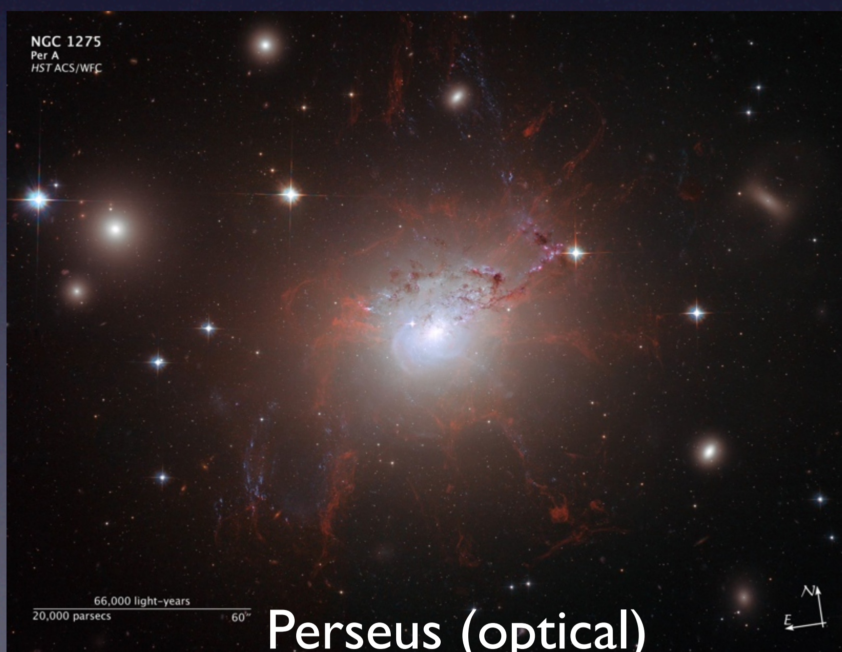
The Biermann Lectures: Adventures in Theoretical Astrophysics

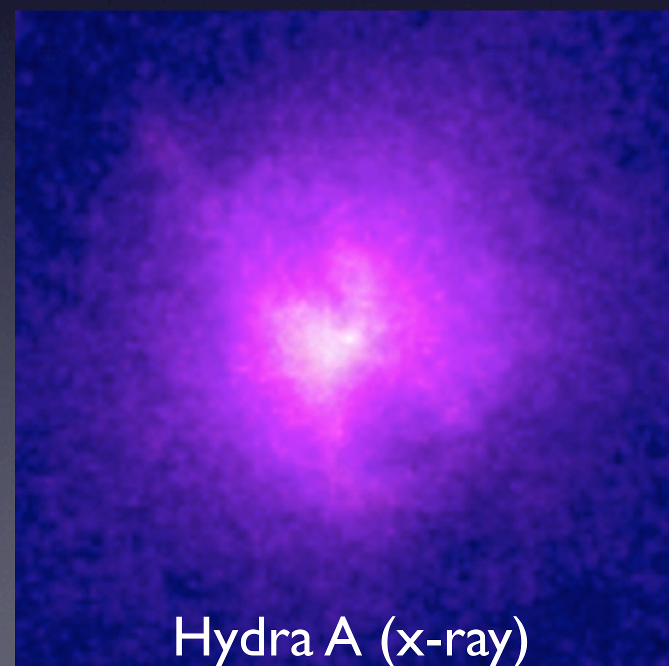
I: The Physics of Galaxy Cluster Plasmas

Eliot Quataert (UC Berkeley)

w/ Mike McCourt, Ian Parrish, Prateek Sharma



Perseus (optical)


Hydra A (x-ray)

The Biermann Lectures: Adventures in Theoretical Astrophysics

- analytic theory + sims w/ students, postdocs
- work on a range of problems: ‘model building’ & studying key processes
  - Compact Object Astrophysics
    - gamma-ray bursts, transients, accretion theory, the Galactic Center
  - Galaxy Formation
    - massive black hole growth, galactic winds, ‘feedback’, star formation in galaxies
  - Plasma Astrophysics
    - plasma instabilities (disks, galaxy clusters, ...), plasma turbulence (incl solar wind)
  - Stellar Astrophysics
    - stellar seismology, tides

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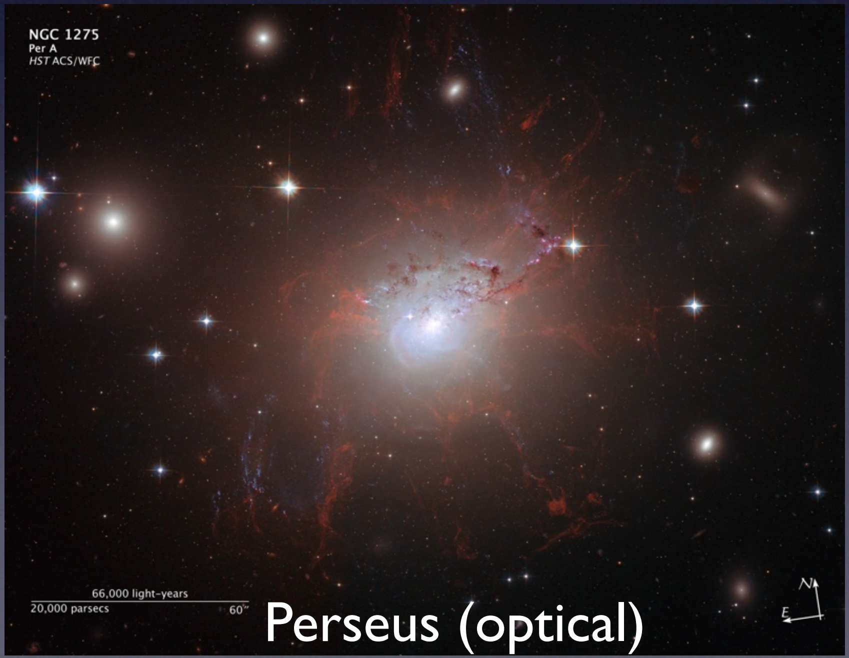

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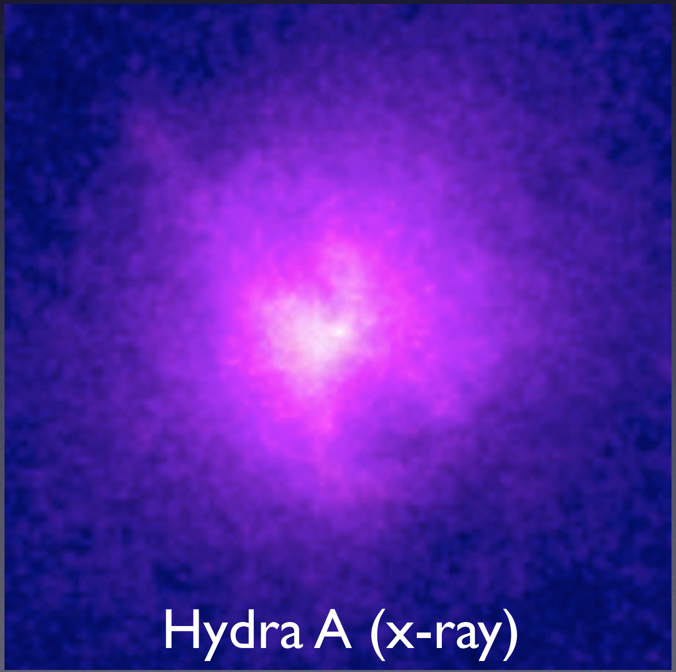
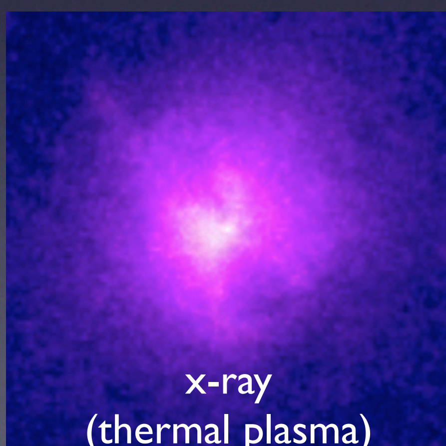
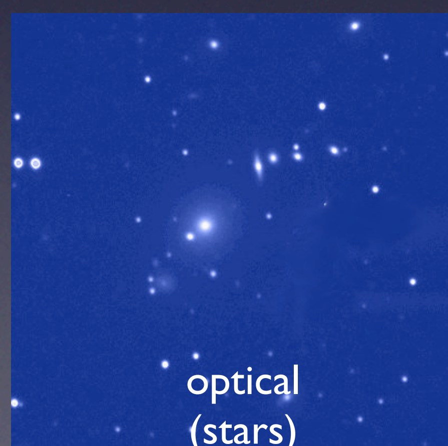

Hydra A (x-ray)

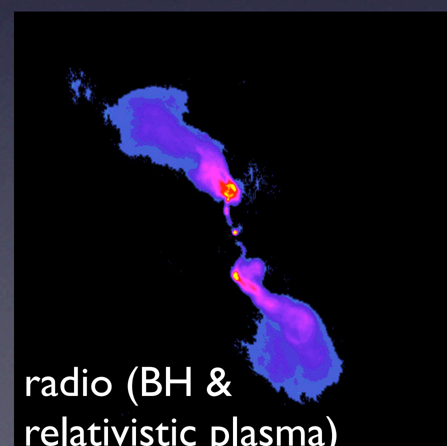
Clusters of Galaxies

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

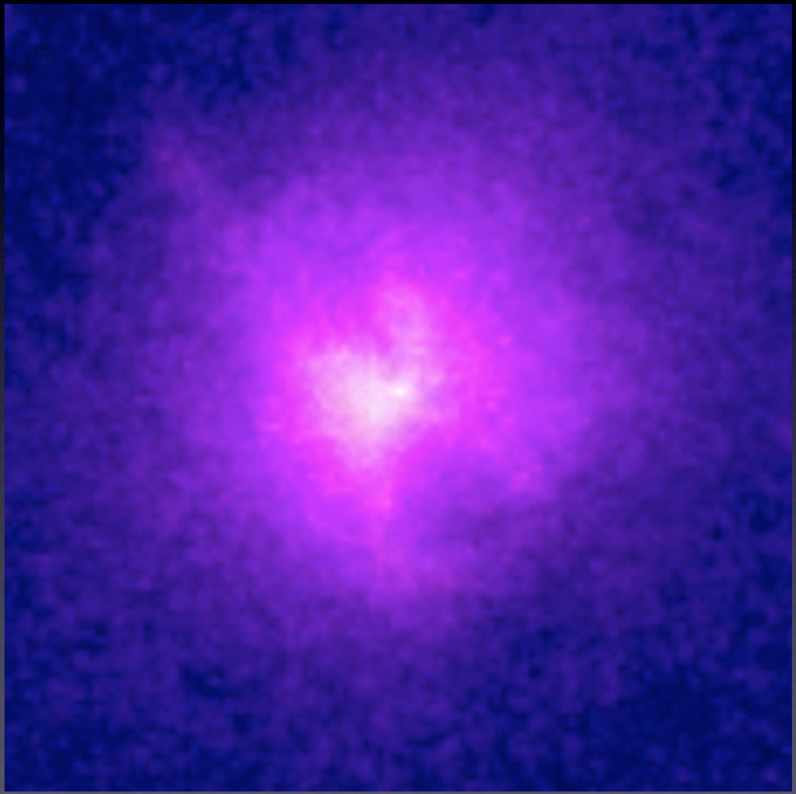

x-ray
(thermal plasma)

