Interactions Between Jets and the Hot Atmospheres of Galaxies & Clusters

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Sesto, June 26, 2007

Organization

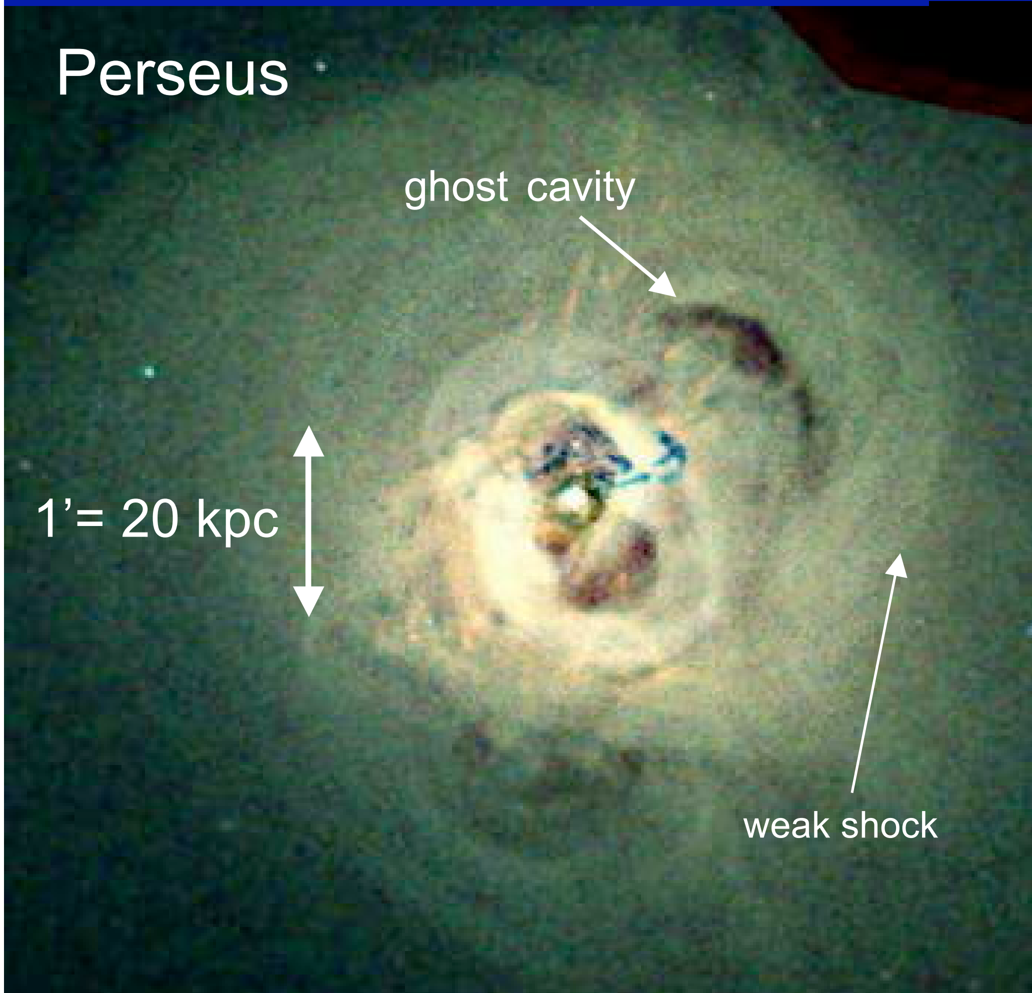
- Cavity phenomenology
- Cavity demography
- Energetics
- Star formation & feedback
- Cluster radio sources themselves
- Cluster scale outbursts
- Summary

