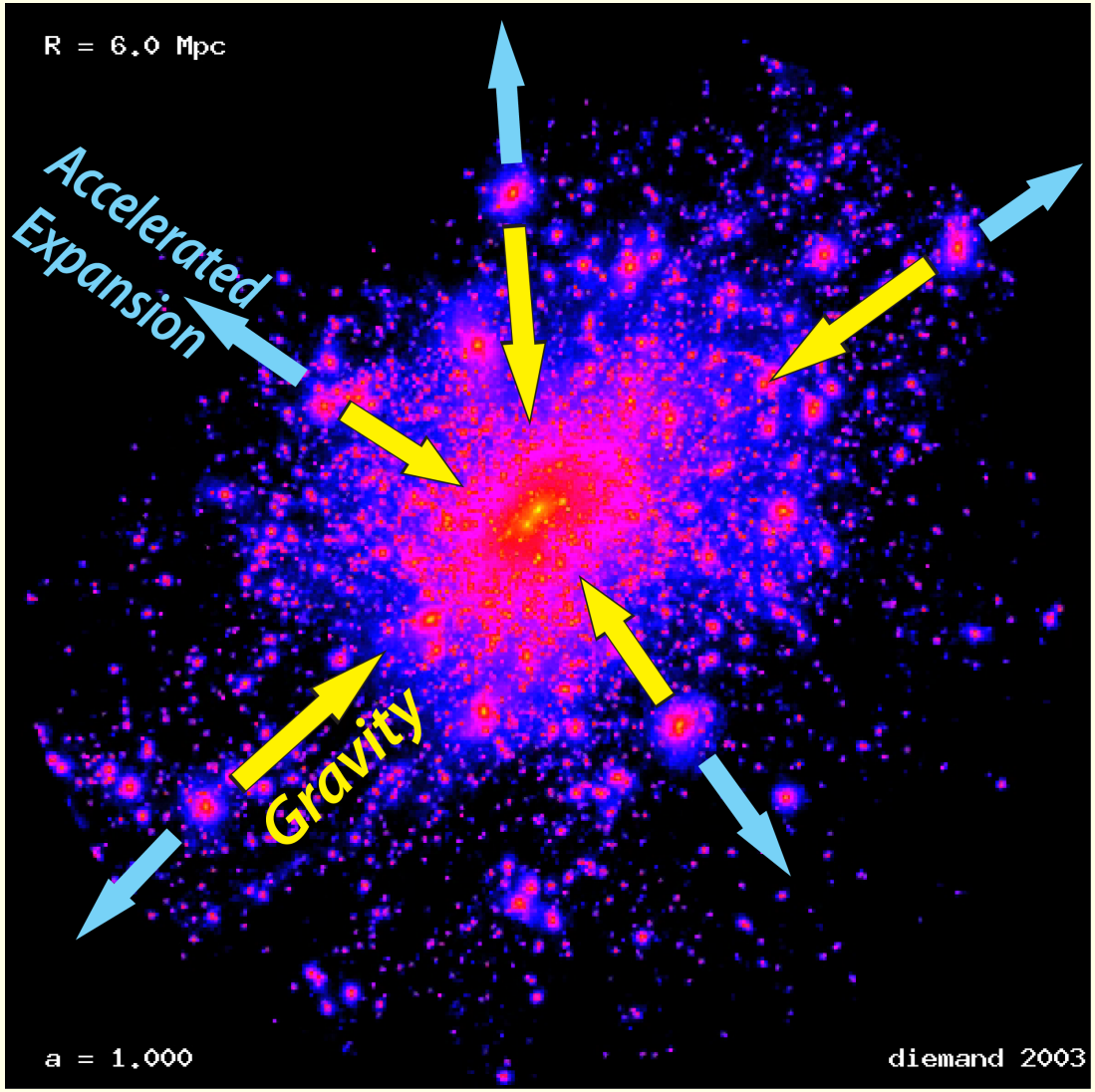
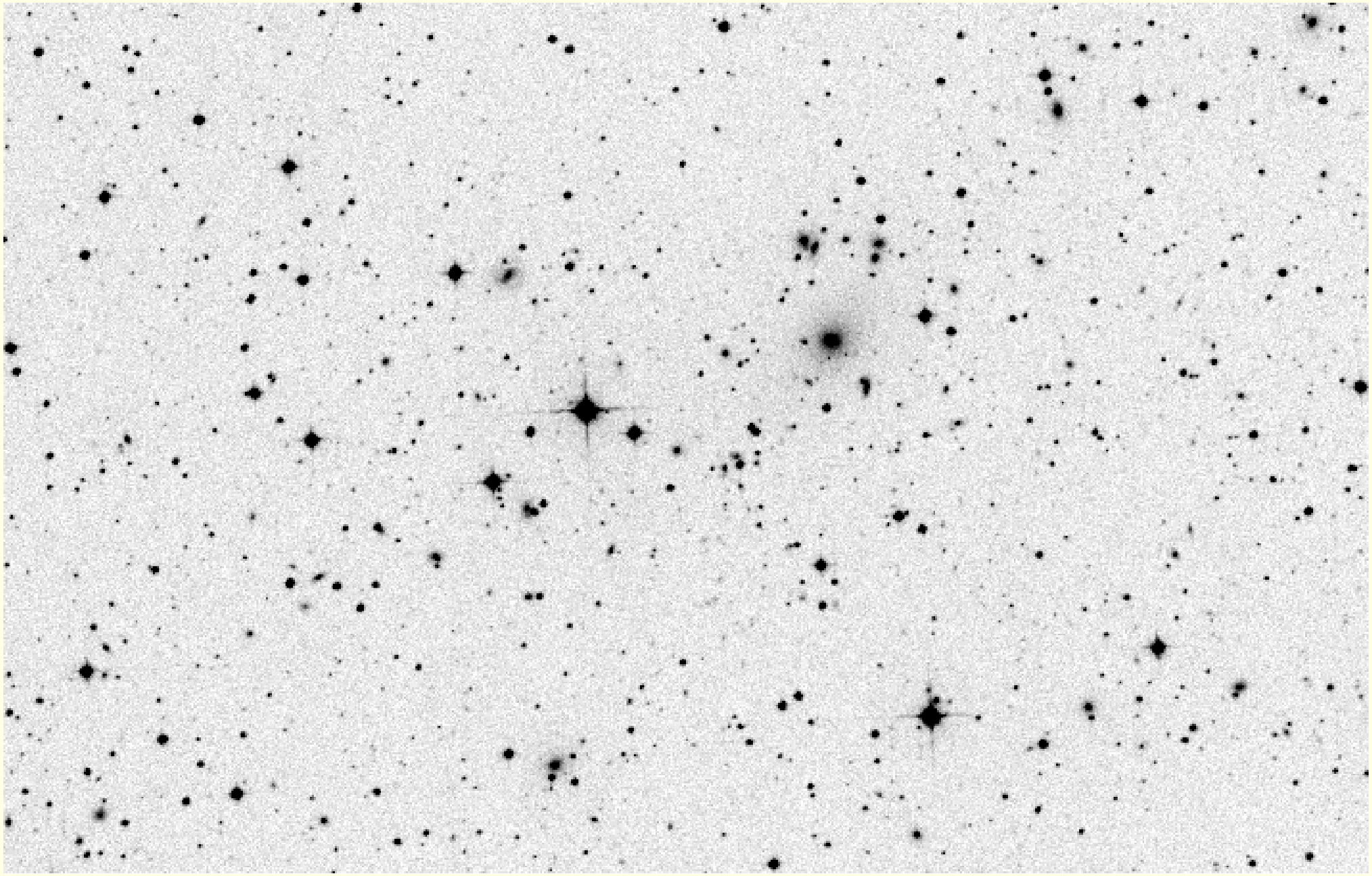
Growth of structure with X-ray clusters

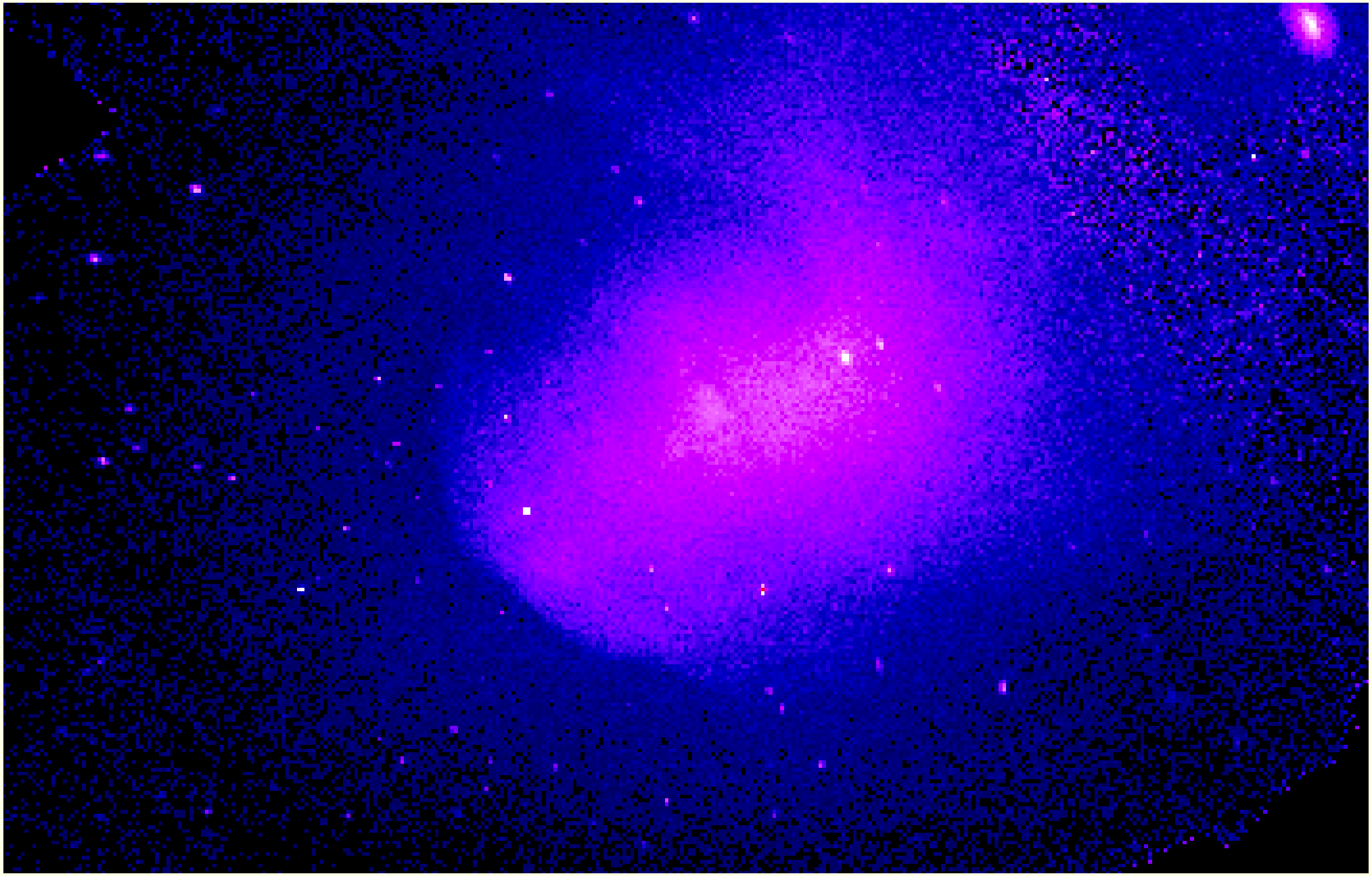


A. Vikhlinin, A. Kravtsov, R. Burenin, H. Ebeling, W. Forman, A. Hornstrup
C. Jones, S. S. Murray, D. Nagai, H. Quintana, A. Voevodkin

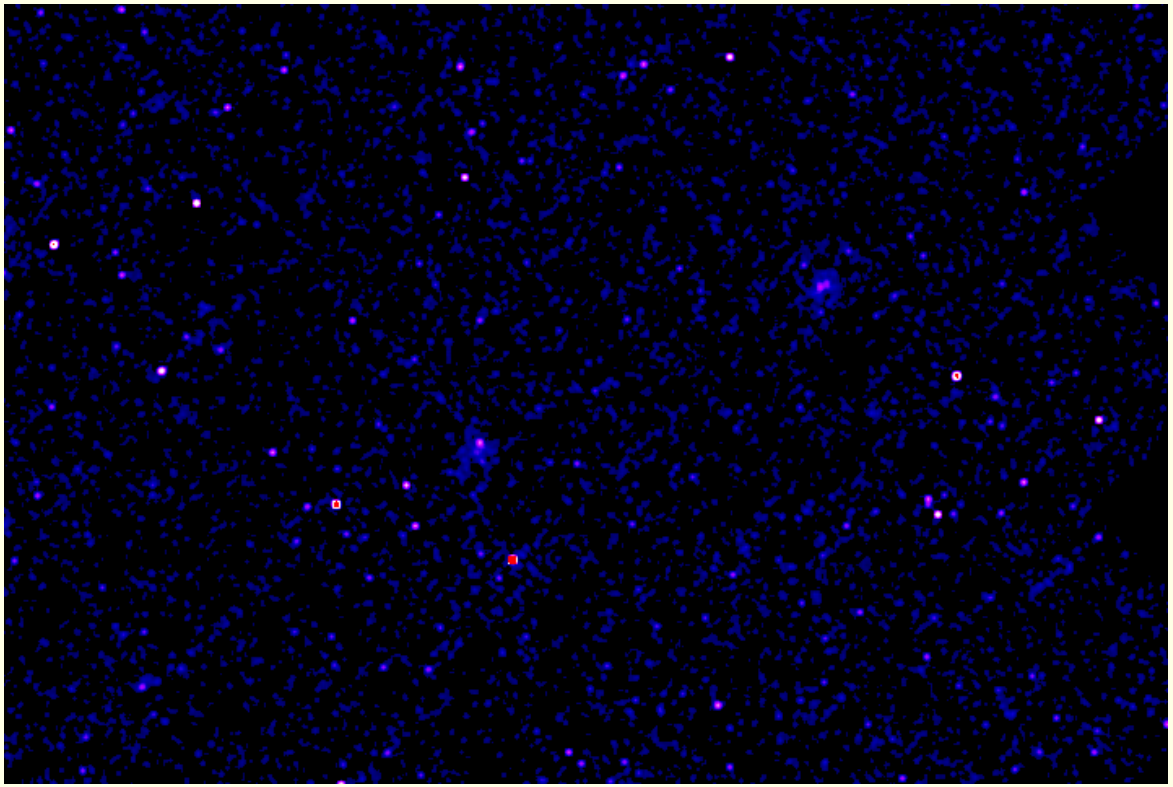
Why X-rays?

