Cosmic Ray Feedback, X-ray Cavities, and the Origin of NCC Clusters

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Physics of the ICM, Ann Arbor 08/25/2010

Talk Outline ---

AGN Feedback in Galaxy Clusters

- The Physics of AGN Outbursts
- The Impact of AGN Outbursts on the ICM

In Collaboration with

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S. Peng Oh (UC Santa Barbara)

Reference –

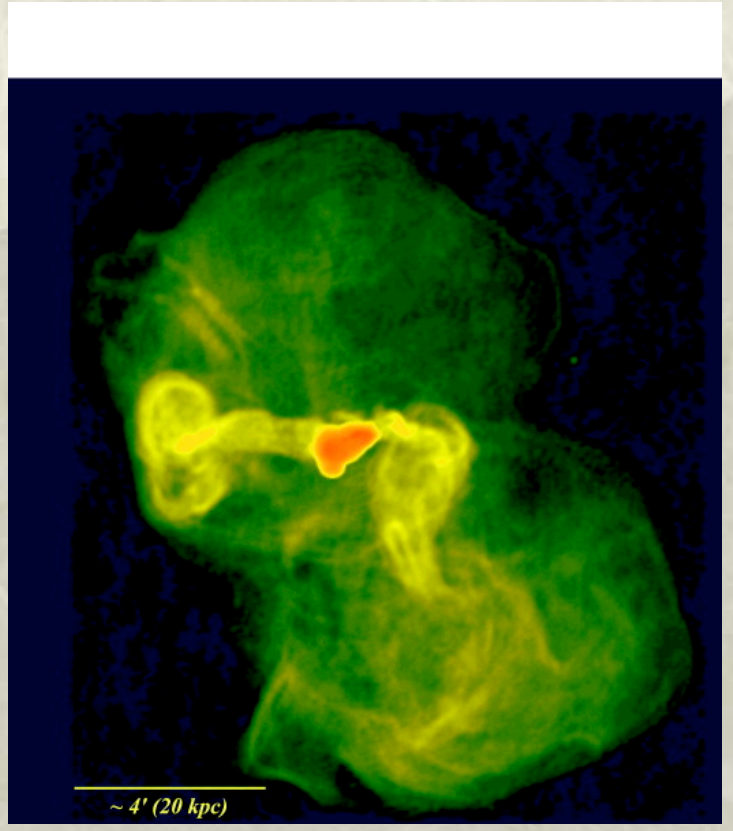
Guo & Mathews, 2010c, in prep
Guo & Mathews, 2010b, ApJ, 717, 937
Guo & Mathews, 2010a, ApJ, 712, 1311
Guo & Oh, 2009, MNRAS, 400, 1992

Motivation

- AGN Feedback is often invoked in galaxy clusters to solve the cooling floor problem and the overcooling problem

- Strong observational evidence of AGN feedback has seen in galaxy clusters – X-ray cavities/radio bubbles

AGN feedback is observed

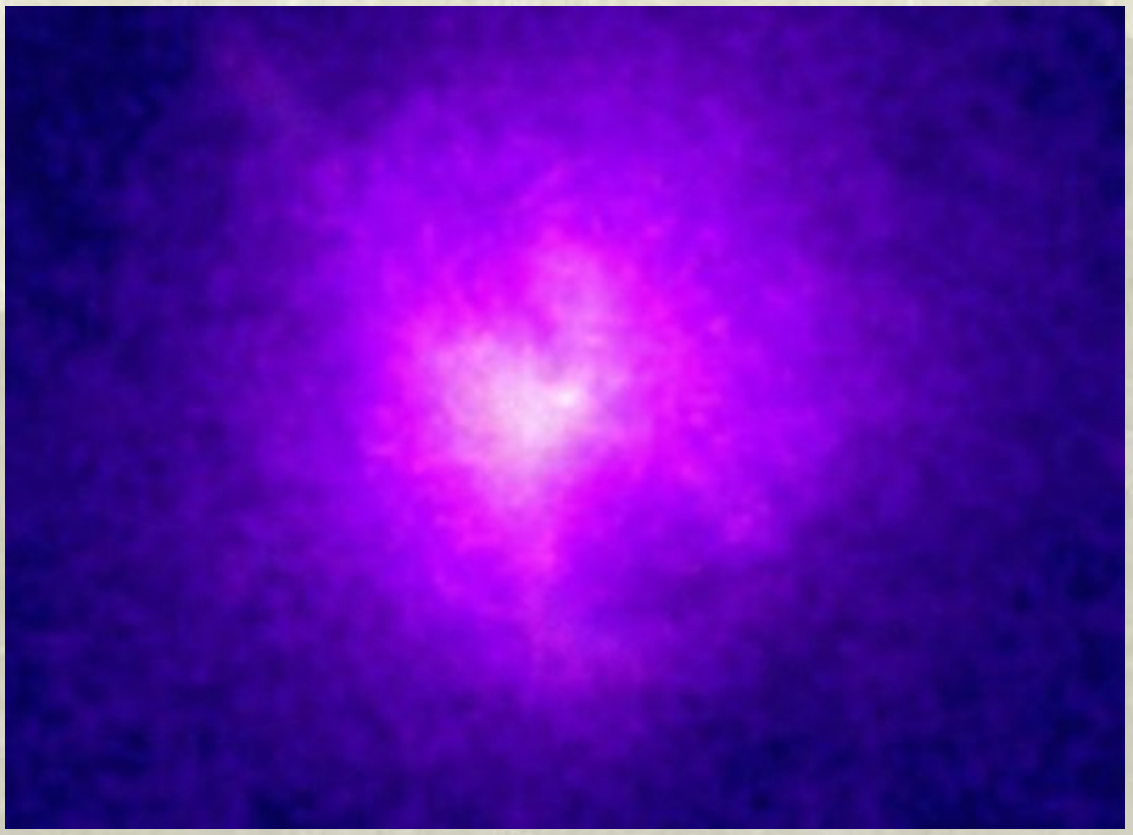


M87 at 90 cm (Owen et al 2000)

in RADIO!

Bubbles/lobes

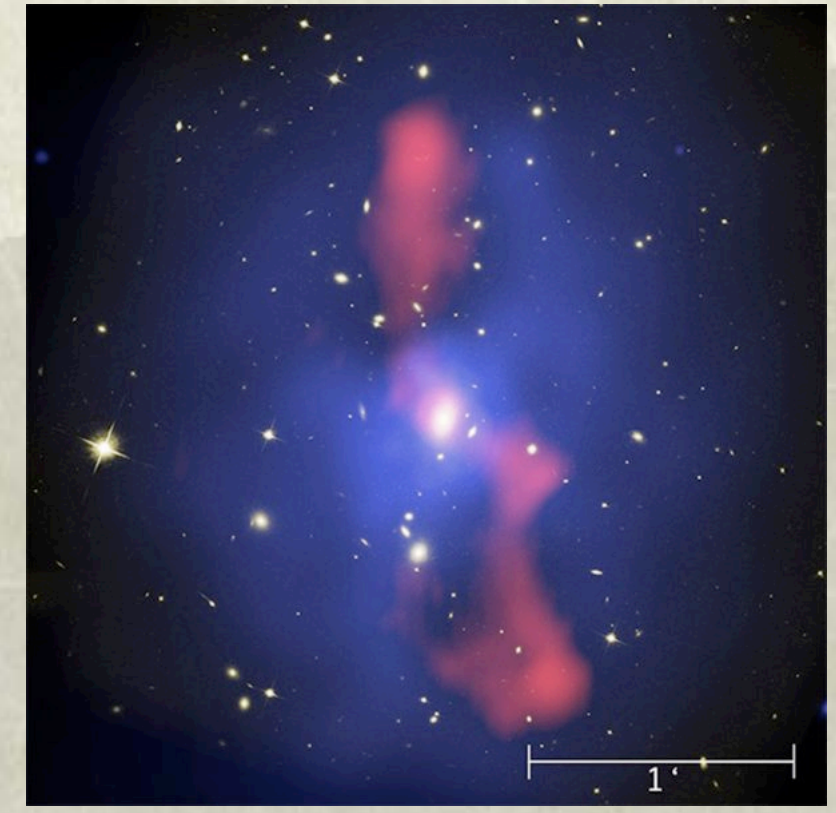
and in X-ray – cavities



Hydra A

Radio lobes are often spatially coincident with X-ray cavities!

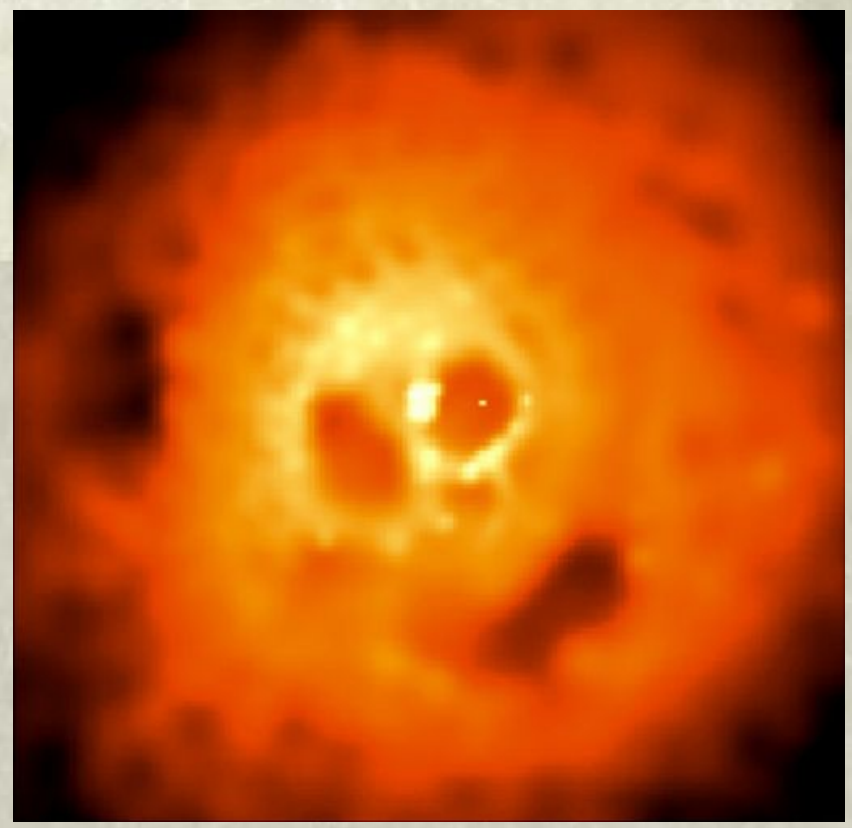
Red : Radio
Blue: X-ray



Inner 700 kpc of MS0735.6+7421 (Mcnamara et al 2009)

- This is the most powerful AGN outburst observed. A pair of X-ray cavities with diameter ~ 200 kpc are detected.

