Radio AGN feedback on galaxy scales: What can Athena show us?

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Jets and lobes in small sources

- Why?
  - RL phase affects environment dramatically: fundamental to understand timescales of SF triggering/quenching and AGN feedback
- Where?
  - Low z for max spatial resolution and S/N
    - Low power systems
    - Early stage high-power systems (less likely in spirals, but see e.g. Hota et. al. 2011)
- How?
  - X-rays + radio to study extended structure

RADIO

OPTICAL

Seyferts and Spirals

- 30+ known Seyferts with extended radio structures (e.g. Hota & Saikia 2006, Gallimore et. al. 2006)
  - Not all Seyferts are spirals!
  - Few examples of powerful radio galaxies in spirals (Hota et. al. 2011, Keel et. al. 2006)
  - Jets and lobes may not be directly visible but they may still be there...
- Jets and lobes in Seyferts are typically a few kpc long, radio cores are very weak (e.g. Middelberg 2004)

SN 1996cr

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Y (X-RAY/OPTICAL)

Bubbles and shocks in small sources

- Jet → ISM E transfer
  - Age ~ 10^6-10^8 yr
  - E ~ 10^{56} erg, equiv to ~10^5 SN
- Overpressure, T jump → shocks
  - M ~ 3-6

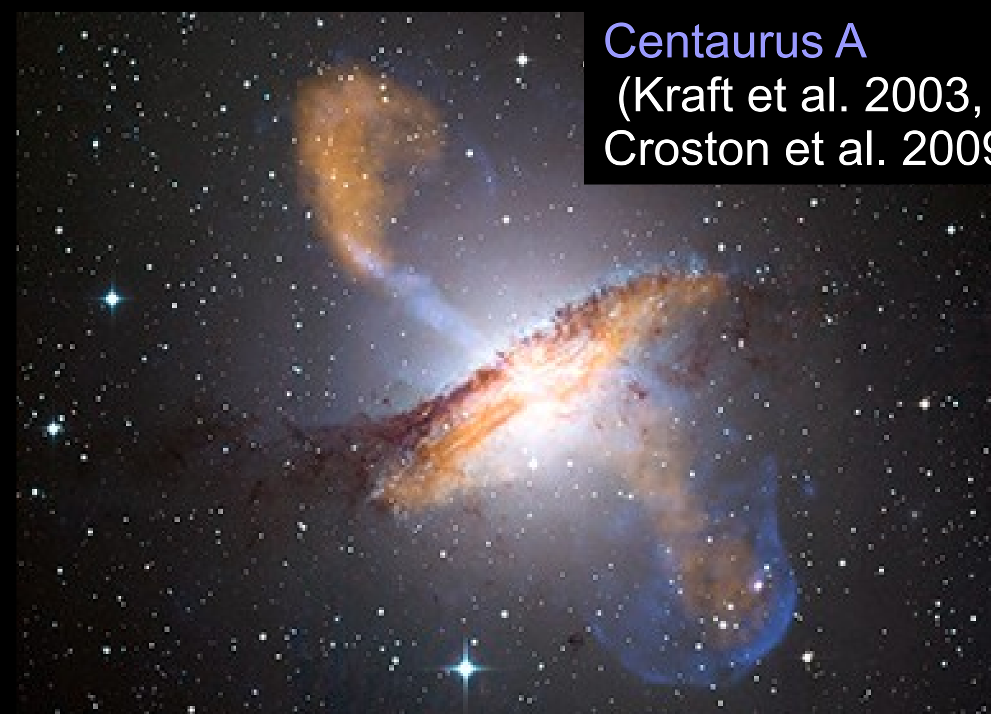
•Energetics (Jet + lobes/bubbles + shock)

•Timescales

•Feedback, SF triggering/quenching

•Power/mass scaling

•Morphology dependence



Centaurus A
(Kraft et al. 2003, Croston et al. 2009)

