Cosmology with Galaxy Clusters (II)

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Re-cap from yesterday

- clusters provide some of the most compelling evidence for the existence and cold, (near-)collisionless nature of dark matter
- the baryonic mass fraction (f_{gas} test) is a sensitive measure of Ω_m, and can be used to constrain the geometry of Universe

- measuring cluster masses is very important for cluster cosmology
- ... but also very difficult
- multi-wavelength approach: use unbiased, high-scatter weak lensing masses to calibrate low-scatter, biased X-ray mass measures (more on this tomorrow)
- gas mass is a good "mass proxy" - easy to measure, correlates tightly with cluster mass

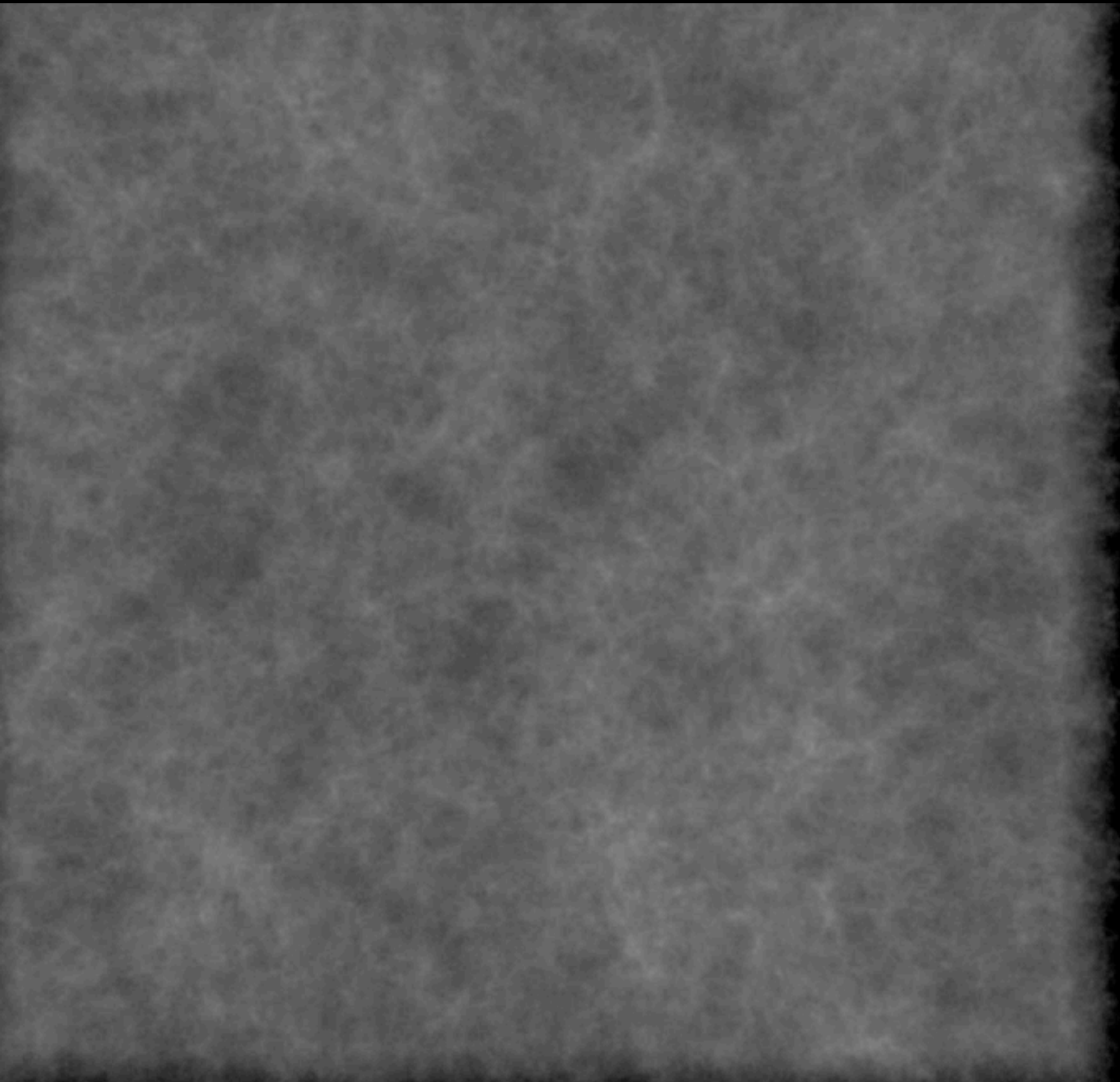
Today:

Cosmology with the cluster mass function

or

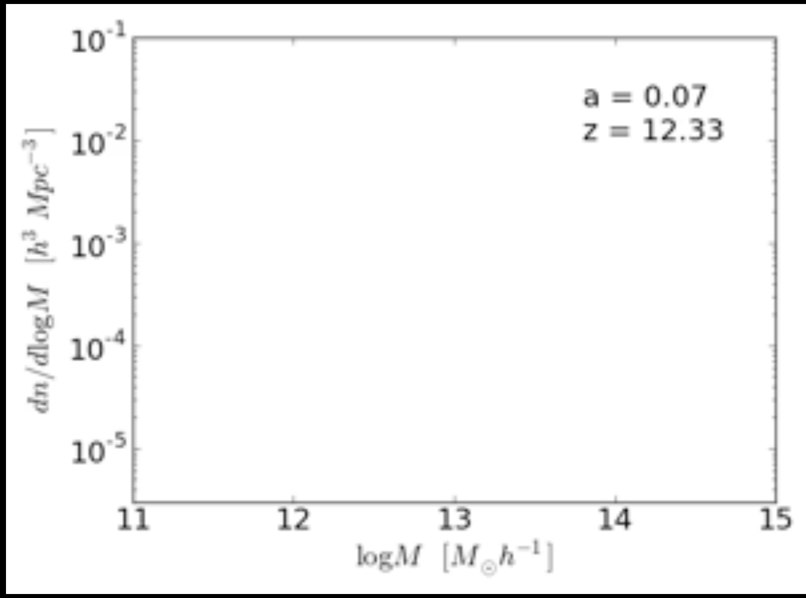
"Counting Clusters"

matter distribution (180 Mpc)

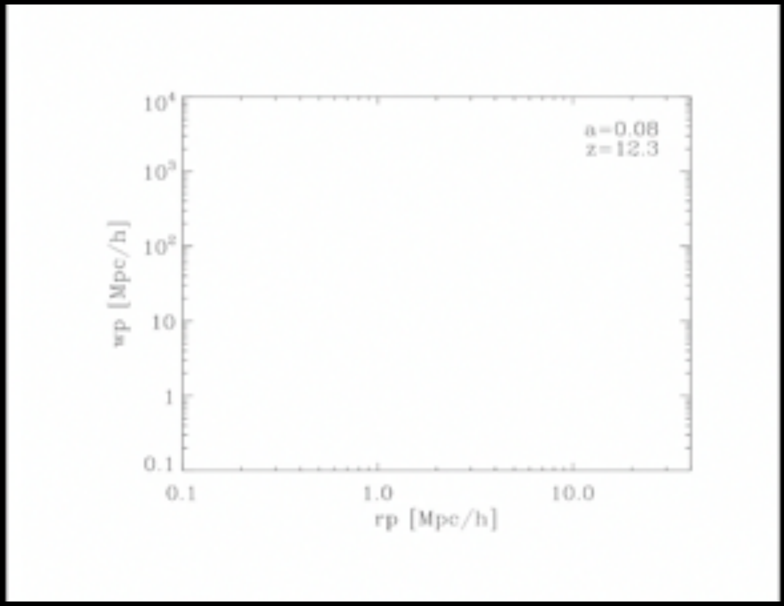


example statistics:

halo mass function



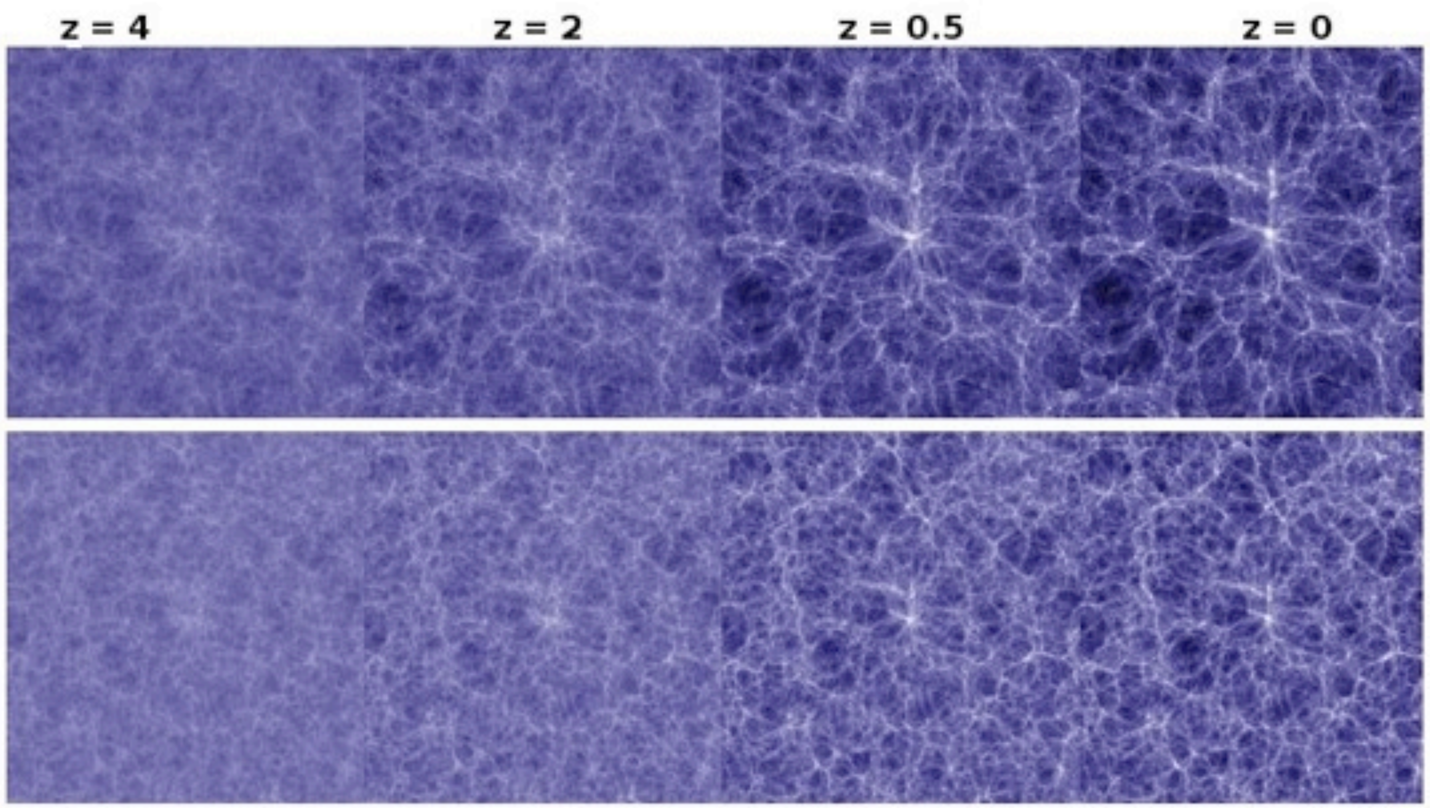
halo
correlation function

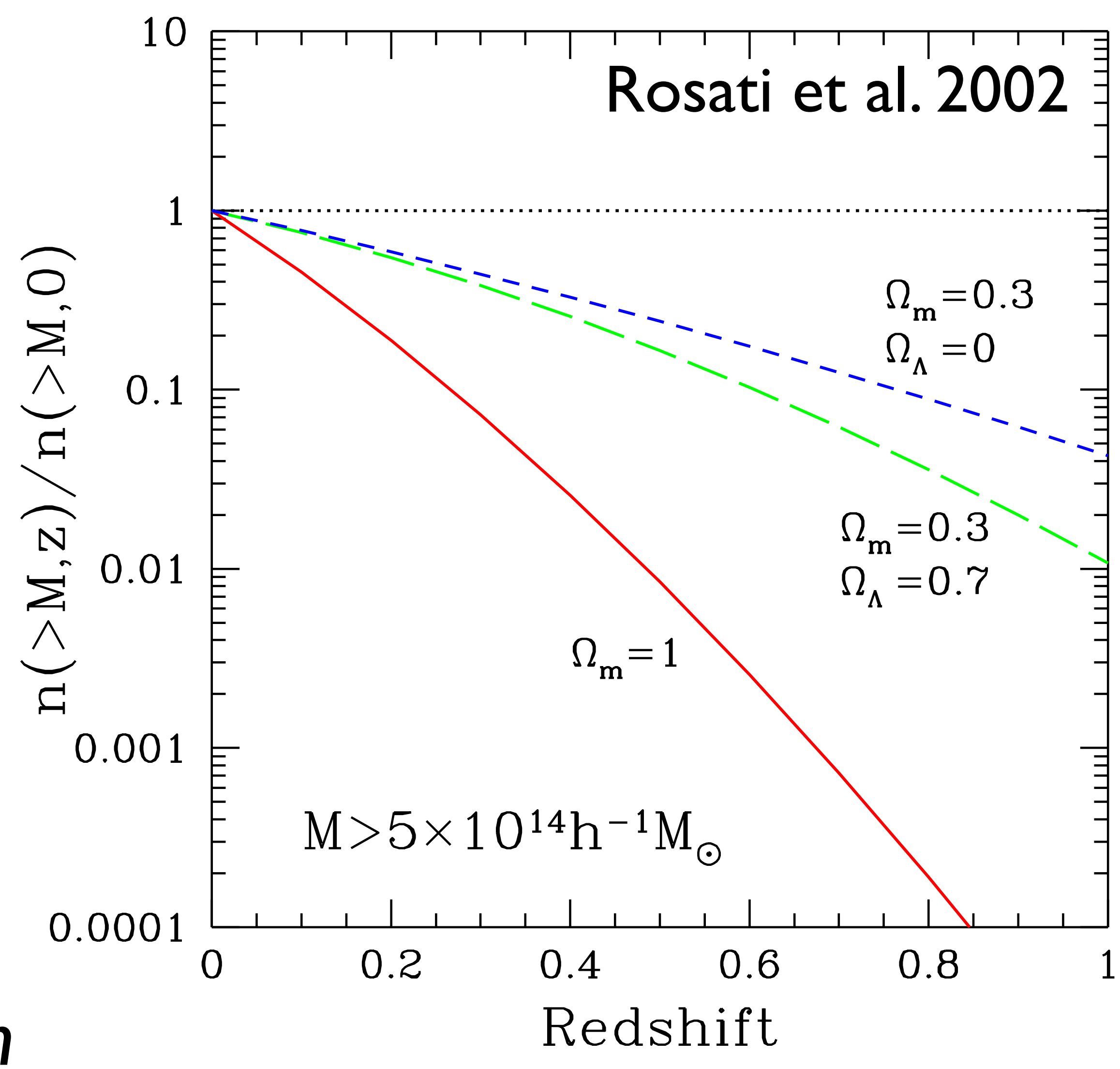


movie, simulation, statistics: Matt Becker, Ralf Kaehler, Yao-Yuan Mao, Rachel Reddick, Risa Wechsler (Stanford/SLAC)

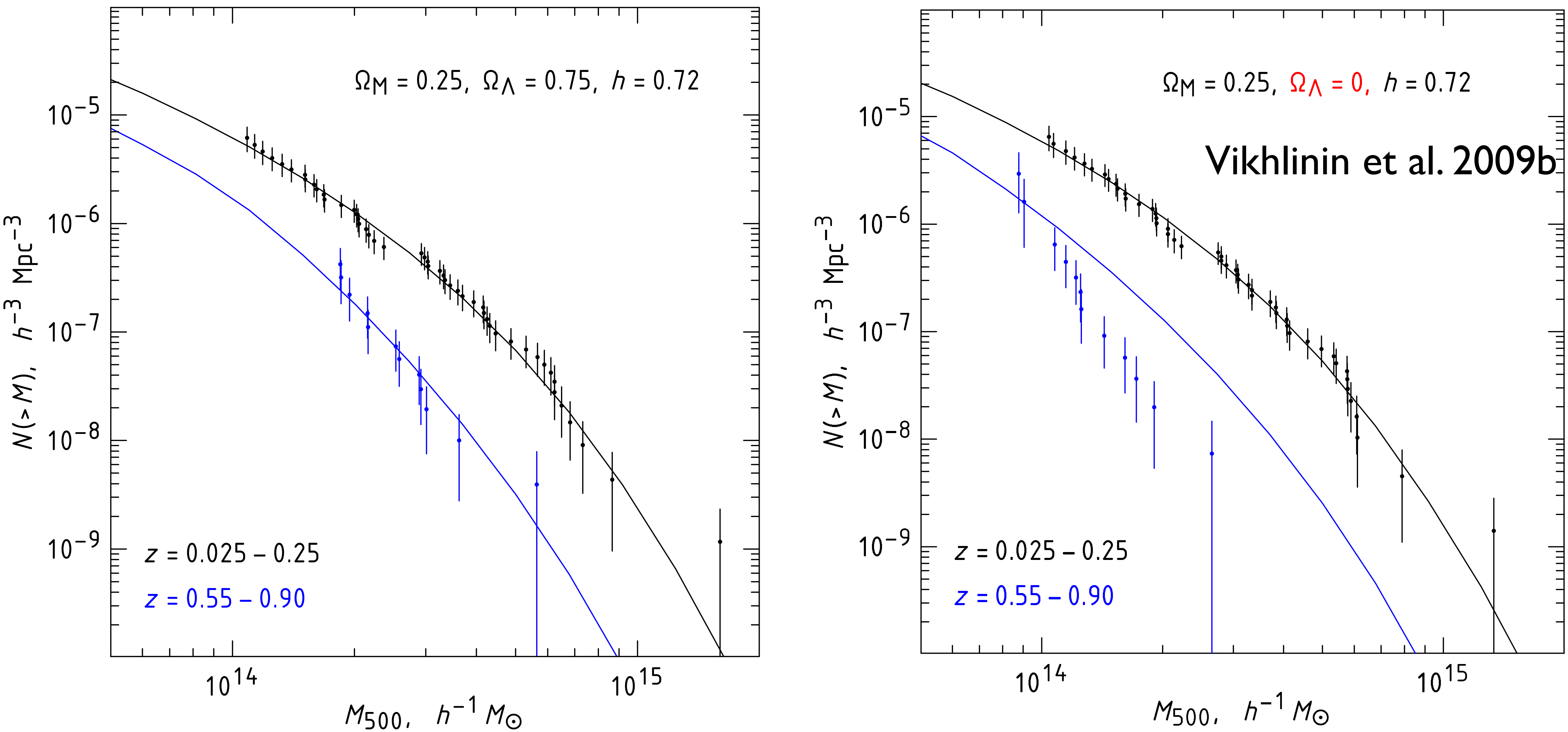
The cluster mass function

- growth of structure dominated by gravity and dark matter
  - can be well predicted by cosmological N-body simulations
  - number of gravitationally bound halos (with mass M, at redshift z) sensitive to cosmological model
- observationally: halos ↔ clusters





- cluster mass function sensitive to both *geometry* of Universe and *structure growth*



- compute cluster masses in trial cosmology, compare to predictions

Ingredients for cluster counts cosmology

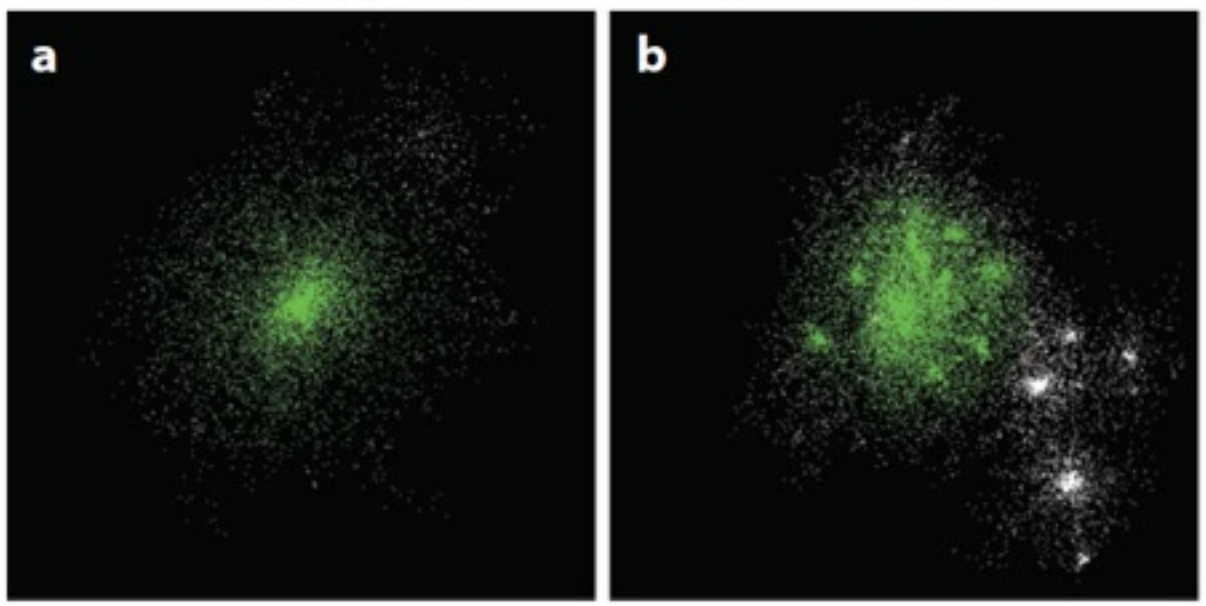
1. prediction for halo mass function
2. cluster survey with well understood selection function
3. relation between survey observable and cluster mass
4. self-consistent statistical framework

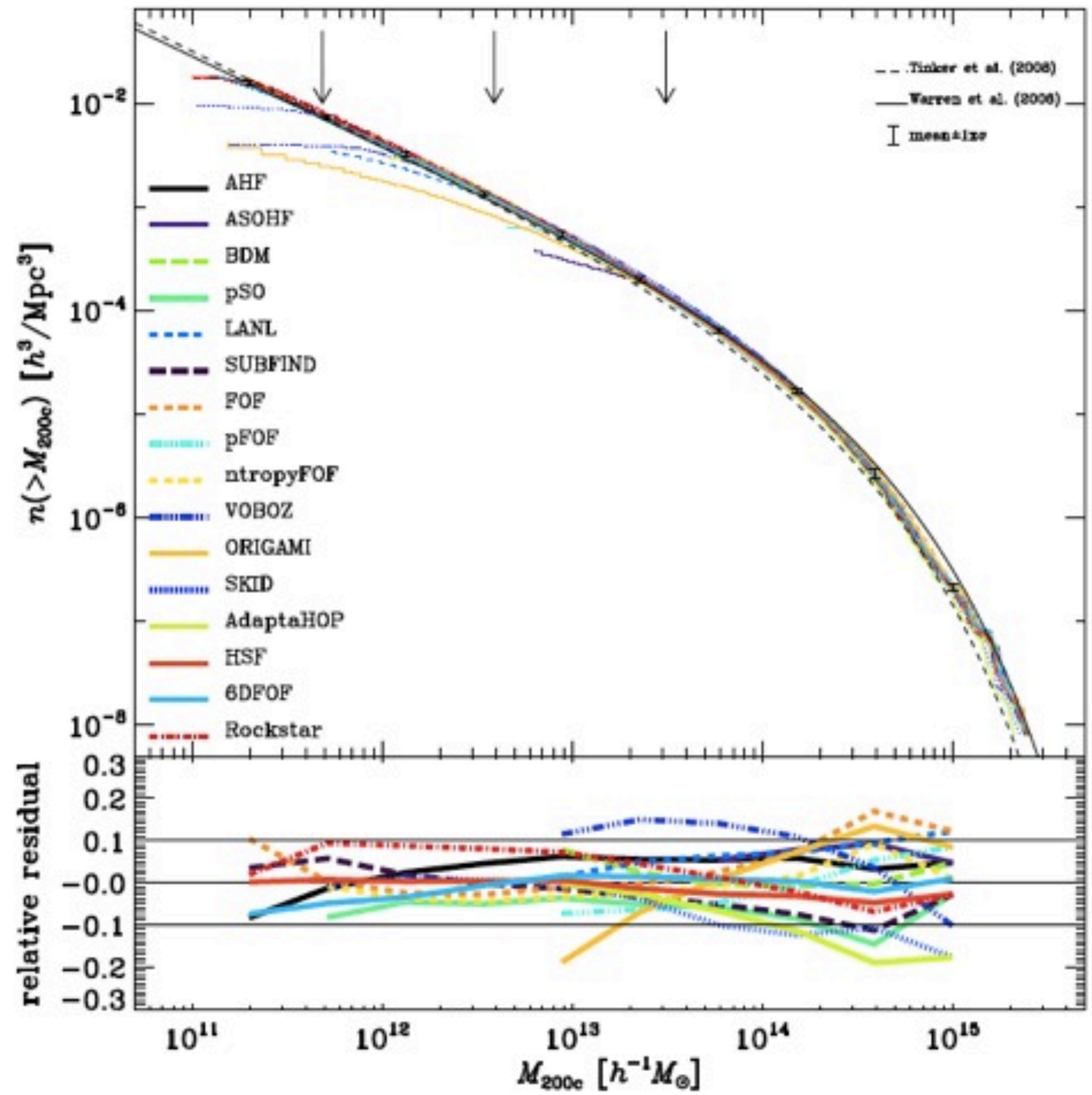
Ingredients for cluster counts cosmology

