Studying the Nature of Dark Energy with Galaxy Clusters

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Clusters and Cosmology

- Baryon fraction,
- *apparent* evolution of gas mass fraction,
- power spectrum,
- baryon wiggles,
- mergers (fraction, evolution),
- mass function (amplitude, shape, evolution),
- ….

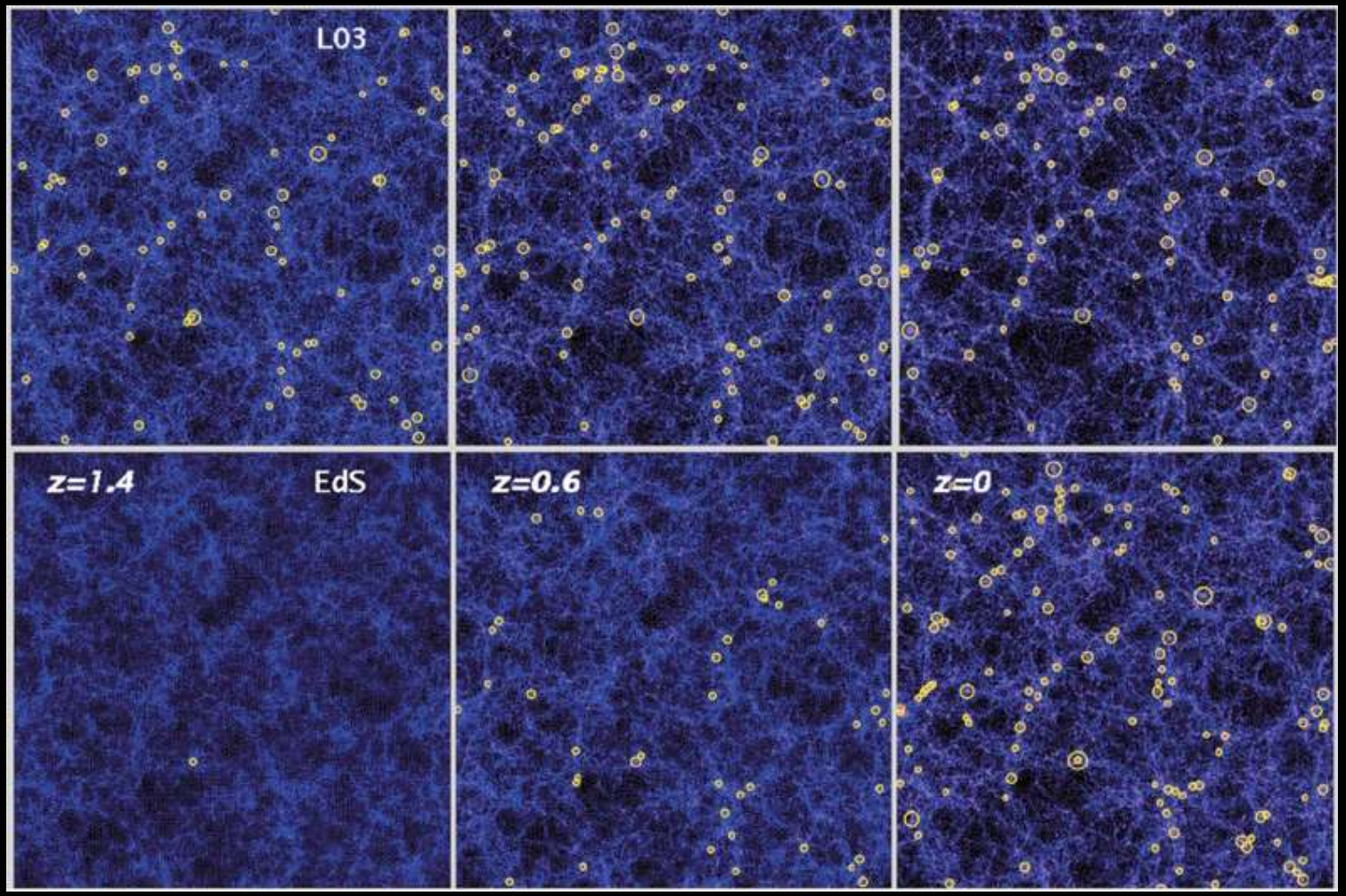
- Optical/infrared (galaxies, lensing),
- radio (SZ-effect, radio halos, WATs / NATs),
- gamma rays (future: GLAST),
- X-rays,
- ….

=> Self-calibrating probes!

Primary Goal: Study Dark Energy

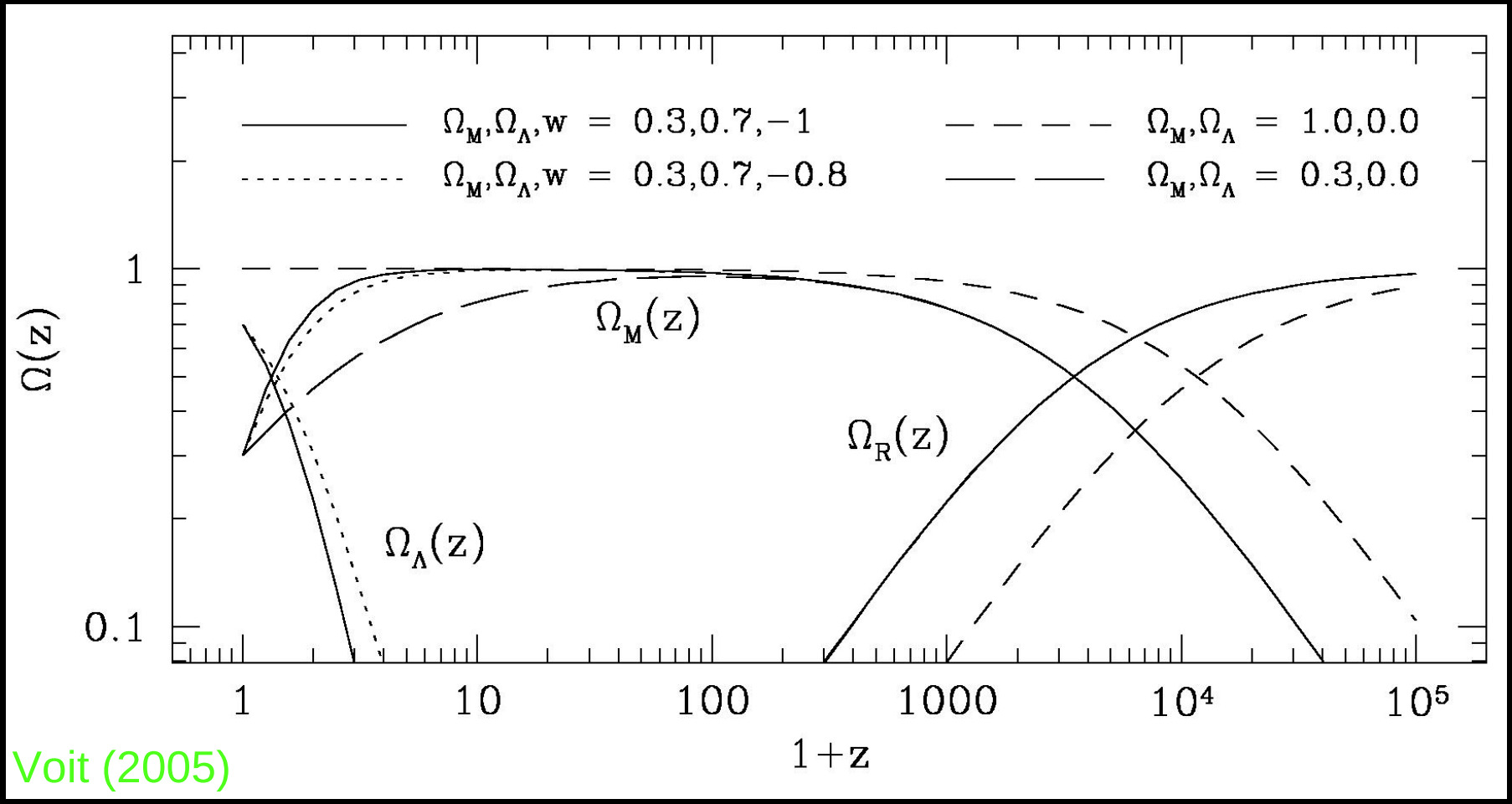
- Primary method: Evolution of cluster mass function (X-ray and optical lensing).

Evolution of Galaxy Clusters

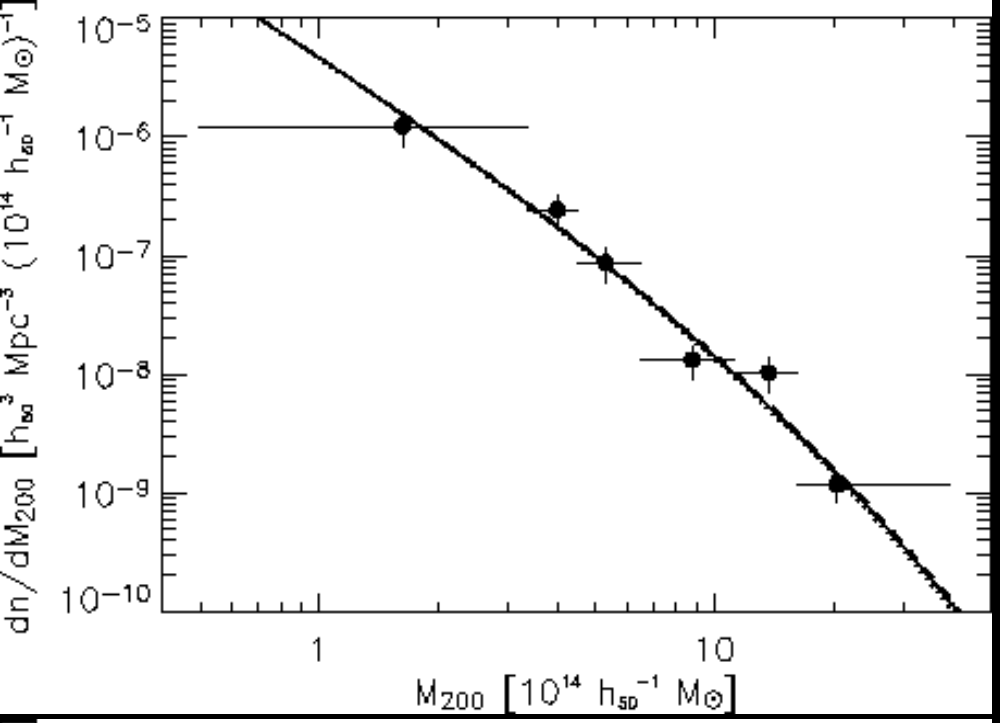


Borgani & Guzzo (2001)

