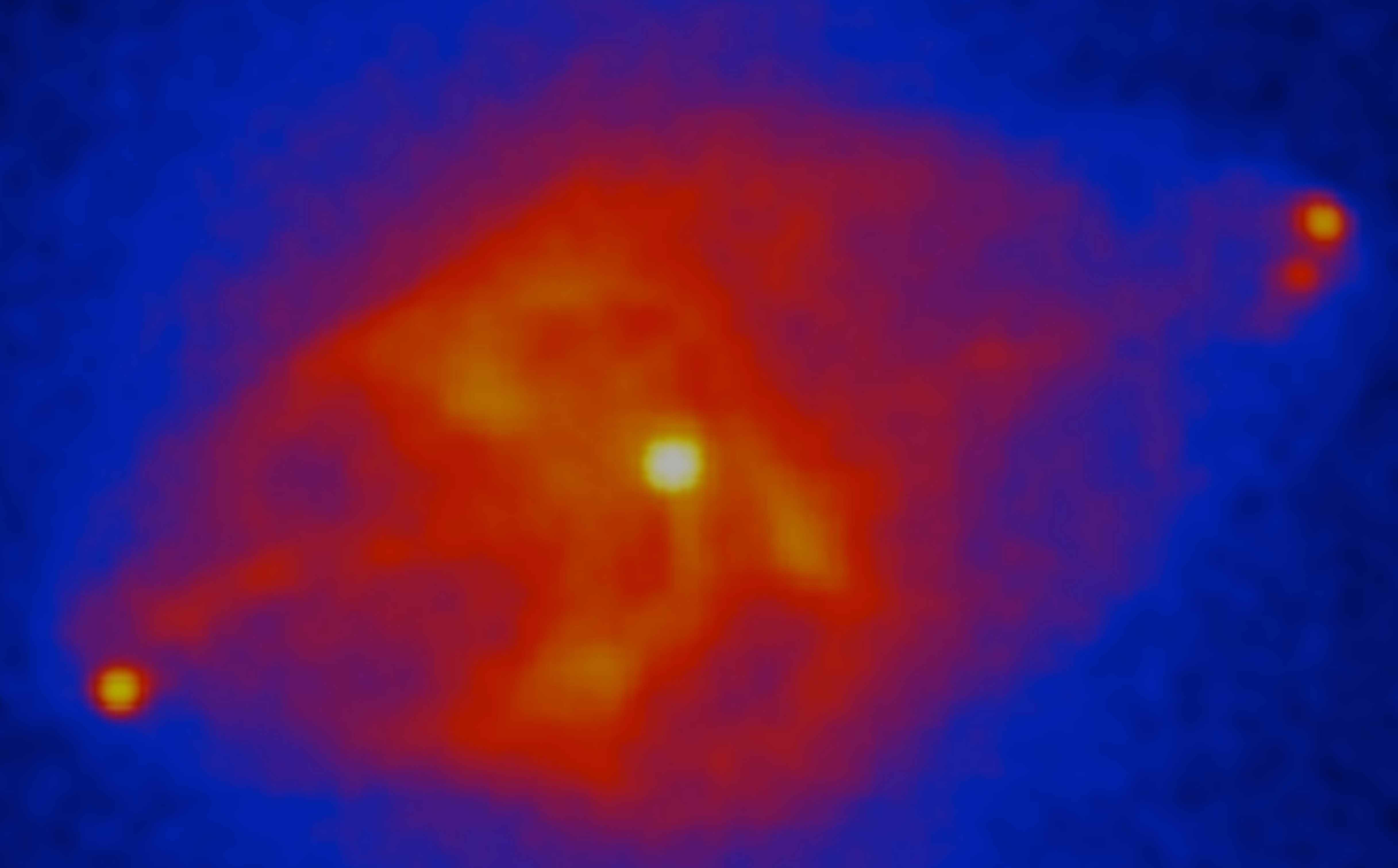
Echoes, Explosions, and Enrichment:

The Impact of AGN on the Cluster Environment



Michael W. Wise

ASTRON / UvA

Winchester Black Hole Workshop

21 July 2011

Echoes, Explosions, and Enrichment:
The Impact of AGN on the Cluster Environment

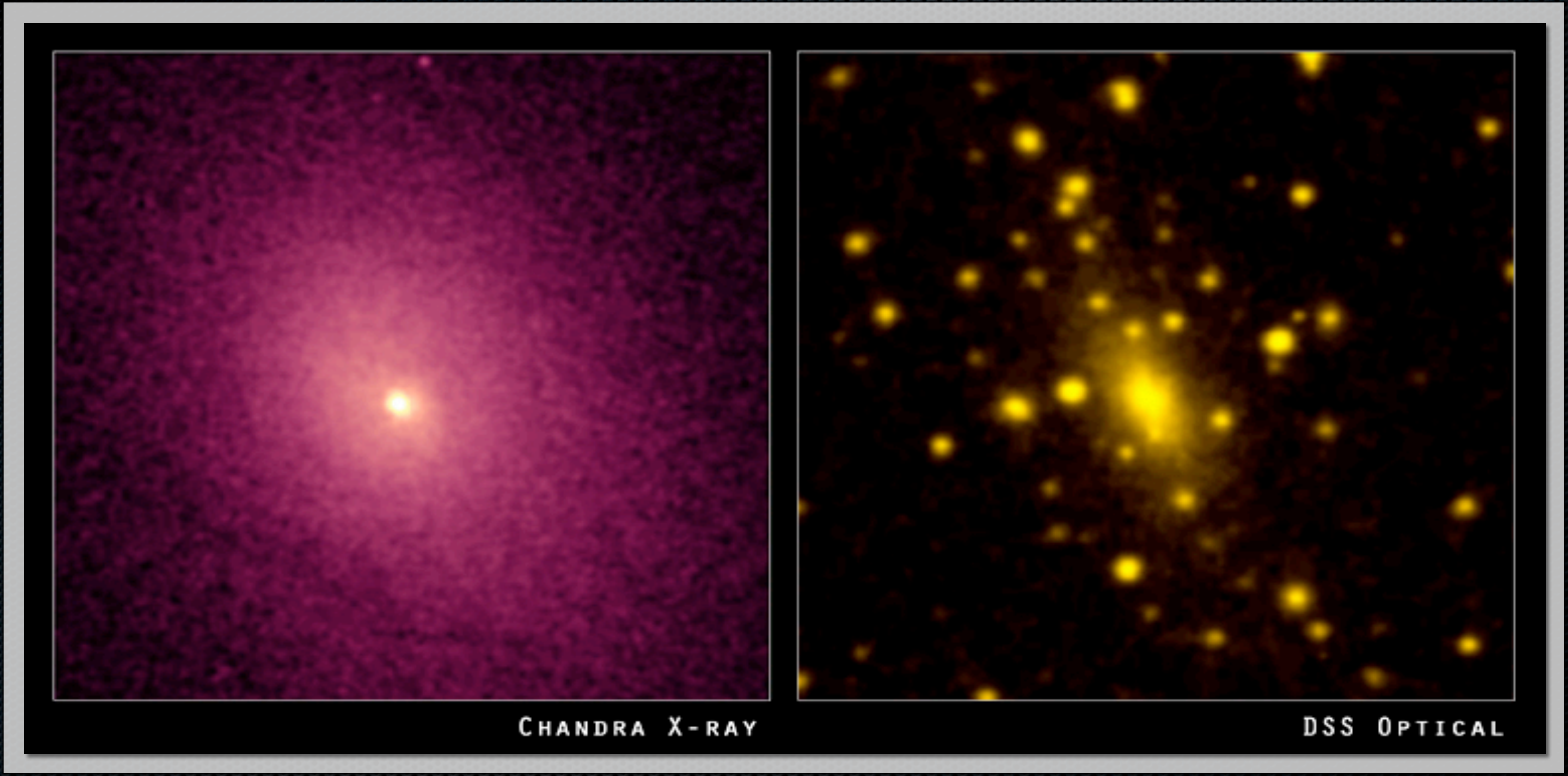
Talk Outline

- ➡ ***Brief History of AGN Feedback***
- ***Cavity and Shock Energetics***
- ***Timescales and Duty Cycles***
- ***ICM Elemental Enrichment***
- ***Future X-ray and Radio Prospects***

Collaborators:

Brian McNamara, Paul Nulsen, David Rafferty, Laura Bîrzan, Myriam Gitti, Mark Birkinshaw, Marcus Brüggen, Chris Carilli, Kenneth Cavagnolo, Alastair Edge, Chiara Ferrari, Bill Forman, Stephen Hamer, Sebastian Heinz, Christine Jones-Forman, Ralph Kraft, John McKean, Raffaella Morganti, Somak Raychaudhury, Huub Röttgering, Helen Russell, Diana Worrall

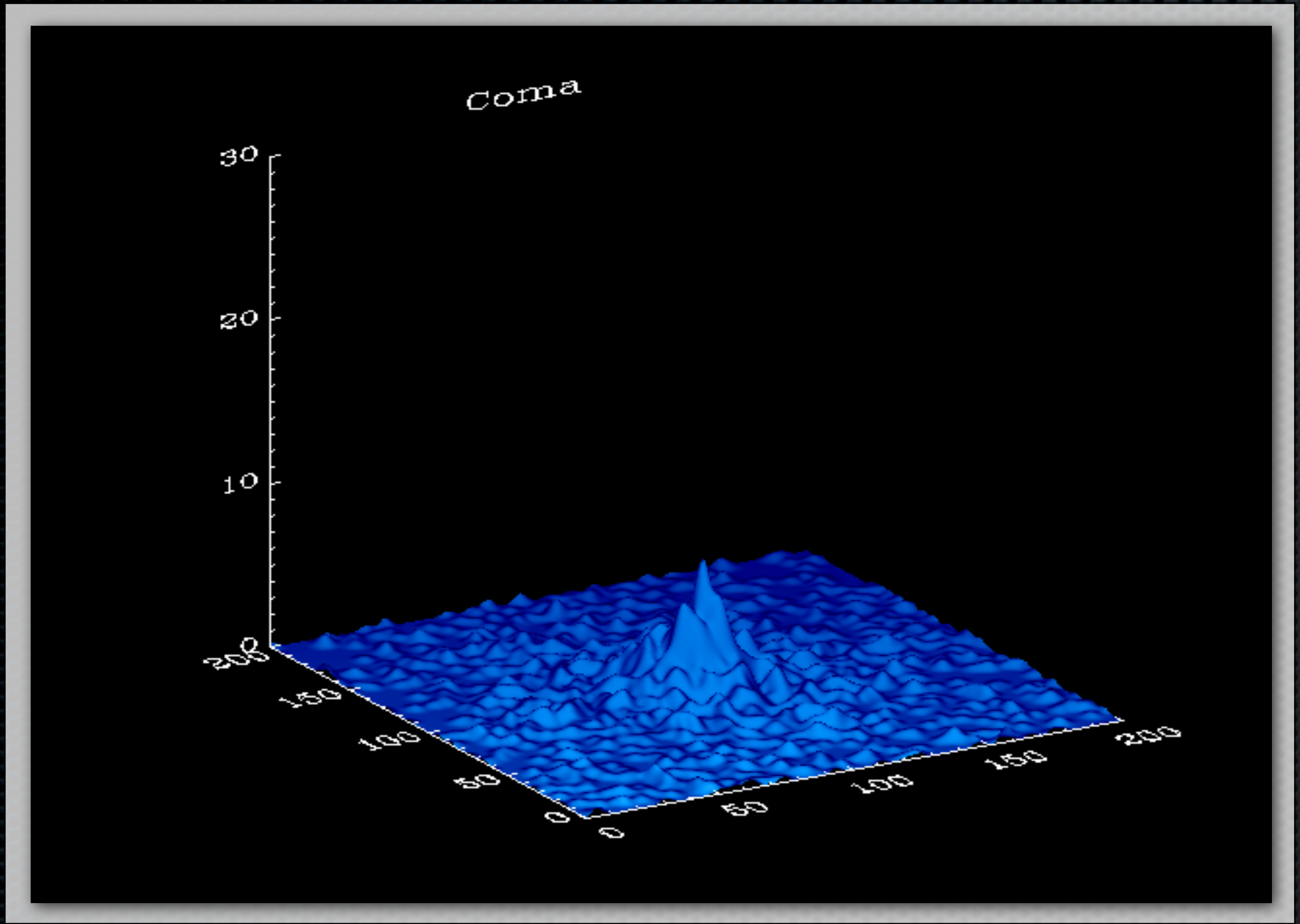
Galaxy Clusters in X-ray & Optical



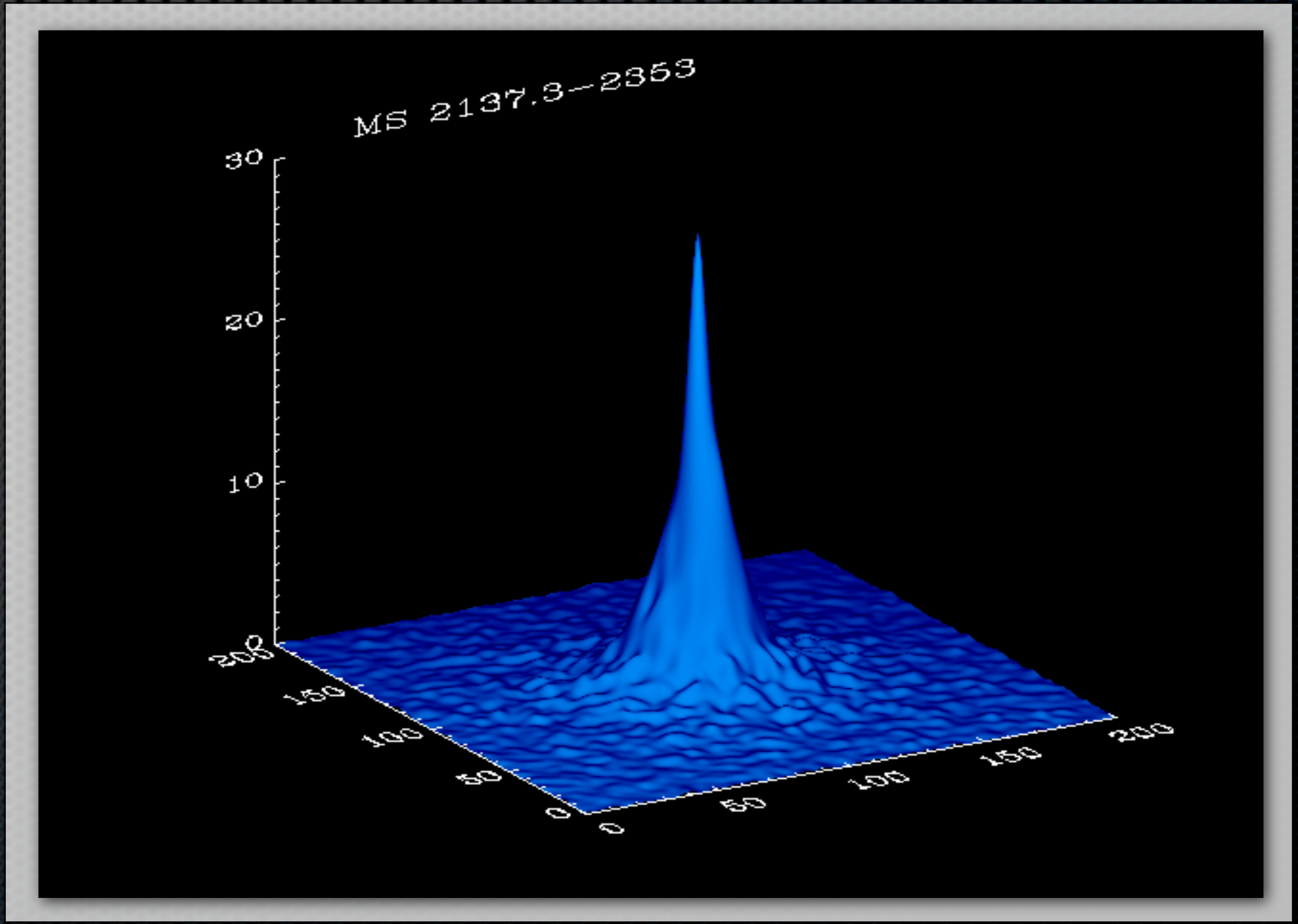
70%-80% dark matter
20%-30% baryons
T_{gas} **~ 4-10 keV**

ICM retains the imprint of the dynamical and thermodynamical history of the cluster

Cool Core and Non-cool Core Clusters



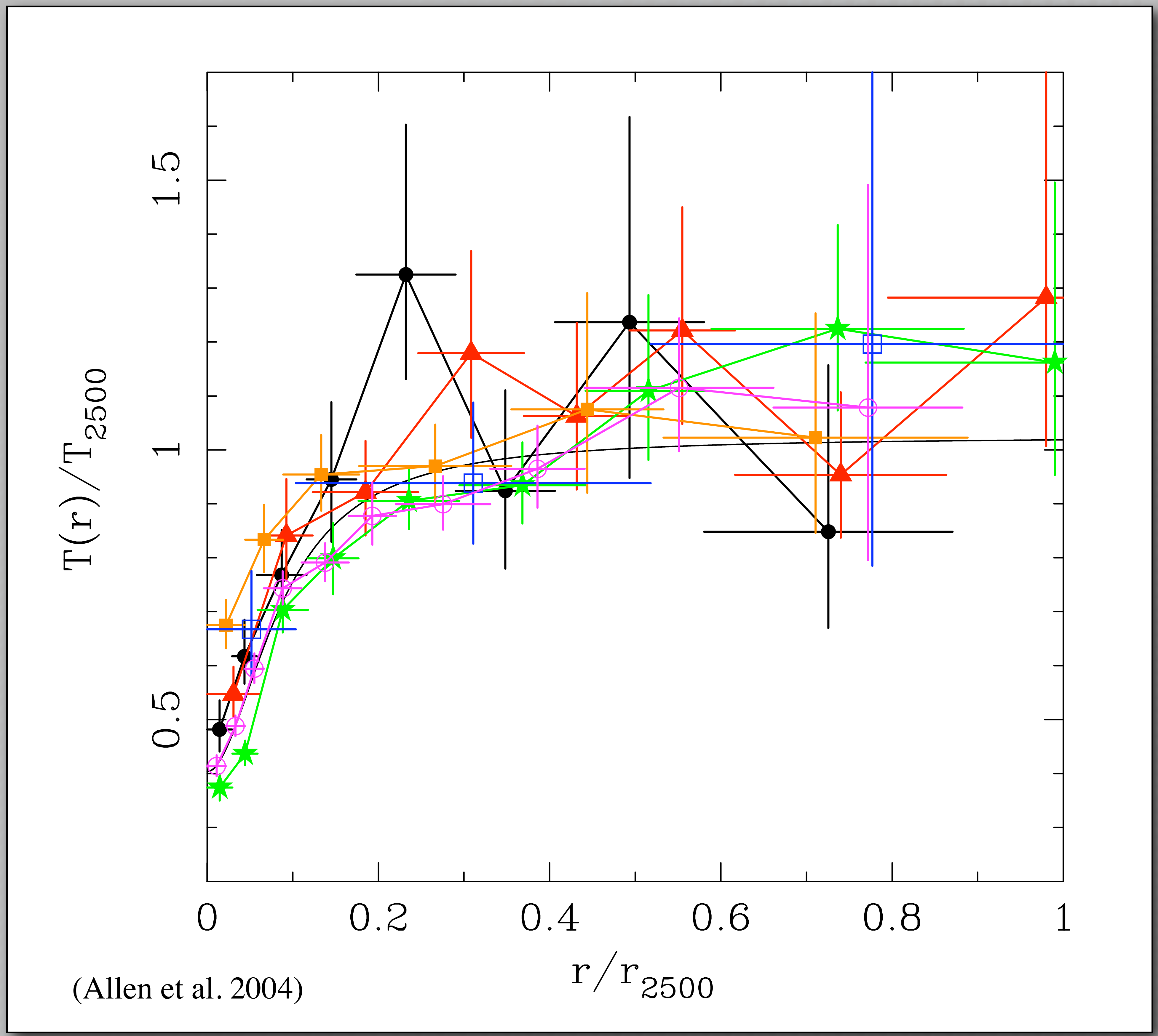
$$L_X \approx \frac{5}{2}\frac{kT}{\mu m_p}\dot{M}_X$$



- Peaked X-ray surface brightness
- Short cooling time ($t_{cool} \sim 10^8$-10^9 yr)
- Observed L_X implies ~10-100's $M_\odot$ yr^{-1}

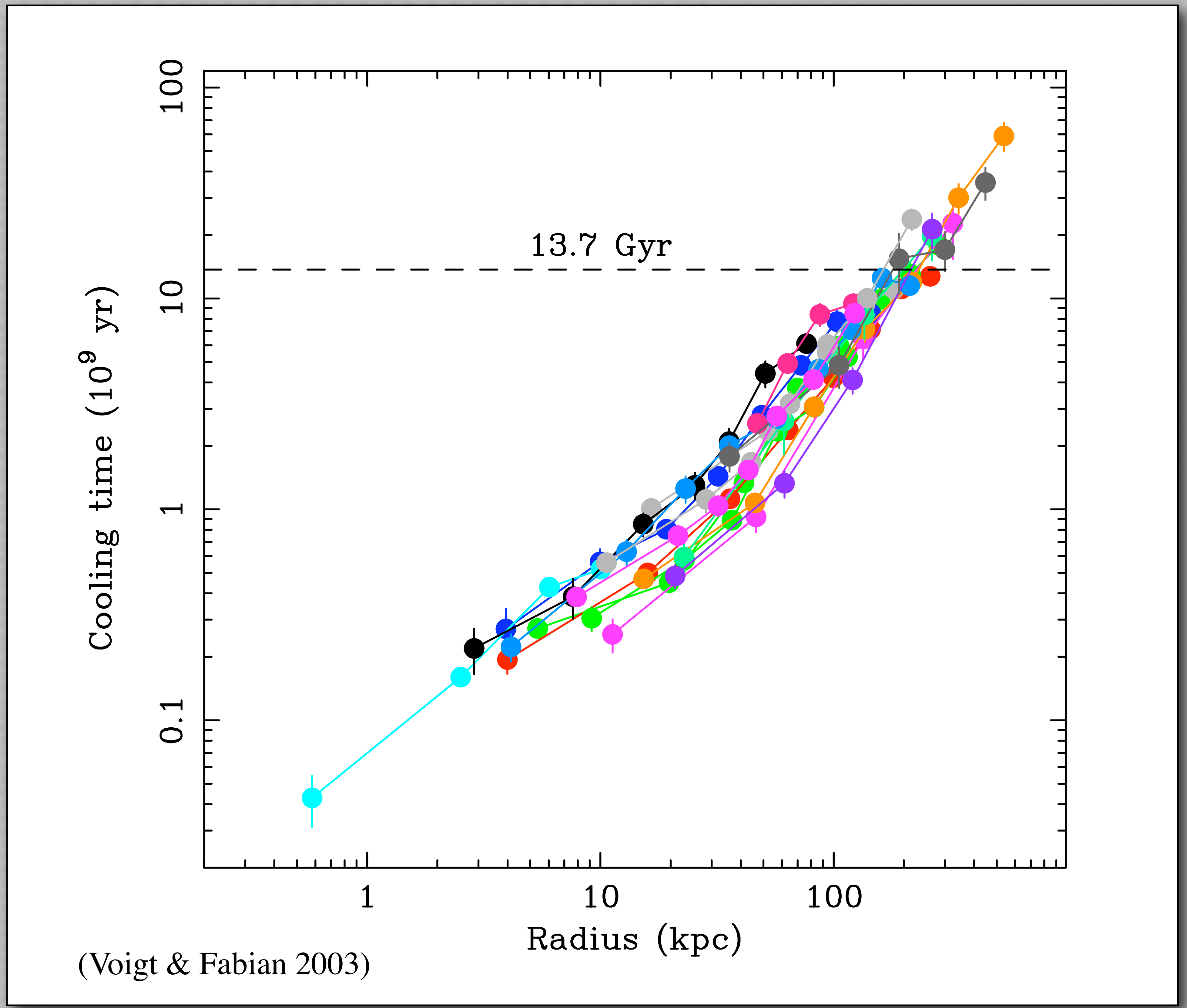
Would produce ~10^{12} $M_\odot$ of cold gas over cluster lifetime

X-ray Evidence for Cool Gas in Cluster Cores



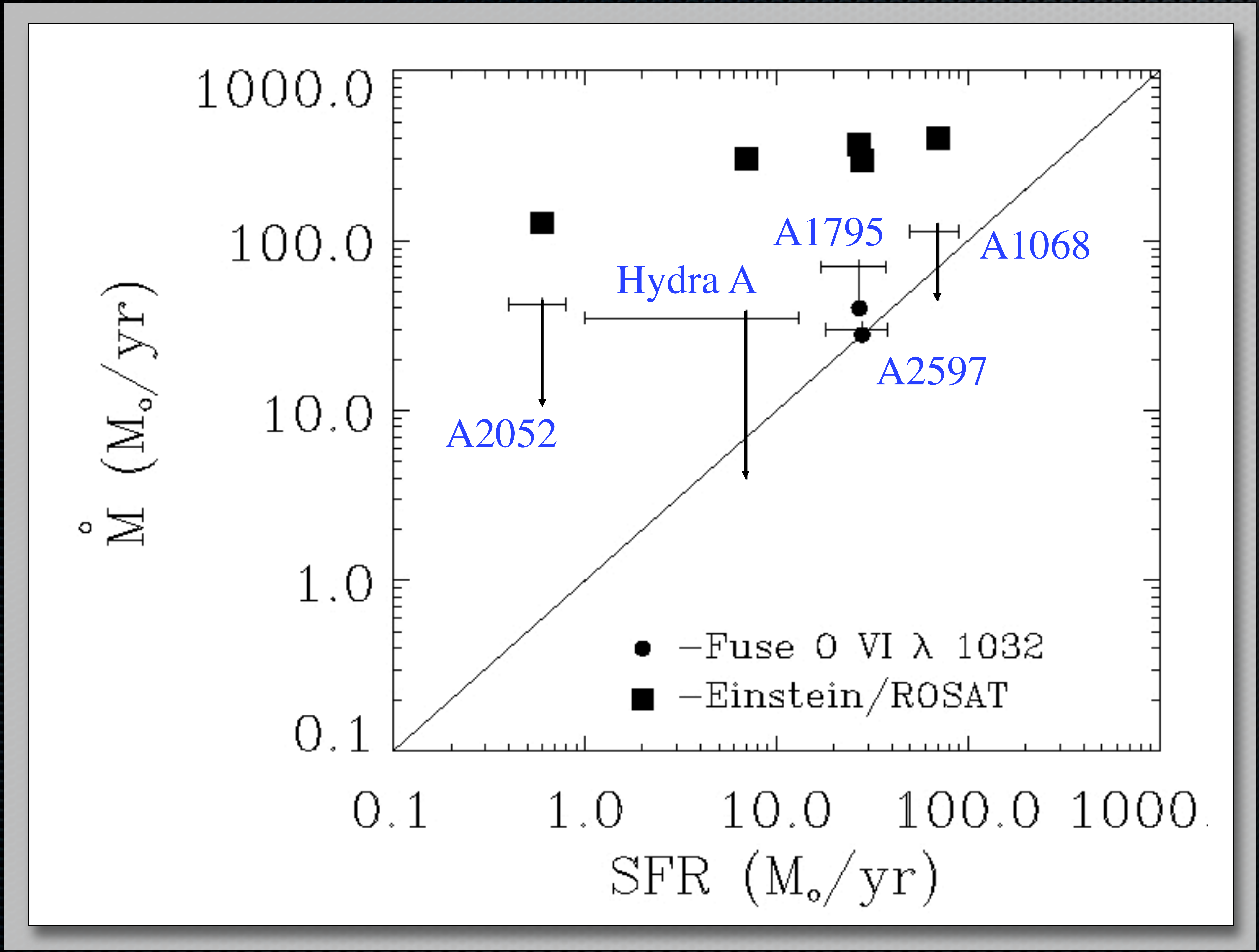
Temperature gradients

Short cooling times



Temperature drops to $T_{min} \sim 0.3\ T_{vir}$ in the core

The Classic Cooling Flow Problem



McNamara et al. (2003)

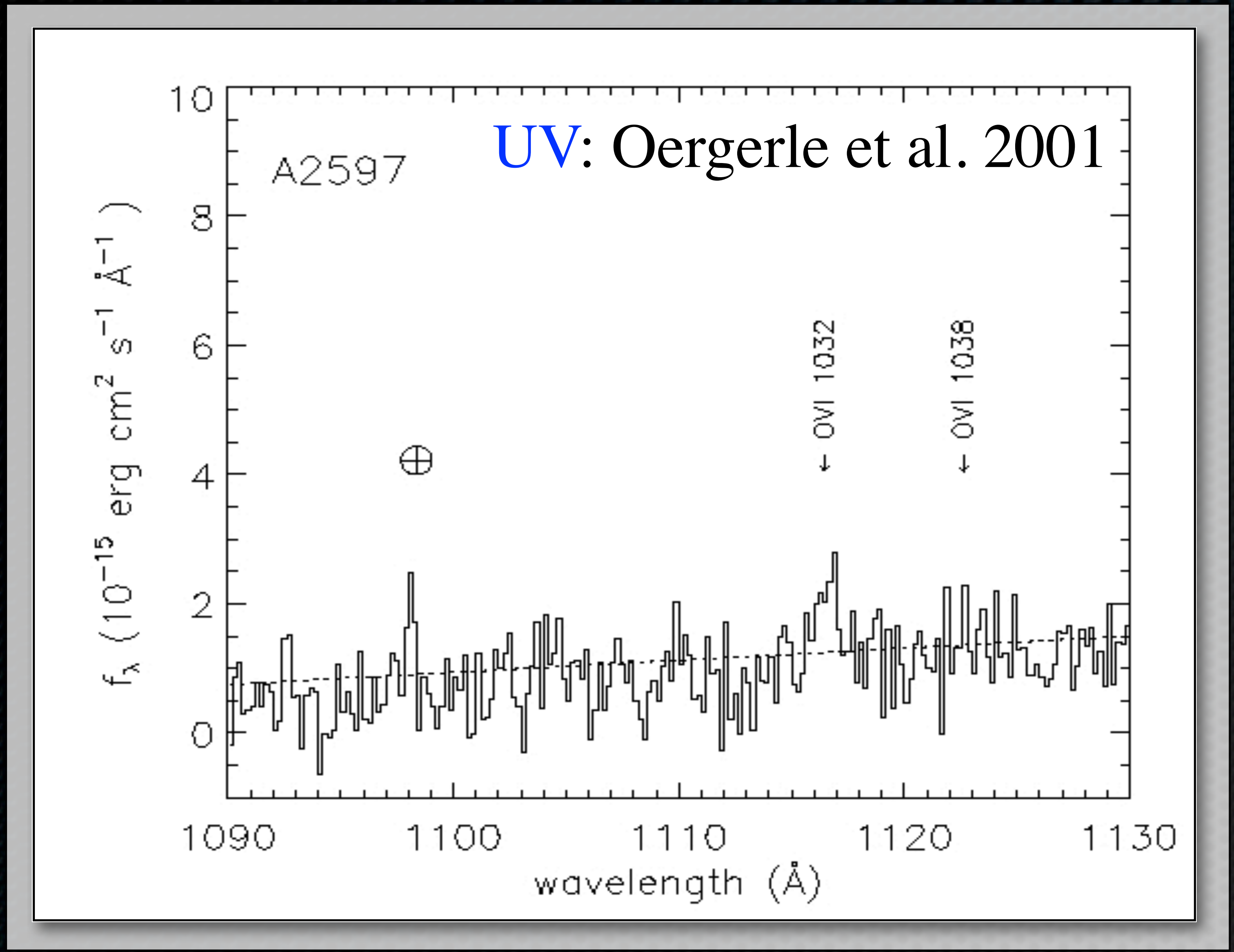
X-ray cooling rates and star formation rates disagree

Could be incorrect cooling rates?

