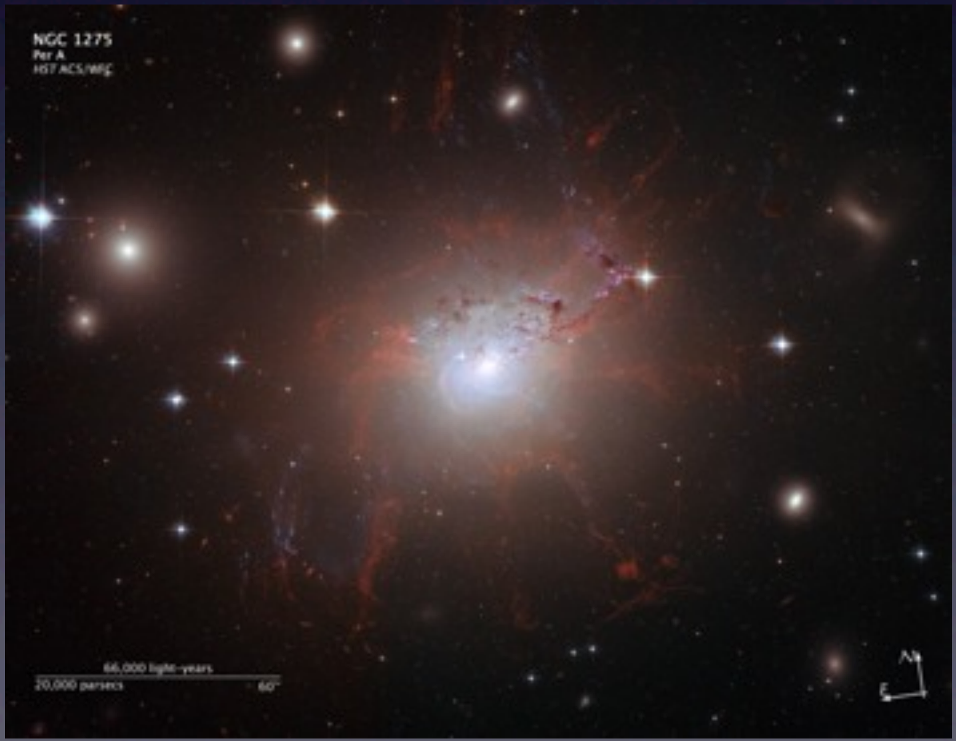
The Thermal Stability of Galaxy Cluster Plasmas

Eliot Quataert (UC Berkeley)

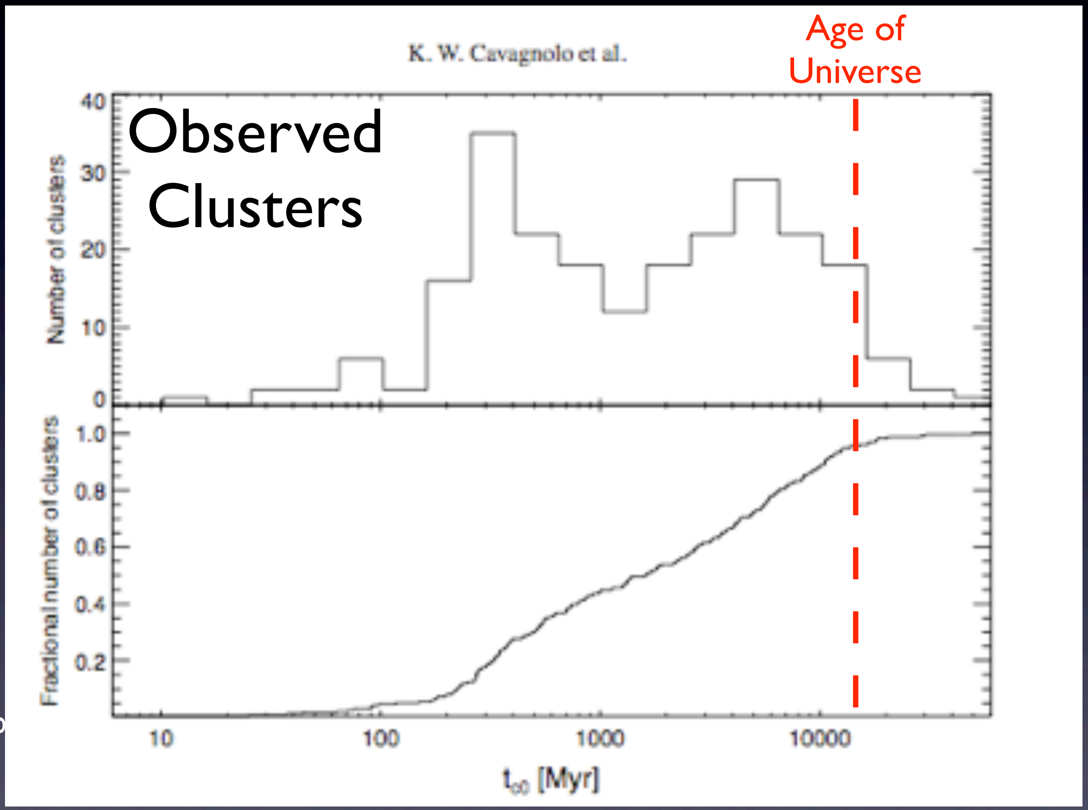


`

in collaboration with

Mike McCourt
Prateek Sharma
Ian Parrish

Galaxy Clusters: a Key to Understanding Massive Galaxy Formation



Cavagnolo et al.

central cooling time (Myr)