~ 0.1 R_{vir}


optical
(stars)


radio (BH &
relativistic plasma)

Hot Plasma in Clusters



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

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

$T \sim$ 1-15 keV

$M_{gas} \sim 10^{13\text{-}14}\ M_\odot$

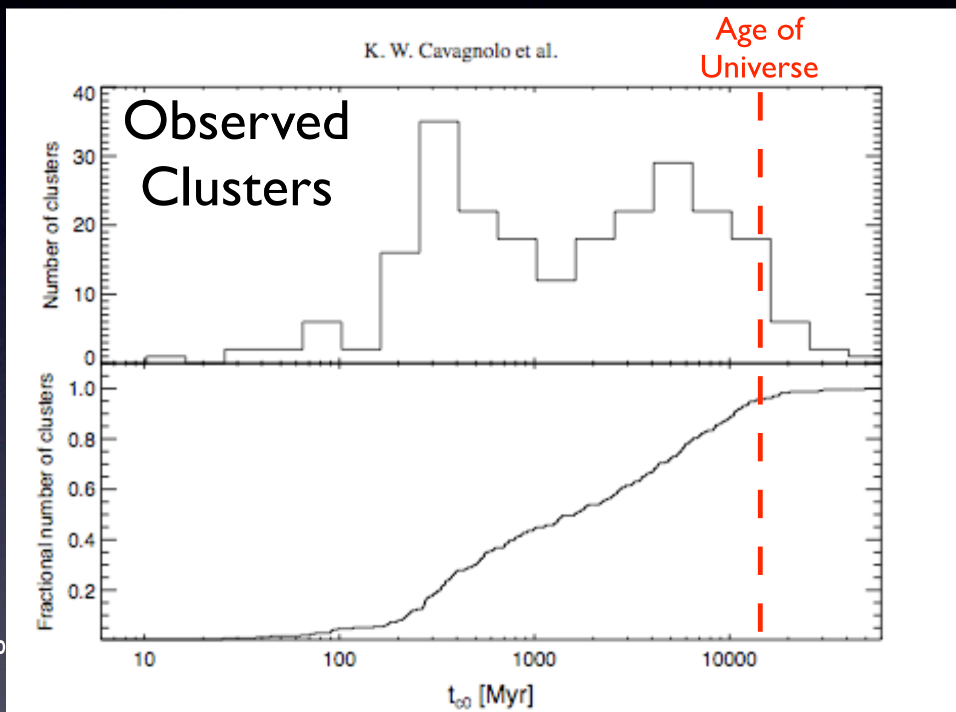
large electron mean free path:

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

→ thermal conduction impt

n, T → radiative cooling impt in cluster cores

Galaxy Clusters: a Key to Understanding Massive Galaxy Formation



Cavagnolo et al.

central cooling time (Myr)

in ~ 2/3 of cluster cores, t_{cool} << age of Universe

absent a heat source: $\dot{M}_{cool} \sim 100\text{-}1000\ M_\odot\ yr^{-1}$

Not Observed

$\dot{M}_{star} \ll \dot{M}_{cool}$

no sufficiently large reservoirs of cold gas

X-ray Spectra: $T_{min} \sim 1/3 \langle T \rangle$

Lack of cooling gas → A heat source! AGN, conduction, ...

Galaxy Clusters: a Key to Understanding Massive Galaxy Formation

understanding the thermal evolution of clusters requires progress on:

- heating, turbulence, heat transport over ~ 4π, interaction btw hot & cold gas, CRs, ...

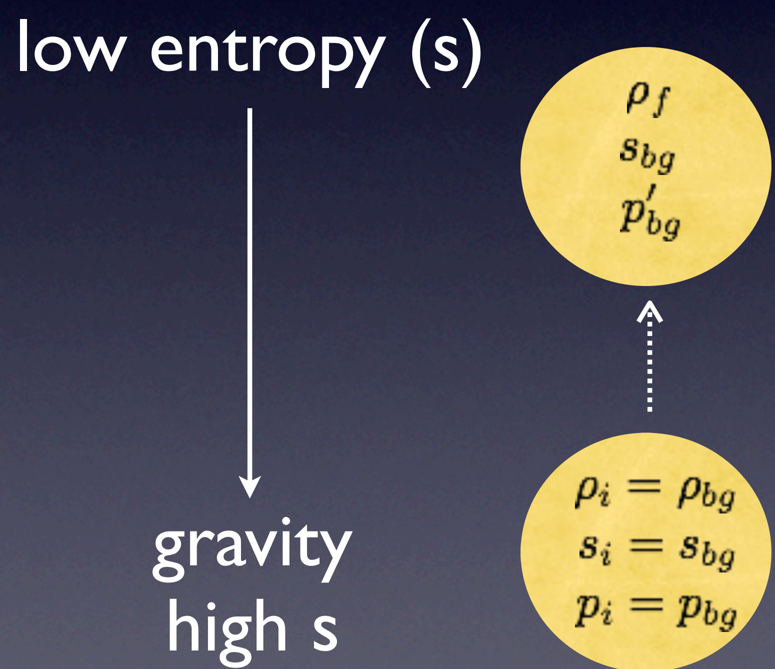
start with the basics: **convection** & **thermal instability**

Hα emission in Perseus

Hydrodynamic Convection

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

  solar interior: t_{sound} ~ hr << $t_{buoyancy}$ ~ month << $t_{diffusion}$ ~ 10^4 yr



background fluid

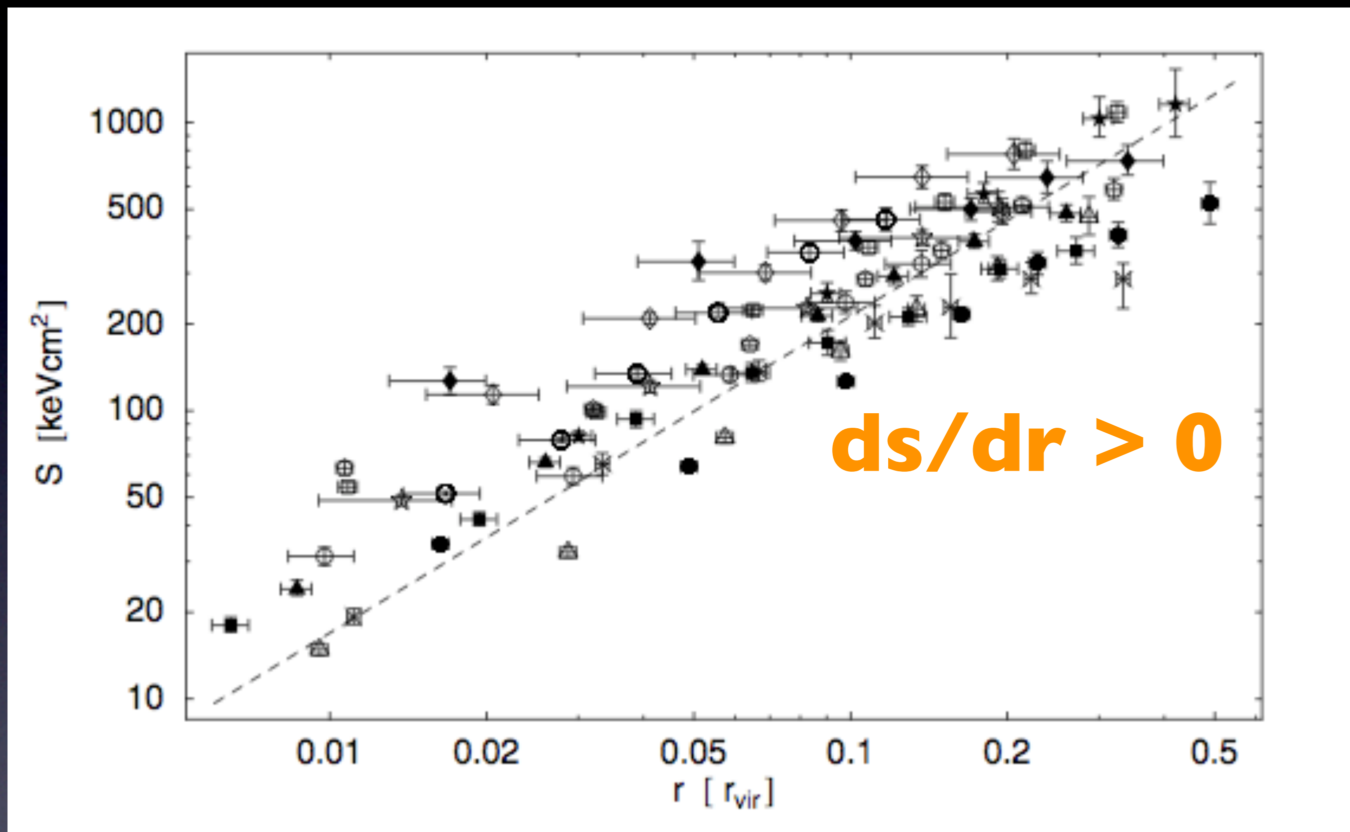
$$s'_{bg} \quad \rho'_{bg} \quad p'_{bg}$$

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

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

convectively unstable

Cluster Entropy Profiles



Entropy

Radius (R_{vir})

Piffaretti et al. 2005

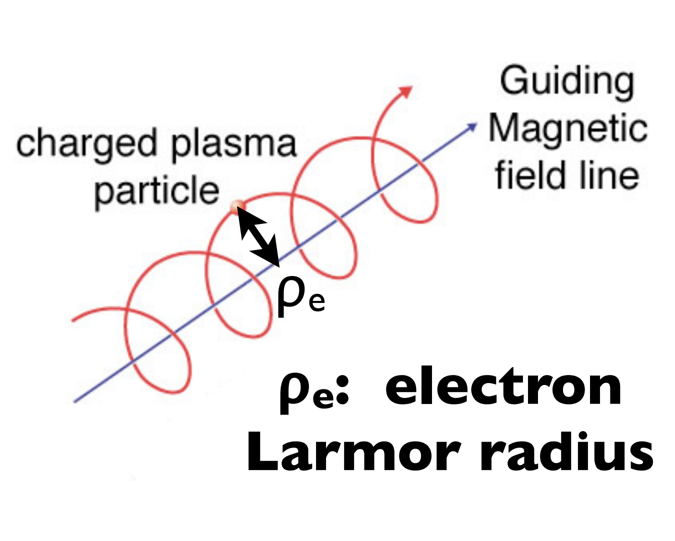
Schwarzschild criterion → clusters are **stable**

Anisotropic Thermal Conduction in Cluster Plasmas

electron mean free path:

