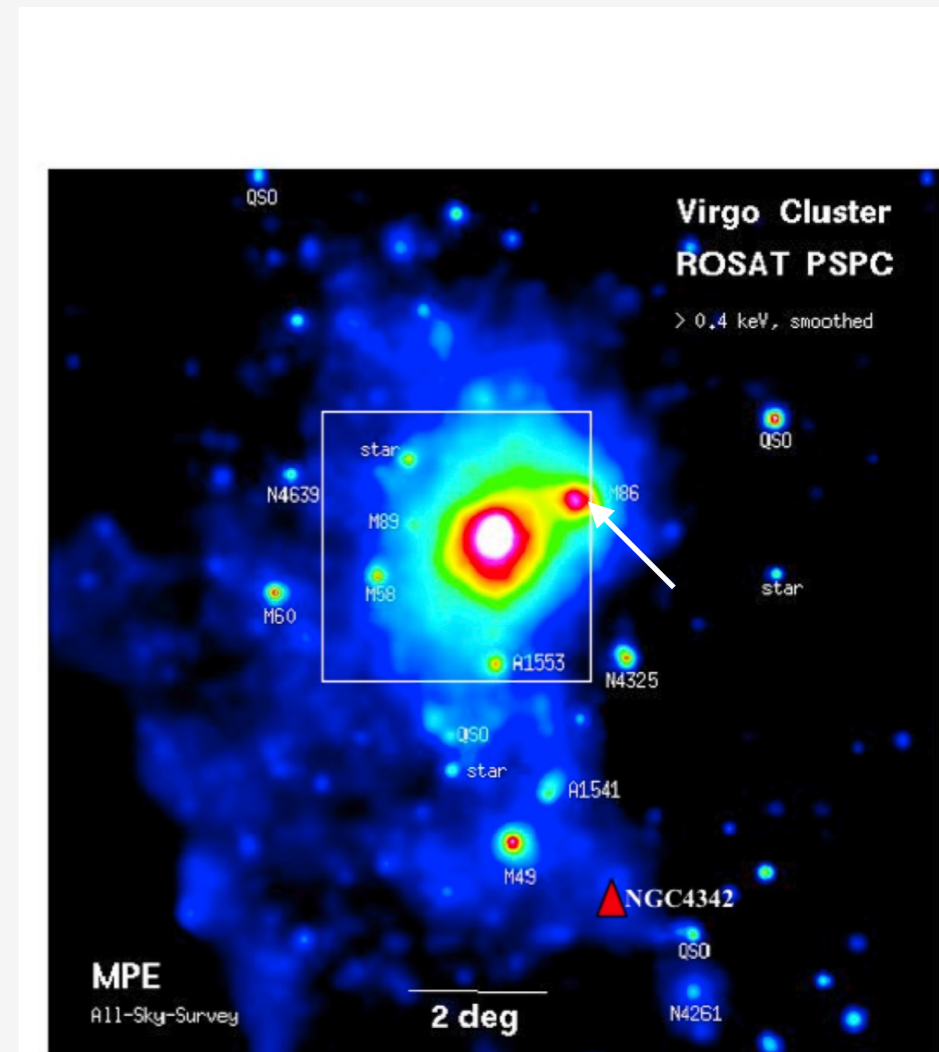
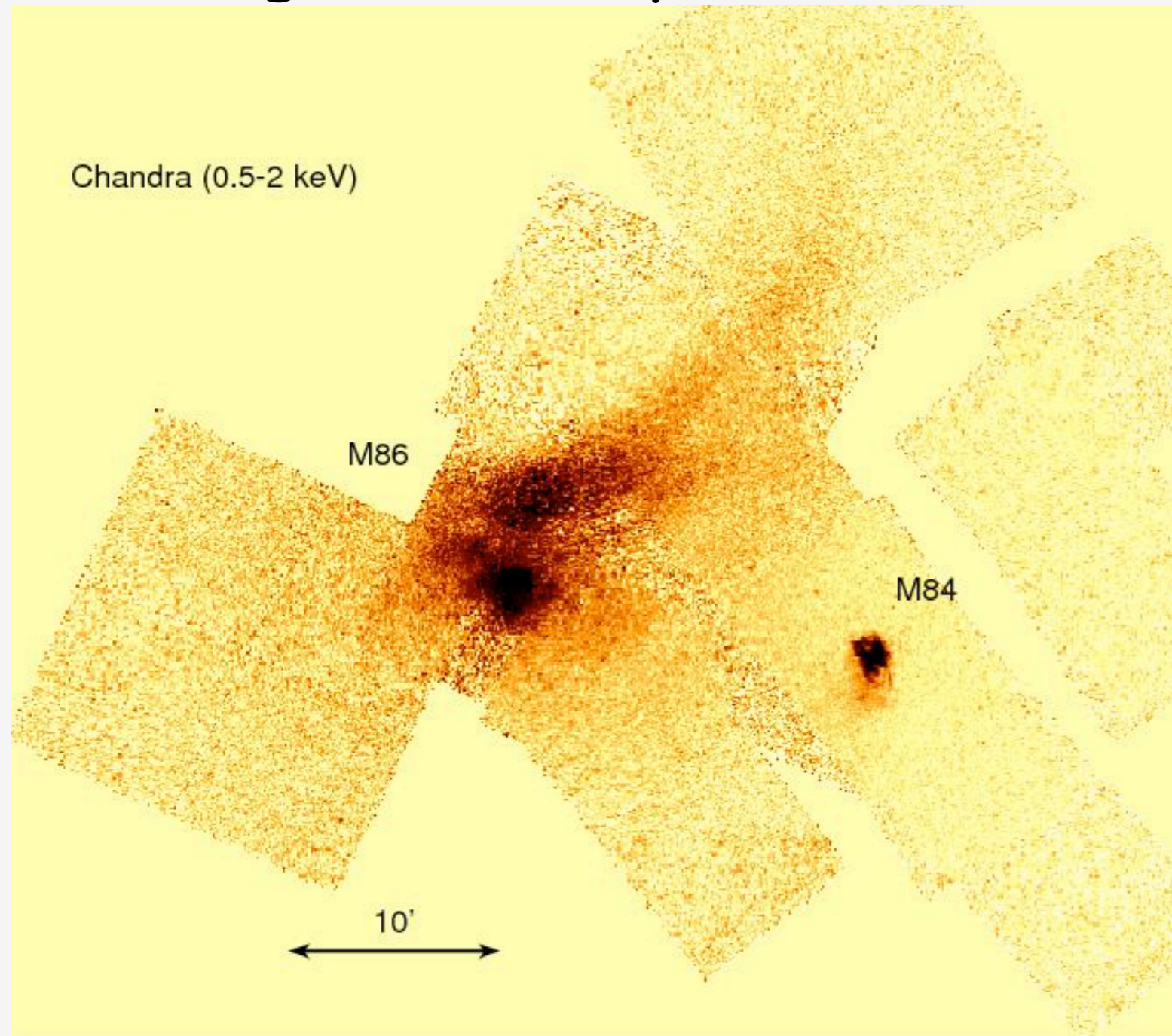


Some of what we can learn from the interaction of an infalling galaxy with a cluster - importance of good spatial resolution and comparison with simulations

Christine Jones , William Forman, Eugene Churazov, Yuanyuan Su, Ralph Kraft, Ming Sun, Scott Randall, Paul Nulsen, John Zuhone, Elke Roediger

The infall of M86 through the Virgo cluster line of sight velocity -1550 km s^{-1} with respect to M87



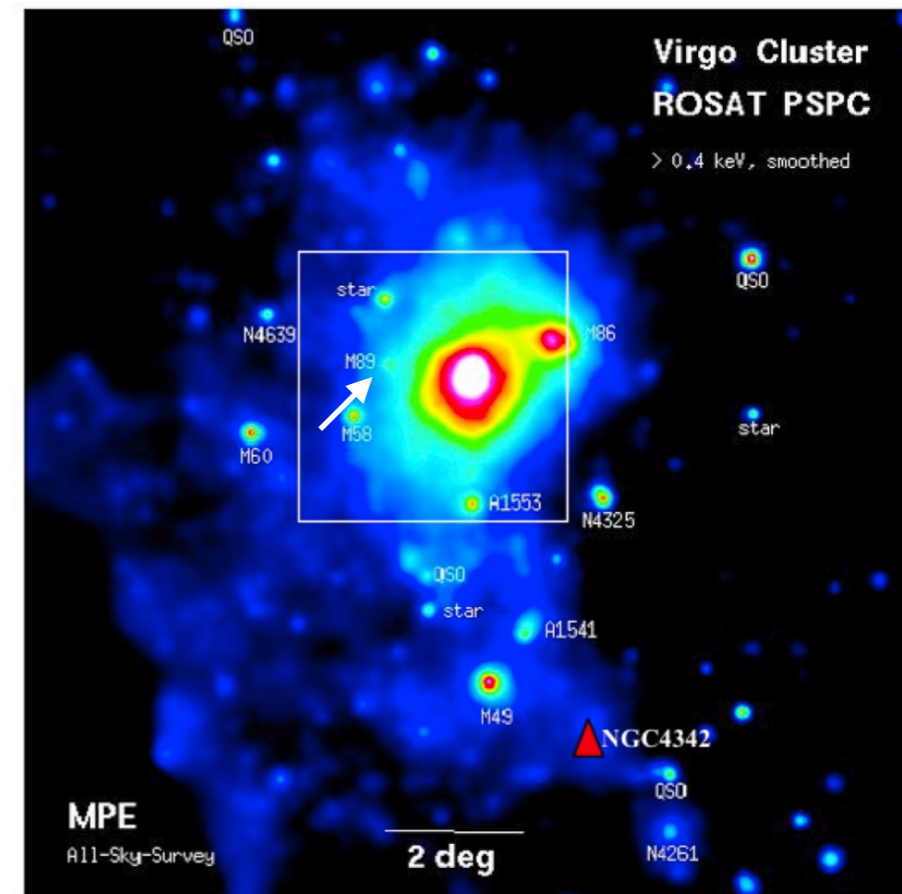
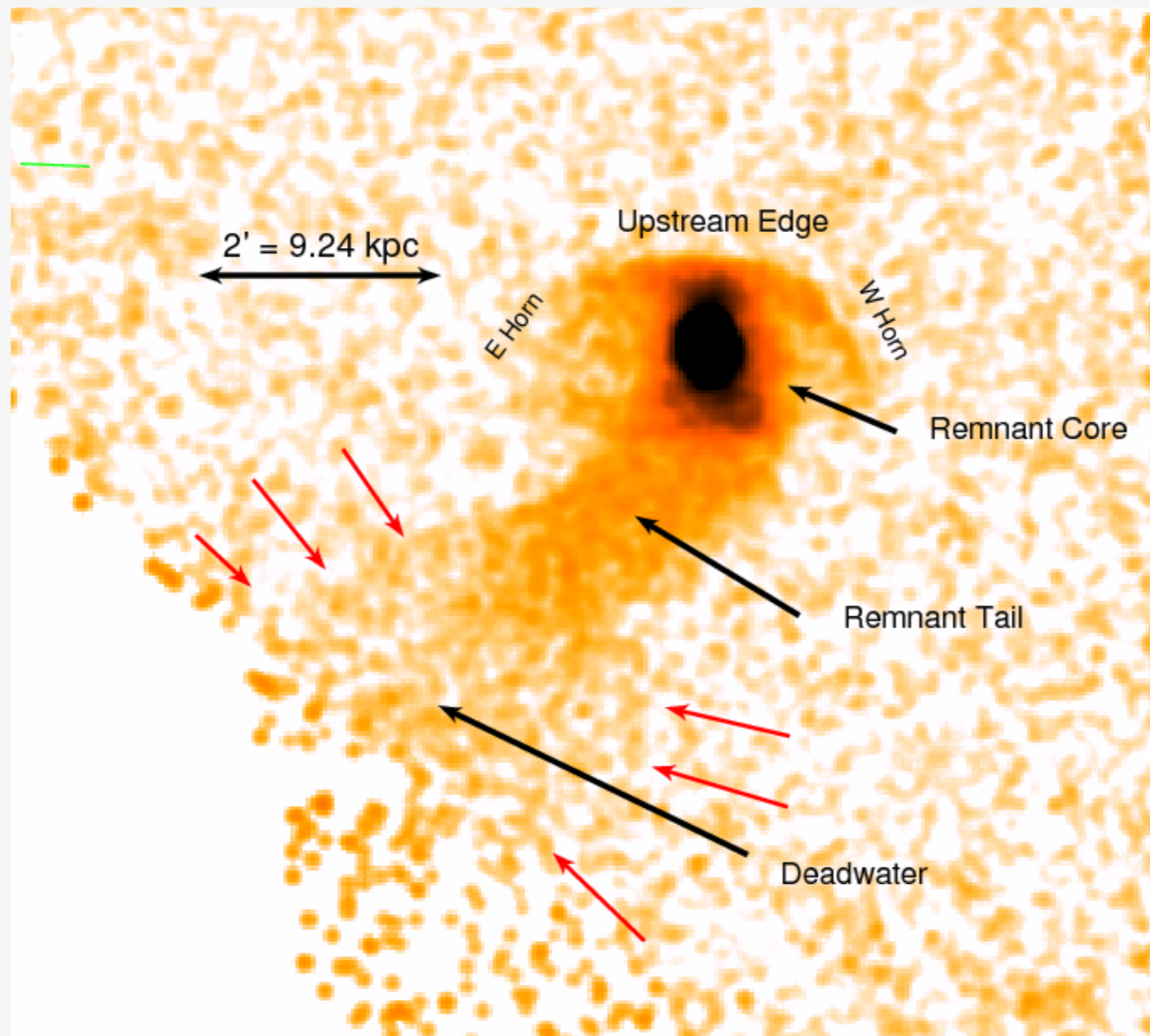
Ram pressure stripped double gas tails 150 kpc in projection and true length >380 kpc Since discovery with Einstein (Forman et al. 1979), observed by every major X-ray observatory. Above is Chandra mosaic (Randall et al. 2008). Also note short tail south of M84.

