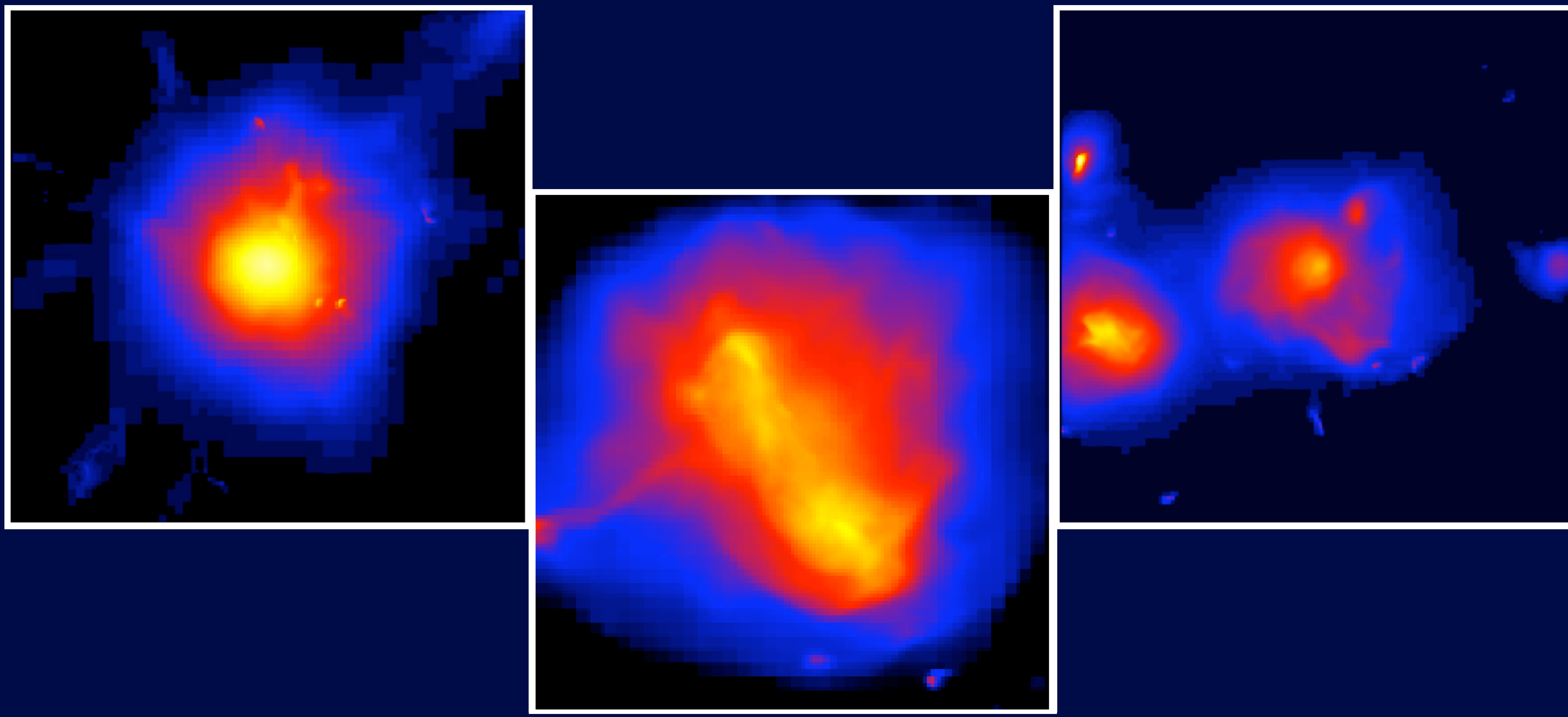
The Morphology of Clusters of Galaxies:
Prospects for Cosmological Constraints



Jeltema et al. 2008
with E. Hallman, J. Burns, and P. Motl

Jeltema et al. 2005
with C. Canizares, M. Bautz, and D. Buote

Outline

- Cosmology with clusters of galaxies
  - Introduction to cosmology with clusters
  - Measuring cluster mass
  - Cluster structure: understanding systematics

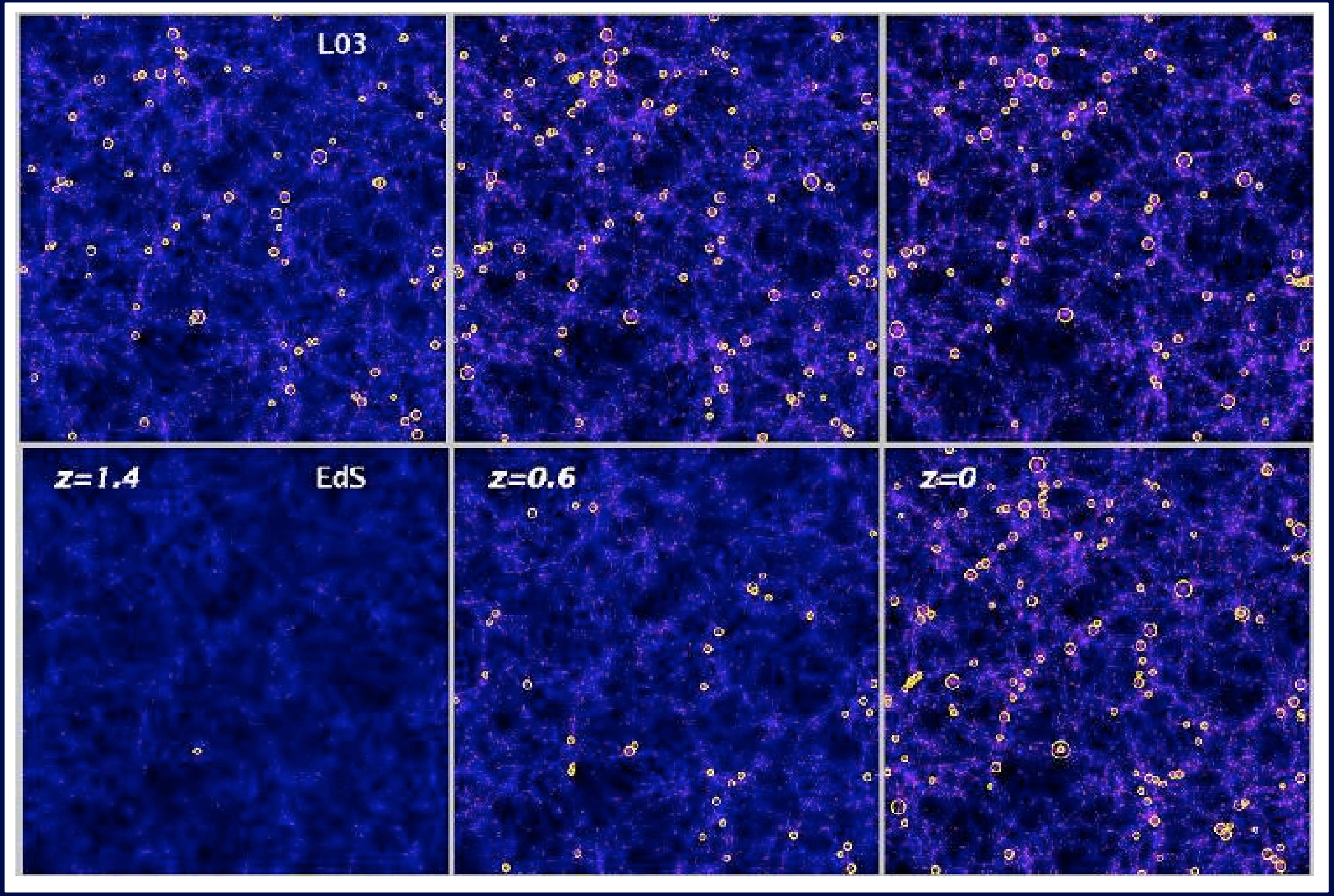
- Cluster structure in simulations
  - Projection
  - Mass scaling relations and hydrostatic equilibrium
    - ➡ Correcting mass estimates based on structure
  - Comparison to observations

Cosmology with Clusters

- Represent highest density initial perturbations.
- Constrain cosmological parameters from the evolution in cluster number density and cluster baryon fraction.

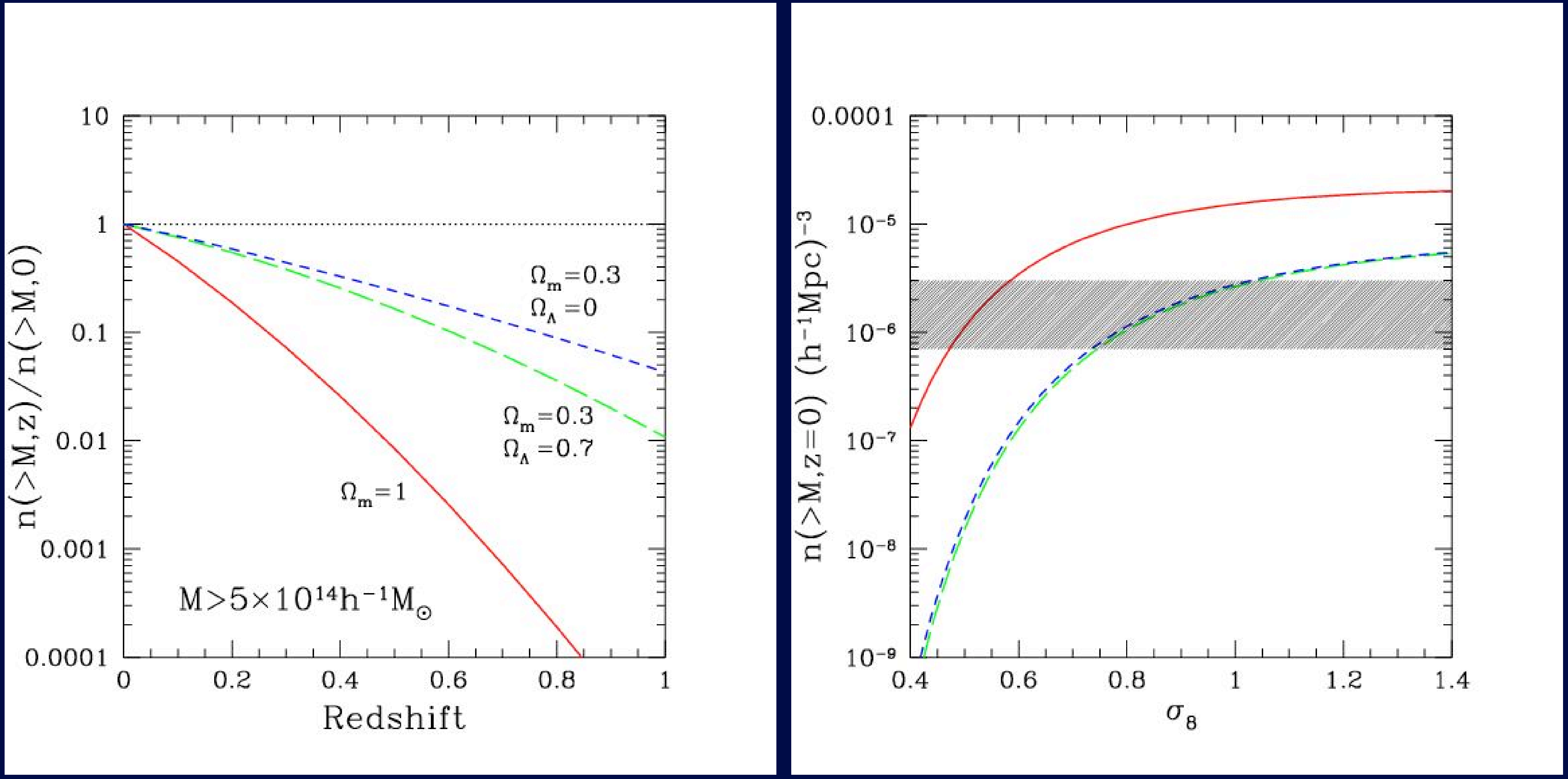
ΛCDM

SCDM



Borgani & Guzzo 2001

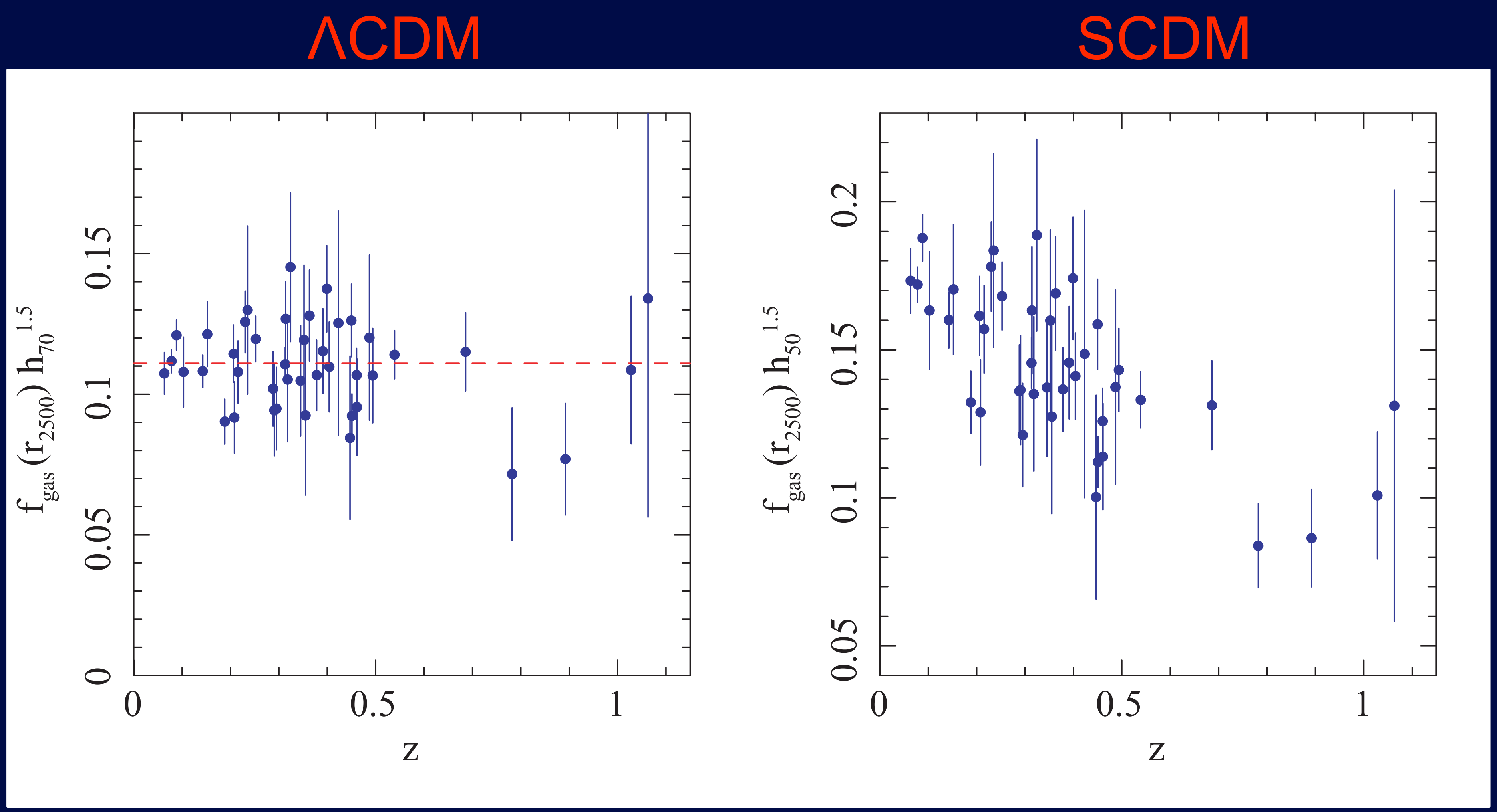
Dependence of Cluster Density on Cosmology



➡ Need to add up the number of clusters of a given mass versus redshift.

Rosati et al. 2002

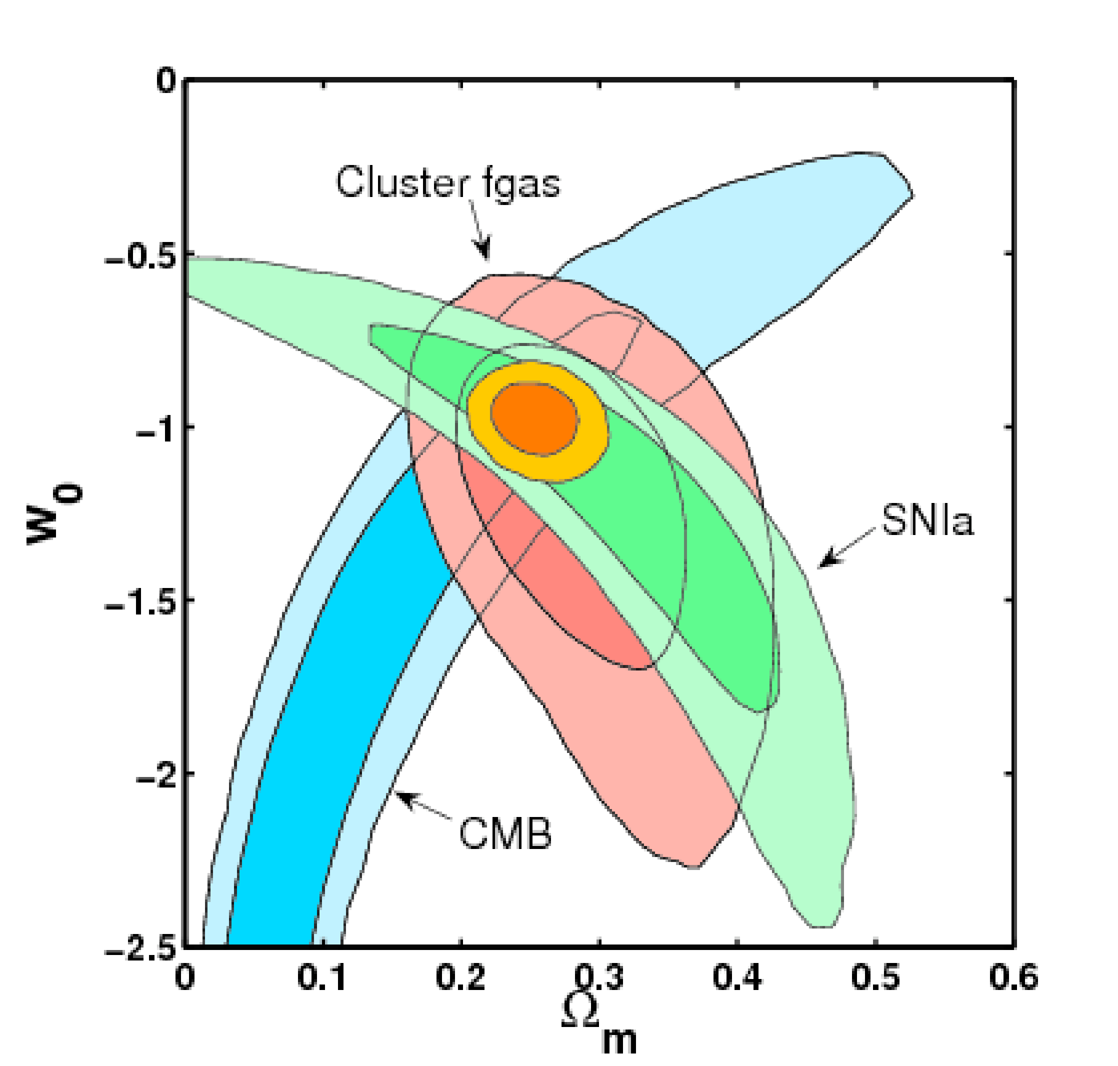
Dependence of Gas Mass Fraction on Cosmology



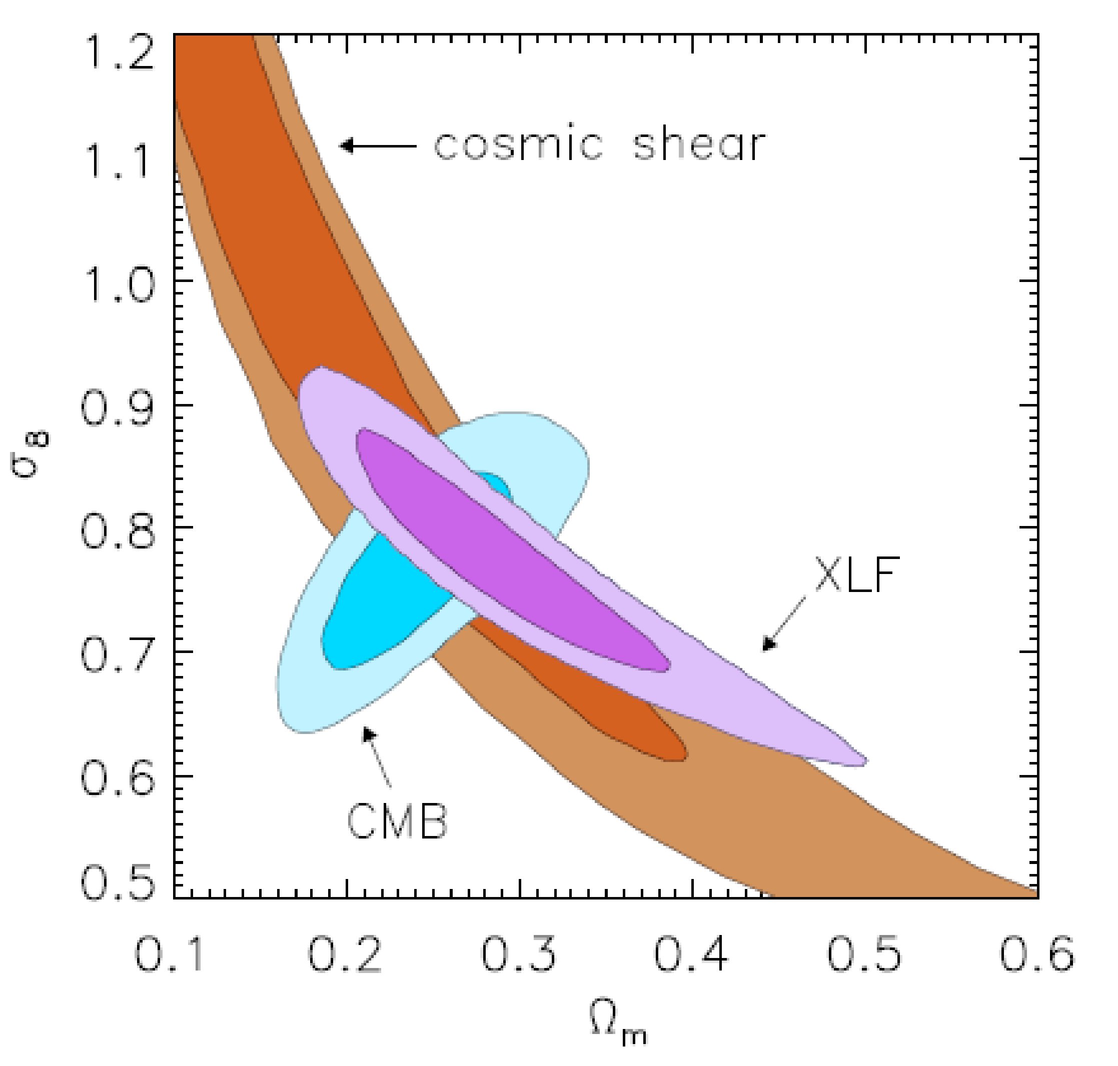
➡ Apparent gas mass fraction depends on the assumed distance of the cluster.

Allen et al. 2007

Comparison to Other Constraints



Allen et al. 2007



Mantz et al. 2007

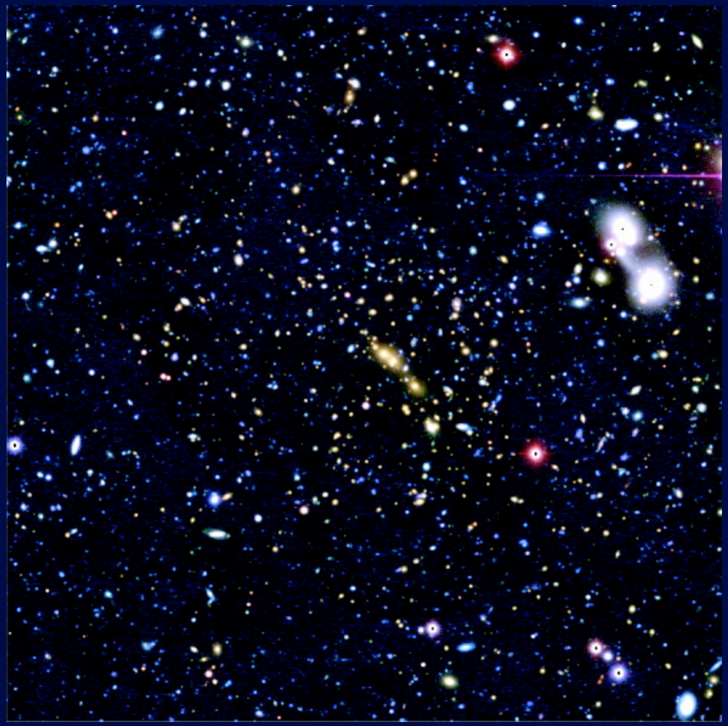
Cluster Observations

- Optical

  observe galaxies (~2% of mass)

  velocity dispersion, richness → M

  projection, large number of galaxies



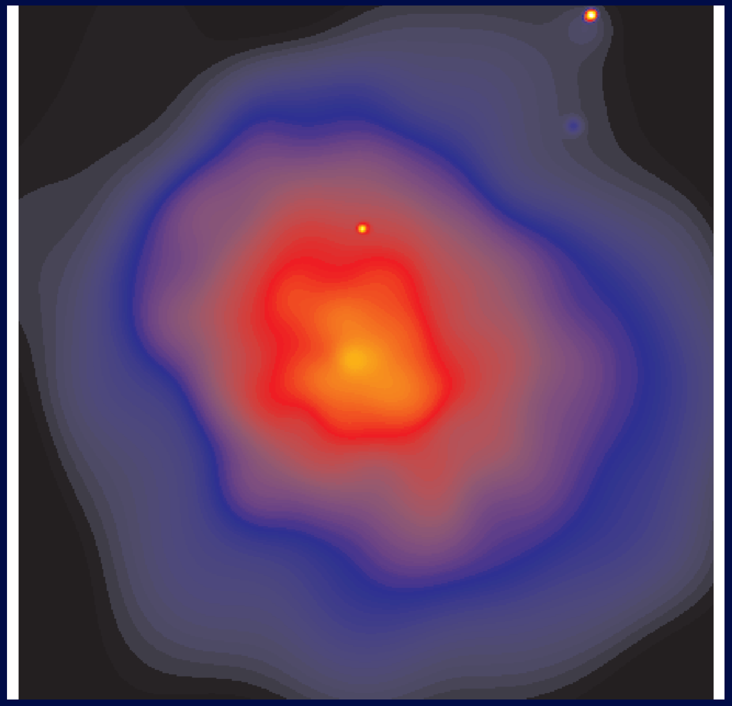
- X-ray

  thermal bremsstrahlung from hot gas (~12% of mass)

  L_x, $T_x \rightarrow M$

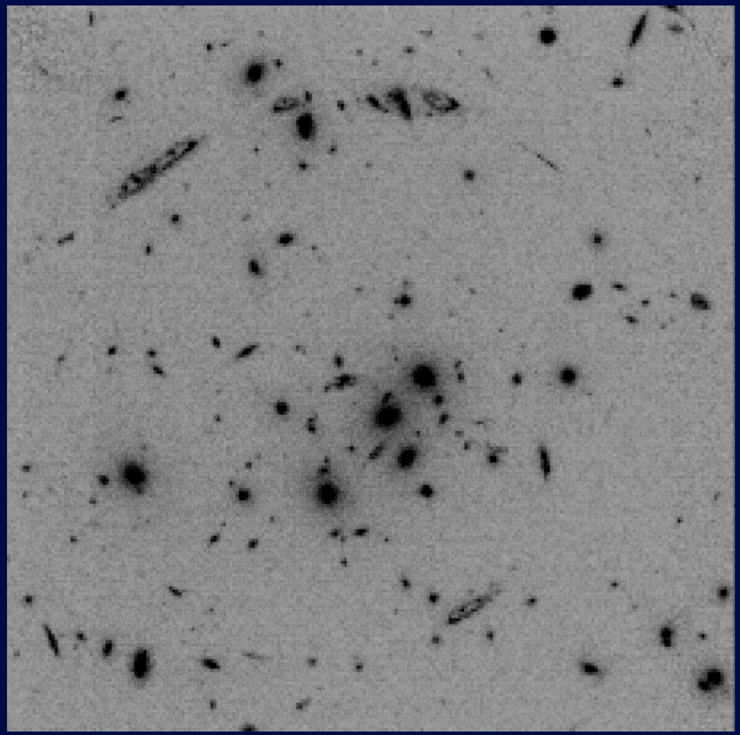
  hydrostatic equilibrium, spherical

  flux limited samples, probes potential

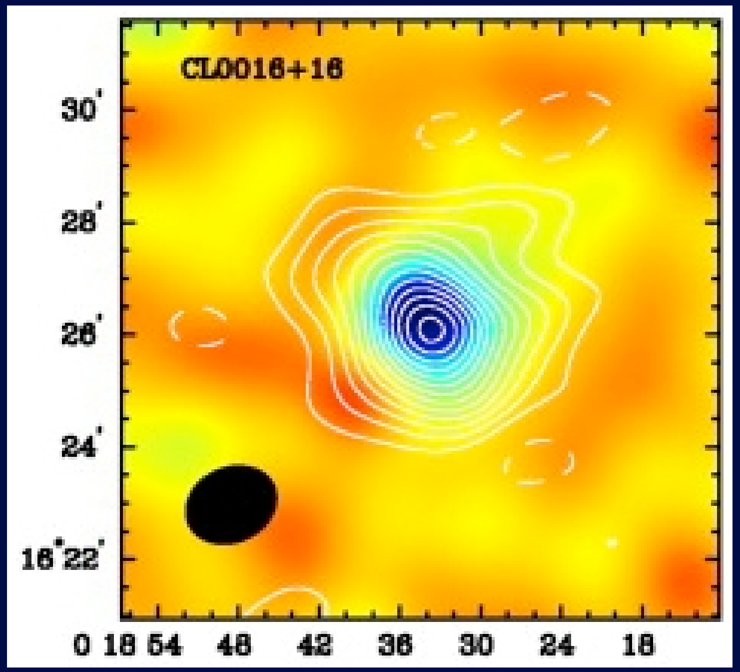


Cluster Observations

- Lensing
  distortion of background galaxies
  (strong or weak)
  probes mass along the line of sight
  sensitive to projection, low resolution



- Sunyaev-Zeldovich Effect
  inverse Compton scattering of CMB off hot gas
  $Y \propto M_{gas} T \rightarrow M$
  hydro. equil., low resolution, projection?
  roughly independent of z



Systematics

Our ability to constrain cosmology is directly related to the accuracy with which we can estimate cluster mass.

- Cluster mergers: deviation from equilibrium and sphericity
- Gas physics: cooling, star formation, AGN feedback

The **CL** technique has the statistical potential to exceed the BAO and SN techniques but at present has the largest systematic errors. Its eventual accuracy is currently very difficult to predict and its ultimate utility as a dark energy technique can only be determined through the development of techniques that control systematics due to non-linear astrophysical processes.

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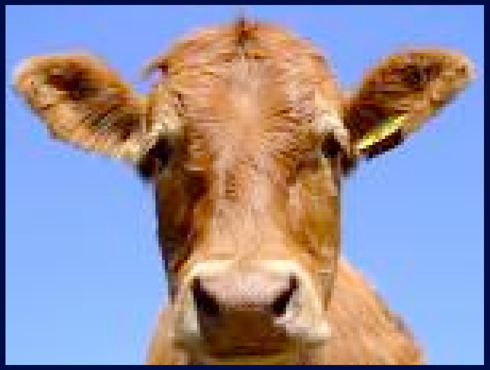

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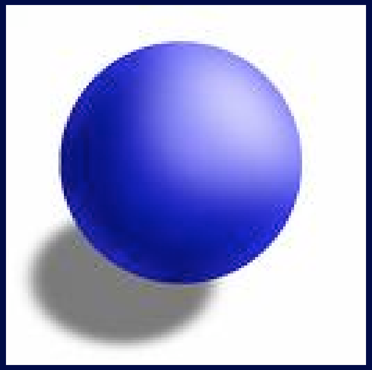

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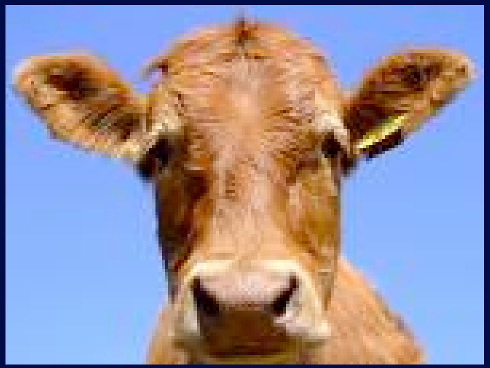

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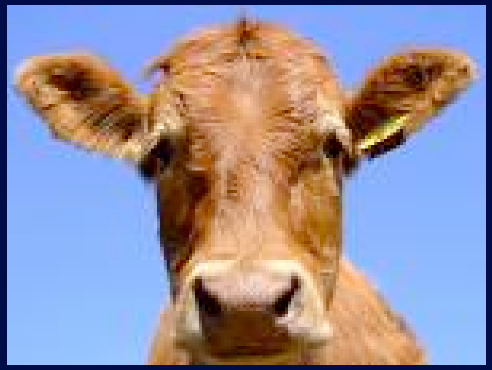

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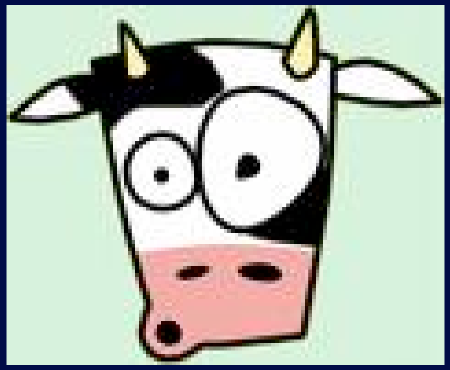


Cluster Substructure

- Clusters form through mergers.
  - Observed as substructure or disturbed cluster morphology

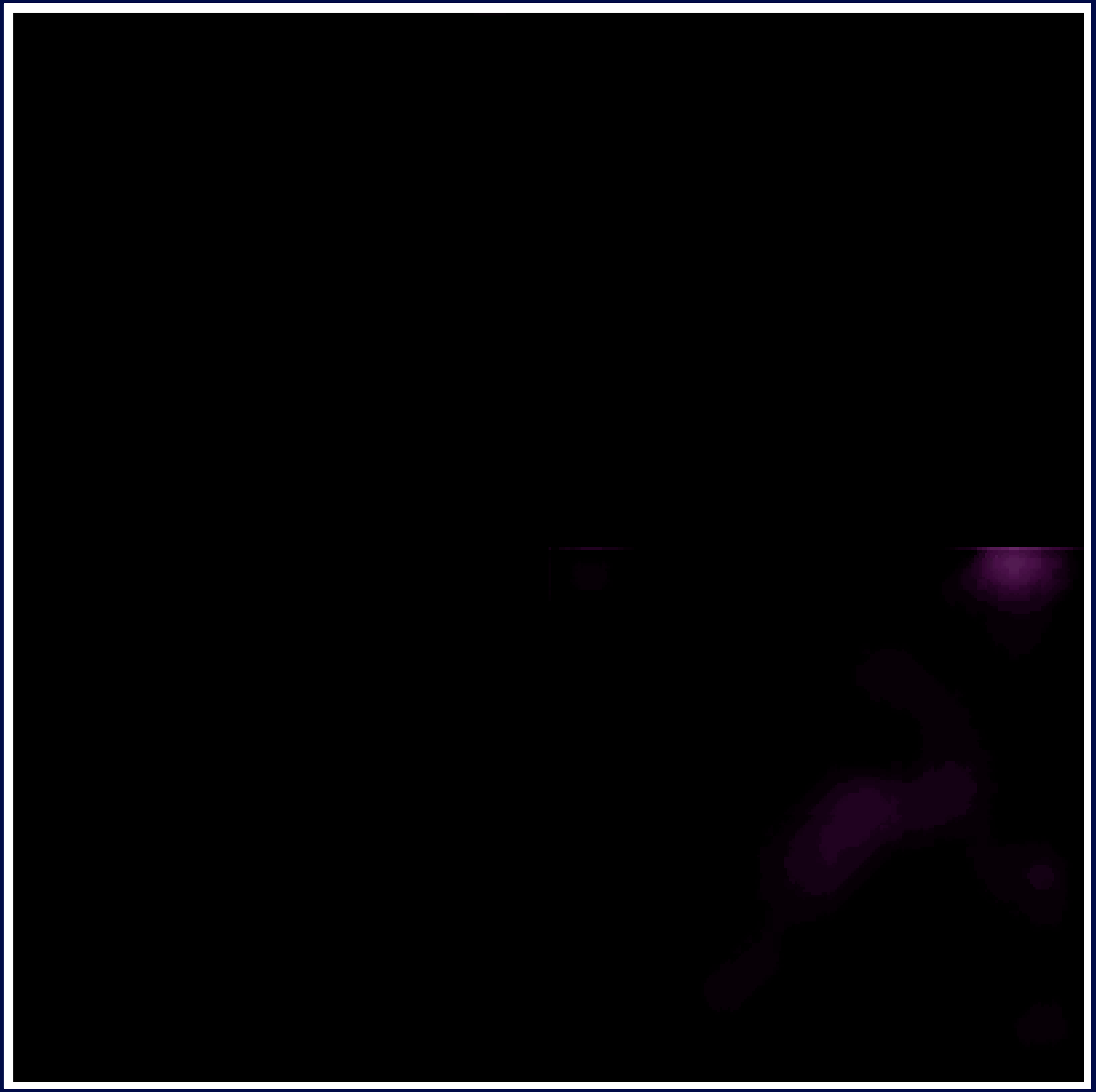
- Formation epoch of clusters depends on cosmology.

