Outflows in Clusters

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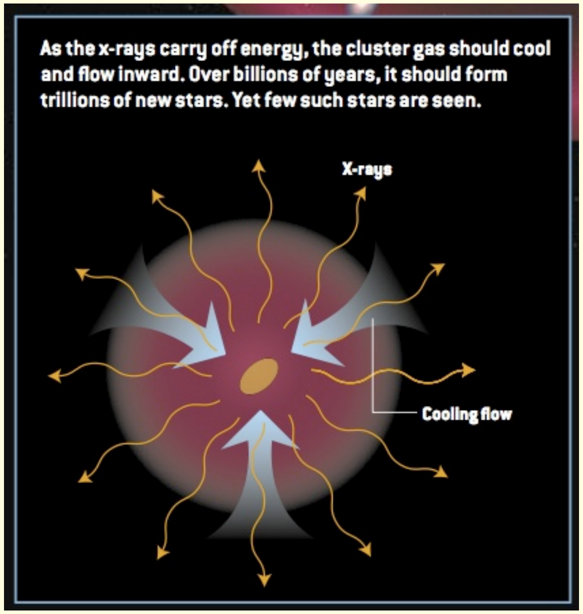
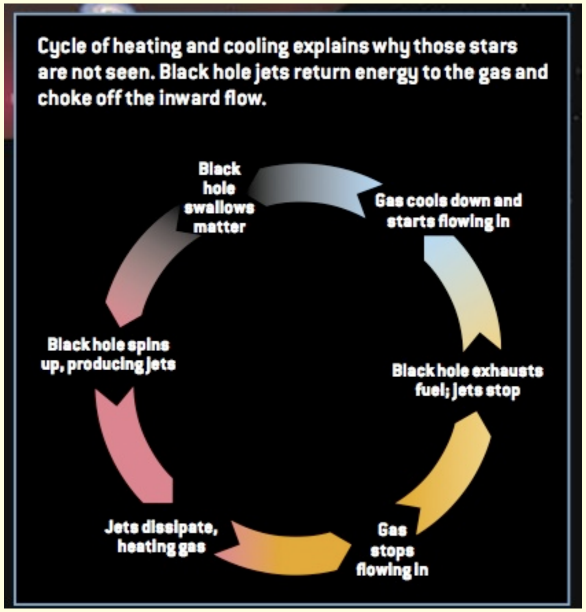
A. Vantyghem & Robert Main (Waterloo)

Mechanical Feedback in Radio AGN





Tucker, Tananbaum, Fabian 07, *Scientific American*

Review:

Radio-mechanical heating in X-ray atmospheres of galaxies, groups, & clusters

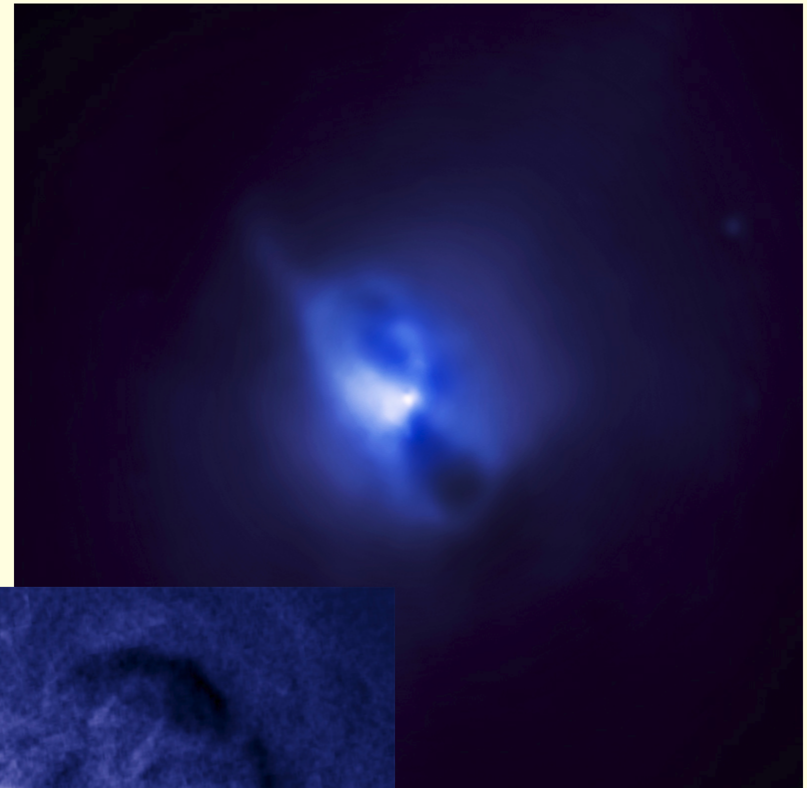
Indications for actual feedback loop: cooling, star formation, AGN

Consequences: quenching of cooling flows, red & dead phenomenon in ellipticals, color dichotomy in ellipticals

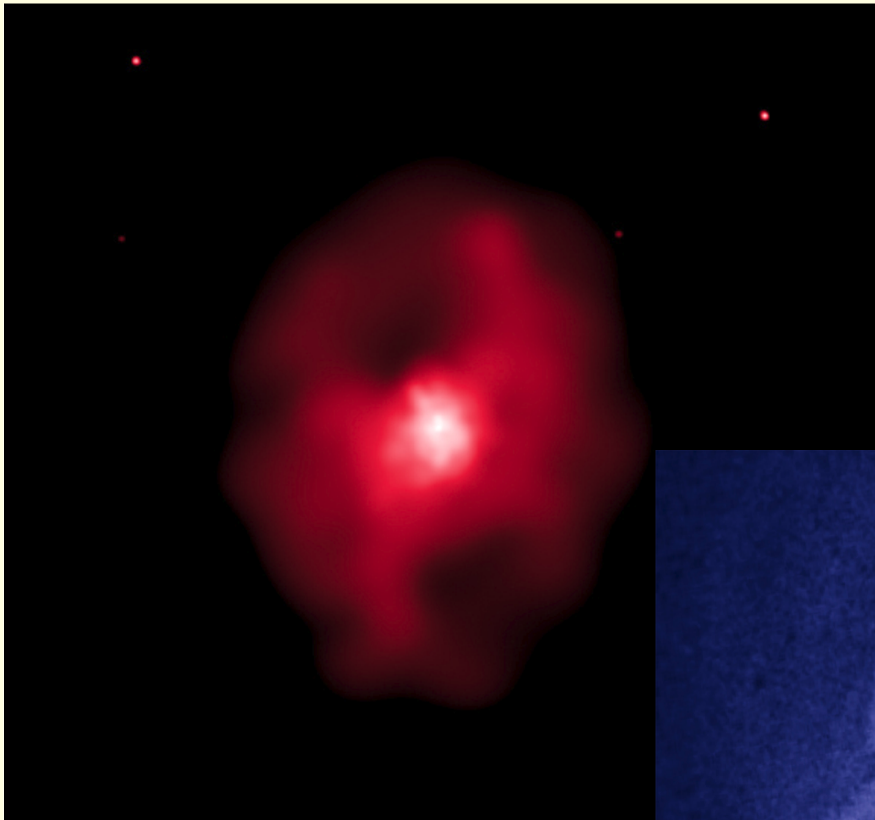
Recent developments:
1. Metal-enriched, *large-scale* outflows in clusters
2. AGN heating of clusters atmospheres over cosmic time
3. (Near) Future

