MHD Turbulence and Cosmic Ray Reacceleration in Galaxy Clusters

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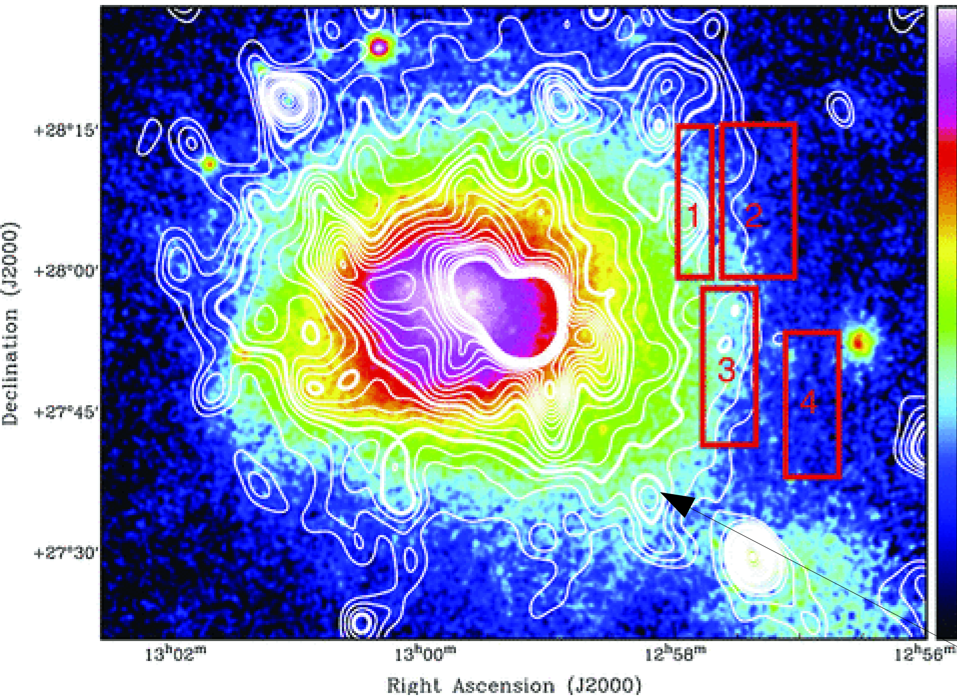
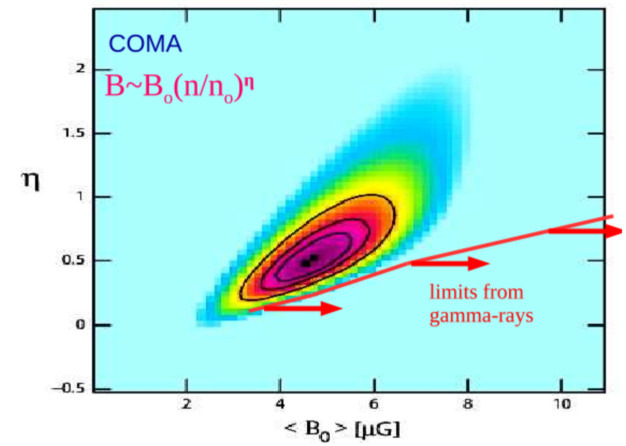
Diffuse radio halos...

...are observed,



Brown & Rudnick, 2011

but assuming electrons are secondary, are incompatible with *not observed* gamma-ray emission!



Bonafede et al 2010, Brunetti 2011

Morphology also suggests a different origin for electrons.

Why electrons are more energetic than we expect?

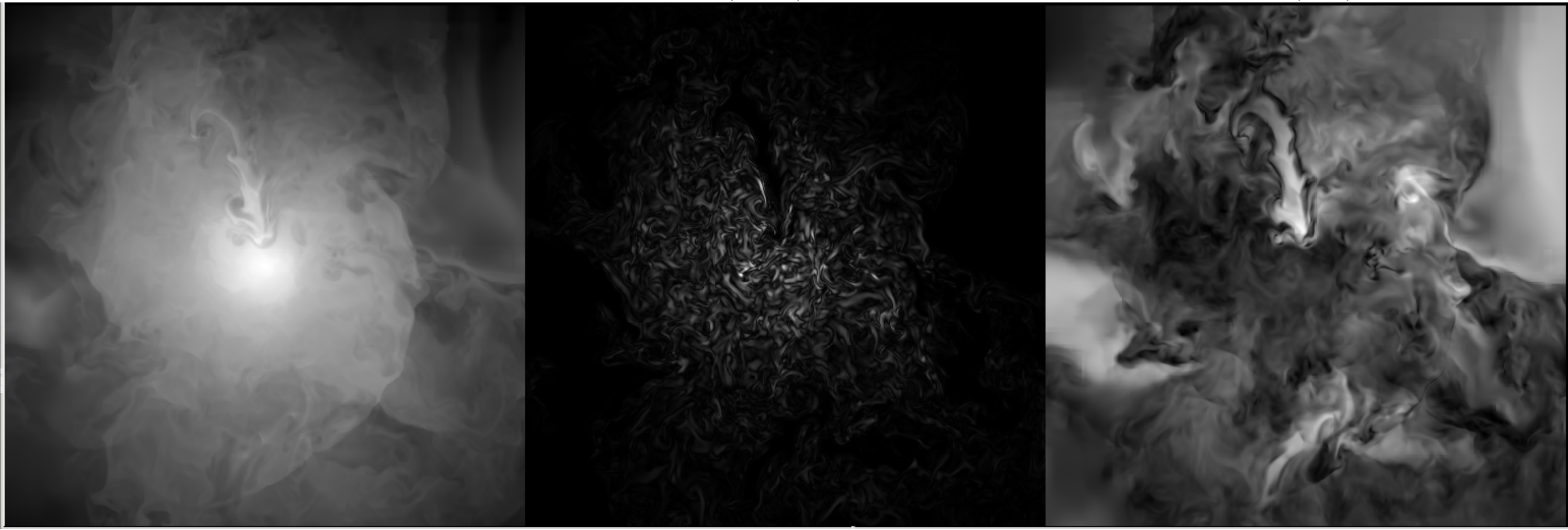
The problem with electrons is that they constantly lose energy due to synchrotron and inverse Compton, and need to be produced at a high rate. What if they are not *produced* but *re-accelerated* by turbulence (see, e.g. *Brunetti & Lazarian 2011*)?

