The Gas Dynamics of NGC 4472 (Multi-scale study of hot gas in round galaxies)

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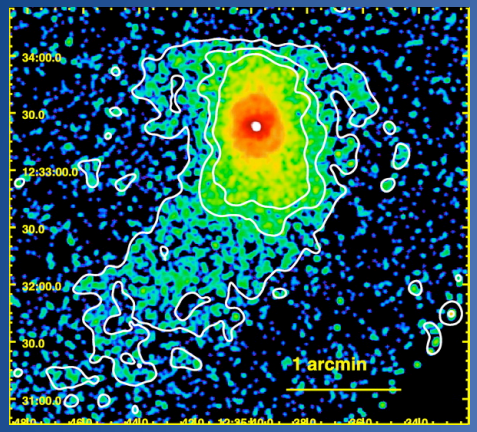
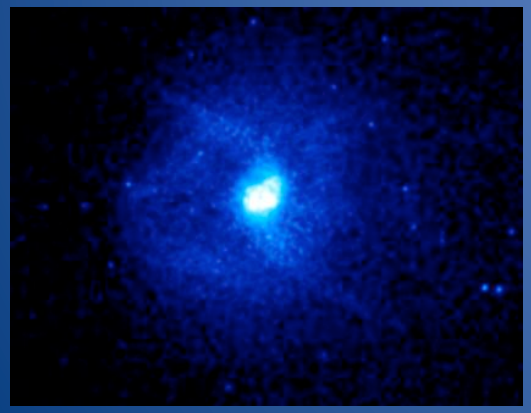
Outline of talk

1. Introduction/Overview
2. The Data
3. Interpretation and Implications
4. Summary and Future work

Big Picture – Mergers and Radio Outbursts in the Early-type galaxies of the Virgo Cluster



NGC 4552 (Machacek et al. 2007)

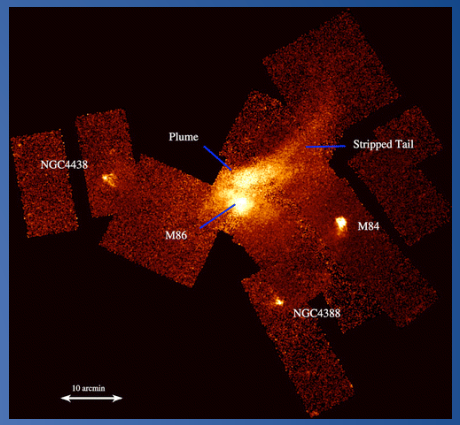


NGC 4636 (Baldi et al. 2009)

The Study of Hot Gas Dynamics in Early-type galaxies tells us about:

1. Feedback between SMBH and ambient gas
2. Formation of structure
3. Growth/fueling of SMBHs
4. Thermal and chemical evolution of galaxies
5. Relationship between baryonic and dark matter
6. Hydrodynamics/transport processes of gas

Virgo cluster galaxies are particularly interesting because of proximity and diversity of structures



M86 (Randall et al. 2008)

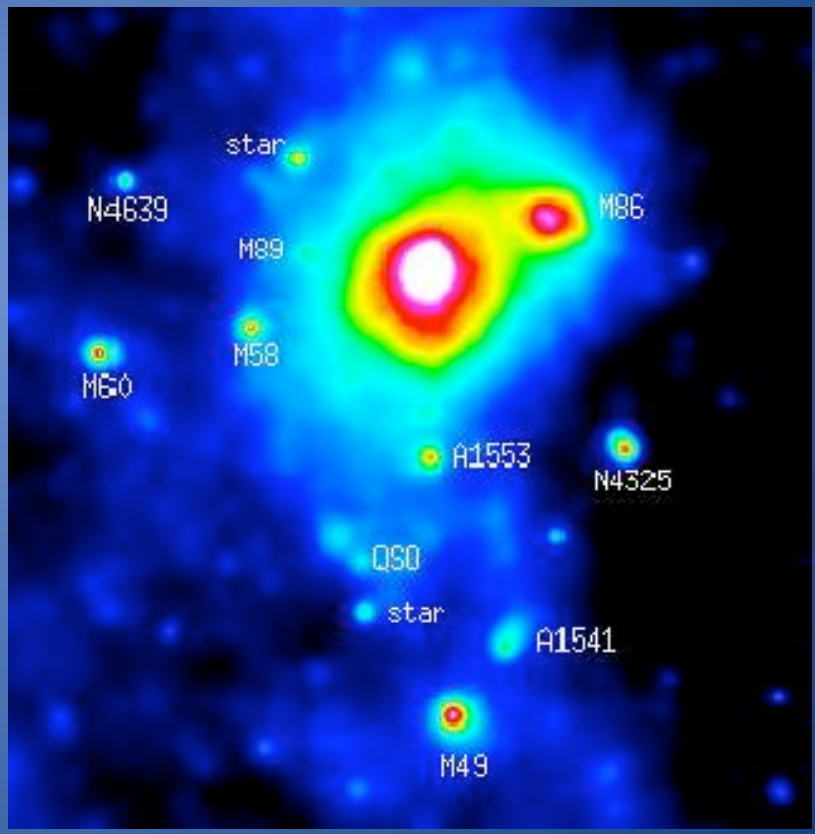
M84 (Finoguenov et al. 2008)