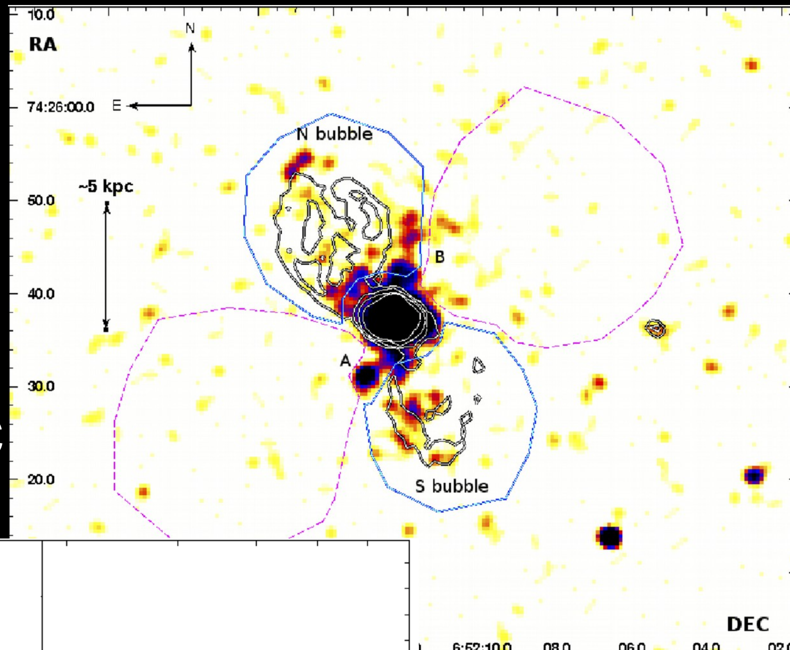
Markarian 6: Chandra/XMM

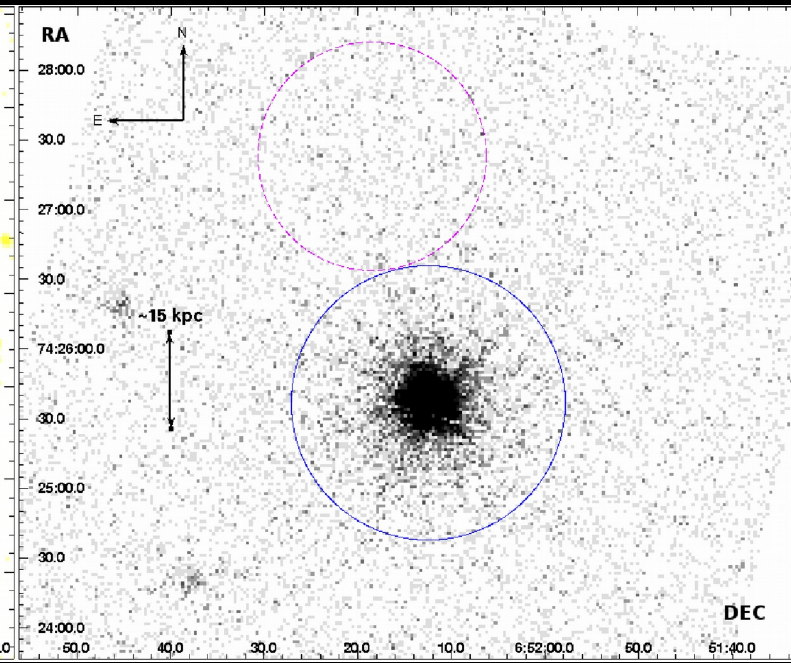
S0

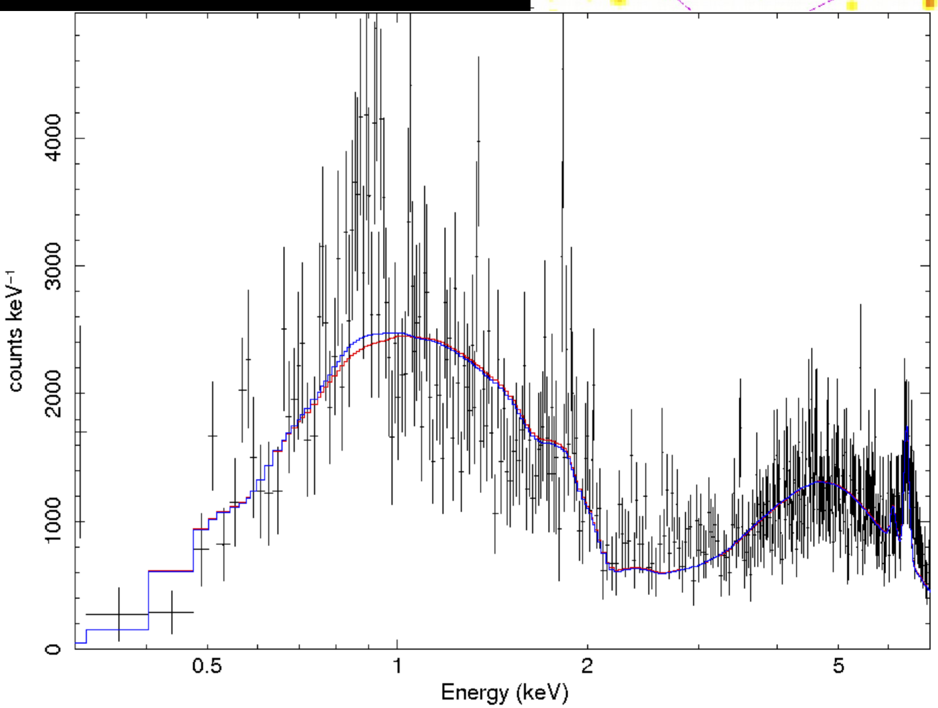
Sy 1.5