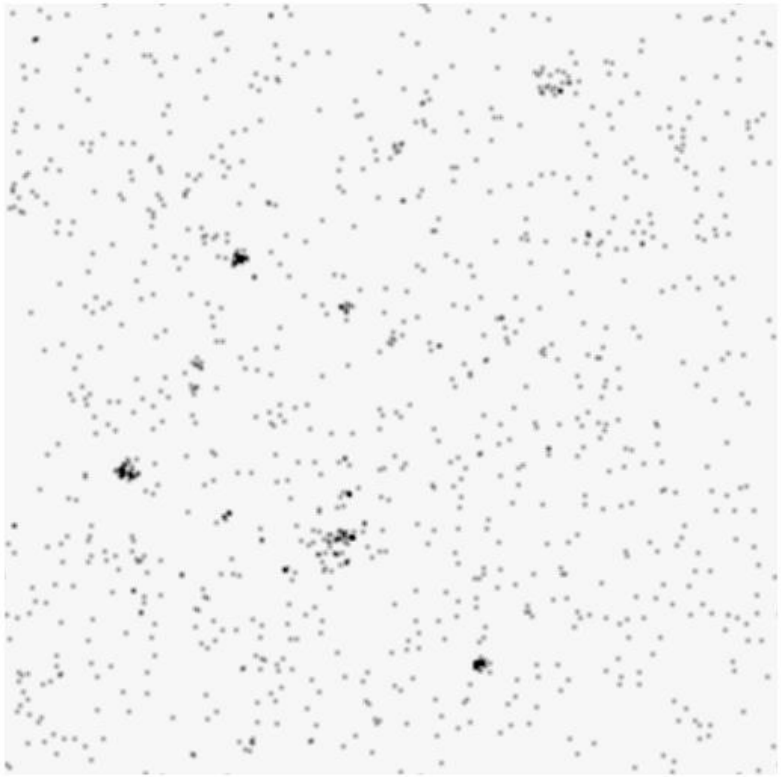


Why X-rays?



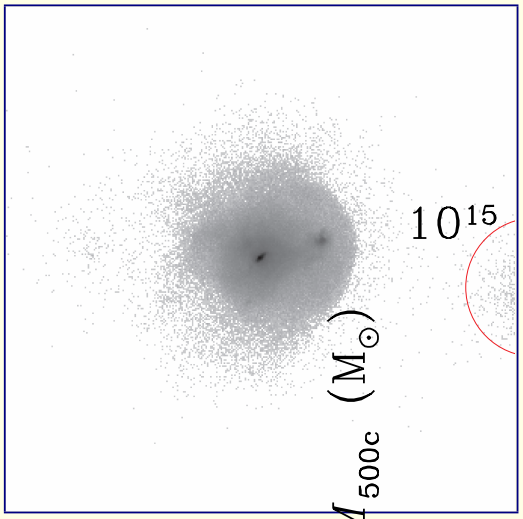
Easy to find ...

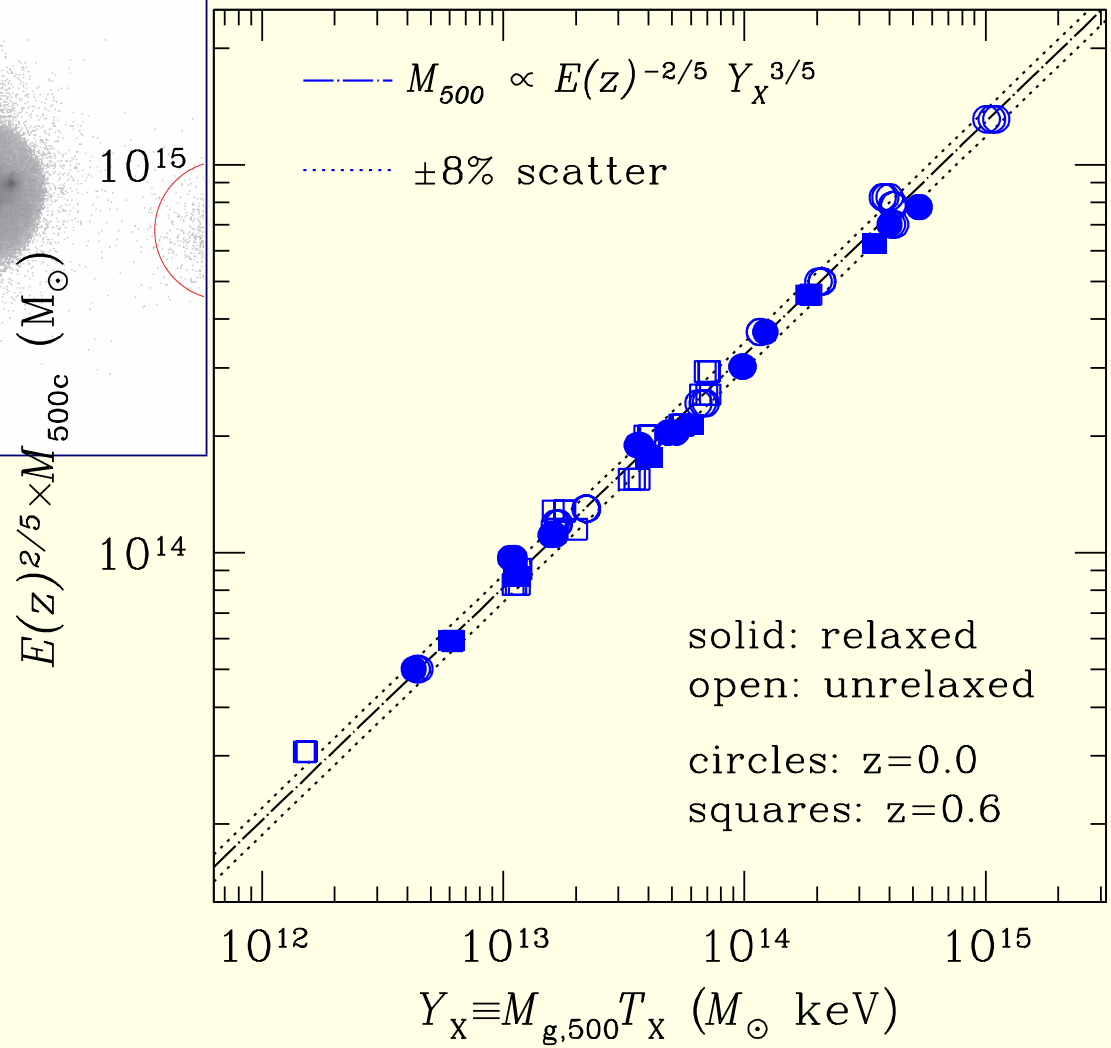


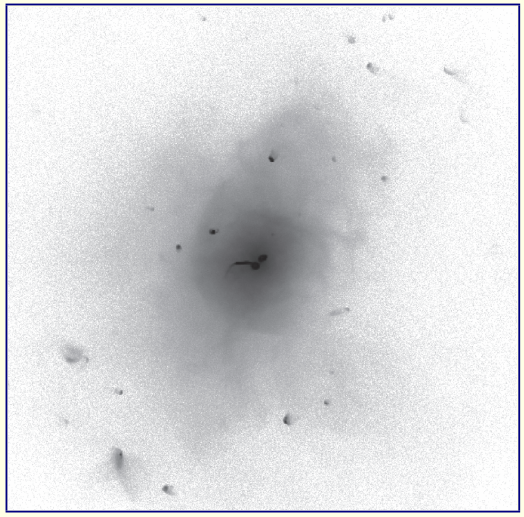


- Observe dominant baryonic component
- Detectable with very few photons ($N_{\mathrm{phot}} < N_{\mathrm{gal}}$)
- Detectable to high z

Easy to measure.



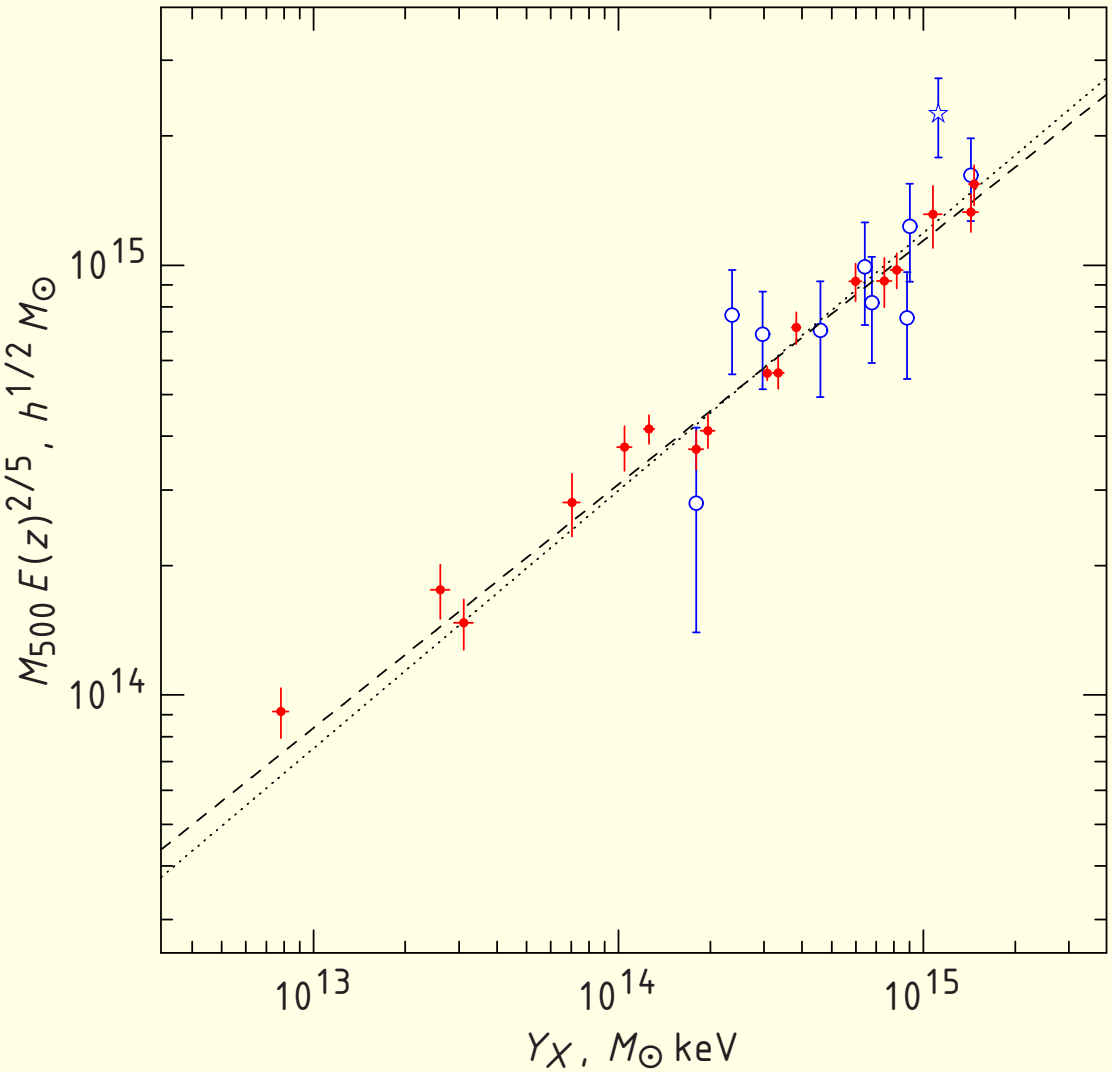


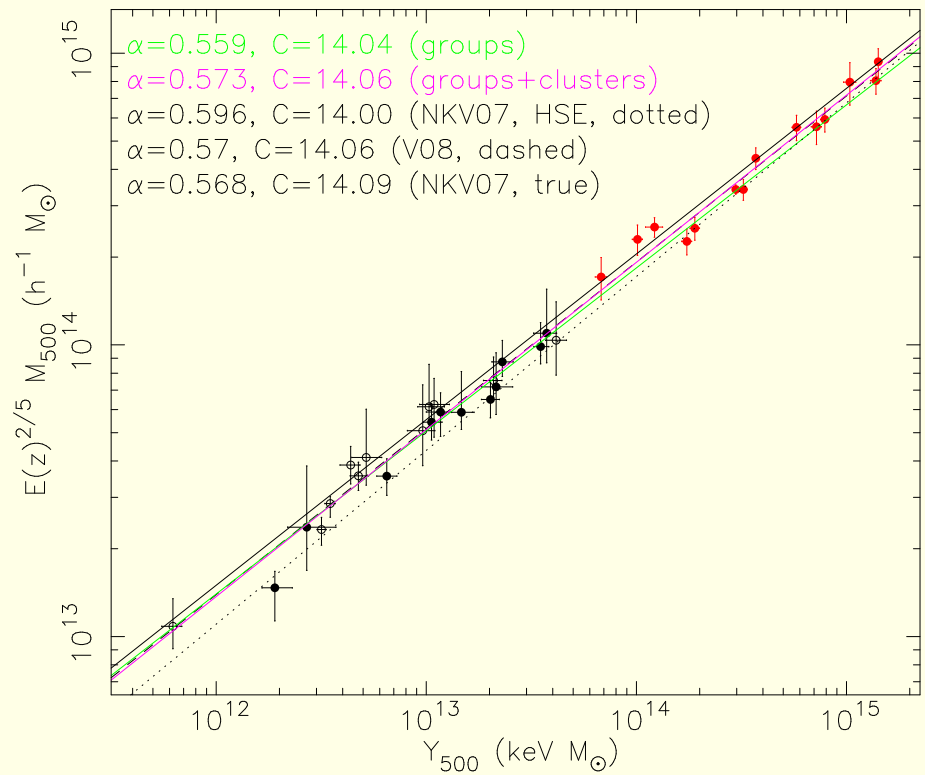


- $M \propto Y_X^{3/5}\ E(z)^{-2/5}$ — follows from self-similarity + virial theorem + "fair sample"
- need 1500 photons to measure Y_X