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

⇒ conduction is energetically impt



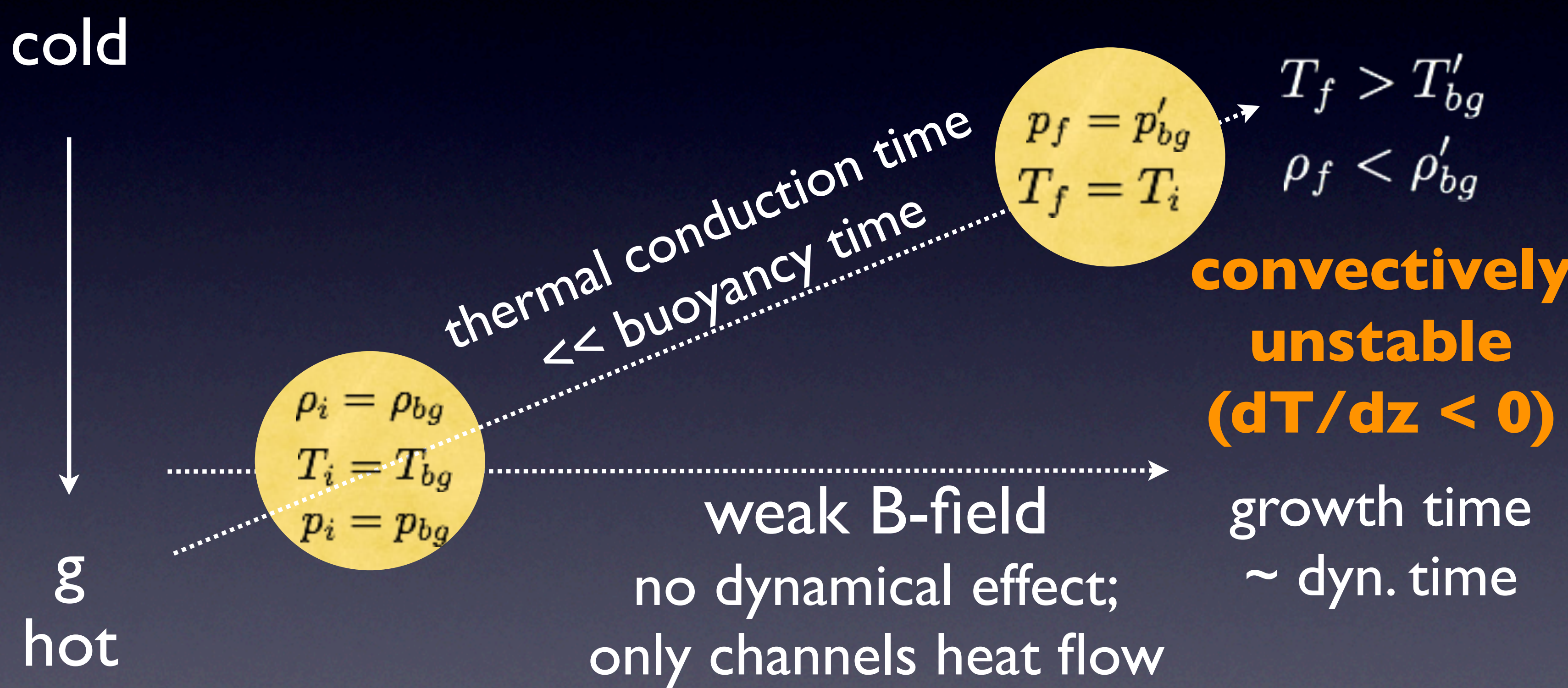
$$\frac{l_e}{\rho_e} \sim 10^{14} \left(\frac{B}{10^{-6}\,\mathrm{G}}\right) \left(\frac{n}{0.01\,\mathrm{cm}^{-3}}\right)^{-1} \left(\frac{T}{3\,\mathrm{keV}}\right)^{-3/2}$$

***l_e* >> ρ_e** ⇒ heat transport is **anisotropic**, primarily along B

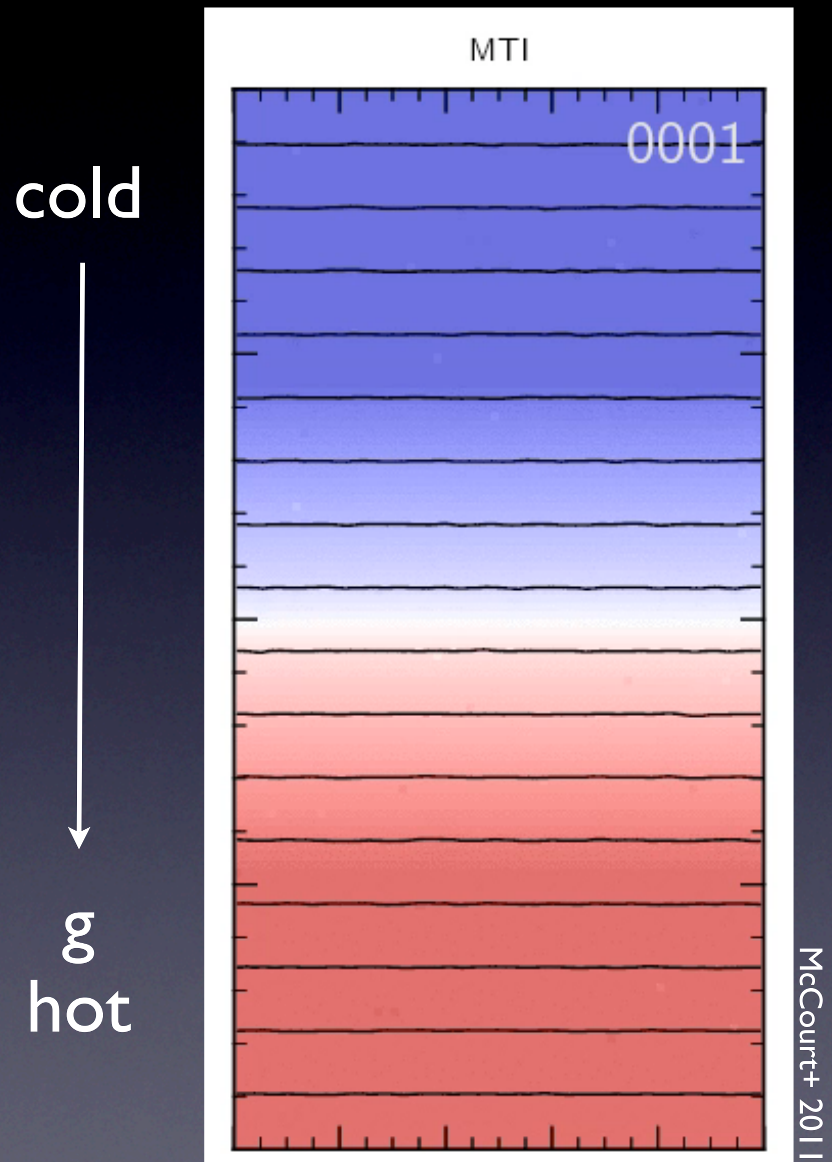
momentum transport is also anisotropic

The Magnetothermal Instability (MTI)

Balbus 2000, 2001; Parrish & Stone 2005, 2007; Quataert 2008; McCourt+ 2011



The MTI



B-field lines & Temp

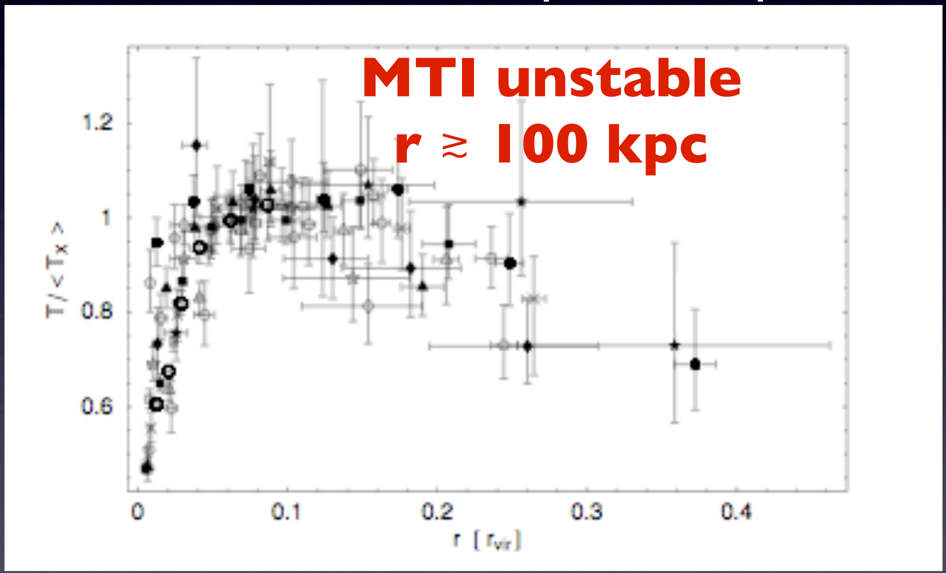
instability saturates by generating sustained convection & amplifying the magnetic field

(analogous to hydro convection)

The MTI in Clusters

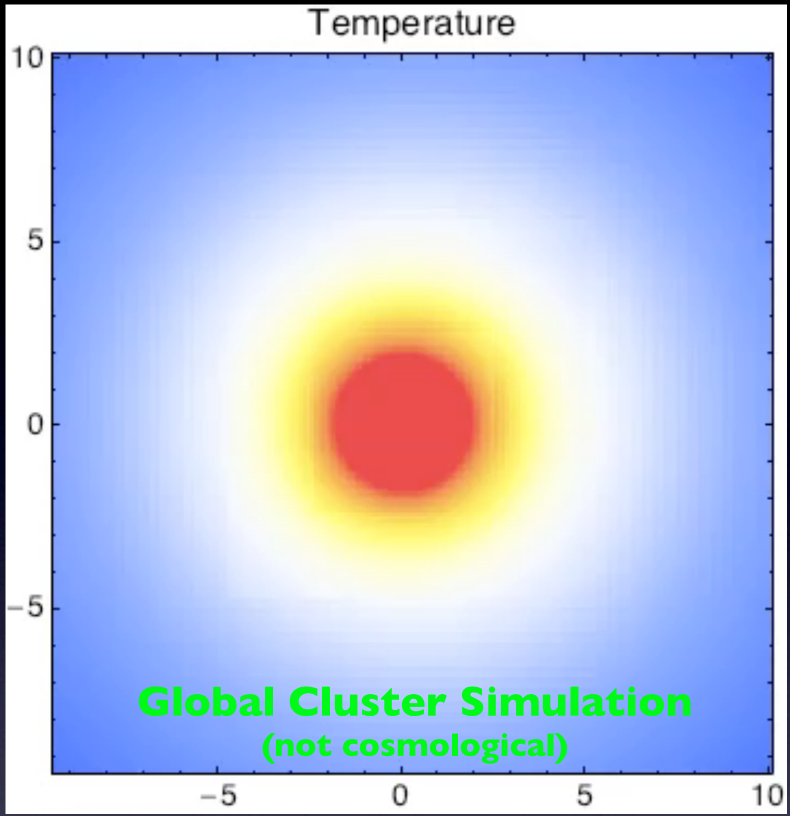
cool core cluster temperature profile

T/<T>



Piffaretti et al. 2005

Radius (R_{vir})



Mach #s ~ 0.3-0.6!

largest near ~ R_{vir}
(impt for X-ray, SZ
mass measurements)

The Heat Flux-Driven Buoyancy Instability (HBI)

