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PROPERTIES OF GALAXY CLUSTERS IN THE HYDRODYNAMICAL N-BODY SIMULATIONS

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NERSC

SZX HUNTSVILLE 2011

Cosmology with X-ray and Sunyaev-Zeldovich Effect Observations of Galaxy Clusters

HUNTSVILLE, AL - SEPT. 19 - 22, 2011

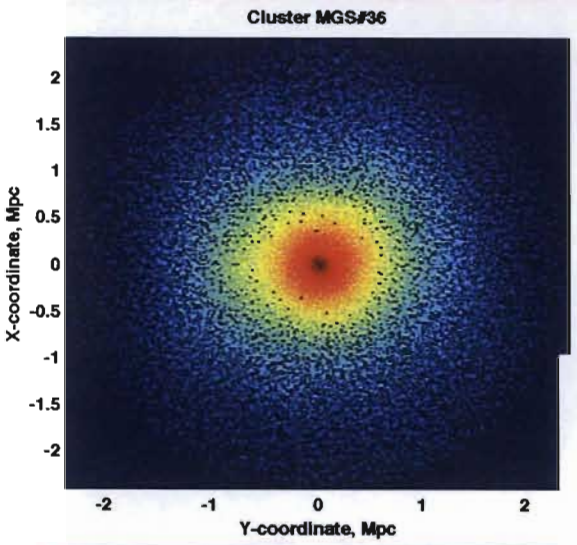
Clusters of galaxies are the largest gravitationally bound structures in the Universe. They include from several dozens to as many as a few thousands of galaxies, and reveal themselves as the most luminous sources in optical, X-ray, and SZ observations. Mass function of the clusters and its evolution is a sensitive probe of large-scale structure formation and evolution in the Universe and can be used to measure cosmological parameters such as Ω_m, normalization and spectrum of primordial density fluctuations, non-Gaussianity and growth parameters. Determination of the parameters with the clusters is important, because it is independent from other methods, like CMB and supernovae studies, and provide orthogonal contours. This however requires reliable and precise modeling for a quantitative description of the non-linear hierarchical growth of the clusters. Present state of the art modeling is achieved in hydrodynamical numerical simulations.

