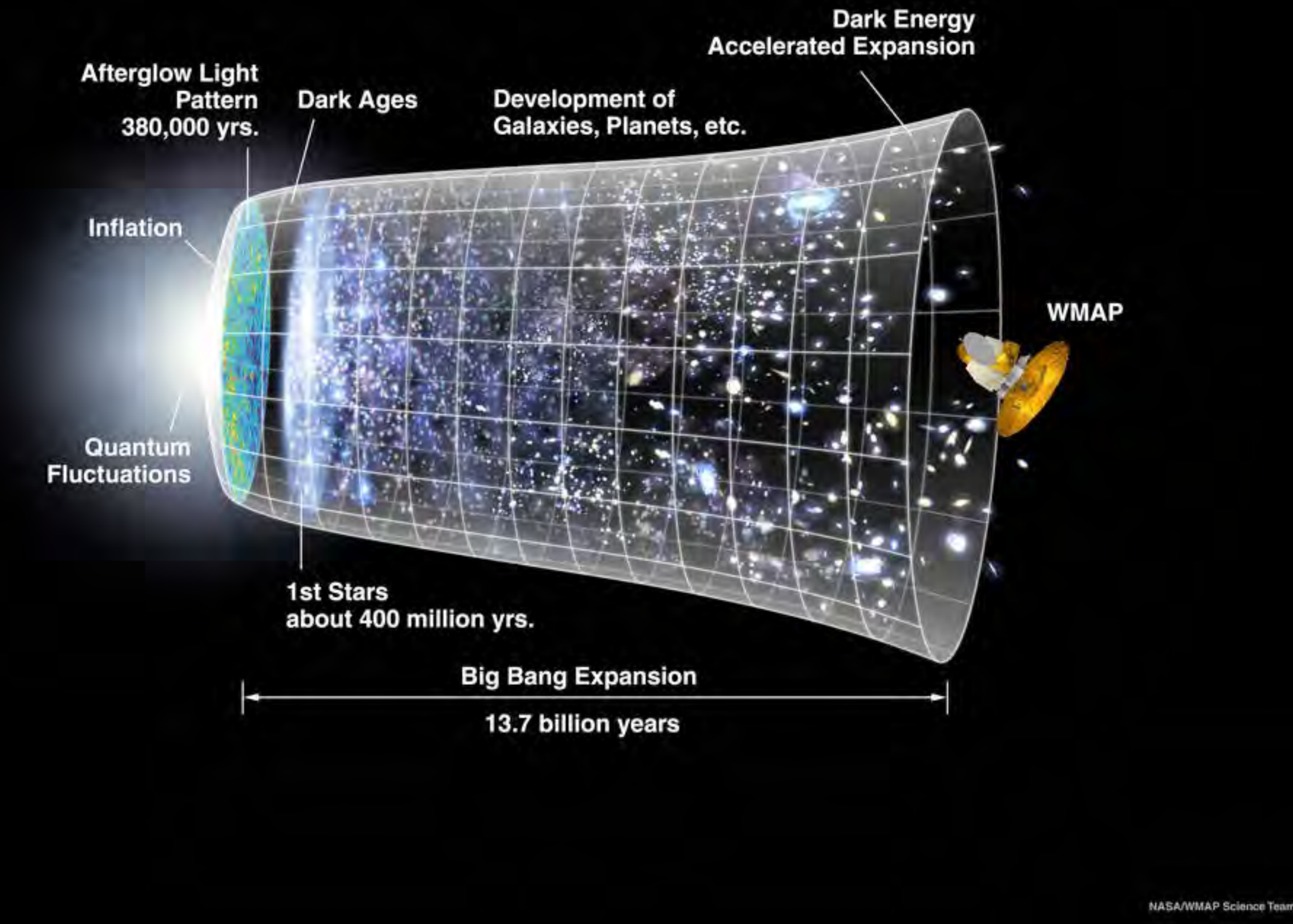
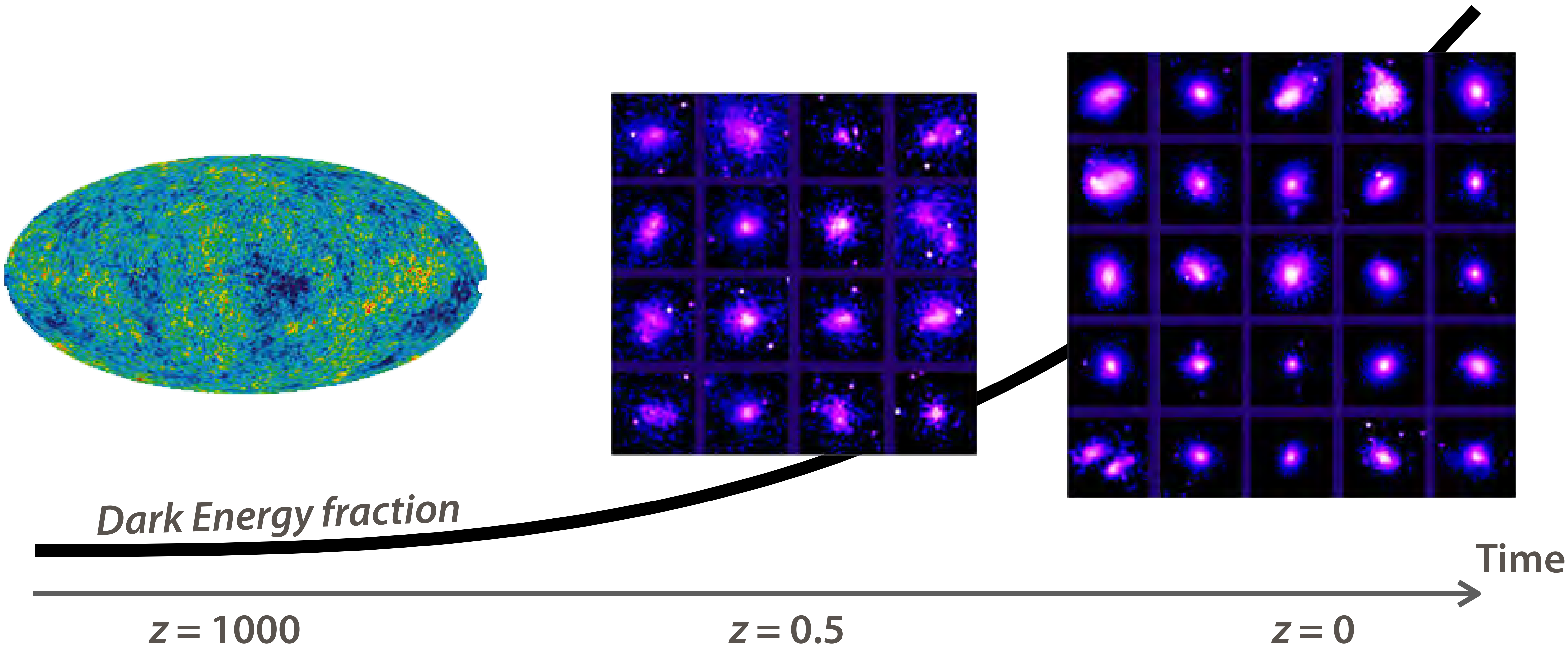
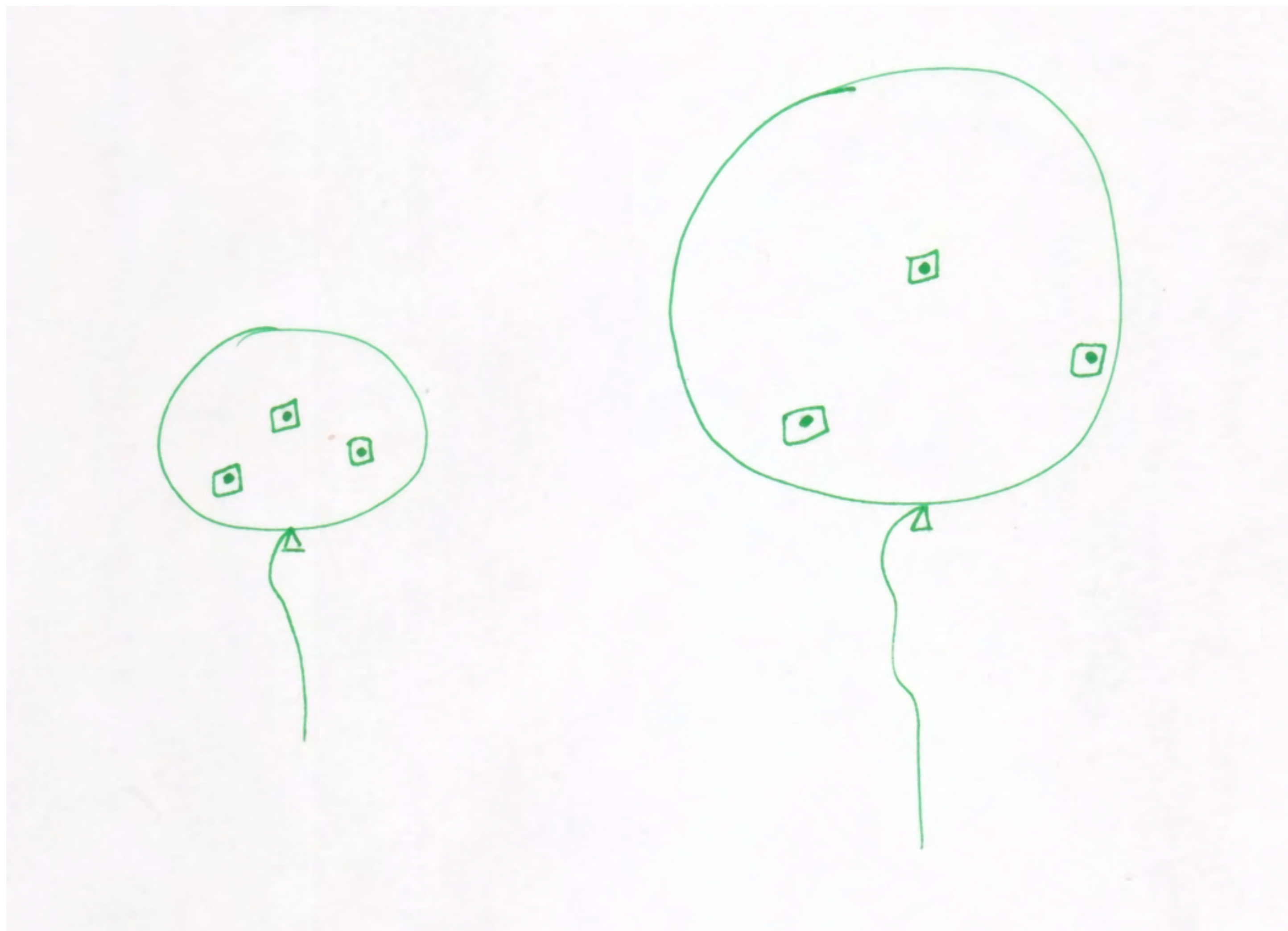

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

Cosmological applications of galaxy clusters



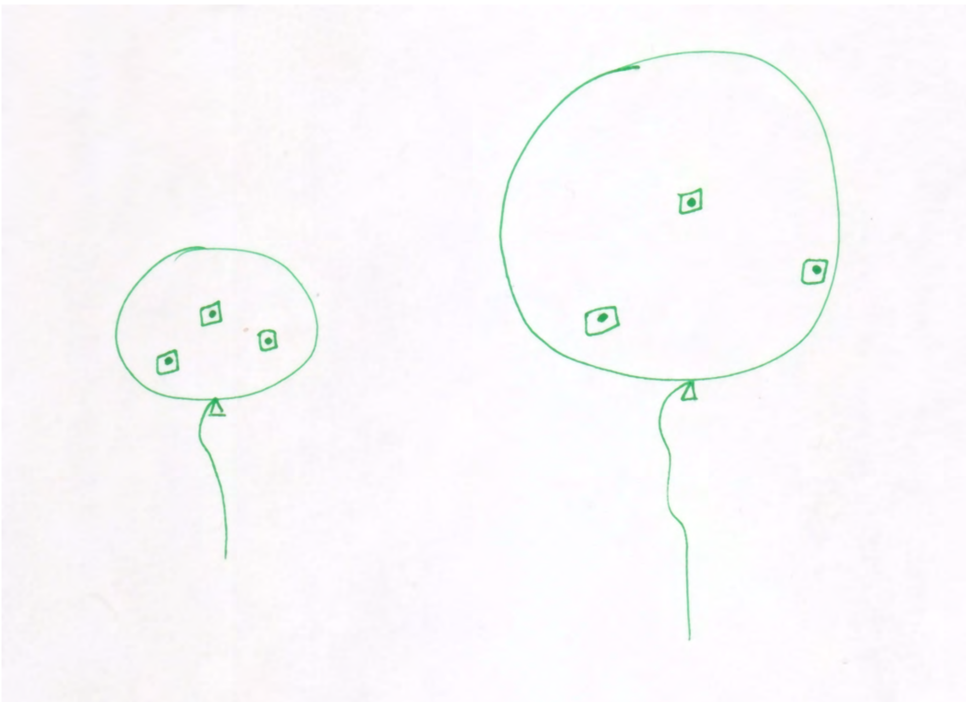
- How does emergence of galaxy clusters reflect the growth of large-scale structure of the Universe at late times?
- What is the current state-of-the-art in finding galaxy clusters and using them for cosmological measurements?
- What are the prospects and unsolved issues for the future?

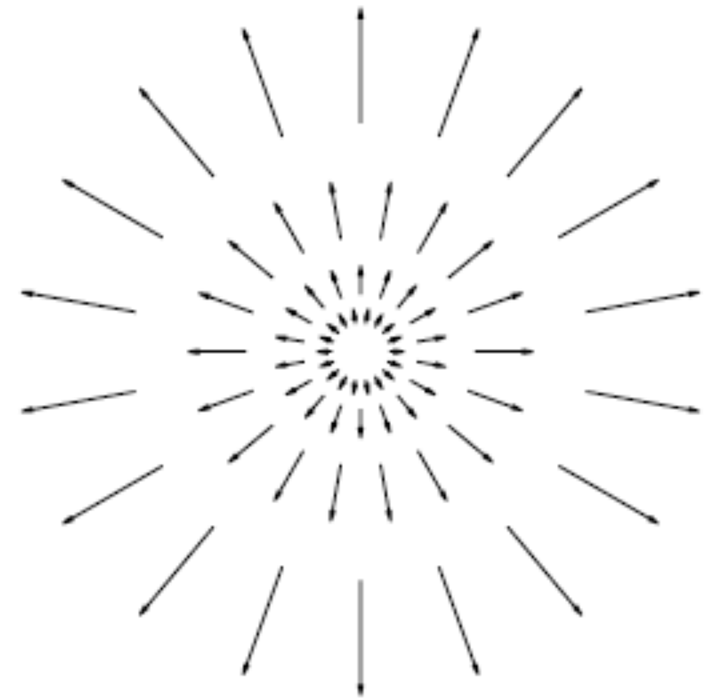
Expansion of the Universe



If the expansion is uniform, $dD/dt \sim D$ at all times. That's the Hubble law.

Expansion of the Universe





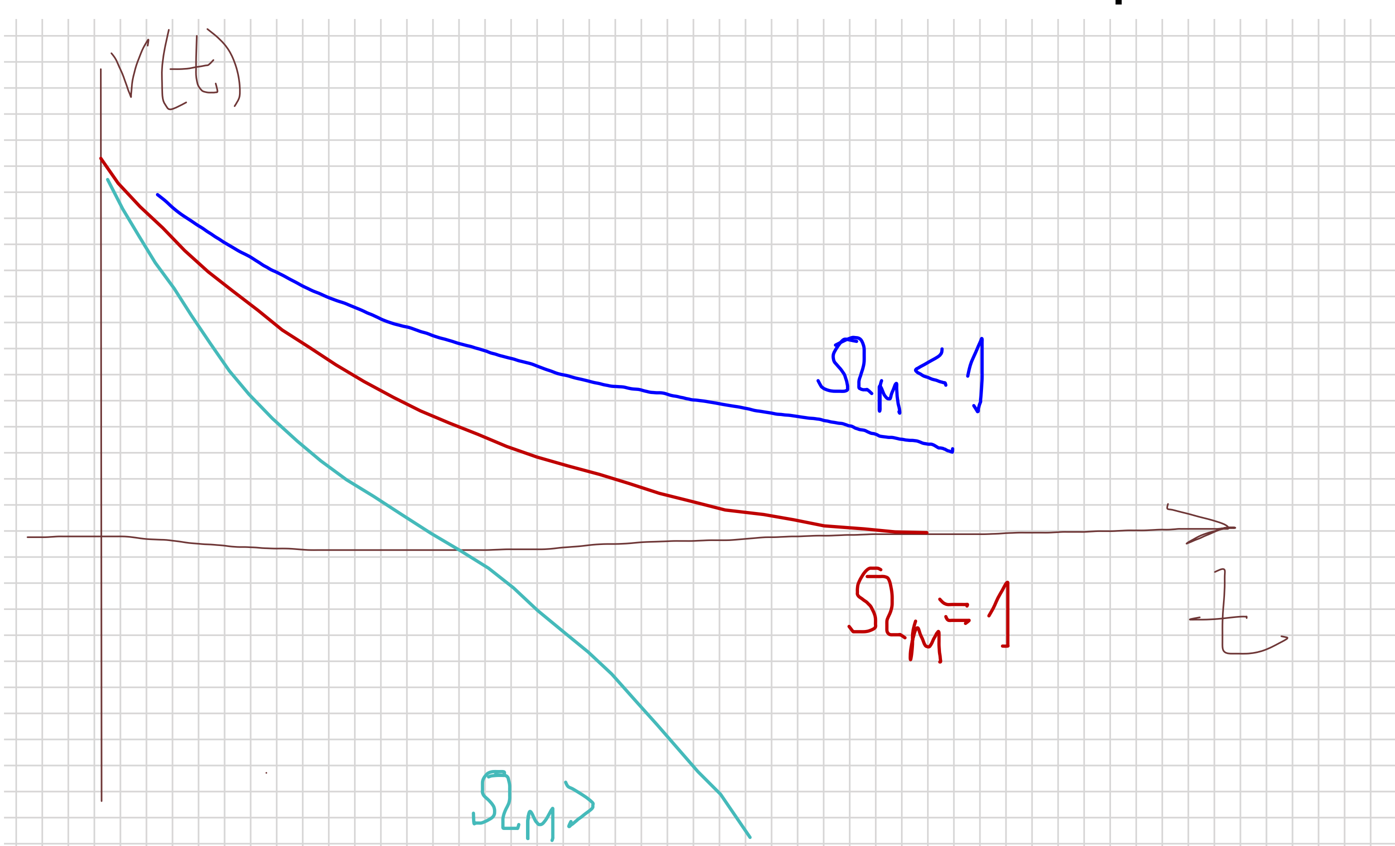
Evolution of the Universe [$R(t)$] is equivalent to the evolution of a ball under self-gravity

$$V = H \times R$$

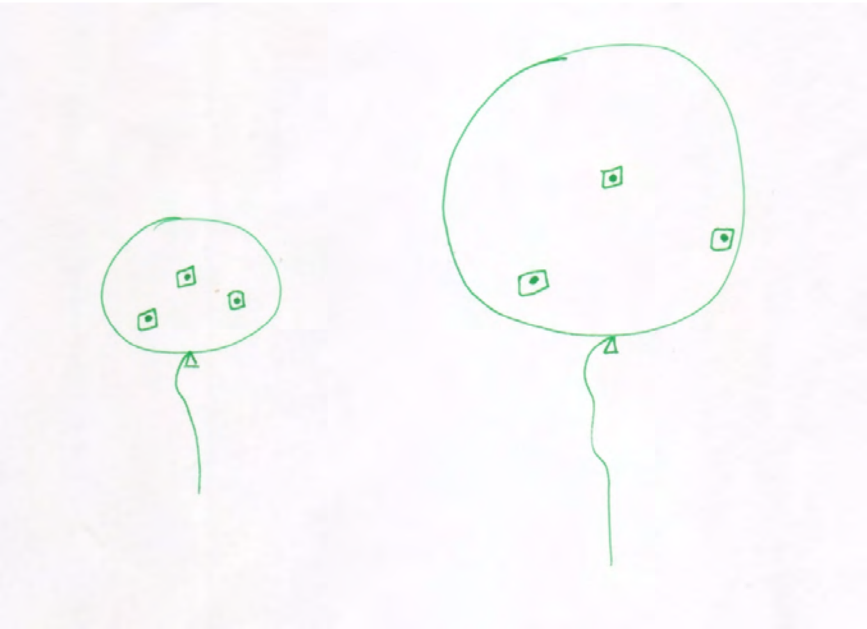
$G\, M^2/R > M\, V^2$

$G\, M^2/R > M\, H^2\, R^2$

$G\, \rho/H^2 > 1$ — the ball recollapses. Equivalent to the $\Omega_M > 1$

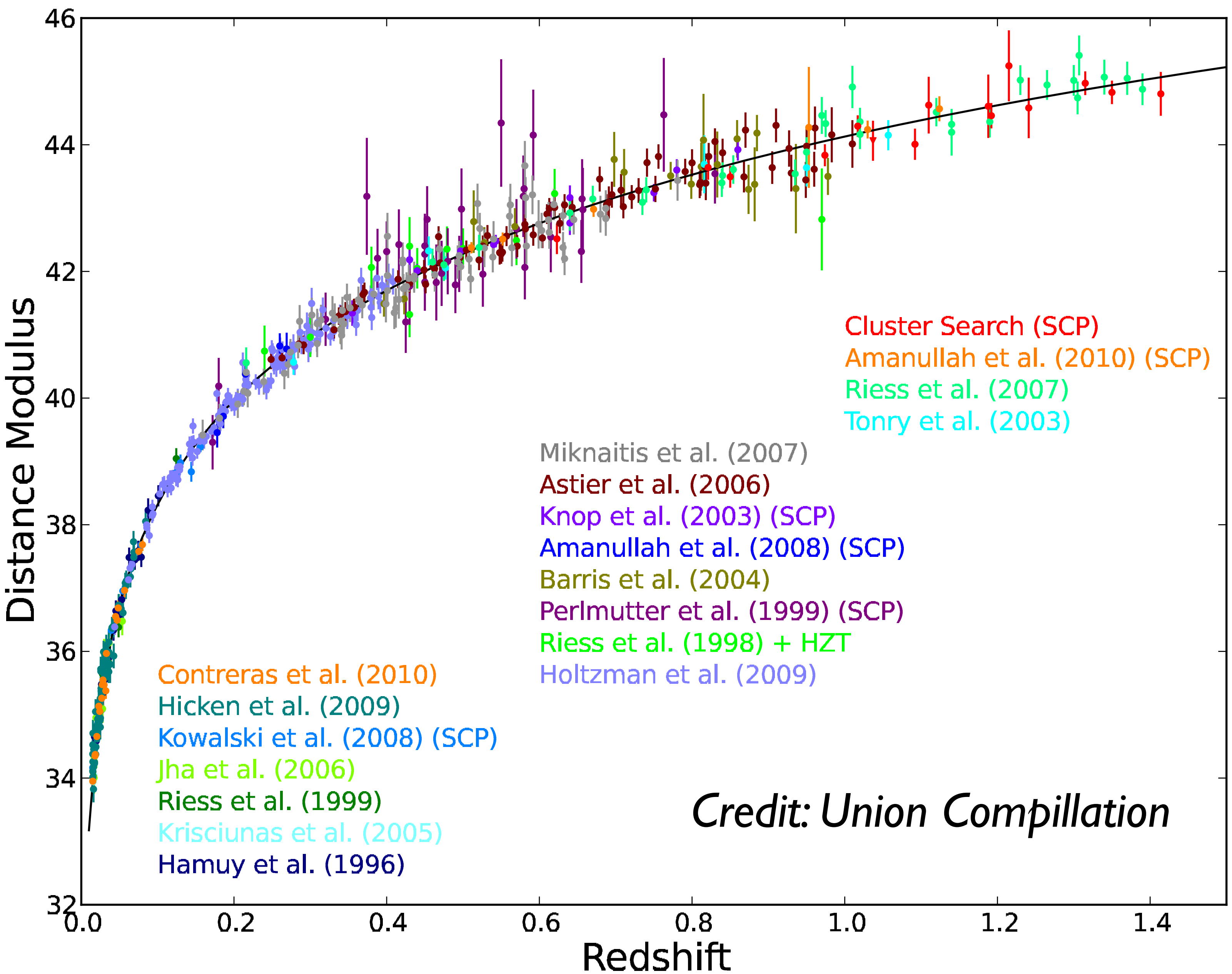


How do we know that the Universe is accelerating?

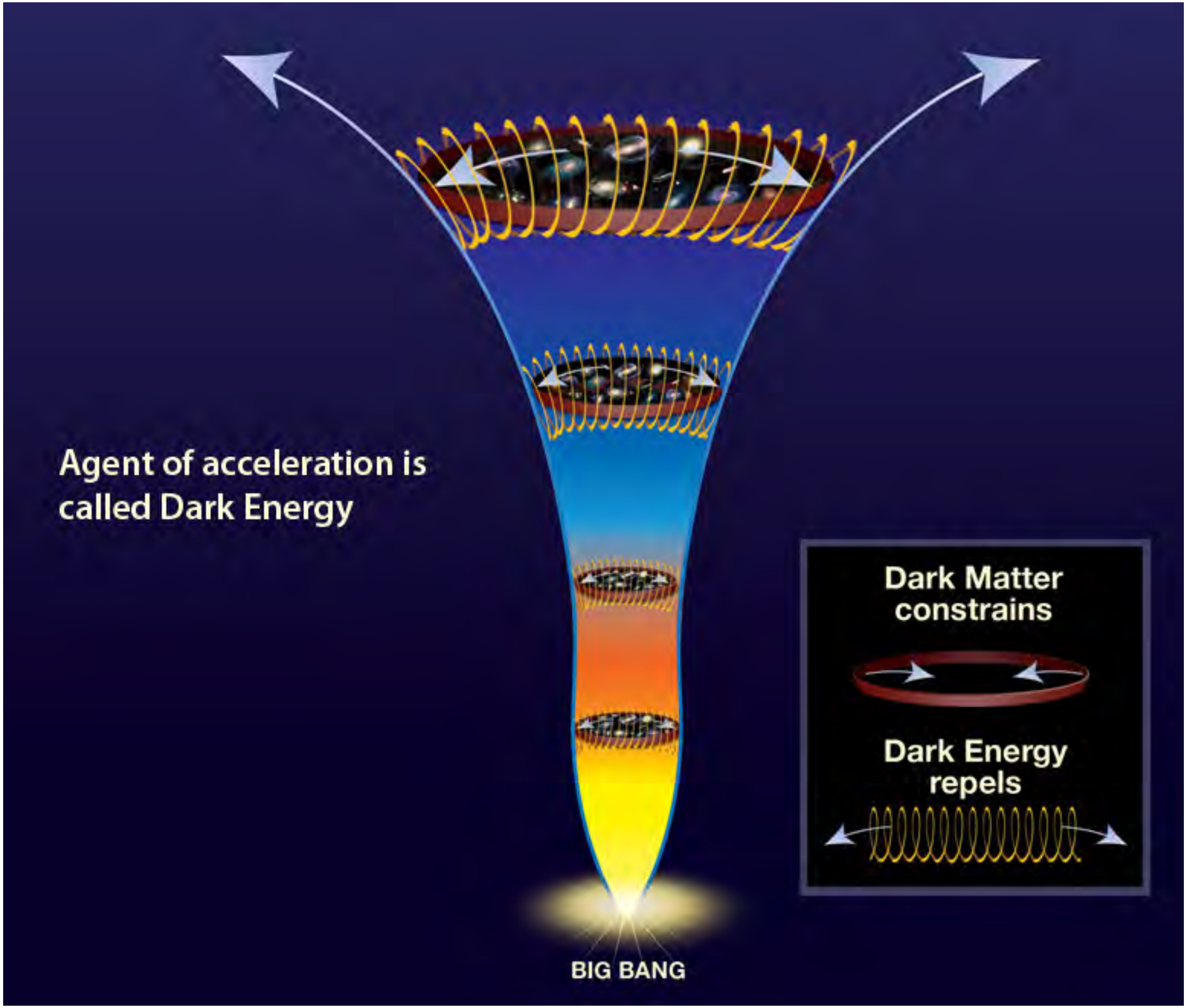


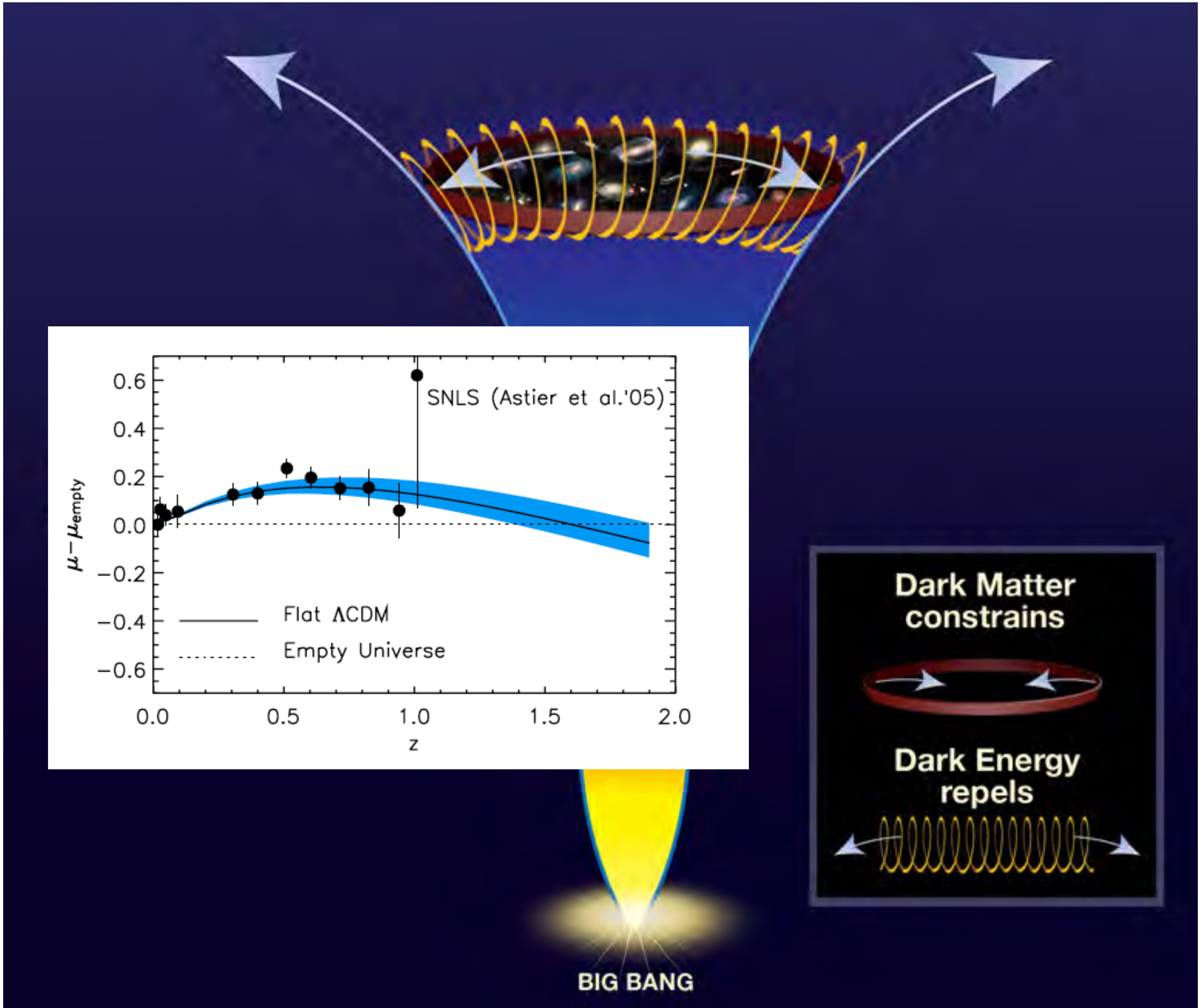
Expansion history of the Universe [$R(t)$] can be recovered by observations of distances to objects at high z

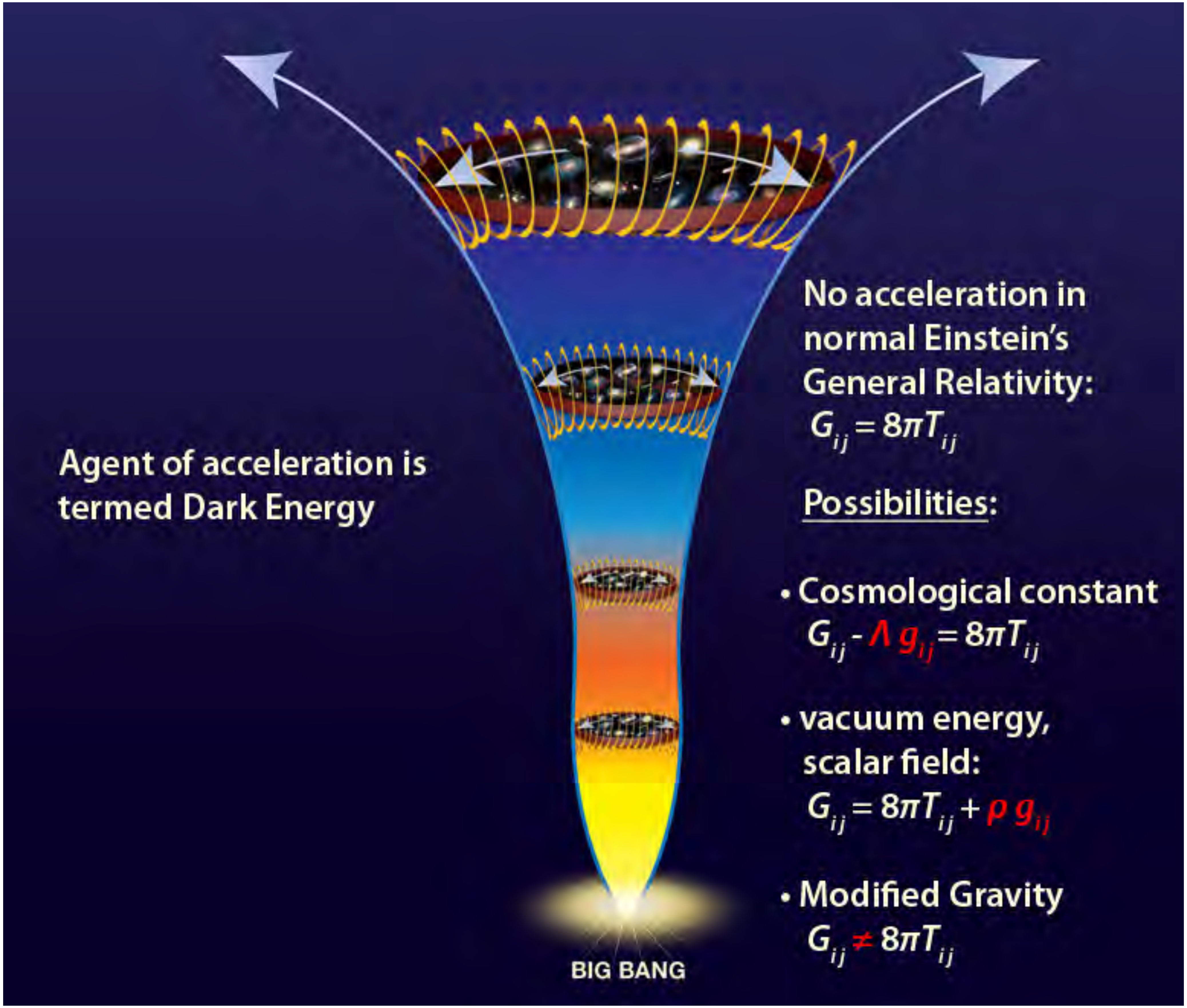
$R(t) \sim (1+z)^{-1}$



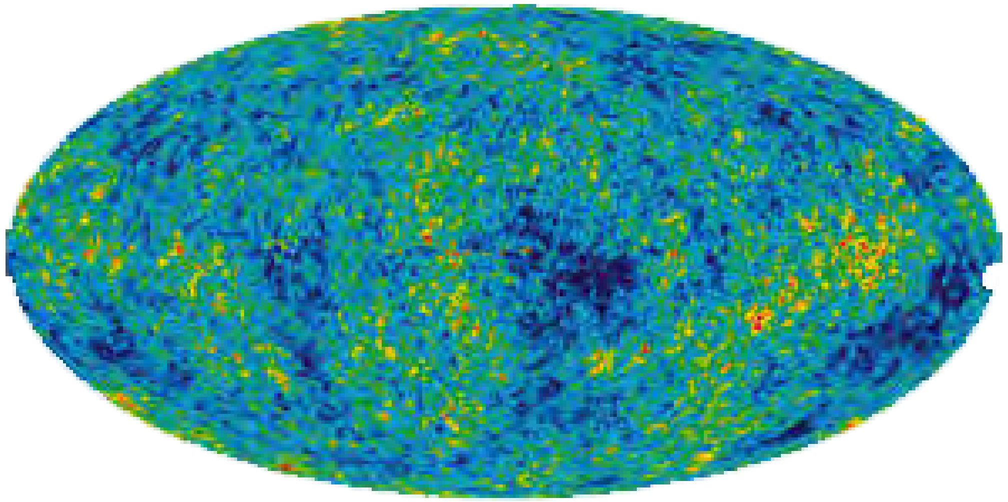
Cosmic acceleration discovered by observations of supernovae implies that $V(t)$ approaches a constant value instead of ever declining

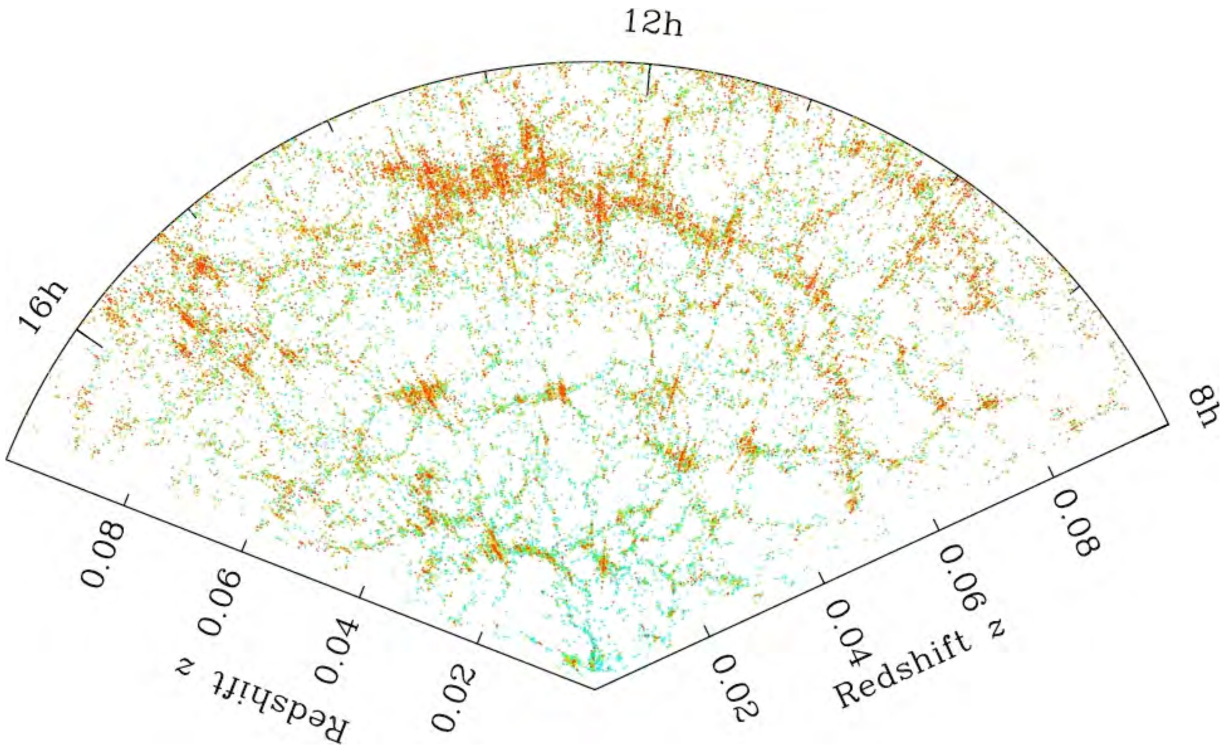

Agent of acceleration is called Dark Energy
Dark Matter constrains
Dark Energy repels
BIG BANG


SNLS (Astier et al.'05)
$\mu - \mu_{empty}$
z
Flat ΛCDM
Empty Universe
Dark Matter constrains
Dark Energy repels
BIG BANG


No acceleration in normal Einstein's General Relativity:
$G_{ij} = 8\pi T_{ij}$
Agent of acceleration is termed Dark Energy
Possibilities:
• Cosmological constant
$G_{ij} - \Lambda g_{ij} = 8\pi T_{ij}$
• vacuum energy, scalar field:
$G_{ij} = 8\pi T_{ij} + \rho g_{ij}$
• Modified Gravity
$G_{ij} \neq 8\pi T_{ij}$
BIG BANG

How do we know that the structure grows?





t = 13.5 bln years ago
Cosmic Microwave Background
$\Delta T/T \sim 10^{-5}$

Today
Distribution of galaxies
$\Delta\rho/\rho \sim 1$

Gravitational instability: Jeans' theory

- Applies to self-gravitating, stationary, infinite medium
- Exponential growth of linear perturbations with the time constant

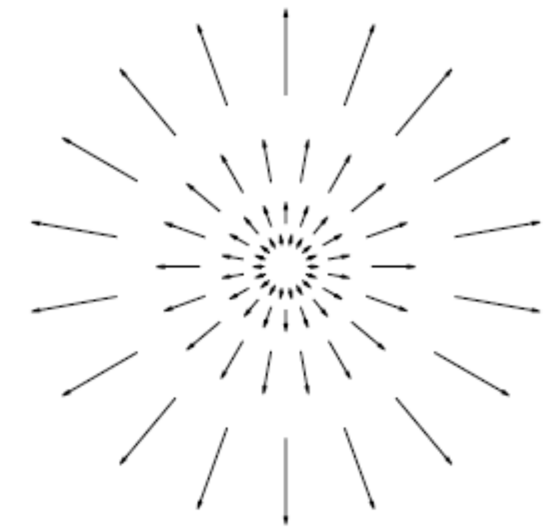
$$\tau = \frac{i}{\sqrt{k^2 c_s^2 - 4\pi\rho_0 G}}$$

- Short-wavelength modes are stabilized by pressure. Gas pressure is unimportant for

$$\lambda \gg \lambda_J = c_s \sqrt{\frac{\pi}{G\rho_0}}$$

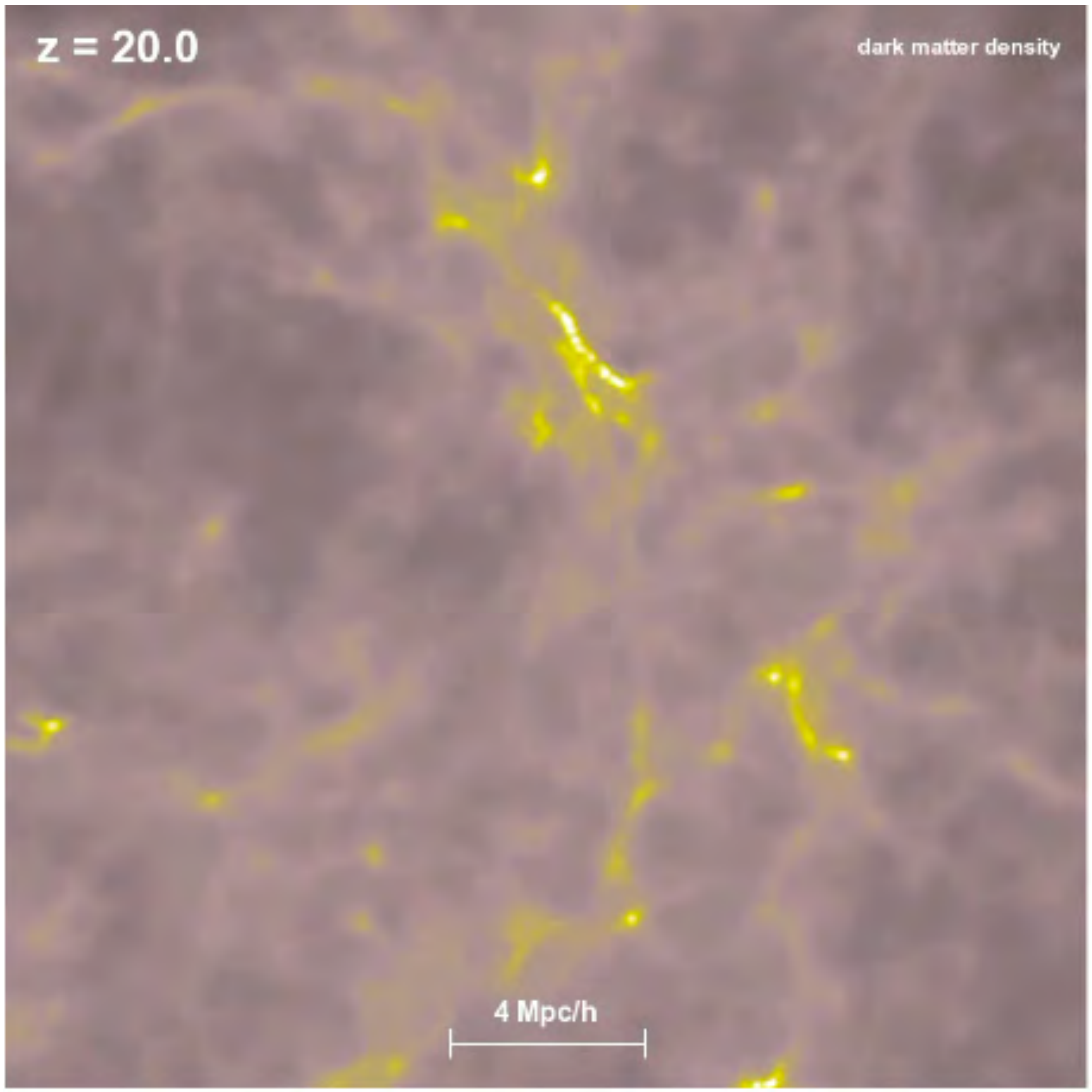
- Qualitatively different growth in expanding Universe, but still useful (synchronous growth for dust-like matter; size of the first baryonic structures, etc.)

