Supermassive Black Holes & Mechanical Feedback

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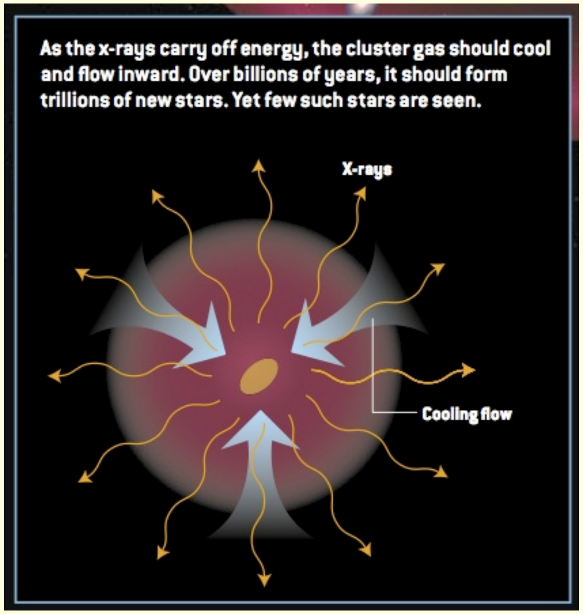
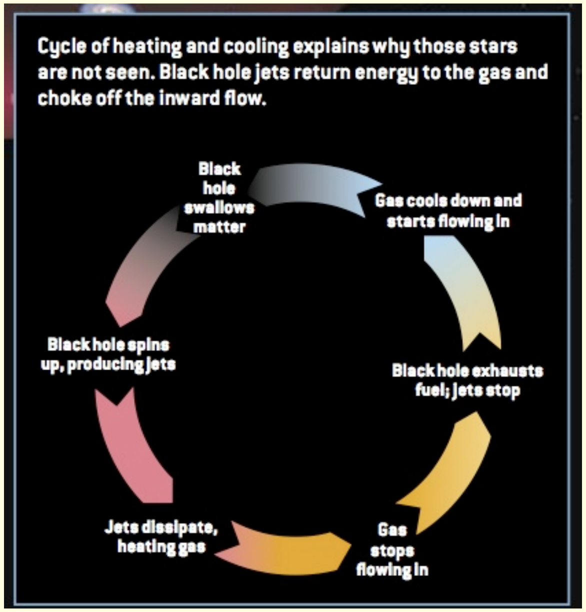
Mechanical Feedback in Radio AGN





Tucker, Tananbaum, Fabian 07, *Scientific American*

Physical basis for "radio mode" (mechanical) feedback hot X-ray atmospheres

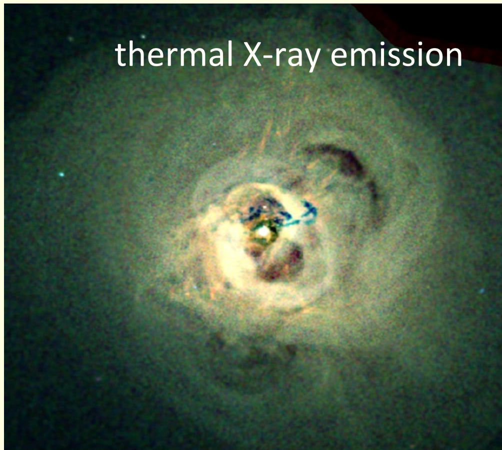
Evidence for self-regulating feedback: cooling, star formation, AGN

Consequences: quenching of cooling flows (Birzan), large scale structure (Schaye)
recovery of galaxy properties in ΛCDM (Benson + , Croton +, Bower+, Springel+)

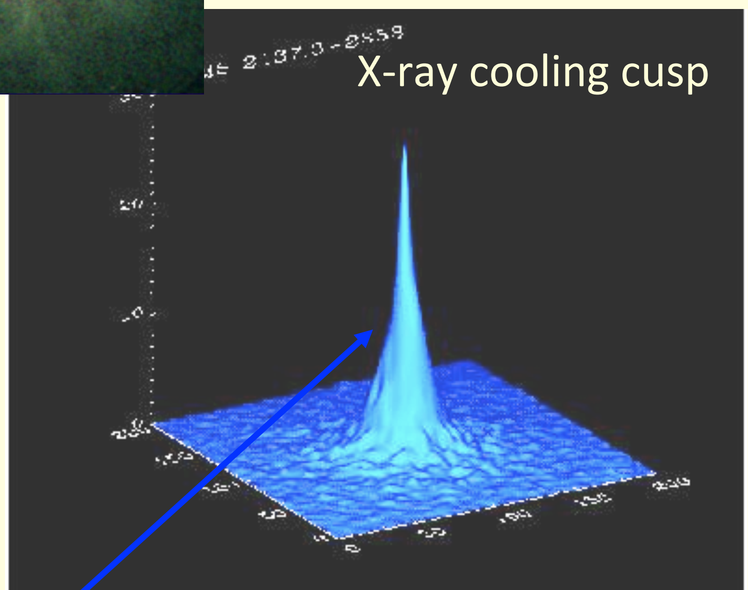
New development: metal-enriched, large-scale outflows in clusters

Issues: what powers radio AGN? How does feedback work?

Cooling flows (cores) in most clusters and all gEs



T≈10^8 K



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

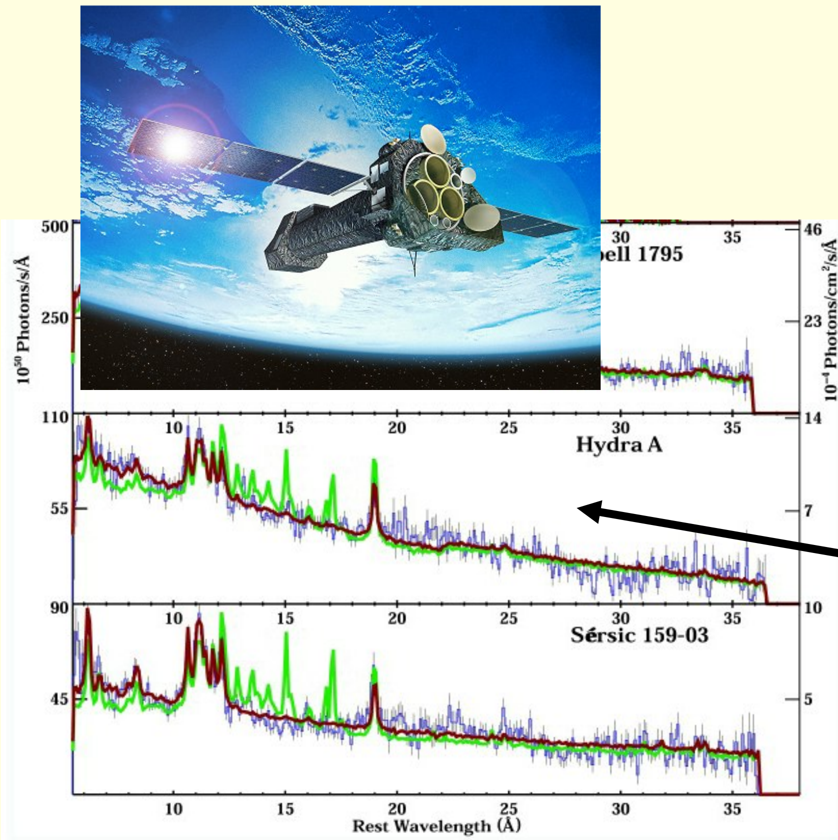
implies cooling flow: n_e ~10^{-1} cm^{-3} $\dot{M}$ = 10-1000 $M_{\odot}$ yr^{-1}

