The X-ray foundation for AGN Feedback

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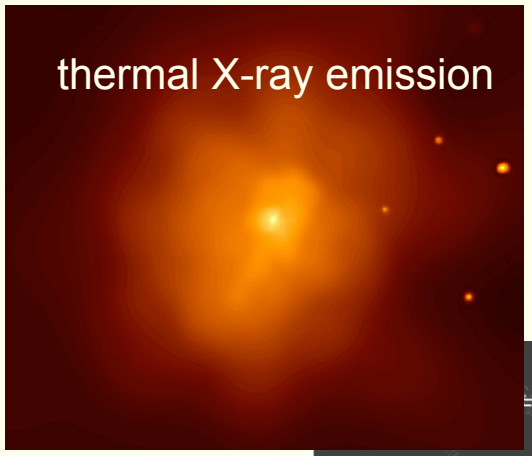
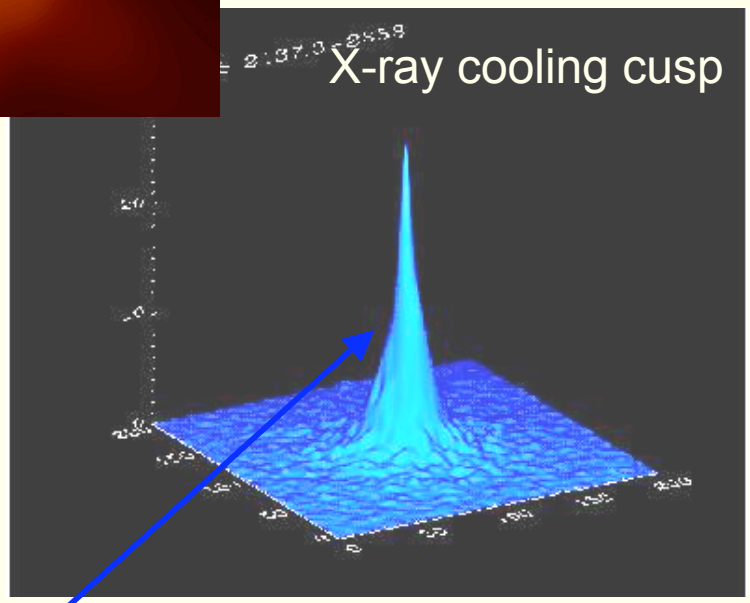
Outline:

- cooling flows
- X-ray cavities, shock fronts: gauges of AGN power
- Implications: clusters, radio sources, SMBH growth & fueling, galaxy formation & cosmic feedback

The X-ray Universe 2008, Granada, May 30, 2008

Cooling Flows





X-ray power $10^{44\text{-}45}$ erg s^{-1} exceeds radio synchrotron power $10^{40\text{-}42}$ erg s^{-1}

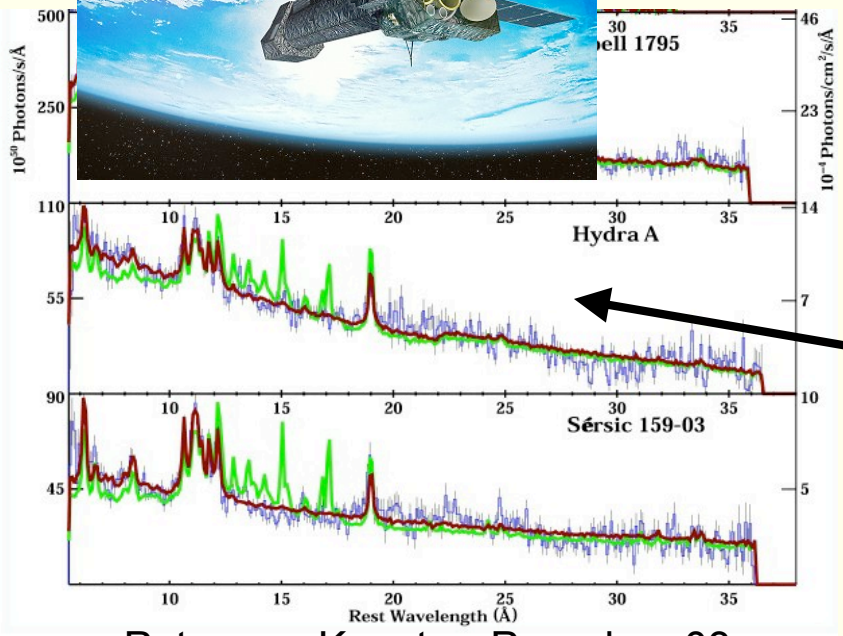
implies cooling flow: $n_e \sim 10^{-1}$ cm^{-3} $\dot{M}$ = 10-1000 Mo yr^{-1}

observer's Cooling flow problem: star formation ~ 1% $\dot{M}$

Key X-ray observations of cooling flows

reduced cooling

XMM-Newton 1999 -

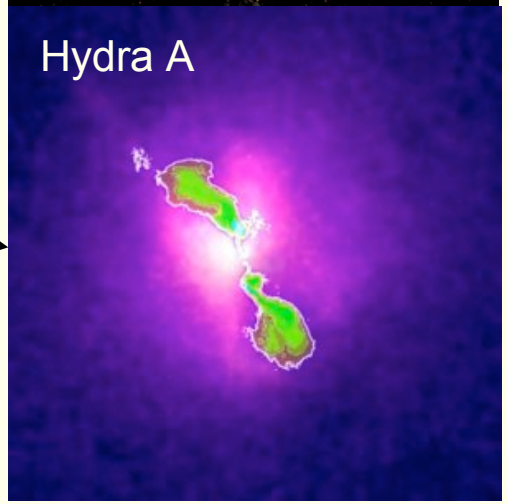


Peterson, Kaastra, Paerels + 03

Sanders + 08 & this conference

AGN interactions

Chandra 1999 -



Mc+00, Fabian +00

…Results foreshadowed by ASCA & Rosat

Implication: Heating, feedback by SMBHs

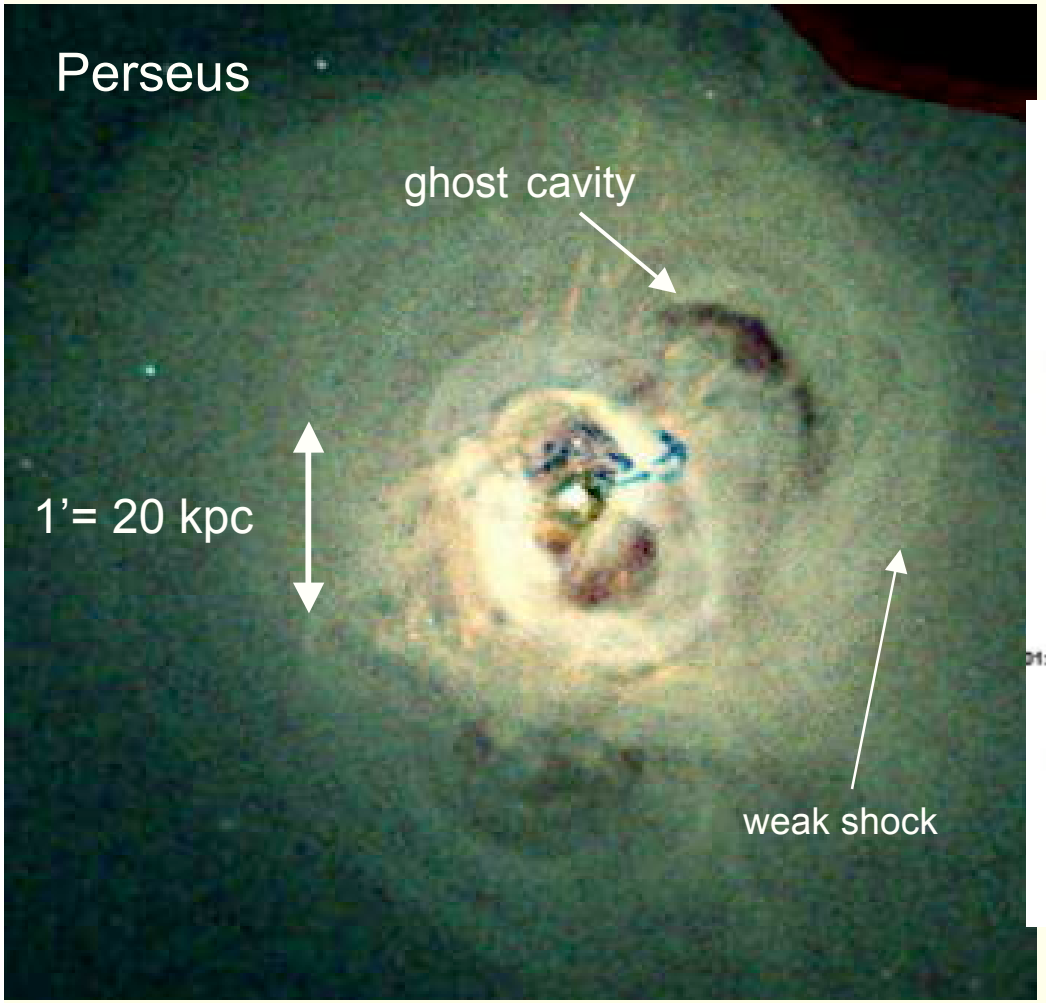
Key Insights from XMM & Chandra

- weak FR I radio sources can be as powerful as Quasars
- AGN in the “radio mode” must heat gently over large volumes
- conditions conducive to operational feedback loop

These insights have lead to significant progress in understanding cooling flows and the role of AGN feedback in galaxy formation.

