Cosmology with Galaxy Clusters

“Now you see me, now you don’t”
- (Some) effects of selection biases

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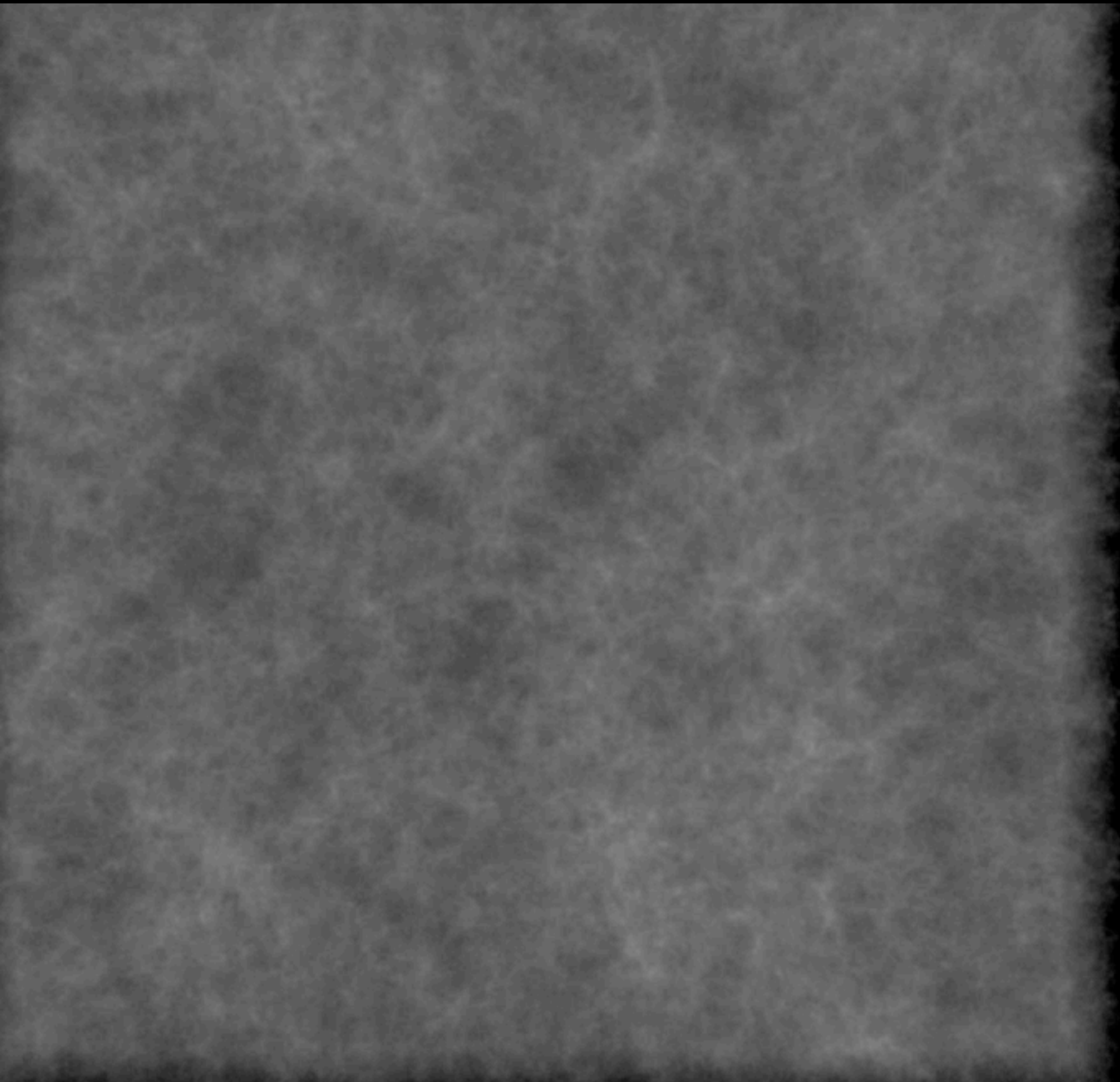
DE School, July 10th, 2017

Stony Brook University

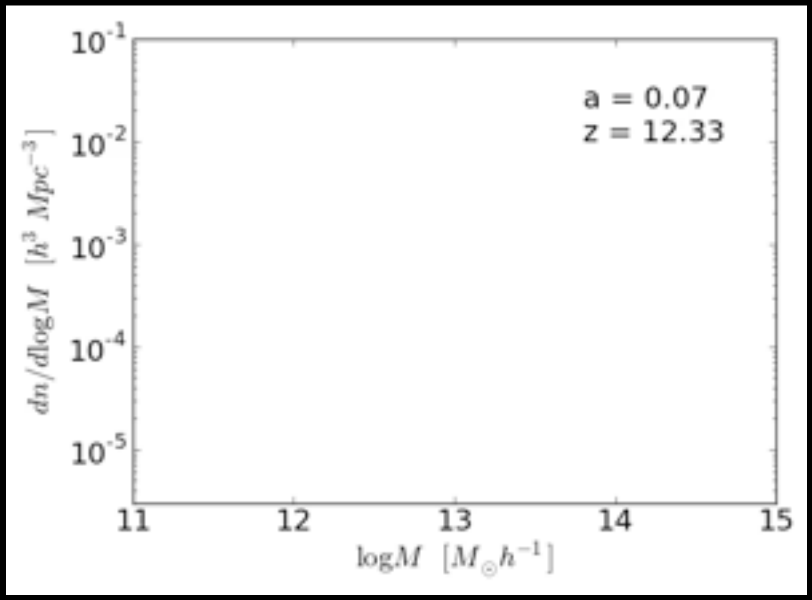
LSST DESC

Dark Energy Science Collaboration

Cosmology with galaxy clusters



halo mass function



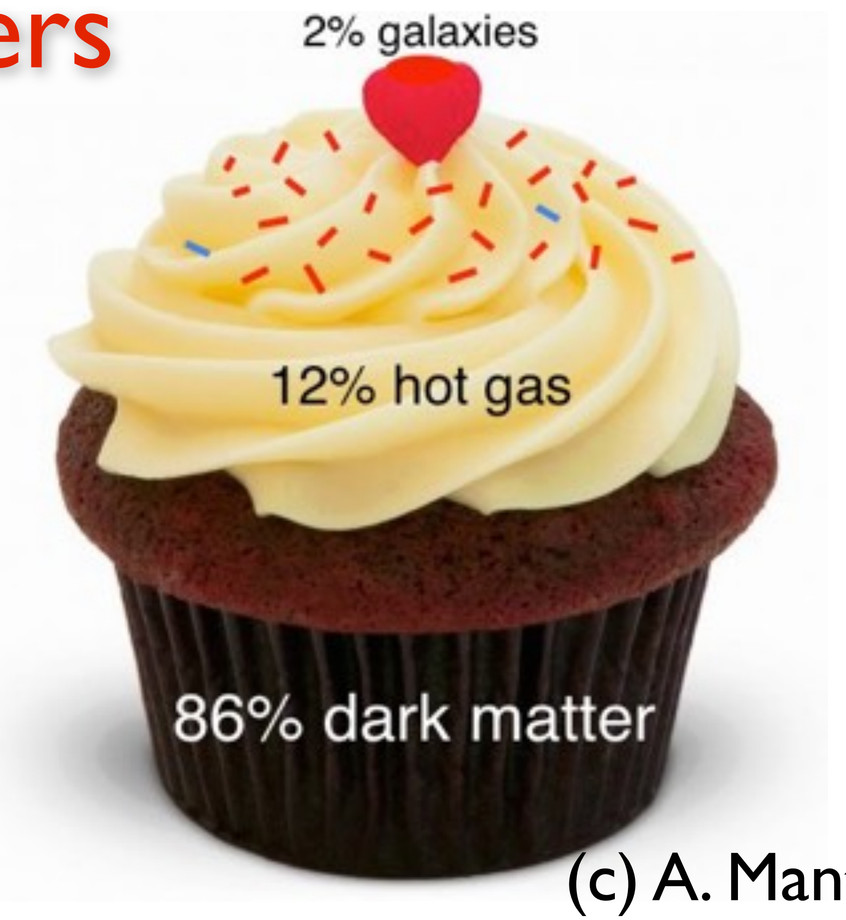
- number of gravitationally bound halos sensitive to cosmological model
- both *geometry* (volume) and *growth of structure* (evolution of mass function)

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

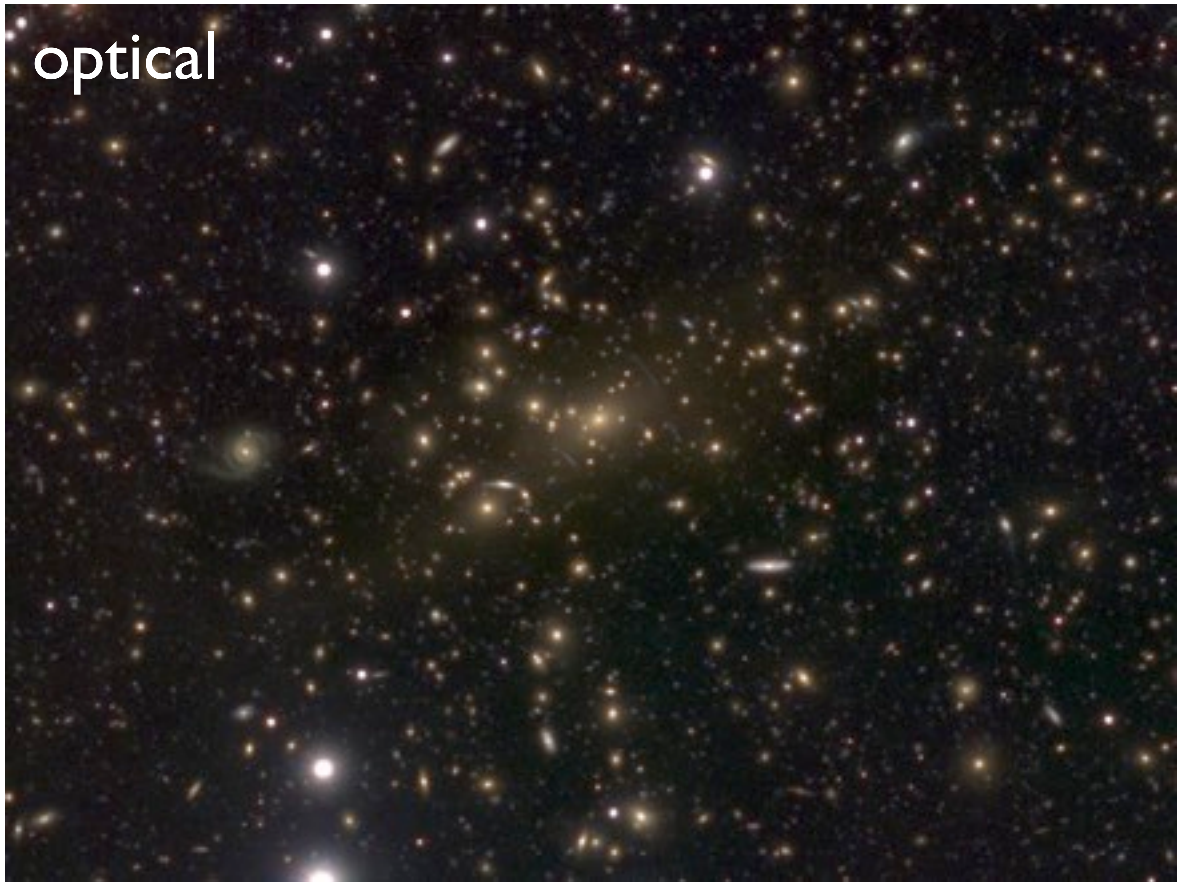
Observationally: Halos $\longleftrightarrow$ Clusters

