Connections

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Smithsonian Astrophysical Observatory

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Frontier Questions

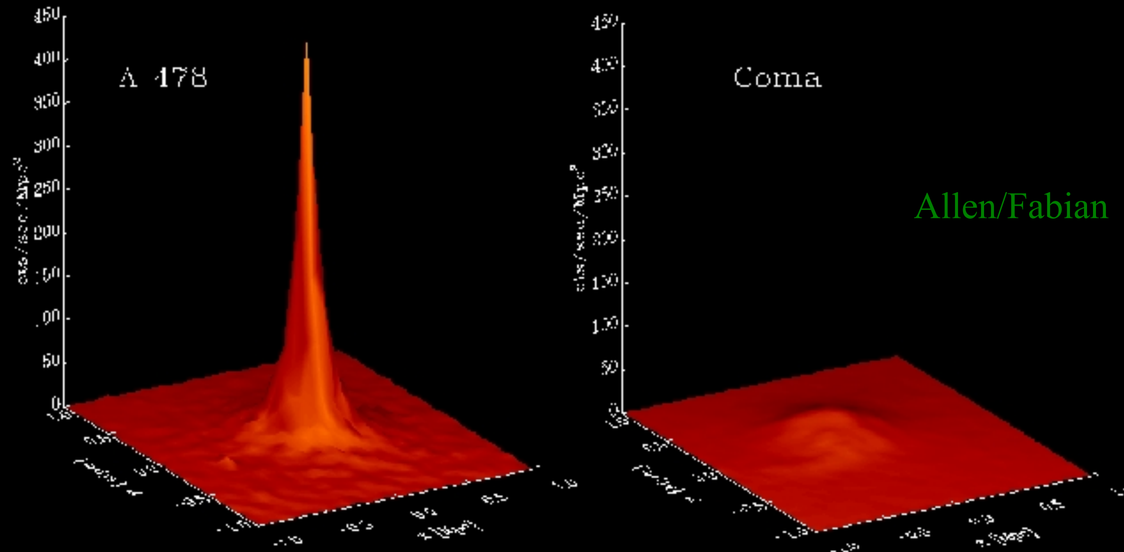
1. How do cosmic structures form and evolve?
2. How do supermassive black holes form and grow?
3. What are the flows of matter and energy?
4. How do black holes influence surroundings?

These can be addressed considering studies of clusters of galaxies and of large scale jets from AGN.

Clusters: X-rays give integrated energy inputs from Radio plasma

Jets: X-rays and Radio from the same relativistic electron spectrum

Cluster cooling flows: the problem



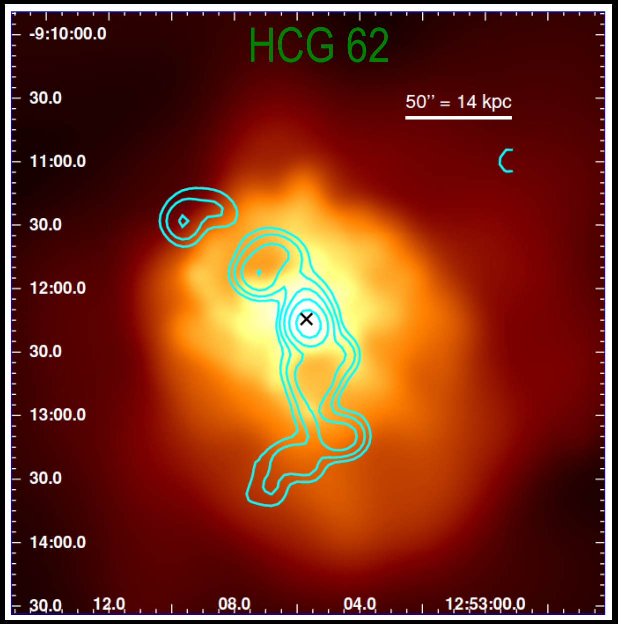
X-ray brightness distributions: examples *with* cooling core *without* cooling core

- Fabian & Nulsen (1977) "Cooling gas in the cores of clusters can accrete at significant rates onto slow-moving central galaxies"
- Strong surface brightness peak → dense gas → short cooling time
- Hot gas radiates – gas must cool unless reheated
- But *large amounts of cool gas are* *<u>not</u>* *detected:*
  X-ray spectroscopy (XMM RGS: Peterson et al 2001, 2002 et seq)
  limits cooling gas to ≤ 10-20% of expectation from a cooling flow model

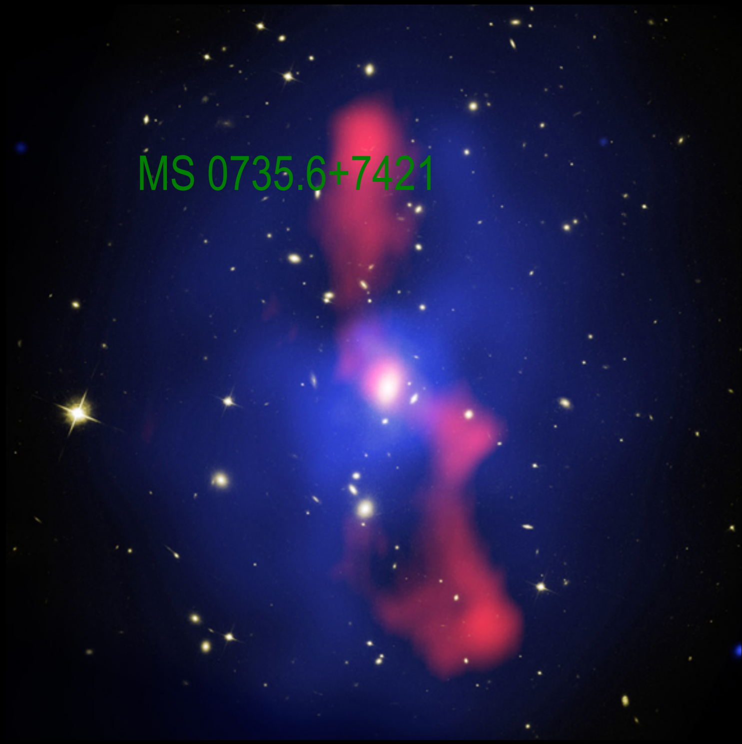
Stopping cluster cooling flows--a (top level) answer: AGN in central elliptical galaxies…

… are the prime candidate for a feedback process that reheats cooling gas and regulates cooling flows

on scales from galaxy groups to massive clusters:

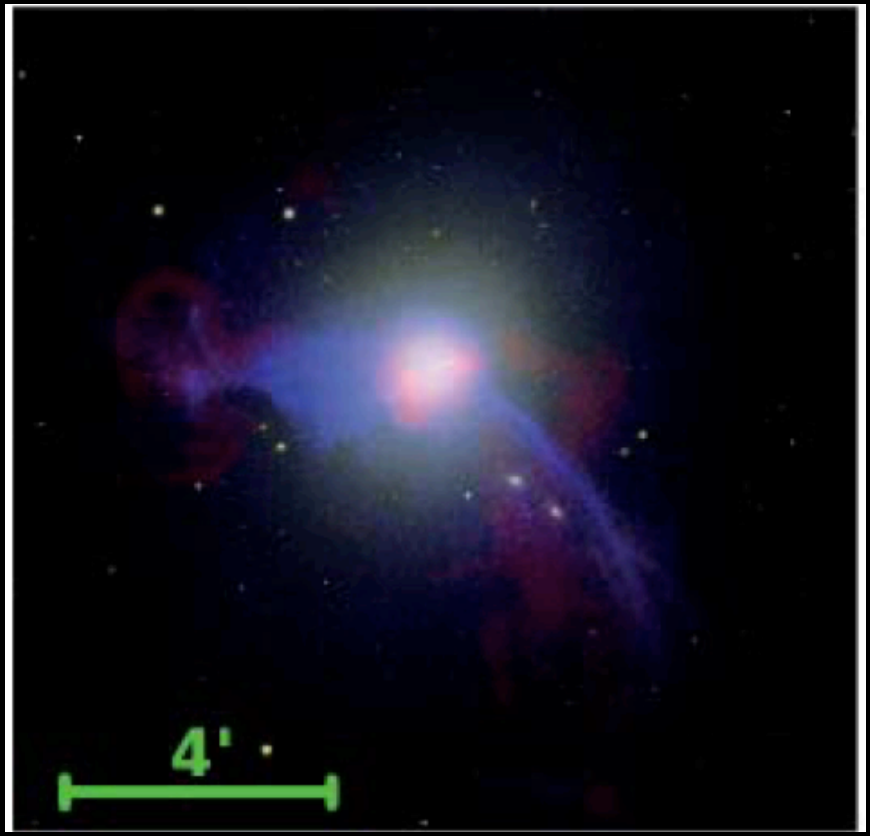


Small X-ray-bright galaxy group (Gitti et al 2010). GMRT 235 MHz contours overlaid on *Chandra* data.



