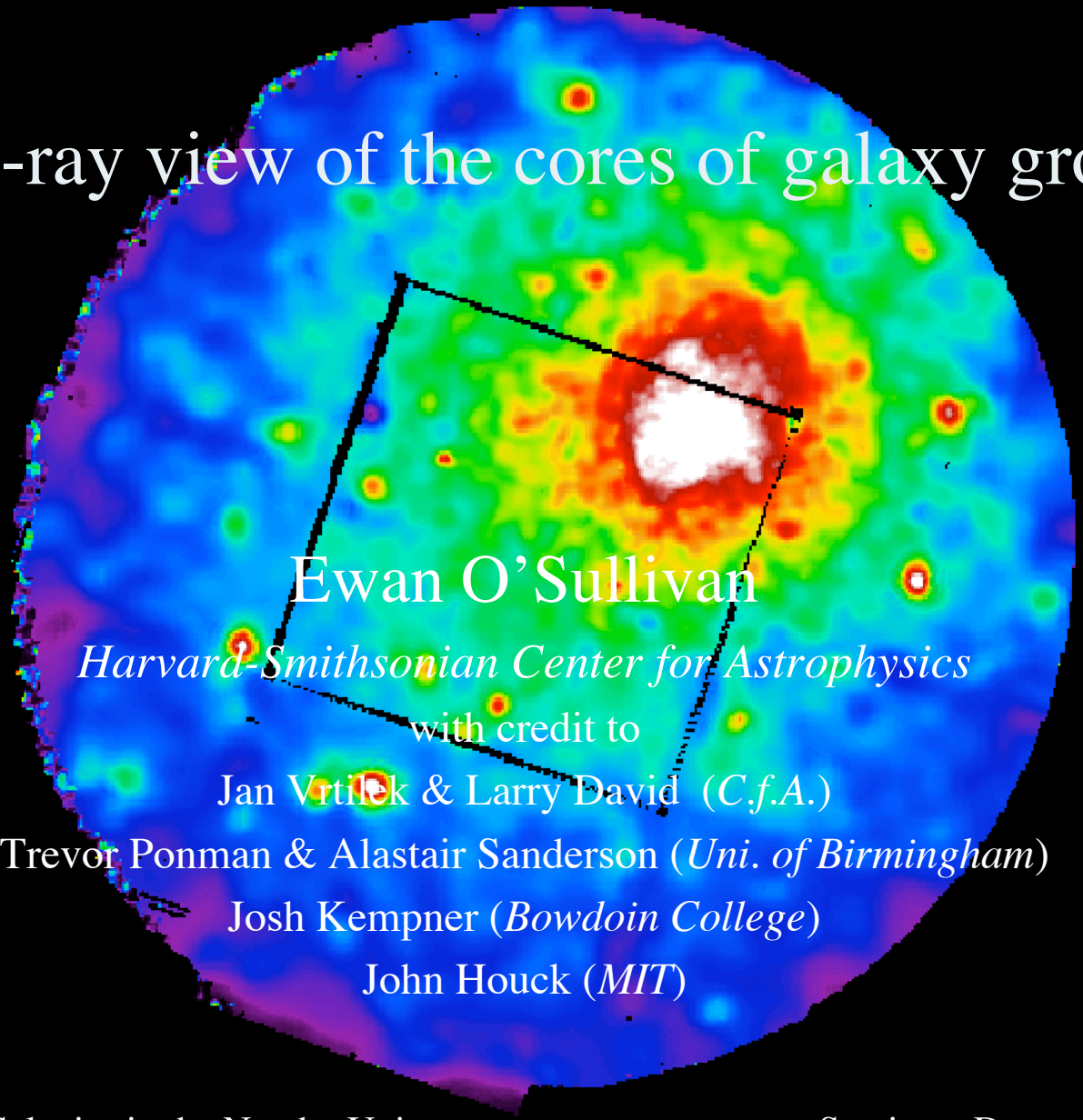
An X-ray view of the cores of galaxy groups



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with credit to

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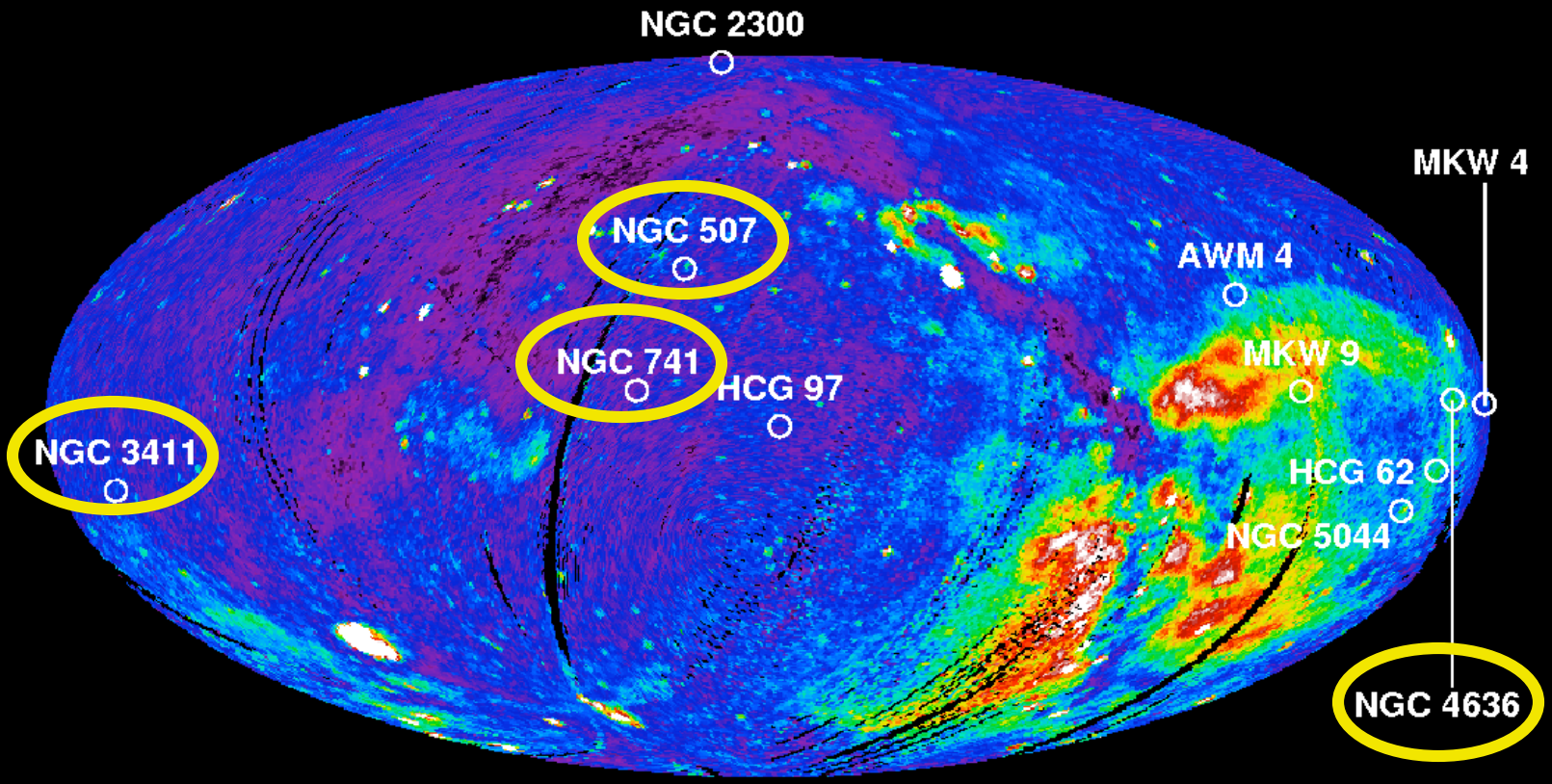
X-ray halos of galaxy groups

