# Modeling Galaxy Cluster Outskirts with Cosmological Simulations

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NSF Graduate Research Fellow, Yale University

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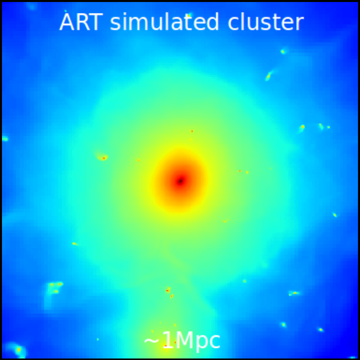
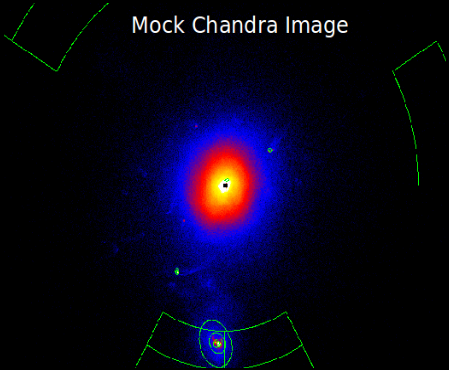
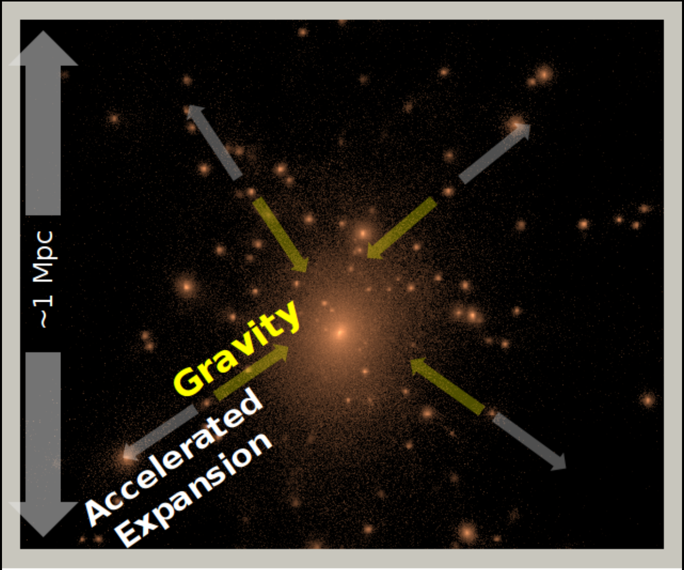


# Clusters Probe the Growth of Structure



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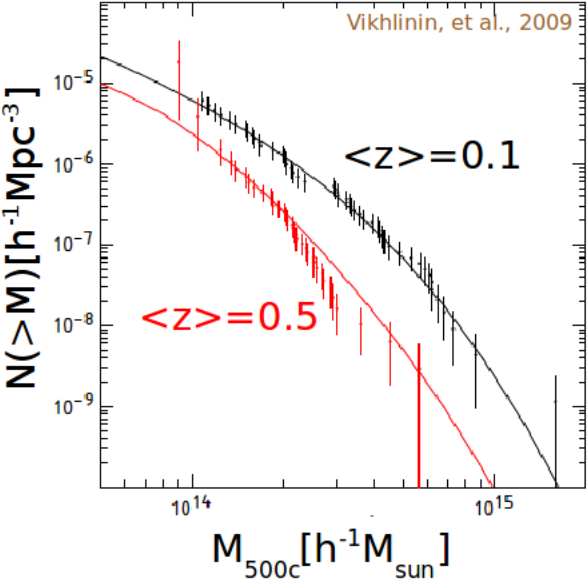
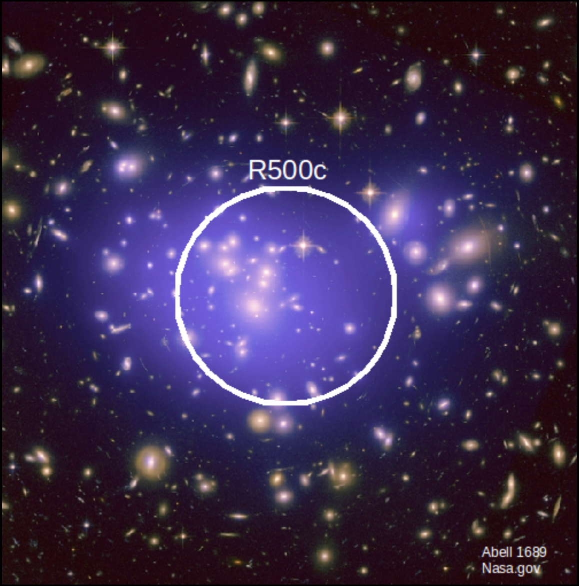


# Masses defined with respect to reference densities



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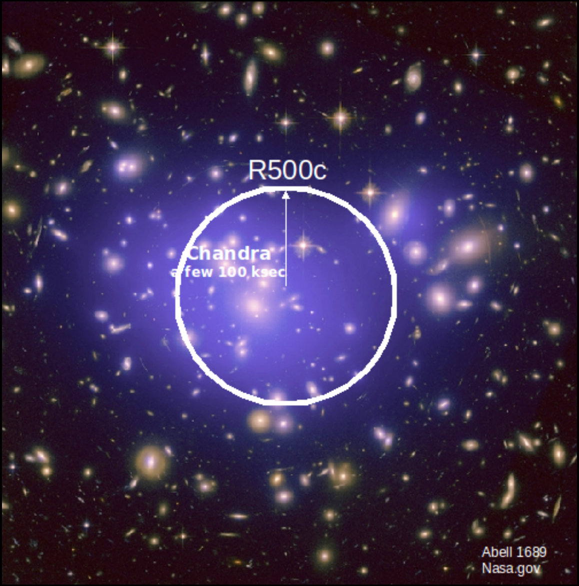