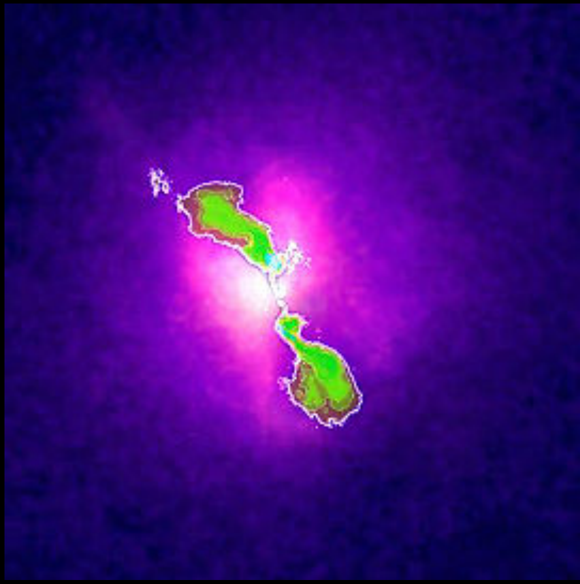
Most powerful measured outburst in a massive cluster (*Chandra*, HST, and VLA: McNamara et al 2006).

Radio (red) and X-ray (blue) Required to understand Feedback



M87. *The X-ray structure was induced by ~10^{58} erg outburst that began 10 Myr ago (Forman et al. 2005). The persistence of the delicate, straight-edge X-ray feature (part of the South West filament) indicates a lack of strong turbulence.*

The regulation of cooling flows in galaxy clusters and groups: Radio/X-ray synergies



Hydra A:
X-ray (Chandra)
with superposed radio

Low-frequency observations: 100's of MHz (continuum)

➔ yield *history and energetics of AGN outbursts*

Now: VLA, GMRT
Future: LOFAR, ASKAP,

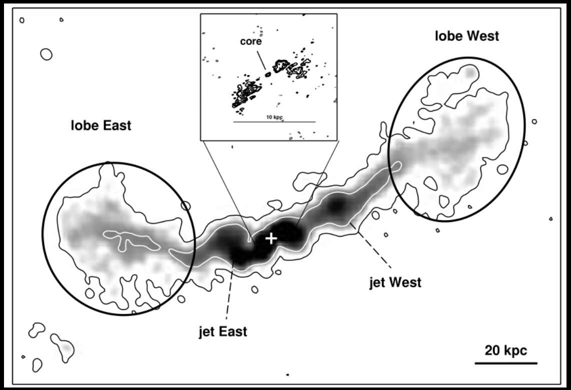
High-frequency observations: 100's of GHz (spectral line)

➔ yield *masses and kinematics of cold molecular gas* (on path to star formation and feeding of central black hole)

Now: SMA, IRAM/PdB
Future: ALMA

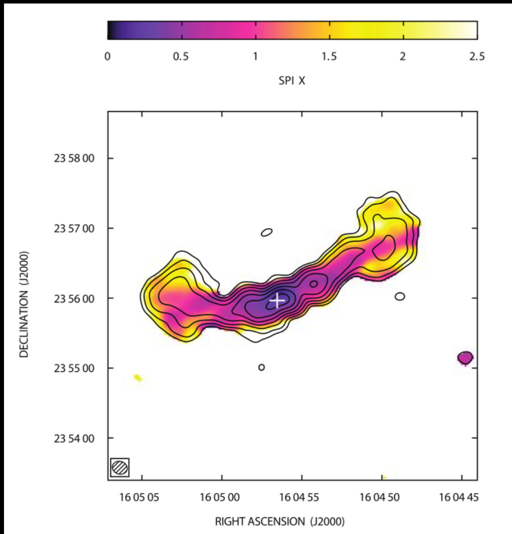
Joint low-frequency radio and X-ray observations yield

- age and history of outburst
- geometry of jets and cavities (sometimes)
- physical parameters of hot gas and estimates of magnetic fields
- measurement of metallicity distributions …



← AWM 4: 610 MHz image (GMRT) with 4.9 GHz insert (VLA) for core

AWM 4: 235-610 MHz spectral index image, with 235 MHz contour overlay →



Giacintucci et al 2008

But important data is missing

- study at higher redshifts ($z \geq 0.5$) needed
- why may powerful outbursts (as revealed by effects on ICM) appear weak in optical and radio?
- mechanisms of jet formation and interaction with surroundings; mechanisms of energy dissipation
- fueling of AGN outbursts
- reduced amount of cooling material => star formation?

} *Molecular line observations: ALMA*

What happens to cluster and group gas that does cool?

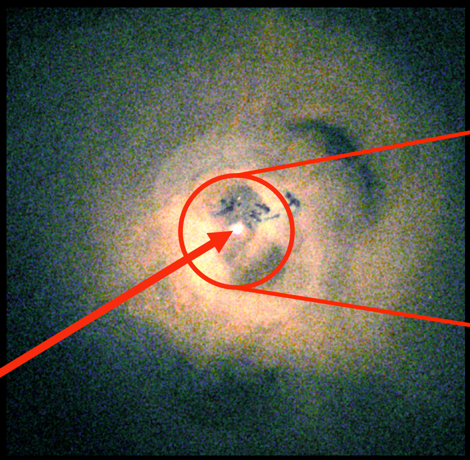
- Star formation
  - Modest rates of SF are common is cluster- and group-center ellipticals
  - Attributed to cooling flows or to mergers
    (but only cooling flows provide the needed feedback mechanism)
- Feeding of central AGN?
  - Could be through accretion of hot atmosphere (Bondi mechanism), stars, or *cold gas*
  - Some cold gas will be molecular, and traceable though line emission
- CO has been detected in cores of central galaxies in cooling-flow clusters
  - Several single-dish surveys (Edge 2001, Salome & Combes 2003 et seq)
  - ~25 – 30% of targets show detections
  - Gas masses few x 10^8 to few x 10^{10} M_{sun}

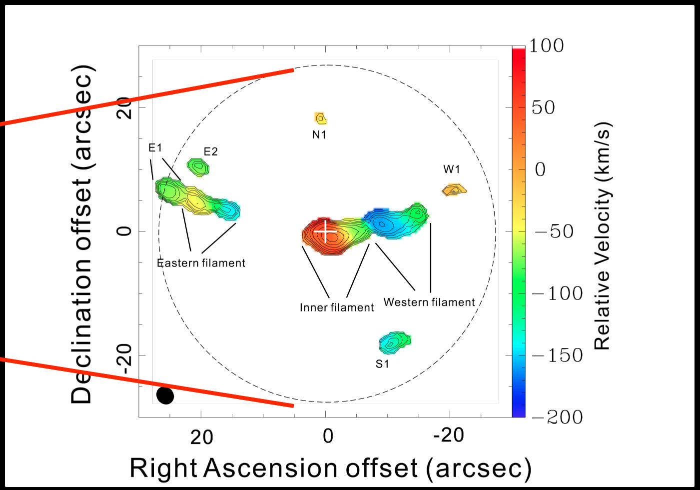
Molecular gas in cooling cores in detail