1. predictions for halo mass function

Knebe et al. 2011

- N-body simulations
- challenges: how to identify halos in simulations



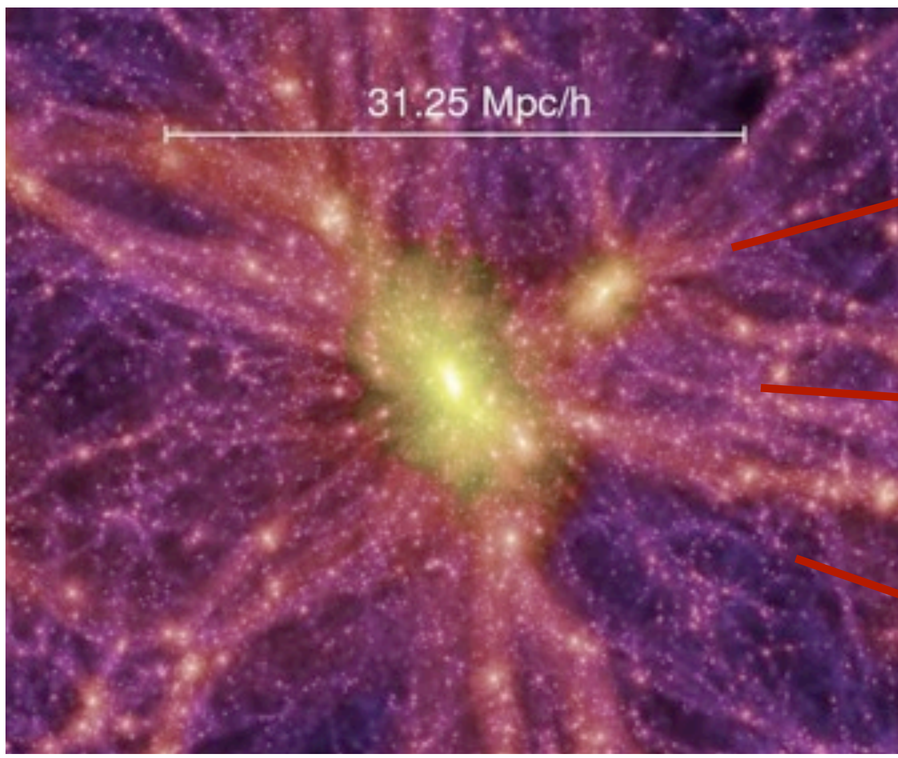


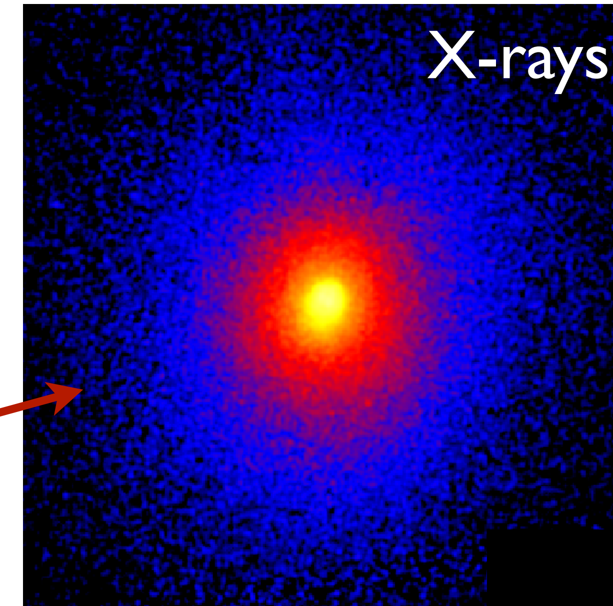
- analytic fitting formula for halo mass function *N(M,z,cosmology)*

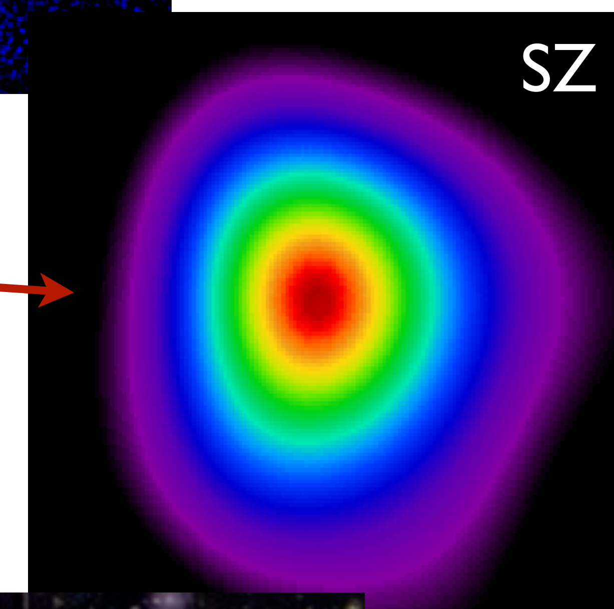
Tinker et al. 2008

Ingredients for cluster counts cosmology

1. prediction for halo mass function
2. **cluster survey with well understood selection function**







- X-rays: thermal bremsstrahlung from Intra-Cluster Medium (ICM)
- millimeter: Sunyaev-Zeldovich effect - inverse Compton scattering of CMB photons on ICM
- optical: galaxy population - overdensity of (red) galaxies

X-ray surveys

- clusters are the only extended extragalactic X-ray sources

✓ fairly insensitive to projection effects

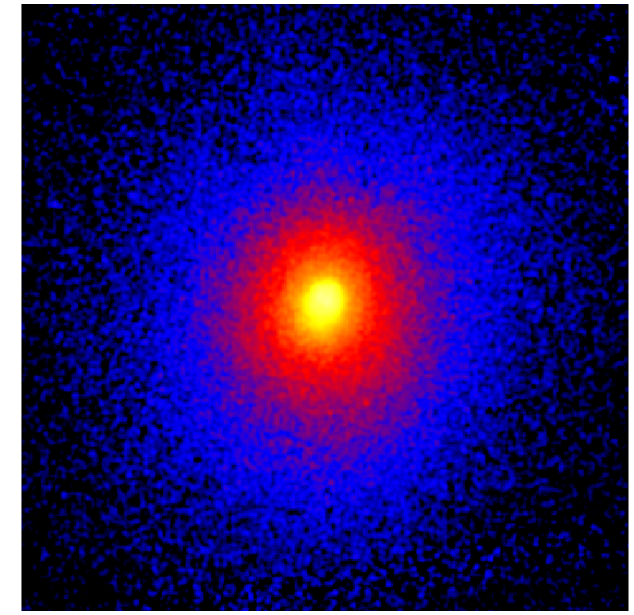
✓ "easy" to construct cluster samples with very high purity and completeness

✓ observable: X-ray luminosity, correlates well with cluster mass

- scatter in L_X - mass relation mainly due to presence of a cool core

- expensive (need space satellite)

- require follow-up observations for cluster redshifts

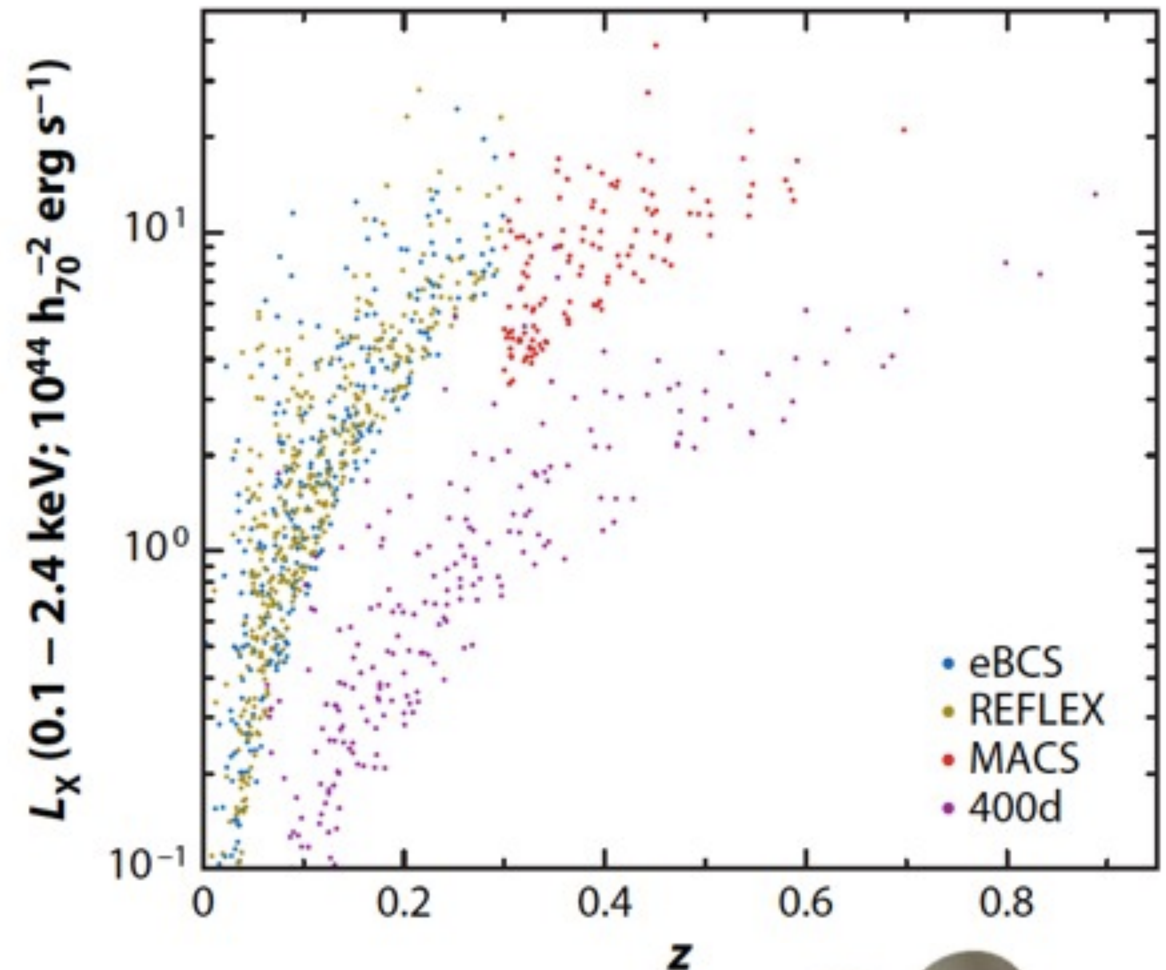


"cool core":

at cluster core, gas density can become high enough to start cooling efficiently by radiation

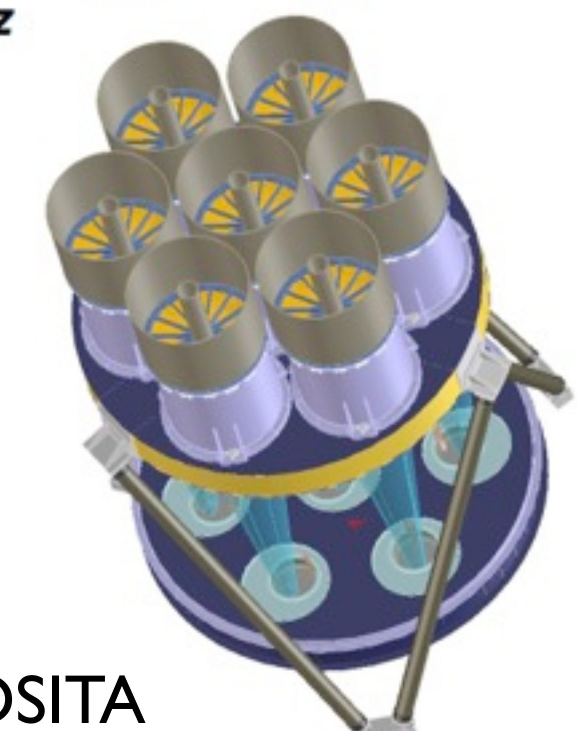
cooler gas ⟶ lower pressure ⟶ more gas ⟶ more cooling ⟶ bright core

X-ray surveys



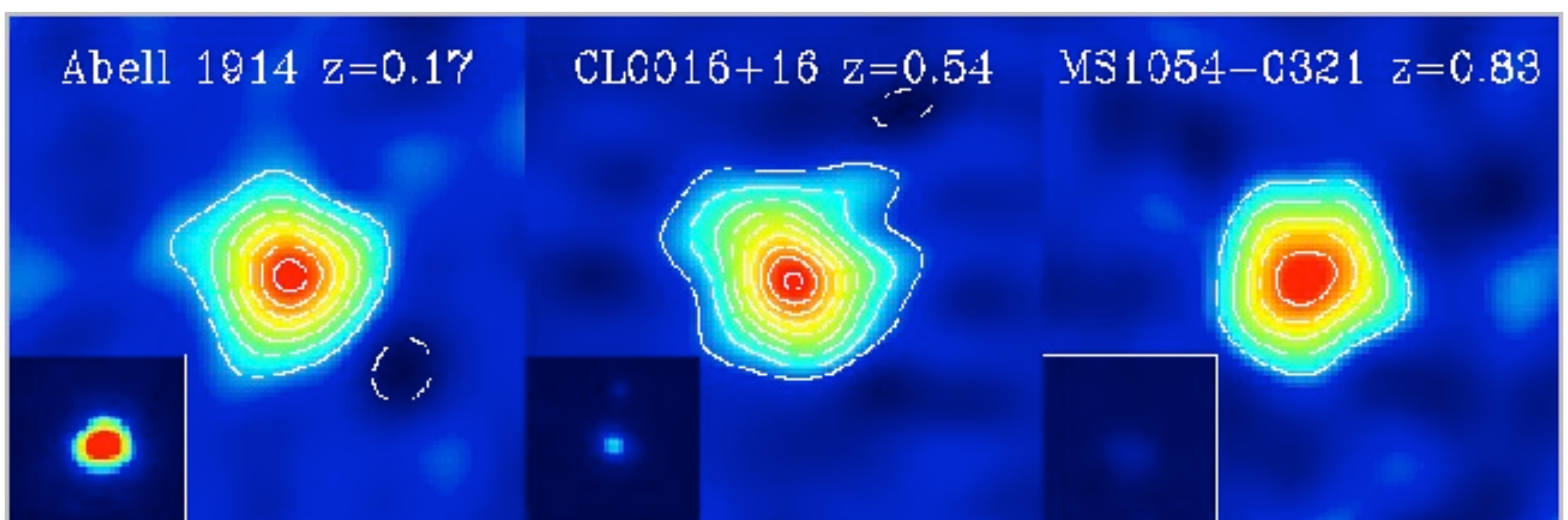
- ROSAT satellite: 1990 - 1999
- all-sky survey (RASS)
- several cluster catalogs, a few hundred clusters

- eROSITA: to be launched in 2016
- more sensitive all-sky survey
- will identify ~100000 clusters



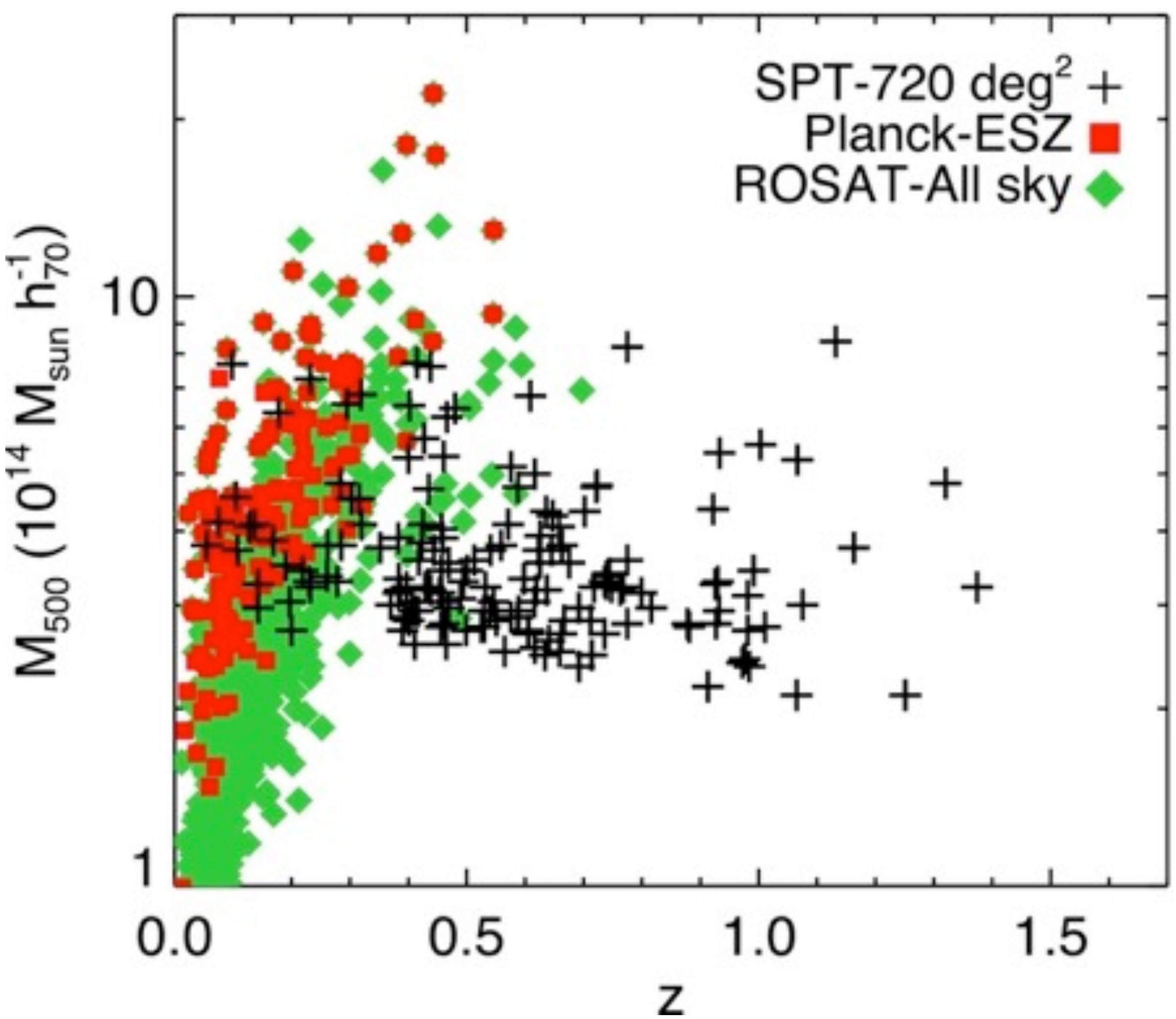
SZ surveys

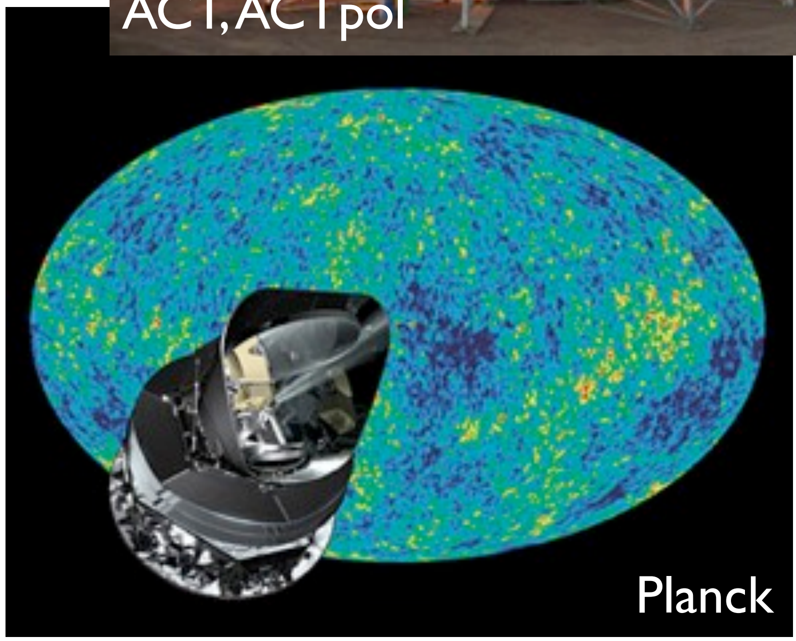
- ✓ SZ signal not subject to cosmological surface dimming ⟶ *great for finding high-redshift clusters!*
- \- more susceptible to projection and triaxiality effects than X-rays
- ✓ scatter SZ - mass less than LX
- \- some contamination / masking by astrophysical sources (e.g. radio galaxies)



SZ surveys

- current SZ surveys: SPT(pol), ACT(pol), Planck
- samples of several hundred clusters each, including massive clusters at z>1
- next stage experiments planned (CMB-S4, Advanced ACTpol)