Simulated clusters

From Xu et al 2010: z=30÷1, standard ΛCDM, B injected by AGN

$$v_A \sim 10^7 \mathrm{cm/s}$$

$\log \rho$ $|B|$ $|v|$



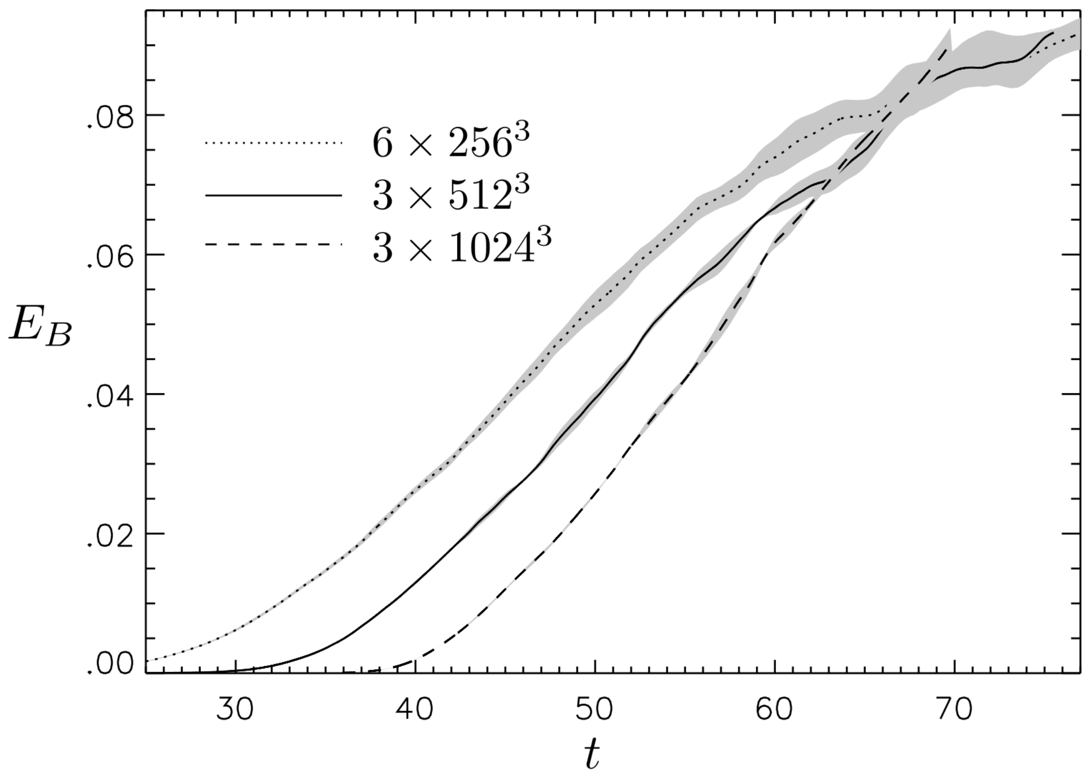
On applicability of MHD vs plasma:

Free energy budget of plasma – $\epsilon t_m \sim \frac{\rho v^2}{2} \left(\frac{t_m}{5 \text{ Gyr}} \right)$

Estimates of the mesoscale are plenty, e.g. Lazarian & Beresnyak (2006) $l_m \sim 10^{-3}$ pc

Nonlinear Small-Scale Dynamo

Run	n	N^3	Dissipation	$\langle\epsilon\rangle$	Re	C_E
M1-6	6	256^3	$-7.6 \cdot 10^{-4} k^2$	0.091	1000	0.031 ± 0.002
M7-9	3	512^3	$-3.0 \cdot 10^{-4} k^2$	0.091	2600	0.034 ± 0.004
M10-12	3	1024^3	$-1.2 \cdot 10^{-4} k^2$	0.091	6600	0.041 ± 0.005
M13	1	1024^3	$-1.6 \cdot 10^{-9} k^4$	0.182	–	0.05 ± 0.005
M14	1	1536^3	$-1.5 \cdot 10^{-15} k^6$	0.24	–	0.05 ± 0.005

