AGN Feedback Heating
in
Clusters of Galaxies

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Collaborators

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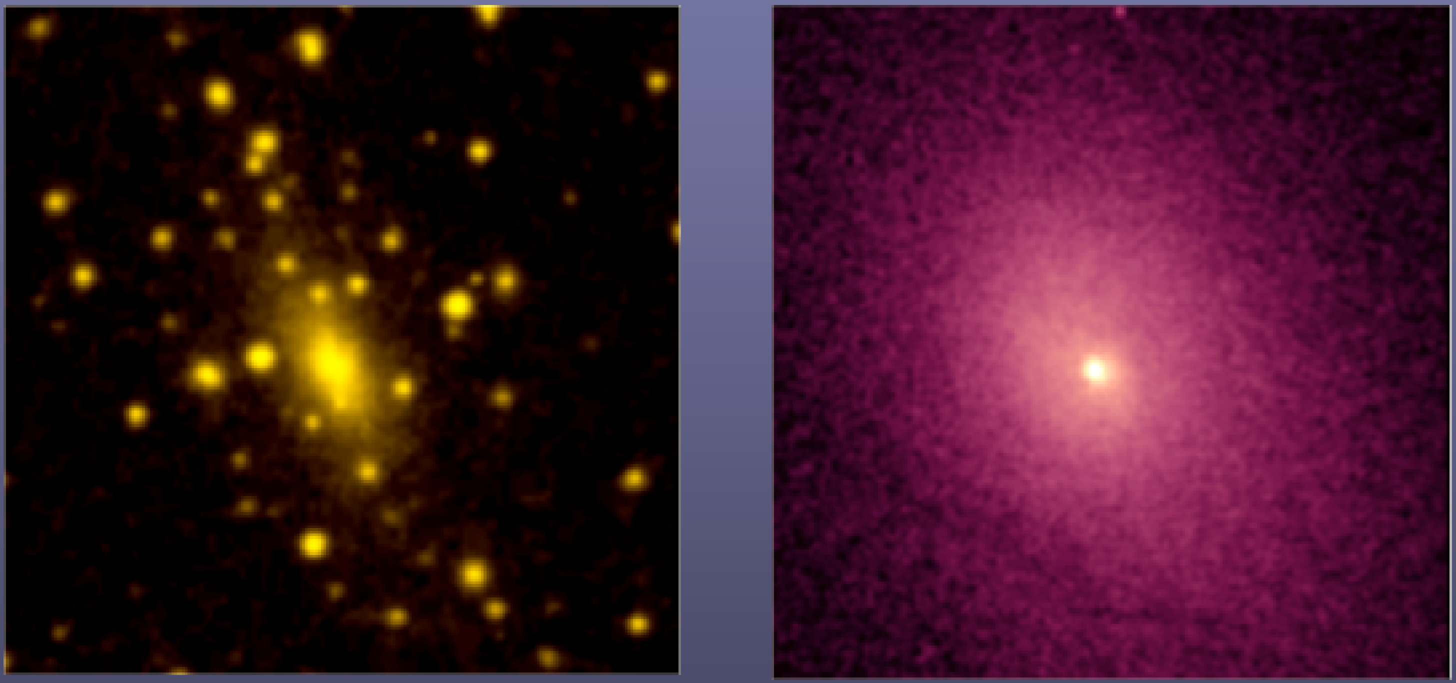
Papers

Guo & Oh, 2008, MNRAS, 384, 251
Guo, Oh & Ruszkowski, 2008, ApJ, 688, 859

Outline

- Introduction --
  - --cool core clusters
  - --why AGN feedback in Galaxy Clusters?
- Heating the ICM -- Conduction vs AGN heating?
- Part I: Cosmic-ray Feedback
- Part II: Global Stability Analysis
- Open Questions and Future Work

A typical cool core cluster -- Abell 2029



DSS Optical

Chandra X-ray

4 arcmin on each side

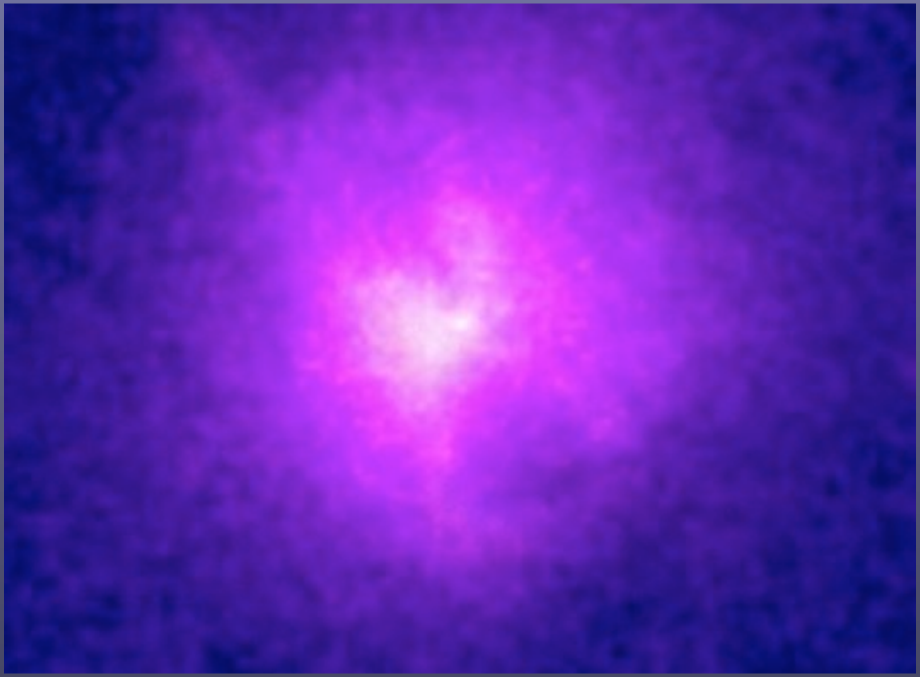
(Peterson & Fabian 2006)

Why AGN Feedback?

(1) The Cooling Flow Problem

- Strong X-ray emission in cluster cores
- Short cooling time at the cluster center (as short as 0.1 - 1 Gyr)

For review papers, see
Fabian 1994
Peterson & Fabian 2006

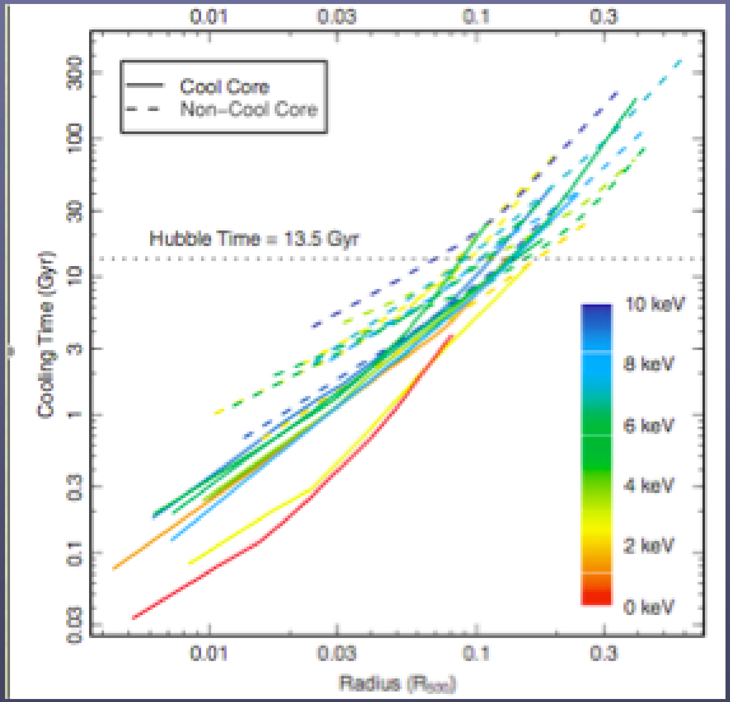


Chandra image of Hydra A

Why AGN Feedback?

(1) The Cooling Flow Problem

- Cool core clusters: lack of emission lines from the gas at temperatures below 1/3 of the ambient T
- Heating is required to suppress strong cooling flows in cool cores



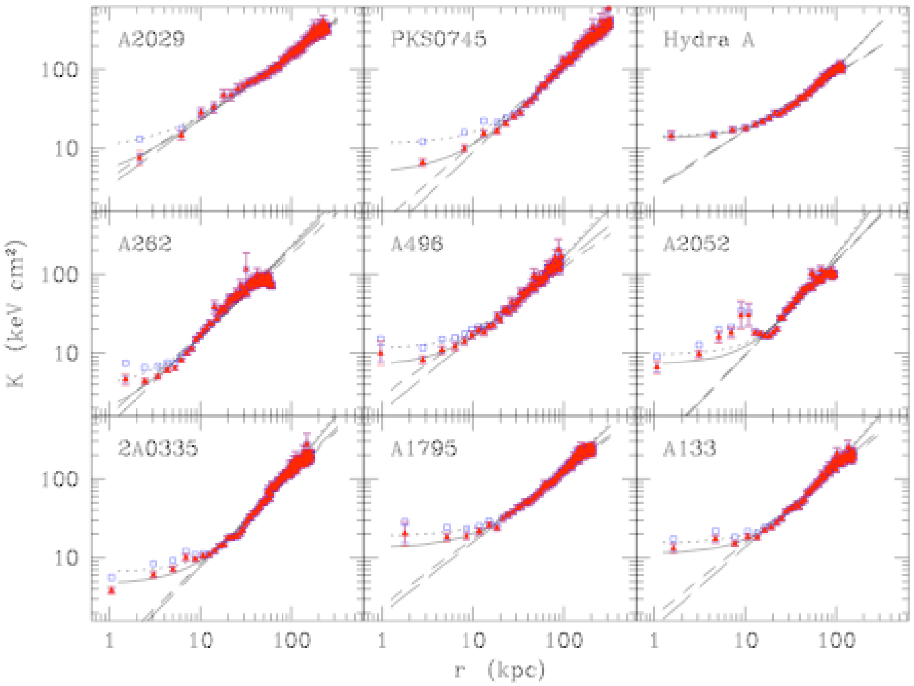
(see Peterson & Fabian 2006 for a review)

Sanderson et al. 2006

Why AGN Feedback (2)?

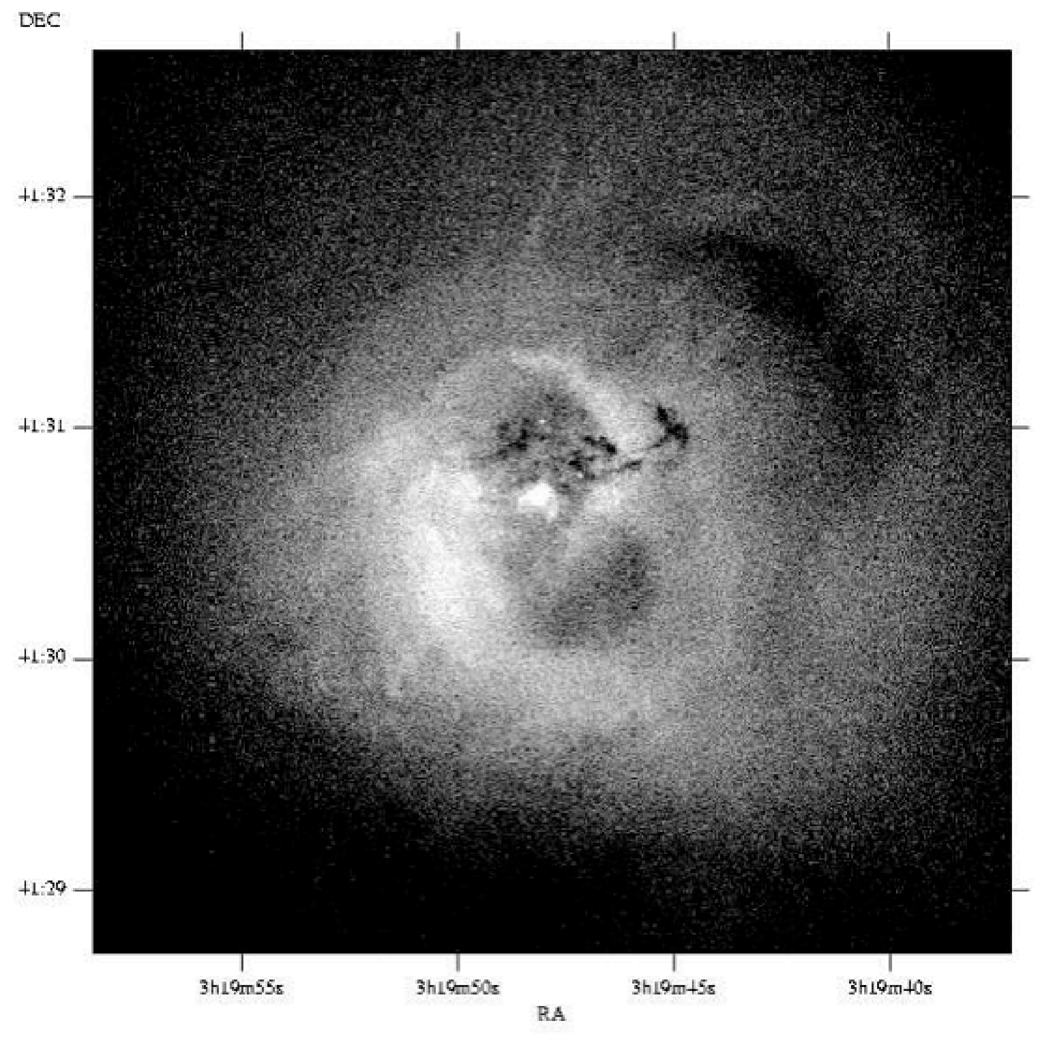
- The flattening of the entropy profile near the cluster center

  (Donahue et al. 2006)



- AGN feedback may be needed to explain the high-luminosity cutoff in the galaxy luminosity function (Croton et al 2006)

Most importantly, we see AGN-induced bubbles (AGN-ICM interactions)!