Reservoir of cold gas not forming stars?

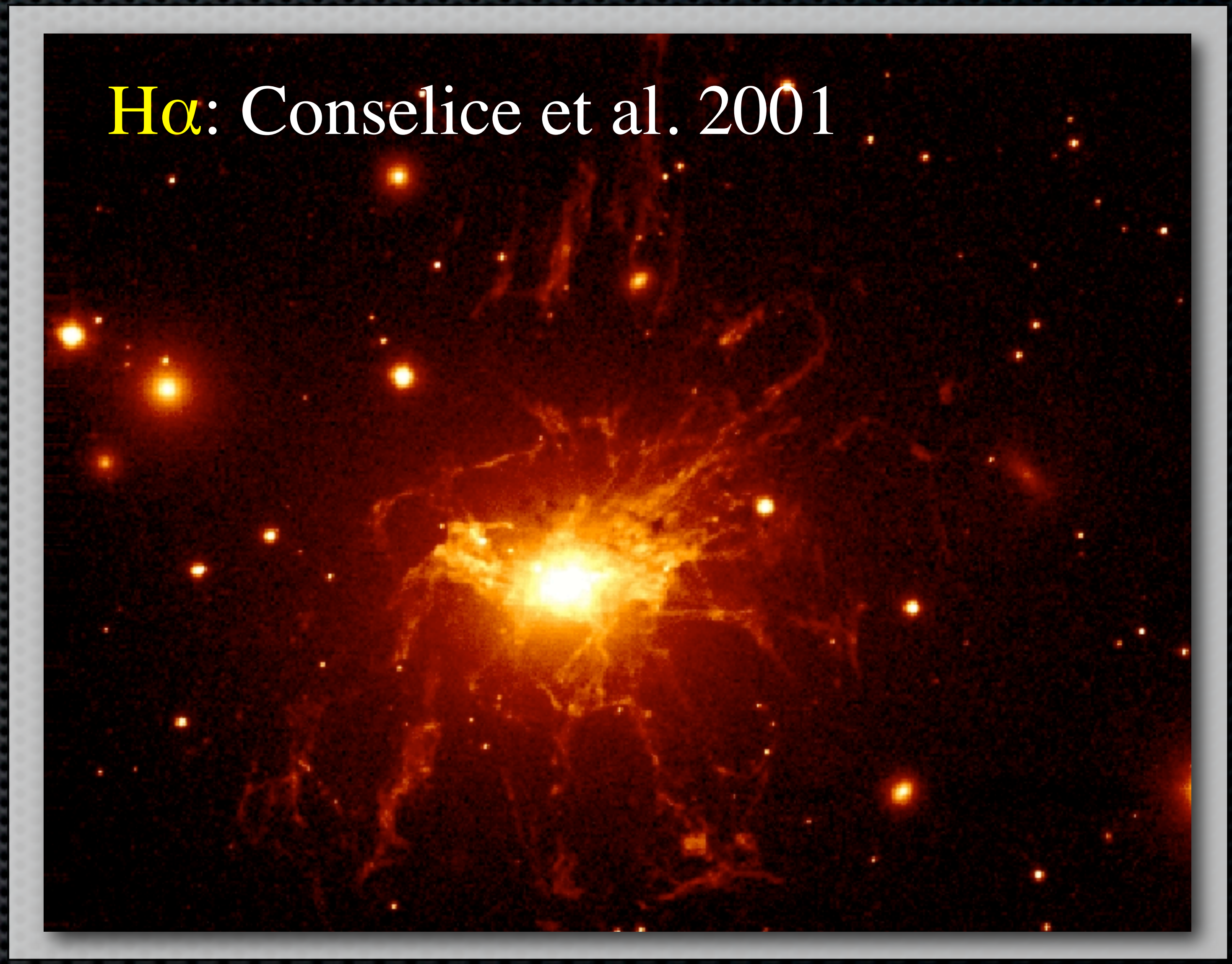
Something is heating the gas?

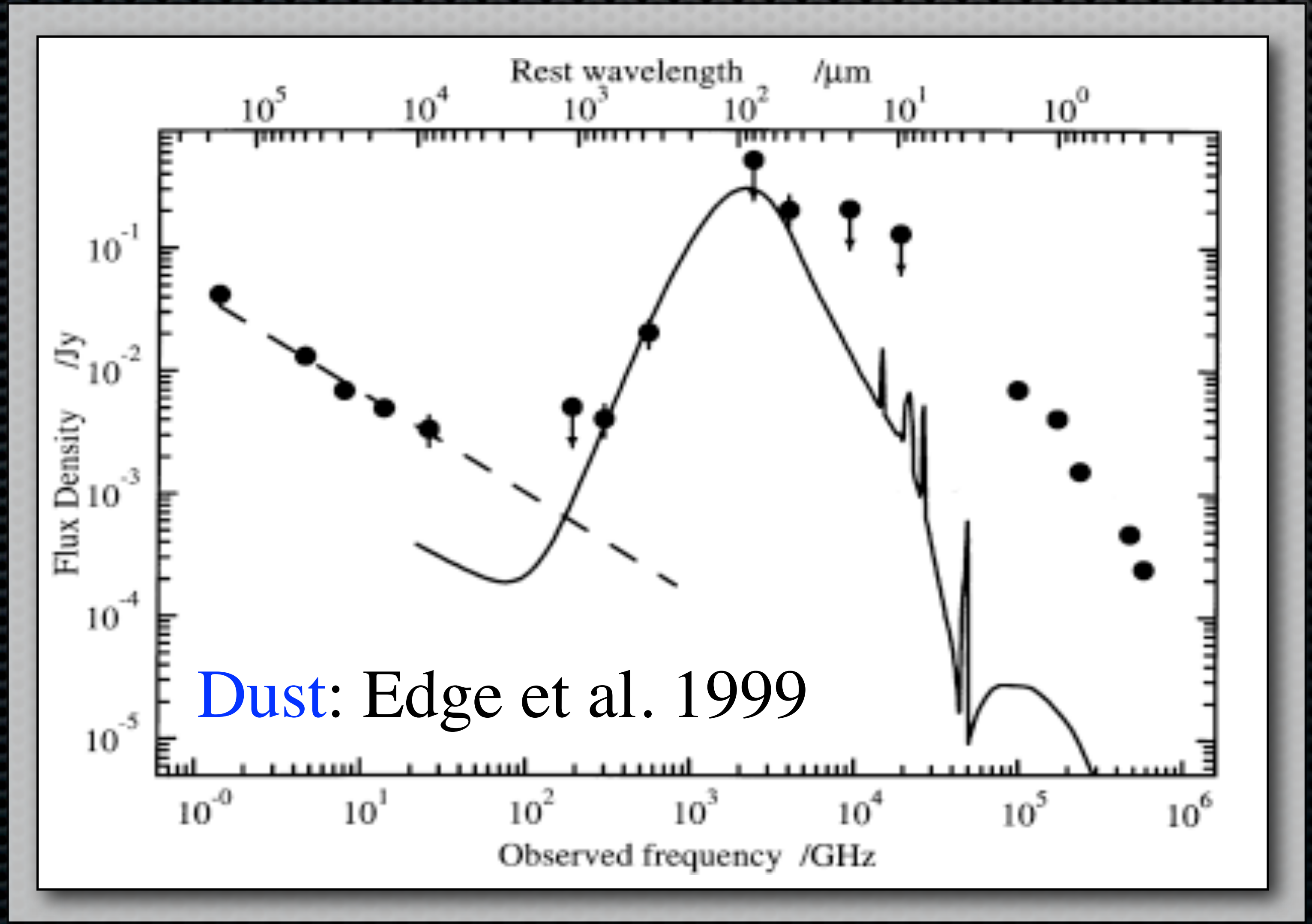
Non-X-ray Evidence for Cool Gas in Clusters

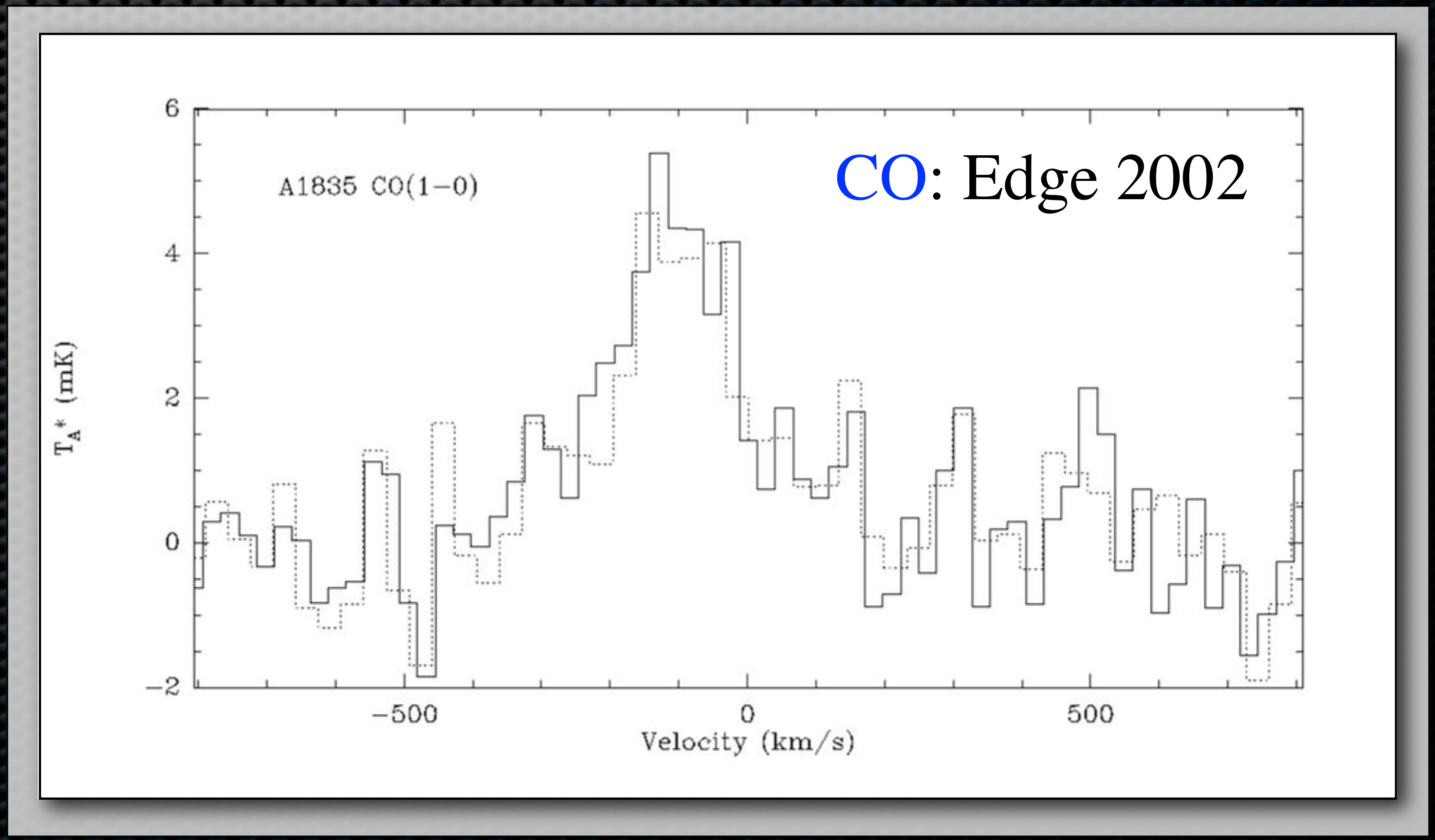


Many searches for cooled gas products

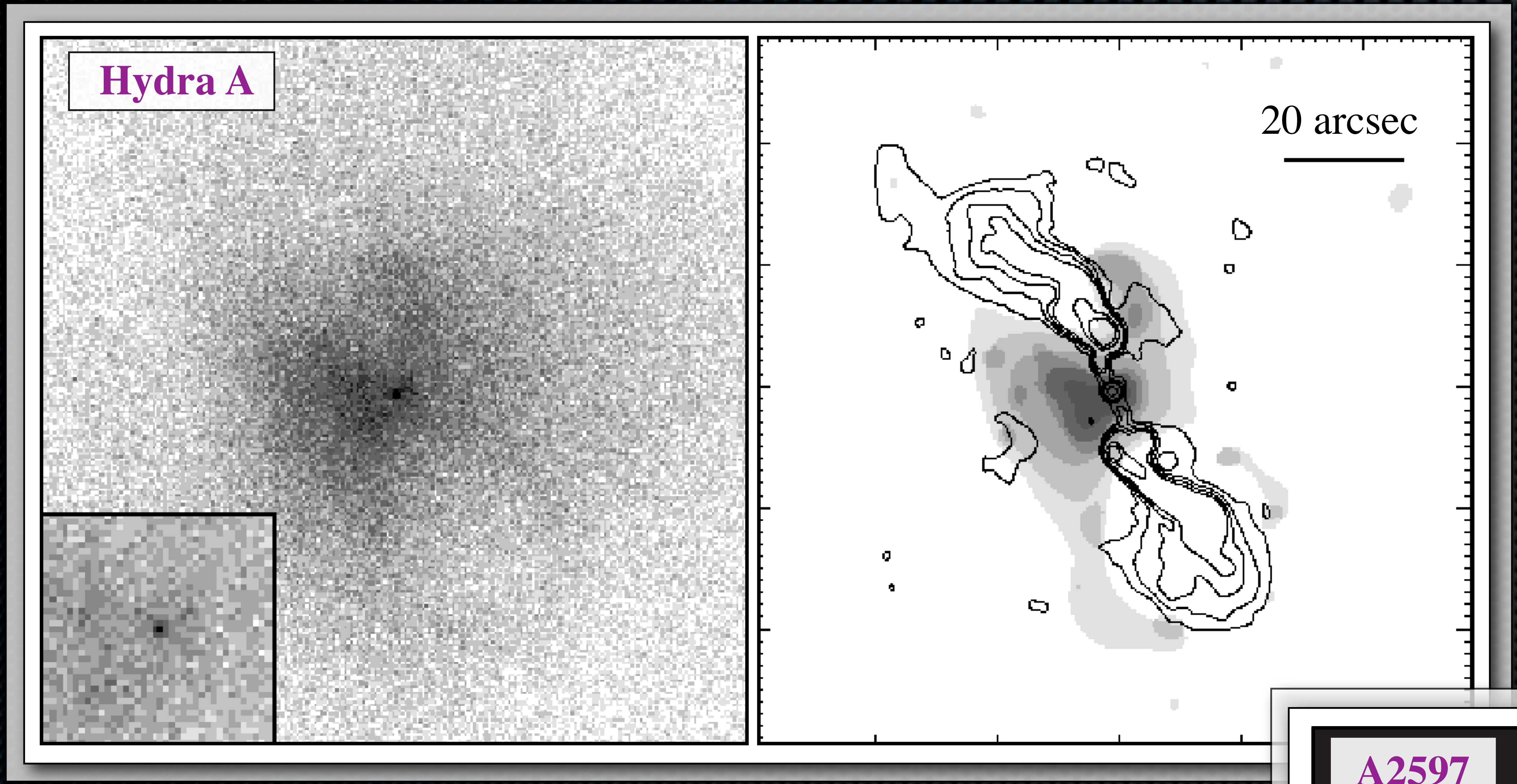
Total mass of cold gas inconsistent with cooling rates







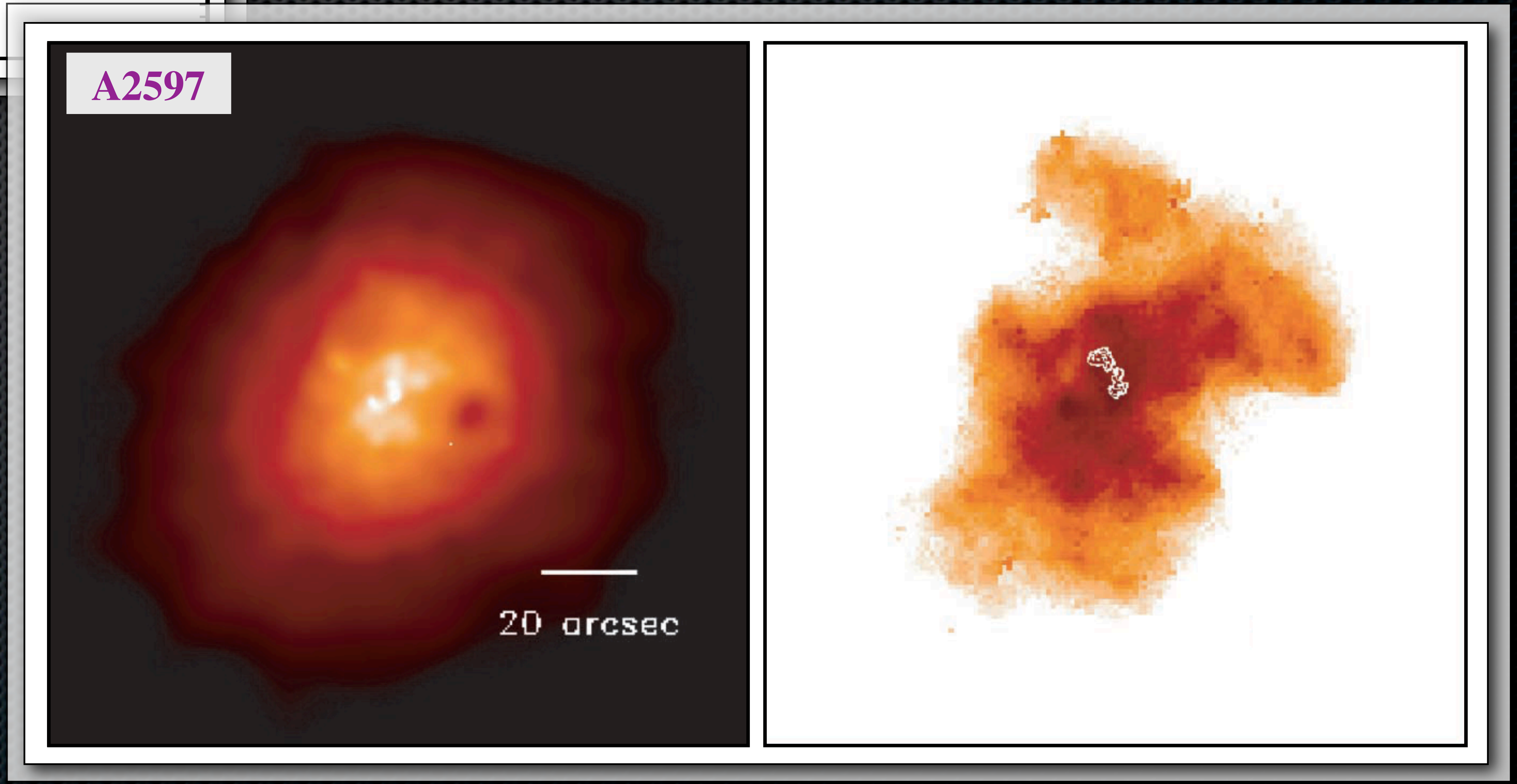
Chandra Detection of X-ray Cavities



Original 40 ksec observation McNamara, Wise, Nulsen et al. (2000)

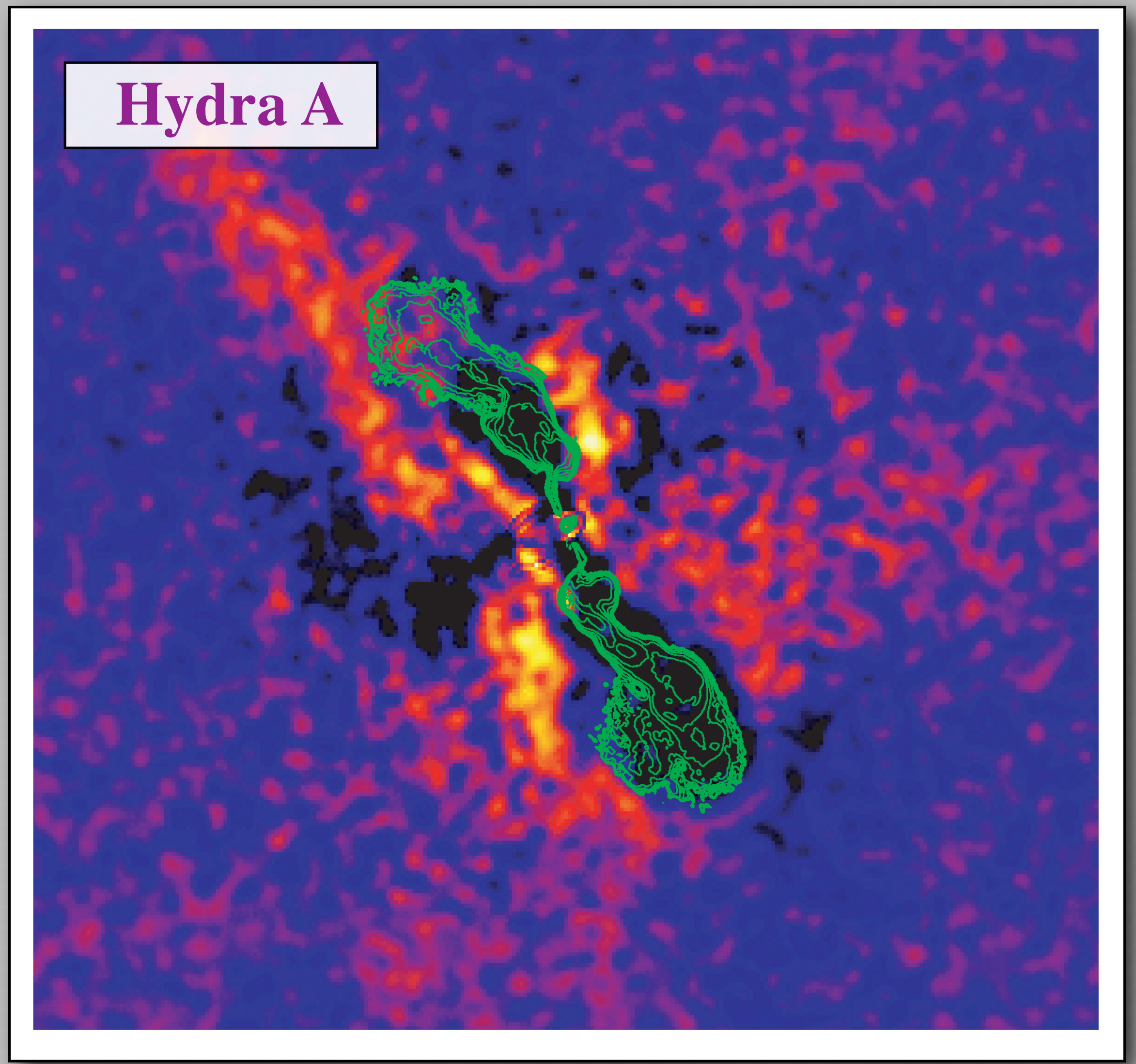
- Discovered immediately after launch
- 20-30 kpc cavity structures seen in X-ray
- Anti-correlated with 1.4 GHz radio emission
- No evidence for shock heating detected
- "Ghost" cavities seen in A2597

Are cluster cavities common?
What is the impact on the gas?
Solution to CF problem?

