Weighing the Giants:
Accurate Weak Lensing Mass Measurements for Cosmological Cluster Surveys

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Fermilab, April 7, 2014

DARK, KIPAC, Brahe, and me

Tycho Brahe: first truly observational cosmologist

Brahe program at DARK: to promote international collaborations in cosmology

Why clusters?

clusters are / can be messy...

however:

- they are big $\longrightarrow$ easy to find !
- there's lots of them $\longrightarrow$ statistically very powerful
- sensitive to both *geometry* of Universe and *structure growth*
- provide several cosmological tests
- accessible at multiple wavelengths
- long-standing history as cosmological probes

Talk outline

I. "counting clusters" - cosmology with the halo mass function

II. the *Weighing the Giants* (WtG) project

III. results: applications of WtG to cosmology

- ROSAT cluster counts
- Planck cluster mass calibration
- the baryonic mass fraction test

IV. outlook

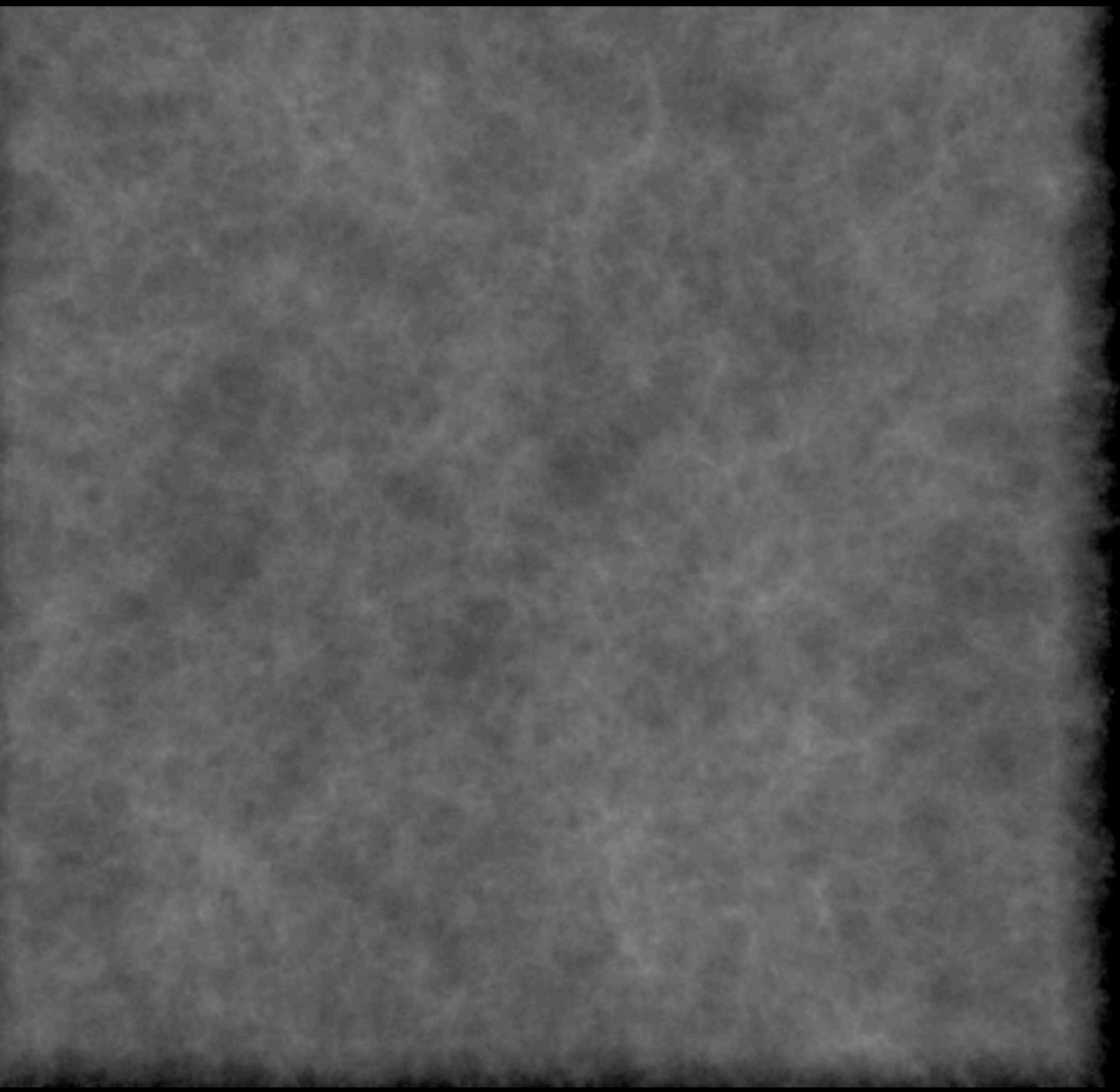
Part I.

Cosmology with the cluster mass function

or

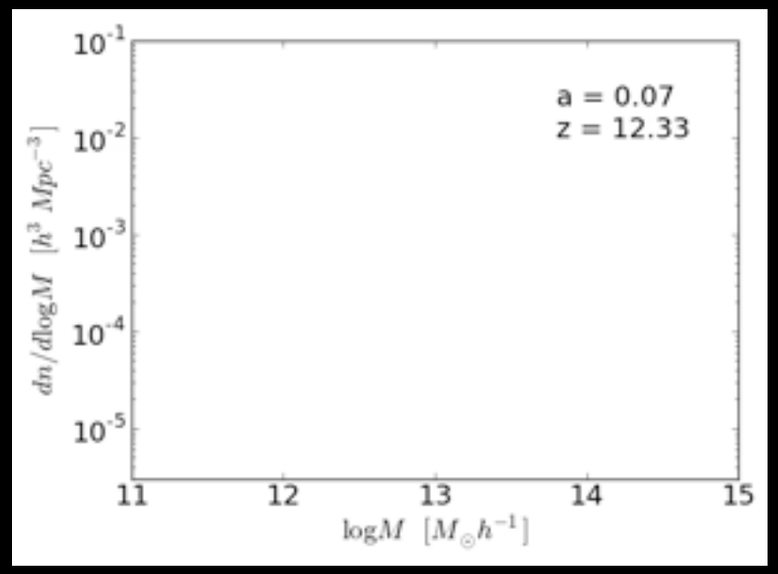
“Counting Clusters”

matter distribution (180 Mpc)

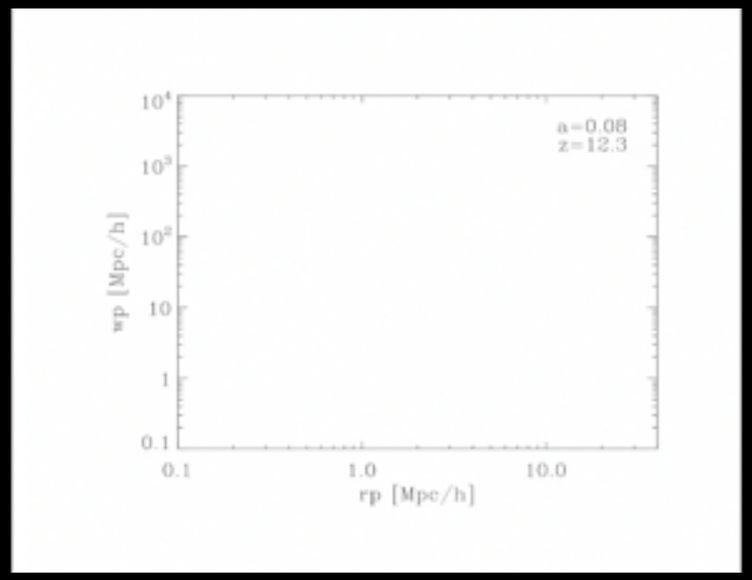


example statistics:

halo mass function



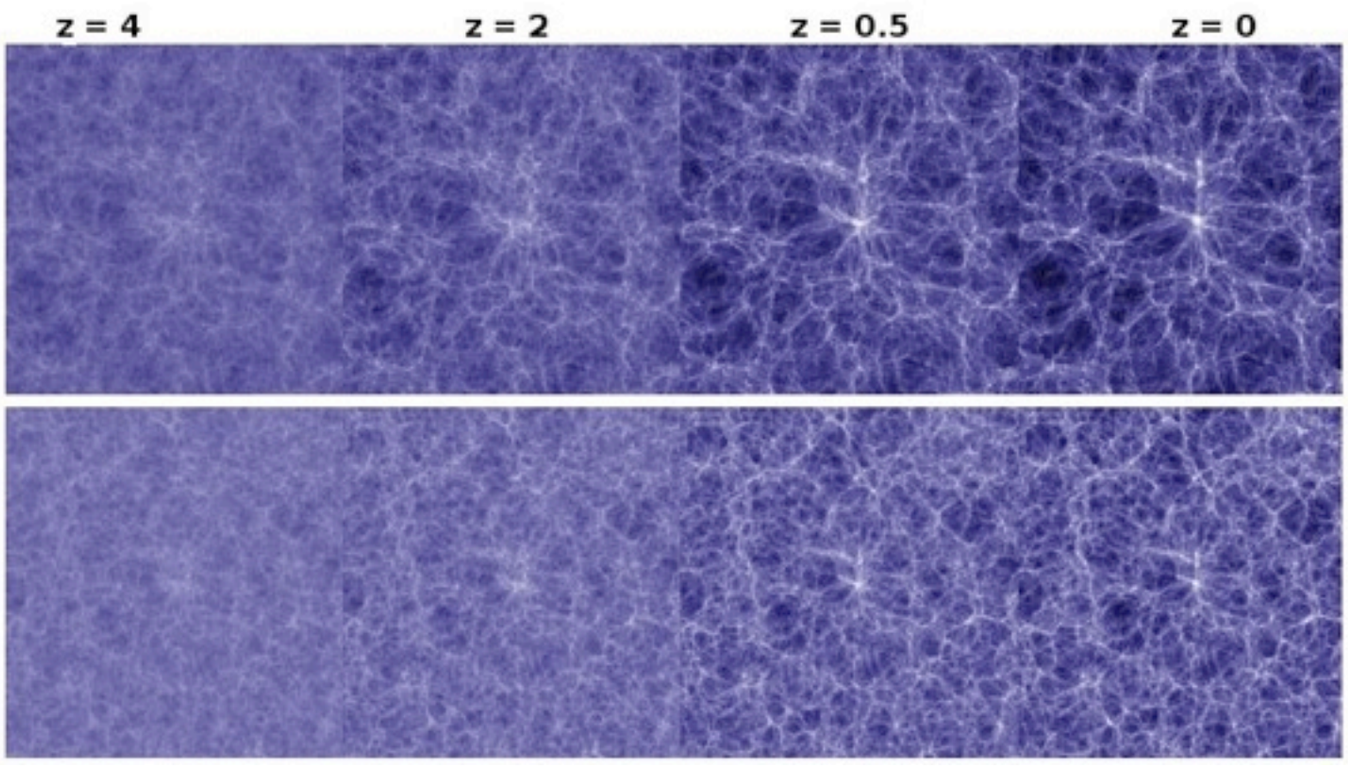
halo
correlation function

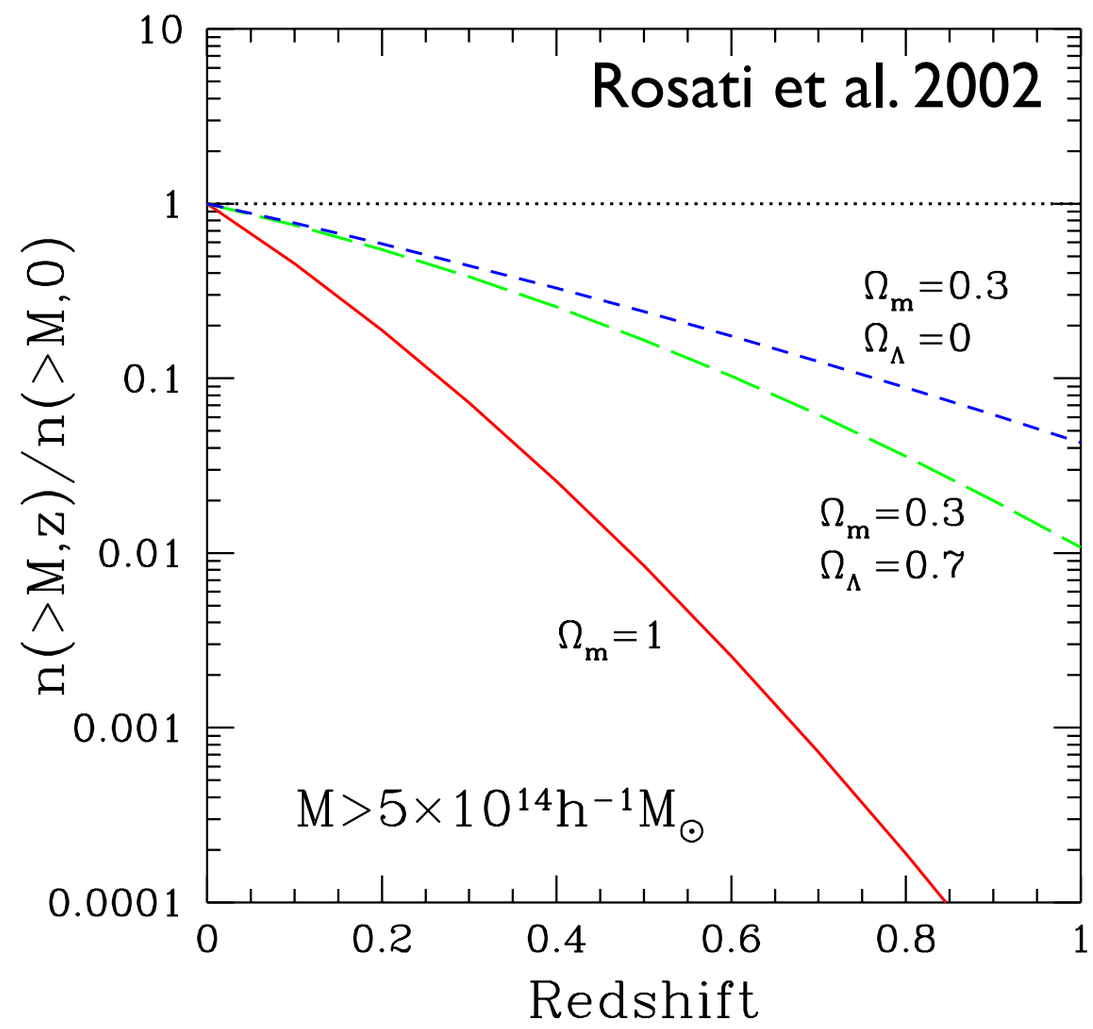


movie, simulation, statistics: Matt Becker, Ralf Kaehler, Yao-Yuan Mao, Rachel Reddick, Risa Wechsler (Stanford/SLAC)

The cluster mass function

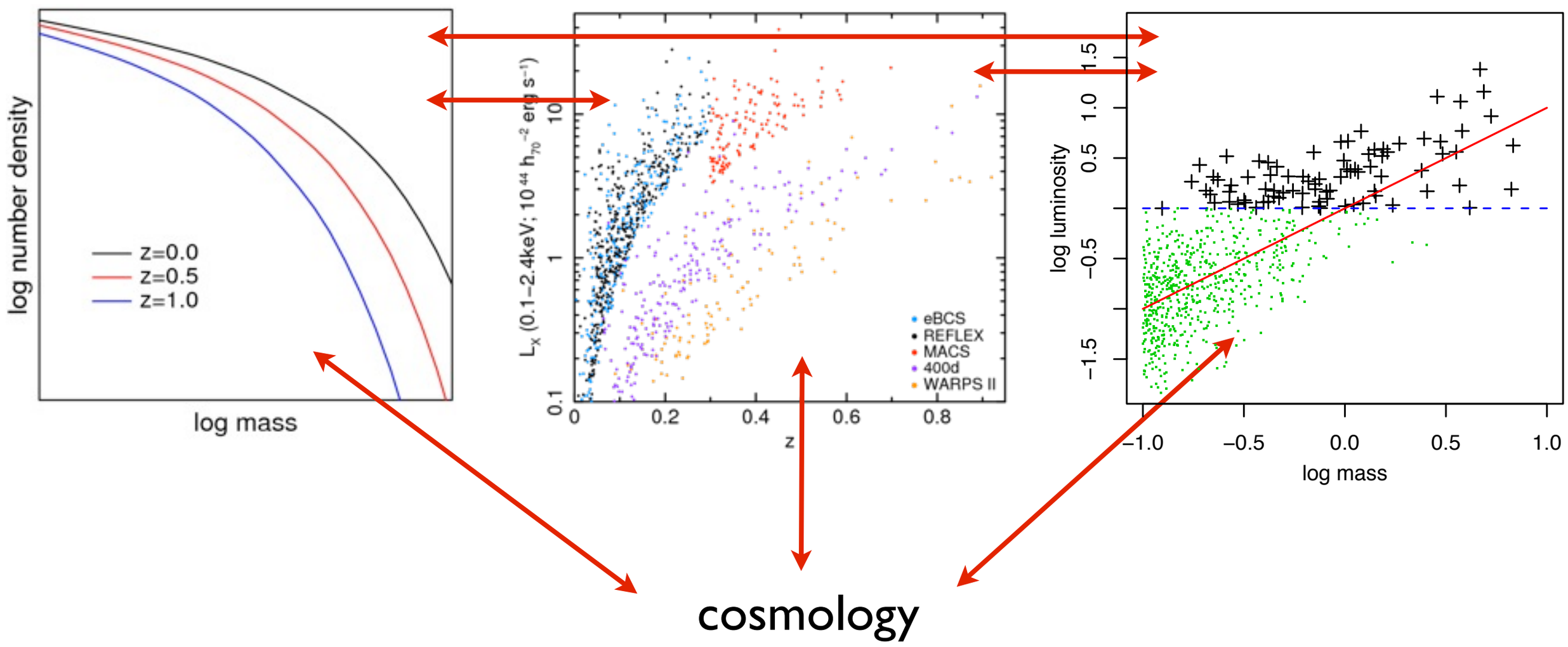
- growth of structure dominated by gravity and dark matter
  - can be well predicted by cosmological N-body simulations
  - number of gravitationally bound halos (with mass M, at redshift z) sensitive to cosmological model
- observationally: halos ↔ clusters