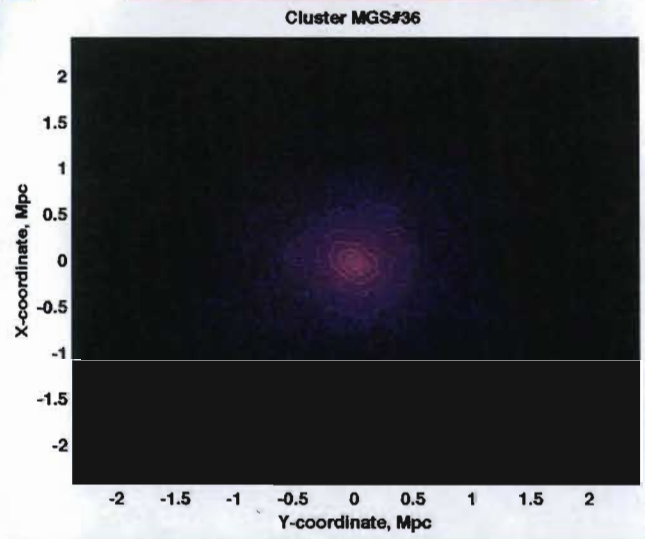
Simulations

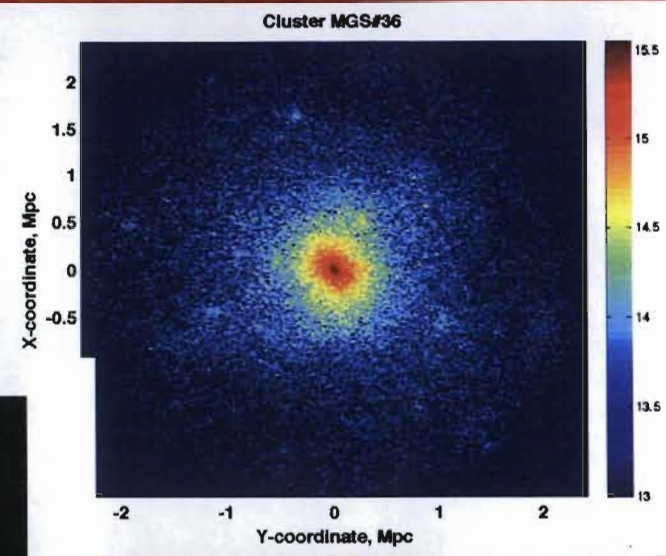
The Millennium Gas Simulation is a resimulation of the original Millennium, a high-resolution, dark-matter-only simulation of a $500h^{-1}$ Mpc volume. The simulations were run with GADGET-2, treating the gas dynamics with smoothed particle hydrodynamics (SPH). The MGS use the initial conditions of the Millennium simulation, with $5 * 10^8$ dark matter particles, each of mass $1.42 * 10^{10}\, h^{-1}\, M_\odot$, and $5 * 10^8$ SPH gas particles, each of mass $3.12 * 10^9\, h^{-1}\, M_\odot$, resulting in a mass resolution about 20 times coarser than the original Millennium N-body simulation. The gravitational softening length is $25h^{-1}$ kpc. The cosmological parameters match the original: $\Omega_m = 1 - \Omega_\Lambda = 0.25$, $\Omega_b = 0.045$, $h = 0.73$, and $\sigma_8 = 0.9$. While some differences between the simulations are expected due to the difference in mass resolution and gravitational softening length, verify the positions of dark matter halos to within $50h^{-1}$ kpc between the original Millennium and the MGS. The value of σ_8 is higher than the currently favored value, but we do not expect it to affect the results of this study.

References: Springel, V. et al. 2005, Nature, 435, 629 (Millenium); Springel, V. 2005, MNRAS, 364, 1105 (GADGET-2); Hartley at el. 2008, MNRAS, 386, 2015 (MGS); Stanek et al. 2010, Astrophysical Journal, 715, 1508 (MGS)

