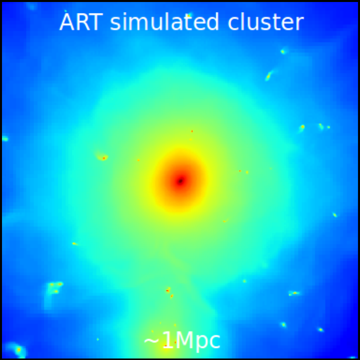
Modeling Galaxy Cluster Outskirts with Cosmological Simulations

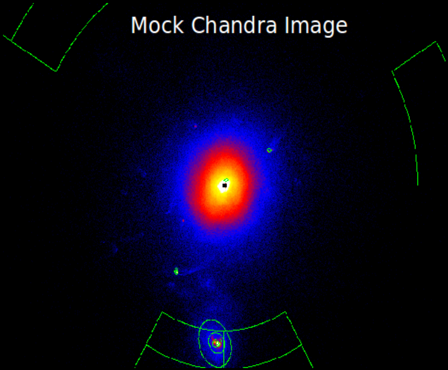
Camille Avestruz

PI: Daisuke Nagai

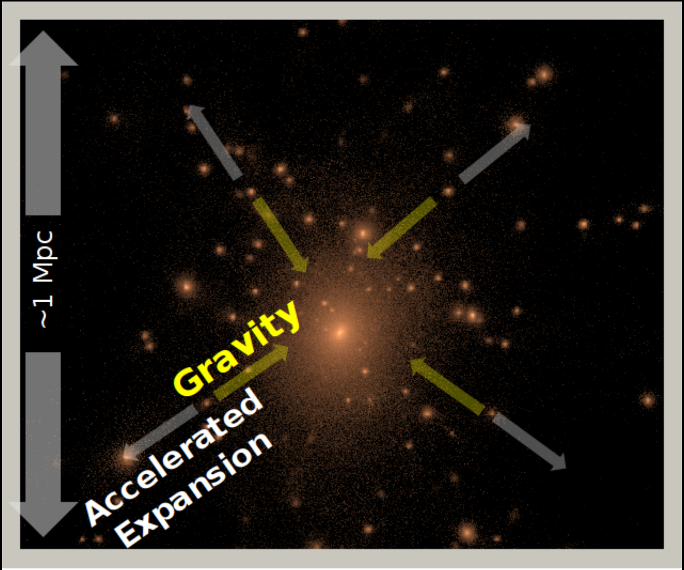
NSF Graduate Research Fellow, Yale University

Berkeley Cosmology, November 27, 2014





Clusters Probe the Growth of Structure



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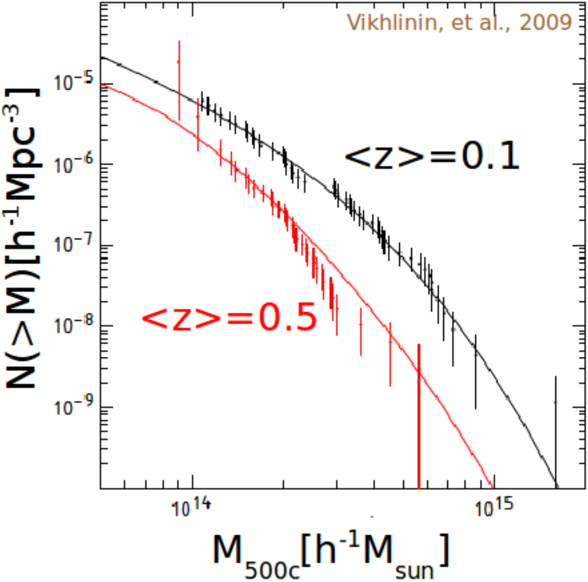
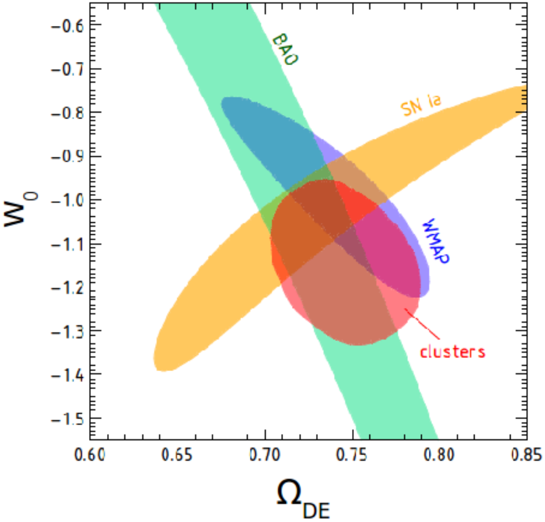
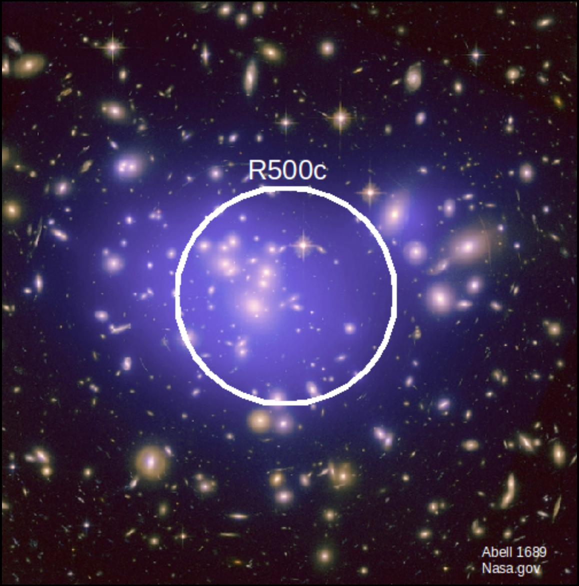


Clusters Provide Constraints on Dark Energy



Key to cluster cosmology: Precise mass measurements

Masses defined with respect to reference densities



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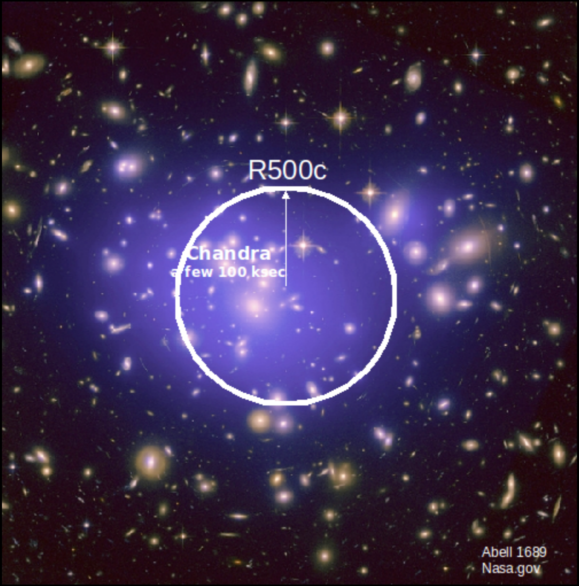

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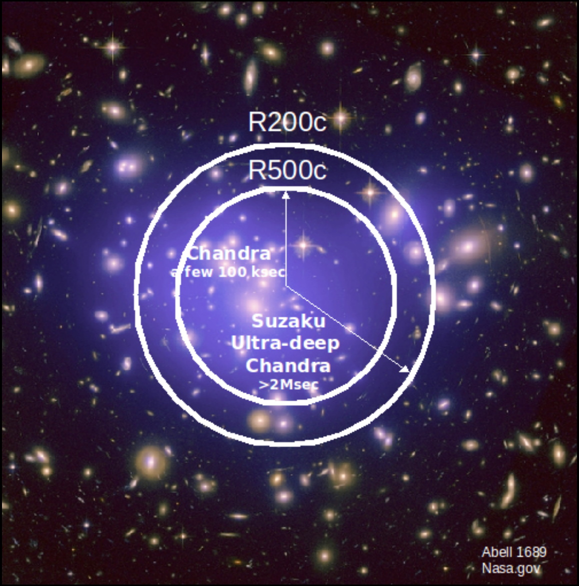

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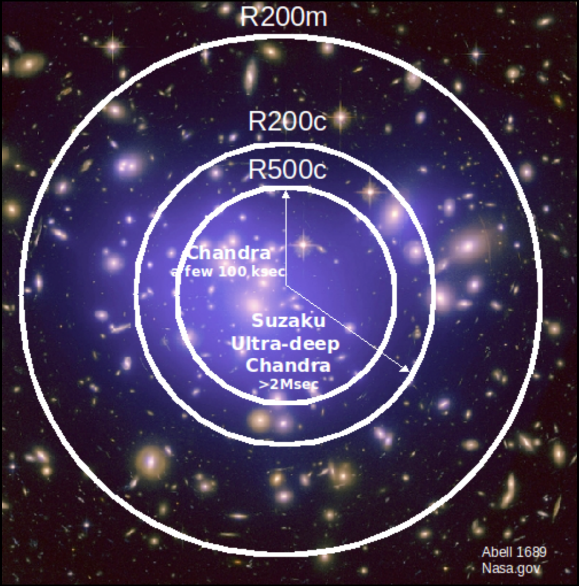

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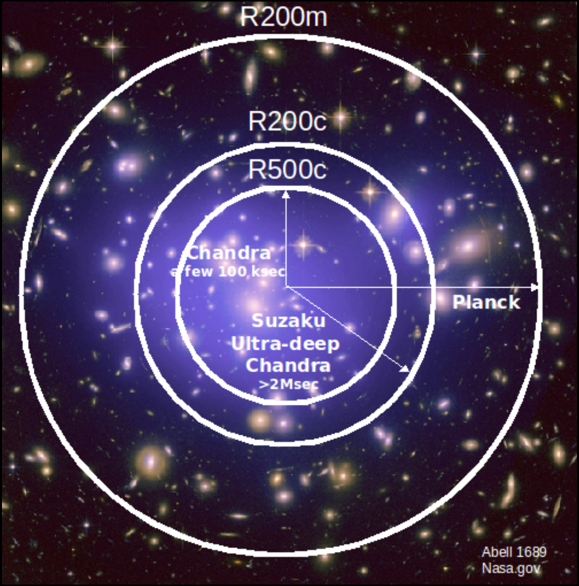
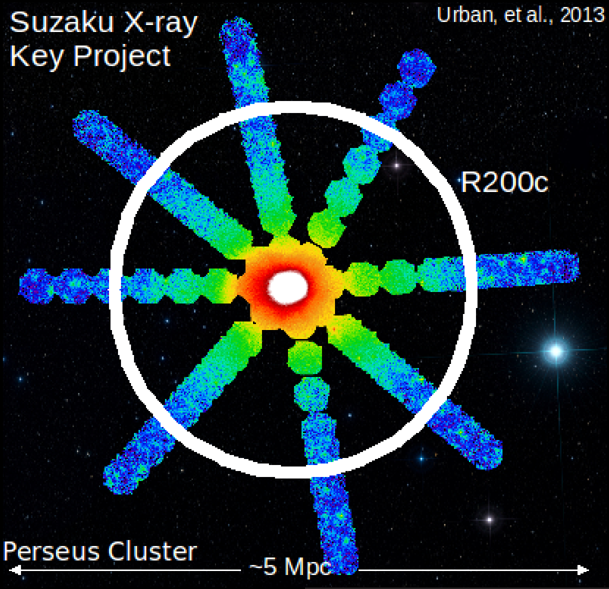
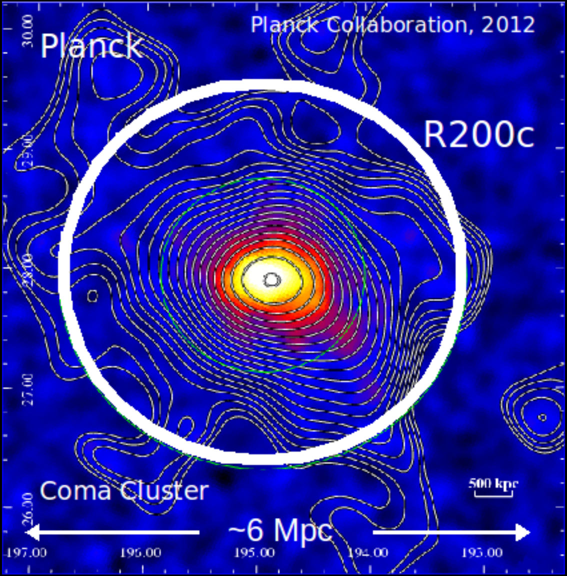