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

Key X-ray observations of cooling flows

reduced cooling

XMM-Newton 1999 -

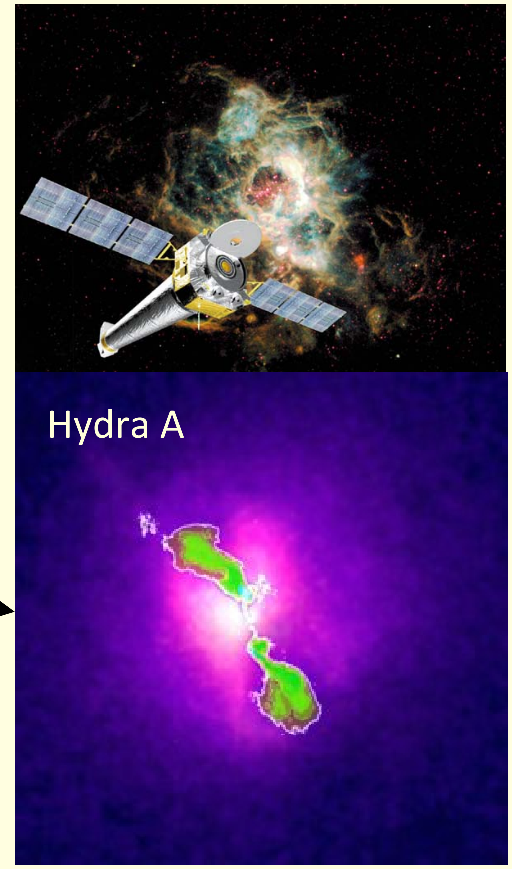


Peterson, Kaastra, Paerels + 03

Sanders + 08, Peterson & Fabian 06

AGN interactions

Chandra 1999 -



Mc+00, Fabian +00

Implication: Heating, feedback by SMBHs

Mechanical Feedback in Cooling X-ray Halos

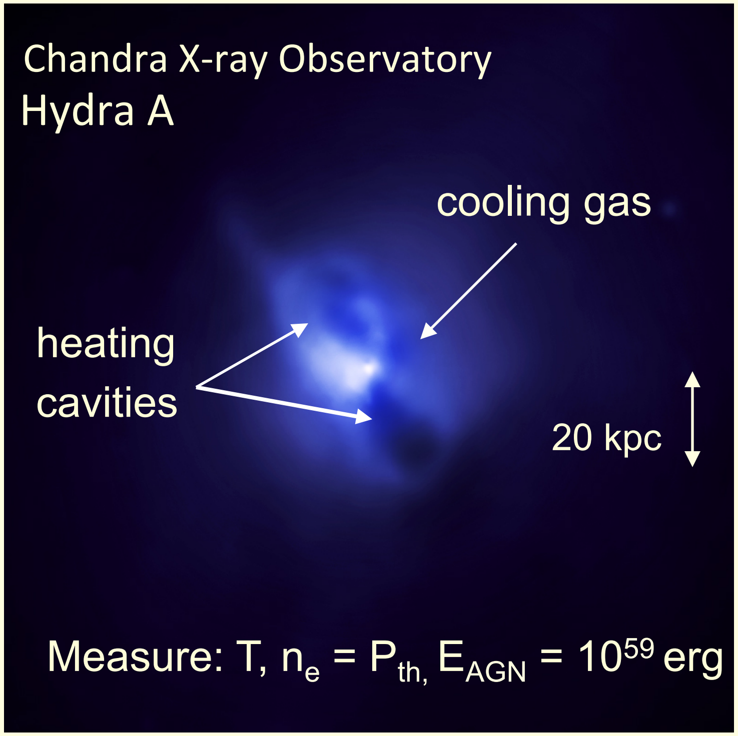
"*radio mode*" feedback

Even weak radio source are mechanically powerful

Radiative cooling - AGN heating of hot gas

thermostatically controlled accretion

==> *feedback loop*



McN+00

Key evidence:

-AGN mechanical power matched to cooling rates

Birzan+04, Rafferty+06, Dunn Fabian 06

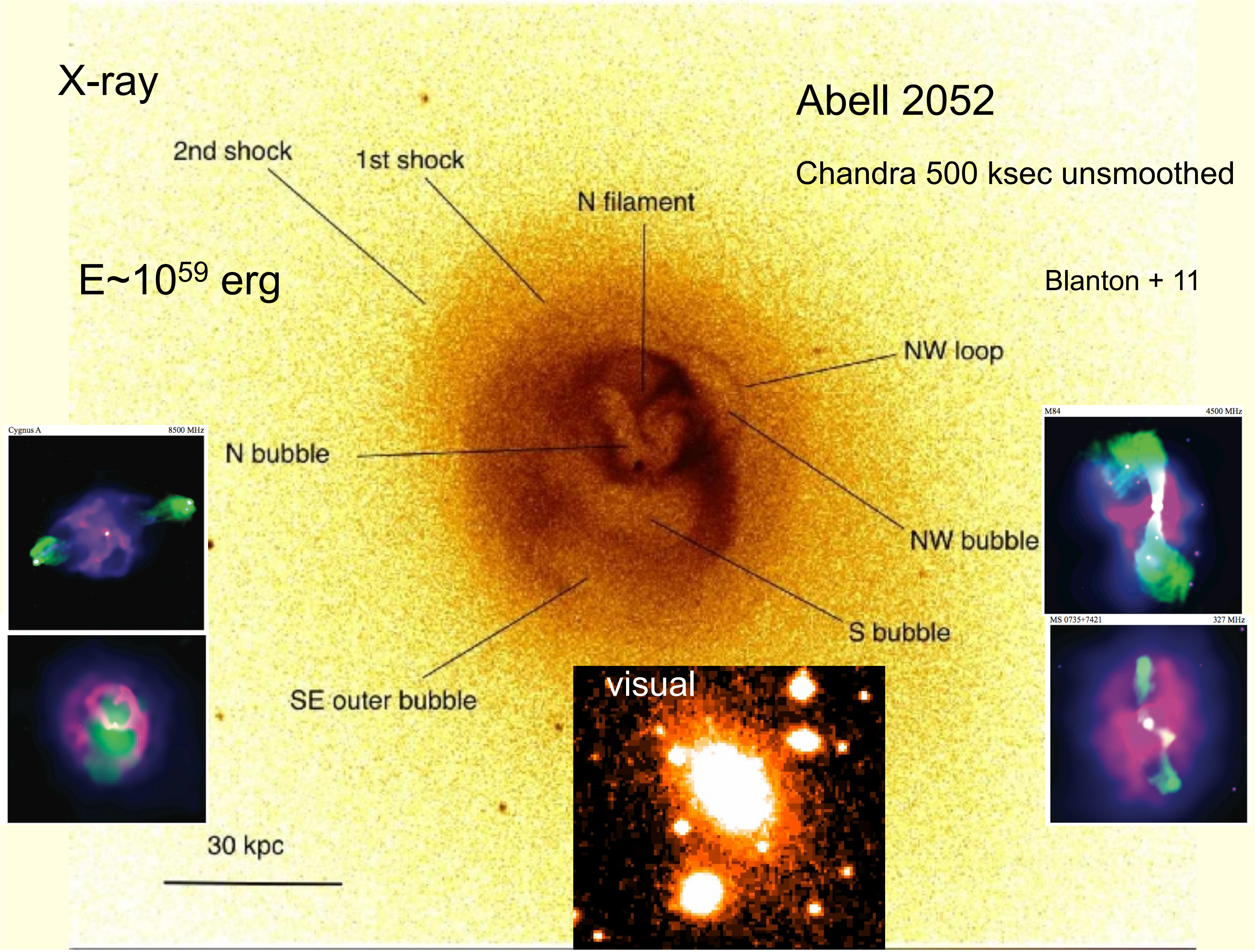
-Short ($<10^9$yr) cooling times in *all* systems