CLUSTER TYPES: RELAXED

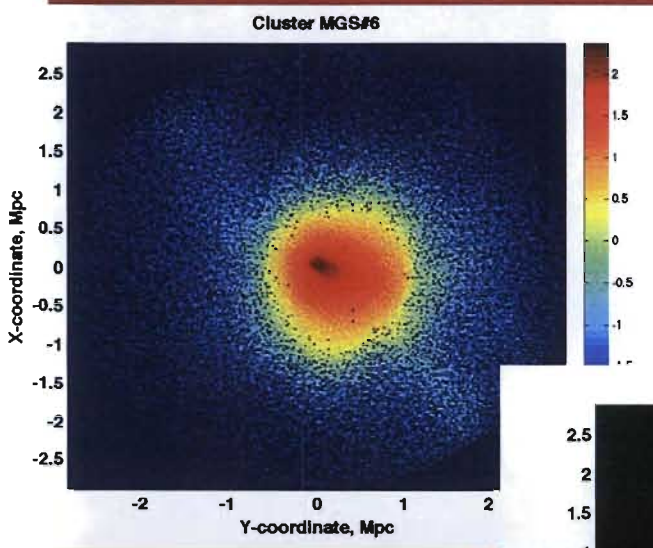


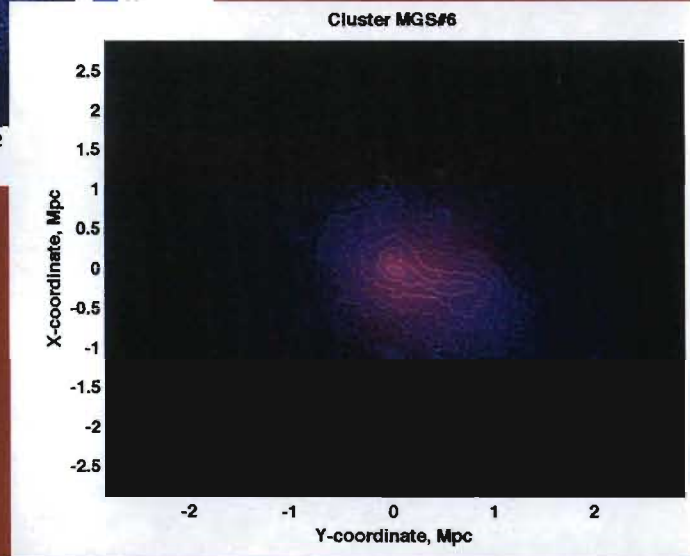


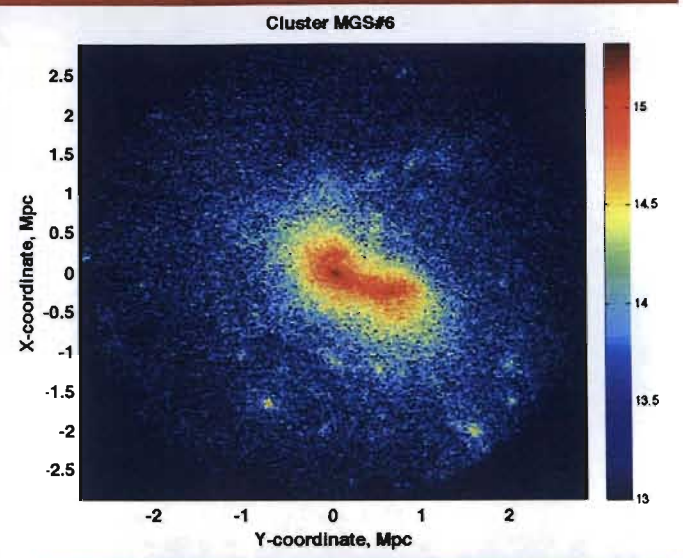


Example of a relaxed cluster from MGS catalog. Both X-ray emission (left panel) and dark matter distribution (right panel) are strongly peaked at the center and spherically symmetric. False colors represent projected integral of gas emissivity and projected mass correspondingly, both in logarithmic scale. Middle panel is the composition of X-ray emission (red) and dark matter (blue) with color intensity representing strength of the signal.

CLUSTER TYPES: MERGERS

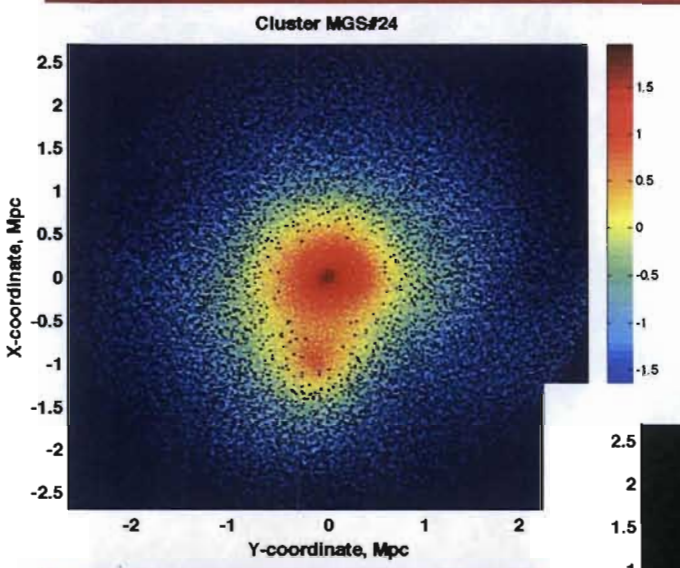


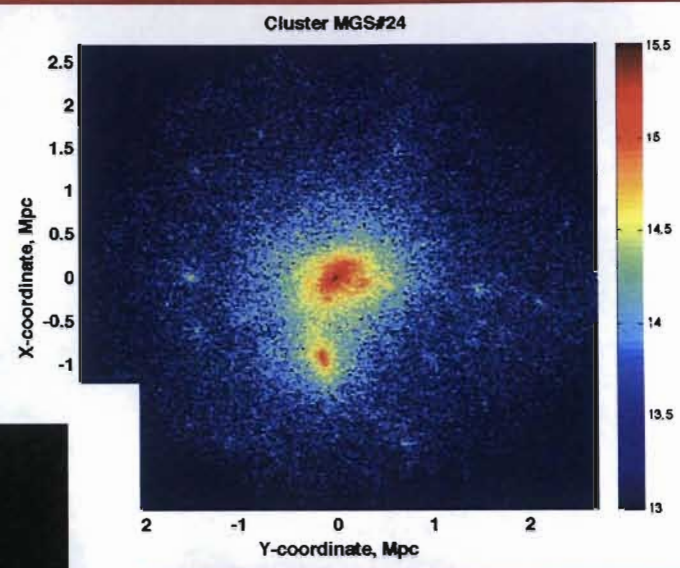


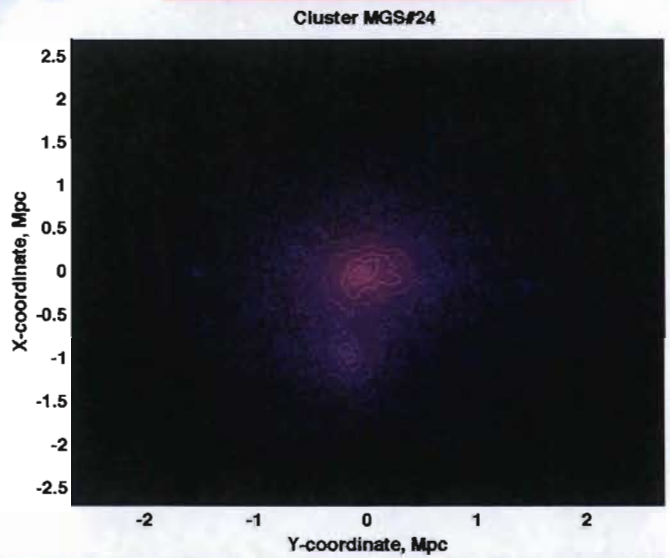


Example of a merging cluster from MGS catalog. Gas emission distribution (left panel) is distinctly different from dark matter distribution (right panel). Shock fronts are clearly seen in the combined image (middle panel).

