New Forms of Convection in Galaxy Cluster Plasmas

(i.e., how do galaxy clusters boil?)

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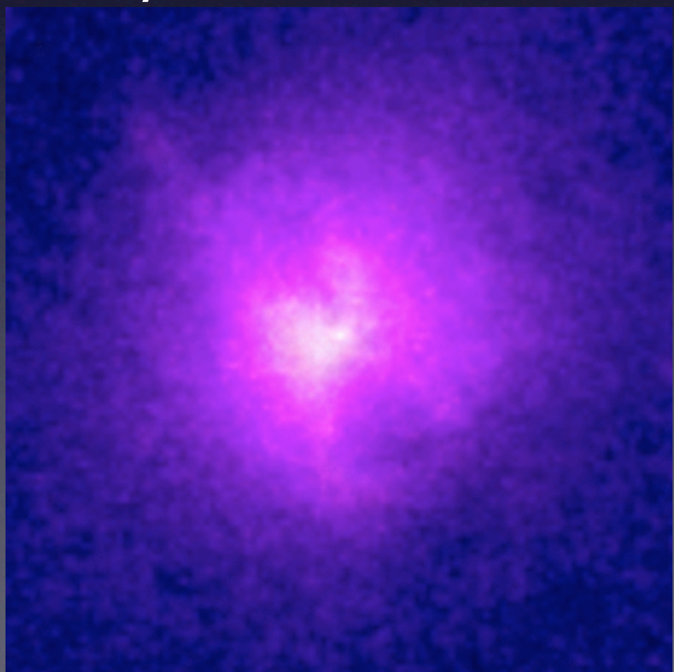
Hydra A w/ Chandra



in collaboration with

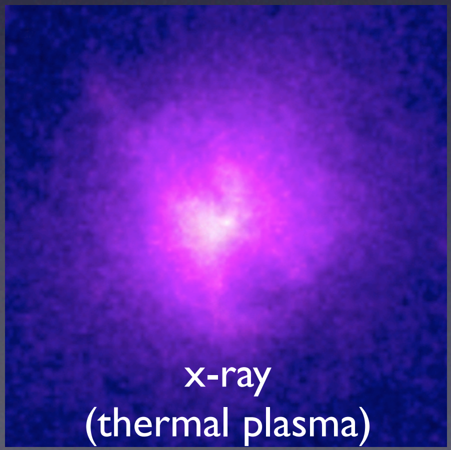
Ian Parrish
Prateek Sharma

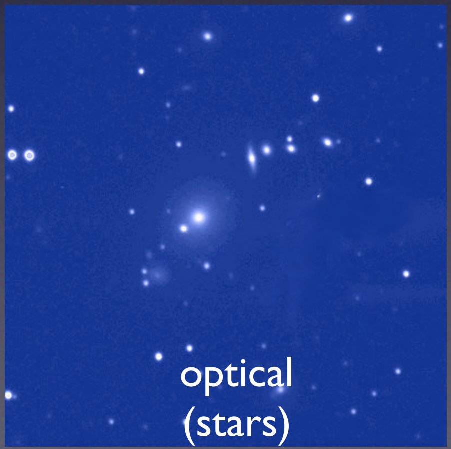
Overview

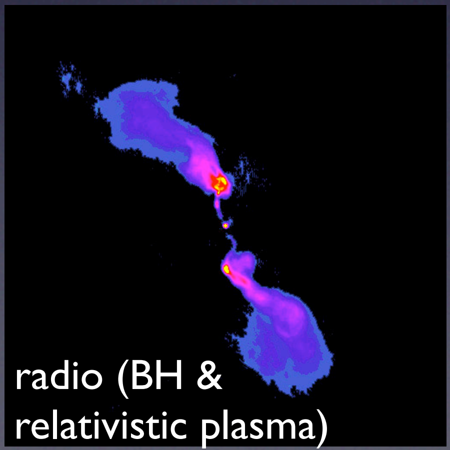
- Hot Plasma in Clusters of Galaxies
- Hydrodynamic Convection ('normal' convection; e.g., the sun)
- Convection induced by Anisotropic Thermal Conduction
  - new convective instabilities: the "MTI" & "HBI"
- Implications for Clusters
  - incl. interaction btw. thermal plasma & cosmic rays from an AGN

Clusters of Galaxies

- largest gravitationally bound objects: $M_{vir} \sim 10^{14\text{-}15}\ M_\odot$
  $R_{vir} \sim 1\text{-}3$ Mpc
  - ~ 84% dark matter; **~ 14 % plasma**; ~ 2% stars
  - on exponential tail of the mass function: useful cosmological probe
  - host the most massive galaxies (~ $10^{12}\ M_\odot$) and black holes (~ $10^{9\text{-}10}\ M_\odot$)



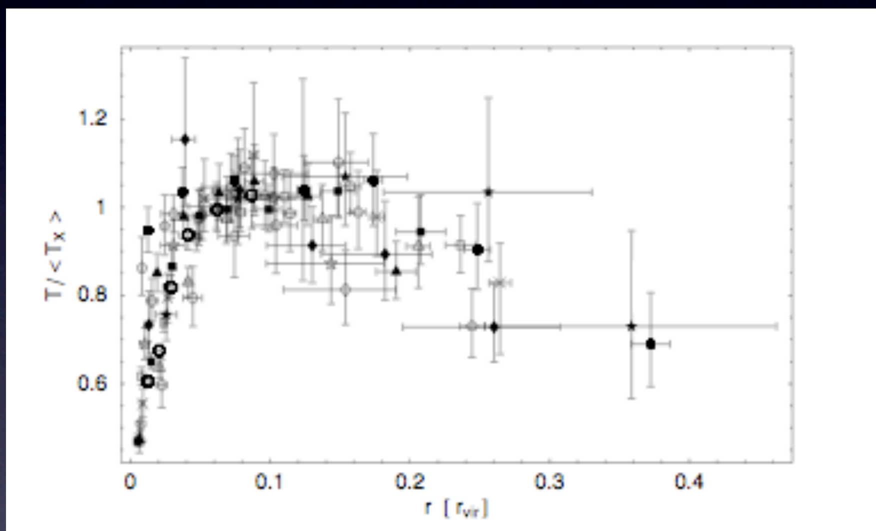




Hot Plasma in Clusters

cluster temperature profiles

T/<T>



Piffaretti et al. 2005

Radius (R_{vir})

$L_X \sim 10^{43\text{-}46}$ erg s^{-1}

$n \sim 10^{-4}$-1 cm^{-3}

T ~ 1-15 keV

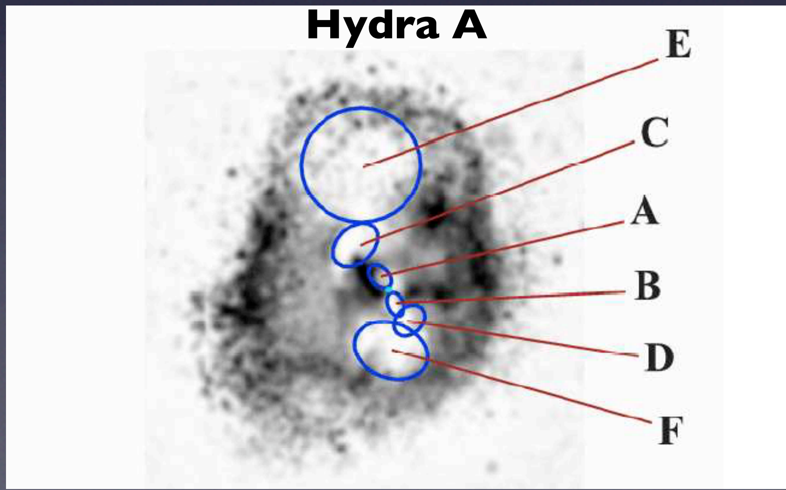
large electron mean free path:

$$\ell_e \simeq 2 \left(\frac{T}{3\,\mathrm{keV}} \right)^2 \left(\frac{n}{0.01\,\mathrm{cm}^{-3}} \right)^{-1} \mathrm{kpc}$$