Cavity Shape and Location



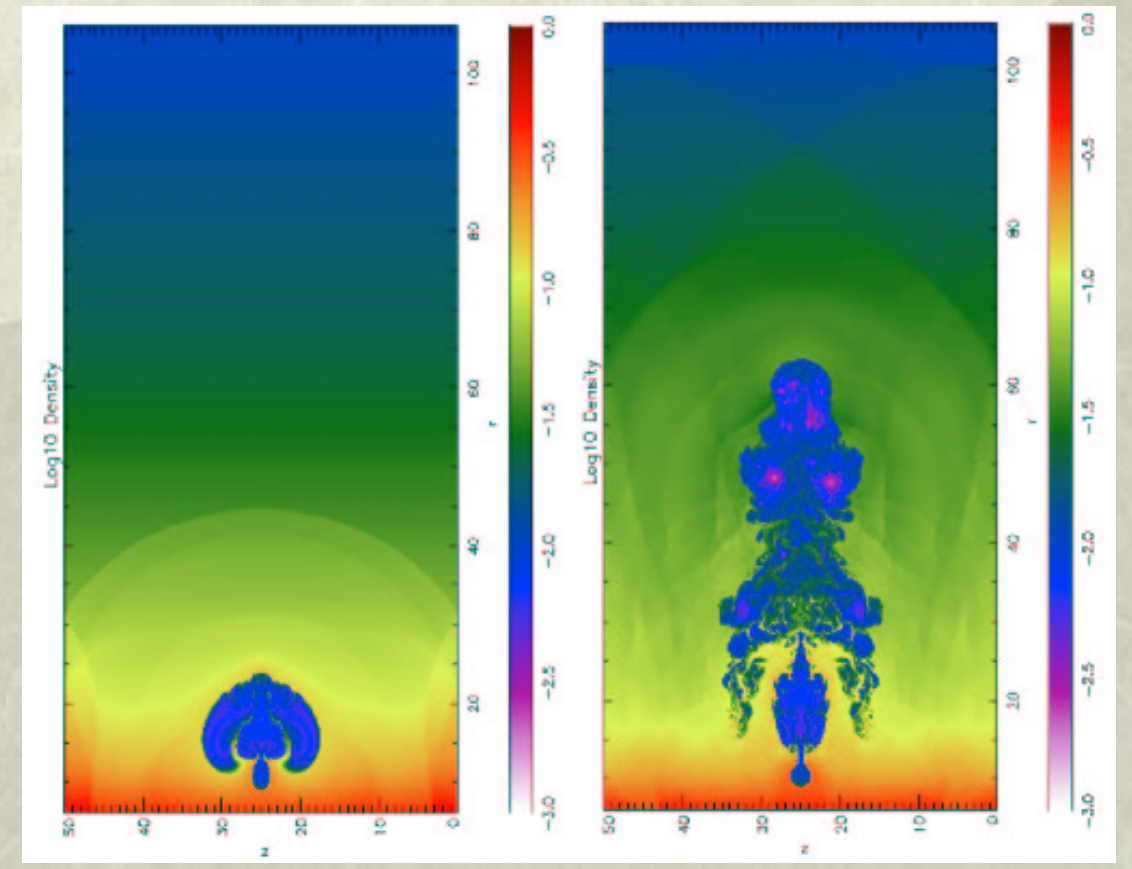
Chandra image of Perseus Cluster

- Most observed cavities are located near cluster centers, and are roughly spherical or elongated in the tangential direction.
- Cavities seem to rise buoyantly in the ICM.

How to study AGN feedback?

- Numerical Simulations!

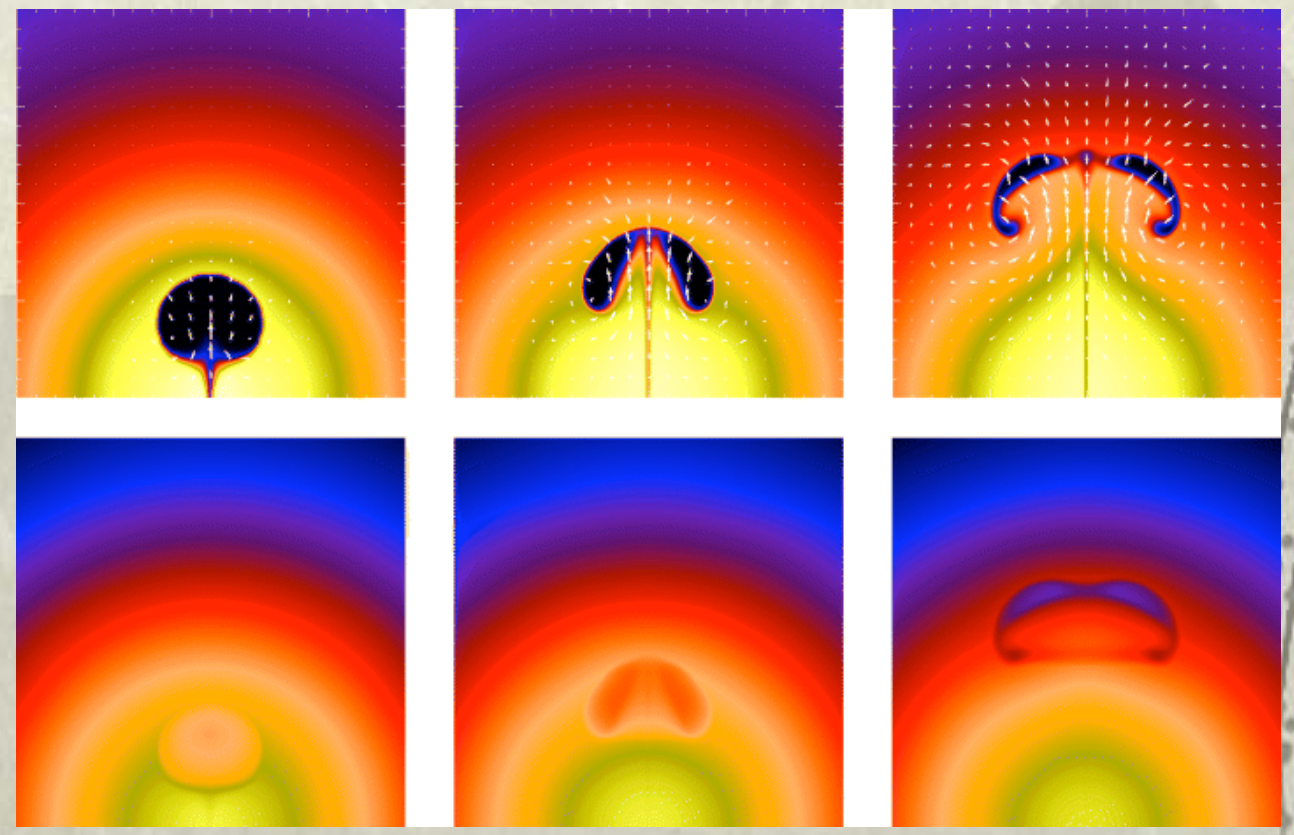
Simulating AGN outbursts I



Brüggen & Kaiser 2002

- Method I --- Hot, buoyant gas is injected into a small region offset from the cluster center.

Simulating AGN outbursts II



Reynolds et al 2005

- Method II --- a cavity containing ultra-hot thermal gas is initialized in the ICM in pressure equilibrium with the ambient gas.

Cavities are formed by AGN jets!

- Ultimately, AGN feedback should be investigated by directly simulating AGN jets

-- the jet evolution in the ICM

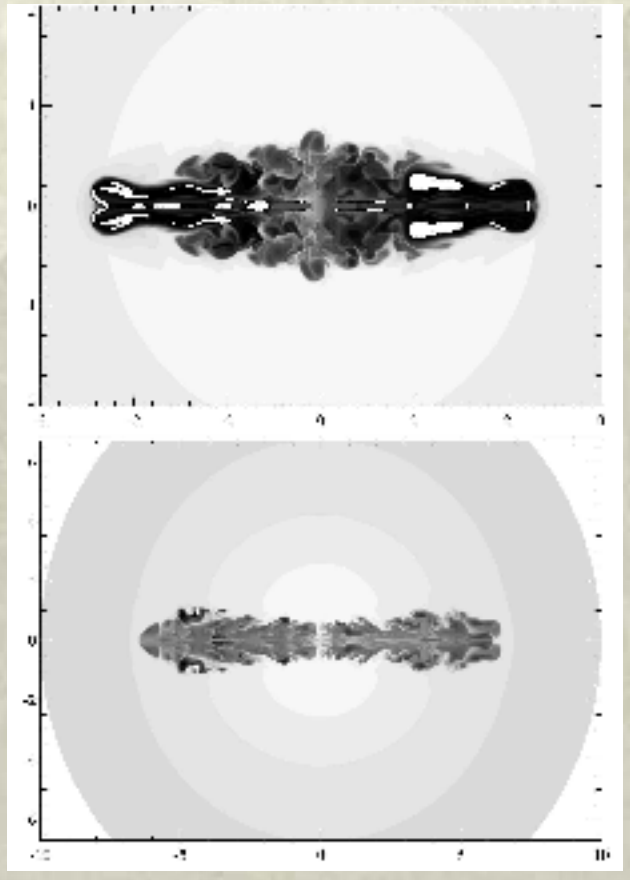
-- the impact of AGN jets on the ICM

Simulating AGN outbursts III

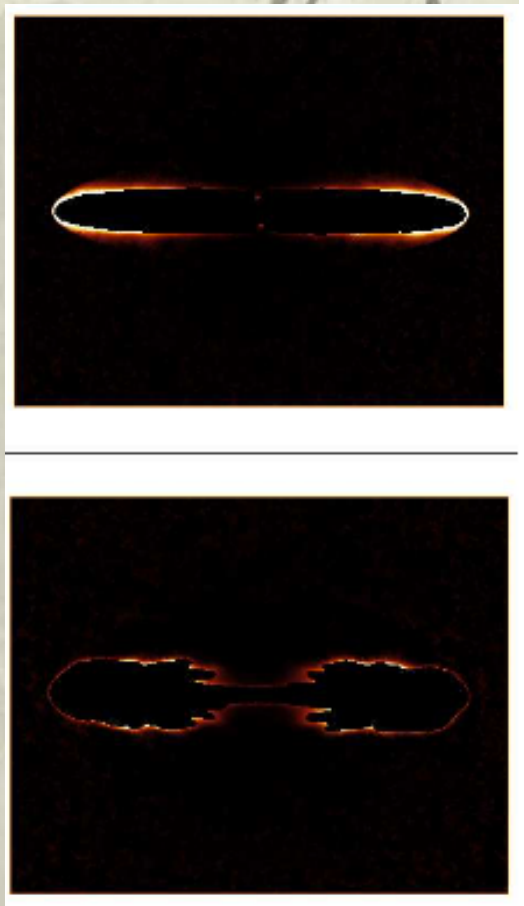
The jet-to-ICM ratio of

-- density 1:100

-- pressure 1:1



Reynolds et al 2008



O'Neill & Jones, 2010

- Method III ---light jet containing ultra-hot gas is initialized to simulate AGN feedback.