in the majority of clusters, t_{cool} << Age of Universe in cluster core

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

Not Observed

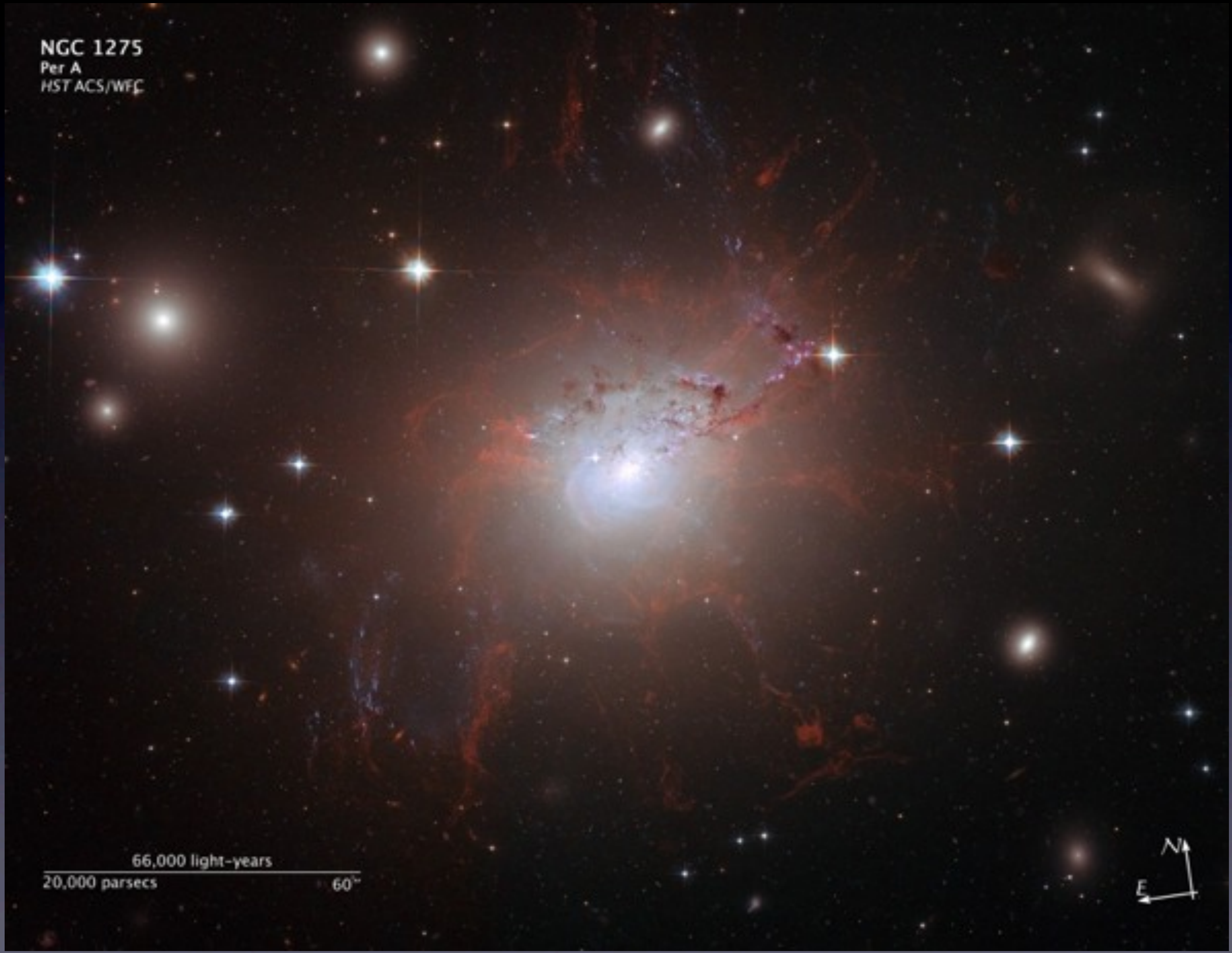
$\dot{M}_{star} << \dot{M}_{cool}$

no sufficiently large reservoirs of cold gas

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

...

but there is cool, dense gas observed in many clusters

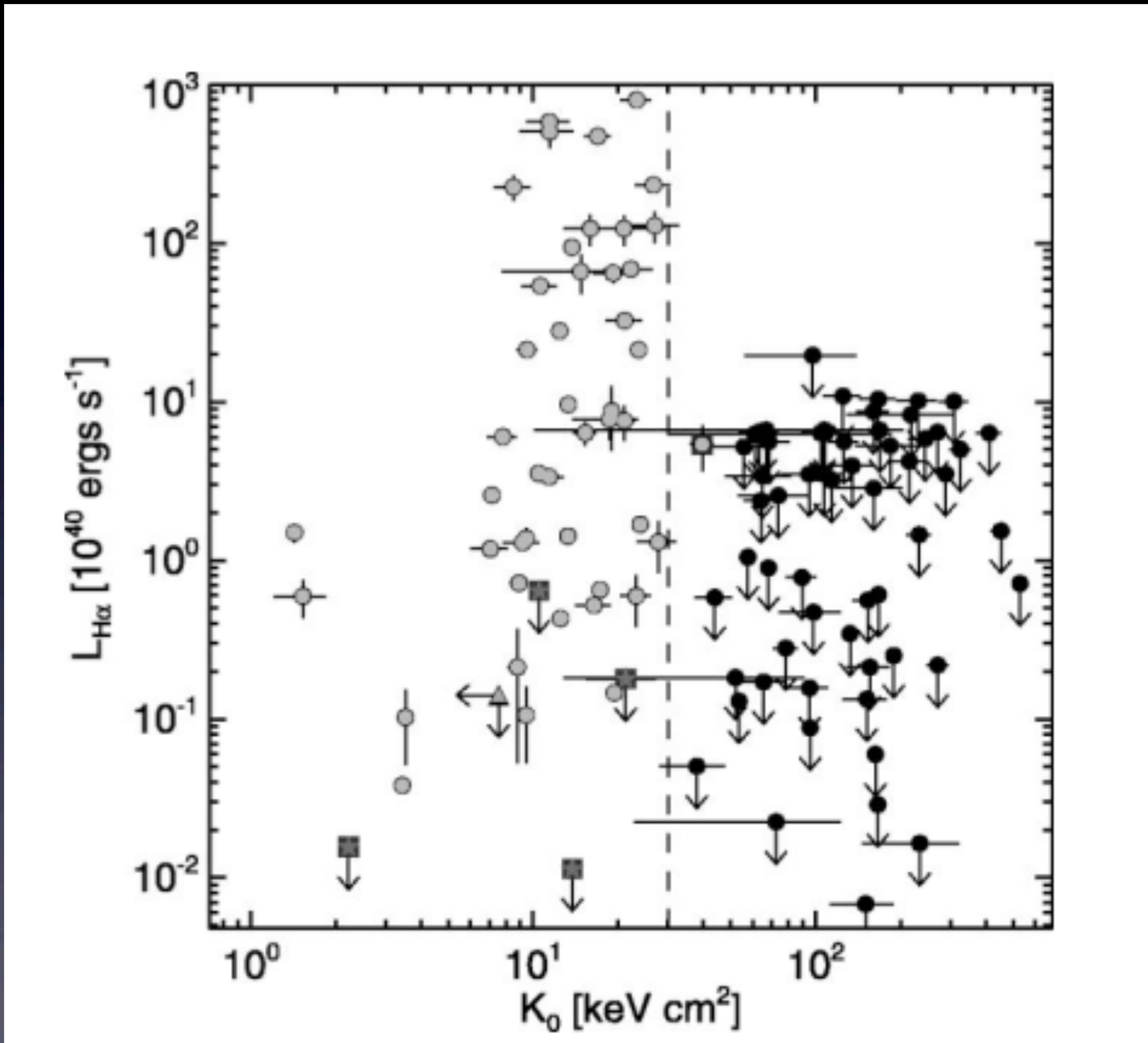


Fabian et al. 2008

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 correlated w/ short cooling times (small K_0)

-- Megan's Talk

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

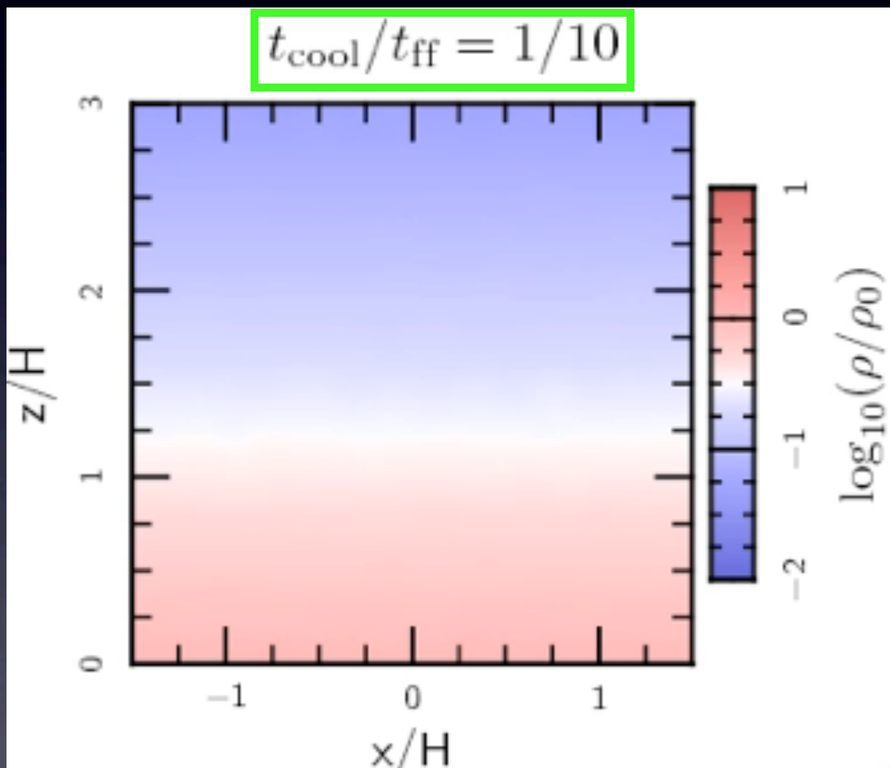
Global Thermal Balance ≠ Local Thermal Balance

- <Heating> = <Cooling> ⇒ no cooling flow
- Heating ≠ Cooling locally ⇒ local thermal instability
  - htg via waves, turbulence, cosmic rays, conduction ... very likely thermally unstable
    (for turbulence/waves htg moderately independent of 'viscosity' on small scales -- set by source physics)
- Subtle physics w/ critical implications for multiphase gas in clusters & the feedback cycle that regulates ICM properties