→ thermal conduction important

"Cool Core" Clusters

- in at least ~ 50% of clusters, t_{cool} < Hubble time for $r \lesssim 100$ kpc
- absent a heat source: $\dot{M}_{cool} \sim 100\text{-}1000\ M_\odot\ yr^{-1}$
  - not observed: $\dot{M}_{star} \lesssim 0.01\ \dot{M}_{cool}$; $T_{min} \sim 1/3\ T_{vir}$
- ➔ a heat source balances radiative cooling
  - ~ spherically out to ~ 100s kpc
- proposed sources of heating include
  - a central (radio loud) AGN ⟷
  - thermal conduction from large R
  - .....



Wise et al. 2007

Hydrodynamic Convection

- Schwarzschild criterion for convection: **ds/dz < 0**
- Motions slow & adiabatic: **pressure equil, s ~ const**

low entropy (s)

gravity
high s

ρ_f
s_{bg}
p'_{bg}

$\rho_i = \rho_{bg}$
$s_i = s_{bg}$
$p_i = p_{bg}$

background fluid

$$s'_{bg} \quad \rho'_{bg} \quad p'_{bg}$$

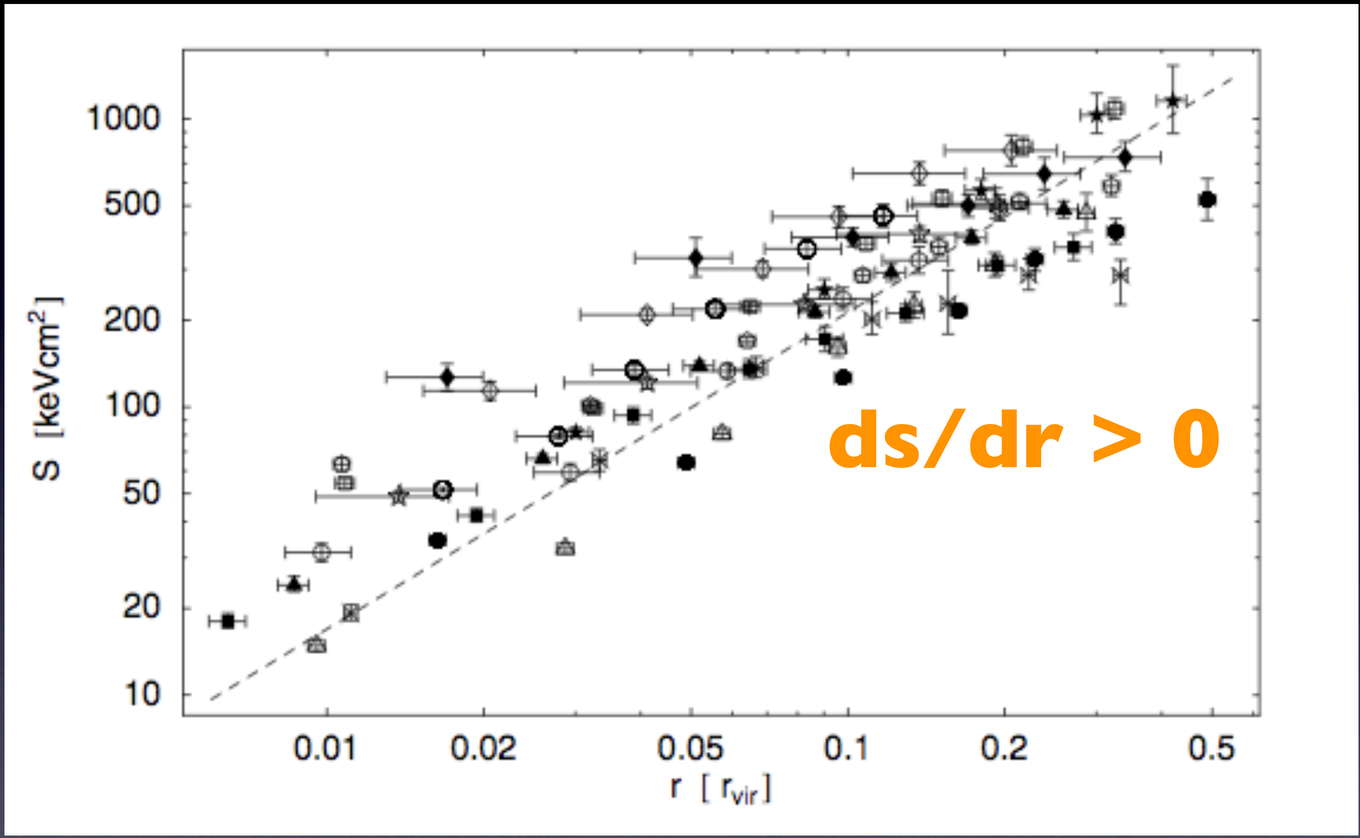
$$s(p,\rho) \propto \ln[p/\rho^{\gamma}]$$

$$\text{if } \mathrm{ds/dz} < 0 \rightarrow \rho_{\mathrm{f}} < \rho'_{\mathrm{bg}}$$

convectively unstable

Cluster Entropy Profiles

Entropy



Piffaretti et al. 2005

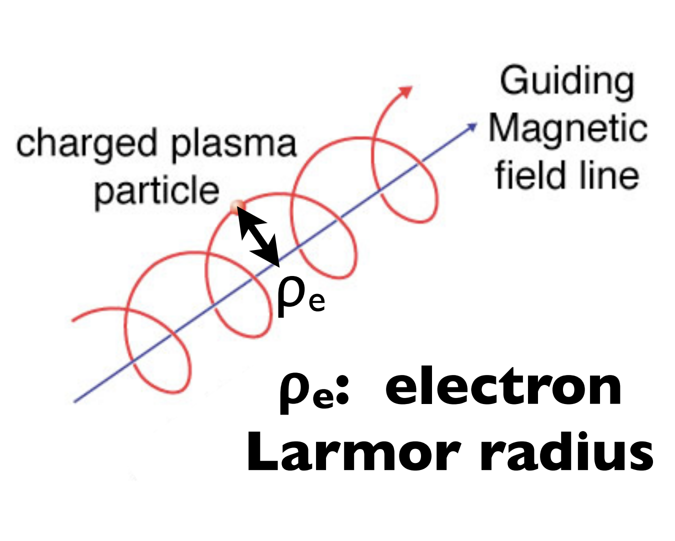
Radius (R_{vir})

Schwarzschild criterion → clusters are **stable**

Anisotropic Thermal Conduction in Cluster Plasmas

electron mean free path:

$$\ell_e \simeq 2 \left(\frac{T}{3\,\mathrm{keV}}\right)^2 \left(\frac{n}{0.01\,\mathrm{cm}^{-3}}\right)^{-1} \mathrm{kpc}$$