Quataert 2008; Parrish & Quataert 2008

hot

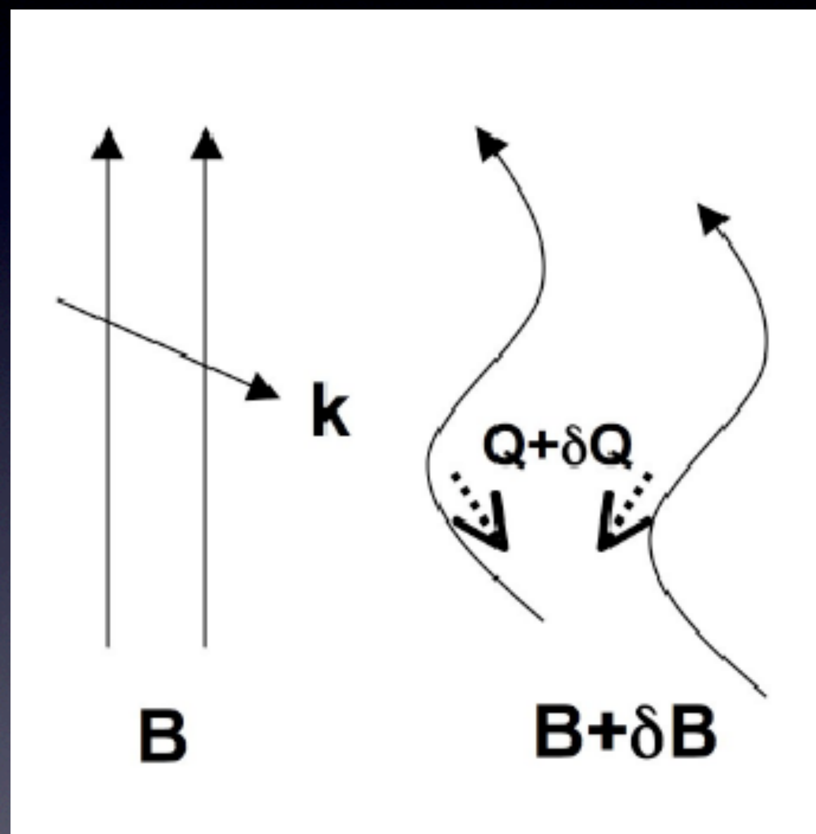
cold

g, Q_z

heat flux

weak

B



converging & diverging heat flux

⇒

conductive heating & cooling

for **dT/dz > 0**

upwardly displaced fluid heats up & rises, bends field more, ...

convectively unstable

The HBI

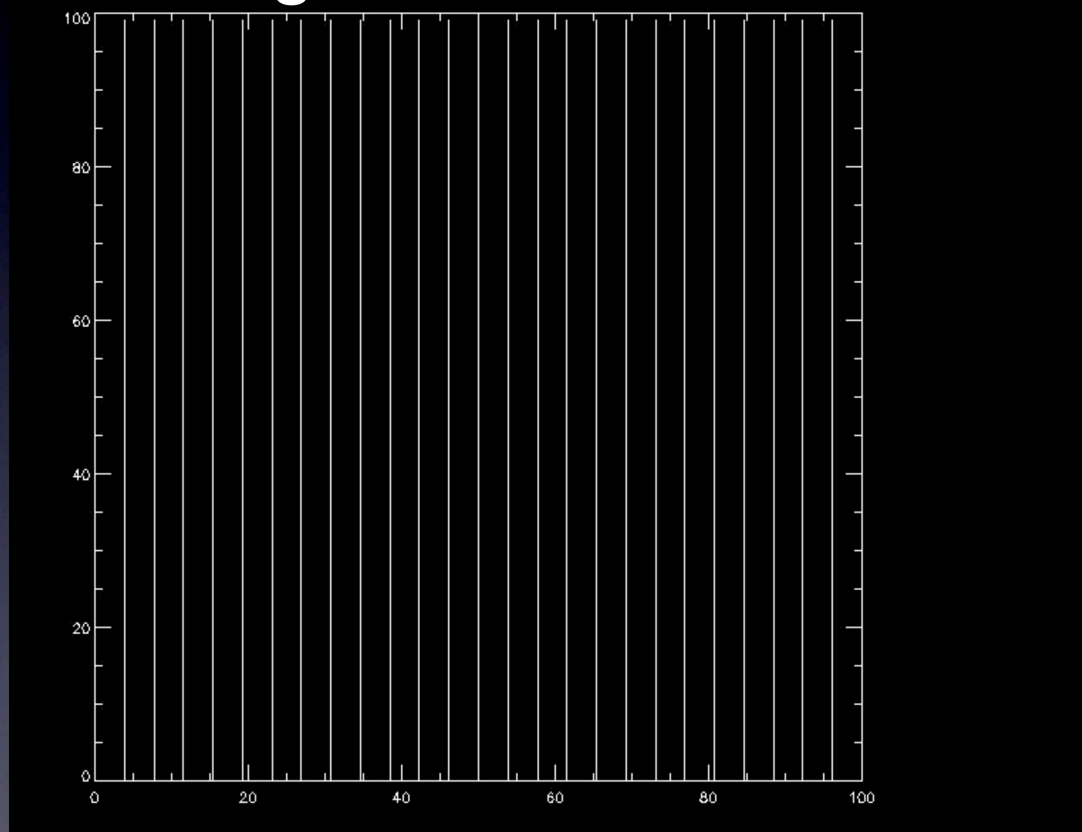
hot

cold

g, Q_z

heat flux

magnetic field lines



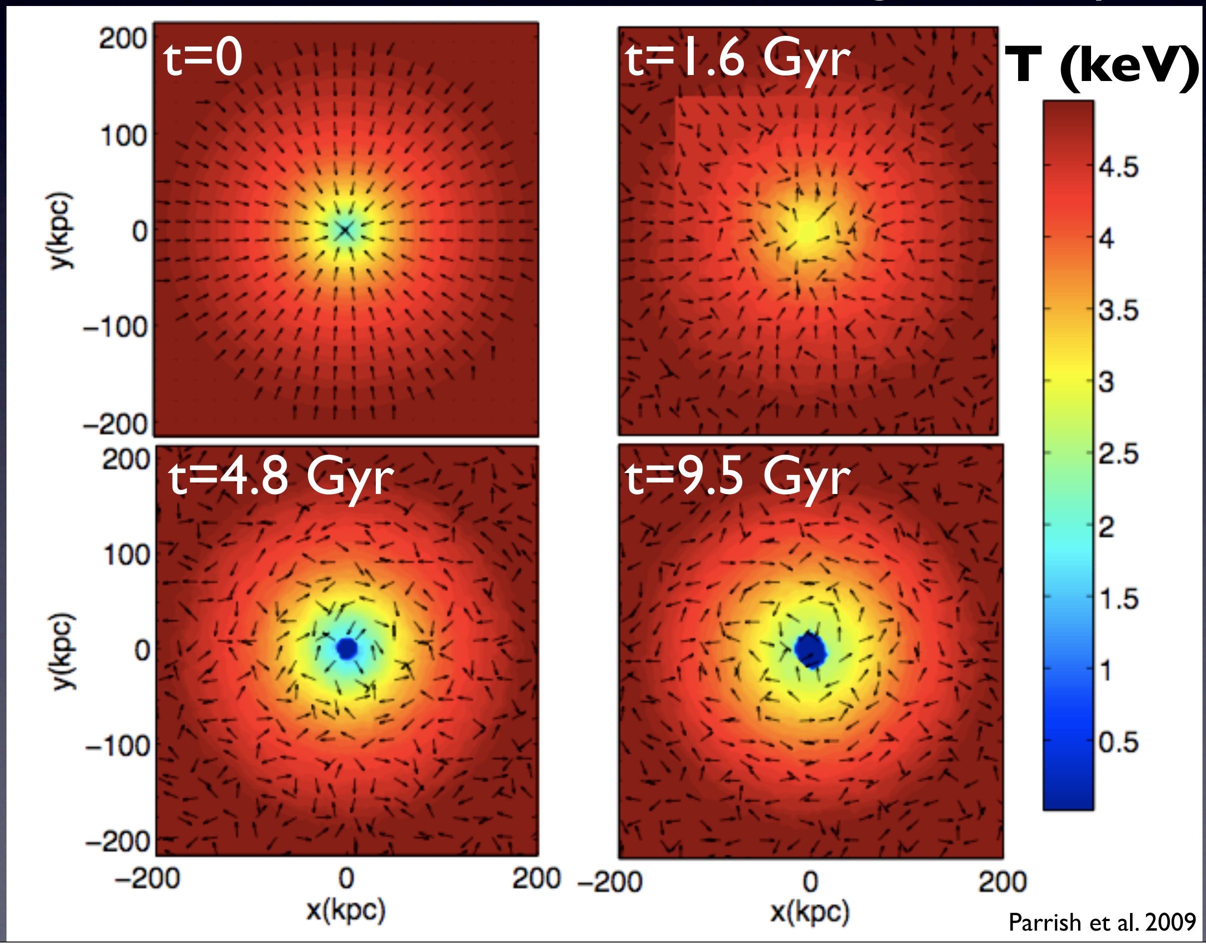
Parrish & Quataert 2008

HBI saturates largely by rearranging B-field & suppressing heat flow in direction of gravity

Global Cluster Simulations

- 3D MHD **w/ cooling, anisotropic conduction**
  - non-cosmological: isolated cluster core (≲ 200 kpc)
  - HBI → conduction cannot halt the cooling catastrophe

Temperature (color) & magnetic field direction (unit vectors)



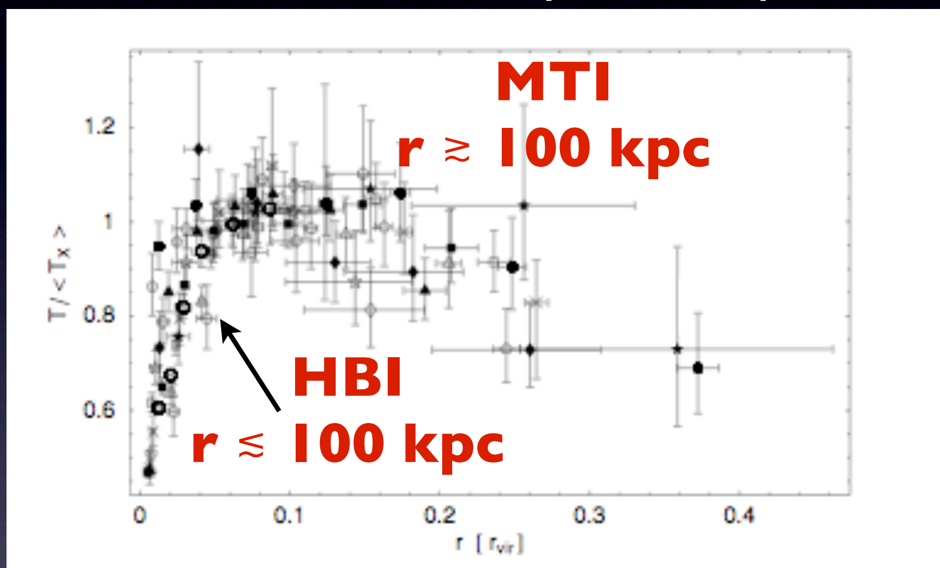
Parrish et al. 2009

initial radial field for visualization (same results w/ tangled fields)

New Forms of Convection in Cluster Plasmas

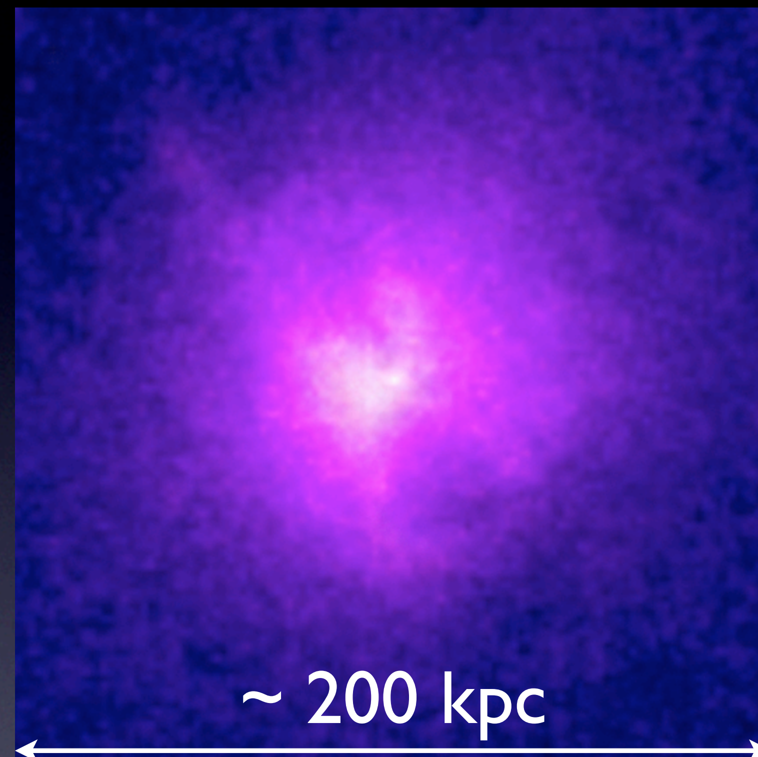
cool core cluster temperature profile

T/<T>



Radius (R_{vir})