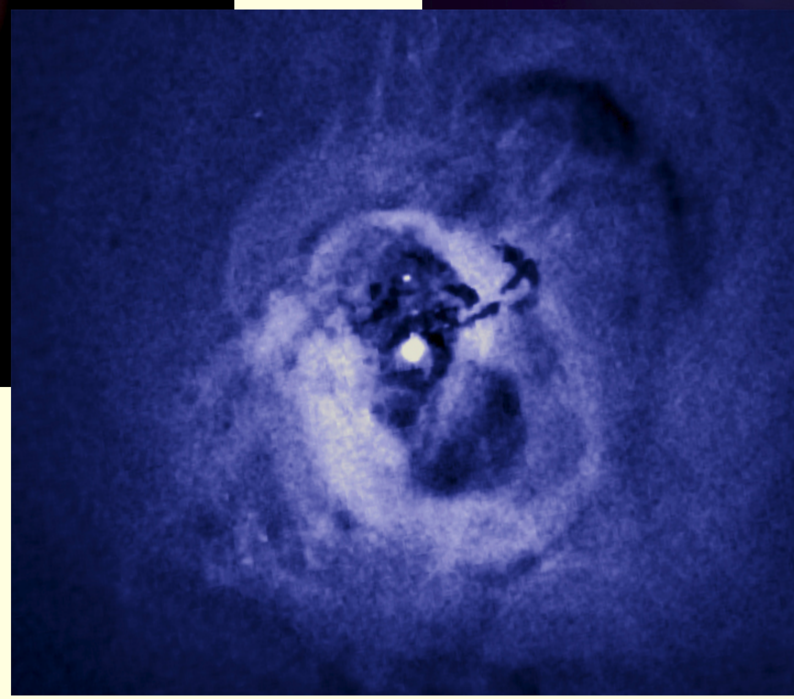
Chandra X-ray Observatory

Hydra A



MS0735

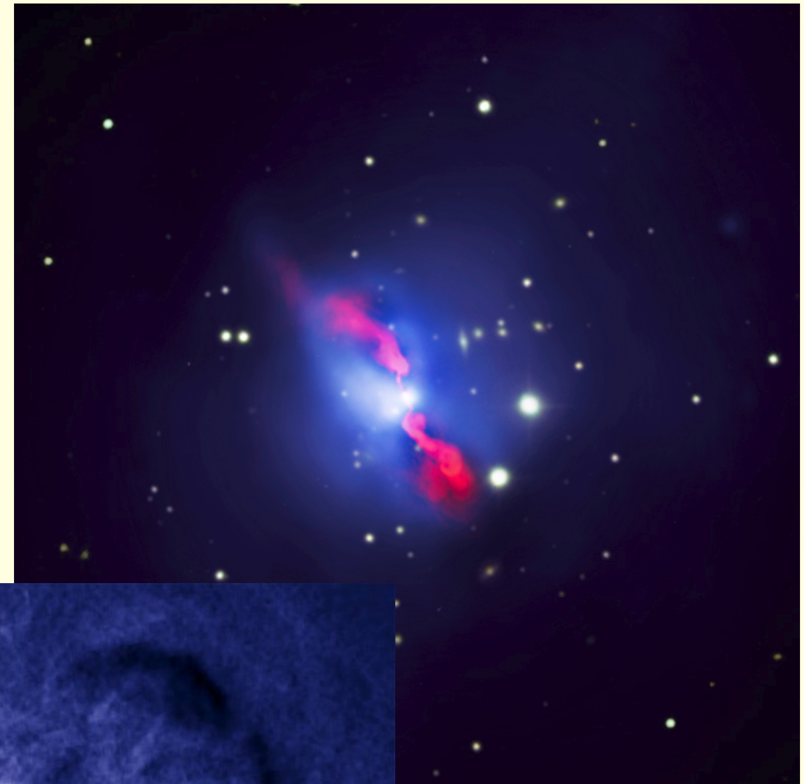




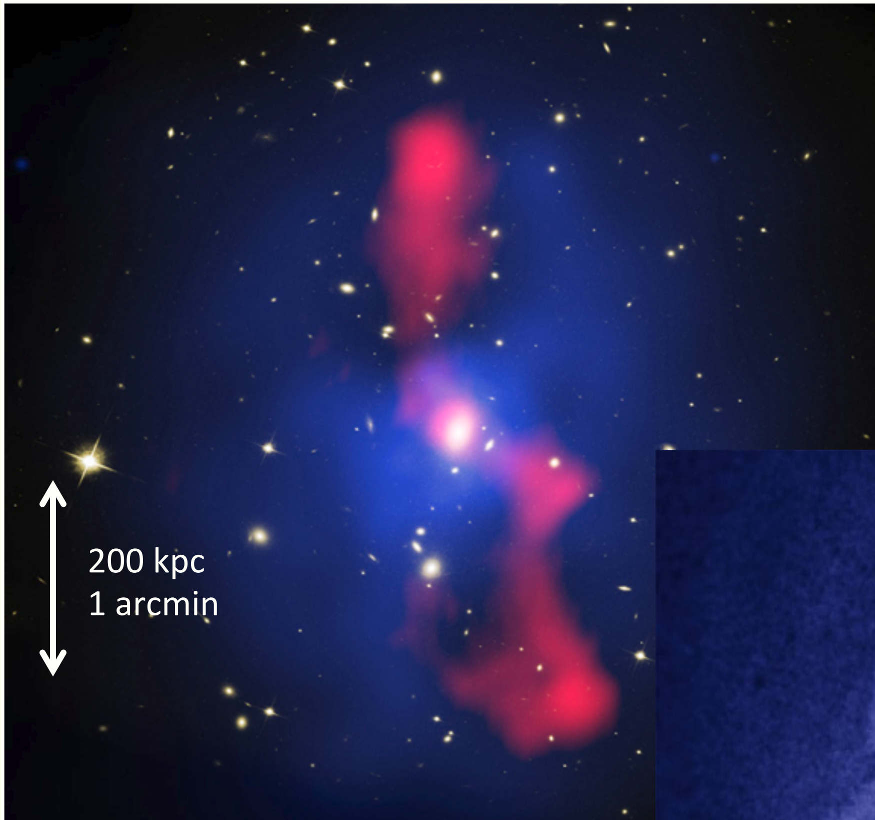
Perseus

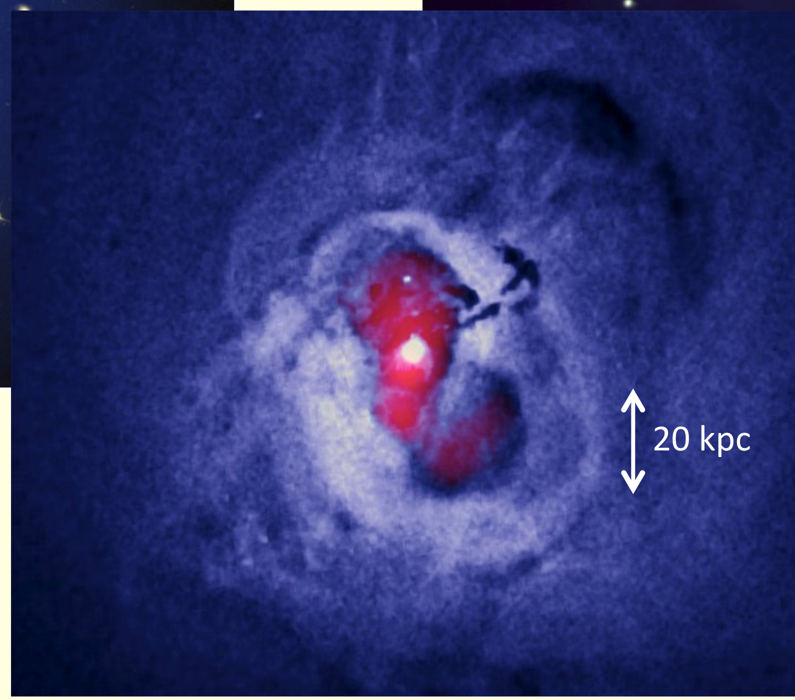
X-ray + radio = mechanical feedback

Hydra A McN +00, Kirkpatrick+11



MS0735 McN + 05,09





Perseus
Fabian et al. 2008

Credit: H. Russell

Mechanical AGN Feedback Regulates Cooling

"*radio mode*" feedback

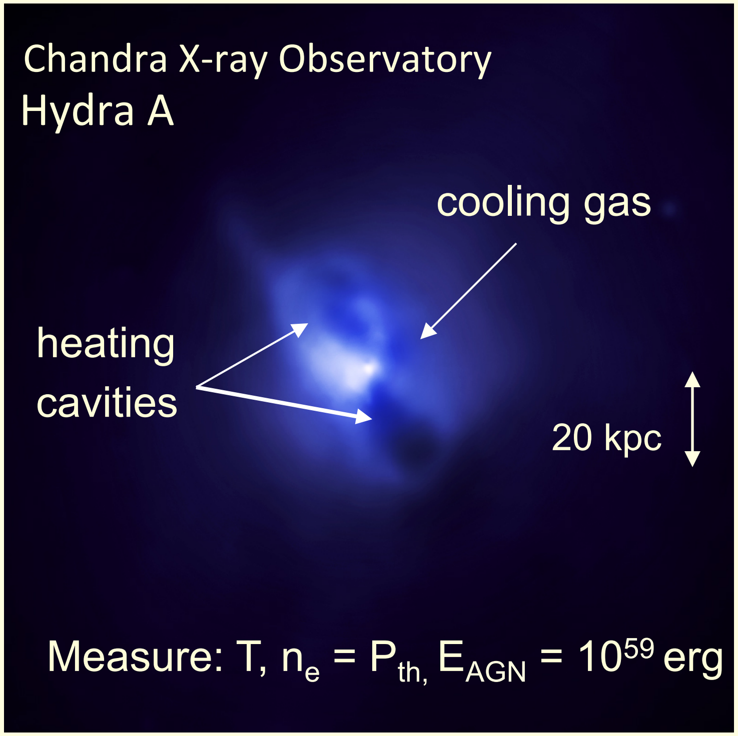
Radiative cooling balanced by AGN heating

thermostatically controlled accretion

$E_{jet} \approx$ 2-4 pV per cavity

McN+00,01, Churazov +01 Birzan+04

==> *feedback loop*



McN+00
Churazov + 01

Key indicators:

-AGN mechanical power matched to cooling rates

Birzan+04, Rafferty+06, Dunn Fabian 06

-Short (<10^9 yr) cooling times in *all* systems

Voigt & Fabian 04

-Flat inner entropy profiles

Donahue + 06, David + 01

Reviewed by McNamara & Nulsen 07 ARAA, McNamara & Nulsen 12, NJP, arXiv:1204.0006

Upshot of all this:

Classical cooling flow problem is now understood:

observed SFR ≈ *classical cooling rate* – (*heating rate* + *outflow rate*)

Rafferty +06, Best + 06

Radio-Mechanical feedback maintains red & dead ellipticals

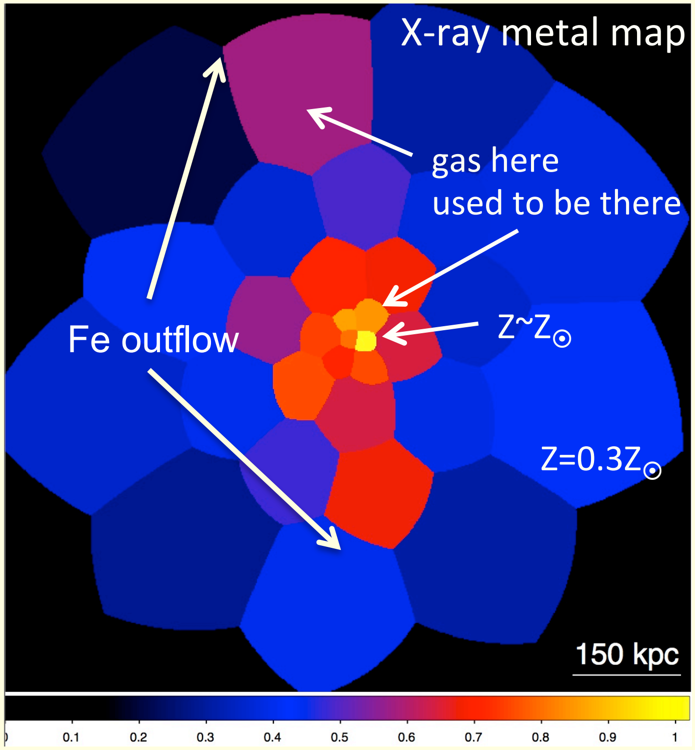
(Bower +06, Croton 06)

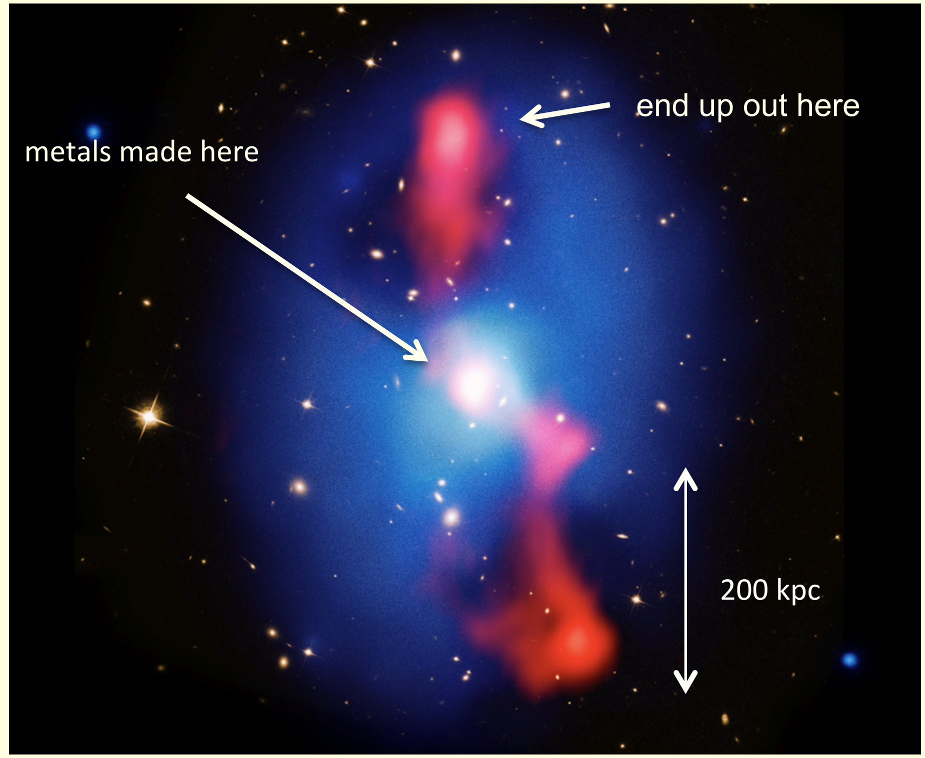
Problems: how does feedback work?, heating microphysics, transport