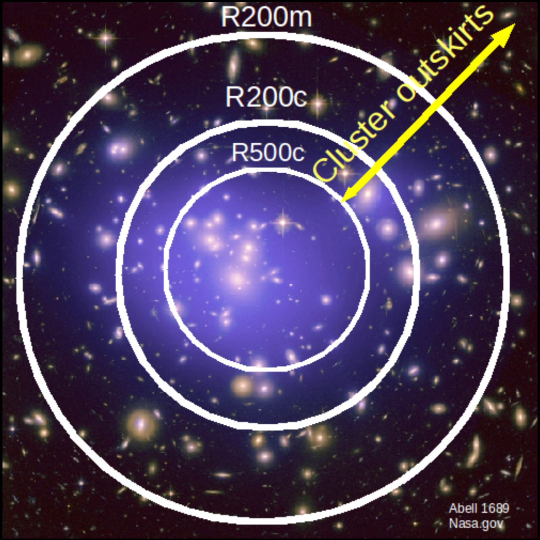
Pioneering X-ray observations of cluster outskirts



Microwave observations of cluster outskirts



Cluster outskirts ideal for mass measurements



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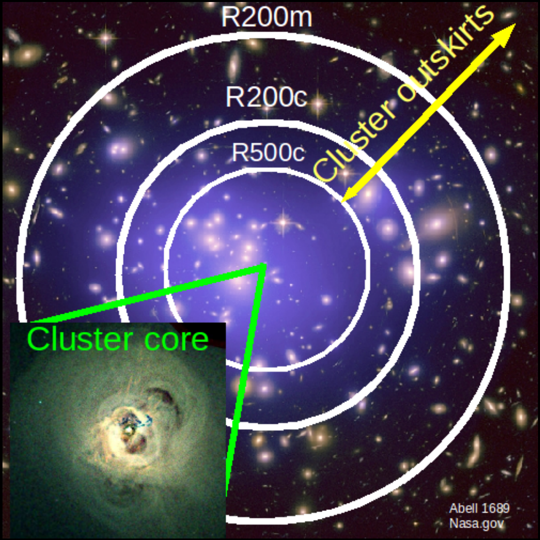
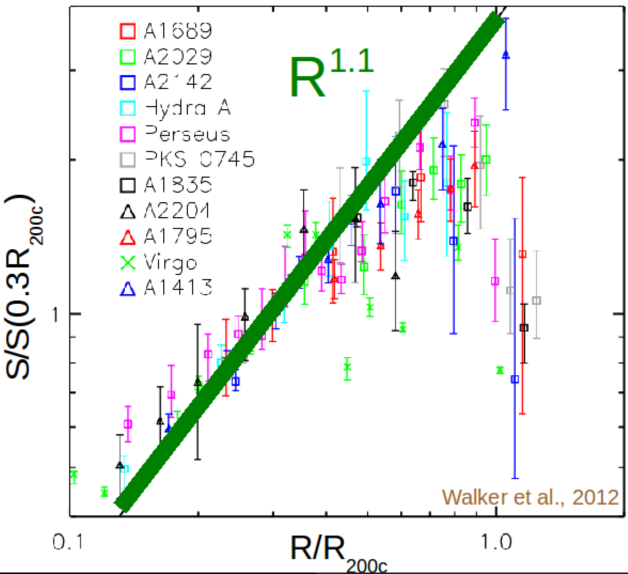
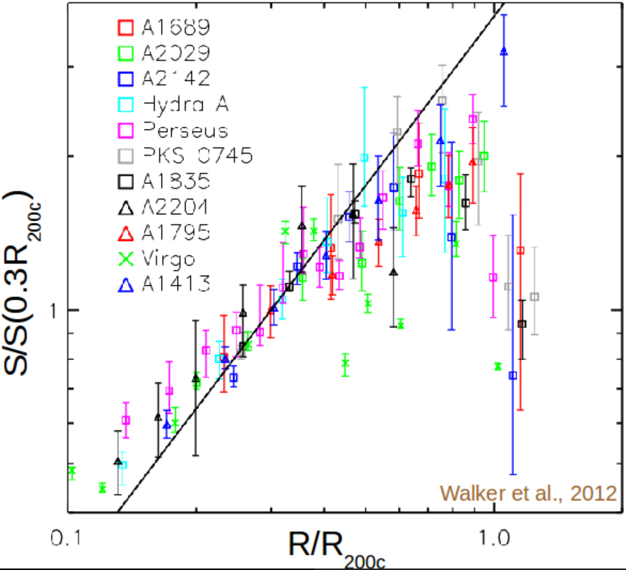


Entropy is expected to scale with radius



Suzaku entropy profiles flatten in outskirts



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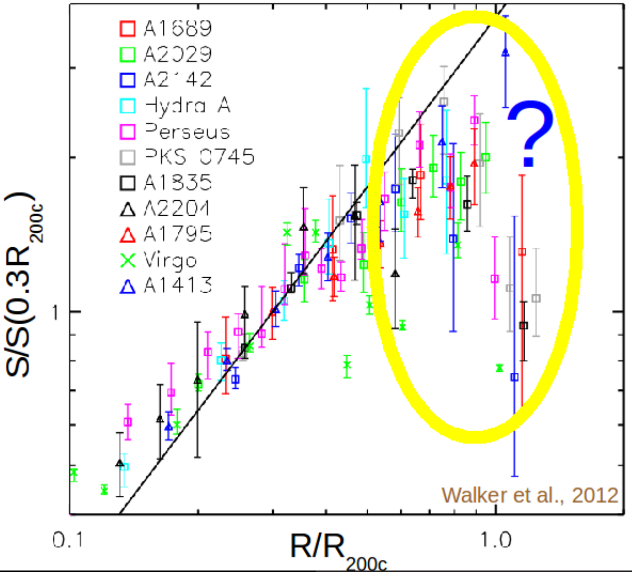
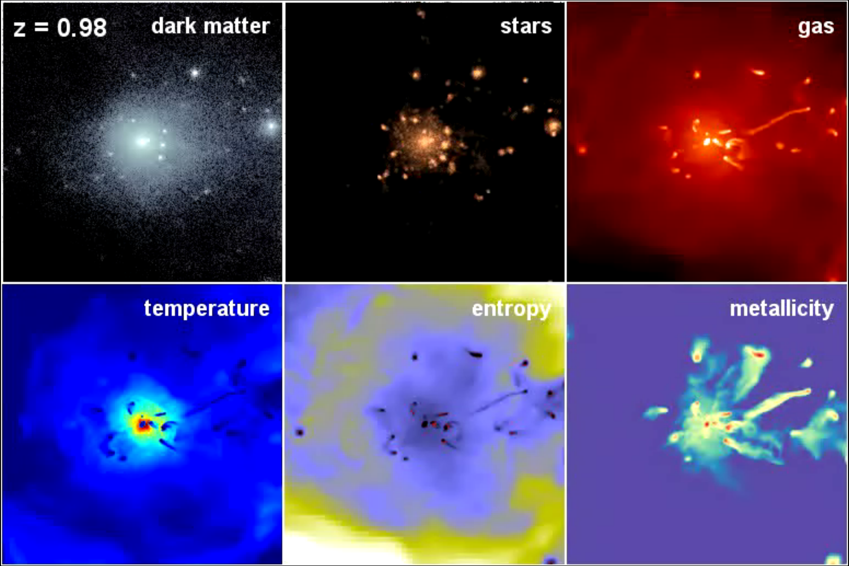


Simulations necessary to interpret observations



Outline

- Introduction
- Observational breakthroughs in cluster outskirts
- Questions to answer with cosmological simulations
    - How can we describe gas flows in cluster outskirts?
    - How do non-equilibrium physics affect observations?
    - How can we use simulations to test for potential observational biases?
- Summary

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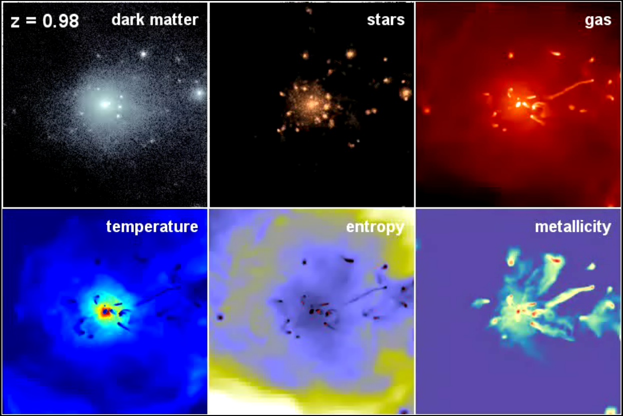
Cosmological Simulations of Galaxy Clusters

Adaptive Refinement Tree (ART) code: N-body+Gasdynamics

Box size ~100 Mpc, Spatial resolution ~few kpc, Region shown ~2 Mpc



Baryonic physics included (e.g. gas cooling, star formation, heating by SNe/AGN, metal enrichment)

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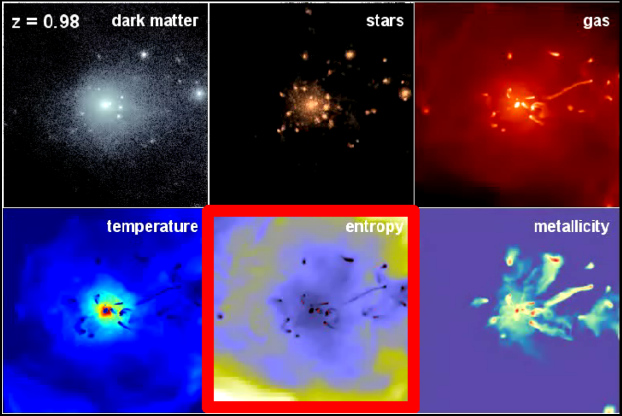