NGC 4472 group merging with Virgo Cluster

What is NGC 4472/M49?

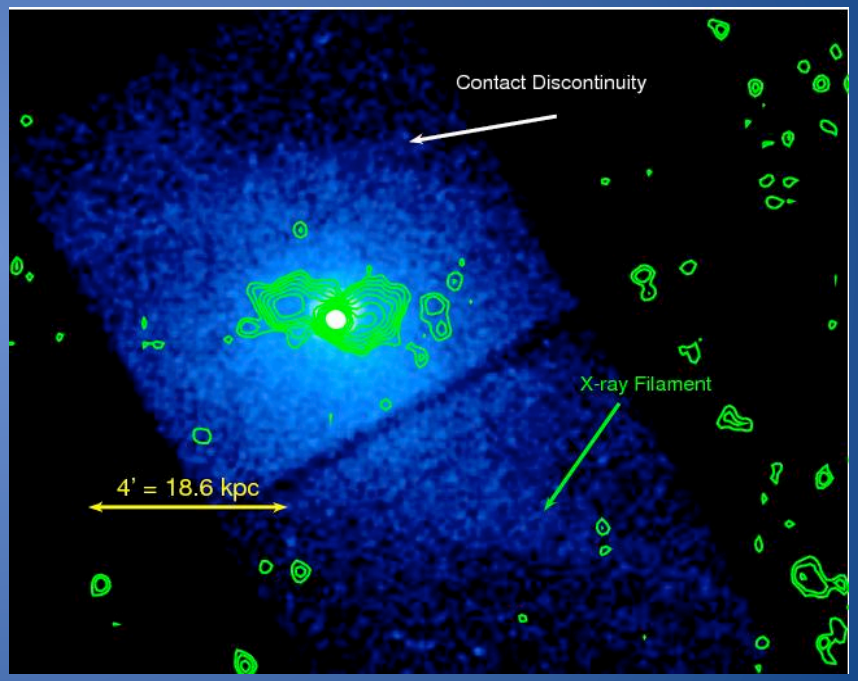
- Massive group merging with Virgo cluster (d=17 Mpc, 1”=80 pc)
- Lies 4 degrees (1.35 Mpc) south of M87
- X-ray bright, massive system – most optically luminous galaxy in Virgo cluster (and in local Universe)
- NGC 4472 known to be merging with Virgo cluster (Irwin and Sarazin 1995)

ROSAT mosaic of Virgo Cluster (Bohringer et al. 1995)