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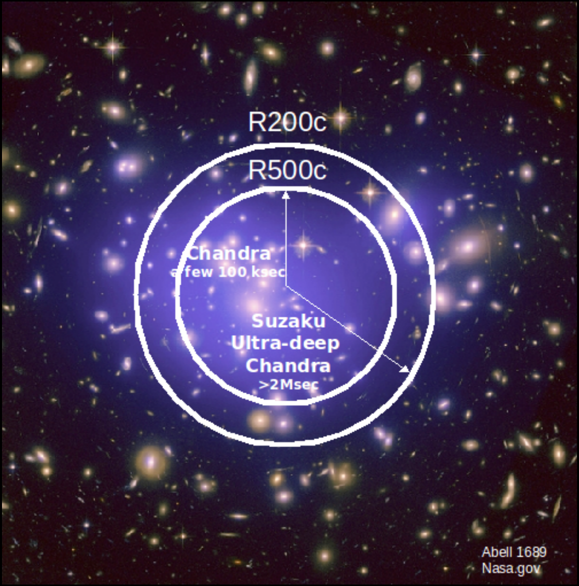

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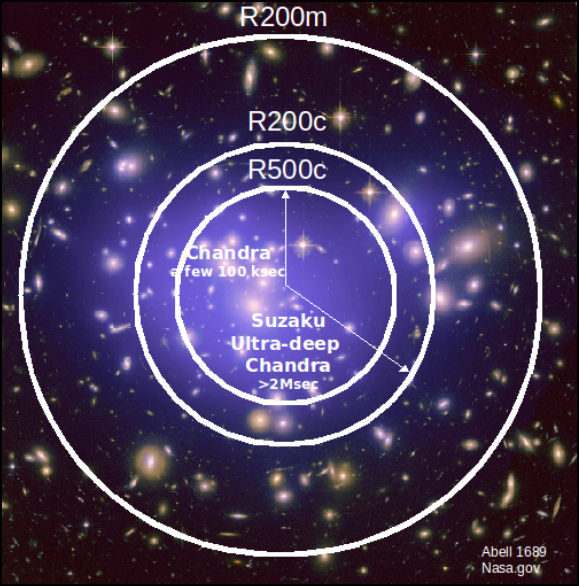

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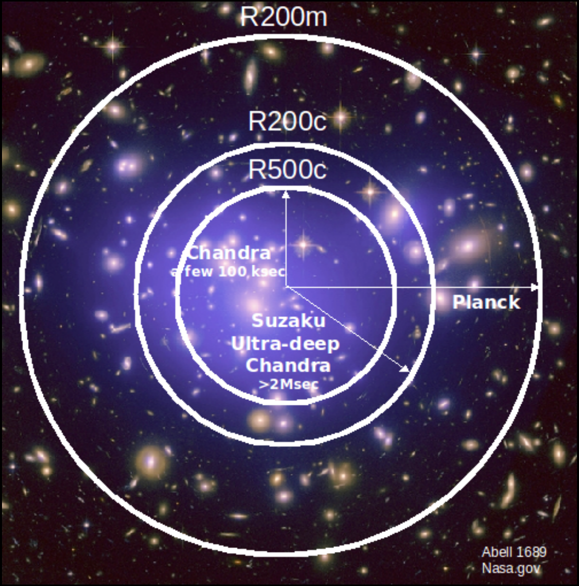
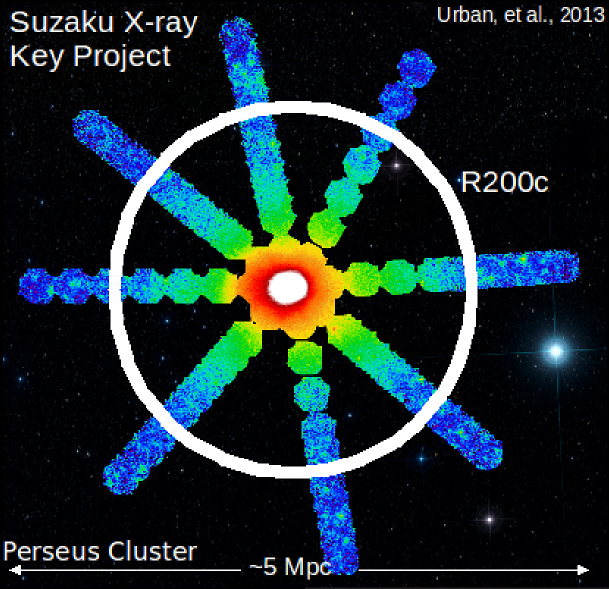
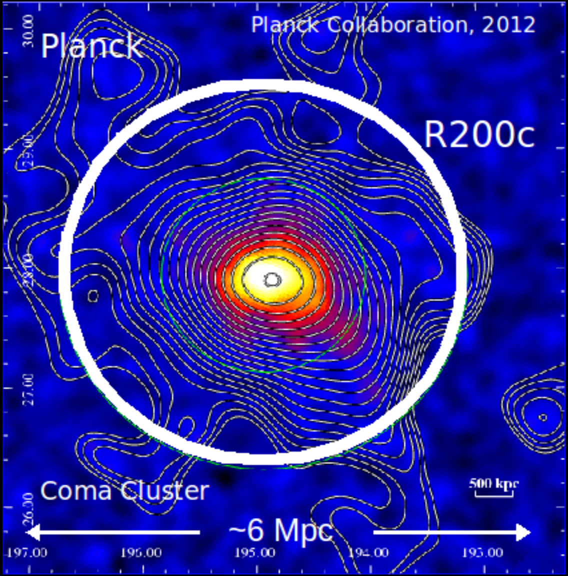


