Title: The imprint of supernovae and AGN feedback on the SZ sky

Date: Apr 27, 2009 09:45 AM

URL: http://pirsa.org/09040032

Abstract: I discuss whether supernovae at high-redshift can result in a detectable SZ signal at small angular scales. I also discuss various aspects of AGN feedback on galaxy clusters.

AGN Feedback Heating in Galaxy Clusters

Peng Oh, UCSB

Collaborators

Fulai Guo (UCSB grad student, soon UC Santa Cruz postdoc)

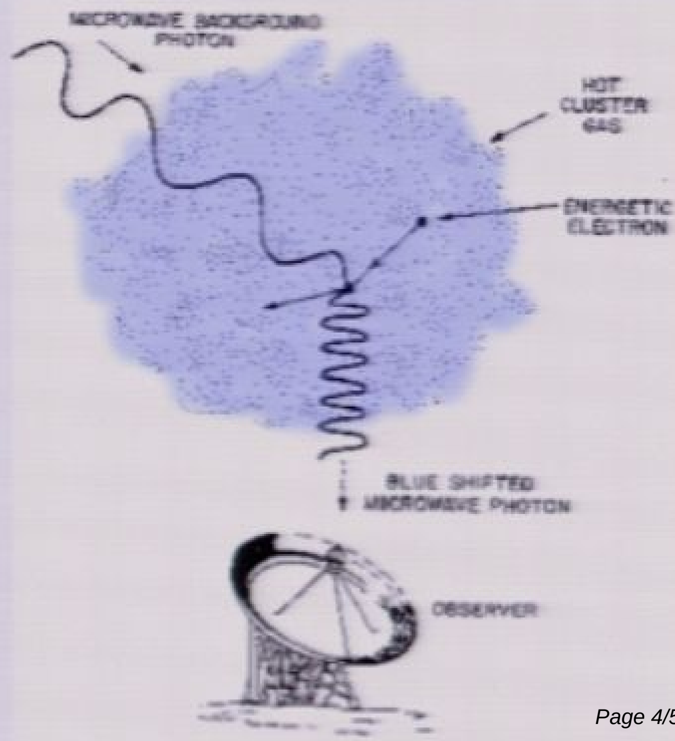
Mateusz Ruszkowski (Michigan)

Papers:

Guo & Oh, 2008, MNRAS, 384, 251

Guo, Oh & Ruszkowski, 2008, ApJ, 688, 859

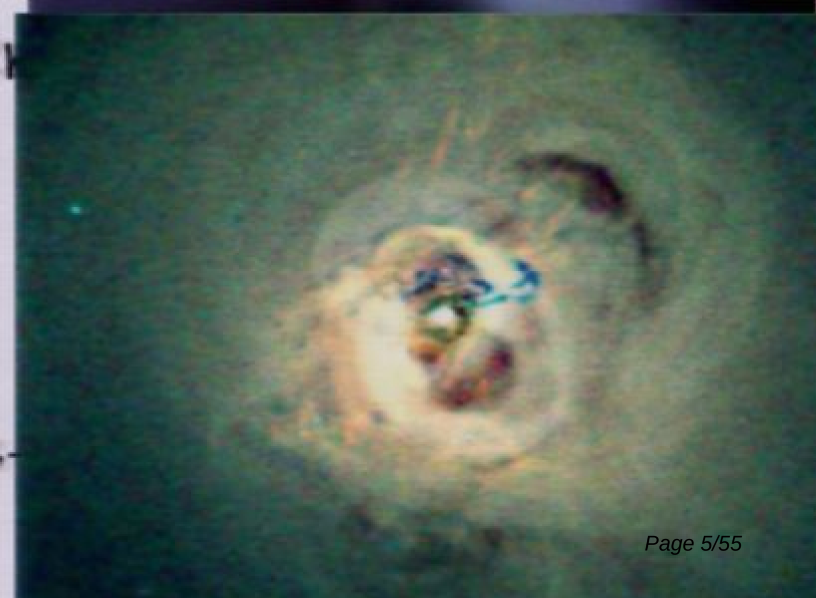
For cosmology, we'd like clusters to be nice spherical cows...



But they often contain a beating heart...

which could affect:

- entropy and pressure profiles
- SZ decrement, y-parameter
- Gas fractions
- Non-thermal pressure support: turbulence, cosmic-rays...

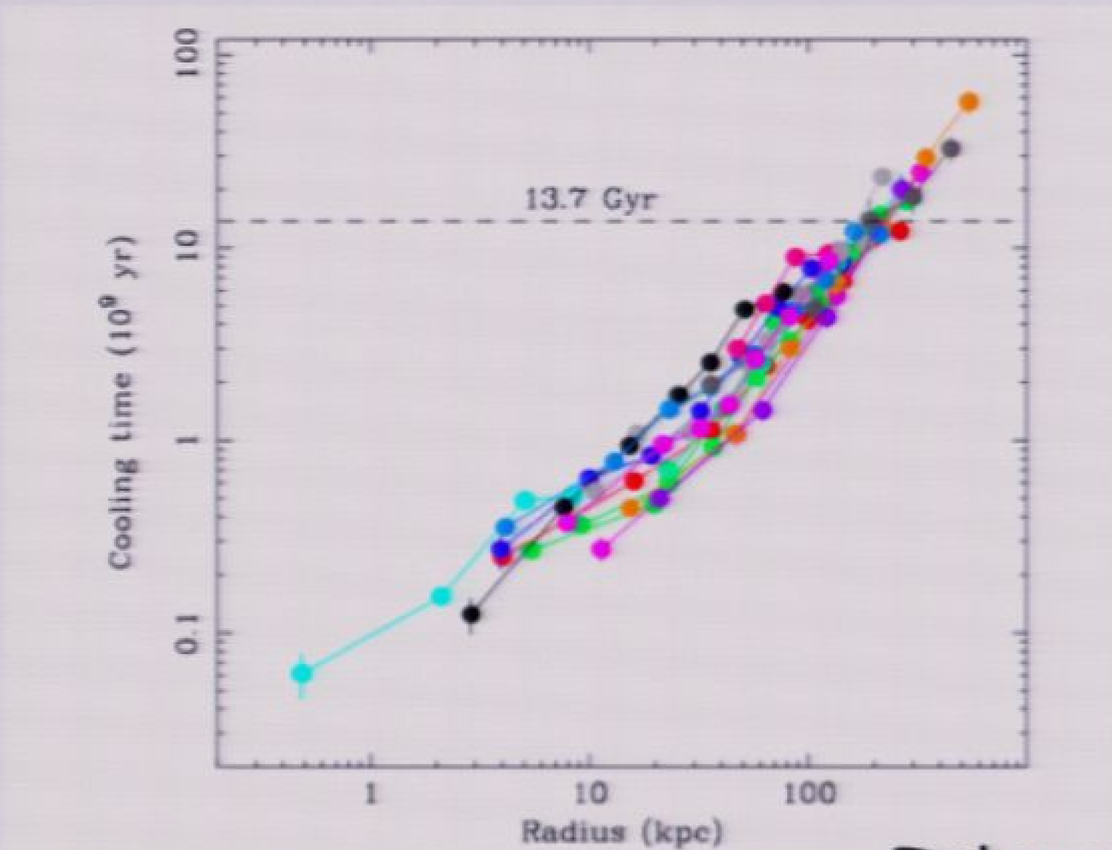


....this talk:

- A model of AGN heating: cosmic ray heating (but see C. Pfrommer's talk)
- A possible explanation for the dichotomy between cool core and non-cool core clusters (many speakers today, incld Babul, Bode, Nagai)

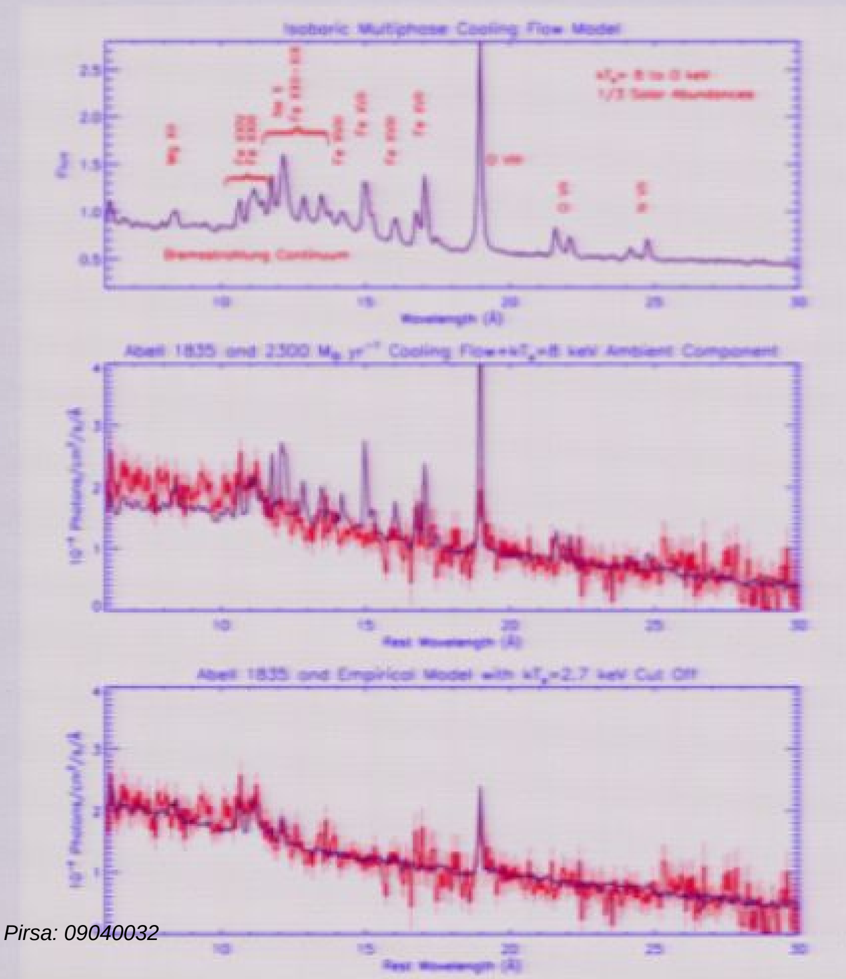
Cosmic-Ray Heating

Although gas cooling times in clusters are often short...



Peterson & Fabian (2006)

Gas does not appear to cool below ~1/3 of T_vir

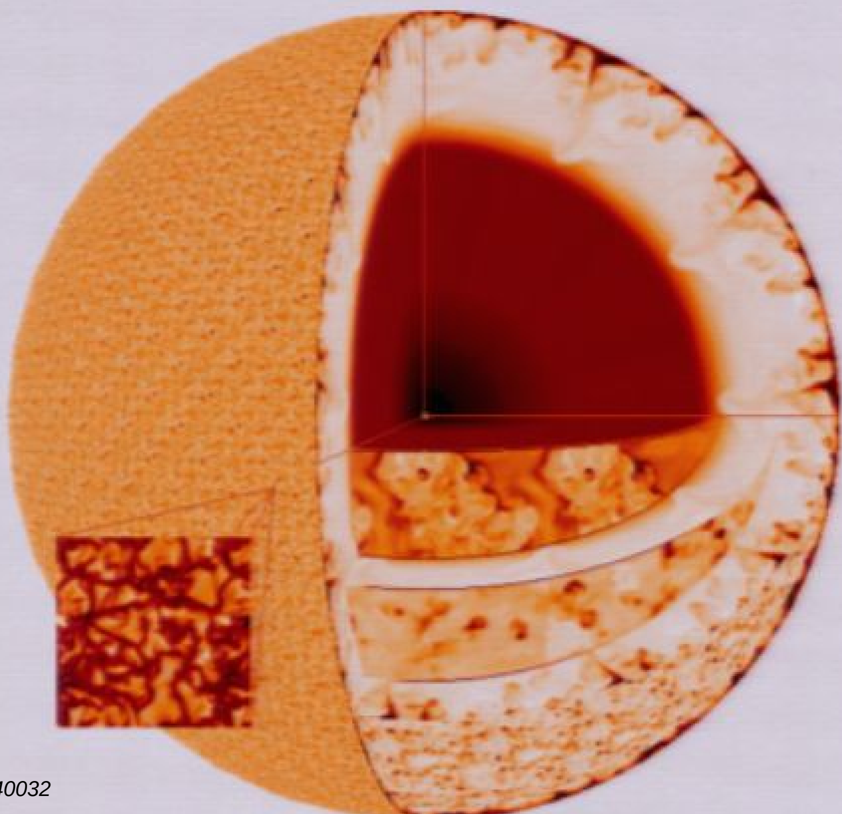


Can only fit spectra if prevent gas from cooling below ~1/3 of ambient temperature

Universal across different cluster temperatures

Peterson et al (2001)

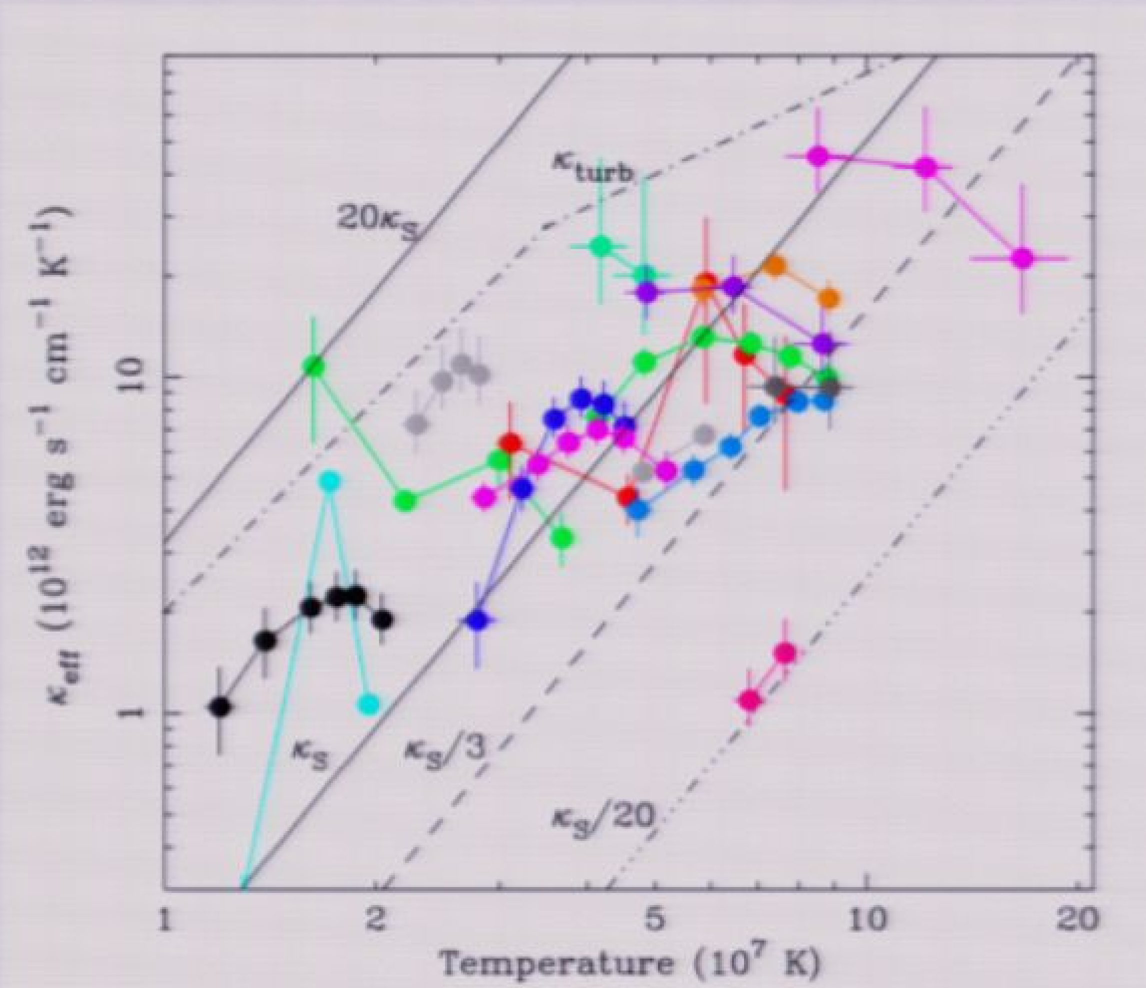
Heating is an attractive solution



Cluster sits in quasi-thermal equilibrium: just like a star!

