Turbulence and dynamo action in galaxy clusters

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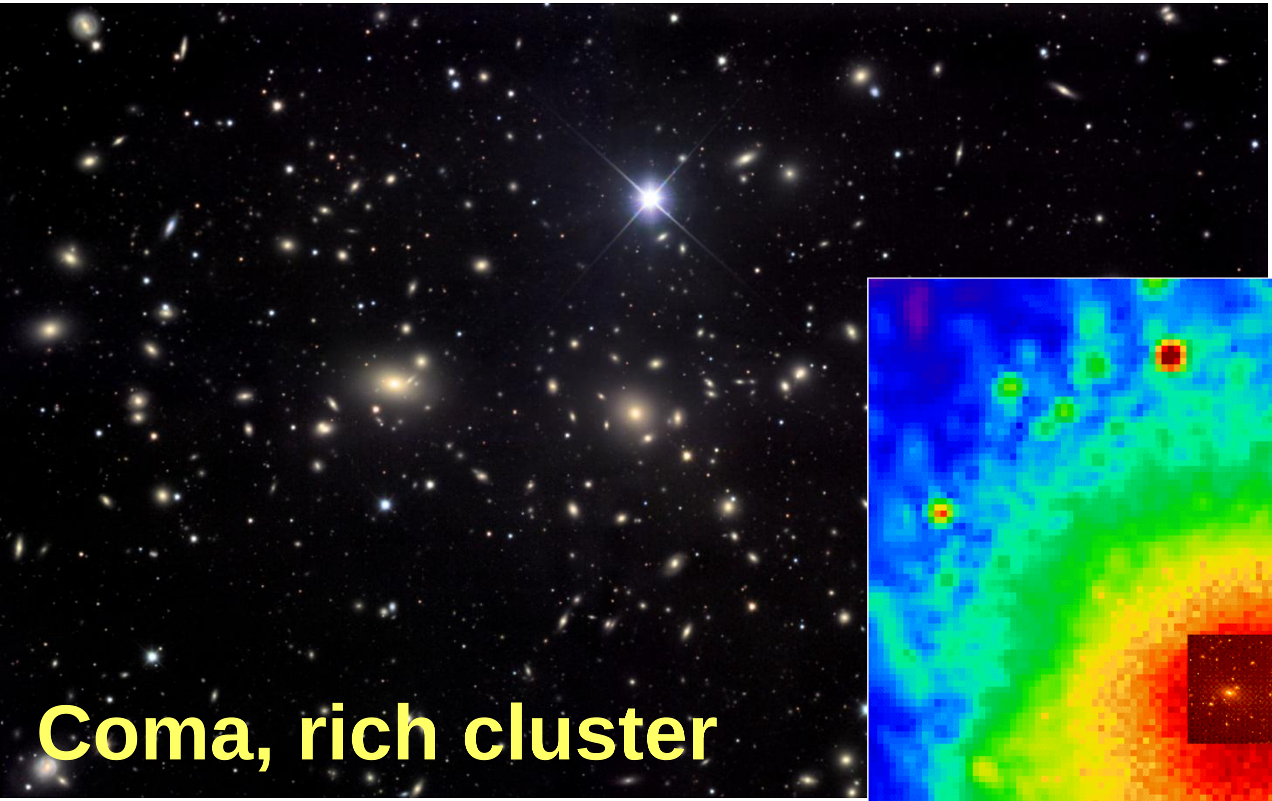
Outline