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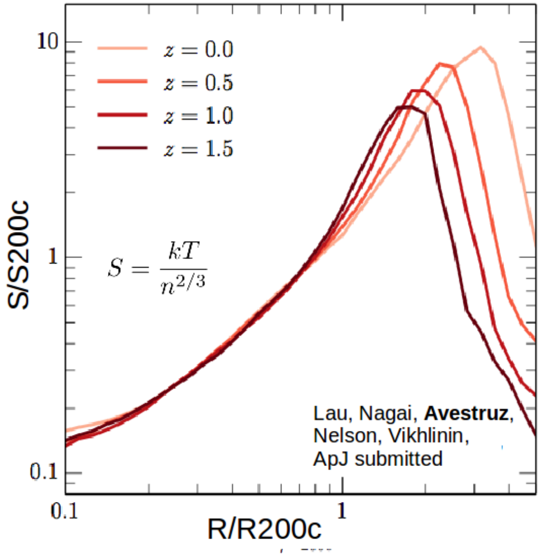
Simulated entropy profiles exhibit self-similarity



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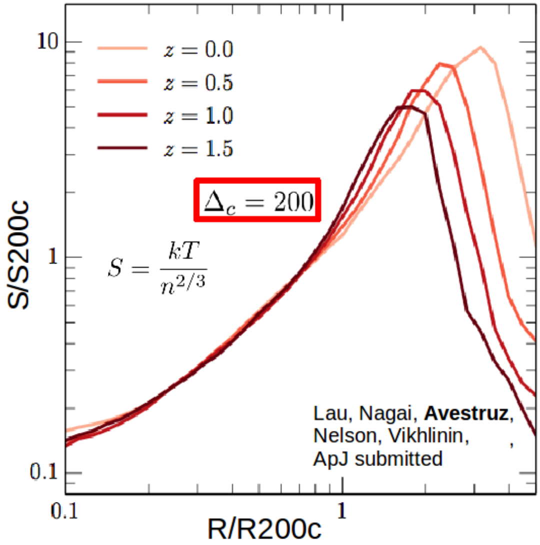

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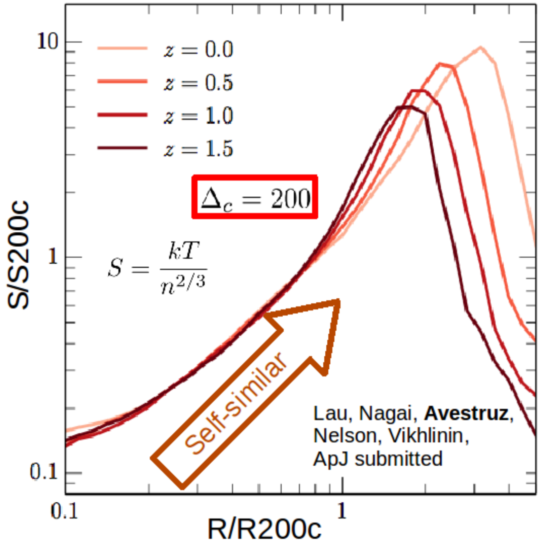

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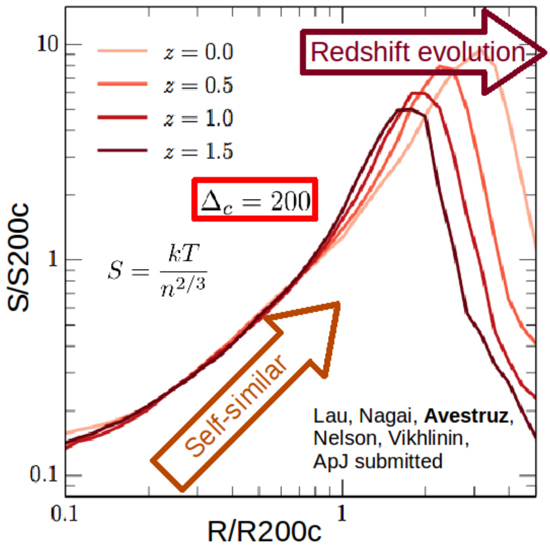

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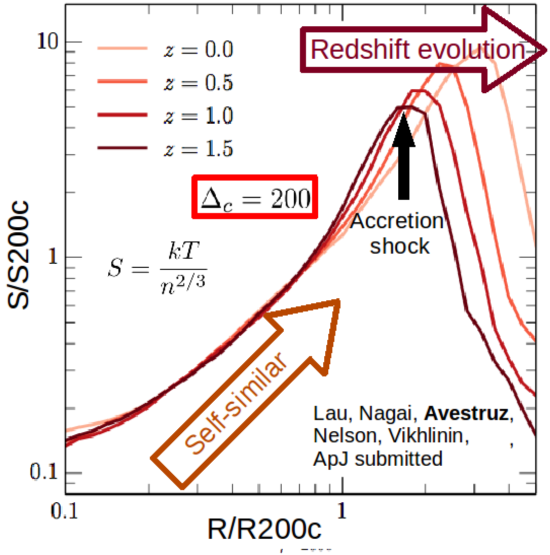

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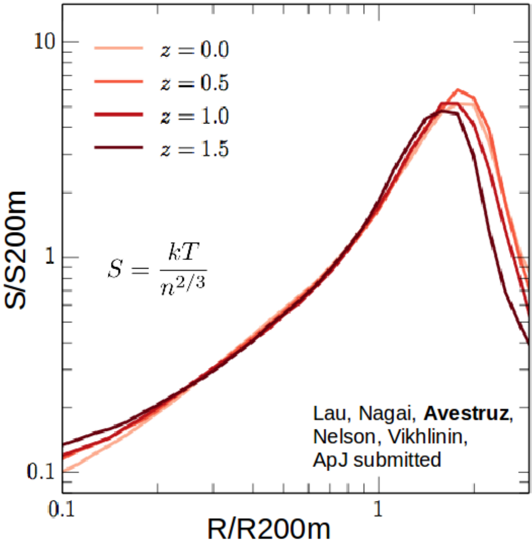

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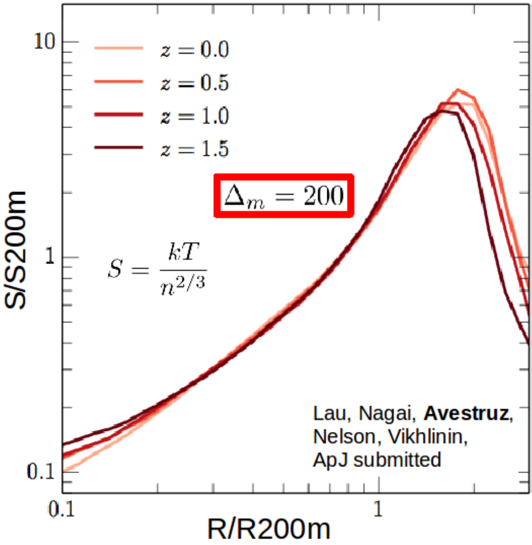

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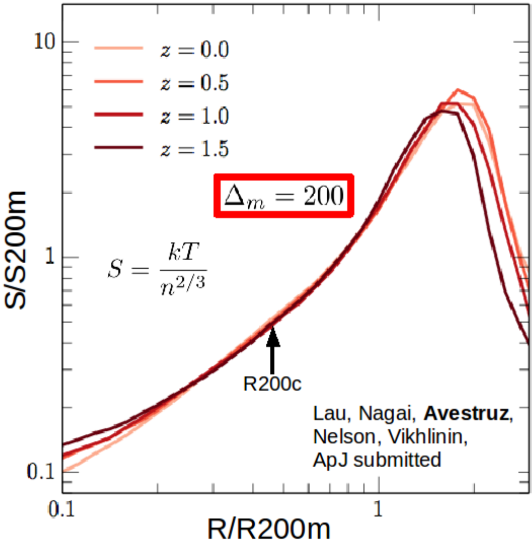

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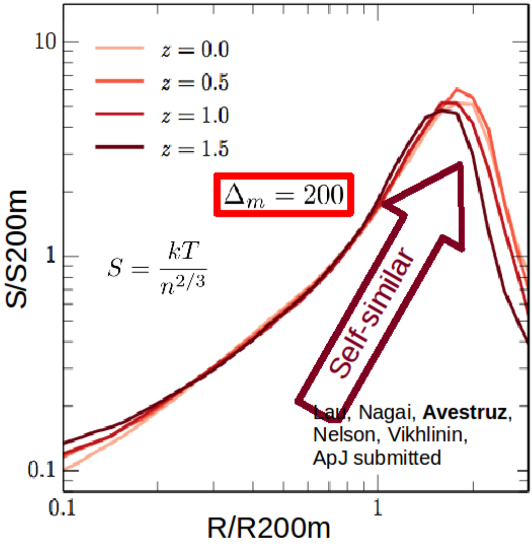

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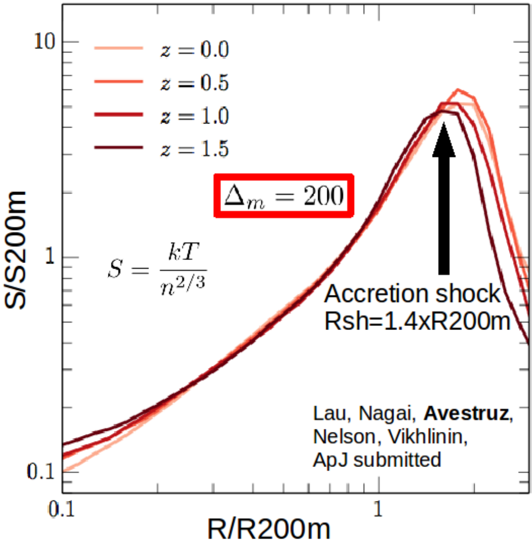

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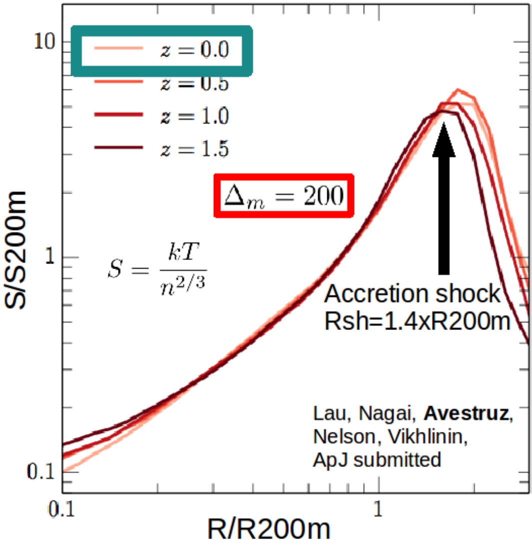
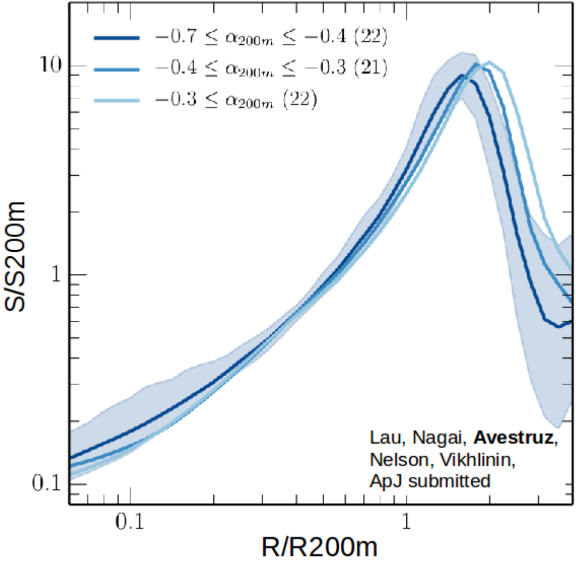


