Title: Supermassive Black Holes: Workhorses of the Universe

Date: Mar 24, 2010 02:00 PM

URL: http://pirsa.org/10030067

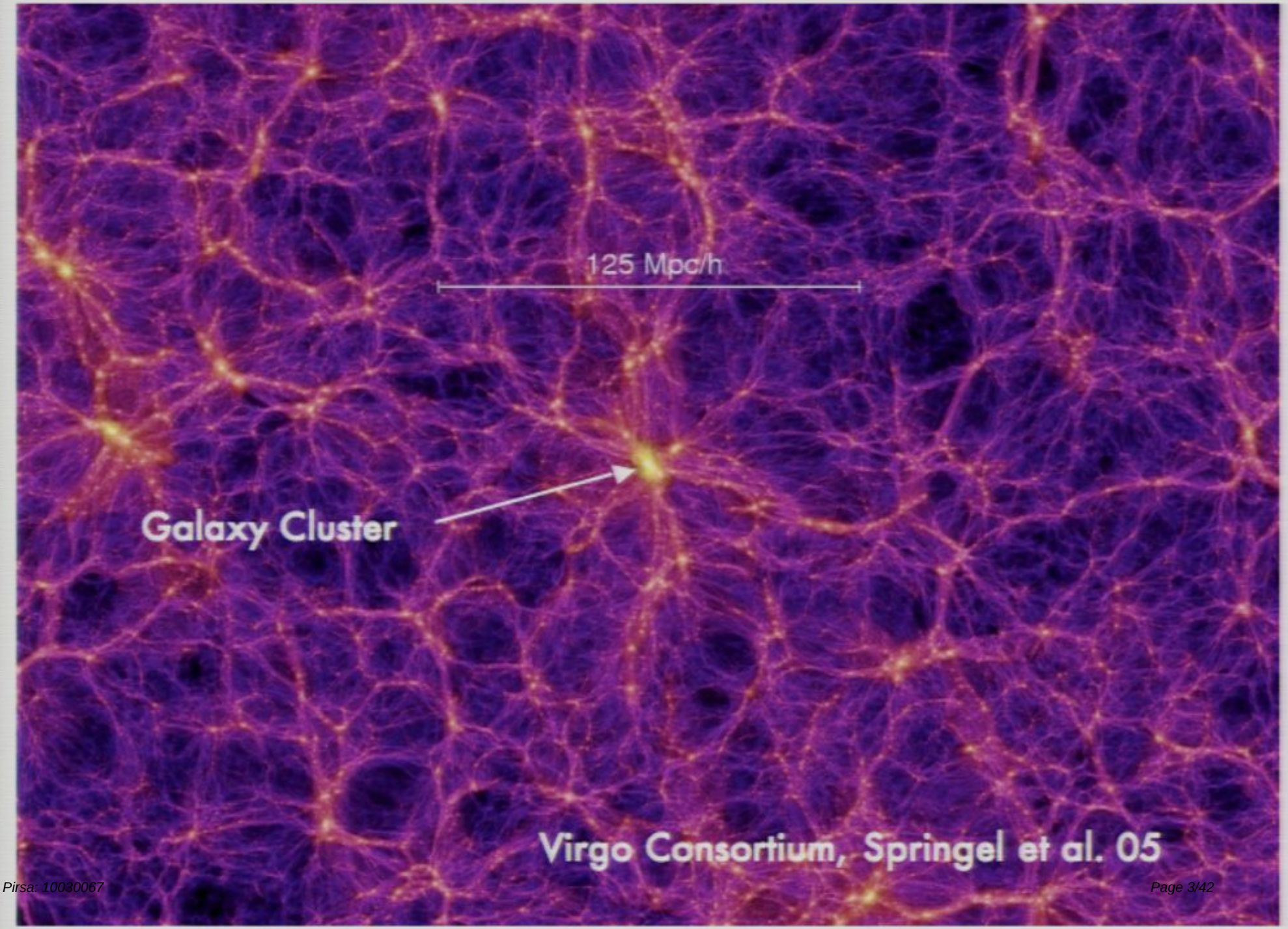
Abstract: The hot, gaseous atmospheres of galaxies and clusters of galaxies are
repositories for the energy output from accreting, supermassive black holes located in the nuclei of galaxies.
X-ray observations show that star formation fueled by gas condensing out of hot atmospheres is strongly suppressed by feedback from active galactic nuclei (AGN). This mechanism
may solve several outstanding problems in astrophysics, including the
numbers of luminous galaxies and their colors, and the excess number of
hot baryons in the Universe. The most energetic AGN outbursts may be powered by rapidly-spinning, ultra-massive black holes.

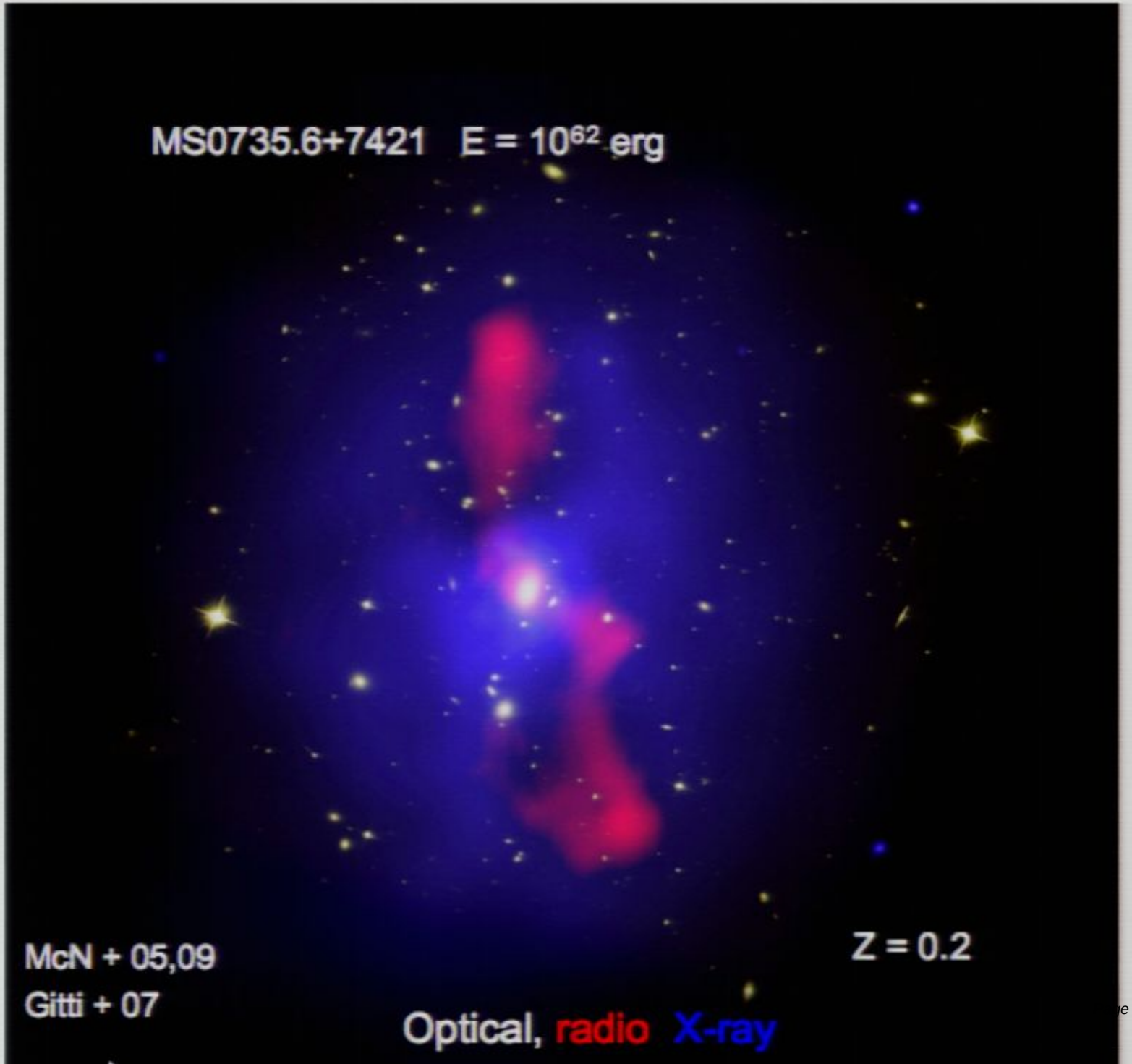
Astronomical Units & Terminology

Kiloparsec	Distance	1000 parsecs = 3×10^{21} cm
Parsec	Distance	3.26 light years

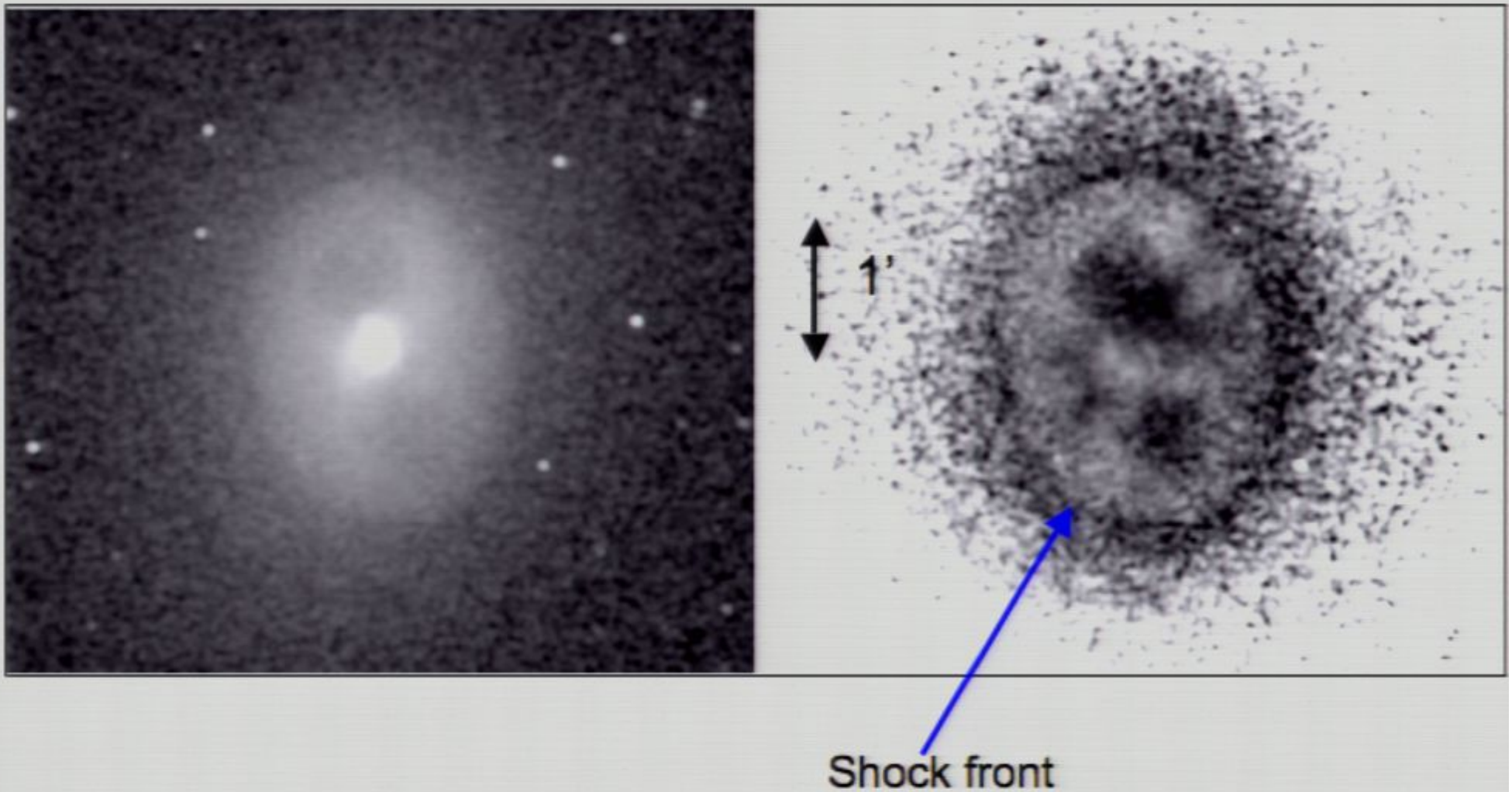
Milky Way Diameter = 100,000 ly = 30 kpc

10^{53} erg	Energy	supernova explosion/GRB
keV	Temperature	1 keV = 1.16×10^{7} K
dynes/cm^2	Pressure	cluster center P=10^{-10} dyne/cm^2
		10^{-16} Atm

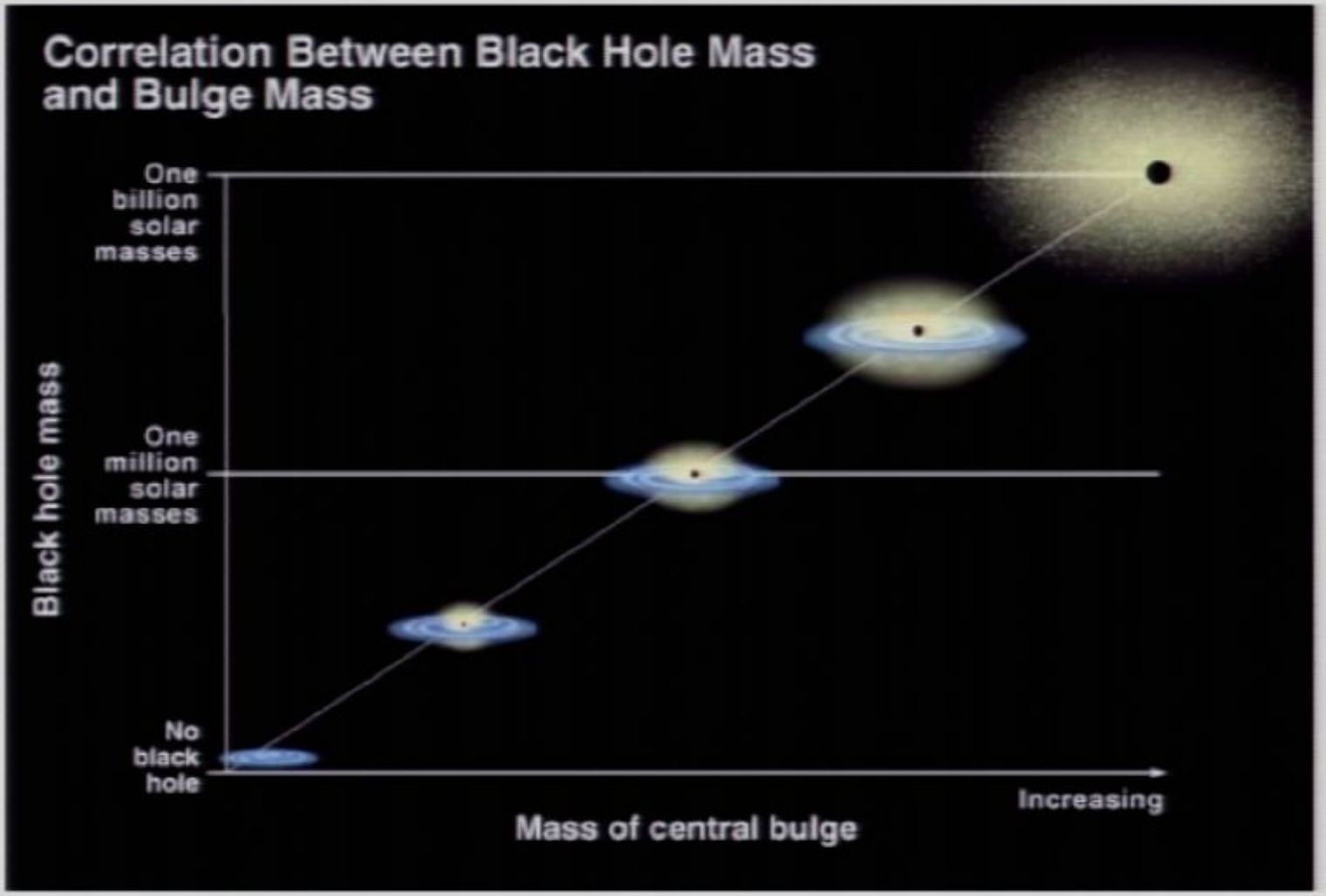

125 Mpc/h
Galaxy Cluster
Virgo Consortium, Springel et al. 05


MS0735.6+7421 E = 10^{62} erg
McN + 05,09
Gitti + 07
Z = 0.2
Optical, radio X-ray

