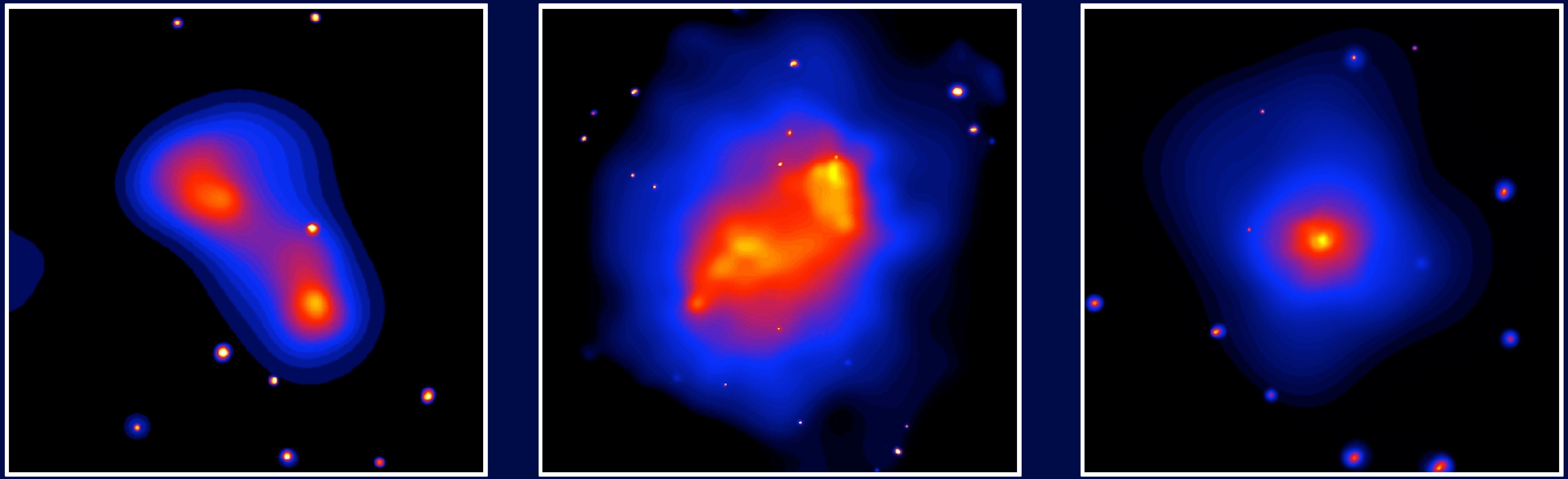
The Evolution of Structure in Clusters of Galaxies



Jeltema et al. 2005

with C. Canizares, M. Bautz, and D. Buote

Jeltema et al. 2007

with E. Hallman, J. Burns, P. Motl, and M. Norman

Outline

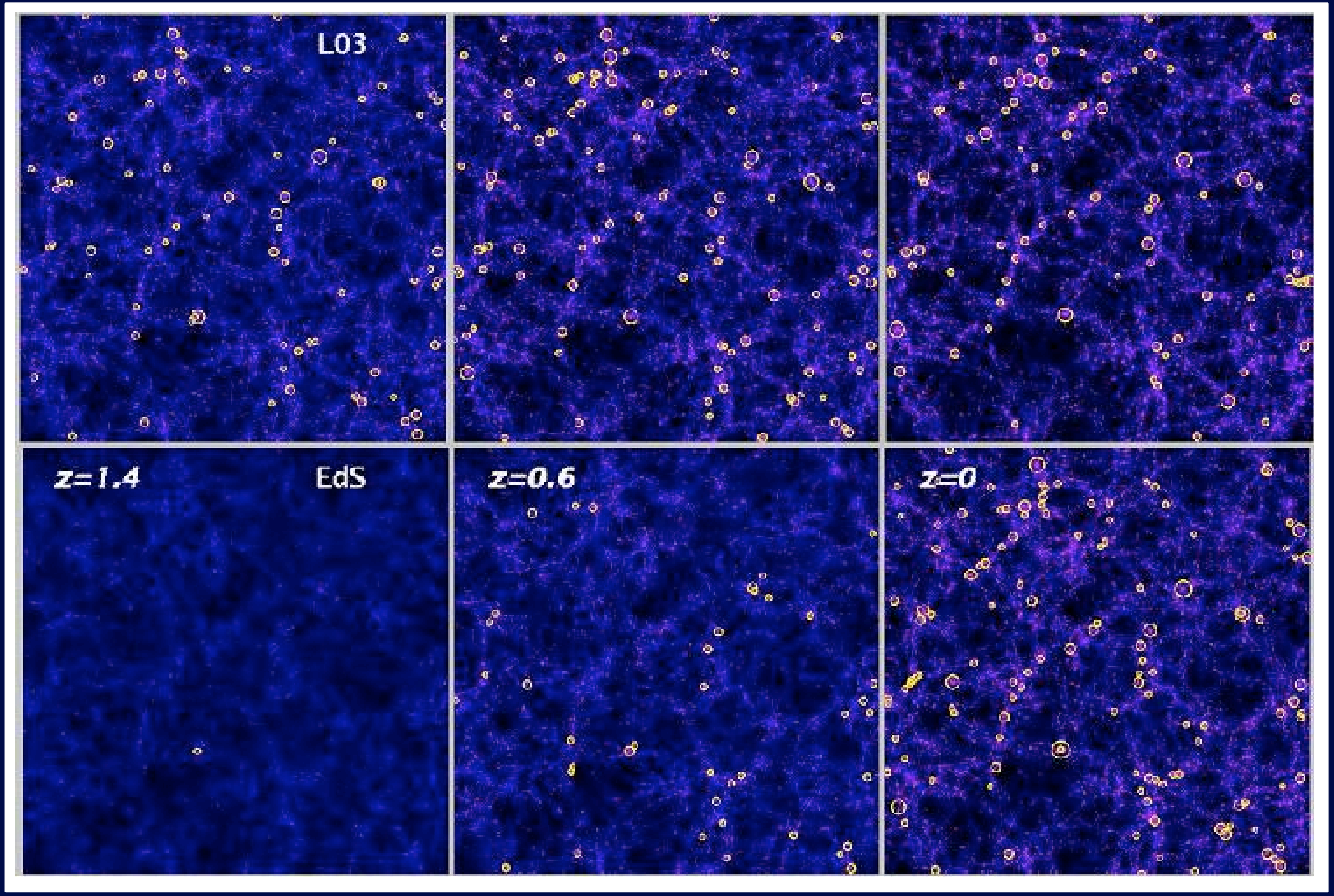
- The observed evolution of cluster morphology
  - Introduction: cosmology with clusters
    cluster mergers
  - Measuring structure
  - Chandra study
- Comparison to simulations
- Structure/mergers on other scales

Cosmology with Clusters

- Represent highest density initial perturbations.
- Constrain Ω_m and σ_8 from evolution in cluster number density and cluster baryon fraction.

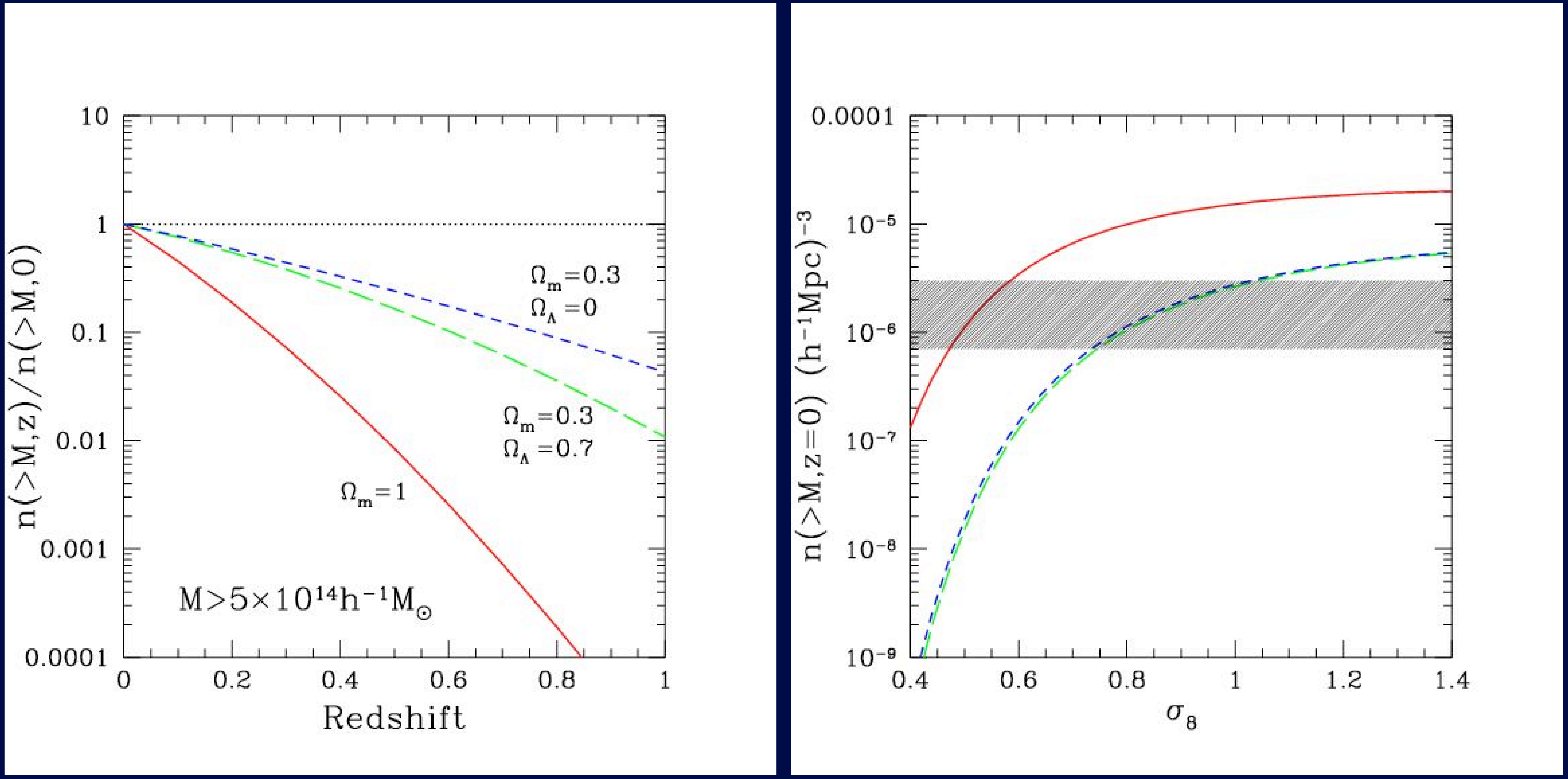
ΛCDM

SCDM



Borgani & Guzzo 2001

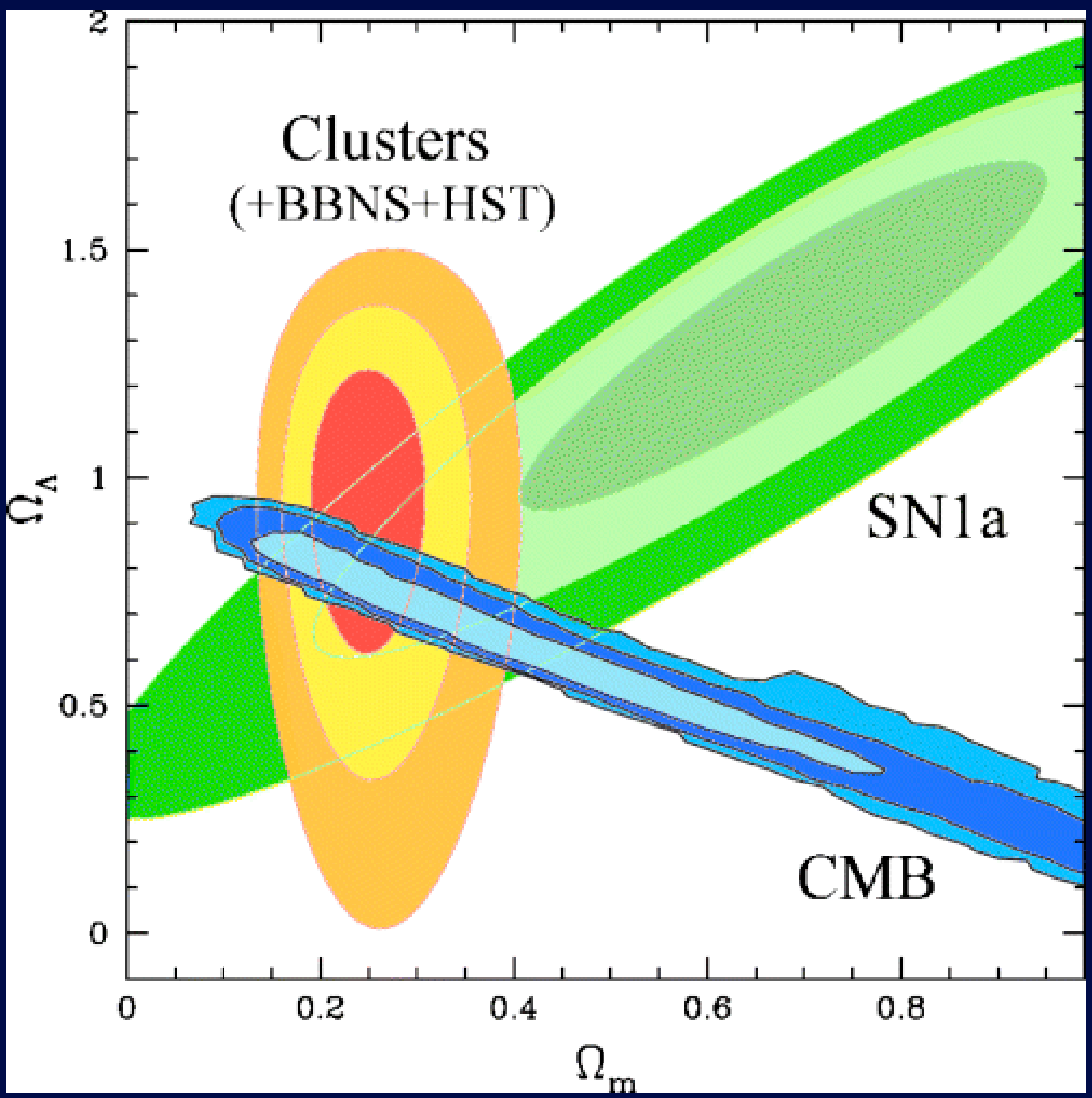
Dependence of Cluster Density on Cosmology



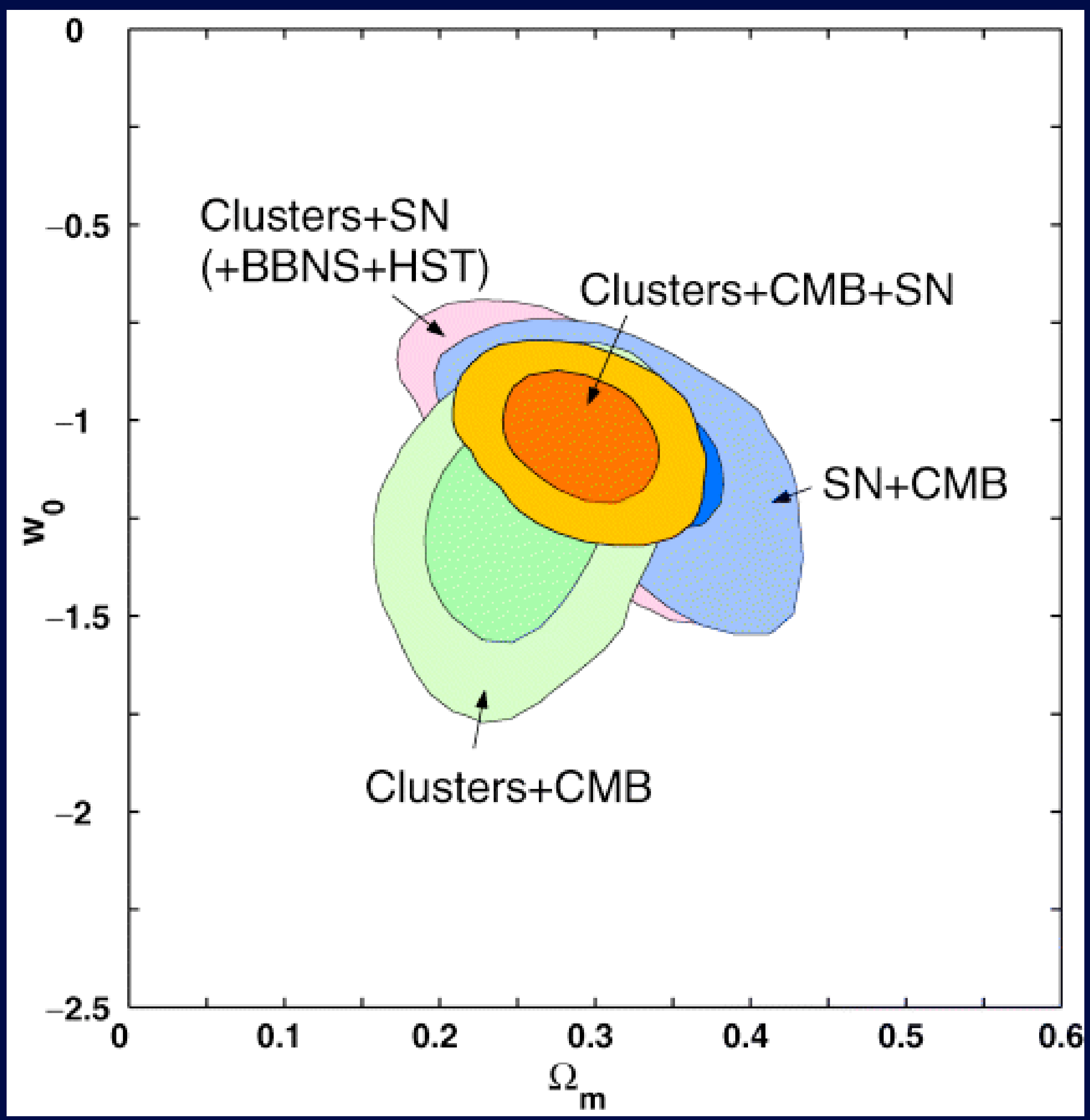
- High-redshift clusters lead to the strongest constraints.
- Slight dependence on Λ

Rosati et al. 2002

Comparison to Other Constraints



Allen et al. 2004

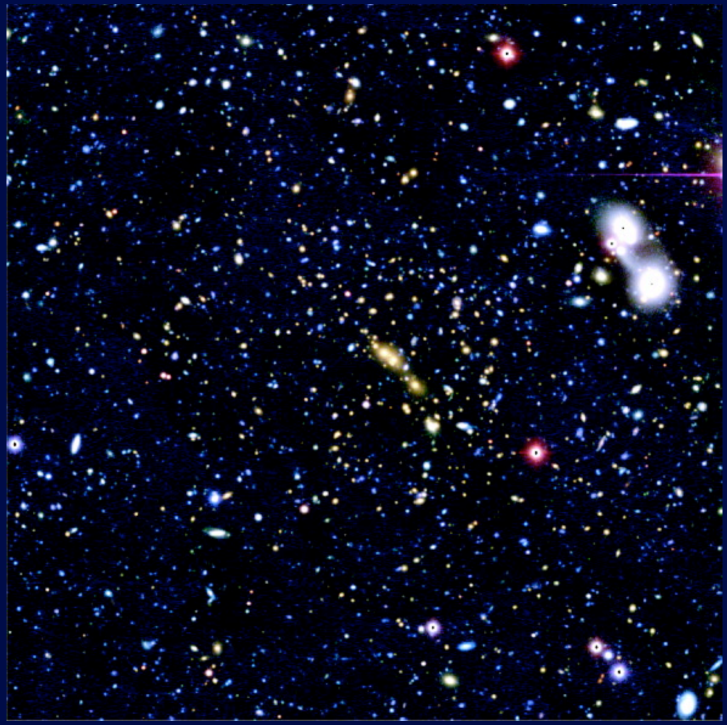


Rapetti et al. 2005

Cluster Observations

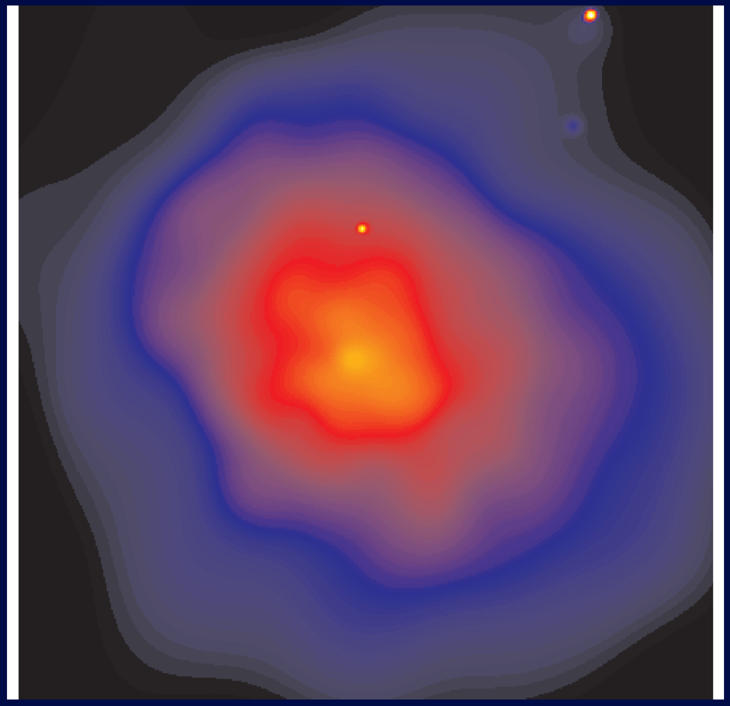
- Optical

  observe galaxies (~2% of mass)
  velocity dispersion, $\sigma_v \rightarrow M$
  need ~500 galaxies for structure



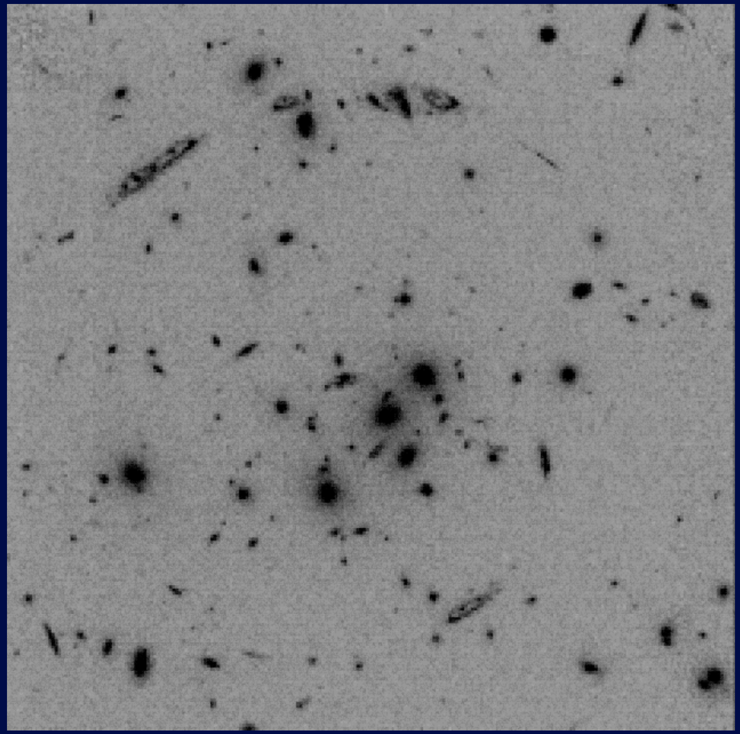
- X-ray

  thermal bremsstrahlung from hot gas
  (~12% of mass)
  $L_x, T_x \rightarrow M$
  flux limited samples, probes potential

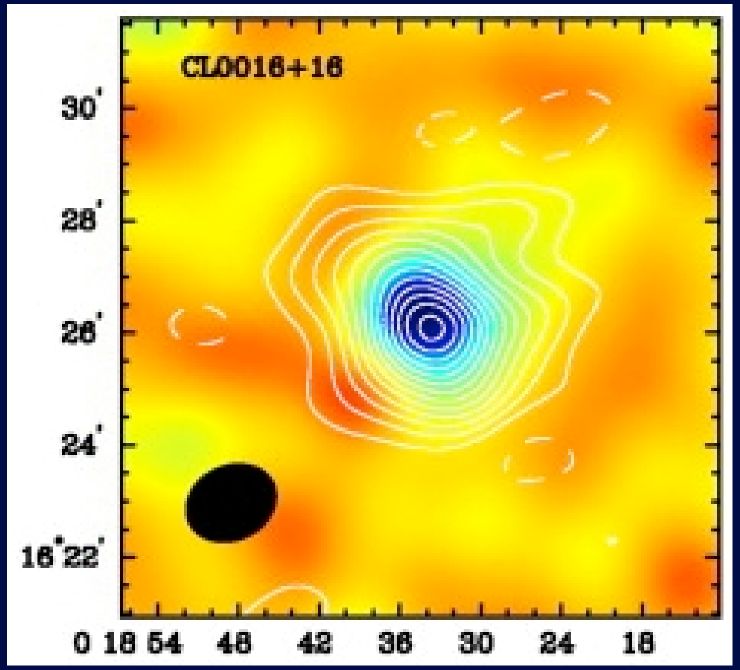


Cluster Observations

- 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
  low resolution

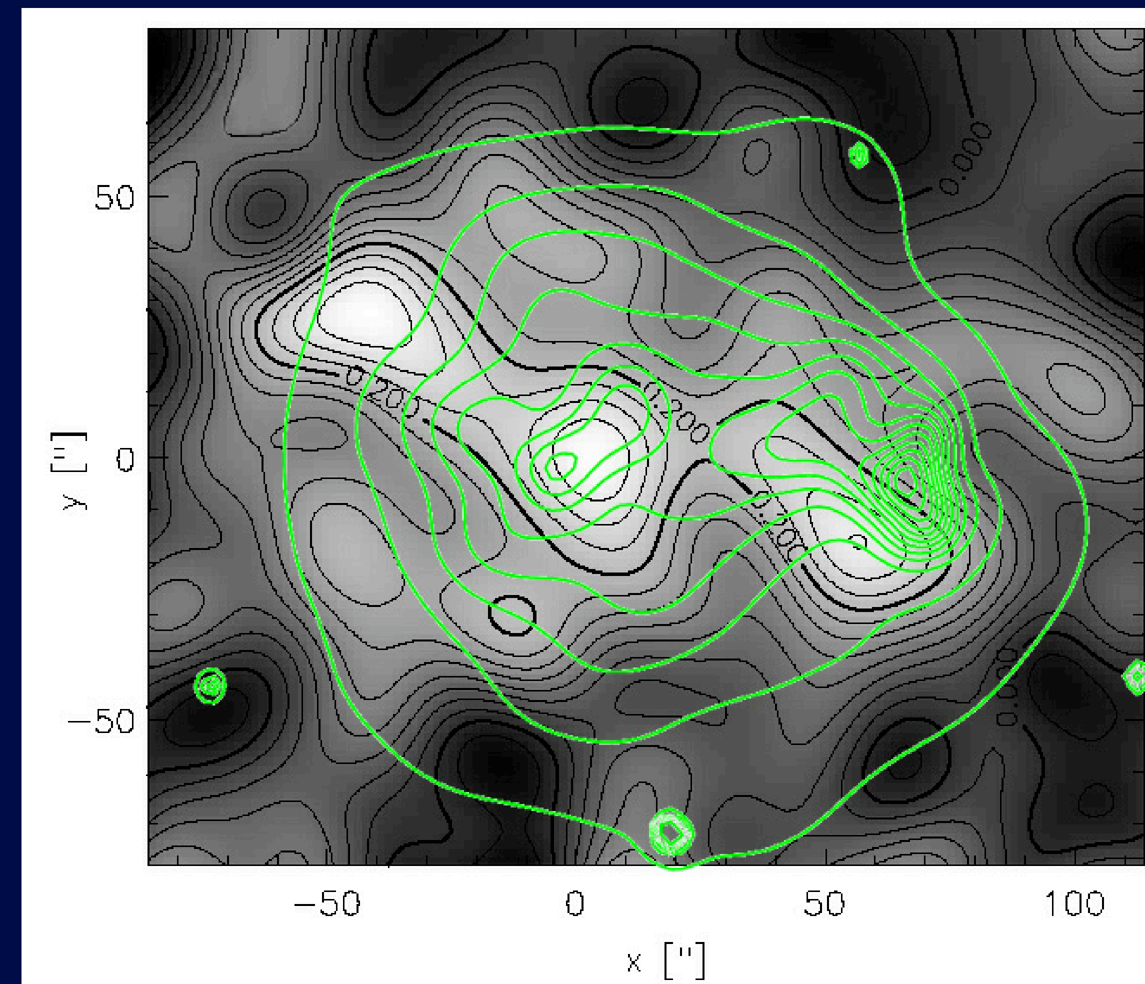


Example Mergers

"Bullet" Cluster, z=0.30

Clowe et al. 2006

MS1054-0321, z=0.83



Jeltema et al. 2001

- MS1054 at z=0.83 alone implies $\Omega_m < 1$, but it is undergoing a major merger.
- Observe temperature variation and offsets from mass distribution