- Cluster morphology affects cluster selection and observable cluster properties.
  - ➡ Mass estimates
  - ➡ Gas mass estimates
  - ➡ Galaxy evolution, etc.

Cluster formation in ΛCDM

Gas Density

Galaxies



SZ Effect

X-
ray

Movie credit to Martin White

Cluster Structure in Simulations

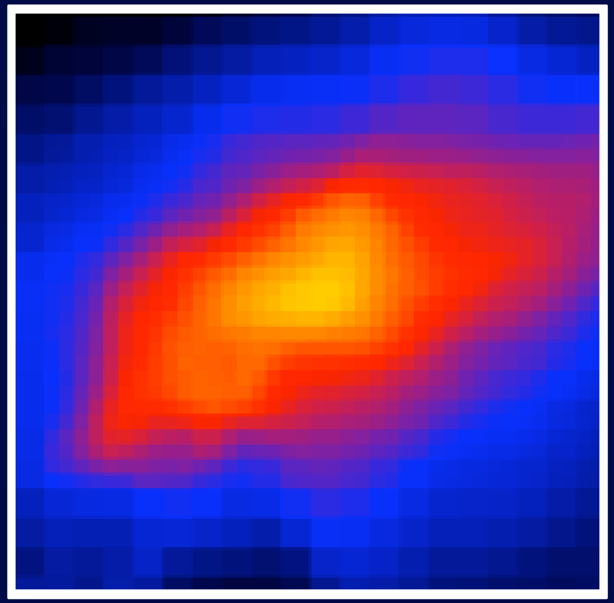
- Test of cosmological models as well as the accuracy of current simulations (gas physics, etc.).

- Simulations using hydro/N-body, AMR code Enzo
  - ΛCDM
  - cooling, star formation and feedback
  - Large volume (256 h^{-1} Mpc) and good resolution (~ 16 h^{-1} kpc)

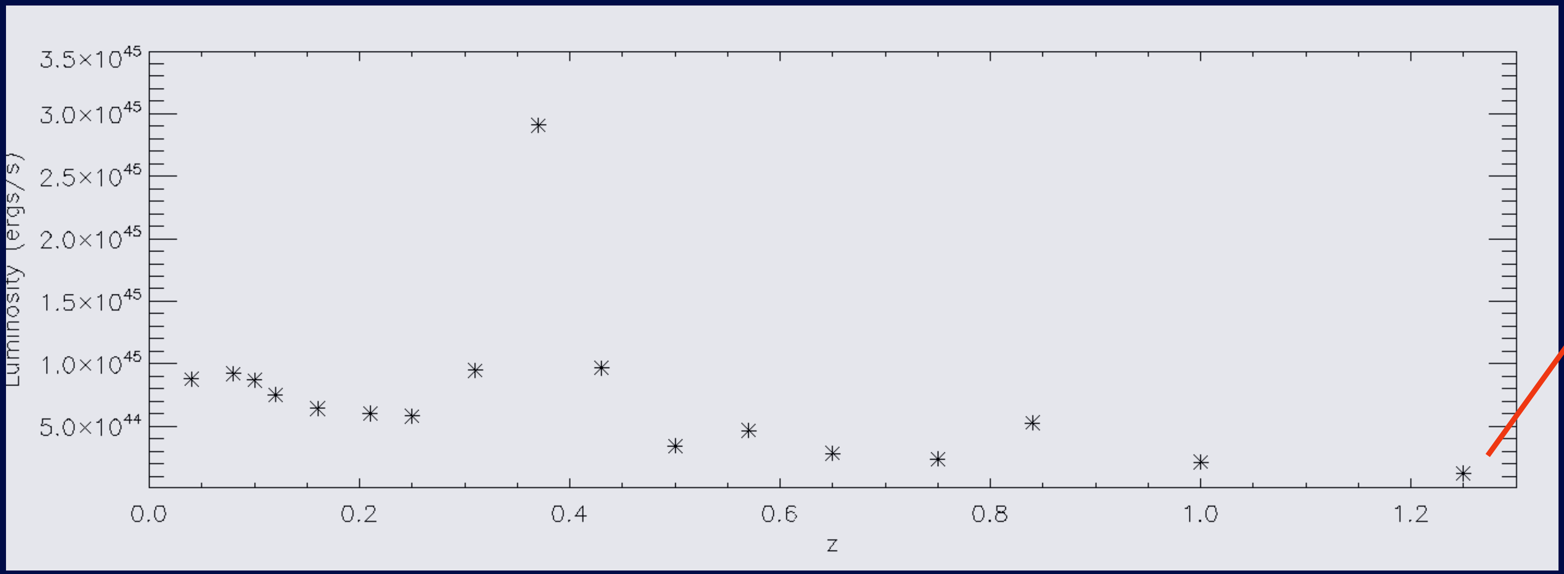
- Select clusters with $M > 2 \times 10^{14} M_{\odot}$ (61 z = 0.04, 25 z = 1.0)

- Remove cool cores, if present, from temperature determination (T_X = average spectral temperature, M_{gas} from deprojection of X-ray images assuming spherical symmetry)

Evolution of a Massive Cluster



Luminosity



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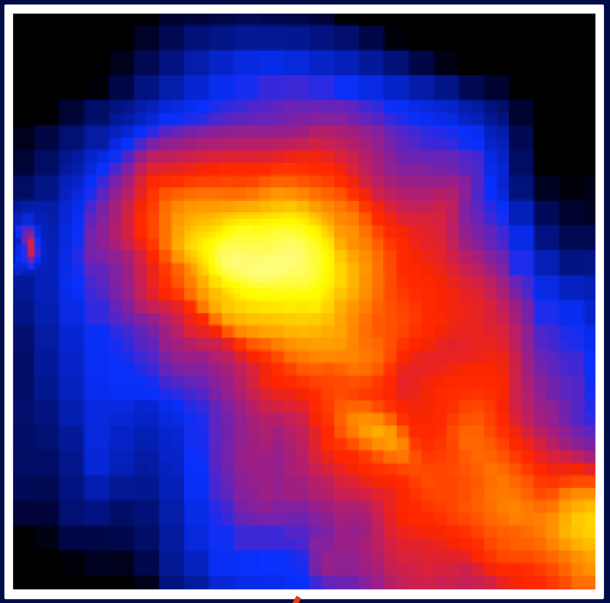

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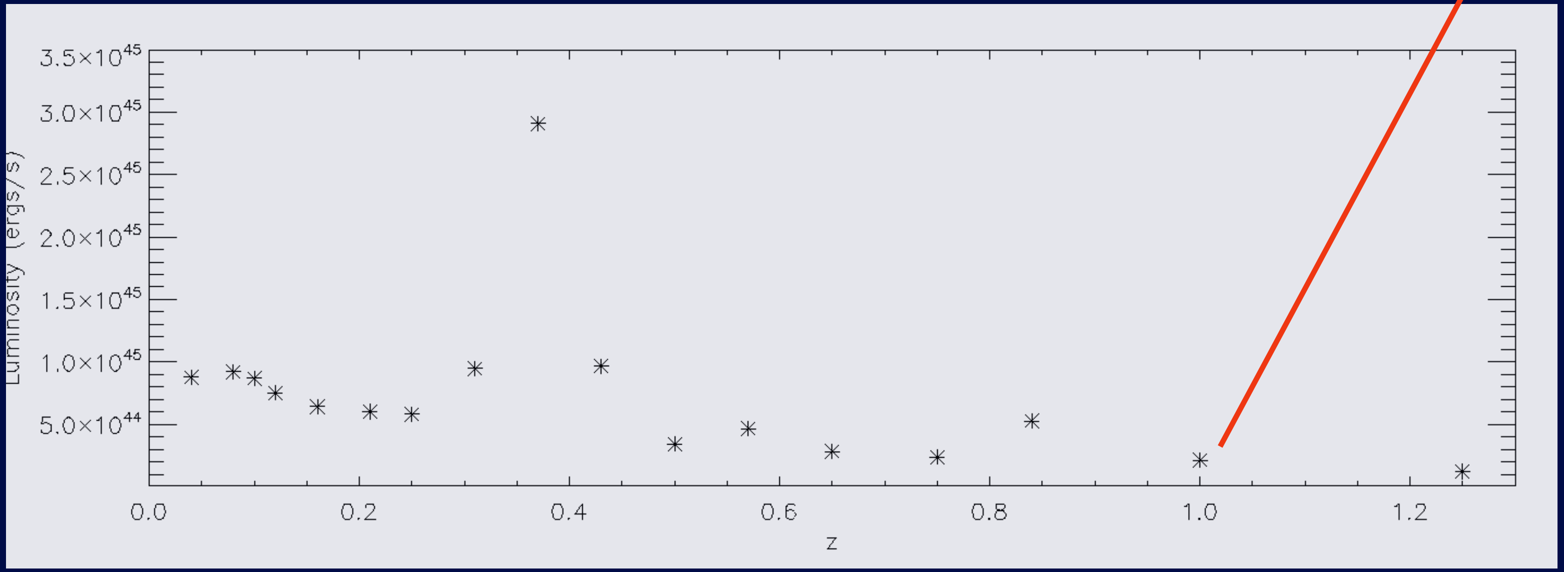

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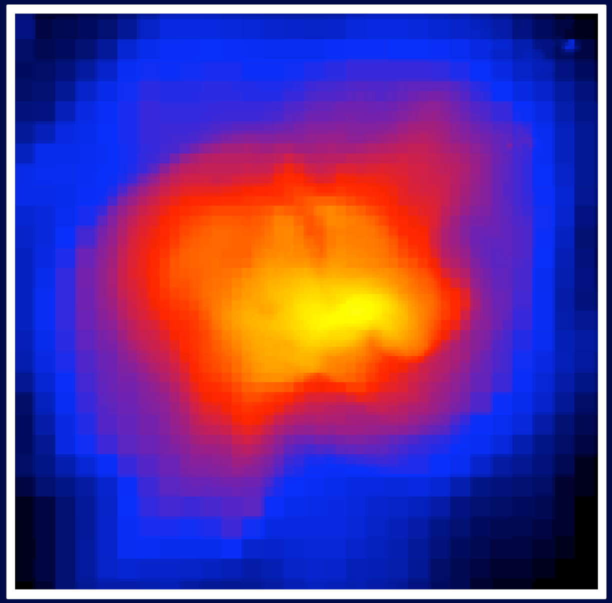

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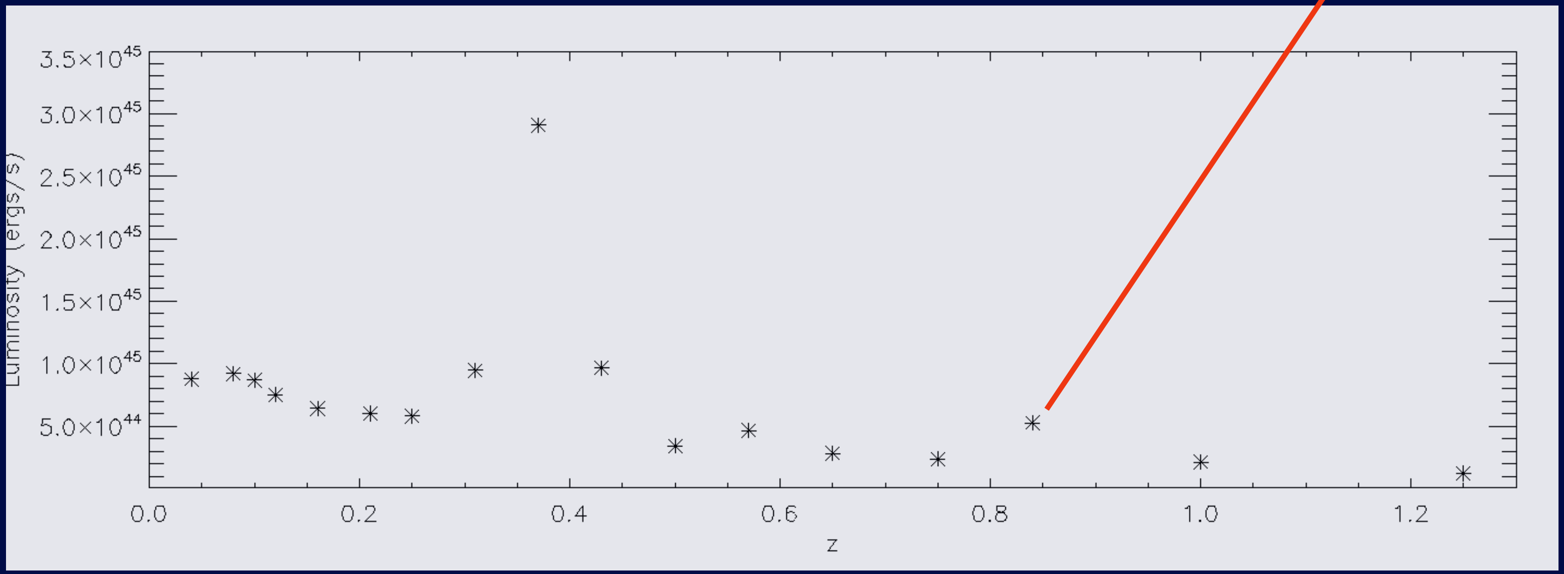

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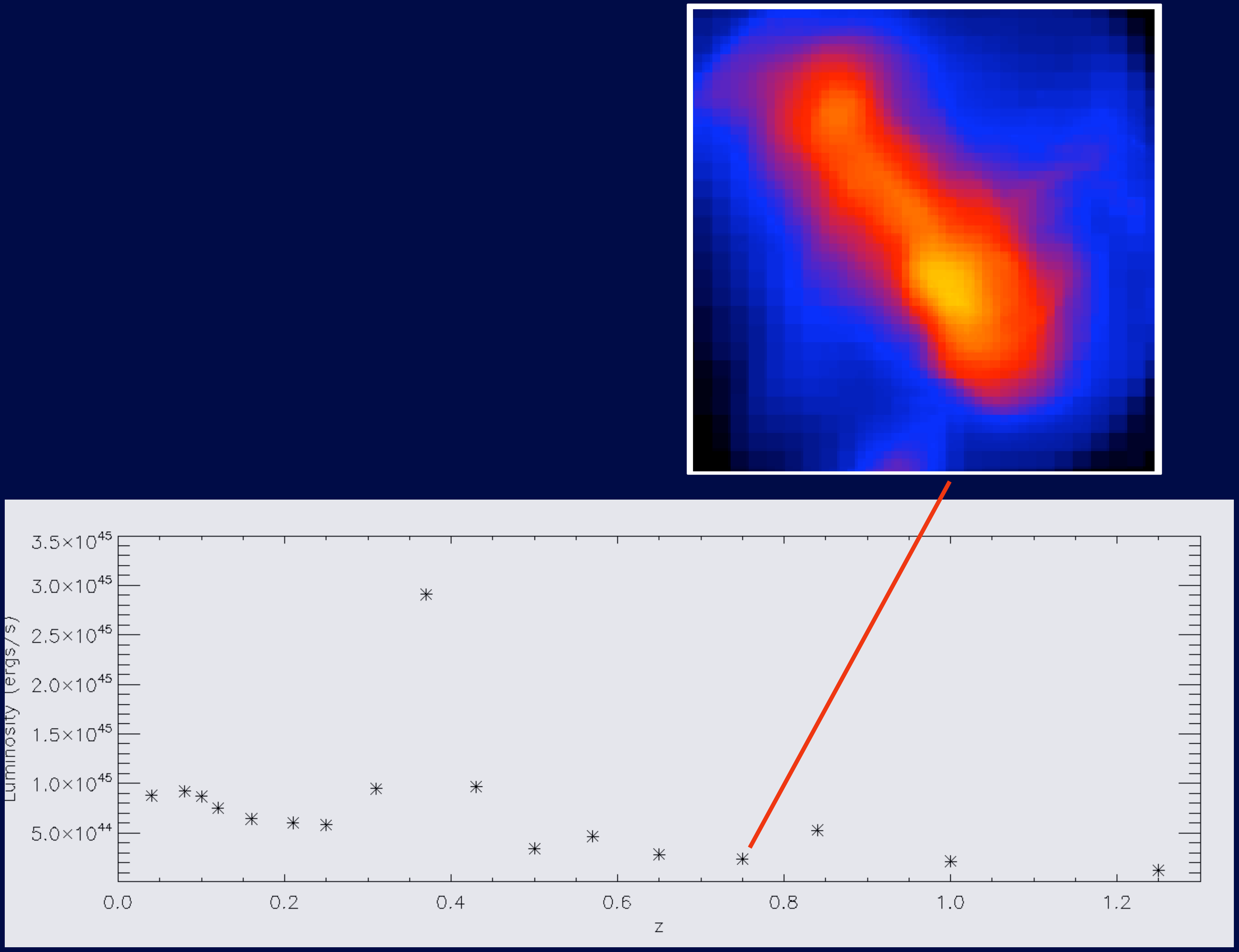

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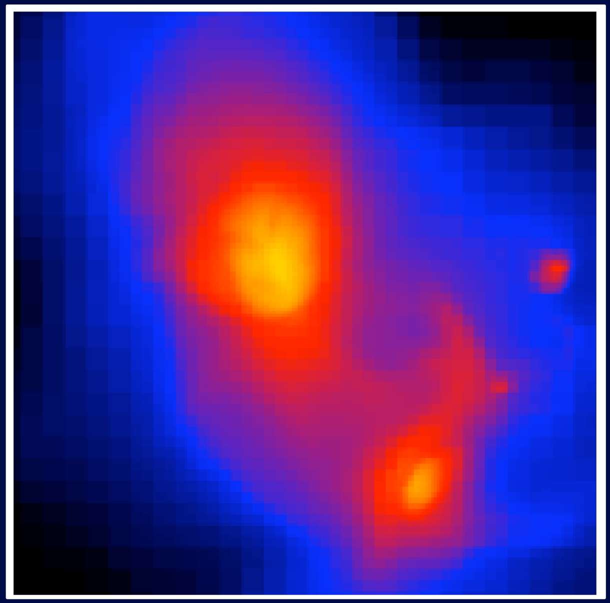

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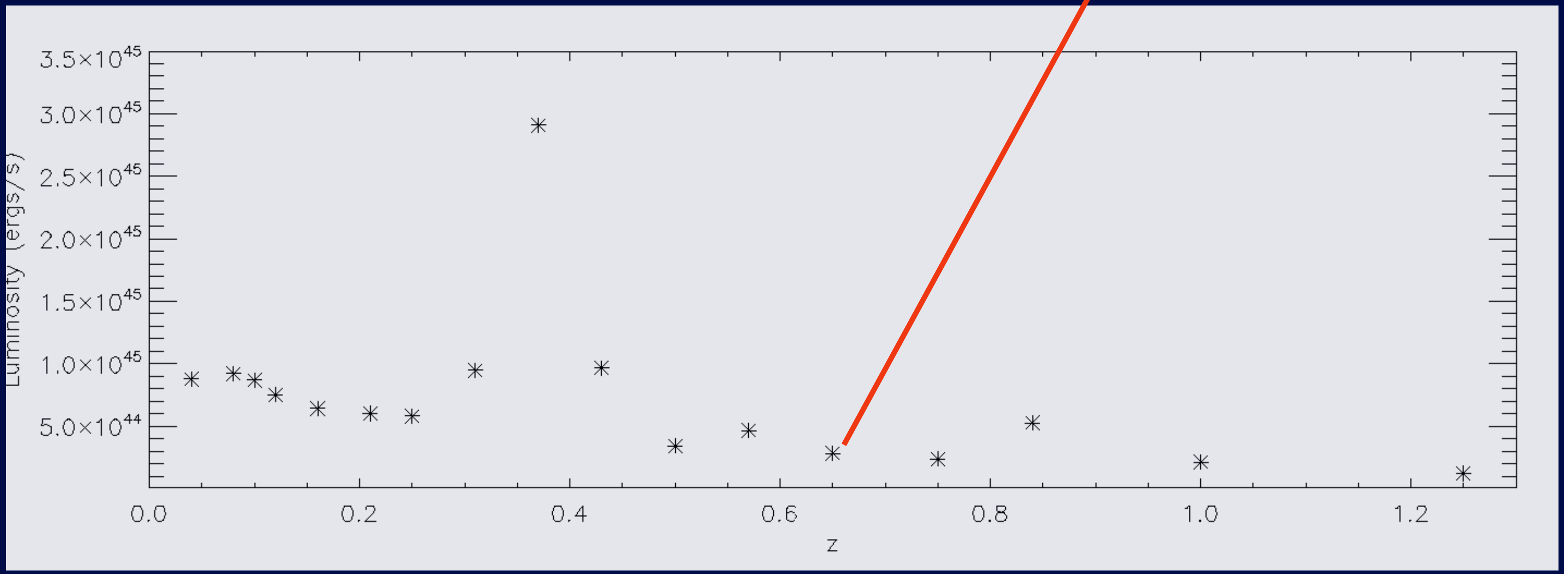

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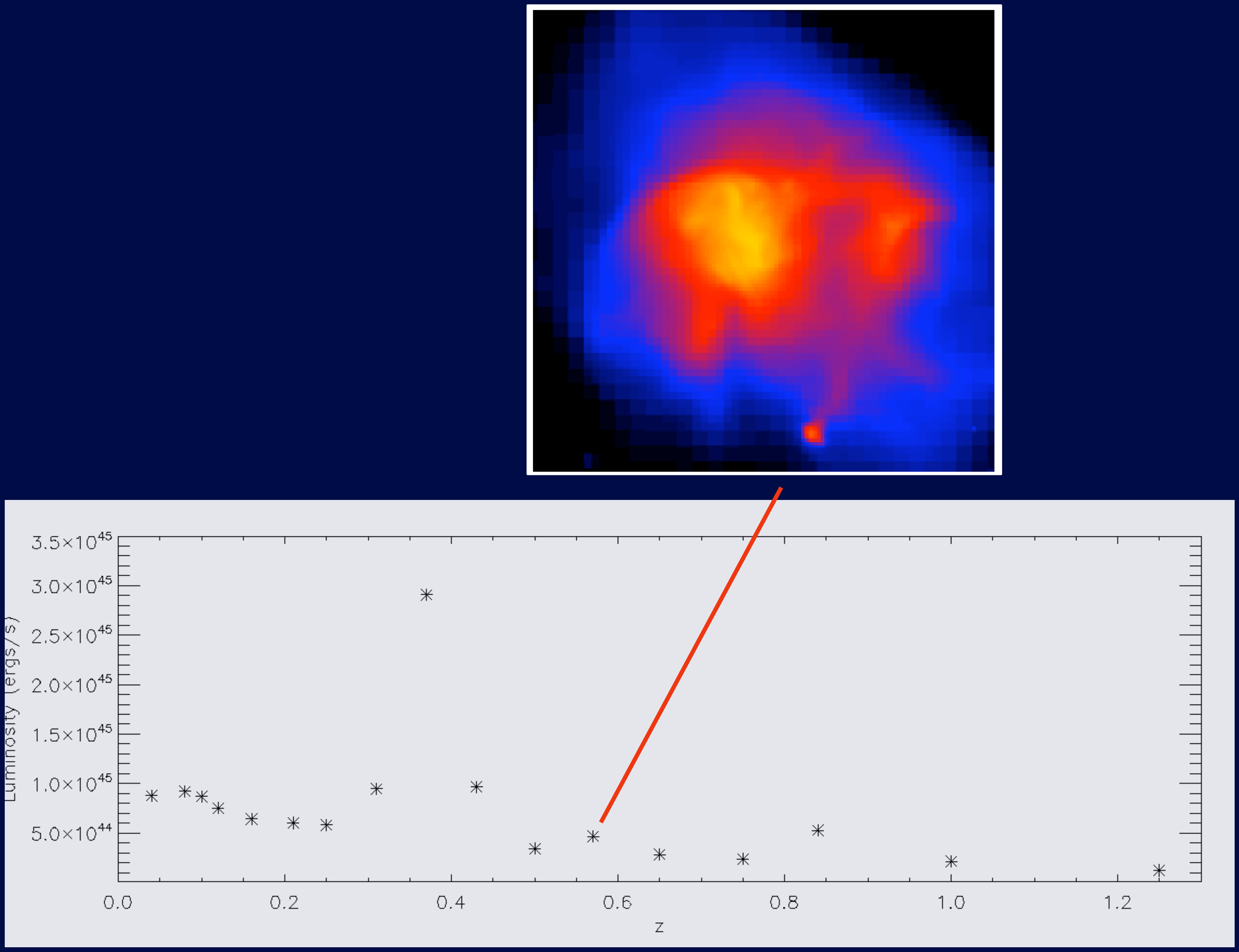

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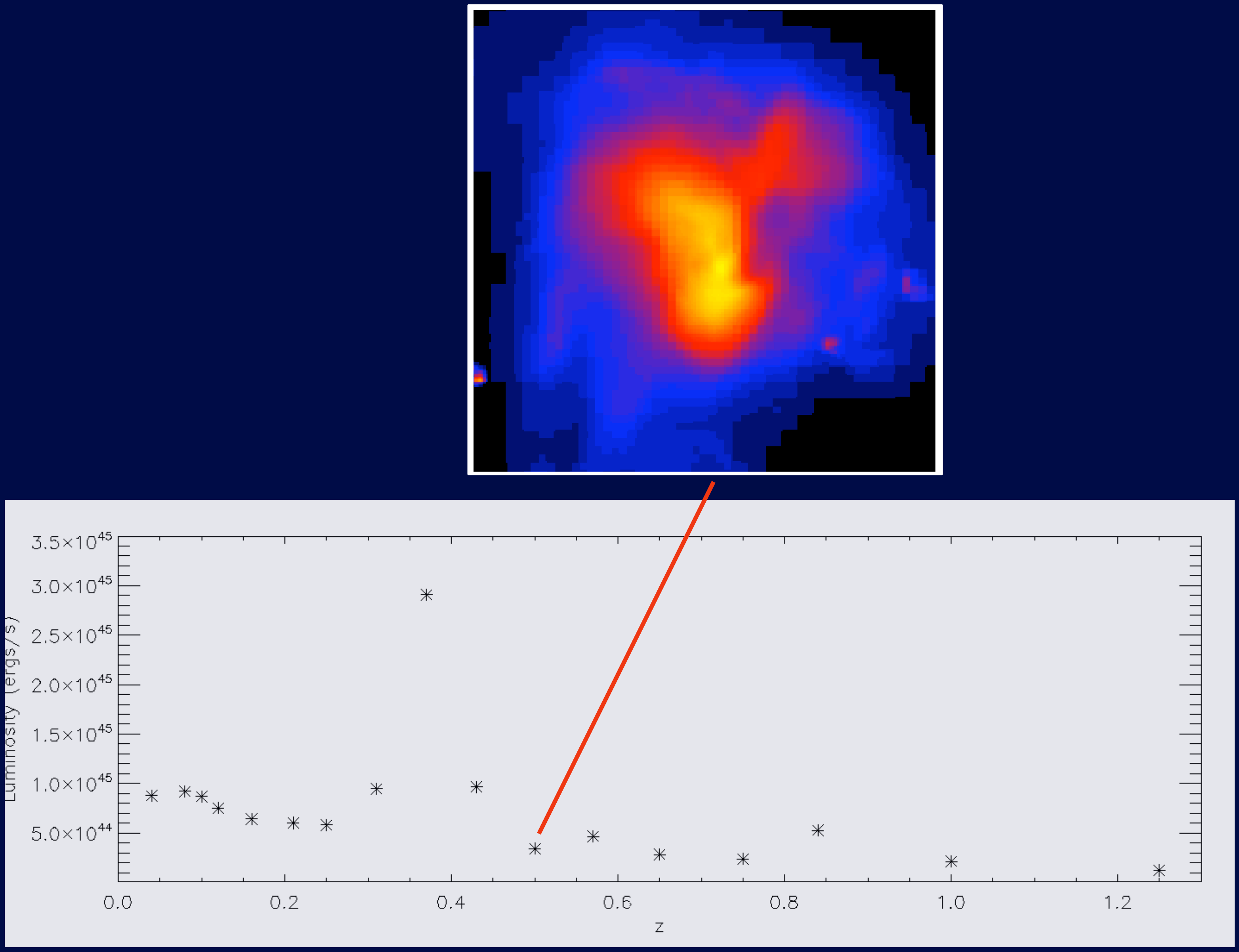

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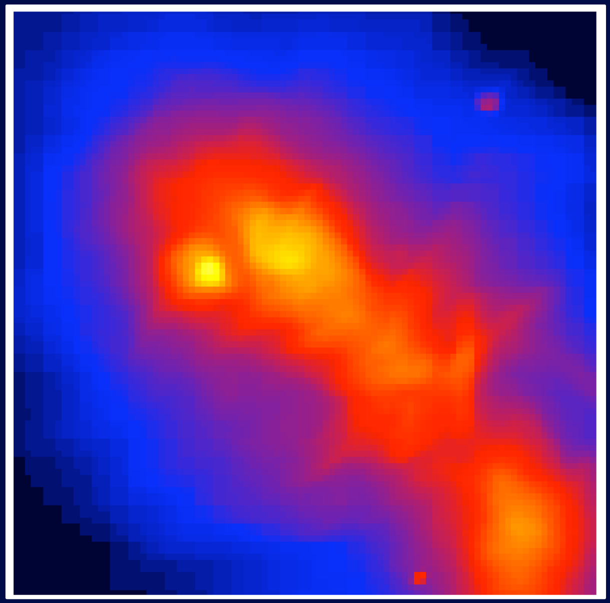

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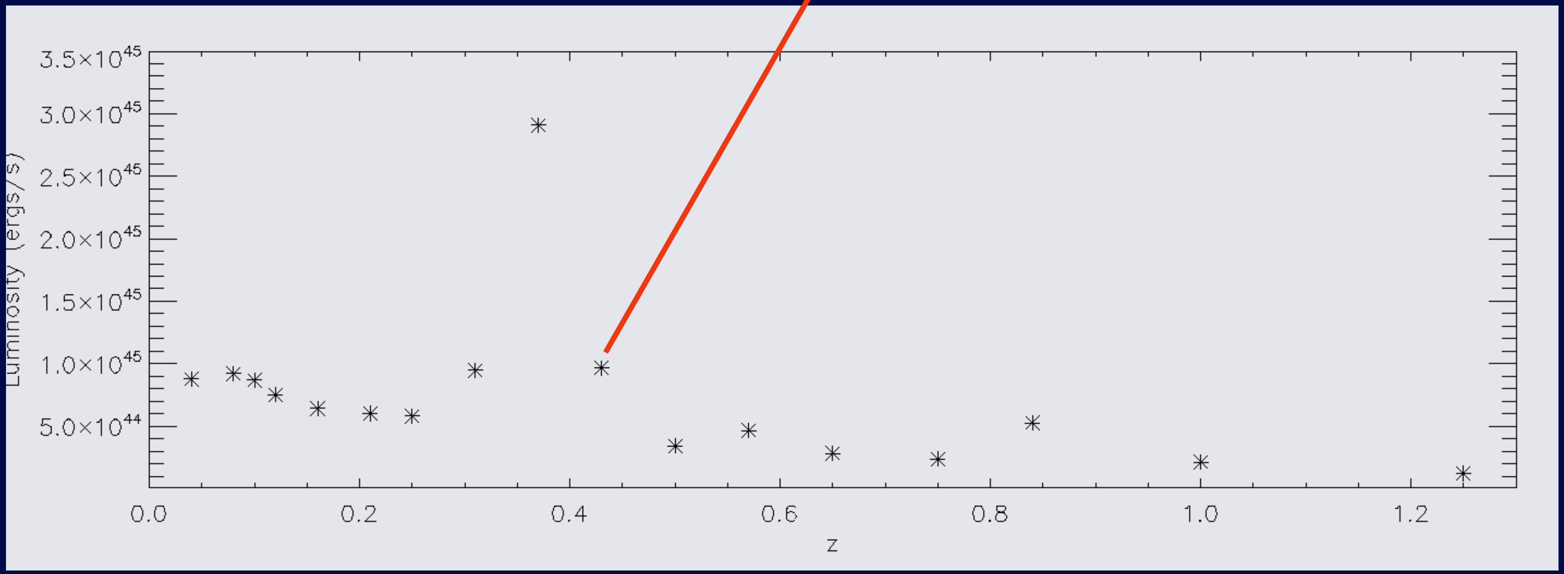

