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STUDYING DARK ENERGY WITH EROSITA

Konstantin Borozdin
Zarija Lukic



NERSC

First eROSITA International Conference

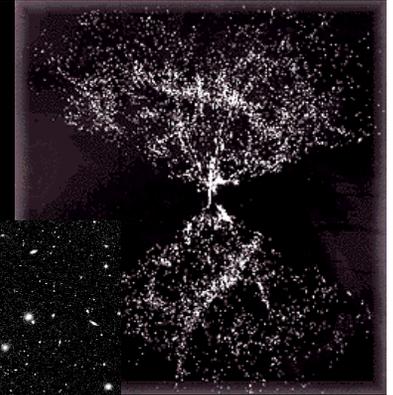
Garmisch-Partenkirchen
17-20 October 2011



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.

MASS HIERARCHY IN THE UNIVERSE

- Clusters: - most massive bound systems in the Universe
 - formed from the largest primordial fluctuations
 - most recently evolved systems



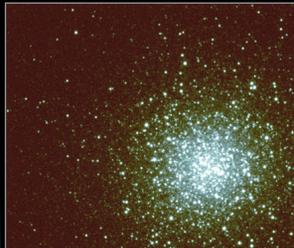
$M \sim 10^{12} - 10^{14} M_{\odot}$



$M \sim 10^{14} - 10^{15} M_{\odot}$



M13 (ヘルクレス座にある球状)

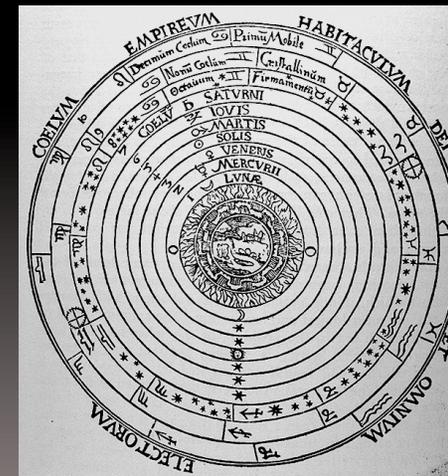


$M \sim 10^9 - 10^{12} M_{\odot}$

Age
Numbers



$\sim 10^4 - 10^6$ stars

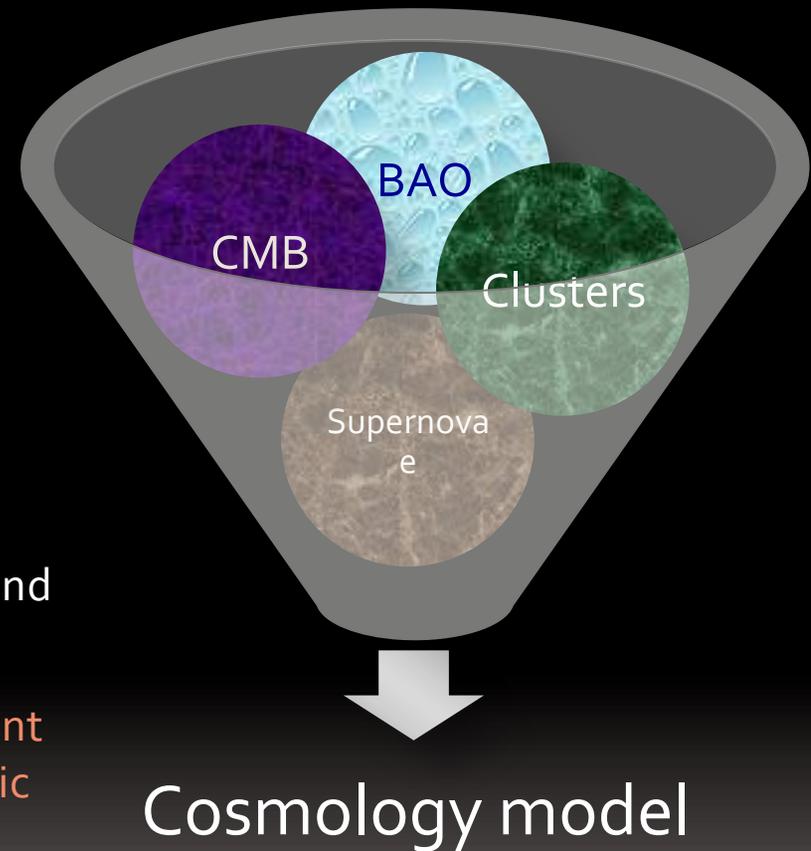


$M \sim 0.1 - 100 M_{\odot}$

Size Mass

GALAXY CLUSTERS – SENSITIVE PROBE OF DARK ENERGY

- Cluster observations directly measure **growth factor**; clusters formation and growth are strongly affected by the cosmic acceleration
- Due to their recent origin, clusters form when DE dominates, making them **exponentially sensitive** to the amount and properties of DE
- Add to **geometrical probes** (CMB, BAO, Supernovae), with different sensitivity and systematics
- **Difficult to extract theoretically important ingredients from observables (systematic errors due to astrophysical factors)**
- **Cosmologically important surveys of clusters have been limited to few hundred of objects**



cluster survey observations

- X-ray (bremsstrahlung from intracluster gas)

- eROSITA on Spectrum-XG satellite

Coverage: Full sky in 0.5 – 5 keV

Launch date: 2013



- SZ effect (secondary anisotropies in microwave sky)