Mass accretion breaks self-similarity



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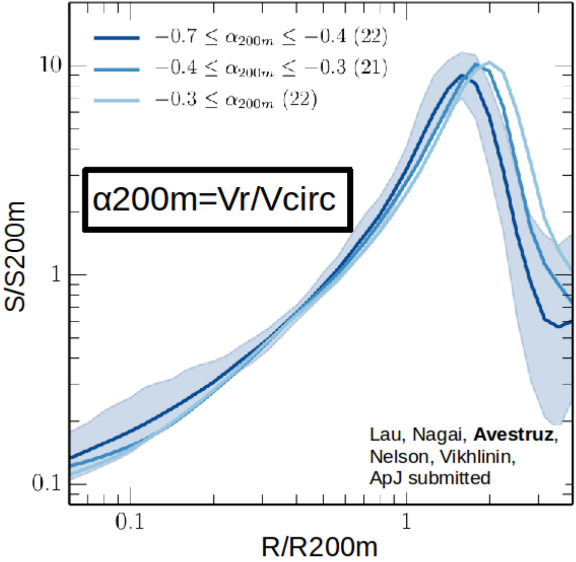

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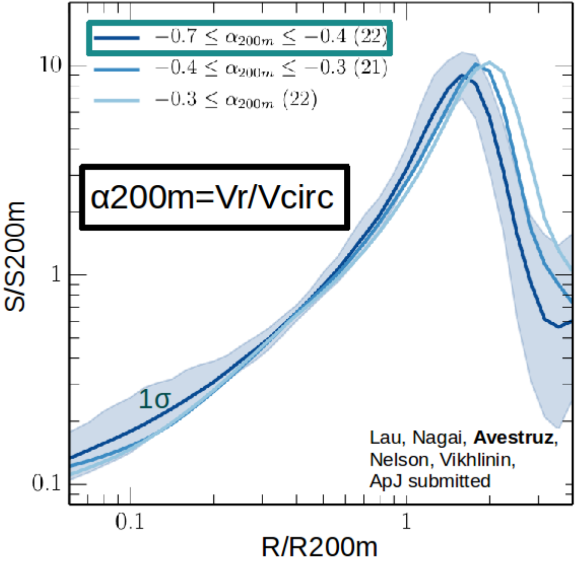

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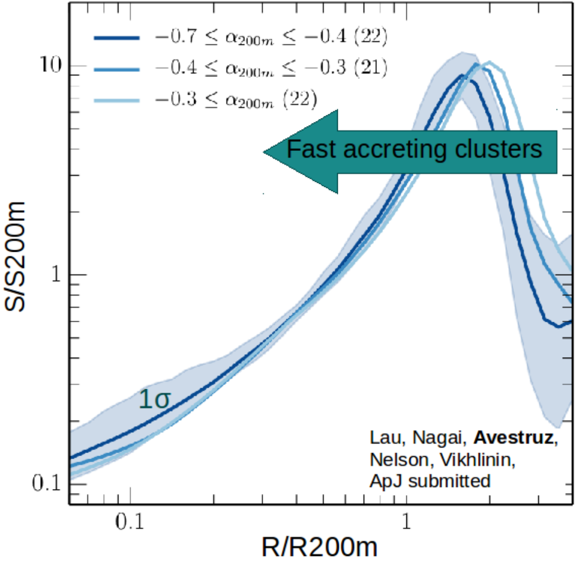
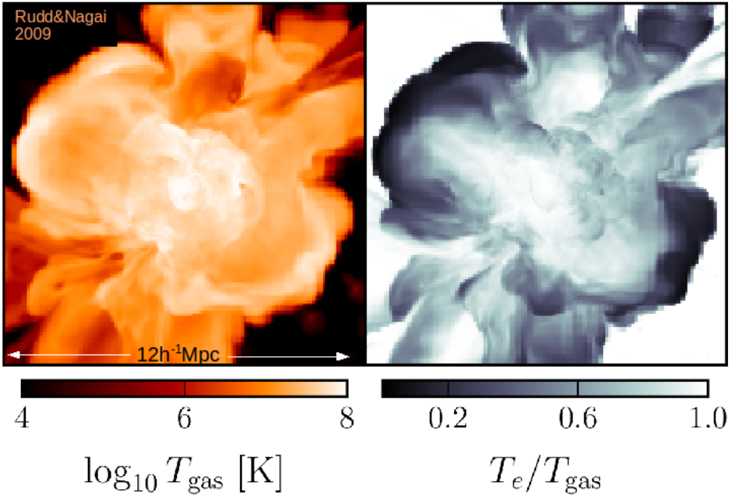


Non-equilibrium electron temperature biased low



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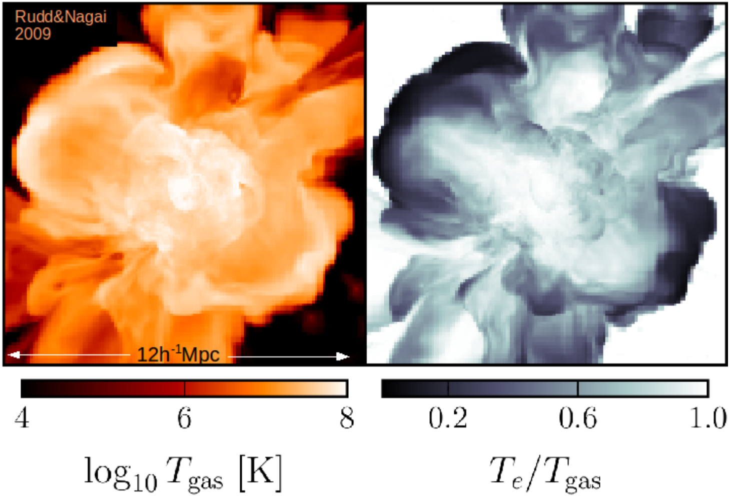

$$t_{ei,Spitzer} = 6.3 \times 10^8 \mathrm{yr} \left(T_e/10^7 K\right) \left(10^{-5} cm^{-3}/n_i\right) \left(40/\ln\Lambda\right)$$

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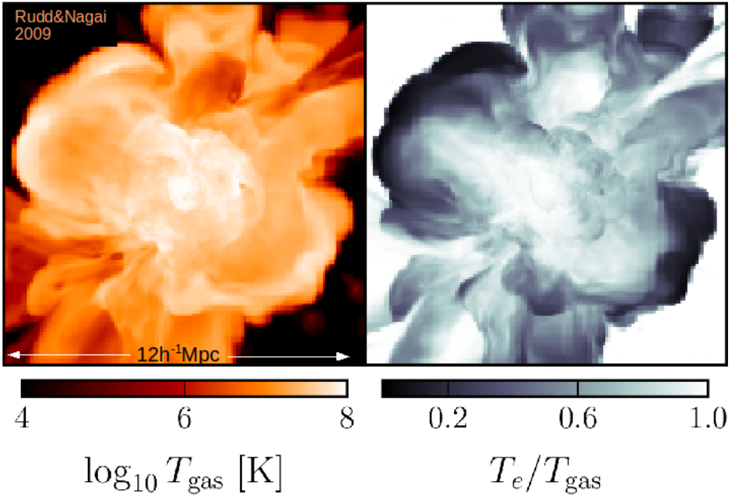

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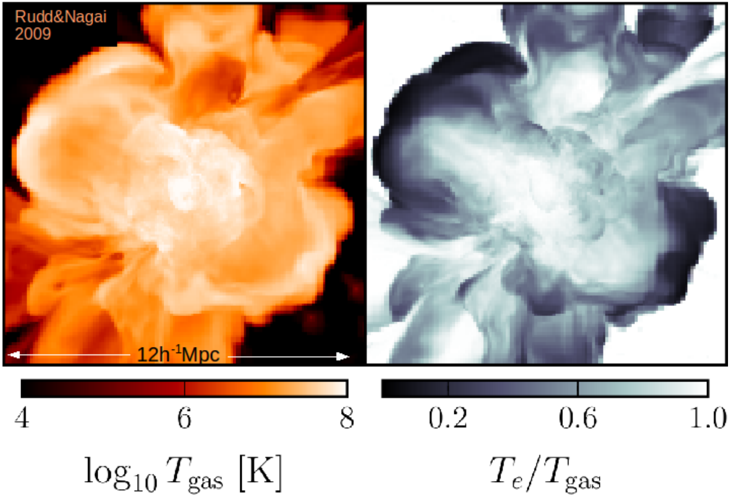

$t_{ei,Spitzer} \rightarrow$ Hubble time

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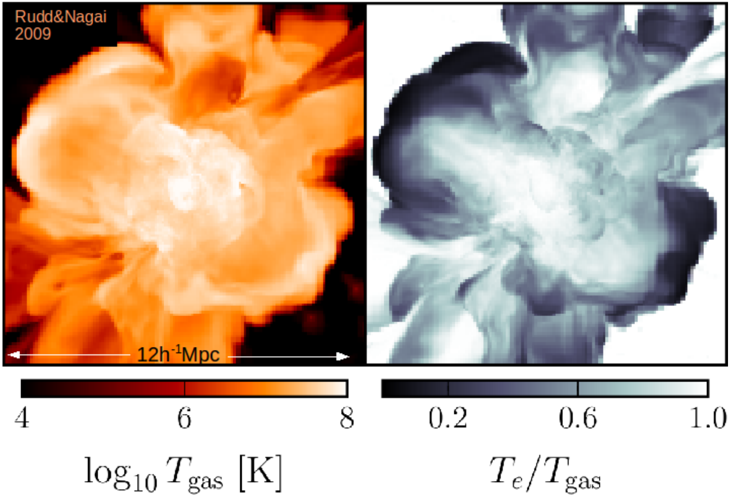
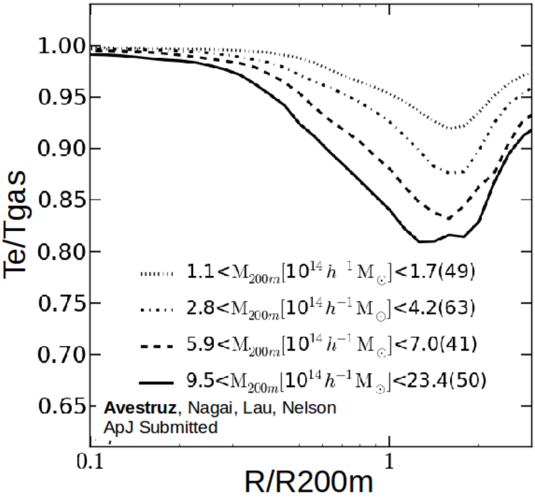