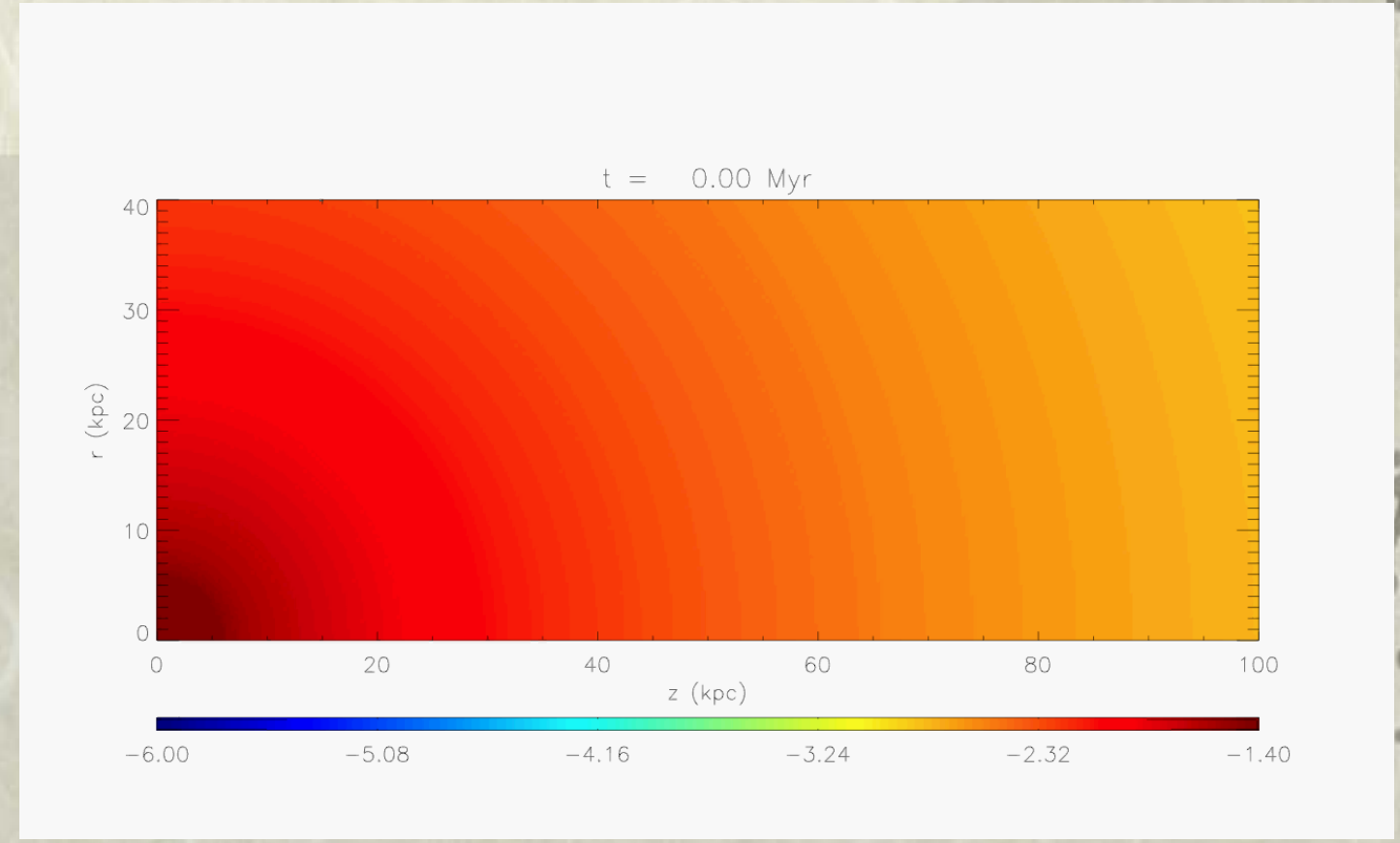
The Cavity Formation Problem

- The energy fluxes of these light thermal jets are dominated by the kinetic energy

- Thermal jets penetrate through the ICM quickly, and form radially-elongated cavities at large radii, unlike observed cavities

The Cavity Formation Problem

Log (Electron number density)



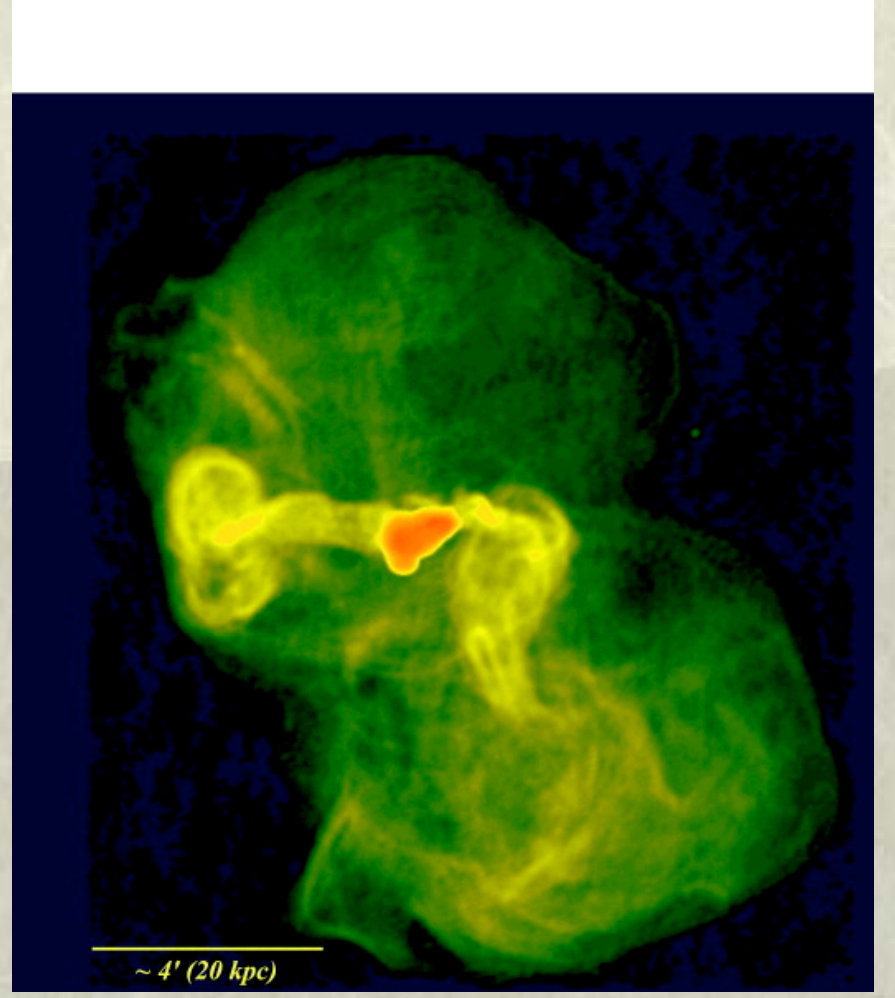
Thermal jet active for 10 Myr

Guo & Mathews 2010c, in prep

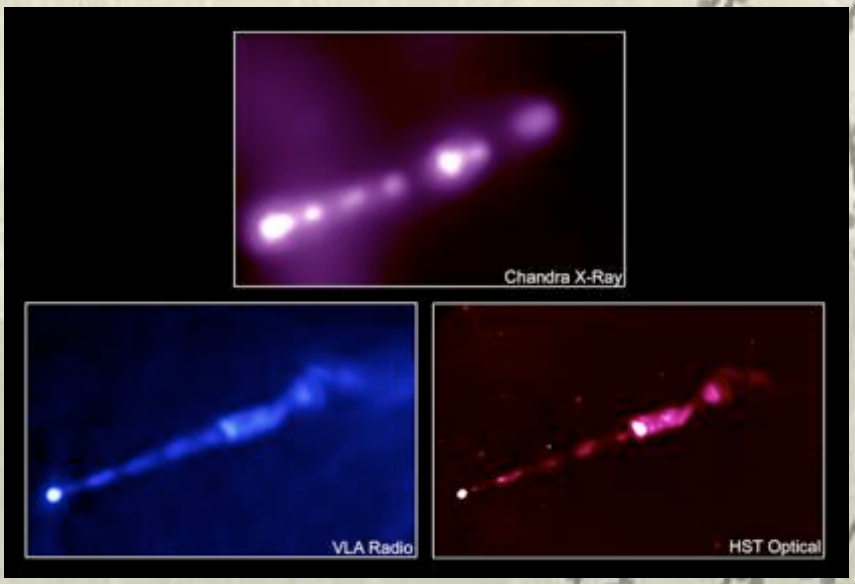
How to solve the cavity formation problem?

- Wide jets with half opening angles >~ 50° (Sternberg et al. 2007)
- fast precessing jets with large precessing angles (Sternberg & Soker 2008)
- Large random gas motions in the ICM (Brüggen et al 2007; Morsony et al 2010)

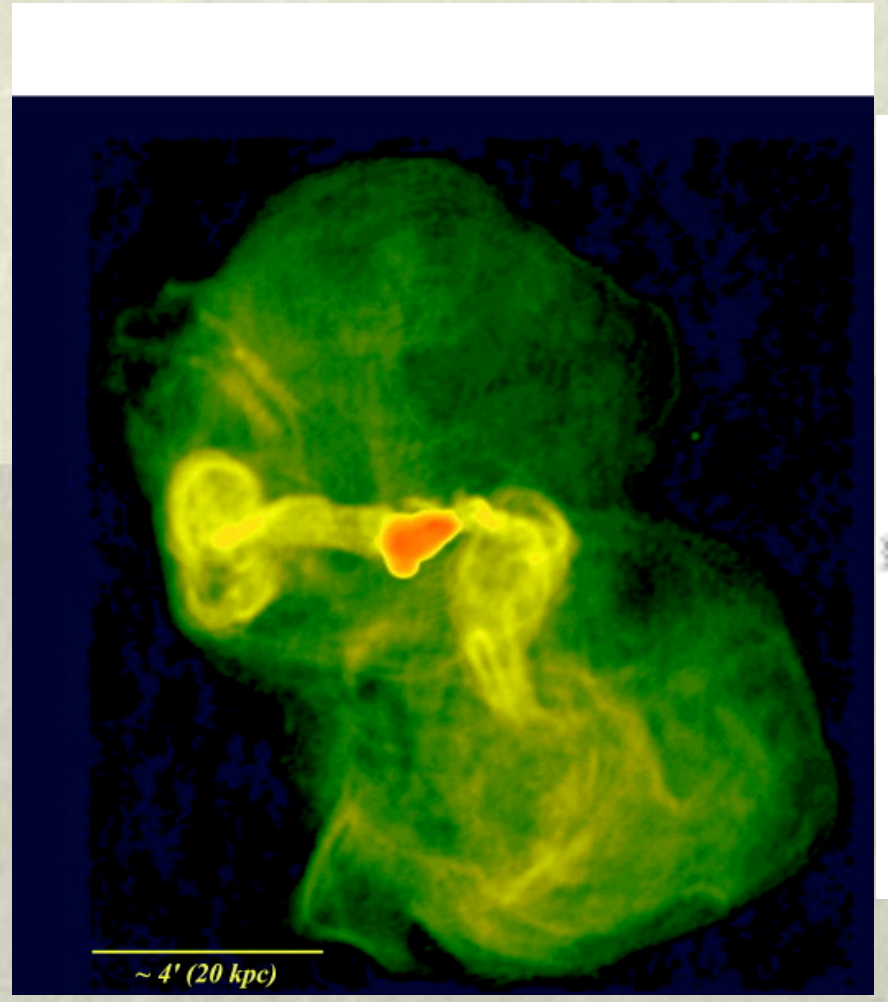
- Is any of there situations common in AGN jets?
- Do we have a more natural way to create fat cavities?