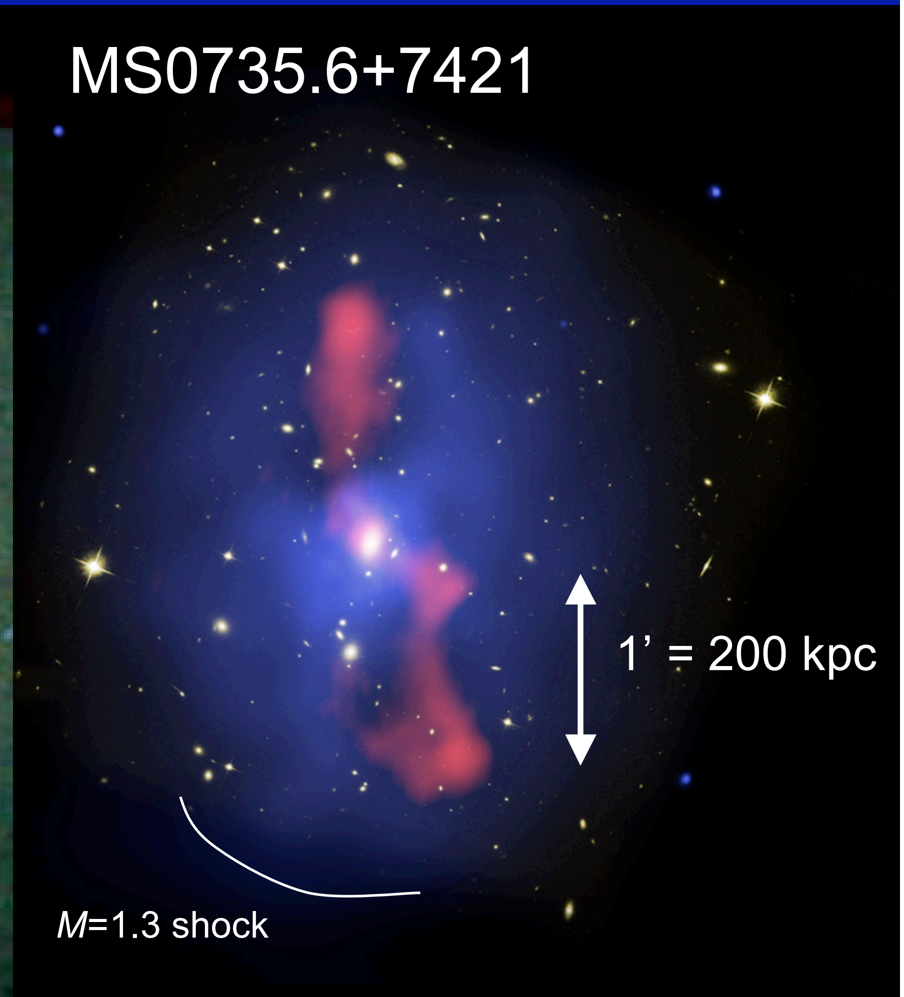
McNamara & Nulsen 07, ARAA

Cluster scale

E ~10^{59} erg

E > 10^{61} erg



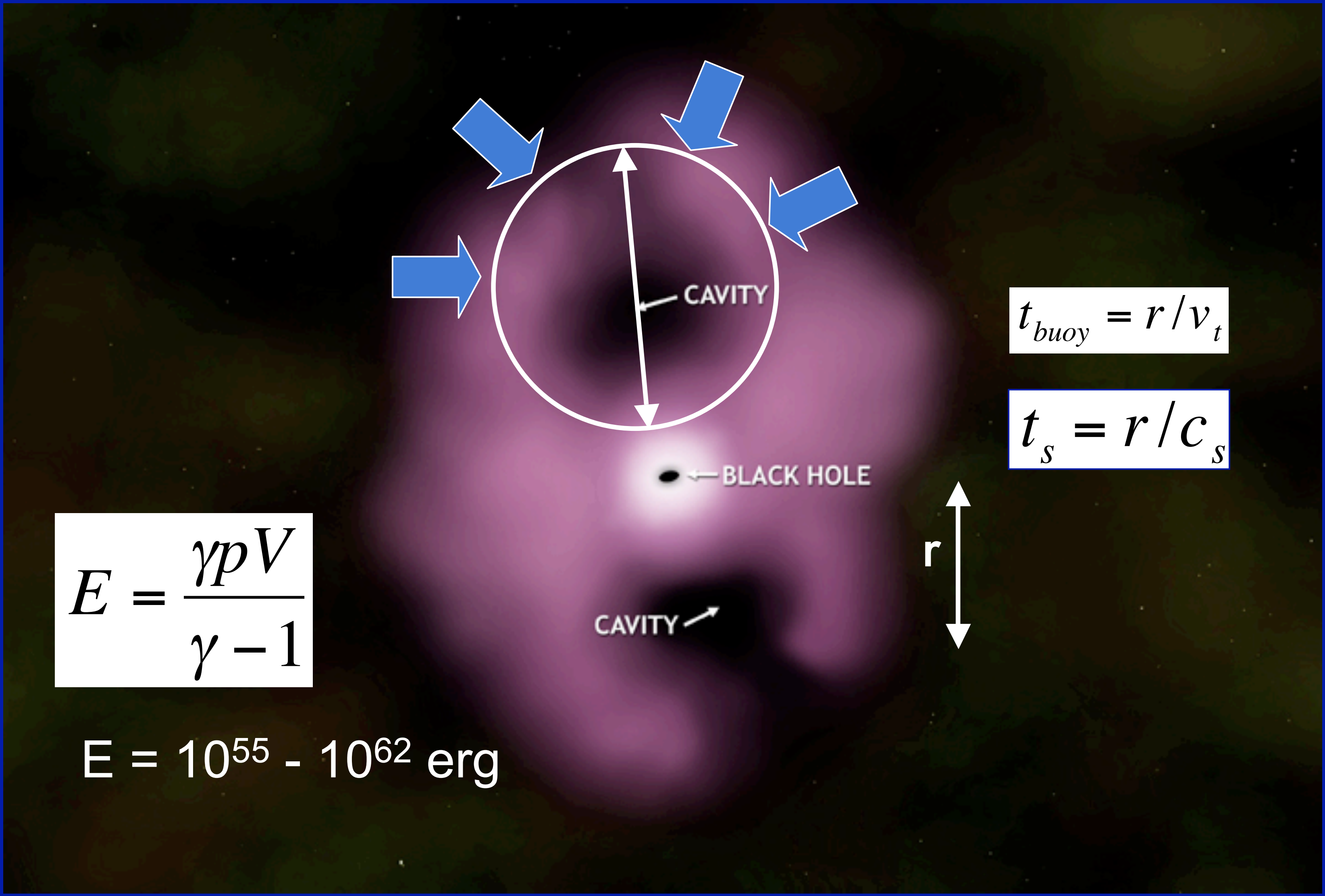


Fabian et al. 05

McNamara et al. 05
Gitti et al. 07

Optical, radio, X-ray

Cavity Energetics & Kinematics



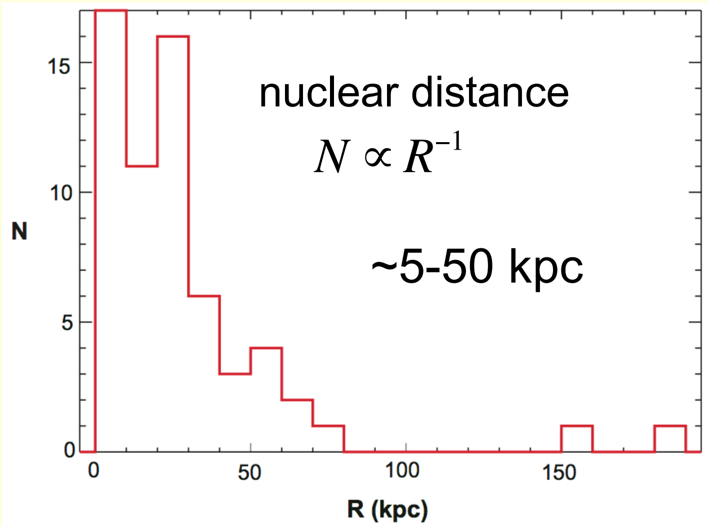
$$E = \frac{\gamma p V}{\gamma - 1}$$

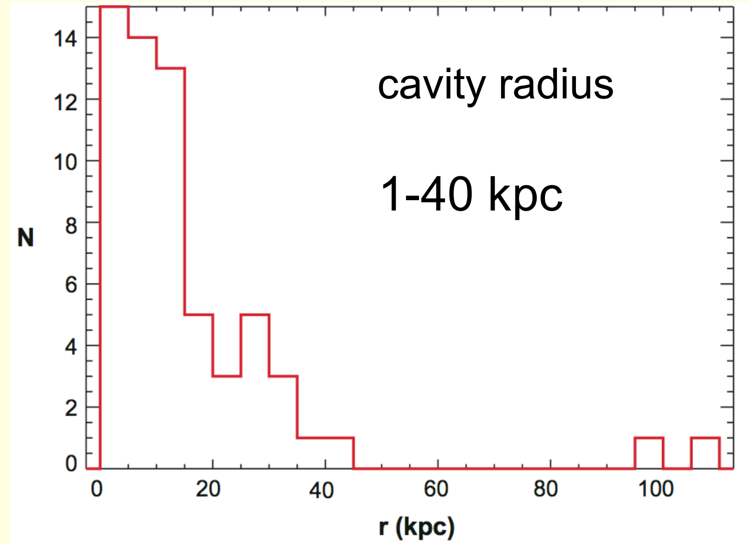
$$t_{buoy} = r / v_t$$

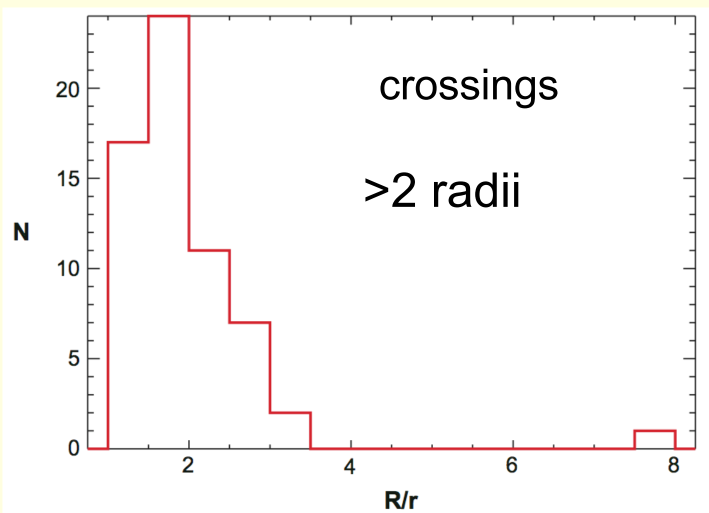
$$t_s = r / c_s$$