Structure growth theory: linear regime

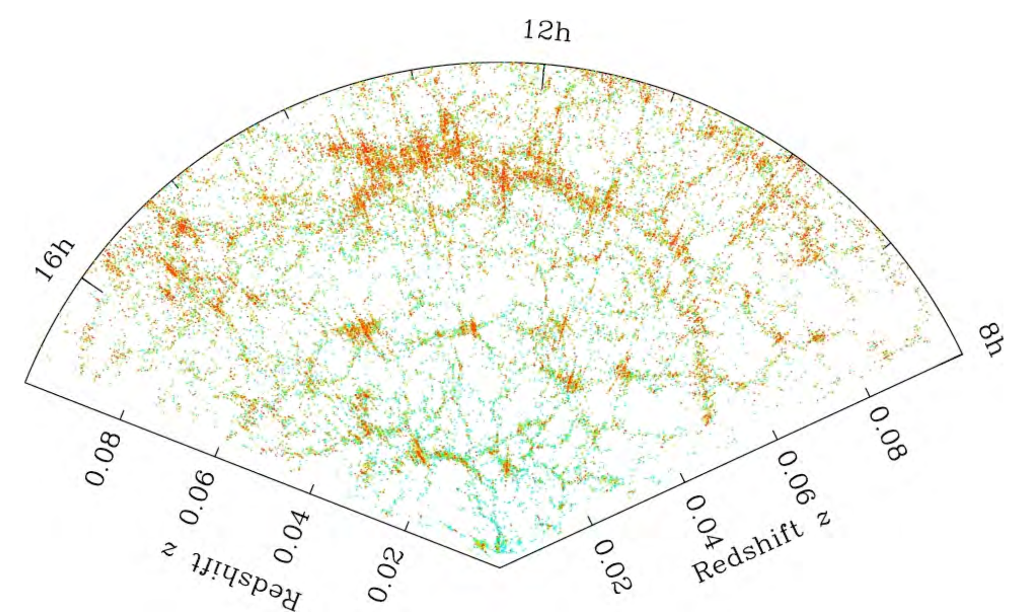


- Expanding background essential. Problem solved by worki
  in comoving coordinates
- Linear growth preserves perturbations' shape
- Amplitude follows $\ddot{\delta} + 2H\dot{\delta} - 4\pi G\langle\rho\rangle\delta = 0$
- With high precision, (power law type) $$\frac{d\ln\delta}{d\ln(1+z)} = -\Omega_M(z)^{0.55}$$
- δ ~ 1/(1+z) at high *z*, growth suppressed as the Universe enters the accelerating phase

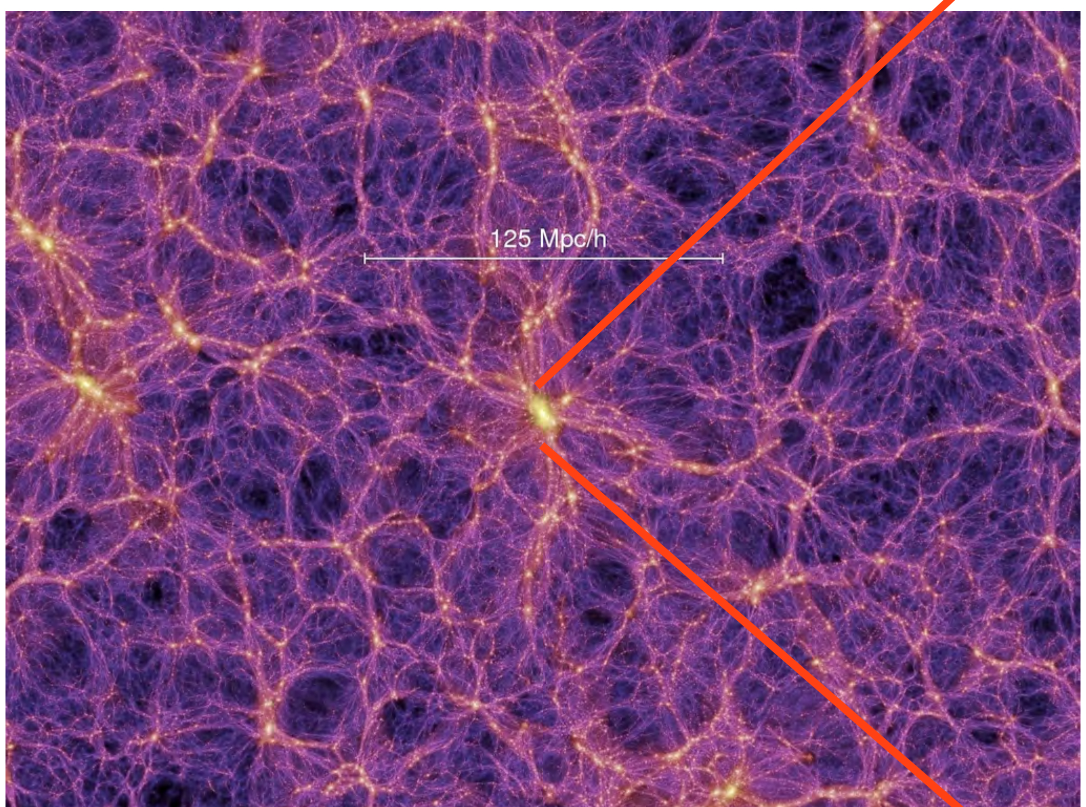
Simulations of the structure growth



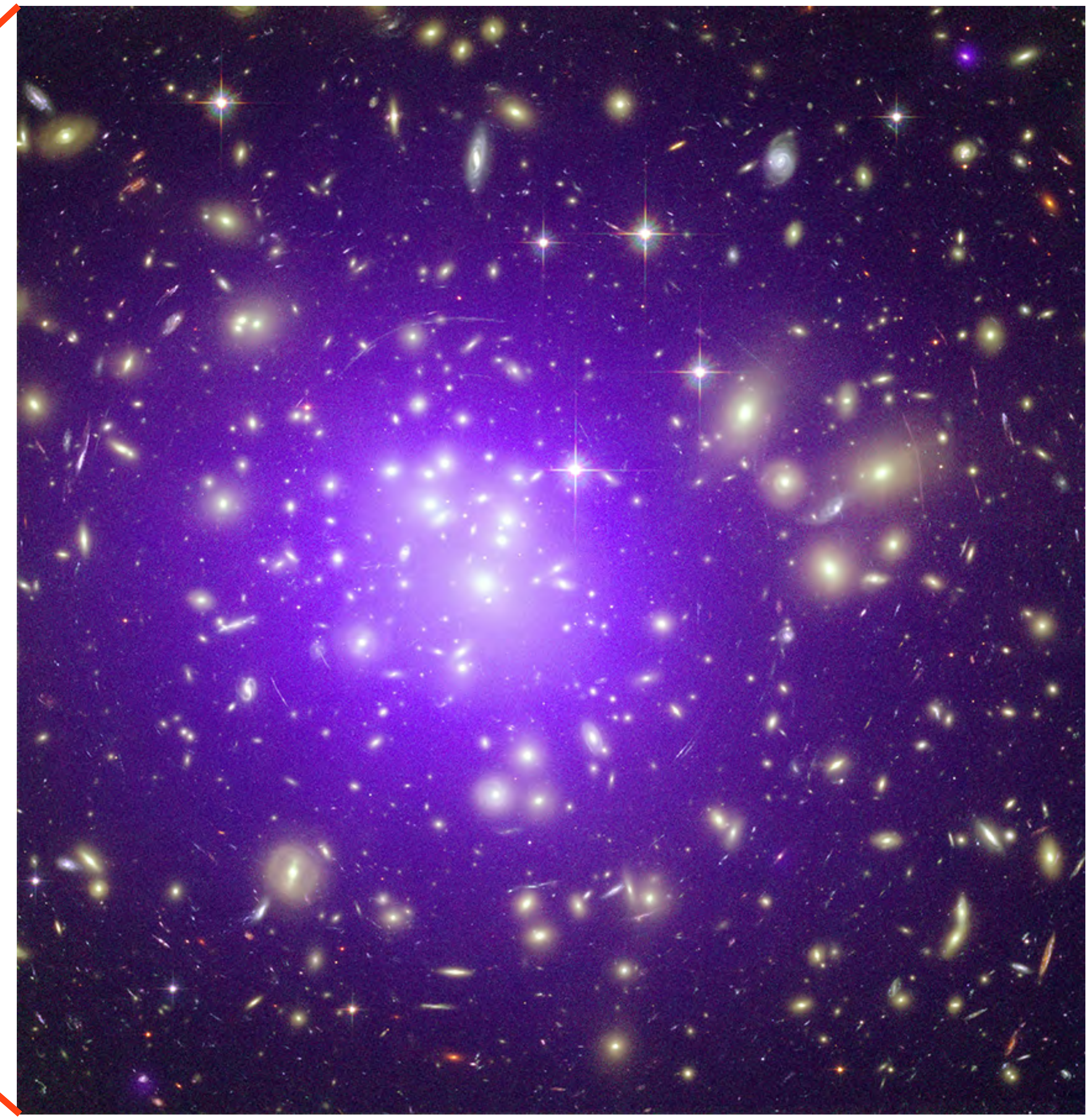
- Fast growth while dark matter dominates
- The growth slows down as the Dark Energy starts to dominate and the Universe enters the acceleration phase



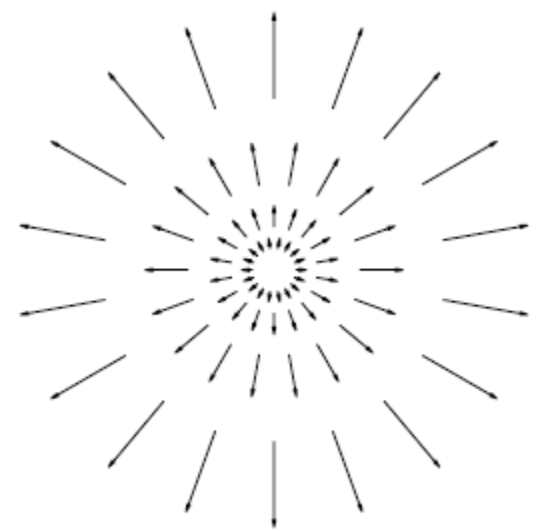
- Galaxy clusters are high-bias tracers of the large scale structure and sensitive "sensors" of its growth, giant objects with large mass and density



“Millenium” simulation of the large-scale structure


Optical and X-ray image of Abell 1689

Formation of non-linear structures. Basics of the gravitational collapse



- Consider evolution of *spherical* perturbations (exact nonlinear solution exists) — in parallel with a formal, linear solution in the critical-density Universe.
- Maximum expansion $\Longrightarrow$ $\delta_{lin} = 1.07$
- Collapse $\Longrightarrow$ $\delta_{lin} = 1.7$

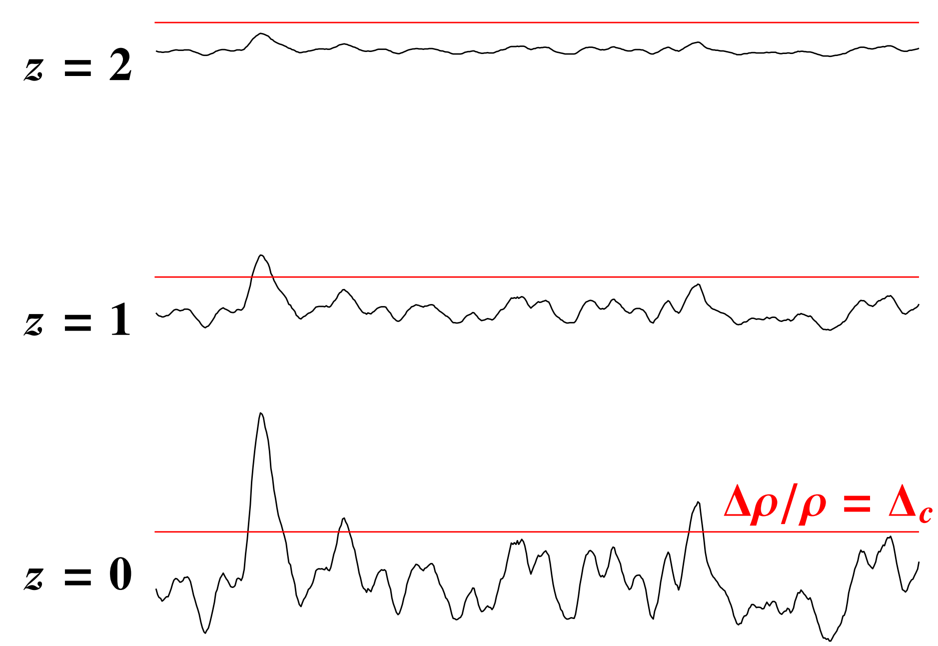
Non-linear collapse and cluster mass function theory

- Spherical perturbations virialize when corresponding linear perturbation reaches density contrast $\Delta \approx 1.7$

- $\sigma(M)$, not M, is a "natural variable"

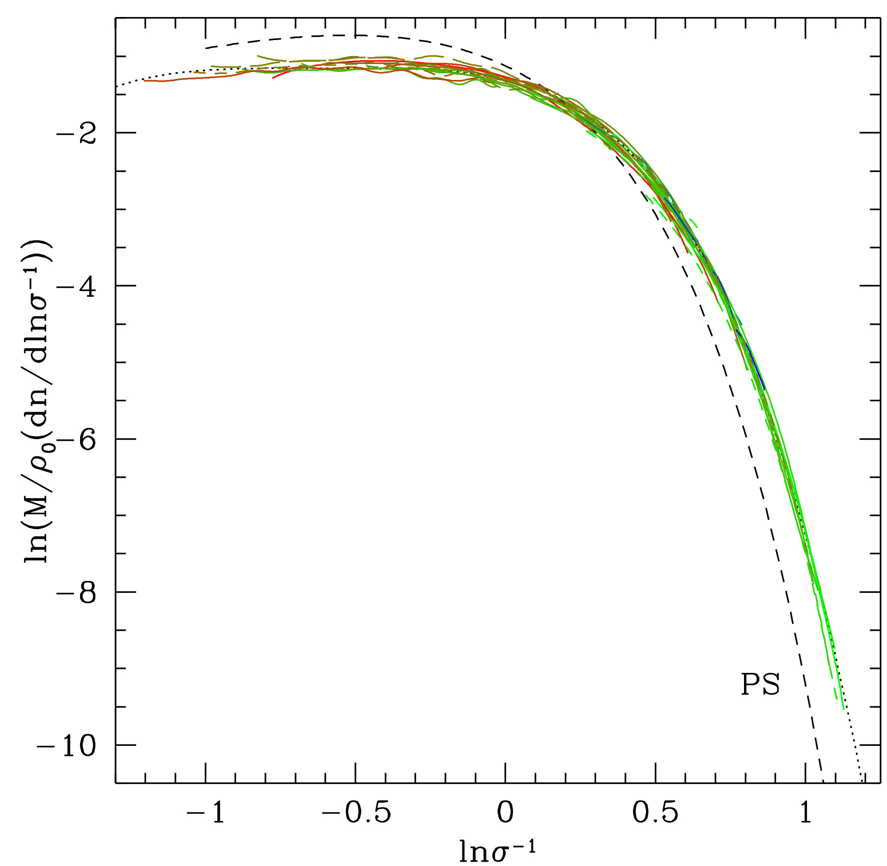
- Press-Schechter formula becomes

$$\frac{dn}{d\sigma} \sim \frac{\Delta_c}{\sigma^2} \exp\left(-\frac{\Delta_c^2}{2\sigma^2}\right)$$

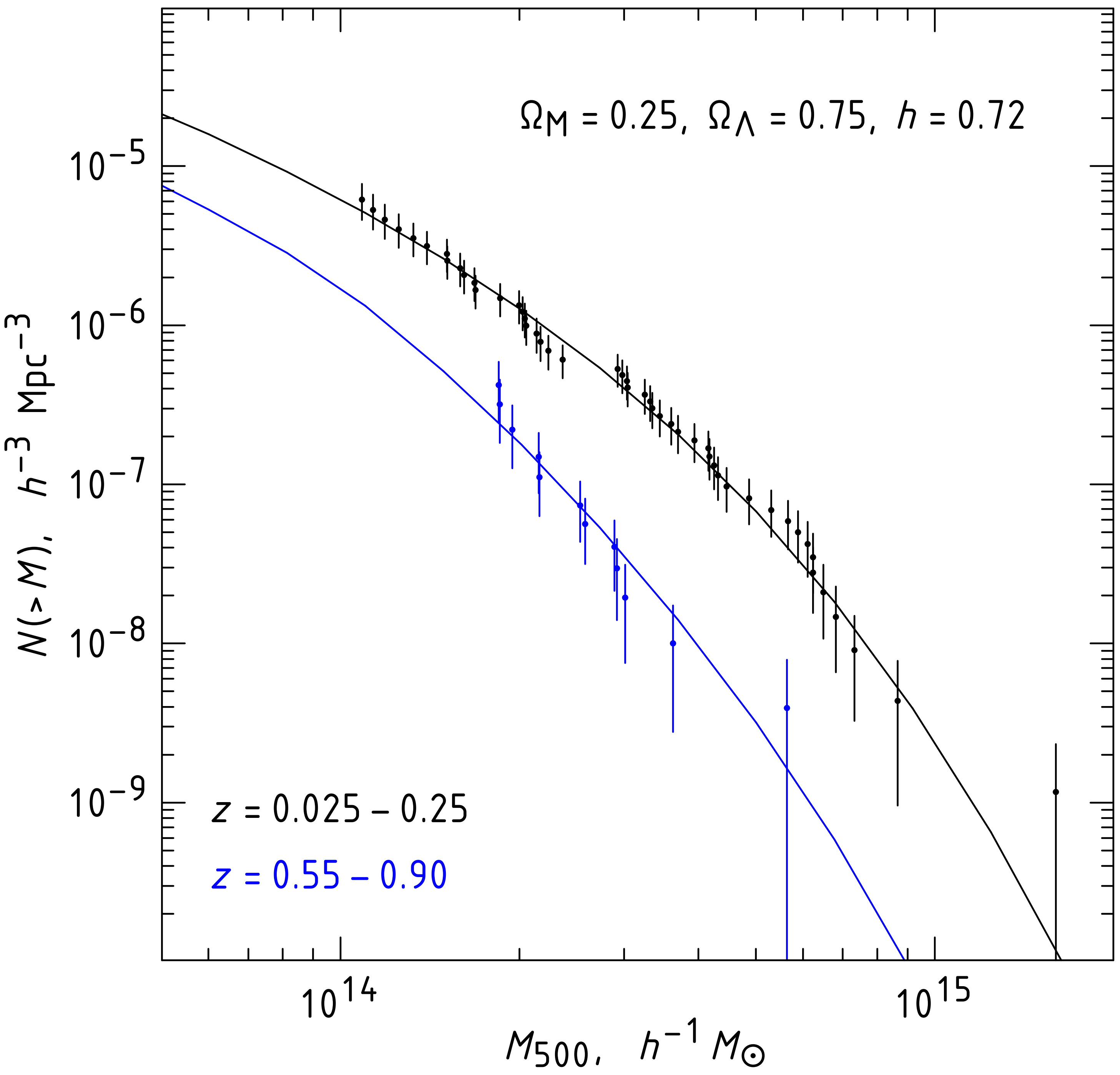


- Universal form for mass function: $n(\sigma(M))$

- Simulations can calibrate $n(\sigma(M))$. Exact form is not Press-Schechter but well-defined and stable for variations of the cosmological parameters



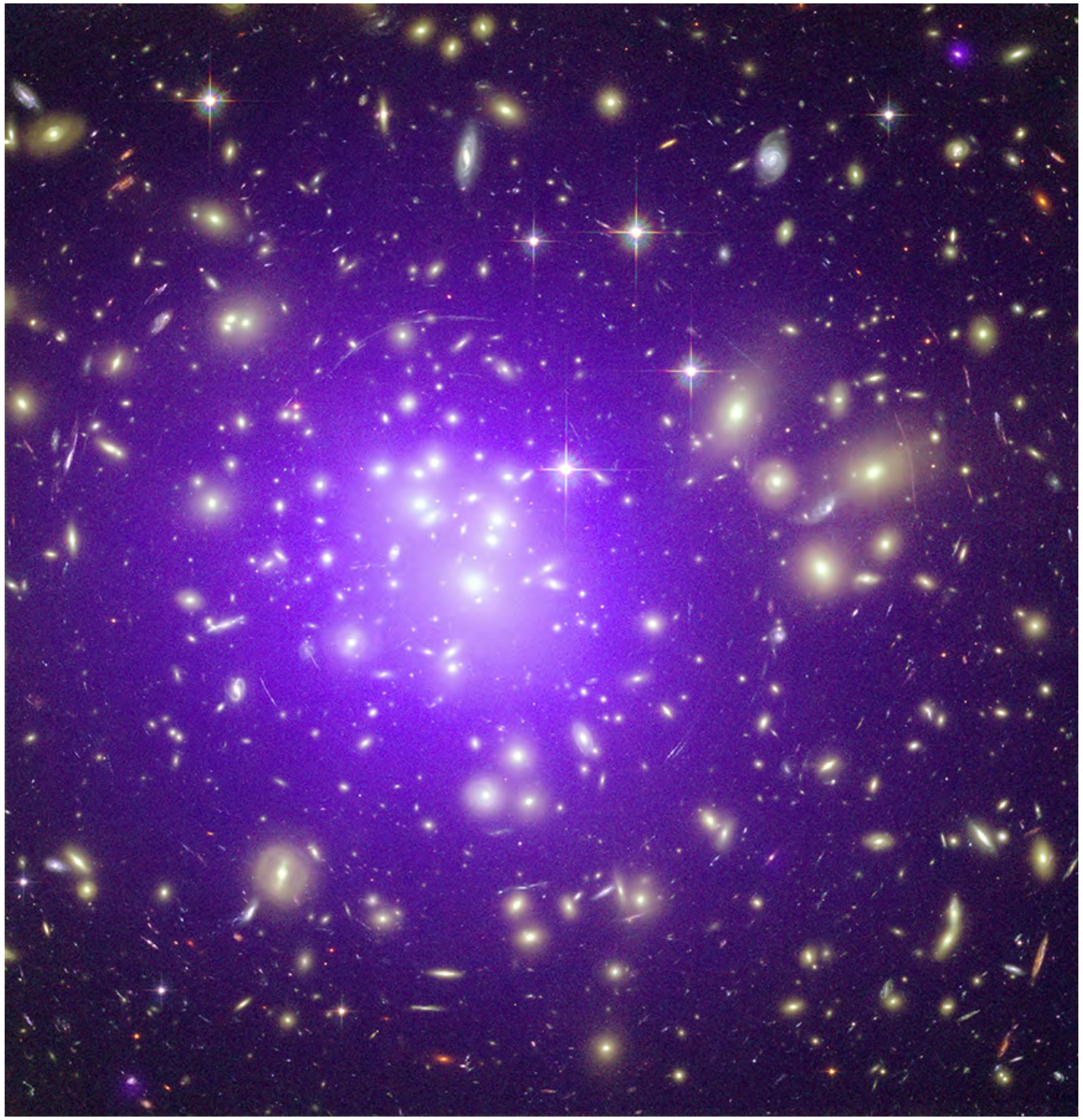
Example of galaxy cluster mass function



- Steep, exponentially sensitive to growth of perturbations

Galaxy cluster observables

Optical and X-ray image of Abell 1689



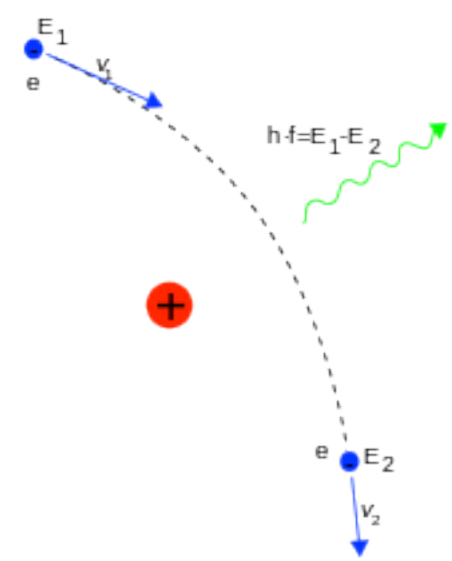
X-ray: $f_x \sim n_e^2 d^{-2}$ ... and more

SZ: $f_{SZ} \sim n_e T_e d^{-2}$

galaxies: $f_{opt} \sim N_{gal}$

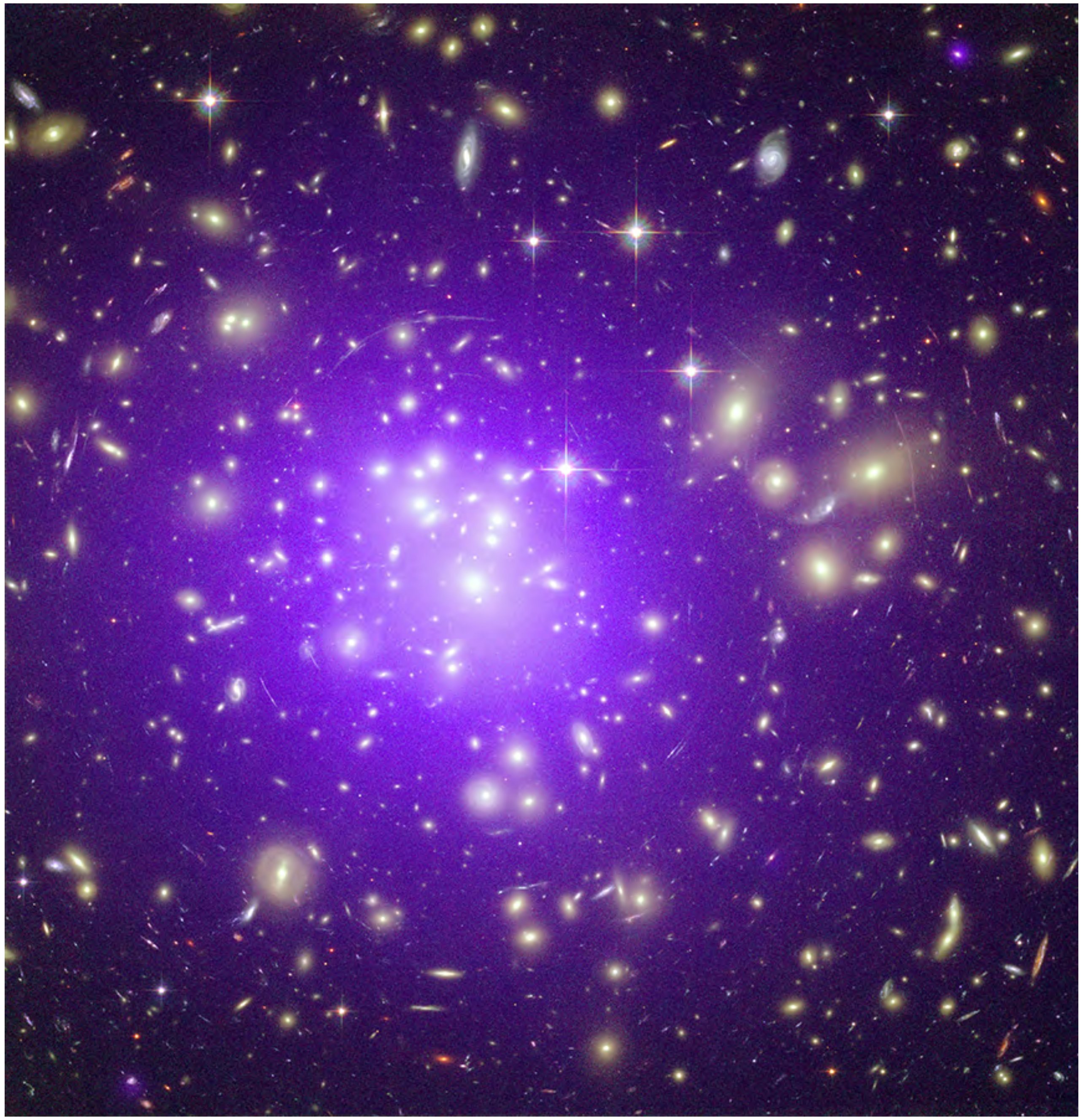
spectra: $f_{spec} \sim \sigma_{gal}$

lensing: $f_{lens} \sim M d^{-1}$



Galaxy cluster observables

Optical and X-ray image of Abell 1689



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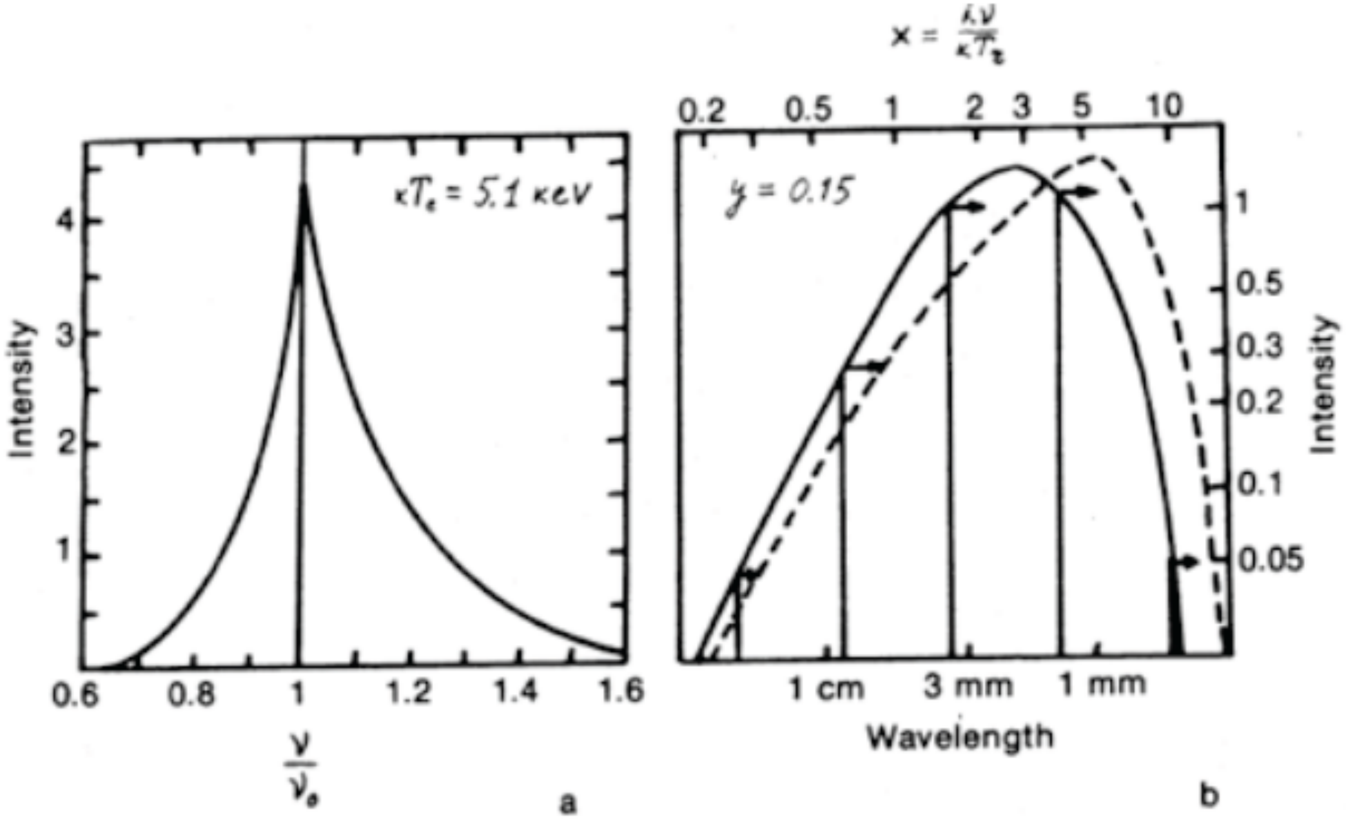
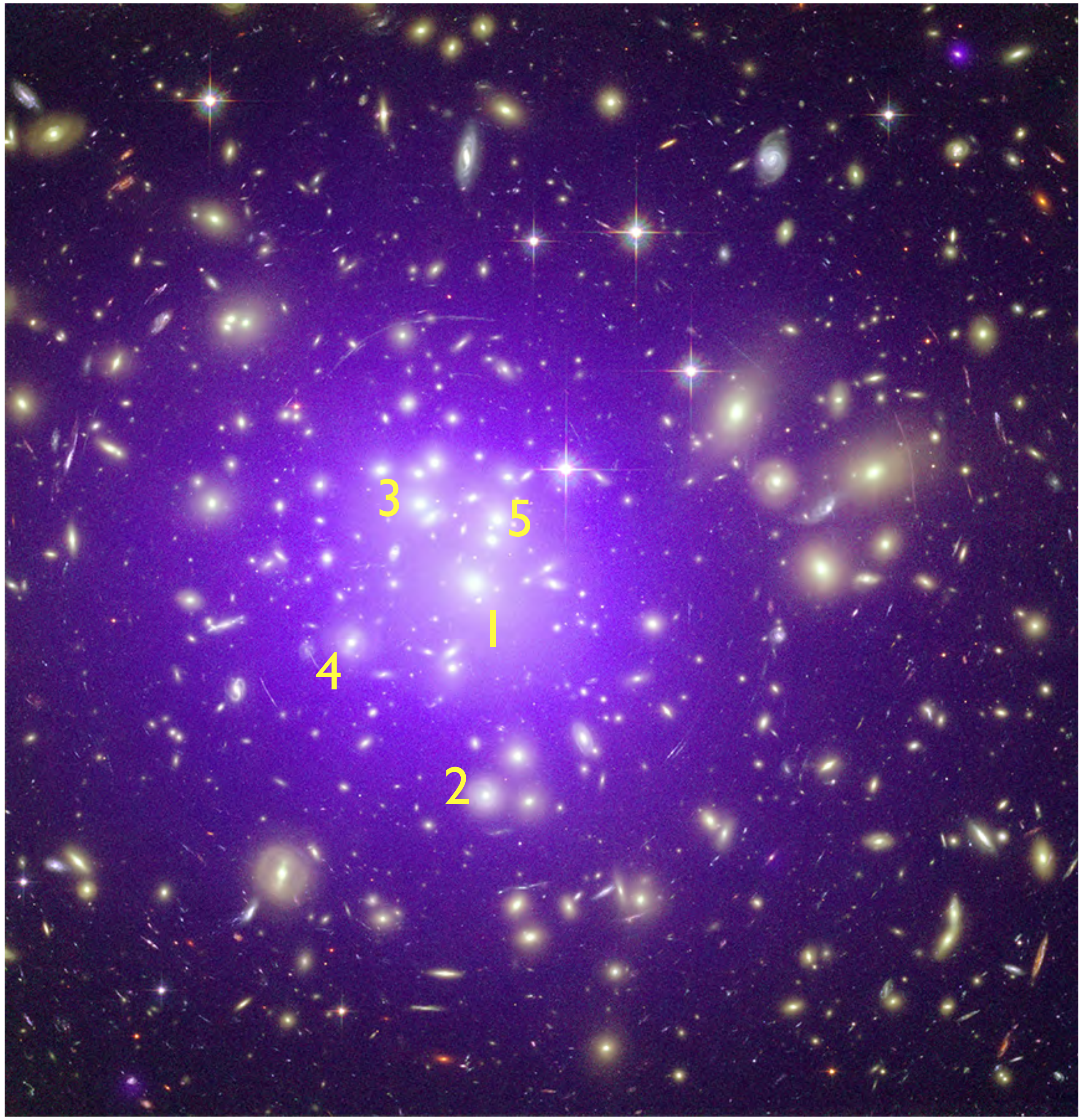


Galaxy cluster observables

Optical and X-ray image of Abell 1689



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Galaxy cluster observables

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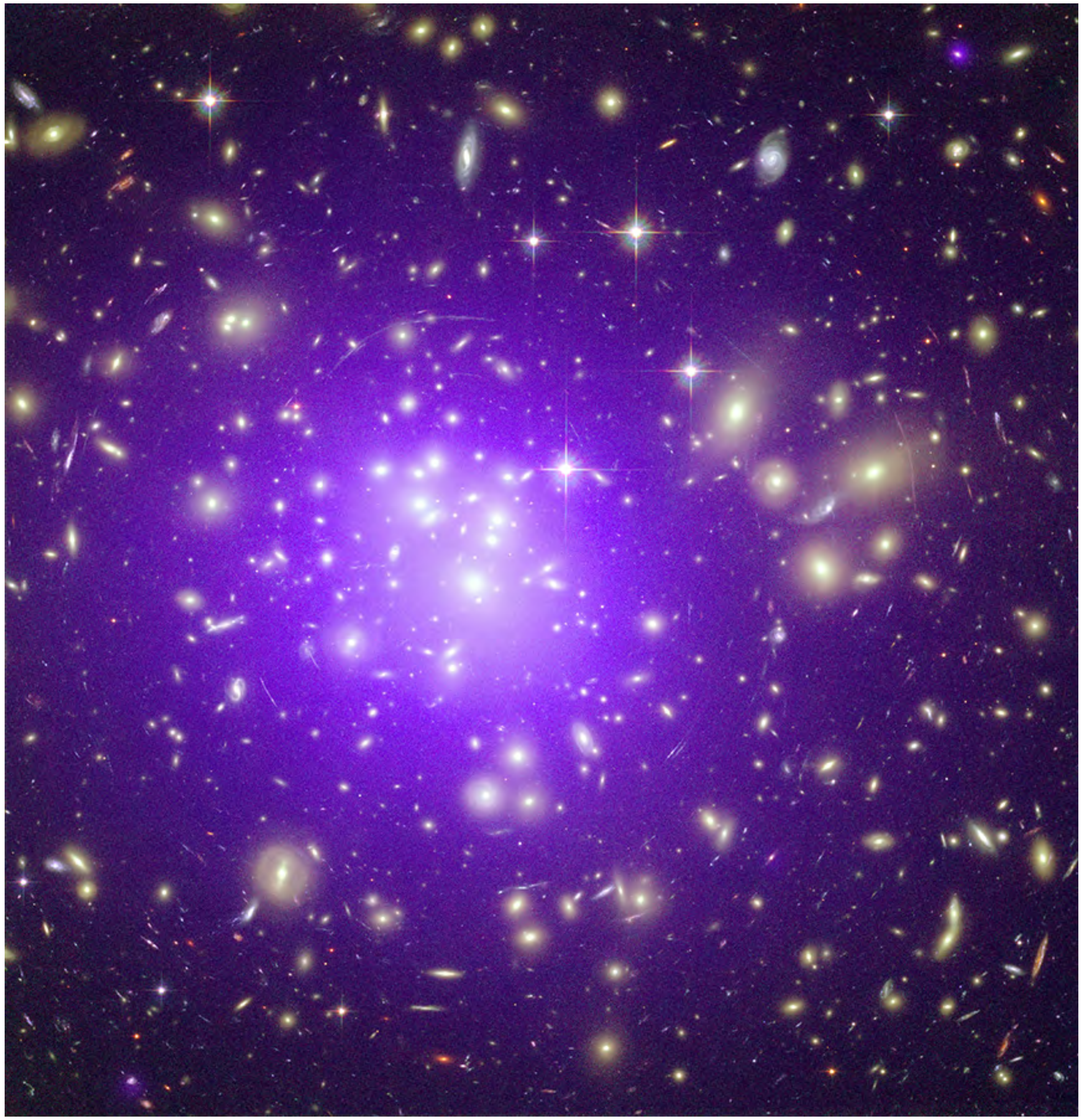