Also explains lack of cold gas/stars

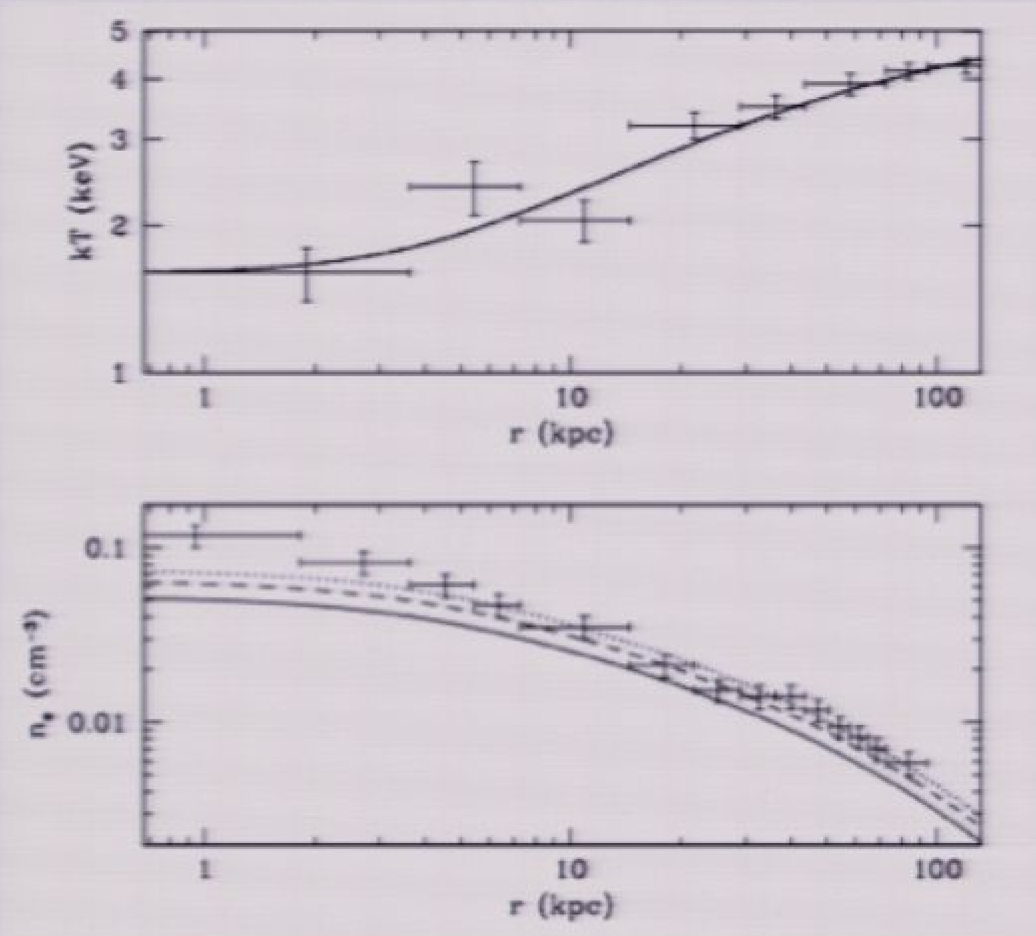
Thermal Conduction



Conduction at fraction of classical Spitzer value close to what's needed.

Coincidence??

Peterson & Fabian (2006)

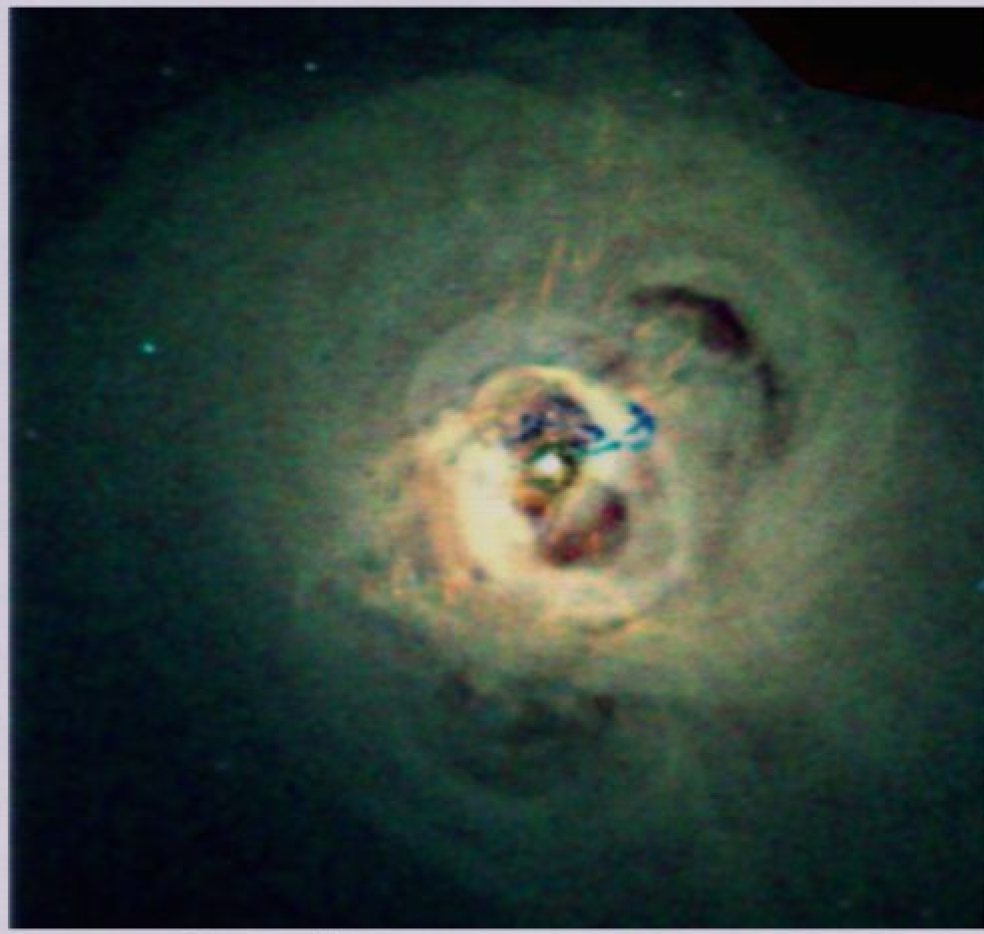


Zakamska & Narayan (2002)

Can build conduction-only models in hydrostatic and thermal equilibrium

But: suffer fine-tuning problems, tend to be globally unstable

AGN/radio galaxy heating



Chandra image, Perseus cluster

Bubbles observed in ICM, filled with hot/relativistic plasma

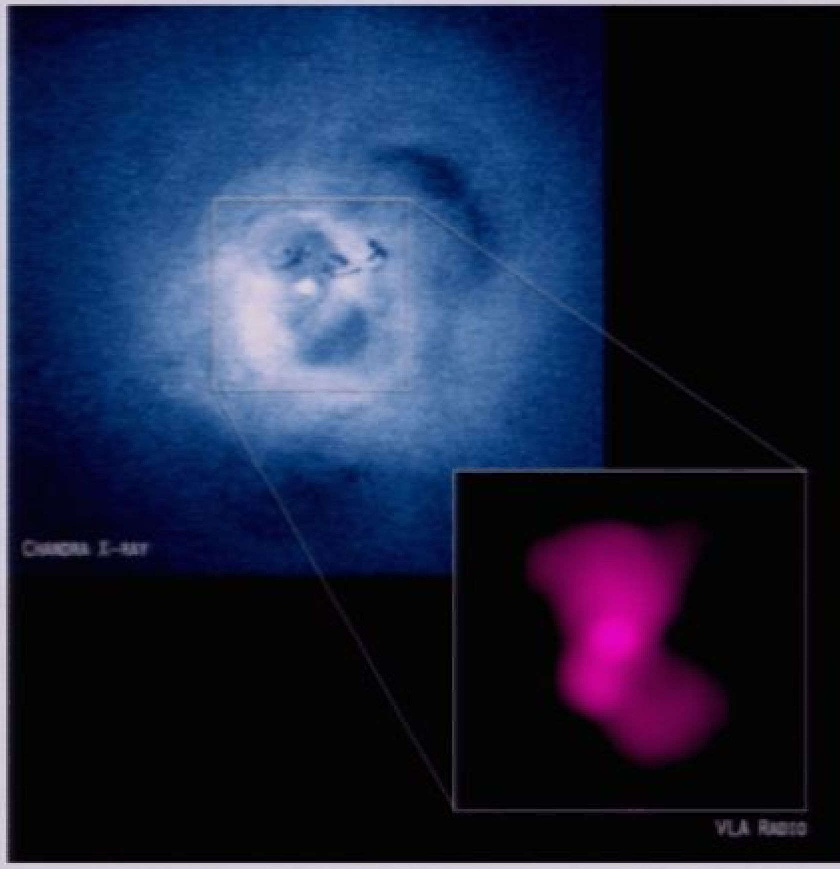
Maybe: entrain cold gas

pdV work

This talk: cosmic ray heating

(Guo & Oh 2008)

Why cosmic rays ?



We see radio synchrotron emission

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, Pfrommer et al 2006)
- But CRs in previous models did not successfully stop cooling flow

A key problem: CR transport is slow

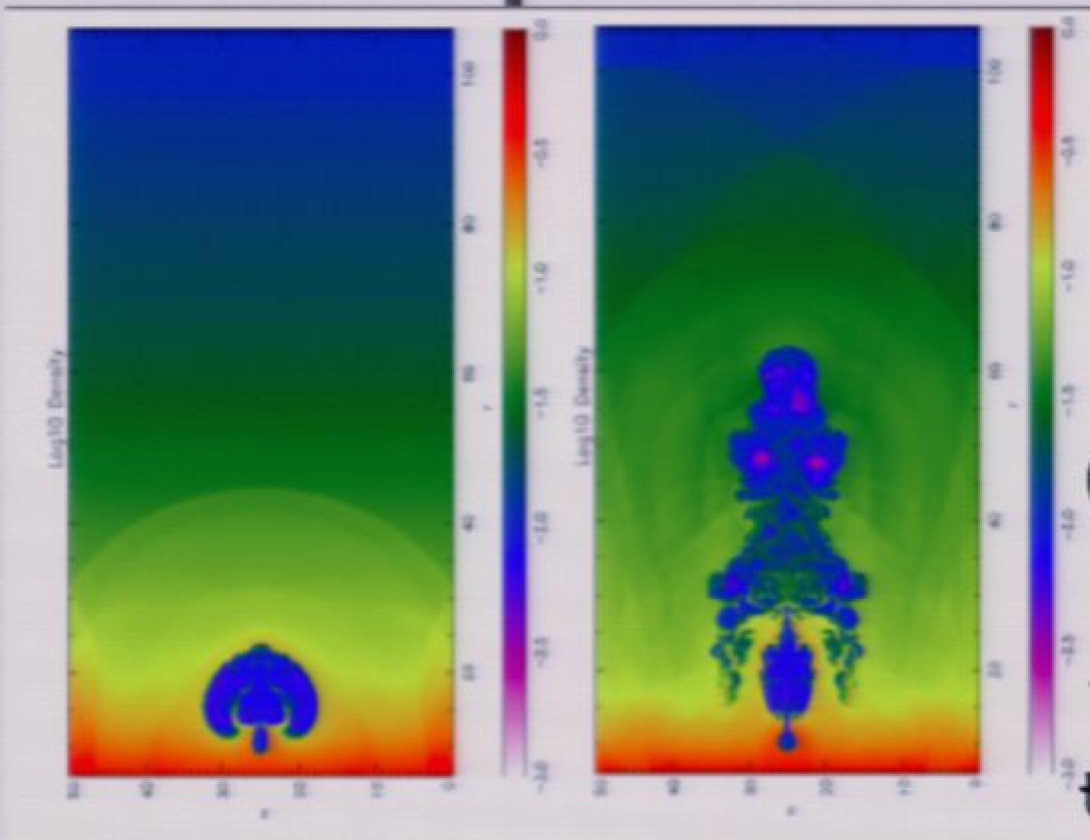
$$\boldsymbol{F}_{\mathrm{c}} = \gamma_{\mathrm{c}} E_{\mathrm{c}}(\boldsymbol{u} + \boldsymbol{v}_{\mathrm{A}}) - \boldsymbol{n}\kappa_{\mathrm{c}}(\boldsymbol{n} \cdot \boldsymbol{\nabla} E_{\mathrm{c}}), \quad \text{(A14)}$$

