Weighing the Giants:

Accurate Weak Lensing Mass Measurements for Cosmological Cluster Surveys

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Dark Cosmology Centre

IACHEC, May 14, 2014

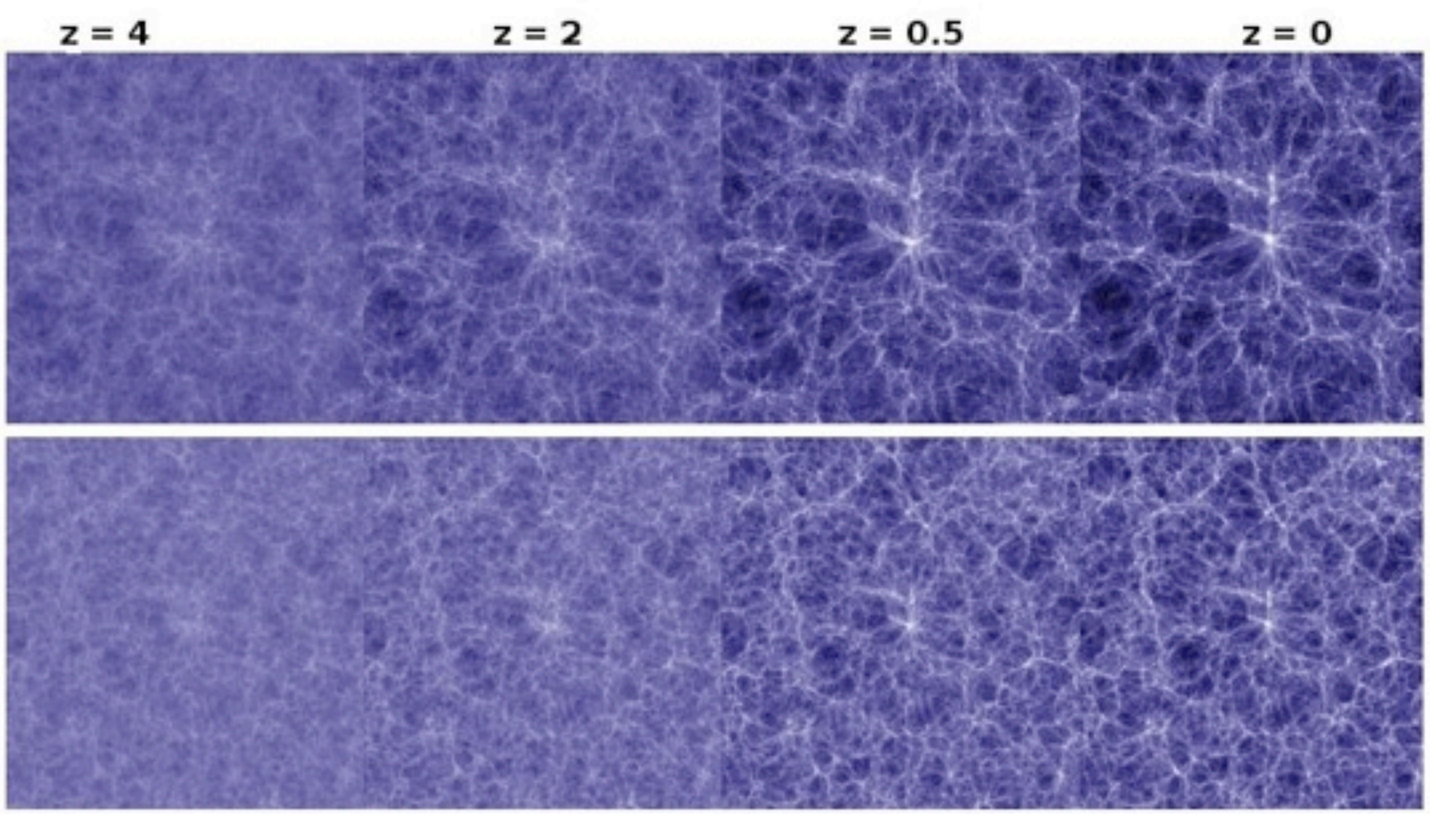
Hello !

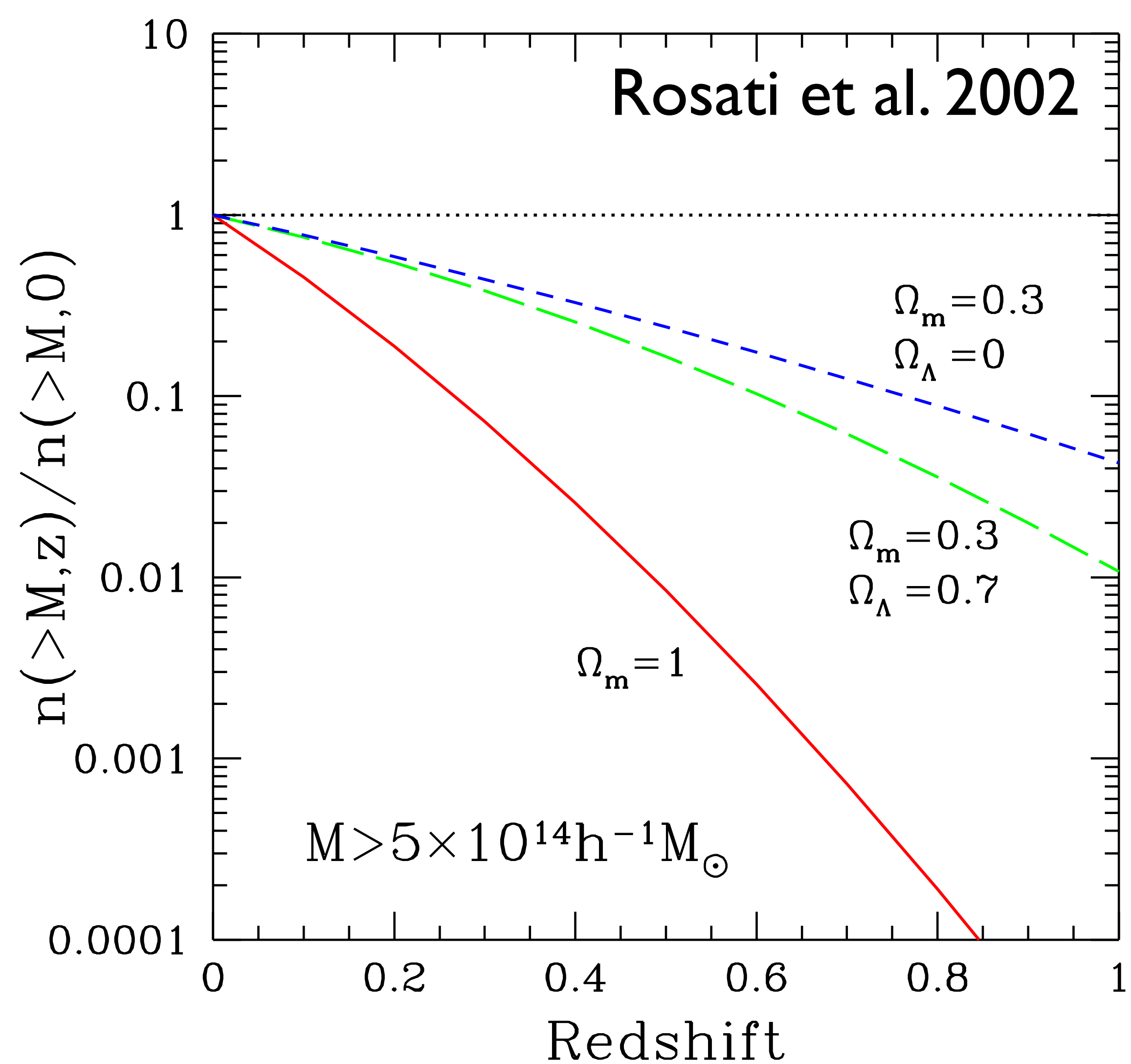
Tycho Brahe: first truly observational cosmologist

Brahe program at DARK: to promote international collaborations in cosmology

The cluster mass function

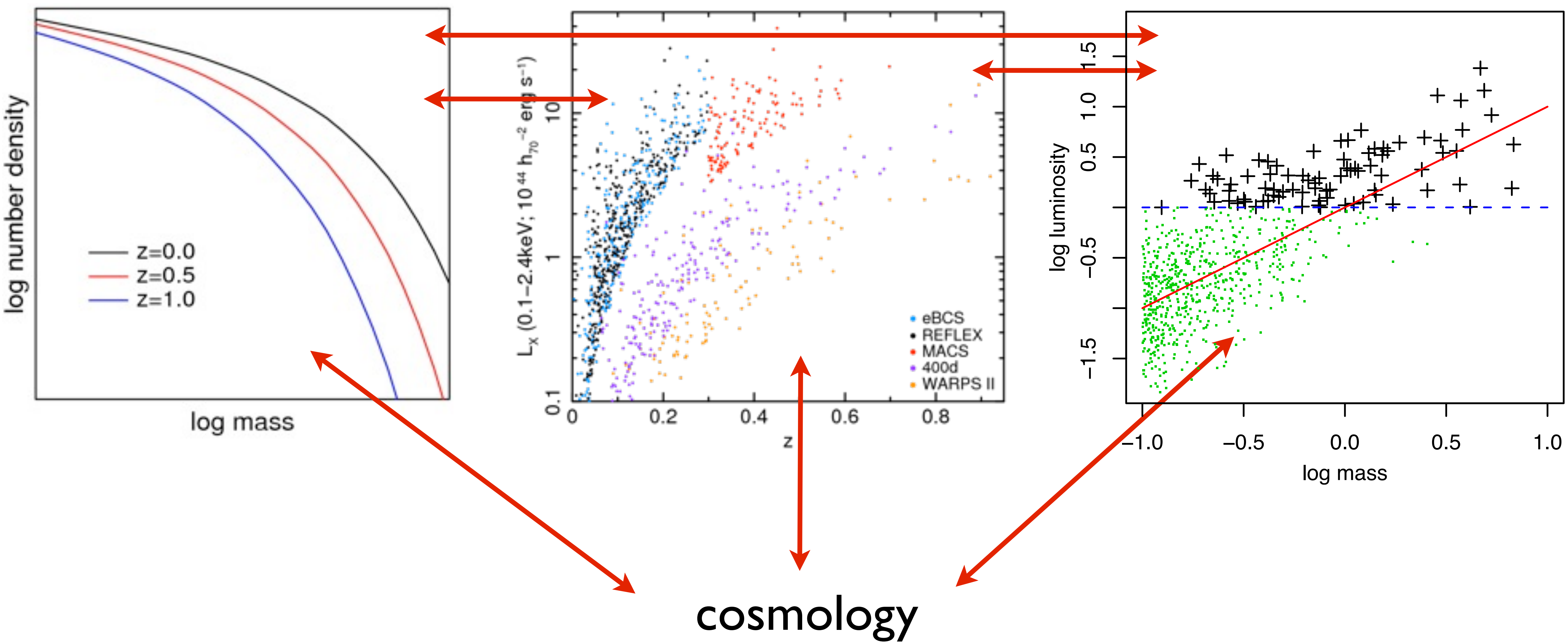
- growth of structure dominated by gravity and dark matter
  - can be well predicted by cosmological N-body simulations
  - number of gravitationally bound halos (with mass M, at redshift z) sensitive to cosmological model
- observationally: halos ↔ clusters





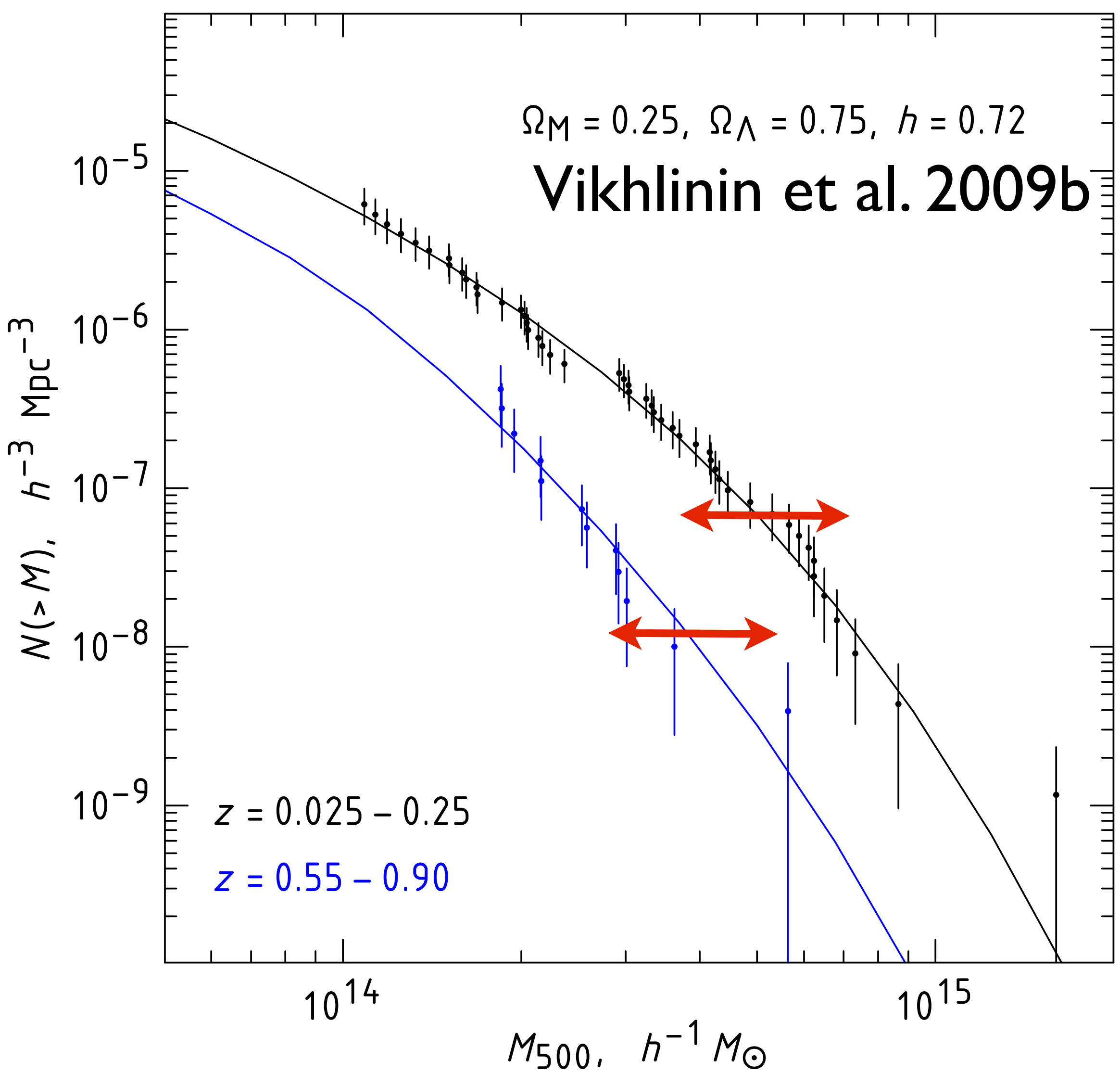
Ingredients for cluster counts cosmology