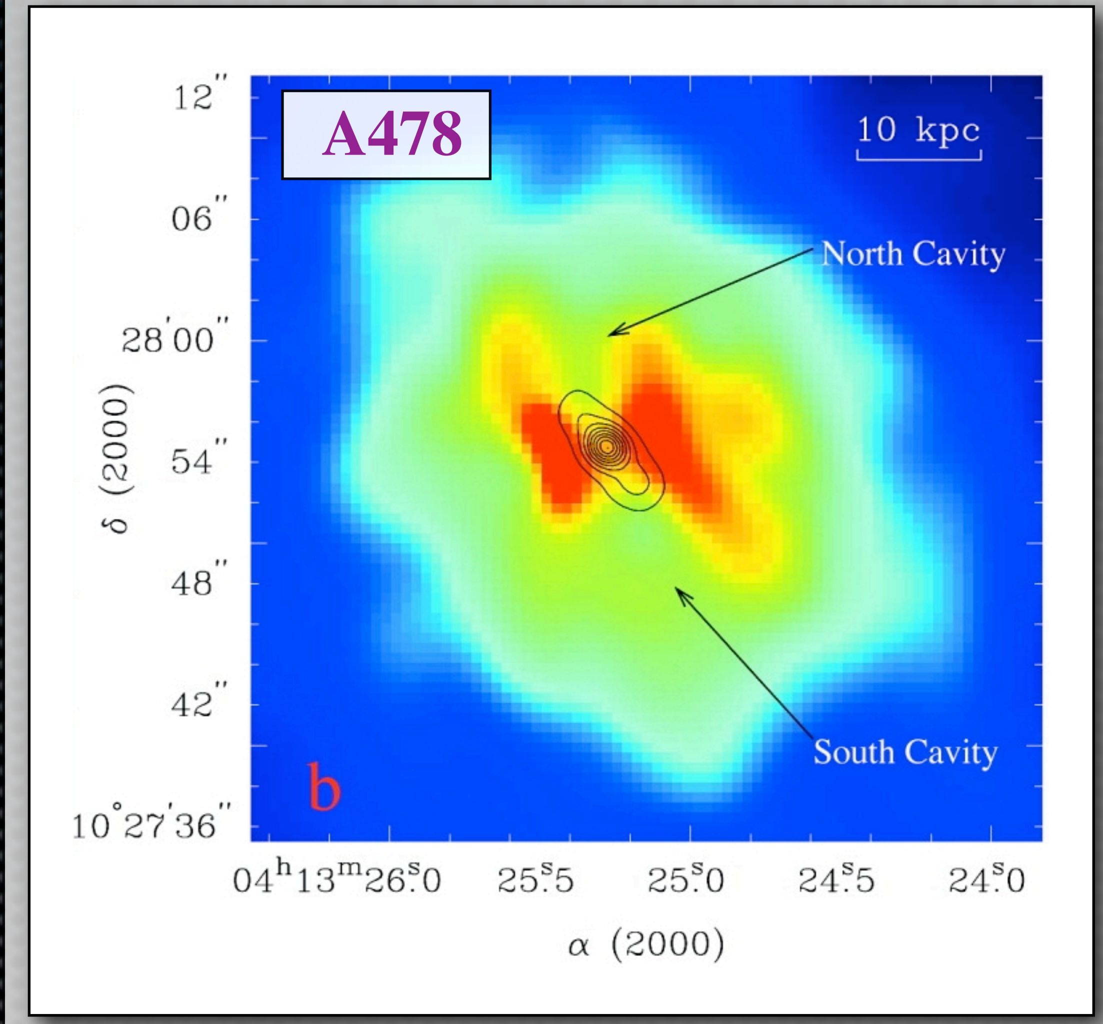


Original 19 ksec observation McNamara, Wise, Nulsen et al. (2001)

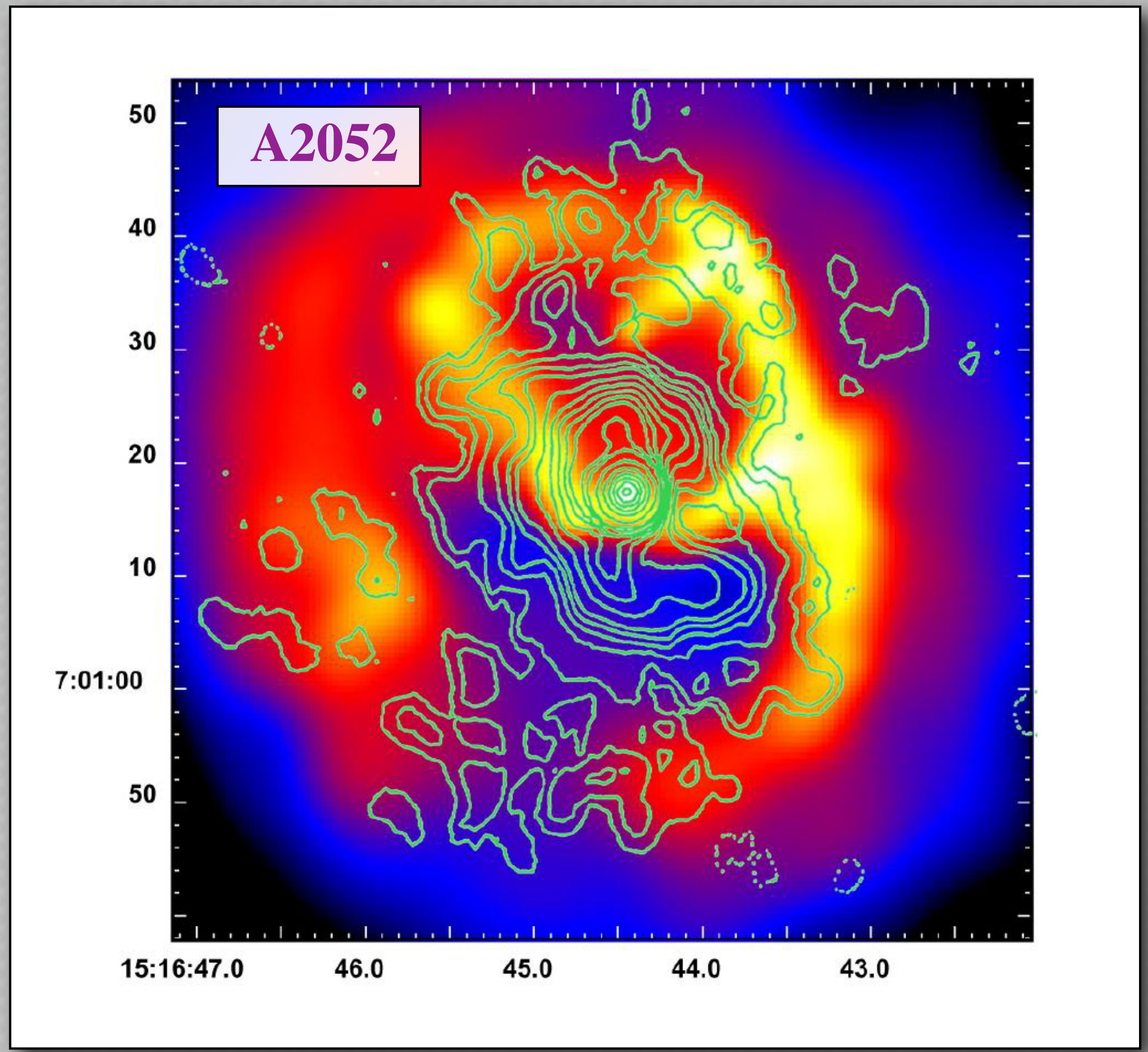
Imprints of AGN heating



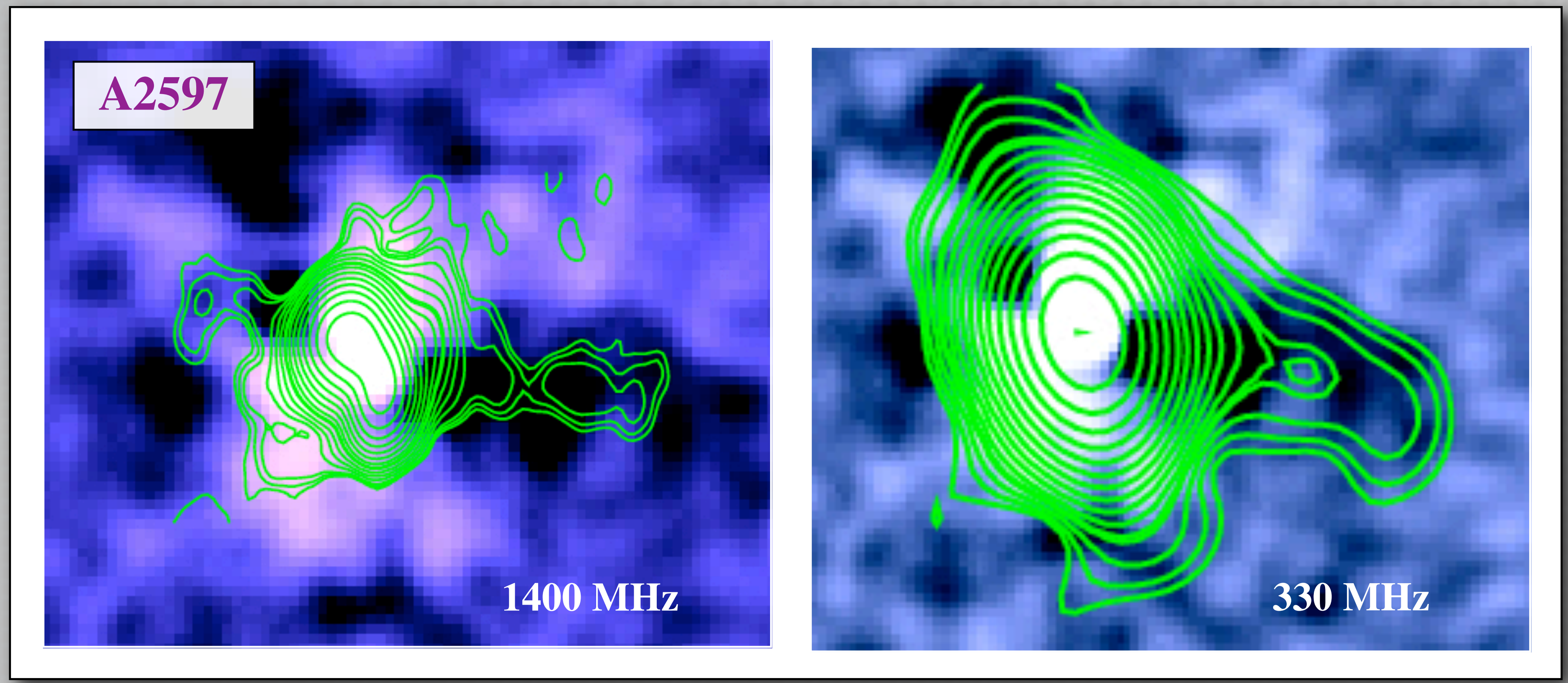
McNamara et al. (2000), Wise et al. (2005)



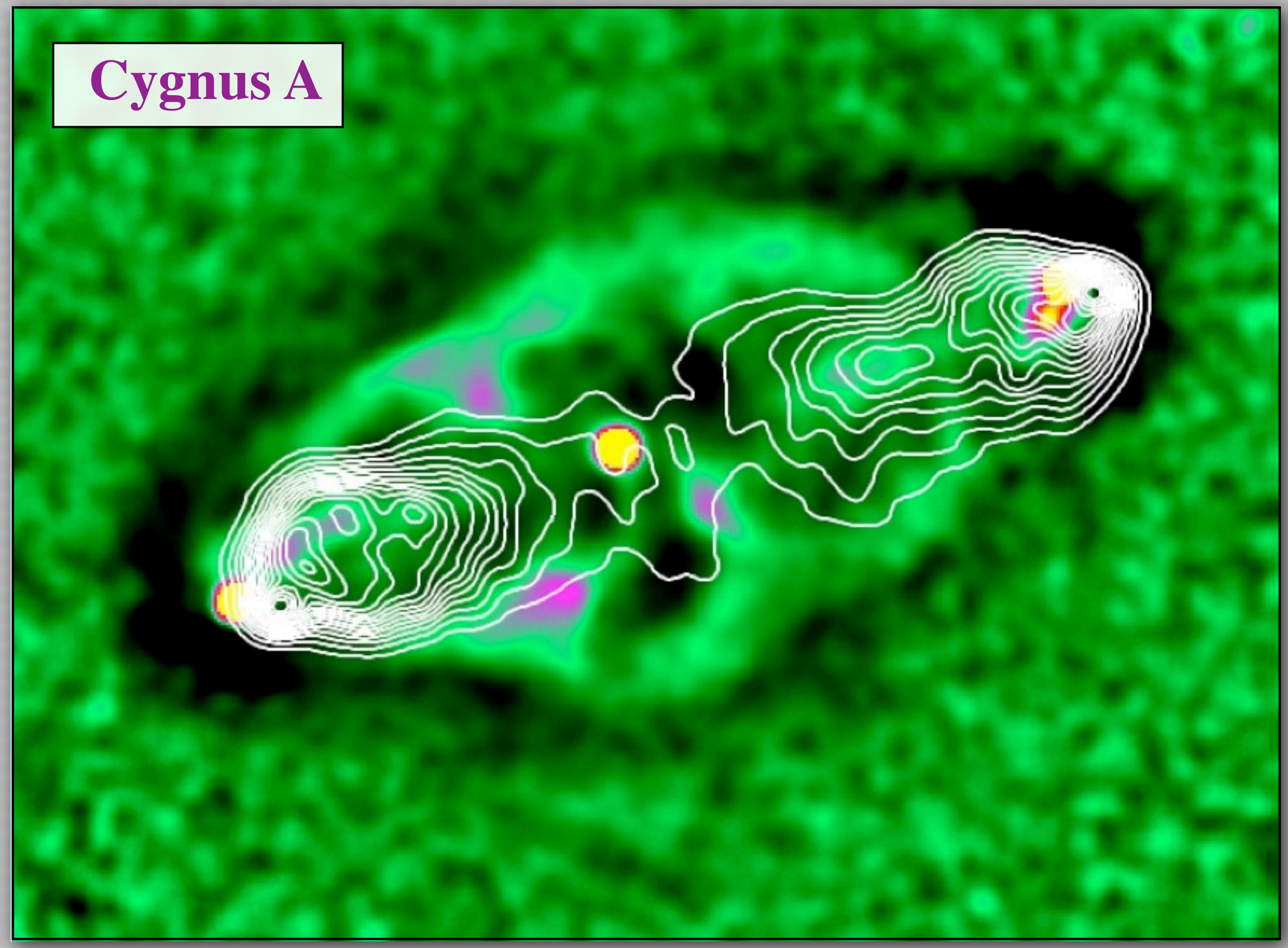
Sun et al. (2003)



Blanton et al. (2001)

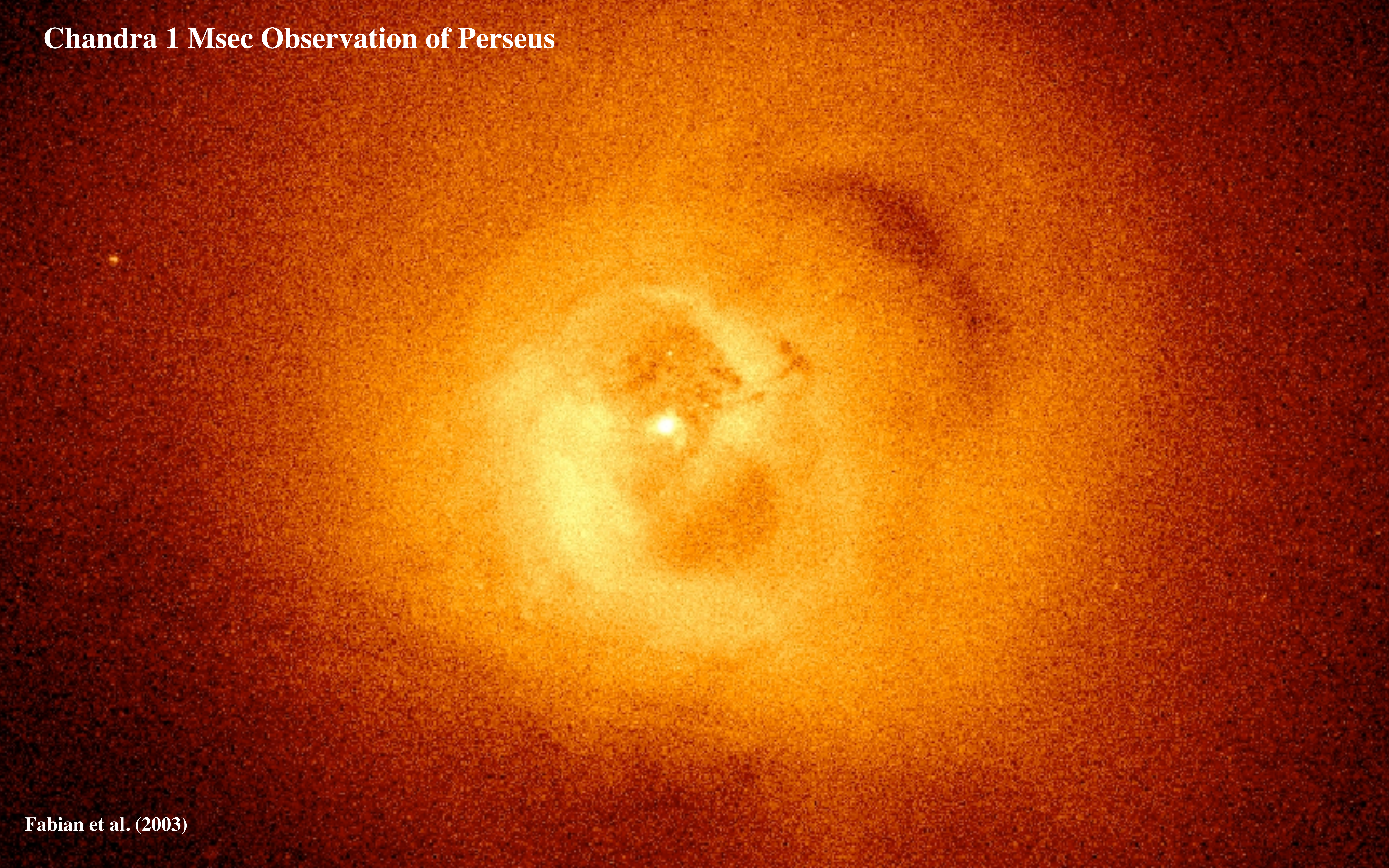


Clarke et al. (2007)



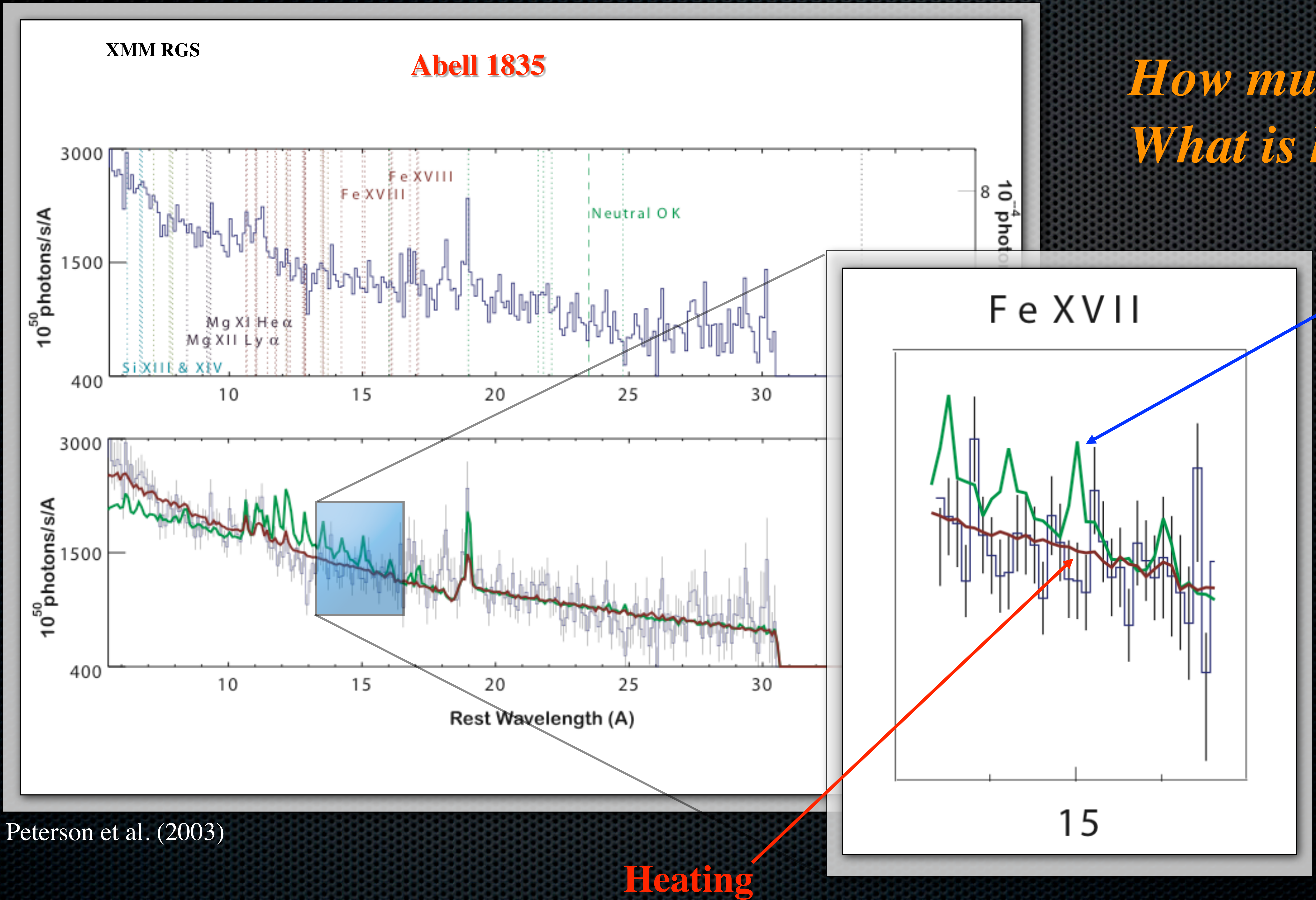
McKean et al. (2011)

Chandra 1 Msec Observation of Perseus



Fabian et al. (2003)

Evidence for Heating in Cluster Cores

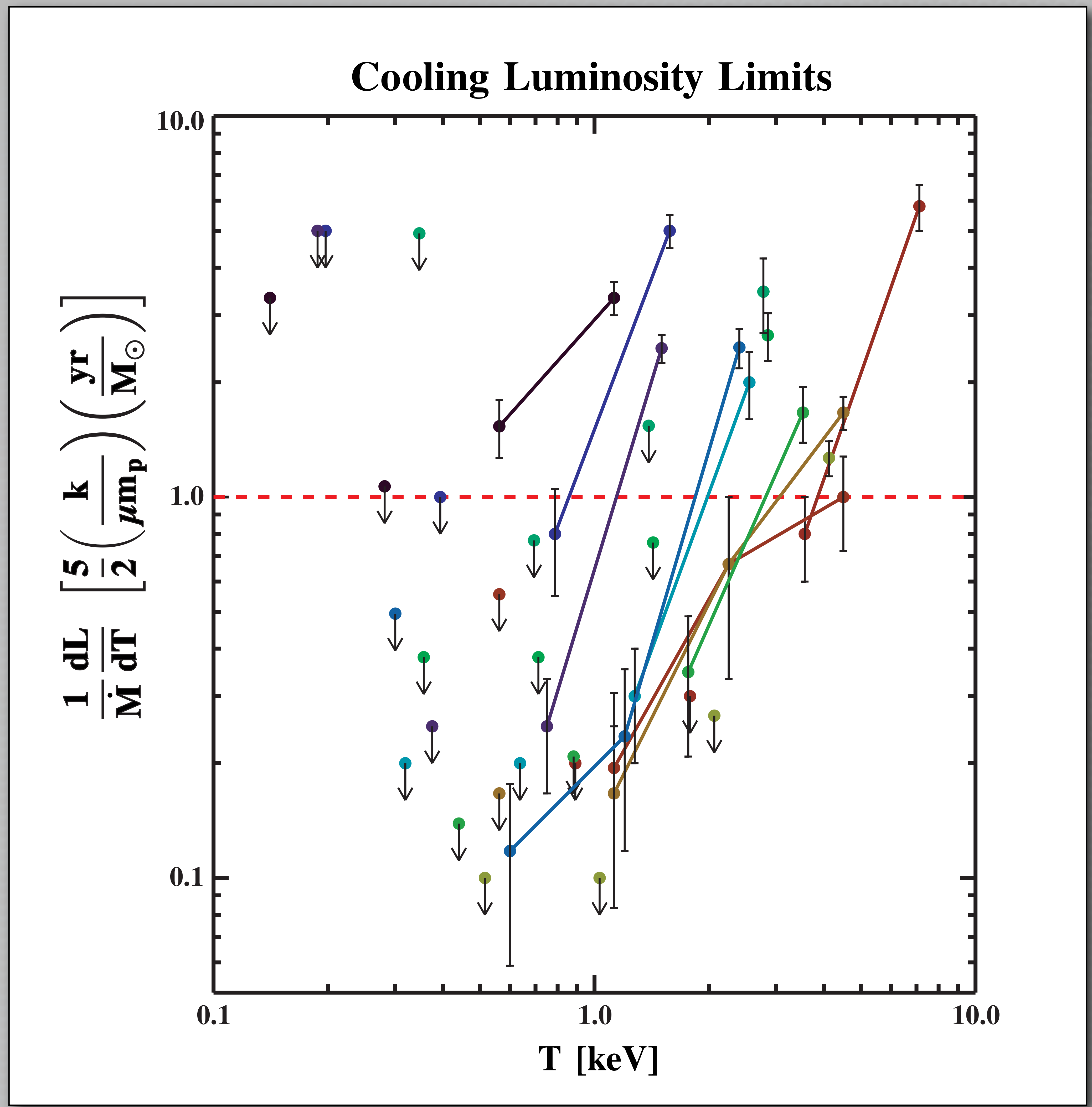


Peterson et al. (2003)

How much gas cools out?
What is heating the gas?

- Canonical CF problem
- Peaked X-ray profiles
- $t_{cool} \sim 10^8$-10^9 yr
- $L_X \sim 10$—100's $M_\odot$ yr^{-1}
- Deficit of soft X-ray lines

Spectral Signatures of Heating



Sample of 14 clusters observed with XMM RGS (Peterson et al. 2003)

Pure isobaric cooling:

$$\frac{dL}{dT} = \frac{5}{2}\frac{k}{\mu m_p}\dot{M}$$

$$T_{min} \sim 0.3\ T_{vir}$$

Including heating:

$$\frac{dL}{dT} = \frac{5}{2}\frac{k}{\mu m_p}\dot{M}(\alpha+1)\left(\frac{T}{T_0}\right)^{\alpha}$$

$\alpha \approx 1\text{-}2$

$\alpha \propto \Delta L_{heat}$

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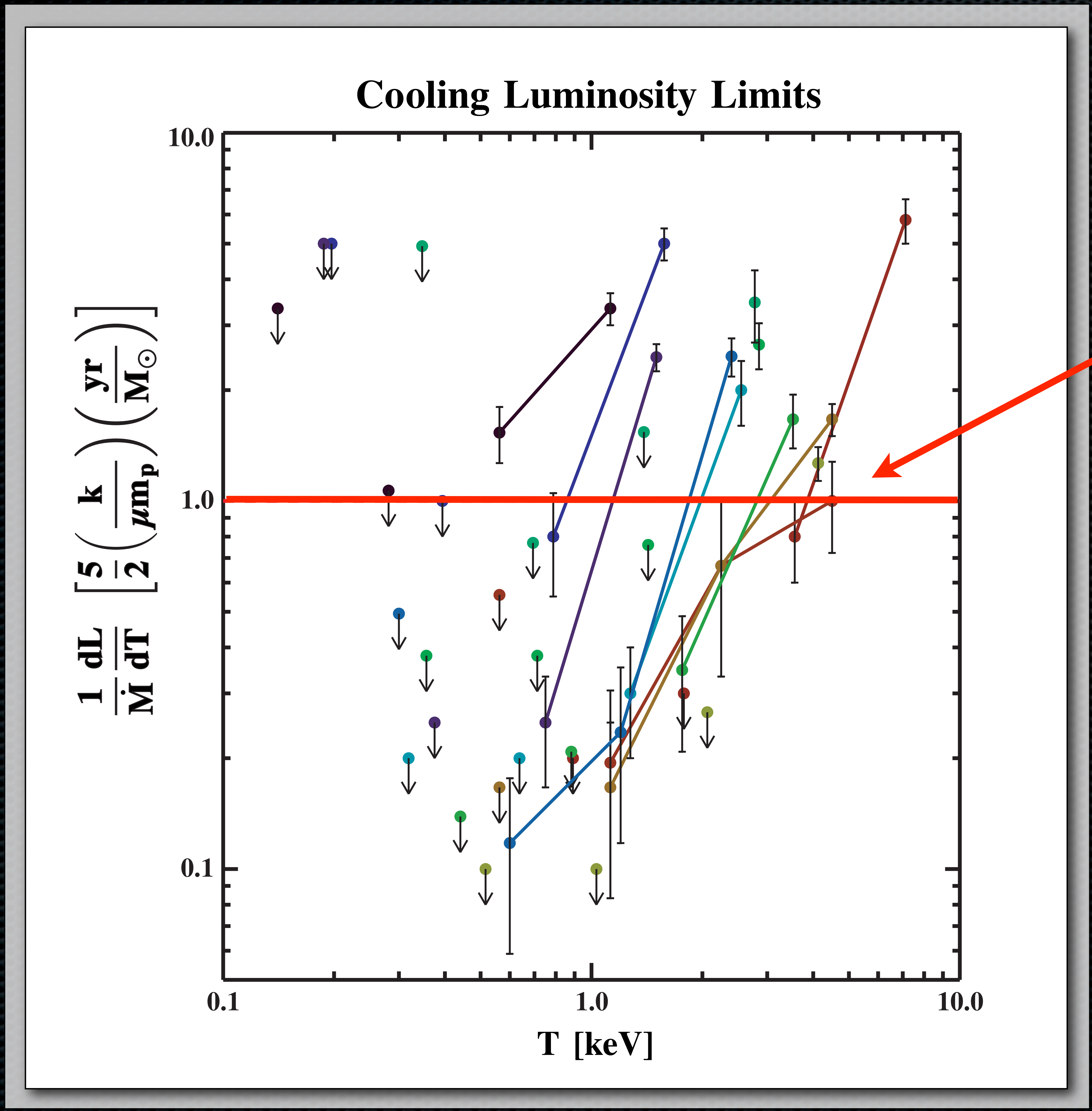

