The Role of the MTI and HBI in the Intracluster Medium

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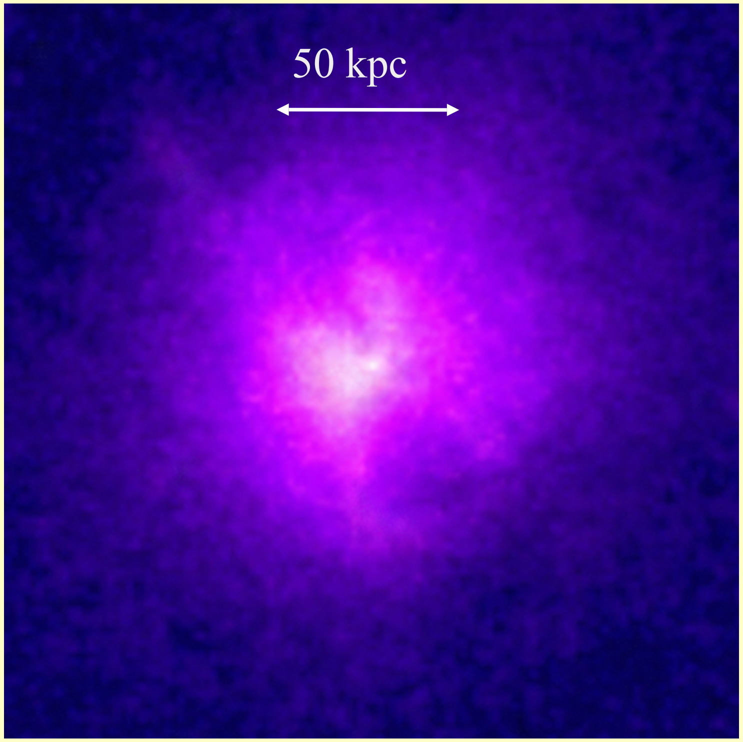
Physics of the Intracluster Medium
August 23, 2010

Motivation



Hydra A Cluster (Chandra)

T ~ 3-5 keV, n ~ 10^{-2}-10^{-3} cm^{-3}

large electron mean free path:

$$\lambda_e \sim 0.1 \left(\frac{T}{3\ \mathrm{keV}}\right)^2 \left(\frac{n_e}{0.03\ \mathrm{cm}^{-3}}\right)^{-1}\ \mathrm{kpc}$$

$$\rho_e \sim 10^3 \left(\frac{T}{3\ \mathrm{keV}}\right)^{1/2} \left(\frac{B}{1\ \mu\mathrm{G}}\right)^{-1}\ \mathrm{km}$$

thermal conduction important & anisotropic

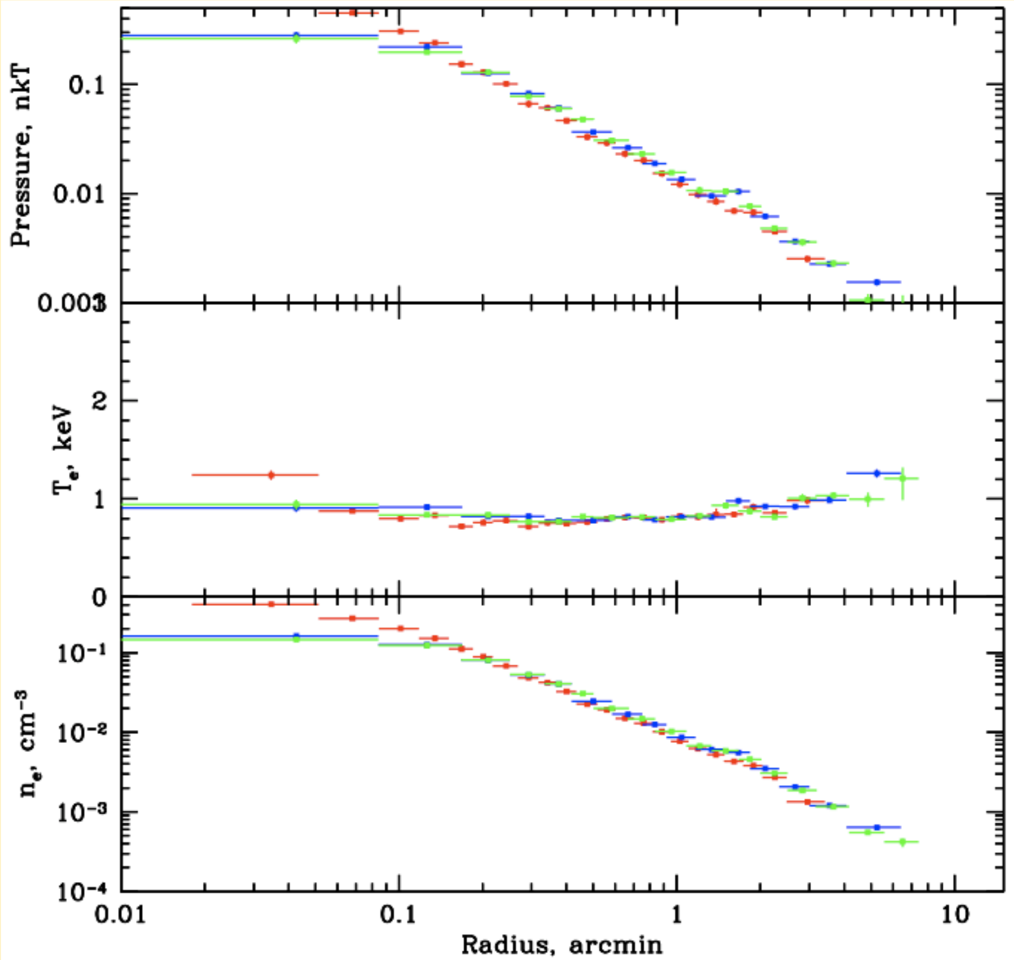
2

Do we really have conduction?

P

T

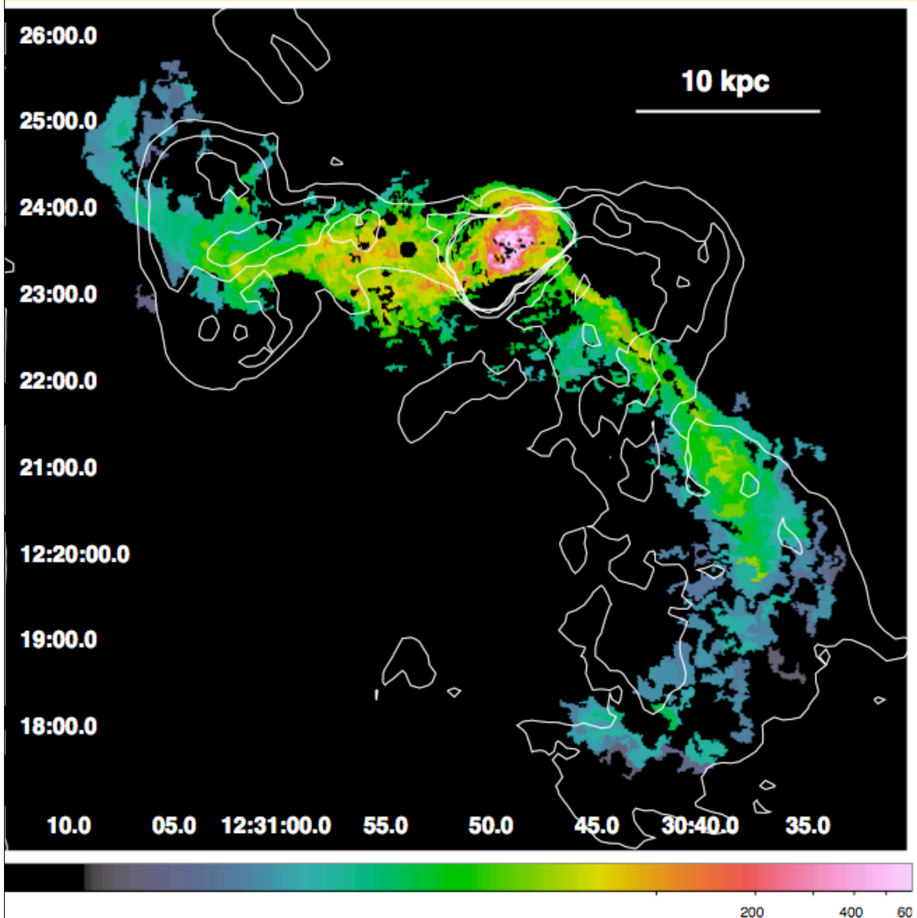
n_e



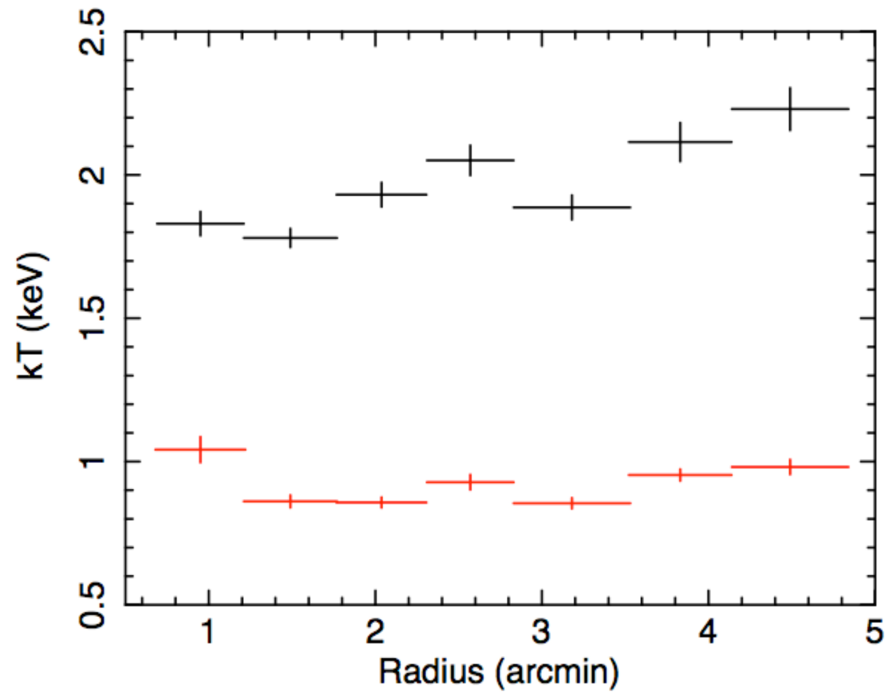
NGC4649
(Churazov & Forman)

Either there is conduction or a vast cosmic conspiracy over 2 1/2 decades in density.

Structure in M87



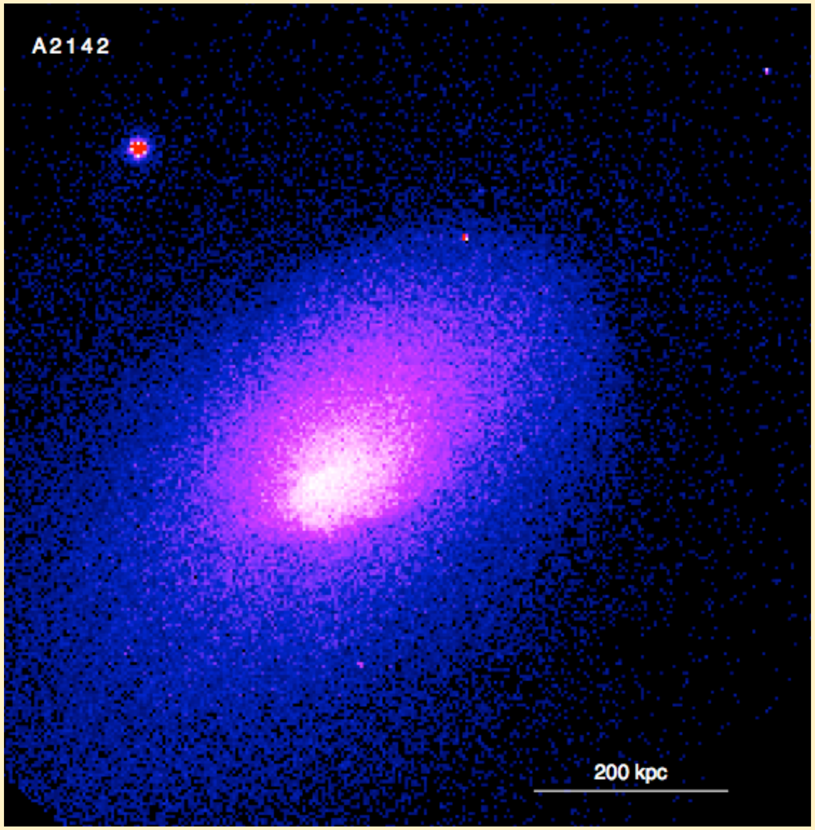
(Werner, et al 2010: arxiv:1003.5334)
Emission measure map of 1 keV plasma