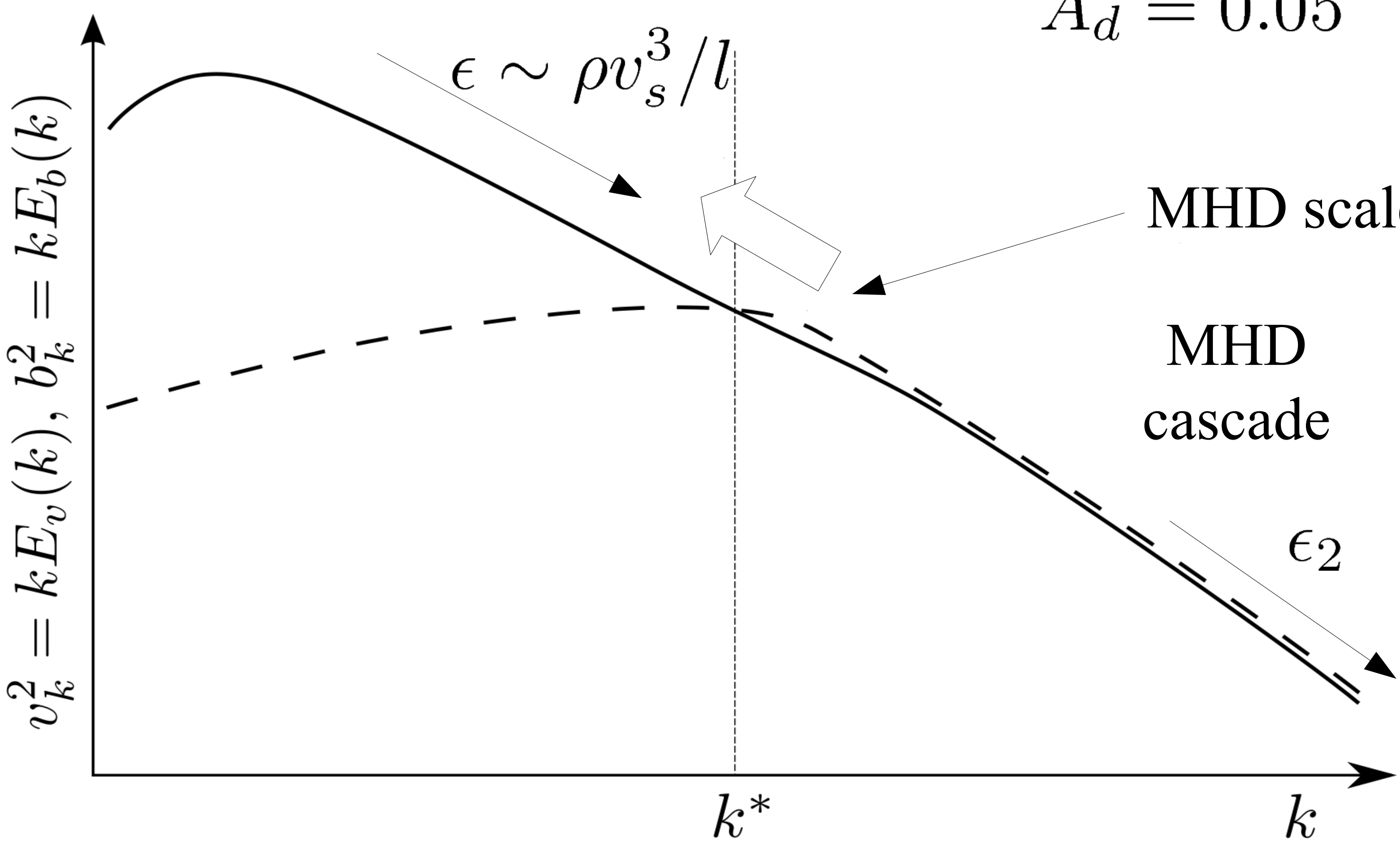


$$C_E = (\epsilon - \epsilon_2)/\epsilon$$

Nonlinear Small-Scale Dynamo

$$\frac{1}{8\pi}\frac{dB^2}{dt} = (\epsilon - \epsilon_2)t = A_d \epsilon t$$

$$A_d = 0.05$$

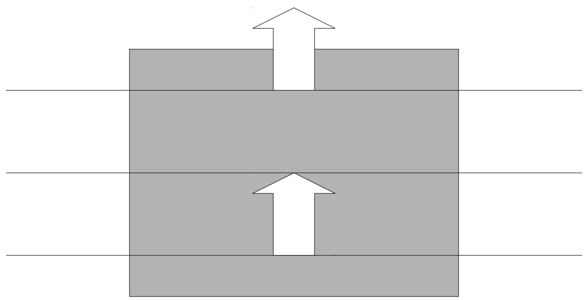


Zeroth Law of Dynamo: *Beresnyak, PRL 108, 035002 (2012)*

Compressible MHD turbulence

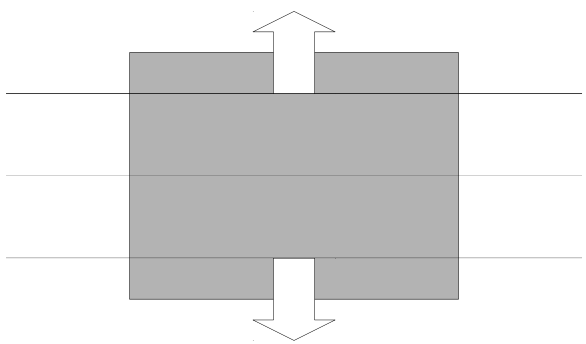
- SubAlfvenic on small scales (mean **B** field dominates)
- Four basic modes: Alfven, slow, fast, entropy

Alfven



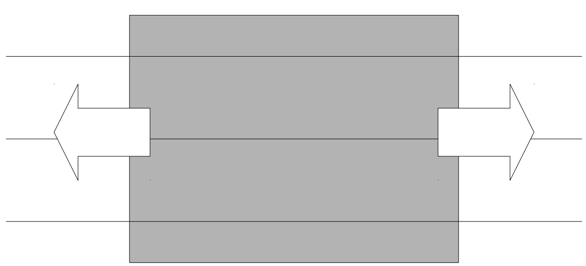
Inertia: fluid,
Restoring force: Lorentz

fast



Inertia: fluid,
Restoring force: Lorentz+pressure

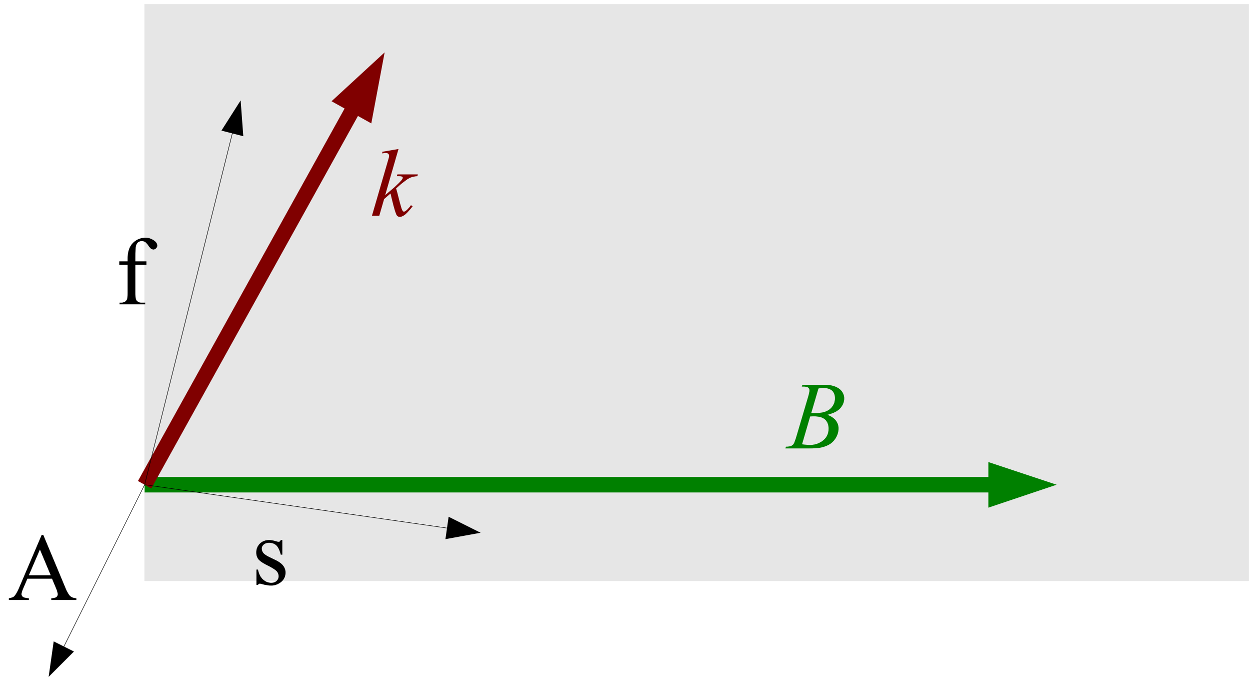
slow



Inertia: fluid,
Restoring force: pressure

Compressible MHD turbulence

- SubAlfvenic on small scales (B_0 dominates!)
- Four basic modes: Alfven, slow, fast, entropy