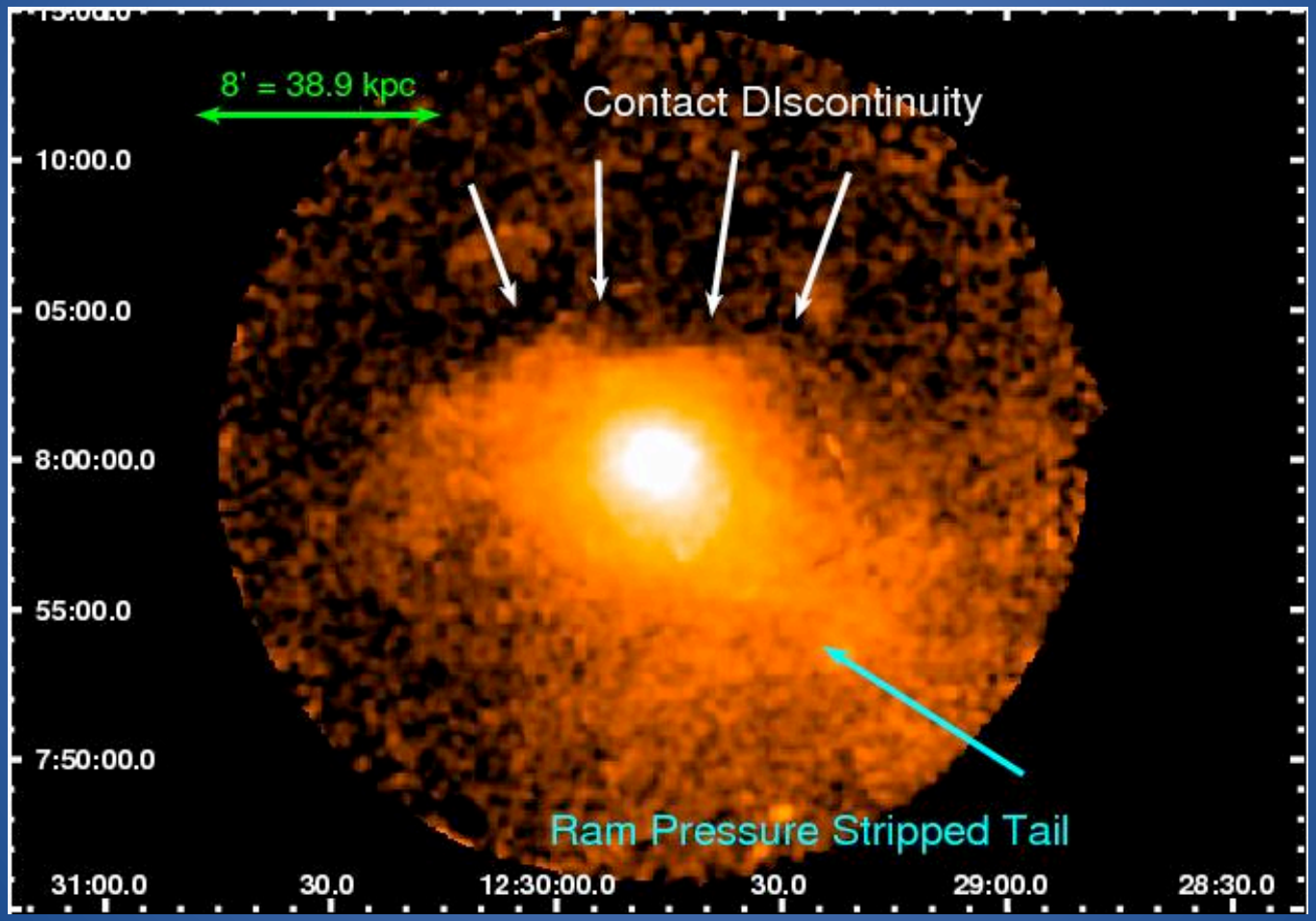


Early Chandra observation revealed complex morphology (Biller et al. 2004)

- Short (30 ks) AO-1 Chandra observation showed
  - Cavities coincident with weak lobes
  - Sharp tail attributed to ram pressure stripping
  - SBD that could be contact discontinuity with Virgo cluster gas