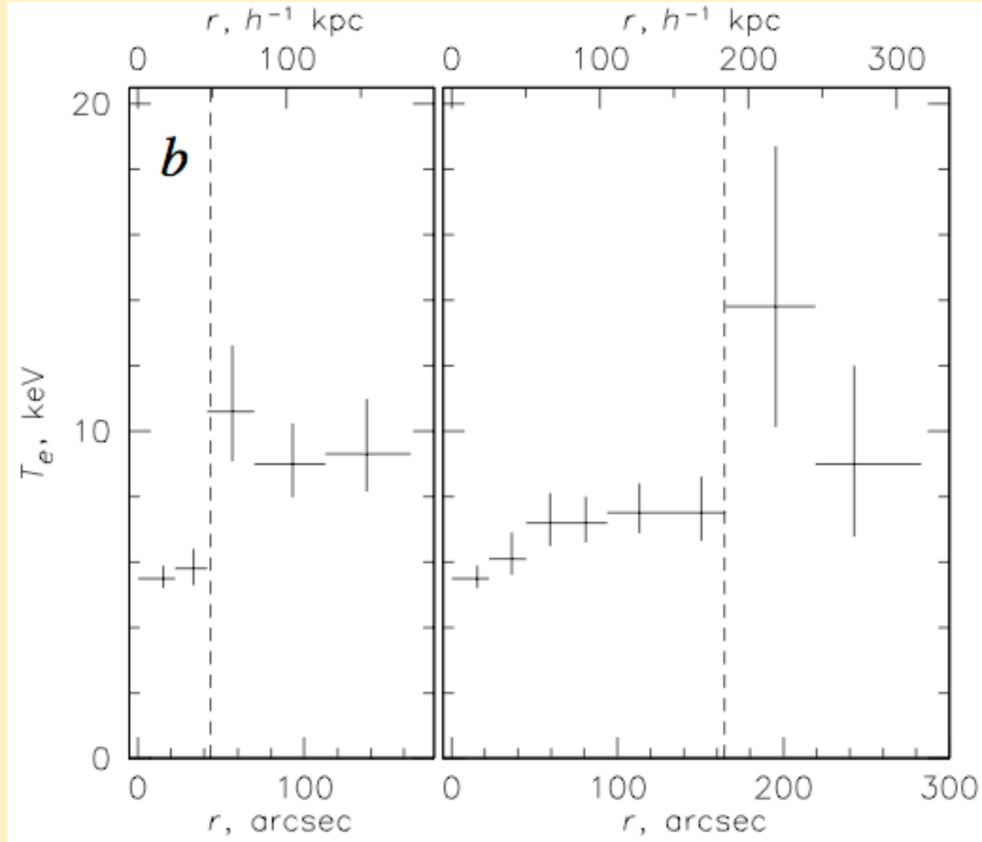


2 Temperature fit to SW arm

Conduction is clearly efficient here.

But...Cold Fronts





(Markevitch & Vikhlinin 2007)

Requires suppression across front of ~100 to Spitzer
See John ZuHone's Talks

Presentation Outline

- Motivation
- Beyond MHD in the Intracluster Medium

  The MTI in Cluster Outskirts.

  The cooling flow problem & the HBI.

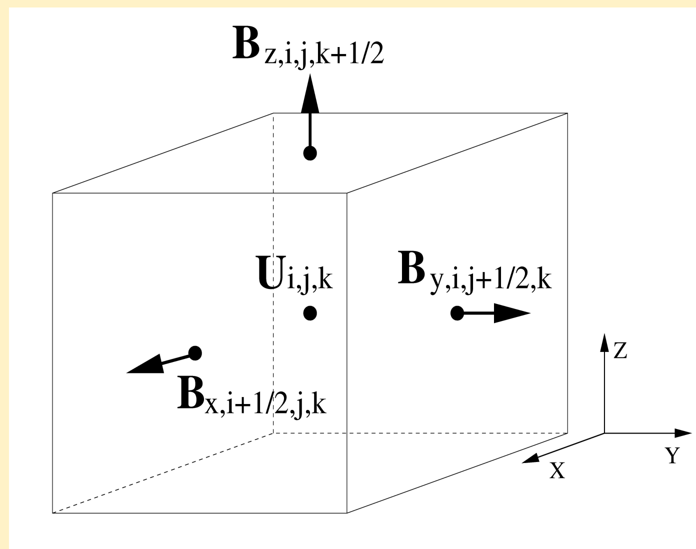
  Turbulence and Bimodality
- Filament Formation
- Conclusions

Algorithm: MHD with Athena

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) &= 0, \\
\frac{(\rho \boldsymbol{v})}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v} + \left(p + \frac{B^2}{8\pi}\right)\boldsymbol{I} - \frac{\boldsymbol{B}\boldsymbol{B}}{4\pi}\right] &= \rho \boldsymbol{g}, \\
\frac{\partial E}{\partial t} + \nabla \cdot \left[\boldsymbol{v}\left(E + p + \frac{B^2}{8\pi}\right) - \frac{\boldsymbol{B}(\boldsymbol{B}\cdot\boldsymbol{v})}{4\pi}\right] &= \rho \boldsymbol{g} \cdot \boldsymbol{v} - \nabla \cdot \boldsymbol{Q}, \\
\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) &= 0.
\end{aligned}
$$

$$\nabla \cdot \boldsymbol{B} = 0$$

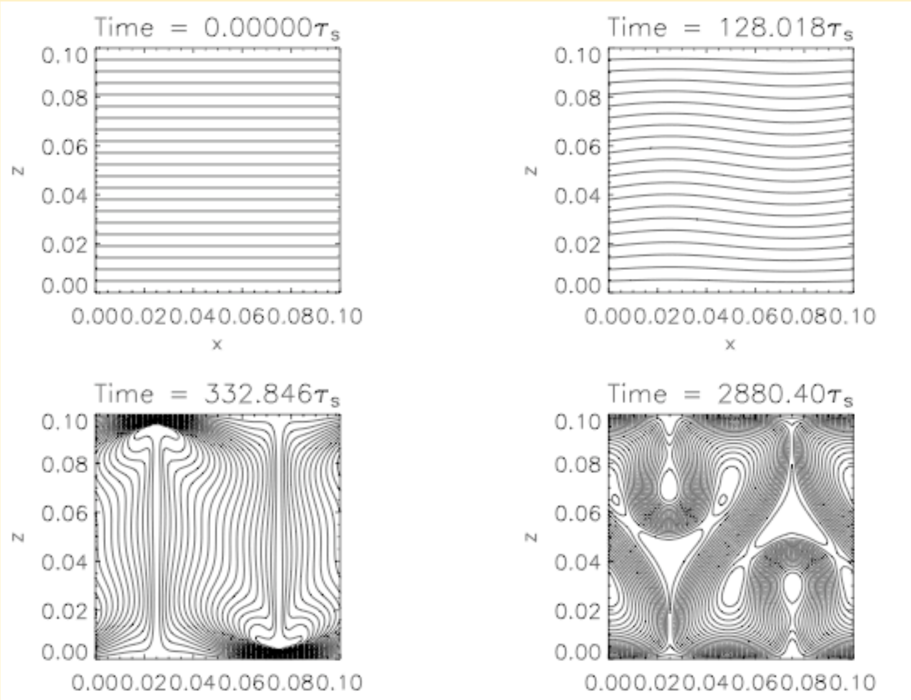
- **Athena**: Higher order Godunov Scheme.
- Constrained transport for preserving divergence free constraint.
- Anisotropic Heat flux (along B fields)



(Gardiner & Stone, 2008; Parrish & Stone, 2005)

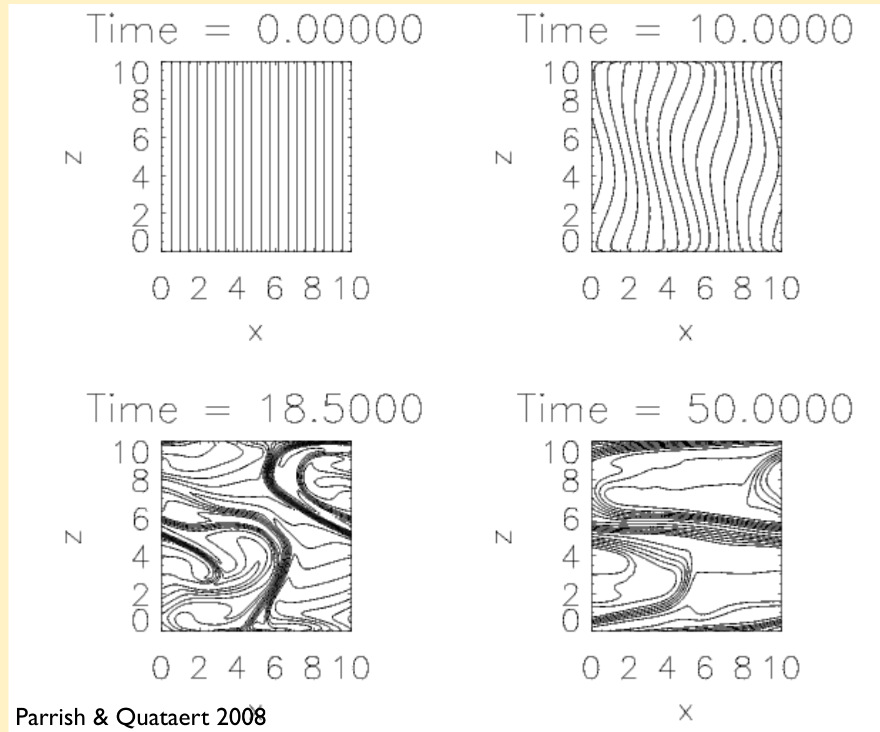
Buoyancy Instabilities in Magnetized Plasmas

MTI (dT/dz < 0)



Parrish & Stone 2005

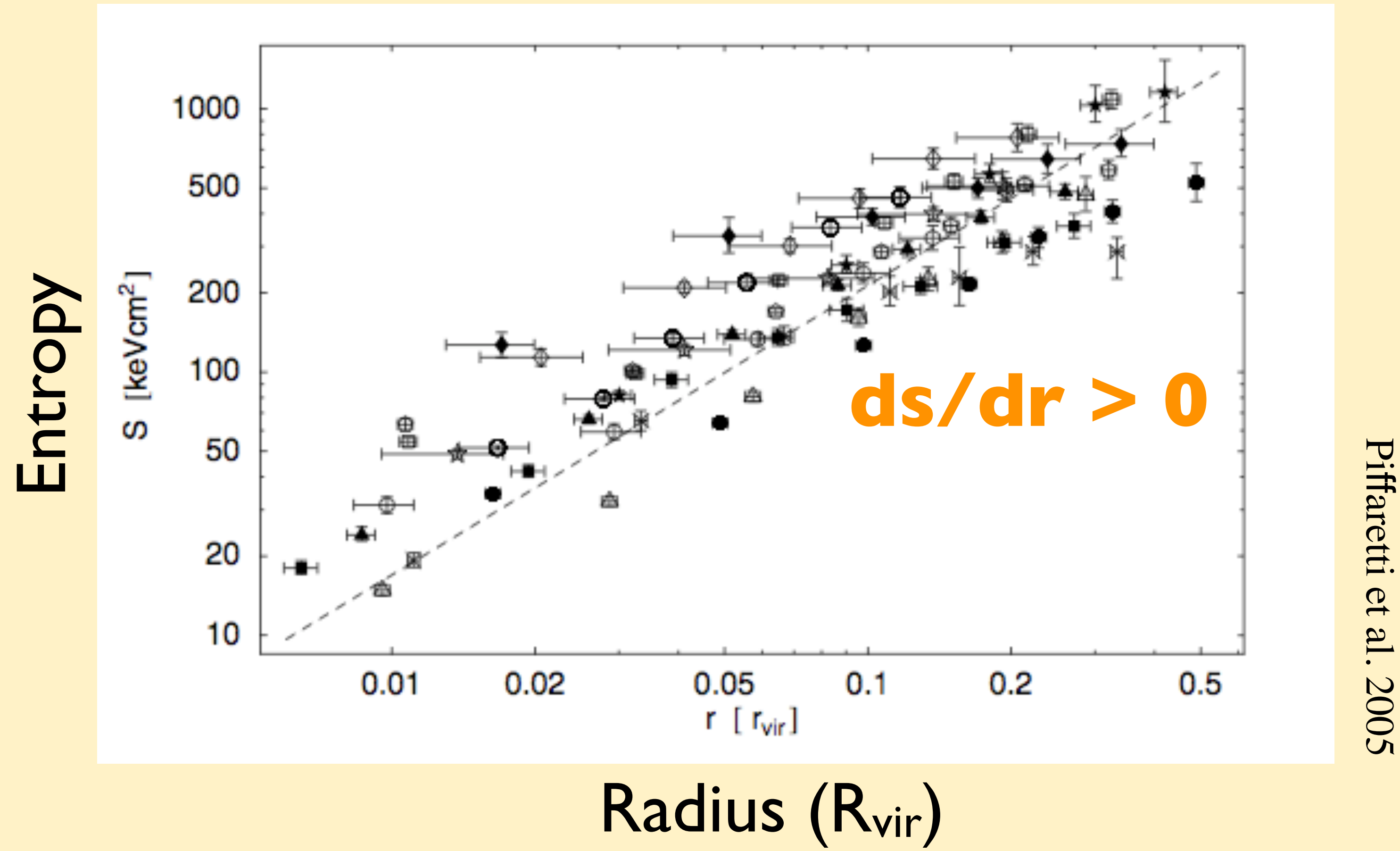
HBI (dT/dz > 0)



Parrish & Quataert 2008

a weakly magnetized plasma with anisotropic heat transport is always buoyantly unstable, independent of dT/dz!