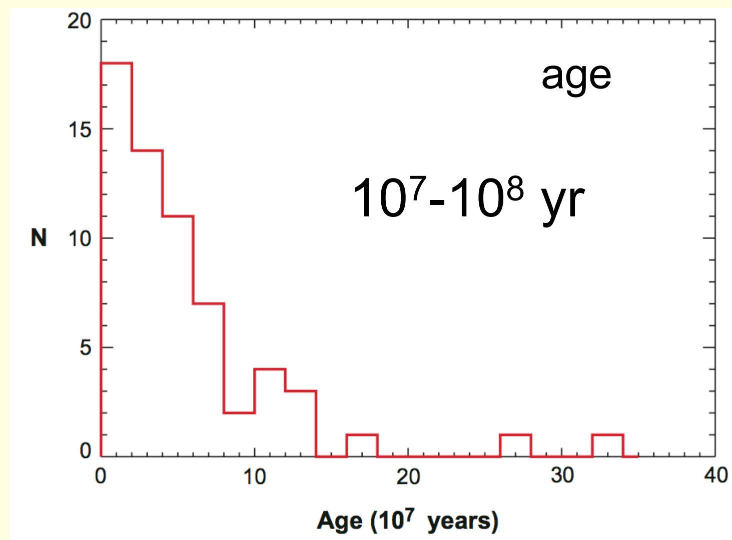
$E = 10^{55} - 10^{62}$ erg

Cavity Demographics





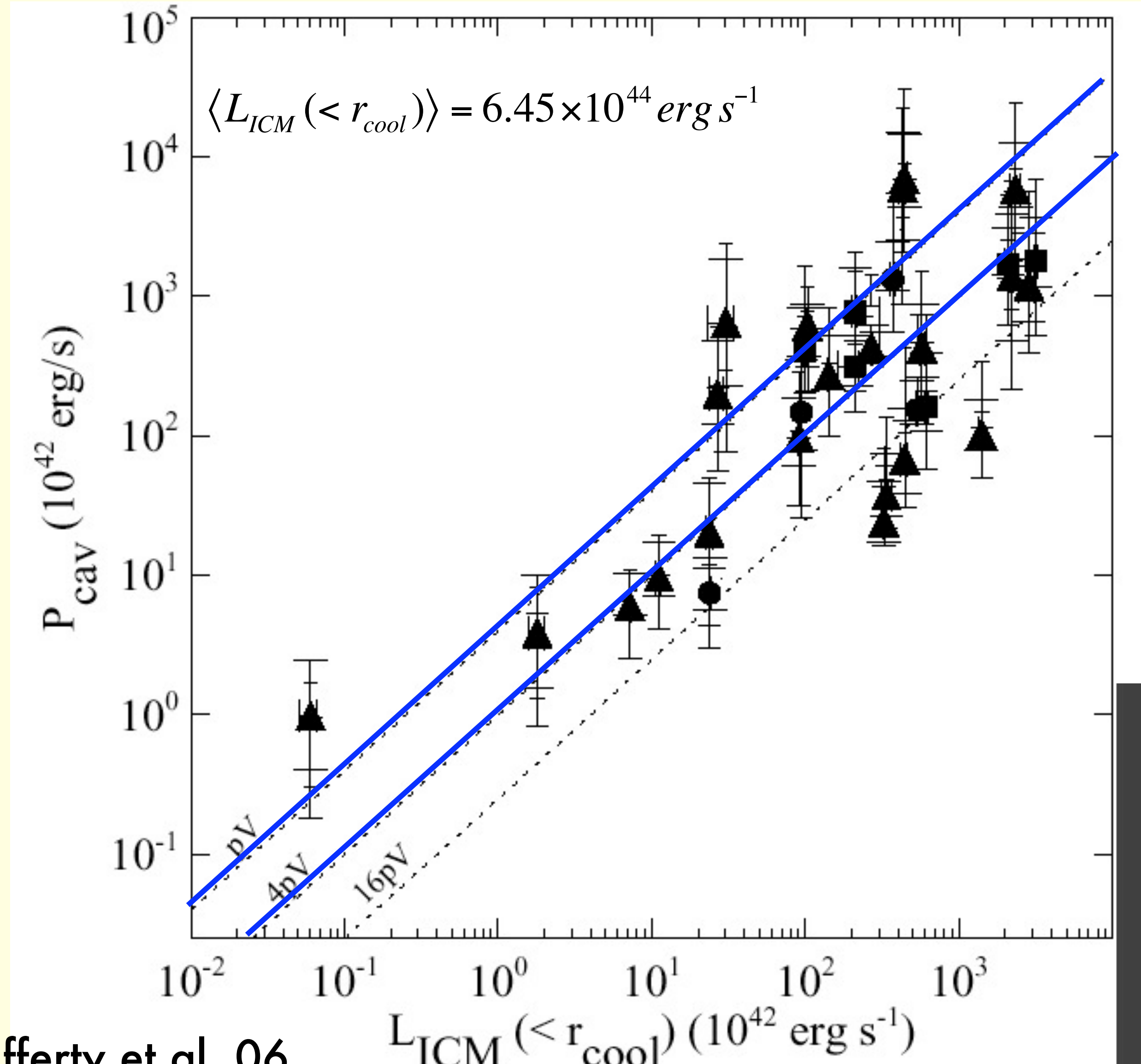




McNamara & Nulsen 07, ARAA

Heating & Cooling Diagram

jet power



X-ray cooling luminosity

Rafferty et al. 06

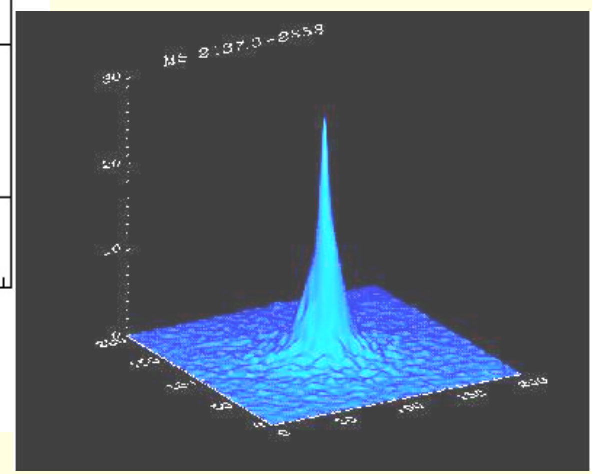
Birzan et al. 04

$$\Phi = \frac{P_{cav} \times f}{\langle L_{ICM}(< r_{cool}) \rangle} = 1.1$$

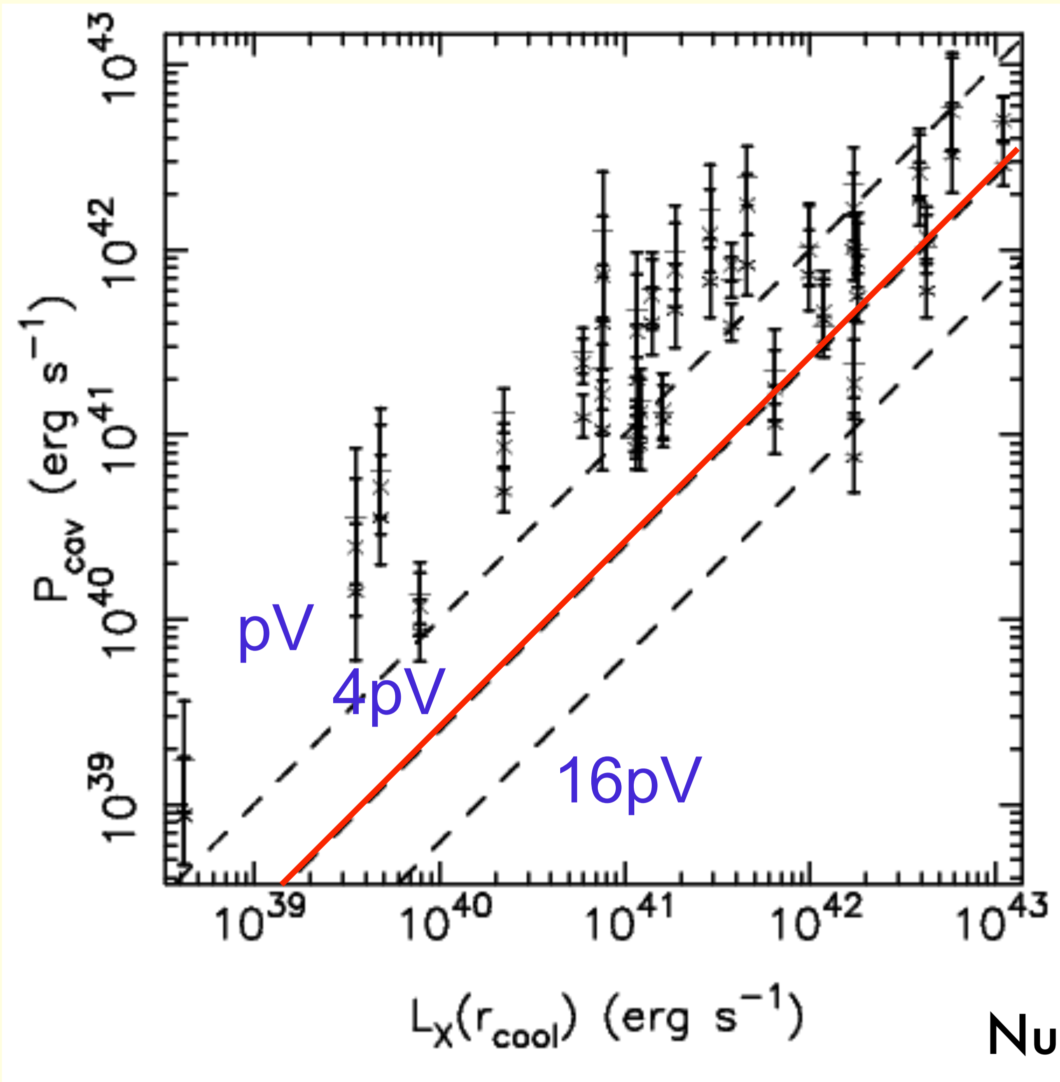
$f = 0.7$ (Dunn & Fabian 06)