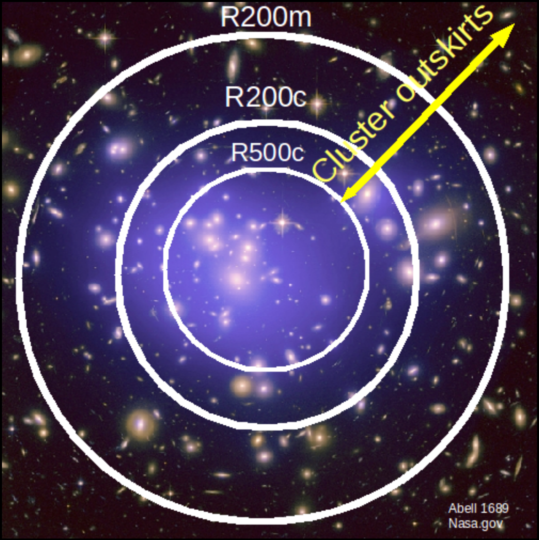
# Pioneering X-ray observations of cluster outskirts



# Microwave observations of cluster outskirts



# Cluster outskirts ideal for mass measurements



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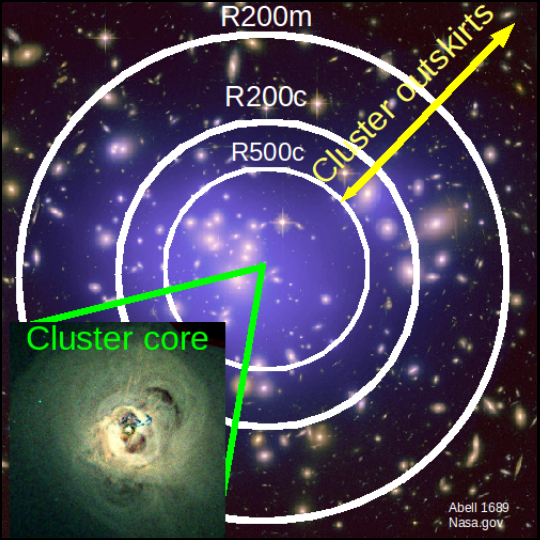
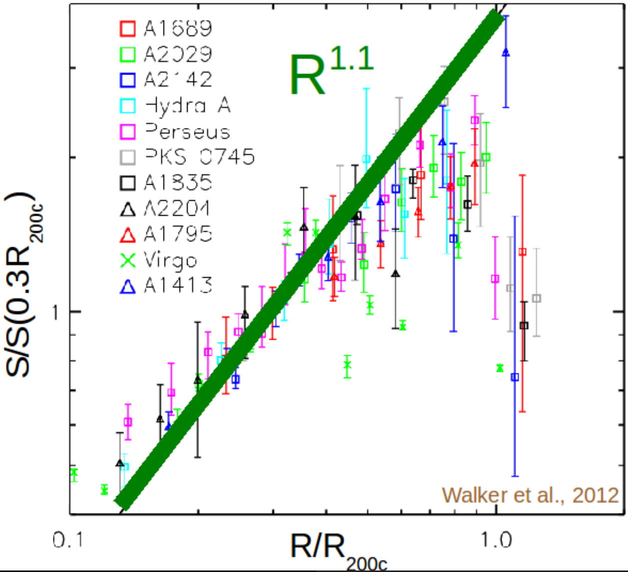
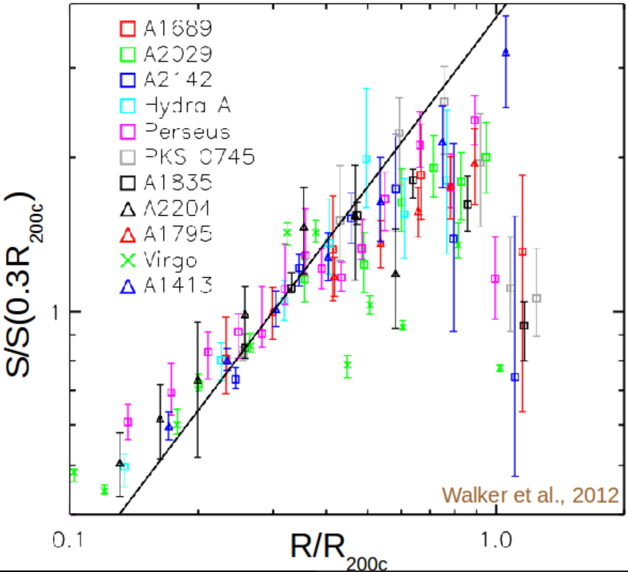


# Entropy is expected to scale with radius



# Suzaku entropy profiles flatten in outskirts



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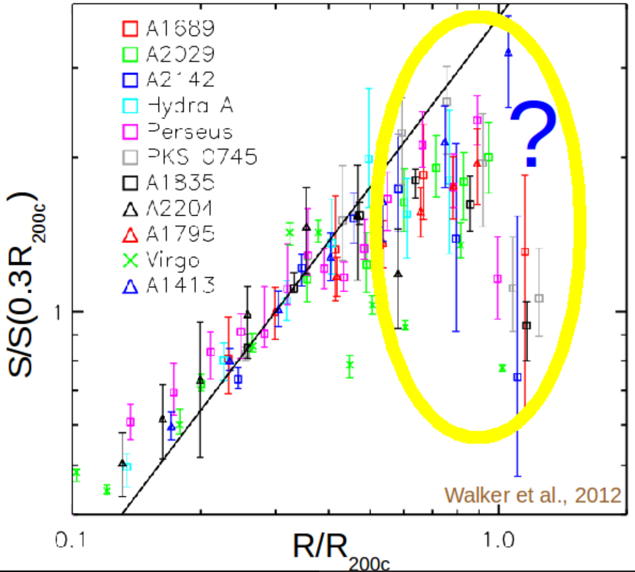
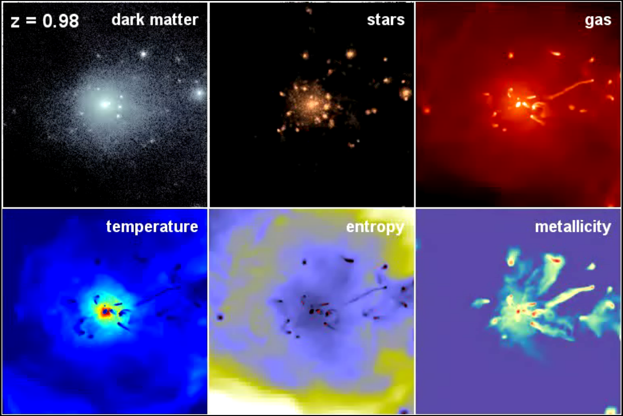