Ingredients for cluster counts cosmology

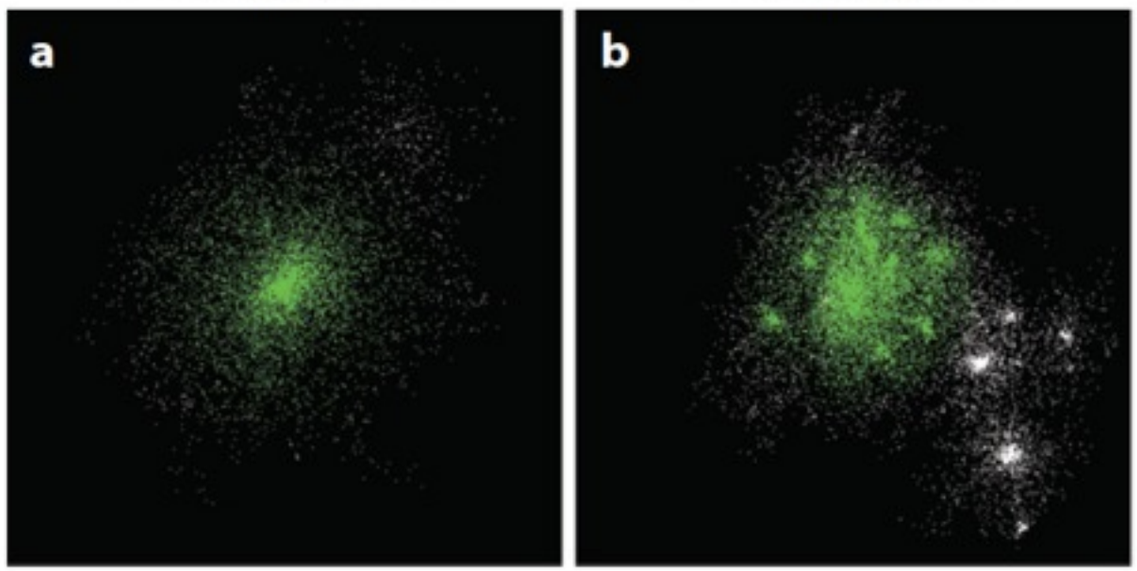
1. prediction for halo mass function
2. cluster survey with well understood selection function
3. relation between survey observable and cluster mass
4. self-consistent statistical framework



Ingredients for cluster counts cosmology

1. predictions for halo mass function

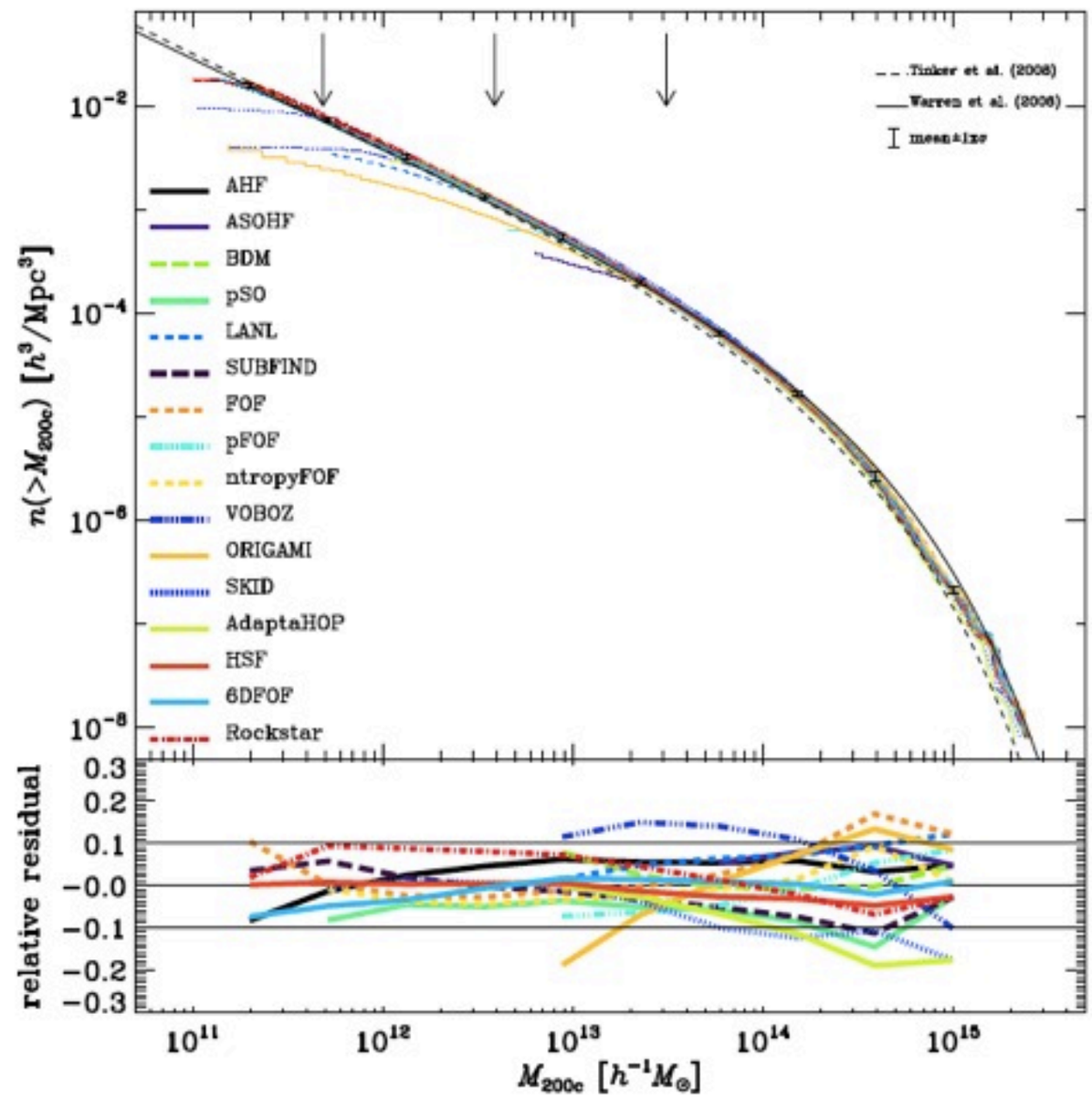
- N-body simulations
- challenges: how to identify halos in simulations



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

Tinker et al. 2008

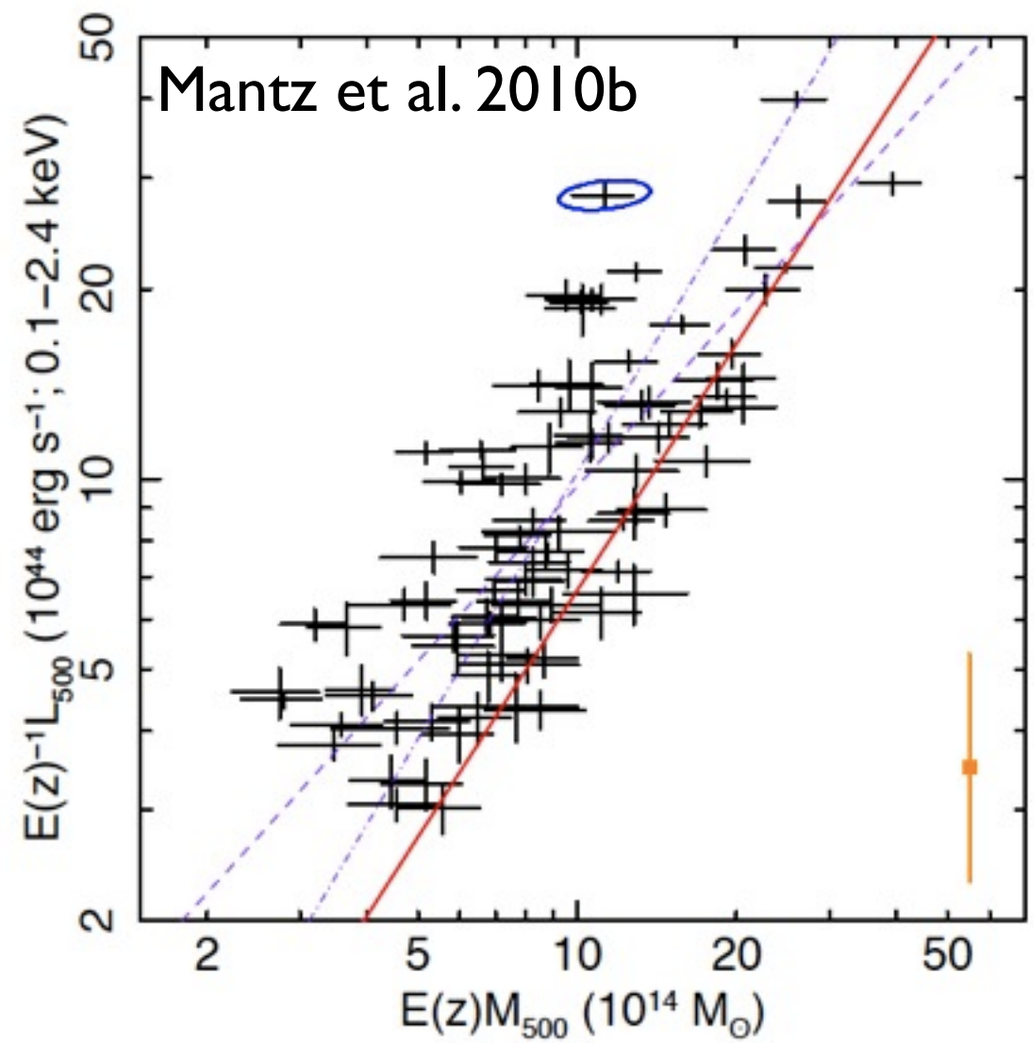
Knebe et al. 2011



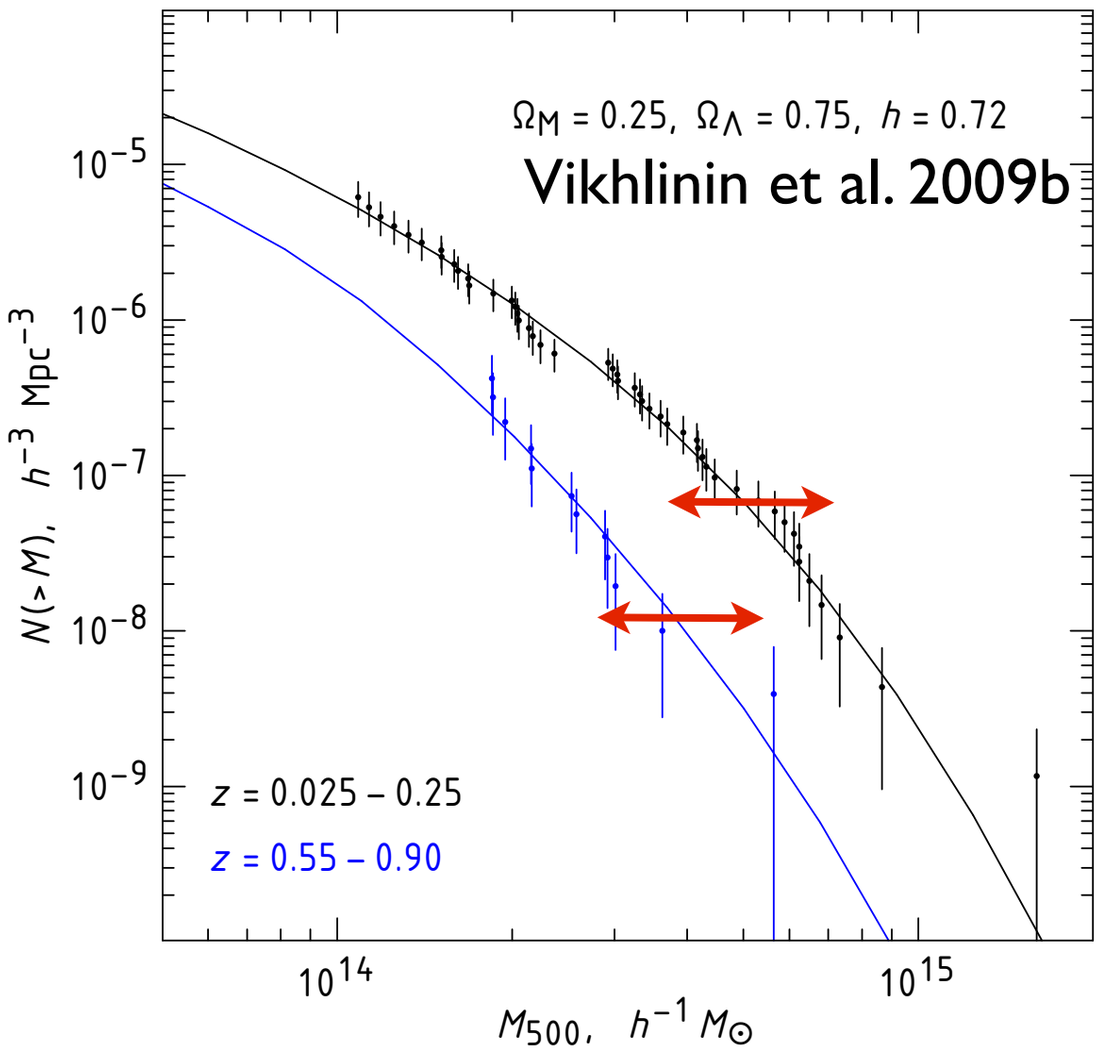
Mass - observable relation

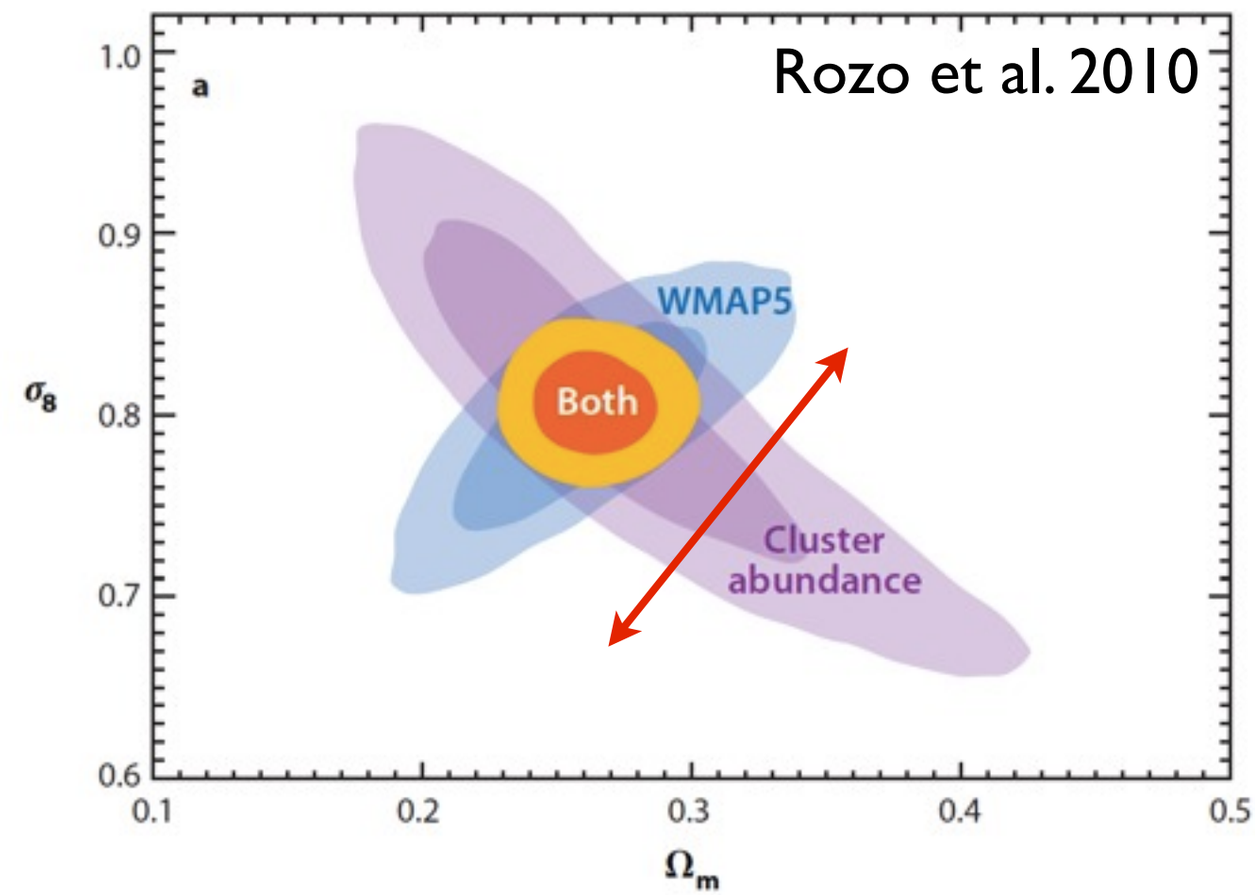
- survey observable (X-ray luminosity, SZ flux, optical richness) does not measure cluster mass directly
  - correlates with mass, but with considerable scatter, (30-40)%
  - *need to measure scaling relation!*

- uncertainties in the mass-observable relations, *especially their mass normalization*, systematically limit current results



Importance of the mass normalization



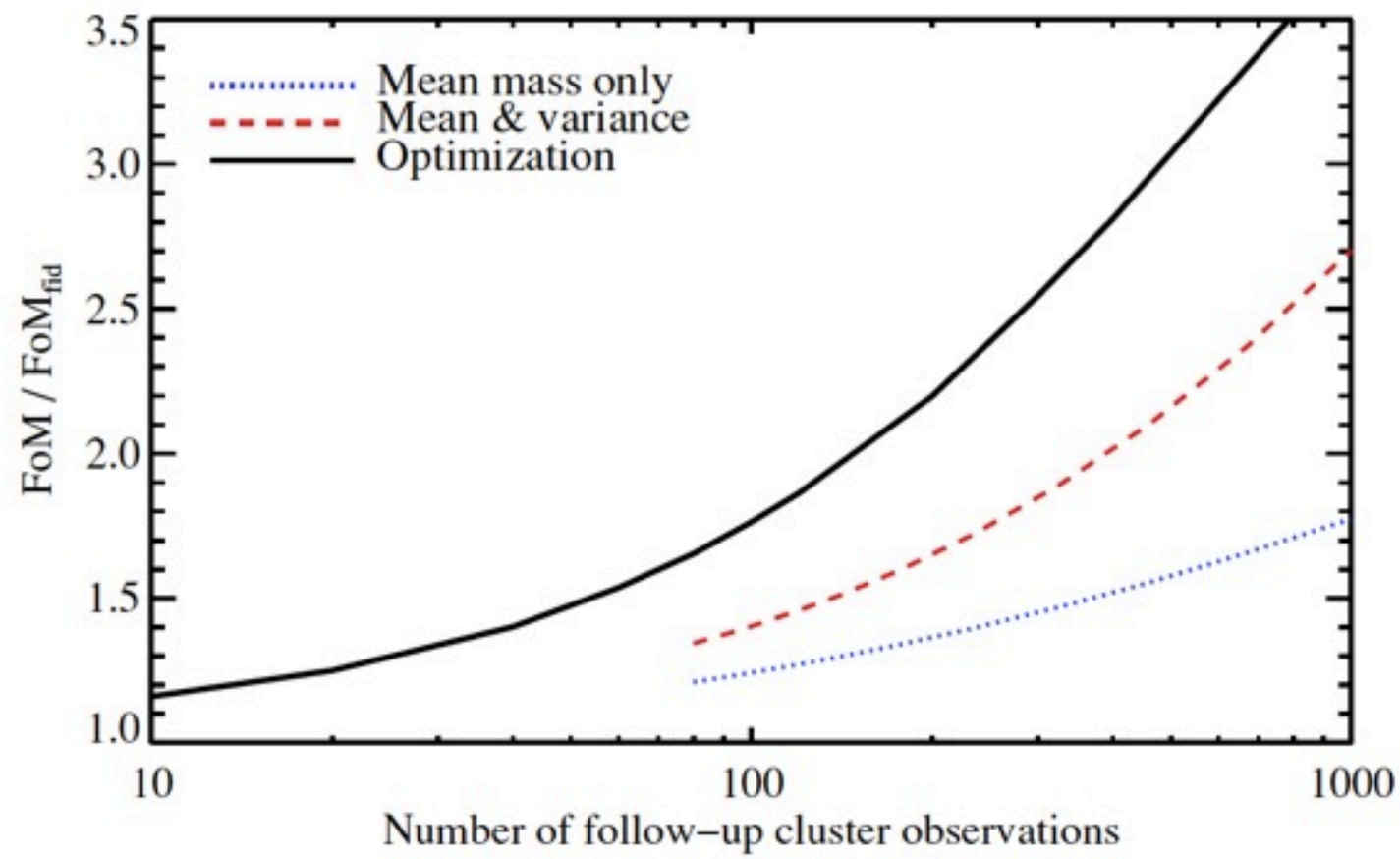


- for σ_8 (+ neutrino masses, etc.) already current results limited by systematic uncertainty in mass normalization
- (most) published results assume (10-15)% uncertainty, *Weighing the Giants* reaches ~7%, DES will require 5%, Euclid + LSST ~ 2%