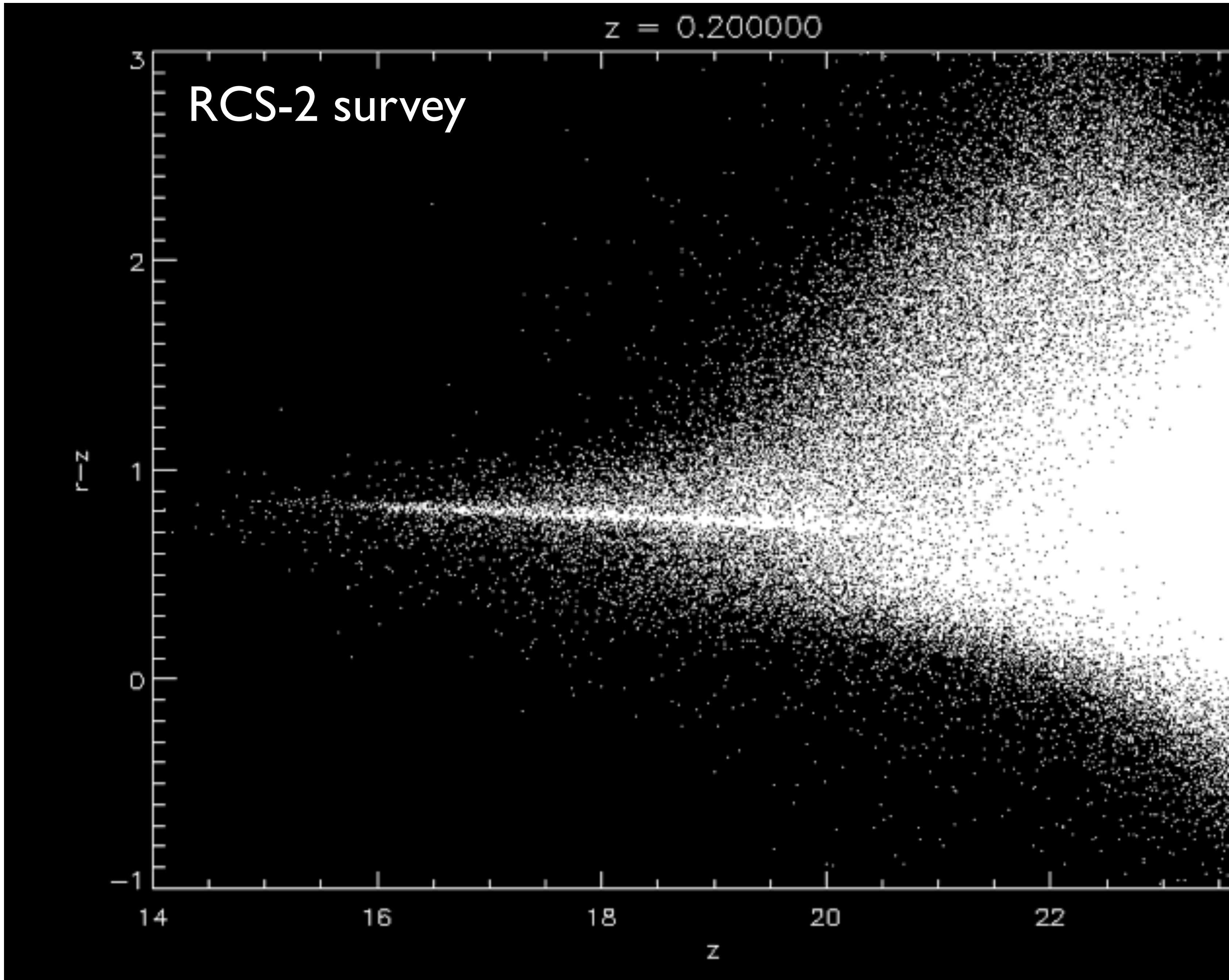




Optical cluster surveys

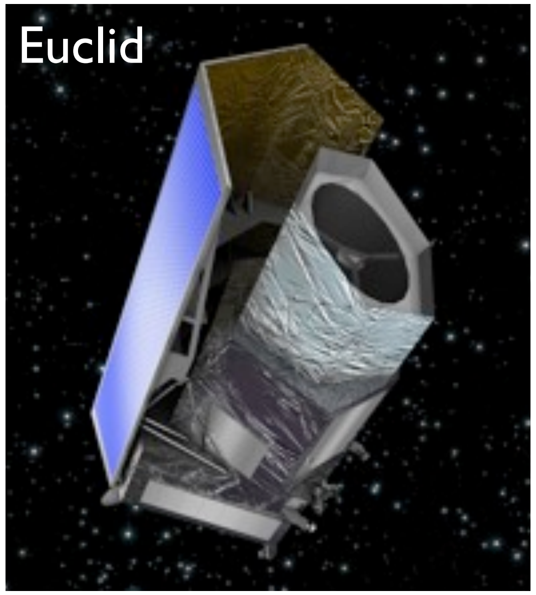
- identify galaxy overdensities
- most successful cluster finders based on red sequence

- large cluster samples
- optical surveys also yield redshifts, weak lensing data
- subject to projection effects
- purity / completeness lower than X-ray / SZ



Optical cluster surveys

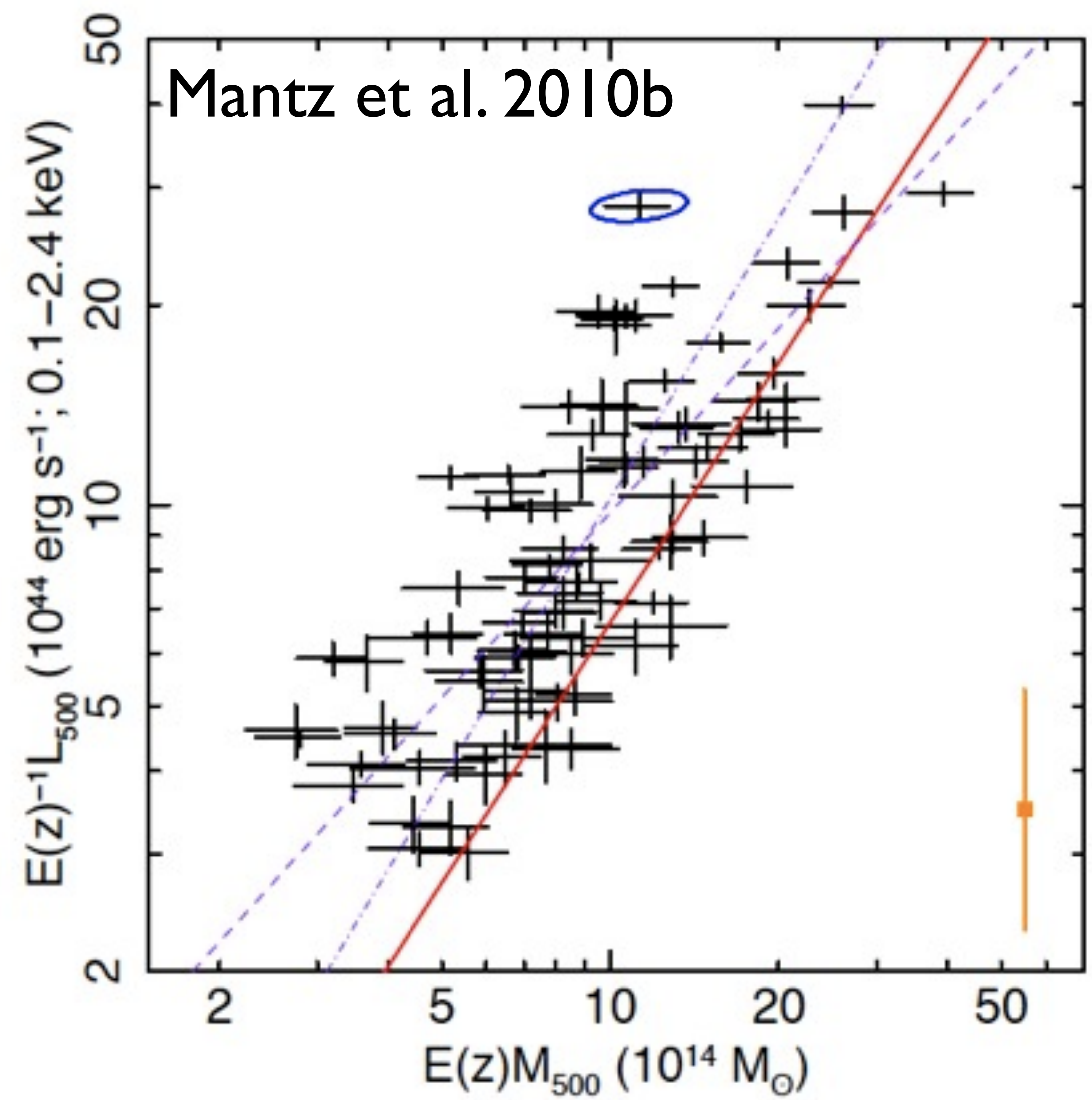
- SDSS: catalogs of several 10 000 clusters
- DES: just started, 5-yr, 5000 sq. degree survey in southern hemisphere
- LSST: will observe ~half the sky to depth and image quality of Subaru
- Euclid: optical + NIR space-based survey of the extragalactic sky



Ingredients for cluster counts cosmology

1. prediction for halo mass function
2. cluster survey with well understood selection function
3. **relation between survey observable and cluster mass**

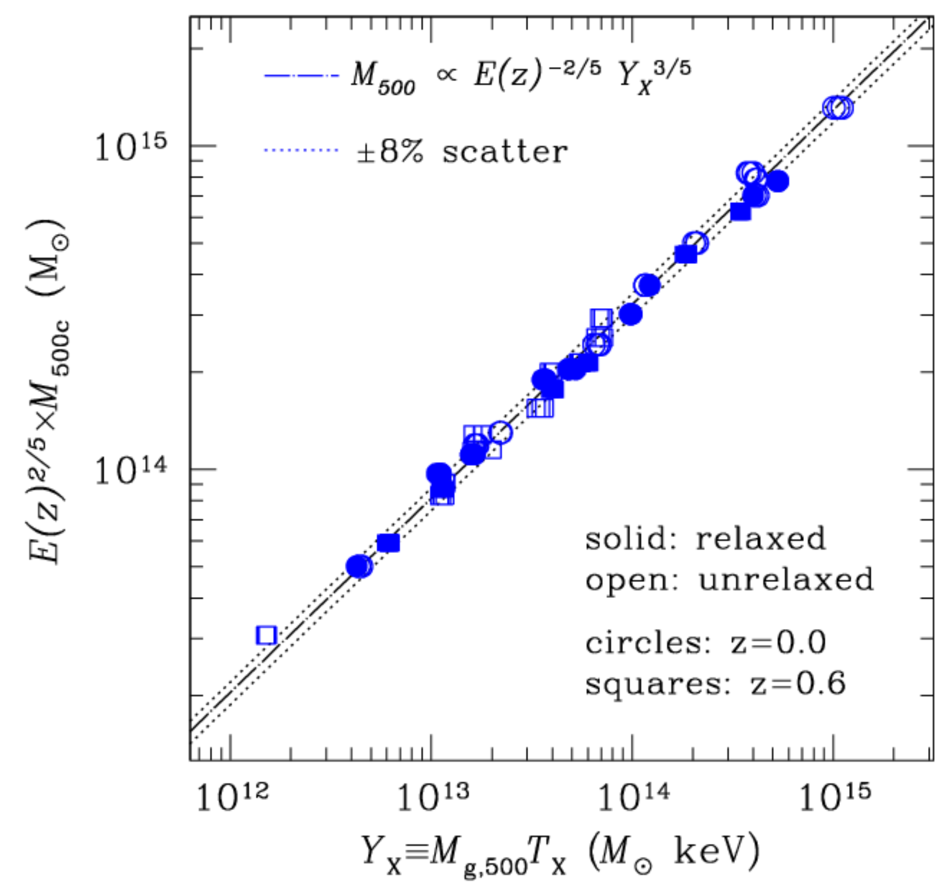
- survey observable (X-ray luminosity, SZ flux, optical richness) does not measure cluster mass directly
  - correlates with mass, but with considerable scatter, (30-40)%
  - need to measure scaling relation

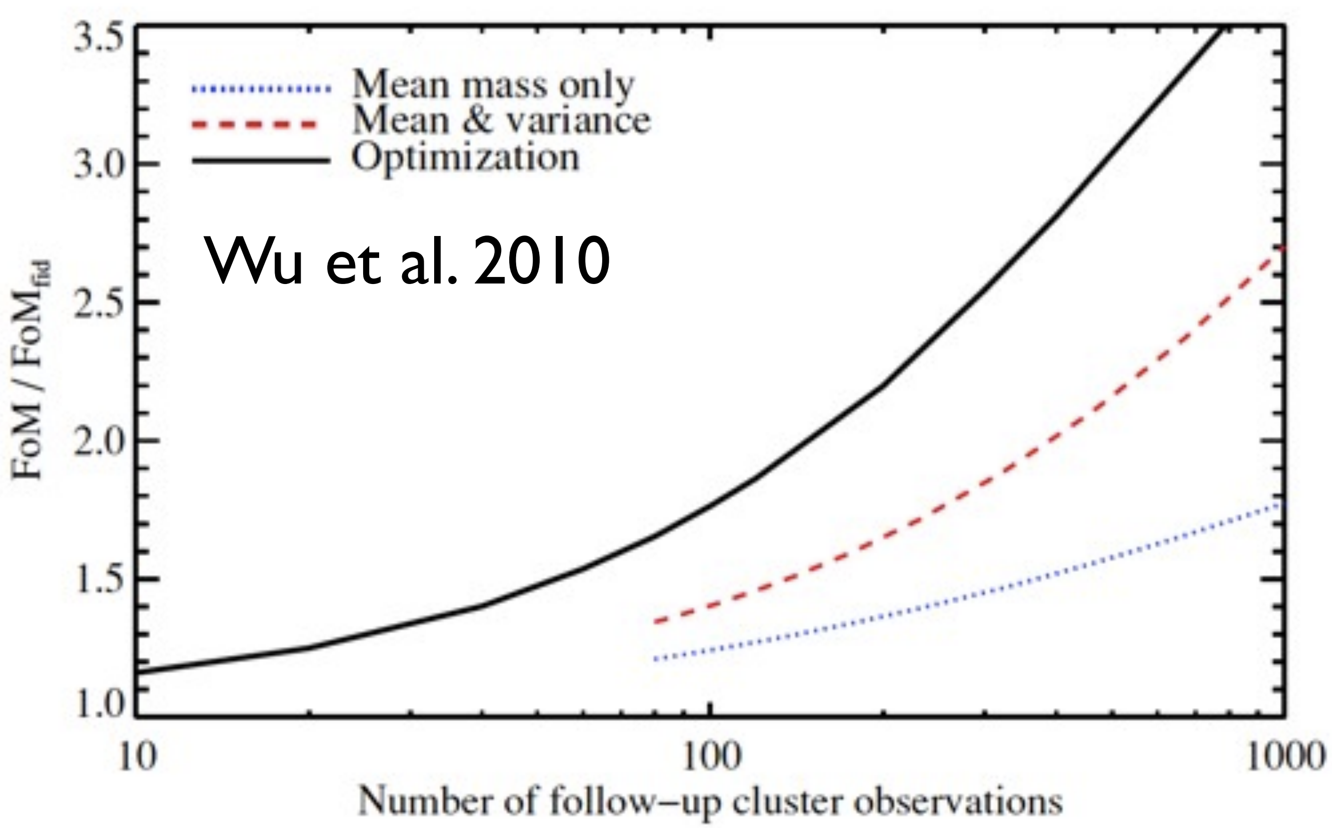


Mass proxies

- (follow-up) X-ray observations can provide a number of low-scatter mass proxies:
  - ICM temperature T_X; gas mass M_{gas}; core-excised luminosity; Y_X
  - essential for measuring shape and scatter of M-O relation
    ➡ significant increase in constraining power
  - do *not* provide absolute mass calibration

Kravtsov et al. 2006



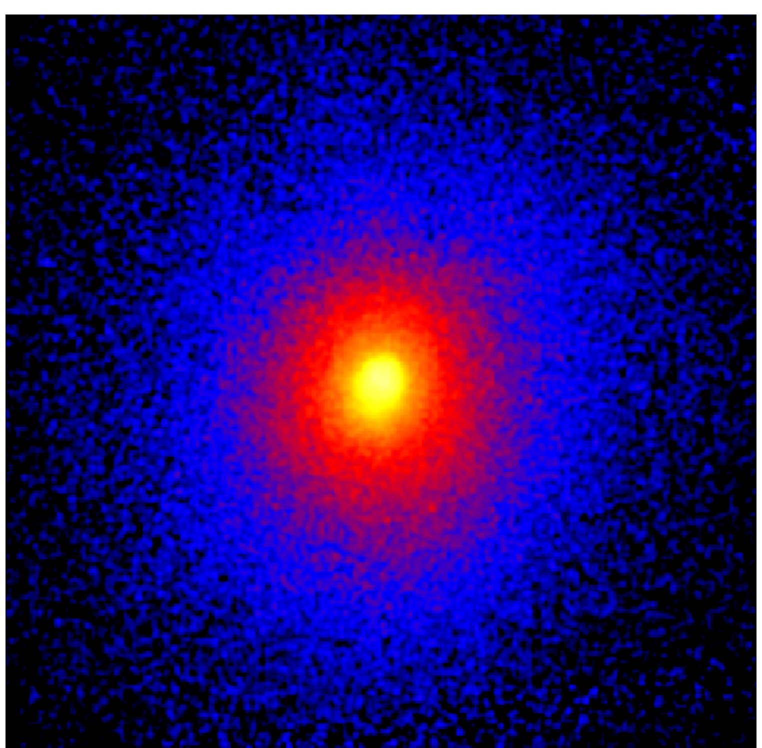


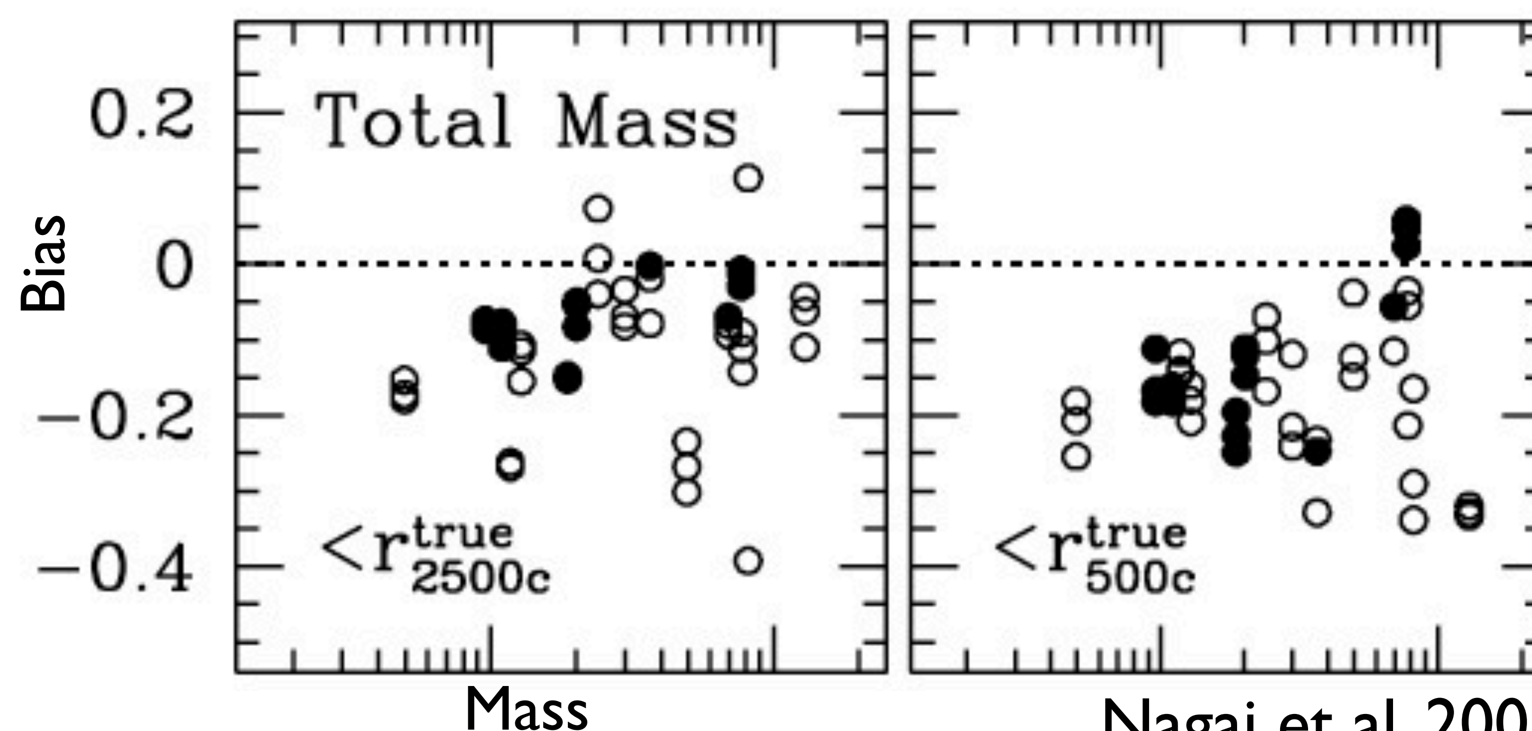
Absolute Masses ?

- hydrostatic mass estimates?
  - assume spherical symmetry and hydrostatic equilibrium
  - expect biased measurements due to non-thermal pressure support, ~20% overall, 5-10% even in dynamically relaxed clusters

    → calibration by simulations sensitive to details of astrophysics

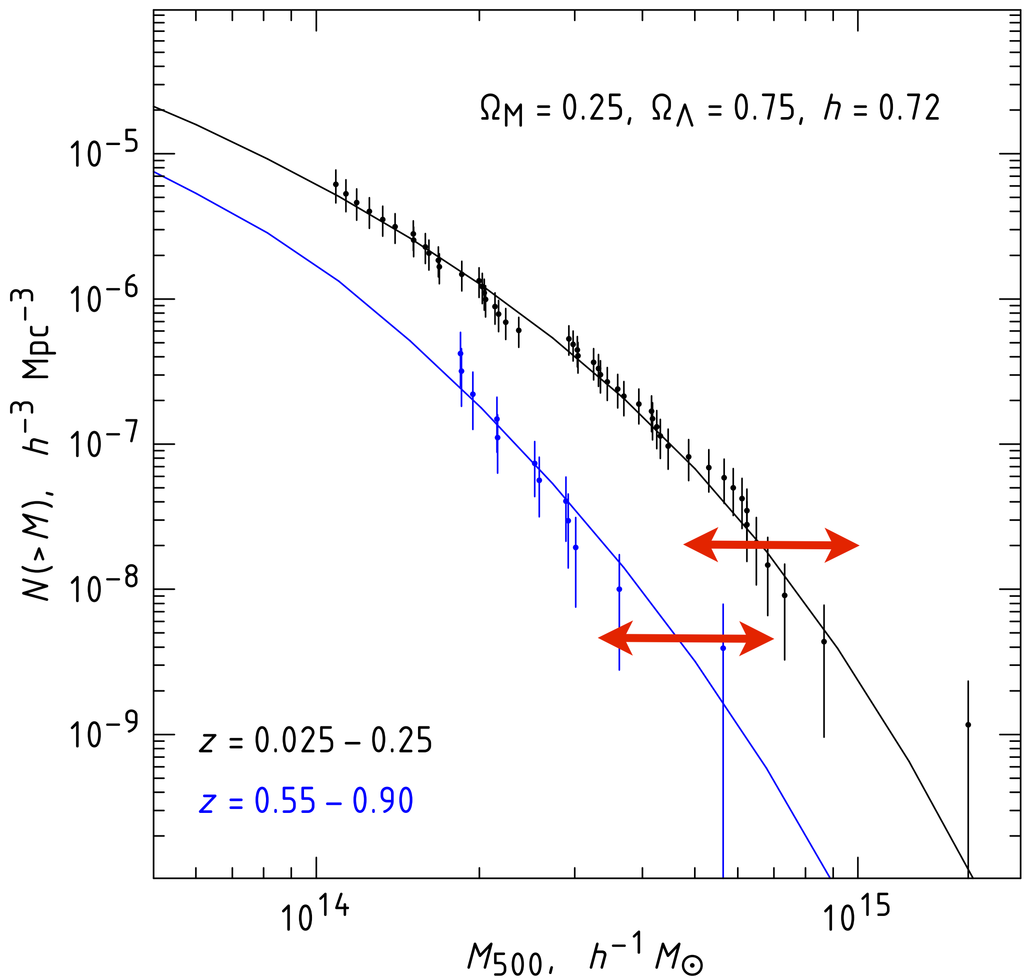
- practical problem:
  - Chandra and XMM T and M_{HE} masses systematically offset