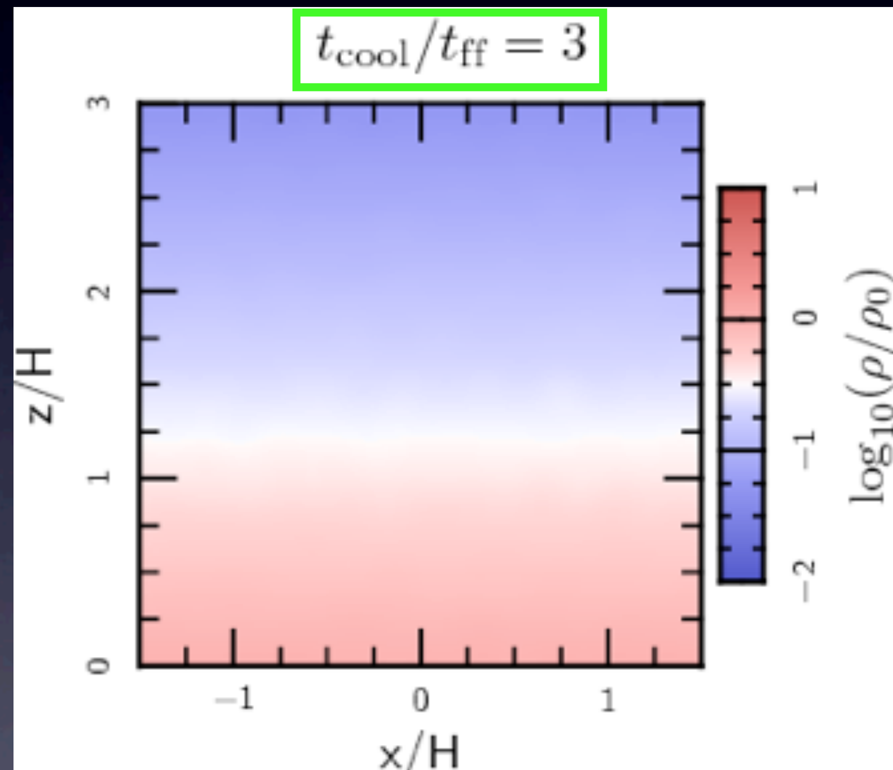
Htg vs. Cooling in Cluster Plasmas

competition btw cooling & gravity (buoyancy): key parameter **t_{cool}/t_{ff}**

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



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



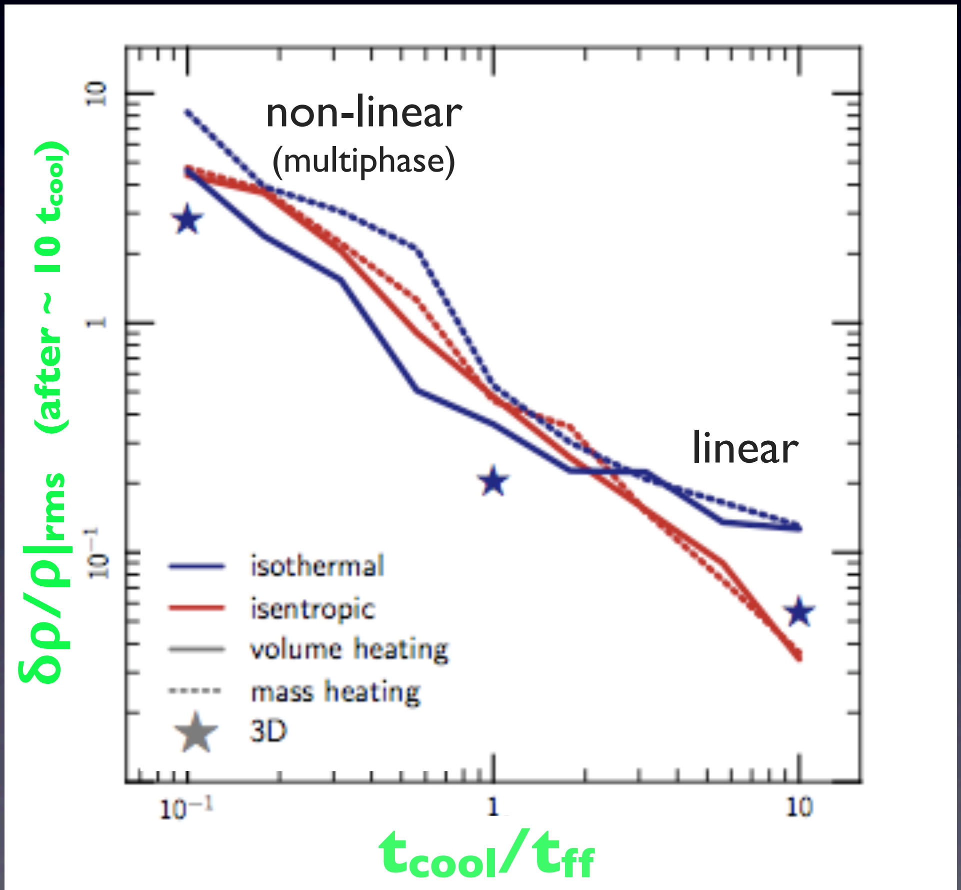
g

Cartesian sims (movies ~ 10 t_{cool})
toy model w/ htg ∋ $H(r) = \langle \mathscr{L} \rangle (r)$
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 (buoyancy): key parameter t_{cool}/t_{ff}



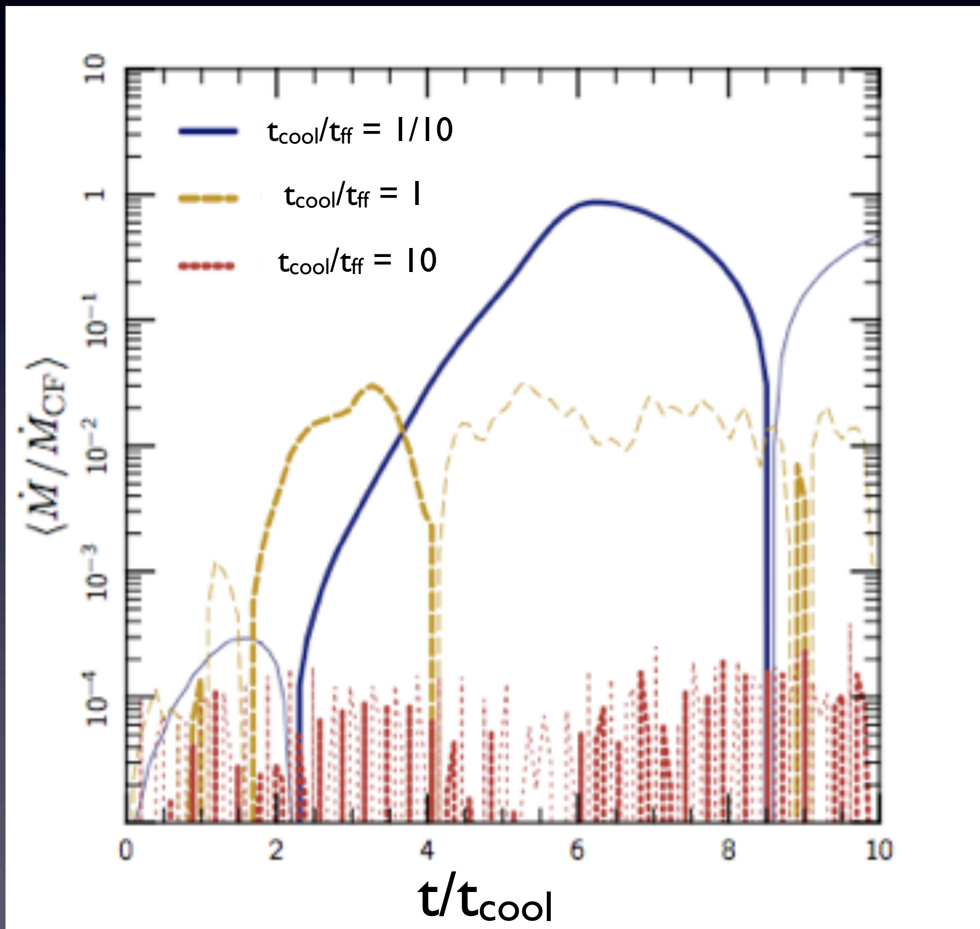
slow cooling, $t_{cool}/t_{ff} \gtrsim$ **few**

thermal instability amplifies density perturbations
but blobs sink ~ H before $\delta\rho/\rho \sim 1$
⇒ no extended multiphase structure

