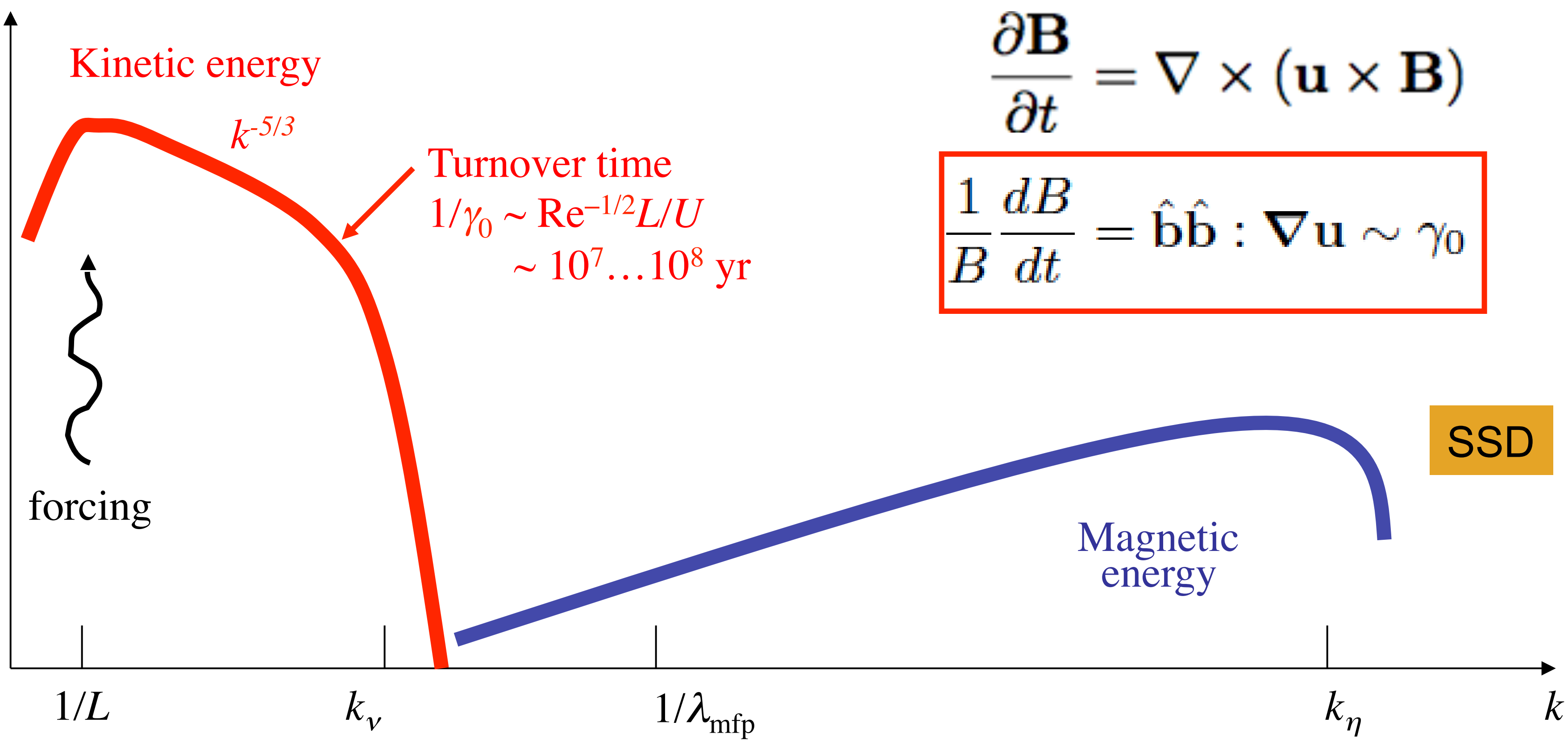


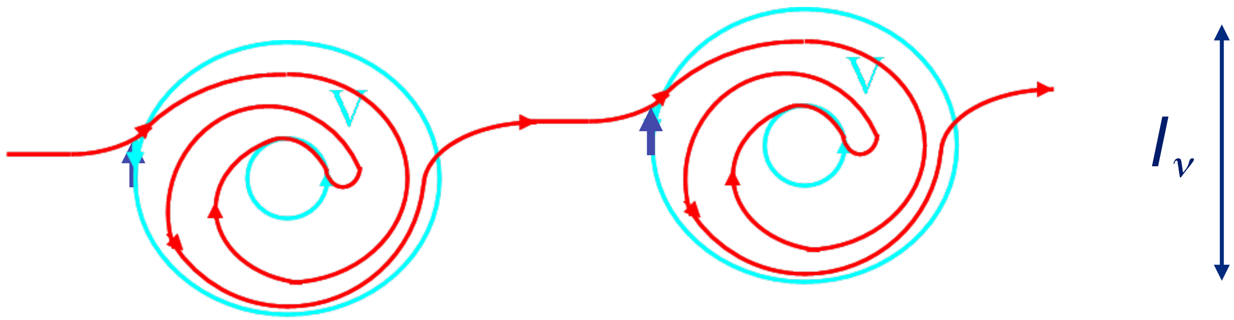
[Schekochihin *et al.*, *ApJ* **612**, 276 (2004)]