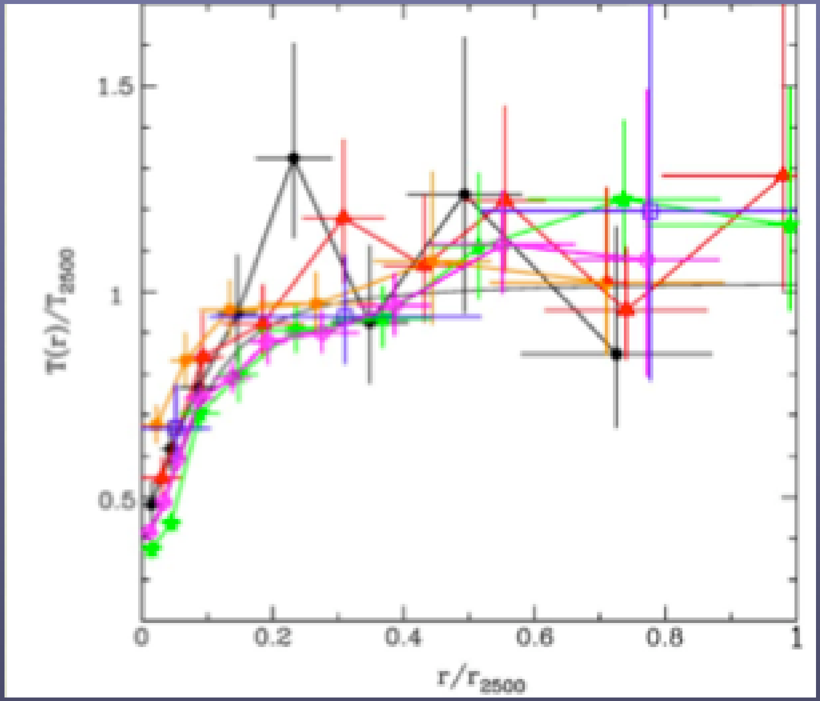
Fabian et al 2003

Perseus Cluster, Chandra image

Heating the ICM

Two main heating mechanisms:

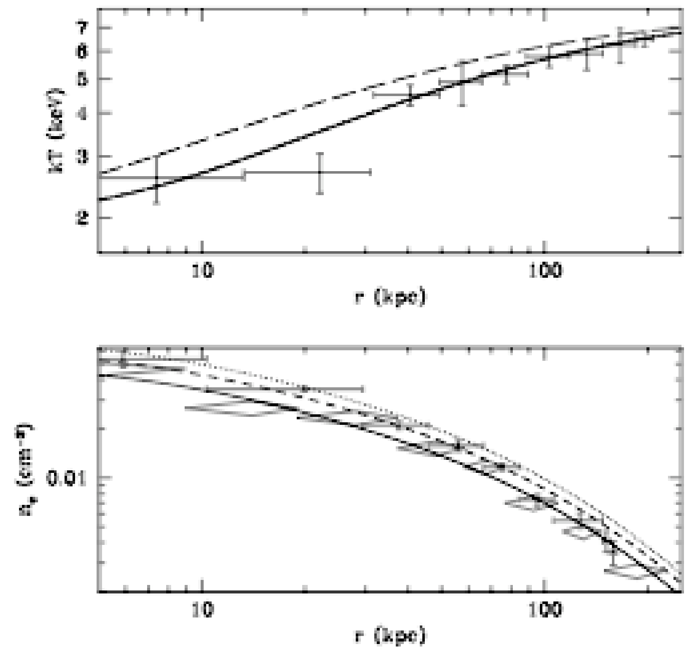
- AGN Heating
- Thermal conduction
  (Bertschinger & Meiksin 1986,
  Narayan & Medvedev 2001,
  Zakamska & Narayan 2003,
  Voigt & Fabian 2004)



Peterson & Fabian 2006

Heating Source: Thermal Conduction?

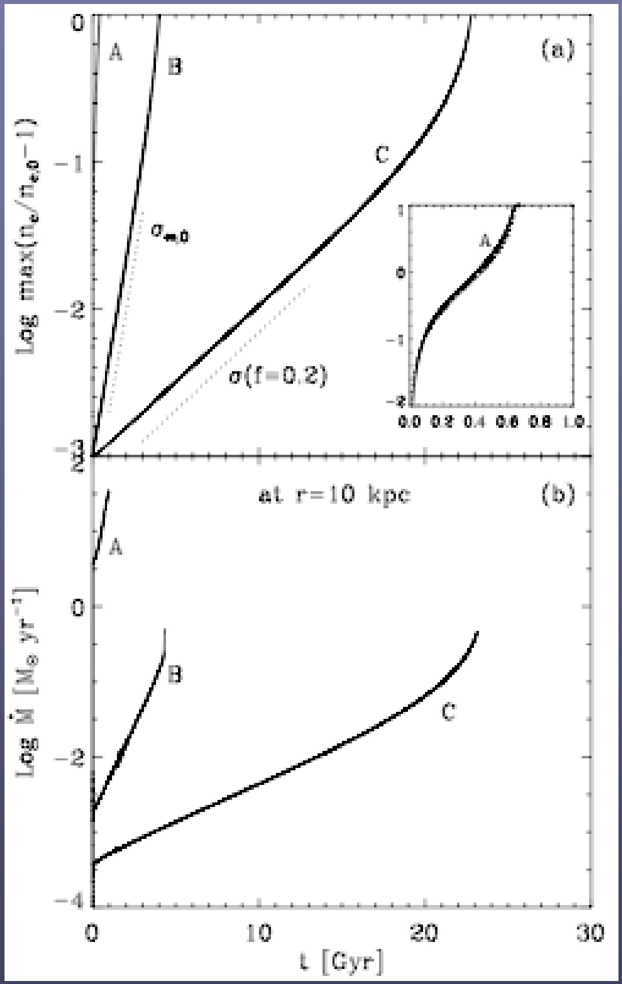
Equilibrium models work well for many clusters



Abell 1795

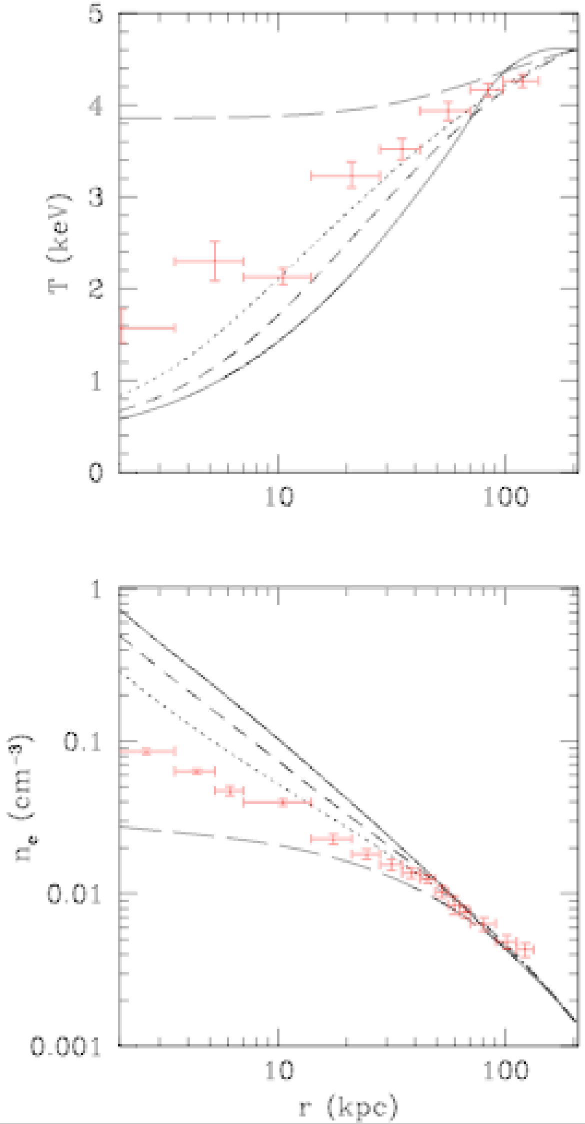
(Zakamska & Narayan 2003)

But, tend to be globally unstable !

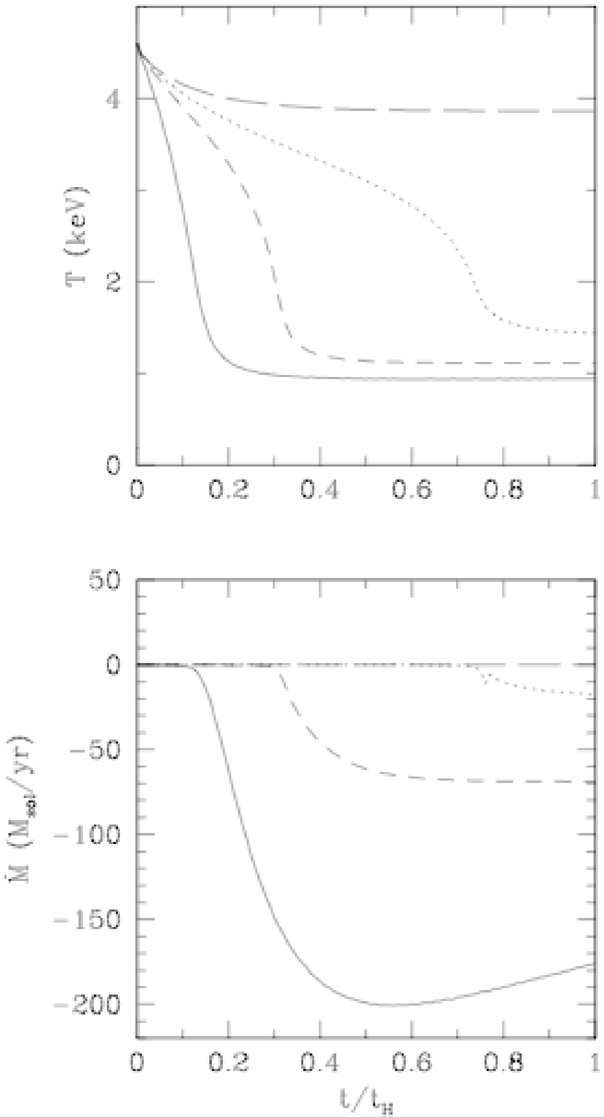


(Kim & Narayan 2003)

and require fine-tuning of conductivity !



f= 0.8
f= 0.6
f= 0.4
f= 0



(Guo & Oh 2008)

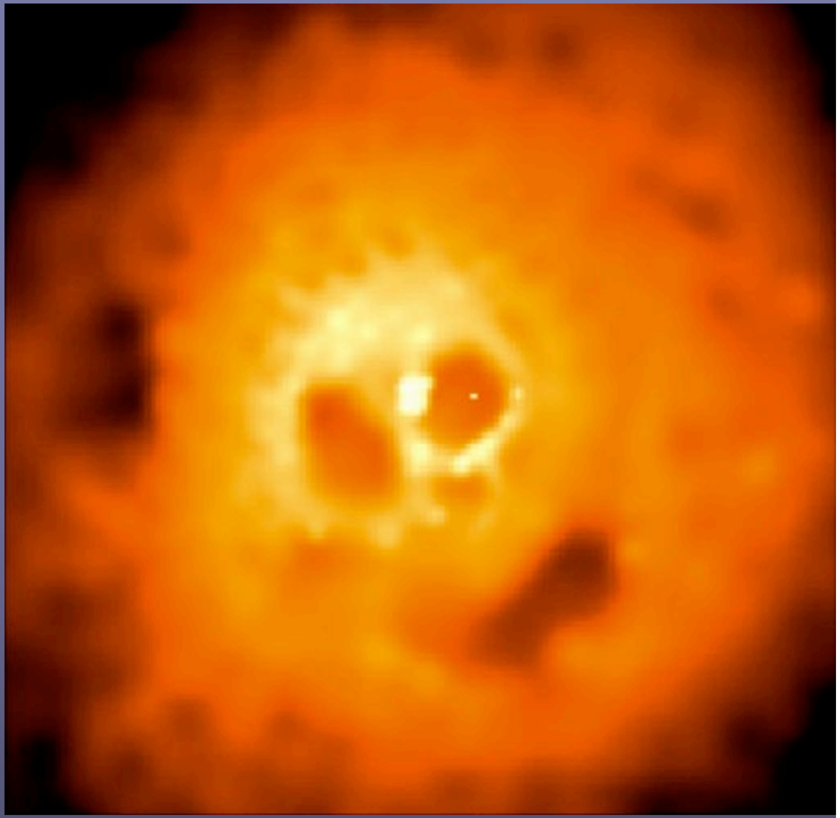
Previous Studies on AGN Heating

♦Analytical studies on spatial distribution of AGN heating
    "bubble" heating with a Gaussian profile (Brighenti & Mathews 2003)
    Effervescent heating (Begelman 2001)
    Cosmic ray heating (Guo & Oh 2008)

♦Simulations of the bubble evolution and its heating effect
    bubble expansion and mixing e.g., Brüggen & Kaiser (2002)
    viscous dissipation of AGN-induced waves, Ruszkowski et al. (2004)
    Outflows, e.g., Vernaleo & Reynolds 2006
    Shocks, Brüggen et al. 2007

Preventing bubble from disruption:
    viscosity --- Reynolds et al. 2005
    magnetic fields -- Ruszkowski et al. 2008

How does AGN heat the ICM?