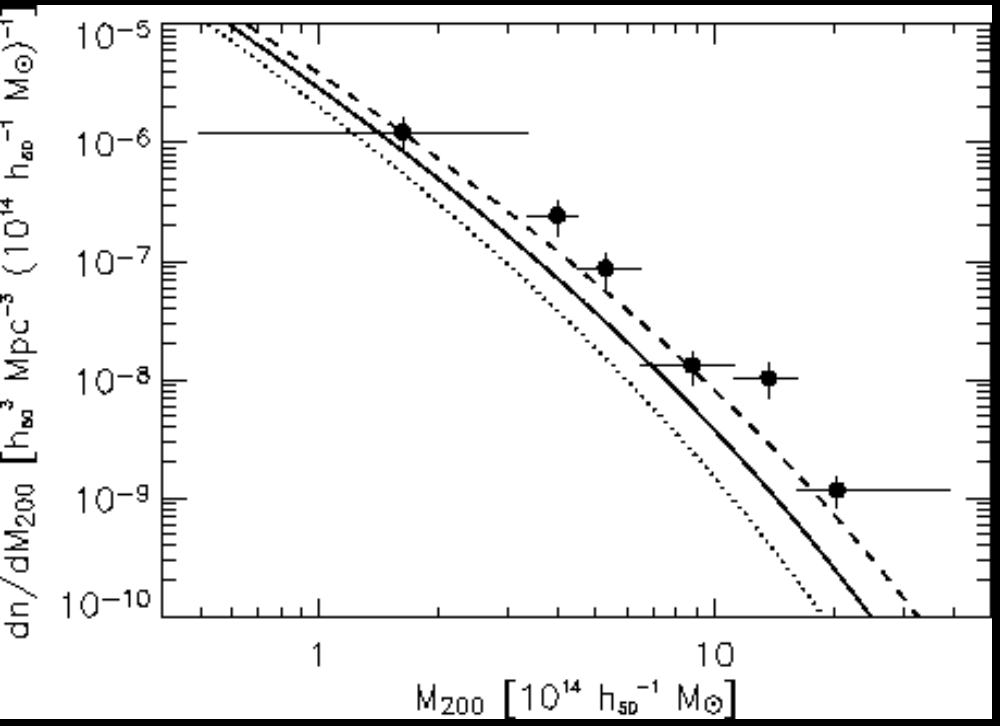
Faster or slower growth of structure with $\Omega_{DE}>0$?



Voit (2005)



z=0.05

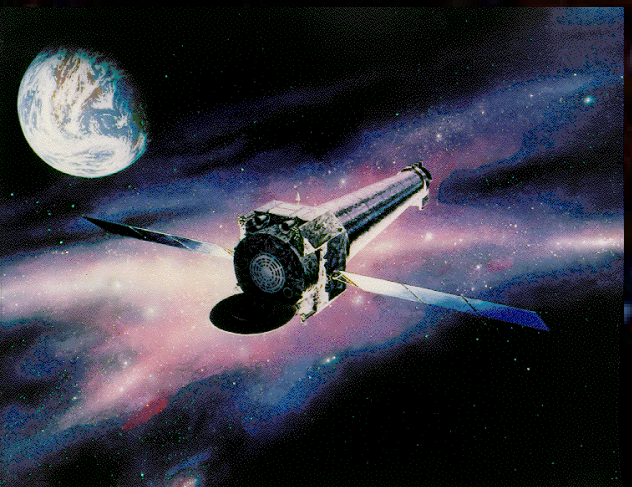


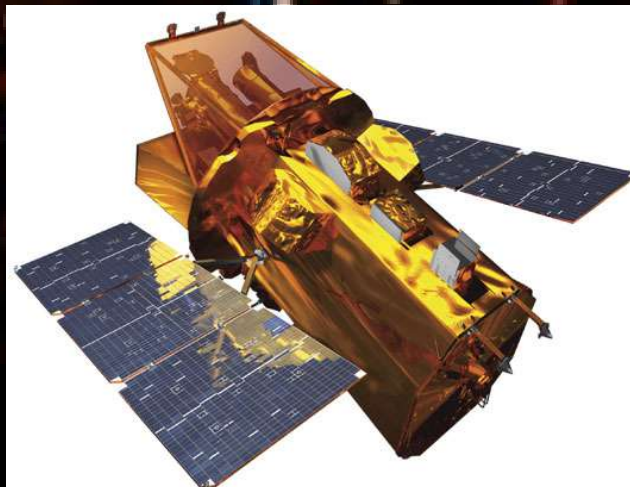
z=0.6

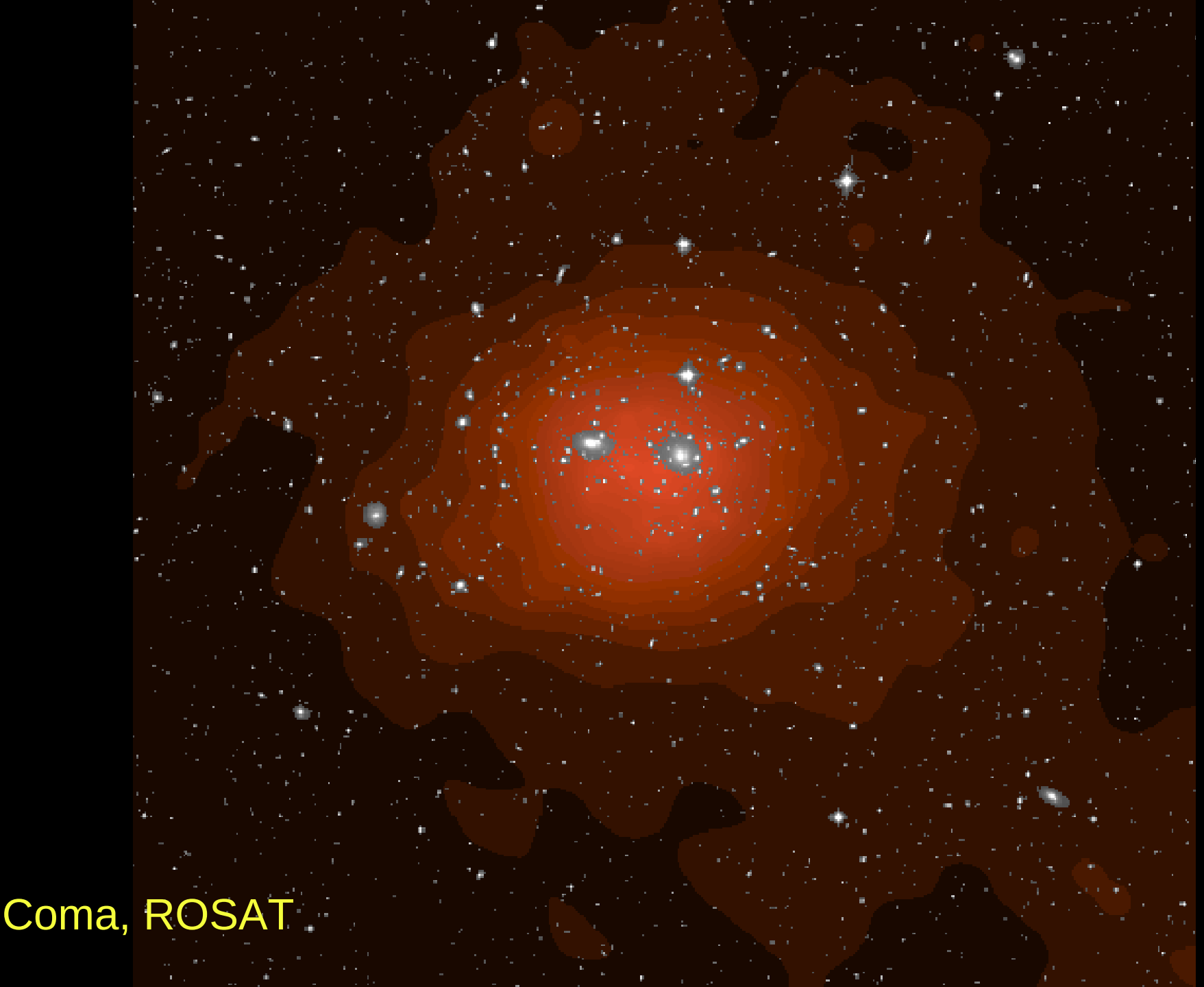
Solid lines: w=-1,
dashed lines: w=-0.5,
dotted lines: w=-1.25.

Cluster *Evolution*

- Need distant *AND* local (complete) sample,
- need “good” selection,
- need “good” masses.






Coma, ROSAT

X-Ray Mass Determination

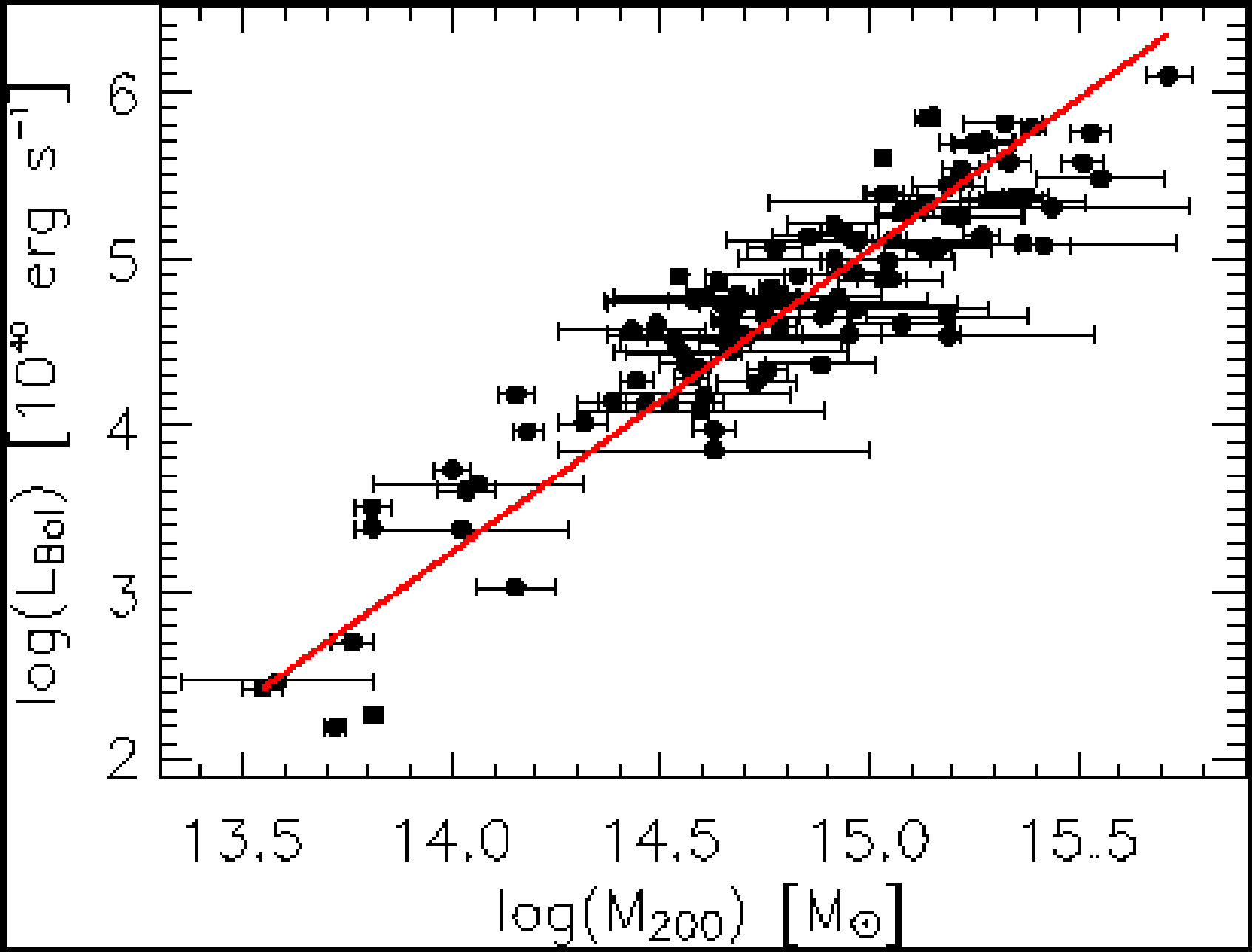
$$\frac{1}{\rho_{\rm gas}}\frac{{\rm d}P}{{\rm d}r} = -\frac{{\rm d}\Phi_{\rm grav}}{{\rm d}r}$$