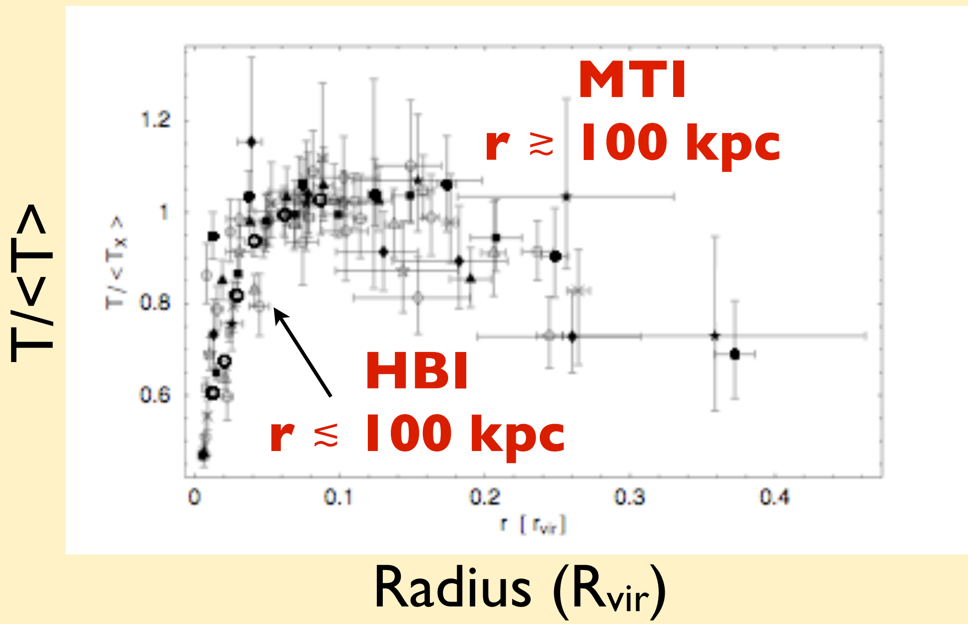
Cluster Entropy Profiles



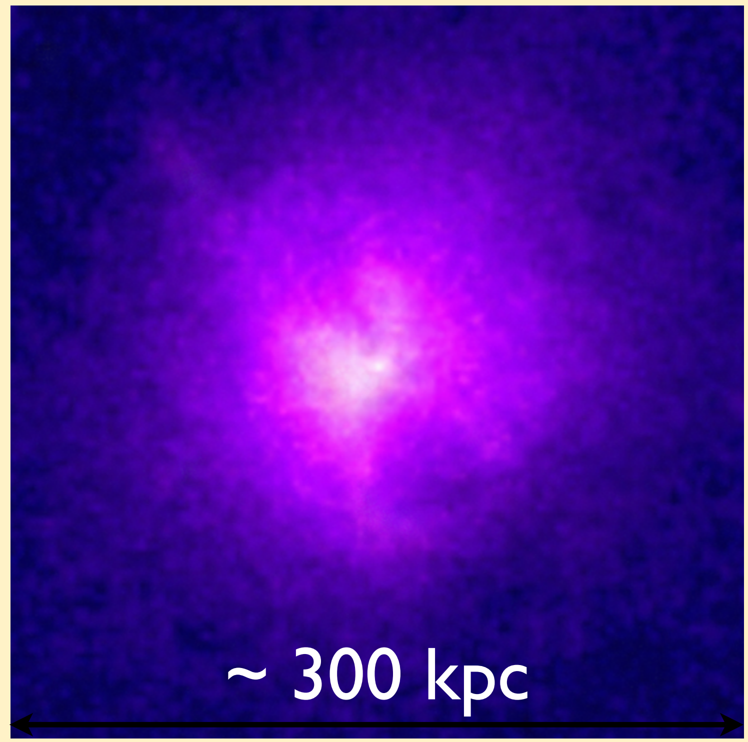
Schwarzschild criterion ➔ clusters are **stable**

The MTI & HBI in Clusters

average cluster temperature profile

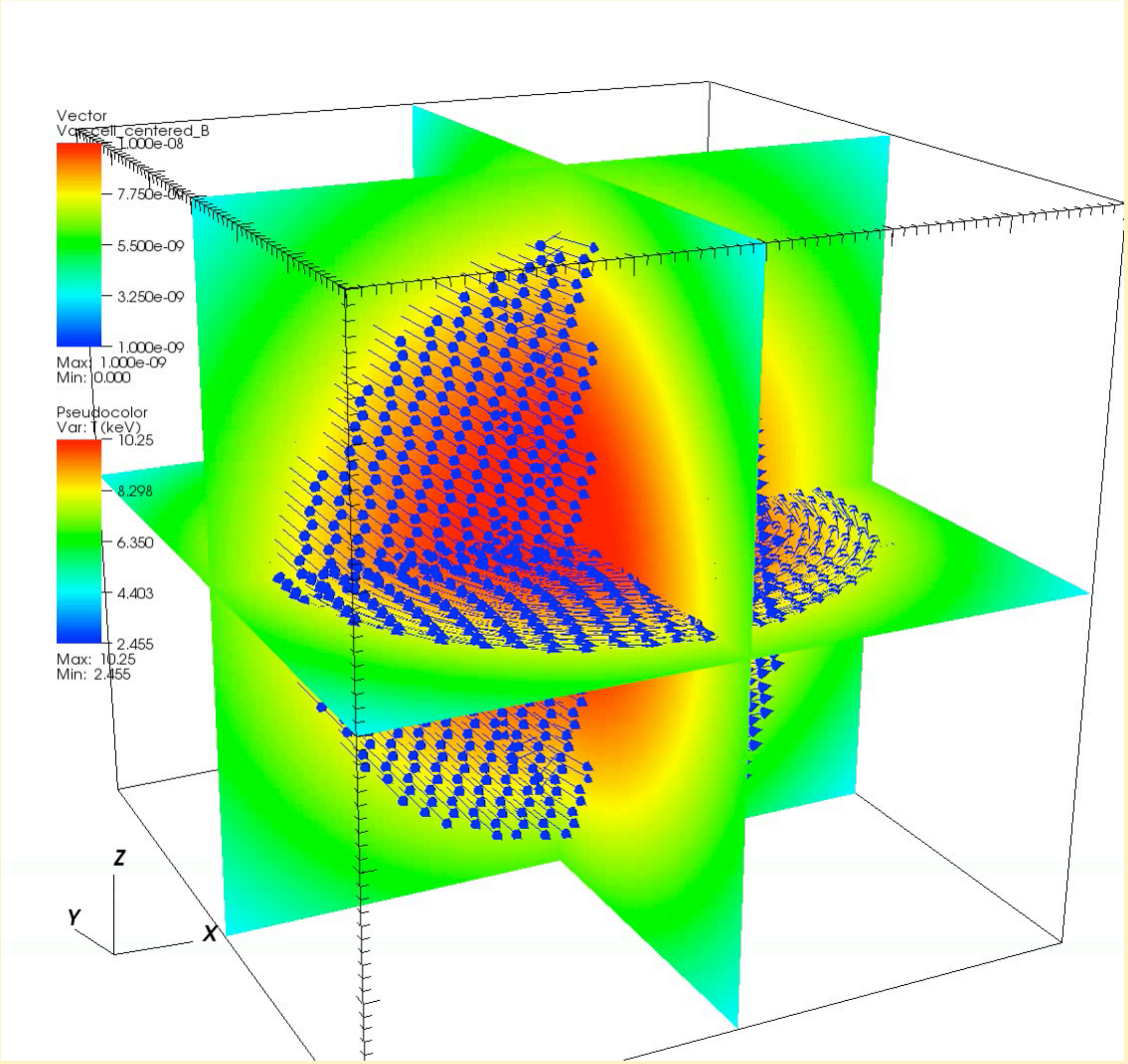


Piffaretti et al. 2005



The Entire Cluster is Convectively Unstable!