- Interferometry required; low-lying CO rotational transitions are preferred
- SMA and Plateau de Bure have been used
- With current instrumentation: “the best target in the sky”: Perseus A = NGC 1275 = 3C84
    - Brightest cluster in X-ray sky
    - Only target at all well-studied in CO

Radio spectral line observations provide key *kinematic information*

X-ray and
radio peak:
active nucleus



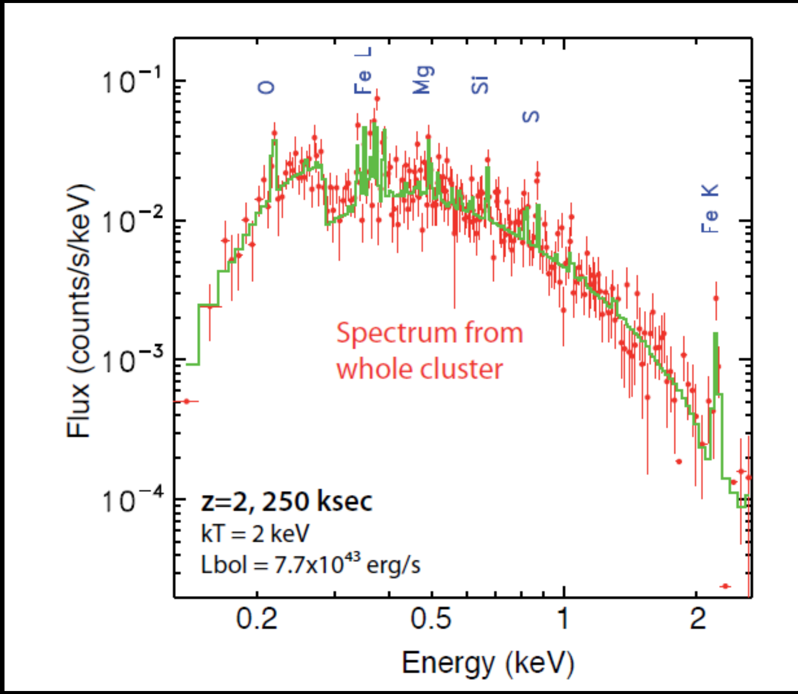


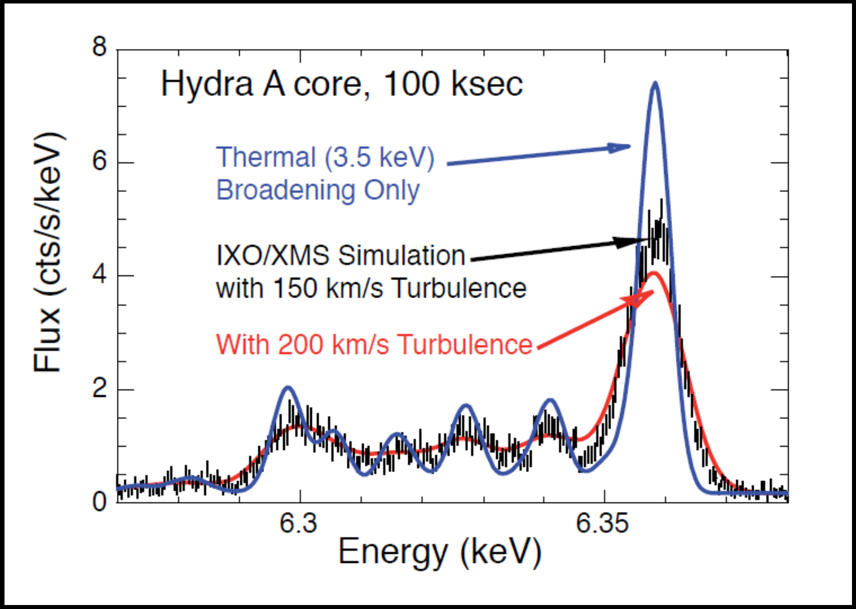
Chandra image of Perseus, showing multiple X-ray cavities

Perseus central 40” in J=2-1 line of CO, from SMA data. (Lim et al 2008)

ALMA will provide this or greater level of detail for *numerous targets*, with *fast integration times*, providing a meaningful overview of role of cold gas.

Accurate X-ray Temperatures and measurement of Turbulence required for S/Z measurements