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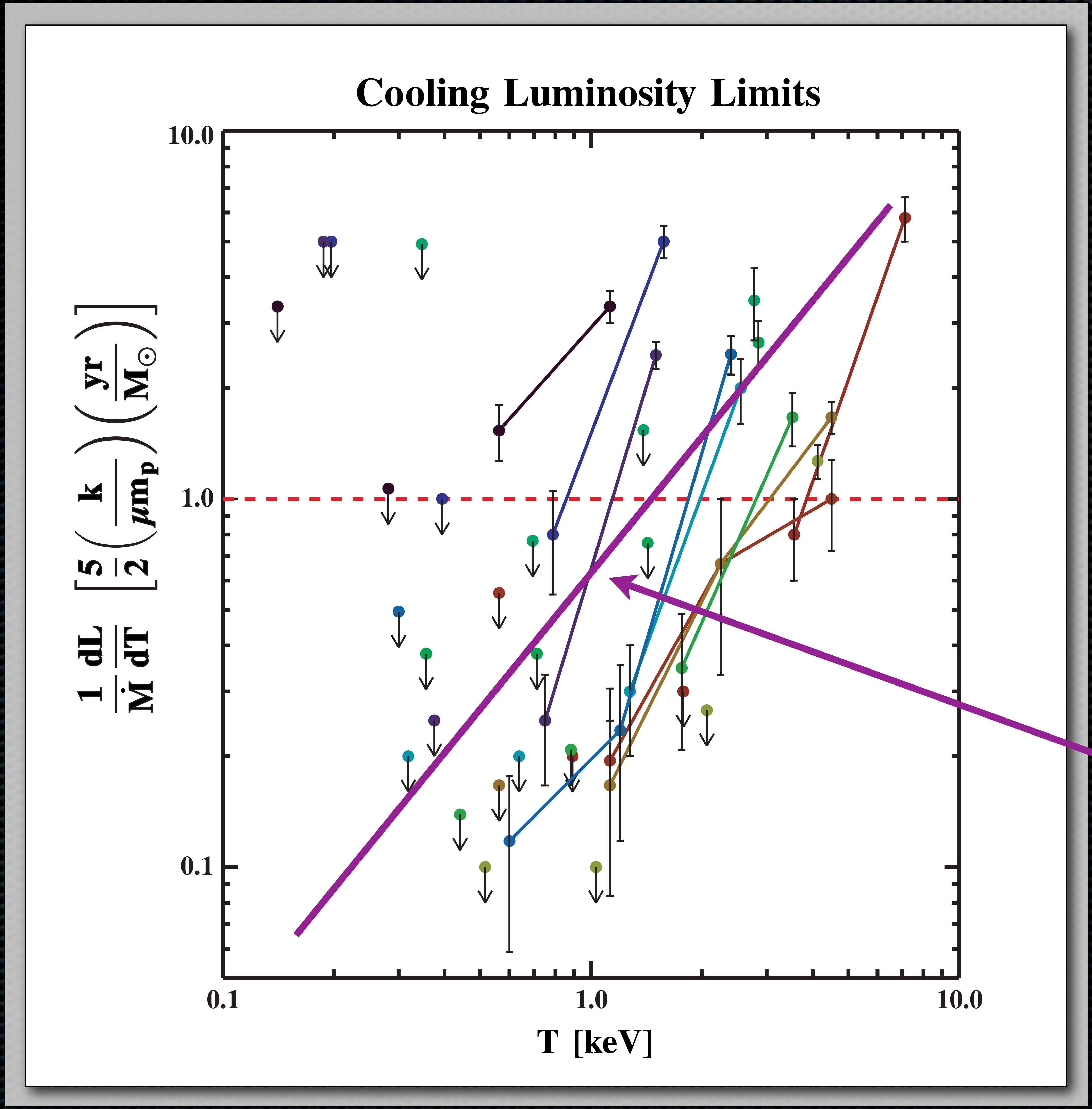

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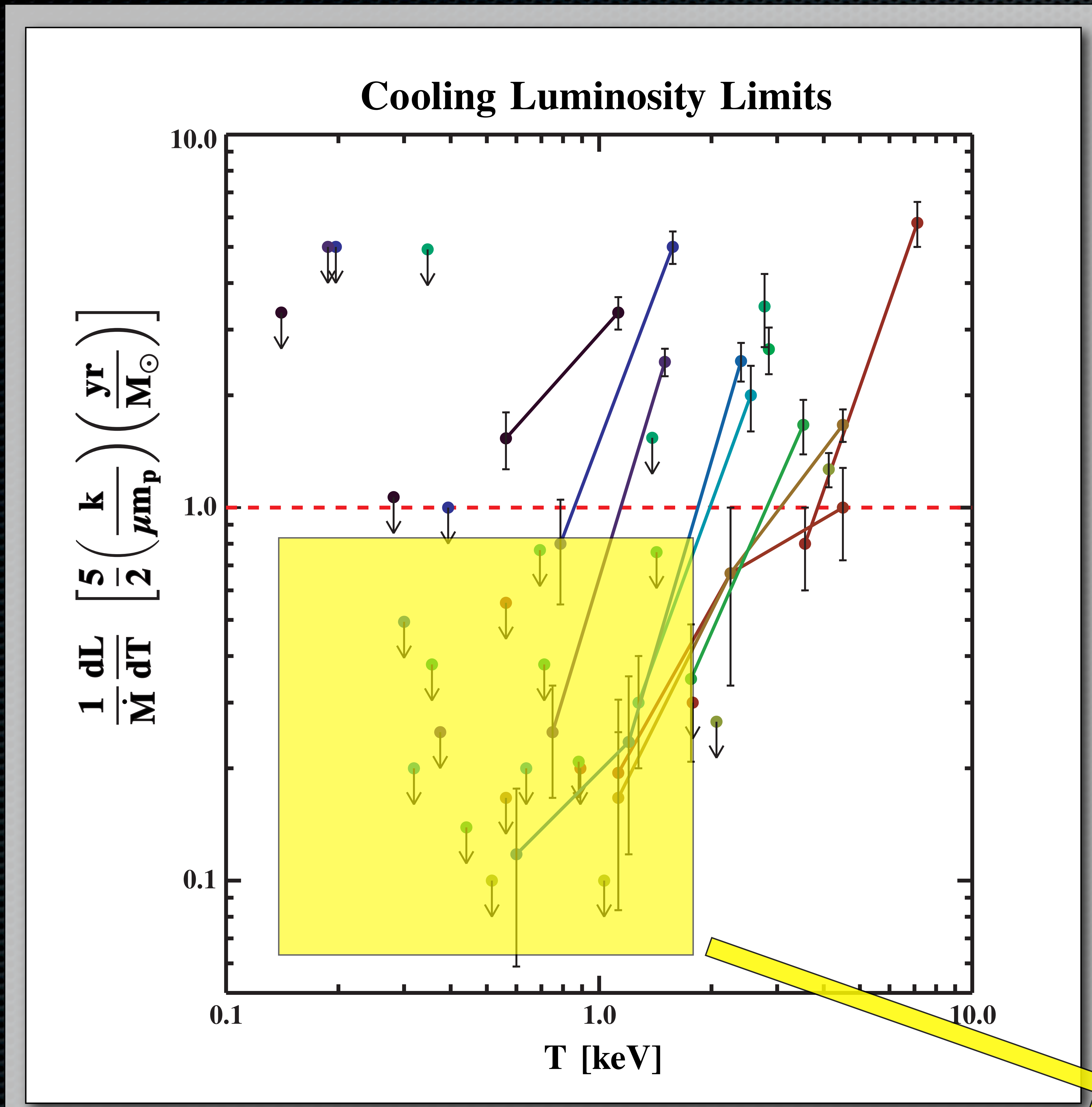

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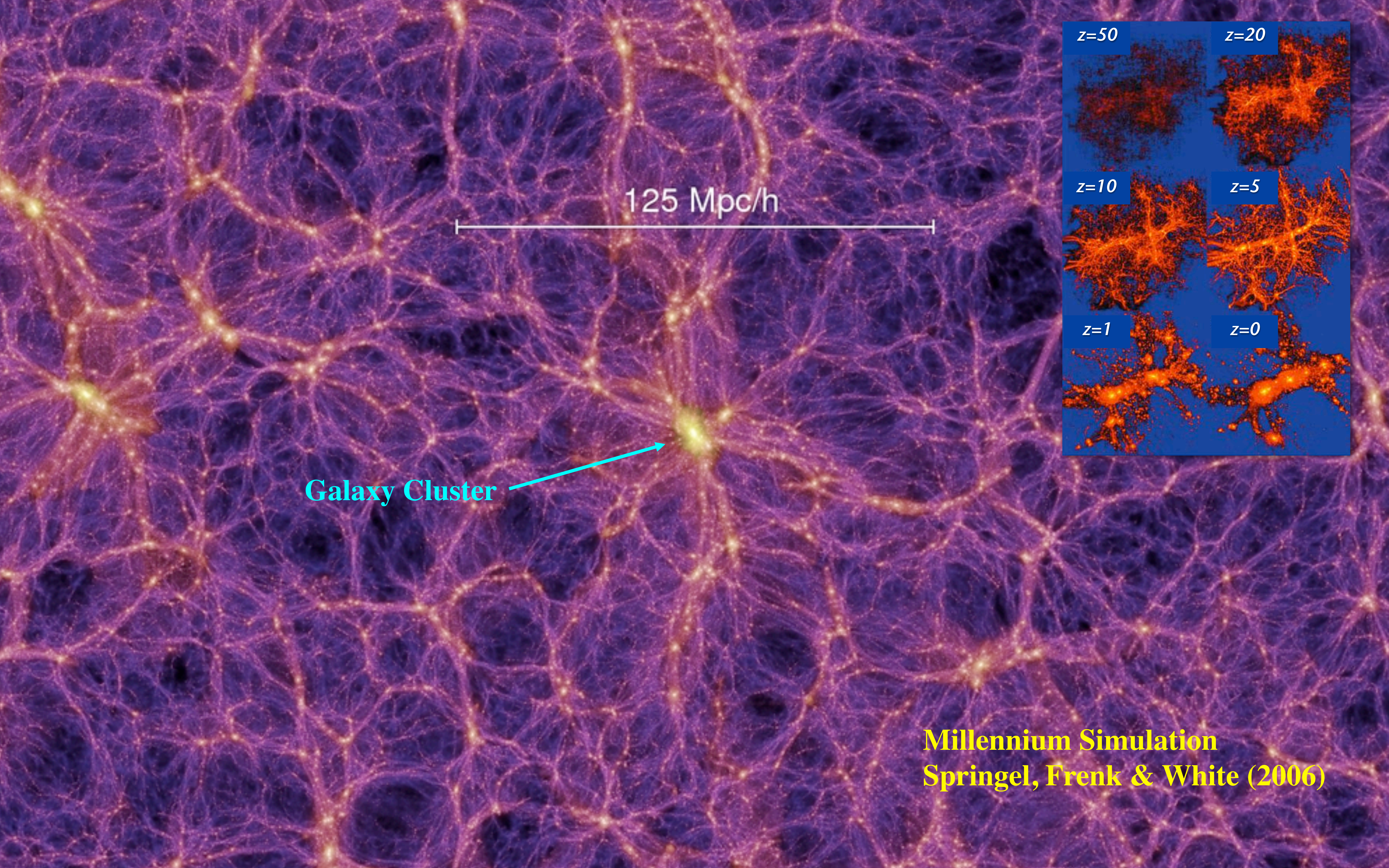
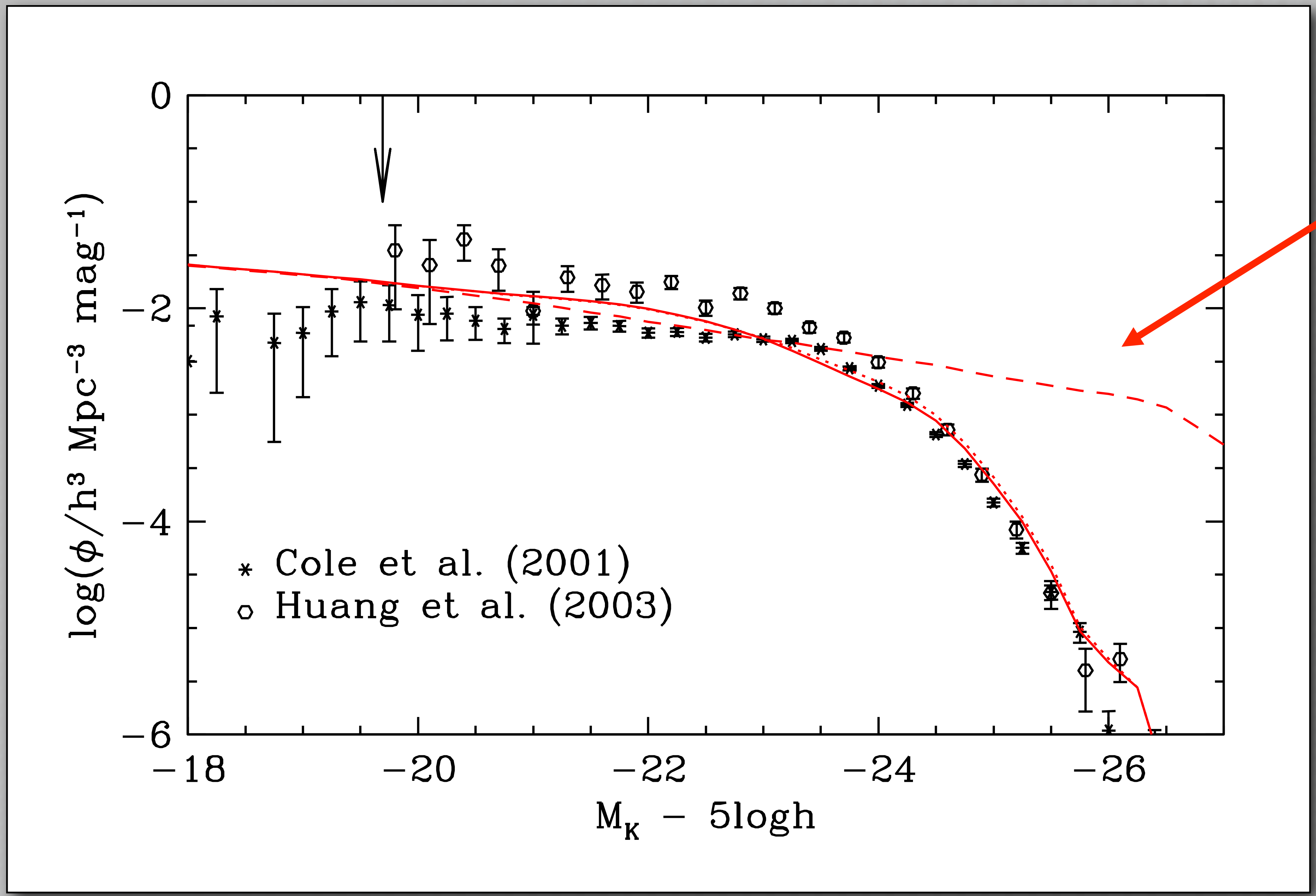
$\alpha \approx 1\text{-}2$

$\alpha \propto \Delta L_{heat}$

Something is either heating the gas or absorbing the emission at low T

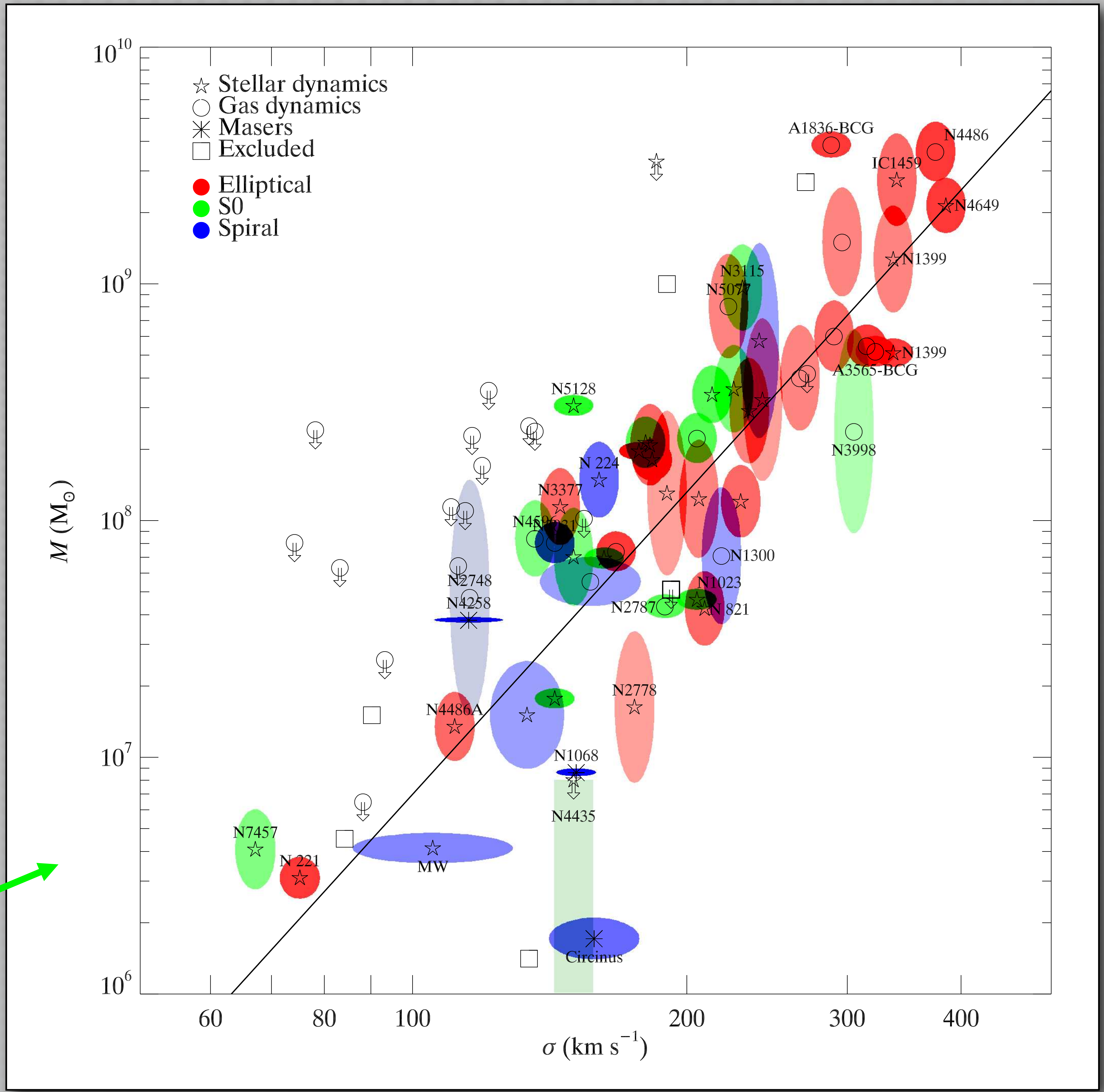

125 Mpc/h
z=50
z=20
z=10
z=5
z=1
z=0
Galaxy Cluster
Millennium Simulation
Springel, Frenk & White (2006)

Fossil Evidence for AGN Feedback



Bower et al. (2006)

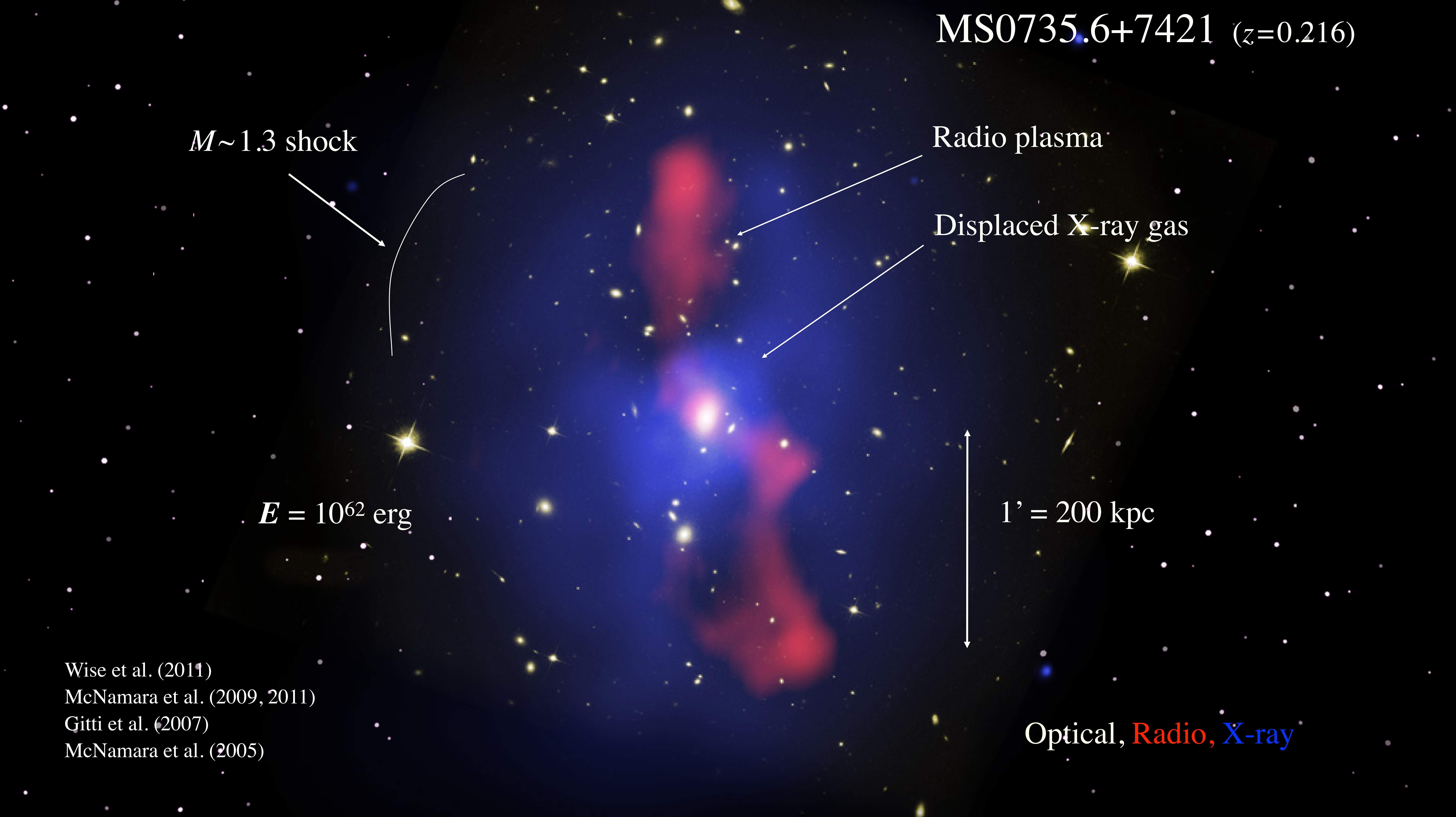
Over-predict high-mass systems
Missing physics, suppressed cooling



Gültekin et al. (2009)

Connection between BH growth and Bulge assembly

Cluster-scale AGN Outbursts



Wise et al. (2011)
McNamara et al. (2009, 2011)
Gitti et al. (2007)
McNamara et al. (2005)

Cavity and Shock Energetics

Cavity Energetics

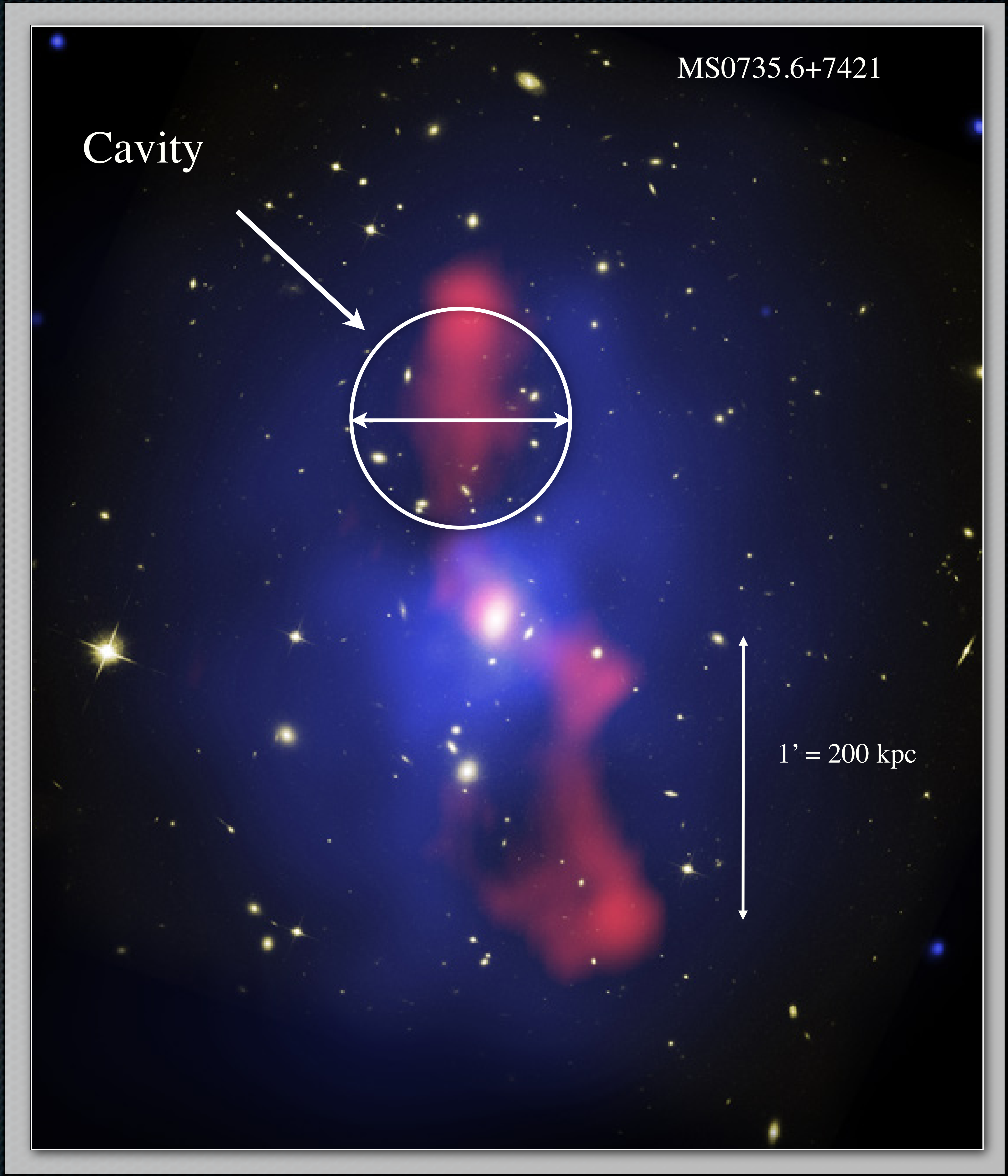
- Measure cavity volumes and surrounding pressures
- Limited by ability to resolve cavity boundaries
- Estimate of the work done to inflate cavities (pV)
- Assumes pressure balance with surrounding gas
- Total free energy given by:

$$E = \frac{\gamma}{\gamma - 1} pV = 2.5 - 4pV$$

- Cavity power:

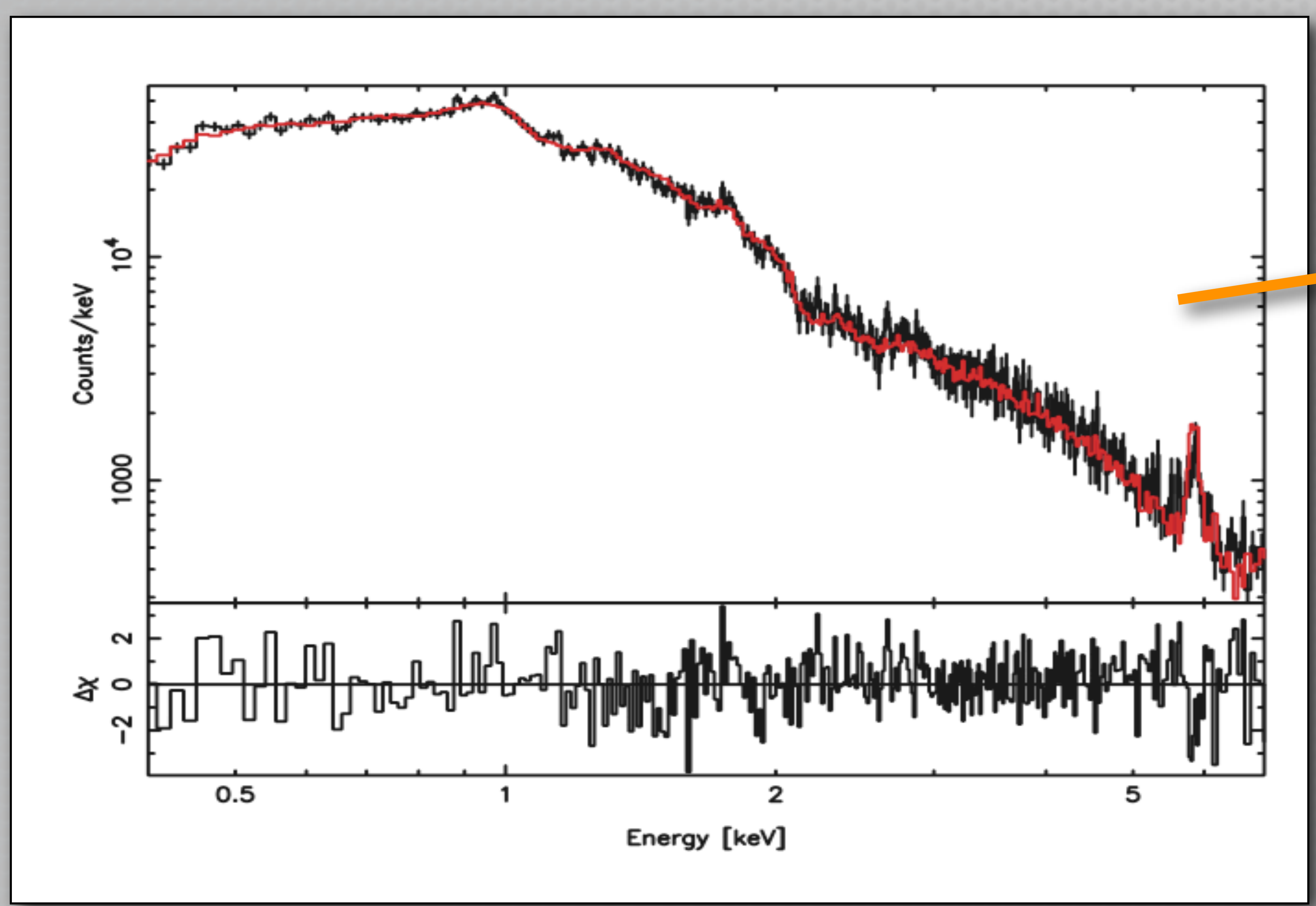
$$P_{cav} = \frac{4pV}{< t >}$$

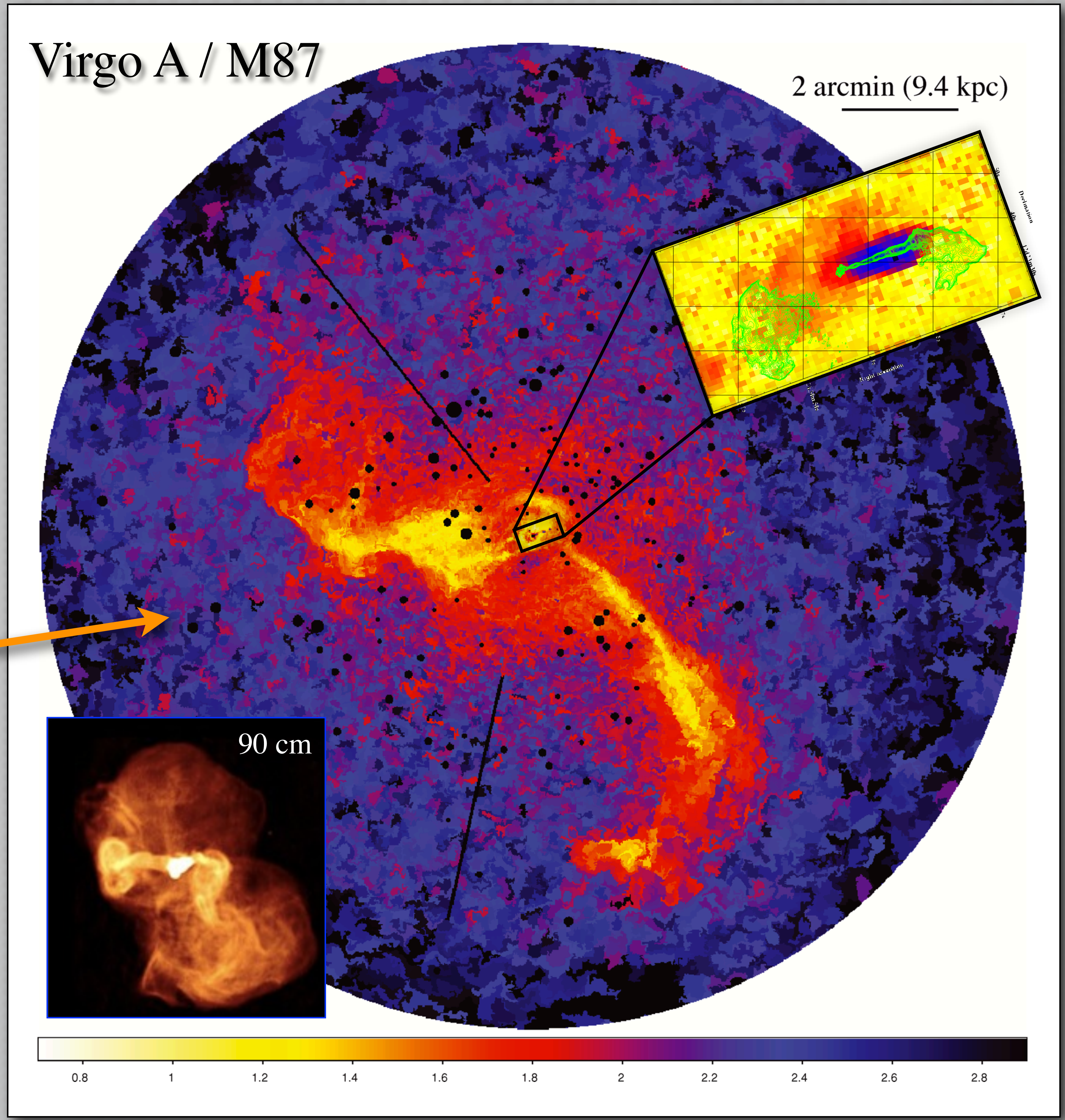
➡ ***Uncertainties due to geometry and gas equation of state***



High Resolution Spectral Mapping

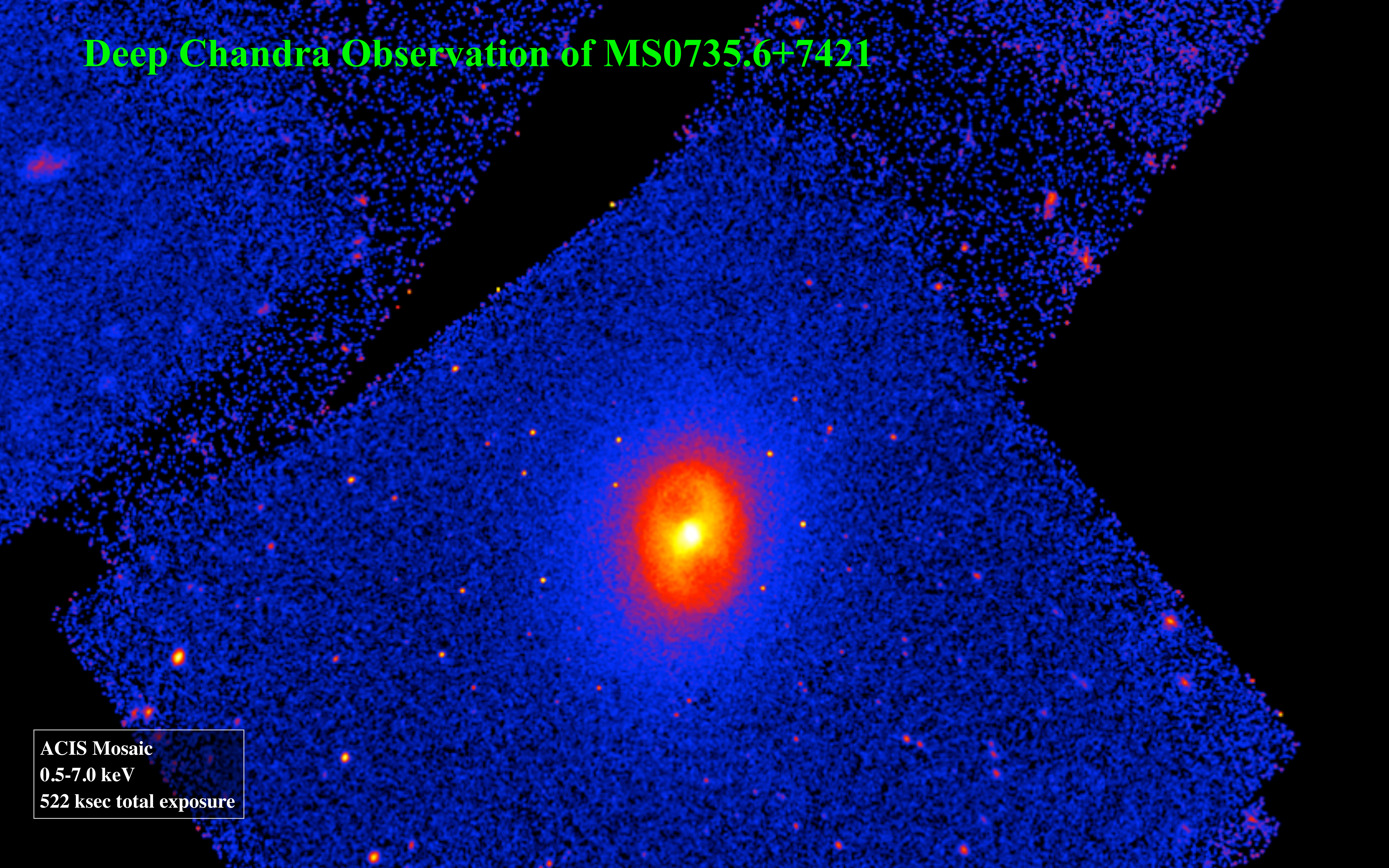
- Map is just many spectral fits (~10^3-10^4)
- Define grid of boxes containing given S/N
- Extract spectrum and calculate response
- Fit spectral model at each grid point
- Can map any spectral parameter





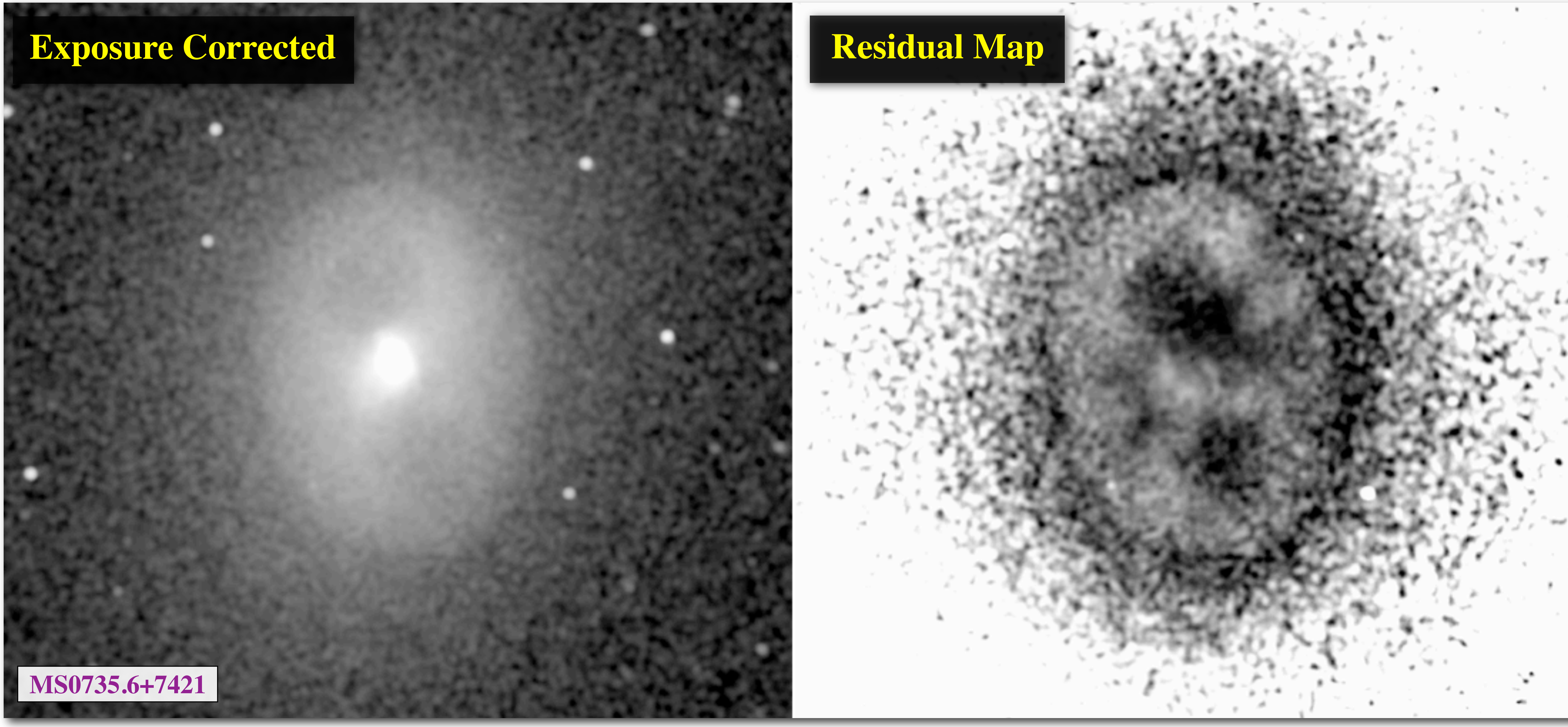
Million et al. (2010)

Spectral mapping at ~1 arcsec is a unique Chandra capability
But you need a lot of counts to do it!


Deep Chandra Observation of MS0735.6+7421
ACIS Mosaic
0.5-7.0 keV
522 ksec total exposure

Cavity Structure and Energetics

Wise et al. (2011)



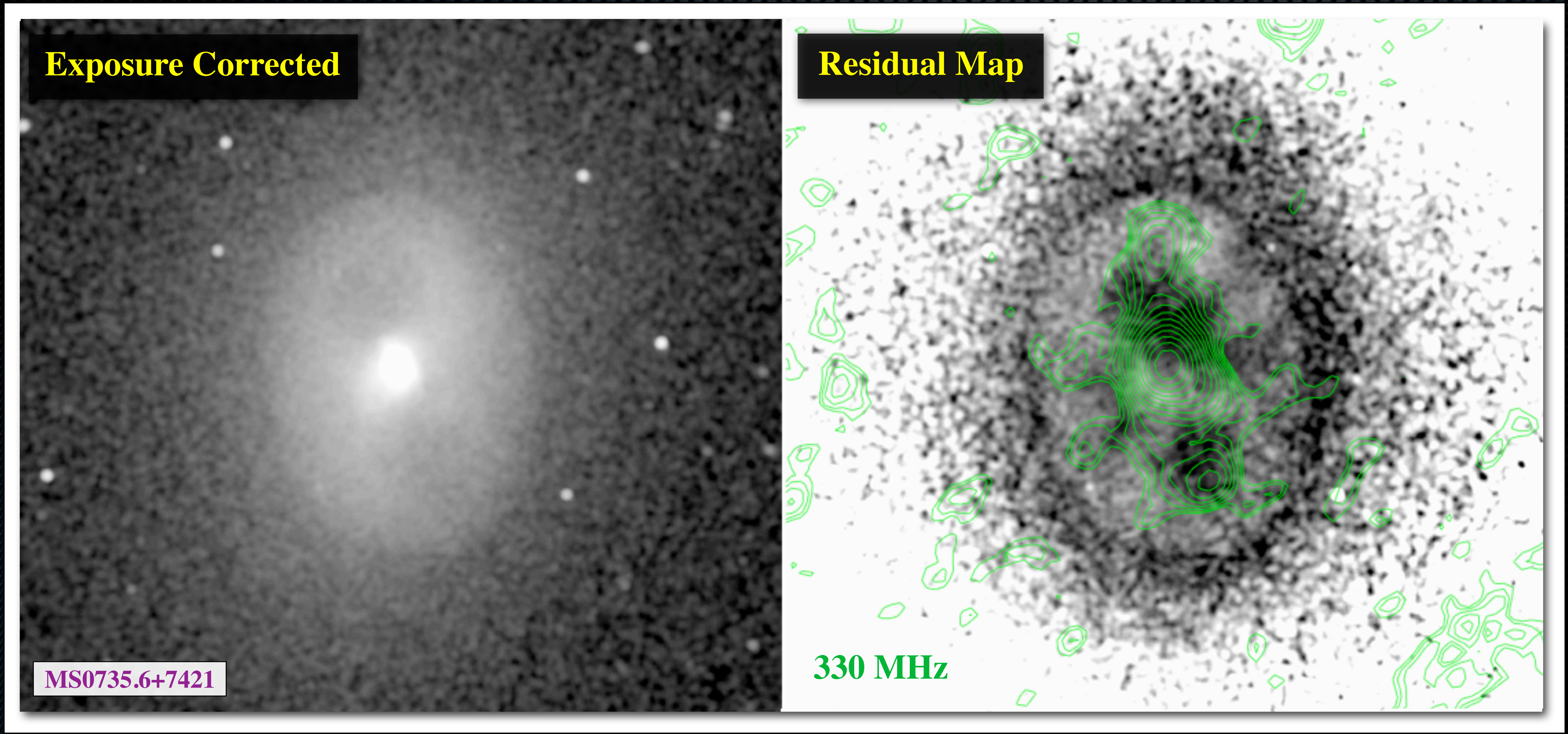
Energy: 6×10^{61} ergs
Cavity Age: 1×10^{8} yrs
Power: 1.7×10^{46} ergs s^{-1}
Displaced mass: $\sim 4\text{-}5 \times 10^{11}\ M_{\odot}$

$P_{cav} \sim 10\ L_X \sim 250\ P_{Perseus} \sim 10^4\ P_{M87}$

Most of energy deposited outside cooling radius

Cavity Structure and Energetics

Wise et al. (2011)



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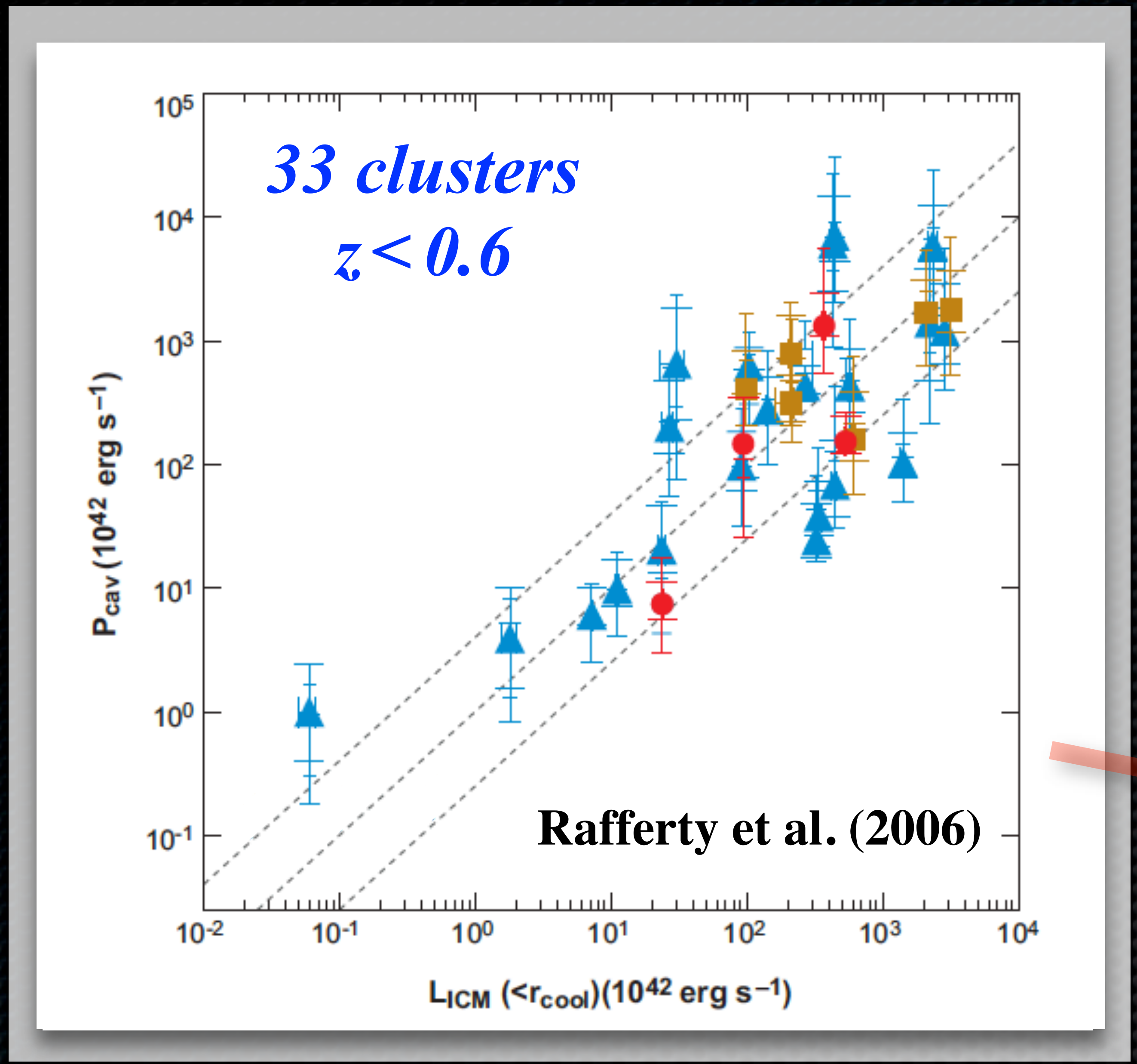
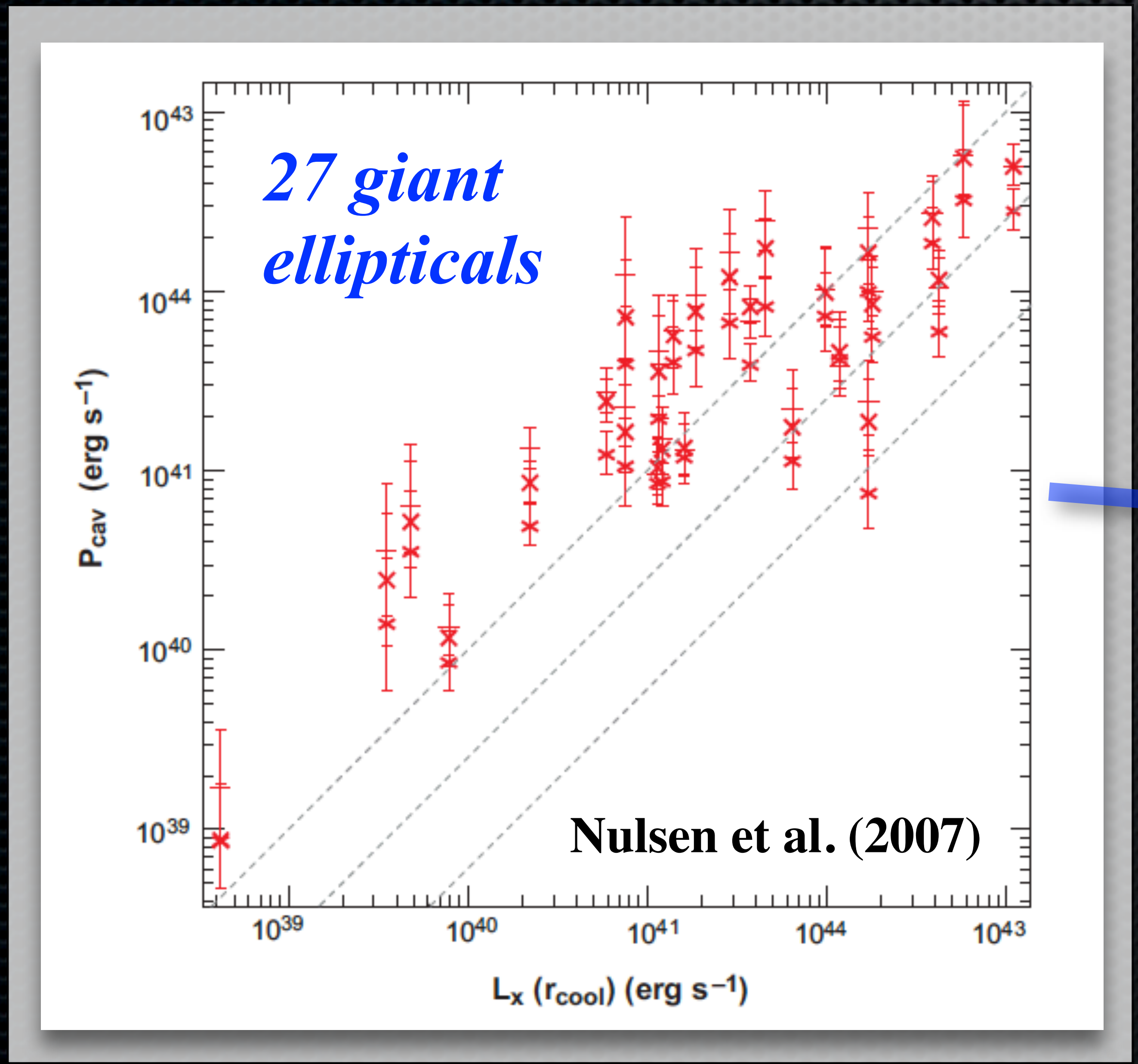
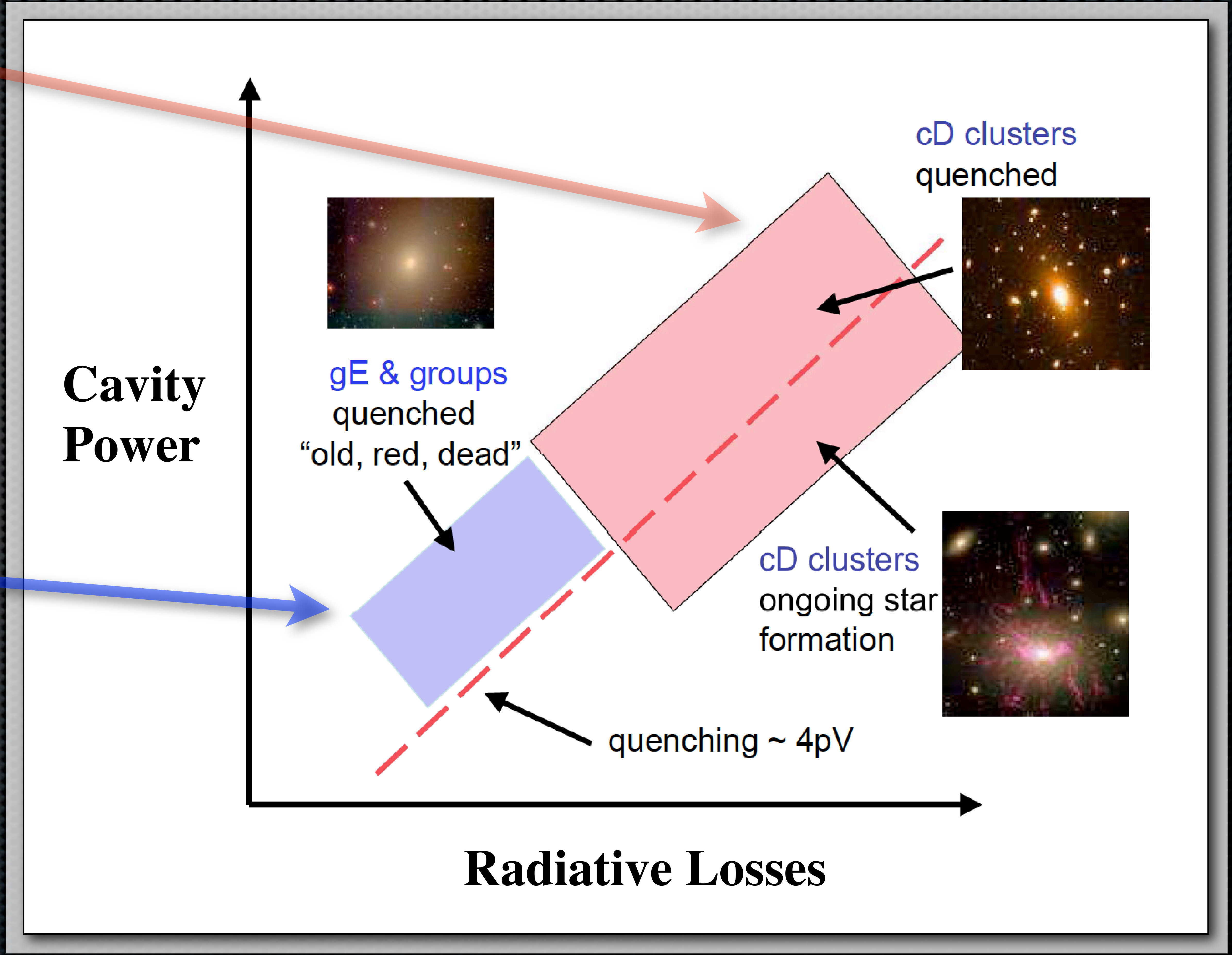
The Feedback Sequence

AGN Heating can balance cooling

What produces the observed scatter?
How do we extend this to high z?