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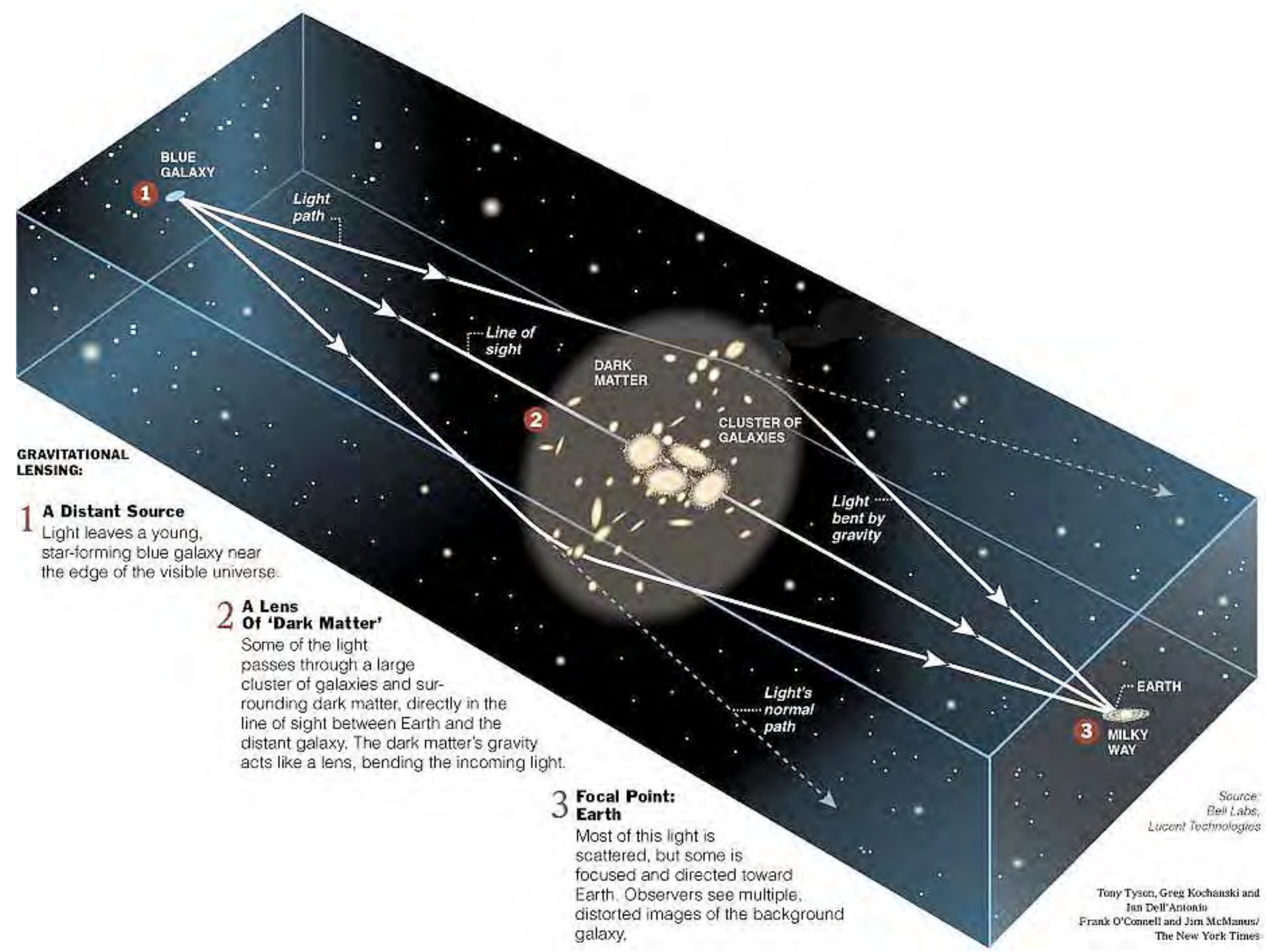
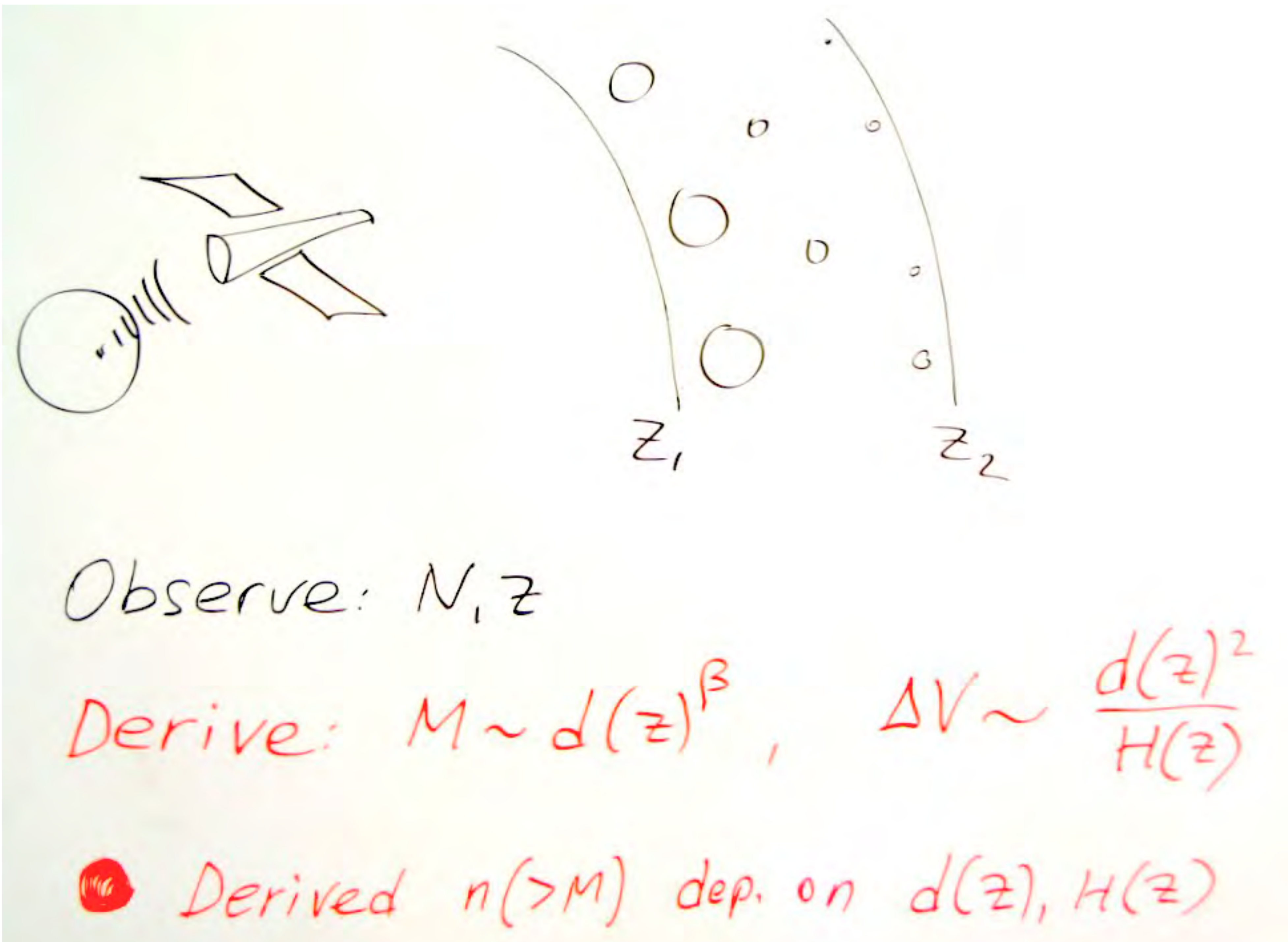
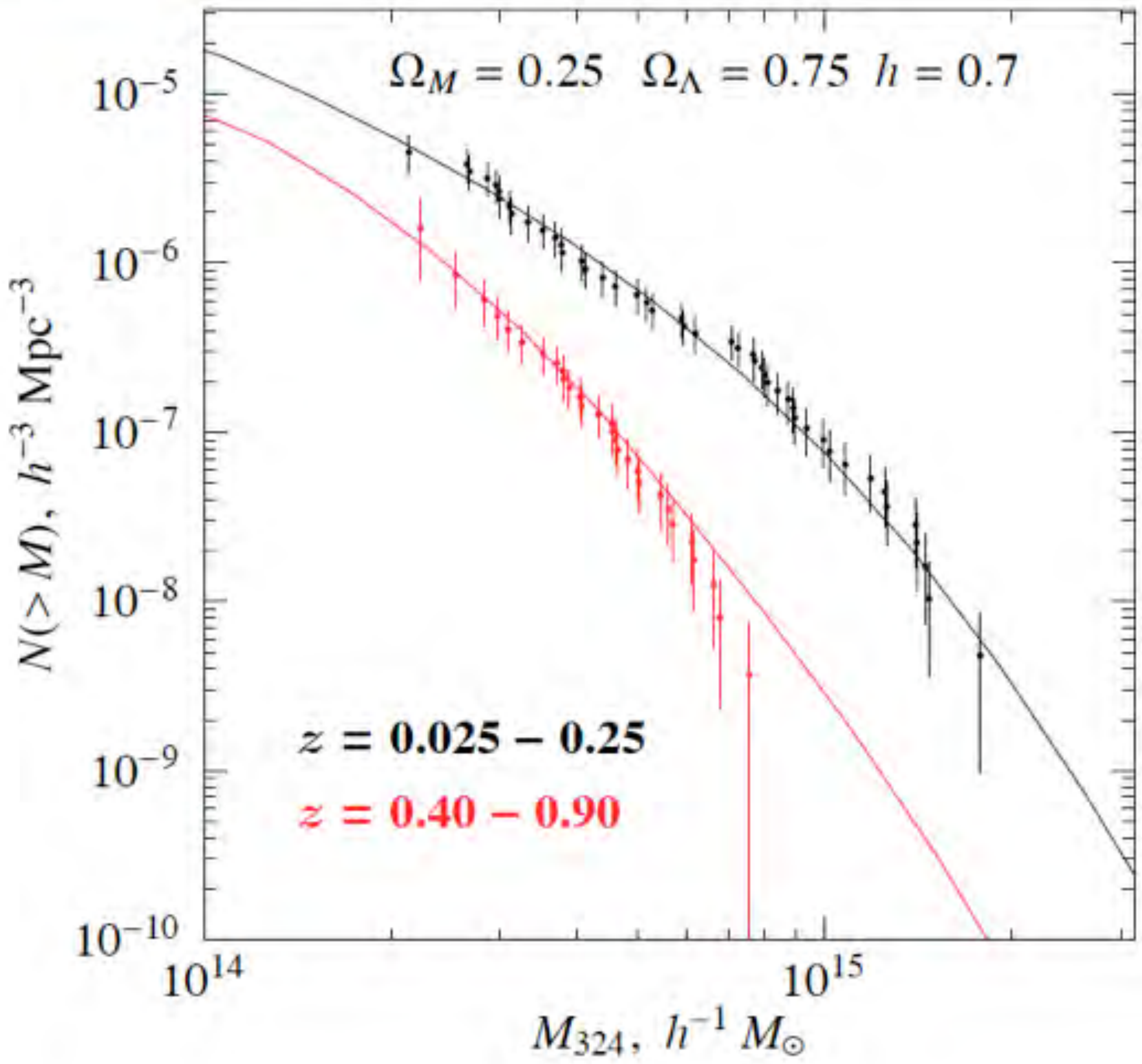


Cluster mass function cosmological test combines sensitivity to structure growth and geometry of the Universe



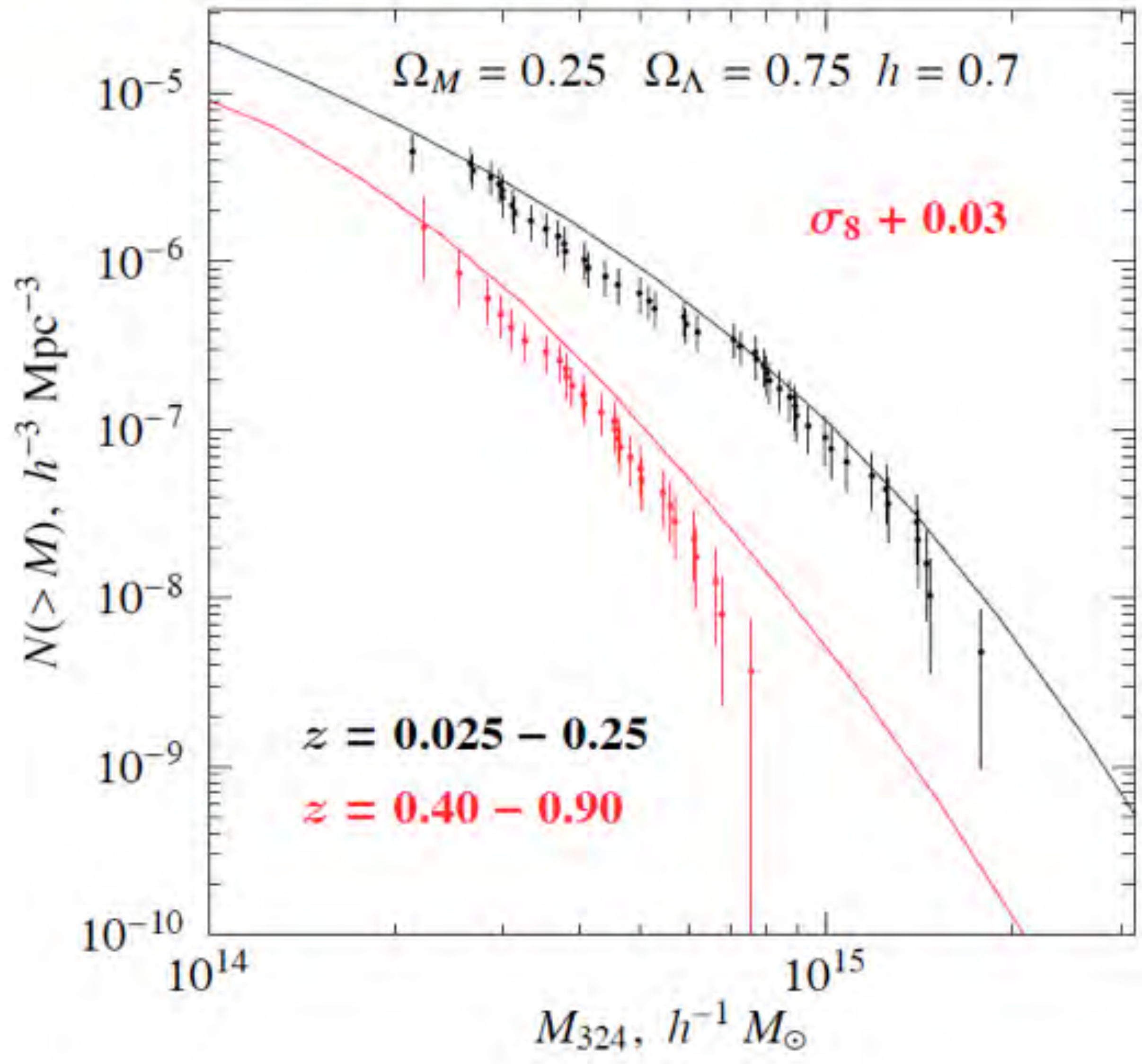
Cluster $n(M)$ — sensitivity to cosmology

In "concordant" cosmology:



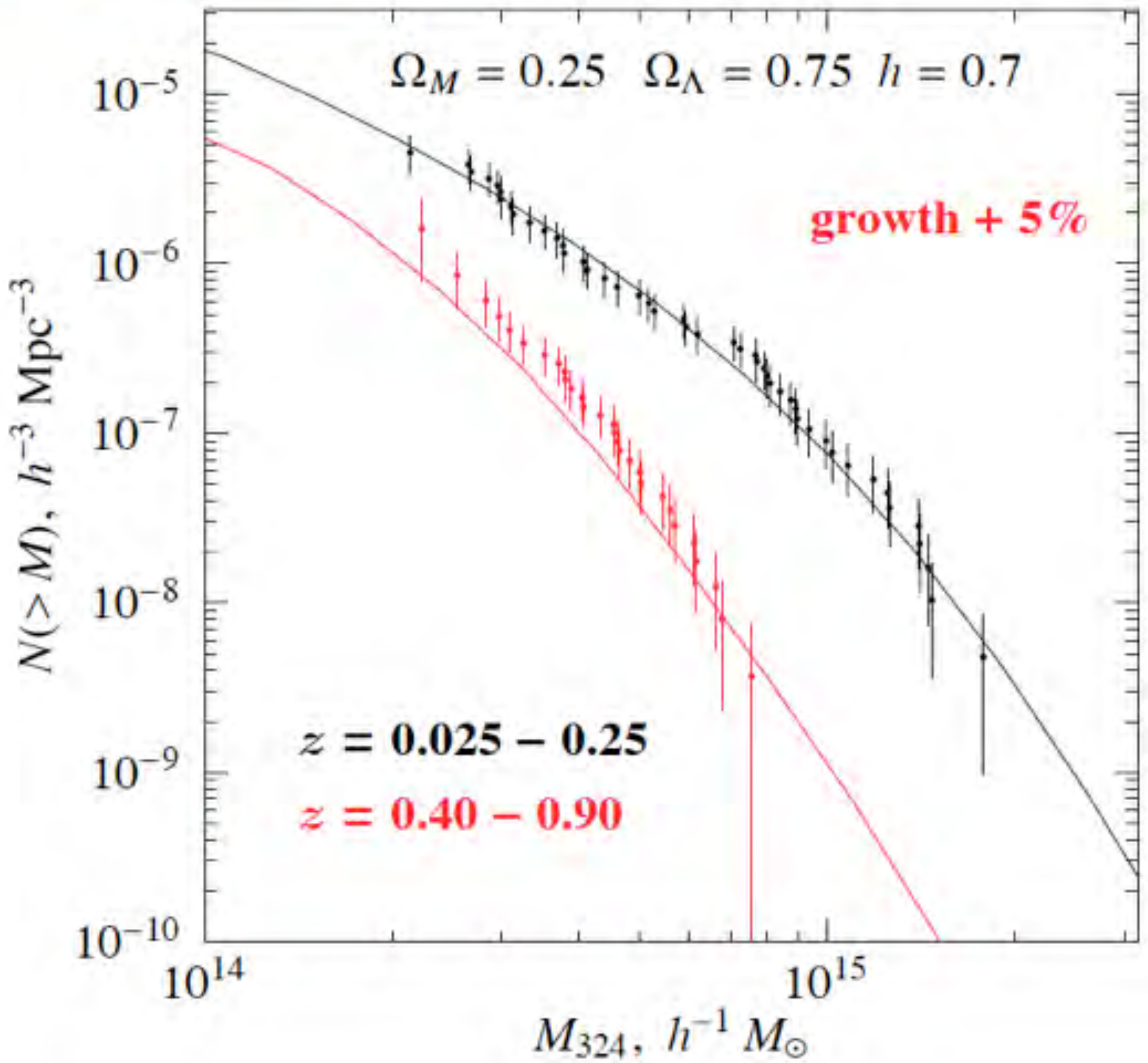
Cluster $n(M)$ — sensitivity to cosmology

Sensitivity to amplitude of density perturbation:



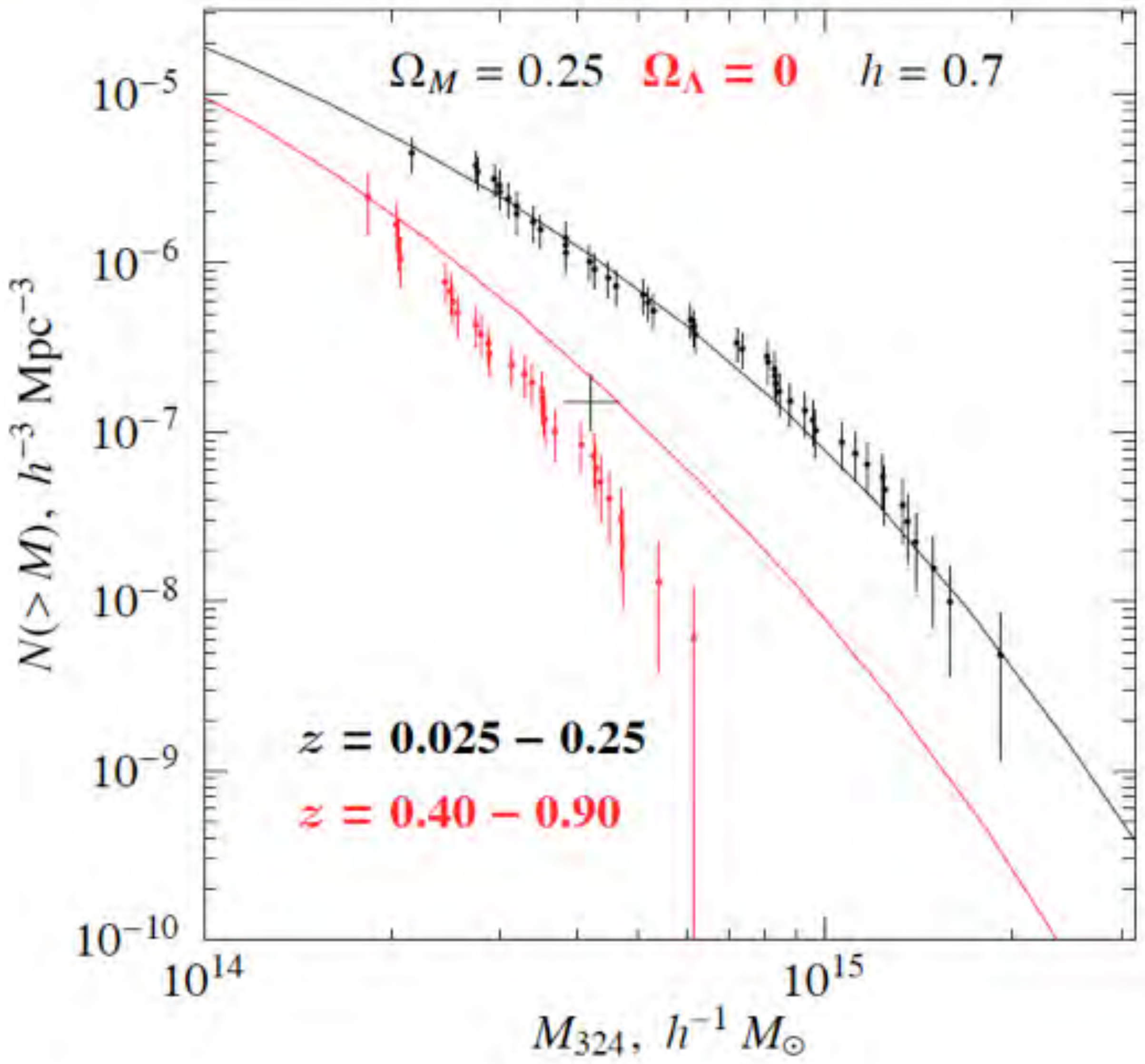
Cluster $n(M)$ — sensitivity to cosmology

Sensitivity to growth of perturbation:

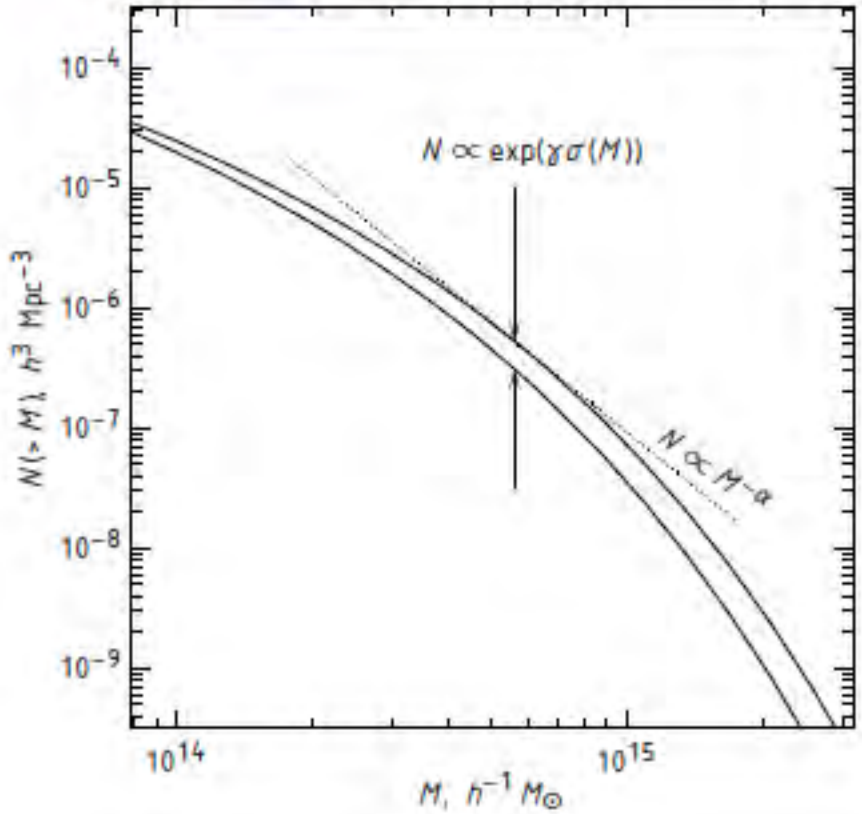


Cluster $n(M)$ — sensitivity to cosmology

wrong cosmology:



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

Very stringent requirements on mass calibration:

- Current results:

  40 clusters, $\Delta w = \pm 0.17$ $\Longleftrightarrow$ $\Delta M/M \simeq 9\%$

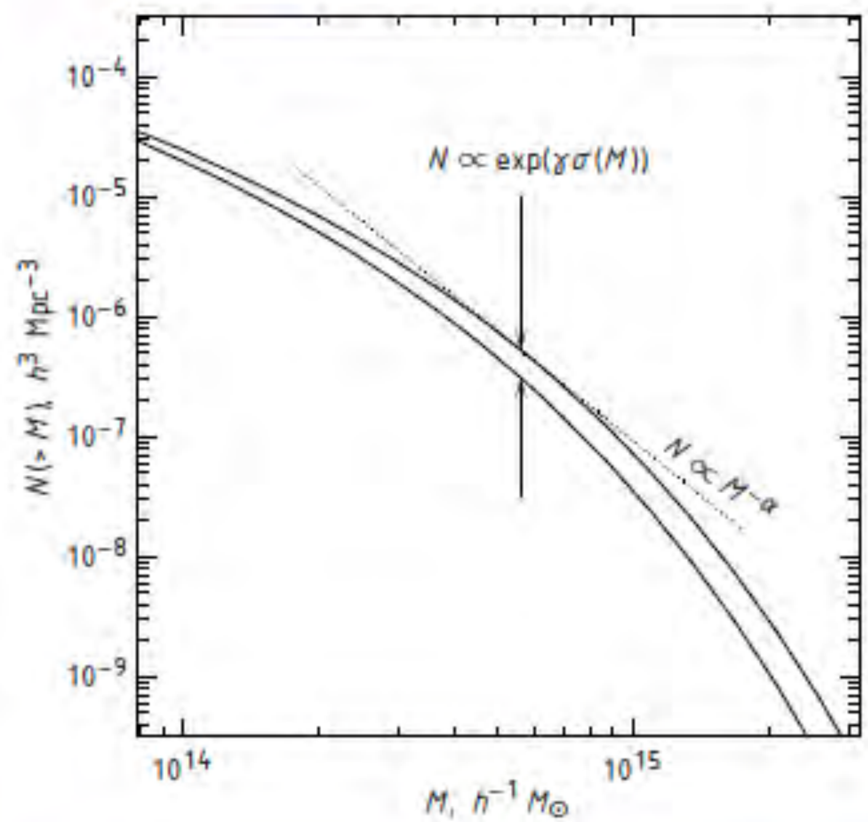
- Future:

  400 clusters, $\Delta w = \pm 0.05$ $\Longleftrightarrow$ $\Delta M/M \simeq 2.5\%$

  4000 clusters, $\Delta w = \pm 0.017$ $\Longleftrightarrow$ $\Delta M/M \simeq 0.9\%$

  100000 clusters, $\Delta w < \pm 0.01$ $\Longleftrightarrow$ $\Delta M/M \lesssim 0.5\%$

Bias and *Scatter* in M



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

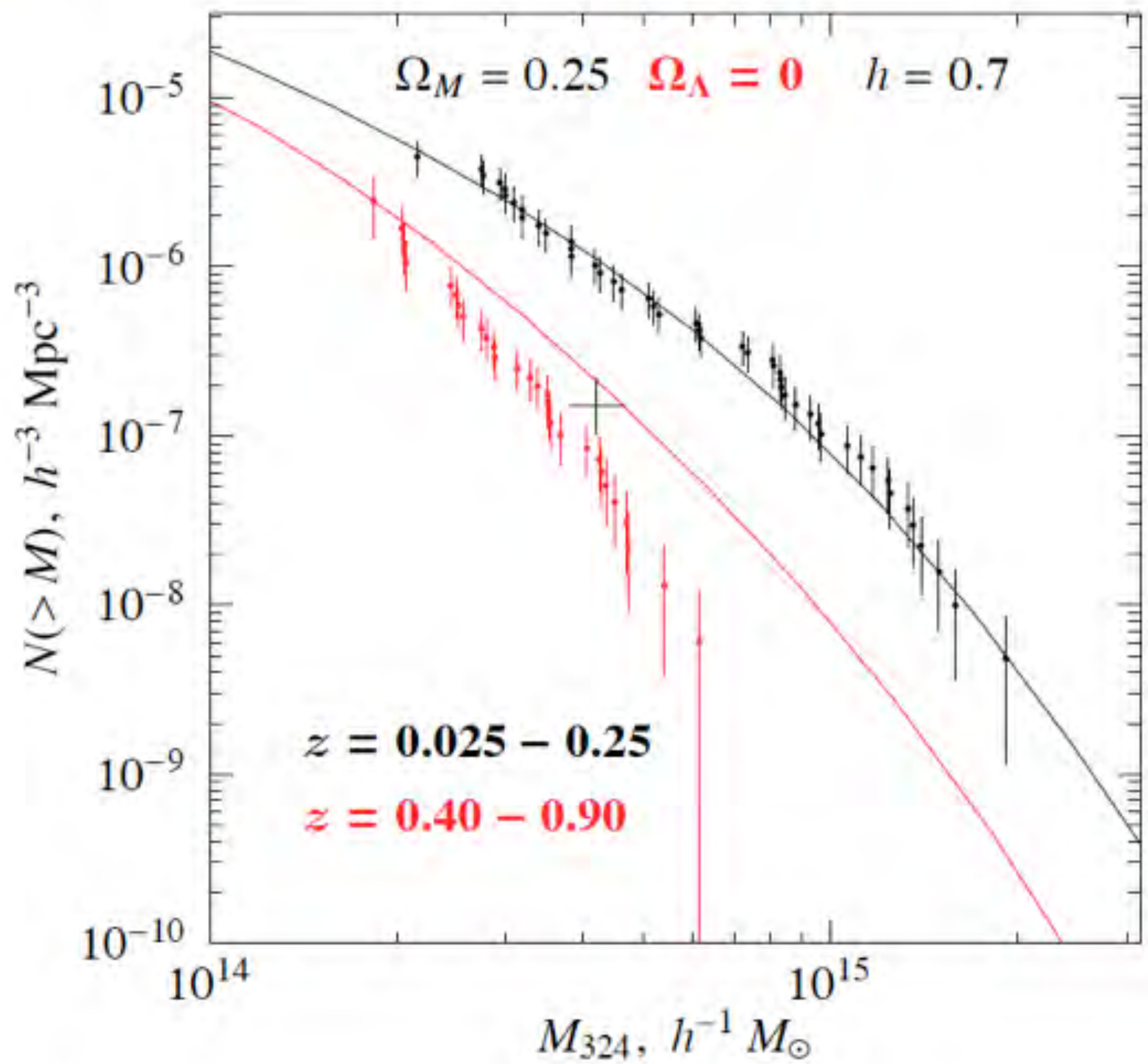
  10% mass proxies are OK, 30% are not.

Part II

Current status of observations and cosmological constraints from clusters

Cluster $n(M)$ — sensitivity to cosmology

wrong cosmology:

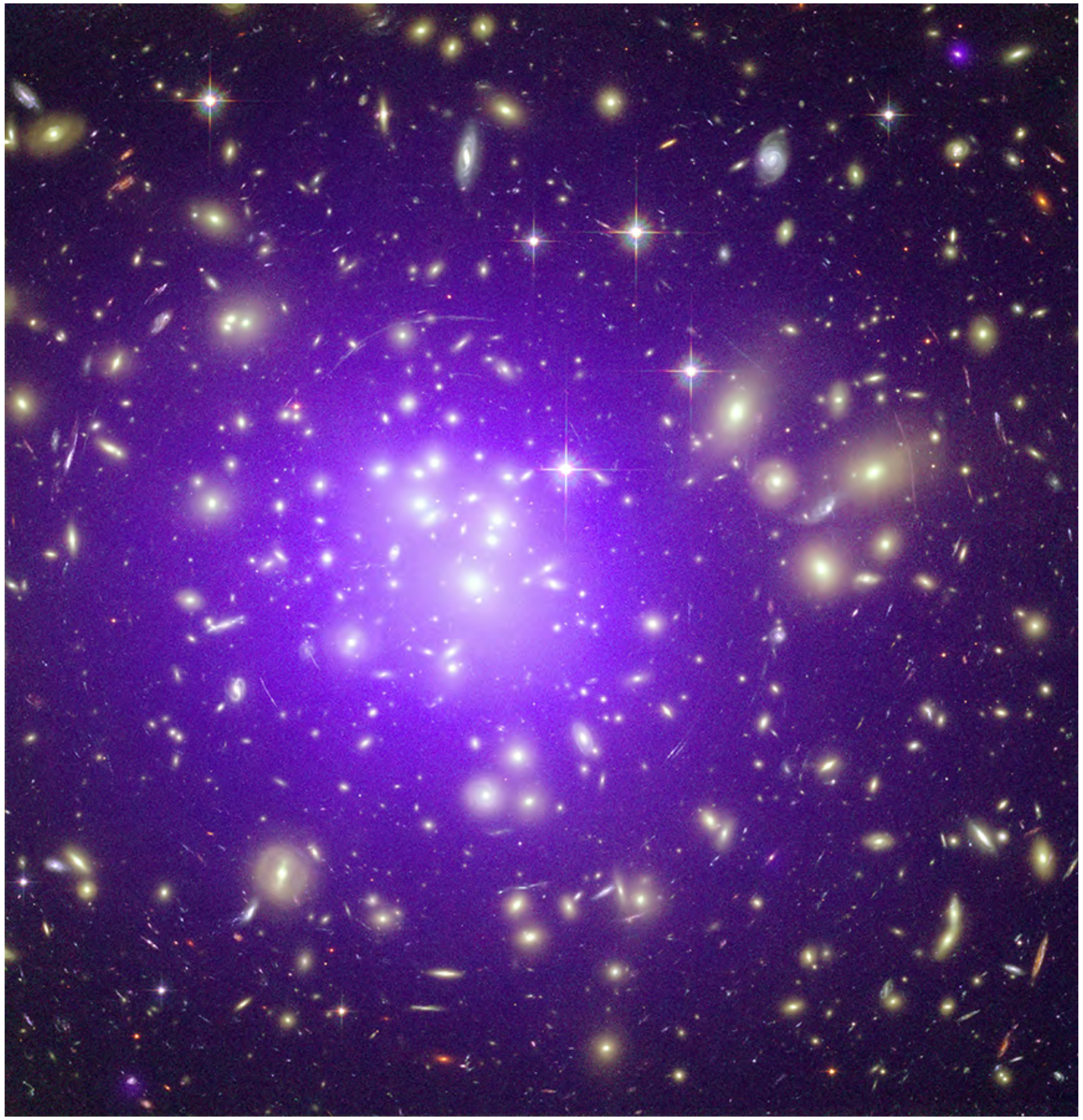


The good:	×2–3 change in the cluster density without Λ
The bad:	this corresponds to only ~ 25% error in mass calibration

challenges: 1) select a complete and pure sample of clusters, and
2) measure their masses to 10% or better

Finding galaxy clusters

Optical and X-ray image of Abell 1689



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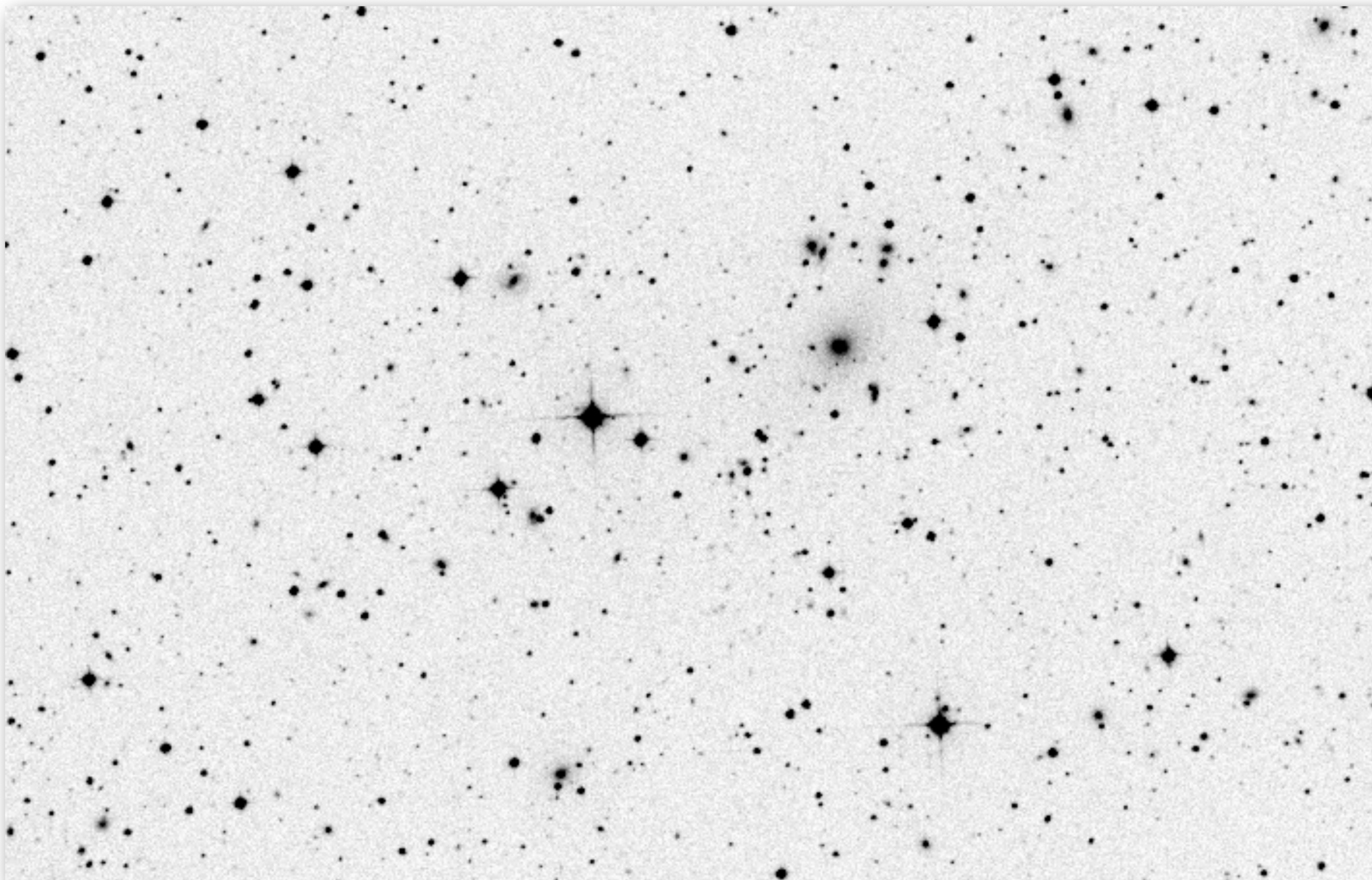
SZ: $f_{SZ} \sim n_e T_e d^{-2}$

galaxies: $f_{opt} \sim N_{gal}$

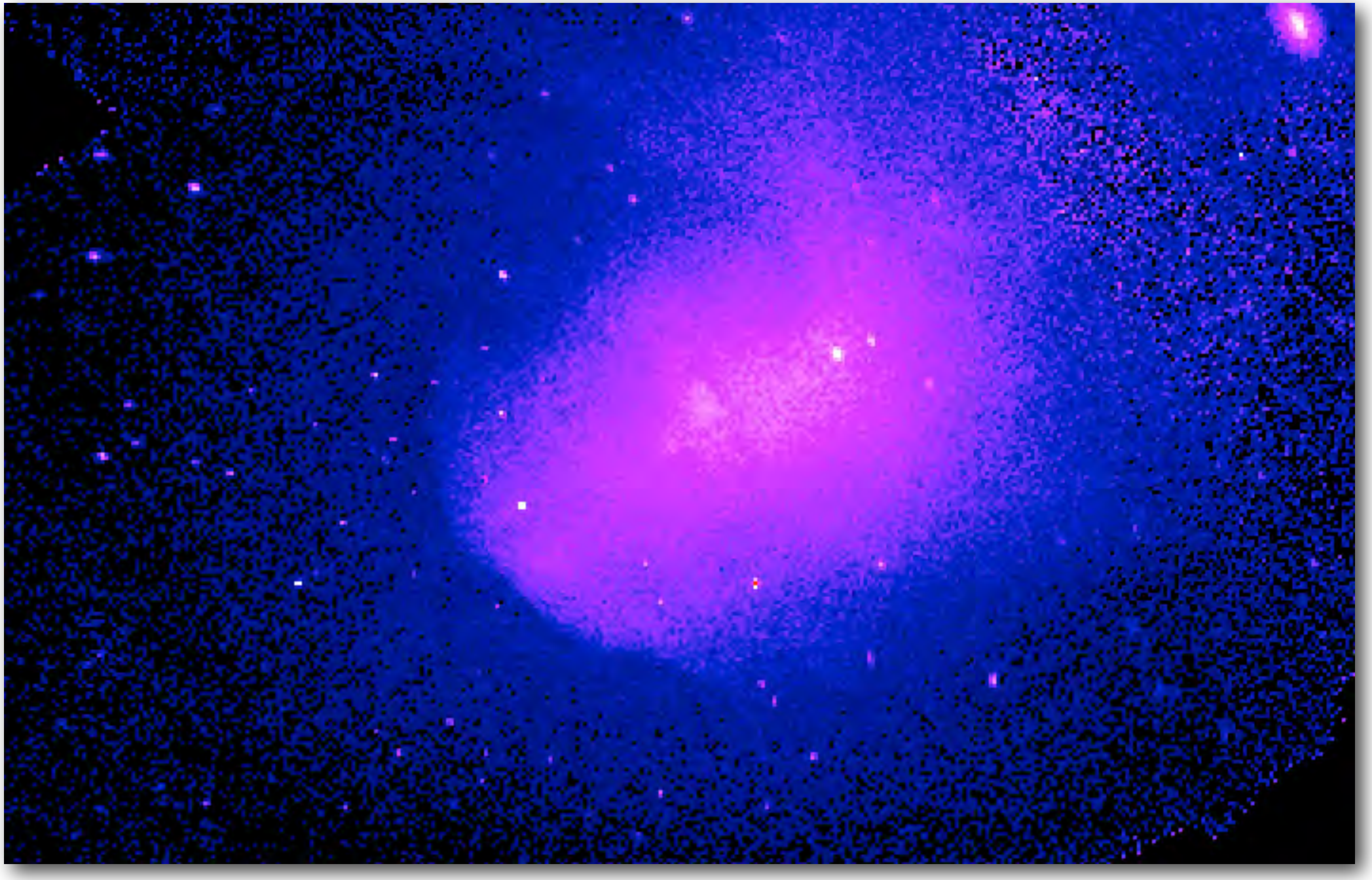
spectra: $f_{spec} \sim \sigma_{gal}$

lensing: $f_{lens} \sim M d^{-1}$

Dark matter: hot gas : galaxies = 60 : 10 : 1
dark matter (lensing) — strongly affected by projection
galaxies — emit most photons, but minor mass component, affected by projection
hot gas — dominates baryons but not mass, observable only in X-ray and mm-wave radio