# Simulations necessary to interpret observations

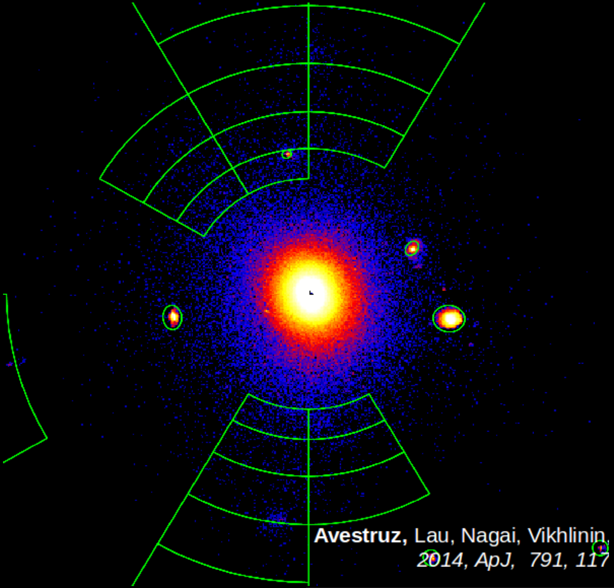
Adaptive Refinement Tree (ART) code: N-body+Gasdynamics

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)

# Mock X-ray pipeline allows us to test observations



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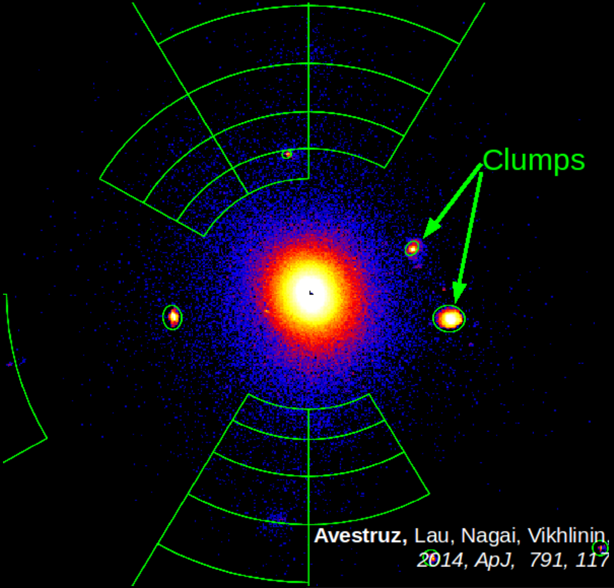

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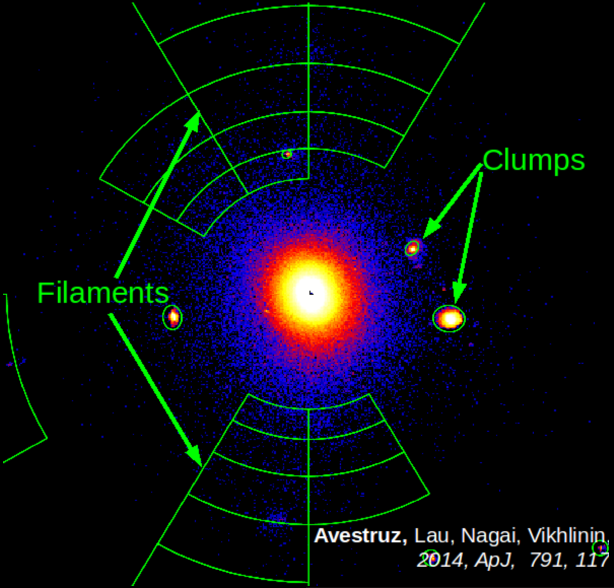

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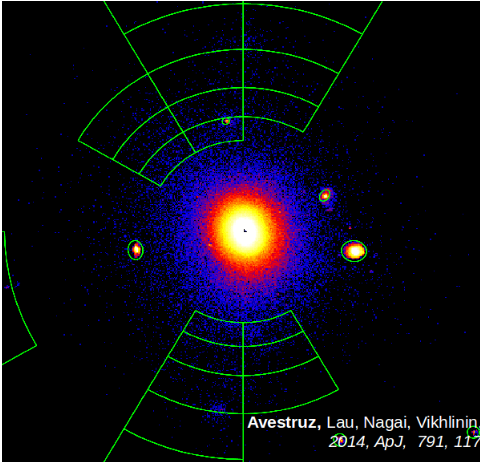


$$XSB = \int dV\, n_e n_p \Lambda(T_X, Z)$$

Photon counts per second

Emission measure:
$EMM = \int n_e n_p \, dl$

Assumed model plasma emissivity

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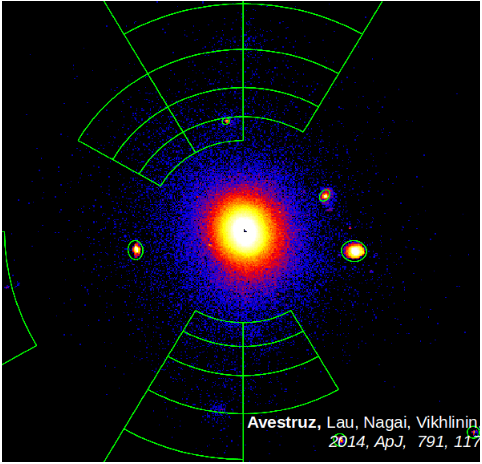