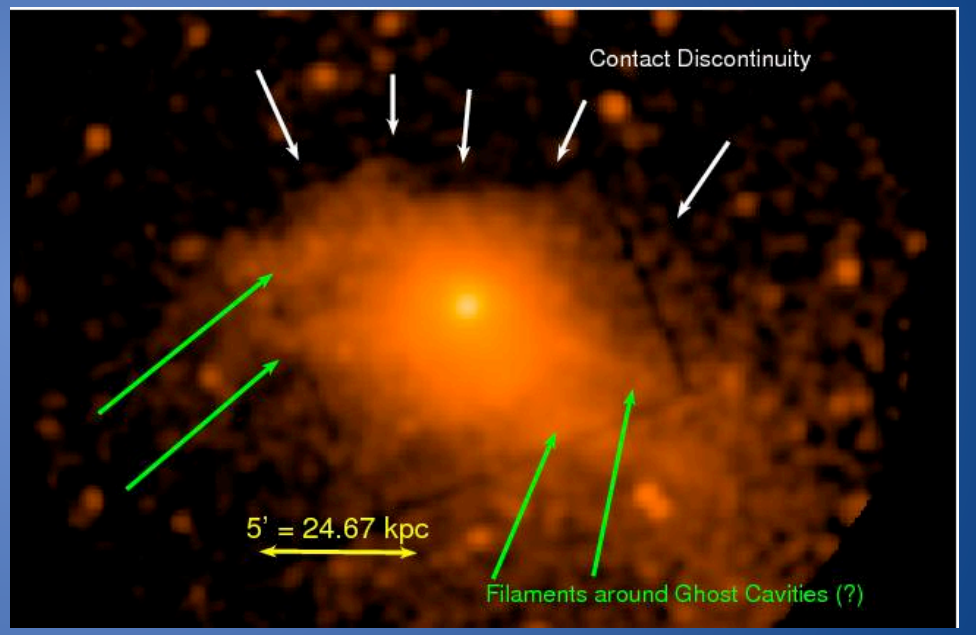


Deep (100 ks) XMM-Newton Observation – MOS1+MOS2 image

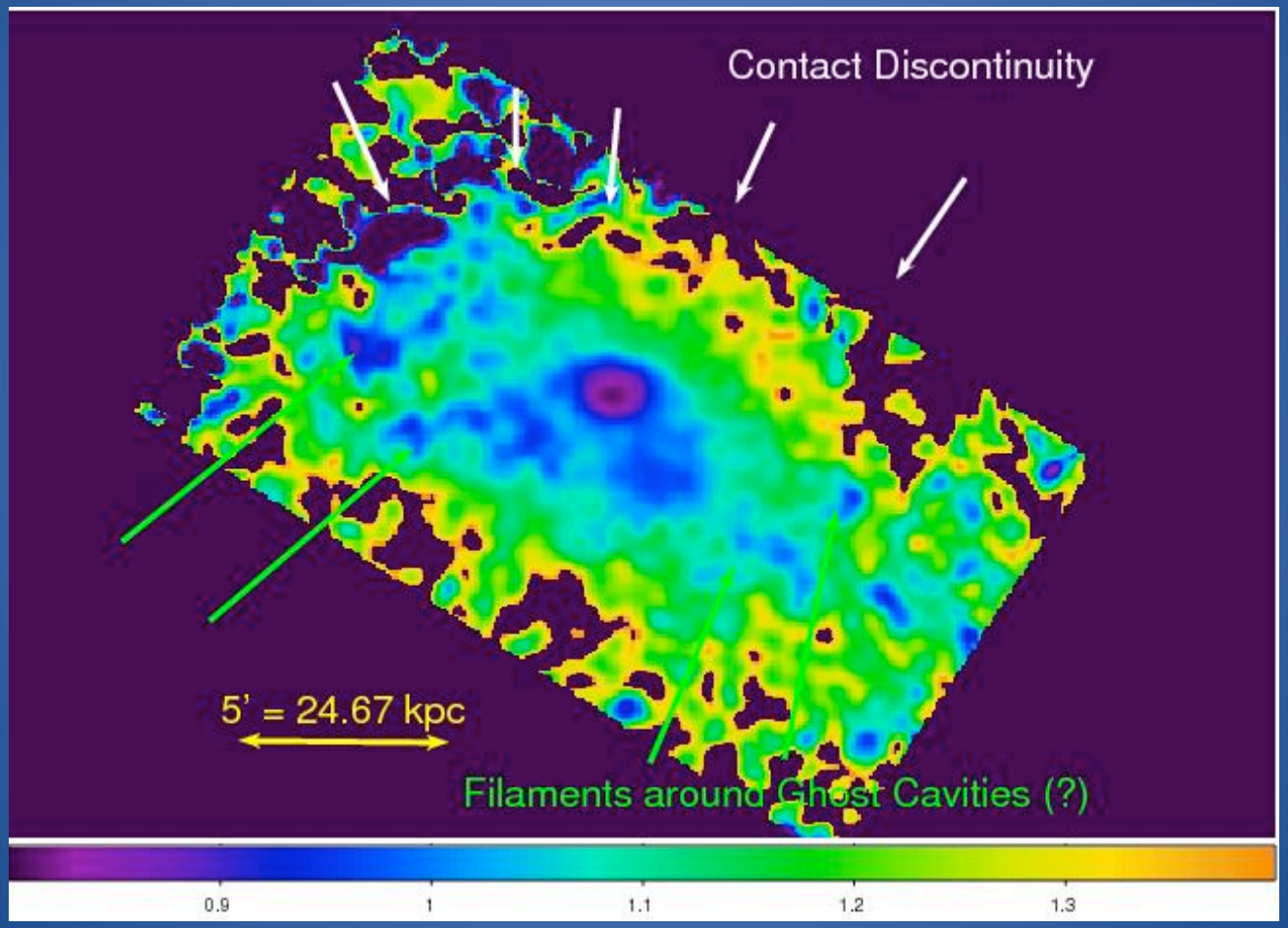


Filamentary Arms/Rims

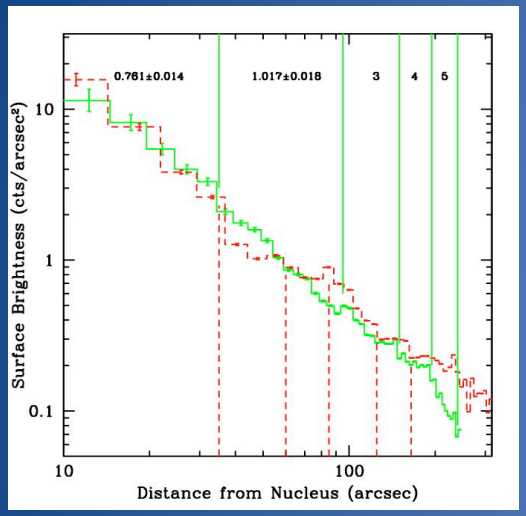
- Four Filamentary Arms seen in soft band (0.5-1.0 keV) XMM-Newton Image
- One arm is coincident with sharp feature seen in Chandra
- All arms are cooler than surrounding gas



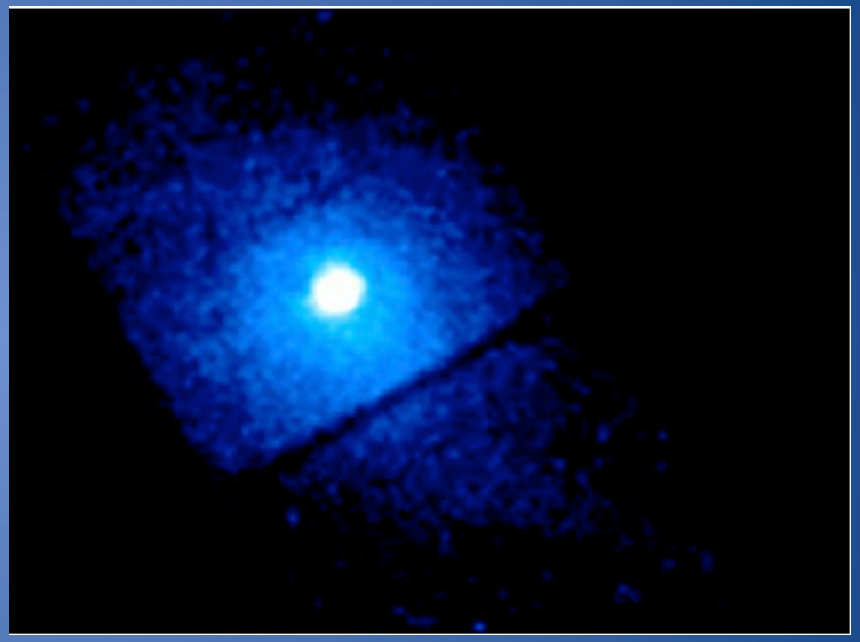