Chandra LP 500 ksec Image of MS0735.6+7421



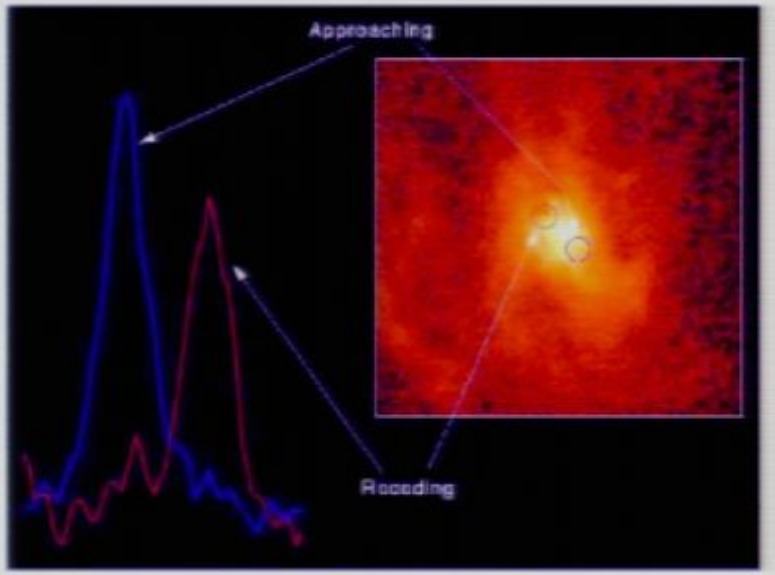
Bulge mass - BH Mass Relation



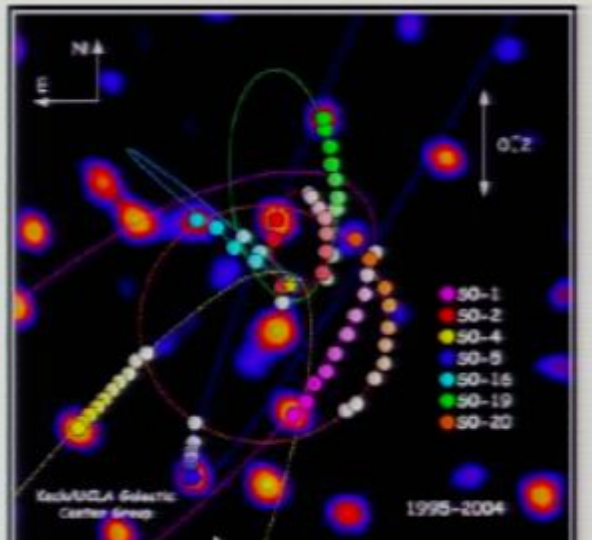
SMBHs and galaxies grow proportionally!!

Evidence for Existence of SMBHs

M87 in Virgo Cluster: 3 - 7 x 10^9 Solar mass black hole



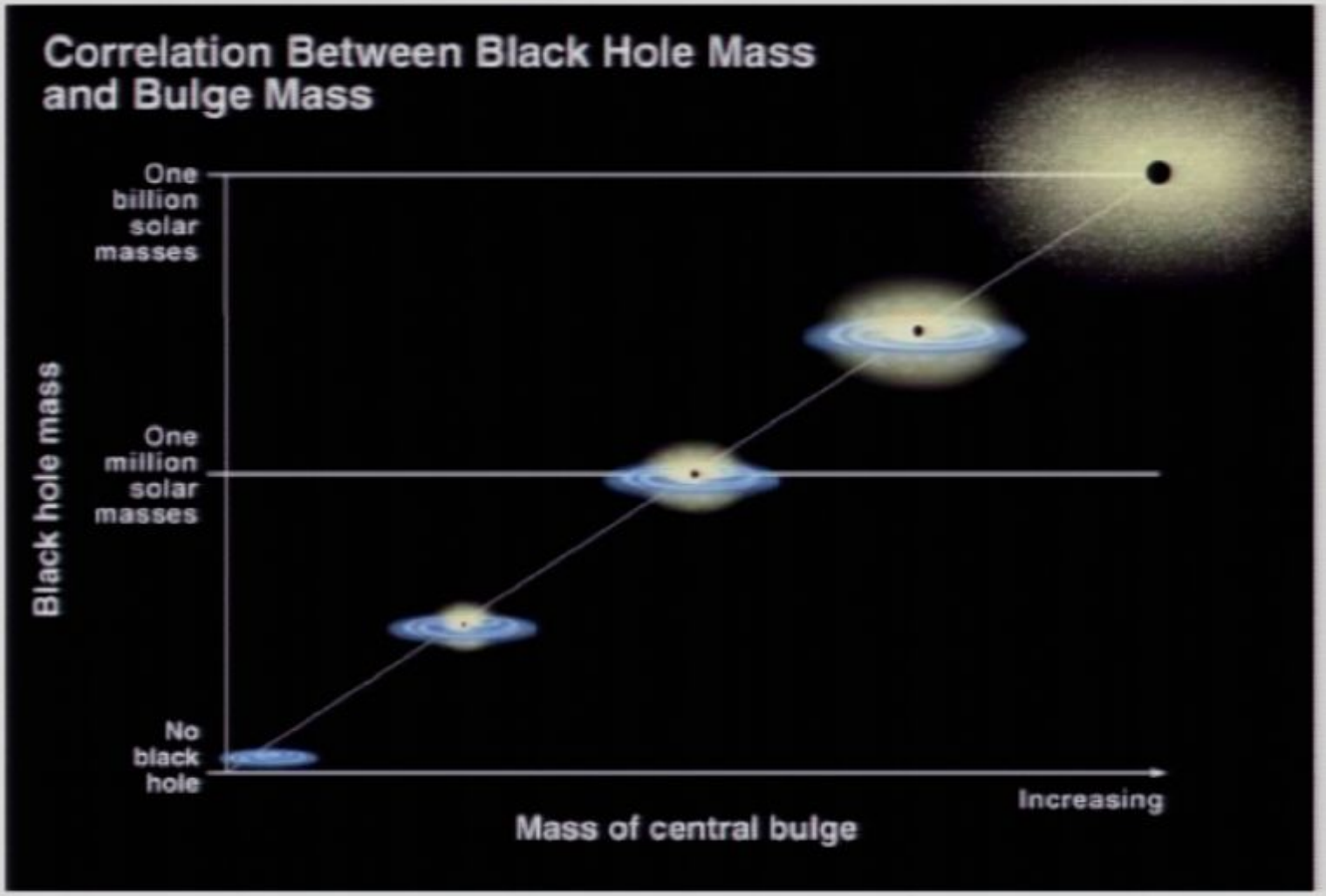
Ford (STScI



- 4 x 10^6 Solar mass black hole at center of Milky Way
- acceleration of *individual* stars

Ghez (UCLA), Genzel (MPE)

Bulge mass - BH Mass Relation



SMBHs and galaxies grow proportionally!!

SMBHs: workhorses of cosmic structure

Fossil Evidence:

- Galaxy mass scales in proportion to supermassive black hole mass
- The 4×10^6 solar mass BH in the Milky Way

Potential Consequences:

- Thermostatically controlled growth of galaxies
- "Broken hierarchy" of galaxy formation:

  a) turnover in luminosity function, "cosmic downsizing"
  b) quenching of cooling flows by "radio-mode" feedback
  c) "old, red, and dead" quandary

Excess number of baryons and entropy in clusters

Voit 04, Balogh + 01

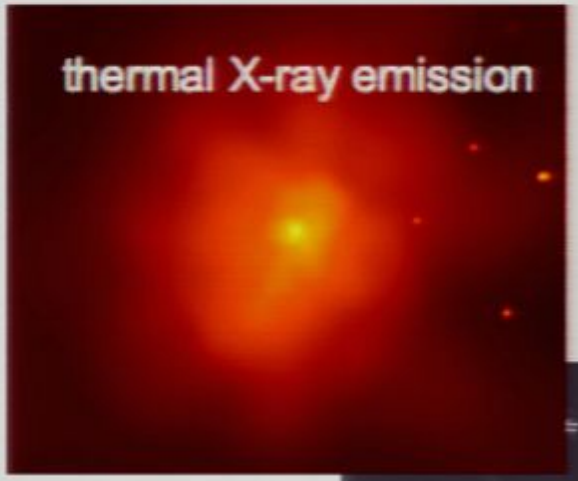
Probing of galaxy formation and feedback

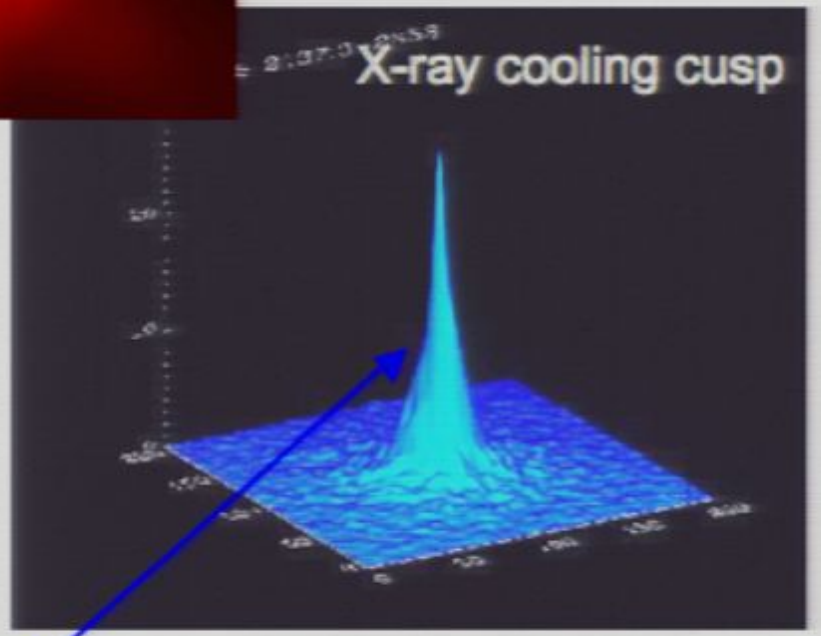
outline of today's talk

- cooling gas and the problem of galaxy formation
- X-ray gauge of accreting SMBHs
- regulated cooling, star formation, SMBH growth
- extragalactic radio jets: What are they, how are they powered?
- summary

Principal Collaborators: L. Birzan, D. Rafferty (Amsterdam), P. Nulsen (CfA
M.Wise (U. Amsterdam), C. Carilli (NRAO), K. Cavagnolo, C. Kirkpatrick(U

Cooling Flows





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

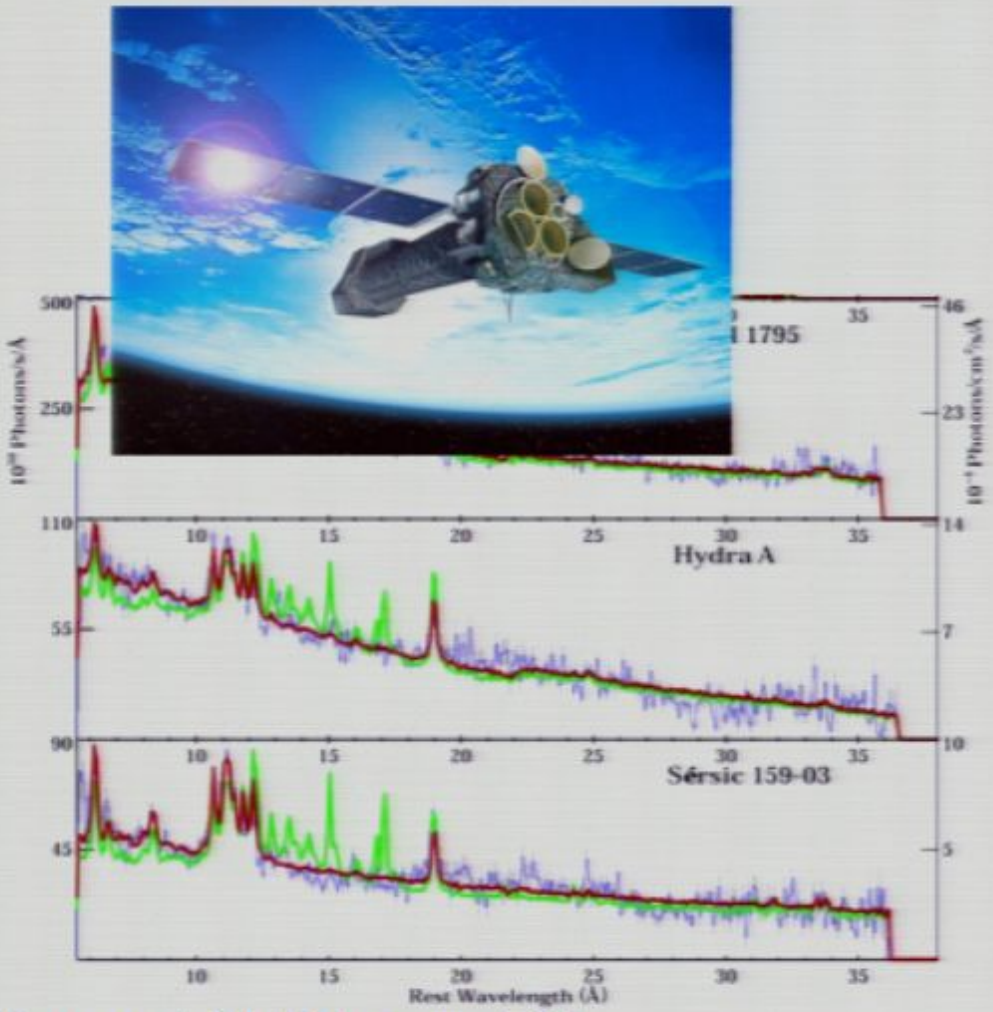
implies cooling flow: $n_e \sim 10^{-1}$ cm^{-3} $\dot{M}$ = 10-1000 Mo yr^{-1}