Infall of M89 (NGC4552) toward M87

(Machacek et al 2006; Kraft, Roediger et al. 2017)

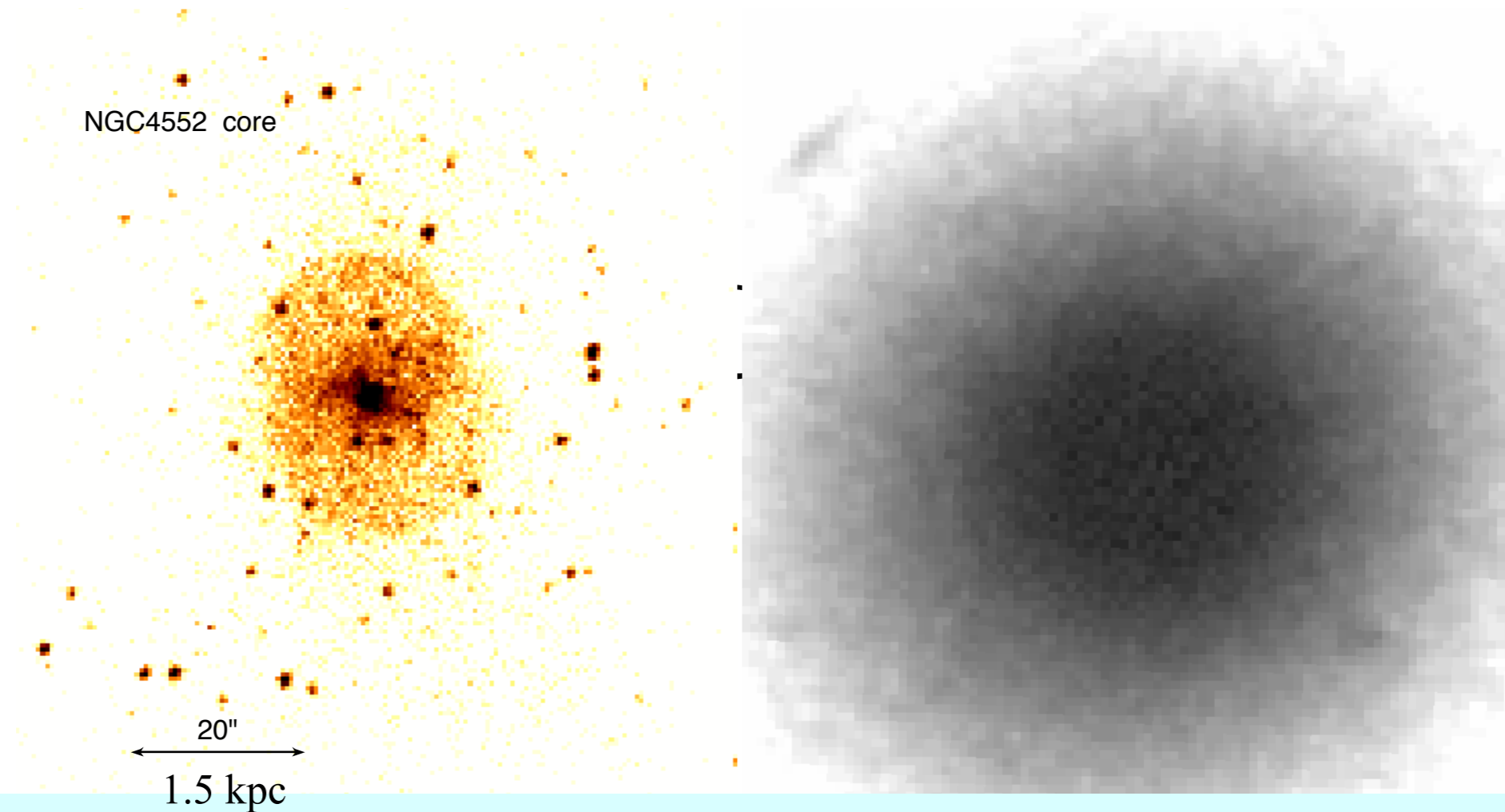
Surface brightness edge to north and 20 kpc X-ray tail.

Motion close to plane of the sky (~ 30 deg); M89 has experienced slow steady increase in ram pressure during infall. Based on a detailed comparison of the tail to simulations, effective viscosity of Virgo ICM is several orders of magnitude below Spitzer value. Note "horns" favor low viscosity gas, but could be result of AGN outburst.



Bipolar Cavities in NGC4552 (M89)

Machacek + 2006



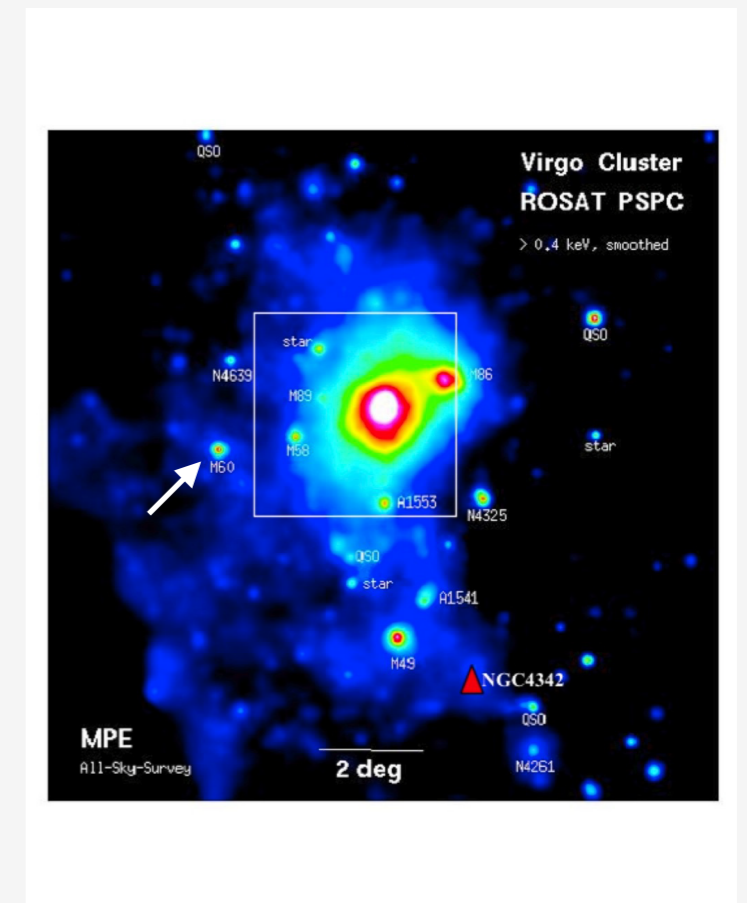
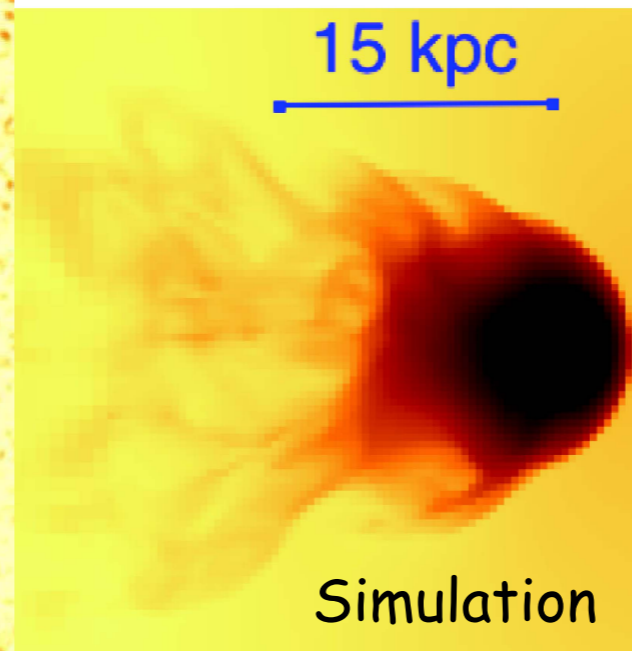
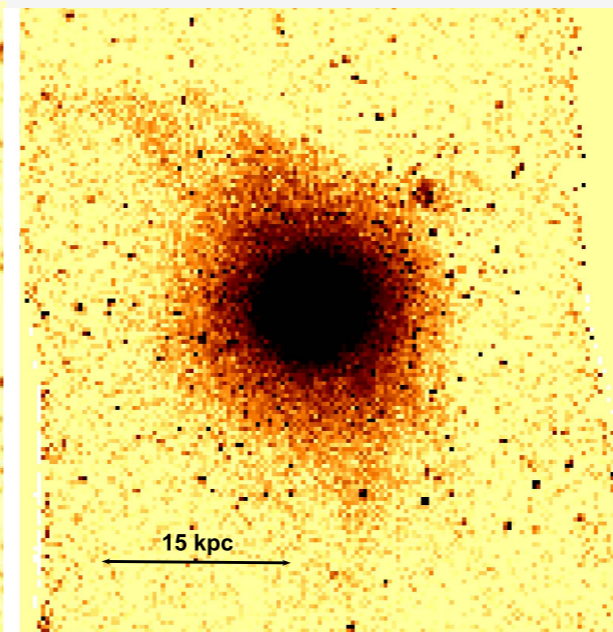
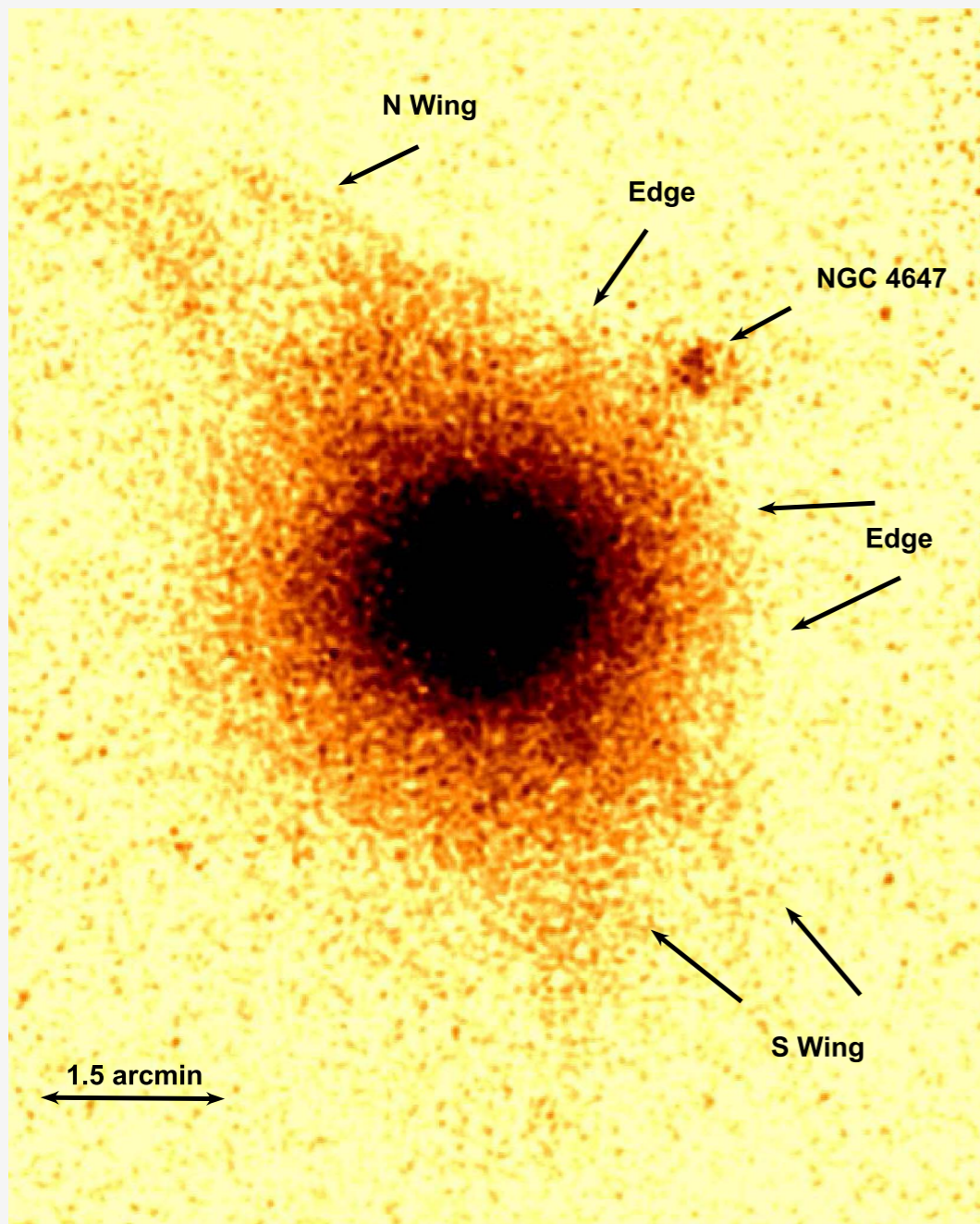
One outburst - one pair of bubbles