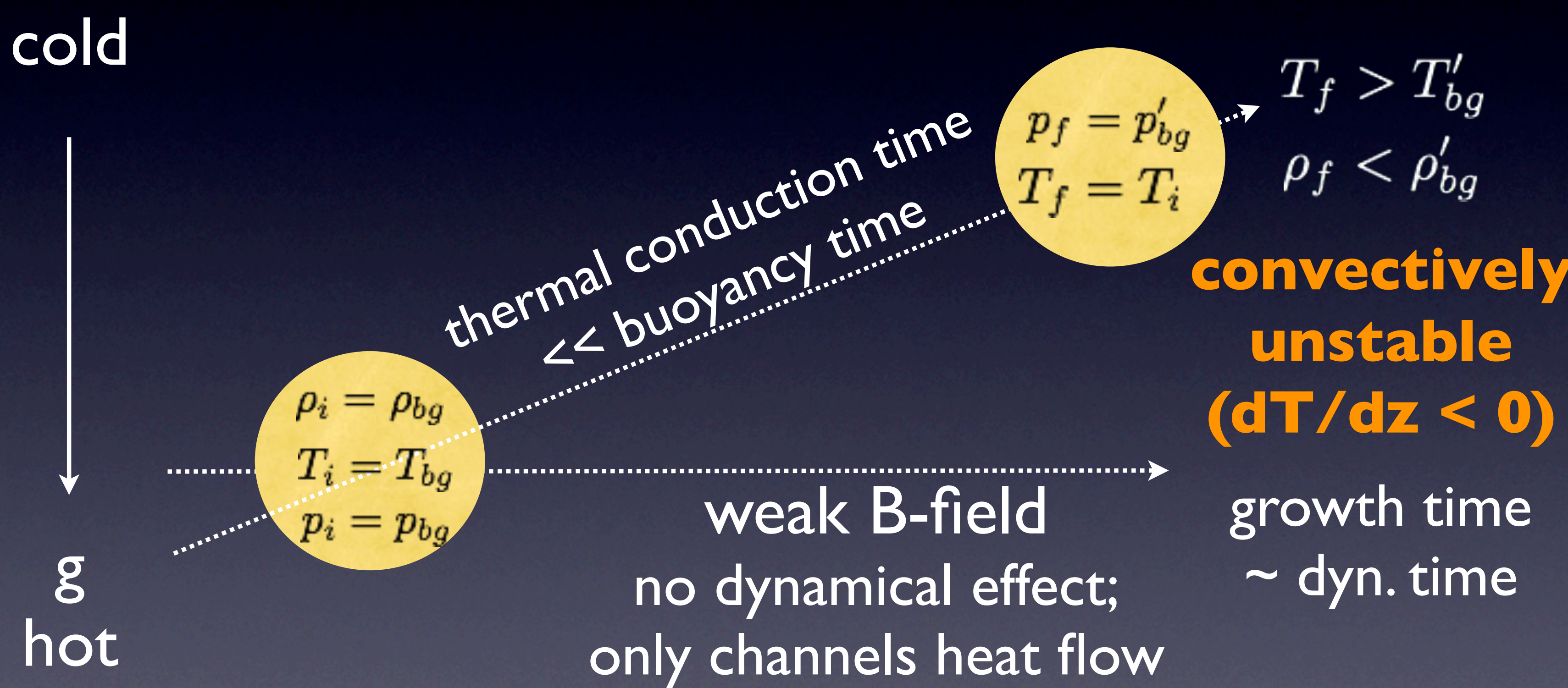


$$\frac{l_e}{\rho_e} \sim 10^{14} \left(\frac{B}{10^{-6}\,\mathrm{G}}\right) \left(\frac{n}{0.01\,\mathrm{cm}^{-3}}\right)^{-1} \left(\frac{T}{3\,\mathrm{keV}}\right)^{-3/2}$$

l_e >> ρ_e $\Rightarrow$ heat transport is **anisotropic** (primarily along B)

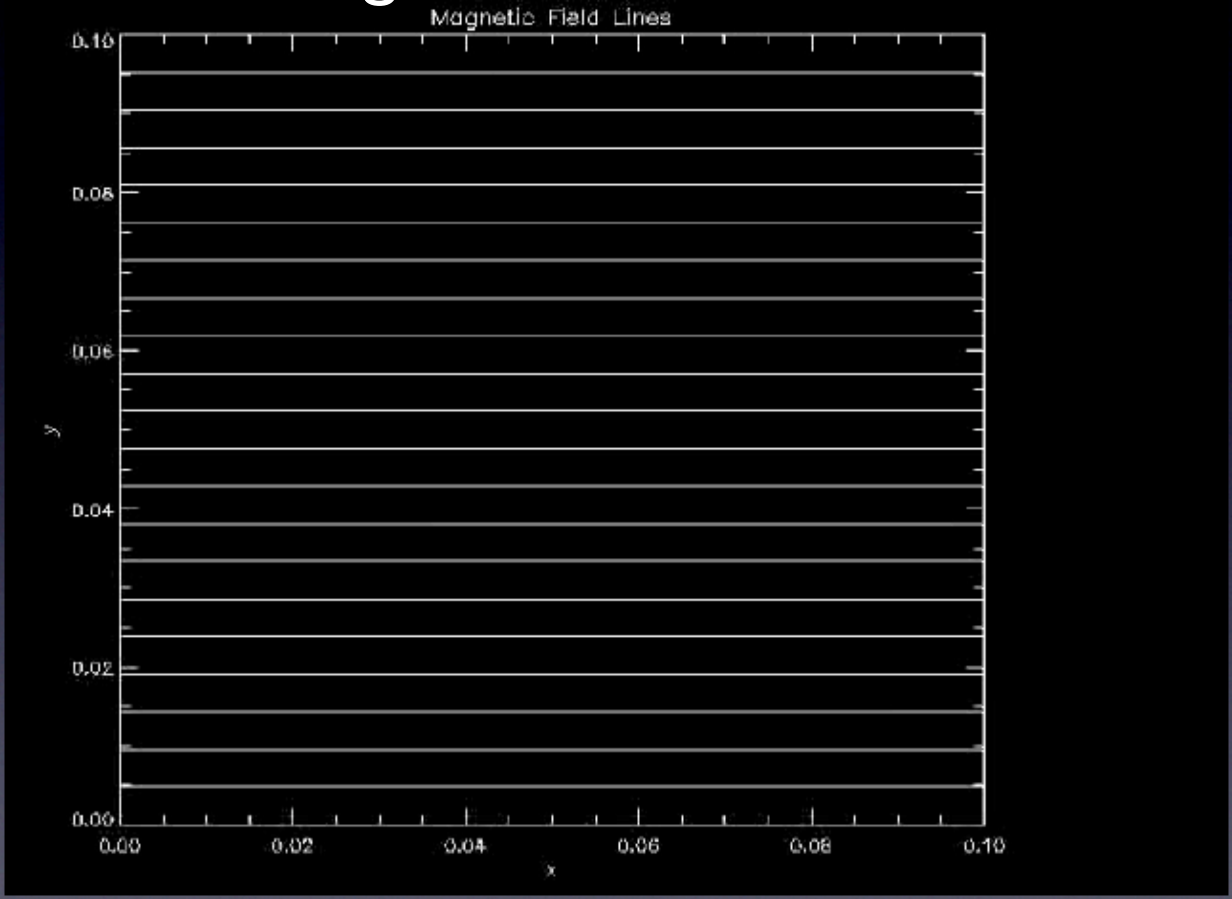
The Magnetothermal Instability (MTI)