- Many (elliptical dominated) groups have X-ray halos which can contain a large fraction of the baryonic mass of the system.
- Can be a record of the history of the system (metal enrichment, mergers, cooling in undisturbed systems, etc)
- Hot gas halos often used to study total mass profile - probably the best available tool for studying the dark matter content & structure (cosmology, group structure, properties of central galaxy)

X-ray halos of galaxy groups: Questions

- Scientific
  - The central cooling time of this gas is generally short (~10^8 yr), but we don't see runaway cooling. What stops it?
  - Mechanism for metal enrichment of group halos still unclear. Lots of metals in central ellipticals, how do we get them out?
- Technical
  - X-ray mass analysis of groups relies on assumptions of Hydrostatic Equilibrium, relaxed halos, spherical symmetry, etc.
  - In clusters, a disturbed or cooling core can often be excluded because halo is visible to large radius - nearby groups often too faint to allow this.

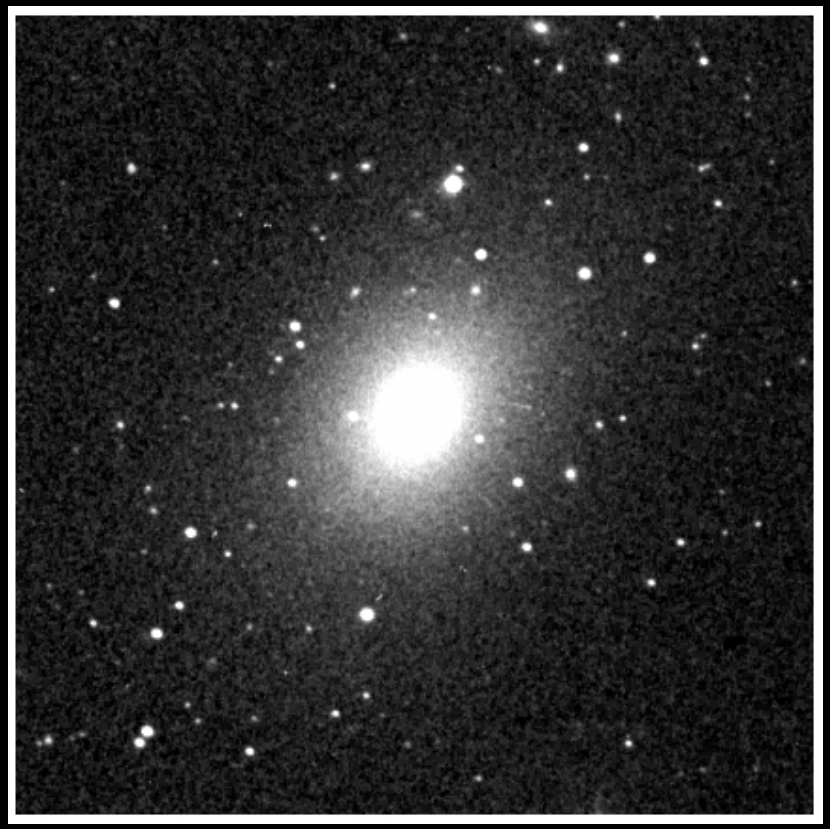
Sample of X-ray bright groups



- 23 Groups from XMM-Newton, 16 from Chandra
- 11 with high quality X-ray data, 6 with have disturbed cores

NGC 4636: shocks, bubbles and outflows

- Often used as example of 'typical', 'isolated' elliptical
- Dominant elliptical of a small (~12 gal) group (Nolthenius 1993)
- Highly X-ray luminous: $L_X=2x10^{41}$ erg s^{-1}
- Weak extended radio source
- Extensive hot gas halo, $T \sim 1$ keV



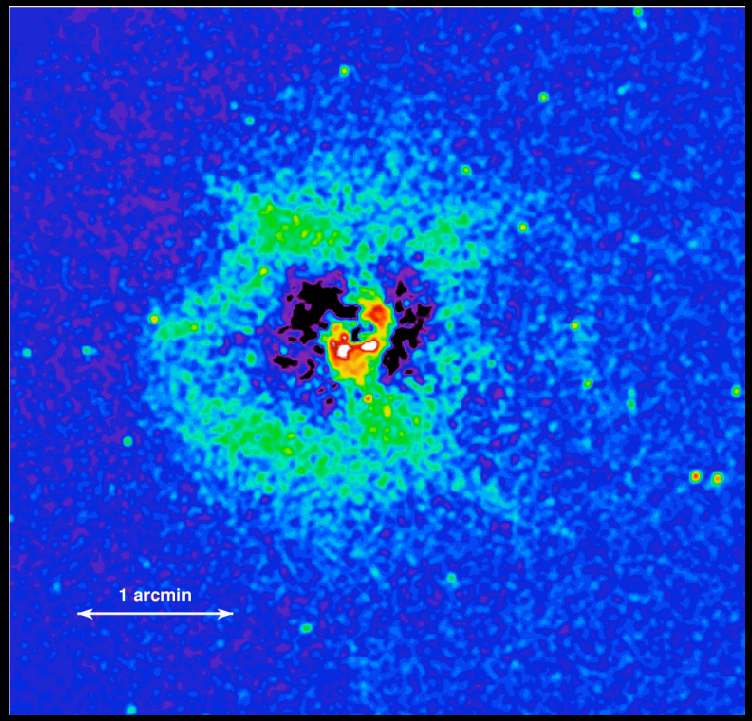
12 arcmin = 50 kpc

NGC 4636

- Strange X-ray structure in an otherwise galaxy core:

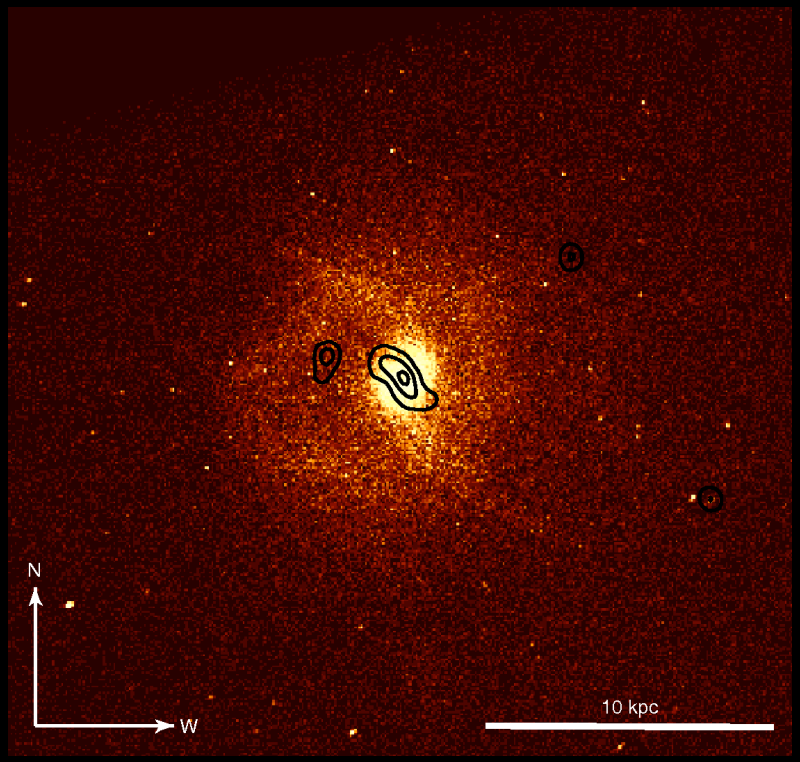
Double pin-wheel-like structure in X-rays! X-ray arms ~8 kpc long.