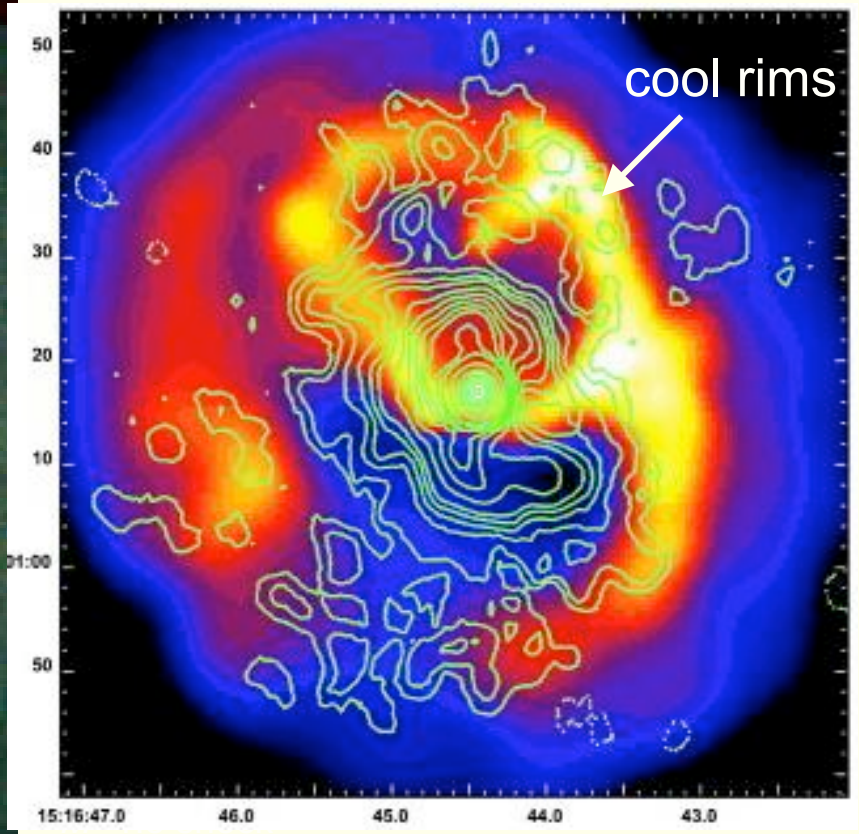
Galaxy-scale AGN Outbursts

E ~$10^{57\text{-}59}$ erg



Fabian + 05

Abell 2597

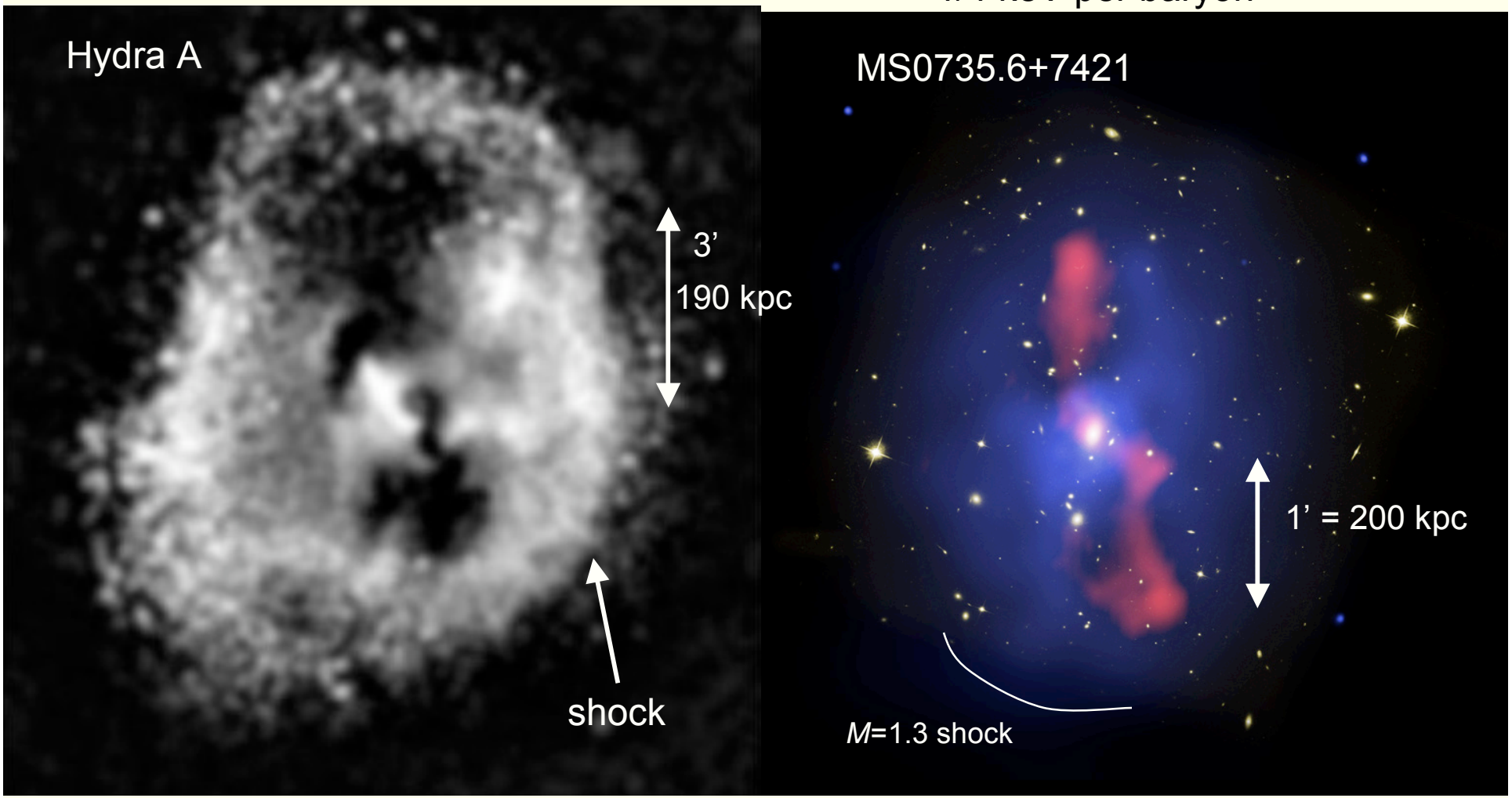


Blanton + 01

Cluster-scale AGN outbursts “preheating” events

E =$10^{61\text{-}62}$ erg

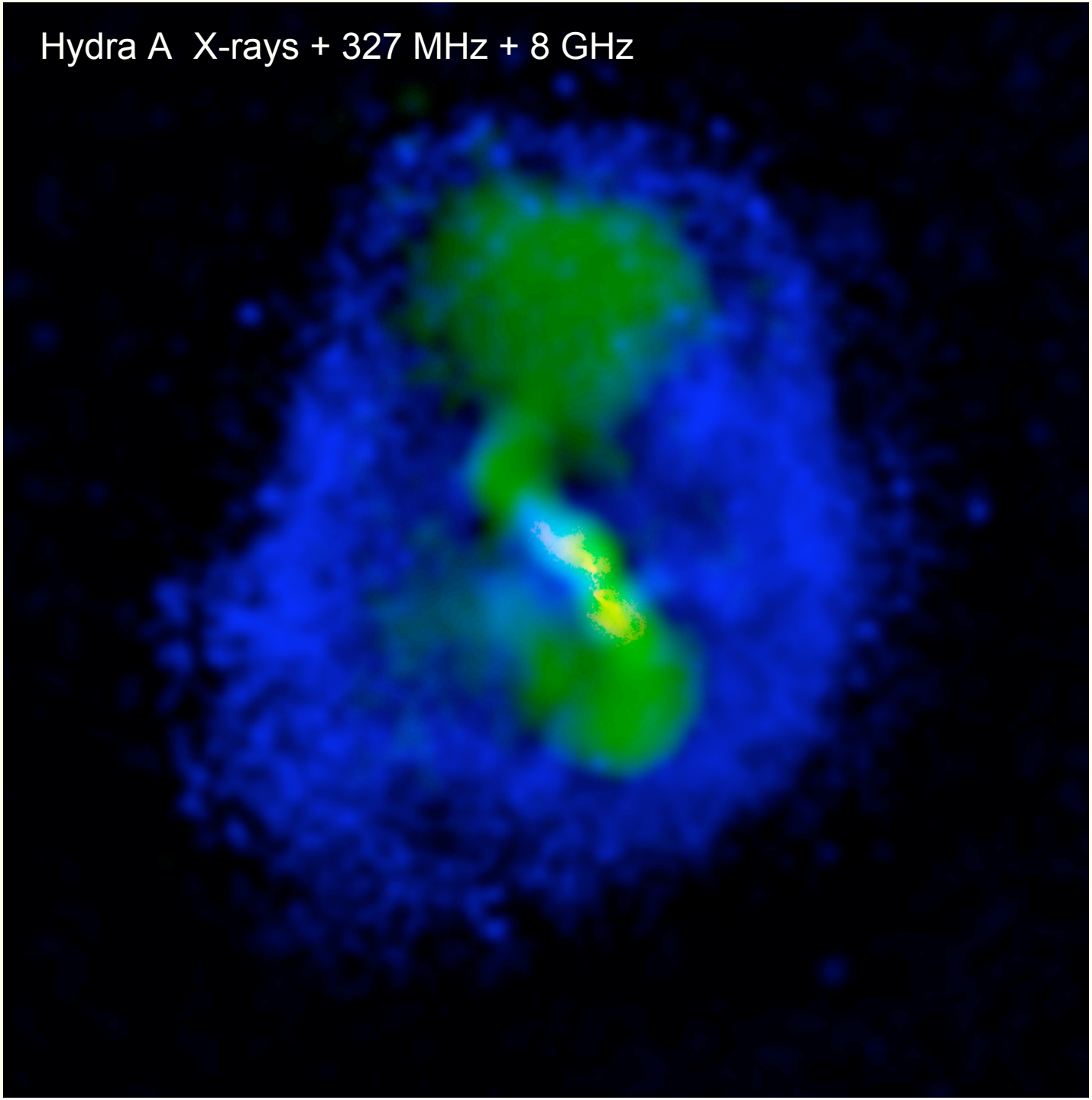
~ 1/4 keV per baryon