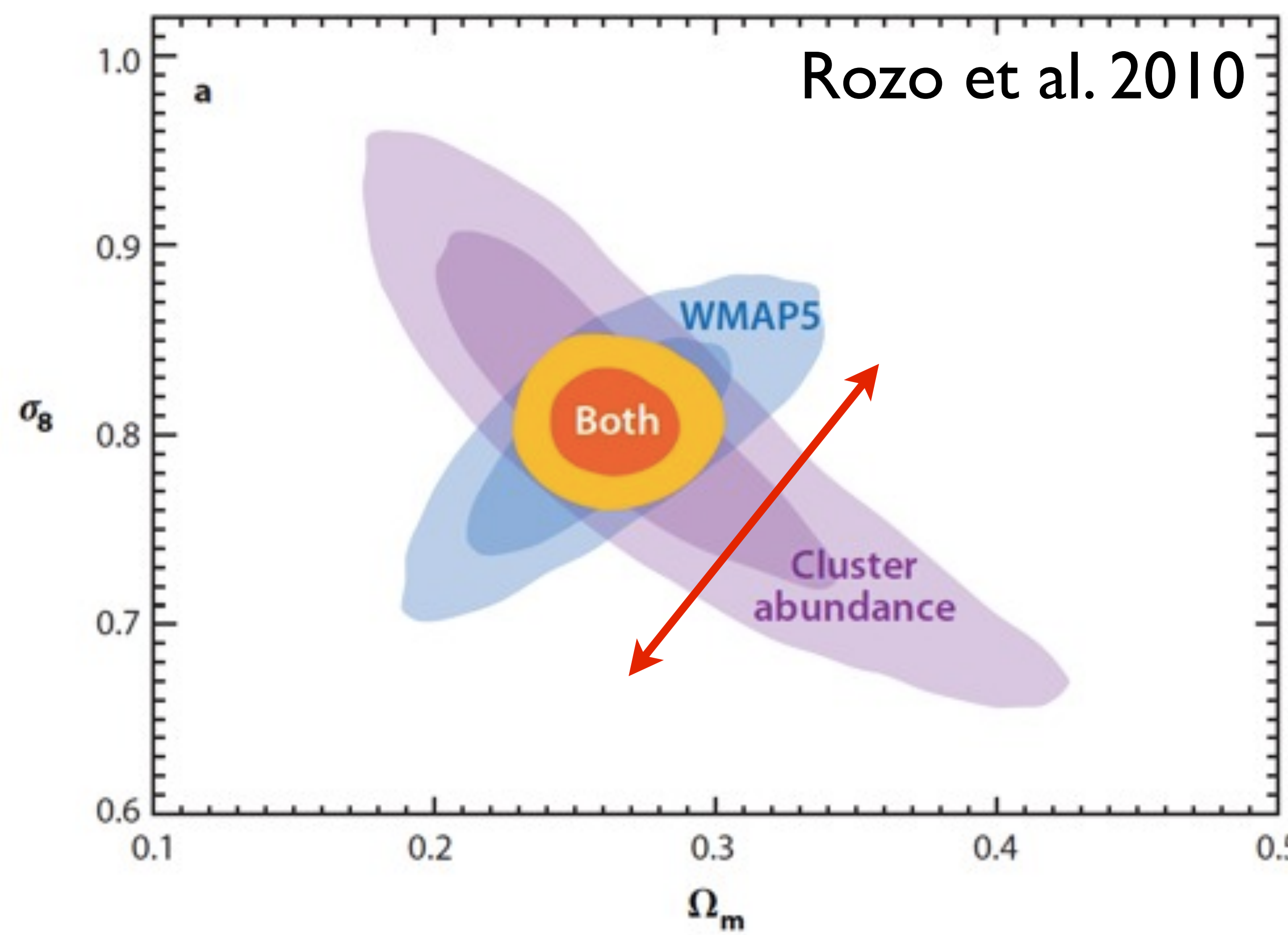
1. prediction for halo mass function
2. cluster survey with well understood selection function
3. relation between survey observable and cluster mass
4. self-consistent statistical framework



Importance of the mass normalization

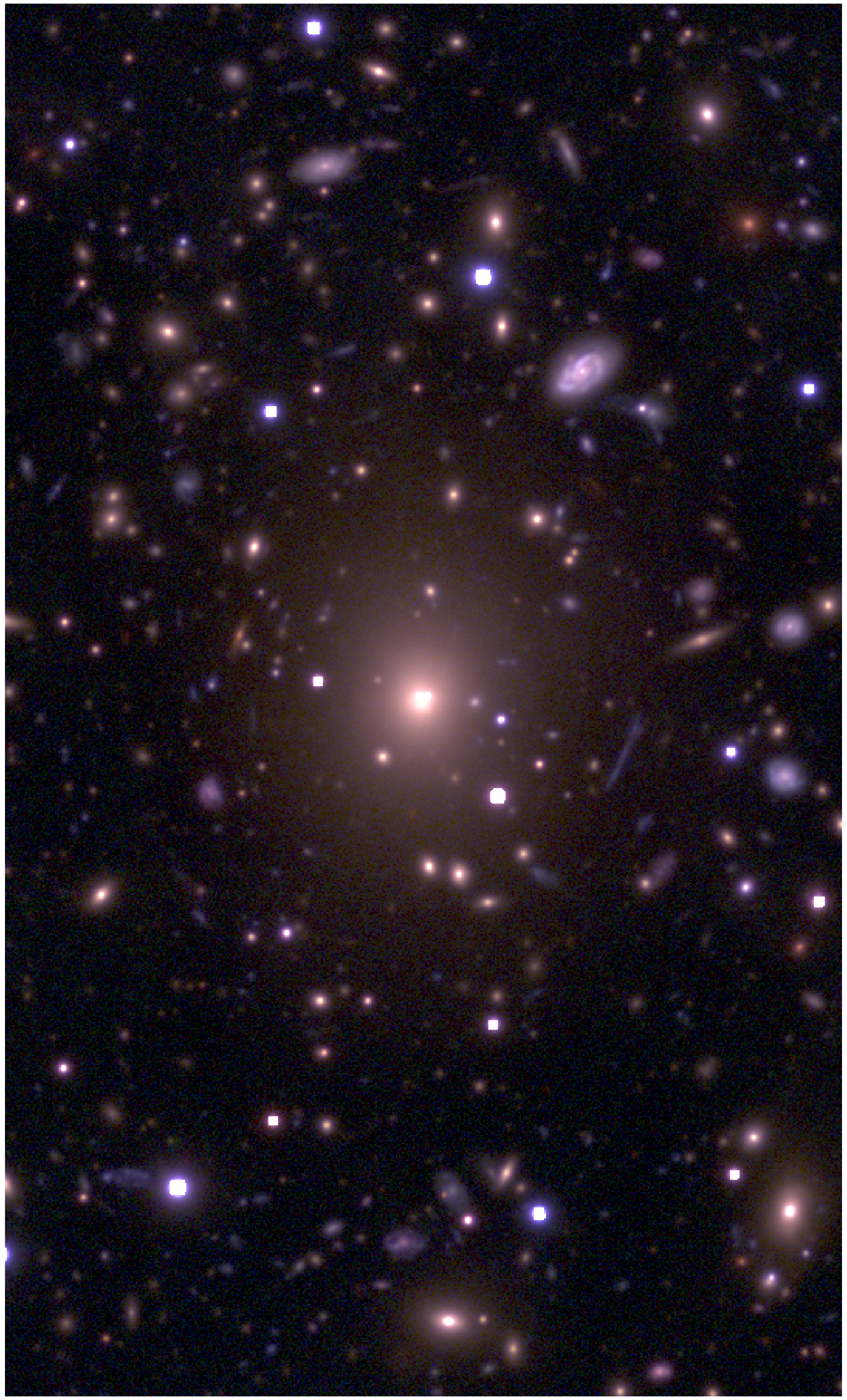
- *all cluster surveys require a mass-observable relation*





- 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%

Calibration by cluster weak lensing



(most) promising observational calibration method:

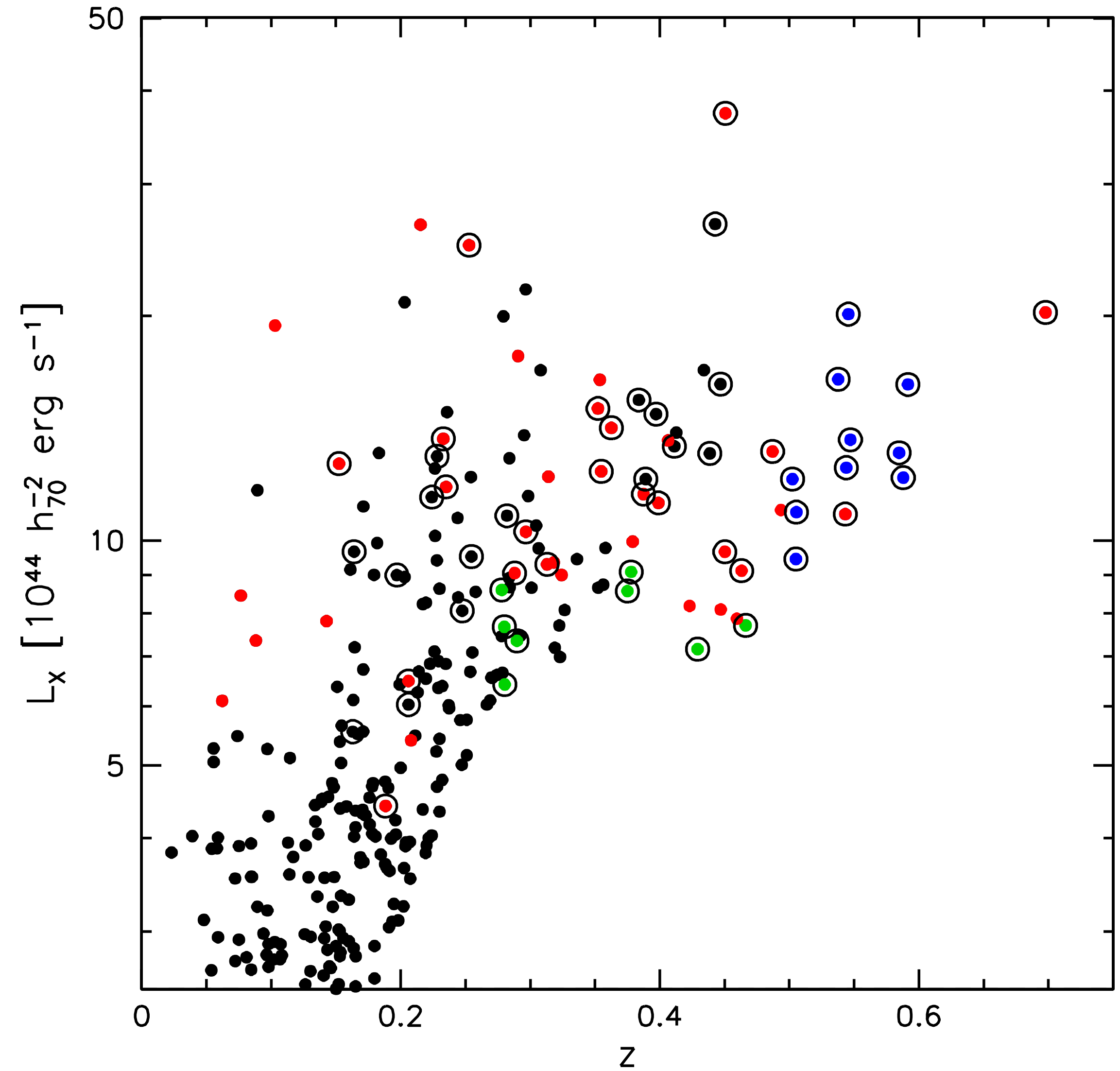
- weak lensing measures total mass
- does not require a baryonic tracer
- no assumption on dynamical state of cluster needed

- comes “for free” with weak-lensing surveys → DES, LSST, Euclid

- 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)