⇒ Shocks from AGN outburst?



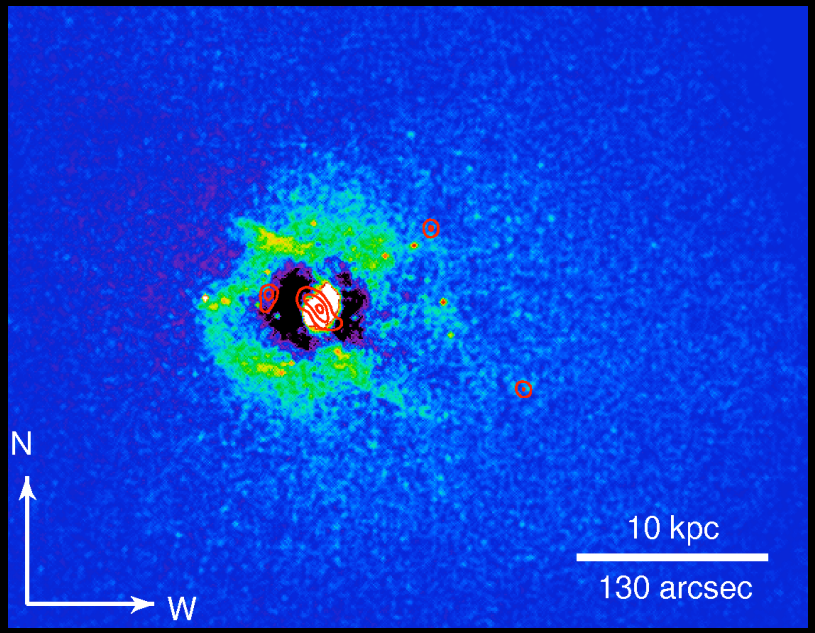
Chandra image with halo model subtracted

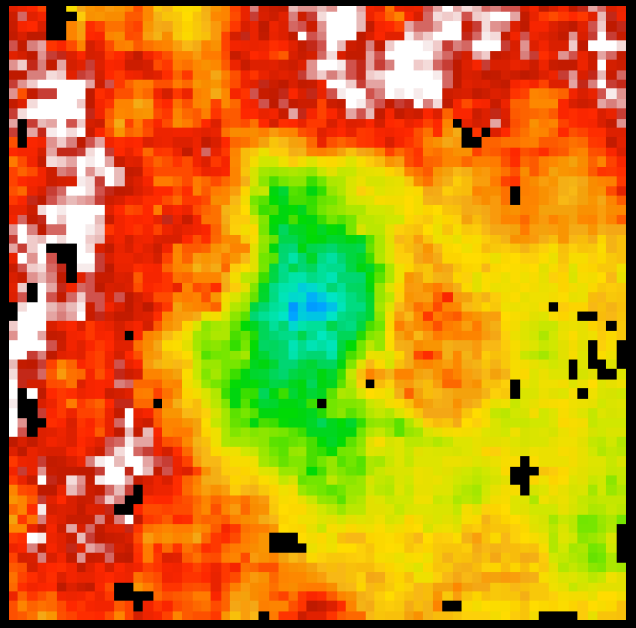
Chandra image with VLA-First contours

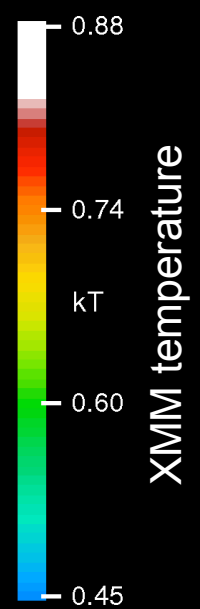


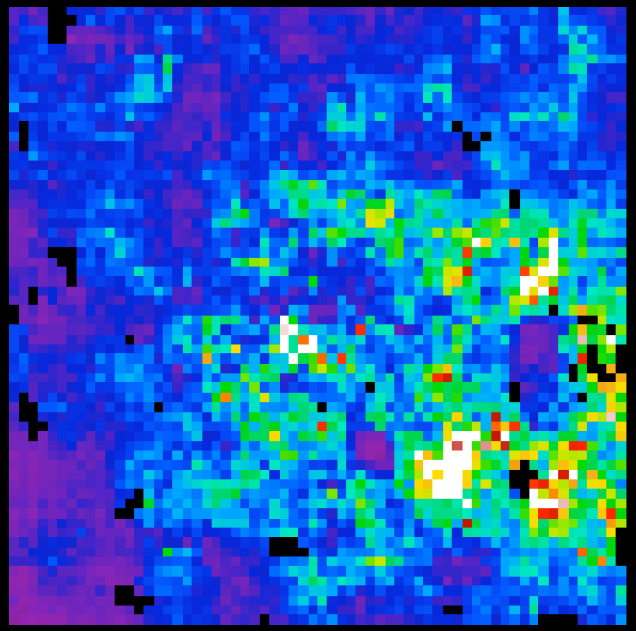
- Ohto et al (2003) find high kT, excess N_H west of core

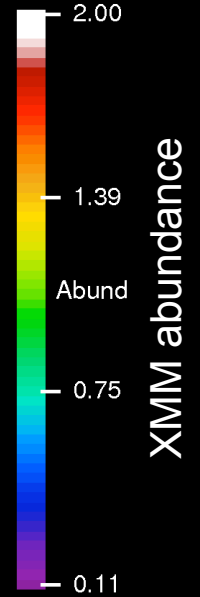
⇒ Cavity caused by AGN jets during previous outburst?