Mach 1.7 shock from 1.4×10^{55} ergs nuclear outburst

Outburst age $\sim 1-2 \times 10^6$ years

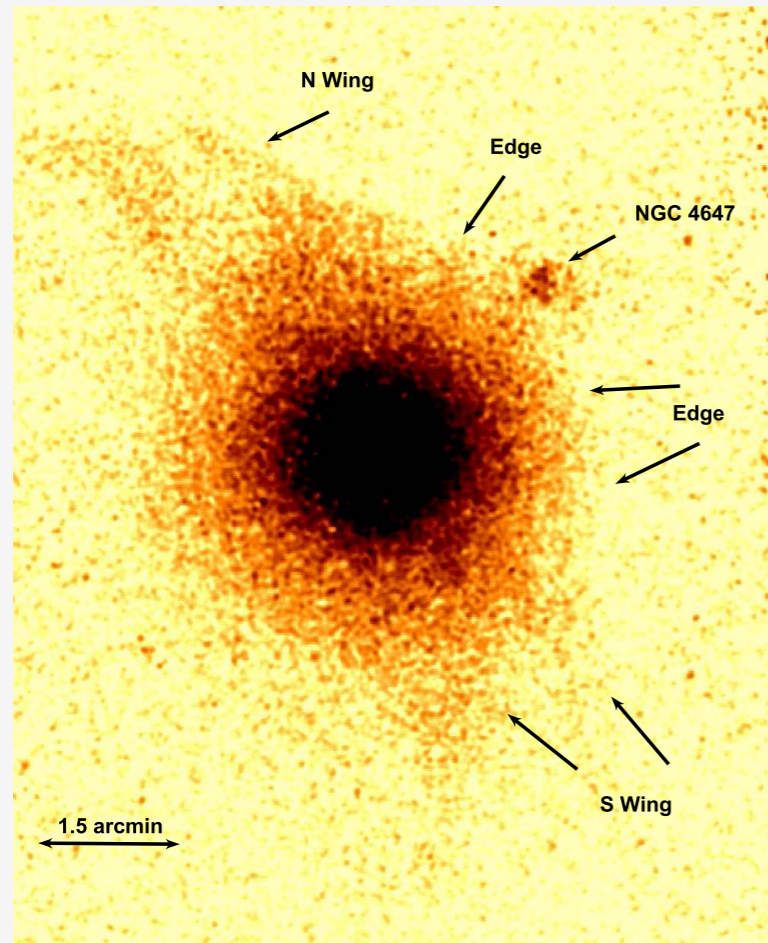
Higher gas temperature in galaxy core suggests directly observing reheating of ISM by nuclear outbursts

M60 - elliptical with short tail, falling toward M87 - 1 Mpc east of M87

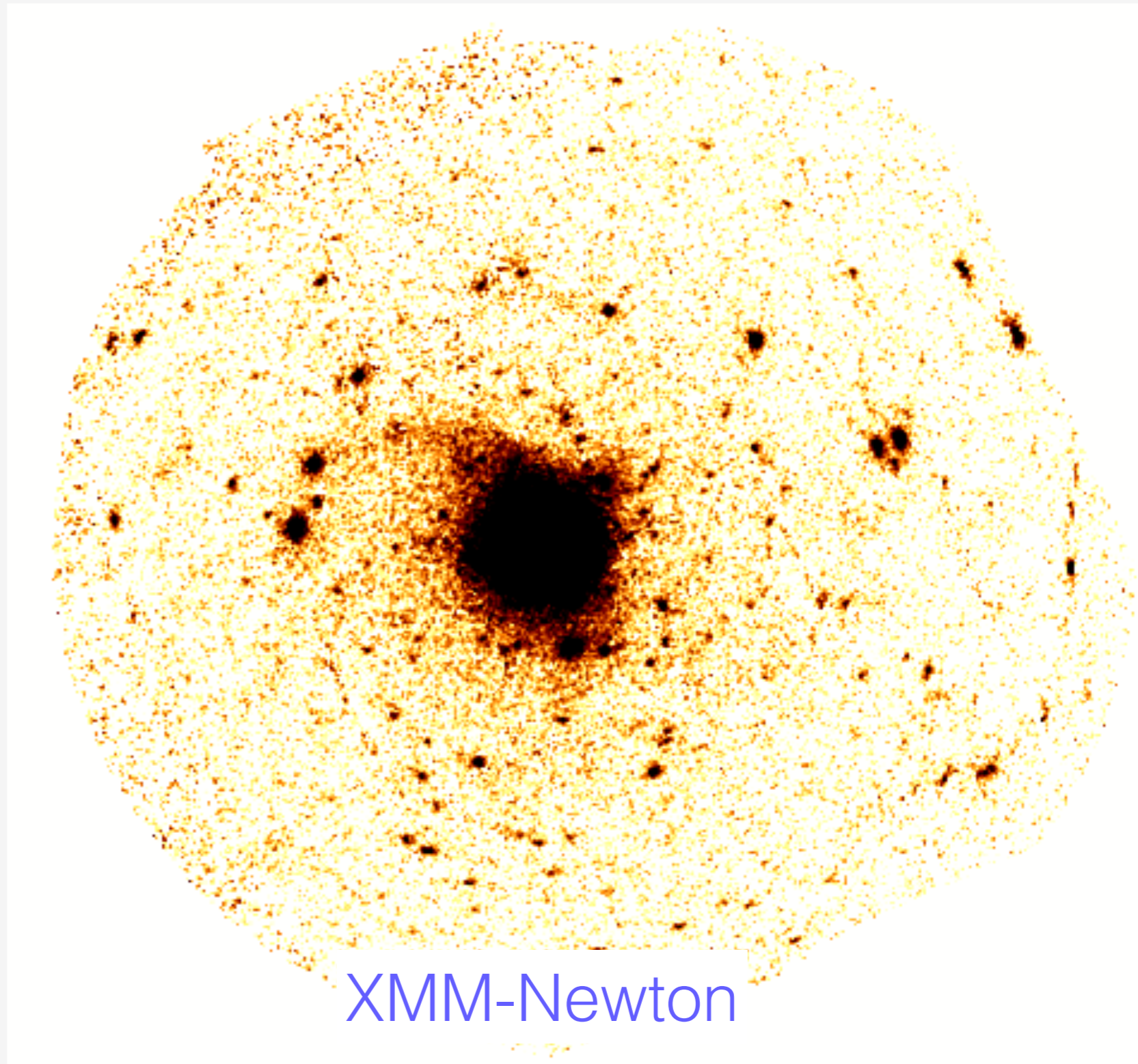


If western edge is a cold front, we measure the pressure across the edge, and determine a Mach number ~ 1.7 . This gives an infall velocity $1030 (180) \text{ km sec}^{-1}$. Short tail is ram pressure stripped gas. "Wings" are K-H instabilities and based on simulations imply gas stripping is close to inviscid (Wood et al. 2017 ApJ 847, 79).