CLUSTER TYPES: PRE-MERGERS





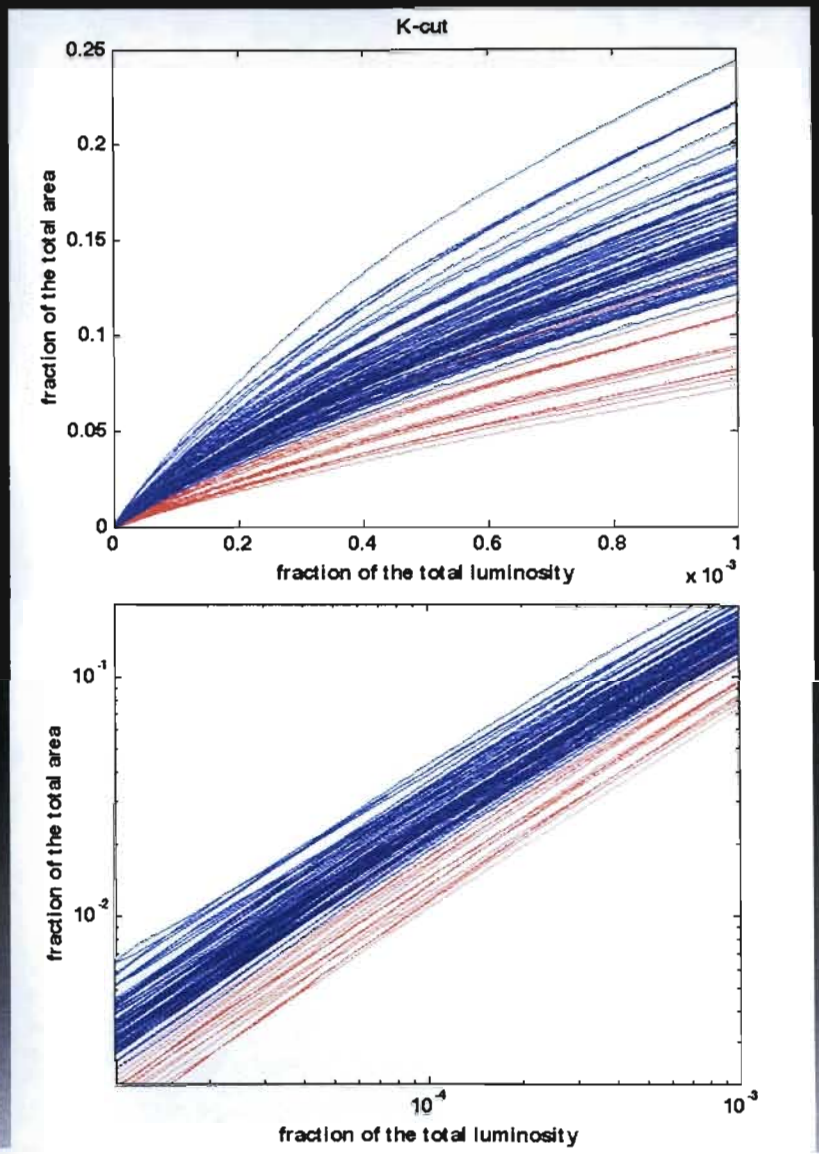


Example of a pre-merger from MGS catalog. Both thermal gas emission (left panel) and dark matter distribution (right panel) display significant substructures with the same general morphology.