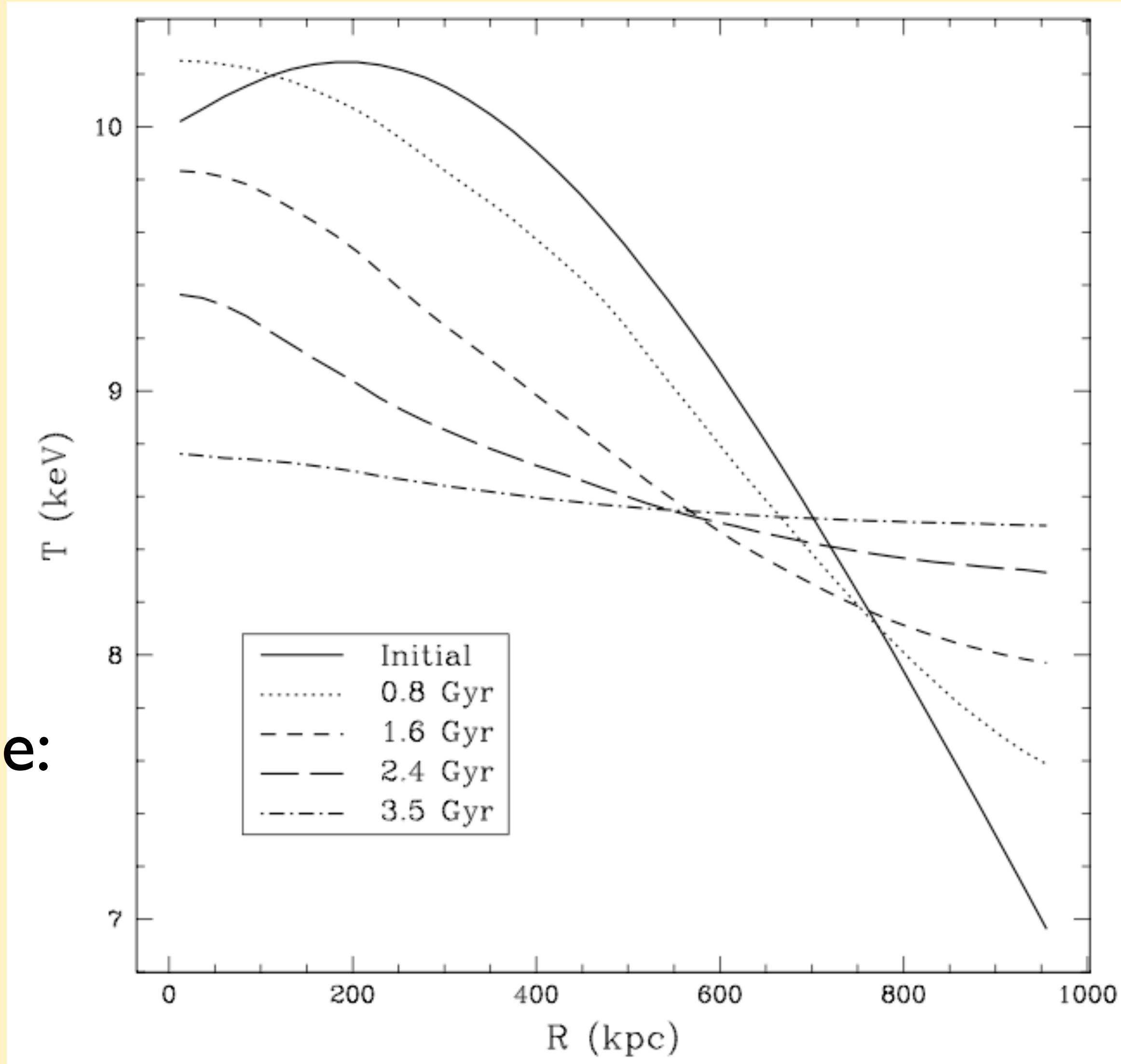
MTI in Clusters



MTI in Clusters

3D Sims of Cluster Model

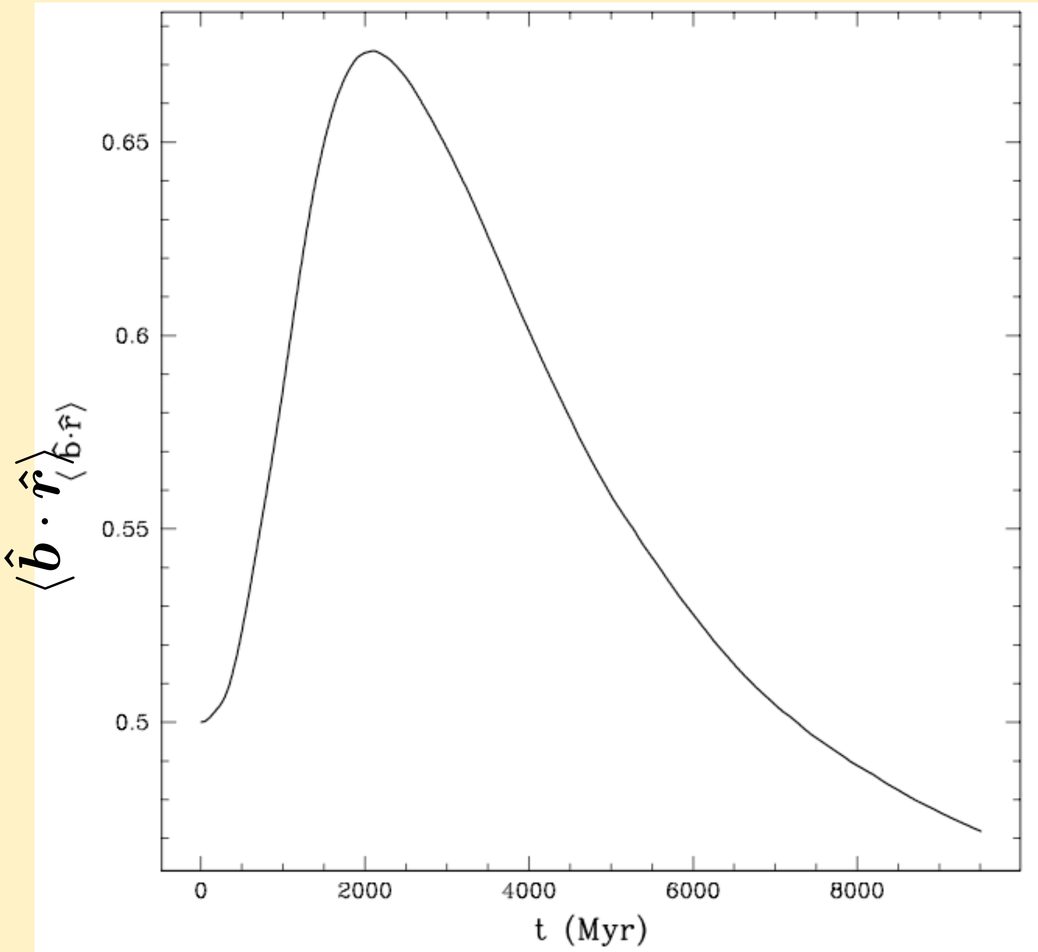
MTI growth time: ~ 800 Myr



(Parrish, Stone, & Lemaster, 2008)

Temperature Profile becomes Isothermal

MTI in Clusters



Magnetic Field Rearrangement:

$$\langle \hat{\boldsymbol{b}} \cdot \hat{\boldsymbol{r}} \rangle$$

Initially: 0.5 (tangled)

Peak: ~0.68

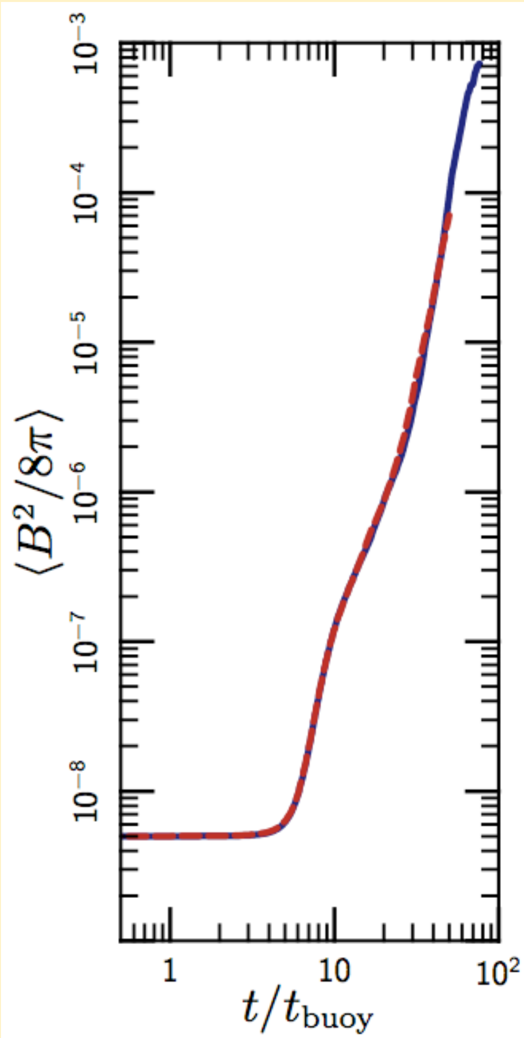
$$\frac{B_f^2}{B_0^2} \approx 100$$

Heat conduction becomes more efficient

(Parrish, Stone, & Lemaster, 2008)

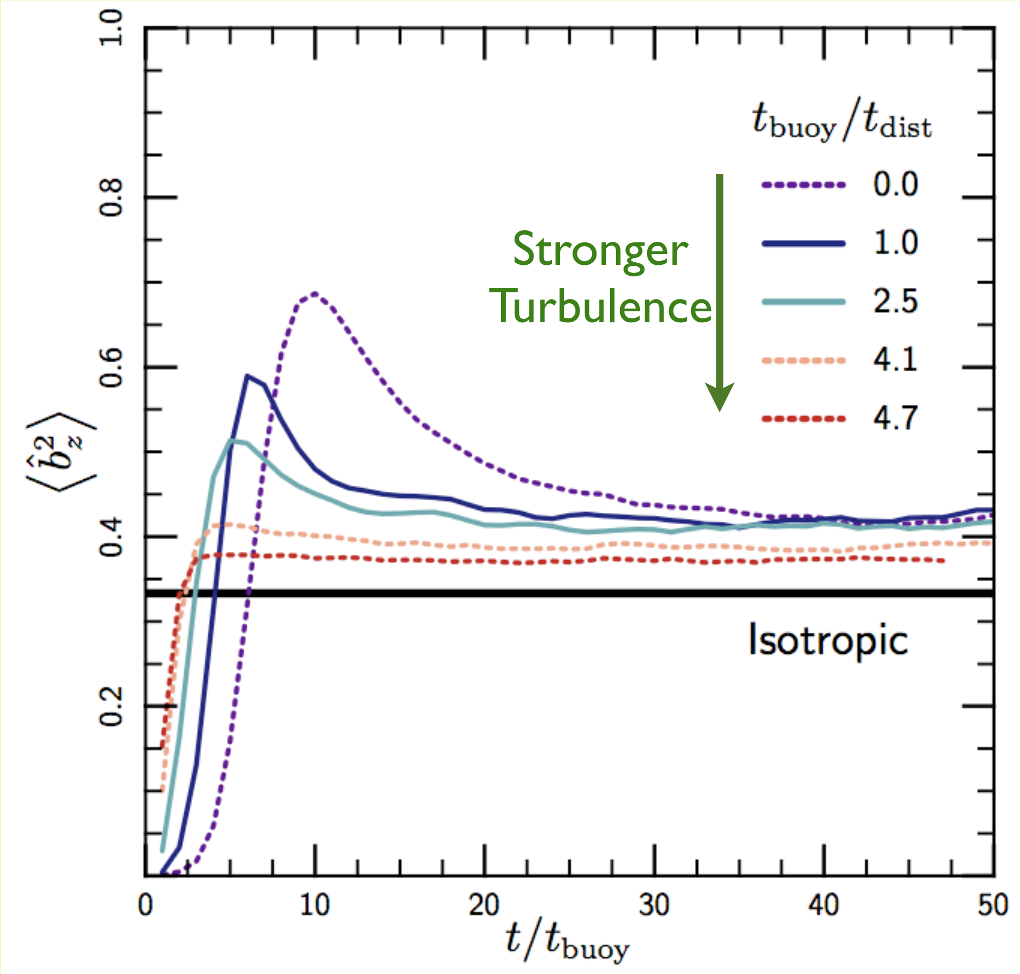
Caveat: observed clusters are rarely isothermal: temperature gradient fixed by cosmological processes & infall.

MTI in Local Simulations



Can drive a strong dynamo, but only ~10 linear growth times in outer parts of ICM.

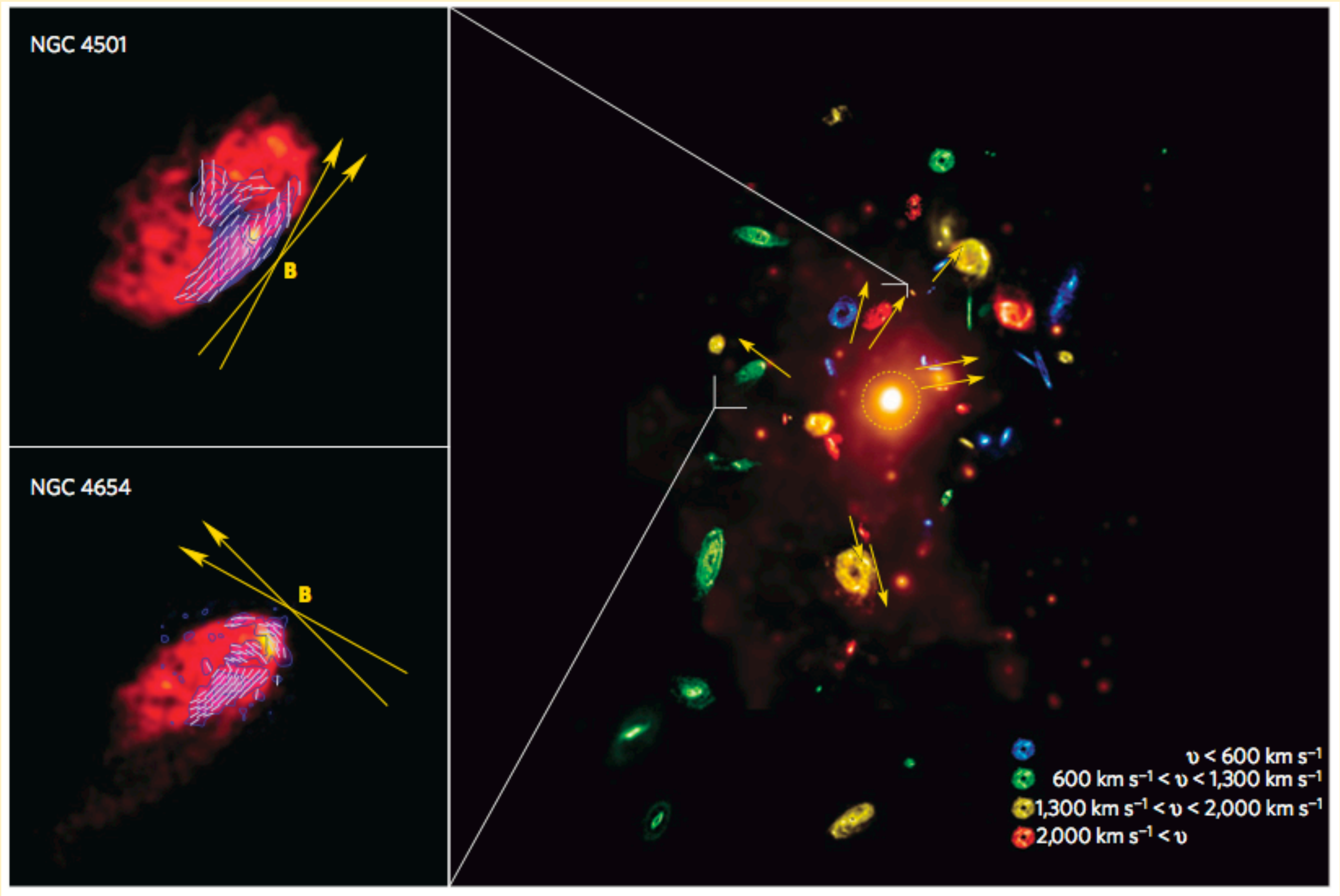
MTI in Local Simulations with Turbulence



Consistent radial bias over isotropic, but small at large *t*.

See talk by Ruskowski on cosmological MTI

MTI Observed in Virgo?



Pfrommer & Dursi, Nature Physics 6 (2010)

Evidence for radially-oriented magnetic fields.