ICM is Magnetised

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})$$

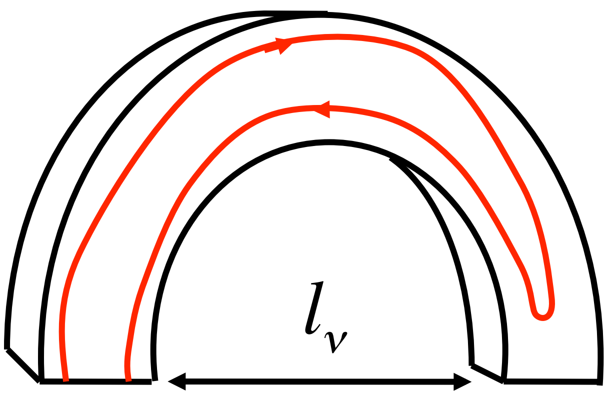
$$\frac{1}{B}\frac{dB}{dt} = \hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla \mathbf{u} \sim \gamma_0$$





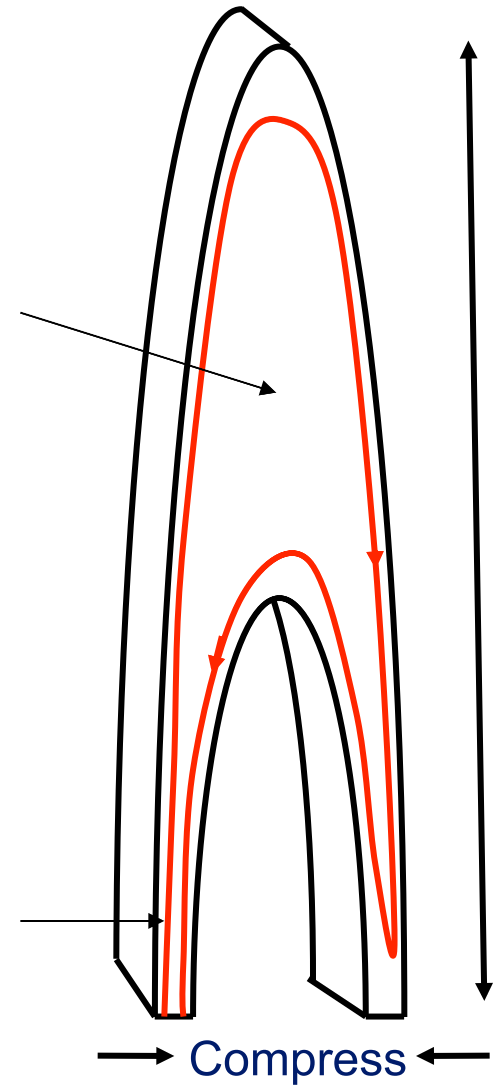
Bending and Stretching.

Bend



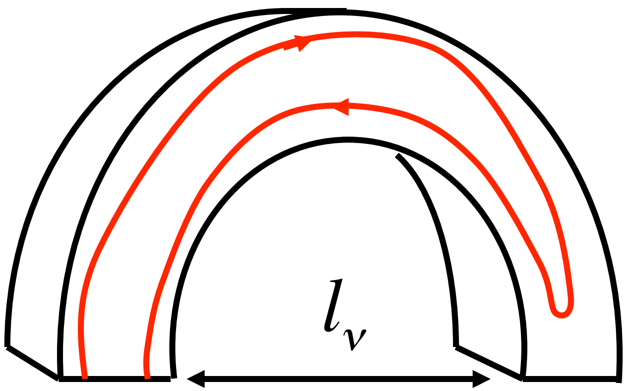
Curvature and |B| anti-correlated.

