How large thermal conduction in clusters of galaxies can be?

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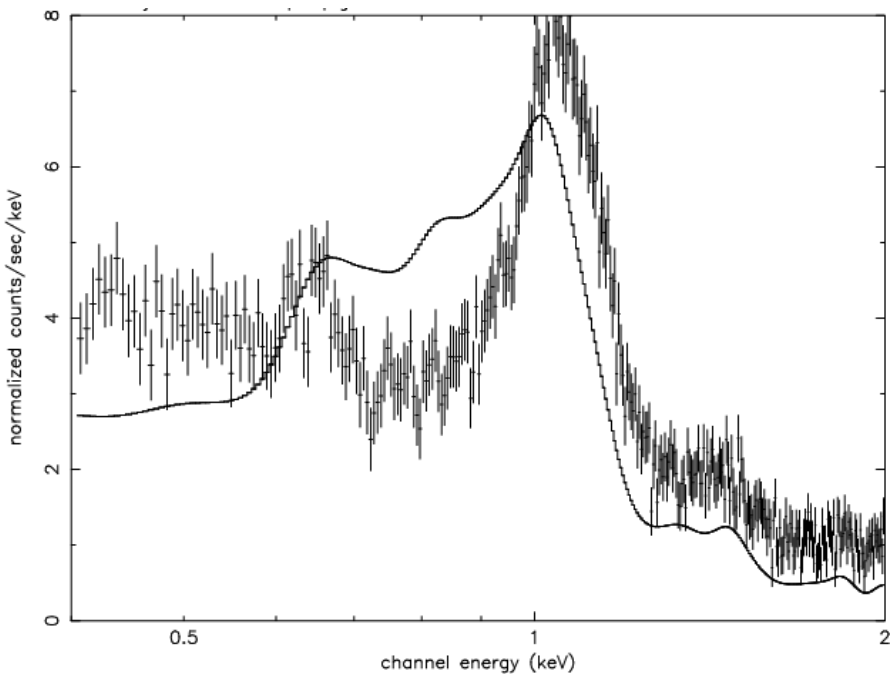
Cosmo−2002, Chicago

Motivation

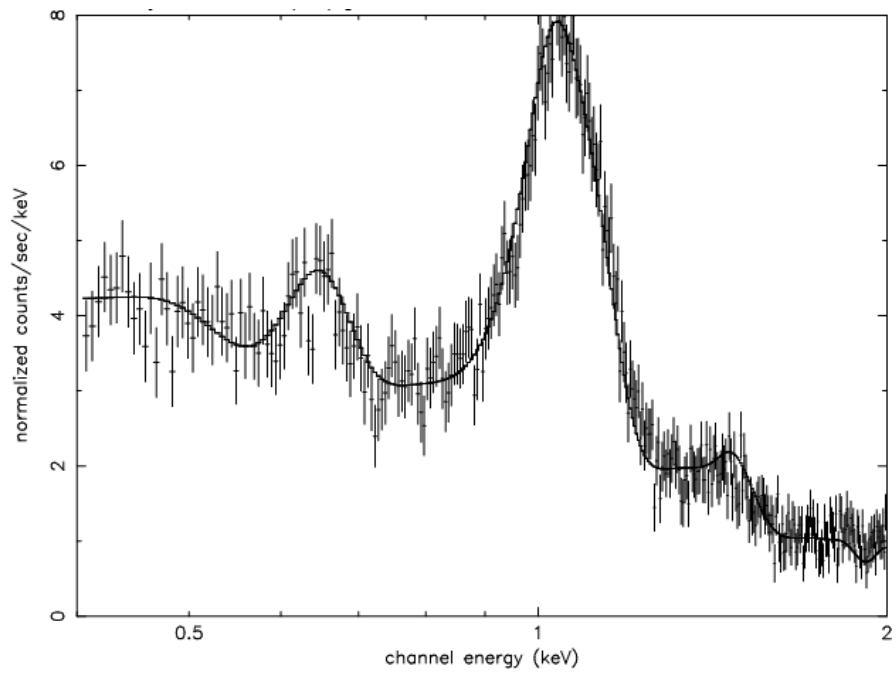
→ *no spectral evidence for cool component in "cooling flows"*
(XMM−Newton & Ghandra)