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

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 time-dependent hydrodynamic equations + CR heating & transport equations
- calculate steady steady CR spectrum, assuming Coulomb, hadronic and Alfven-wave energy loses (latter dominates):

$$\Gamma_{wave} = v_A \frac{dP_c}{dr}$$

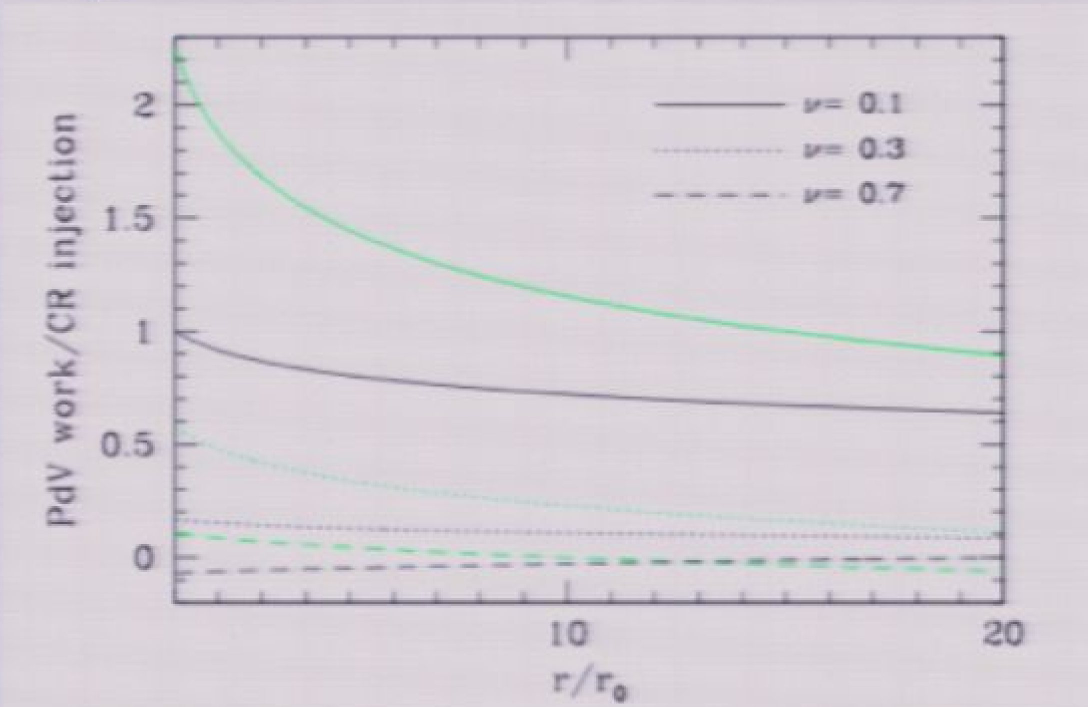
- Assume energy density in bubbles is a power-law with radius (note: CR injection rate depends on gas cooling---feedback effect)

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

$$\begin{aligned} Q_{\rm c} = \nabla \cdot \mathbf{F}_{\rm bubble} &\sim -\frac{1}{4\pi r^2}\frac{\partial L_{\rm bubble}}{\partial r}\left[1 - e^{-(r/r_0)^2}\right] \\ &\sim -\frac{\nu \epsilon \dot{M}_{\rm in} c^2}{4\pi r_0^3}\left(\frac{r}{r_0}\right)^{-3-\nu}\left[1 - e^{-(r/r_0)^2}\right], \end{aligned} \quad (19$$

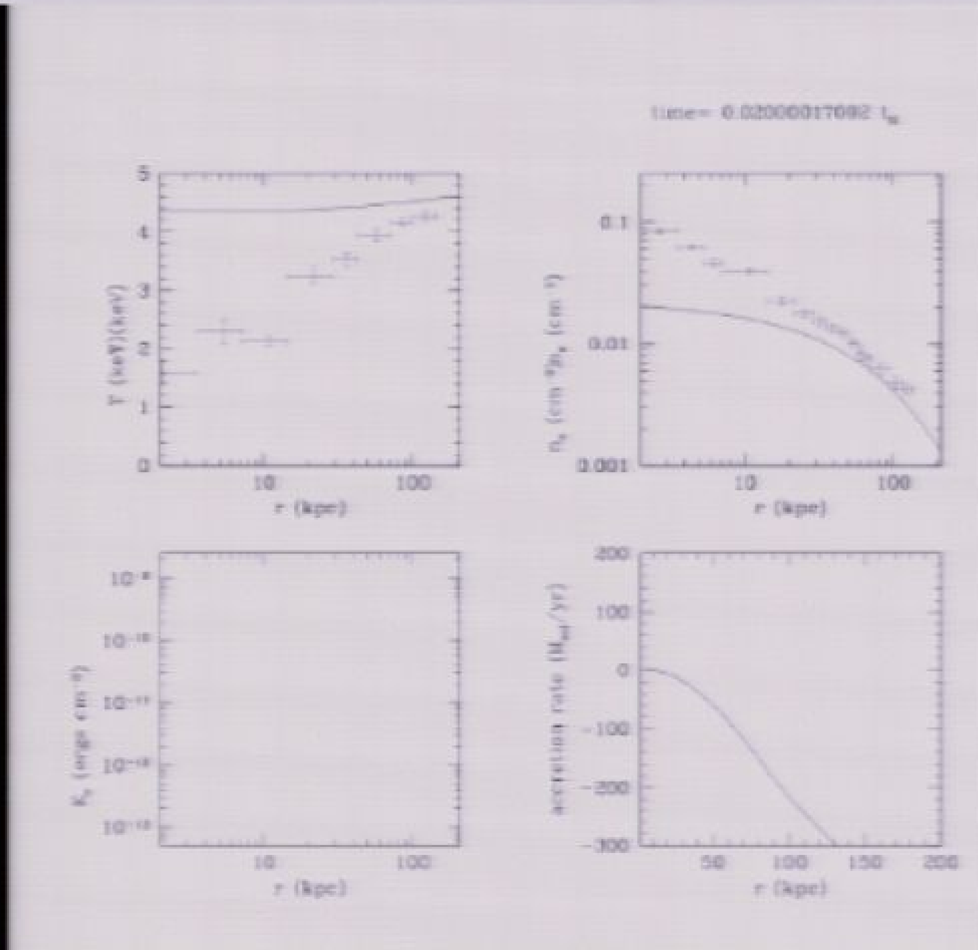
Slope is free parameter, implicitly specifies bubble disruption rate

- Amount of energy lost to pdV work is small, at most comparable to the bubble disruption rate



(pdV work can also heat ICM, we ignore it)

Bottom line: it works!



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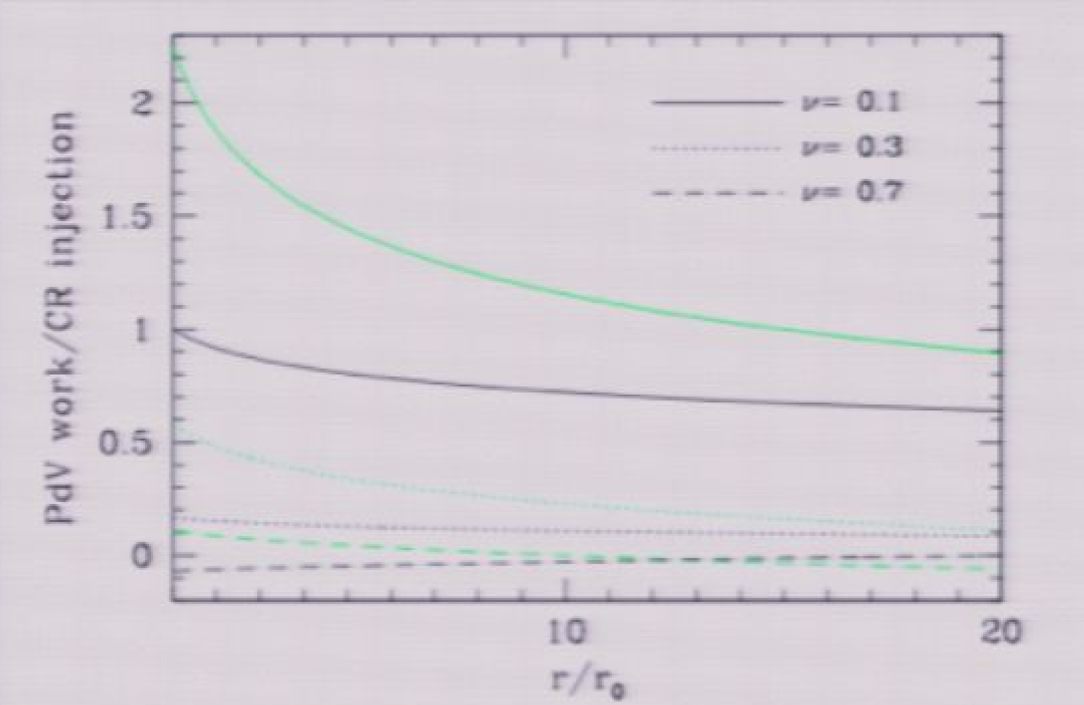

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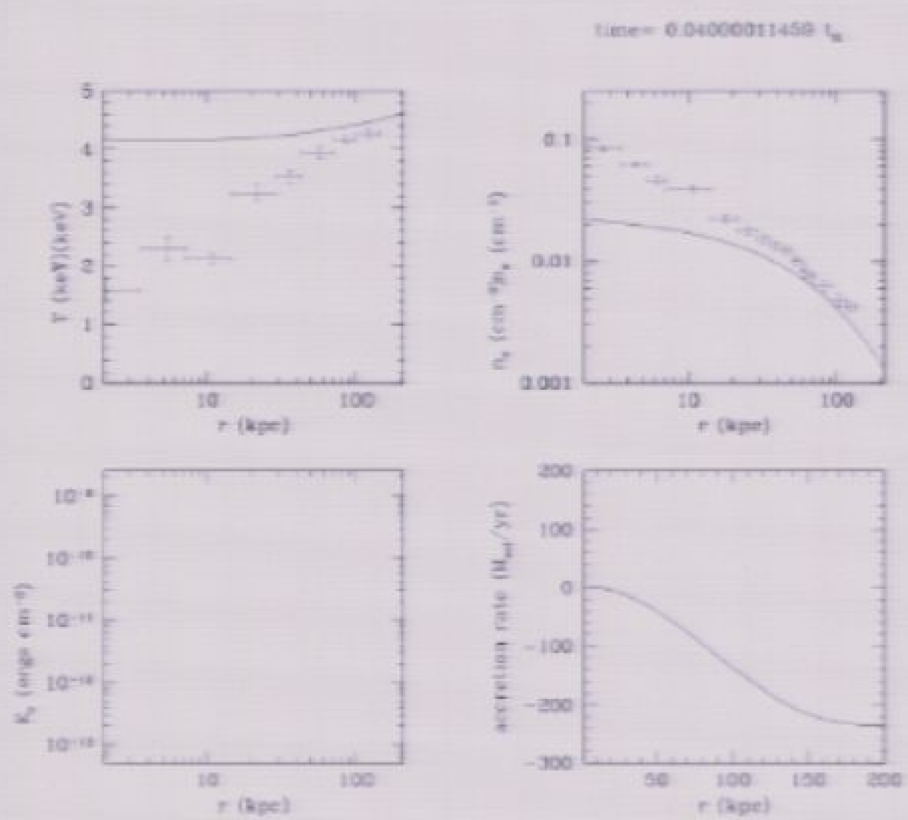

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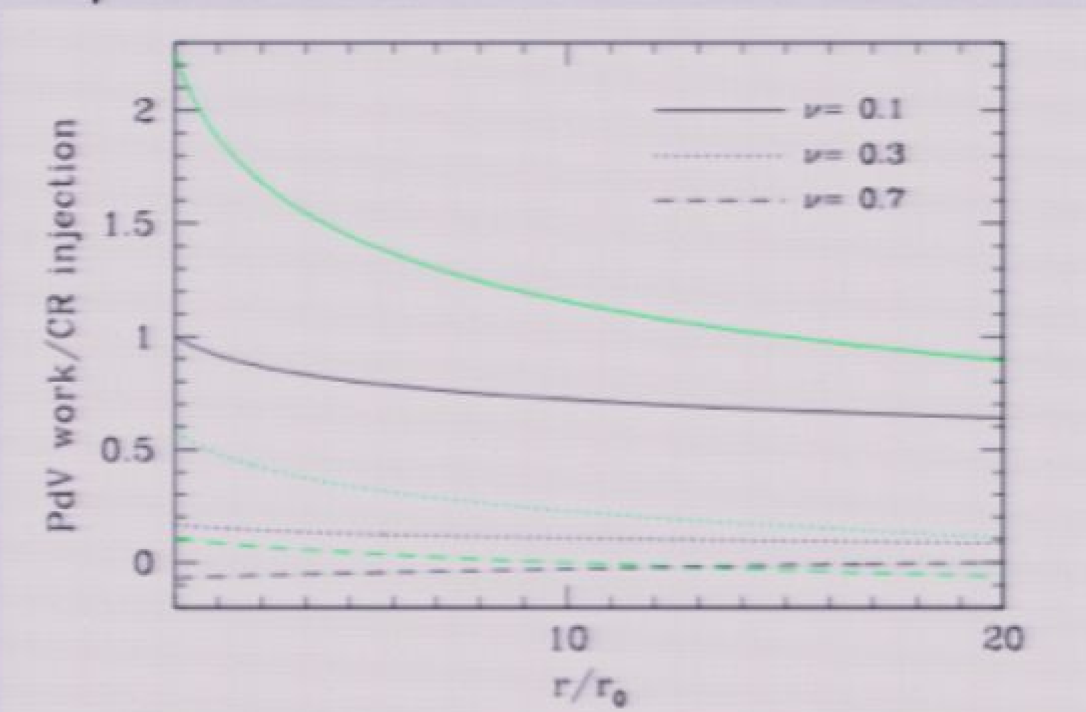