heating ~ cooling

McNamara & Nulsen 07
ARAA



Heating-cooling Diagram for gEs



$\Phi \approx 1$

quenched

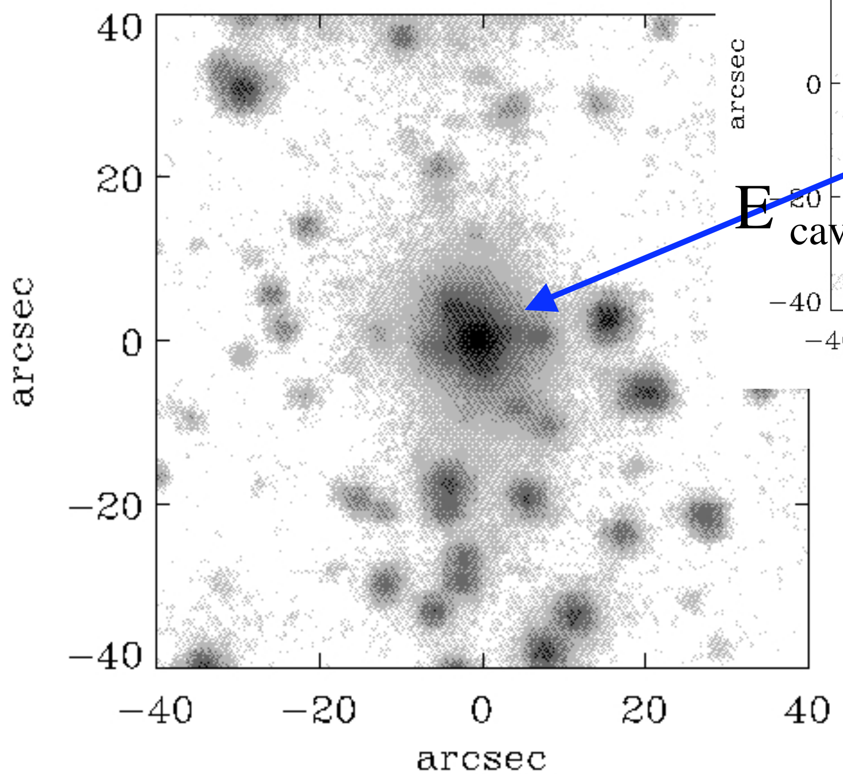
Nulsen et al. 06

McNamara & Nulsen 07, ARAA

Star formation rate consistent with net cooling rate

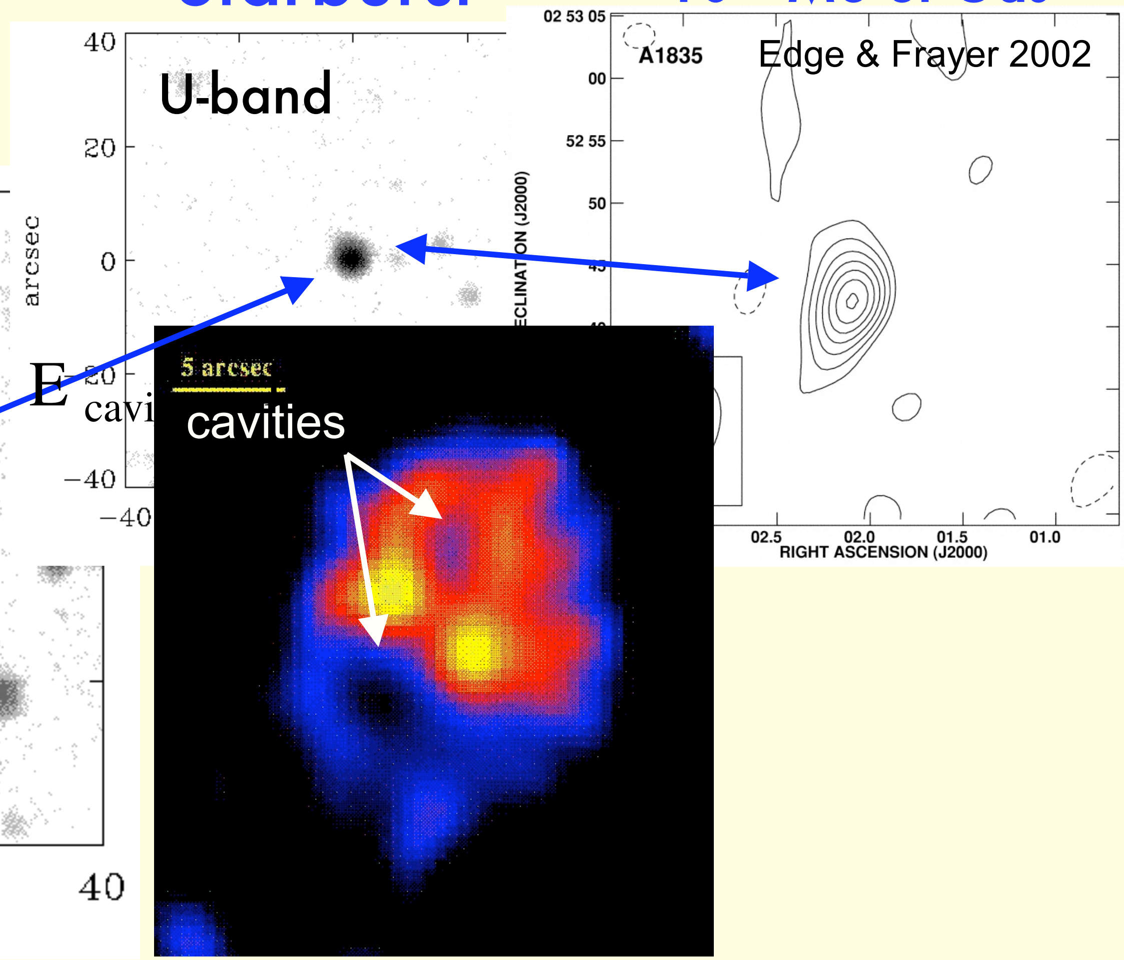
Abell 1835

R-band



Starburst

10^{11} Mo of Gas