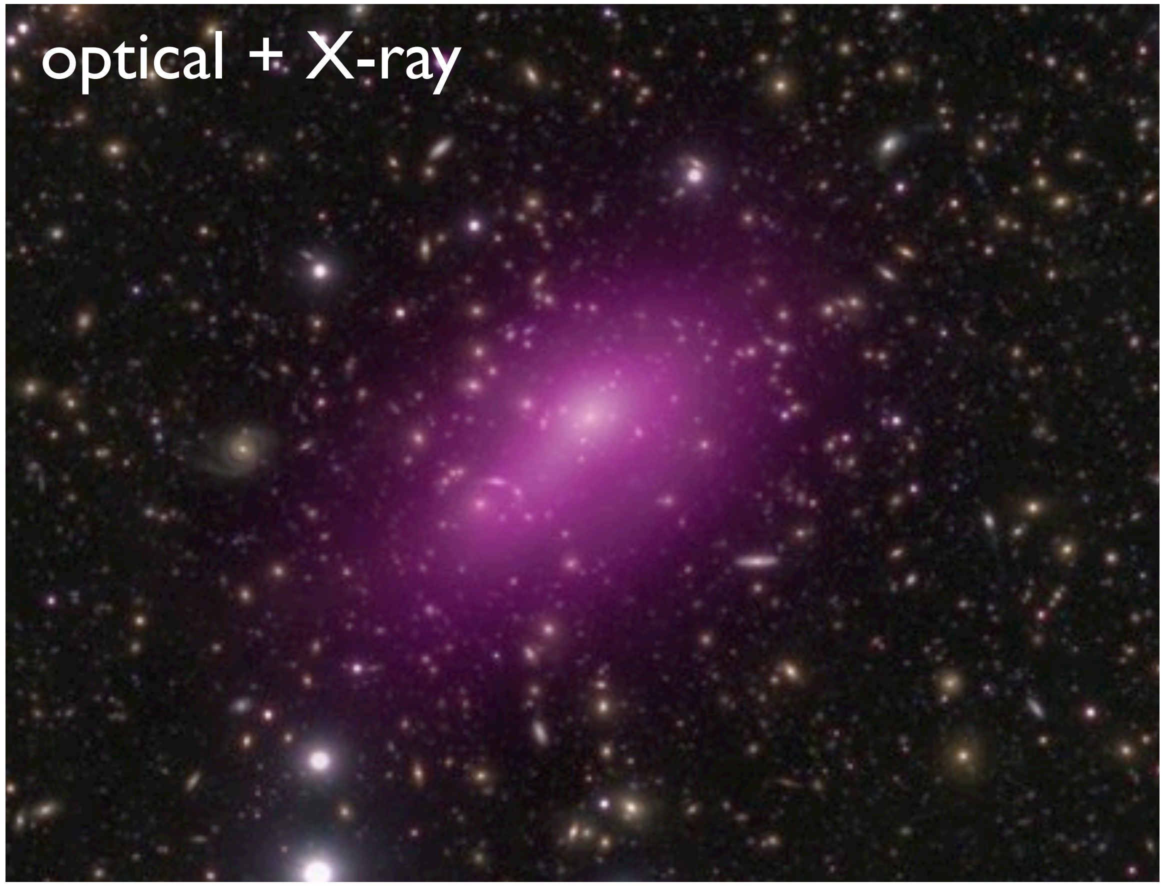
typical cluster properties:

$$
\begin{aligned}
M &\gtrsim 10^{14}\ M_\odot \\
kT &\gtrsim 10^{7}\ \mathrm{K} \\
R &\gtrsim 1\ \mathrm{Mpc} \\
\sigma_v &\gtrsim 700\ \mathrm{km/s}
\end{aligned}
$$