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

Wu et al. 2010



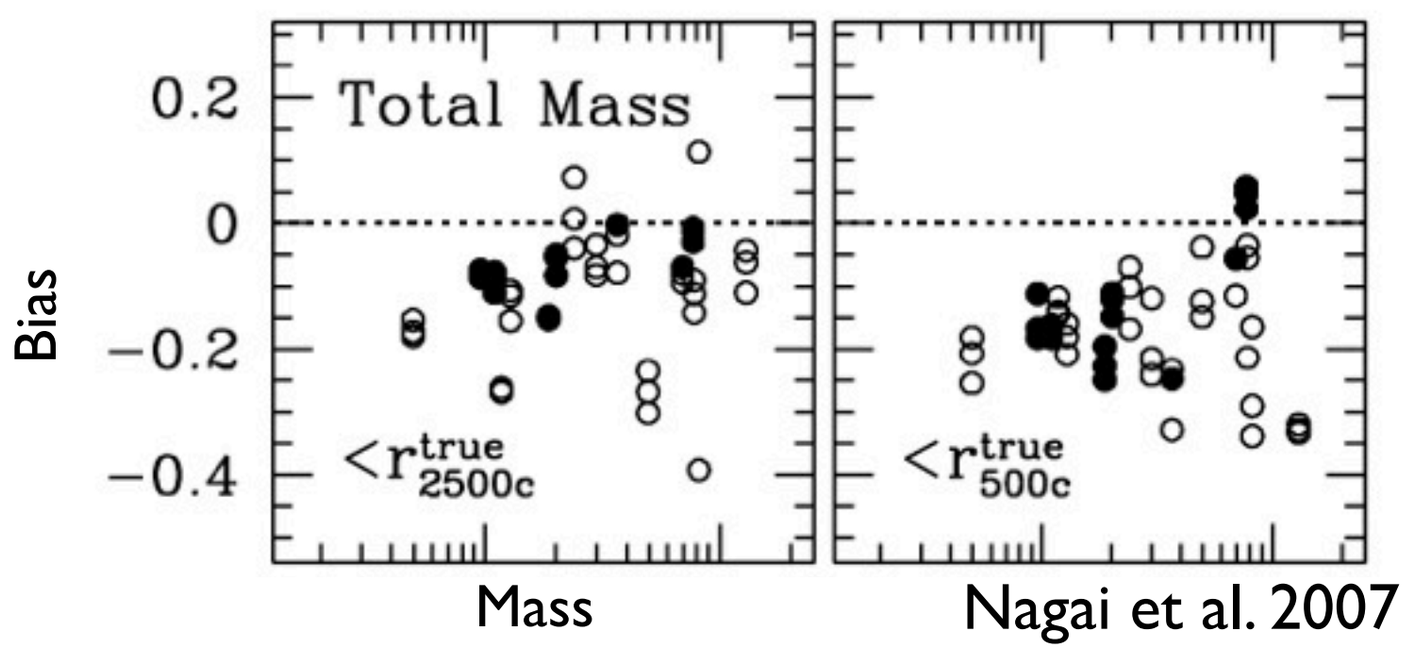
- essential for measuring shape and scatter of M-O relation
  - ➡ significant increase in constraining power
- do *not* provide absolute mass calibration

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

- note: dynamical mass estimates from galaxy velocities subject to similar biases

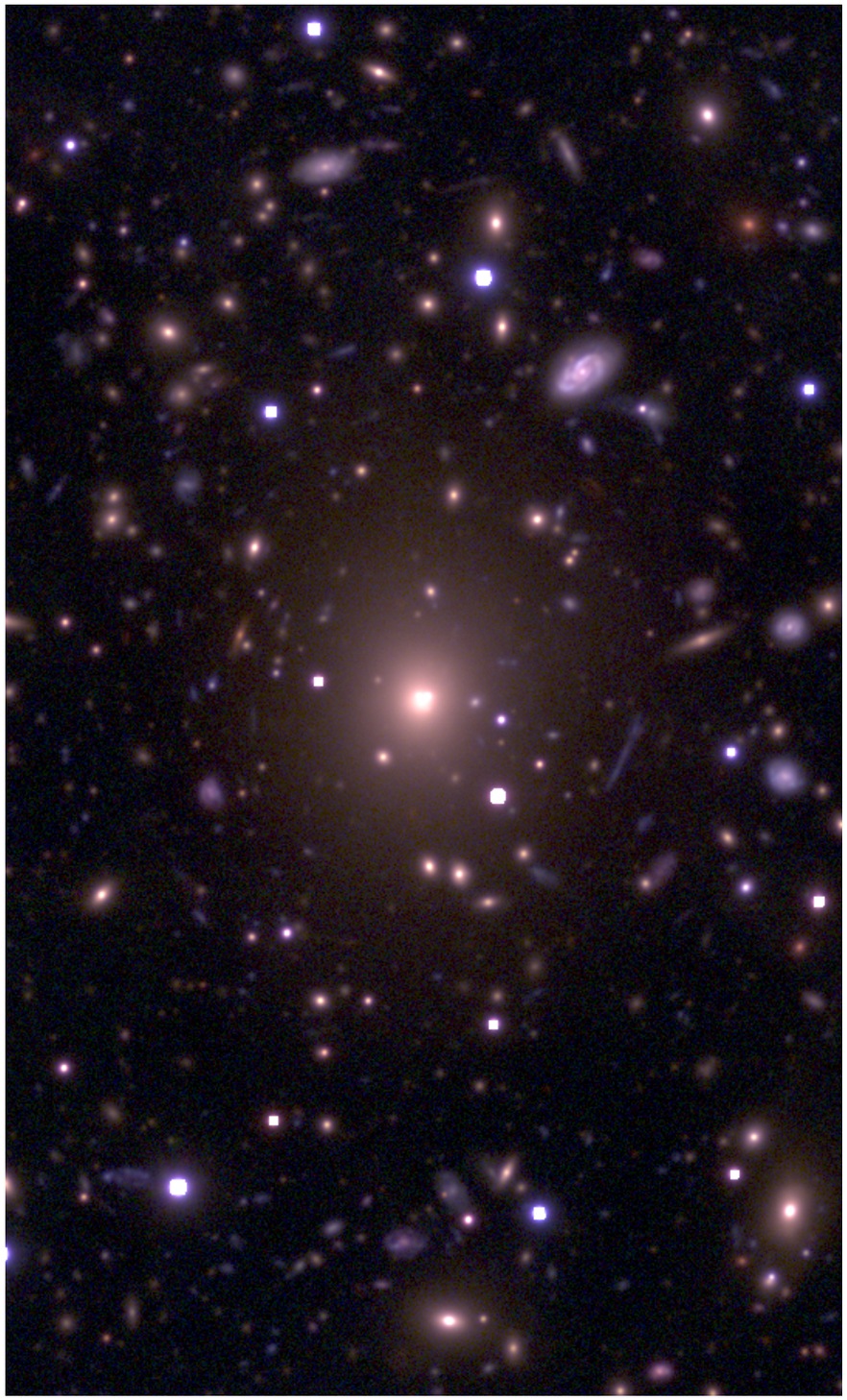
Part II.

Cluster masses from weak lensing

and

Weighing the Giants

Calibration by cluster weak lensing



(most) promising observational calibration method:

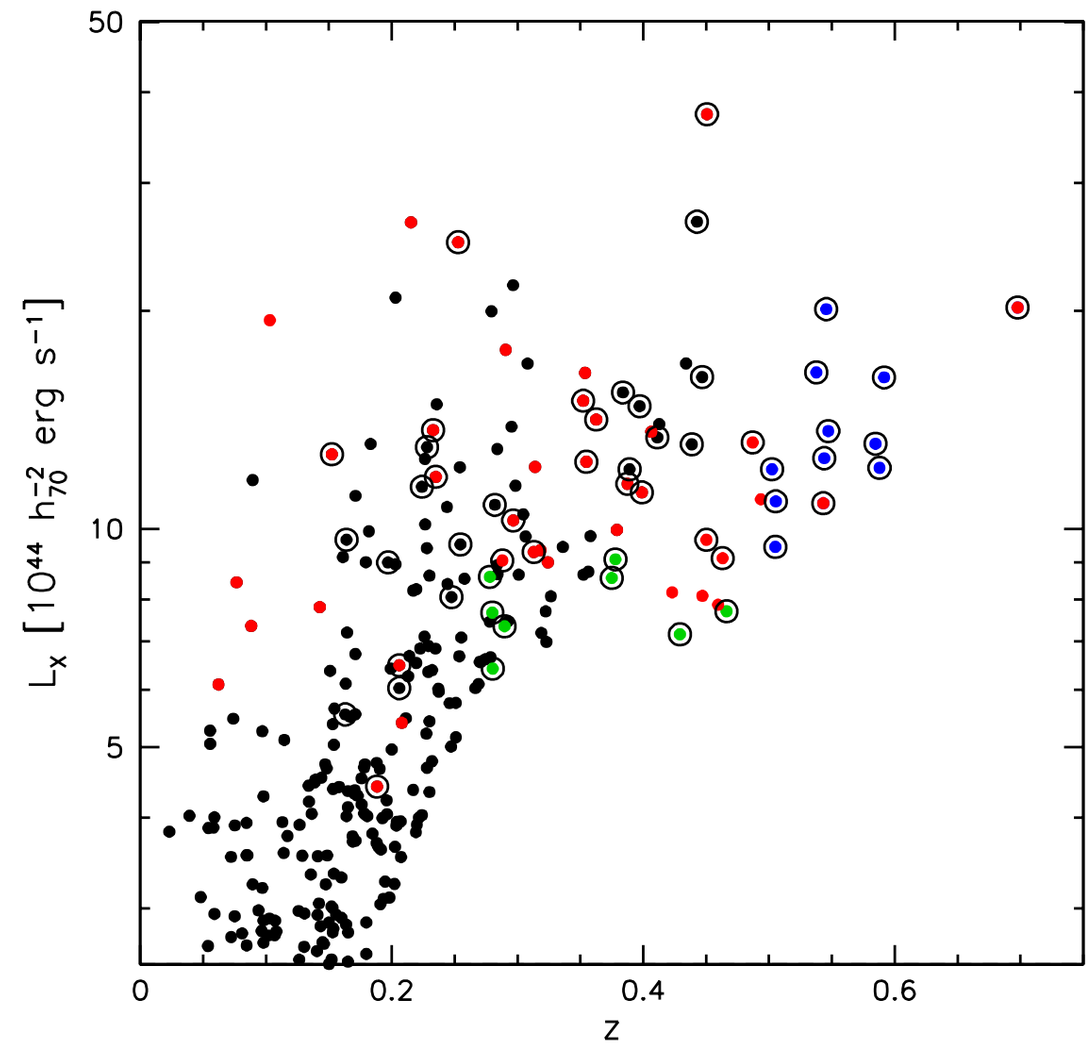
- weak lensing measures total mass
- does not require a baryonic tracer
- no assumption on dynamical state of cluster needed

- comes "for free" with weak-lensing 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. 2014a
WtG II	Photometry, photo-z's	Kelly, AvdL et al. 2014
WtG III	Cluster mass measurements	Applegate, AvdL et al. 2014

(Cluster) (Weak) Lensing

mass deflects light

→ *measure light deflection to estimate cluster mass*

sensitive to total mass (no baryonic tracer required)

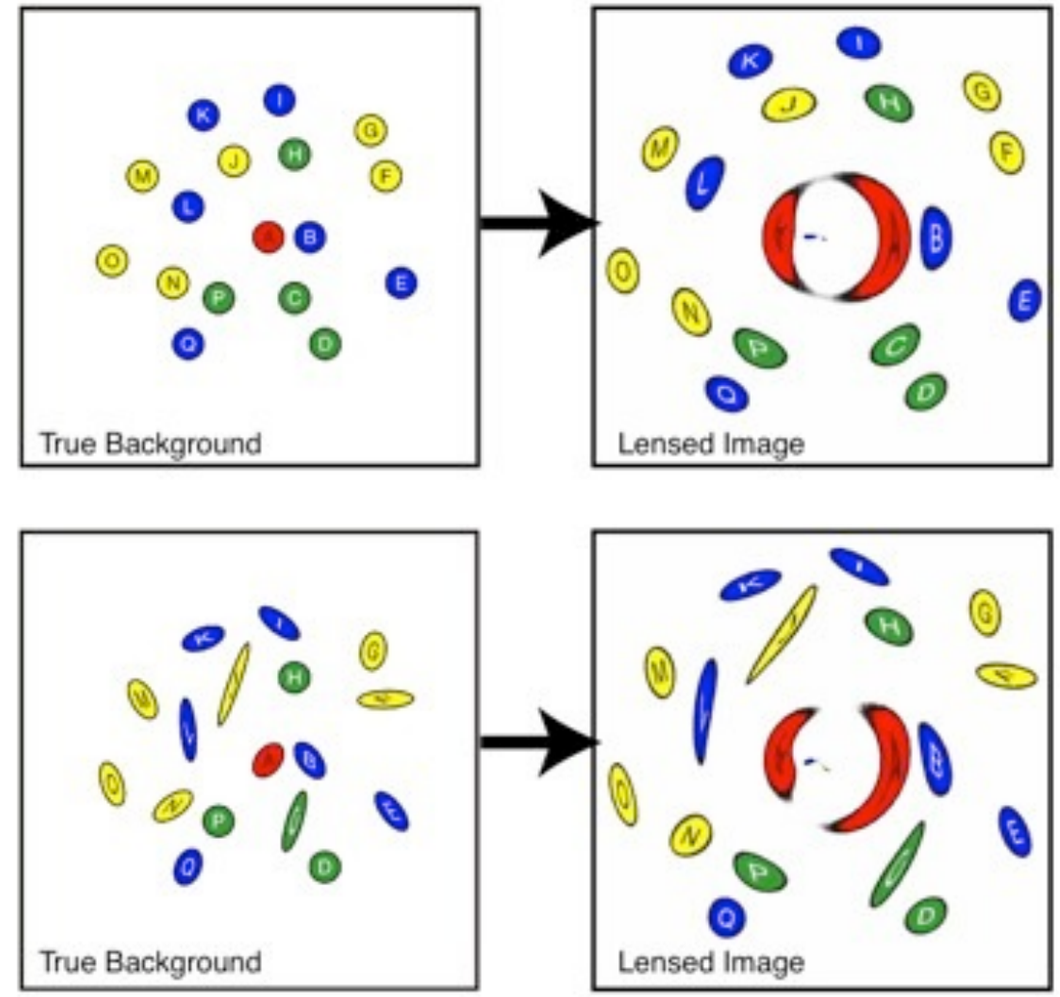
no assumption on dynamical state

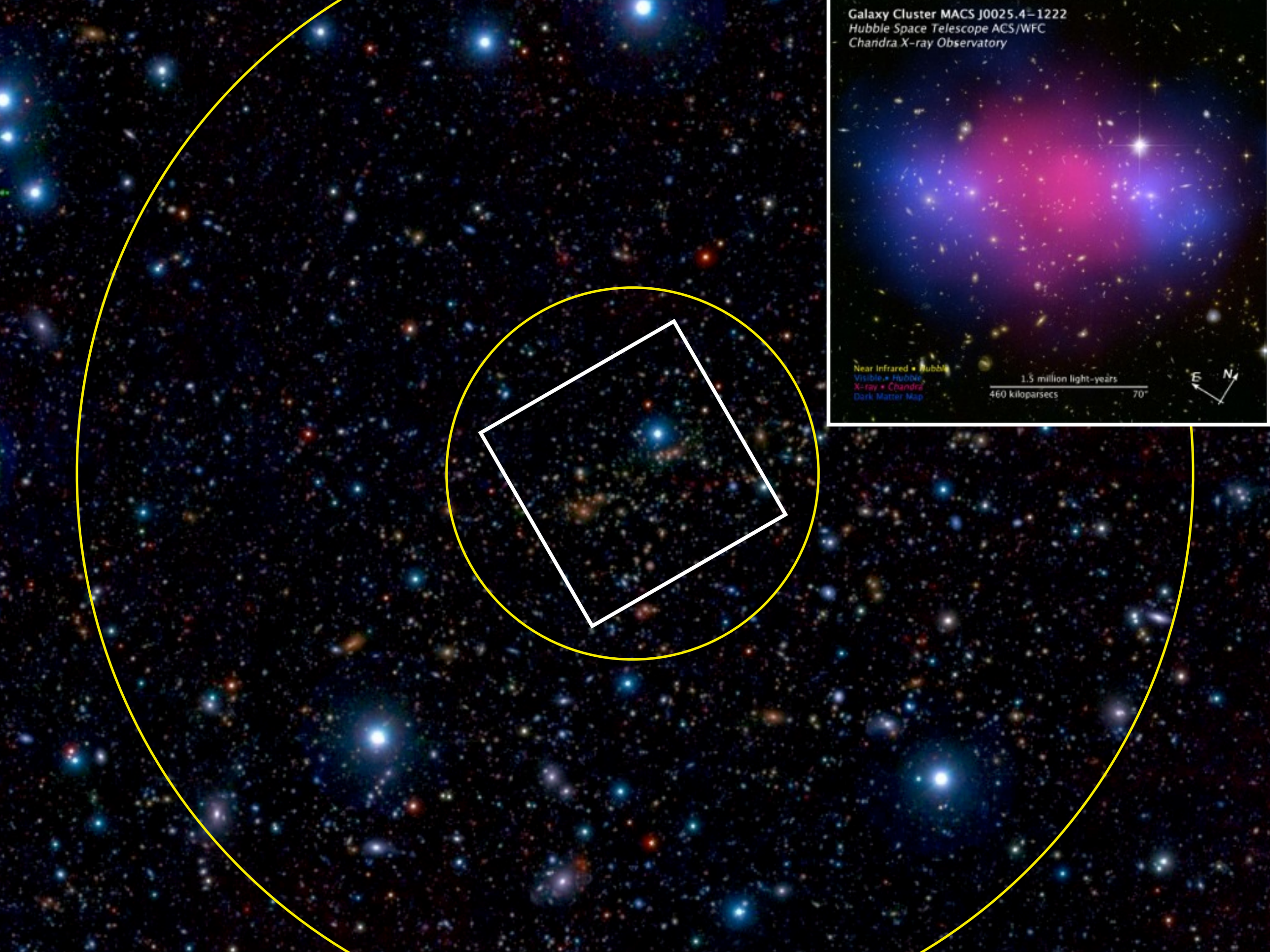
strong lensing:

- multiple images, arcs
- probes *cluster core*

weak lensing:

- statistical tangential alignment
- probes *mass on large scales*
- each background galaxy unbiased, noisy estimator of local deflection (shear)




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

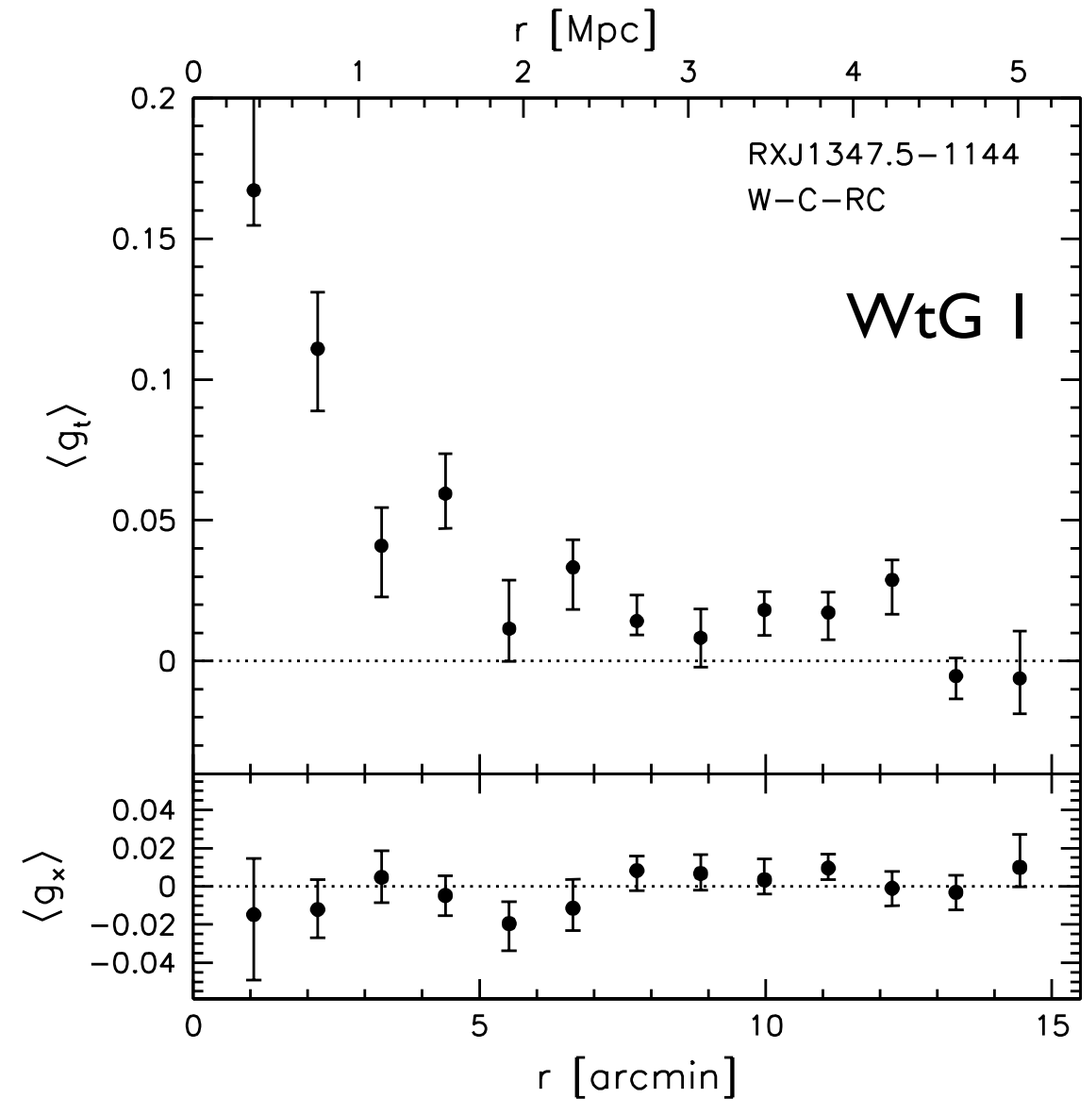
Shear induced on background galaxy depends on:

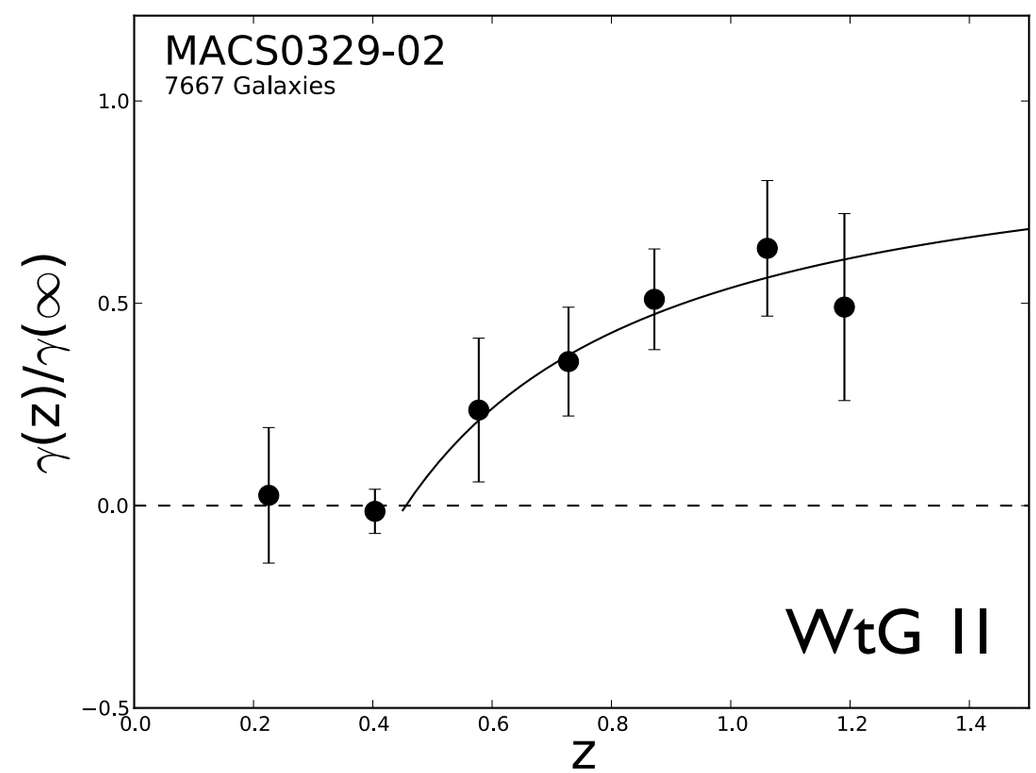
- cluster mass (distribution)
- redshift

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!





WtG III

Uncertainty Source	% of Mean Cluster Mass	
	Color-Cut Method	P(z) Method
Shear Measurements		
Multiplicative Shear Bias Cor	3%	
STEP PSF Mismatch	2%	
Coaddition & PSF Interpolation	1%	
Mass Model		
Triaxiality & LOS Structure	3%	4%
Profile Uncertainty	3%	
Photo-z Measurements		
Residual Photometry Systematics	3%	
Simulated Photo-z Bias	1%	
Depth & Filter Mismatch	1%	
Method Cross-Calibration	4%	-
Total Systematic Uncertainty	7%	7%

STEP

$\sqrt{N}$

NFW?

p(z) bias

~ factor x2 improvement in precision !

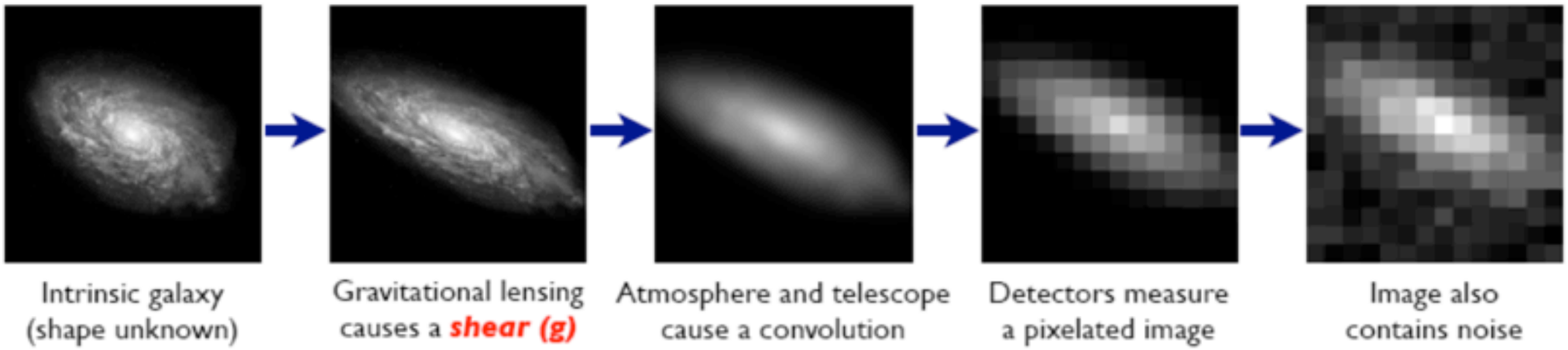
no principle roadblock (at least for $z_{cluster} \lesssim 0.7$)

LSST DESC Dark Energy Science Collaboration

future improvements from synergy
with cosmic shear and simulation efforts

(1) Shear measurements

- unbiased shear measurements are difficult



- WtG greatly benefited from efforts by the cosmic shear community to calibrate shear estimators (STEP; Massey et al. 2006, Heymans et al. 2007)
- but there are cluster-specific distinctions:
  - shear in clusters is larger
  - dense fields: deblending, background subtraction
  + need to calibrate to (only) ~1%, cf. ~10^{-4} for cosmic shear

  → for WtG: *avoid inner cluster regions* (< 750 kpc)
  (also reduces sensitivity to miscentering and concentration)

➡ future efforts require additional, but feasible simulations

(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 $\gtrsim 20\%$

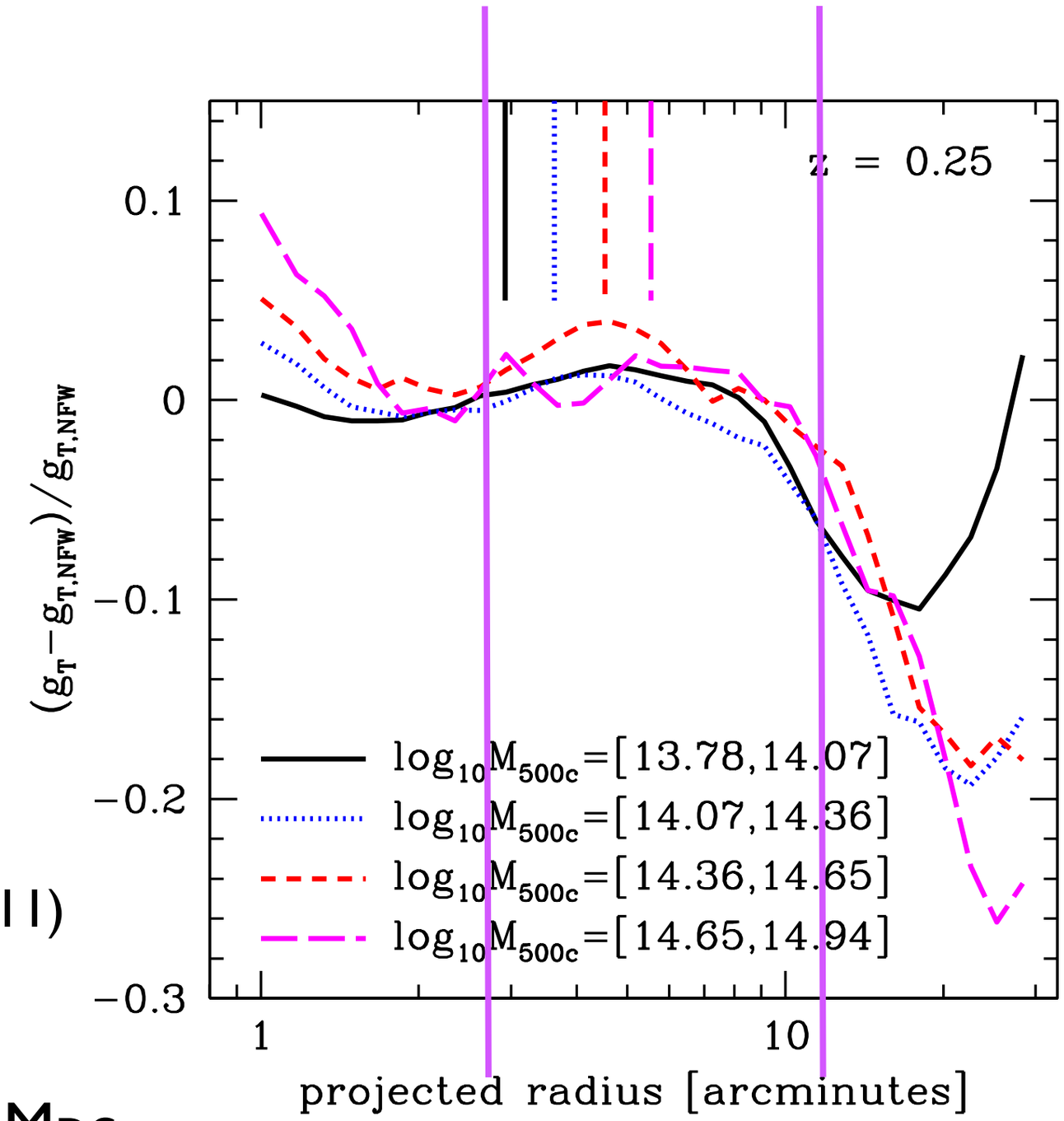
Becker & Kravtsov 2011

(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%

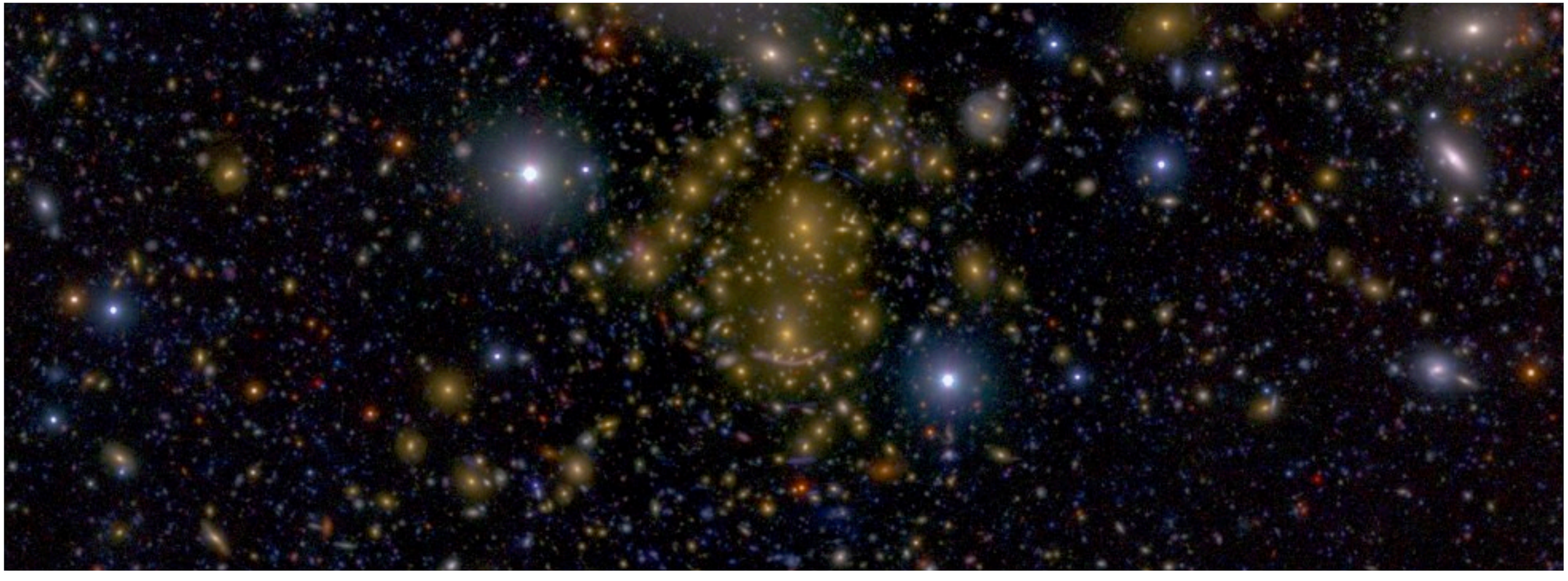
(Becker&Kravtsov 11, Bahe+12, Oguri+11)



- for massive clusters: r_{500} ~ 1.5 Mpc
- WtG: fit from 0.75 Mpc to 3 Mpc, measure within 1.5 Mpc
- could iterate, if needed