M87 at R = 1−2 arcmin

Cooling Flow model (~1 M_sun/yr)



Gas Emission in T = 1.4−2 keV range



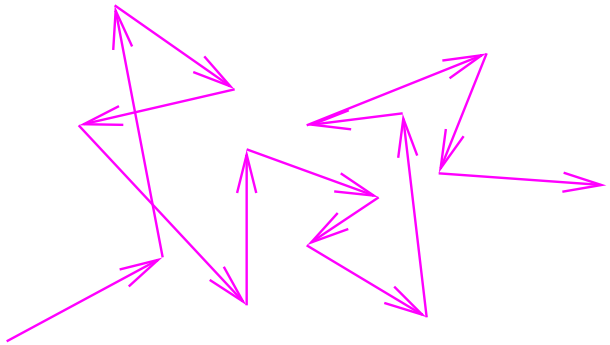
(Bohringer, et al. 2002, A&A, 382, 804)

Thermal Conduction. B=0

Spitzer (collisional) thermal conduction

Mean−free−path

$$\lambda \sim 30\,(T/10\,\mathrm{keV})^{2}\,(n/10^{-3})^{-1}\ \mathrm{kpc}$$



Diffusivity $\kappa_{Sp} \sim \lambda^2/\tau$

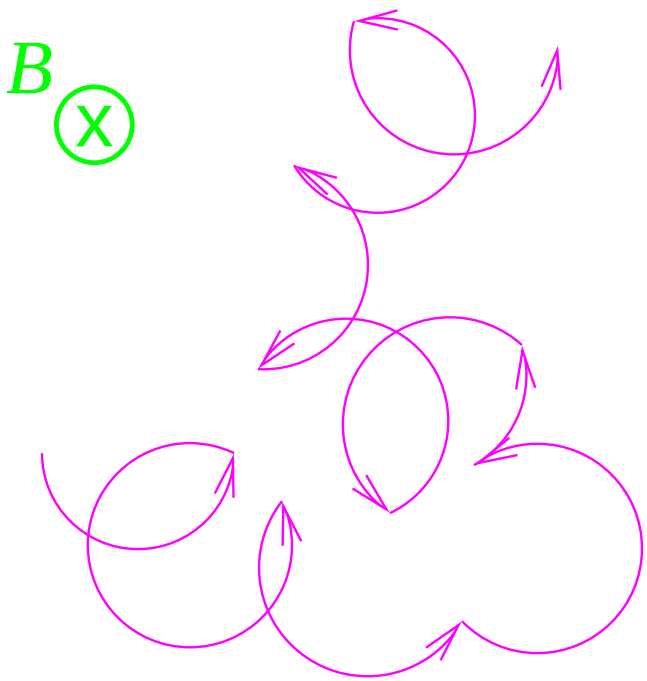
Thermal conductivity $\kappa_c = n\,k\,\kappa_{Sp}$

Conduction time

$$t_{Sp} \sim R^2/\kappa_{Sp} \sim 8 \times 10^{6}\,(T/10\,\mathrm{keV})^{-5/2}\,(n/10^{-3})\,(R/100\,\mathrm{kpc})\ \mathrm{yr}$$