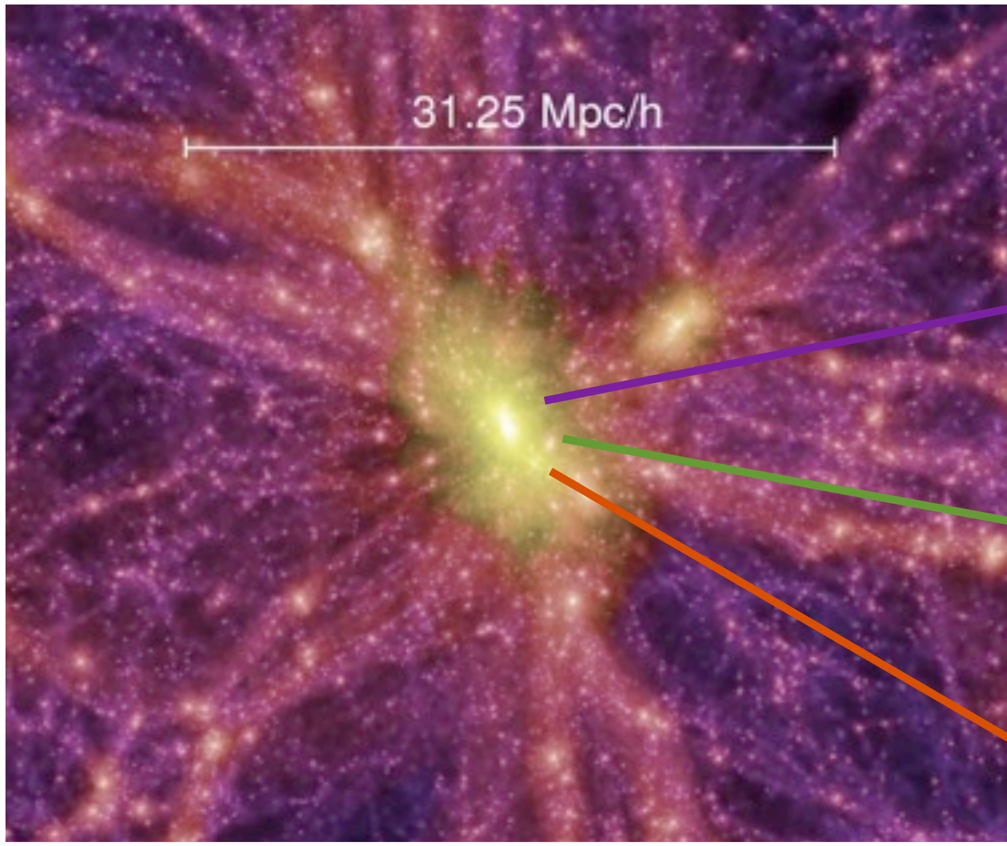
(c) A. Mantz

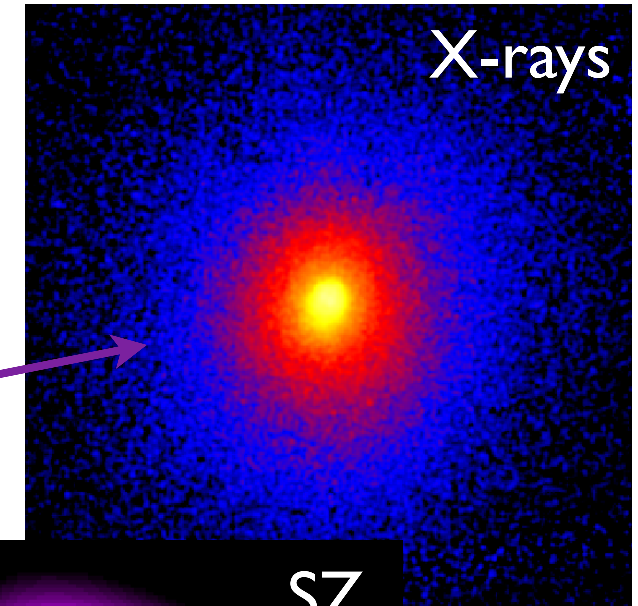


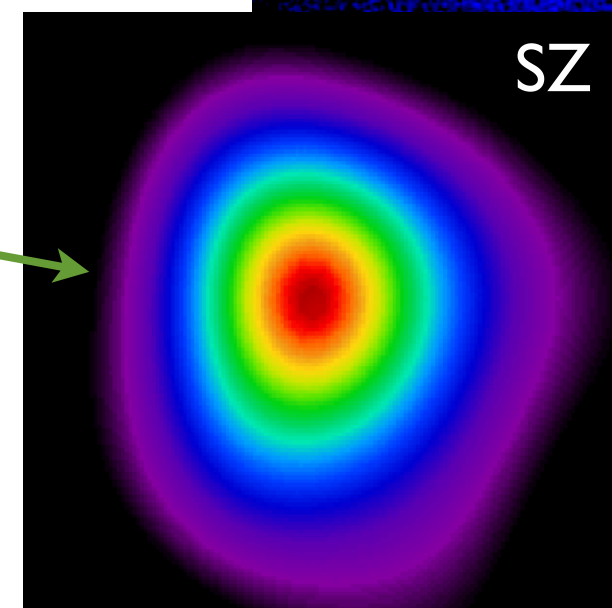


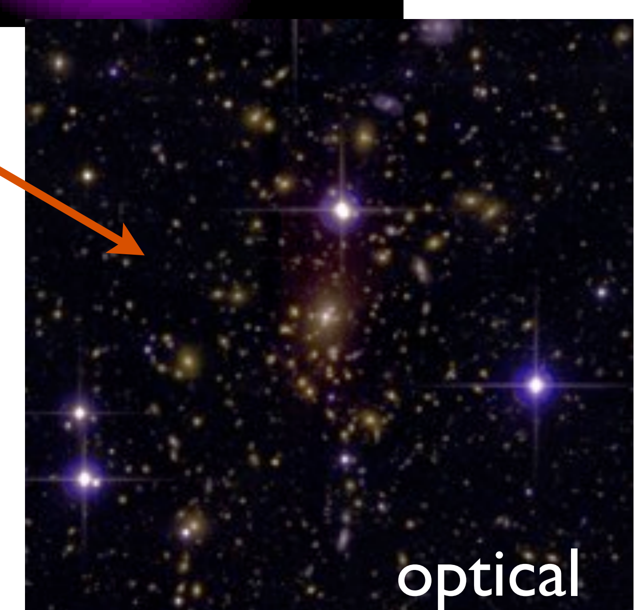
Finding clusters

observationally: halos ⟷ clusters





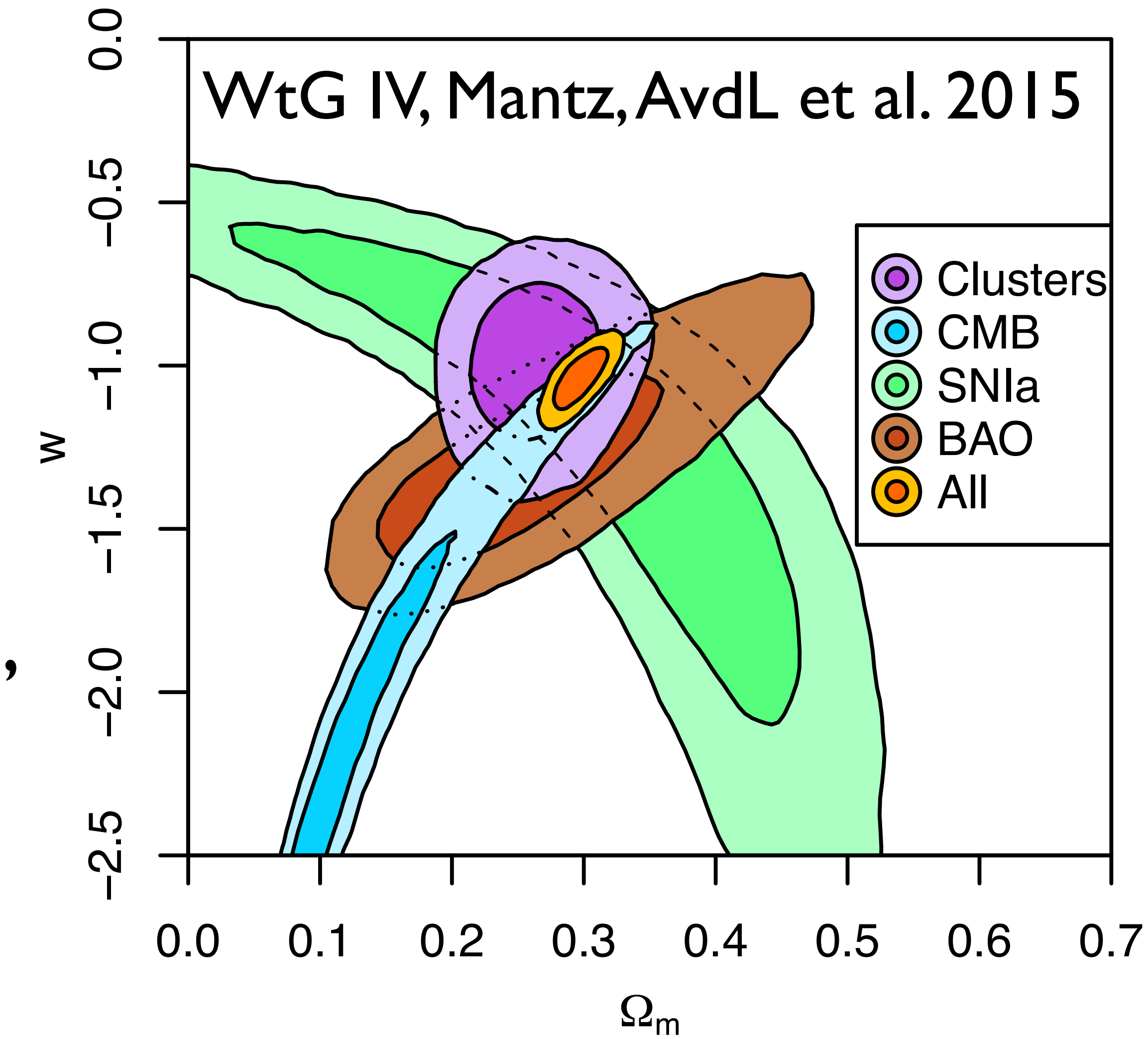




- X-rays: thermal bremsstrahlung from Intra-Cluster Medium (ICM)
- millimeter: Sunyaev-Zeldovich effect - inverse Compton scattering of CMB photons on ICM
- optical: galaxy population - overdensity of (red) galaxies

State of the Art

Weighing the Giants alone places 15% constraint on *w*; one of the tightest single-probe constraints today



WtG based on

- only(!) ~200 X-ray-selected (ROSAT), most massive clusters at $z<0.5$
- 50 with weak-lensing masses
- 90 with *Chandra* imaging

competitive constraints also from optical and SZ cluster surveys; DES cluster constraints coming this year!

~next decade: 10 000s of clusters, multiple selection methods (optical, SZ, X-ray), to z~2, LSST, Euclid, WFIRST weak lensing → tremendous potential

Cosmic Visions Report (2016): " The number of massive galaxy clusters could emerge as the most powerful cosmological probe *if the masses of the clusters can be accurately measured*."

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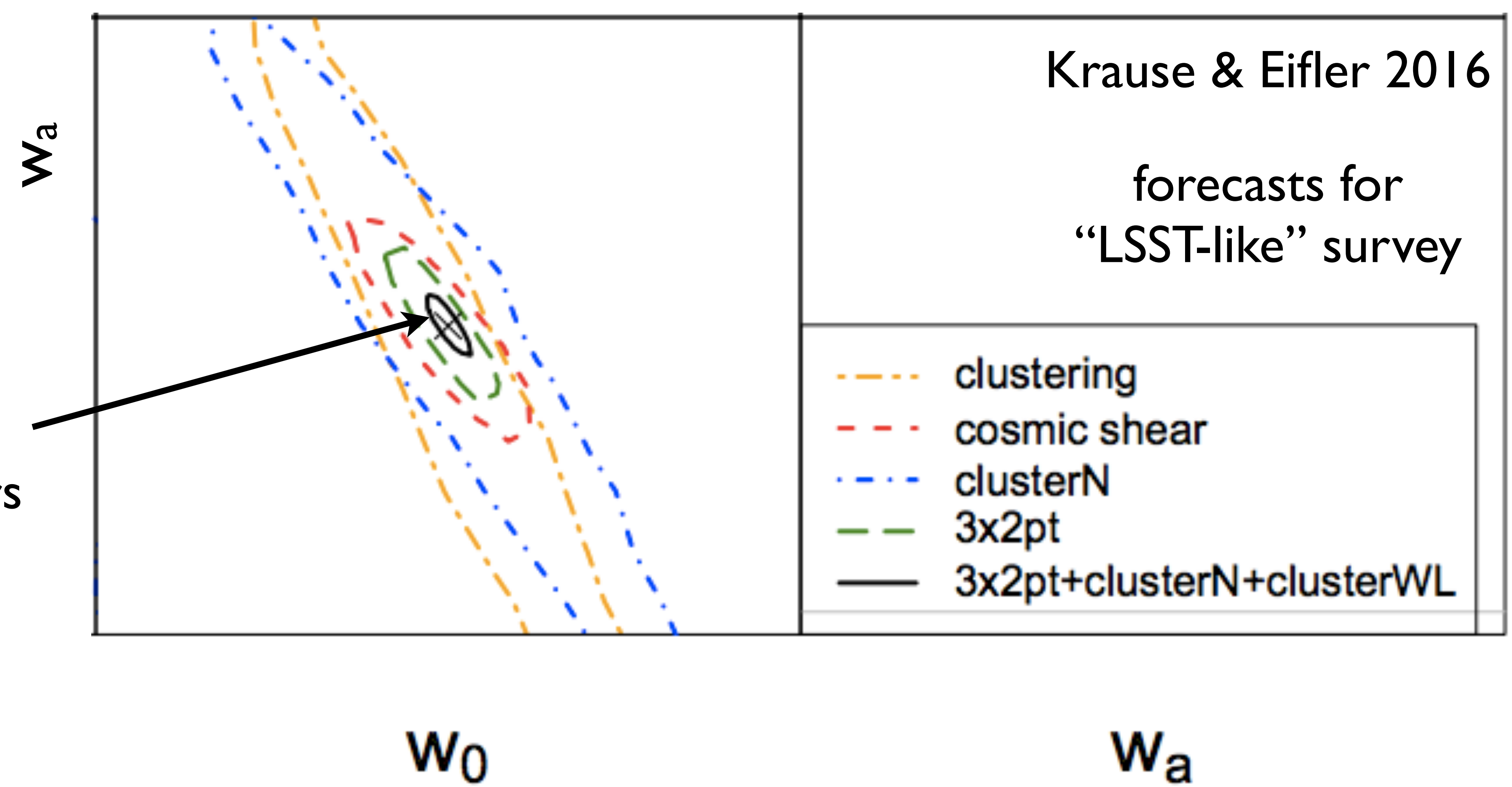
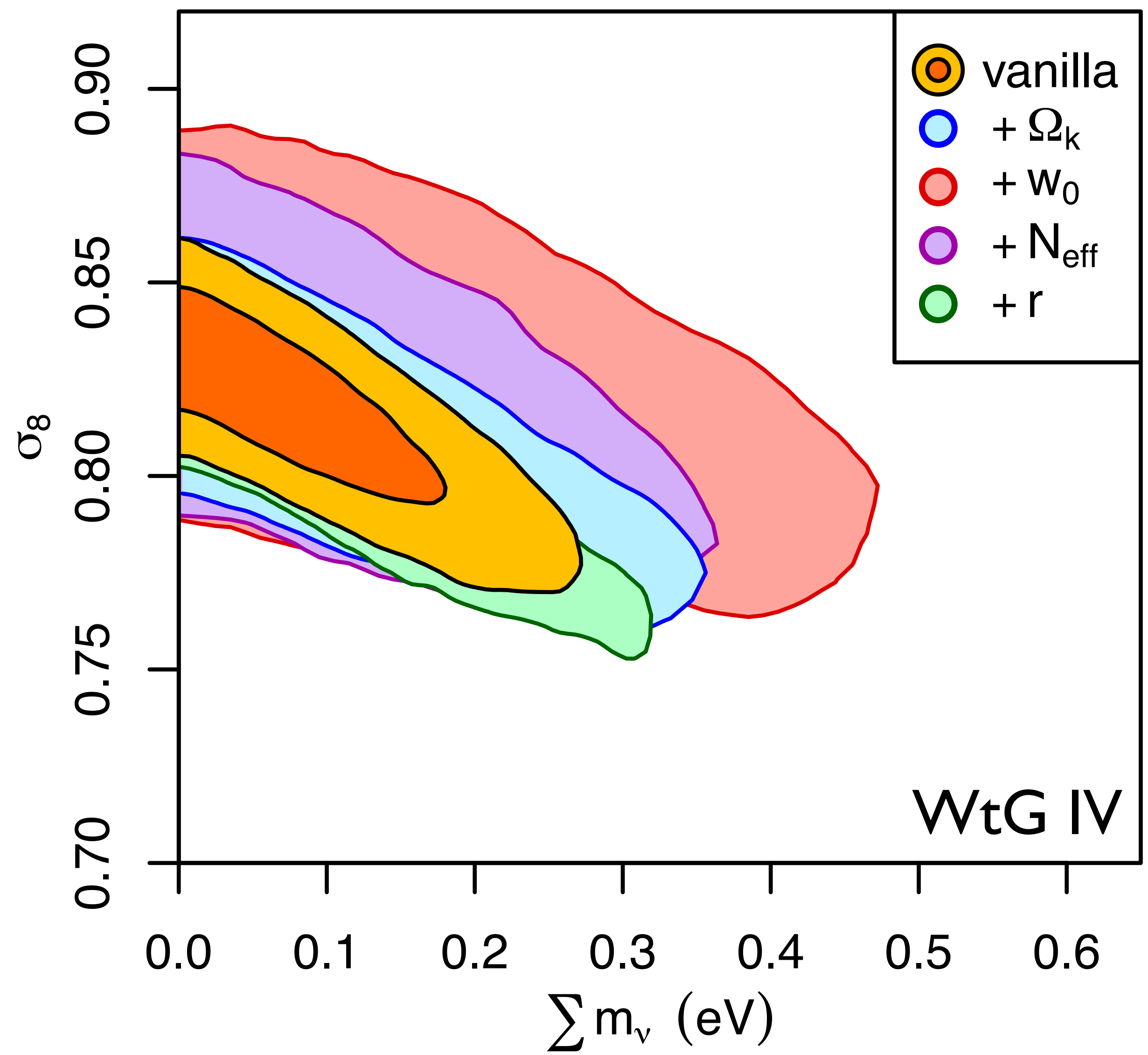


note improvement when adding clusters w/ WL mass calib

Not just dark energy

also:

- neutrino masses nearly independent of dark energy model
- evolving dark energy
- modified gravity
- ...



LSST and Cluster Cosmology

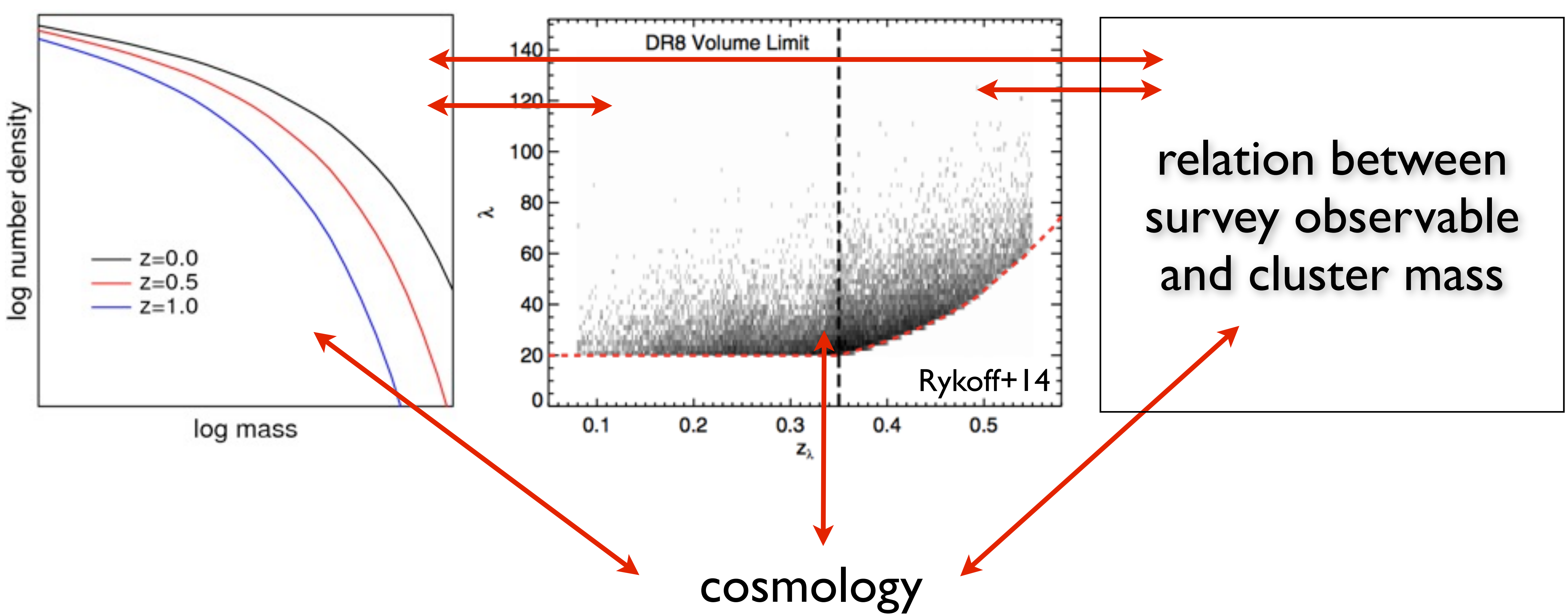
- cluster finding:
  - identify clusters via galaxy overdensities
  - most successful methods use red sequence (e.g. redMaPPer)
  - large, highly complete cluster samples

- cluster weak lensing
  - mass calibration: connect observables to halo mass function
  - key qualities: image quality, depth, good photo-z's

best cosmology constraints will come from addition of multi-wavelength follow-up / survey data

Ingredients for cluster counts cosmology

1. prediction for halo mass function
2. cluster survey (X-rays, SZ, optical) with well understood selection function
3. relation between survey observable and cluster mass
4. self-consistent statistical framework



Measuring masses

- survey observables (optical richness X-ray luminosity, SZ decrement) do not measure cluster mass directly
  - correlate with mass, but with considerable scatter, (20-40)%
  - *need to determine mass-observable relation (MOR)*

Cluster mass here:

- same as in simulations that predict halo mass function
- usually 3D overdensity mass:

$$M_\Delta = \frac{4\pi}{3}\Delta\rho_c(z)r_\Delta^3$$

Mass-Observable Relations

simplest assumption:

- the *mean* of the observable follows a power-law relation with mass

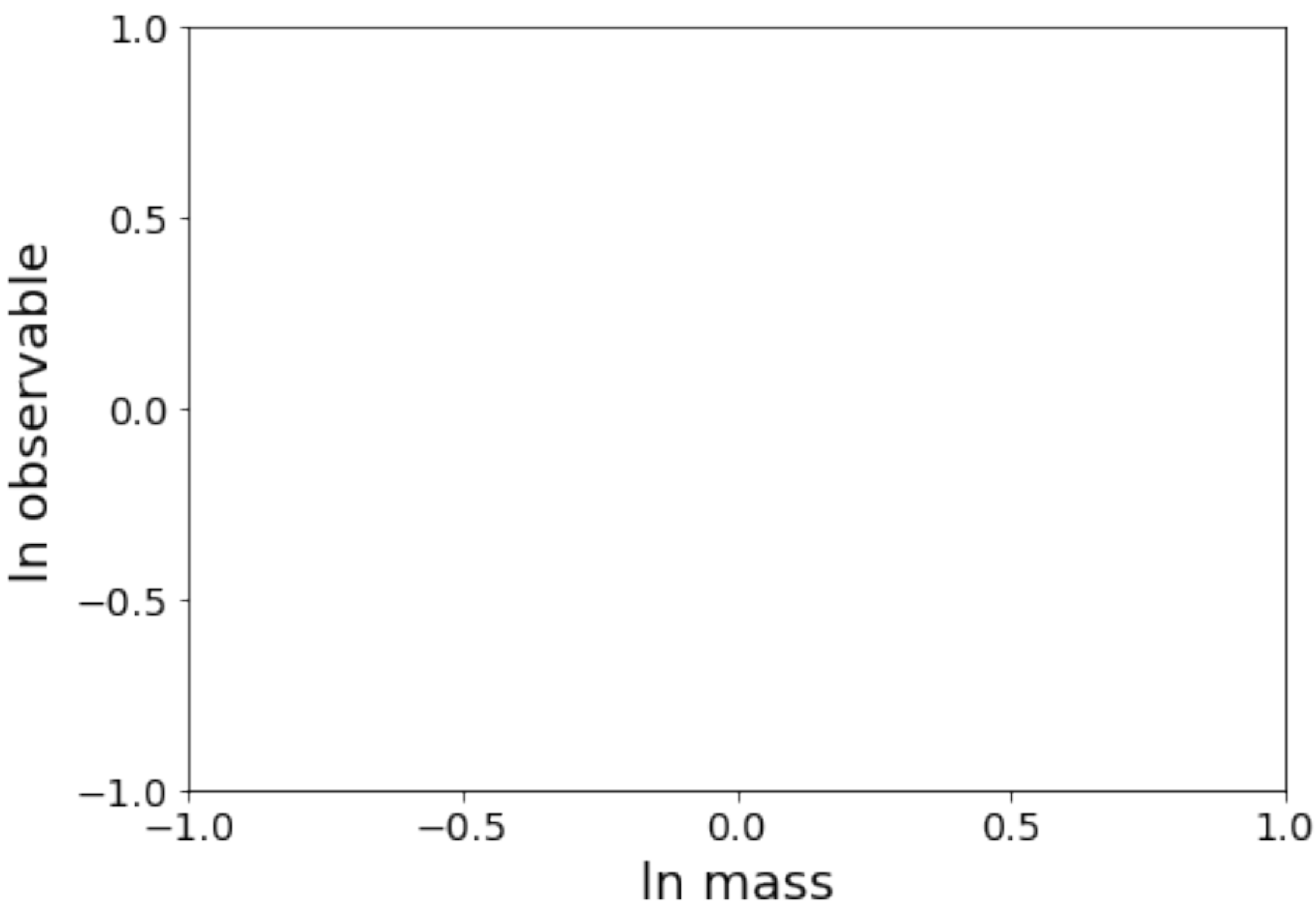
$$\langle \mathrm{obs} \rangle = \alpha \times M^{\beta}$$