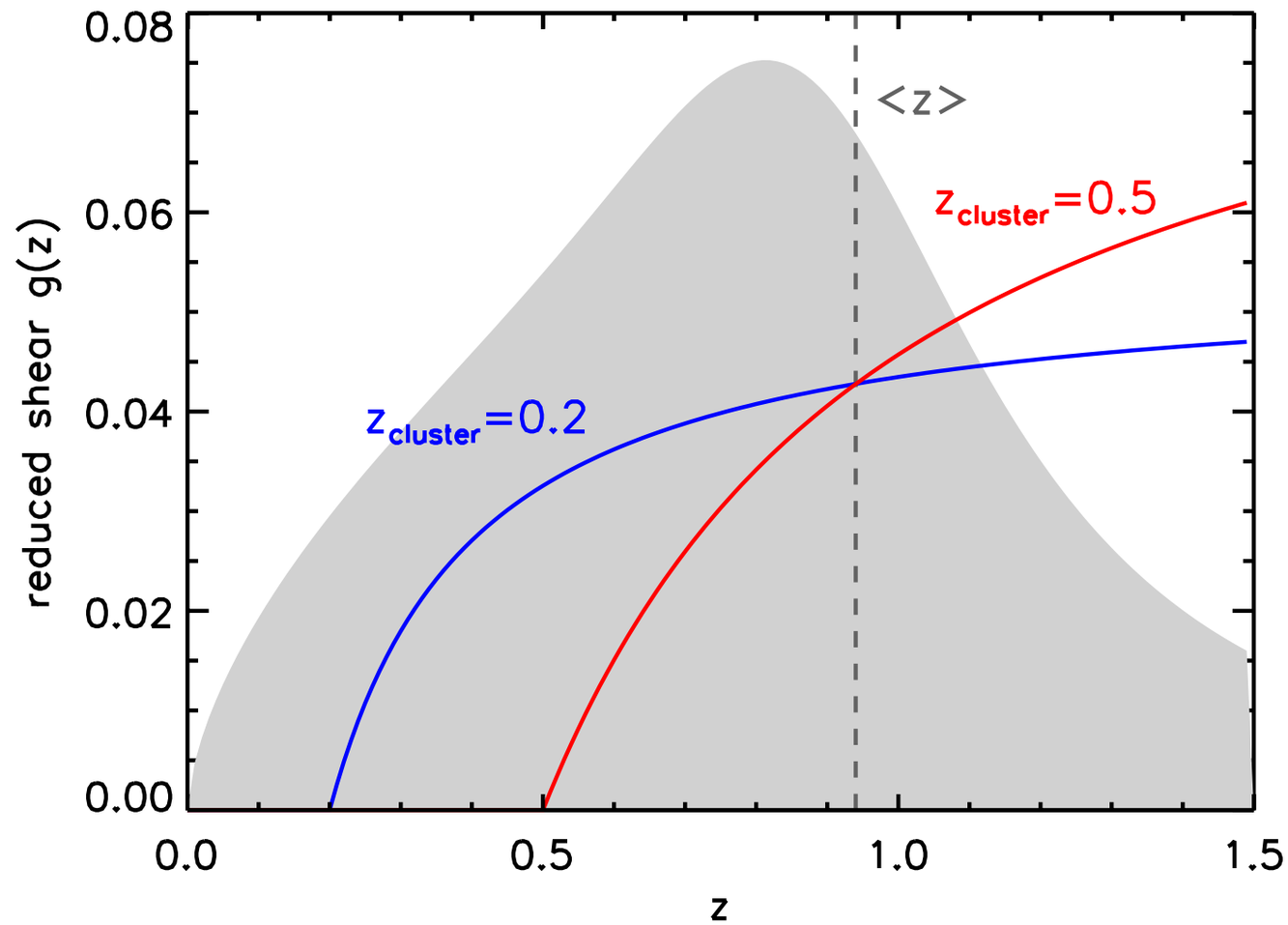
average lensing mass unbiased, but scatter of $\gtrsim$ *30%*

- ➡ 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)*

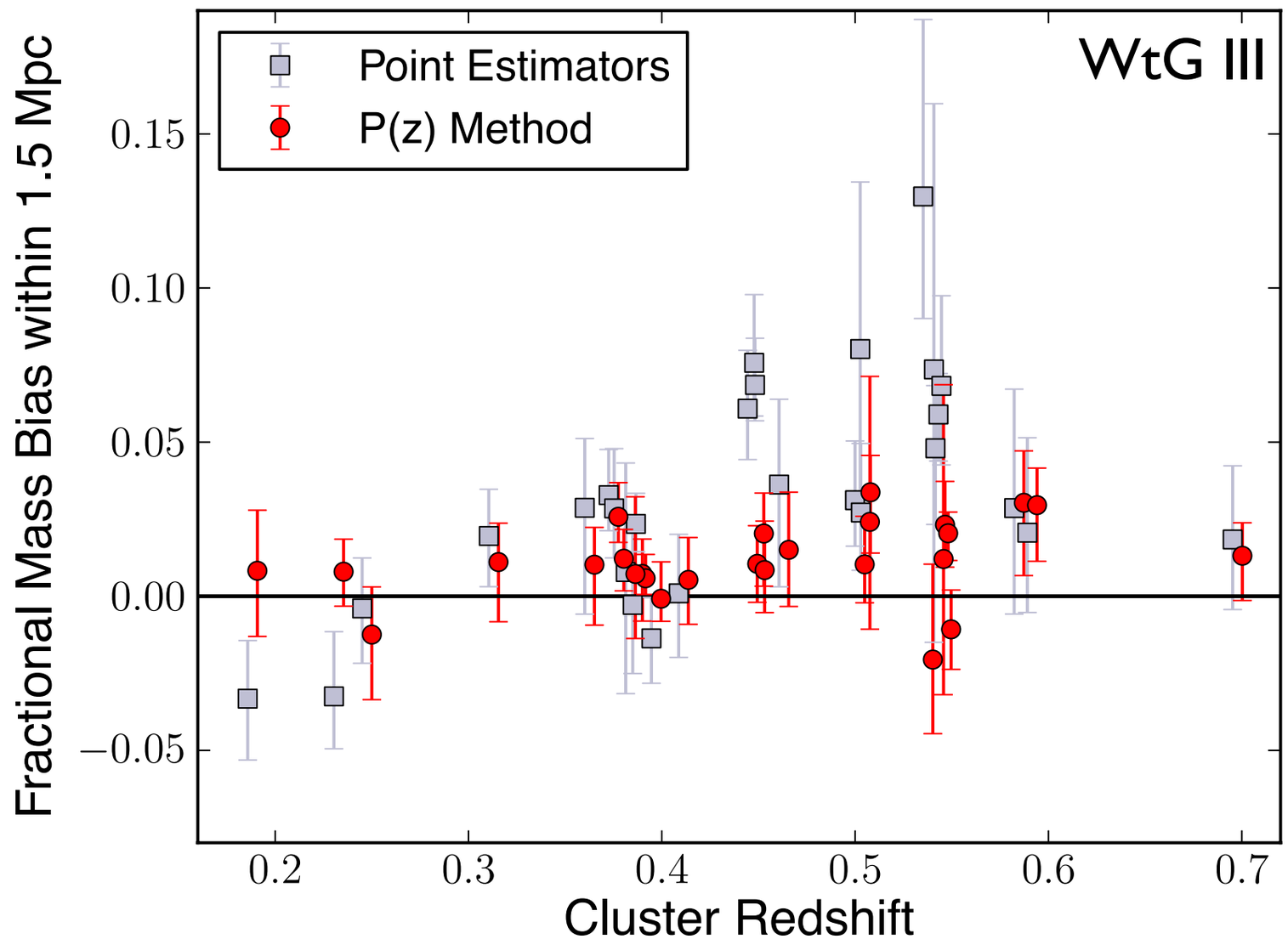
➡ use photometric redshifts instead

WtG testbed: COSMOS "simulations"

- COSMOS survey:
  - 2 sq. degrees with 30-band photometry (Capak et al. 2009)
  - high-fidelity photo-z's (Ilbert et al. 2009)
  - includes SuprimeCam BVriz, MegaPrime u (match to our data)

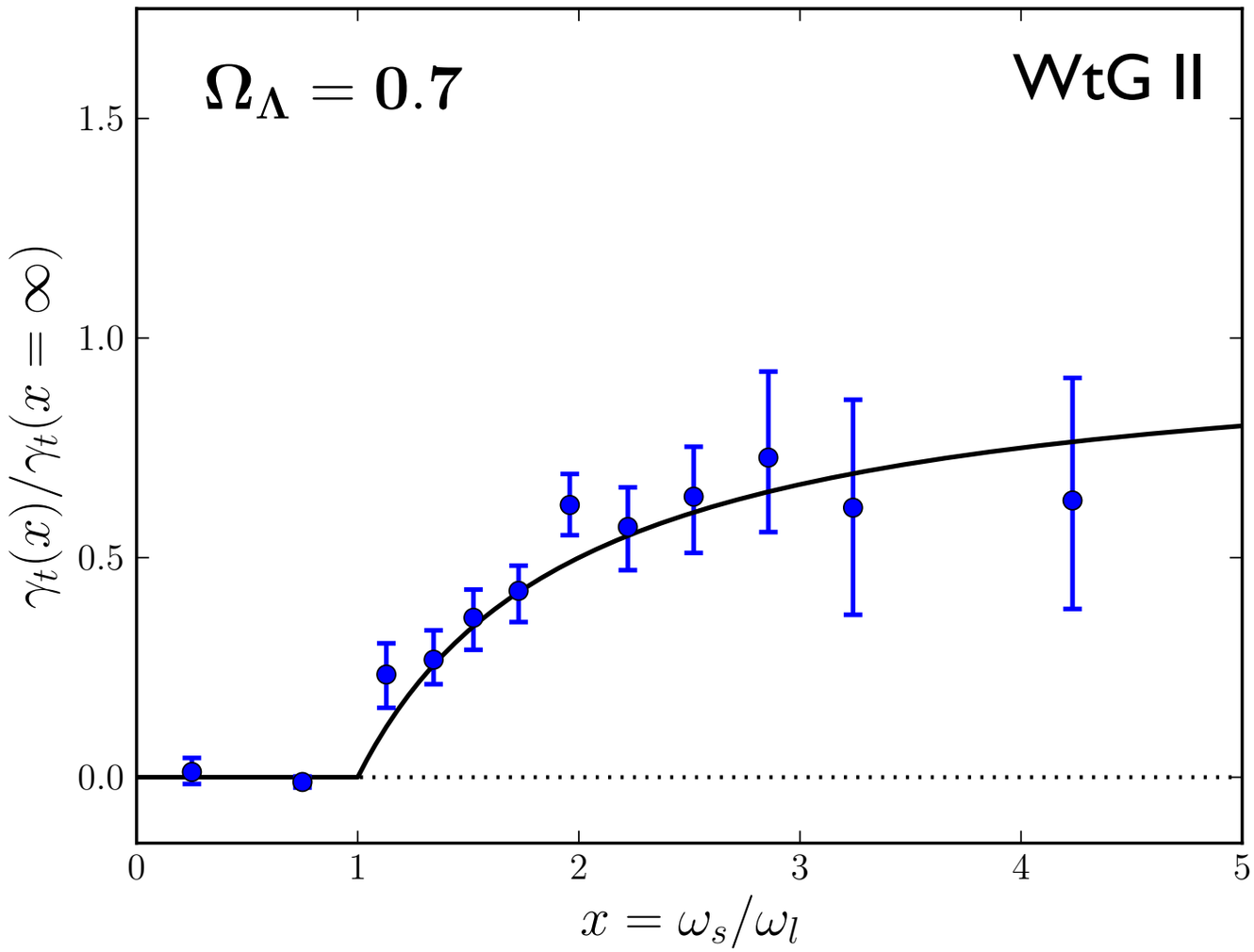
- excellent testbed for methodology:
  - for each cluster field, apply same cuts (magnitude, color) as in data
  - COSMOS-30 photo-z is "truth"
  - simulate shear field: NFW halo, true redshift, shape noise
  - estimate our photo-z from (u)BVriz
  - apply method

Need to use full p(z) !



- using simple point estimates (z_{best}) leads to bias at z > 0.4 (due to large [non-gaussian] uncertainty on z_{best} and non-linear shear-redshift scaling)
- using full p(z) in maximum likelihood analysis:
  expected mean ratio 1.012 ± 0.003 → almost unbiased!

Side-Note: Tomography

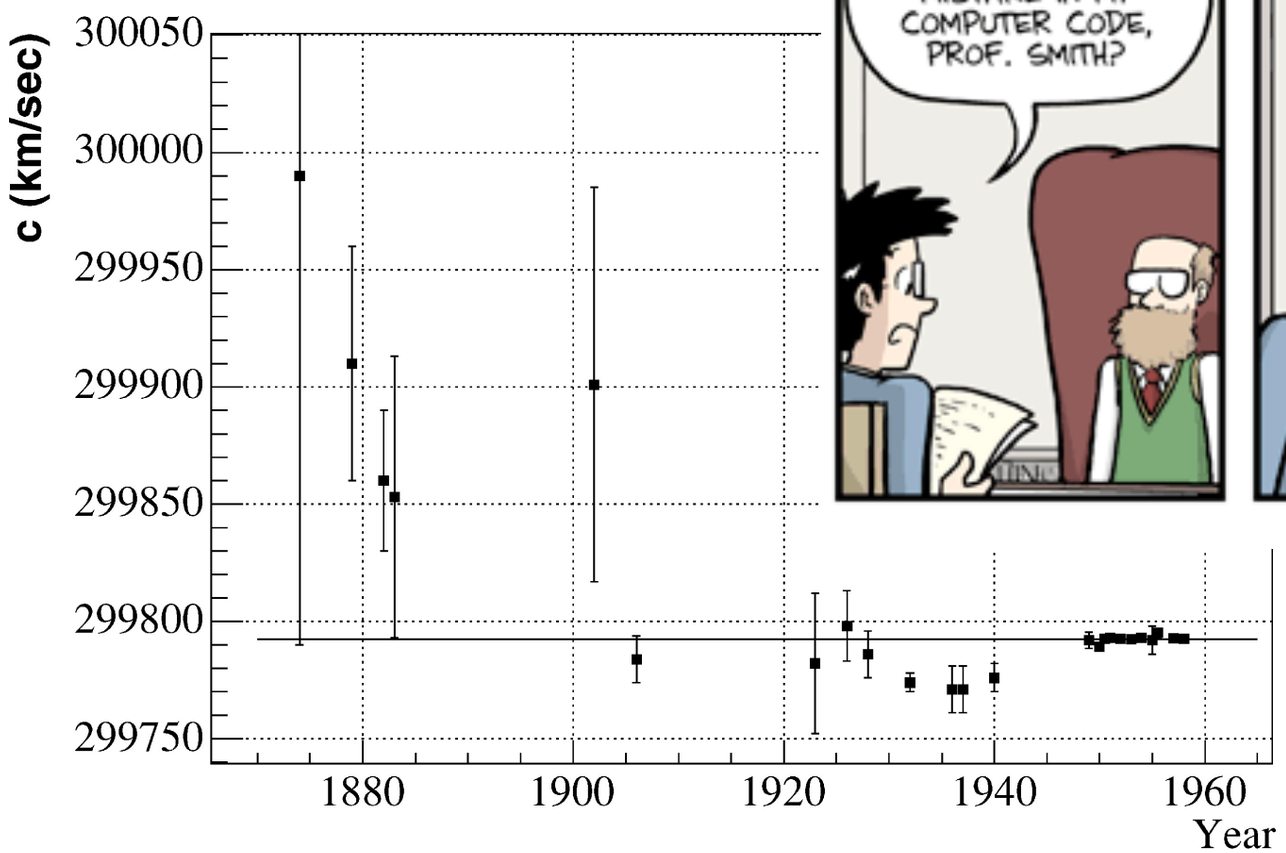


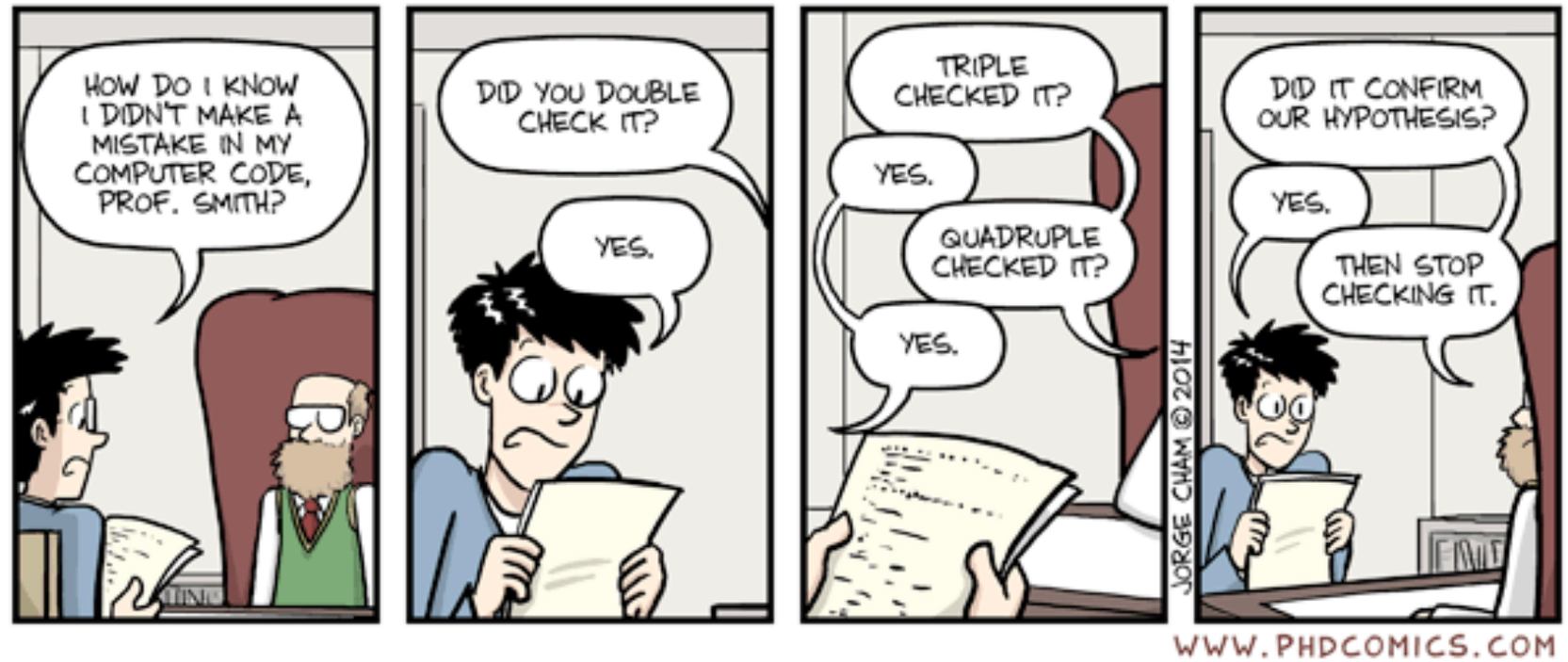
- ratio of shear measured at different redshifts sensitive to geometry of Universe

Taylor et al. 2007

- method very, very sensitive to photo-z errors

On the use of blind analyses





- clear expectation for this project: agreement with X-ray masses
- WtG: "blinded" analysis - no comparison to other mass measurements until mass measurements finalized
- *requires extensive testing - builds confidence that results are reliable*

Part III: first cosmological applications of WtG

1. new constraints from ROSAT clusters counts

Mantz, AvdL et al., in prep.