MORPHOLOGICAL CLASSIFICATION WITH QUANTILES

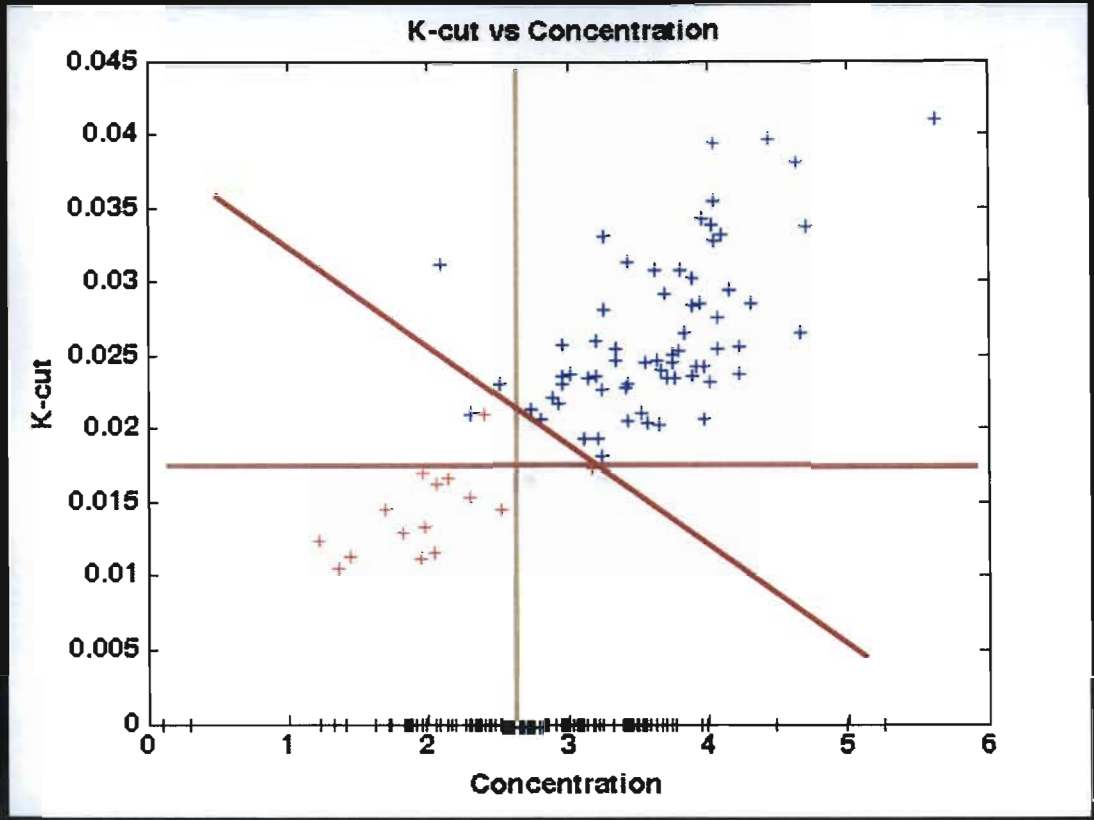
Emission of relaxed clusters (blue) is strongly peaked, so their small central area contributes more to the total luminosity of the cluster in comparison to mergers (red).

The function value at area fraction 10^{-4} provides an optimal discrimination between relaxed and merging clusters.



QUANTILES AND CONCENTRATION PARAMETER

Concentration parameter is widely used to characterize the dynamical state of a cluster. Relaxed clusters have in general higher concentration. Our K-cut parameter based on quantiles is correlated with concentration parameter and provides even better separation for our sample.