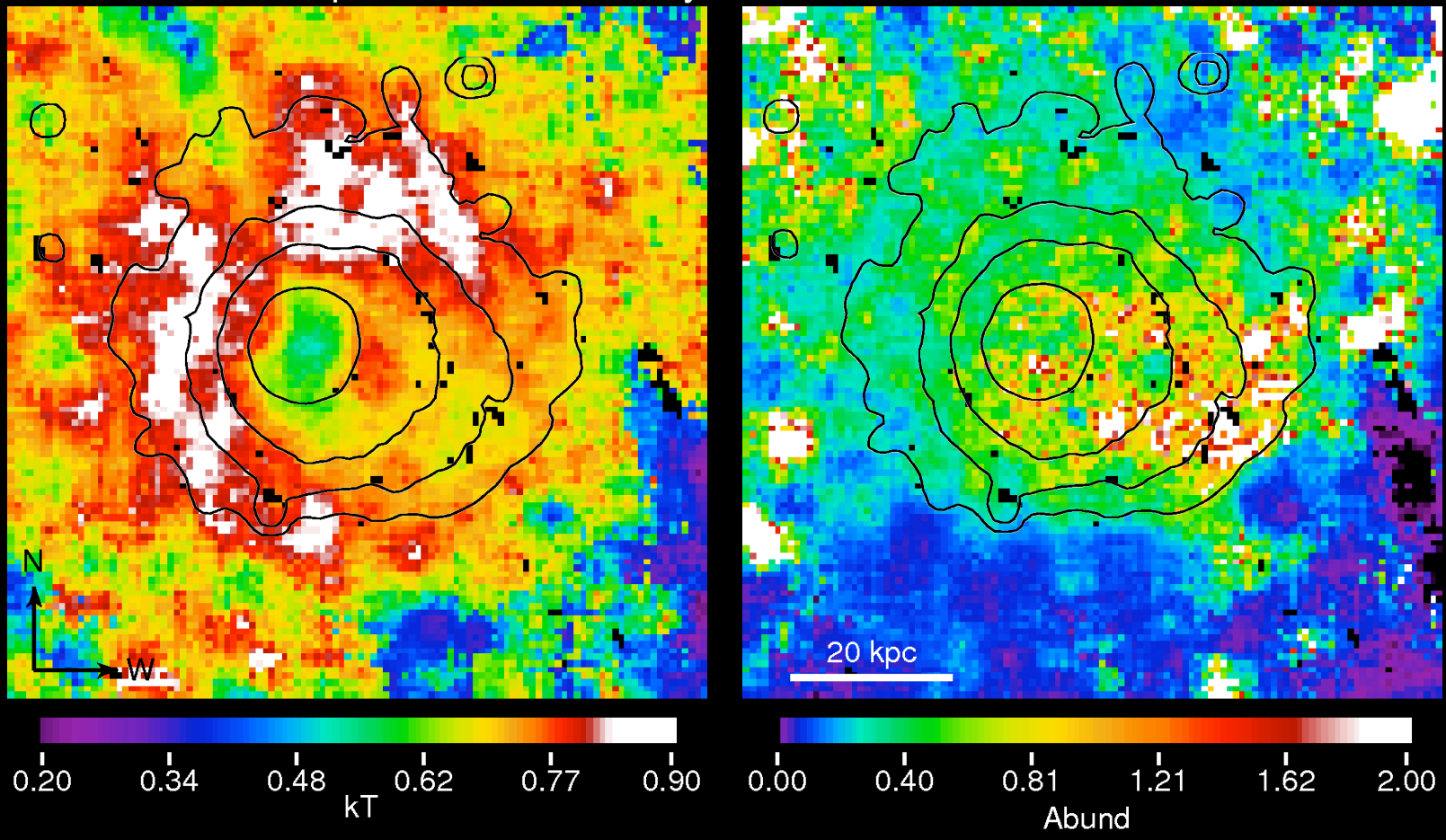




- Cavity to E clearly visible
- SW ‘Spiral arm’ marks cavity boundary
- Highest abundance gas outside galaxy core? Complex spectra…

NGC 4636 spectral maps

XMM Temperature Intensity contours XMM Abundance



- Highest abundance and low T to SW ⇒ entrained gas?

NGC 4636: AGN heating and gas mixing

- Energy in shock ~6×10^{56} ergs, with an age of ~3×10^{6} yr.
- Energy to inflate cavity 3-15×10^{50} ergs, depending on inflation timescale.
- Plume to SW suggests previous bubbles have drawn out material.

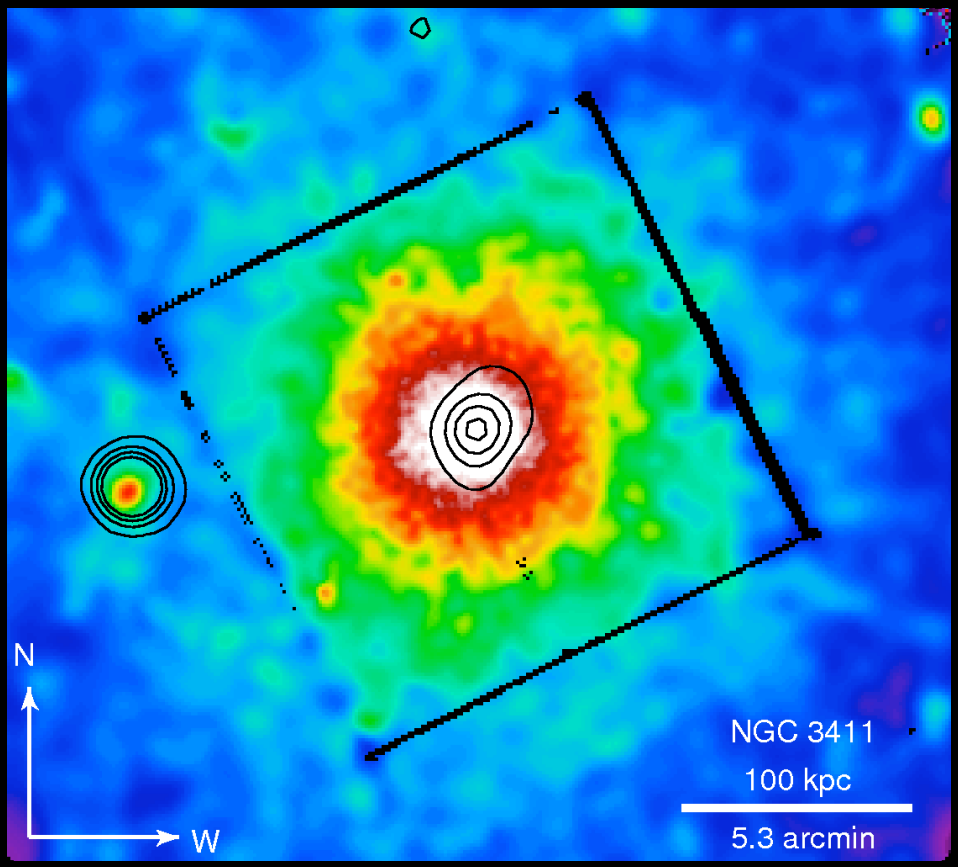
$\Rightarrow$ Multiple AGN outbursts

$\Rightarrow$ Shocks probably main source of energy input to gas

- Radiative loss from a cooling flow (within 70 kpc) is ~10^{43} ergs s^{-1}. Outbursts every few 10^{7} years are enough to reheat the gas.
- Gas mixing may help prevent cooling and effectively move metals out from central galaxy.

NGC 3411: Ongoing merger or the beginning of AGN reheating?

- Group of 5 major galaxies (Ramella et al 2002).
- Distance ~61 Mpc
- Apparently relaxed, extended X-ray halo.
- Temperature ~1 keV, high luminosity, $L_X=3x10^{42}$
- Slightly extended NVSS radio source (~30 mJy)