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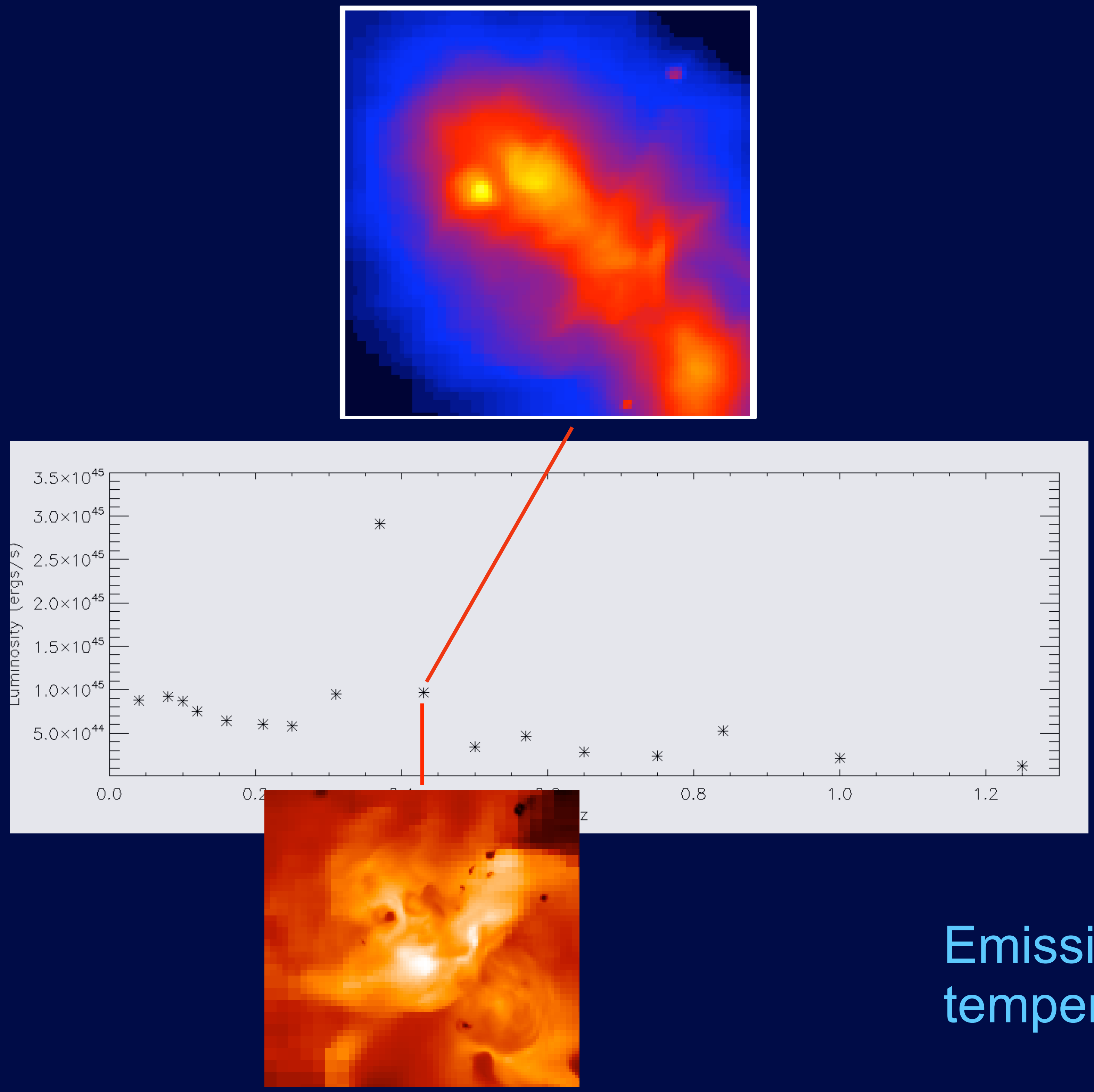
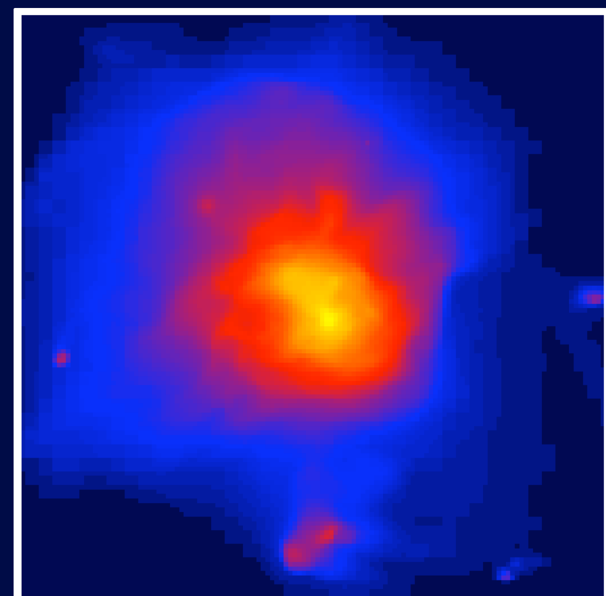
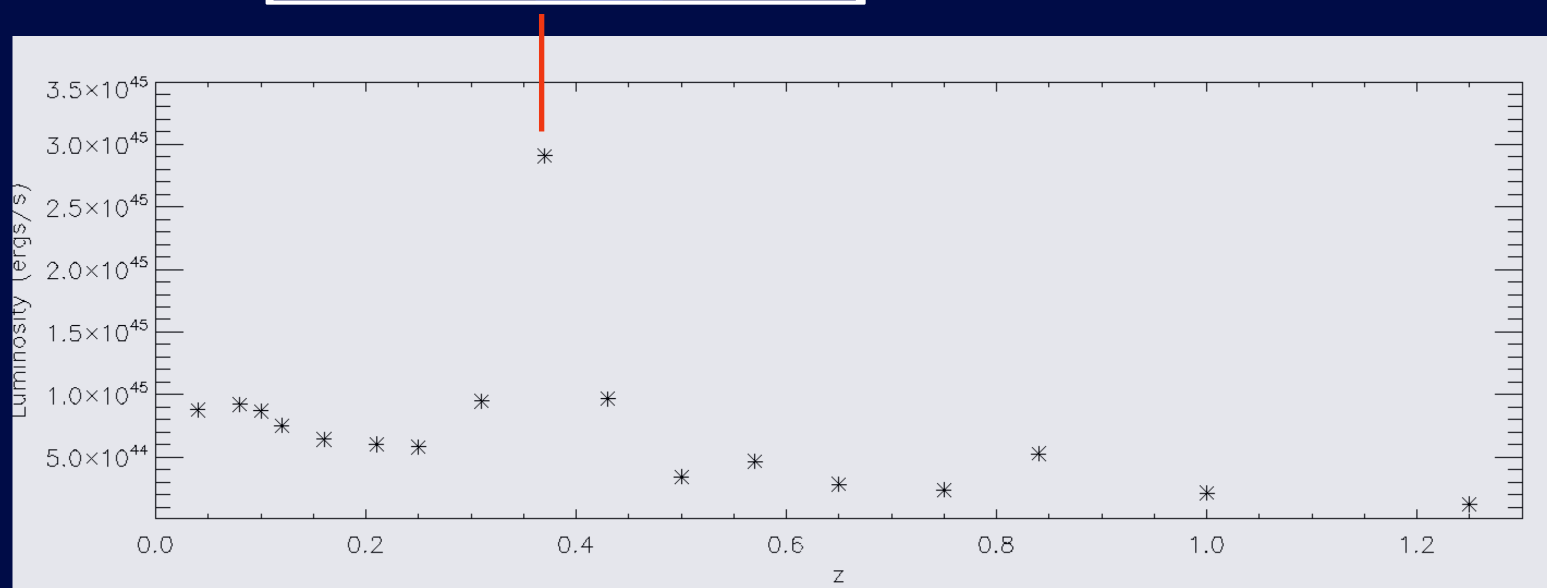


Emission-weighted temperature map

Evolution of a Massive Cluster





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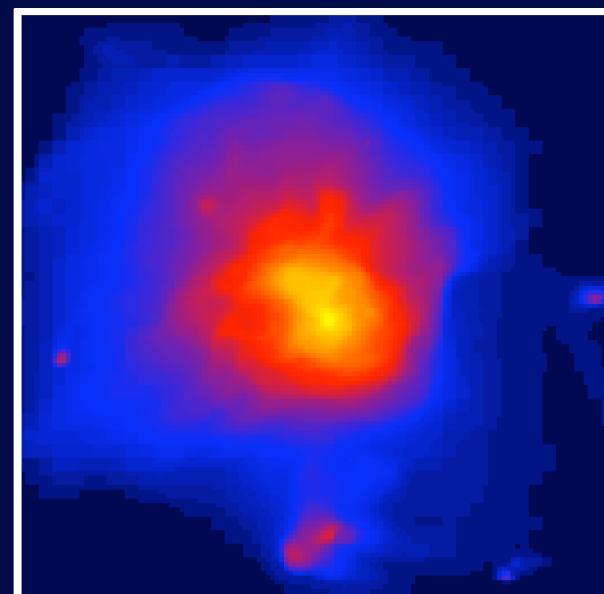

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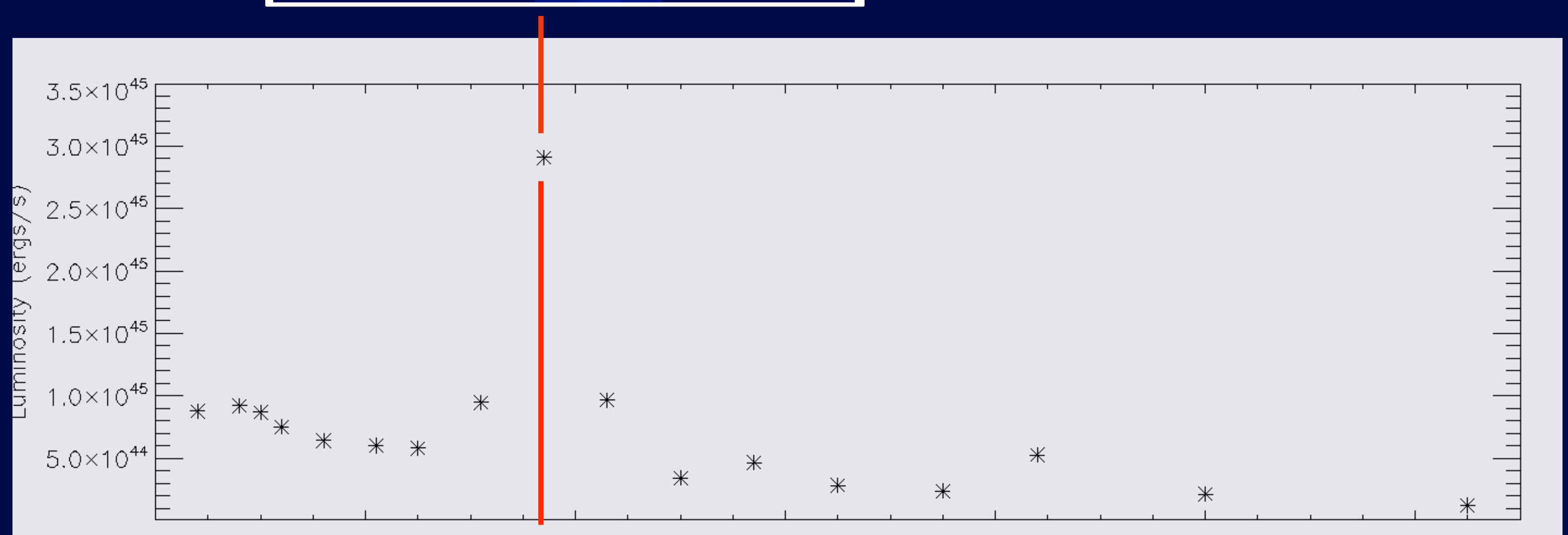

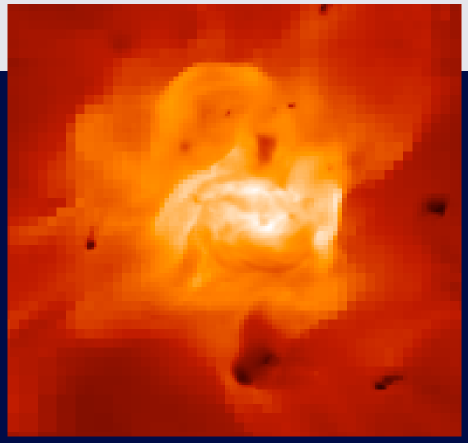

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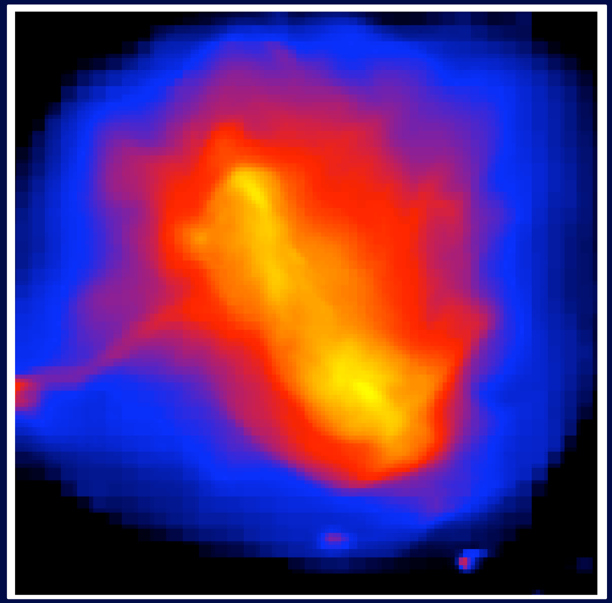

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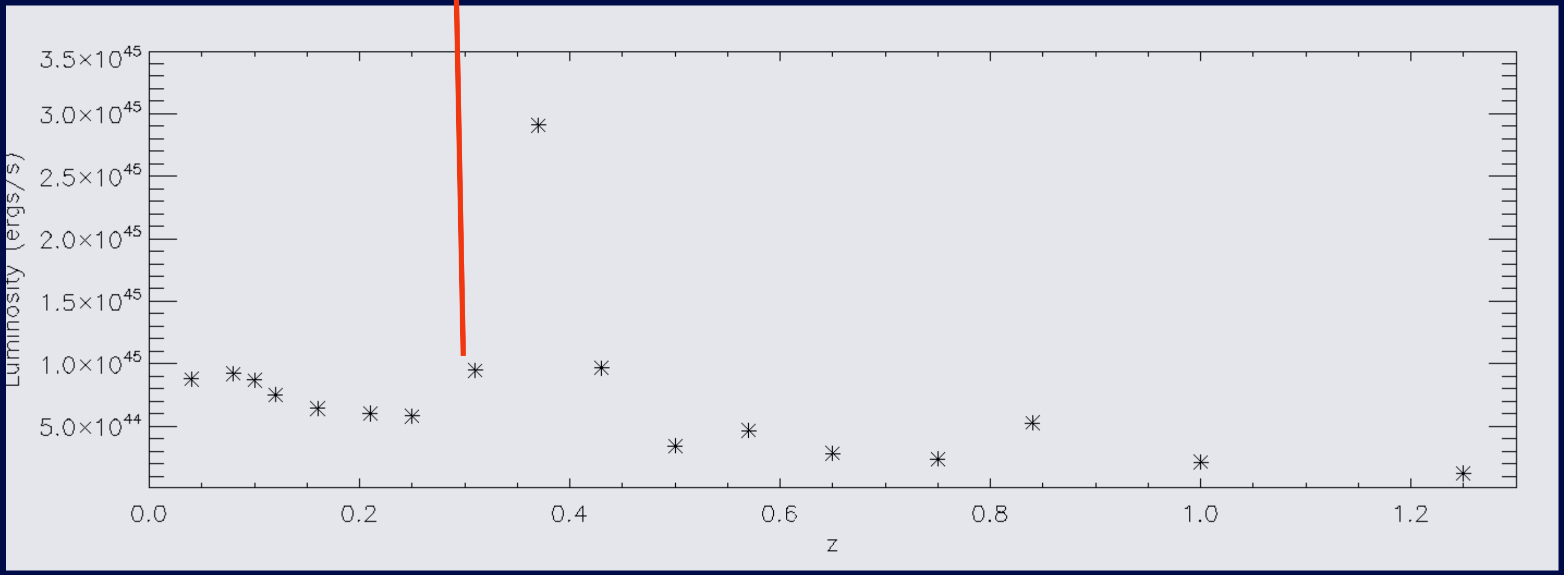

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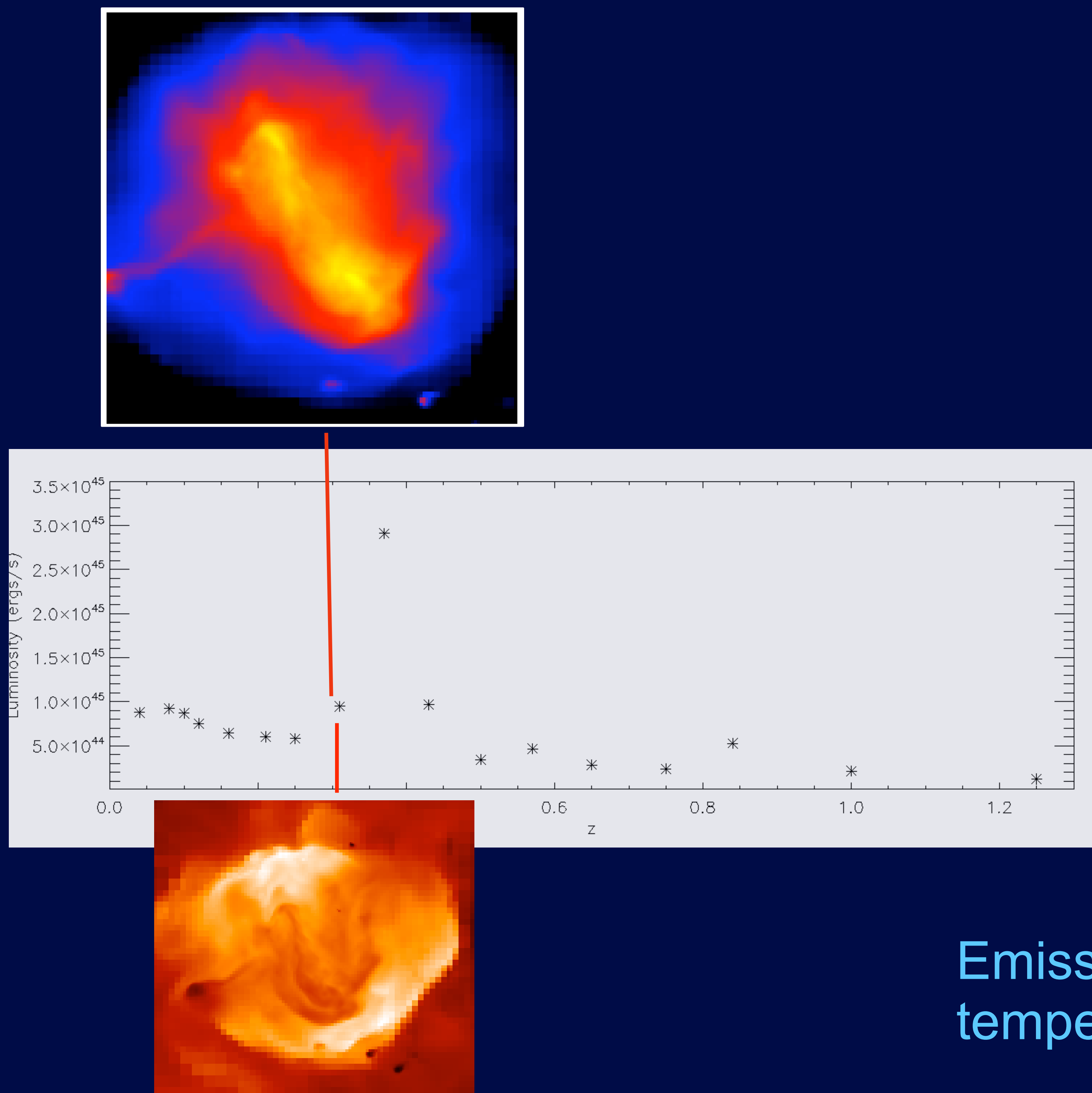

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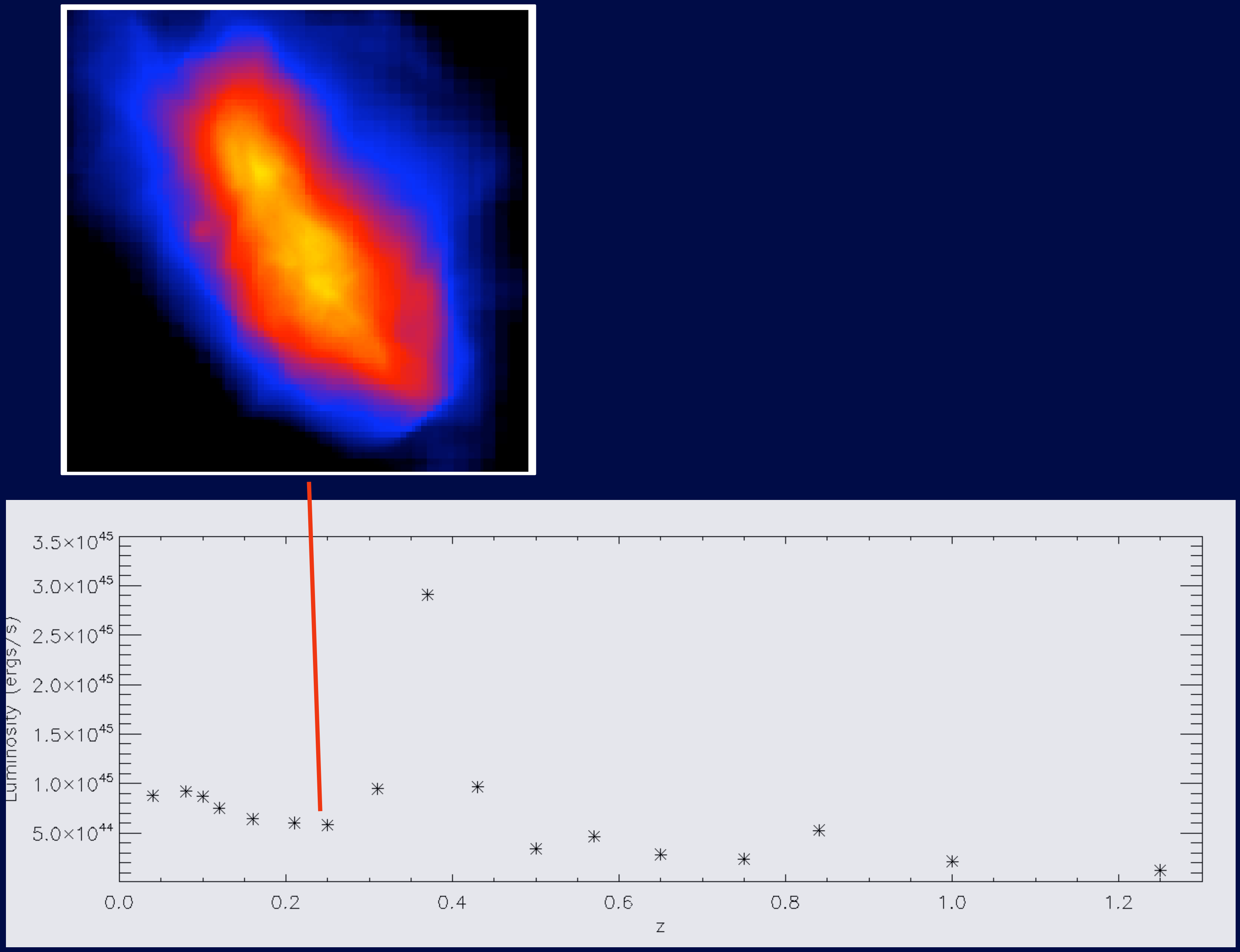

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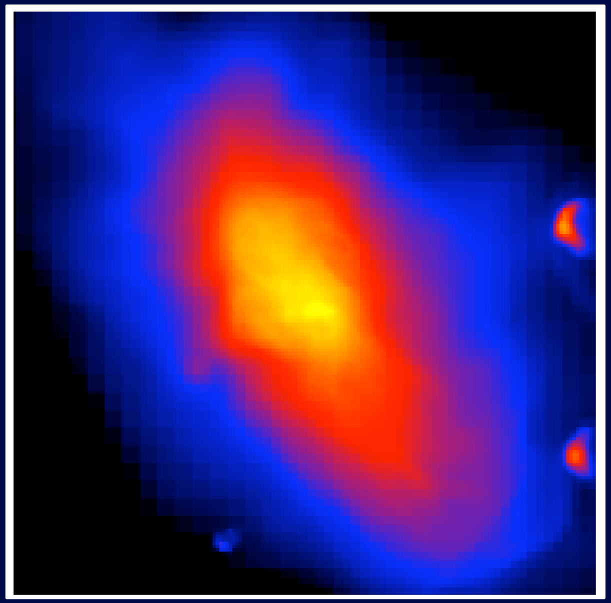

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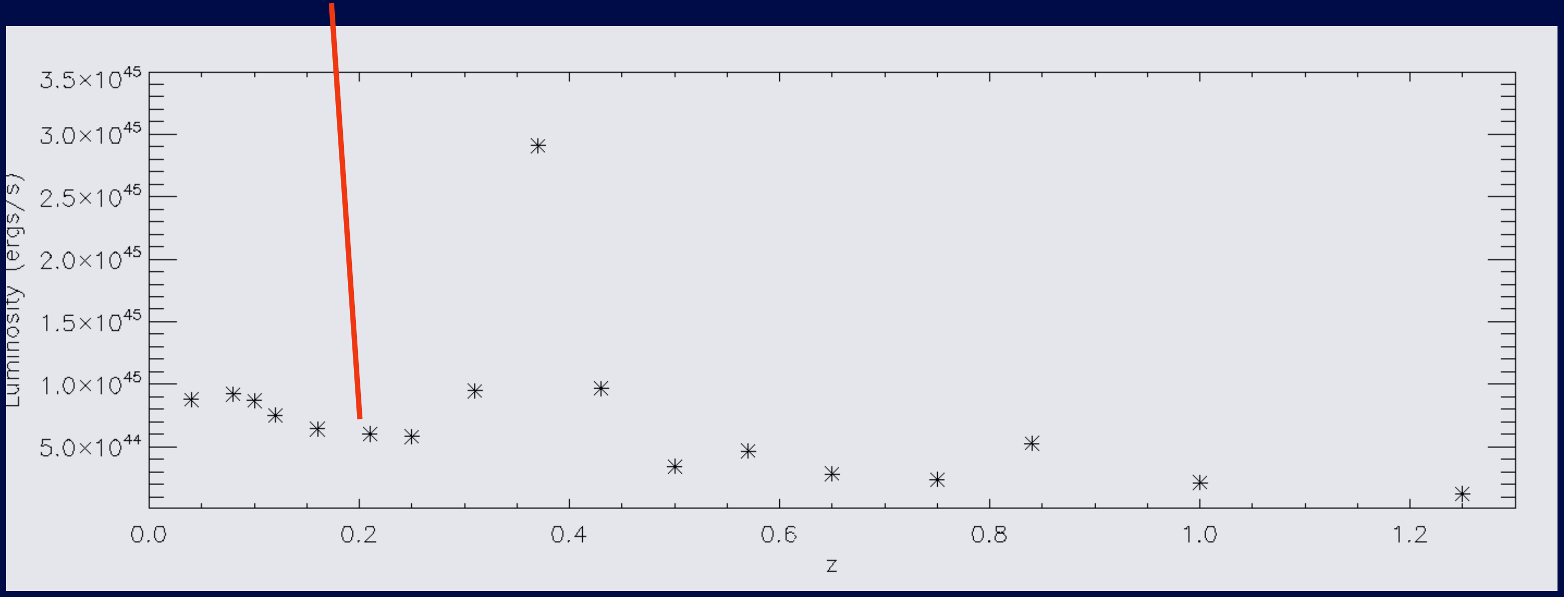

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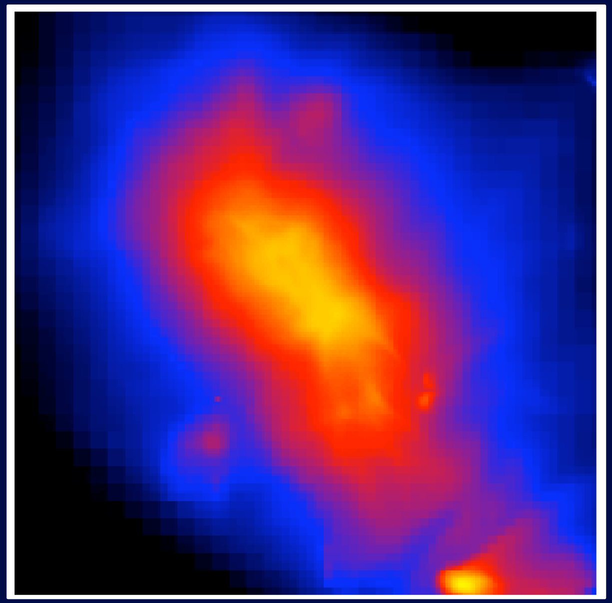

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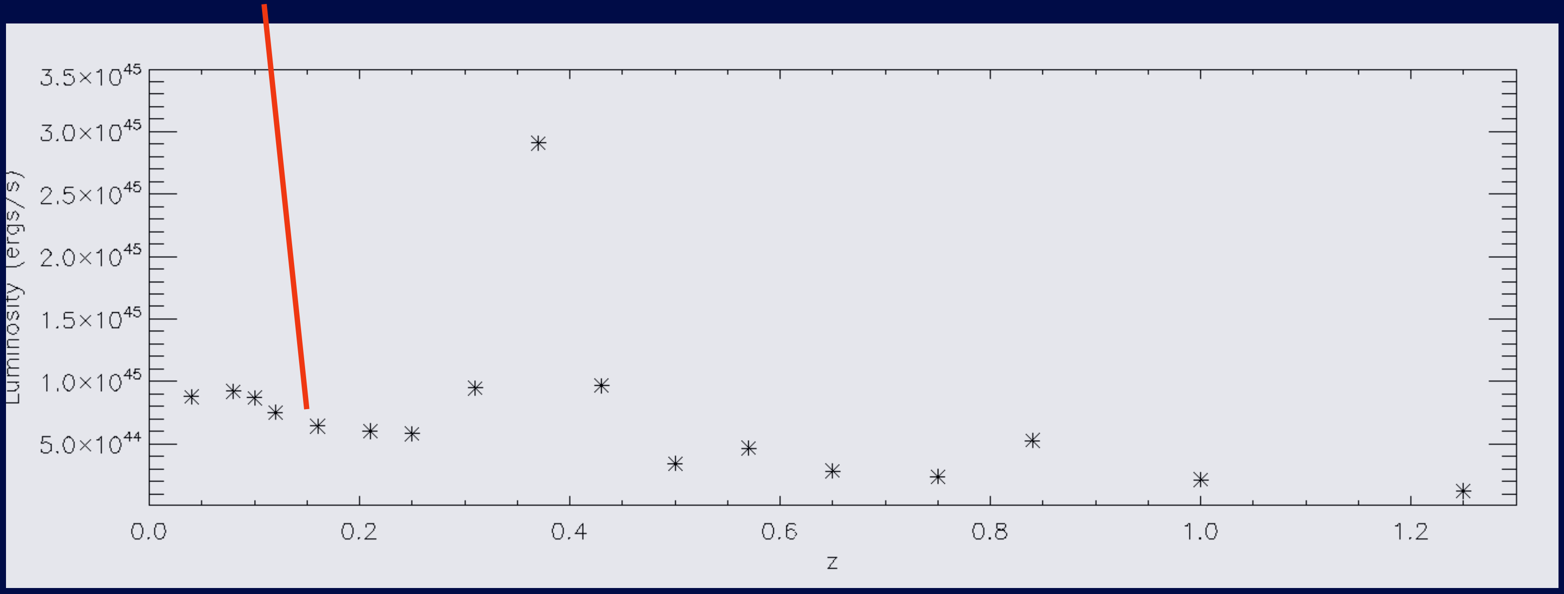

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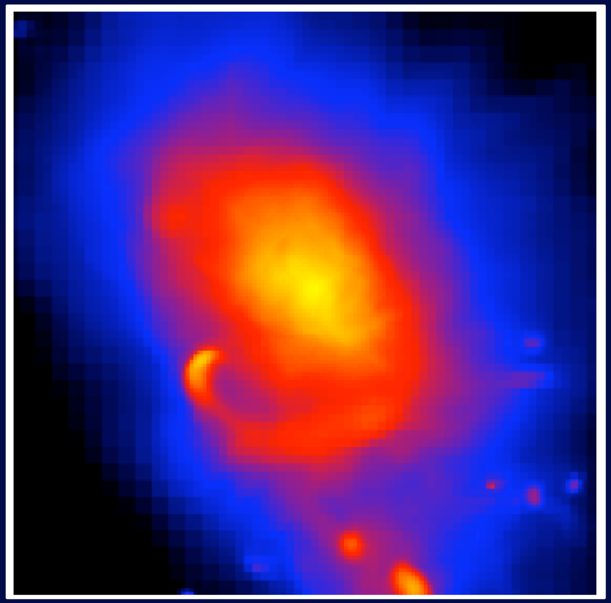