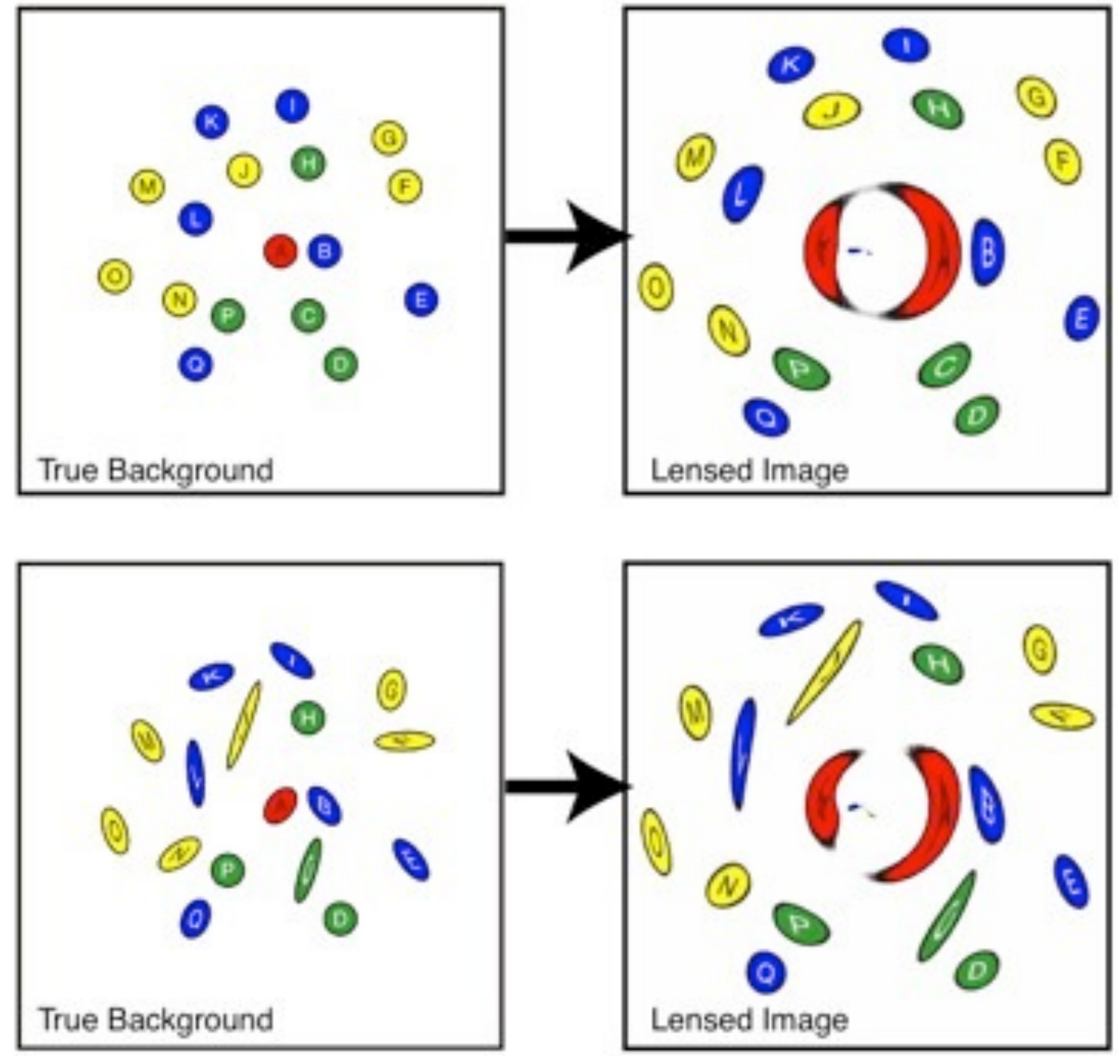
no assumption on dynamical state

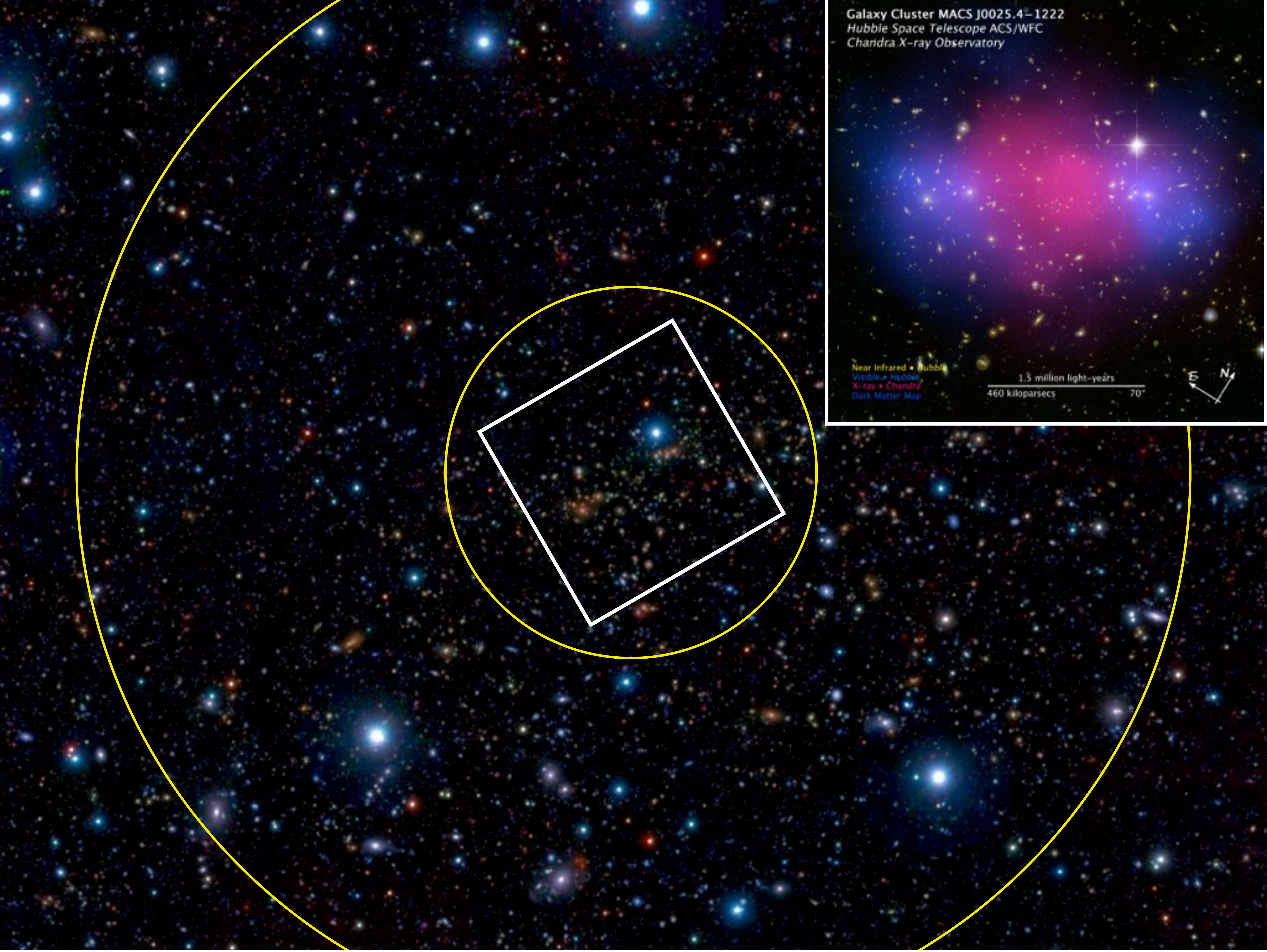
strong lensing:

- 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)



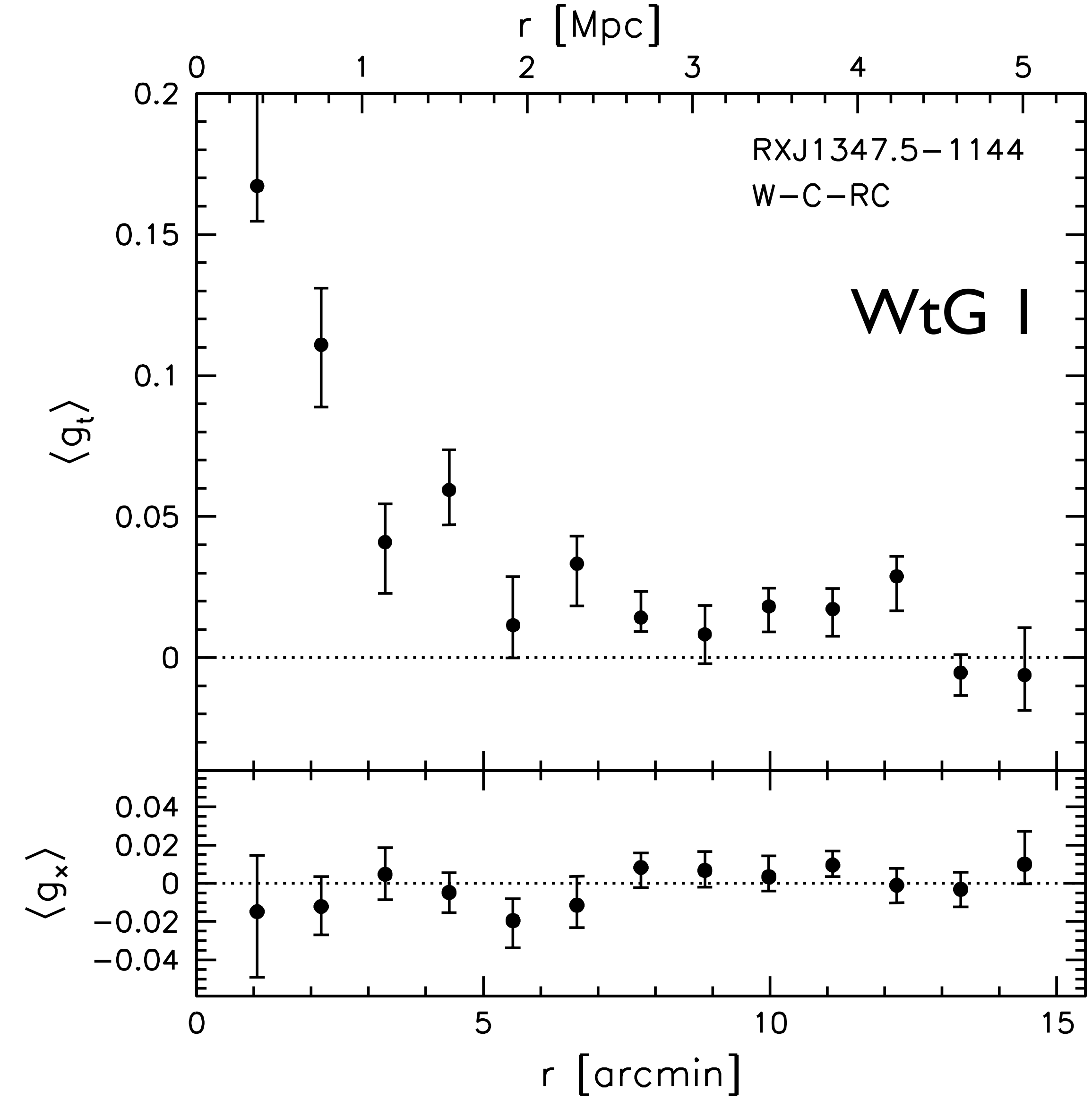


Galaxy Cluster MACS J0025.4−1222
Hubble Space Telescope ACS/WFC
Chandra X-ray Observatory
Near Infrared • Hubble
Visible • Hubble
X-ray • Chandra
Dark Matter Map
1.5 million light-years
460 kiloparsecs
70"
E
N

Ingredients for cluster mass measurements

Shear induced on background galaxy depends on:

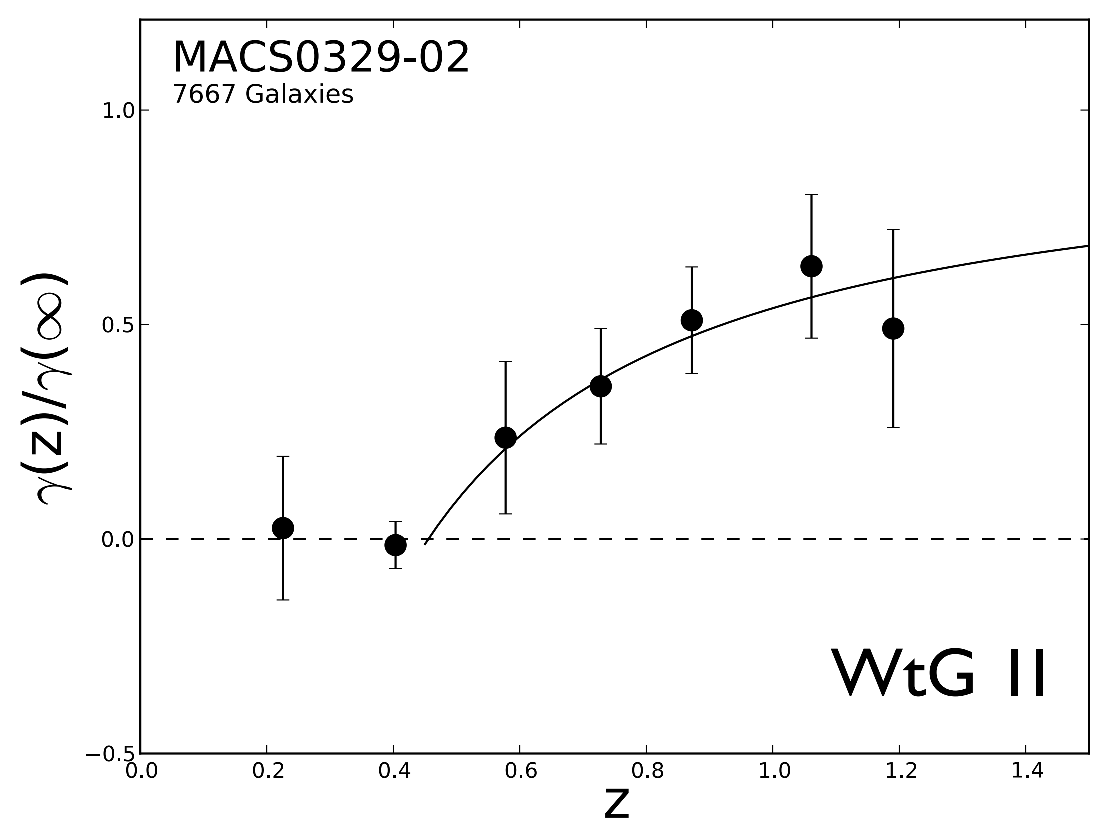
- cluster mass (distribution)
- redshift



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

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

STEP (Multiplicative Shear Bias Cor, STEP PSF Mismatch)

$\sqrt{N}$ (Triaxiality & LOS Structure, P(z) Method)

NFW? (Profile Uncertainty)

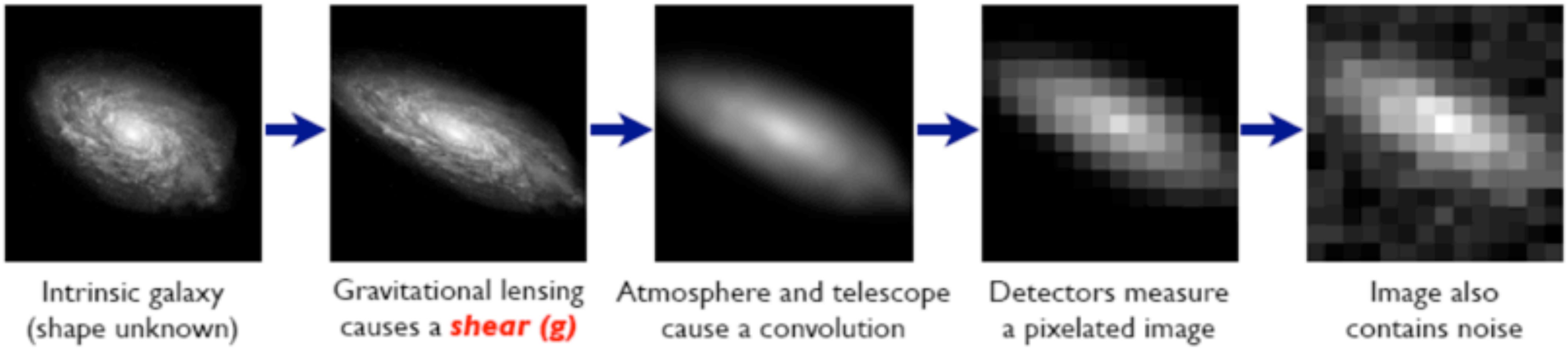
p(z) bias (Simulated Photo-z Bias)

~ factor x2 improvement in precision !