<u>intrinsic</u> scatter around the mean is log-normal

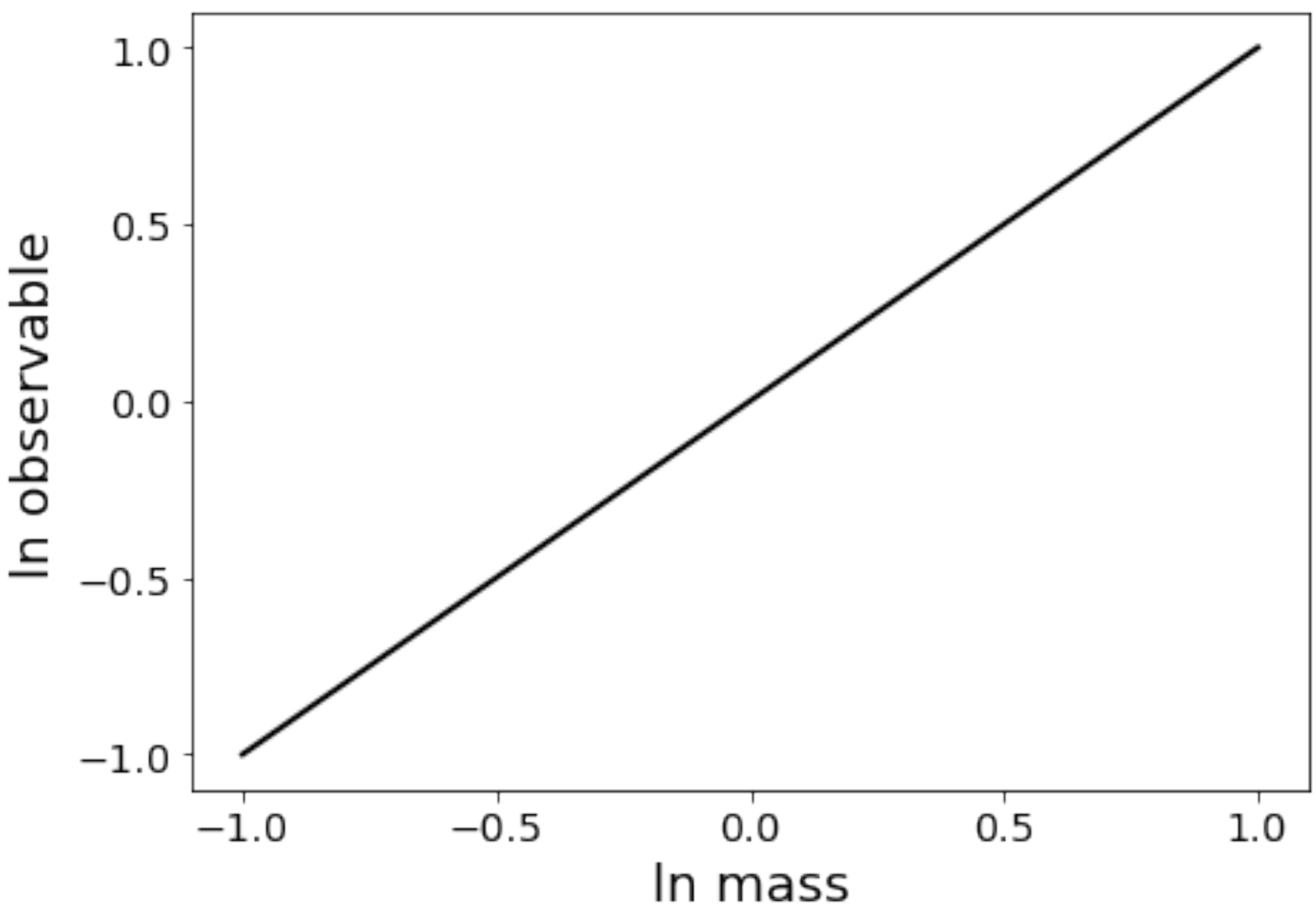
motivation: assumption of self-similarity (Kaiser 1984)

1. sketch a *mean* mass-observable relation (use logarithmic axes)
2. sketch an actual realization, i.e. clusters drawn from the mean relation with log-normal scatter

$$\langle \mathrm{obs} \rangle = \alpha \times M^{\beta}$$



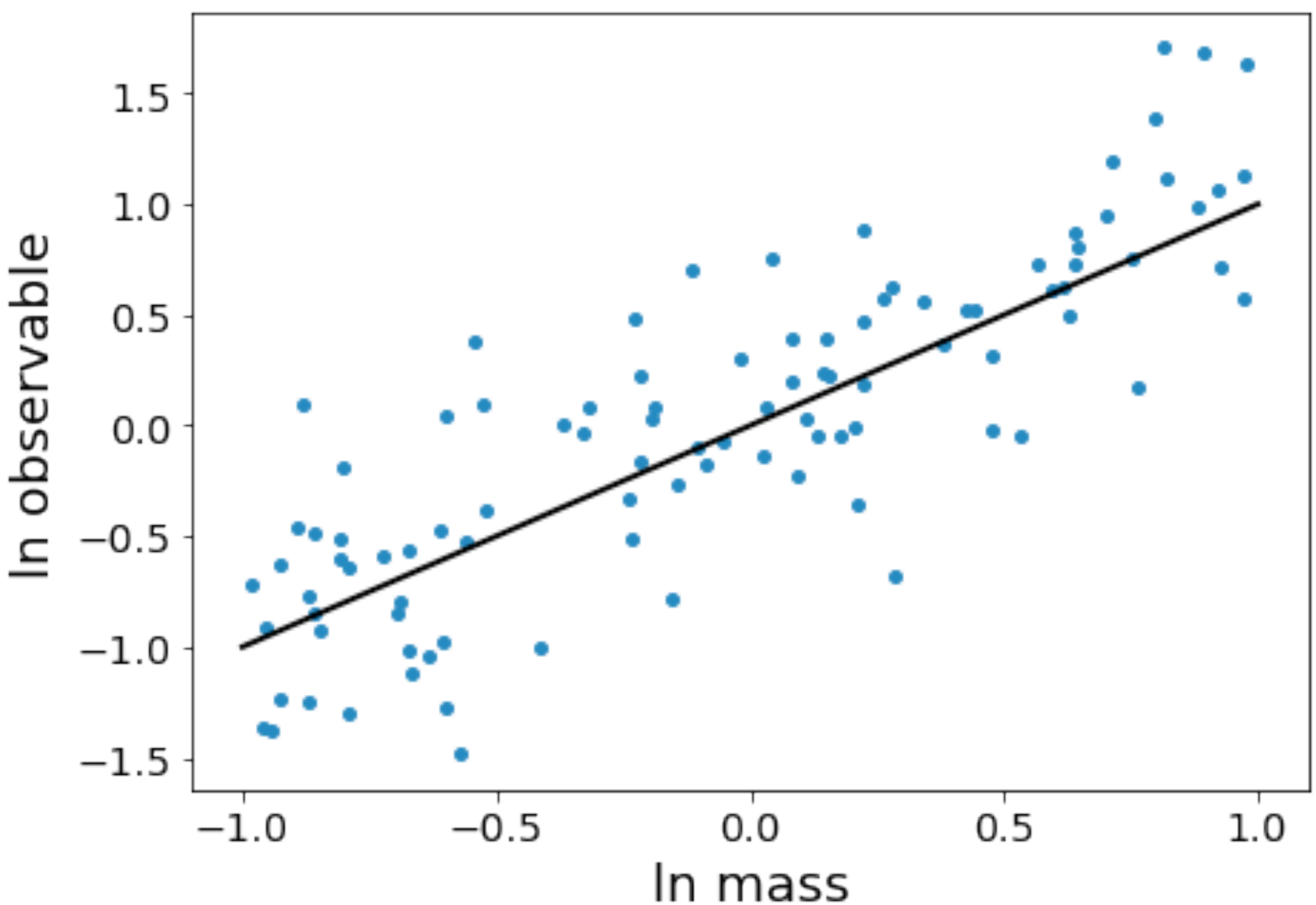
a *mean* mass-observable relation



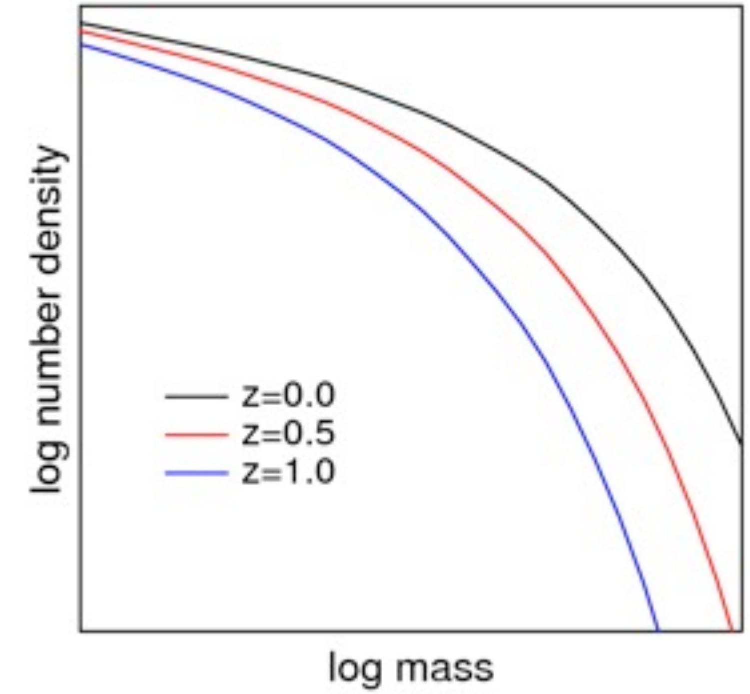
a *mean* mass-observable relation

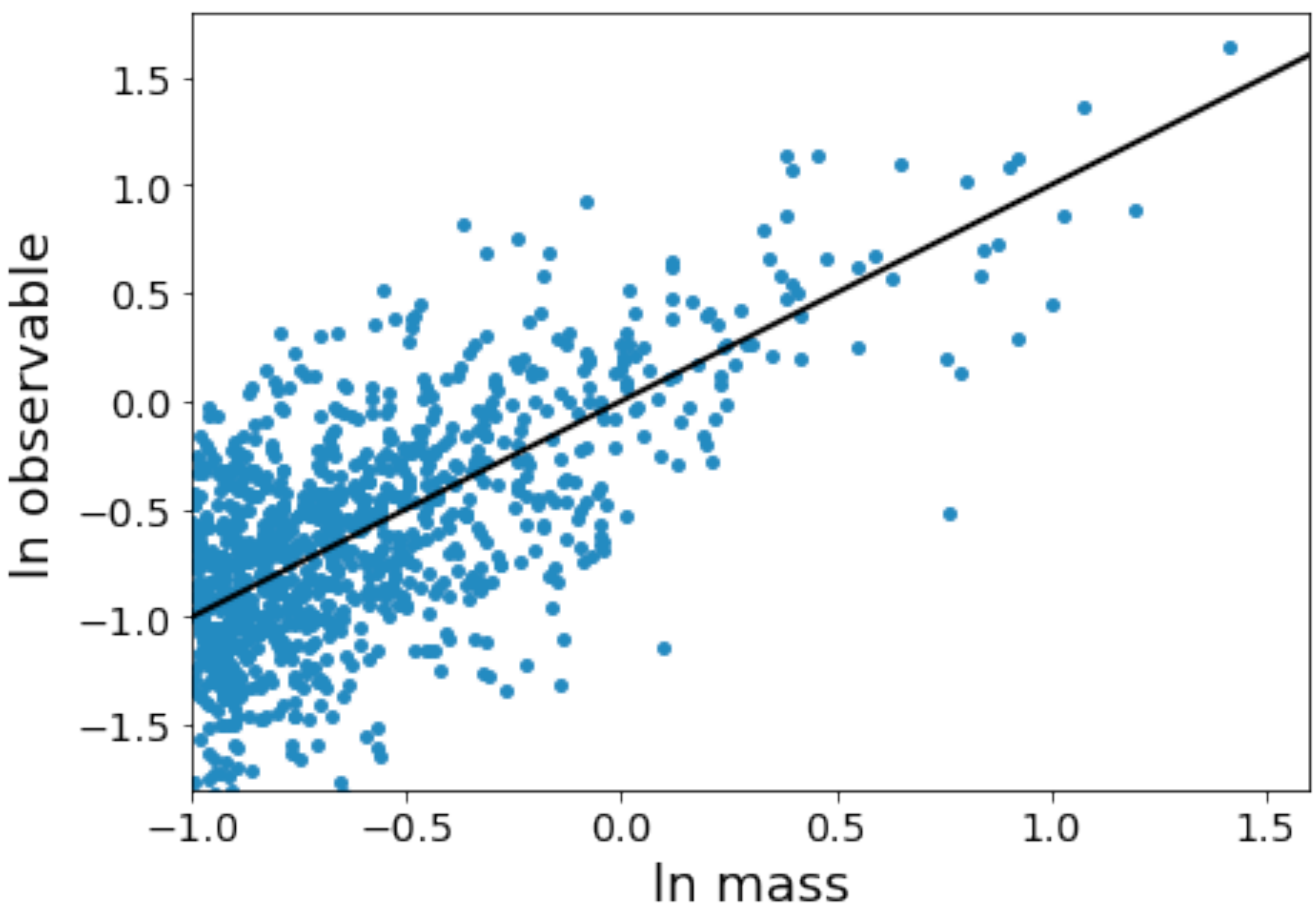
... and a realization

in this case, `ln(mass)` is uniformly distributed



there are more low-mass clusters than high-mass clusters; the high-mass tail of the mass function drops off exponentially