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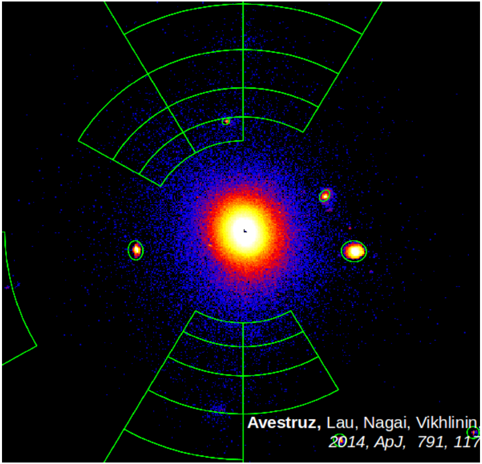


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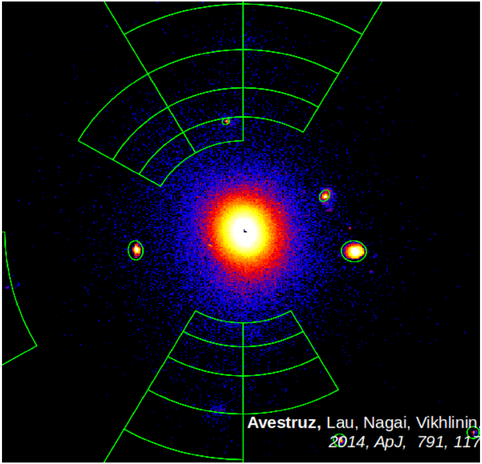


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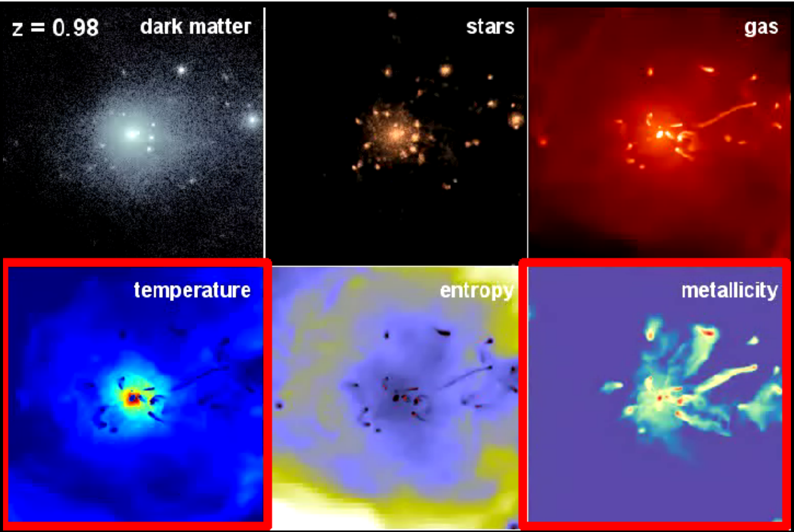
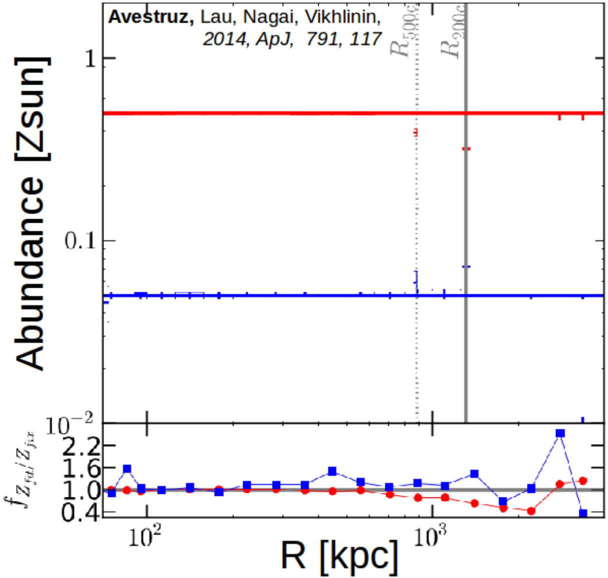


# We can test metal abundance with known input



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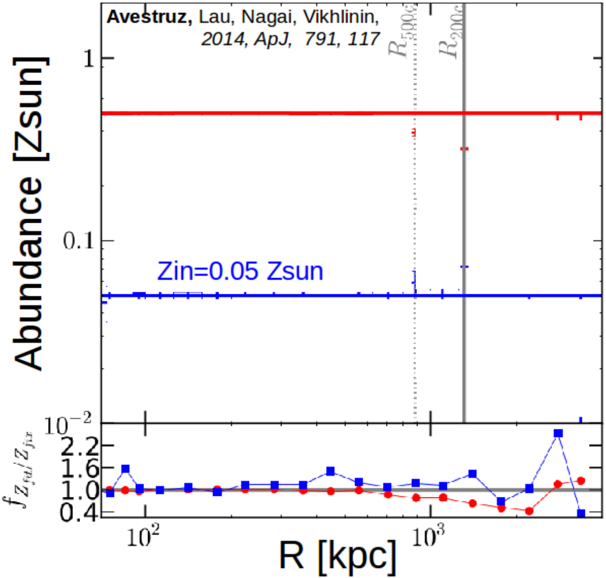