Stretch

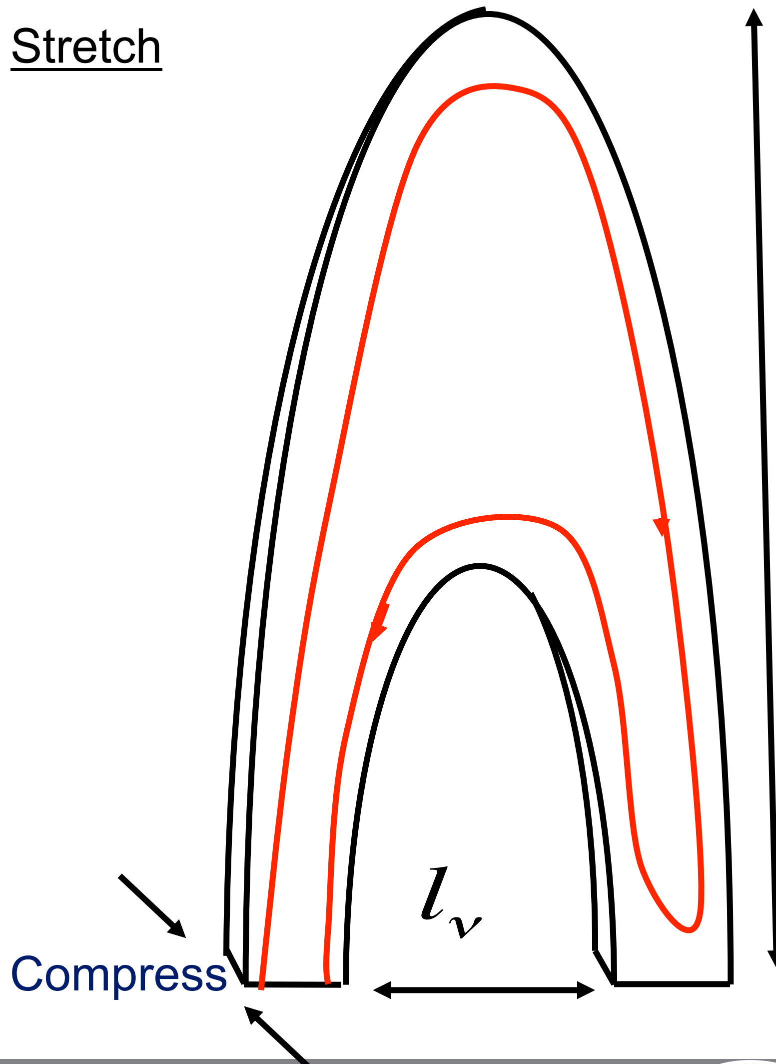


Amplification without generating smaller scales.