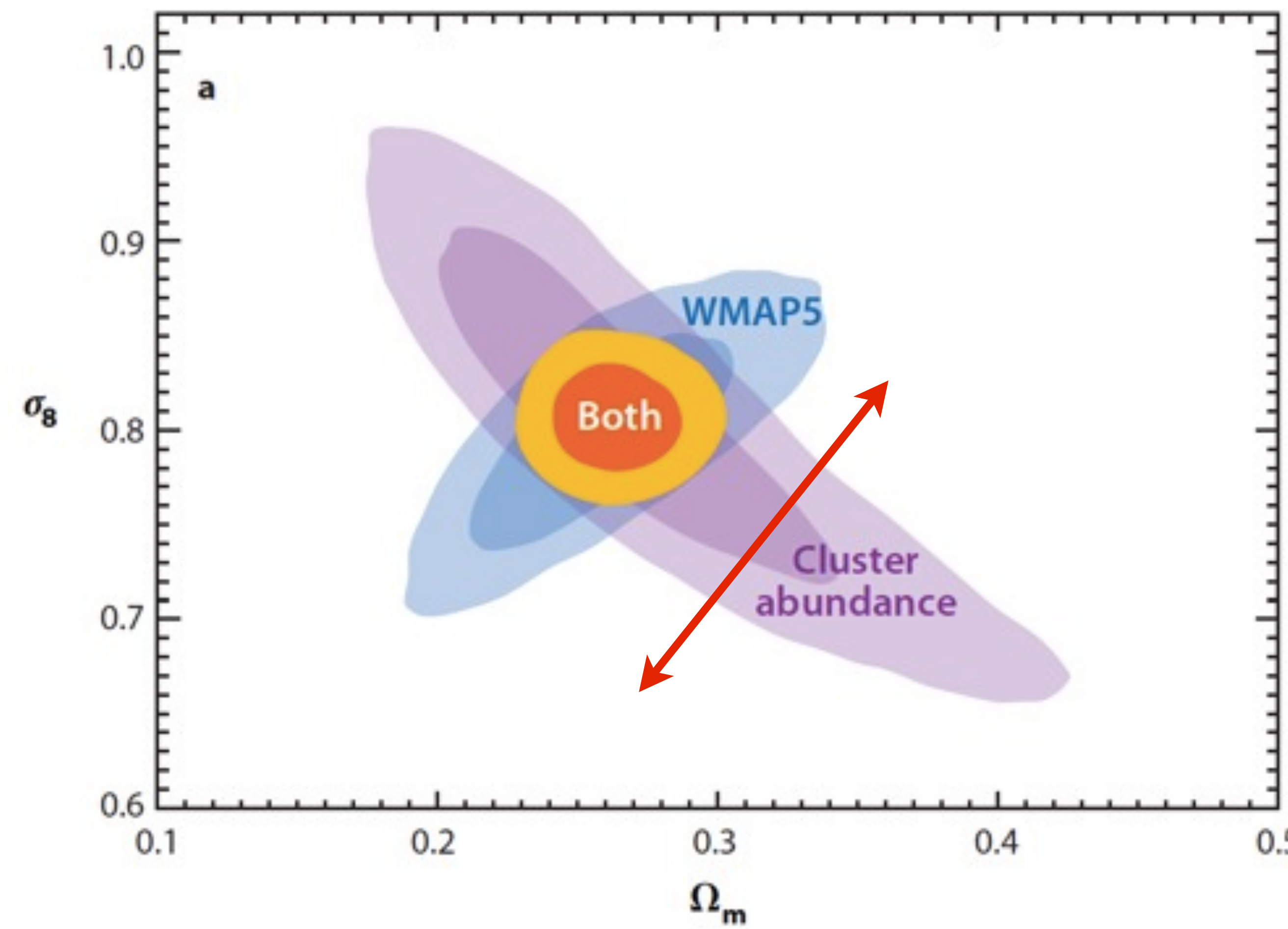




Nagai et al. 2007

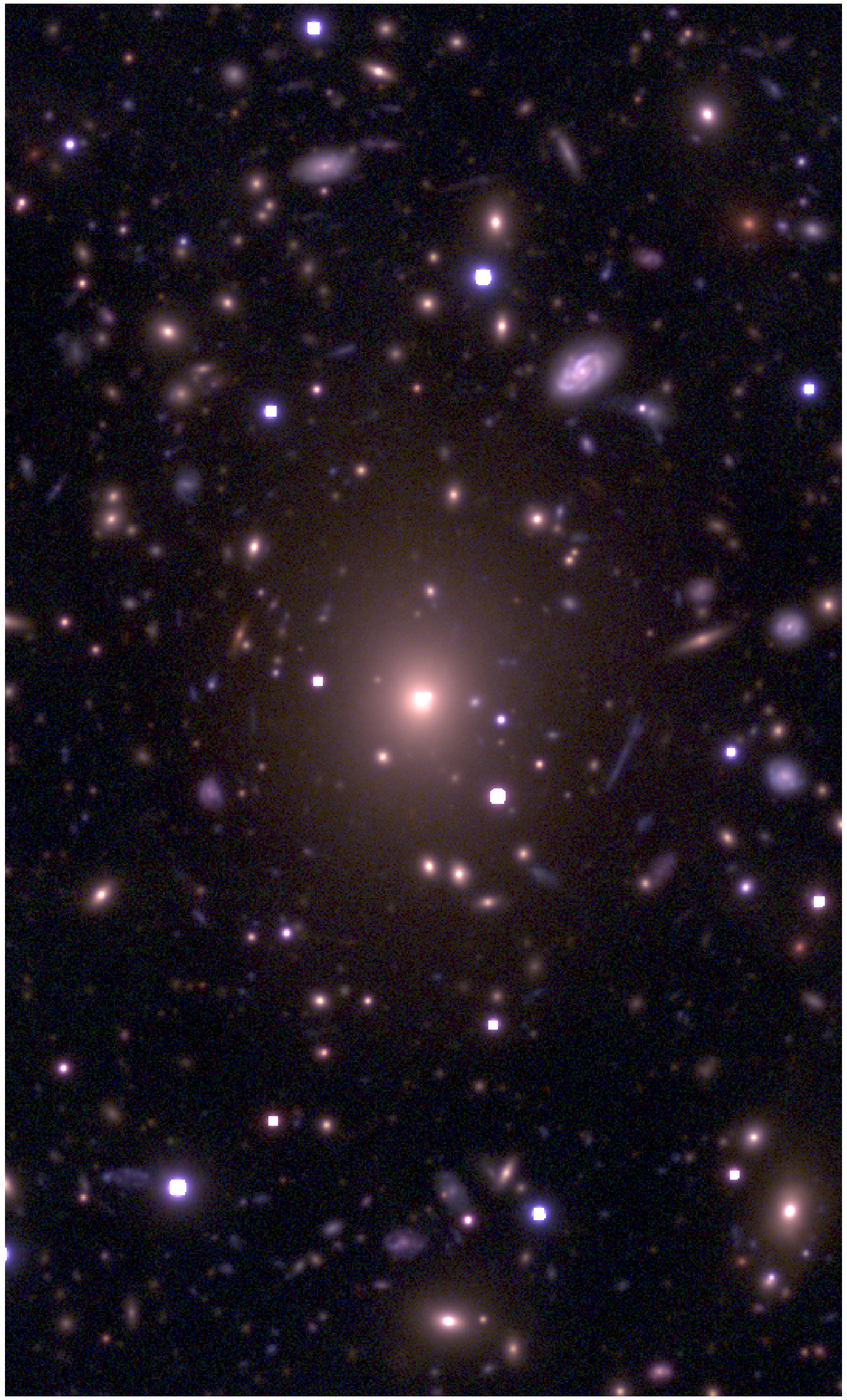
Importance of Absolute Mass Normalization





- for σ_8 (+ neutrino masses, etc.) already current results limited by uncertainty in mass normalization
- (most) published results assume (10-15)% uncertainty, *Weighing the Giants* reaches ~7%, DES-like will require 5%, *LSST* 2%
- biggest challenge in cluster cosmology today

Calibration by cluster weak lensing



(most) promising observational calibration method:

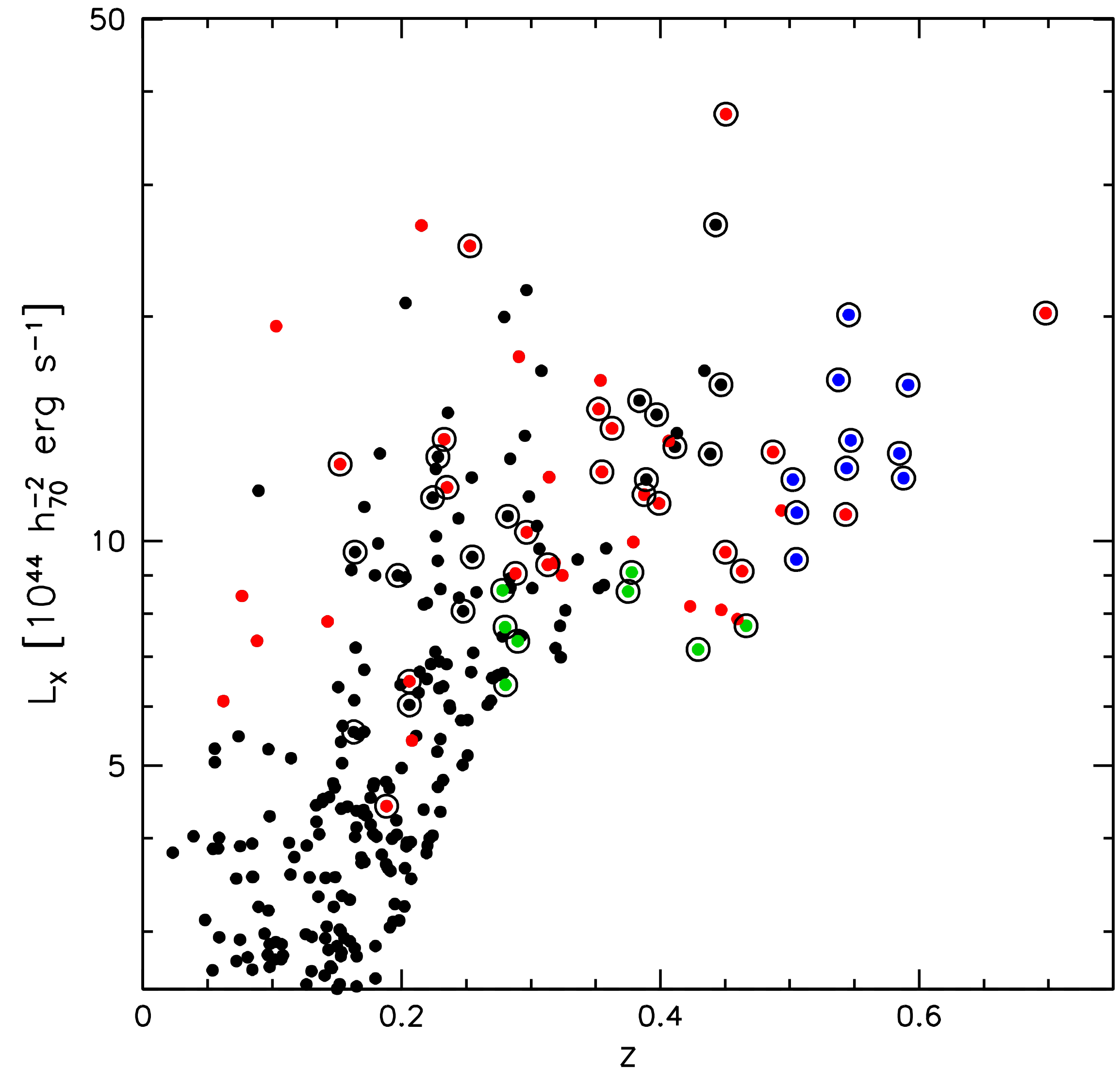
- weak lensing measures total mass
- does not require a baryonic tracer
- no assumption on dynamical state of cluster needed

- comes for free with optical surveys !

- key development: control of systematic uncertainties

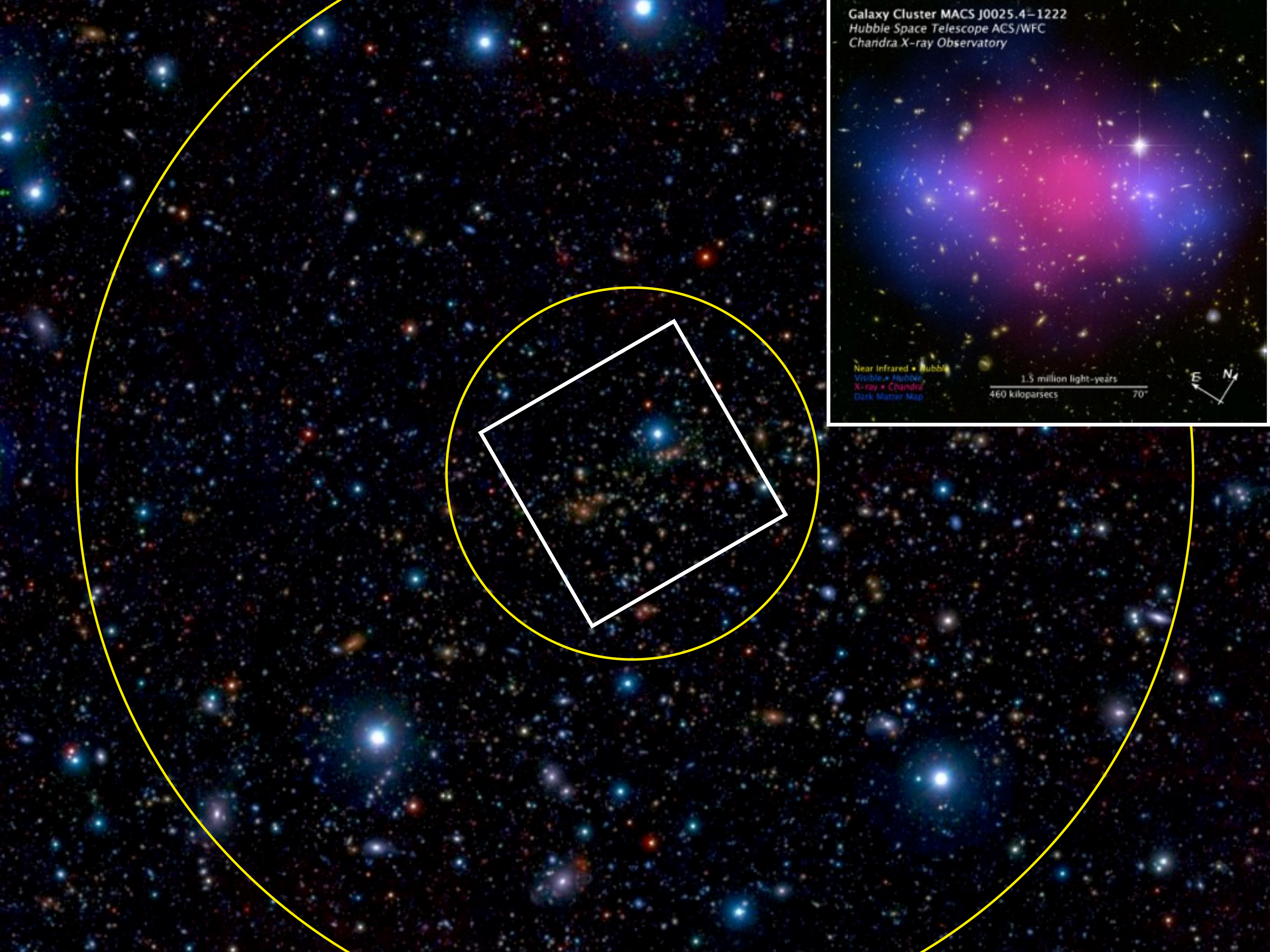
Weighing the Giants

- WL masses for 51 massive, X-ray selected clusters at 0.15<z<0.7
- clusters selected from BCS, REFLEX, MACS
- SuprimeCam imaging in 3 filters for all; in 5 filters for 27 clusters
- precursor to LSST in depth, seeing



Anja von der Linden (KIPAC), Doug Applegate (KIPAC), Patrick Kelly (KIPAC), Mark Allen (KIPAC), Steve Allen (KIPAC), Harald Ebeling (Hawaii), Patricia Burchat (KIPAC), David Burke (KIPAC), Roger Blandford (KIPAC), Peter Capak (Caltech), Oliver Czoske (Vienna), David Donovan (Hawaii), Thomas Erben (Bonn), Adam Mantz (Chicago), Glenn Morris (KIPAC)

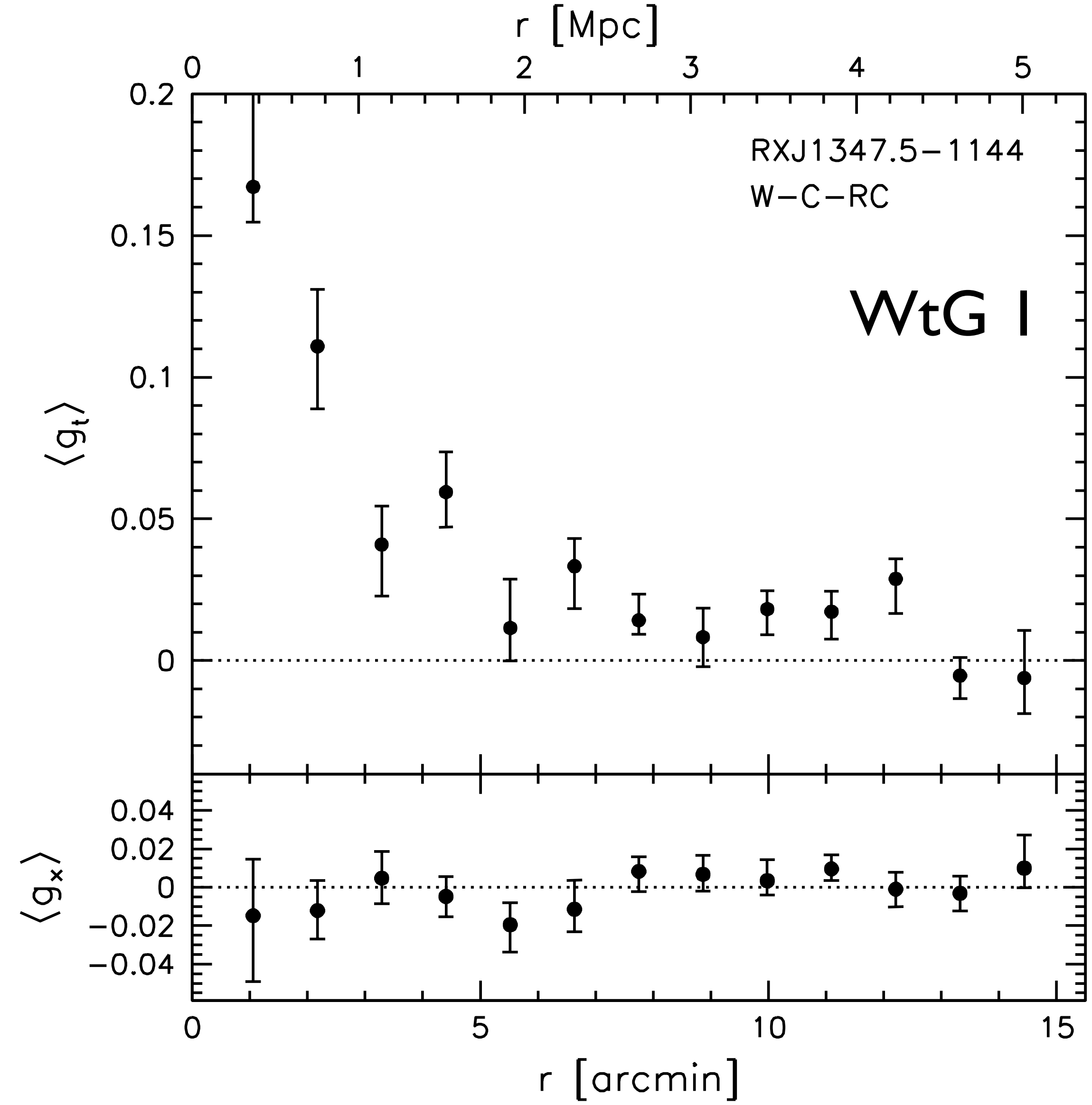
WtG I	Overview, data reduction	AvdL et al. 2014	arXiv:1208.0597
WtG II	Photometry, photo-z's	Kelly et al. 2014	arXiv:1208.0602
WtG III	Cluster mass measurements	Applegate et al. 2014	arXiv:1208.0605


Galaxy Cluster MACS J0025.4−1222
Hubble Space Telescope ACS/WFC
Chandra X-ray Observatory
Near Infrared • Hubble
Visible • Hubble
X-ray • Chandra
Dark Matter Map
1.5 million light-years
460 kiloparsecs
70"
E
N

Ingredients for cluster mass measurements

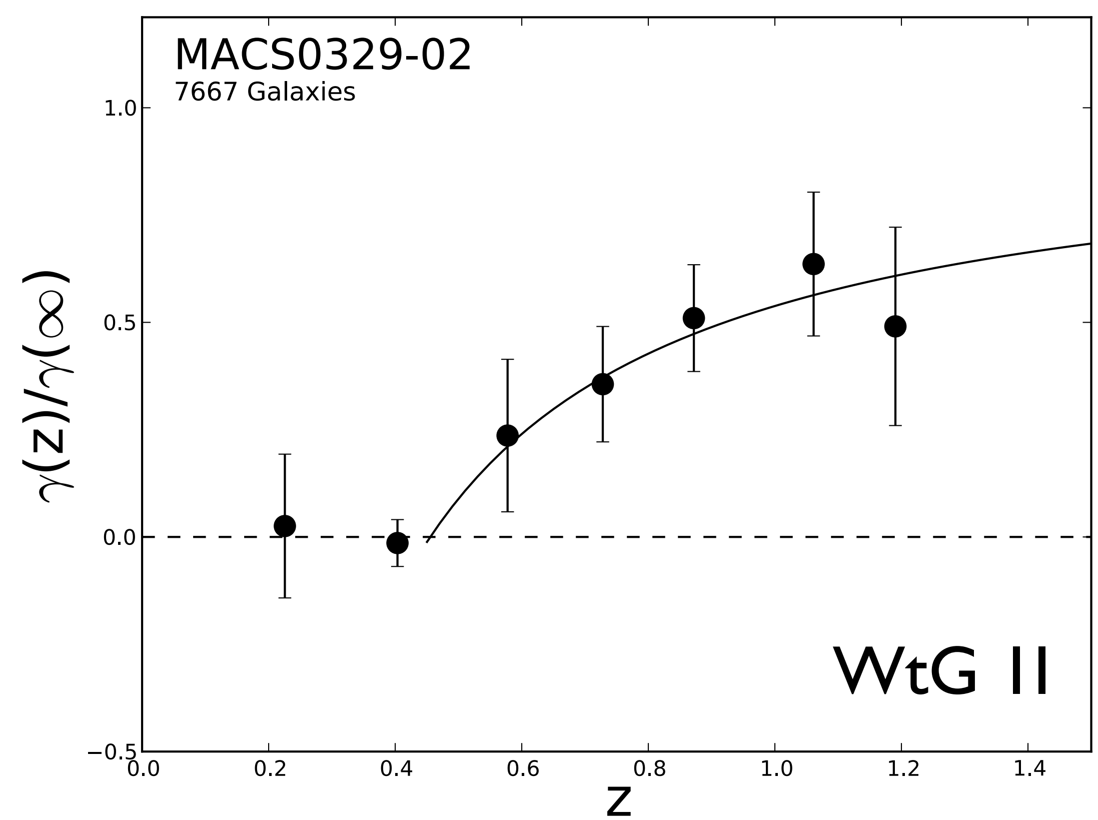
Shear induced on background galaxy depends on:

- cluster mass (distribution)
- redshift



To measure cluster mass, need

1. reduced shear measurements
2. (some) assumption on mass distribution
3. redshifts / redshift distribution



... and need to understand the systematics of each!