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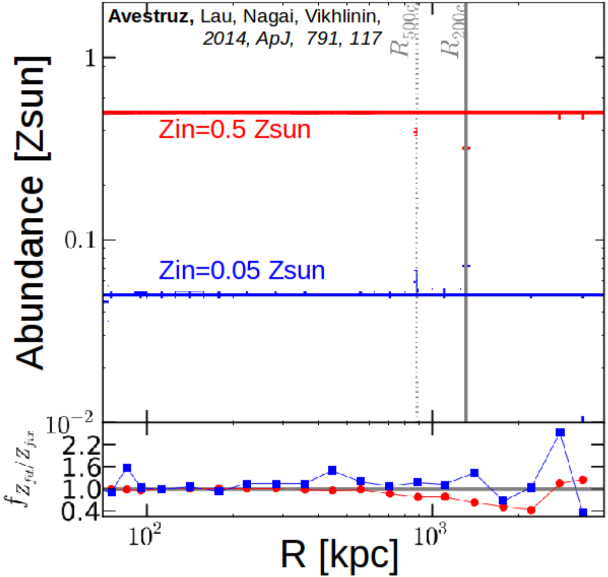
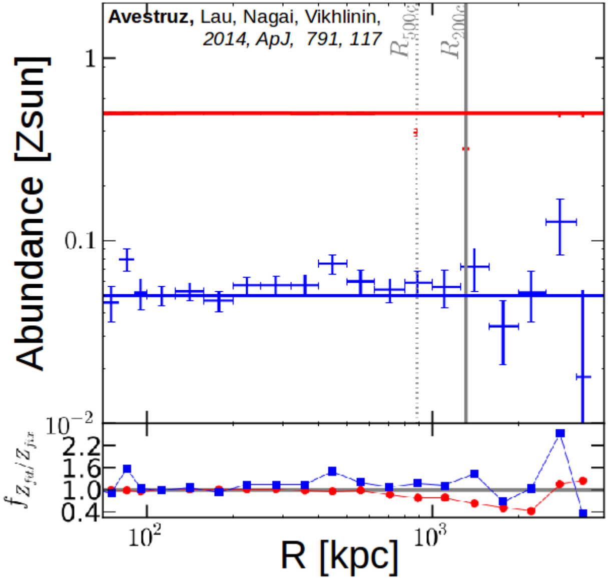
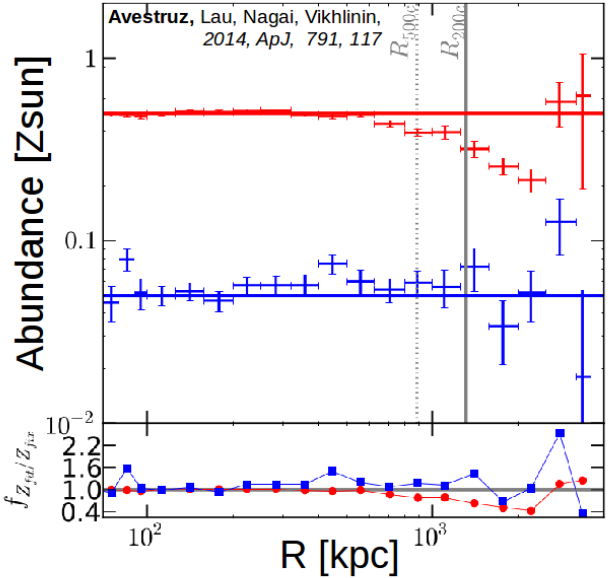


# Weak metal contributions are scattered



# Stronger metal contributions biased low



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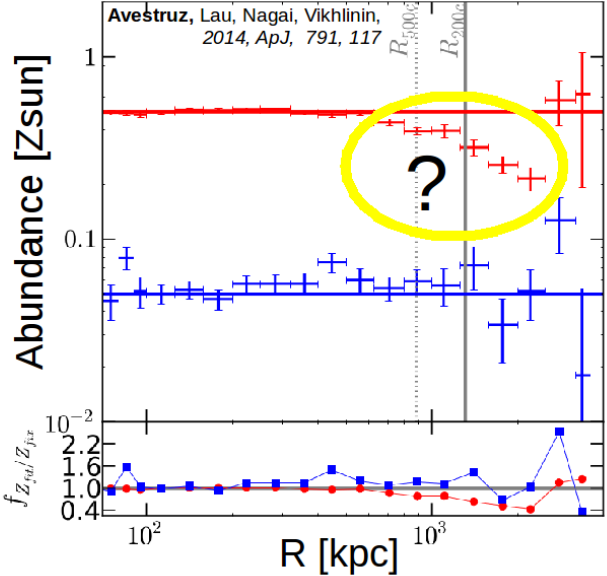

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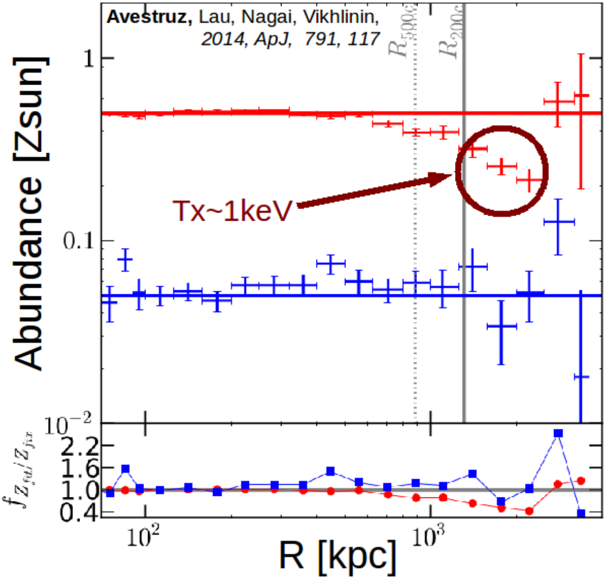
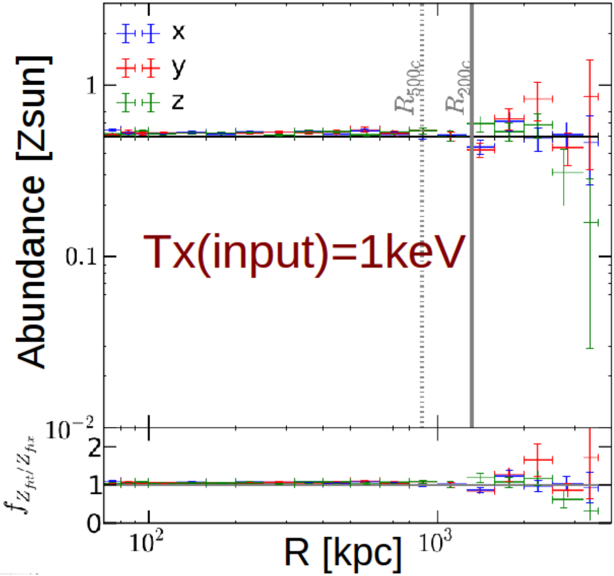
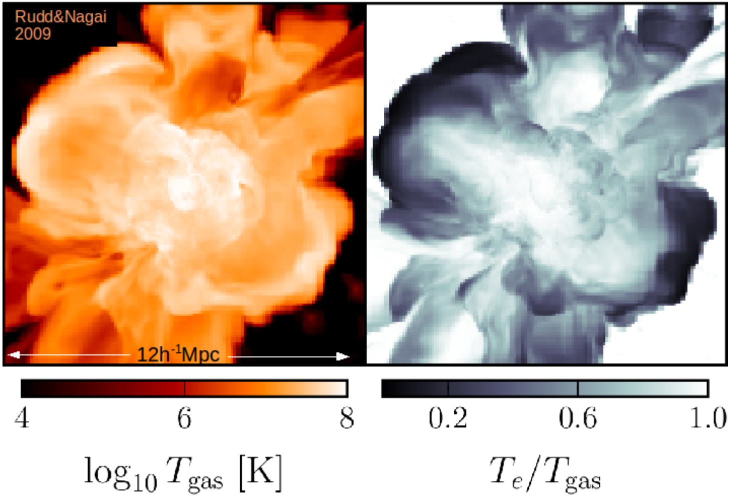