*$t_{ei,Spitzer}$ sets an *upper limit* on the temperature bias

Electron temperature bias exhibits self-similarity



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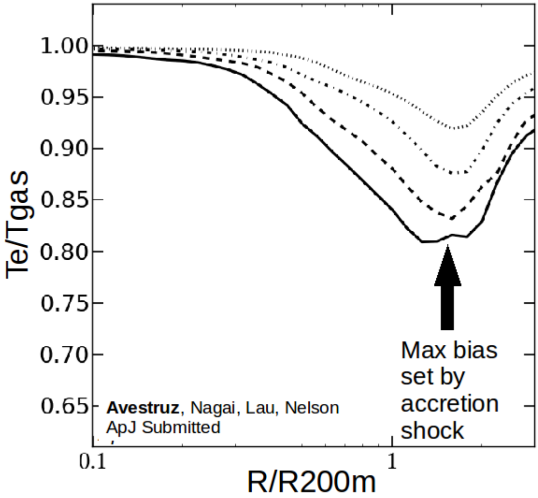

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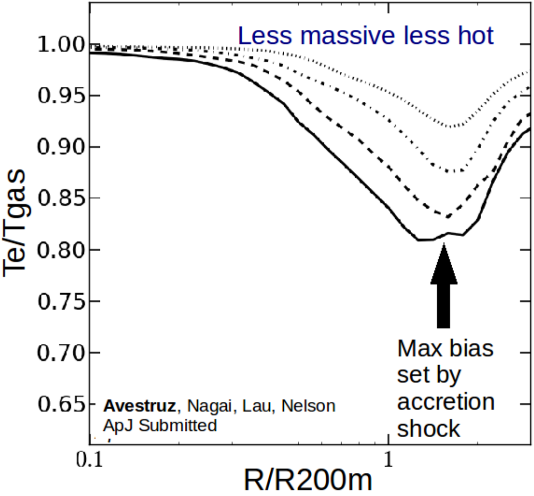

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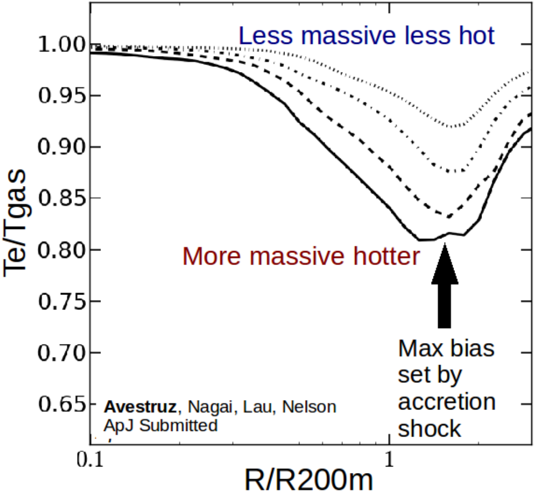

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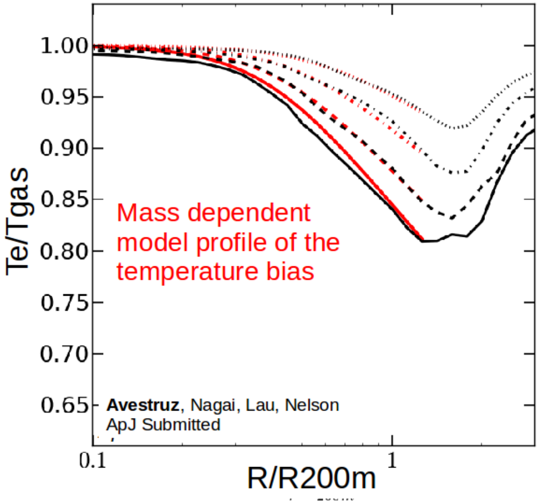

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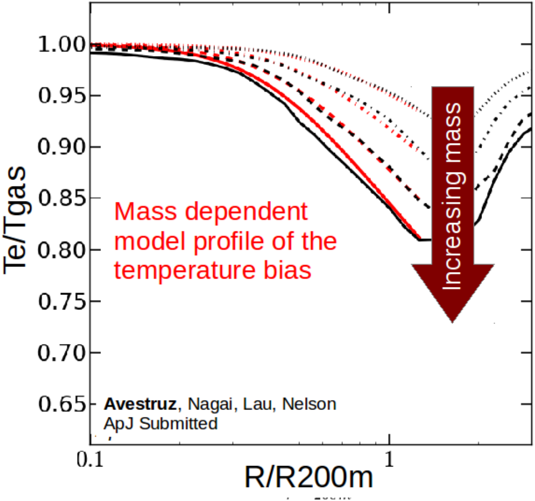
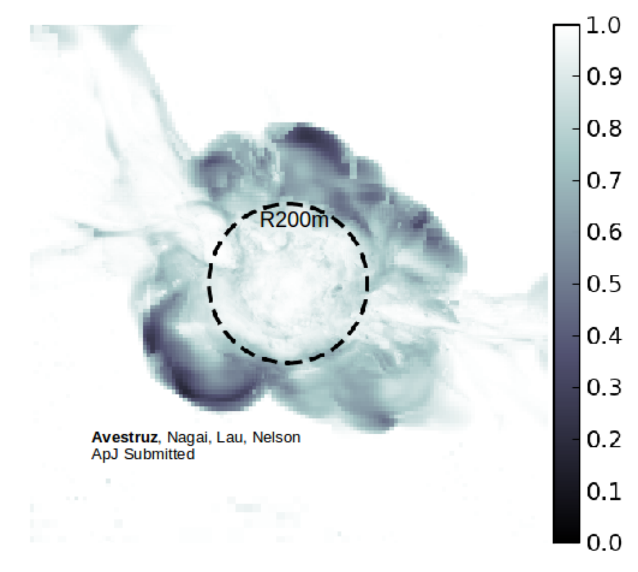


Temperature bias is azimuthally asymmetric



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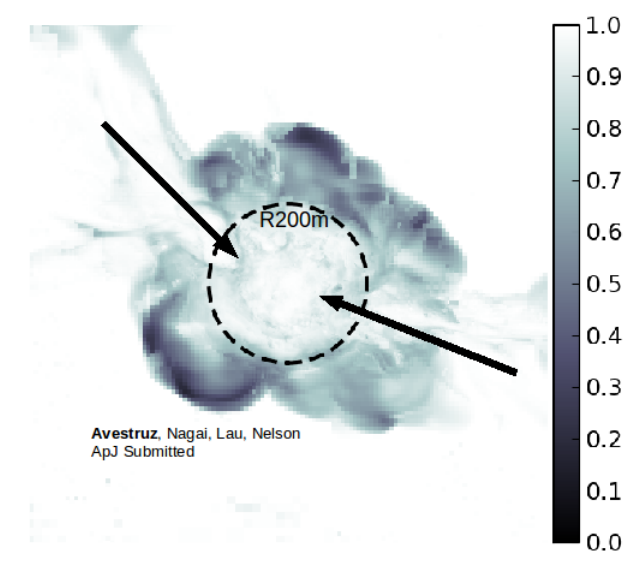

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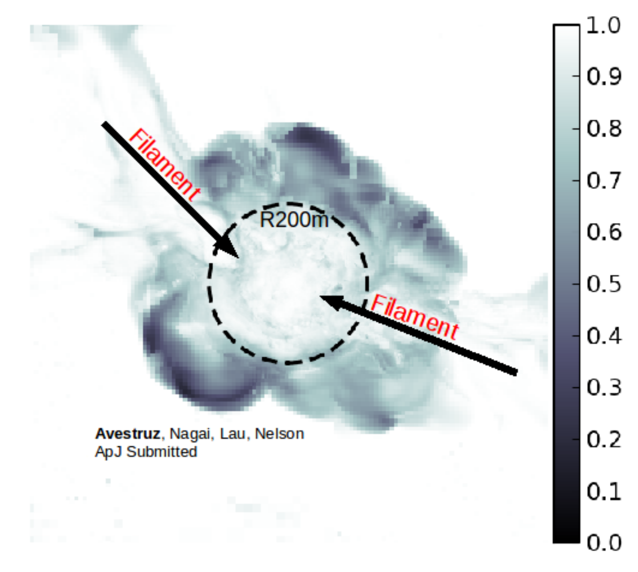

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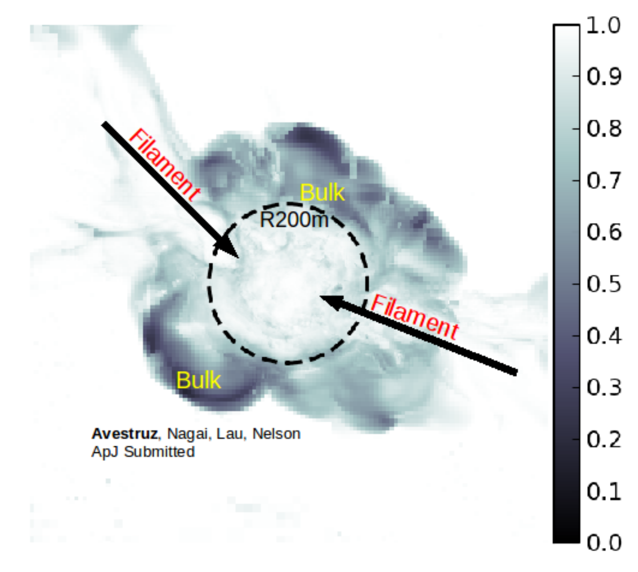

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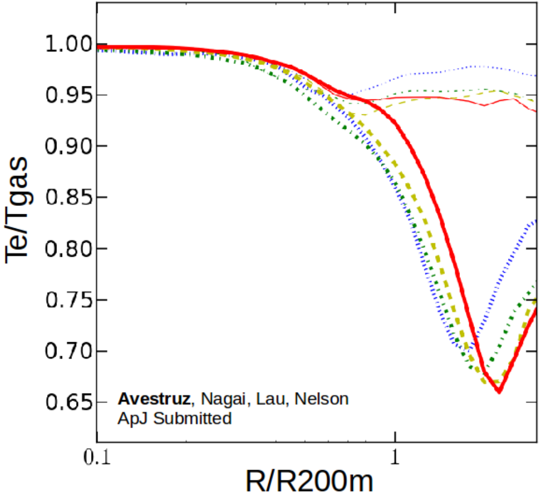

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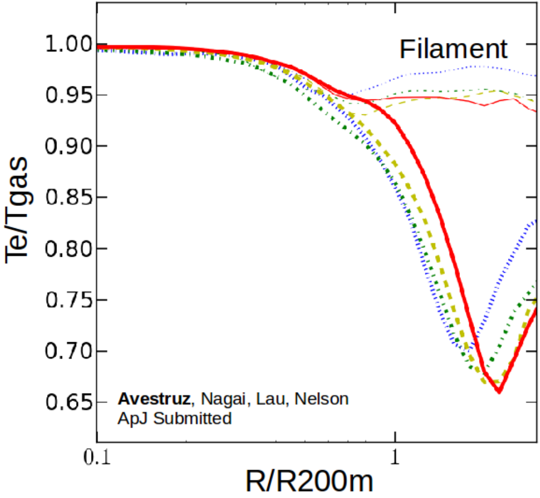