Applegate et al. 2012

<table>
<tr><th rowspan="2">Uncertainty Source</th><th colspan="2">% of Mean Cluster Mass</th><th rowspan="2"></th></tr>
<tr><th>Color-Cut Method</th><th>P(z) Method</th></tr>
<tr><td>Shear Measurements</td><td colspan="2"></td><td></td></tr>
<tr><td>Multiplicative Shear Bias Cor</td><td colspan="2">3%</td><td>STEP</td></tr>
<tr><td>STEP PSF Mismatch</td><td colspan="2">2%</td><td>STEP</td></tr>
<tr><td>Coaddition & PSF Interpolation</td><td colspan="2">1%</td><td></td></tr>
<tr><td>Mass Model</td><td colspan="2"></td><td></td></tr>
<tr><td>Triaxiality & LOS Structure</td><td>3%</td><td>4%</td><td>$\sqrt{N}$</td></tr>
<tr><td>Profile Uncertainty</td><td colspan="2">3%</td><td>NFW?</td></tr>
<tr><td>Photo-z Measurements</td><td colspan="2"></td><td></td></tr>
<tr><td>Residual Photometry Systematics</td><td colspan="2">3%</td><td></td></tr>
<tr><td>Simulated Photo-z Bias</td><td colspan="2">1%</td><td>p(z) bias</td></tr>
<tr><td>Depth & Filter Mismatch</td><td colspan="2">1%</td><td></td></tr>
<tr><td>Method Cross-Calibration</td><td>4%</td><td>-</td><td></td></tr>
<tr><td>Total Systematic Uncertainty</td><td>7%</td><td>7%</td><td></td></tr>
</table>

factor x2 improvement in precision !

no principle roadblock → excellent prospects for future surveys

(1) Shear measurements

- measured shear commonly underestimated → biases mass estimates !
- WtG greatly benefited from efforts by the Cosmic Shear community:

  STEP (Massey et al. 2006, Heymans et al. 2007)
  GREAT08,10,3 (Bridle et al. 2010, Kitching et al. 2012)

- STEP2: real galaxy images + SuprimeCam PSF → excellent match to our data

- shear in inner cluster regions not-so-weak

  - *shear calibration needs to extend to g > 0.1*
  - also problems due to crowded field, cluster galaxies

  → for WtG: *avoid inner cluster regions* (≲ 700 kpc)
  (also reduces sensitivity to miscentering and concentration)

(2) Mass model

- *lensing sensitive to all mass along line-of-sight*
  - measures projected 2D masses
  - for relation to halo mass function, need to infer 3D mass

- galaxies are intrinsically elliptical → weak lensing is noisy
- *can typically measure only one parameter reliably*

➡ fit spherically symmetric radial profile (e.g. NFW)
(also breaks mass-sheet degeneracy)

- measured (3D) mass depends on cluster triaxiality / orientation / substructure, structure along LOS

e.g. Meneghetti et al. 2010, Hoekstra 2003, 2011

- (3D) lensing masses have **inherent, irreducible scatter** of $\gtrsim$20%

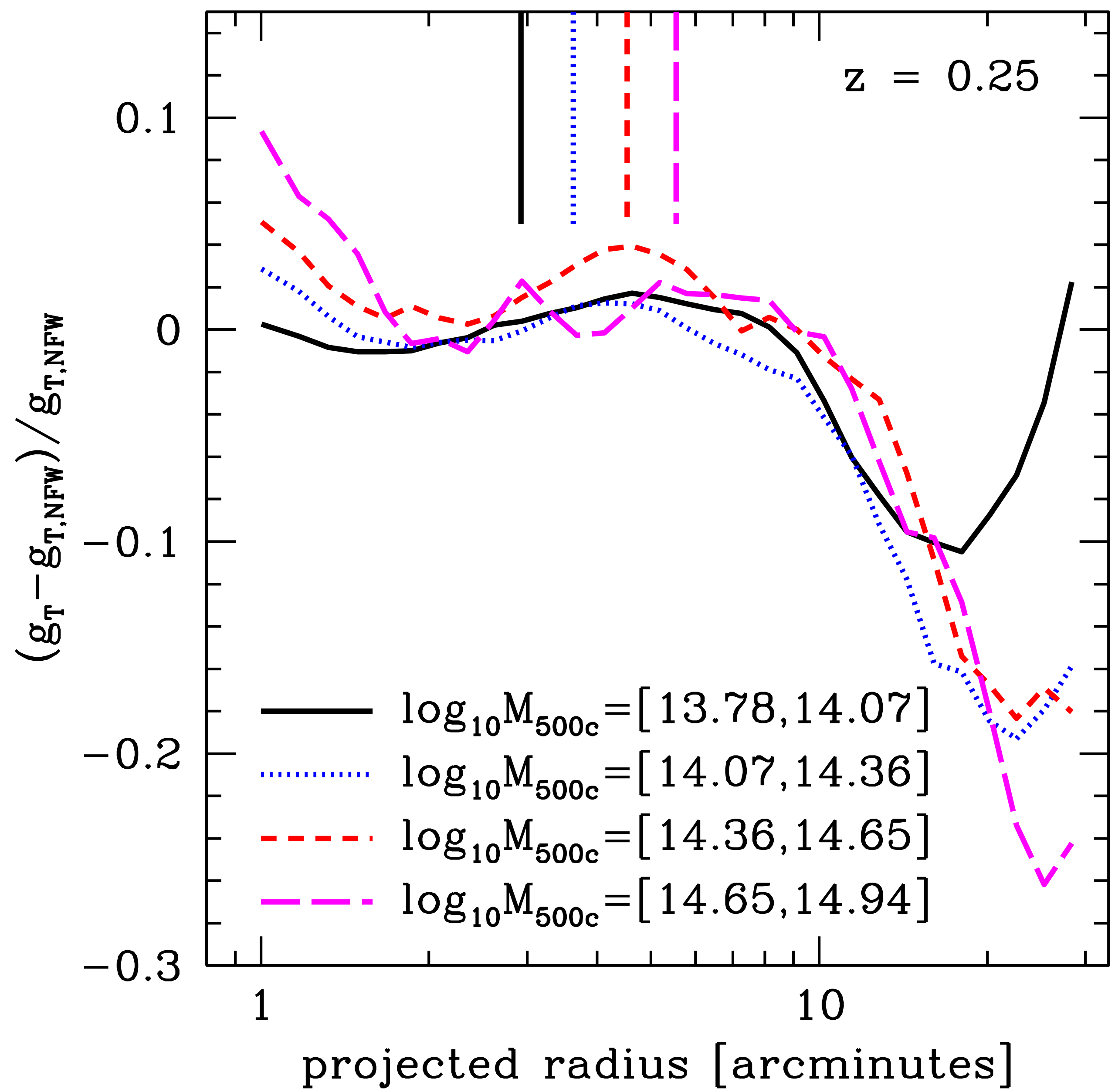
Becker & Kravtsov 2011

(ground-based: scatter from shape noise also ~20% ⇒ total scatter: ~30%)

Is the *average* lensing mass ~~(un-)biased~~ calibratable?

- *methodology can be well tested on N-body simulations*
- NFW profile good description only to virial radius
- if fit beyond R_{vir} → bias of ~-10% (e.g. Meneghetti+10)
- **IF** fit over restricted radial range (<R_{vir}), mass unbiased within 1%

(Becker&Kravtsov 11, Bahe+12, Oguri+11)



need to determine from simulations:

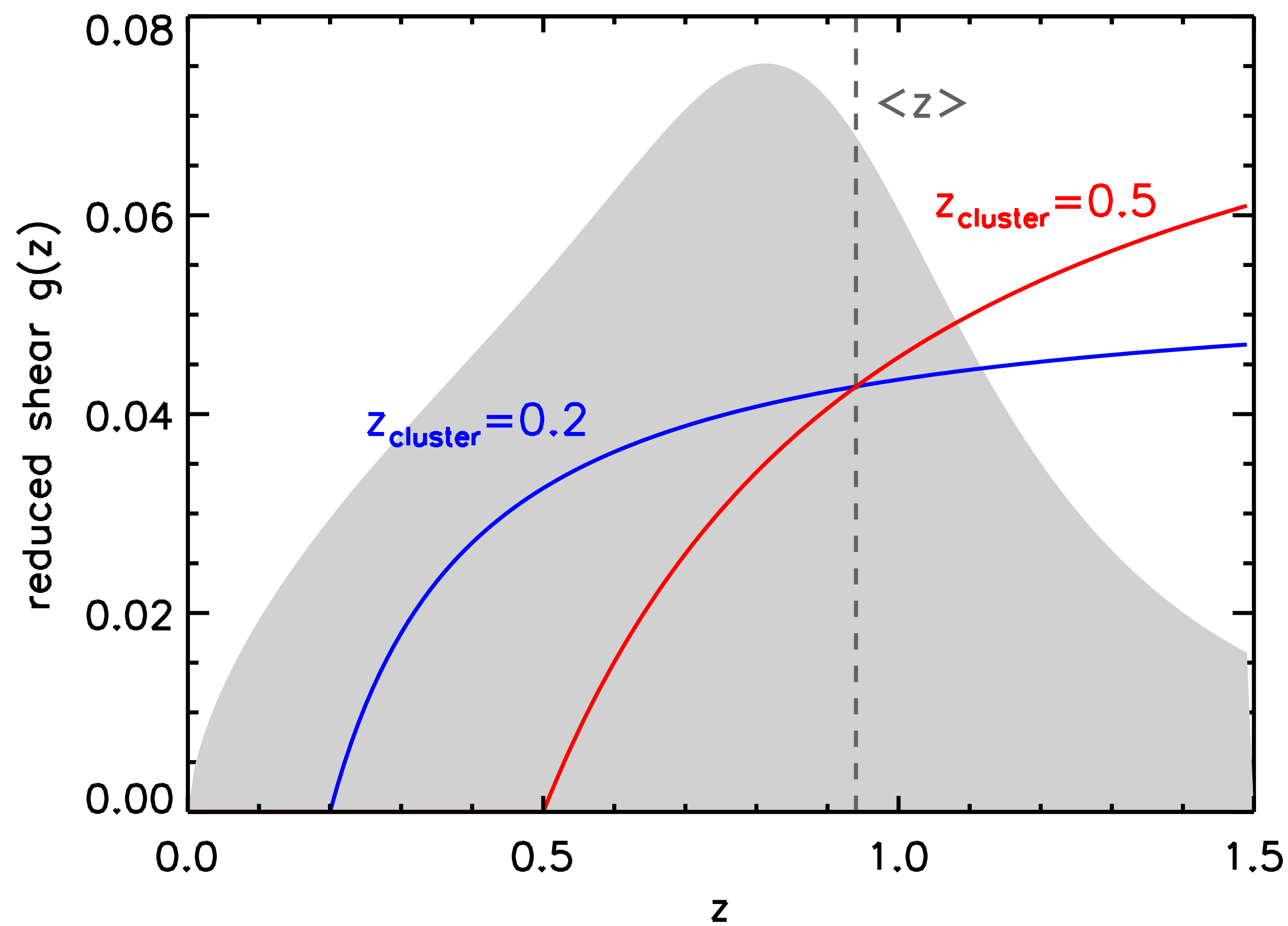
- what profile to fit? (or use aperture masses?)
- over what radial range?
- how to stack ?

average lensing mass unbiased, but scatter of $\gtrsim$ *30%*

- ➡ need large cluster samples
- ➡ CANNOT select on lensing properties
- ➡ strategy: compare *weak lensing* masses (no bias, large scatter) to *X-ray* mass proxies (low scatter, unknown bias)

(3) Shear - redshift scaling

- shear on background galaxy depends on redshift
- mass measurement requires accurate knowledge of redshifts of background galaxies
- associated error on mass depends on cluster redshift

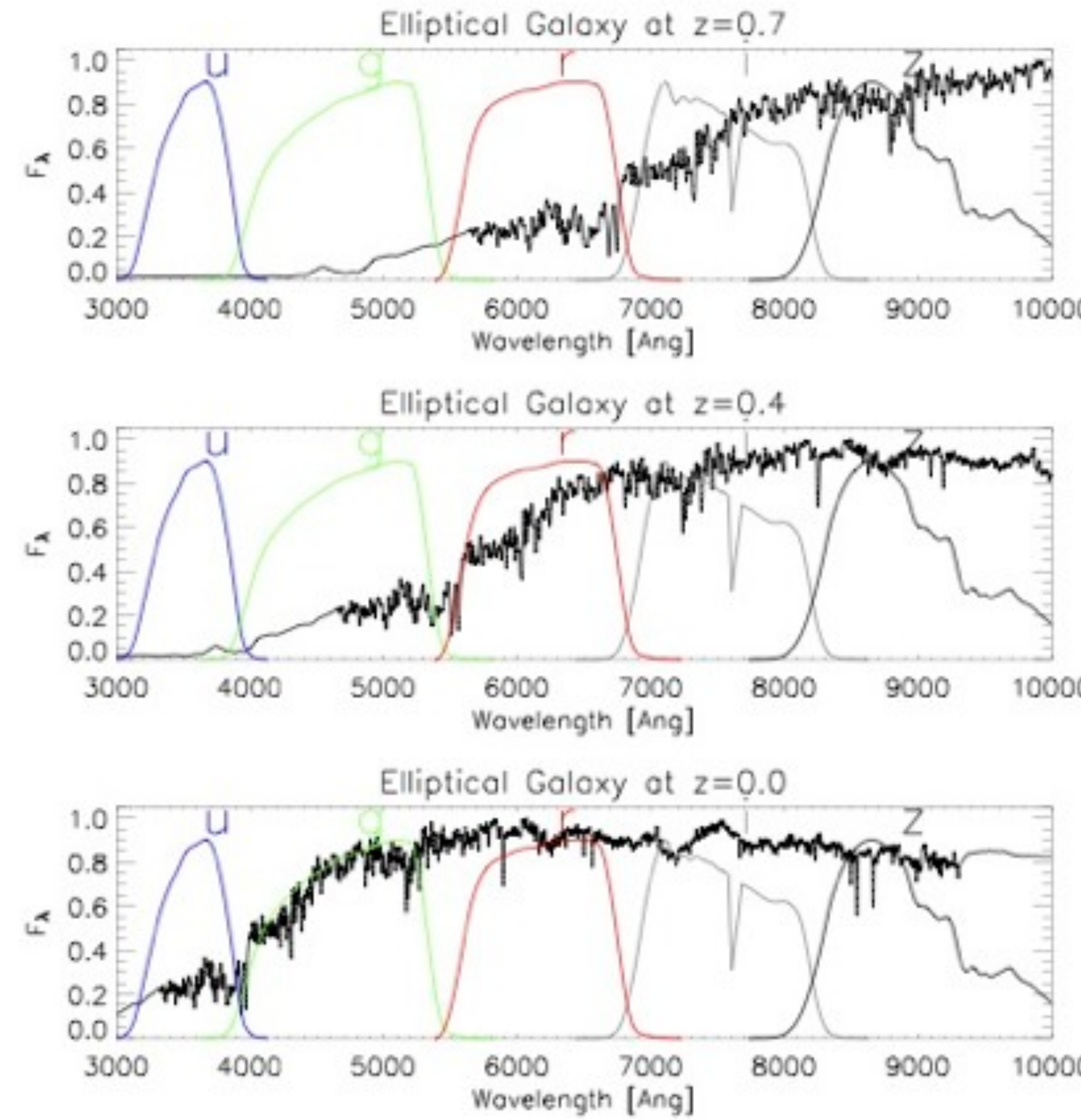


- previous works used only 1-3 filter observations
  - "color-cut" method: assume an effective redshift for all galaxies
  - strong assumptions on contamination by cluster galaxies
  - *percent-level control of systematics difficult (esp. at z>0.4)*

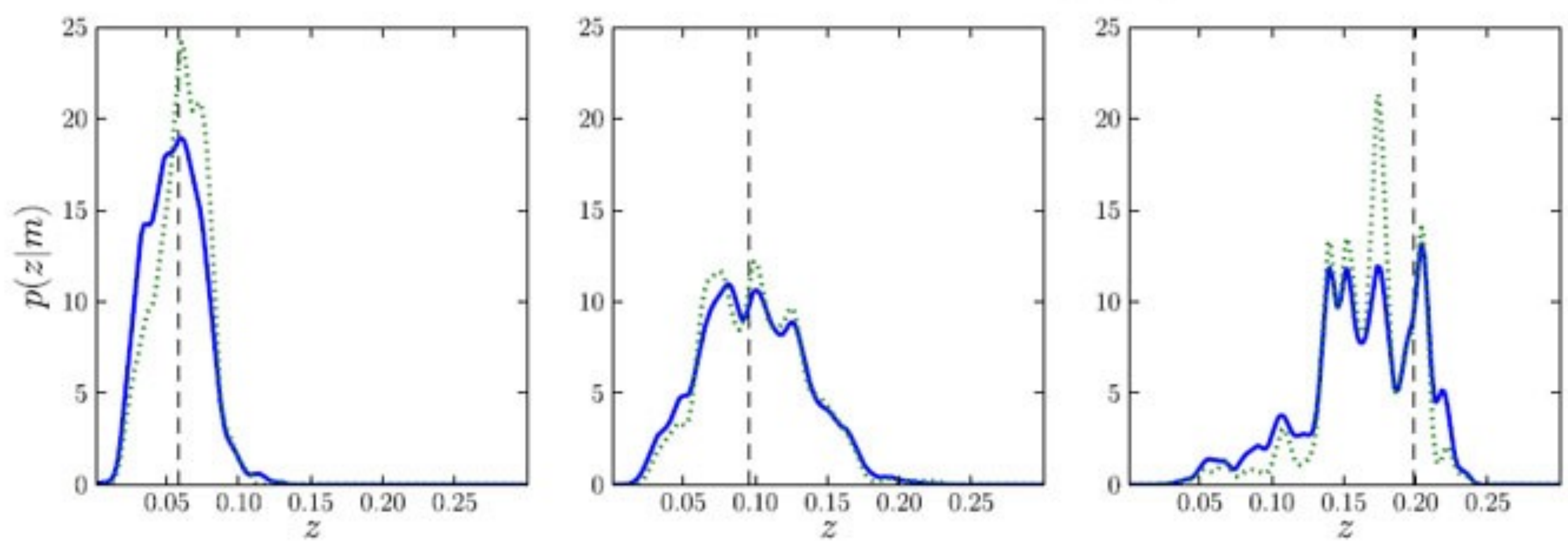
➡ use photometric redshifts instead

Photometric redshifts

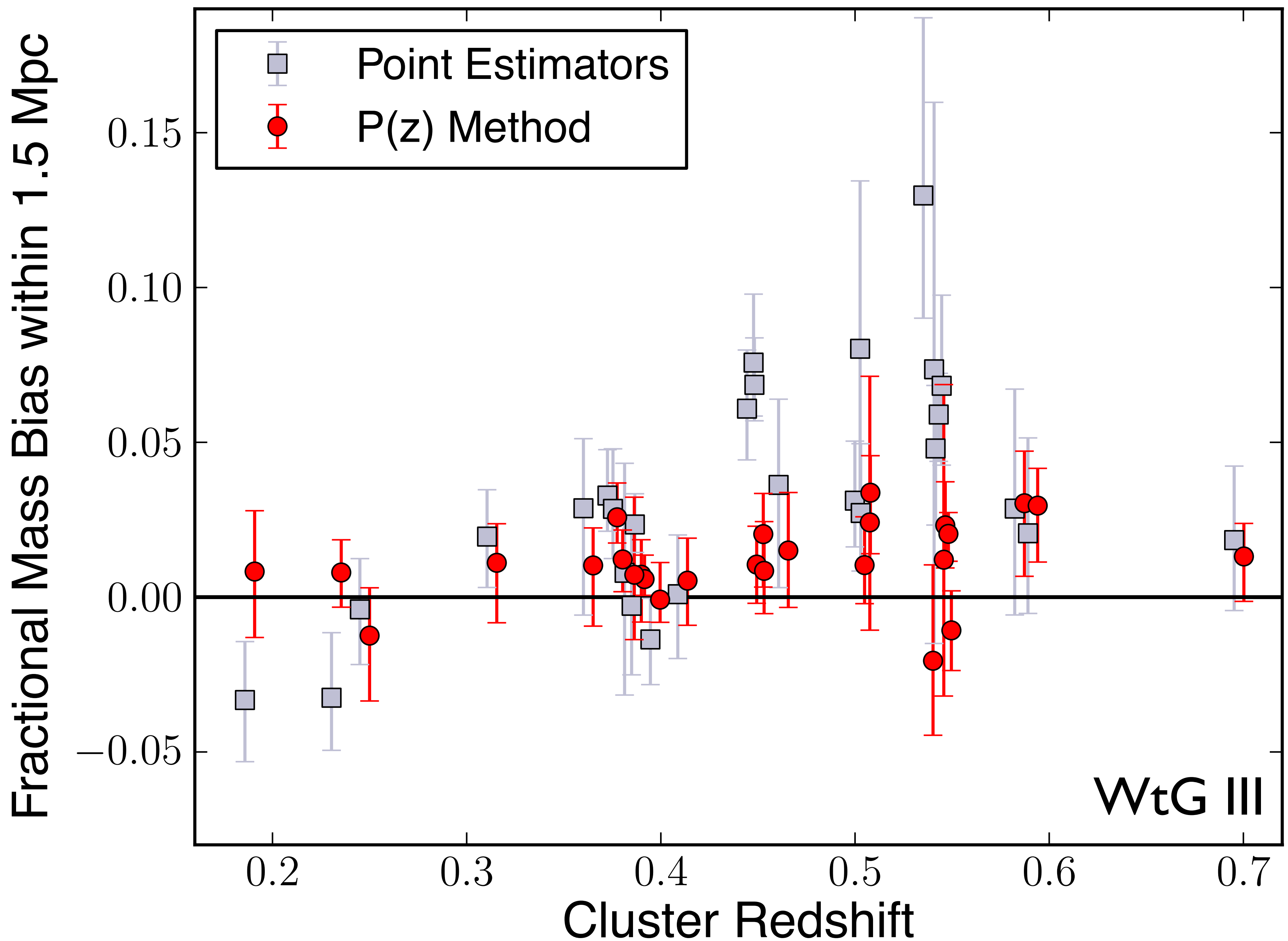
- imaging in ≳ 5 filters: “very low-resolution” spectroscopy
- fit template spectra to observed colors
- facilitated by limited variety in galaxy spectra (“blue” or “red”), but still a non-trivial problem



- yields redshift probability distribution p(z)

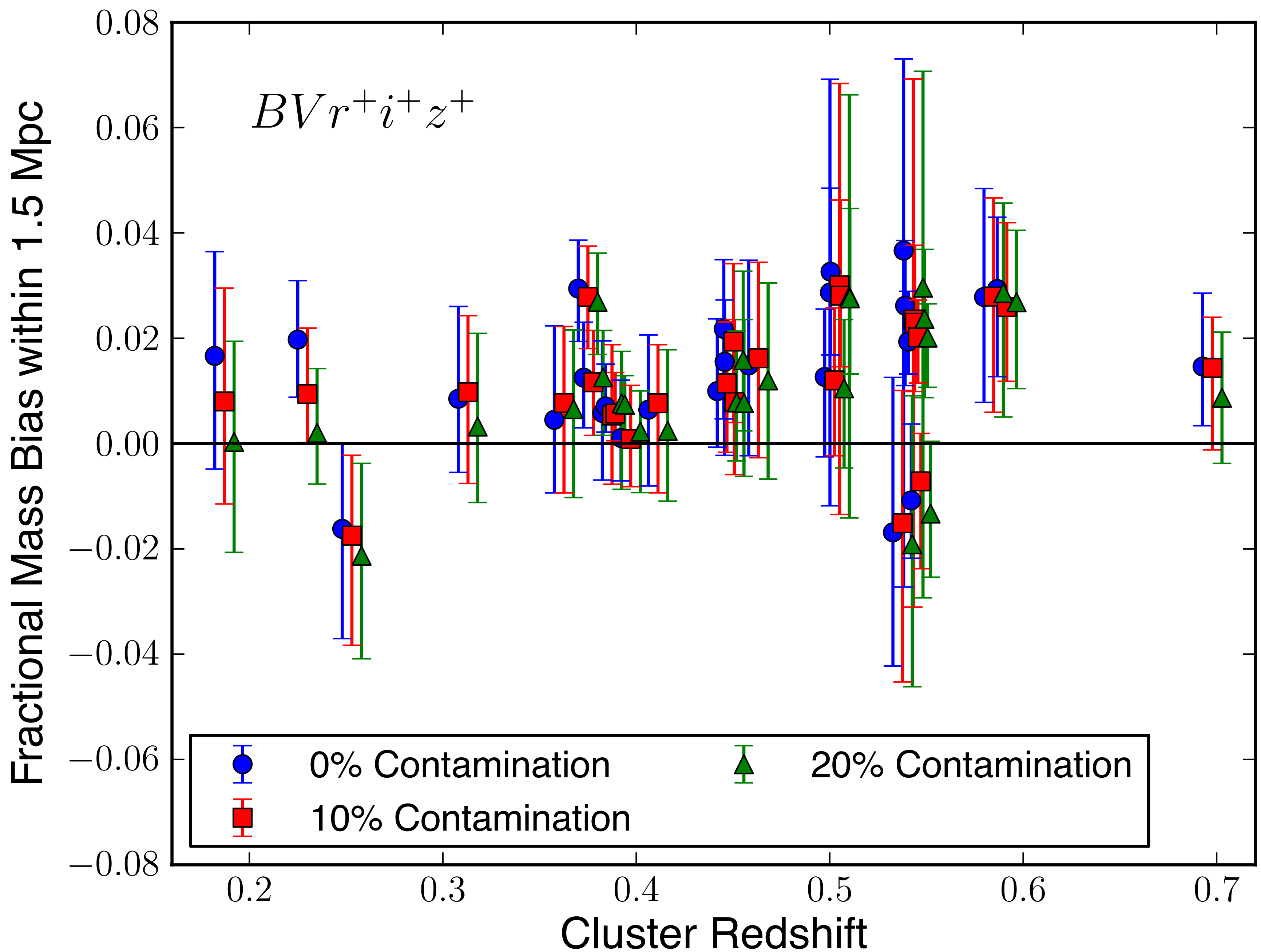


Need to use full p(z) !