Balbus 2000, 2001; Parrish & Stone 2005, 2007; Quataert 2008; Sharma, Quataert, & Stone 2008



The MTI

magnetic field lines



cold

g

hot

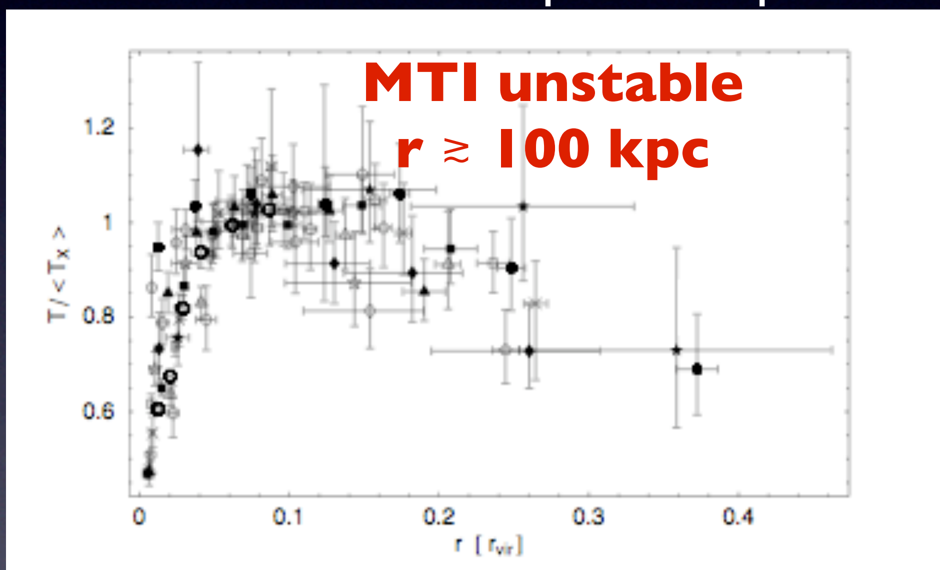
2D simulation from Ian Parrish

instability saturates by rearranging magnetic field lines

The MTI in Clusters

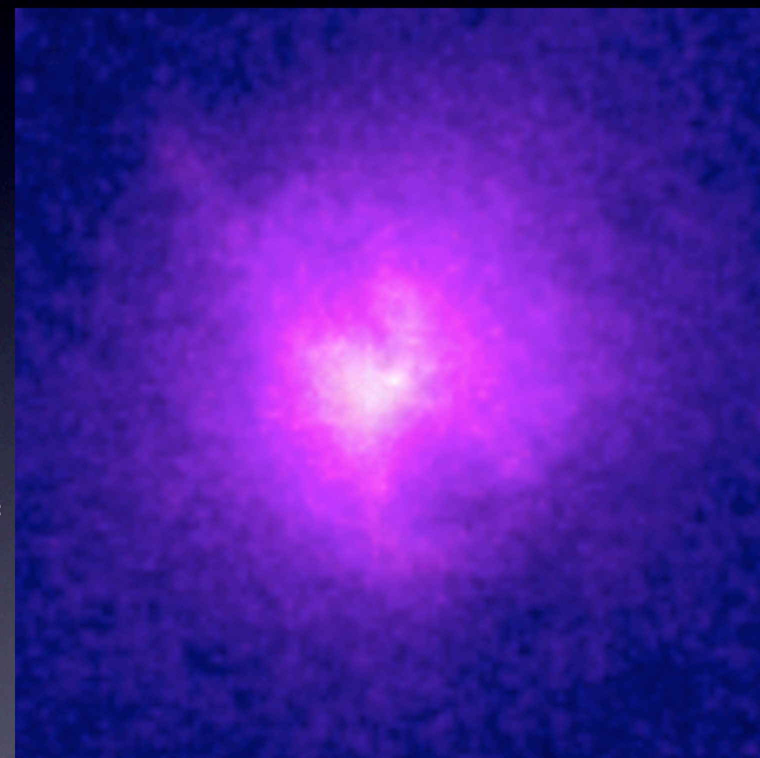
cool core cluster temperature profile

T/<T>



Radius (R_{vir})

Piffaretti et al. 2005



~ 200 kpc

The Heat Flux-Driven Buoyancy Instability (HBI)