Voigt & Fabian 04

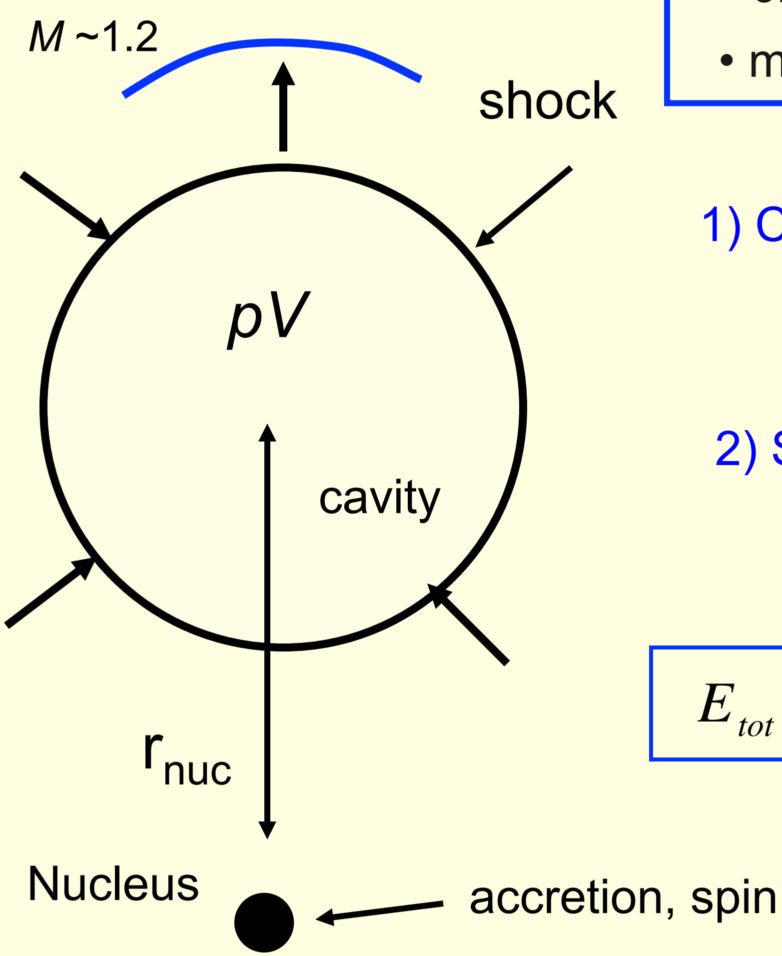
consequences

- heat hot halos; regulates growth of galaxies & SMBHs

See McNamara & Nulsen 07 ARAA


X-ray
Abell 2052
Chandra 500 ksec unsmoothed
E~10^59 erg
Blanton + 11
2nd shock
1st shock
N filament
NW loop
N bubble
NW bubble
S bubble
SE outer bubble
30 kpc
visual
Cygnus A
8500 MHz
M84
4500 MHz
MS 0735+7421
327 MHz

Measuring Jet Power using X-ray Cavities



- *energy & age measured directly*
- measure mechanical (not synchrotron) power

1) Cavity enthalpy (pV work + internal energy)

$$E_{cav} = \frac{\gamma pV}{\gamma - 1} = 2.5\,pV - 4\,pV$$

$$t_{cav} = r_{nuc} / v_{buoy}$$

2) Shock energy

$$E_{shock} \approx \Delta pV \qquad t_{shock} \approx r_{shock} / c_s$$

$$E_{tot} = E_{cav} + E_{shock} + (E_{photon}) = 10^{55} - 10^{62}\, erg$$

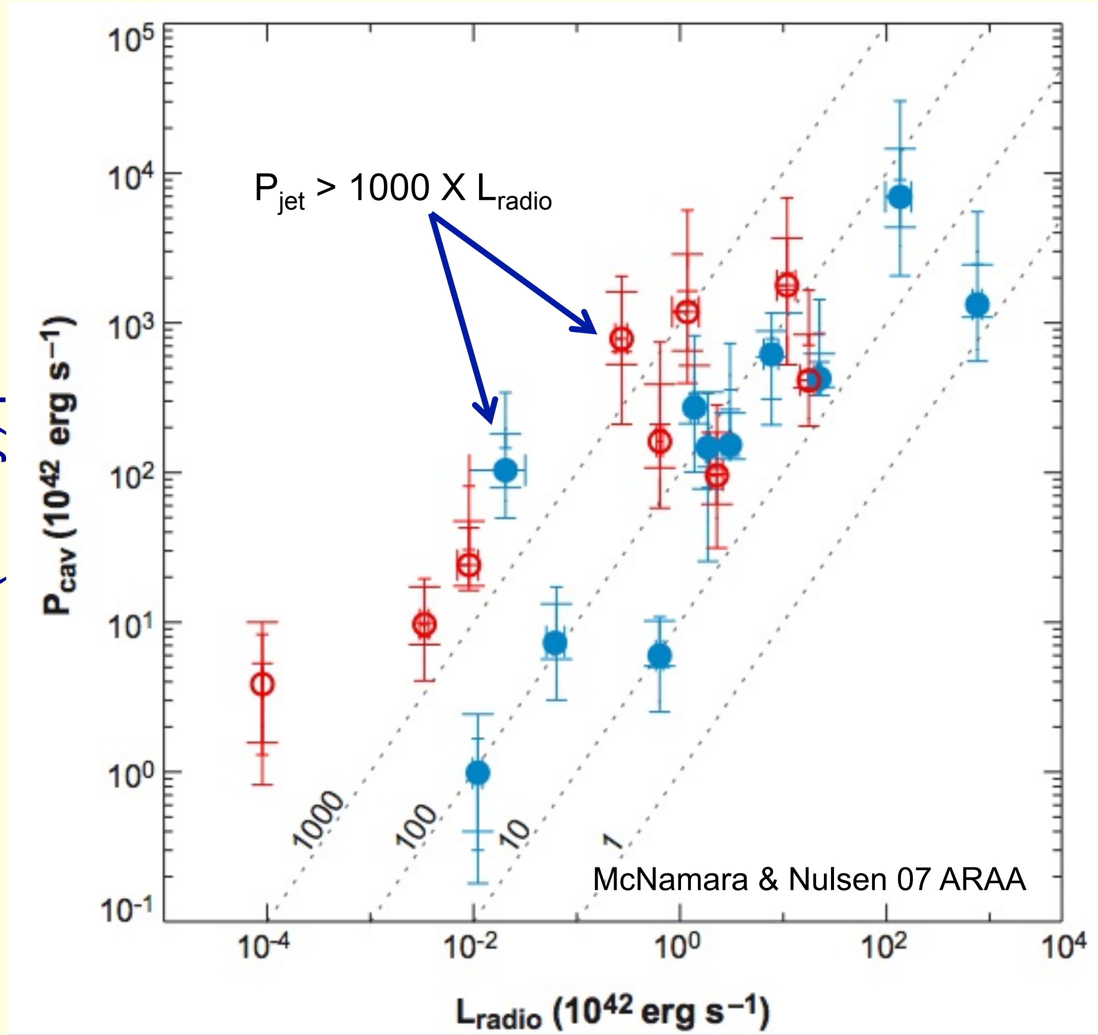
McNamara + 00,01; Birzan + 04

Theory: Ruszkowski, Heinz, Bruggen, Begelman, Voit, Churazov, T. Jones, etc.