- South Pole Telescope and Atacama Cosmology Telescope



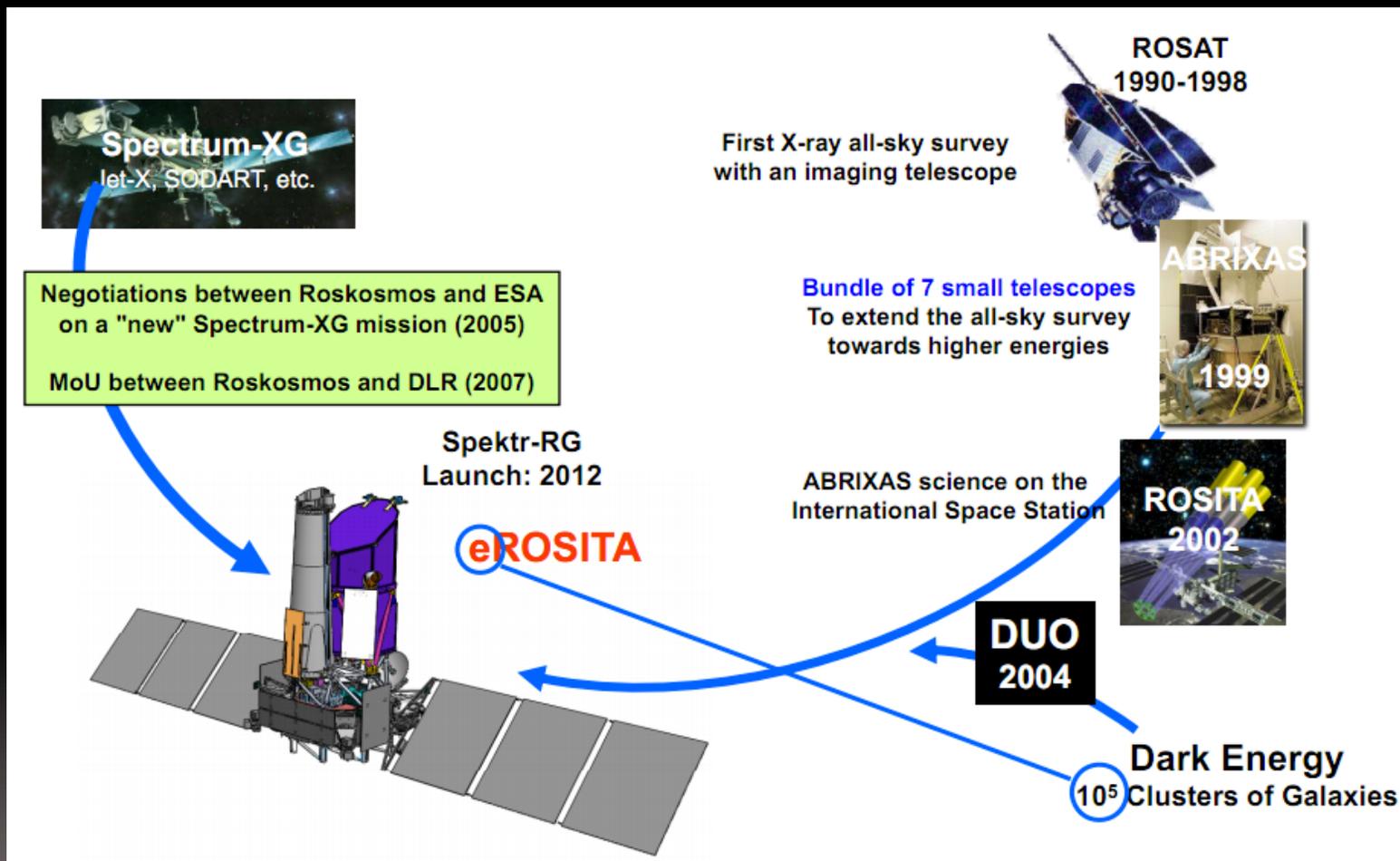
Modeling cluster observations is important to infer cosmological model

Coverage: 4,000 deg²

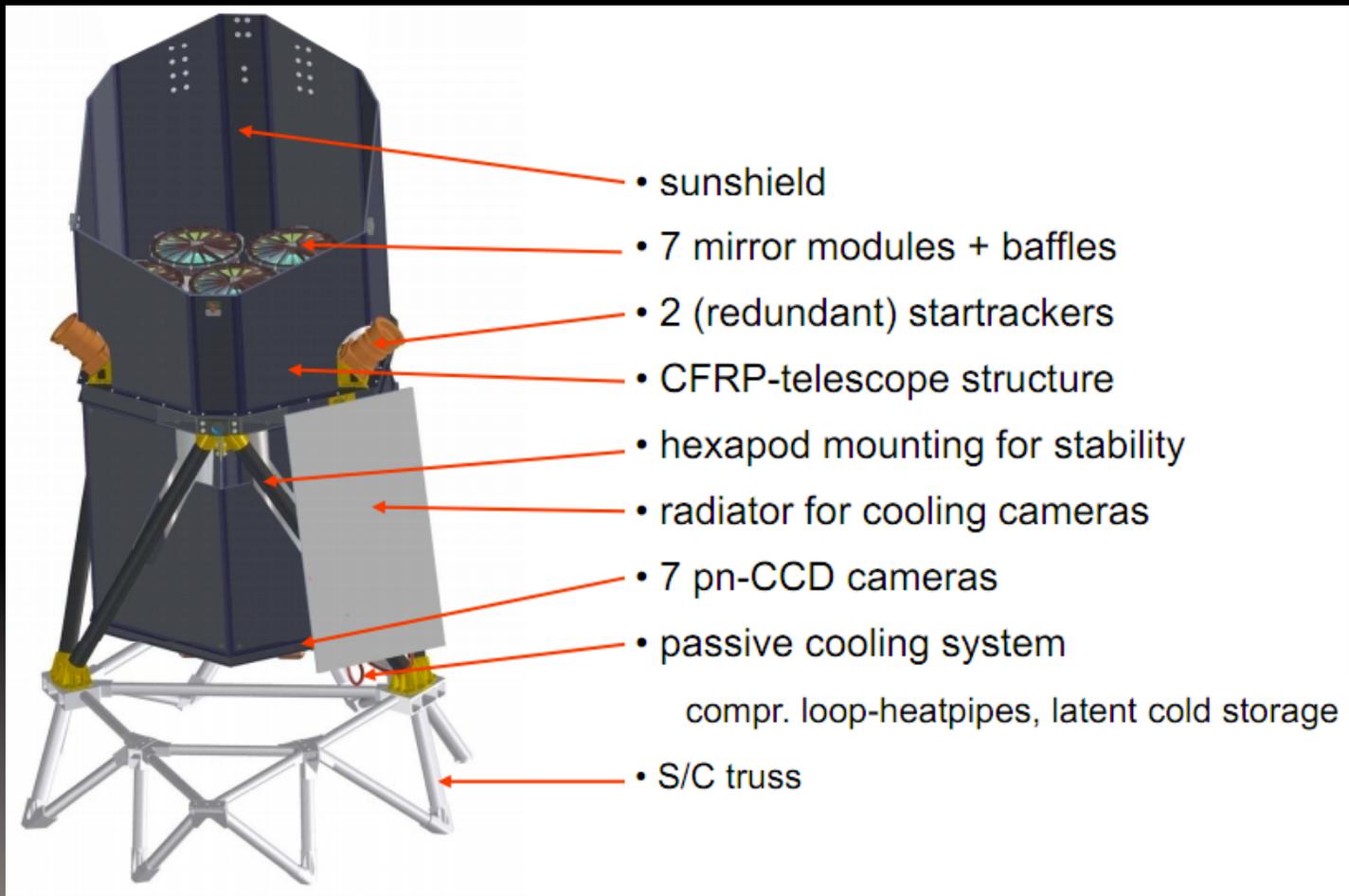
Start date: 2009

- Optical (galaxies)