# Bias disappears in single temperature medium



# Non-equilibrium electron temperature biased low



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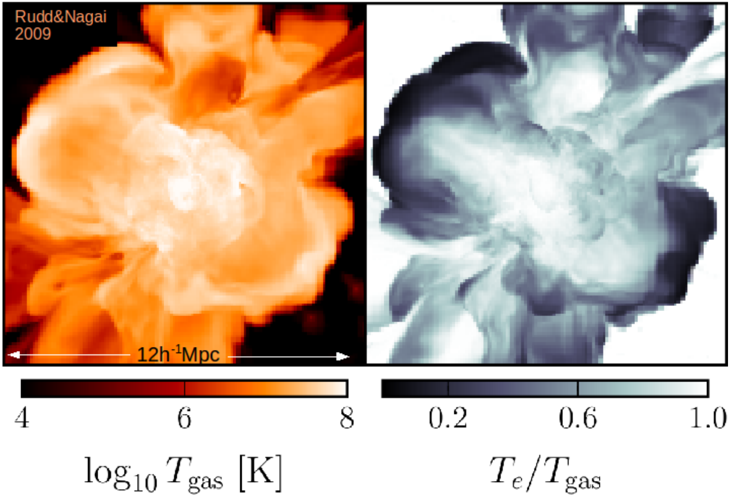


$$t_{ei,Spitzer} = 6.3 \times 10^8 \mathrm{yr} \left(T_e/10^7 K\right) \left(10^{-5} cm^{-3}/n_i\right) \left(40/\ln\Lambda\right)$$

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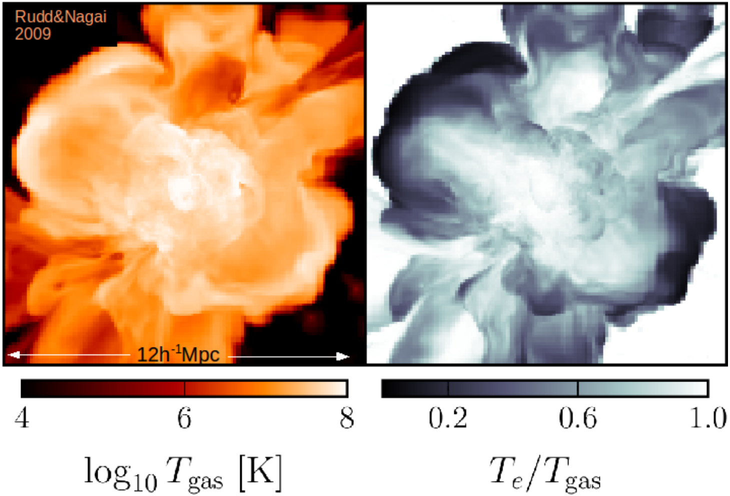


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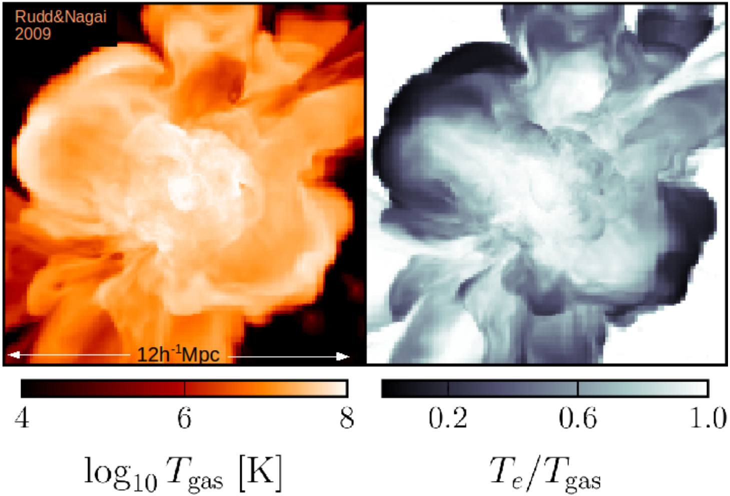