Hot Outflows on Cluster Scales

Clif Kirkpatrick + 09, 10, 12 in prep

MS0735 Cool, metal-enriched outflow





McN+09, 12

R_{Fe}~300 kpc

500 ks Chandra image
VLA, HST

Powerful thrust: $P_{jet} \sim 3\times10^{46}$ erg s^{-1}

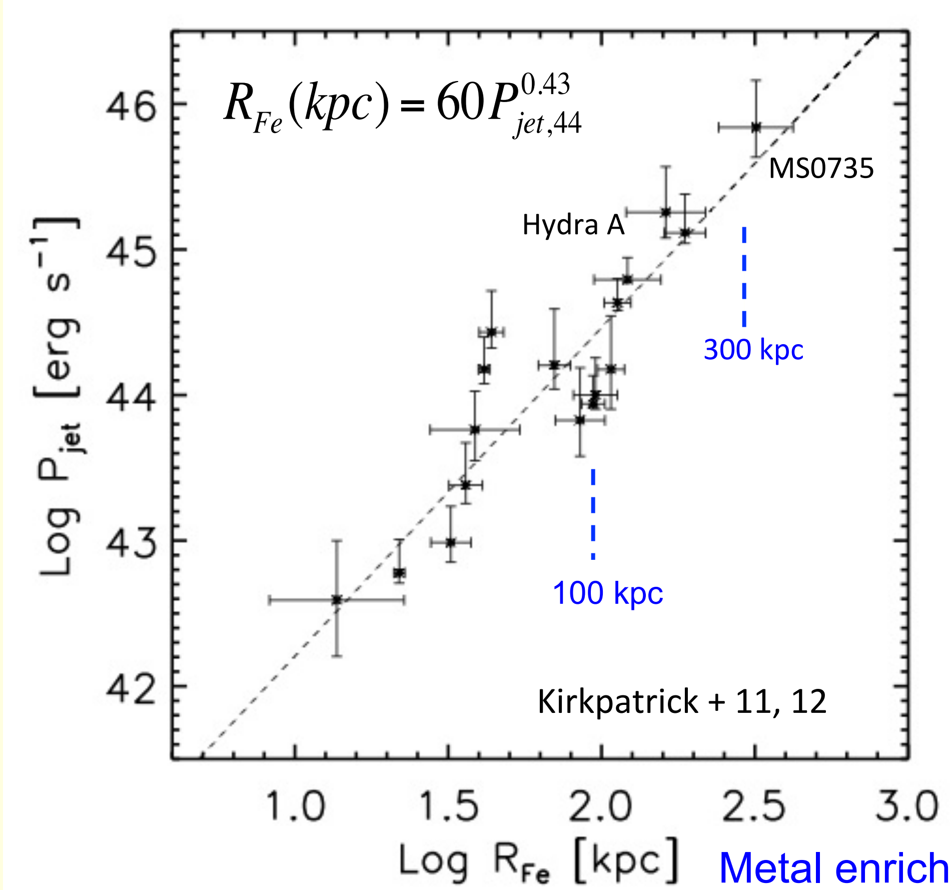
$E_{jet} \sim 10^{62}$ erg

Lifted/displaced mass ~ 10^{10} $M_{\odot}$ ~200 $M_{\odot} yr^{-1}$

See also Simionescu + 08, Kirkpatrick 09,11

Iron enrichment radius scales with Jet power: drives hot gas out of galaxy

AGN jet power



Metal enrichment radius

- Theory: 3D Hydro

$R_i \sim P_{jet}^{1/3}$

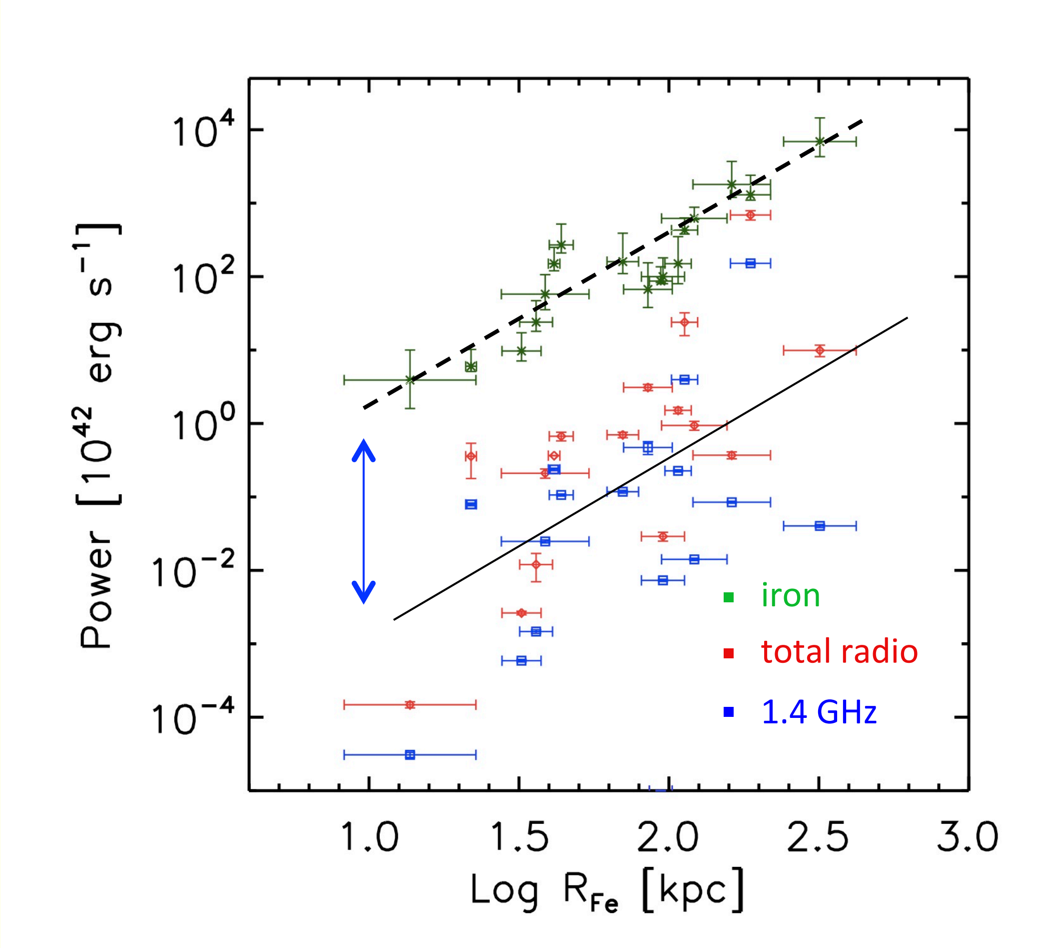
Morsony, Heinz, Bruggen+ 10

- Observations;

- slope probably flatter
- circulating flow?