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

Key X-ray developments in cooling flows

Reduced cooling

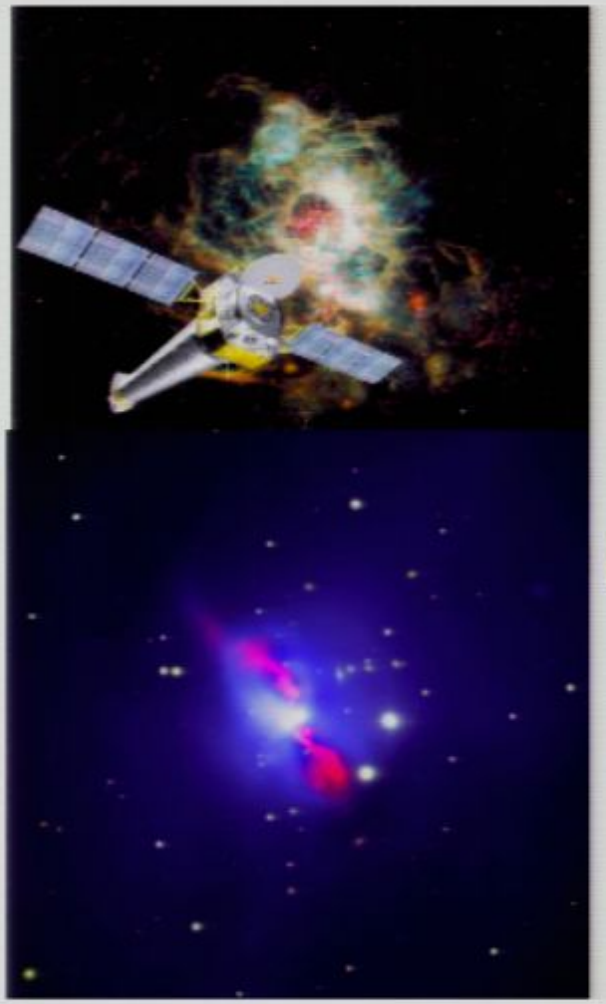
XMM-Newton 1999 -



Tamura + 01, Peterson + 03

AGN interactions

Chandra 1999 -



Hydra A

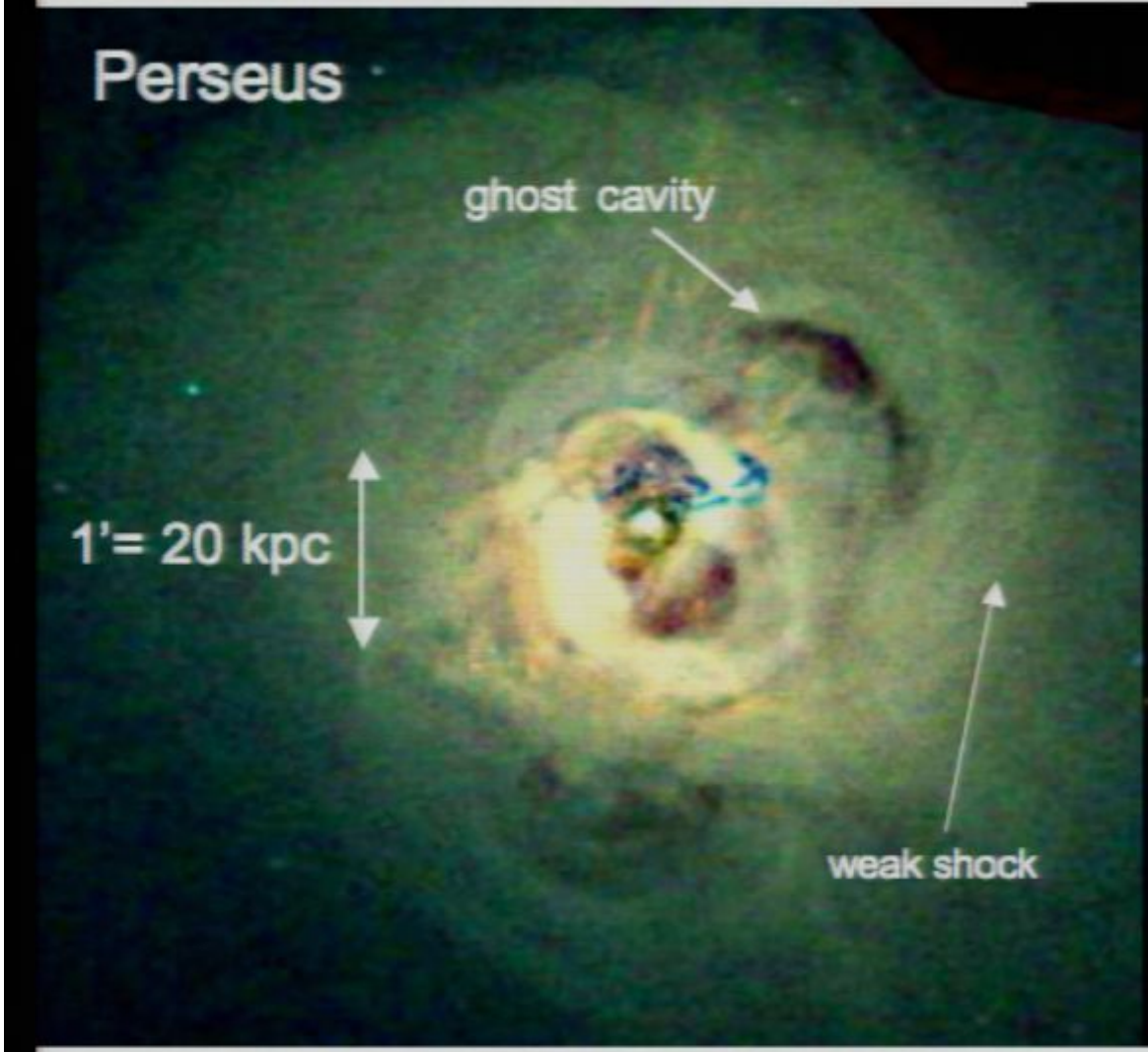
McNamara + 00 Fabian + 00

Implication: Heating, feedback by SMBHs

Evidence for AGN Feedback in Clusters

Galaxy-Scale Outbursts

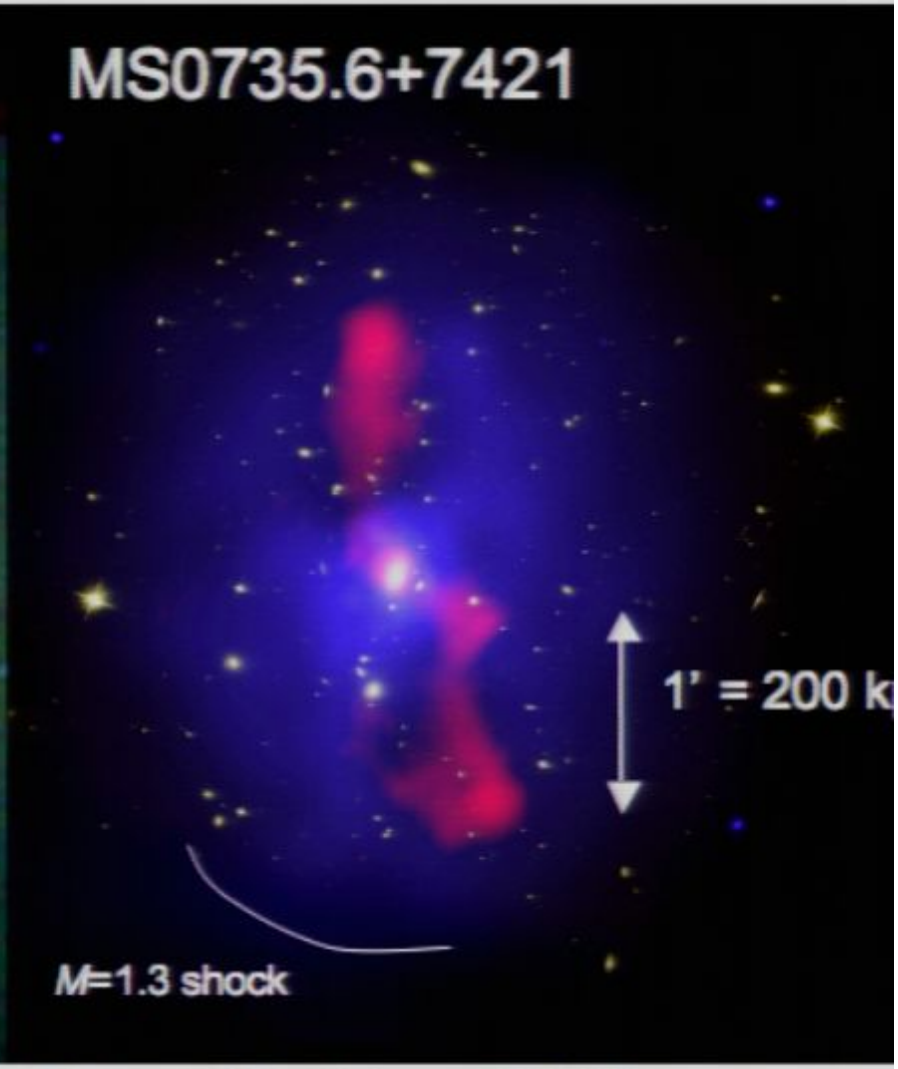
E ~10^{59} erg



Fabian + 05

Cluster-Scale Outbursts

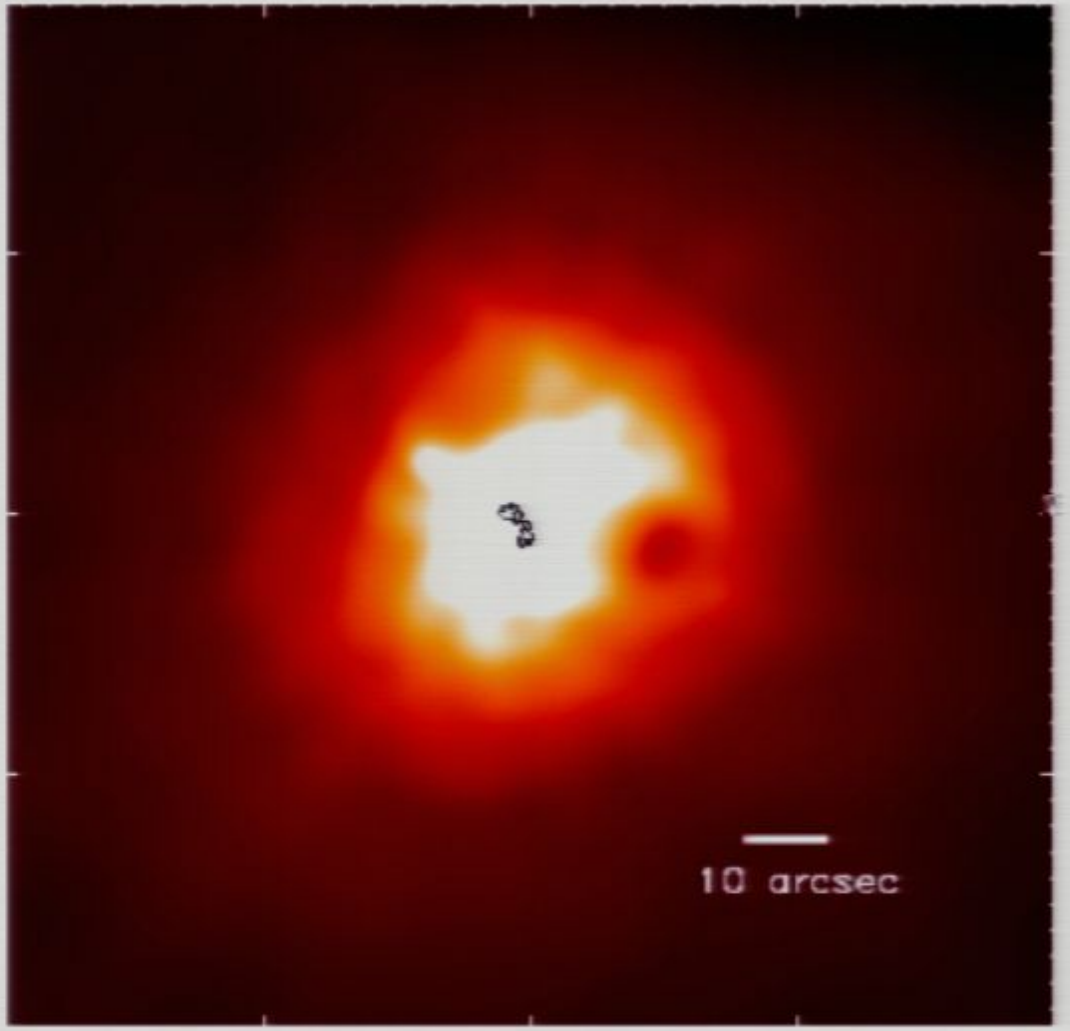
E ~ 10^{62} erg



McN + 2005, Nature, 433, 35
Gitti + 07

Optical, radio, X-ray

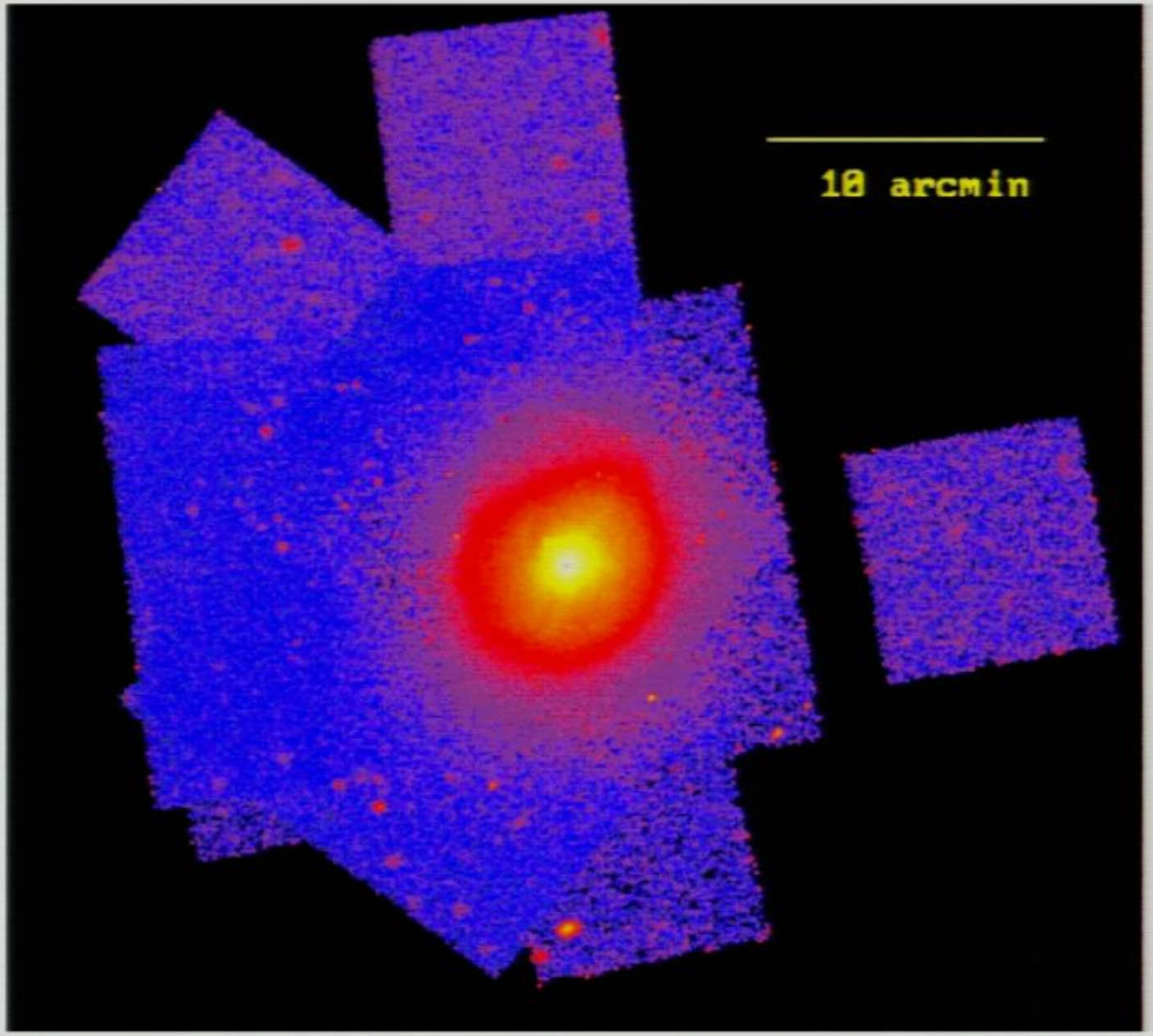
Abell 2597



McNamara+01