D ~78 Mpc

Lobes ~7.5 kpc







Mingo et. al. 2011

Shock ~15% flux 0.7-1.1 keV

KT ~ 0.9 keV

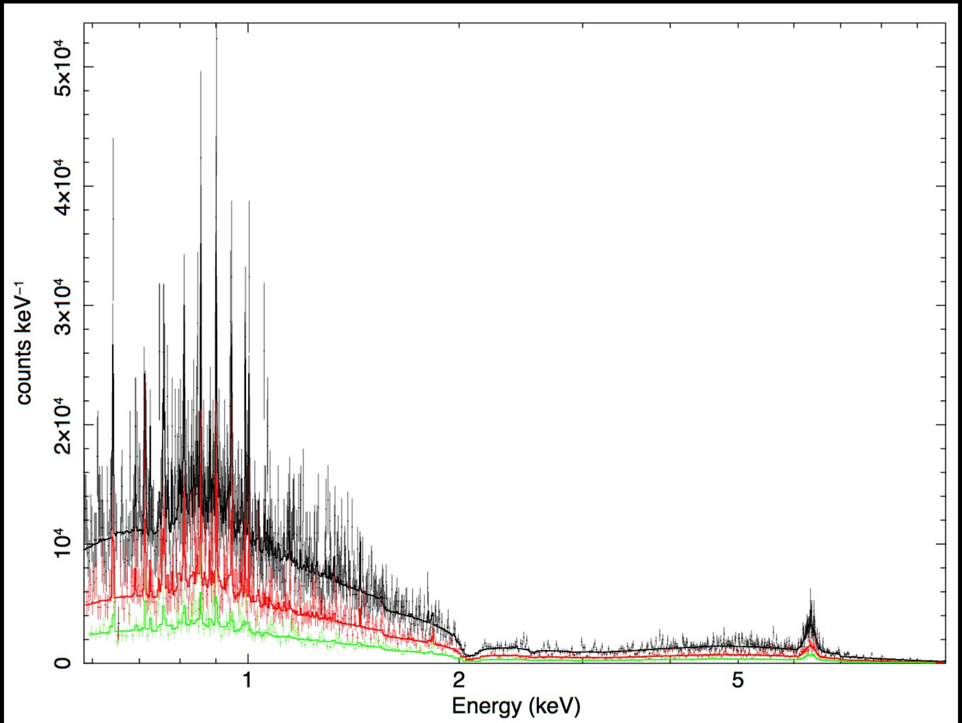
Mach number: 3.9 (+1.9 -1.0)