Bend

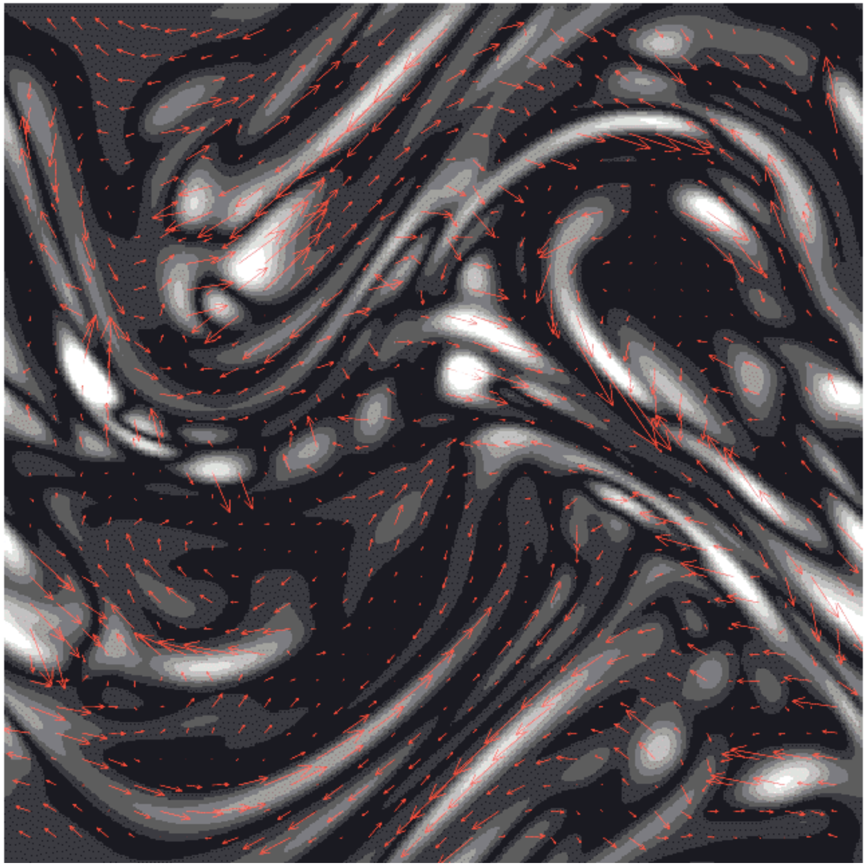


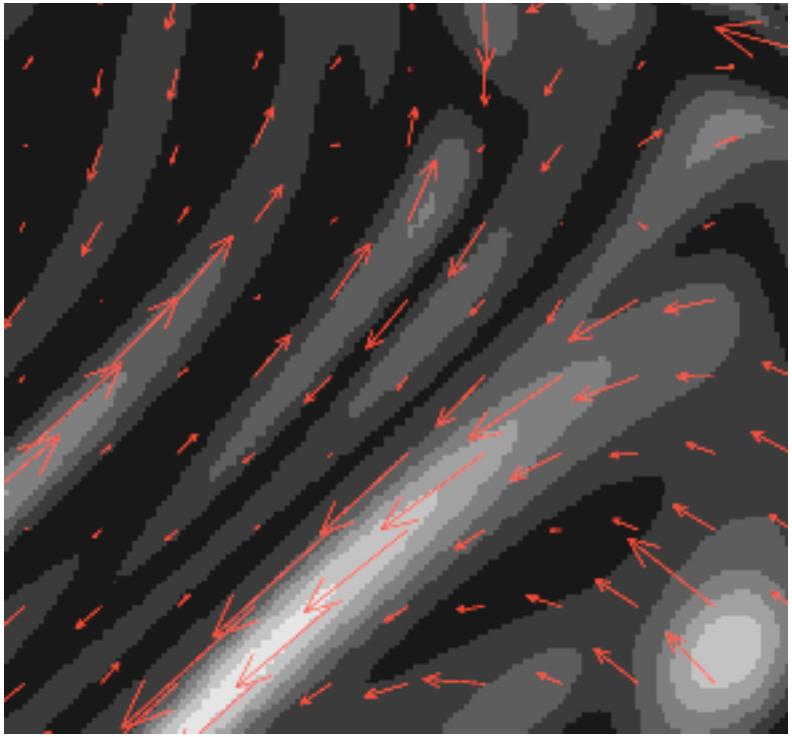
Stretch



Compress in the direction along which **B** doesn't change. Only some of the random motions do this.

Folded Structure Visualised

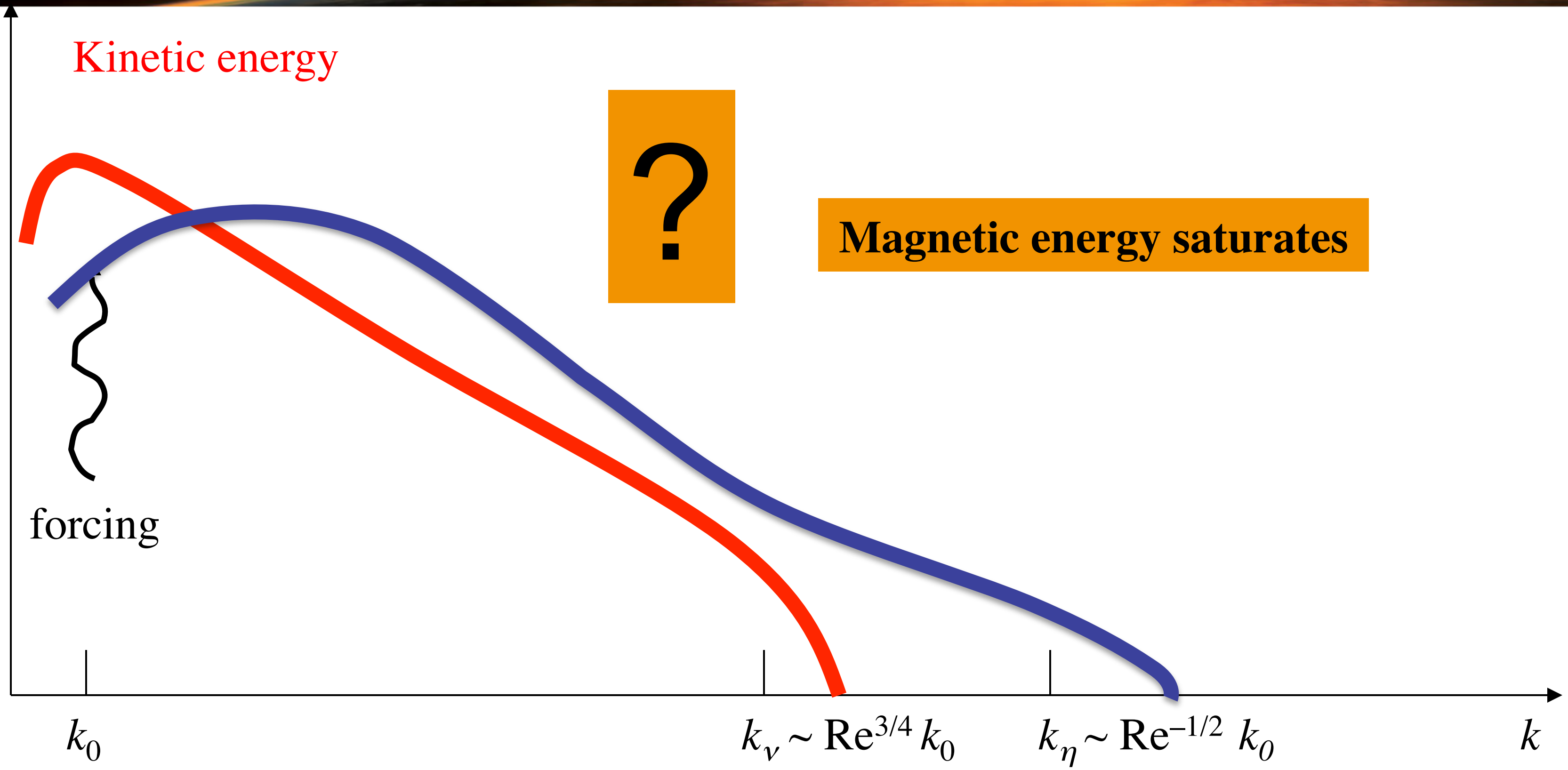




[see Schekochihin *et al*. 2004, *ApJ* **612**, 276; Schekochihin & Cowley, astro-ph/0507686 for an account of theory and simulations]

Fold thickness is resistive scale $k_\perp \sim k_\eta$
Fold length is size of stretching eddy $k_\parallel \sim k_\nu$.