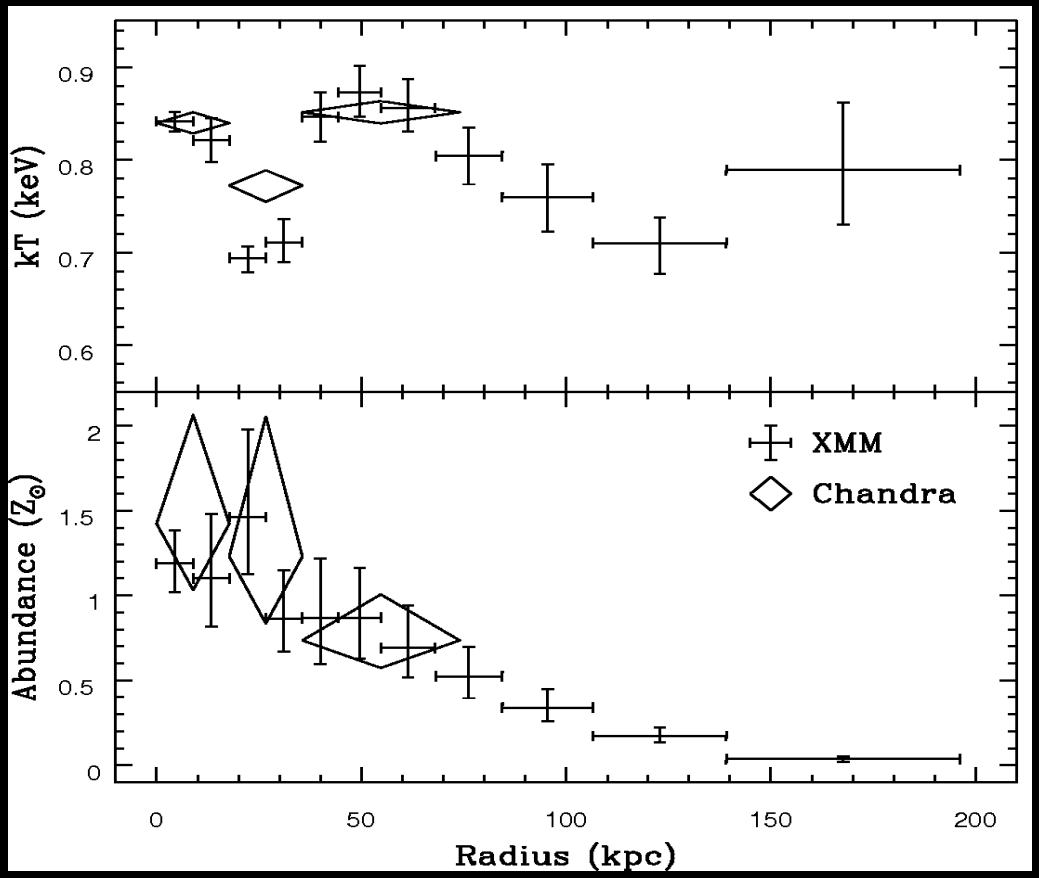


NGC 3411: Temperature Profile

- Abundance profile fairly typical
- Highly unusual central temperature structure - inner peak with‘dip’ at 20-40 kpc

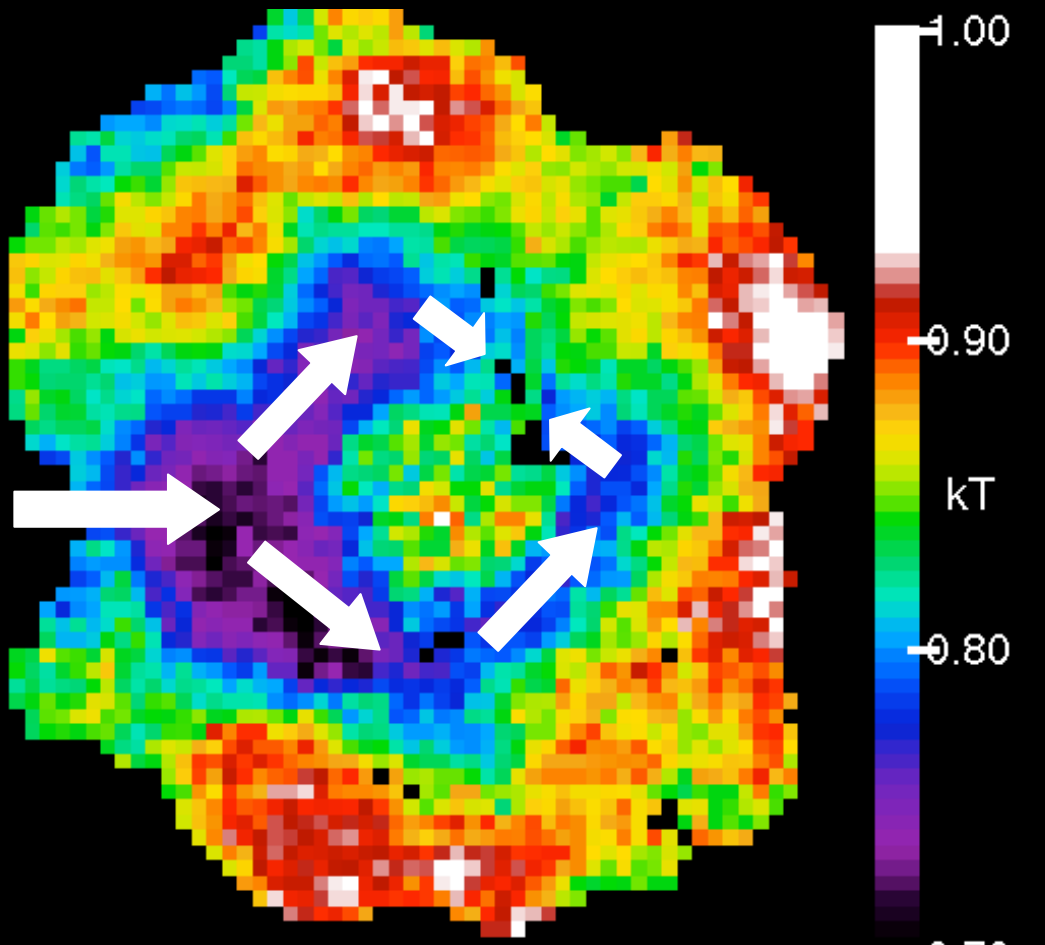
⇒ A shell of cool gas around a hot core.

- What could cause such a structure?



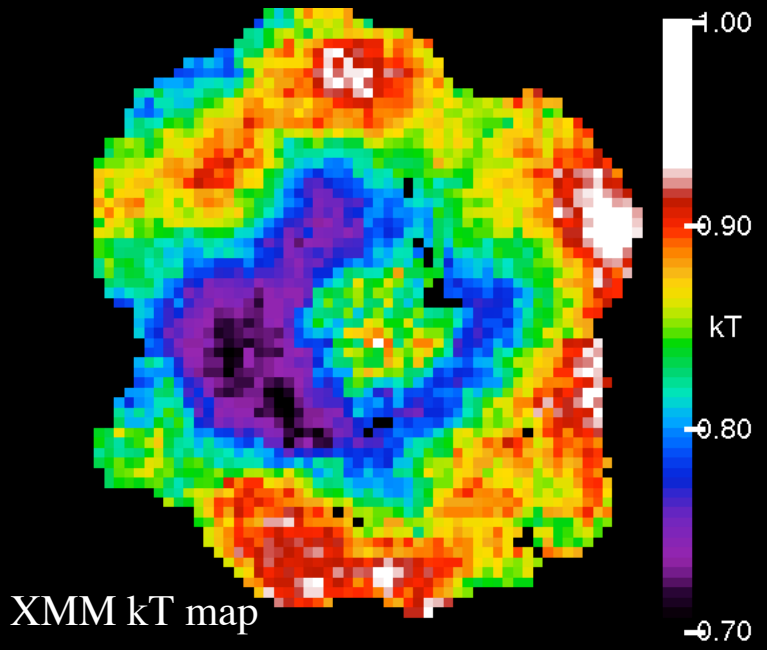
NGC 3411: Merger option

- Cool gas from merger of Elliptical galaxy?
- Stripped gas sinks until point of equal entropy is reached
- Gas then wraps around hot, low entropy core
- $M_{gas}=3.4x10^9$ ✓
- Problem: where is the galaxy?