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

Htg vs. Cooling in Cluster Plasmas

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



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

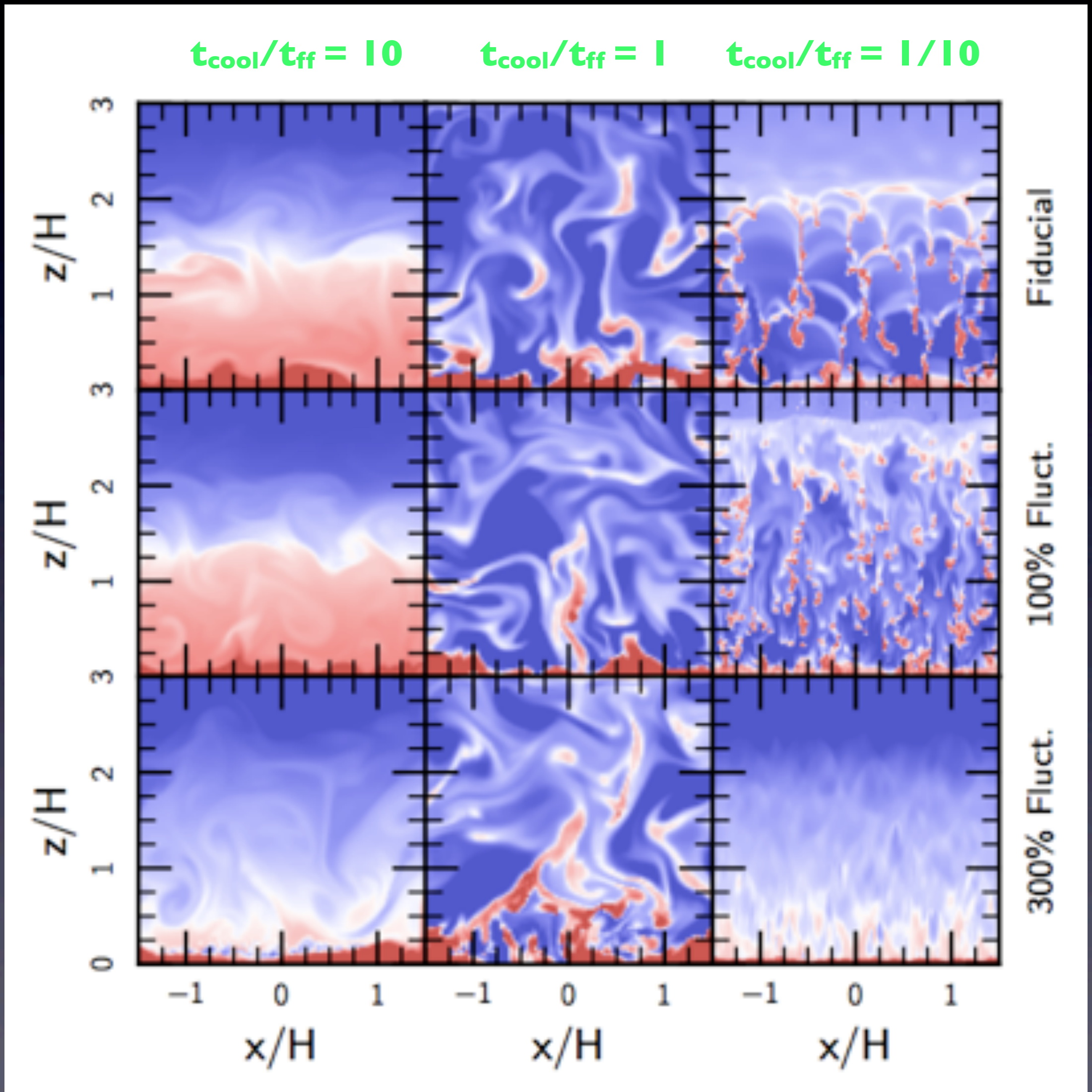
thermal instability amplifies density perturbations
but blobs sink ~ H before $\delta\rho/\rho \sim 1$
⇒ no extended multiphase structure

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

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

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

Htg vs. Cooling in Cluster Plasmas



local Cartesian simulations; no B-fields or conduction

Results Robust to
Large Spatial & Temporal
Fluctuations in Heating ⇒

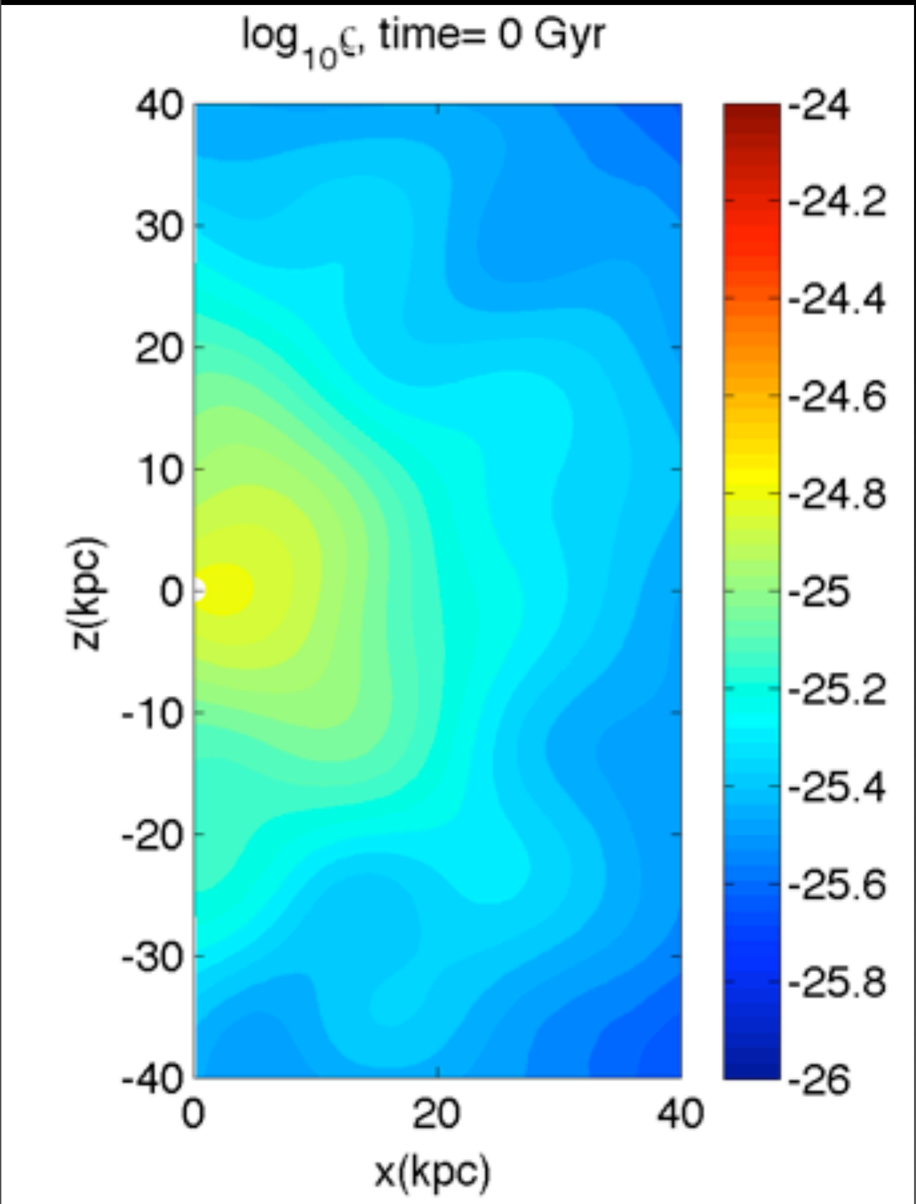
Generic to Local TI in
Globally Stable System