papers by Nagai, Kravtsov, & AV

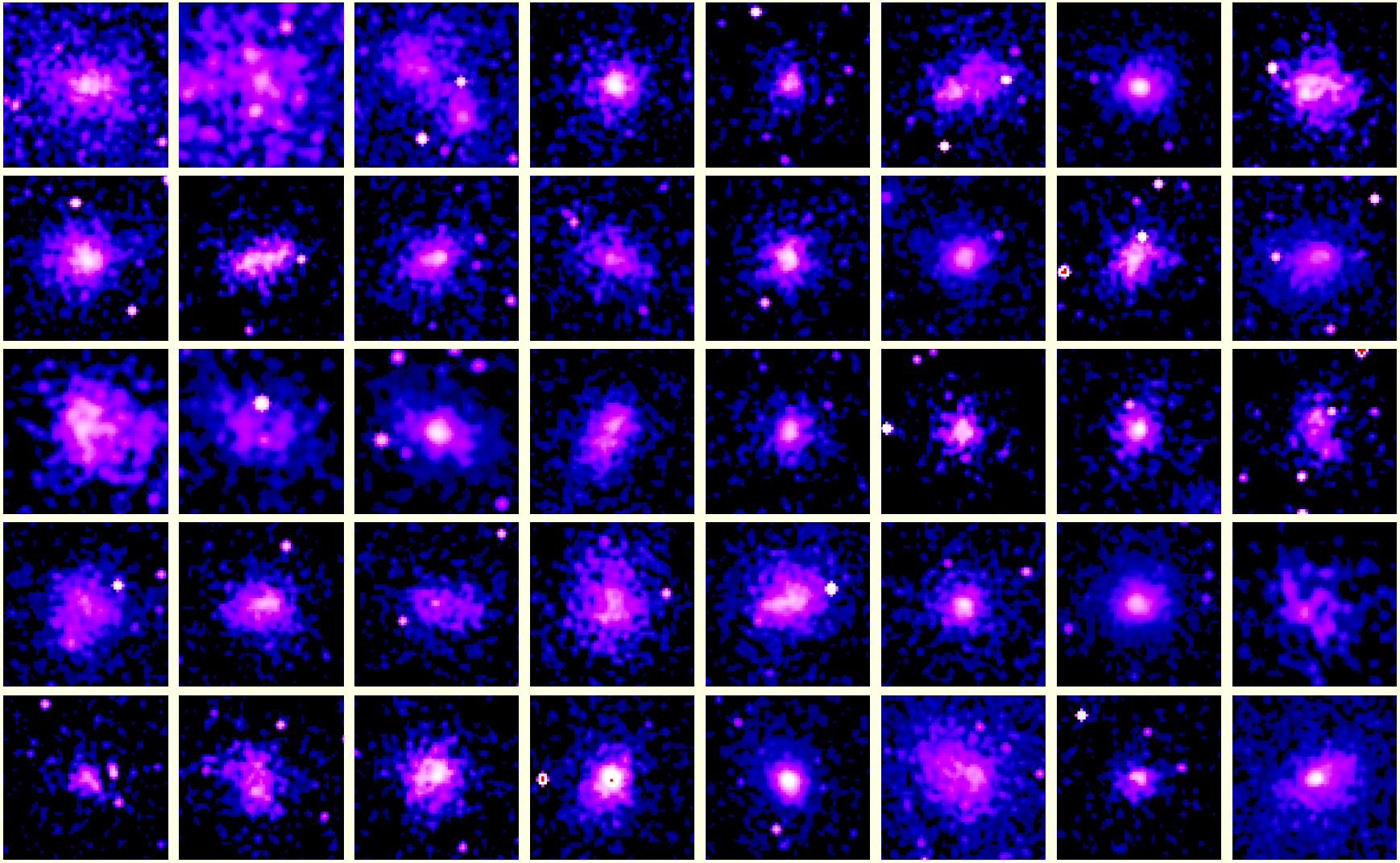
With good data, everything fits together





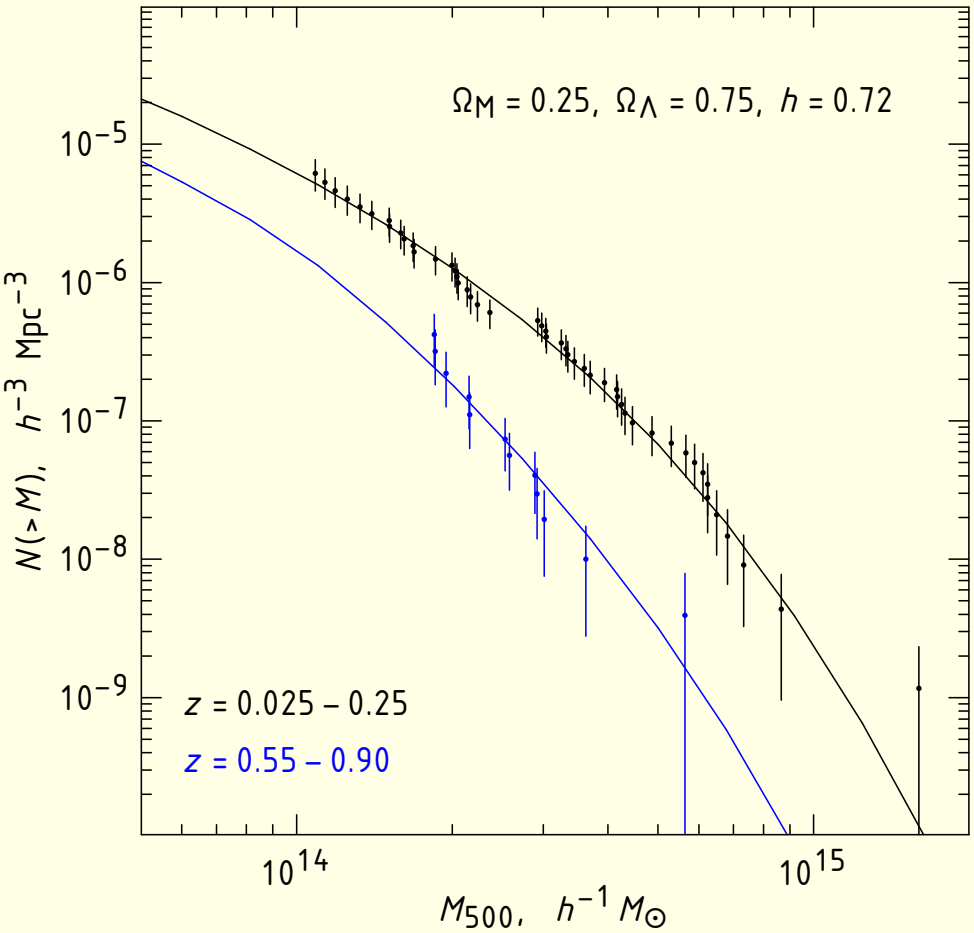
• — *Chandra*, hydrostatic; • — weak lensing, Hoekstra '07; • — groups, Sun etal '09

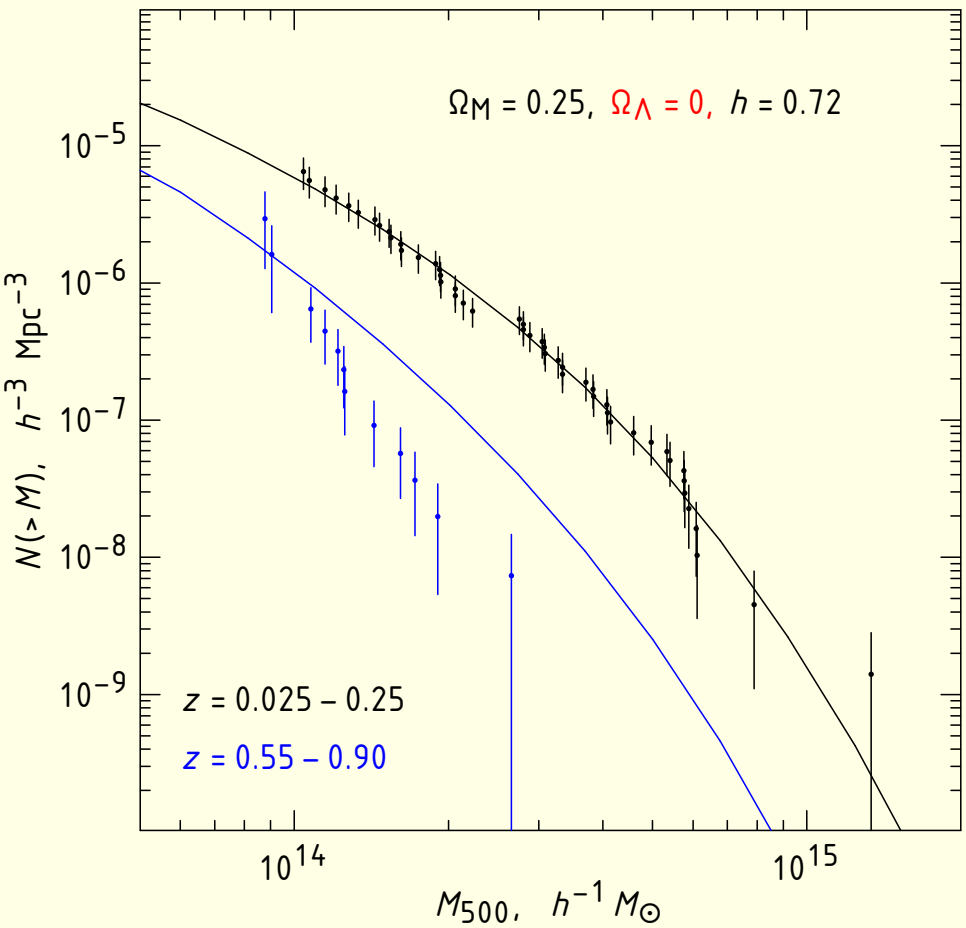
- **Systematic errors:** $\Delta M/M < 9\%$ at $z = 0$ $\quad \Delta \dfrac{M(z=0.5)}{M(z=0)} < 5\%$



- **36 clusters at $z > 0.35$ from 400d** `http://hea-www.harvard.edu/400d`
- **48 at $z \sim 0.05 - 0.15$ from ROSAT All-Sky Survey**
- **Measure Y_X, $M_{\rm gas}$, T_X in all with *Chandra***

