The Unseen: Clumping in the Outskirts of Galaxy Clusters

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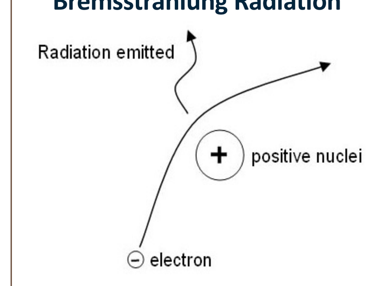
Introduction

- Galaxy clusters are the largest gravitationally bound structures in the universe.
- They contain 100s to 1000s of galaxies.
- The Intra-cluster-medium (ICM), which is a hot gas (~10^7 K) in between galaxies is detectable in the X-ray range via Bremsstrahlung radiation.
- ICM thermodynamical properties are extremely important for cosmology, i.e., how the universe formed and how it is evolving.
- Entropy in particular is essential to understand the dynamical properties of a cluster, including its evolution.
- Observations have shown unexpected results in derived entropy profiles for clusters.
- Gas clumping, denser and cooler pockets of gas can affect how we measure entropy.
- Current telescopes cannot see these clumps.
- STAR-X should be able to detect these clumps.
- This work simulates what STAR-X will see when looking at galaxy clusters.

Bremsstrahlung Radiation



The ICM is so hot that the gas is ionized. When electrons get deflected through interactions with ions, X-ray radiation is produced.

STAR-X

The Survey and Time-domain Astronomical Research eXplorer (STAR-X) was proposed in the last Mid-Sized Explorer Class Mission (MIDEX) call by NASA at the end of 2021. It will have a low particle background due to its low altitude orbit and will be able to detect cluster outskirts. In a low Earth orbit, the Earth's magnetosphere will protect STAR-X from high energy charged particles. It also will be more efficient than previous missions (less exposure time, faster slewing). STAR-X is also designed with a large field of view, large effective area, and an optimum Point-Spread Function (PSF) to minimize noise and gather as much information about a cluster as possible.

Goals

- To reproduce observed entropy profiles using simulated observations and to determine what clumping properties yield observed results.
- To investigate clump properties (size, temperature, density, amount).
- Determine if clumps would be detectable by STAR-X.

Methods

Simulation:

Building Data Grids:

- Two sets of 3D arrays are generated based on a given temperature (Eqn. 1) and density (Eqn. 2) profile.
- Clumps are "injected" into the arrays randomly in 3D space with their selected properties (temperature, density, number of clumps).
- The datasets are loaded into yt, which processes information from computer simulations in order to produce mock observations.

Simulating Photons:

- The yt datasets are processed using pyXSIM.
- pyXSIM generates a 3D photon list, based on a thermal source model (apec).
- The output is a 3D array that describes how light would emanate from each cell of the grid based on the temperature and density at that point.

Projecting Photons to Simulate Images:

- The photon list can then be projected along an axis to generate a mock observation of a cluster at a given redshift.
- A 2D event file is then produced and using SOXS (an instrument simulator), a mock observation can be created that simulates the response and background of a telescope.

Spectral Analysis:

- Point sources and clumps are subtracted out using wavdetect.
- Spectra are extracted from concentric annuli centered at the X-ray emission peak.
- The data is fitted to find temperature and surface brightness values and then used to construct a radial profile for both temperature and density.
- An entropy profile can then be derived (Eqn. 3).

Eqn 1: $$T_{3D}(r) = T_0 \frac{\left(\frac{r}{r_t}\right)^{-a}}{\left(1+\left(\frac{r}{r_t}\right)^b\right)^{\frac{c}{b}}} \frac{\left(\frac{r}{r_{cool}}\right)^{a_{cool}} + \frac{T_{min}}{T_0}}{\left(\frac{r}{r_{cool}}\right)^{a_{cool}} + 1}$$

Eqn 2: $$n_p n_e = n_0^2 \frac{(r/r_c)^{-\alpha}}{(1+r^2/r_c^2)^{3\beta-\alpha/2}} \frac{1}{(1+r^\gamma/r_s{}^\gamma)^{\varepsilon/\gamma}} + \frac{n_{02}^2}{(1+r^2/r_{c2}^2)^{3\beta_2}}$$