100% Fluctuations
about H = <$\mathscr{L}$>:
results ~ same

300% Fluctuations
about H = <$\mathscr{L}$>
induce cooling flow

global cluster sim: $\Delta R/R \sim 0.005$

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



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

criterion valid for both

toy model w/ $H = \langle \mathscr{L} \rangle$ &

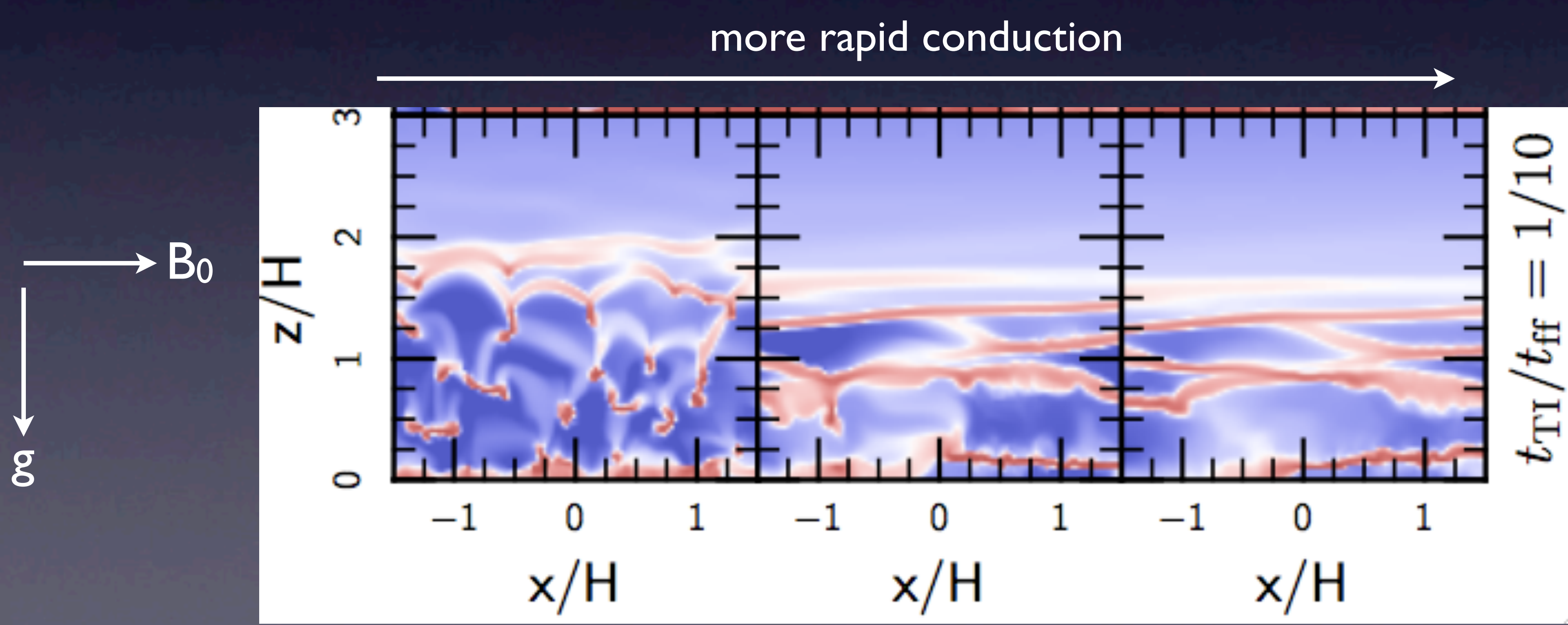
physically motivated feedback model $H = \varepsilon \dot{M} c^2$

(aside: this criterion is a multi-D extension of cold vs. hot accretion in galaxy formation that applies ∀ radii)

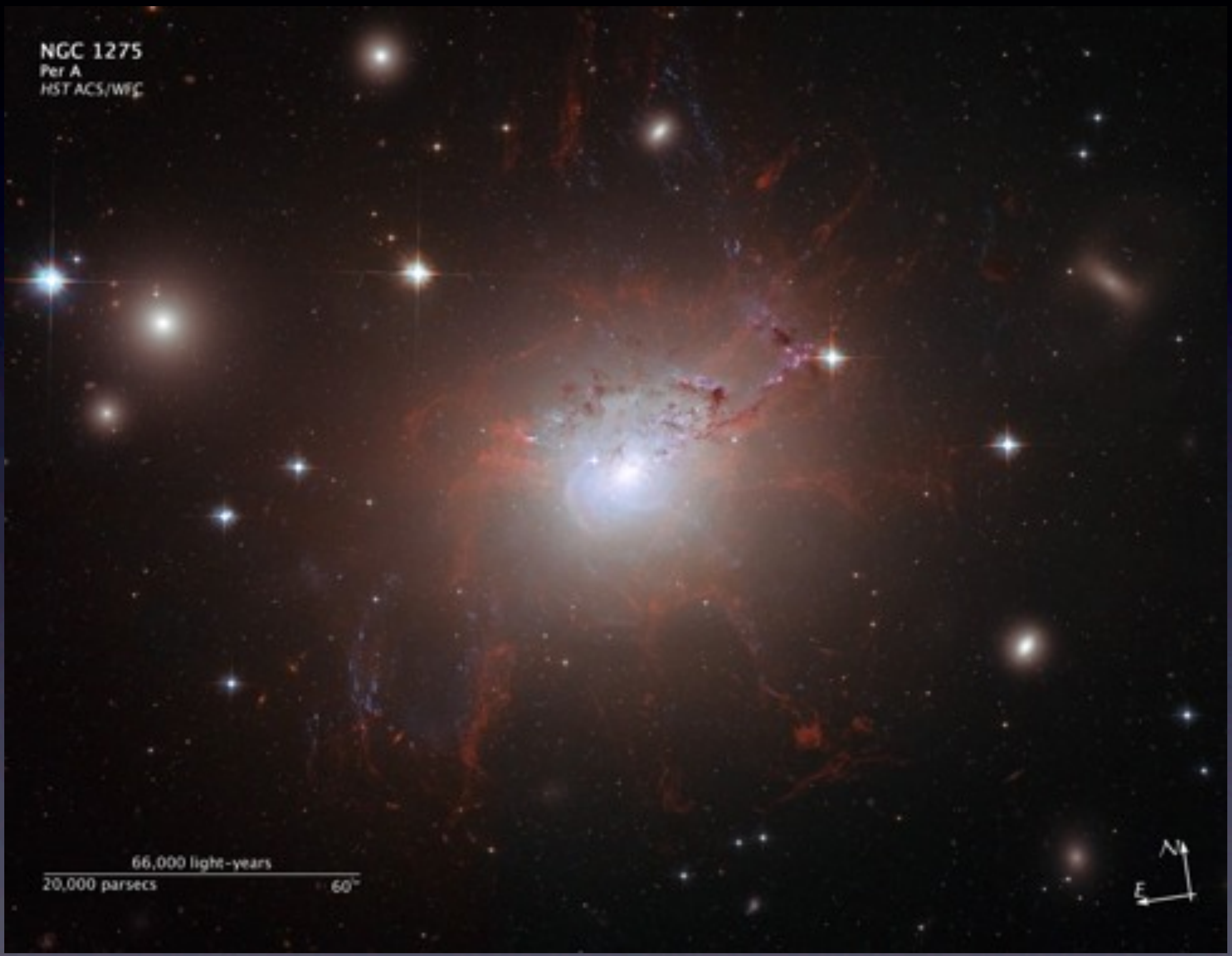
log[mass density ρ]

Htg vs. Cooling in Cluster Plasmas

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



$\log_{10}[\rho/\rho_0]$ in local Cartesian sim cool, dense ‘filamentary’ gas observed in many clusters