Chandra image of the Perseus Cluster

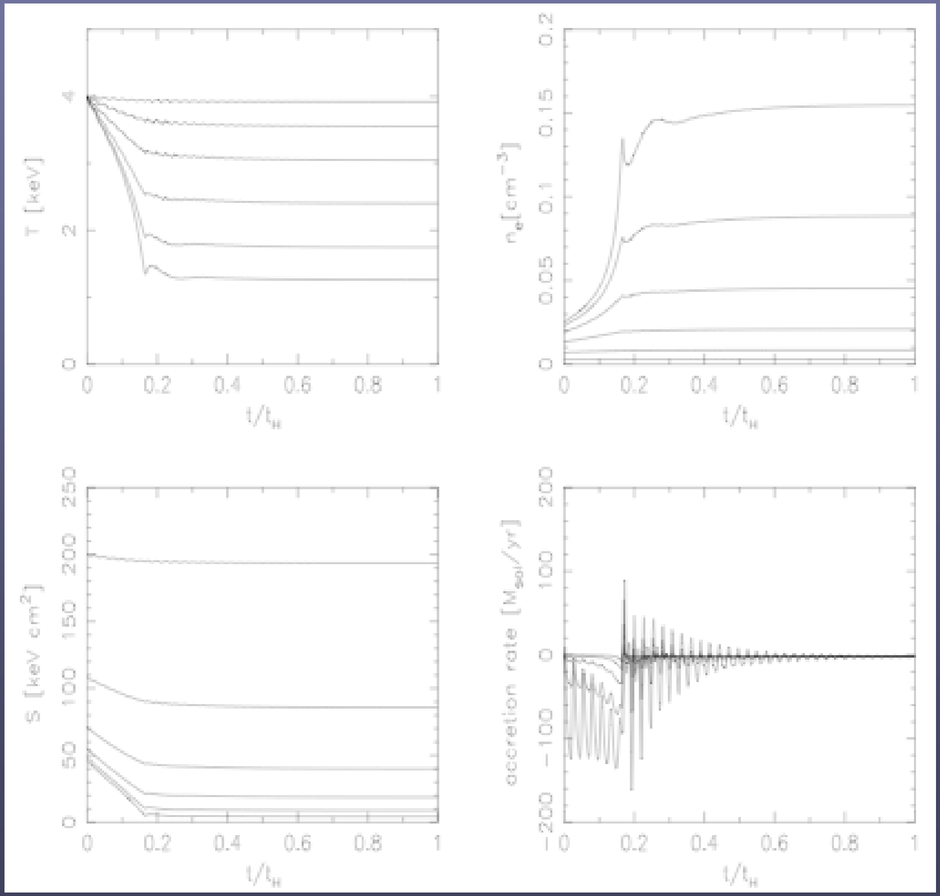
- X-ray cavities or bubbles are seen clearly.
- The buoyantly-rising bubble expands and heats the ICM through PdV work. This is the effervescent heating model proposed by Begelman (2001).
- The cosmic rays may leak out from the bubbles into the ICM, and heat it (Guo & Oh 2008)

AGN Effervescent Heating

Ruszkowski & Begelman 2002

♦The bubble loses energy only through PdV work

Spherically integrated bubble flux :

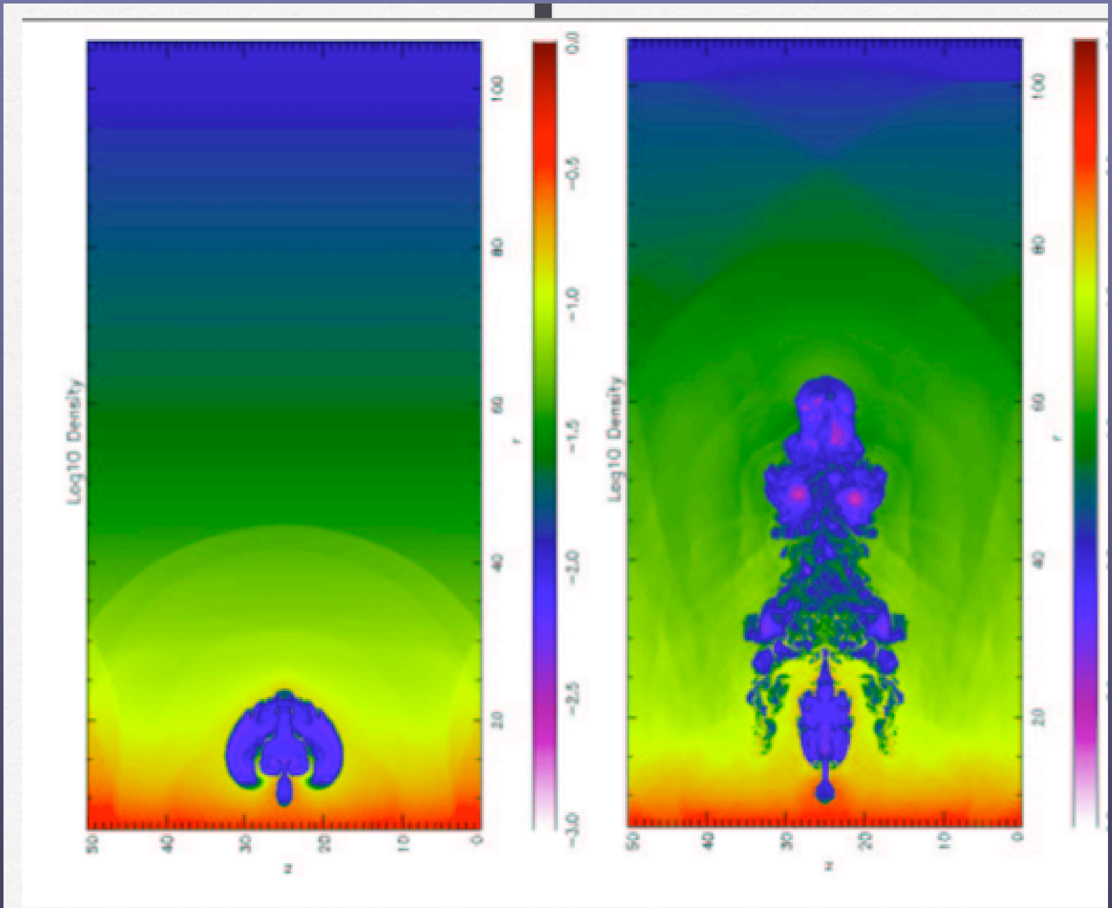


♦ AGN luminosity is proportional to the central mass accretion rate:

$$L_{\rm agn} = -\epsilon \dot{M}_{\rm in} c^2$$

Part I: Cosmic ray heating (Guo & Oh 2008)

Why Cosmic Rays?



Bruggen & Kaiser (2002)

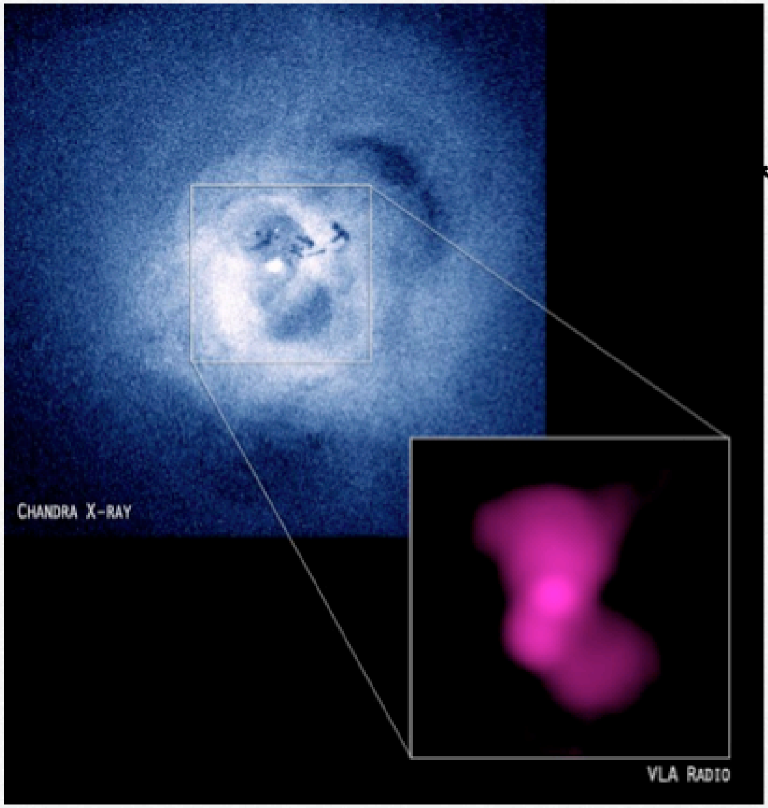
Bubbles may be disrupted

Cosmic rays may leak into the ICM.

Observational Signatures?

....

Why cosmic rays ?



We see radio synchrotron emission

Spallation products indicate CRs could be present (Nath, Madau & Silk 2005)

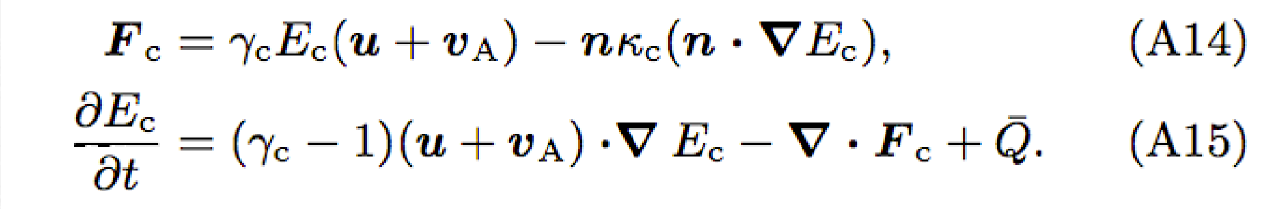
Many sources: jets, accretion shock, SN

Provide gentle, distributed heating

It’s been tried before…

- Authors have considered dynamical and heating effects (via Coulomb, hadronic and Alfven wave interactions) (Boehringer & Morfill 1988, Loewenstein et al 1991, Repaheli & Silk 1995, Colafrancesco et al 2004, Jubelgas et al 2006, Prommer et al 2006)
- None have constructed models where CRs successfully stop cooling flow

A key problem: CR transport is slow



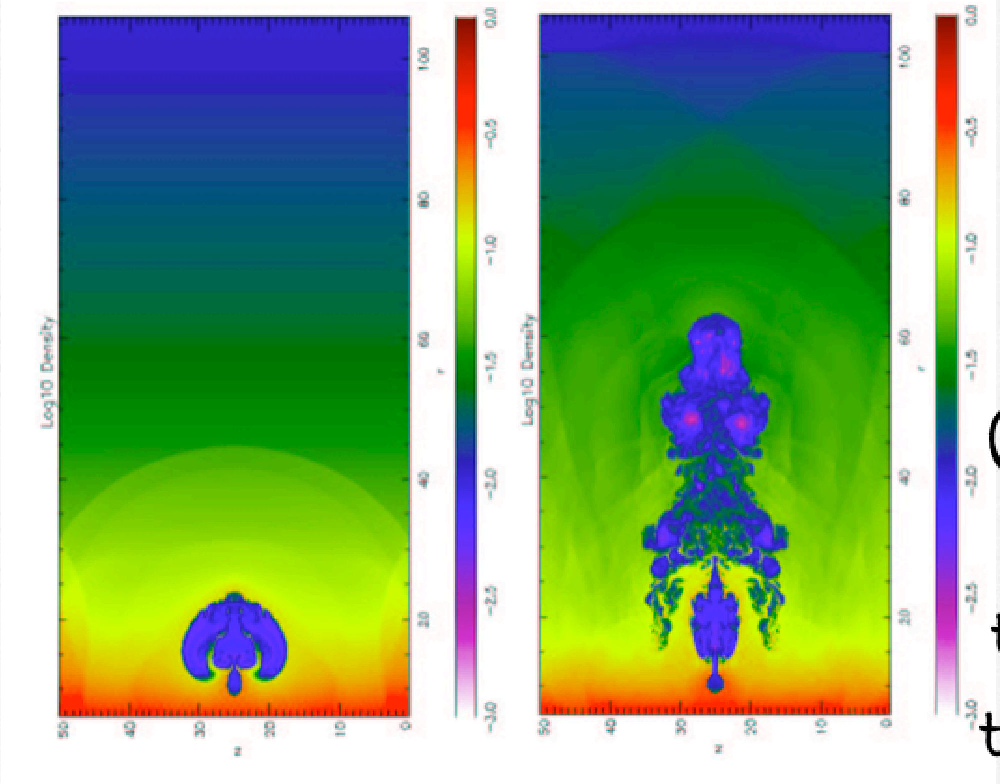
$$\boldsymbol{F}_{\mathrm{c}} = \gamma_{\mathrm{c}} E_{\mathrm{c}} (\boldsymbol{u} + \boldsymbol{v}_{\mathrm{A}}) - \boldsymbol{n} \kappa_{\mathrm{c}} (\boldsymbol{n} \cdot \boldsymbol{\nabla} E_{\mathrm{c}}), \tag{A14}$$

$$\frac{\partial E_{\mathrm{c}}}{\partial t} = (\gamma_{\mathrm{c}} - 1)(\boldsymbol{u} + \boldsymbol{v}_{\mathrm{A}}) \cdot \boldsymbol{\nabla} E_{\mathrm{c}} - \boldsymbol{\nabla} \cdot \boldsymbol{F}_{\mathrm{c}} + \bar{Q}. \tag{A15}$$

Diffusive and other CR transport timescales are long

Leads to overpressured center with insufficient heating at outskirts (though may drive turbulent convection: Chandran & collaborators)

Our model: use bubbles to transport CRs



Bruggen & Kaiser (2002)

Bubbles disrupted by Rayleigh-Taylor & Kelvin-Helmholtz instabilities as rise

(Also: CRs diffuse out)

Fast way of transporting CRs: rise time ~ sound crossing time

Method

- 1D ZEUS code: solve hydrodynamic equations + CR heating and CR transport, CR energy evolution

- Assume CR energy density in bubbles is a power law with radius (cosmic ray injection rates depend on gas cooling---feedback)