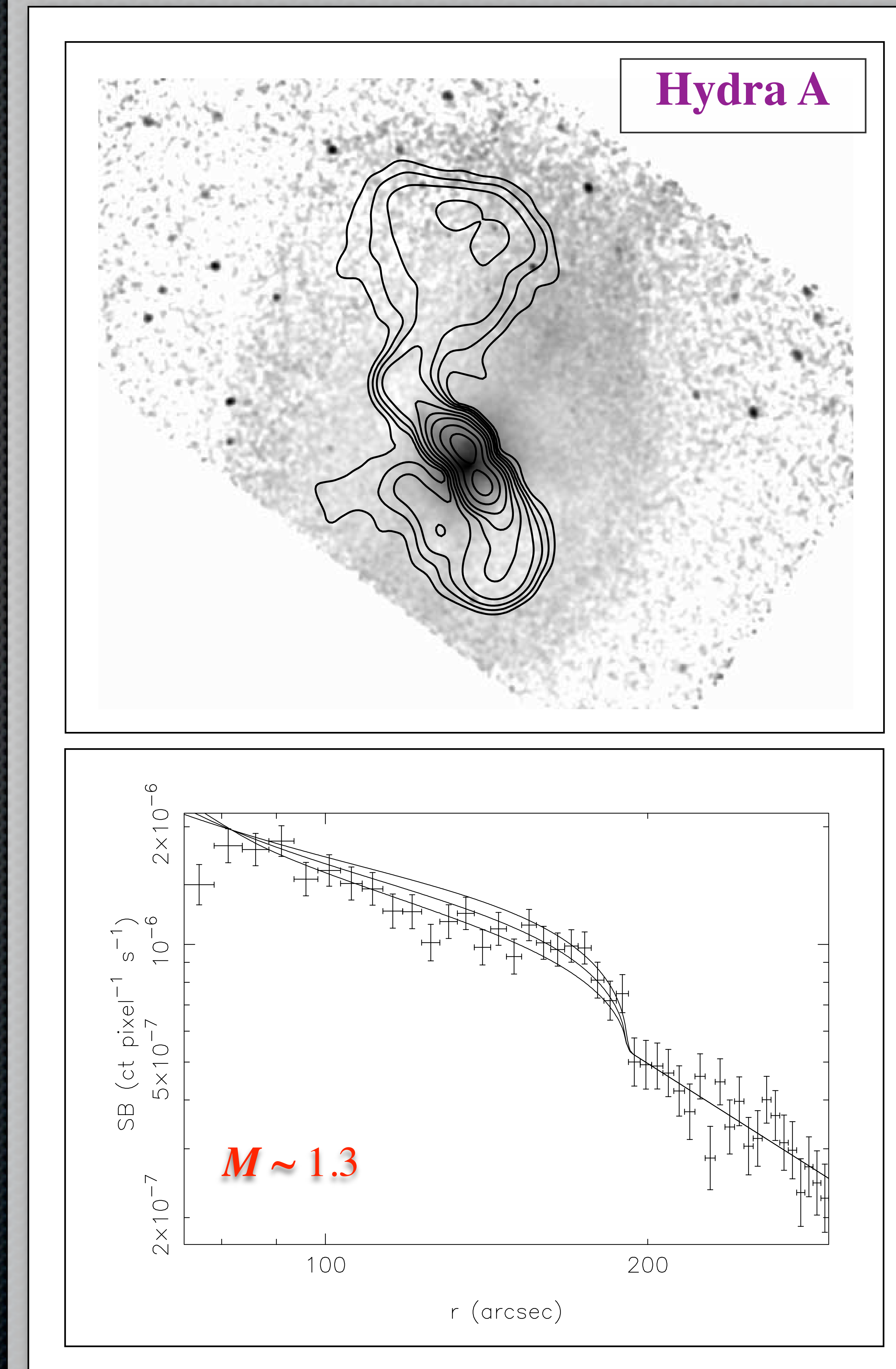




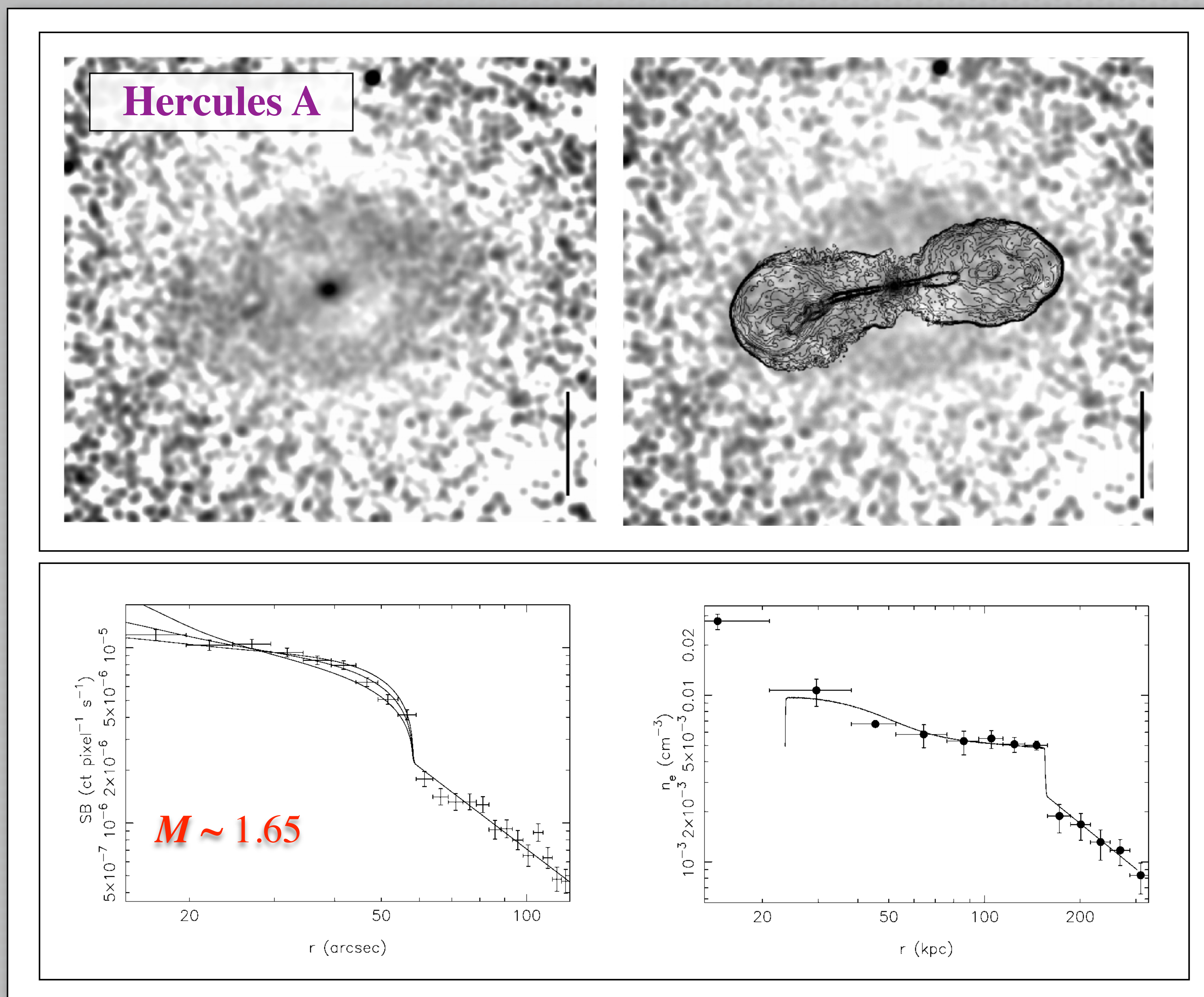
Shocks from AGN Outbursts

Weak shocks seen in several objects
Temperature jump generally not seen

$E \sim 1 \times 10^{61}$ ergs, $t_{age} \sim 140$ Myr



Nulsen et al. (2005)

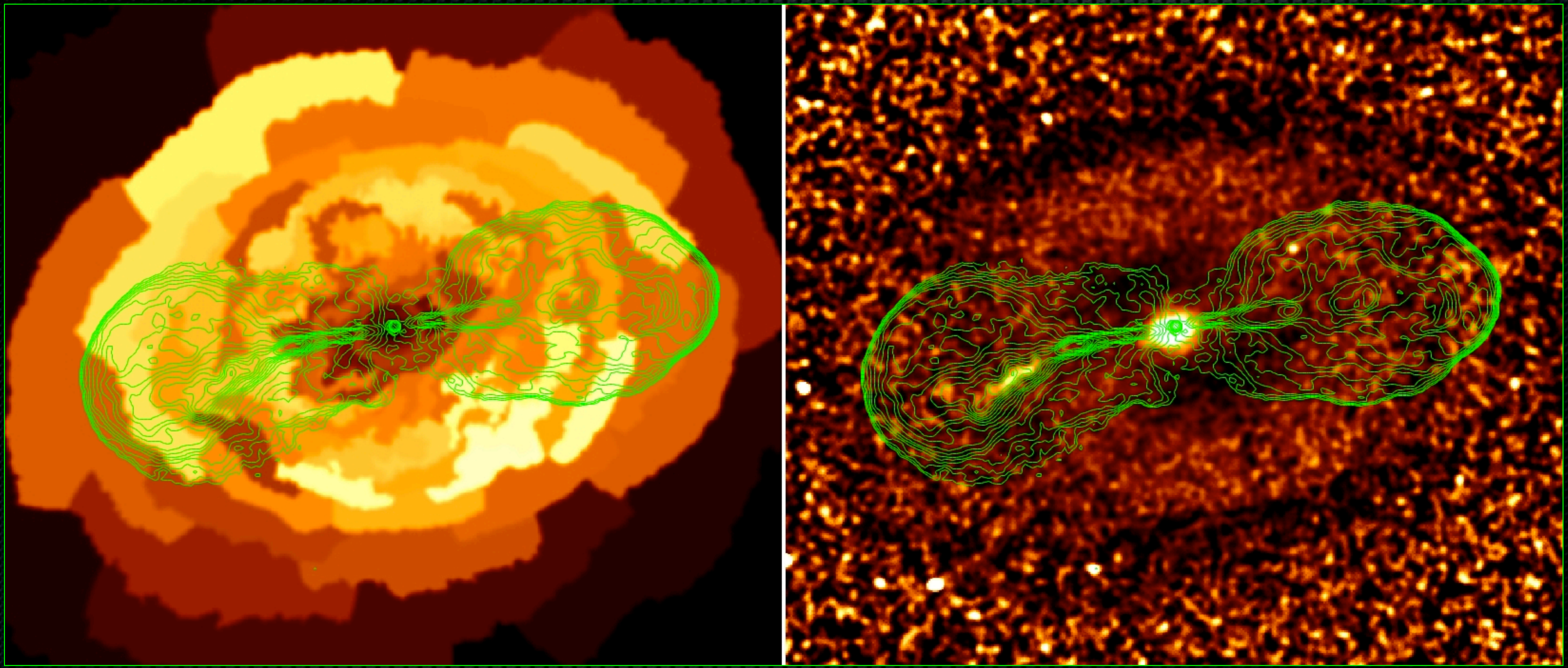


$E \sim 3 \times 10^{61}$ ergs, $t_{age} \sim 59$ Myr

Nulsen et al. (2005)

Hercules A

Nulsen & Wise (2011)

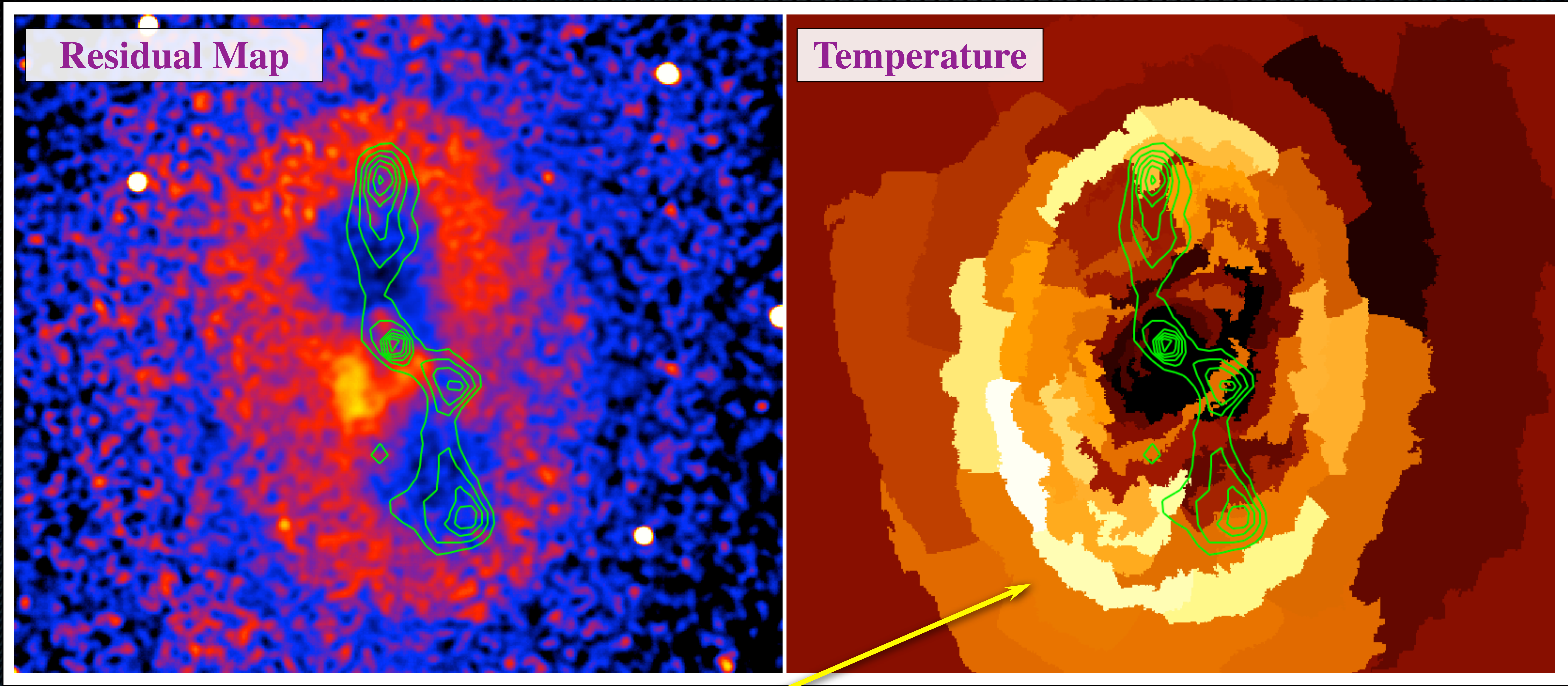


- Second most powerful AGN outburst known ($E_{tot} > 10^{61}$ erg)
- Synchrotron power on par with Cygnus A, FRII-like
- Radio morphology is jet-dominated, no hotspots, FRI-like
- Spherical, M~1.6 shock surrounding the cavities

Shock contains 100× the power radiated by gas inside cooling radius!

MS0735.6+7421

$$\frac{T_2}{T_1} = \frac{(\gamma+1)\rho_2/\rho_1 - (\gamma-1)}{[(\gamma+1)-(\gamma-1)\rho_2/\rho_1]\rho_2/\rho_1}$$



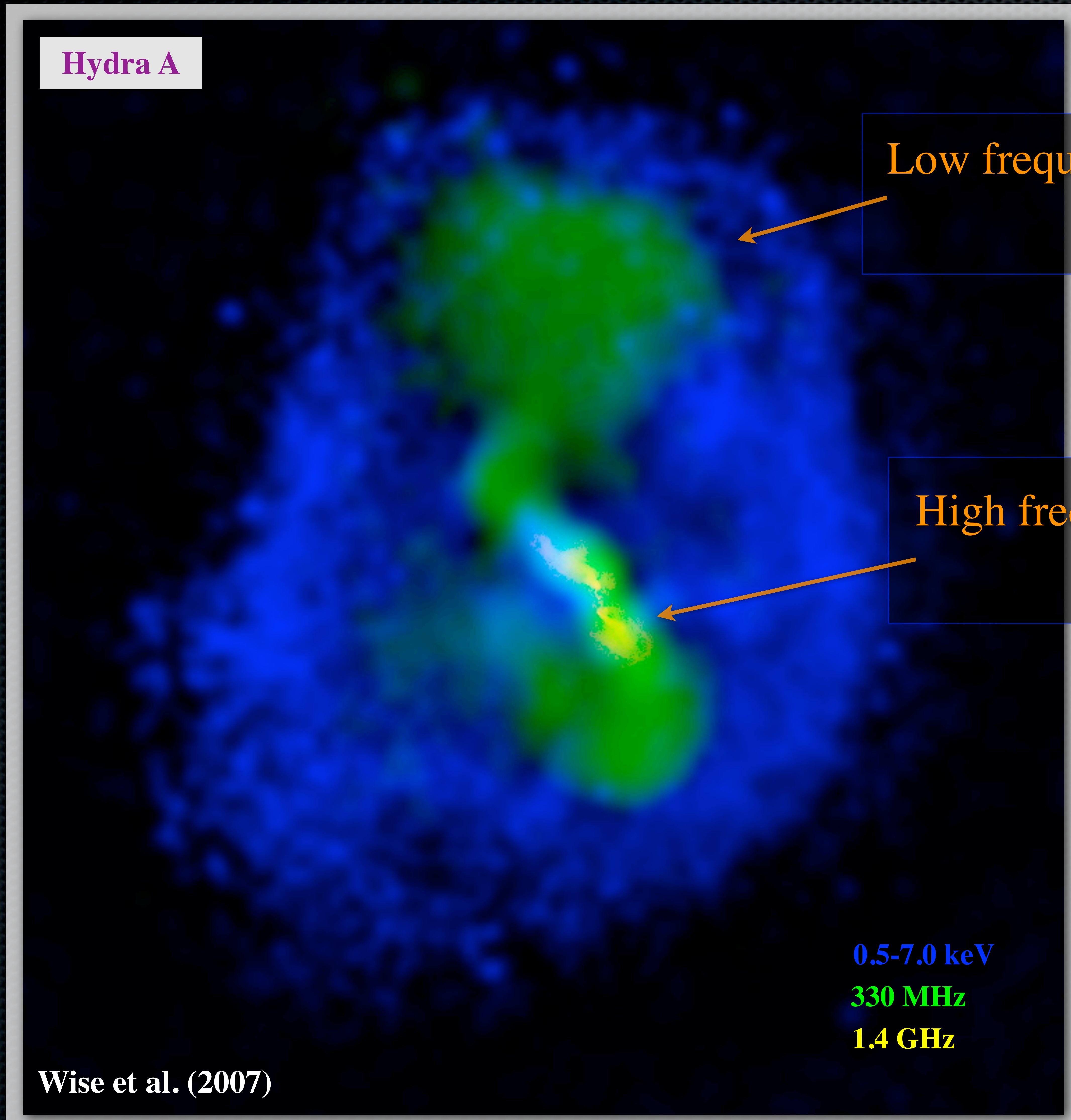
McNamara et al. (2011), Wise et al. (2011)

Evidence for shocked gas

Expected: $\frac{T_2}{T_1} = 1.3 \quad (M \sim 1.3)$ **Observed:** $\frac{T_2}{T_1} \sim 1.4$

Timescales and Duty Cycles

Cavity Systems Trace History of AGN Output



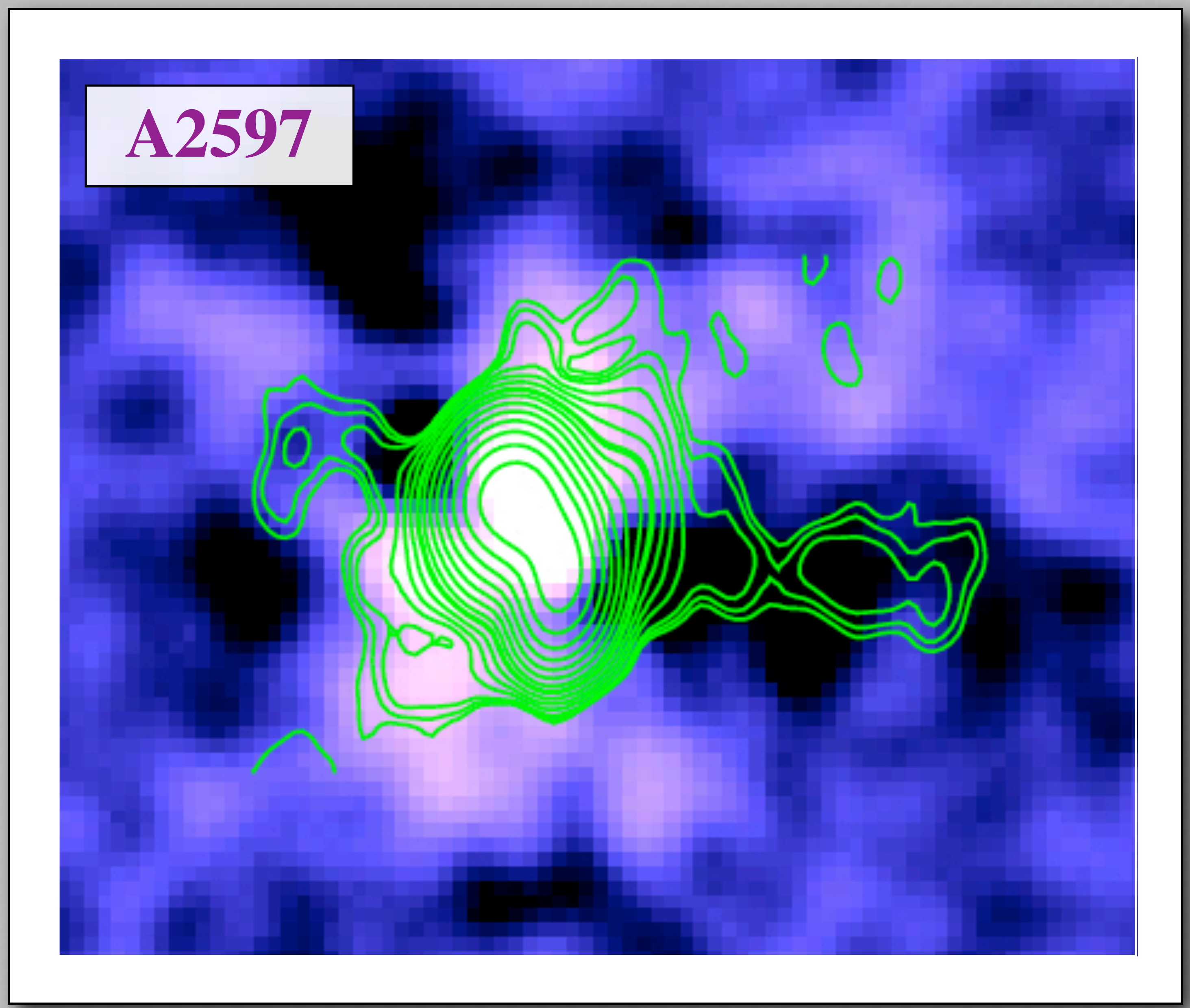
Low frequency ⇒ integrated history
$t > 200$ Myr