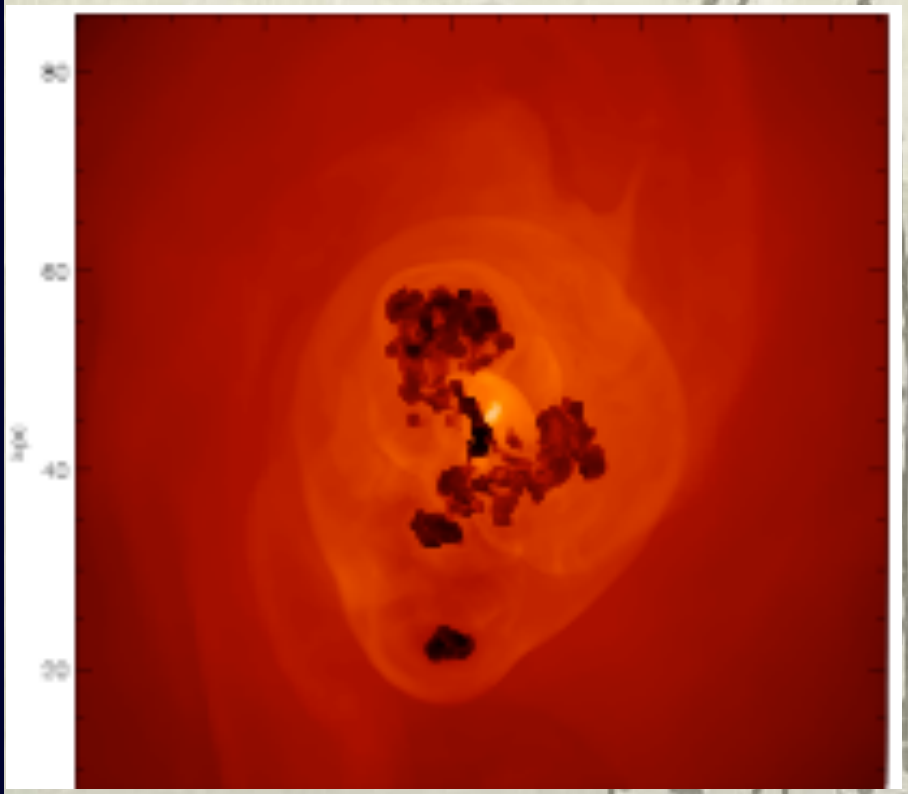


The Virgo Cluster



M87 jet



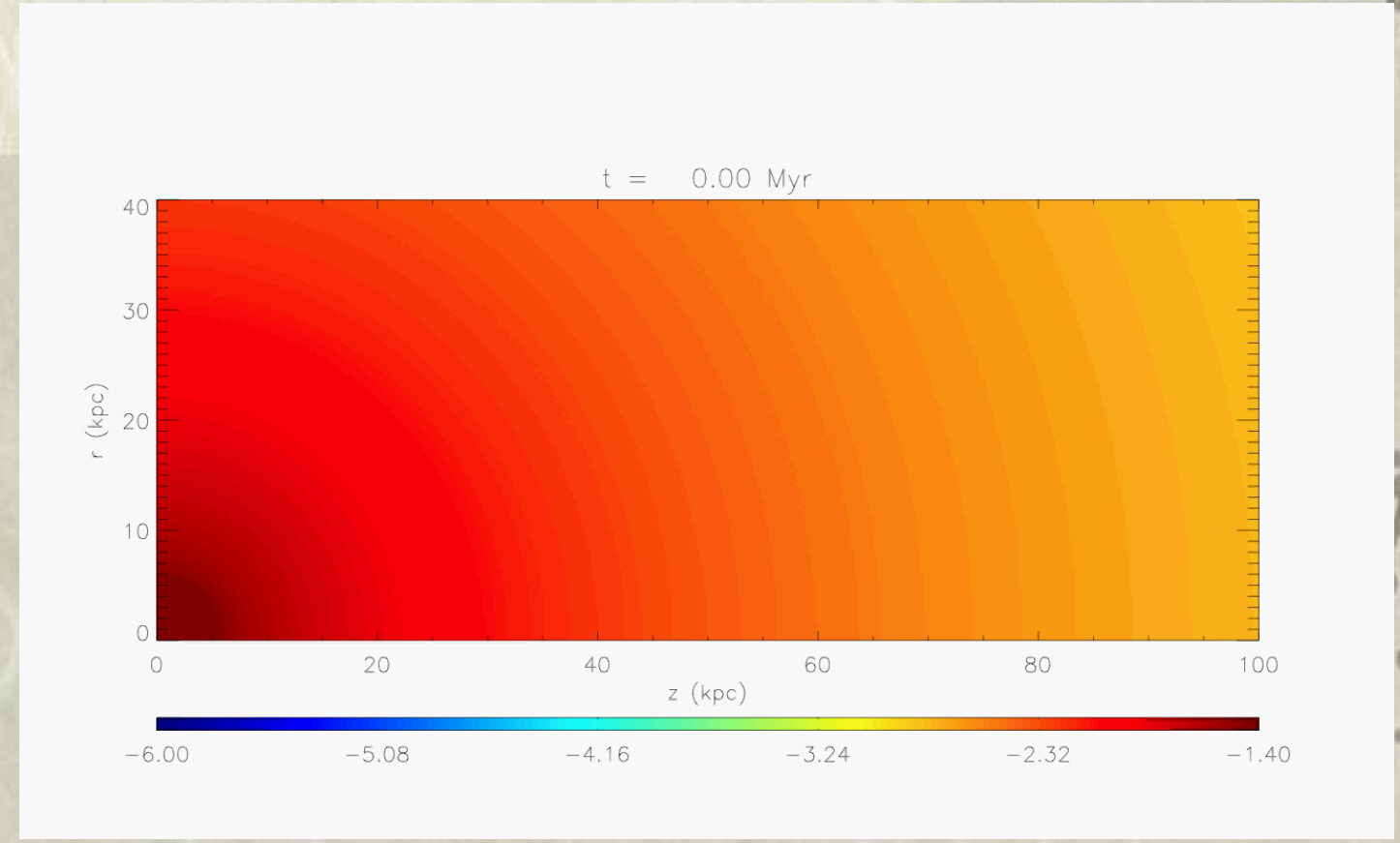


Brüggen et al 2007

The Virgo Cluster

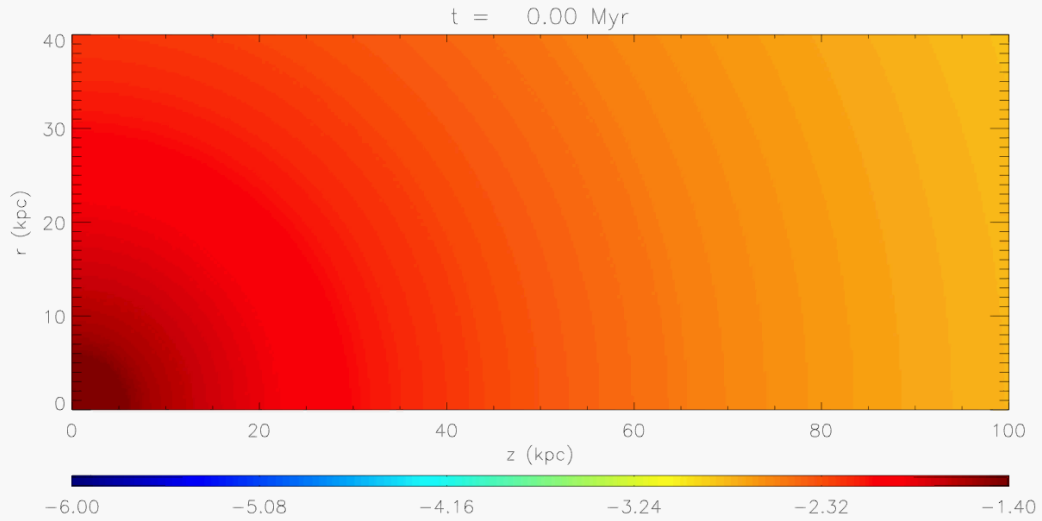
Cosmic-ray-dominated Jets

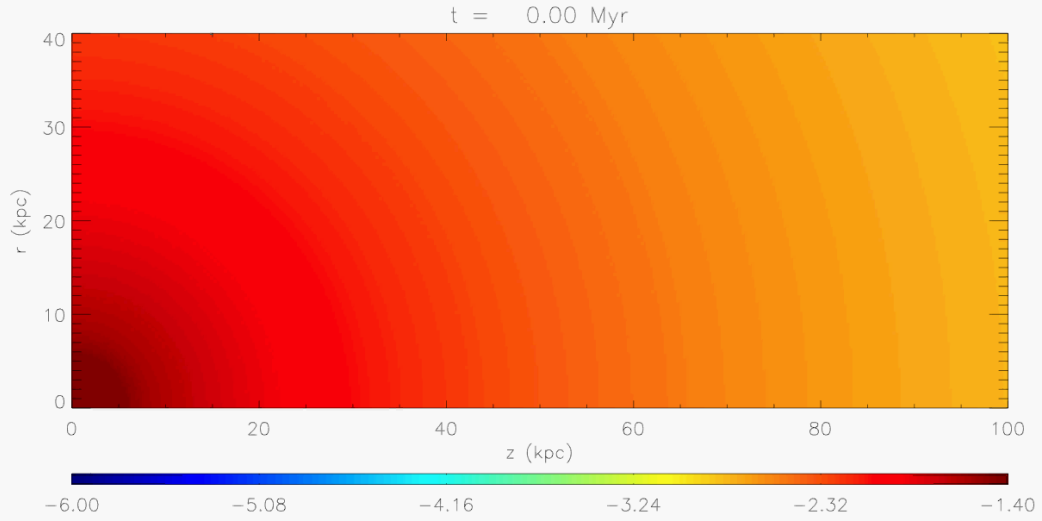
If the jet is very light (e.g., η=1/10000), and dominated by CRs …