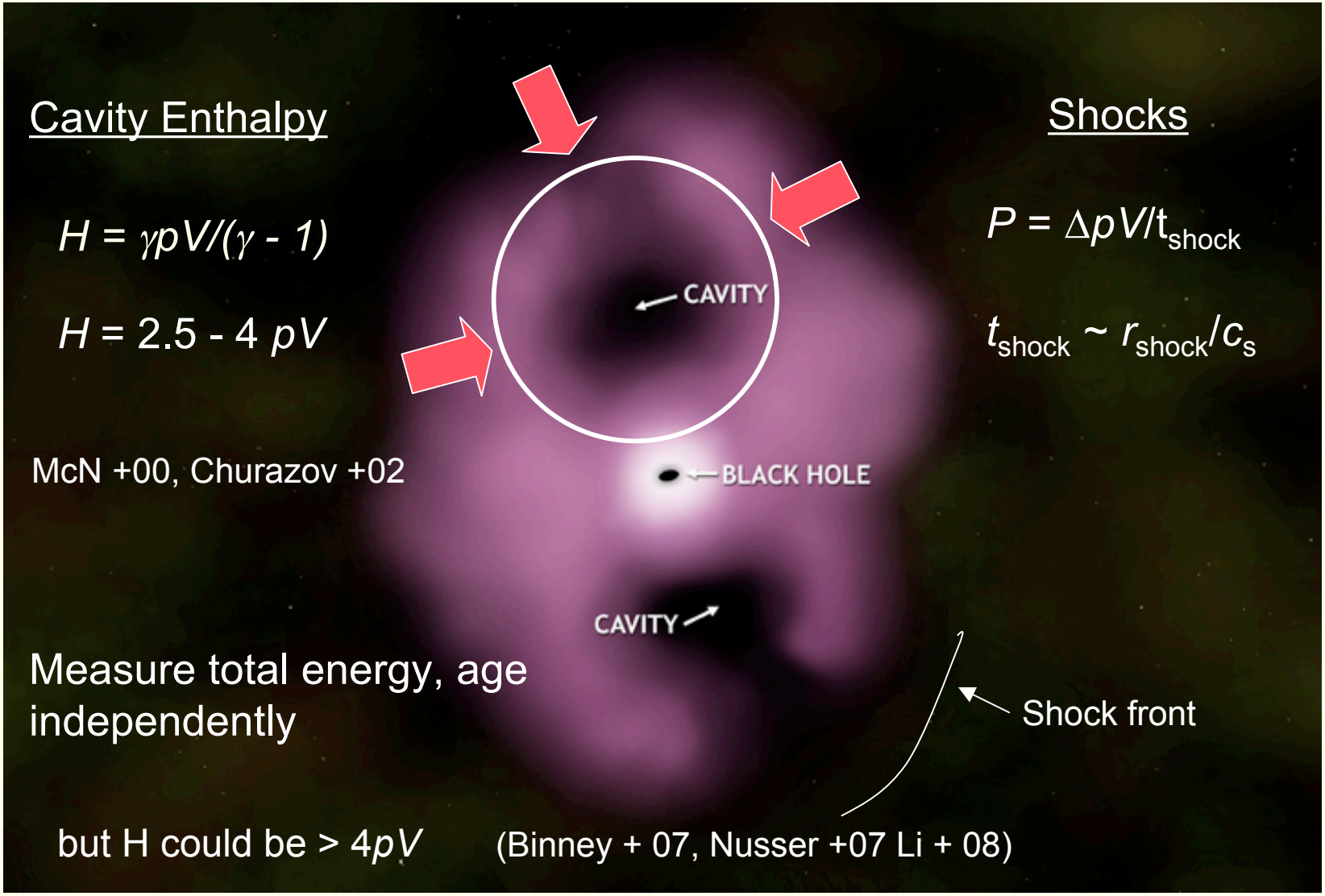
Nulsen + 05
Wise + 07

McN + 05
Gitti + 07

Optical, radio, X-ray

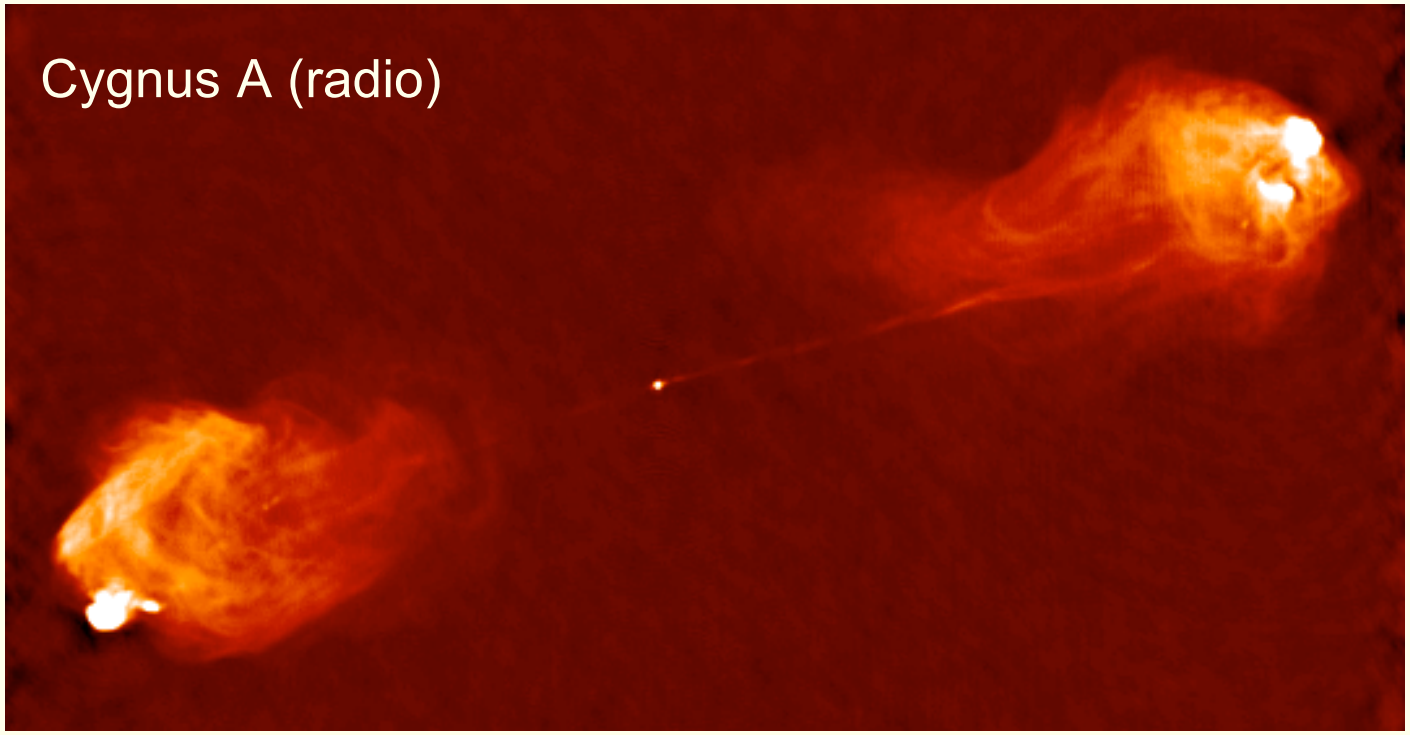

Hydra A X-rays + 327 MHz + 8 GHz

Taking the measure of AGN (jet) power



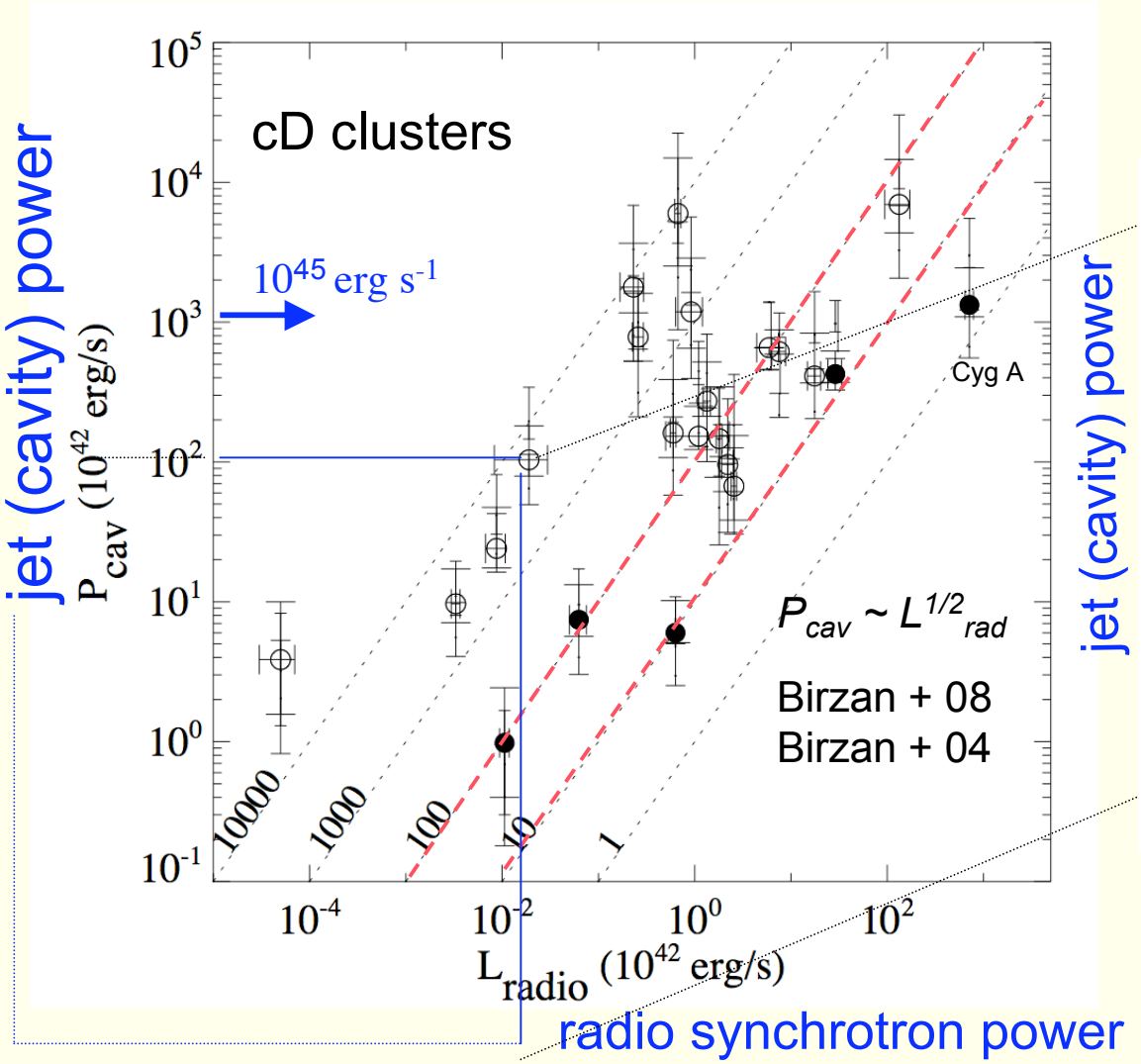
How Powerful are Extragalactic Radio Sources?

What are they made of?