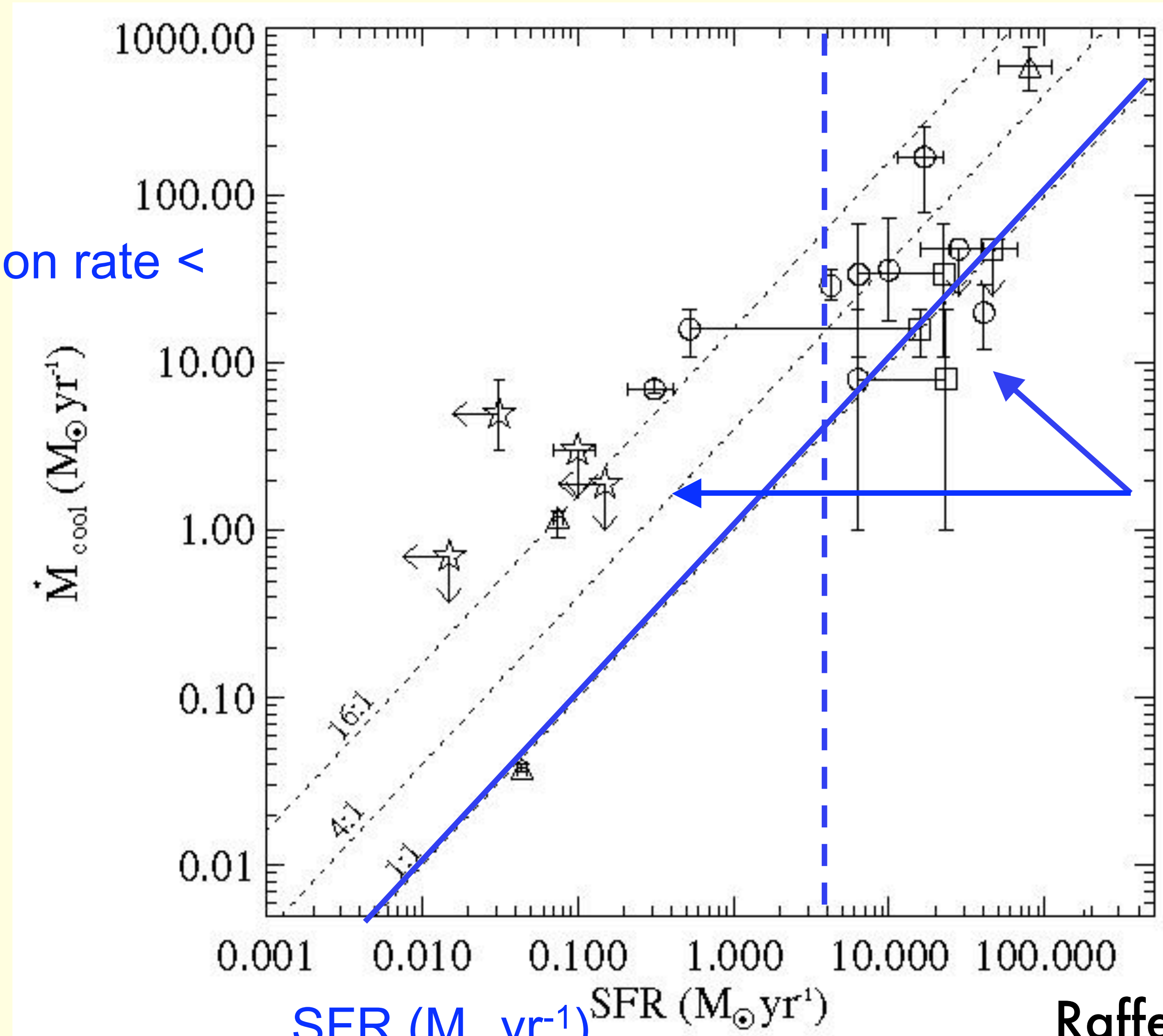
SFR = 100 - 200 Mo yr^{-1} = $L_{x,spec}$

McNamara et al. 06

$E_{cavity} = 1.7\times10^{60}$ erg

$P_{cavity} = 1.4 \times 10^{45}$ erg s^{-1} ~ $L_{x,cool}$

Star formation rates ~ upper limits on condensation rates



condensation rate <

SFR (M_o yr^{-1})

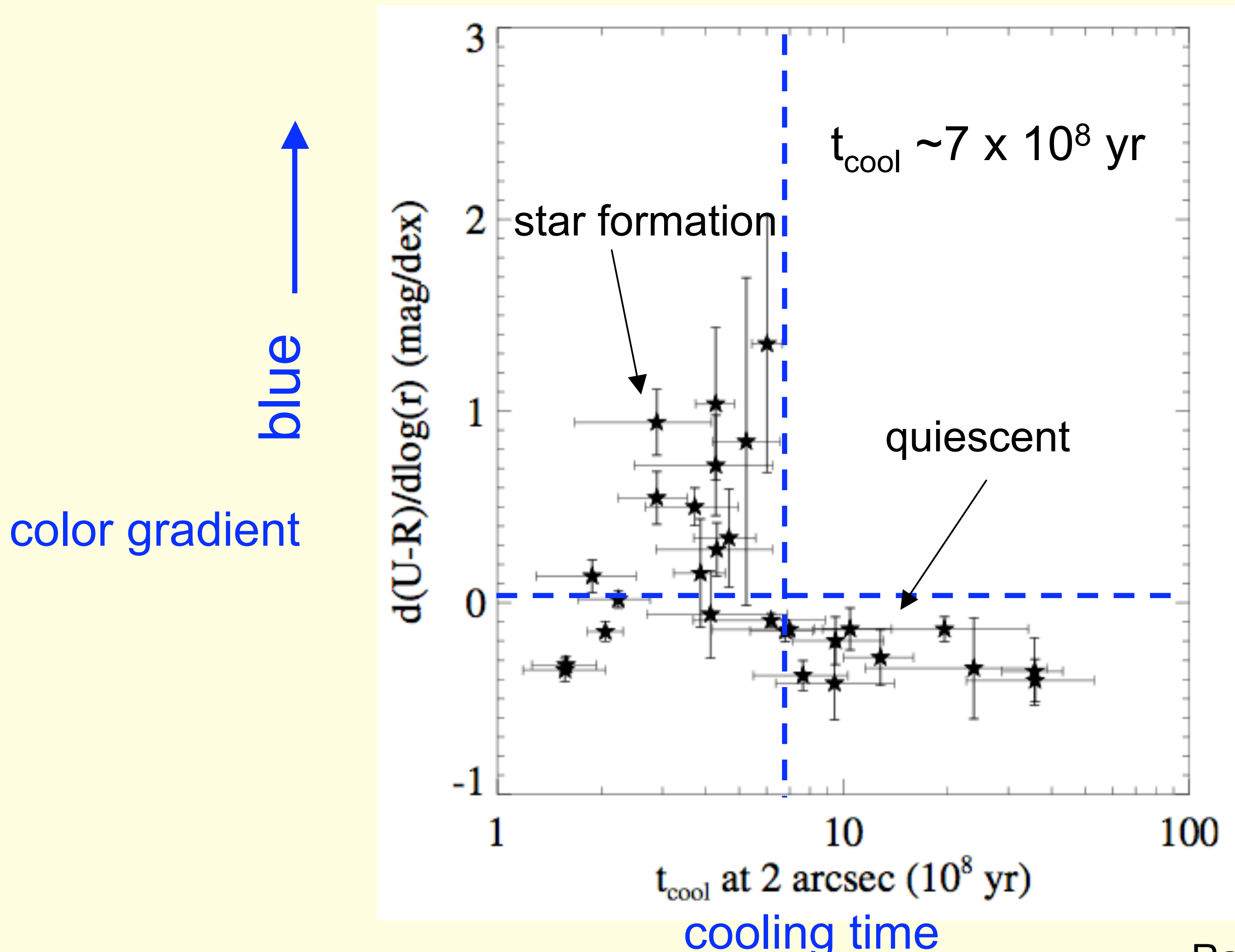
Need!!