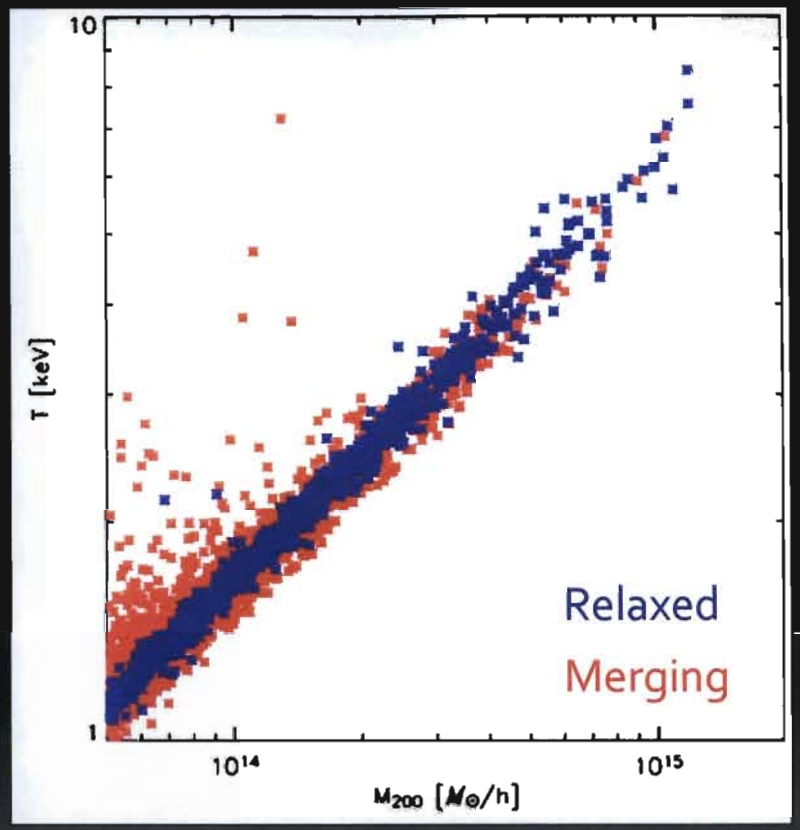


$$\rho(r) = \frac{\delta_c \, \rho_c}{(r/r_s)(1 + r/r_s)^2}$$

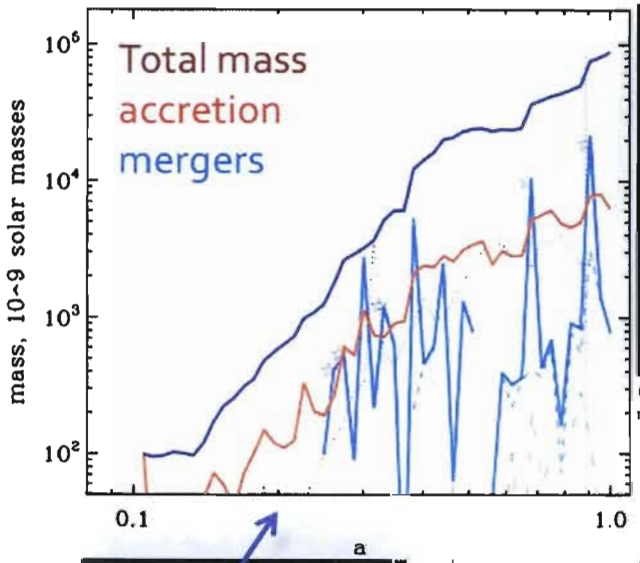
Navarro, Frenk, White, Astrophysical Journal v.462, p.563

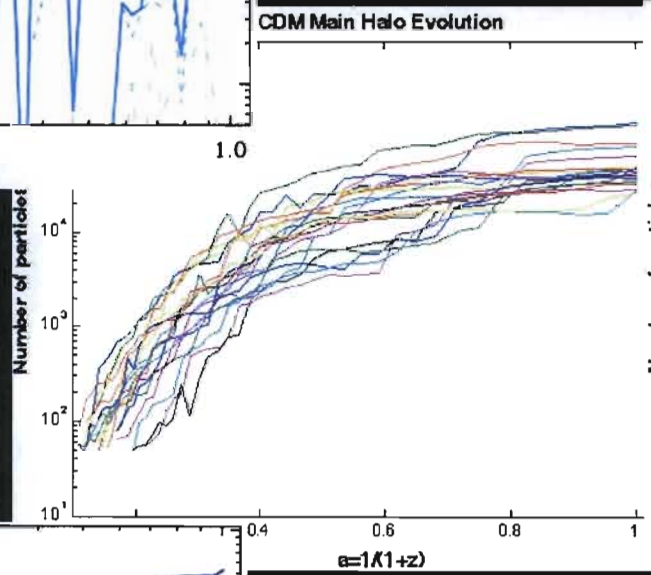
TACKLING GREATEST UNCERTAINTY

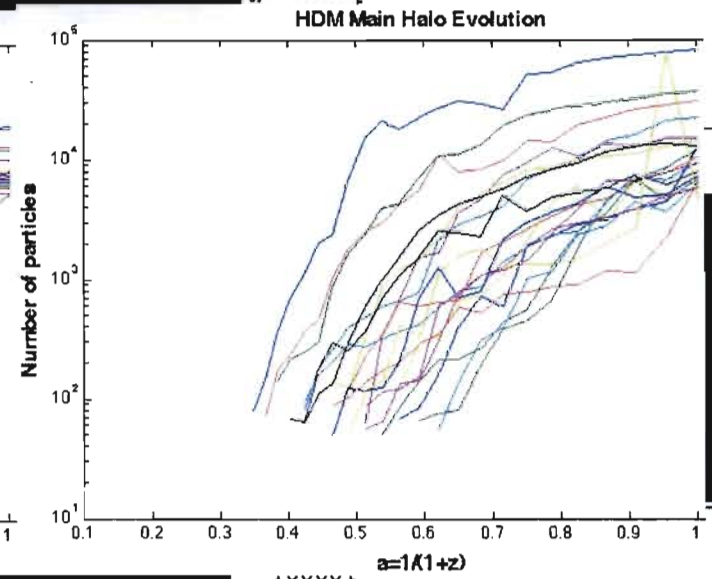
- The biggest obstacle in cluster cosmology is determining cluster masses from observables
- It is important to have accurate description of both mean and scatter in mass-observable scaling relations
- Smaller scatter greatly improves quality of predictions as cluster mass function is exponential
- Selecting clusters into different populations can improve scaling relations
- Work in progress