$$P = \frac{k_{\rm B}}{\mu m_{\rm p}}\rho_{\rm gas}T_{\rm gas}$$

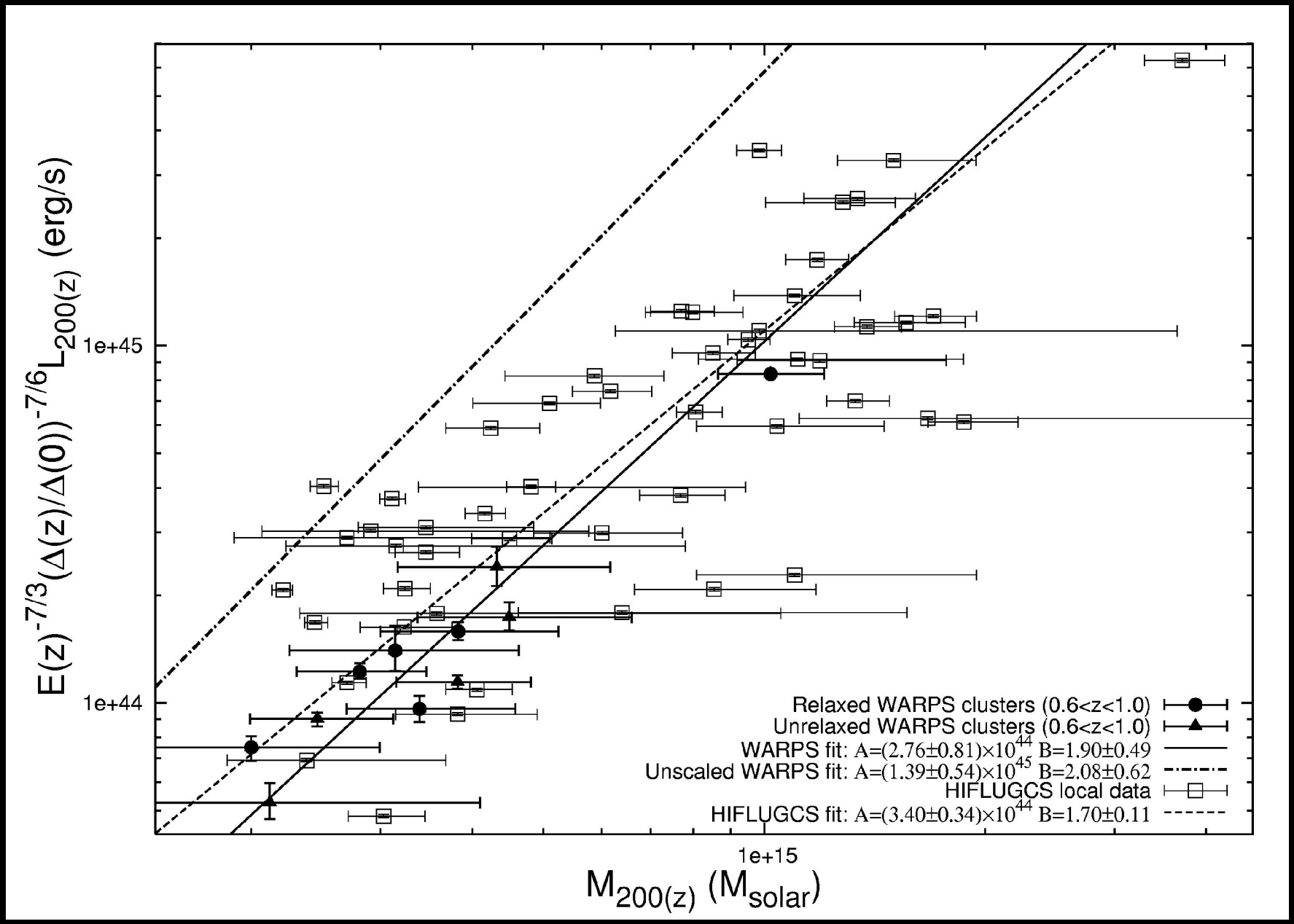
$$\frac{1}{\rho_{\rm gas}}\frac{{\rm d}P}{{\rm d}r} = \frac{k_{\rm B}T_{\rm gas}}{\mu m_{\rm p}}\frac{1}{r}\left(\frac{{\rm d}\ln\rho_{\rm gas}}{{\rm d}\ln r} + \frac{{\rm d}\ln T_{\rm gas}}{{\rm d}\ln r}\right)$$

$$\frac{{\rm d}\Phi_{\rm grav}}{{\rm d}r} = \frac{GM_{\rm tot}(<r)}{r^2}$$

$$M_{\rm tot}(<r) = -\frac{k_{\rm B}T_{\rm gas}r}{G\mu m_{\rm p}}\left(\frac{{\rm d}\ln\rho_{\rm gas}}{{\rm d}\ln r} + \frac{{\rm d}\ln T_{\rm gas}}{{\rm d}\ln r}\right).$$



Reiprich & Böhringer (2002) HIFLUGCS, z = 0.05

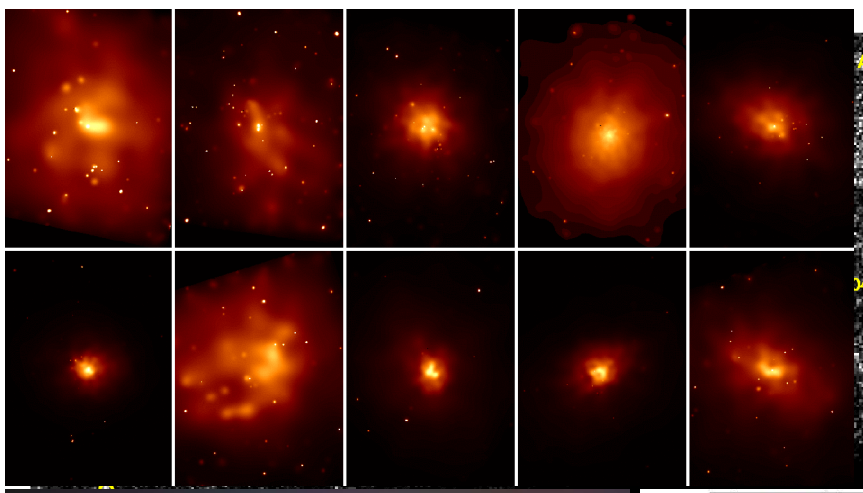


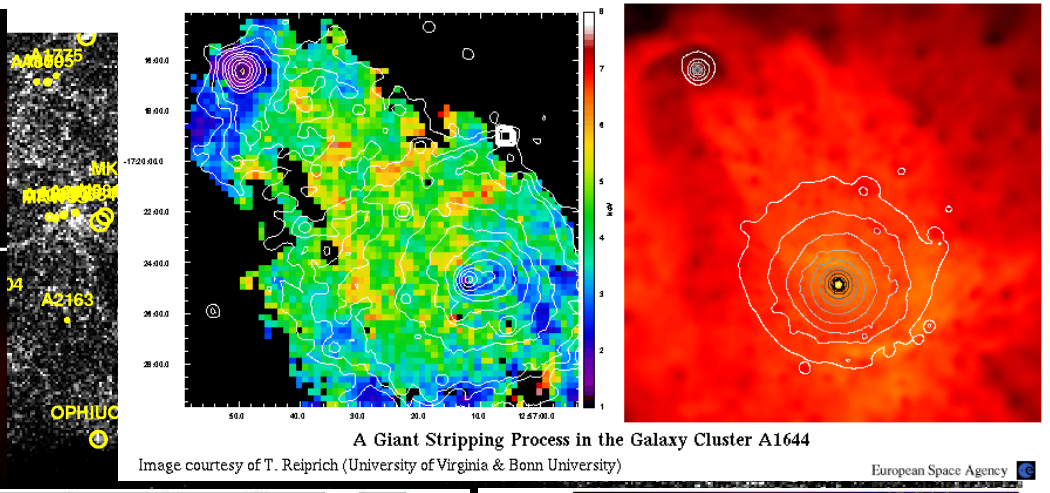
Maughan et al. (2005) WARPS, $0.6 < z < 1.0$

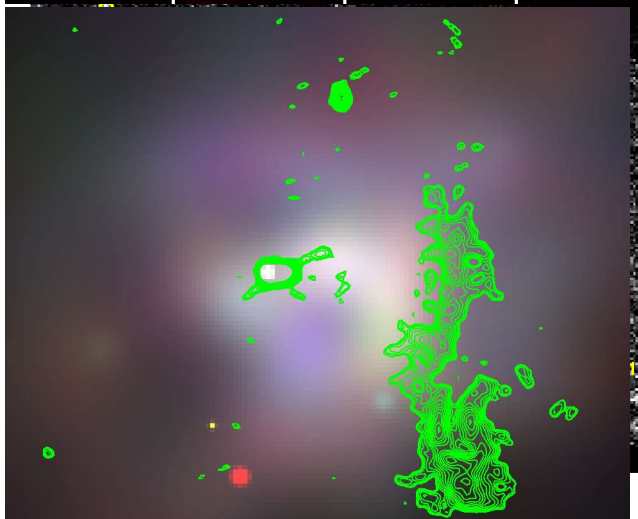
X-ray emission “good” to select clusters!