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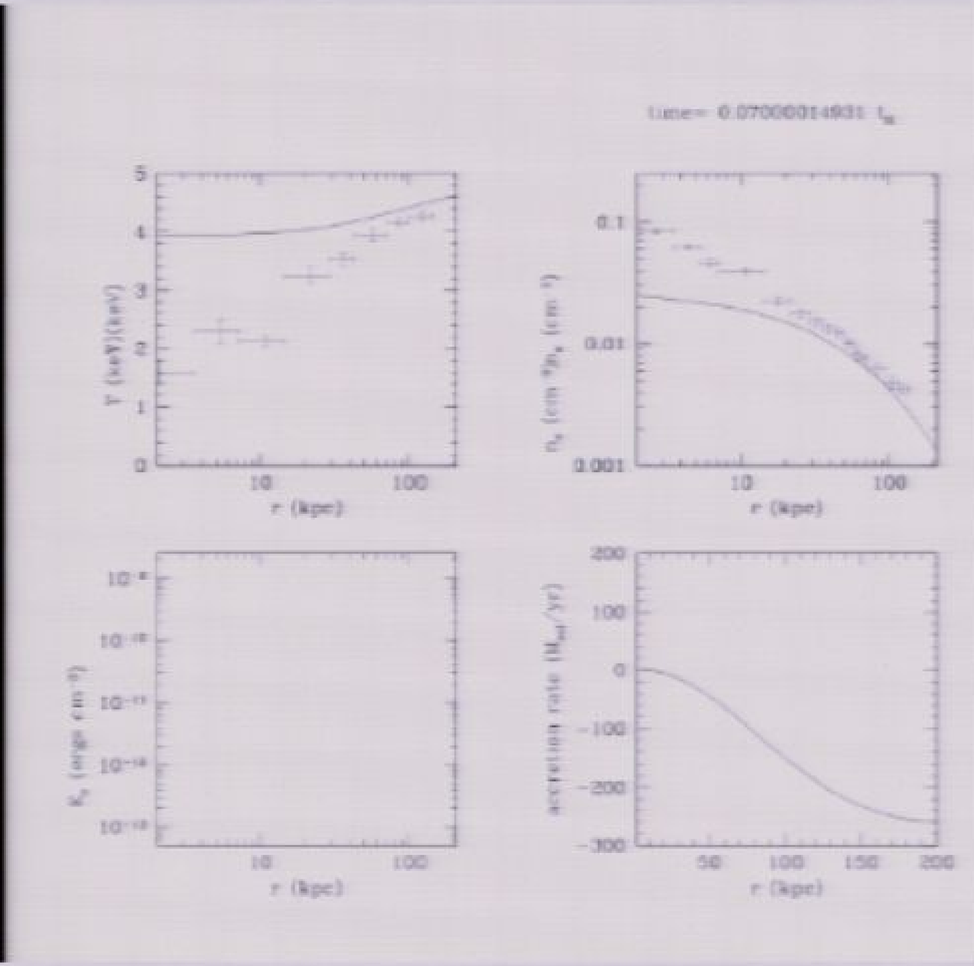
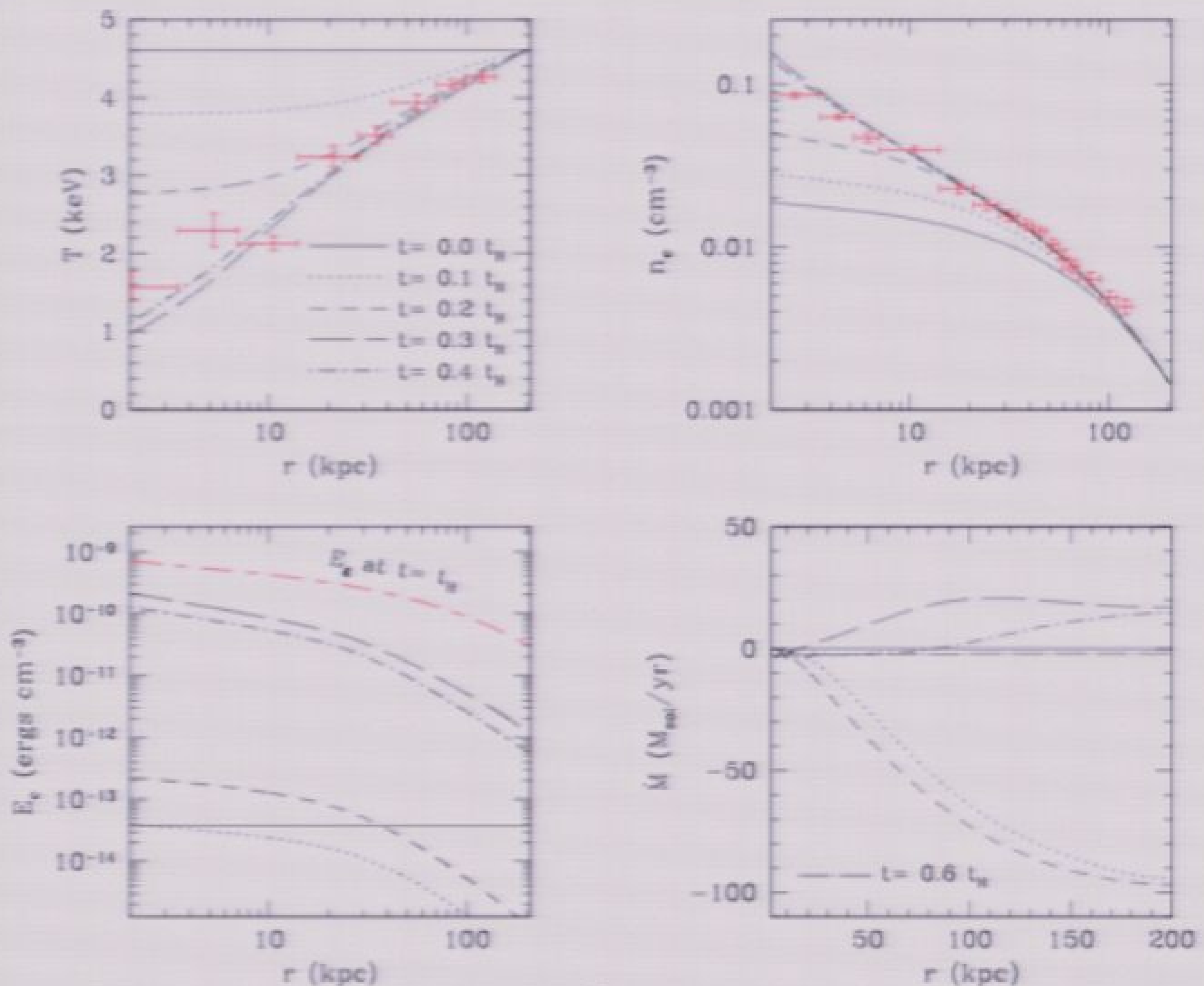
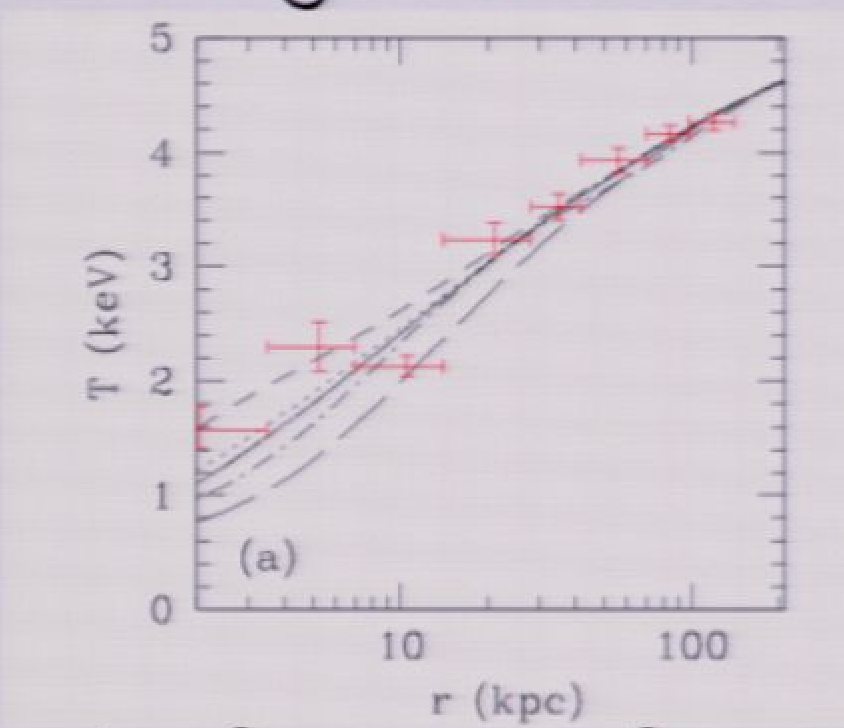




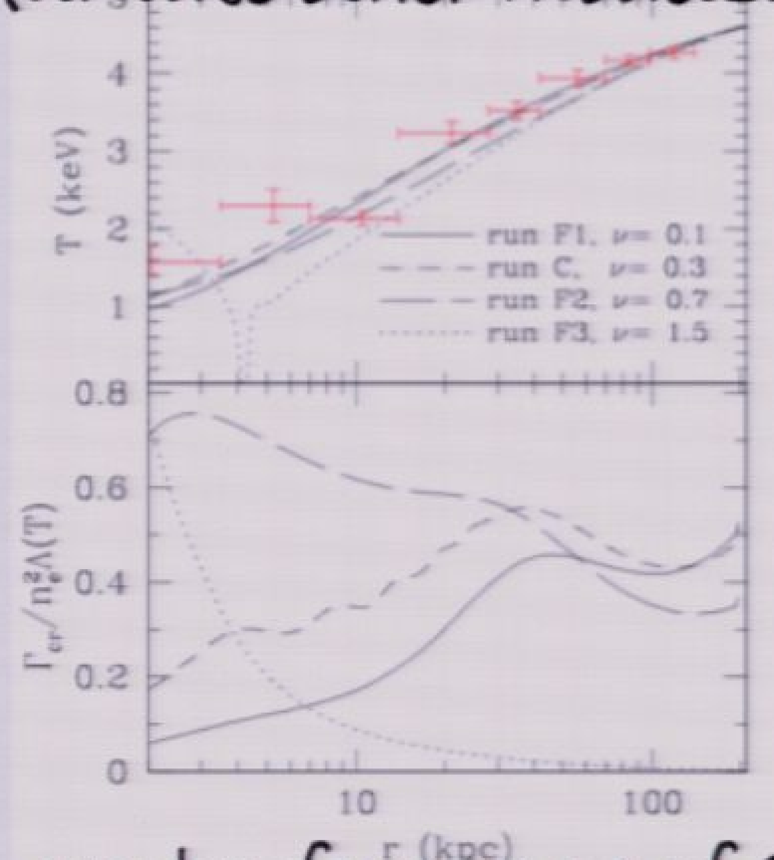
Note that CR pressure is much less than thermal pressure

No fine tuning

Works (i.e., no massive cooling flow) starting from arbitrary initial conditions (unlike other models...)



works for range of AGN + conduction parameters



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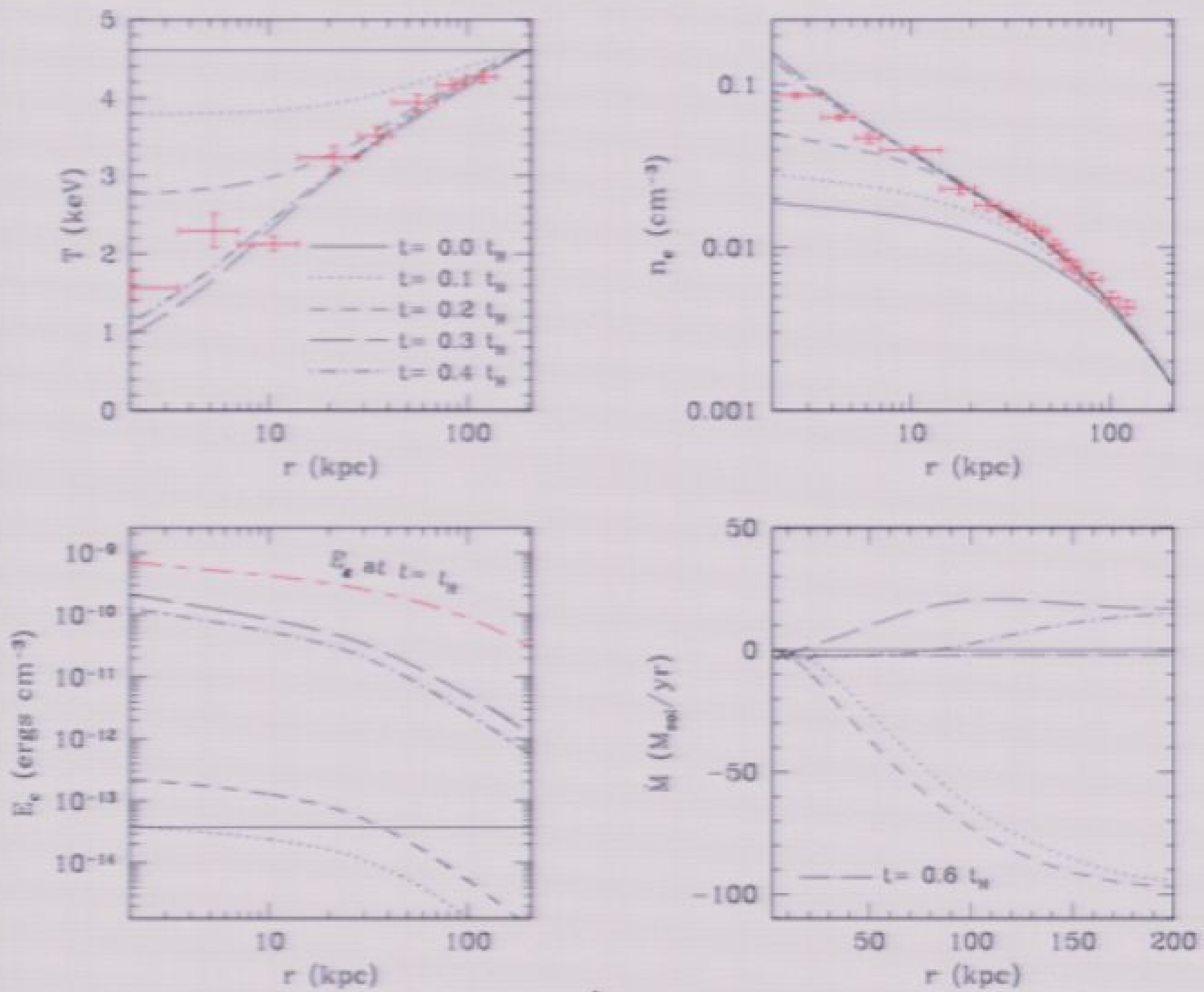