Galaxy clusters



Size $L \cong 1$ Mpc

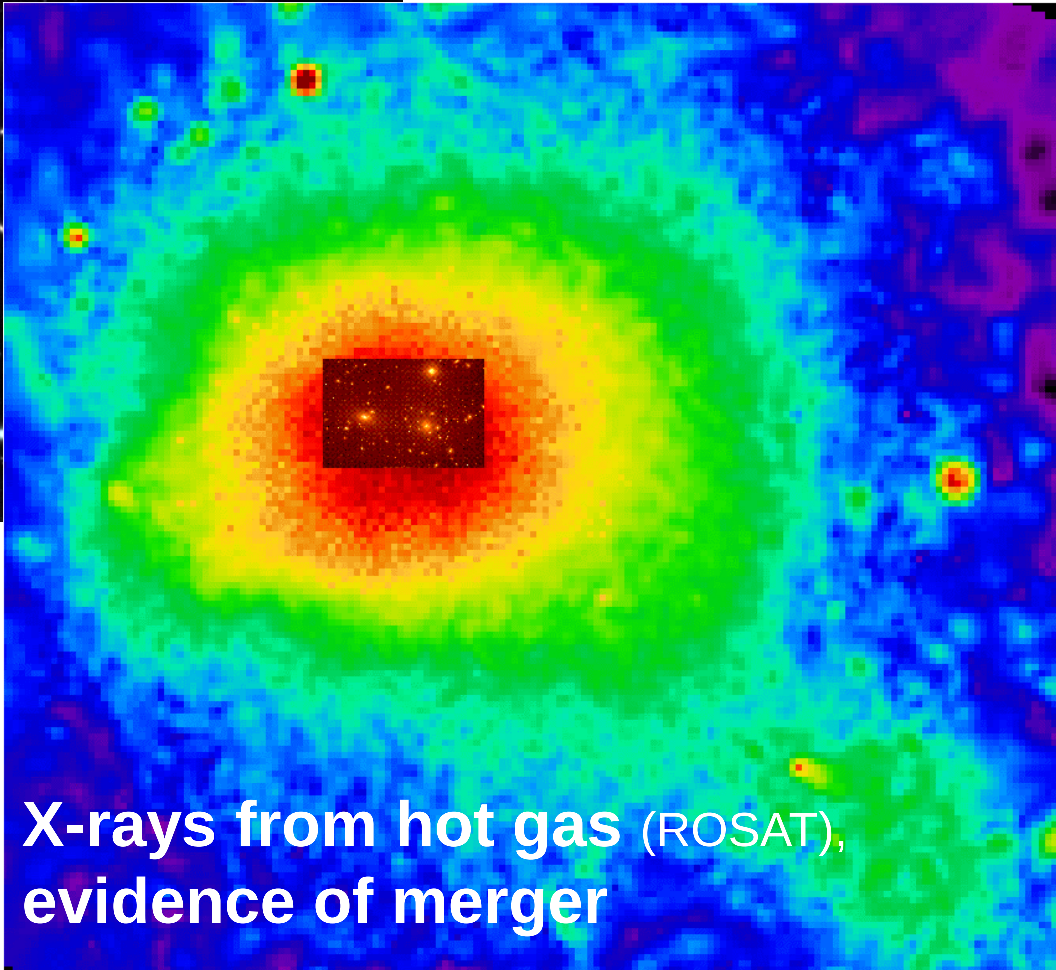
$N \cong$ 1000's galaxies

Gas density $n \cong 3\times10^{-3}$ cm^{-3}

Temperature $T \cong 10^8$ K

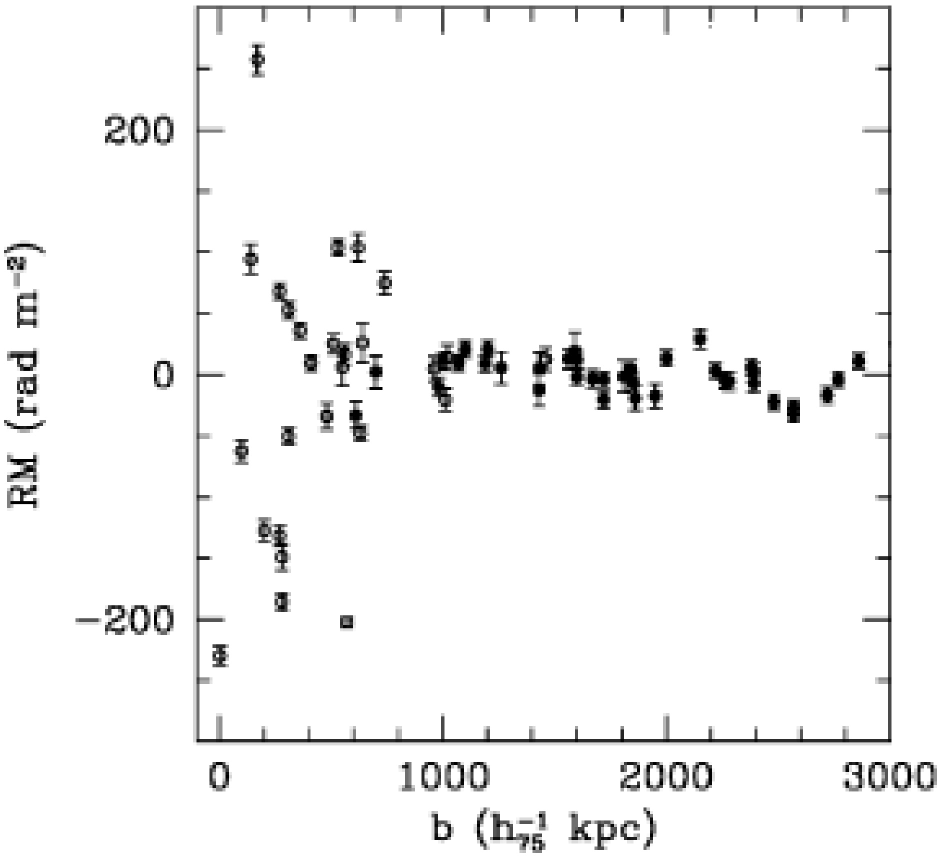
Sound speed $c_s \cong 10^3$ km/s

Mean free path $\lambda \cong 5$ kpc



Evidence of intracluster magnetic field

- Synchrotron emission (from a dozen clusters)
- Faraday rotation in a random magnetic field (from many clusters)



$\sigma_{RM} \cong 100\text{–}200\ \mathrm{rad/m^2}$

$\ell_B \cong 10\text{–}20$ kpc

$B \cong (5\text{–}10)(\ell_B\ /10\ \mathrm{kpc})^{-1/2}\ \mu\mathrm{G}$

RM of background radio sources vs. impact parameter for 16 galaxy clusters; filled symbols: field sources (Clarke et al., 2001)

A few words on the fluctuation dynamo

1. Linear (kinematic) behaviour

(Zeldovich et al., The Almighty Chance, World Sci., 1990)

- Any random flow can generate random magnetic field if only $R_{\mathrm{m}} > \mathrm{R}_{\mathrm{m,cr}} \simeq 30\text{–}100$.
- e-folding time of B_{rms} due to motions at scale ℓ: $\tau(\ell) \simeq \ell / v(\ell)$.
- For $v(\ell) \propto \ell^{1/3}$, *B* grows faster at smaller scales, $\tau(\ell) \propto \ell^{-2/3}$.
- Intermittent magnetic field is (i.e, not volume-filling); magnetic filaments & sheets, thickness $\ell_B \simeq \ell_0 R_{\mathrm{m}}^{-1/2}$.

2. Non-Linear behaviour: controversial

- Saturation at $\frac{1}{8\pi} B_{\mathrm{rms}}^2 \simeq \frac{1}{2}\rho v_0^2 \,.$????