1) better X-ray spectra

2) better star formation rates

Rafferty et al. 06

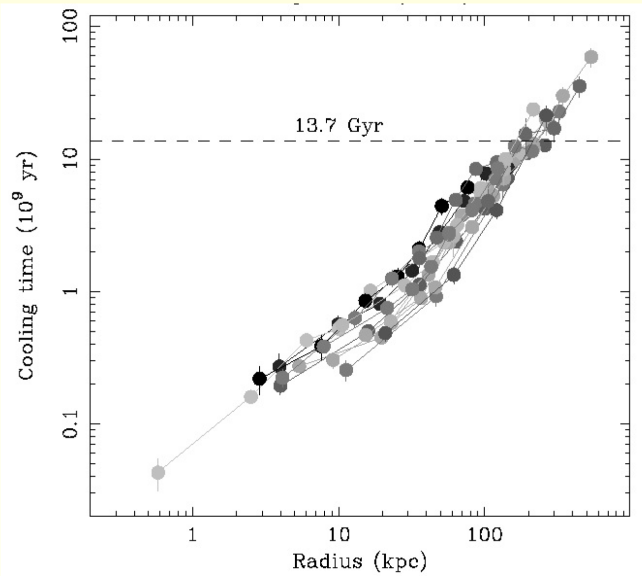
star formation found in cDs with central cooling time < 7 x 10^8 yr

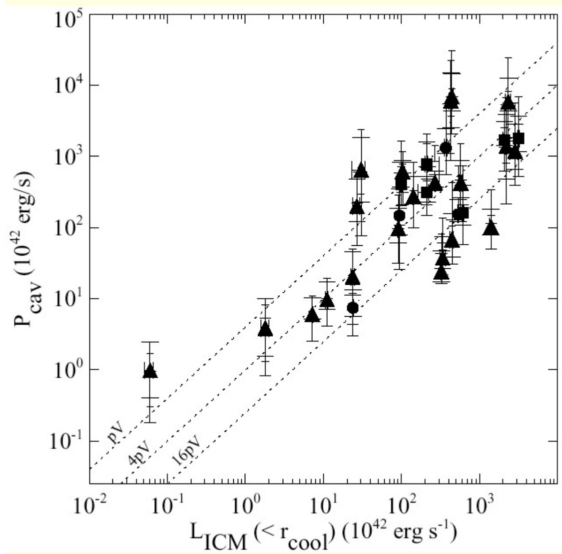


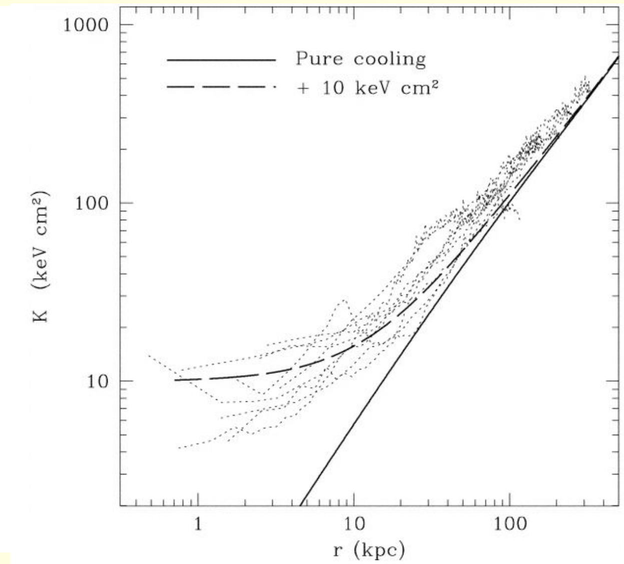
Rafferty et al. 07

see also Edwards et al. 07

Conditions for AGN-Regulated Feedback Loop







Voigt & Fabian 04

Rafferty et al. 06
Birzan et al. 04

Voit & Donahue 05
Donahue et al. 06
Voit 05

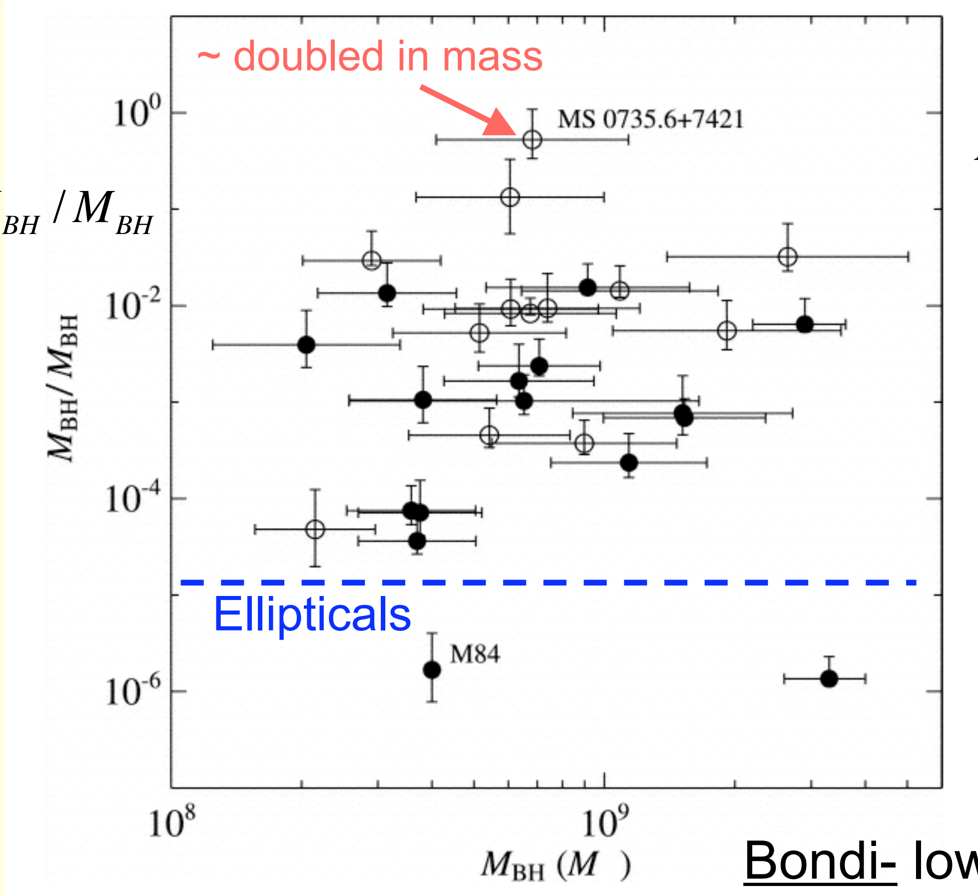
1) t_{cool} ~ 10^8 yr

2) L_{AGN} ~ L_x

3) Entropy floors

See McNamara & Nulsen 2007 ARAA

SMBH Specific Accretion per Event



Rafferty et al. 06

$$\dot{M}_{BH} = \left(\frac{\varepsilon}{0.1}\right)^{-1}\left(\frac{P_{cavity}}{5.67x10^{45}\, erg\, s^{-1}}\right) M_{\oplus} yr^{-1}$$

$$\langle \dot{M}_{BH} \rangle \approx 0.1 M_{\oplus}\, yr^{-1}$$

(clusters)