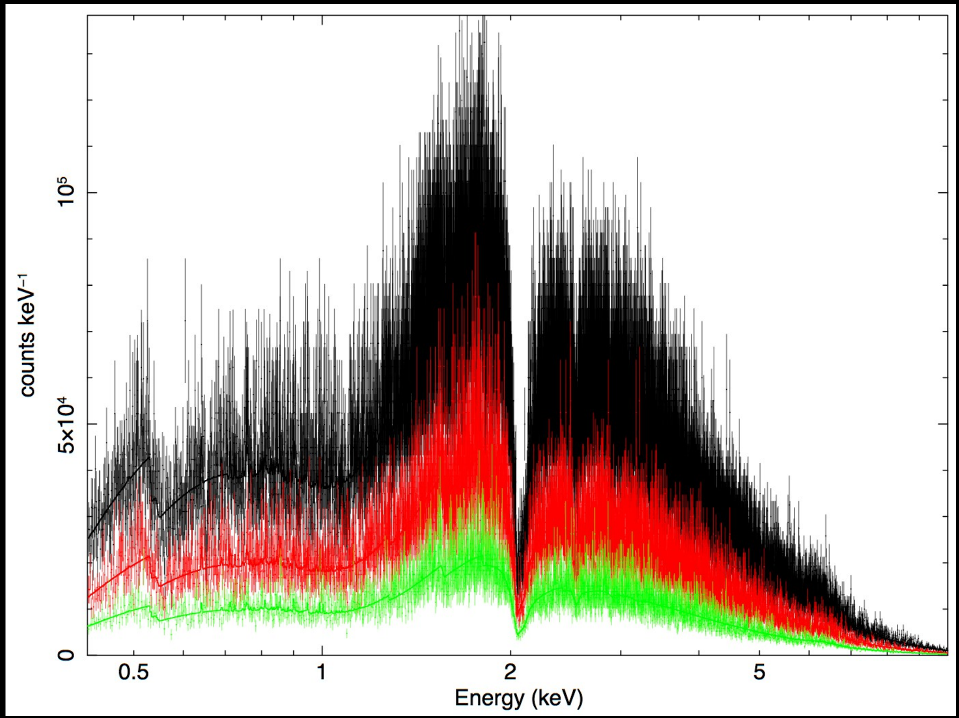
Total E (thermal + kinetic): 2.6-4.6x10^{56} erg