2. a look at the Planck cluster mass calibration

Robust weak-lensing mass calibration of Planck galaxy clusters

AvdL et al., MNRAS, submitted, arXiv:1402.2670

3. new results from the cluster baryon fraction test

Cosmology and Astrophysics from Relaxed Galaxy Clusters II: Cosmological Constraints

Mantz et al., MNRAS, accepted, arXiv:1402.6212

WtG mass calibration for RASS

coming soon:

cosmology from ROSAT All-Sky Survey cluster counts ($\gtrsim$ 200 clusters at z $\lesssim$ 0.5) with WtG mass estimates for 51 clusters

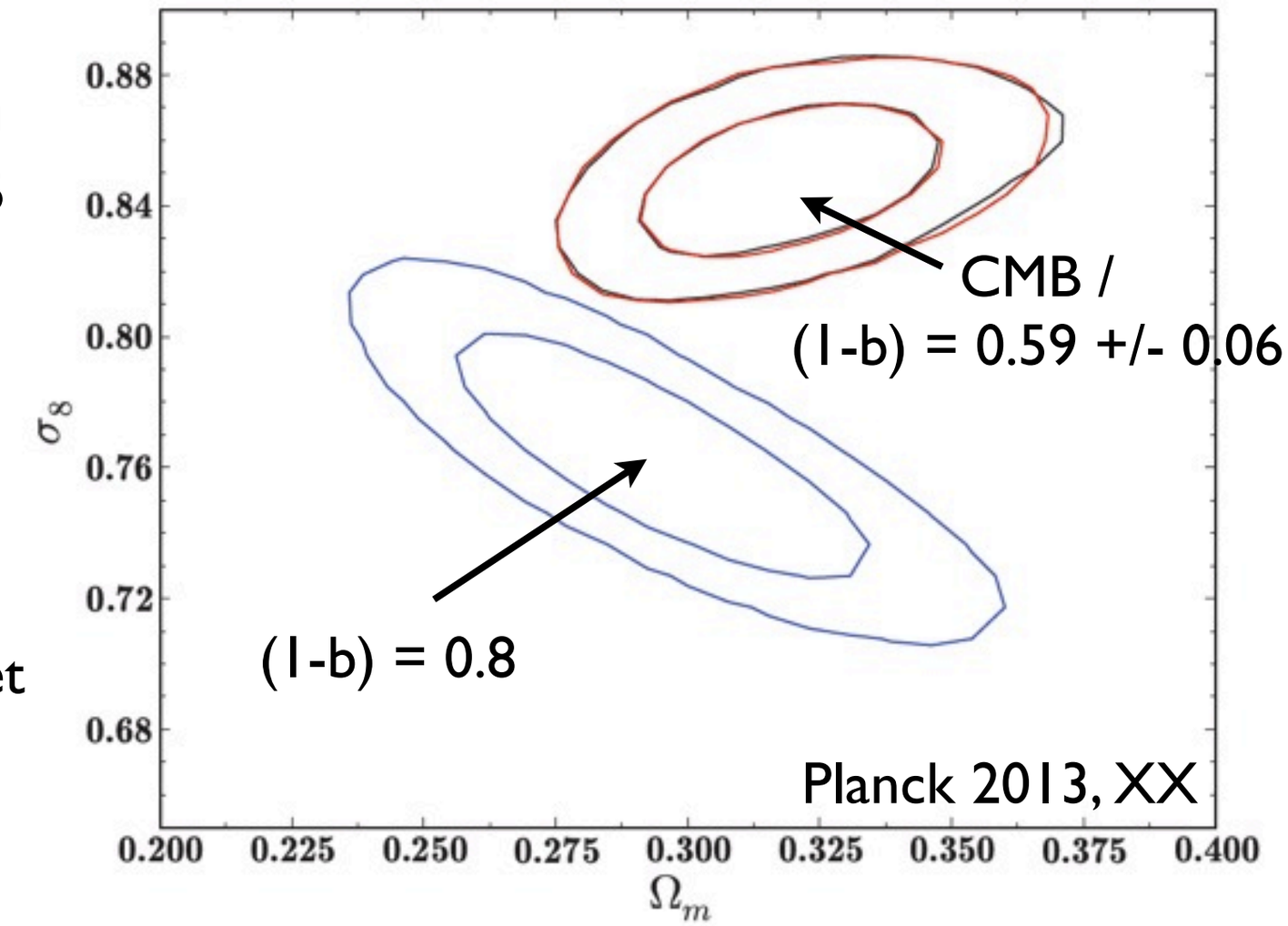
Mantz, AvdL et al., in prep.

clusters
CMB: WMAP, SPT, ACT
SNIa: Union 2.1
BAO: 6df, SDSS, BOSS
combined

WMAP $\longrightarrow$ Planck

Planck cluster counts

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



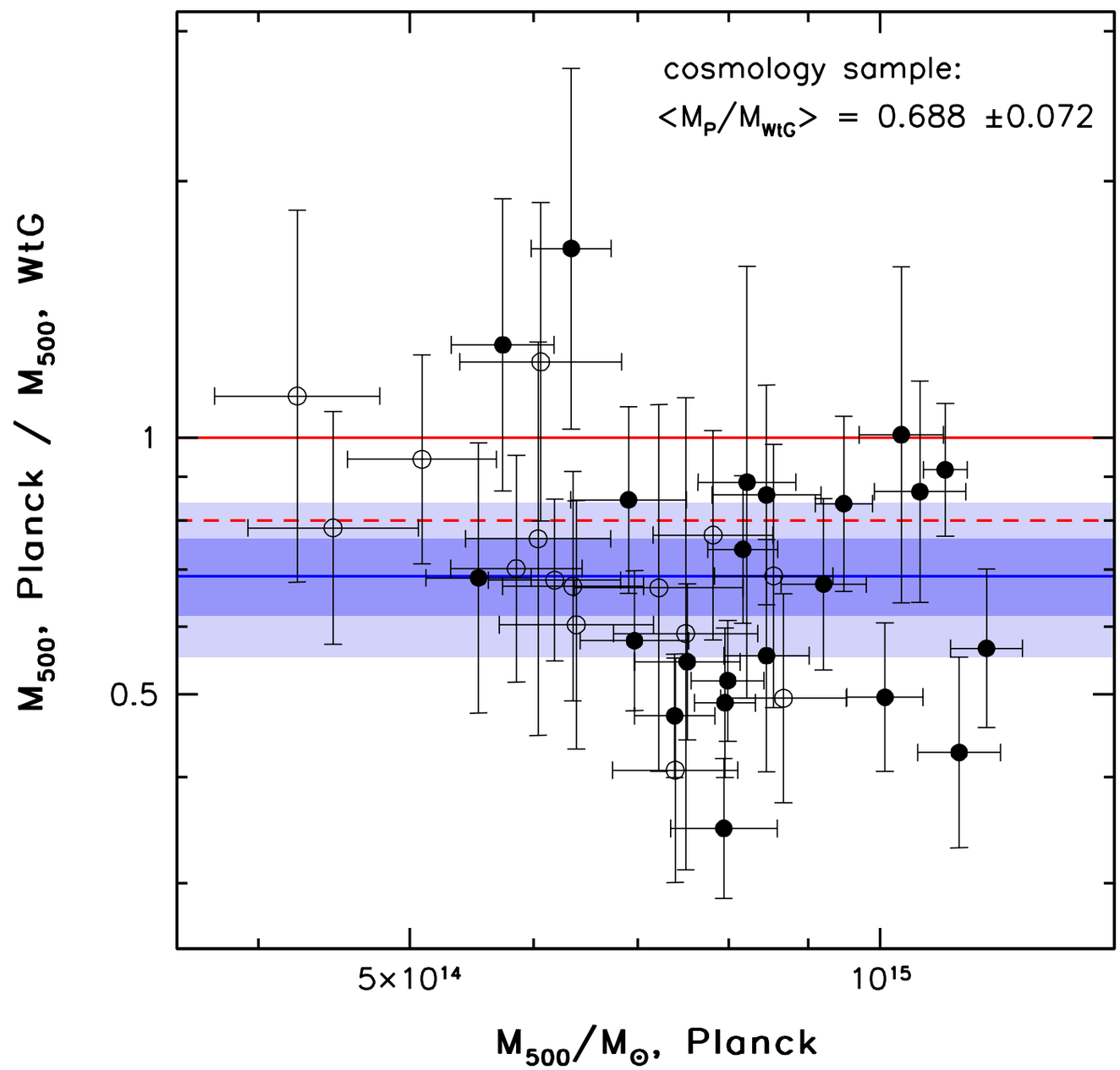
suggested explanations:

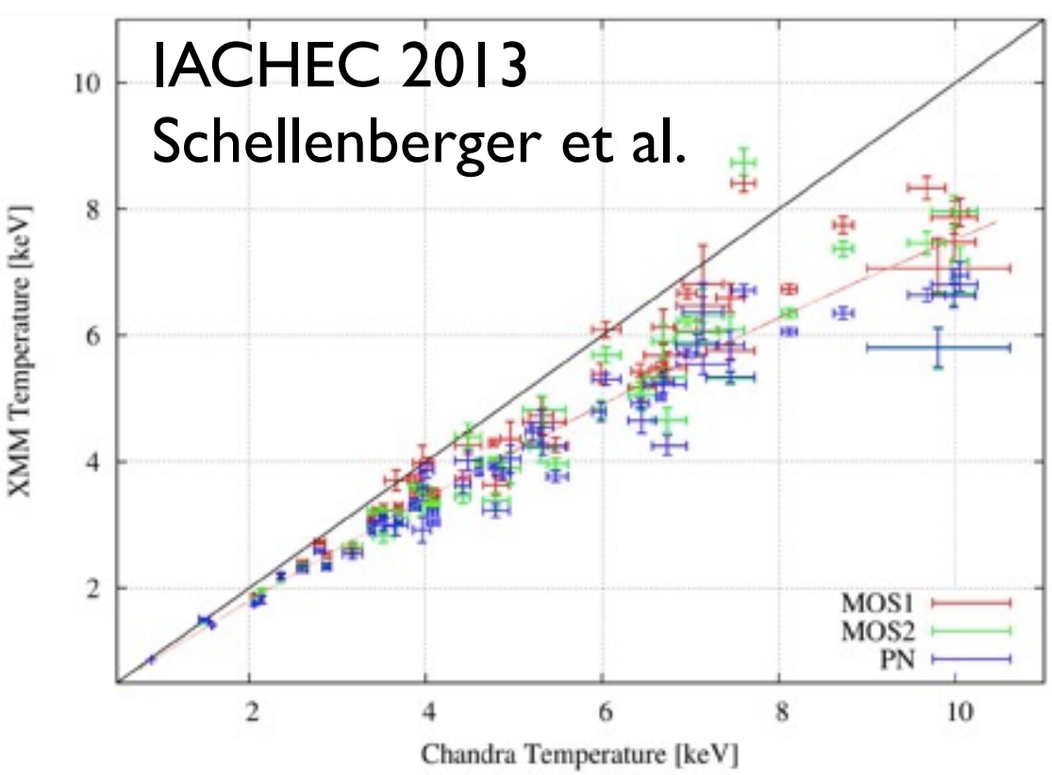
- mass bias underestimated (and no accounting for uncertainties)
- 2.9σ detection of neutrino masses: Σm_ν = (0.58 +/- 0.20) eV (Planck+WMAPpol+ACT+BAO: Σm_ν < 0.23 eV, 95% CL)

WtG mass calibration for Planck

- comparison of Planck and WtG mass estimates: $M_{Planck} / M_{WtG} = 0.69 \pm 0.07$
- adopting WtG mass calibration would substantially reduce tension, eliminate need for "new physics"

AvdL et al., arxiv:1402.2670





suspected cause: XMM temperatures biased low

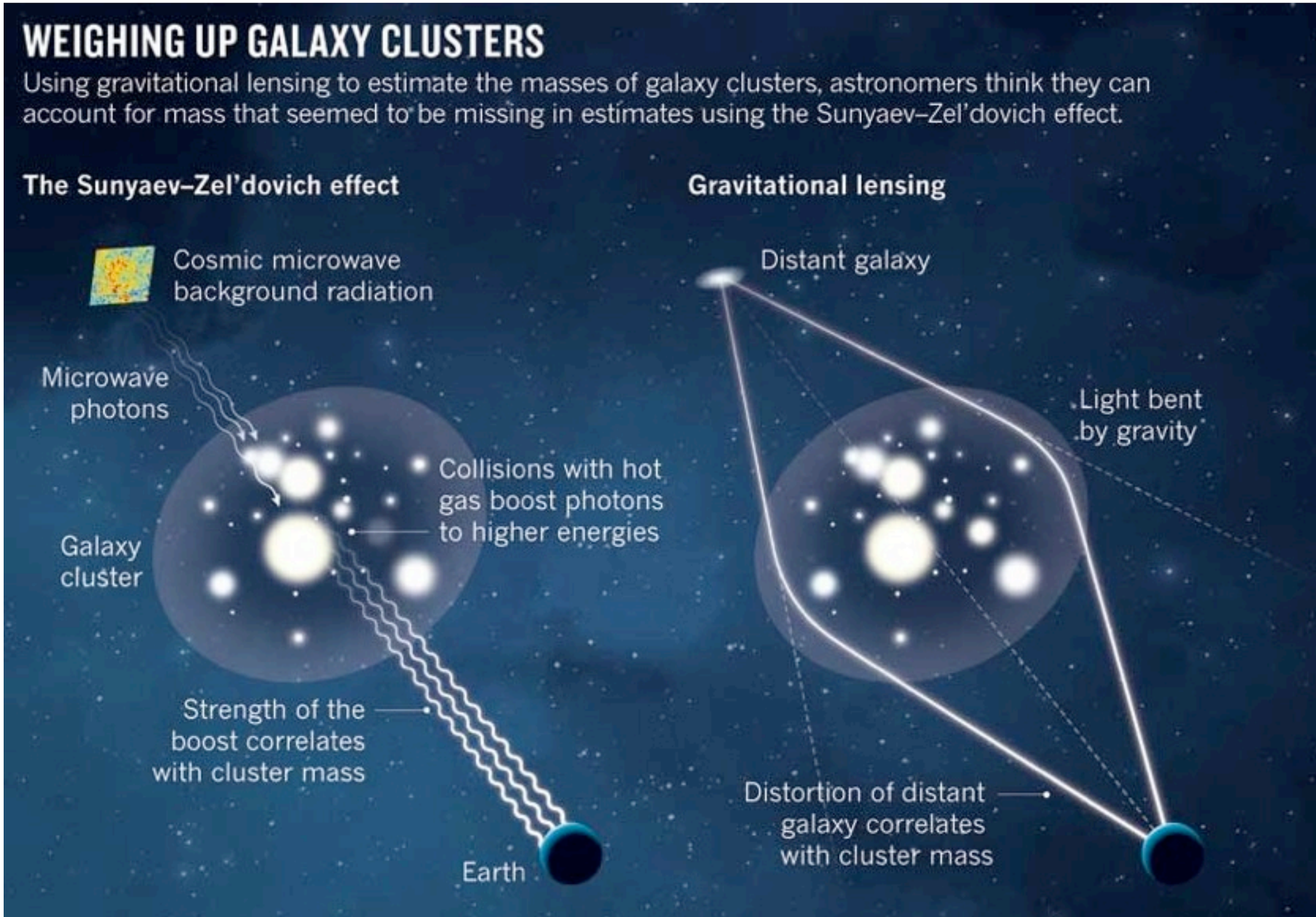
NATURE | NEWS

Missing galaxy mass found

Gravitational lensing solves puzzle from the Big Bang's echo.

Eugenie Samuel Reich

18 February 2014



The baryonic mass fraction (f_{gas}) test - Ω_m

- clusters are so large that their matter content provides a ~ fair sample of the matter content of the Universe
- baryonic mass mostly in X-ray-emitting hot gas

$$f_{\rm gas} = \frac{M_{\rm gas}}{M_{\rm tot}} = \Upsilon \frac{\Omega_{\rm b}}{\Omega_{\rm m}}$$

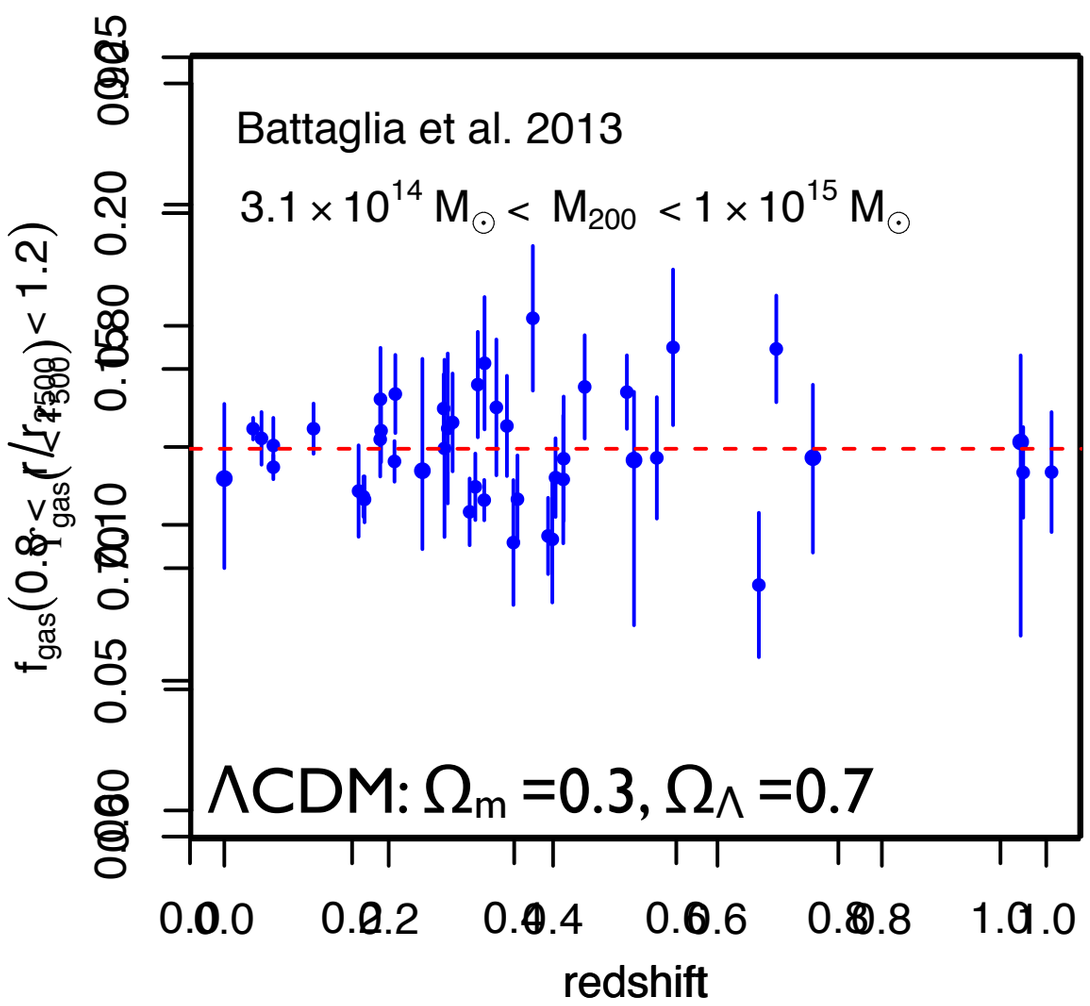
- Υ: depletion factor, can be well modeled by hydrodynamical simulations (outside cluster core)
- measure M_{gas} and M_{tot} from X-ray observations of most massive, most relaxed clusters (to apply hydrostatic equilibrium)
- with minimal external datasets ($\Omega_b h^2$ from BBN, h), clusters can sensitively constrain Ω_m
- White (1993): Ω_m ~0.3 (problem with then-paradigm, $\Omega_m = \Omega_0 = 1$)