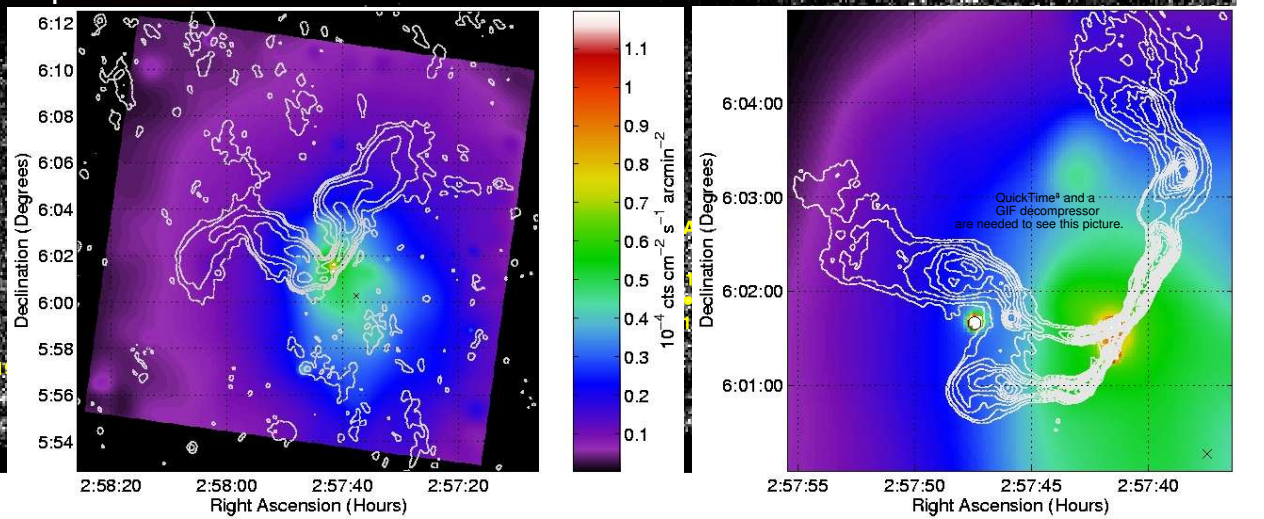
Local Sample: *HIFLUGCS*

- ~60 X-ray brightest clusters in sky (Reiprich & Böhringer 2002),
- ~completely covered with *both* Chandra (Hudson et al., in prep.) and XMM-Newton (Nenestyan et al., in prep.).

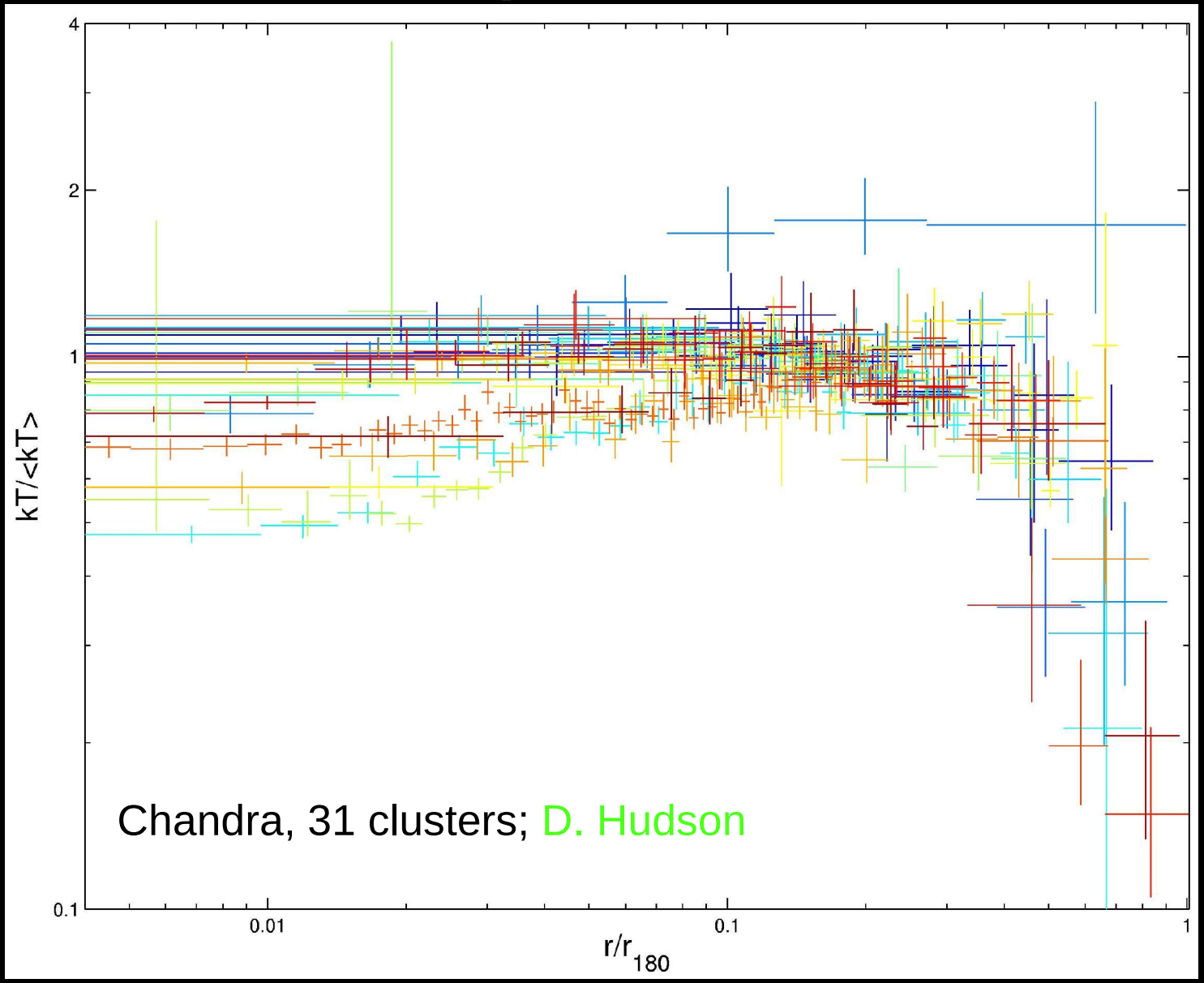


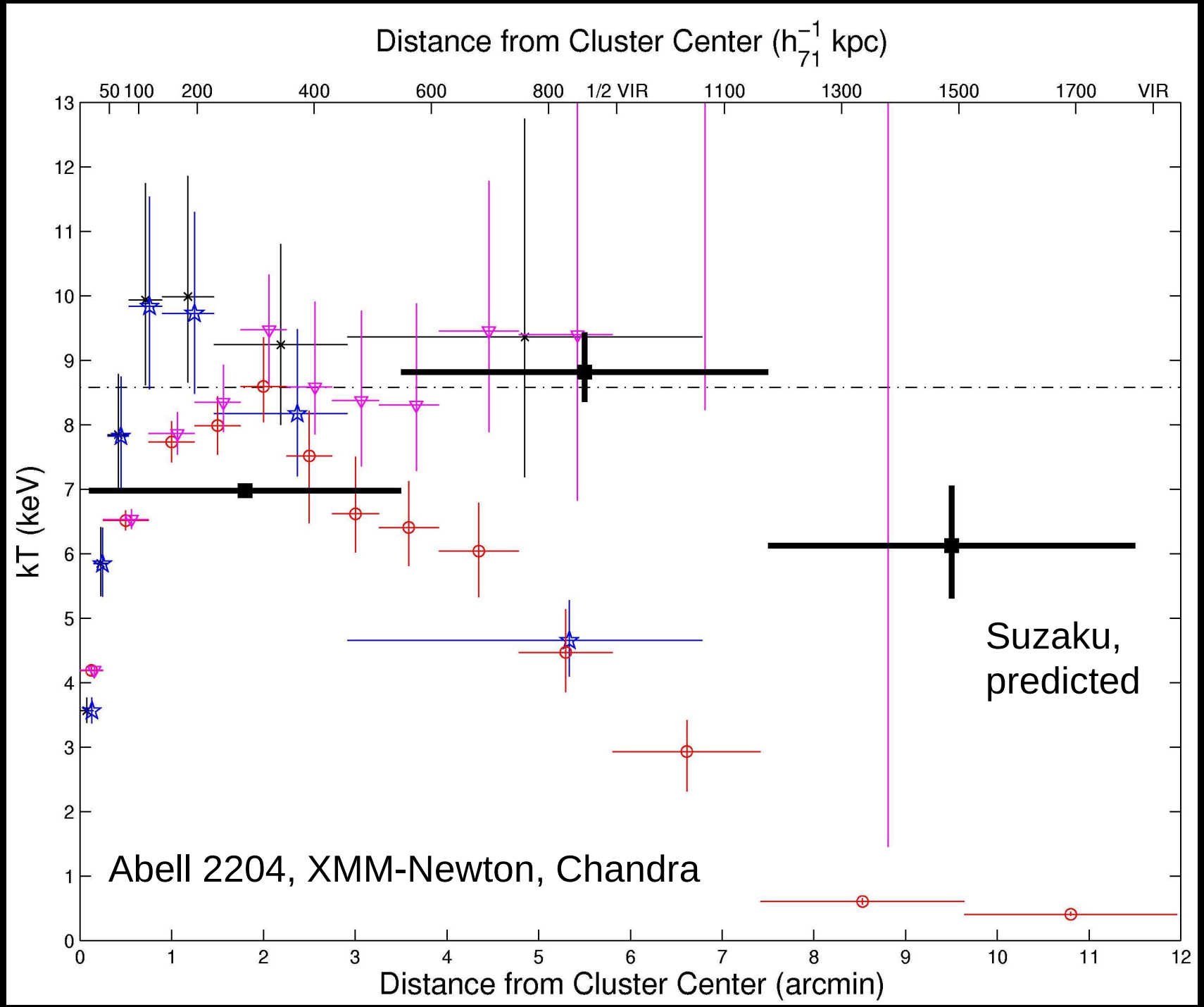


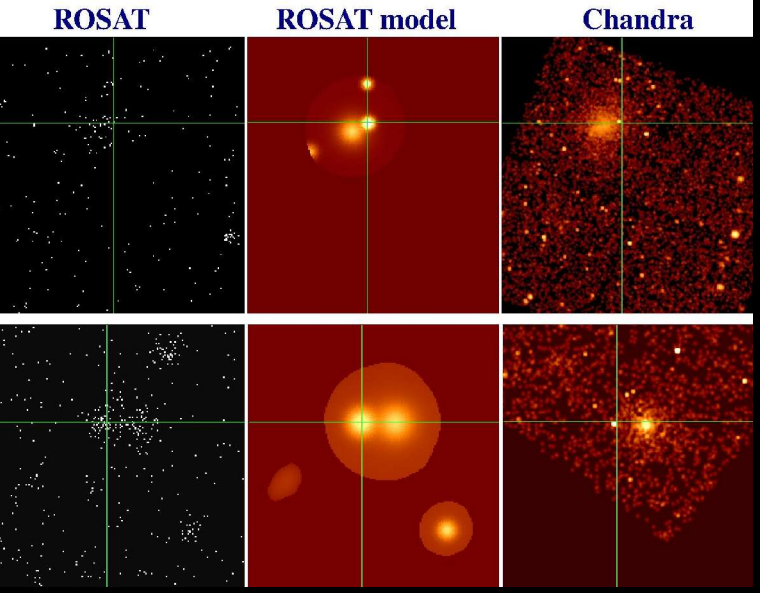




Local Sample: *HIFLUGCS*




Distance from Cluster Center (h_{71}^{-1} kpc)
50 100 200 400 600 800 1/2 VIR 1100 1300 1500 1700 VIR
kT (keV)
Distance from Cluster Center (arcmin)
Suzaku, predicted
Abell 2204, XMM-Newton, Chandra