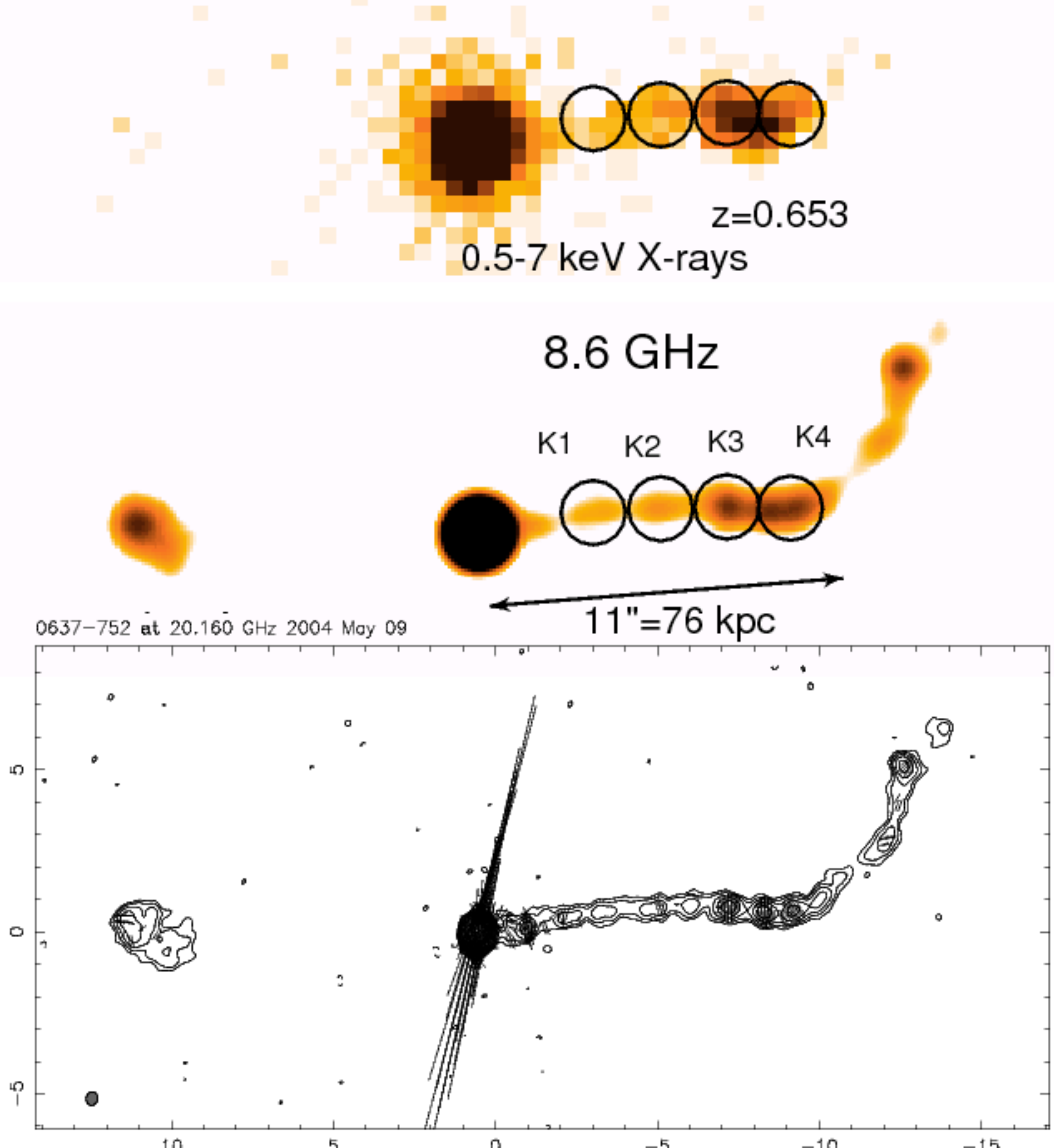


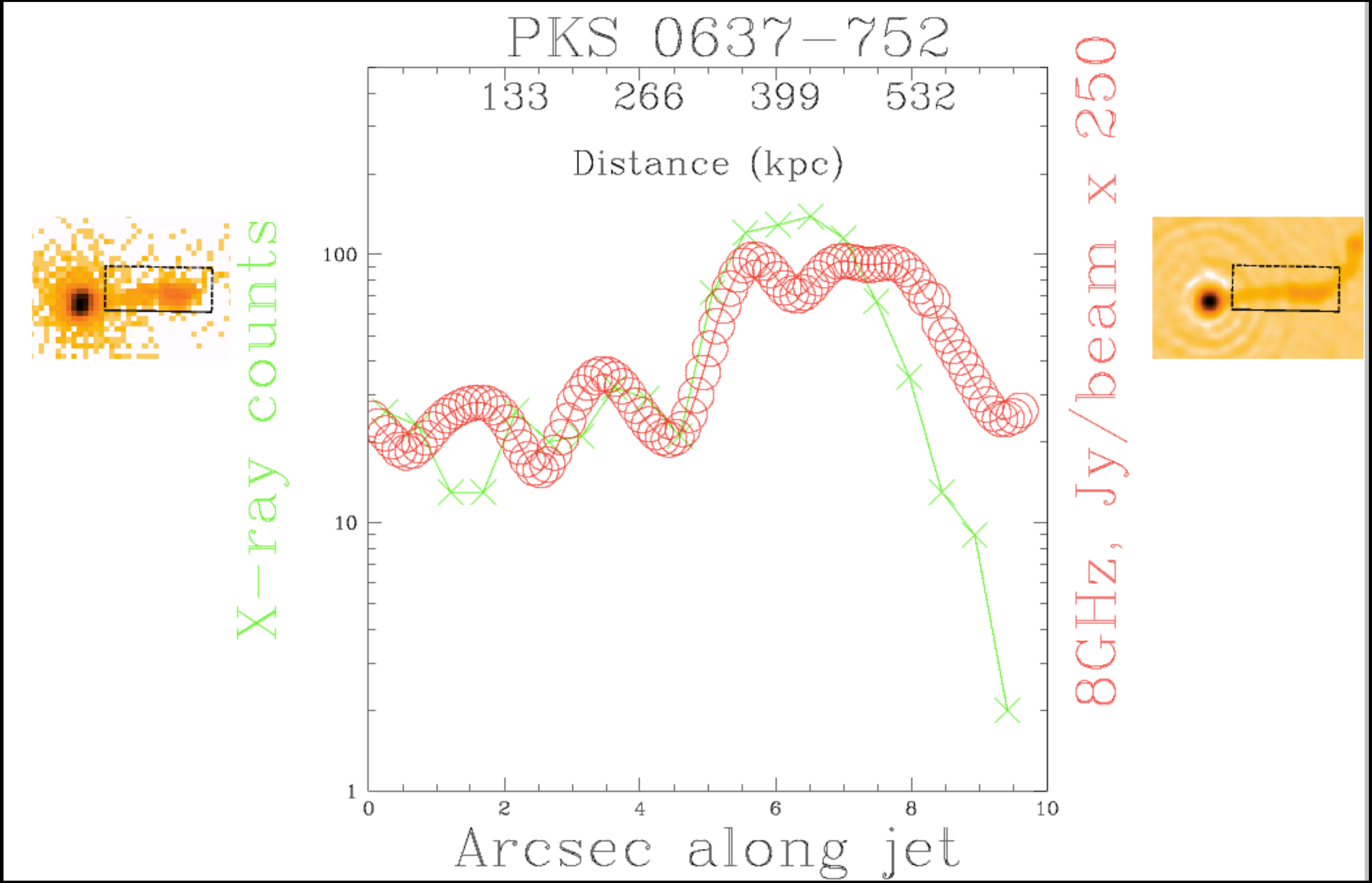


At z=2, the global temperature and abundances can be measured to an accuracy of ±3% for kT, and to ±3.5% for O and Mg, ±25% for Si and S, and ±15% for Fe.

IXO spectrum of Fe XXV lines shows that turbulence of ~150 km/s or ~200 km/s may be distinguished from thermal broadening alone. Simulated IXO/XMS data in black, models in color.

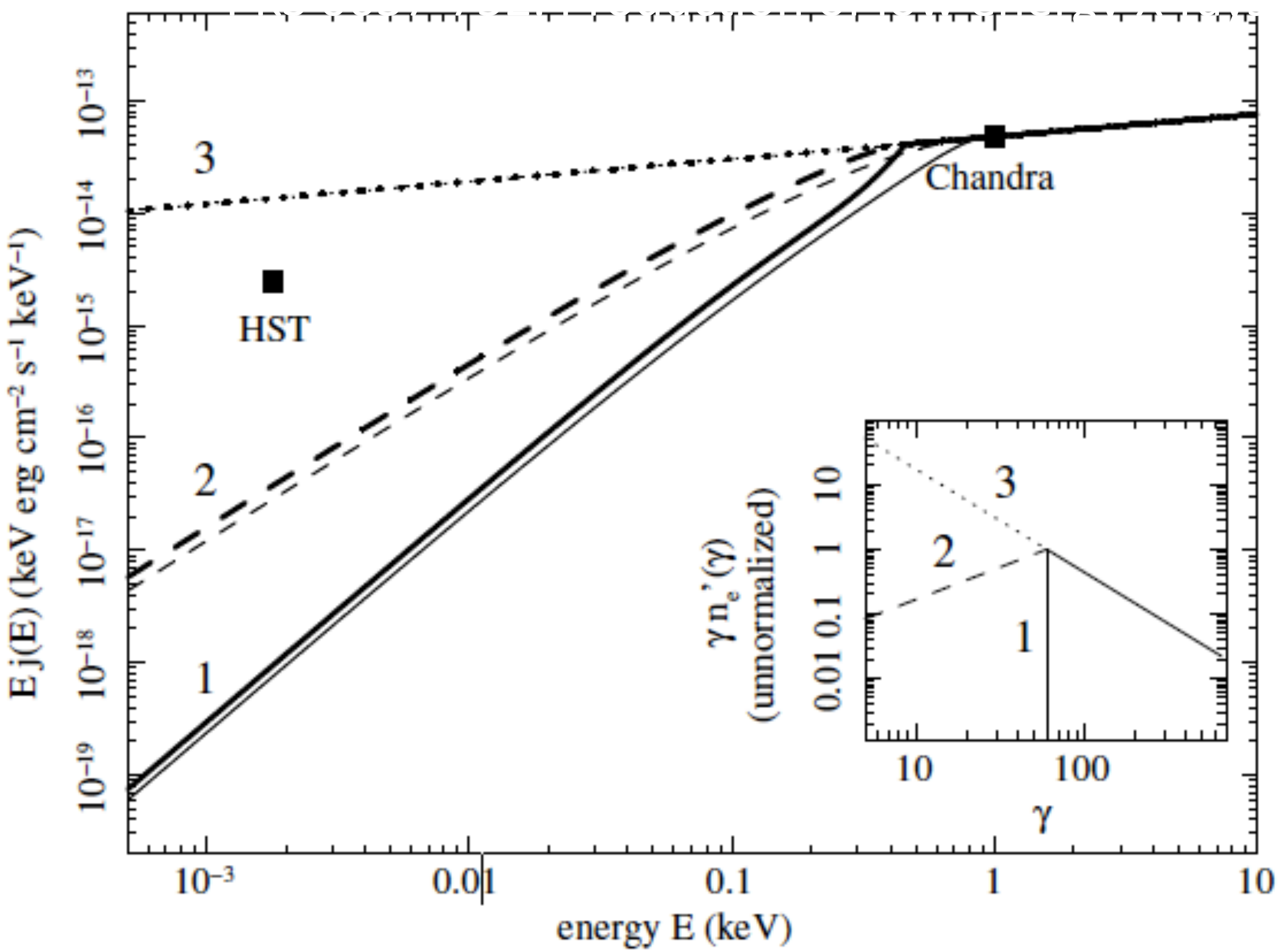
PKS 0637-752


z=0.653
0.5-7 keV X-rays
8.6 GHz
K1
K2
K3
K4
11"=76 kpc
0637-752 at 20.160 GHz 2004 May 09