slow gas motions < $c_{s,}$ gentle heating

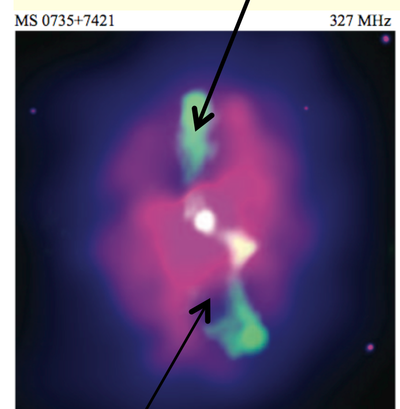
Jet (cavity) power vs radio power

Jet (cavity) power



Radio Luminosity

radio

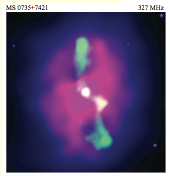


cavity

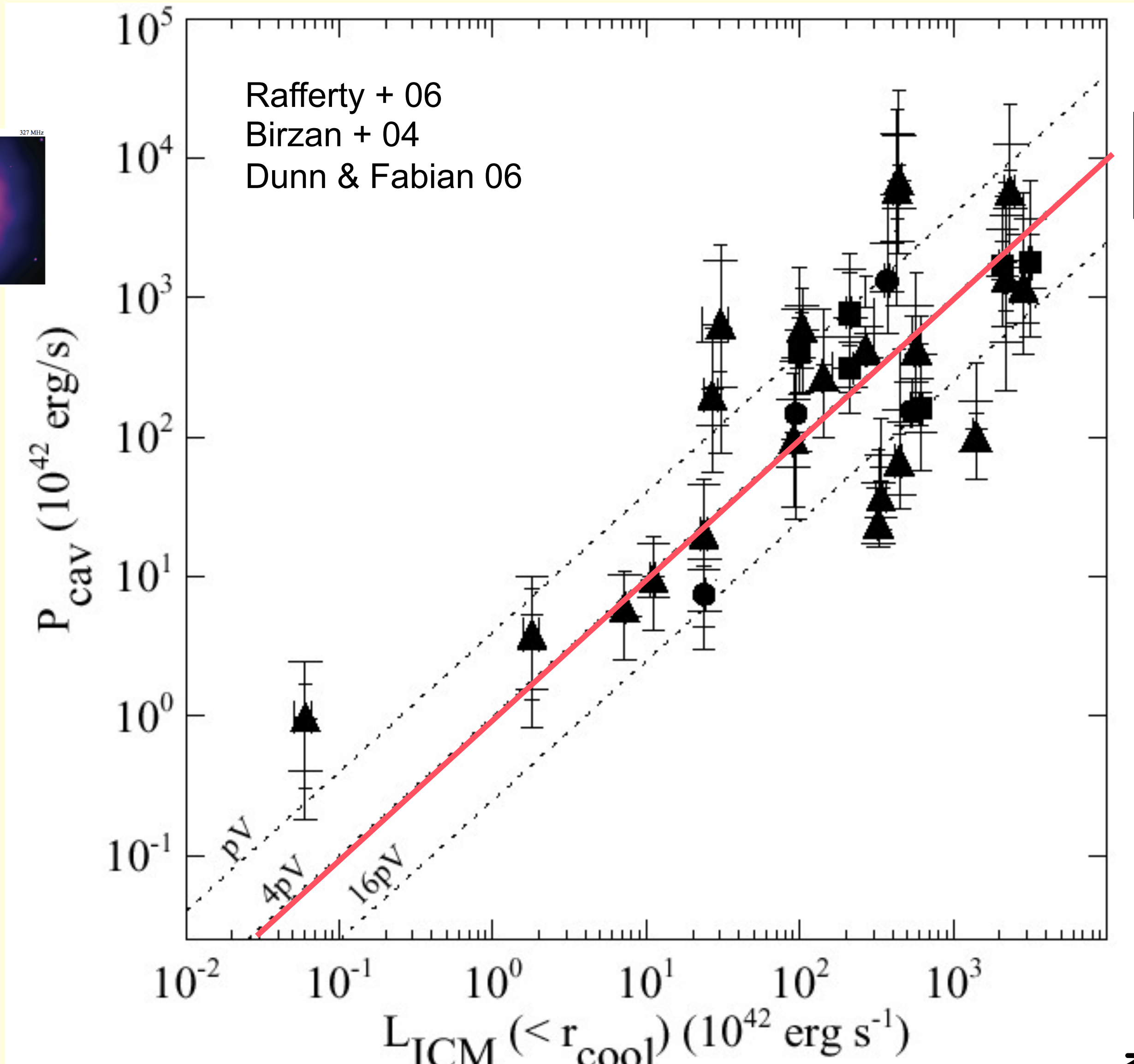
Birzan + 04

Key breakthrough: even weak radio sources mechanically powerful enough power to regulate or quench cooling, X-ray atmospheres

AGN heating balances cooling in gE's & Clusters



jet power

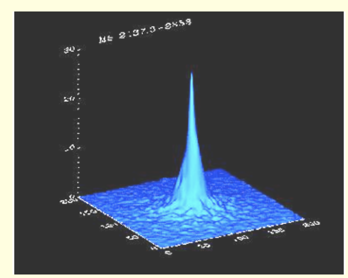


<heating> ≈ cooling

trend shows:
cooling, jet power
are correlated

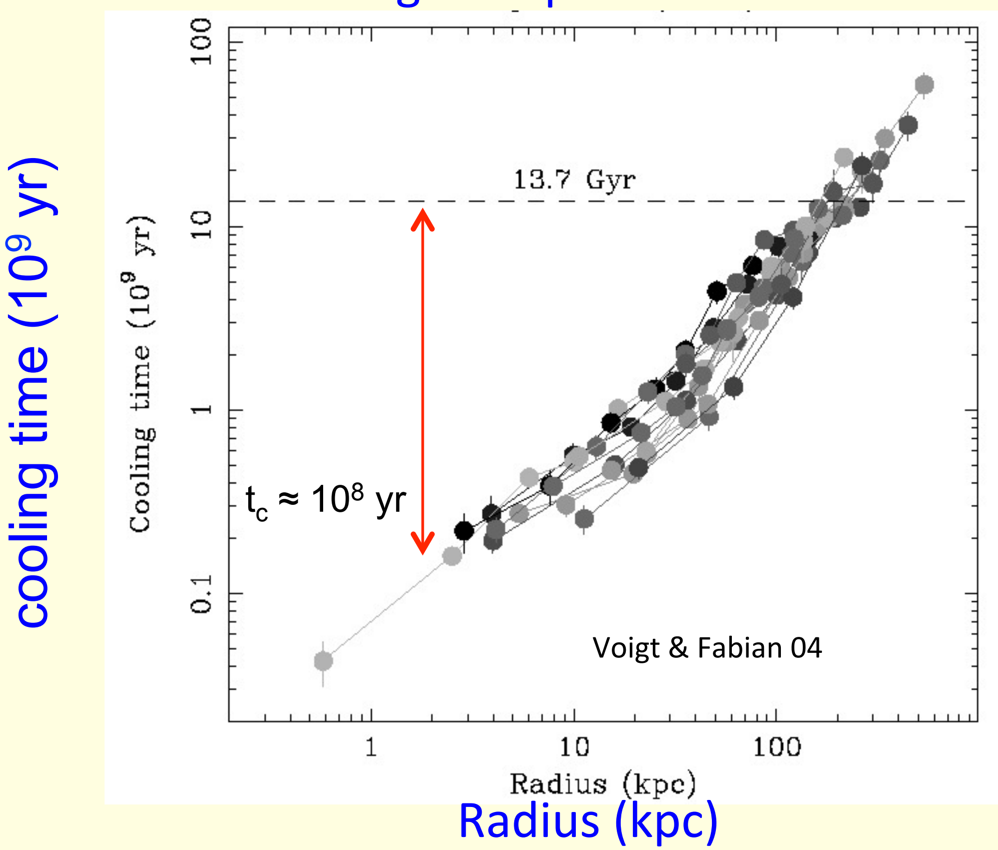
cooling, heating know
about each other!