Piffaretti et al. 2005

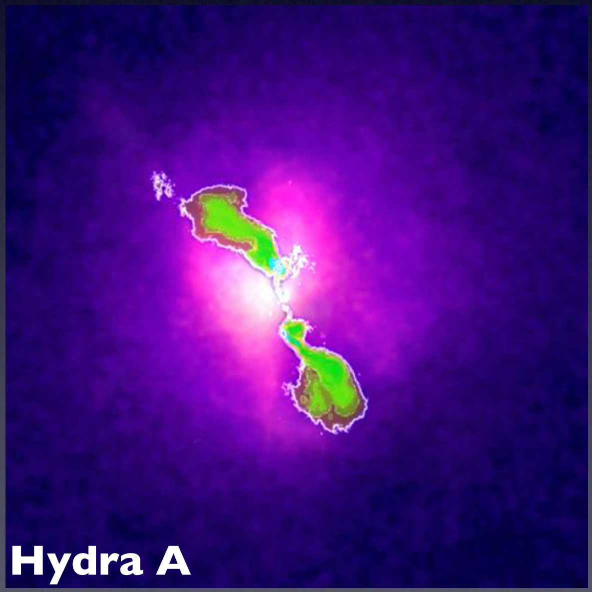


The Entire Cluster is Convectively Unstable

a number of other astrophysical applications ... instabilities only suppressed by 1. strong B (e.g., solar corona) or 2. isotropic heat transport >> anisotropic transport (e.g., solar interior)

Galaxy Clusters: a Key to Understanding Massive Galaxy Formation

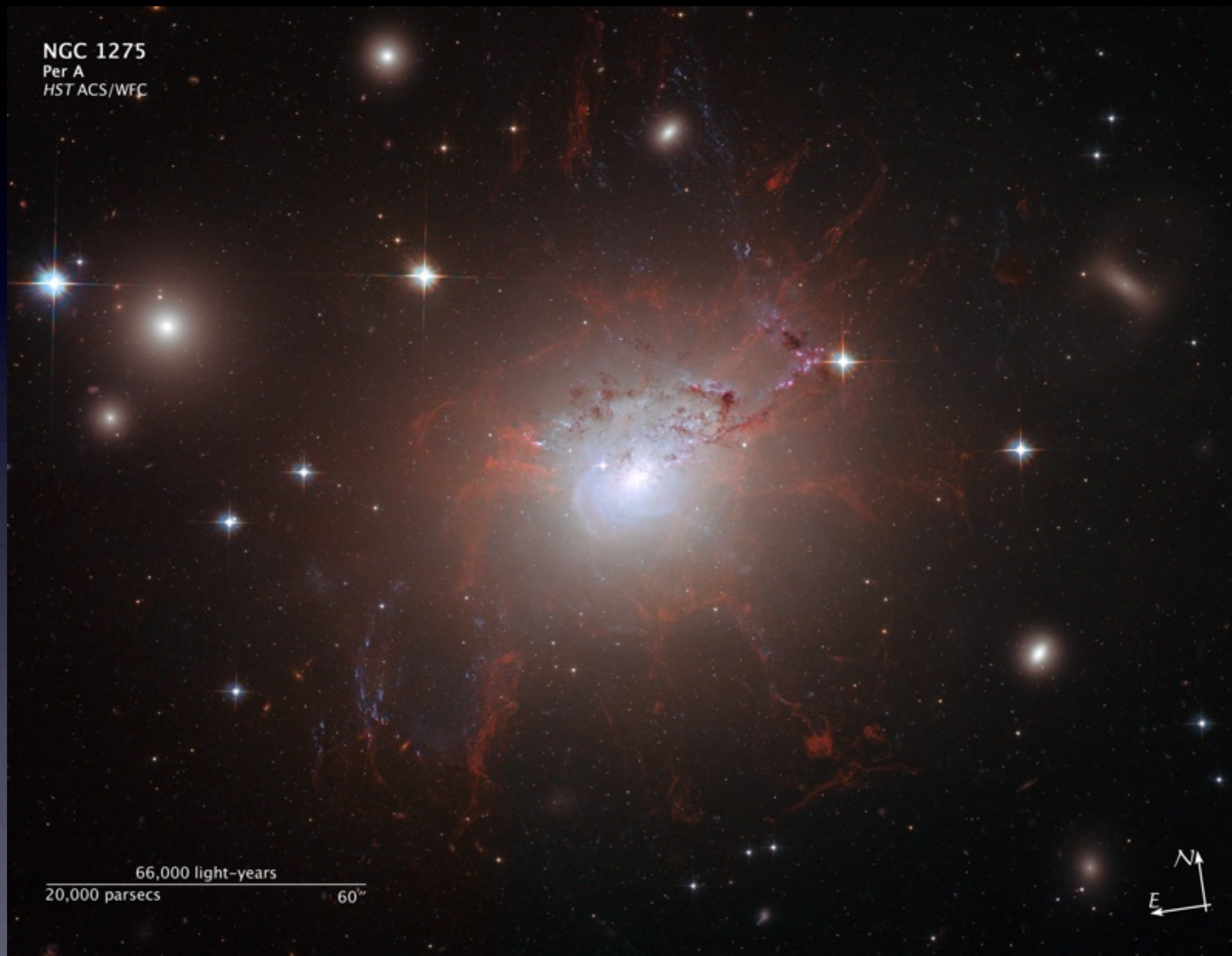
- Cluster cores: $t_{cool} << t_{Hubble}$ But most of the gas isn't cooling
- Lack of cooling gas → A heat source must balance radiative losses
- Plausible source of heating: an AGN in the cluster's central galaxy



Observationally, Energy Required to Inflate Bubbles/Jets ~ L_X of hot ICM

Why this 'Feedback' is more subtle than you thought:
Local Thermal (In)Stability

there is *some* cool, dense gas observed in many clusters



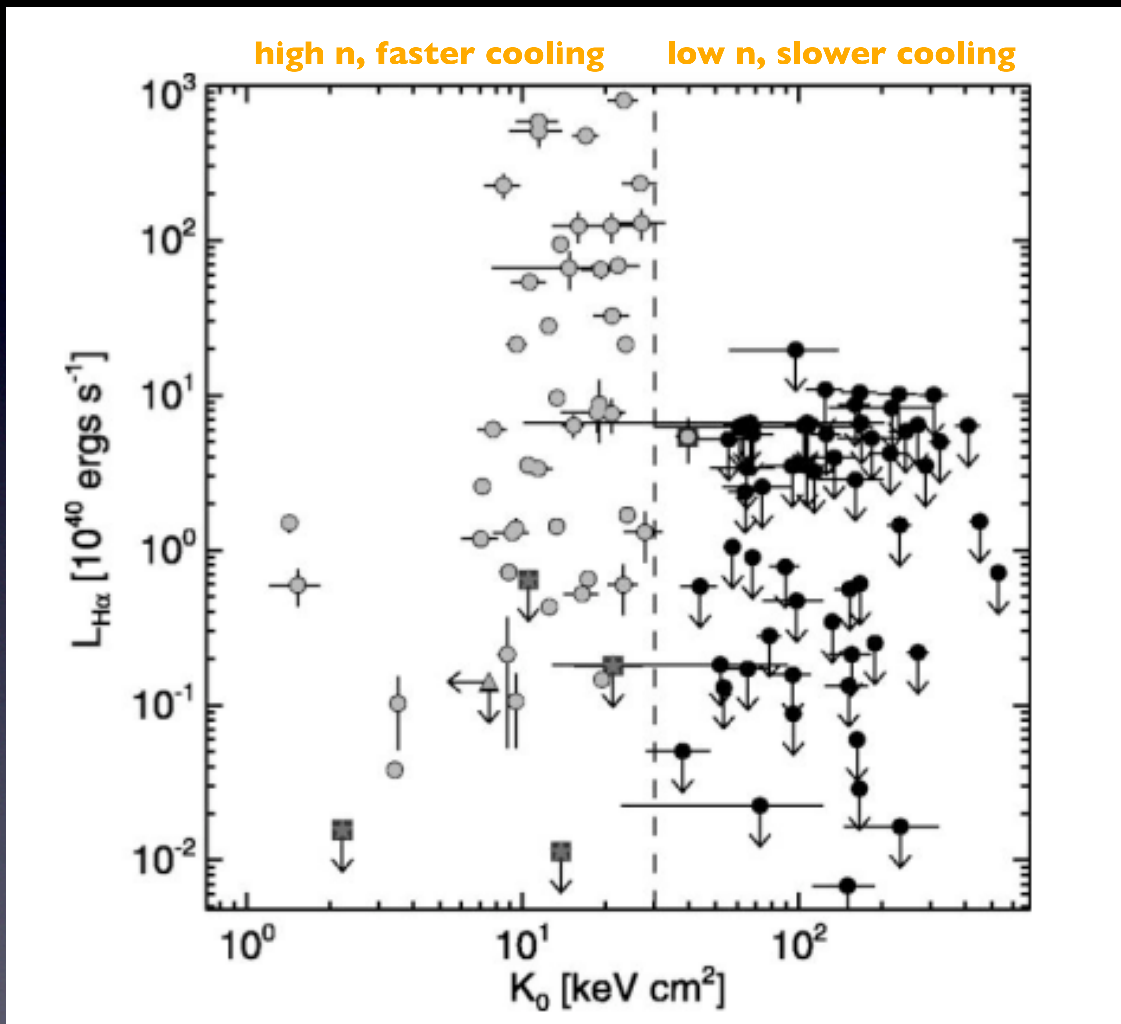
Fabian et al. 2008

Hα emission ('filaments') in Perseus

Evidence for Cool, Dense Gas Ubiquitous in 'Cool-Core' Clusters

Hα emission

Cavagnolo et al. 2008



Cluster Central 'Entropy' ($K_0 = kT/n^{2/3}$)

Hα emission spatially extended in many cases

McDonald+ 2010

molecular gas (CO, HCN)

star formation & AGN activity (radio power) also correlate w/ short cooling times

origin of cold gas?
role of cold gas in feedback/heating cycle?