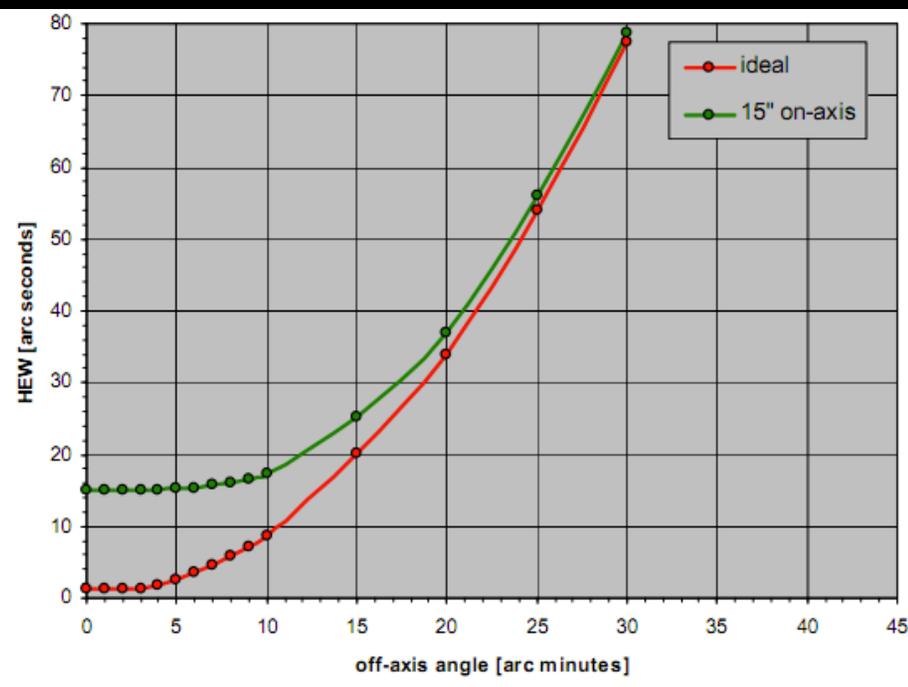
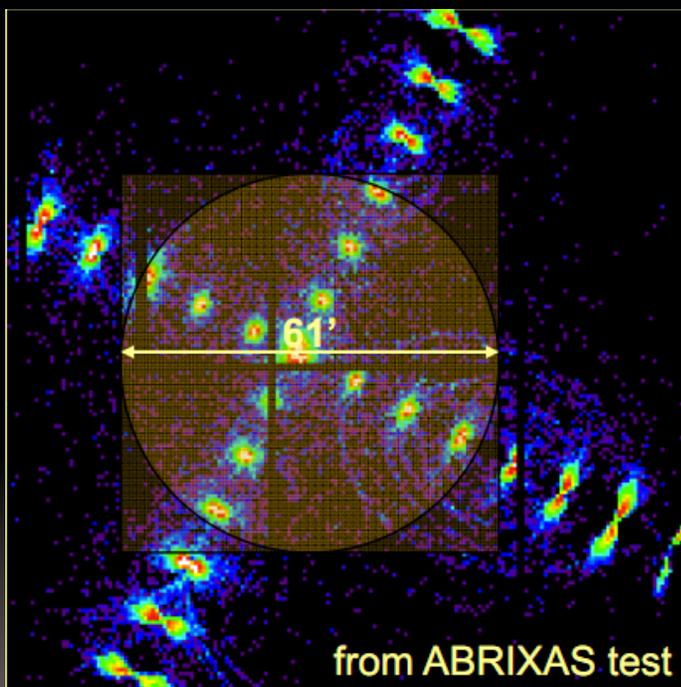
From ROSAT to eROSITA