X-ray and radio track within a factor 2
=>Origin from a single electron population

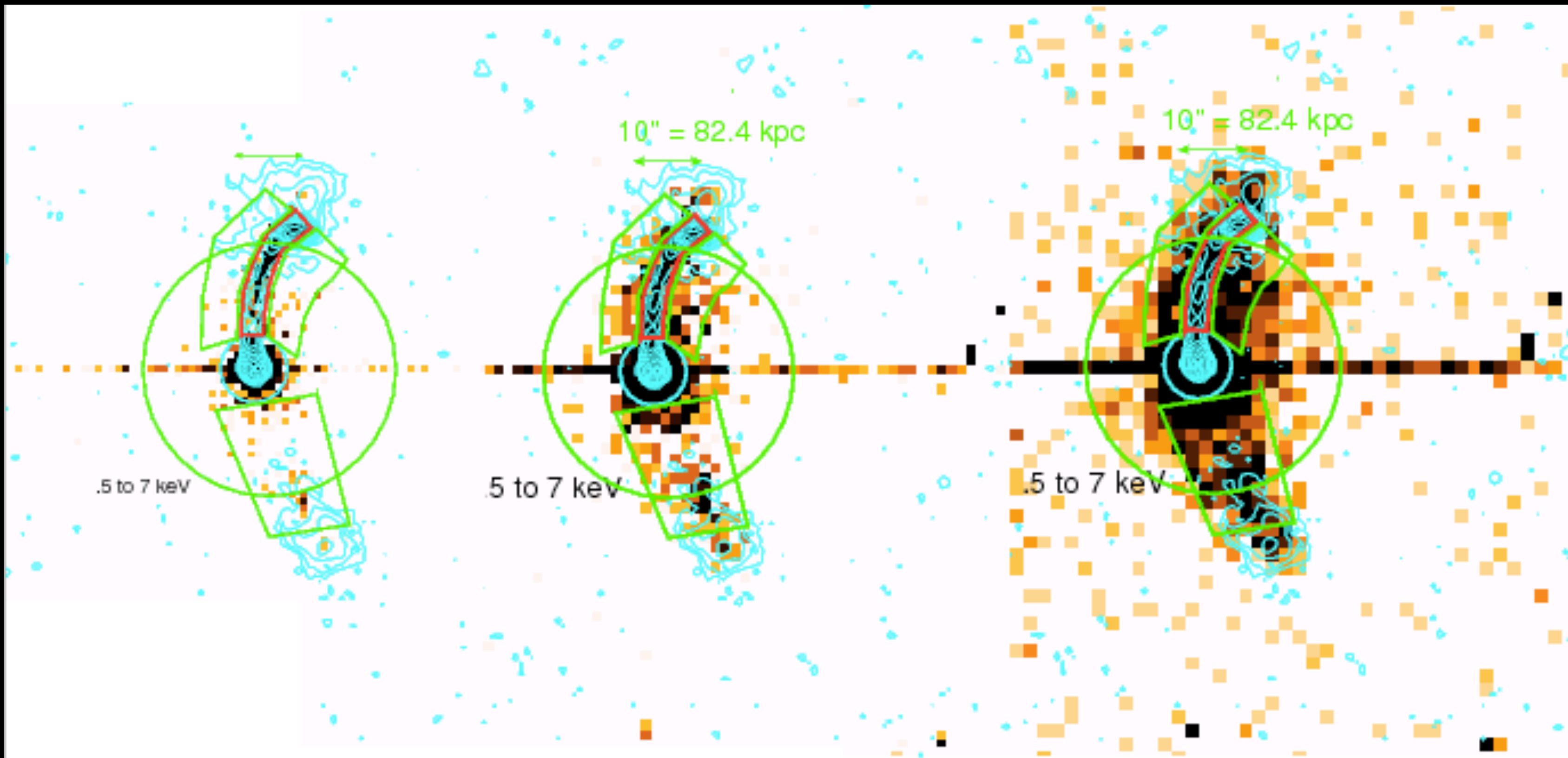
Low energy cutoff to the relativistic electrons:



Mueller and Schwartz, 2009ApJ...693..648

PKS 1055+210

z=1.11

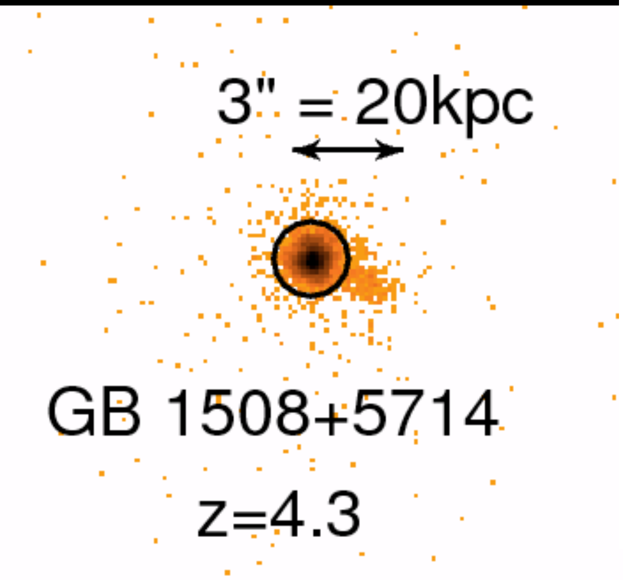


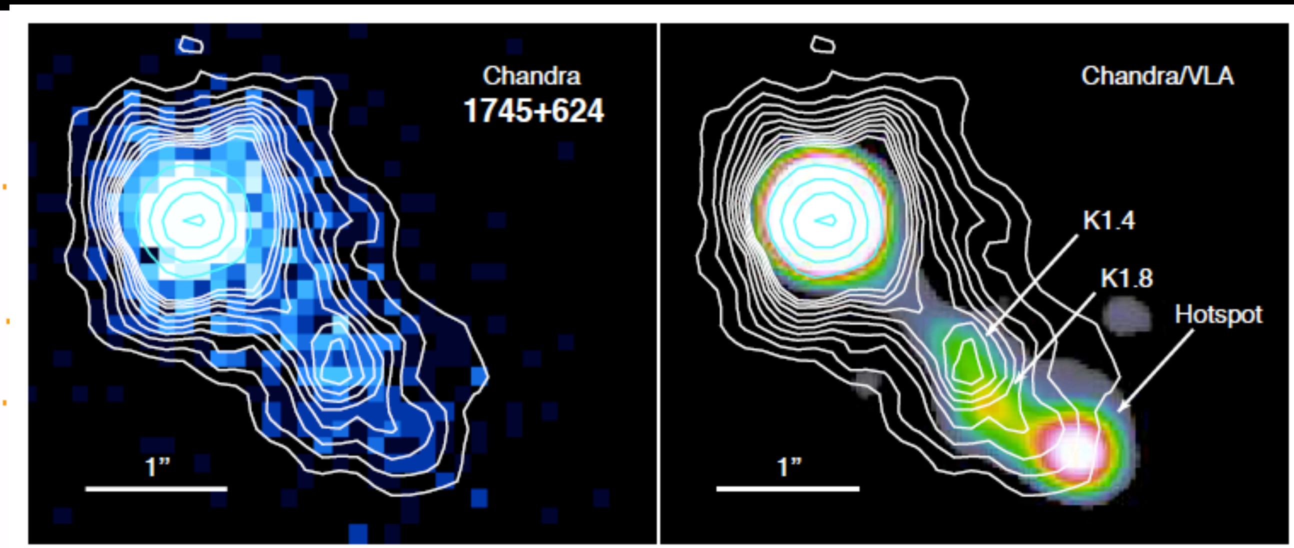
Jet Lobes Cluster?