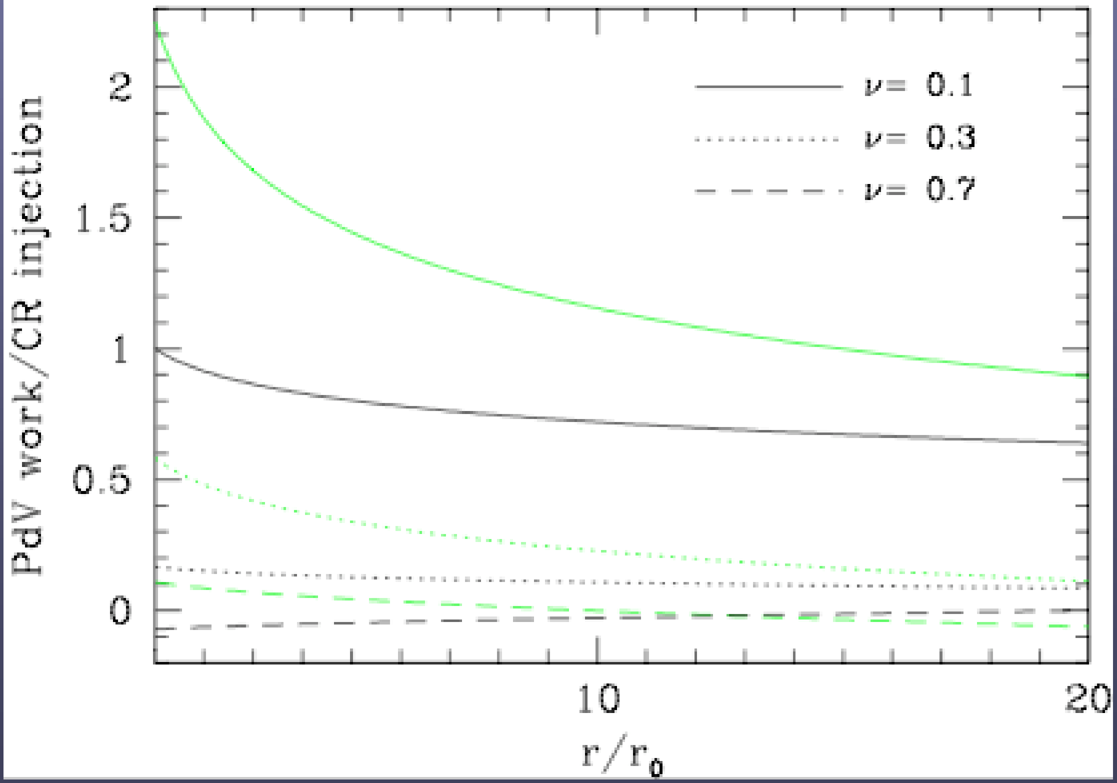
$$L_{\rm bubble} \sim -\epsilon \dot{M}_{\rm in} c^2 \left(\frac{r}{r_0}\right)^{-\nu} \qquad \text{for } r > r_0,$$

$$\begin{aligned} Q_c = -\nabla\cdot\mathbf{F}_{\rm bubble} &\sim -\frac{1}{4\pi r^2}\frac{\partial L_{\rm bubble}}{\partial r}\left[1-e^{-(r/r_0)^2}\right] \\ &\sim -\frac{\nu\epsilon\dot{M}_{\rm in}c^2}{4\pi r_0^3}\left(\frac{r}{r_0}\right)^{-3-\nu}\left[1-e^{-(r/r_0)^2}\right], \end{aligned}$$

Slope is a free parameter, implicitly specifies CR injection rate

* Bubbles also heat the ICM through PdV work. For a range of ν, bubble disruption dominates. We ignore PdV work.

Bubble expansion vs. bubble disruption



Cosmic ray heating (Guo & Oh 2008)

Cosmic-ray physics

Cosmic rays provide pressure support.

CR energy-loss mechanisms:

Coulomb interactions ------ heat the ICM
Hadronic Collisions ------- most energy will escape
Generation of Hydromagnetic waves --- heat the ICM

Cosmic ray transport : advection and diffusion in radial direction

Cosmic ray heating (Guo & Oh 2008)

Simulation Setup

Spherical symmetry, From 1 - 200 kpc
Resolution N=400
Boundary Condition: constant T, E at outer boundary

Code: ZEUS-3D modifed to include additional physics:

- Radiative cooling
- background potential----a dark matter NFW profile
  a King profile for central galaxy
- thermal conduction
- Cosmic-ray heating
- Cosmic-ray pressure support
- Cosmic-ray transport
- Cosmic-ray energy equation

Cosmic ray heating (Guo & Oh 2008)

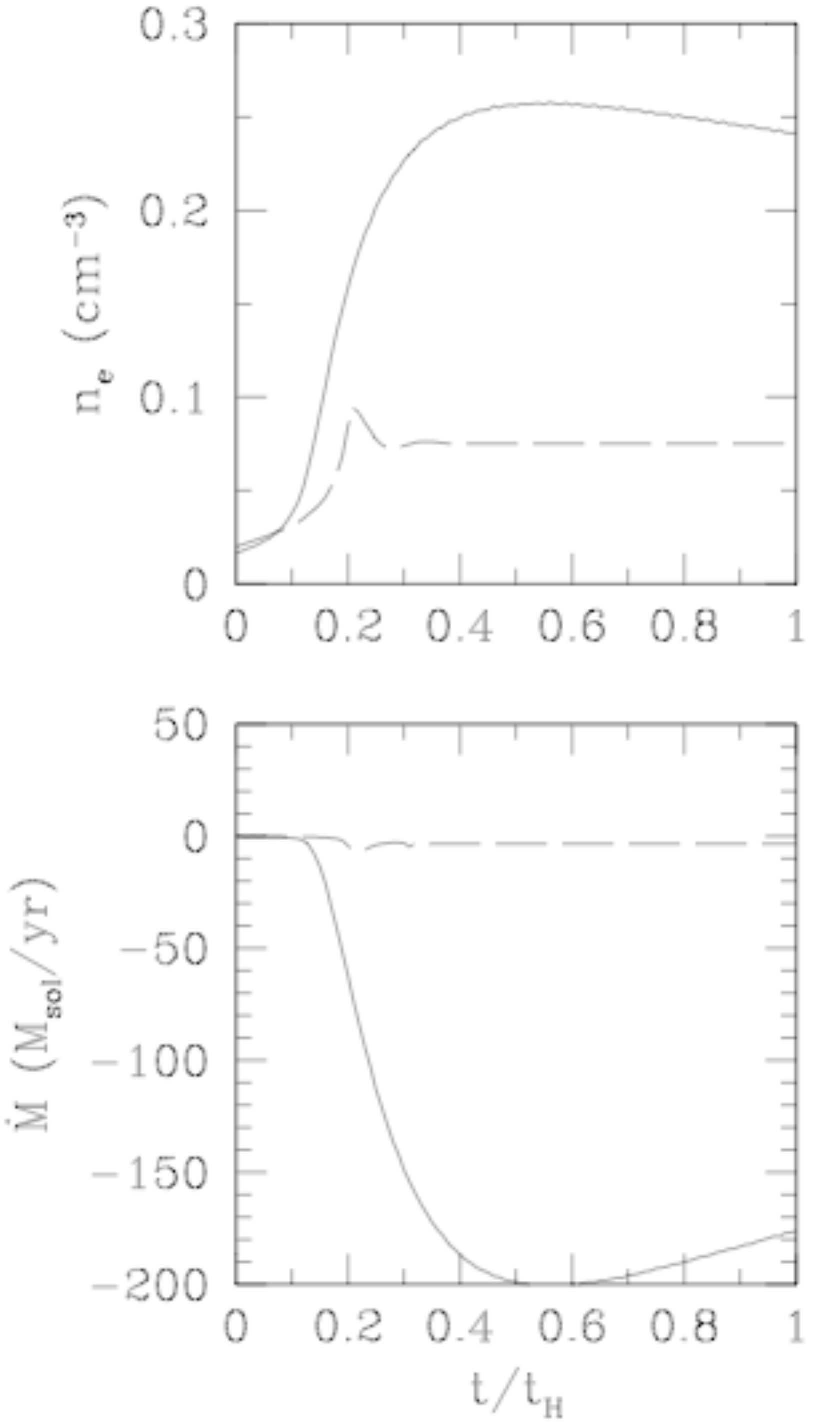
RESULTS

Comparison between our model
With a cooling flow model

Our model: efficiency 0.003
f=0.3 (Abell 2199)

- Cooling catastrophe quenched

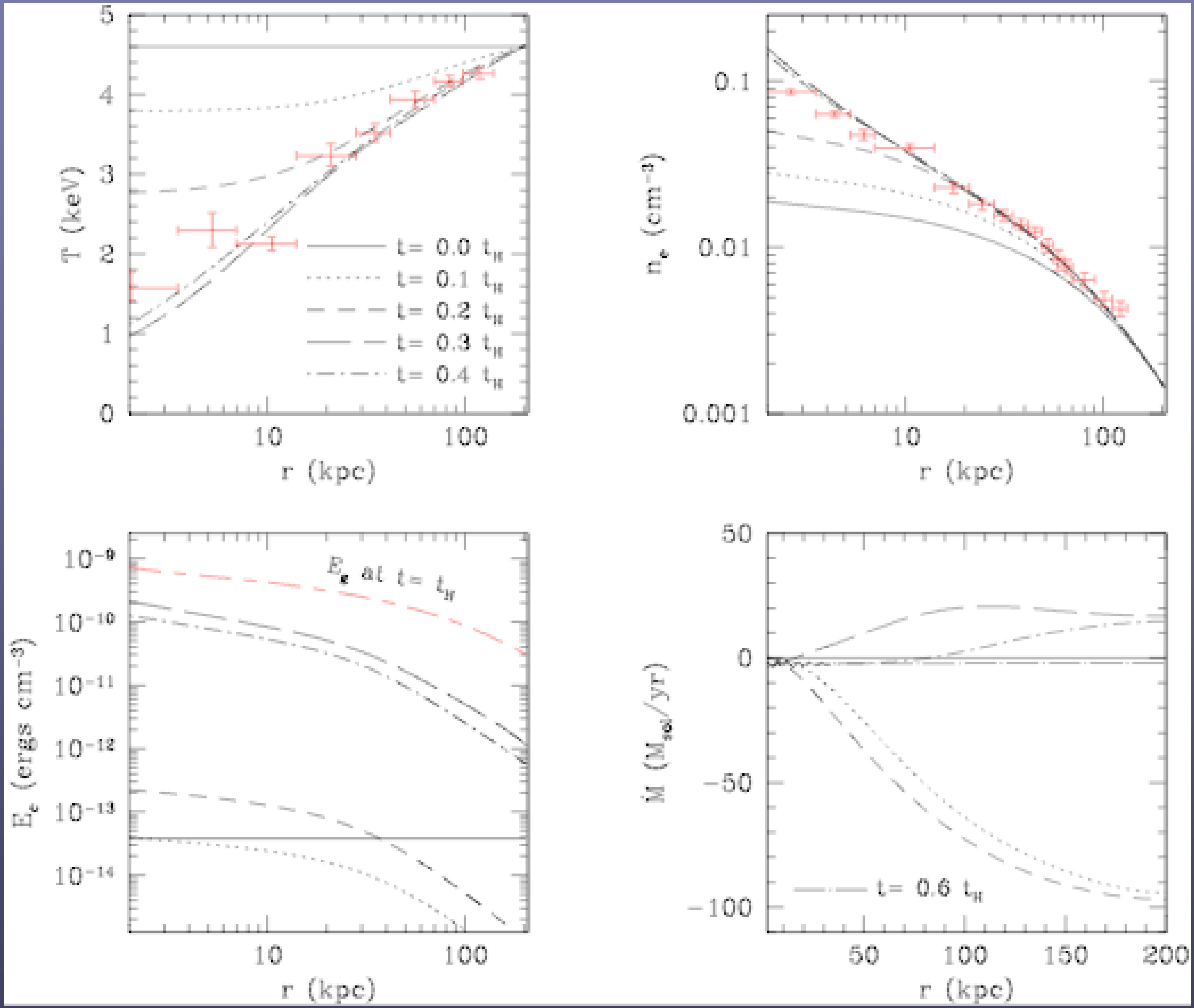
- Cooling flow strongly suppressed---------
final accretion rate about 2 solar mass/yr



Evolution of the simulated cluster (1)

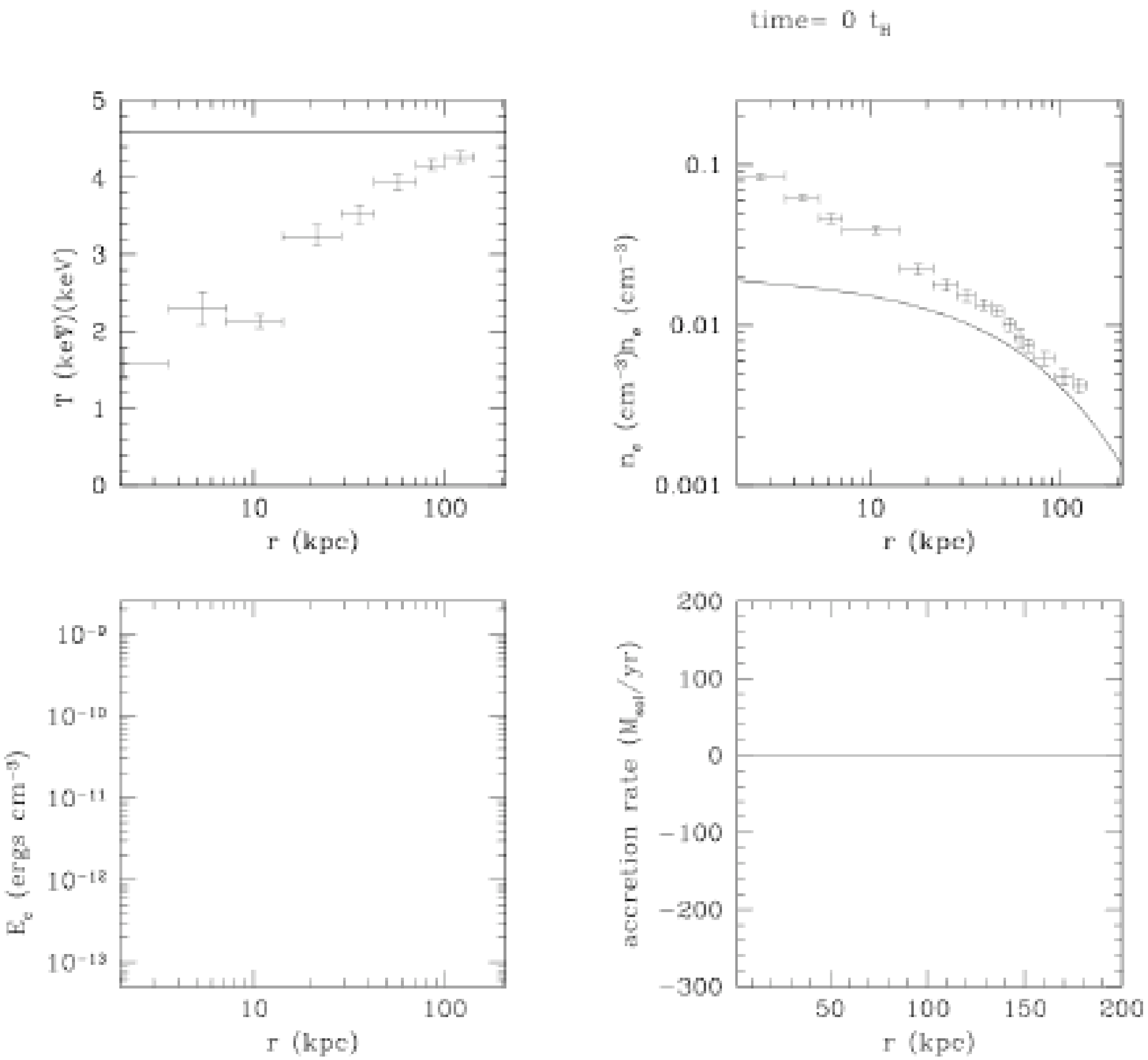
Abell
2199

Initial State of our simulations -- solid line:



Cosmic ray heating (Guo & Oh 2008)

IT WORKS!!!