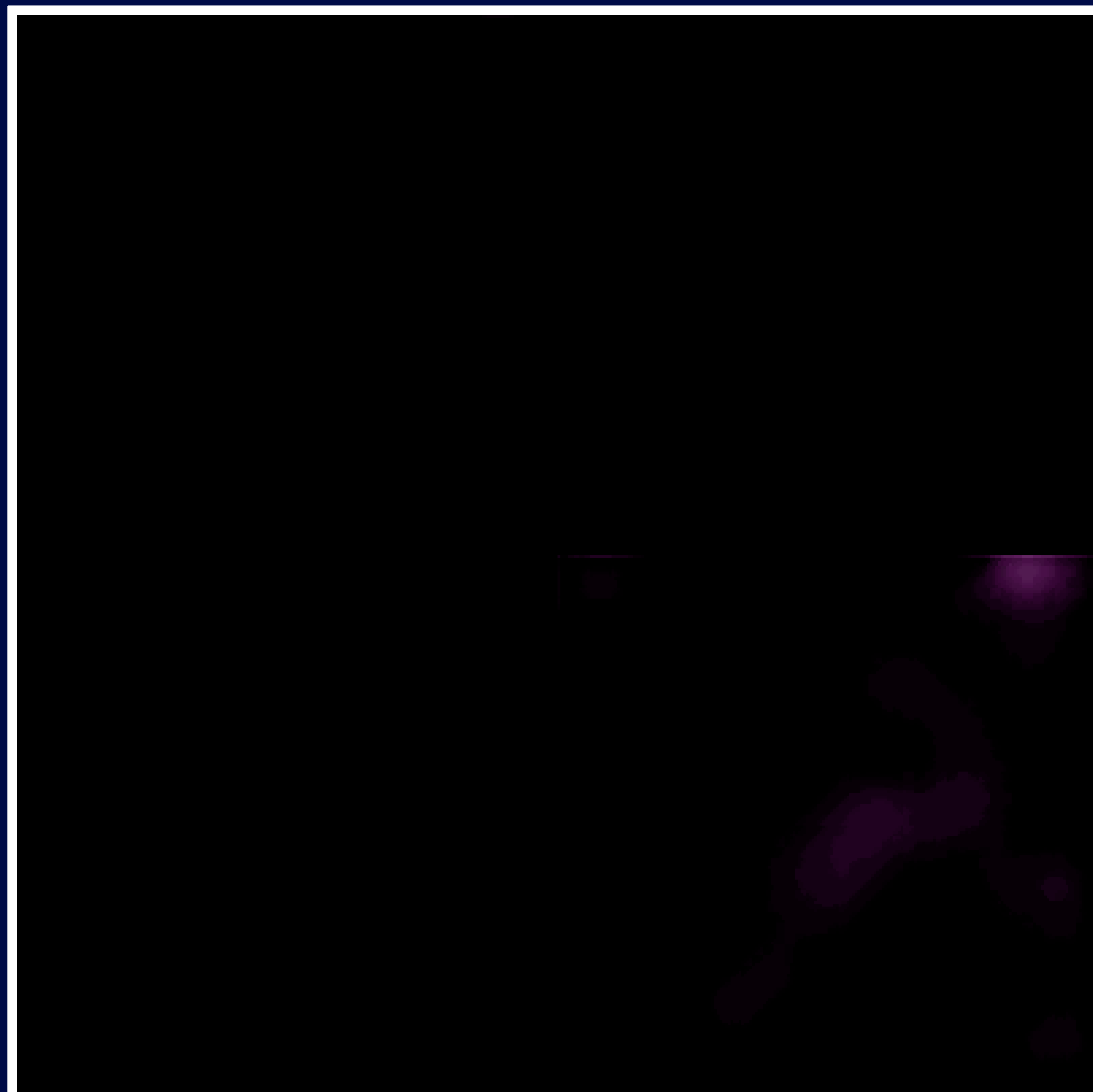
Cluster Substructure

- Clusters form through mergers.
    - Observed as substructure or disturbed cluster morphology
- Formation epoch of clusters depends on cosmology.
- Cluster morphology affects the study of many cluster properties.
    - Mass
    - Gas mass fraction
    - Galaxy evolution, etc.

Cluster formation in ΛCDM

Gas Density

Galaxies

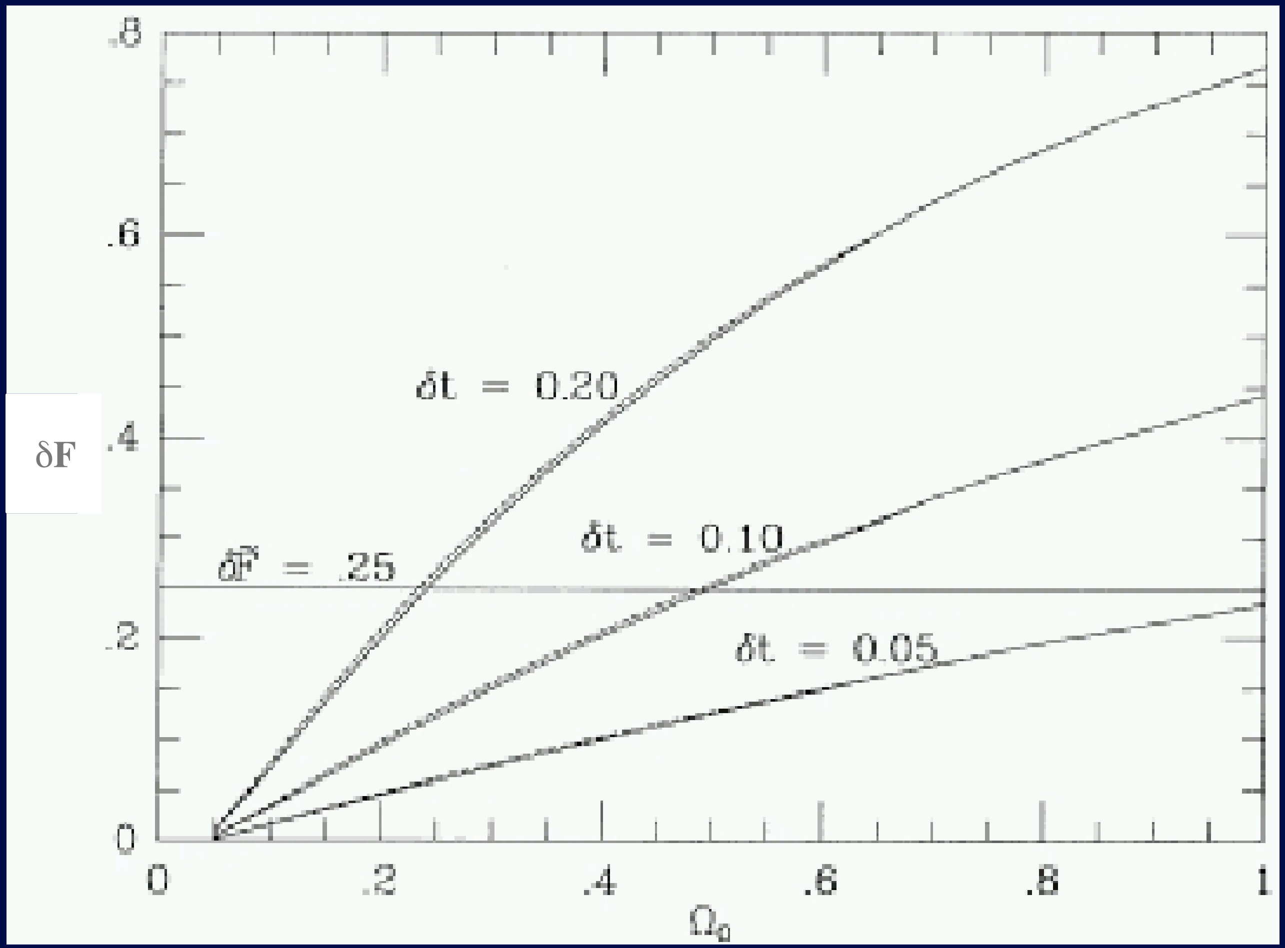


SZ Effect

X-
ray

Movie credit to Martin White

Cluster Structure and Cosmology



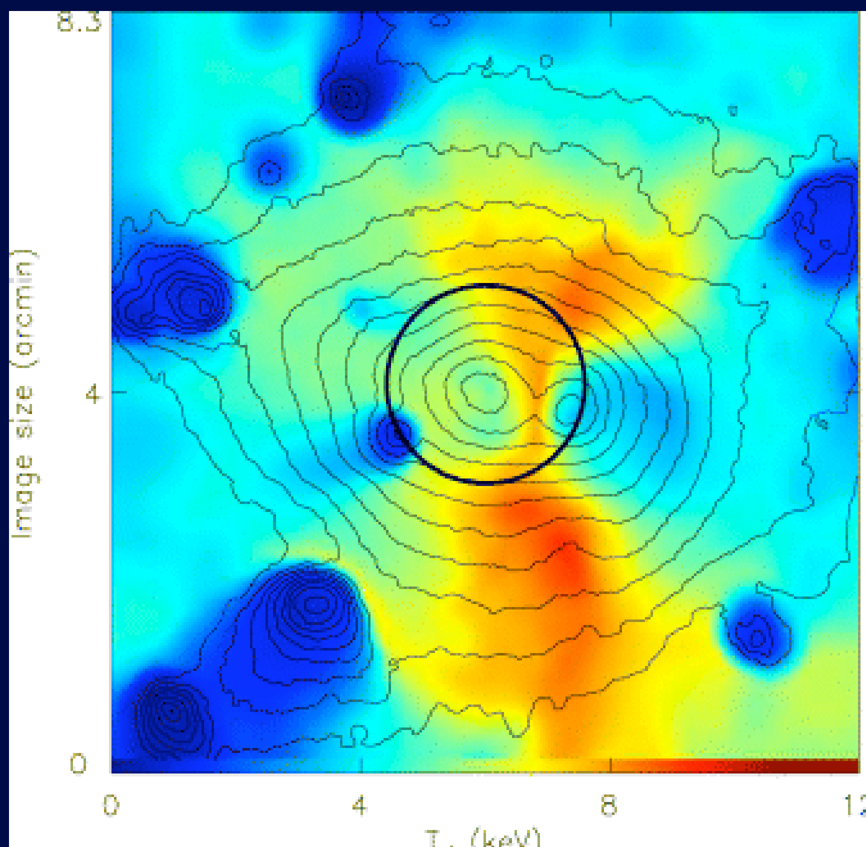
Richstone et al. 1992

The fraction of clusters with substructure and the rate at which this fraction evolves with z → Ω_m, Λ

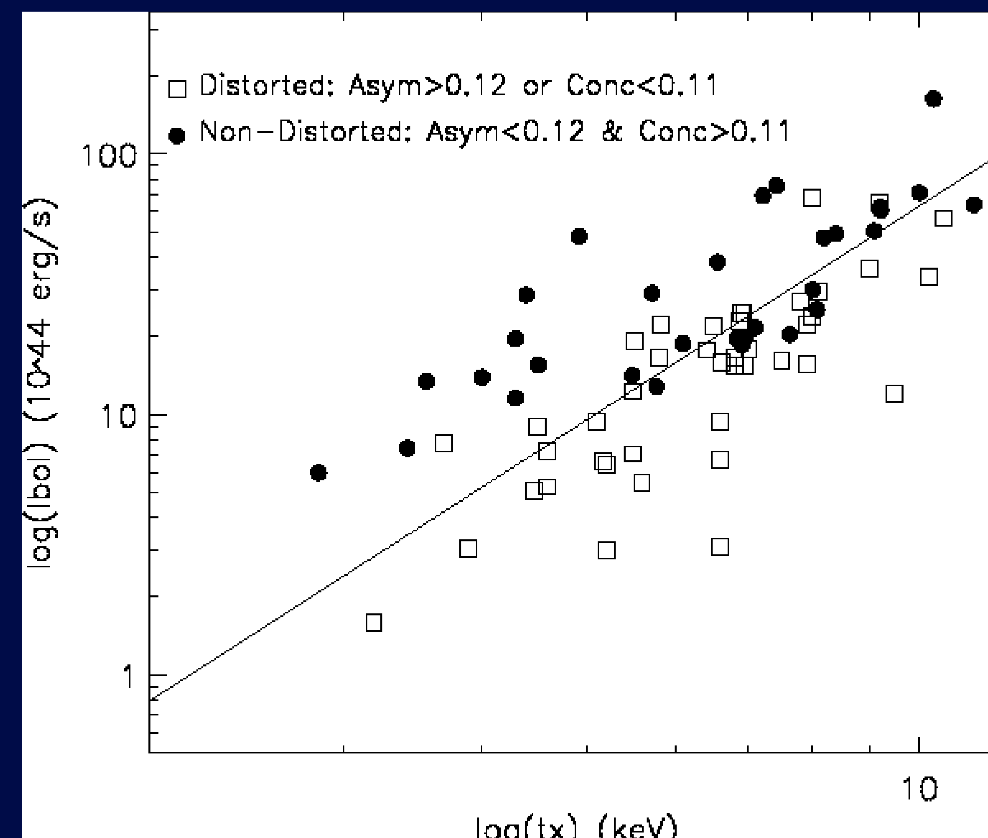
Substructure affects mass estimates.

Mergers and Mass Estimates

- Mergers cause variations in L_x, T_x, and velocity dispersion.



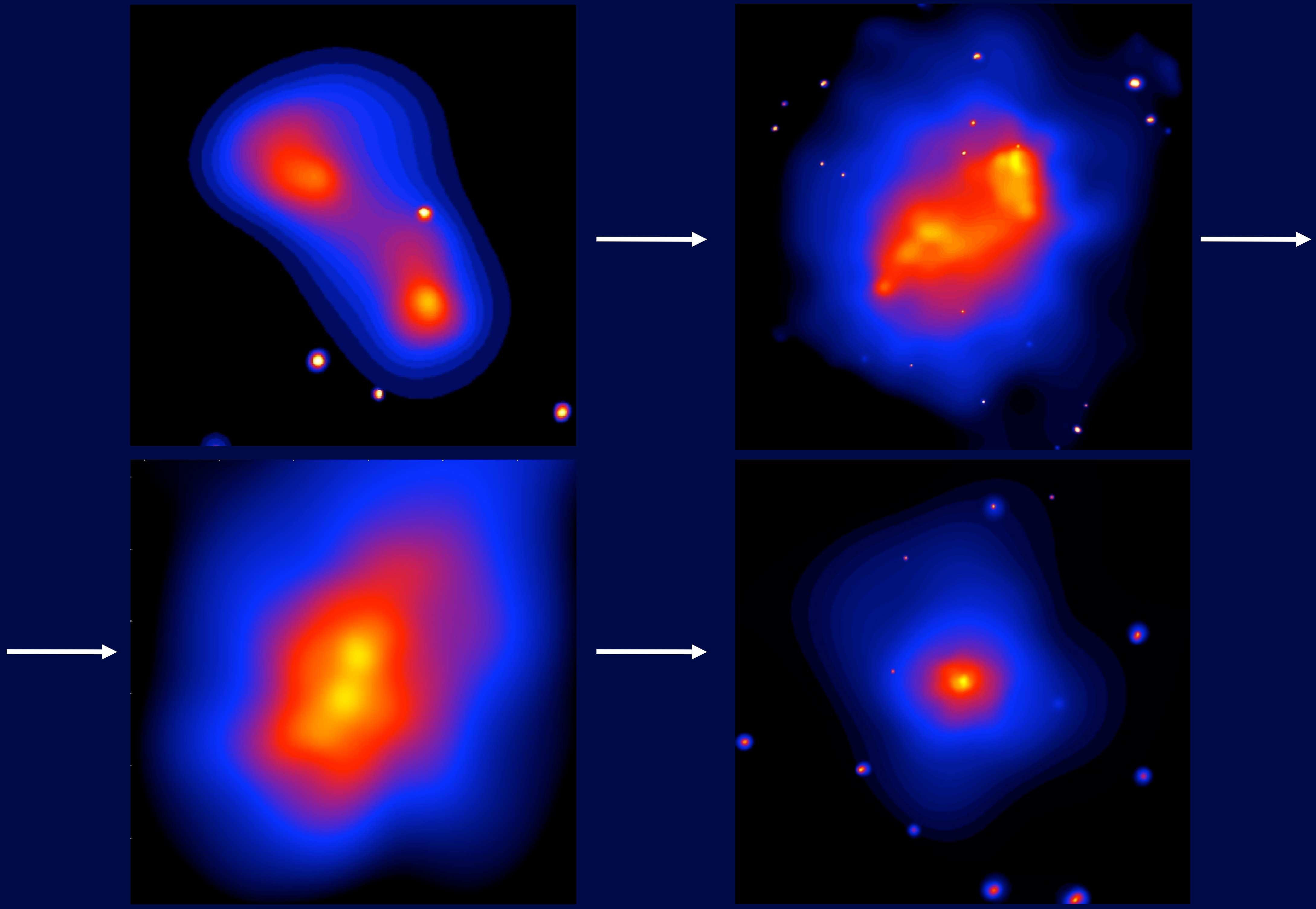
Mazzotta et al. 2004



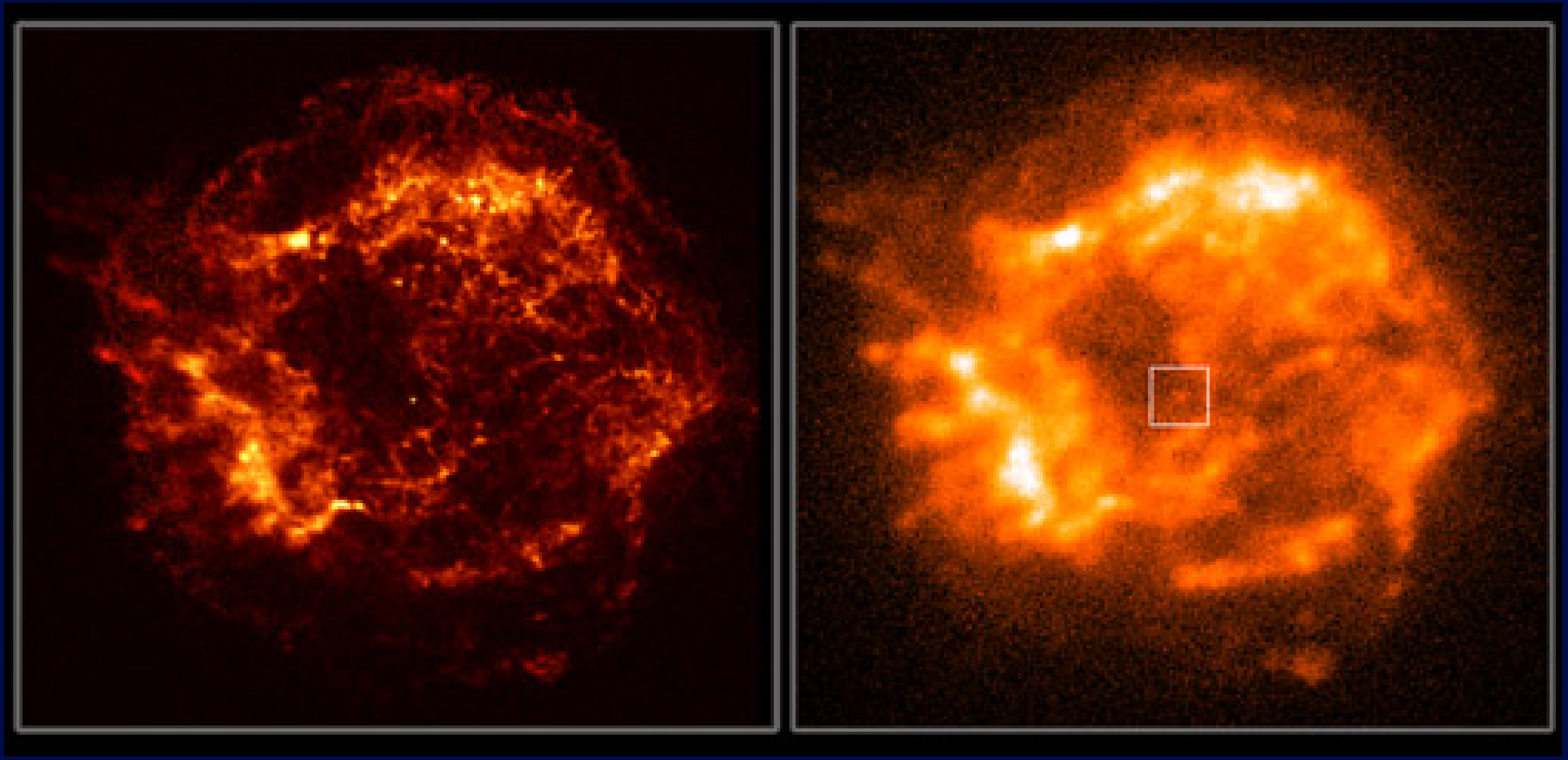
Hashimoto et al. 2007

- Smith et al. 2004 find unrelaxed lensing clusters 40% hotter, and Hashimoto et al. 2007 find offset in L_x-T_x relation.

Observing Mergers



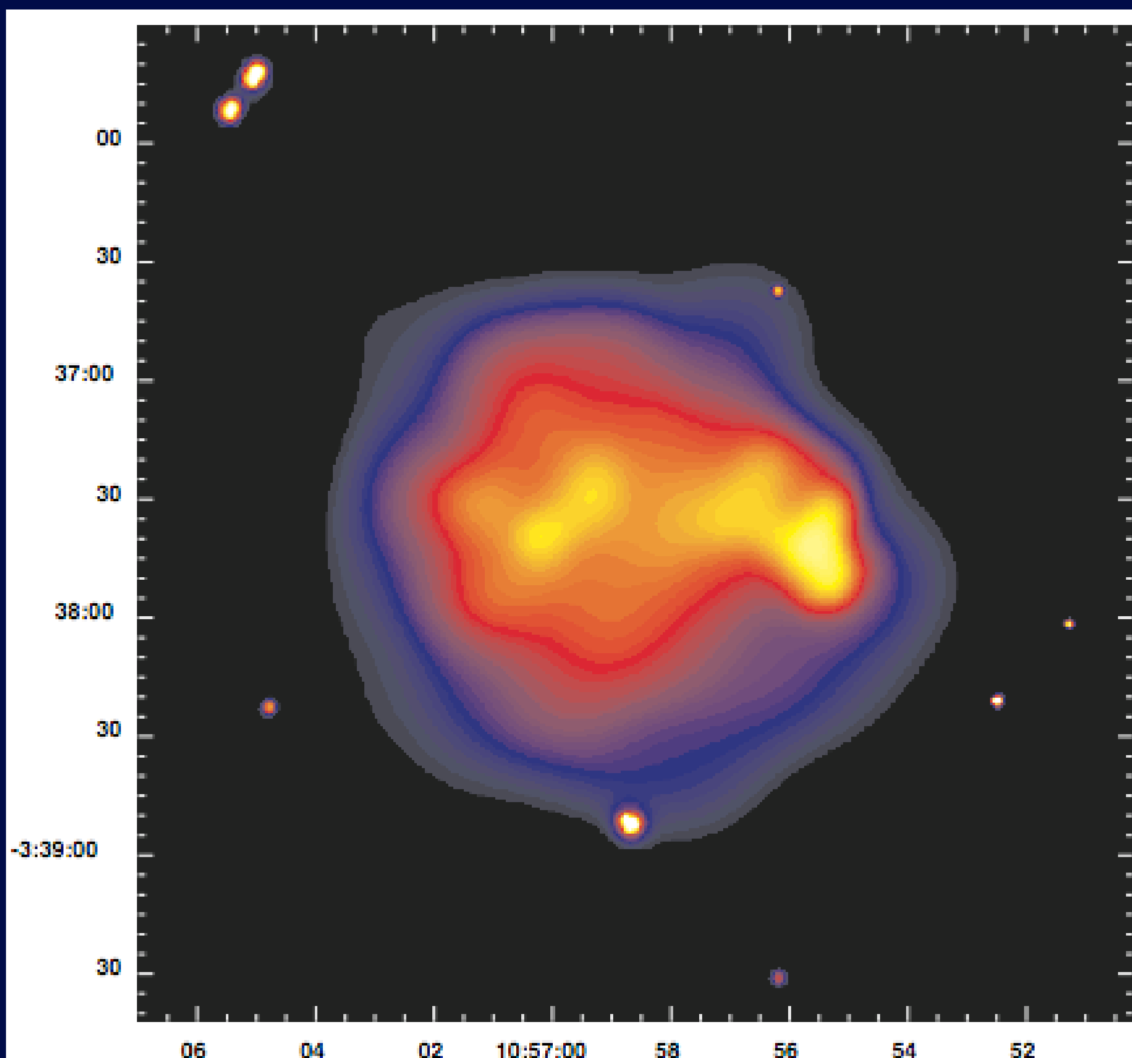
Cassiopeia A: Chandra vs. ROSAT



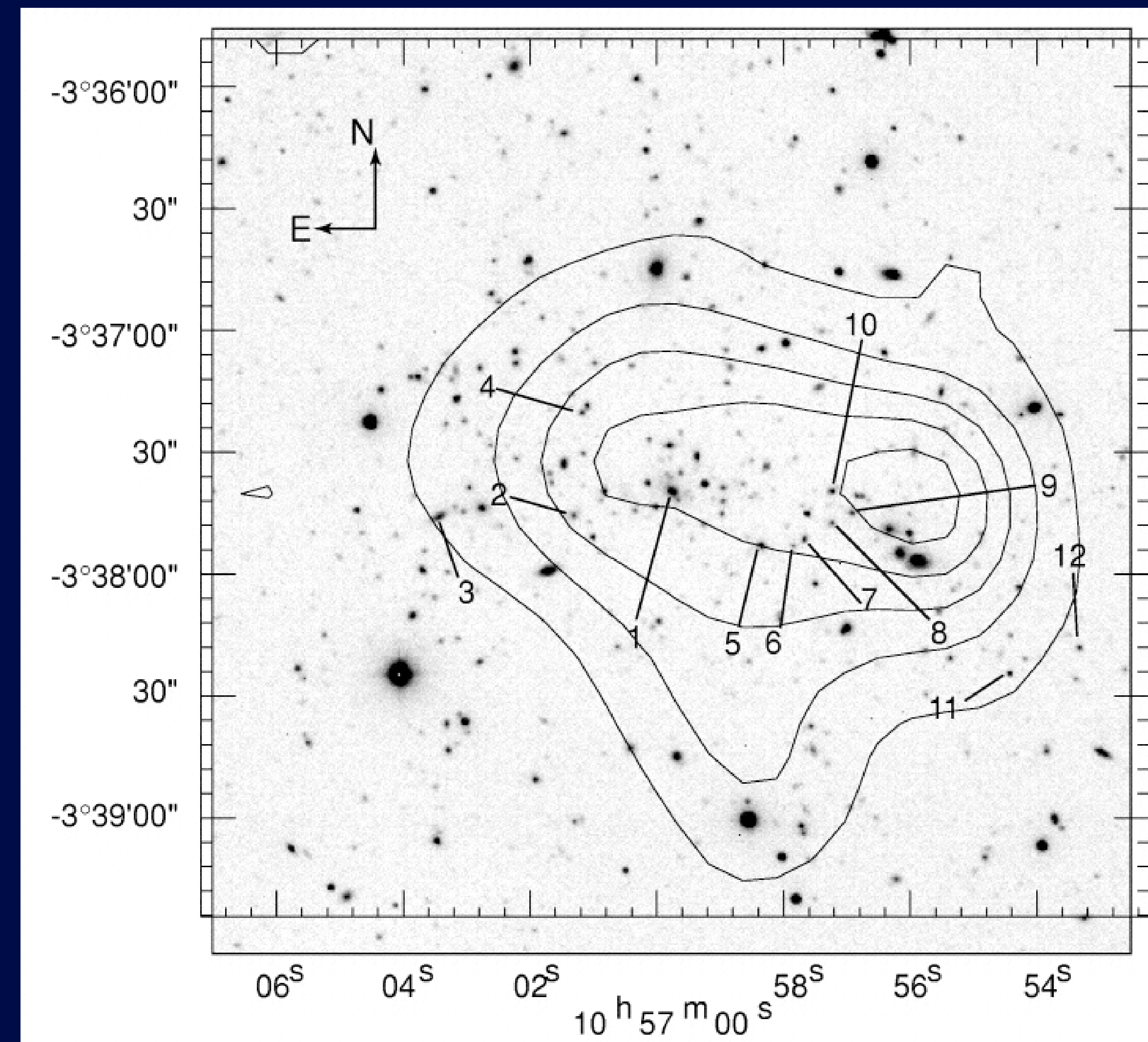
- Chandra on axis resolution: 0.5”
- ROSAT HRI: 4” and XMM-Newton: 20”

Clusters with Chandra

MS1054 at z=0.83



Jeltema et al. 2001

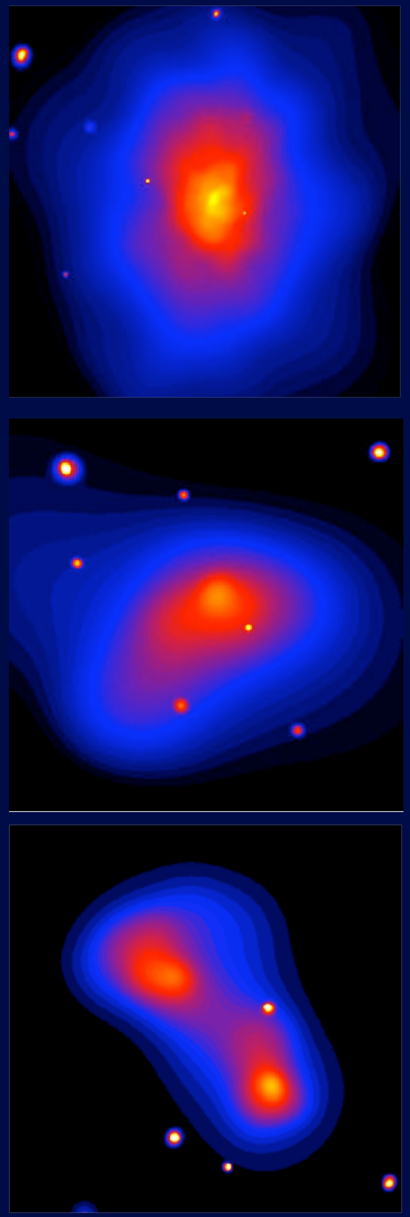


Donahue et al. 1998

- Exclusion of point sources and increased sensitivity to structure in high-z clusters.