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

(I) 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

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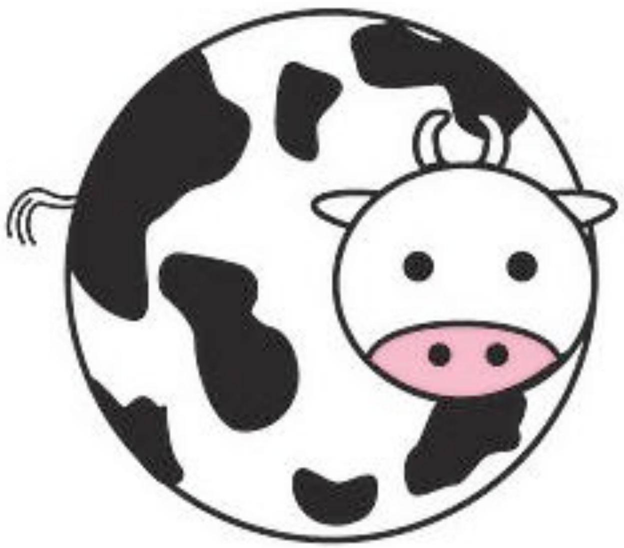

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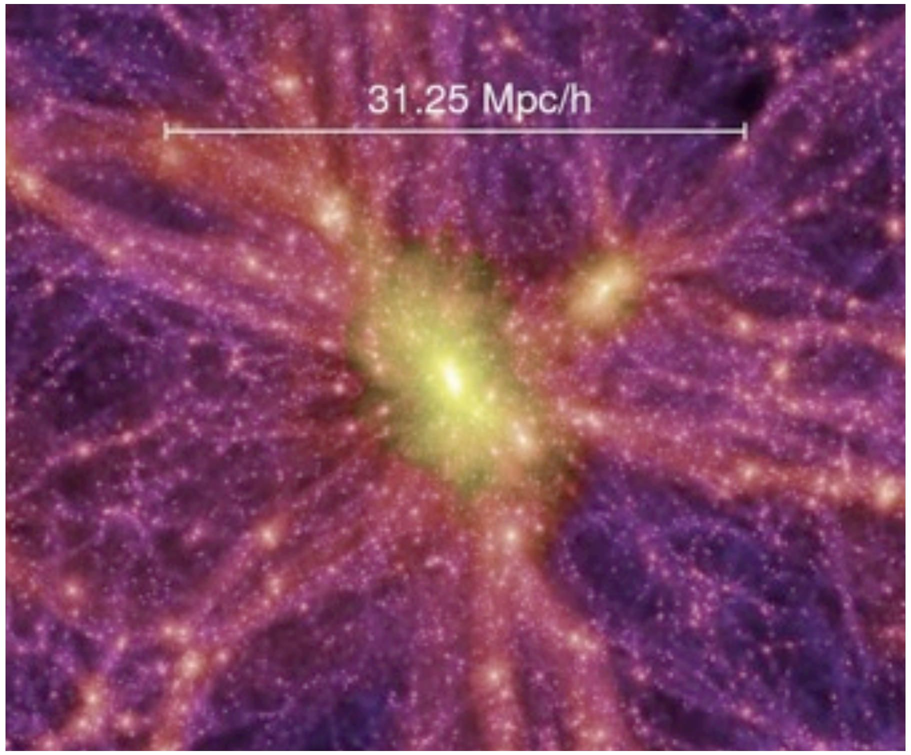
- measured (3D) mass depends on cluster triaxiality / orientation / substructure, structure along LOS

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



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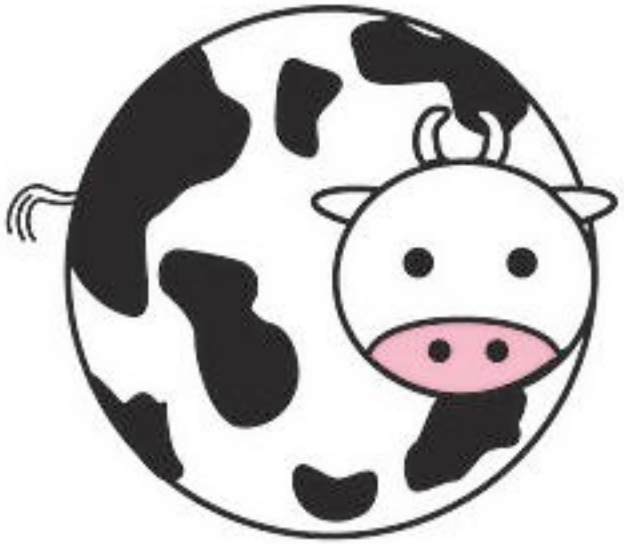

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- (3D) lensing masses have **inherent, irreducible scatter** of $\gtrsim$20% (ground-based: scatter from shape noise also ~20% ⇒ total scatter: ~30%)
- fitting NFW-profile within ~ R_{vir} : average mass nearly unbiased

Becker&Kravtsov 2011

WtG: fit range 0.75 - 3 Mpc

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

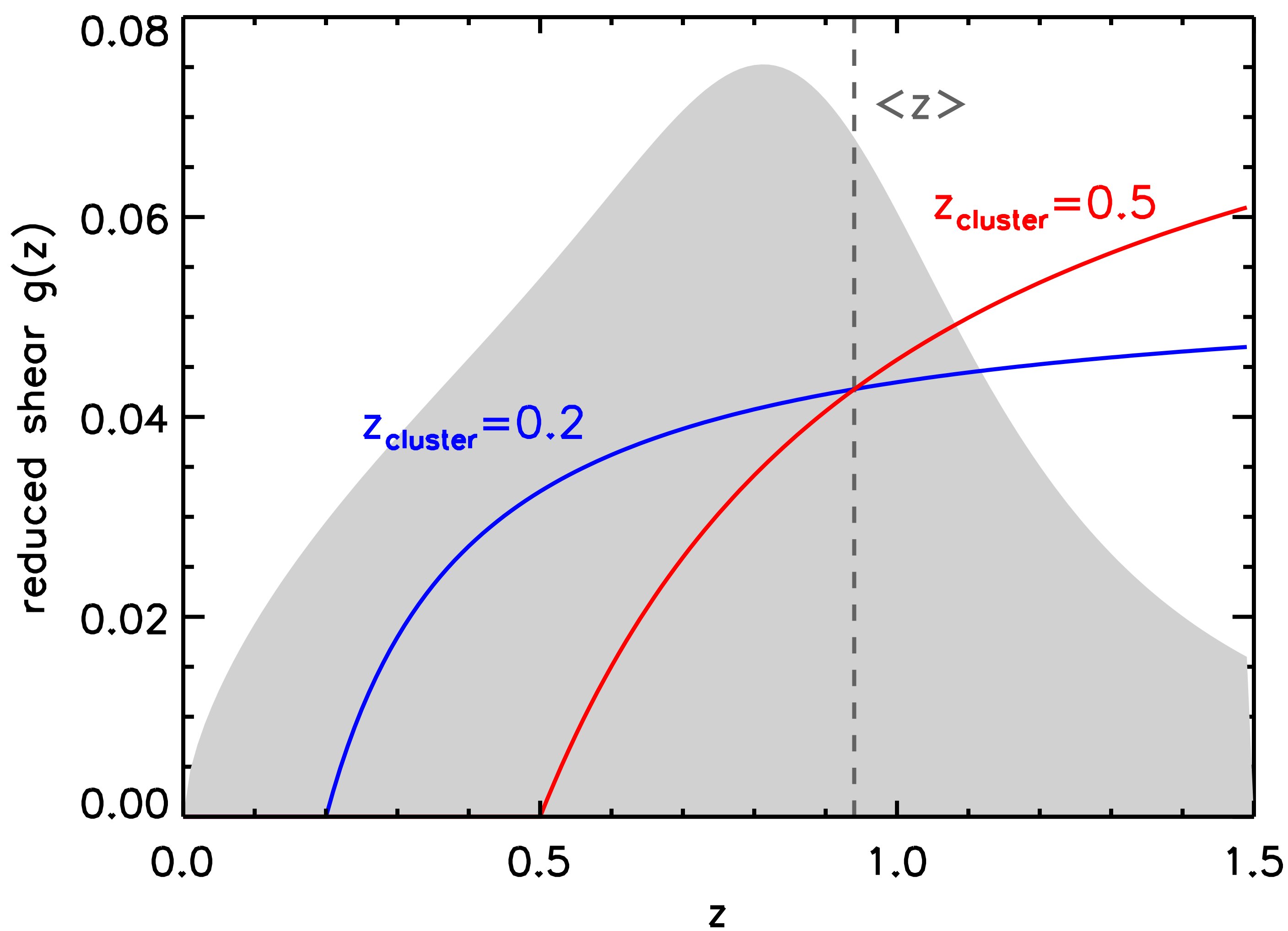
➡ need large cluster samples

➡ 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



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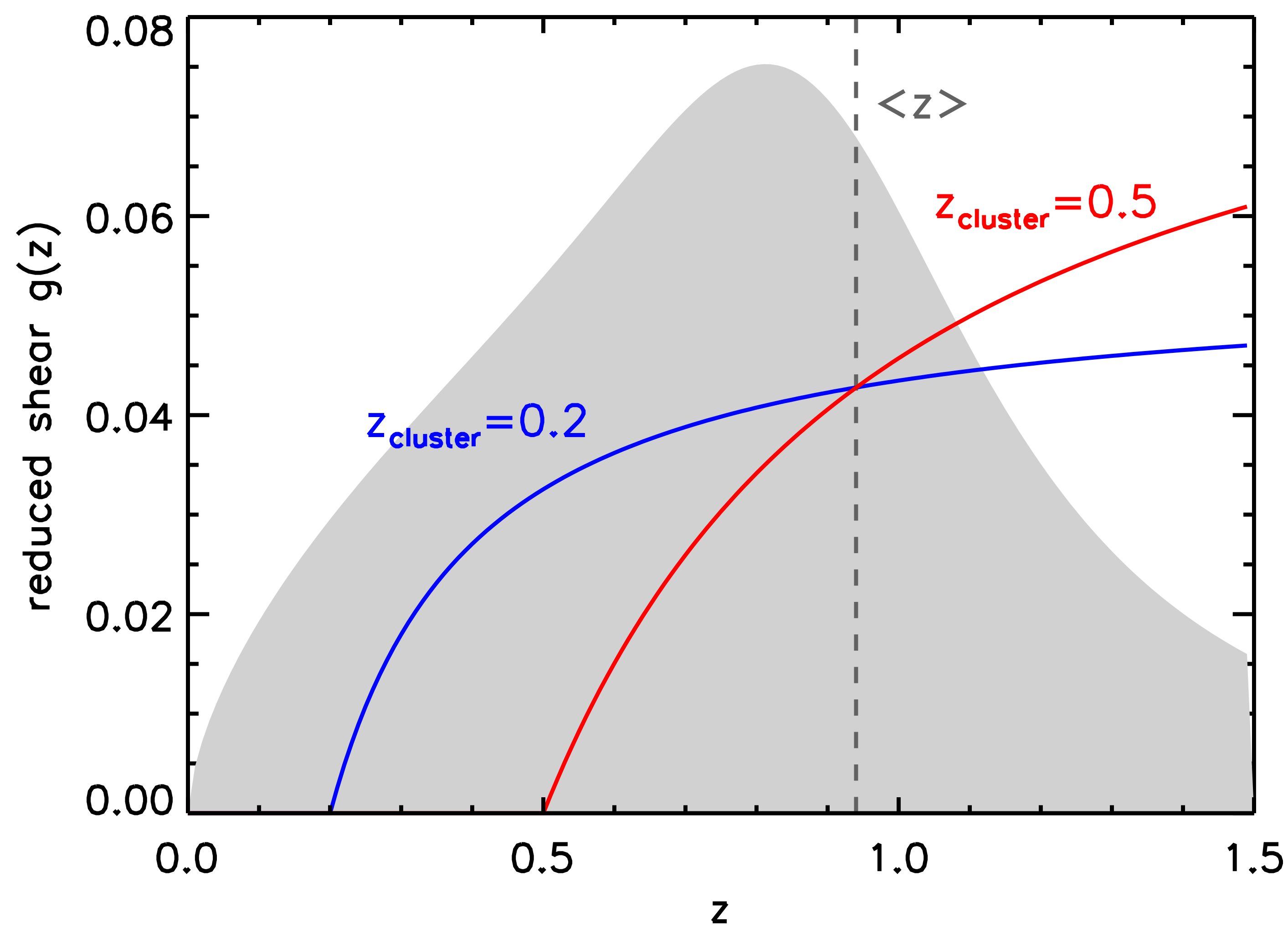
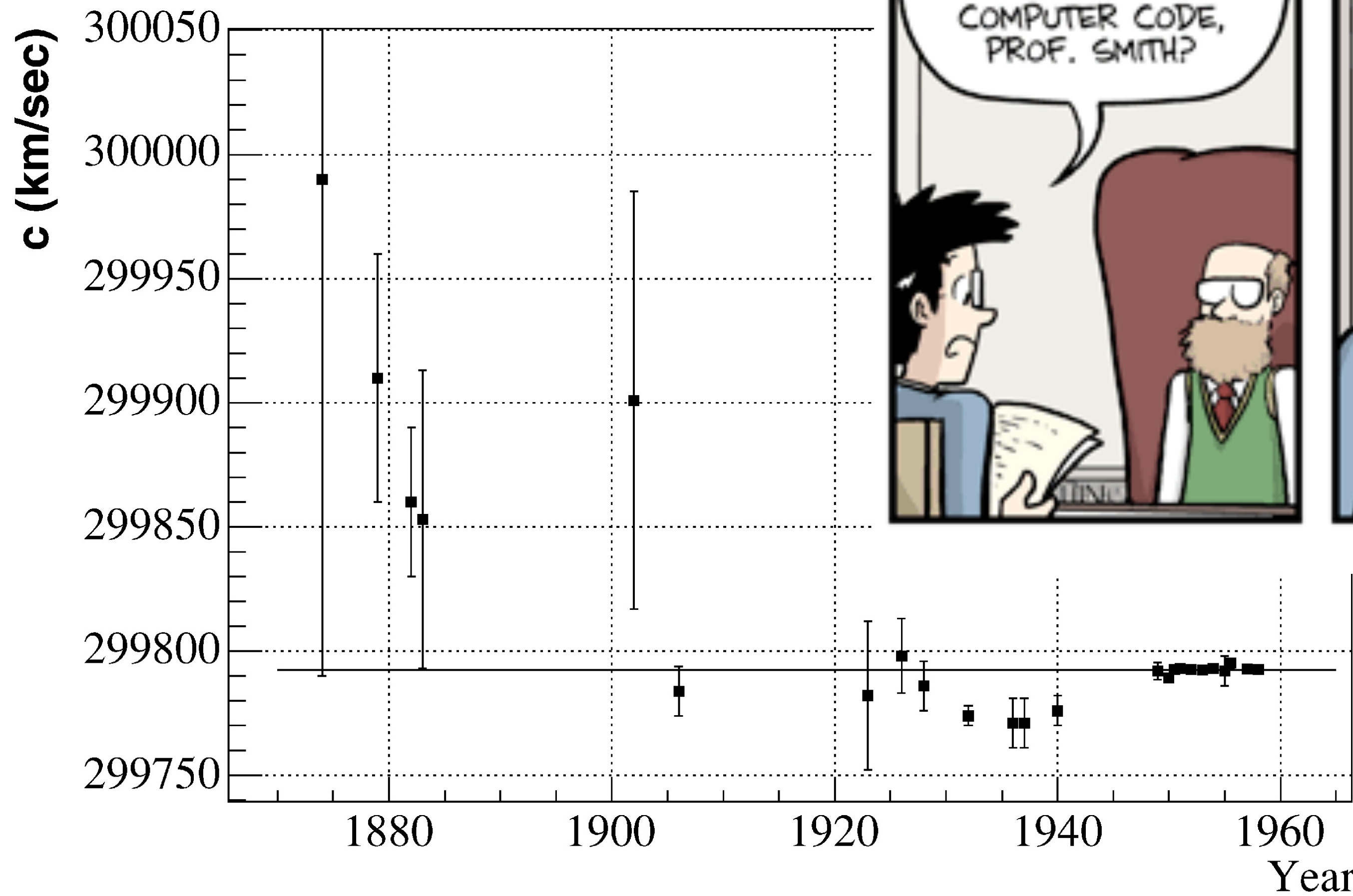
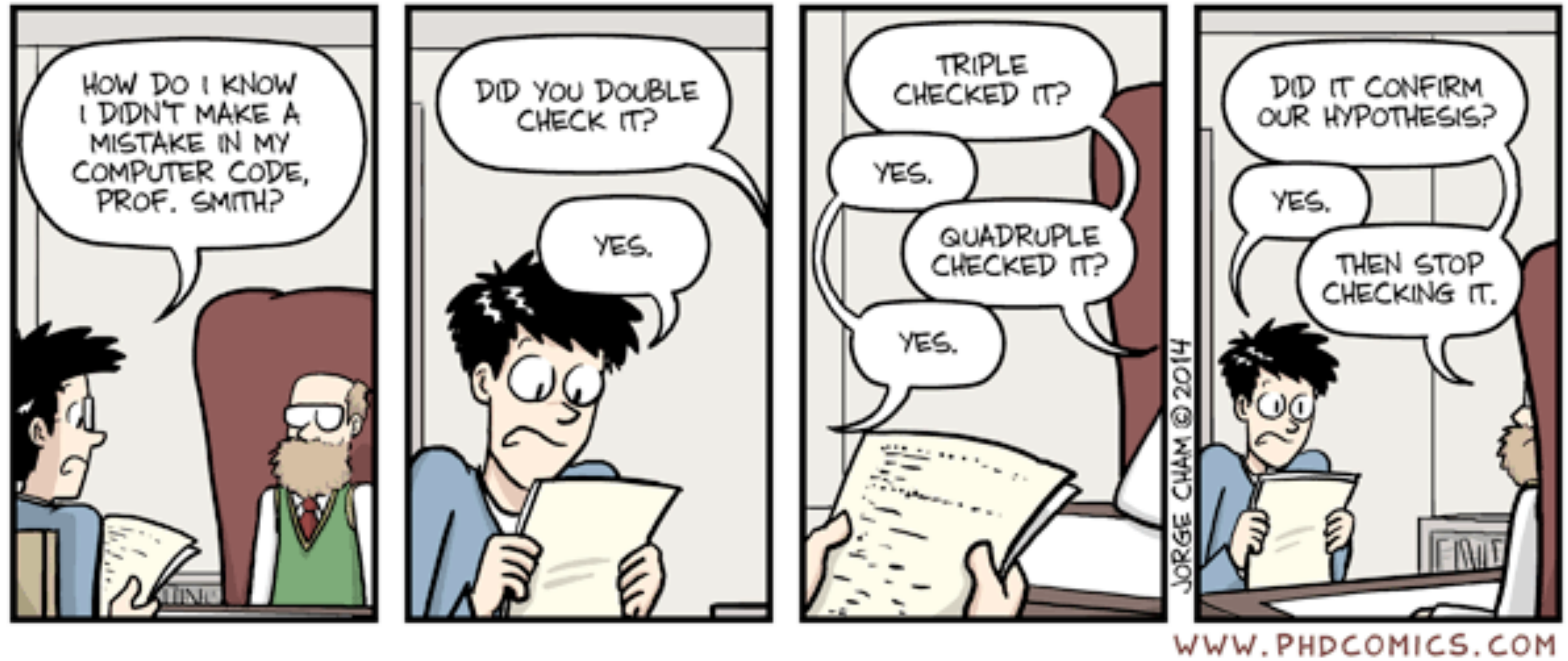