CR-dominated jet active for 10 Myr

Guo & Mathews 2010c, in prep


t = 0.00 Myr
r (kpc)
z (kpc)
0
10
20
30
40
0
20
40
60
80
100
−6.00
−5.08
−4.16
−3.24
−2.32
−1.40


t = 0.00 Myr
r (kpc)
z (kpc)
0
10
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30
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20
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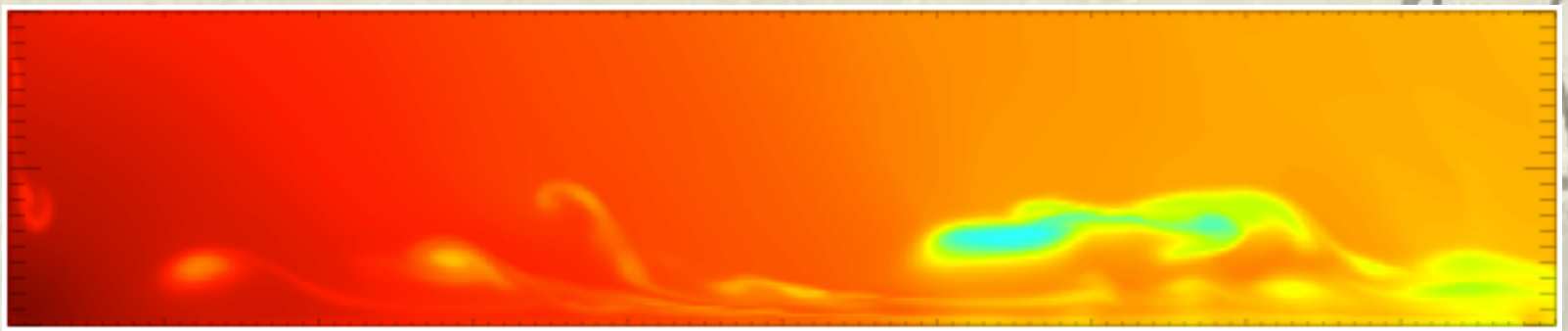
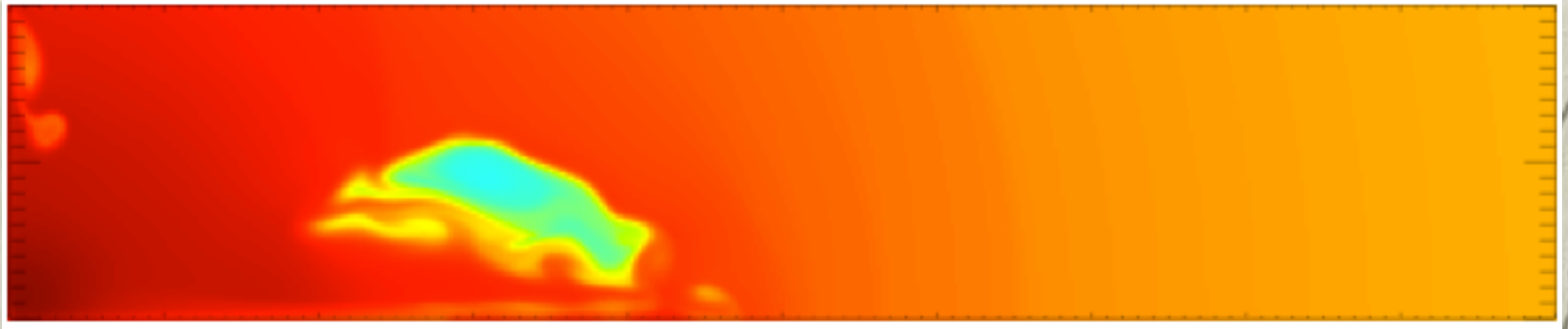
−1.40

Thermal jet



CR jet



Why CR-dominated jets form fat cavities near cluster centers?

- Low jet inertia and momentum
- Lateral expansion induced by the CR pressure
- For more details, see Guo & Mathews (2010c), which should be posted on astro-ph within one or two weeks

The Physics of AGN Outbursts

- Light CR-dominated AGN jets naturally produce fat X-ray cavities near cluster centers

- More studies on AGN feedback should be done with extremely light CR-dominated jets!

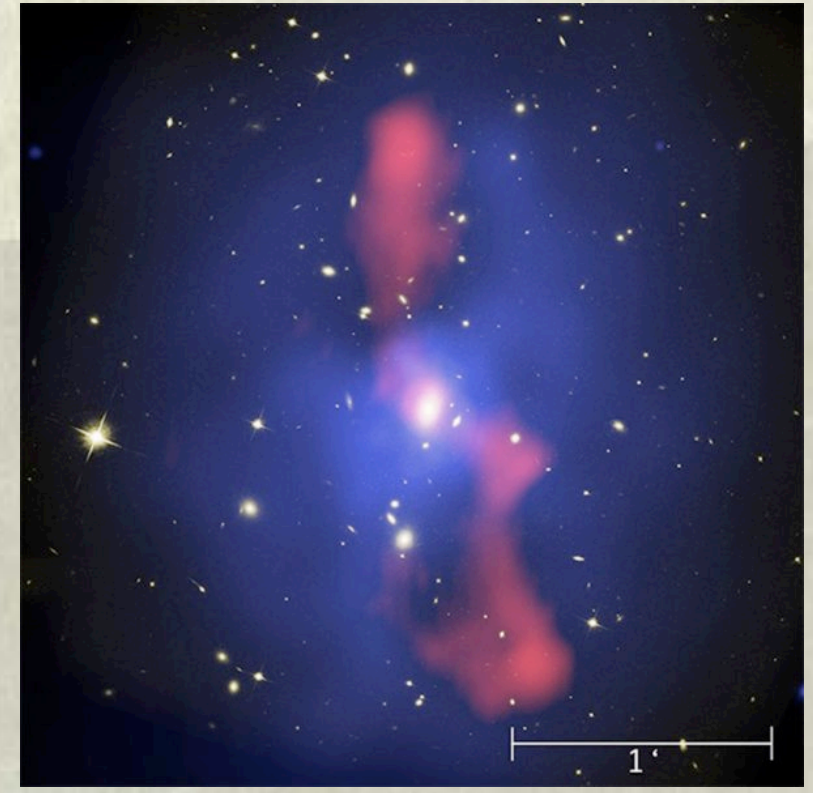
Impact of AGN Outbursts on the ICM

- Suppress cooling flows

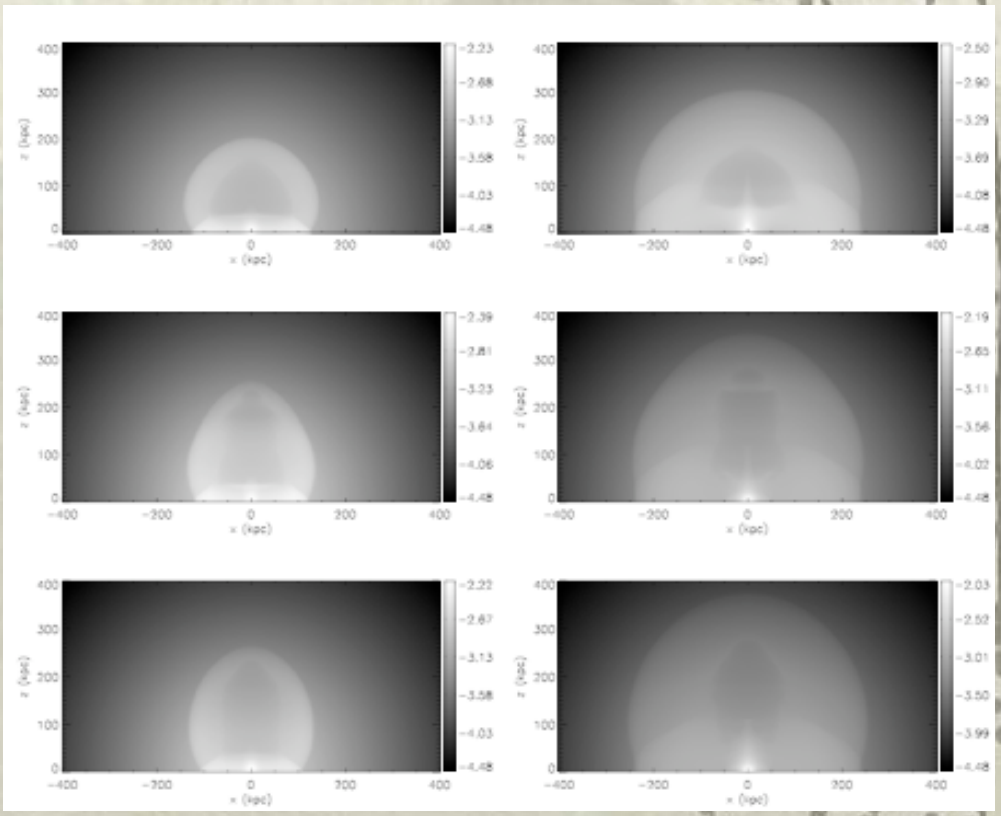
- Extreme cases – Powerful AGN Outbursts

  AGN energy ~10^61 - 10^62 erg

Powerful AGN outbursts create huge X-ray cavities : diameter ~ 200 kpc



MS0735.6+7421 (Mcnamara et al 2009)



Guo & Mathews 2010a

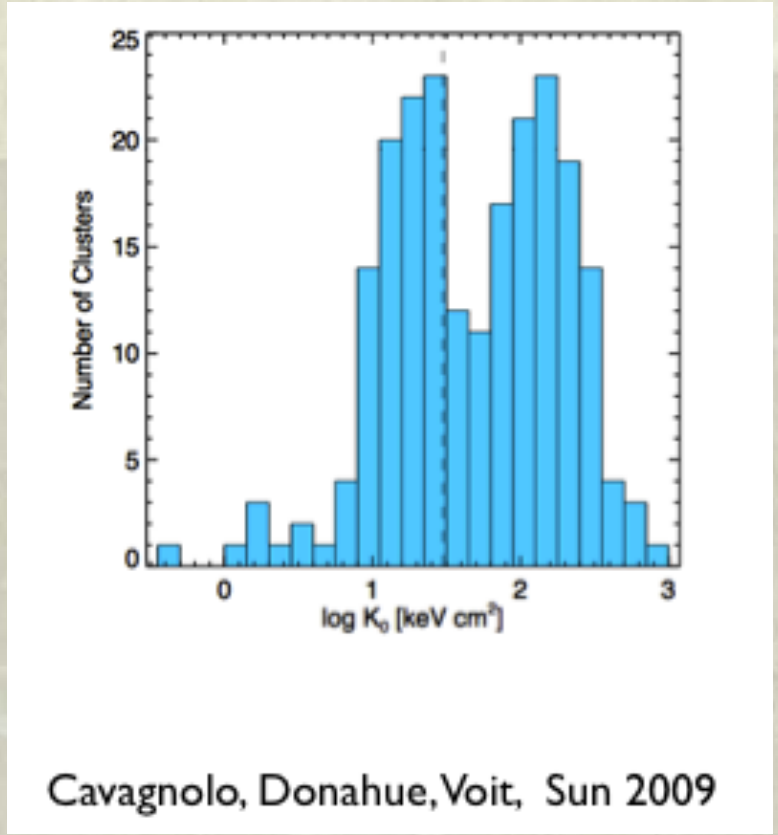
Powerful AGN Outbursts

Remove cool cores?

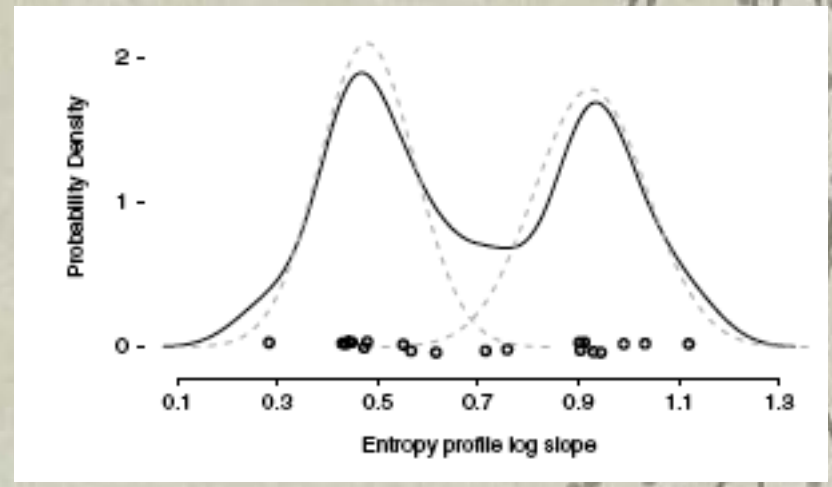
- If a fraction of its energy is injected near the center, could powerful AGN outbursts remove cool cores and produce a non cool core cluster?