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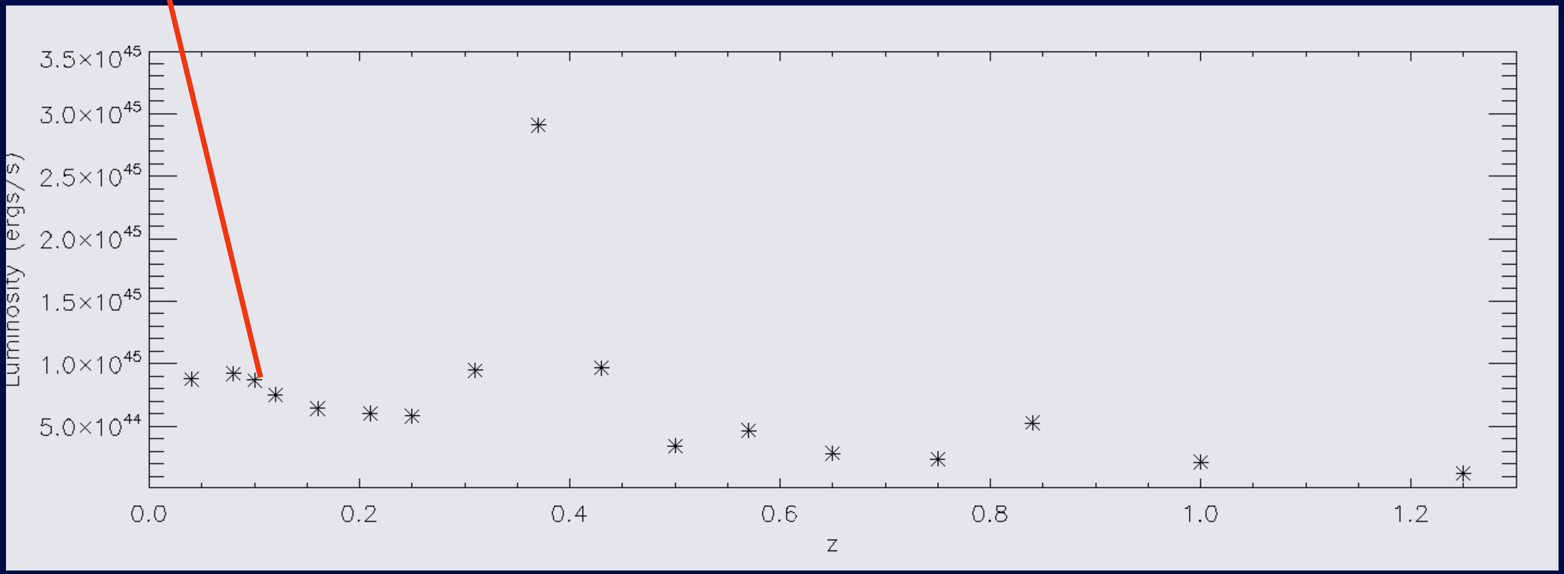

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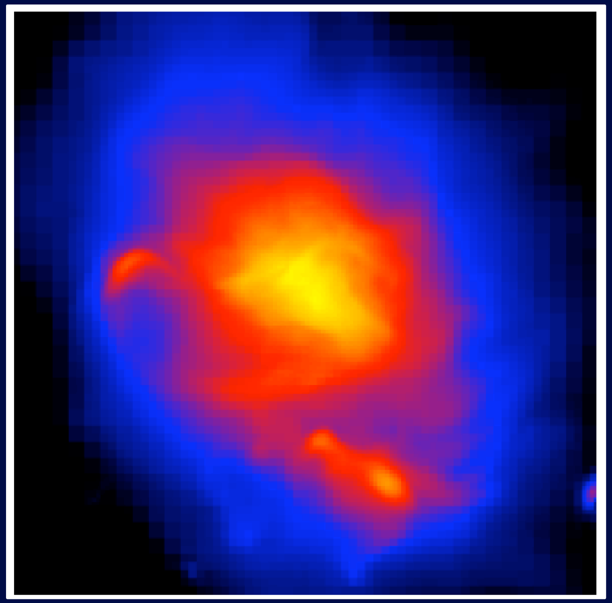

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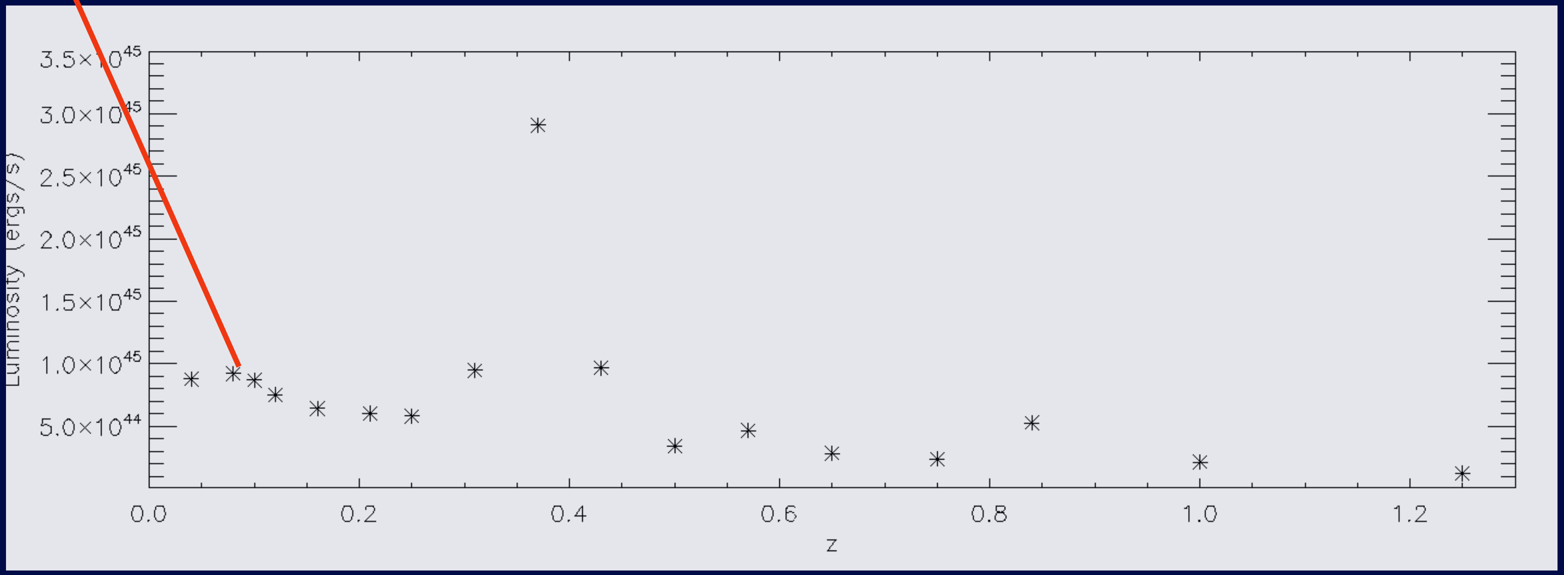

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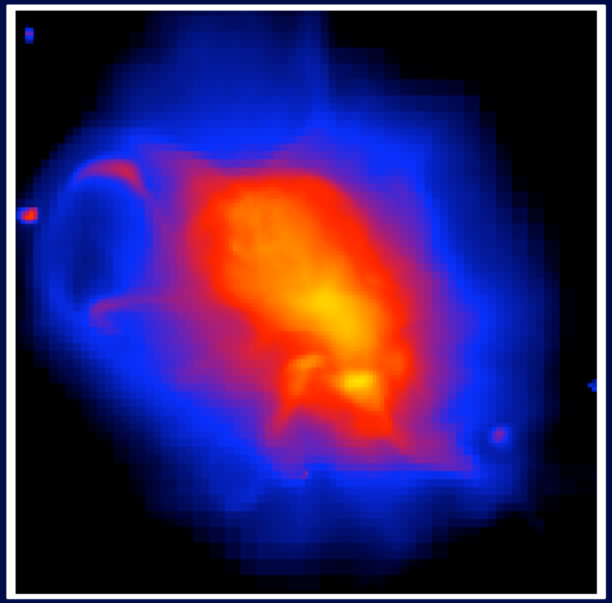

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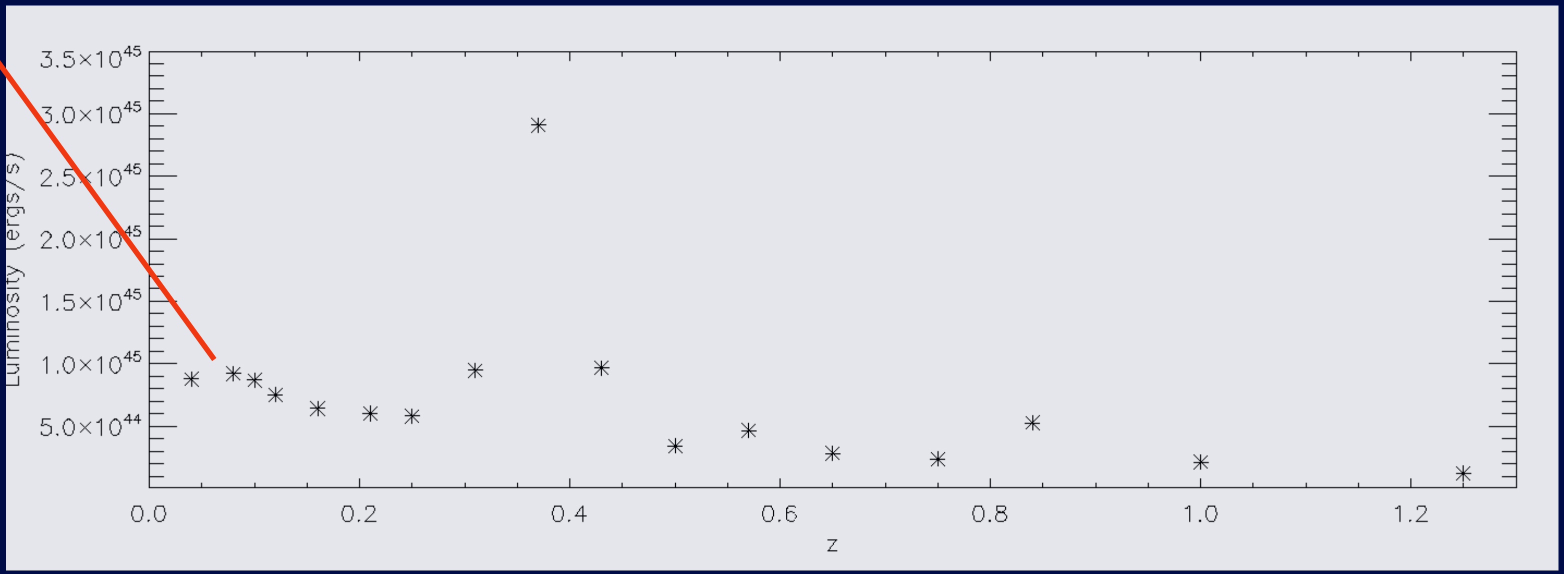

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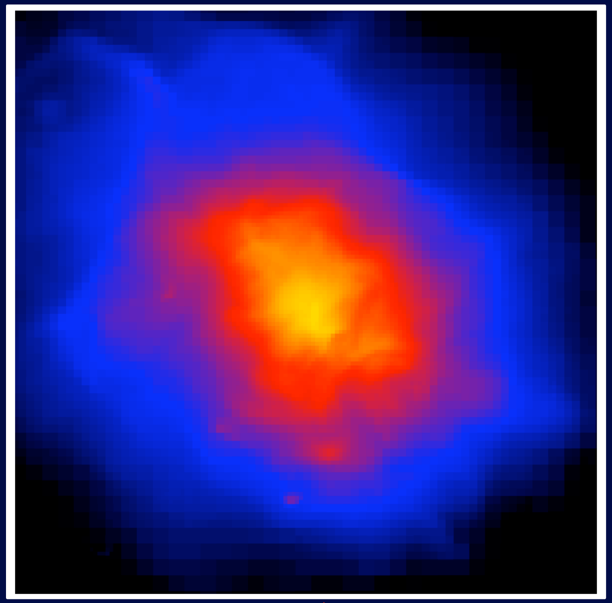

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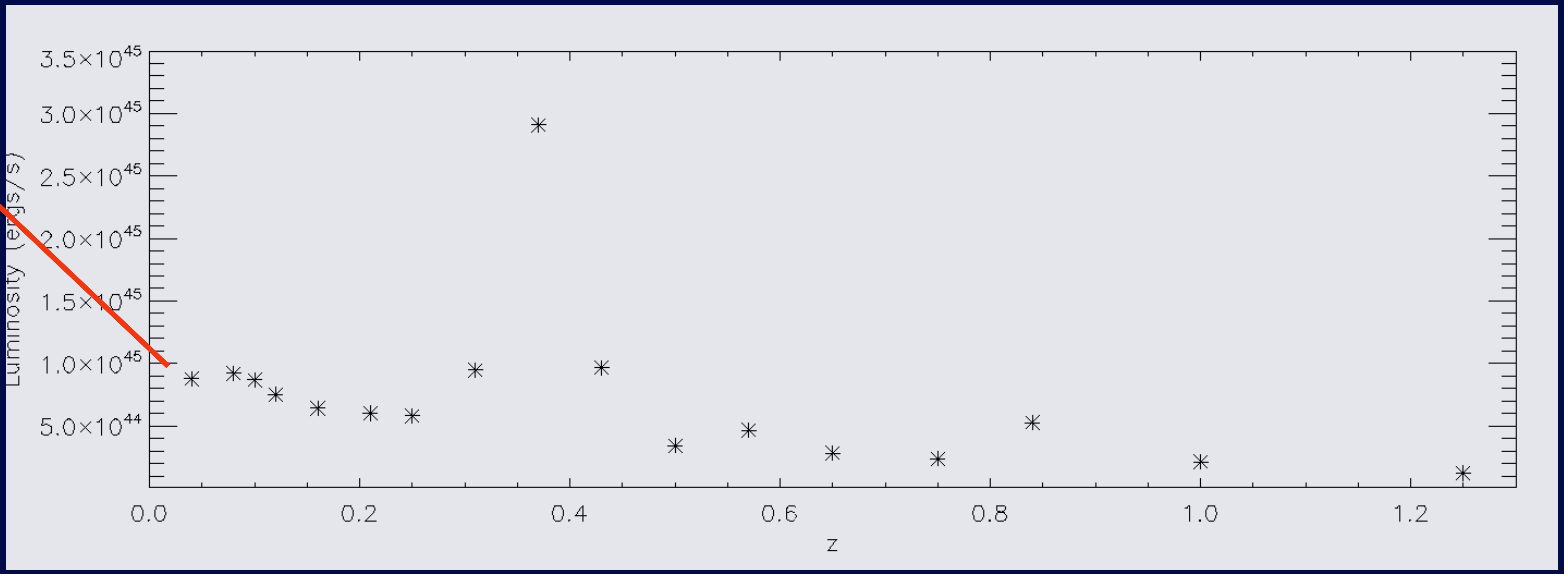
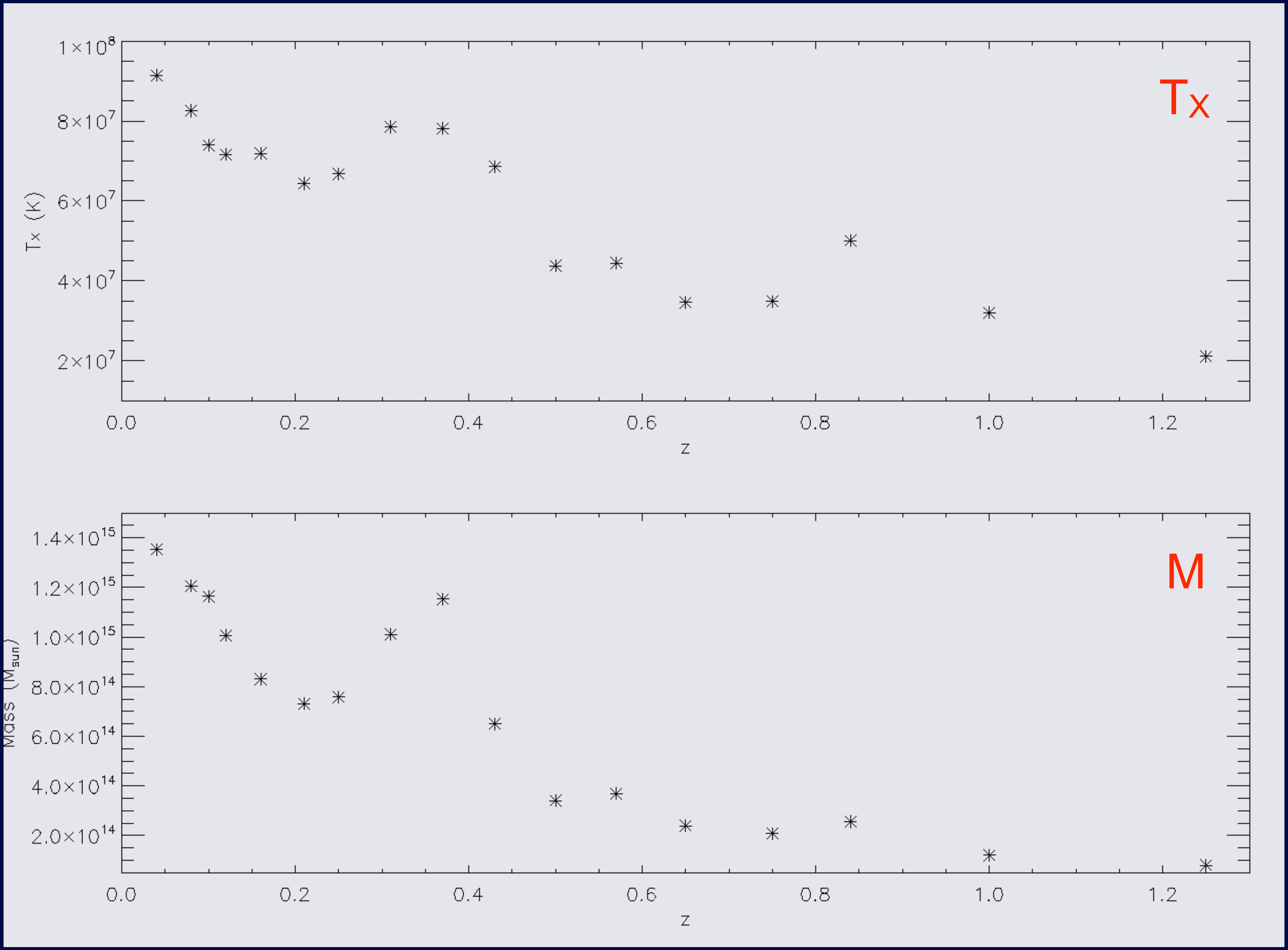
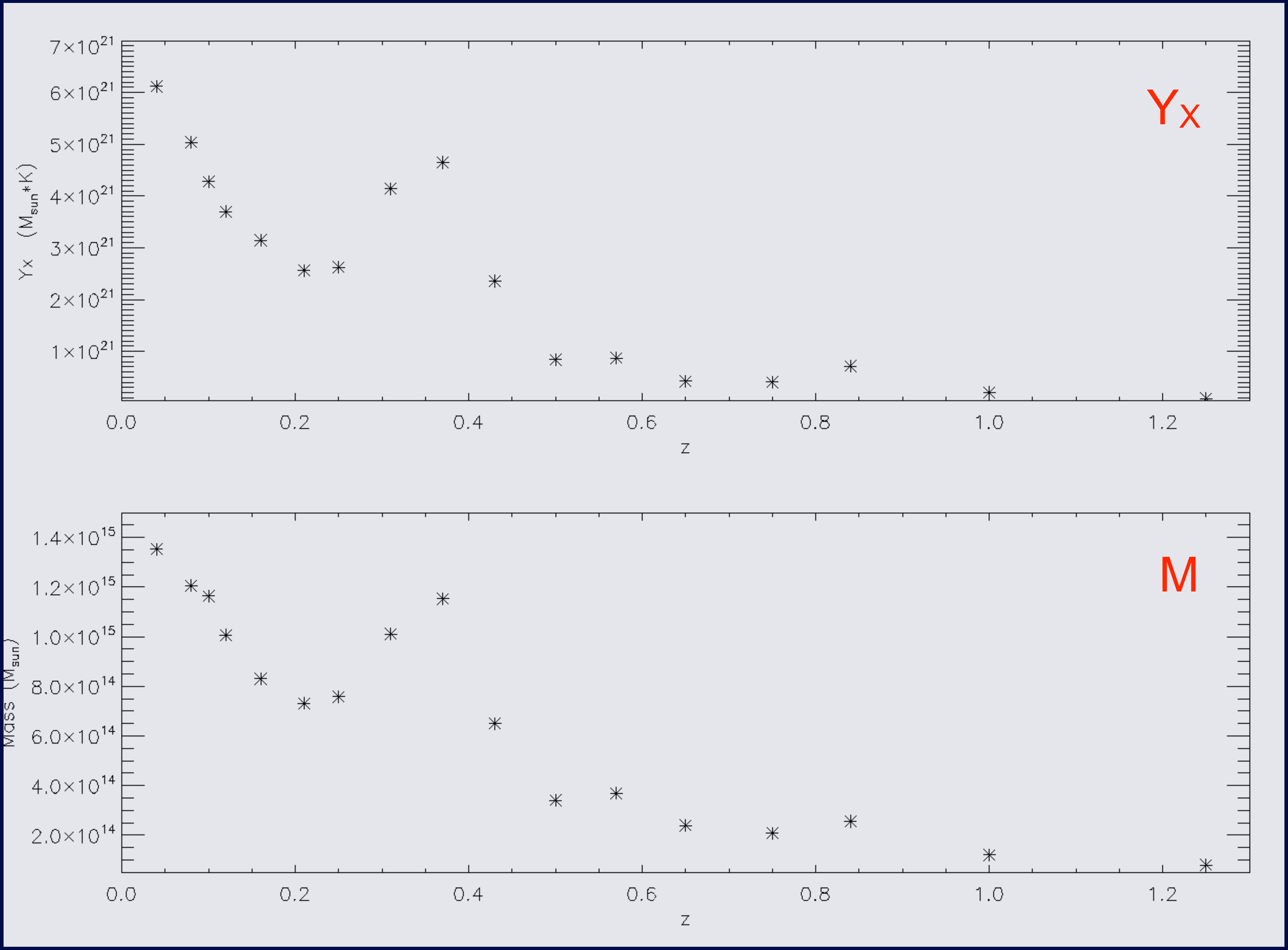


Mass vs. Temperature Evolution



Mass vs. Y_X Evolution

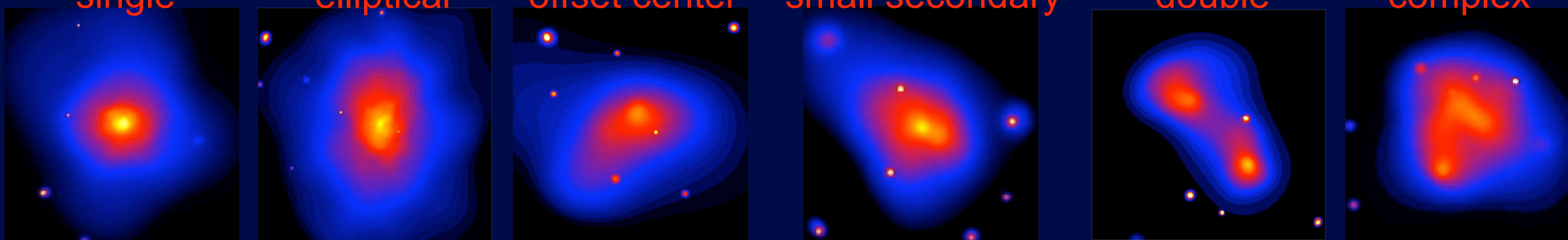


$Y_X = M_g T_X$, similar to integrated SZ flux and proportional to the total thermal energy of the cluster.

see Motl et al. 2005, Kravtsov et al. 2006

Measuring Structure: Centroid Shift and Power Ratios

- Jones & Foreman (1992):



- Centroid or Center-of-mass shift

  (Mohr et al 1995, Poole et al. 2006, Maughan et al. 2007)

  – Calculate centroid within R = 0.1 R_{500}, 0.15 R_{500}, ..., R_{500}.

  – Centroid shift, w, is the standard deviation of the distance between centroid and peak.

Power Ratio Method

- Constructed from moments of the X-ray surface brightness

$$a_m(R) = \int_{R' \le R} \Sigma(x')(R')^m \cos(m\phi')d^2x'$$
$$b_m(R) = \int_{R' \le R} \Sigma(x')(R')^m \sin(m\phi')d^2x'$$

$$P_0 = [a_0 \ln(R)]^2$$
$$P_m = \frac{1}{2m^2R^{2m}}\left(a_m{}^2 + b_m{}^2\right)$$

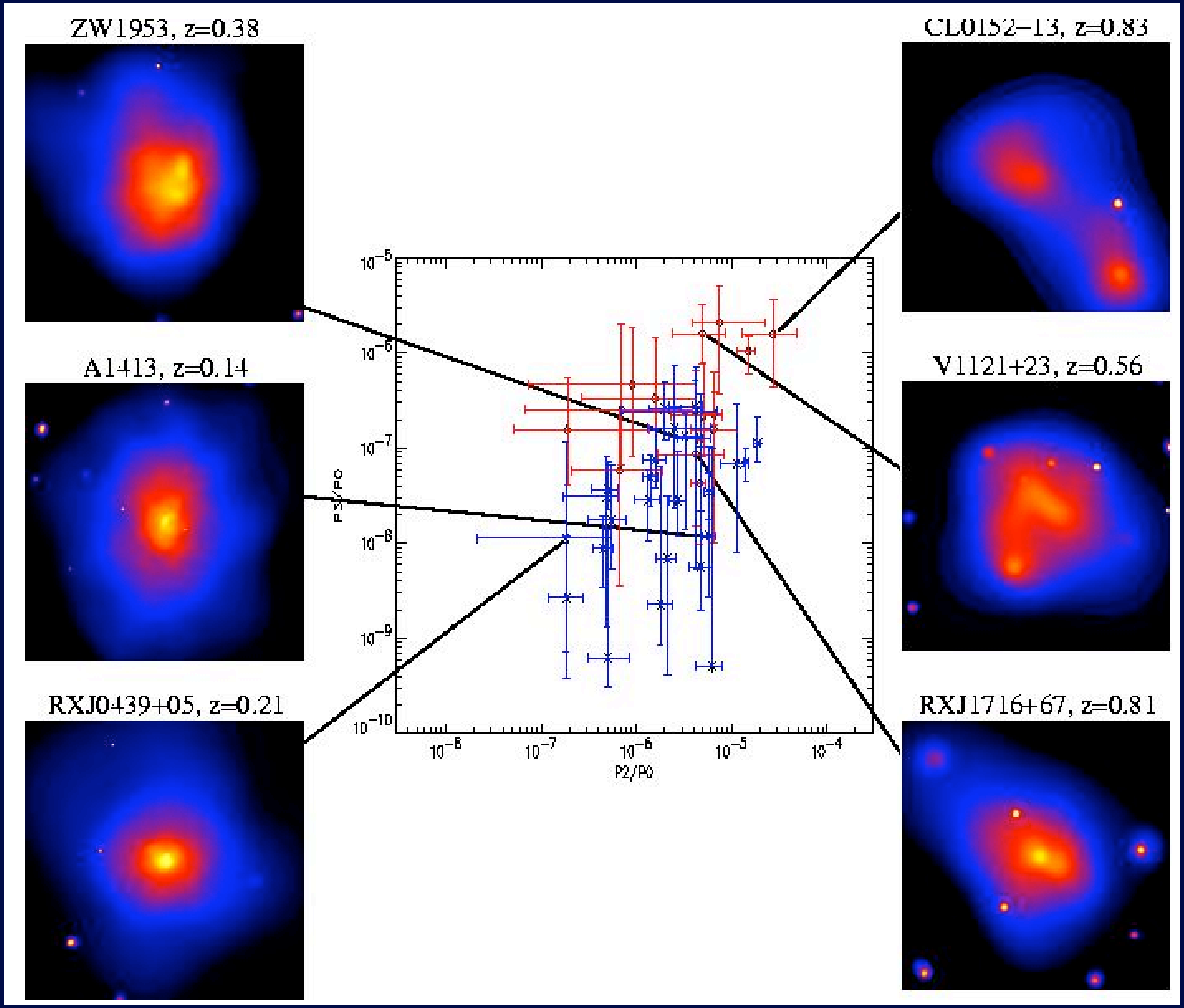
- Related to the multipole expansion of the 2D gravitational potential

$$\frac{P_m}{P_0} = \frac{\left\langle (\Psi_m)^2 \right\rangle}{\left\langle (\Psi_0)^2 \right\rangle}$$

- Calculate P_2/P_0, P_3/P_0, and P_4/P_0 within R_{500} centered on the cluster centroid (where $P_1/P_0 = 0$).

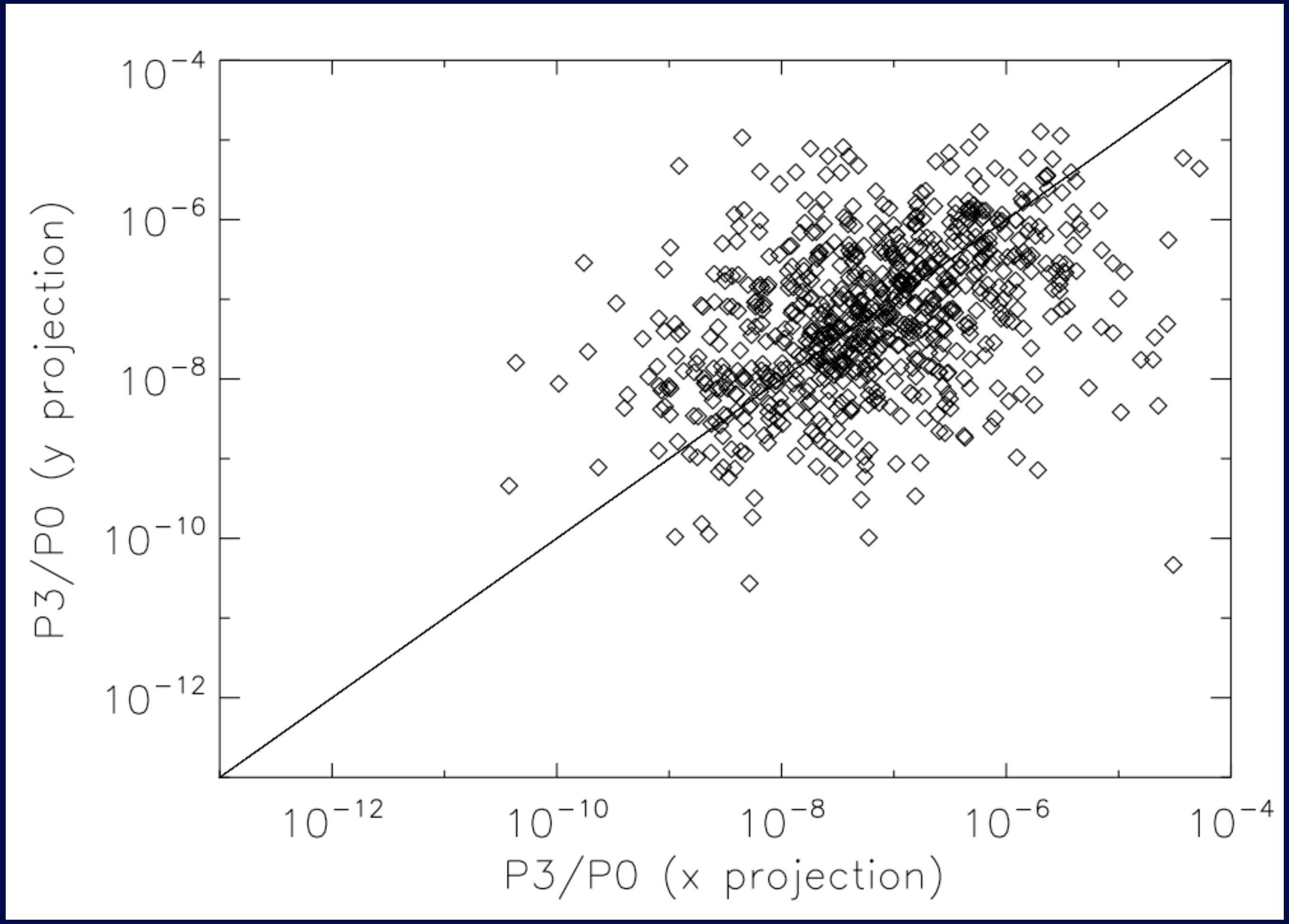
Buote & Tsai 1995, 1996

P_2/P_0 vs. P_3/P_0



Jeltema et al. 2005

Projection: Problem #1



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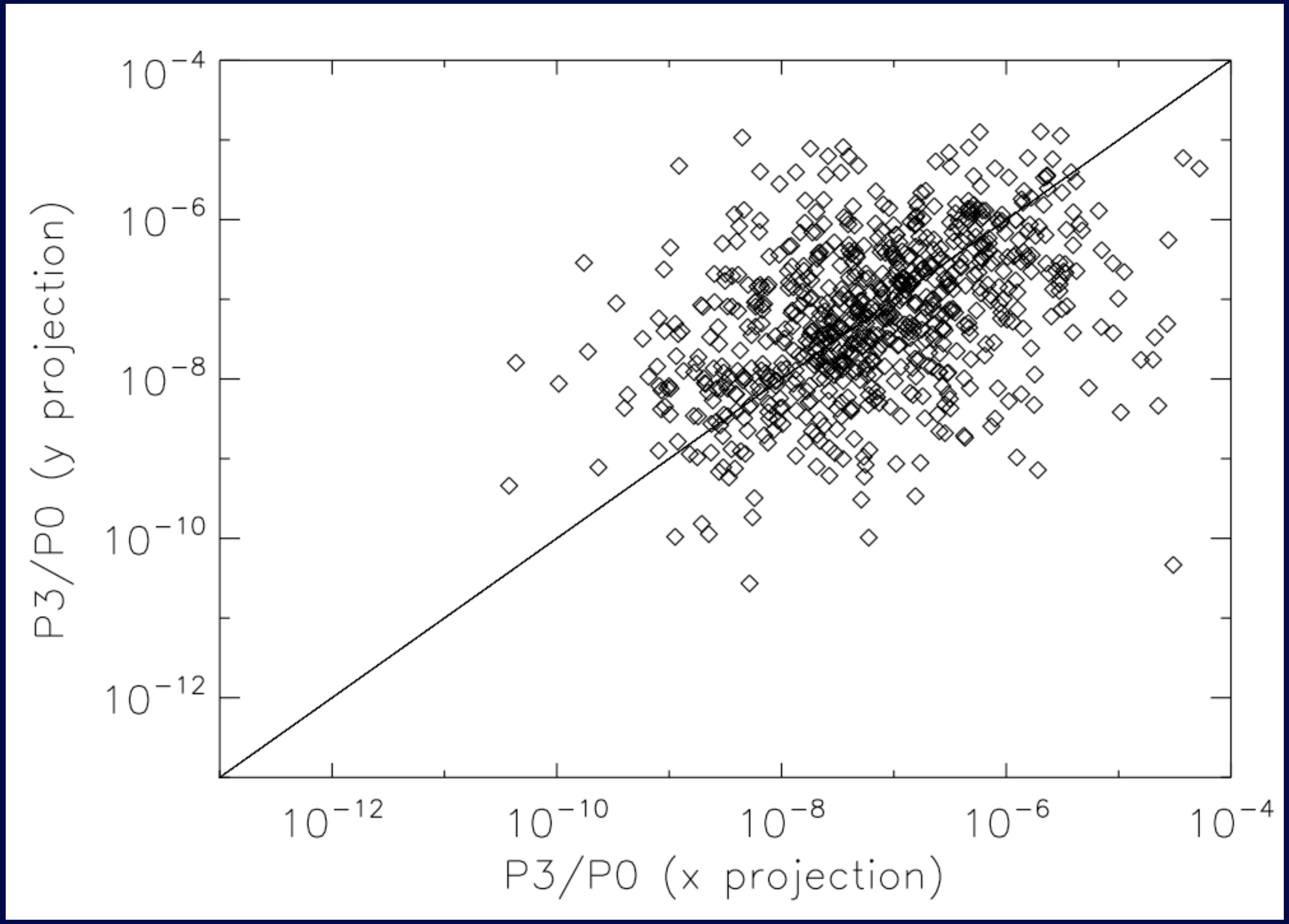
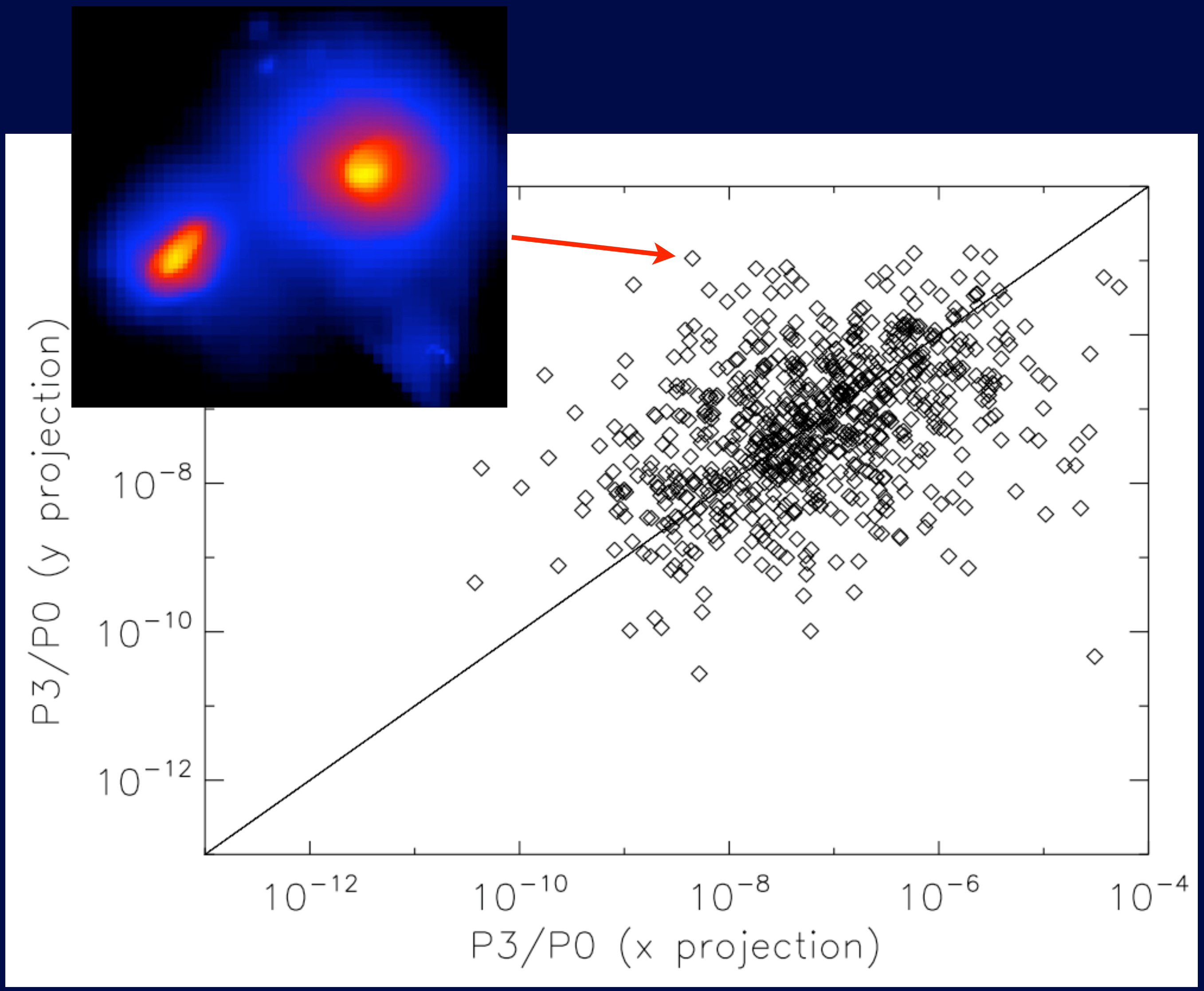