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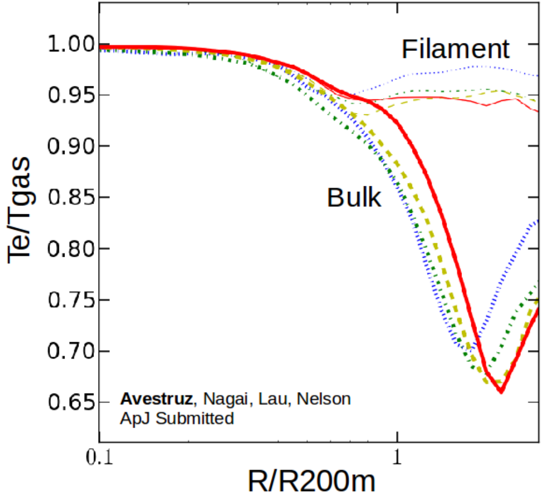
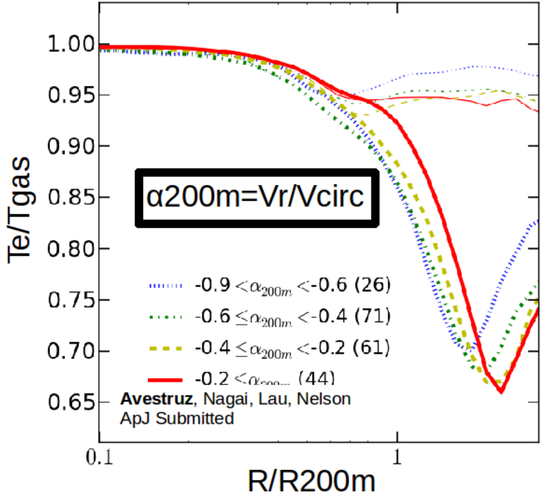


Mass accretion breaks self similarity



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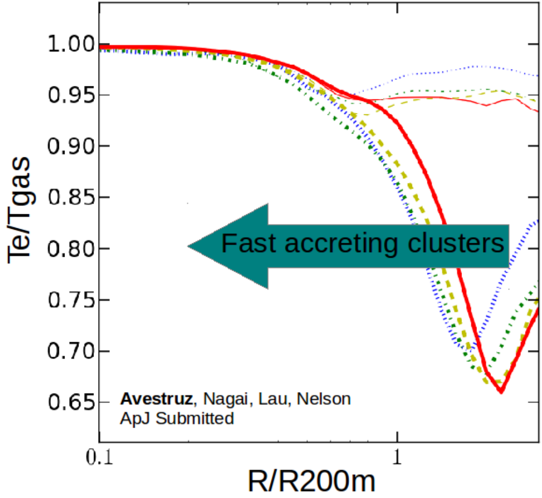
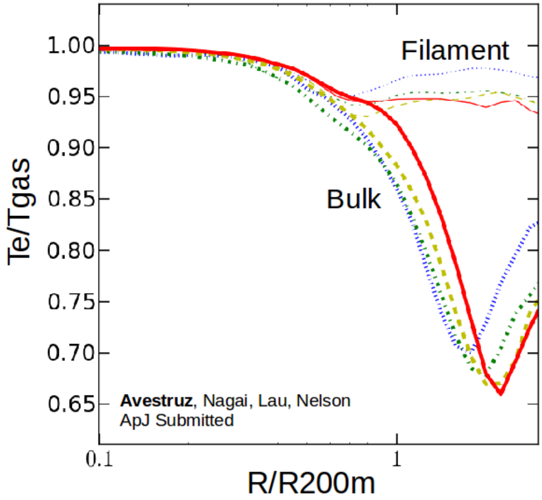
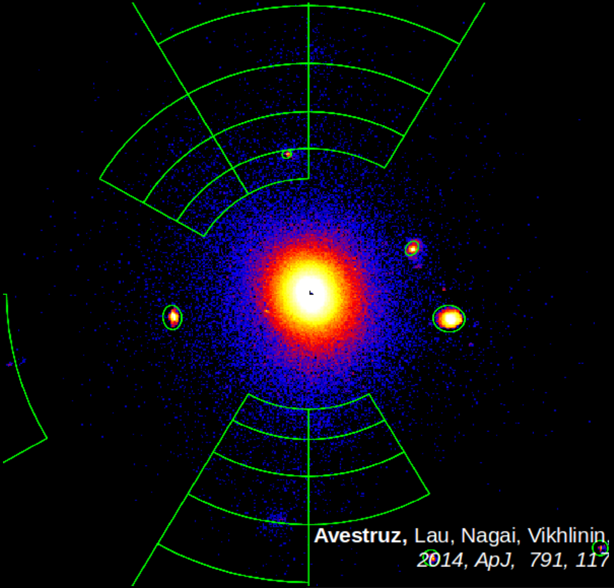


Bulk/Filament decomposition is important



Mock X-ray pipeline allows us to test observations



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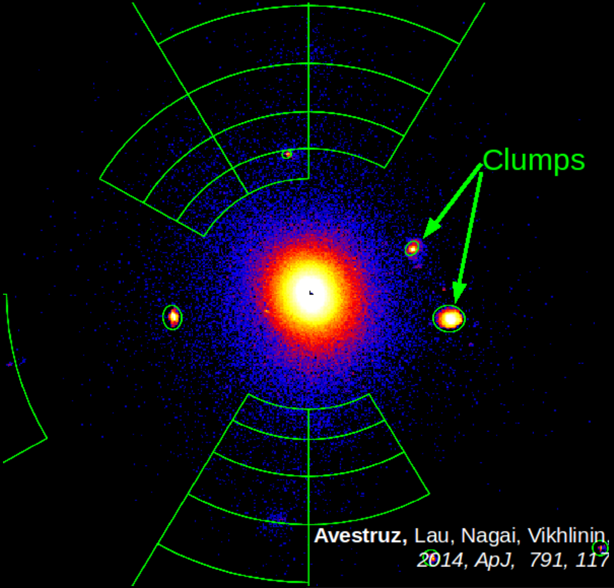

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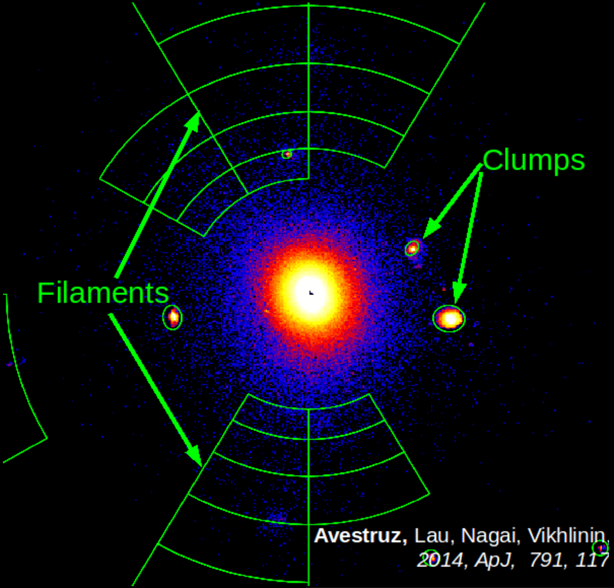

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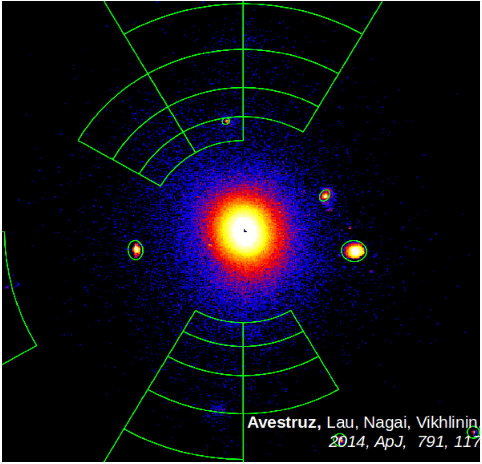

$$\mathrm{XSB} = \int dV\, n_e n_p \Lambda(T_X, Z)$$

Photon counts per second

Emission measure:
$\mathrm{EMM} = \int n_e n_p \; dl$

Assumed model plasma emissivity

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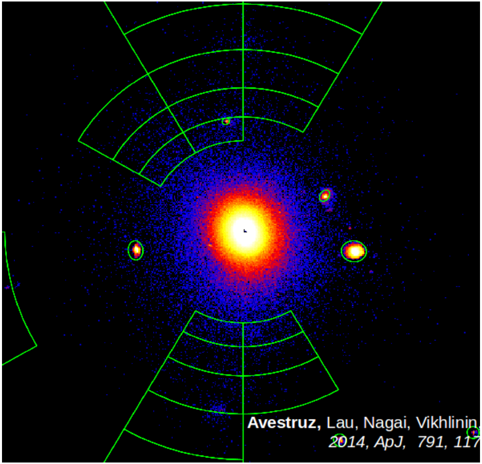

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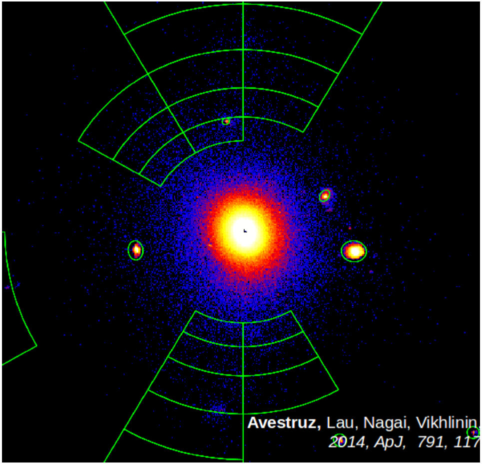

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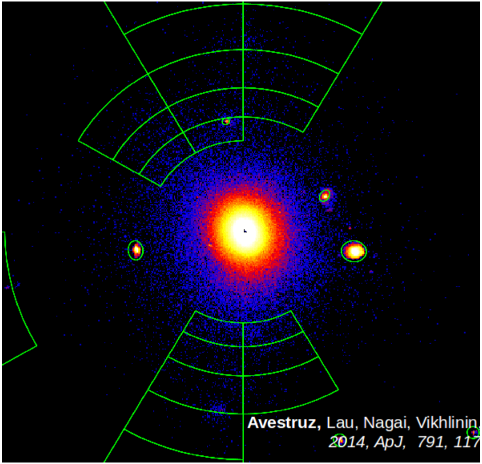