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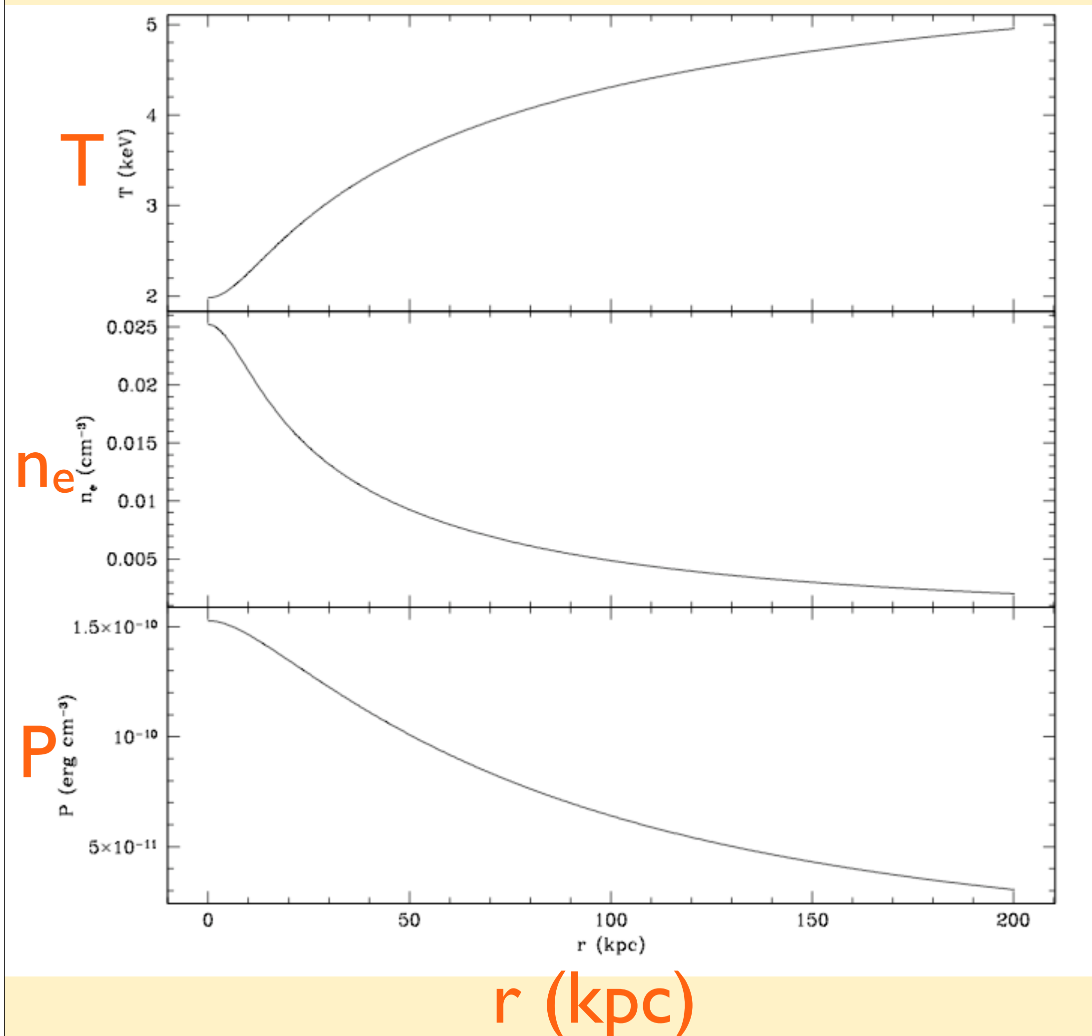
HBI in Clusters: Abell 2199



(Parrish, Quataert, & Sharma 2009)
(Bogdanovic, et al 2009)

Cluster Parameters:

- Mass 3.8 x 10^{14} M_{sun}
- r_s ~ 390 kpc (Johnstone, et al 2002)
- Hydrostatic Equilibrium
- Thermal Equilibrium

Tangled Magnetic Fields

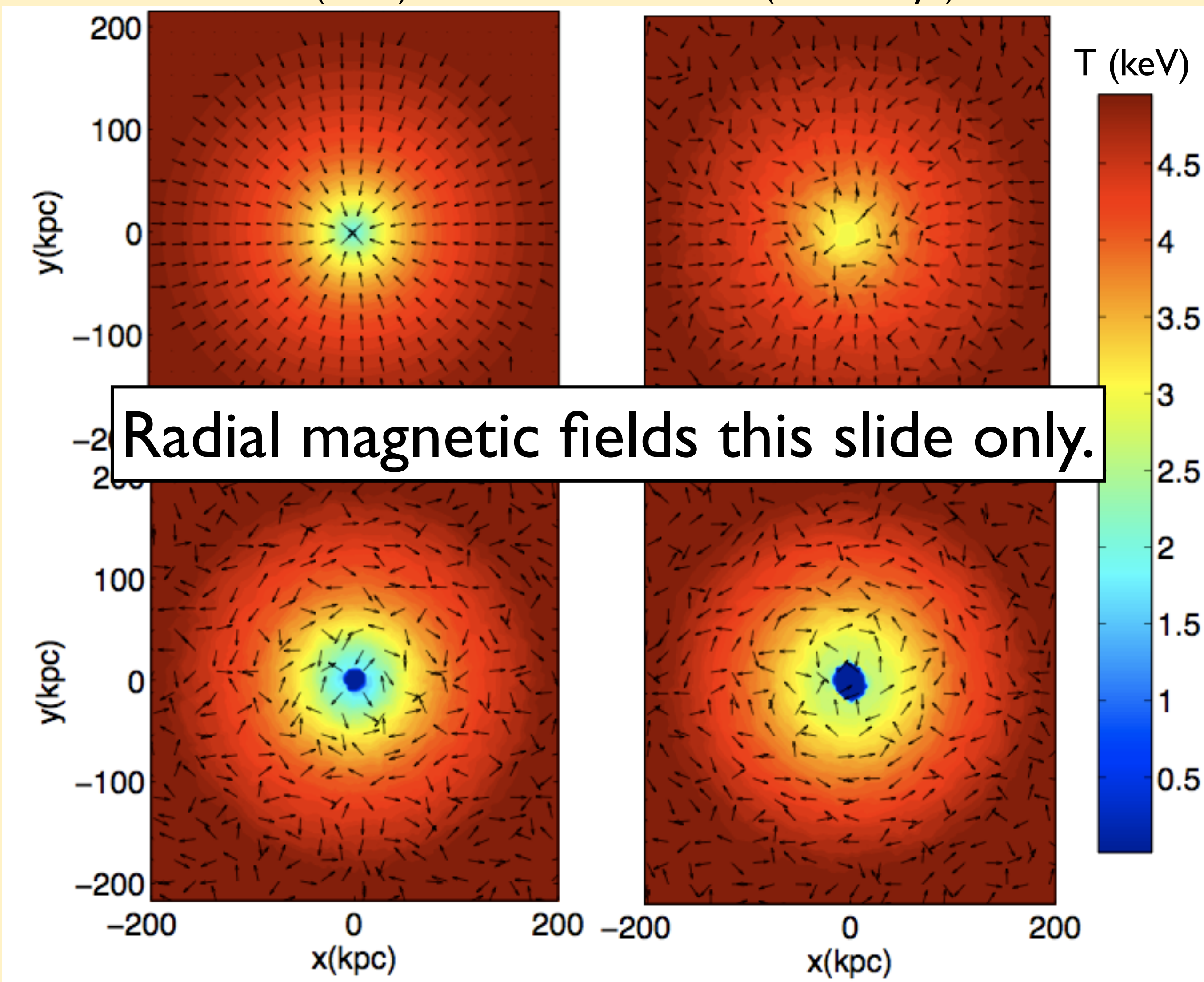
$$\tilde{A} = \tilde{A}_0 \left(\frac{k}{k_{\rm peak}} \right)^{-\alpha}$$

$$\boldsymbol{B} = \nabla \times \boldsymbol{A}$$

HBI Growth Time: 120 Myr

HBI in Clusters: Radial Fields

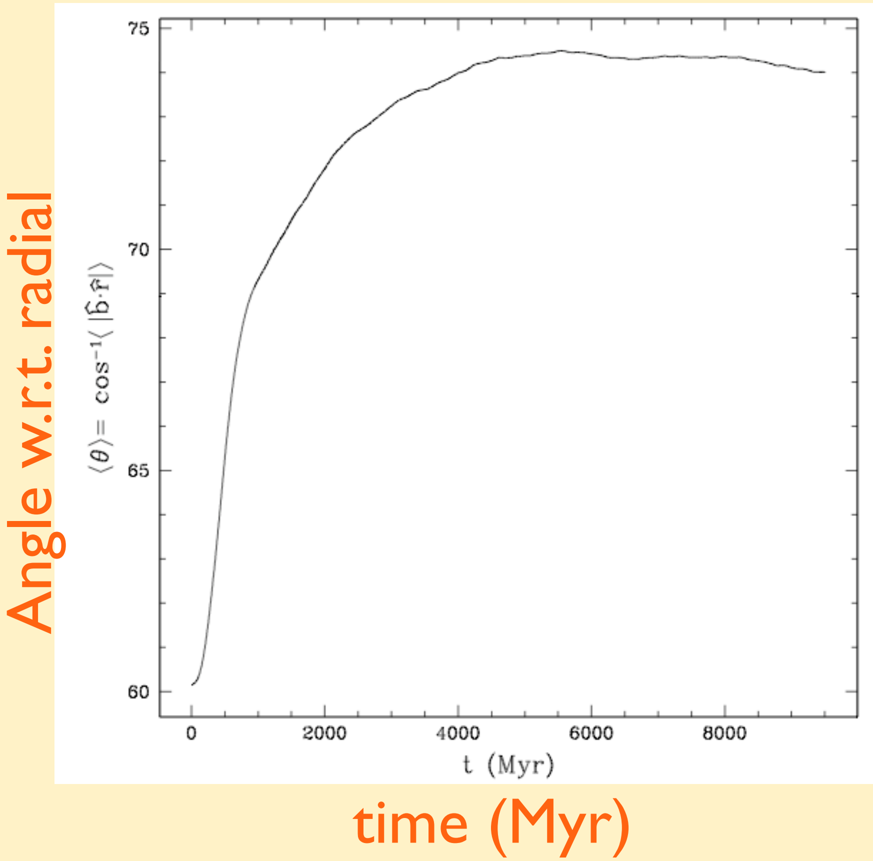
(*t* = *0*) (*t* = 1.6 Gyr)

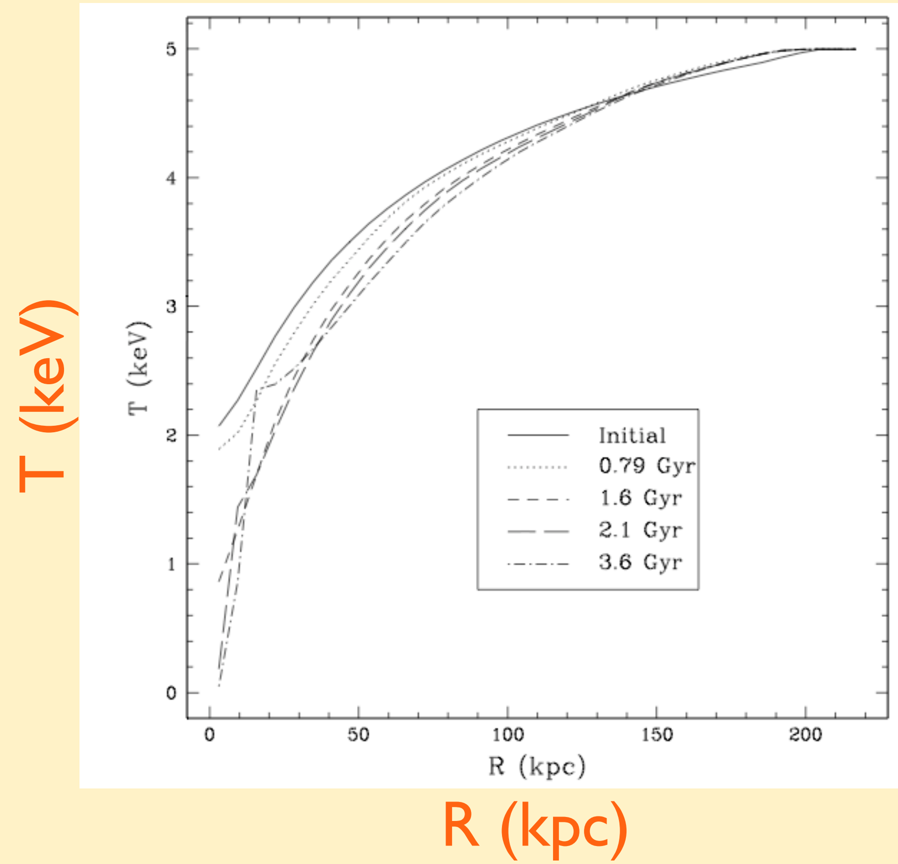


Radial magnetic fields this slide only.