- 38% of "relaxed" clusters are relaxed in all projections. (45% for centroid shift)

relaxed: single, lowest ~20% of power ratios ($P_3/P_0 < 1.5 \times 10^{-8}$)
disturbed: major merger, highest ~20% of power ratios ($P_3/P_0 > 4.5 \times 10^{-7}$)

Projection: Problem #1



- 38% of "relaxed" clusters are relaxed in all projections. (45% for centroid shift)

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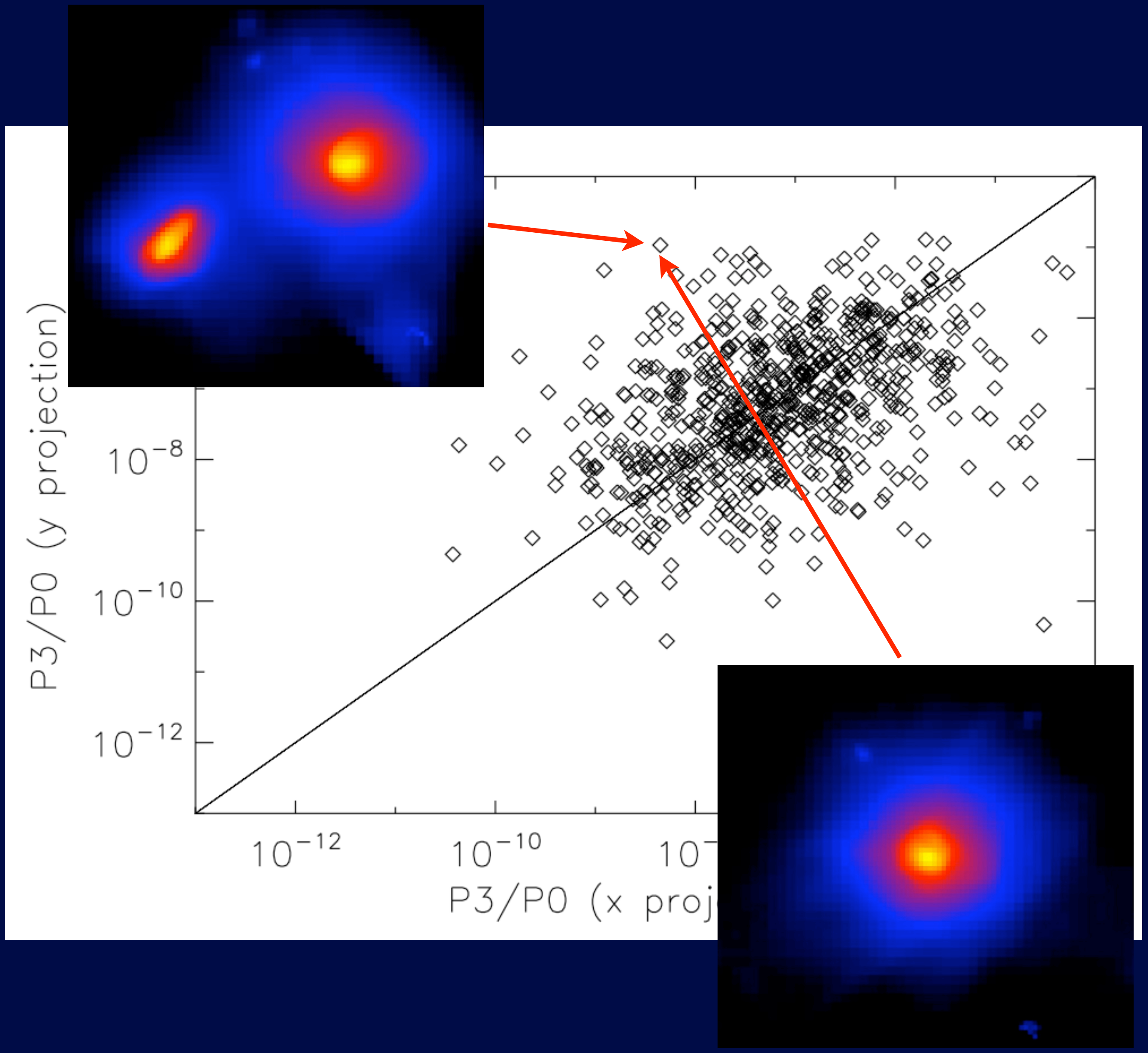

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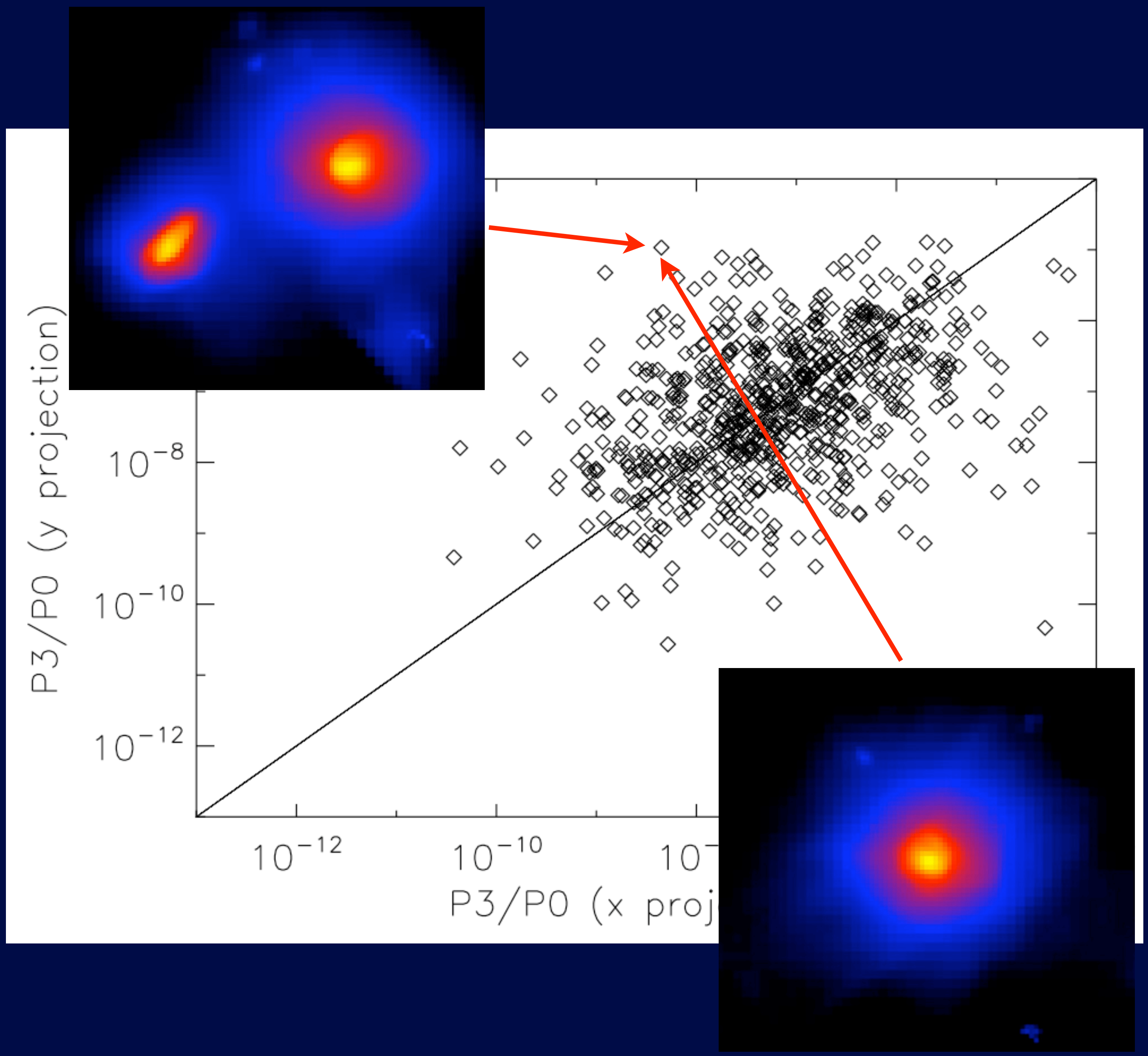
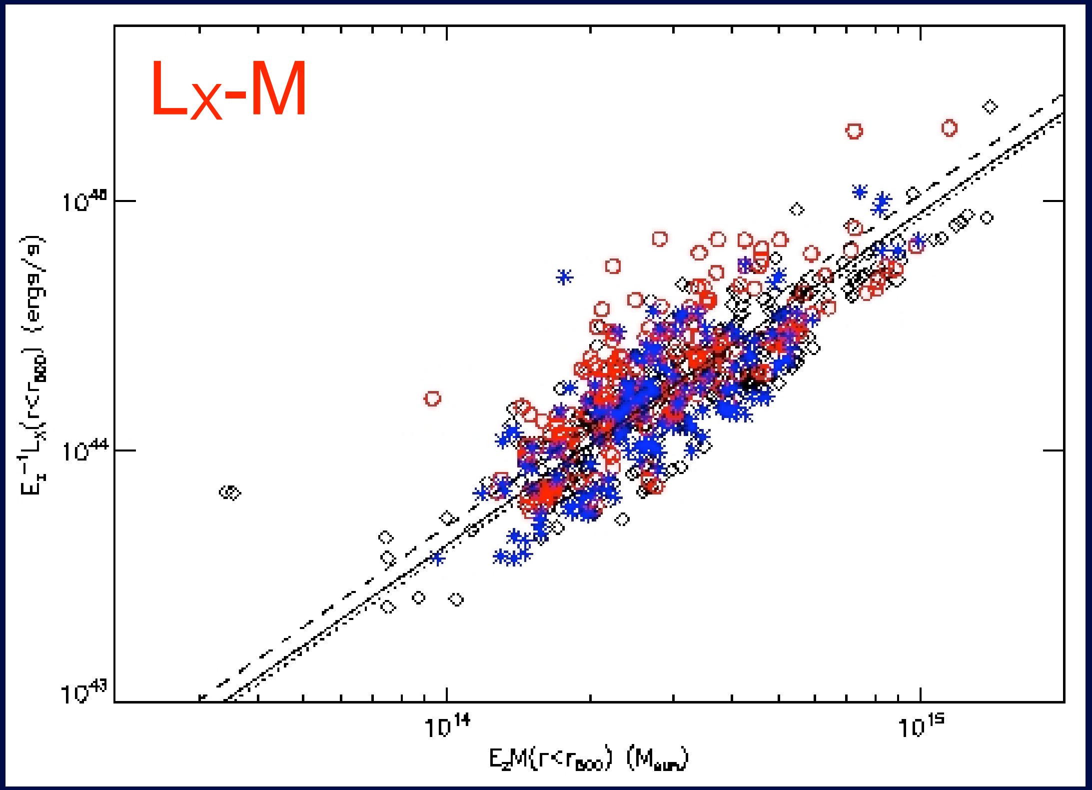
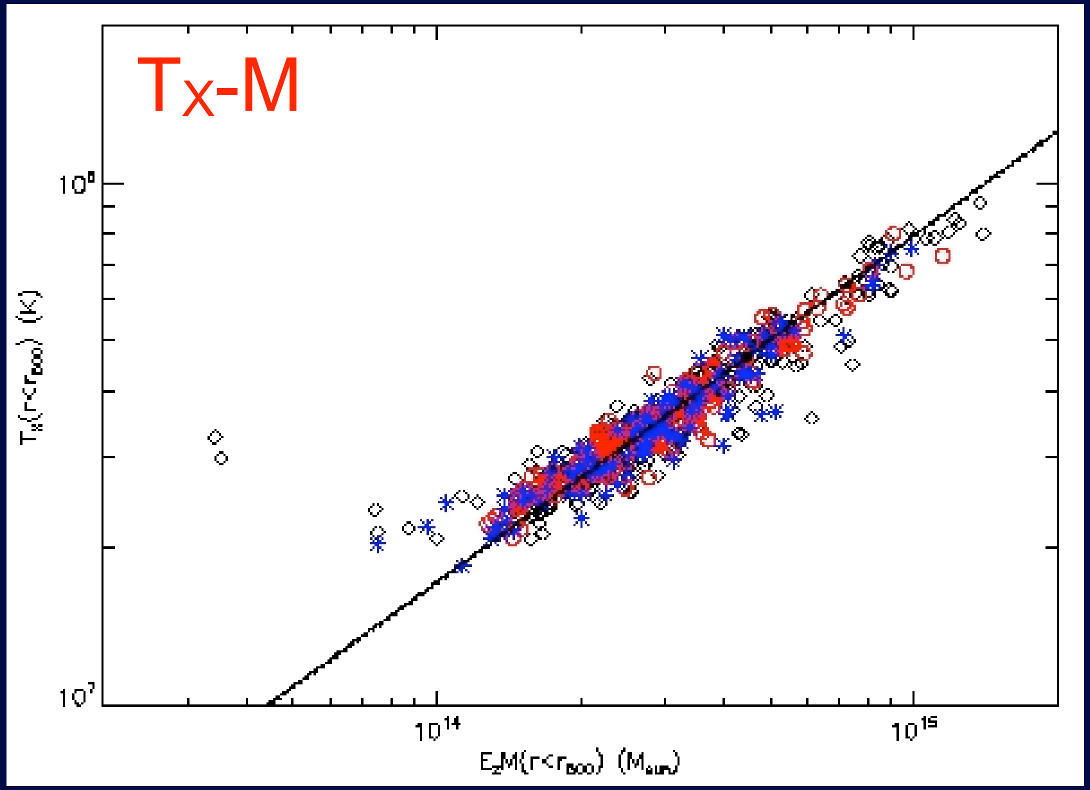


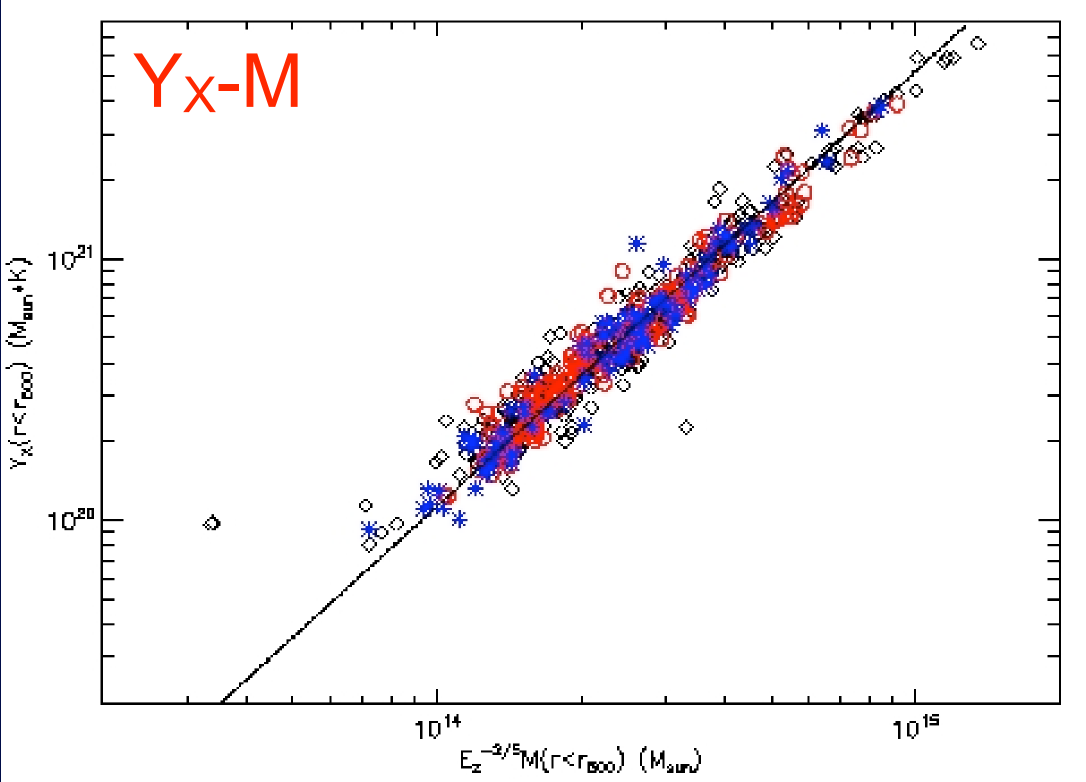
- 38% of “relaxed” clusters are relaxed in all projections. (45% for centroid shift)
- 8% of “relaxed” clusters are actually disturbed. (4% for centroid shift)

relaxed: single, lowest ~20% of power ratios ($P_3/P_0 < 1.5 \times 10^{-8}$)
disturbed: major merger, highest ~20% of power ratios ($P_3/P_0 > 4.5 \times 10^{-7}$)

Mass Scaling Relations







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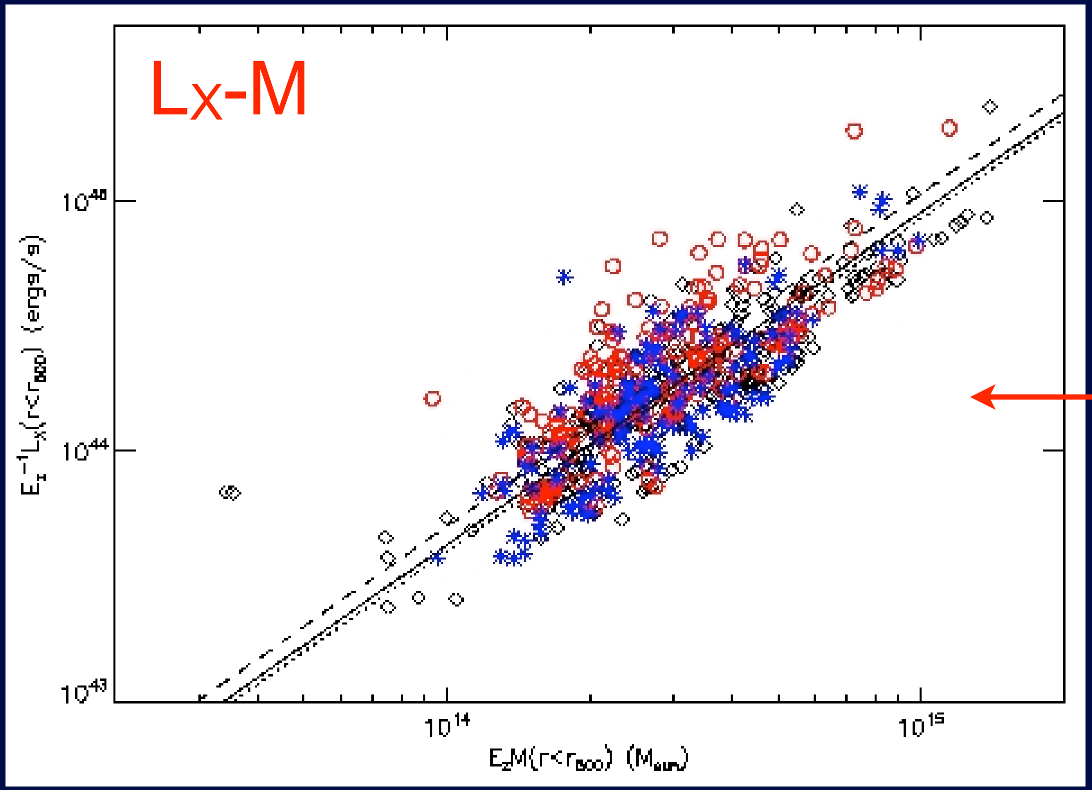
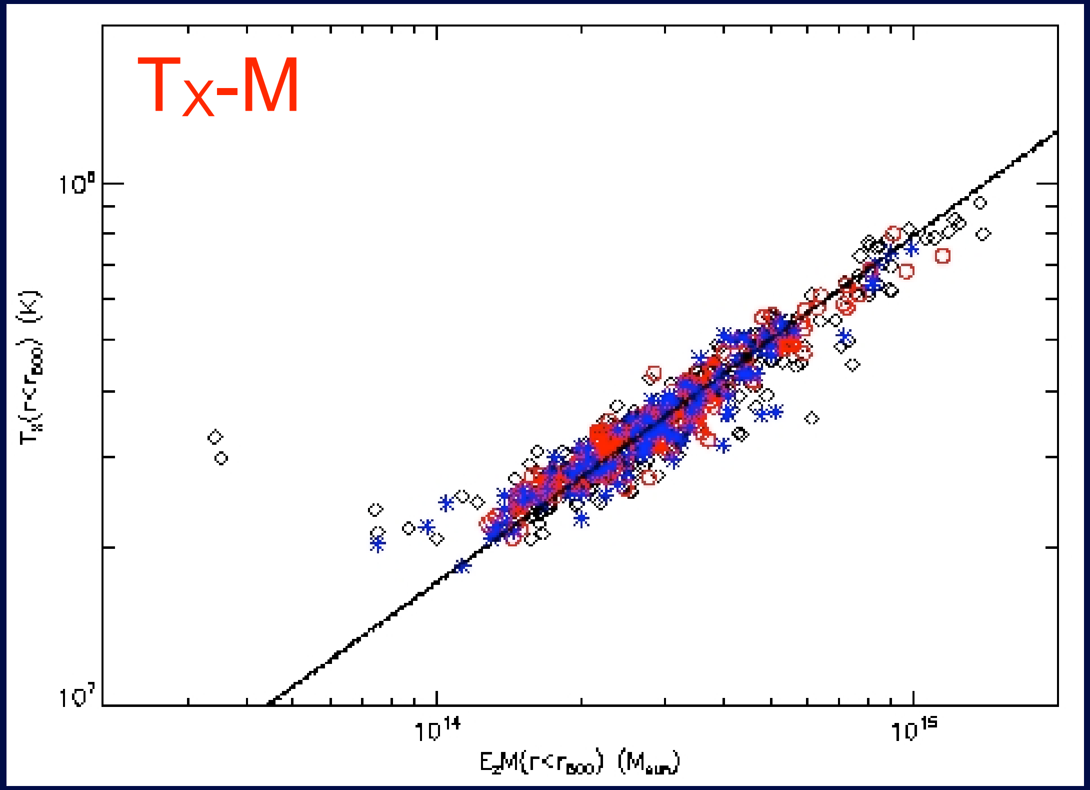
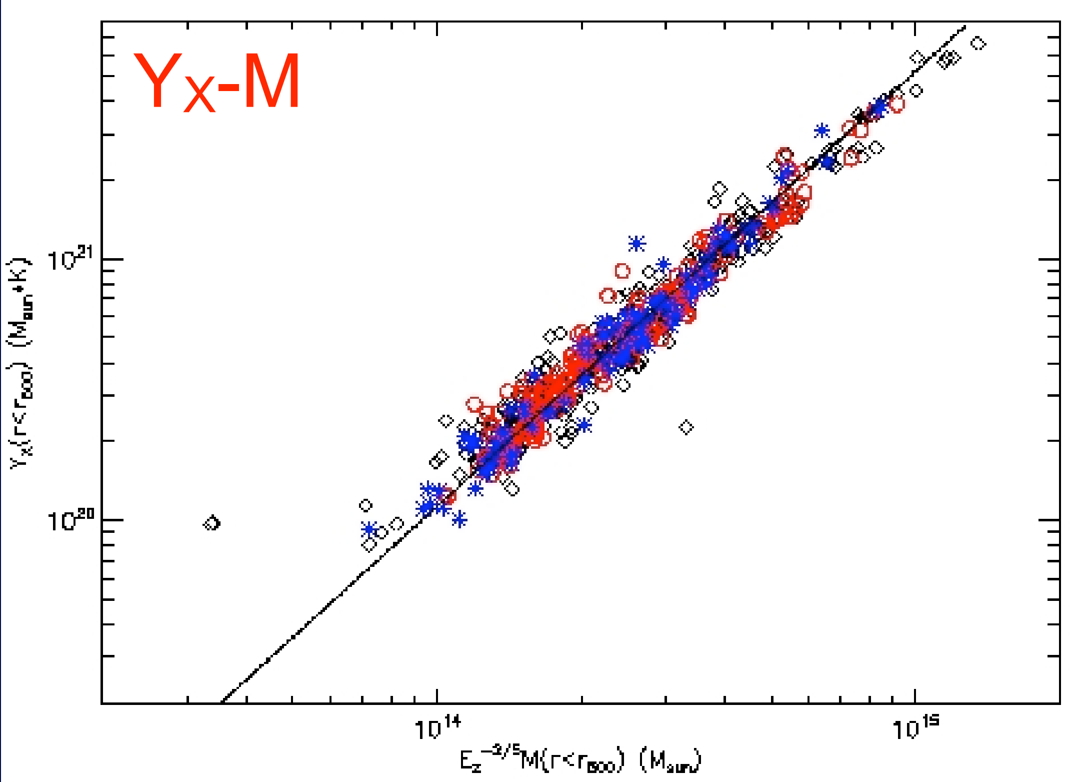