Temperature Map – Created from centroid of Fe L complex



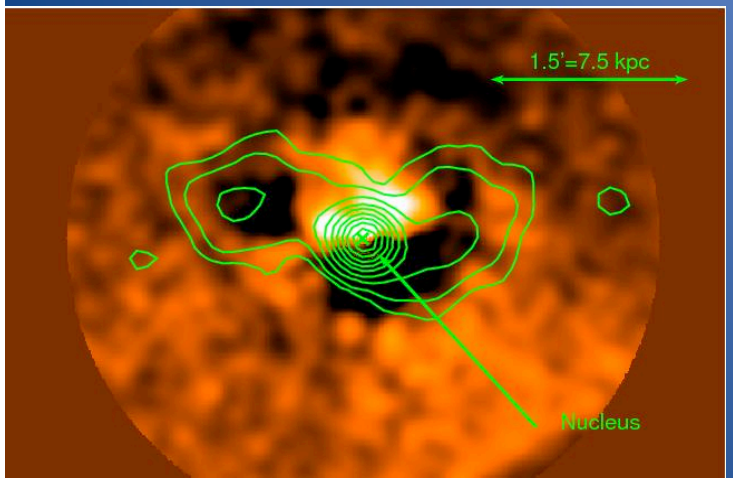
Surface Brightness Discontinuities in Gas (Chandra/ACIS-S) – pressure generally continuous across jumps



SBP in two 30 degree wedges (NW NE) . Pressure continuous across jumps.



Smoothed Chandra image in 0.5-5.0 keV band



Unsharp mask image of NGC 4472 with radio contours

Interpretation – What does it mean?