- Outflow rates of tens to >100 $M_{\odot} yr^{-1}$ – star formation quenched by heating and *removal* of metal-enriched, cooling X-ray *gas out of BCG* and into ICM

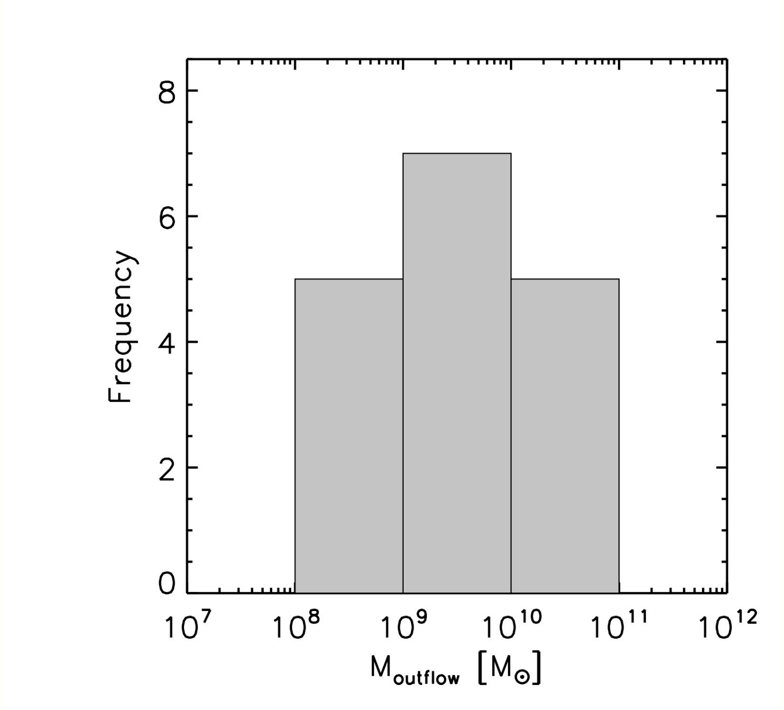
Fe radius correlates less well with radio synchrotron power

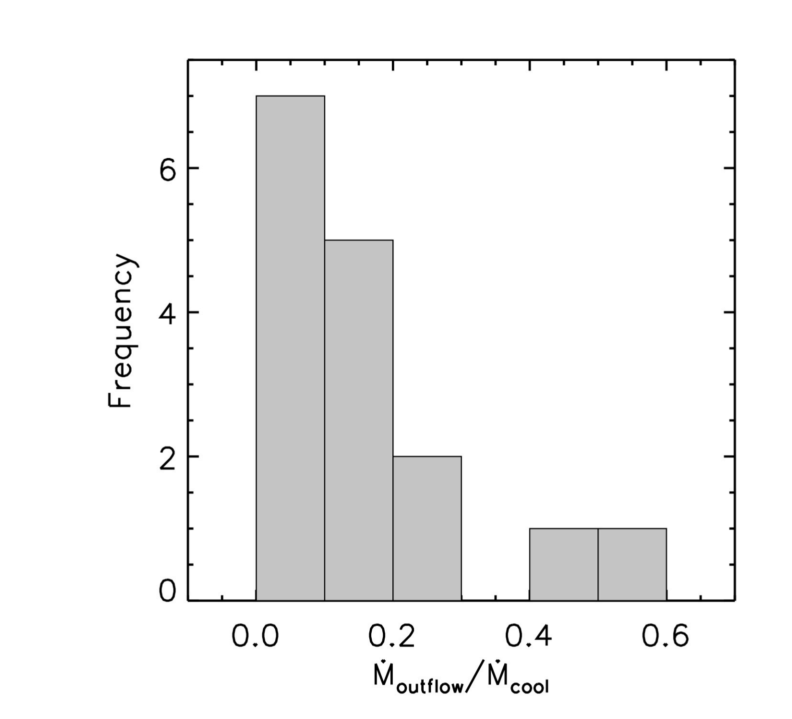


Displaced metals trace AGN mechanical power
Radio luminosity not as good a probe of total jet power

Kirkpatrick & McNamara in prep

Outflows Augment the Regulation of Cooling & Star Formation





- Outflow rates several to a few hundred solar masses per year
- A few to a few tens of % of the cooling gas is re-circulated
- Consequence: SMBHs growing by $10^8 – 10^9$ $M_\odot$

Kirkpatrick & McNamara in prep

Radio AGN Heating of Cluster Atmospheres Over Cosmic Time

C.J. Ma

Problems:

1. Hot atmospheres are ≈1 keV per particle "hotter" than expected?
aka, "preheating" problem Evrard & Henry (1991), Kaiser (1991)

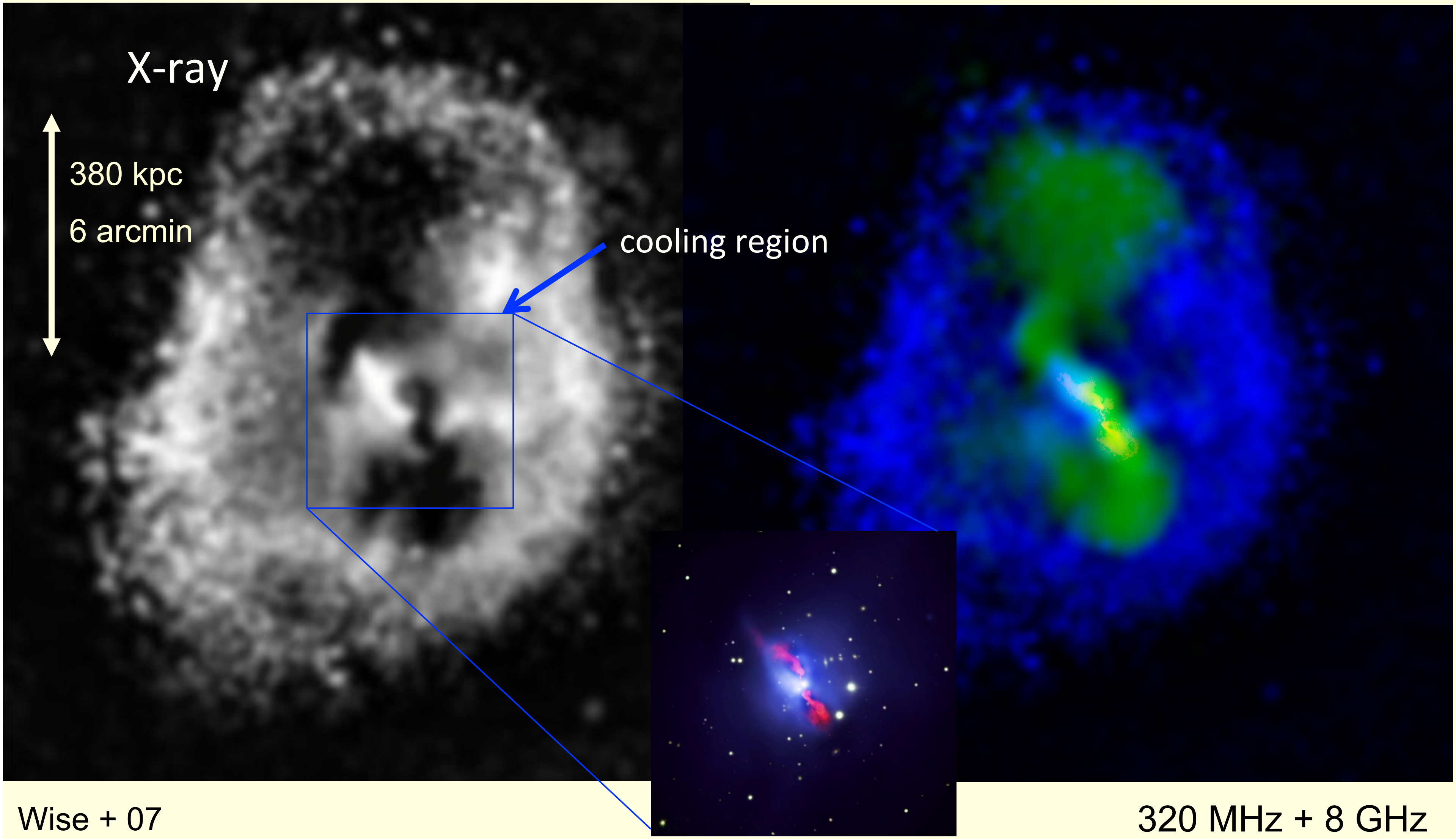
2. Quenching & declining numbers of distant cooling flows (Vikhlinin 07, Samuele + 11)