(*t* = 4.8 Gyr) (*t* = 9.5 Gyr)

HBI in Clusters: A2199, Time Evolution



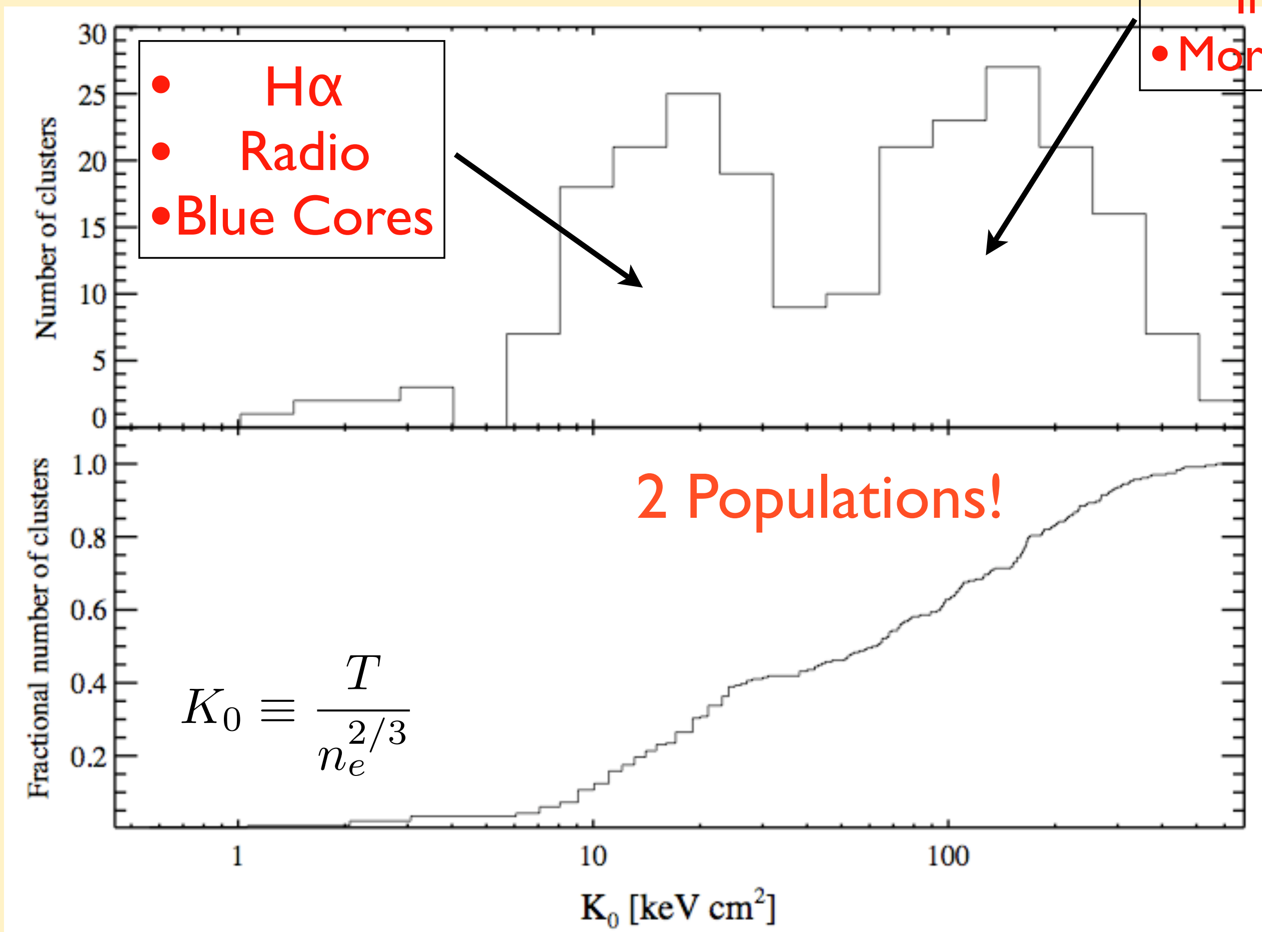


- Magnetic geometry reorients to highly azimuthal
- Conduction is reduced, $f_{Sp} \rightarrow 0.13$.
- HBI exacerbates cooling flow problem.

(Cooling catastrophe at 2.7 Gyr)

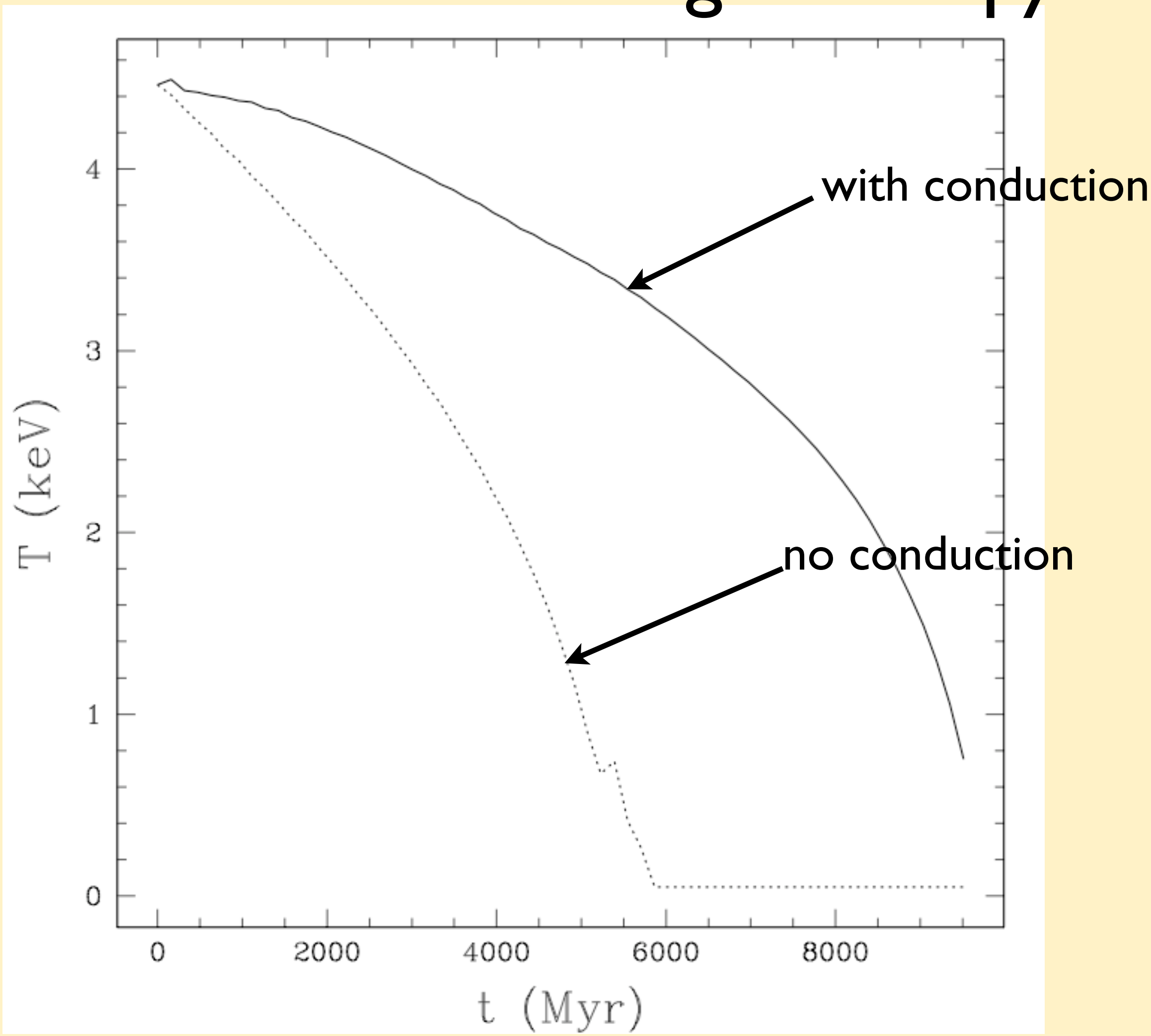
Clusters and Entropy

- No Feedback Indicators
- More isothermal



Cavagnolo, Voit, Donahue, et al (2009)

Effect of Conduction on High Entropy Cores



K_0 = 123, central cooling time = 9.3 Gyr (estimated)

Turbulence in Clusters & Cooling

Sources of Turbulence:
- *Galaxy Wakes*
- Substructure
- AGN
- Mergers

ESO 137-001 leaves a wake

X-Ray + Hα in A3627
Sun, Donahue, & Voit 2007
NASA/CXC/SOAR

Kolmogorov Turbulence:

Drive on outer scale *L* with velocity *V(L)*

$$v(\lambda) = v(L)\left(\frac{\lambda}{L}\right)^{1/3}$$

Eddies turn over on timescale

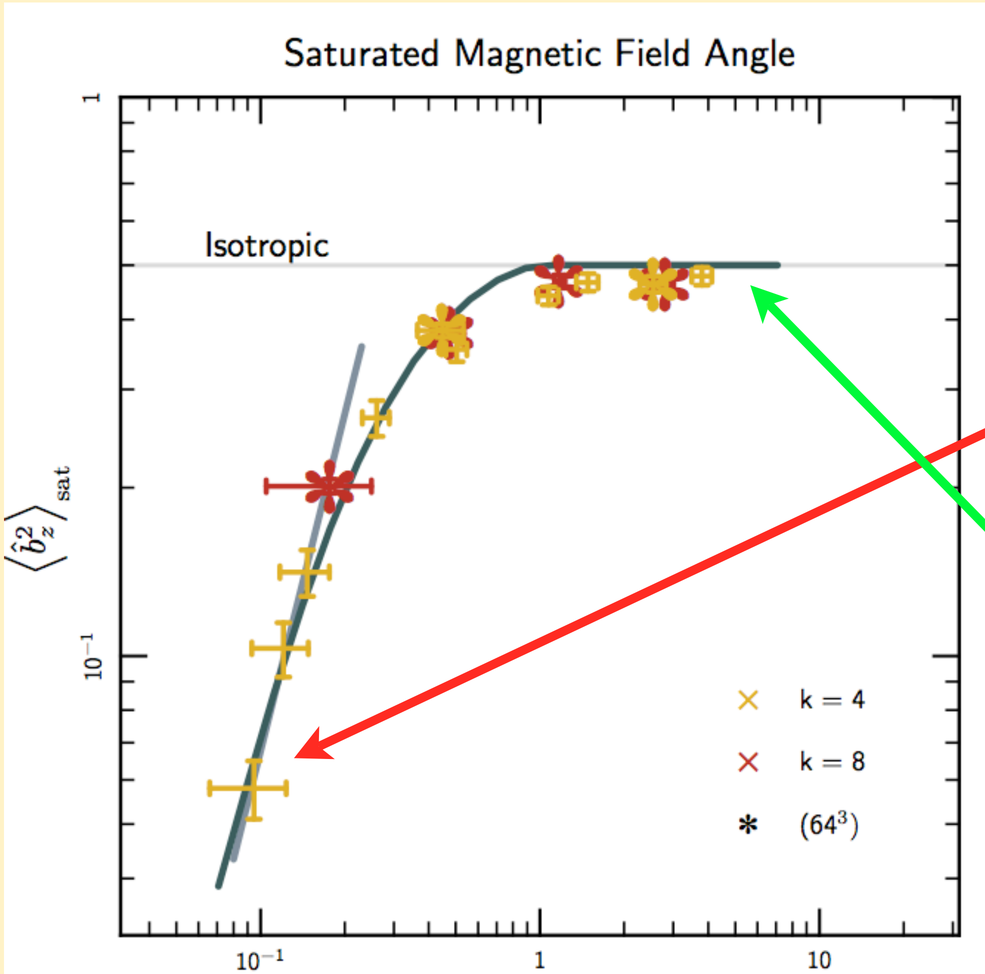
$$t_{\rm eddy}(L) = L/v(L)$$

Galactic Wake Estimate
- 5 galaxies of mass $10^{11}\ M_\odot$ within the central 200 kpc.
- Outer turbulent scale of *L ~ 40* kpc.
- Turbulent Velocity: $\delta v \sim 0.1 c_s$
- Turbulent Energy:

$$\dot{e}_{\rm turb} \simeq \frac{\rho(\delta v)^3}{L} \approx 7.5\times10^{-30}\,\frac{\rm erg}{\rm cm^3\,s}$$

$$\ll \dot{e}_{\rm cool} \sim 10^{-27}\,\frac{\rm erg}{\rm cm^3\,s}$$

The HBI and Turbulence



Saturated Magnetic Angle

$t_{\rm HBI}/t_{\rm eddy}$

Local Simulations by McCourt

Two Limits:

1) HBI efficient:

$$t_{\rm HBI} < t_{\rm eddy}$$

$$f_{\rm Sp} \rightarrow 0$$

2) Turbulence wins:

$$t_{\rm HBI} > t_{\rm eddy}$$

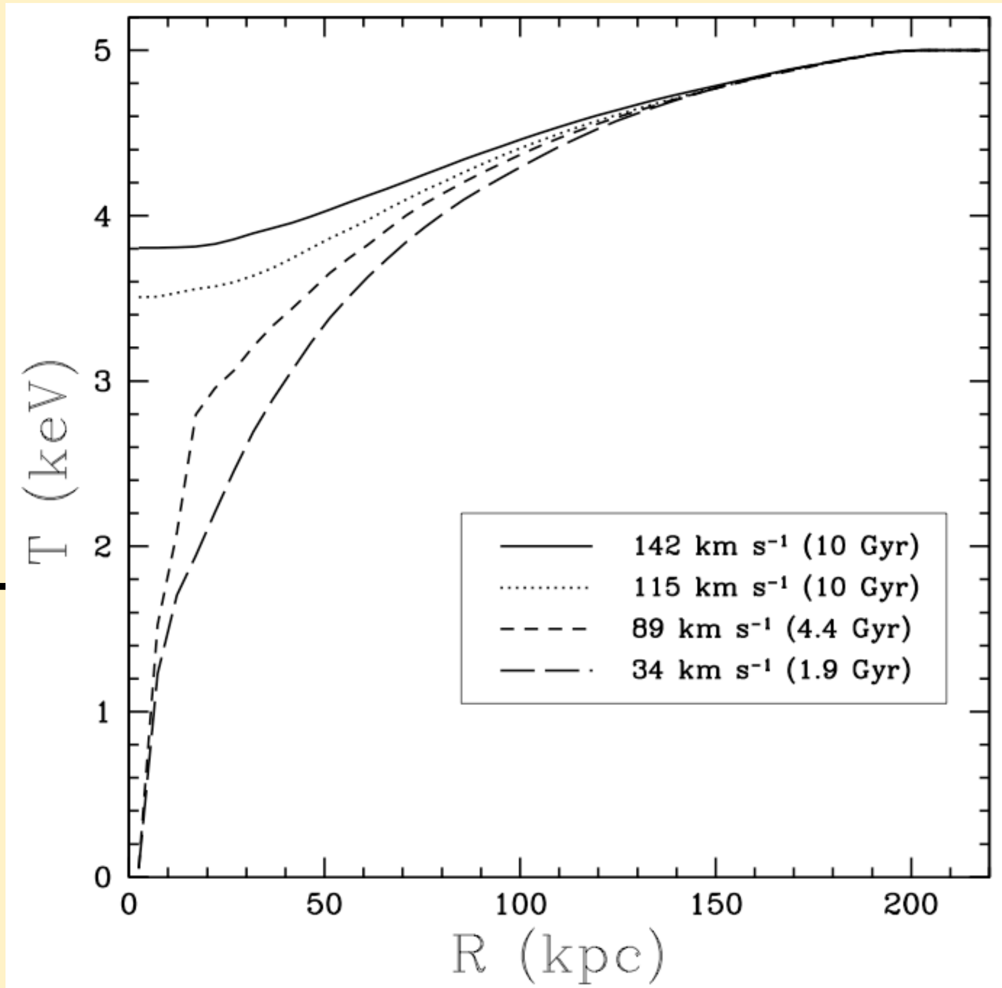
$$f_{\rm Sp} \rightarrow \frac{1}{3}$$

Richardson Number (Ri)

$$\mathrm{Ri} = \mathrm{Fr}^{-1/2}$$

Turbulence and Bimodality

Final Temperature Profiles



Parrish, Quataert, & Sharma (2010)
See also Ruszkowsi & Oh (2010)

Exact Same
Initial Conditions
Turbulence of *L* = *40* kpc.

$$t_{\rm HBI} \approx 100\,{\rm Myr}$$
$$t_{\rm cool} \approx 400\,{\rm Myr}$$
$$t_{\rm eddy} \approx 100 - 450\,{\rm Myr}$$

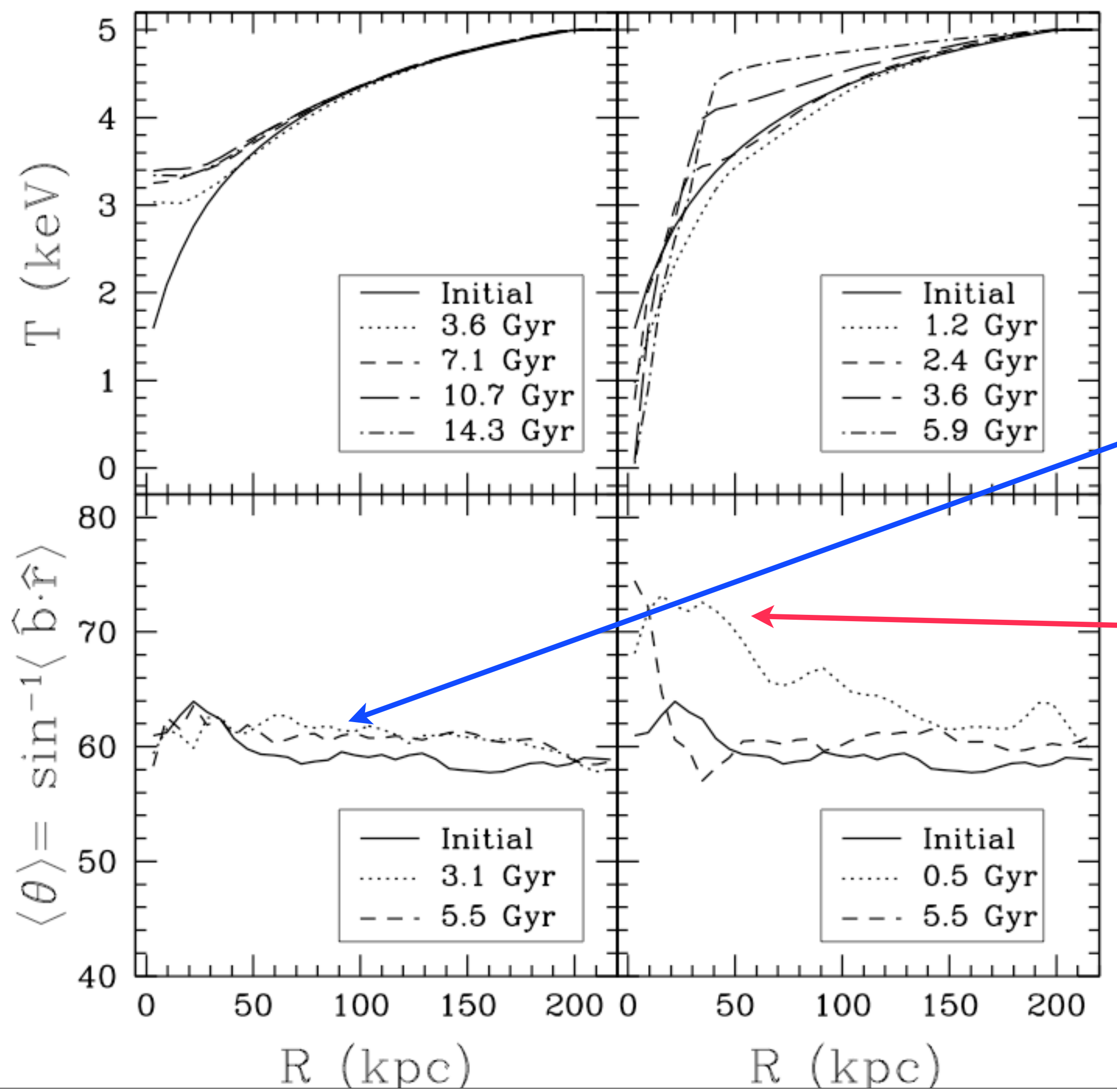
Clear Bimodality:

~25 km/s velocity difference

- Stable ~isothermal profile
- Cooling Catastrophe

Turbulence and Bimodality

L = 40 kpc   L = 100 kpc



Same δv ~ 115 km/s

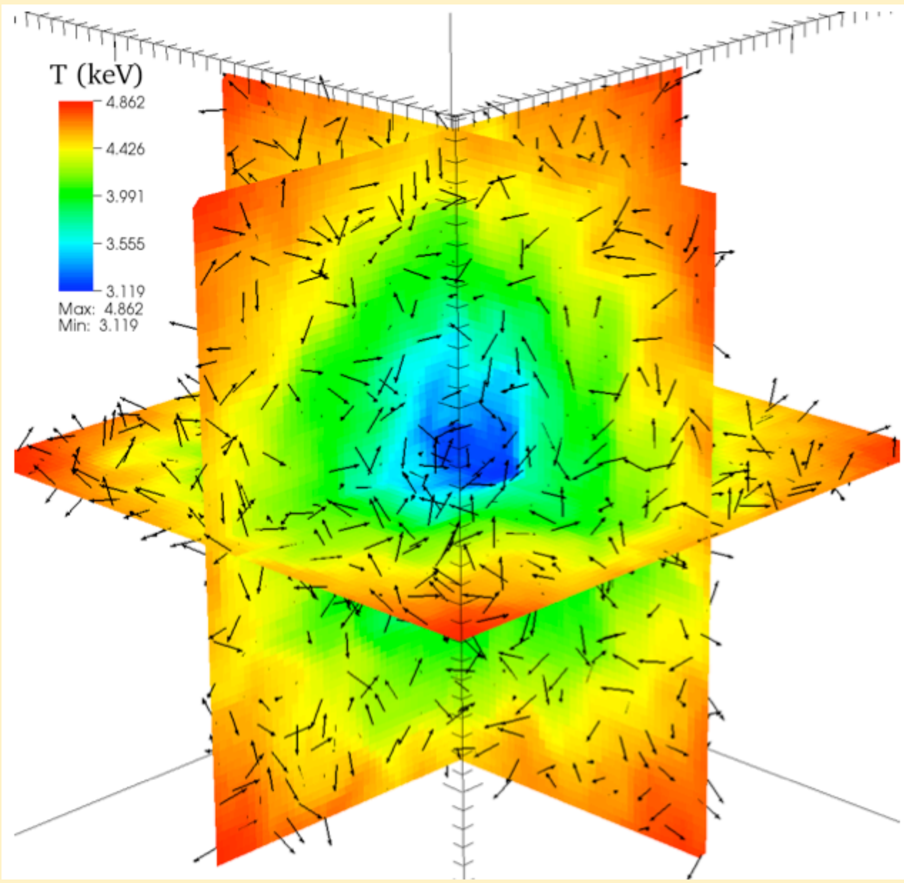
$$t_{\rm eddy} \sim L/\delta v$$

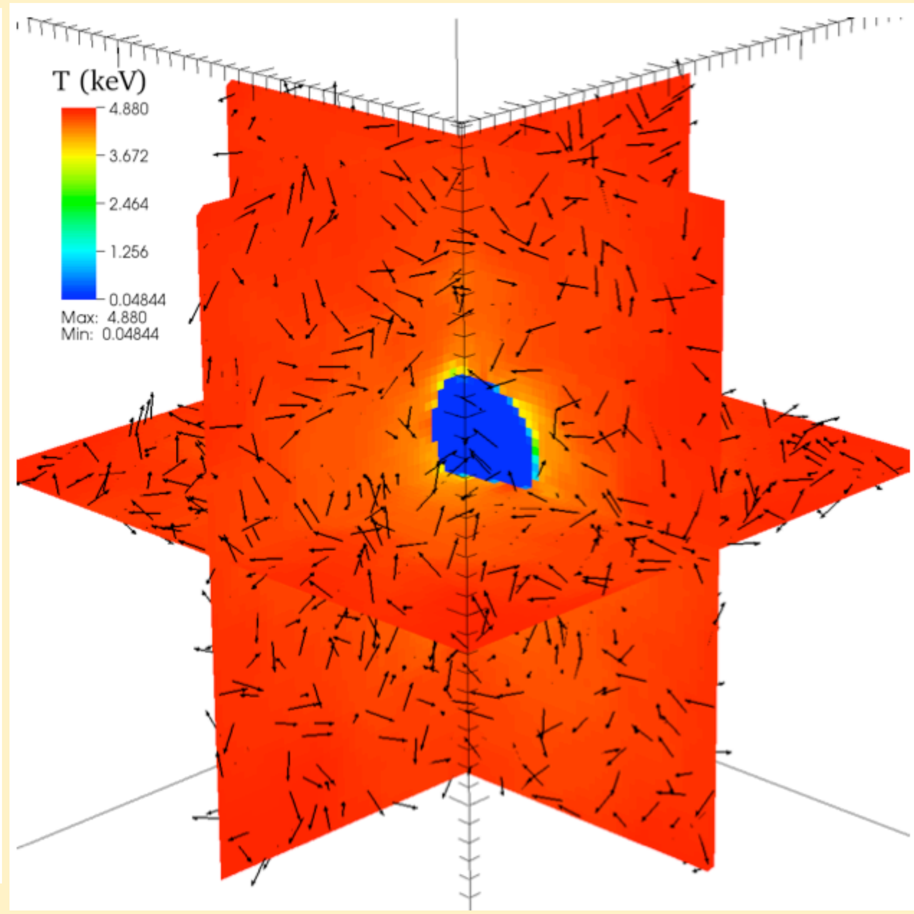
Turbulence keeps conduction at f_{sp}~1/3.