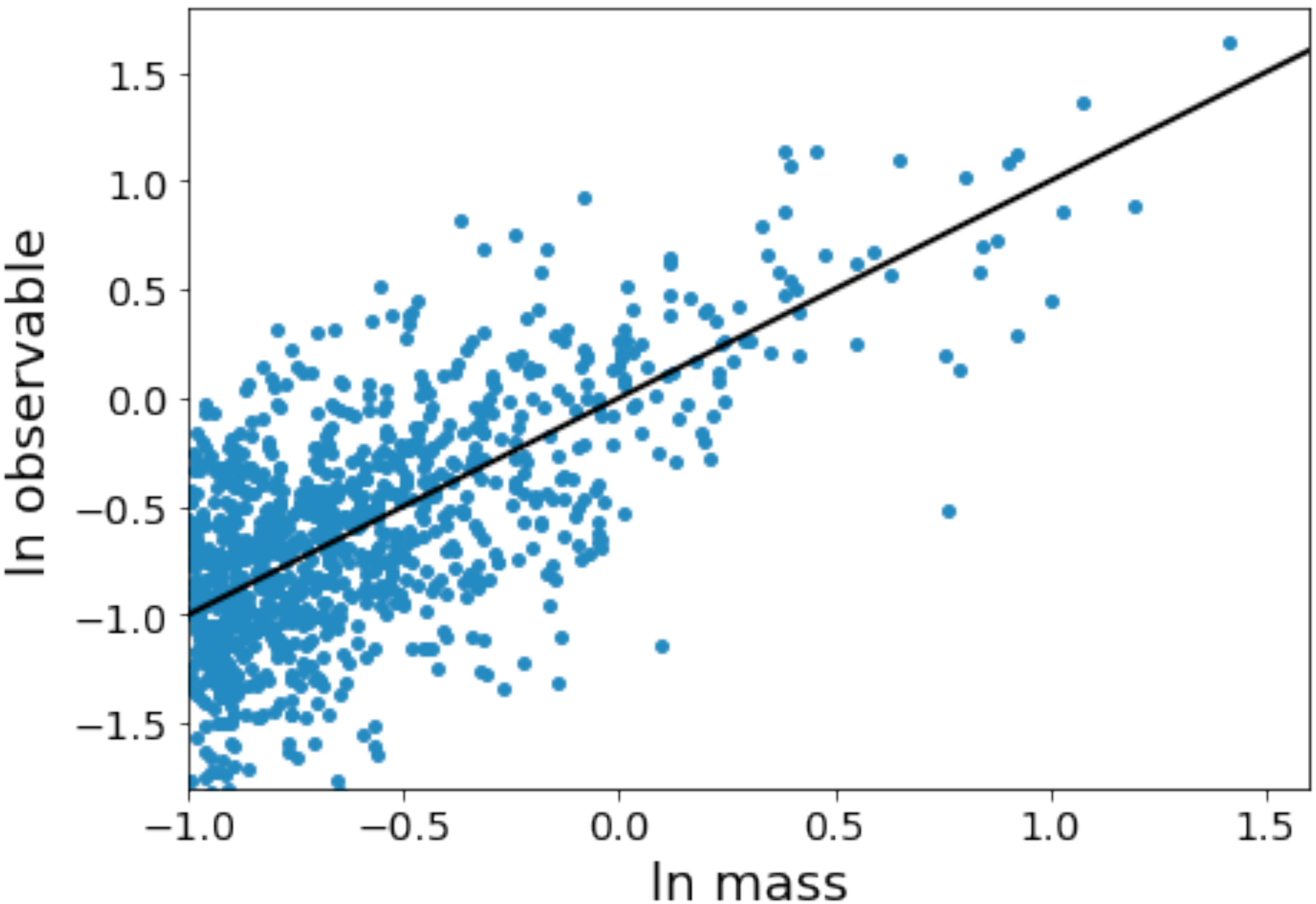




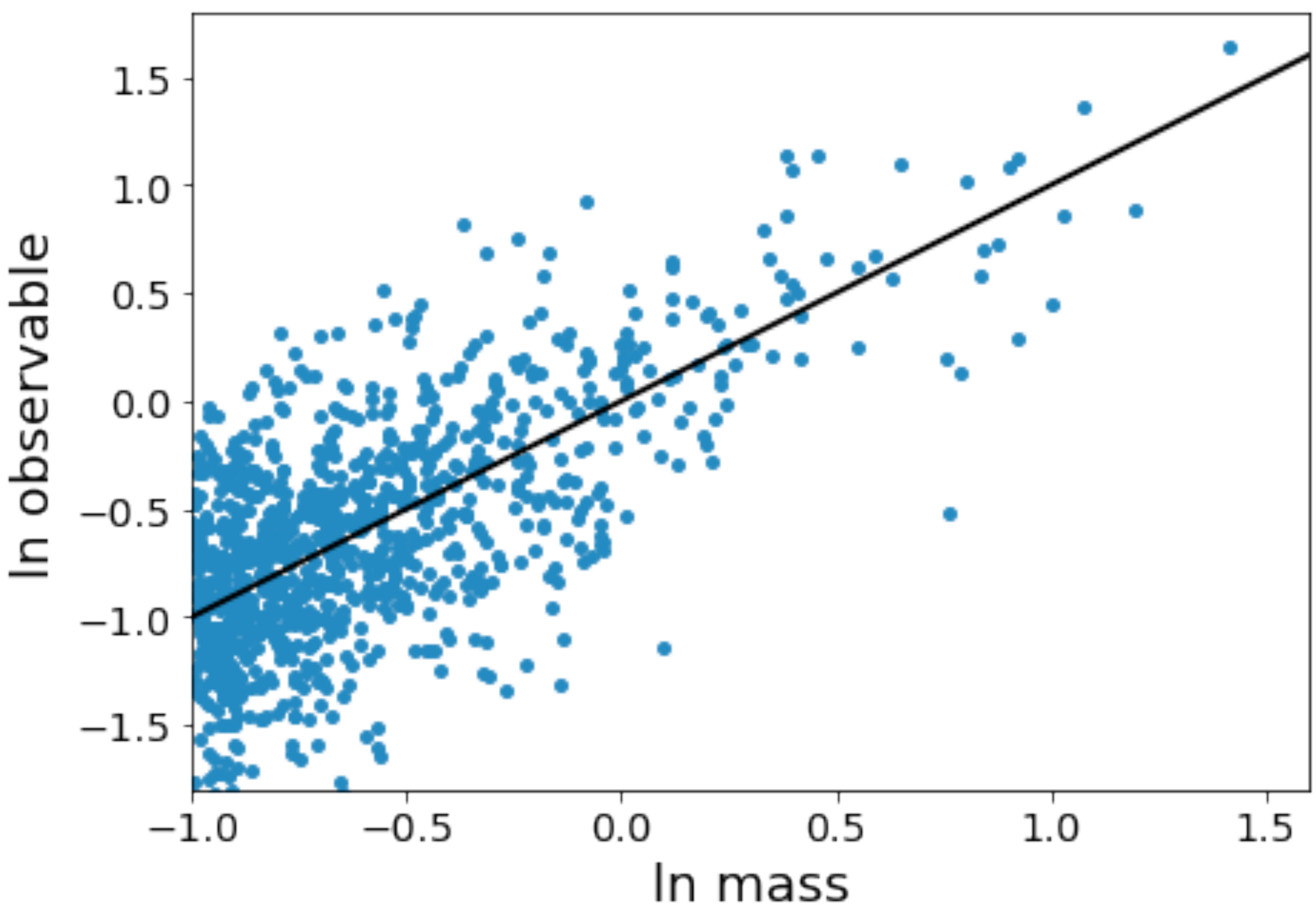
Note: this is only an illustration of our model of the MOR!