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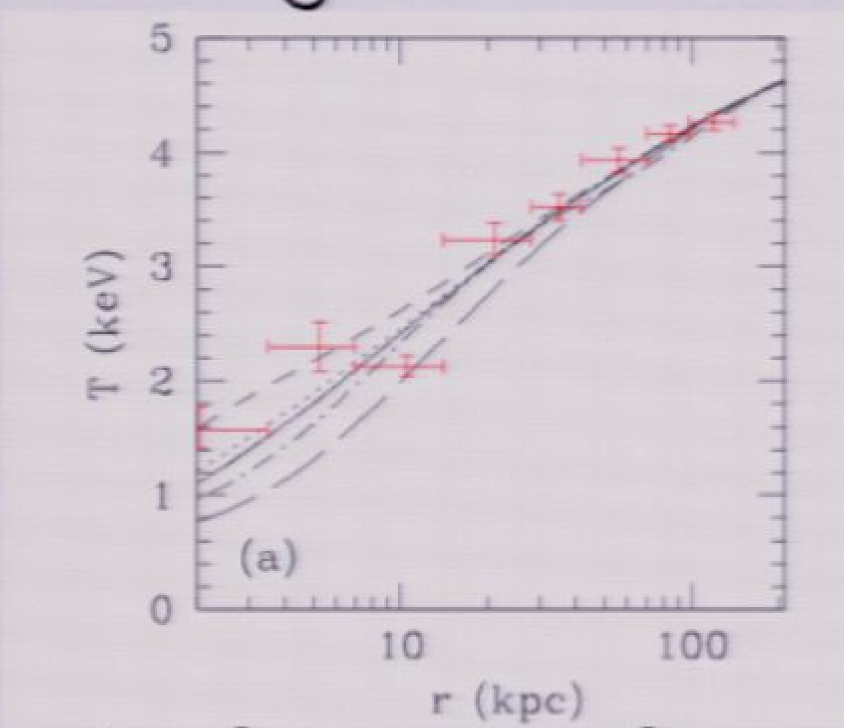

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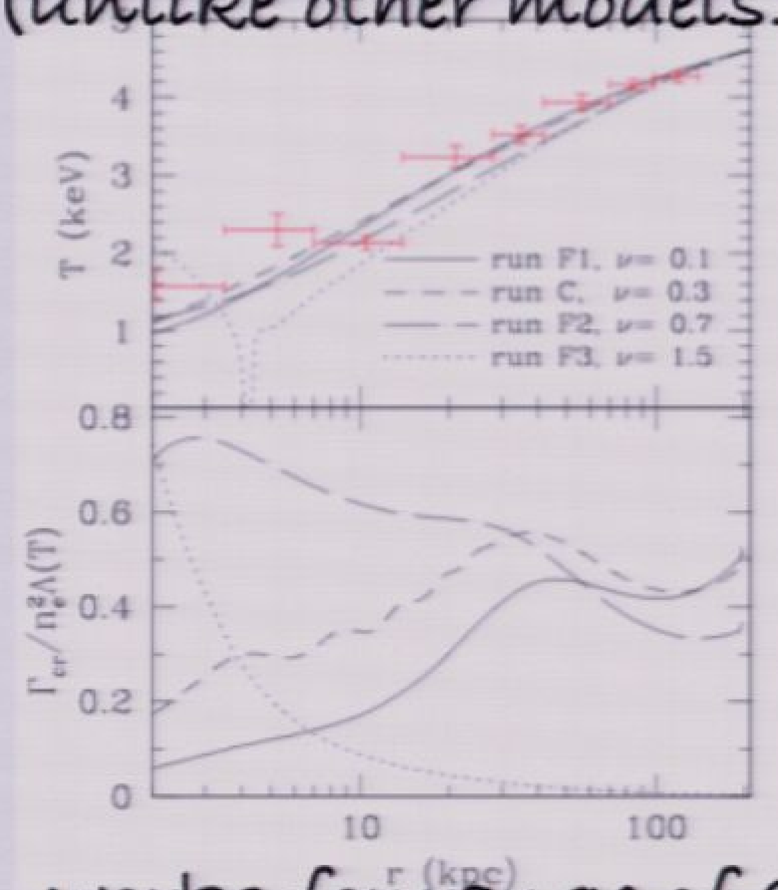
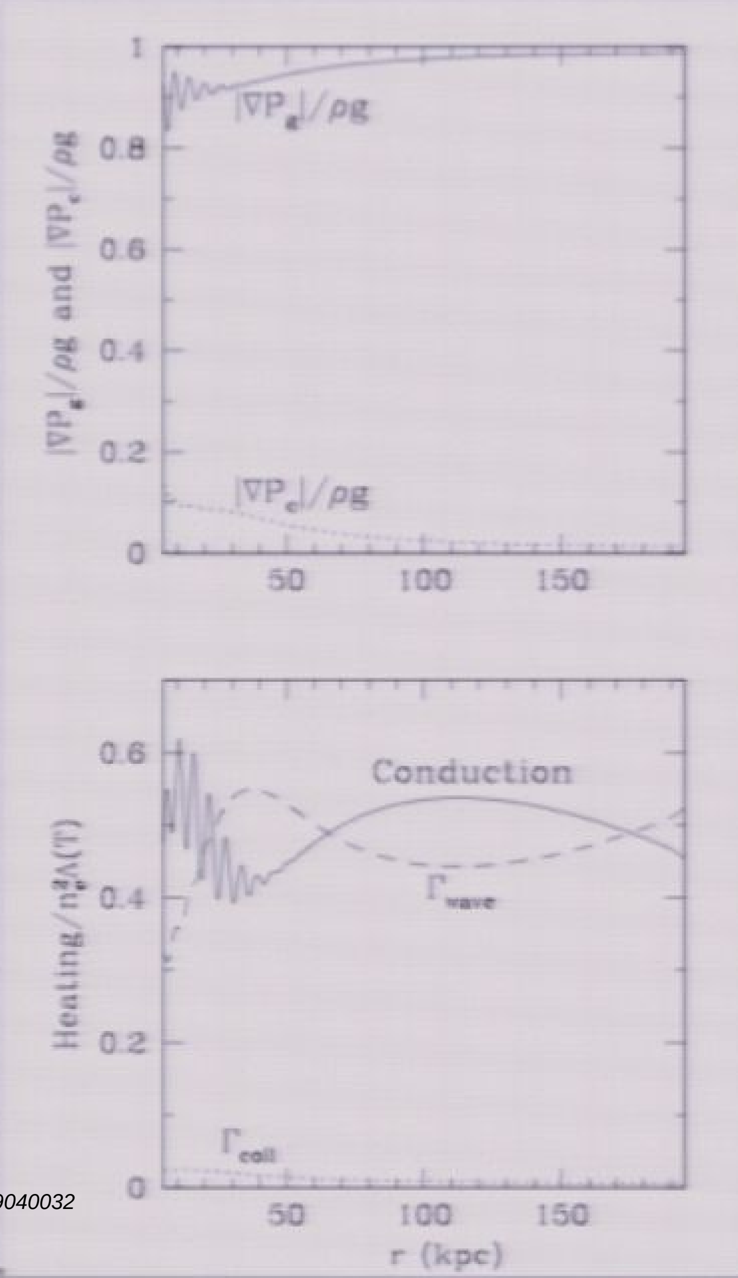


works for range of CR profiles

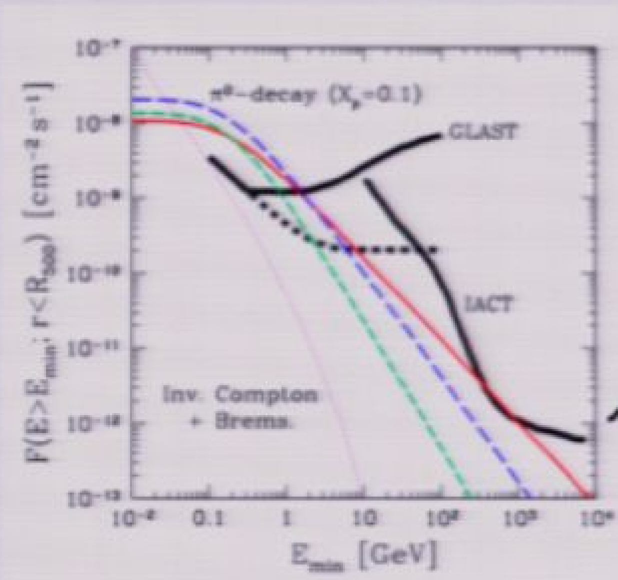
Required CR pressure gradients OK



Small fraction of thermal pressure gradient

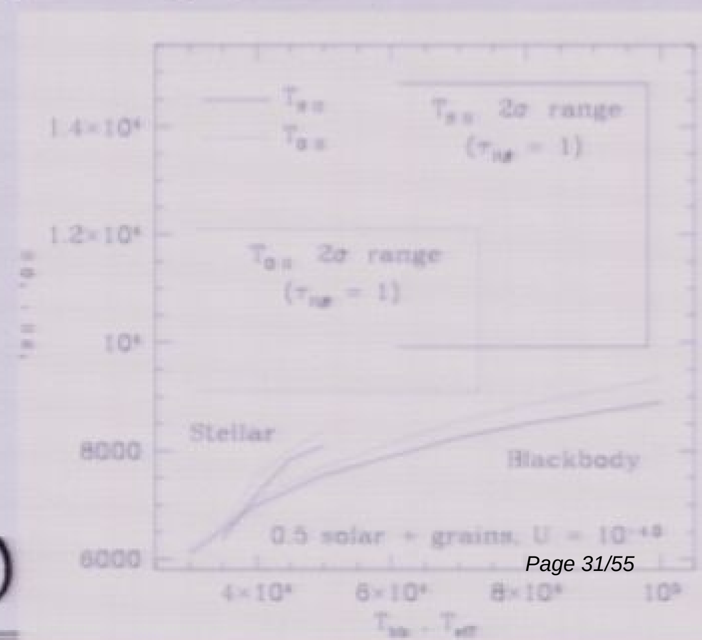
most heating is wave heating

Observational tests



See gamma-rays from pion-decay with GLAST

Ando & Nagai (2007)

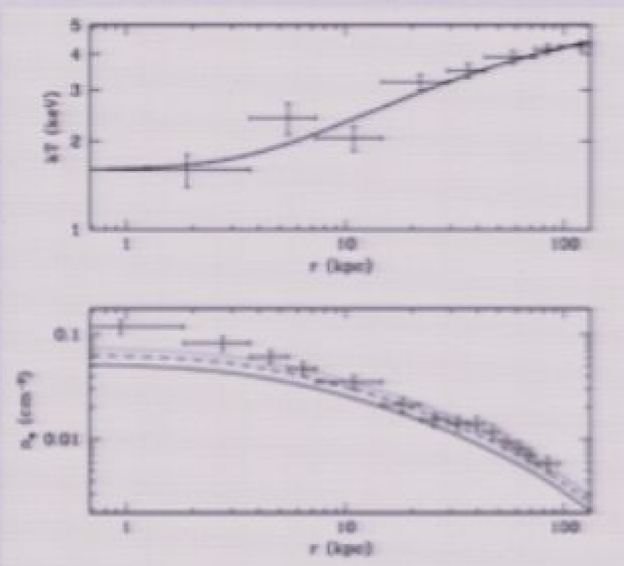


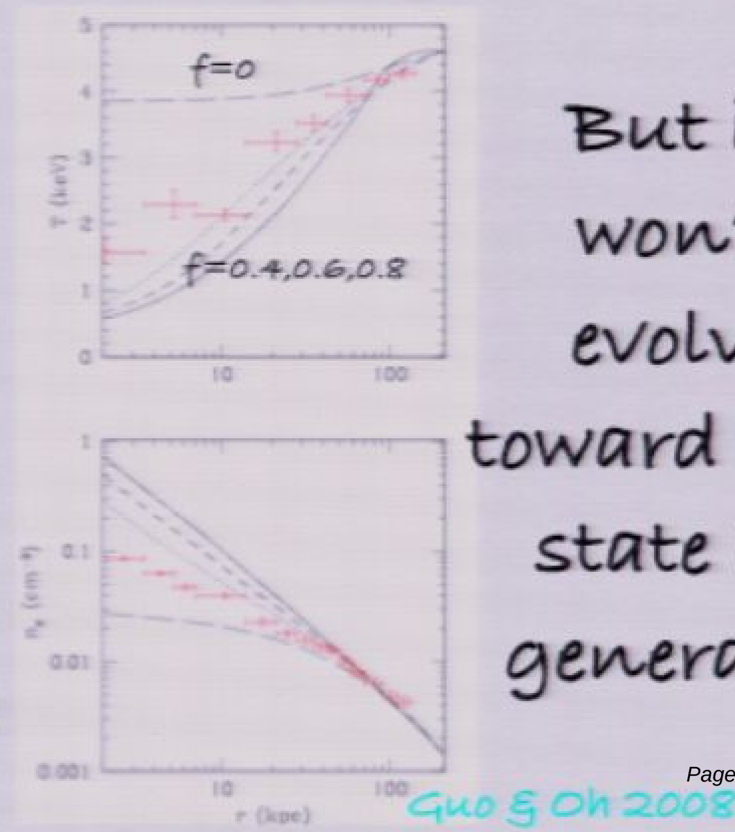
Optical filaments: need source of anomolous heating?

Voit & Donahue (1997)

Global Stability in Cool Core vs. Non-Cool Core Clusters

Let's look more closely at fine-tuning issues for conduction models..



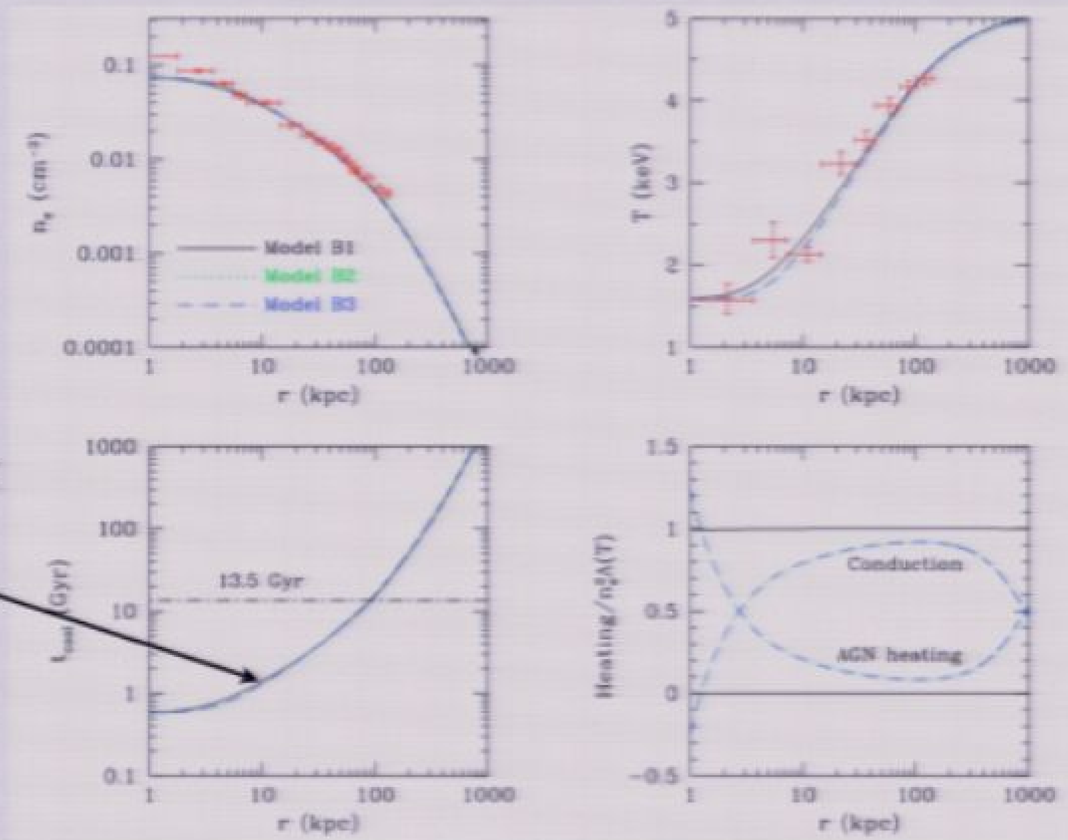


But it won't evolve toward this state in general...