Measuring Structure

- Jones & Foreman (1992): single, elliptical, offset center, primary w/ small secondary, double, complex
- Ellipticity
- Centroid or Center-of-mass shift
  (Mohr et al 1995)
- Power ratios
  (Buote & Tsai 1995)



Sample

- 40 clusters from Chandra archive with 0.1 < z < 0.9

  z < 0.5: 26 clusters with <z> = 0.24

  z > 0.5: 14 clusters with <z> = 0.71

- Selected from flux-limited X-ray surveys and have $2x10^{44}$ ergs/s < L_x < $2x10^{45}$ ergs/s.

Power Ratio Method

- Capable of distinguishing different cluster morphologies

- 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

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

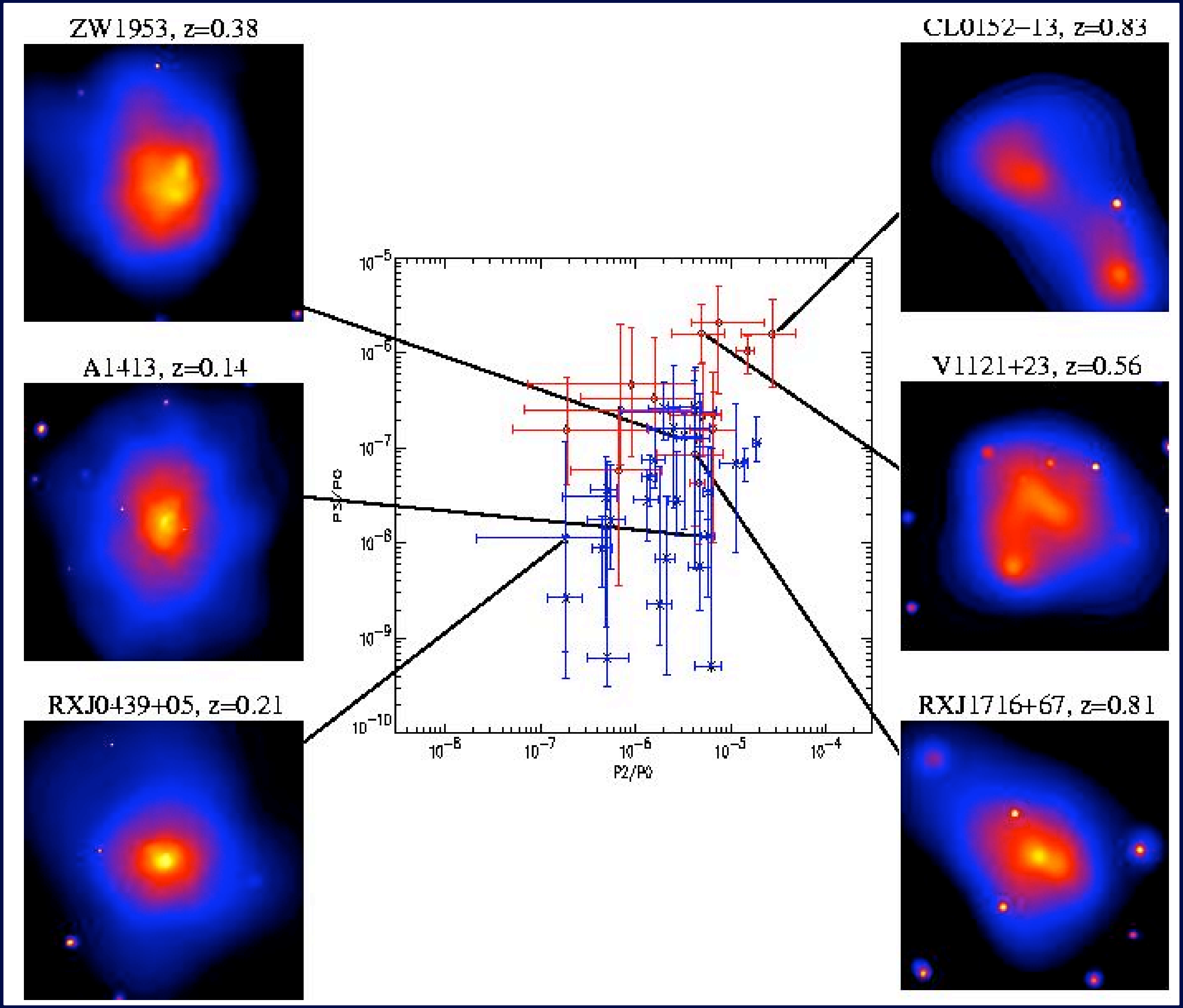
(Buote & Tsai 1995, 1996)

Power Ratios cont.

- Calculate powers in a circular aperture with R = 0.5 Mpc centered on the cluster centroid.

- Find P_2/P_0, P_3/P_0, and P_4/P_0. $P_1/P_0 = 0$ with origin at centroid.

P_2/P_0 vs. P_3/P_0



ZW1953, z=0.38
A1413, z=0.14
RXJ0439+05, z=0.21
CL0152−13, z=0.83
V1121+23, z=0.56
RXJ1716+67, z=0.81
P3/P0
P2/P0

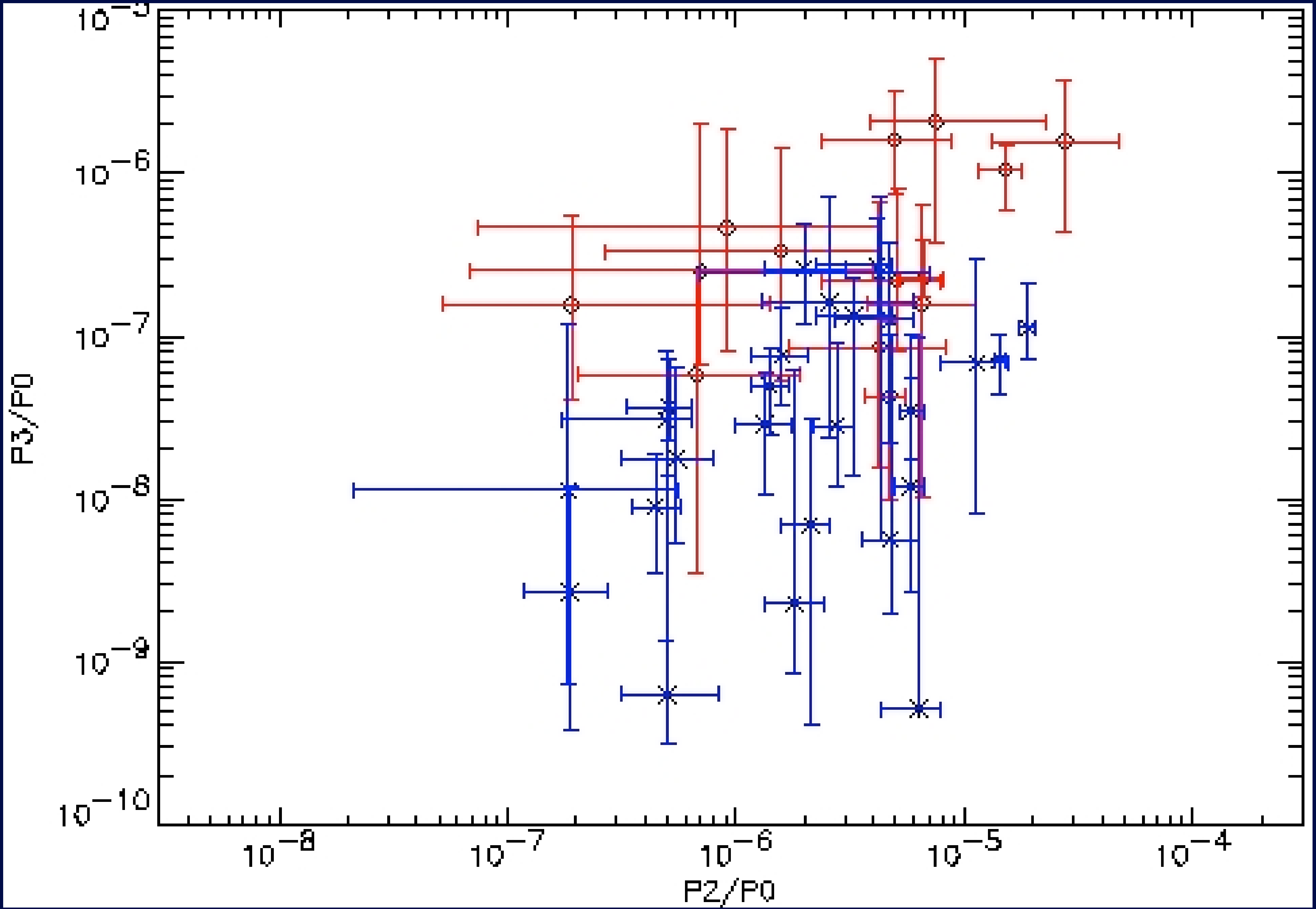
Estimating Uncertainties

Estimated uncertainties through a Monte Carlo technique

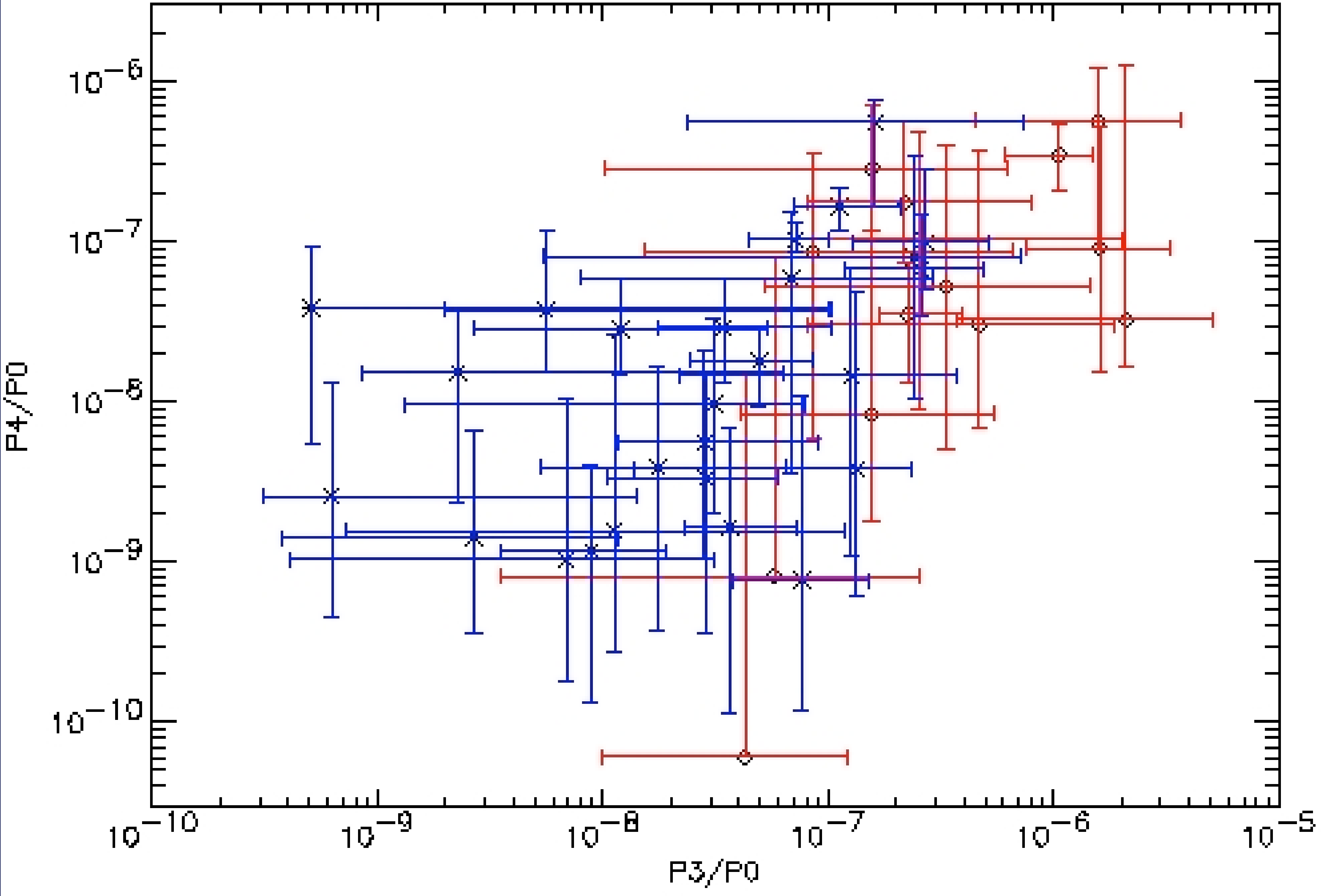
- Created 100 mock cluster observations for each cluster with appropriate Poisson noise.

- 90% confidence limits defined as 5th highest and 5th lowest power ratios.

P_2/P_0 vs P_3/P_0



P_3/P_0 vs. P_4/P_0



Statistical Significance

- A rank-sum test shows that high-redshift sample has significantly higher mean P_3/P_0 and P_4/P_0.
- A Kolmogorov-Smirnov test shows that the distributions of P_3/P_0 and P_4/P_0 are significantly different for the two samples.

Power Ratios(1)	Average Low-*z*(2)	Average High-*z*(3)	Rank Sum Prob.(4)	K-S Prob.(5)	Average RS Prob.(6)	Average K-S Prob.(7)
P_2/P_0...	3.92E-6	6.16E-6	0.10	0.34	...	...
P_3/P_0...	6.93E-8	5.95E-7	4.6E-5	0.00064	0.00036	0.0023
P_4/P_0...	5.20E-8	1.30E-7	0.025	0.041	0.0082	0.037

Statistical Significance

- Including the uncertainties, the difference between the high and low-z samples is still significant.
- Also find a significant correlation between P_2/P_0-P_3/P_0, P_2/P_0-P_4/P_0, and P_3/P_0-P_4/P_0.

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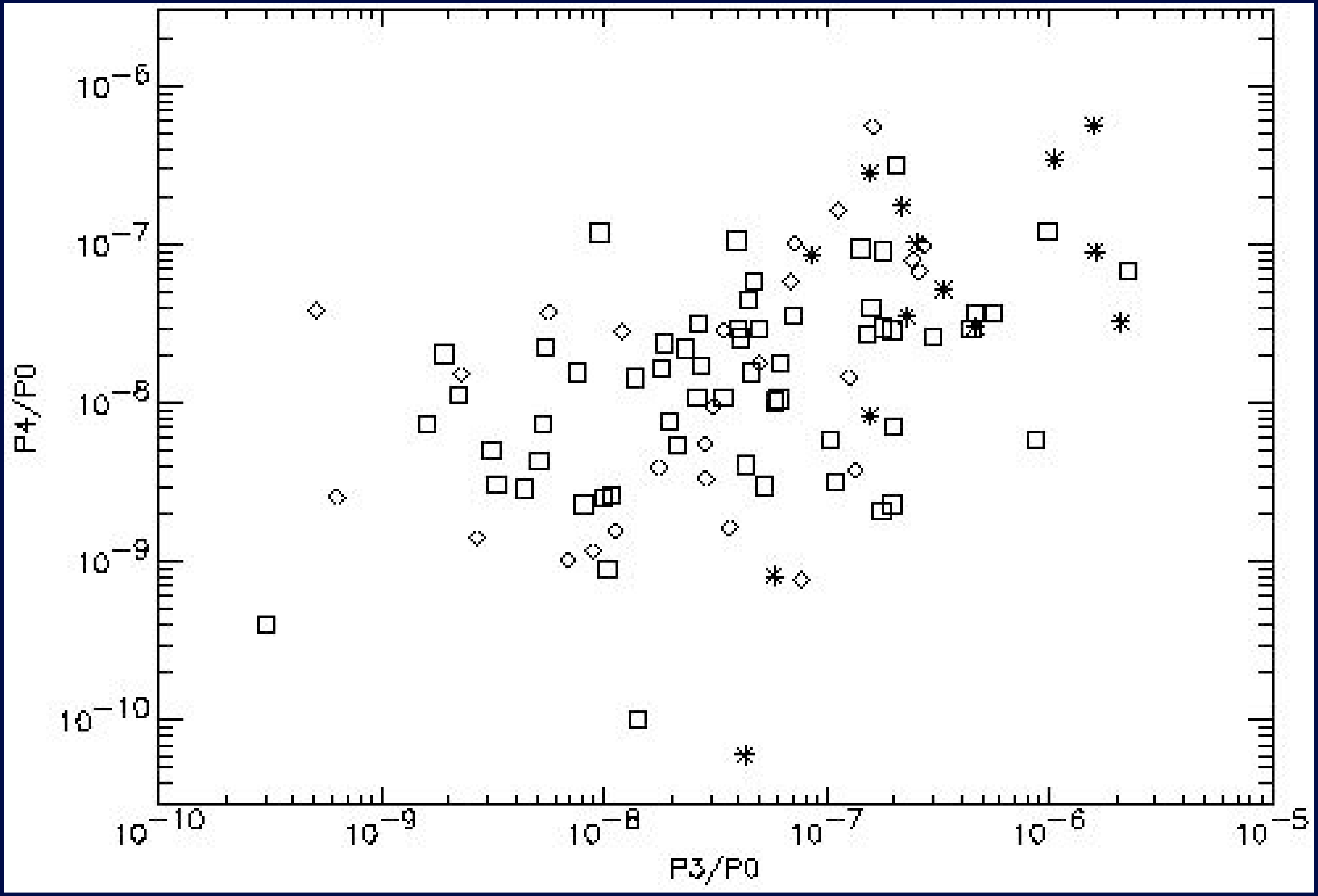
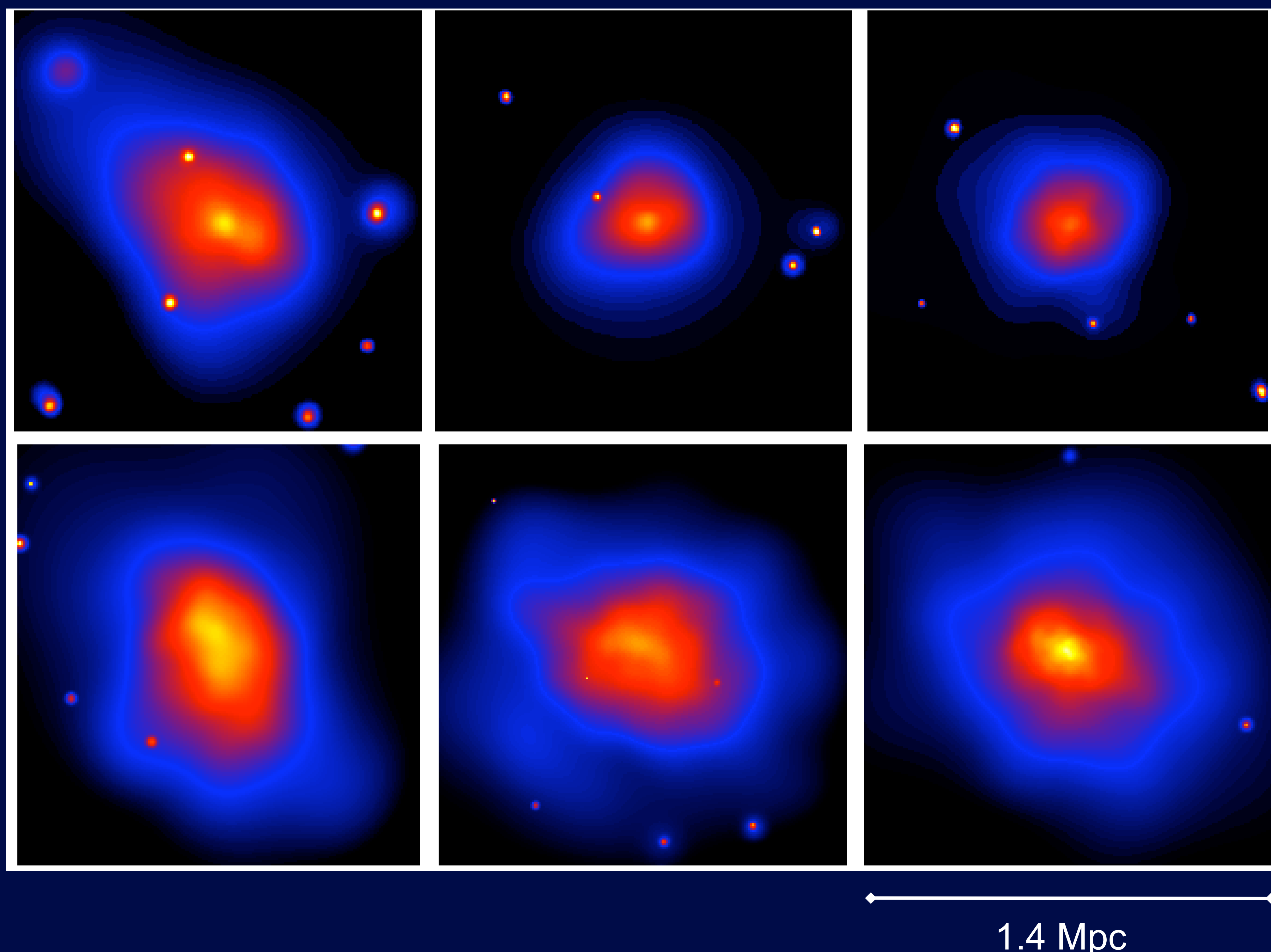
Comparison to Buote & Tsai (1996)



Lowest P_3/P_0



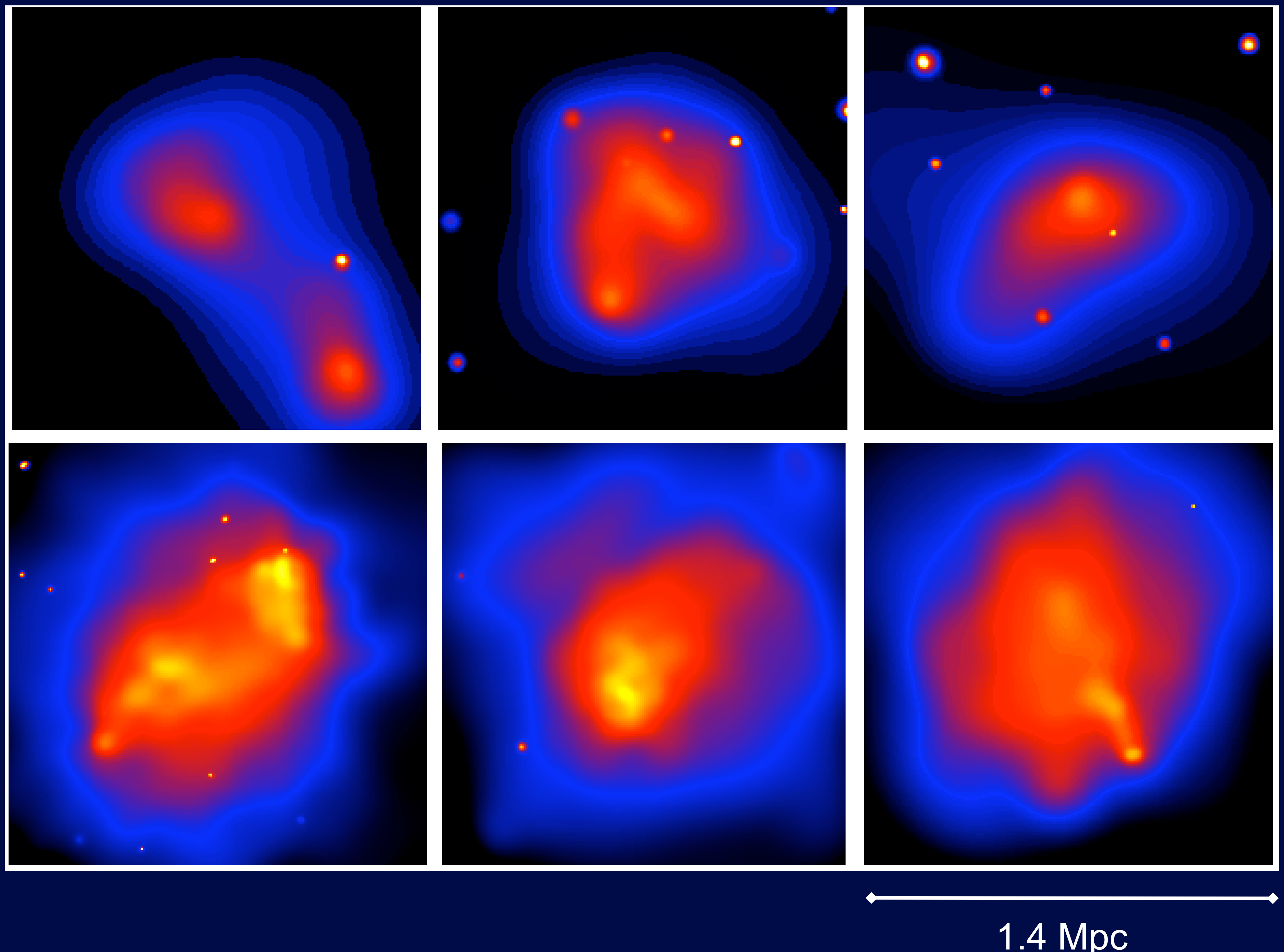
High z

$P_3/P_0 =$
-3.0×10^{-8}

Low z

$P_3/P_0 =$
-1.7×10^{-8}

Highest P_3/P_0



High z

$P_3/P_0 =$
1.4×10^{-6}

Low z

$P_3/P_0 =$
2.0×10^{-7}

Summary of Observations

- High-redshift clusters have more substructure and are dynamically younger than low-redshift clusters.