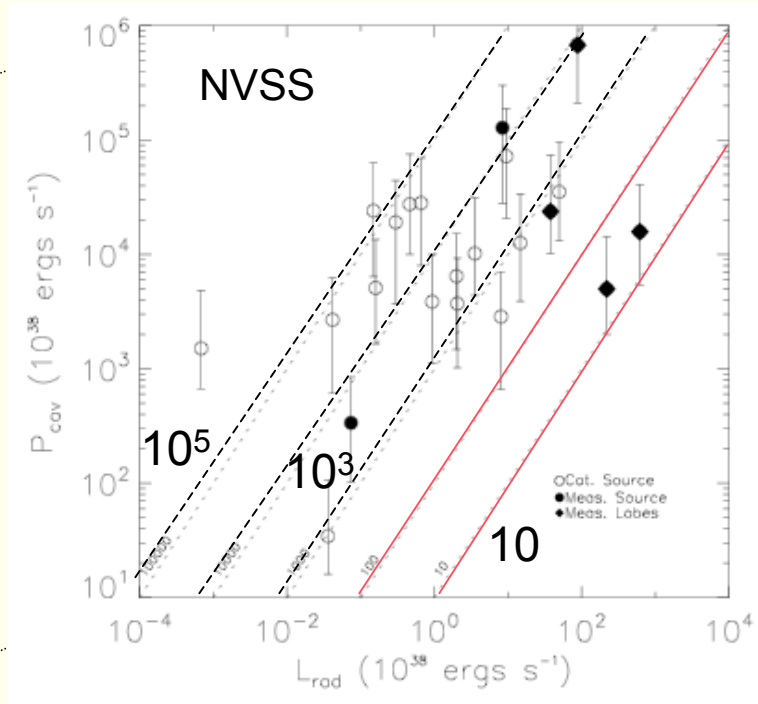


Burbidge 56, Scheuer 74, Blandford & Rees 74, Begelman, Blandford, Rees 84,

FR Is: low radiative efficiency, mechanically-dominated, powerful



giant ellipticals



jet (cavity) power

L_{radio} (erg s^{-1})

Nulsen, Jones + 08

see also Merloni & Heinz 07
for core power relation

Implications for Clusters

- Cluster “preheating” ~ 1 keV per baryon needed (Wu+ 00, Voit 04)
- Quenching of cooling flows
- Scaling relations eg. *L*-*T* (Nusser & Silk 2007, Gitti + 07)
- S-Z relation (Pfrommer + 06,Colafrancesco 08)
- Stripping galaxies by large-scale sonic booms (Fujita 07)
- UHE particle & photon accelerators (Hinton + 07, Benford + 08)

Implications for Extragalactic Radio Sources

- Heavy jets: ratio of energy in protons to electrons, $k >> 1$
- Radio lobes out of equipartition

De Young 06 Dunn + 04, 05
Birzan + 04,08, Hinton + 08

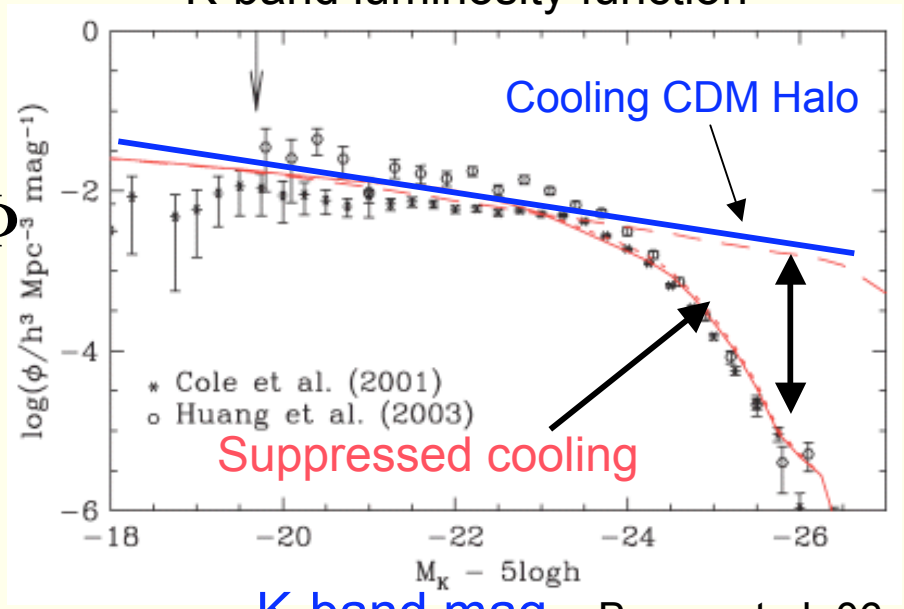
- Magnetic (Poynting) jets? (Diehl + 08, Li + 08)

…potential implications for galaxy formation:

The broken hierarchy of galaxy formation

standard CDM fails …Bower + 06

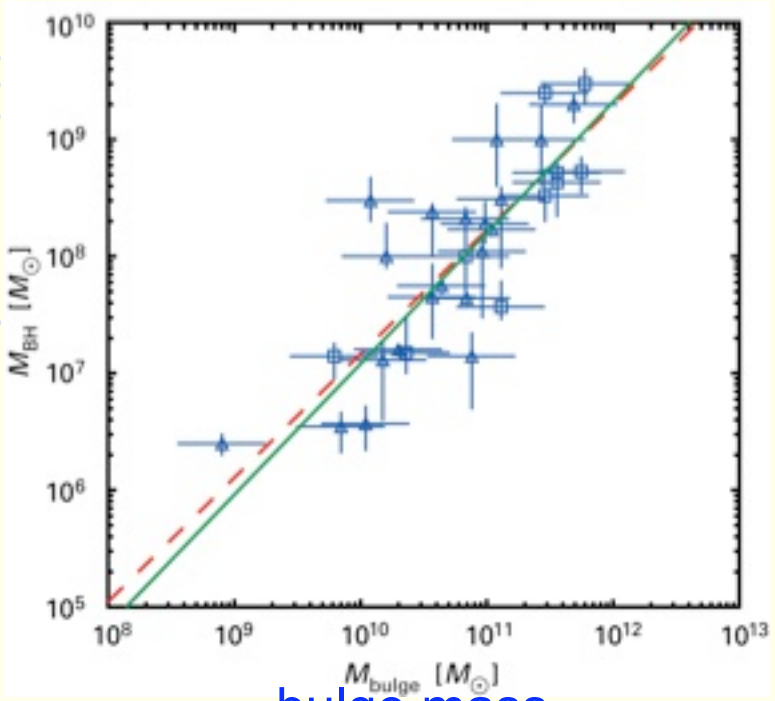
K-band luminosity function



K-band mag

Bower et al. 06

SMBH-bulge mass relation

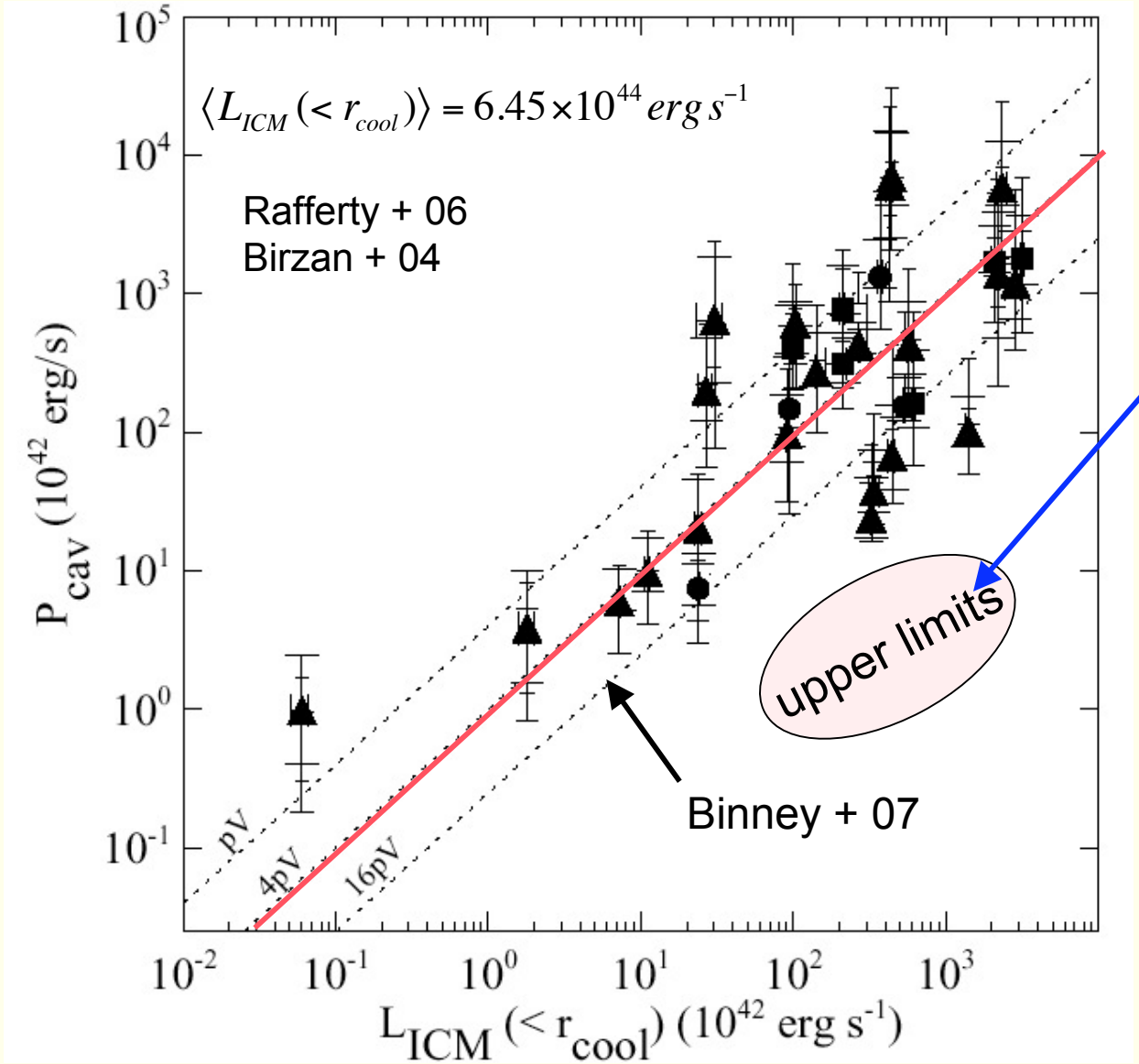


bulge mass

fossil evidence for self-regulation or feedback

ongoing feedback in clusters: does it work?

