# ATHENA WFI and XIFU Observations of the Fornax and Virgo Clusters: Gas Dynamics, Merger History, and Elemental Enrichment

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**ABSTRACT:** The Fornax cluster is a cool (kT~1.5 keV), nearby cluster (d~20 Mpc) that is in the late stage of merging with a small group. In this presentation, we describe how an Athena WFI survey of the cluster gas to the virial radius combined with specifically targeted XIFU observations would transform our understanding of the merger history, gas dynamics, and the distribution of heavy elements in the ICM. Due to its proximity, angular size, high surface brightness, and relatively cool temperature, the Fornax cluster is one of the key benchmarks that informs our understanding of the dynamics of groups and poor clusters. This cluster has been deeply observed by both Chandra and XMM-Newton, and we created detailed hydrodynamical simulations of the infall and merger of NGC 1404 into the Fornax cluster. These data and simulations will be used to make detailed predictions for mock Athena observations of this cluster. Fornax is the perfect Athena target - cool, nearby, clean merger - for understanding the microphysics, enrichment, and evolution of the plasma that is the dominant baryonic component of the Universe and which is fully revealed in galaxy clusters as it is heated to the virial temperature.

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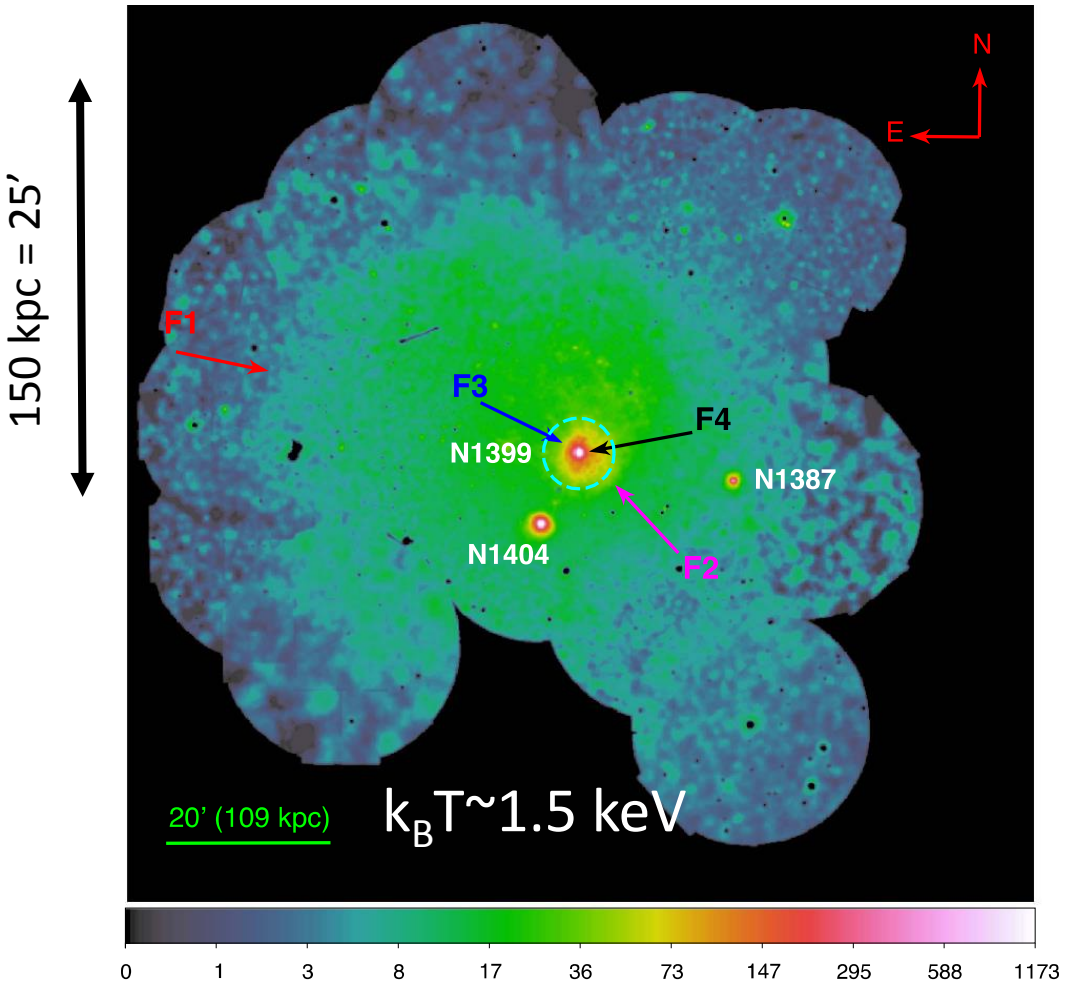
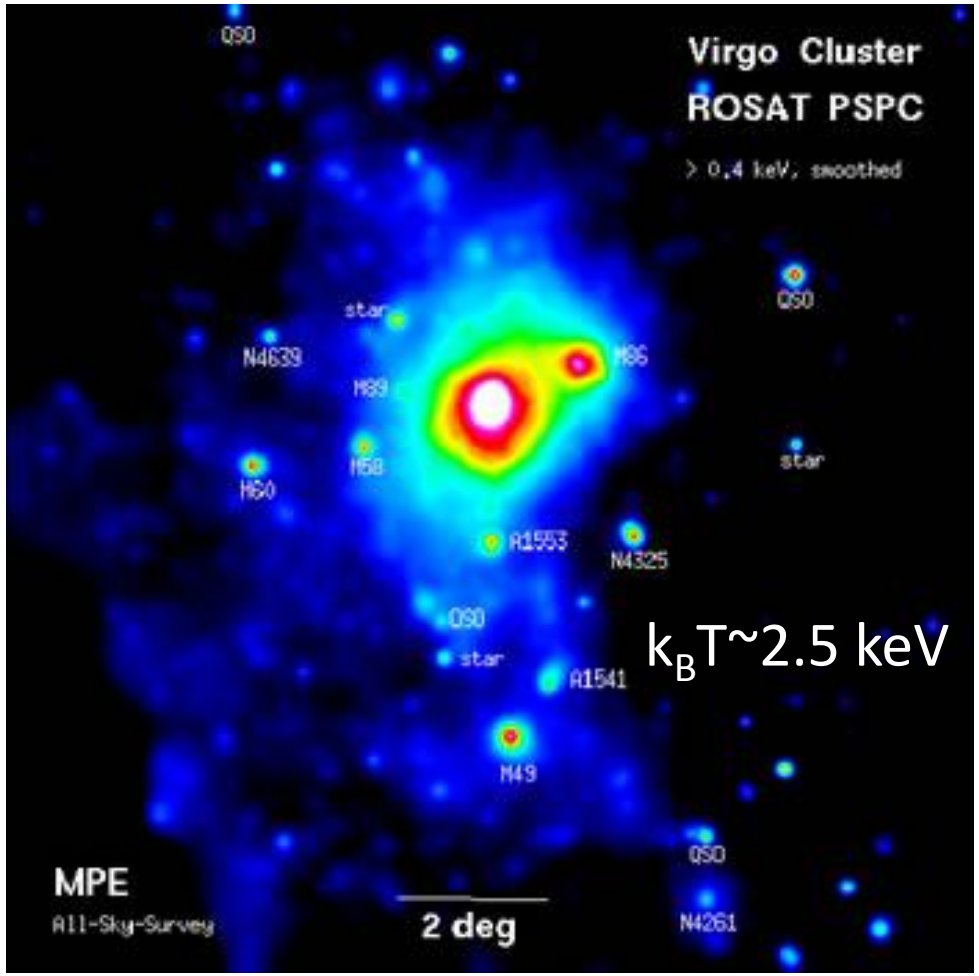
# ATHENA studies of nearby groups and clusters

- Nearby clusters offer highest linear resolution and sensitivity – can probe spatial scales inaccessible in other targets.
- Difficult to study globally with current generation of X-ray observatories because they are too extended (degrees).
- ATHENA is well-suited for these investigations because of the large effective area and FOV of the WFI and the high spectral resolution of the XIFU.
- Lots of consideration has been given to Perseus and Coma clusters, but all of the nearby clusters and groups will be fantastic ATHENA targets.
- **Goal of this talk – describe some potential investigations of individual galaxies and global properties of the Fornax and Virgo clusters** (or, how to have fun with FLASH and SIXTE)