The CC/NCC Bimodality

Central entropy



Entropy profile log slope

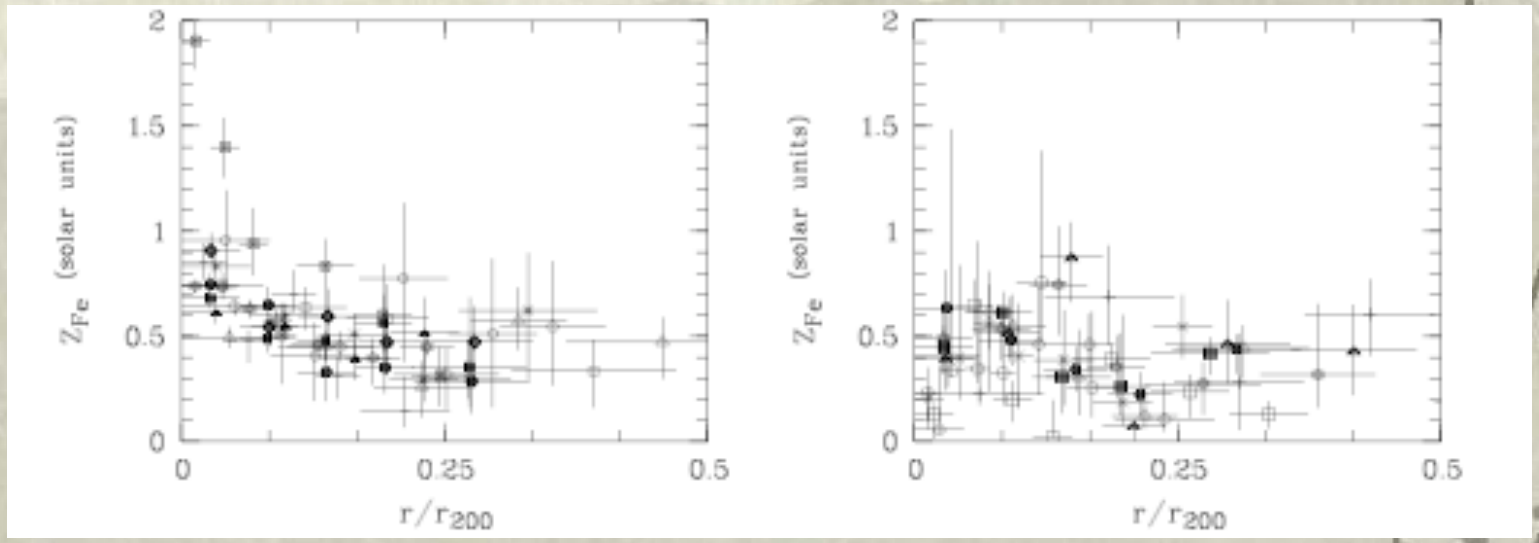


Sanderson et al. 2009

Metal Distribution in Observations

CC clusters

NCC clusters

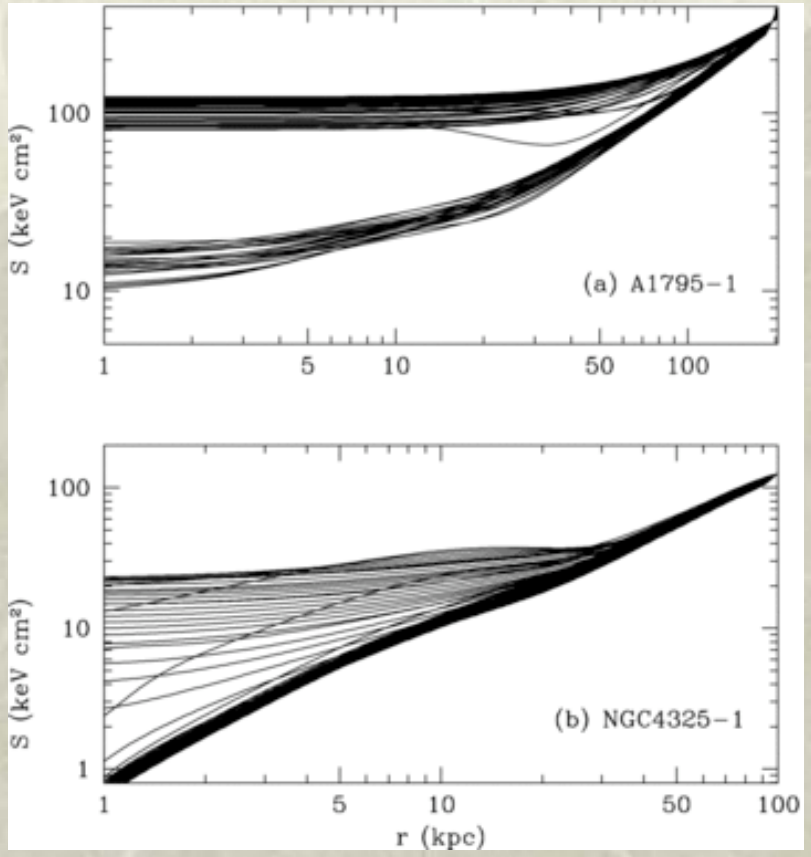


De Grandi et al 2004

However, recent observations suggest that some NCC clusters have central metallicity peaks!

Our 1D feasibility study confirms that such injected energy is large enough!

Entropy



Radius (kpc)