Quataert 2008; Parrish & Quataert 2008

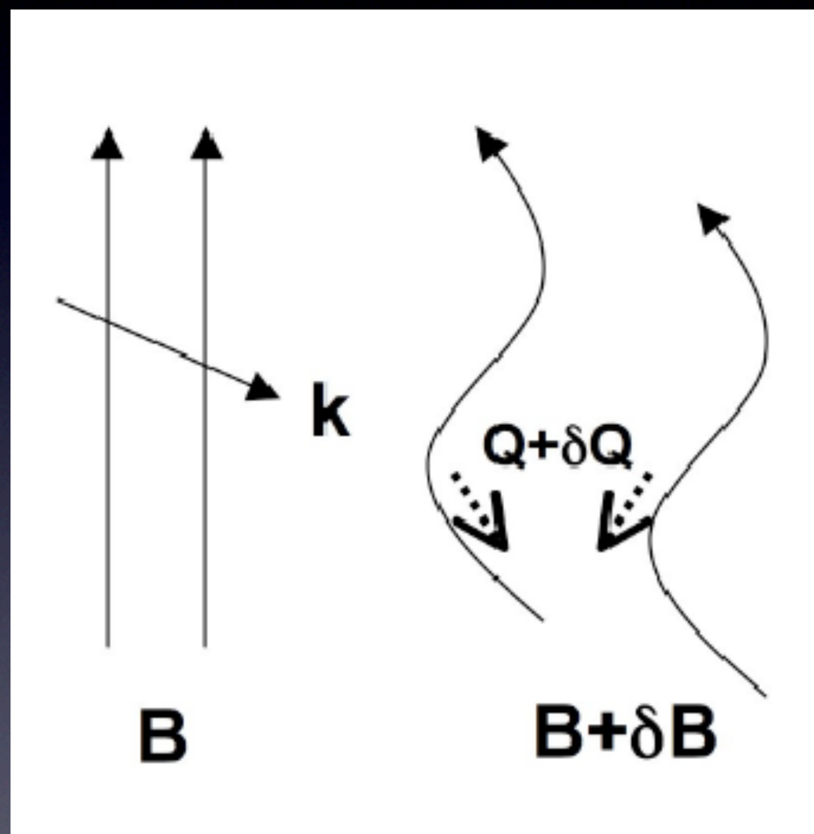
hot

cold

g, Q_z

heat flux

weak B



converging & diverging heat flux

⇒

conductive heating & cooling

for **dT/dz > 0** upwardly displaced fluid is heated & rises

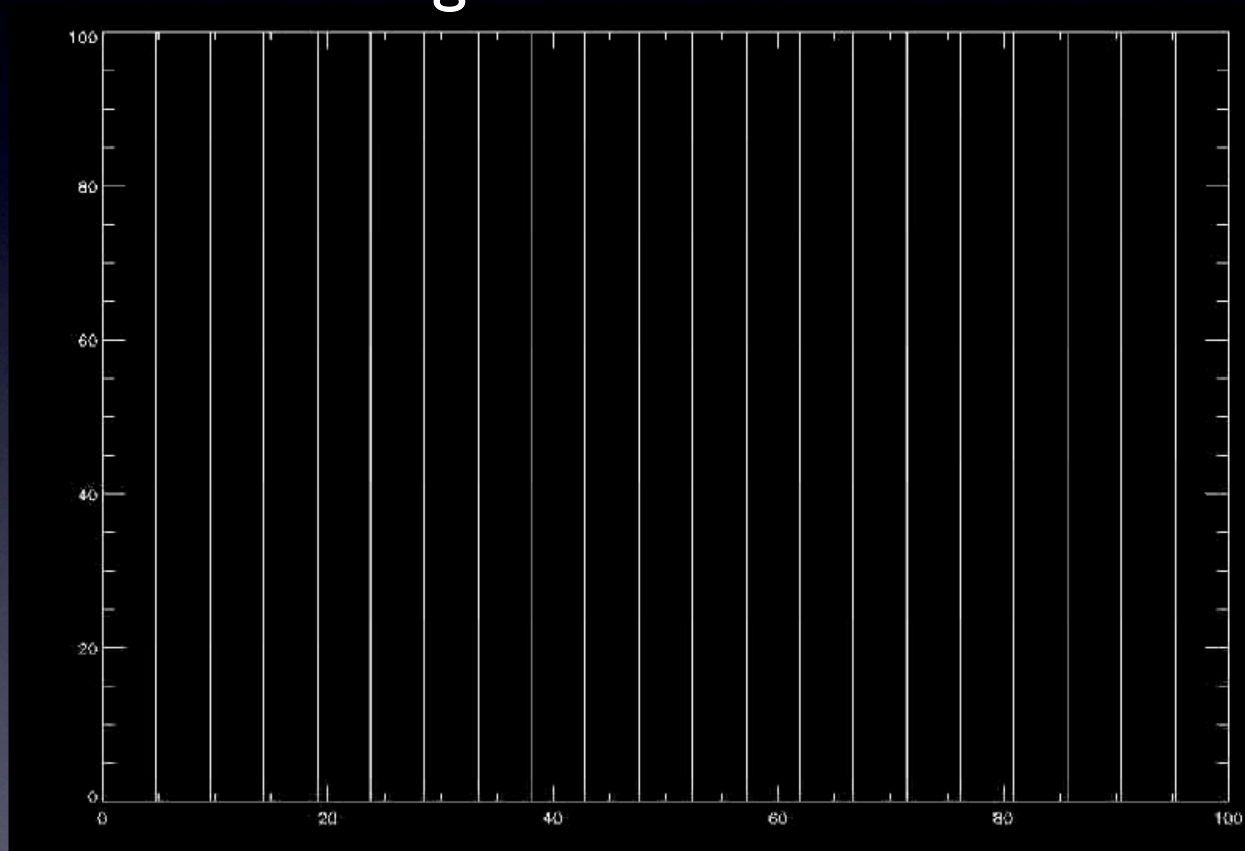
convectively unstable

The HBI

magnetic field lines

hot

cold
g, Q_z
bg heat
flux

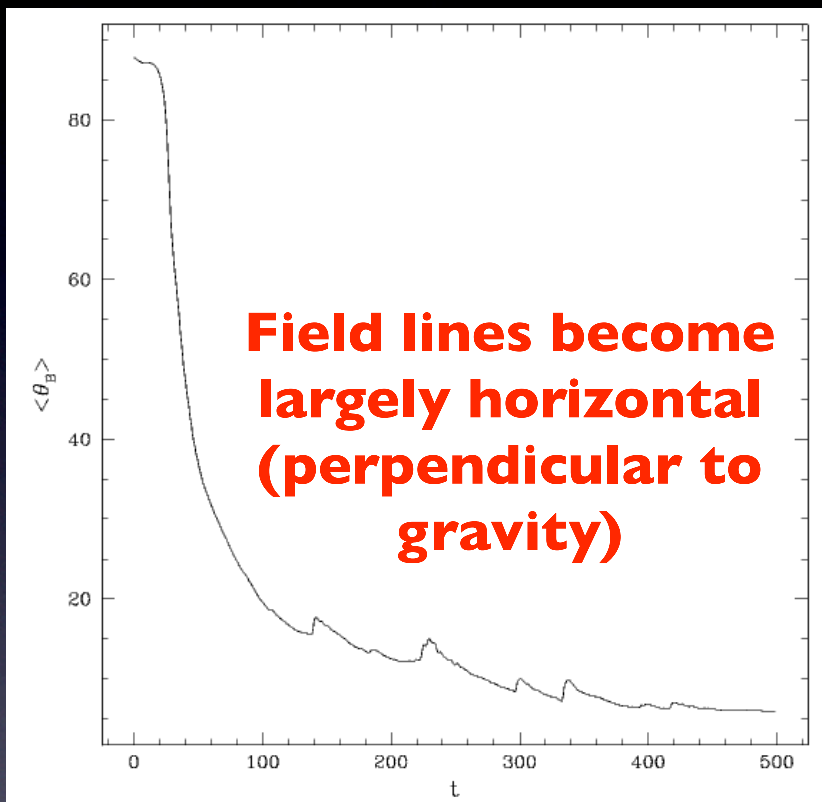


Parrish & Quataert 2008

HBI saturates by rearranging the magnetic field lines

Nonlinear Evolution: HBI

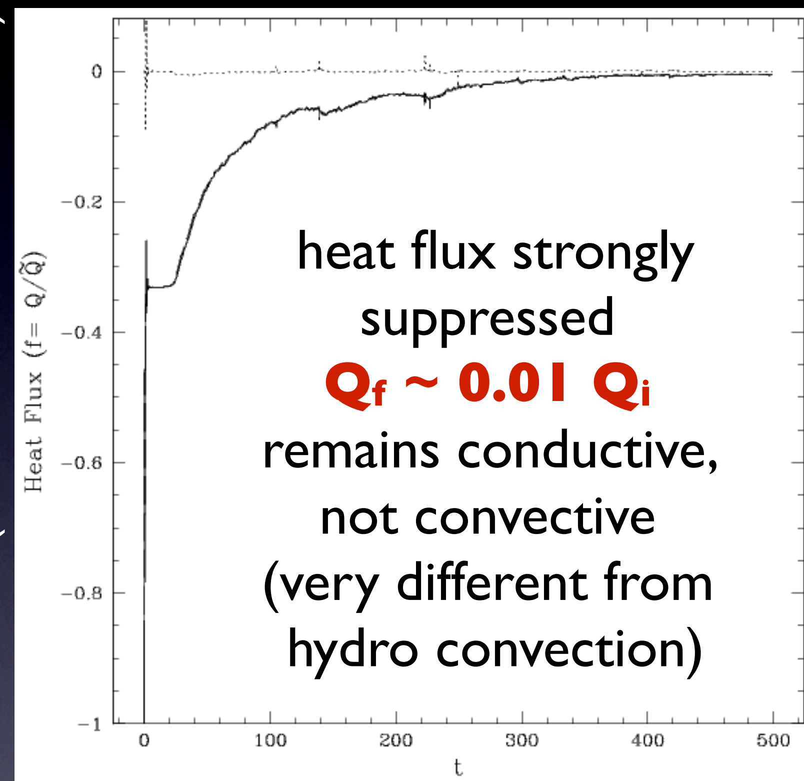
Angle wrt Horizontal



time (dynamical time)