Heating & Cooling Diagram



jet power

X-ray cooling luminosity

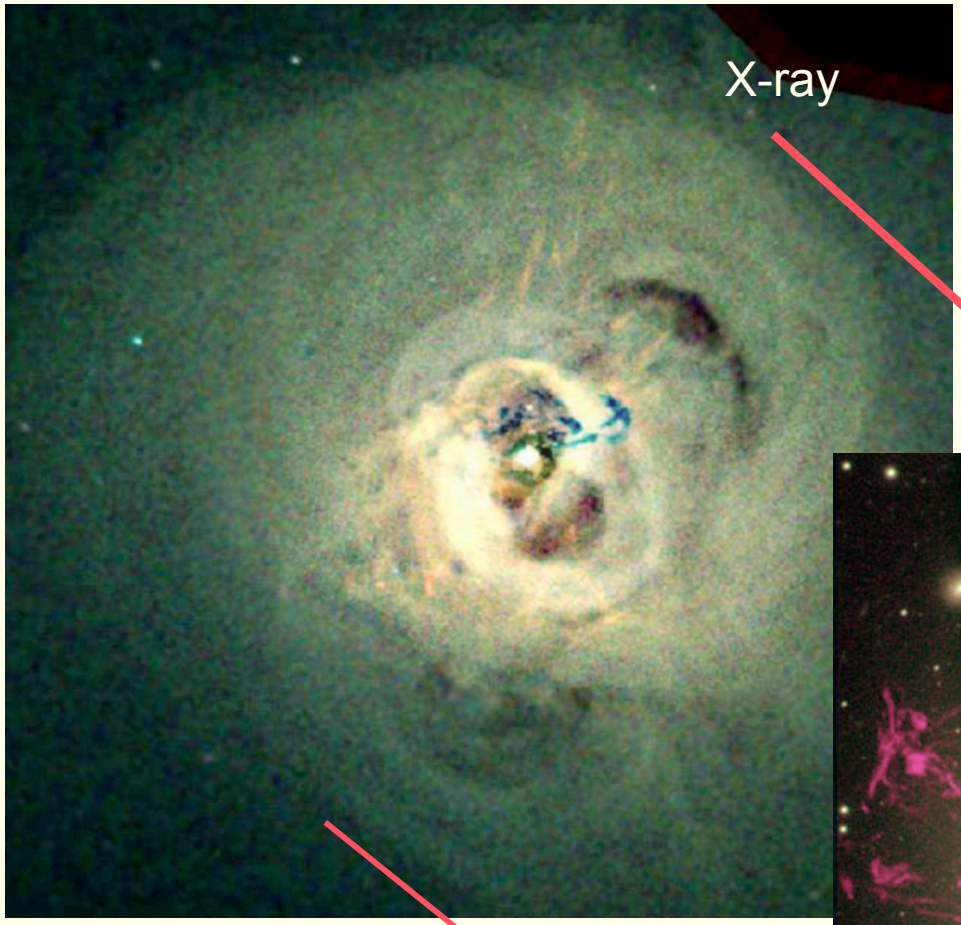
$$\Phi = \frac{P_{cav} \times f}{\langle L_{ICM}(< r_{cool})\rangle} = 1.1$$

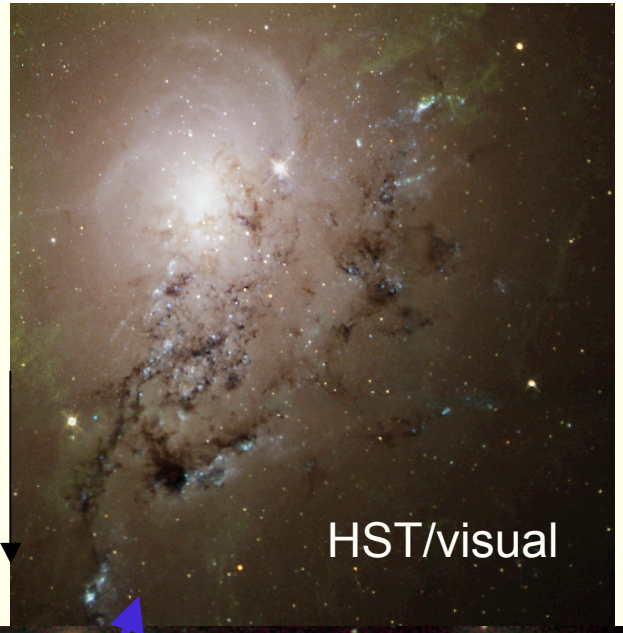
$f = 0.7$
(Dunn & Fabian 06)

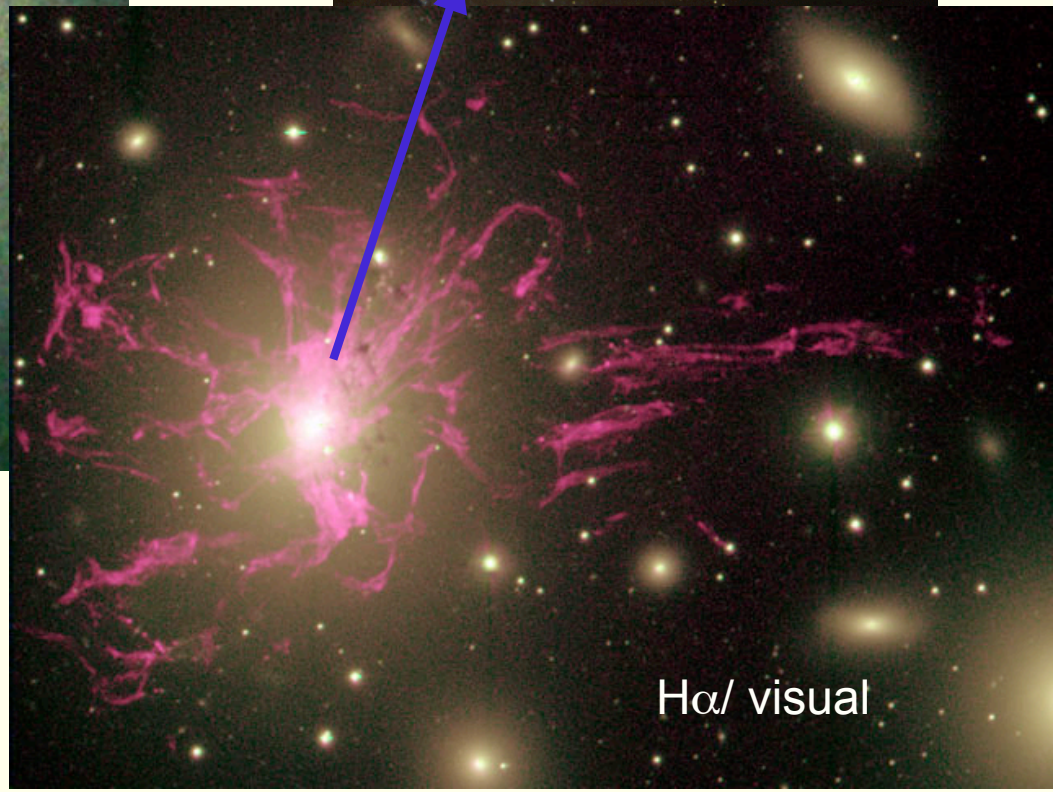
heating ~ cooling

Star formation is prevalent in cooling flows

connection between feedback & galaxy formation



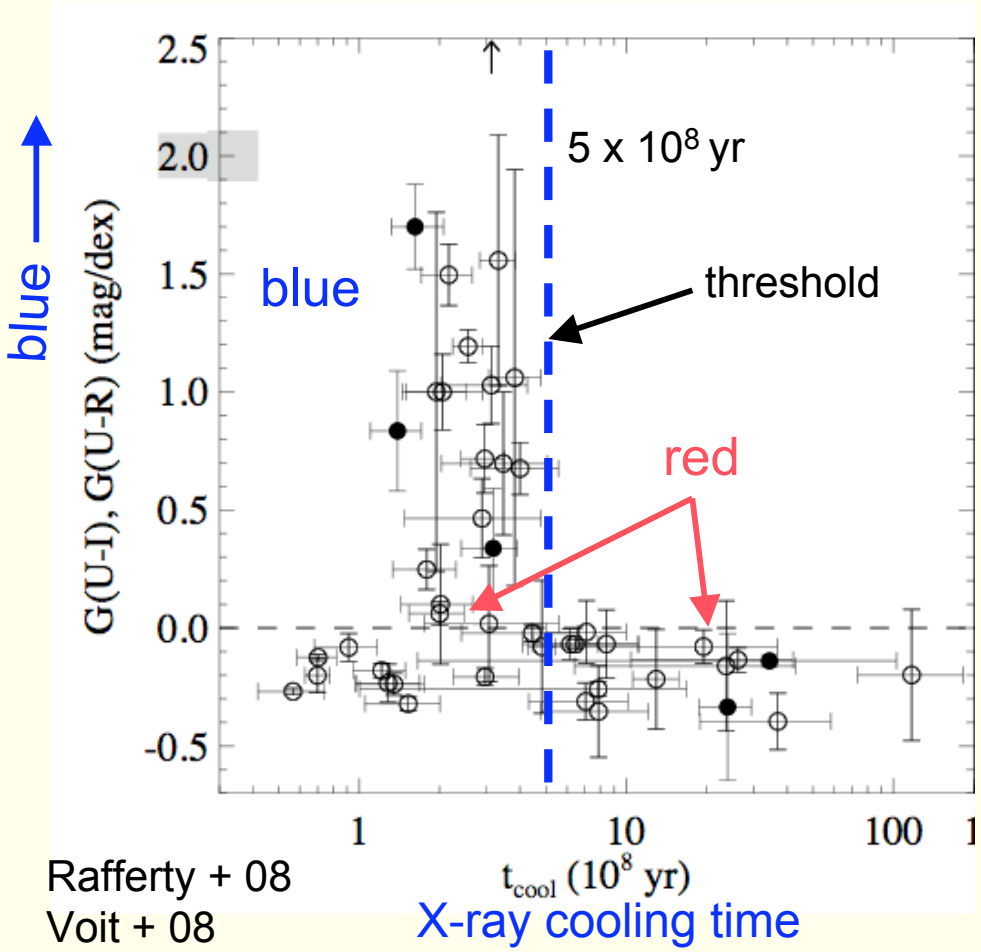




Fabian, Conselice & co

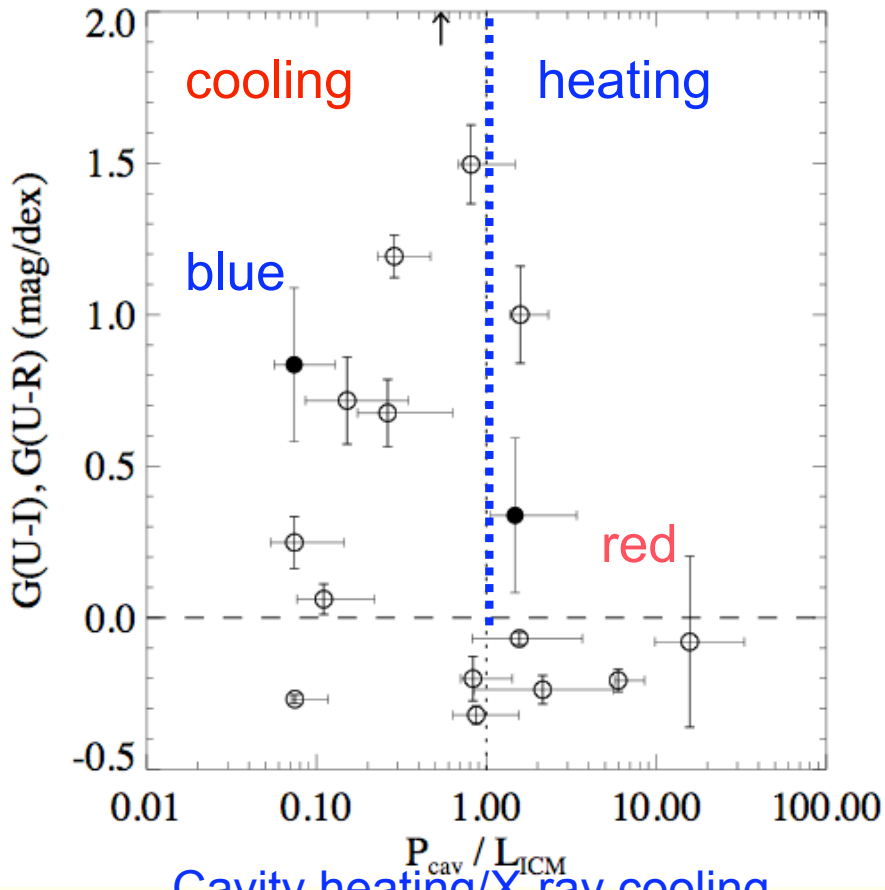
star formation threshold: t_{cool} ~ 500 Myr