# The Fornax and Virgo Clusters

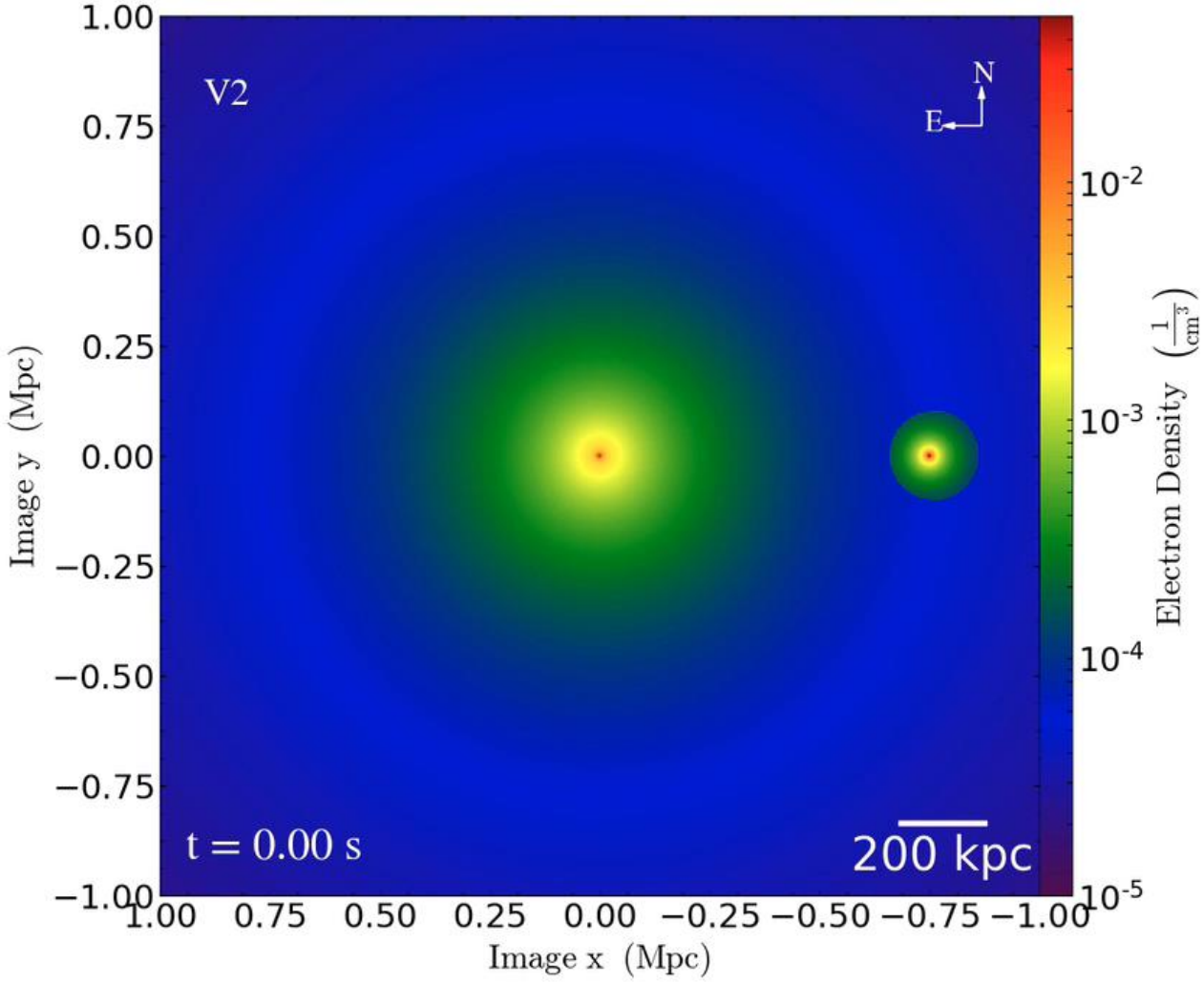


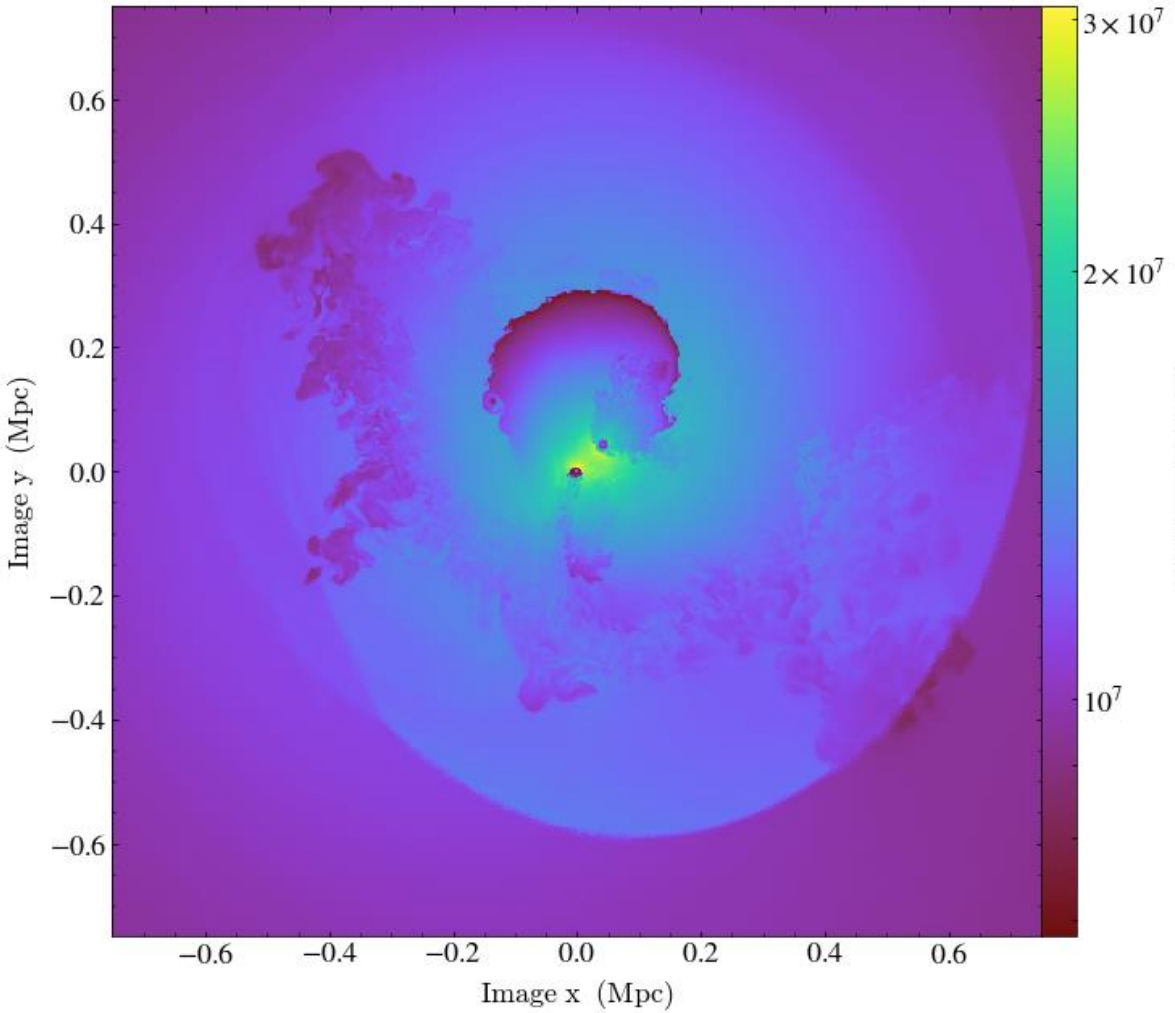

XMM-Newton mosaic of the Fornax cluster (left – $d_L$=20 Mpc, Su+2017) and ROSAT mosaic of the Virgo cluster (right – $d_L$=17 Mpc, Bohringer+1995).

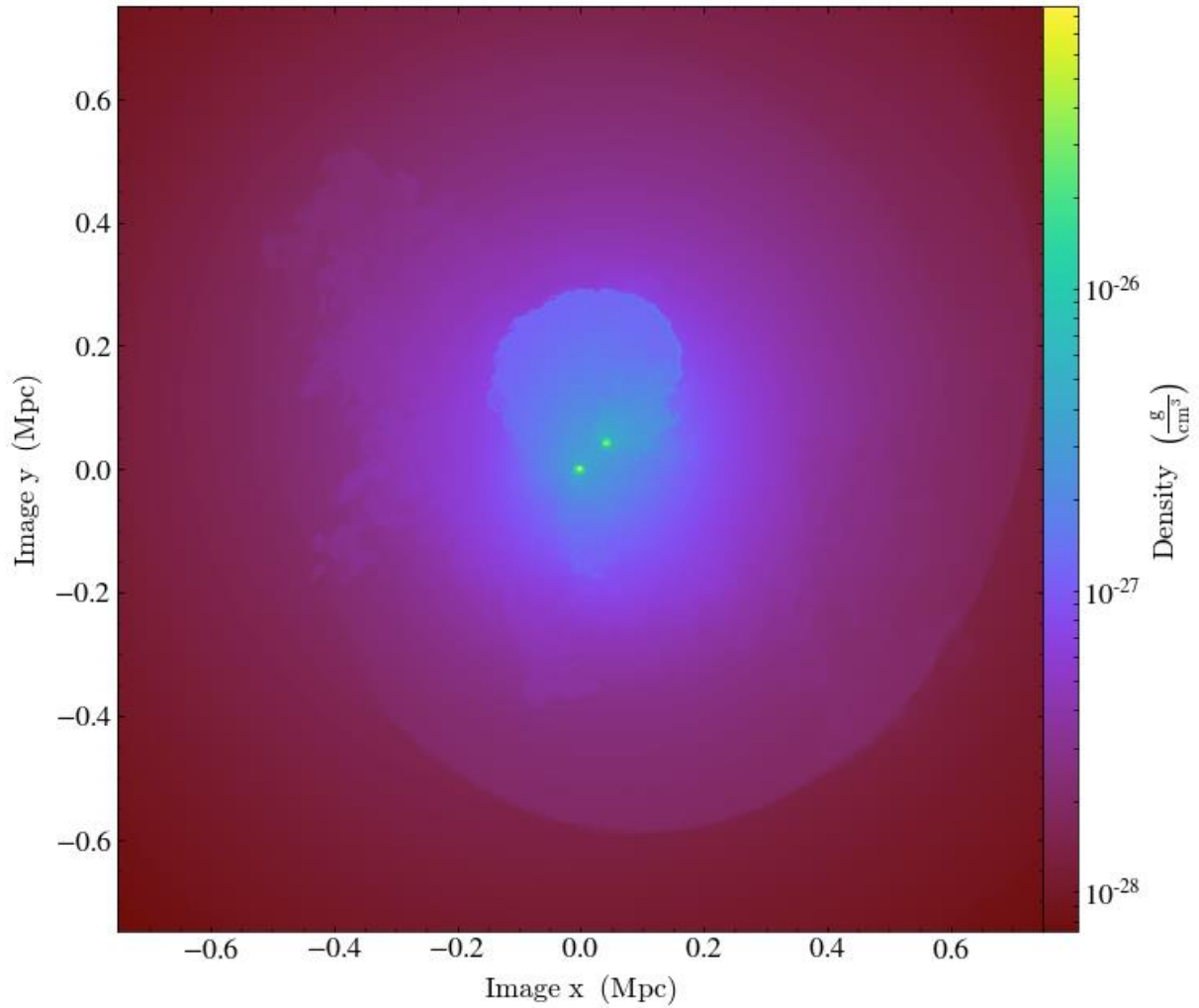
# Zoom-in on the Fornax Cluster

- Simulation of infall of NGC 1404 into Fornax cluster using FLASH (Sheardown+2018)
- Non-magnetic, inviscid
- Includes gravity solver
- Initial conditions derived from X-ray observations (temperature and surface brightness) and stellar profiles
- Properties of ram-pressure stripped core and sloshing cold front match observations quite well