Symmetric lobes show the existence of “invisible,” symmetric counterjet.

High Redshift Jets

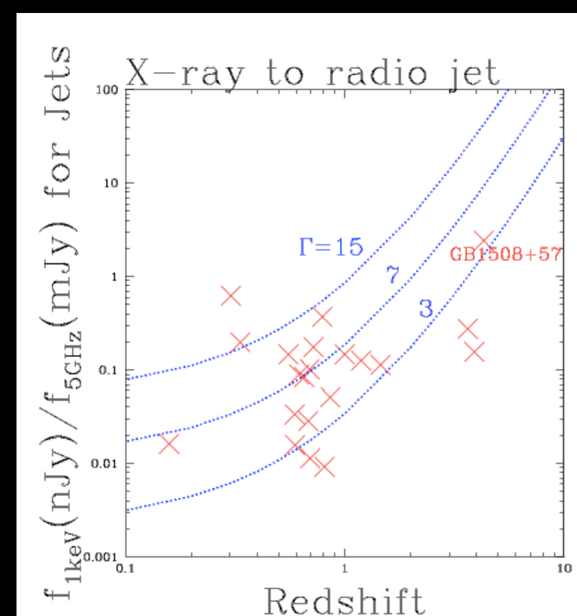
Cheung et al., 2006ApJ..650..679





z=3.89

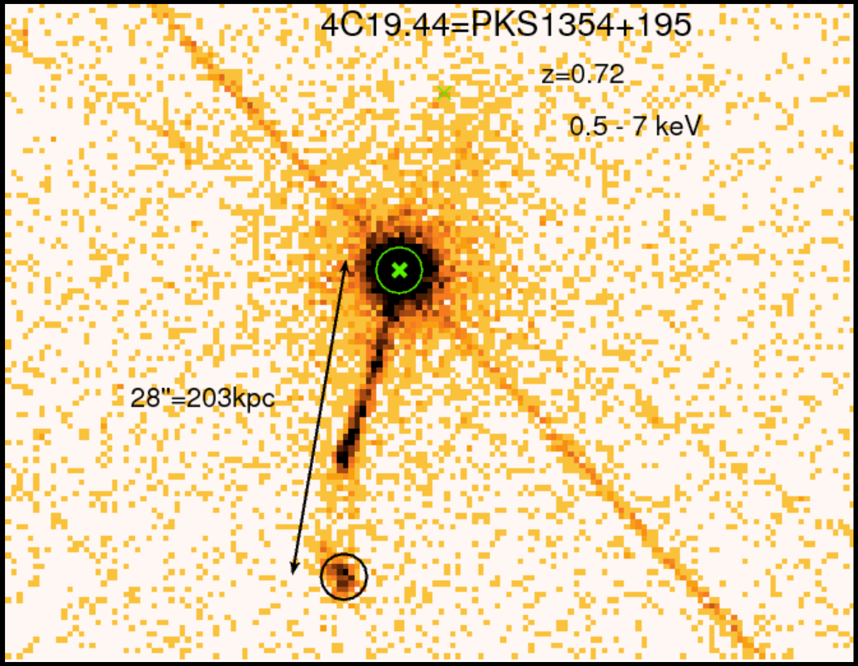
Siemiginowska et al.
2003ApJ...598L..15



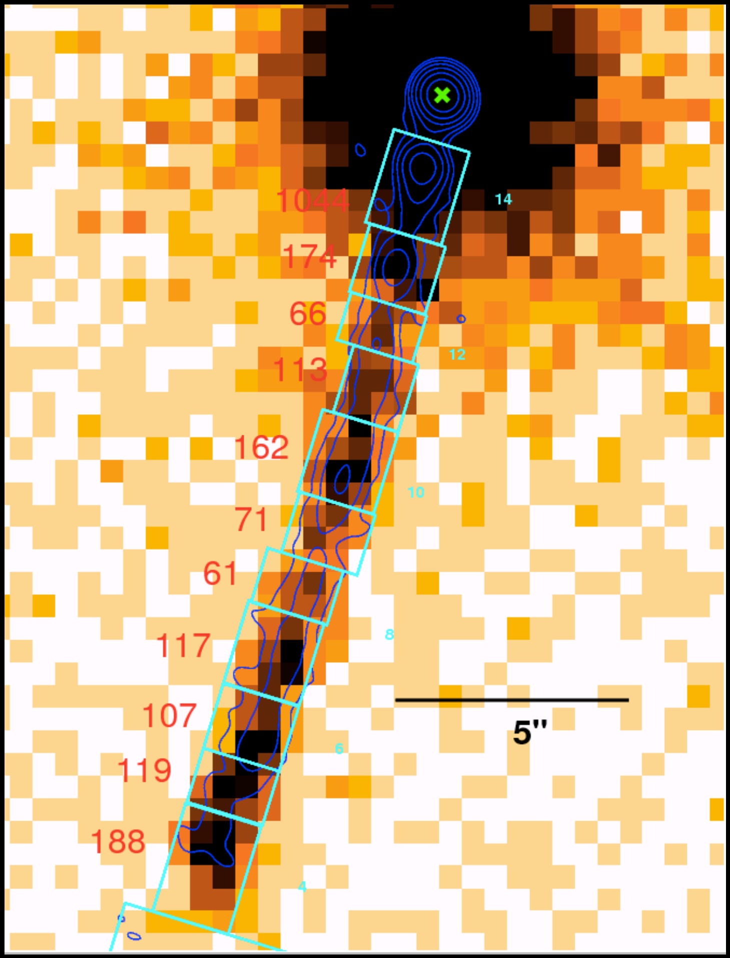
Activity in the early universe.