3. Growth of Massive Black Holes in Central Galaxies (Lauer + 06)

Reviewed by McNamara & Nulsen 12, NJP

See Ma + 11, 12

We can't do analysis like this in distant clusters!

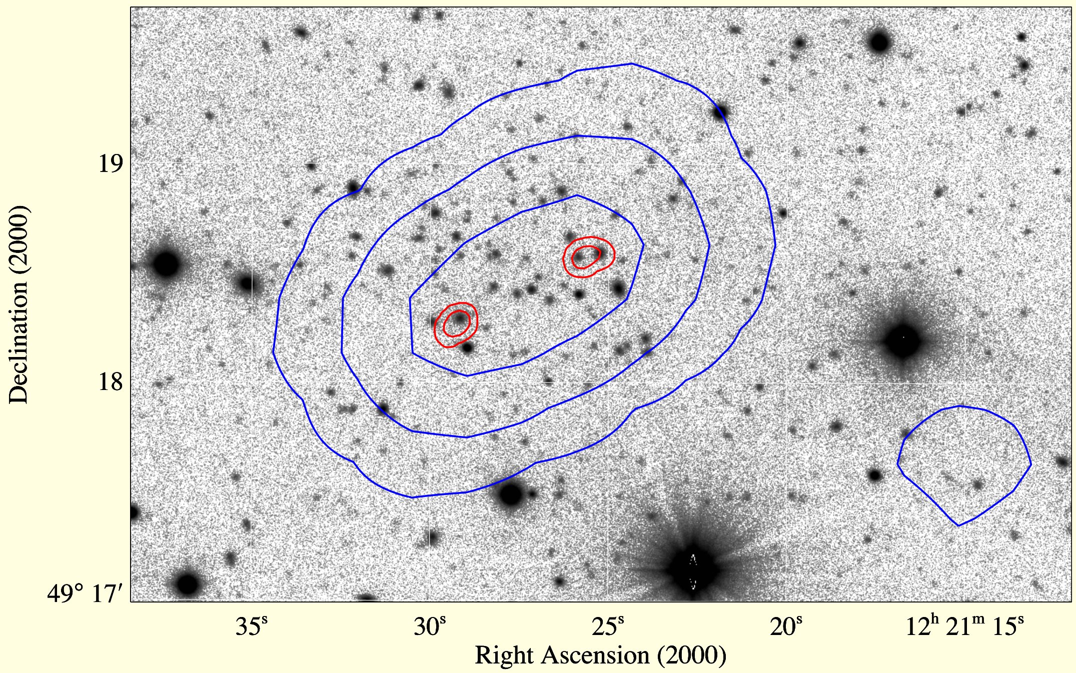


Wise + 07
Nulsen + 05
McN + 00

320 MHz + 8 GHz

So we… sample hundreds of Clusters from *ROSAT*

NRAO-VLA Sky Survey (NVSS)
ROSAT X-ray Imaging



J1221+4918
z = 0.7
Lx = 1.2×10^{45} erg s^{-1}
kT = 6.5 keV

Ma + 11, 12

Host galaxies cannot be identified using NVSS images

X-ray cavities cannot be identified in short X-ray exposures

AGN Heating in Distant Clusters

Sample: 8 serendipitous & all-sky X-ray surveys: 685 ROSAT clusters

Procedure:

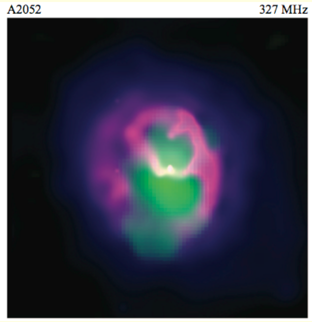
C.J. Ma + 2011, and in prep

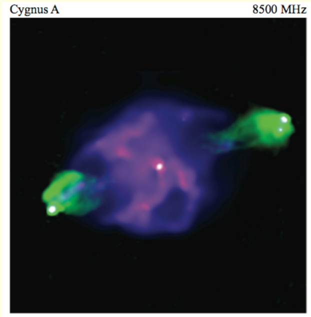
- Cross Correlate cluster X-ray positions with NRAO VLA Sky Survey radio sources
- $10^{43} < L_x < 10^{46}$, $0.1 < z < 0.6$
- Radio detection threshold > 3 mJy
- Correct for background as function of flux
- Calculate jet power using *cavity power scaling relation at 1.4 GHz*
- Calculate heating rate per particle

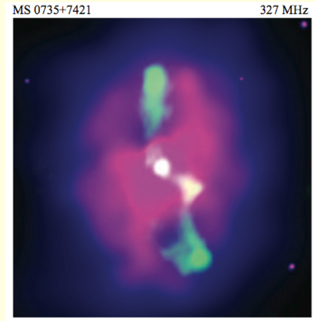
Challenge: sample selection, jet power proxy