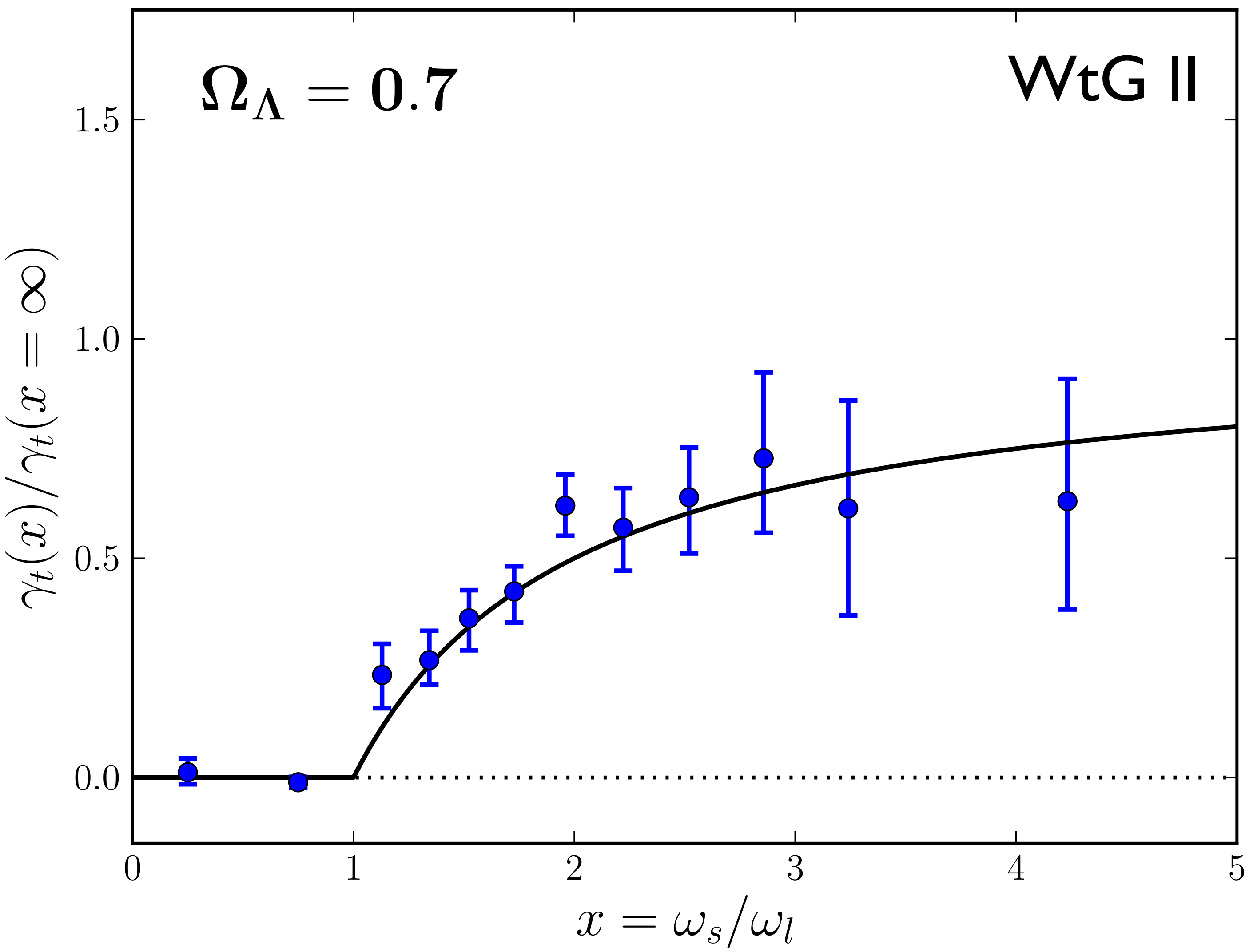
- expected mean ratio 1.012 ± 0.003 → almost unbiased!

Cluster galaxy contamination?



- simulated by adding blue galaxies from COSMOS catalog
- overall shift in mass < 1%

Side-Note: Tomography



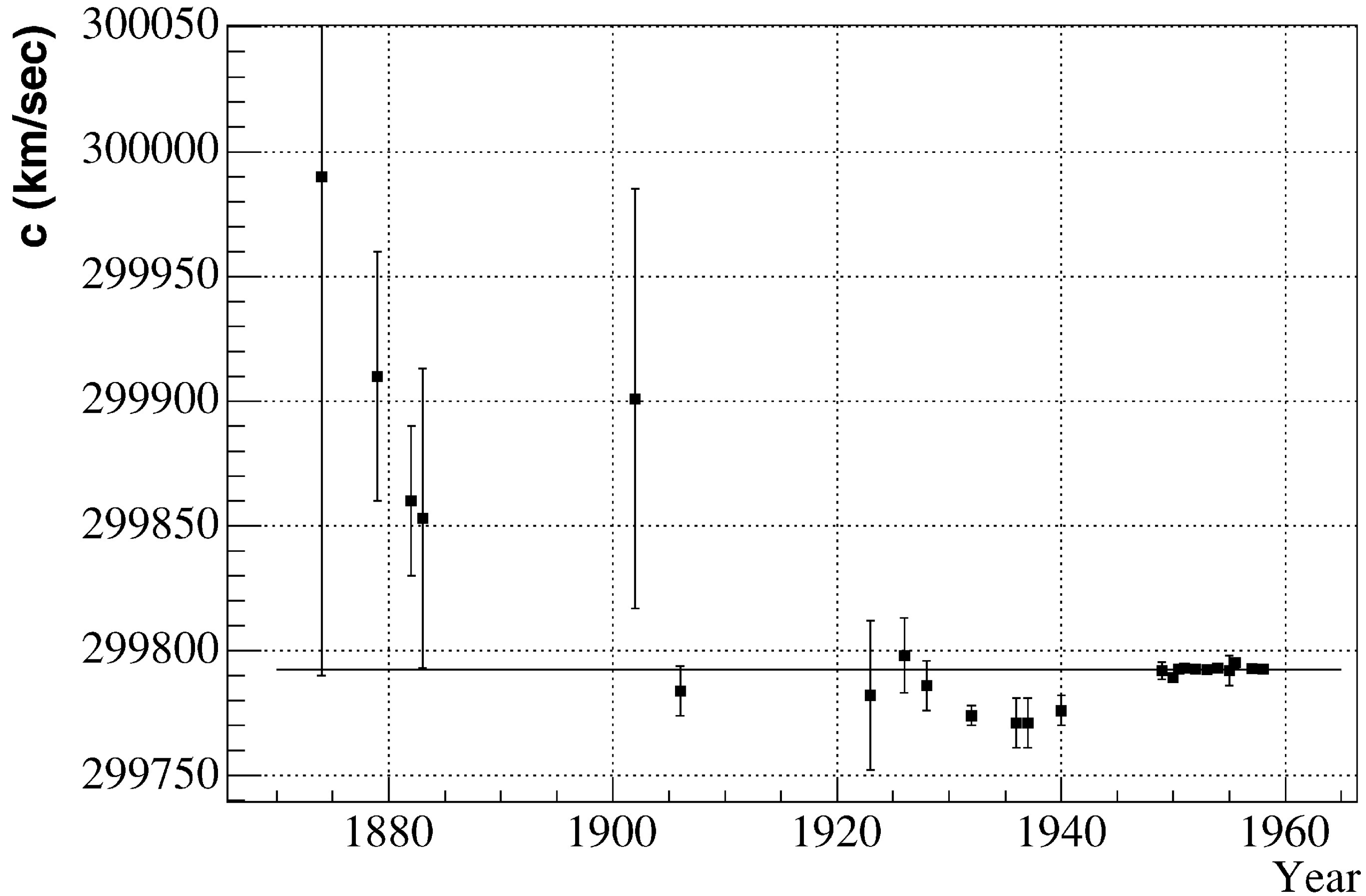
Taylor et al. 2007

- ratio of shear measured at different redshifts sensitive to geometry of Universe
- method very, very sensitive to photo-z errors

Towards future surveys

1. Shear measurements
   - good news: much less stringent than CS (~1% vs. ~0.01%)
   - complications:
     - shear is large
     - dense fields
     - implementation into simulations should be straightforward
2. Mass model
   - need to calibrate on simulations
3. Photo-z's
   - sources close behind lenses → good photo-z's are critical !
   - contamination from cluster galaxies

On the use of blind analyses



Klein JR, Roodman A. 2005.
Annu. Rev. Nucl. Part. Sci. 55:141–63

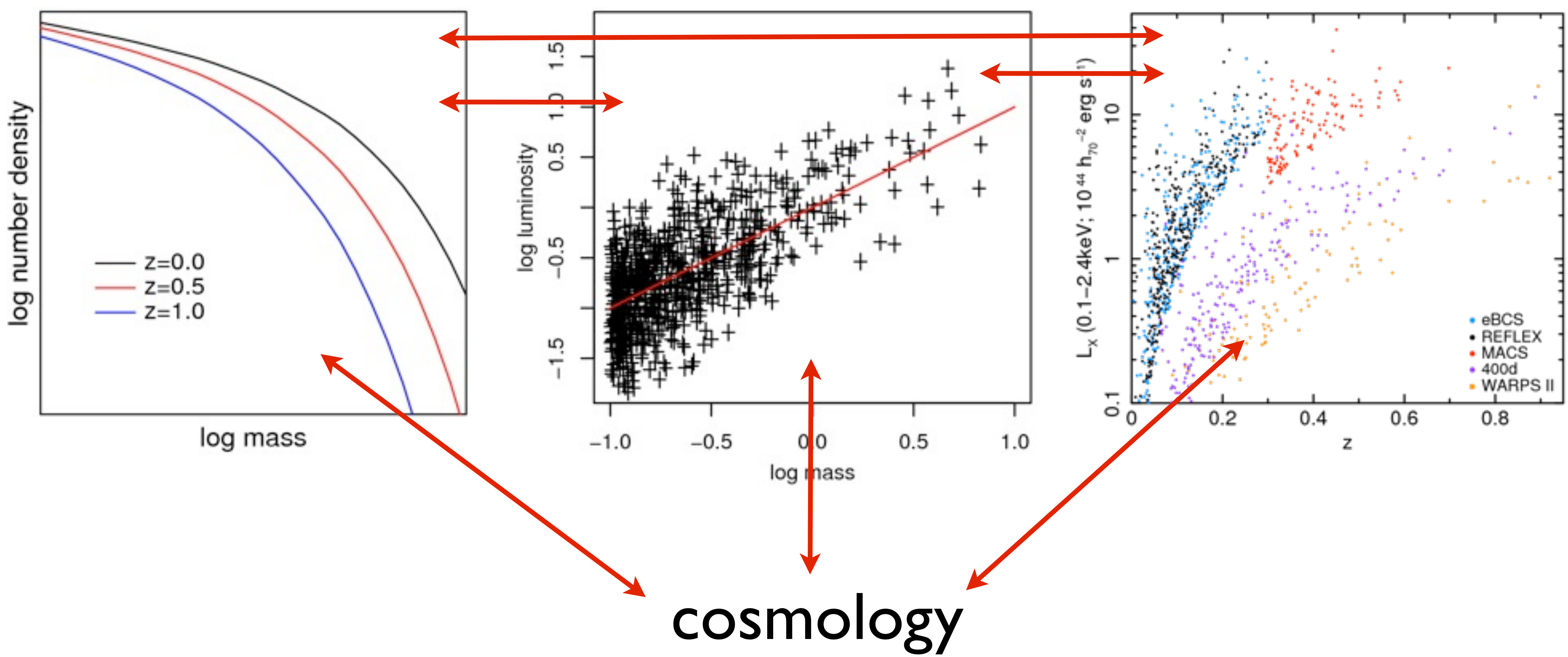
Croft & Daly 2011:

[...] For example, of the 28 measurements of Ω_Λ, only 2 are more than 1σ from the WMAP results. [...]

- WtG: "blinded" analysis - no comparison to other mass measurements until mass measurements finalized
- requires extensive testing - builds confidence that results are reliable
- consider early on: what to blind? how? what tests need to be made?

Ingredients for cluster counts cosmology

1. prediction for halo mass function
2. cluster survey with well understood selection function
3. relation between survey observable and cluster mass
4. **self-consistent statistical framework**



Determining scaling relations

mass measurements

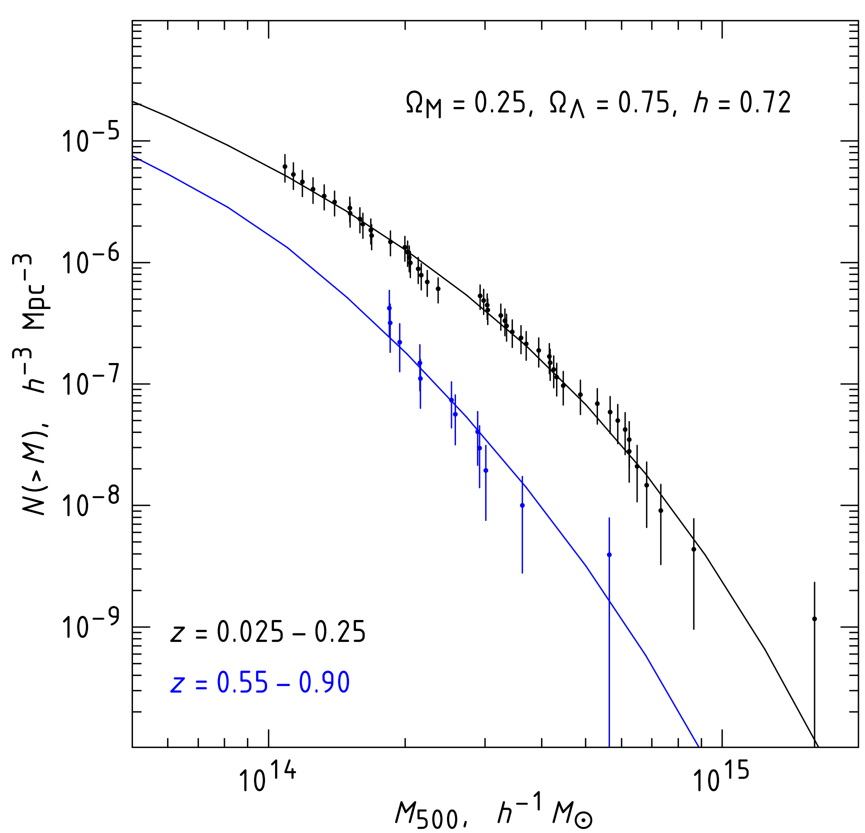
↻ depend(s) on ↻

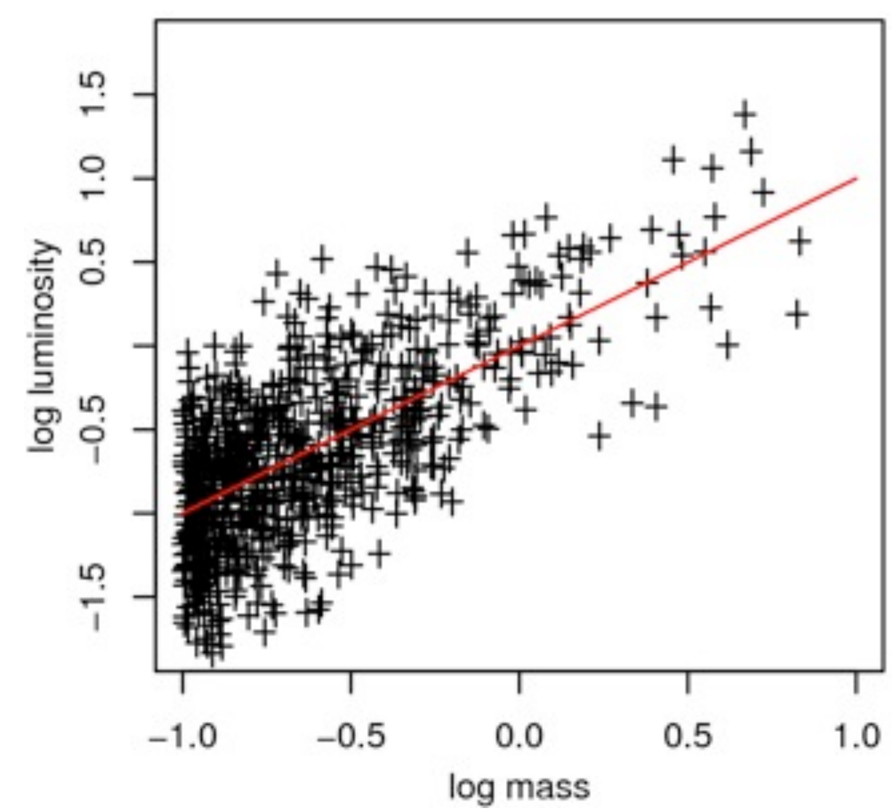
cosmology

- e.g. X-ray luminosity ∝ (measured flux) x (distance ^2)