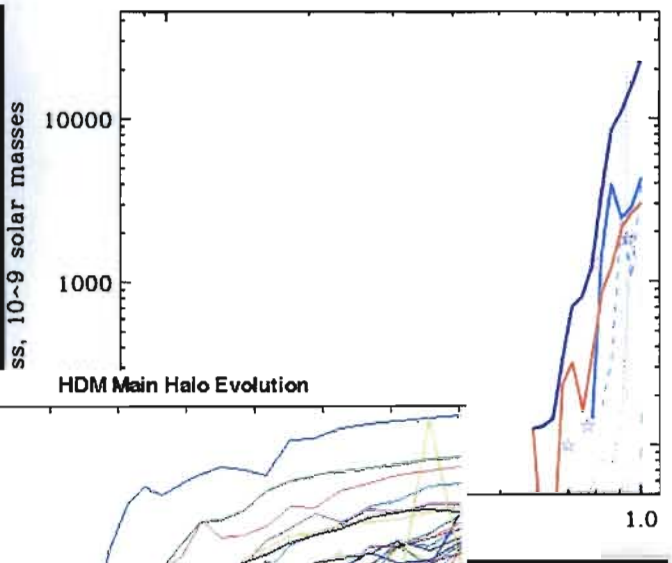


GROWTH OF STRUCTURE IN DIFFERENT COSMOLOGIES

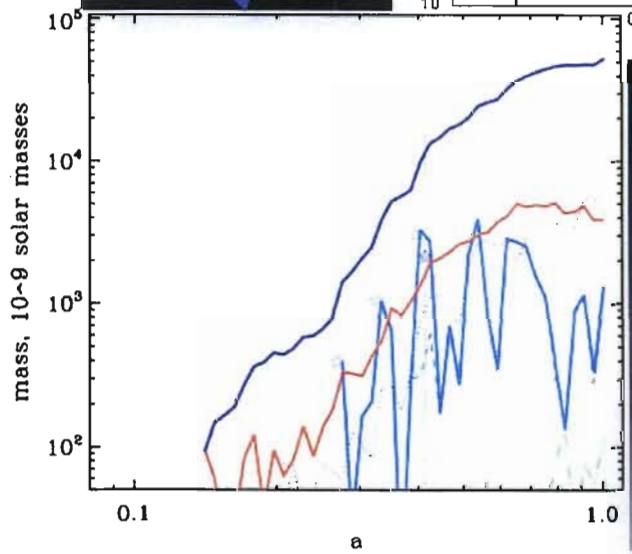




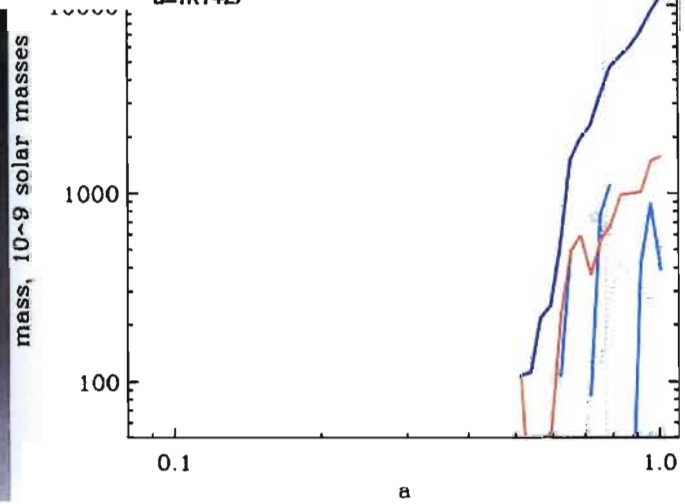




Individual halos

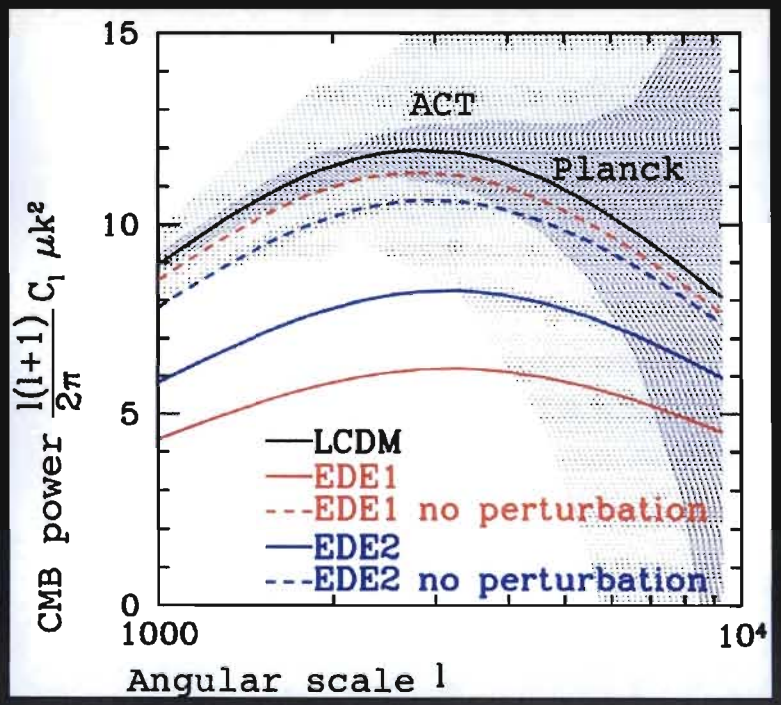


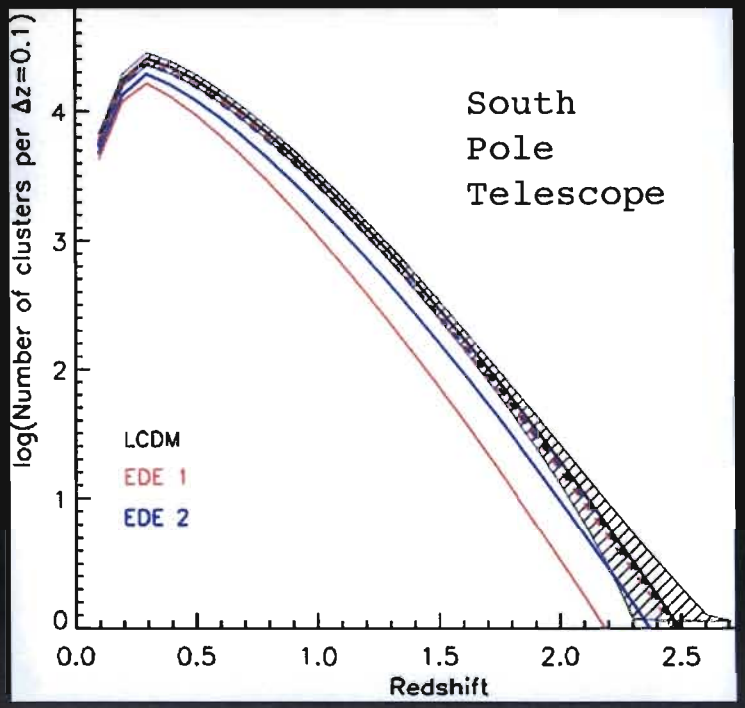
Structure formation process strongly depends on dark matter parameters.
Structure forms much later and grows much faster in hot dark matter simulations



PERTURBATIONS OF DYNAMICAL DARK ENERGY

- If dark energy is not cosmological constant, it will always have perturbations.
- Neglecting them leads to strong biases in estimates of cluster observables.





Alam, Lukić, and Bhattacharya, 2011, Astrophysical Journal, 727, 87

- To account for the perturbations, new approach to simulations is needed

NYX – NEW CODE FOR COSMOLOGY

- Existing cosmological codes solve linear Poisson equation, ignoring DE perturbations; Nyx will solve non-linear Poisson equations and model the perturbations
- Multigrid (MG) solvers will be used to get the accurate solution more effectively (building on the existing adaptive mesh refining structure of the code)
- With MG solvers we will model dynamical DE (scalar fields) and gravity beyond GR
- Petaflop/s capability (>100,000 processors on Hopper [NERSC], and Jaguar [ORNL])
- Hybrid (MPI + OpenMP)
- Main developers: Ann Almgren and Zarija Lukić [LBL], Jens Niemeyer [Göttingen]

Implemented physics:

- Gravity (relaxation MG technique)
- Hydrodynamics (finite volume, compressive CFD)
- Heating and cooling (subgrid modeling)