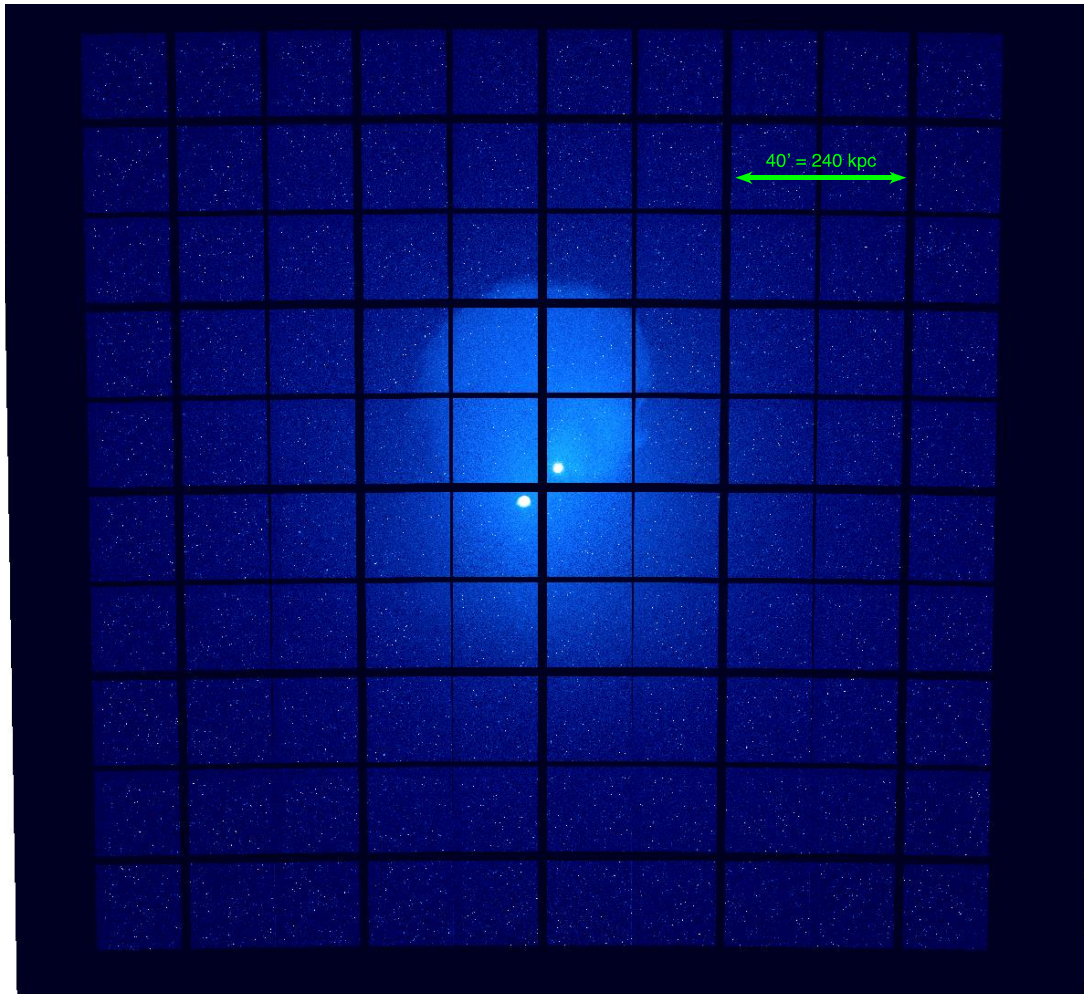


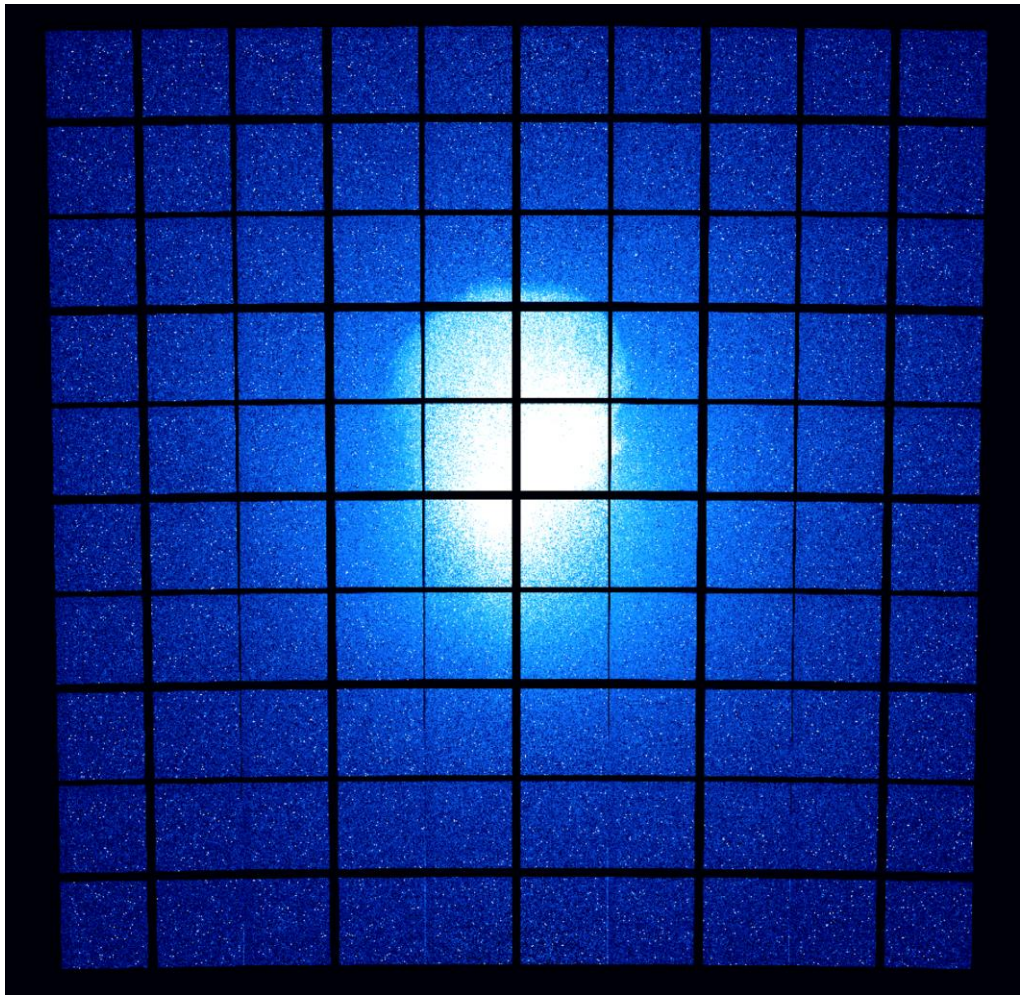
# Time slice of temperature and density – present epoch



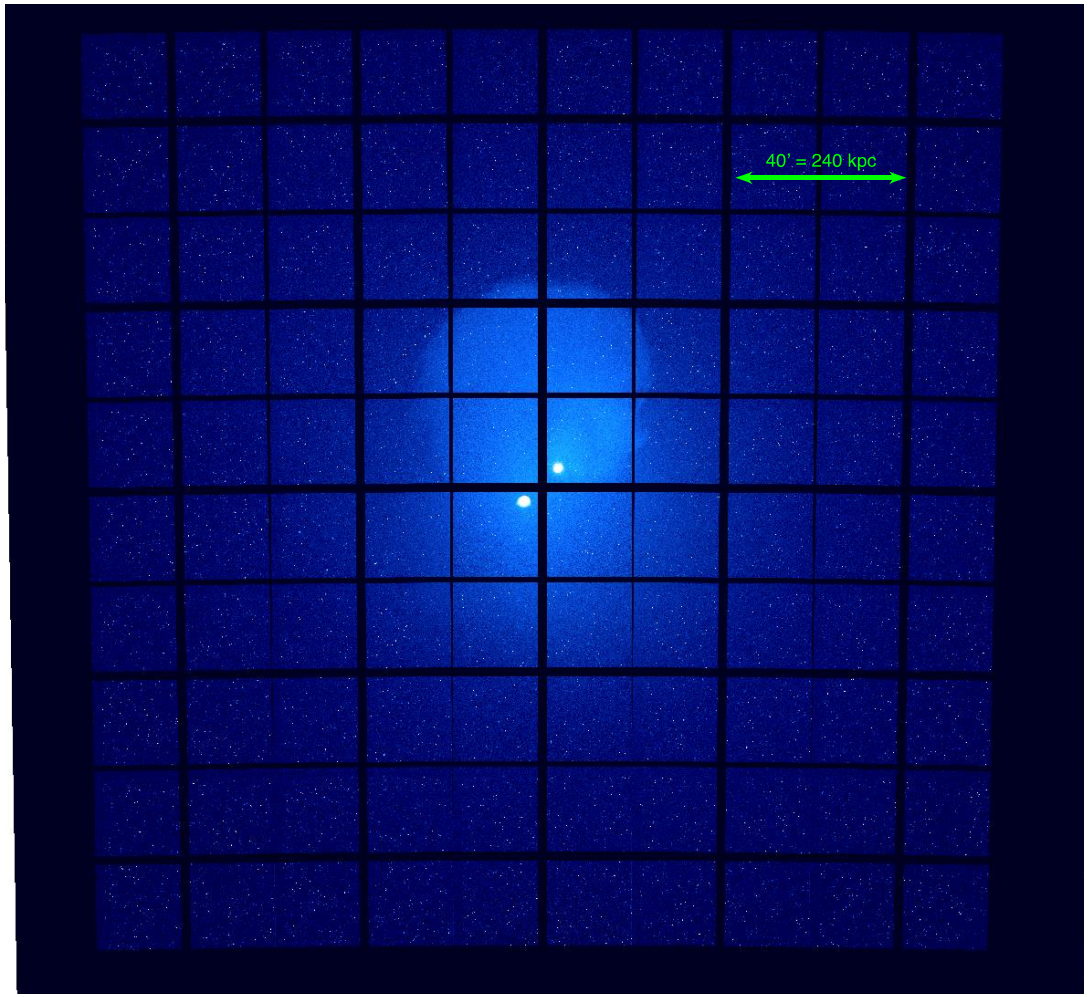
# Simulated WFI mosaic of Fornax Cluster derived using FLASH simulation + SIXTE

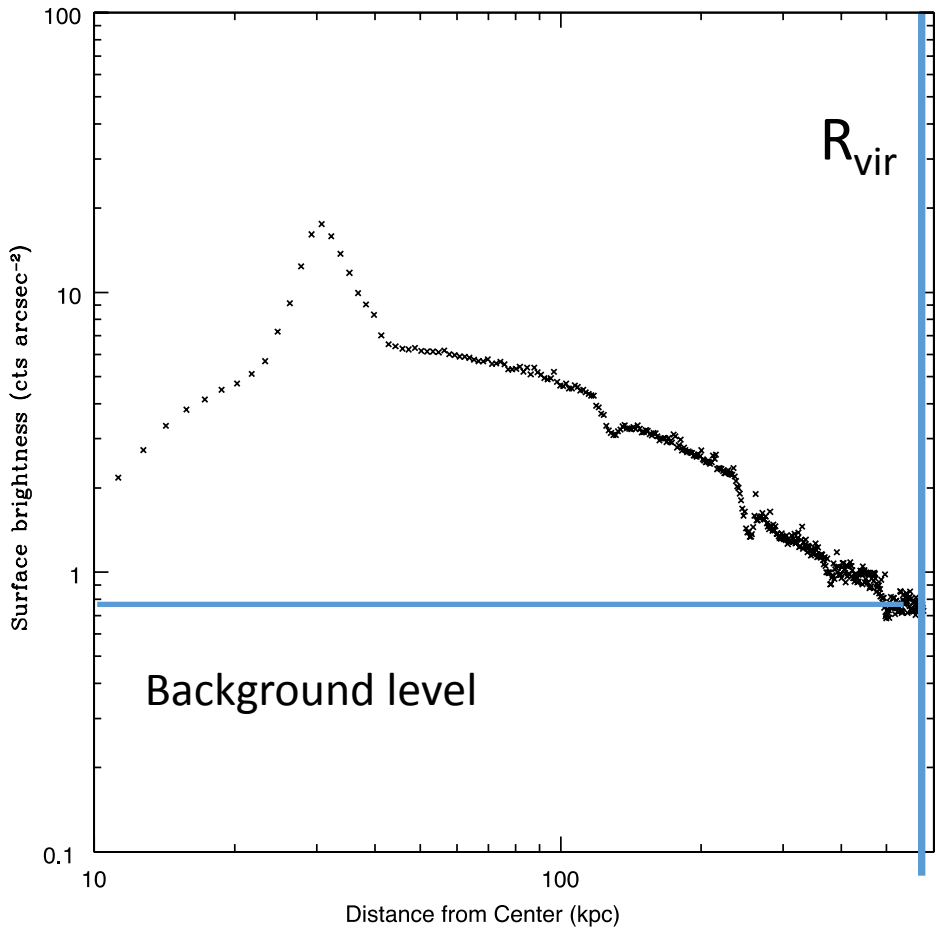


Simulated 5x5 mosaic of 70 ks WFI observations of Fornax cluster

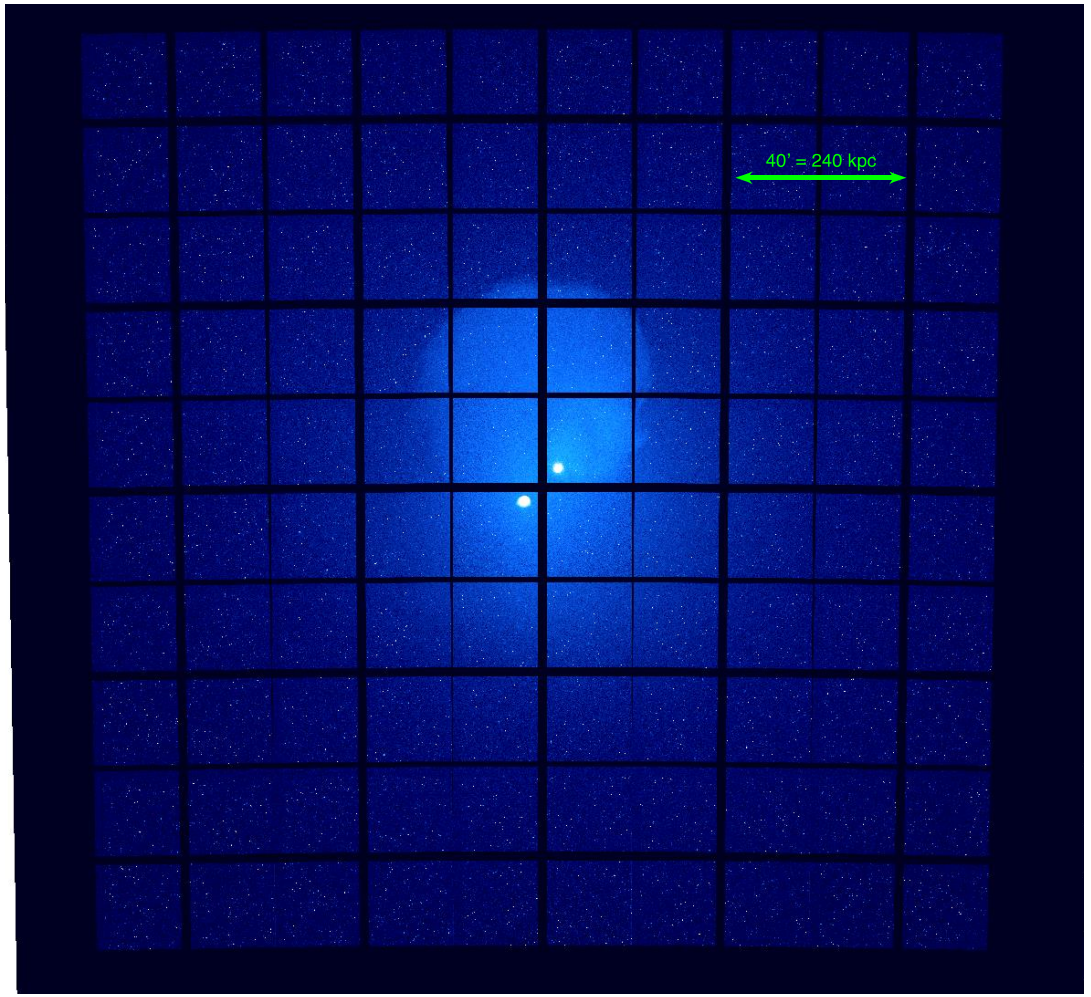
# Simulated WFI mosaic of Fornax Cluster derived using FLASH simulation + SIXTE