E~3 × 10^{61} erg

E~2 × 10^{59} erg

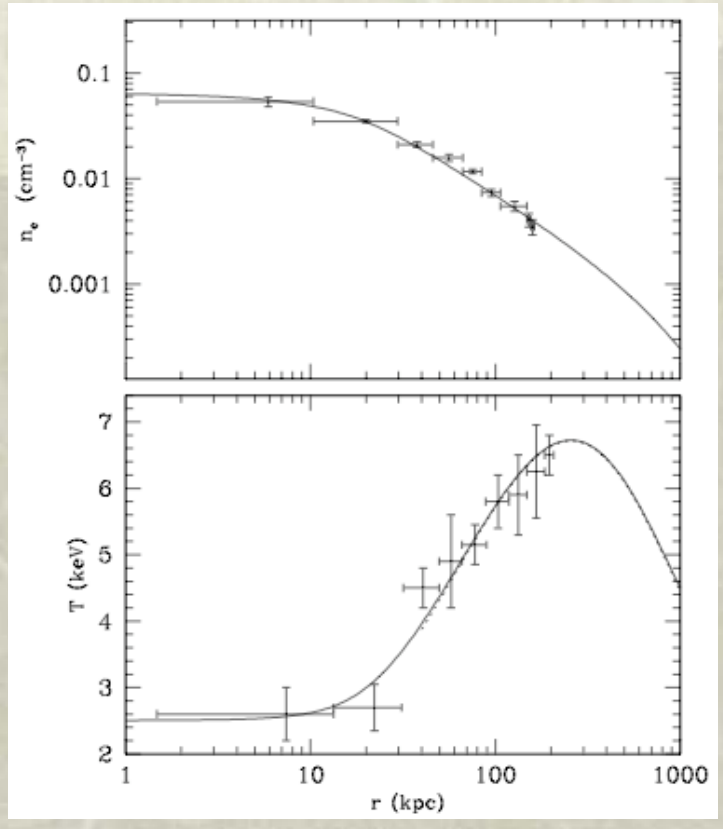
Guo & Oh 2009

Simulations of AGN outbursts

Using our CR feedback model for a typical CC cluster A1795…

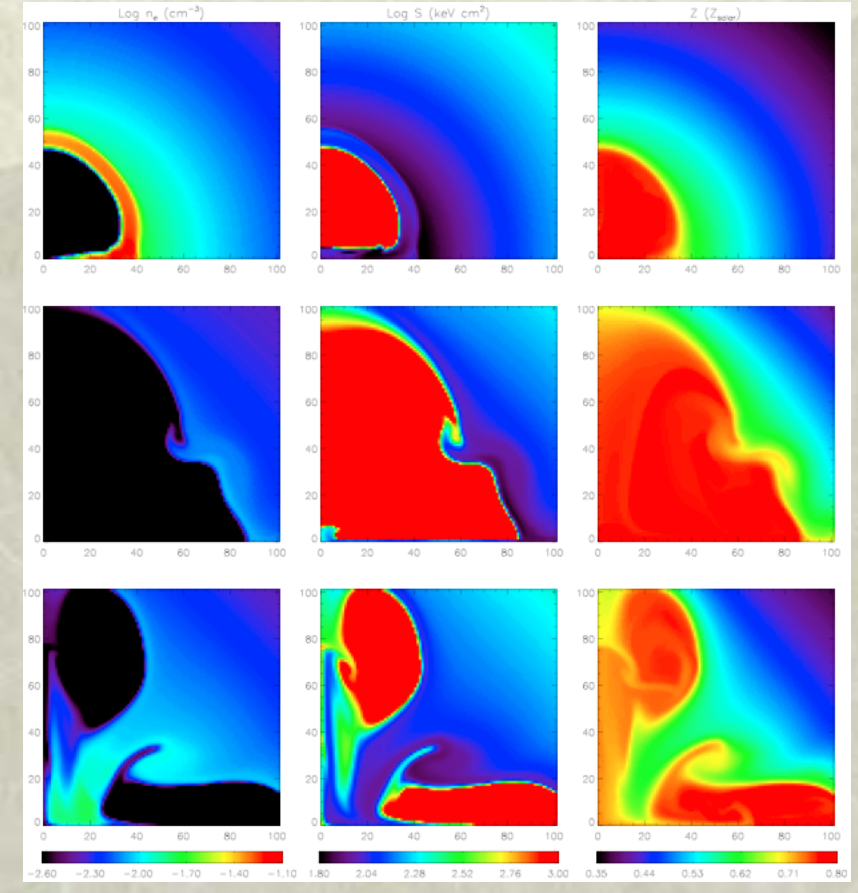
Density

Temperature



Guo & Mathews 2010b

When AGN energy is injected near the center…



E~3 × 10^{61} erg

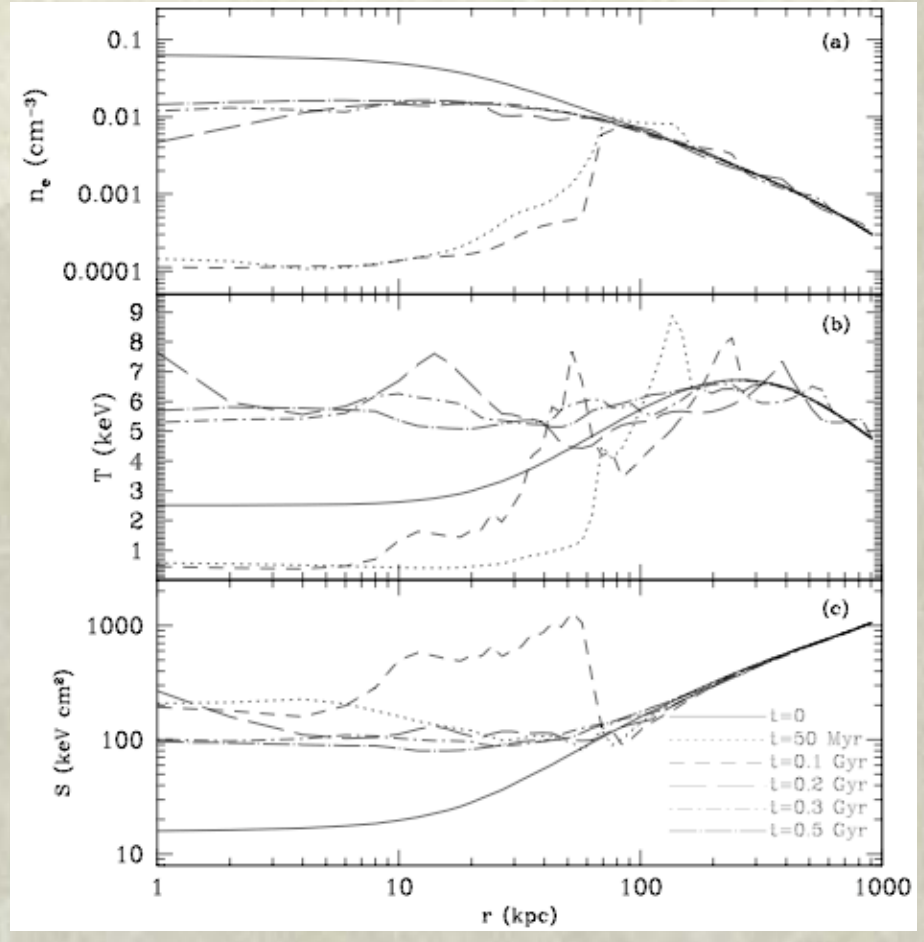
Guo & Mathews 2010b

The cluster relaxes to NCC state!