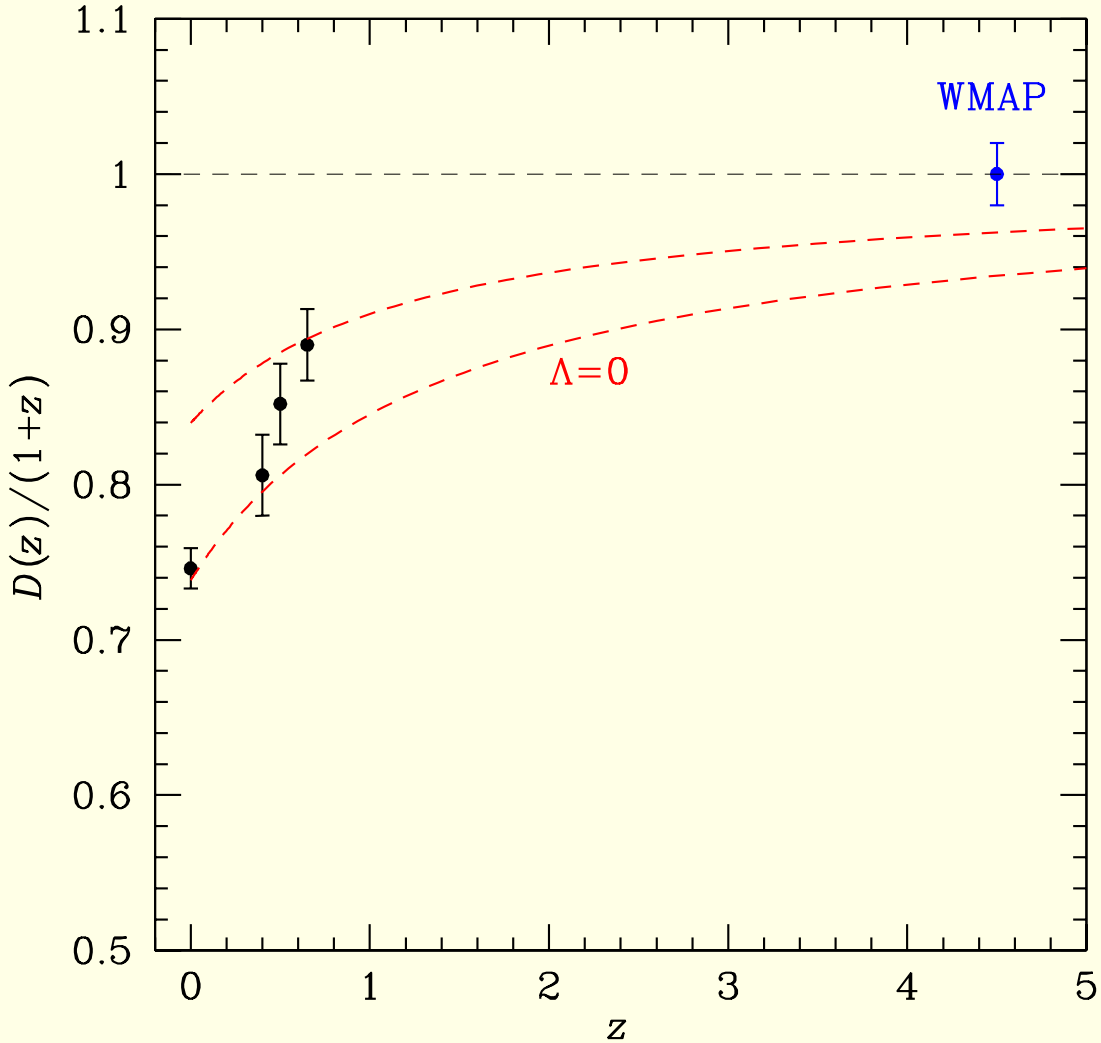
Mass functions, detection of Λ





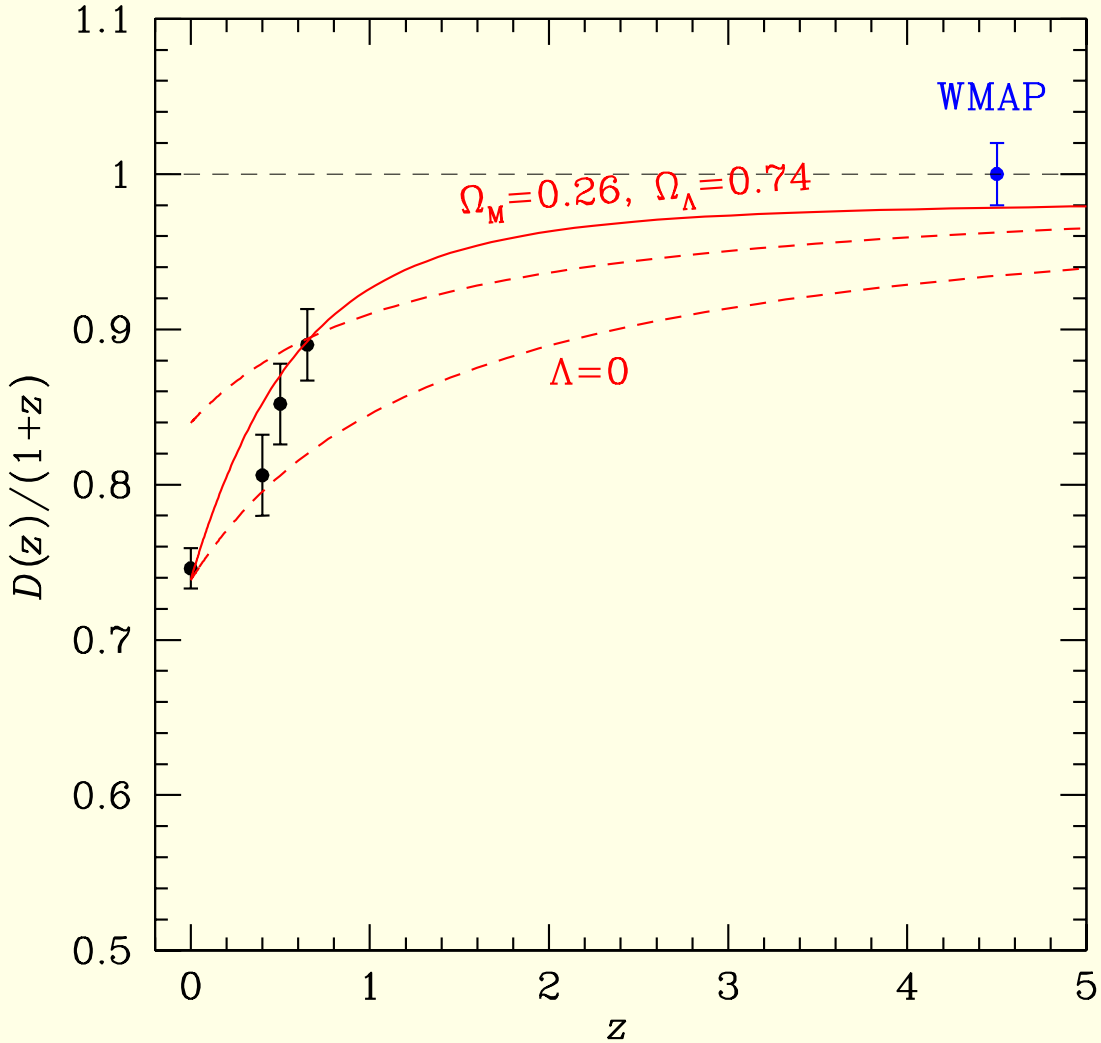
- **$\Lambda > 0$ at ~ 5σ required by mass functions**

Growth history



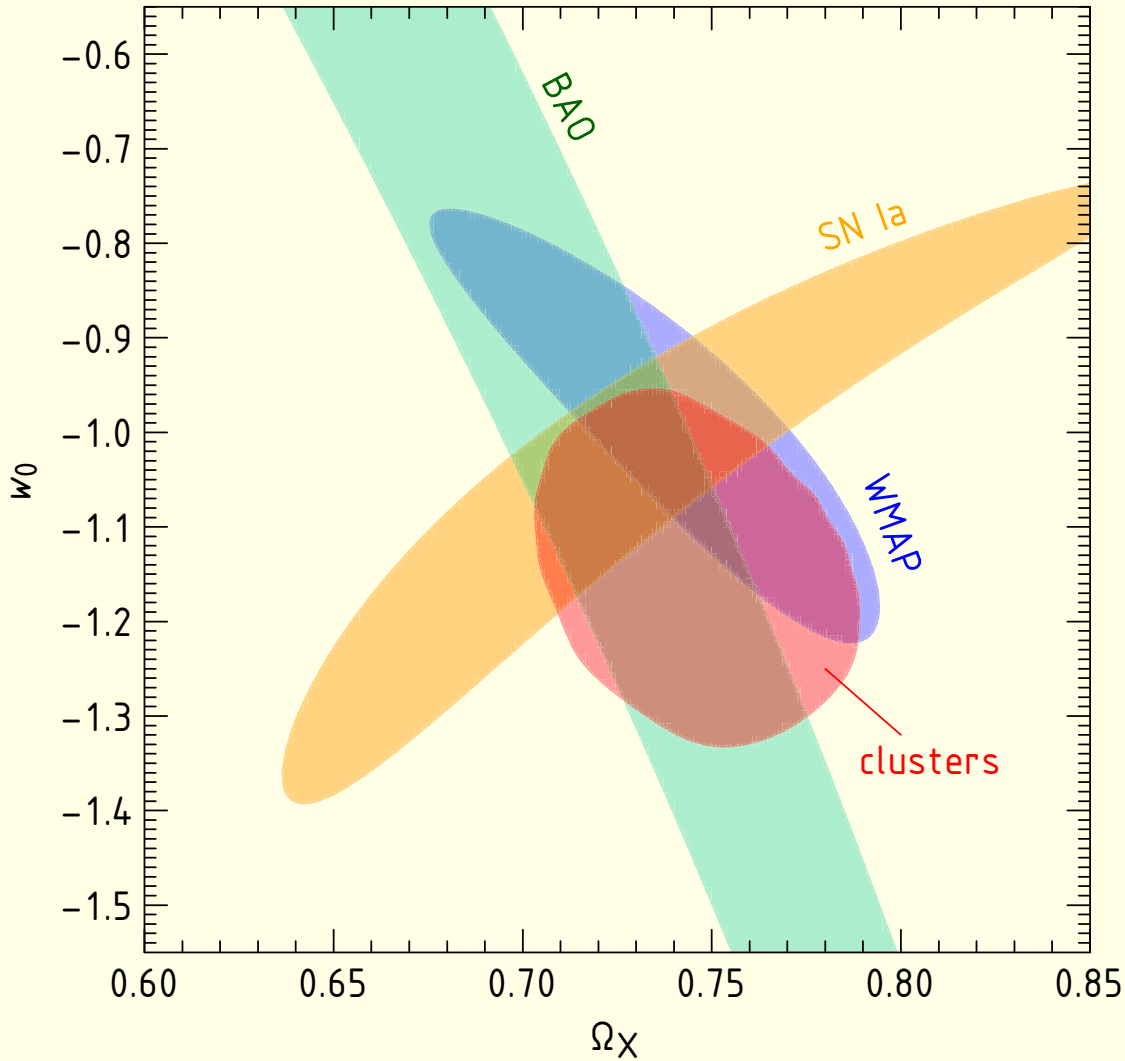
$d(z)$ fixed at concordance cosmology; $D(z)/(1+z) = 1$ for $\Omega_M = 1$

Growth history



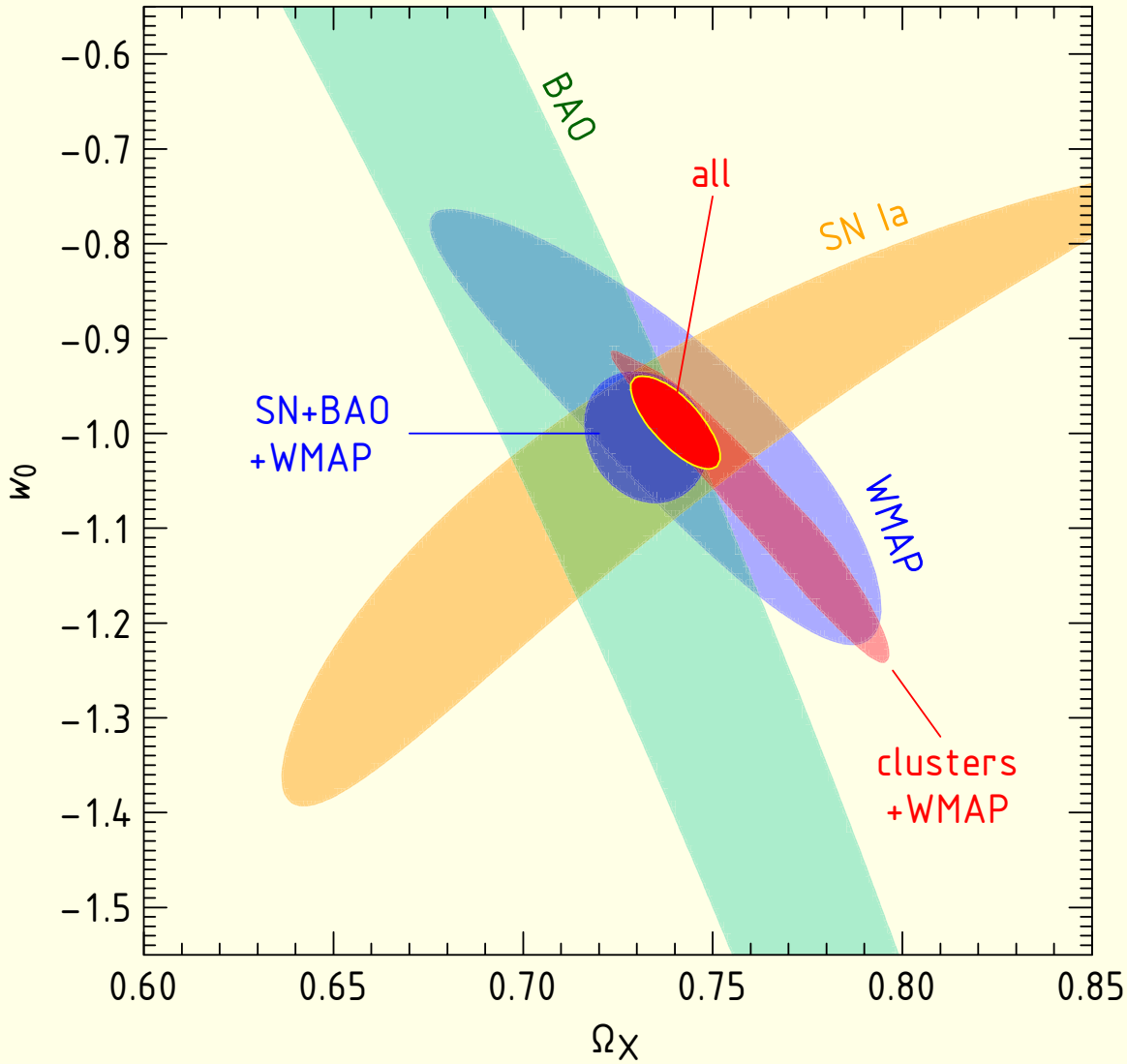
$d(z)$ fixed at concordance cosmology; $D(z)/(1+z) = 1$ for $\Omega_M = 1$