Observational Results

1. Contact discontinuity – highly distorted
2. Ram-pressure stripped tail
3. Cold filaments or rims No known large scale radio emission
4. Complex distribution of SBDs and structure in temperature map

Interpretation

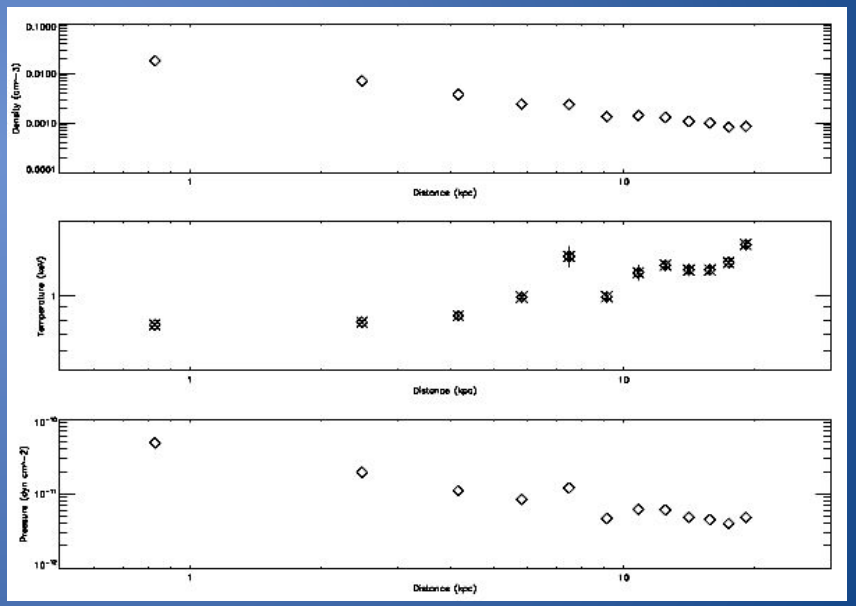
- SBD to the north is clearly contact discontinuity between NGC 4472 group gas and Virgo cluster gas
- Tail due to ram pressure stripping
- Four filamentary arms/rims are ghost cavities due to previous epoch of nuclear activity
  - Energy/power of this putative outburst must have been relatively modest ($E=2\times10^{56}$ ergs roughly 2×10^{8} yrs ago)
- Complex gas motions in core the result of both merger dynamics and nuclear outbursts – reminiscent of sloshing
- Distortion of CD may be due to radio outburst (implies bubble not buoyant)

Interpretation - Interaction with Virgo Cluster

Ram Pressure Stripping

- Extrapolation of Virgo cluster density profile (Bohringer and Nulsen 1995) yields $n_H=10^{-4}$ cm^{-3}
- Sub/transonic stripping requires $n_{ext}=4x10^{-4}/$ $sqrt(d_{200kpc})$ cm^{-3} where d_{200kpc} is path length through gas
- No evidence of a shock
- Temperature of external gas – 1.6 keV

Density/Temperature/Pressure Profile (deprojected with projct)