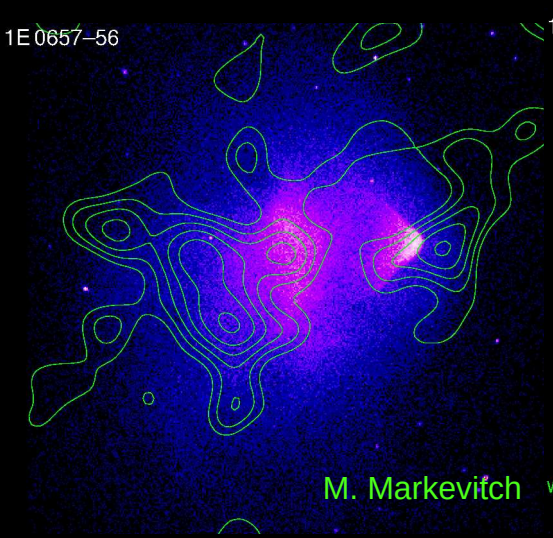
Distant Sample: 400d

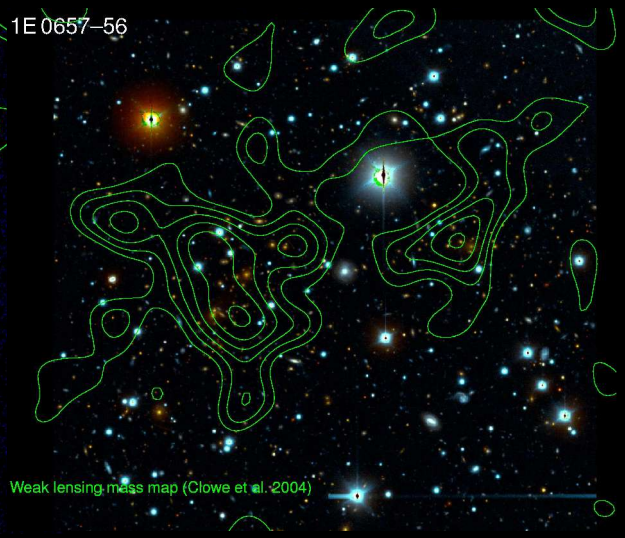
- 400 Square Degree Survey (Vikhlinin, Burenin, Quintana, Hornstrup, Ebeling et al., in prep.), clusters serendipitously detected in “all” useful PSPC obs, volume > V(z<0.1), continuation of 160d (Vikhlinin et al., Mullis et al.);
- use complete subsample of ~40 X-ray luminous clusters with z > 0.35 (~20 with z > 0.5), completely covered with Chandra.

“Good” local and distant cluster samples in place!

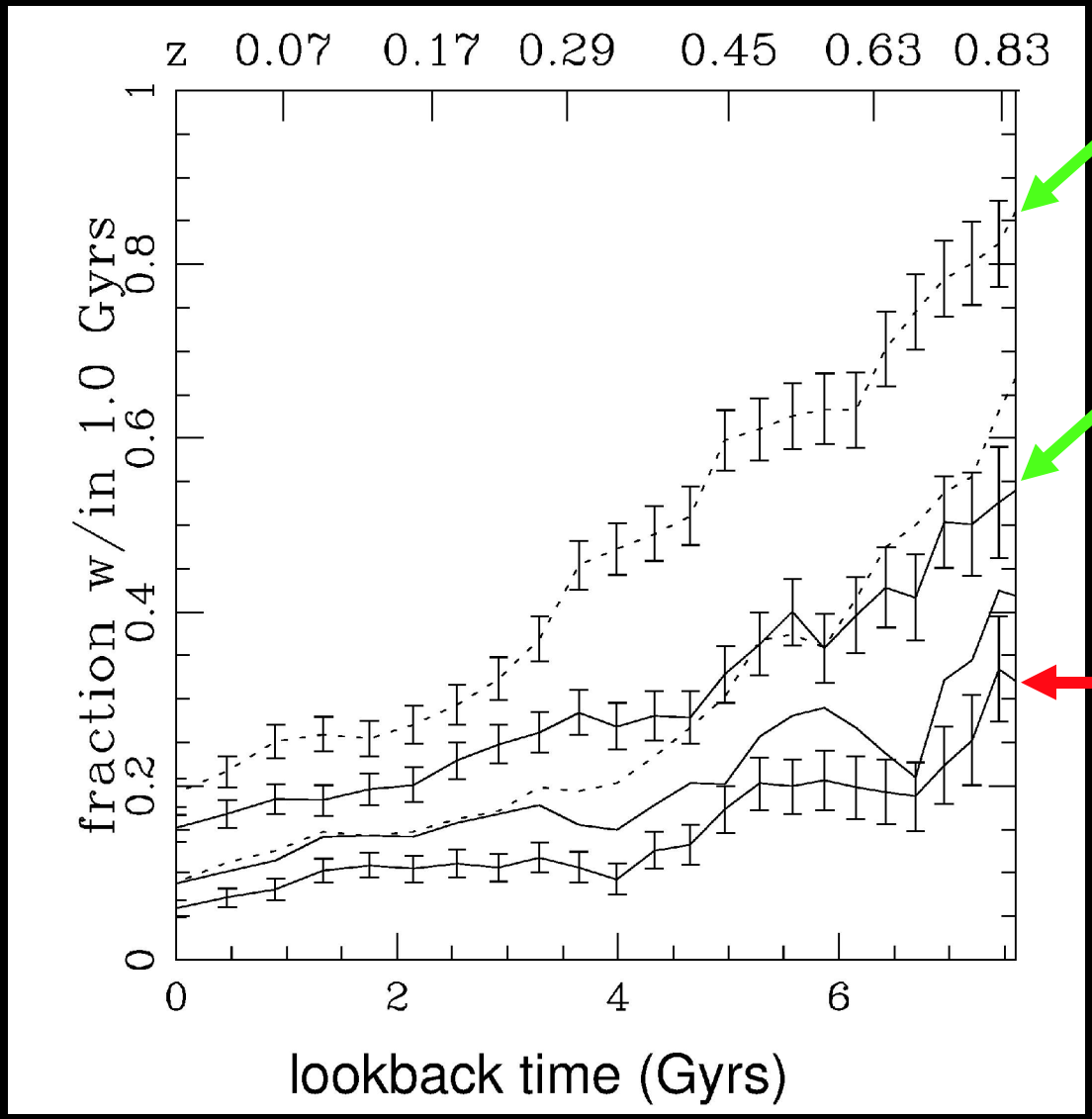
Distant Sample

- X-ray photon statistics poorer,
- merger fraction higher (hydrostatic/virial equilibrium?)?





Cluster Merger Fraction (z)



Mergers + Accretion

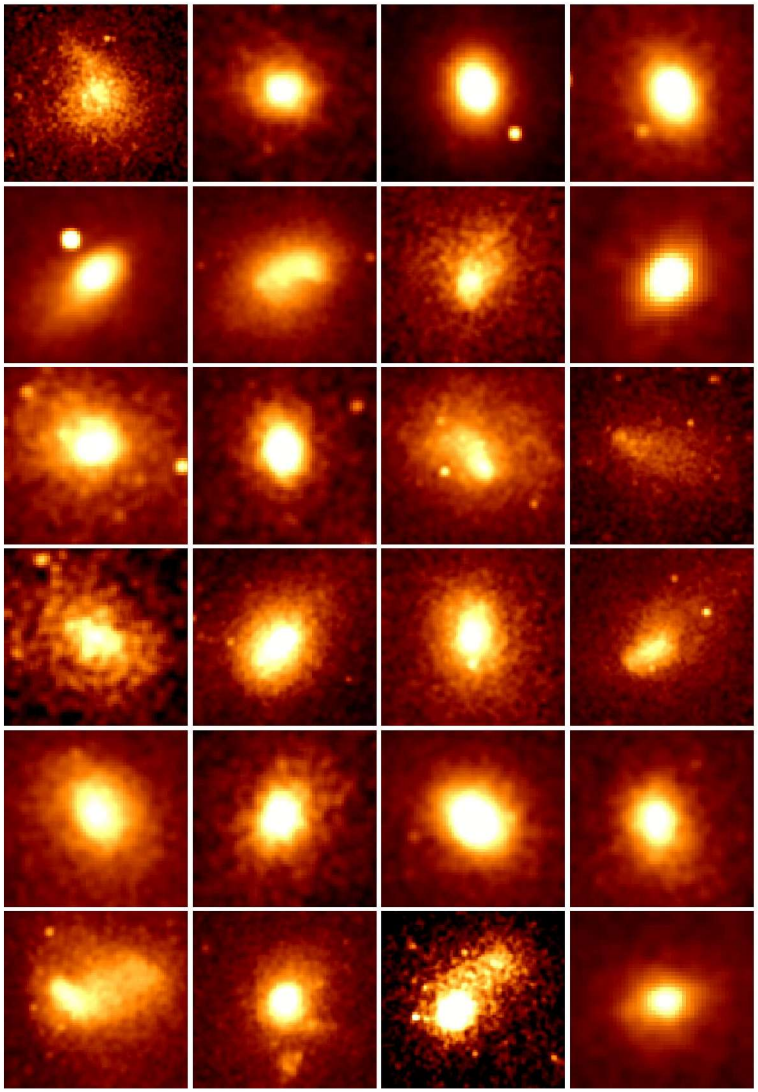
≥ 1:10 Mergers

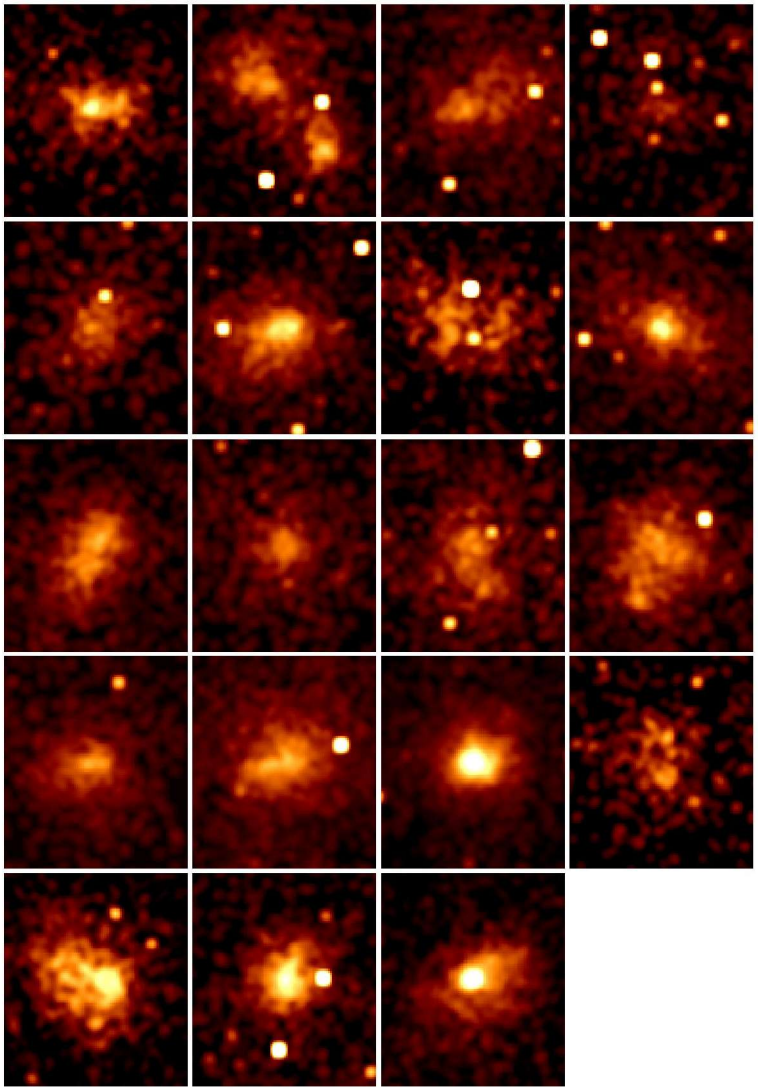
≥ 1:3 Mergers

LCDM, σ_8=0.8

Cohn & White (2005)