Eqn 3: $$K = \frac{T}{n^{\frac{2}{3}}}$$

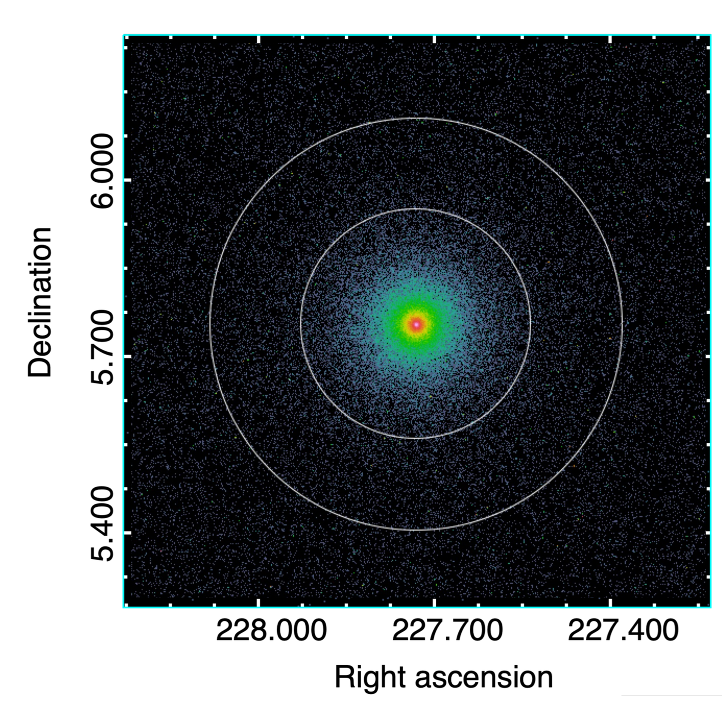


Figure 1: Reconstructed image of Abell 2029 based on Chandra best fit models. Annulus 4 is shown in white.

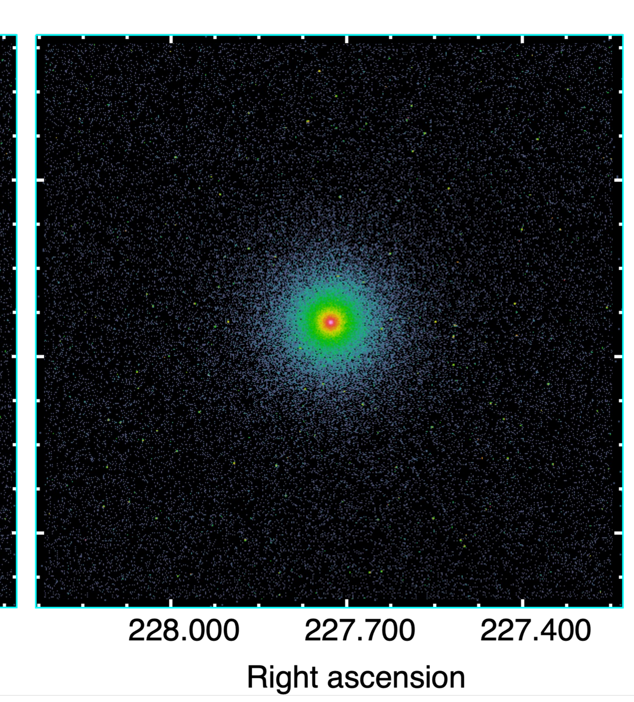
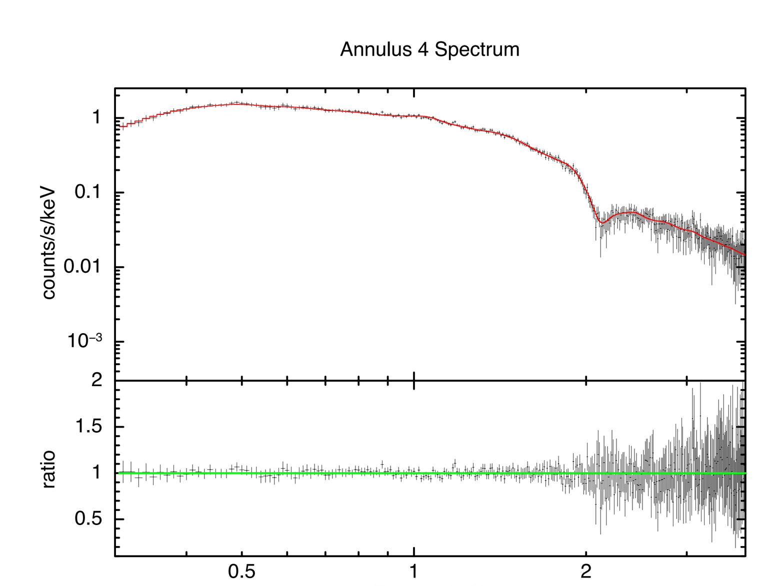
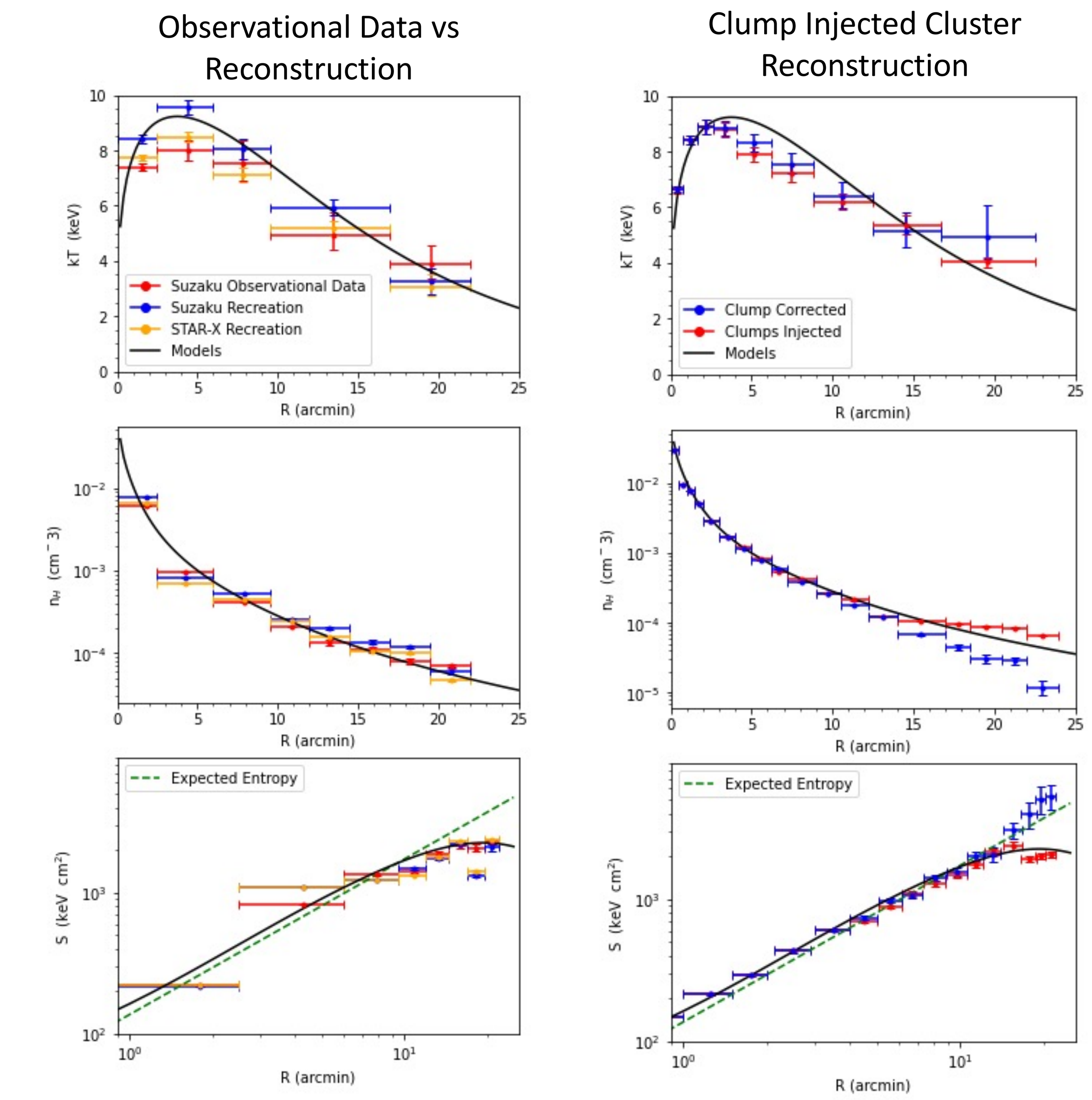