M60 - hot gas halo, but no long gas tail



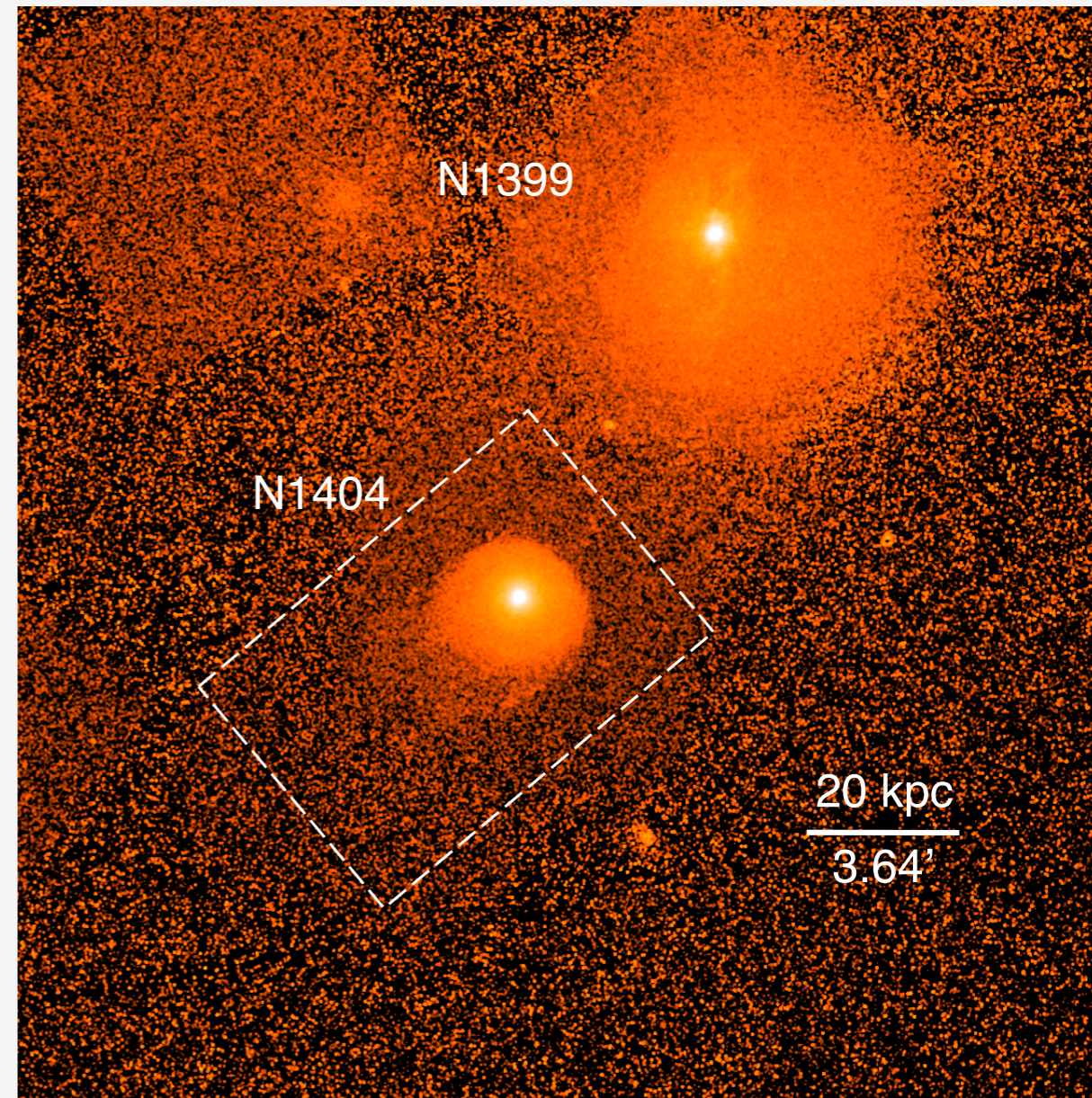
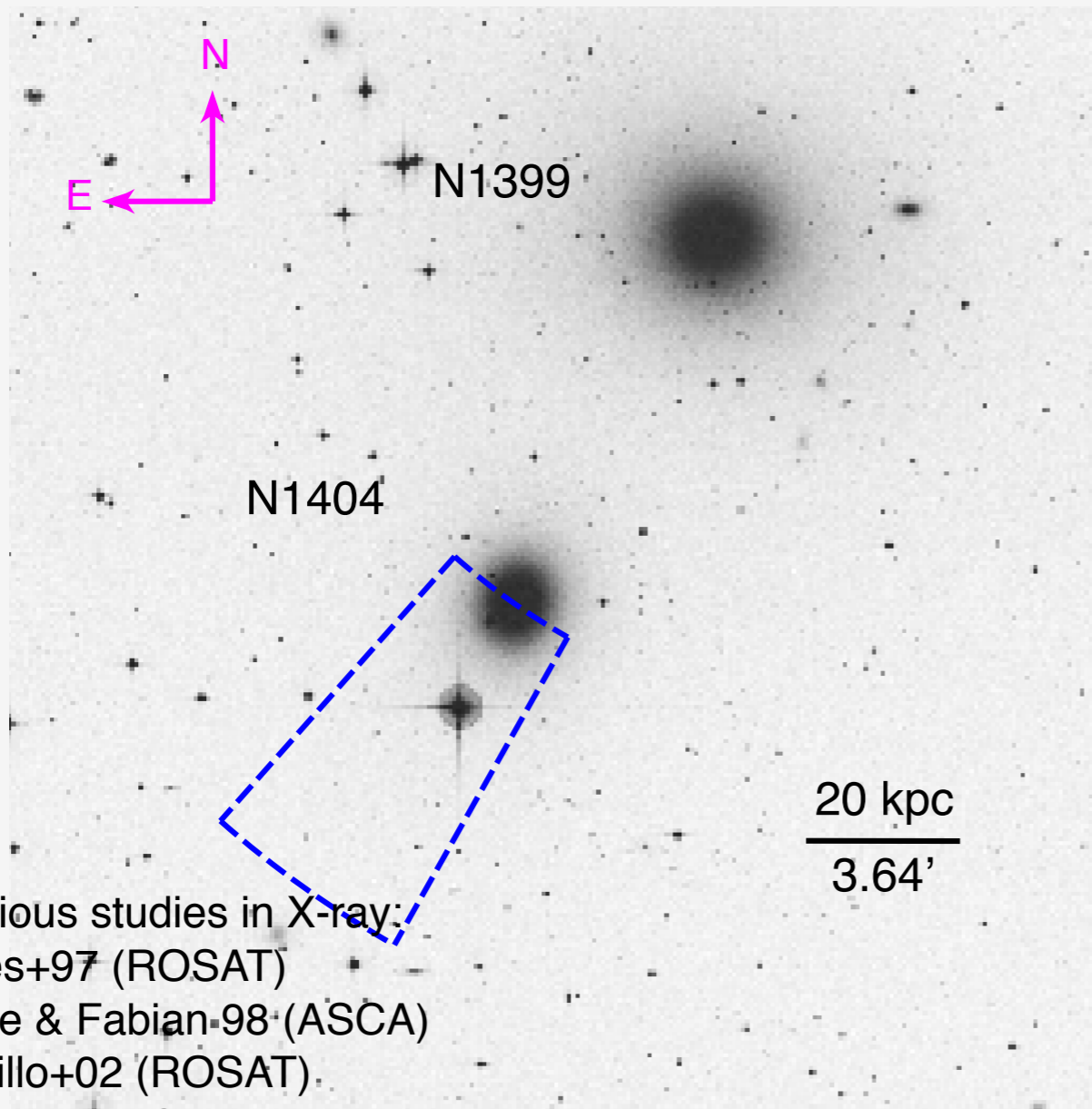
Chandra



XMM-Newton

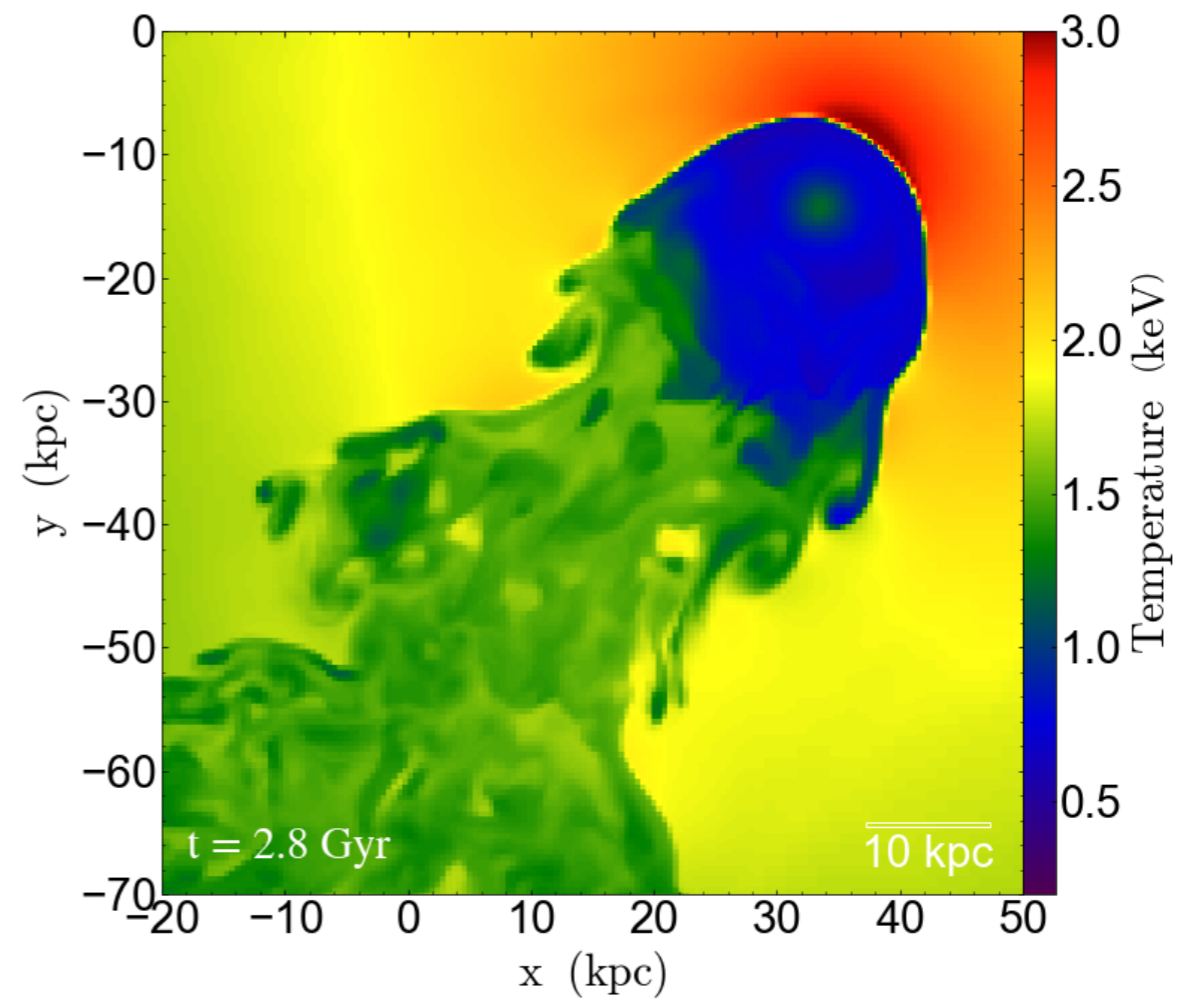
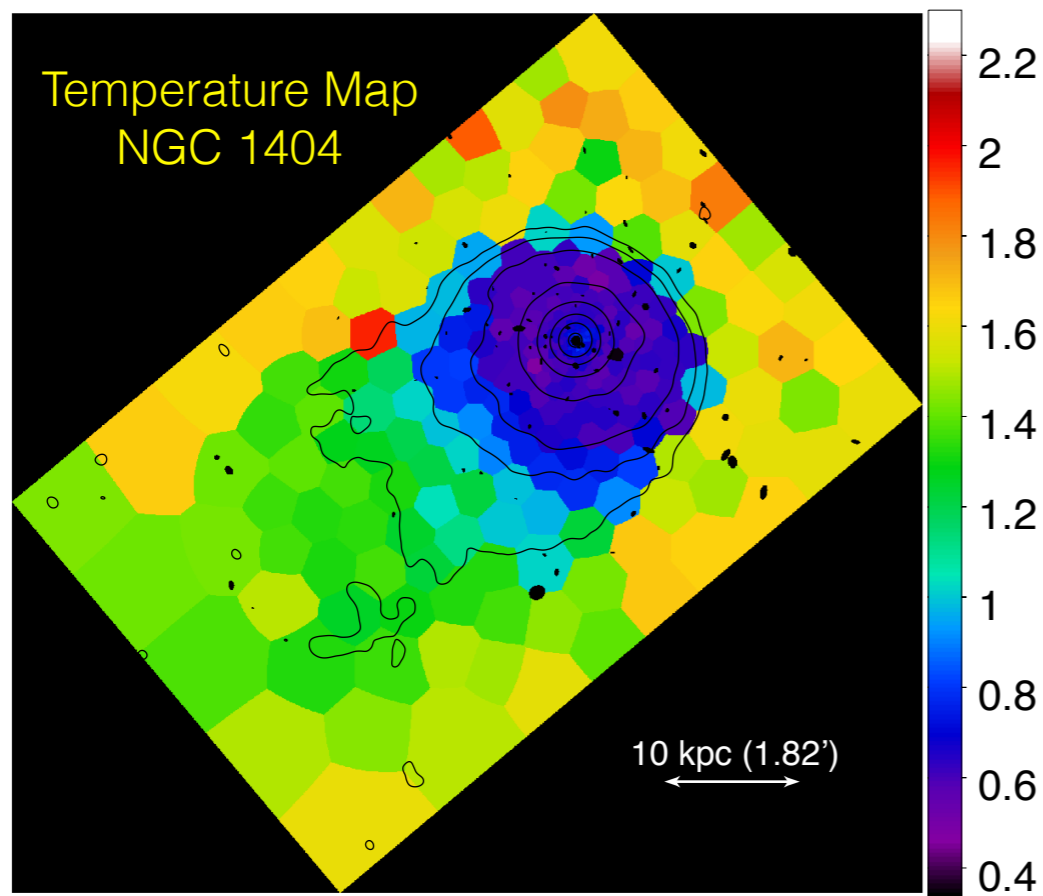
M60 falling into Virgo. Ram pressure stripped gas. (Wood et al 2017 ApJ)