Fabian et al. 2008

Hα emission in Perseus

Global Cluster Sims

Criterion for multiphase structure:

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

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

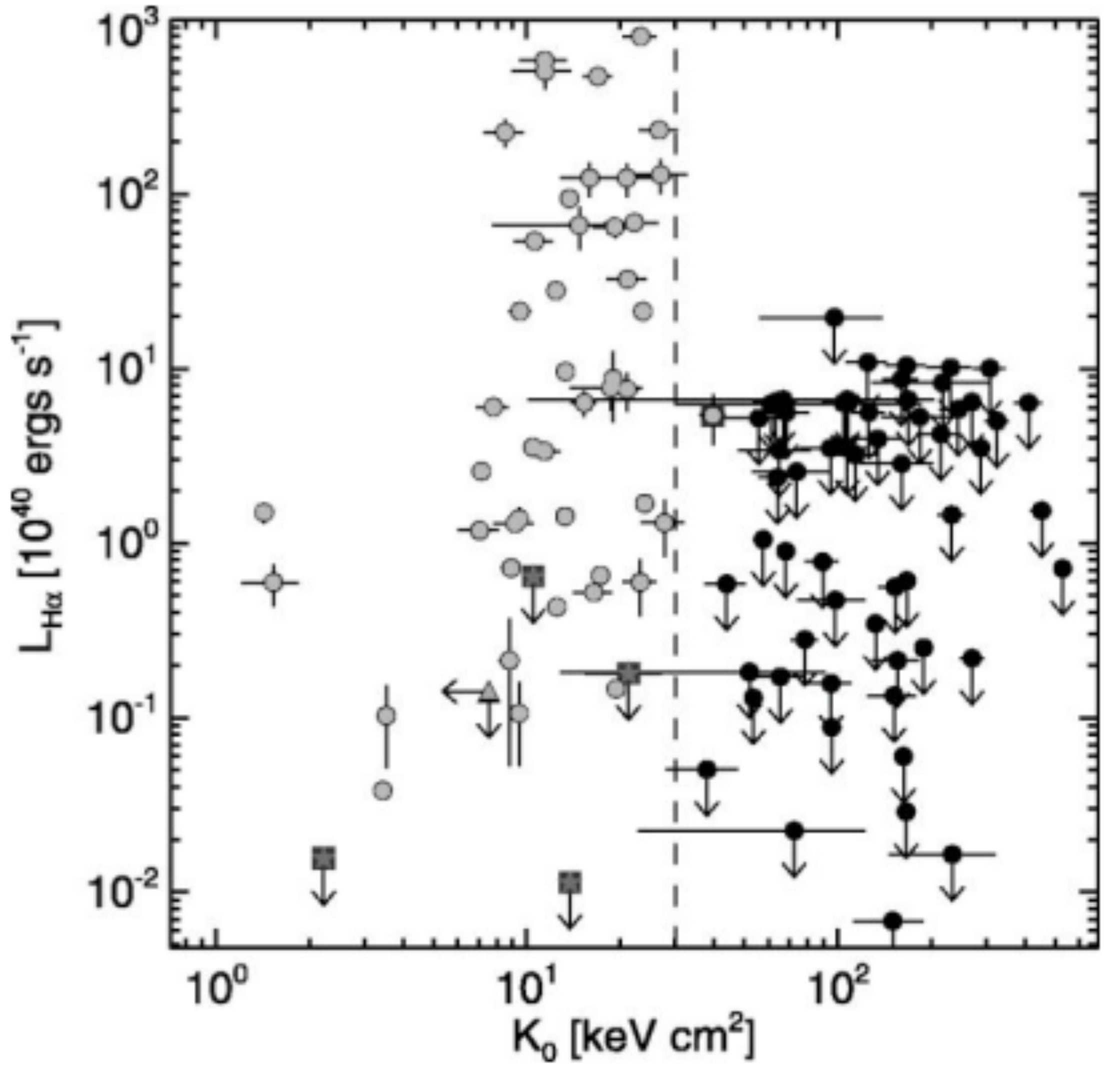
$$\frac{\dot{M}}{\dot{M}_{CF}} \sim \left(\frac{t_{ff}}{t_{cool}}\right)^2 \ll 1$$

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

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

Hα emission

Cavagnolo et al. 2008



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

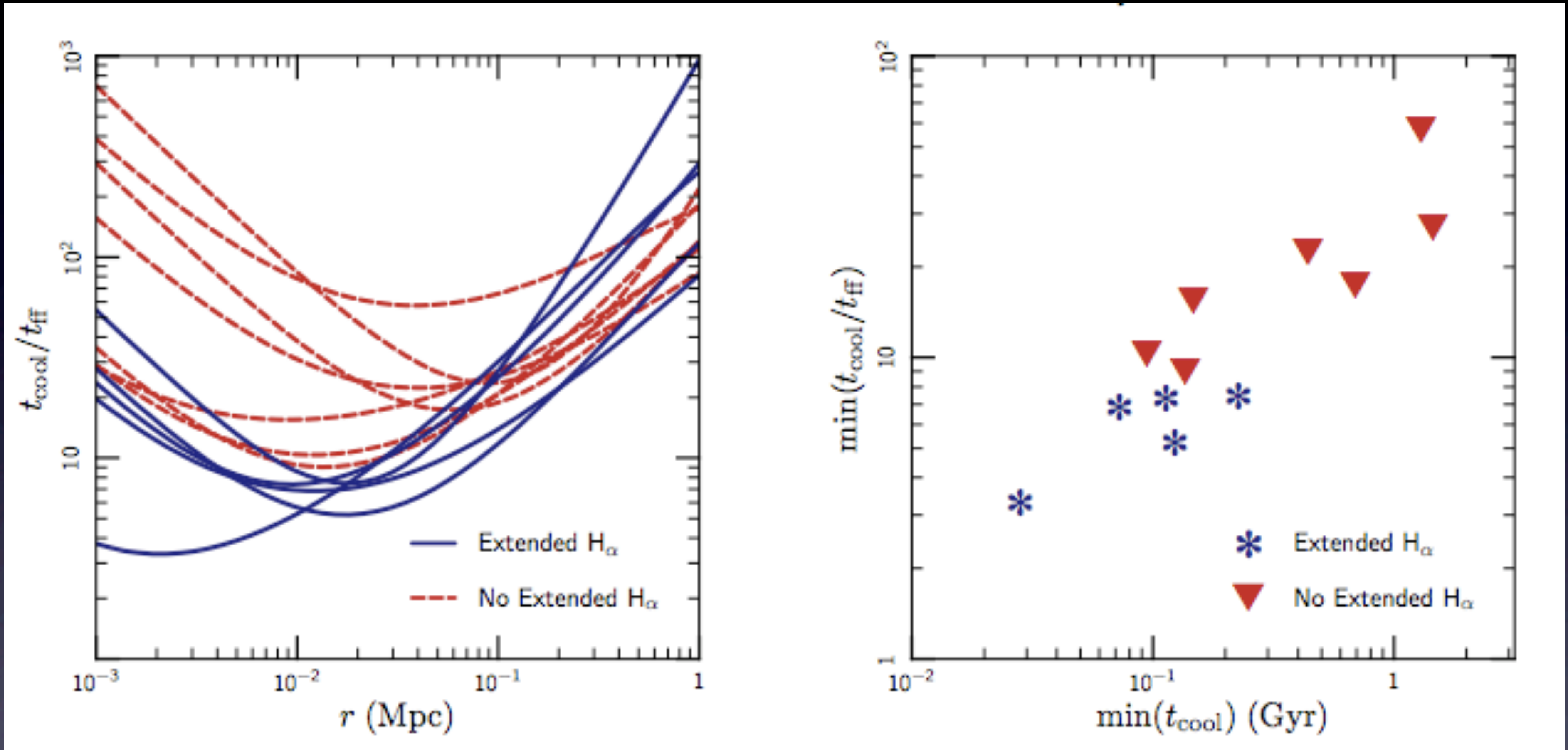
star formation & AGN activity also correlated w/ $K_0 \lesssim 30$ keV cm^2 (& satisfy $\dot{M} << \dot{M}_{CF}$)