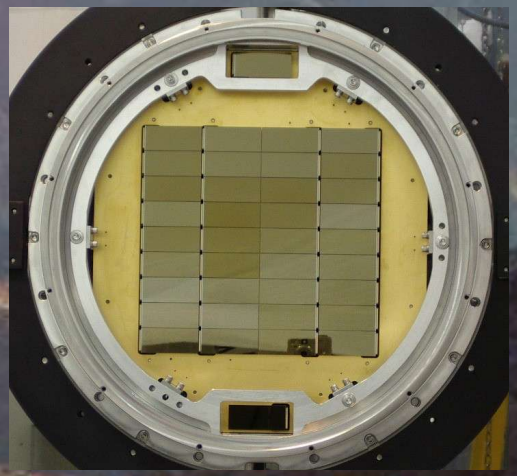
Substructure



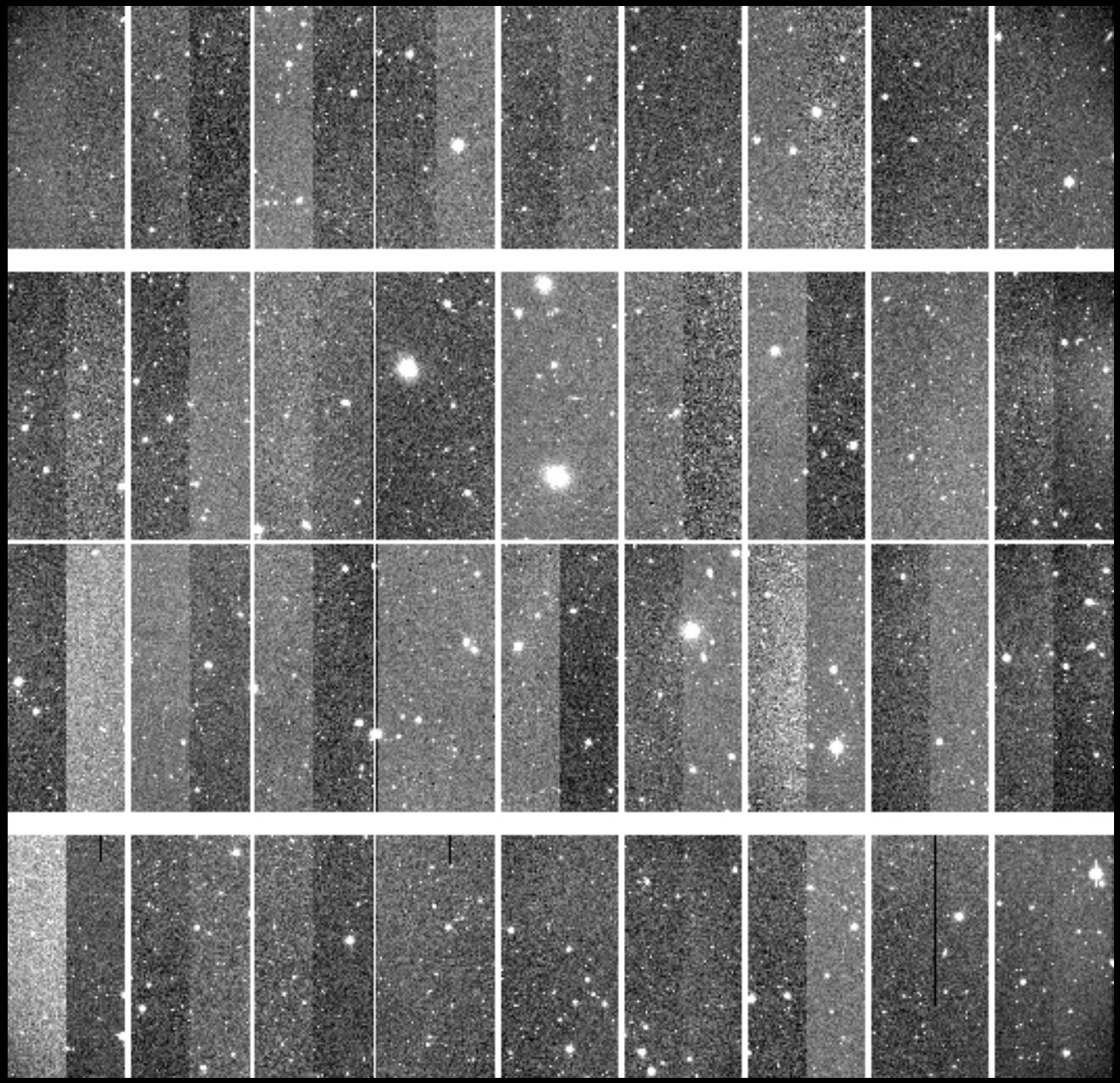


$z < 0.1$ From A. Vikhlinin $z > 0.45$ (see also Jeltema etal)