Infall of NGC1404 into Fornax cluster



Previous studies in X-ray:
Jones+97 (ROSAT)
Buote & Fabian-98 (ASCA)
Paolillo+02 (ROSAT)
Scharf+05 (Chandra)
Machacek+05 (Chandra)
Churazov+10 (Chandra+XMM)
Murakami+11 (XMM+Suzaku)
and more

X-ray tail and cold front in NGC1404 (no AGN outburst) Su et al. ApJ 2017



Su et al. 2017

Importance of comparing observations to simulations.



3D Motion Reconstruction

Su et al. 2017 ApJ, 835, 19

Input

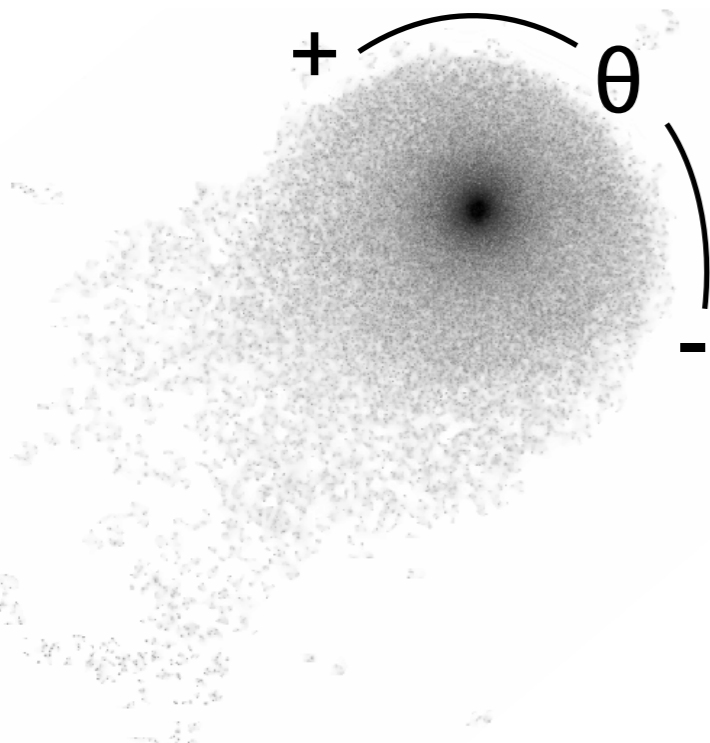
- ★ Radial velocity
- ★ Azimuthal pressures $P(\theta)$
- ★ ICM density profile

- ★ Bernoulli equation
- ★ Jump condition

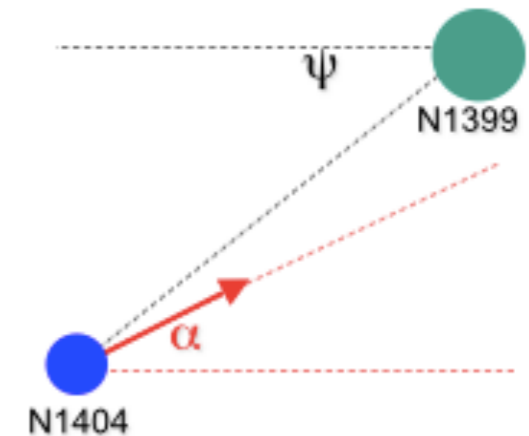
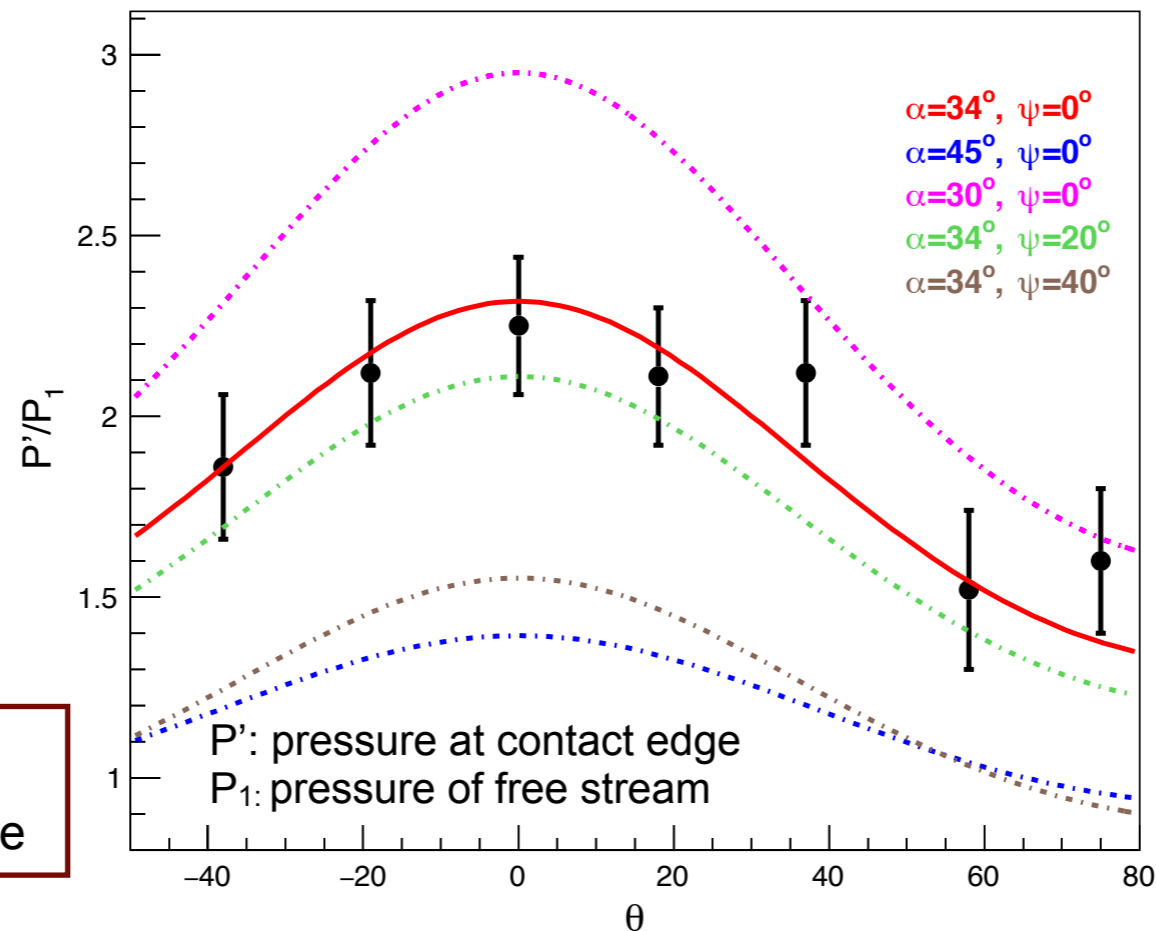


Output

- ★ 3D velocity field
- ★ 3D position



We measure P_θ
the azimuthal variation of pressure



We obtain
 $\alpha \sim 34^\circ$ and $\psi \sim 0^\circ$
 Mach number: 1.3

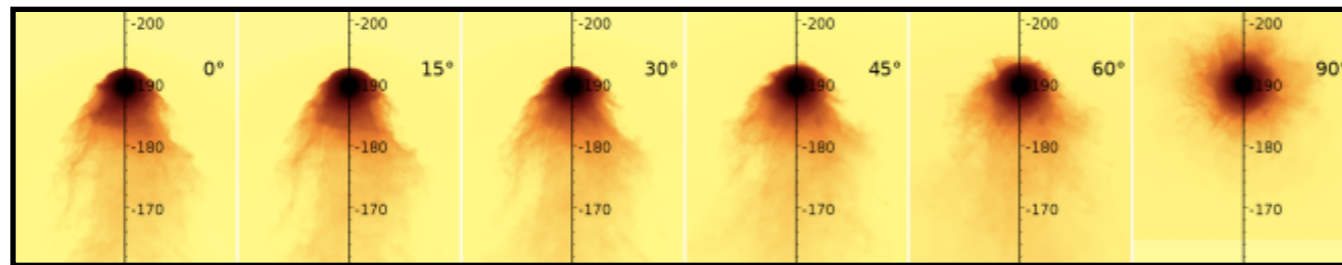
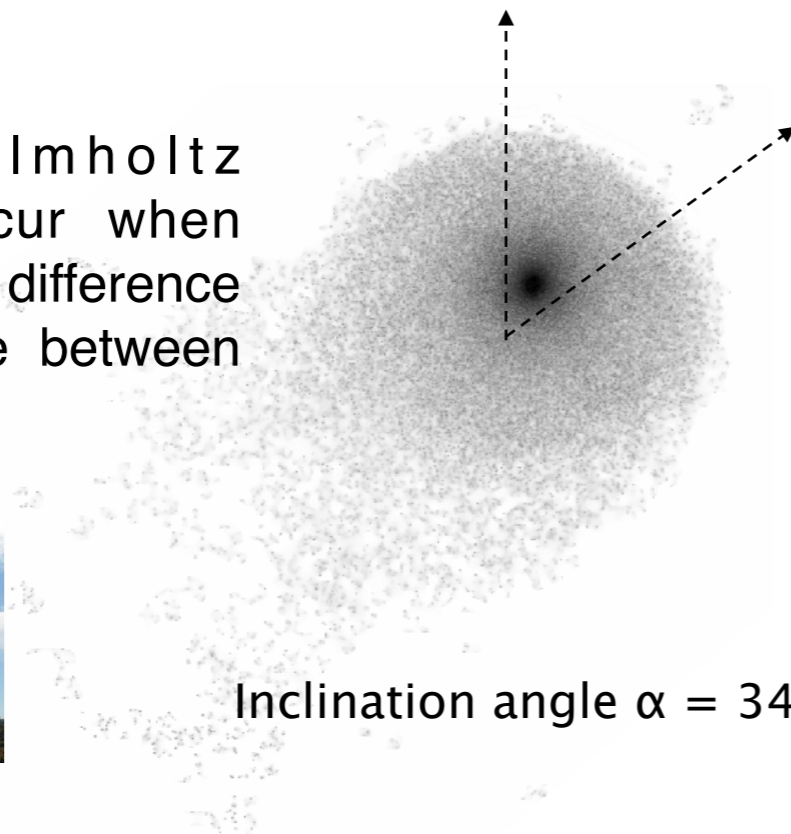
NGC 1404 — Traveling through the ICM