often $t_{Sp} \lesssim t_{cool}$

Thermal Conduction. Homogeneous B



$\kappa_{\parallel} \sim 1/3\ \kappa_{Sp}$

$\kappa_{\perp} \sim \rho_e^2/\tau \sim (\rho_e/\lambda)^2 \kappa_{Sp}$

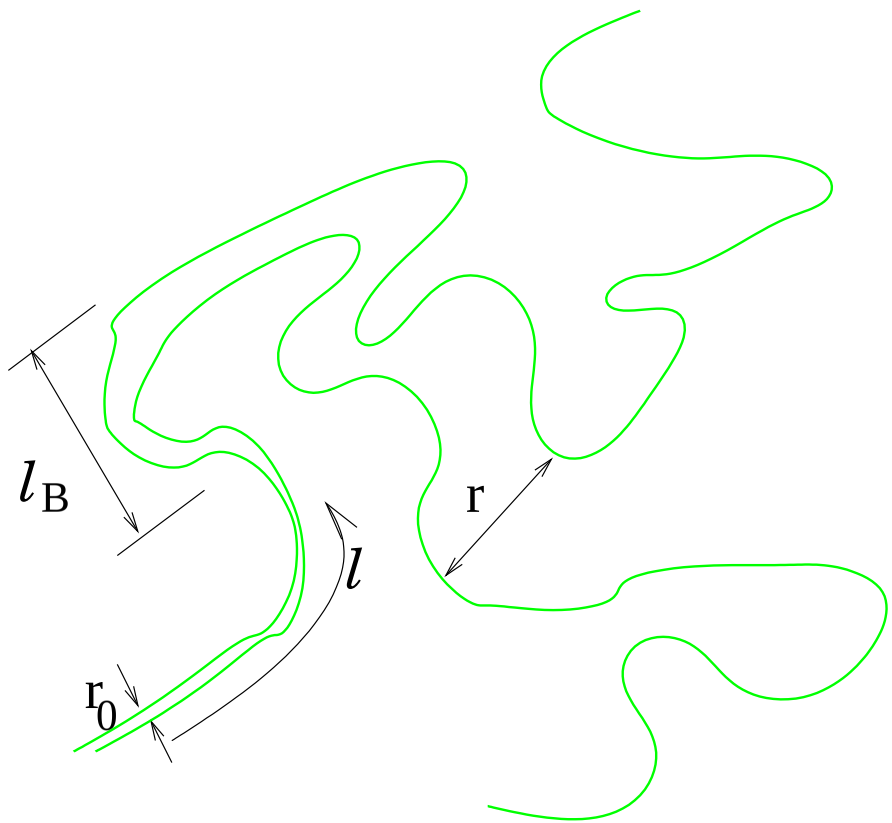
In clusters

$\rho_e \sim 10^{-12} \lambda$ for $B \sim 10^{-6}$ G

$\kappa_{\perp} <<< \kappa_{\parallel}$

Thermal Conduction. Chaotic B

Chaotic field lines $r \sim r_0 \exp(l / L_{Lyap})$ *and* $L_{Lyap} \sim l_B$



Rechester−Rosenbluth length

$r \sim l_B$ *when* $l \sim L_{RR}$

$L_{RR} \sim l_B \ln(l_B/\rho_e) \sim 30\, l_B$

3D RMS displacement

$R_*^2 \sim L_{RR} l_B \sim 30\, l_B^2$

|| *diffusion (collisions)*

$t_* \sim L_{RR}^2 / \kappa_{||}$

Effective diffusivity $\kappa_* \sim R_*^2 / t_* \sim (l_B / L_{RR})\, \kappa_{||} \sim 10^{-2} \kappa_{Sp}$

Thermal Conduction. Turbulent B

- Back to the single-scale case:

if $r < l_B$ – chaos; $\quad \langle r^2 \rangle \propto \exp(l/l_B) \;\rightarrow\; \dfrac{d\langle r^2 \rangle}{dl} \sim 2\dfrac{\langle r^2 \rangle}{l_B}$

if $r > l_B$ – diffusion; $\quad \langle r^2 \rangle \propto \sqrt{(l/l_B)} \;\rightarrow\; \dfrac{d\langle r^2 \rangle}{dl} \sim \dfrac{l_B^2}{l_B} = l_B$

- Field with multiple scales:

Anisotropic Goldreich-Sridhar ($\alpha = 2/3$) turbulence

$$\boxed{(l_{\|}/l_B) \sim (l_{\perp}/l_B)^{\alpha},} \quad l_{\perp,\min} < l_{\perp} < l_B$$