HBI shuts off conduction

Turbulence and Bimodality

Snapshots at 7 Gyr

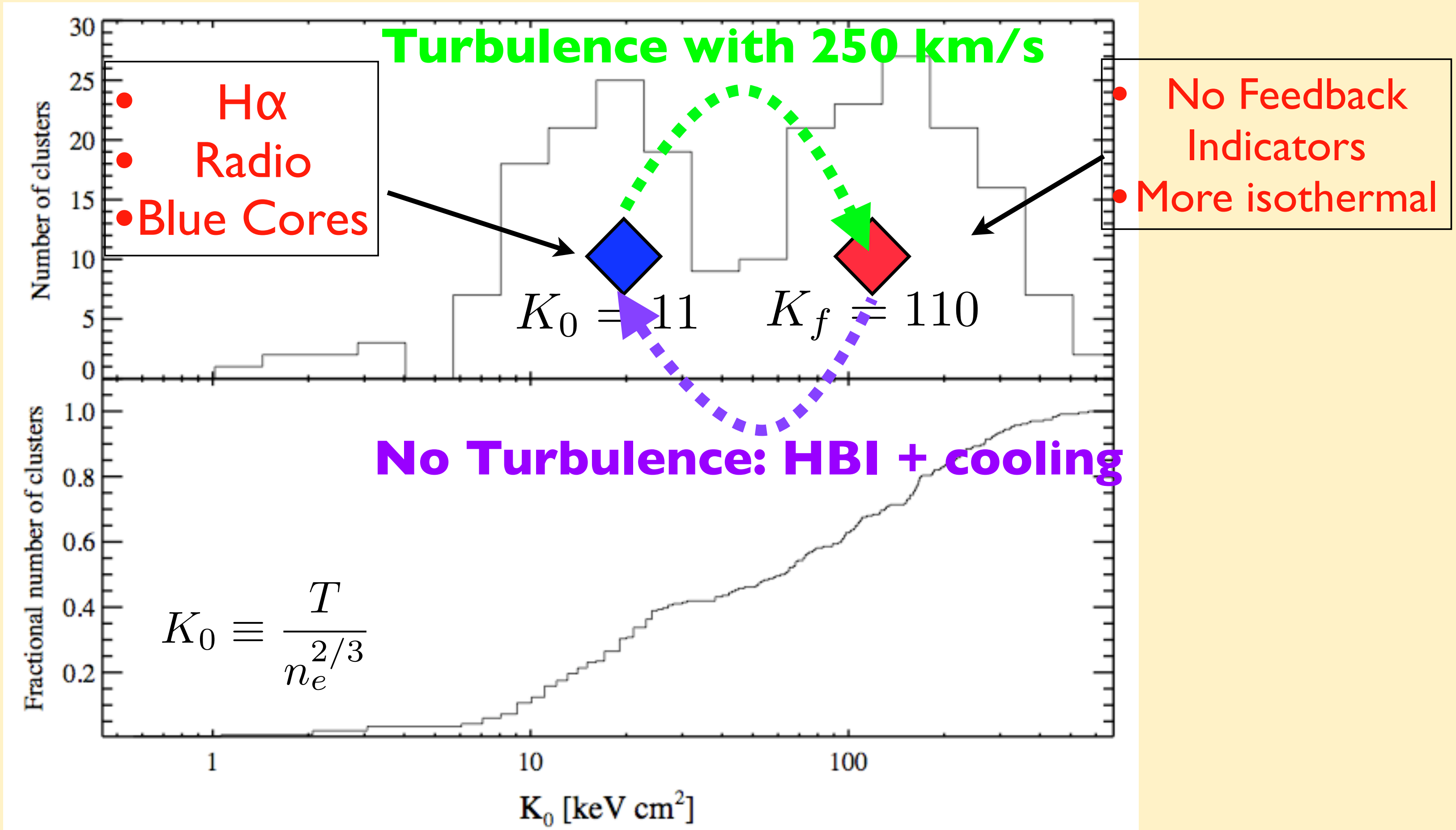




Stable

Cooling Catastrophe

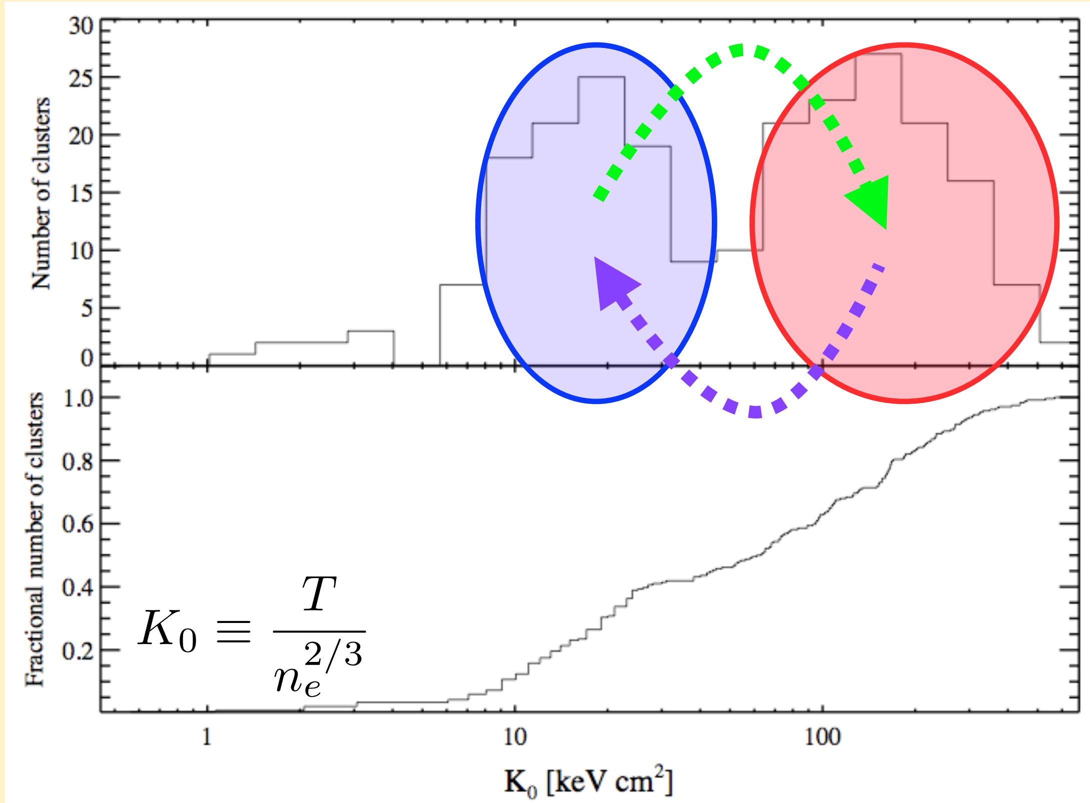
Turbulence and Entropy



•Conduction is a natural way to *volumetrically* raise entropy

•Turbulence (energetically weak) can be a catalyst for changing the cool core/non-cool core state.

Conclusions on Bimodality



- The HBI can shut off conduction and precipitate a cooling catastrophe.
- Conduction alone ***cannot*** stably heat a low-entropy, cool core cluster. These are mainly heated by feedback from a central AGN (bubbles, jets, etc).
- Conduction ***can*** stably heat high entropy, fairly isothermal clusters...consistent with disturbed clusters being high entropy.
- Small changes in turbulence naturally lead to a strong bimodality between these states.

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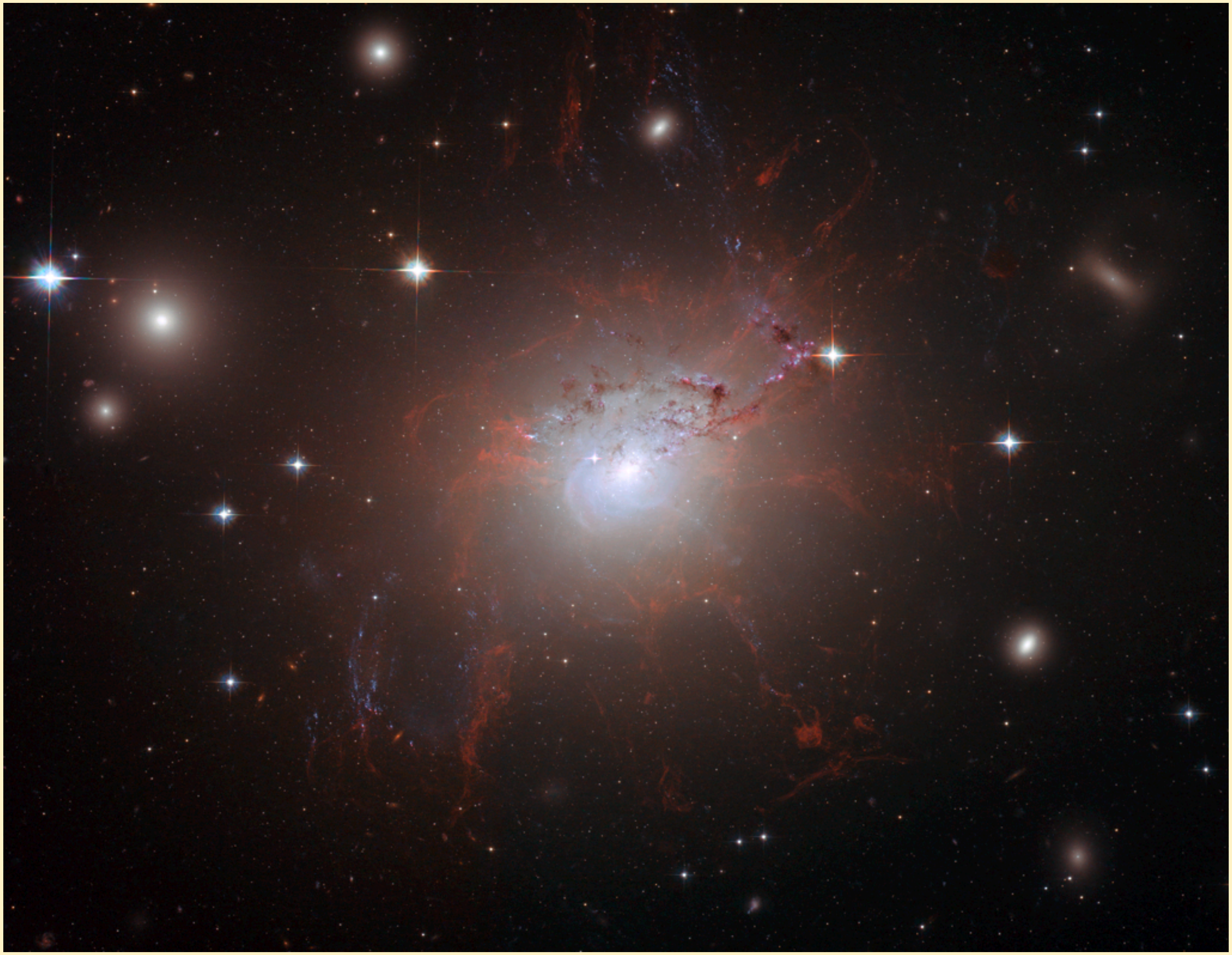
- **Filament Formation**

Filament Observations in Perseus



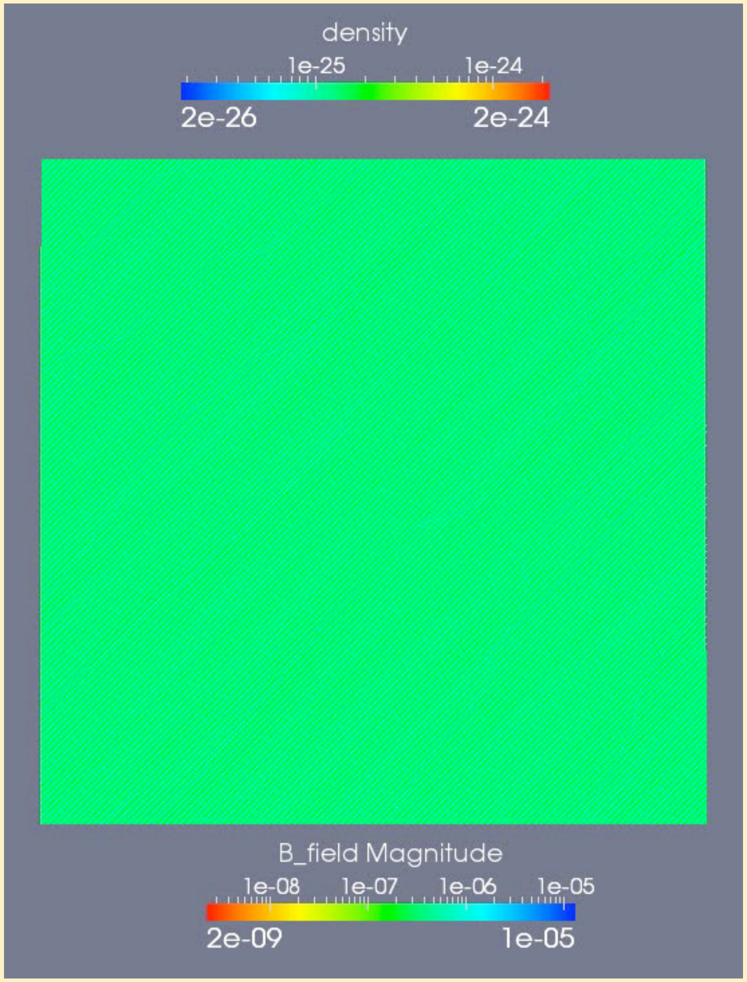
NGC 1275: Observations (Fabian, et al)

Formation of Filaments with Anisotropic Conduction

Field's Length $\lambda_F = \left[\frac{T\kappa(T)}{n_e n_p \Lambda(T)}\right]^{1/2}$

Conduction Anisotropic

$\lambda_{F,\parallel} \ggg \lambda_{F,\perp}$



- Cold, dense filaments aligned with magnetic field enhanced by flux freezing.
- Velocities of up to 100 km/s preferentially aligned with filaments.

Sharma, Parrish, & Quataert, arXiv:1003.5546, Accepted to ApJ