consistent w/ predictions for multiphase structure from thermal instability

anisotropic conduction also critical

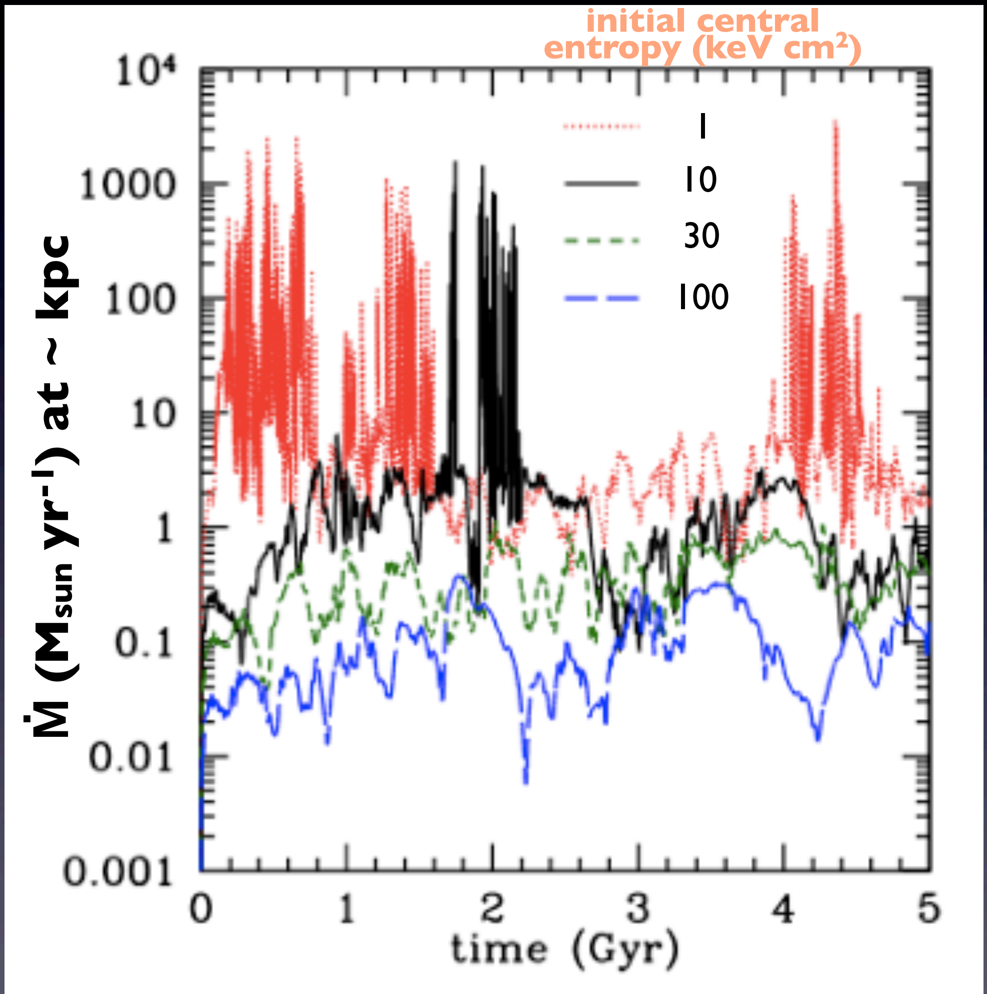
$$\lambda_F \sim 140 \left(\frac{K_0}{30\,\mathrm{keV\,cm^2}} \right)^{3/2} \mathrm{kpc}$$

Clusters in both ACCEPT & McDonald+2010 Hα survey



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

Feedback & the Self-Regulation of Cool-Core Clusters

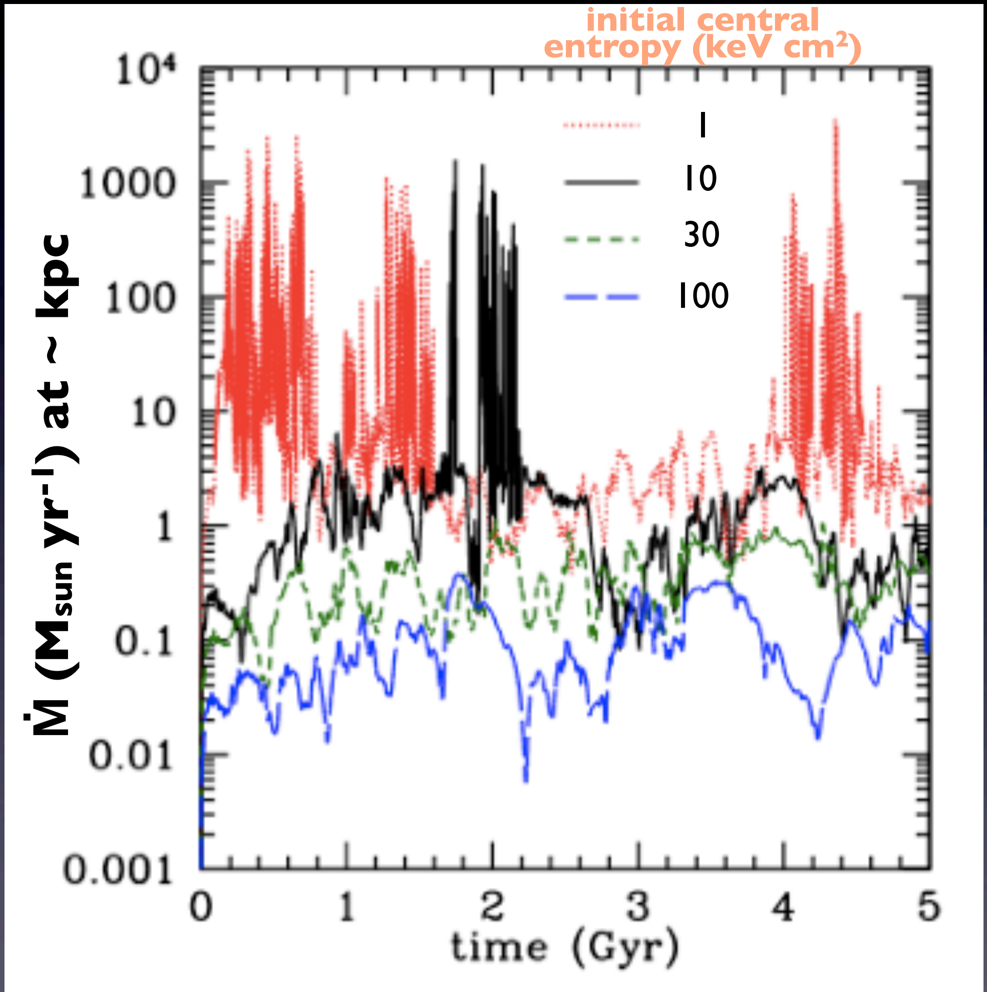


global axisymmetric cluster simulations
in global thermal equilibrium (H ~ $\mathscr{L}$)

Net cooling rate & inflow to small radii strongly suppressed only if $t_{cool}/t_{ff} \gtrsim$ few-10, i.e., $K_0 \gtrsim$ 10-30 keV cm^2

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

Feedback & the Self-Regulation of Cool-Core Clusters



global axisymmetric cluster simulations 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, i.e., $K_0 \gtrsim$ 10-30 keV cm^2

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

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

(AGN, SNe, ...)