Parrish & Quataert 2008

Heat Flux (relative to initial value)



time (dynamical time)

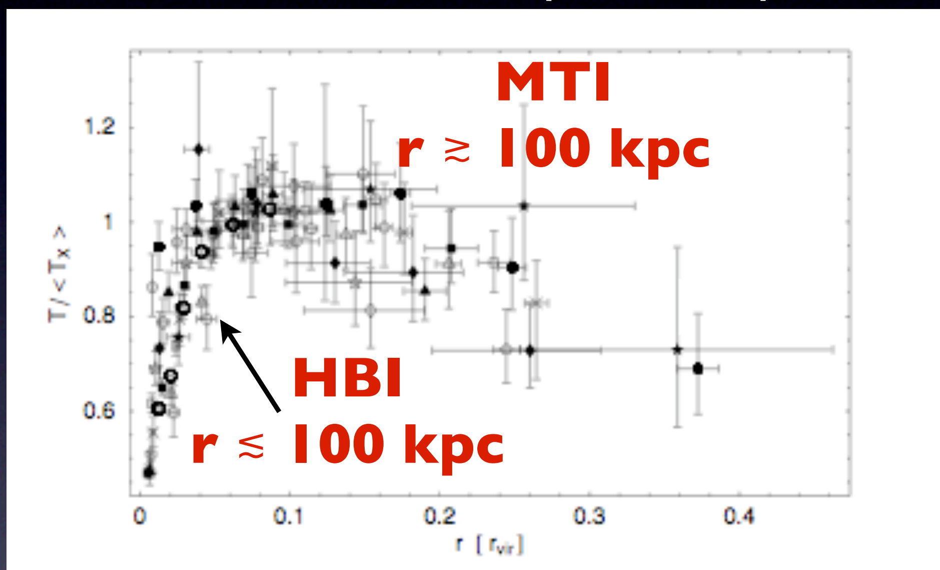
B-field energy amplified by ~ 100

Local 3D Simulations
initially weak B; no cooling

The MTI & HBI in Clusters

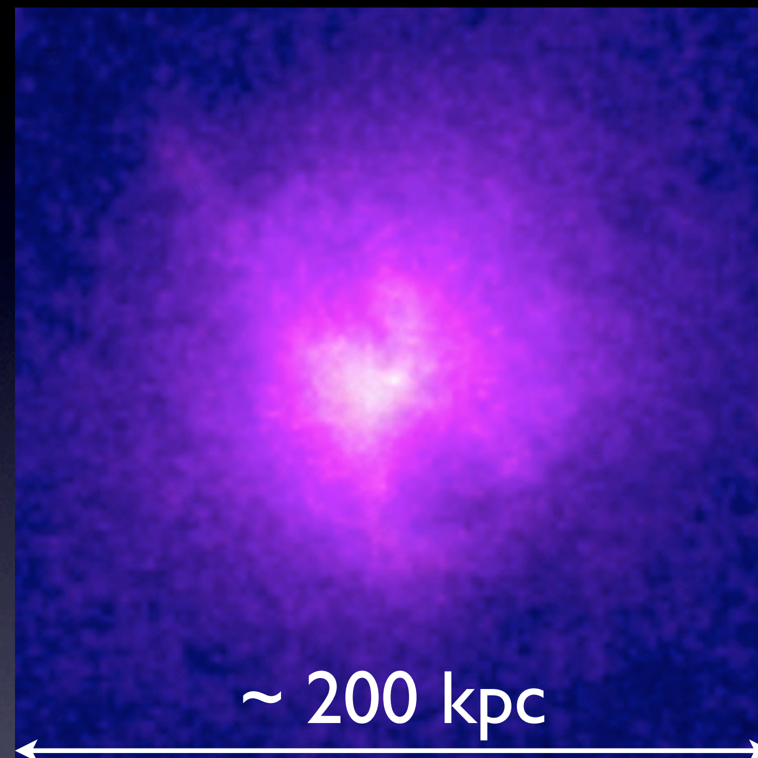
cool core cluster temperature profile

T/<T>



Radius (R_{vir})

Piffaretti et al. 2005

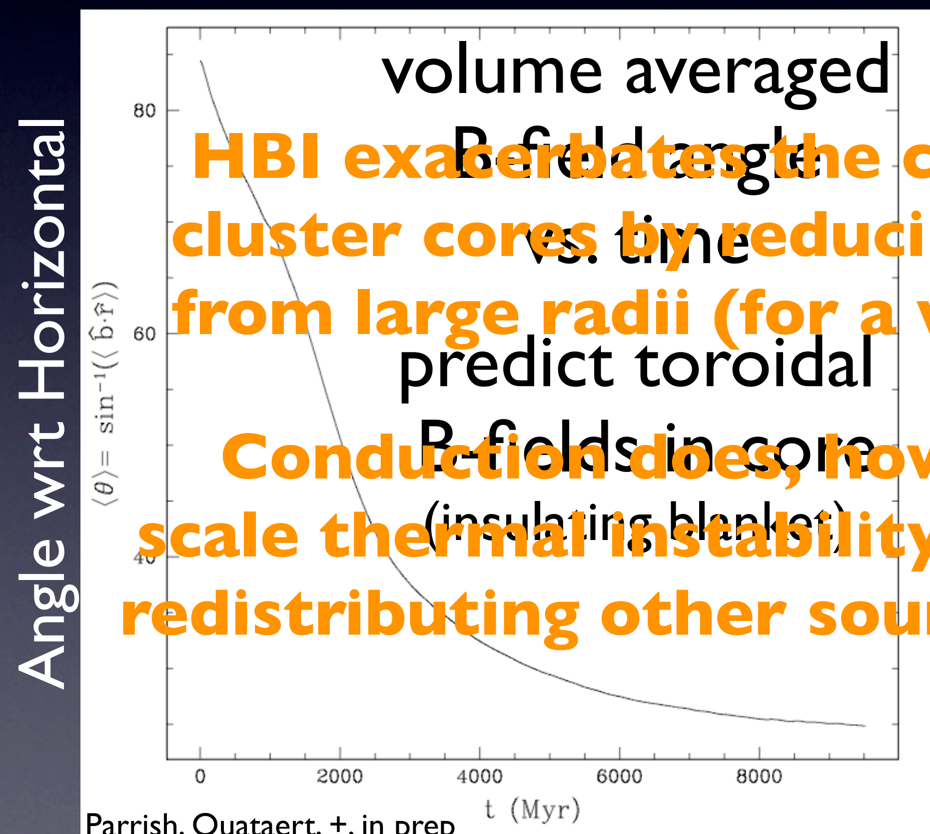


The Entire Cluster is Convectively Unstable!