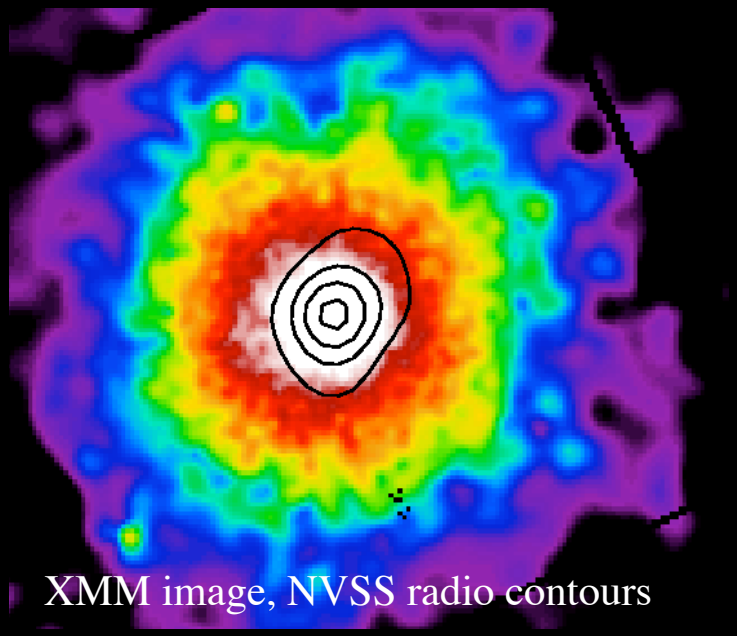


XMM temperature map

NGC 3411: AGN heating option



XMM kT map



XMM image, NVSS radio contours

- Alternatively, could this be reheating of a cooling flow?
- Cool infalling gas feeds AGN in NGC 3411⇒ outburst
- AGN heated core surrounded by remnant of cooled gas
- Radio/X-ray features similar, but is it a jet? VLA proposal

NGC 3411: what is going on?

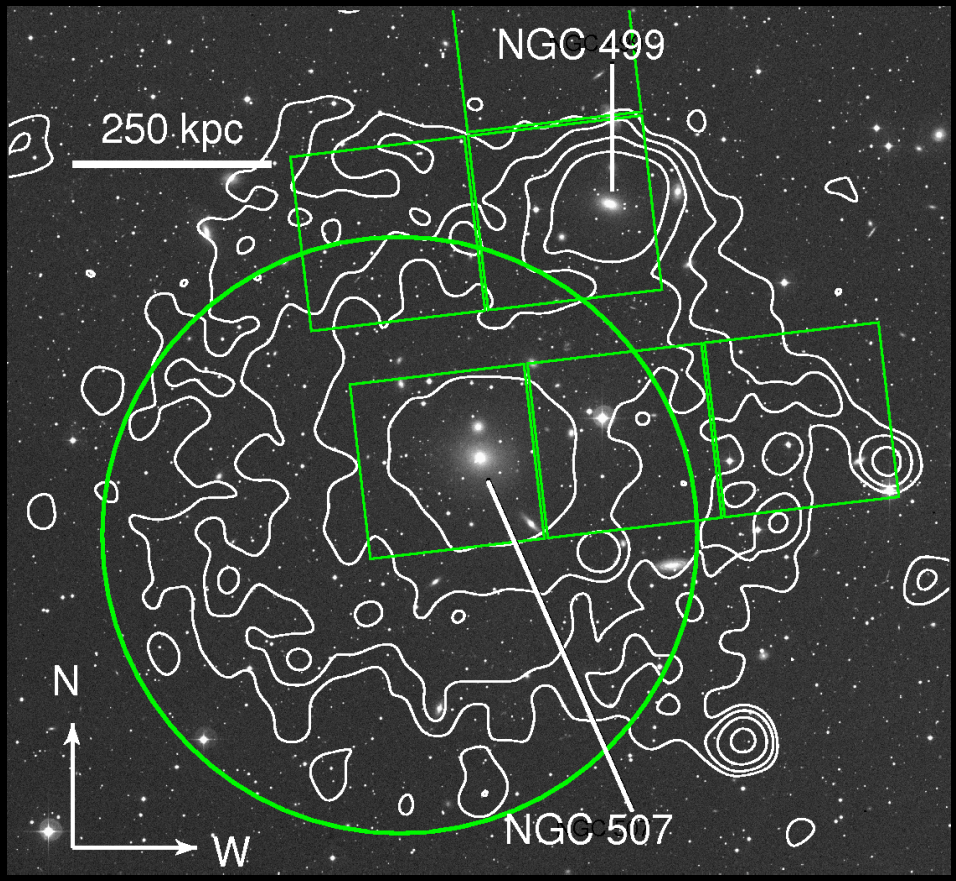
- Short (~1hr) exploratory VLA pointing confirms source extended, longer exposure proposed.
- Best candidates for infalling galaxy are relatively small S0s (L_B~5x10^9 $L_\odot$), no obvious substructure.
- If at beginning of outburst, AGN heating were very strong, we might see entropy inversion - no sign of this. Mean entropy of core is lower than that of cool shell due to high gas densities.
- Probably AGN heating, but we aren't sure yet…

NGC 507: AGN + merger stresses?

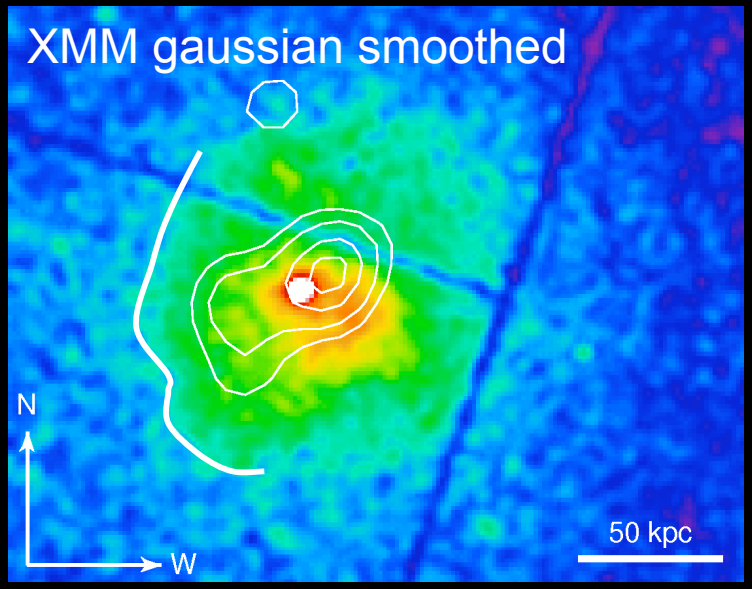
- FR-I radio galaxy (Parma et al 1986)
- AGN power sufficient to stop cooling
- Kraft et al (2004) find abundance edge NE of core
- NGC 499 center of second peak in group X-ray halo