Figure 2: A reconstruction of Abell 2029, with clumps injected.



Fit of the spectrum extracted from Annulus 4 as shown in Fig 1. Data is shown in the upper black curve, red curve represents the model, and the ratio demonstrates the goodness of the fit.

Results



Projected temperatures (top), deprojected Hydrogen number density (middle), and derived entropy (bottom). Black lines are best fit Vikhlinin model from Chandra observations. Dashed green lines on bottom plots signify the expected entropy (r^1.1). **Left:**. Observed results of Abell 2029 from Suzaku (red), simulated results from Suzaku (blue), and simulated results from STAR-X (orange). **Right:** Results from the reconstruction of Abell 2029, each profile is extracted from the same simulated image (Fig 2). Red signifies the cluster with clumps injected. Blue signifies clump-corrected data.

Discussion

- The extracted temperature (top), density (middle), and entropy profiles (bottom) from the reconstruction of Abell 2029 from Suzaku (left, blue) and STAR-X (left, orange) follow the same trends as observational Suzaku data (left, red).
- **Simulation produces realistic cluster data.**
- The extracted profiles from the reconstructed cluster with clumps injected follow the same trends as the best fit model from observational Chandra data (black lines).
- **Injected clumps can recreate observed drop in entropy.**
- Correcting for clumping (right, blue) yields the expected entropy profile (bottom, dashed green).
- **The expected entropy profile can be recovered through clump detection.**

Future Work

- Identify most probable clumping scenarios using mock Suzaku observations and place limits on detectable clump properties for STAR-X.

References

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