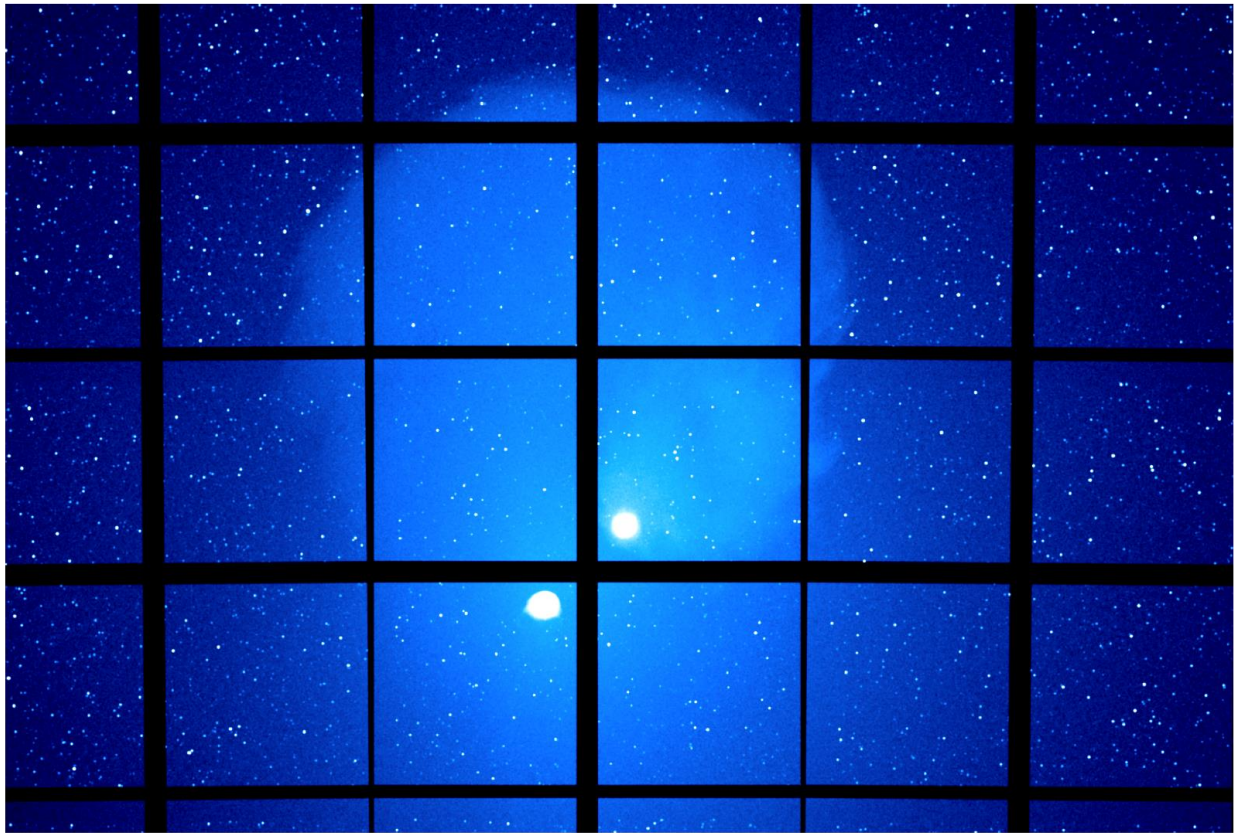



Simulated 5x5 mosaic of 70 ks WFI observations of Fornax cluster and large scale surface brightness profile

# Simulated WFI mosaic of Fornax Cluster derived using FLASH simulation + SIXTE



Simulated 5x5 mosaic of 70 ks WFI observations of Fornax cluster

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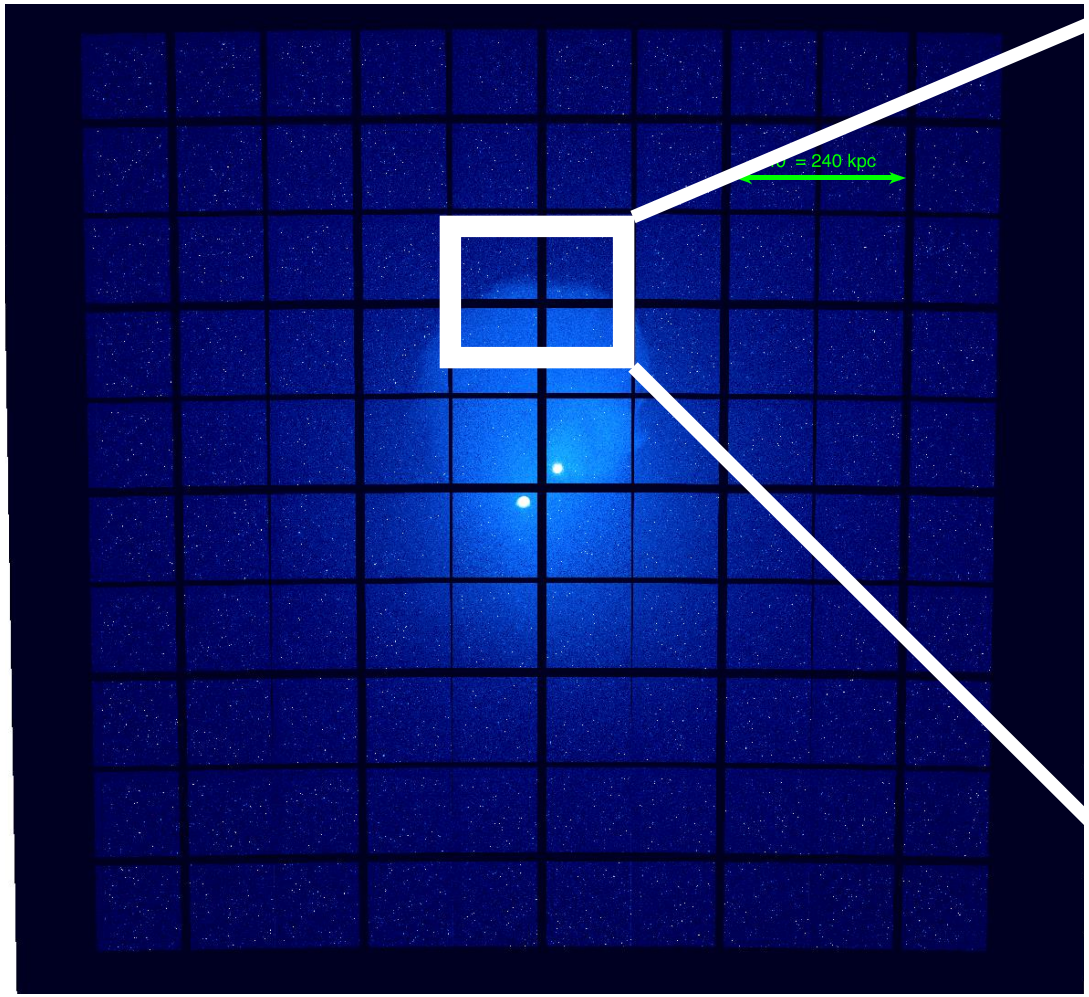
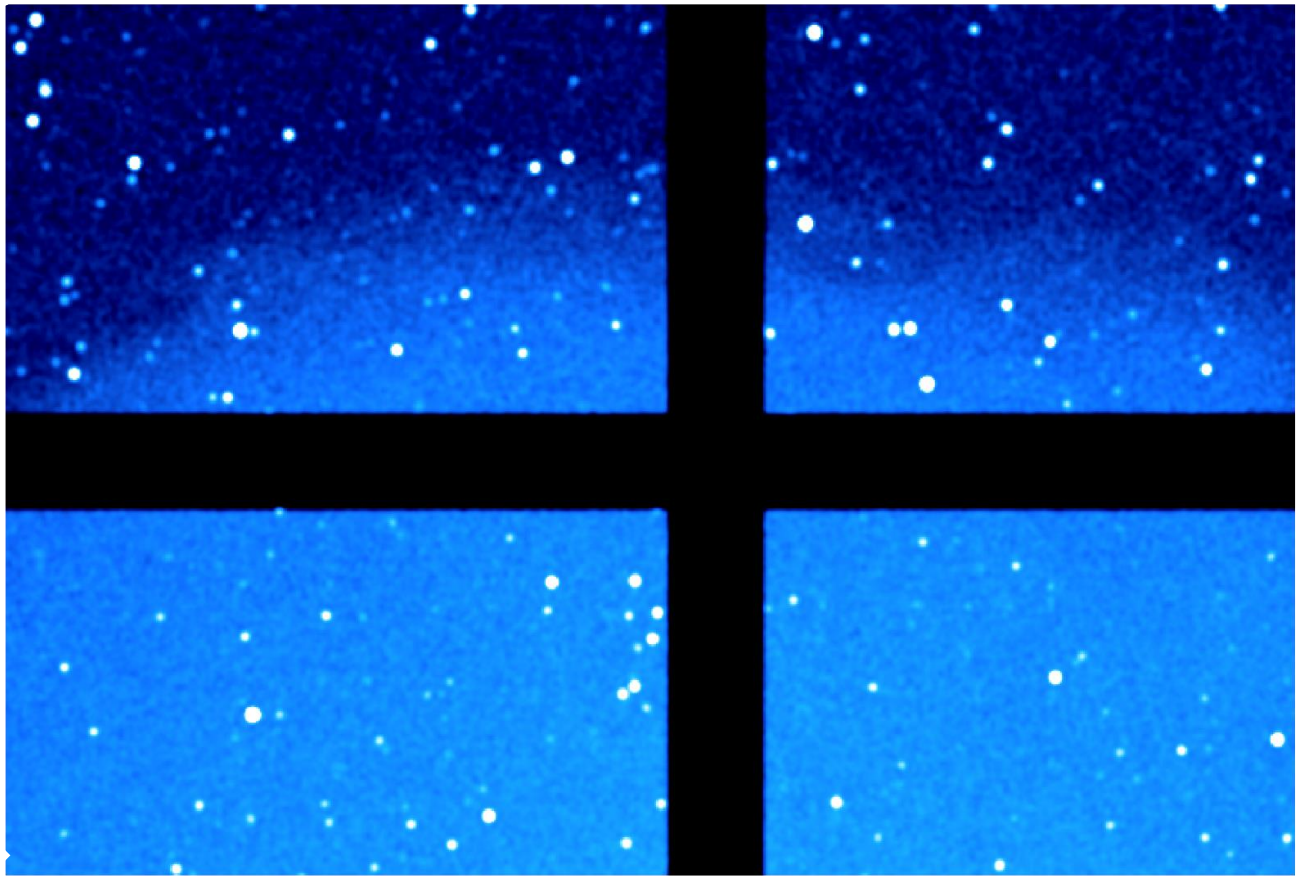
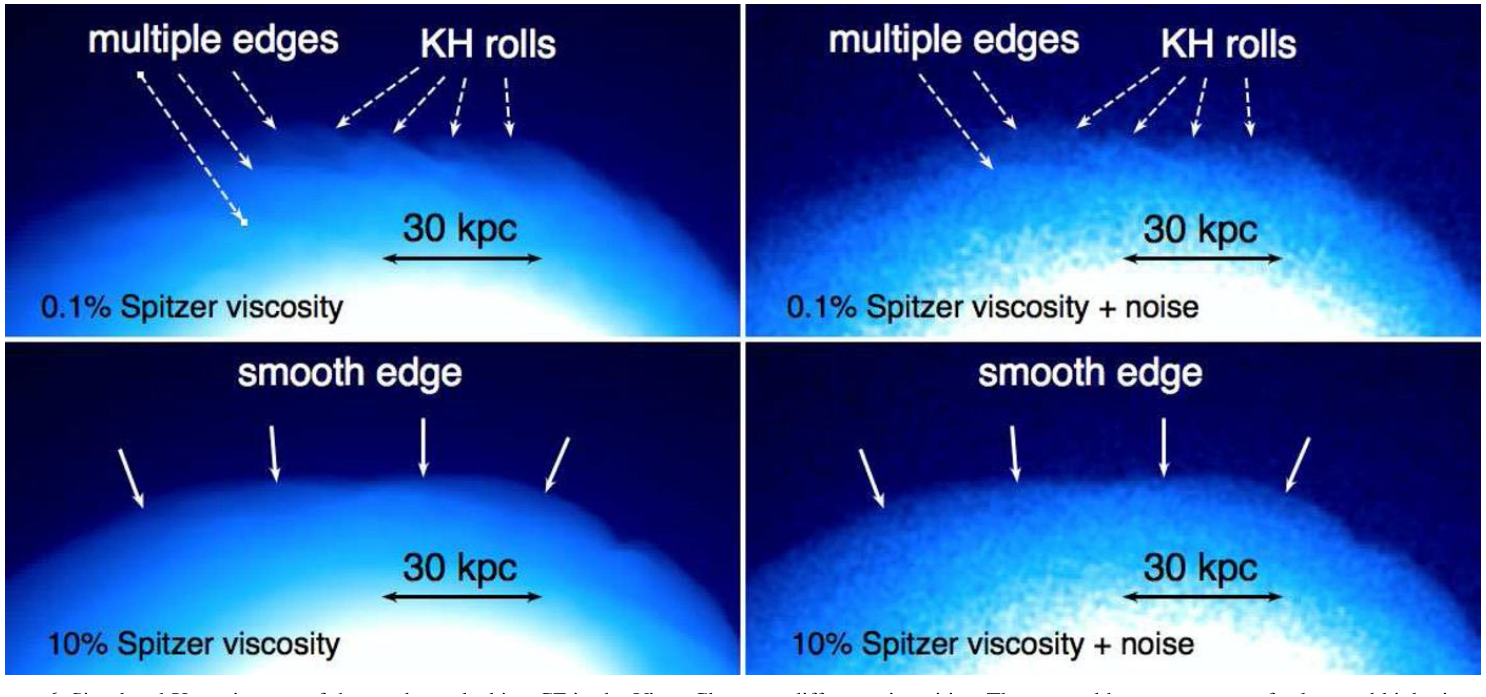
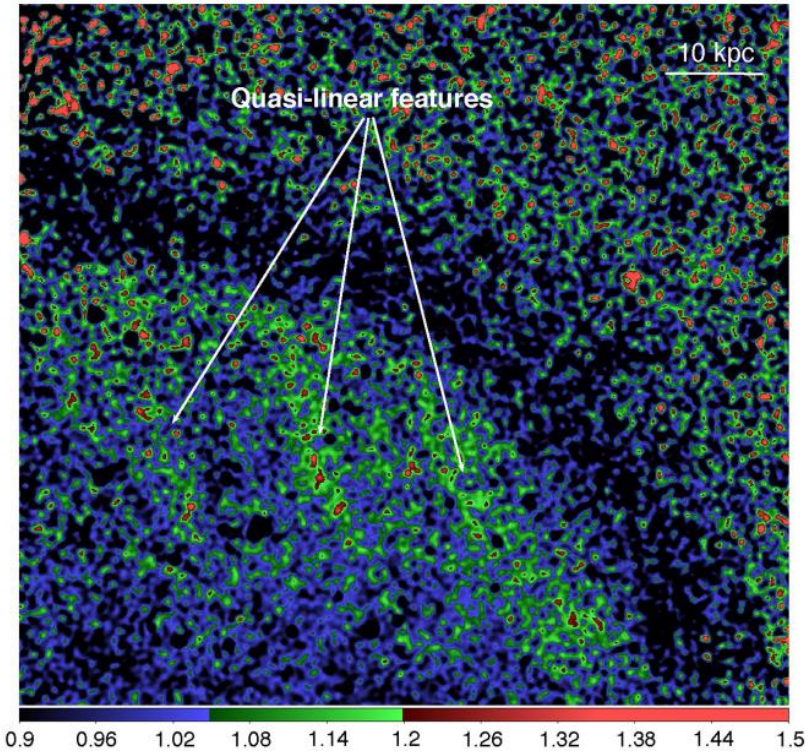