- Thicker magnetic sheets:

$\ell_B \cong \ell_0 \, R_{\mathrm{m,cr}}^{-1/2}$, $\mathrm{R}_{\mathrm{m,cr}} \cong 30\text{–}100$ (Subramanian, *PRL* 1999)

(other opinion: Schekochihin et al. 2004)

Cluster turbulence & magnetic fields: three evolutionary stages

Stage 1. Cluster formation, $0 < t < 4$ Gyr

- Volume-filling random flow, $v_0 \simeq 300$ km/s, $\ell_0 \simeq 150$ kpc,
- produced in a major merger event;
- $\mathrm{Re} > 100 \Rightarrow$ turbulence

- **Fluctuation dynamo**: *B* amplified by a factor $A > 3000$,
- magnetic sheets, $B \simeq 2\ \mu$G, $\ell_B \simeq 20$–30 kpc (if $B_0 > 10^{-9}$ G),
- $\sigma_{\mathrm{RM}} \simeq 200$ rad/m^2

Stage 2. Decay after major mergers, $4 < t < 9$ Gyr

When the driving ceases, turbulence decays, $v_0 \propto t^{-3/5}$, $\ell_0 \propto t^{2/5}$

$\Rightarrow v_0 \cong 150$ km/s, $\ell_0 \cong 300$ kpc at $t = 9$ Gyr,

but magnetic field remains maintained by dynamo action,

$A > 2\times10^4$, $B \cong 1\ \mu$G, $\ell_B \cong 40$ kpc

R_m, Re $\propto t^{-1/5}$, $\sigma_\mathrm{RM} \propto t^{-2/5}$

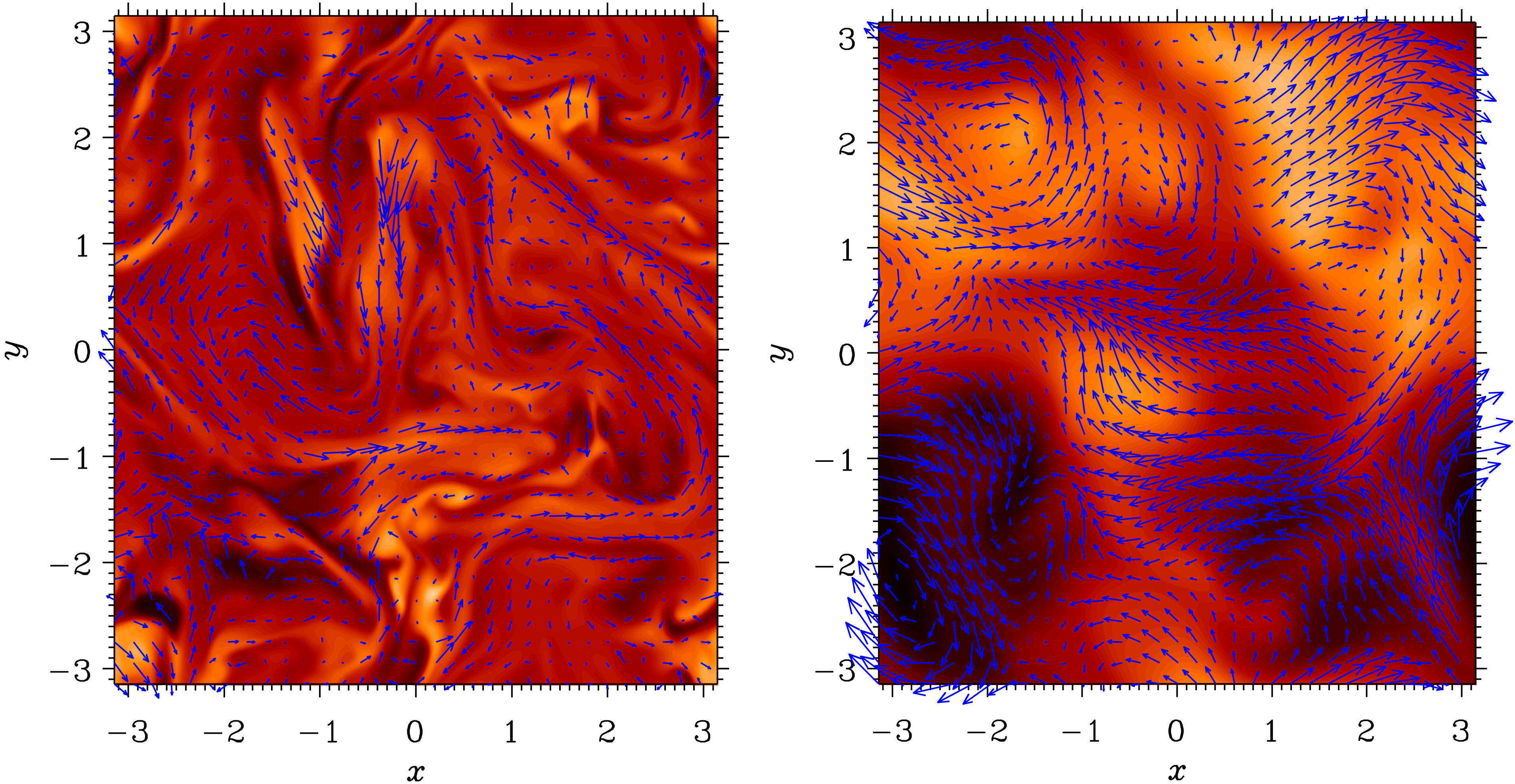
Magnetic field in turbulent flow

3D, 256^3 resolution, $\ell_0 = L_{\mathrm{box}}/1.5$, $\mathcal{M} = 0.1$, $\mathrm{Re} = R_{\mathrm{m}} = 420$.