High frequency ⇒ recent activity
$t \sim 50$ Myr

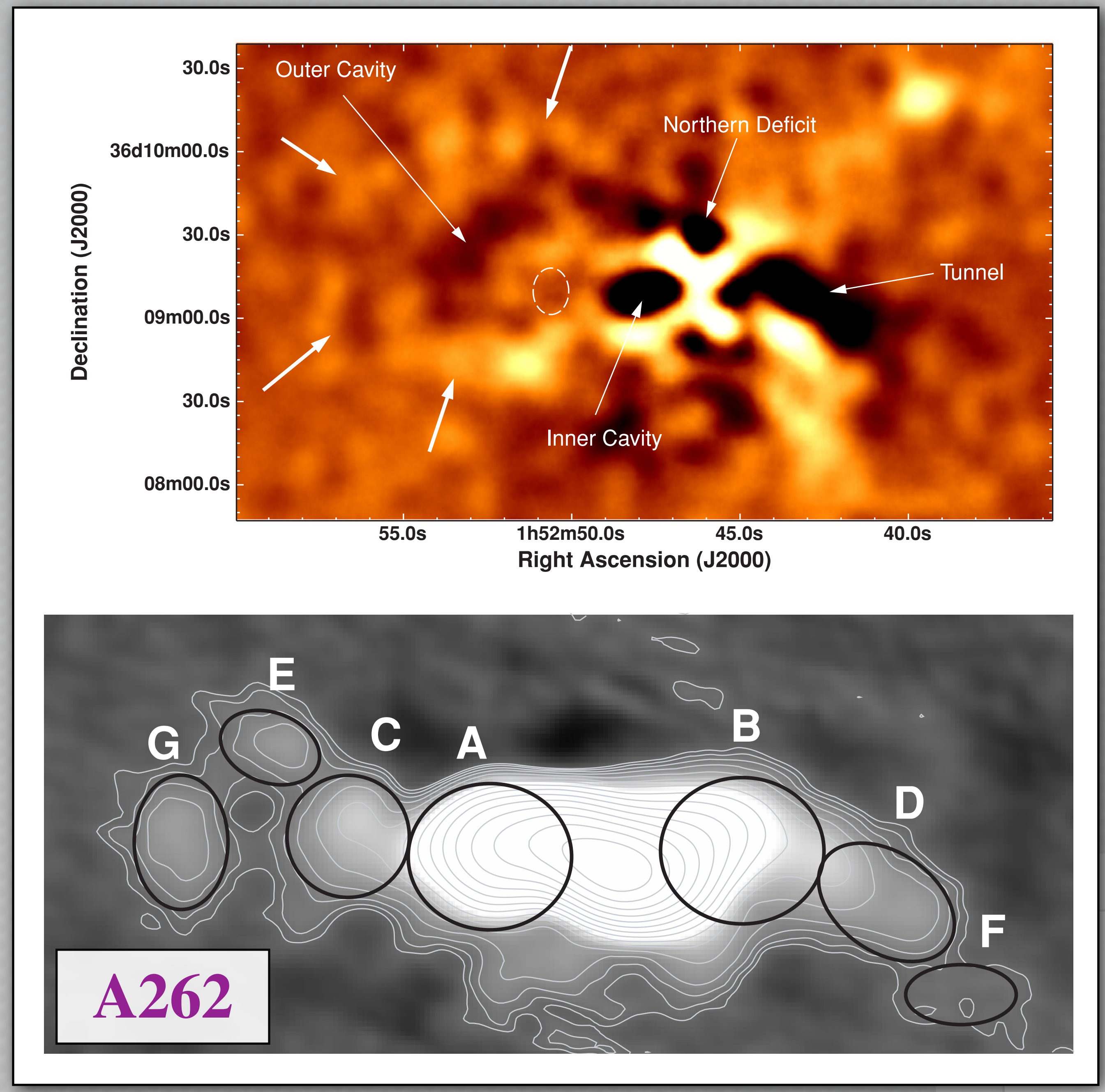
Diffuse emission
Steep spectrum

Traces integrated AGN output

AGN Duty Cycle and SMBH Growth

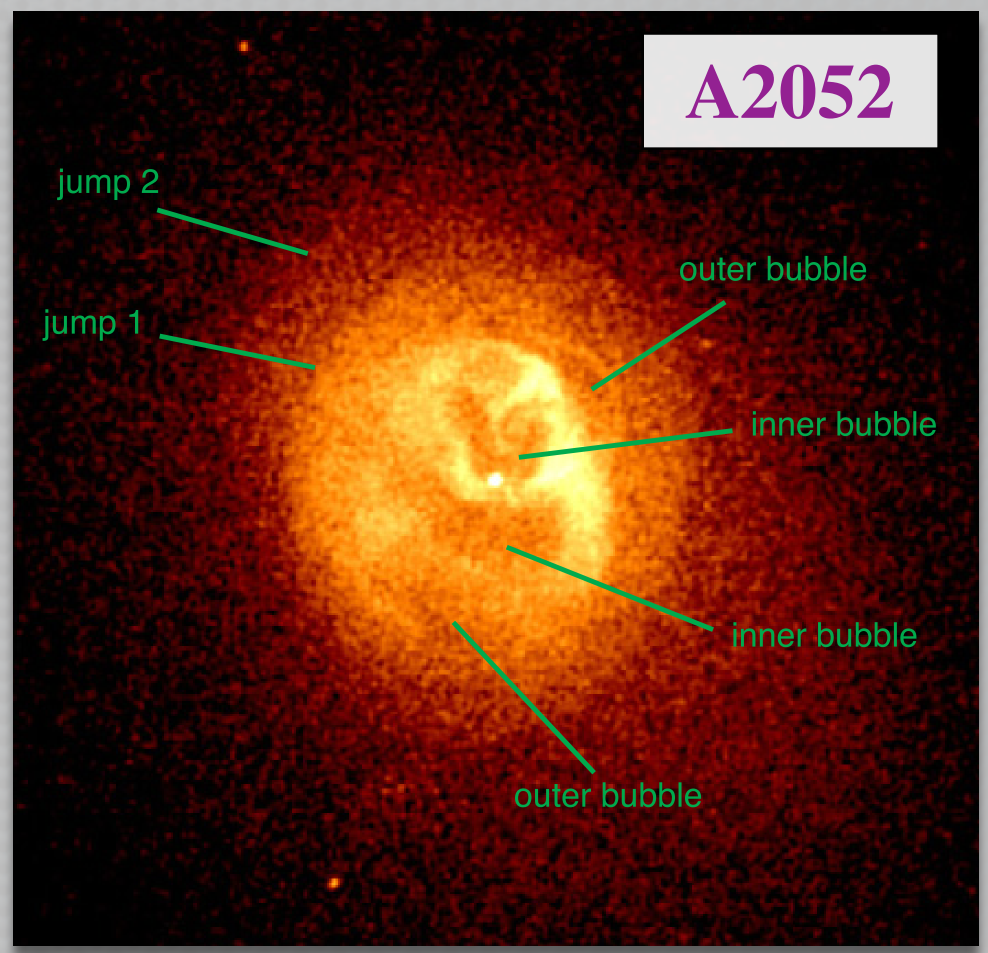


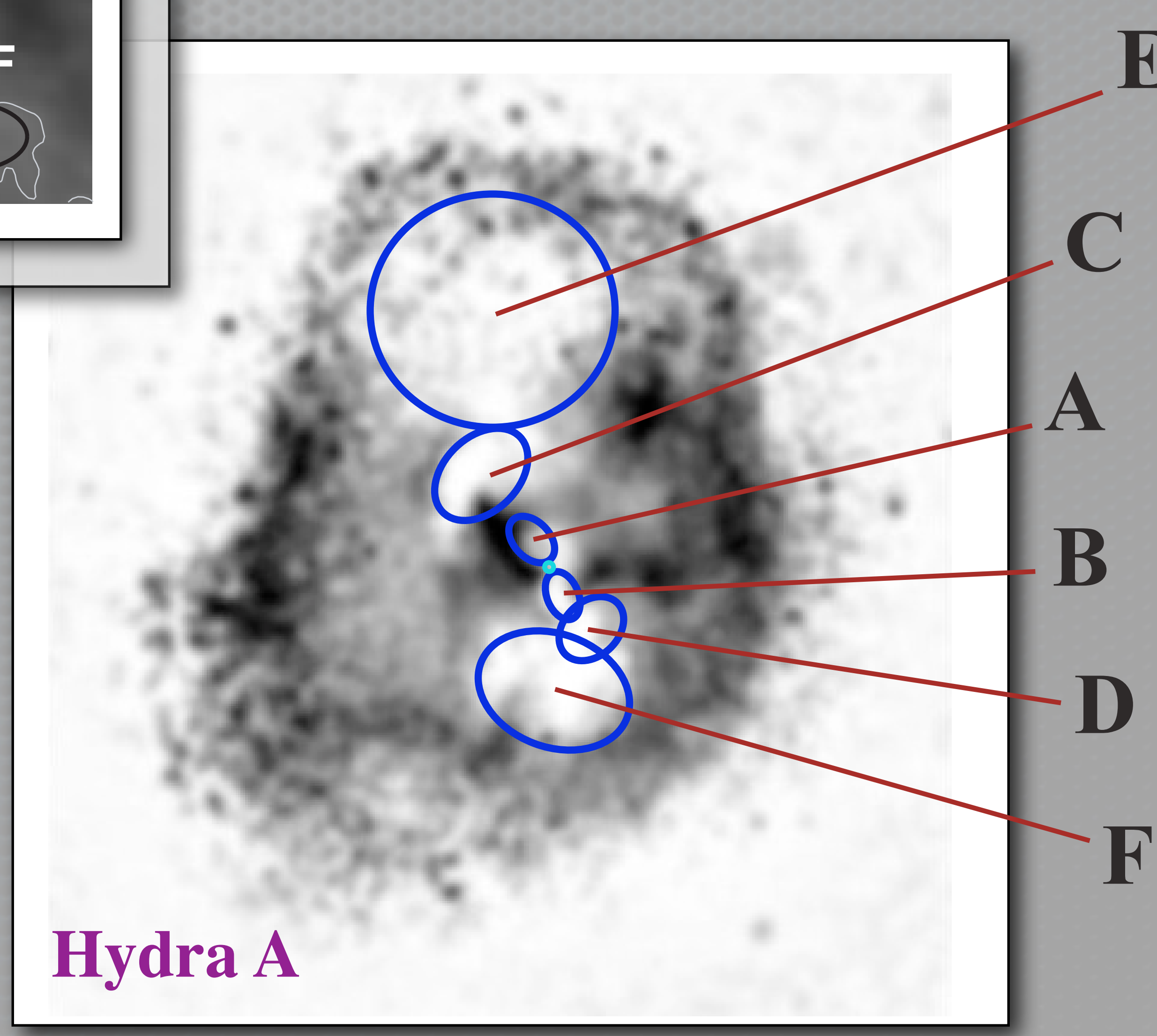
Clarke et al. (2007)



Clarke et al. (2009)

Blanton et al. (2007)



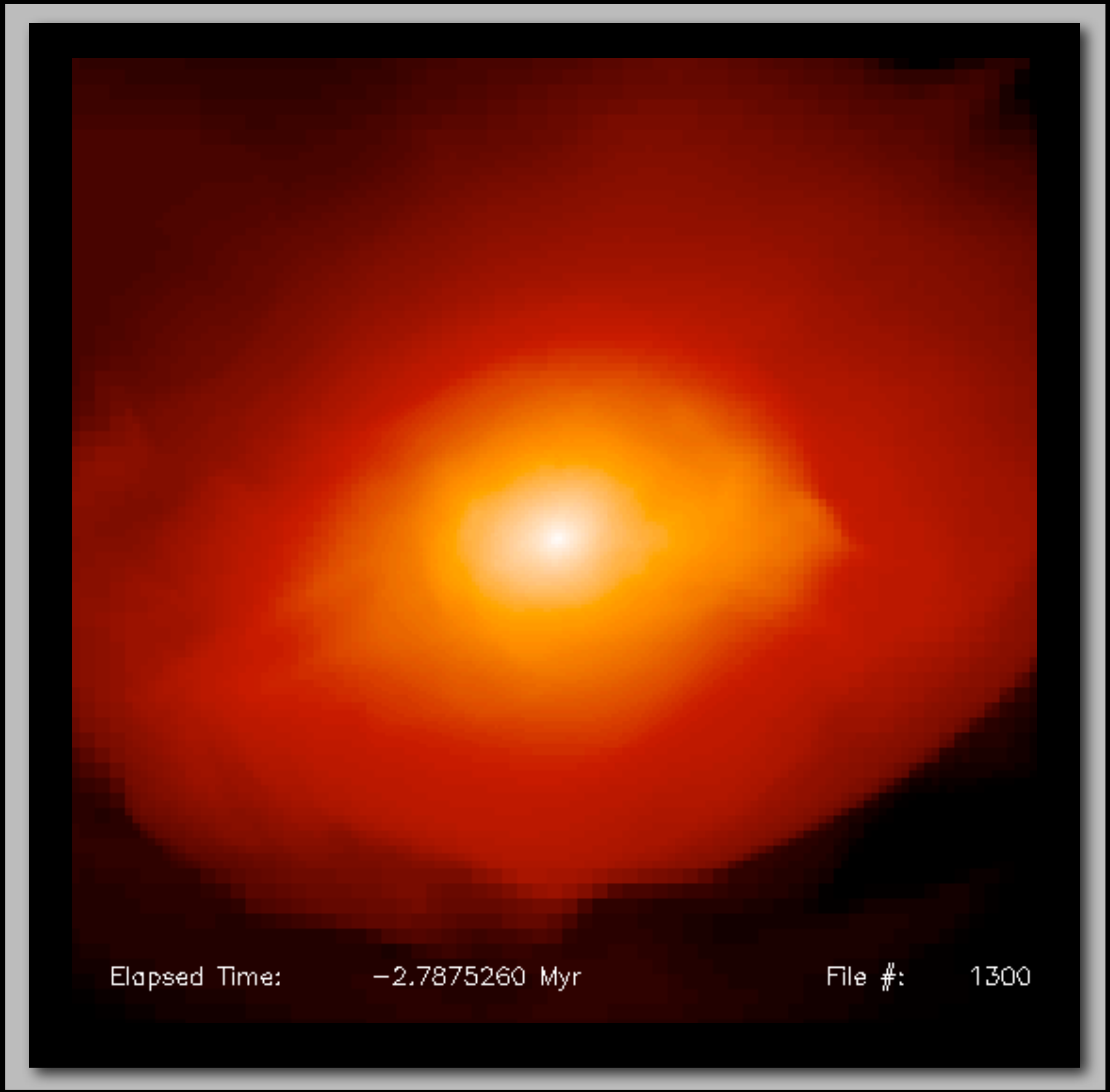


Wise et al. (2007)

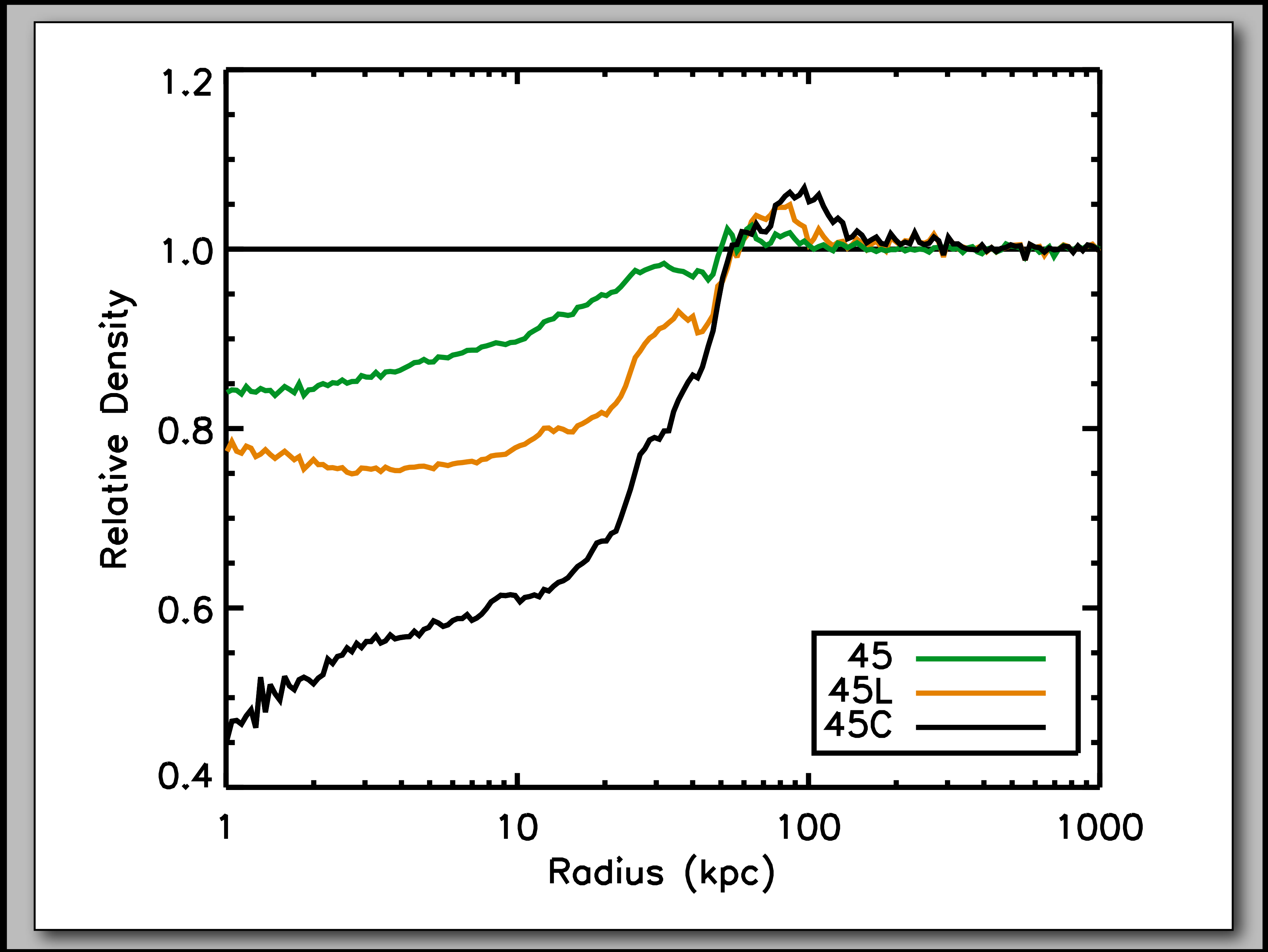
- Multiple cavities detected in X-ray maps
- Imply multiple AGN outbursts over ~200 Myr
- Limits on rate of BH growth:

$$M_{acc} = \frac{E_{cav}}{\epsilon c^2} \qquad \Delta M_{BH} = (1-\epsilon) M_{acc}$$

Cluster weather: AGN "Sphere of Influence"



Heinz et al. (2006), Morsony et al. (2007)



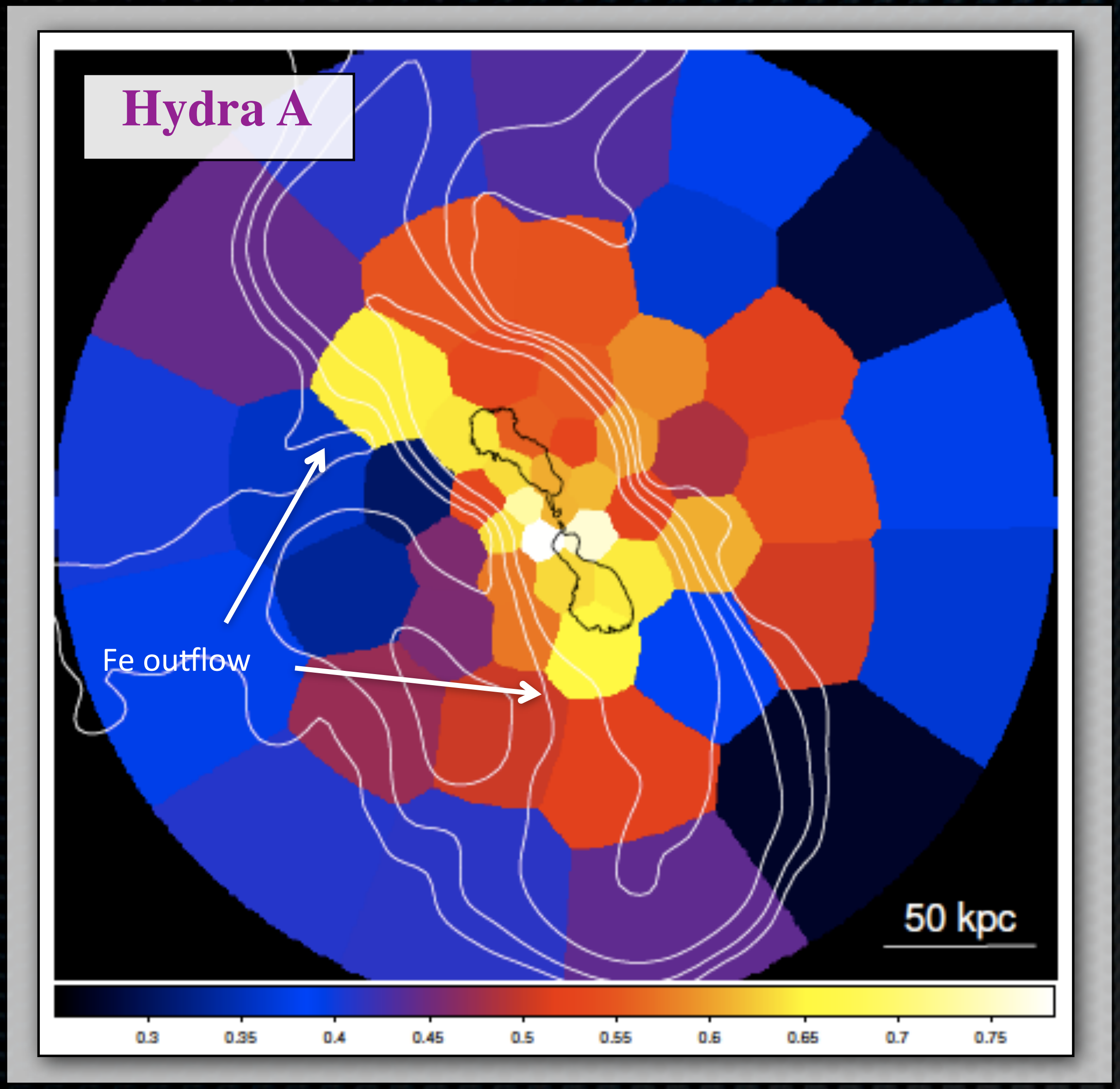
- $P_{jet} \sim 10^{45}$ ergs/s with durations:
  - 30 Myrs
  - 50 Myrs
  - Continuously
- Excavated zone stationary, just deeper
- Radius of influence: $R \sim P^{1/3}$

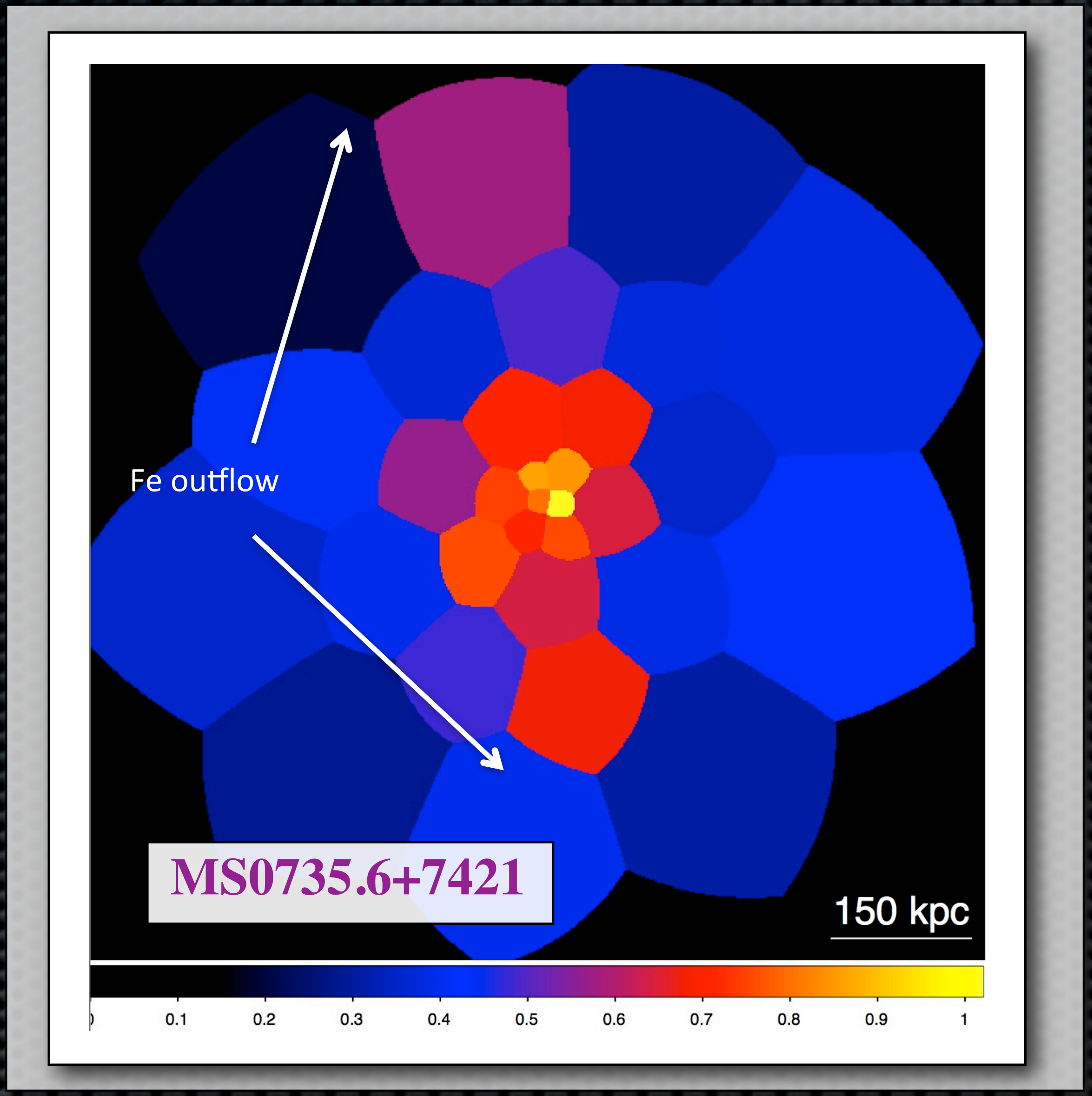
Cluster weather limits "sphere of influence"

Multiple cavities ≠ Intermittency

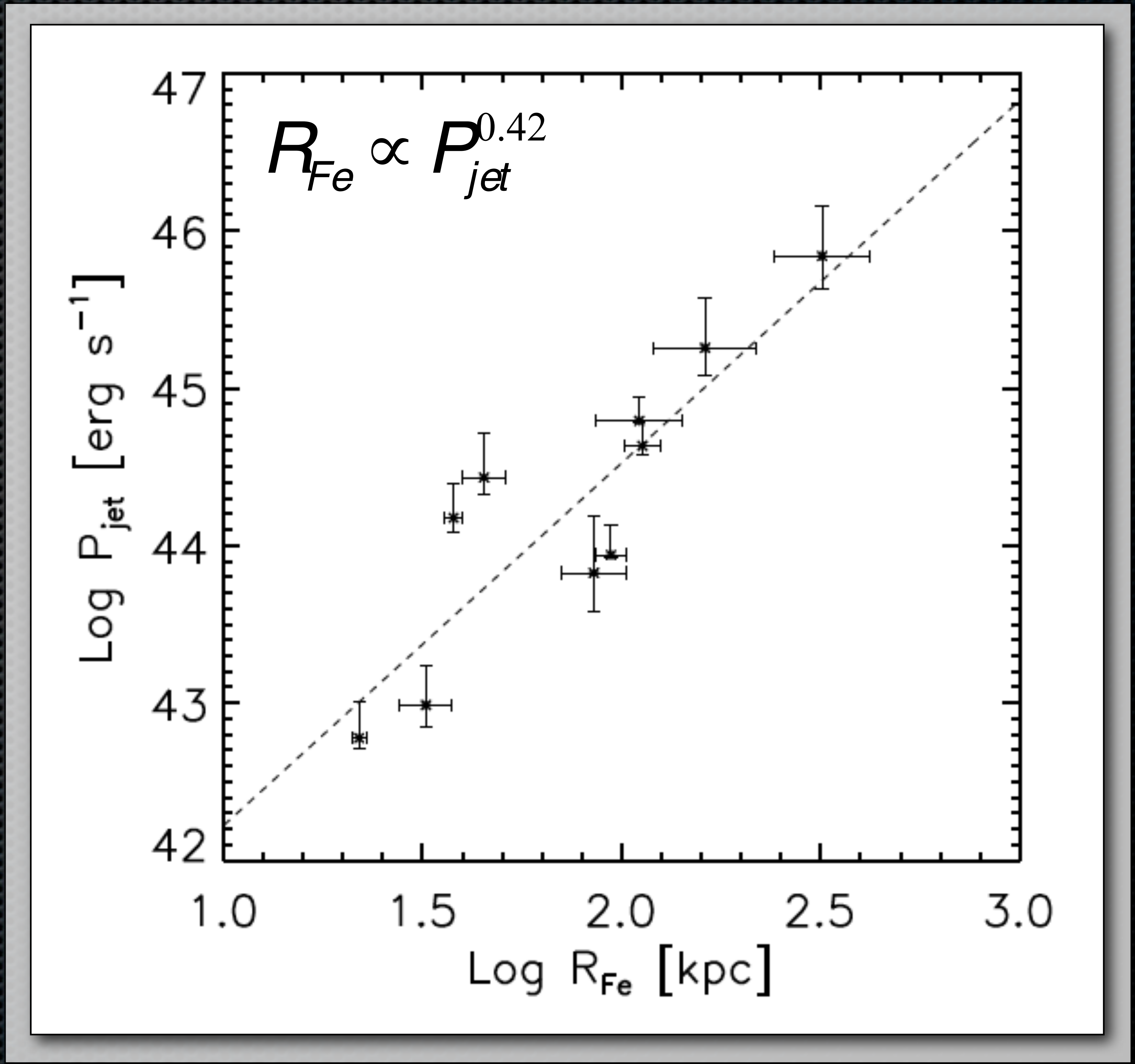
ICM Elemental Enrichment

Enrichment of IGM by Outbursts





Kirkpatrick et al. (2009, 2011)



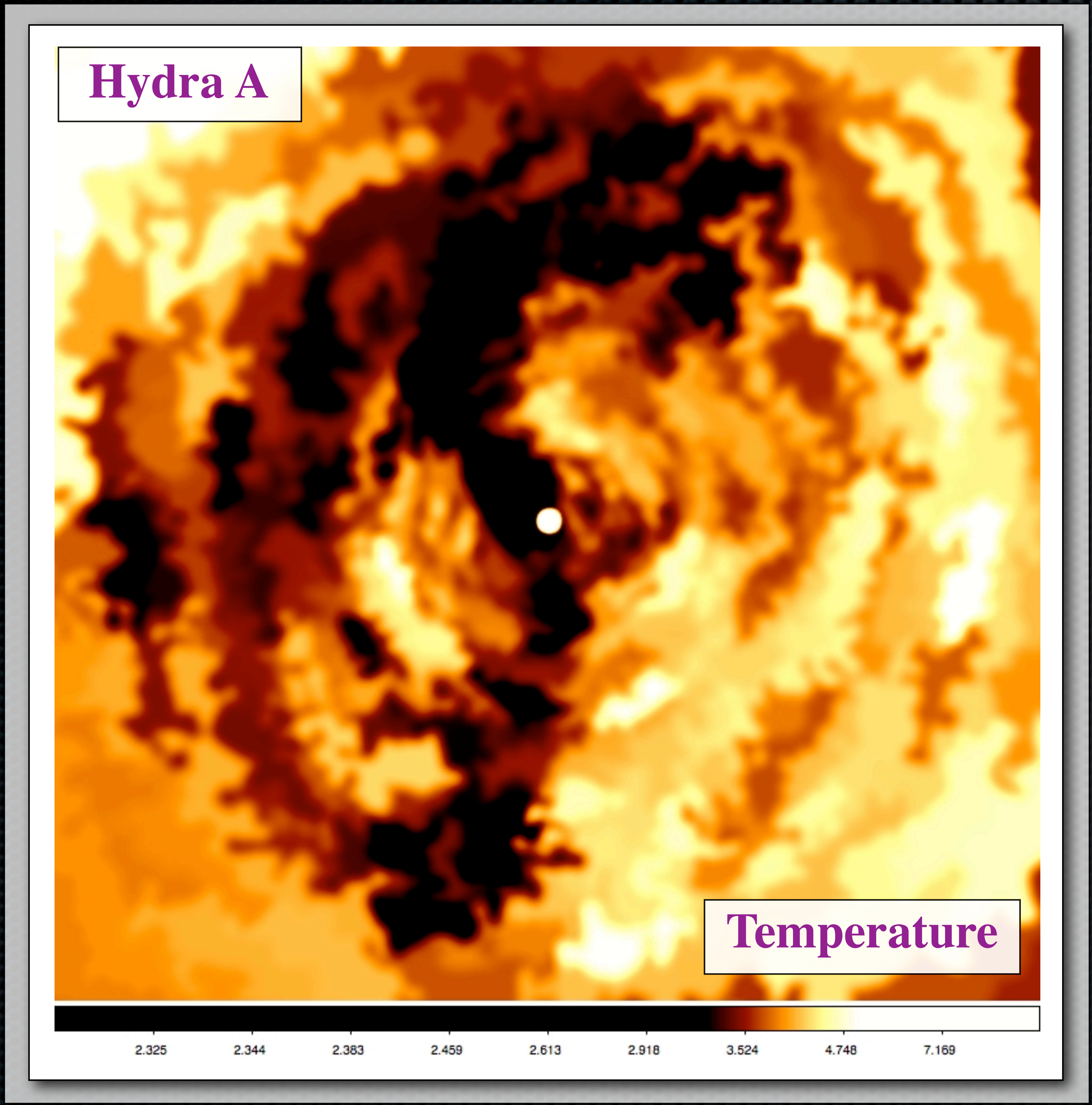
$R_{Fe} \sim 120$ kpc
$P_{jet} \sim 1 \times 10^{44}$ erg s^{-1}

$R_{Fe} \sim 300$ kpc
$P_{jet} \sim 3 \times 10^{46}$ erg s^{-1}

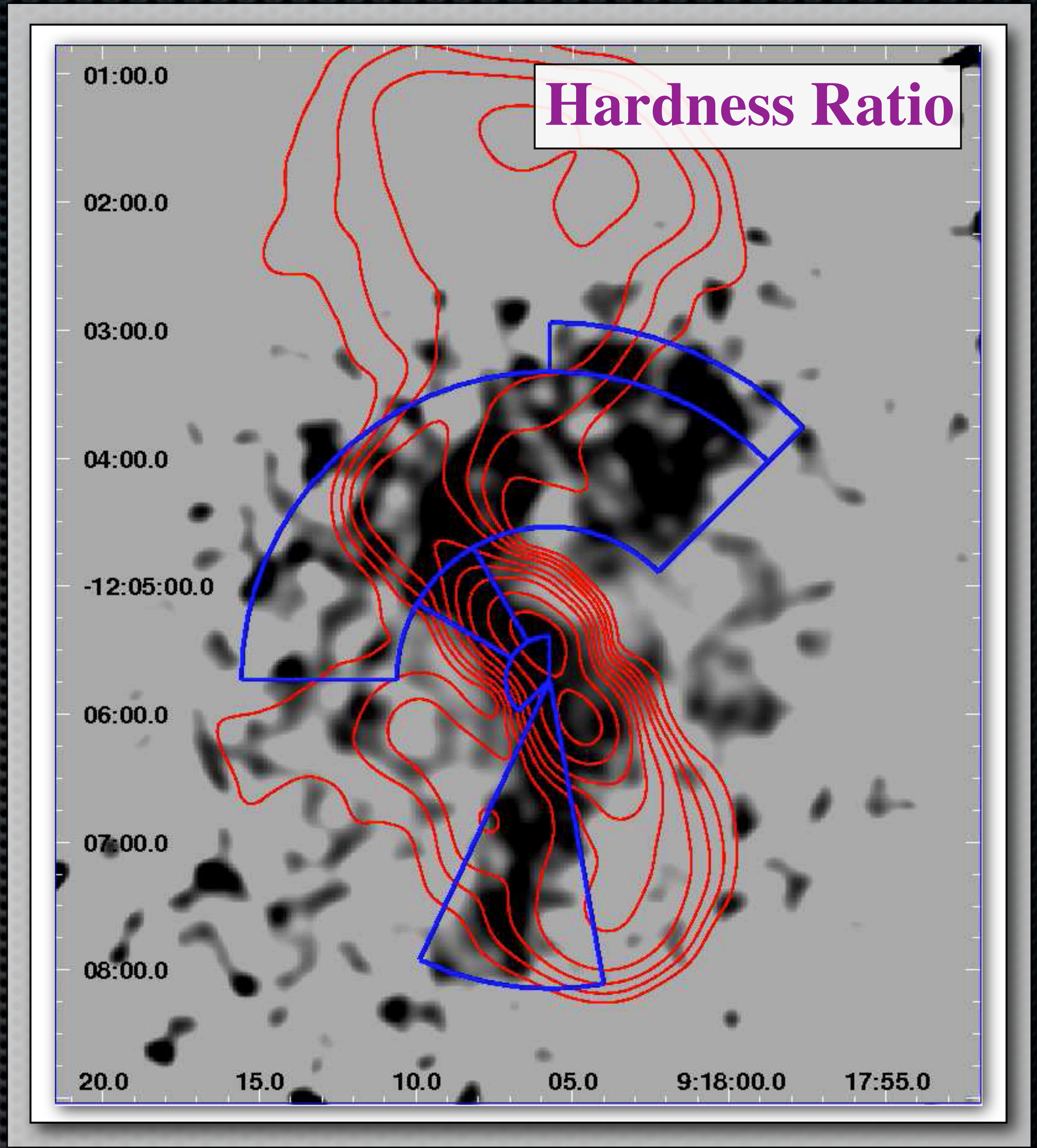
- Sample of 10 clusters with deep Chandra observations
- Excess metals observed to ~0.3 Mpc
- Outflow direction correlates with radio and cavity orientation
- General Fe scaling relation: $R_{Fe} \sim P_{jet}^{0.42}$
- Consisent with radius of Jet influence: $R_{jet} \sim P_{jet}^{0.33}$
- To lift metals to 1 Mpc requires $P_{jet} > 10^{47}$ erg s^{-1}

AGN-Jets disperse metals in the ICM!