Simulated 5x5 mosaic of 70 ks WFI observations of Fornax cluster

# Observations and simulations of Virgo Cluster sloshing cold front

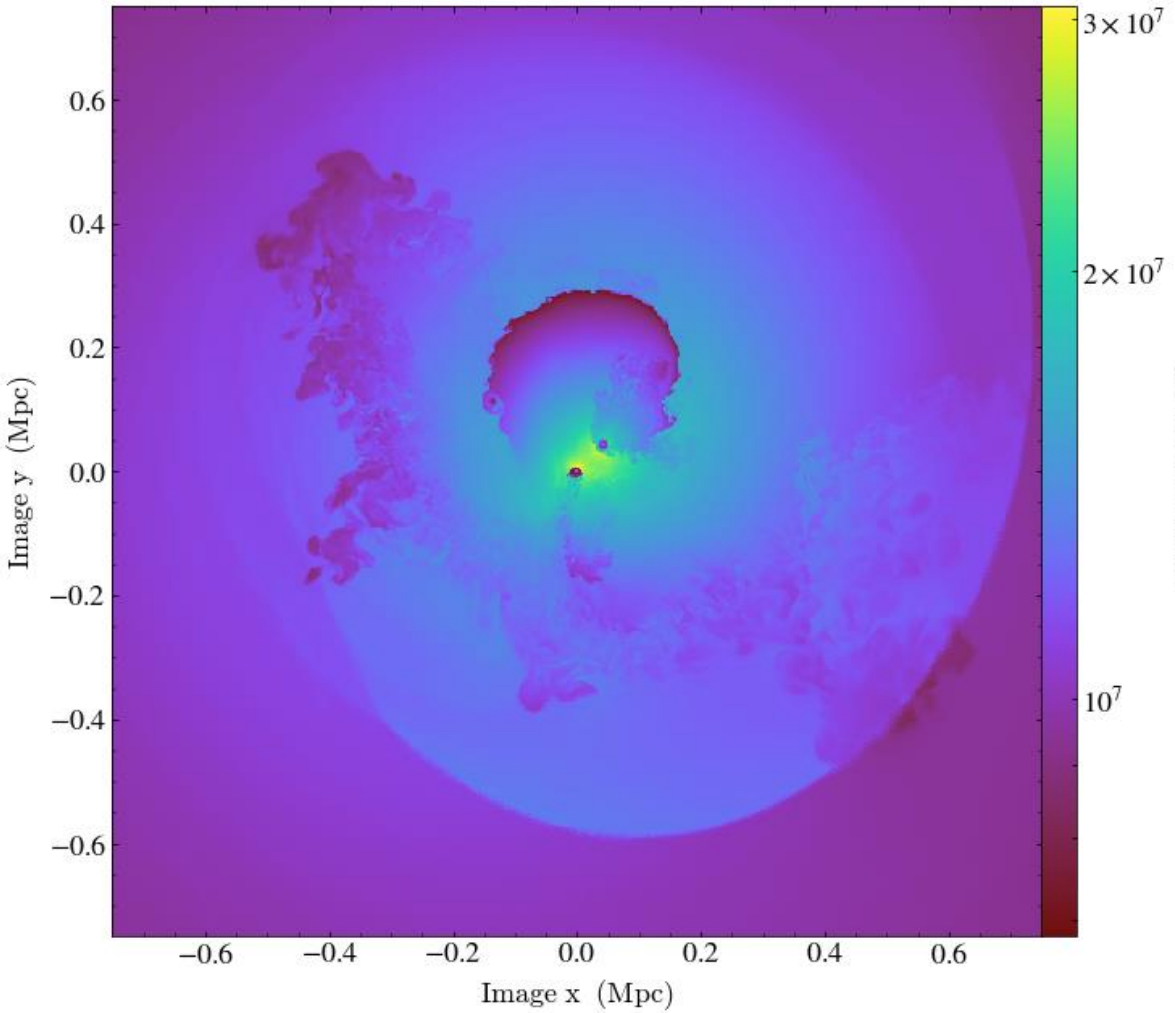


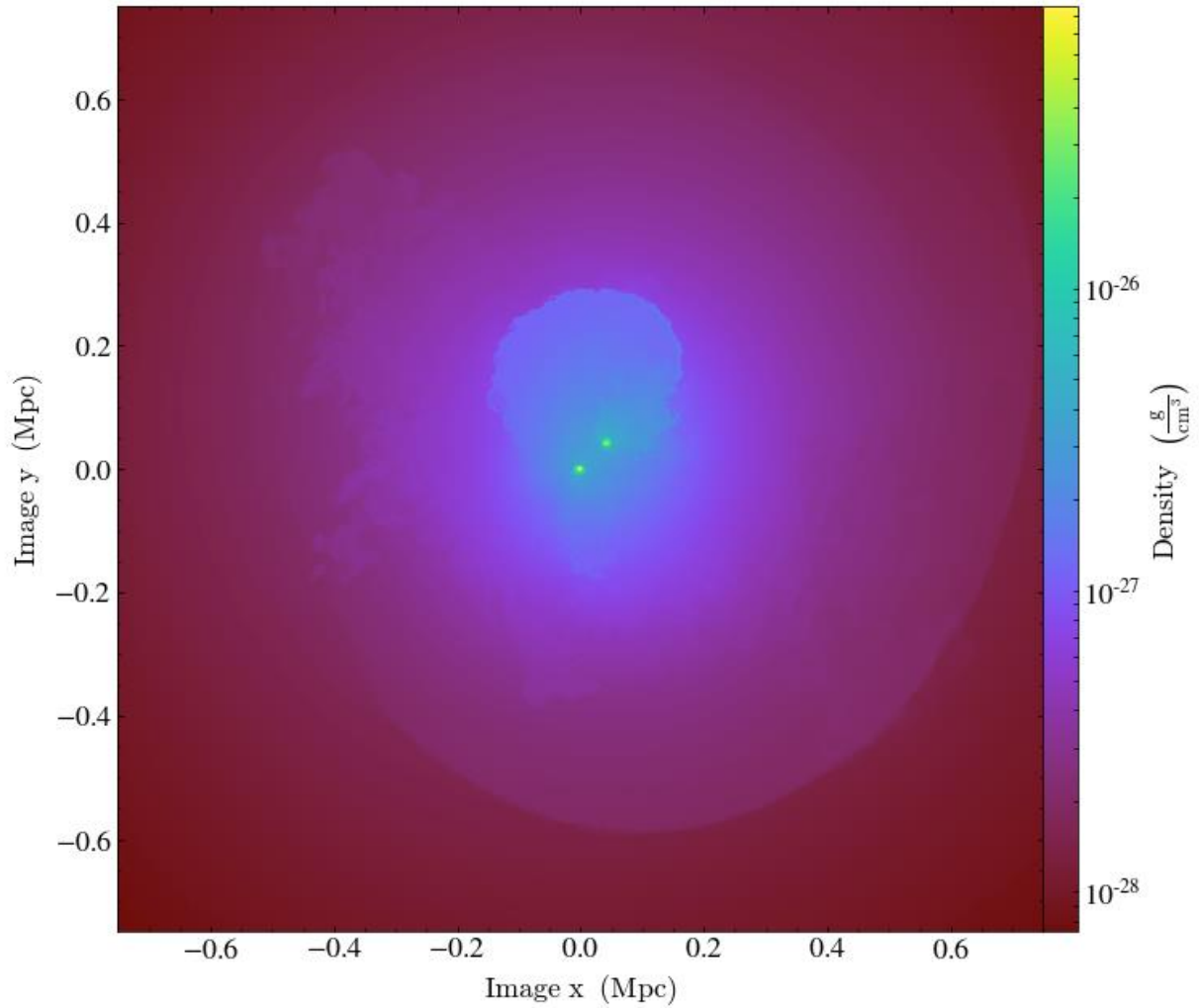




Surface brightness of simulated Virgo cluster sloshing cold front derived from inviscid (top row) and viscous (bottom row) hydrodynamic simulations (Roediger+2013).