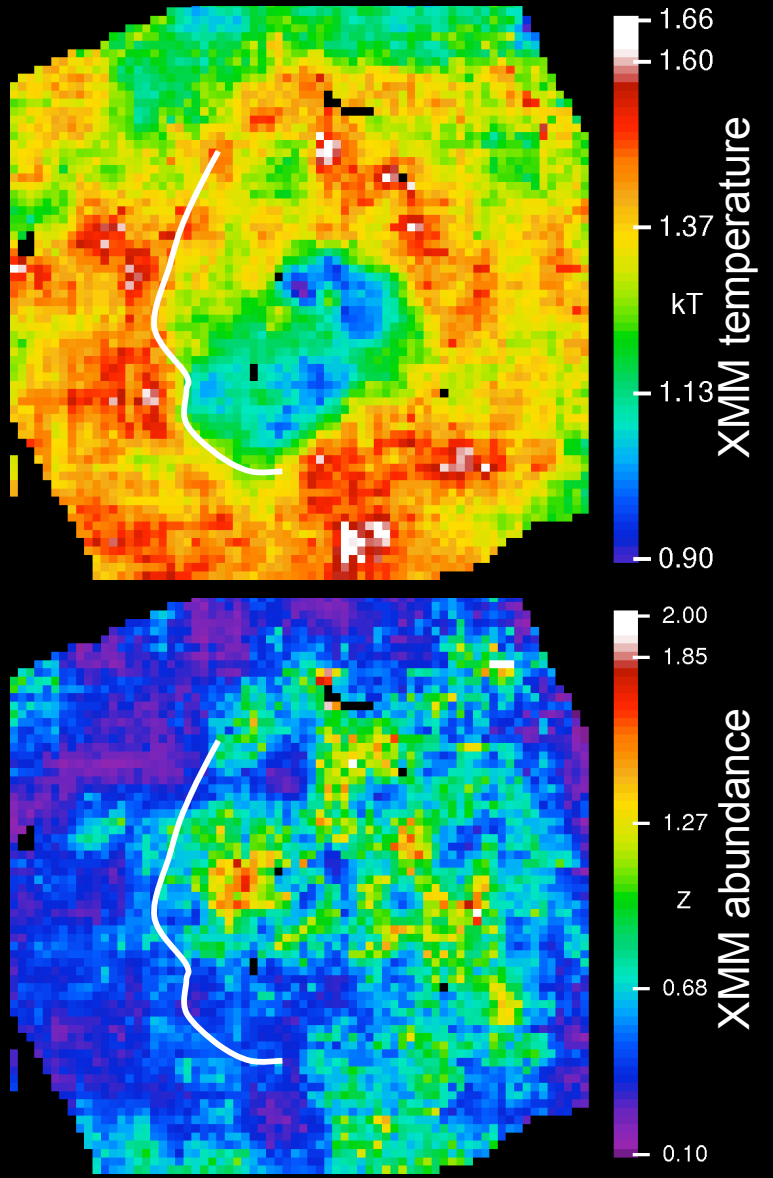
⇒ Likely group/group merger, but is NGC 499 going N or S?

- Brief Chandra observation misses area between galaxies
- XMM observation only covers NGC 507



ROSAT PSPC contours on DSS image



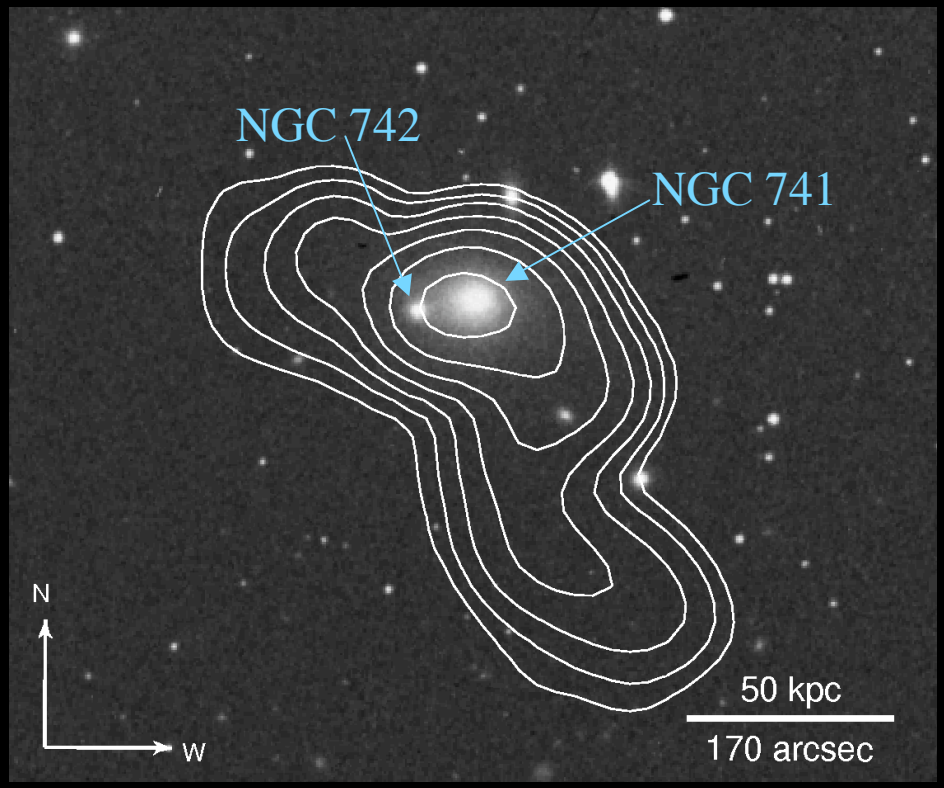


- Coolest gas south of galaxy core and radio emission
- Clumped abundance distribution
- Surface brightness edge caused by a mix of low temperature / high abundance gas
- Could AGN activity and distortion be caused by a past NGC 499 interaction?

NGC 741: galaxy collision?

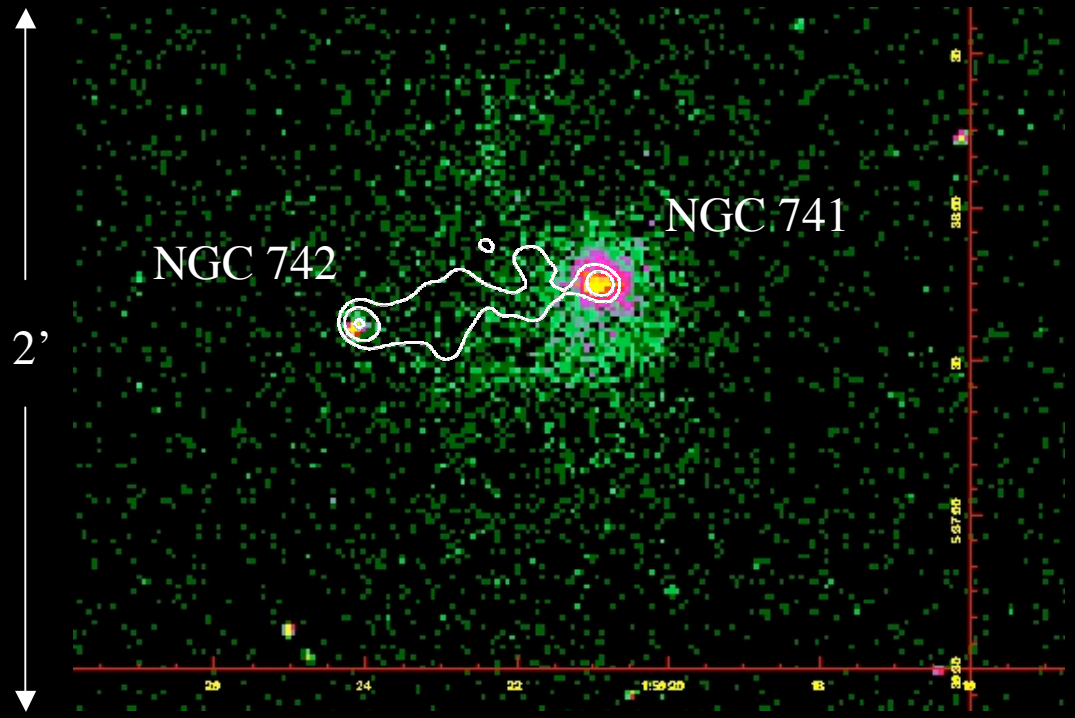
- Dominant elliptical of group of ~40 galaxies (Zabludoff & Mulchaey 1998)
- Group has $L_X \sim 10^{42}$, $\sigma_r = 410$ km s^{-1}
- Extended, bent radio structure, centred on NGC 741
- NGC 742 is close on sky, has concordant redshift

$\Rightarrow$ Ongoing interaction?