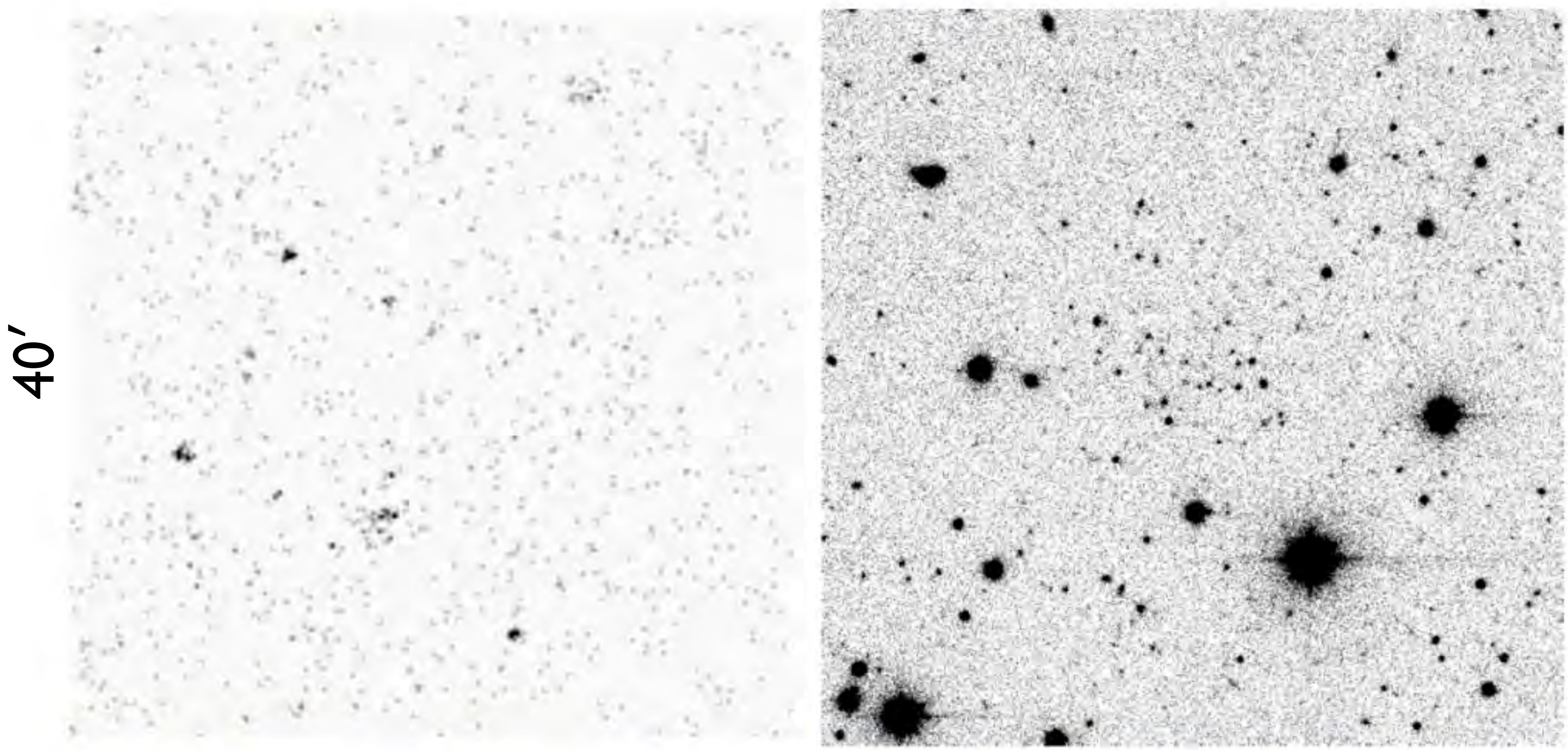
Abell 3667, optical image



Abell 3667, *Chandra* X-ray image

Cluster detection in X-rays

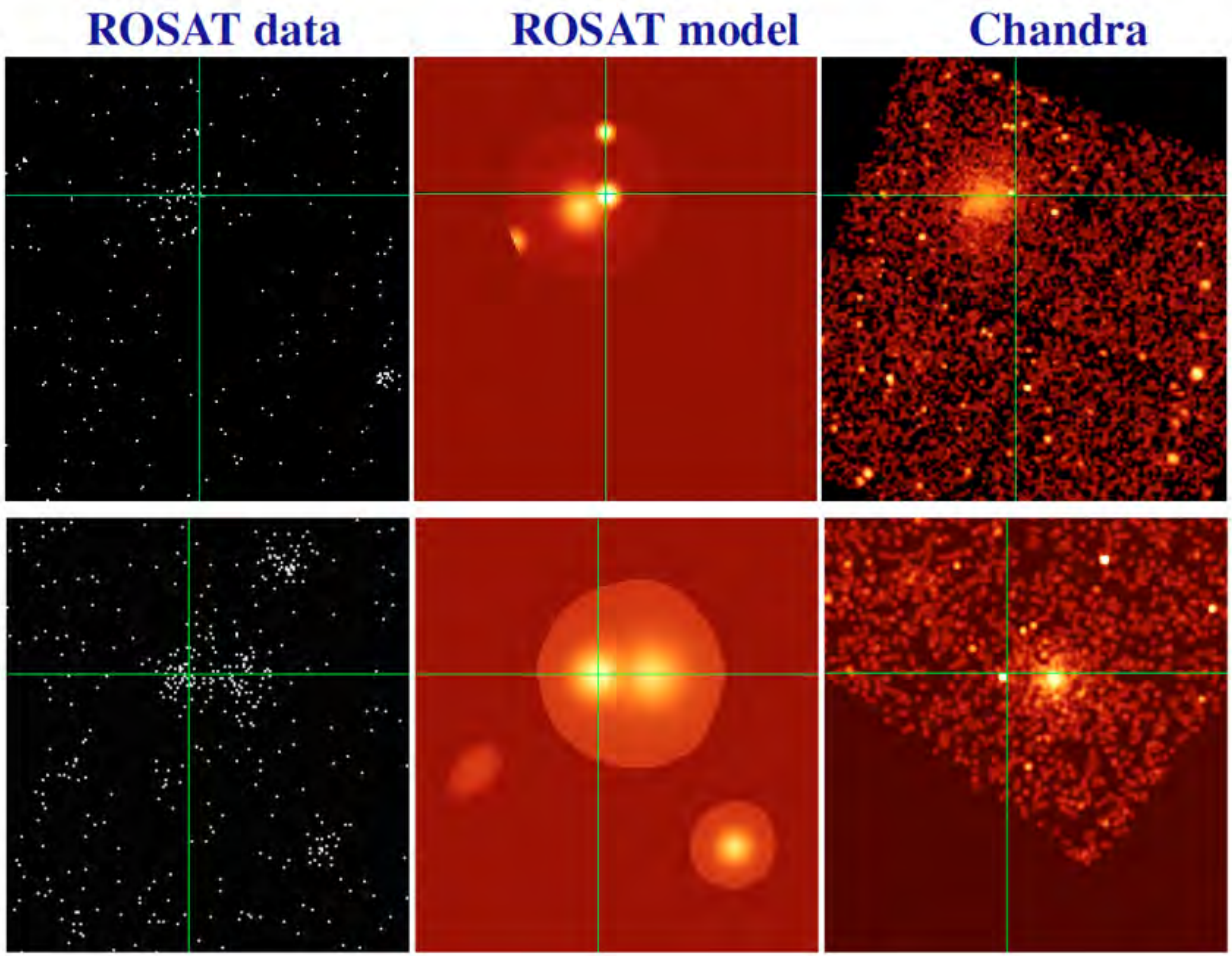
10% of cluster mass is H+He gas → heated to $T = 1 - 10$ keV →
$L_x \sim 10^{44}$ erg s^{-1} → easily detectable at high z



ROSAT, 2800 sec, 40 photons | **1.2m telescope, 5min in R; $z = 0.70$**

Clusters stand out as point sources with PSF $\lesssim 30''$
AGN contamination & confusion negligible with PSF $\lesssim 15''$

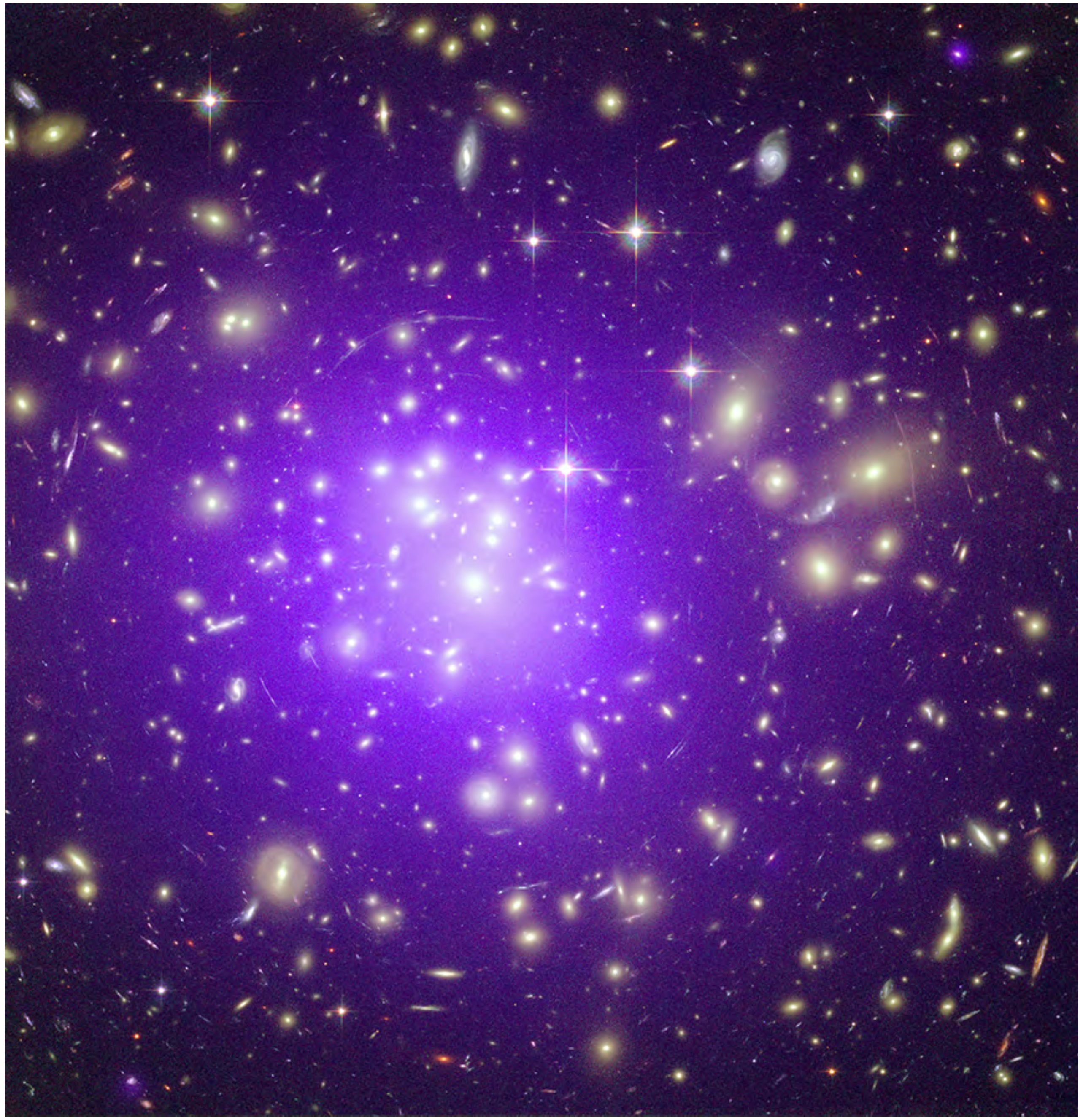
Cluster detection in X-rays: difficult cases

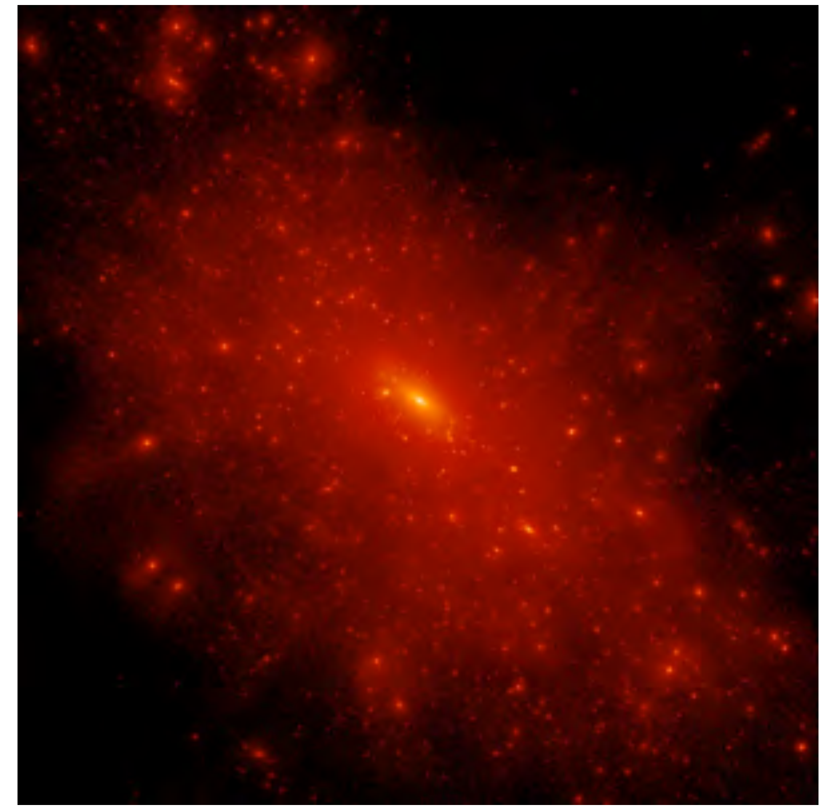


Designing a proper algorithm is difficult but doable. > 400 deg2 surveyed using ROSAT pointed observations; 100's of clusters discovered; ~10 at $z \approx 1$.

Cluster mass?

Optical and X-ray image of Abell 1689





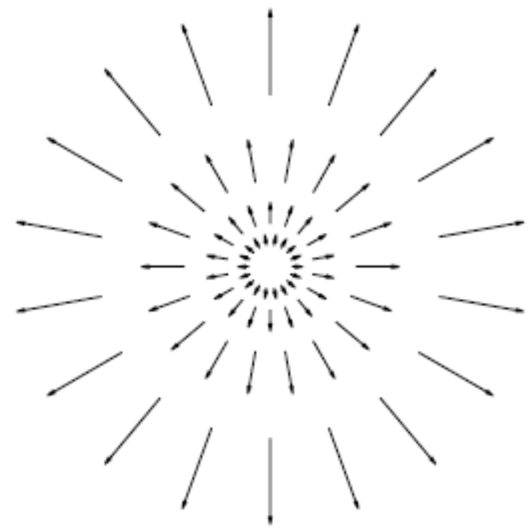
Credit: Bolshoi simulation

No well-defined boundary!
Divergent mass profile!

X-ray: $f_x \sim n_e^2 d^{-2}$
SZ: $f_{SZ} \sim n_e T_e d^{-2}$
galaxies: $f_{opt} \sim N_{gal}$
spectra: $f_{spec} \sim \sigma_{gal}$
lensing: $f_{lens} \sim M d^{-1}$

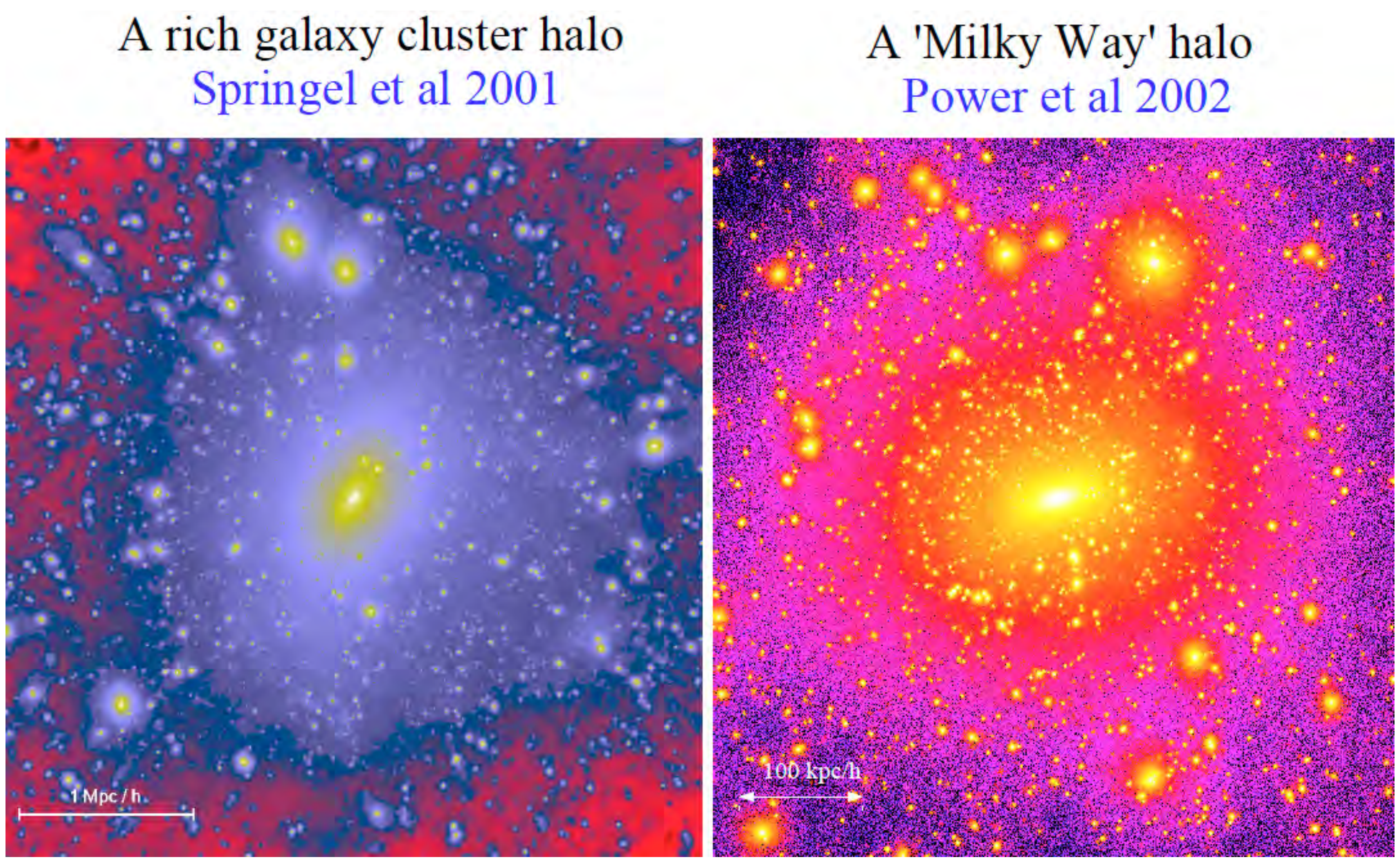
— either indirect or noisy measures of mass

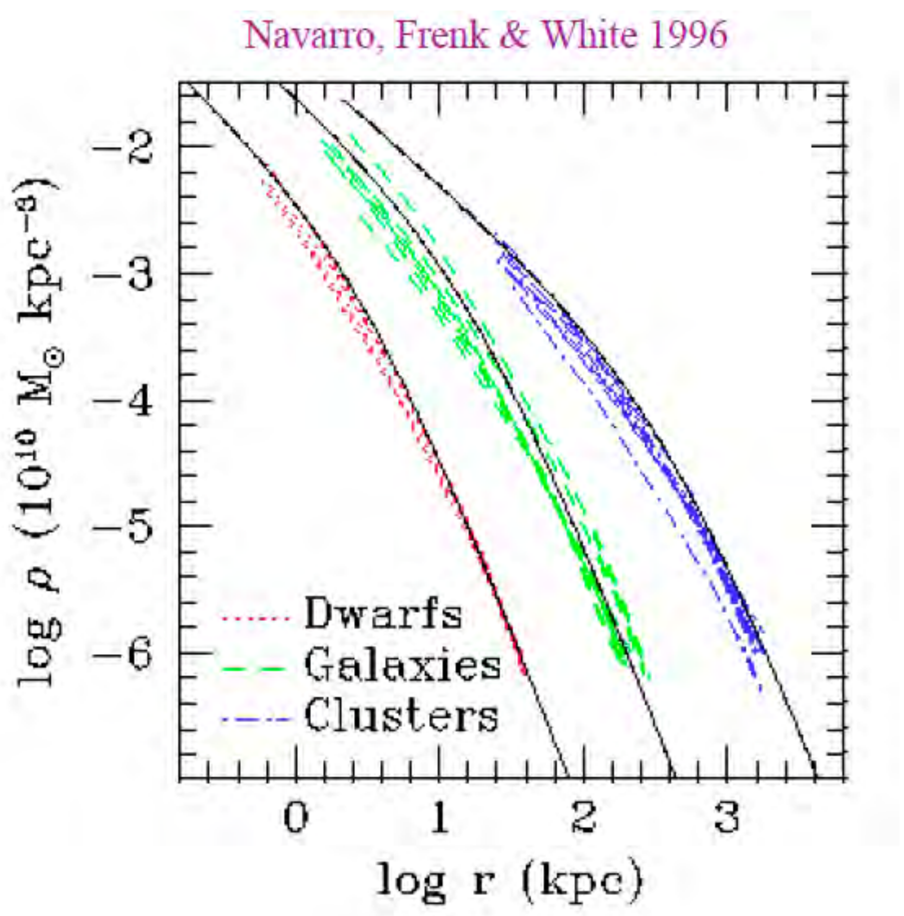
Formation of non-linear structures. Basics of the gravitational collapse



- Consider evolution of *spherical* perturbations (exact nonlinear solution exists) — in parallel with formal linear solution
- Maximum expansion $\Longrightarrow$ $\delta_{lin} = 1.07$
- Collapse $\Longrightarrow$ $\delta_{lin} = 1.7$
- Non-linear overdensity after collapse — $\delta_{non\text{-}lin} = 180$
- Clusters expected to have ≈ equal densities & exhibit self-similar scalings

Expectations: self-similar profiles and scaling relations





$$M \propto T^{3/2} E^{-1}(z)$$

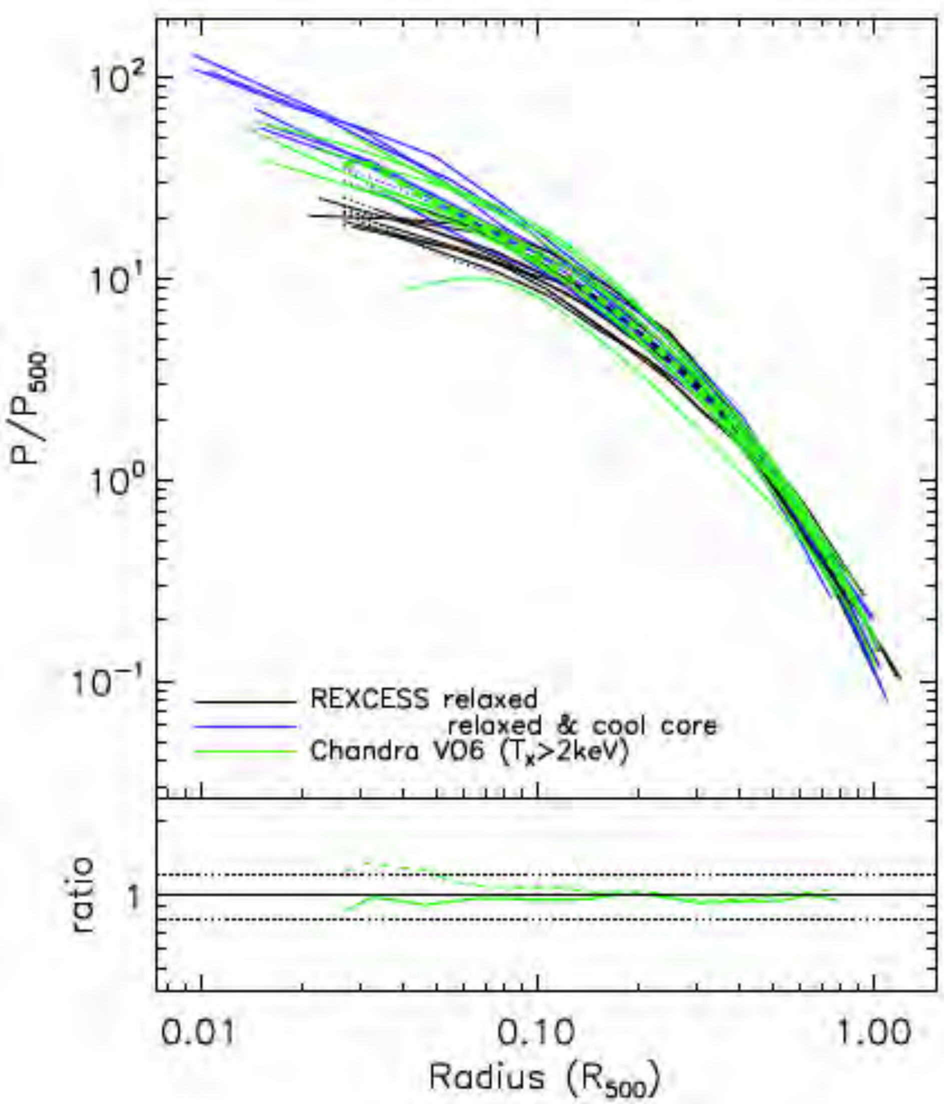
$$M \propto M_{\rm gas}$$

$$Y = M_{\rm gas} T \propto M^{5/3} E^{2/3}(z)$$

$$E^2(z) = \Omega_M (1+z)^3 + (1 - \Omega_M - \Omega_\Lambda)(1+z)^2 + \Omega_\Lambda$$

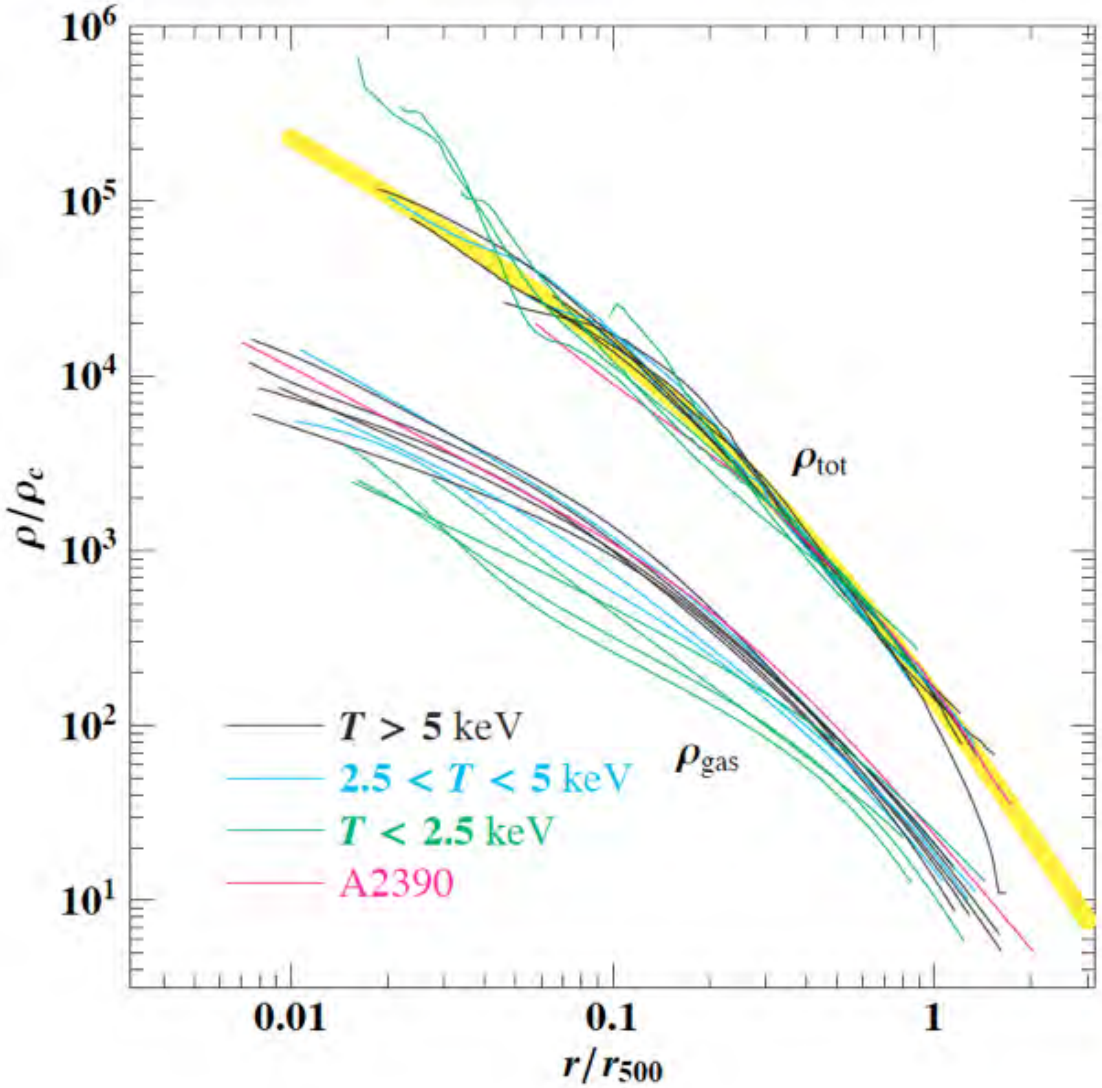
Observed regularity of cluster properties

Scaled gas pressure profiles



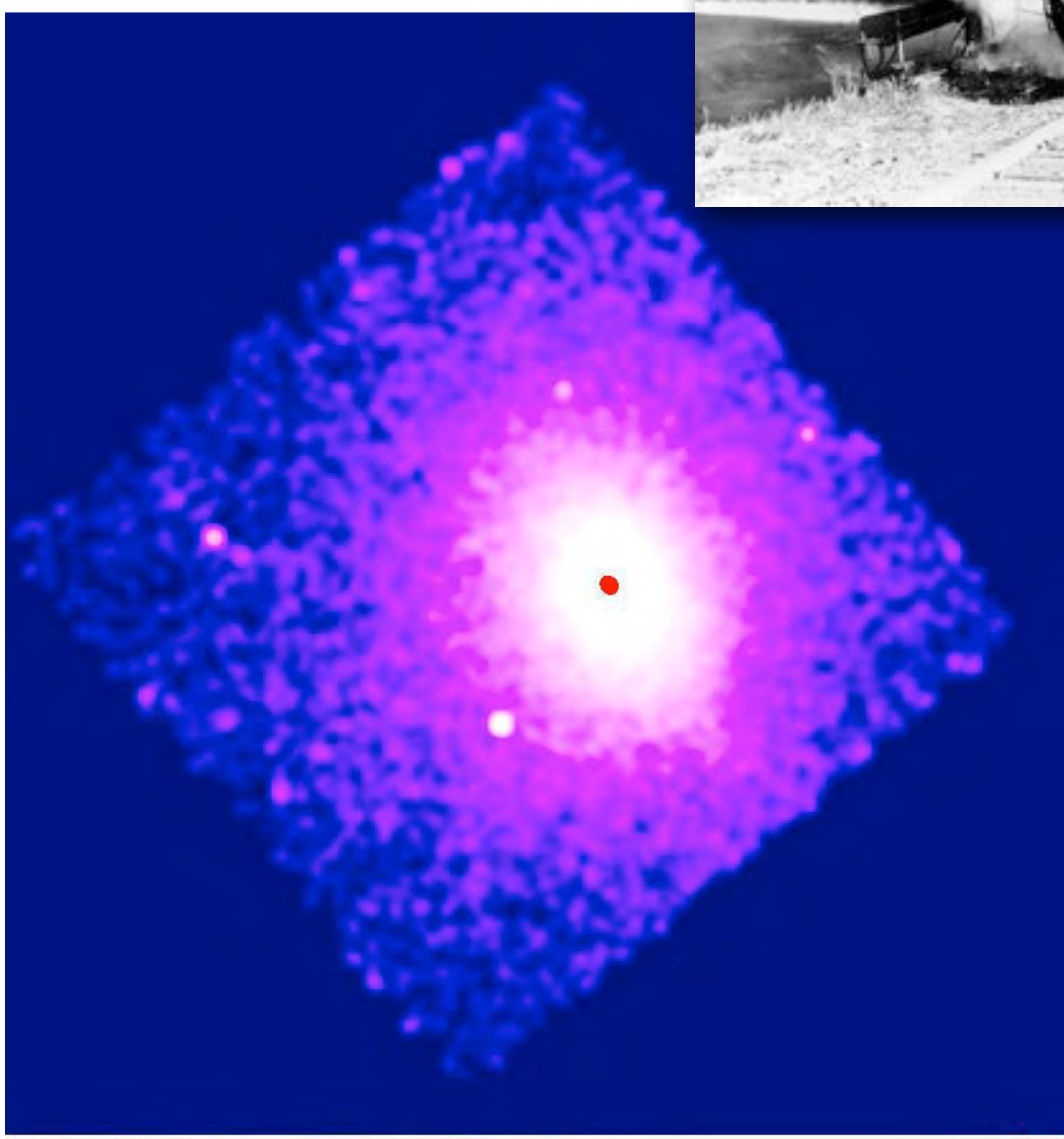
Arnaud et al. '09

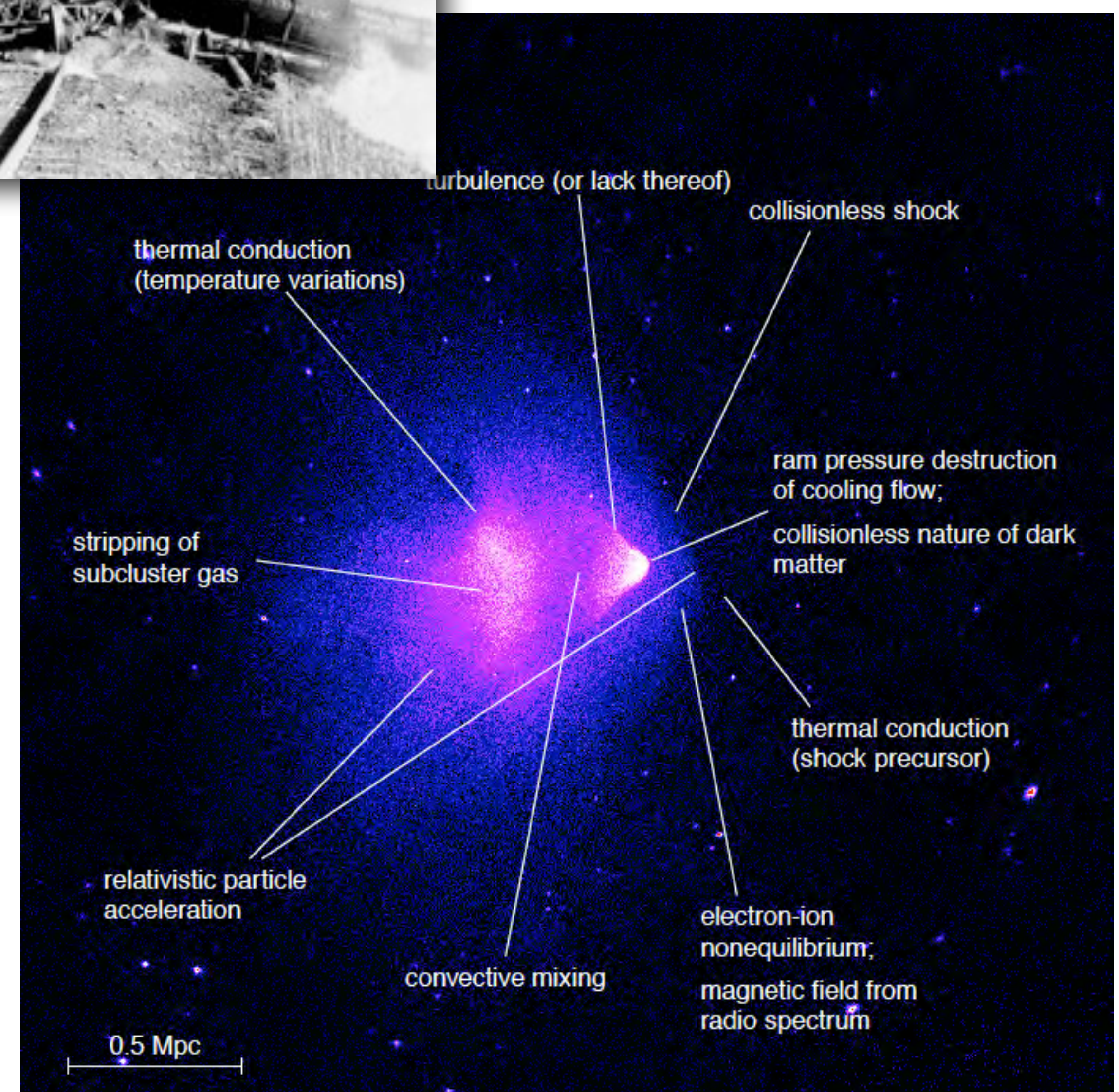
Scaled density profiles



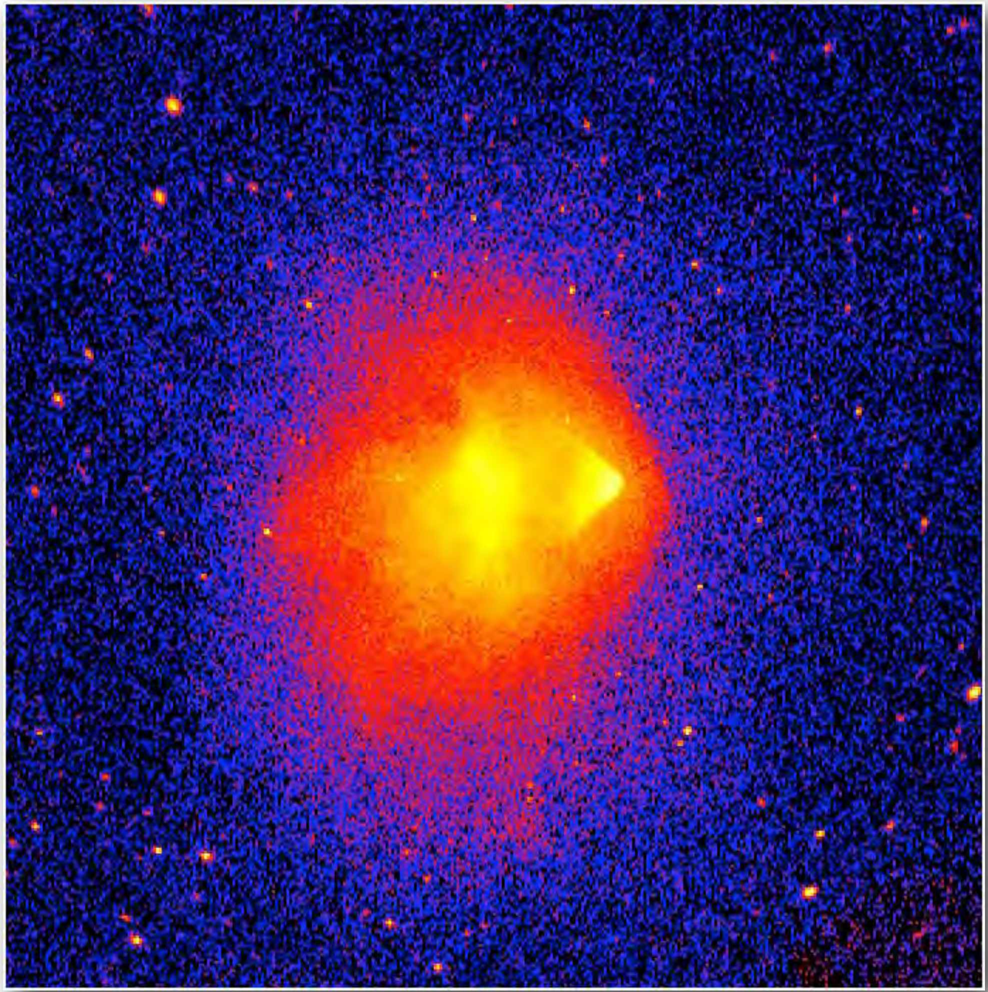
V06

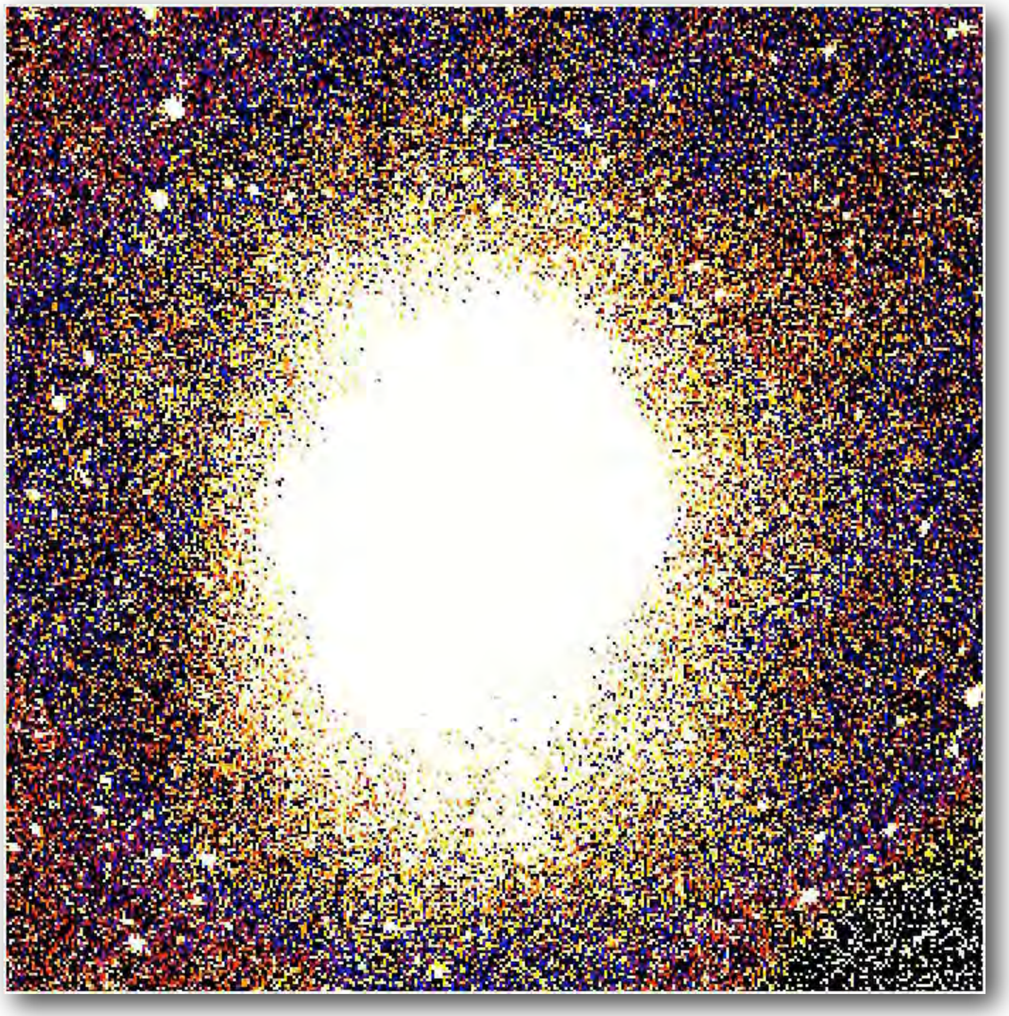
What about “train wrecks” from mergers?