Timescale: 0.3-1.1x10^{7} years

Variable nuclear obscuration

Markarian 6: Athena





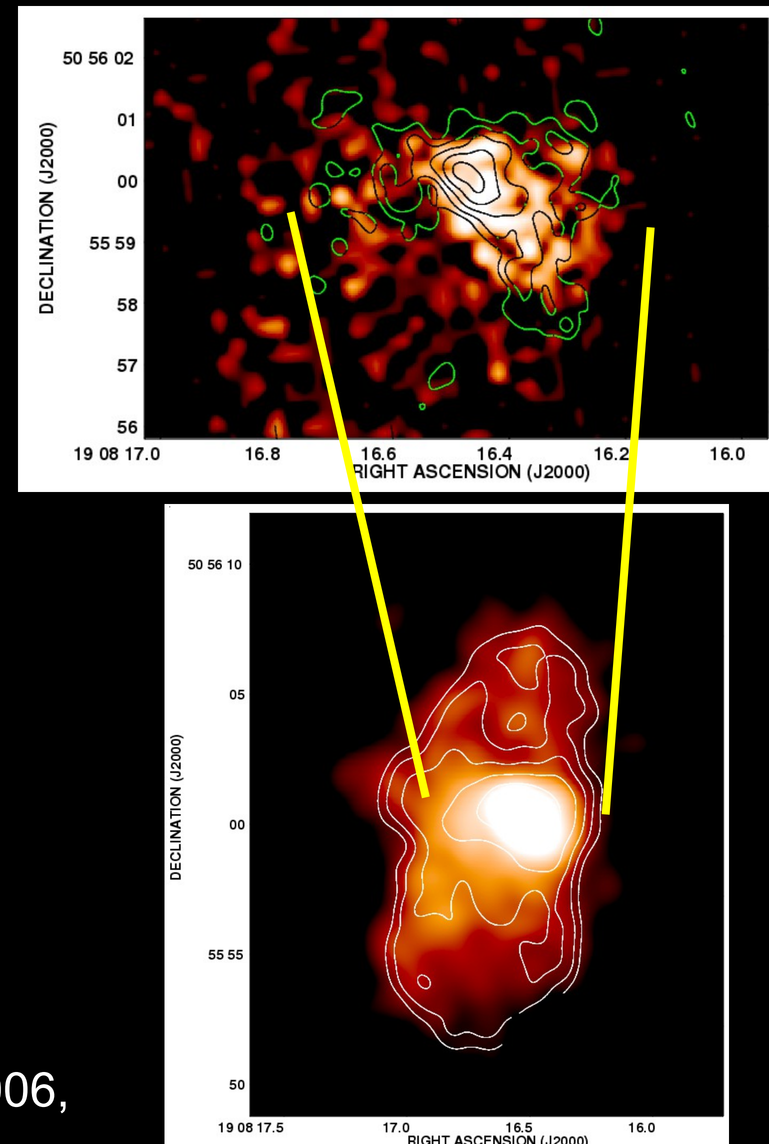
NH ~3x10^23
20 ks constrain kT with >90% accuracy

NH ~2x10^22
20 ks constrain kT with ~80% accuracy

→ Possible to catch shocked gas with short exposures
(if we know what we are looking for...)

Other candidates: NGC 6764

- The X-ray bubbles (~ 2kpc) are 2x more luminous than the starburst wind → jet-driven shock
- V~740 km/s, E~10^{56} erg, t~10^{6} yr
- Emission is not clearly edge-brightened, perhaps because of very dense ISM (Sy2 in SB barred spiral)



Croston et. al. 2008, Hota & Saikia 2006, Kharb et. Al. 2010

Other candidates: the Circinus Galaxy

Shock heating $\frac{\rho_{out}}{\rho_{shell}} \rightarrow \frac{\Gamma+1}{\Gamma-1} = 4$