Can have equilibrium model which fits observations (solve eigenvalue problem)

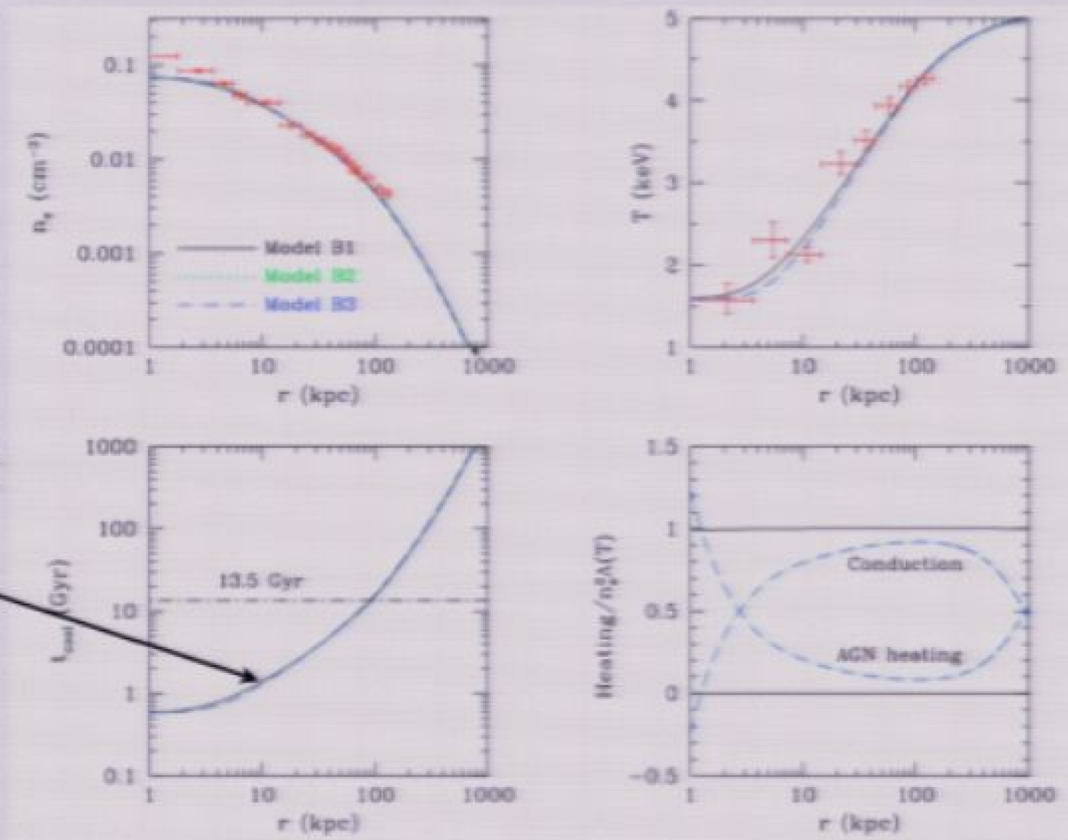
...look at differences with AGN feedback model

note short cooling time



First, build a background equilibrium solution

...look at differences with AGN feedback model



note short cooling time

First, build a background equilibrium solution

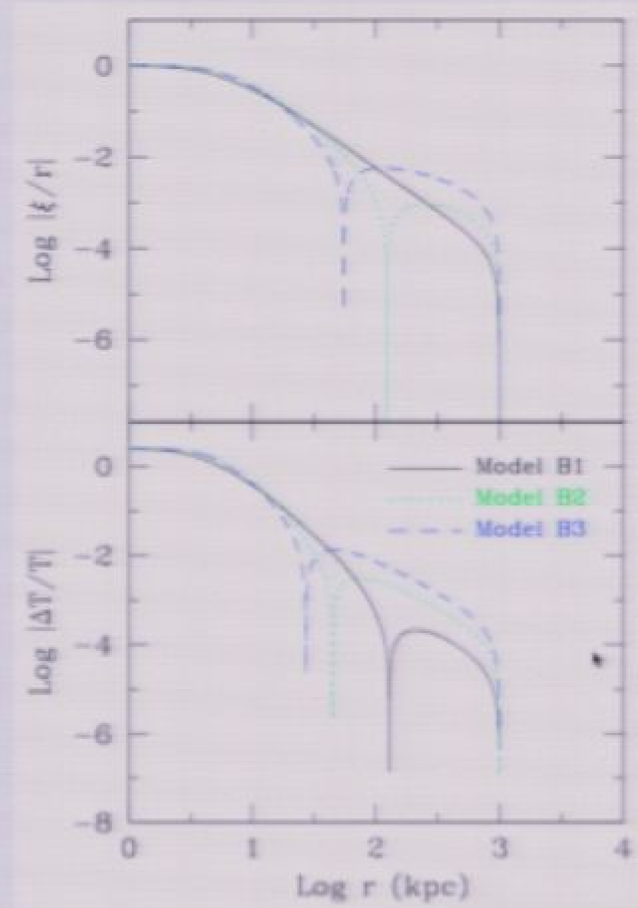
...and perform a **global** stability analysis

~~WKB~~

$$\left(\frac{P}{\rho}-v^2\right)\frac{d}{dr}(\nabla\cdot\boldsymbol{\xi}) = \left(r\sigma^2 + r\frac{d^2\Phi}{dr^2}\right)\frac{\xi}{r} + \frac{1}{\rho}\frac{d}{dr}\left(P\frac{\Delta T}{T}\right) - 2v^2\frac{d}{dr}\left(\frac{\xi}{r}\right) + \left(2\sigma v + v\frac{dv}{dr} - \frac{1}{\rho}\frac{dP}{dr}\right)\frac{d\xi}{dr} \quad (33)$$

$$\kappa T\frac{d}{dr}\left(\frac{\Delta T}{T}\right) = F\left[\frac{7}{2}\frac{\Delta T}{T} - r\frac{d}{dr}\left(\frac{\xi}{r}\right) + \frac{\xi}{r}\right] + \frac{\Delta L_r}{4\pi r^2} \quad (34)$$

$$\frac{1}{4\pi r^2}\frac{d}{dr}\Delta L_r = (P\sigma - \rho^2\mathcal{L}_\rho - \mathcal{H})(\nabla\cdot\boldsymbol{\xi}) - \Delta\mathcal{H} + \left(\frac{P\sigma}{\gamma-1} + \rho T\mathcal{L}_T + \frac{v}{\gamma-1}\frac{dP}{dr} - \frac{\gamma v}{\gamma-1}\frac{P}{\rho}\frac{d\rho}{dr}\right)\frac{\Delta T}{T} + Pv\frac{d}{dr}(\nabla\cdot\boldsymbol{\xi}) + \frac{Pv}{\gamma-1}\frac{d}{dr}\left(\frac{\Delta T}{T}\right) \quad (35)$$



Growth rate is an eigenvalue of analysis

Explore parameter space rapidly!

Global unstable modes suppressed with AGN!

Suppression depends on efficiency

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

The crucial term: feedback

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

Observations:

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TIMESCALES FOR THE CLUSTERS SHOWN IN TABLE 1

Name	$t_{cool,0}$ [a] (Gyr)	$t_{\infty,0}$ [b] (Gyr)	ϵ_{min} [d]	Model	t_{grow} [c] (Gyr)
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A2199	0.6	0.4	0.17	B1	2.8
				B2	4.4
				B3	16.9
A2052	1.1	0.7	0.14	C1	6.2
				C2	5.9
				C3	20.0
A2597	0.4	0.3	0.12	D1	1.8
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$\epsilon \sim 0.3$ (Heinz et al 2007)

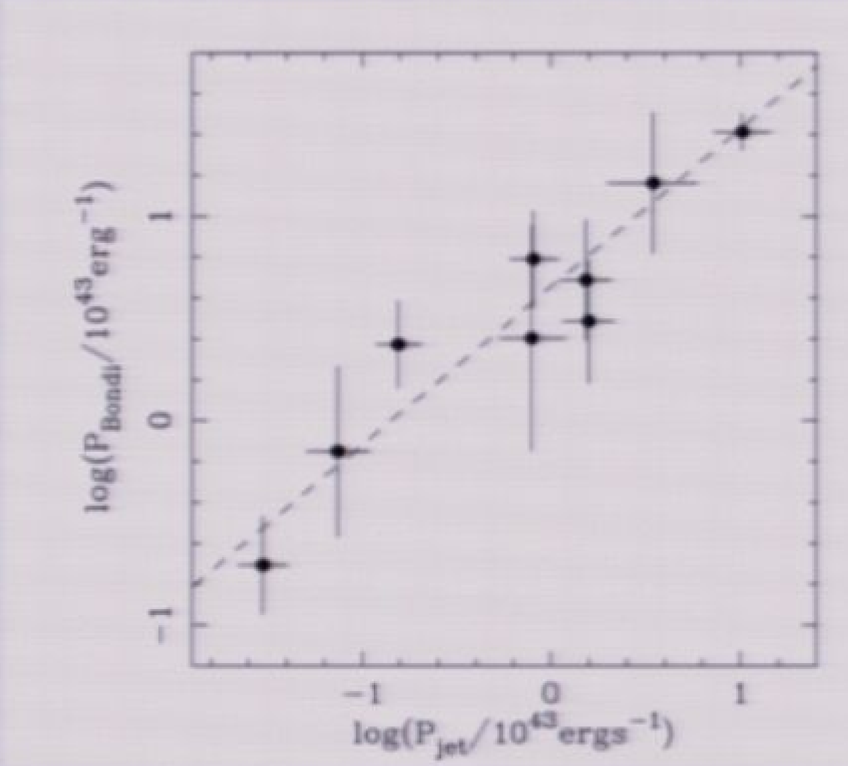
$\epsilon \sim 0.01 - 0.1$ (Allen et al 2006; Merloni & Heinz 2007)

some observations suggest

$$\epsilon \propto \dot{M}^{0.3-0.6}$$

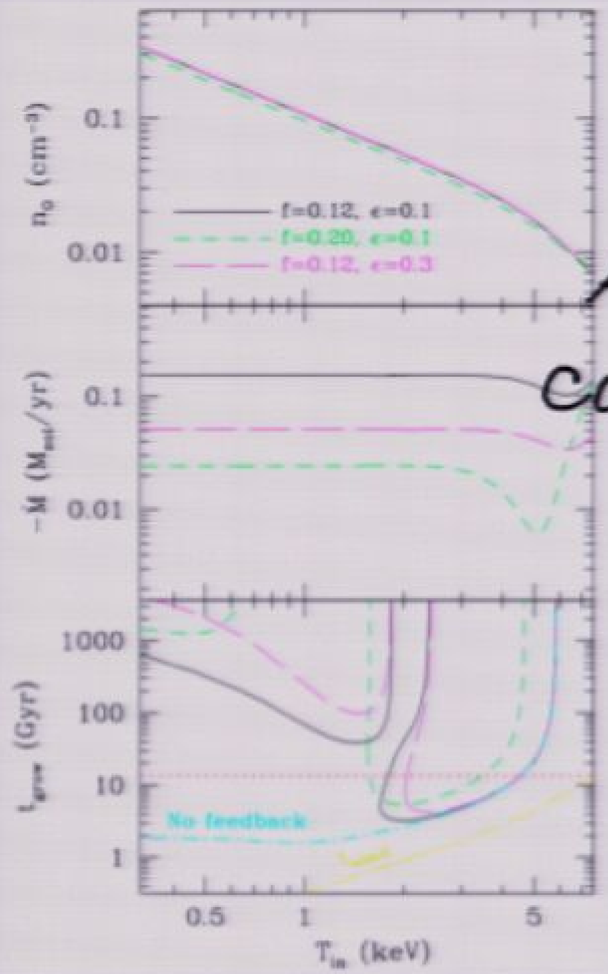
Stronger feedback,

$\epsilon_{\min}$ reduced



Allen et al 2006

Dependence on background profile

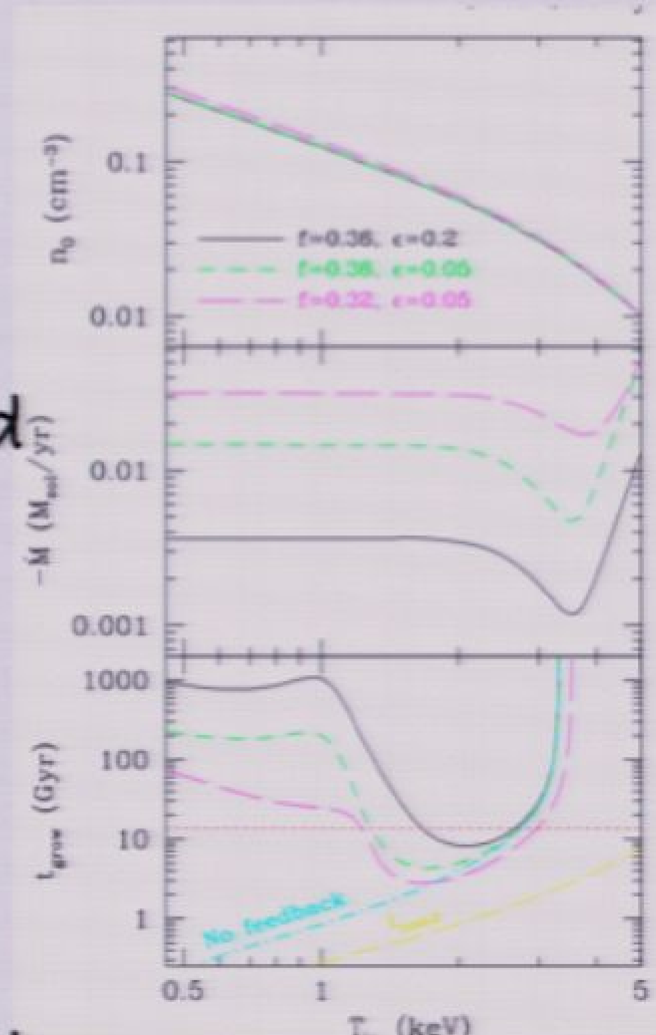


Appears bimodal!