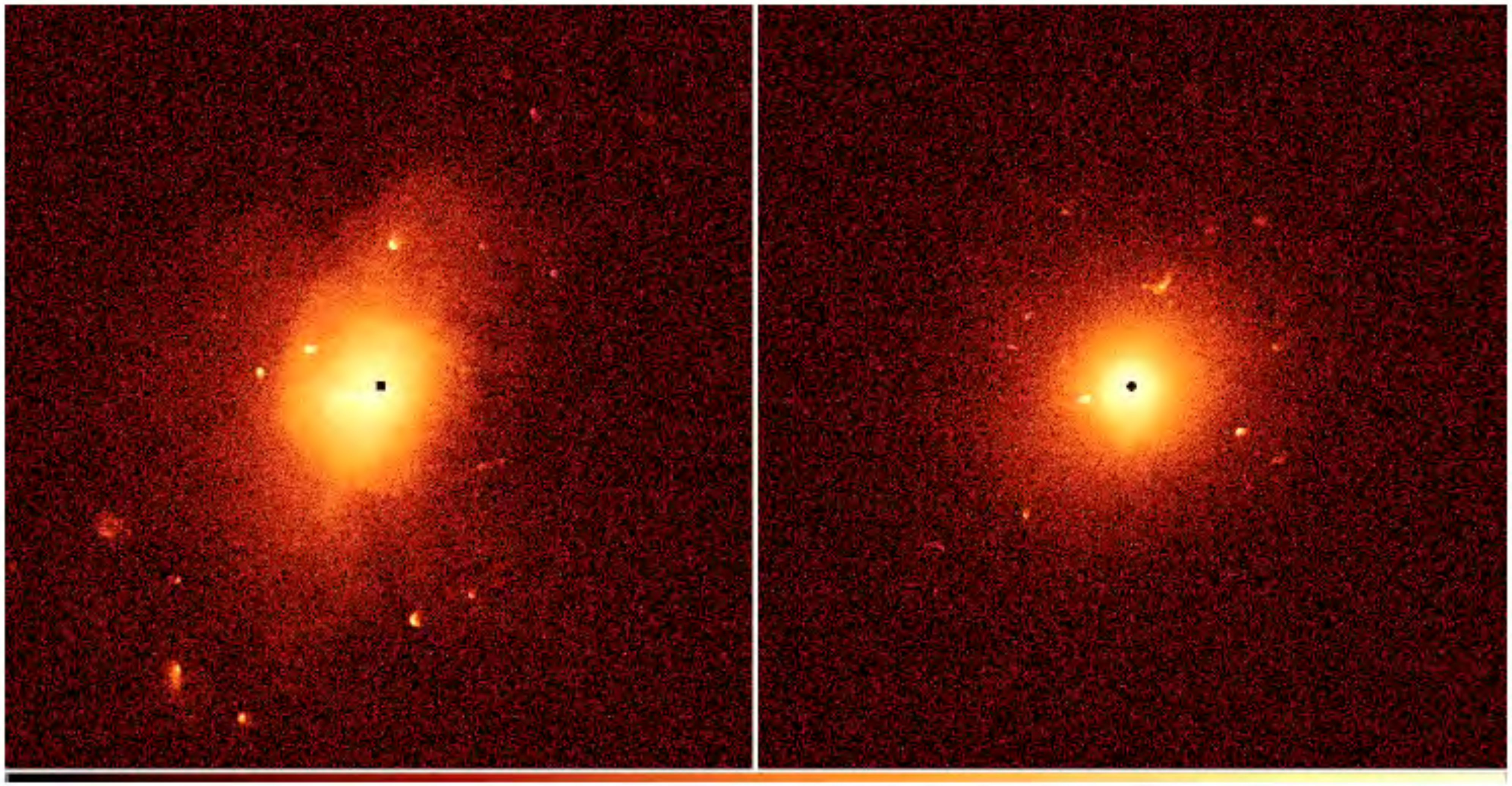
What about “train wrecks” from mergers?





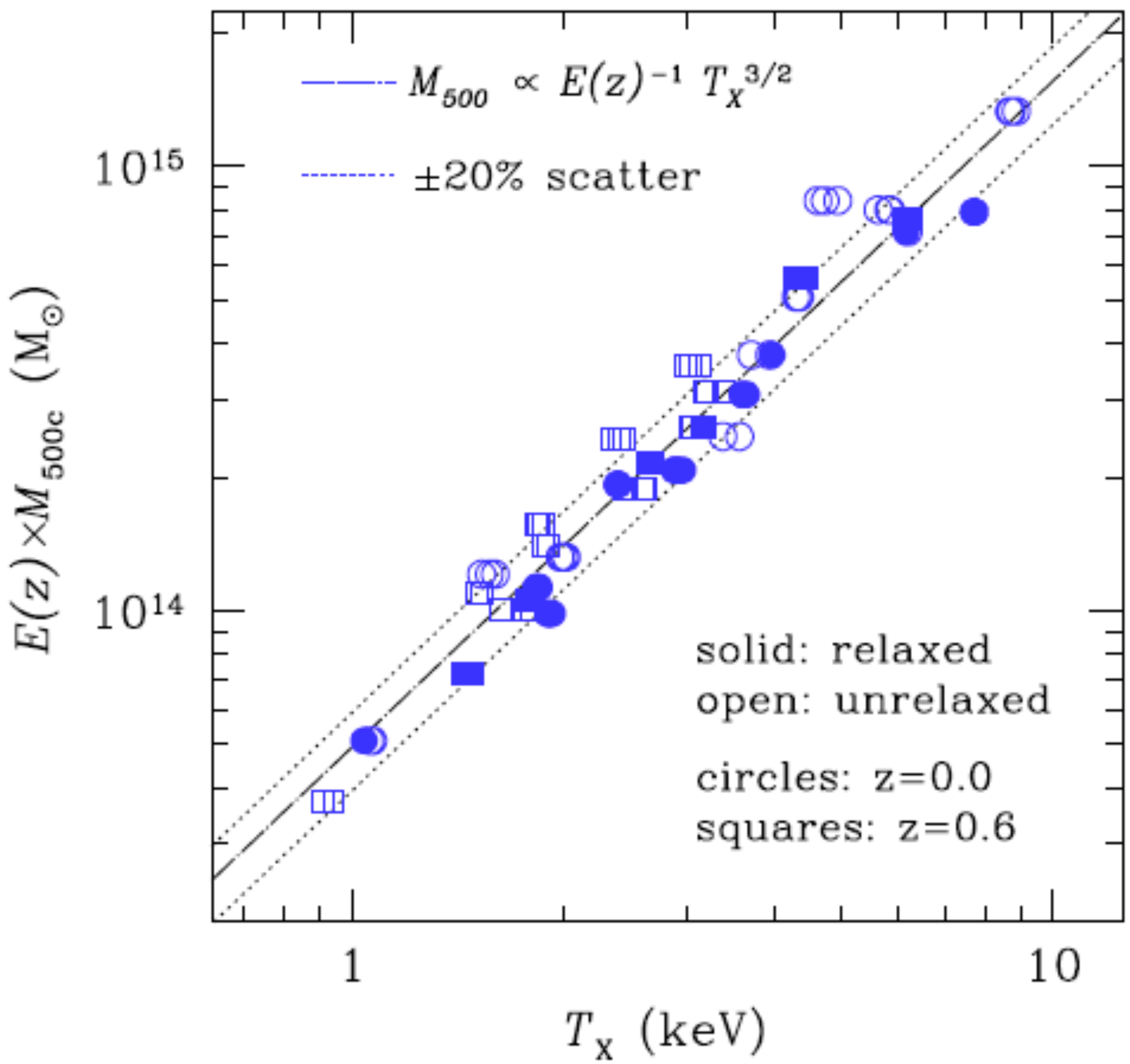
Cluster “train wrecks” are most of the time ~ 1:10 mass ratio merges. Merger energy ≲ binding energy of the system. Spectacular effects in the center, mild distortions to the most of the cluster body.

How do we involve numerical simulations?

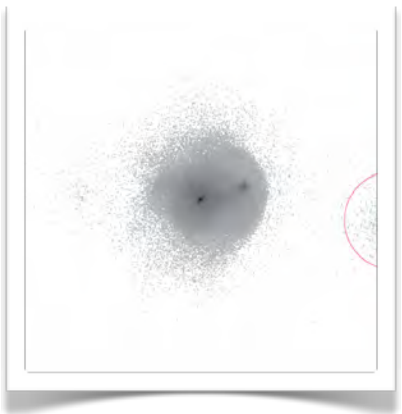


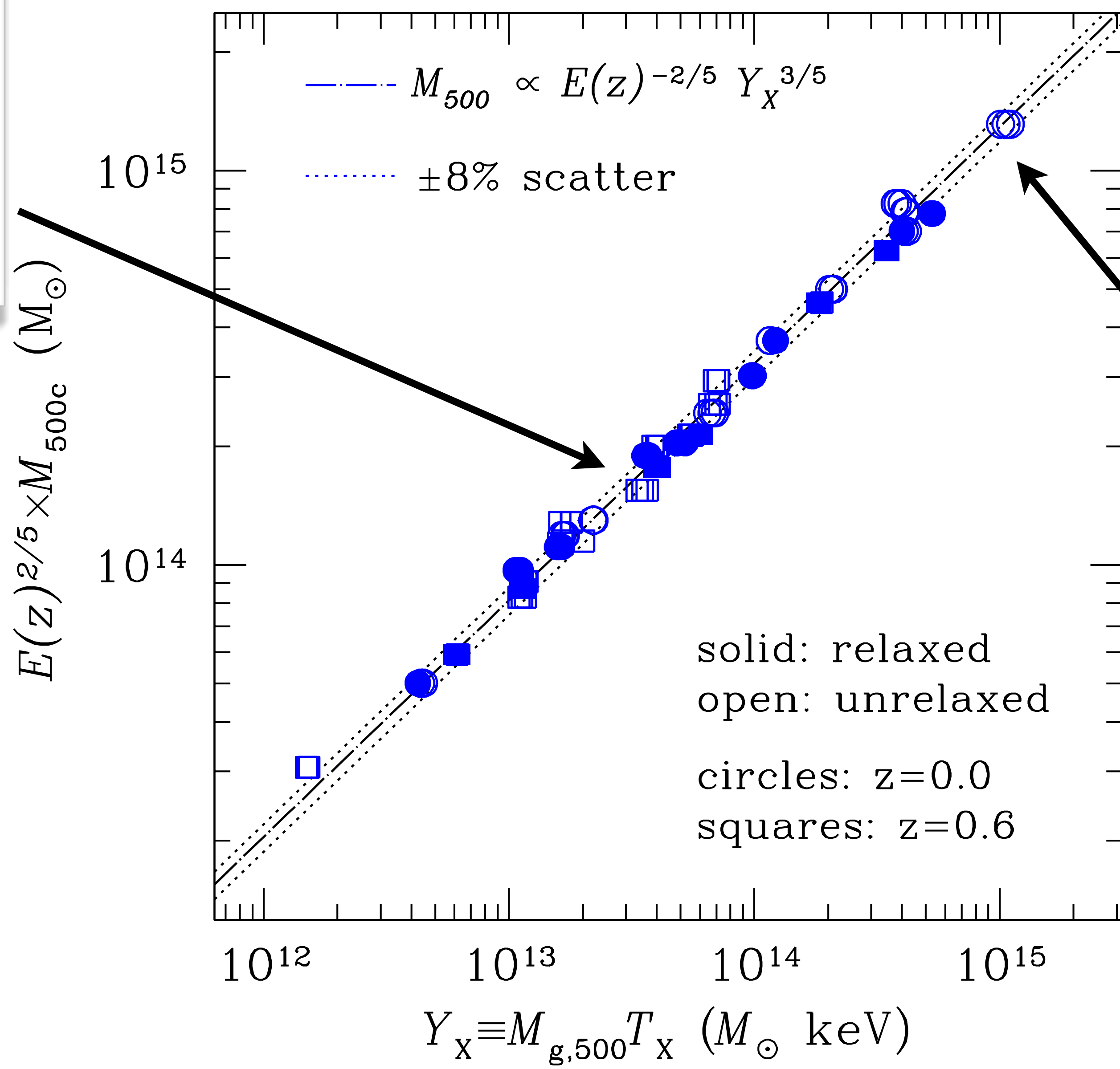
- Use *robust* results from simulations to identify good proxies for M_{tot}
  - low-scatter
  - evolution as in self-similar theory
  - insensitive to dynamical state
- Calibrate the M–proxy relation observationally
- *Possibly*, use first-order corrections to normalization and evolution of the *M*-proxy relation

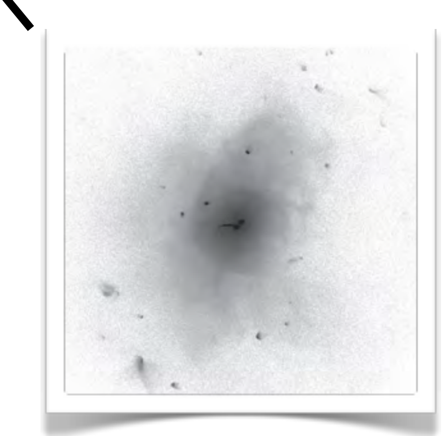
Mass vs. gas temperature relation



There are good mass proxies even for mergers!



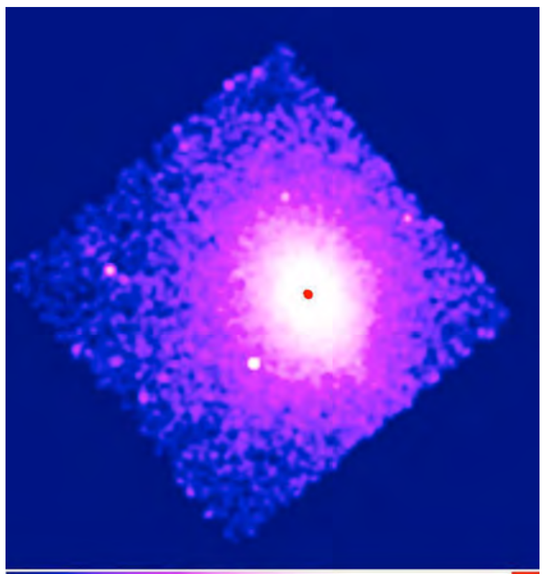


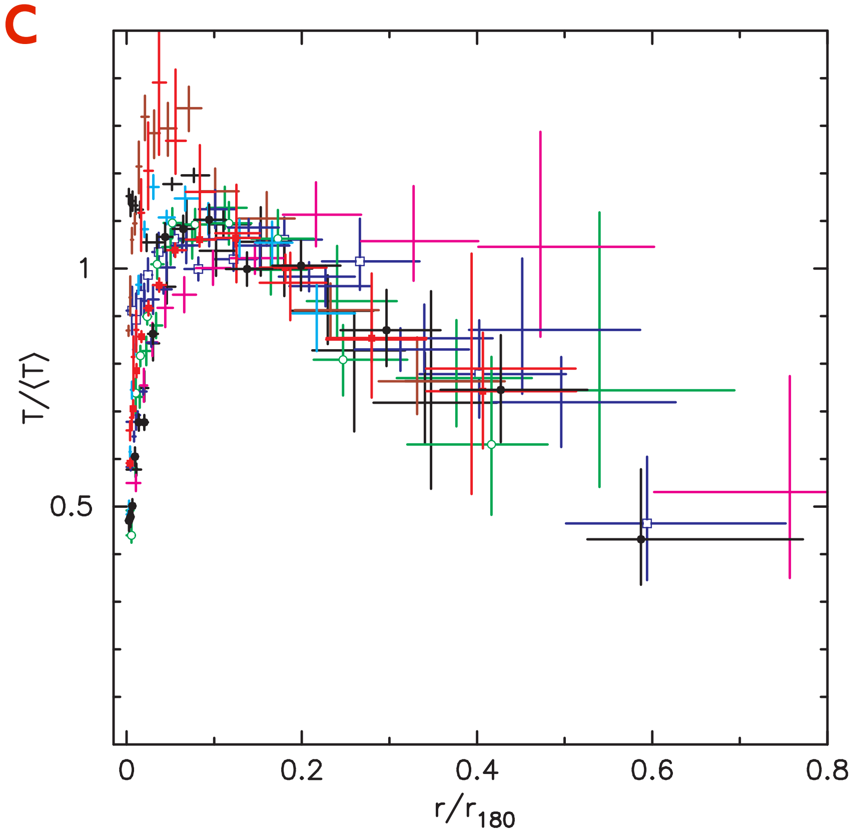


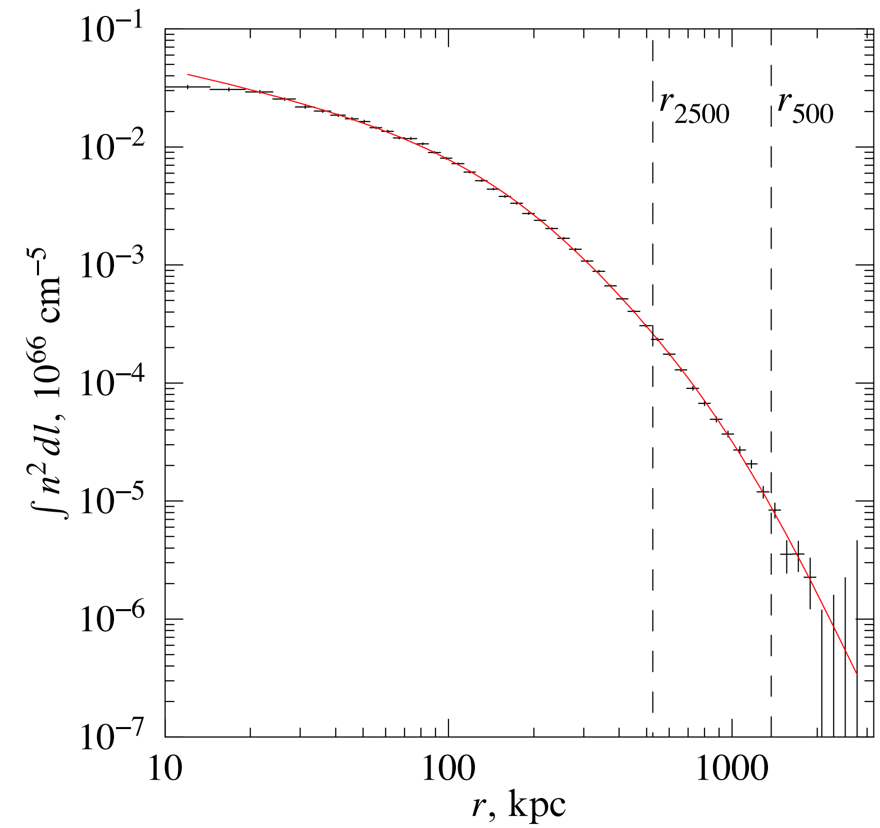
$M \propto Y_X^{3/5}\, E(z)^{-2/5}$ – self-similarity + virial theorem + “fair sample”

Calibration of cluster masses

X-rays (hydrostatic equilibrium):





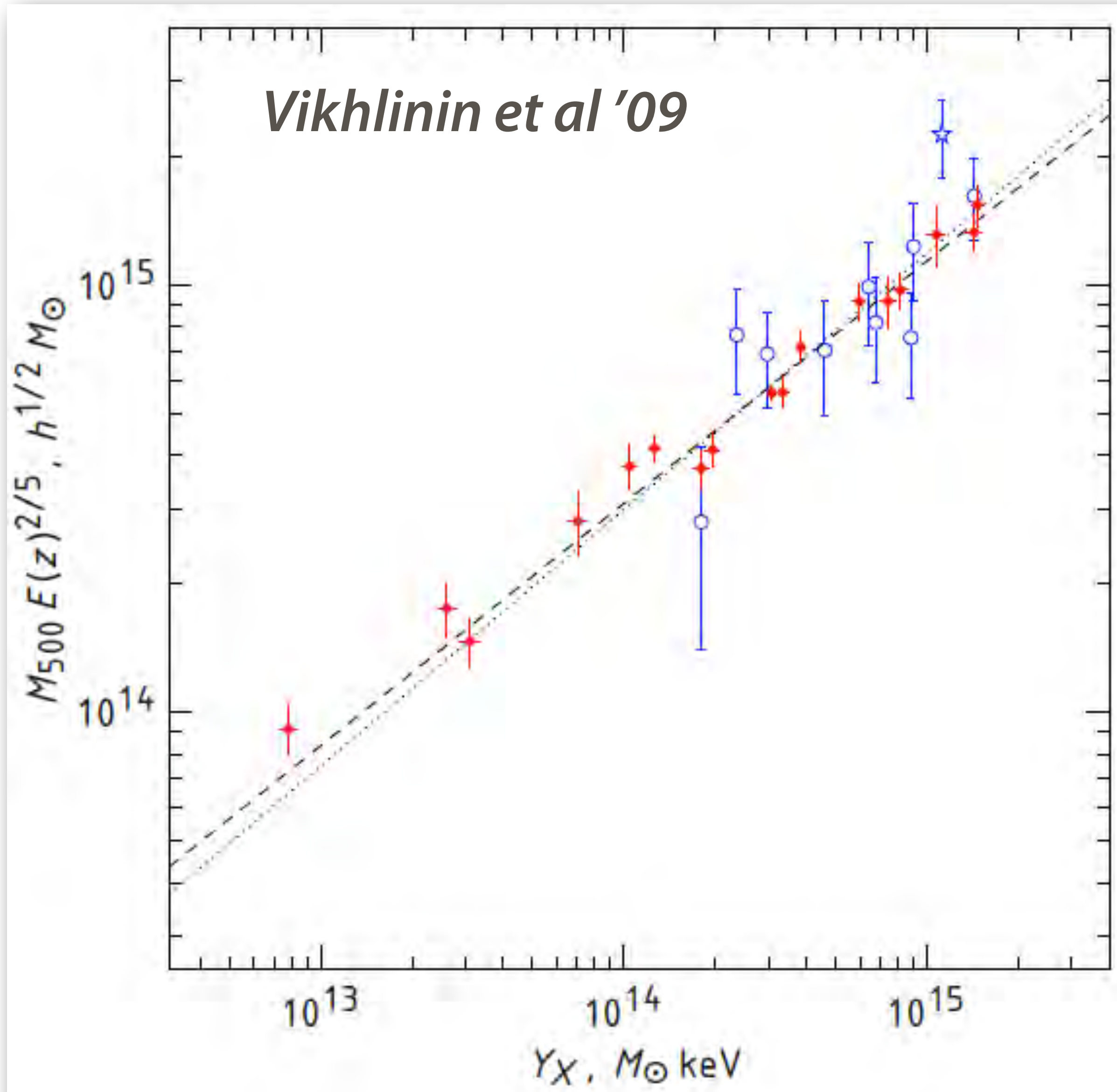


brightness gives M_{gas}; spectrum gives T_{gas}; $M_{tot} = -\frac{r^2}{G}\frac{\nabla P_g}{\rho_g} \propto T(r)\, r \left(\frac{d\ln\rho_g}{d\ln r} + \frac{d\ln T}{d\ln r}\right)$

Lensing: distortions and redshift distribution of background galaxies give M_{tot}

Galaxy velocities: give M_{tot} either through the virial theorem or caustics

Calibration of cluster masses



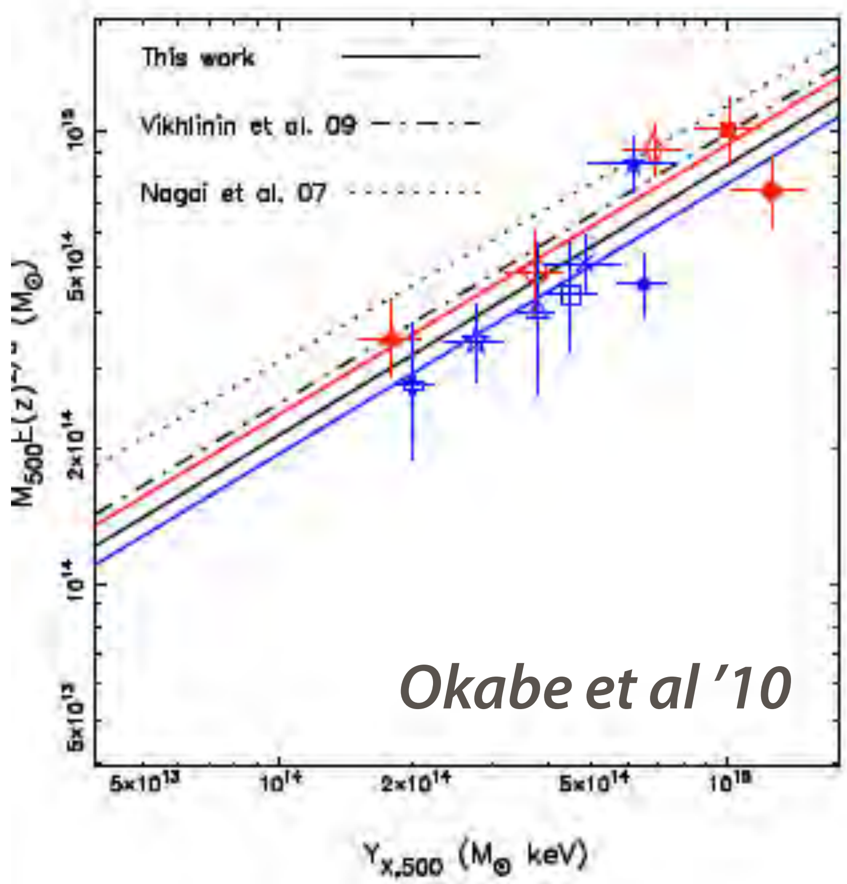
• – *Chandra*, hydrostatic ○ – Weak lensing, Hoekstra '07

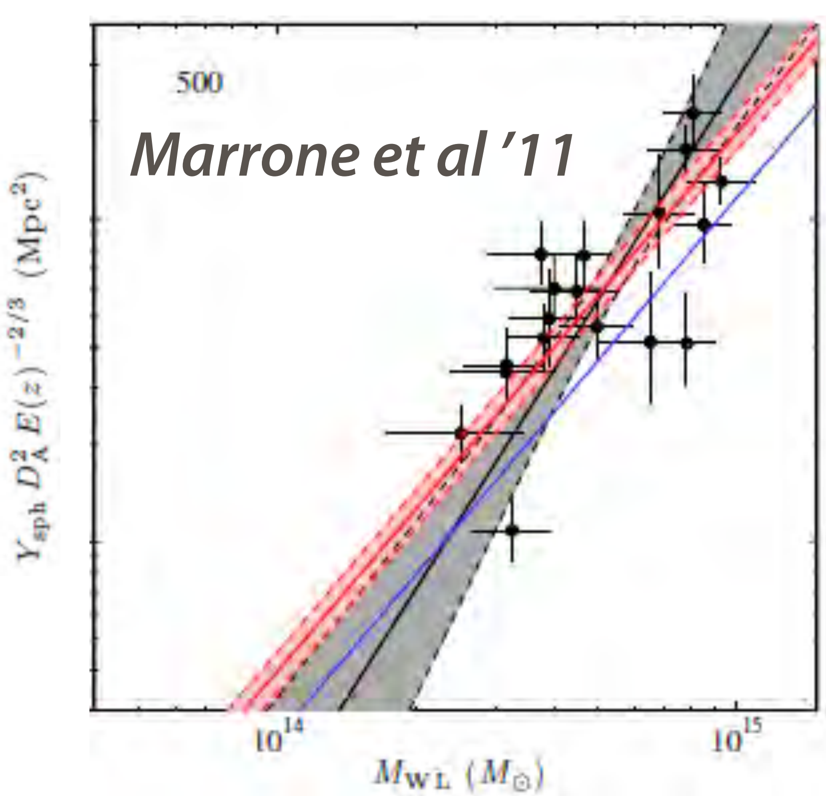
Systematic errors:

$\Delta M/M < 9\%$ at $z=0$

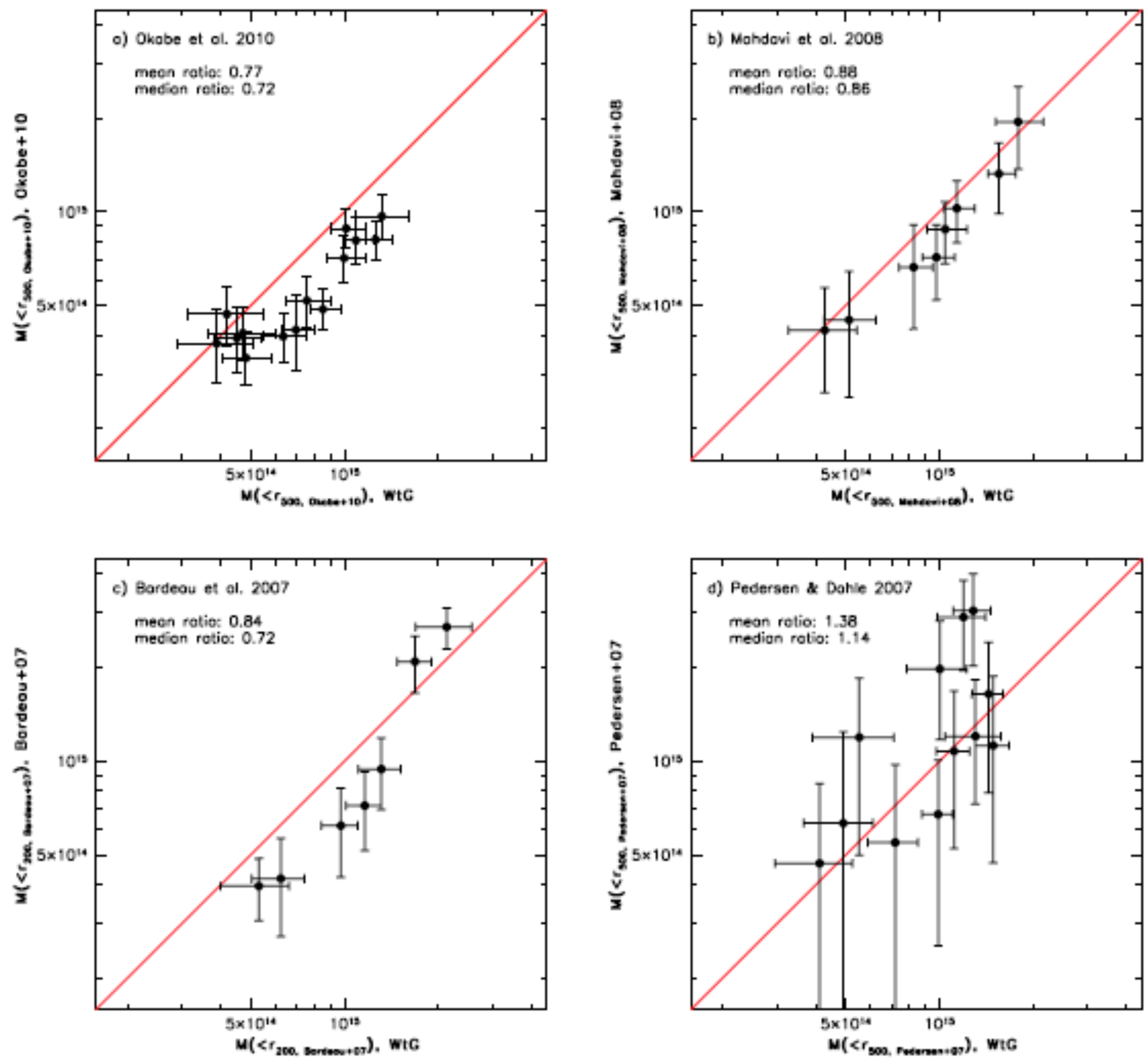
$M/Y^{0.6} \sim E(z)^{-2/5} \pm 5\%$ at $z=0.5$

Calibration of cluster masses: newer results



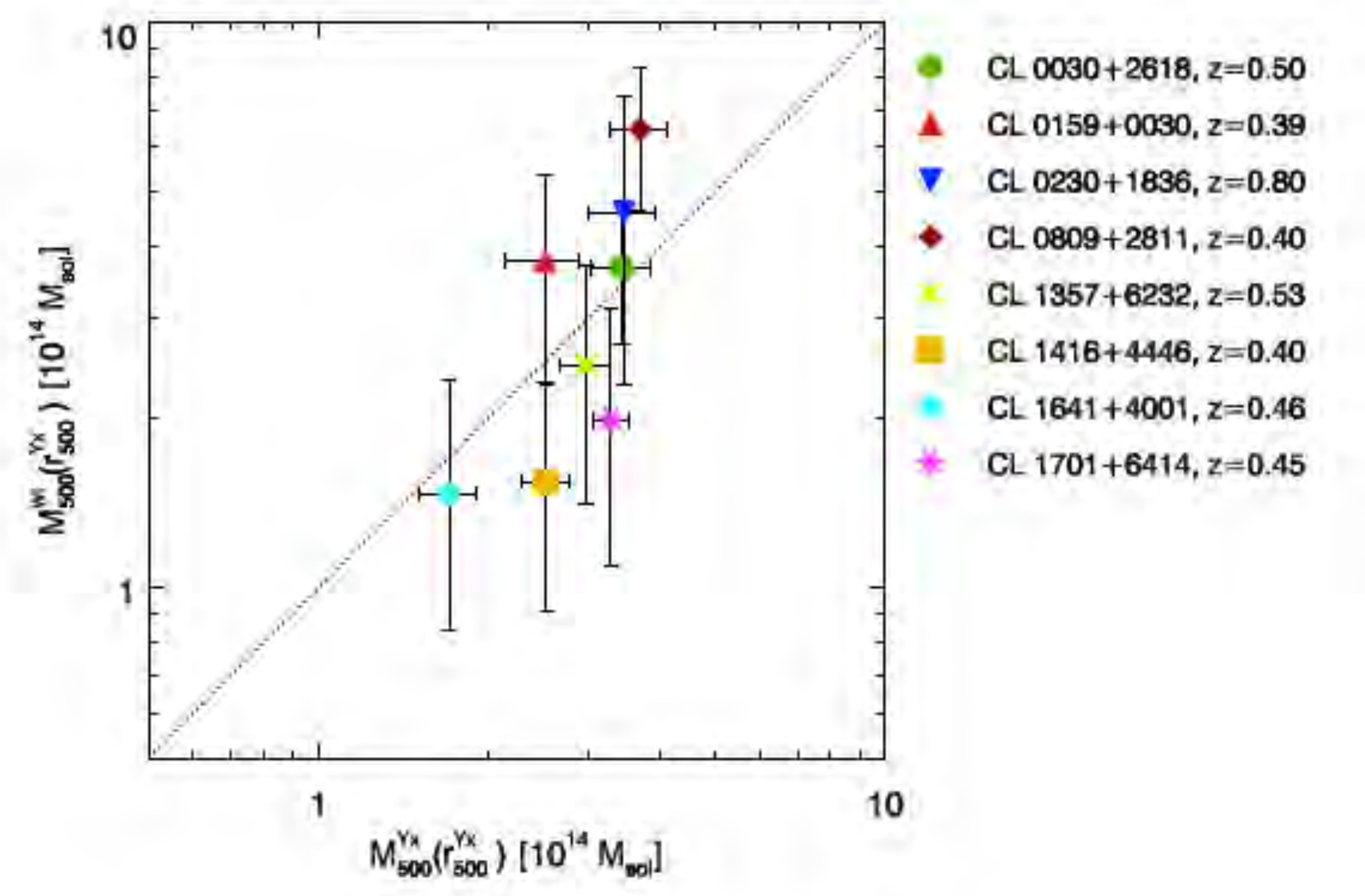


Applegate et al '12. **Probably, the best WL dataset available:**

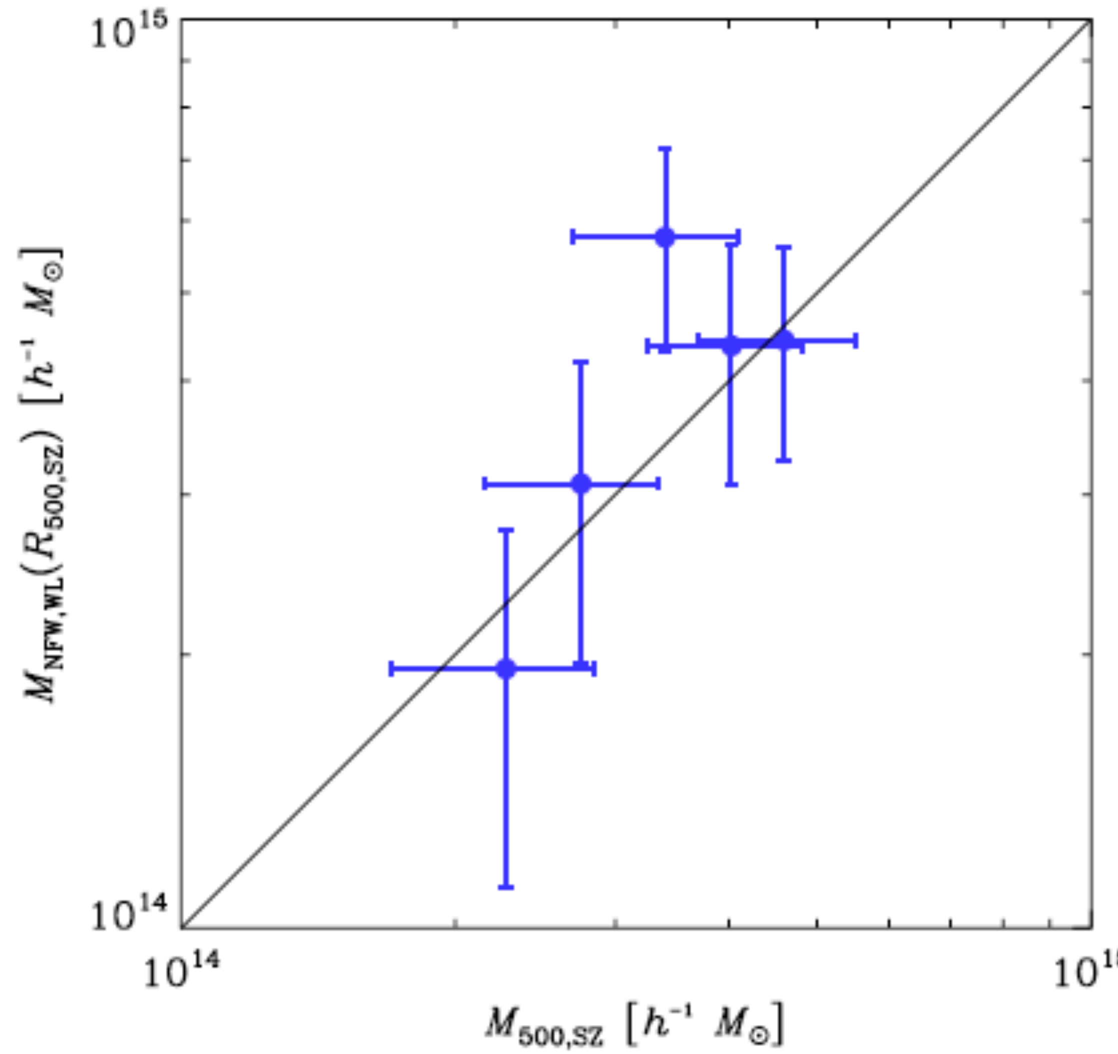


~10–15% agreement with everybody but Okabe et al.
Excellent agreement on average with Hoekstra '07.