- previous works used only 1-3 filter observations
  - "color-cut" method: assume an effective redshift for all galaxies
  - strong assumptions on contamination by cluster galaxies
  - *percent-level control of systematics difficult (esp. at $z>0.4$)*

➡ use photometric redshifts instead

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*

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

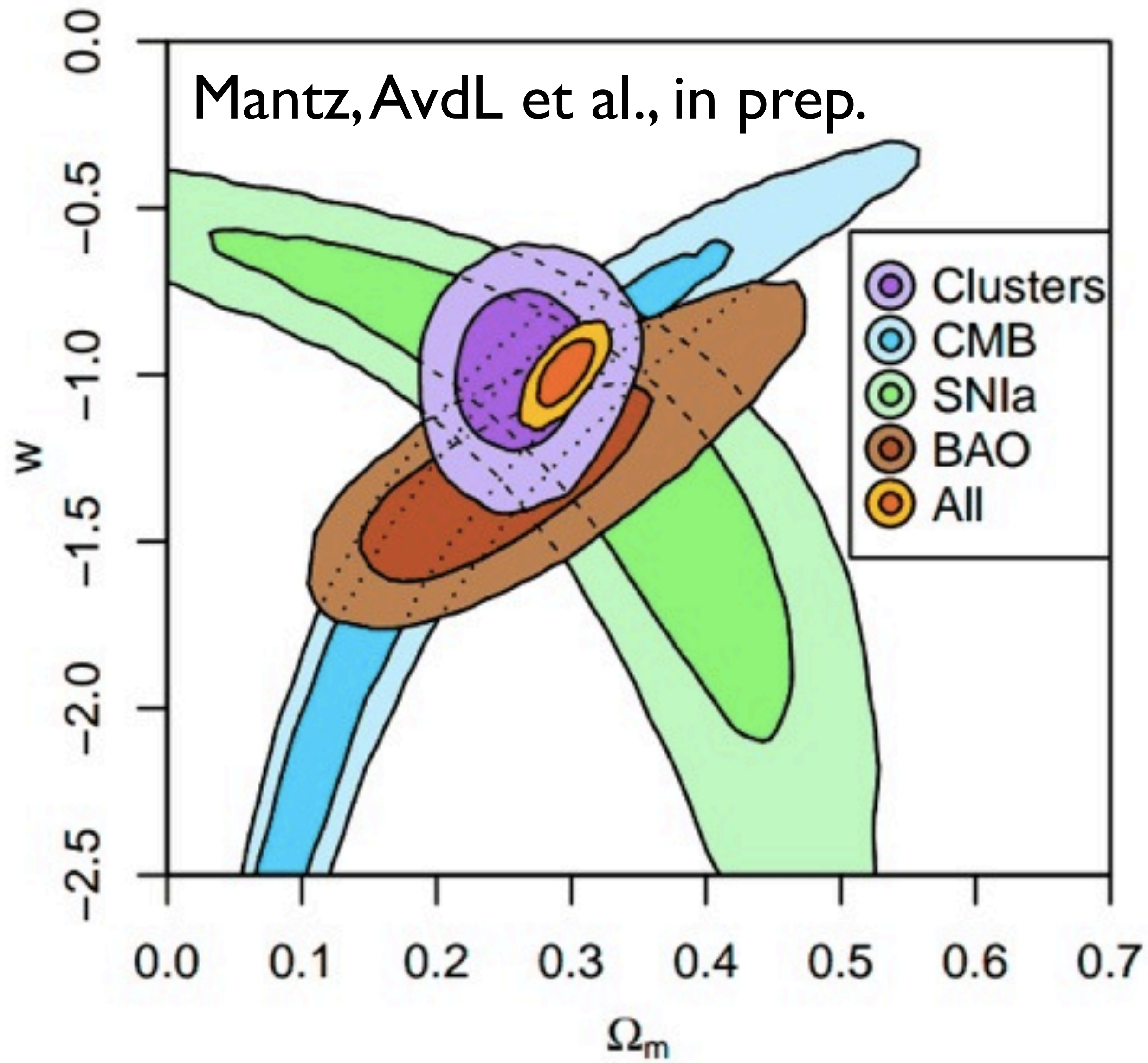
Cosmology and Astrophysics from Relaxed Galaxy Clusters II: Cosmological Constraints