Relaxed clusters more luminous

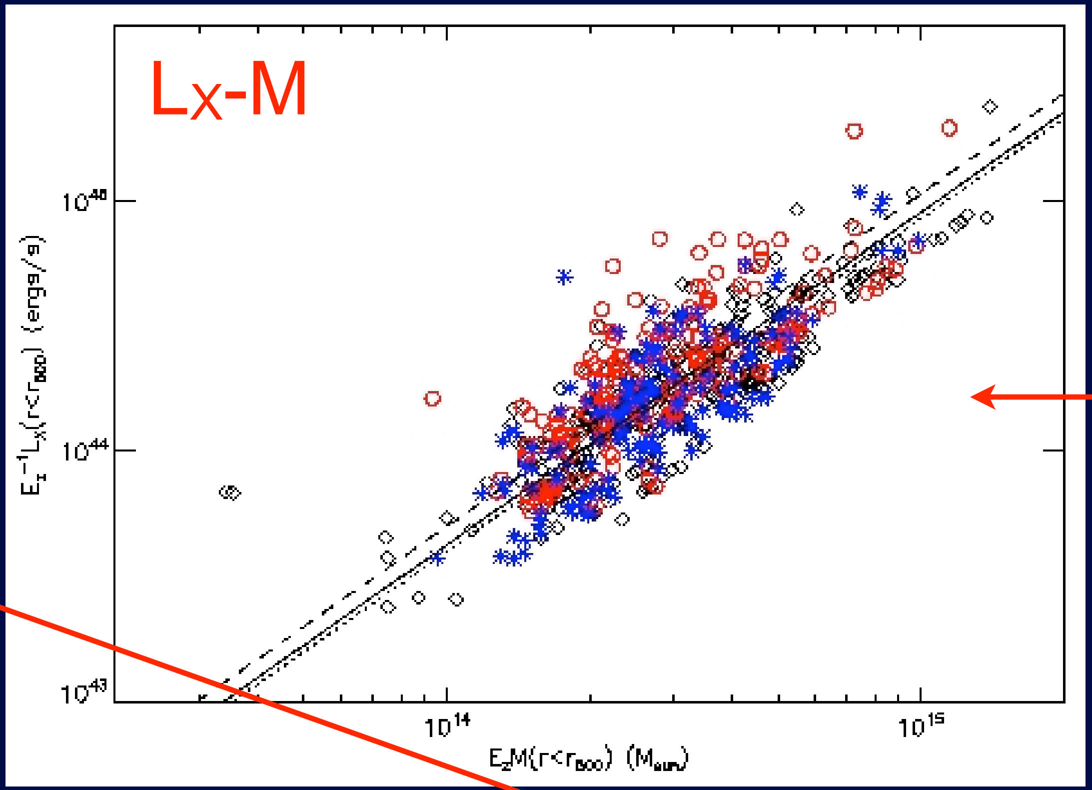


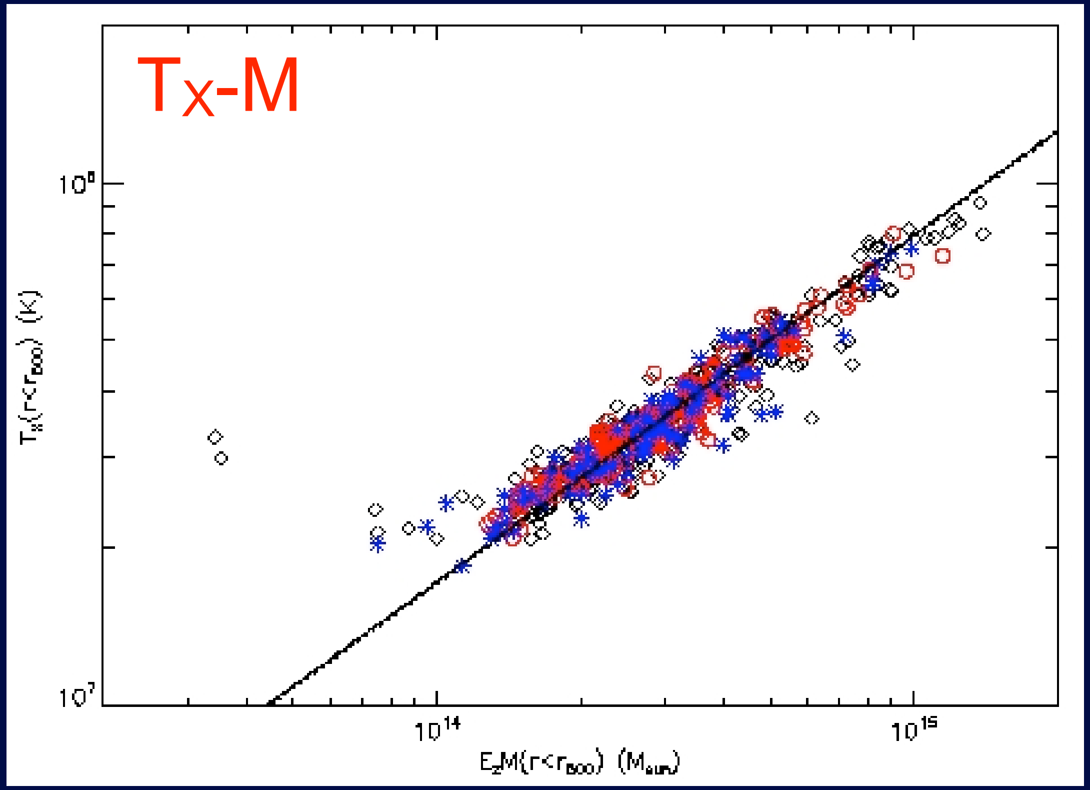


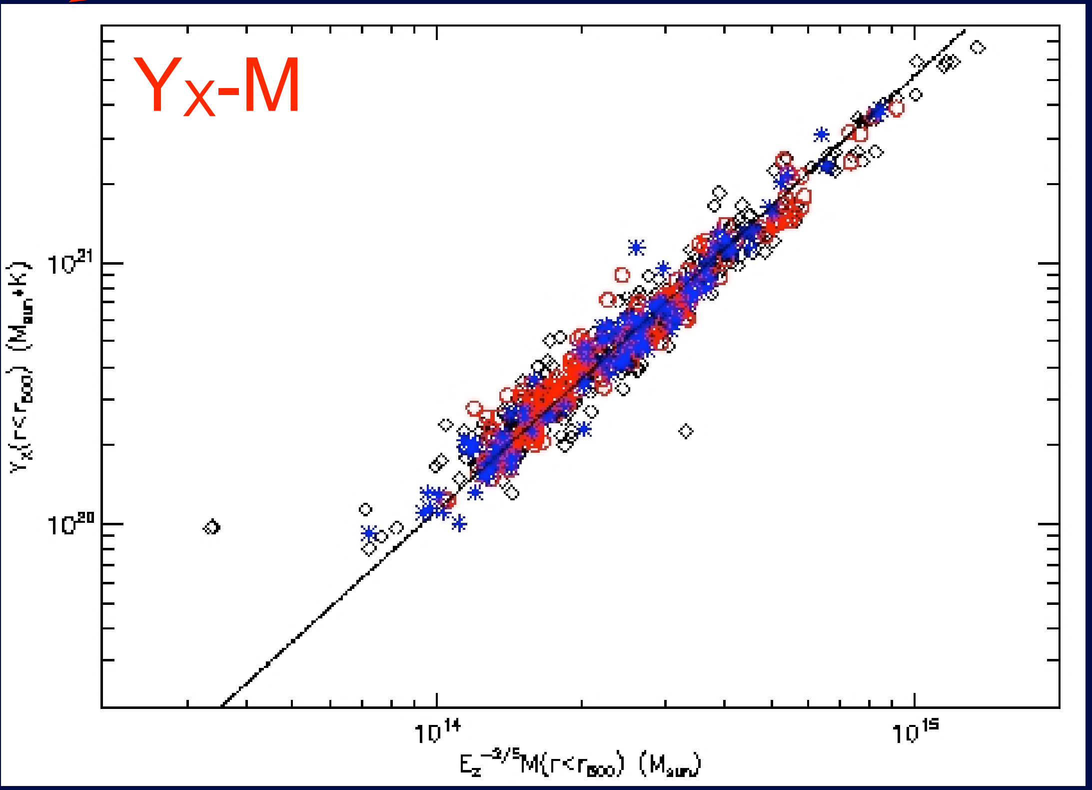
Mass Scaling Relations

No significant offset in T_X or Y_X

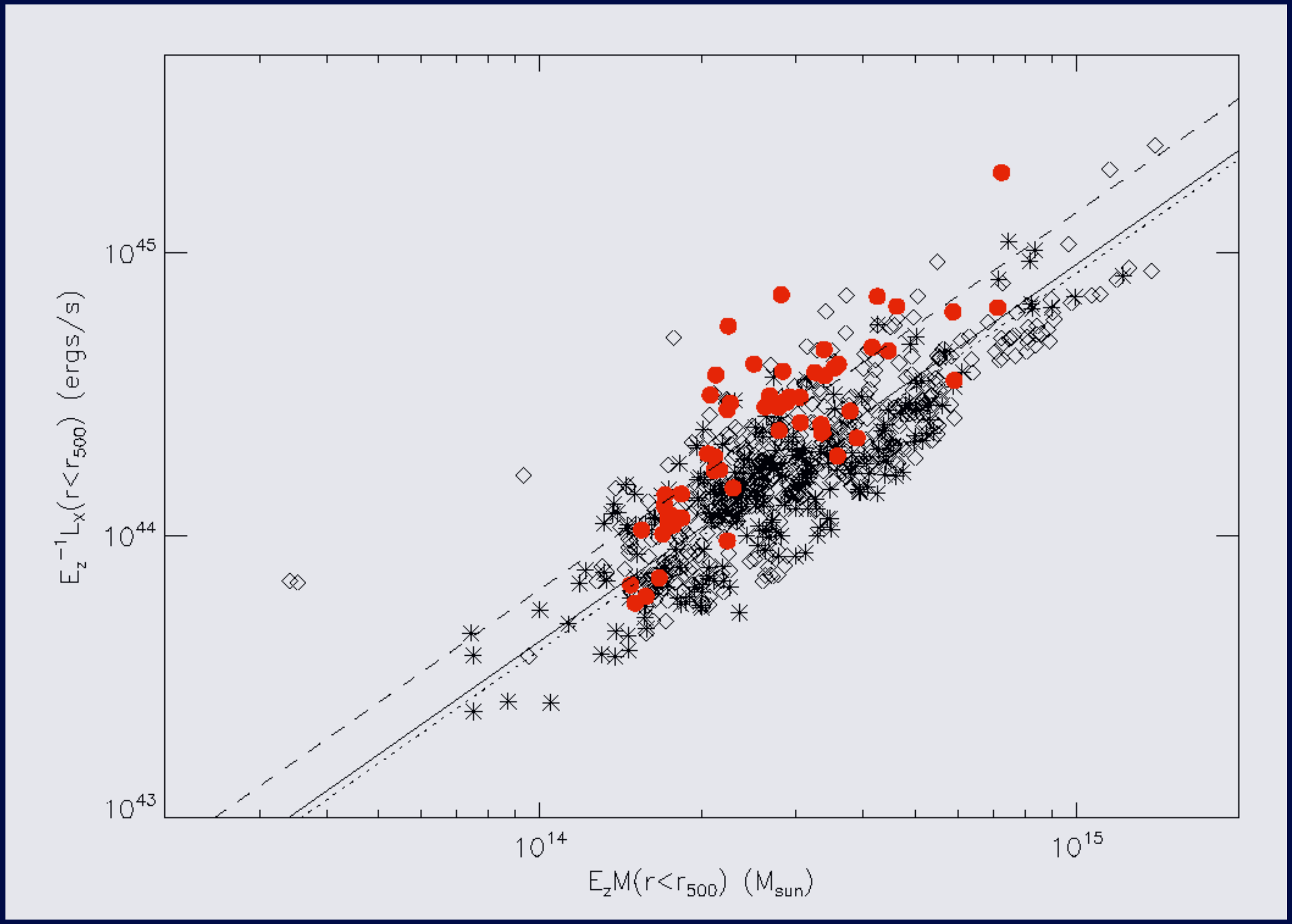
Relaxed clusters more luminous

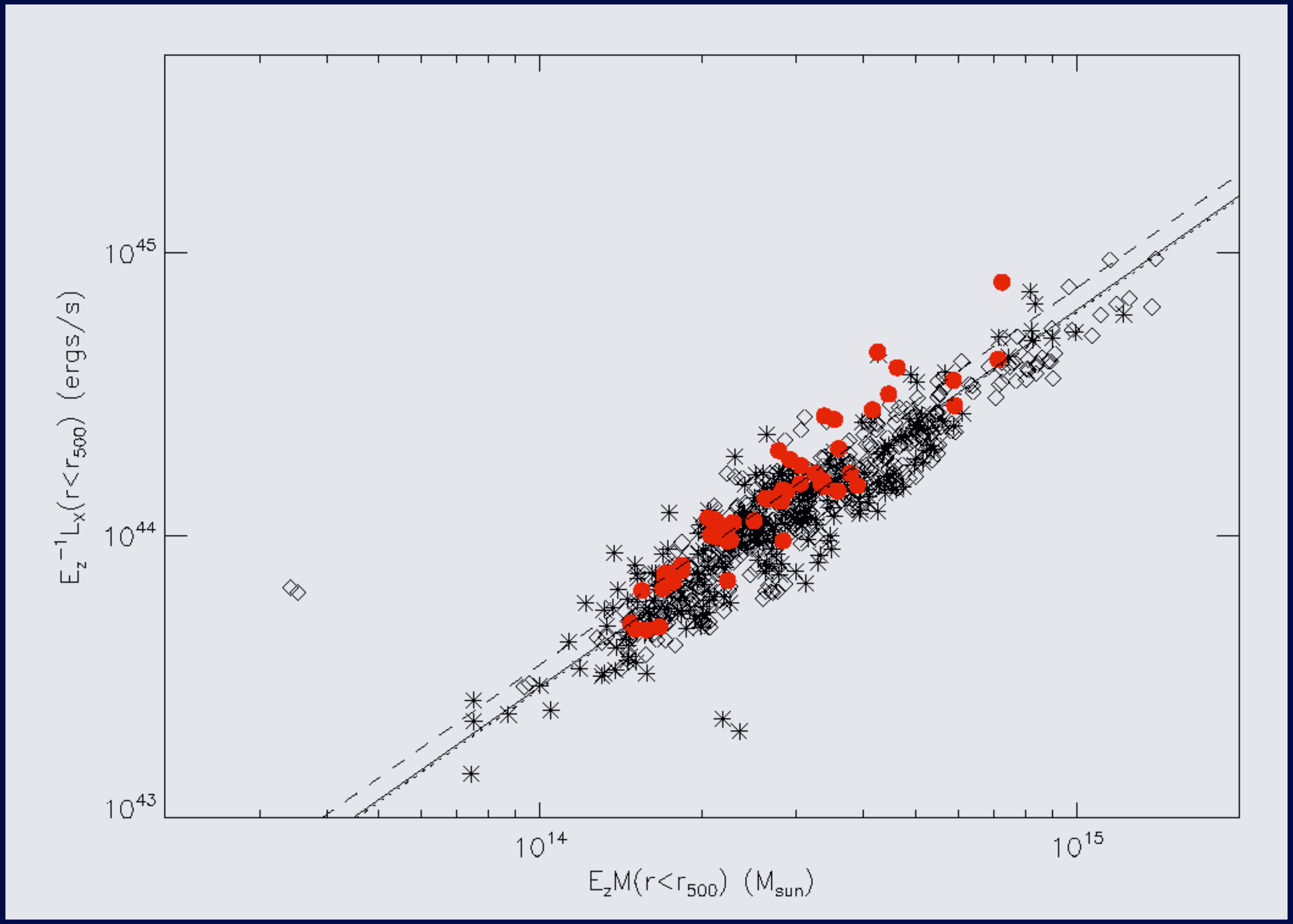






L_X-M: Effect of Cool Cores

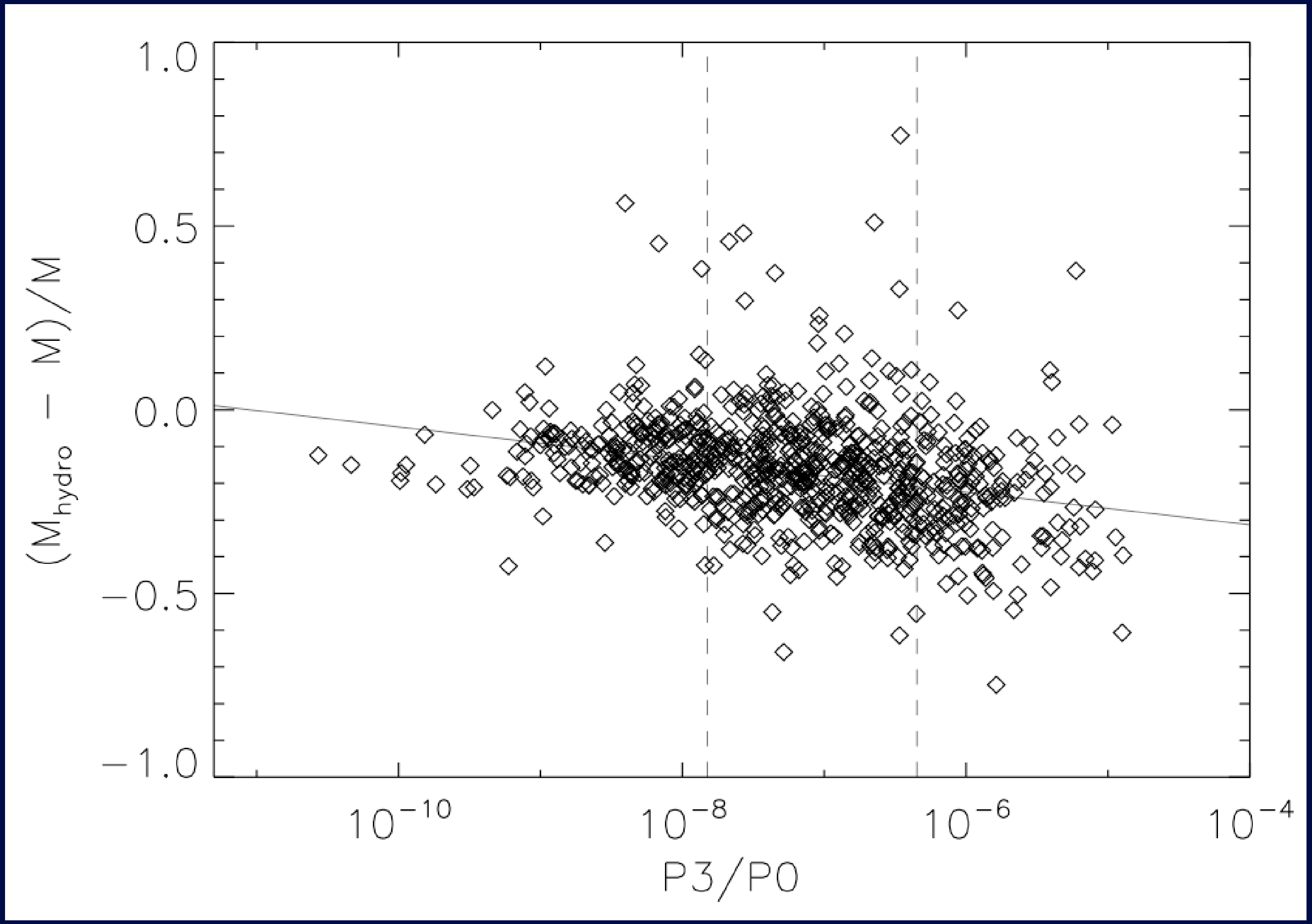




- Cool cores significantly increase luminosity and scatter in the L_X-M relation.

Mass Assuming Hydrostatic Equilibrium: Problem #2

Mass error vs. P_3/P_0



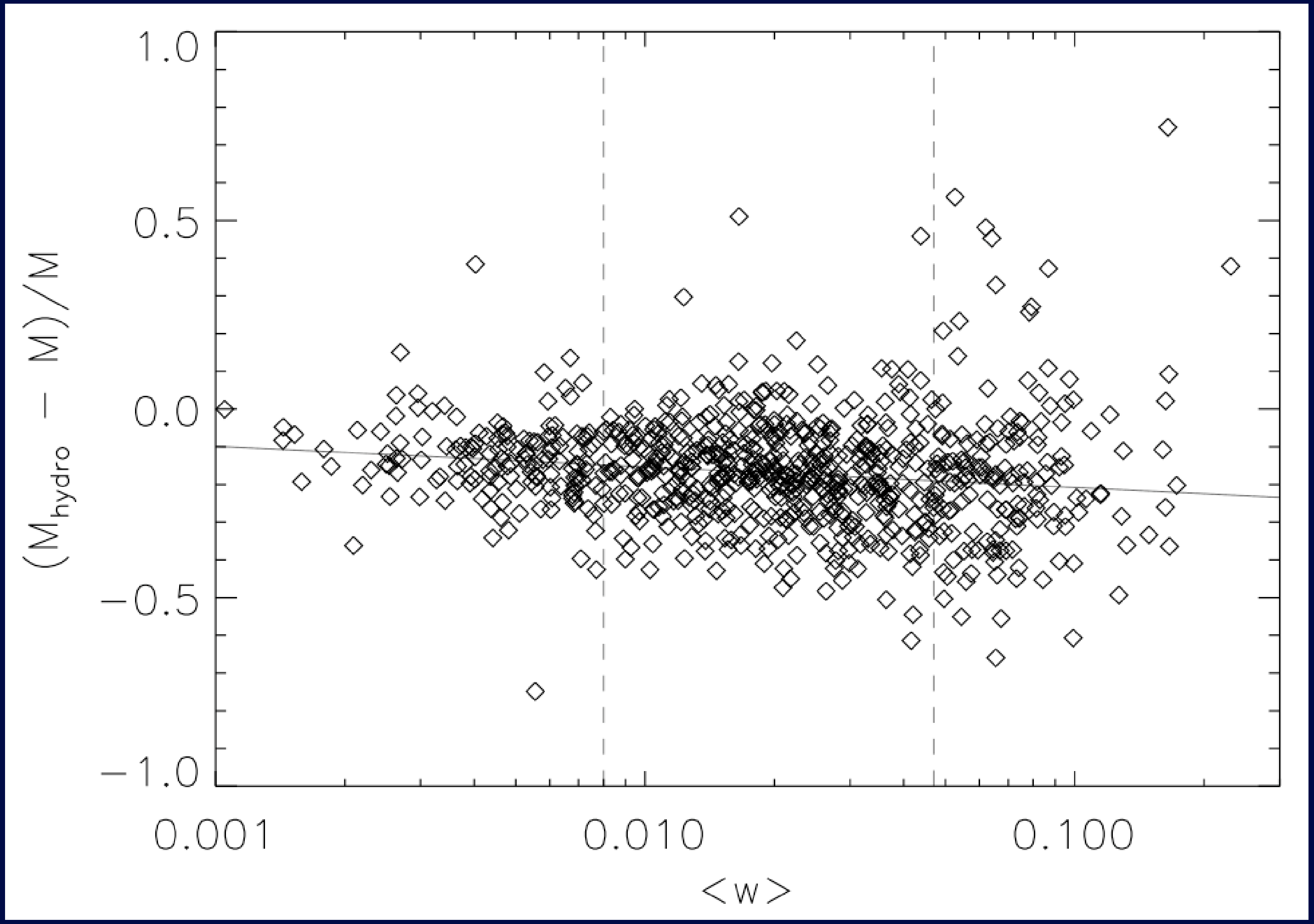
relaxed: ΔM/M ~ 12%

disturbed: ΔM/M ~ 24%

- Hydrostatic mass systematically underestimates true mass.
- Error strongly correlates with cluster structure.

Mass Assuming Hydrostatic Equilibrium: Problem #2

Mass error vs. w



similar, but weaker trend with centroid shift

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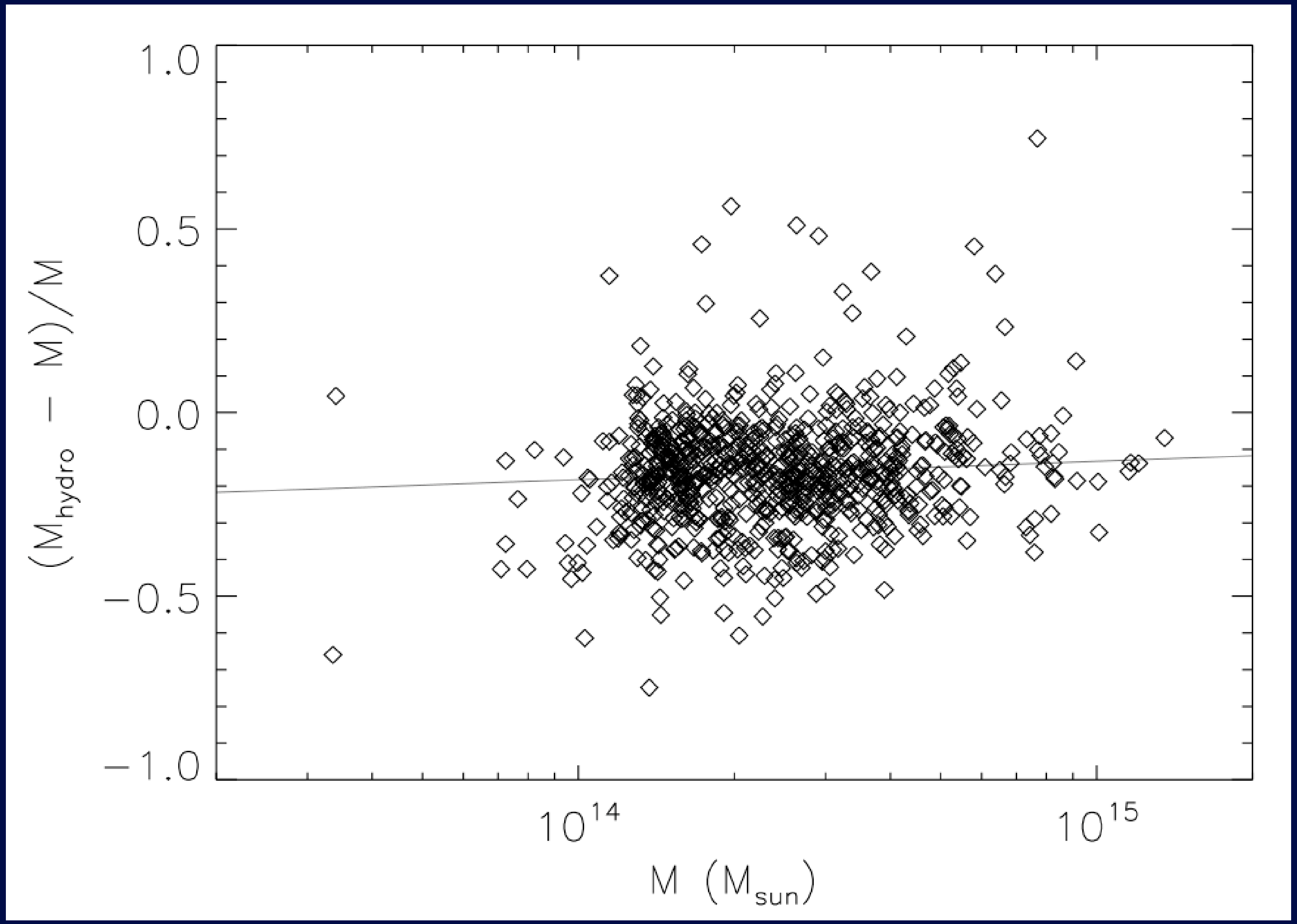
Mass Assuming Hydrostatic Equilibrium: Problem #2

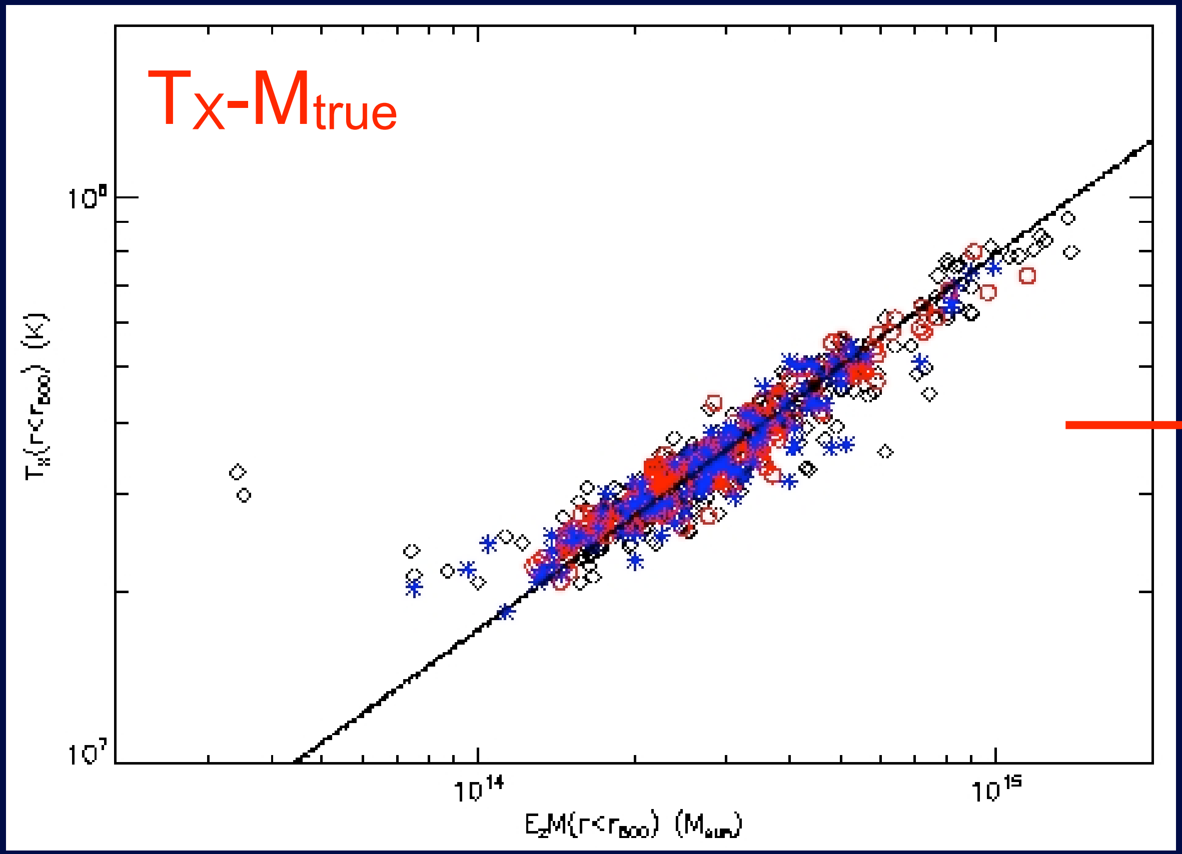
Mass error vs. M

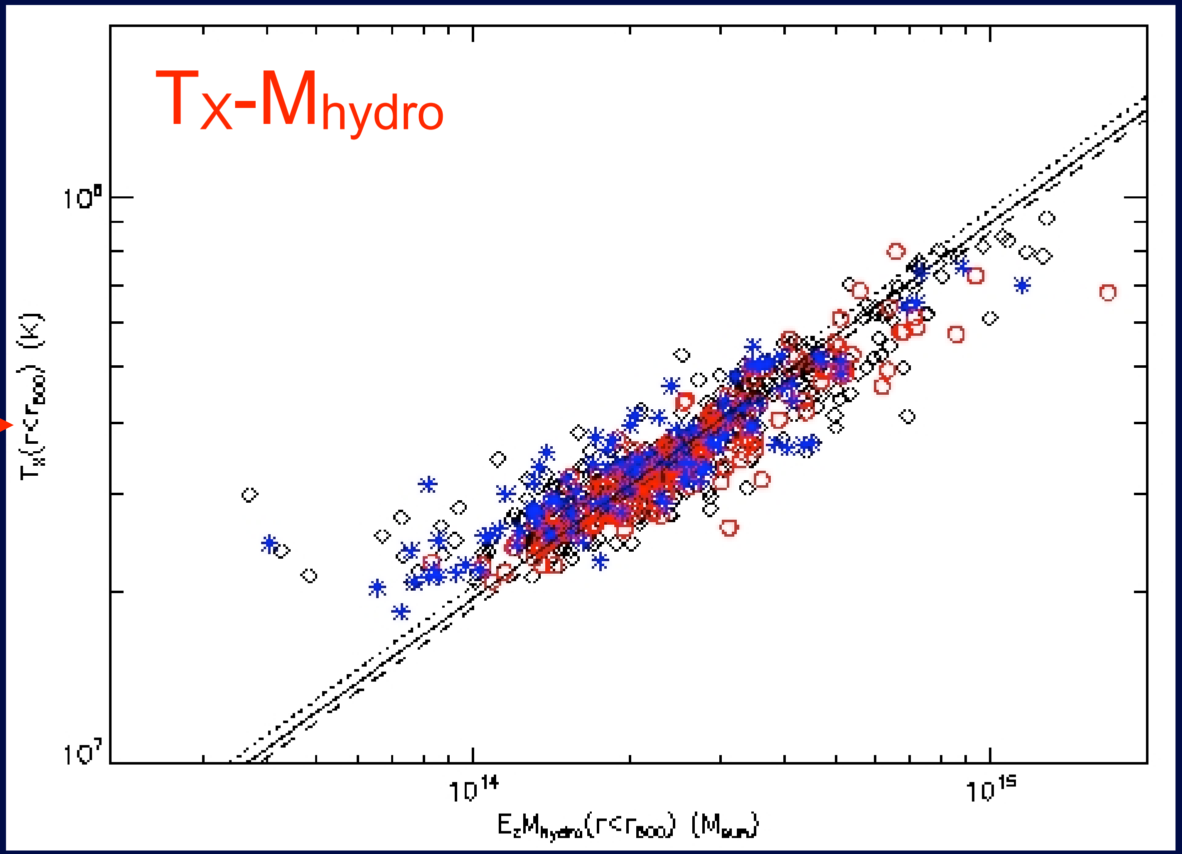


weak trend of increasing error for decreasing mass

- Hydrostatic mass systematically underestimates true mass.
- Error strongly correlates with cluster structure.

Hydrostatic Mass Scaling Relations





Using hydrostatic mass estimates:

- relaxed and disturbed clusters are significantly offset
- scatter significantly increases
- even relaxed clusters offset from true relations

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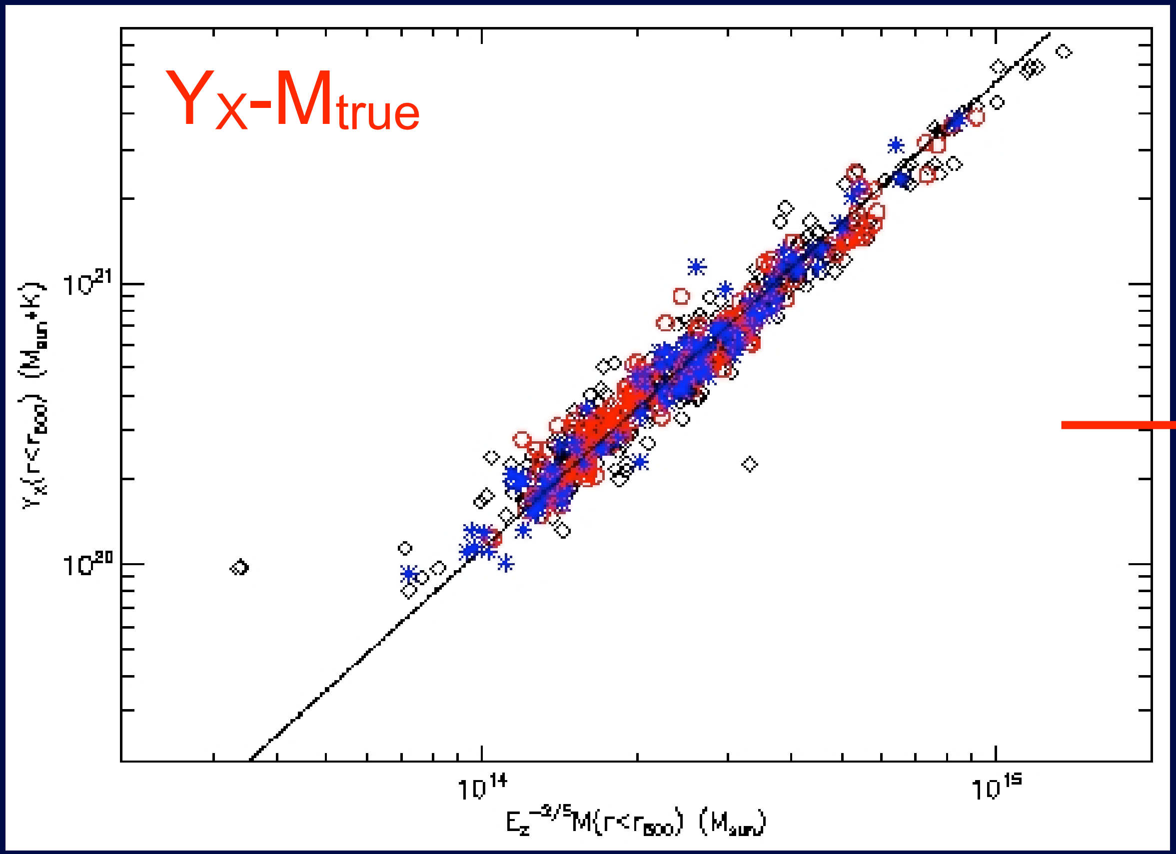

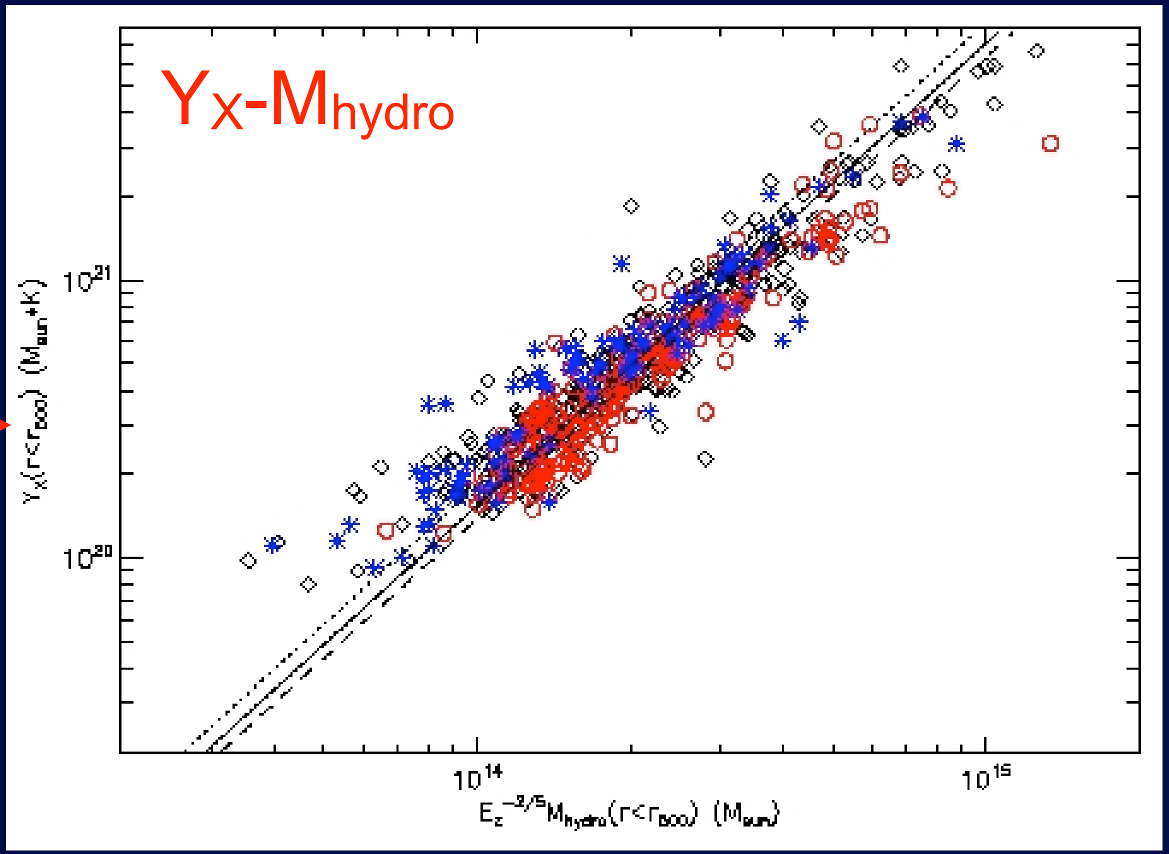

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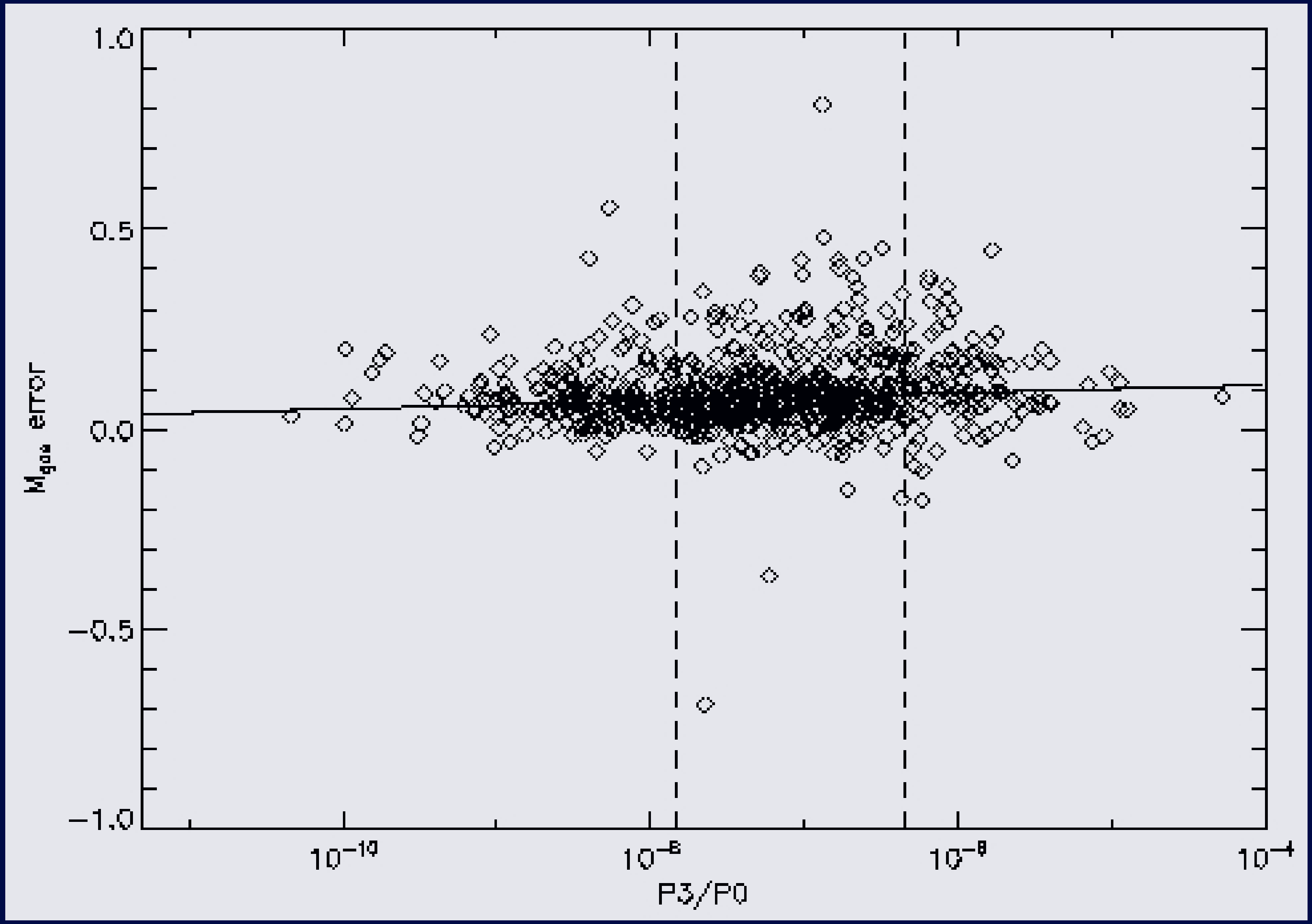
Gas Mass and Structure