Hydra A: Cluster-Scale Heating Event

Z=0.053



Hydra A

10^{61} erg

Nulsen + 05

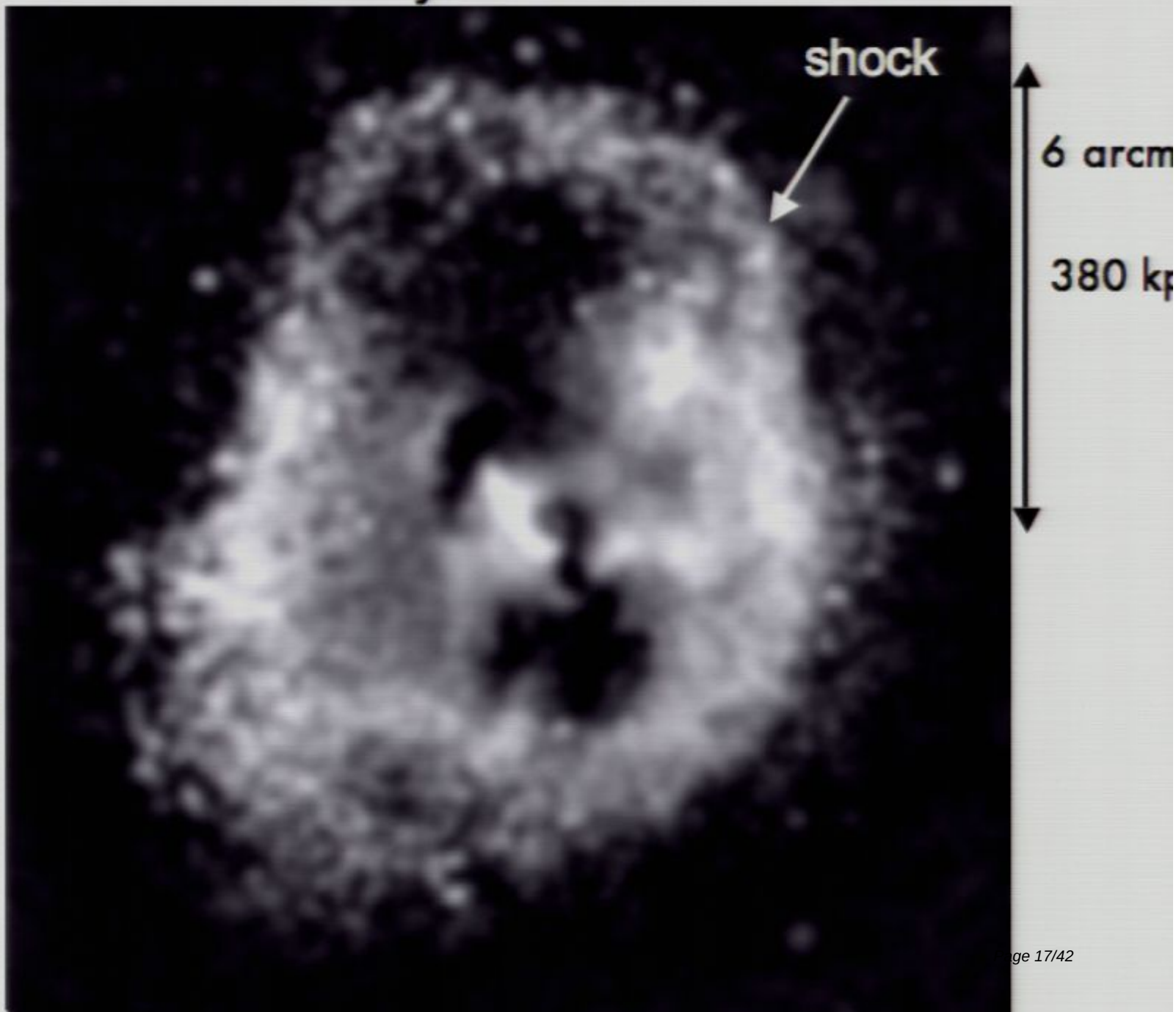
Wise + 07

t_{shock}= 140 Myr

t_{buoy}= 220 Myr

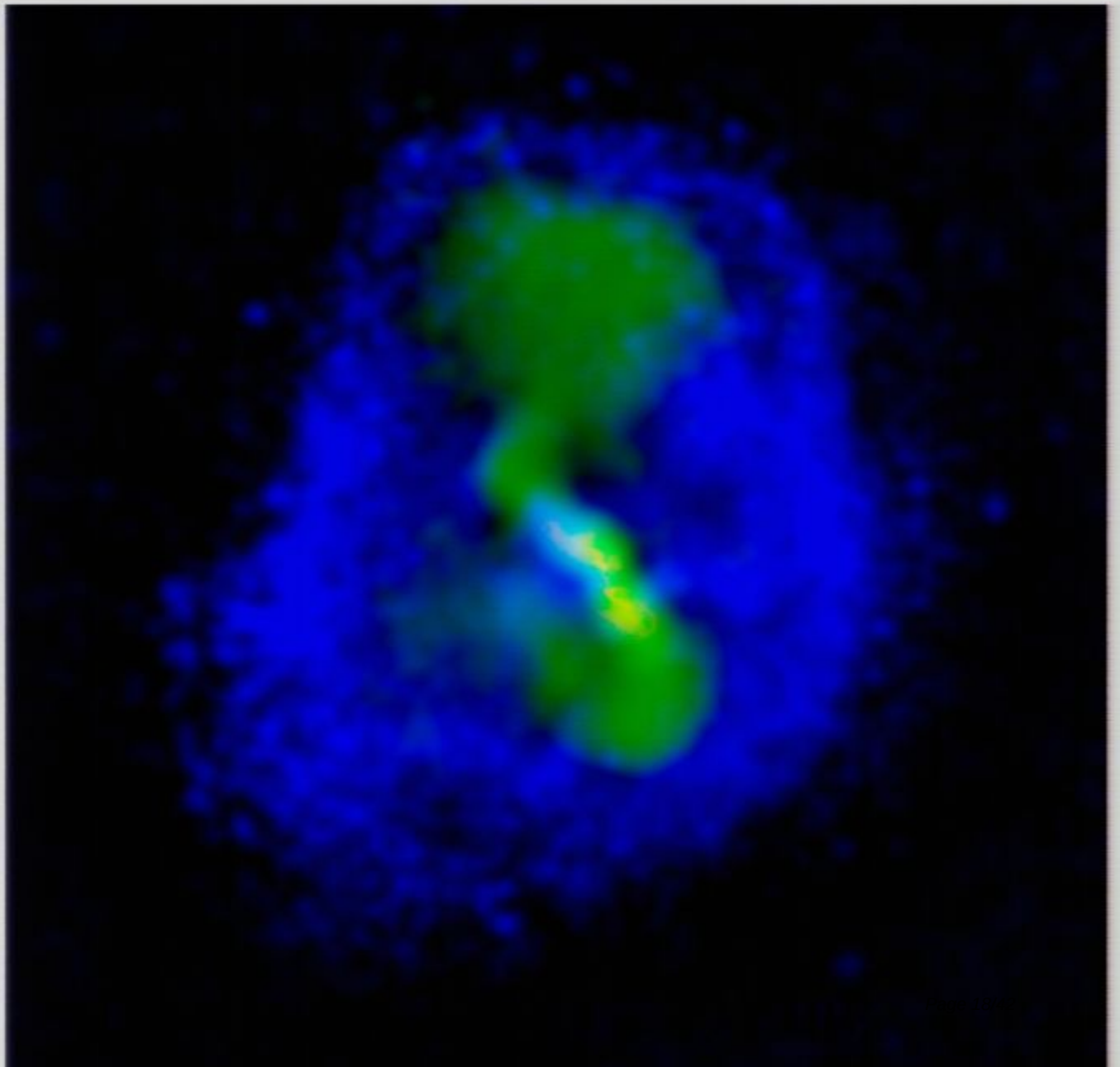
$t_{buoy} > t_{shock}$

M=1.3



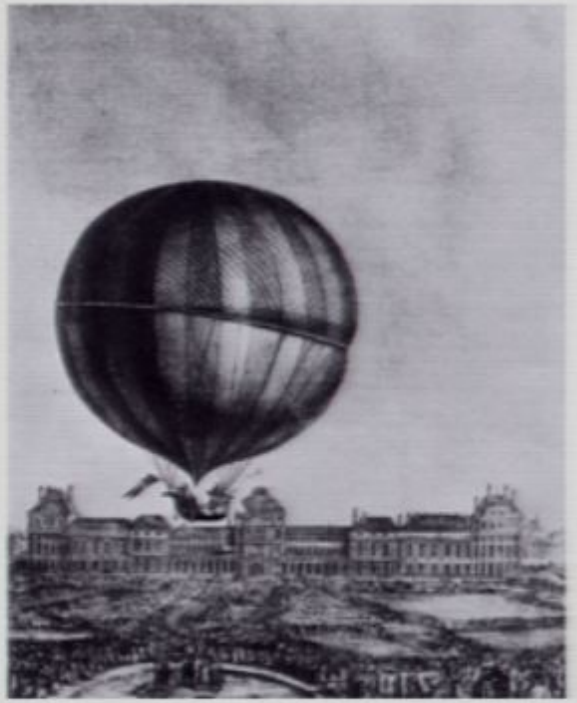
Low Radio Frequency Traces Energy

300 MHz

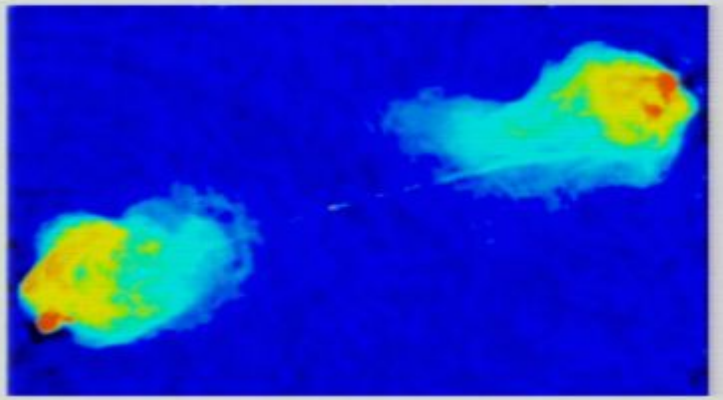


Wise + 07
Lane + 05

Gauging jet power and heating of hot atmospheres

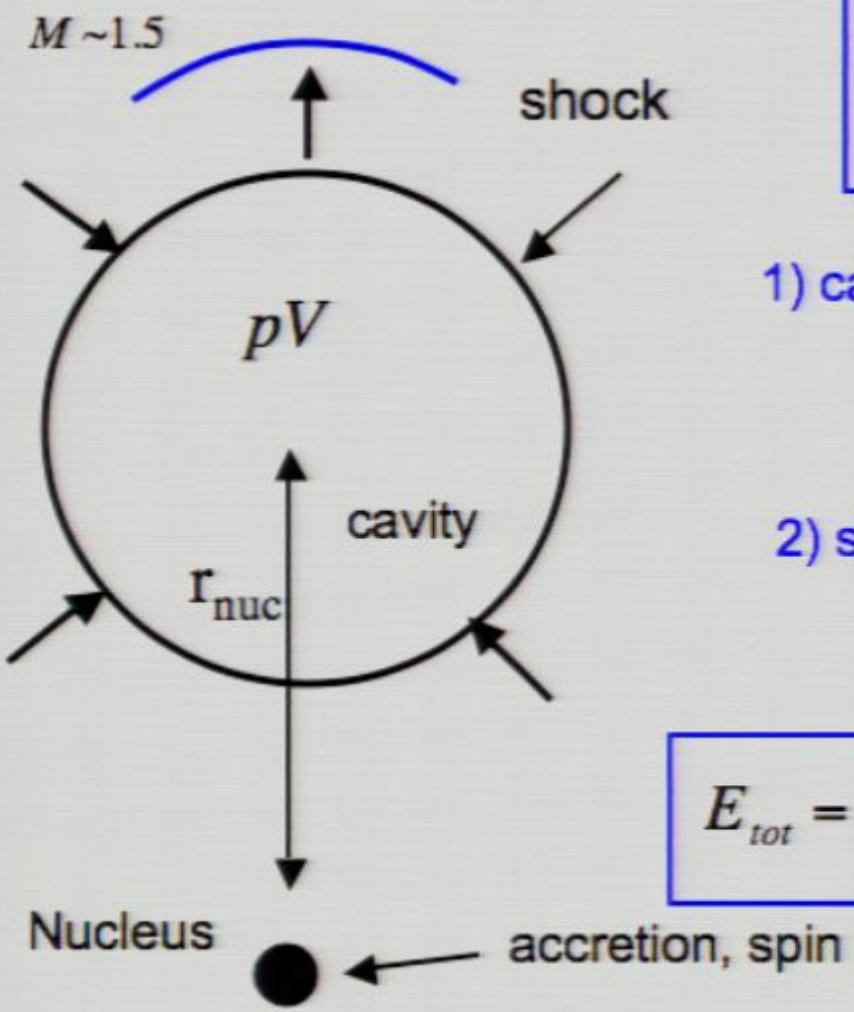


atmospheric physics: buoyancy



Jet physics

Measuring Jet Power with X-ray Cavities



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

1) cavity

$$E_{cav} = \frac{\gamma pV}{\gamma - 1} = 2.5\,pV - 4\,pV \qquad t_{cav} = r_{nuc} / v_{buoy}$$