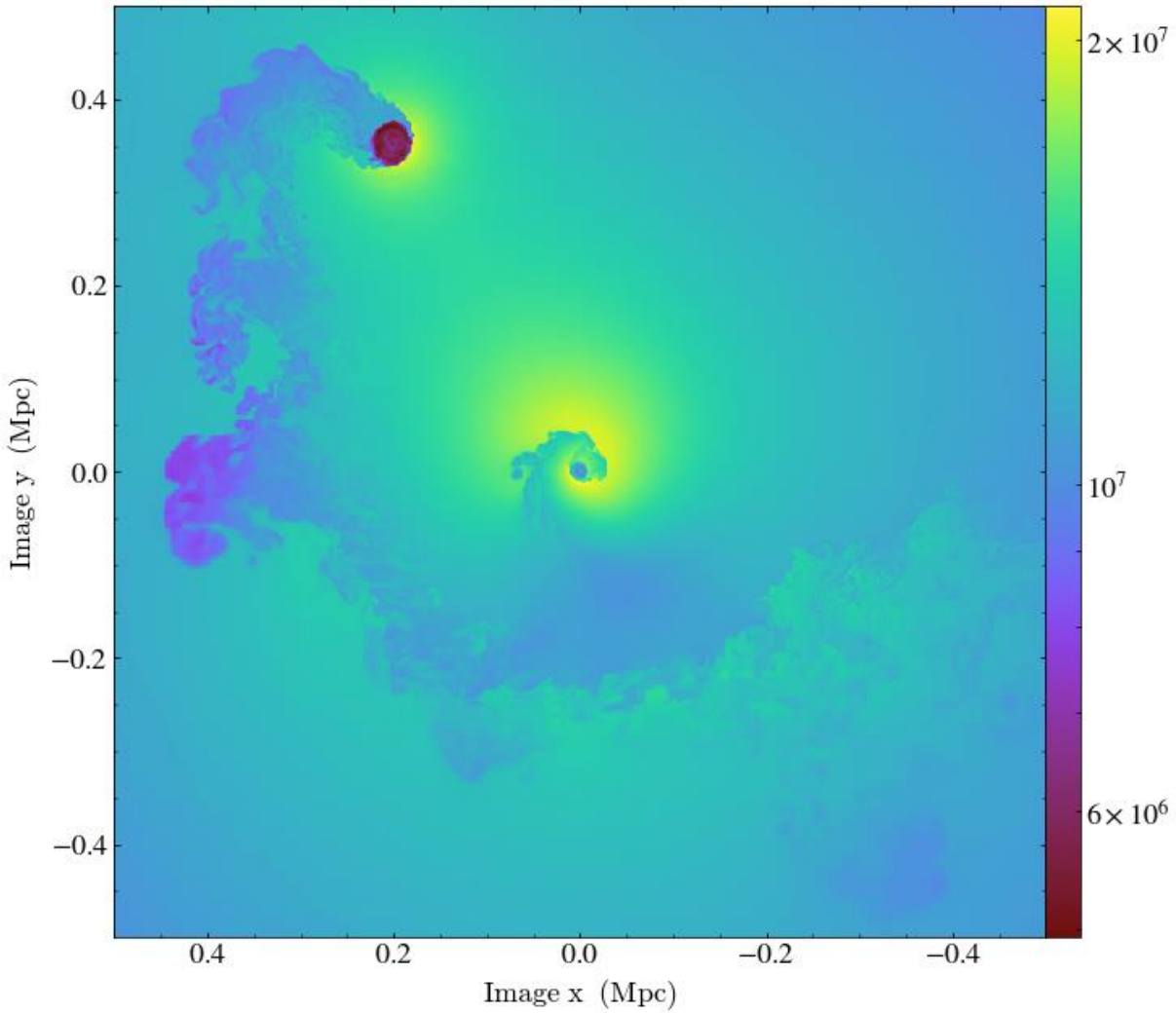
Deep (500 ks) Chandra observation of Virgo cluster sloshing cold front (Werner+2016). Linear features along front suggestive of magnetic compression/filamentation.

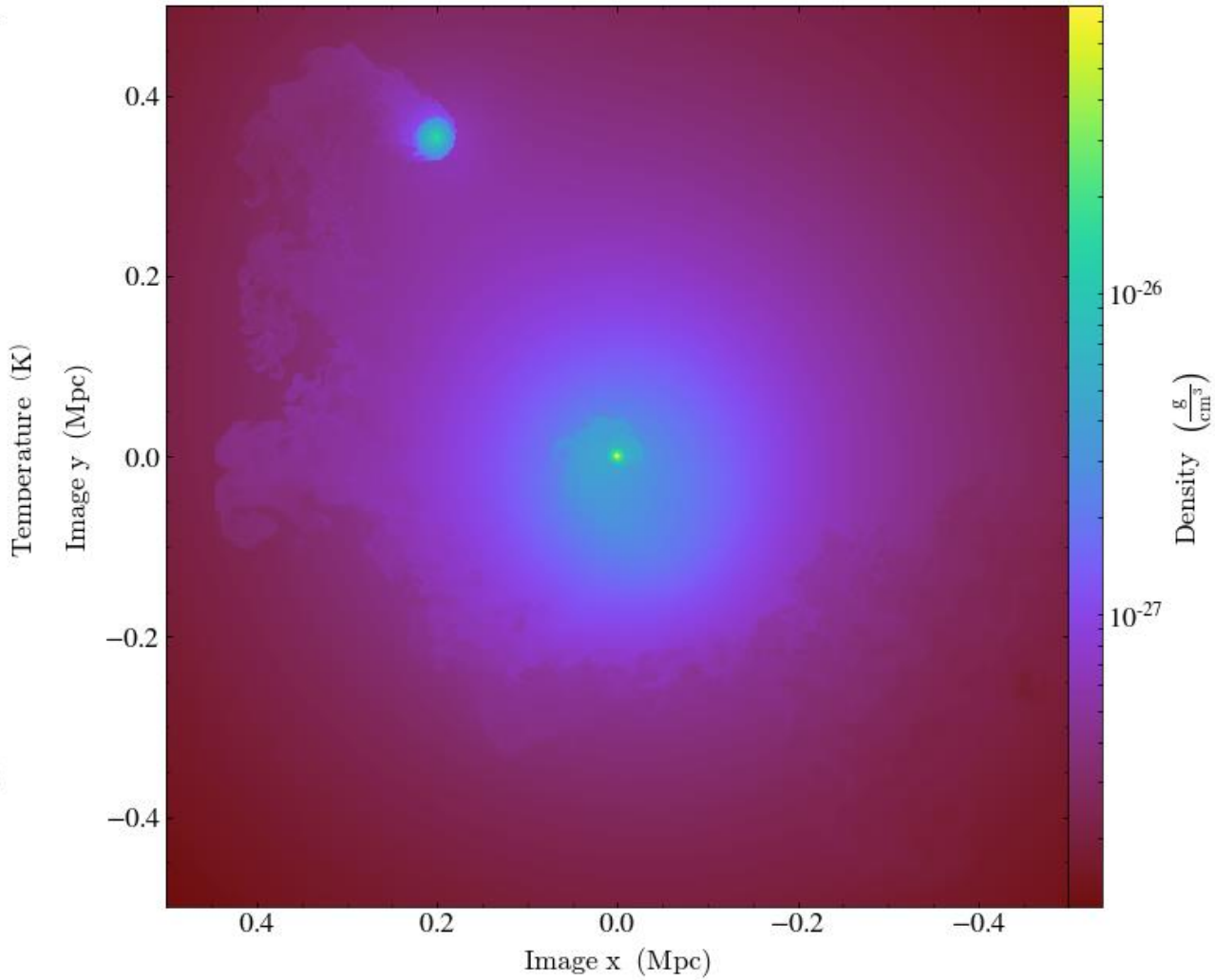
# Time slice of temperature and density – present epoch