Saturation



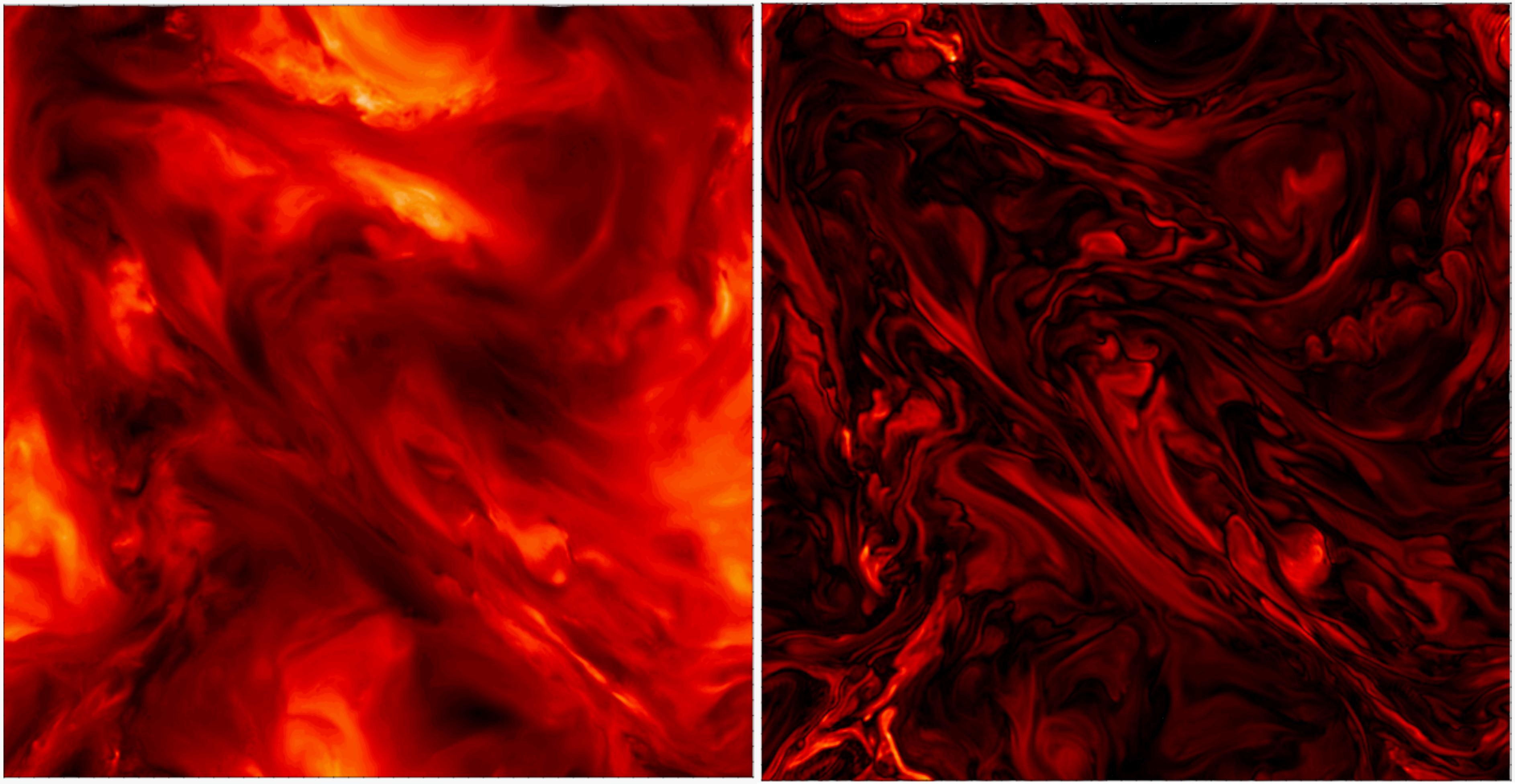
Nonlinear growth/selective decay/fold elongation continue until

$l_s \sim l_0 \longrightarrow \langle B^2 \rangle \sim \langle u^2 \rangle$

and $l_\eta \sim \mathrm{Rm}^{-1/2}\, l_0$

[Schekochihin *et al*. 2002, *NJP* **4**, 84]

Current Sheets Go Unstable?