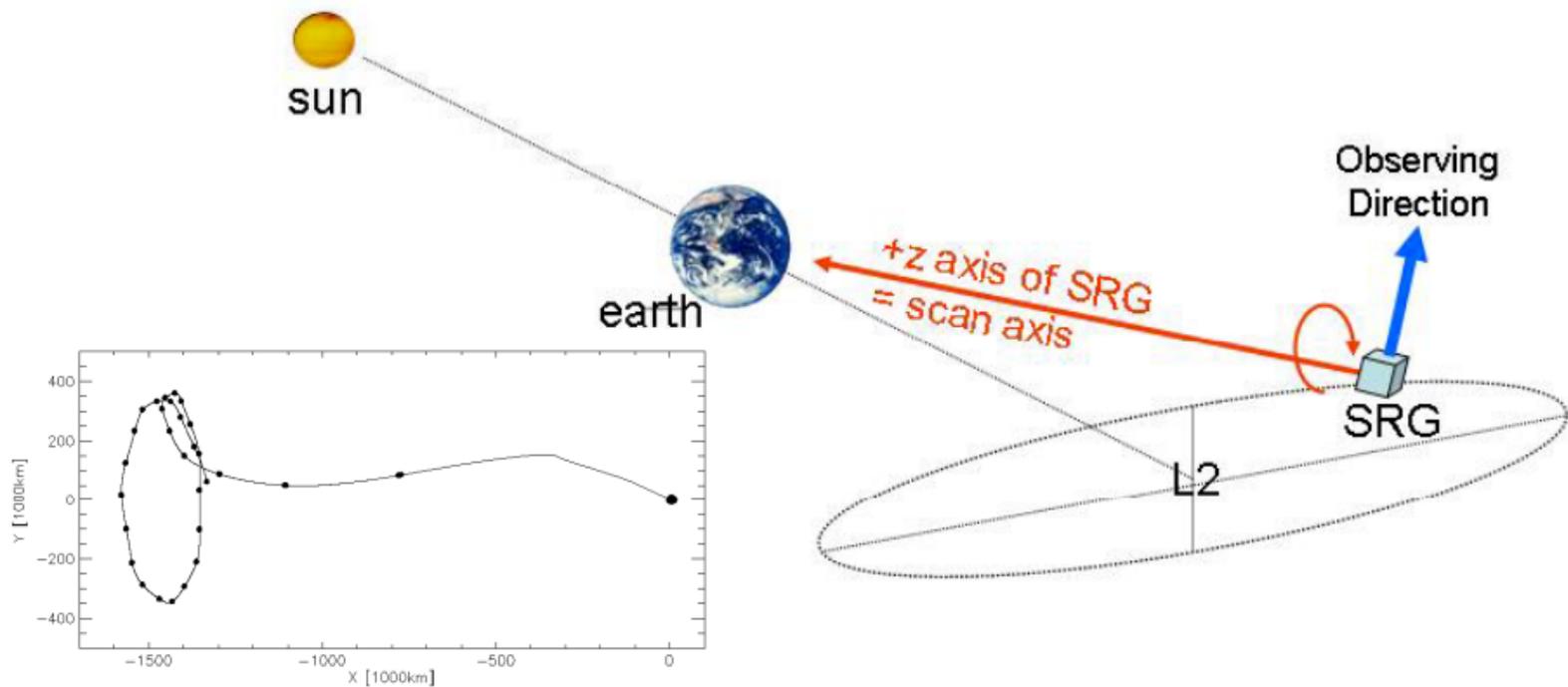
eRosita X-ray Telescopes



Mirrors PSF

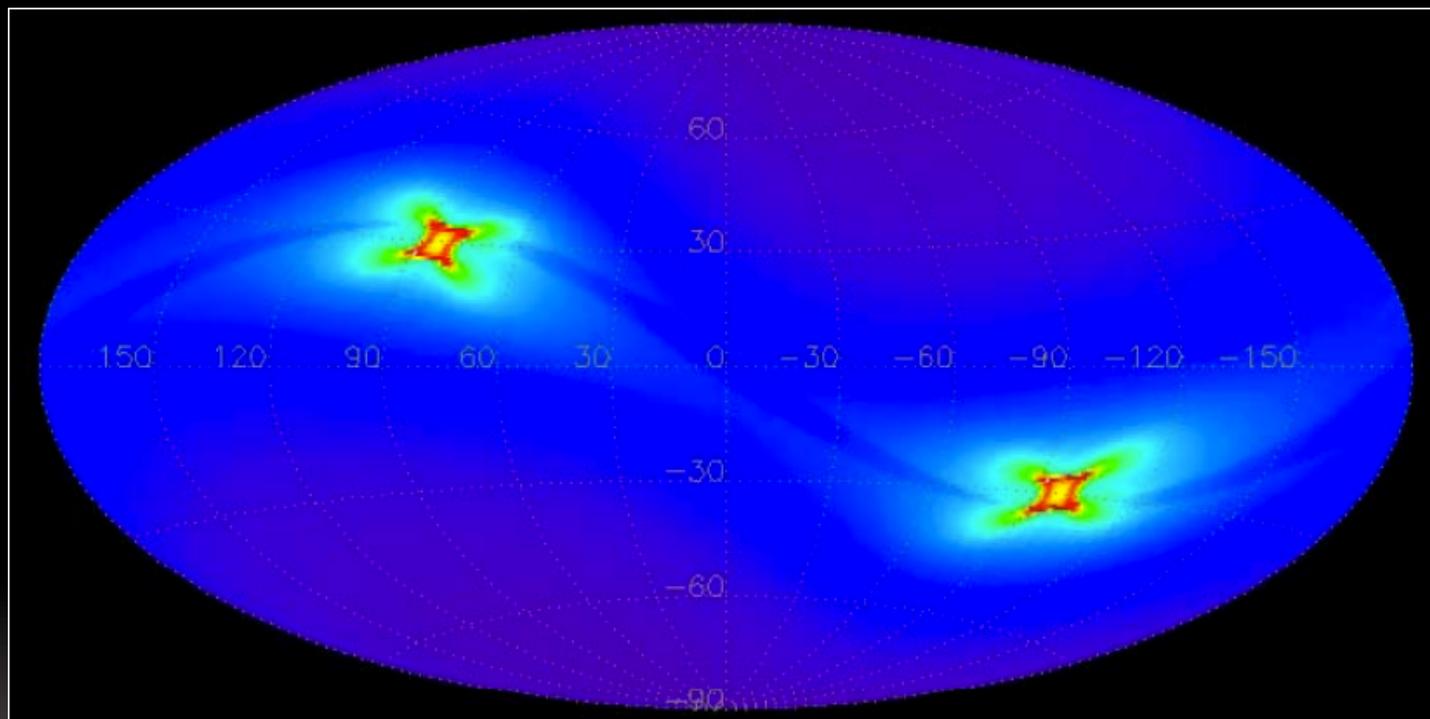


SRG Mission



Angle between sun and Earth max. 13°
Scan-Axis always pointing towards Earth (antenna!)
Scanspeed less than in LEO, $\sim 4\text{h/revolution}$

Sky Exposure



3ksec

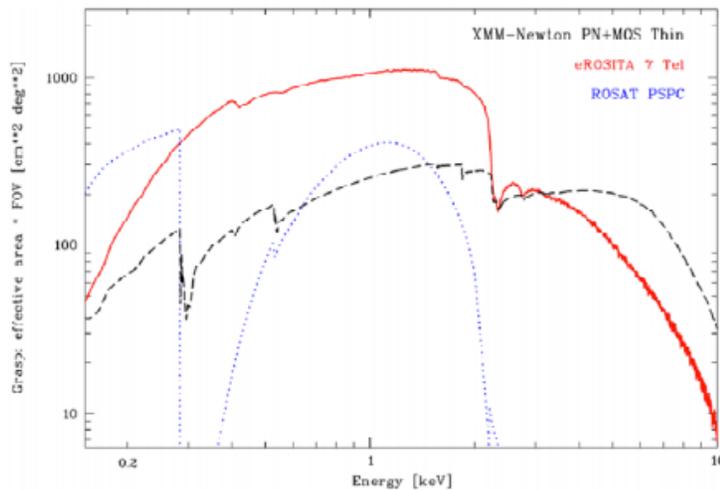
5ksec

30ksec

After 4 years

Survey Sensitivity

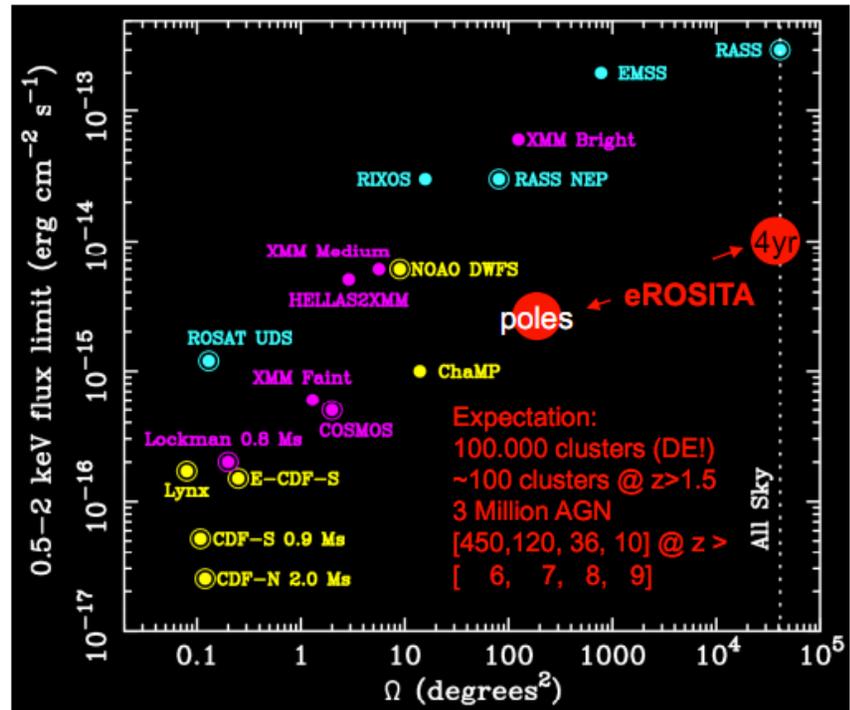
Grasp



7 telescopes, 350 cm² each
large field of view (61 arcmin Ø)

~ 2 × XMM-Newton (MOS+PN)