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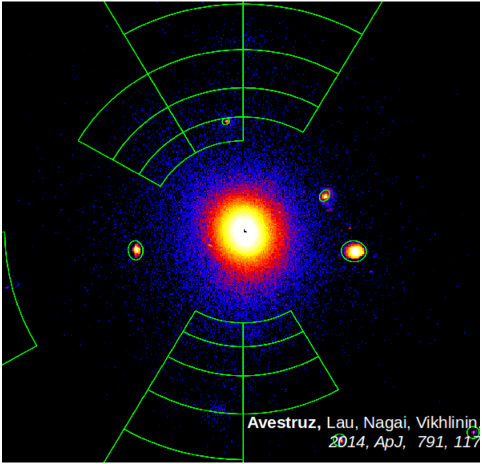


$T_X = 4.11$ keV

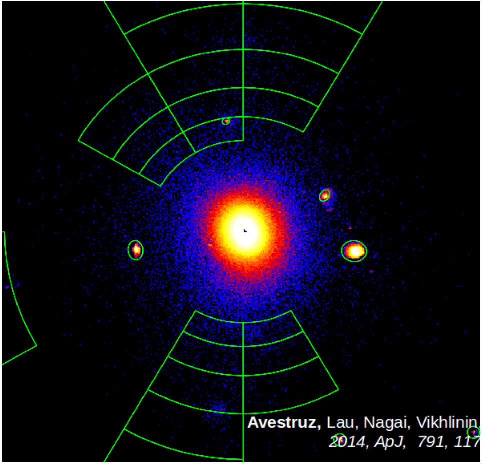
2 Msec exposure time

Convolved Chandra response

(Similar to Abell 133)

Test metallicity and temperature

Mock X-ray pipeline allows us to test observations



$T_X = 4.11$ keV

2 Msec exposure time

Convolved Chandra response

(Similar to Abell 133)

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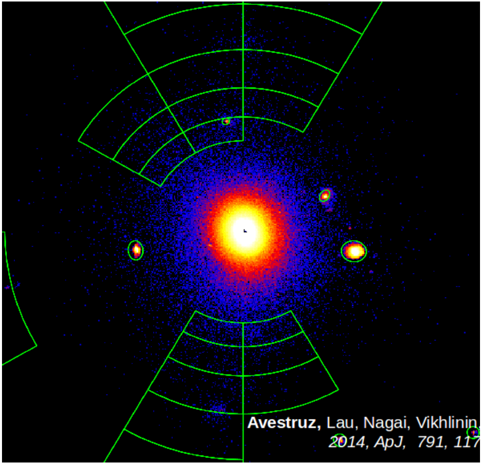

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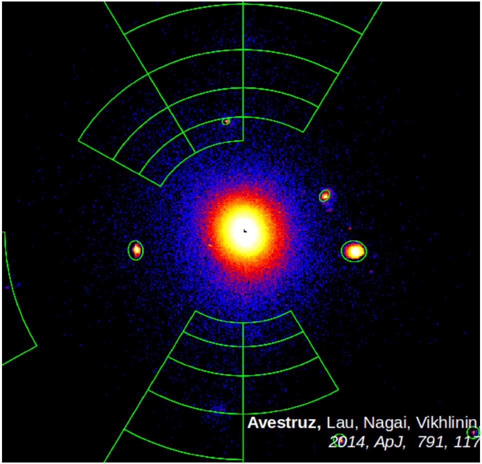

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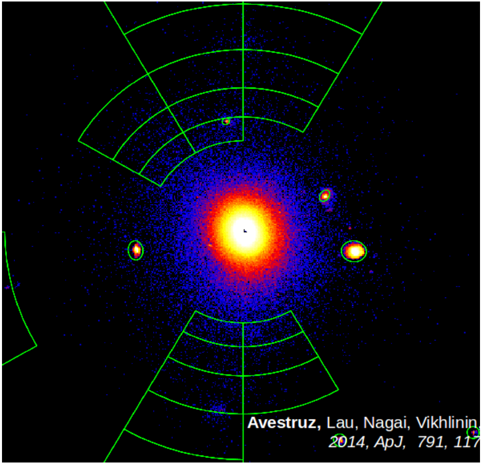

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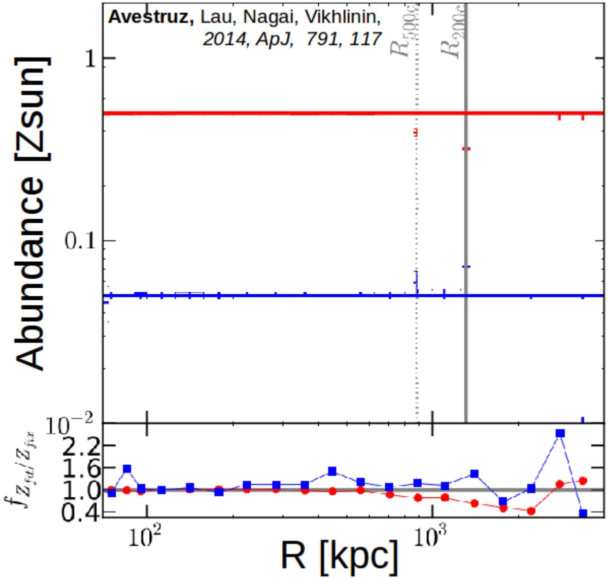

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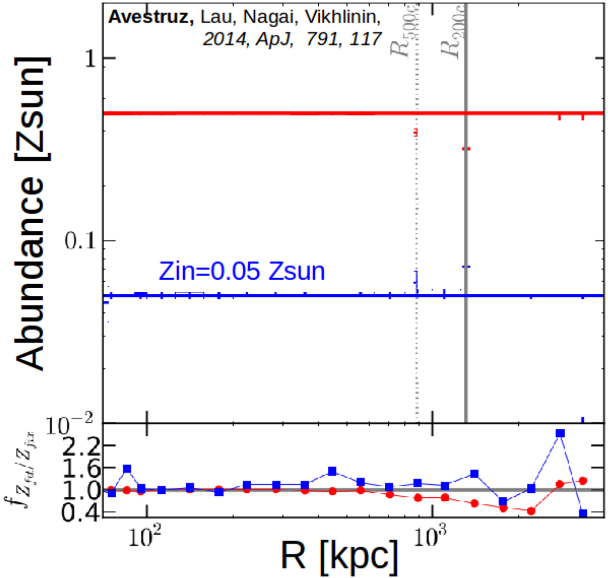

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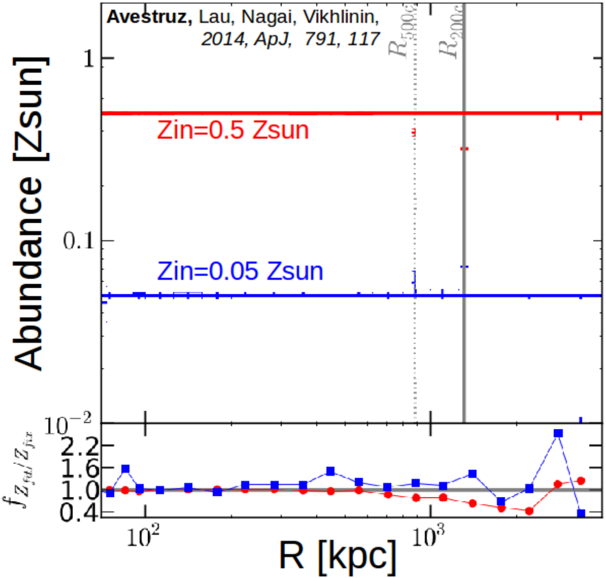
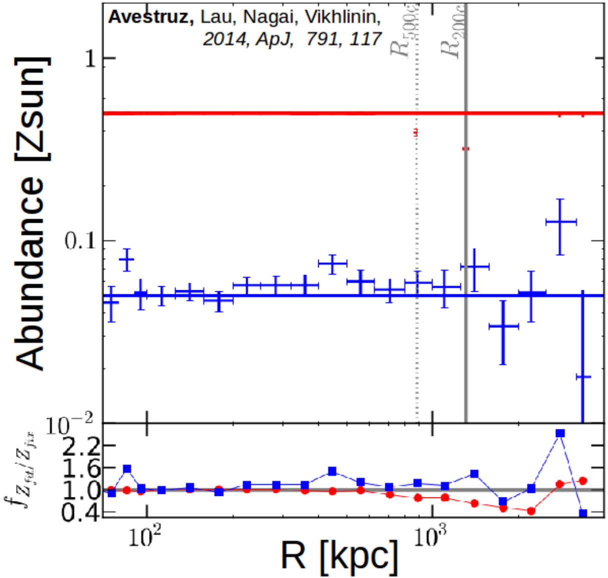
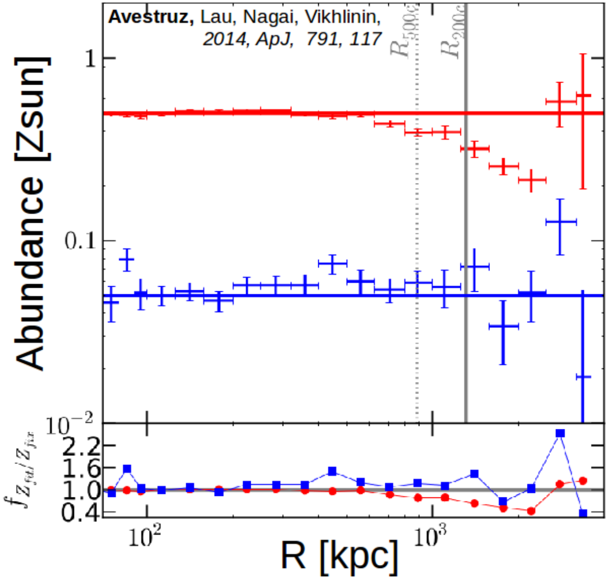


Weak metal contributions are scattered



Stronger metal contributions biased low



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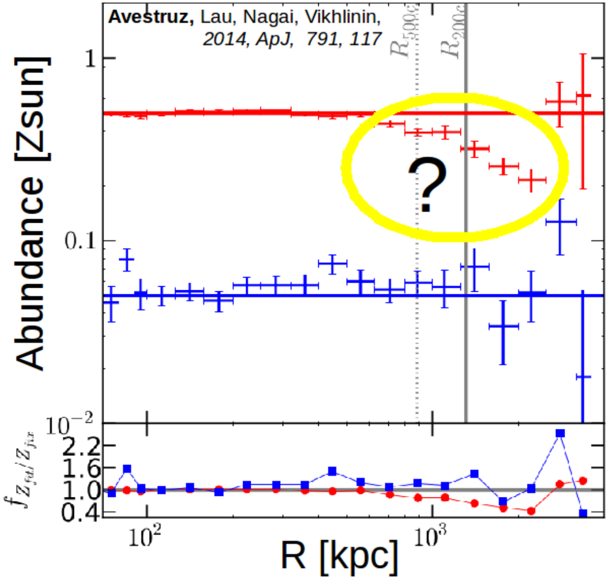