Equation of state constraints



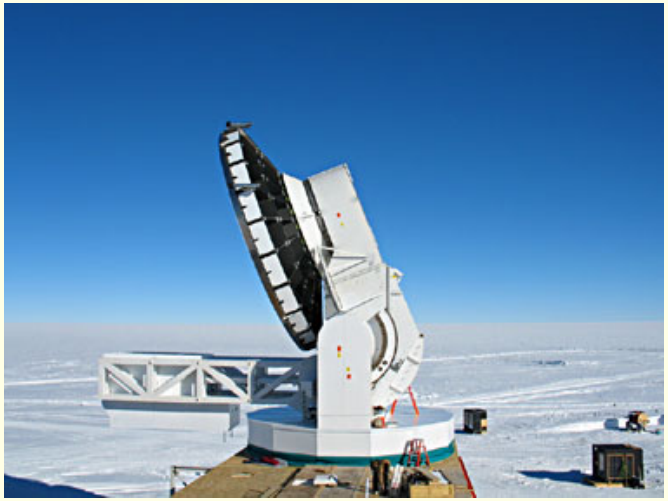
$w_0 = -1.14 \quad \pm 0.21\ (\text{stat}) \quad \pm 0.13\ (\text{sys})$

w_0 constraints

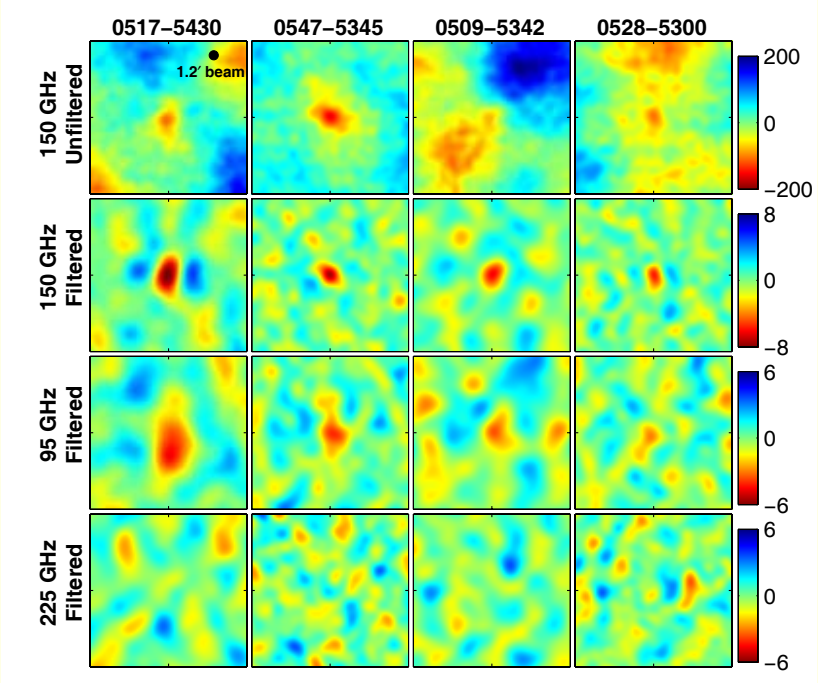


- $w_0 = -0.99 \pm 0.045$ (stat) compare with ± 0.067 without clusters
- More stable to systematics:
  $\Delta w = 0.076$ (SN) $\longrightarrow$ $\Delta w = 0.039$ (0.022 from SN and 0.033 from clusters)

Future projects: SPT (SZ)



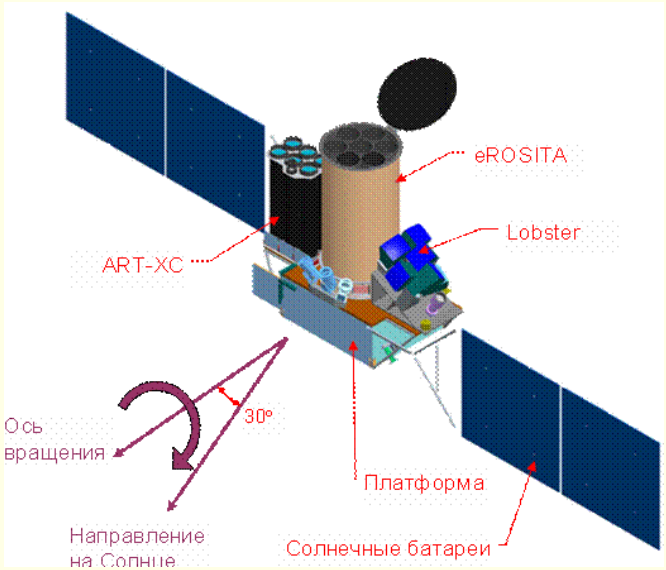
- On-going, first detections published
- 1,000 deg^2 survey

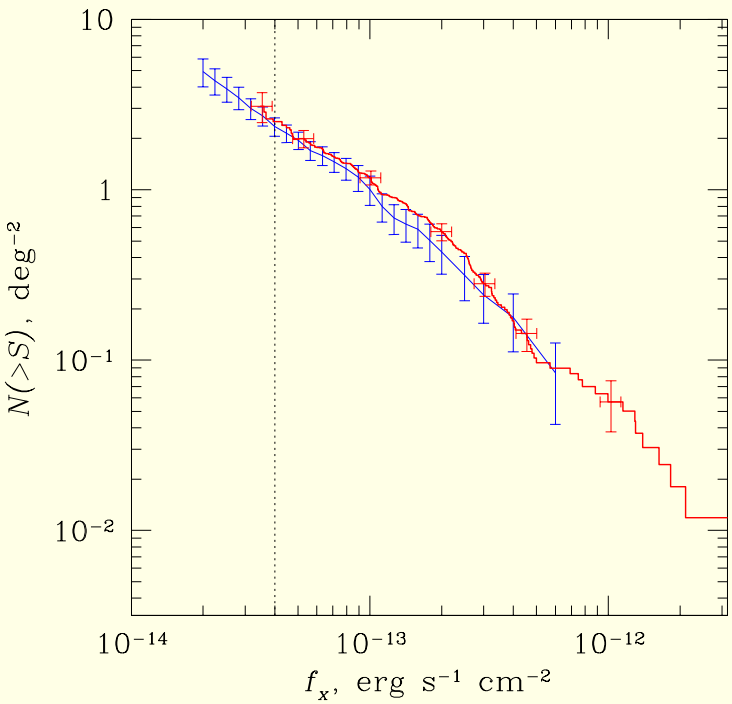


Staniszewski et al. 2008

- 100–1,000 clusters
- $z_{\mathrm{max}} \approx 1 - 2$?

Future projects: SRG/eRosita (X-ray)

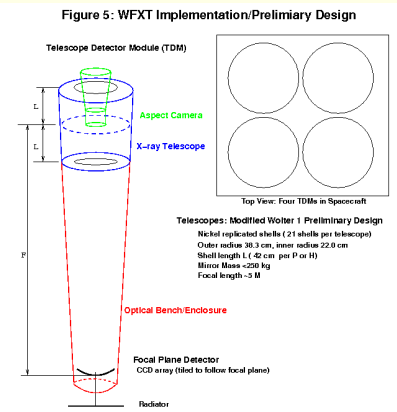


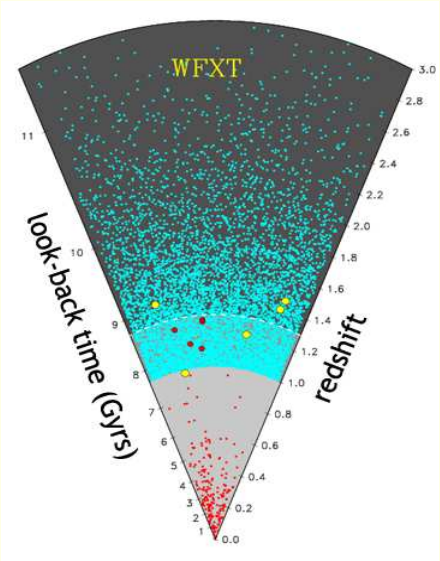


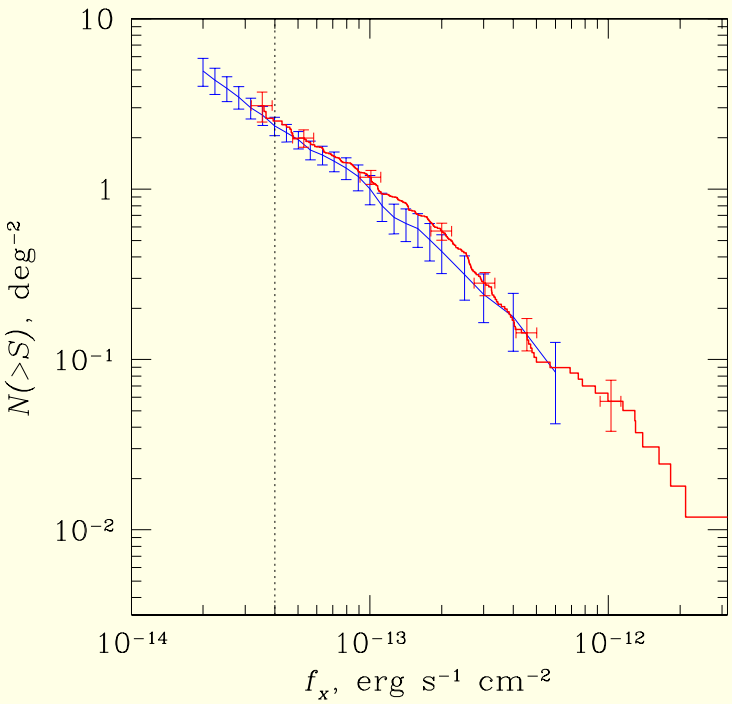
- **Funded, launch in 2012+**
- **Effective area ~ *XMM***
- **Angular resolution ~ *ROSAT***
- **0.5 deg^2 FOV**
- **all-sky survey,**
  $f_{\rm min} = (2-4) \times 10^{-14}$ erg s^{-1} cm^{-2}

- **100,000–200,000 clusters**
- **$z_{\rm max} \approx 1.5$**

Future projects: WFXT (X-ray)



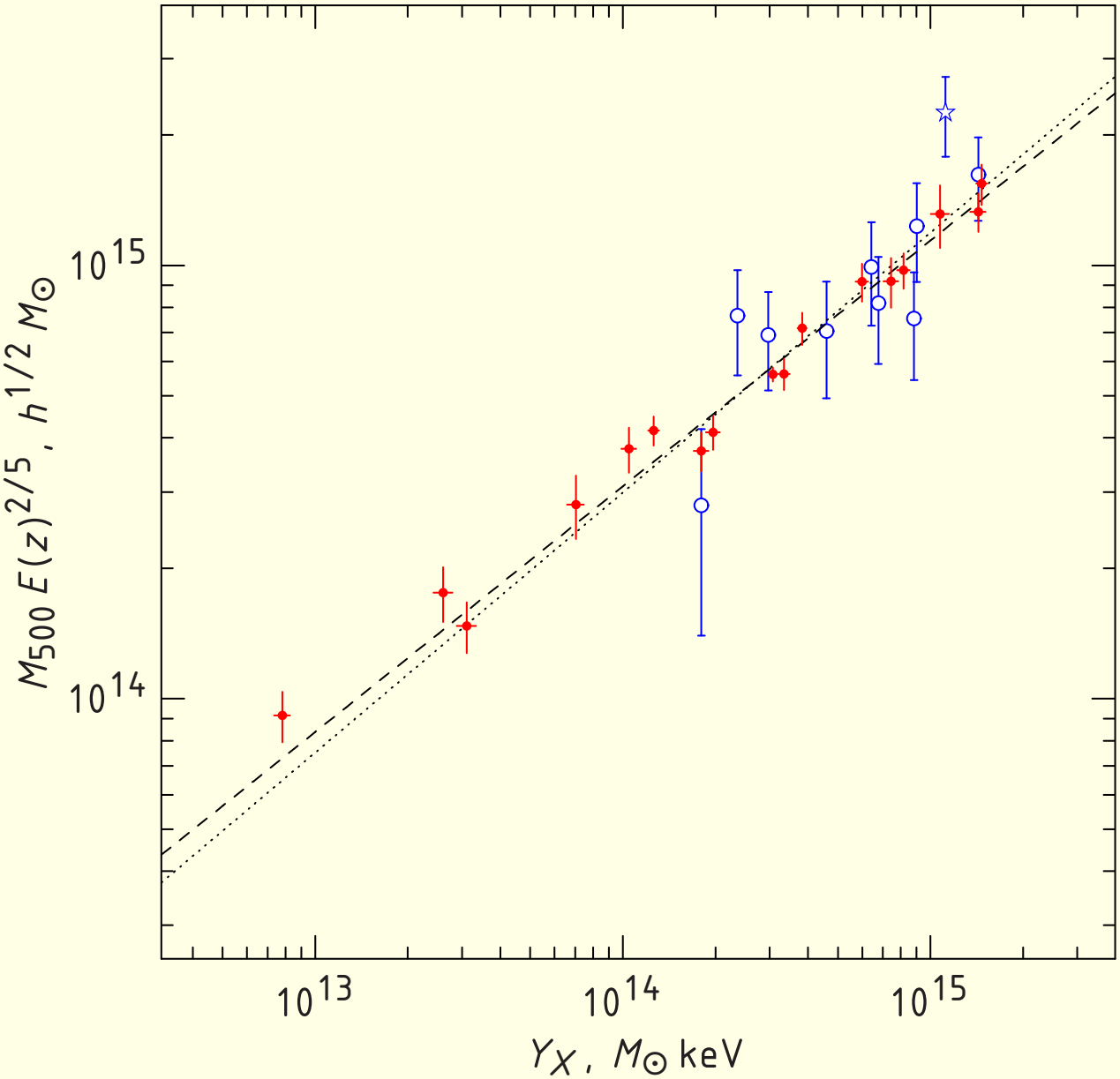




- **Proposed**
- **Effective area ~ *Con-X***
- **Angular resolution ~ *XMM***
- **1 deg^2 FOV**
- **a few × 10^3 deg^2 survey,**
  $f_{\rm min} = 10^{-15}$ erg s^{-1} cm^{-2}