  (confirmed by Hashimoto et al. 2007; Maughan et al. 2007)

- The evolution in P_3/P_0 is significant even considering uncertainty from noise and systematic effects.

  Slope = $4.09^{+3.94}_{-3.27} \times 10^{-7}$ (90%)

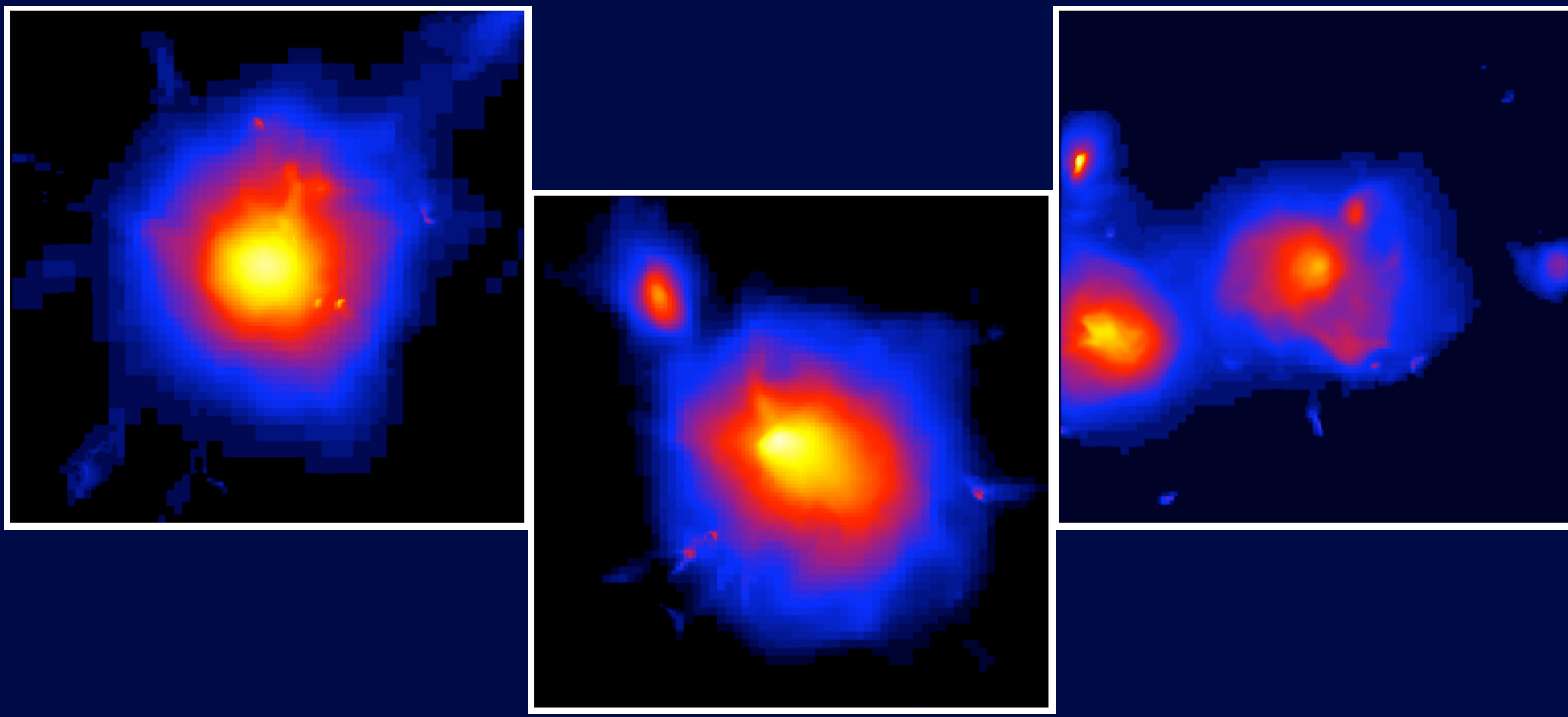
  Slope greater than zero at 99.5% confidence

- Structure evolution should be considered in cosmological studies.

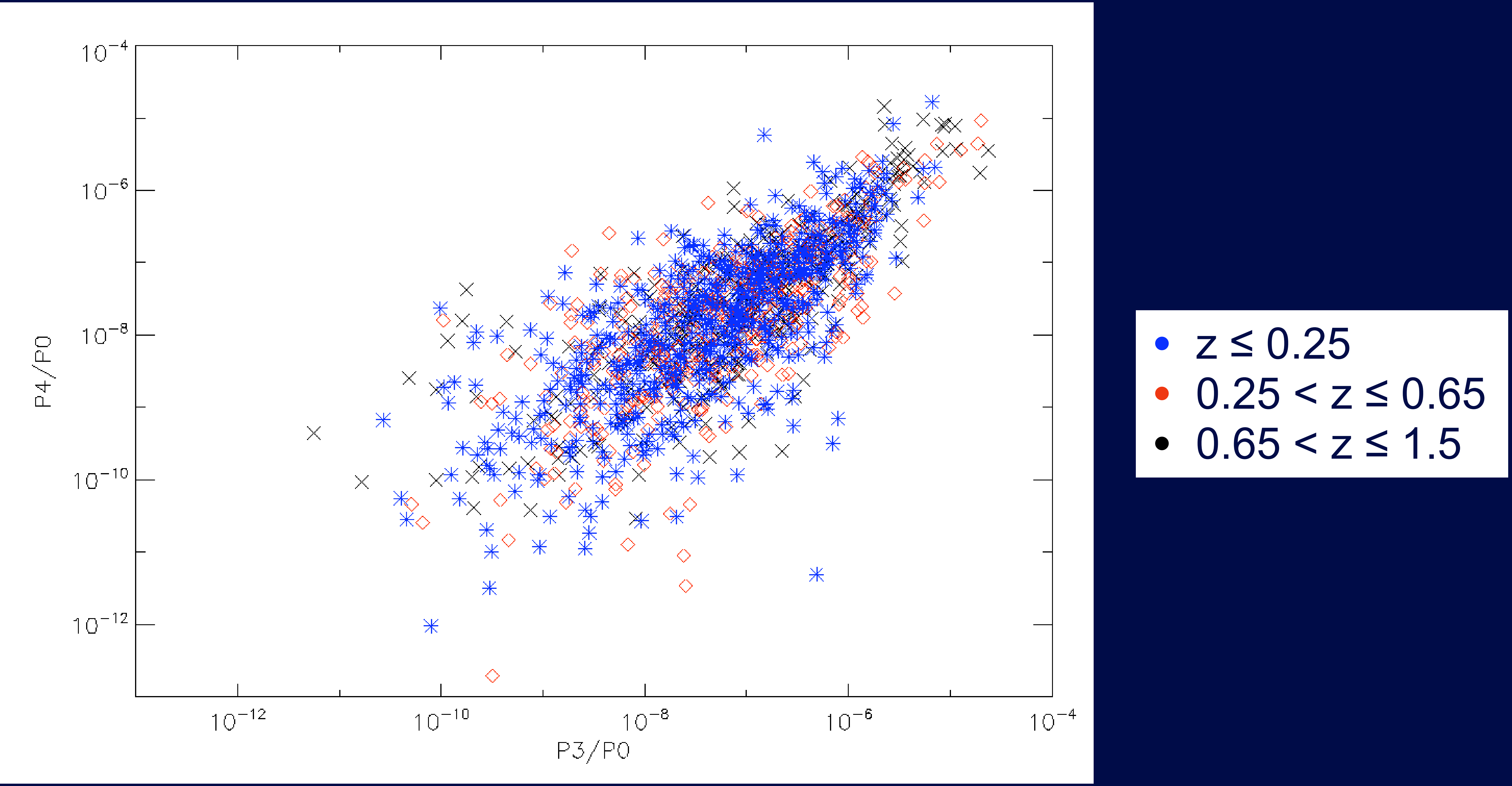
Comparison to Simulations
(work in progress)

- Test of cosmological models as well as the accuracy of current simulations (gas physics, etc.).
- The simulations: Motl, Hallman, Norman, and Burns
  - hydrodynamic, ΛCDM, AMR simulations
  - Four runs: adiabatic then adding cooling, star formation and feedback
  - Large volume and good resolution (~ 16 h^{-1} kpc)
  - Other simulations? (Valdarnini, Kravtsov, ...)

Simulated Clusters



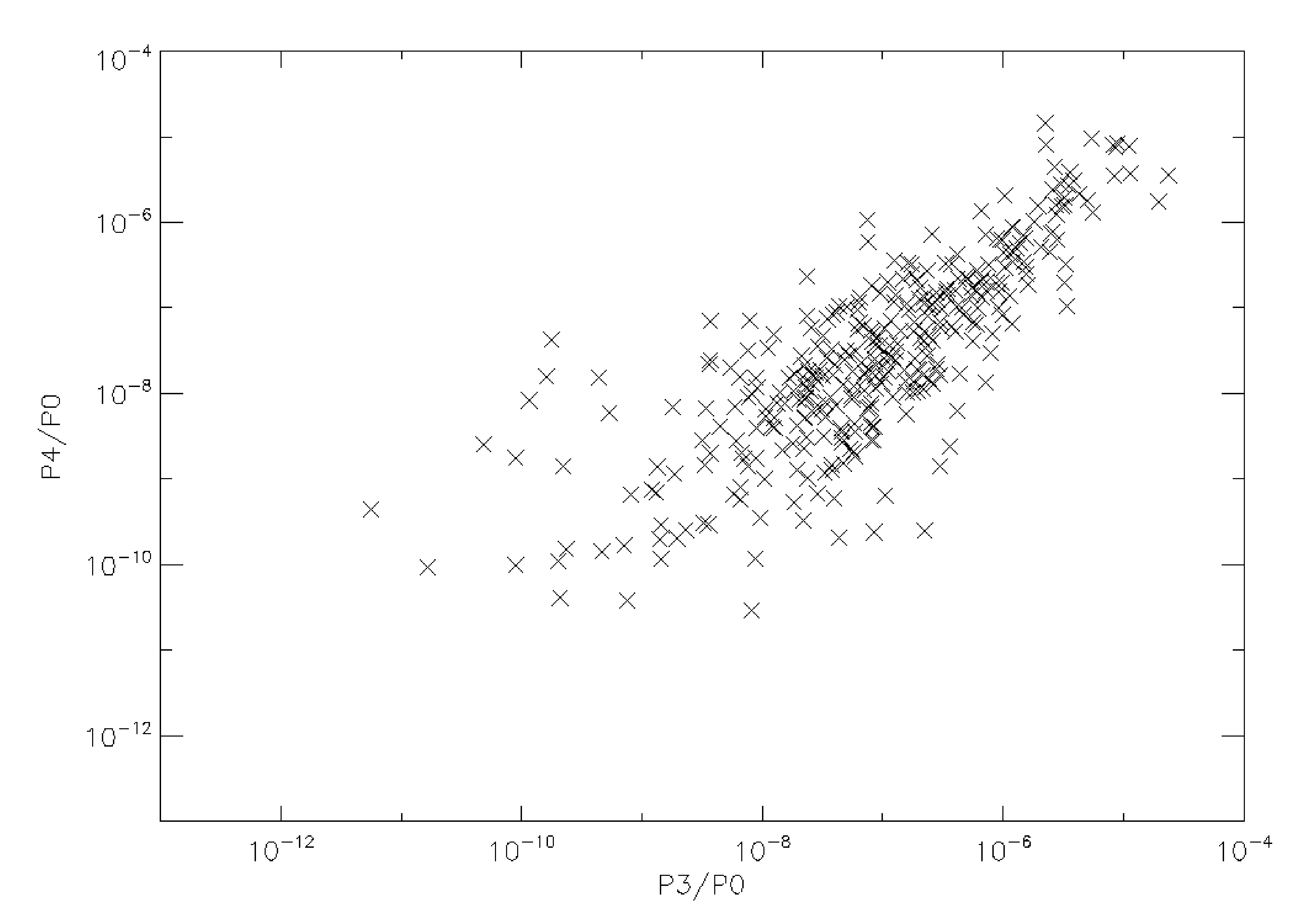
P_3/P_0 vs. P_4/P_0 in Simulations

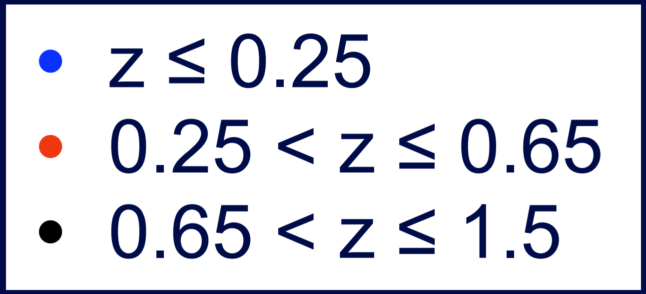


- Strong correlation in power ratios.
- Some evolution, but not strong.

Jeltema et al. 2007

P_3/P_0 vs. P_4/P_0 in Simulations





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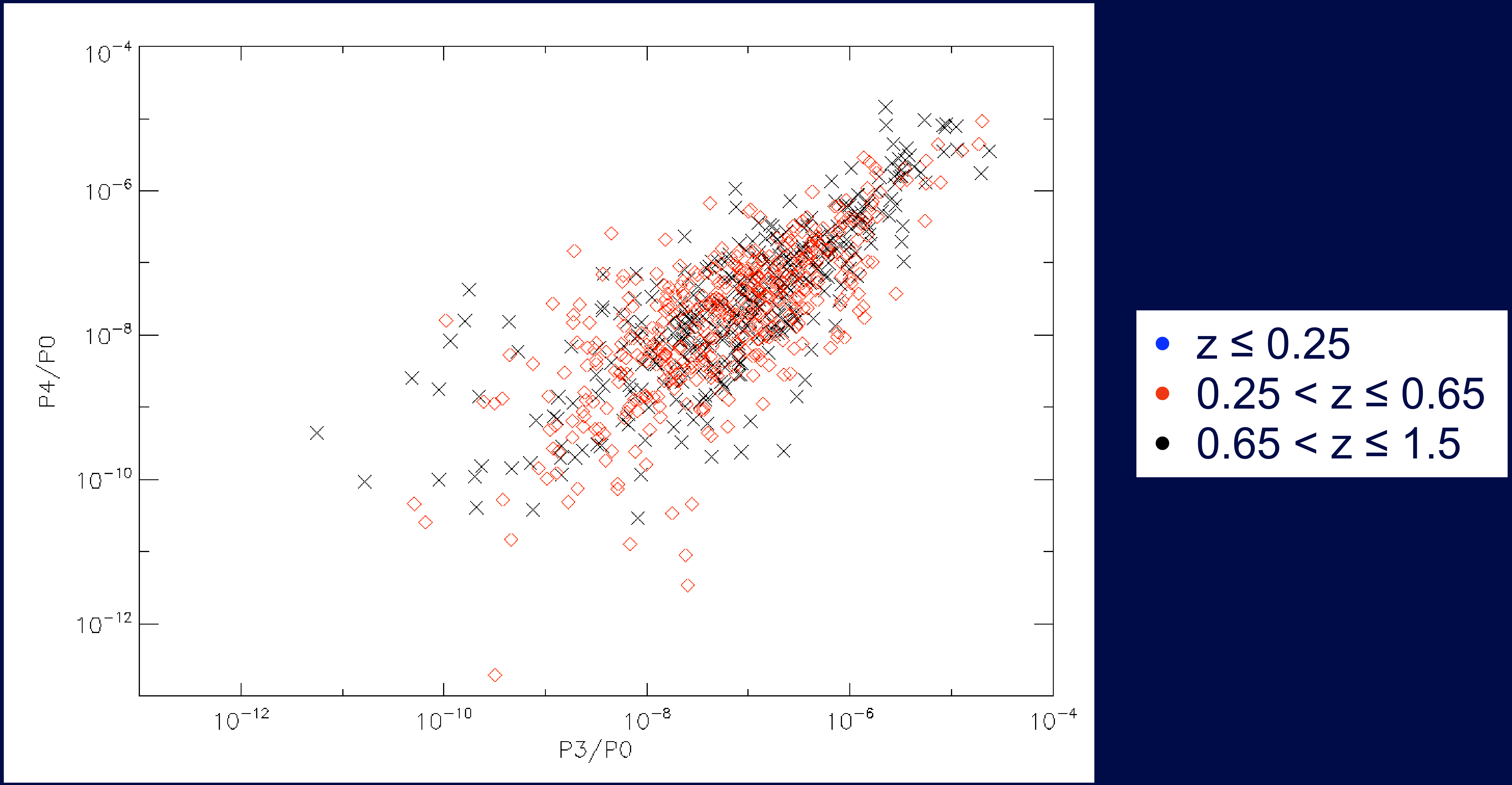

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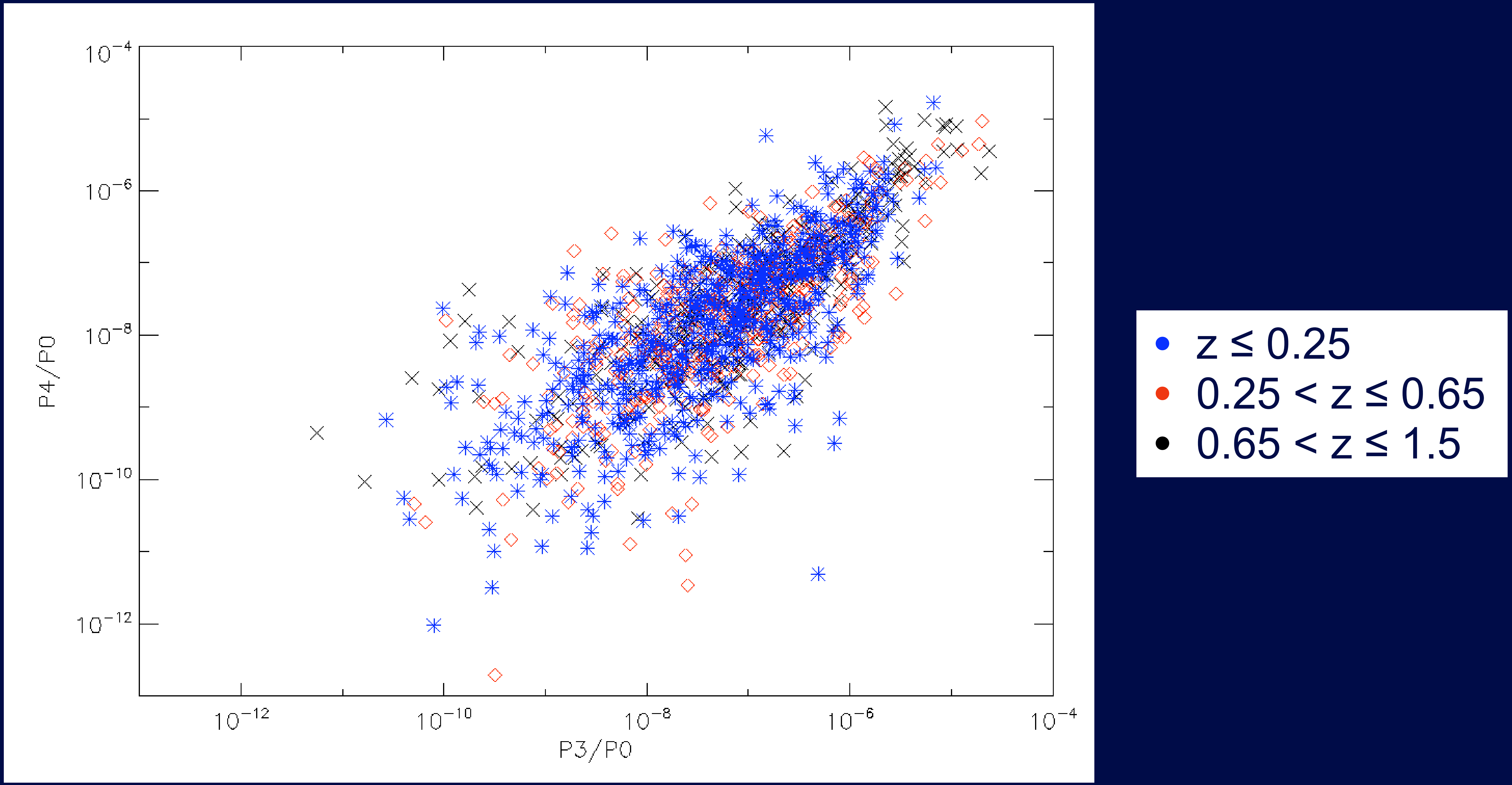

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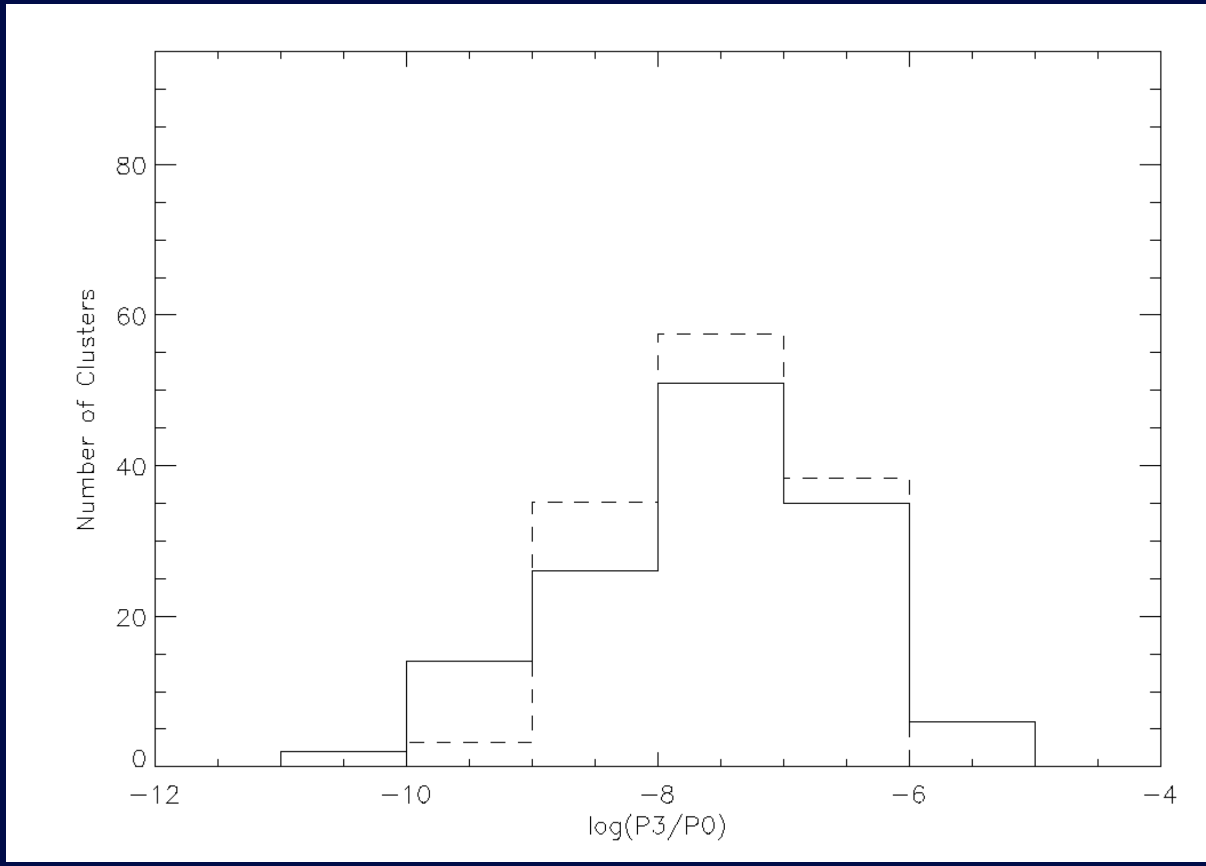
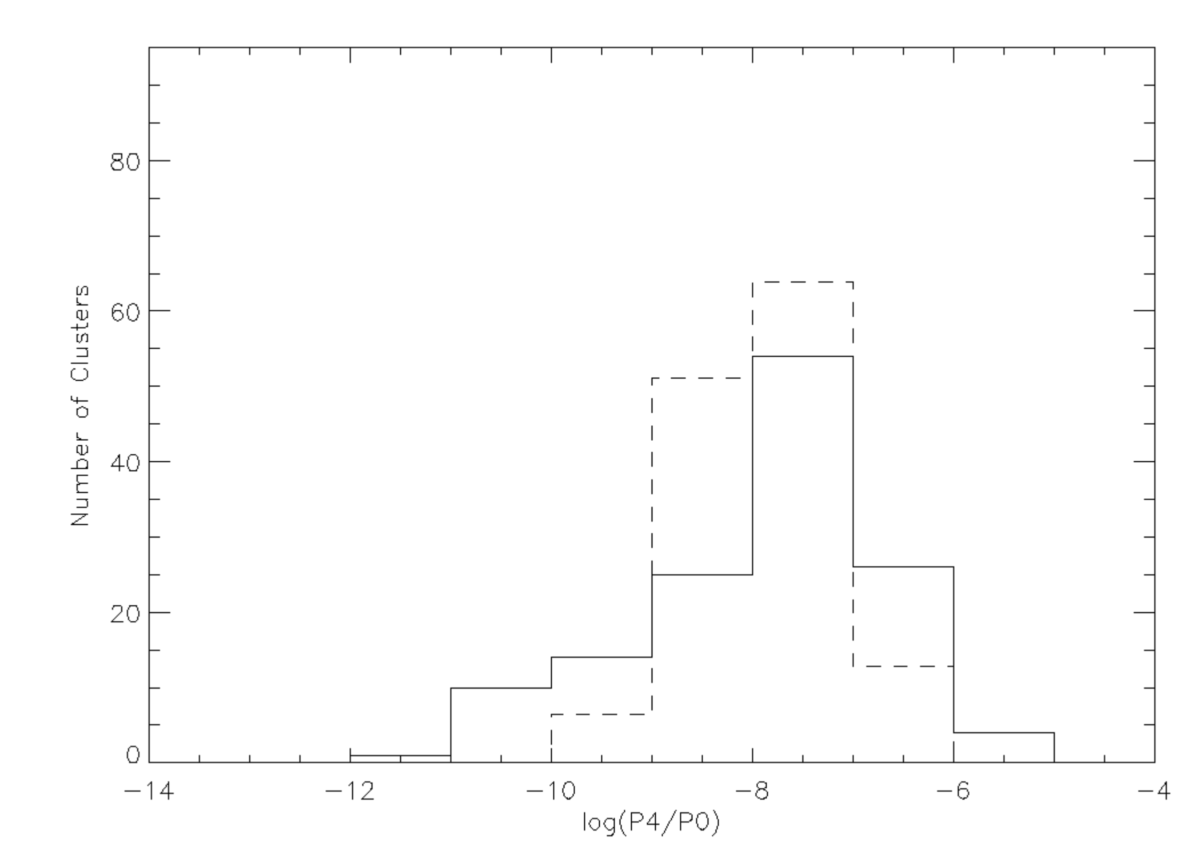
Jeltema et al. 2007

Comparison to Observations

Low Redshift (z<0.1)



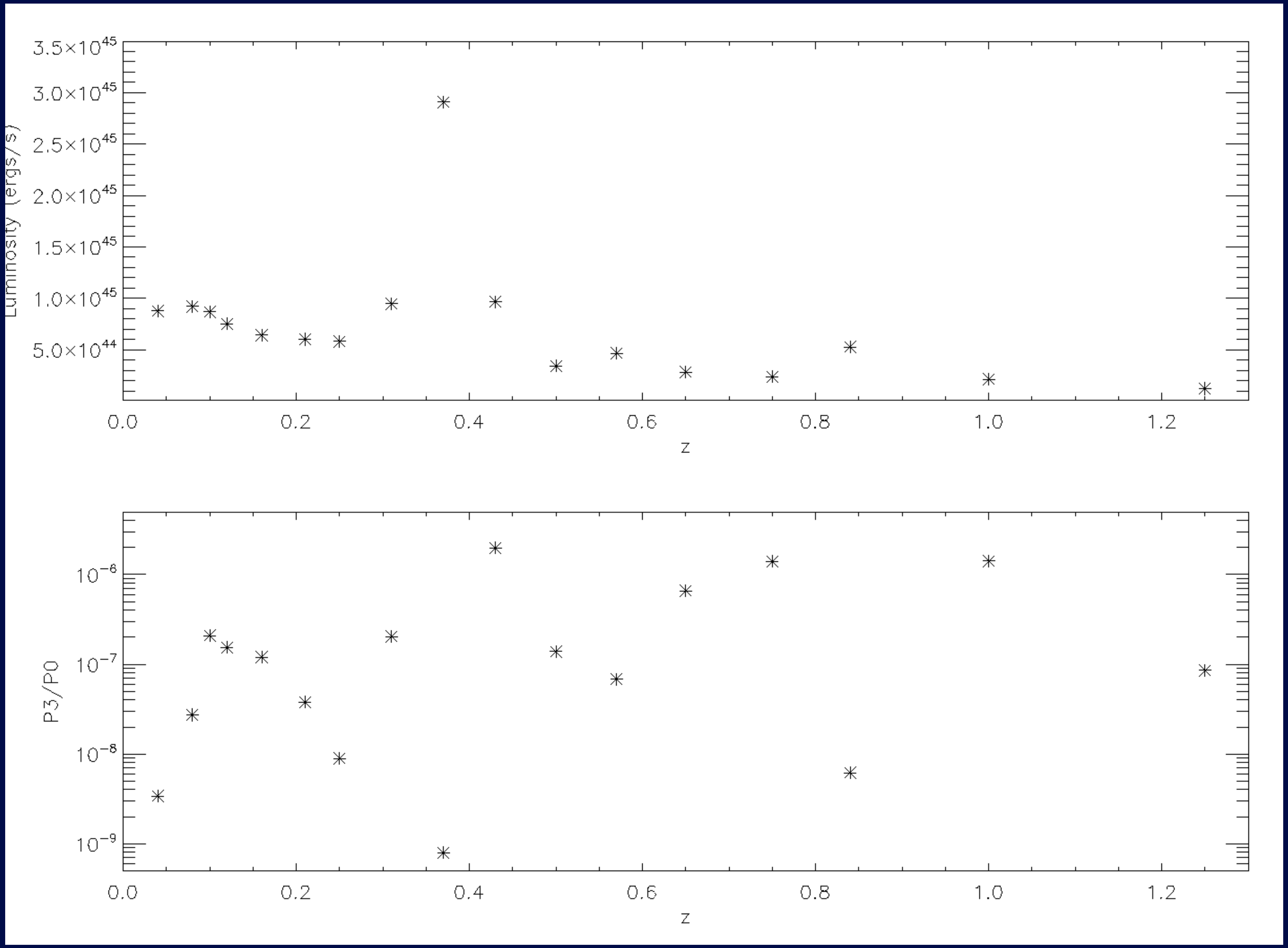


- Similar power ratio distributions.
- Possibly more clusters in the wings of distribution in simulations.