‣ have to solve for scaling relations and cosmology simultaneously

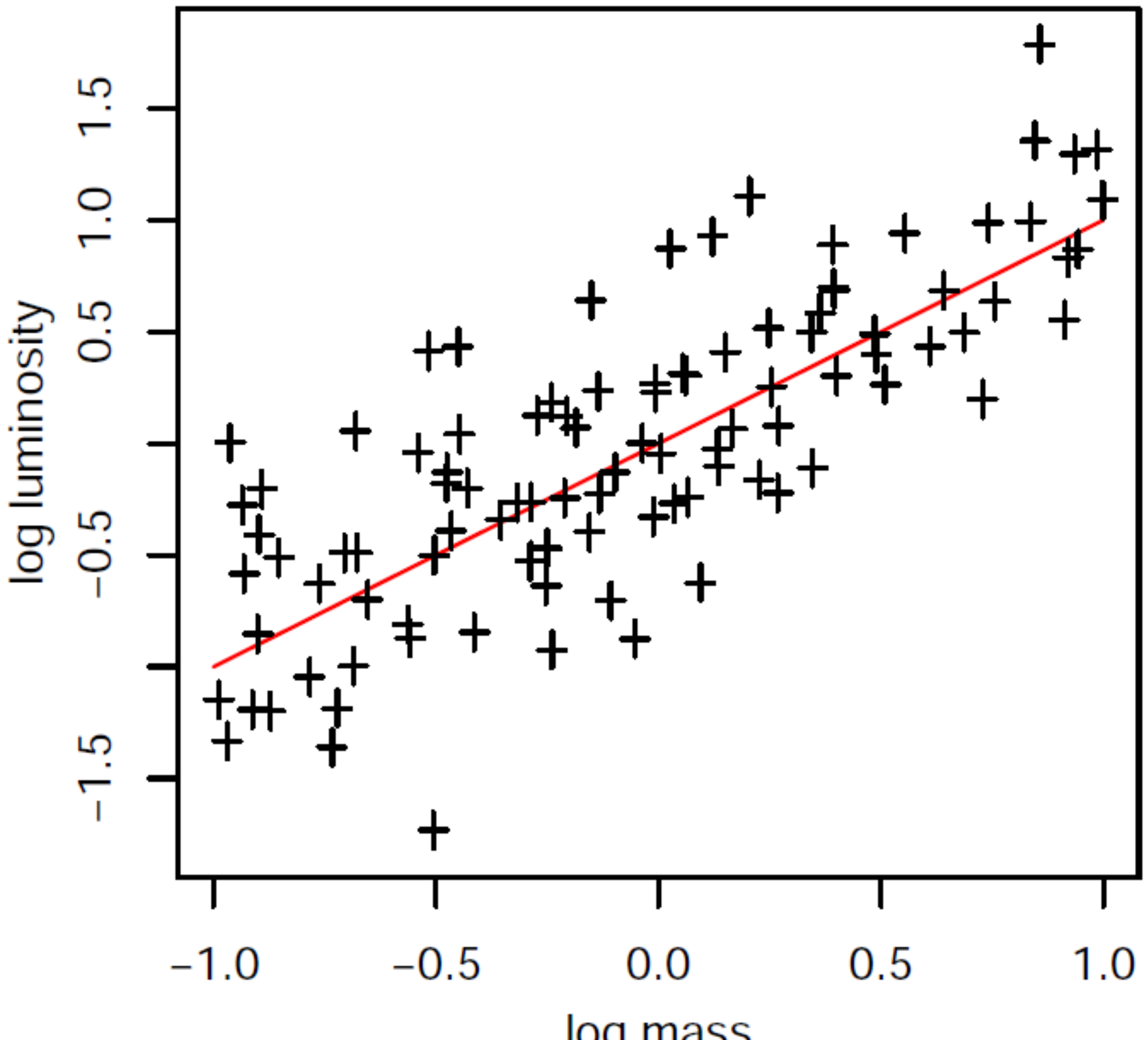
Mantz et al. 2010b

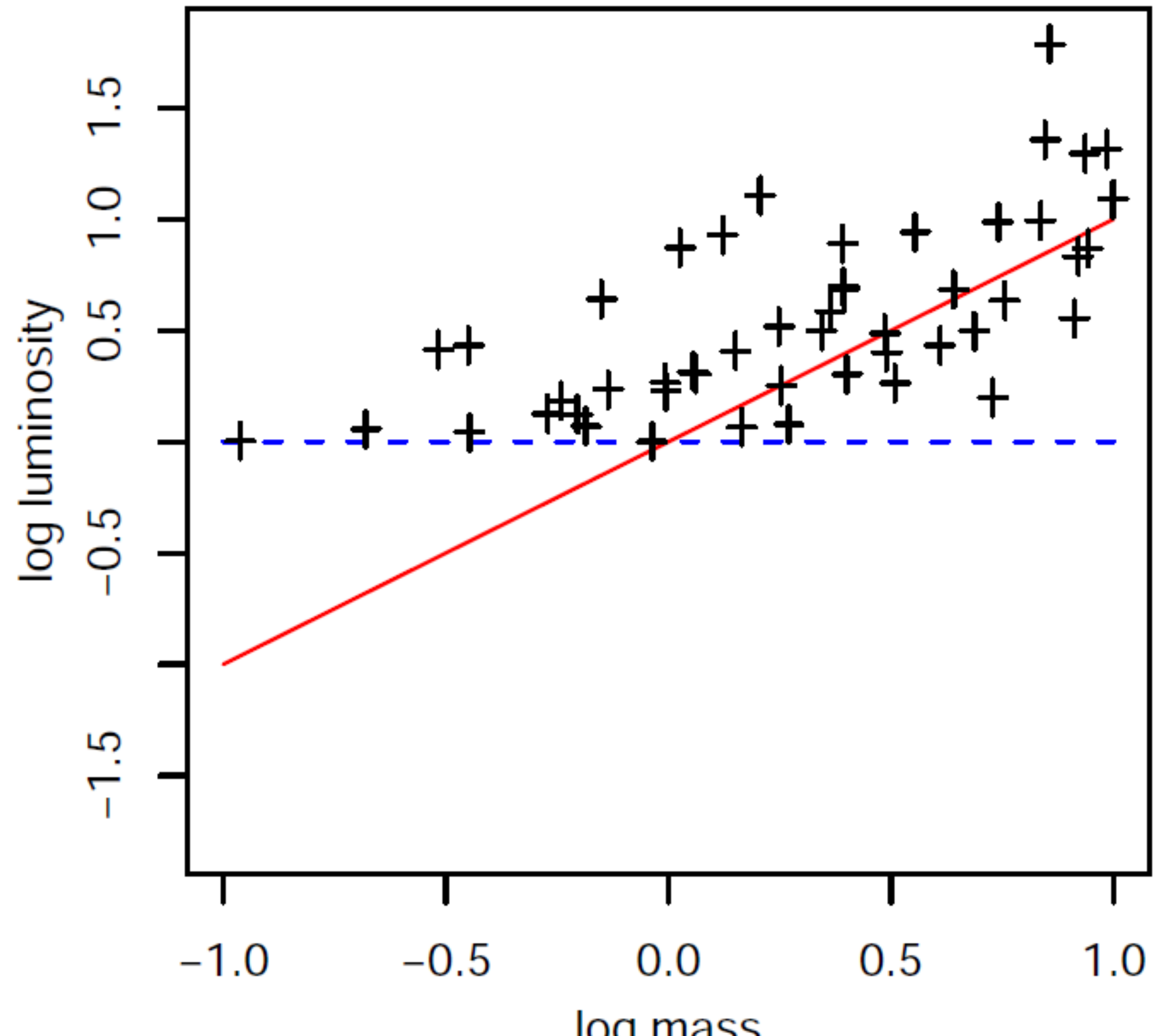




Selection effects

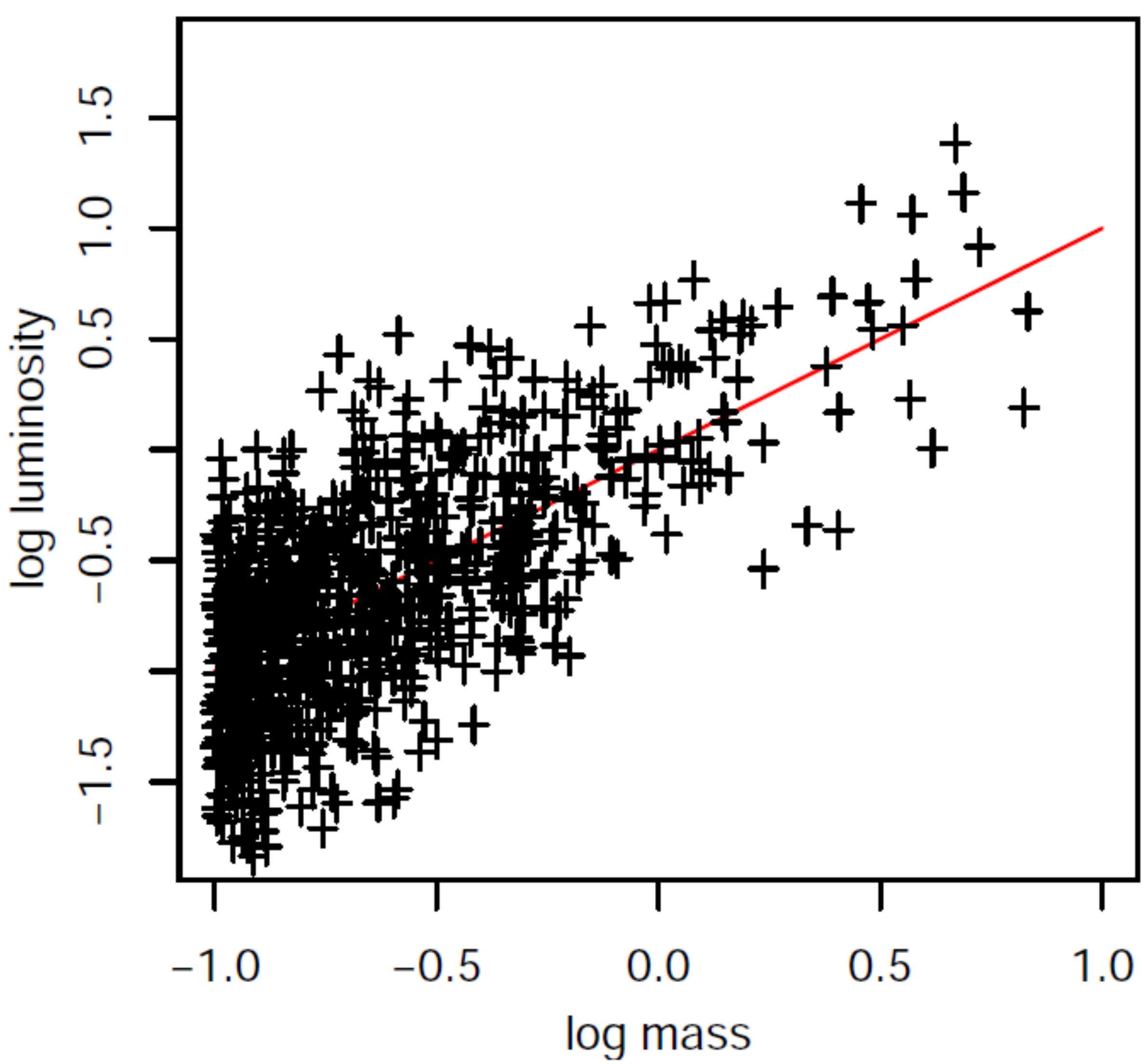
- Malmquist bias: brighter objects are easier to find
- consider cluster sample uniformly distributed in log(mass), with log-normal scatter about true mass-luminosity relation
- impose luminosity threshold: observed distribution is offset from underlying relation

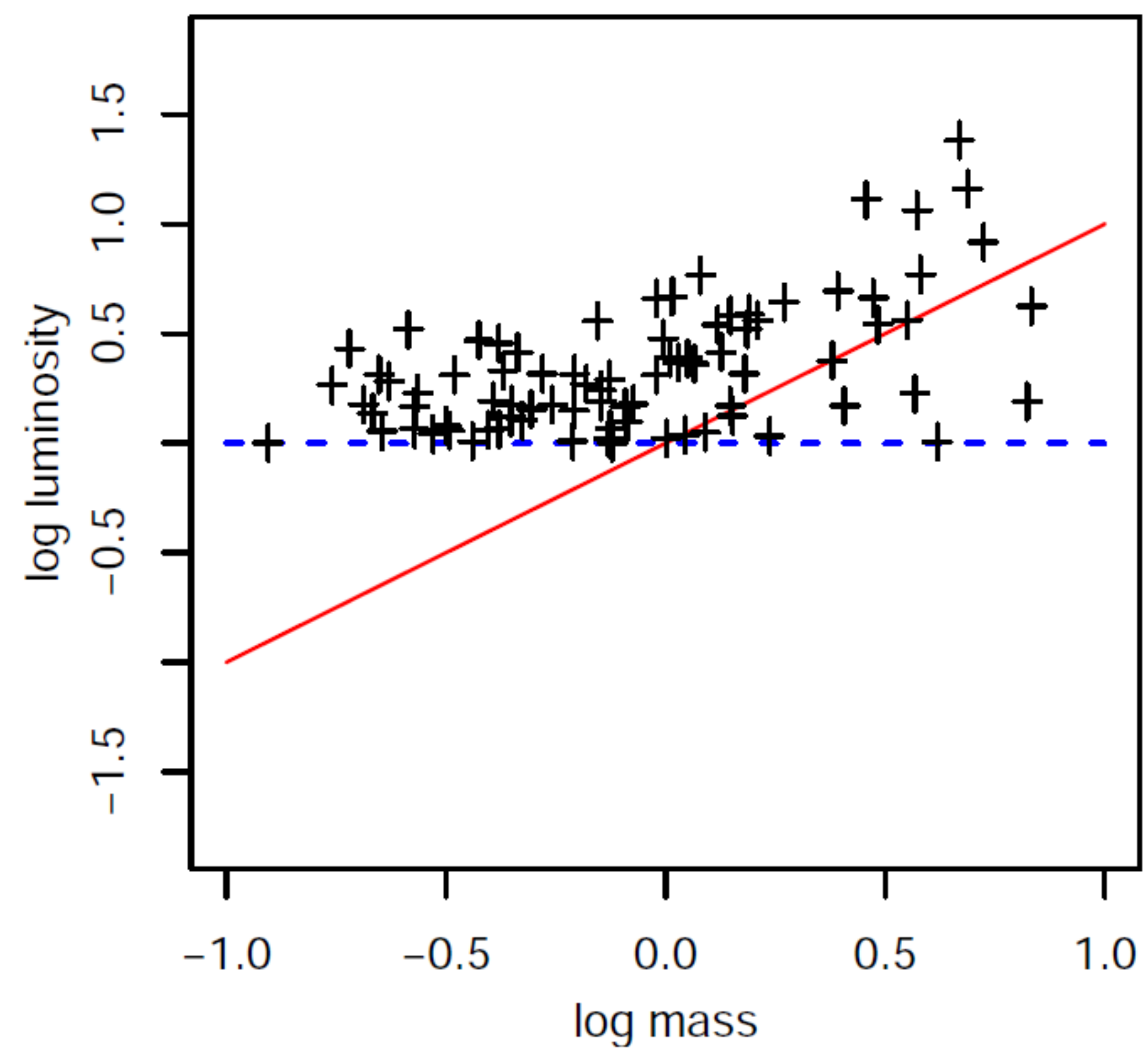




Selection effects

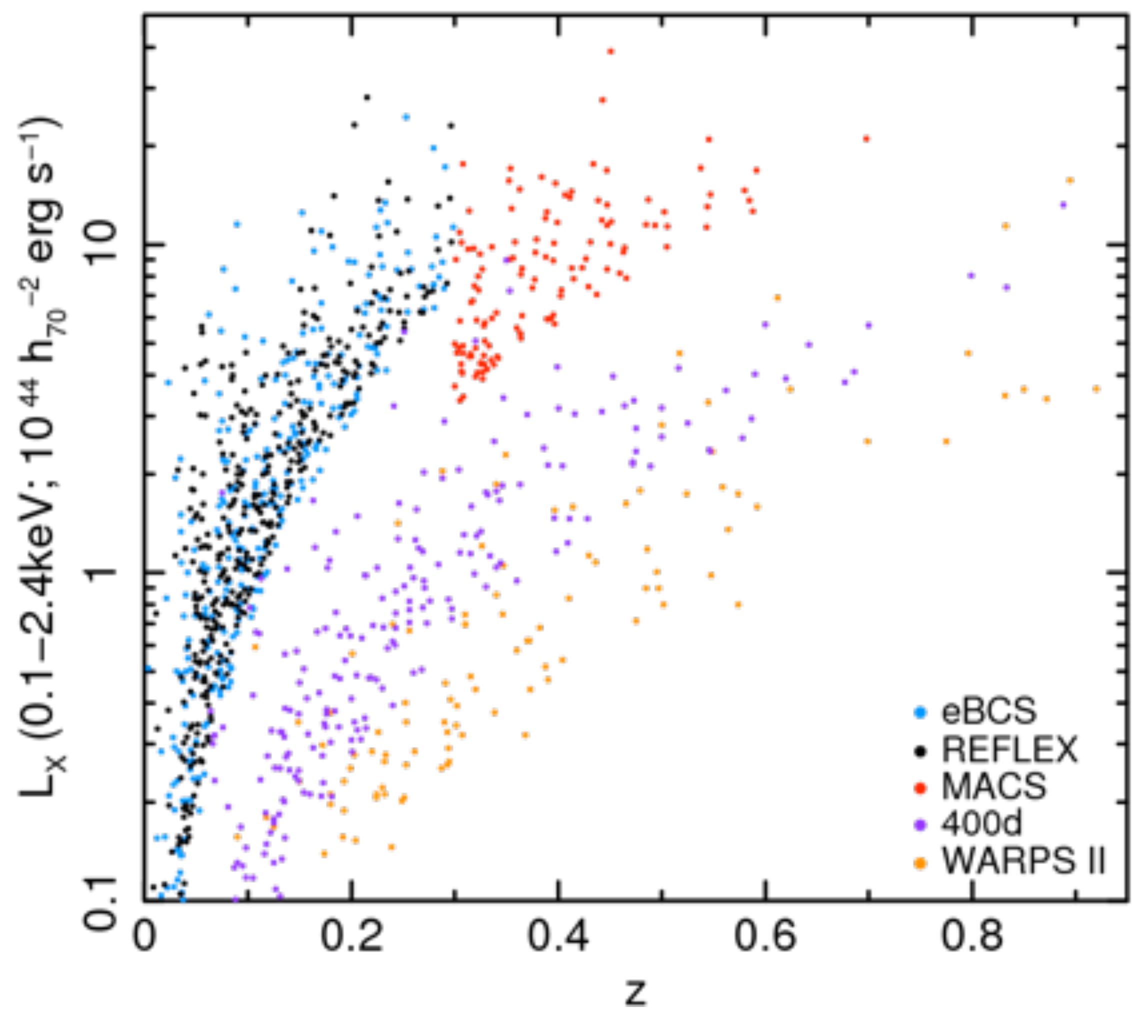
- Eddington bias: "contamination" by less massive clusters
- consider cluster sample *exponentially* distributed in log(mass), with log-normal scatter about true mass-luminosity relation
- impose luminosity threshold: observed distribution is *clearly* offset from underlying relation





Selection effects

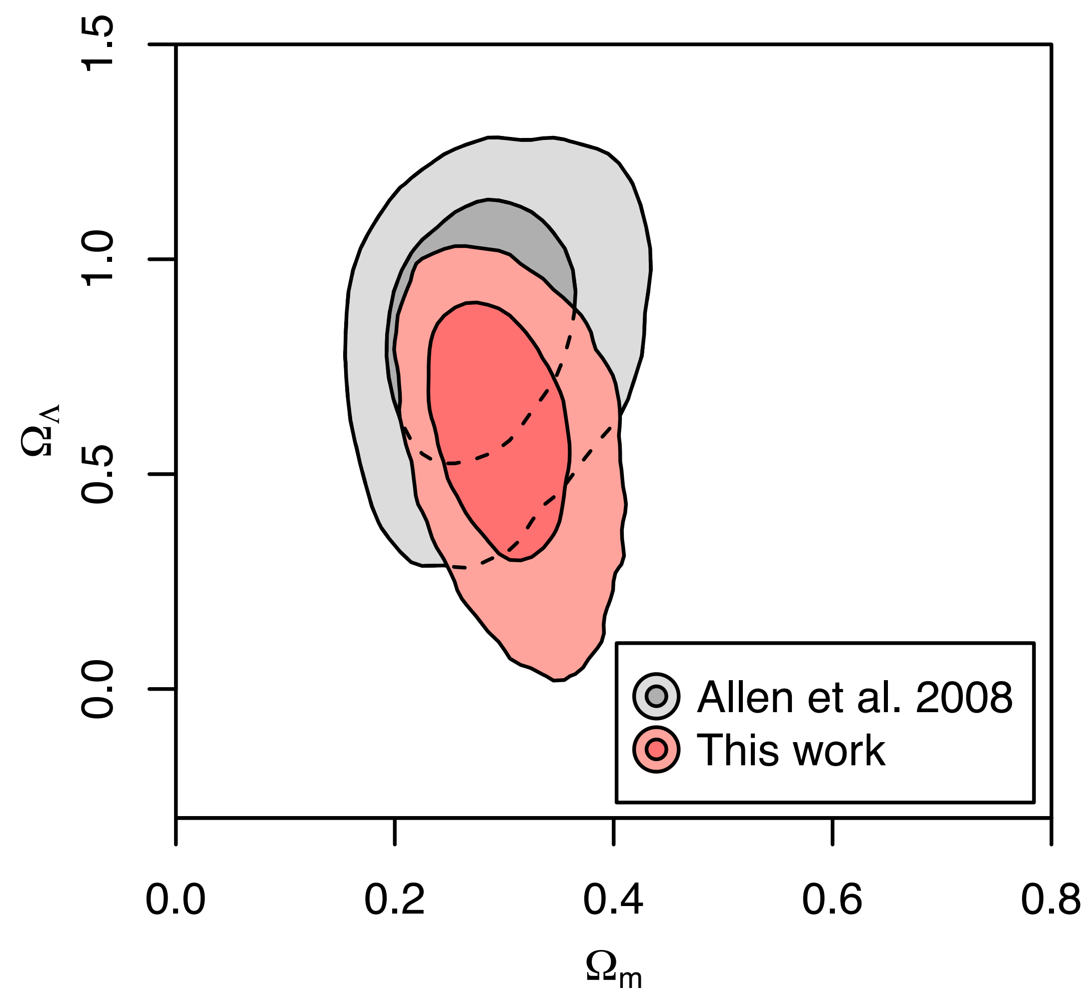
- use flux-selected (not luminosity-limited) cluster samples
- simultaneously model scaling relations (with scatter!), selection effects and cosmology



Ingredients for cluster count cosmology

1. predictions for halo mass function
   → N-body simulations
2. cluster finder with well-known purity and completeness
   → can be tested and quantified on mock catalogs
   → BUT: role of cluster astrophysics? e.g. cool cores, AGN feedback
3. relation between survey observable and cluster mass
   → normalization, shape (power-law?) and scatter (log-normal?)
   → utilize weak lensing
   → significant boost from external, low-scatter mass proxies
   → "most difficult and complex stage"
4. self-consistent statistical framework
   → cosmology and scaling relations not independent
   → fully account for selection effects

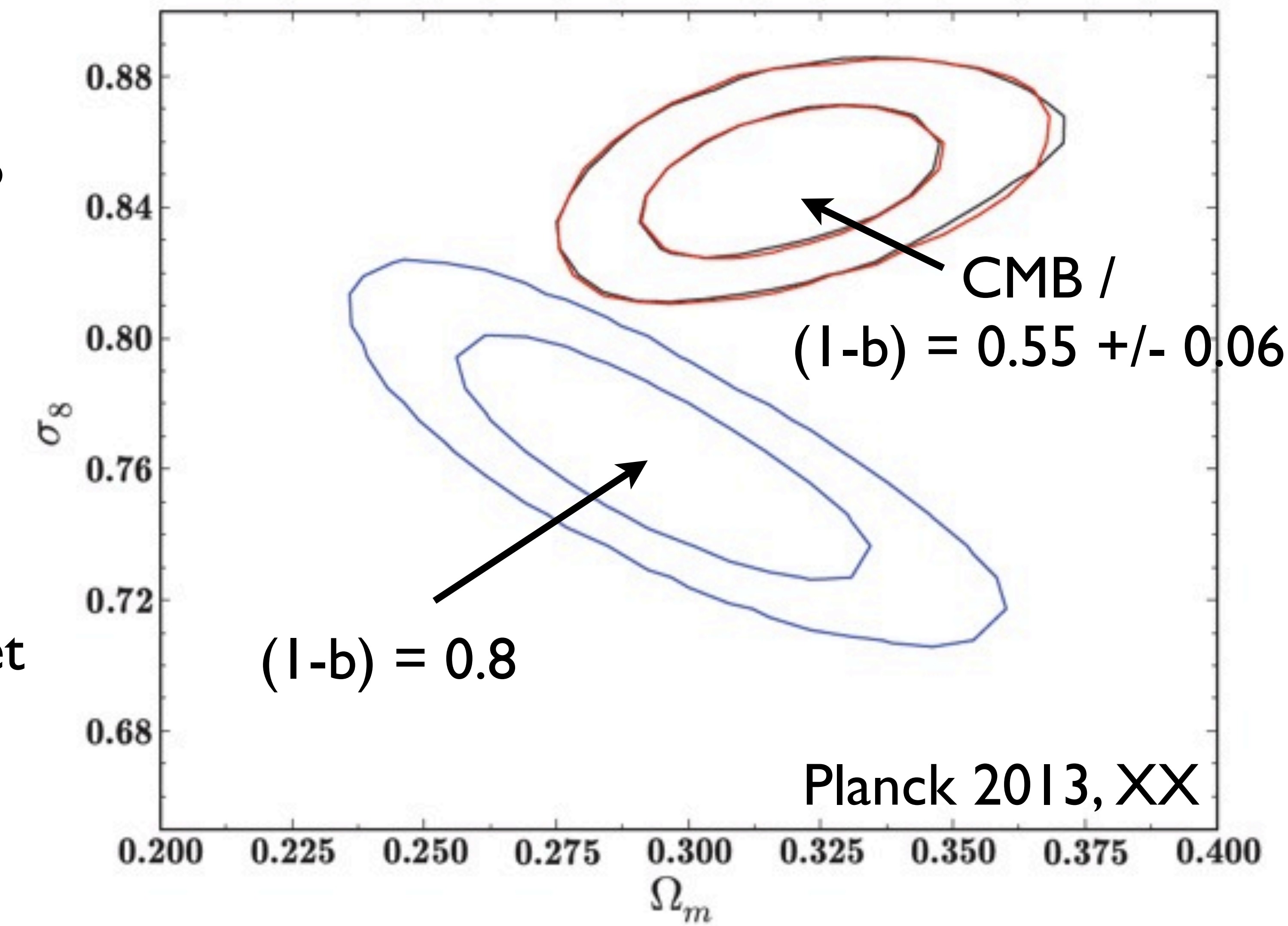
Results: WtG for cosmology



- fgas test (yesterday):
- mass calibration based on 12 relaxed clusters significantly strengthens constraints on Ω_m

Results: WtG for cosmology

- Planck: 3σ tension between SZ cluster counts and CMB cosmology
- assumes $M_{Planck} / M_{true} = (1\text{-}b) = 0.8$
- calibrated with XMM hydrostatic masses (Arnaud et al. 2010) + simulations