$$M = \sqrt{\frac{4(\Gamma+1)(T_{shell}/T_{out})+(\Gamma-1)}{2\Gamma}}$$

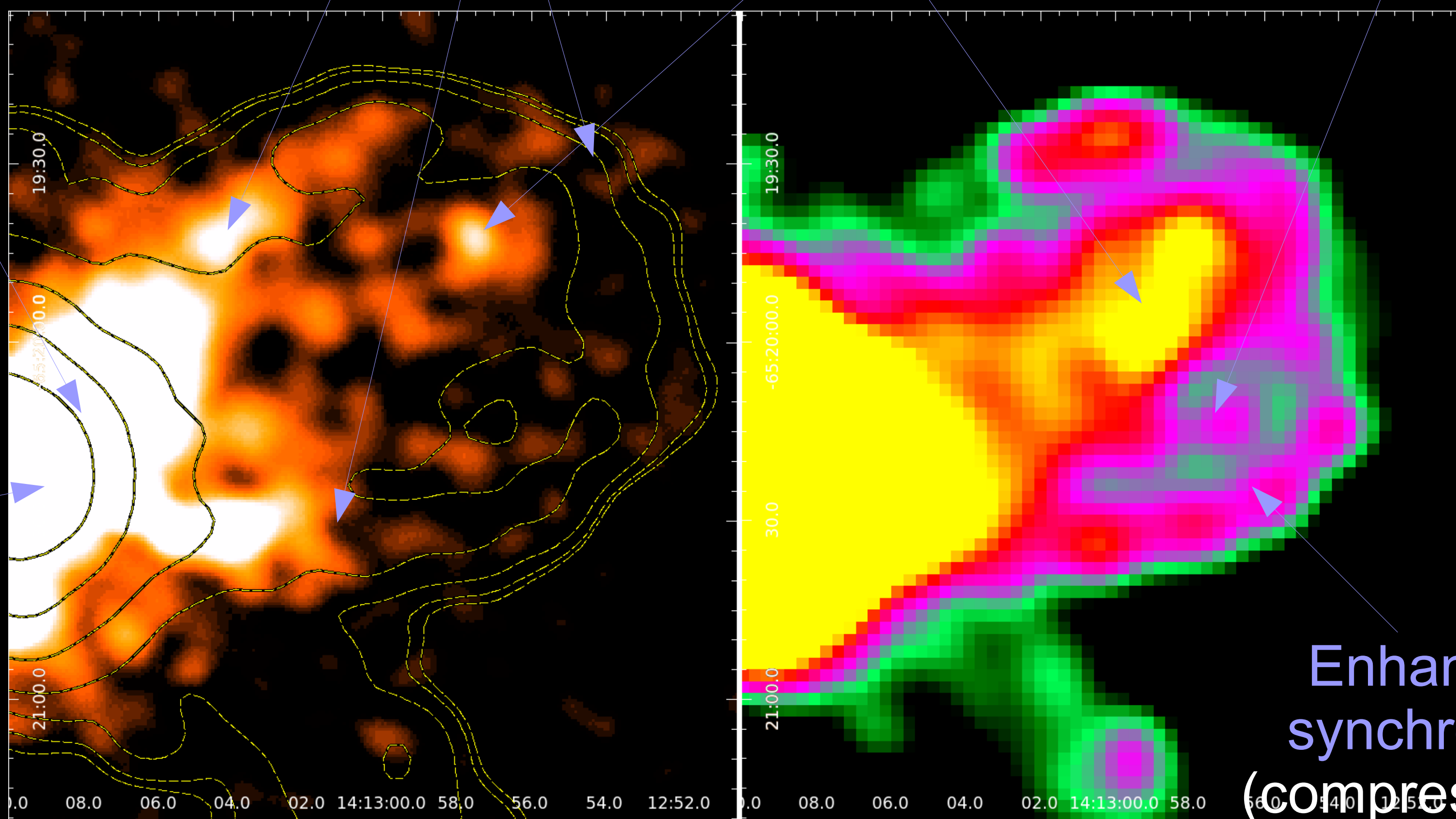
Synchrotron

$$\nu_S = \frac{\gamma^2 e B}{2\pi m_e c} \qquad \tau = \frac{5\times10^8}{B^2\gamma}\ s$$

Photoionization

Hotspot

Mingo et. al. 2012



AGN
(nearest Sy2)

Enhanced synchrotron (compression + B amplification)