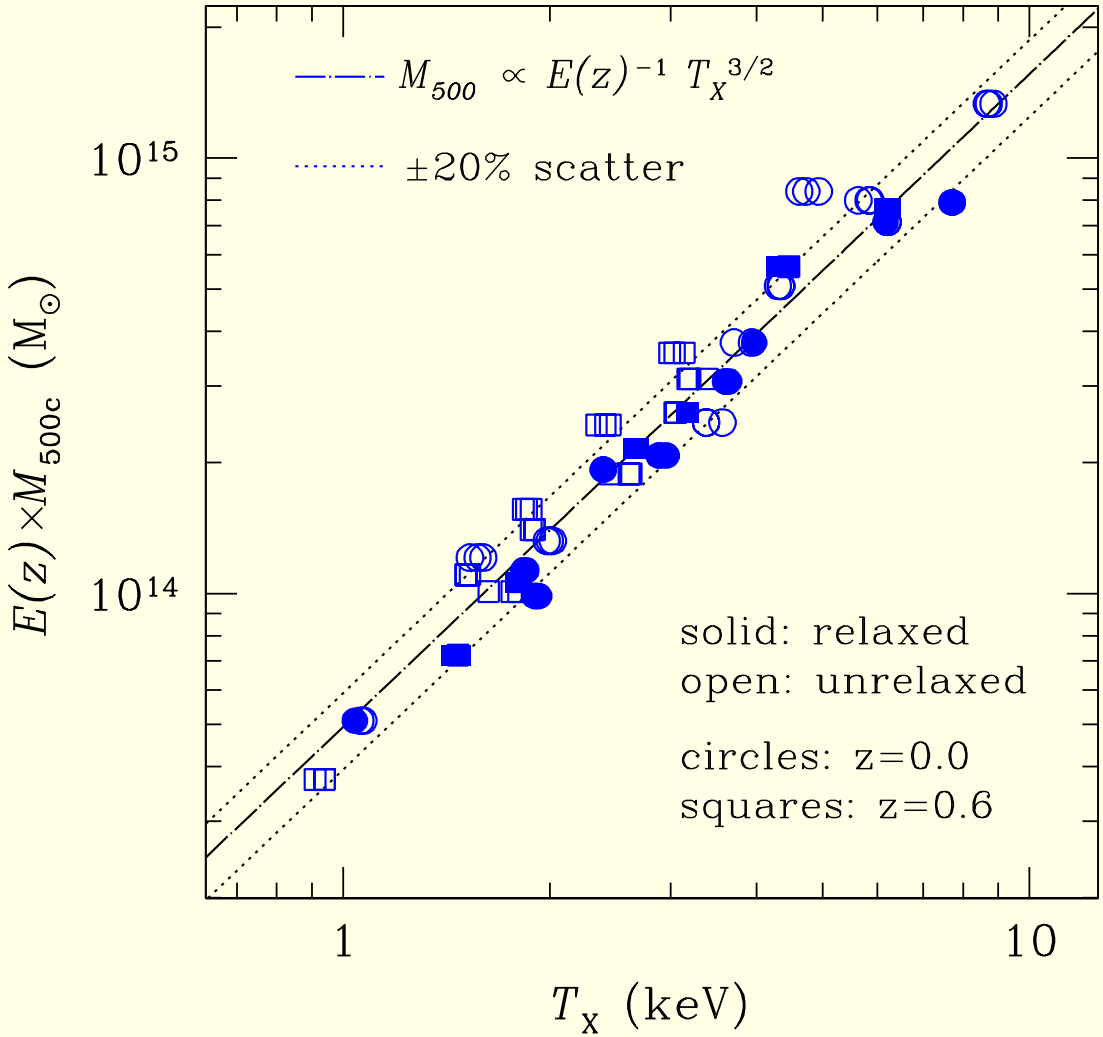
- **$N \gg 10^5$ clusters**
- **$z_{\rm max} > 2$**

Future progress: more weak lensing masses



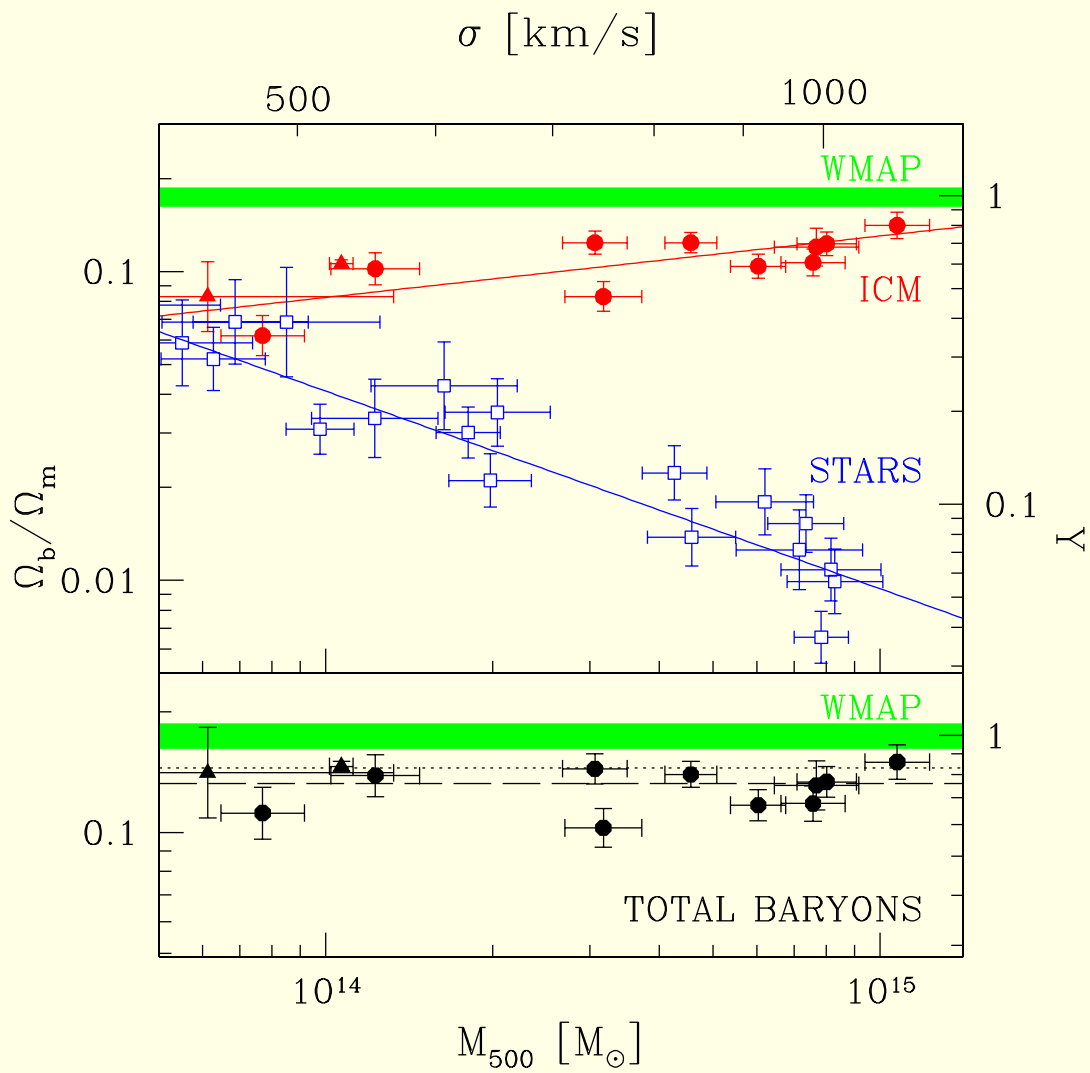
• — *Chandra*, hydrostatic; • — weak lensing, Hoekstra '07;

Small effects in *M*–proxy relations



- ~ 15% offset between relaxed and non-relaxed clusters

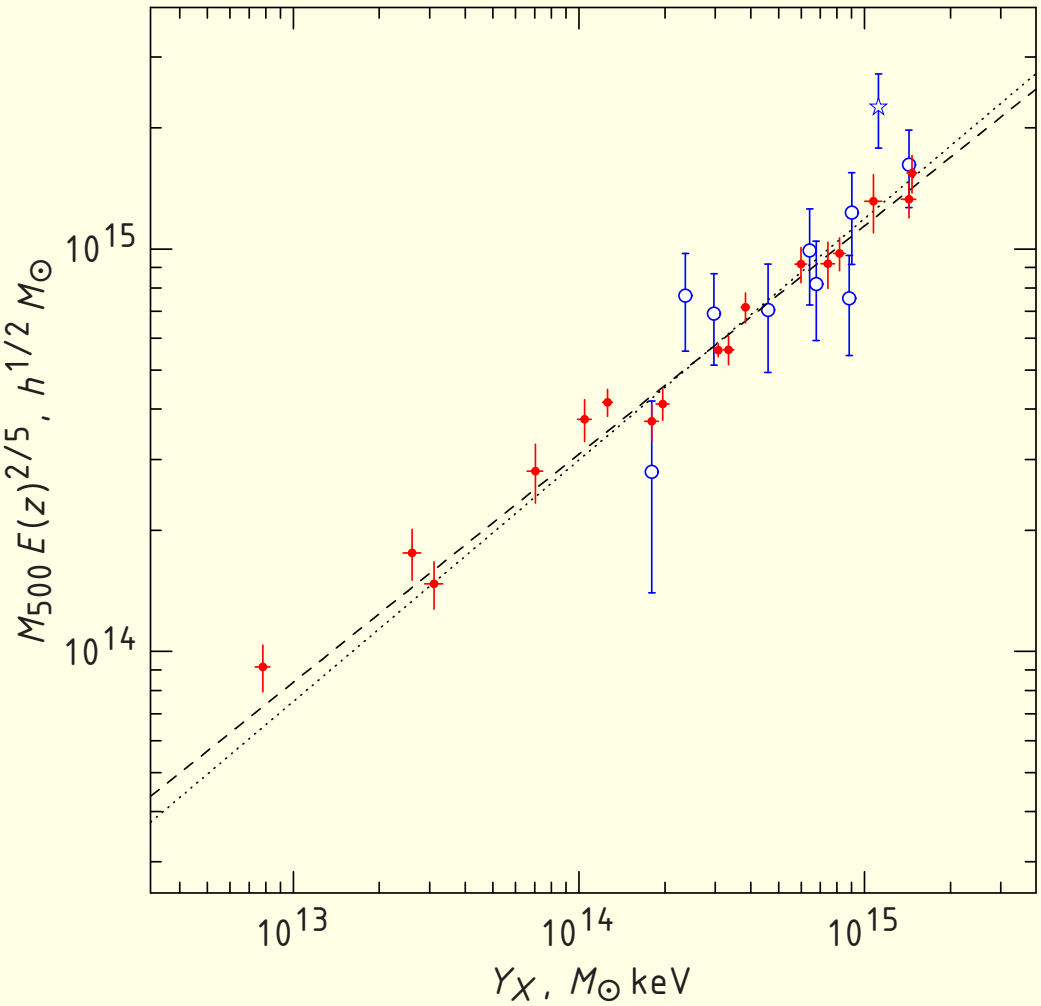
Baryon fraction within clusters and groups

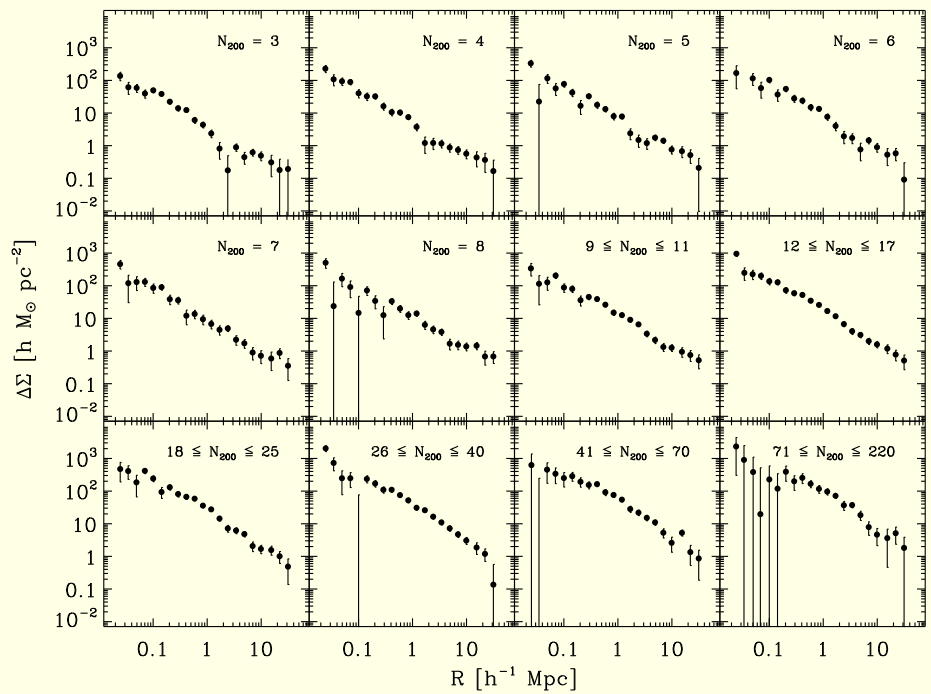


- **Problem: f_g trend, $f_g + f_* < \Omega_b/\Omega_M$**

Gonzalez etal.