$$\mathbf{A} \sim (\mathbf{k} \times \mathbf{B})$$

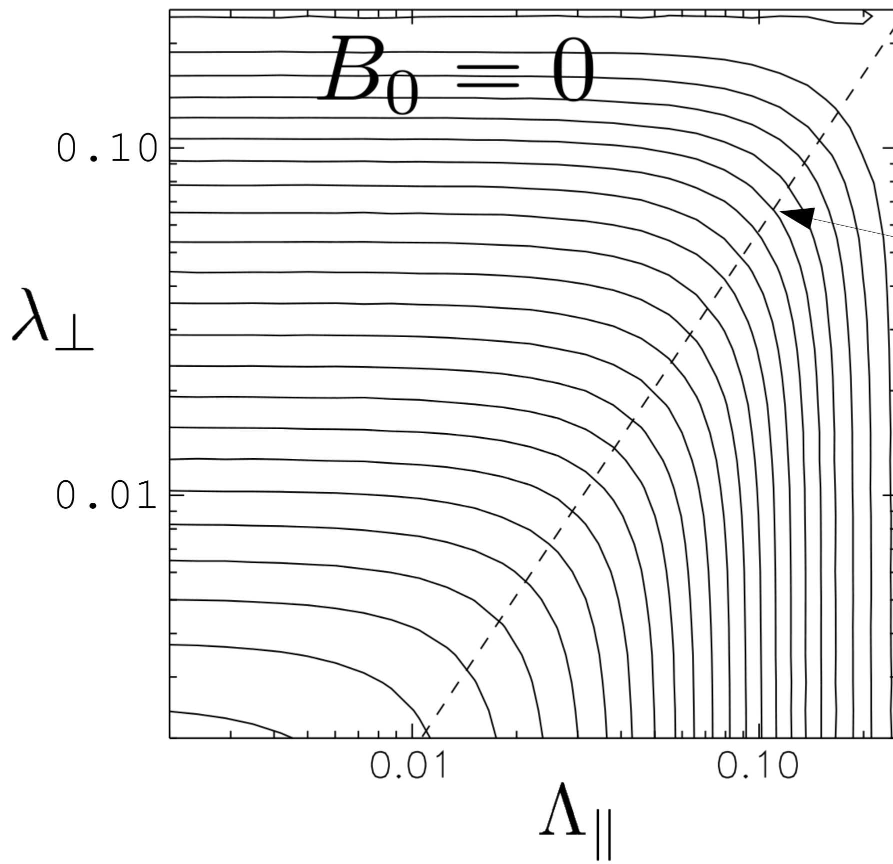
Anisotropy of MHD Turbulence

Structure function $\mathrm{SF}^2(w^{\pm}, \Lambda, \lambda) = \langle (w^{\pm}(\mathbf{r} + \Lambda \hat{\mathbf{b}}_{\lambda} + \lambda \hat{\mathbf{n}}_{\lambda}) - w^{\pm}(\mathbf{r}))^2 \rangle_{\mathbf{r}}$

calculated with respect to the <u>local</u> magnetic field

You <u>do not need</u> to have a mean field B_0

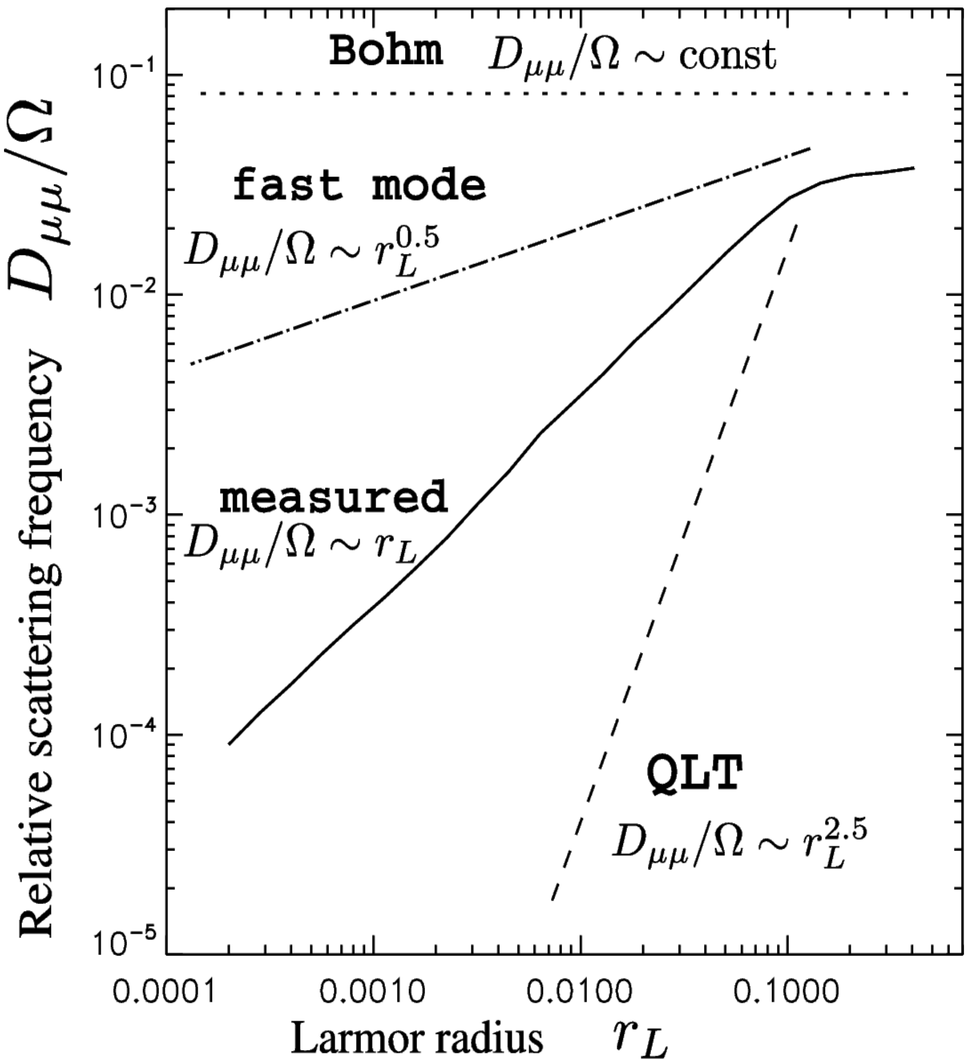
Isotropically driven MHD turbulence



GS anisotropy

Beresnyak & Lazarian (2009)