X-ray cooling luminosity

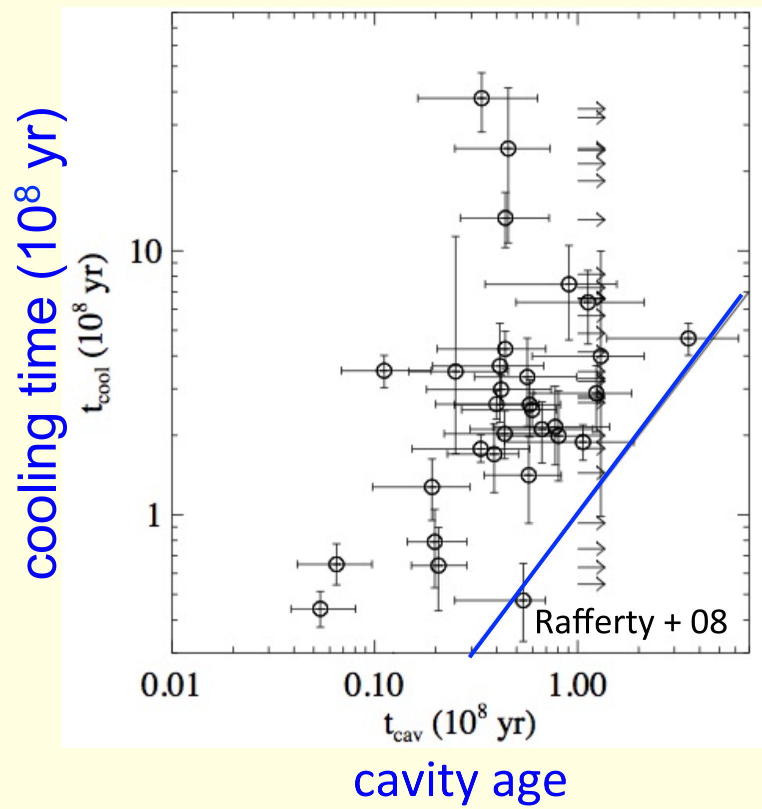


Conditions for AGN Feedback Loop

cooling time profiles



$t_{cool} > t_{cav}$



Despite large AGN heating rates, central cooling times are short < Gyr

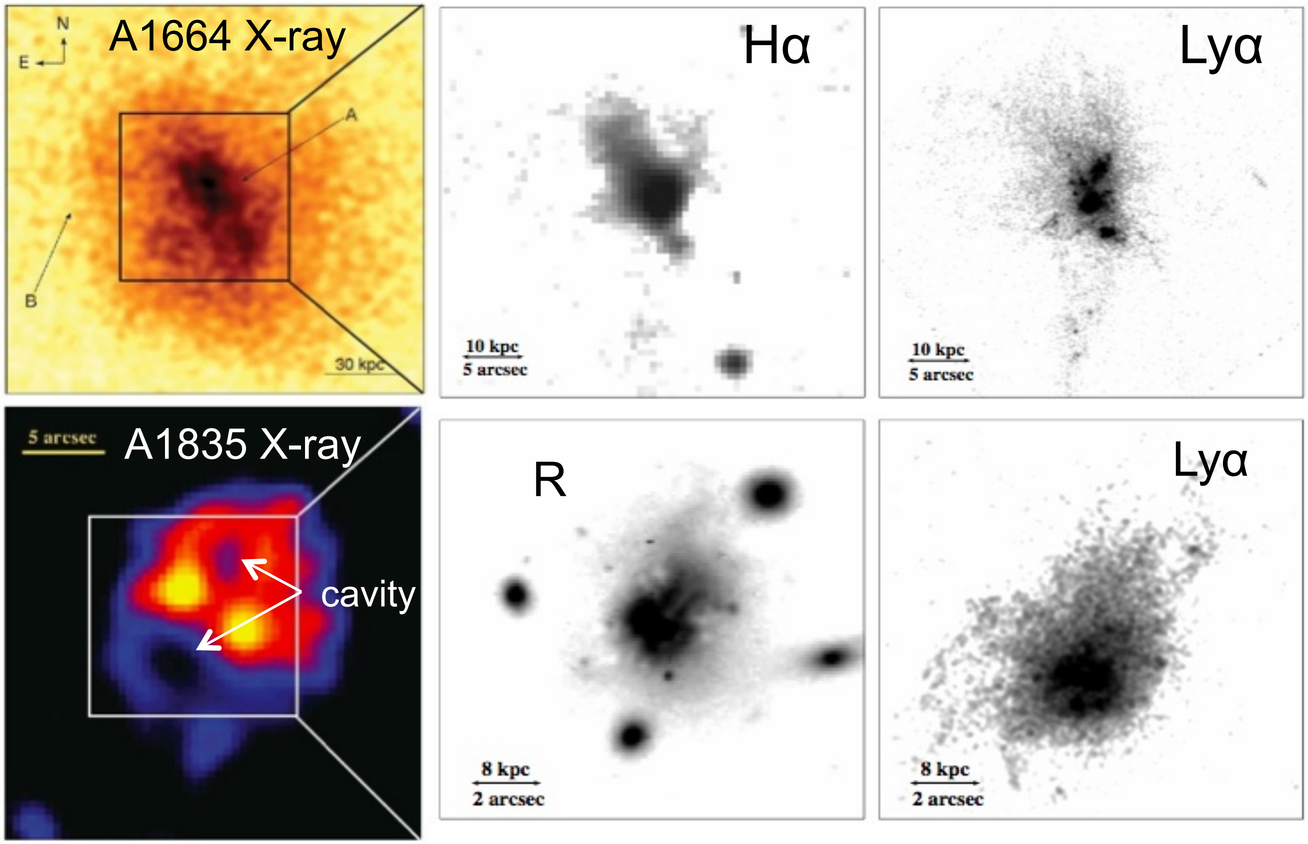
AGN outbursts & cooling on comparable timescales

Conditions for feedback

H

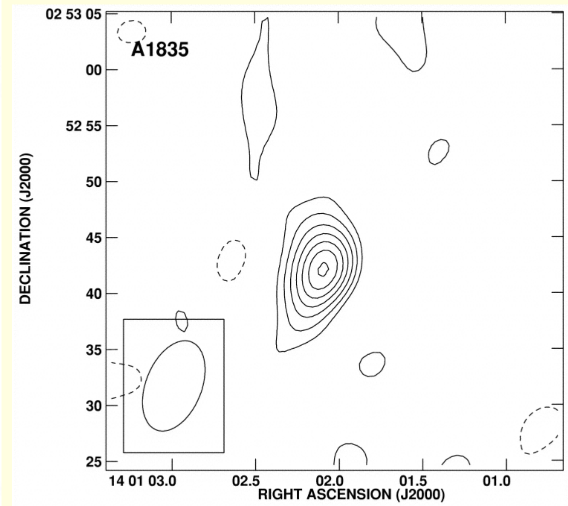
See Voit & Donahue 05, Peterson & Fabian 06, McNamara & Nulsen 07 ARAA

UV emission from star formation in molecular-gas-rich BCGs



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

Edge & Frayer 02



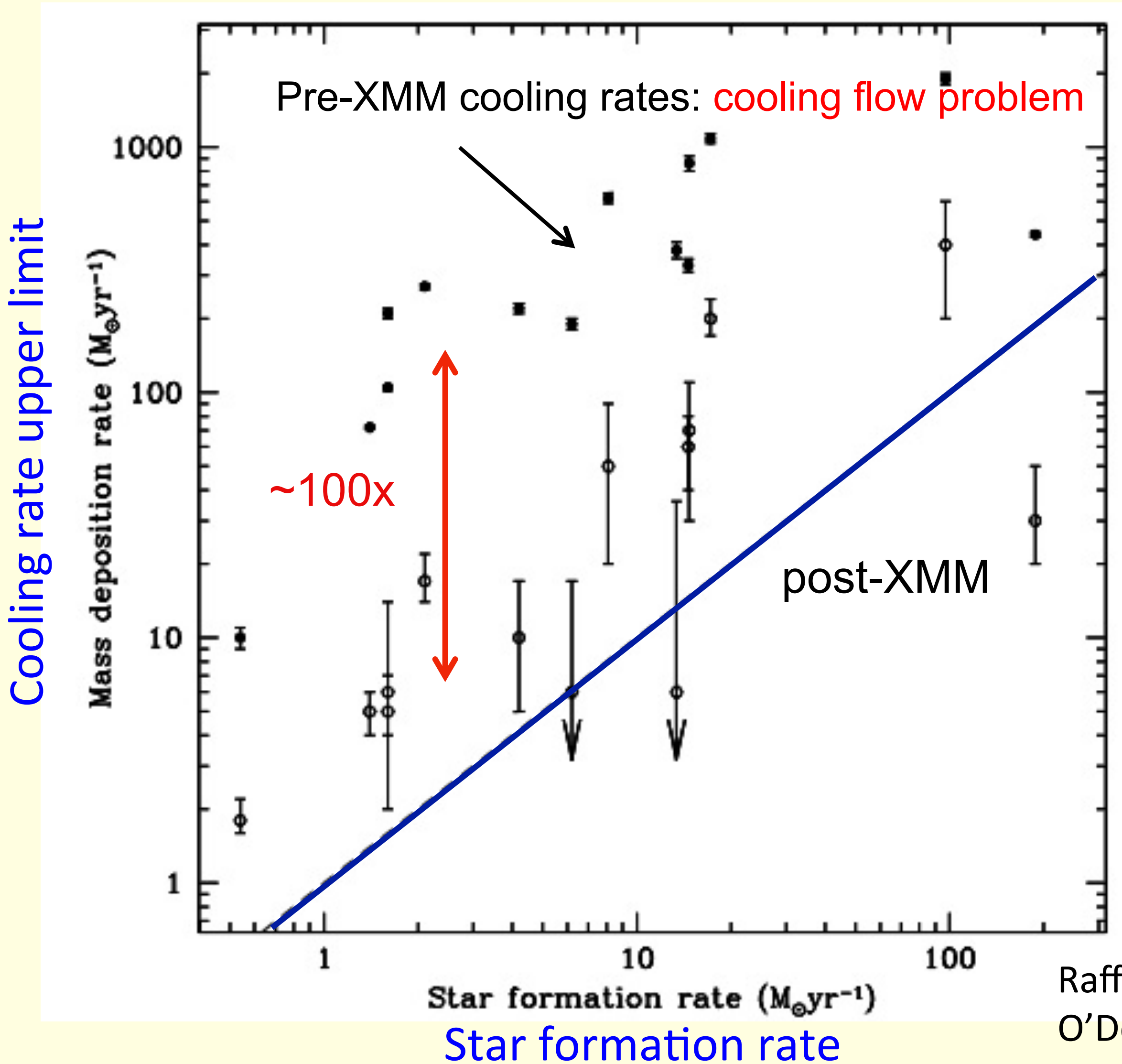
O' Dea + 10

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

- Fuel *directly linked* to cooling hot halo (not mergers)