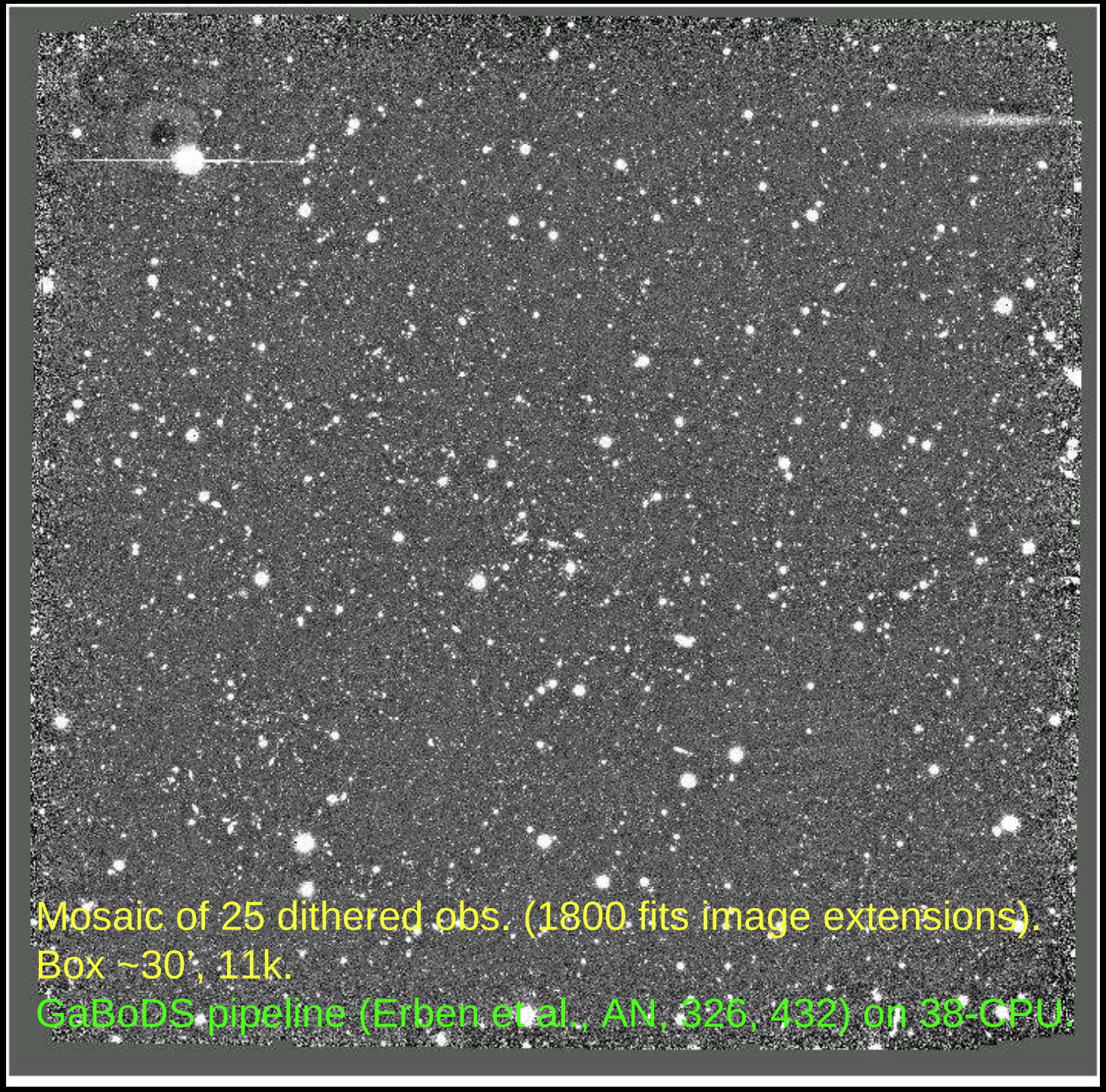
Megacam @ MMT 6.5m



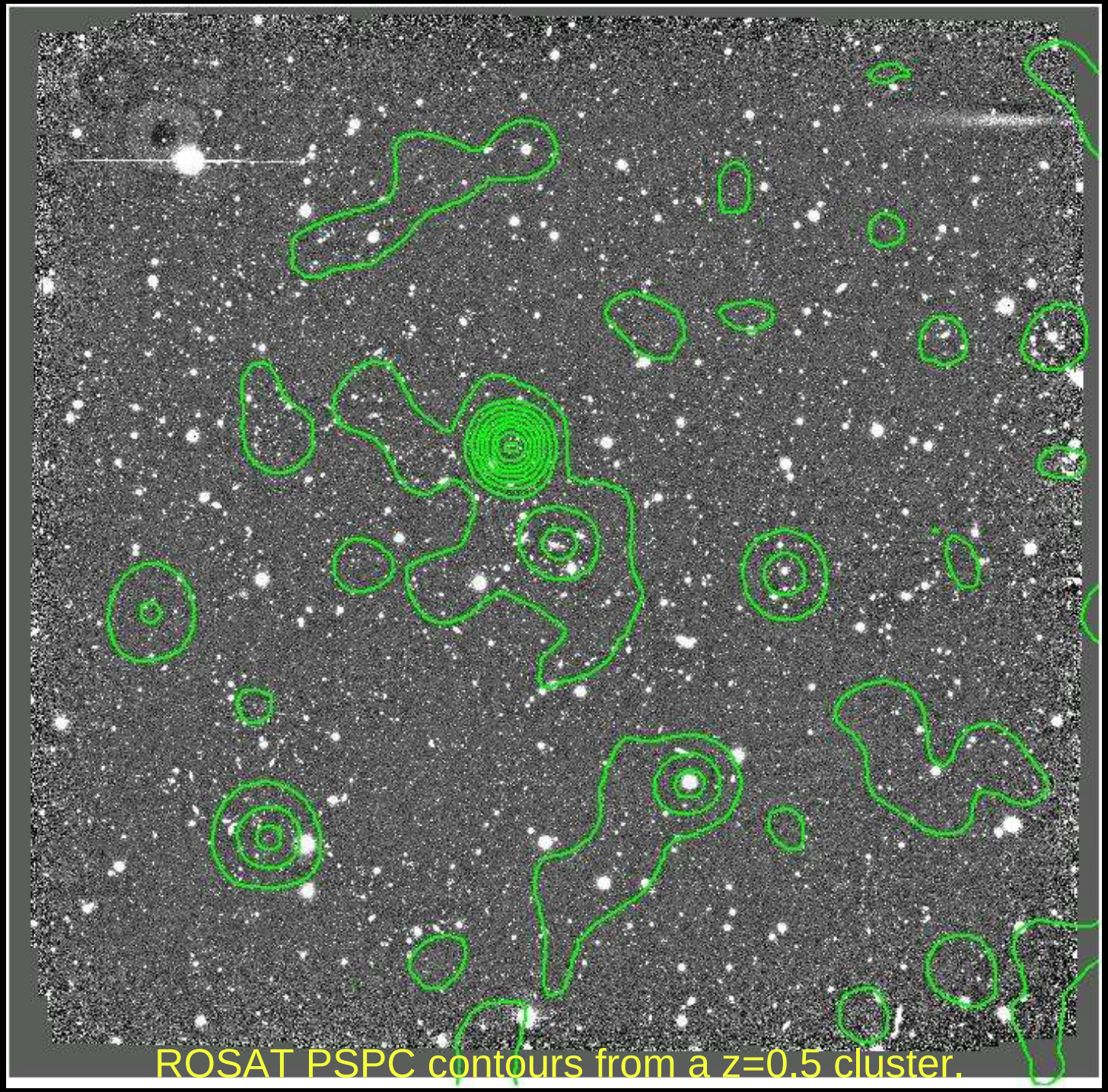
+ IMACS @ Magellan 6.5m….
Collab with UVa and CfA.



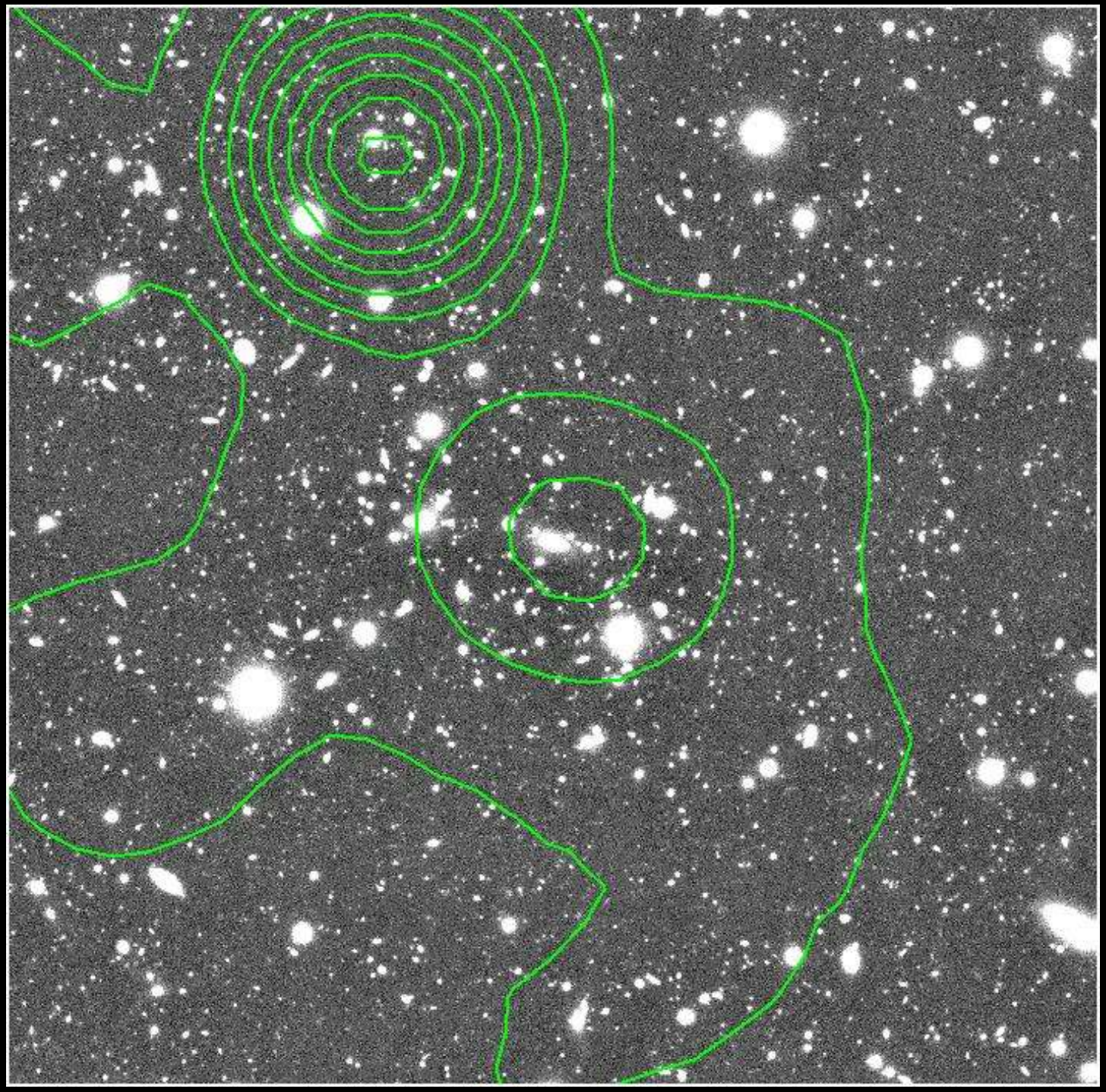
36 (2kx4k) CCDs, 2 readouts/CCD, 2x2 binning, unbinned (0.08”/pixel) ~800MB.