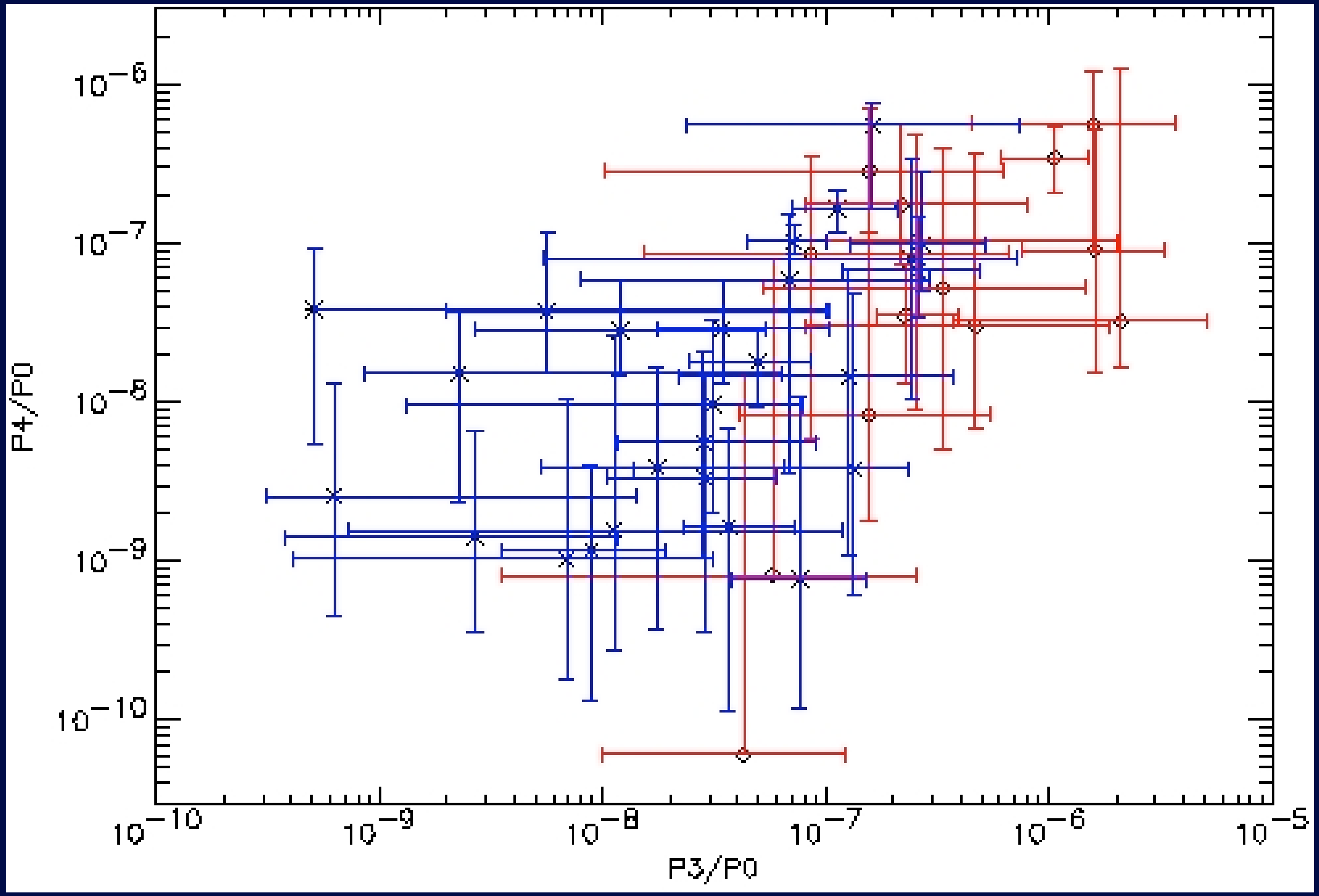


- Error in gas mass also correlates with cluster structure.
- M_{gas} overestimated by ~10% for disturbed clusters and < 5% for relaxed clusters.

Structure Evolution: Problem #3

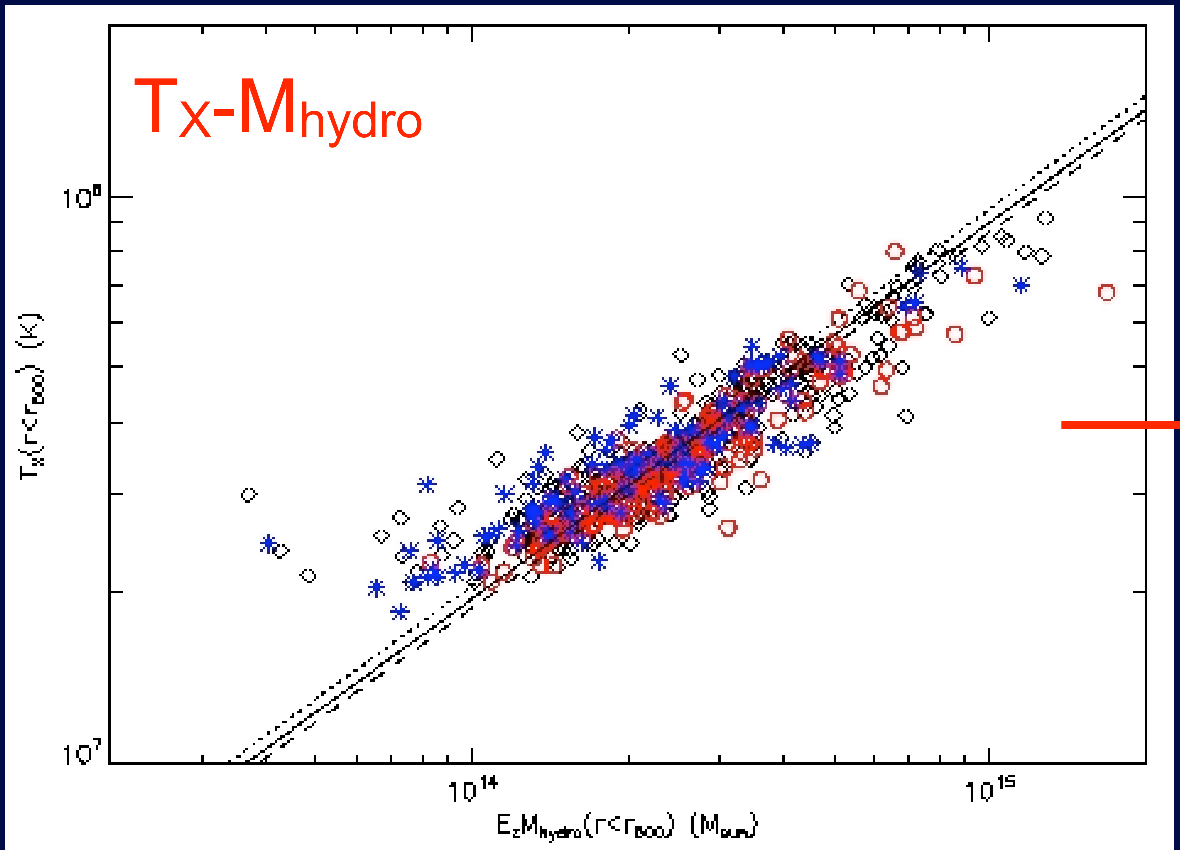
- Chandra observations show that high-z clusters have more substructure than low-z clusters.

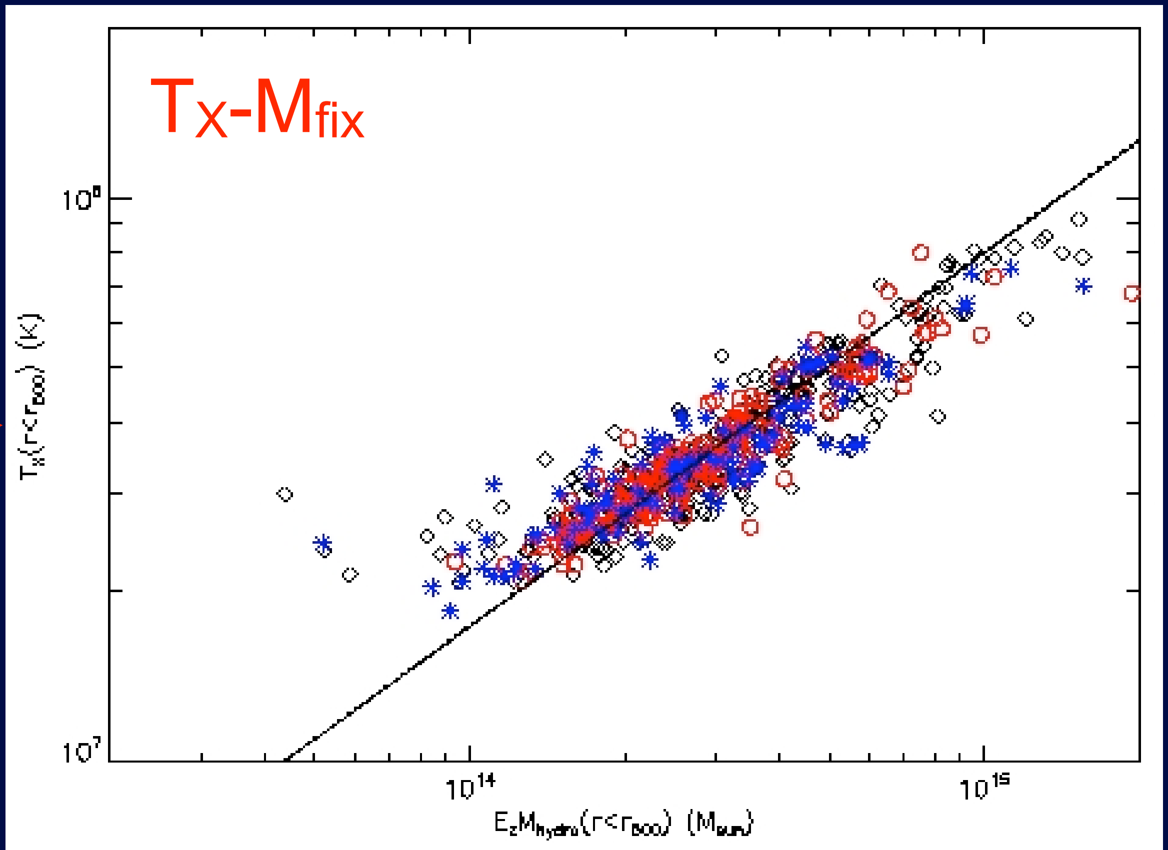
Jeltema et al. 2005



- Confirmed by Hashimoto et al. 2007, Maughan et al. 2007

Correcting Mass with Structure





Correcting hydrostatic mass based on P_3/P_0:

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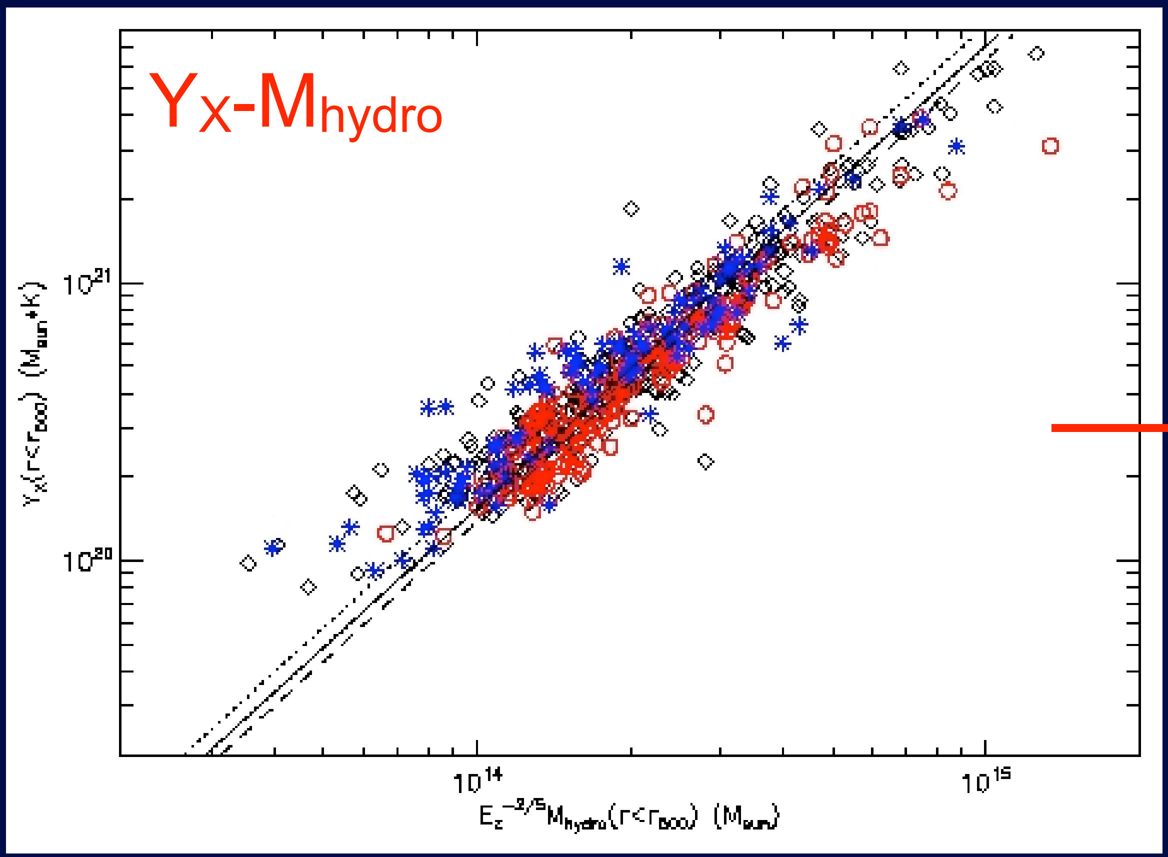

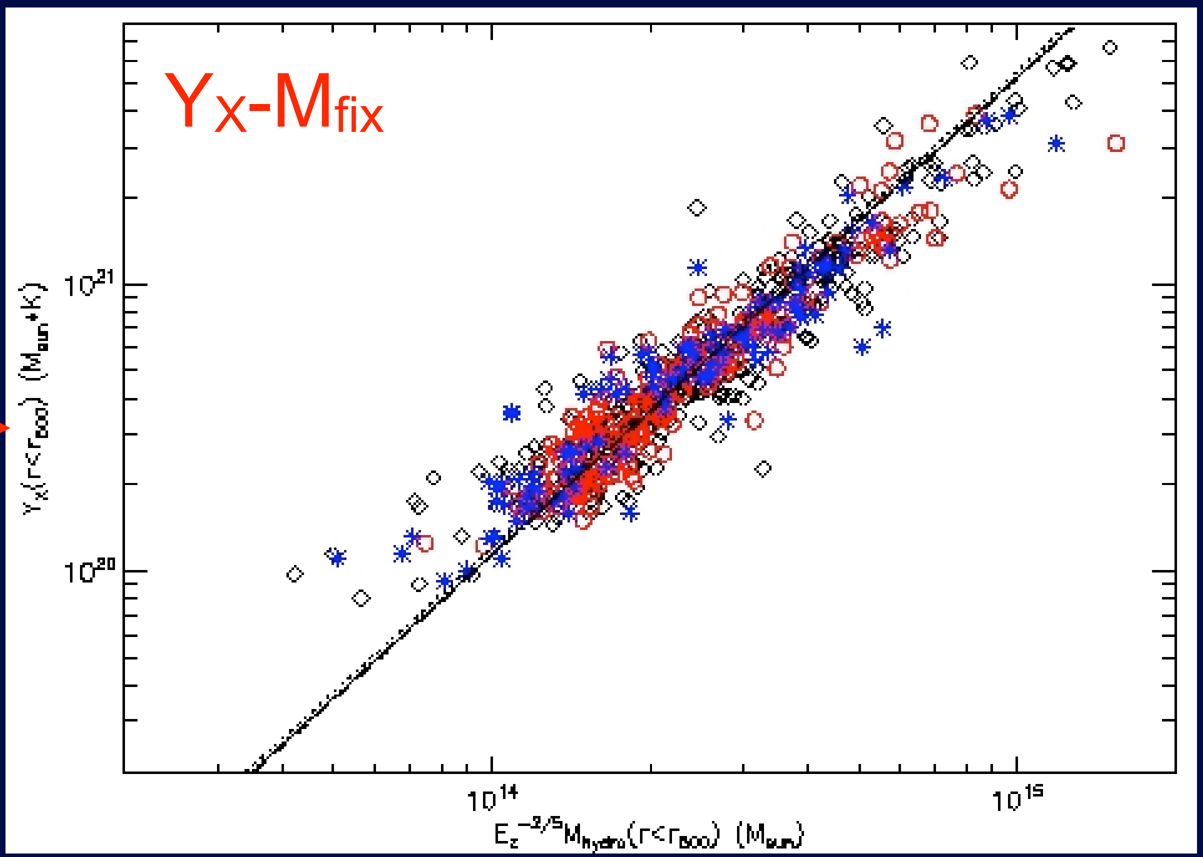

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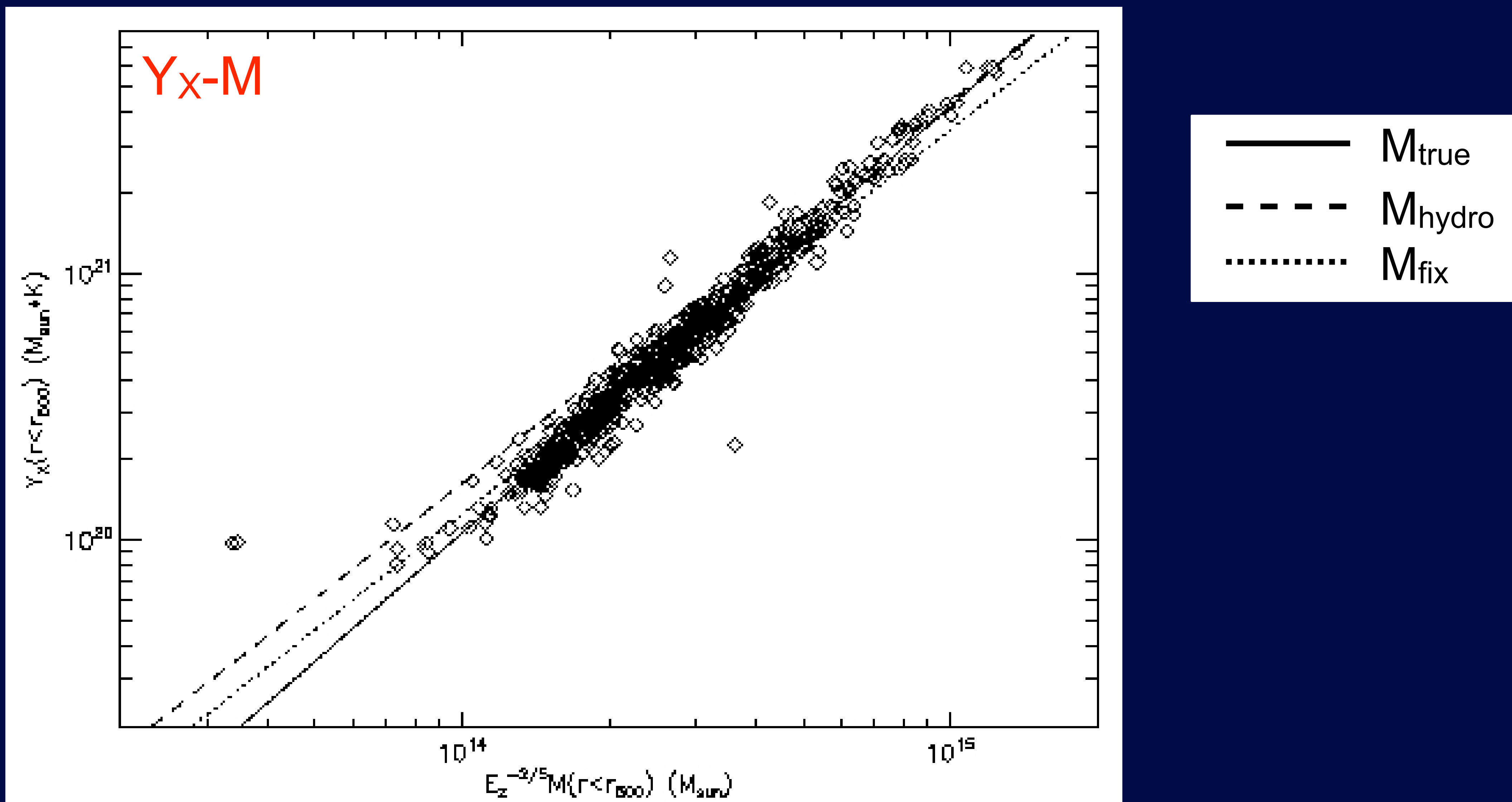
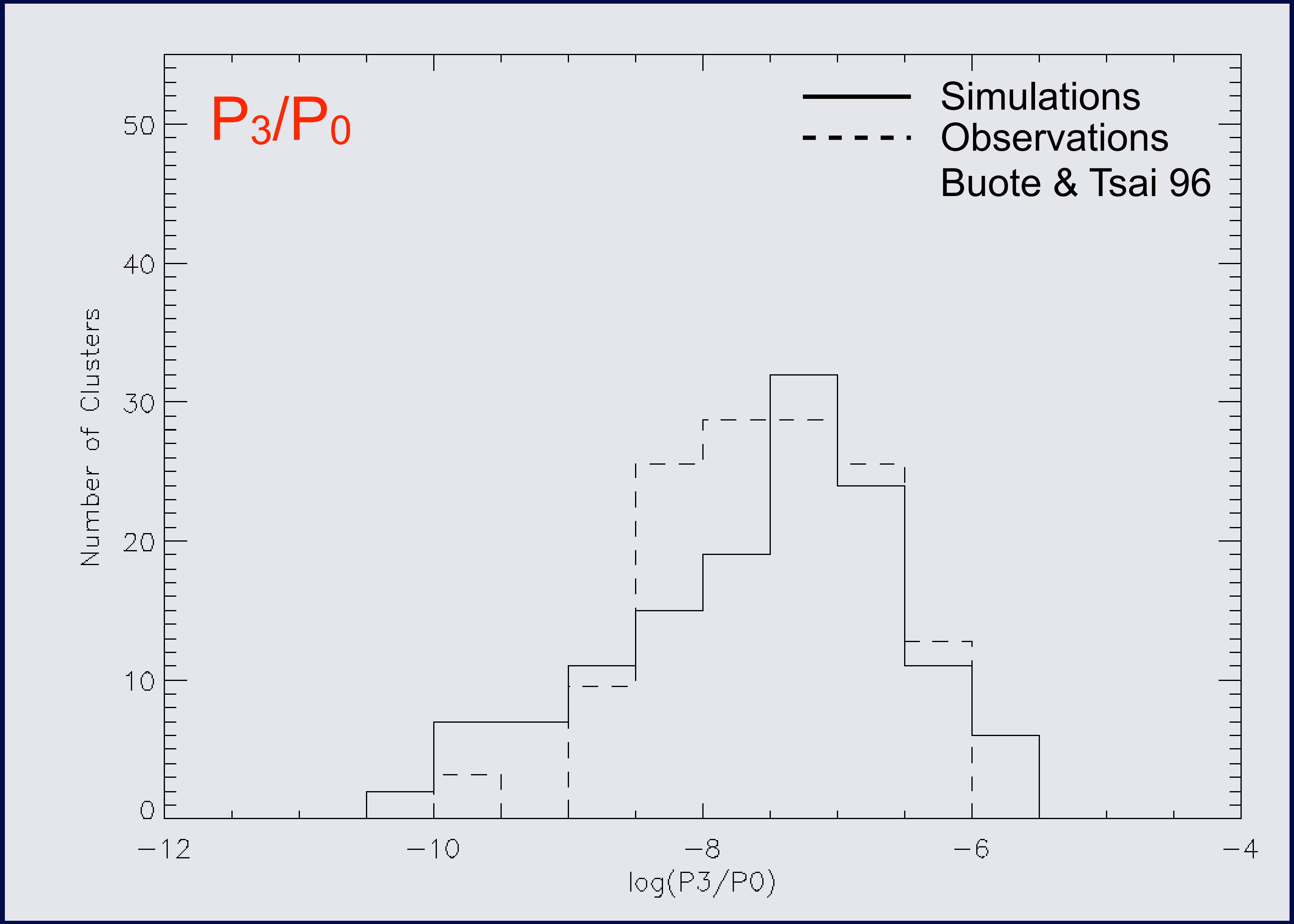


- Slope flatter than true slope due to correlation of ΔM with M.
- Power ratios more successful than centroid shift, but both work.

Comparison to Observations

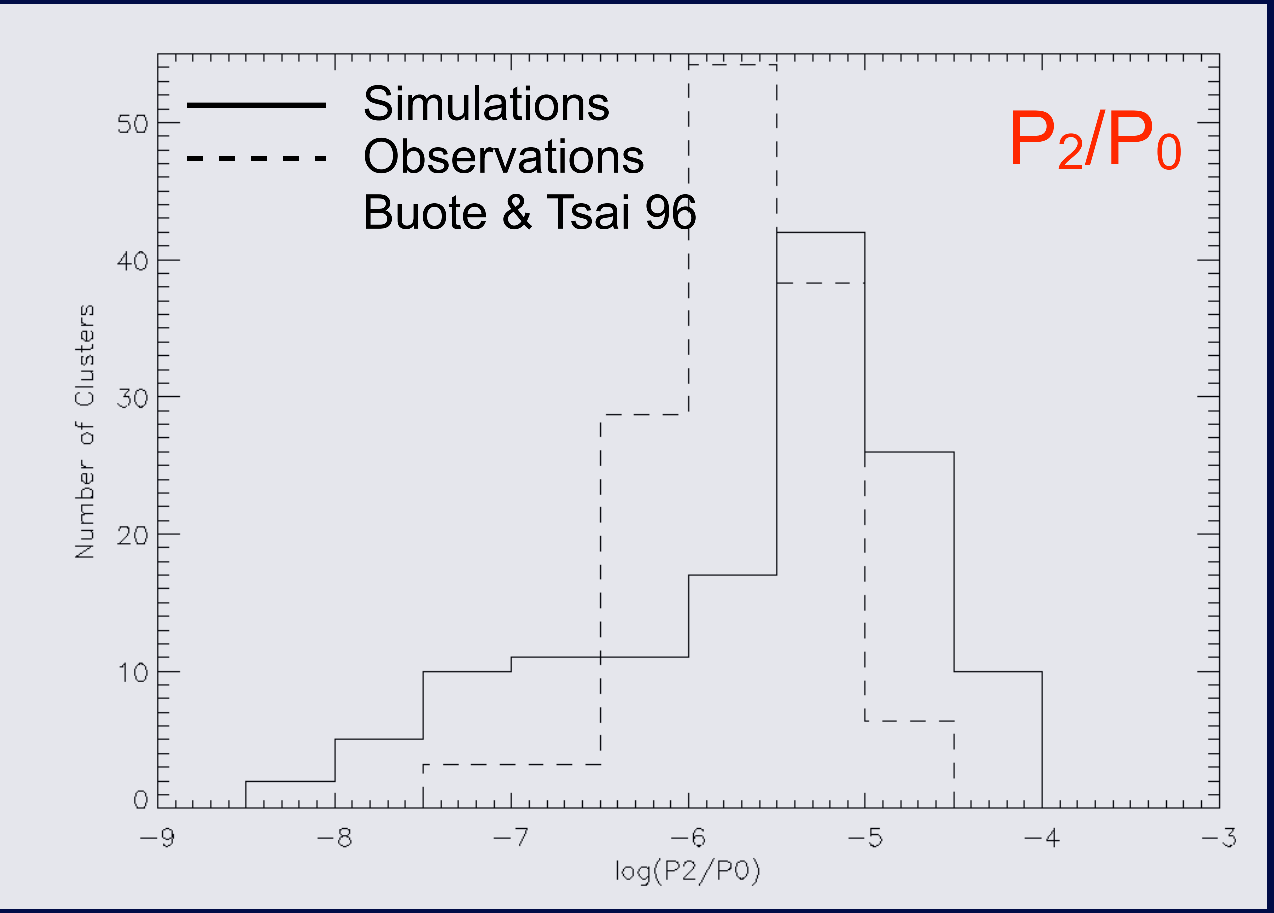
Low Redshift (z<0.1)

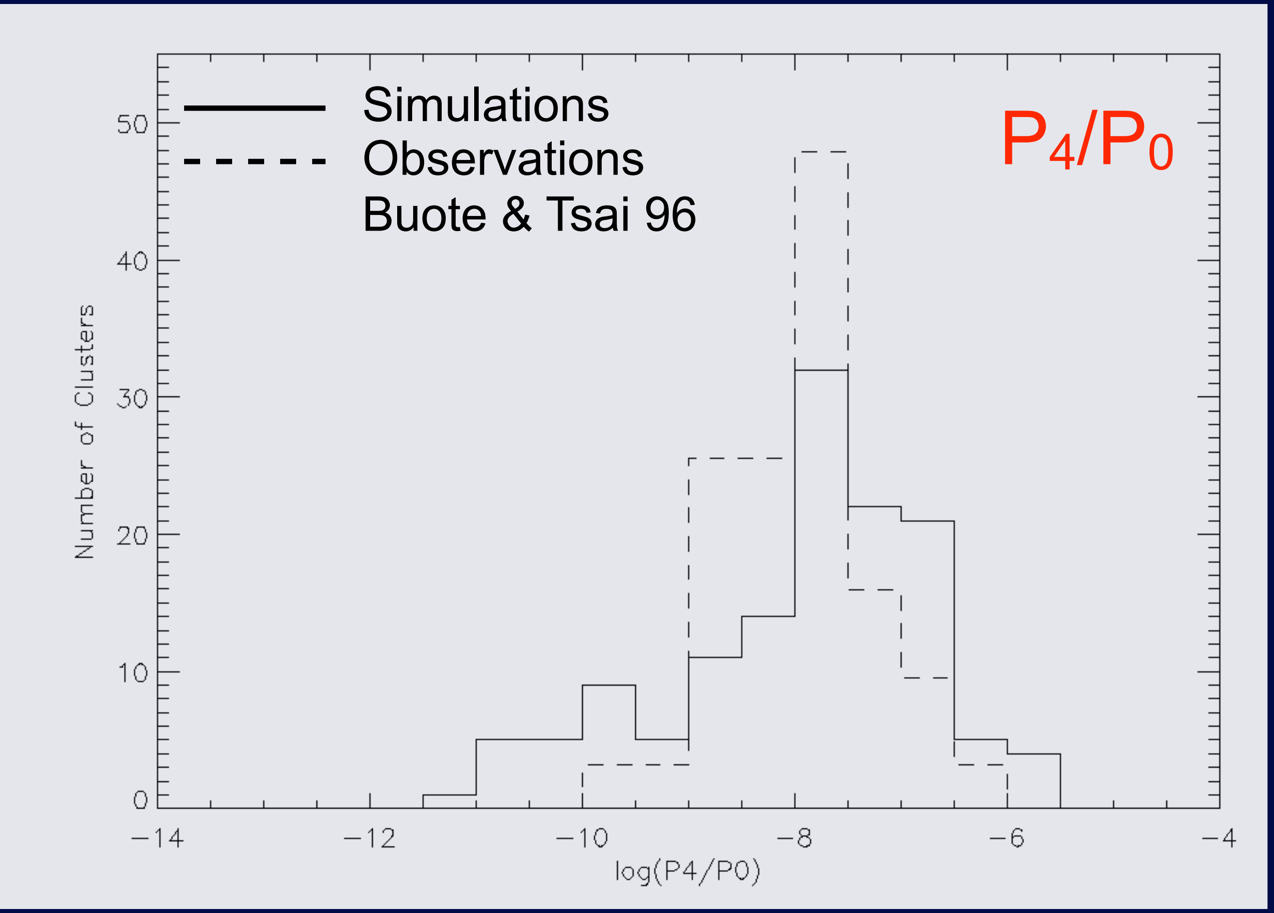
Comparison to Observations
Low Redshift (z<0.1)



- Cluster structures in simulations consistent with observed clusters.