suppressed by active feedback



Rafferty + 08
Voit + 08

X-ray cooling time

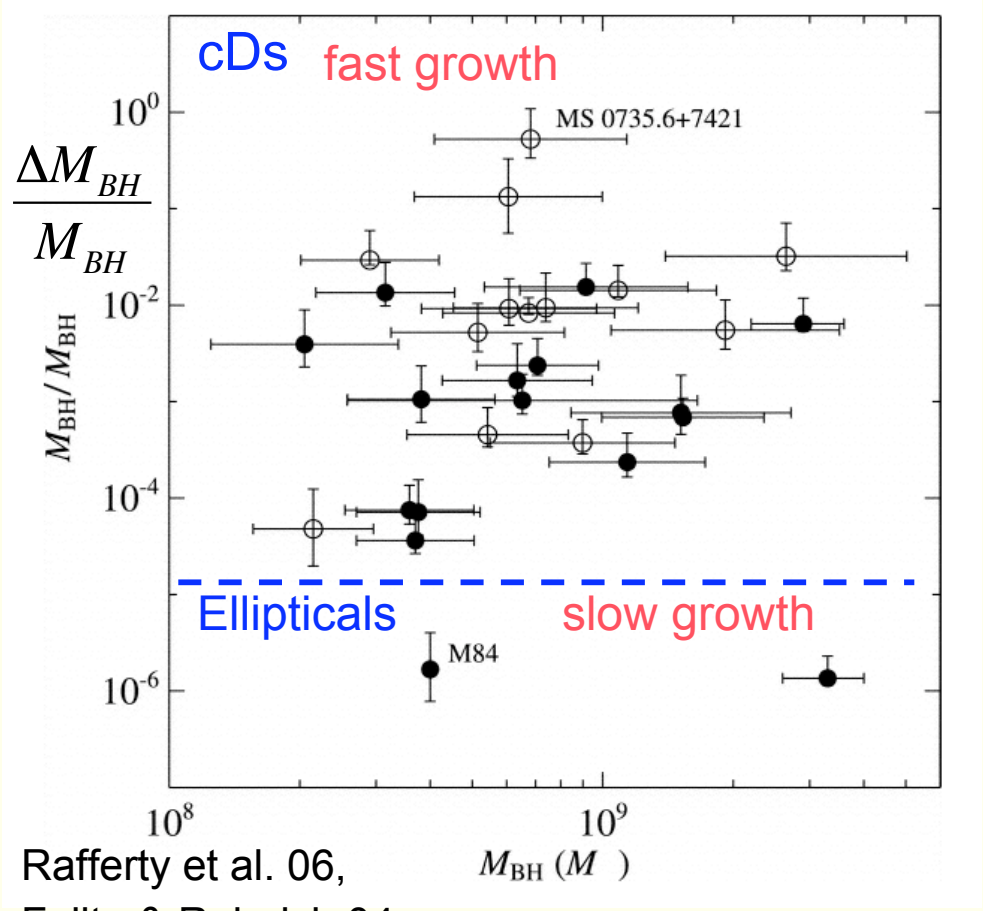


Cavity heating/X-ray cooling

- star formation rates nearing XMM cooling limits
- "observer's cooling flow problem" *nearing resolution*

Rafferty + 06,
O'Dea + 08

Significant SMBH growth at late time!



Rafferty et al. 06,
Fujita & Reiprich 04

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

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

(clusters)

sub-Eddington accretion

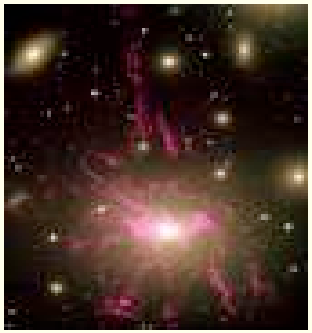
Does Bulge + SMBH growth follow Magorrian?

Feedback Sequence

gE & groups
quenched
“old, red, dead”

cD clusters
quenched

cD clusters
ongoing star
formation



quenching ~ 4pV

Jet Power

X-ray cooling luminosity

McNamara & Nulsen 07 ARAA and McNamara + 07 arXiv:0708.0579 for reviews

Problem: How do jets heat?

strong shocks not observed in clusters

..are seen in a few gEs (Kraft + 03, Croston + 07)

- Thermalization of Enthalpy as cavity rises

  Begelman 01, Churazov+02, Bruggen & Kaiser 02, Reynolds, Heinz, Begelman 02

- Weak shocks, sound damping

  Fabian+03,05, McN+05, Forman+07, Ruszkowski, Bruggen, Begelman +04,05

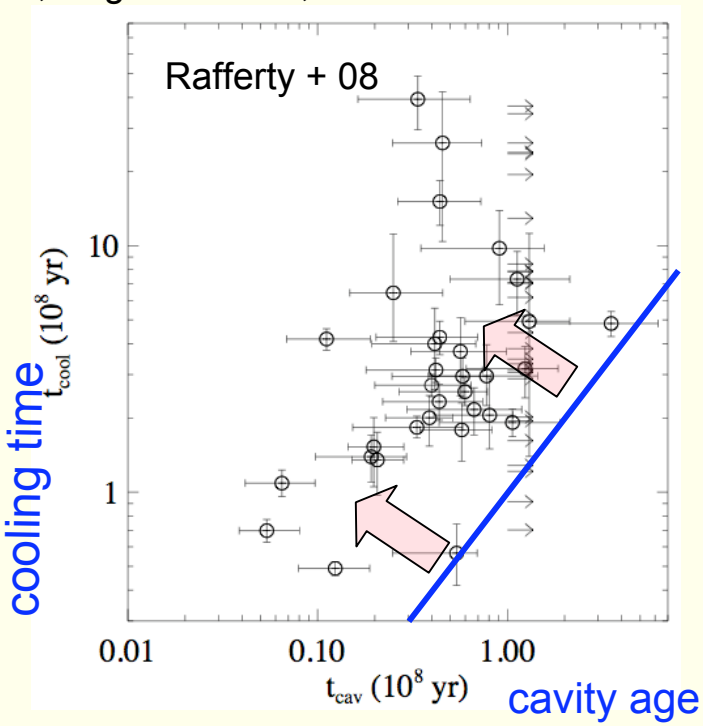
- Cosmic rays (heavy jets)

  Sijacki, Pfrommer+08,Guo & Peng 08, Ruszkowski +08

- Hybrid models: AGN + Conduction

  Ruszkowski & Begelman 02 Voit & Donahue 05

gentle, distributed heating



see

McNamara & Nulsen 07, ARAA

for a review

Problem: How are outbursts powered?

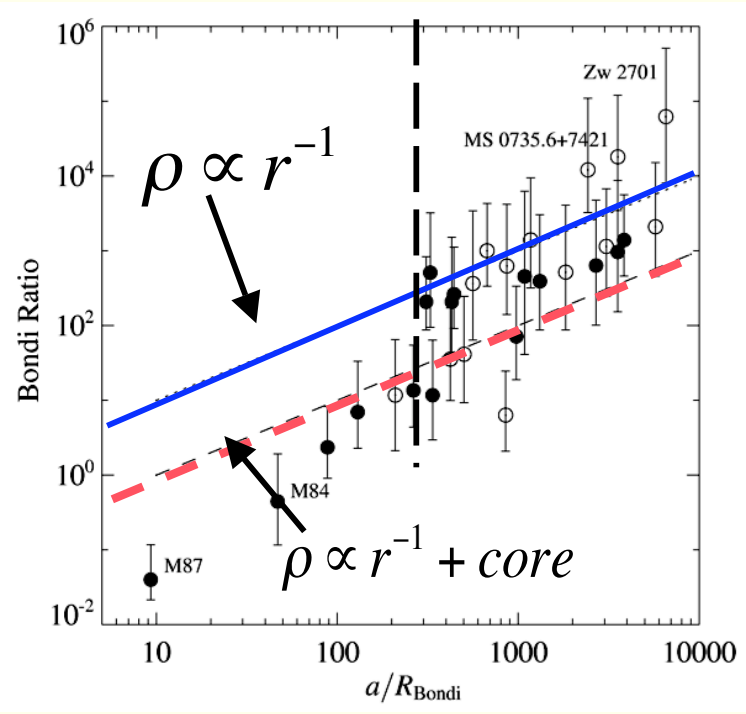
Accretion Mechanisms

- Bondi - low power systems
  (Churazov + 02, Allen 06); won't work in high power systems.
- Stars - hard to regulate, hard to power - (Wang + 05, Syer + 99)
- Gas - very likely, short supply in some systems (Rafferty 06, Soker +07)
- Hybrid - good bet