2) shock

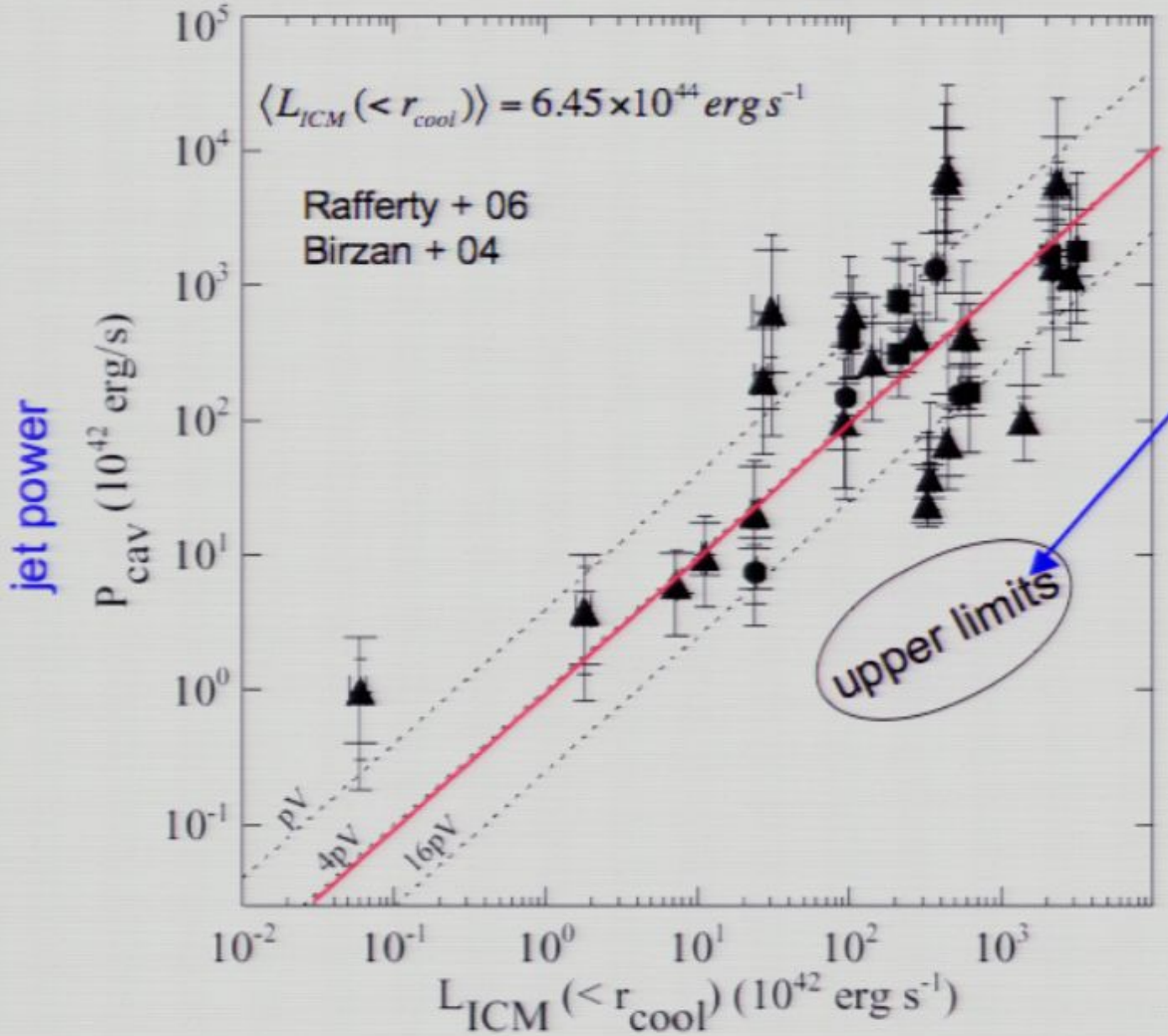
$$E_{shock} \approx \Delta pV \qquad t_{shock} \approx r_{shock} / c_s$$

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

McNamara + 00,01
Birzan + 04

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

Heating & Cooling Diagram: CFs Quenched



jet power

$$\Phi = \frac{P_{cav} \times f}{\langle L_{ICM}(< r_{cool})\rangle} = 1$$

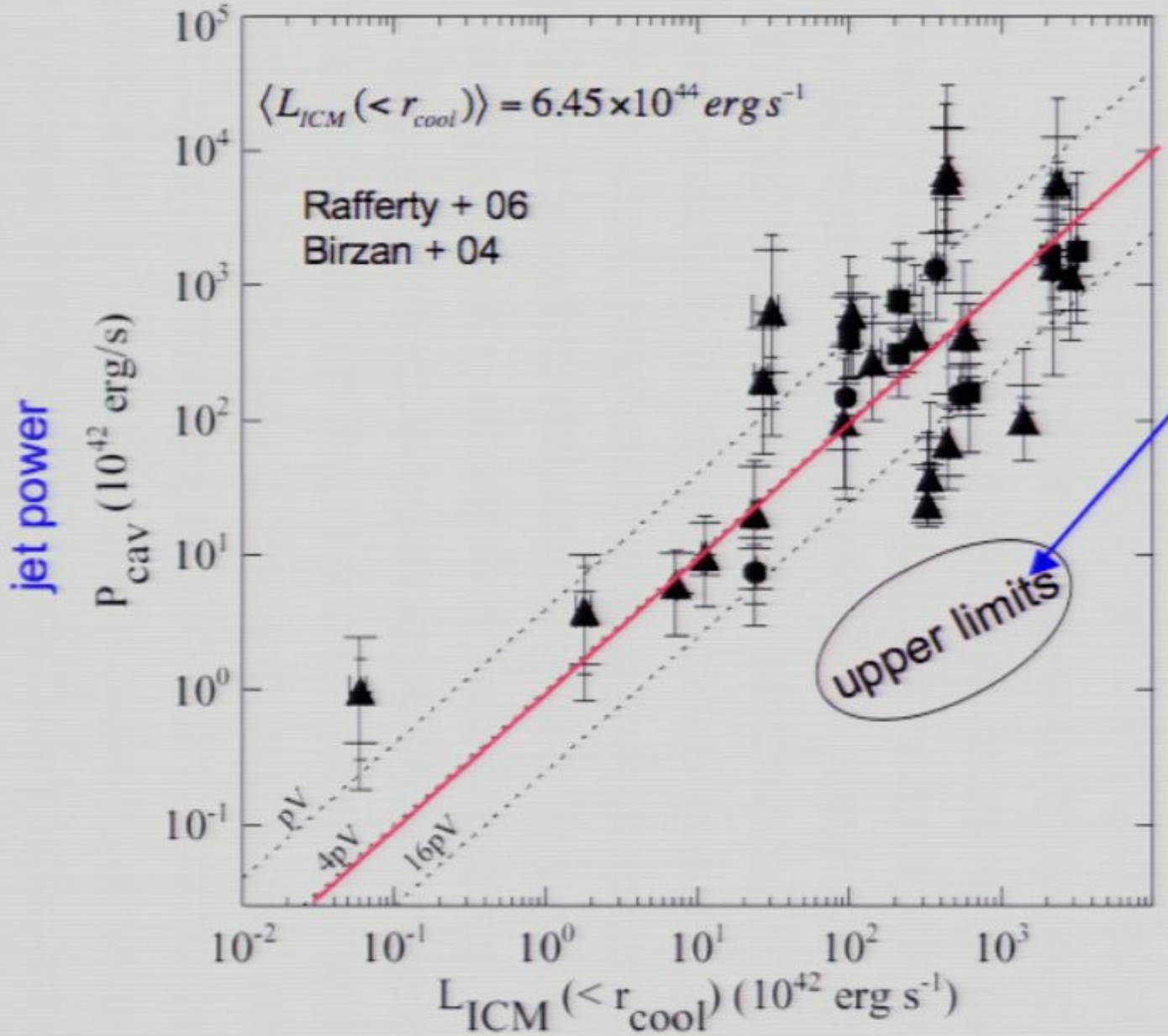
$f = 0.7$
(Dunn & Fabian 06)

heating ~ cooling

X-ray cooling luminosity

Self-regulated galaxy and SMBH formation: direct evidence for feedback

Heating & Cooling Diagram: CFs Quenched



jet power

X-ray cooling luminosity

$$\Phi = \frac{P_{cav} \times f}{\langle L_{ICM}(< r_{cool})\rangle} = 1$$

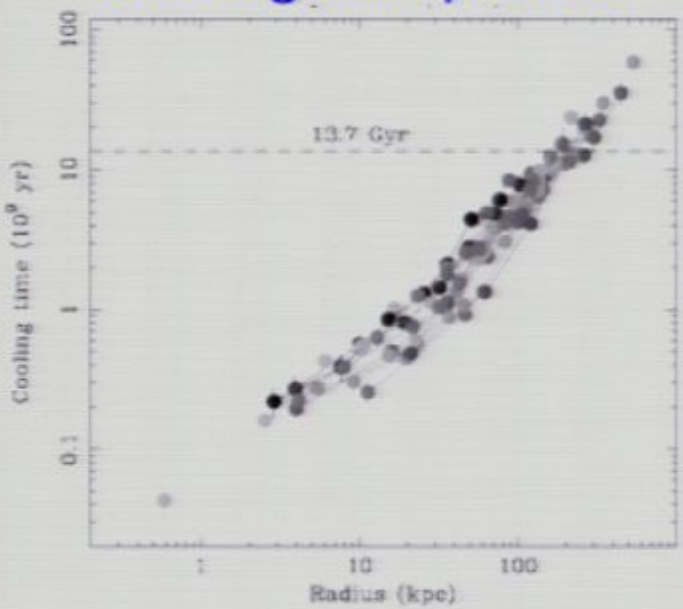
$f = 0.7$
(Dunn & Fabian 06)

heating ~ cooling

Self-regulated galaxy and SMBH formation: direct evidence for feedback

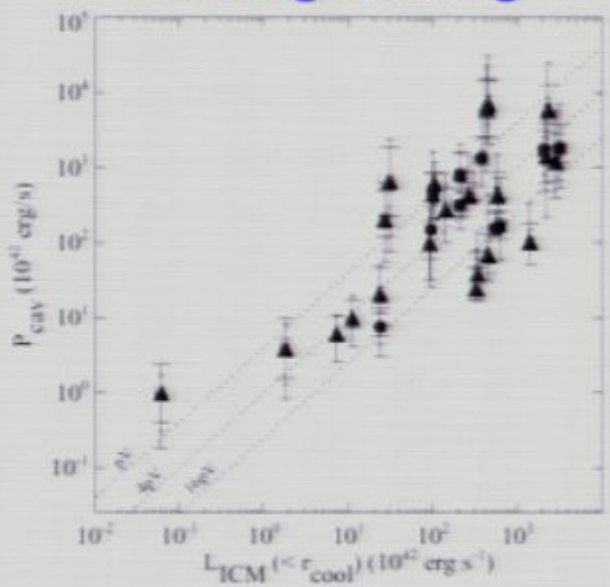
Conditions for AGN-Regulated Feedback Loop