Comparison to Observations
Low Redshift (z<0.1)





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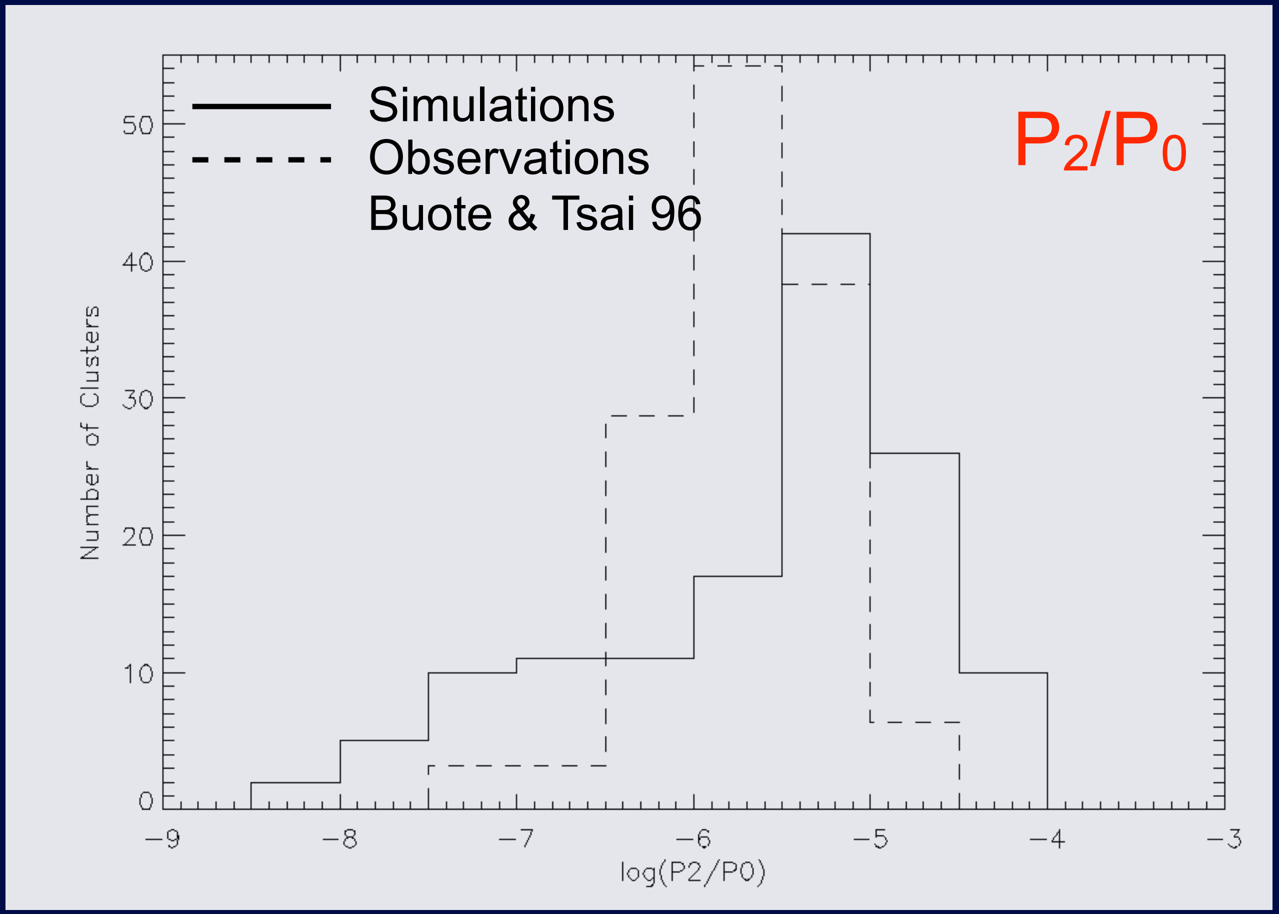

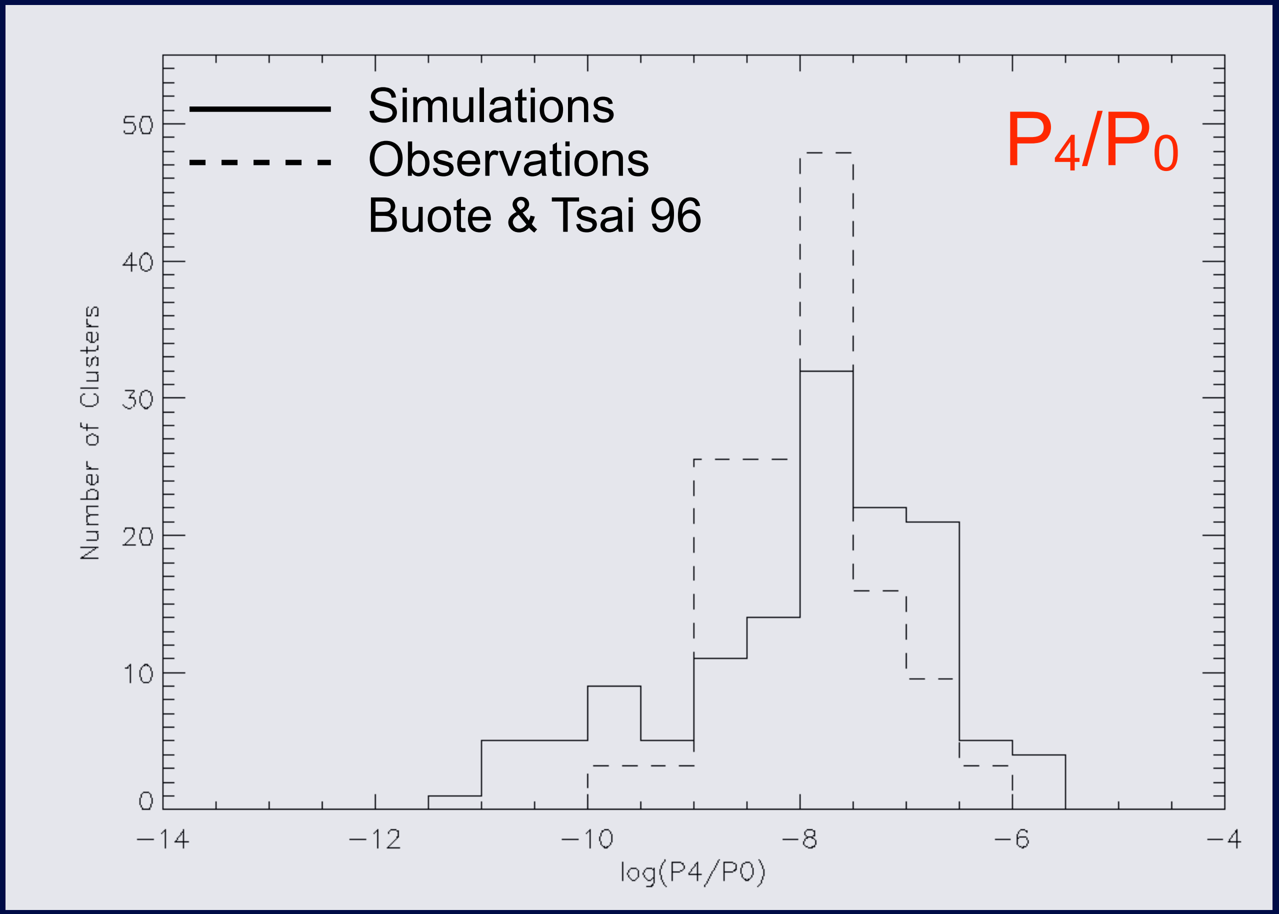

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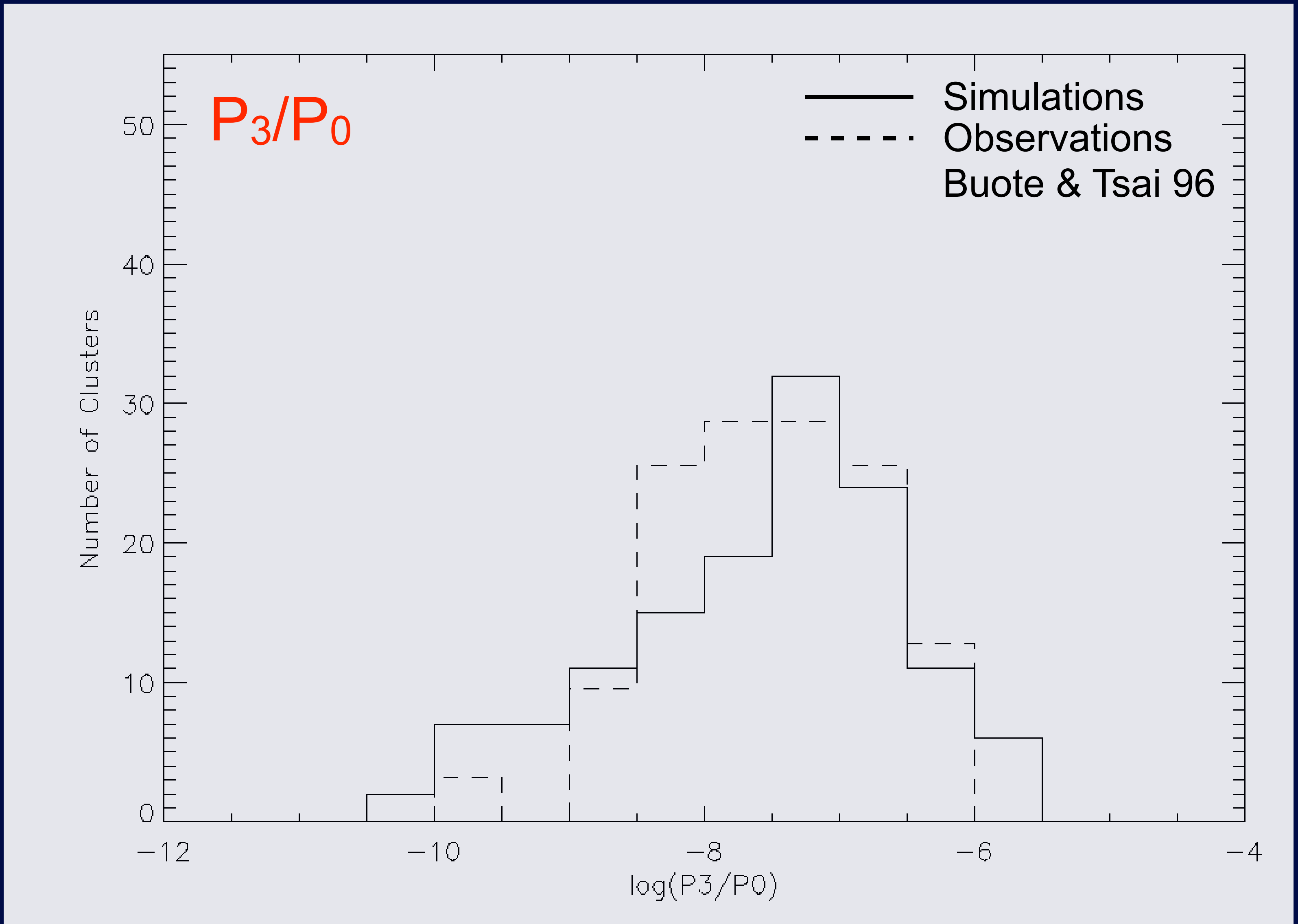

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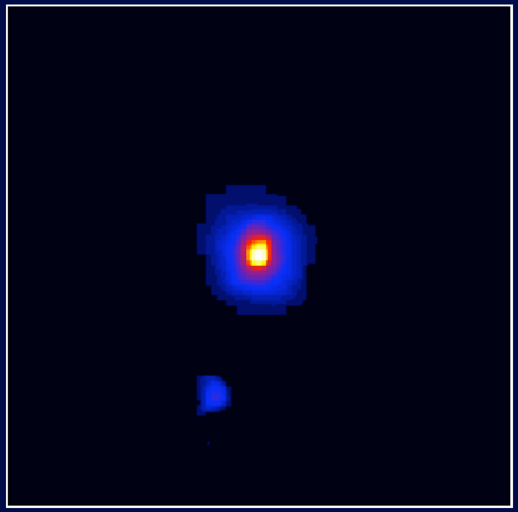

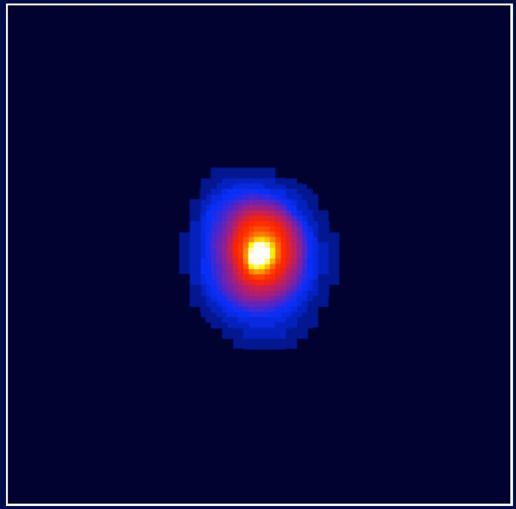

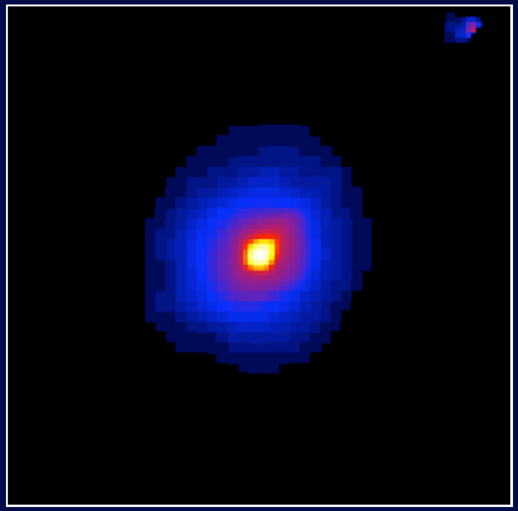

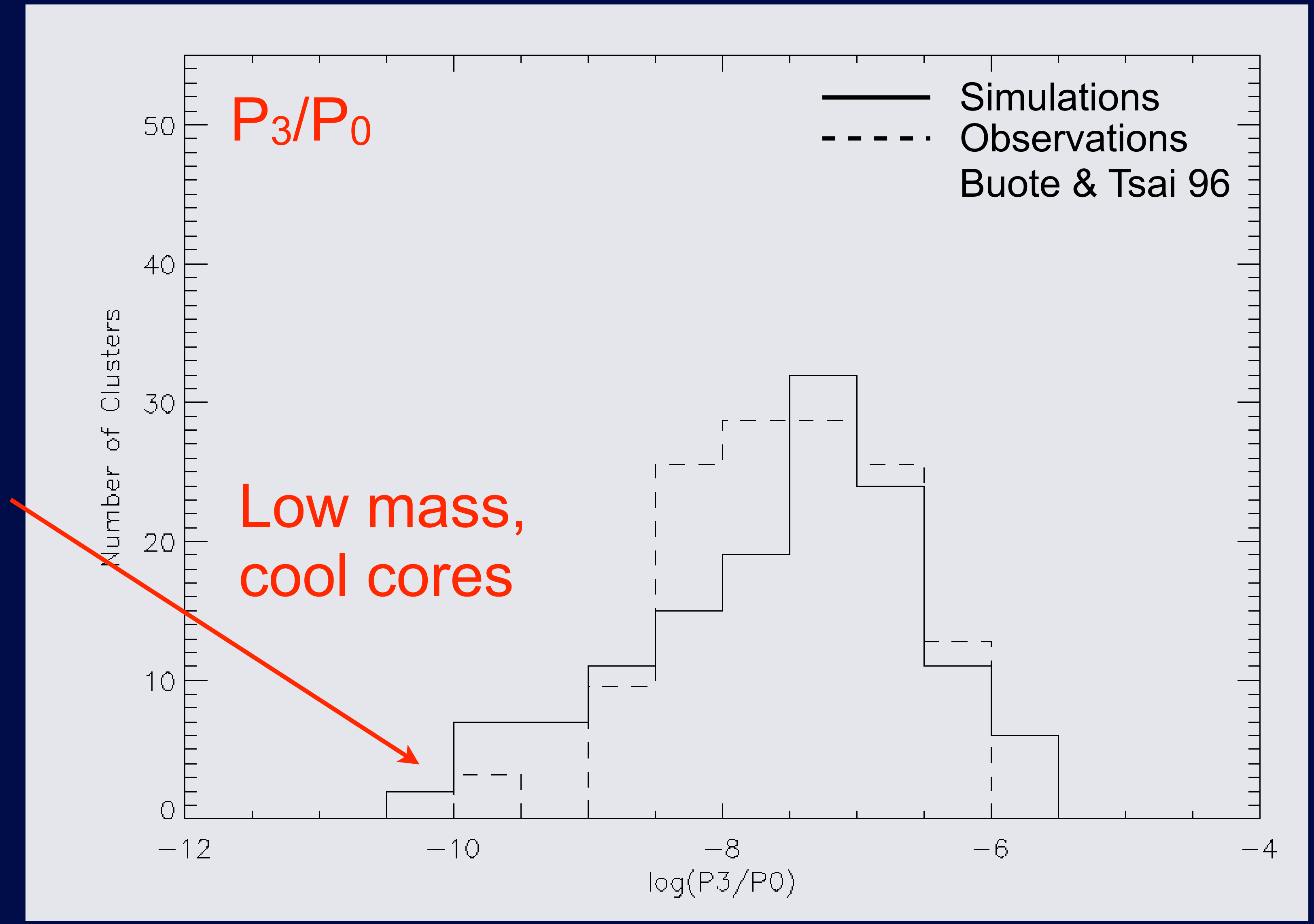

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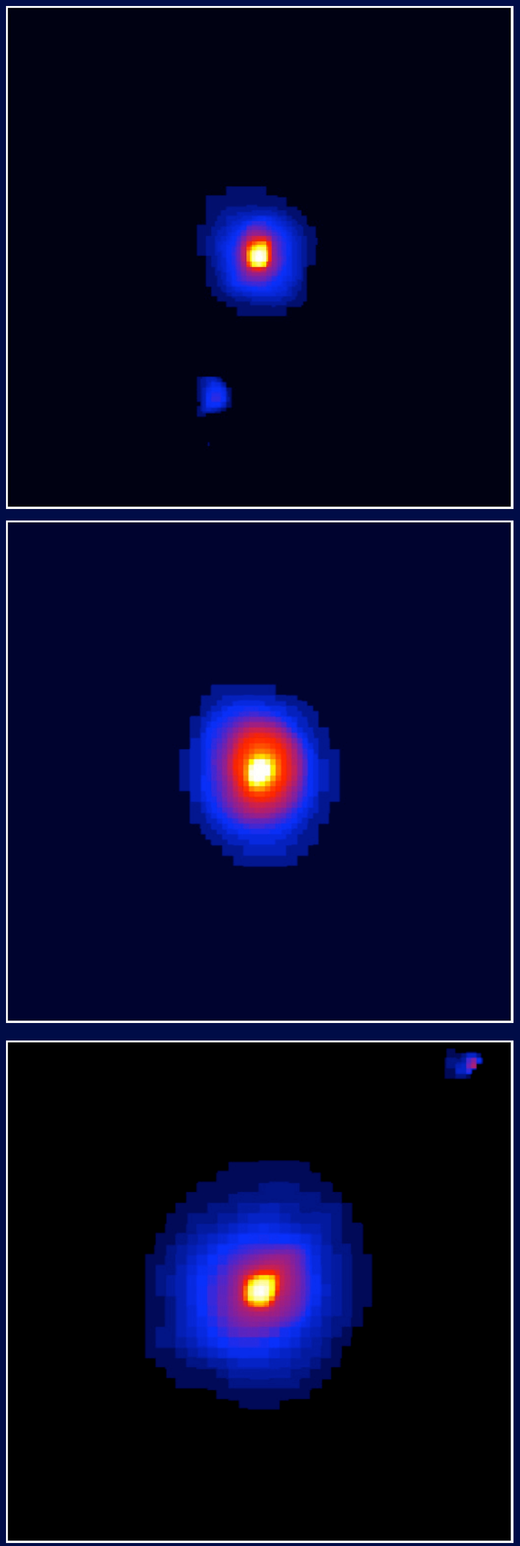

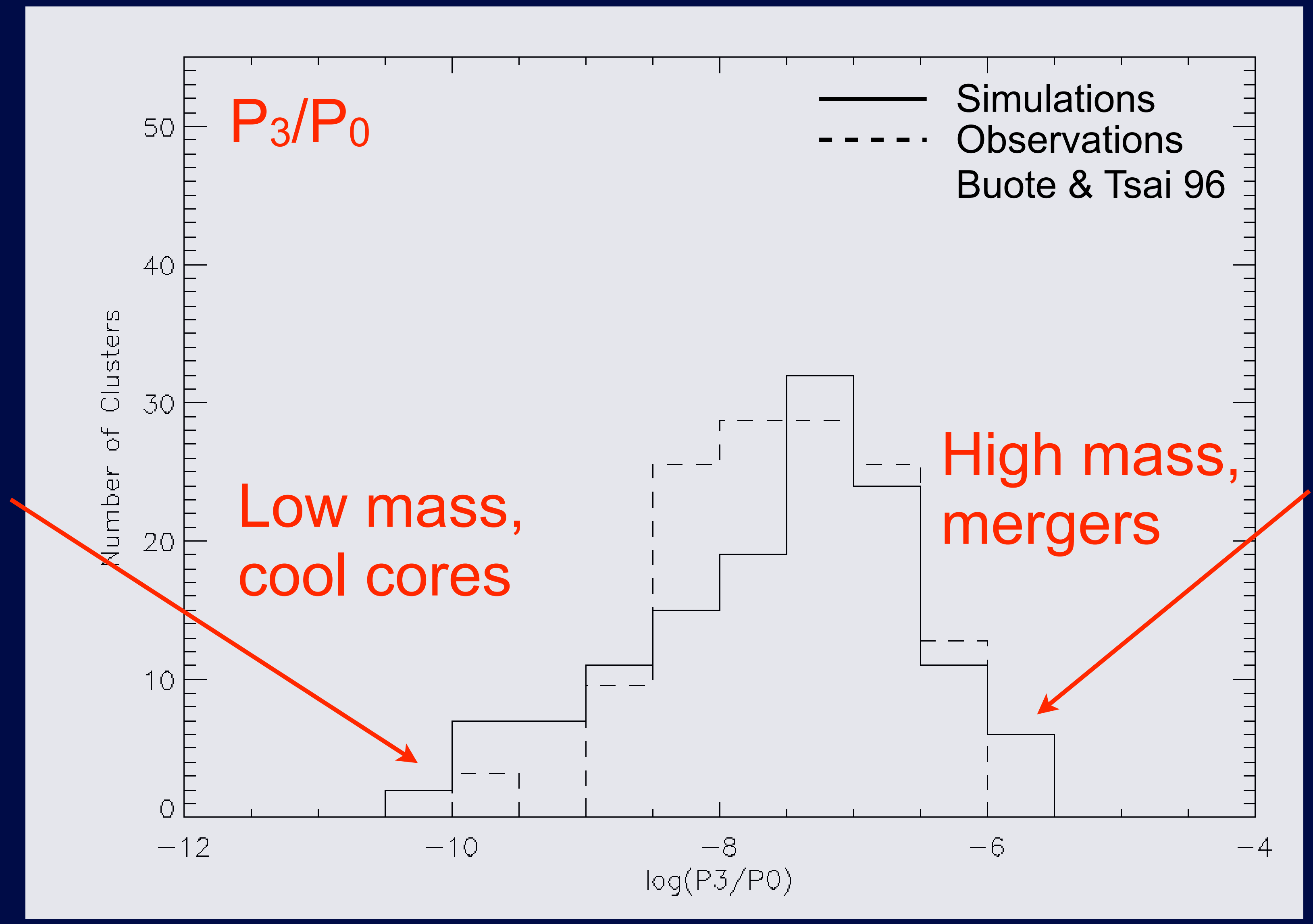

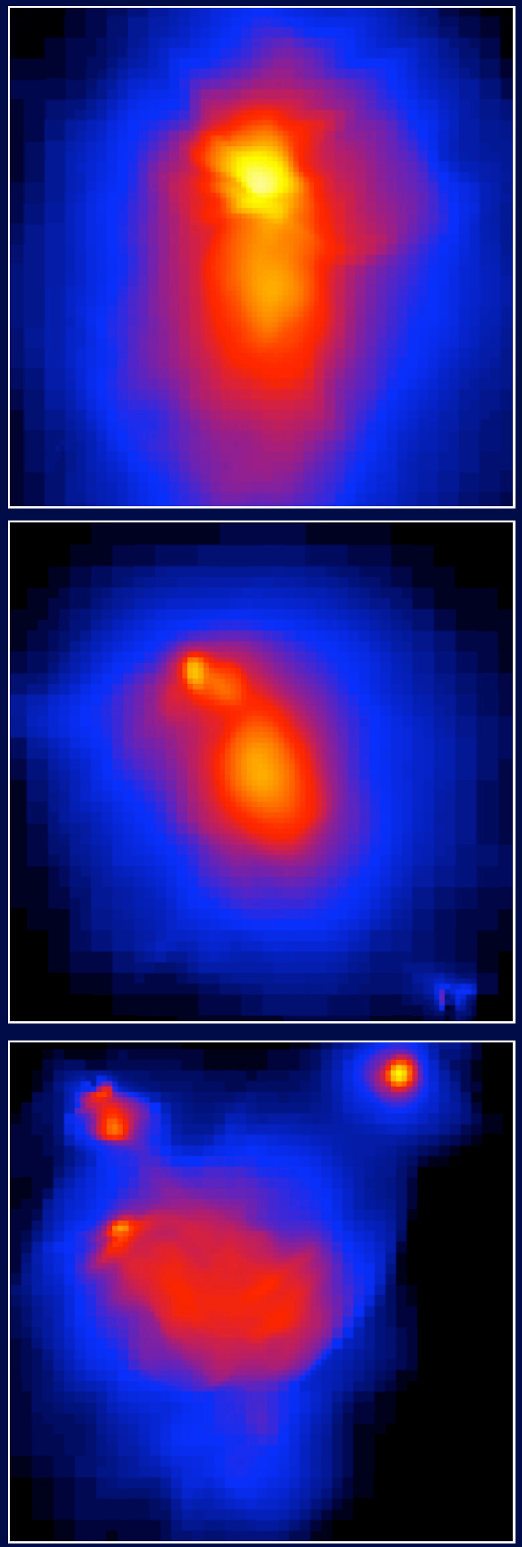

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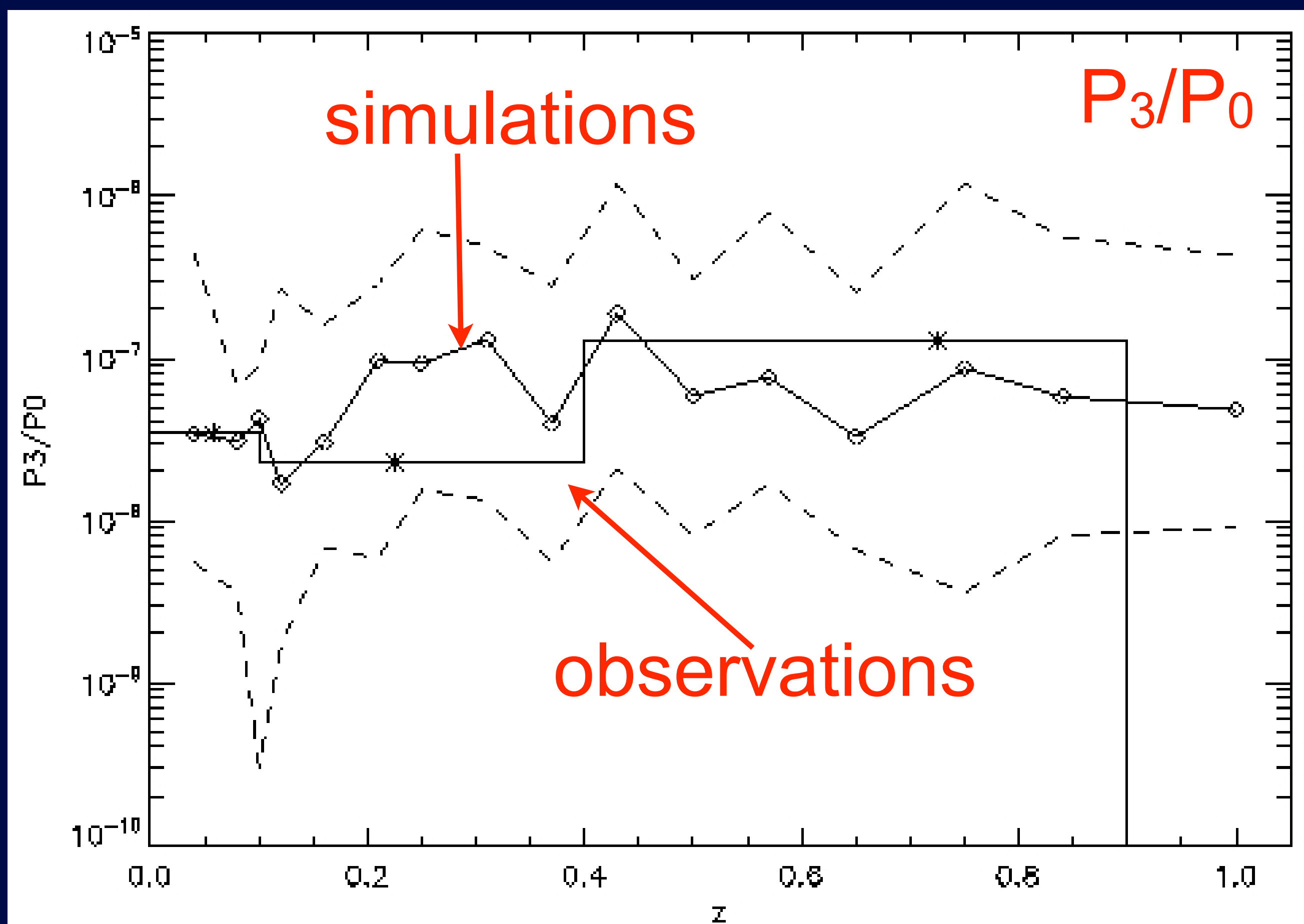
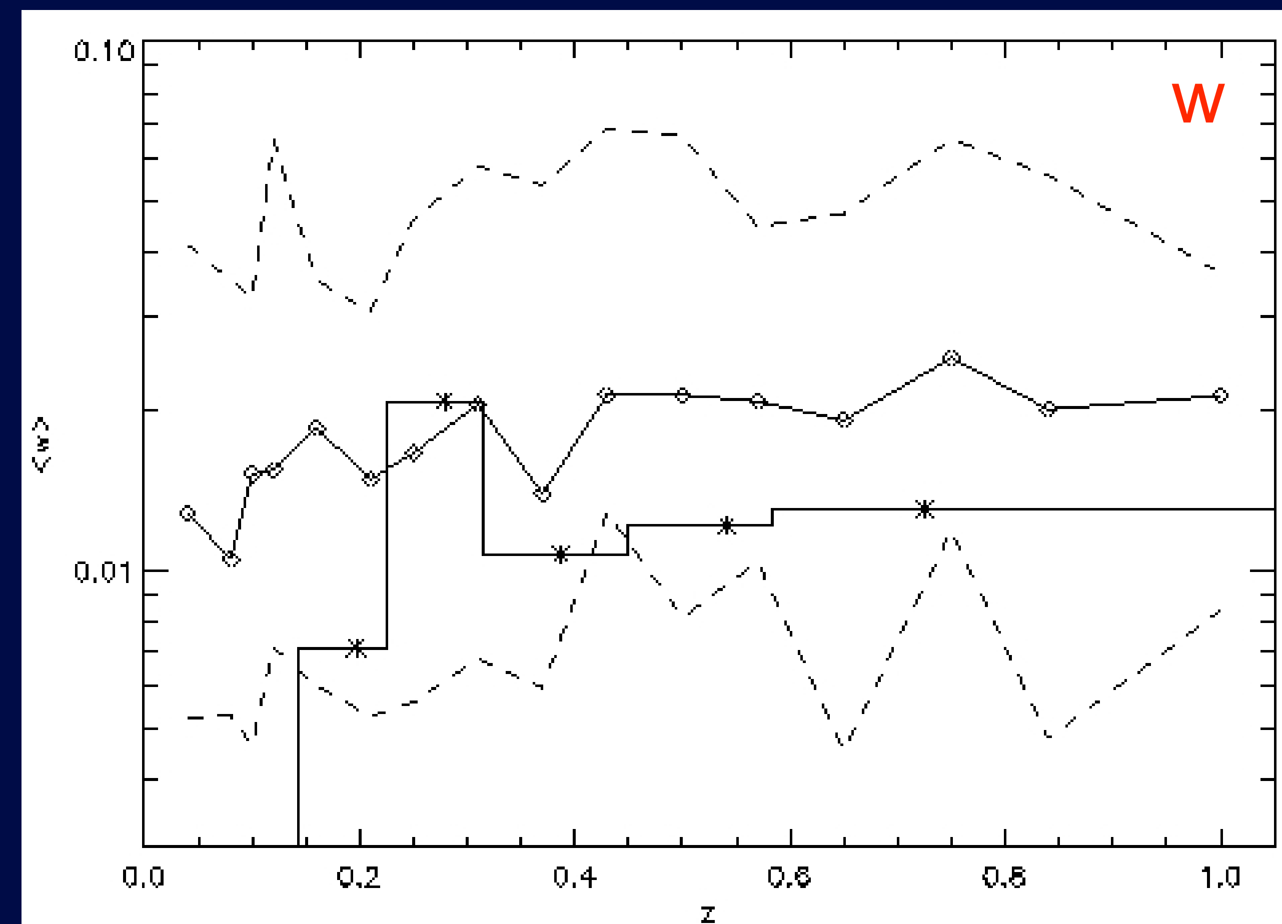
Structure Evolution in Simulations



Jeltema et al. 2005
Buote & Tsai 1996



Maughan et al. 2007

- Significant, but mild evolution
- Large range of morphologies at all redshifts

Summary

- Projection
  - Some disturbed clusters are mistakenly classified as relaxed
  - Leads to increased scatter in the mass scaling relations
- Mass scaling relations
  - Observable structure measures correlate strongly with deviations from hydrostatic equilibrium
  - Observed structure can be used to correct mass scaling relations
- Comparison to observations
  - Simulated cluster structure similar to observed
  - Possible test of gas physics in simulations