Implications

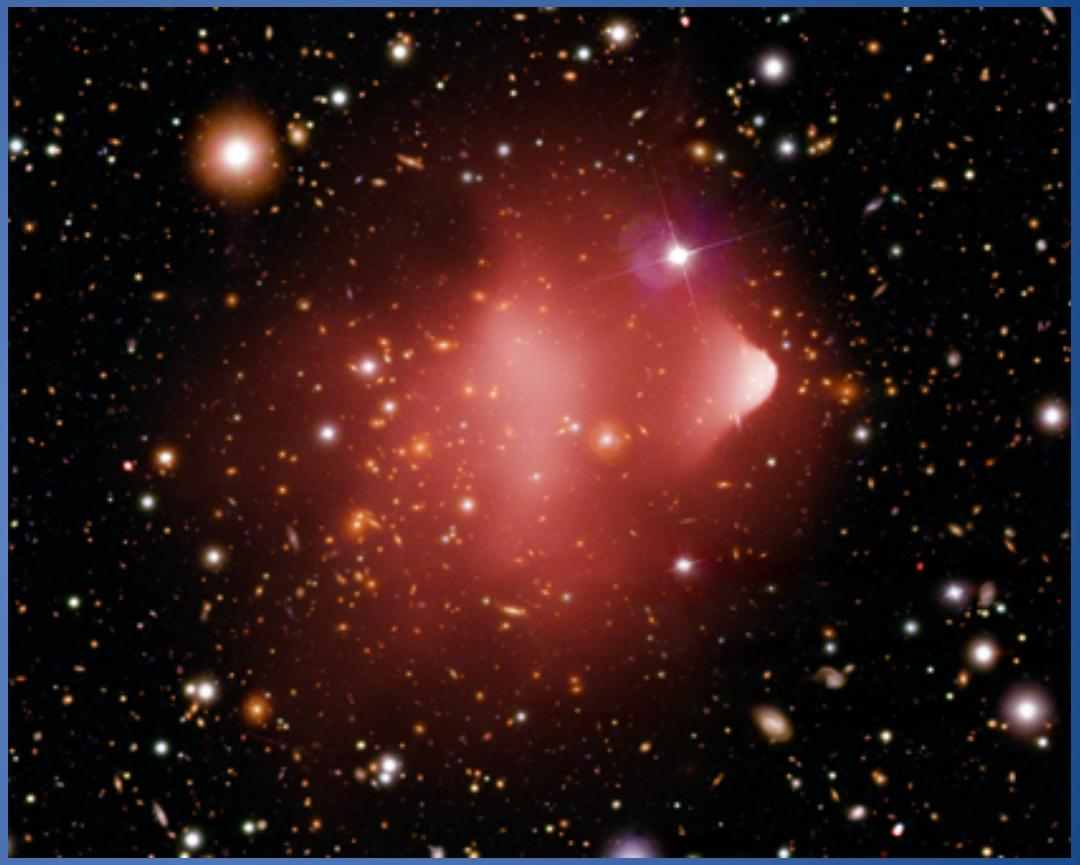
Merging with Virgo Cluster

Transonic infall implies v_{in}=650 km s^{-1}

Probably overestimates infall velocity for two reasons

1. Interior gas is being driven out by nuclear activity
2. Virgo cluster gas falling back into potential of NGC 4472 group (see Springel and Farrar 2007)

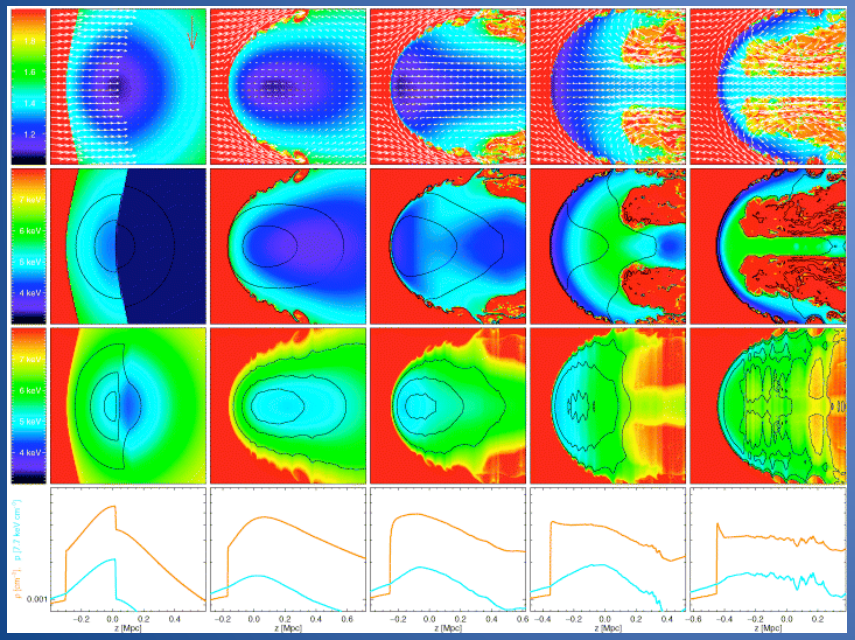
We are probably seeing NGC 4472 fall into Virgo through a filament – is this the WHIM(?)



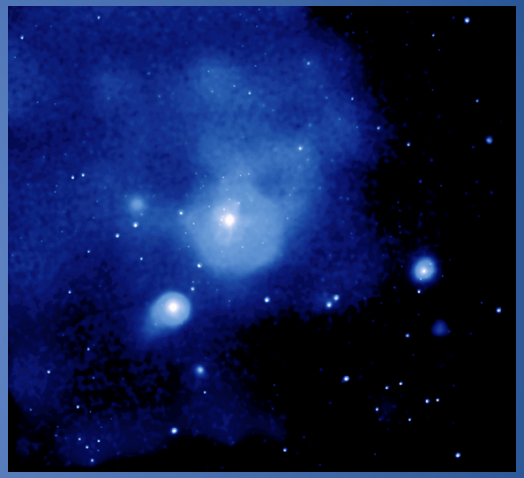
Bullet Cluster (image from CXC website)