cooling time profiles



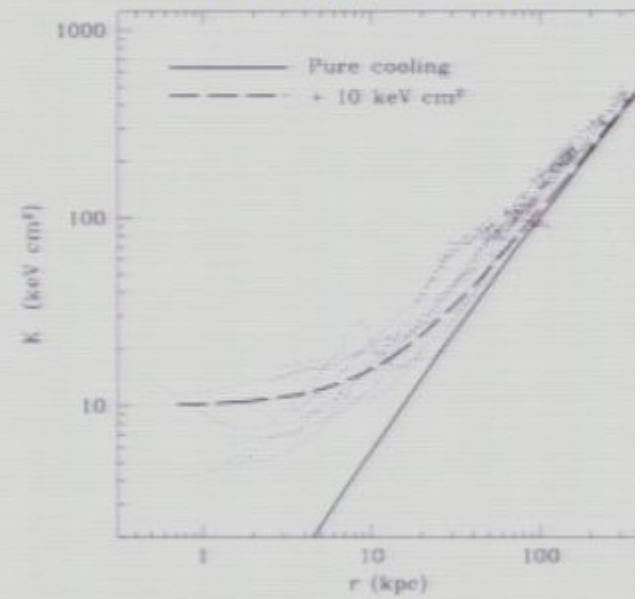
Voigt & Fabian 04

heating/cooling



Rafferty et al. 06
Birzan et al. 04

entropy profiles



Voit & Donahue 05
Donahue et al. 06
Voit 05

1) $t_{cool} \sim t_{cav} \sim 10^8$ yr

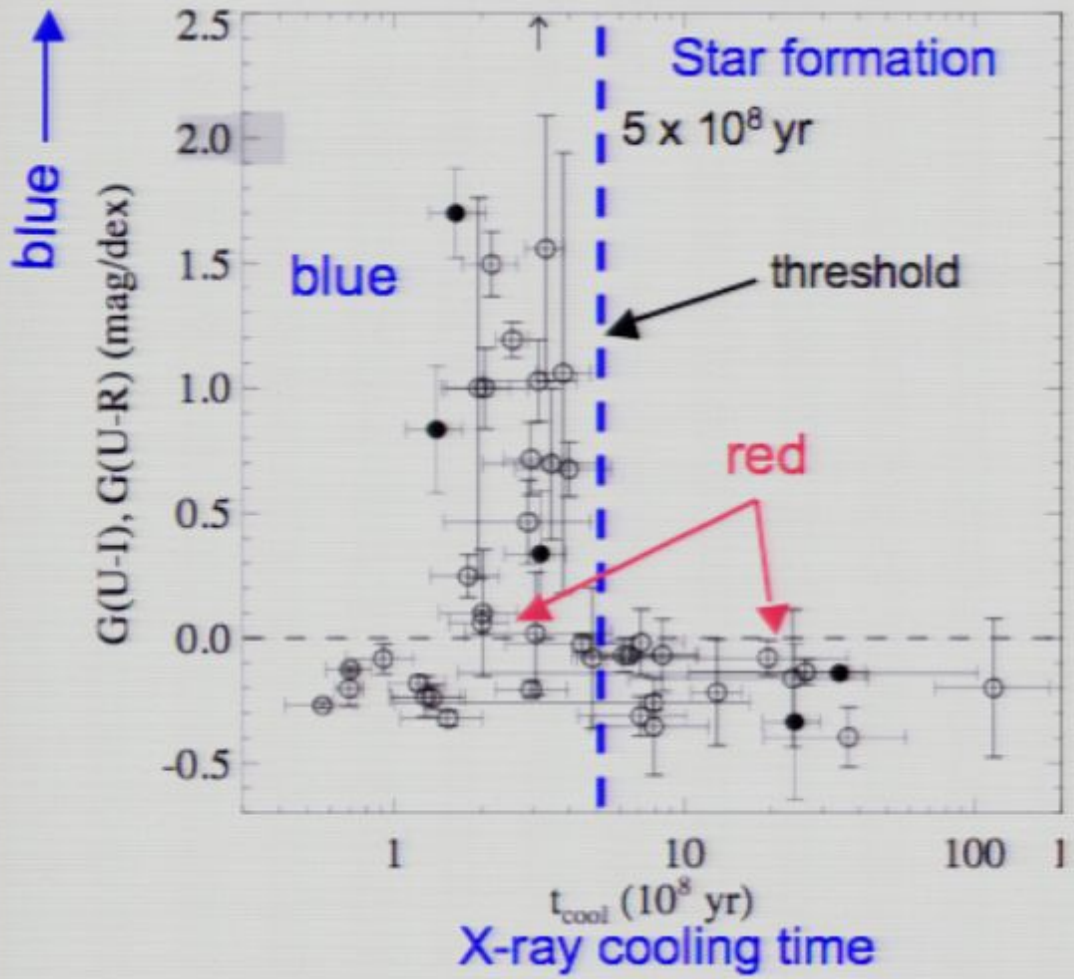
2) $L_{AGN} \sim L_x$

3) Entropy floors

See Voit & Donahue 05, McNamara & Nulsen 07 ARAA

star formation & Halpha threshold: t_{cool} ~ 500 Myr

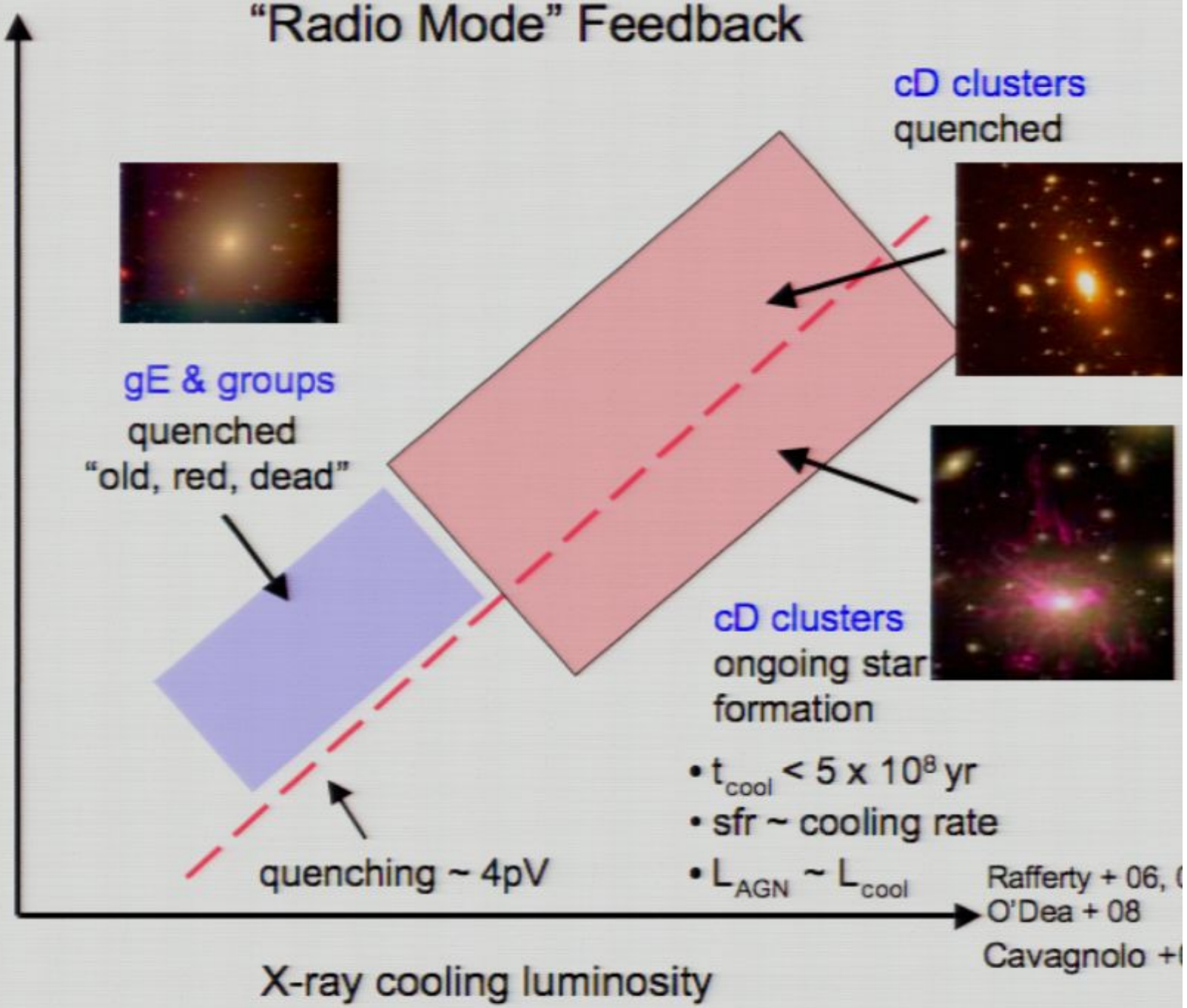
suppressed by active feedback



- Star formation linked to cooling, hot X-ray atmospheres
- See Cavagnolo + 08 for similar effect in Halpha & radio

Rafferty + 08

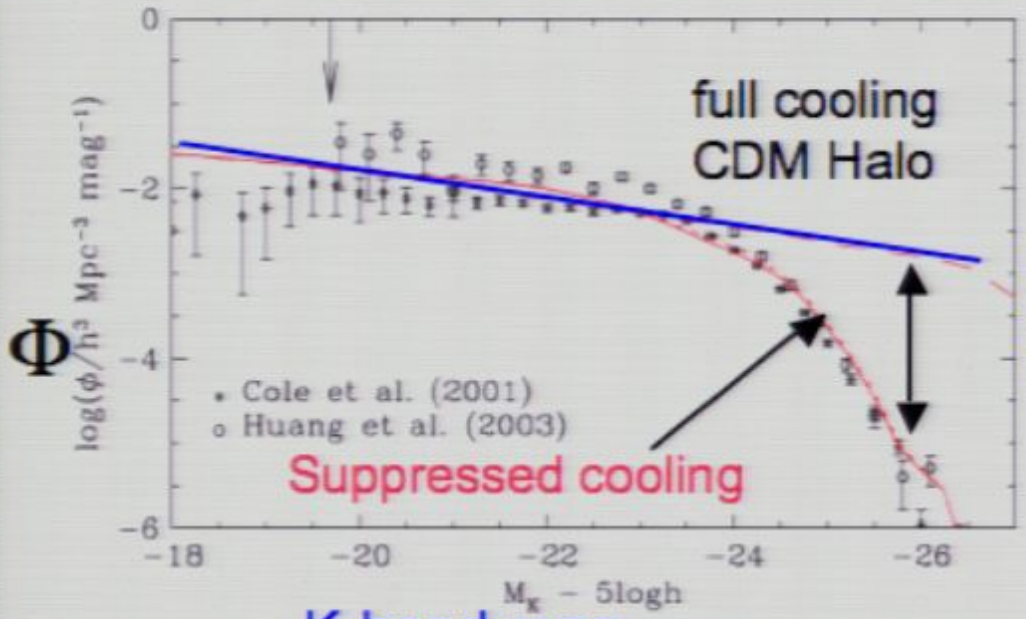
"Radio Mode" Feedback



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

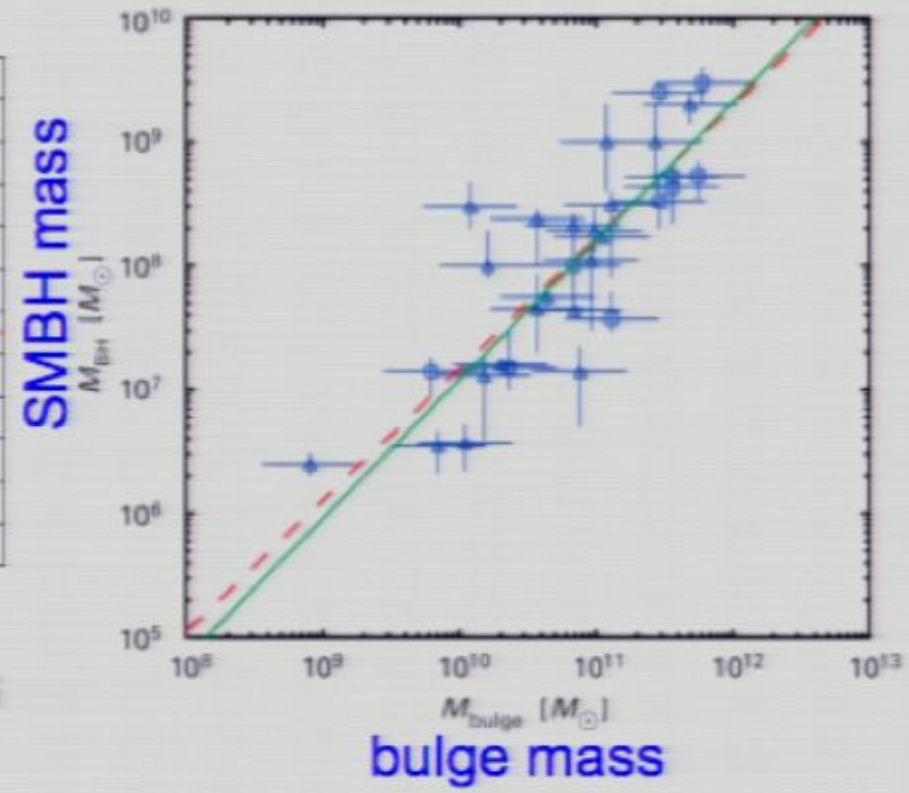
The broken hierarchy of galaxy formation

K-band luminosity function



Bower et al. 06

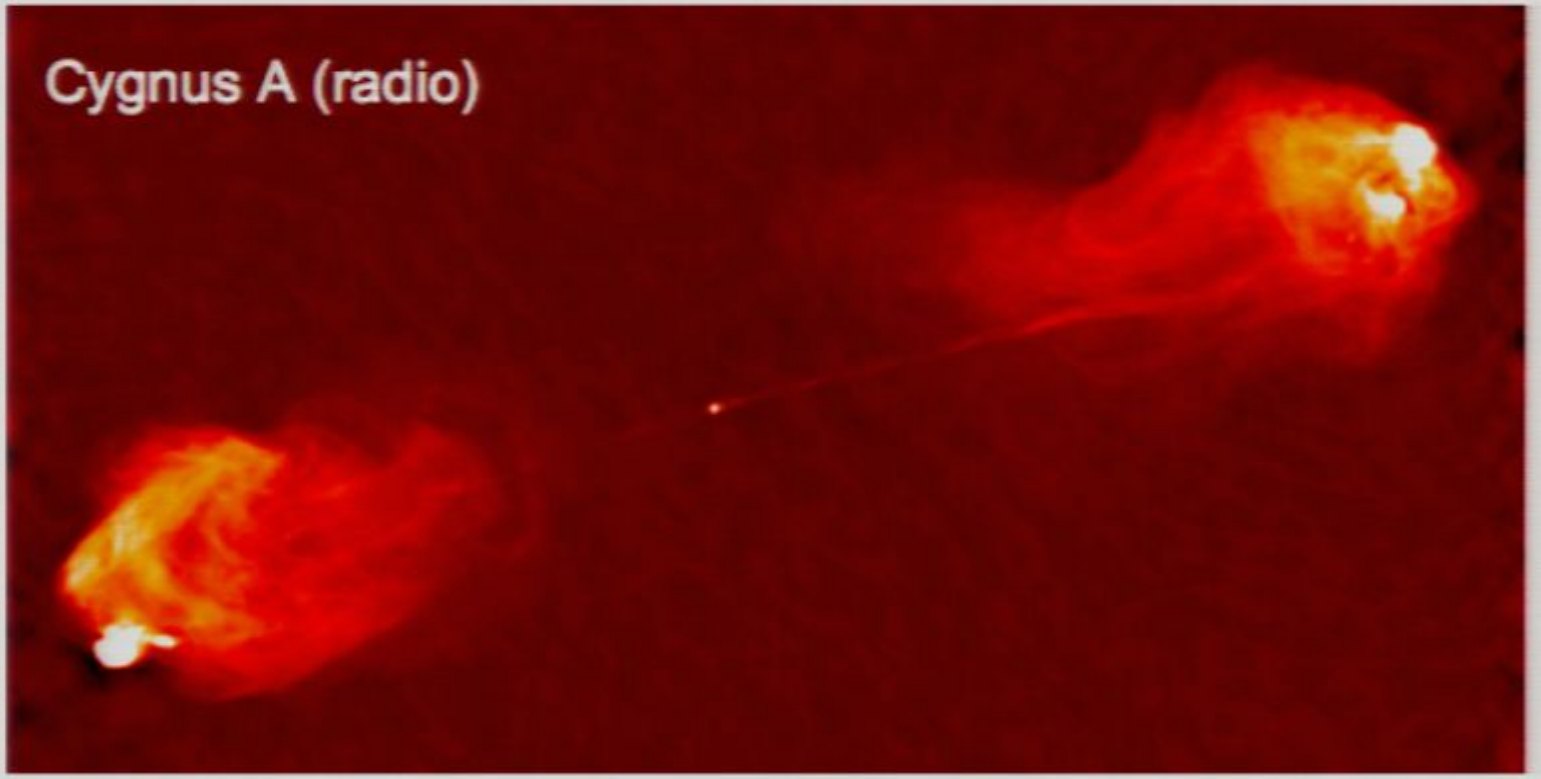
SMBH-bulge mass relation



fossil evidence for self-regulation or feedback

Jet energetics, radiative efficiency, and composition:

How Powerful are Extragalactic Radio Sources?
Can they quench cooling & regulate star formation?

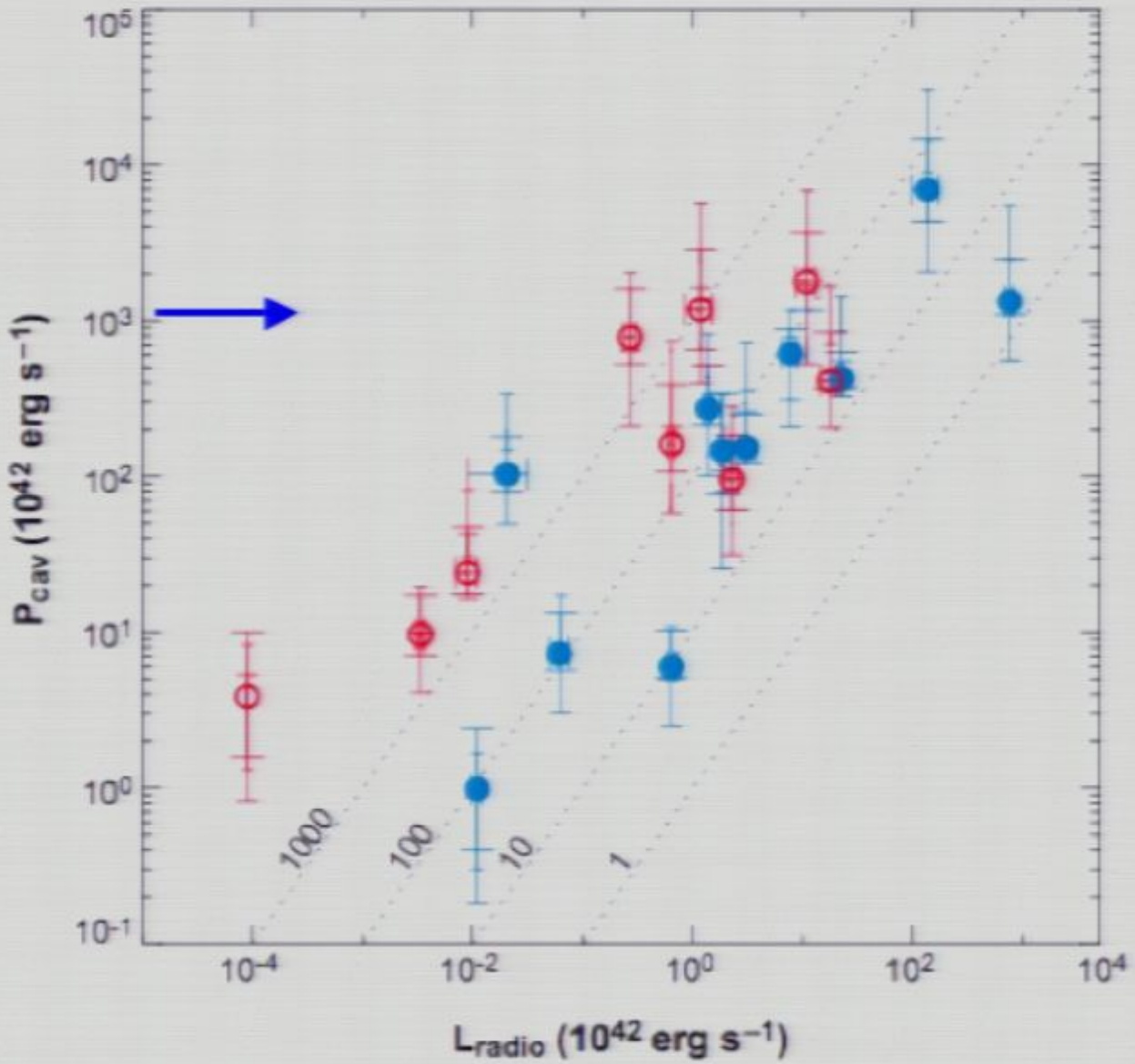


Burbidge 56, Scheuer 74, Blandford & Rees 74, Begelman, Blandford, Rees 84,

H.