Ratio f_X/f_R should increase ≈ $(1+z)^4$

Calculation of Kinetic Flux: PKS 1354+195

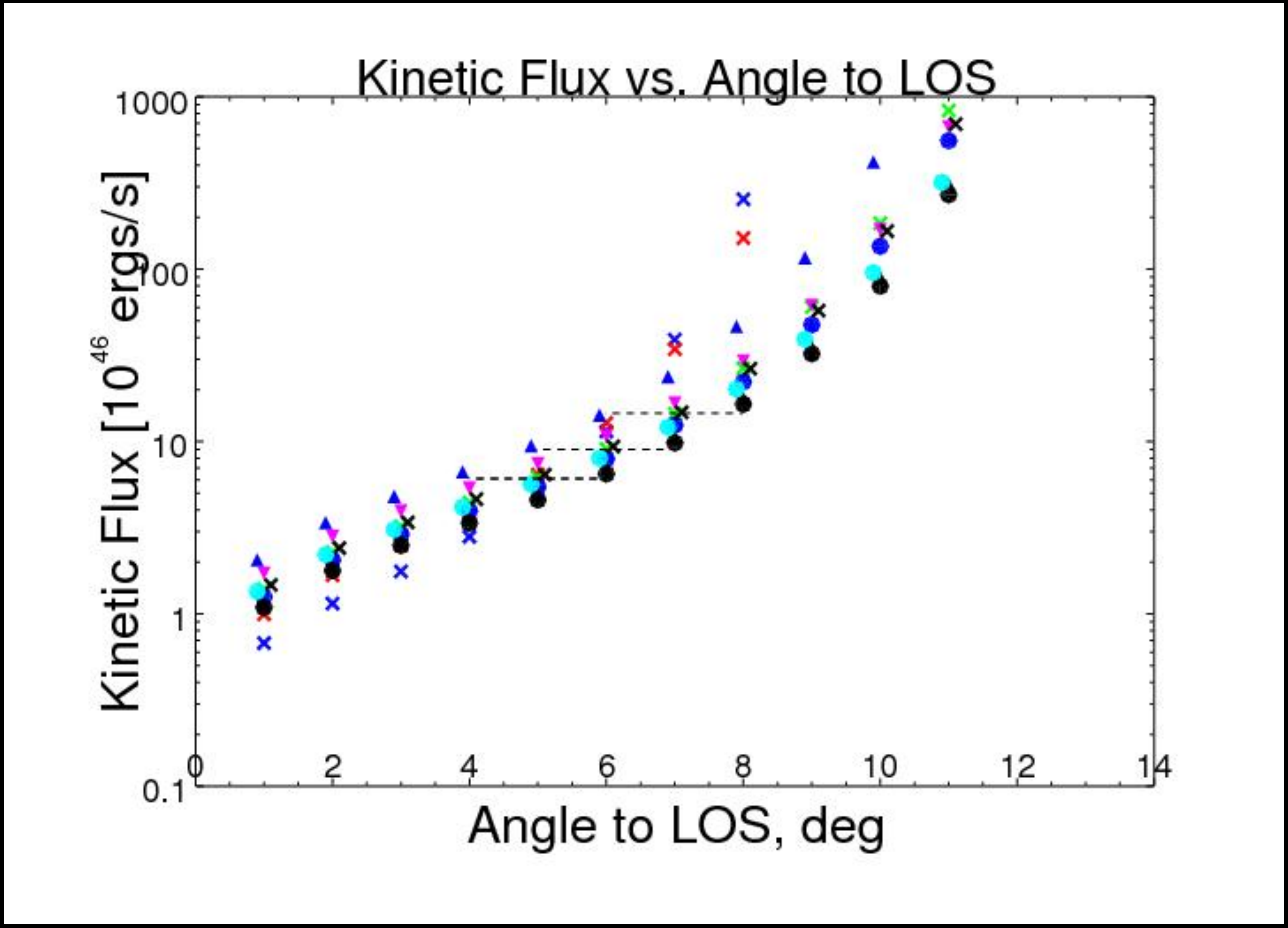


Harris et al, in preparation
Schwartz et al., in preparation



Long, straight jet. Angle and geometry may be nearly constant along jet. Allow Γ≠δ, assume kinetic flux is constant!

Kinetic Flux: PKS 1354+195



Mean angle, 5° to 7°. Angle deviation $\delta\theta \approx \pm 1°$. Kinetic Flux = $9x10^{46}$

Chandra Joint Programs

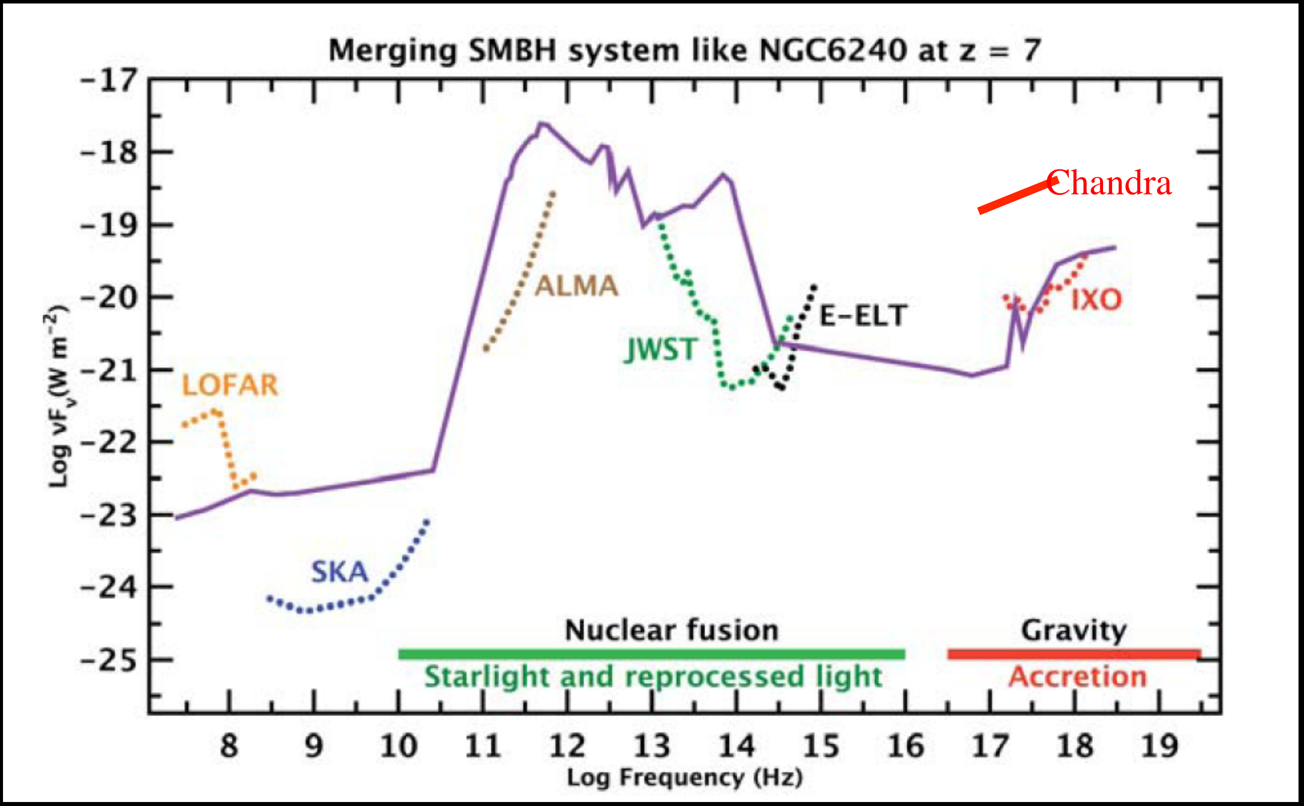
- Chandra peer review can award time on our Joint Partner facilities, for projects that are “fundamentally multiwavelength”
- Avoids proposal double jeopardy
- Standards are high and CXO full allotments *rarely* used

Joint Partner Agreements

- HST: 100 orbits, 400ks reciprocal
- XMM: 400 ksecs, reciprocal
- Spitzer: 60 hours
- Suzaku: 500ksec
- NOAO: up to 5% of all telescopes
  - Full proposal needed for Gemini (int’l TAC)
- NRAO: 3% of EVLA, VLBA and GBT observing time
  - maximum of 5% in any configuration/time period
  - looking forward to including ALMA (int’l TAC)