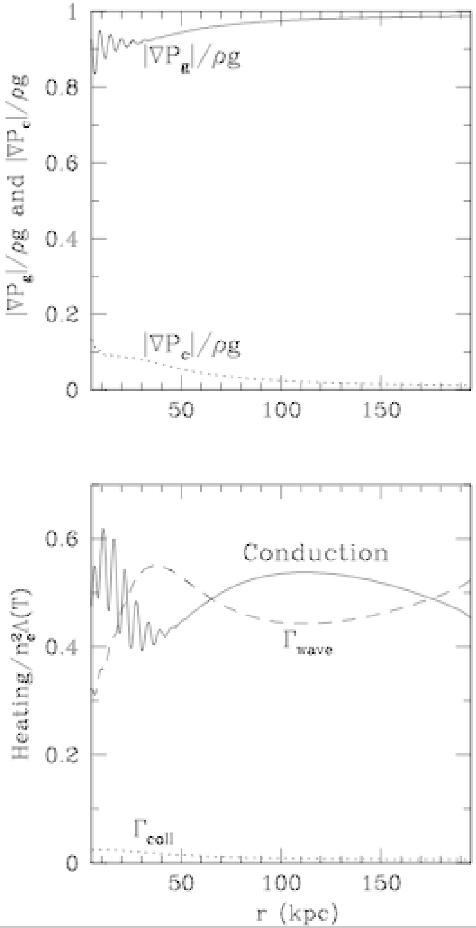

time= 0 t_H
T (keV)(keV)
5
4
3
2
1
0
10
100
r (kpc)
n_e (cm^-3)n_e (cm^-3)
0.1
0.01
0.001
10
100
r (kpc)
E_c (ergs cm^-3)
10^-9
10^-10
10^-11
10^-12
10^-13
10
100
r (kpc)
accretion rate (M_sol/yr)
200
100
0
−100
−200
−300
50
100
150
200
r (kpc)

Final Steady State

CR pressure gradients OK!

- Thermal pressure support dominates over the whole cluster

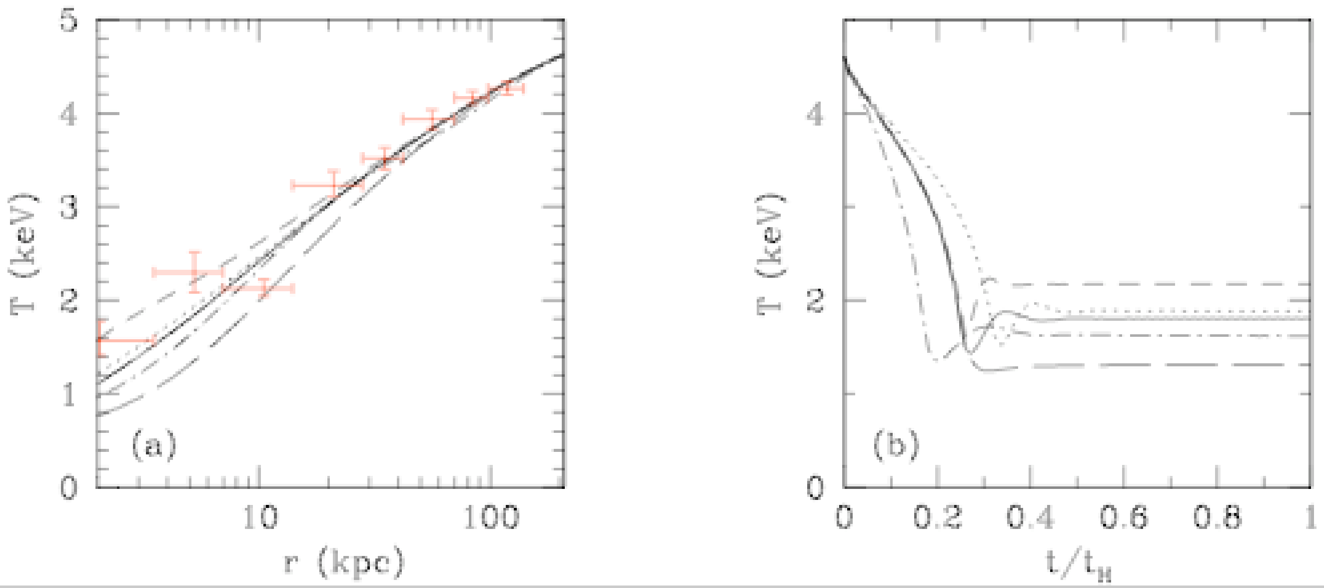
- Cosmic ray heating is dominated by wave heating



Parameter Study (1) -- No fine-tuning!

-- works for range of thermal conductivity and
the AGN feedback efficiency

f=0.3, ε= 0.05
f= 0.4, ε= 0.003
f=0.3, ε= 0.003
f=0.1, ε= 0.003
f=0.3, ε= 0.0003

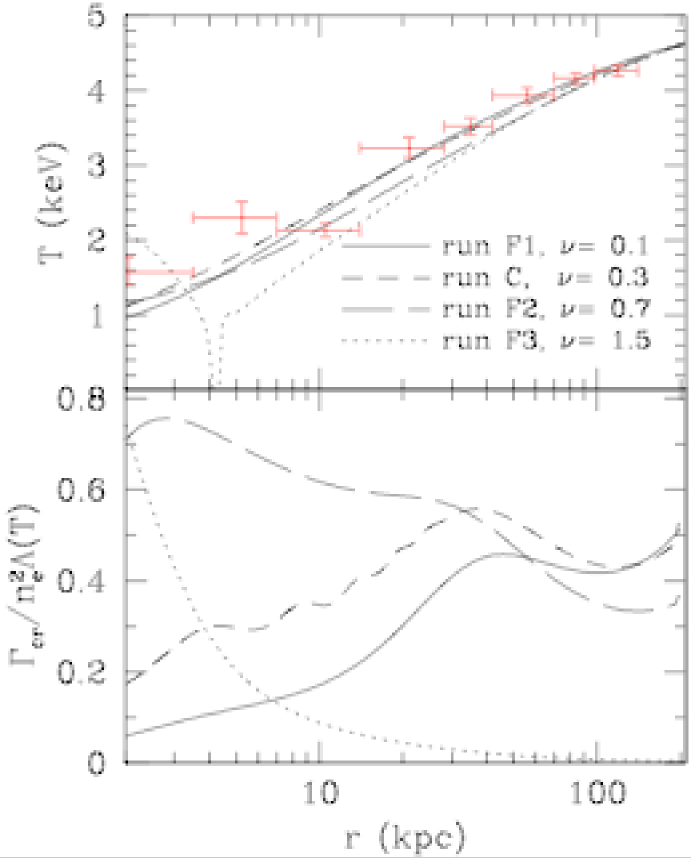


(Guo & Oh 2008)

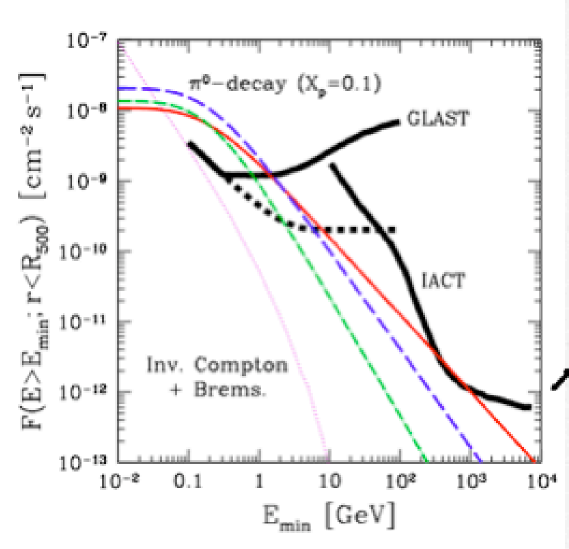
Parameter Study (2)

-- works for a range of cosmic ray profiles
(Guo & Oh 2008)

Our results are also quite robust to CR diffusion coefficient and magnetic field profile.



Observational tests

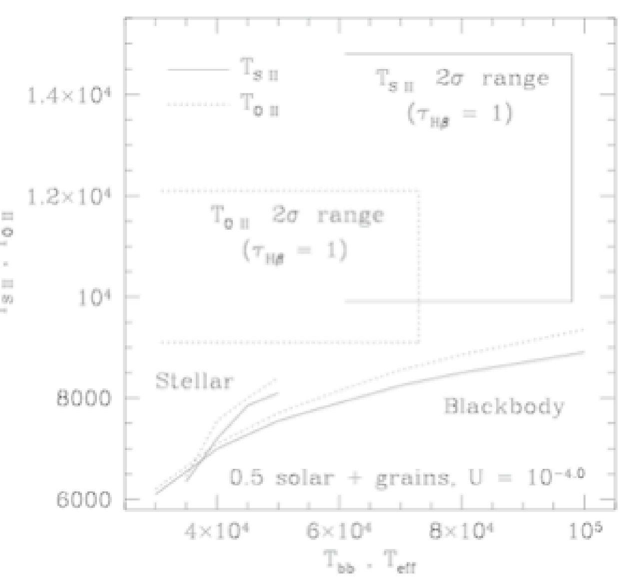


See gamma-rays from
pion-decay with GLAST

Ando & Nagai (2007)

Optical filaments: need source
of anomolous heating?

Voit & Donahue (1997)



Part II:Global Stability Analysis of Feedback Models

Motivation:

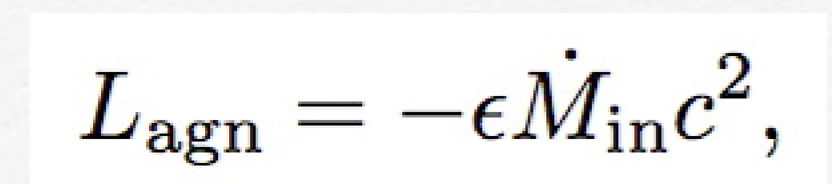
- ♦A successful model for the ICM must be globally stable
- ♦ Stability analysis allows for quick parameter study and helps to build physical intuition.
- ♦To understand what the role of AGN feedback in stably maintaining the ICM at keV temperatures
  - -- Is a feedback mechanism really required?

Background States

They are chosen to be steady-state cluster profiles.

Why not equilibrium states?

Because AGN heating is a feedback mechanism!