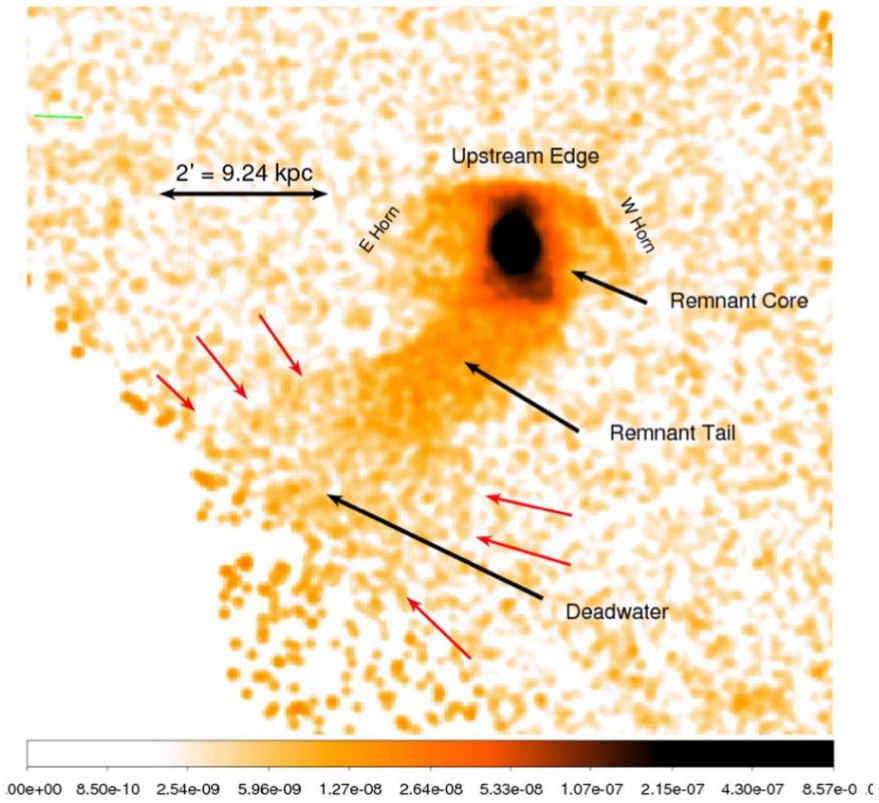



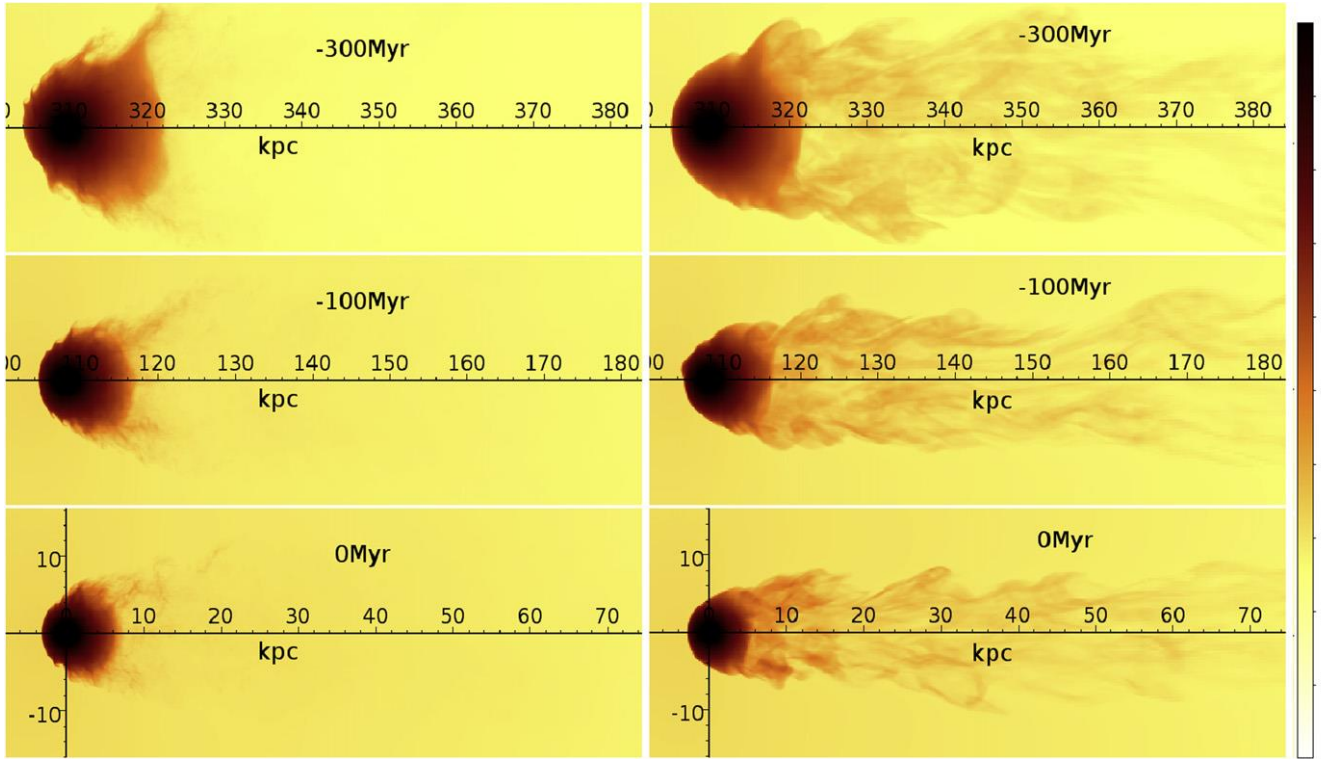
# Time slice of temperature and density



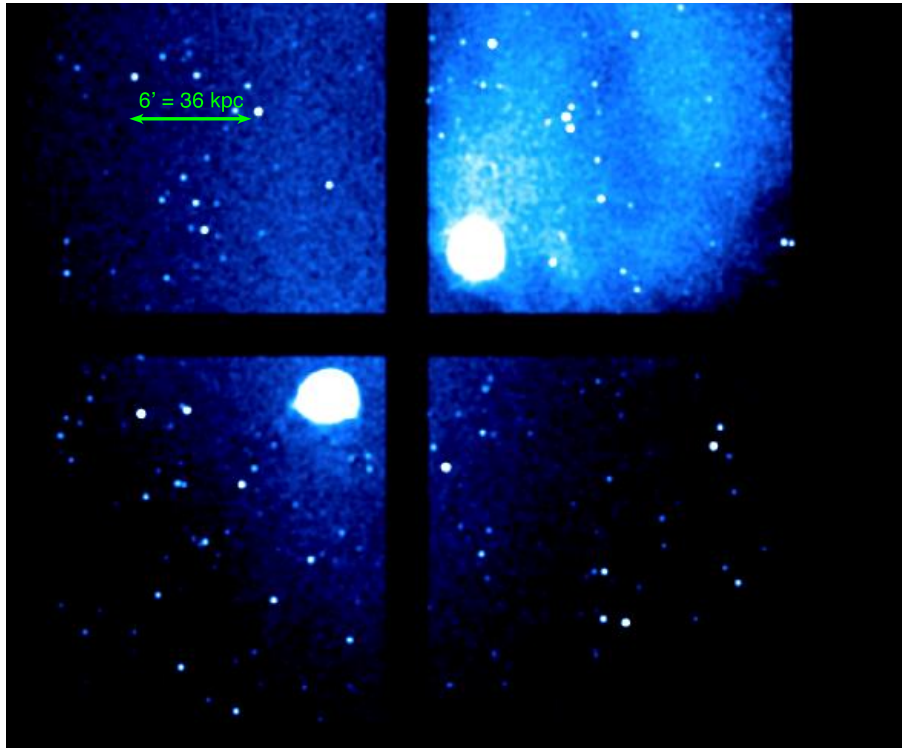
# Ram pressure stripping of N1404 tail and stolen atmosphere

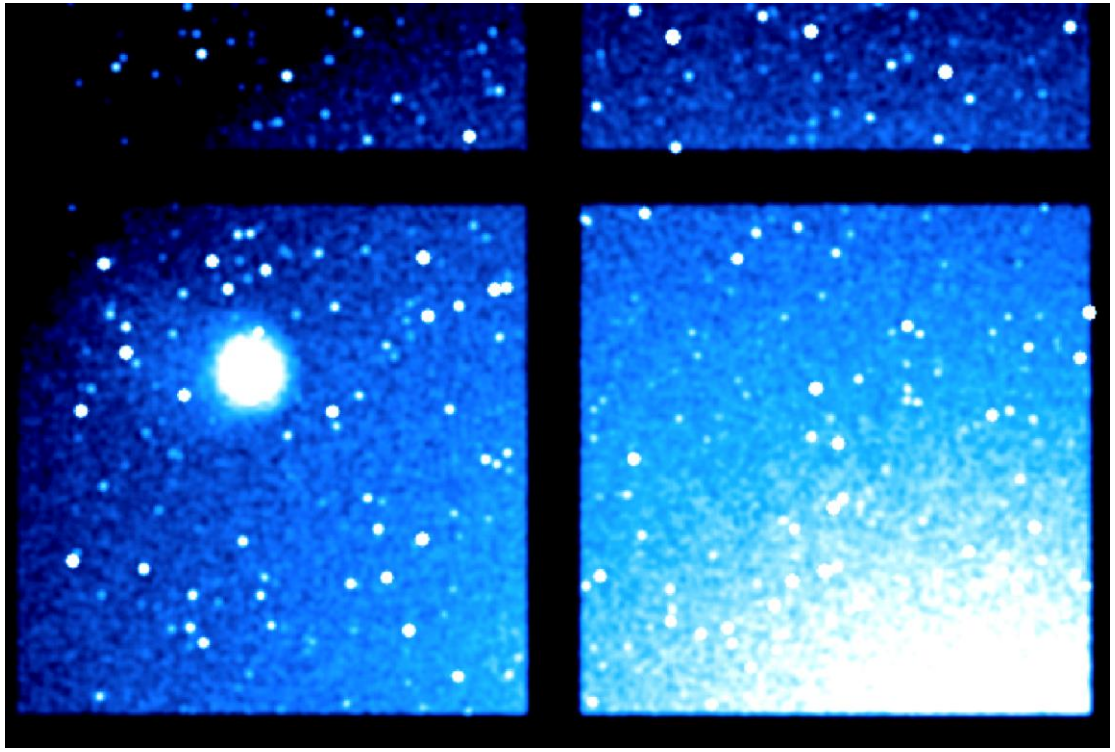



Deep (200 ks) Chandra observation of NGC 4552 in the Virgo cluster (left – Kraft+2017) and simulated images of ram pressure stripping assuming viscous and inviscid ICM (right - Roediger+2015).

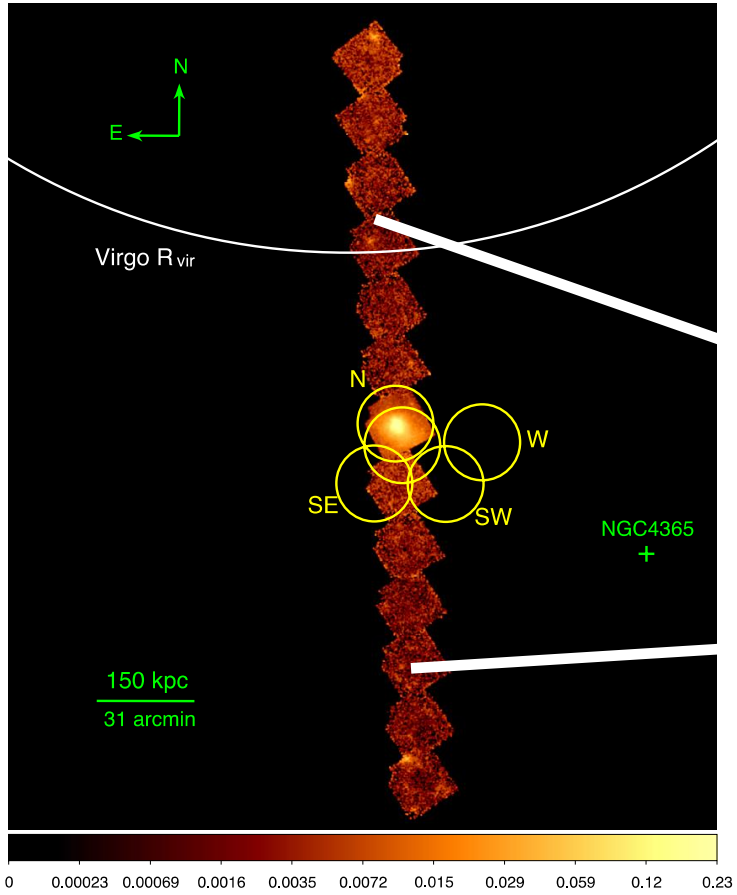
# Ram pressure stripping of N1404 tail and stolen atmosphere