`Evolution:`

- when $\boxed{r \equiv \langle r^2 \rangle^{1/2} < l_{\perp,\min}}$ — *chaos*

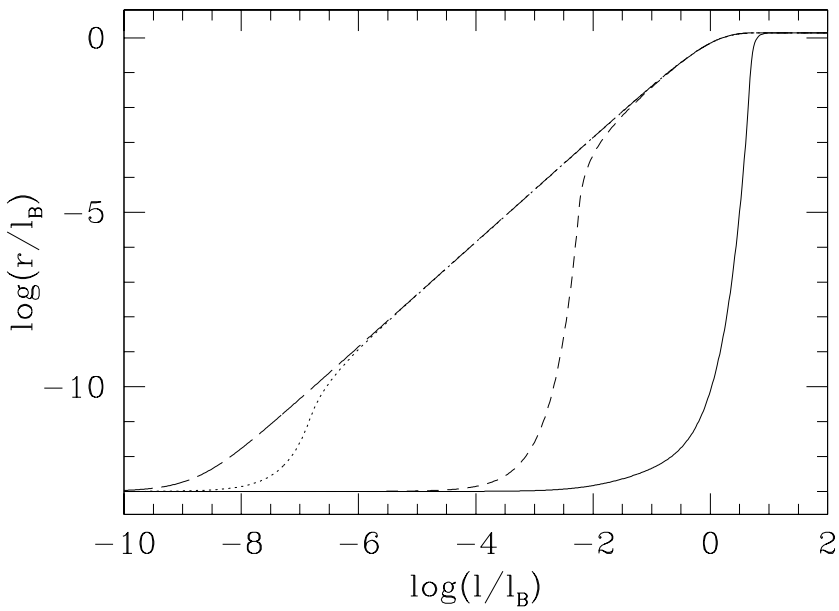
$$\frac{d\langle r^2 \rangle}{dl} \sim 2\langle r^2 \rangle \int_{1/l_B}^{1/l_{\perp,\min}} \frac{d\ln k_{\perp}}{l_{\|}(k_{\perp})} \quad \text{where} \quad k_{\perp} = 1/l_{\perp}$$

- when $\boxed{l_{\perp,\min}^2 < \langle r^2 \rangle < l_B^2}$ — *chaos + diffusion*

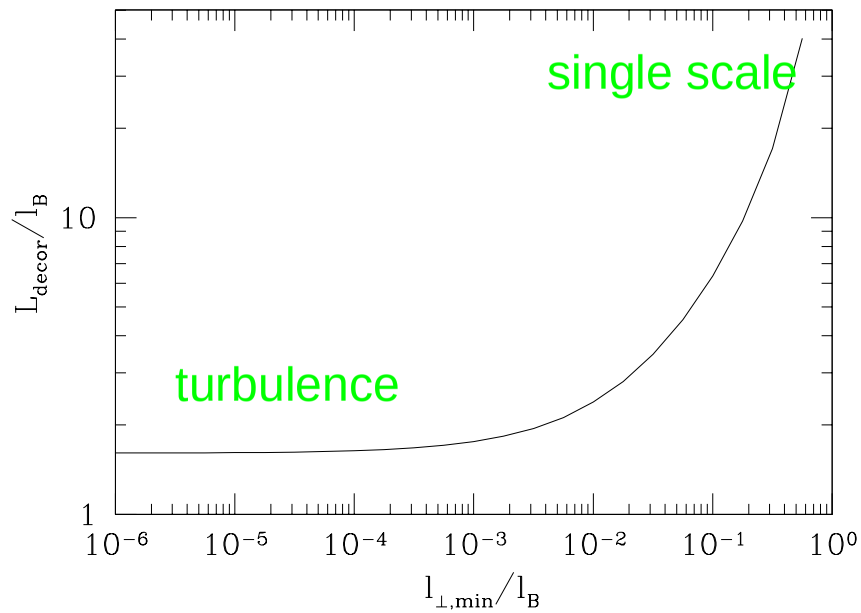
$$\frac{d\langle r^2 \rangle}{dl} \sim 2\langle r^2 \rangle \int_{1/l_B}^{1/r} \frac{d\ln k_{\perp}}{l_{\|}(k_{\perp})} + \int_{1/r}^{1/l_{\perp,\min}} d\ln k_{\perp} \frac{l_{\perp}^2(k_{\perp})}{l_{\|}(k_{\perp})}$$