Spin & BH Mergers- energetics ok, hard to regulate

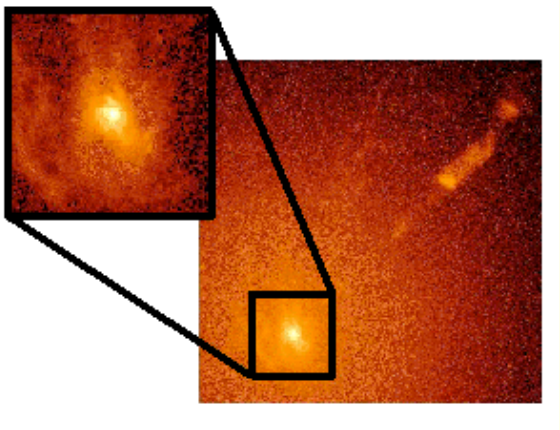
M87: Note cold gas within R_{Bondi}

$$\frac{\dot{M}_{\rm Bondi}}{M_\odot\ {\rm yr}^{-1}} = 0.012 \times \left(\frac{n_{\rm e}}{{\rm cm}^{-3}}\right)\left(\frac{kT}{\rm keV}\right)^{-3/2}\left(\frac{M_{\rm BH}}{10^9 M_\odot}\right)^2$$



Rafferty + 06

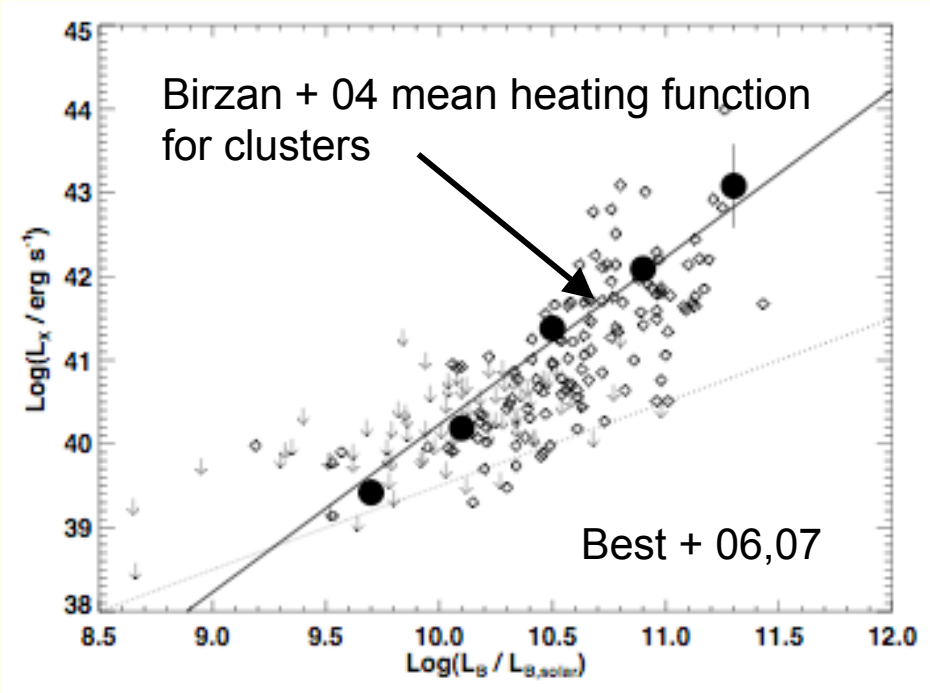
M87's gas disk



Future of Feedback: enabling larger surveys

Goal: universal relationship between radio power and jet power

Radio probes feedback across the Universe



$$P_{jet} \propto L_{rad}^{\alpha} \alpha \sim 0.35 - 0.75$$

α(frequency, radio age, etc.)

Birzan + 08

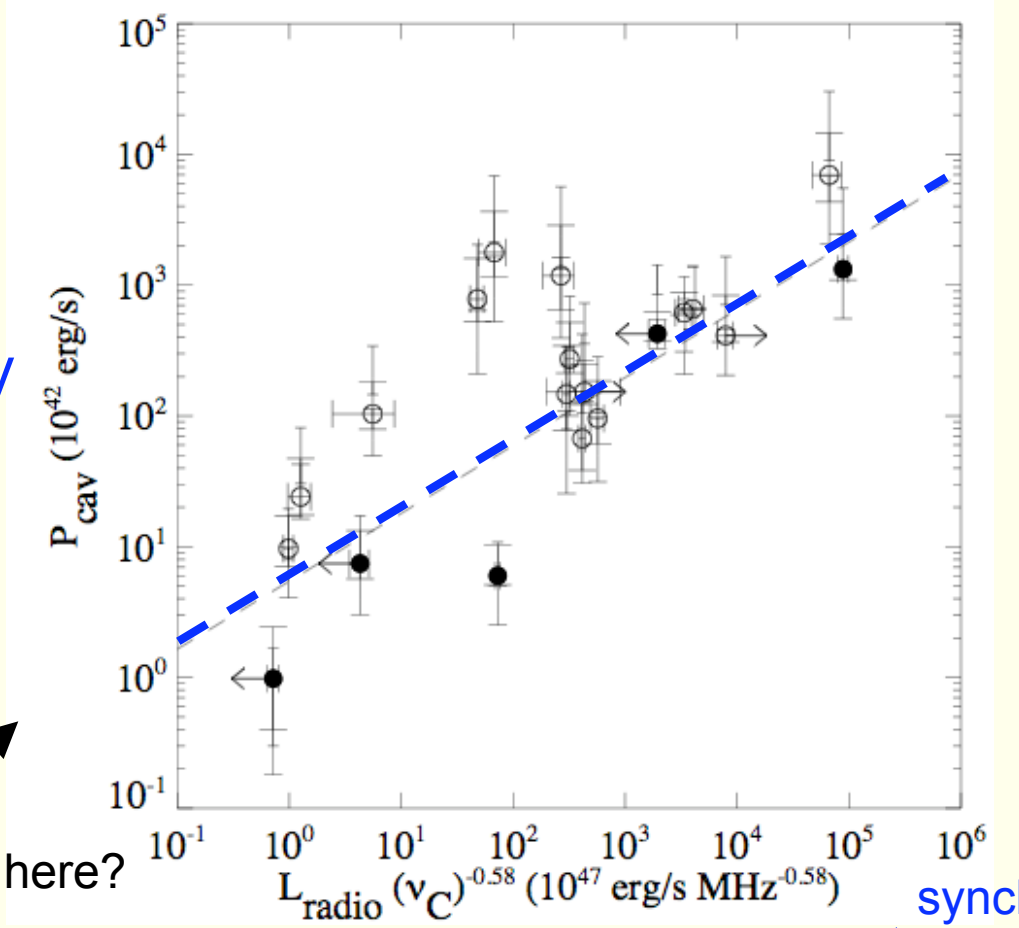
Foundations of "radio mode" feedback rest on high resolution X-ray observations

Issues:

1) heating function for ellipticals not yet established
2) big scatter in cavity power-radio power: *underestimates* heating-- must model
3) heating function frequency dependent (Birzan + 08)
4) feedback is selective: knows about X-ray atmosphere (Dunn + 06)

Tighter scaling jet power and synchrotron power:

X-ray



what happens here?

Radio

synchrotron break frequency

$$\frac{P_{cav}}{L_{radio}} = (4.11 \pm 0.86)(\nu_c)^{-(0.58\pm0.19)}$$

Birzan + 08

Summary

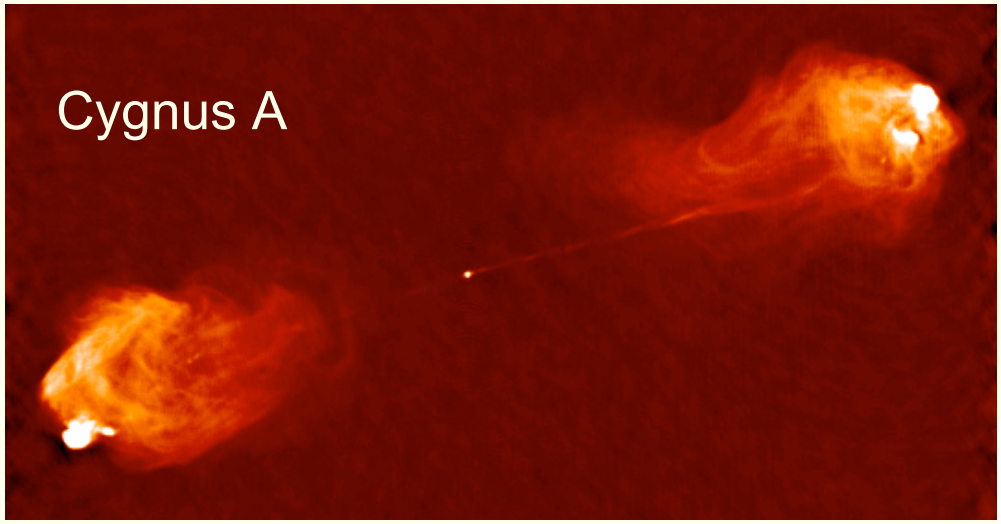
Modern X-ray observations have lead to:

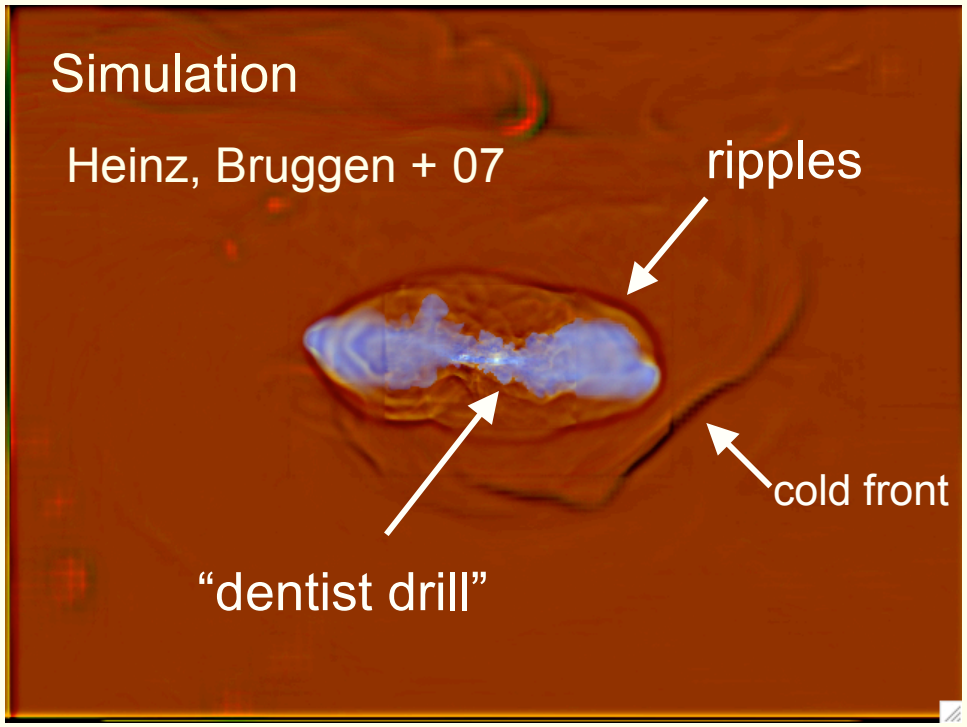
- Deeper understanding of cooling flows and AGN feedback
- Direct measurements of heating/cooling and SMBH growth
- reliable measurements of mechanical efficiency (heating) and contents of extragalactic radio sources
- Motivated development of realistic jet & X-ray halo models
- Foundation for AGN feedback