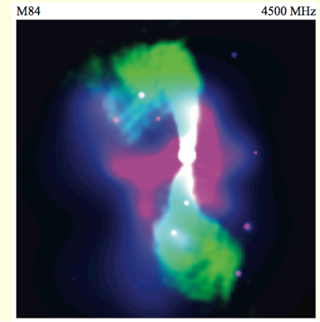
Scaling between jet cavity (mechanical) power and radio luminosity

$$P_{cavity} \propto L_{radio}^{0.7}$$

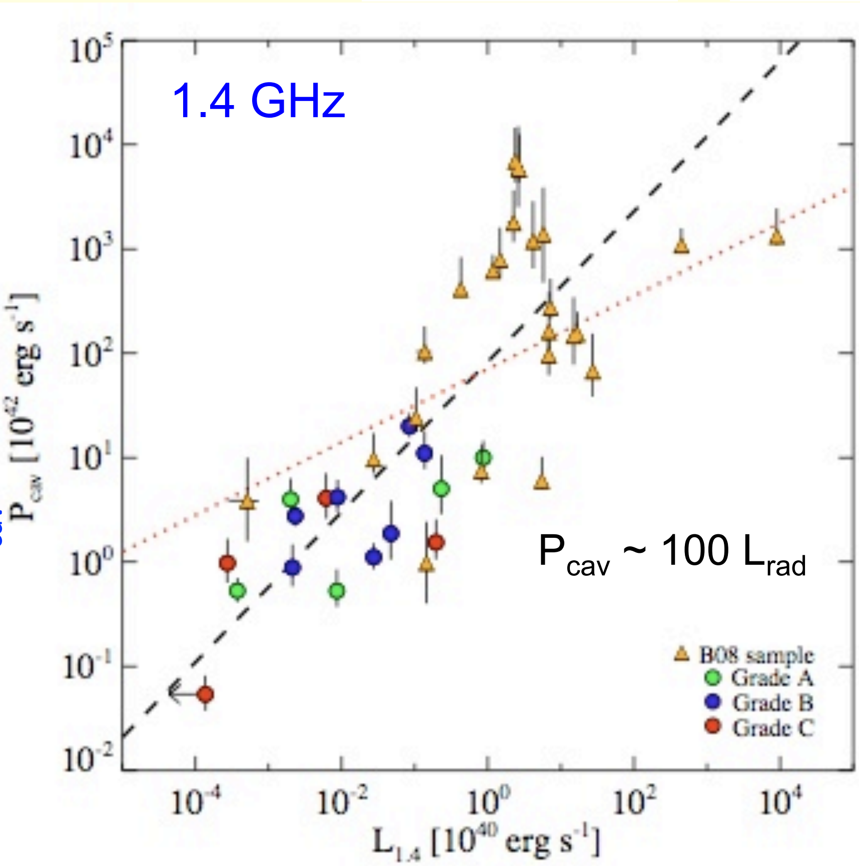


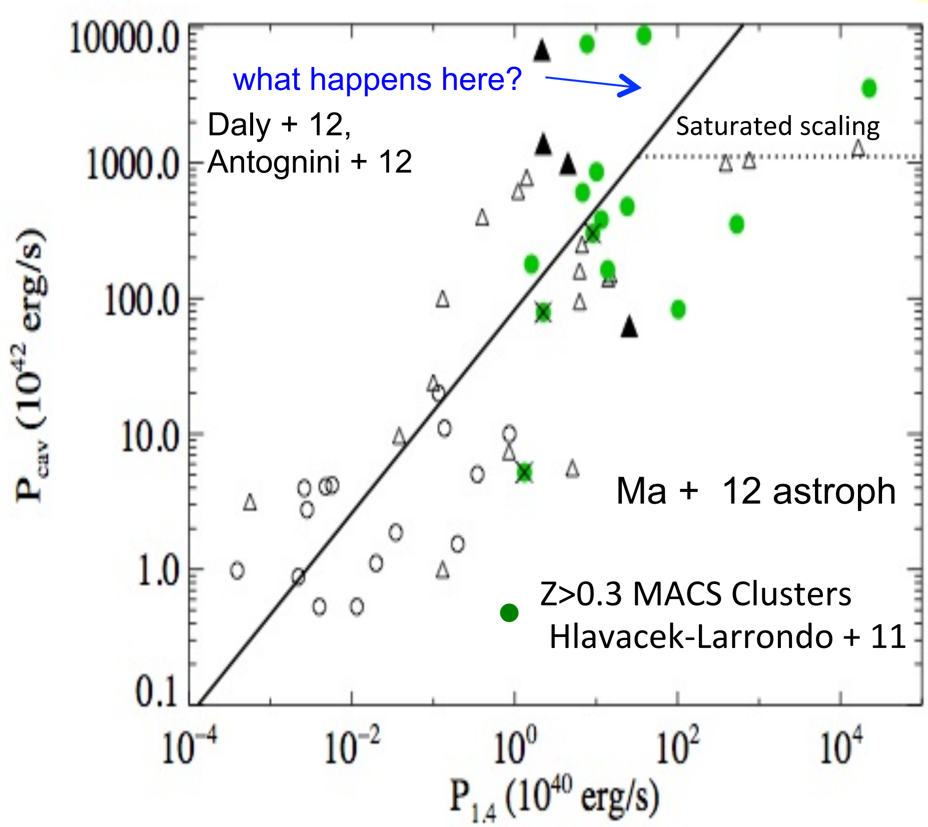






P_{cav} (10^{42} erg s^{-1})



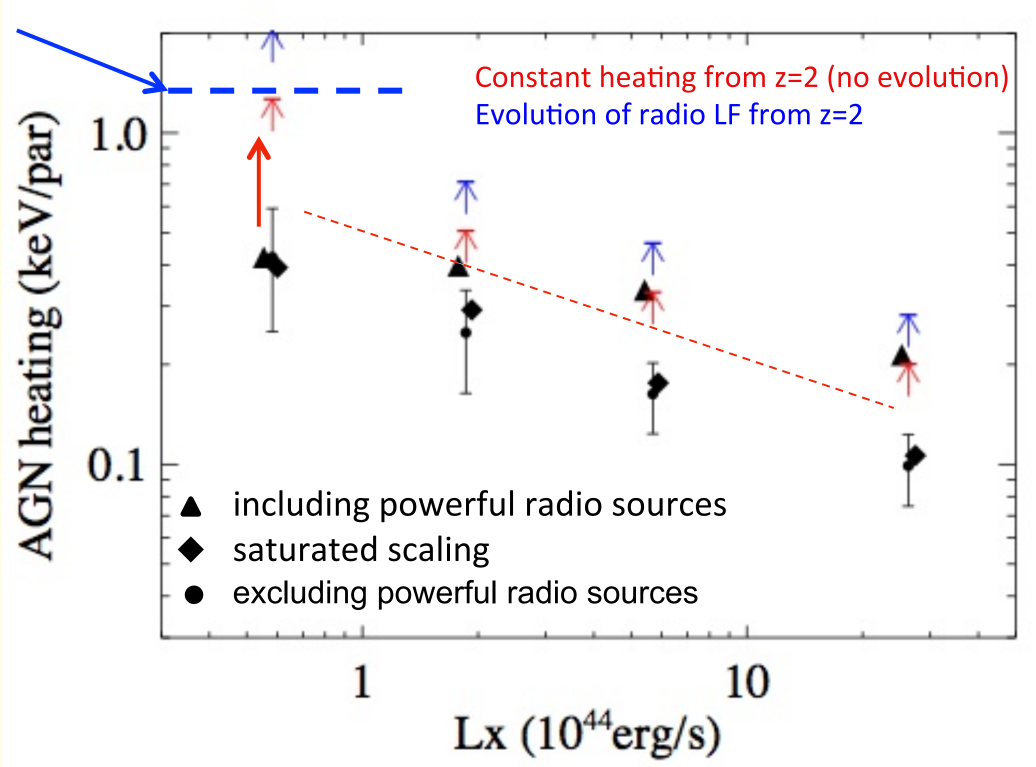


Cavagnolo + 10
Birzan + 04,08

L_{radio} (10^{40} erg s^{-1})