Backup slide

Eleven Decades in Frequency Required to understand Growth of SMBH

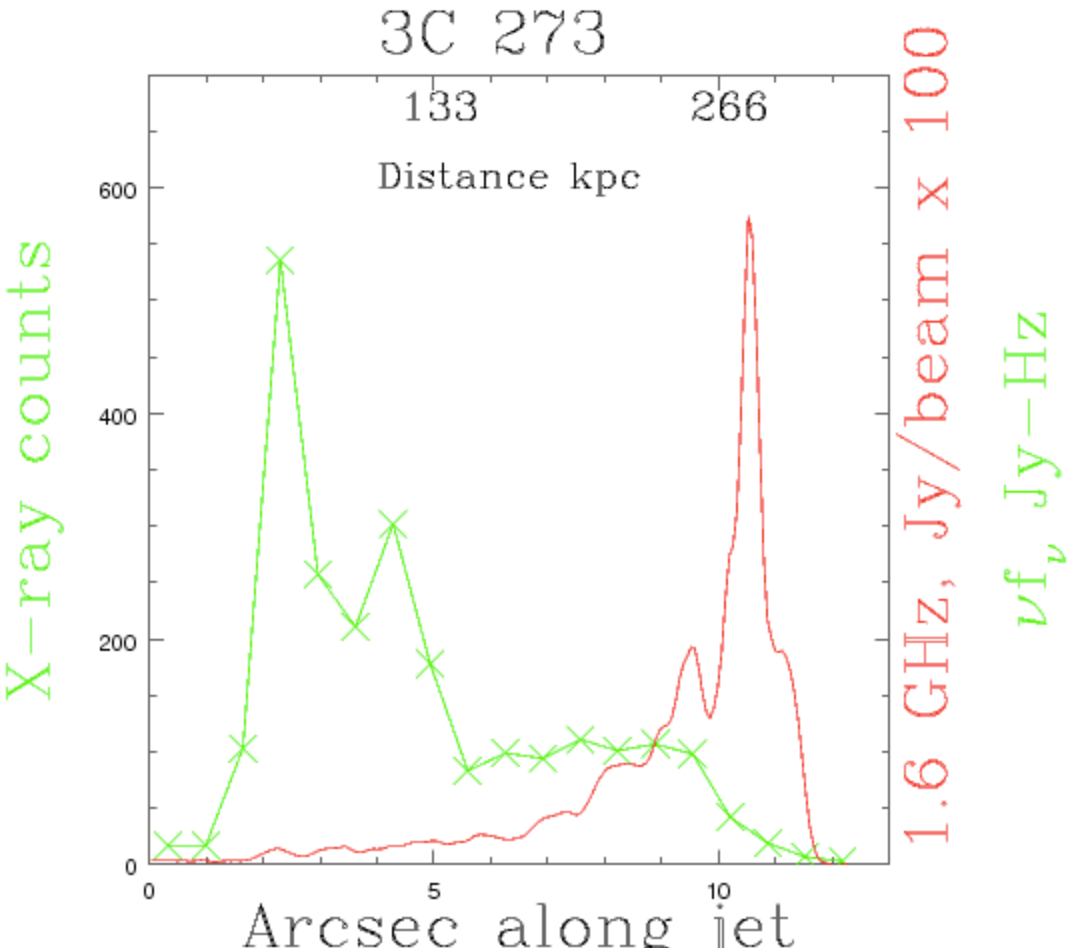


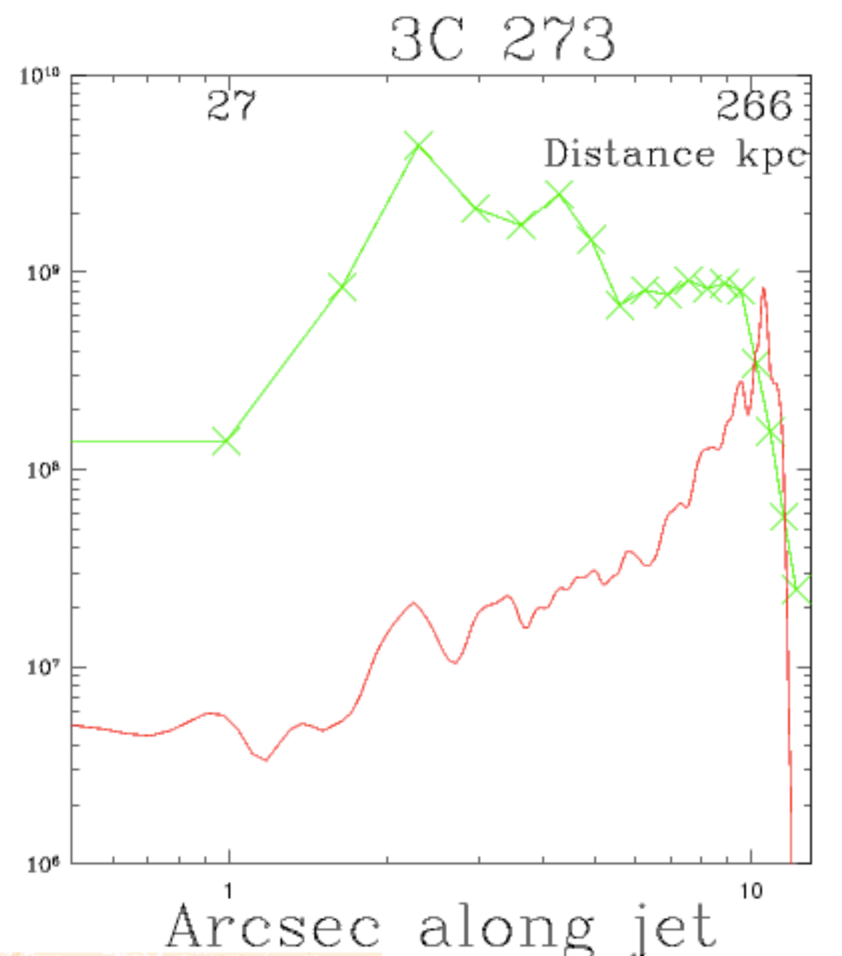
Sensitivity of future key observatories, along with the spectrum of a galaxy with strong star formation and a merging massive binary black hole, like NGC 6240 at z=7. Below 10^{16} Hz emission is ultimately due to nuclear fusion and above to gravity. Only IXO is able to detect unambiguously the direct signal from an accreting binary super-massive black hole.

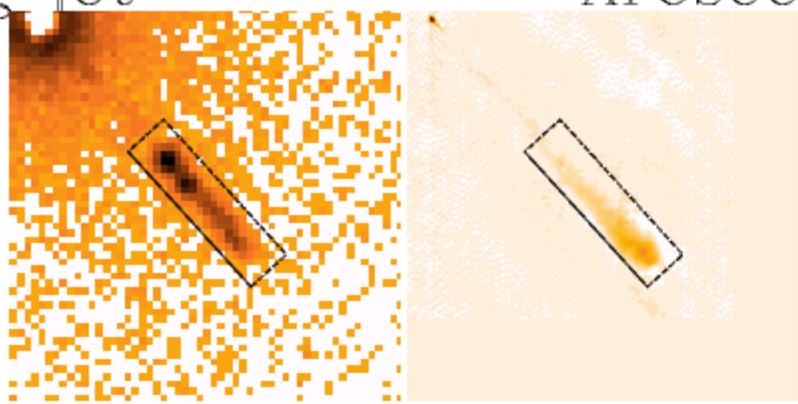
Outbursts from Clusters to Galaxies

SOURCE	SHOCK RADIUS (kpc)	ENERGY (10^{61} erg)	AGE (My)	MEAN POWER (10^{46} erg/s)	ΔM (10^{8} M_{sun})
MS0735.6	230	5.7	104	1.7	3
Hydra A	210	0.9	136	0.2	0.5
M87	14	0.0008	11	0.0024	0.0005
NGC4636	5	0.00006	3	0.0007	0.00003

- Clusters to galaxies (kT = 5, 2.5, 0.7)
- Late growth of SMBH in "old" stellar population systems
- Grow stellar mass as well - see moderate star formation
- Birzan et al. (2004) - enough energy in bubbles to balance cooling in 50% of systems


3C 273
133
266
Distance kpc
600
400
200
0
0
5
10
Arcsec along jet
X−ray counts
1.6 GHz, Jy/beam x 100


3C 273
27
266
Distance kpc
10^{10}
10^9
10^8
10^7
10^6
1
10
Arcsec along jet
νf_ν Jy−Hz



Deriving magnetic field, H, and Lorentz factor, Γ

Doppler factor $\delta = 1/(\Gamma(1-\beta \cos\theta))$

$H_{min} = H / \delta$

$H_{cmb} = \Gamma H_{FM}$

$H_{cmb} = H_{min}$

Unknown angle usually finessed by taking $\Gamma=\delta$, or $\Gamma=$ some fixed number.