Particle scattering: Alfven and slow modes are inefficient

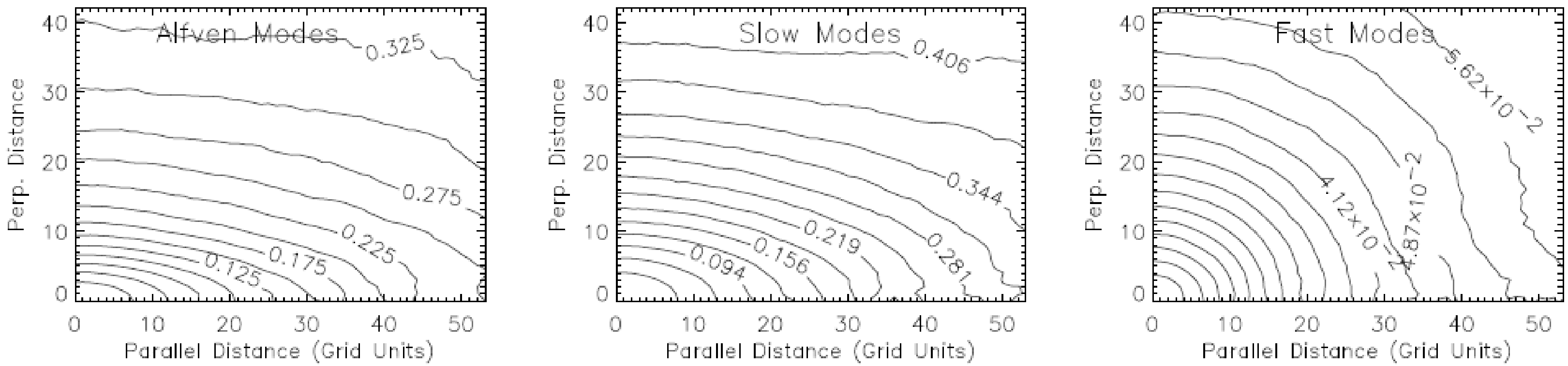


from Beresnyak et al 2011

Bottom line: you have to measure mode amplitudes to understand CR scattering

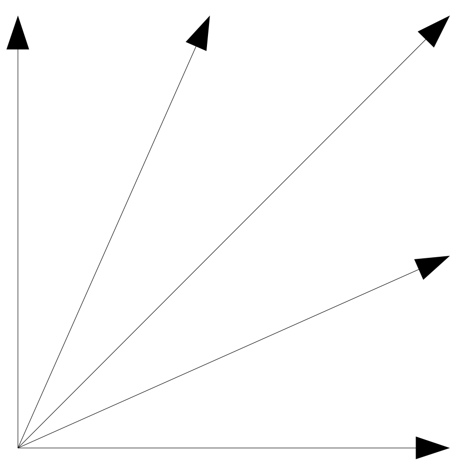
Mode decomposition, previous work

Cho & Lazarian (2003): relies on a **global** mean field



Wavelets? Impossible to use wavelets directly: k-space is too discrete

k=0,1,2,4,8...



Kowal & Lazarian (2010)

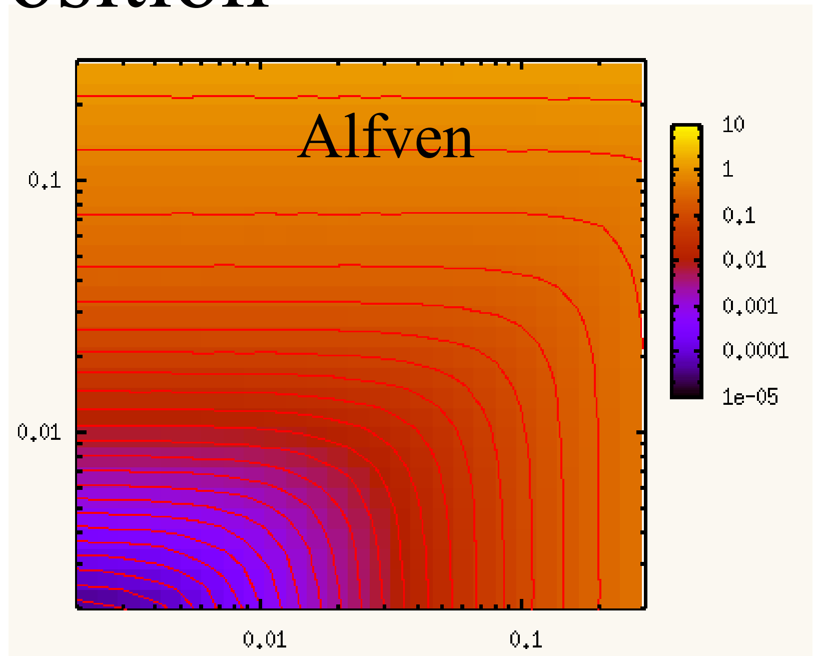
Does a Fourier transform of each wavelet -- slow!