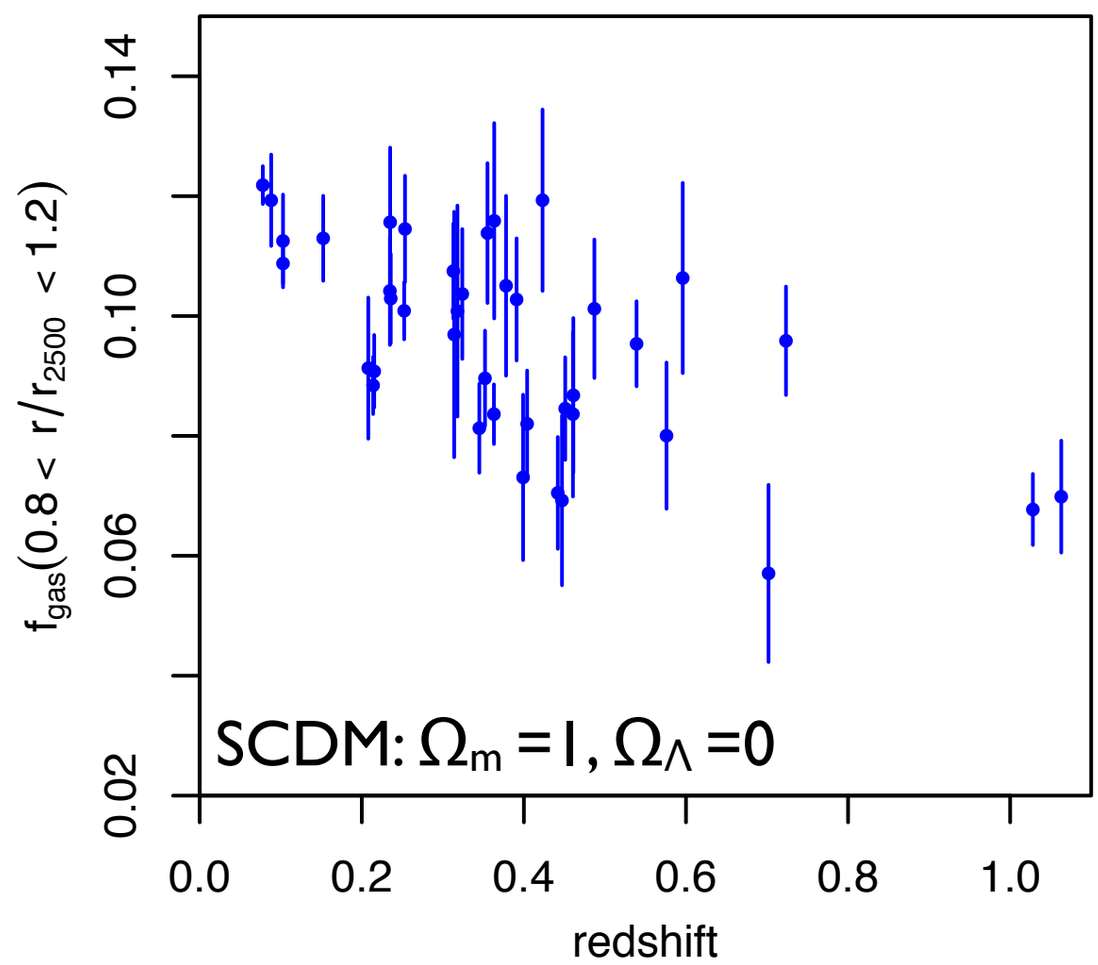
The baryonic mass fraction (f_{gas}) test - Ω_Λ

- for the most massive clusters, f_{gas} is a standard quantity (constant with mass and time/redshift)
- measurement depends on cluster distance as $f_{gas} \propto d^{3/2}$ (combination of angular diameter and luminosity distances)

observations:

simulations:



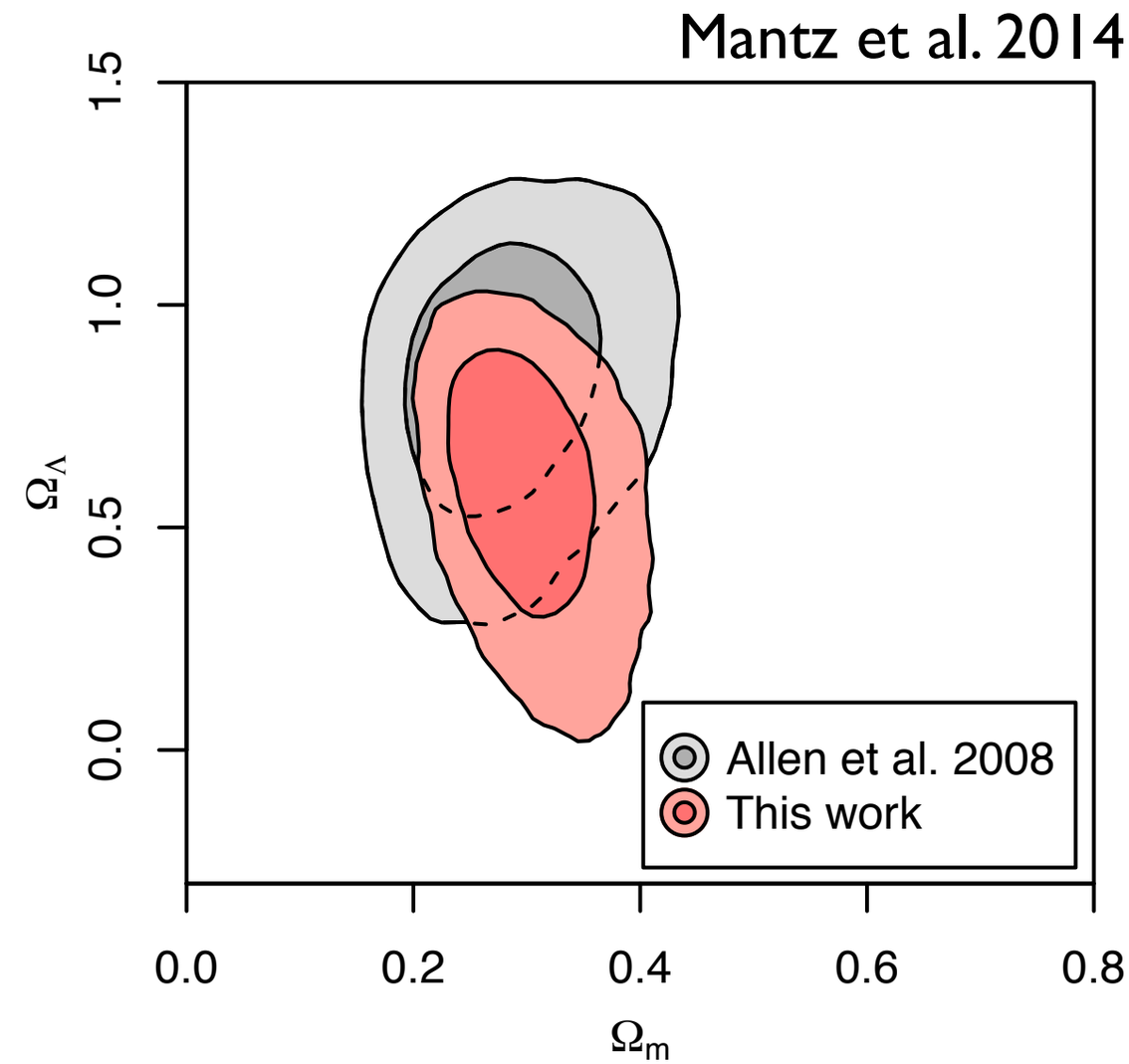


WtG mass calibration for f_{gas}

- 12 clusters both in WtG and new f_{gas} analysis → mass calibration for relaxed clusters
- lensing mass calibration to ~10%
- significantly tightens Ω_m constraints

$$\Omega_{\rm m} = 0.29 \pm 0.04$$

$$\Omega_\Lambda = 0.63 \pm 0.19$$



Part IV.

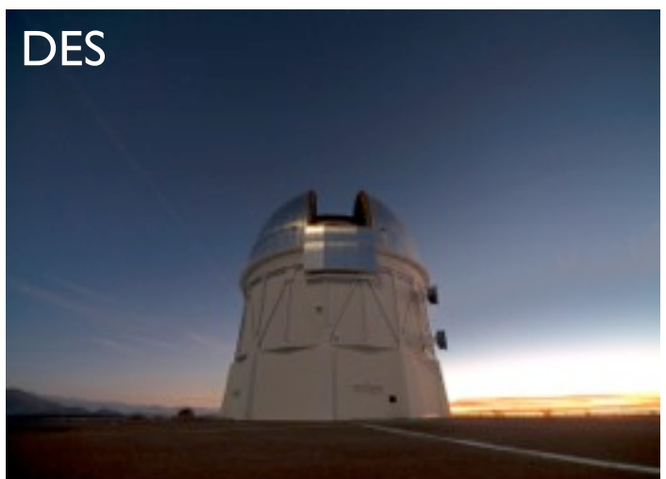
Outlook

A multi-wavelength approach

exciting times are ahead: many surveys on-going, starting, or planned; with excellent follow-up prospects

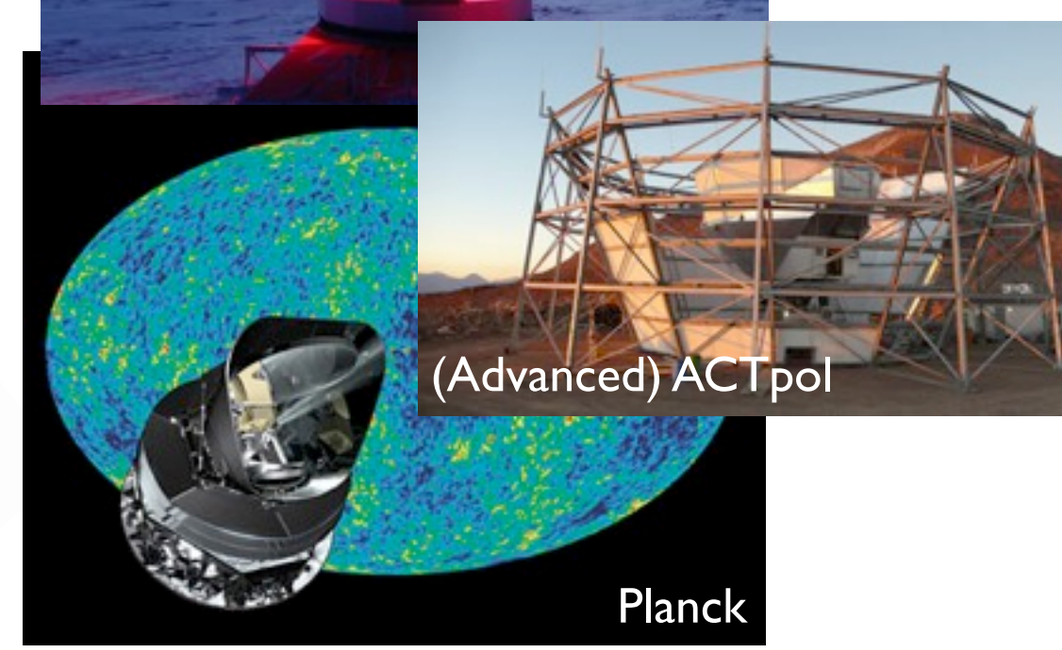
great synergy prospects for cluster surveys !

SZ



optical

X-rays



WtG → LSST (+ Euclid)

LSST Dark Energy Science Collaboration (DESC) cluster WG:
high priority tasks based on WtG findings

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
   - need more data, including spectroscopy and NIR imaging

Best preparation: more data

cosmological precision with WtG limited by number of clusters with 5-filter imaging for p(z) method

on-going observational efforts:

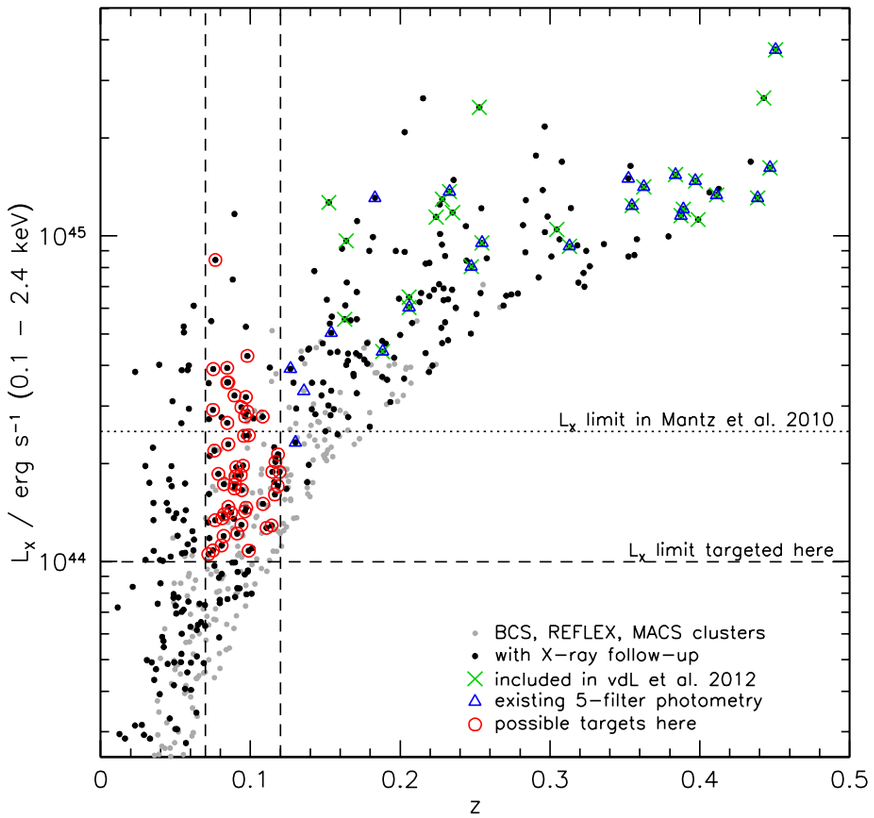
- RASS clusters
- relaxed clusters
- SPT clusters

turning things around:

500 ksec Swift XRT program to estimate L_X for optically selected, medium-richness clusters

Less massive clusters

- on-going program with DECam:
- extend mass calibration to lower L_X
- target RASS clusters at z ~ 0.1
- great match to DECam's wide FOV