Ultimate mass calibration



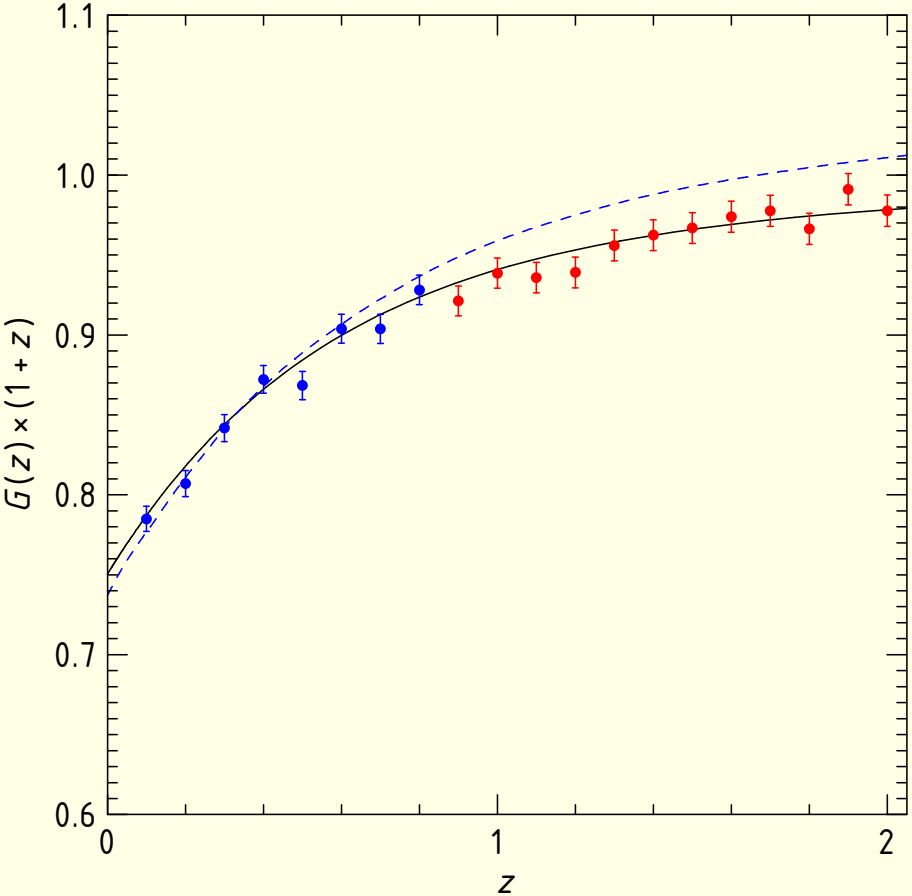


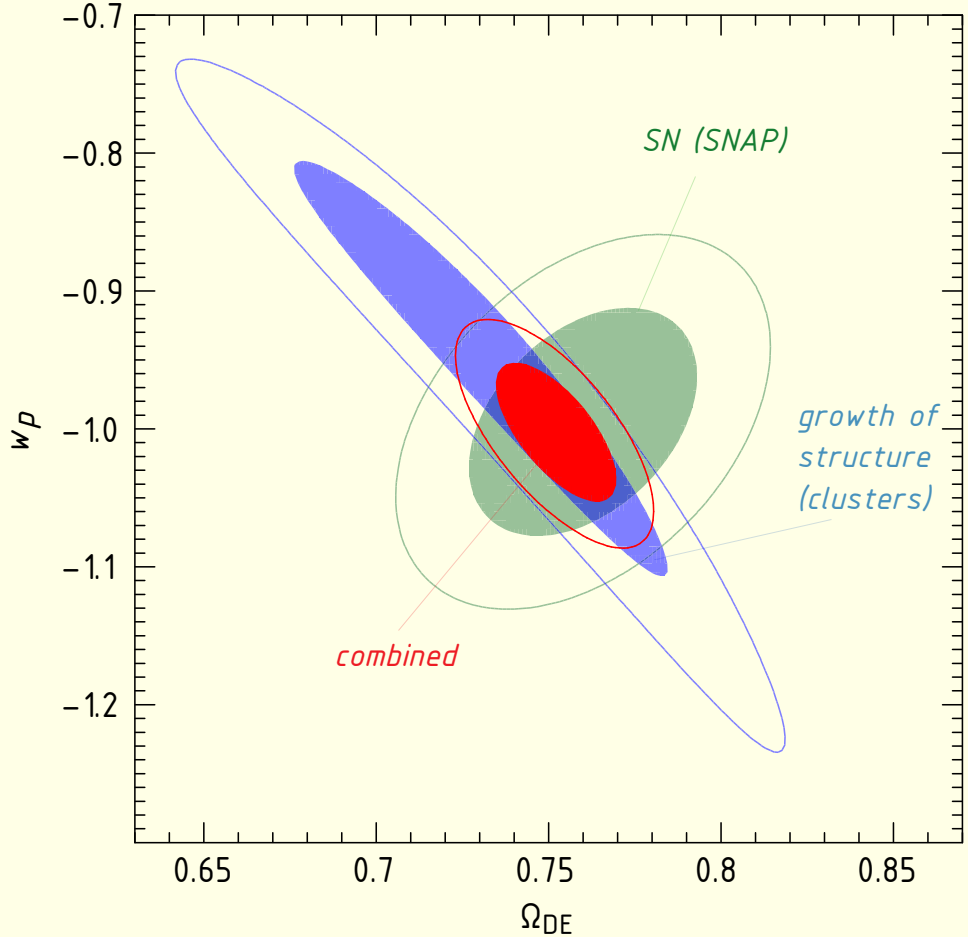
Stacked lensing, SDSS clusters (Sheldon etal)

- **WL — low bias, large scatter; X-rays — low scatter, potential bias**
- **100 clusters with Y_X (*IXO*) and M_{WL}**

$\Longrightarrow$ **3% in $M - Y_X$** $\Longrightarrow$ **1% in growth factor *per bin***

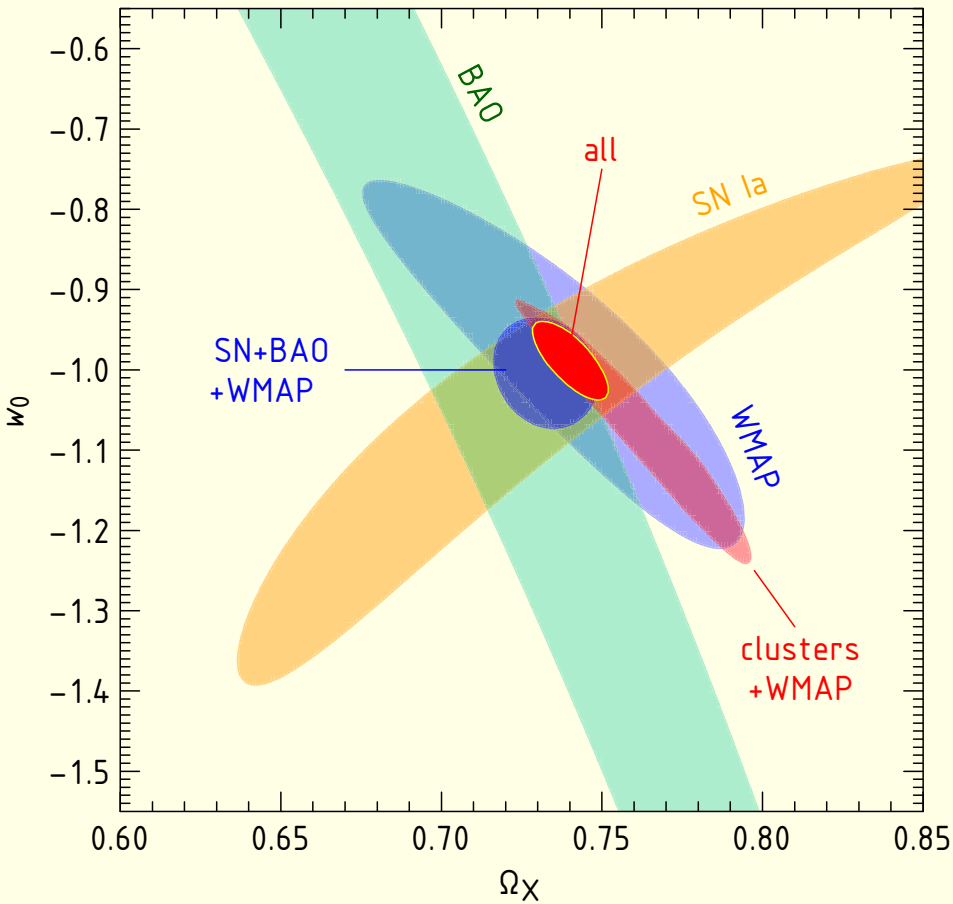
Flavor of results



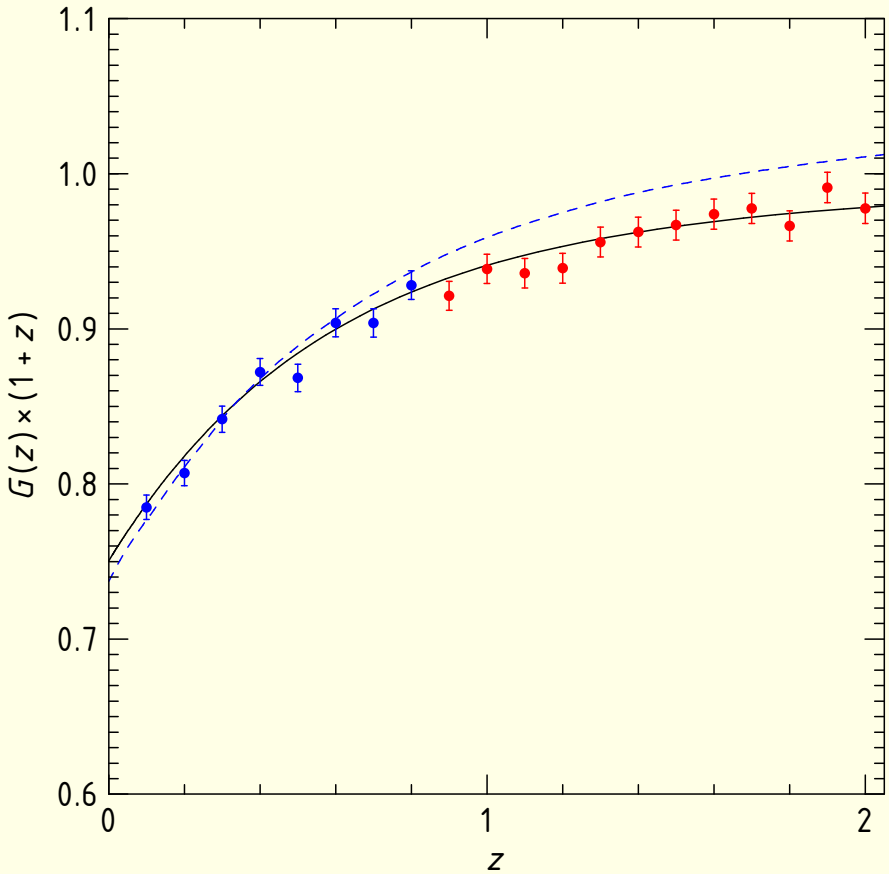


- Measure growth(z) to z = 2
- ~ 2.5-fold improvement for Δw in combination with distance(z)
- Test of non-GR theories