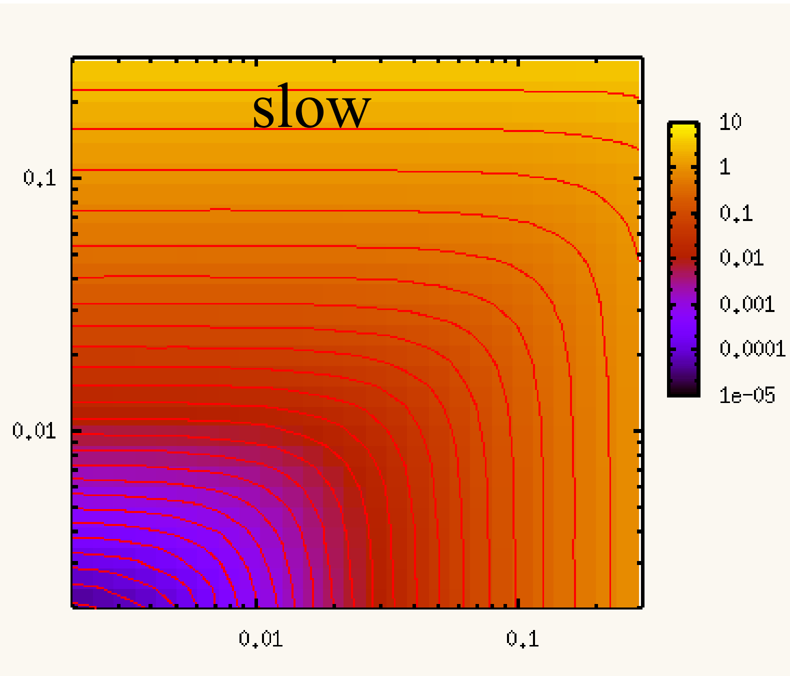
Mode decomposition

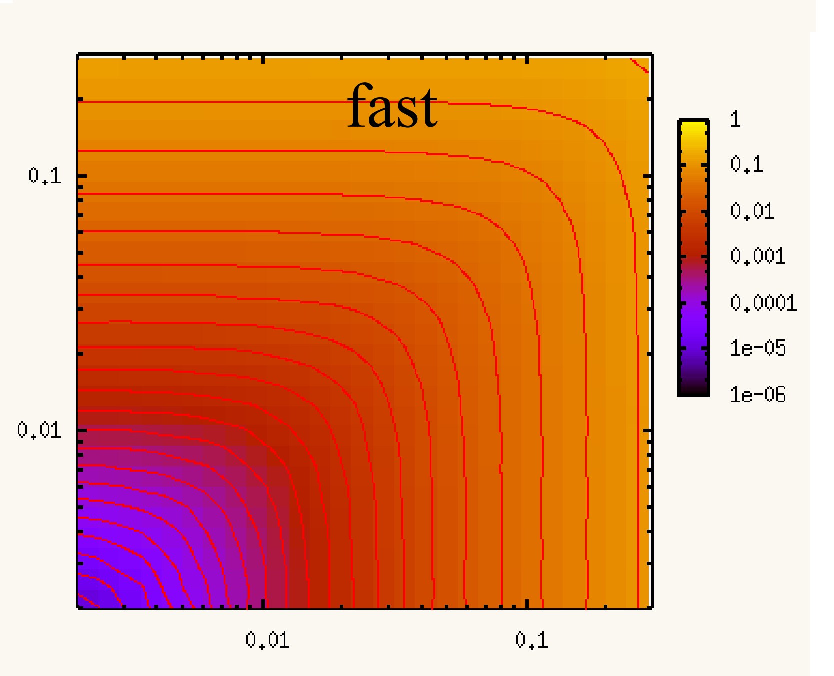
Beresnyak, 2011

Direct structure function method

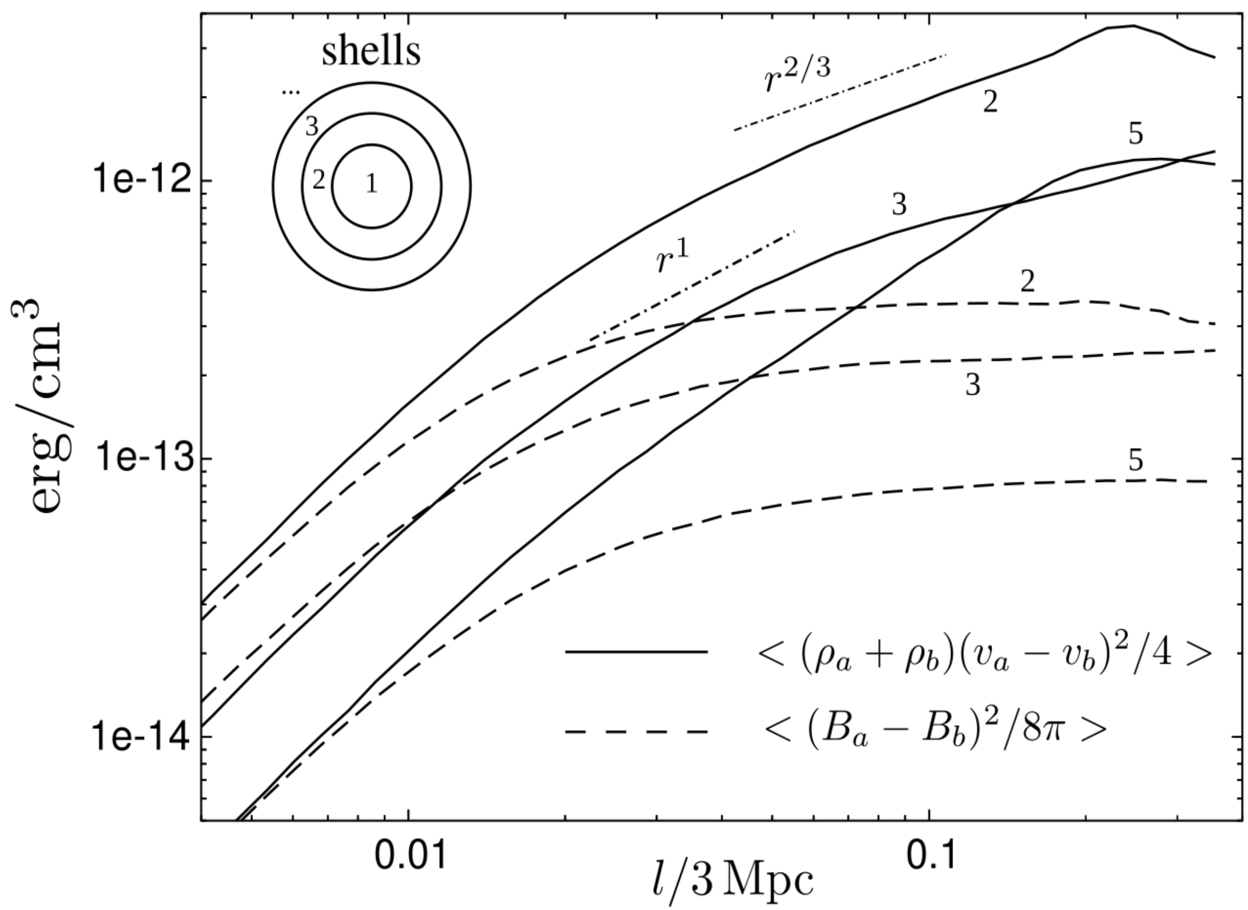
- Doesn't rely on a global mean field
- Relies on a 3-point structure function
- ...
- FAST!