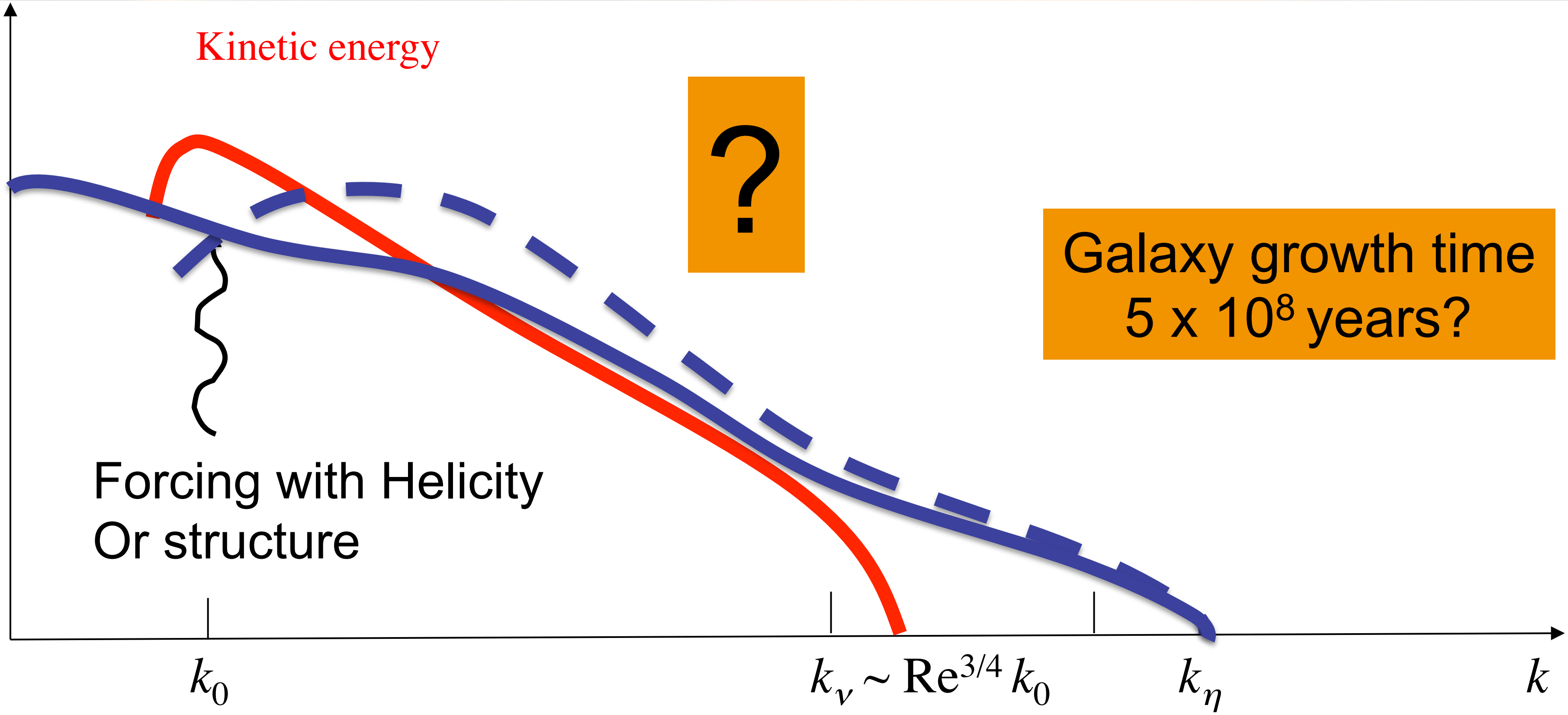


|u| |B|

Pm = 50, Re ~ 300

[Alexey Iskakov]

Mean Field Growth?



$l_s > l_0$

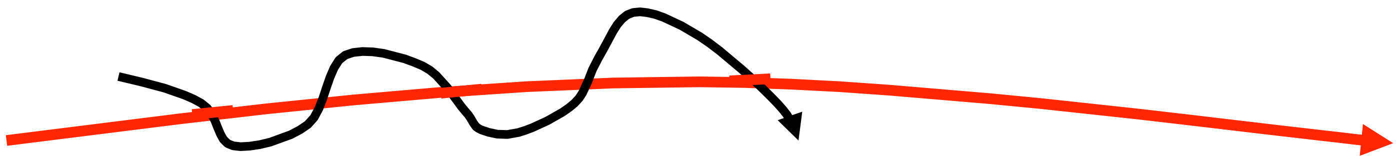
$\langle B^2 \rangle \sim \langle u^2 \rangle$??

$<\mathbf{B}>^2/<\mathrm{B}^2>$??

Collisionless Micro-Instability.

What does it do to the macroscopic behaviour.