Evolution of Individual Clusters

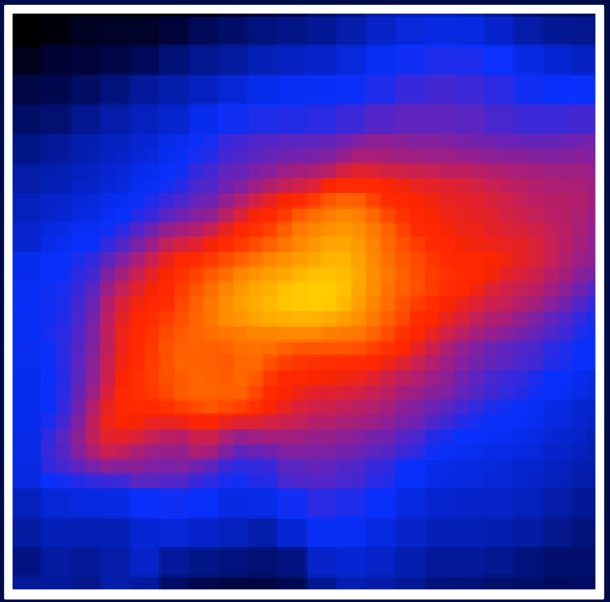
Luminosity

P3/P0



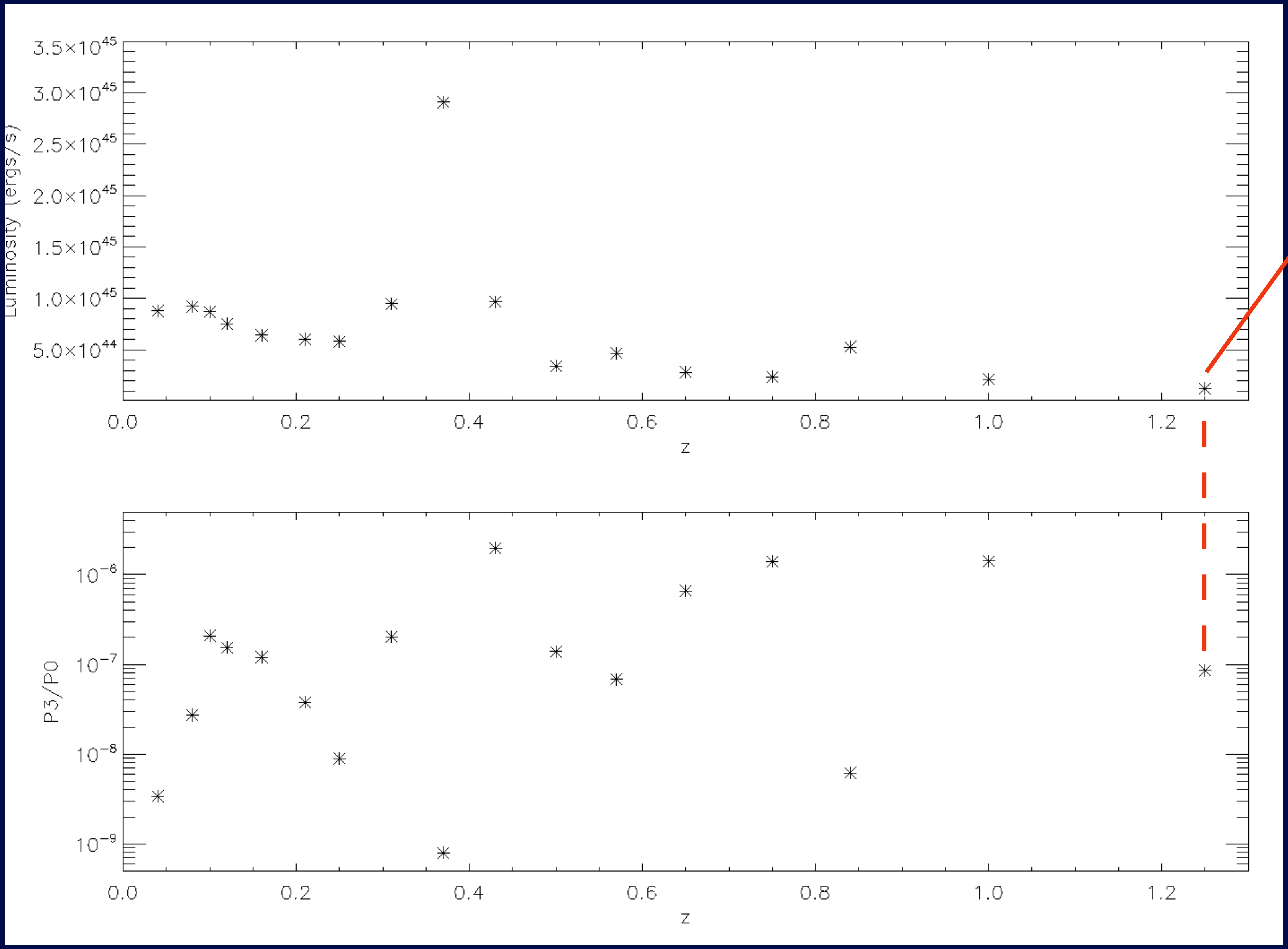
Jeltema et al. 2007

Evolution of Individual Clusters



Luminosity

P3/P0



Jeltema et al. 2007

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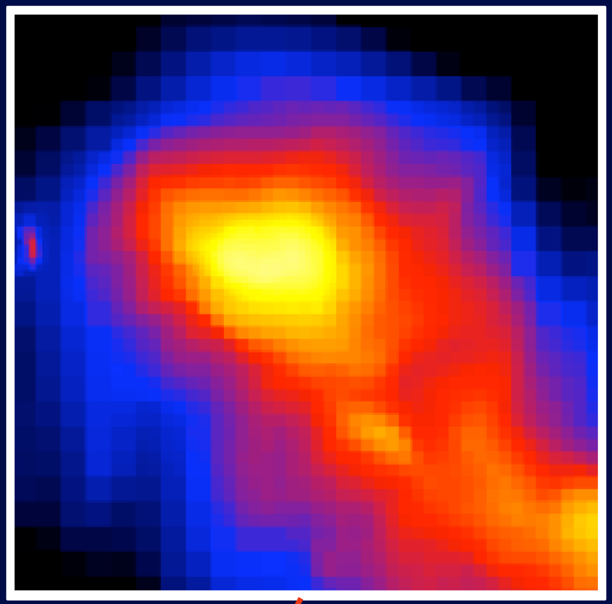

Luminosity

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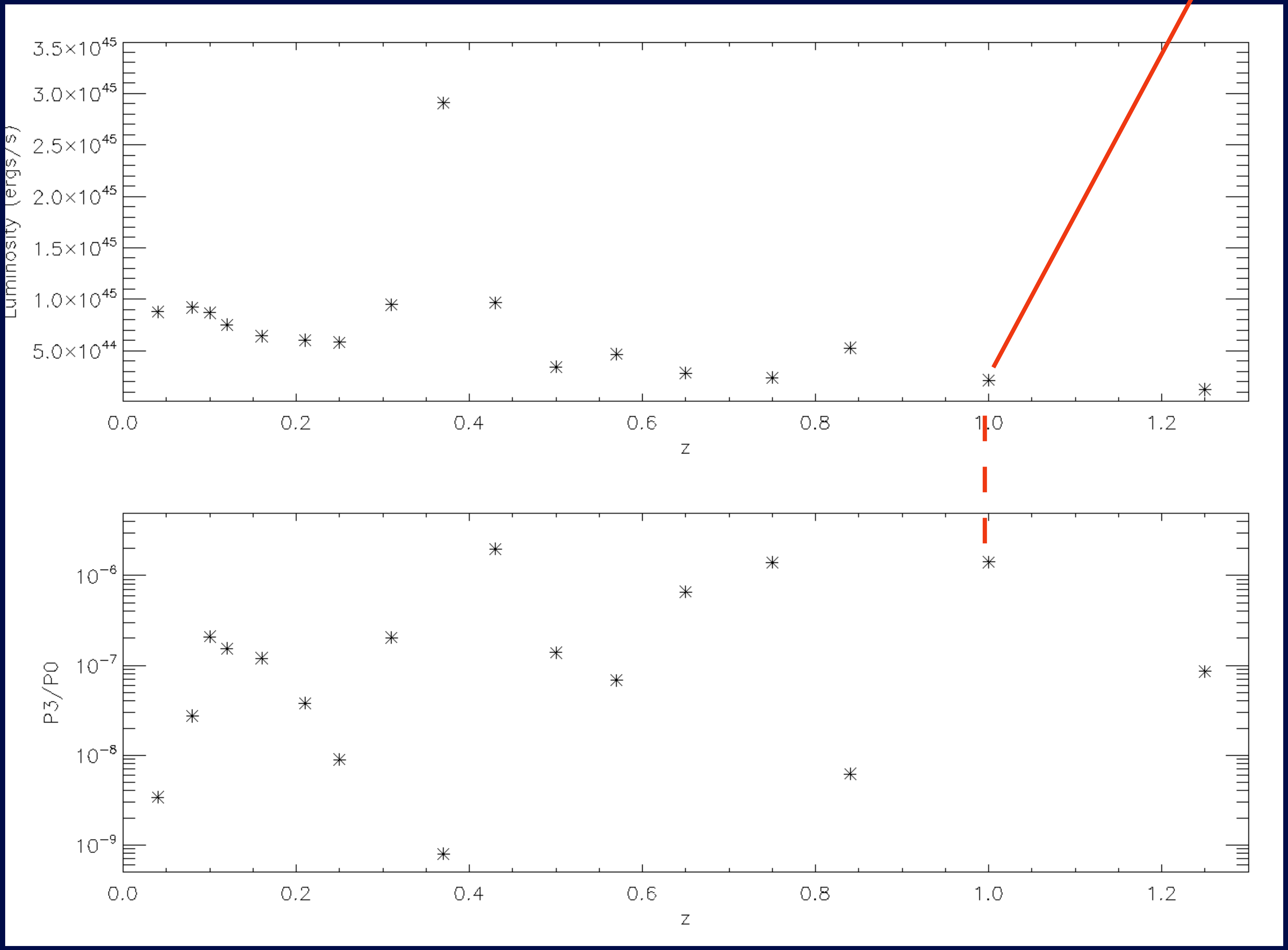

Jeltema et al. 2007

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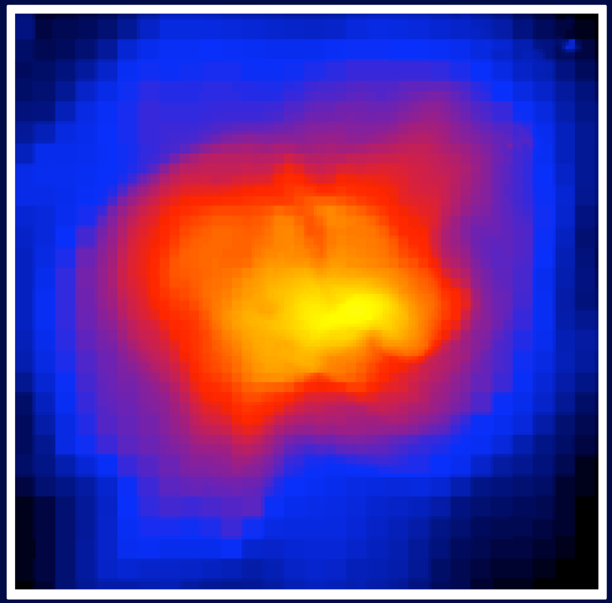
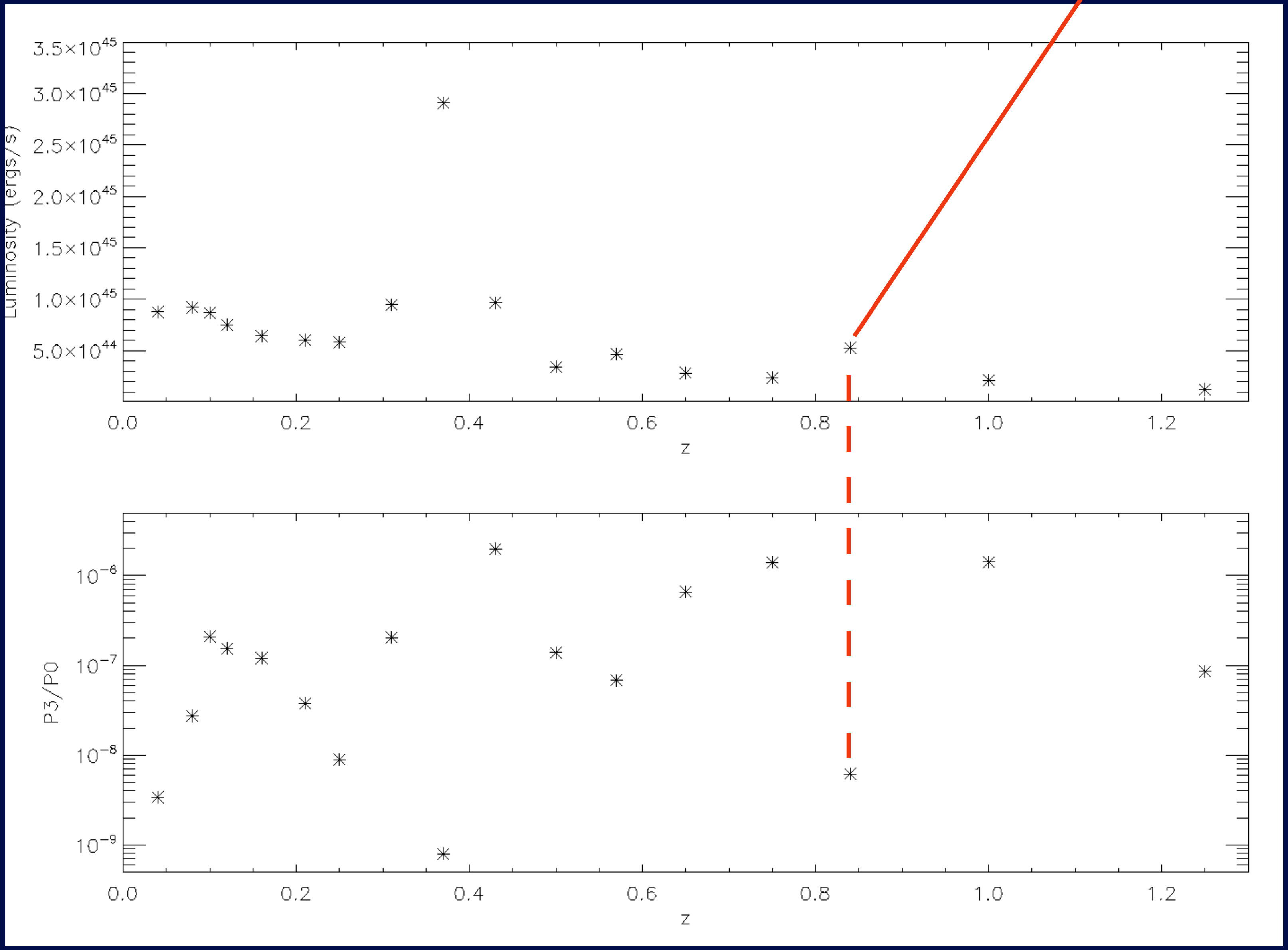


Luminosity

P3/P0



Jeltema et al. 2007

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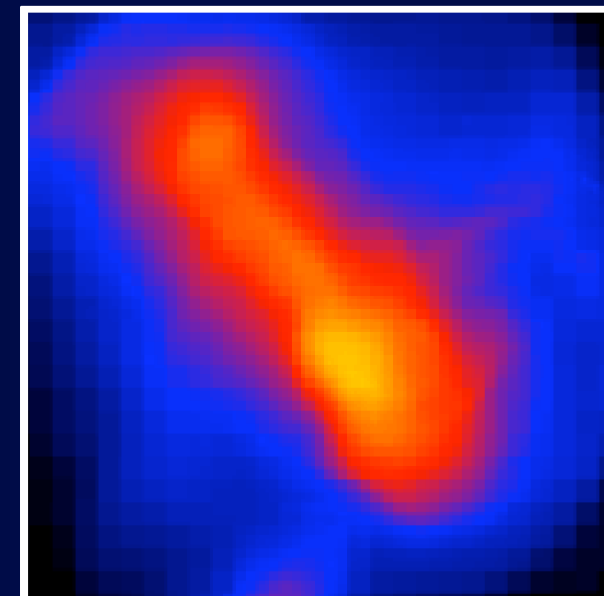
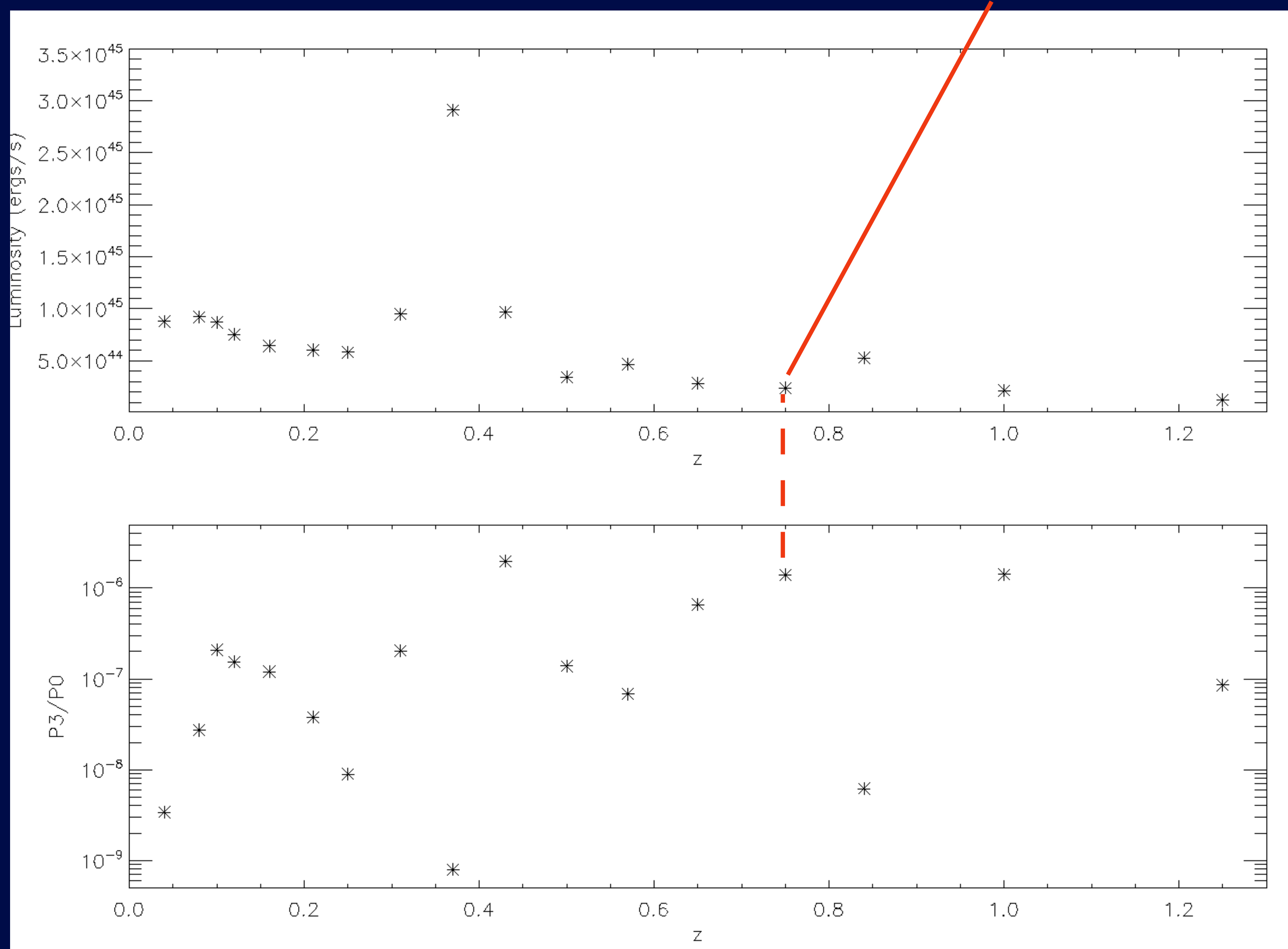


Luminosity

P3/P0



Jeltema et al. 2007

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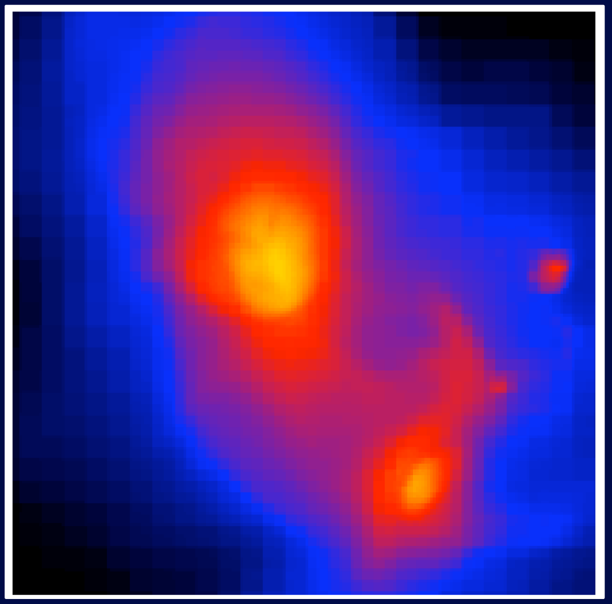

Luminosity

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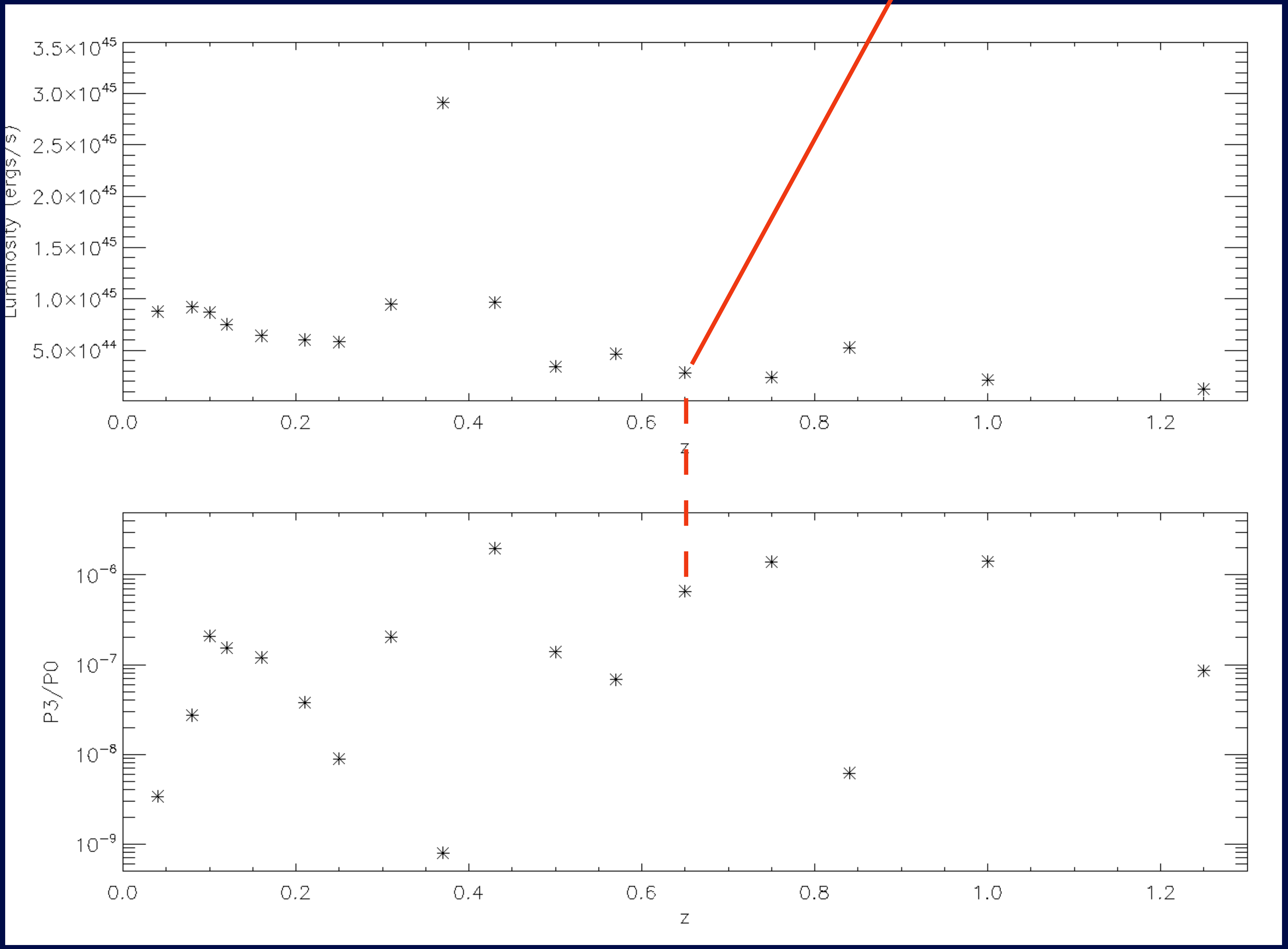
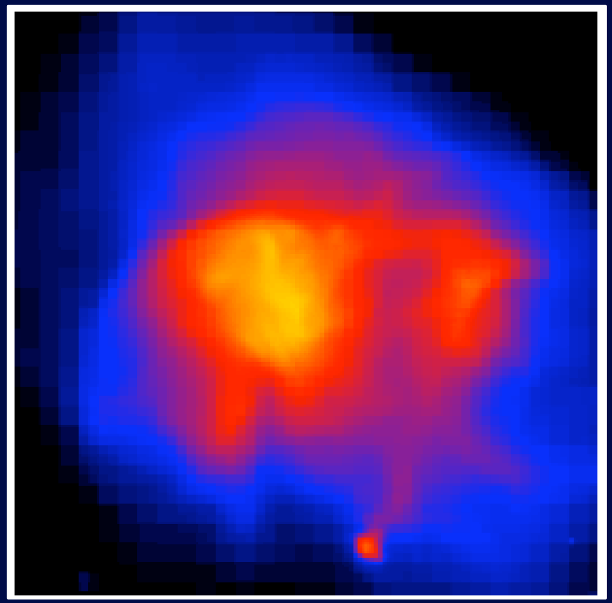