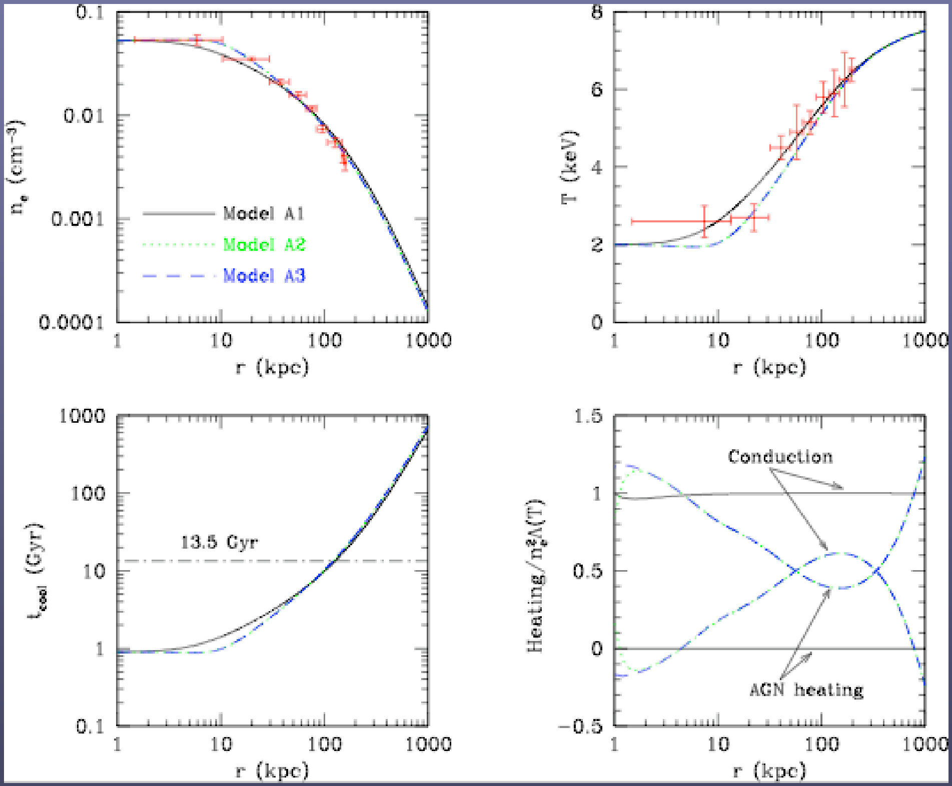
$$L_{\rm agn} = -\epsilon \dot{M}_{\rm in} c^2,$$

Quasi-equilibrium cluster models

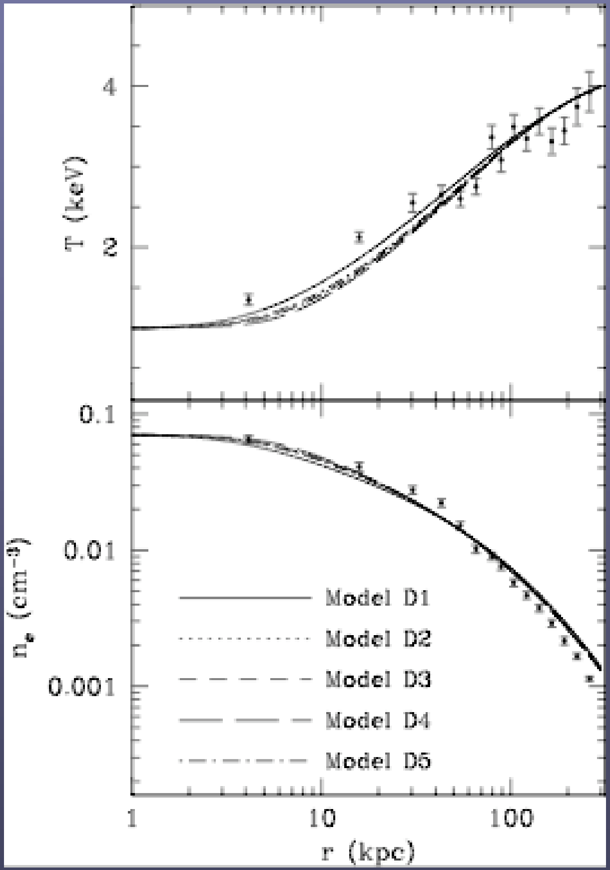
- Steady state -- the mass accretion rate is a constant in radius
- Hydrostatic equilibrium - gravity is supported by pressure gradient
- Thermal equilibrium -- cooling is balanced by thermal conduction and AGN feedback heating
- AGN FEEDBACK -- $L_{\rm agn} = -\epsilon \dot{M}_{\rm in} c^2 \ ,$
- Model parameters -- conductivity, AGN efficiency, mass accretion rate

Background profiles

fit observations quite well.



Abell 1795



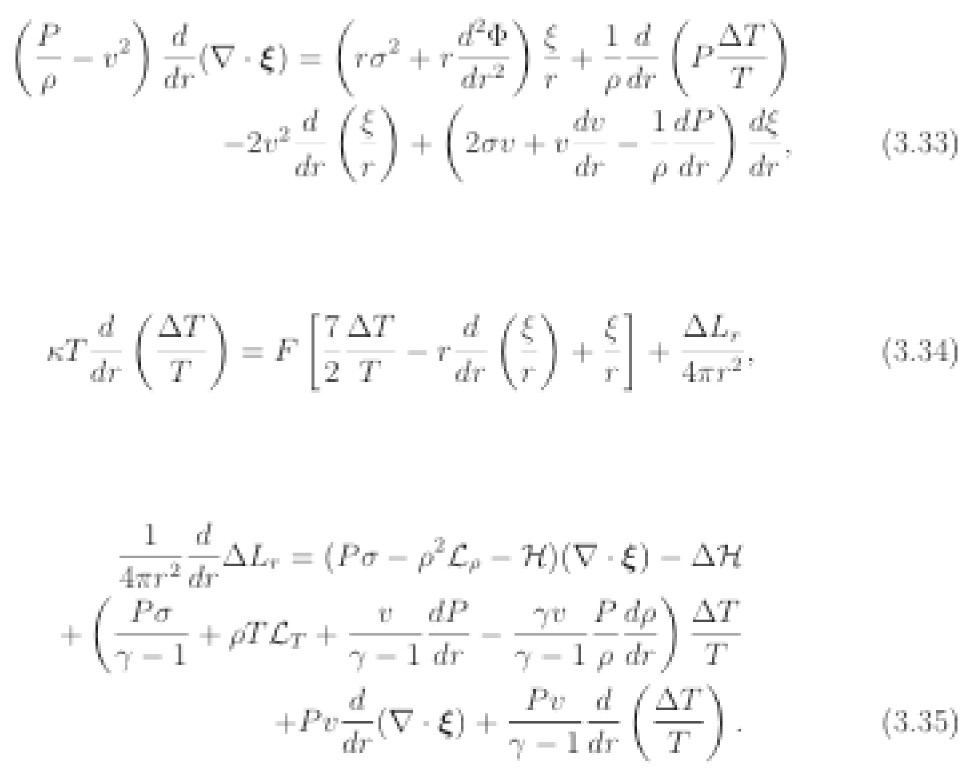
Abell 2597

Guo et al. 2008

Then perform a Lagrangian global stability analysis……

No WKB!

$$\Delta = \delta + \boldsymbol{\xi} \cdot \nabla, \qquad (3.21)$$



$$\left(\frac{P}{\rho} - v^2\right) \frac{d}{dr}(\nabla \cdot \boldsymbol{\xi}) = \left(r\sigma^2 + r\frac{d^2\Phi}{dr^2}\right)\frac{\xi}{r} + \frac{1}{\rho}\frac{d}{dr}\left(P\frac{\Delta T}{T}\right) - 2v^2\frac{d}{dr}\left(\frac{\xi}{r}\right) + \left(2\sigma v + v\frac{dv}{dr} - \frac{1}{\rho}\frac{dP}{dr}\right)\frac{d\xi}{dr}, \qquad (3.33)$$

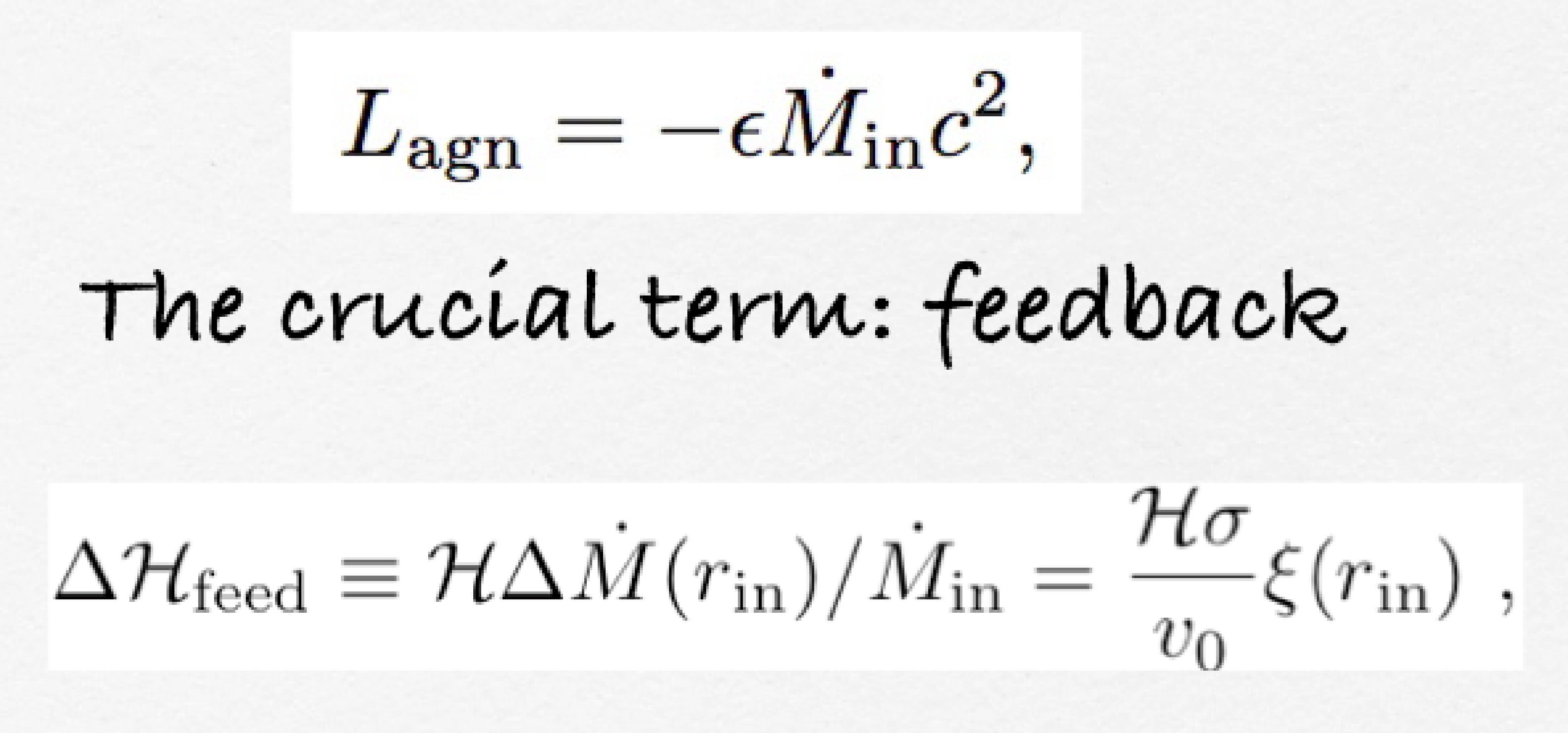
$$\kappa T \frac{d}{dr}\left(\frac{\Delta T}{T}\right) = F\left[\frac{7}{2}\frac{\Delta T}{T} - r\frac{d}{dr}\left(\frac{\xi}{r}\right) + \frac{\xi}{r}\right] + \frac{\Delta L_r}{4\pi r^2}, \qquad (3.34)$$

$$\frac{1}{4\pi r^2}\frac{d}{dr}\Delta L_r = (P\sigma - \rho^2\mathcal{L}_\rho - \mathcal{H})(\nabla \cdot \boldsymbol{\xi}) - \Delta\mathcal{H} + \left(\frac{P\sigma}{\gamma - 1} + \rho T\mathcal{L}_T + \frac{v}{\gamma - 1}\frac{dP}{dr} - \frac{\gamma v}{\gamma - 1}\frac{P}{\rho}\frac{d\rho}{dr}\right)\frac{\Delta T}{T} + Pv\frac{d}{dr}(\nabla \cdot \boldsymbol{\xi}) + \frac{Pv}{\gamma - 1}\frac{d}{dr}\left(\frac{\Delta T}{T}\right). \qquad (3.35)$$

- * Growth rate is an eigenvalue of the analysis
- * Explore parameter space rapidly!

Globally unstable modes suppressed by AGN!

* Suppression depends on the feedback efficiency



$$L_{\rm agn} = -\epsilon \dot{M}_{\rm in} c^2,$$

The crucial term: feedback

$$\Delta\mathcal{H}_{\rm feed} \equiv \mathcal{H}\Delta\dot{M}(r_{\rm in})/\dot{M}_{\rm in} = \frac{\mathcal{H}\sigma}{v_0}\xi(r_{\rm in}) \;,$$

First consider….

Local Stability Analysis

Consider local WKB perturbations ~ $\exp(ikr + \sigma t)$

Simplifications:
Plane-parallel approximation; wavelength much shorter than any spatial scale; ignore high-frequency sound waves.

Results:

1) Without any heating, X-ray emitting gas is thermally unstable

2) Thermal conduction stabilizes short-wavelength perturbations

3) AGN heating ($\sim \partial P / \partial r$) reduces the growth rate of local thermal instability.

Results: Globally Unstable Modes

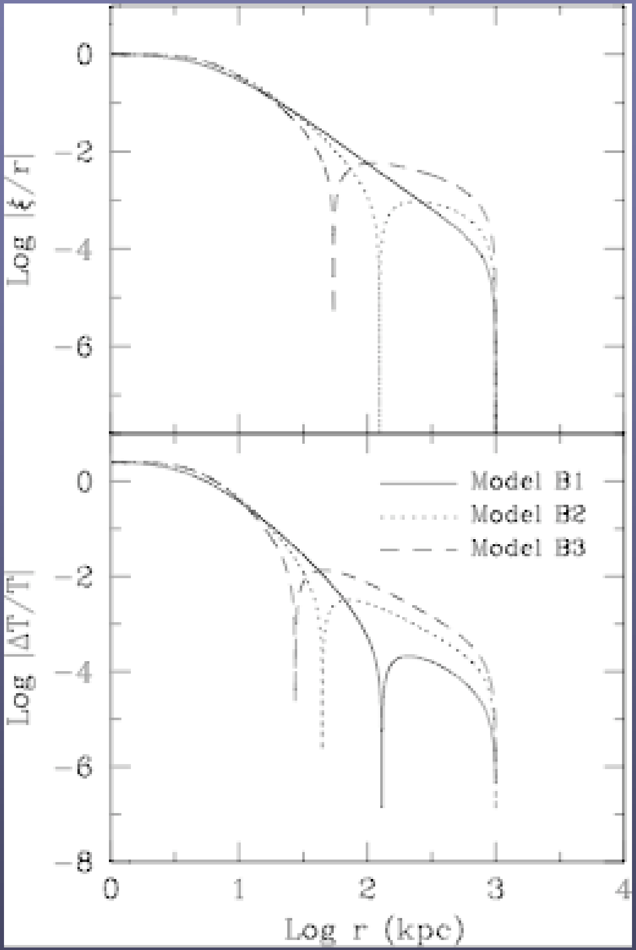
Consider Abell 2199

–Model B1: pure conduction model with instability growth time 2.8 Gyr.

–Model B2: efficiency = 0.05 with instability growth time 4.4 Gyr.

–Model B3: efficiency = 0.2 with instability growth time 16.9 Gyr.

–Model B3 without feedback: instability growth time 2.2 Gyr.