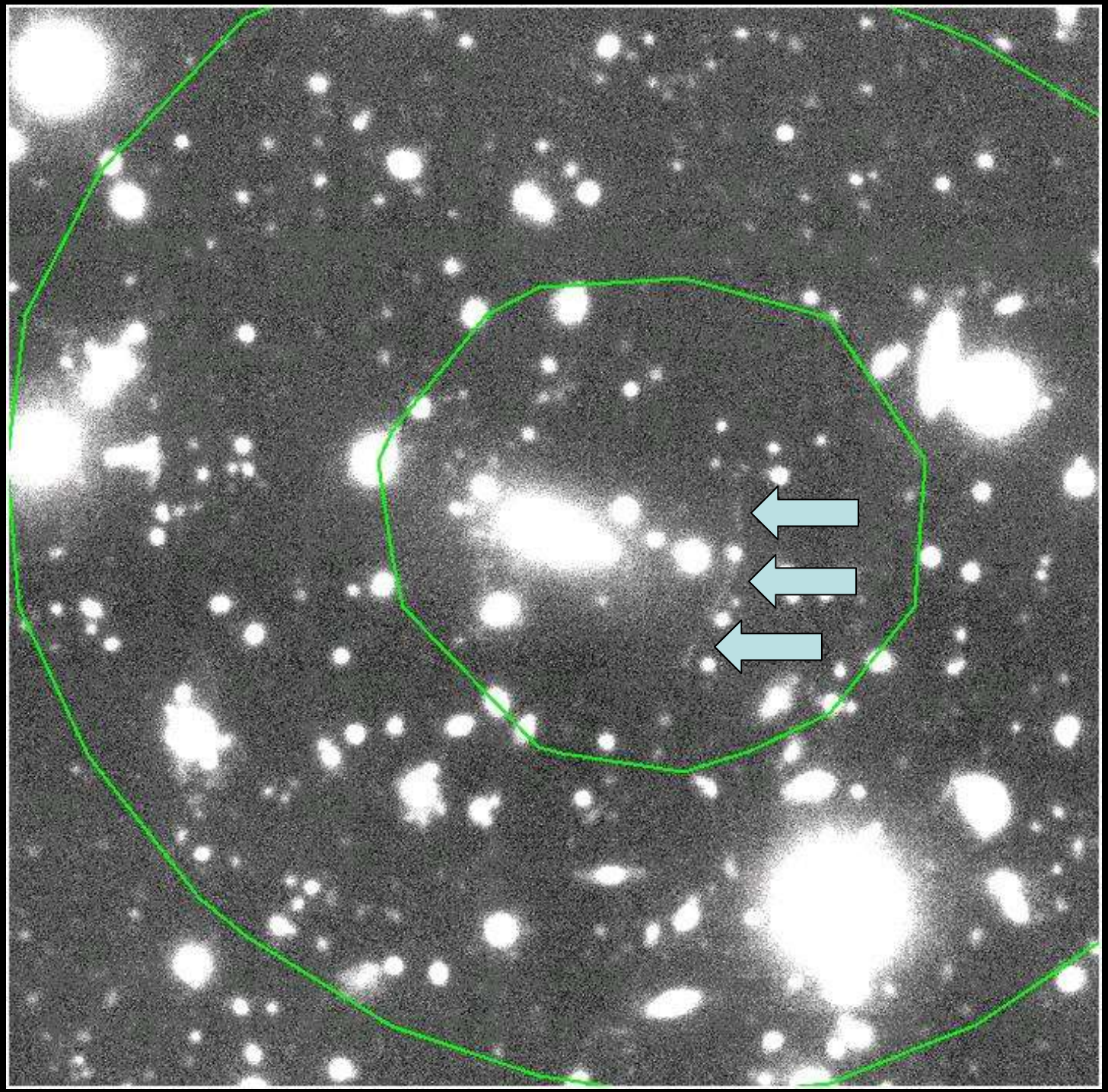


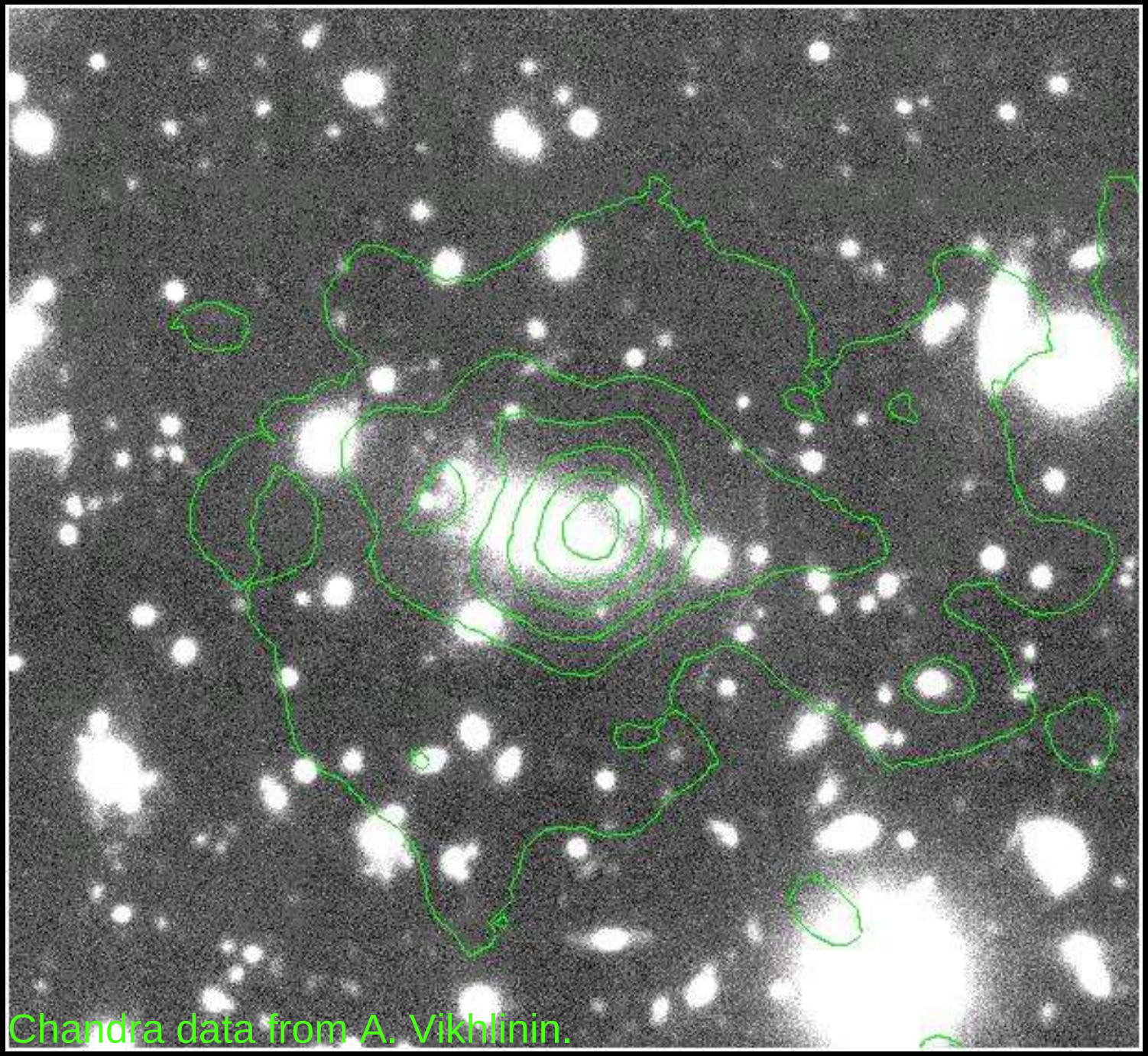
Mosaic of 25 dithered obs. (1800 fits image extensions).
Box ~30', 11k.
GaBoDS pipeline (Erben et al., AN, 326, 432) on 38-CPU.

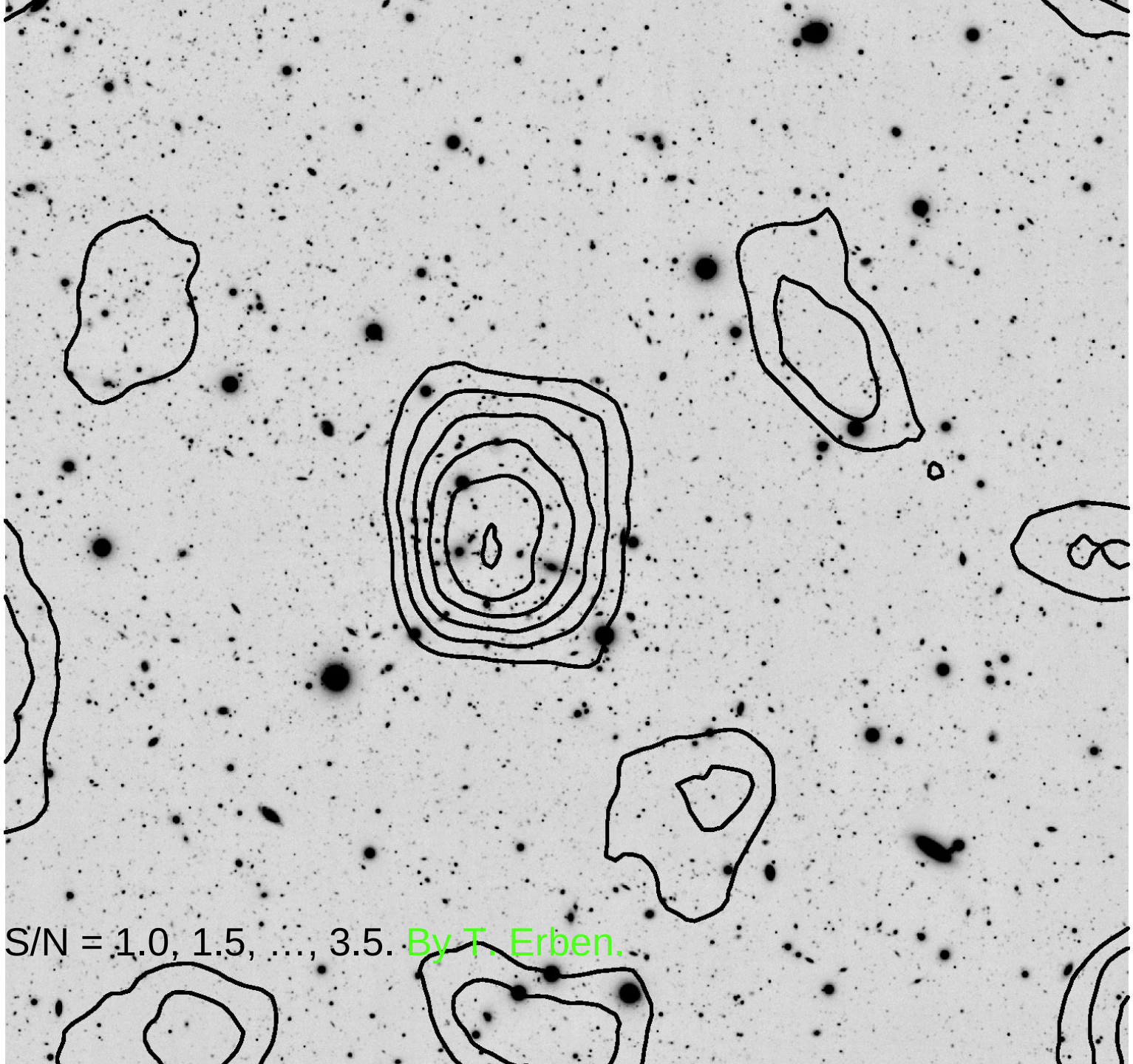


ROSAT PSPC contours from a z=0.5 cluster.






Chandra data from A. Vikhlinin.

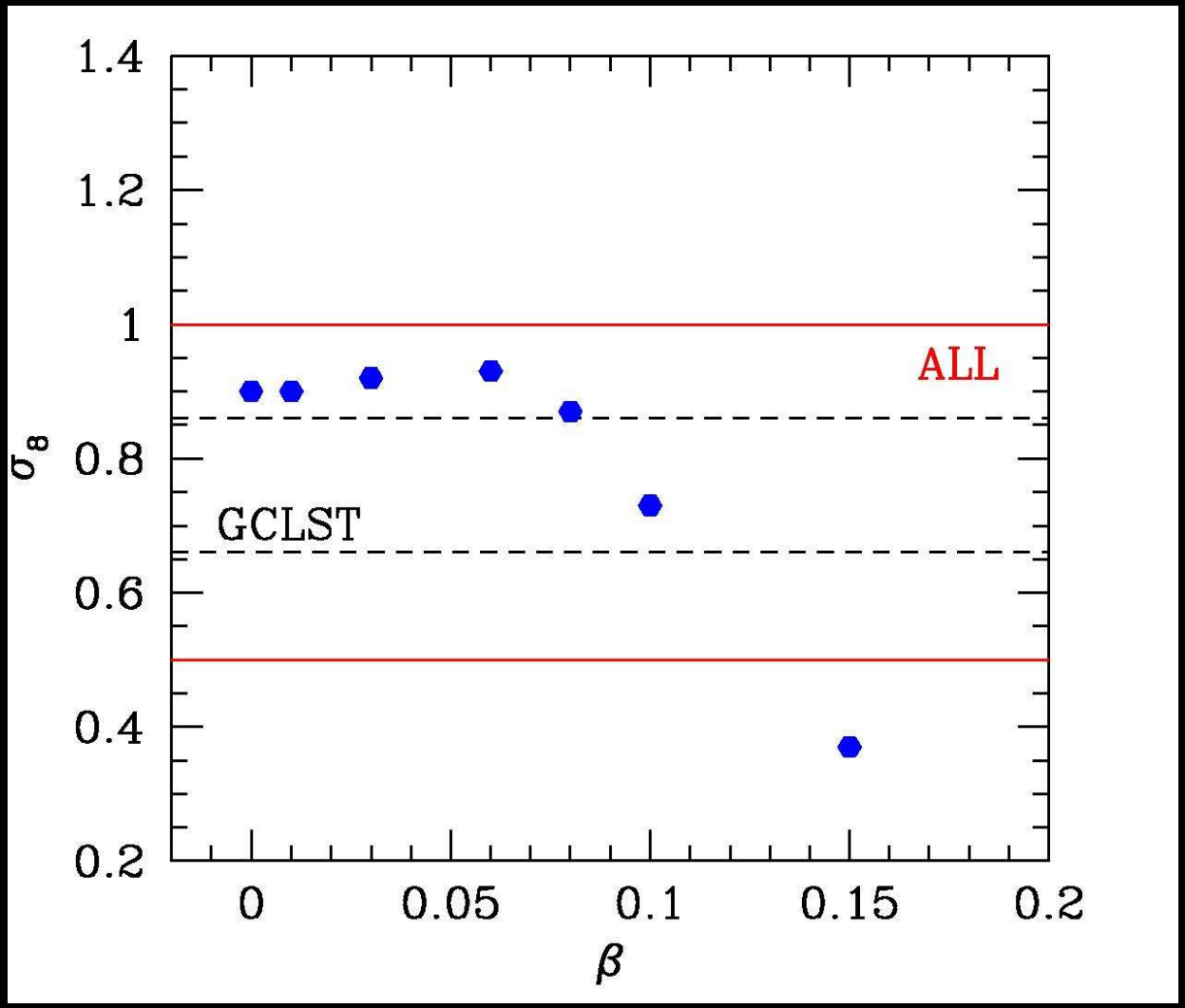


S/N = 1.0, 1.5, …, 3.5. By T. Erben.

What is our universe made of ?

Basic questions , high public interest

Interaction between DE/DM? Coupled Quintessence?



σ_8-CMB $\neq$ σ_8-cluster $\Rightarrow \beta \neq 0 \Rightarrow$ non-zero non-gravitational coupling

Schuecker (2005), based on Amendola (2000).

Summary

- Clusters great cosmological tools,
- good samples, selection, masses,
- will get useful constraints on (constant) DE equation of state, w, *from clusters alone* (<25-50%; flat universe) - soon,
- ground work for future large surveys (check self-cal, e.g., z-dependent scatter in L-M).

Thanks to http://chandra.harvard.edu and http://www.mpa-garching.mpg.de/galform.