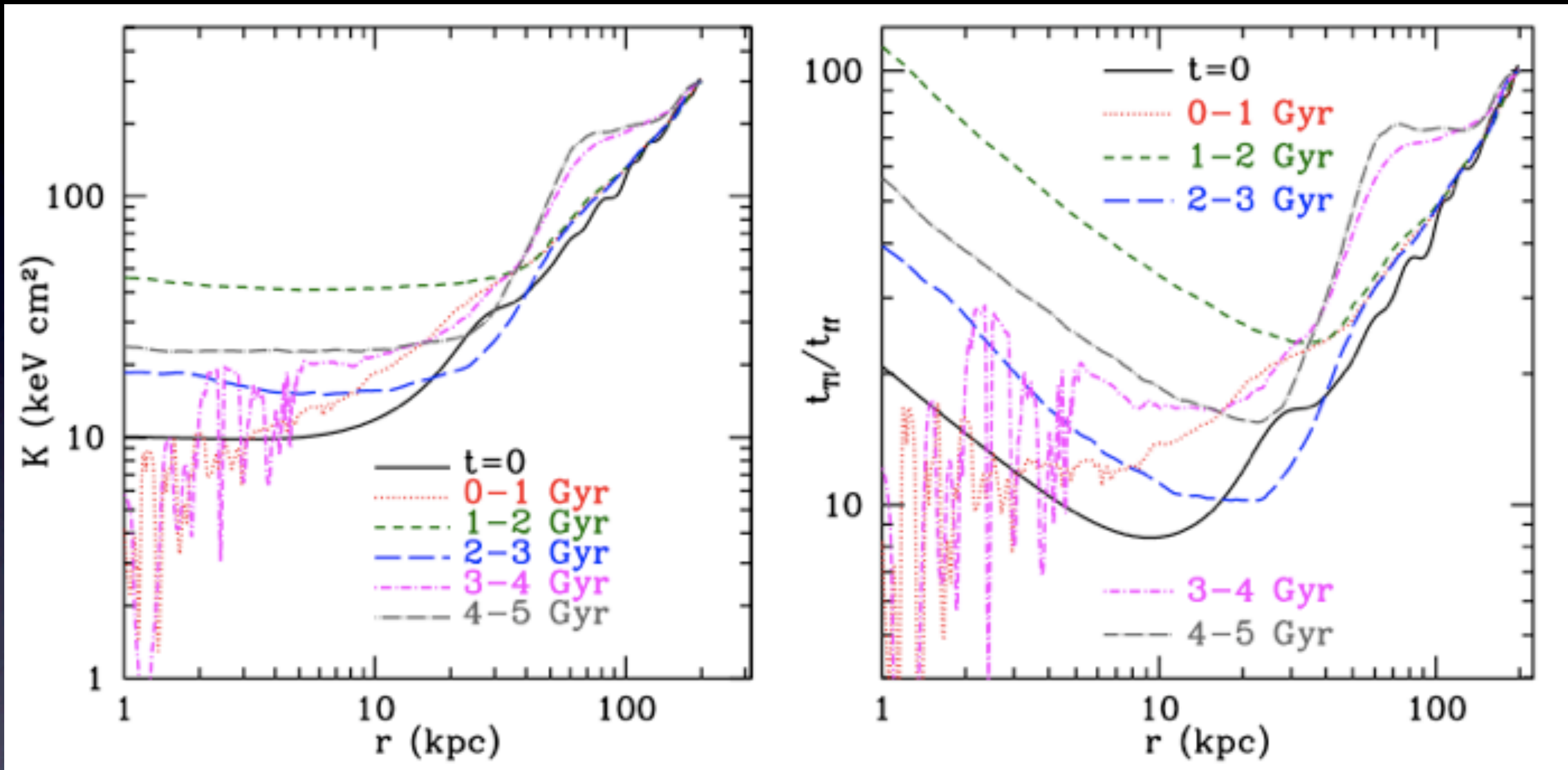
⇒ clusters self-regulate to

min(t_{cool}/t_{ff}) ~ 10,

K_0 ~ 10-30 keV cm^2

(nothing to do w/ details of heating; Ṁ cold &/or hot gas; intrinsically multi-D physics -- not in 1D models)

Feedback & the Self-Regulation of Cool-Core Clusters

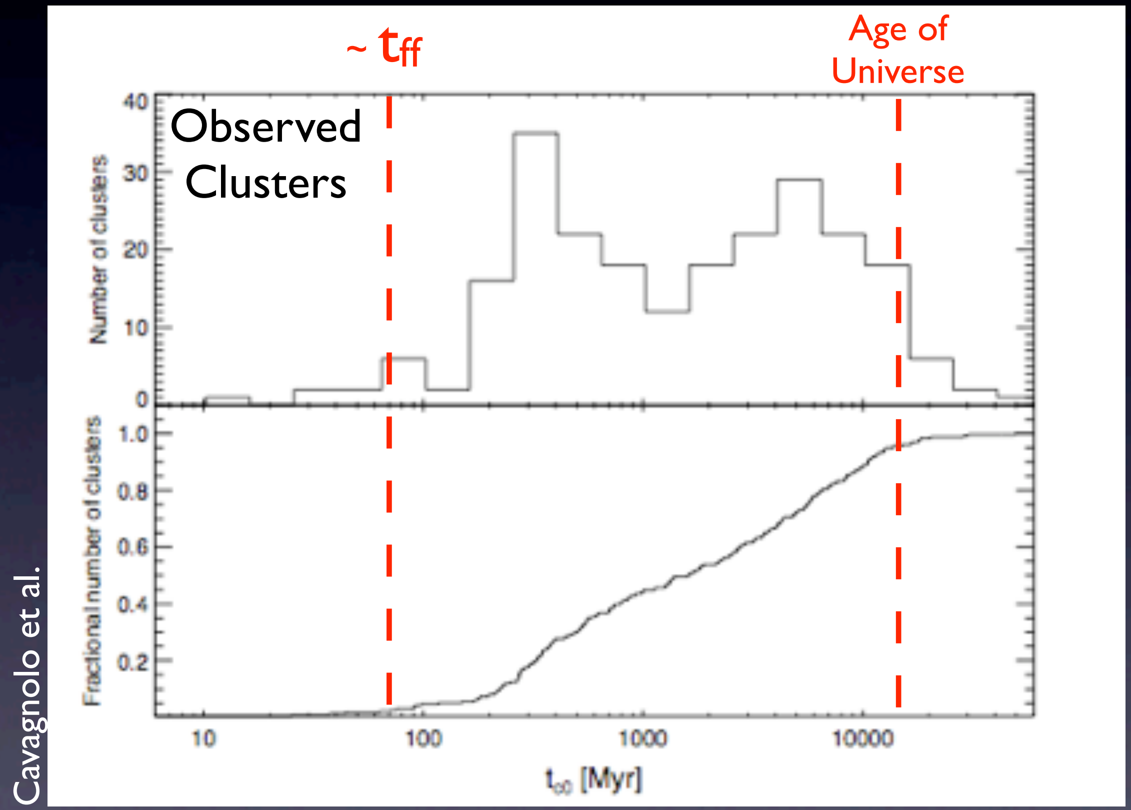


If Heating ~ $\epsilon \dot{M} c^2$ (AGN, SNe, ...) ⇒ clusters self-regulate to min

$(t_{cool}/t_{ff}) \sim 10$ $\quad$ $K_0 \sim 10\text{-}30$ keV cm^2

(nothing to do w/ details of heating; $\dot{M}$ cold & hot gas;
intrinsically multi-D physics -- not in 1D models)

Feedback & the Self-Regulation of Cool-Core Clusters



central cooling time (Myr)

observed central cooling times peak at ~ 5-10 t_{ff} consistent w/ suggested ‘feedback’ loop with $\dot{M}$ induced by TI

The Thermal Stability of Galaxy Cluster Plasmas

- Clusters are empirically in ~ global thermal equilibrium
  - but still prone to local thermal instability: embrace it!
- Local TI: competition btw cooling & gravity, key parameter t_{cool}/t_{ff}
- $t_{cool}/t_{ff} \gtrsim 10 \Rightarrow$ no multi-phase structure
- $t_{cool}/t_{ff} \lesssim 10 \Rightarrow$ significant multi-phase structure
  - consistent w/ correlations btw K_0, star formation, $H\alpha$, ... $\Rightarrow$ dense gas originates via local TI
- $\dot{M} << \dot{M}_{CF}$ only if $t_{cool}/t_{ff} \gtrsim$ 3-10 (i.e, not too much dense gas via TI)
  - feedback regulates $\min(t_{cool}/t_{ff}) \sim 10$, $K_0 \sim 30$ keV cm^2: consistent w/ cool-core clusters