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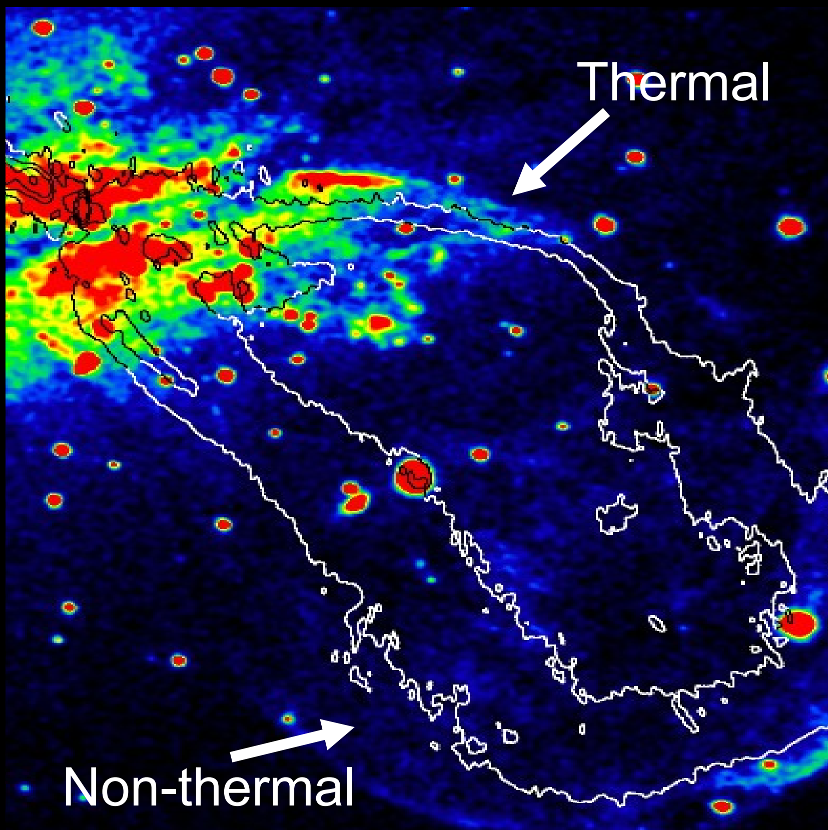
Other candidates

- NGC 1068 (Young et. el. 2001)

L (2-10 keV) ~ 10^41 erg/s

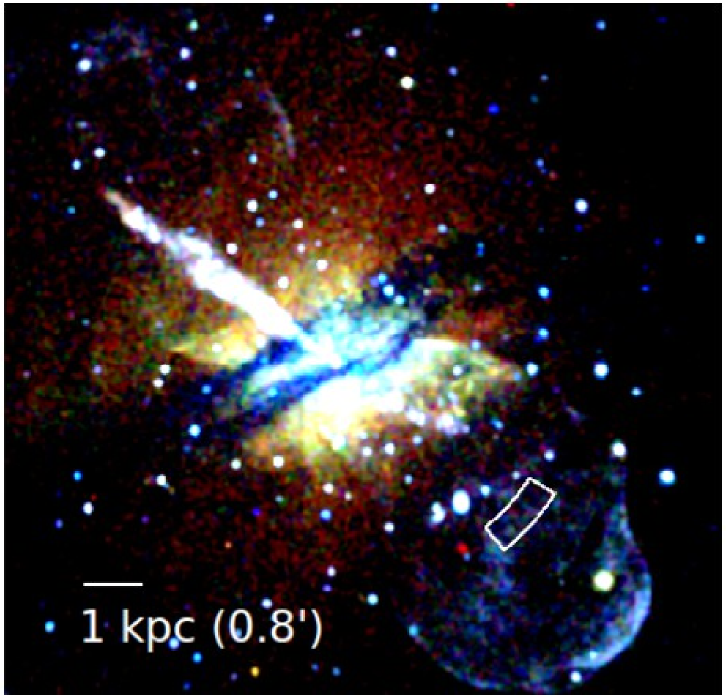
- M 51 (Terashima & Wilson 2001)
  - V~690 km/s, E_th~10^{54} erg (< E_kin)
- NGC 3079
  - Coexistence of jet-driven and star-driven outflows (Cecil et. al. 2001, Irwin & Saikia 2001)
- See also Hota & Saikia 2006