density

Temperature

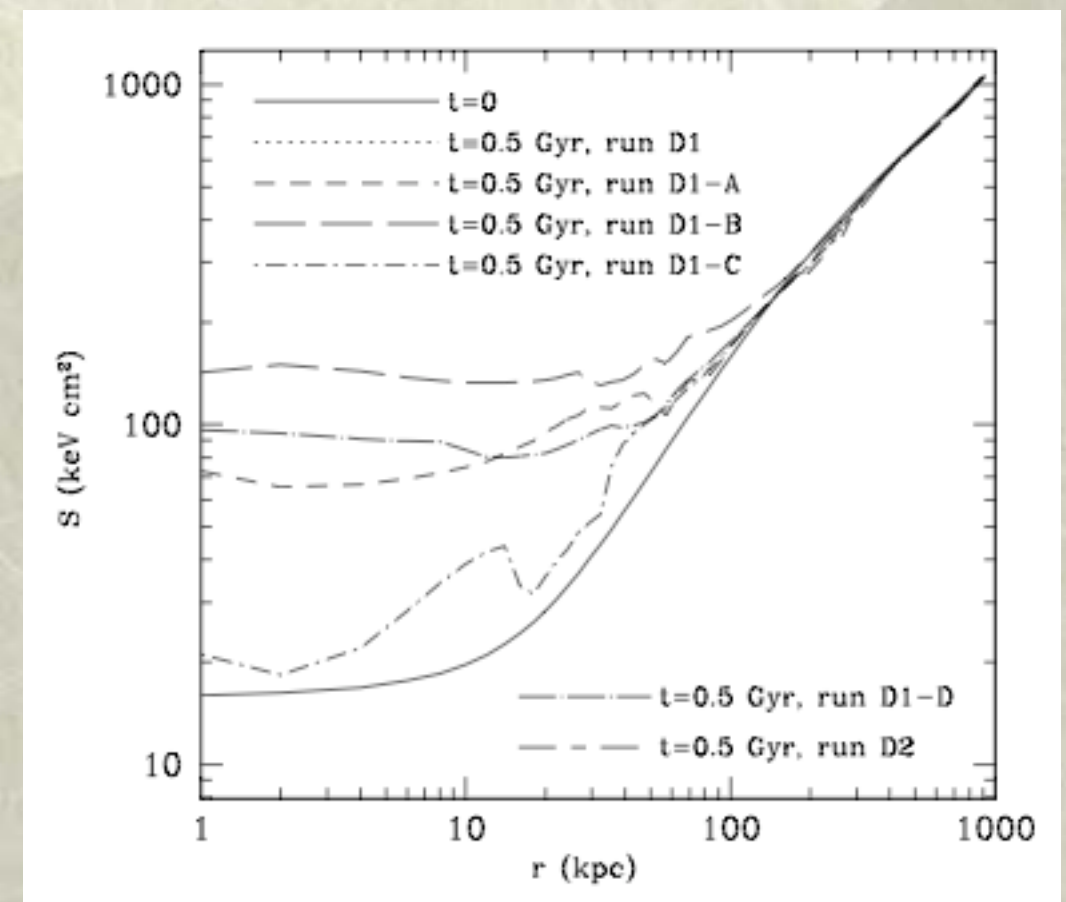
entropy



E~3 × 10^{61} erg

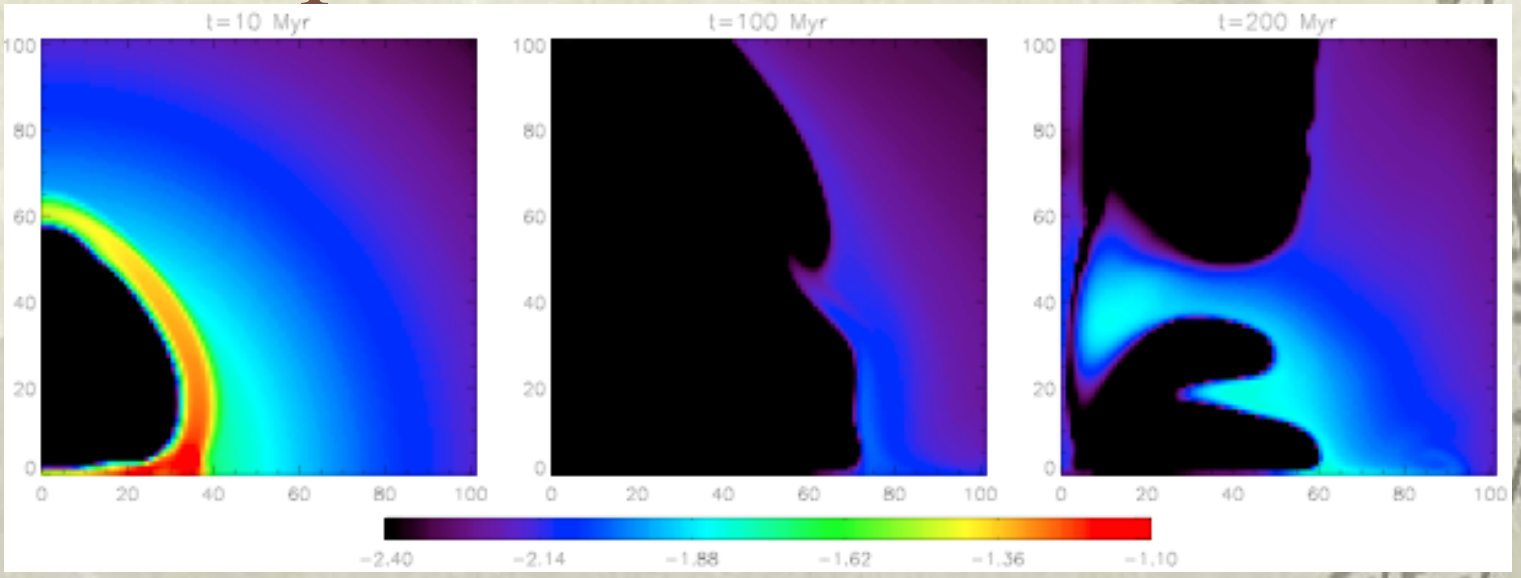
Guo & Mathews 2010b

Some energy must be dissipated near the cluster center

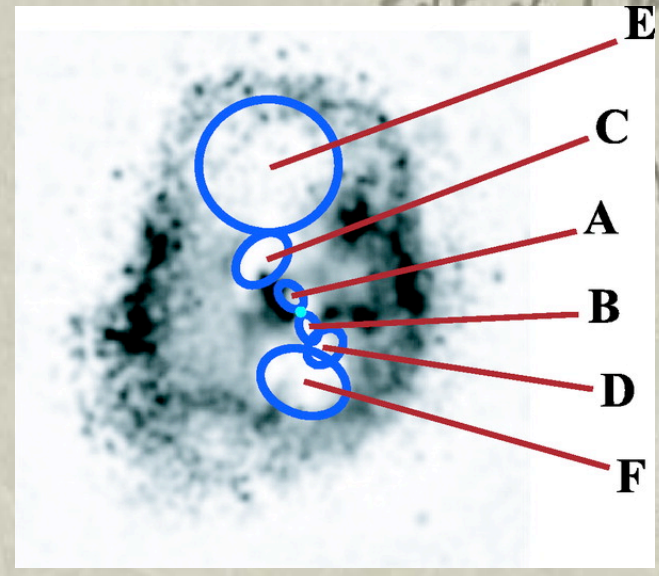


Guo & Mathews 2010b

Compare with observations



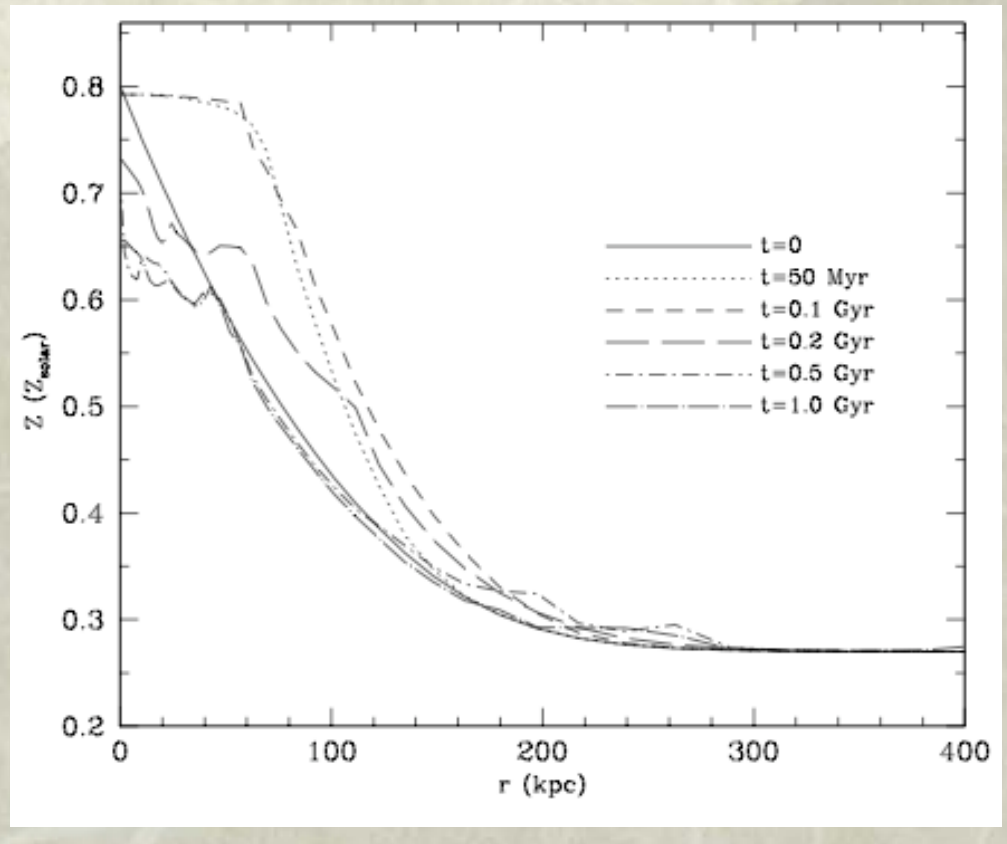
Guo & Mathews 2010b



Wise et al 2007

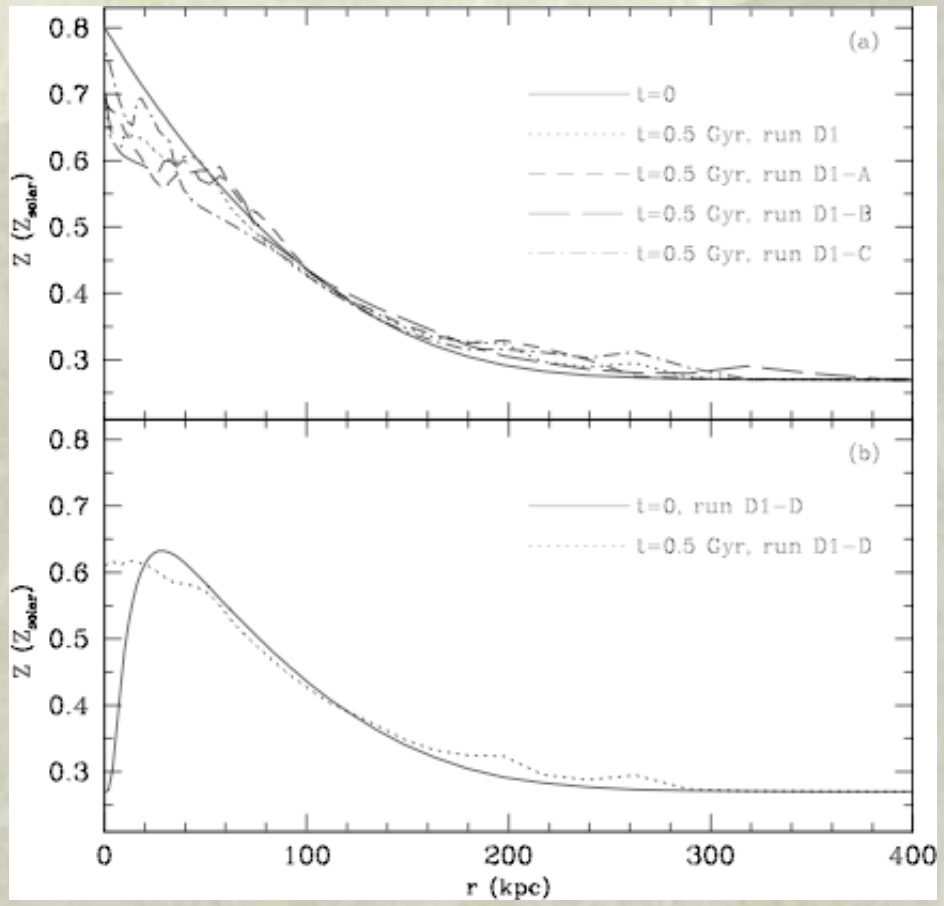
Even more interestingly,

Evolution of metallicity profile



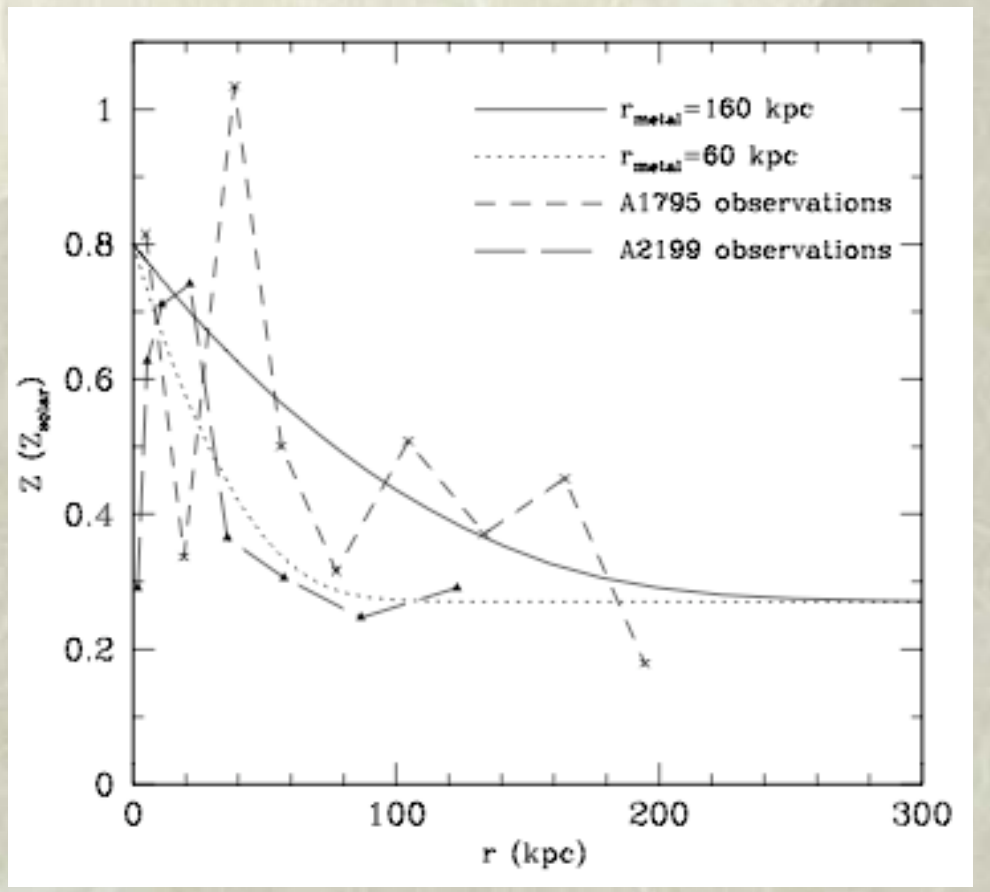
Guo & Mathews 2010b

Central metallicity peak is difficult to be removed!



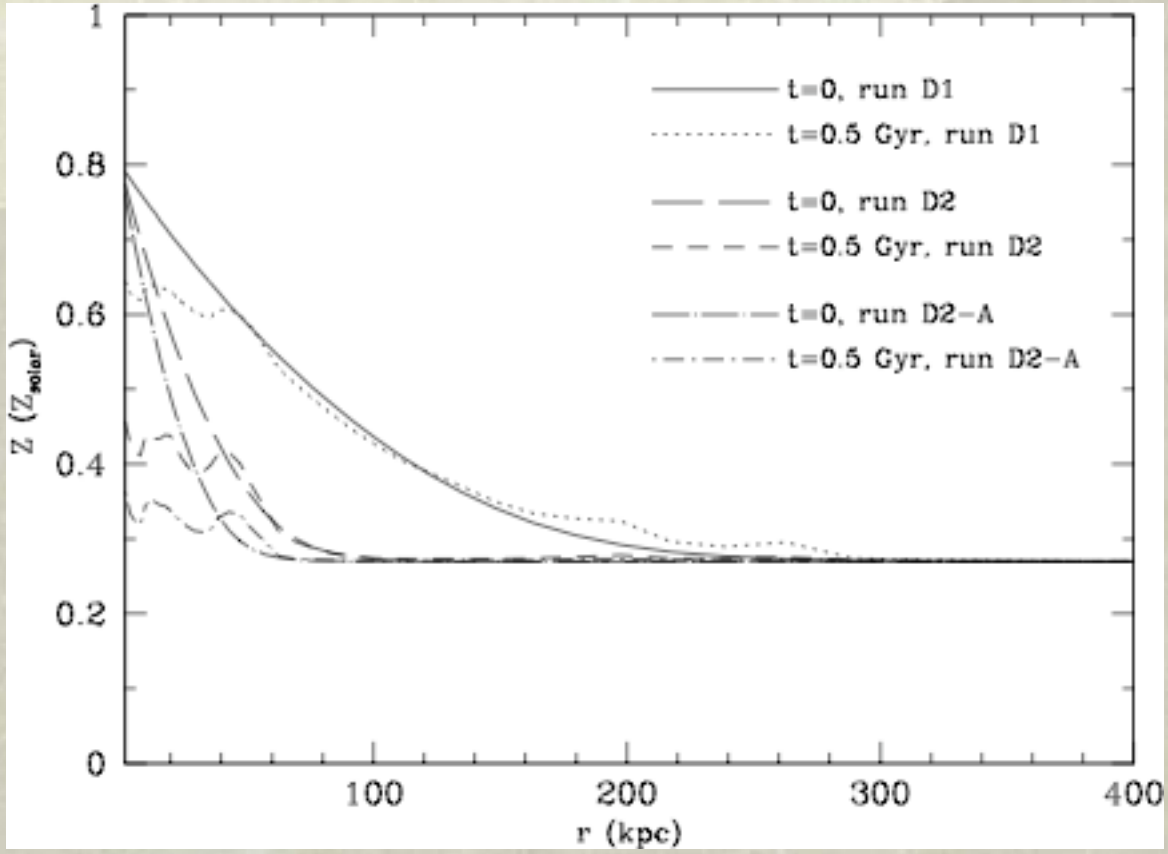
Guo & Mathews 2010b

Metal distribution in observations!



Guo & Mathews 2010b

When can AGN remove central metallicity peaks?



We need CC clusters with narrow central metallicity peaks!

Guo & Mathews 2010b

Impact of Powerful AGN Outbursts Cosmic Evolution of Metallicity Profiles

- Central metallicity peaks are produced by cluster central galaxies (De Grandi et al 2004)
- AGN feedback events broaden the central metallicity peak (Rebusco et al 2005)
- Broad central metallicity peaks are very robust (Poole et al 2008; Guo & Mathews 2010b); powerful AGN outbursts produce NCC clusters with central metallicity peaks.
- Most low-redshift CC clusters have broad central metallicity peaks (De Grandi et al 2004)
- NCC clusters without central metallicity peaks may form from CC systems with narrow central metallicity peaks at slightly higher redshifts (Guo & Mathews 2010b)