Conjecture: Signature of Local Thermal Instability in a Globally Stable System

Global Thermal Balance $\neq$ Local Thermal Balance

<Heating> ~ <Cooling> $\Rightarrow$ no cooling flow

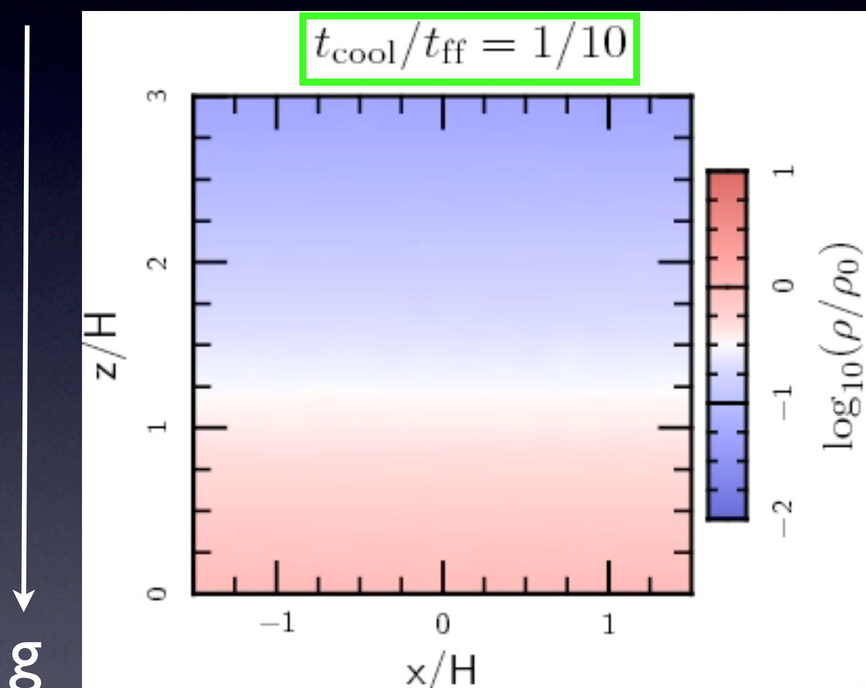
Heating $\neq$ Cooling locally $\Rightarrow$ local thermal instability

Subtle physics w/ critical implications for multiphase gas in clusters & the feedback cycle that regulates ICM properties (analogous to the ISM of galaxies)

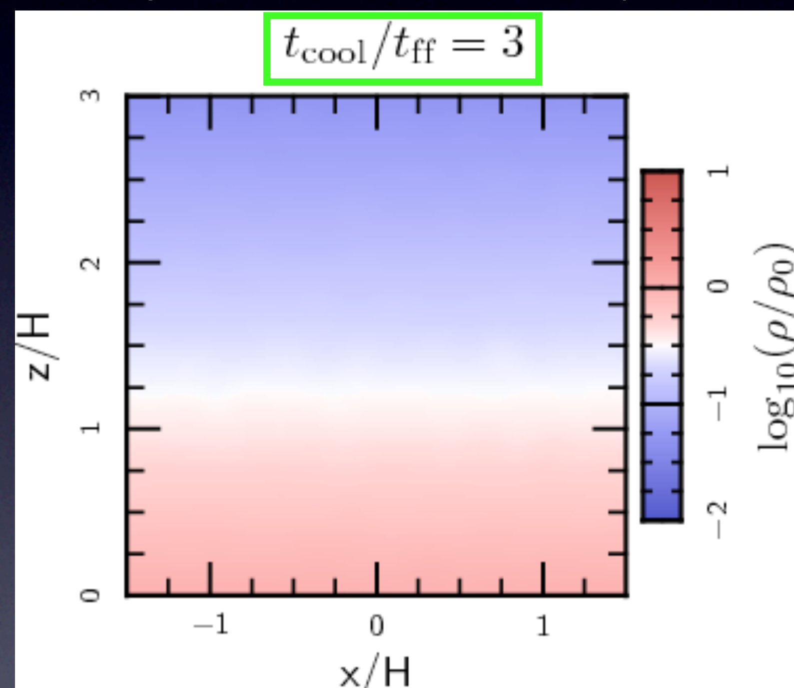
Htg vs. Cooling in Cluster Plasmas

competition btw cooling & gravity: key parameter $\mathbf{t_{cool}/t_{ff}}$

rapid cooling: $\delta\rho/\rho$ non-linear ⇒ multiphase structure



slow cooling: $\delta\rho/\rho$ ~ linear ⇒ no extended multiphase structure



Cartesian sims (movies ~ 10 t_{cool})

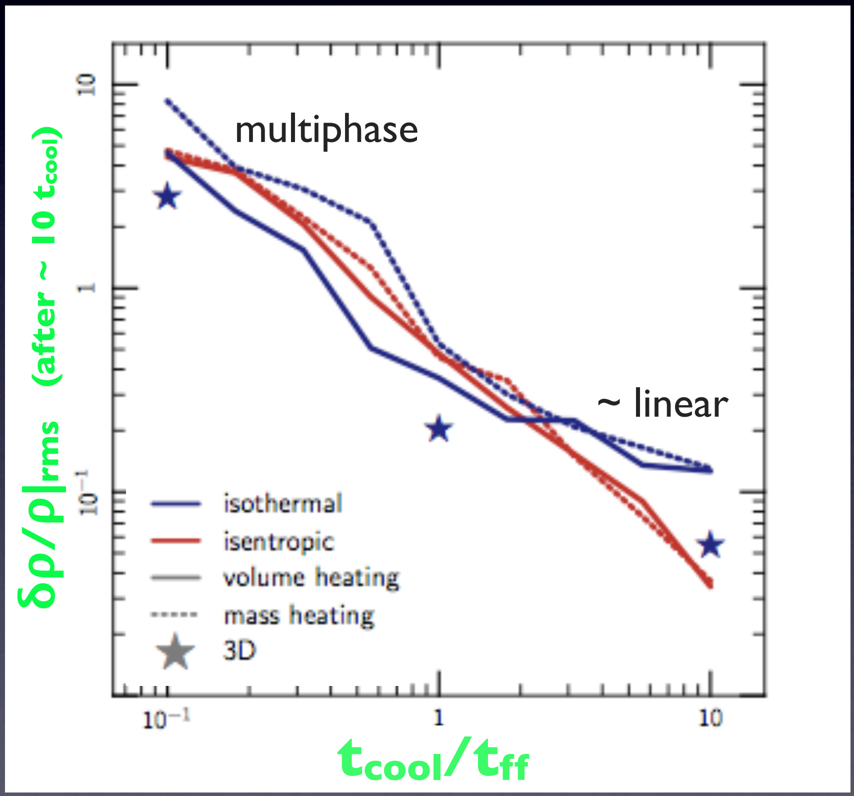
toy model w/ htg ∋ H(r) ~ <ℒ>(r)

no B-fields or conduction

significant dense gas via thermal instability iff $t_{cool}/t_{ff} \lesssim$ few

Htg vs. Cooling in Cluster Plasmas

competition btw cooling & gravity: key parameter $\mathbf{t_{cool}/t_{ff}}$



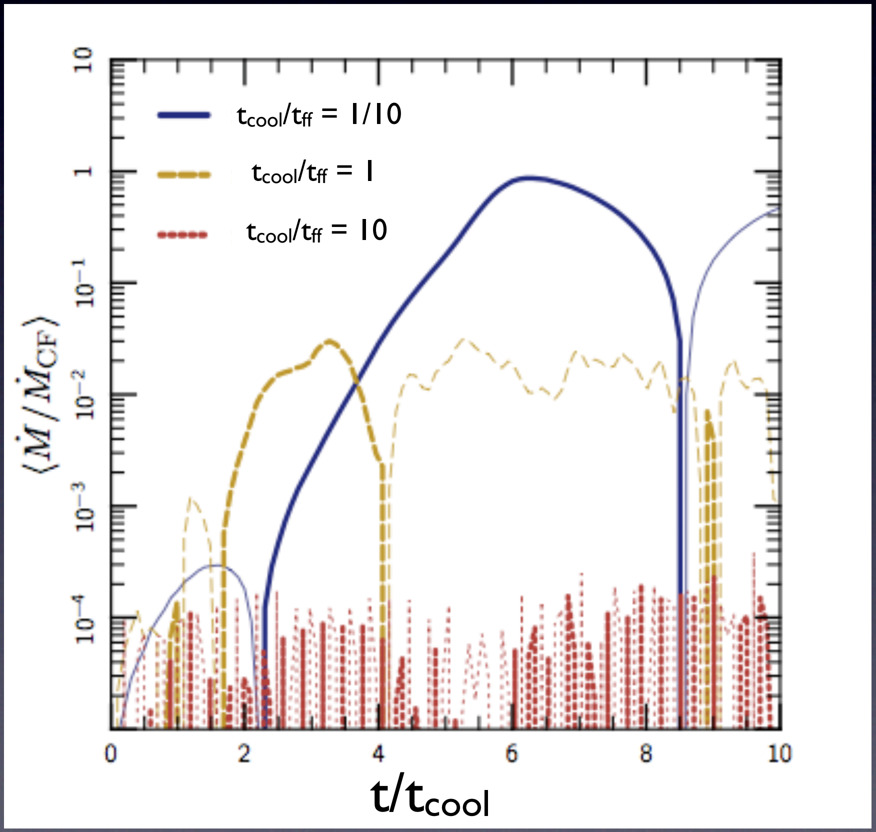
slow cooling, $\mathbf{t_{cool}/t_{ff} \gtrsim}$ **few**

thermal instability amplifies density perturbations
but blobs sheared apart before $\delta\rho/\rho \sim 1$
$\Rightarrow$ no multiphase structure

$$\text{analytically} \quad \frac{\delta\rho}{\rho} \sim \frac{t_{ff}}{t_{cool}}$$

Htg vs. Cooling in Cluster Plasmas

competition btw cooling & gravity: key parameter $\mathbf{t_{cool}/t_{ff}}$



slow cooling, $\mathbf{t_{cool}/t_{ff} \gtrsim}$ **few**

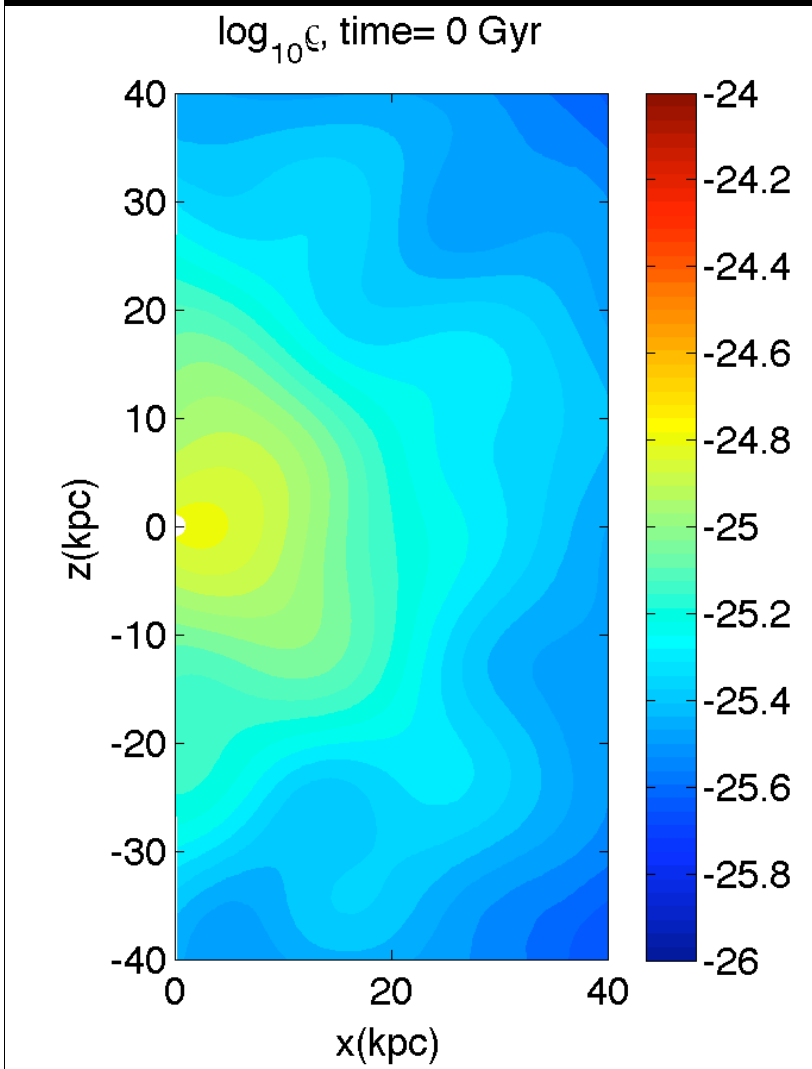
thermal instability amplifies density perturbations
but blobs sheared apart before $\delta\rho/\rho \sim 1$
⇒ no multiphase structure

$$\text{analytically} \quad \frac{\delta\rho}{\rho} \sim \frac{t_{ff}}{t_{cool}}$$