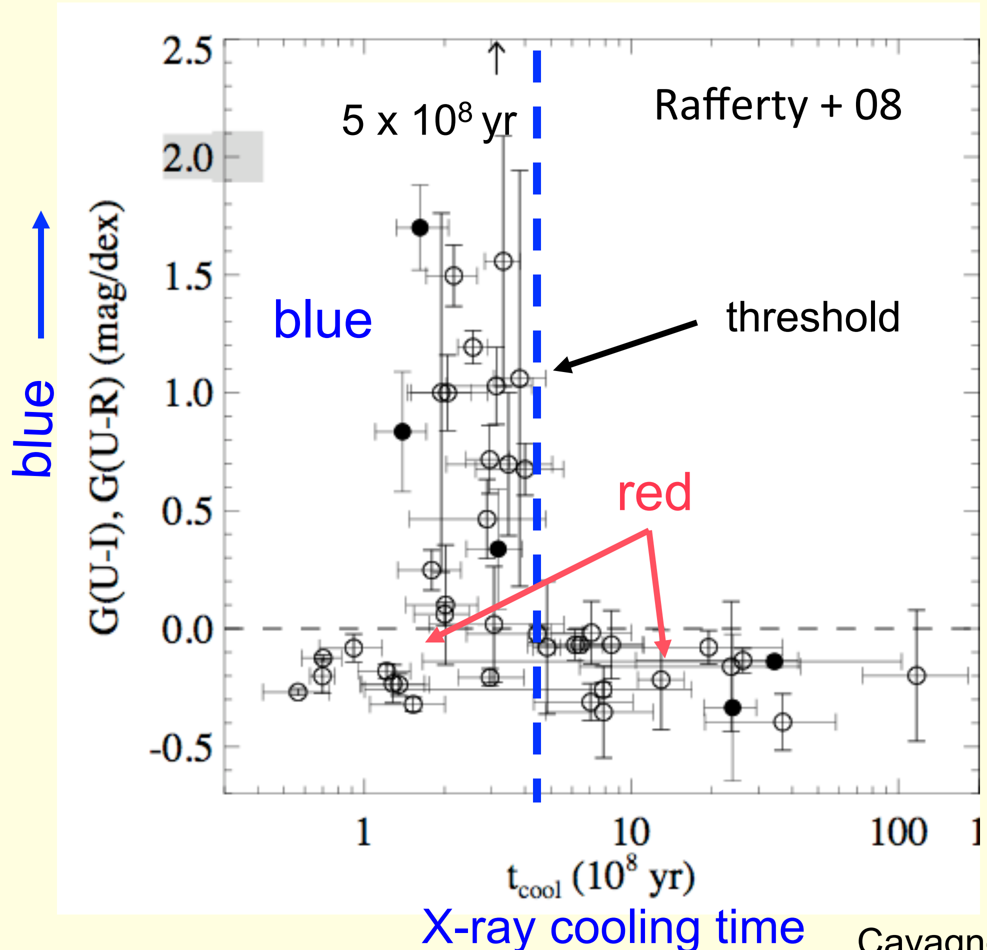
Rafferty+08, Cavagnolo+08, Kirkpatrick + 08

Star formation rates comparable to X-ray cooling Rates



Rafferty + 06
O'Dea + 08

star formation cooling time threshold: t_{cool} ~ 500 Myr

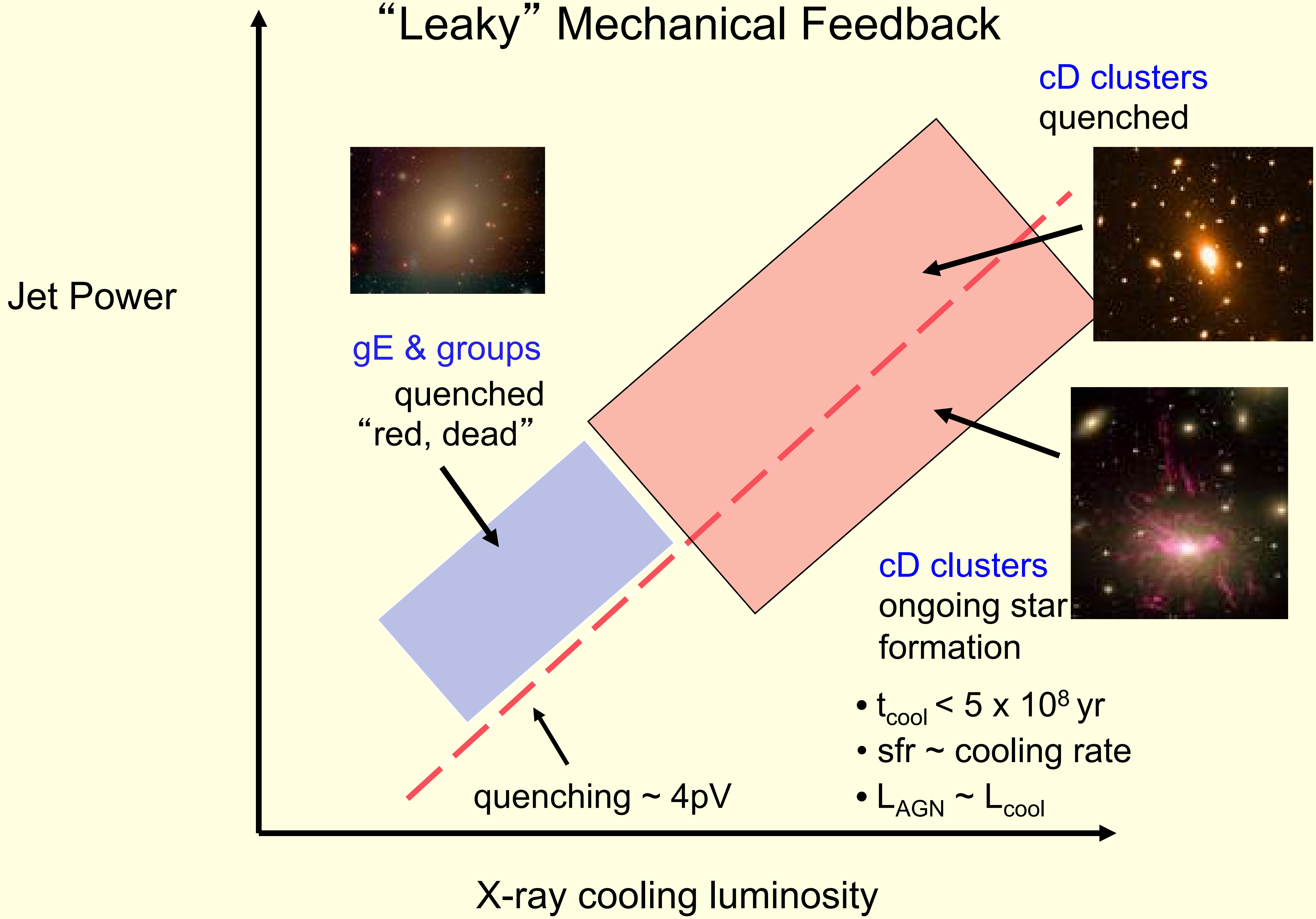


Not a property of mass!