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



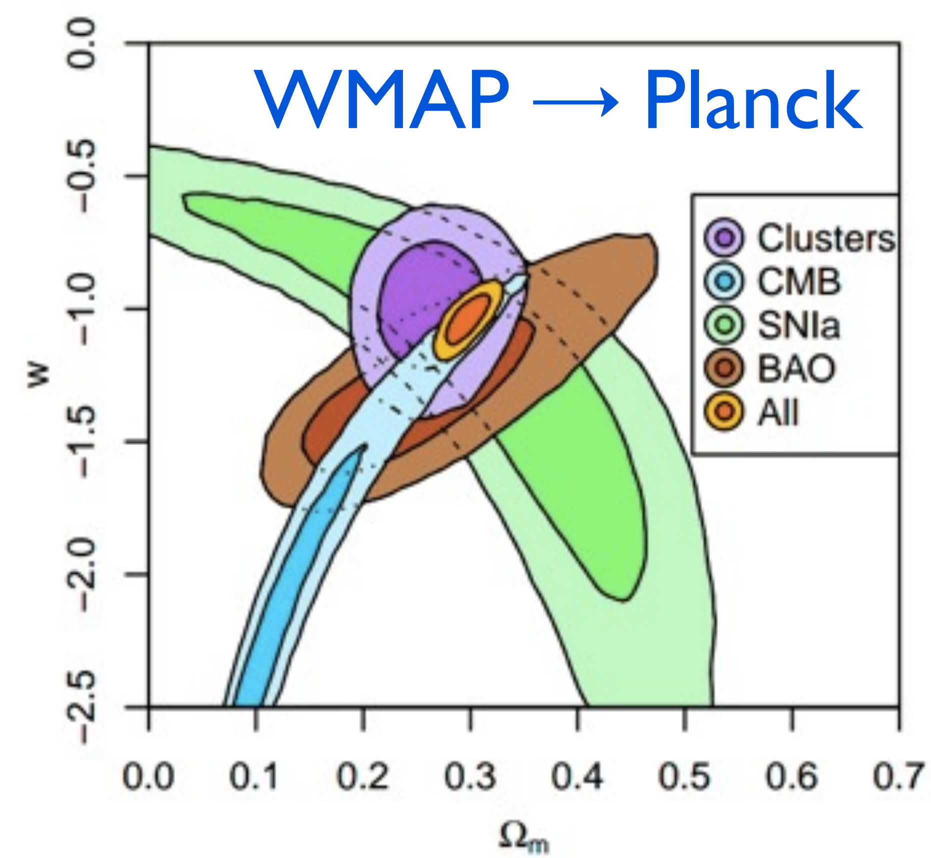
clusters

CMB: WMAP, SPT, ACT

SNIa: Union 2.1

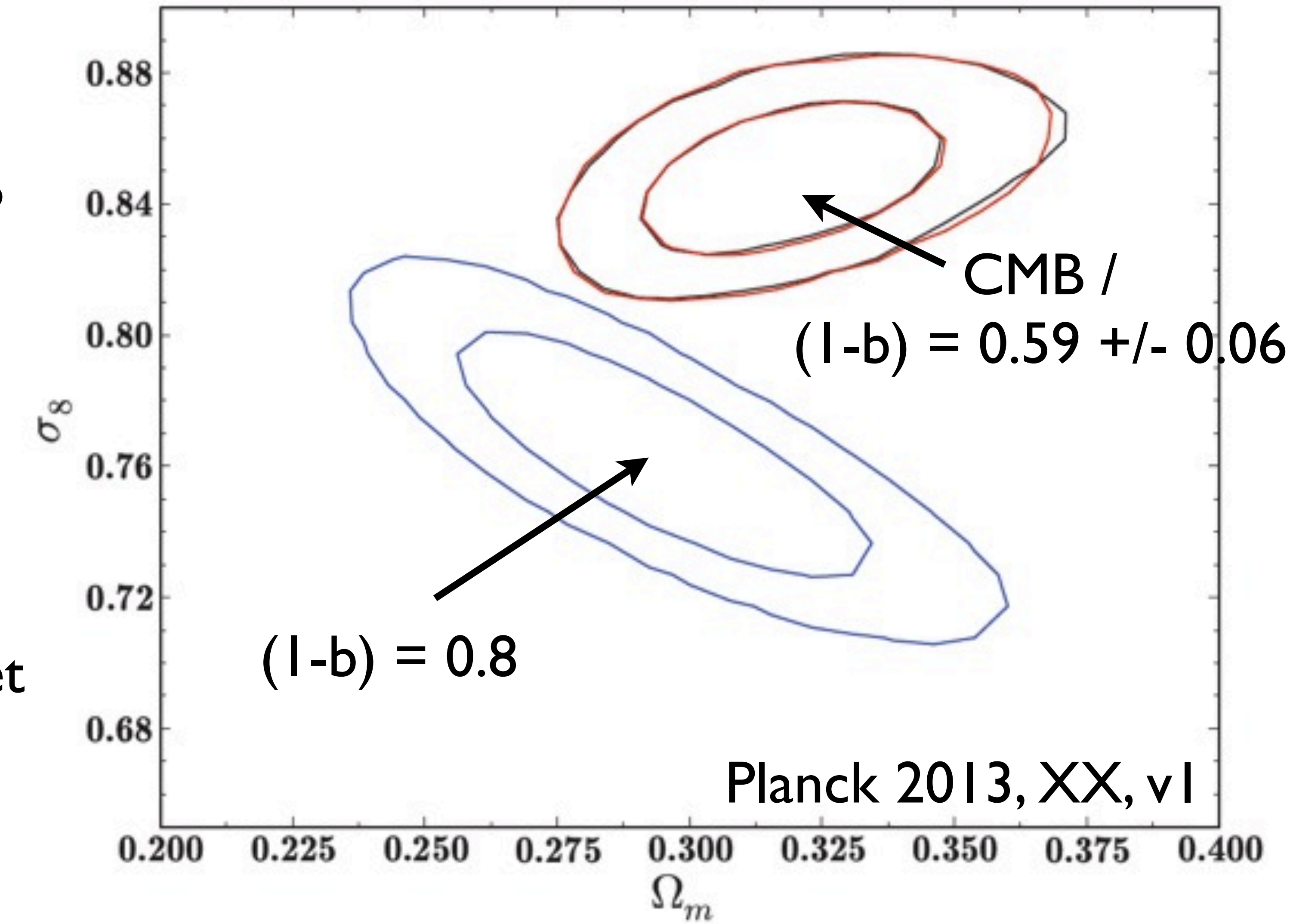
BAO: 6df, SDSS, BOSS

combined



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



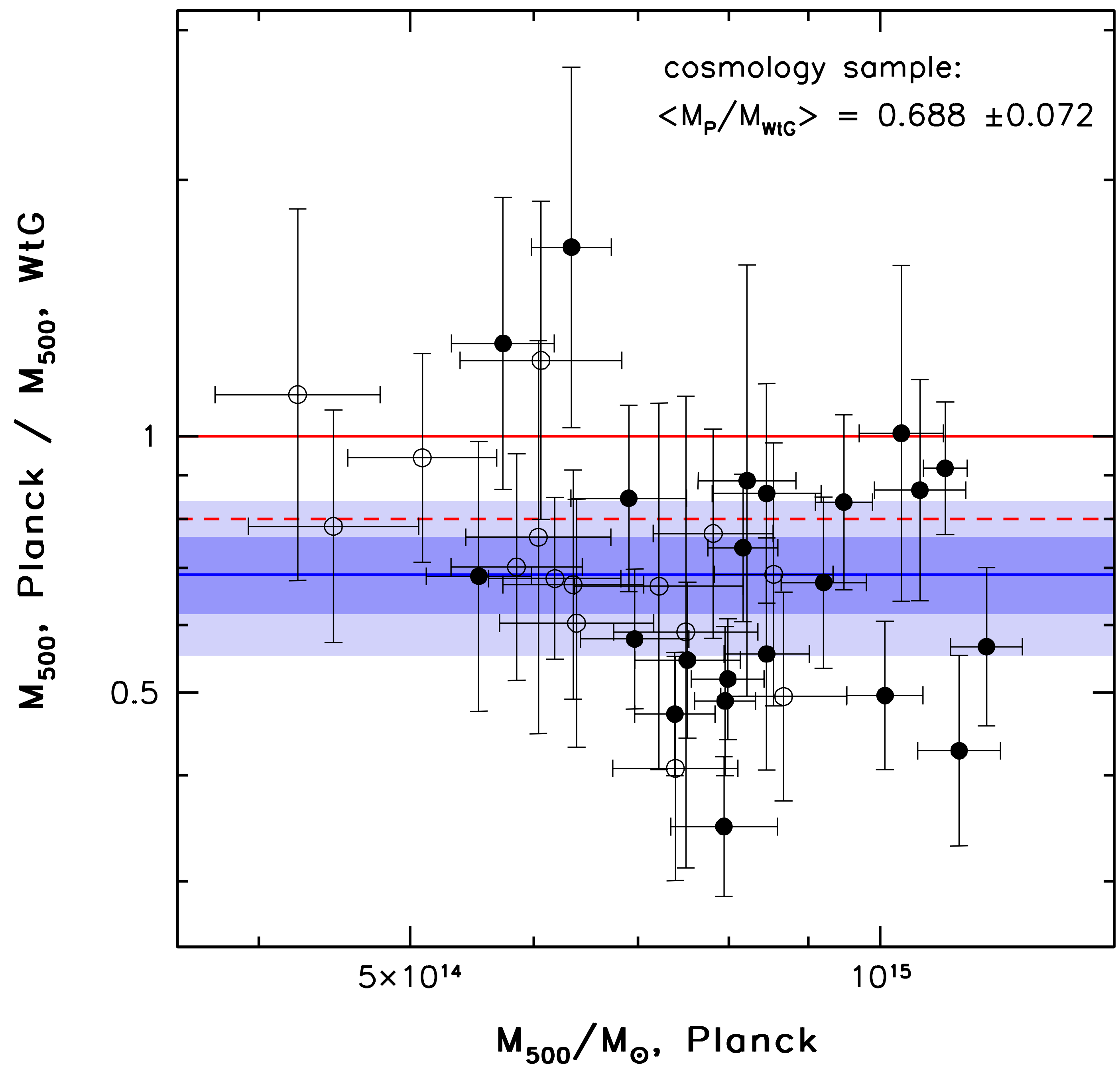
suggested explanations:

- 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

- Planck and RASS both all-sky surveys of the most massive clusters
  → good overlap

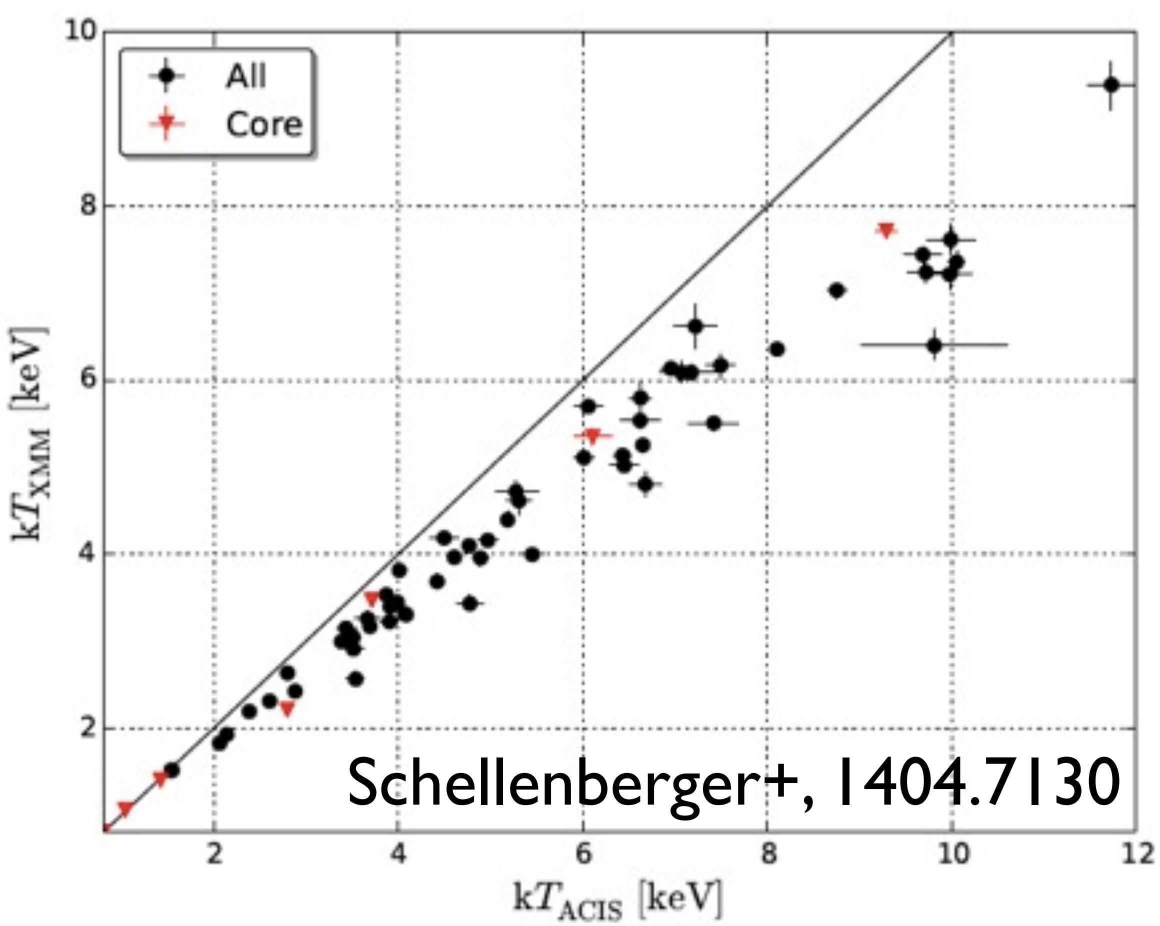
- 38 clusters in Planck sample part of WtG
- 22/38 part of Planck cosmology sample
- comparison of Planck and WtG mass estimates: $M_{Planck} / M_{WtG} = 0.69 \pm 0.07$

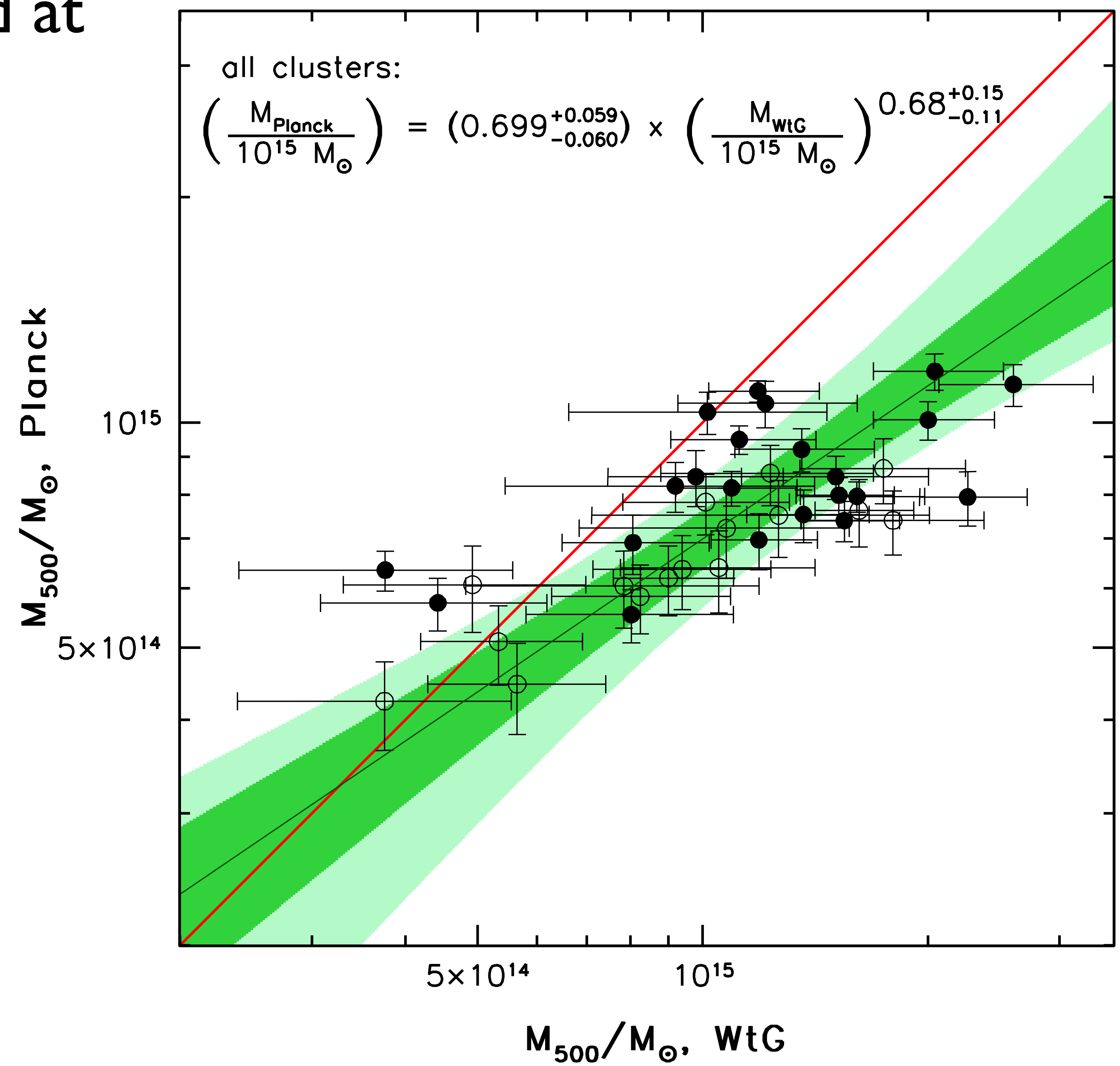


AvdL et al., arxiv:1402.2670

WtG mass calibration for Planck

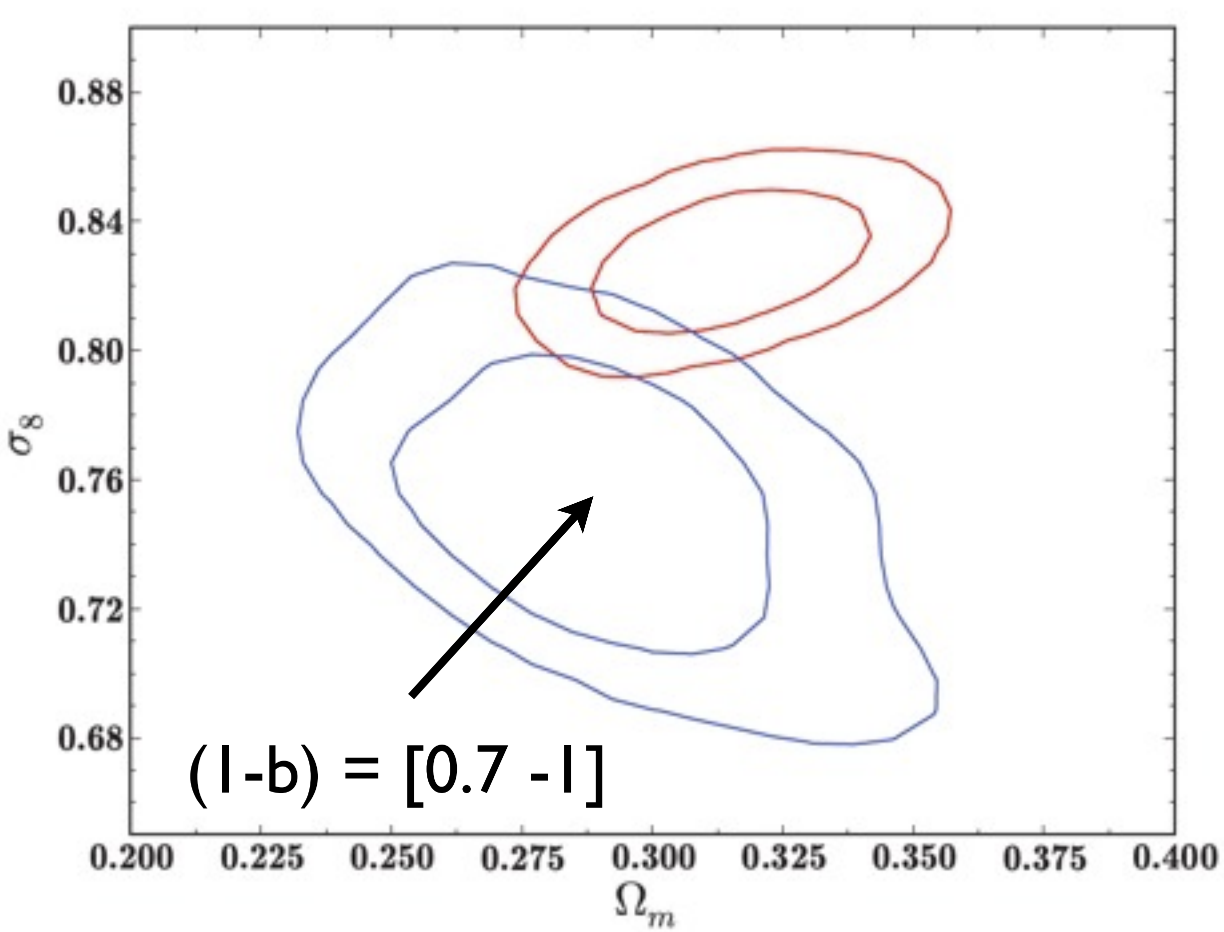
- is there a mass-dependent bias?
- no mass-dependence disfavored at 95% confidence level
- if it's real, what causes it?
- lensing - unlikely, based on simulations
- X-ray mass calibration?