Net cooling rate & inflow to small radii
strongly suppressed **only if** $\mathbf{t_{cool}/t_{ff} \gtrsim}$ **few**

$$\frac{\dot{M}}{\dot{M}_{\rm CF}} \sim \left(\frac{t_{\rm ff}}{t_{\rm cool}}\right)^2 \ll 1$$

global cluster sim (NFW halo)
min(t_{cool}/t_{ff}) ~ 10



log[mass density ρ]

Global Cluster Sims

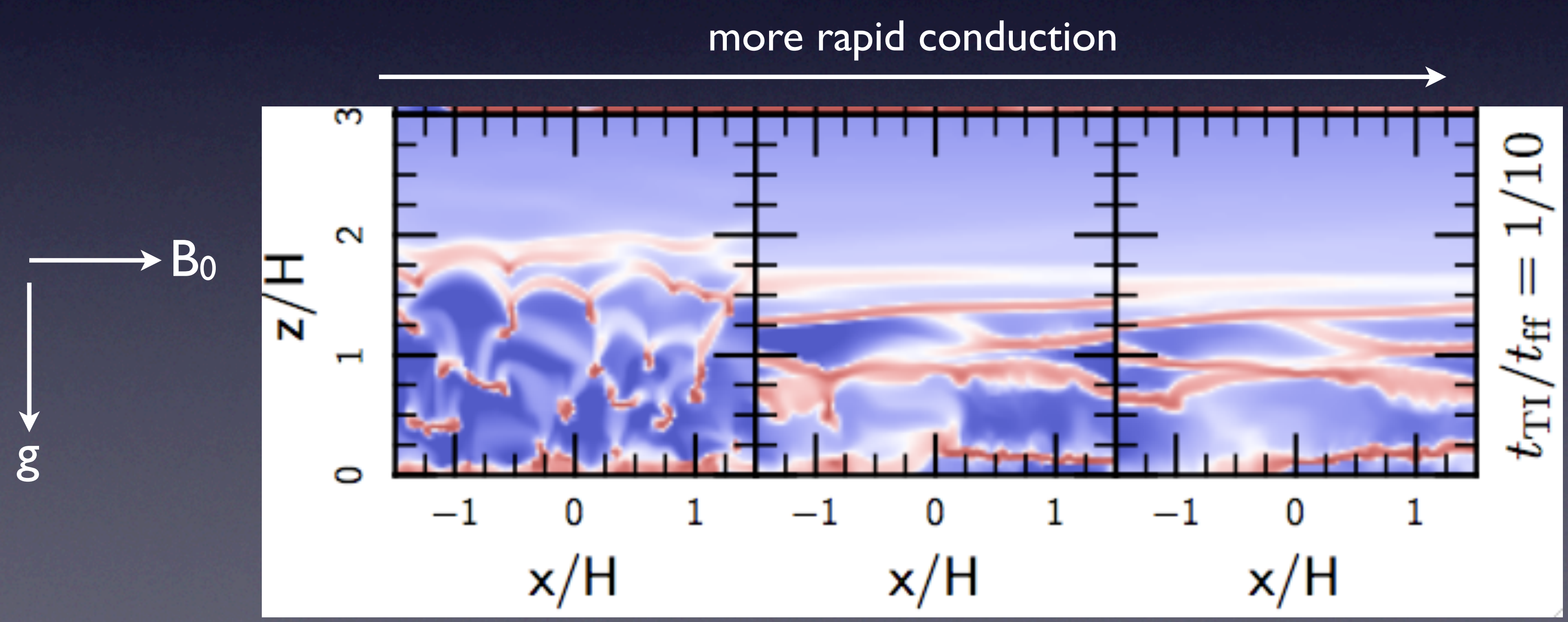
Criterion for multiphase structure:

$$t_{cool}/t_{ff} \lesssim 10$$

somewhat less stringent than cartesian bec.
of compression during inflow in spherical systems

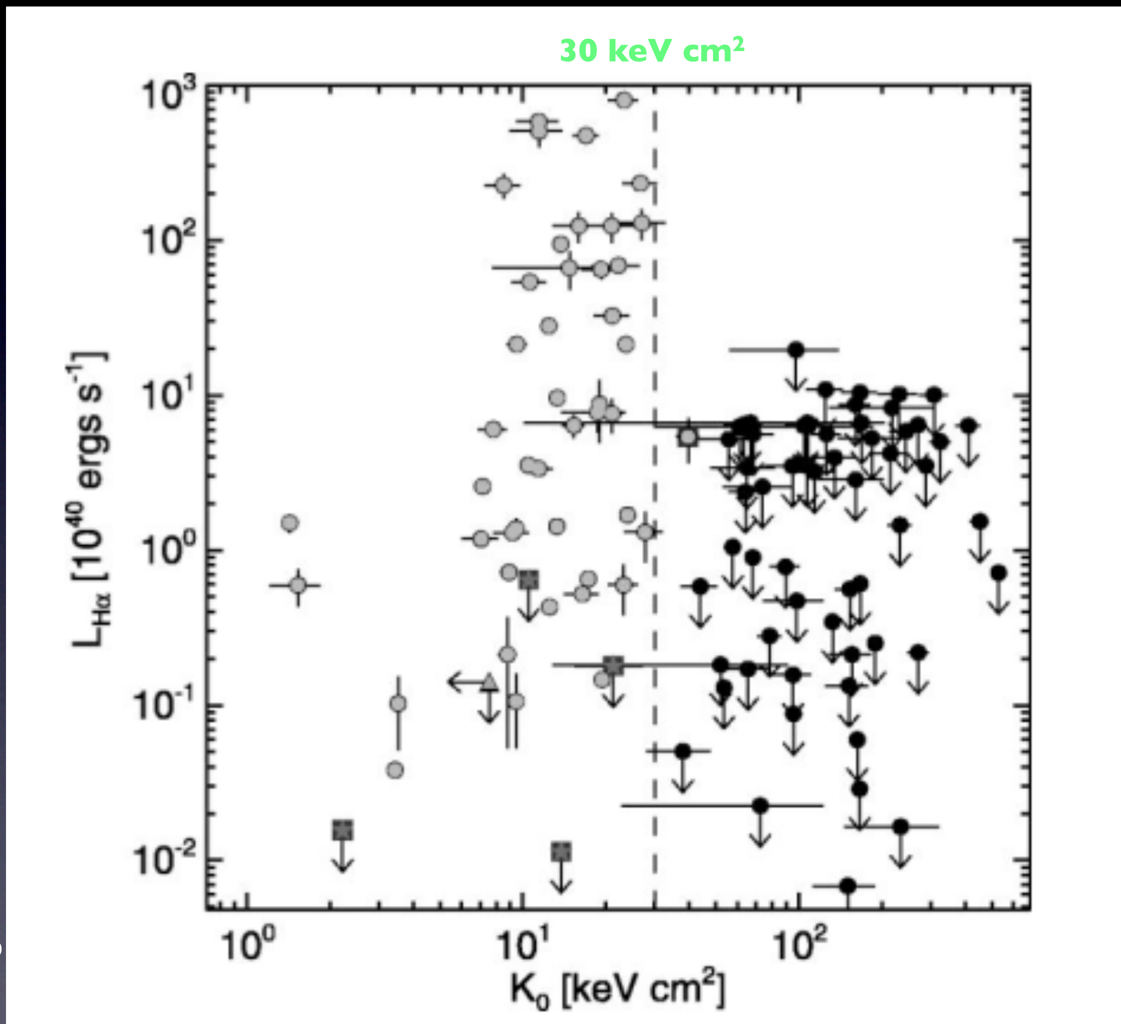
Htg vs. Cooling in Cluster Plasmas

- Thermal Instability w/ Realistic Physics ⇒ **Cold Filaments** (not cold blobs)
  - Realistic = B-fields, anisotropic conduction/viscosity, & cosmic-rays
  - filaments typically aligned along local B-field
  - CR pressure significant in filaments



$\log_{10}[\rho/\rho_0]$ in local Cartesian sim

Evidence for Cool, Dense Gas Ubiquitous in Cool-Core Clusters



Hα emission

Cavagnolo et al. 2008

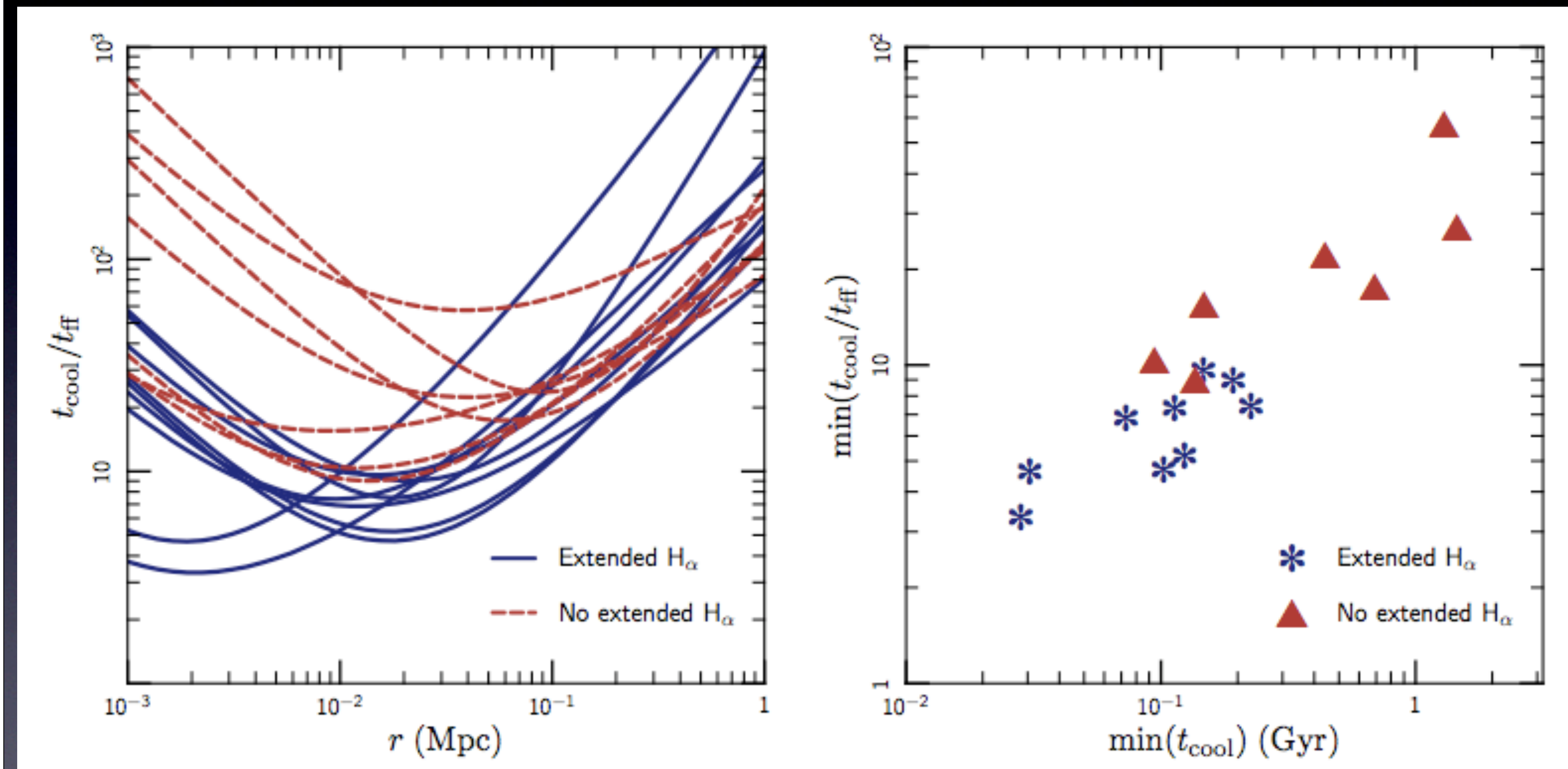
Cluster Central 'Entropy' ($K_0 = kT/n^{2/3}$)