- ☆ Presence of Kelvin Helmholtz (KHI) Rolls ~ 200 pc
- ☆ **Viscosity and/or strong ordered magnetic field can suppress KHI (Chandrasekhar 1961)**

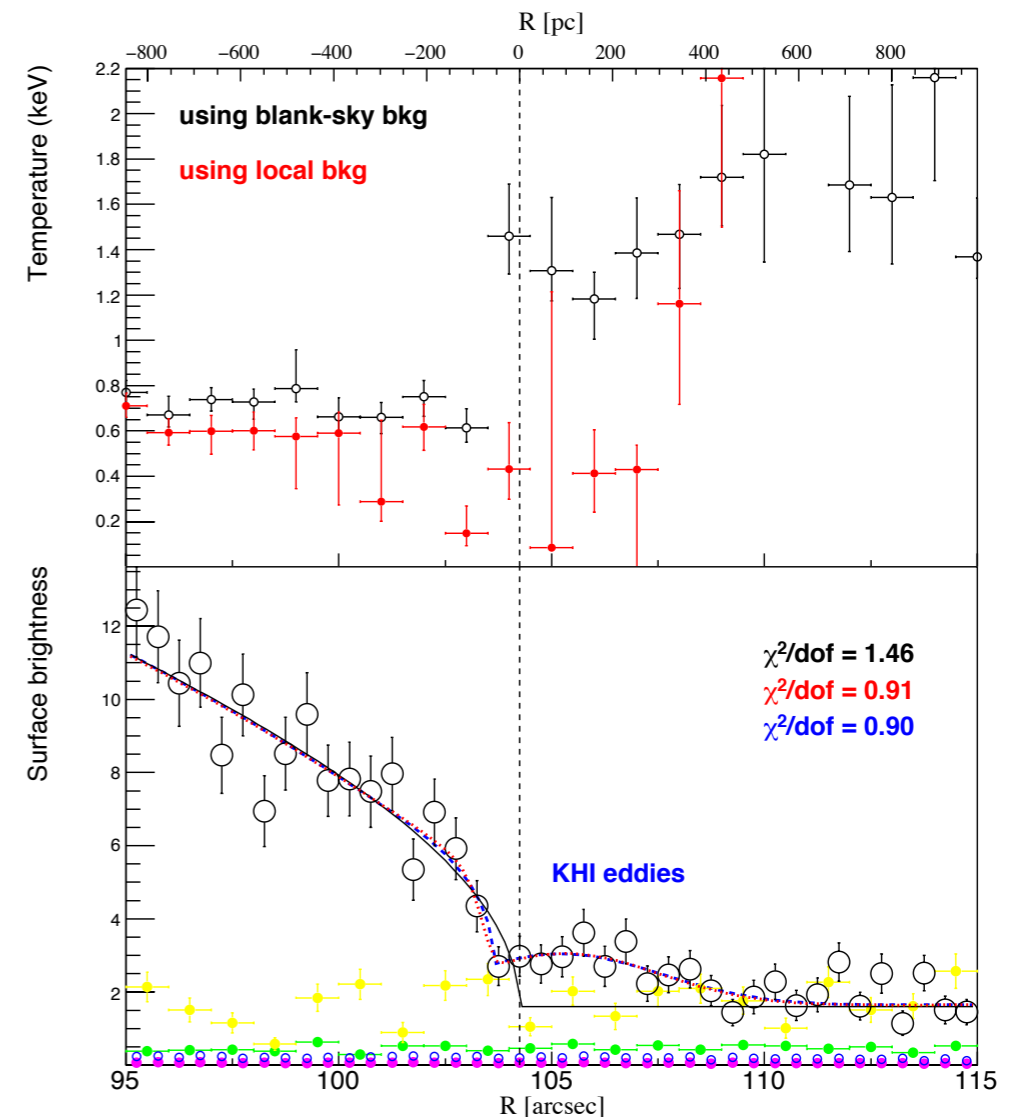


- ☆ **Viscosity < 1% Spitzer**
- ☆ **Magnetic field < 5 μG**

- ☆ The Kelvin–Helmholtz instability can occur when there is a velocity difference across the interface between two fluids.



Su et al. 2017 ApJ, 834, 74





THE HOT AND ENERGETIC UNIVERSE:

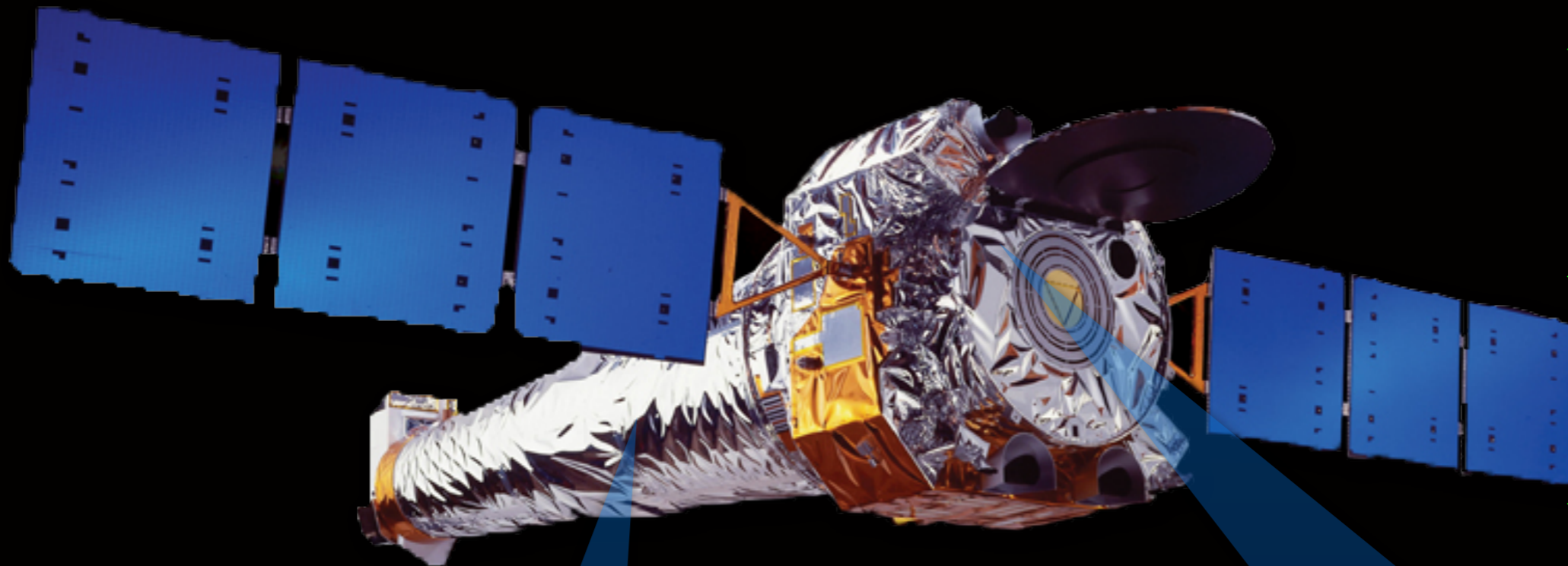
1. How does ordinary matter assemble into the large scale structures we see today?
2. How do black holes grow and influence the Universe?

Primary Cluster Science Goals

- 2m effective area at 1 keV
- 5'' angular resolution
- 0.3 - 12 keV
- Wide Field imager 40' FOV
- Calorimeter 5' FOV

Trace the evolution of clusters and groups to $z=1$
Measure velocities, thermodynamics, chemical composition of hot gas to quantify non-gravitational heating and turbulence

LYNX (formerly X-ray Surveyor) under study for the 2020 decadal



✓ **Technology incorporates IXO development and *Chandra* heritage**

✓ **No spacecraft requirements beyond those achieved for *Chandra***

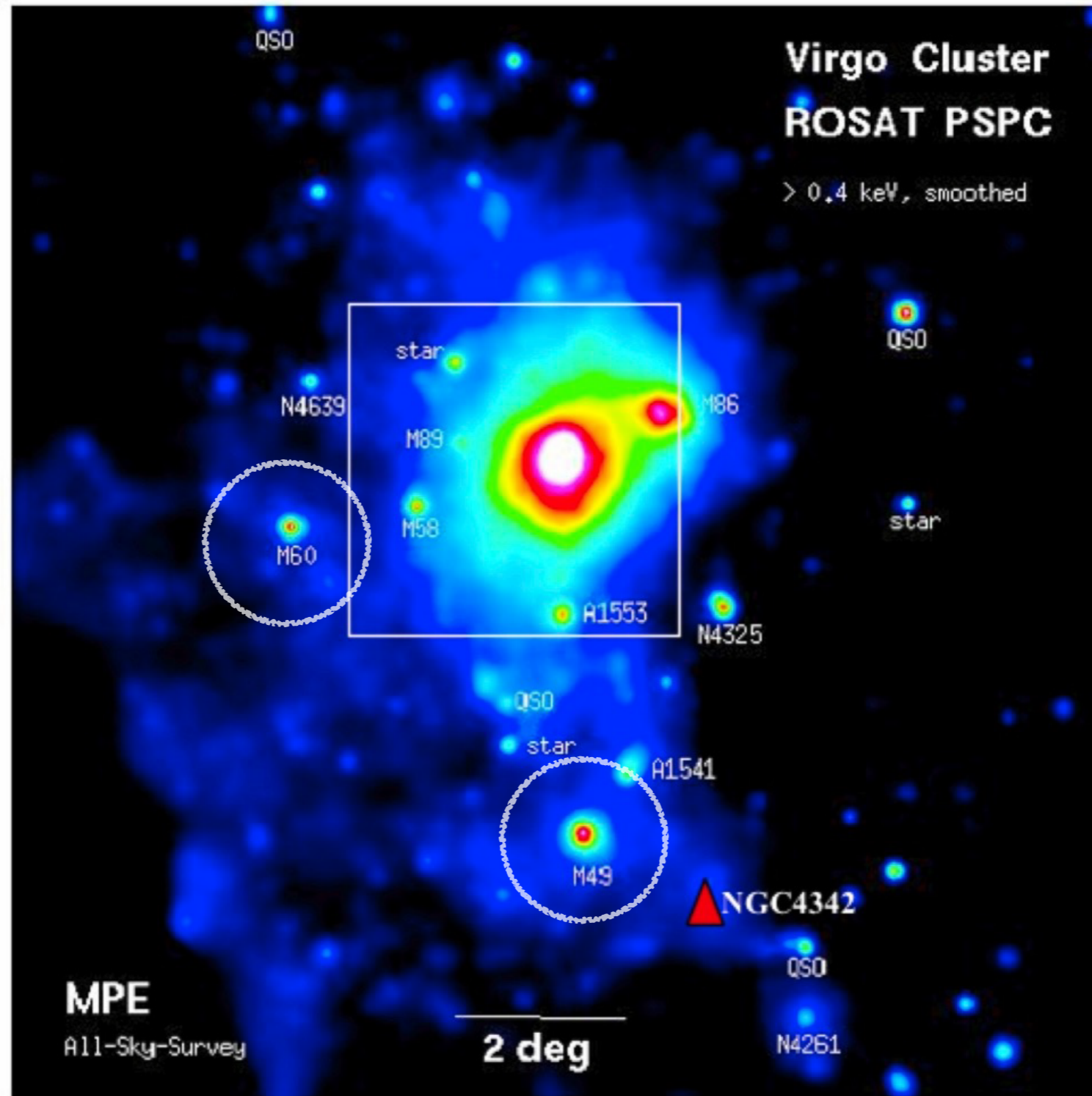
✓ ***Chandra*-like cost**

Next-generation science instruments, e.g.:

- 5×5' microcalorimeter with 1" pixels and high spectral resolution, 0.2–10 keV
- 22×22' CMOS imager with 0.33" pixels, 0.2–8 keV
- insertable gratings, R = 5000, 0.2–1.2 keV

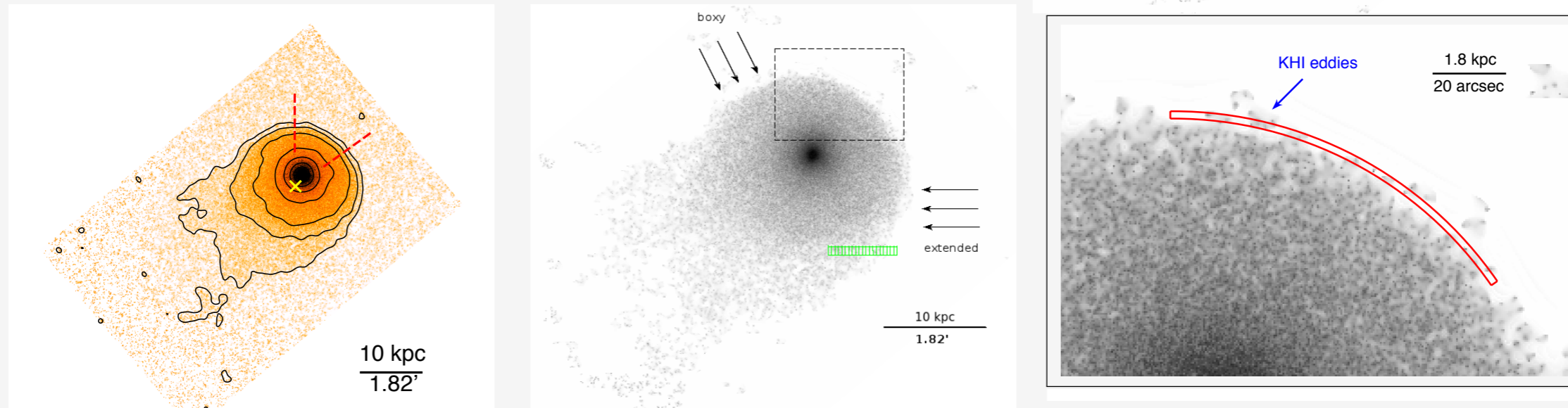
“Smart” mirror system. Lower weight, same angular resolution, same focal length as *Chandra*'s. **A factor of 30 more effective area. Sub-arcsec imaging over 15×15' field.**

M86, M89,
M60, M49
all infalling
toward M87



NGC1404 infalling into Fornax cluster - investigating the gas physics

Su, Kraft, Roedinger et al. 2017



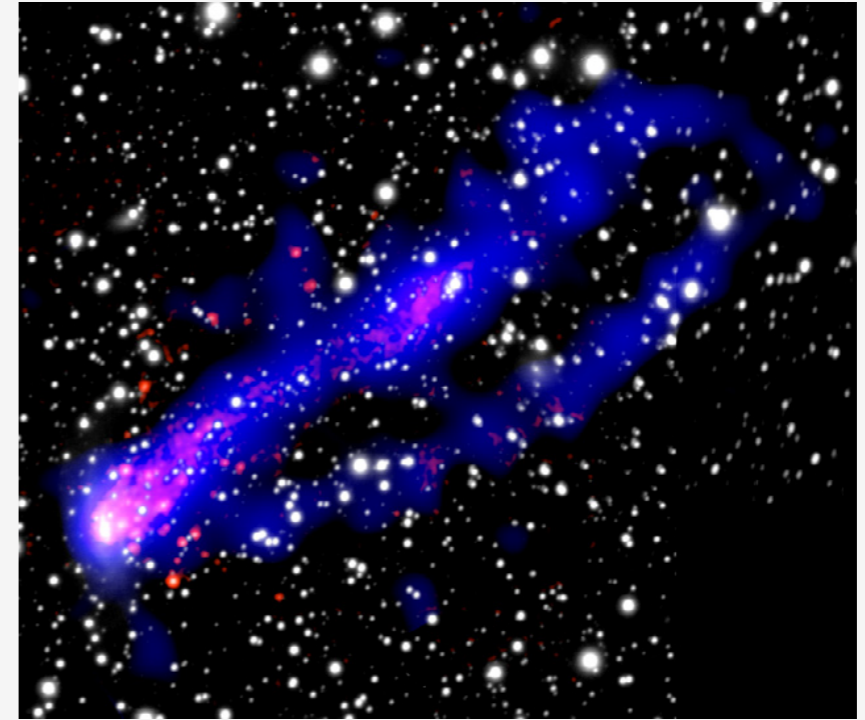
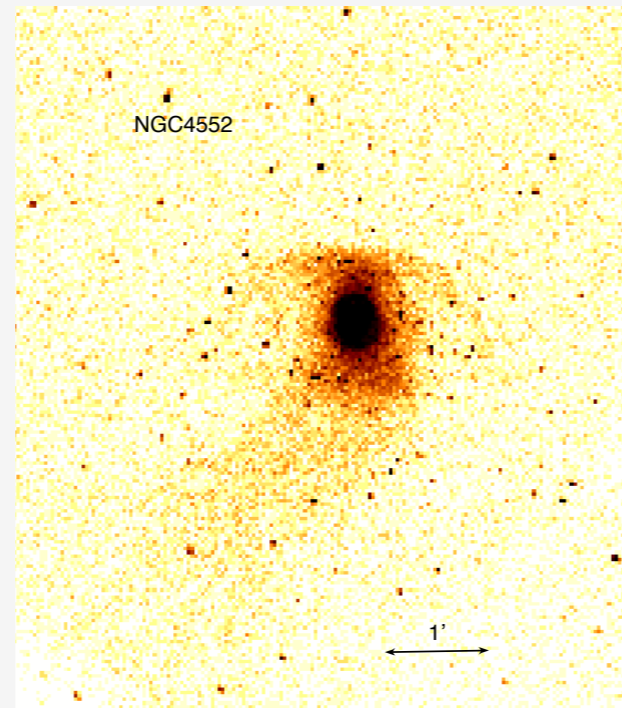
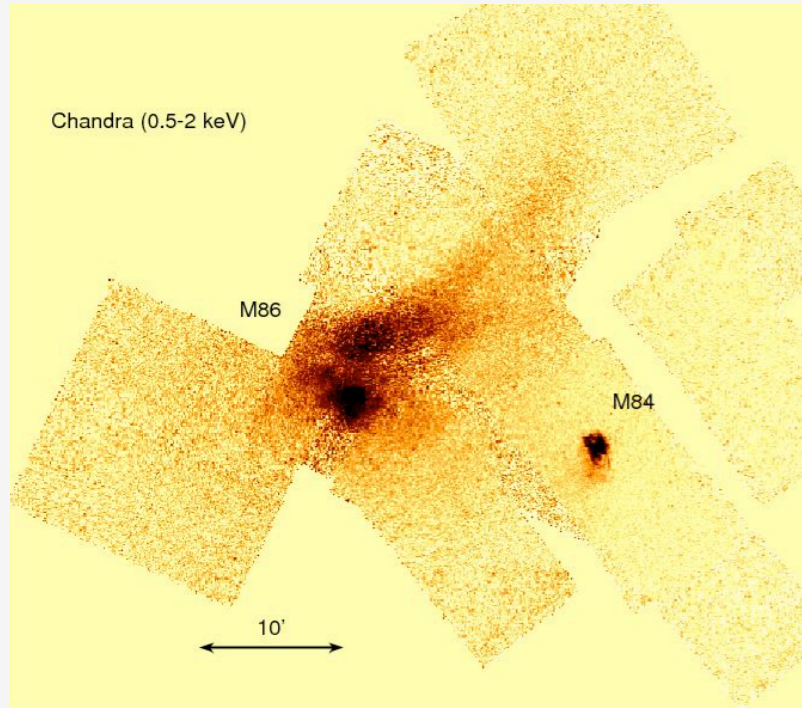
KH instabilities along cold front/contact discontinuity

Isotropic viscosity of gas $< 5\%$ Spitzer.

Mixing of the hot cluster gas and the cooler galaxy gas in the downstream stripped tail provides further evidence of a low viscosity plasma.

Ordered magnetic fields in the ICM smaller than 5 microG to allow KHI.

Galaxies with long X-ray tails



M86

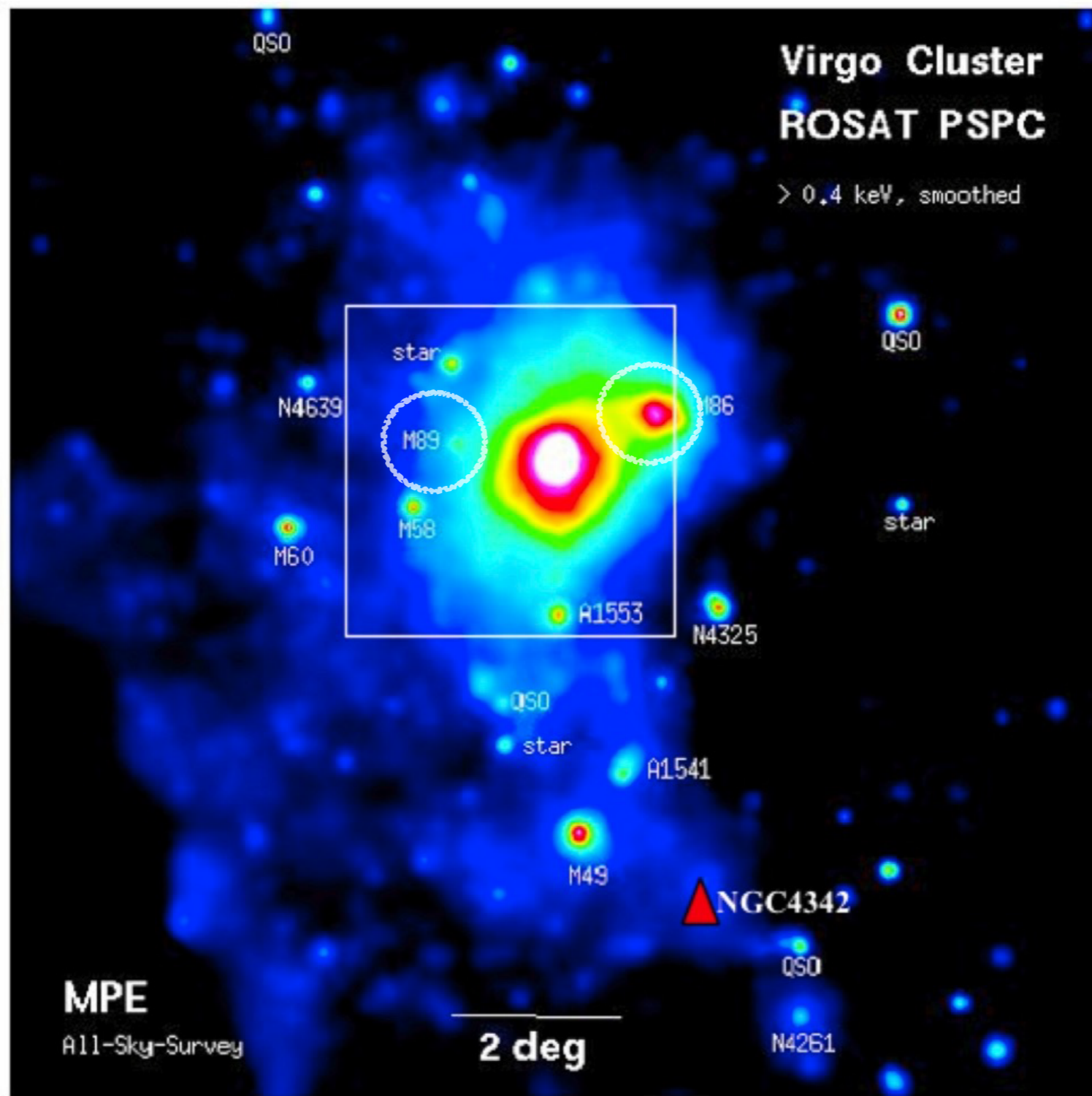
Falling into Virgo. Ram pressure stripped gas. (Forman et al. 1979; Randall et al. 2008)