Mass calibration at z ~ 0.5 and above



Holger Israel's thesis — Yx vs. weak lensing masses at z=0.5 for 400d clusters

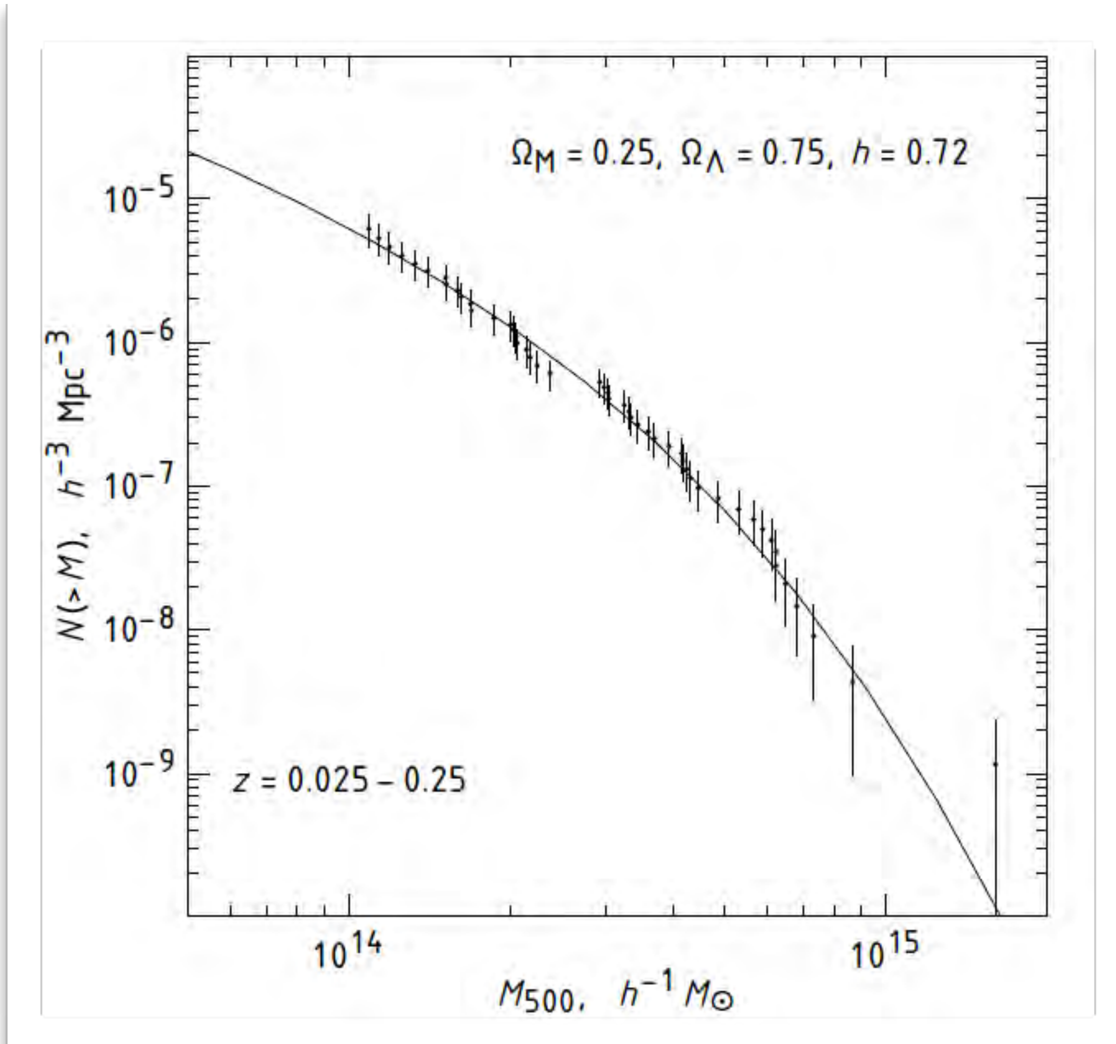


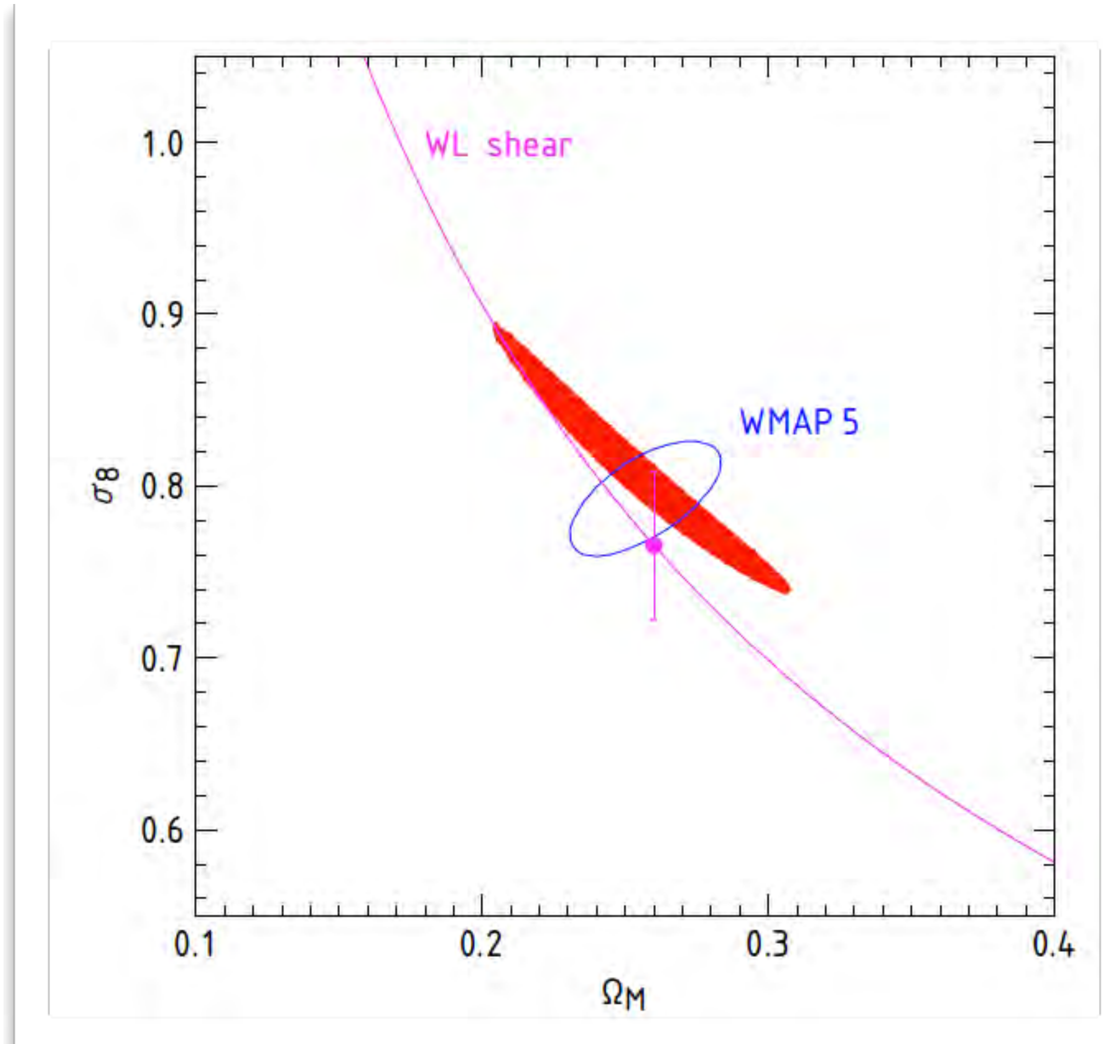
High et al. '12 — SZ significance vs. weak lensing masses at z=0.5 for SPT clusters

±10% uncertainty on average mass at ⟨z⟩=0.5

±18% uncertainty on average mass at ⟨z⟩=0.35

Cosmological results: σ_8

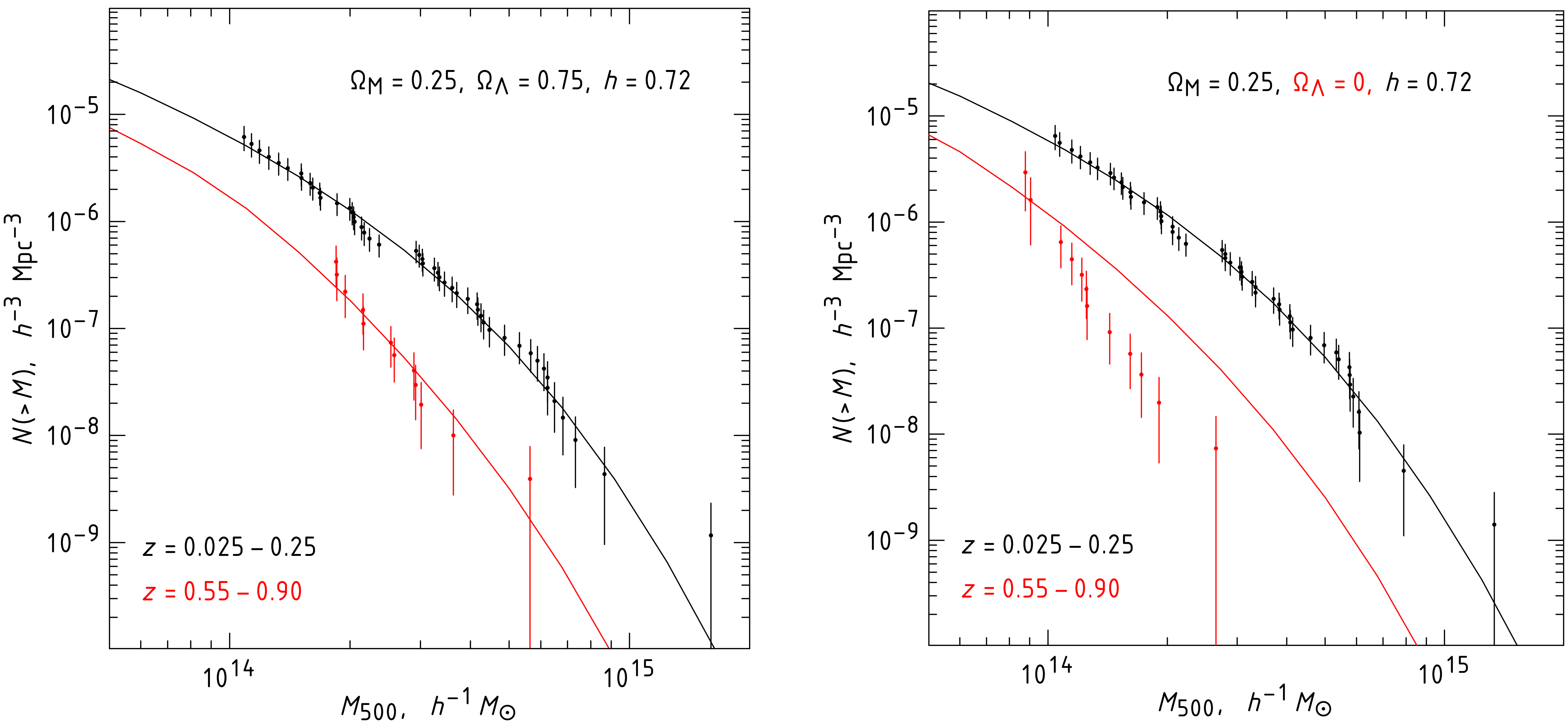




- **50 clusters $\Longrightarrow$ σ_8 to ±1.5% (±3% sys)**

2009 ApJ 692 1060

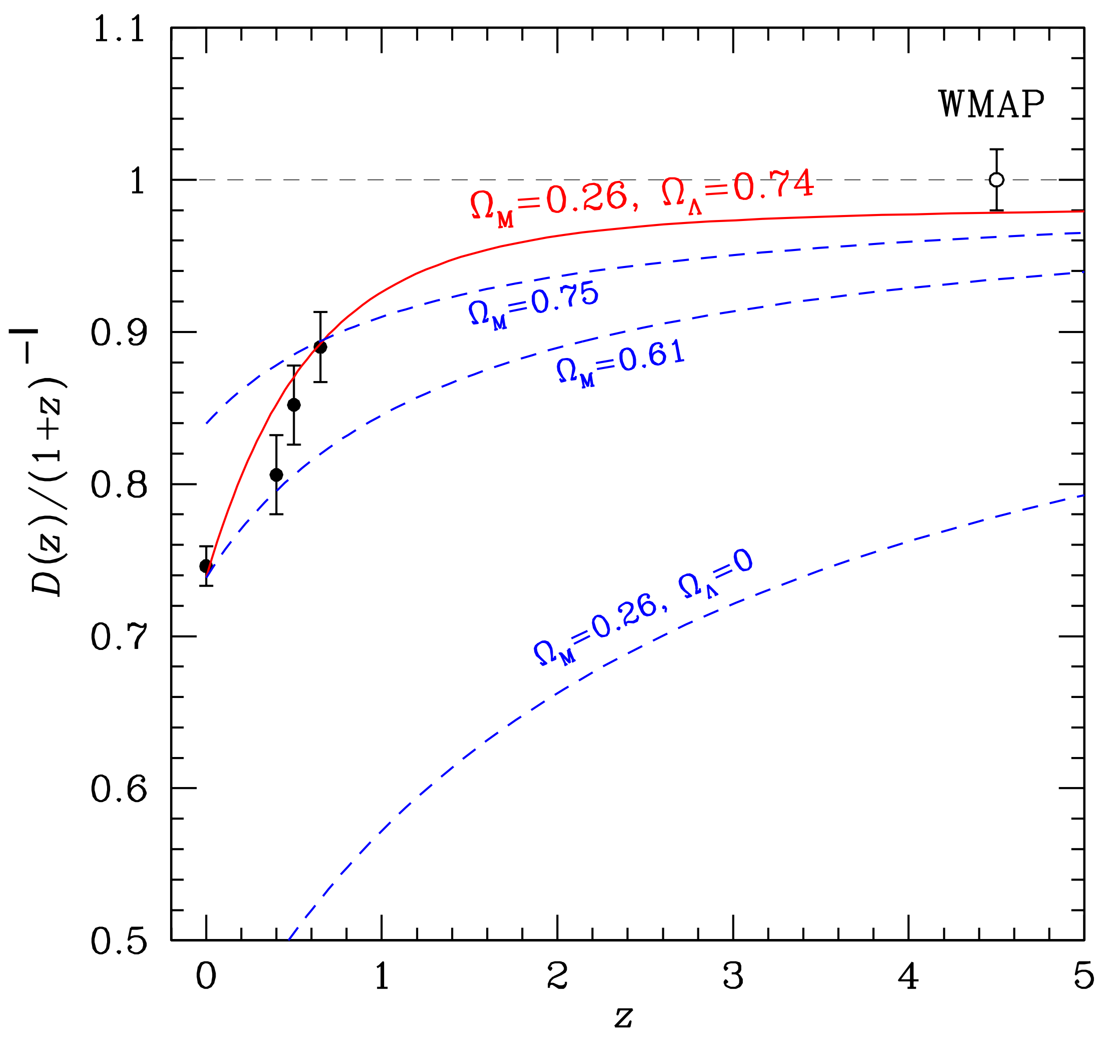
Clusters detect Λ

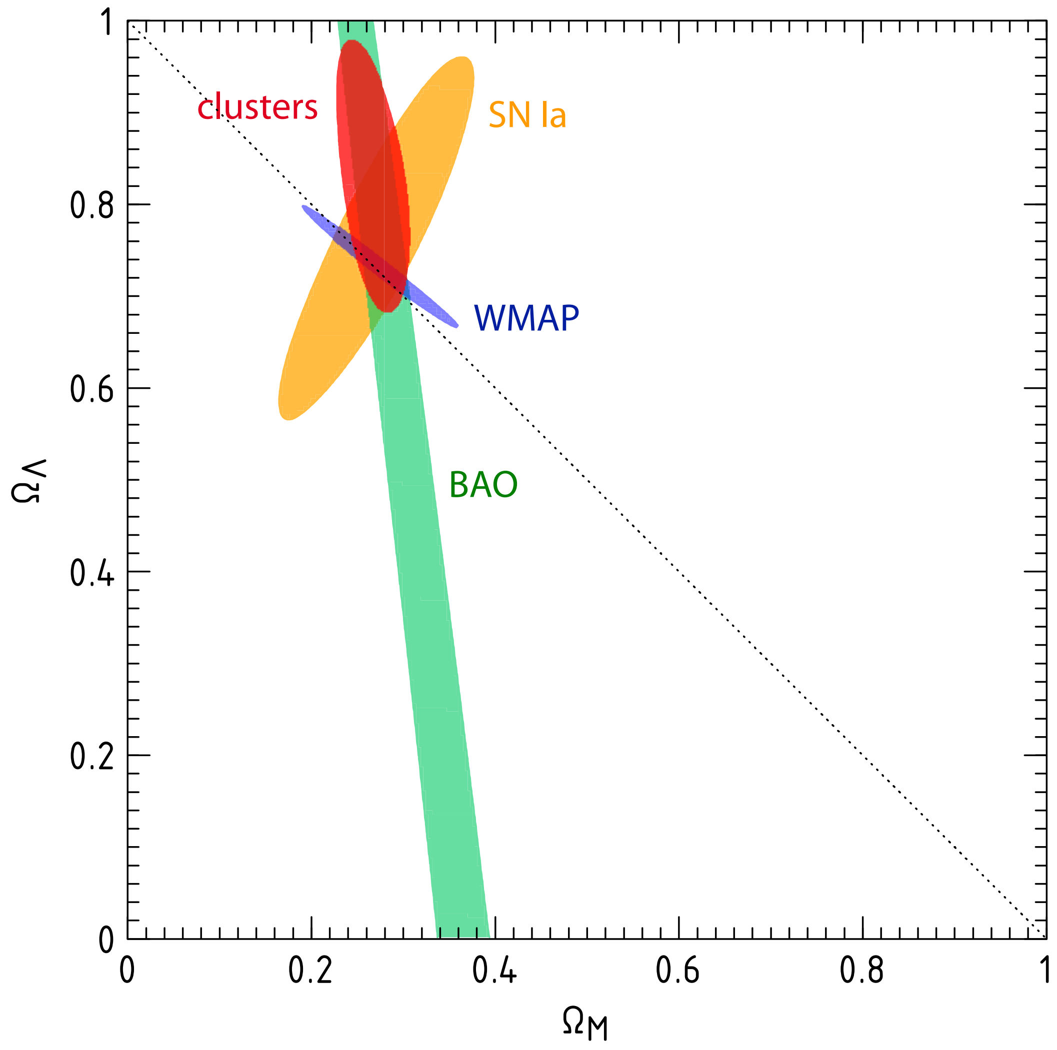


- **Λ > 0 at ~5σ**

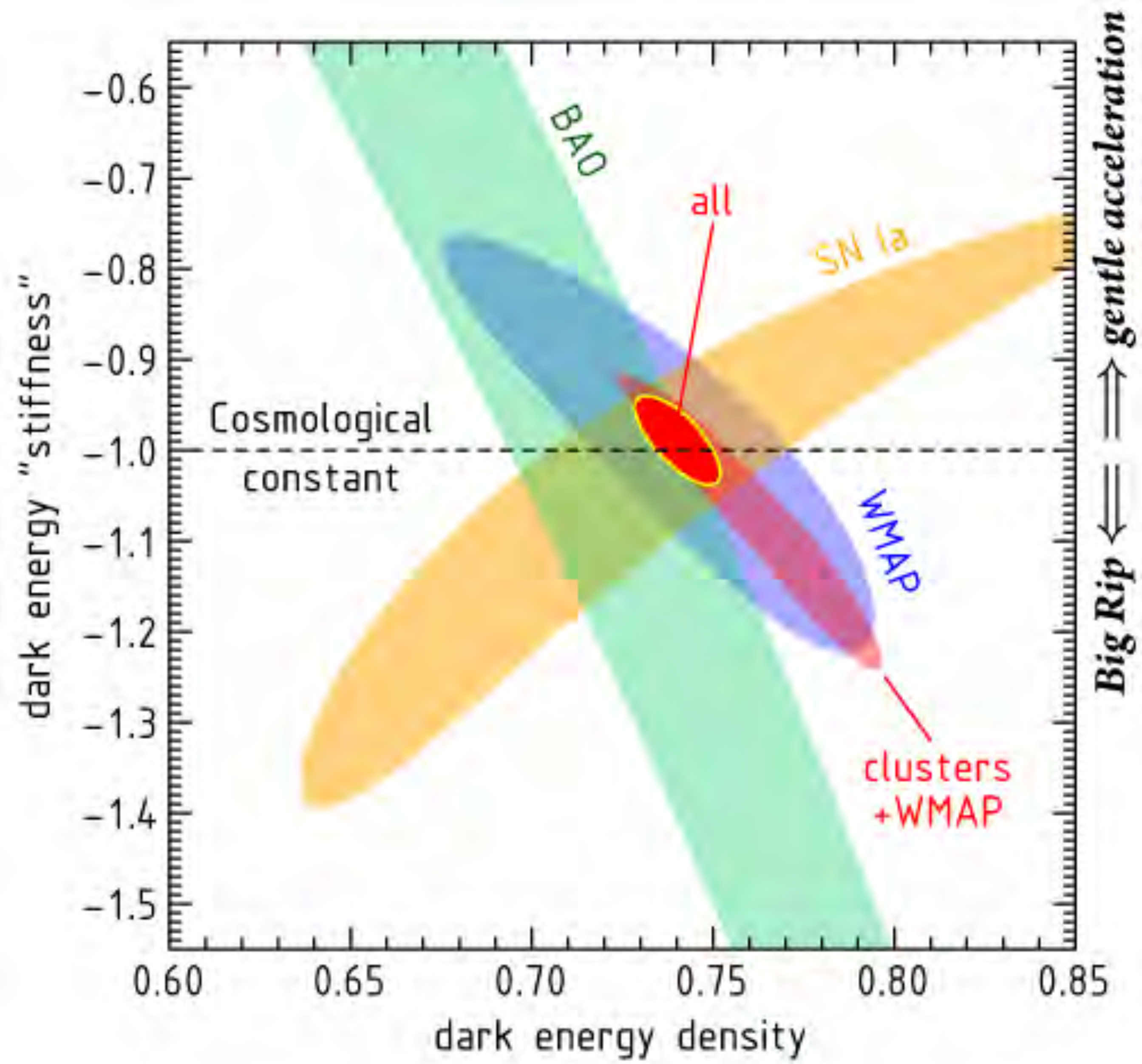
2009 ApJ 692 1060

Clusters detect Λ





w_0 from combination of methods



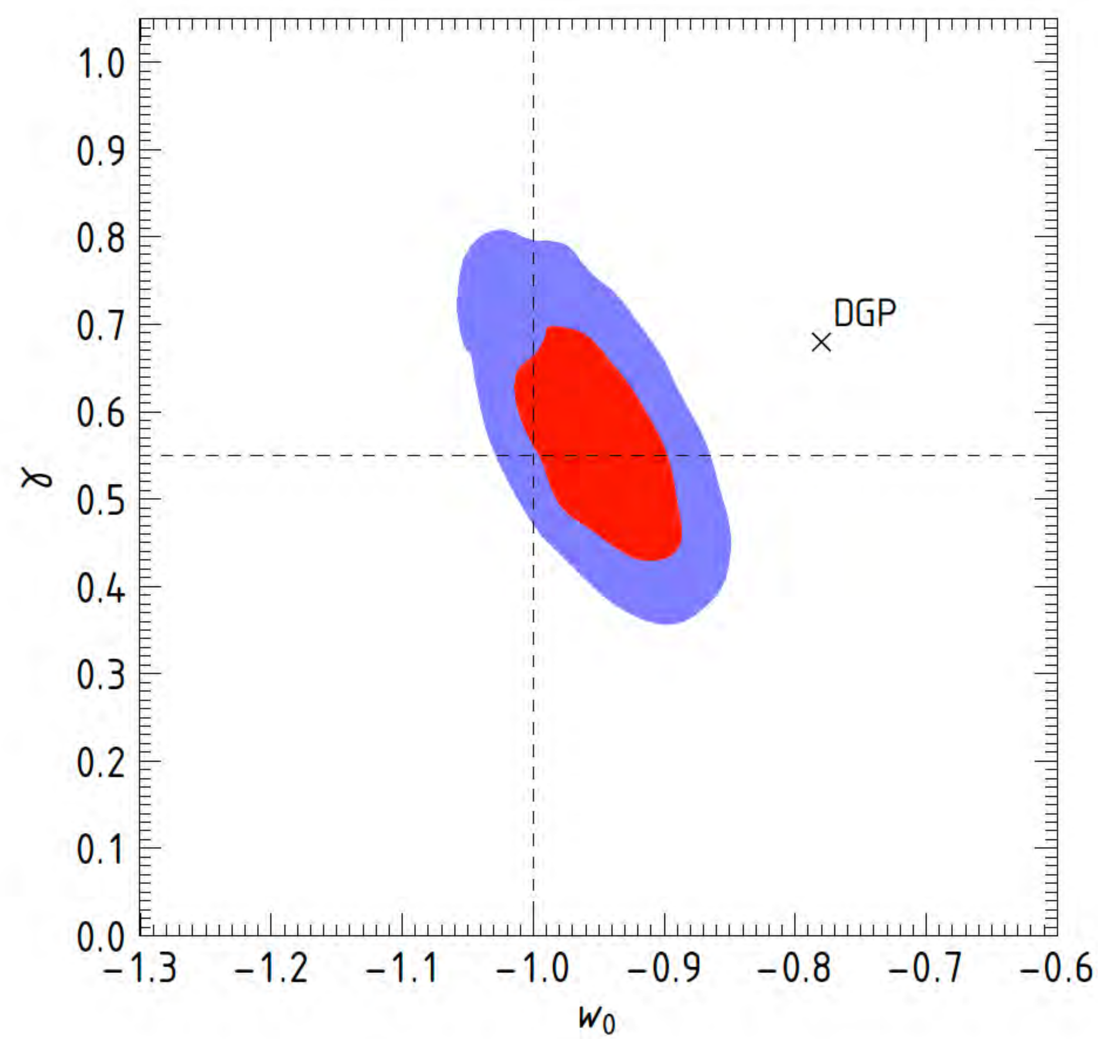
Is Dark Energy dangerous?

$w_0 = -0.99$ ± 0.045 (stat) (± 0.067 without clusters)

± 0.039 (sys) (± 0.076)

2009 ApJ 692 1060

Testing GR with clusters: growth index



- **Growth index, γ:**

$$d\ln D/d\ln a = \Omega_M(a)^\gamma$$

- **$\gamma \approx 0.55$ for wCDM**
- **$\gamma = 0.55 \pm 0.08$ measured ± 0.10 without WMAP reference**

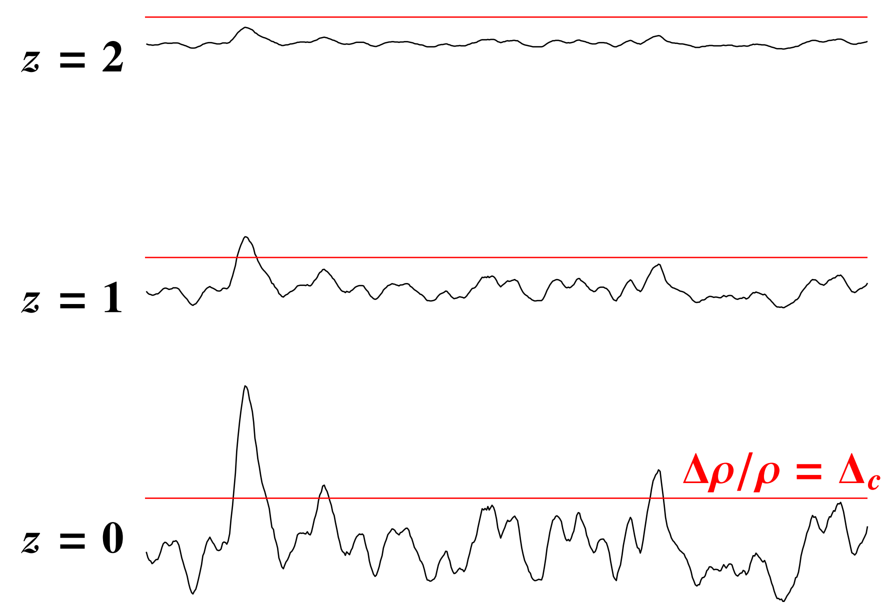
(For published results, see Rapetti et al '10)

GR & cluster formation theory

- **Linear growth:**

$$\ddot{\delta} + 2H(z)\,\dot{\delta} - \tfrac{3}{2}H(z)^2\Omega_M(z)\,\delta = 0$$

- **Non-linear collapse:**



Universal form for $dN/d\sigma(M)$

- **Mass-observable relations:**

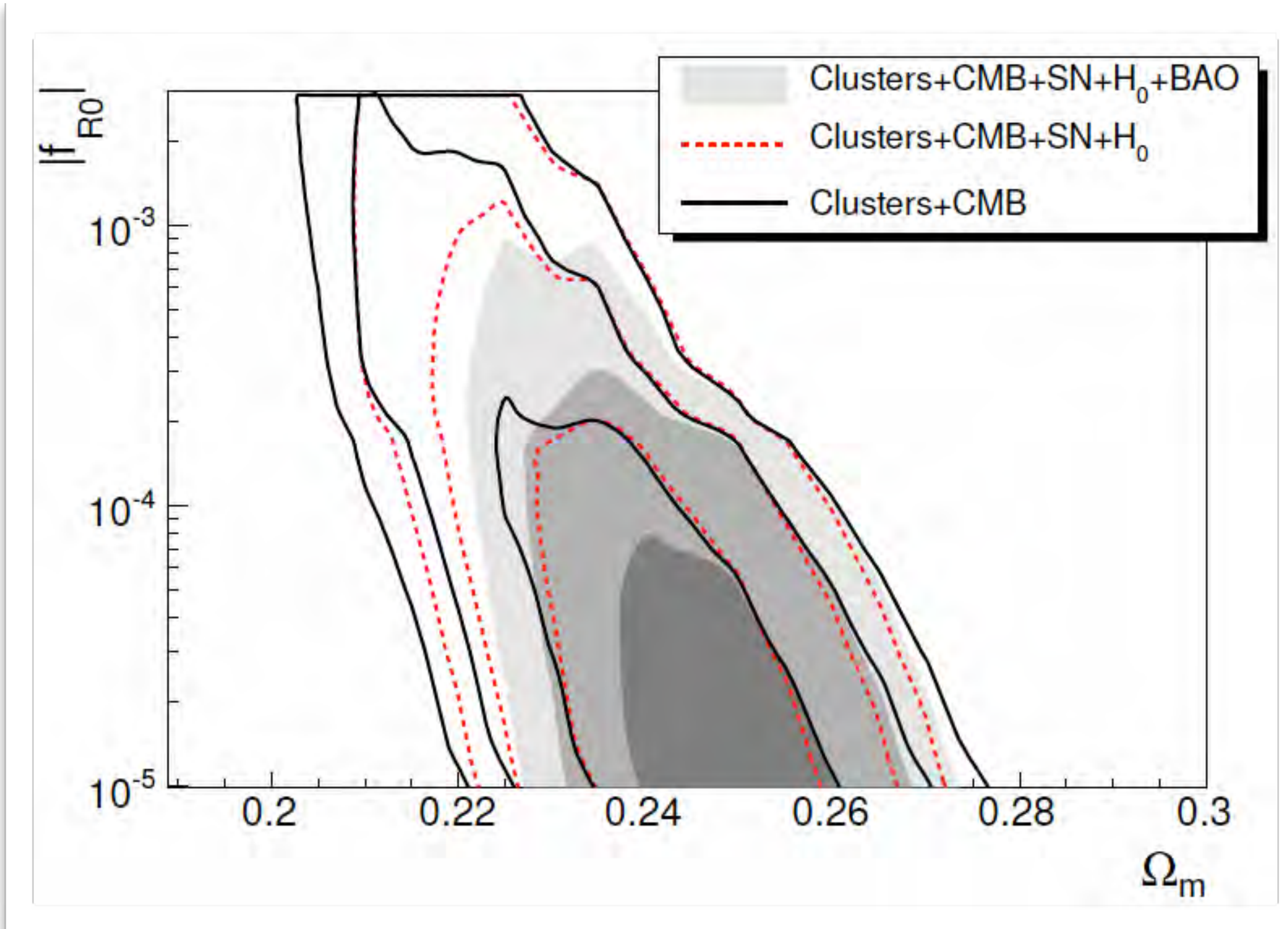
Some affected: $M \sim T^{3/2}H(z)$, some not: $M \sim M_{\rm gas}$

Testing GR: self-consistent treatment of an f(R) model

- $16\pi G\,\mathcal{L}_g = R + f(R) = R - 16\pi G\rho_\Lambda - f_R \times R_0{}^2/R$
- Chameleon effect: in the strong field regime ($R \gg 0$), gravity —> GR
- distances modified by $O(f_R)$ — indistinguishable from ΛCDM
- $\lambda_C \approx 32\,(f_R/10^{-4})^{1/2}$ Mpc in the background today
- On scales $< \lambda_C$, gravity = GR; on scales $> \lambda_C$, forces enhanced by 33%
- Lensing potential modified by $1+f_R$ —> $M_{lens} = M_{true}$

Schmidt & Hu

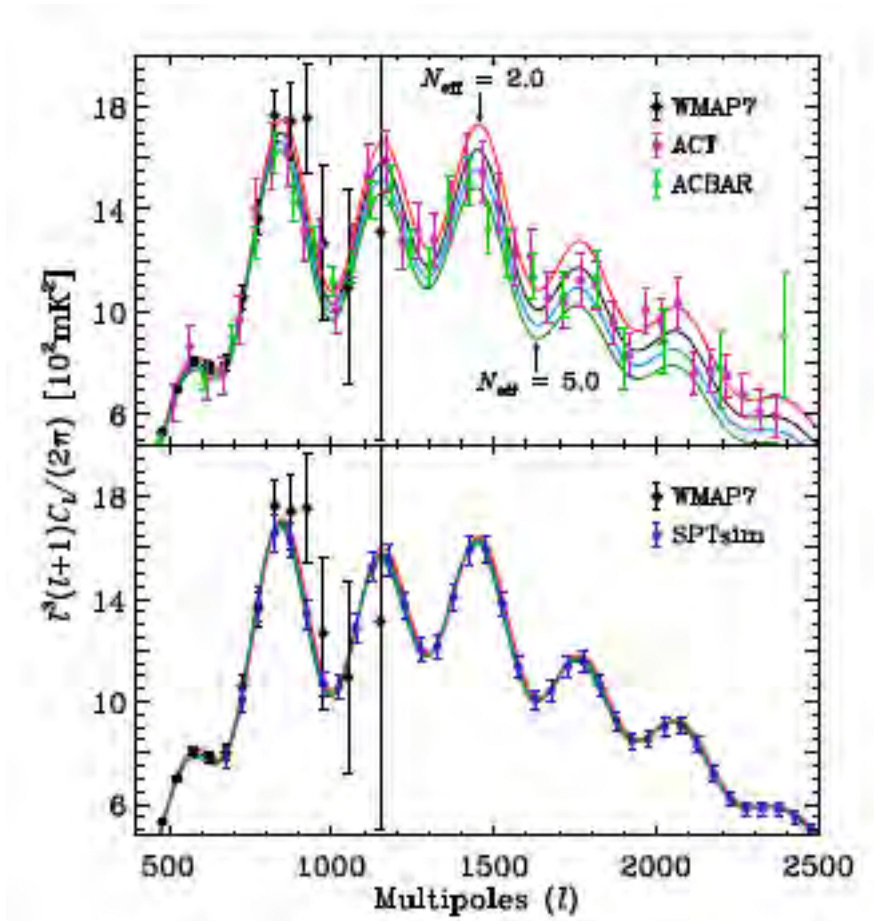
Testing GR: self-consistent treatment of an f(R) model

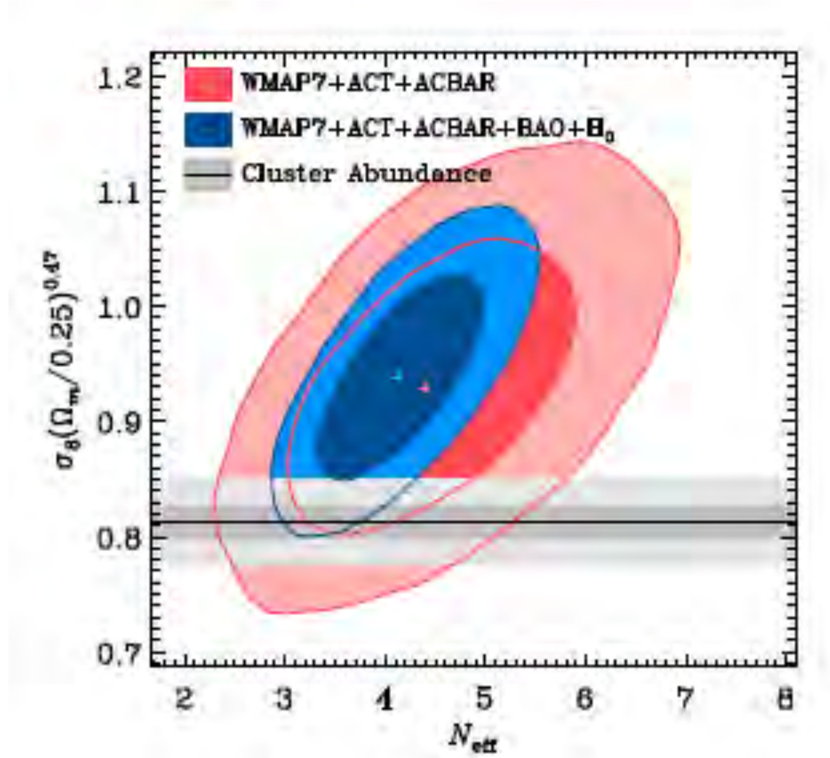


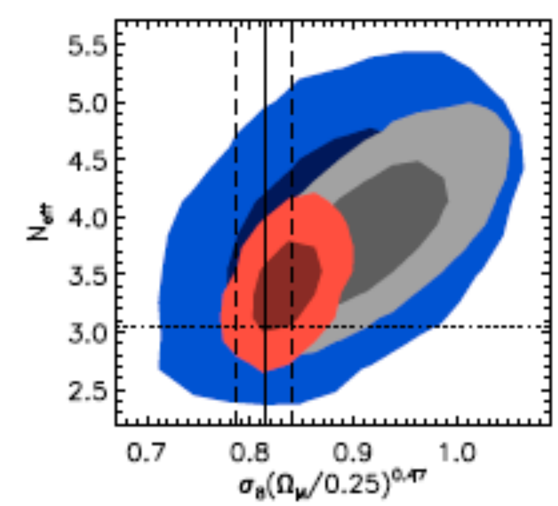
$$16\pi G\,\mathcal{L}_g = R + f(R) = R - 16\pi G\rho_\Lambda - f_R \times R_0{}^2/R \qquad f_R < \text{a few} \times 10^{-4}$$

Schmidt, Hu & AV 2009

Neutrino constraints







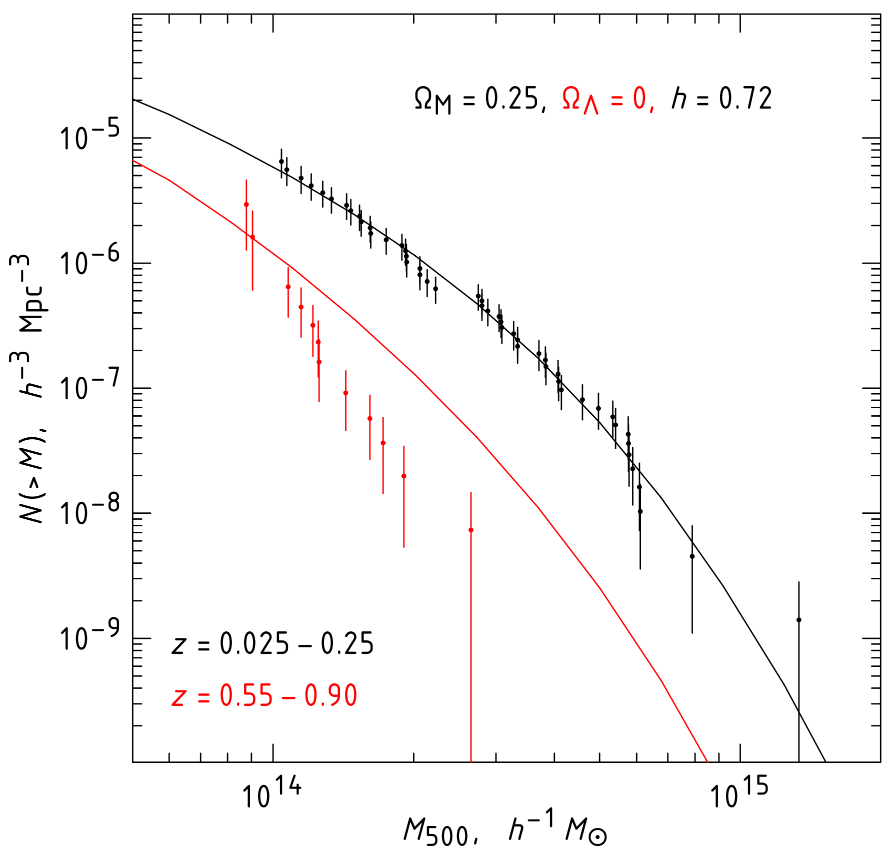
CMB + clusters gives
N_{eff} ~ 3 if m_ν=0
or
sum m_ν < 0.3 eV if N_{eff} = 3.05 — but watch for new developments

Part III

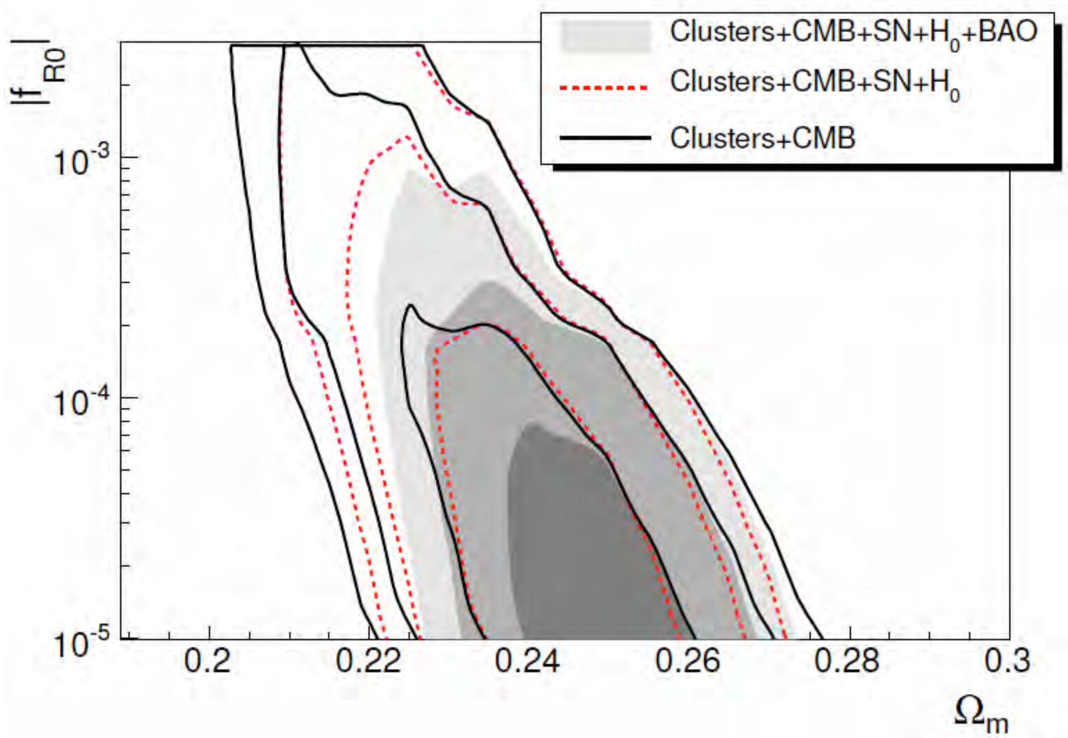
Prospects and issues for the future of cluster cosmology

With just 100 well-observed clusters:

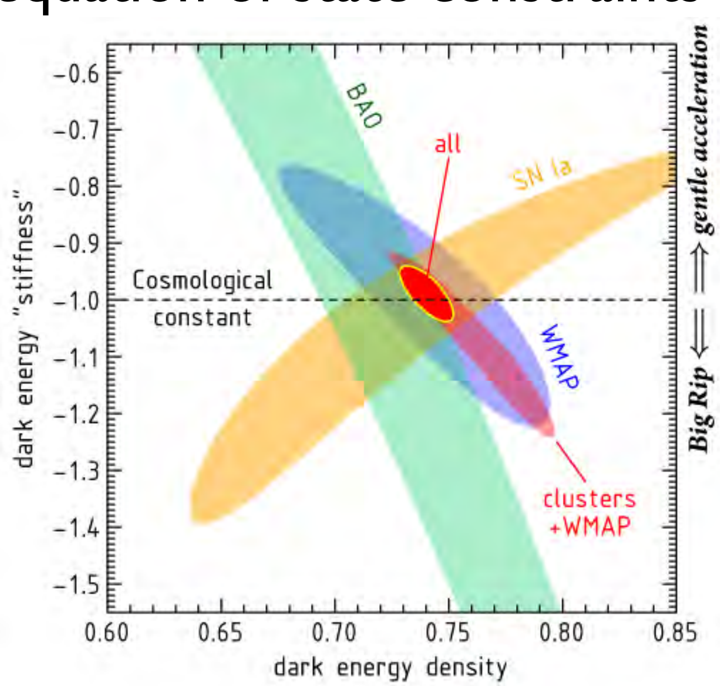
5-sigma detection of Dark Energy



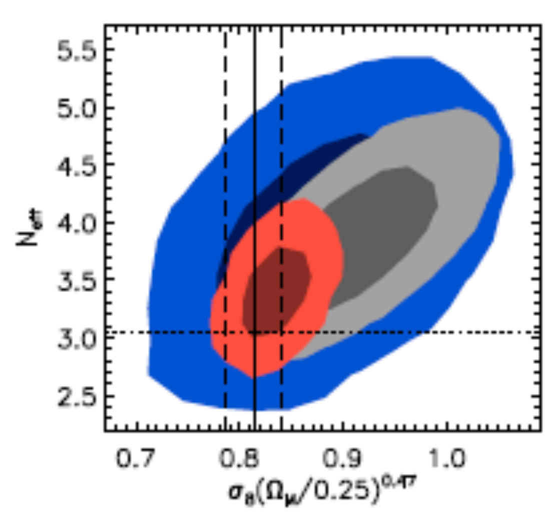
0.01% constraints on certain modifications of GR



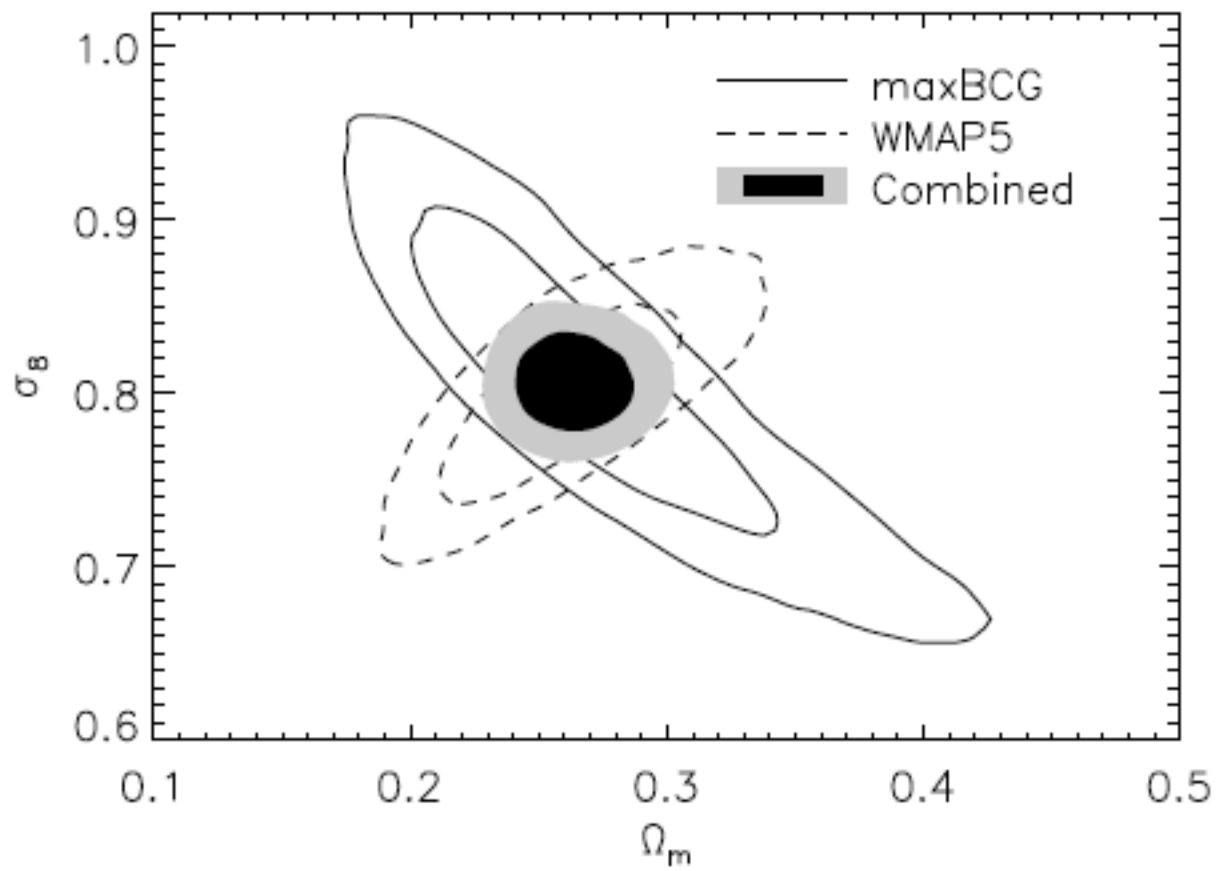
equation of state constraints



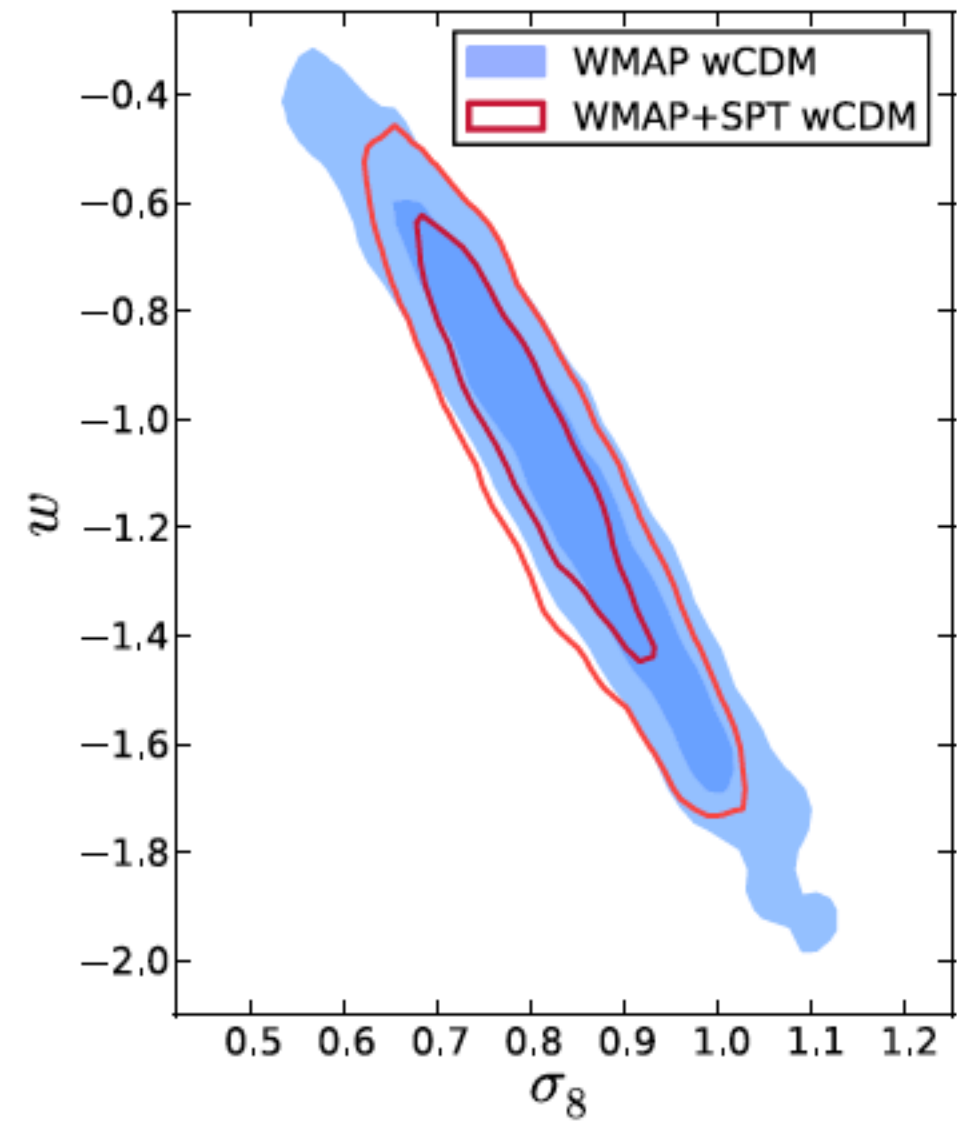
~ 0.3 eV constraint on the total mass of light neutrinos



With with not so well-observed clusters:



SDSS results, Rozo et al.