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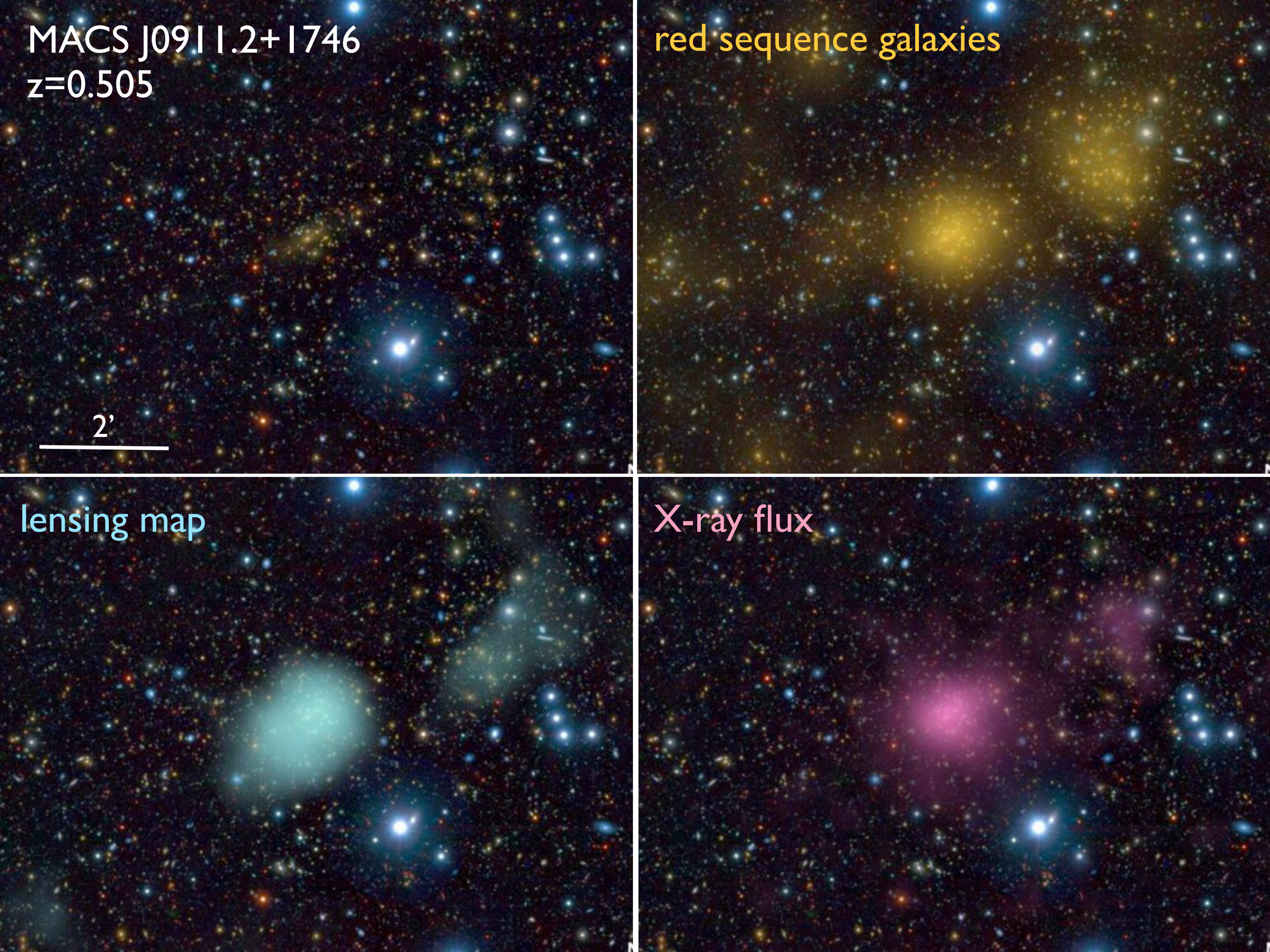
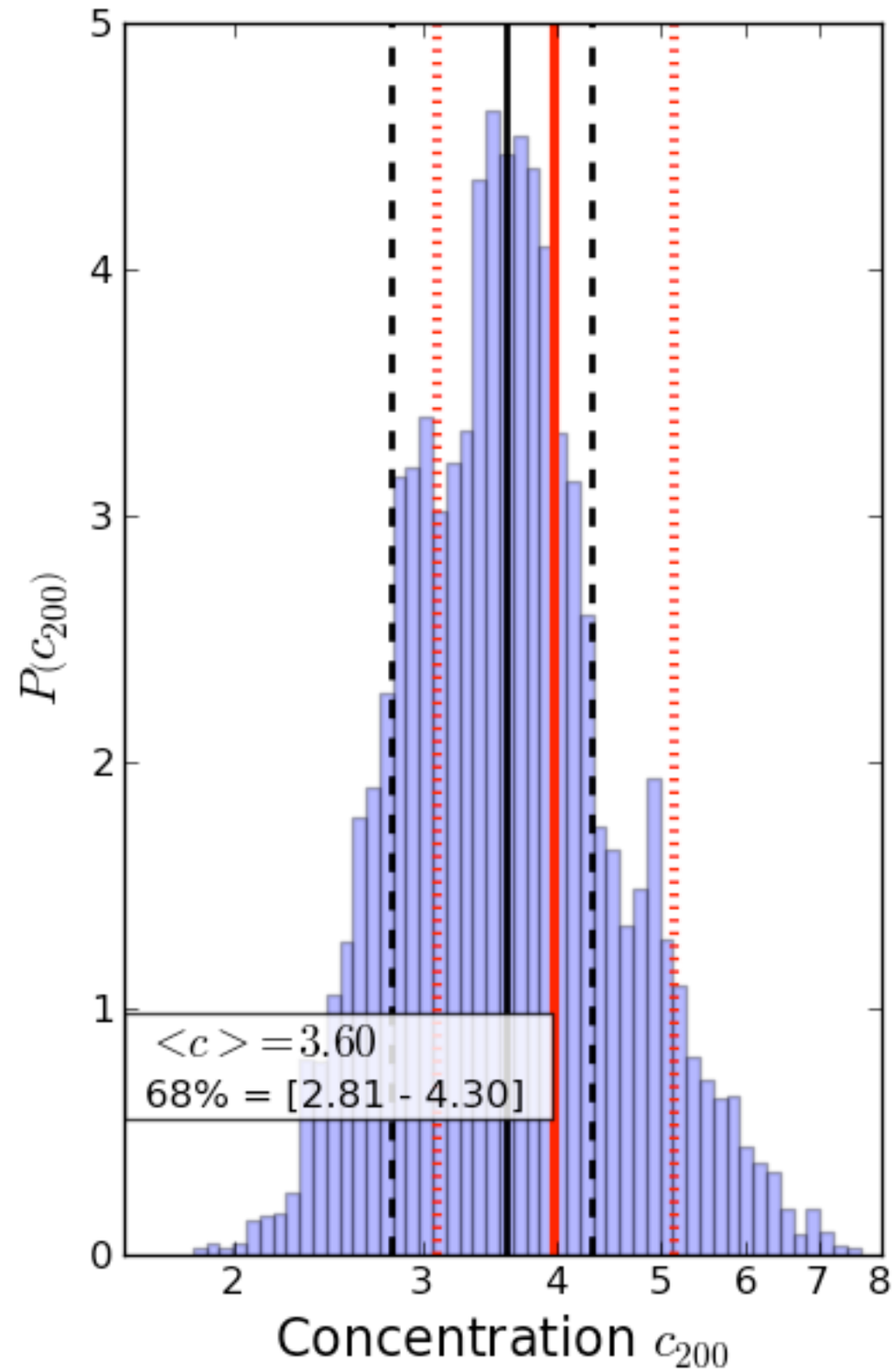

MACS J0911.2+1746
z=0.505
2'
red sequence galaxies
lensing map
X-ray flux

Choice of mass profile

- WtG: marginalize over distribution in c predicted by simulations (Neto et al. 2007)
- change in c within reasonable margins (50%) : only percent-level change in M
- fit at large radii (>750 kpc) - profile not very susceptible to c
- joint analysis of 27 clusters: c consistent with assumptions

- other profiles?

truncated NFW (Oguri et al. 2011) → 2% shift



Applegate et al., in prep.

Scaling relations / cosmology

mass measurements

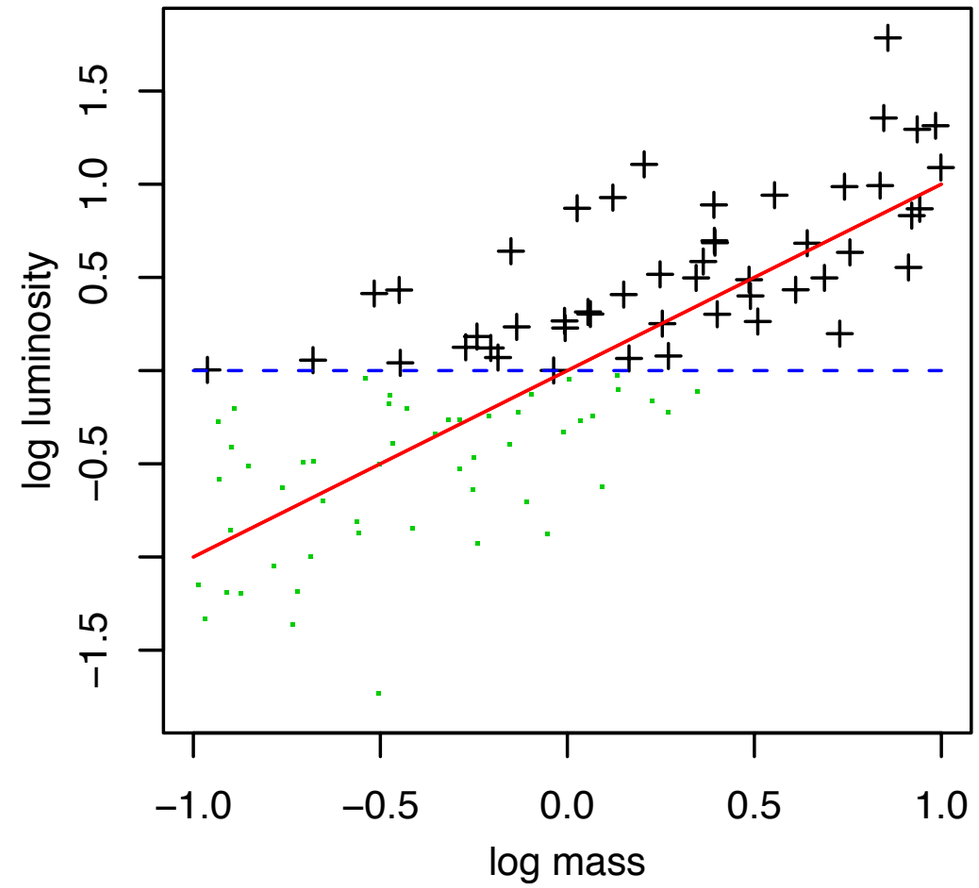
depend(s) on

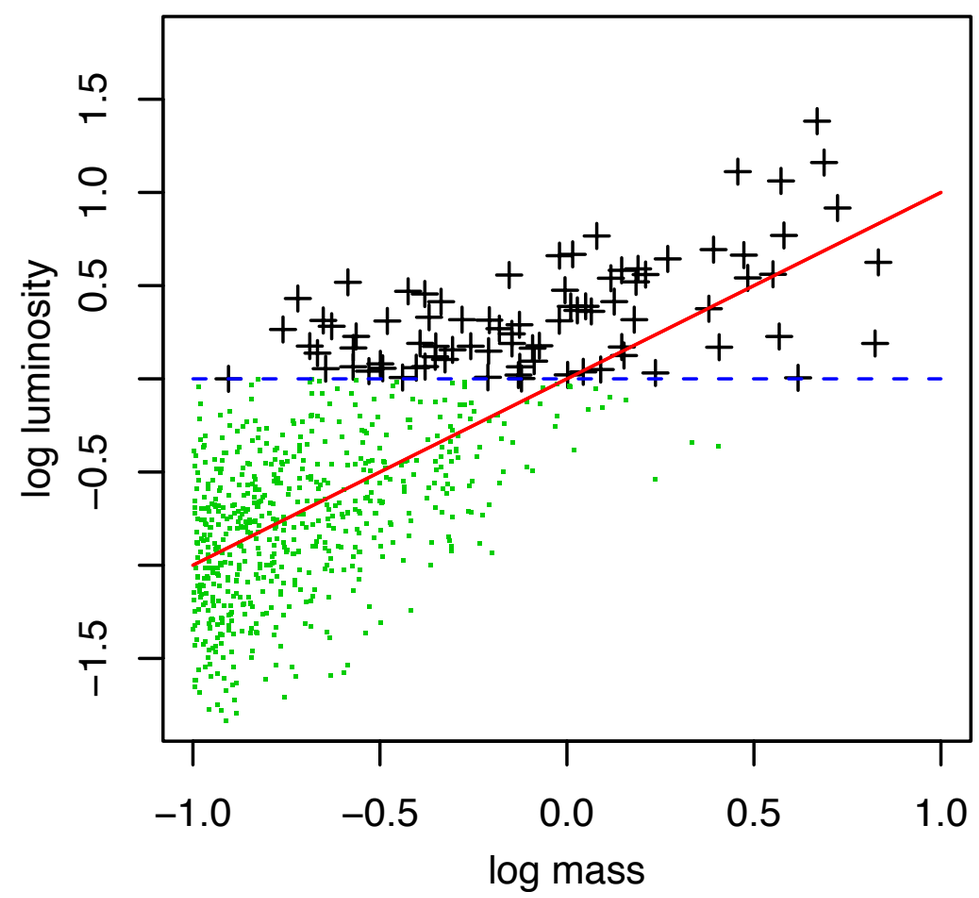
cosmology

- selection effects (Malmquist, Eddington biases) affect measured relation
- need to account for selection effects and underlying mass function (and cosmology)

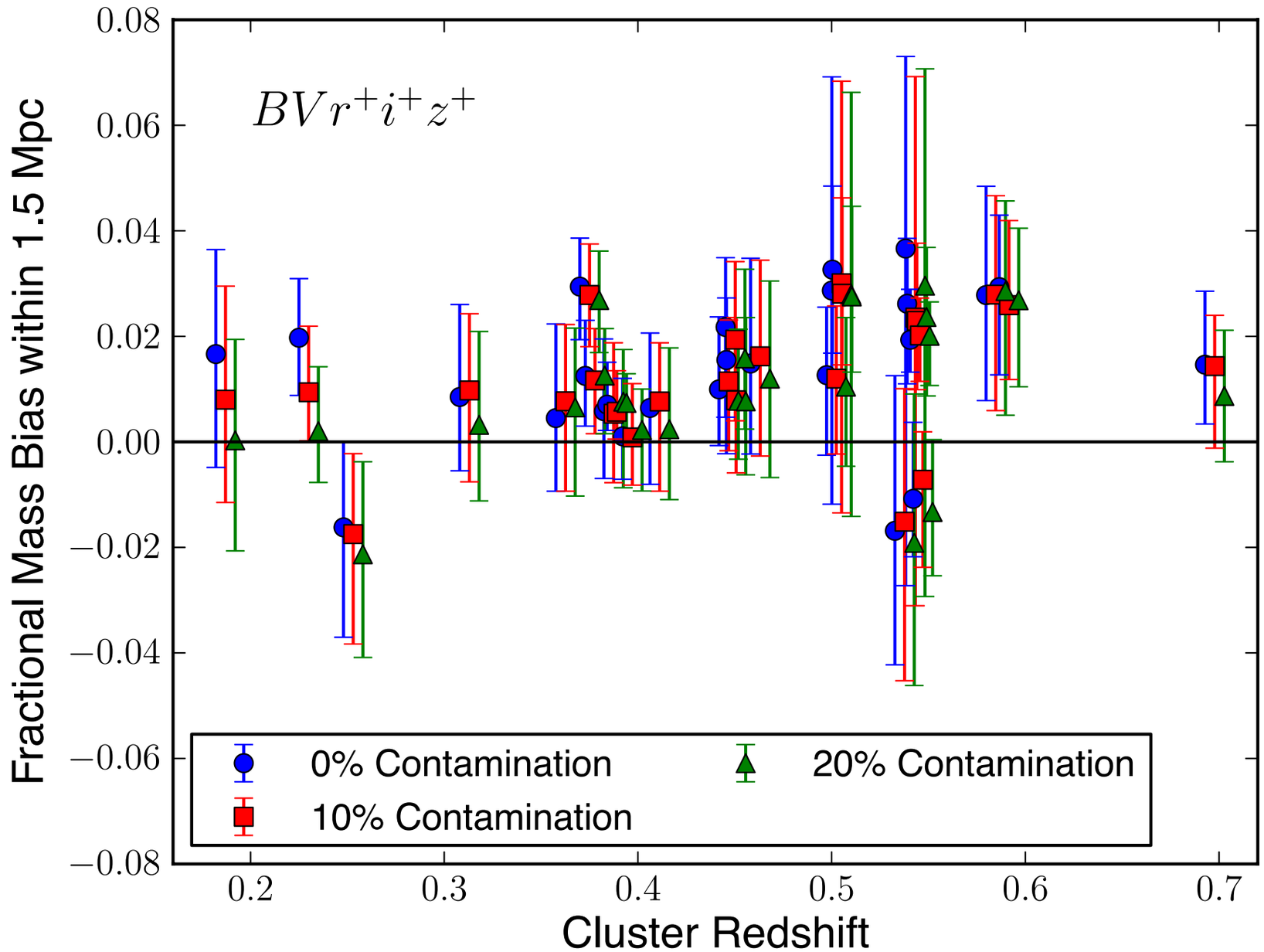
▸ solve for scaling relations and cosmology simultaneously

Mantz et al. 2010b



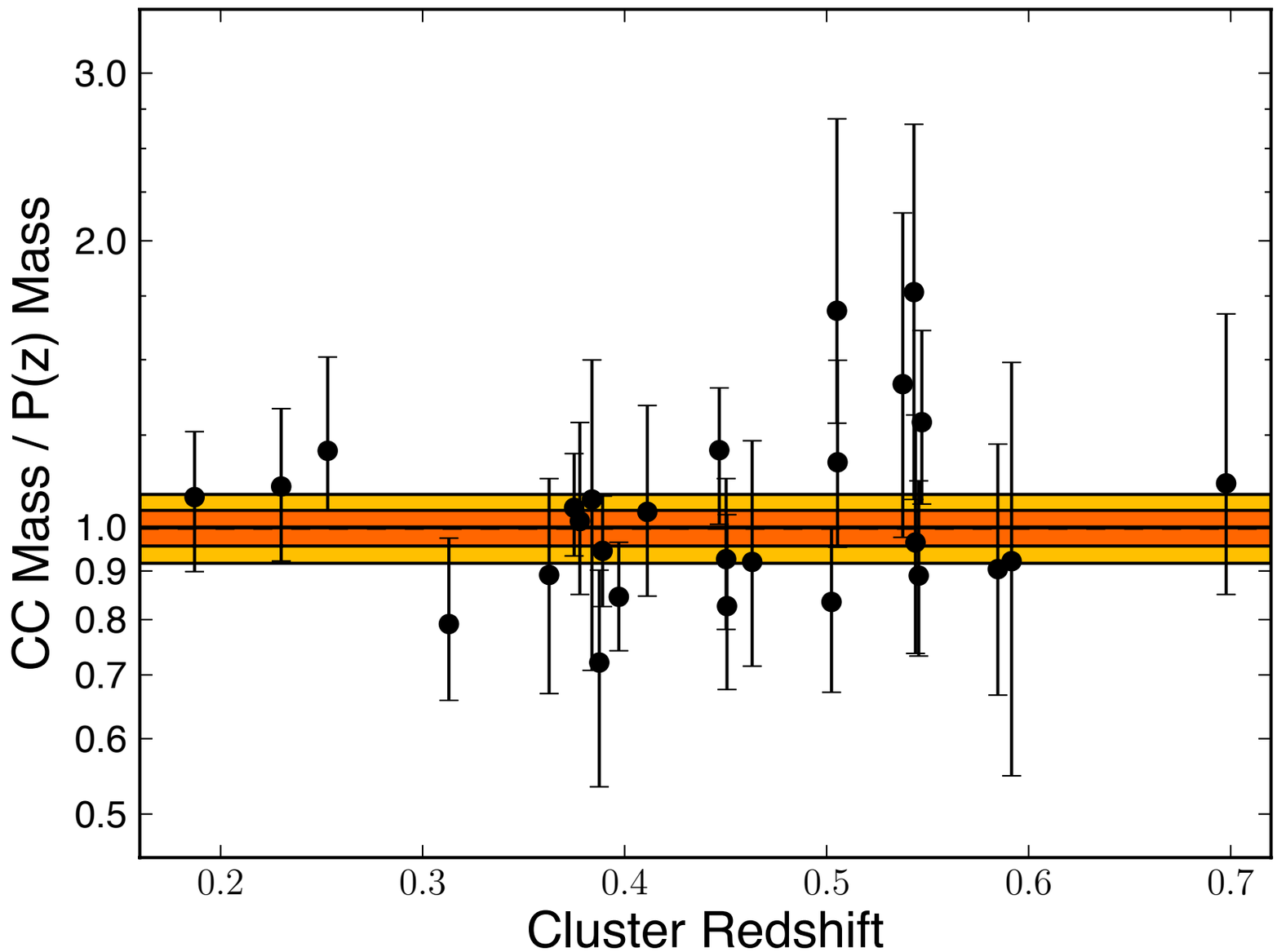


Cluster galaxy contamination?



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

Color-cuts vs. photo-z's



- only 27 / 51 clusters have photo-z's
- calibrate color-cut masses from p(z) masses
- excellent agreement: ratio 1.00 ± 0.04