"fundamental test" for jet heating and feedback models

Heinz, Bruggen, Reynolds, Croton, Springel, Li, and others…

Realistic Jet Models



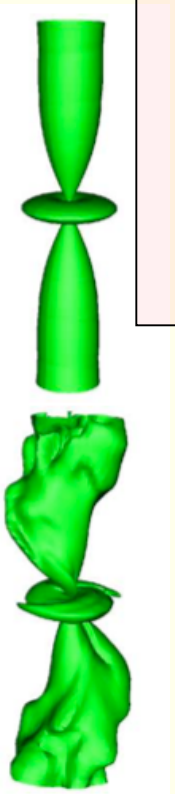


- Static jet/atmosphere models don’t heat

Vernaleo, Reynolds 06

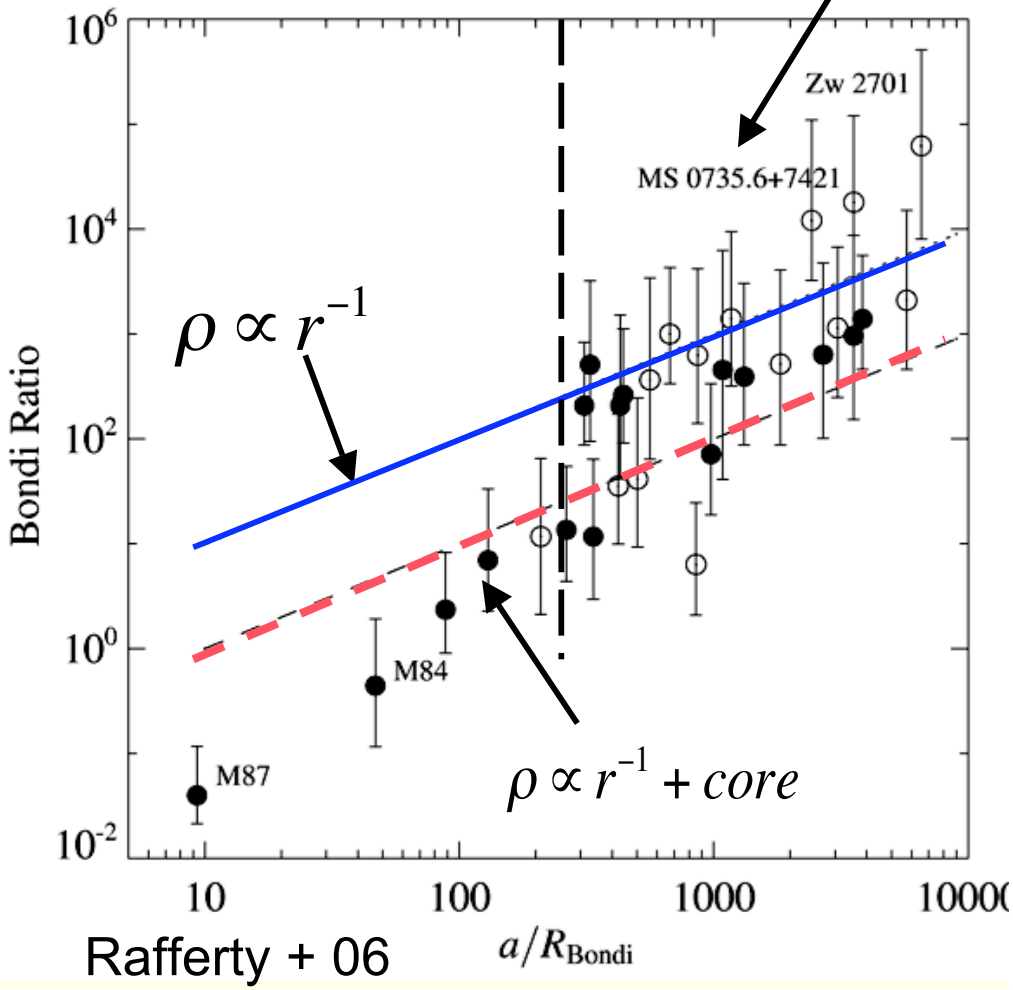
Realistic Jet models In CDM context

Isotropic heating:
a) jet precession
b) weak shocks



Kurosawa, Proga 07
Sternberg, Soker 08

Bondi accretion problem for clusters



Rafferty + 06

$$\frac{\dot{M}_{\rm Bondi}}{M_\odot\ {\rm yr}^{-1}} = 0.012 \times \left(\frac{n_{\rm e}}{{\rm cm}^{-3}}\right)\left(\frac{kT}{\rm keV}\right)^{-3/2}\left(\frac{M_{\rm BH}}{10^9 M_\odot}\right)^2$$

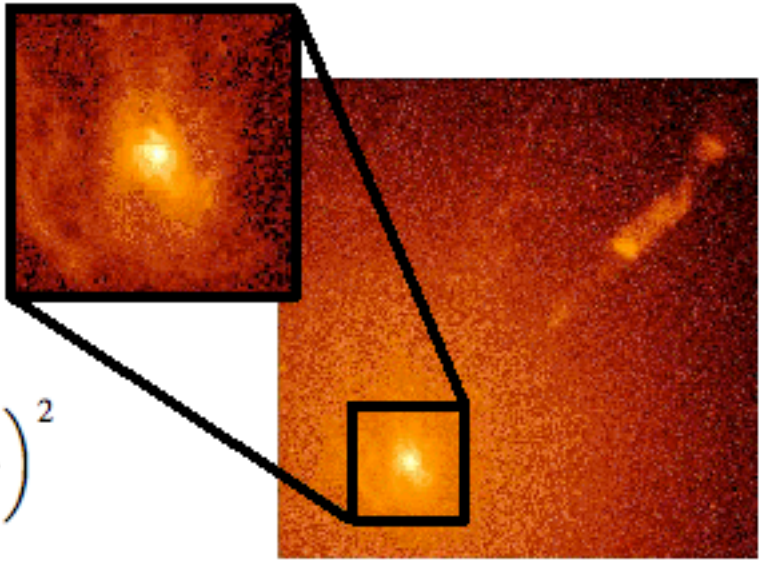
Accretion Mechanisms

Bondi- low mass systems (Allen 06)

Stars - hard to regulate

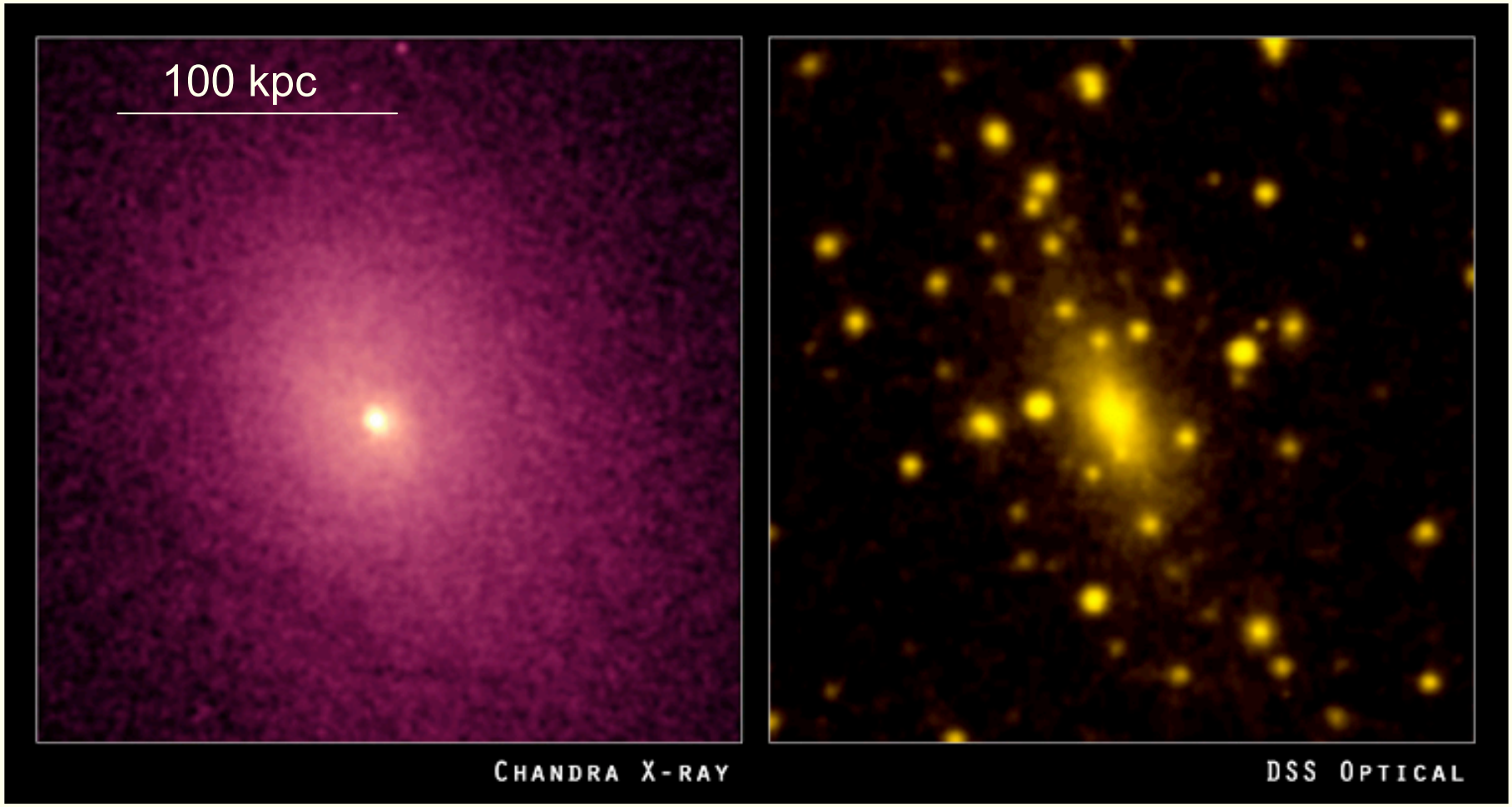
Gas - very likely (Rafferty 06)

M87's gas disk



Galaxy Cluster at X-ray & Visual wavelengths

X-ray visual



Buote +

70%-80% dark matter, 20%-30% baryons, most baryons @~ 5 keV