$t_{ei,Spitzer} \rightarrow$ Hubble time

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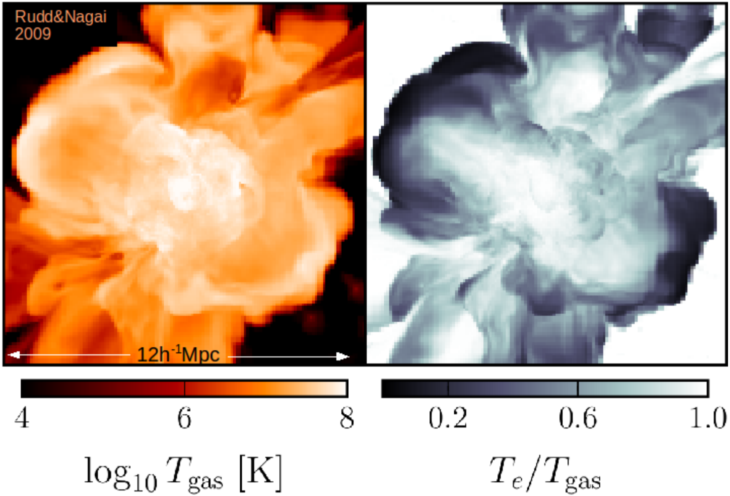
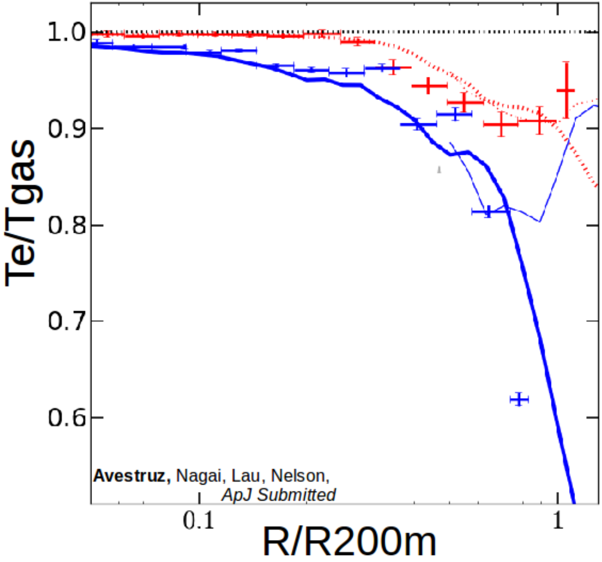



*$t_{ei,Spitzer}$ sets an *upper limit* on the temperature bias

# Non-equilibrium electrons can affect measured $T_X$



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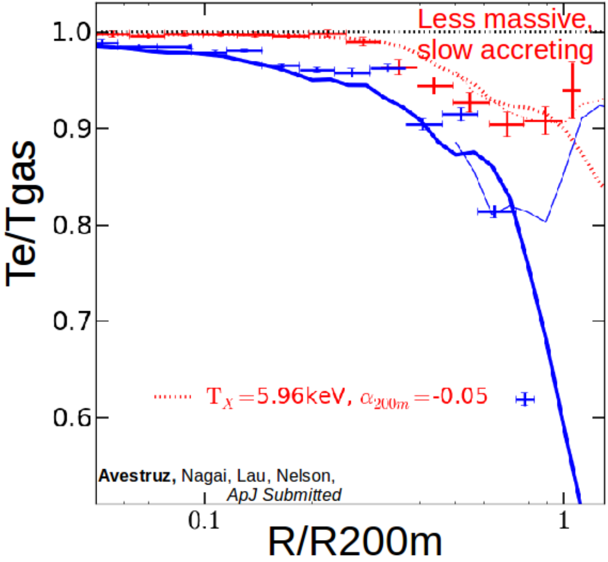

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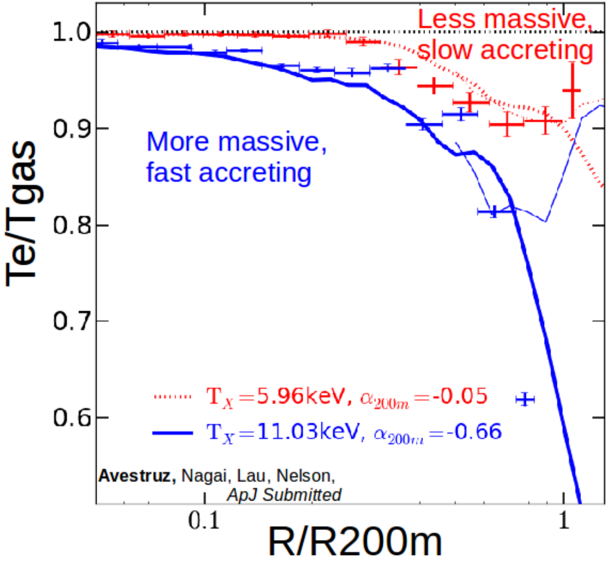

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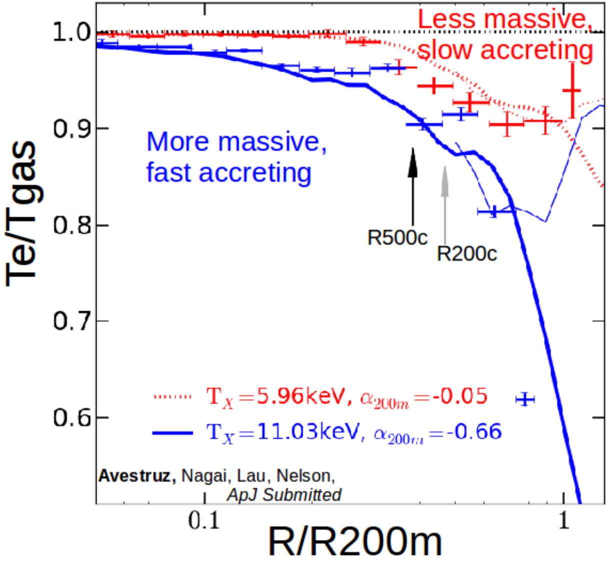
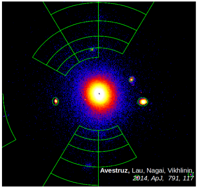
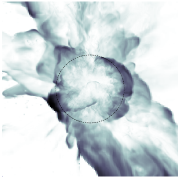


# Summary

1. Inhomogeneities in the intracluster medium contribute to observational biases

2. Non-equilibrium electrons are a potential source of systematic uncertainties



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