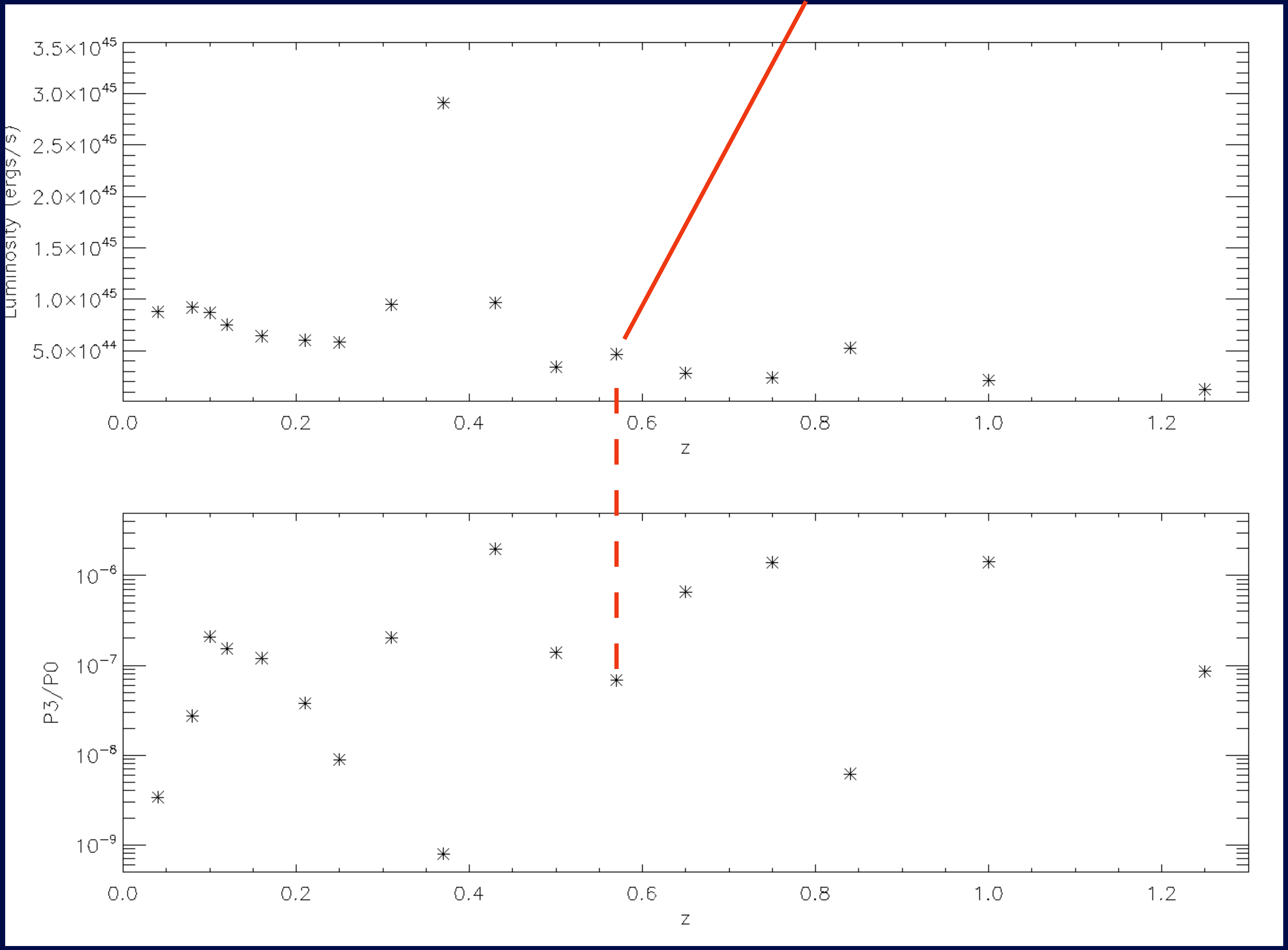
Jeltema et al. 2007

Evolution of Individual Clusters



Luminosity

P3/P0

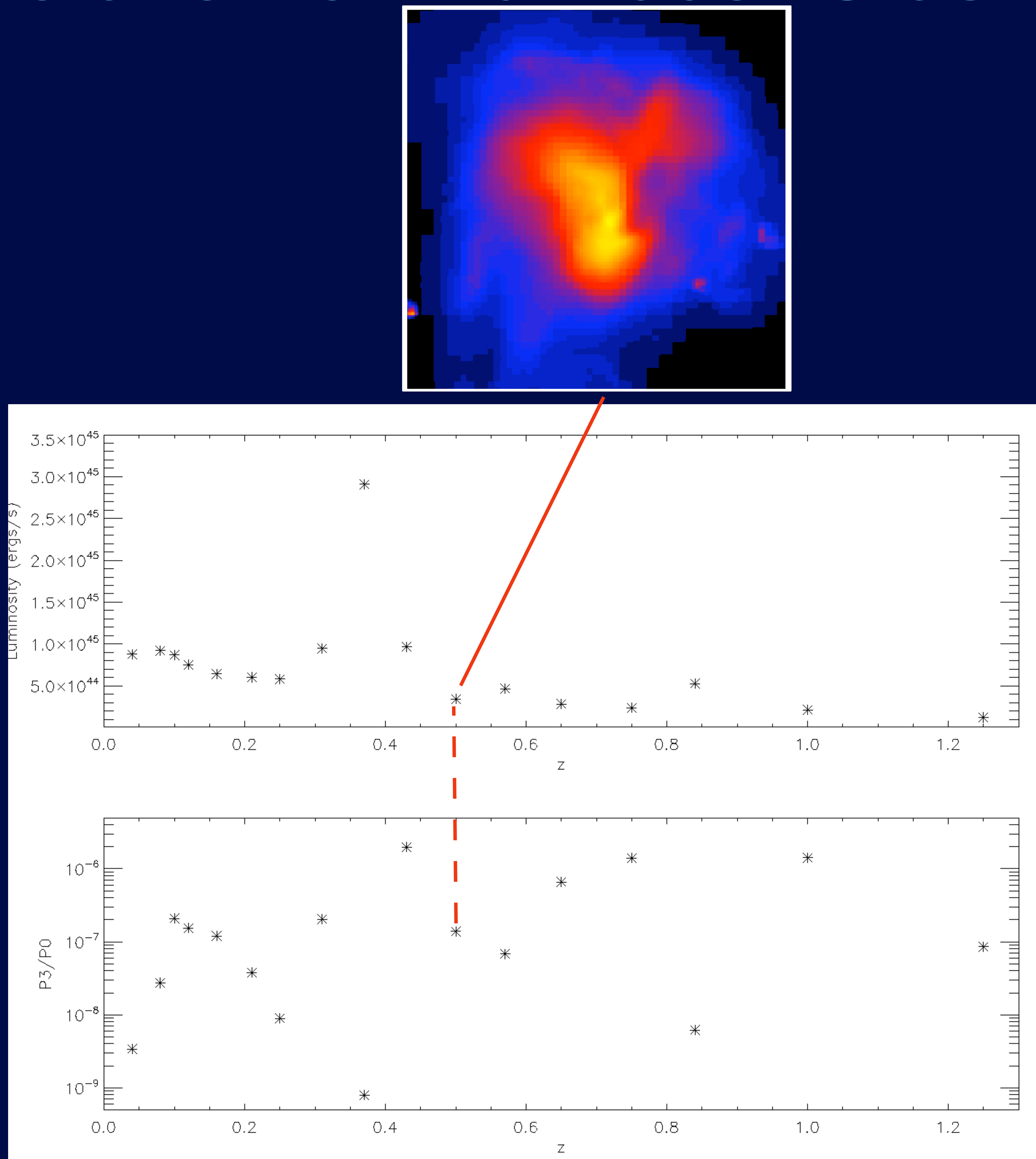


Jeltema et al. 2007

Evolution of Individual Clusters

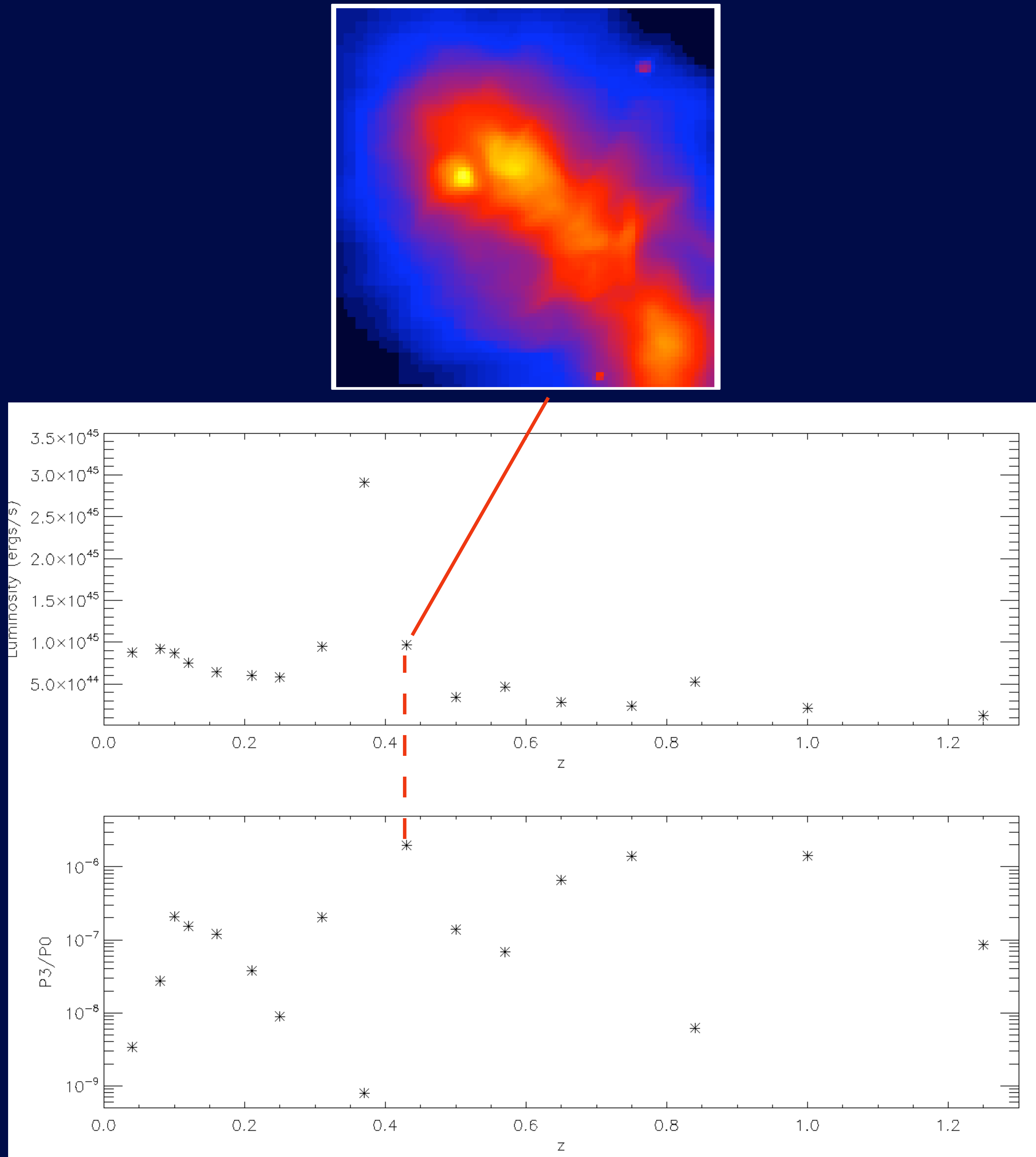
Luminosity

P3/P0



Jeltema et al. 2007

Evolution of Individual Clusters



Luminosity

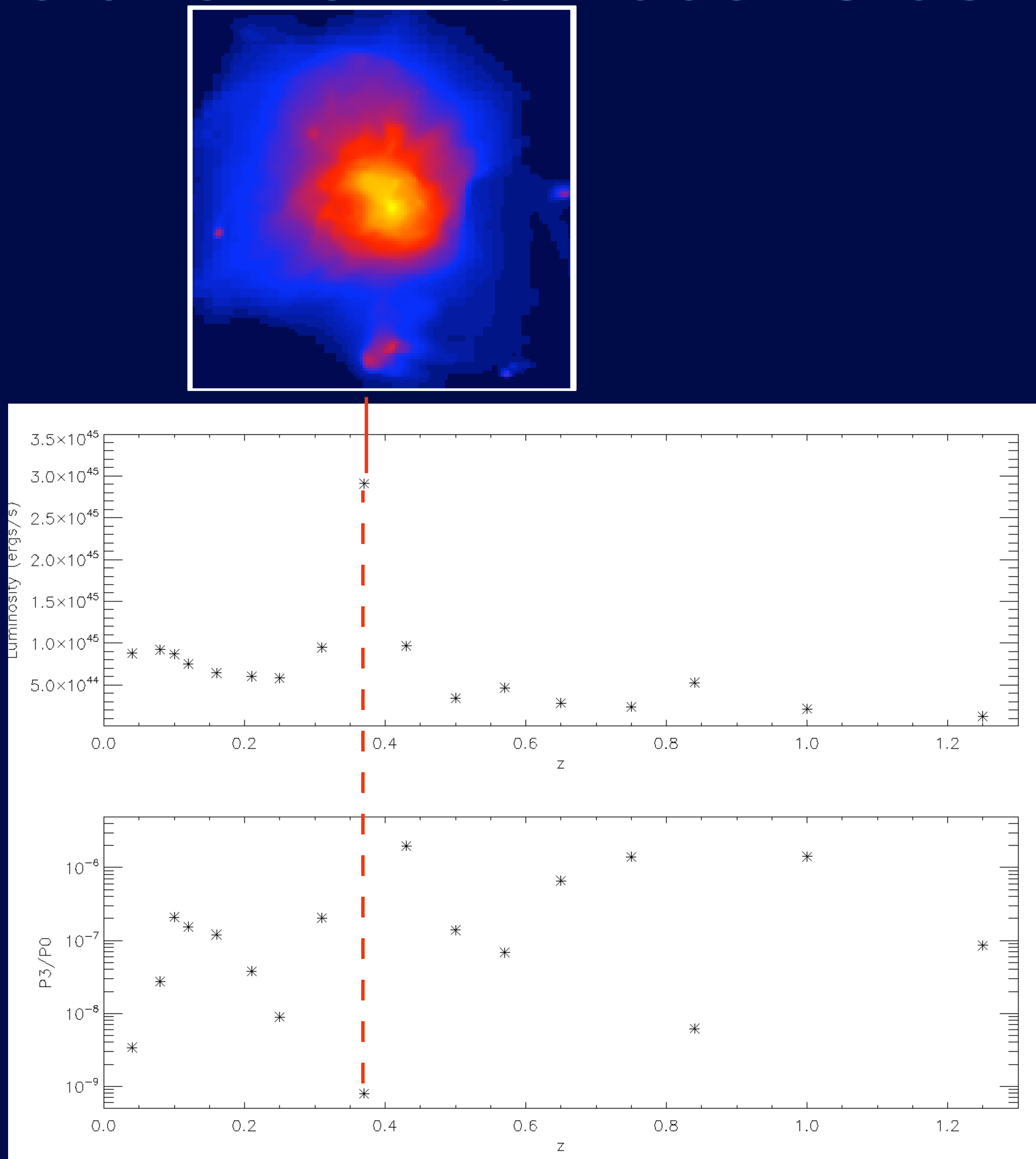
P3/P0

Jeltema et al. 2007

Evolution of Individual Clusters

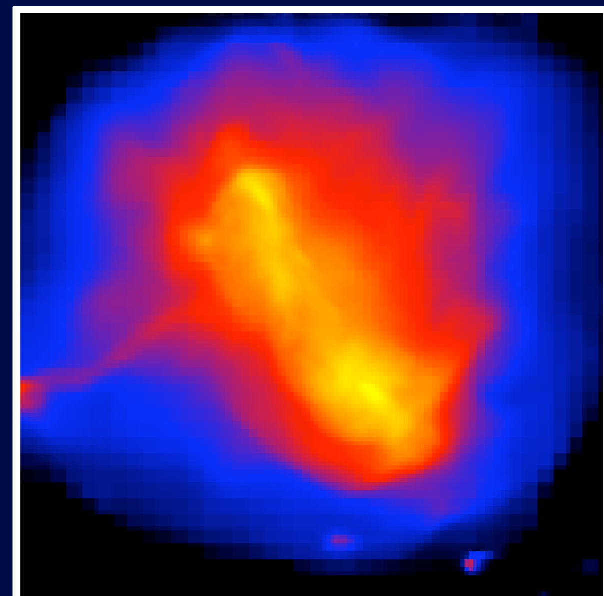
Luminosity

P3/P0



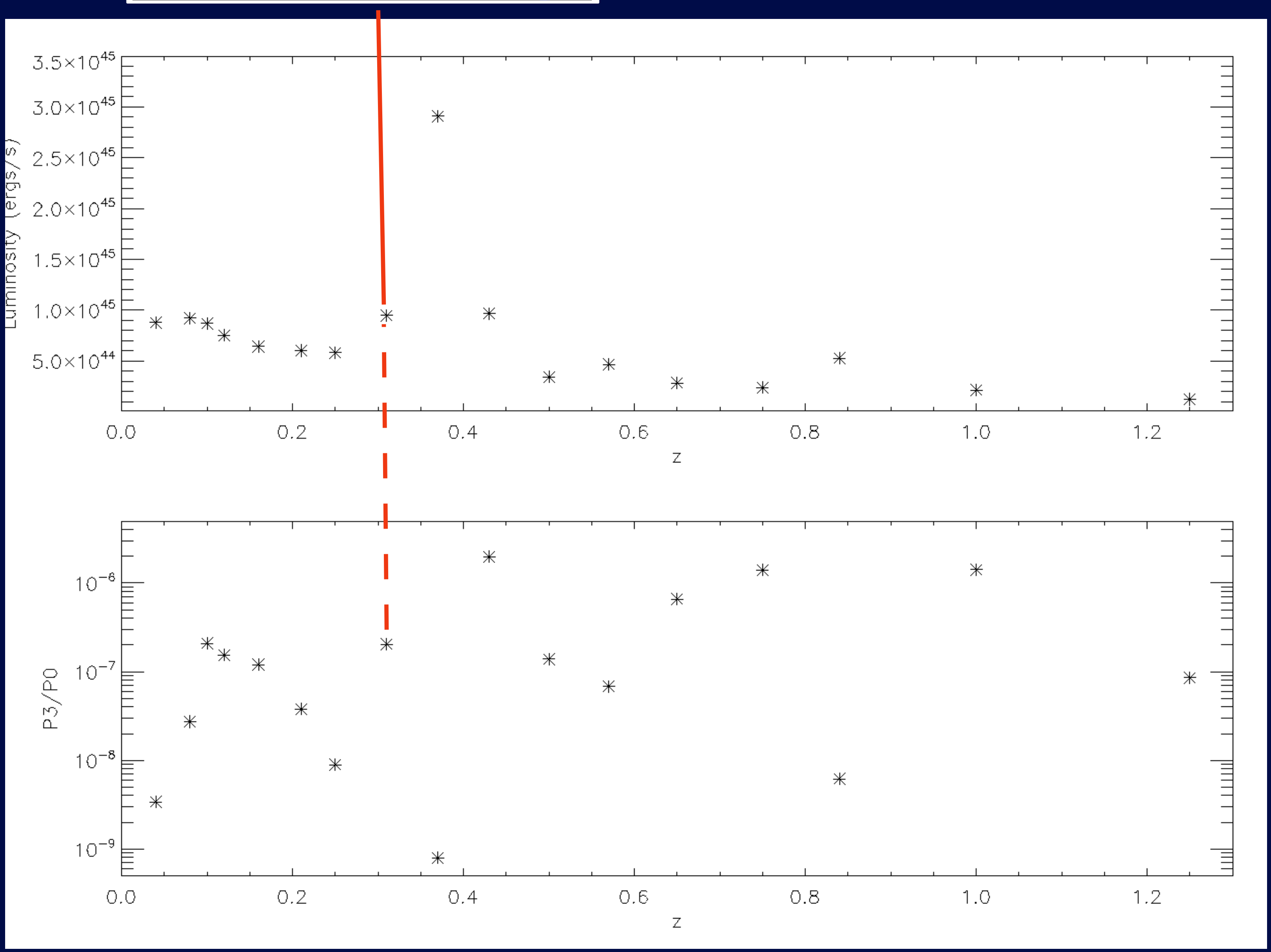
Jeltema et al. 2007

Evolution of Individual Clusters



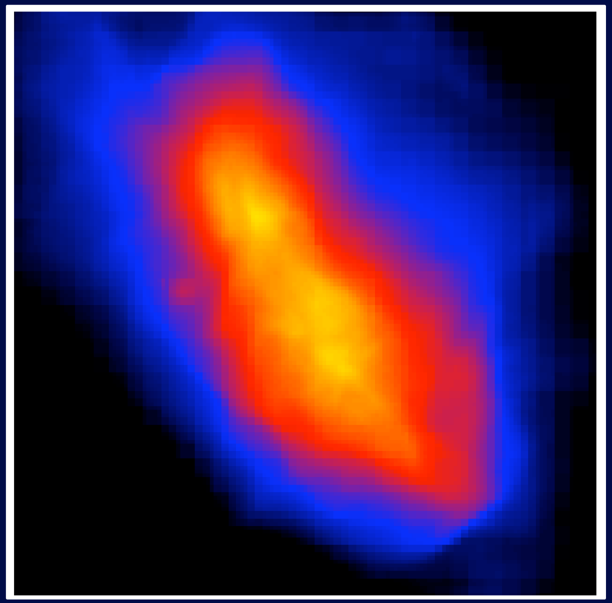
Luminosity

P3/P0



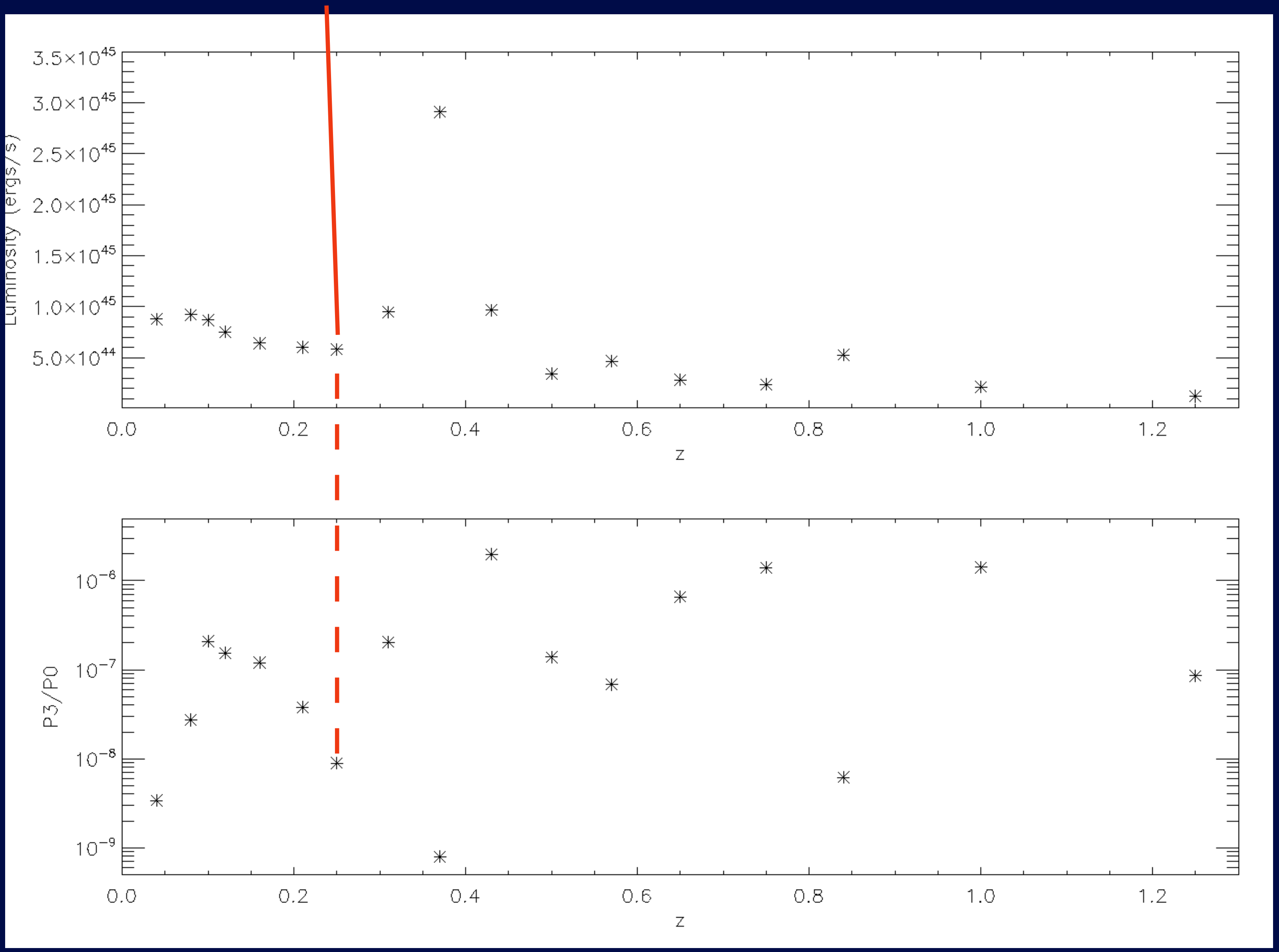
Jeltema et al. 2007

Evolution of Individual Clusters



Luminosity

P3/P0

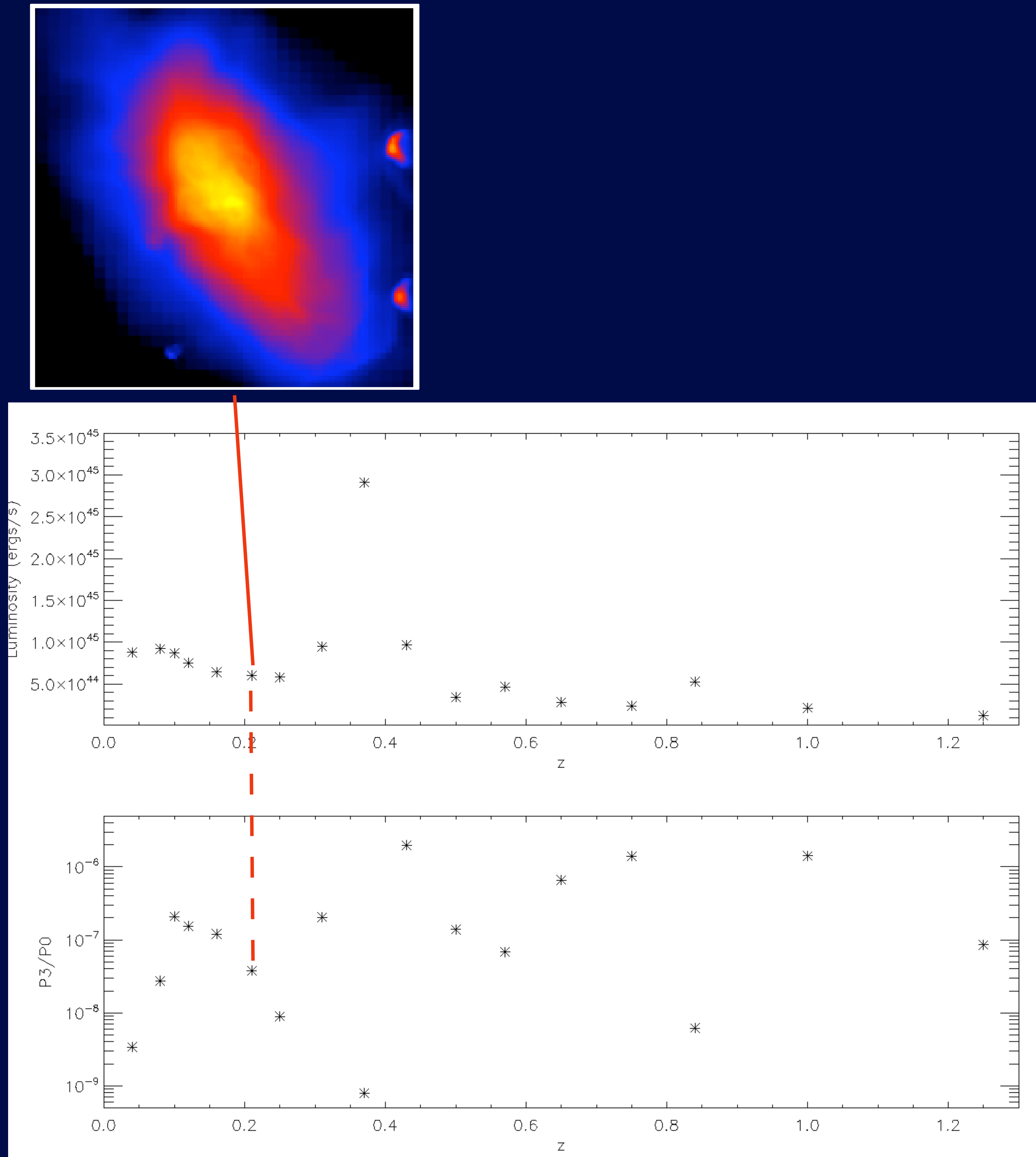


Jeltema et al. 2007

Evolution of Individual Clusters

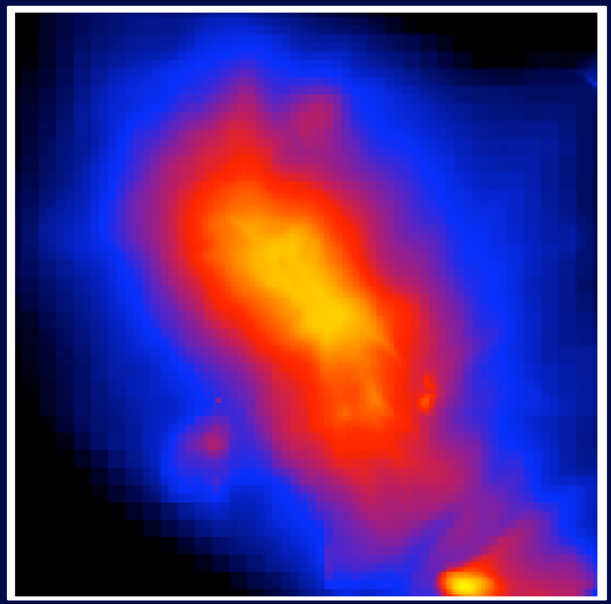
Luminosity

P3/P0



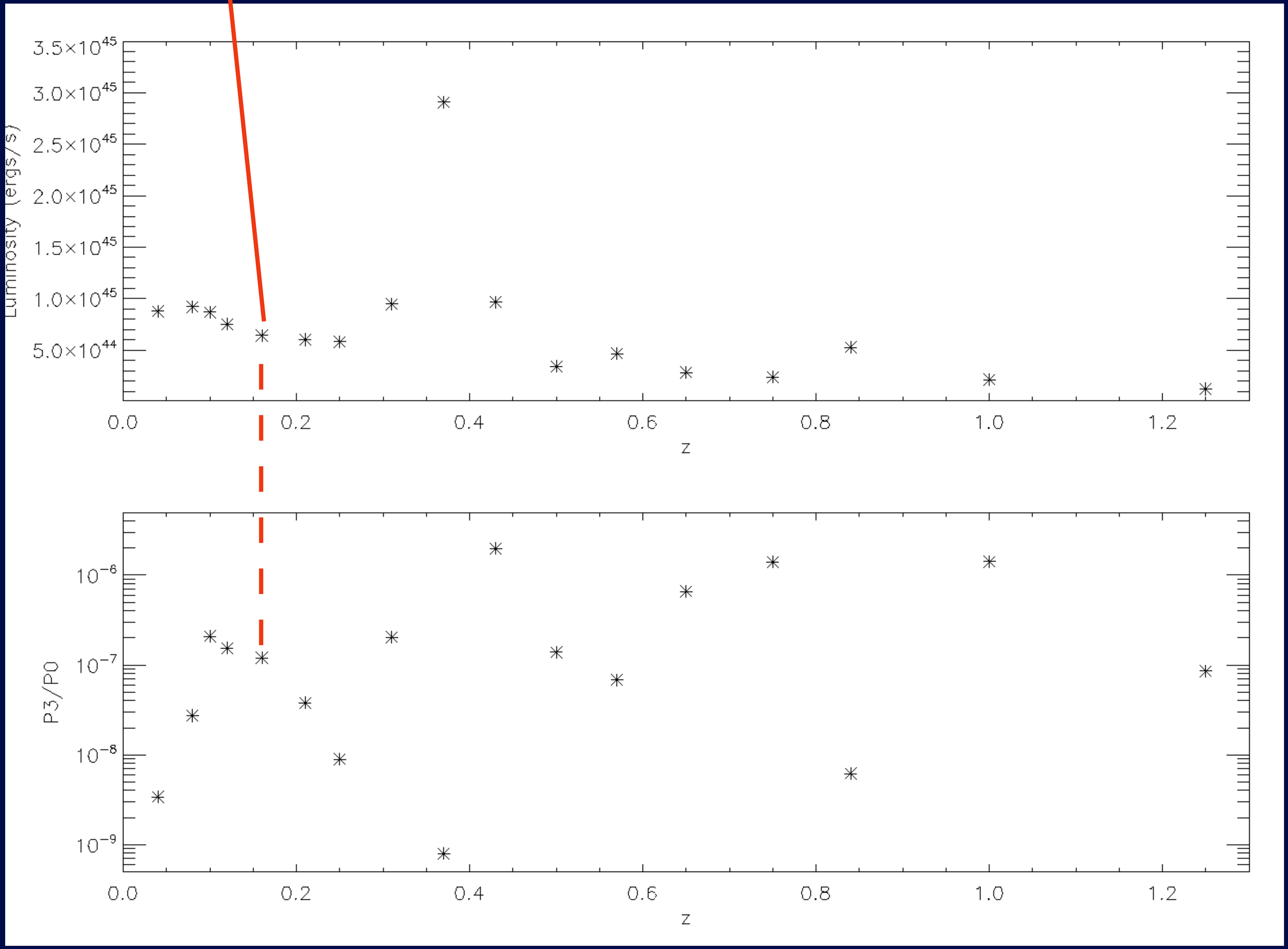
Jeltema et al. 2007

Evolution of Individual Clusters



Luminosity

P3/P0



Jeltema et al. 2007

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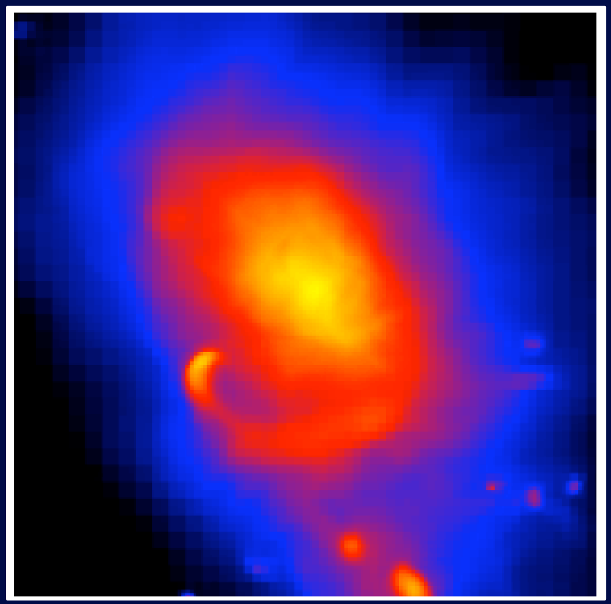
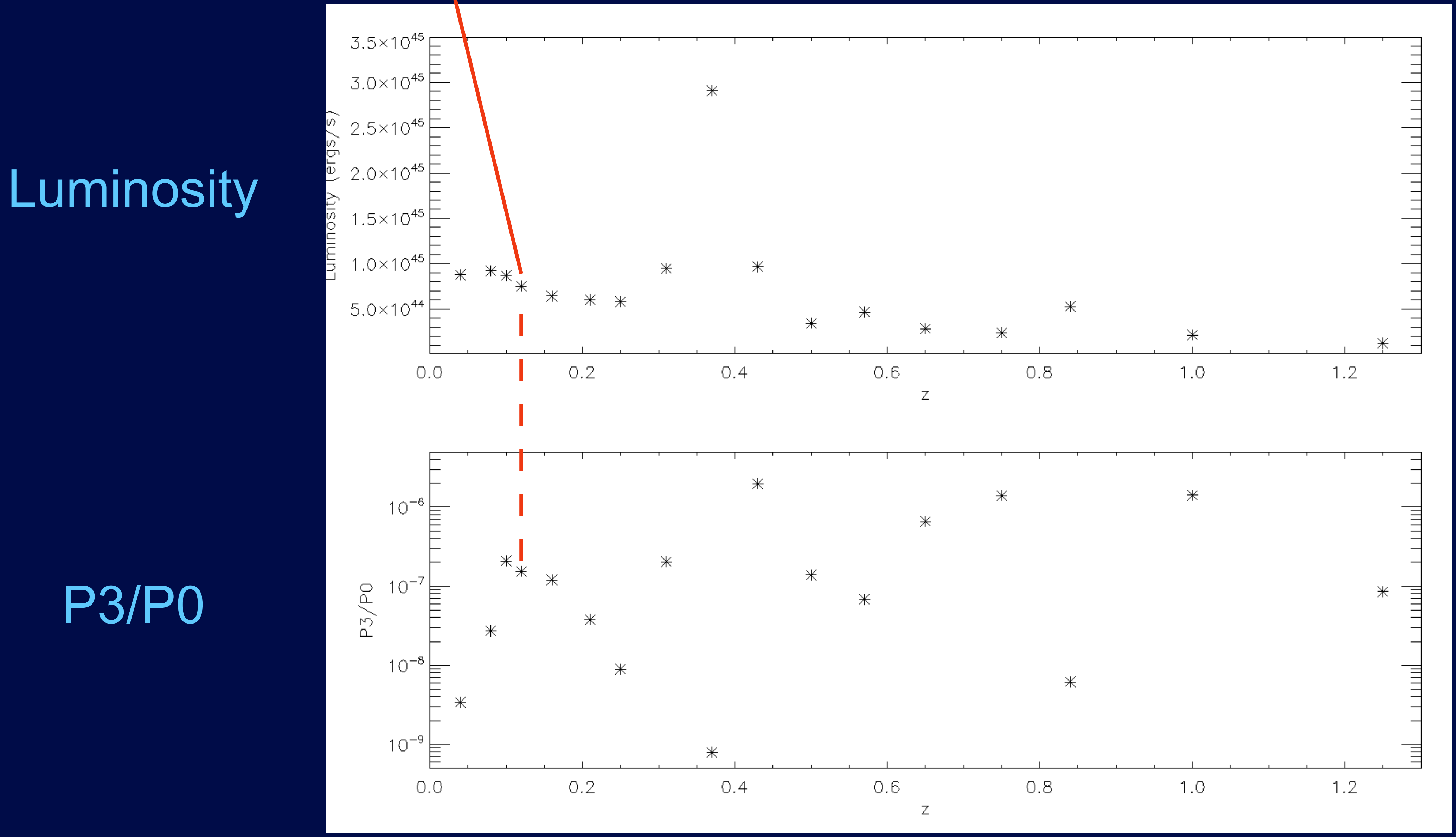
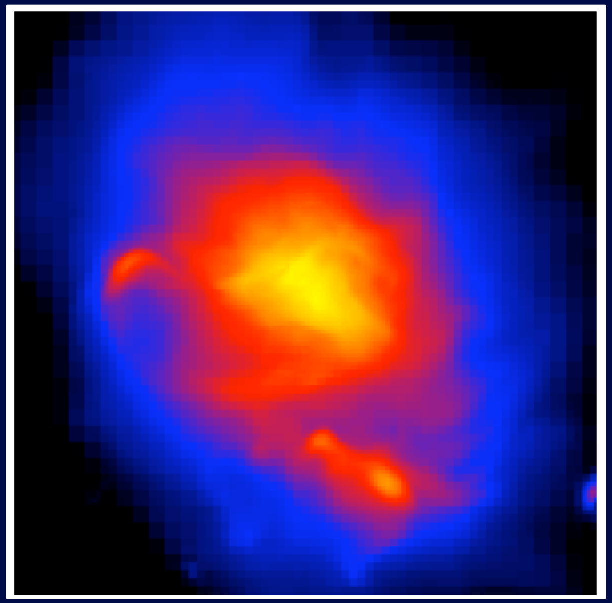