Gas Dredge-up by Outbursts



Wise et al. (2011)



Gitti et al. (2011)

Displaced cool gas mass: ~ $9 \times 10^{10}\ M_\odot$

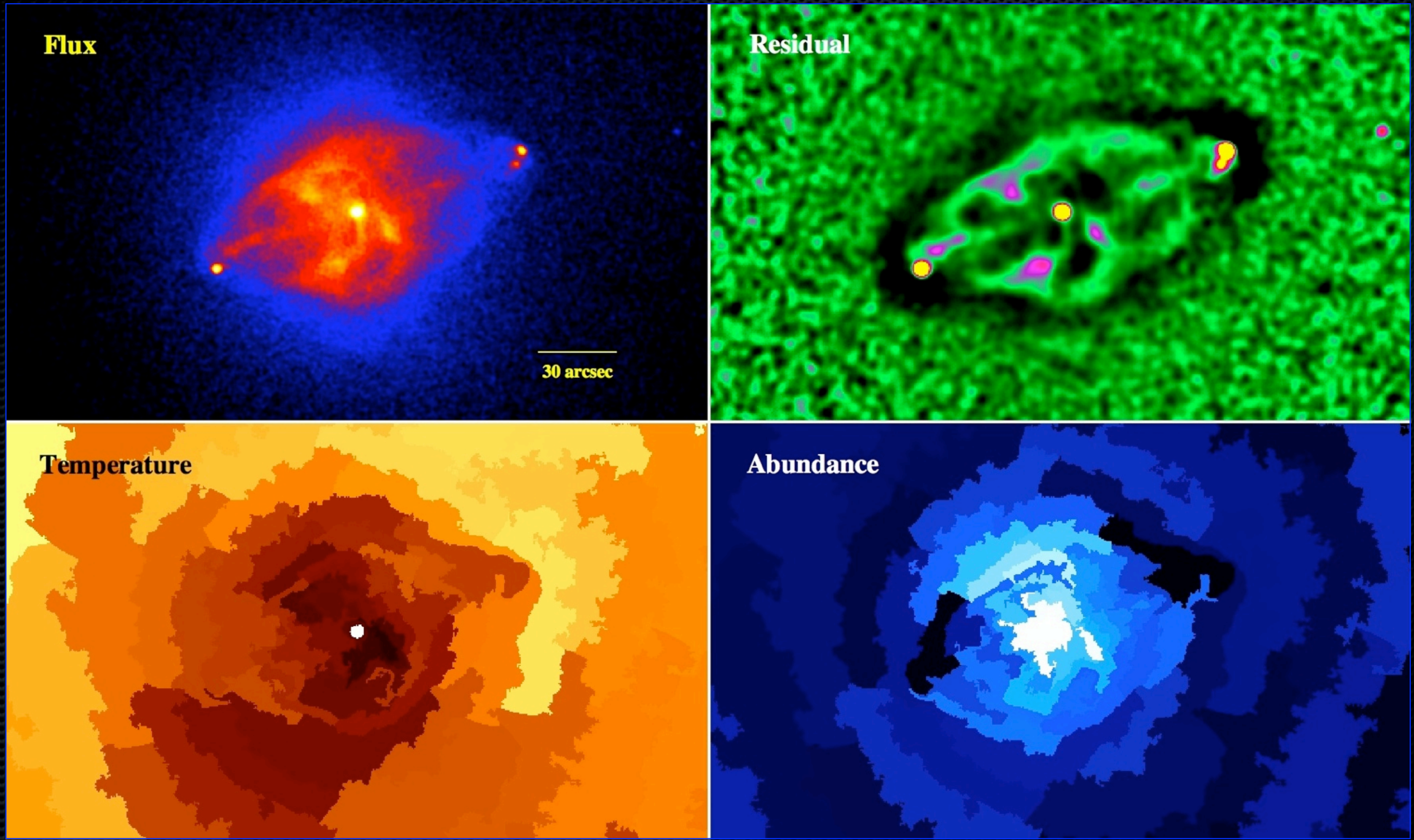
Entropy of displaced gas: ~ 30 keV cm^2

$$\Delta E = \frac{M_{\rm cool}\, c_{\rm s}^2}{\gamma} \ln\left(\frac{\rho_i}{\rho_f}\right) \approx 2.2 \times 10^{60} \text{ ergs}$$

Dredge-up of low entropy material by the rising lobes

Future X-ray and Radio Prospects

Deeper Chandra and XMM Observations



- Fully map the cocoon shock and measure T jumps
- Map the spectral index of the jets, lobes, and hotspots
- Constrain metal outflows and older outbursts

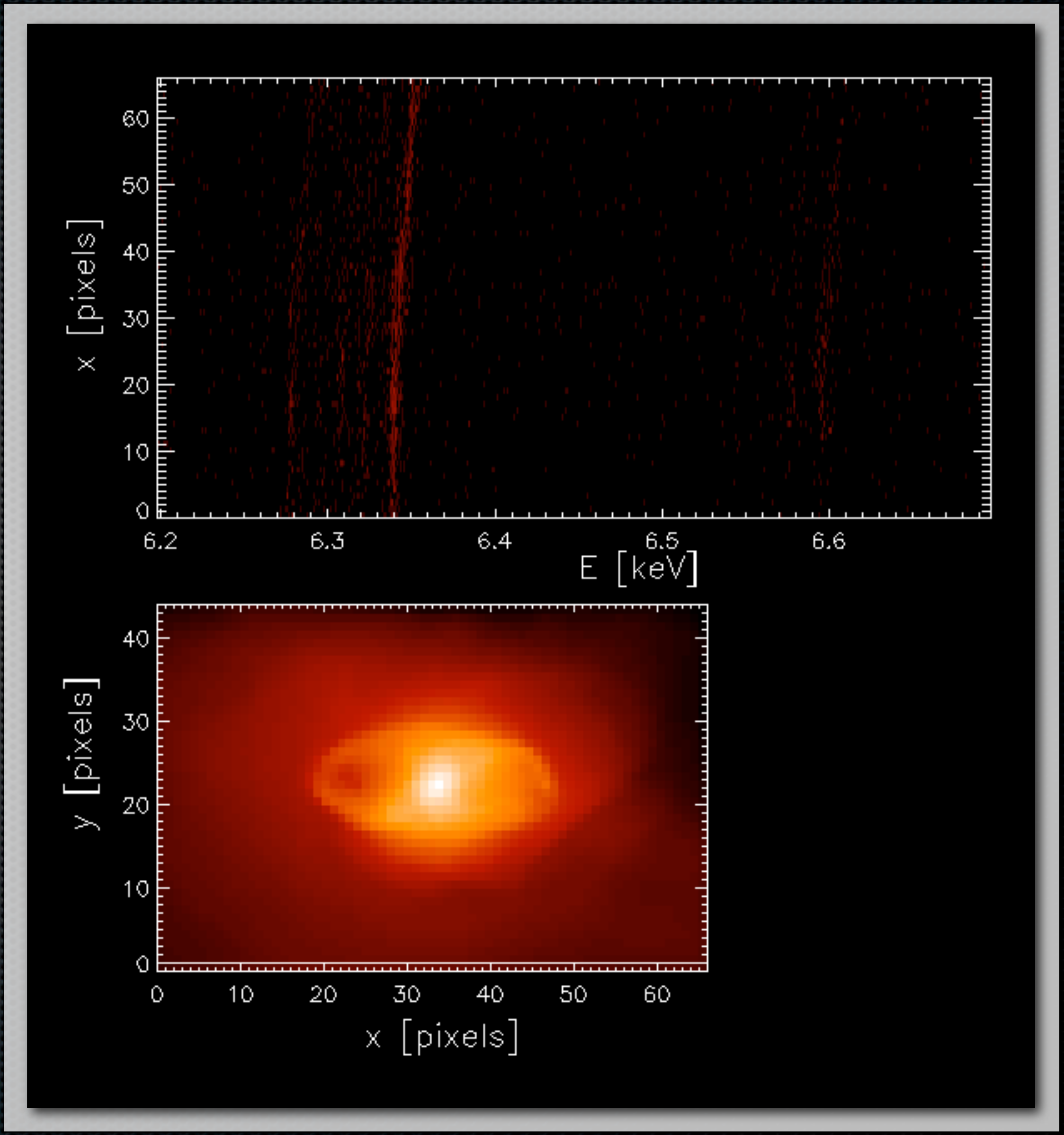
Resolution ~1 arcsec at S/N~100 implies ~Msecs

Possible Future Cavity Studies with IXO

Simulated 250 ksec IXO data of Cygnus A

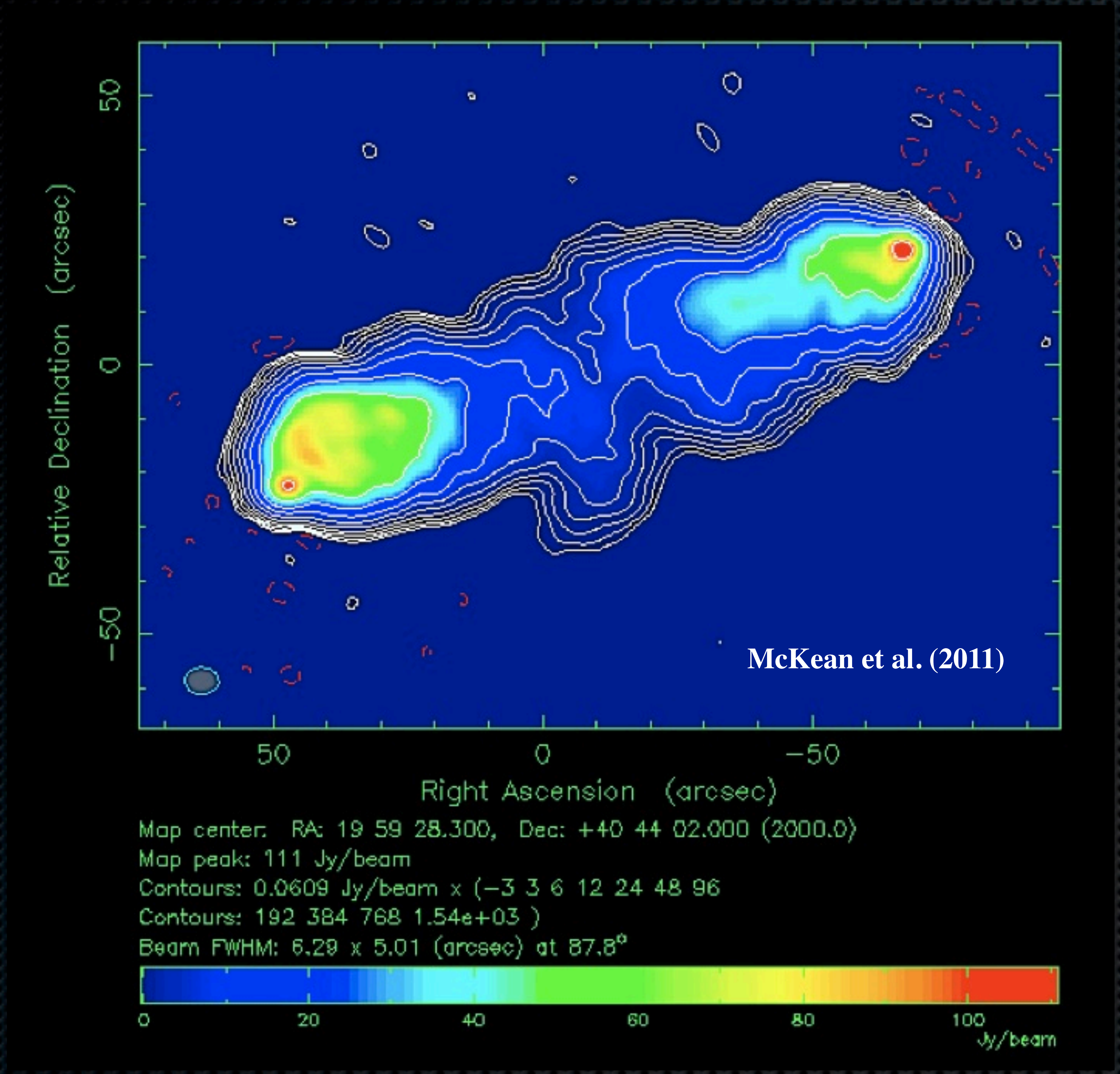
- Fe XXV and XXVI Kα line
- Line structure reflects expansion of cavity
- Measure expansion velocity directly
- Ages (no more t_{sonic}, $t_{buyoant}$, $t_{whatever}$)
- Unambiguous cavity and jet powers

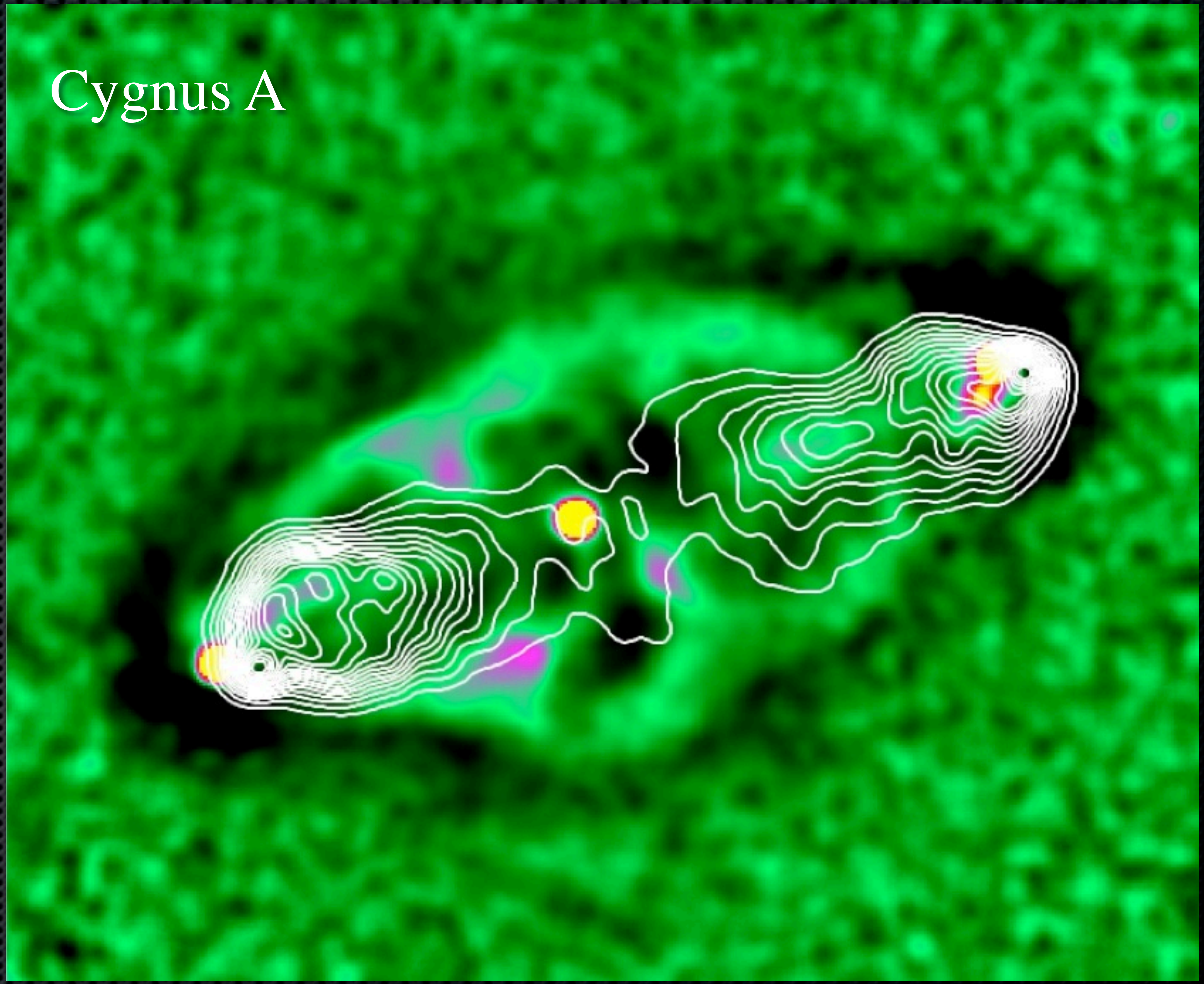
IXO could easily resolve velocity structures from feedback



Heinz & Brüggen (2009), Heinz et al. (2011)

Radio Spectral Mapping with LOFAR

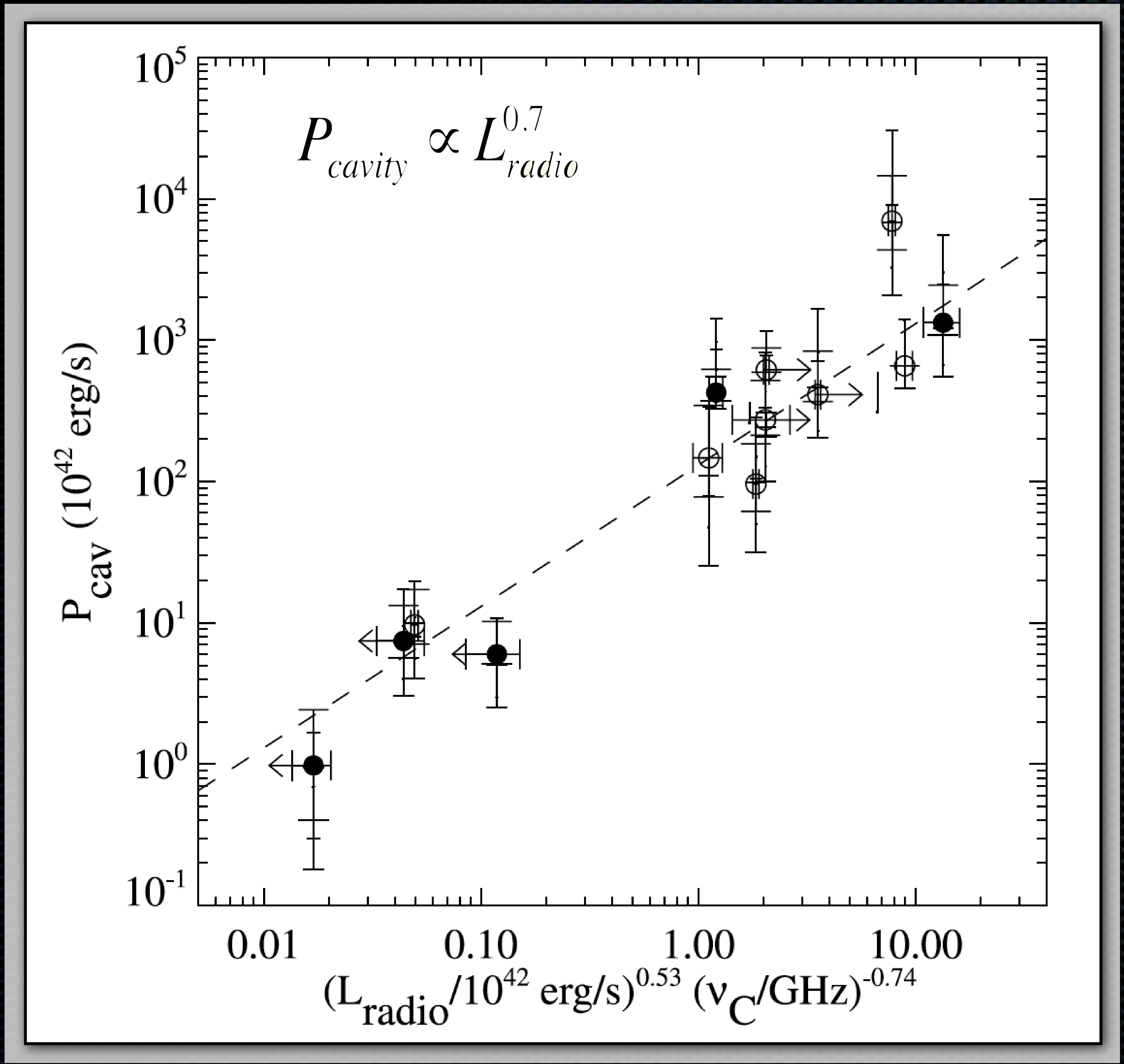




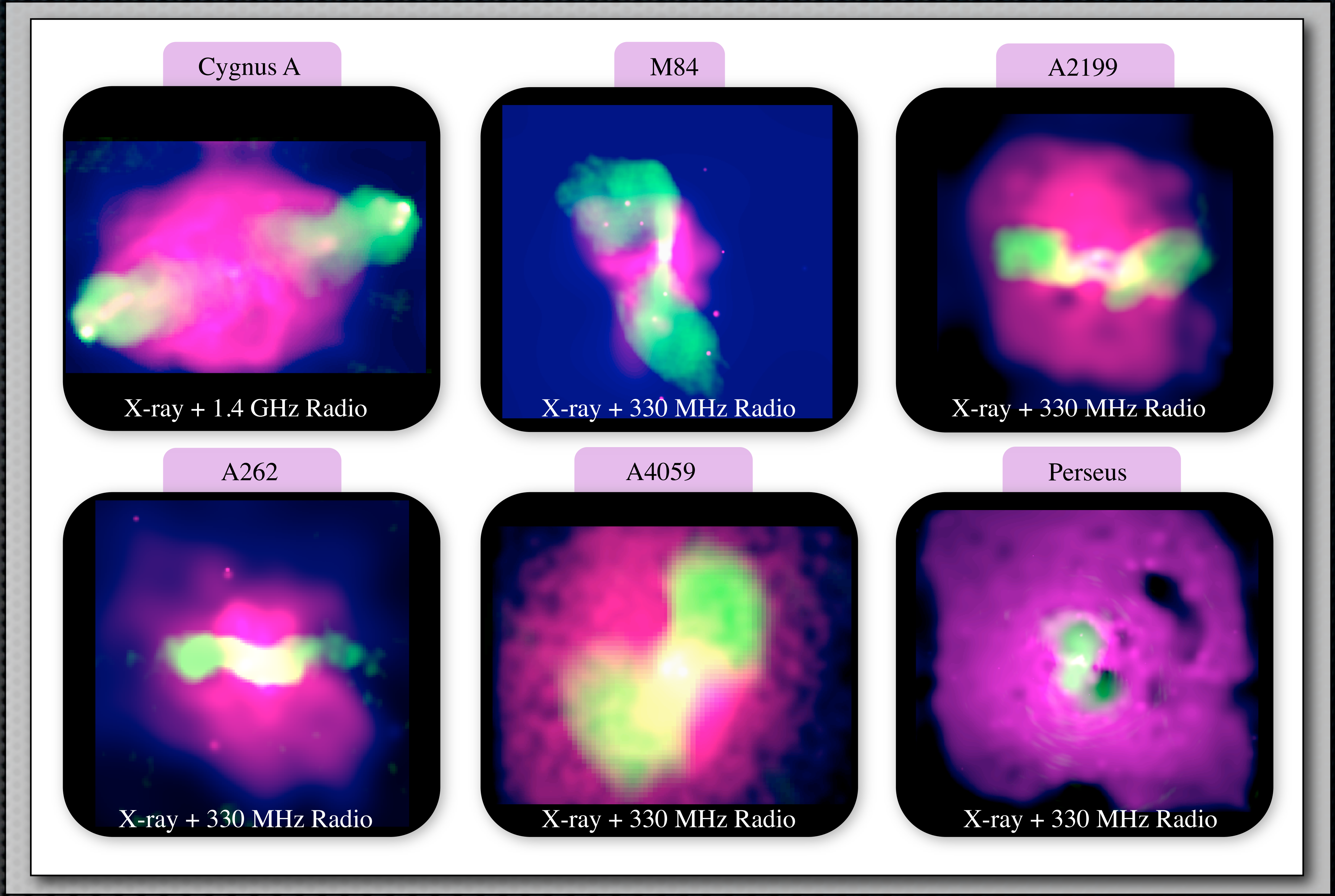
- Resolutions of ~0.2-2.0 arcsec over 30-240 MHz
- Spectral index maps over broad frequency range
- Determine spectral ageing of e^- population
- Determine jet and lobe particle content
- Place constraints on strength and topology of B fields

Correlate directly with X-ray spectral maps on equivalent spatial scales!

L_{radio} as proxy for P_{cavity}



Bîrzan et al. (2008)



- 24 cavity systems from Chandra Archive
- Low to moderate redshift ($0.0035 < z < 0.545$)
- VLA data: 330 MHz, 1.4 GHz, 4.5 GHz and 8.5 GHz
- Combine X-ray + Radio
- Depends on source extent

Calibrate at low-z ⇒ Extrapolate to high z

Summary

- AGN outbursts have a huge impact on their environment
- Imprints of these outbursts reflect the growth of the BH
- Provide constraints on energetic output and duty cycle
- Evidence for ICM metal enrichment by outbursts
- Outbursts dredge-up low entropy material from core
- Deeper X-ray data needed to calibrate low z feedback
- LF radio can be used to identify cavity systems at high-z
- LOFAR observations will calibrate the P_{cavity} vs. L_{radio} relation
- Detailed picture of feedback in clusters from present to z~2