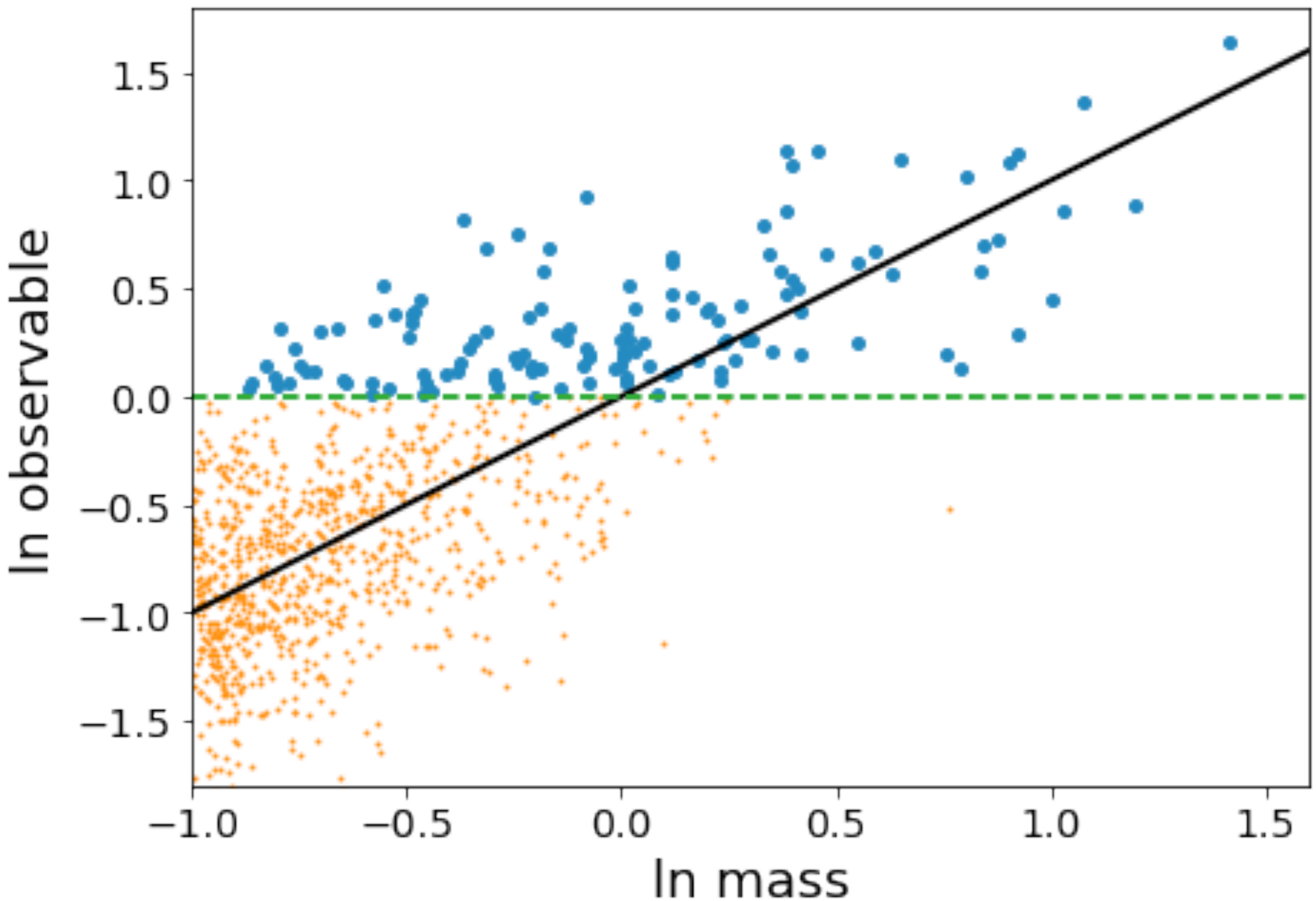
We need to remember that

- we only detect clusters above a certain threshold
- our survey data delivers only the y-values on this plot



3. impose a detection threshold on your data (e.g. `ln(obs)>0`)
4. draw a histogram of your data

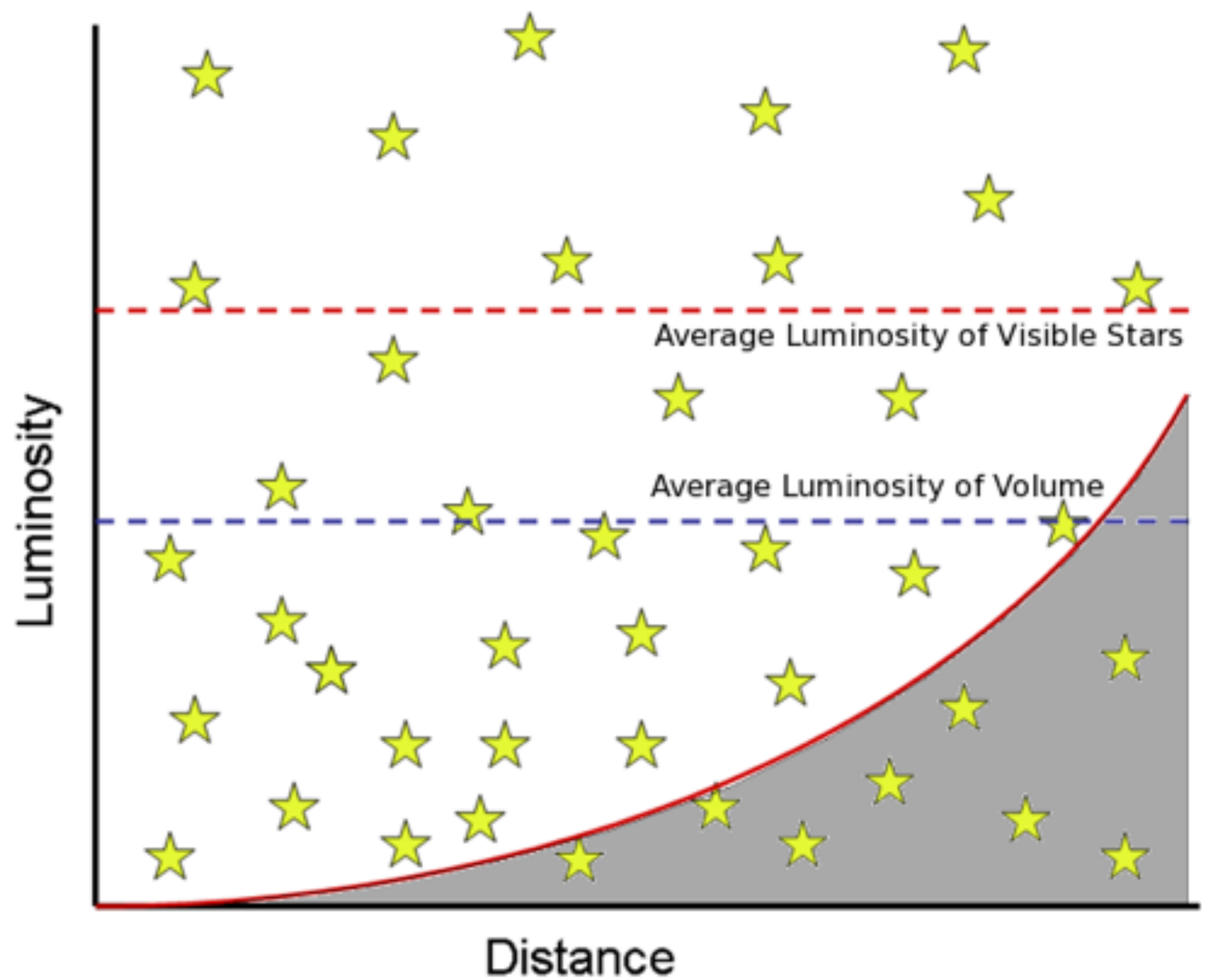




1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
ln observable
−1.0
−0.5
0.0
0.5
1.0
1.5
ln mass

Selection biases

Malmquist bias: preferential detection of intrinsically bright objects

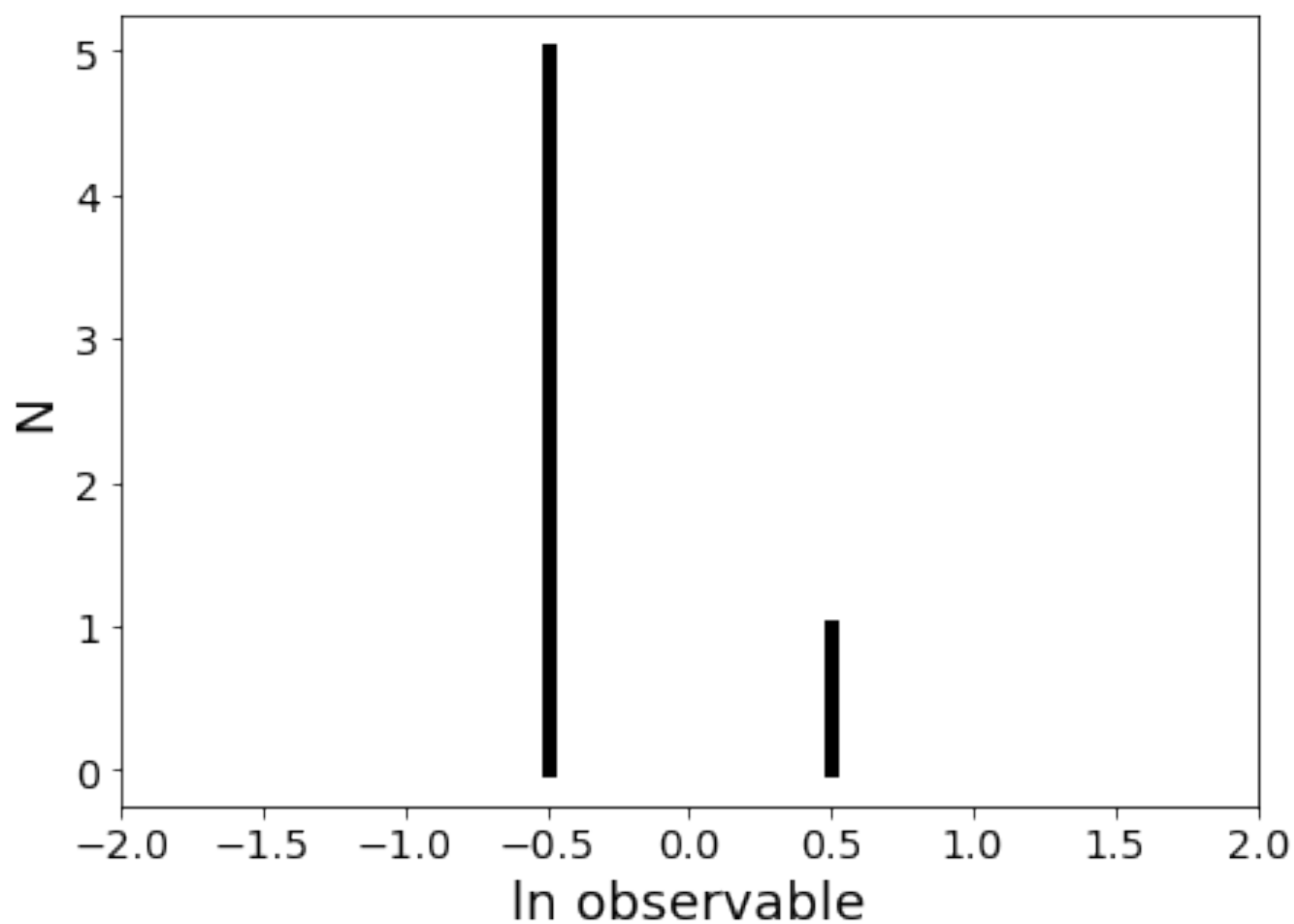


source: wikipedia

Selection biases

Malmquist bias: preferential detection of intrinsically bright objects

Eddington bias: scatter (intrinsic or measurement) causes overlap of intrinsically distinct populations