DSS optical image with NVSS radio contours

NGC 741: high resolution imaging



Chandra counts image VLA radio contours

- 31 ks Chandra image
- NGC 741 dominates X-ray structure
- Weak X-ray deficient “bubble” found to SW in region of large-scale radio tail
- X-ray point sources in NGC741 and NGC742, suggests AGN activity
- Vrtilek et al (2006)

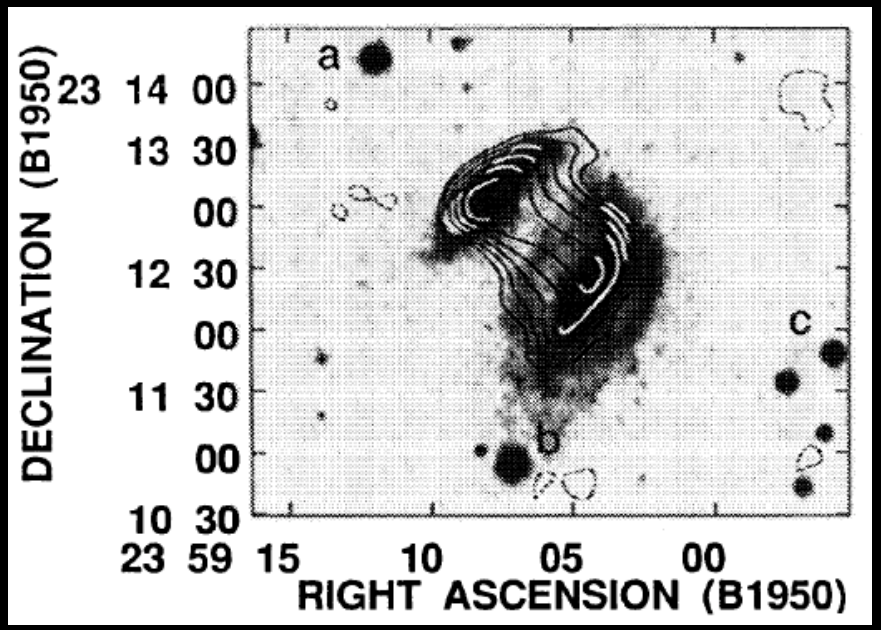
• Narrow X-ray filament connects NGC 741 & NGC 742, second filament to north
• Narrow radio filament also connects galaxies

"Taffy galaxies" in X-ray as well as radio?

- UGC 12914/12915: radio bridge caused by gas and magnetic fields between postcollision galaxies (Condon et al 1993)

⇒NGC 741/742 an "X-ray analog"?

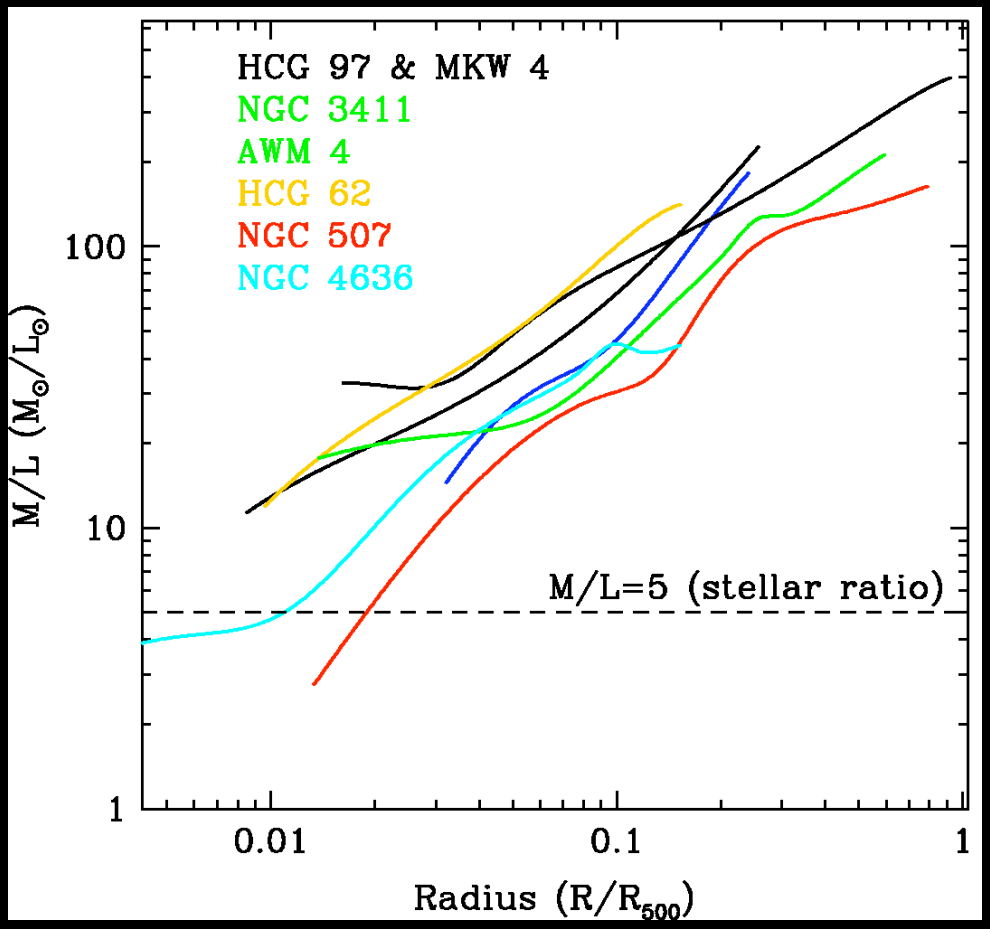
- Narrow bridge due to greater concentration of gas in ellipticals than spirals?
- Age: ~few x 10^7 yrs since (nearly) head-on collision.



• Cool cores of ellipticals NOT destroyed in what might have been a (nearly) head-on encounter!

Effects of disturbance on analysis

- Use standard analysis techniques
- Derived M_{total}/L_B is often lower than expected in the most disturbed systems
- Not just Me!
- Humphrey et al (2005) also find M/L~2-9 within r_e for 7 ellipticals/groups (astro-ph/05108190)
- GC mass estimate in NGC 4636 is higher than Loewenstein & Mushotzky X-ray estimate (Romanowsky)



Conclusions

- Many of the best observed groups have disturbed structures in their cores (+ maybe others we can't see?)
- Signs of AGN feedback are common, if you have the data to see them - Cooling is probably mainly prevented by AGN, just as in clusters.
- AGN may well be able to mix gas, moving metals out into the group halo.
- How does this affect our ability to measure mass and other properties? We need simulations of these messy systems to see how serious the effects may be.