M89 (NGC4552)

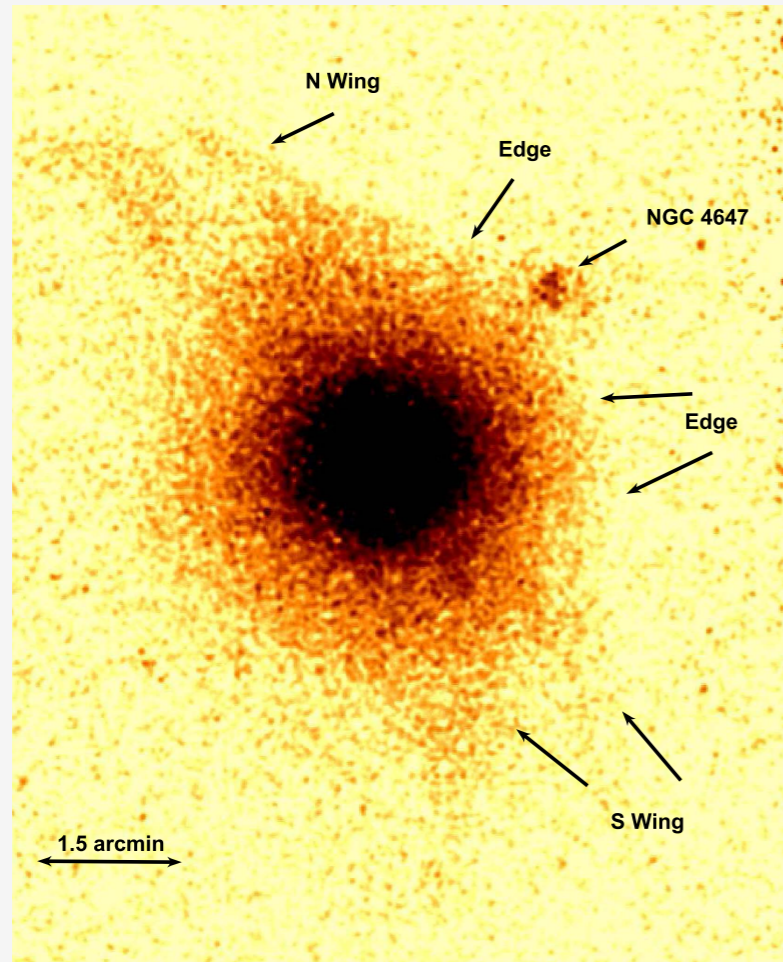
Falling into Virgo. Ram pressure stripped gas. (Machacek + 2006; Kraft + 2017)

ESO 137-001 (A3627)

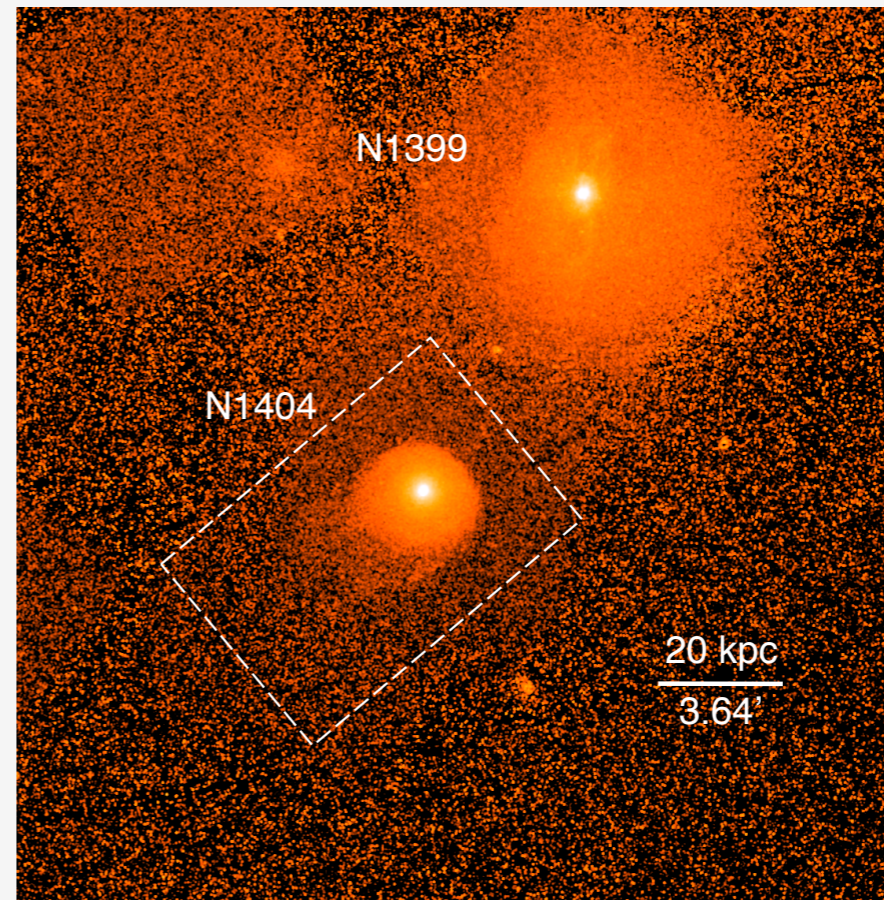
Spiral falling into A3627. Ram pressure stripped gas, 80 kpc long. "pink is H α ; ULX's in tail, star formation in tail of hot gas. (Sun + 2010)



2) Galaxies falling into clusters with short tails M60 (Virgo), NGC1404 (Fornax)

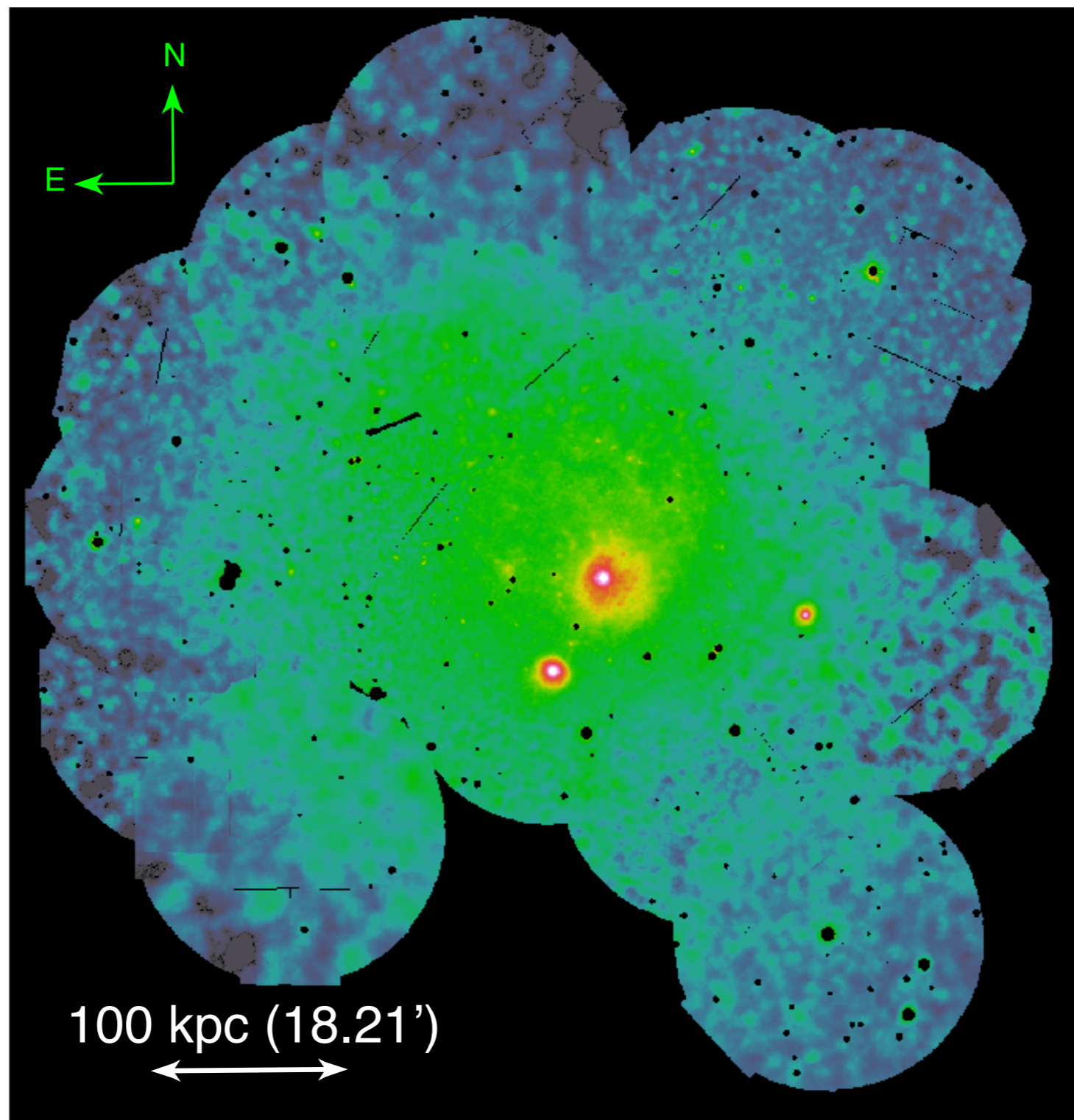


M60 galaxy group falling into Virgo. Ram pressure stripped gas and "wings".
(Wood et al. 2017)



X-ray tail and cold front in NGC1404 (no AGN outburst)
Su et al. ApJ 2017

The Fornax cluster



mosaic image of 17 XMM pointing

Stripping of hot gas in spiral galaxy ESO137-001 in A3627

Sun et al. *ApJ* 708, 947, 2010