Thermal Conduction. Turbulent B

solution: r vs. l



decorrelation length (r ~ l_B)



in turbulence $L_{RR} \longrightarrow L_{dec} \sim l_B$

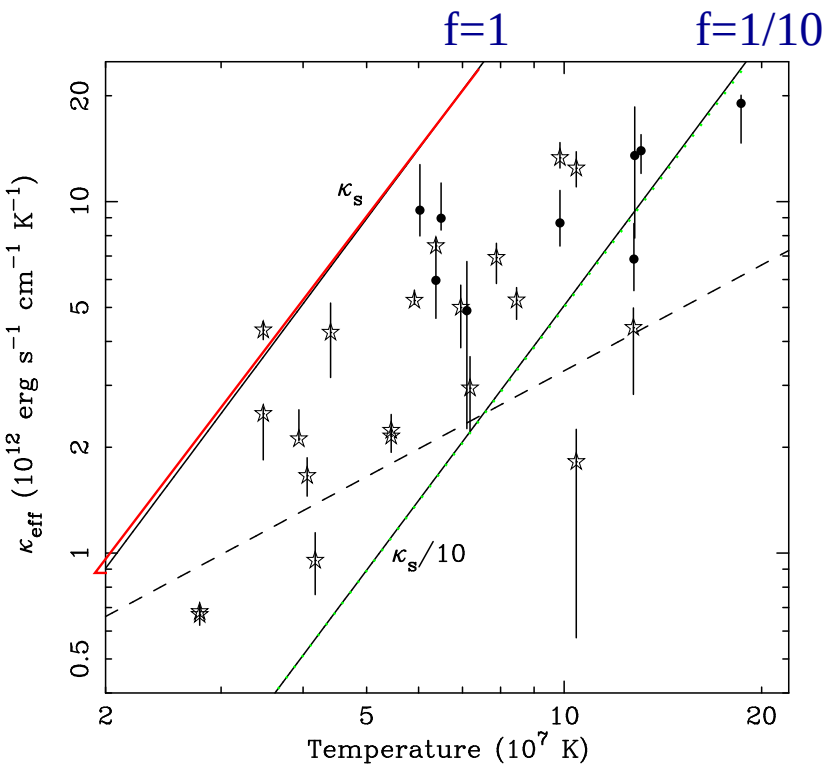
$$\kappa_* \sim (L_{dec} / l_B) \, \kappa_{||} \sim f \, \kappa_{Sp}$$

$f \sim 1/5$

(Narayan & Medvedev, ApJ, 562, L129)

Cluster Data

sample of 29 clusters



(Fabian et al 2002)

(Voigt et al 2002)

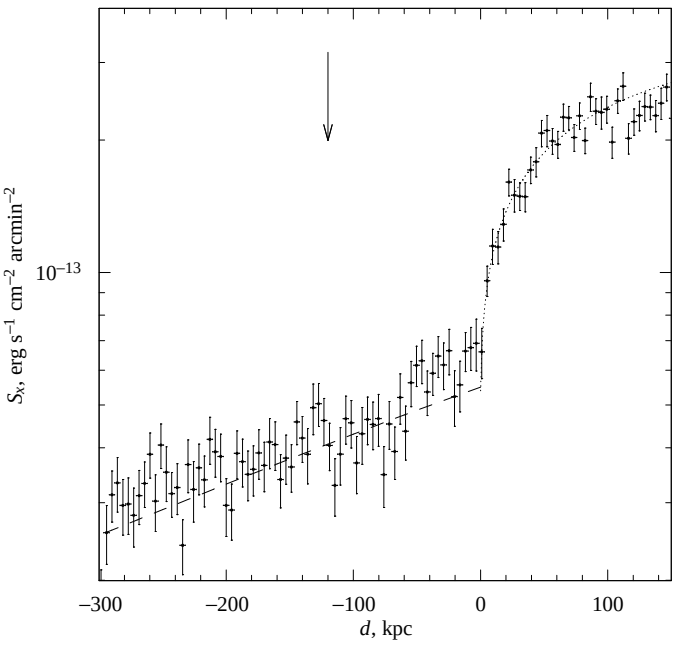
cluster	f (best fit)	cluster	f (best fit)
Abell 1795	0.2	Abell 2199	0.4
Abell 1835	0.4	Abell 2390	0.3
Abell 2052	0.6	Abell 2597	2.4
RXJ 1347.5 1145	0.3	Hydra A	1.5
Sersic 159	5.6	3C 295	1.0