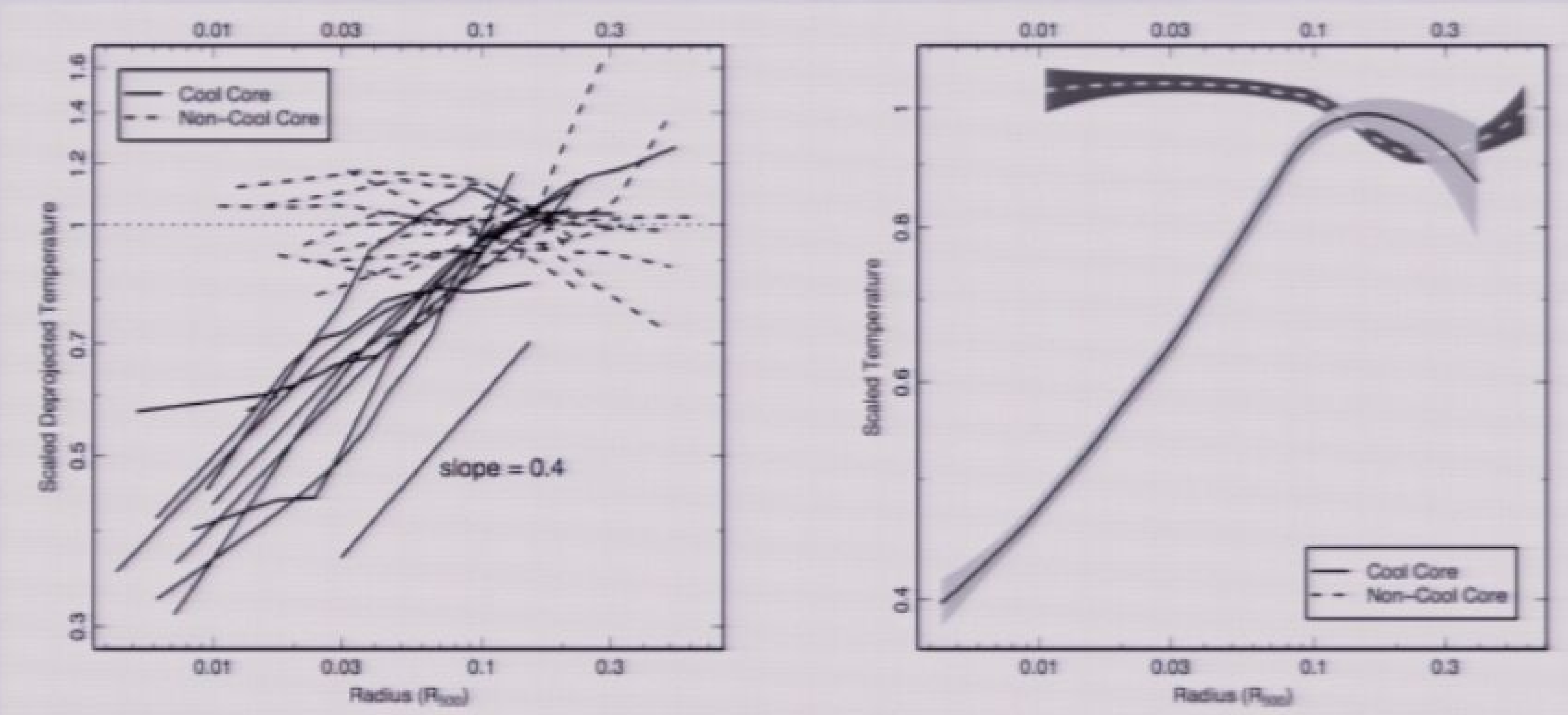
Cool core--stabilized by AGN

Non cool core--stabilized by conduction

Intermediate temperatures unstable

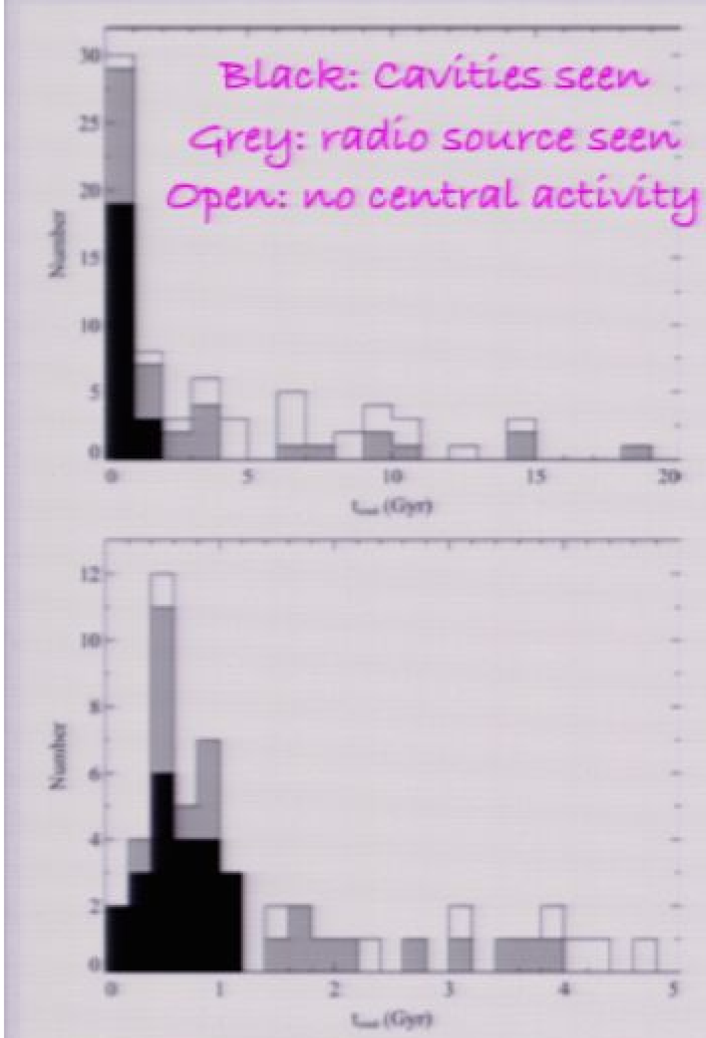


Consistent with observations



Sanderson et al (2006)

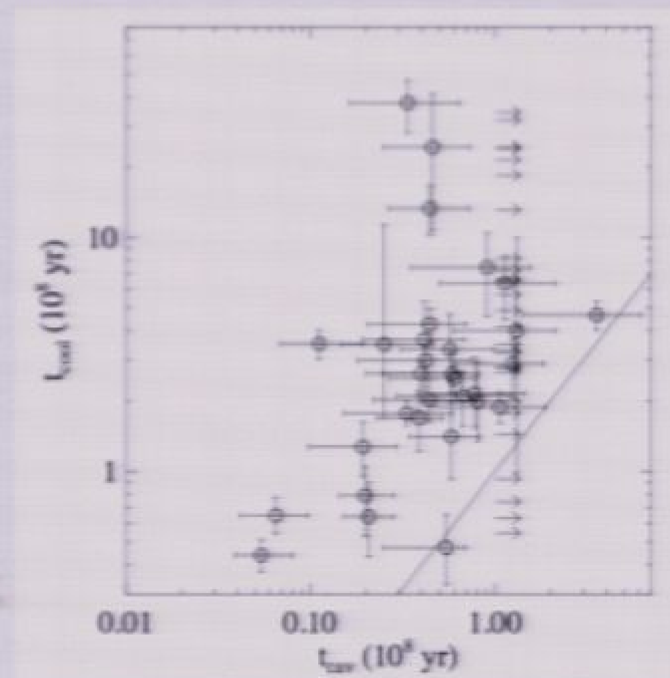
Bimodal cool-core/non-cool core population



Dunn & Fabian (2008)

More AGN activity is seen in systems with cool core systems (shorter central cooling time)

Shorter central cooling times correlate with younger cavities



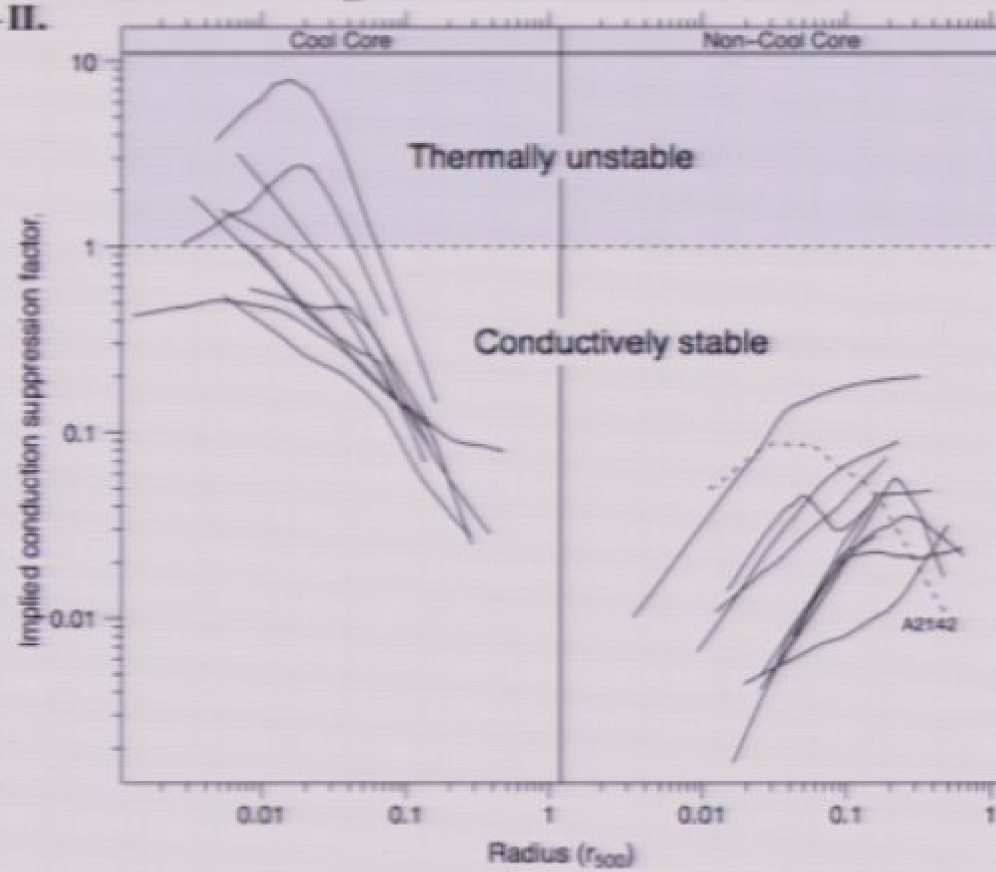
Rafferty et al (2008)

More recently...

A statistically-selected Chandra sample of 20 galaxy clusters – II. Gas properties and cool-core/non-cool core bimodality

Alastair J. R. Sanderson[1*], Ewan O'Sullivan[2] and Trevor J. Ponman[1]
[1] School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

Some more observational support for this picture!



found in CC clusters whereas the flatter slope population are all non-CC clusters. We explore the role of thermal conduction in stabilizing the ICM and conclude that this mechanism alone is sufficient to balance cooling in non-CC clusters. However, CC clusters appear to form a distinct population in which heating from feedback is required in addition to conduction.

Open Questions

- What determines the final state a cluster relaxes toward (fastest decaying eigenfunction)?
- 3D simulations
- How to get gas to black hole--is Bondi accretion the whole story? (outflows, angular momentum, hot vs. cold accretion)

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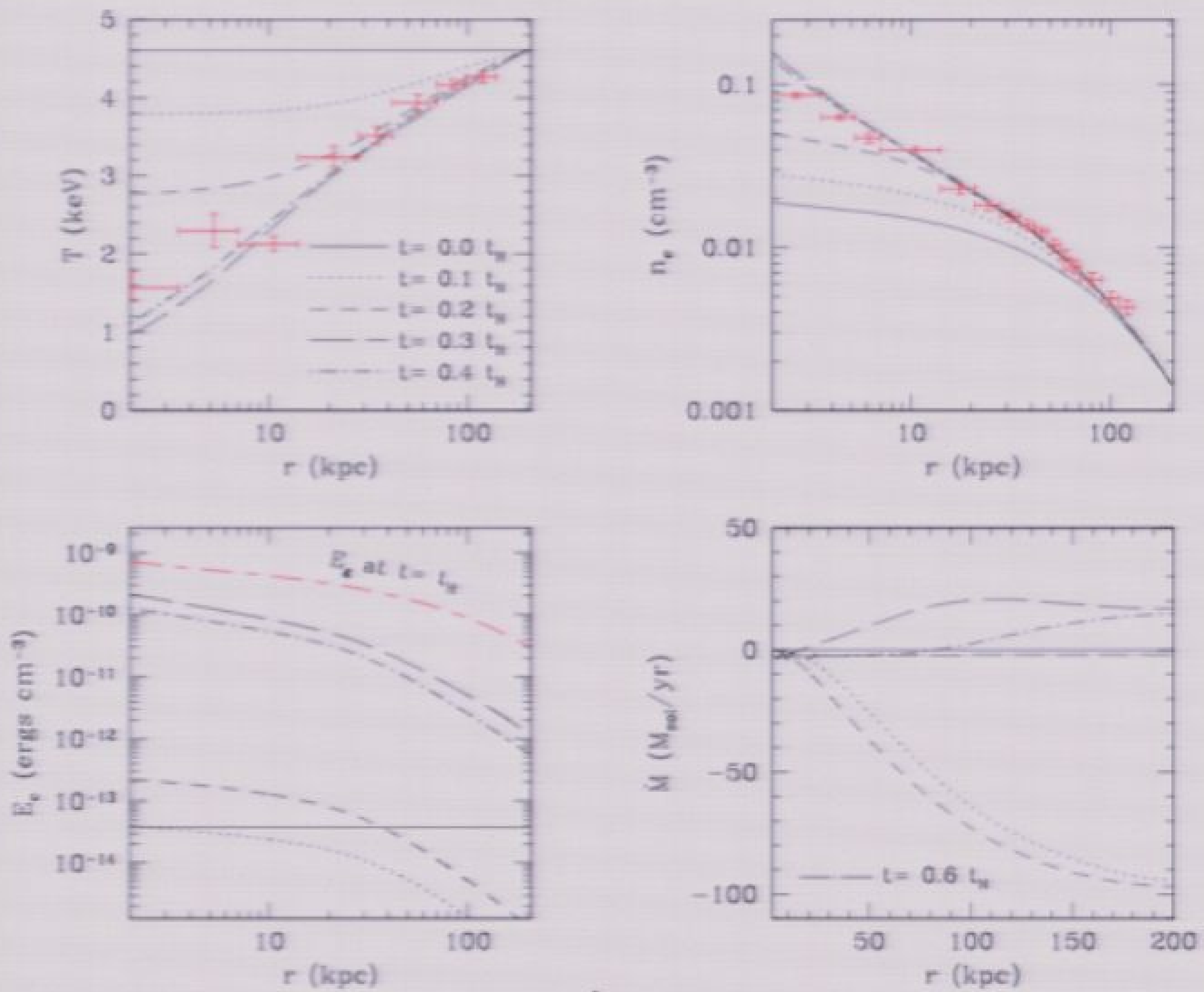