- sub-Eddington

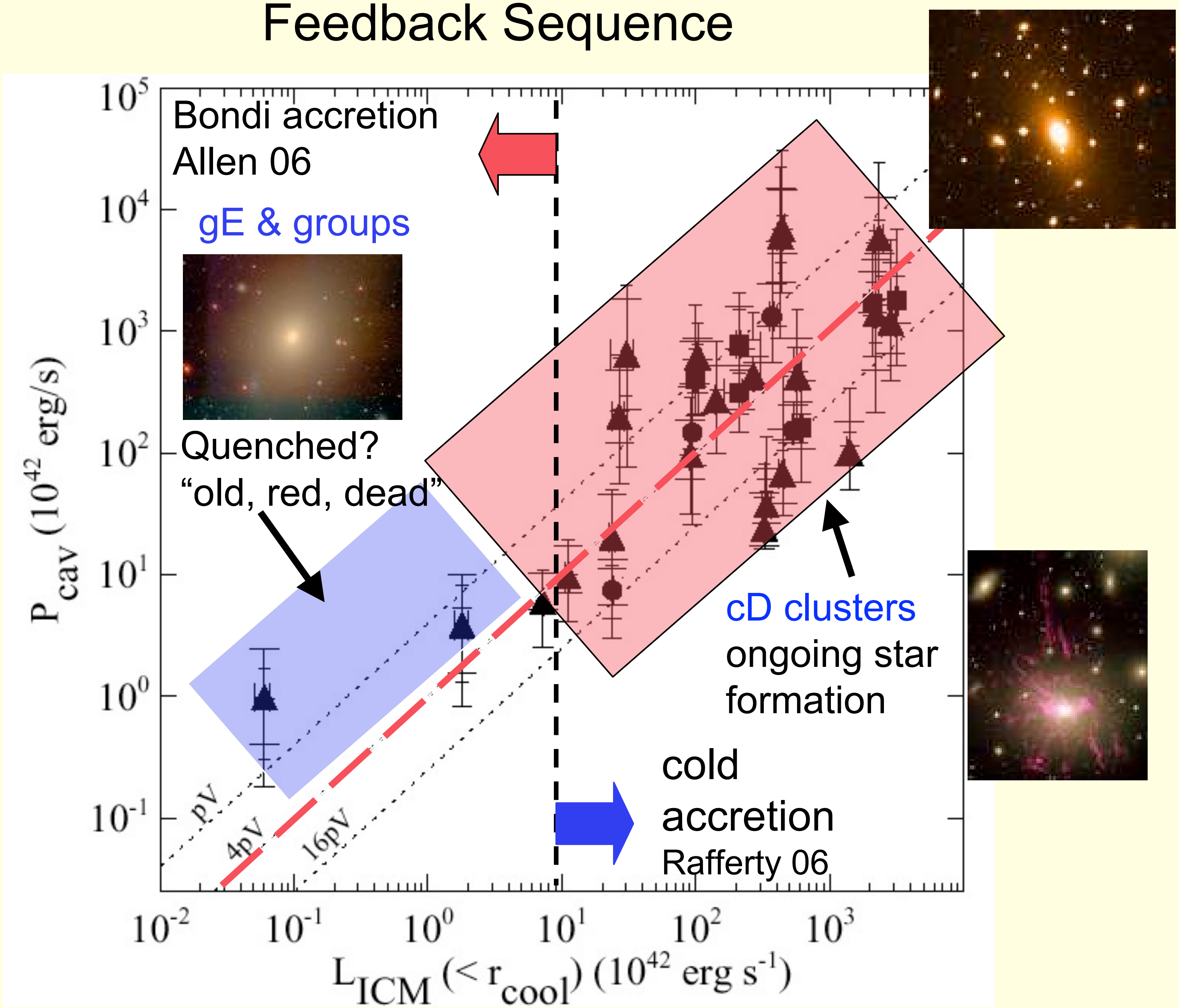
Accretion Mechanisms

Bondi- low mass systems (Allen 06)

Stars - intermittent, not enough

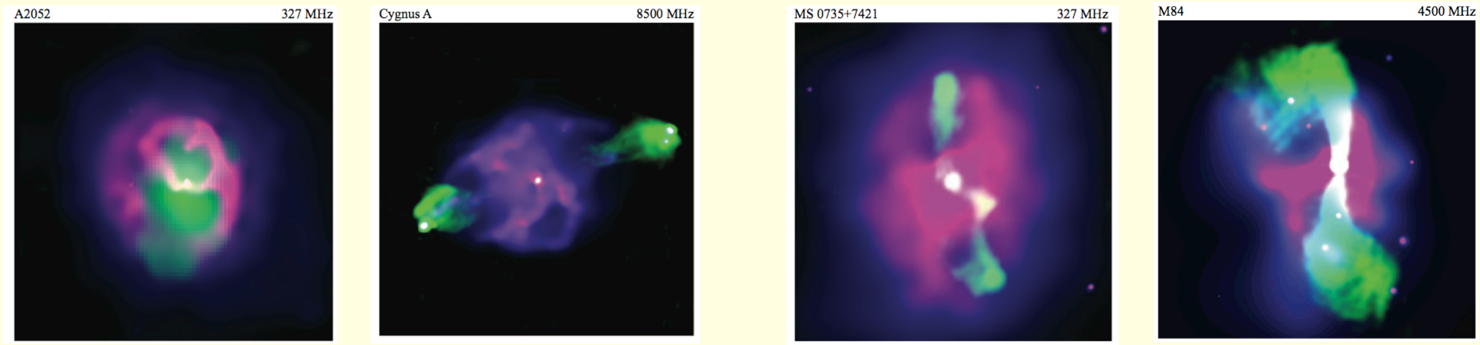
Gas - likely, but hard to regulate (Rafferty 06)