star formation & AGN activity also correlated w/ $K_0 \lesssim 30$ keV cm^2

consistent w/ predictions for multiphase structure from thermal instability

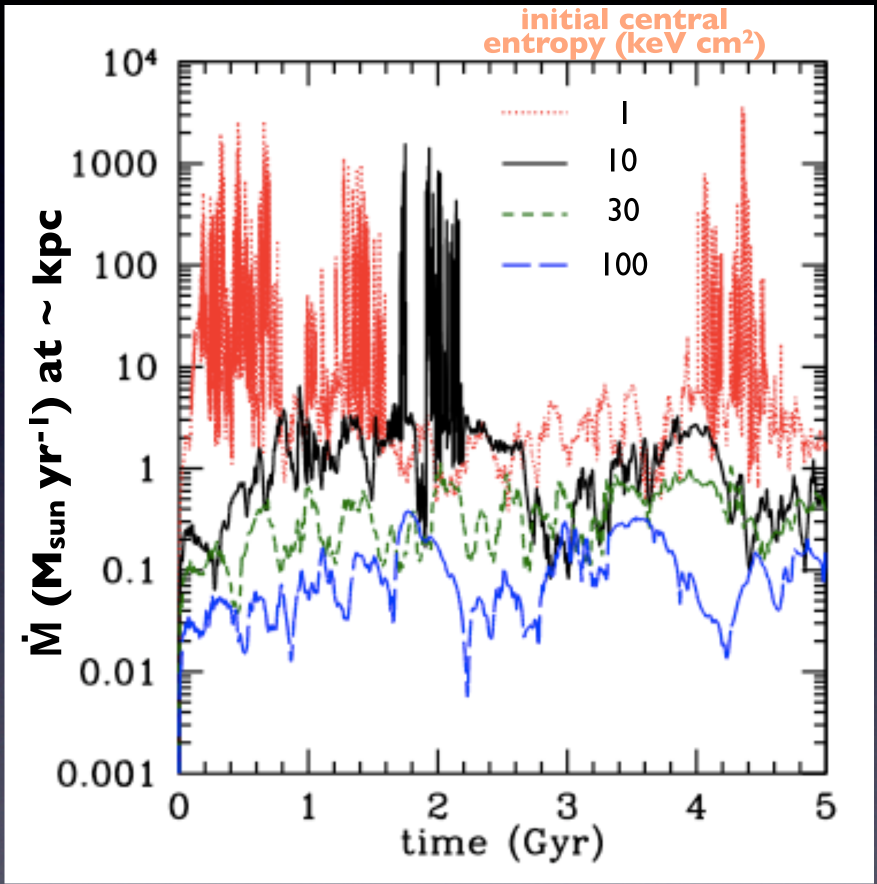
$$\frac{t_{\rm cool}}{t_{\rm ff}} \sim 5 \frac{(K/30 \text{ keV cm}^2)^{3/2}}{T_{\rm keV}^{1/2} \, \Lambda_{-22.8} \, (t_{\rm ff}/100 \, \text{Myr})}$$

Clusters in both ACCEPT & McDonald+2010 Hα survey



$\min(t_{cool}/t_{ff})$ at ~ 10-30 kpc ~ observed radii of filaments

Feedback & the Self-Regulation of Cluster Properties



axisymmetric global cluster sims (NFW halo) in global thermal equilibrium (H ~ $\mathscr{L}$)

Net cooling rate & inflow to small radii strongly suppressed only if $t_{cool}/t_{ff} \gtrsim$ few-10,

$$\frac{\dot{M}}{\dot{M}_{CF}} \sim \left(\frac{t_{ff}}{t_{cool}}\right)^2 \ll 1$$

If Heating ~ $\varepsilon \dot{M} c^2$

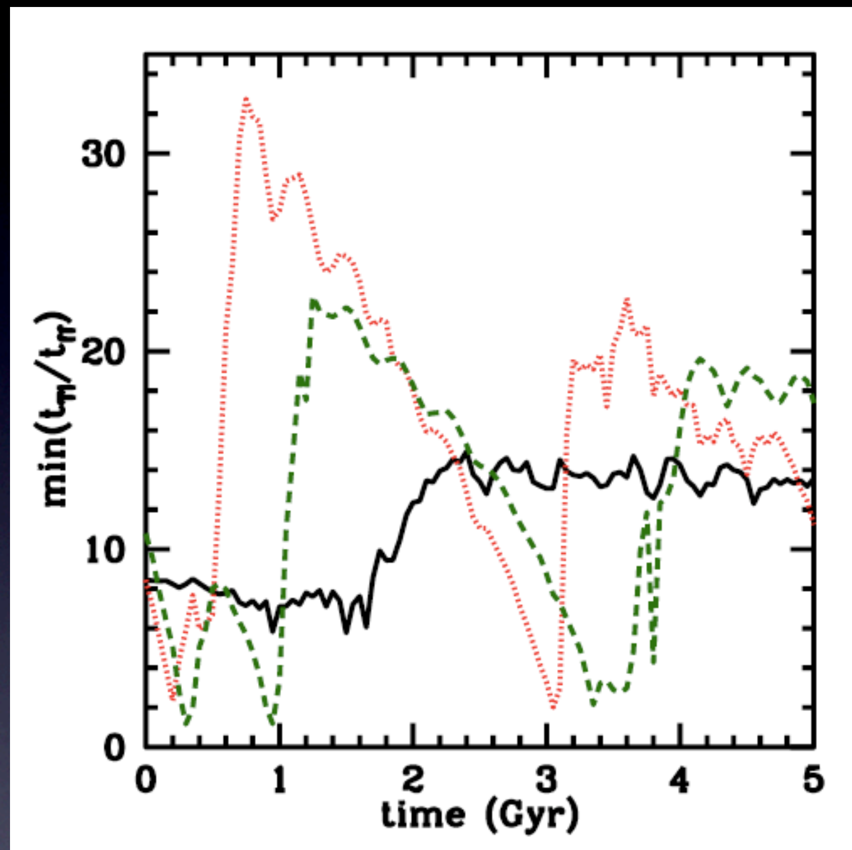
(AGN, SNe, ...)

⇒ clusters self-regulate to

$\min(t_{cool}/t_{ff}) \sim 10$

$\min(\text{entropy}) \sim 10\text{-}30$ keV cm^2

Feedback & the Self-Regulation of Cluster Properties



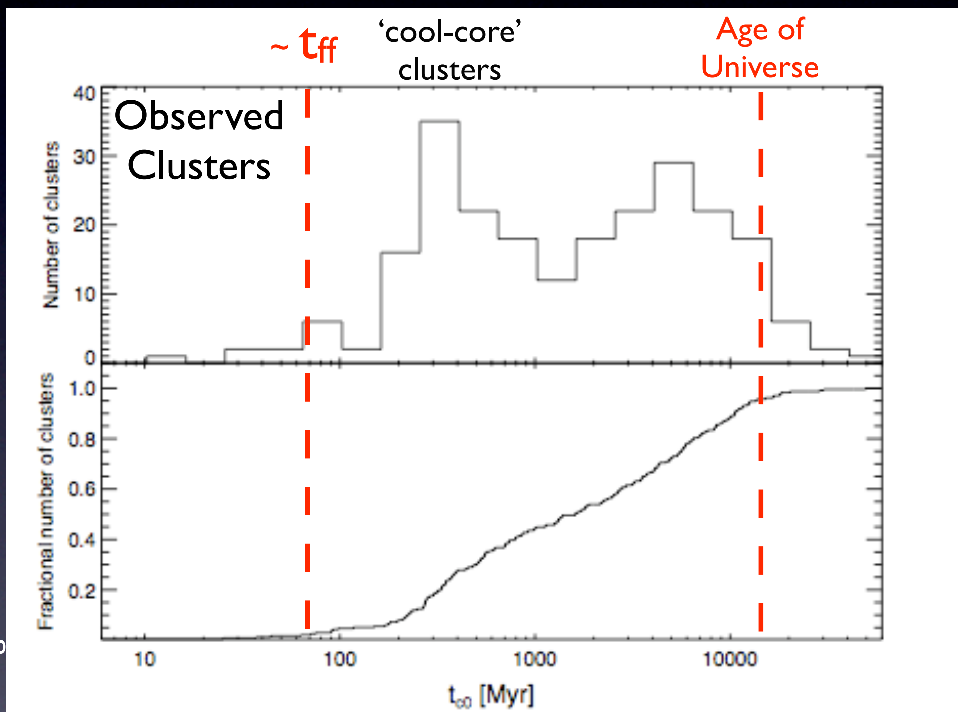
If Heating ~ $\varepsilon \dot{M} c^2$ (AGN, SNe, ...) ⇒ clusters self-regulate to

$\min(t_{cool}/t_{ff}) \sim 10$

(weakly dependent on details of heating;
intrinsically multi-D physics -- not in 1D models)

Feedback & the Self-Regulation of Cluster Properties

Cavagnolo et al.



central cooling time (Myr)

observed central cooling times peak at ~ 5-10 t_{ff} consistent w/ 'feedback' loop in which is $\dot{M}$ induced by local thermal instability

The Thermal Physics of Galaxy Cluster Plasmas

- Clusters are convectively unstable at all radii!
  - induced by anisotropic thermal conduction (accept no substitute)
  - these mediate heat transport in clusters & drive turbulence at all radii

- Clusters are in ~ global thermal equilibrium, but are locally unstable
- Local TI: competition btw cooling & gravity: t_{cool}/t_{ff}
  - $t_{cool}/t_{ff} \lesssim 10 \Rightarrow$ significant multi-phase structure
  - $\dot{M} << \dot{M}_{CF}$ iff $t_{cool}/t_{ff} \gtrsim$ 3-10 (i.e, not too much dense gas via TI)
  - feedback $\Rightarrow$ min(t_{cool}/t_{ff}) ~ 10, K_0 ~ 30 keV cm^2: consistent w/ data

Next Time