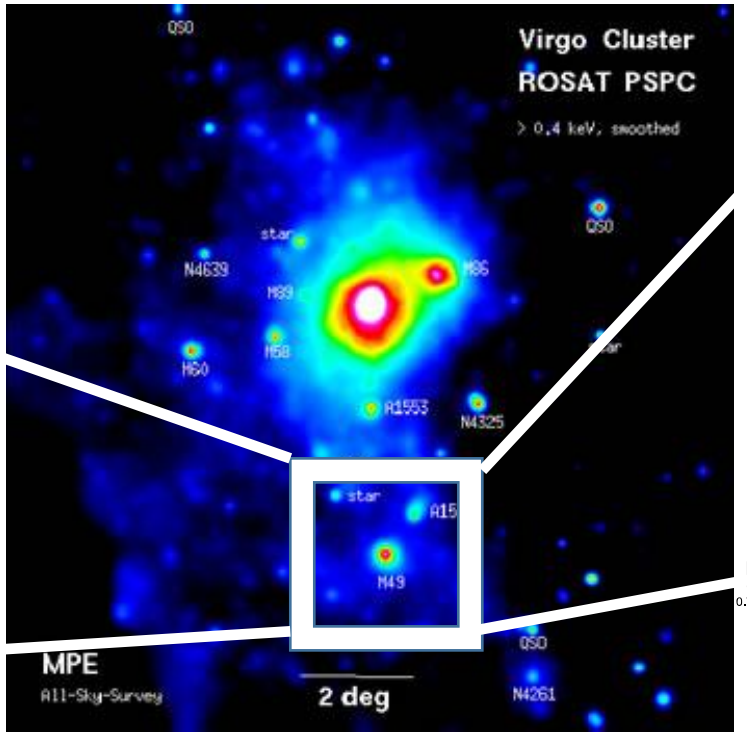


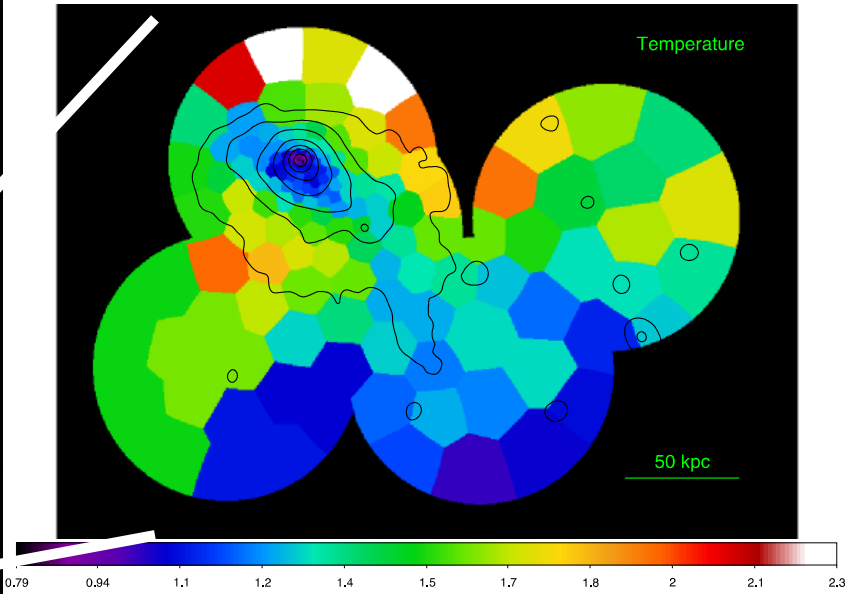



70 ks ATHENA WFI observations of NGC 1404 derived from FLASH simulation. The present epoch is shown in the left figure and a an earlier (~300 Myr) epoch in the right.

# NGC 4472 – infalling into Virgo cluster – most optically luminous galaxy in the local Universe

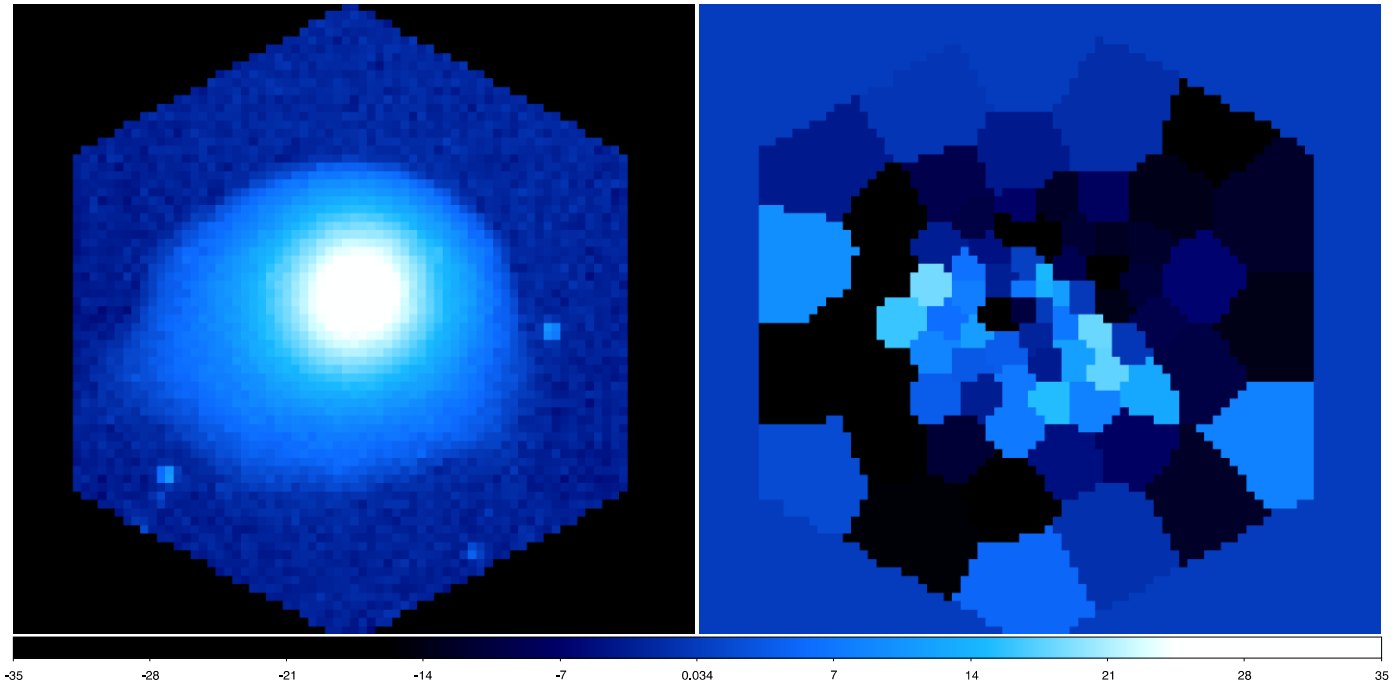


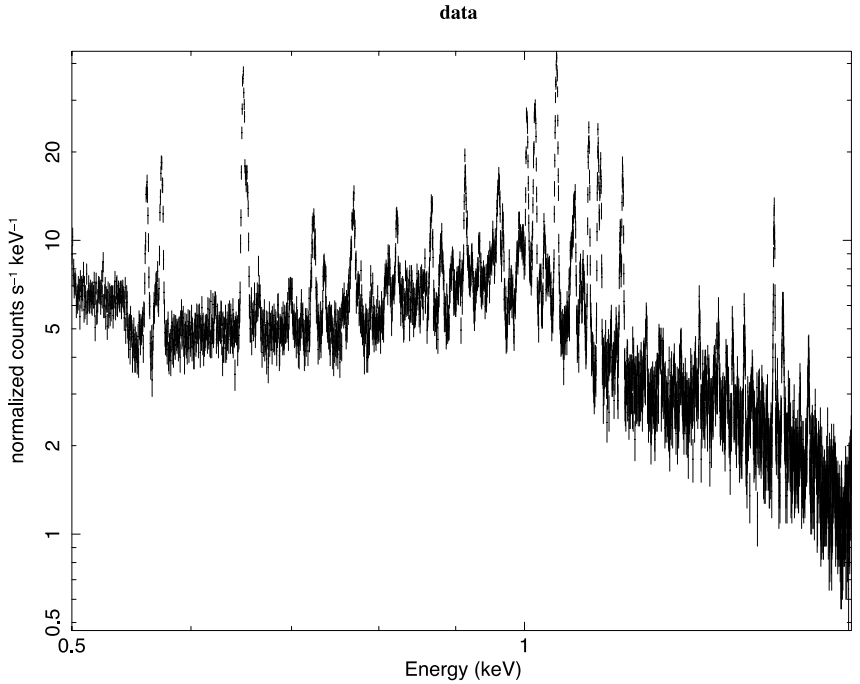




Suzaku (left) and XMM-Newton (right) temperature map mosaics of NGC 4472 (Su+ in preparation). Is this the first or second infall for NGC 4472?

# XIFU observation of subsonic gas motions in NGC 1404



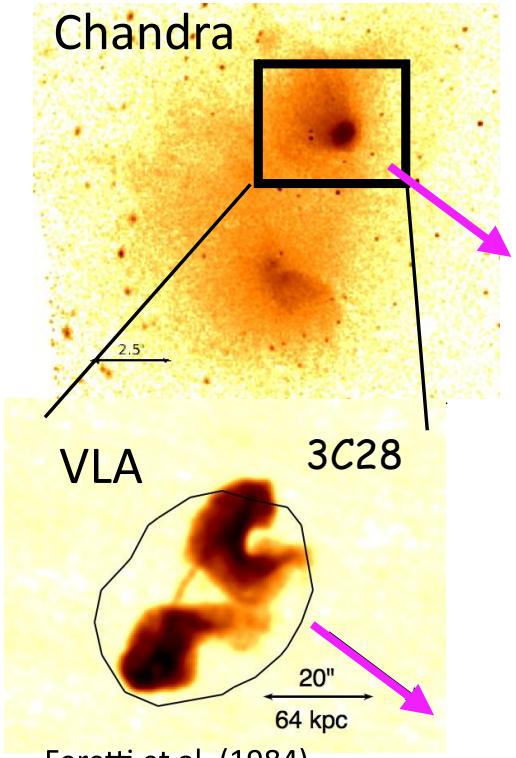




Simulated XIFU image of NGC 1404 using FLASH simulation (left), velocity map derived from XIFU spectrum (center), and broadband spectrum of emission.

# Distorted radio galaxy 3C 28 in double cluster Abell 115 (W. Forman+2017)

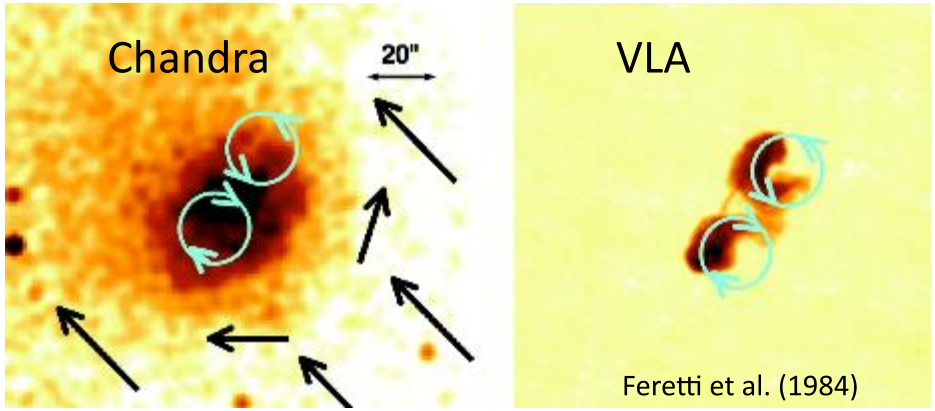
## A115-N hosts 3C28

- A115-N hosts 3C28
  - Jets extending to outer edges of radio lobes
    - Terminate at boundary of X-ray sub-cluster
    - Magnetic draping around X-ray plasma disrupts/confines jet/lobes?
  - Jets apparent but nucleus is quiescent
    - No nuclear emission detected in either X-ray ($L_X$<2x10$^{41}$ erg/s) or radio ($L_R$<1.4x10$^{21}$ W/Hz-sr (0.2mJy) at 5 GHz)
  - Radio lobes show tails extending **in the direction of sub-cluster motion!!!**



Feretti et al. (1984)

## Gas Flow Around A115-N Drives Gas Circulation in A115-N Core to Produce Peculiar 3C28 Morphology



Feretti et al. (1984)

- A115-N moving to the SW and interaction establishes gas circulation within the subcluster core; external gas flow (black arrows) can be used to estimate parameters of circulation (assuming ideal potential flow) seen as cyan circles
- Circulation simulated by Heinz et al. (2003) for A3667 merger
- Based on gas temperature jump, very roughly Mach ~2 (systematics from projection and uncertain geometry)
- Gas flow velocity around sub-cluster core about 1300 km s$^{-1}$ and sets the circulation velocity and timescales for gas motions within the core (for ideal potential flow)

# Take-away points

- **The combination of the ATHENA WFI, the XIFU, and specifically-tailored (magneto-)hydrodynamic simulations will be a powerful combination for understanding gas dynamics in galaxy clusters**
- The entire assembly history of (all of) the nearby clusters will be revealed by ATHENA
- ATHENA will transform our understanding microphysics of the ICM