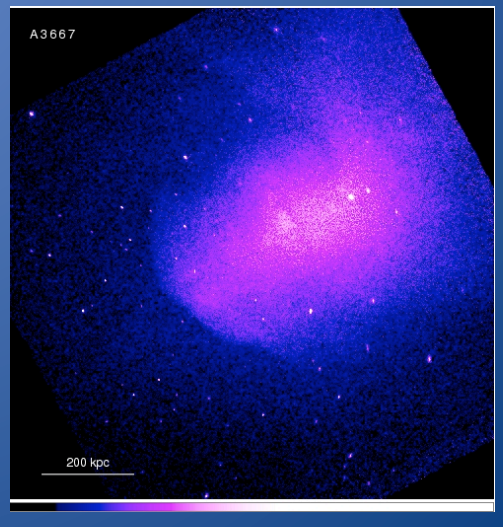
Dynamics of Ram Pressure Stripping

Circulation induced in dense cores of stripped gas (Heinz et al. 2003) – top, middle bottom panels are entropy, temperature, and emission weighted temperature



NGC 1404 (top) falling into Fornax cluster (Chandra CXC, Machacek et al. 2005) – Abell 3667 (bottom – Vikhlinin et al. 2001)





Gas motions on kpc scales in NGC 4472 appear to be much more complicated!

Filamentary arms or rims – buoyant bubbles

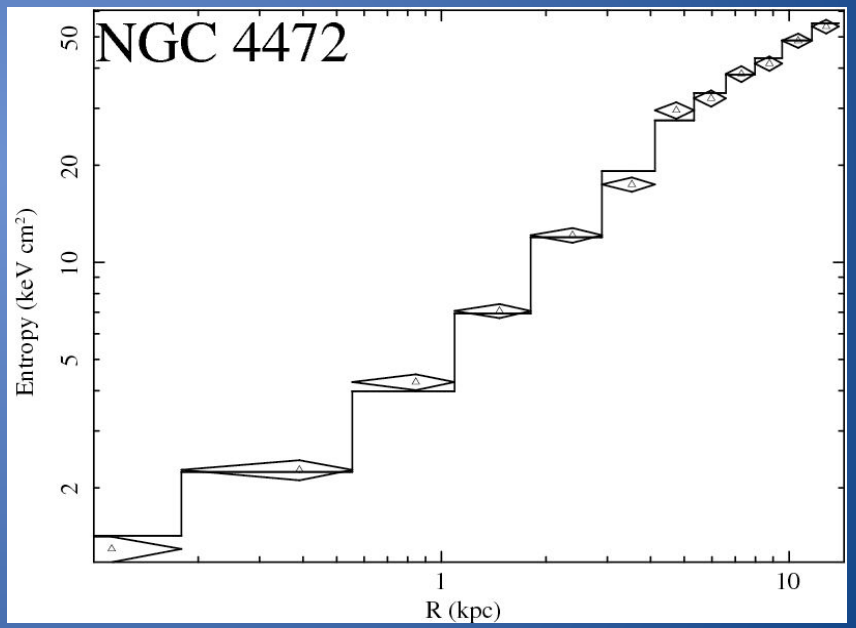
- Buoyantly rising bubbles drag up low entropy material from group/ cluster core (Churazov et al. 2003)
- For example, filamentary arms of M87 (image on right, Forman et al. 2007)
- Energy of NGC 4472 bubbles about 2×10^{56} erg s^{-1} if buoyant – comparable to energy of current outburst

‘Weighing’ the central SMBH and testing the Bondi Accretion paradigm

Bondi accretion

- Gas temperature and density profile can be used to `weigh’ central SMBH (Humphrey et al. 2008, 2009)
- Can actually go much further – entropy profile can be used to DIRECTLY evaluate Bondi accretion paradigm
- Require deep (400+ ks) Chandra observations of gas rich early-type galaxies

Weighing the SMBH – Entropy profile NGC 4472 (Humphrey et al. 2009)



Summary and Conclusions

- XMM-Newton observation finds complex structures in gas
  - Contact discontinuity between N4472 gas and Virgo cluster + ram pressure stripped tail
  - 25+ kpc long filamentary arms – rims of ghost cavities
  - Core gas appears to be moving in a different direction than tail – contrary to simulations of merging
  - Hints of features to be studied with Chandra
  - XMM data constrains abundance of O, Fe, and Si – we find [Si]>1, and [O] consistent with 0 (less than 0.4 Solar) with no evidence for radial dependence.
  - Paper in preparation (Kraft et al. 2009)

Future Work

- XMM-Newton
  - Large scale survey of gas around NGC 4472
  - Study of connection NGC 4472 to M87
- Radio
  - Low frequency radio observation – aged radio plasma
- Chandra
  - Deep Chandra observation of core could constrain Bondi accretion and study small scale gas motions of merger and nuclear activity for comparison with simulations
  - Larger scale study of filaments and merger dynamics