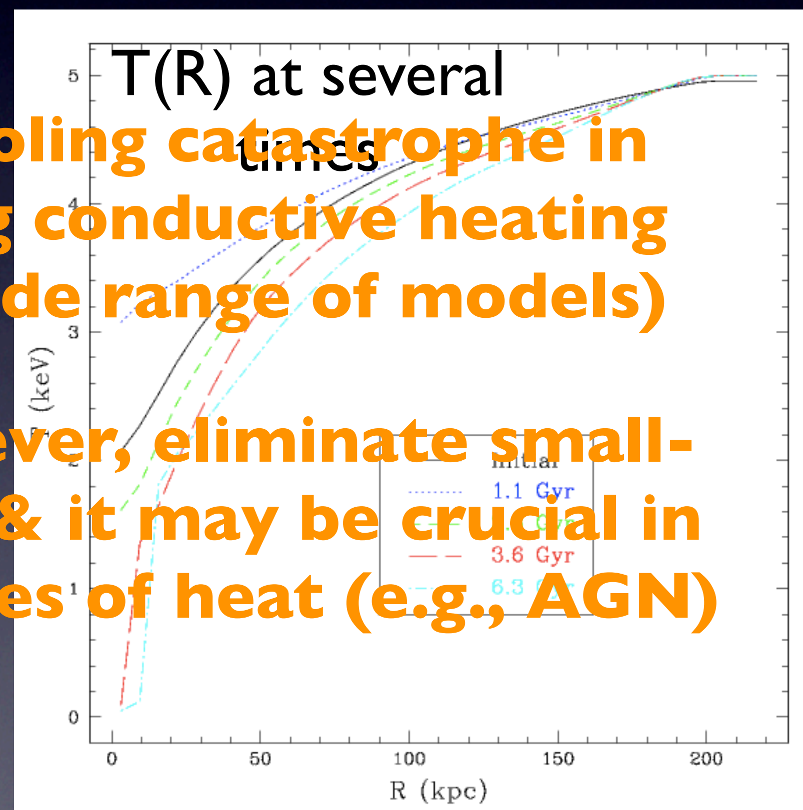
Instabilities suppressed by 1. strong B (e.g., solar corona) or
2. isotropic heat transport >> anisotropic heat transport (e.g., solar interior)

Global Cluster Simulations

- 3D **w/ cooling & anisotropic conduction** (Athena)
  - non-cosmological: isolated cluster core (≲ 200 kpc)
  - conductive flux is not a "free parameter"; depends on dynamics!



Parrish, Quataert, +, in prep



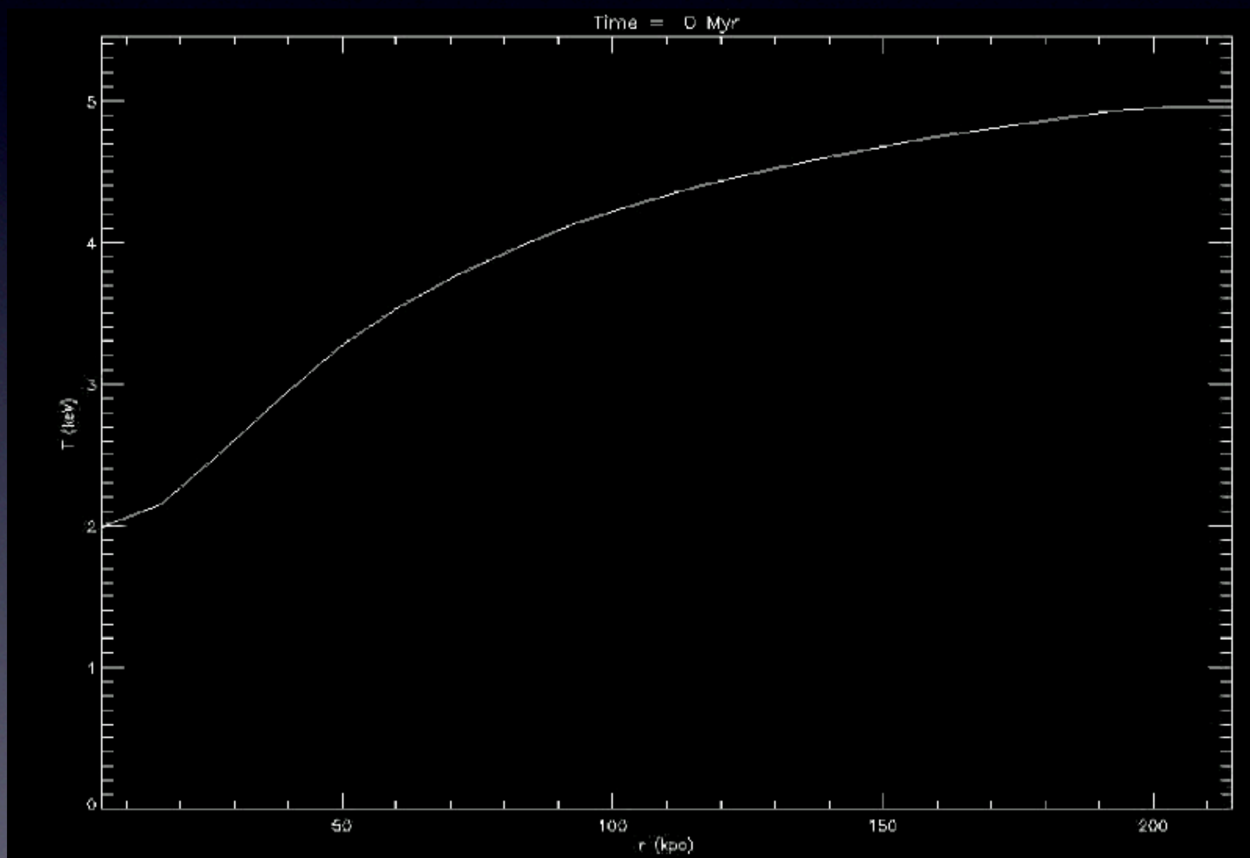
HBI exacerbates the cooling catastrophe in cluster cores by reducing conductive heating from large radii (for a wide range of models)

Conduction does, however, eliminate small-scale thermal instability; & it may be crucial in redistributing other sources of heat (e.g., AGN)

Global Cluster Simulations

- 3D **w/ cooling & anisotropic conduction** (Athena)
  - *artificial* source of heating to balance cooling at < 20 kpc ("AGN")

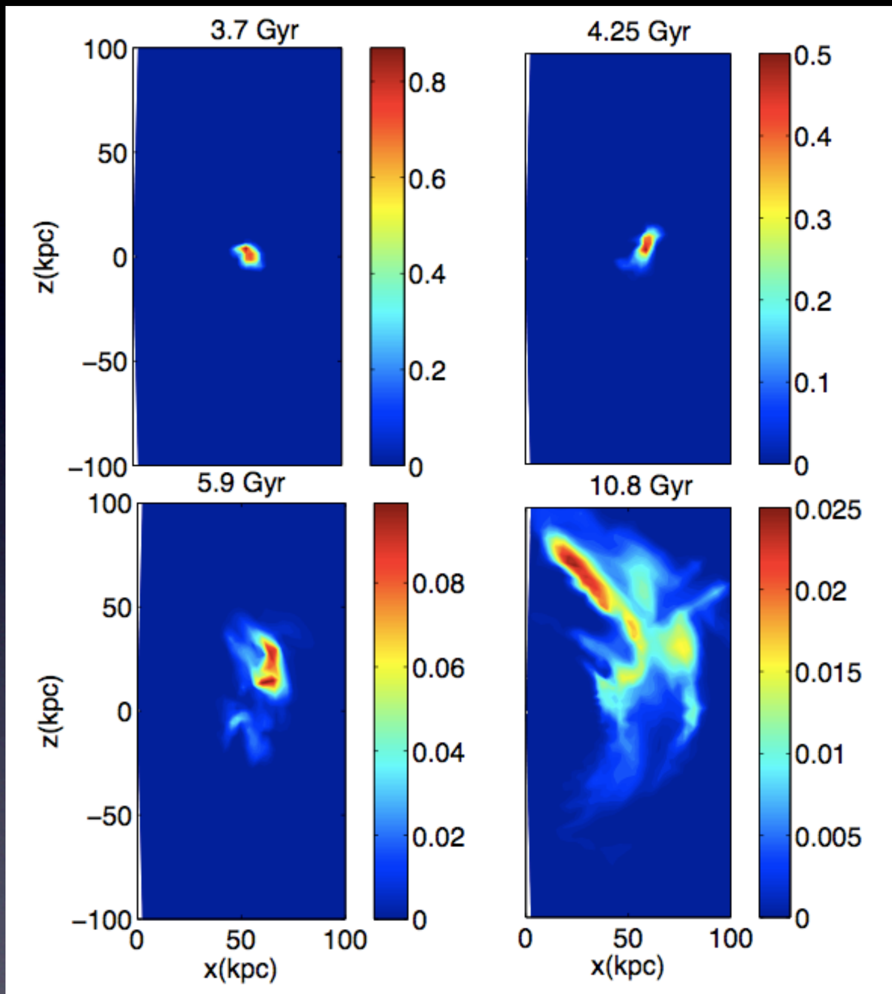
Temperature (keV)