Feedback Sequence

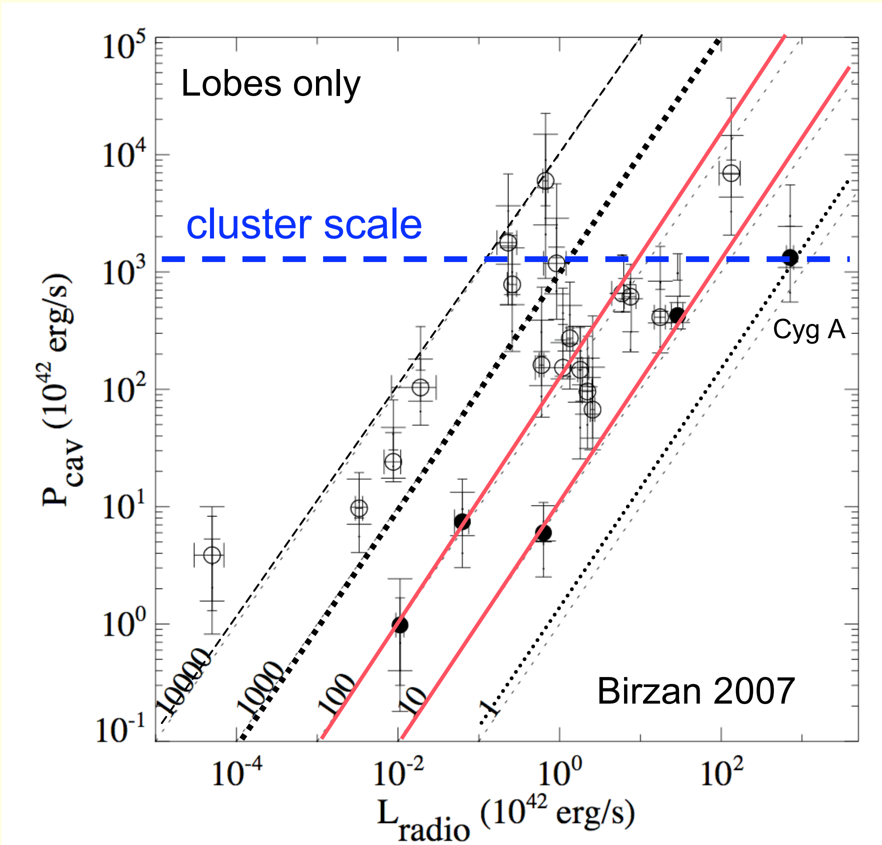


AGN heating: $10^{39\text{-}46}$ erg s^{-1} seven orders: gEs to rich clusters

Enormous range in jet/lobe radiative efficiency



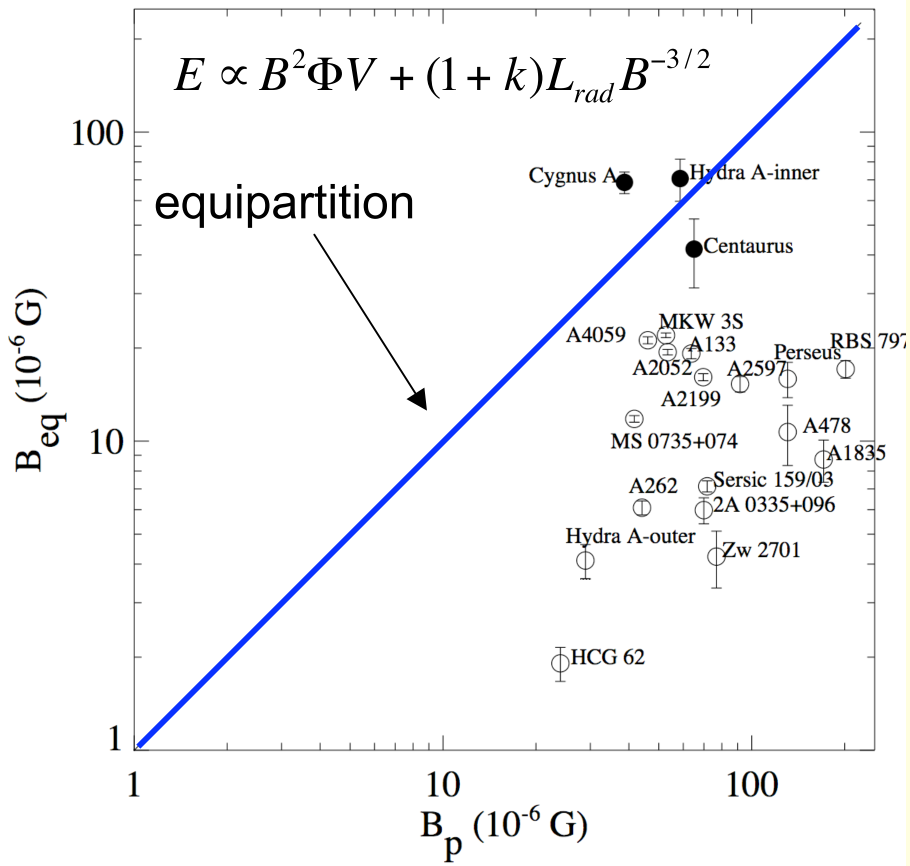
- no simple relationship between P_{jet} & L_{sync}
- Synchrotron cooling negligible
- variance: age, adiabatic losses, Intrinsic
- suggests heavy hadronic jets/lobes or Poynting jets
- out of equipartition
- global heating dominated by variance



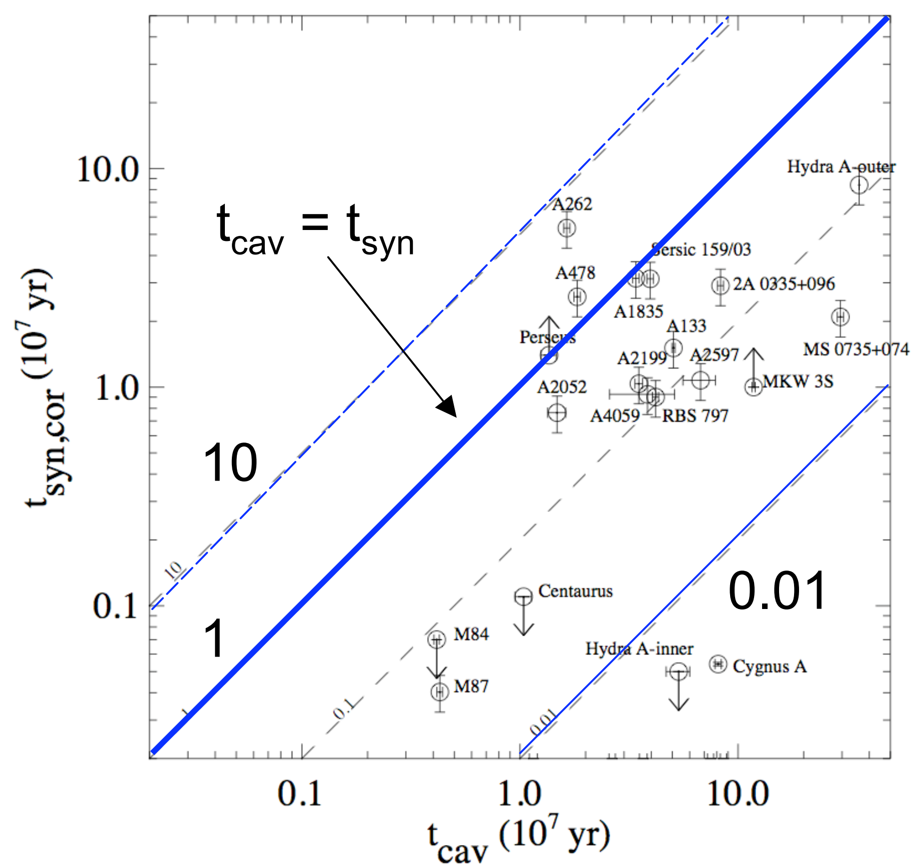
$\langle P_{cav}/L_{rad} \rangle = 2800$ $\{P_{cav}/L_{rad}\}_{med} = 120$

Radio Properties Constrained by Cavities

Lobes out of equipartition with e$^-$



$t_{cav} > t_{syn}$



pressure balance $k = 1$

Heavy jets/lobes: $\frac{protons}{electrons} = k >> 1 \quad B \approx 50 \mu G$

Birzan 2007, PhD

Dunn & Fabian 04

Summary

- SFRs in cDs approaching XMM/Chandra cooling rates
- AGN feedback comparable to cooling luminosity in ellipticals, groups, galaxies
- Powerful, cluster-scale outbursts can dominate heating: L-T, ex-entropy
- Significant SMBH growth in cDs
- Mechanical power dominates radio power by 10s to 10,000s
- Out of equipartition
- Heavy jets

AGN ⇒

- Regulate galaxy & SMBH formation
- Exponential turnover in galaxy luminosity function
- Cluster & group excess entropy?
- plausible mechanism for global baryon cooling problem

Major Issues: 1. How AGN heat the gas 2. how feedback operates