F/Ω



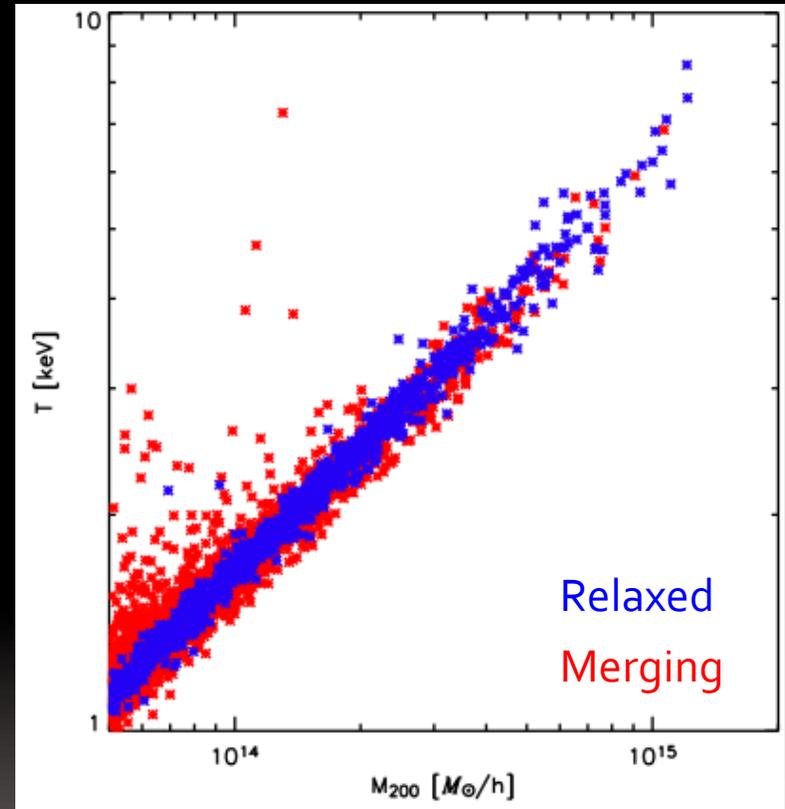
Role of simulations

- Understanding the systematics
- Modeling different cosmologies
- Testing data analysis

- Hydro/DM simulations are needed for X-ray and SZ signals (e.g., Gadget-2, MPA)
- High-resolution dark matter only simulations for weak lensing, optical surveys (e.g., HOT, LANL)

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



MORPHOLOGICAL CLASSIFICATION OF CLUSTERS

with Nick Hengartner, Benoit Thieurmel

Use logistic regression on
“features”
to predict type of cluster:
Relaxed, Pre-merger and Merger

Geometric features:

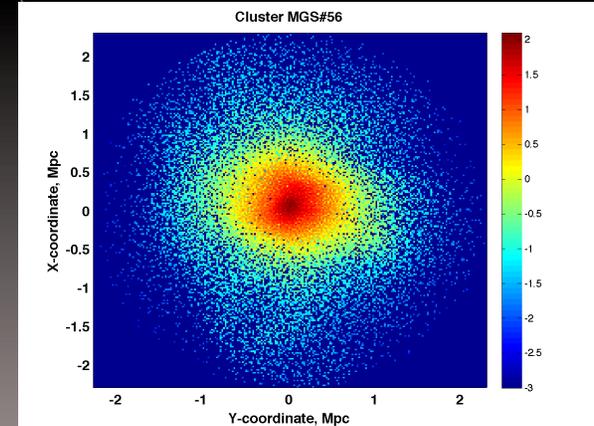
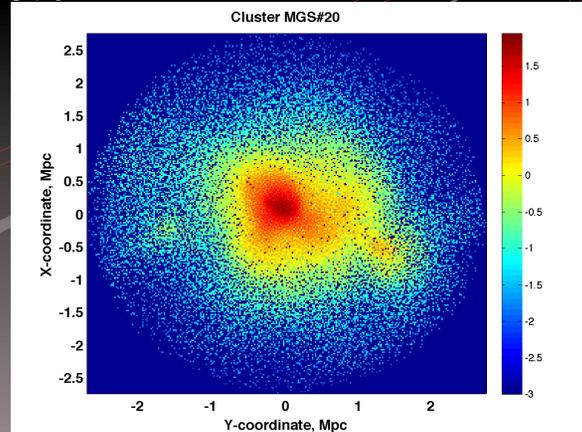
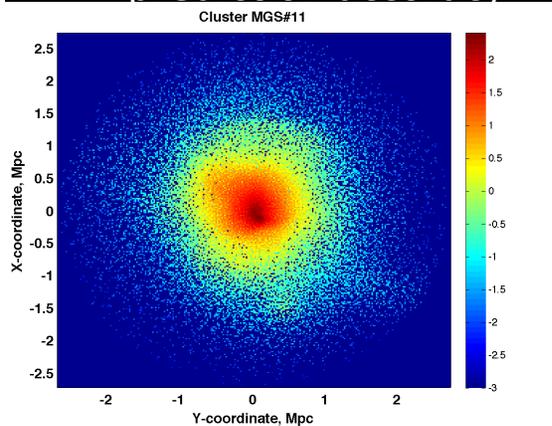
- > Spherical Harmonics
- > Departures from Gaussian
- > Attempt to capture invariances

Result: Out of sample
prediction accuracy ~ 70%

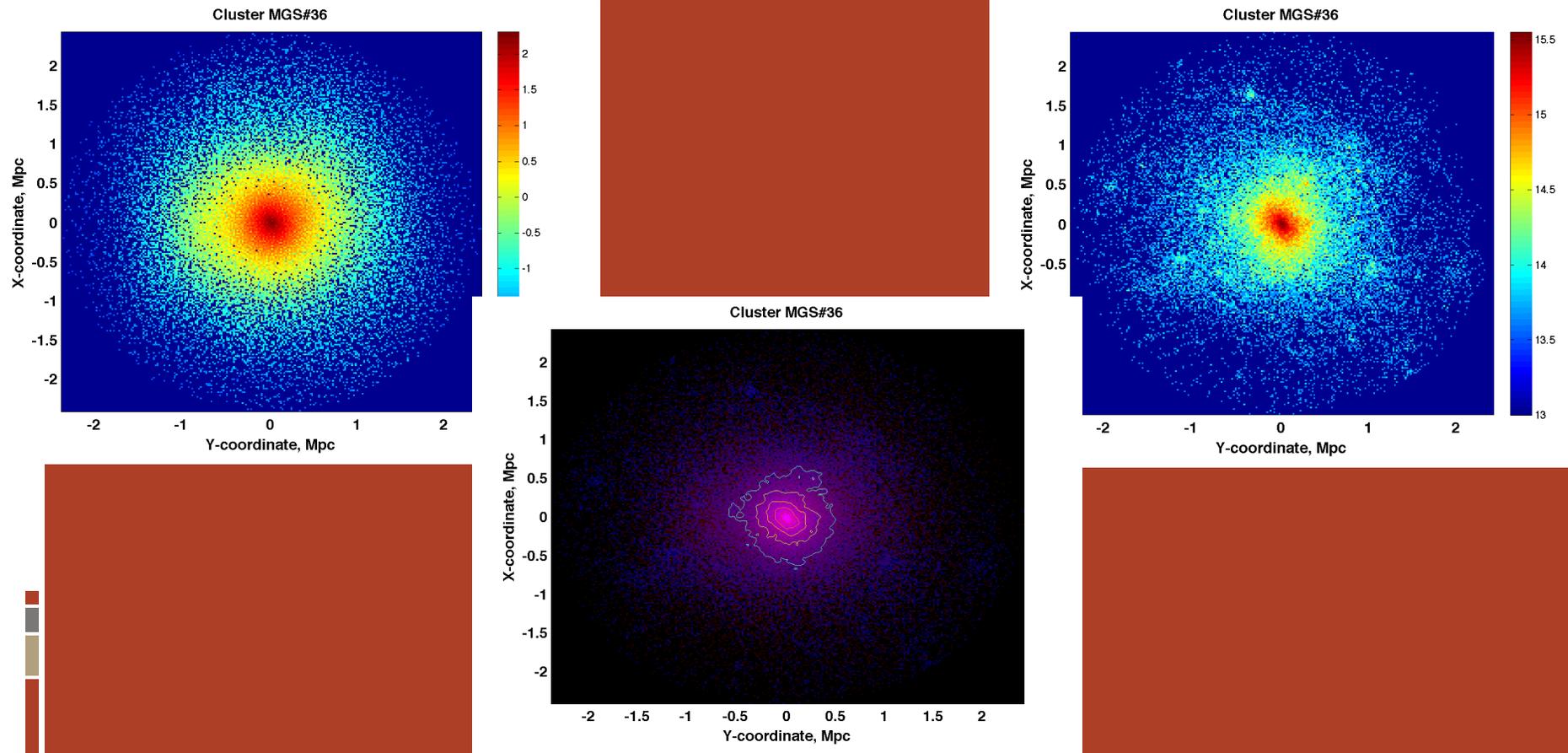
Automatic feature Extraction:

1. Smooth image
2. Extract Level curves (3 to 7)
3. Rotation/scaling using PCA

Result: Out of sample
prediction accuracy 80%

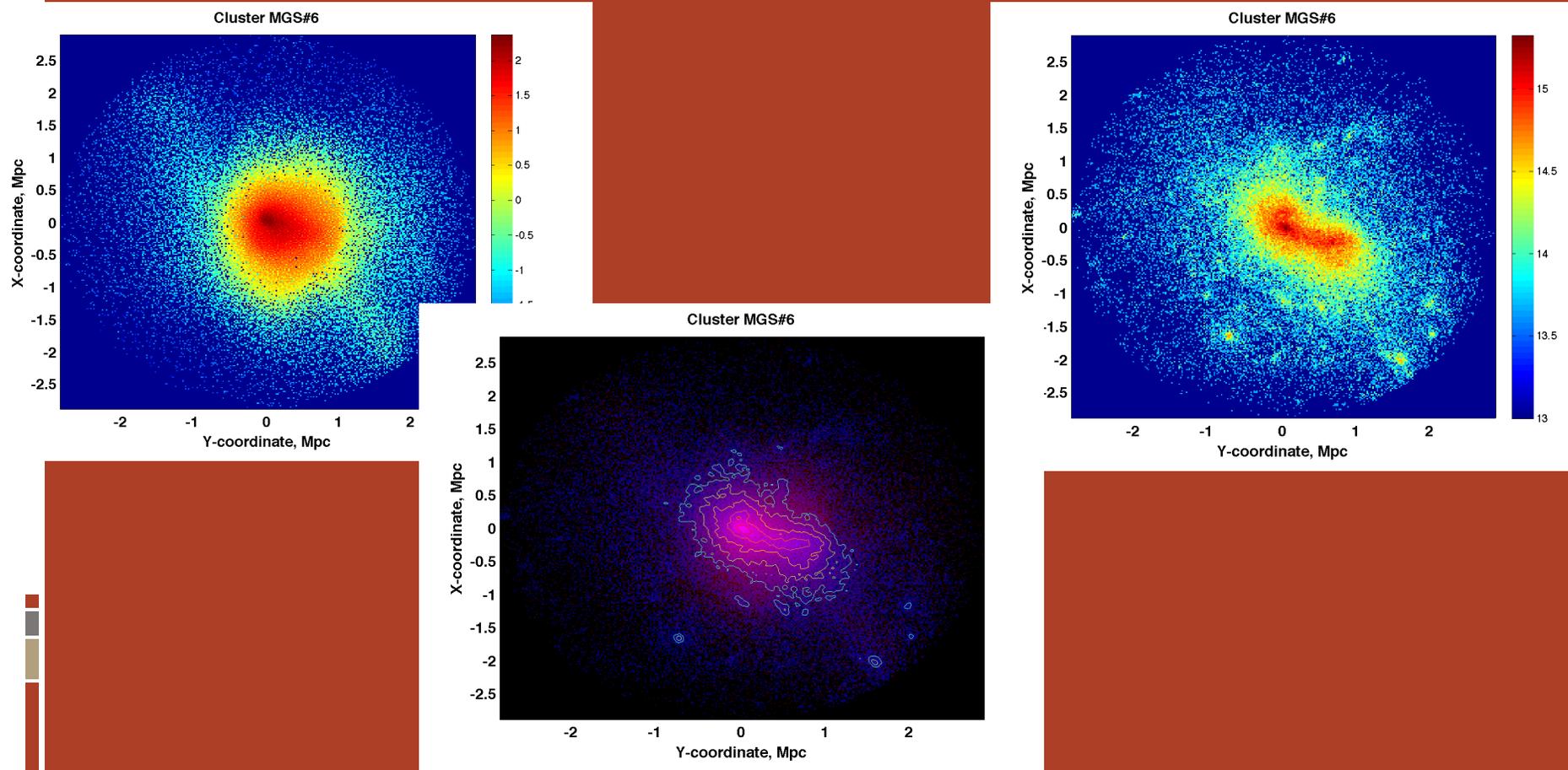


CLUSTER TYPES: RELAXED



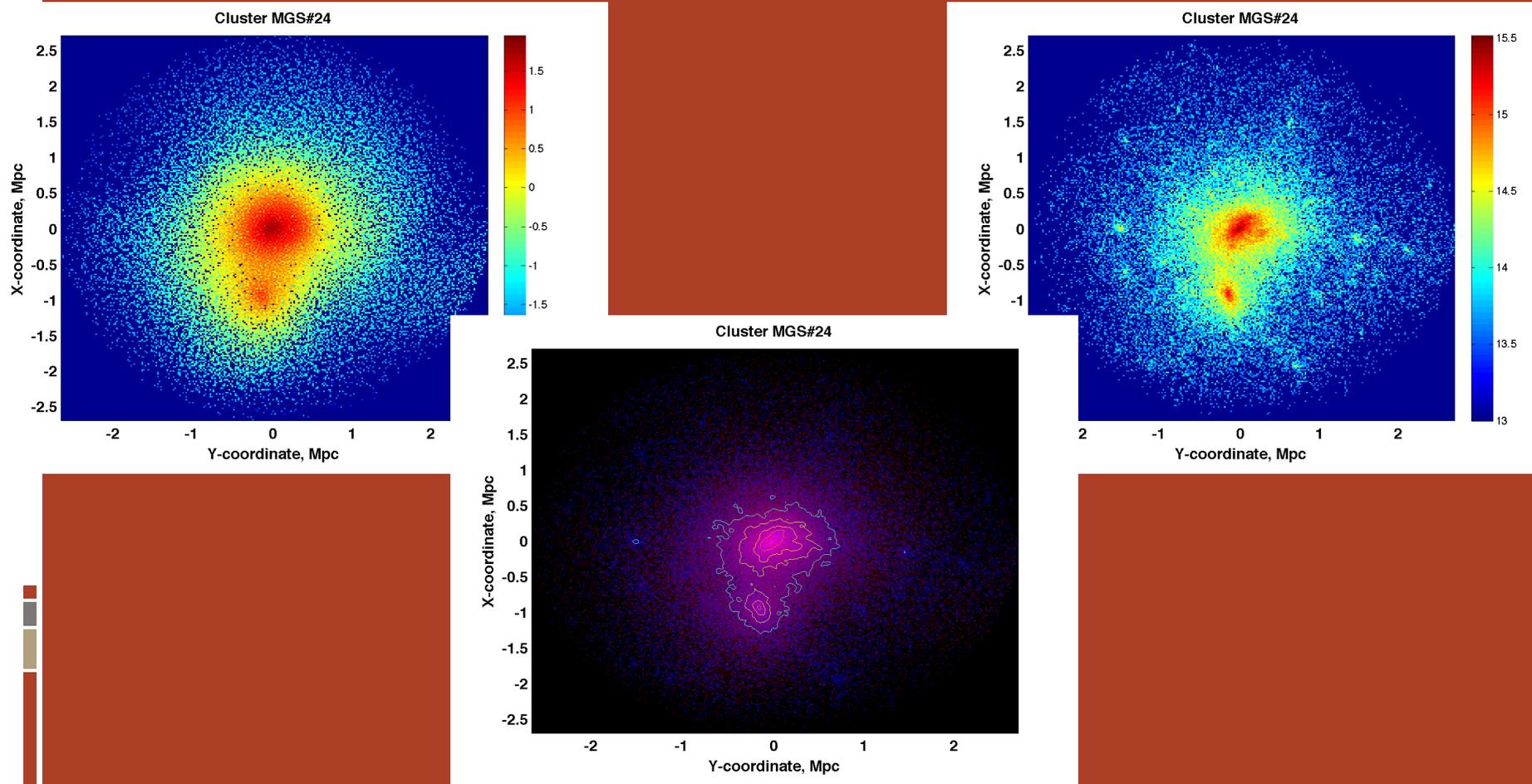
Example of a relaxed cluster from MGS catalog. Both X-ray emission (left panel) and dark matter distribution (right panel) are strongly peaked at the center and spherically