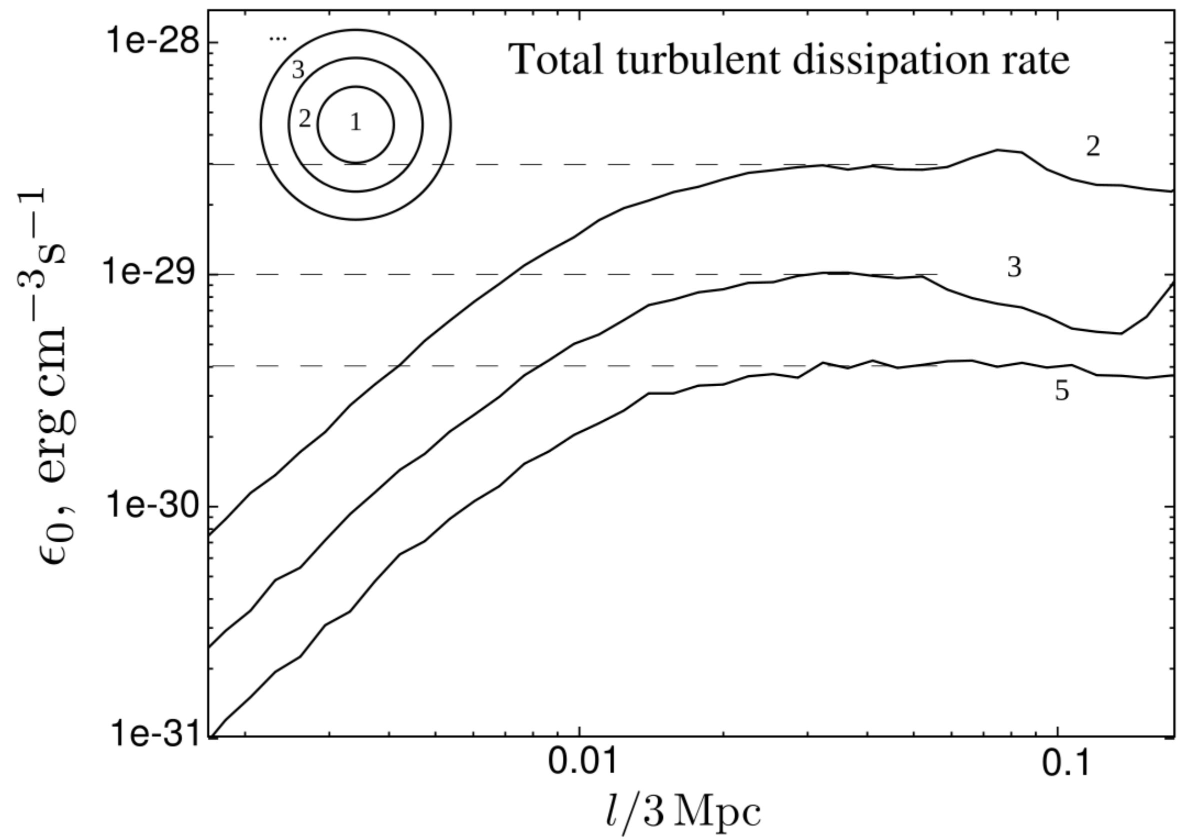




1. Introduce local measurement with structure functions



2. Measure turbulent dissipation rate



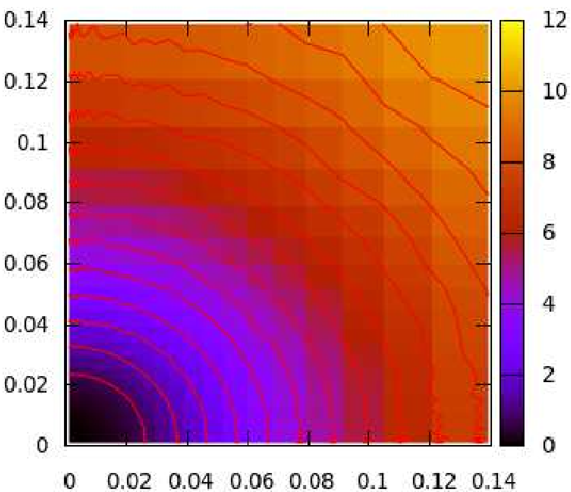
lifetime

$\sim 3 \times 10^9$years

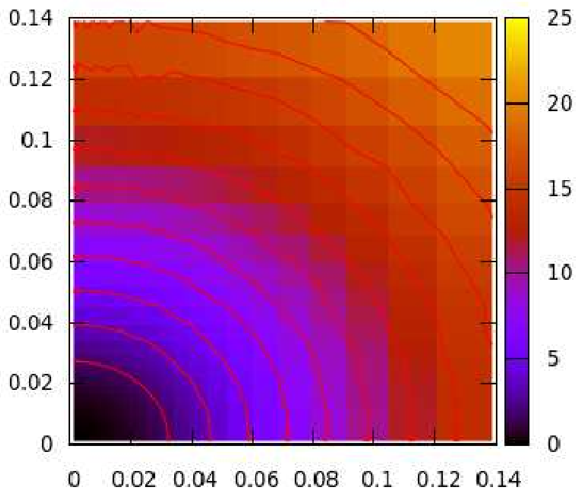
$\sim 8 \times 10^9$years

3. Decompose into modes

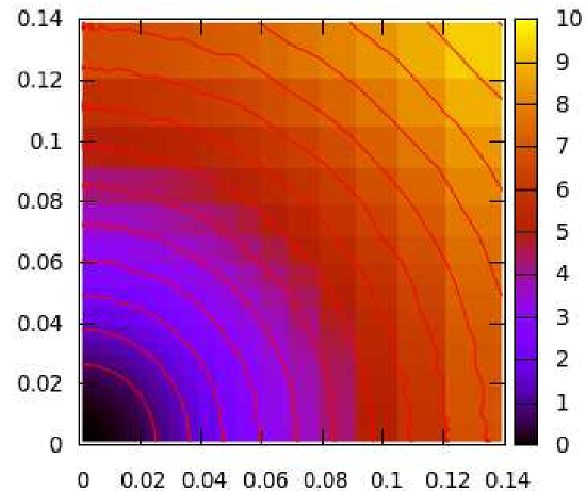
Alfven



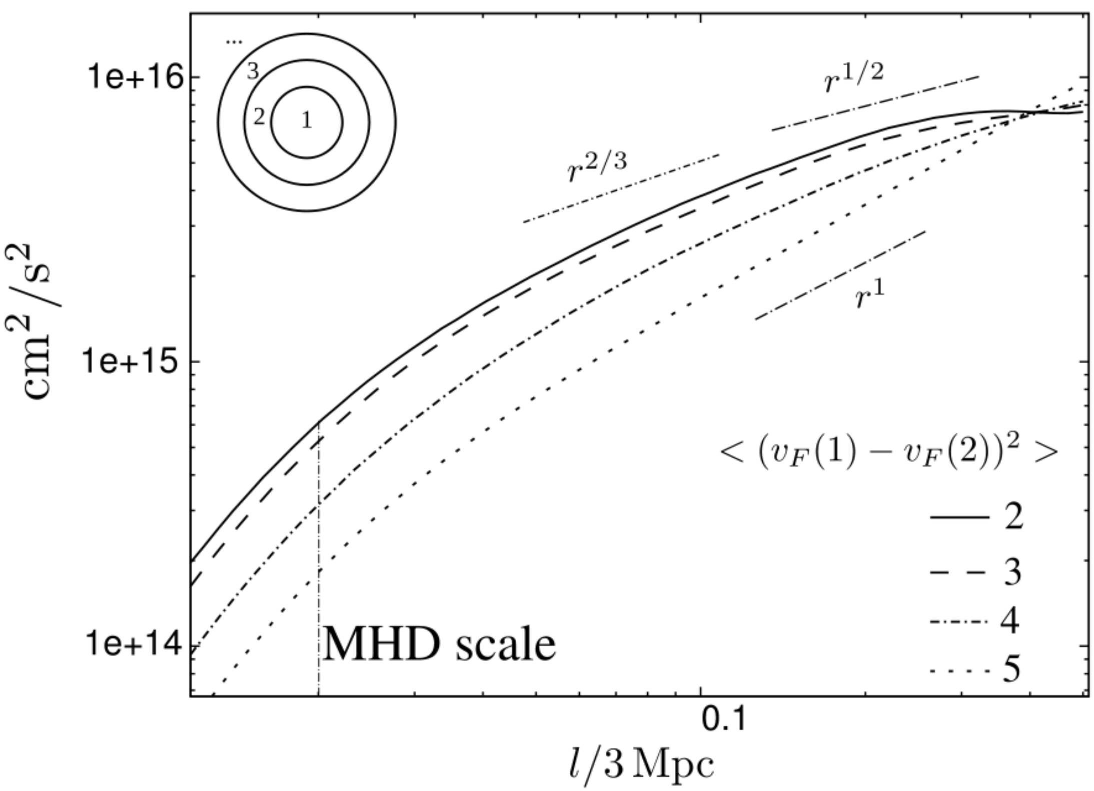
slow



fast



4. Measure a fraction of the dissipation rate pertaining to the fast mode



A model in Cho & Lazarian (2003) predicts fast mode amplitude fraction

$$e_f \sim M_s^2/M_A$$

for subsonic case. This is much smaller than $e_f \sim 0.25$ that we observe

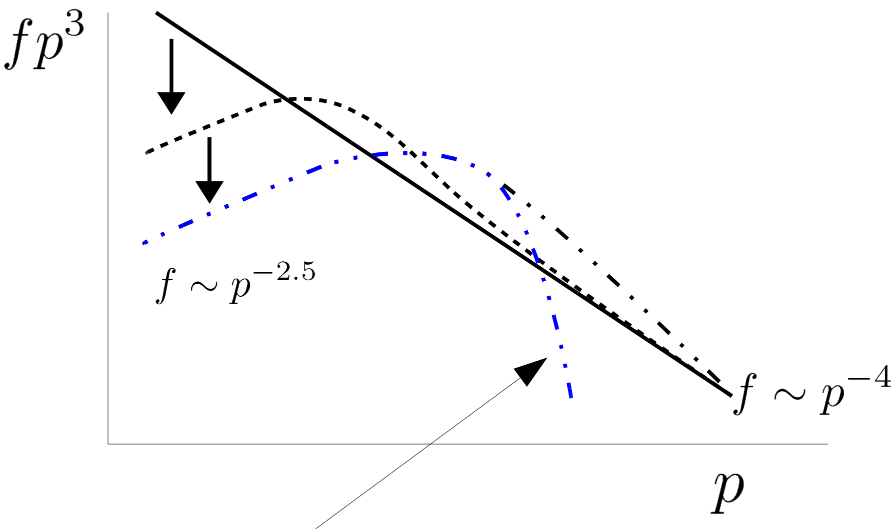
$$\epsilon \sim \epsilon_0 e_f^2 M_s \sim 0.02\epsilon_0$$

$$E_F(k) = C_{\mathrm{KF}} \epsilon^{1/2} c_s^{1/2} k^{-3/2}$$

What is the nature of electron acceleration?

Flux of particles through momentum space

$$F = -4\pi p^2 D_{pp} \partial f / \partial p$$



$$f \sim p^{-5/2} \exp(-(p/p_s)^{3/2})$$

cut-off due to losses

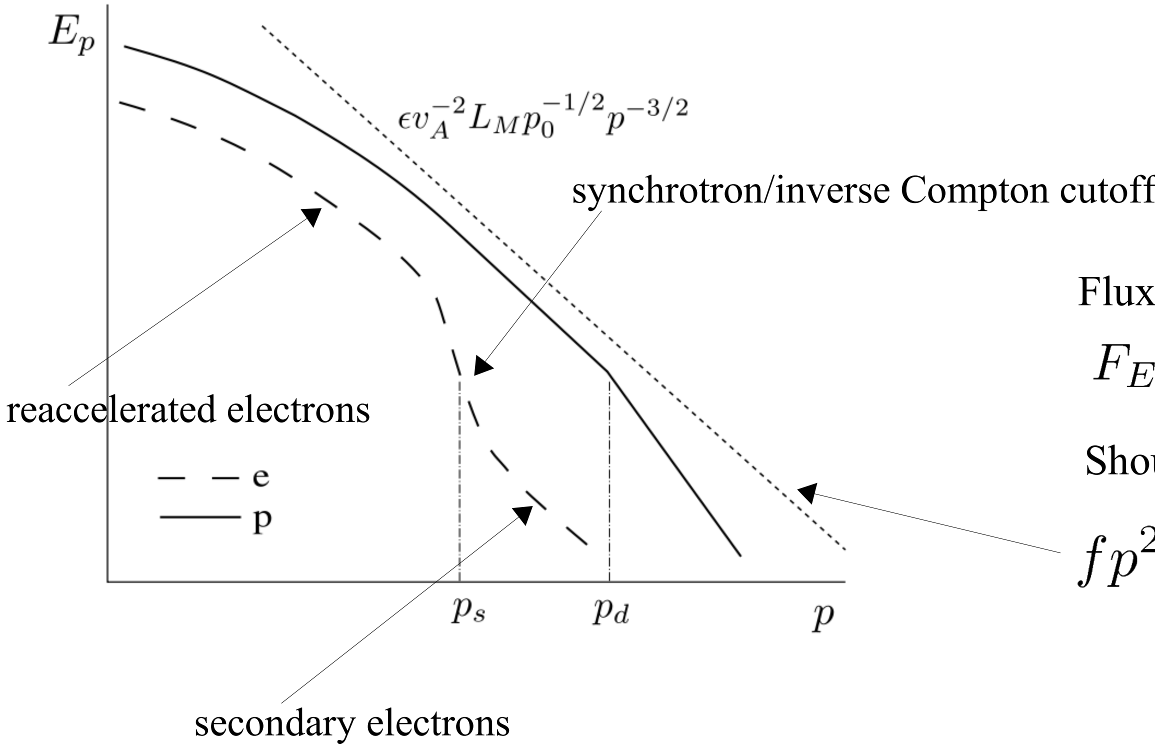
Is this what's really happening?

Flux of *energy* through momentum space:

$$F_E = pcF = -4\pi c p^3 D_{pp} \partial f / \partial p$$

Should be *smaller* than the dissipation rate!