(Zakamska & Narayan 2002)

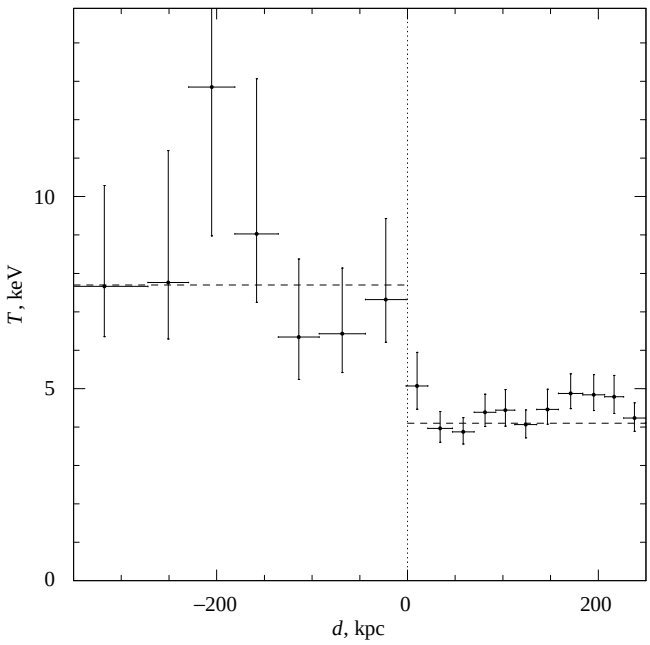
Cold Fronts

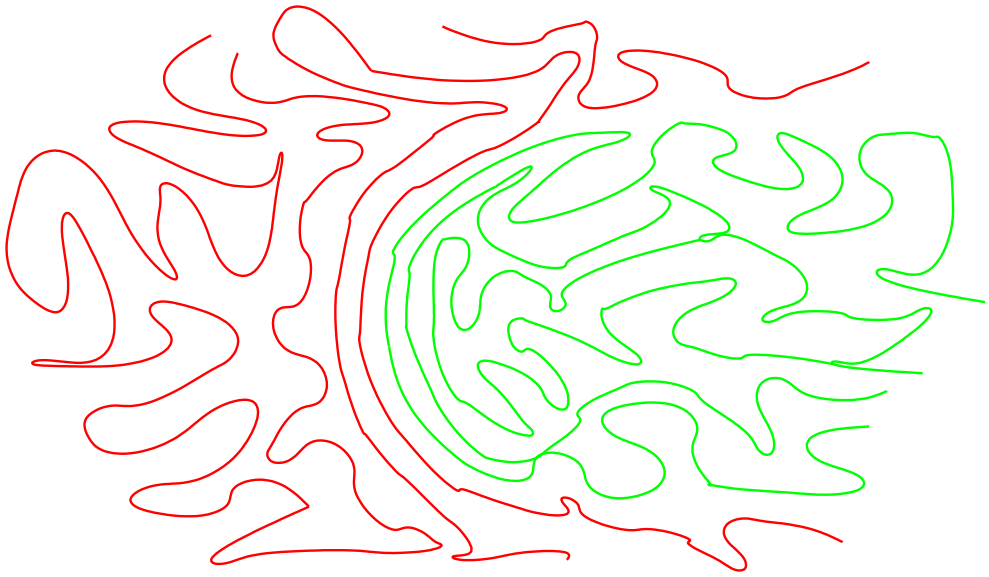
A3667

surface brigtness



temperature



(Vikhlinin et al 2001)

structure of field lines