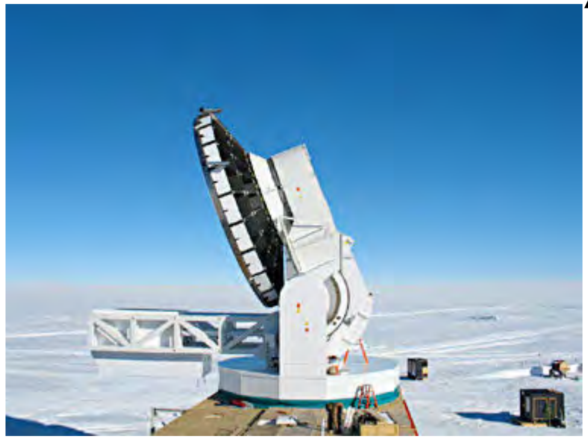
SPT, Vanderlinde et al.

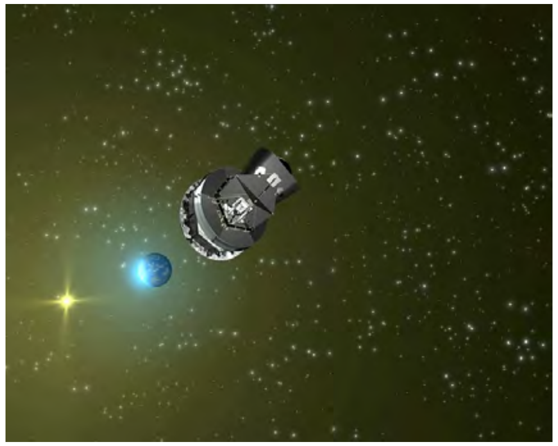
- **X-rays: 50 clusters $\Longrightarrow$ σ_8 to $\pm 1.5\%$ ($\pm 3\%$ sys)**
- **SDSS: 10,000+ clusters $\Longrightarrow$ σ_8 to $\pm 3.3\%$**

Future Projects

SZ

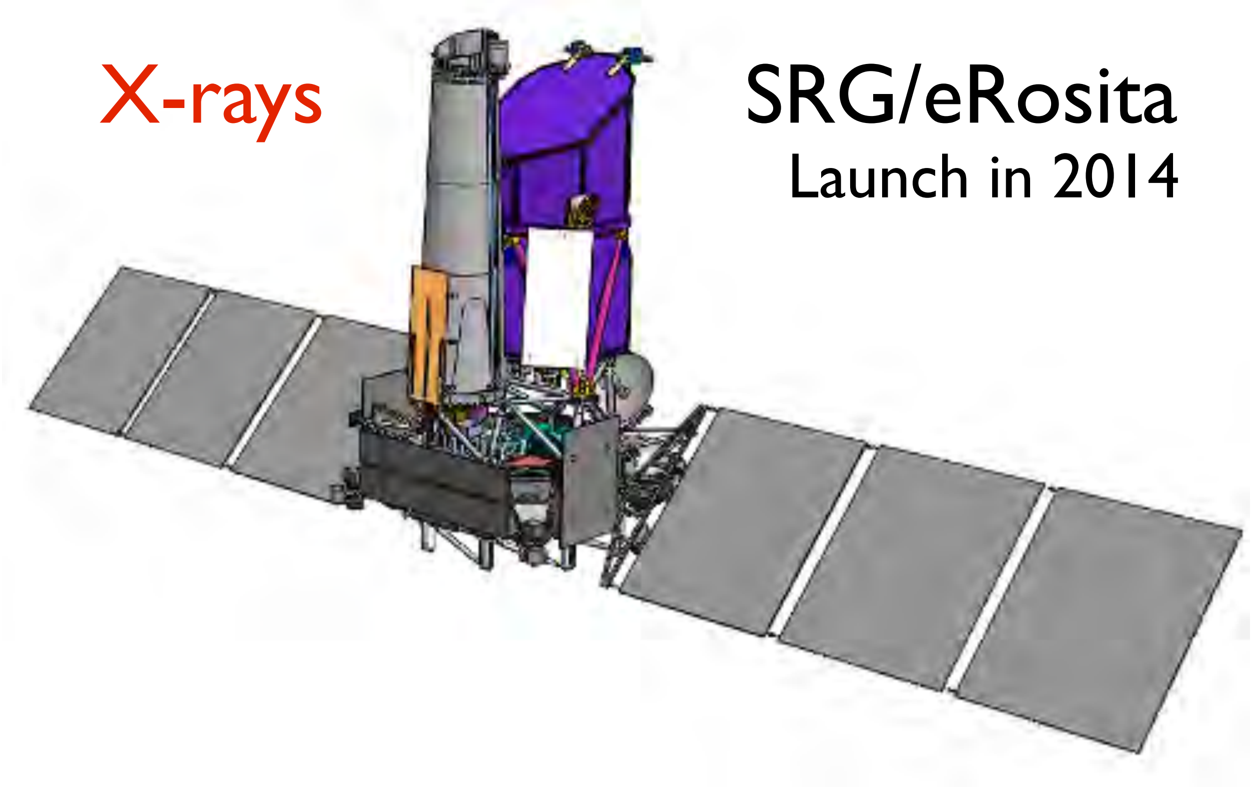
SPTpol, ACTpol, Planck, Mustang-2, CARMA, ... up to a few thousand very massive clusters





Optical & IR

X-rays



SRG/eRosita
Launch in 2014

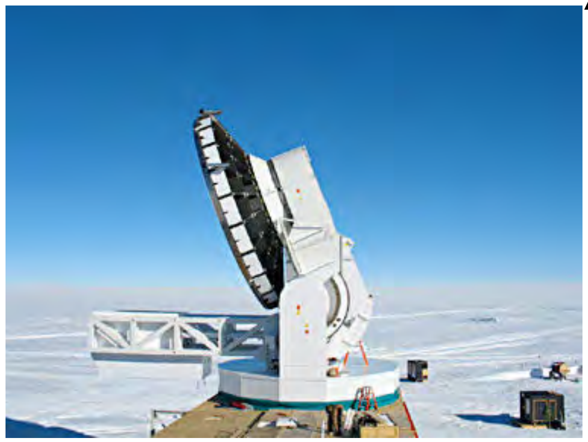
DES, Euclid, LSST, WFIRST

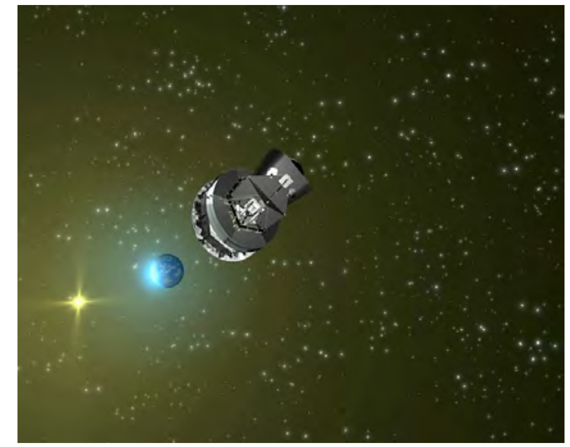
10^5–10^6 clusters to $z \sim 2$–3

- 100,000 – 200,000 clusters, $z_{max} \approx 1.5$
- all clusters in the Universe with T>4.5 keV

Future Projects

SPTpol, ACTpol, Planck, Mustang-2, CARMA, ... up to a few thousand very massive clusters

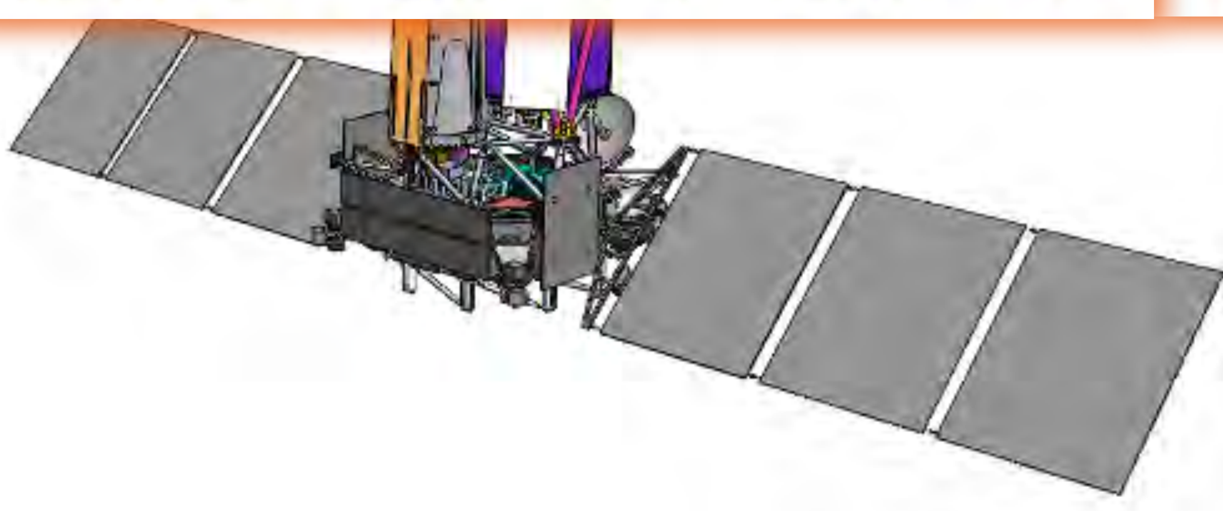




Very stringent requirements on mass calibration:

- **Current results:**
  40 clusters, $\Delta w = \pm 0.17 \iff \Delta M/M \simeq 9\%$

- **Future:**
  400 clusters, $\Delta w = \pm 0.05 \iff \Delta M/M \simeq 2.5\%$
  4000 clusters, $\Delta w = \pm 0.017 \iff \Delta M/M \simeq 0.9\%$
  100000 clusters, $\Delta w < \pm 0.01 \iff \Delta M/M \lesssim 0.5\%$




- 100,000 – 200,000 clusters, $z_{max} \approx 1.5$
- all clusters in the Universe with T>4.5 keV

DES, Euclid, LSST, WFIRST

10^5–10^6 clusters to z ~ 2–3

The Issues

- Survey selection function to 0.1%

  — currently, ~5% in X-rays

- Cluster mass scale to sub-1%

  — currently, ~10%

- Scatter in the mass-observable relations to $\delta(\text{scatter}^2) \approx 0.00025$

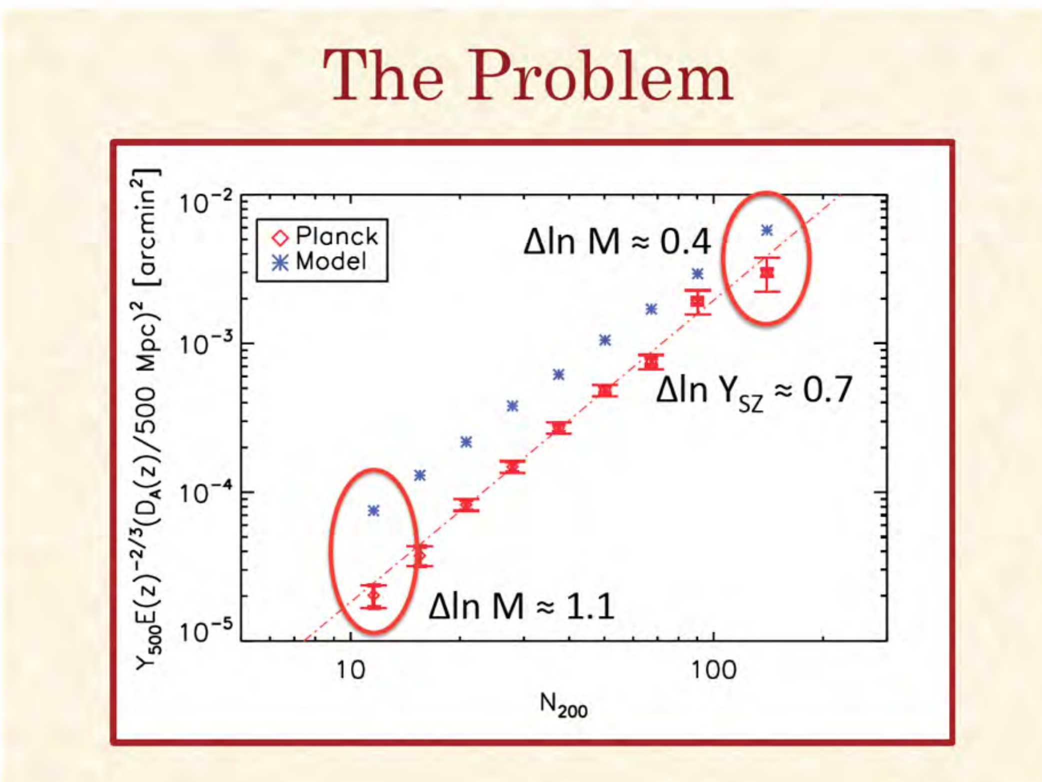
  — currently, 0.003 at best

- Given stated goals (dark energy, non-GR, detection of neutrino masses), *radically* improve understanding of clusters

Selection in the optical & IR

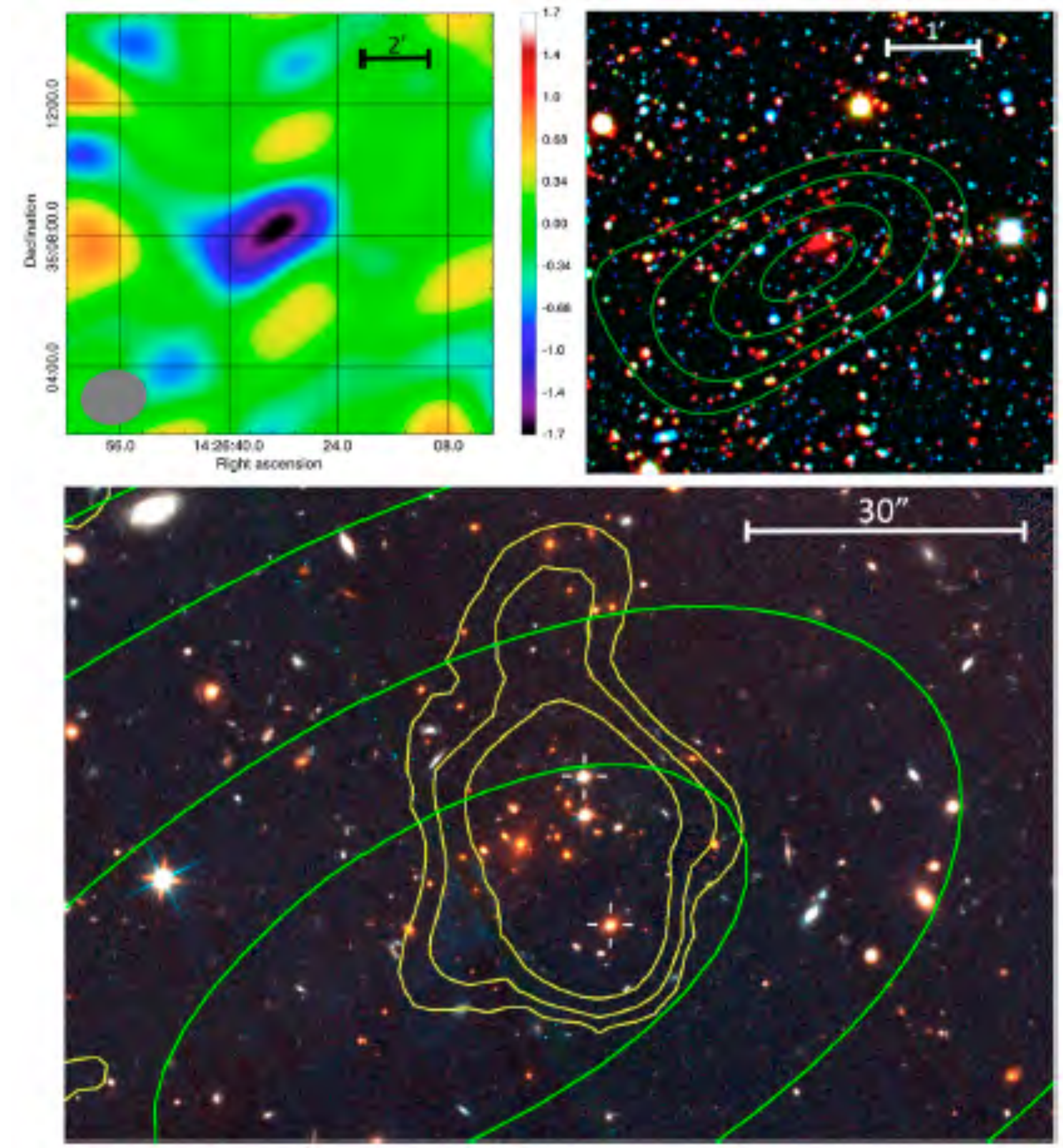
In the optical red sequence selected samples

- "X-ray dark" clusters (~10%)
- a factor of ~2 scatter in richness for fixed Lx
- the "SDSS vs. Planck" problem:



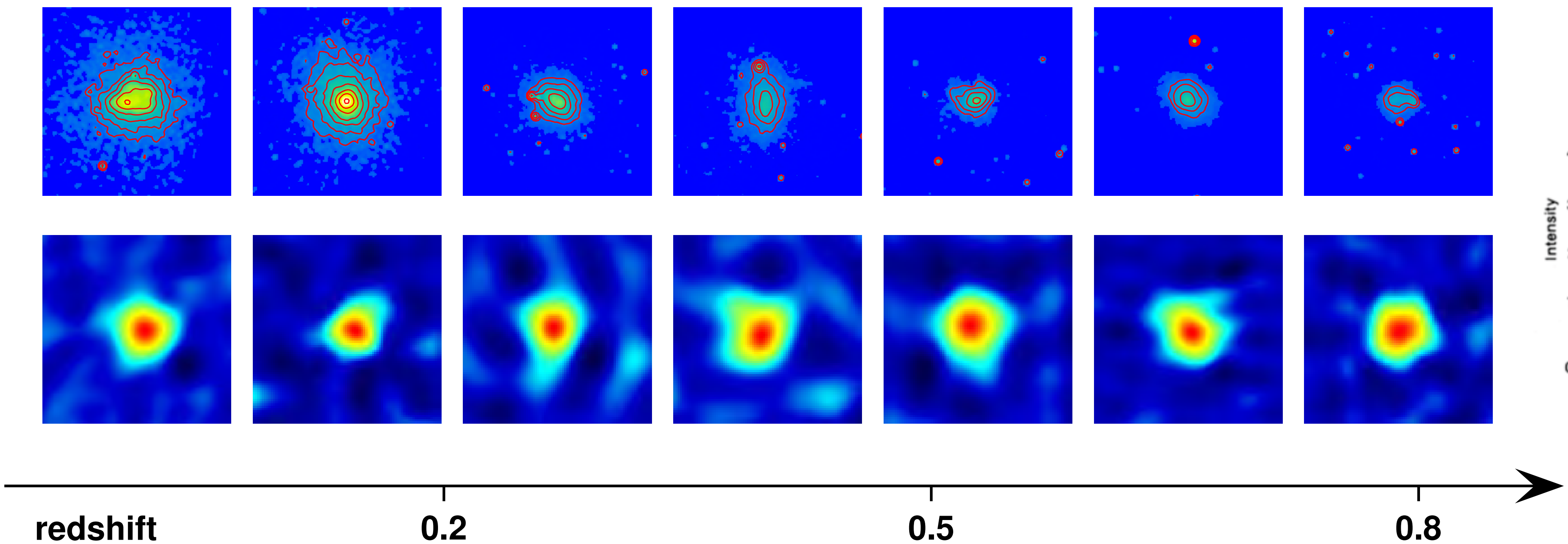
See Rozo et al. '12 for discussion

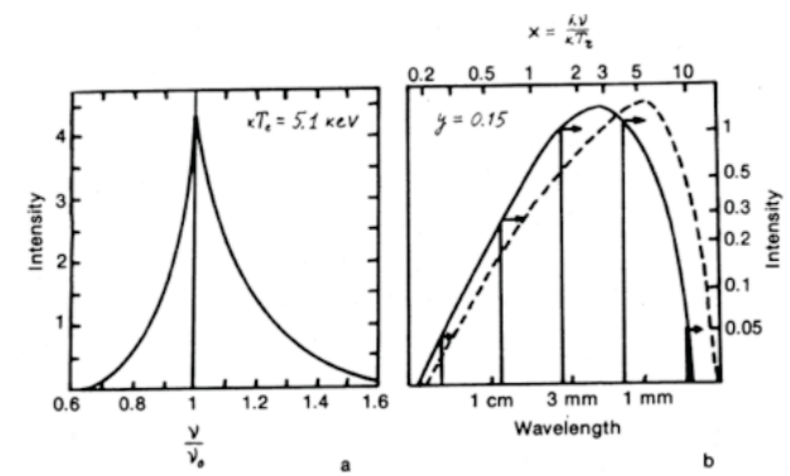
May be better in the IR.



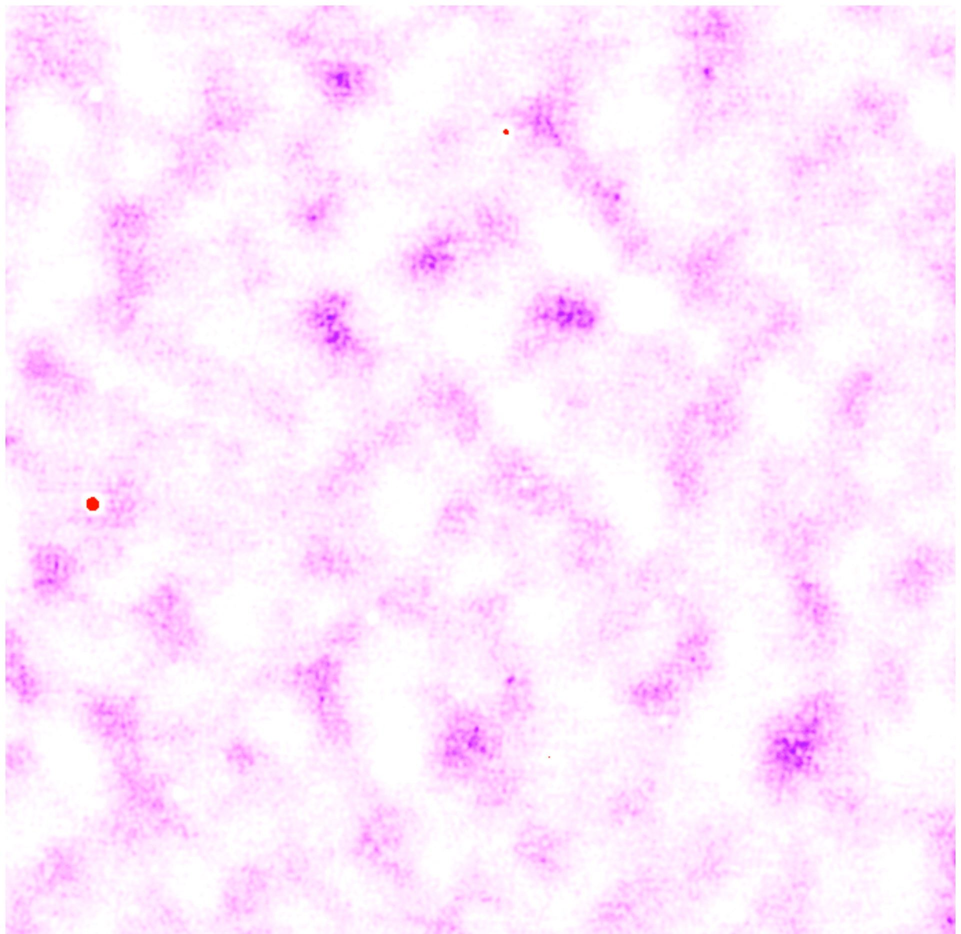
Detection of a Coma progenitor at z=1.75 in the Spitzer/IRAC survey. Brodwin et al. 2012

Selection in the SZ



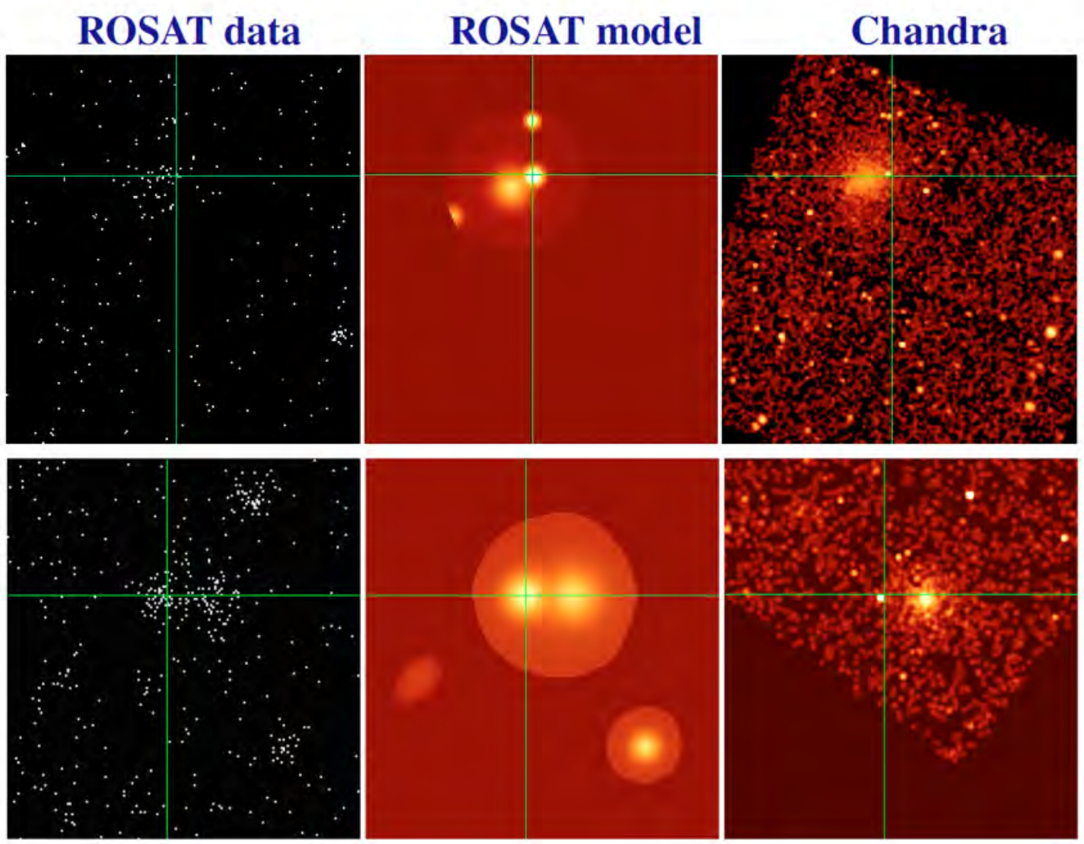


- Does being "redshift independent" really mean being equally faint at all redshifts?
- Realistic surveys never far from detection threshold.
- Need extensive mock catalog simulations and a library of realistic cluster templates

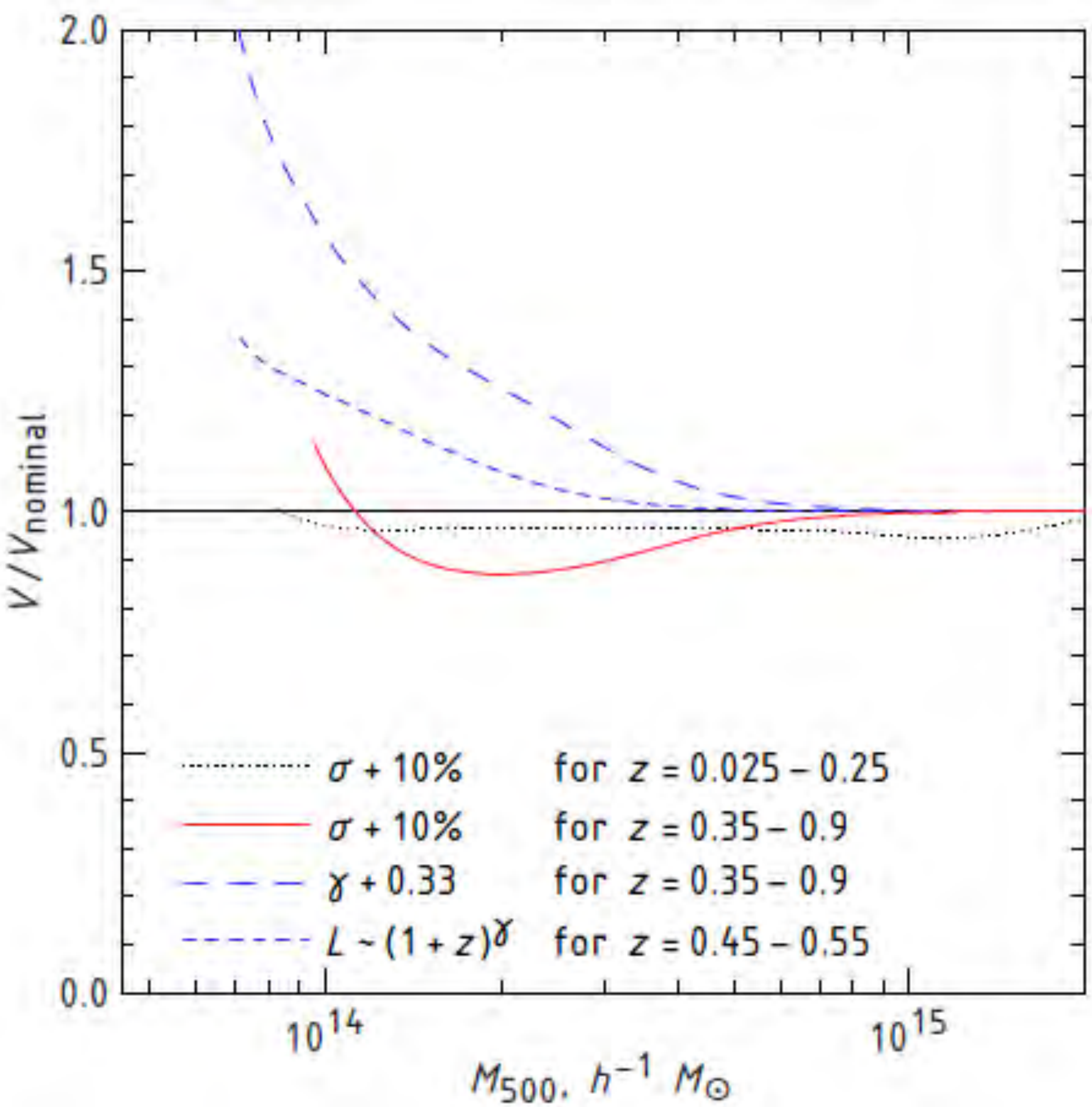


Section of the first-season 150 GHz map from SPT

Selection in X-rays



- Confusion with AGNs
- Any "X-ray dark" clusters?
- 40% scatter in Lx for given mass

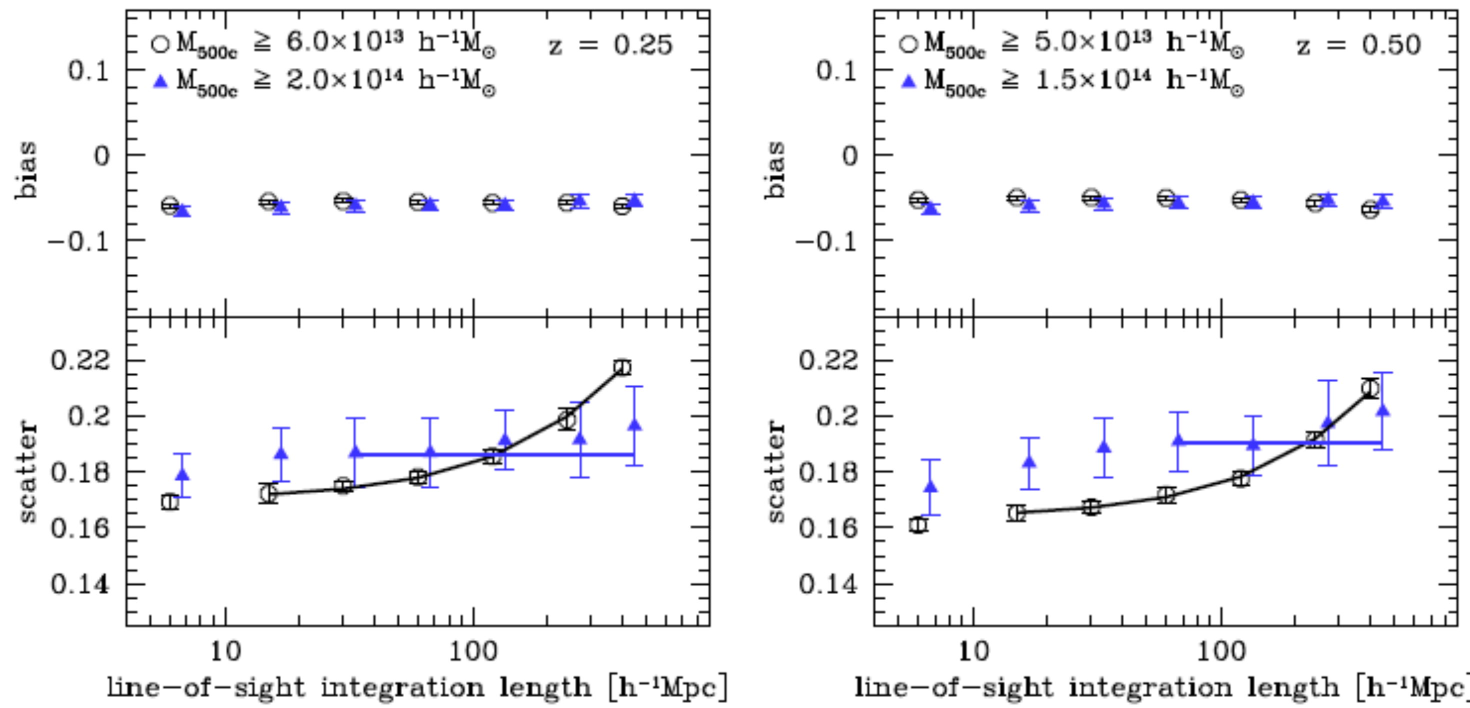


— effect of uncertainties in the Lx-mass relation on the calibration of the selection function

Calibration of cluster masses

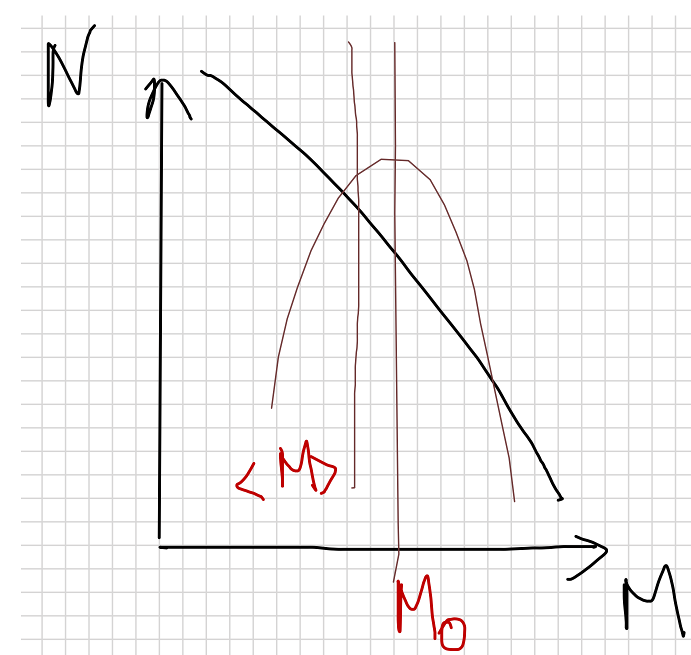
- Weak lensing measurements are the best hope of getting accurate measurements on average
- But are they accurate?