Radio Calorimetry: low radiative efficiency, mechanically-dominated, *powerful, 'heavy lobes'*

jet (cavity) power



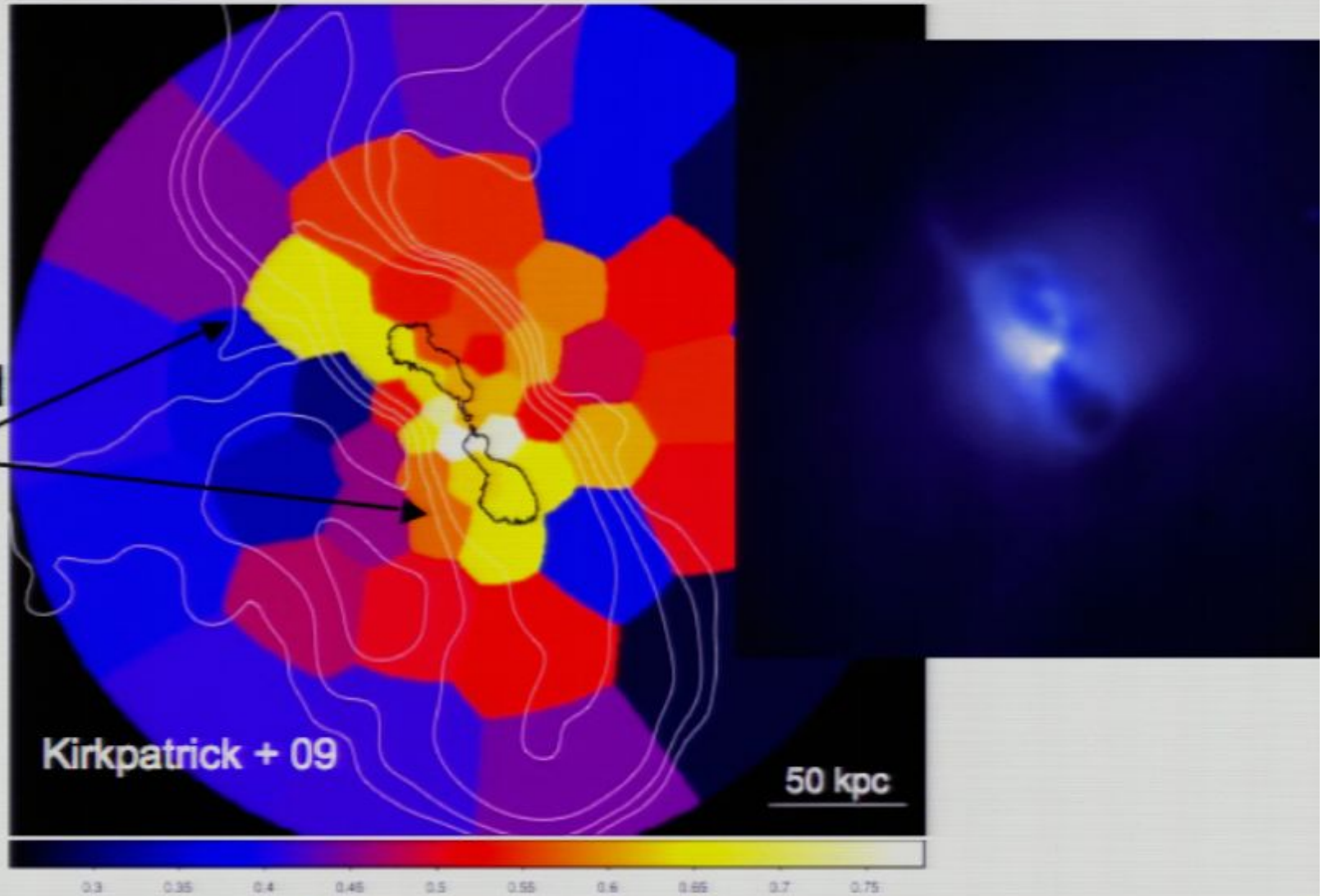
McNamara & Nulsen, 07 ARA&A

radio synchrotron power

New Stuff

- Outflows & redistribution of metals
- Black hole spin
- Molecular gas vs jet power
- Ultramassive ($<10^{10}$ Mo) black holes

Hydra A Metal Enriched Outflow



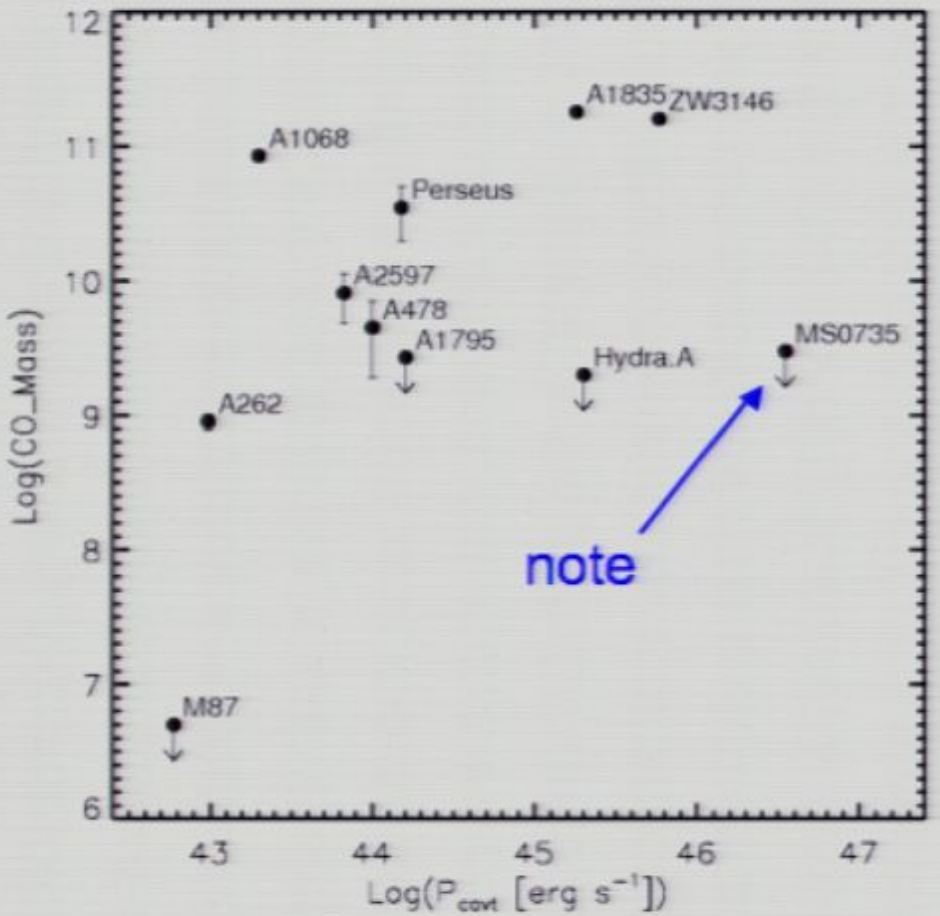
Iron enriched outflow

$$\Delta M_{Fe} = 2 - 7 \times 10^{7} M_{0}$$

R~120 kpc

AGN-Jets disperse metals throughout ICM

Molecular Gas Mass vs Jet Power



Data: Rafferty+06, Edge 01, Salome & Combes 03

- No trend CO mass with jet power
- Large CO range at given jet power

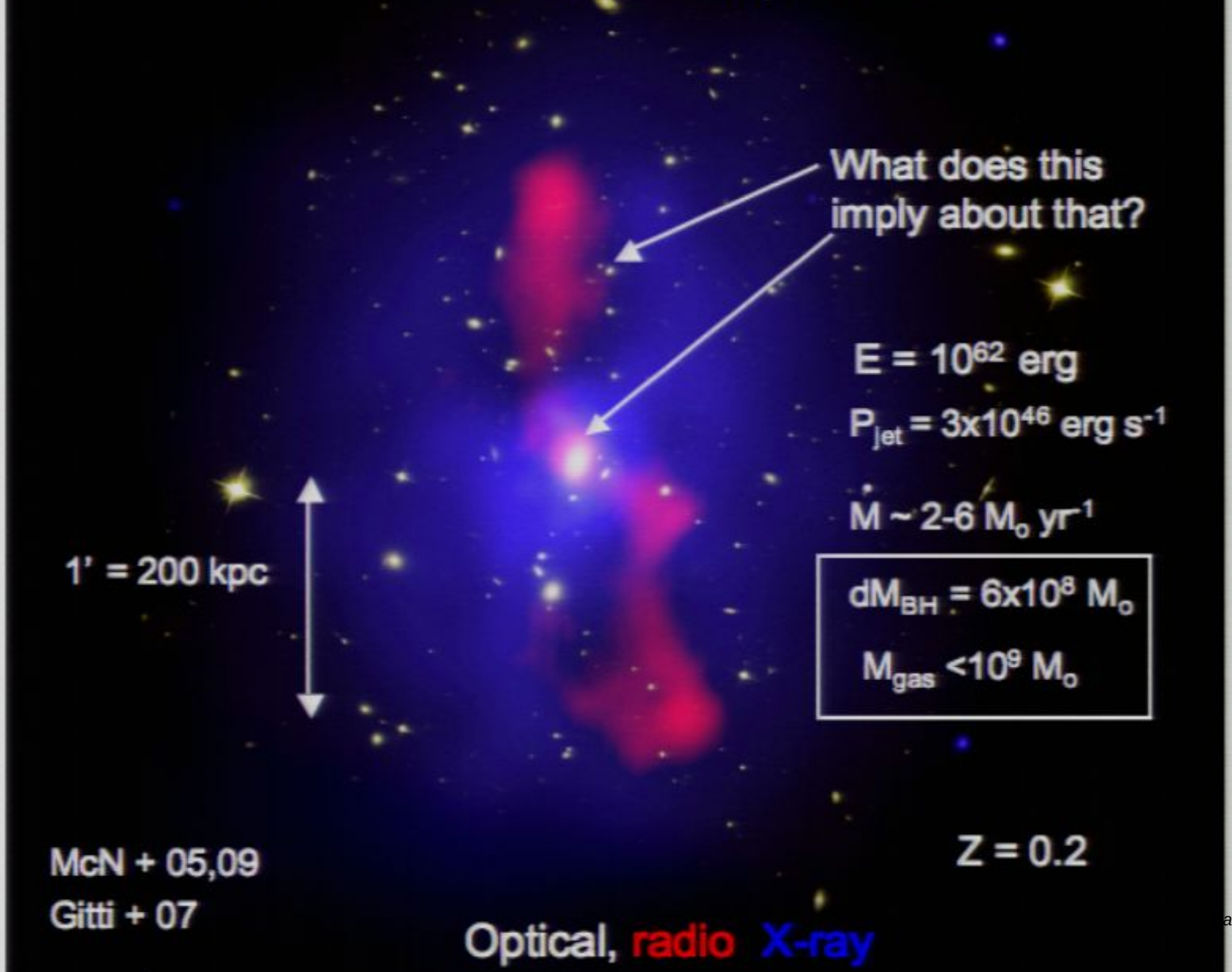
Gas supply alone does not determine Jet power

Variables may include:

Spin, accretion rate, winds angular momentum, black hole mass

Good Candidate for Spin Powering

MS0735.6+7421 Nucleus is parched!



$E = 10^{62}$ erg

$P_{jet} = 3\times10^{46}$ erg s^{-1}

$\dot{M} \sim 2\text{-}6\ M_o\ yr^{-1}$

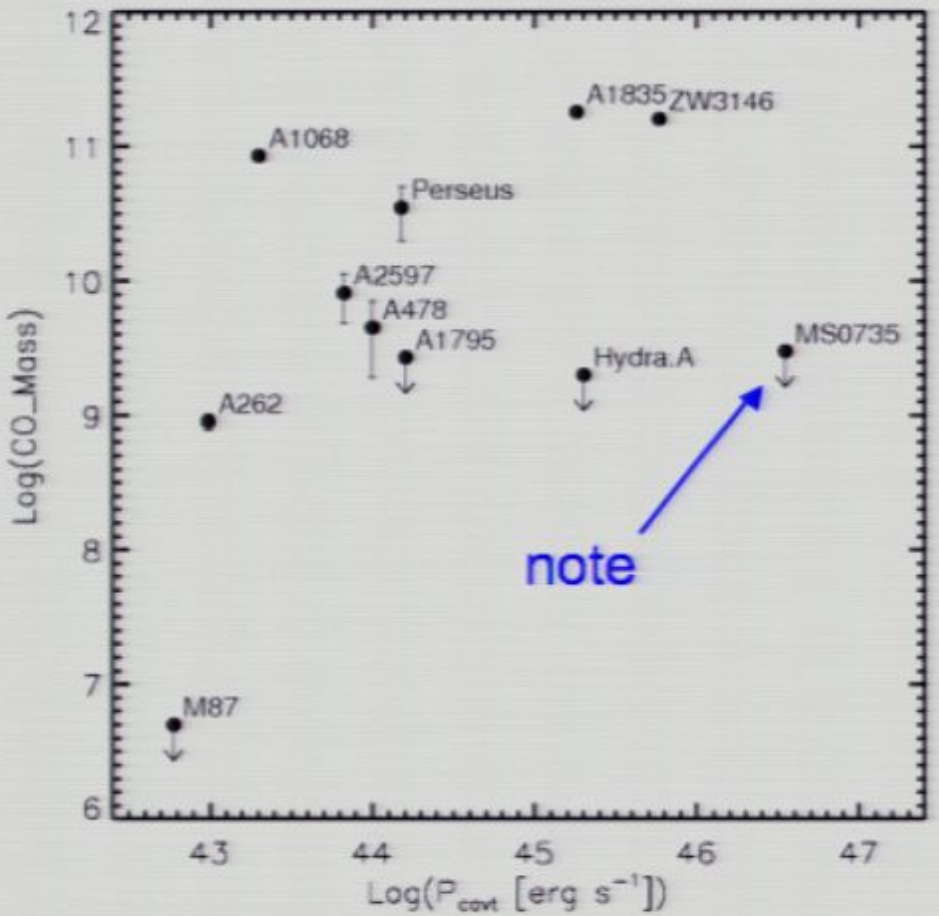
$dM_{BH} = 6\times10^{8}\ M_o$

$M_{gas} < 10^{9}\ M_o$

McN + 05,09

Gitti + 07

Molecular Gas Mass vs Jet Power



Data: Rafferty+06, Edge 01, Salome & Combes 03

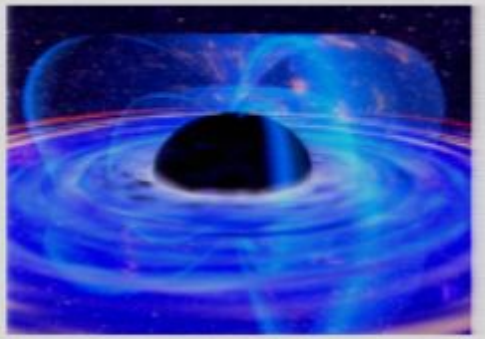
- No trend CO mass with jet power
- Large CO range at given jet power