Radius (kpc)

Stable for ~ 10 Gyr

HBI-induced Turbulence



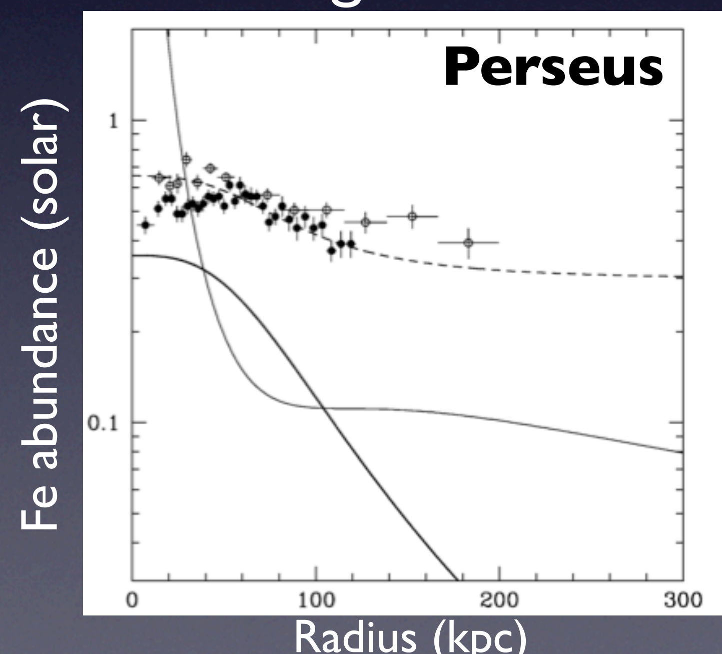
Sharma +, in prep

Density of Passive Scalar
Linear Color Scale
(red/blue = high/low density)

$v_{turb} \sim 0.01\text{-}0.1\ c_s$

detectable w/ next generation x-ray calorimeters

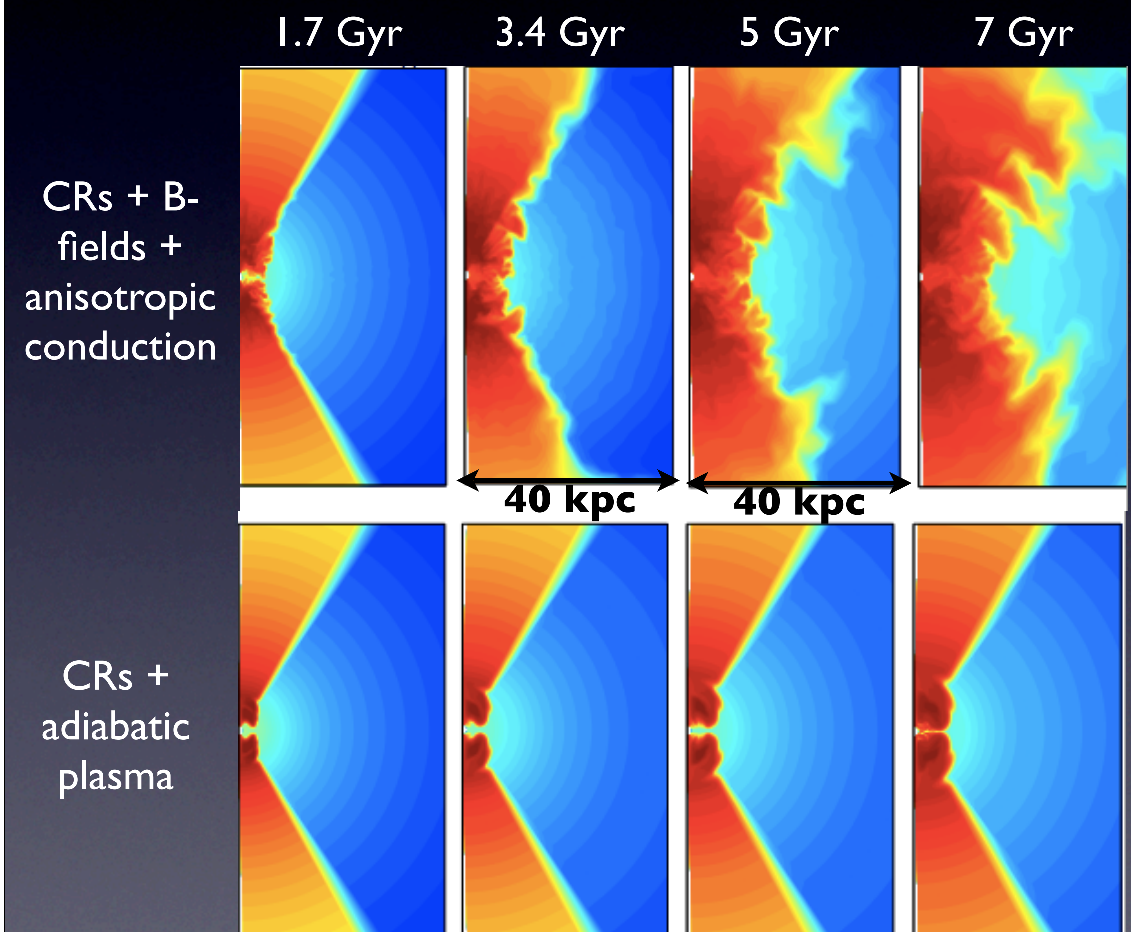
mixing of metals



Robusco et al. 2005

Effects on CR Mixing

AGN heating is the most promising mechanism balancing cooling; but precise physical mechanism & how it couples **throughout** the cluster core unclear



"real" cluster plasma: buoyantly unstable & easier to mix CRs

adiabatic plasma: buoyantly stable & harder to mix CRs

p_{CR}/p logarithmic scale; red/blue = high/low p_{CR}

Summary

- Understanding the thermal history of galaxy cluster cores is a key to understanding the process of massive galaxy/BH formation
- Recent Surprises: the plasma throughout a galaxy cluster is convectively unstable (MTI & HBI)!
  - key role of anisotropic thermal conduction (accept no substitutes)
  - HBI inhibits conductive heating of cluster cores
- The Future: interplay between AGN heating, cosmic rays, and realistic cluster thermodynamics