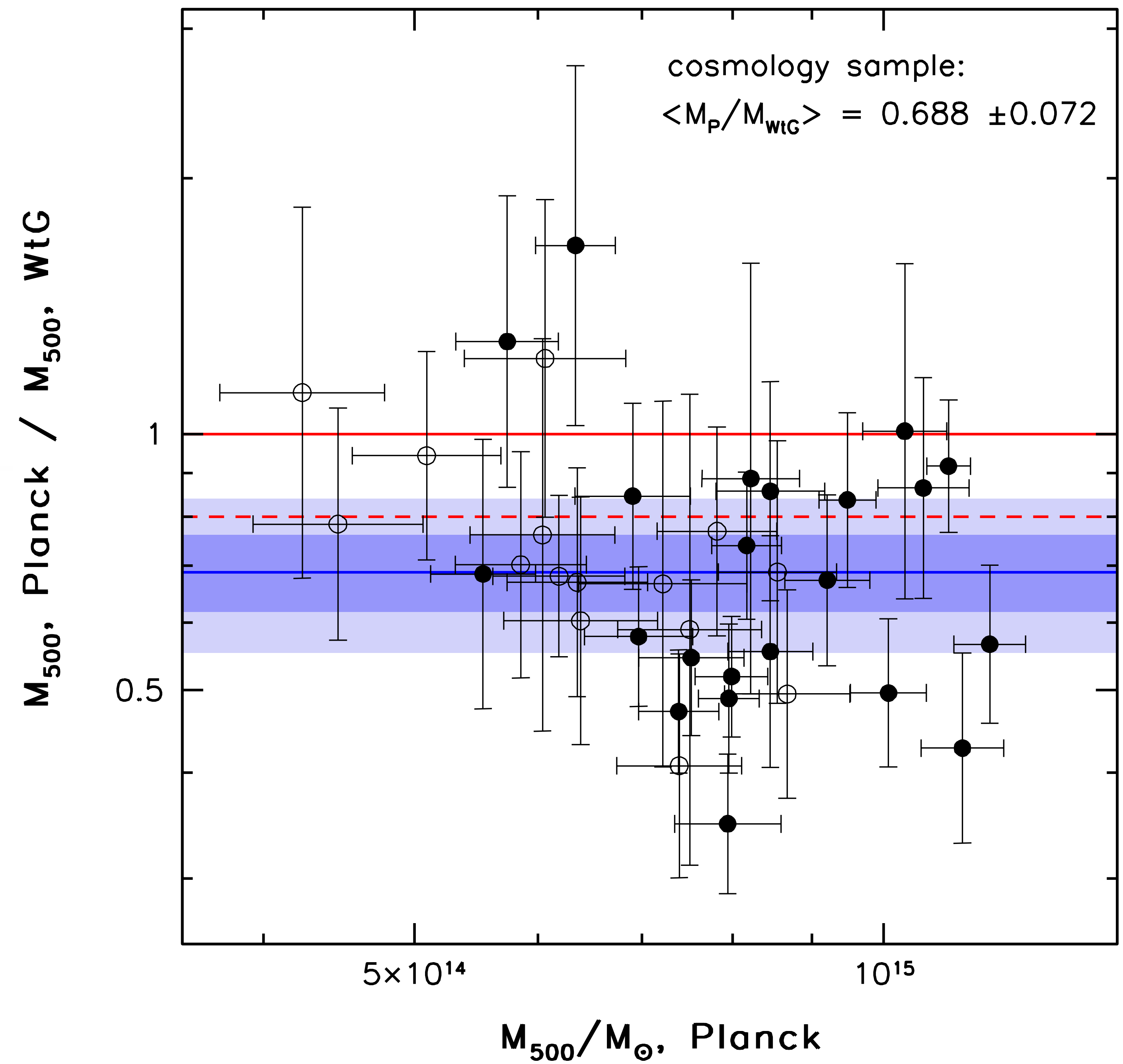




WtG mass calibration for Planck

- marginalizing over mass uncertainty alleviates tension
- adopting WtG mass calibration would further reduce tension, eliminate need for "new physics"



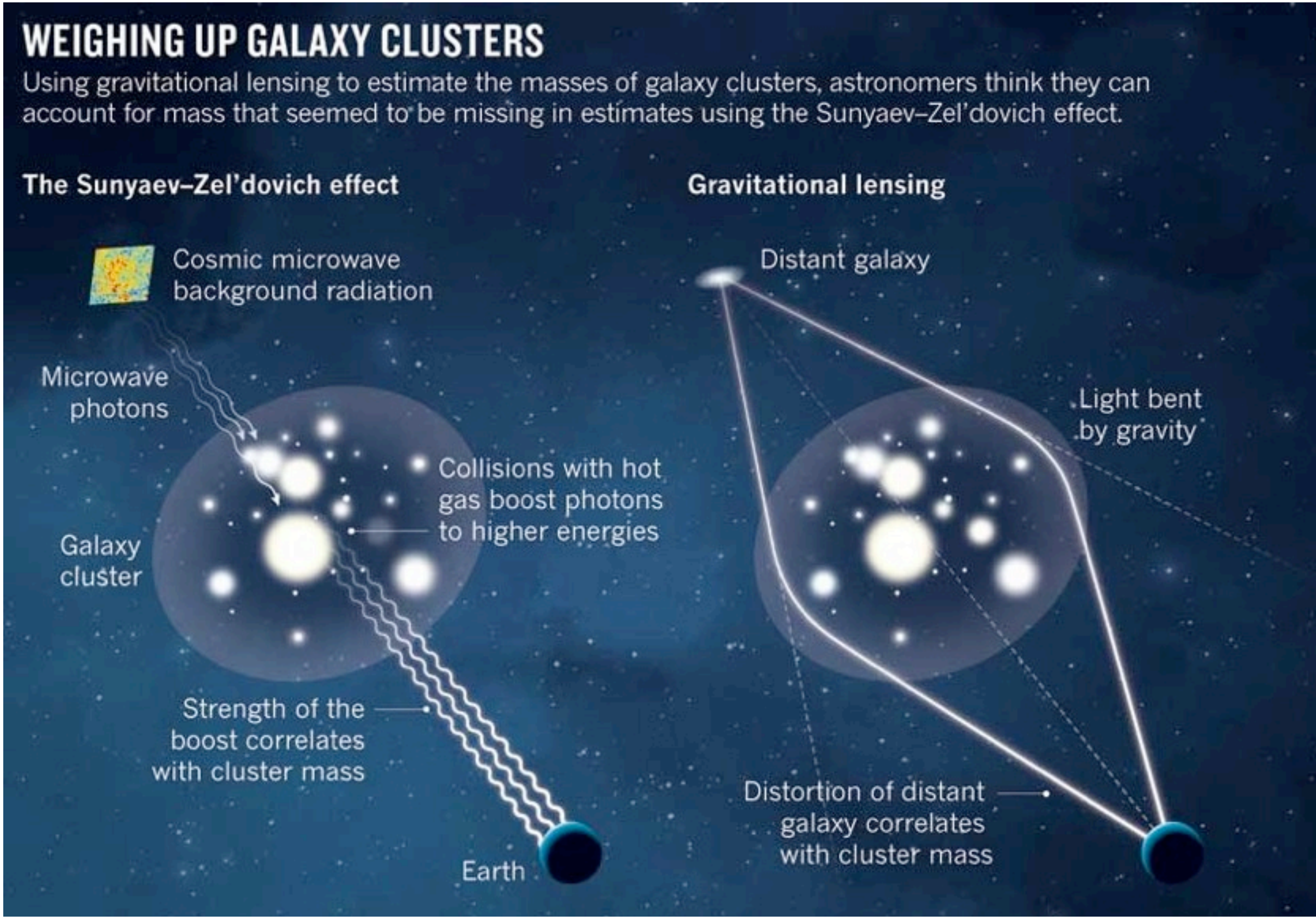


Missing galaxy mass found

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

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

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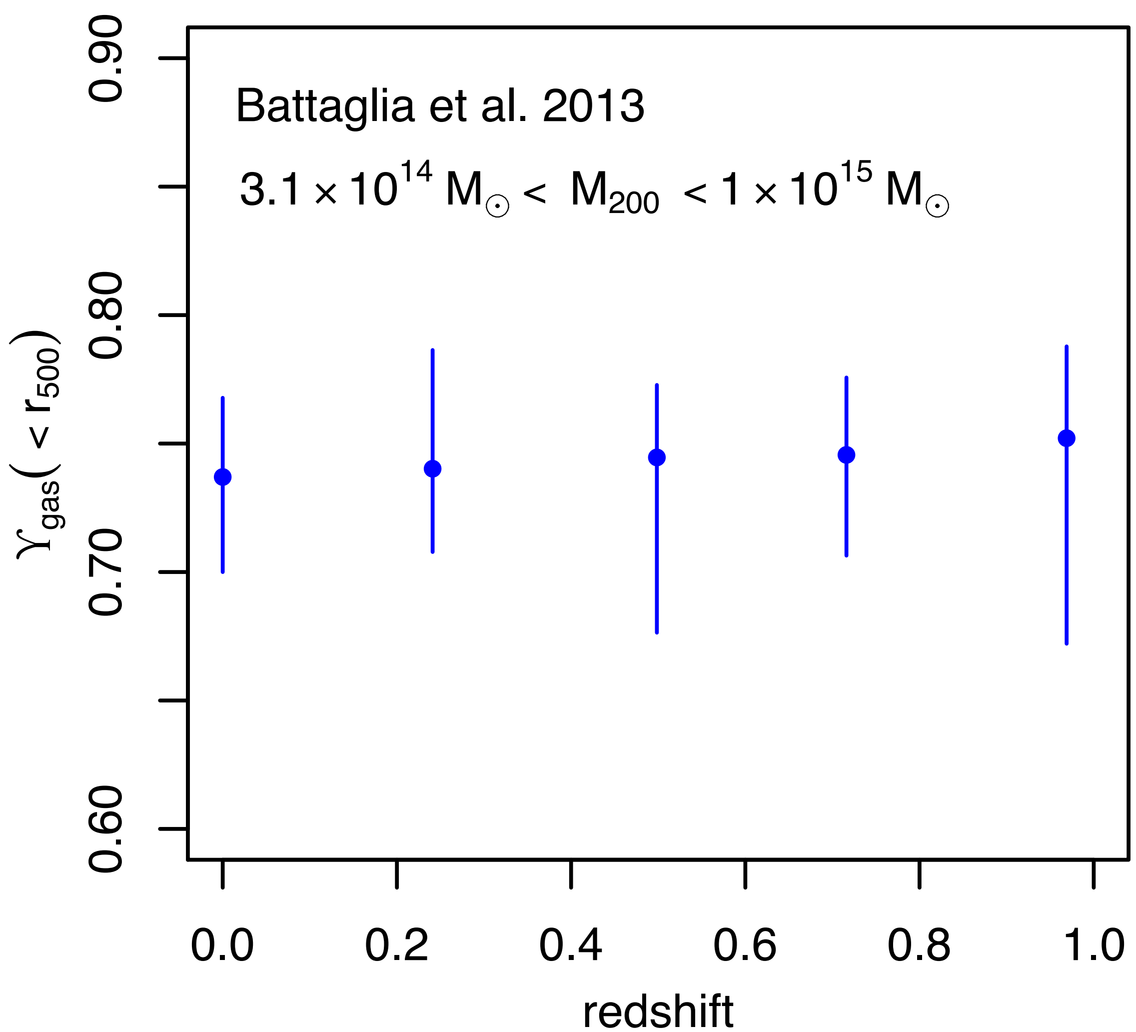
$$f_{\mathrm{gas}} = \frac{M_{\mathrm{gas}}}{M_{\mathrm{tot}}} = \Upsilon \frac{\Omega_{\mathrm{b}}}{\Omega_{\mathrm{m}}}$$

- 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

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)

simulations:



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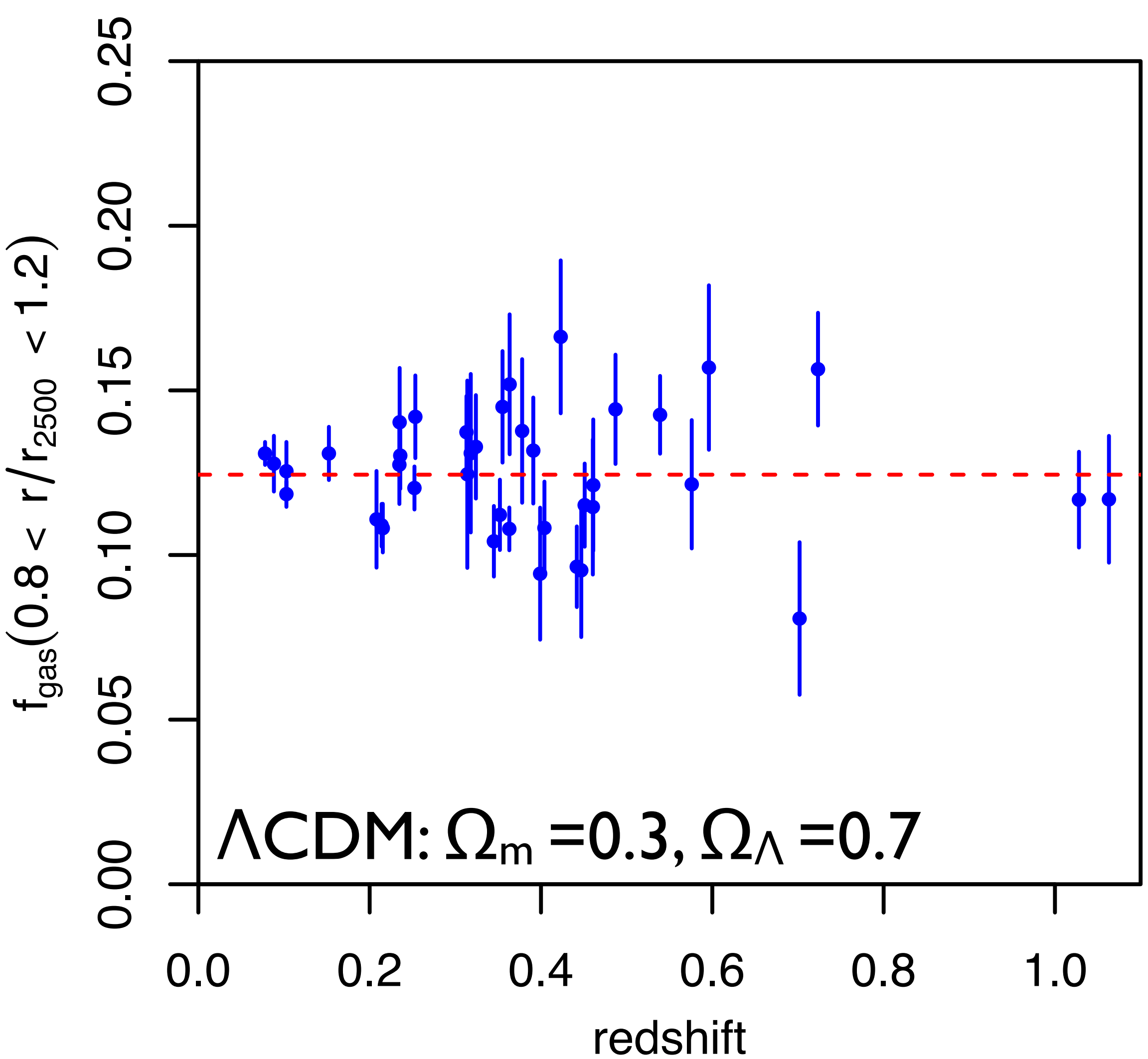
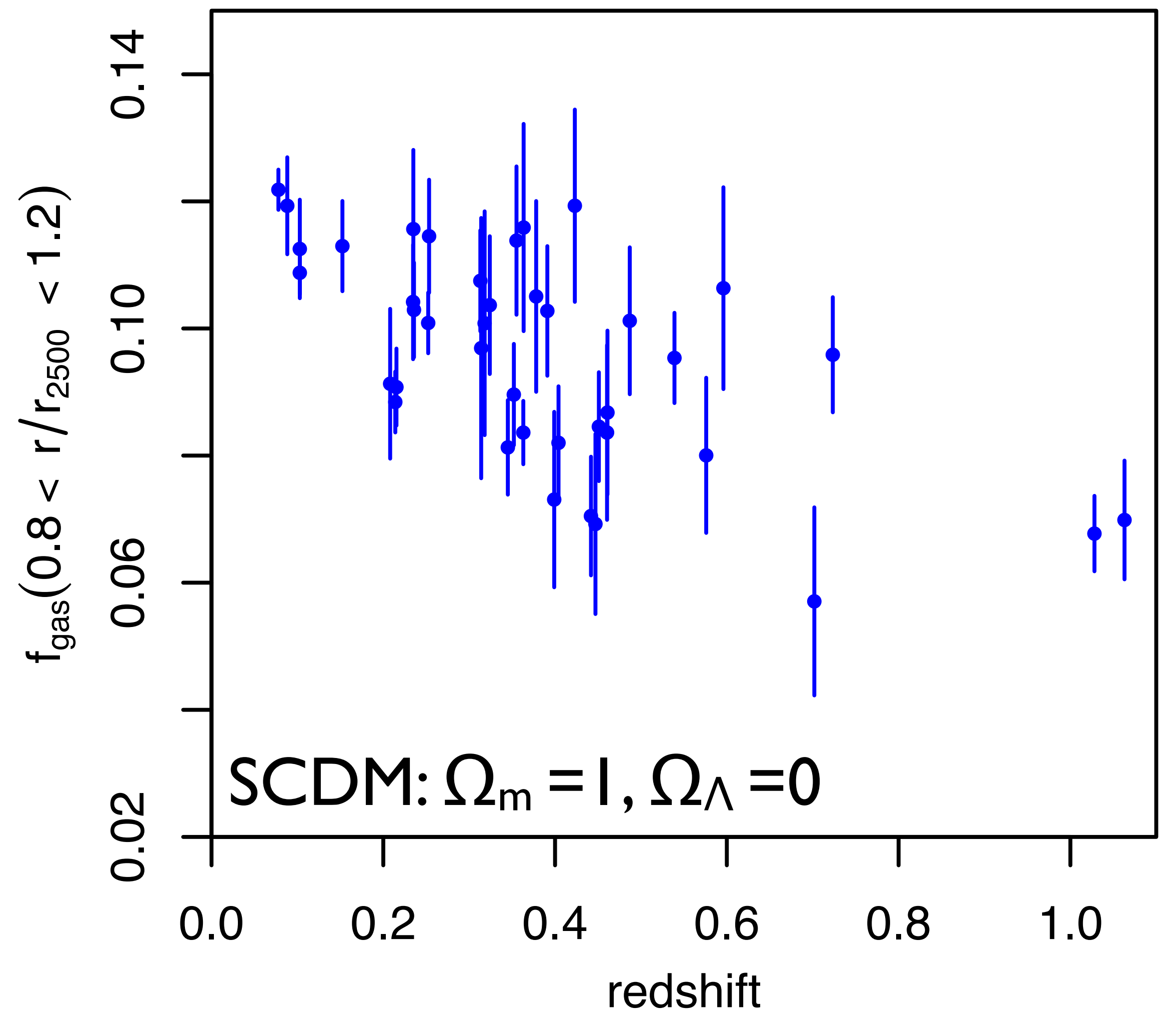
observations:





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%:

$$K = \frac{M_{\mathrm{WtG}}}{M_{\mathrm{Chandra}}} = 0.90 \pm 0.09$$

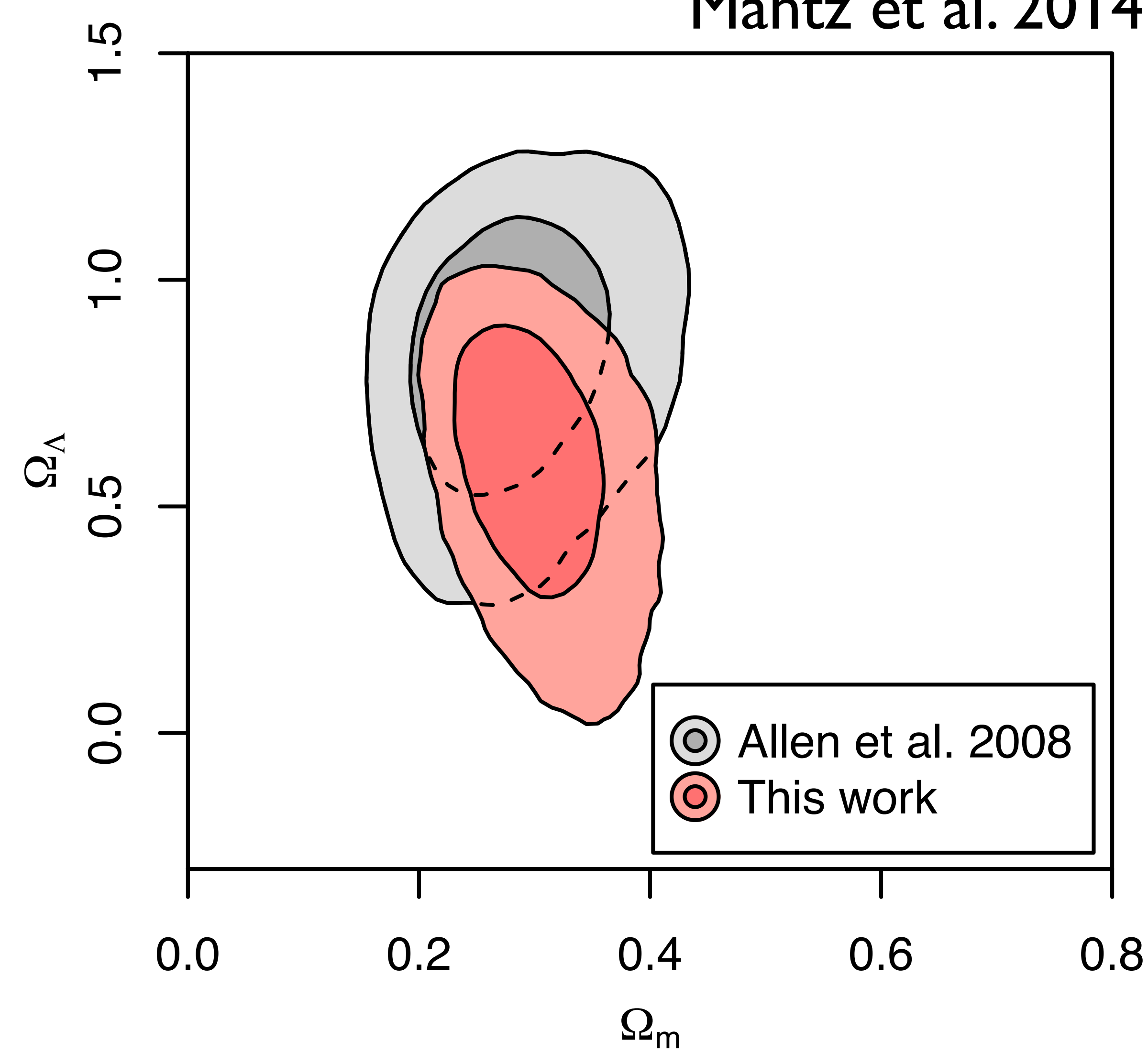
Applegate et al., in prep.

- significantly tightens Ω_m constraints

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

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

Mantz et al. 2014



Summary

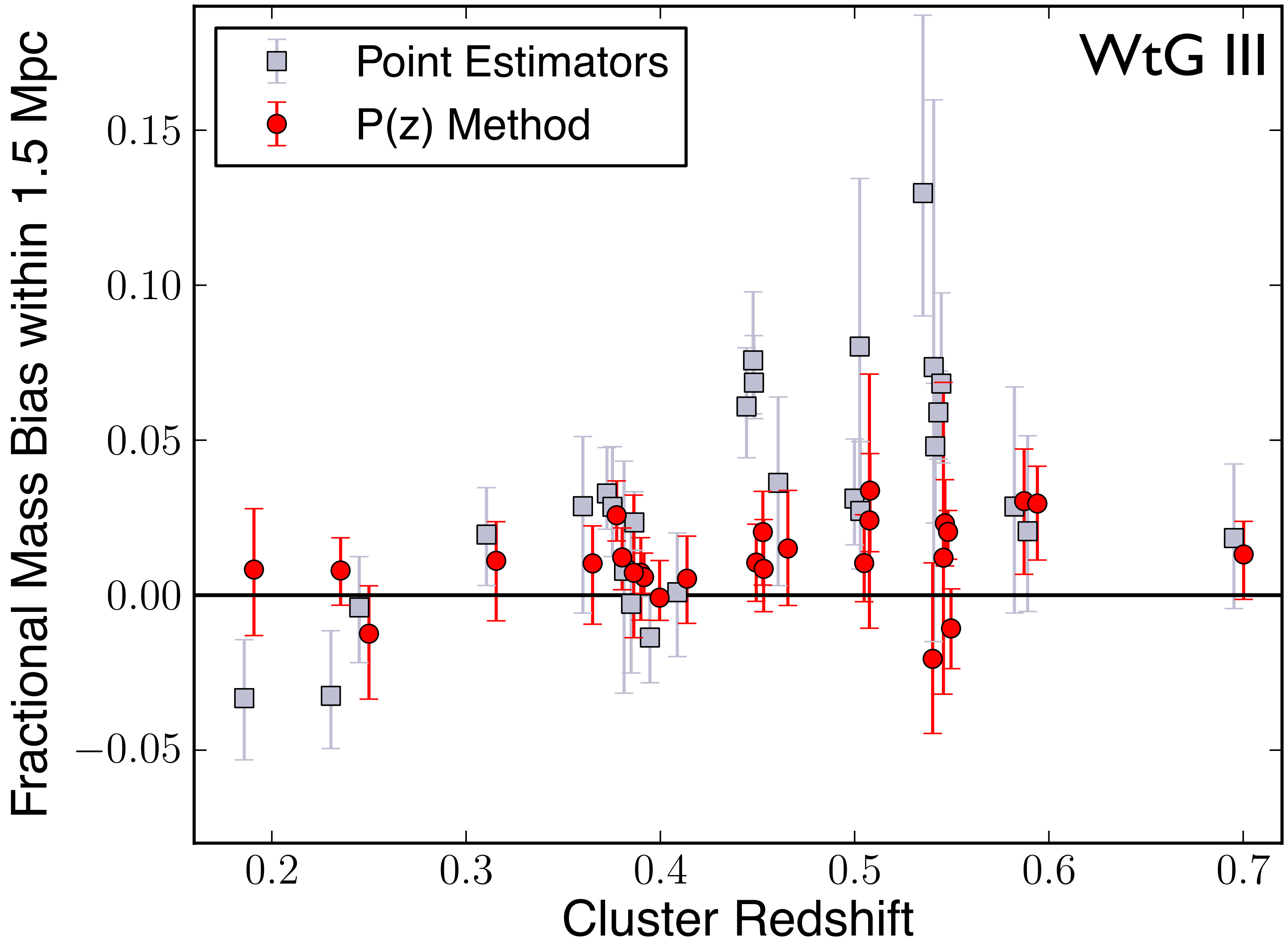
- weak lensing cluster mass estimates powerful complement for cluster surveys

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

➡ best strategy: compare *weak lensing* masses (no bias, large scatter) to *X-ray* mass proxies (low scatter, unknown bias)

- weak lensing masses can be used to measure *combined* mass bias of X-ray hydrostatic mass estimates (HE bias + T calibration)

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 $\rightarrow$ almost unbiased!