Gas supply alone does not determine Jet power

Variables may include:

Spin, accretion rate, winds angular momentum, black hole mass

Accretion & Spin Paradigms



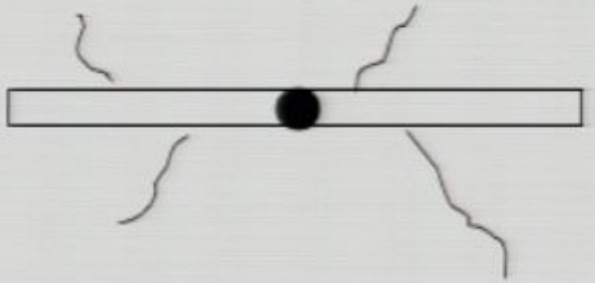
Accretion

thin disk + slowly spinning hole = radiation

$$L_{opt} \geq 1.7 \times 10^{12} L_{\odot} m_9^{1.27} \left(\frac{\dot{m}}{0.1} \right)^{0.6}$$

Not observed

Meier 99

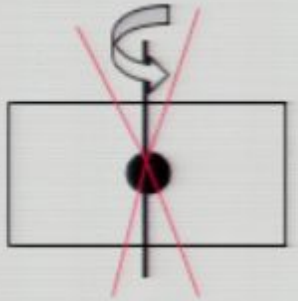


Spin

hybrid = thick disk + fast spinning hole + ADAF = powerful jet

$$L_{jet} = 10^{46} \left(\frac{B_p}{10^4 G} \right)^2 m_9^2 j^2$$

Meier 99



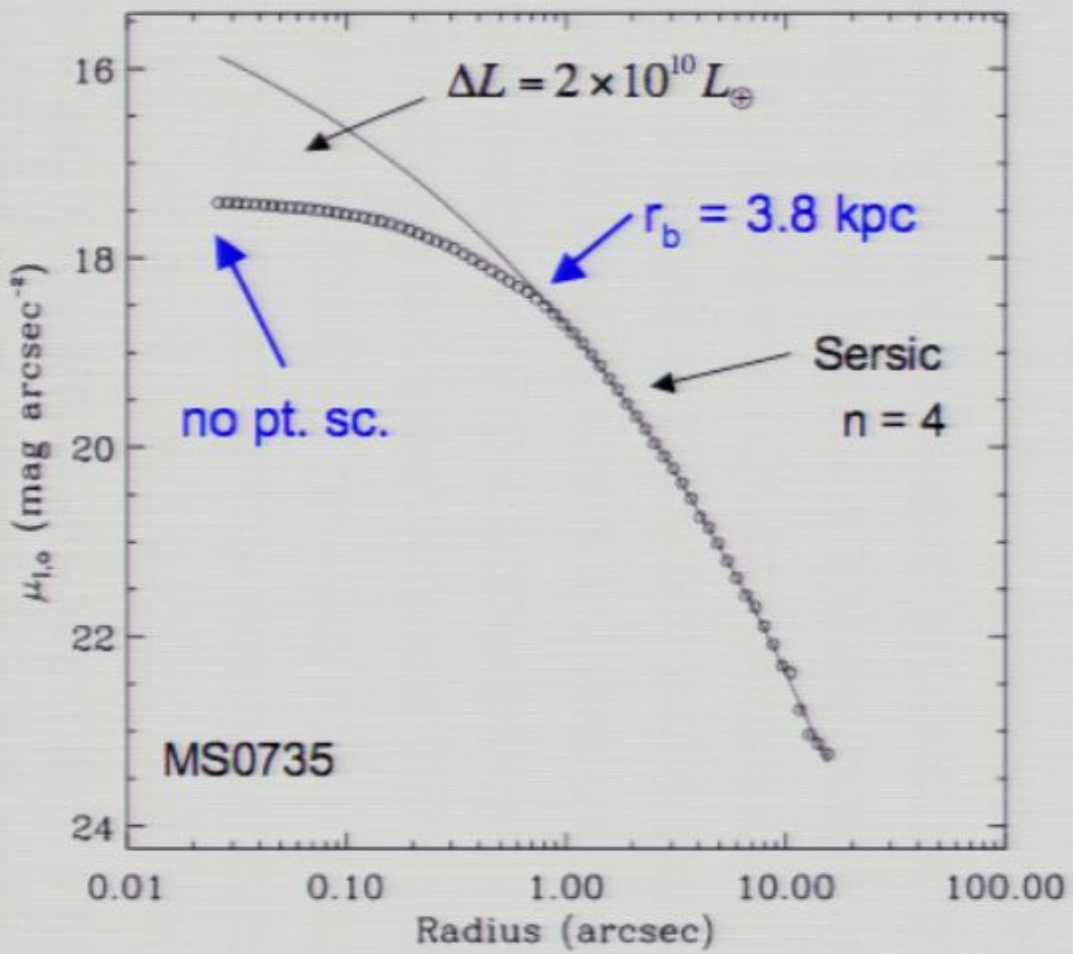
$B_p^2 \propto \dot{m}$ in BZ-based models

Link to feedback

Can we test this?

Problem: spin power & accretion power are coupled

MS0735 Huge Break Radius ➡ Ultramassive Black Hole ?



- no light cusp - no vestigial SF
- efficient & persistent feedback

Light deficit method of Merritt & co

$$\Delta M_s = \frac{M}{L} \times \Delta L \approx 6 \times 10^{10} M_{\odot}$$

$$M_{\bullet} \sim \Delta M_s$$ (large uncertainty)

BH mass ∝ light deficit

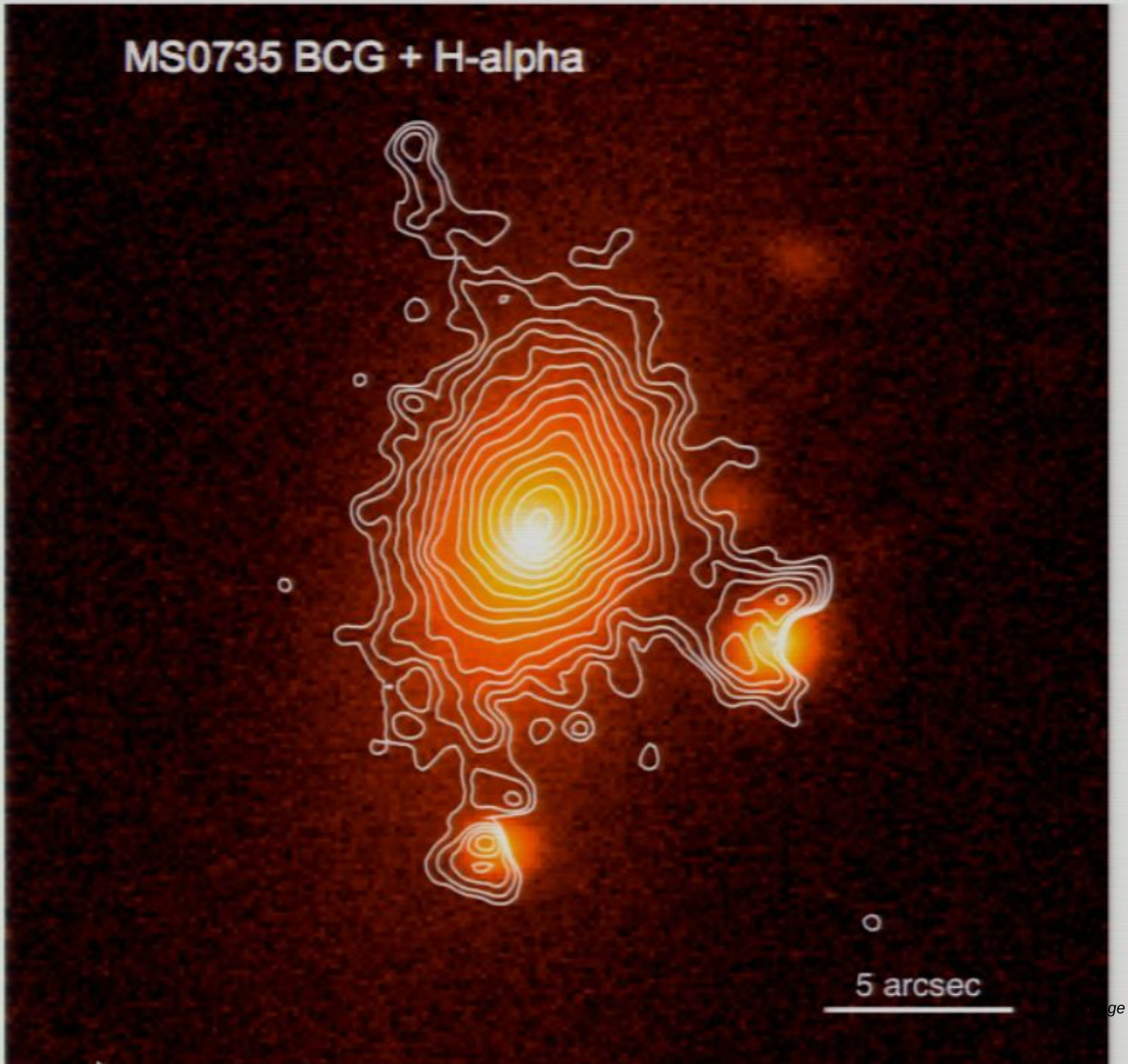
Kormendy & Bender 09

.. but see Hopkins+09

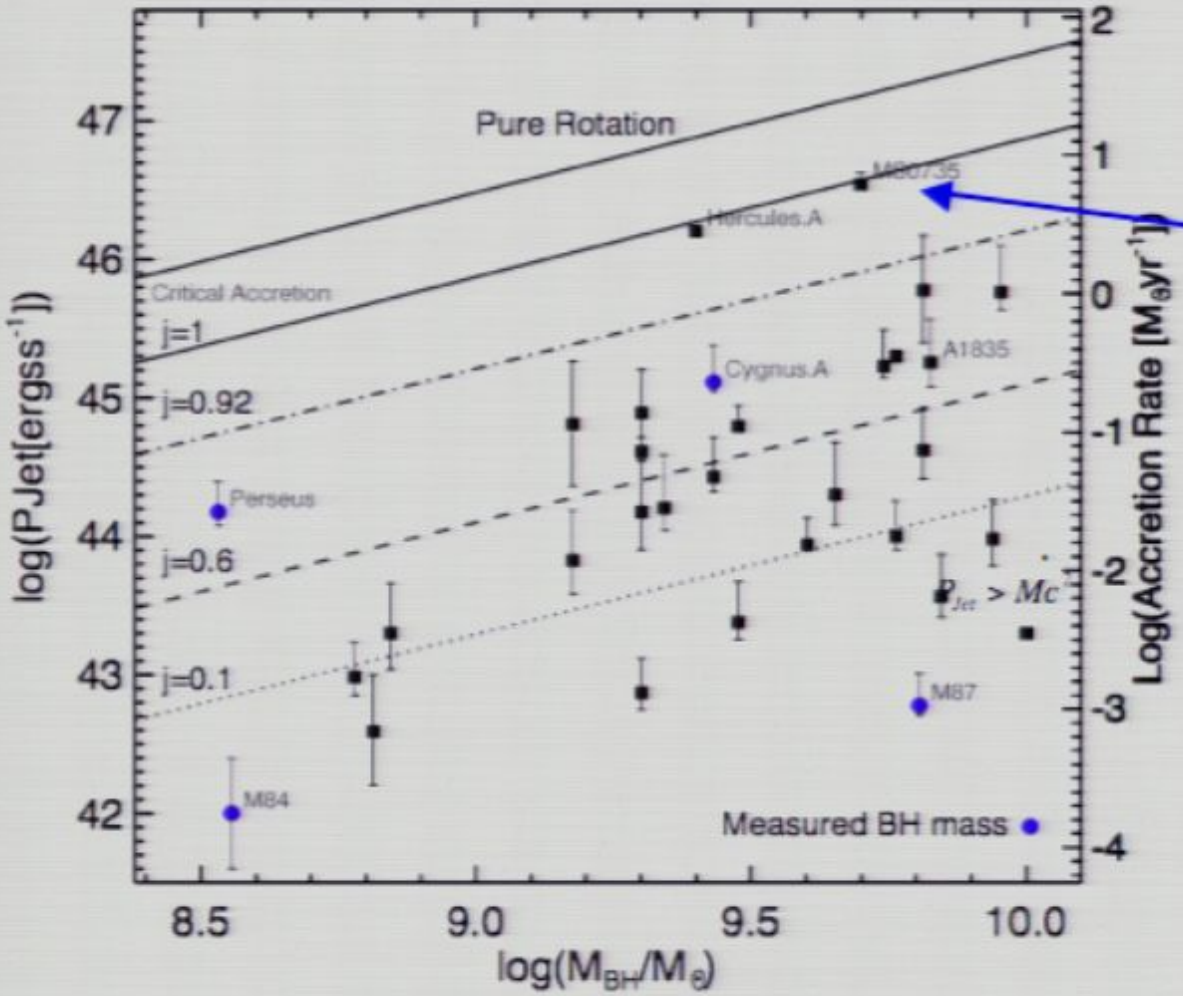
Ultramassive Black Hole?

If true, Bondi accretion becomes plausible McN+09

Interesting consequences for cusp/core dichotomy in gEs Kormendy+09


MS0735 BCG + H-alpha
5 arcsec

Best Constraints with Powerful AGN: *Spin Boosting*



- Not enough fuel to power by accretion alone
- Low nuclear emission likely ADAF

critical accretion $\dot{m}_{crit} \sim 0.02$

McNamara + 09

$$j \rightarrow 1 \quad P_{Jet} > \dot{M}c^2$$

McN + 09, Benson & Babul 09

Theoretical Issues

How does feedback work?

How does jet power couple to surrounding gas?

What is the role of thermal conduction & magnetic fields?

How is energy from spinning BH tapped?

Why do some powerful AGN emit so little radiation?

What is the structure of the nucleus?

Theoretical Issues

How does feedback work?

How does jet power couple to surrounding gas?

What is the role of thermal conduction & magnetic fields?

How is energy from spinning BH tapped?

Why do some powerful AGN emit so little radiation?

What is the structure of the nucleus?