Colour: $B_{//}$; vectors: $\mathbf{B}_{\perp}$

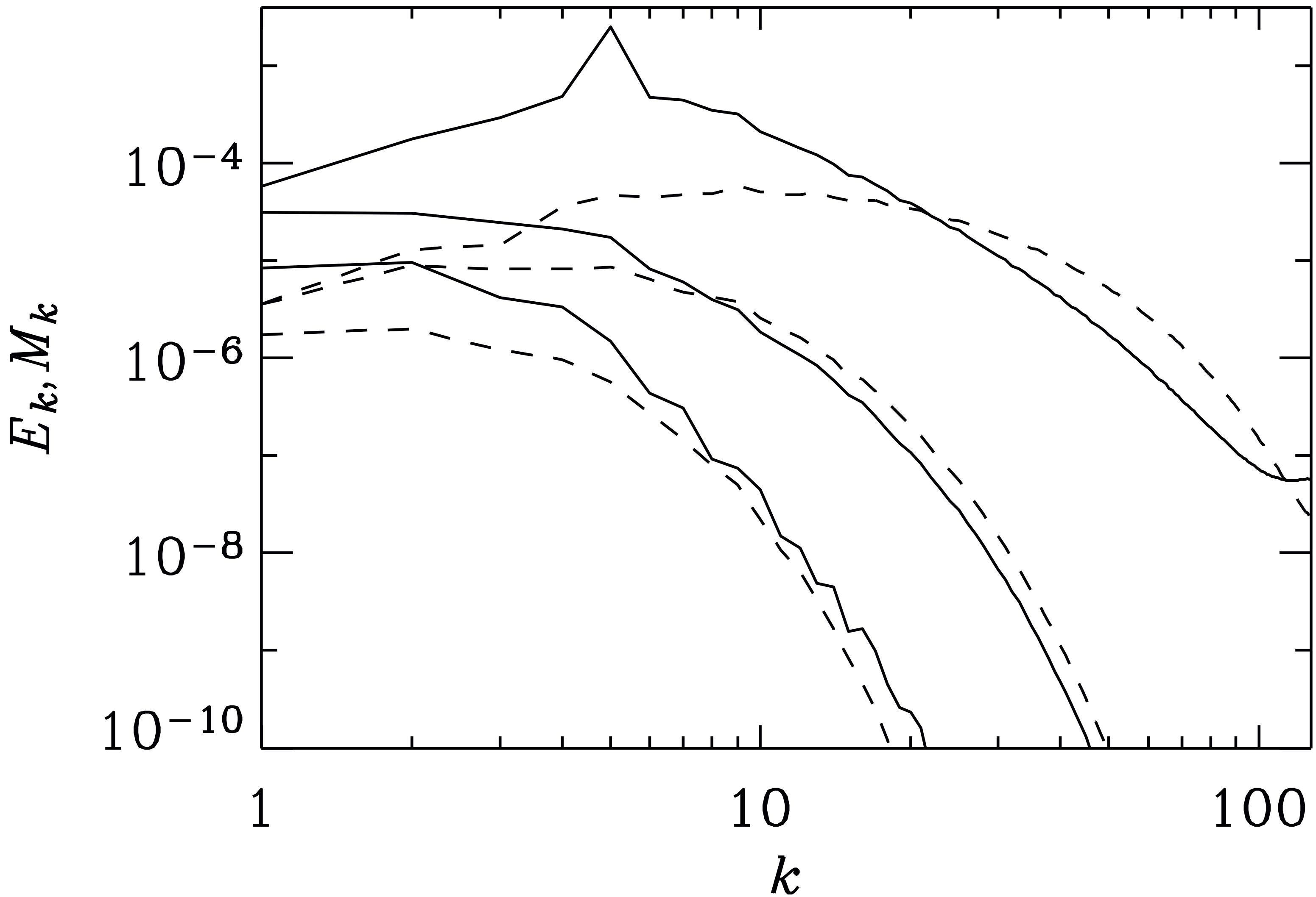
Steady state

Decaying turbulence



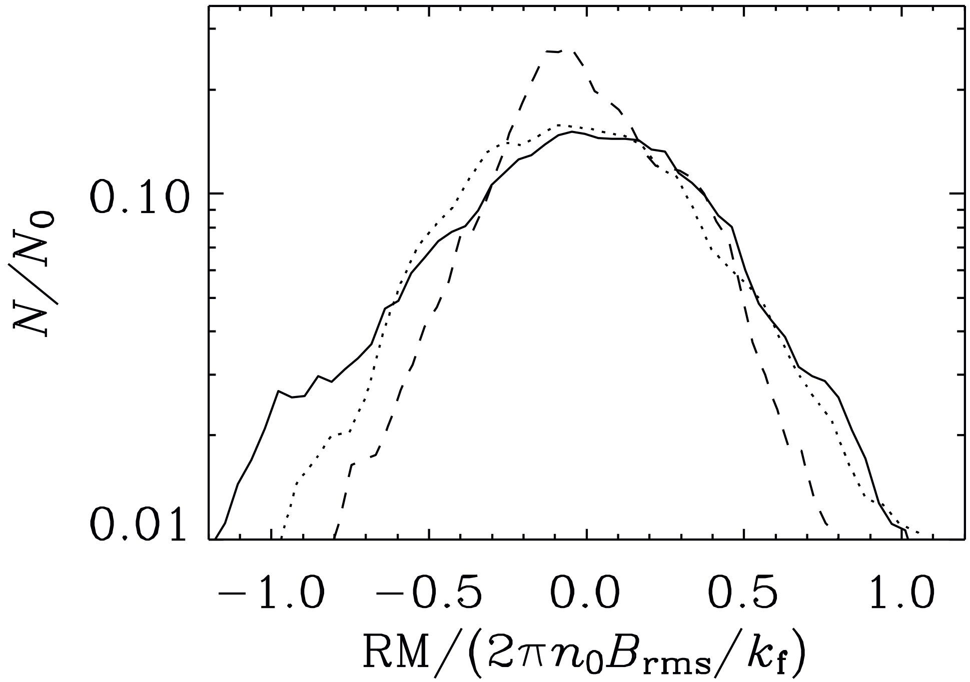
Dynamo action in decaying turbulence:

energy spectra: kinetic (solid) & magnetic (dashed),
$t/t_{0\mathrm{i}}$ = 0, 10, 50



Observational signatures

- Random Faraday rotation, $\sigma_{RM0} \simeq 200$ rad/m^2, $\sigma_{RM} \propto t^{-2/5}$



Histogram (PDF) of RM, 256^3 simulation, steady state:

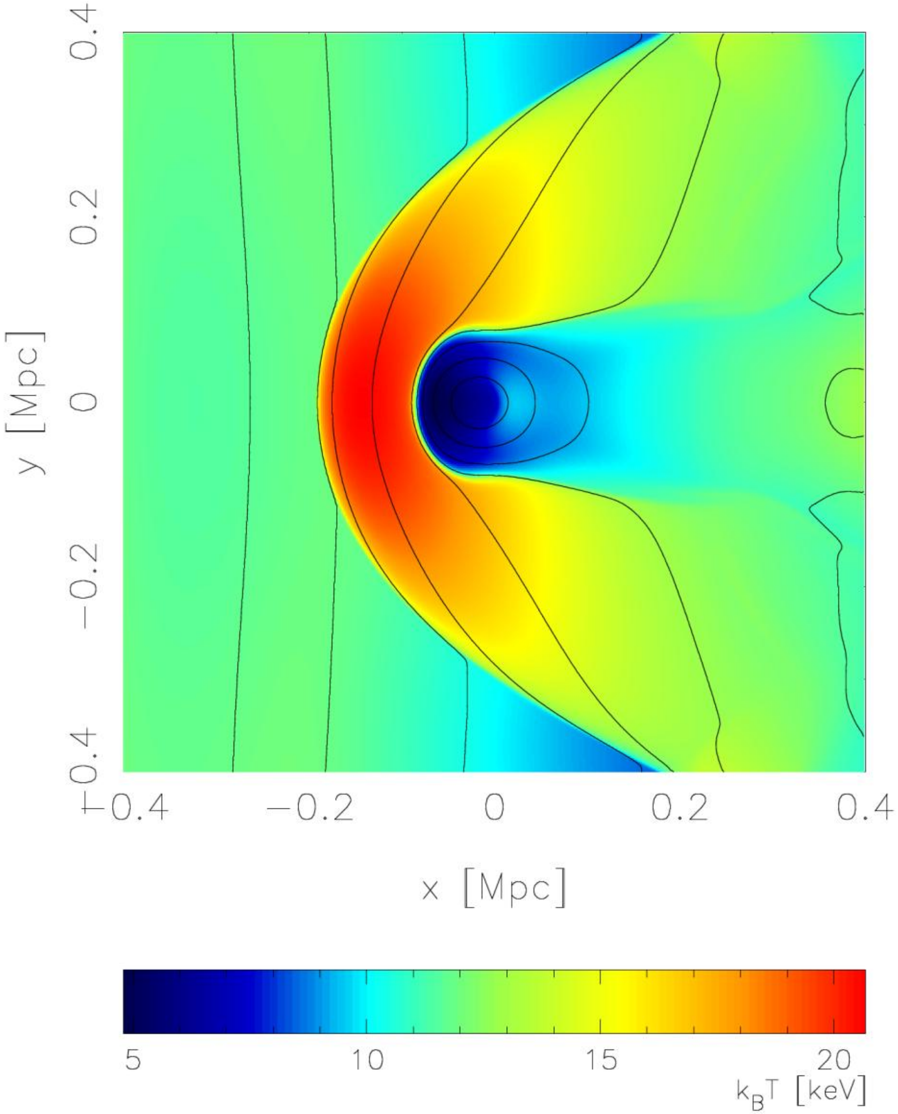
- $P_m = 1$ (solid),
- $P_m = 1/4$ (dotted),
- $P_m = 30$ (dashed)

- Only a few turbulent cells along a line of sight ⇒ polarization of synchrotron emission, $p/N^{1/2} \simeq$ a few % at 6 cm, filamentary structures