Cavagnolo + 08 Ha threshold
Voit + 09

Cool gas & Star formation linked to cooling, X-ray atmospheres

"Leaky" Mechanical Feedback



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

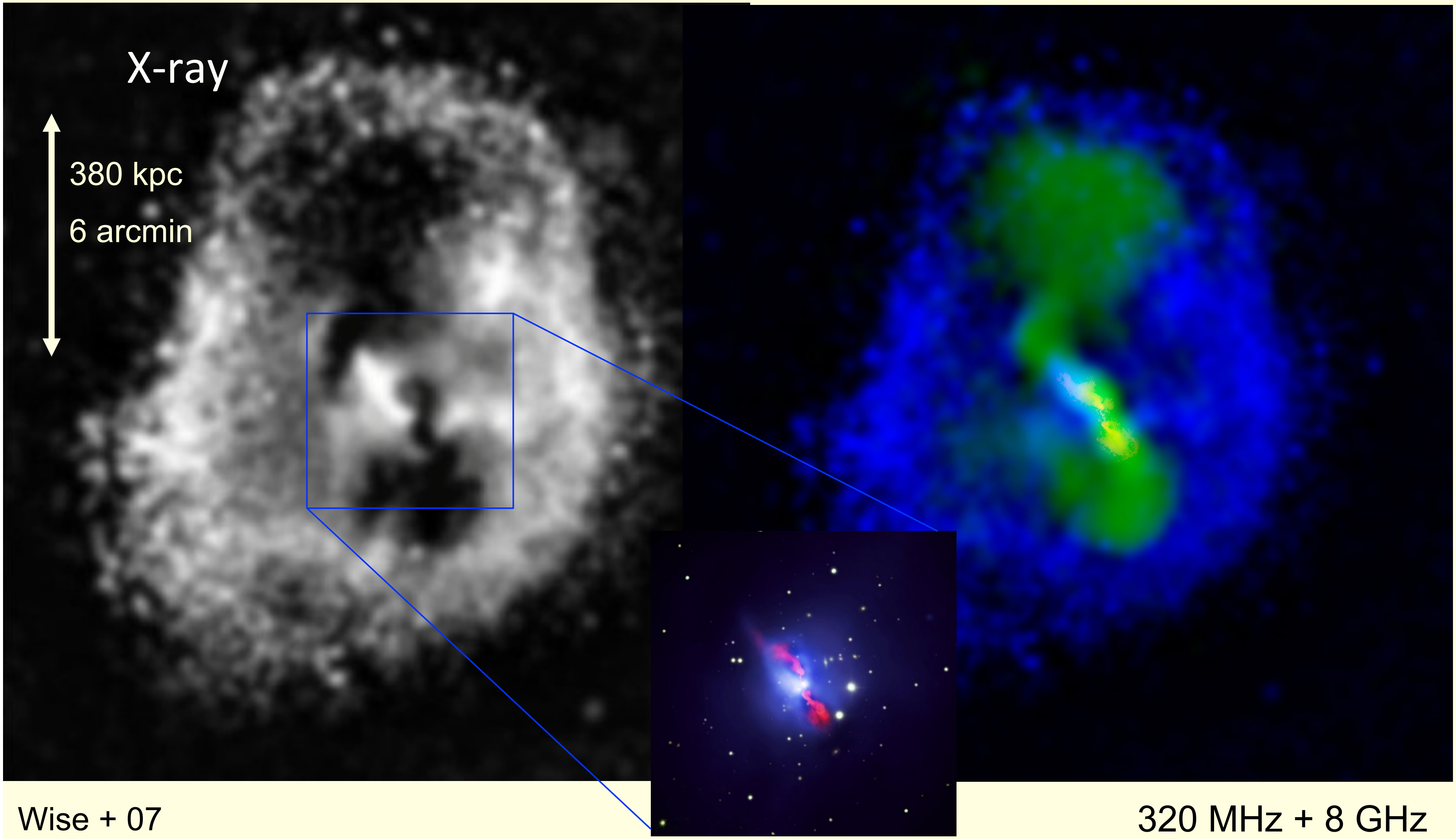
AGN Feedback on Cluster Scales

re. J. Shaye's review

New stuff…

Hydra A Cluster z=0.05

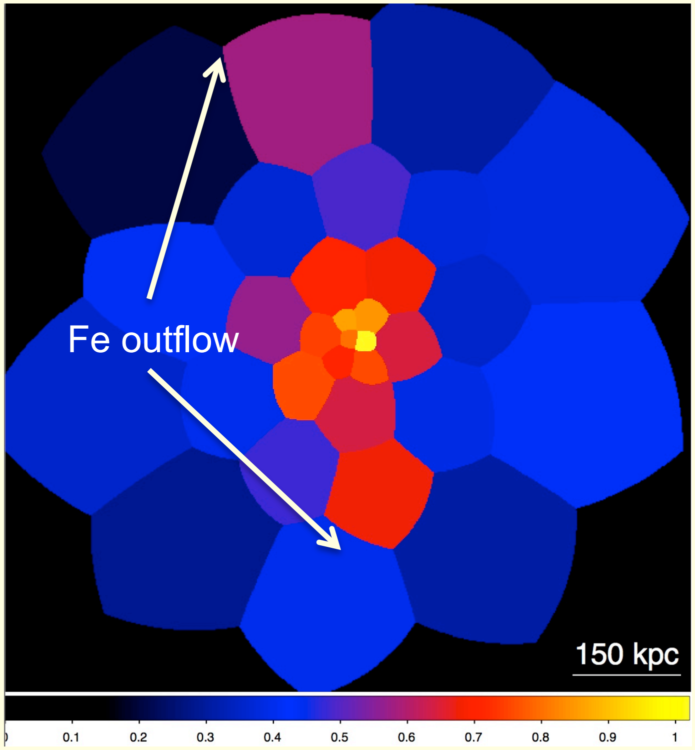
$E_{jet} > 10^{61}$ erg AGN outburst: swiss cheese morphology to hot atmosphere