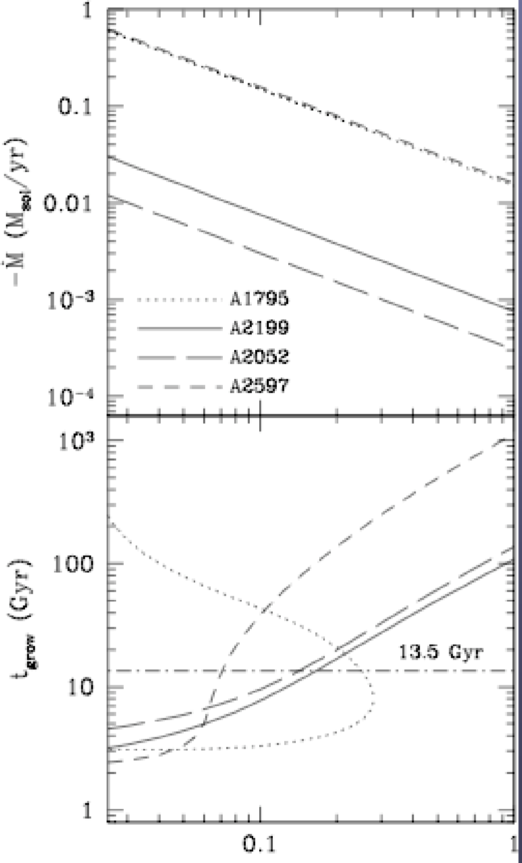


Guo et al. 2008

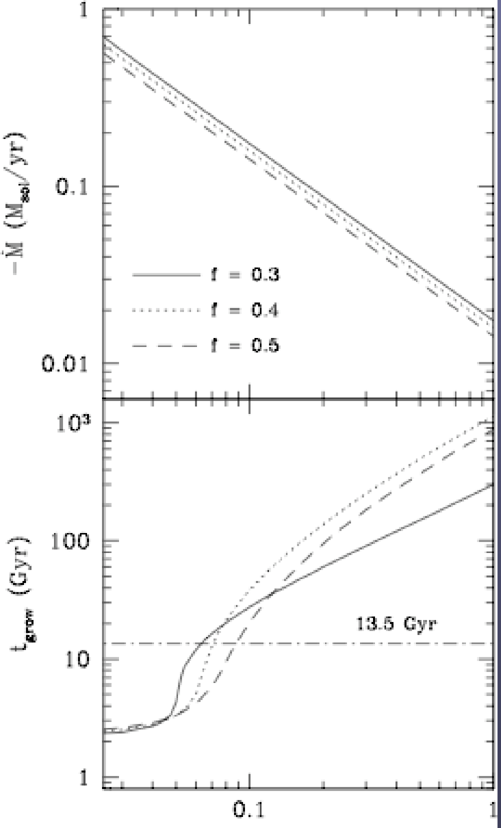
Thus, AGN feedback mechanism is essential to suppress global instability

Dependence of Stability on Feedback Efficiency

For a specific cluster model, the cluster becomes stable when the feedback efficiency is greater than a lower limit.



holds for different conductivity



A2597

Parameter Study (1) -- No fine-tuning!

-- works for range of thermal conductivity and
the AGN feedback efficiency

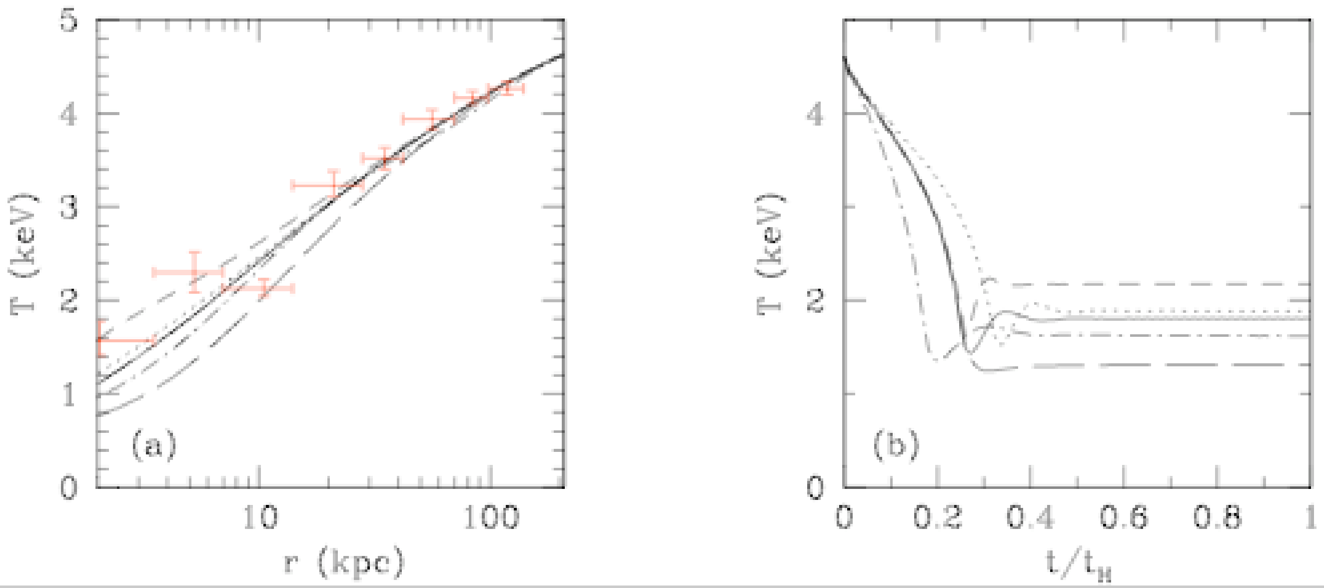
$\varepsilon = 0.05$

$f = 0.4$

$f = 0.3$, $\varepsilon = 0.003$

$f = 0.1$

$\varepsilon = 0.0003$



(Guo & Oh 2008)

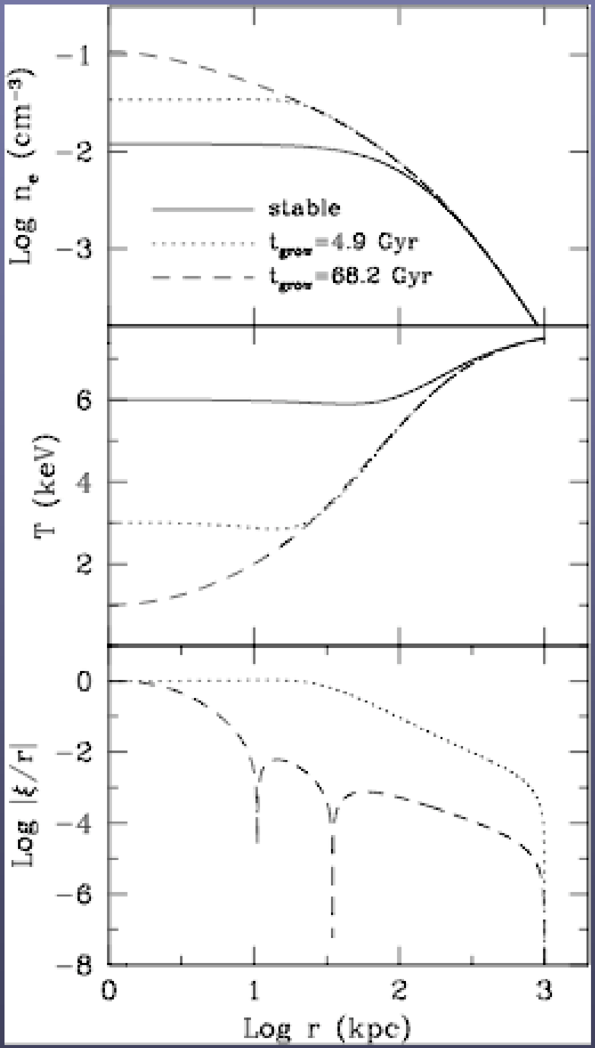
Dependence on background profiles:bimodality

Fix the outer temperature, density, AGN efficiency and conductivity, while varying the central temperature

–Non-cool core models (Tin>4.5 keV) are stable

–Models with Tin<1.7 keV are stable

–Intermediate central temperatures typically lead to globally unstable solutions



A1795

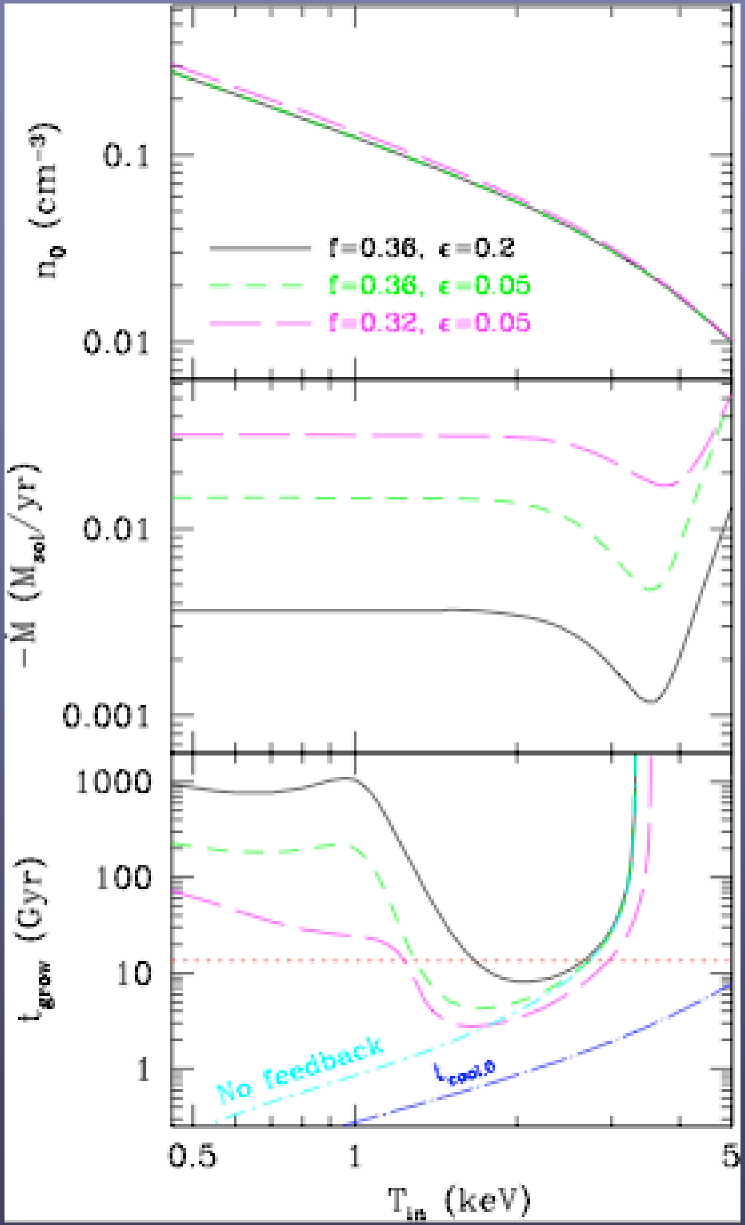
Bimodality

Globally stable clusters are expected to have either

1) cool cores stabilized by both AGN feedback and conduction

2) non-cool cores stabilized primarily by conduction.