What is the nature of electron acceleration?



Flux of *energy* through momentum space:

$$F_E = pcF = -4\pi c p^3 D_{pp} \partial f / \partial p$$

Should be *smaller* than the dissipation rate!

$$f p^2 = E_p < \epsilon v_A^{-2} L_M p_0^{-1/2} p^{-3/2}$$

$$p_0 \approx 12 eBL_M / c$$

$$p_d \sim 2 \cdot 10^{-6} p_0 \ \sim 2 \text{ PeV}$$

$$p_s = mc(16\pi^2 eBmc^2/\sigma_T^2 L_M B_*^4)^{1/3} (v_A/c)^{4/3} \sim 20 \text{ GeV}$$

In the energy range important for ~1 GHz radio, electron spectrum is concave due to combination of secondary electrons plus synchrotron cutoff of reaccelerated electrons

Summary

- Diffuse radio halos is an important diagnostic of clusters
- Electron acceleration is required to explain diffuse radio halos
- The key to study in-situ turbulent acceleration is MHD modes
- We use an efficient and simple method to extract modes from any MHD simulation (without mean field, inhomogeneous, etc)
- We obtained fast mode fraction which is much larger than was predicted earlier. We think this is because ICM turbulence is driven by mergers, compressible transsonic motions.
- A limit, imposed by the energy flux constraint of the fast mode turbulence leads to a steeper spectrum, which has an cutoff at lower energies for electrons and could explain soft radio spectra.