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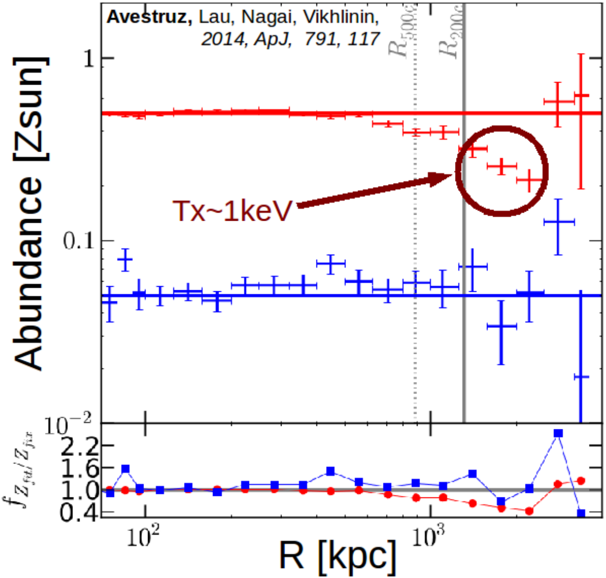
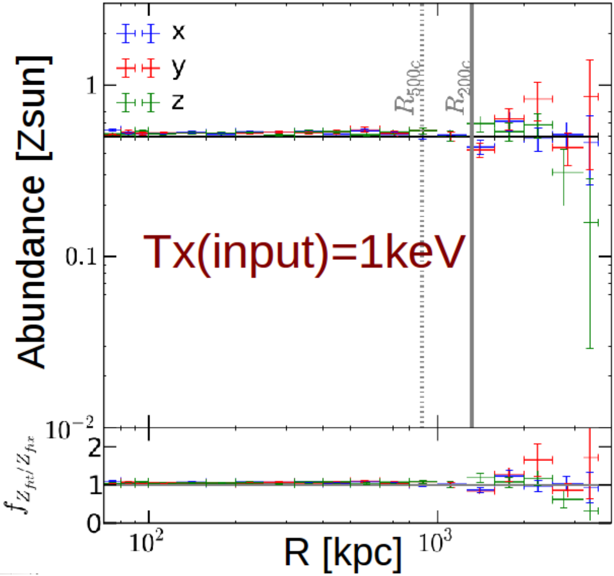
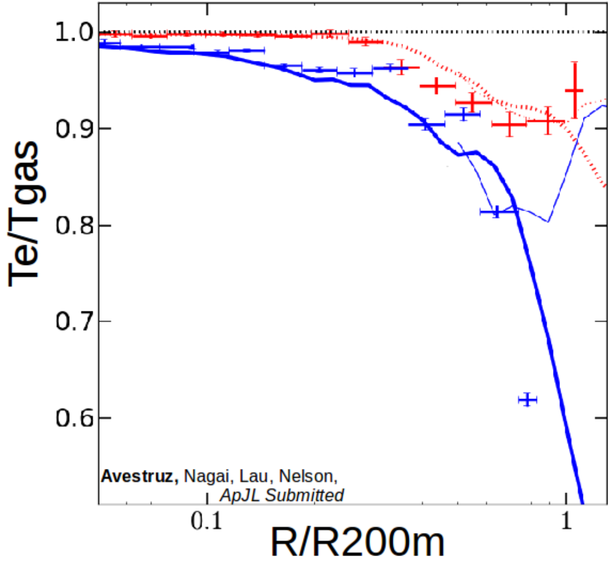


Bias disappears in single temperature medium



Non-equilibrium electrons can affect measured T_X



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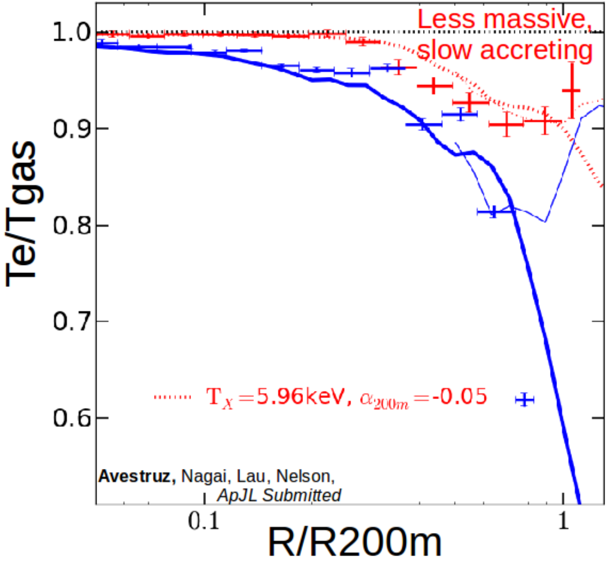

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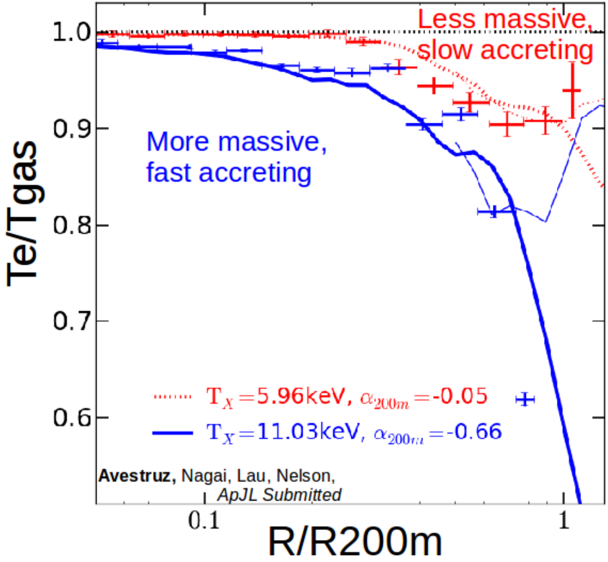

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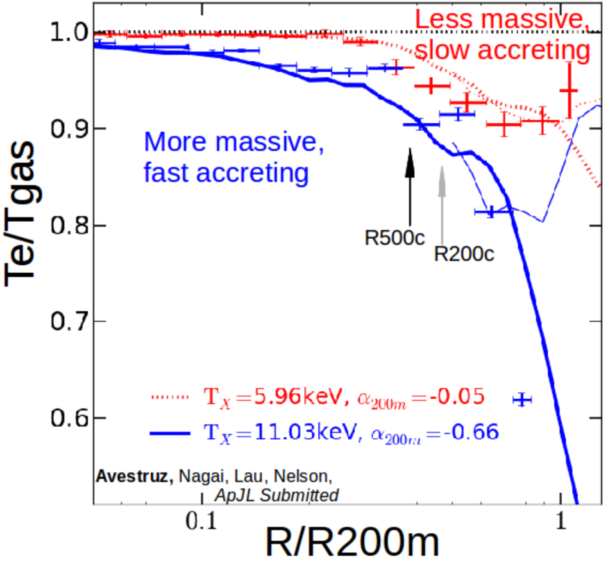
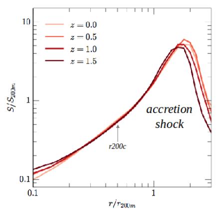
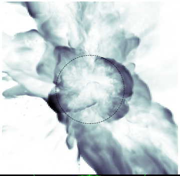
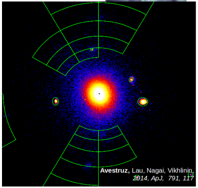


Summary

1. Cluster outskirts are best described with respect to R_{200m}
2. Non-equilibrium electrons are a potential source of systematic uncertainties
3. Inhomogeneities in the intracluster medium contribute to observational biases







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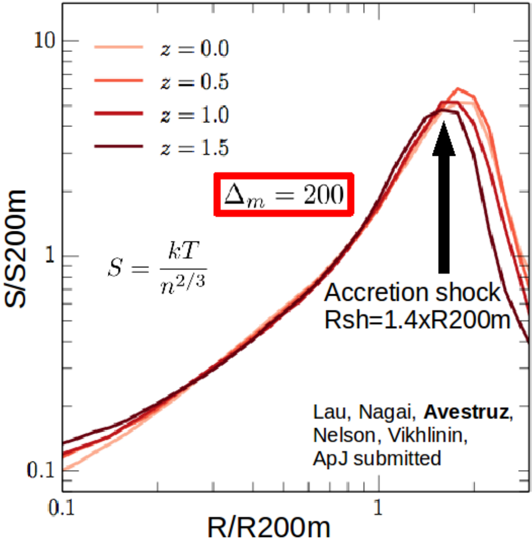
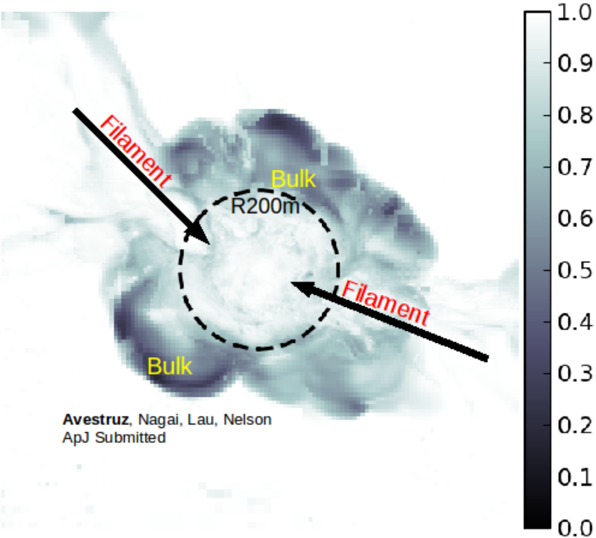


2. Non-equilibrium electrons at lower temperatures



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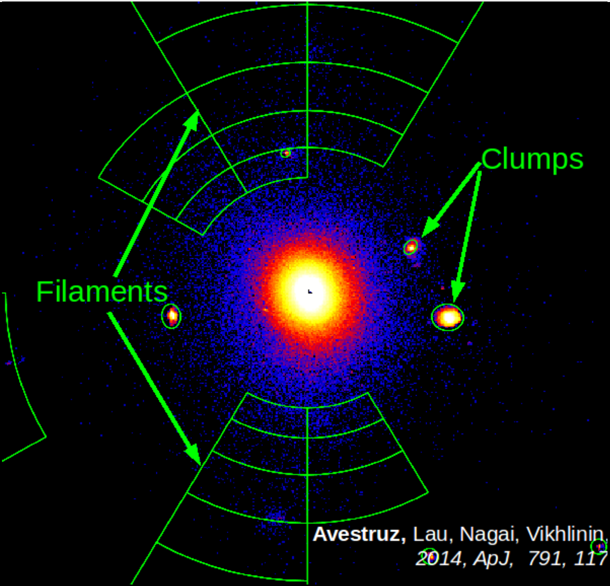

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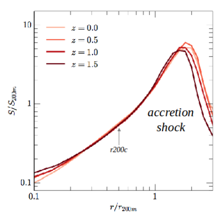

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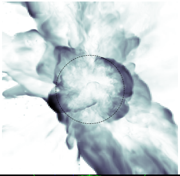
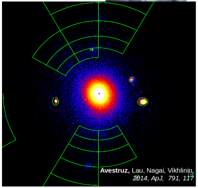


3. Inhomogeneities in the intracluster medium contribute to observational biases



End