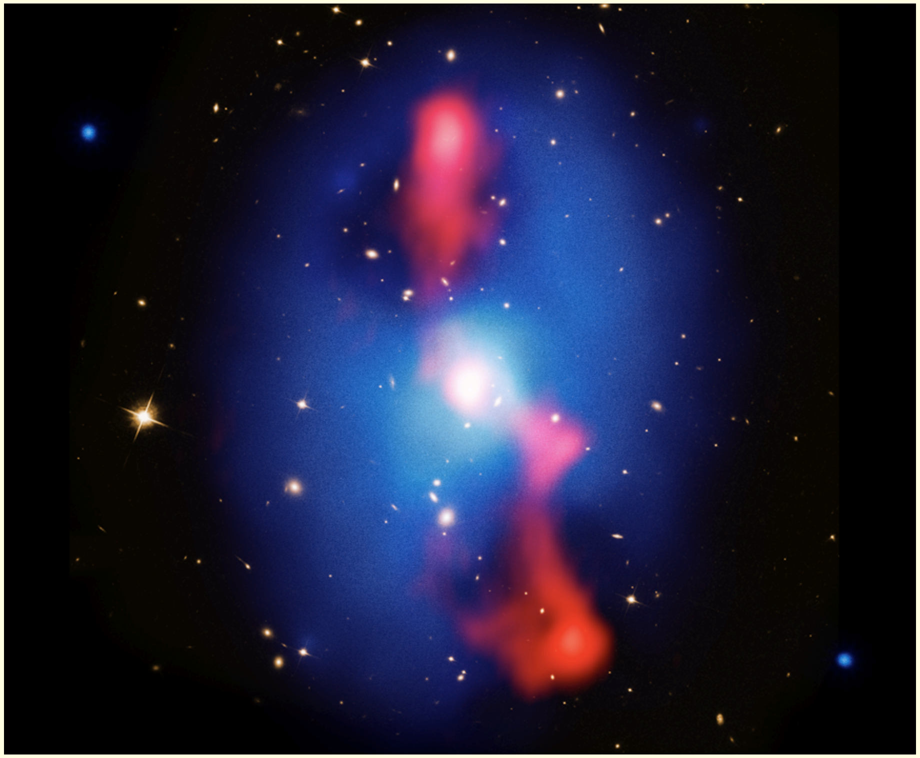


Wise + 07
Nulsen + 05
McN + 00

320 MHz + 8 GHz

MS0735 Cool, metal-enriched outflow





McN+11

500 ks Chandra image

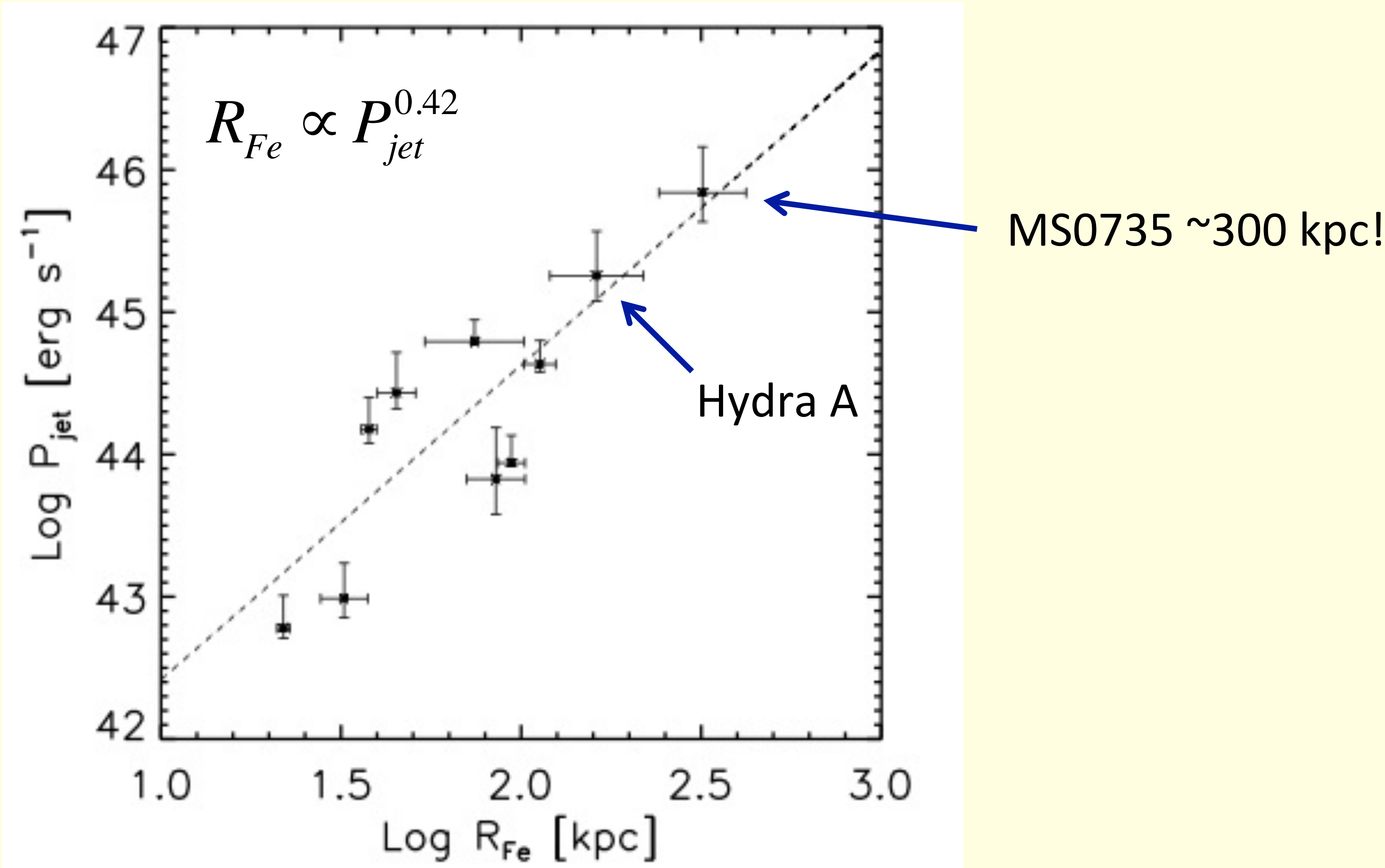
VLA, HST

R_{Fe}~300 kpc

P_{jet}~ $3x10^{46}$ erg s^{-1}

E_{jet} ~ 10^{62} erg

iron outflow limiting radius correlates with Jet power



Kirkpatrick + 11

Orientation of outflow correlates with radio and cavitiy orientation: jet driven outflows

Problem: How are AGN outbursts powered?

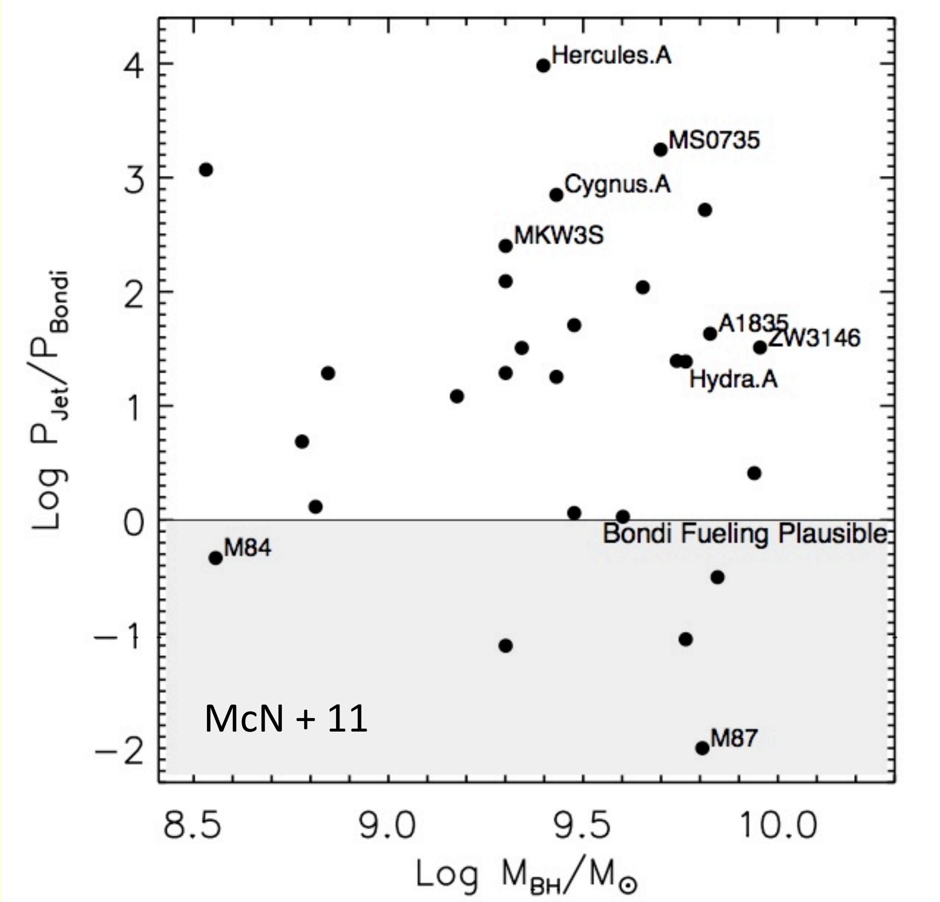
Powering Mechanisms

- Hot gas Bondi Accretion –
  ok for low power systems
  (Churazov + 02, Allen 06, Narayan & Fabian 11);
  won't work in high power systems
  (McN+11, Rafferty +06)
- Cold Gas Accretion

  likely, short supply in some systems

- Black Hole Spin- potentially important
  (McN+11)

  ALMA will lead to great progress



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

Other issues:

Must understand heating, microphysics: conduction, transport processes

AGN Heating of hot atmospheres *significant* in distant clusters (Ma + 11)

Summary

Relatively weak radio AGN can be mechanically powerful

Powerful enough to suppress cooling hot halos

Strong evidence for a self-regulating feedback loop

Star formation, jets linked to central X-ray cooling time

Suppress star formation, disperse metals throughout LSS

Questions:

Why do powerful AGN live in gas-poor hosts?

What powers AGN: cold accretion, hot accretion, spin?

How does AGN feedback work and heat the gas?