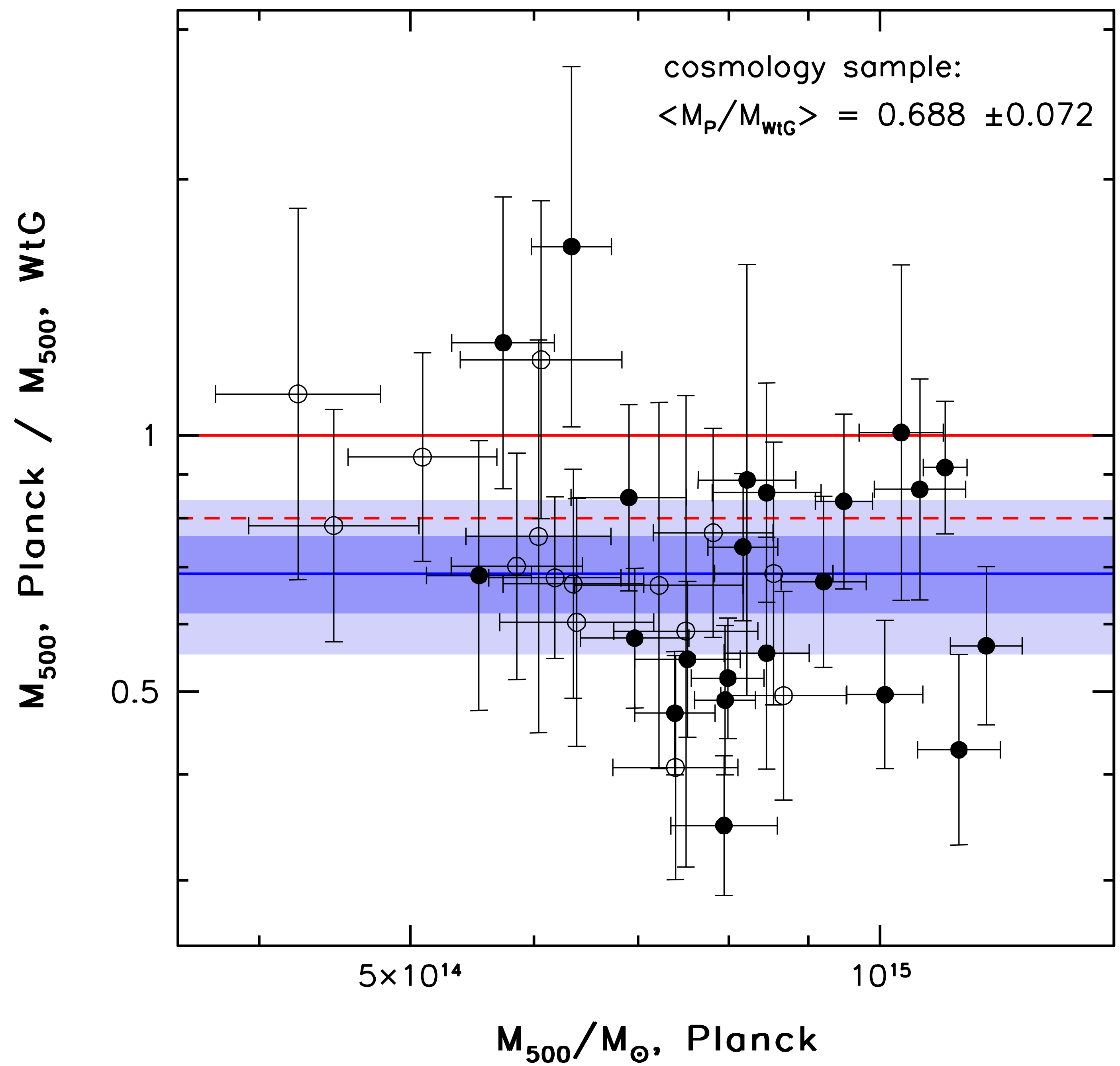
suggested explanations:

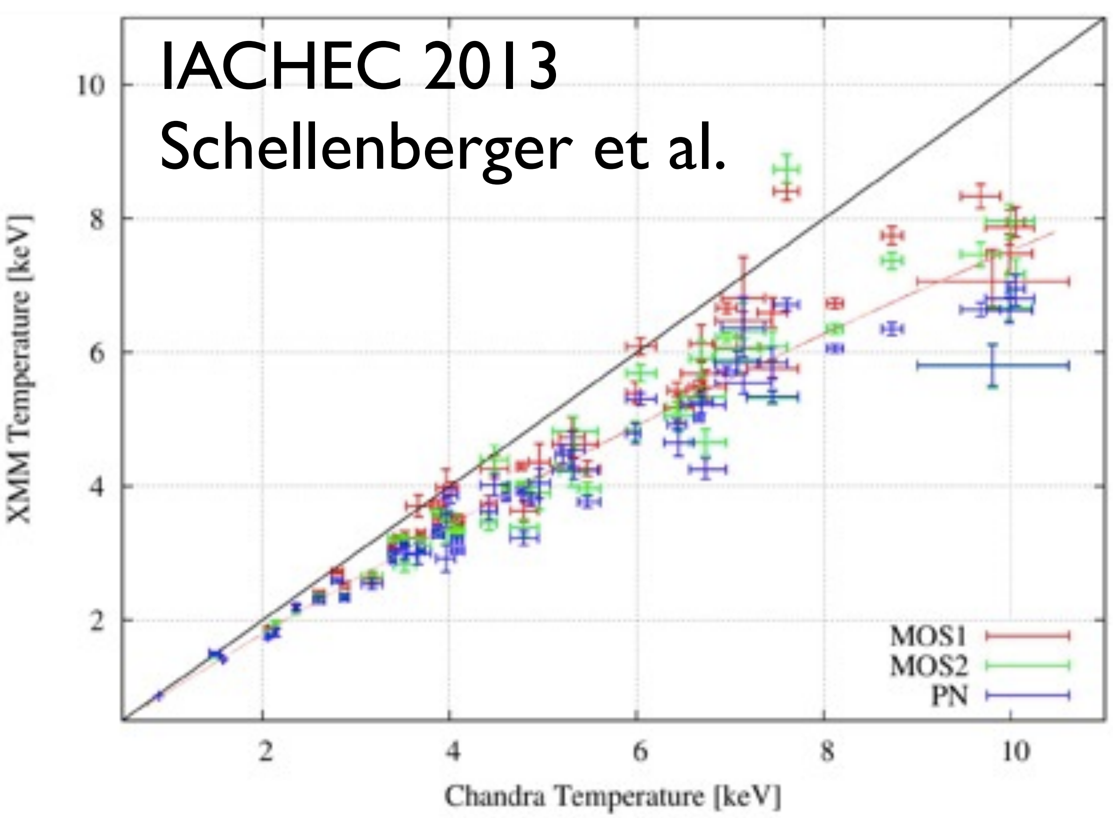
- mass bias underestimated (and no accounting for uncertainties)
- 2.9σ detection of neutrino masses: Σm_ν = (0.58 +/- 0.20) eV (Planck+WMAPpol+ACT+BAO: Σm_ν < 0.23 eV, 95% CL)

Results: WtG for cosmology

- comparison of Planck and WtG mass estimates: $M_{Planck} / M_{WtG} = 0.69 \pm 0.07$
- adopting WtG mass calibration would substantially reduce tension

AvdL et al., arxiv:1402.2670





suspected cause: XMM temperatures biased low

Results: WtG for cosmology

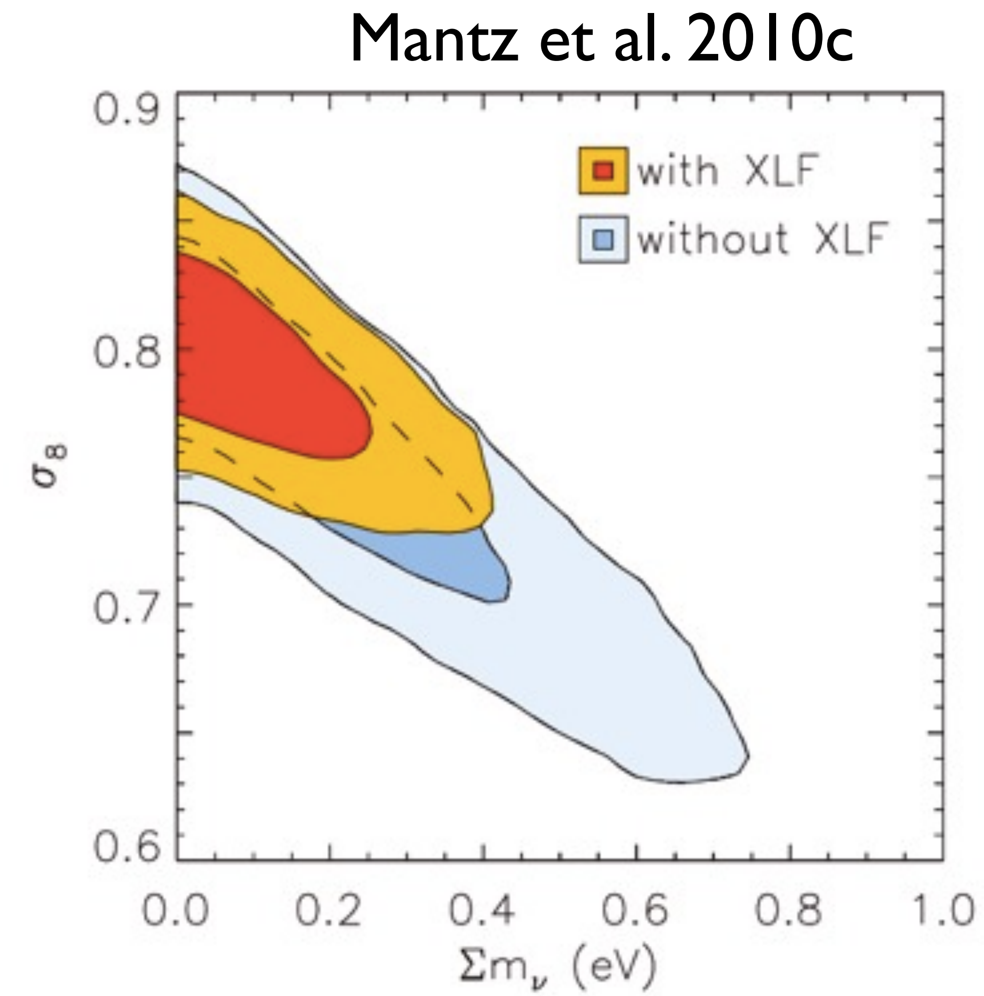
coming soon:

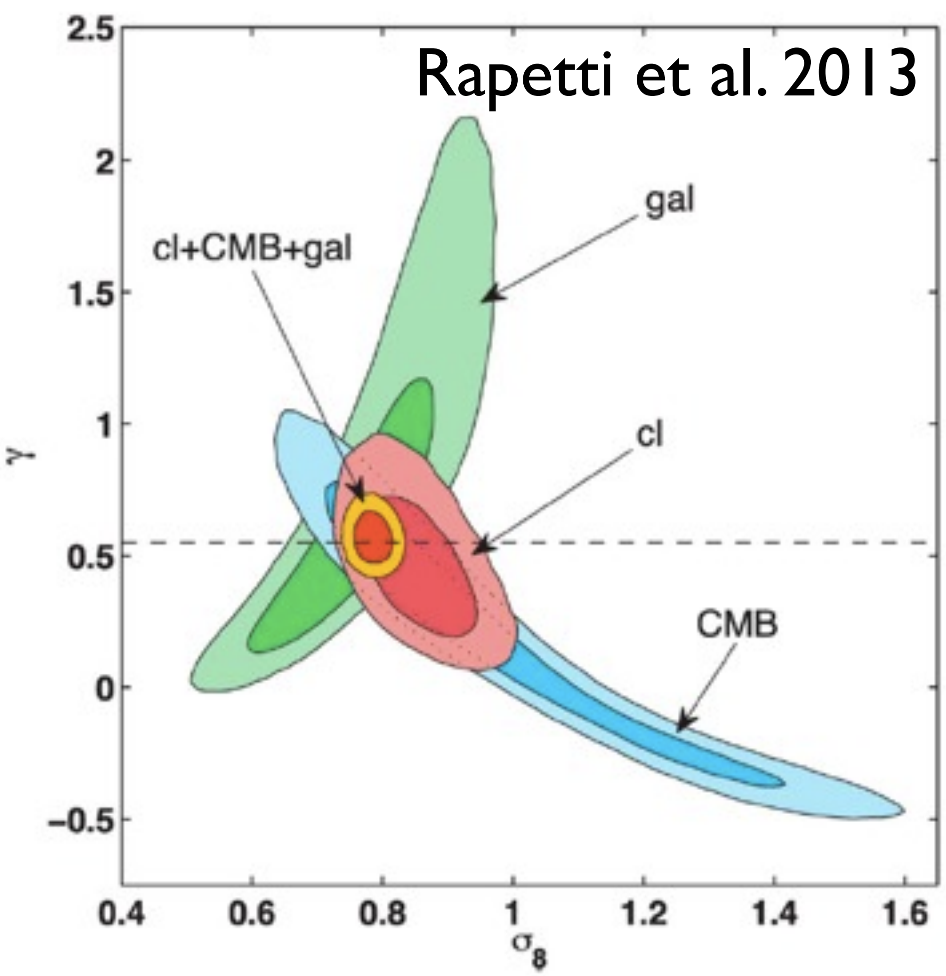
cosmology from RASS cluster counts (238 clusters) with WtG mass estimates

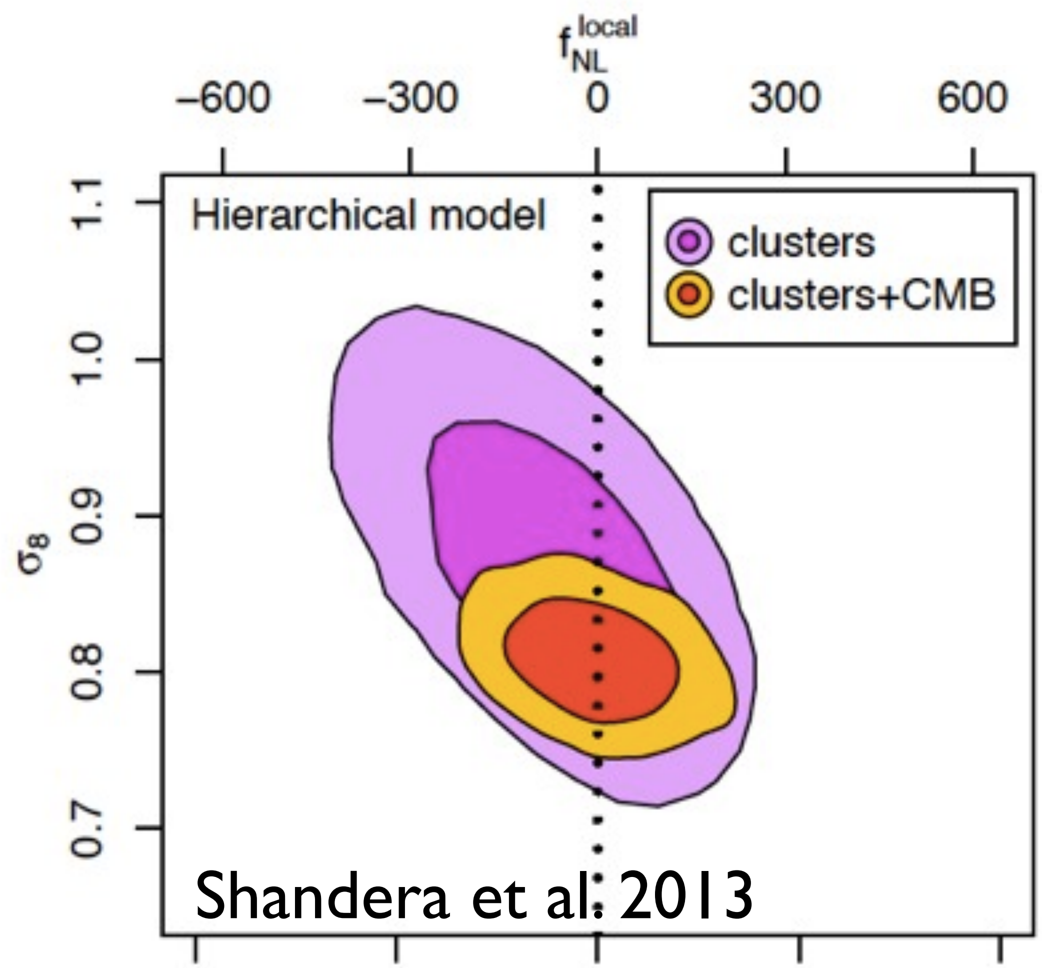
In addition...

cluster abundances can constrain:

- (sum of) neutrino masses
- non-Gaussianity
- modified gravity



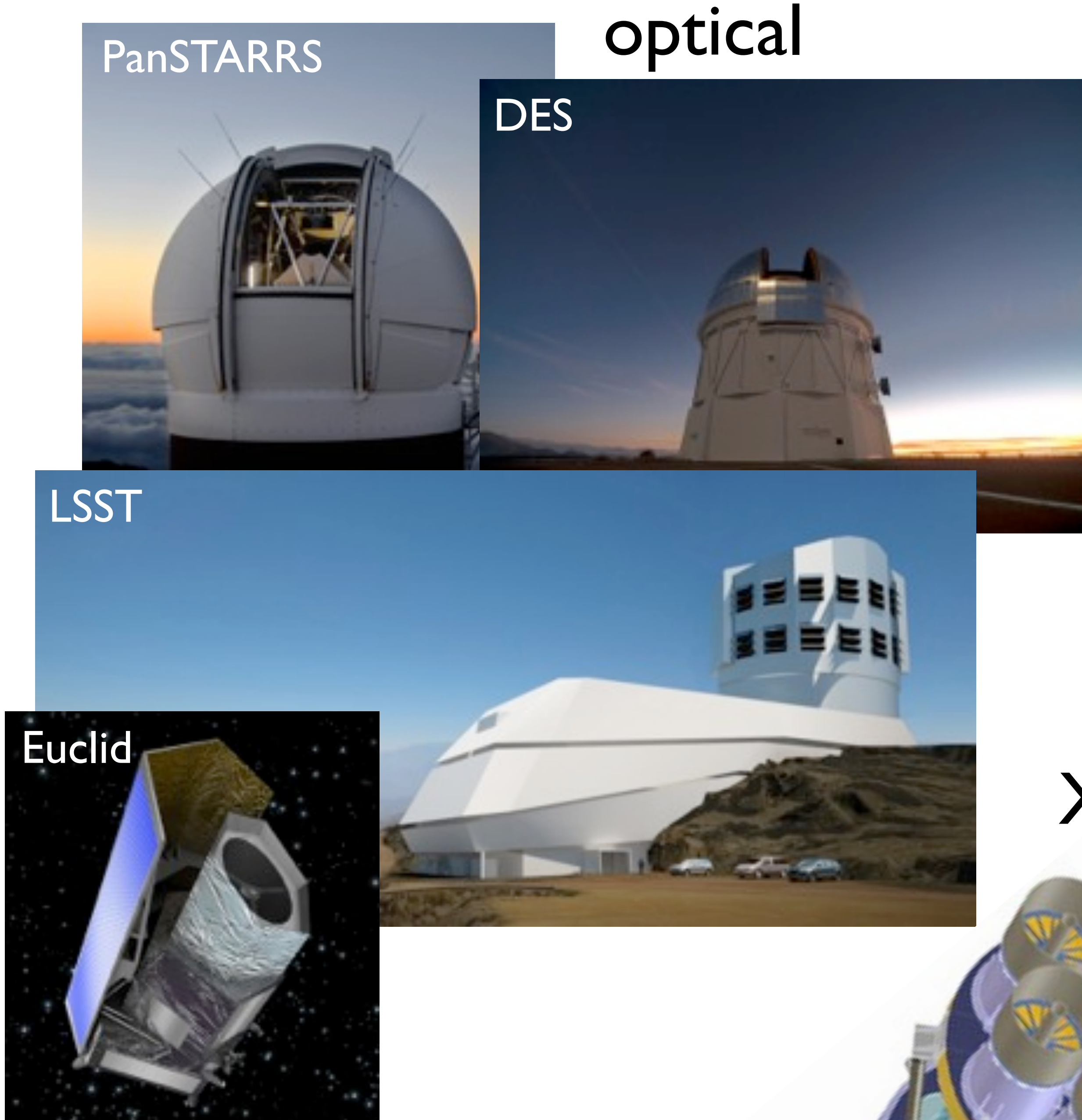




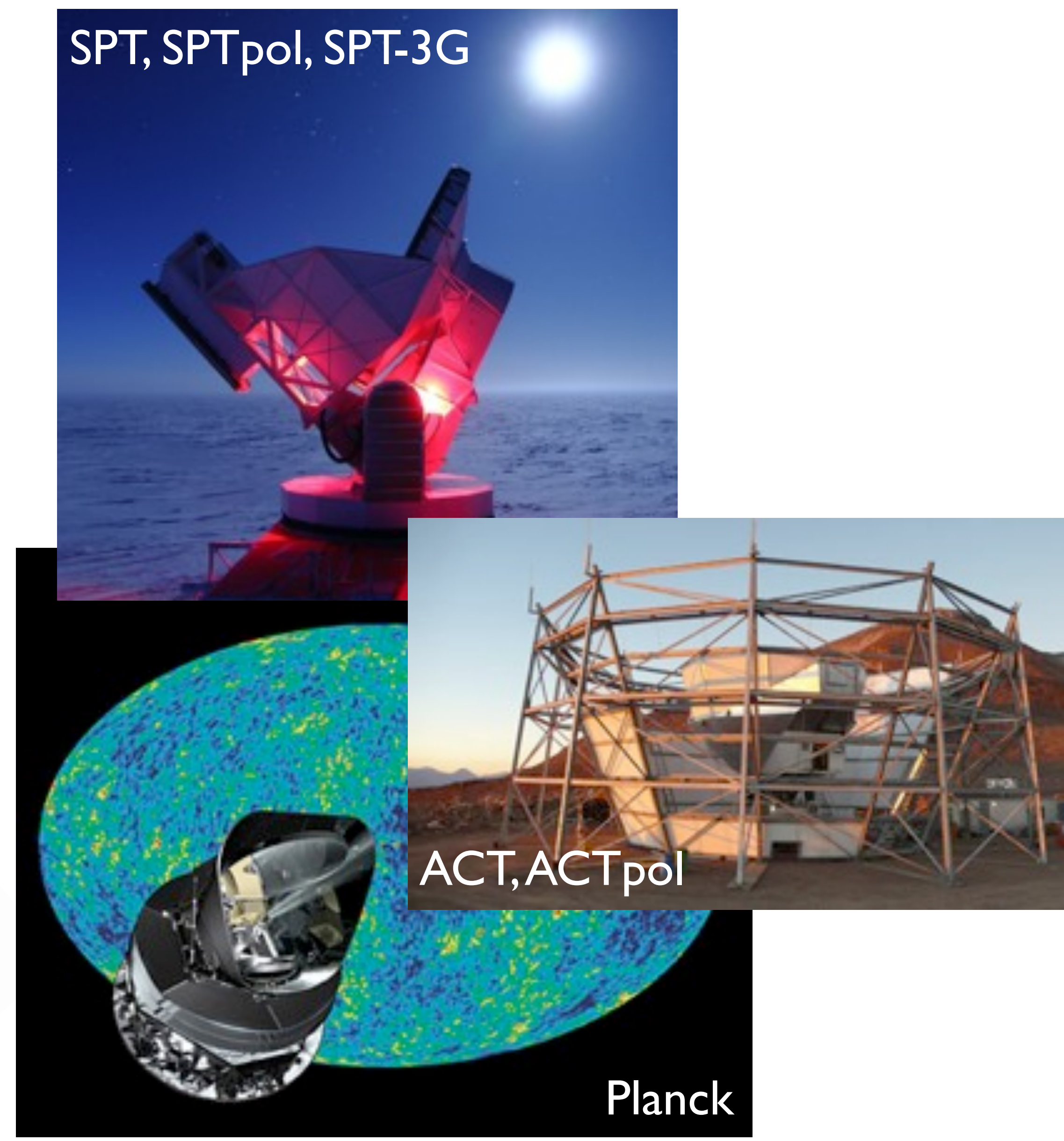
A multi-wavelength approach

exciting times are ahead: many surveys on-going, starting, or planned

optical



SZ



X-rays