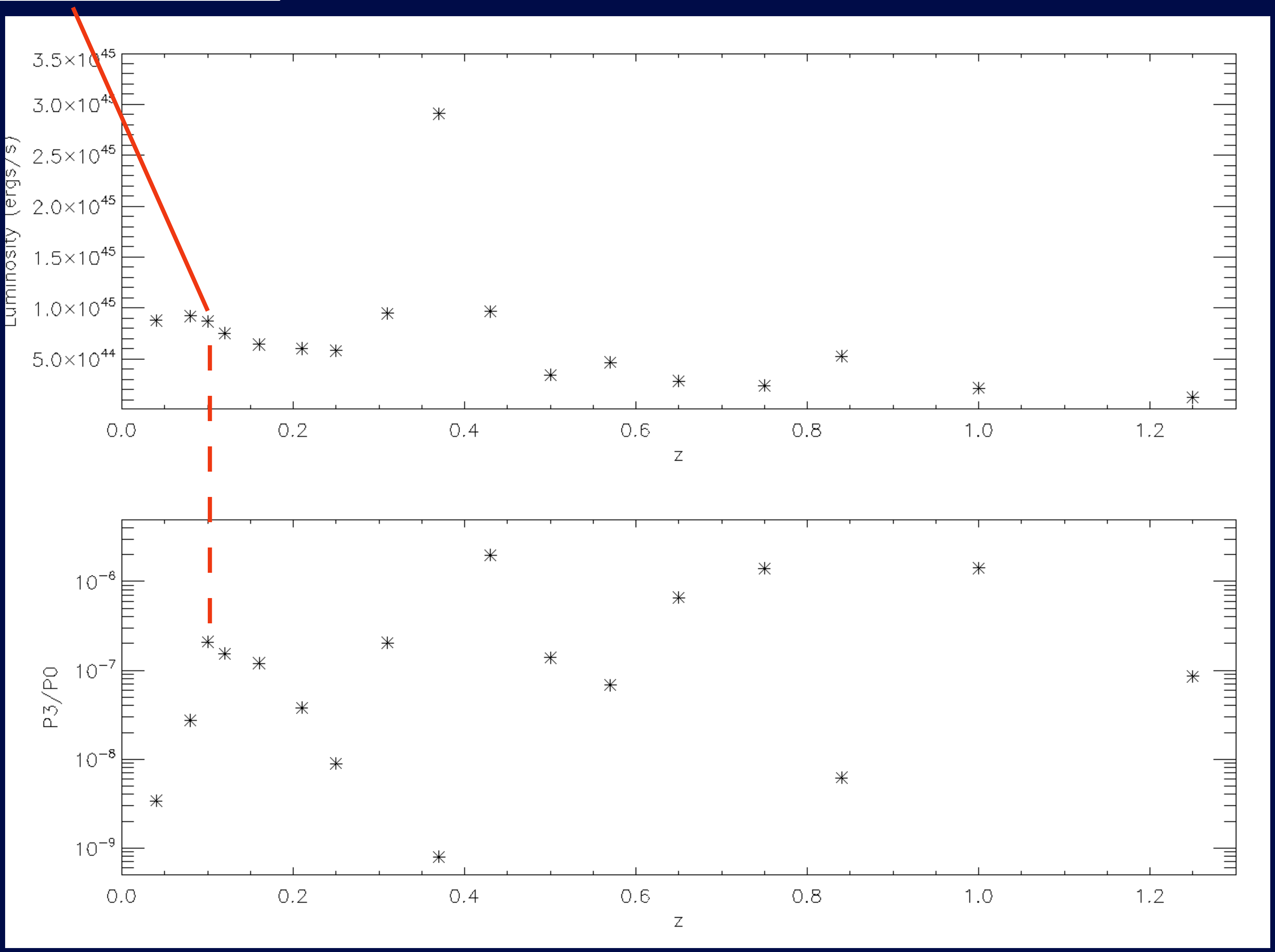
Jeltema et al. 2007

Evolution of Individual Clusters



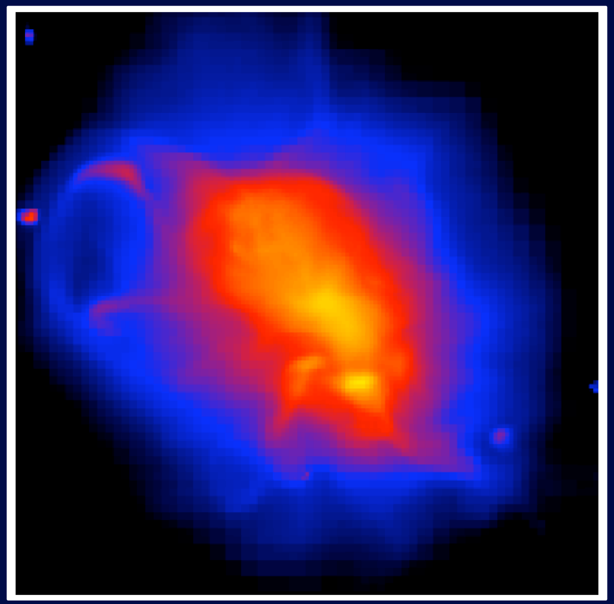
Luminosity

P3/P0



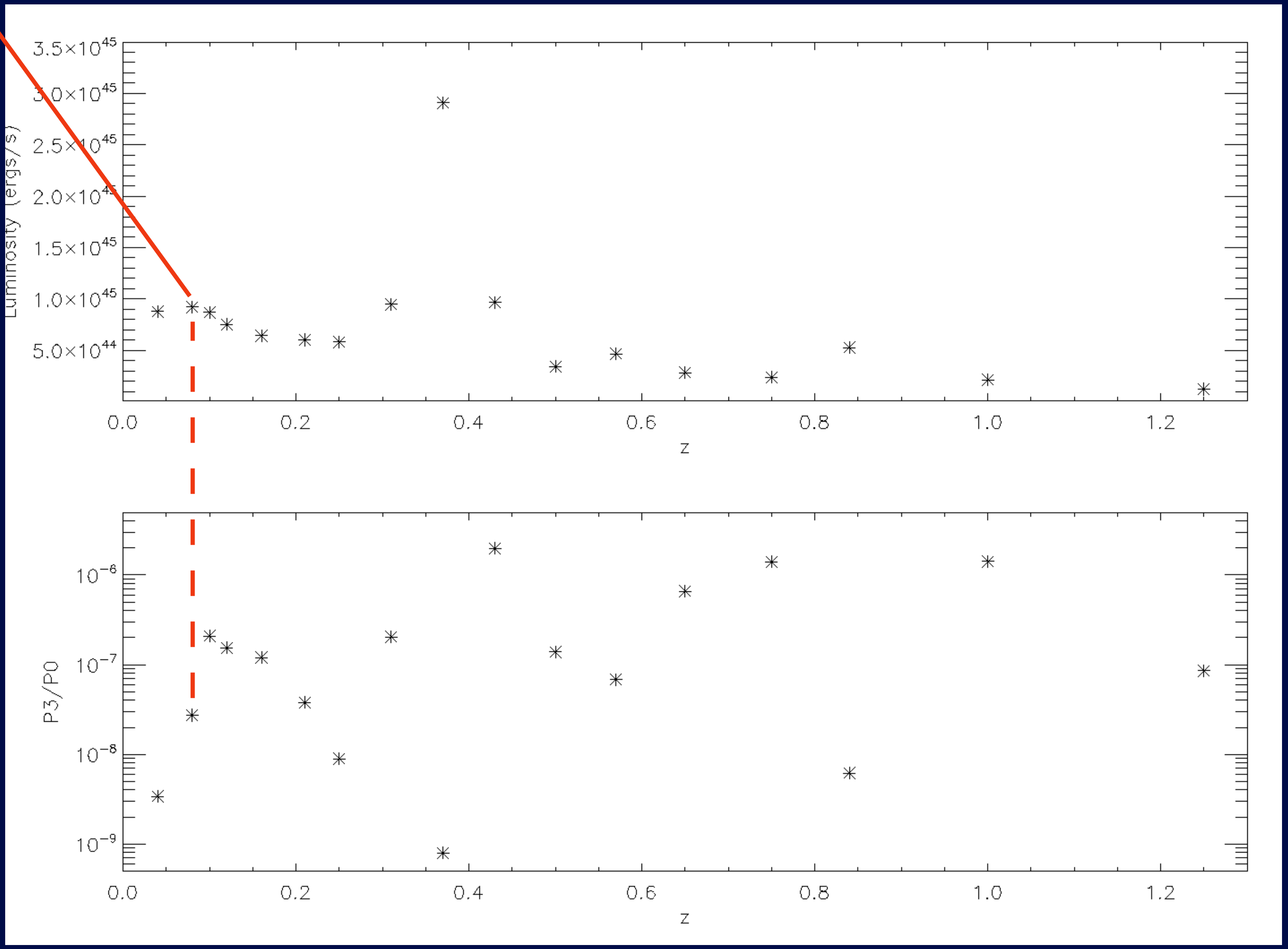
Jeltema et al. 2007

Evolution of Individual Clusters



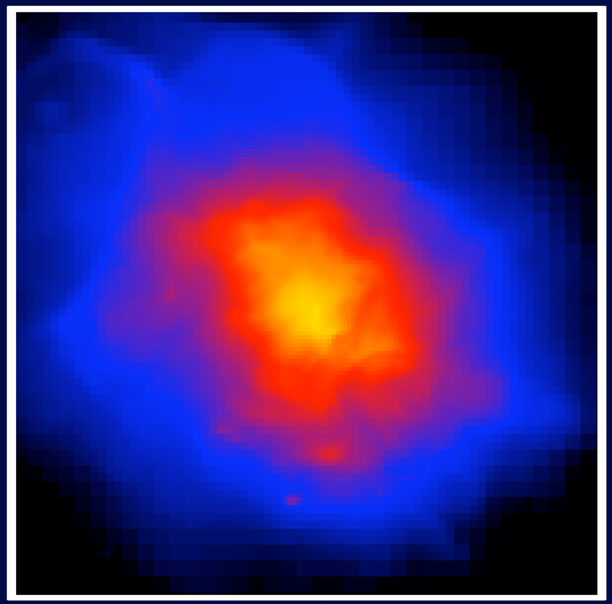
Luminosity

P3/P0



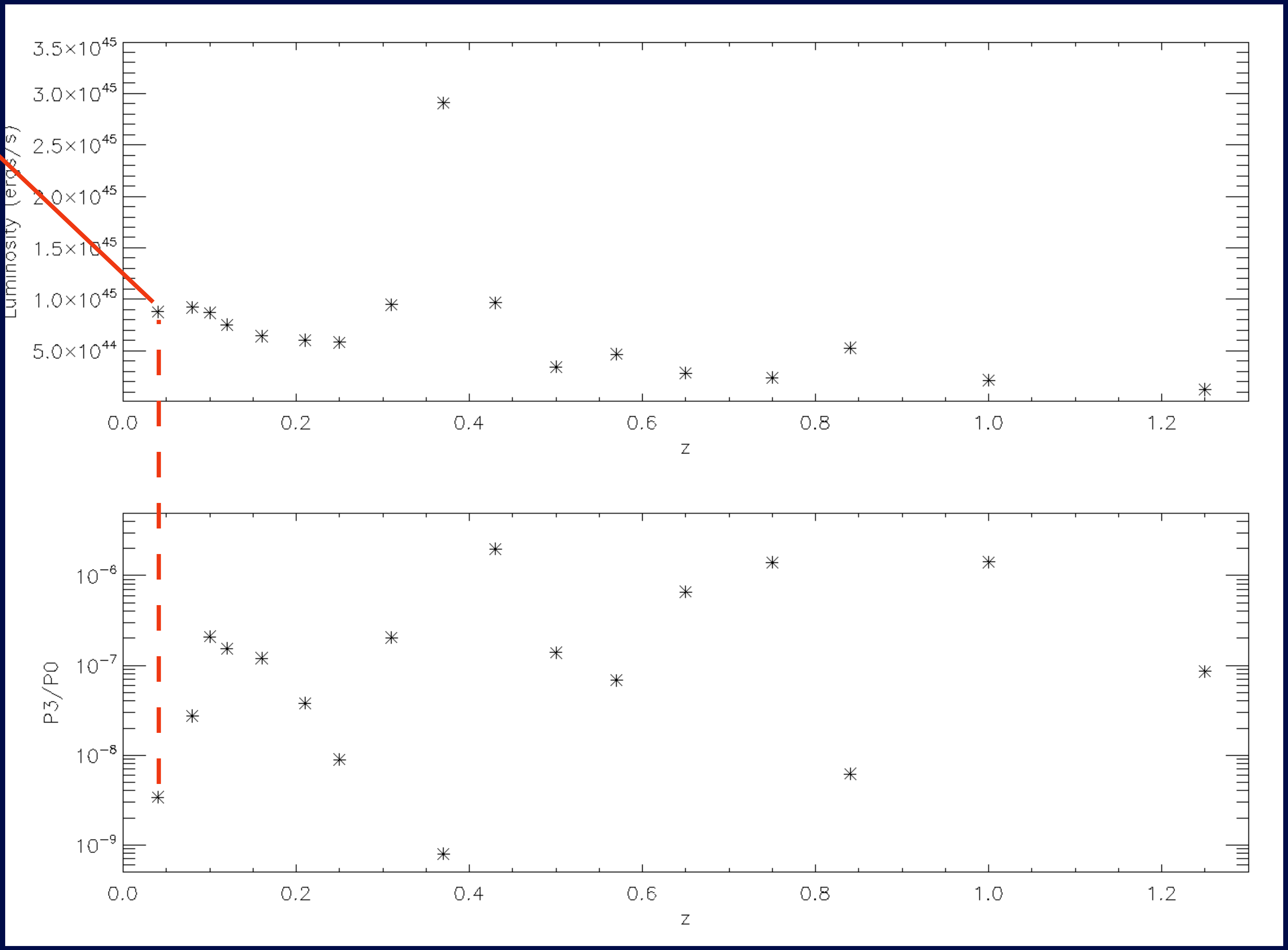
Jeltema et al. 2007

Evolution of Individual Clusters



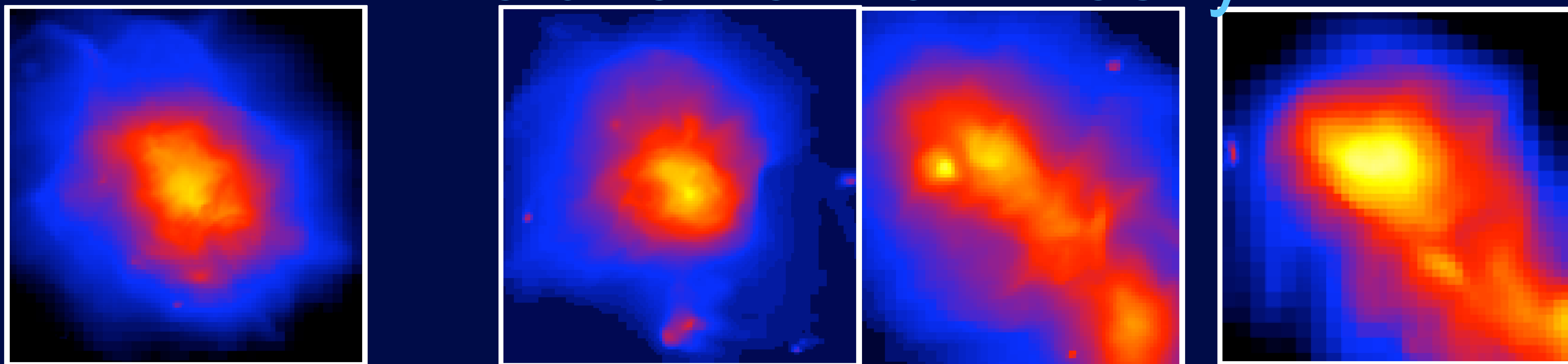
Luminosity

P3/P0



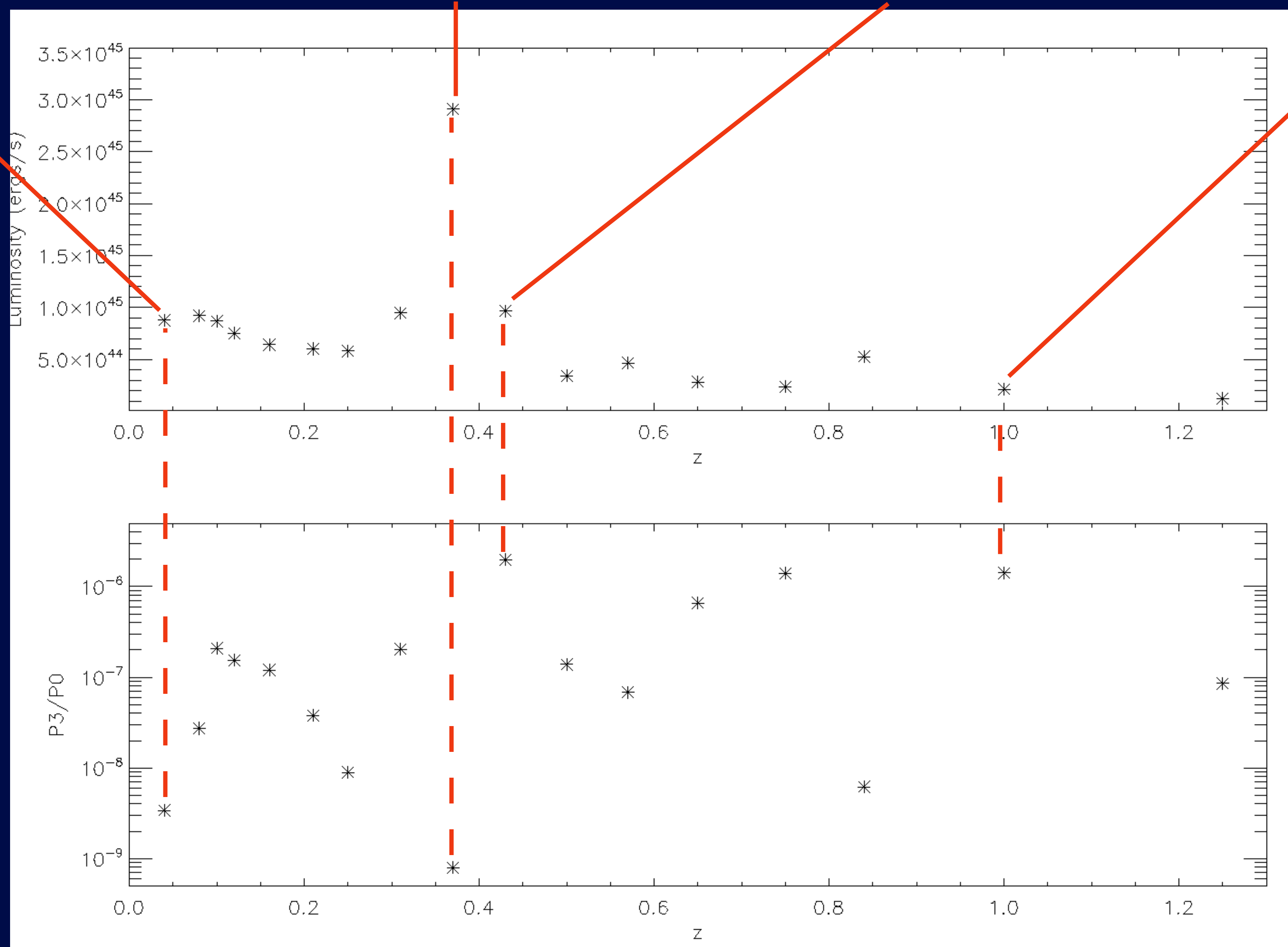
Jeltema et al. 2007

Evolution of Luminosity



Luminosity

P3/P0



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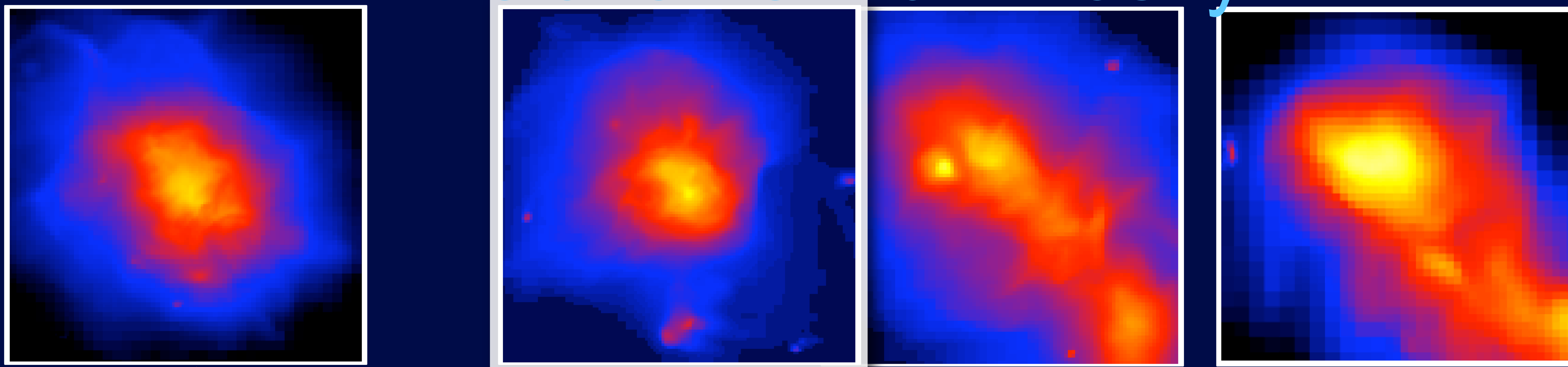
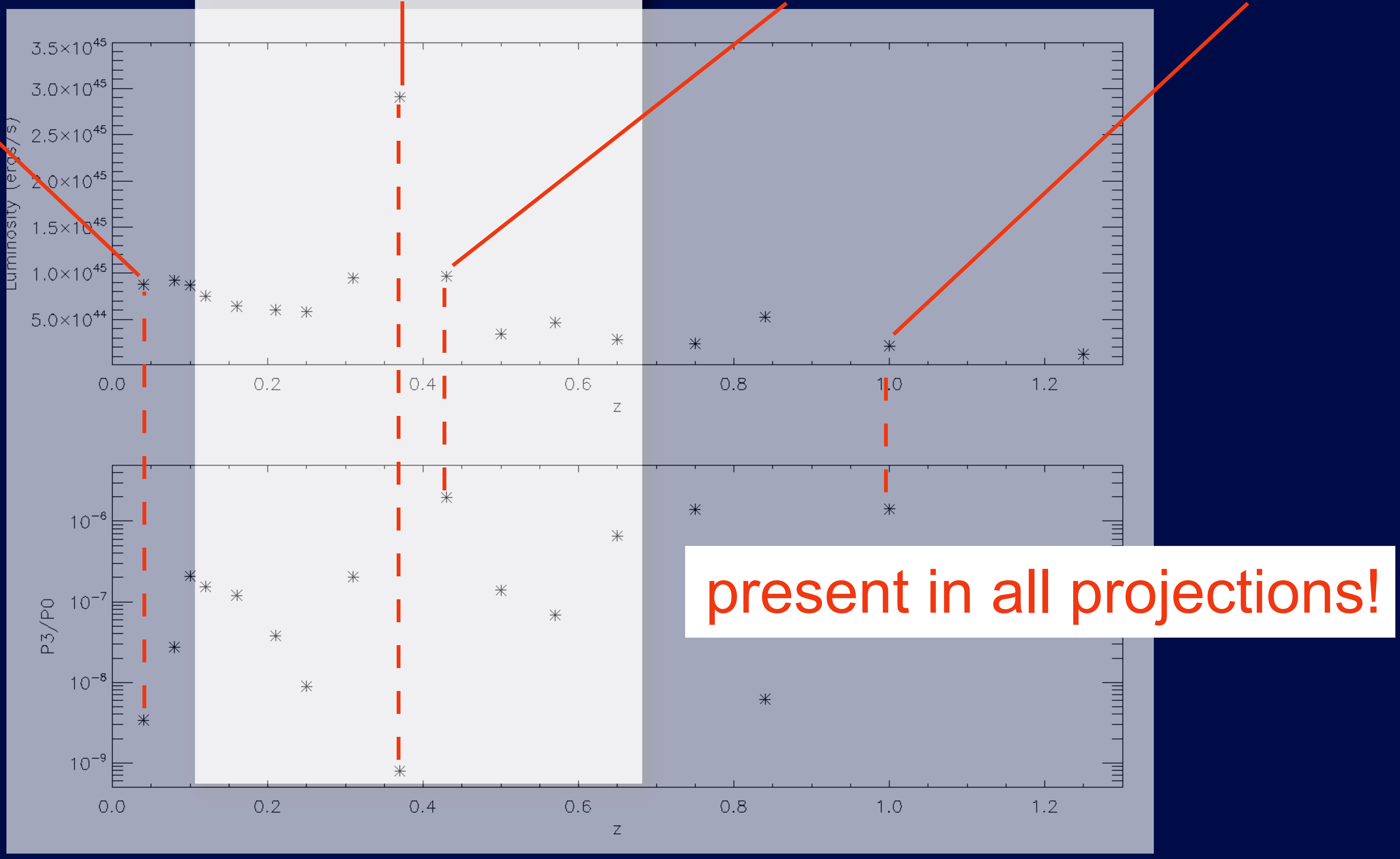
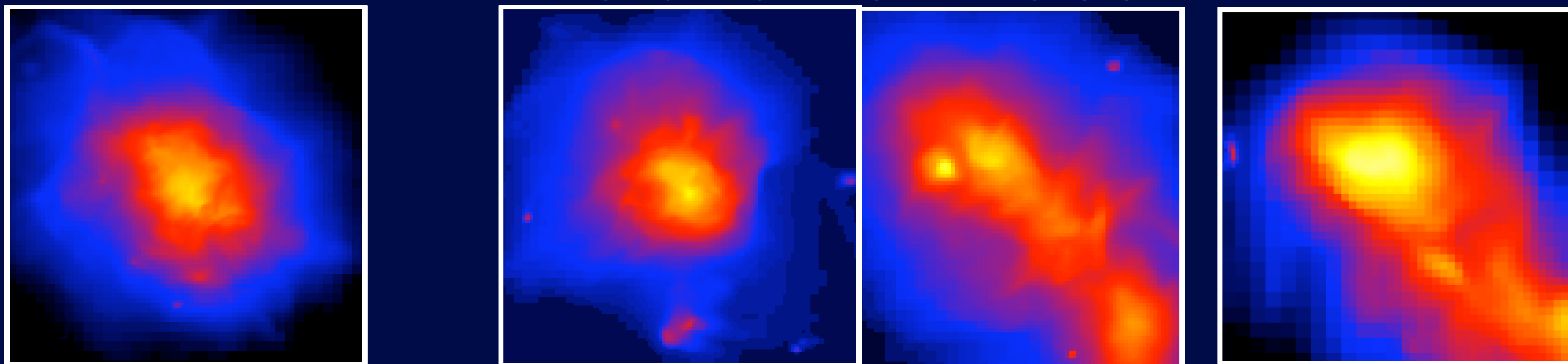


Luminosity