Intermediate central temperatures typically lead to globally unstable solutions

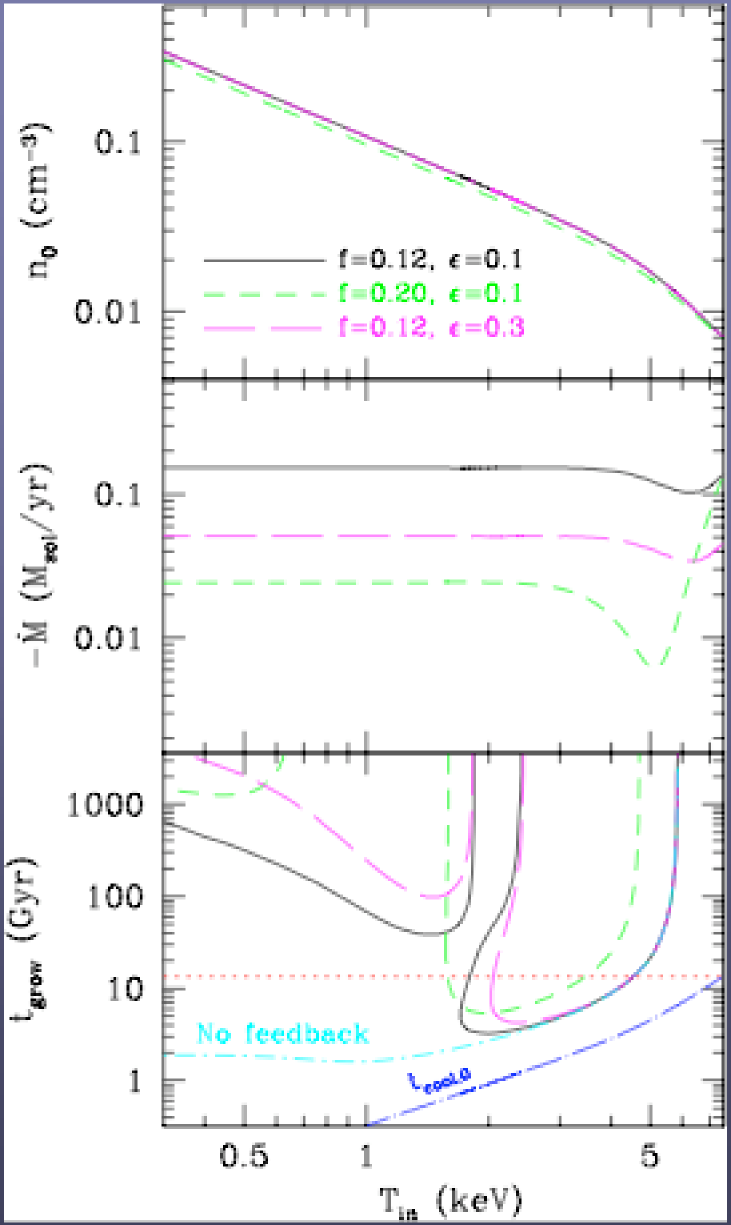


Guo et al 2008

A2199

Bimodality

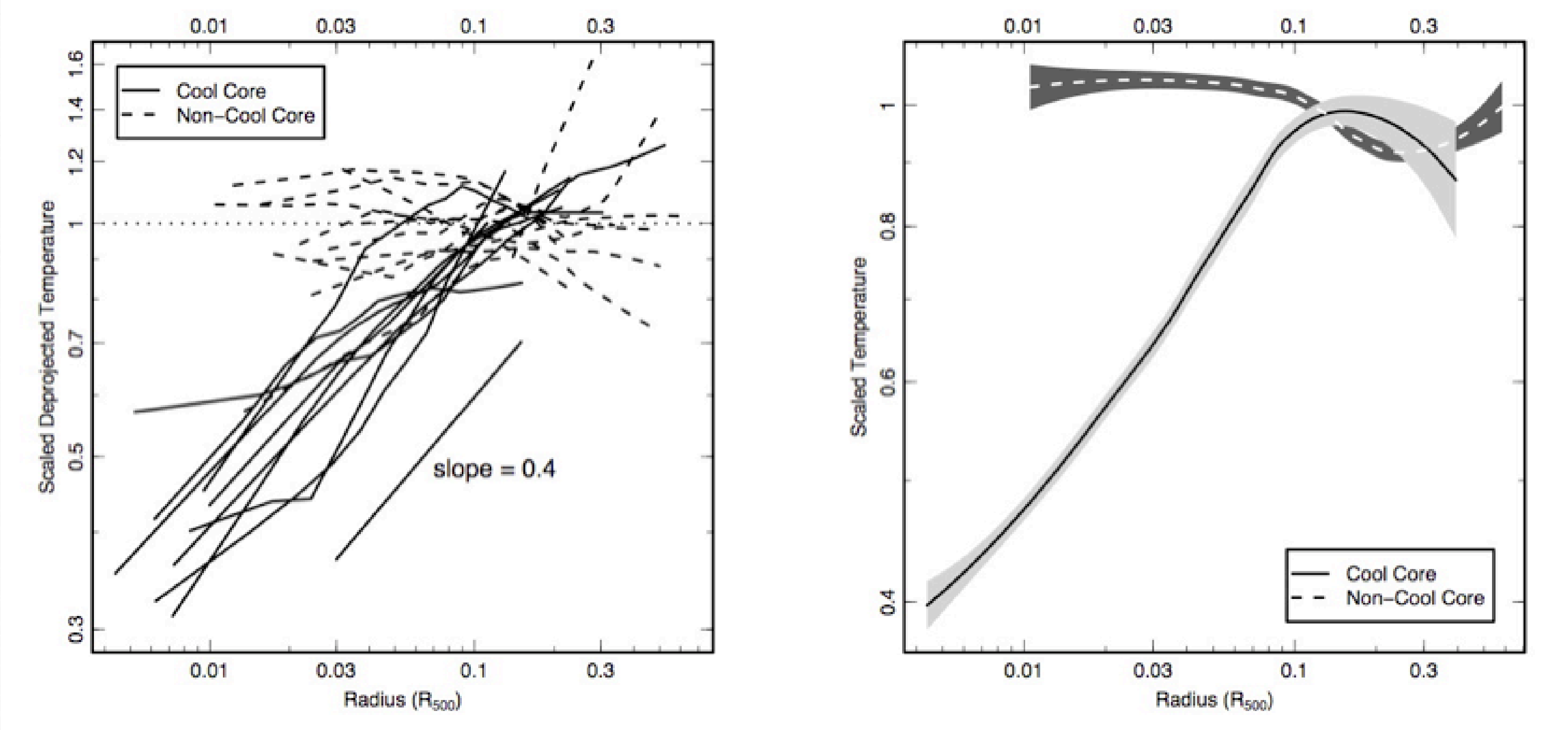
Another cluster, still bimodality



Guo et al 2008

A1795

Consistent with observations



Sanderson et al (2006)

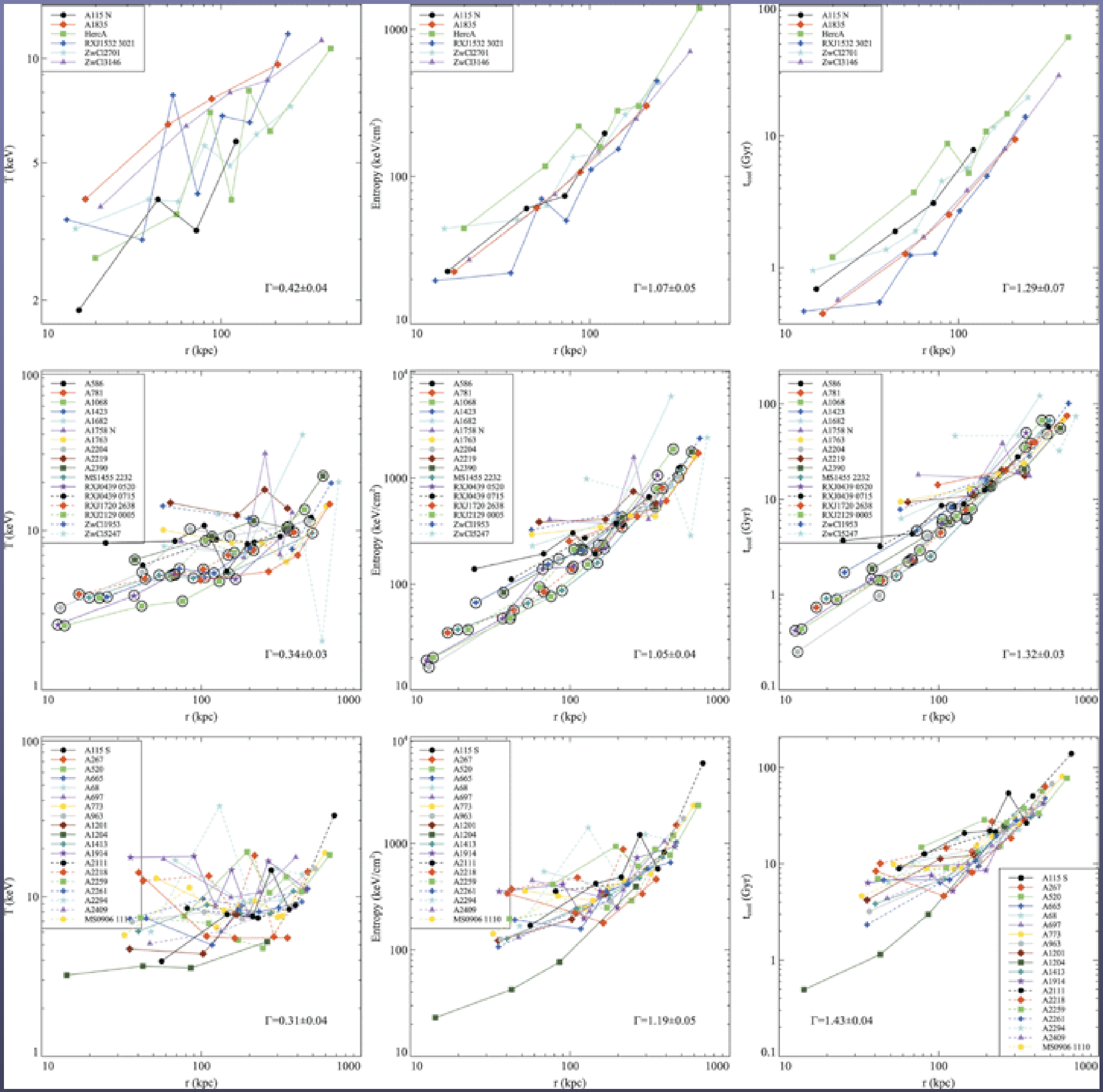
There appear to be 2 distinct types of clusters in nature...

OBSERVATION

X-ray-deficient bubbles--

Central radio activity--

No radio activity---



Dunn & Fabian 2008

Open Questions and Future Work

- Black-hole accretion and AGN feedback: How to get gas to black hole? Is Bondi accretion the whole story (outflows, angular momentum, hot vs cold accretion, etc)?
- 2D and 3D simulations of cosmic-ray bubbles: the bubble evolution and cosmic-ray heating. Preliminary studies on the bubble evolution with CR pressure support and diffusion has been performed by Mathews & Brighenti (2008).
- Bubble stability: what is bubble disruption rate? Viscosity, magnetic shielding, cosmic ray diffusivity…..
- How to distribute heat isotropically? 3D jet-heating simulations show anisotropic heating, resulting in cooling catastrophe. Weak shocks, sound waves, spinning jets?

Open Questions and Future Work

- Topology of magnetic fields? Could it be regulated by cooling flows, AGN outflows? Could cool, non-cool core clusters be the two aspects Of the same phenomenon, viewed at different times?

- Effect of AGN feedback in cosmological simulations of clusters

- What determines the final state the cluster relaxes toward (fastest decaying eigenfunction)?

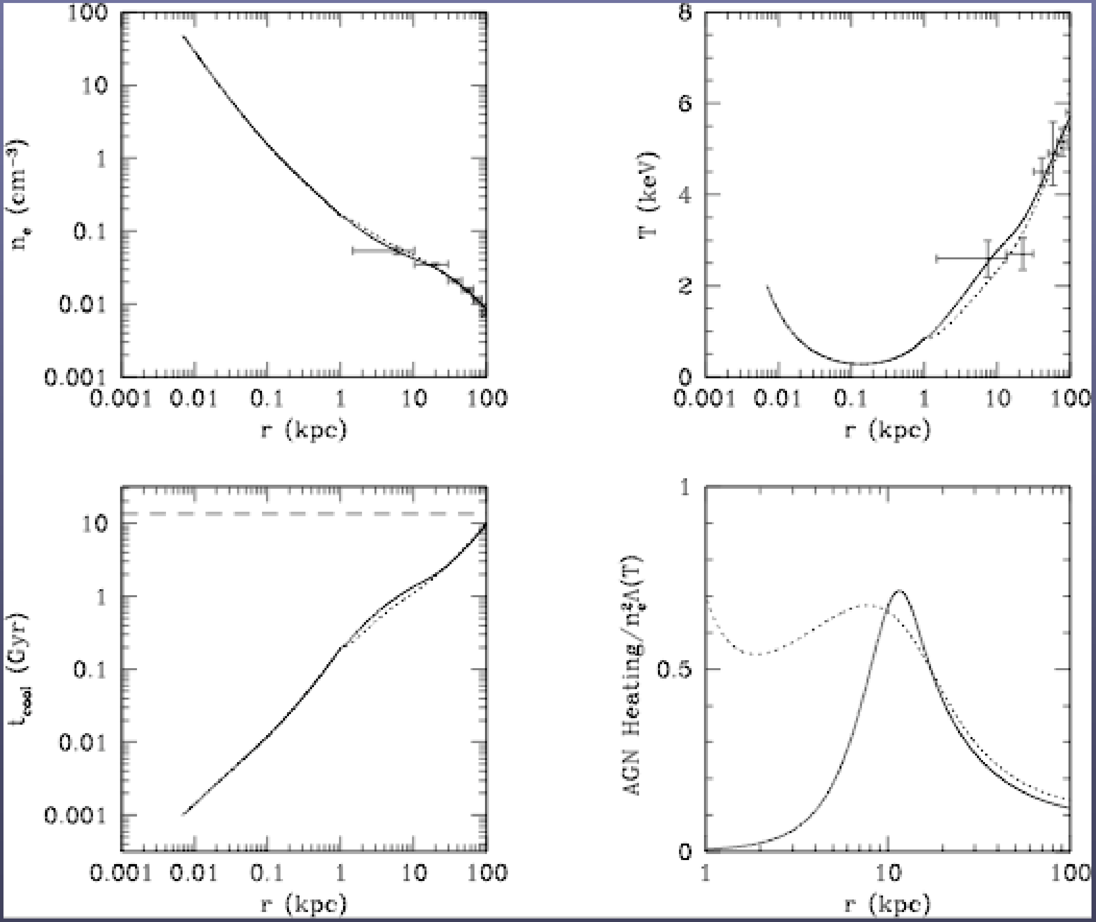
- Thermal balance in galaxy groups: very shorter central cooling times. Conduction is not sufficient to offset cooling.

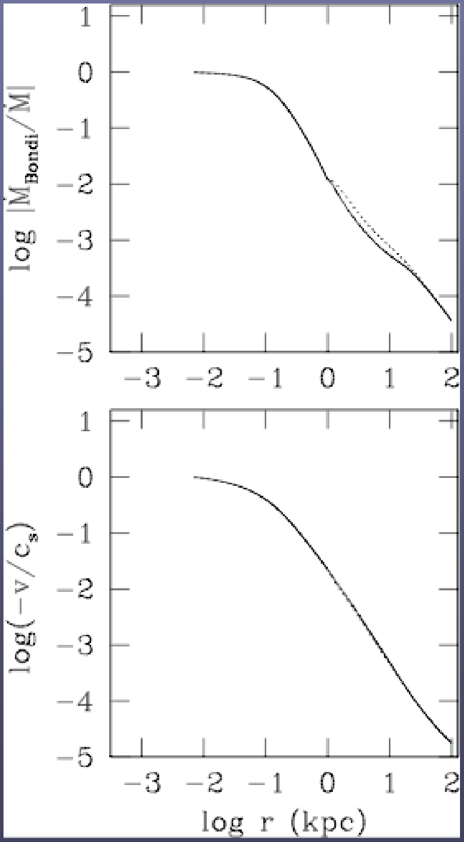
The Bottom Line

- Cosmic ray heating can be important in clusters ----- rising bubbles (eventually disrupted) provides a fast means of transport them.

- Global stability analysis provides a fast way of exploring parameter space. Predict (1) minimum level of heating efficiency (2) bimodal central temperatures.

AGN heating seems to be consistent with BH accretion!





Bondi accretion
near black hole