Becker & Kravtsov '11



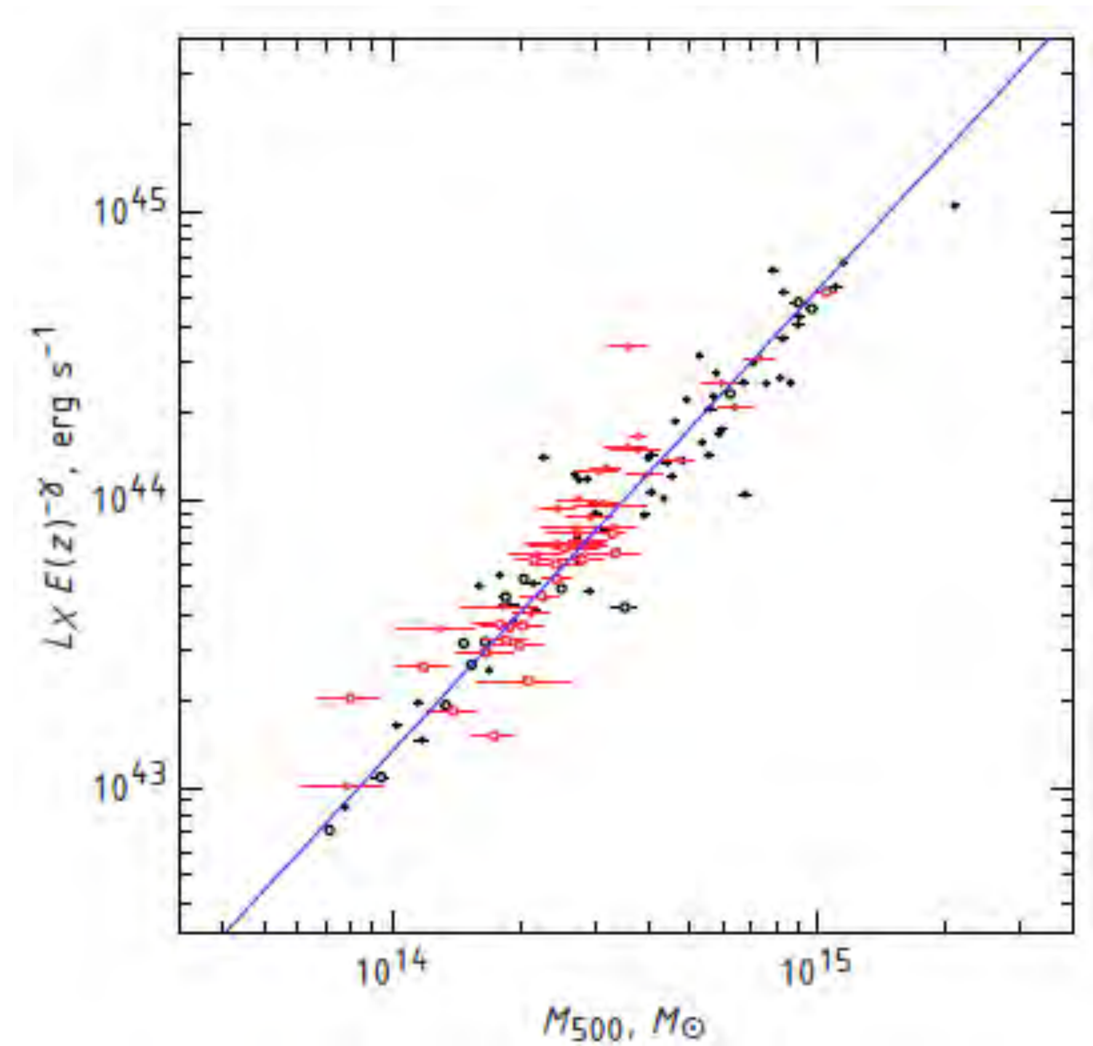
- Pay attention when you stack the lensing signal:

$$\text{shift} = \exp\left[(1-2\alpha)\sigma^2/2\right] = 1.9 \text{ if } \sigma=0.4$$
$$= 1.3 \text{ if } \sigma=0.25$$
$$= 1.026 \text{ if } \sigma=0.08$$



Calibration of scatters

- Scatter measurements within the sample are affected by selection



- Large scatter estimated from within the sample leads to a finite error in the mass function estimate:

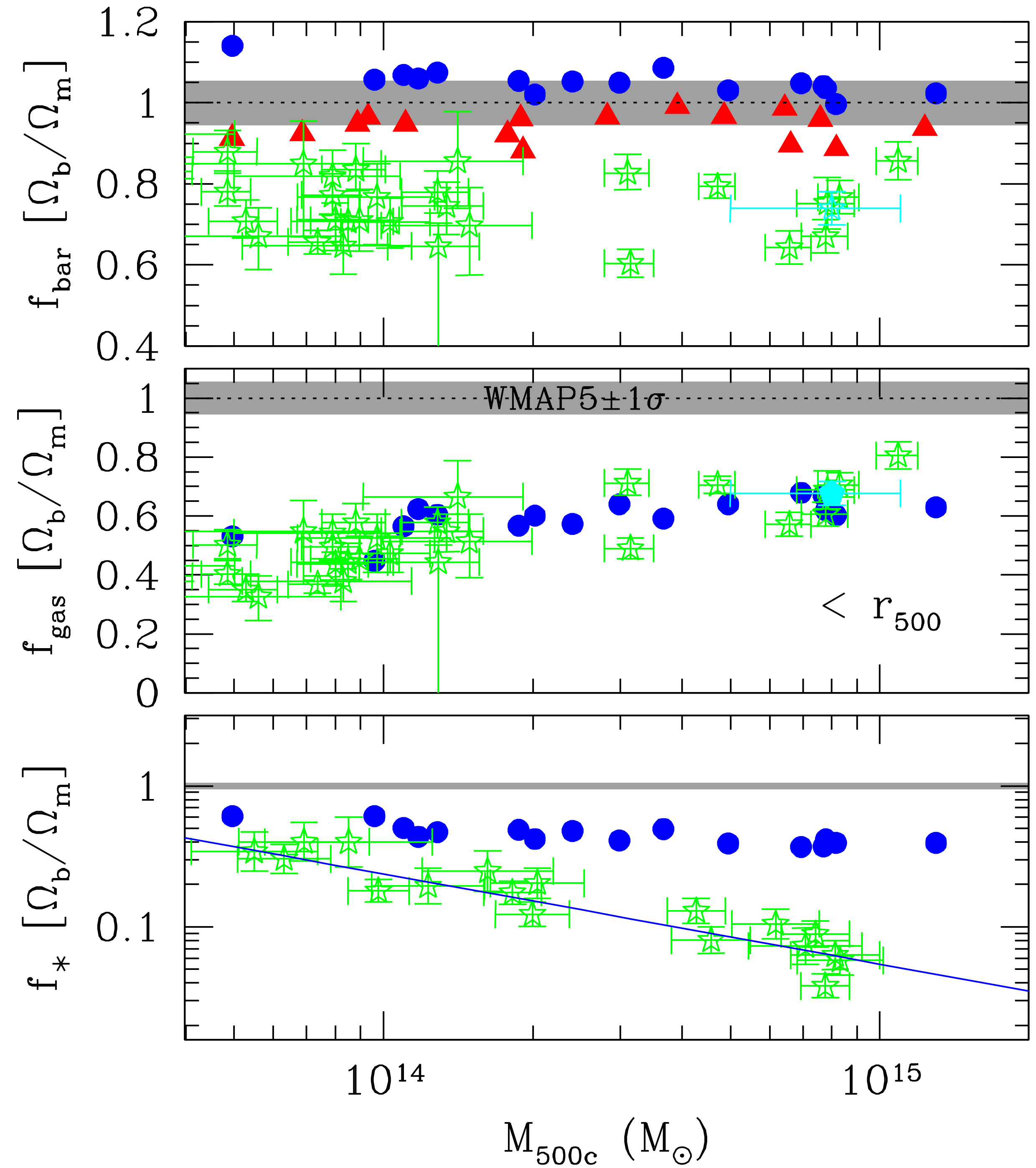
bias in $n(M)$ = exp $[\alpha^2\sigma^2/2]$

$\Delta\sigma^2 = \sigma^2(2/N)^{1/2}$ from a sample of N measurements

we want $\alpha^2\, \Delta\sigma^2/2 = 1/N^{1/2}$ or $\alpha^2\, \sigma^2(2/N)^{1/2}/2 = 1/N^{1/2}$

sys/stat = $\alpha^2\sigma^2/2^{1/2}$ = 1 if σ=0.3 or less for α=4

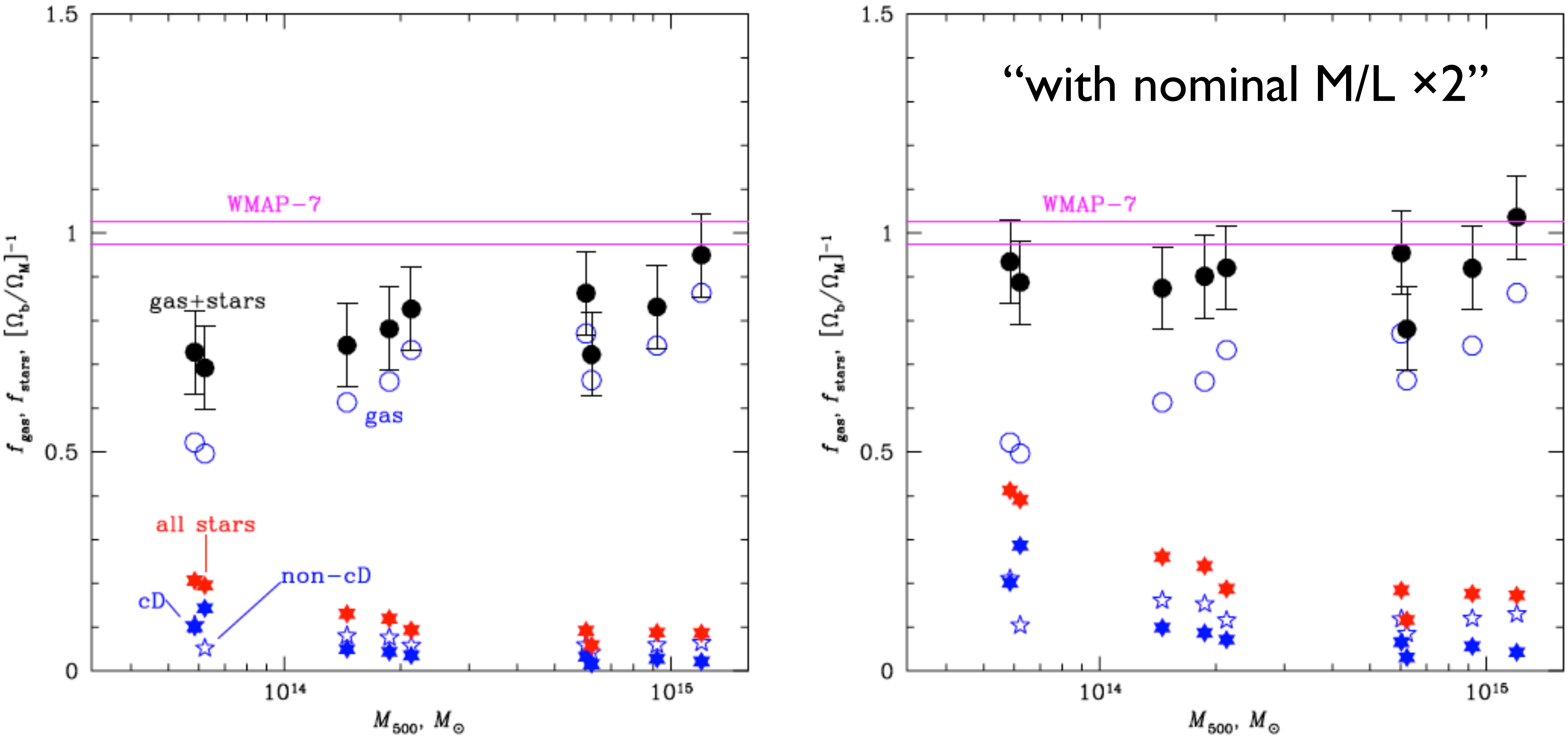
Understanding clusters: I Baryon budget



Compilation from Kravtsov et al. Astro10 White Paper

Understanding clusters: I Baryon budget

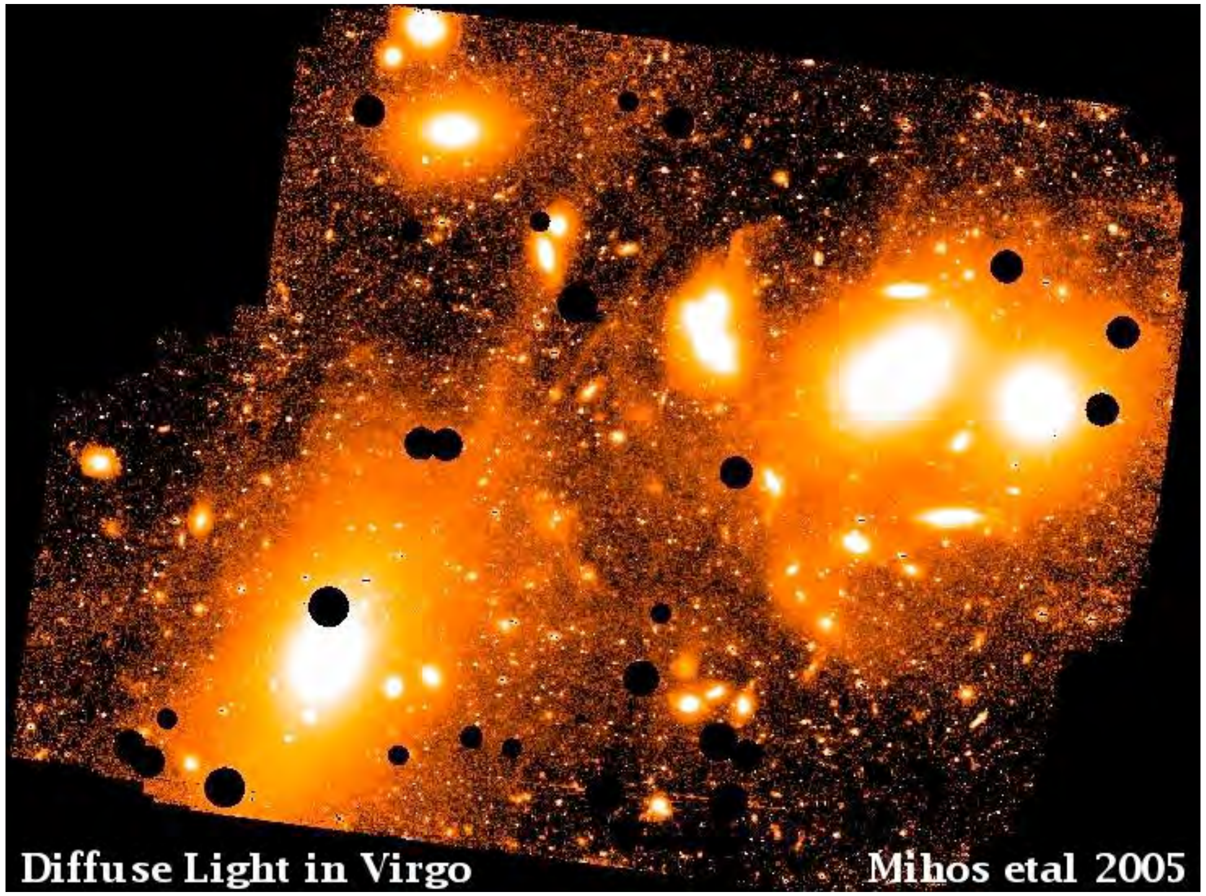
Mescheryakov & AV, forever in prep.

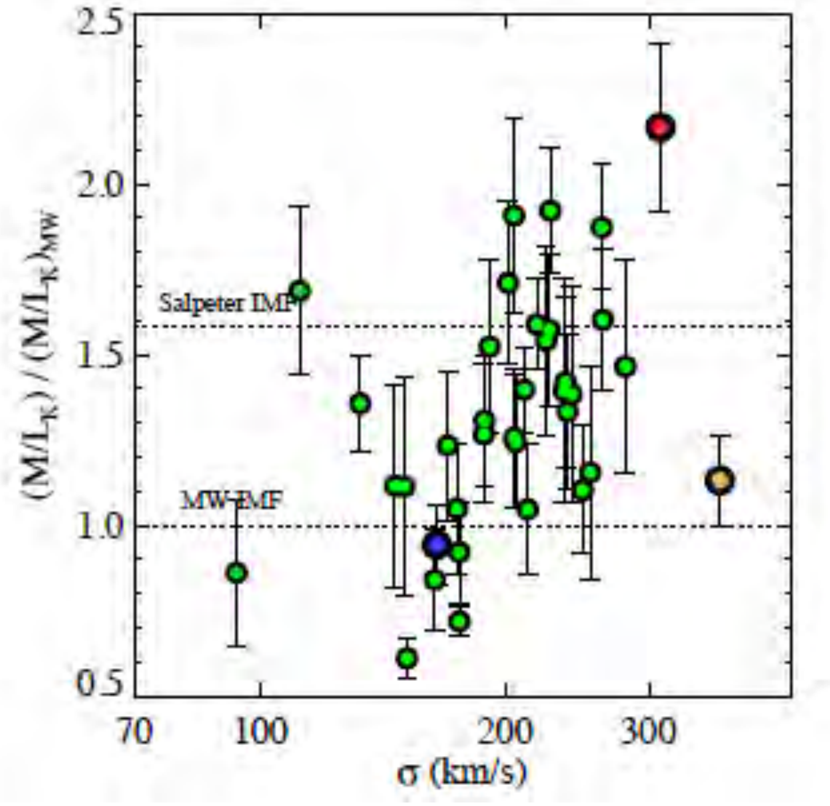


Understanding clusters: I Baryon budget

Possible solutions:

- Is baryon closure achieved at radii > R500? (Humphrey et al.)
- Is M/L for largest galaxies indeed a factor of 2 higher (Conry & Van Dokkum)?
- Is there a lot is intracluster light?

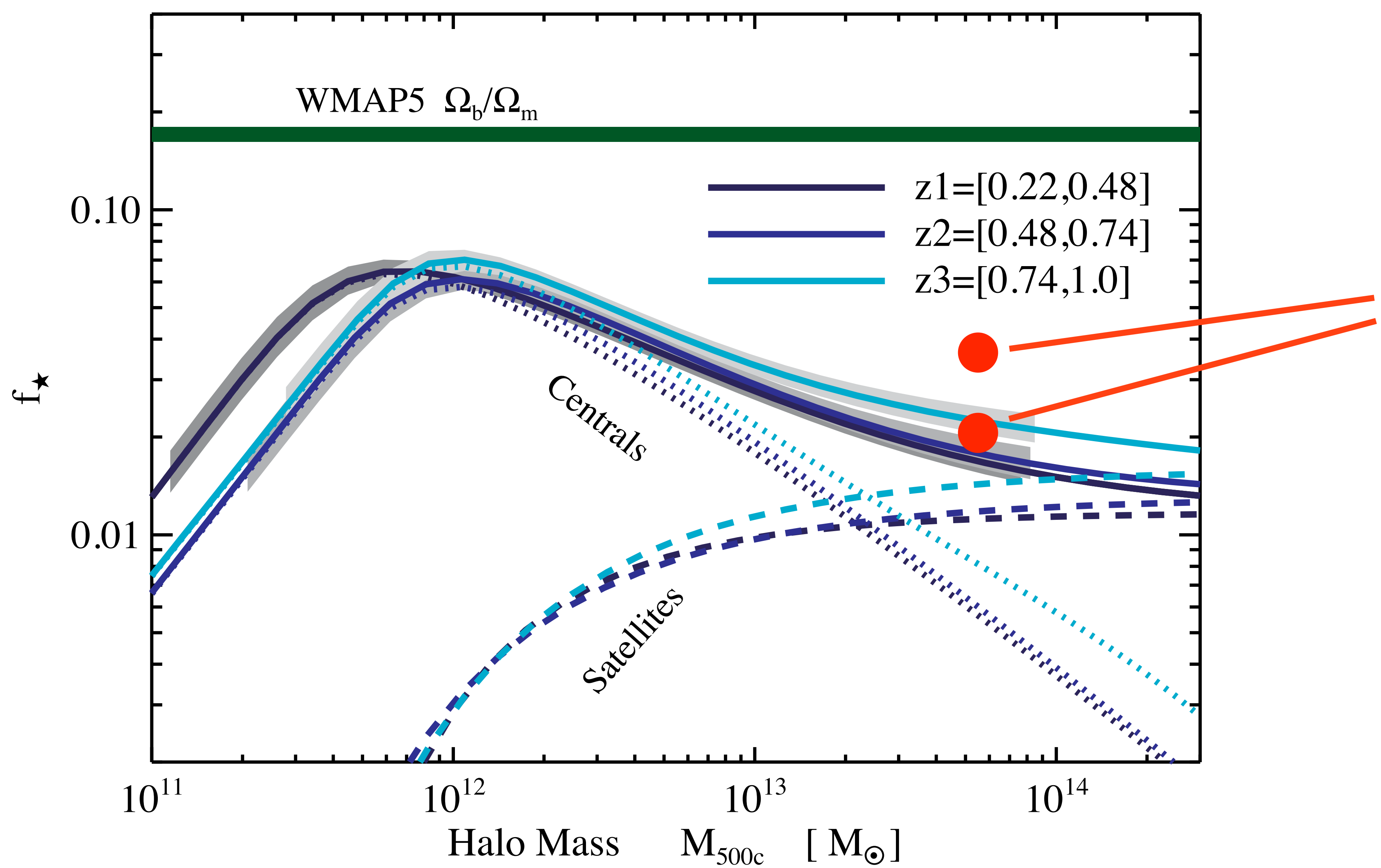




Understanding clusters: II Star formation efficiency

- M_* / M_{tot} can be estimated from matching the galaxy luminosity function and mass function of dark matter halos. Leauthaud et al. 2011, Behroozi et al. 2012 to start with

- This analysis shows a peak in star formation efficiency for MW-mass objects, and decline to higher masses

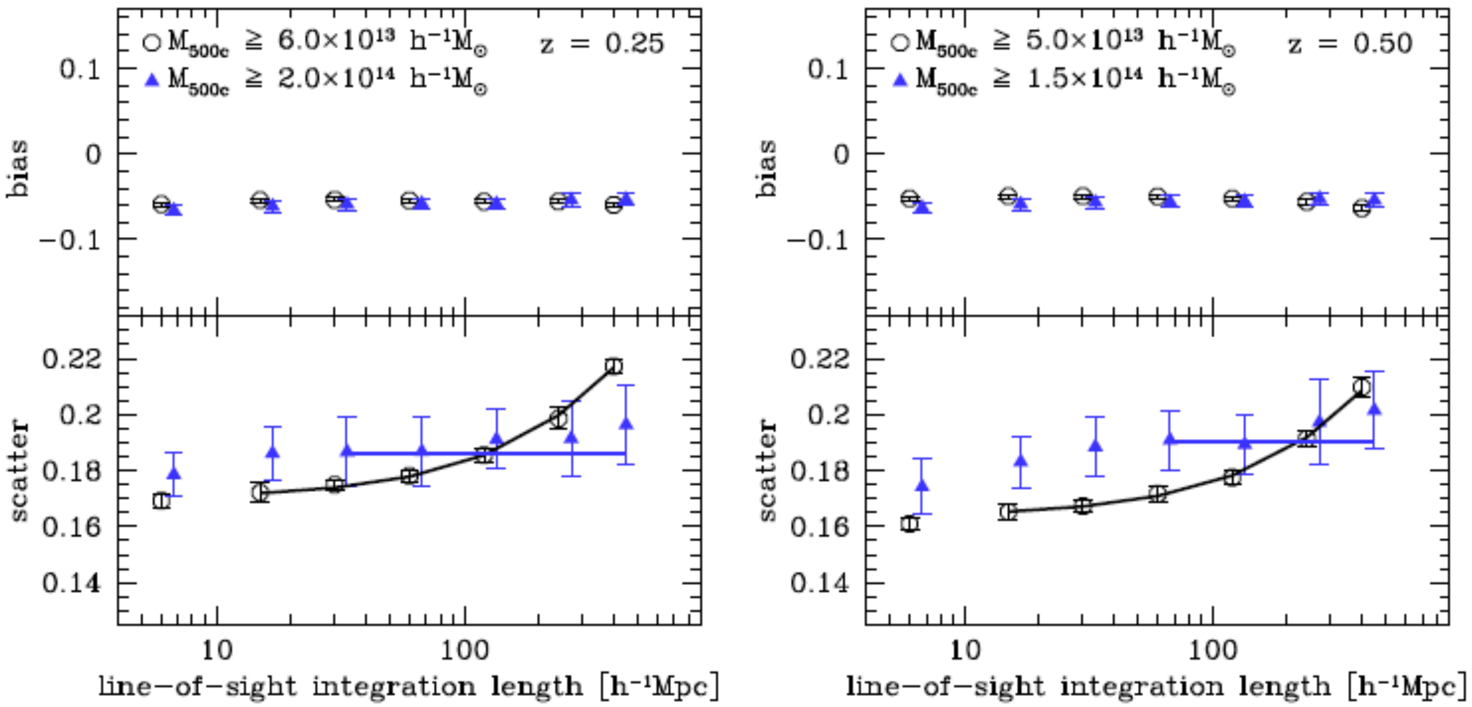


From direct measurements in X-ray selected groups.

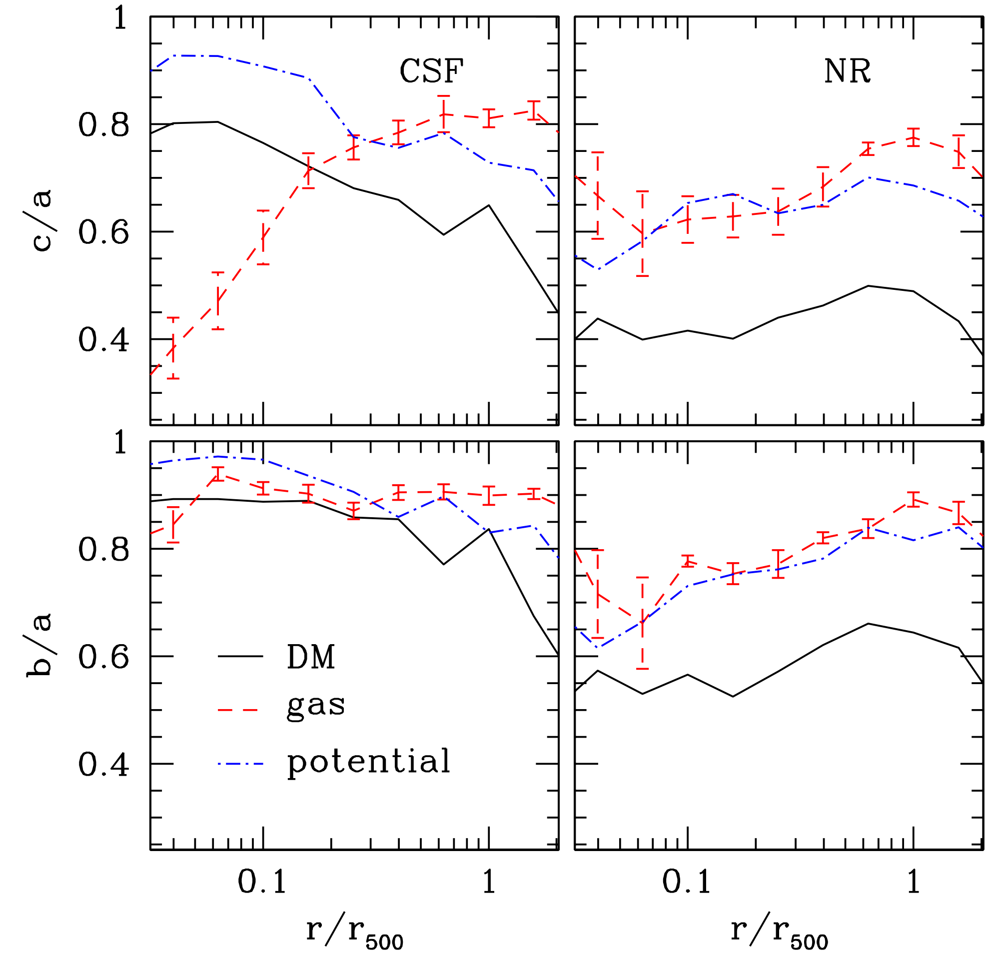
Are clusters special places for star formation? Why?

Significance for cluster mass estimates

Becker & Kravtsov '11



Lau et al. '11



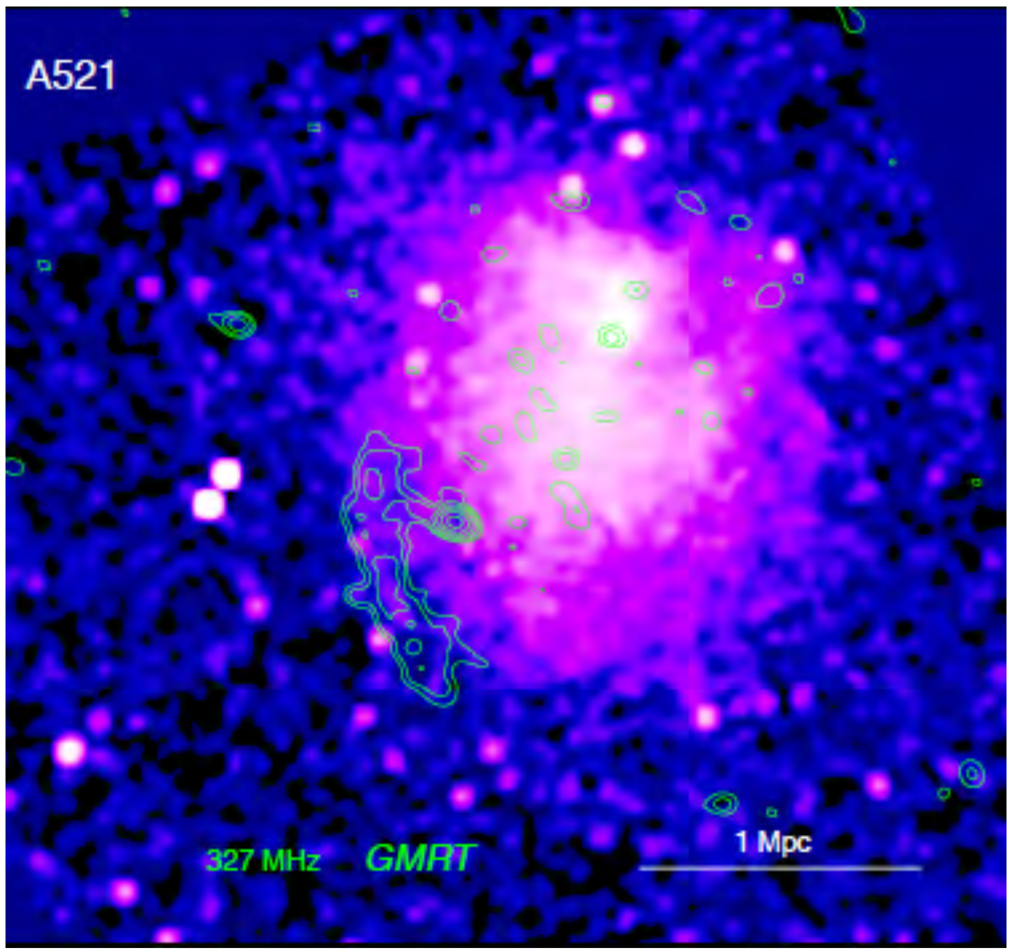
~5% bias in WL masses due to triaxiality

vs.

potentially, ~50% effect on triaxiality due to galaxy formation

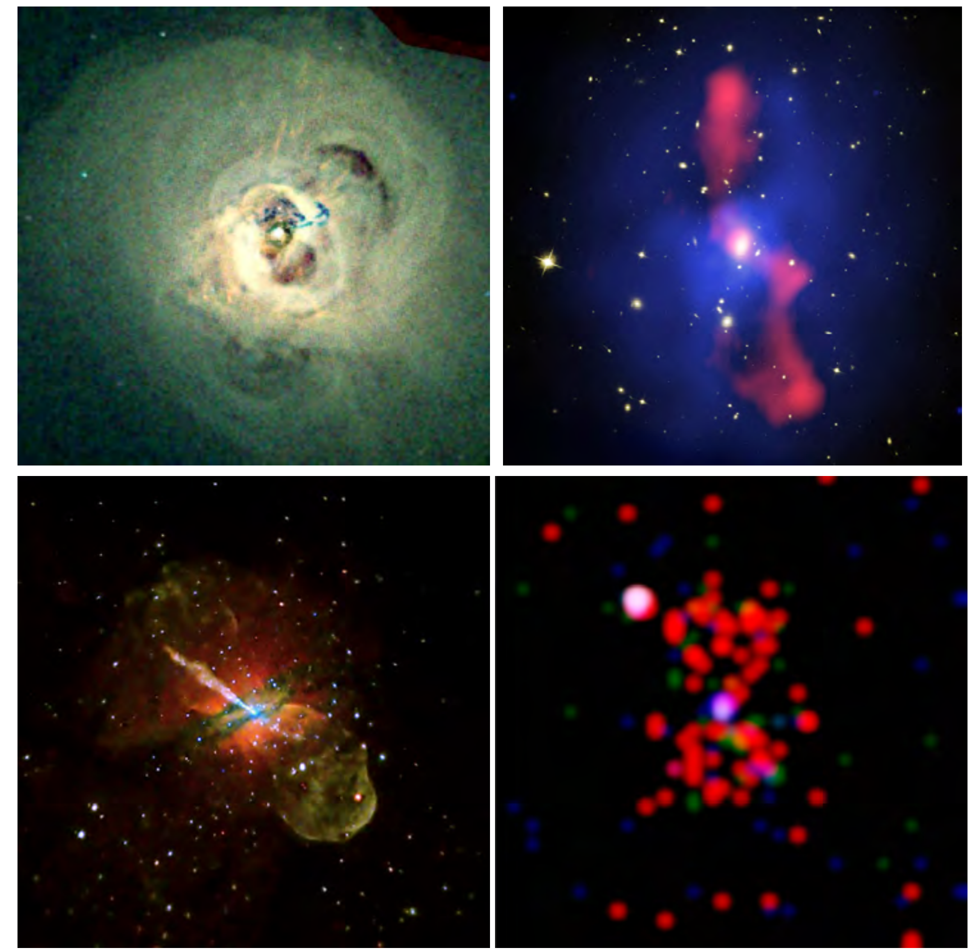
1% effects? ... you name it ...

Relativistic particles & magnetic fields; generated in shocks?



Giacintucci et al '08

AGN feedback & strong blasts

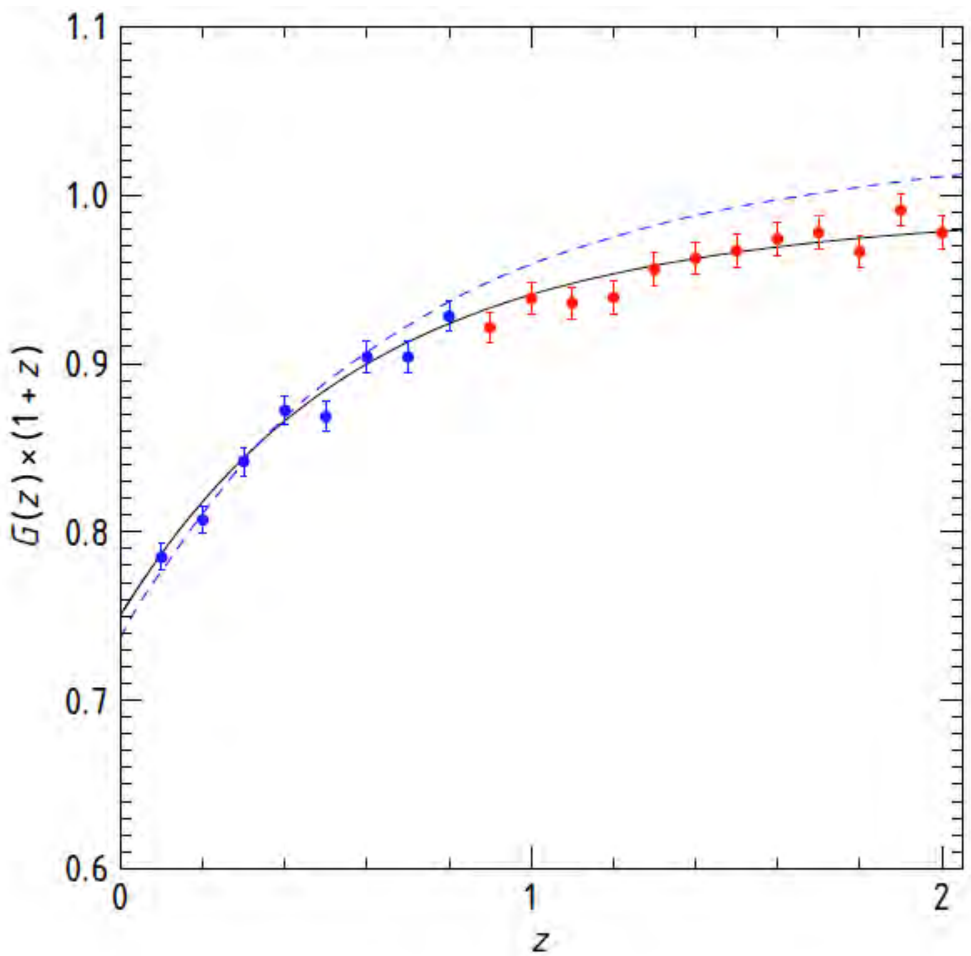


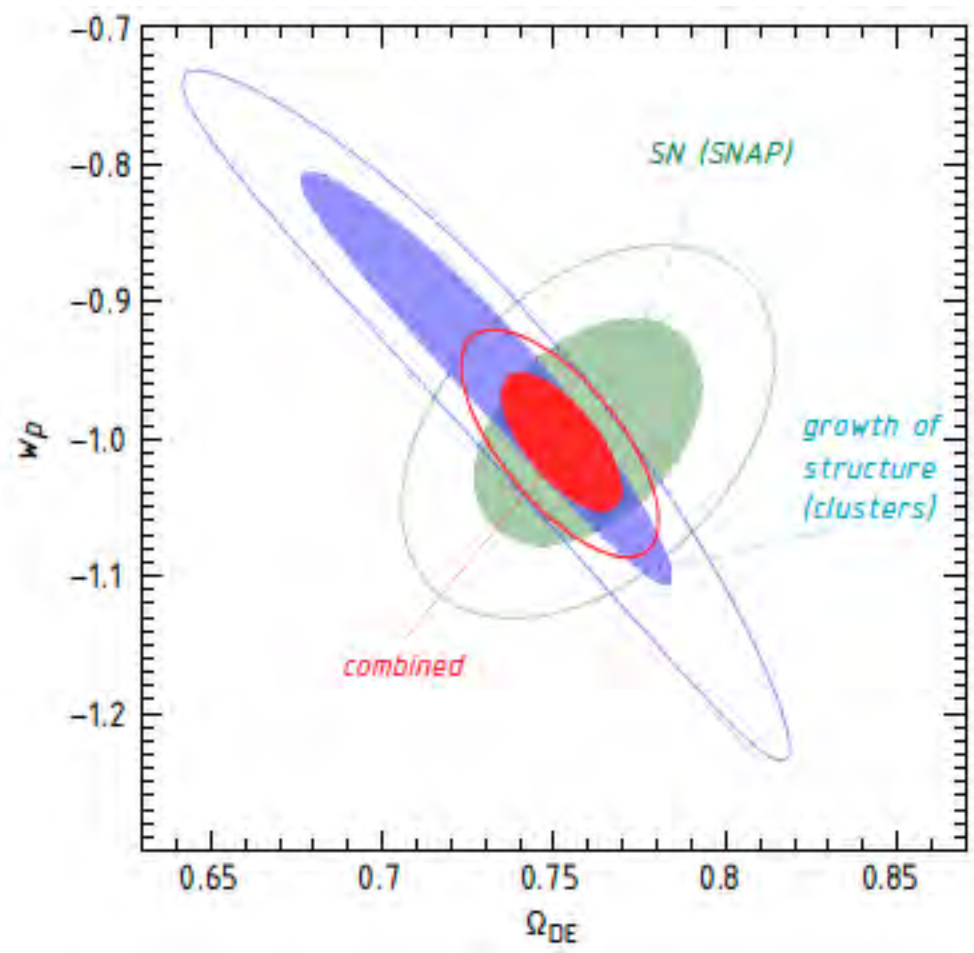
- What does this do to star formation?
- How much energy deposited into IGM?
- Ultimate fate of relativistic particles in bubbles?
- Statistics of catastrophic explosions?
- Relation of high-z AGNs to large-scale structure?

Can anything be done at all?

- Change paradigm? How?
- Explore self-calibration (start with good observables; use direct constraints on the cluster properties as much as possible; ...)
- Or, reduce appetite:
  - target ~ 1000 cluster samples; 1–2% requirement on the mass calibration
  - select these 1000 clusters well above all detection thresholds, and use a multi-stage procedure. E.g., the richest Euclid clusters, followed by X-ray snapshots, followed by SZ pointings. This solves the selection function problem.
  - Observe the selected clusters really well in X-rays, SZ, and grav. lensing
  - Empirically calibrate M–Y relation with weak lensing at all redshifts. The only required assumption is that the scatter in M–Y is low.
  - still very useful!

Expectations for a 1000-clusters experiment:





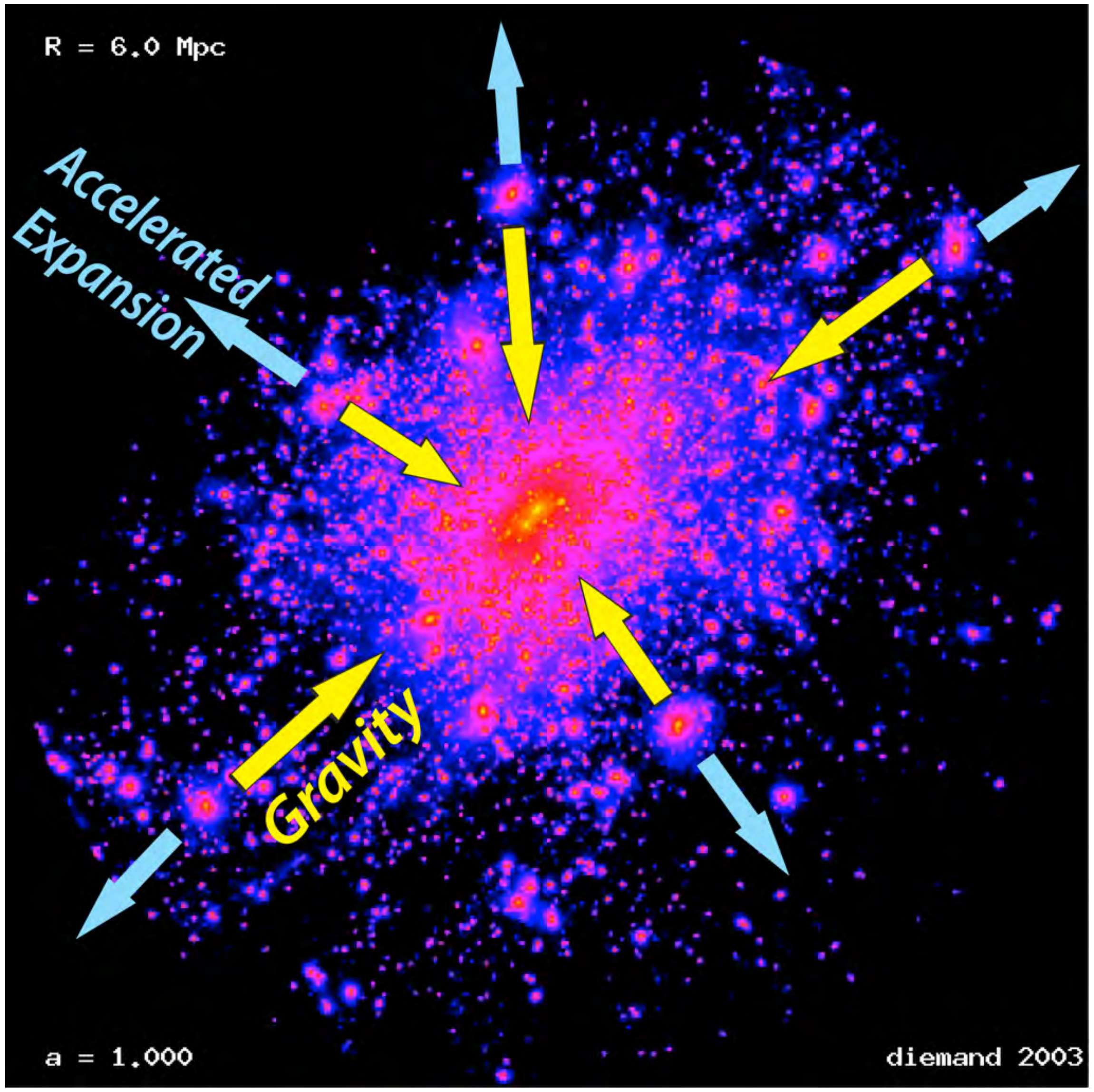
- WL – low bias, large scatter; X-rays – low scatter, potential bias
- 100 clusters with Y_X and M_{WL} $\Longrightarrow$ 3% in M–Y_X, 1% in growth *per bin*
- measure growth(z) to z ≈ 1 and possibly, 1.5–2; combine with z=2–4 measures to reconstruct the cosmic structure growth history
- test non-GR theories (growth index, γ, to ±0.02)
- ×2 improvement in *w* in combination with distance(z) tests
- implementable with SXG/eRosita + IXO or Wide Field X-ray Telescope or sensitive SZ instrument

IXO White Paper by Vikhlinin, Allen etal

Galaxy cluster cosmology:

Fundamental questions about the Universe

- What is the agent of cosmic acceleration?
- Do we see any departures from General Relativity?
- Are there any departures from "concordance cosmology"?



— *and* fundamental astrophysics

- Star formation
- Plasma physics in the intra-cluster medium
- AGN growth and energy feedback, now and in the past
- Recycling of matter through galaxies