Shocks in radio galaxies: Centaurus A



- Original motivation: from min E arguments we know RG lobes have to drive shocks
- Thermal emission → shock conditions
- Pressure jump ~10x near the nucleus → M~2.8, V~860 km/s
- Best example of shocks, IC in the lobes
  - IC is elusive! E.g. in Circinus IC X-ray L is ~100x smaller than the thermal L

Centaurus A



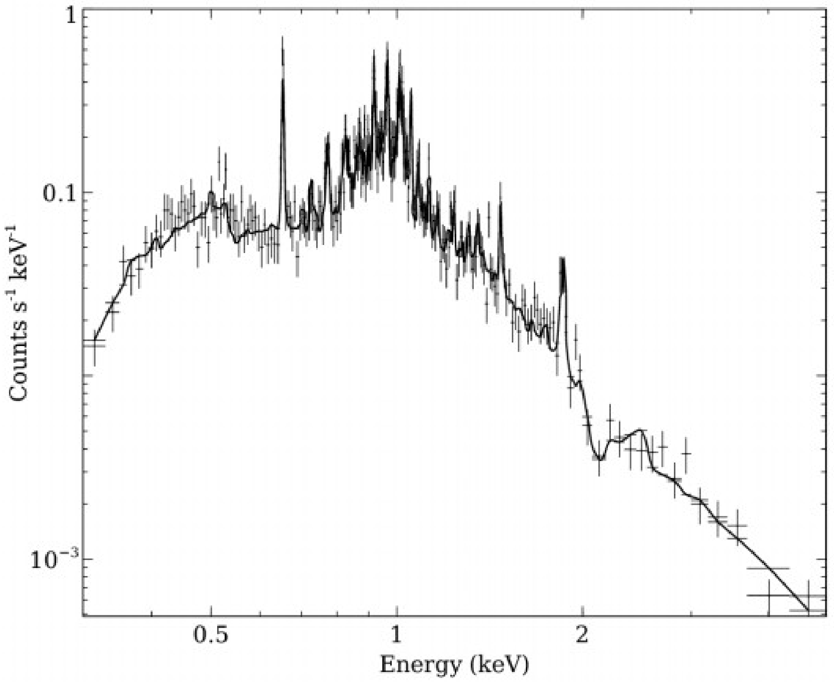


Fig. 5. Simulated WFI pseudo-colour image (l) and X-IFU spectrum (r) from the region indicated, for a 50-ks observation of Centaurus A, demonstrating *Athena+*'s ability to obtain the first direct measurements of advance speed for a strong radio-lobe shock. The shock speed can be determined to within 10% via measurements of line broadening from small regions of the X-ray shell emission dominated by thermal emission (Croston et al. 2009).

See Croston, Sanders et al's Athena science paper (arXiv:1306.2323)

Power scaling

System	Type	L 1.4 GHz W/Hz/sr	E_tot (erg)
Cen A	E	1.5×10^{23}	10^{57}
NGC 3801	E	1.2×10^{23}	2×10^{56}
M 51	Sb	1.5×10^{21}	$>10^{54}$
Mrk 6	S0	1.7×10^{23}	$3\text{-}5 \times 10^{56}$
NGC 6764	Sb	1.1×10^{21}	10^{56}
Circinus	Sb	2.2×10^{20}	2×10^{55}

That is 10^4-10^6 SN explosions! (assuming 10^{51} erg SN)

→ environment must be affected

e.g. in NGC 3801 this E corresponds to the total thermal E in the ISM within 11 kpc, and 25% of the E within 30 kpc (Croston et. al. 2007)

Conclusions

- Shocks and bubbles are common in Seyferts
  - Athena won't have the spatial resolution to find them, but we have already done that and know where to look!
  - X-IFU has the spectral resolution to help us determine abundances, shock speeds, characterise the external medium...
- X-IFU → Constraints on low and high power radio sources (even with reduced effective area)
  - Characterise AGN feedback from Sgr A* to powerful RL QSO