Magnetized Viscosity --Anisotropic Pressure



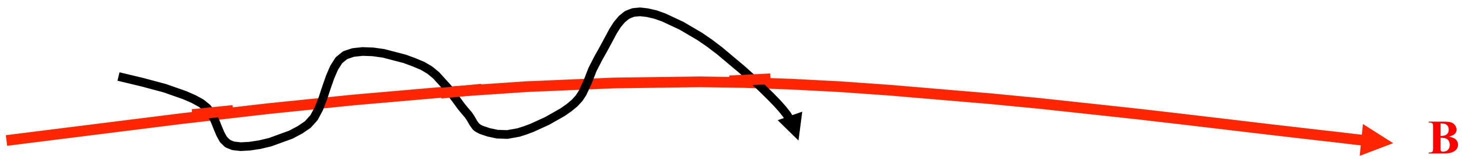
$$\mathbf{P} = \int \mathbf{v}\mathbf{v} f_i(\mathbf{v}, \mathbf{r}, t) d^3\mathbf{v}$$

DEFINITION OF PRESSURE TENSOR.

Anisotropic pressure tensor in magnetized plasma. Because of fast motion around the field the tensor must be of the form:

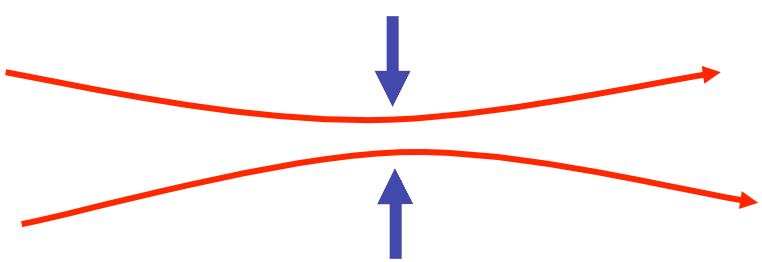
$$\mathbf{P} = P_\perp(\mathbf{I} - \mathbf{bb}) + P_{||}\mathbf{bb} \quad P_\perp = < \frac{1}{2} m_i v_\perp^2 > \quad P_{||} = < m_i v_{||}^2 >$$

Magnetized Viscosity.



$$\mu = \frac{v_\perp^2}{B} = \quad constant$$

Collisionless particle motion restricted to being close to field line and conserving μ.



Compressing Field

$$\frac{1}{B}\frac{dB}{dt} \sim \frac{1}{< v_\perp^2 >}\frac{d < v_\perp^2 >}{dt}$$

Collisionless.
Relaxed by Collisions.

$$P_\perp - P_\| \sim \frac{1}{\nu B}\frac{dB}{dt} \quad \mathrm{P}$$

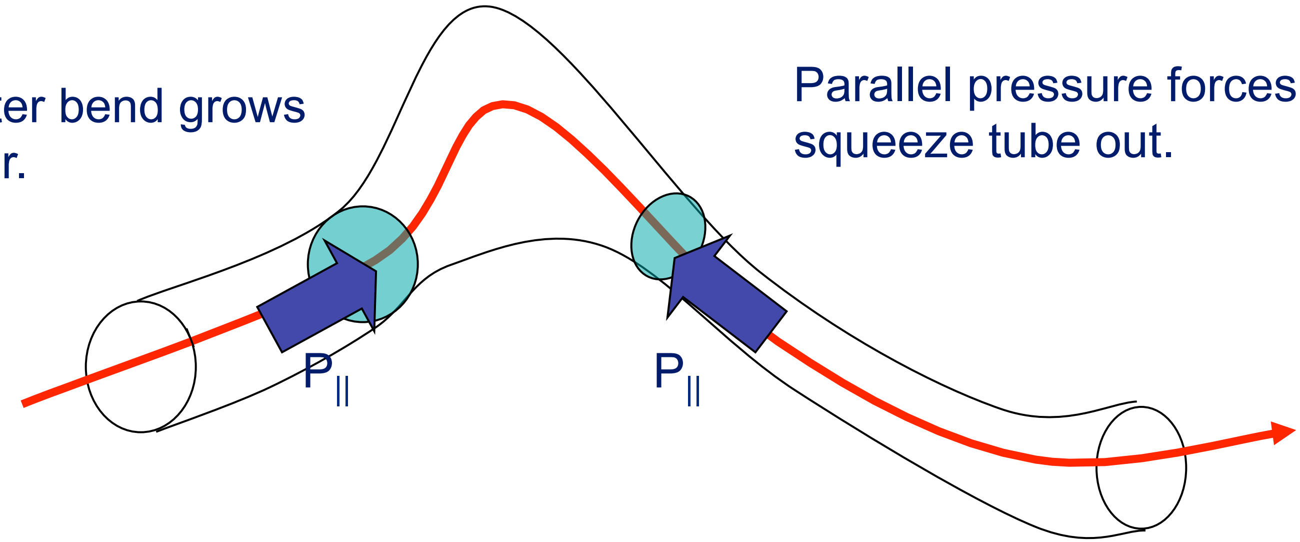
Firehose.