symmetric. False colors represent projected integral of gas emissivity and projected mass correspondingly, both in logarithmic scale.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

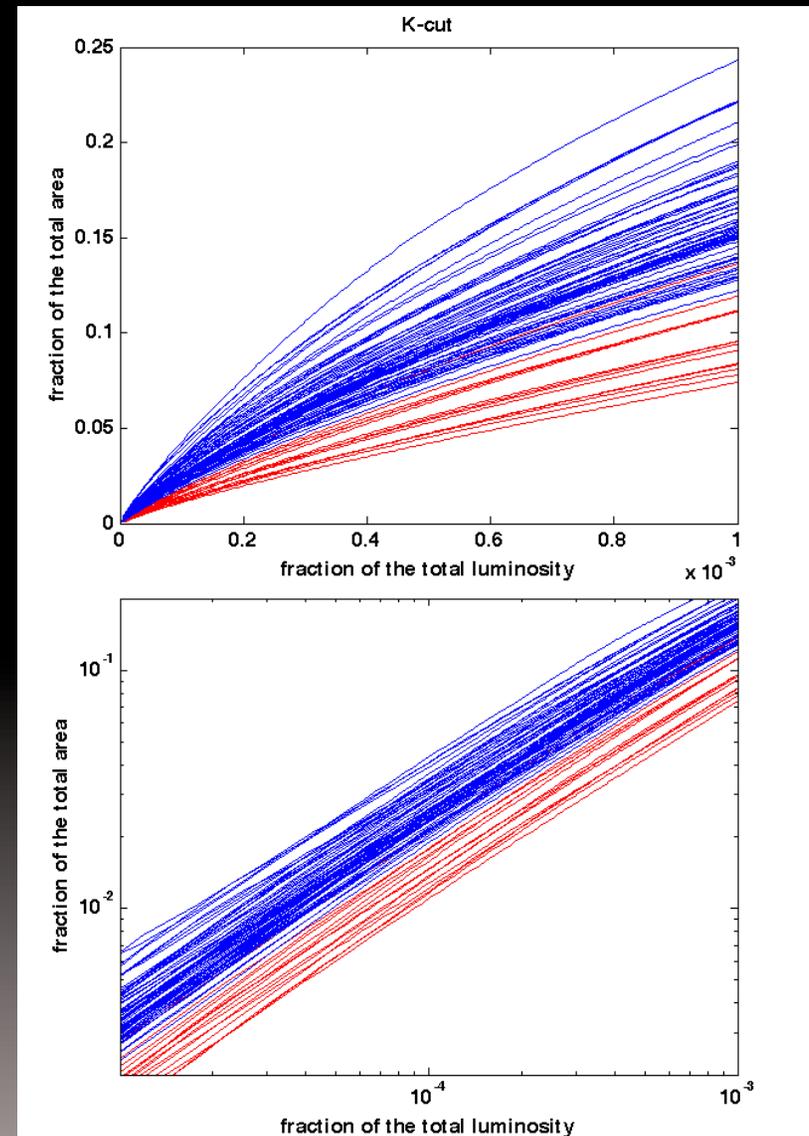


Example of a pre-merger from MGS catalog. Both thermal gas emission (left panel) and dark matter distribution (right panel) display significant substructures with the same general morphology.