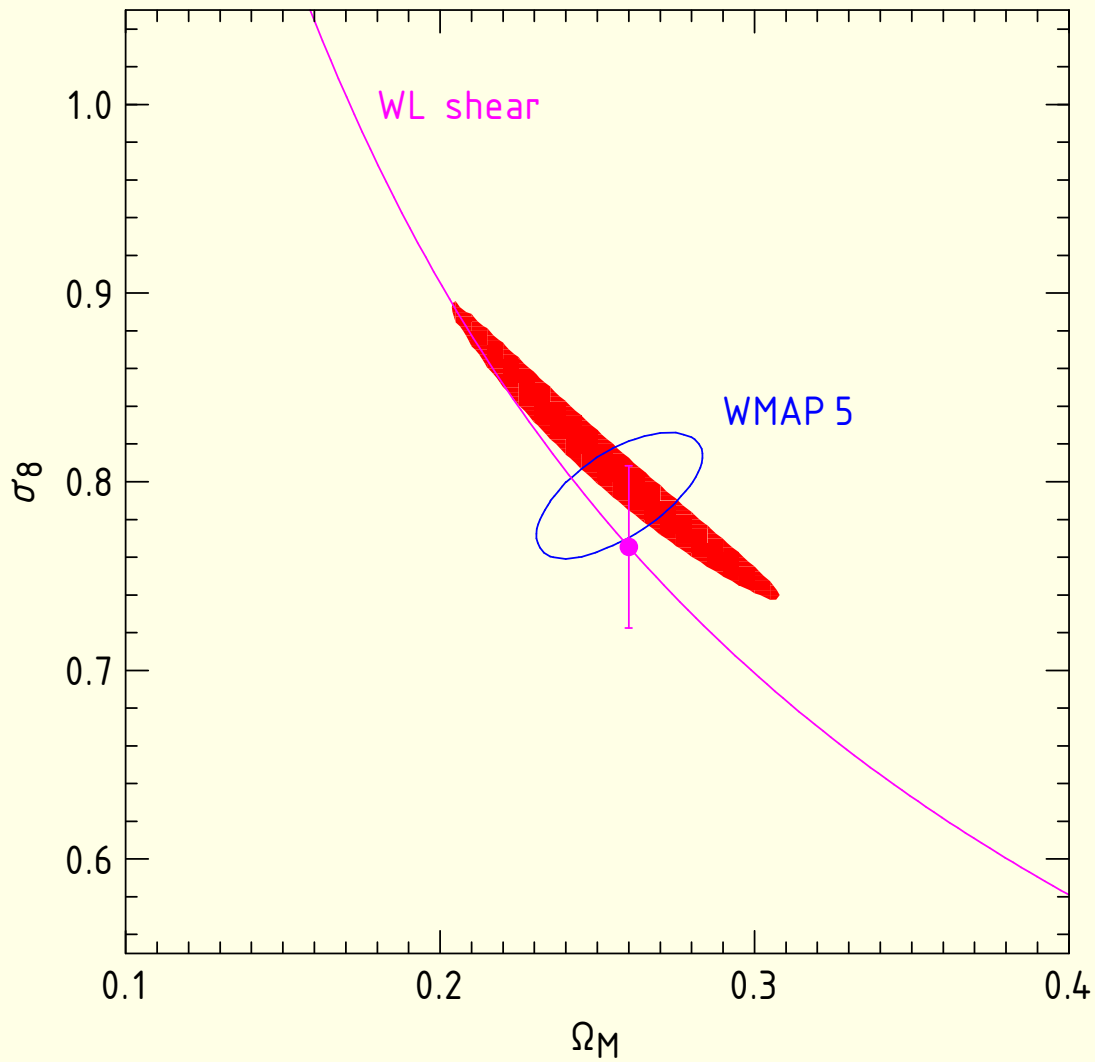
The Present



and The Future

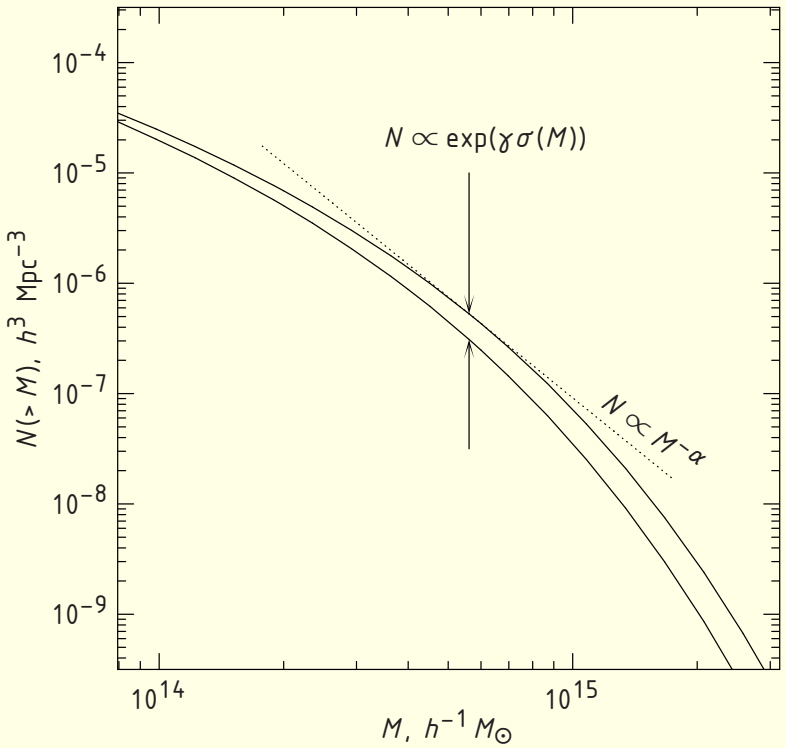


σ_8



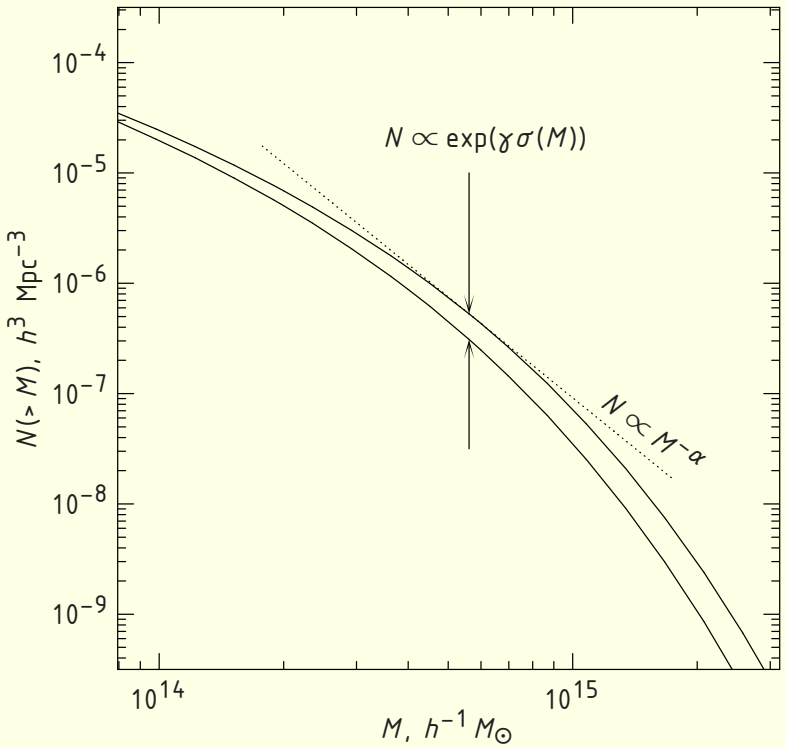
For Ω_M = 0.25: σ_8 = 0.813 ±0.013 (stat) ±0.024 (sys)

Bias and Scatter in M



- $\alpha = 2 - 6$
- $\gamma = (3 - 5) \times \alpha$
- **Rule of thumb:** 5% error in M $\Longrightarrow$ 2% error in growth

Bias and *Scatter* in M

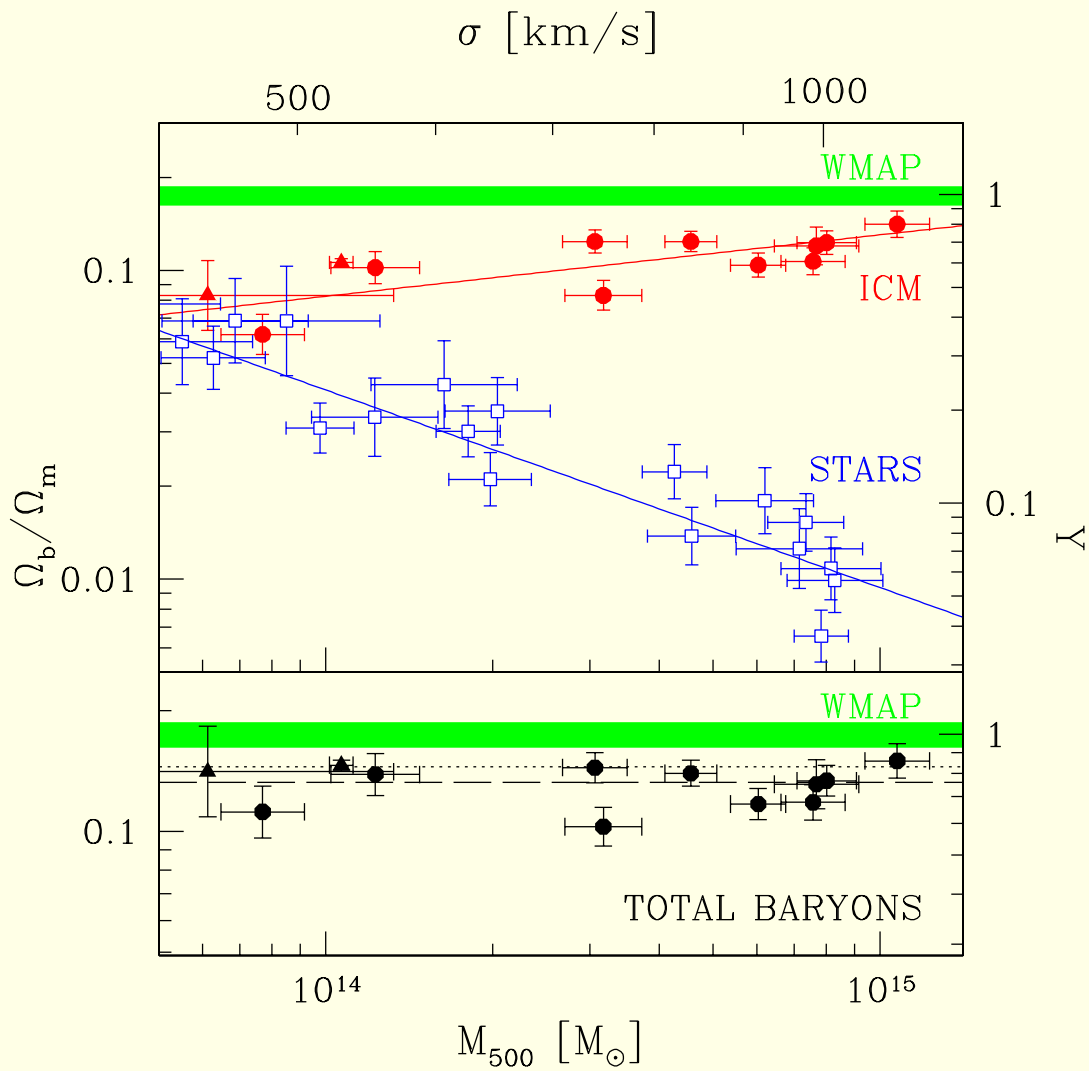


- $M^{-\alpha} \otimes$ log-normal $\delta_{\ln M} \quad \Longrightarrow \quad M^{-\alpha} \times \exp\left(\alpha^2 \delta^2_{\ln M}/2\right)$
- Rule of thumb: need to know $\delta^2_{\ln M}$ to 0.01 $\Longrightarrow$

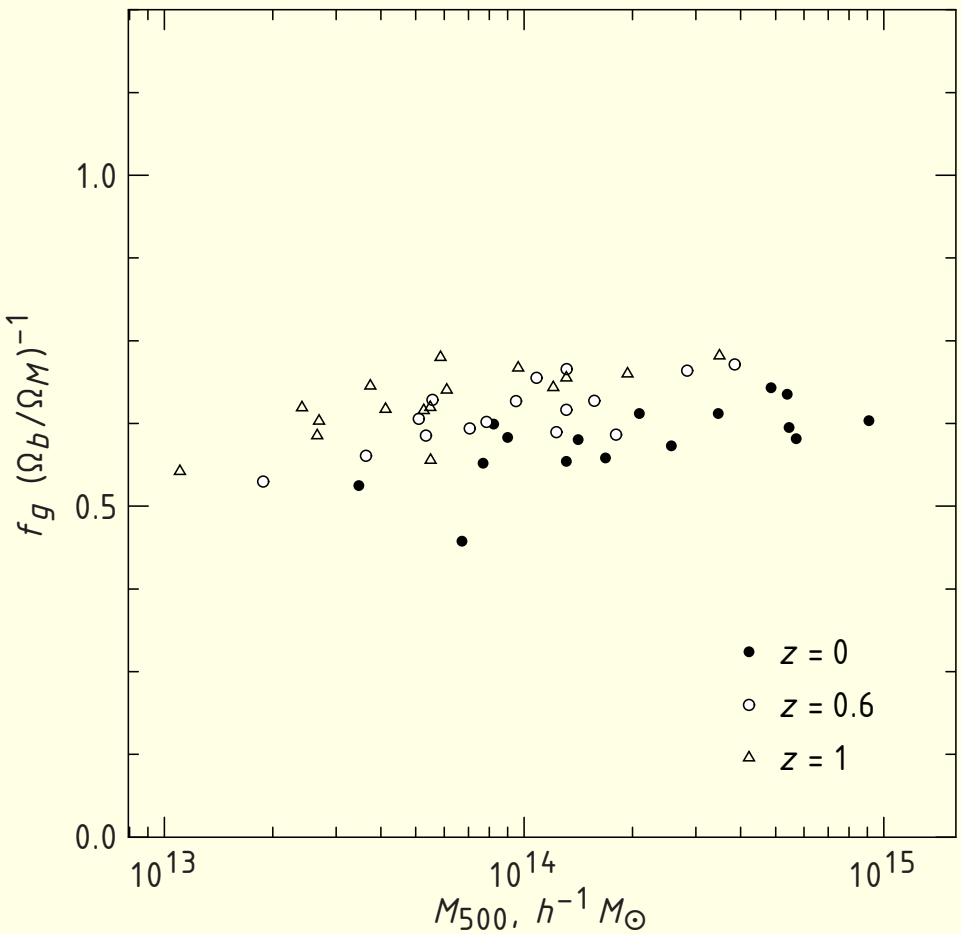
  10% mass proxies are OK, 30% are not.

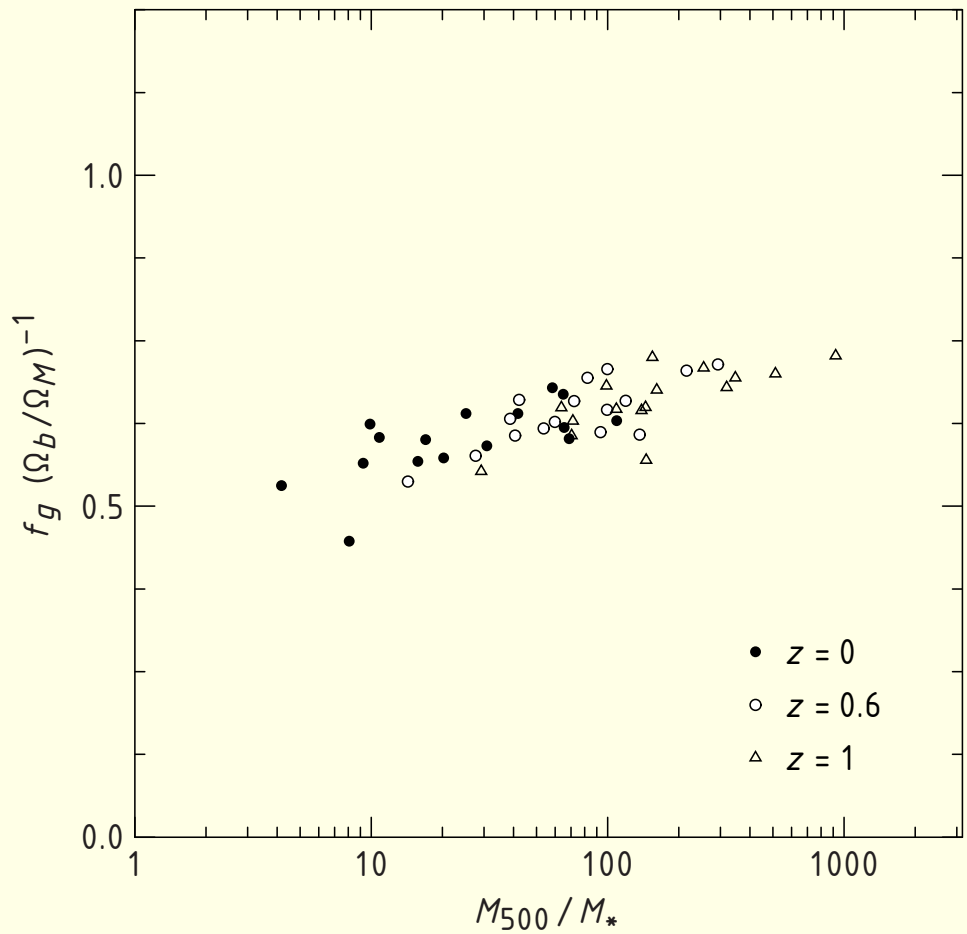
Physics of f_g trend

- In the Kravtsov et al. simulations, $f_g + f_{\rm stars} \approx \Omega_b/\Omega_M$
- Some observational support — Gonzalez et al:



Scaling of $f_g(M, z)$





- $f_g(M, z) = f_g(M/M_*)$
- **Overall correction $\Longrightarrow$ 11% in M at $z = 0.5$**
- **Estimated systematic errors — 5% in M at $z = 0.5$**