Unstable when $P_{\|0} - P_{\perp 0} = \frac{P_0 v_0}{\nu L_0} > B_0^2$

Growth rate at negligible B $\gamma = k_{\|} C_{sound} \sqrt{\frac{v_0}{\nu L_0}}$ VERY FAST

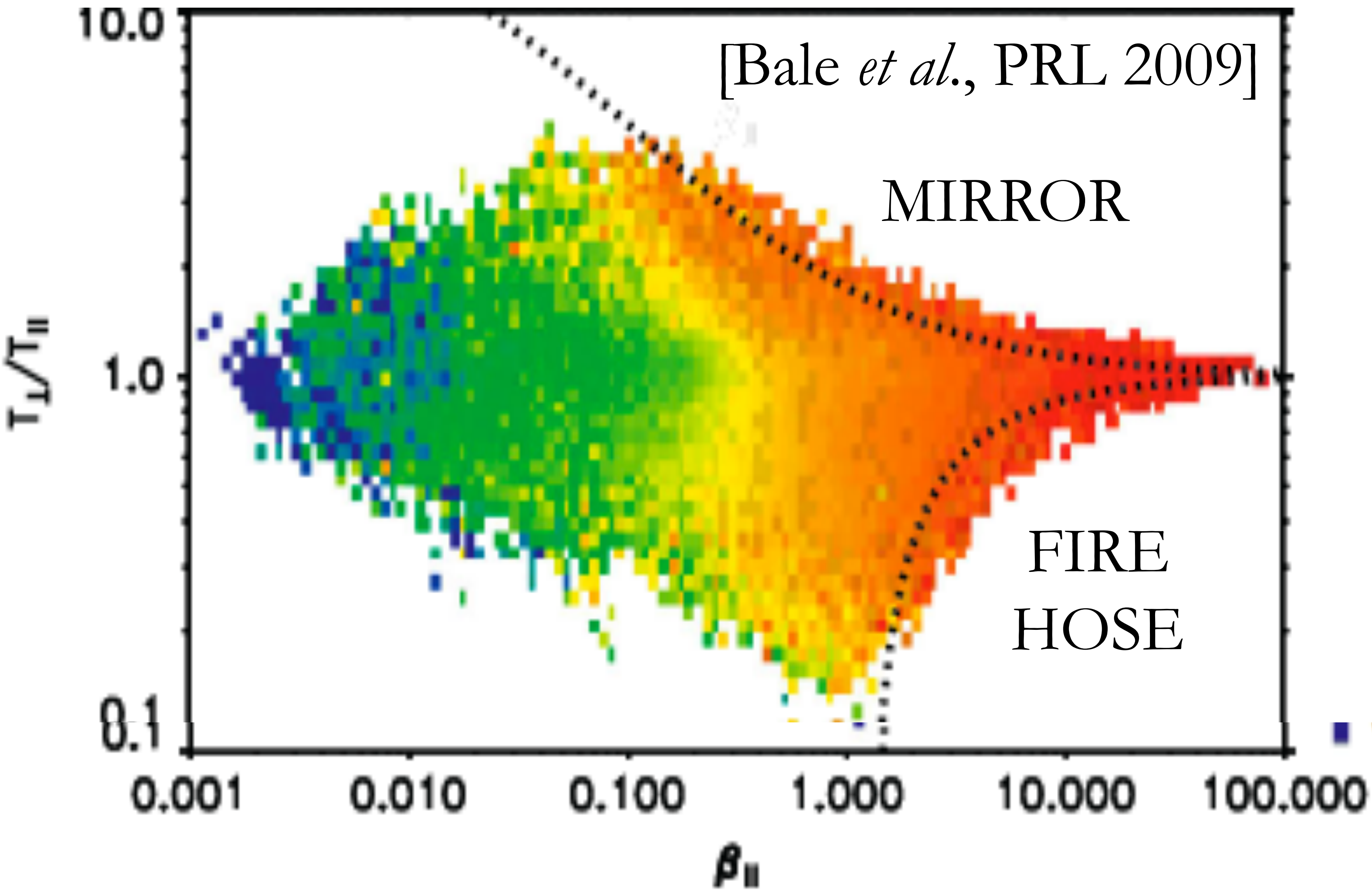
Tighter bend grows faster.

Parallel pressure forces squeeze tube out.



Rosenbluth 1956
Southwood and Kivelson 1993

Marginal Instability



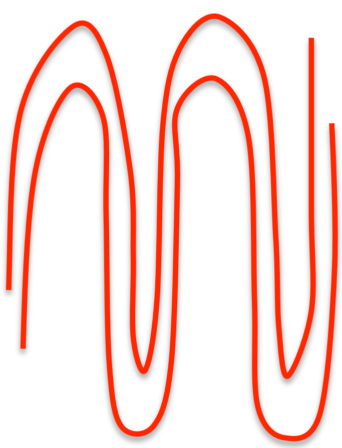
HOW DO WE ENFORCE MARGINAL INSTABILITY

- MORE COLLISIONS? – mode scatters particles.

effective collision rate

$$\nu_{eff} = \frac{P_0 v_0}{B_0^2 L_0}$$

- FOLD FIELD TO ENFORCE $\frac{dB}{dt} = 0$



There is lots to do. You will Learn about these things and more in much greater detail here.

ENJOY