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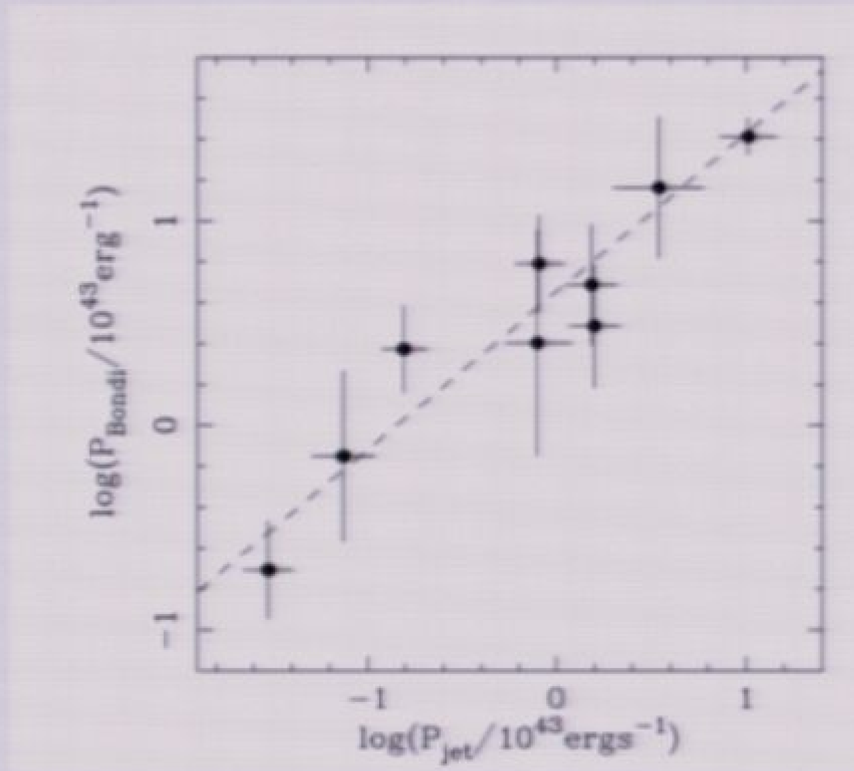

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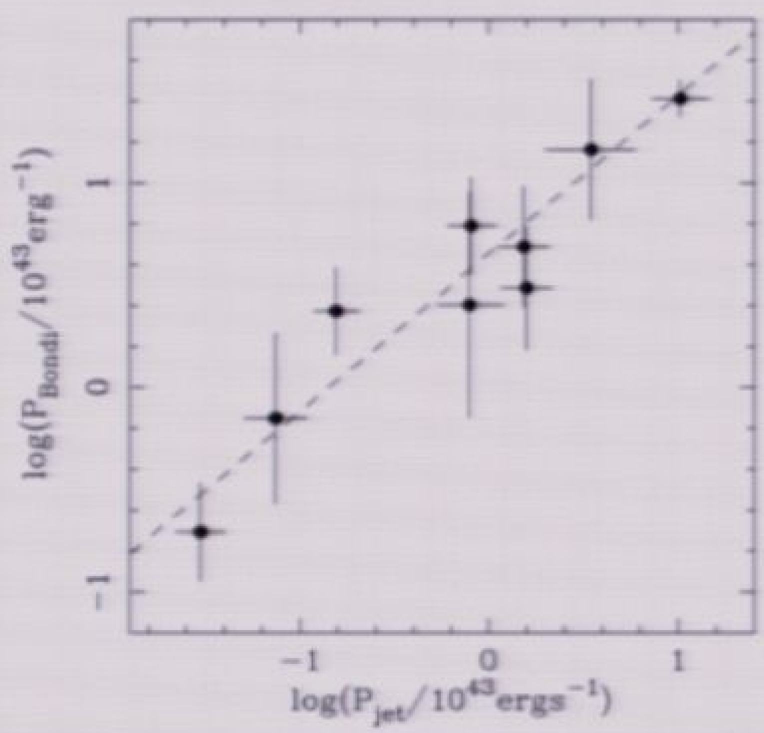

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- How to distribute heat isotropically: decaying turbulence, spinning jets...?
- Bubble stability: at what rate are bubbles disrupted? 'Magnetic shielding', CR diffusivity, etc....
- Topology of magetic field lines: could hot/cold core clusters be two aspects of the same phenomenon, viewed at different times?

- How to distribute heat isotropically: decaying turbulence, spinning jets...?
- Bubble stability: at what rate are bubbles disrupted? 'Magnetic shielding', CR diffusivity, etc....
- Topology of magetic field lines: could hot/cold core clusters be two aspects of the same phenomenon, viewed at different times?

The Bottom Line

- Cosmic ray heating can be important in clusters---rising bubbles (eventally disrupted) provide a fast means of transporting them
- Global stability analysis fast way of exploring parameter space. Predict: (i) minimal level of heating efficiency, (ii) bimodal central temperatures

Open Questions

- What determines the final state a cluster relaxes toward (fastest decaying eigenfunction)?
- 3D simulations
- How to get gas to black hole--is Bondi accretion the whole story? (outflows, angular momentum, hot vs. cold accretion)

More recently...

A statistically-selected Chandra sample of 20 galaxy clusters – II. Gas properties and cool-core/non-cool core bimodality

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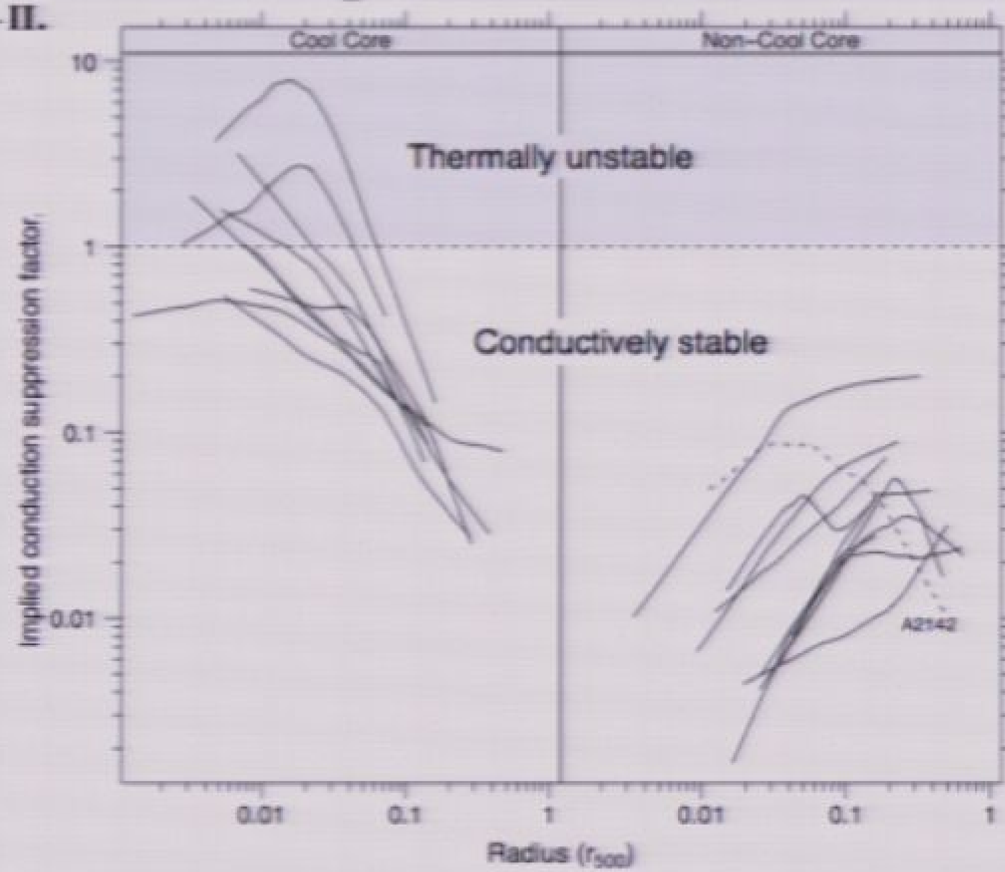
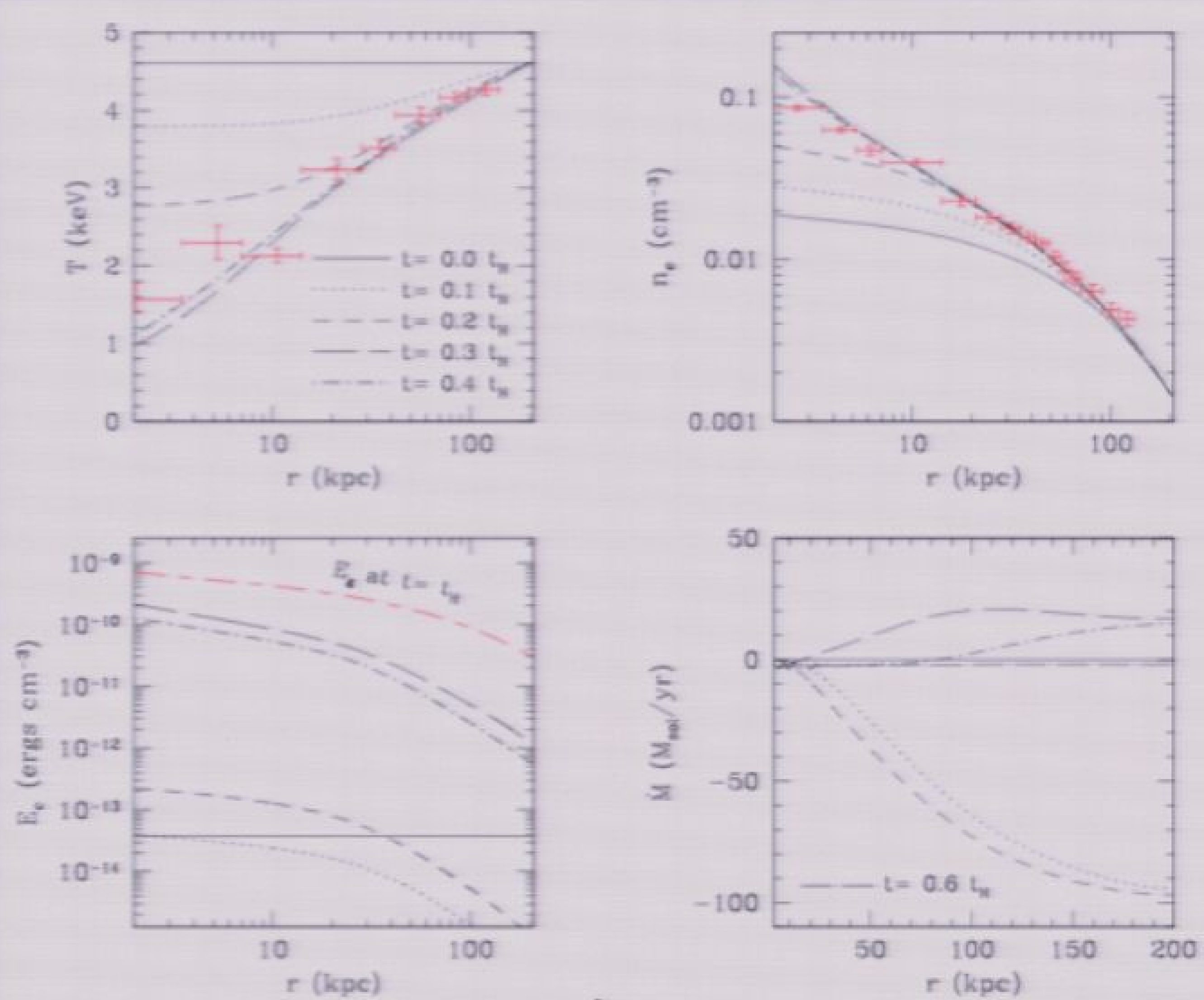


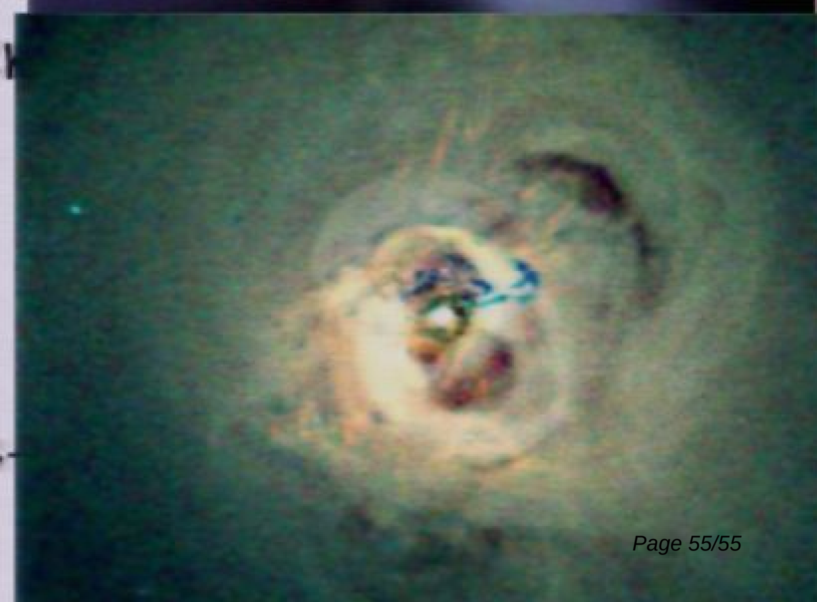
Some more observational support for this picture!

found in CC clusters whereas the flatter slope population are all non-CC clusters. We explore the role of thermal conduction in stabilizing the ICM and conclude that this mechanism alone is sufficient to balance cooling in non-CC clusters. However, CC clusters appear to form a distinct population in which heating from feedback is required in addition to conduction.



Note that CR pressure is much less than thermal pressure

But they often contain a beating heart...



which could affect:

- ☐ entropy and pressure profiles
- ☐ SZ decrement, y-parameter
- ☐ Gas fractions
- ☐ Non-thermal pressure support: turbulence, cosmic-rays...