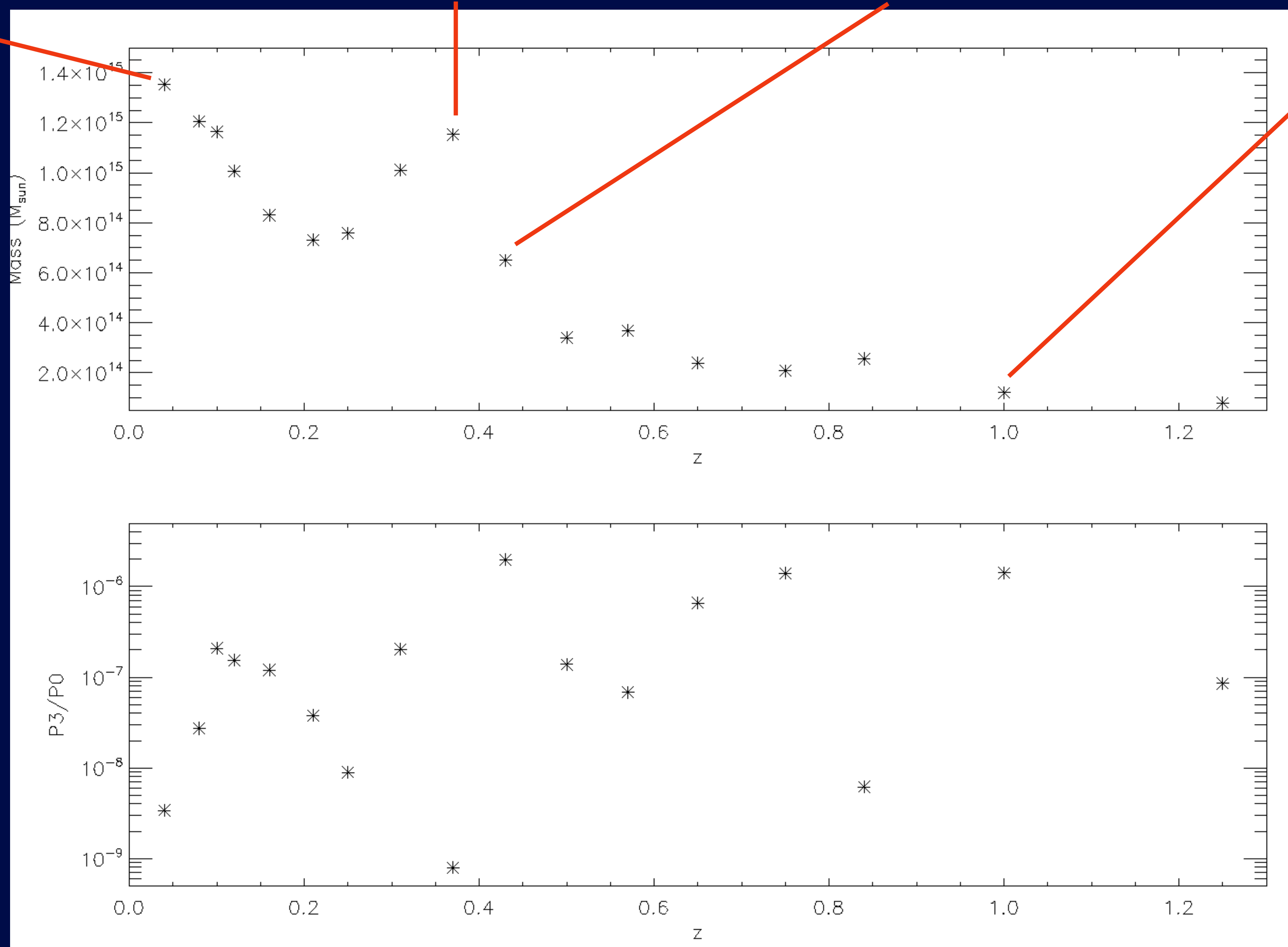
P3/P0

Evolution of Mass

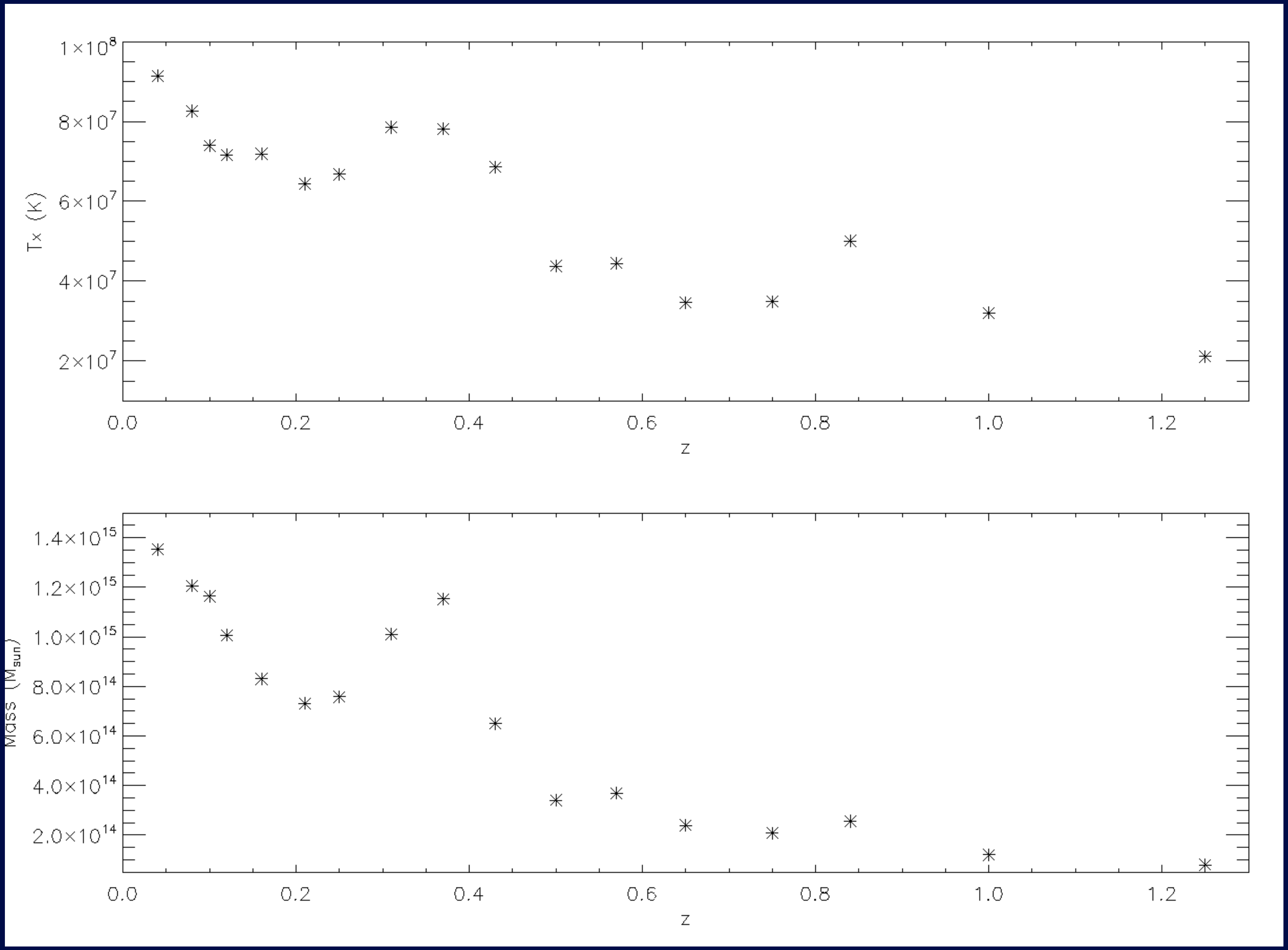


Mass

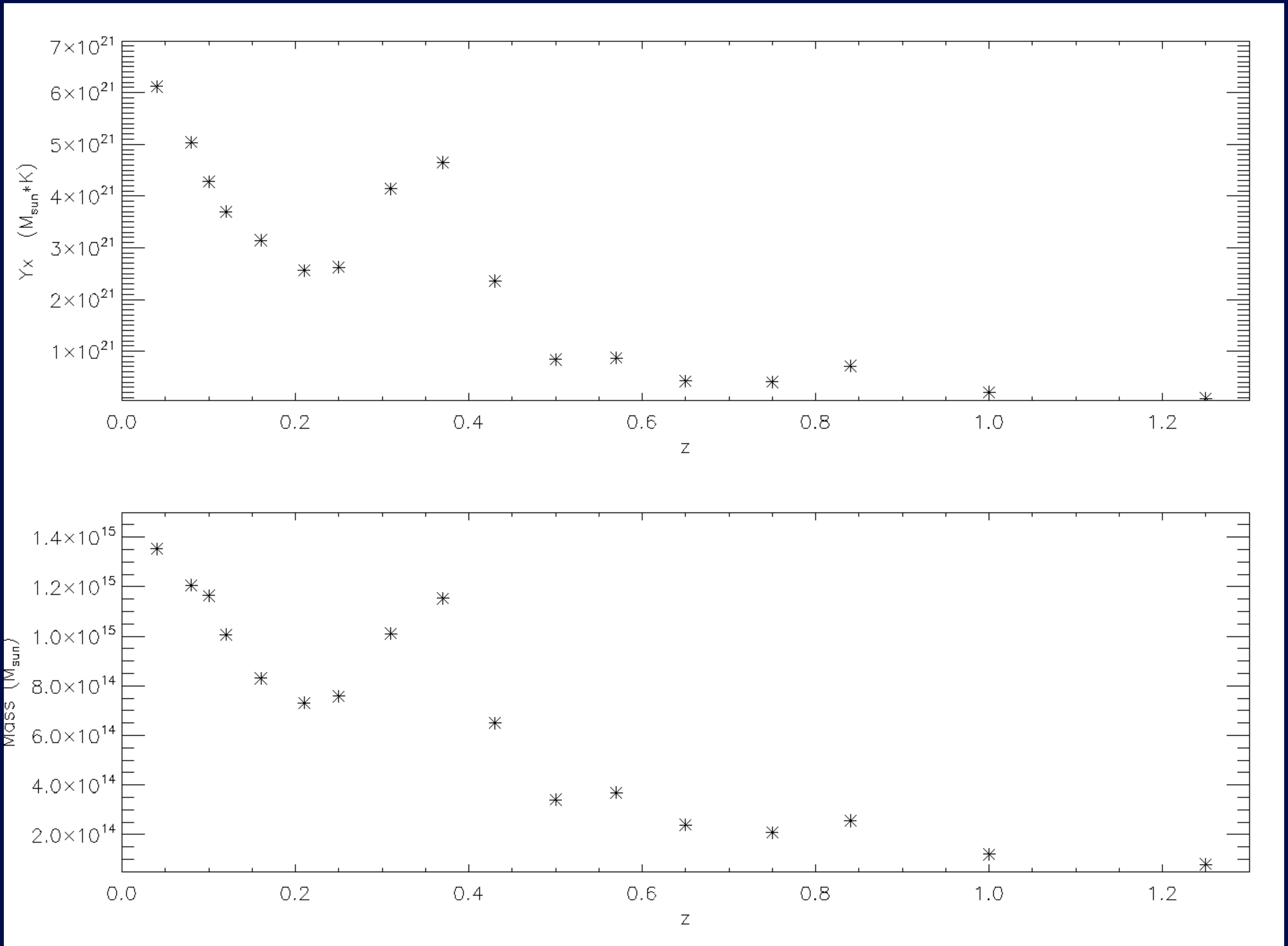
P3/P0



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

Questions and Plans

Simulations:

- How is cluster structure effected by

  gas physics? (not much)

  projection? (significantly)

- How similar is simulated structure to observed structure?

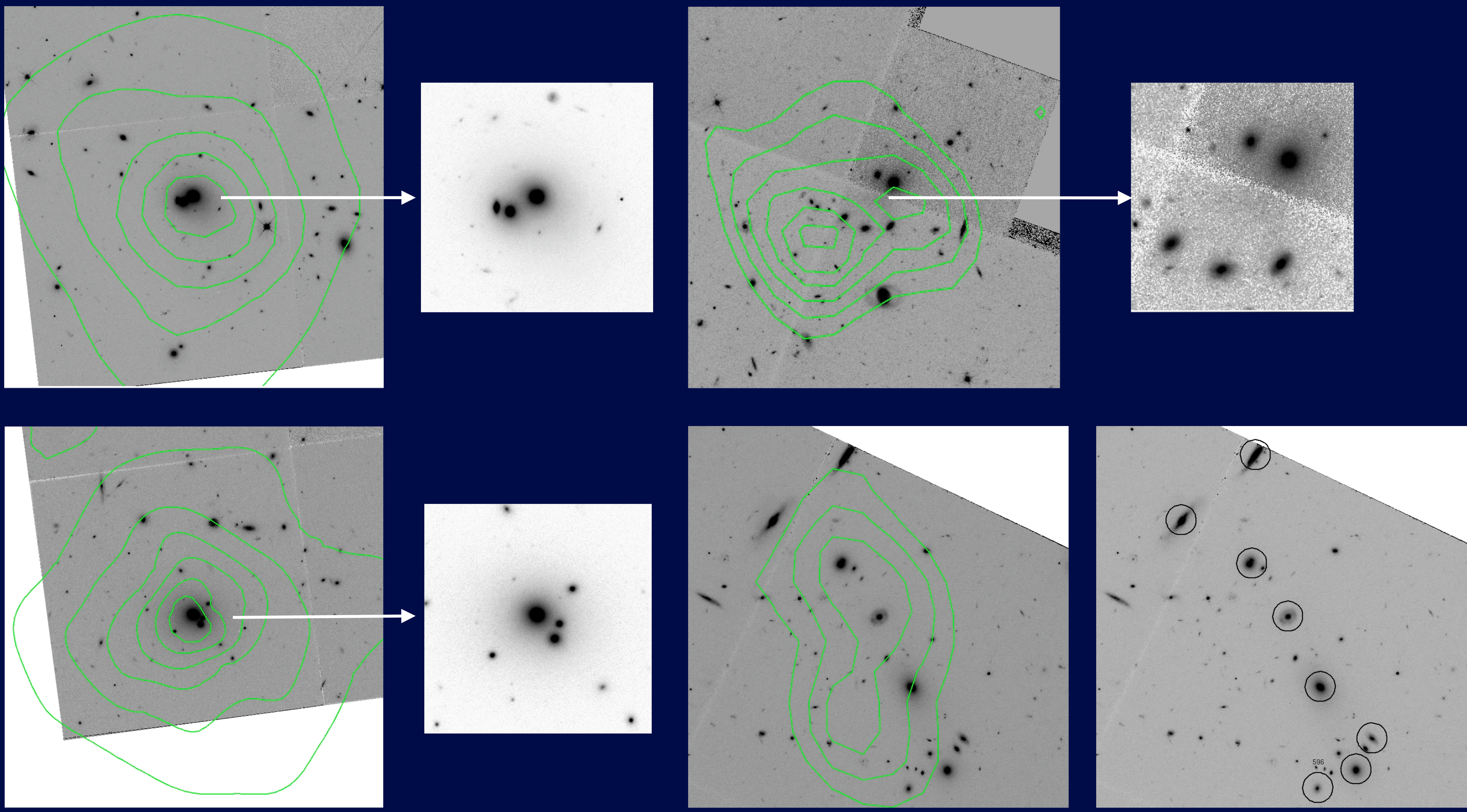
- How do cluster observables and observable-mass relations correlate with structure?

- How frequent are major mergers/core passage phase?
  - How does dynamical state affect selection in surveys?

Observations:

- Expanding sample with 400 deg^2 survey.

Structure on Smaller Scales: Groups



Jeltema et al. 2007, Jeltema et al. 2006, Mulchaey et al. 2006