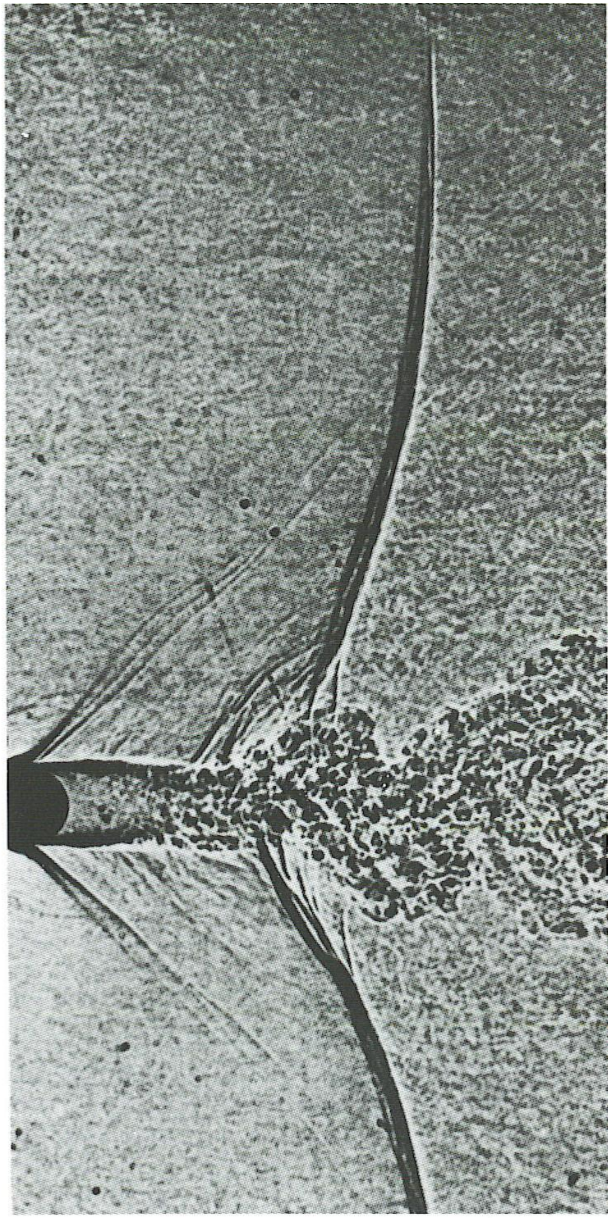
Stage 3. Mature cluster: turbulence in the wakes of galaxies and galaxy groups

- Clumps $m = 3\times10^{13} M_\odot$ falling into cluster $M = 10^{15} M_\odot$ every $\Delta t \propto m^{-1/2} \cong 0.3$ Gyr (Lacey & Cole 1993),
- gas stripping radius $R_0 \cong 100$ kpc,
- wake length $\frac{X}{R_0} = 27 \left(\frac{\mathrm{Re}}{10^3}\right)^3$ (Prandtl's turbulent wake)
- $v_0 \cong 250$ km/s, $\ell_0 \cong 200$ km/s, $B \cong 2\ \mu$G, $\ell_B \cong 30$ kpc.
- Volume filling factor: $f_V \simeq 0.02 \left(\frac{\mathrm{Re}}{10^3}\right)^5$
- Area covering factor: $f_S \simeq 0.2 \left(\frac{\mathrm{Re}}{10^3}\right)^4$
- Other sources of turbulence? – see Jim Stones' talk this morning

Wake of a subcluster $1.4 \times 10^{14} M_{\odot}$ falling radially to $8.6 \times 10^{14} M_{\odot}$ cluster, X-ray surface brightness, $\mathcal{M} \cong 0.9$
(Takizawa 2005)



Turbulent wake behind a cylinder, $\mathcal{M} = 0.95$ (Van Dyke 1982, No. 222)



Turbulence, magnetic fields & Faraday rotation

Evolution stage	Duration [Gyr]	v_0 [km/s]	l_0 [kpc]	t_0 [Gyr]	B_{eq} [μG]	l_B [kpc]	$\langle B^2 \rangle^{1/2}$ [μG]	σ_{RM} [rad/m^2]
Major mergers	4	300	150	0.5	4	25	1.8	200
Decaying turbulence	5	130	260	2.0	2	44	0.8	120
Subcluster wakes		260	200	0.8	4	34	1.6	110
Galactic wakes		300	8	0.03	4	1.4	1.6	5