MORPHOLOGICAL CLASSIFICATION WITH QUANTILES

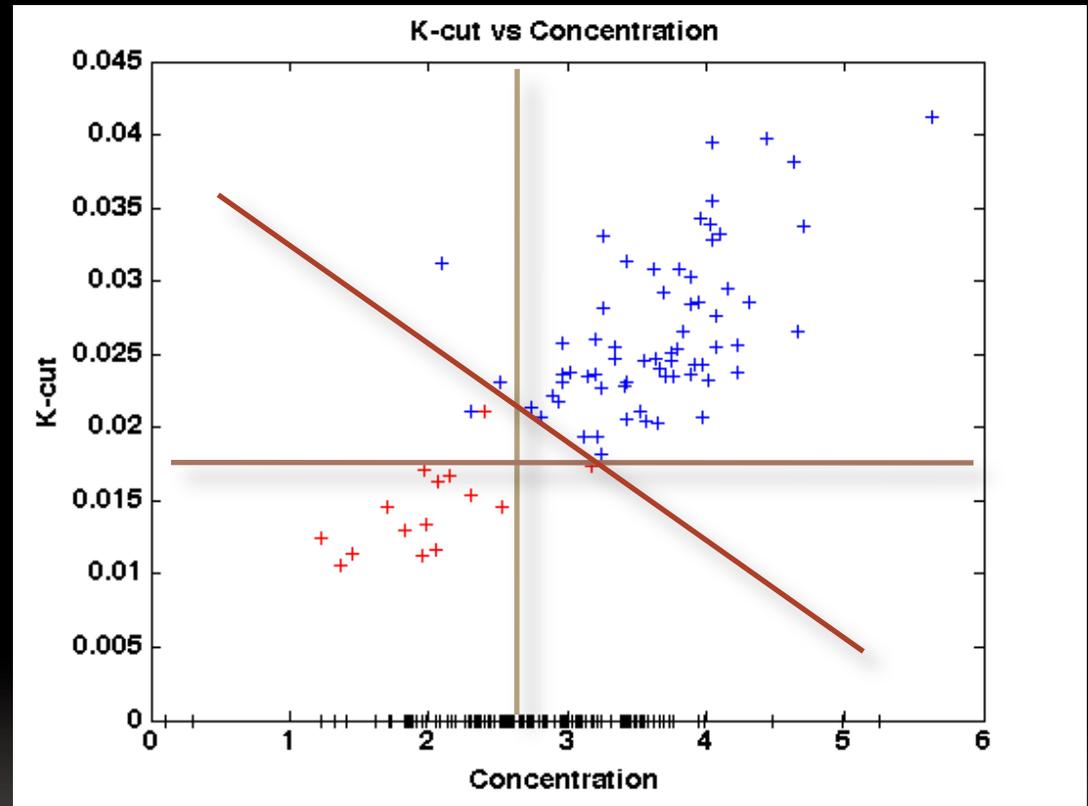
Emission of relaxed clusters (blue) is strongly peaked, so their small central area contributes more to the total luminosity of the cluster in comparison to mergers (red).

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



QUANTILES AND CONCENTRATION PARAMETER

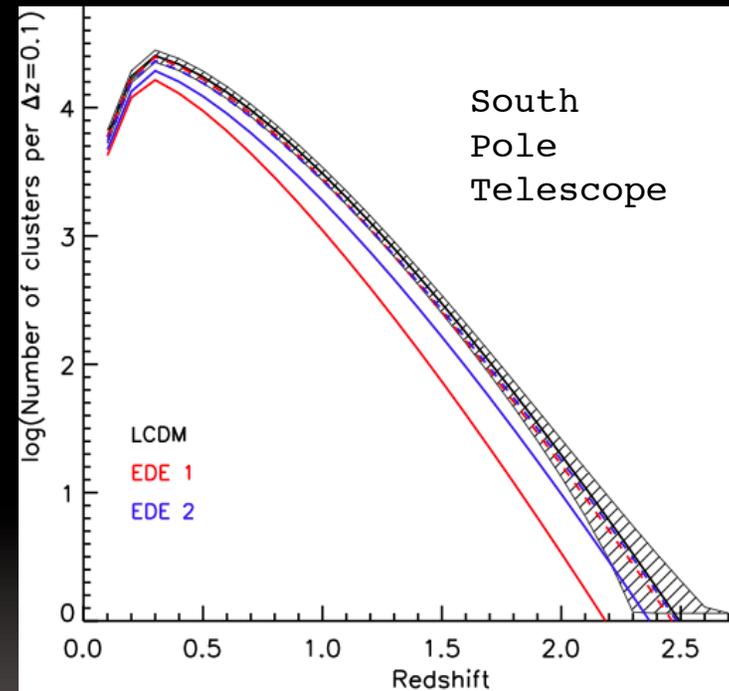
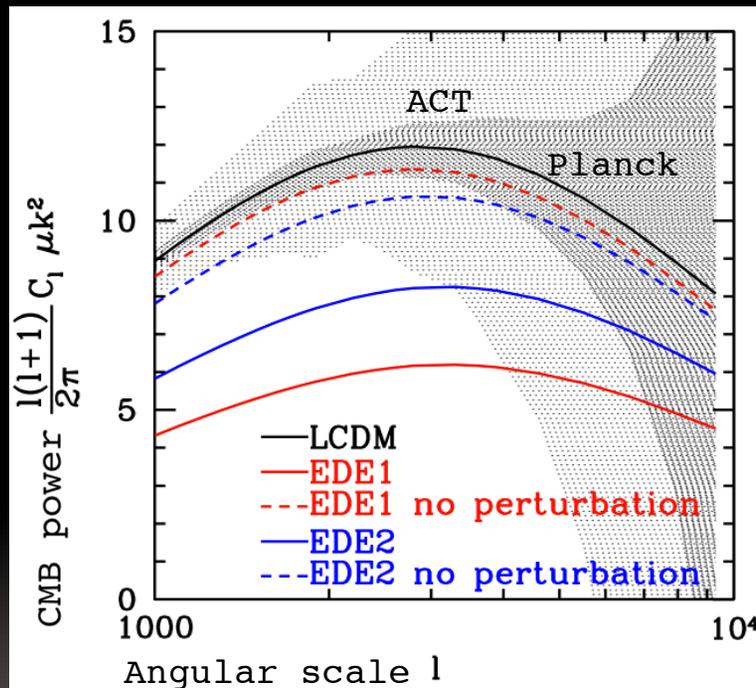
Concentration parameter is widely used to characterize the dynamical state of a cluster. Relaxed clusters have in general higher concentration. Our K-cut parameter based on quantiles is correlated with concentration parameter and provides even better separation for our sample.



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

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)

Computational Resources at LANL

Open Collaborative Network (Turquoise)

| | | | | | | | | | |
|----------------------------------|-----------------------|----------------|---|------|---------------------------|----------------|------------------------------|------|----------------|
| Cerrillos RRP3 ² (IC) | AMD opteron + Cell BE | Linux Fedora 9 | 2 | 180 | 8 (4xAMD + 4xCell) / 2880 | 33GB / 11.8TB | Voltaire InfiniBand | 152 | 1.1 PB Panasas |
| Conejo (IC) | Intel Xeon x5550 | Linux (Chaos) | 1 | 620 | 8 / 4960 | 24GB / 14.8TB | Mellanox Infiniband | 52.8 | 1.1 PB Panasas |
| Garnet RRP3 ² (IC) | AMD opteron + Cell BE | Linux Fedora 9 | 1 | 12 | 8 (4xAMD + 4xCell) / 48 | 33GB / 396GB | Voltaire InfiniBand | 5.09 | 1.1 PB Panasas |
| Lobo TLCC ³ (ASC) | AMD opteron | Linux (Chaos) | 2 | 136 | 16 / 4,352 | 32GB / 8.7TB | Voltaire InfiniBand | 38.3 | 1.1 PB Panasas |
| Mapache (ASC) | Intel Xeon x5550 | Linux (Chaos) | 1 | 592 | 8 / 4736 | 24GB / 14.2TB | Mellanox Infiniband | 50.4 | 1.1 PB Panasas |
| Mustang (IC) | AMD Opteron 6176 | Linux (Chaos) | 1 | 1600 | 24 / 38,400 | 64GB / 102.4TB | Mellanox Infiniband Fat Tree | 353 | 1.1 PB Panasas |