Radio/Mechanical Heating Rate in clusters from z = 0.2-0.6

“preheating rate”



$<P_{jet}> = 3x10^{44}$ erg s^{-1}

R<250 kpc

Ma + 12 arXiv

- *Heating (jet power) rises slowly with X-ray atmospheric luminosity, and redshift*
- Heating per gas particle *highest in low-luminosity clusters*
- Continual heating over time significant w/r to Kaiser’s “preheating” scenario

Potential Consequences: excess entropy in clusters (Evrard & Henry 91, Voit 05, Kaiser 91), break in L-T? declining numbers of distant cooling flows (Santos 10, Vikhlinin 06, Samuele 11)

SMBHs grow by $10^9 M_{\odot}$ as they heat their atmospheres >> curvature in M-Sigma relation (e.g., Lauer + 06)

The Near Future

- Molecular inflow/outflow in central cluster galaxies?

    HI and CO outflows observed in HZRGs

    see Morganti, Lehnert, Nesvadba

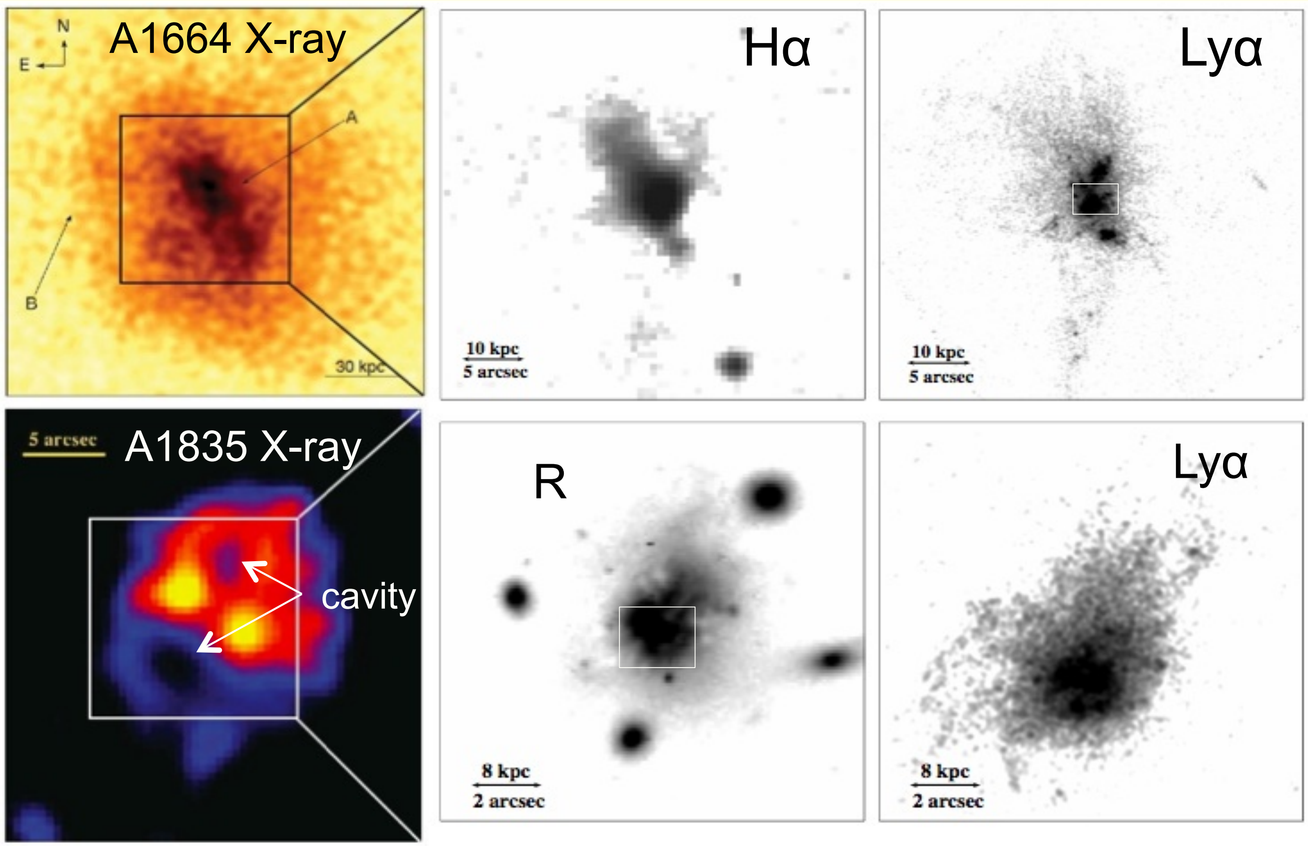
- The abyss between the Bondi sphere and horizon:

    emergent properties from sub-mm (ALMA) through X-ray emission

    see Merloni, Heinz and others

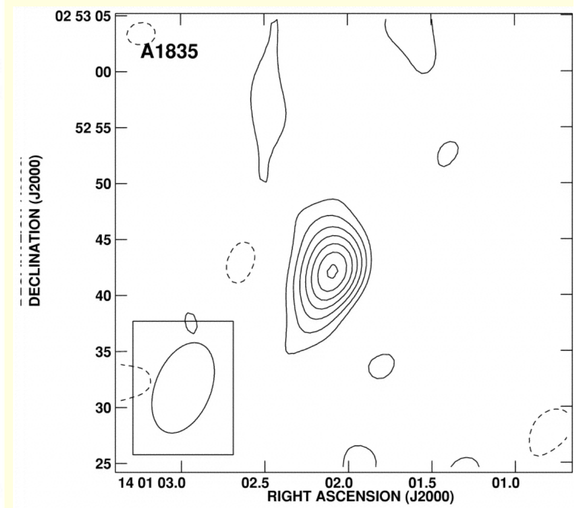
- Russell + 2012

Residual cooling: UV emission from star formation in molecular-gas-rich BCGs



~10^{10} - $10^{11} M_o$ of gas

Edge & Frayer 02



O' Dea + 10

A1664 SFR ~ 20 M_o yr^{-1} A1835 SFR = 100 - 200M_o yr^{-1} P_{cav} ~ 10^{45} erg s^{-1}

- Fuel *directly linked* to cooling hot halo (not mergers)
- X-ray cooling rate near star formation regions match SFR

McN+ 06 Rafferty+08, Cavagnolo+08, Kirkpatrick + 08

ALMA data will ~~arrive~~ shortly! has arrived!

Summary

- Outflows suppress star formation, disperse metals throughout LSS
- Continual AGN heating important *over more than half the age of universe*
- Low-luminosity X-ray halos heated more efficiently
- Continual AGN heating significant at ≈ 1 keV per particle
- Molecular outflows/inflows!!

See McNamara & Nulsen 12, NJP & arXiv for recap of this talk