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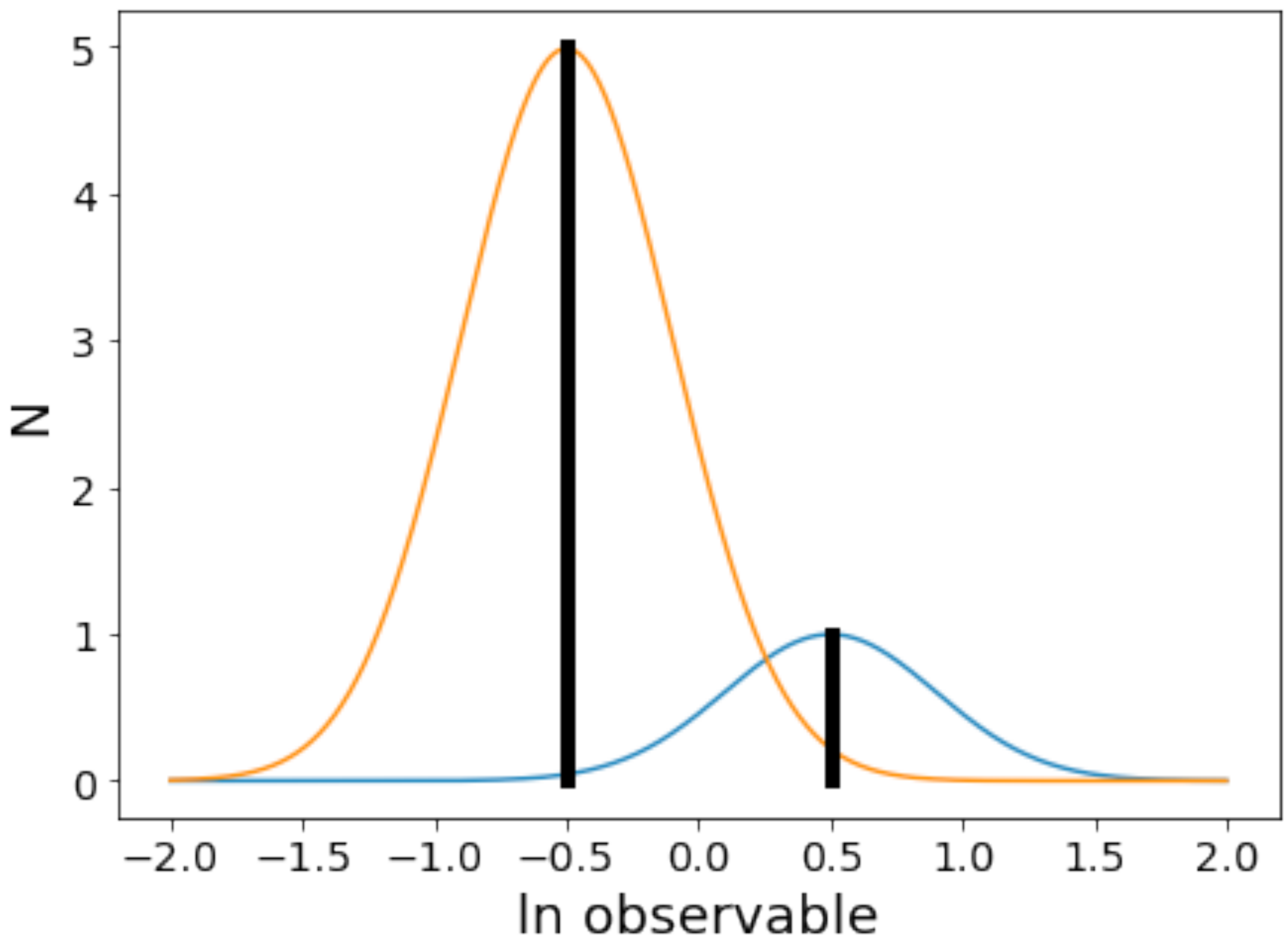

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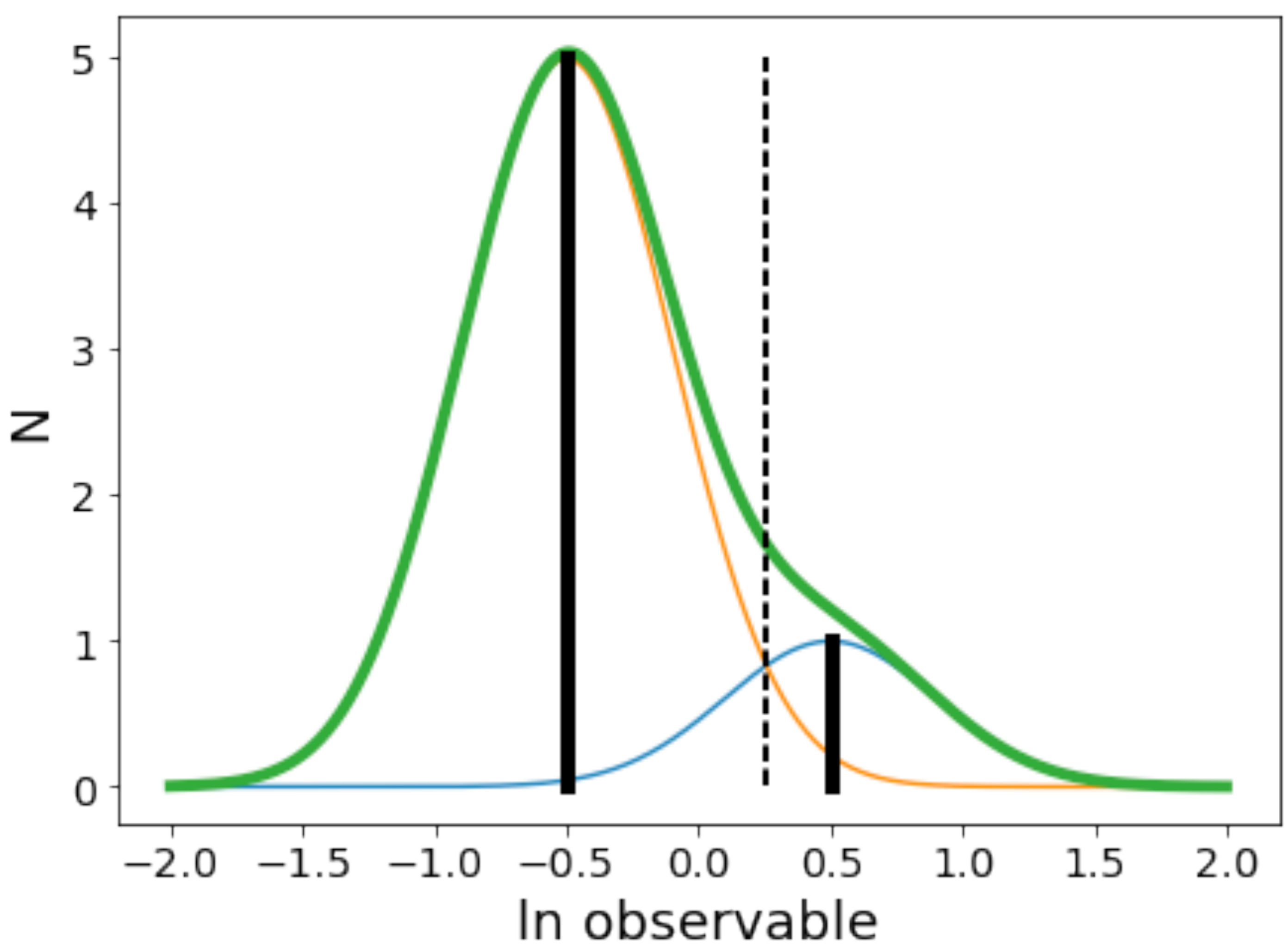
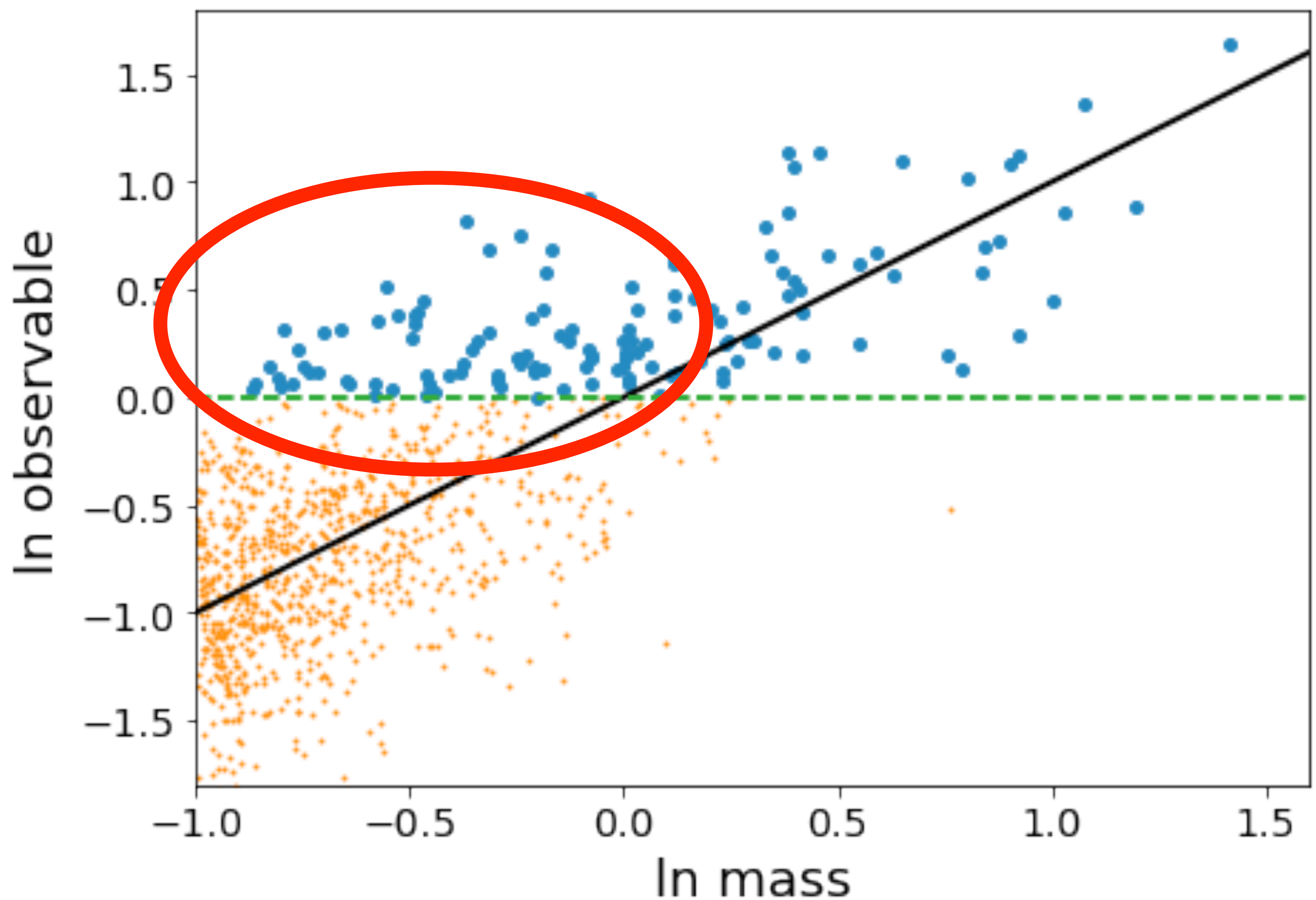


Selection biases

here, both Malmquist and Eddington bias are at play and lead to a large fraction of heavily biased (significantly up-scattered) clusters



the cartoon shown here is similar to those in Mantz et al. 2010b, Allen et al. 2011

Selection biases

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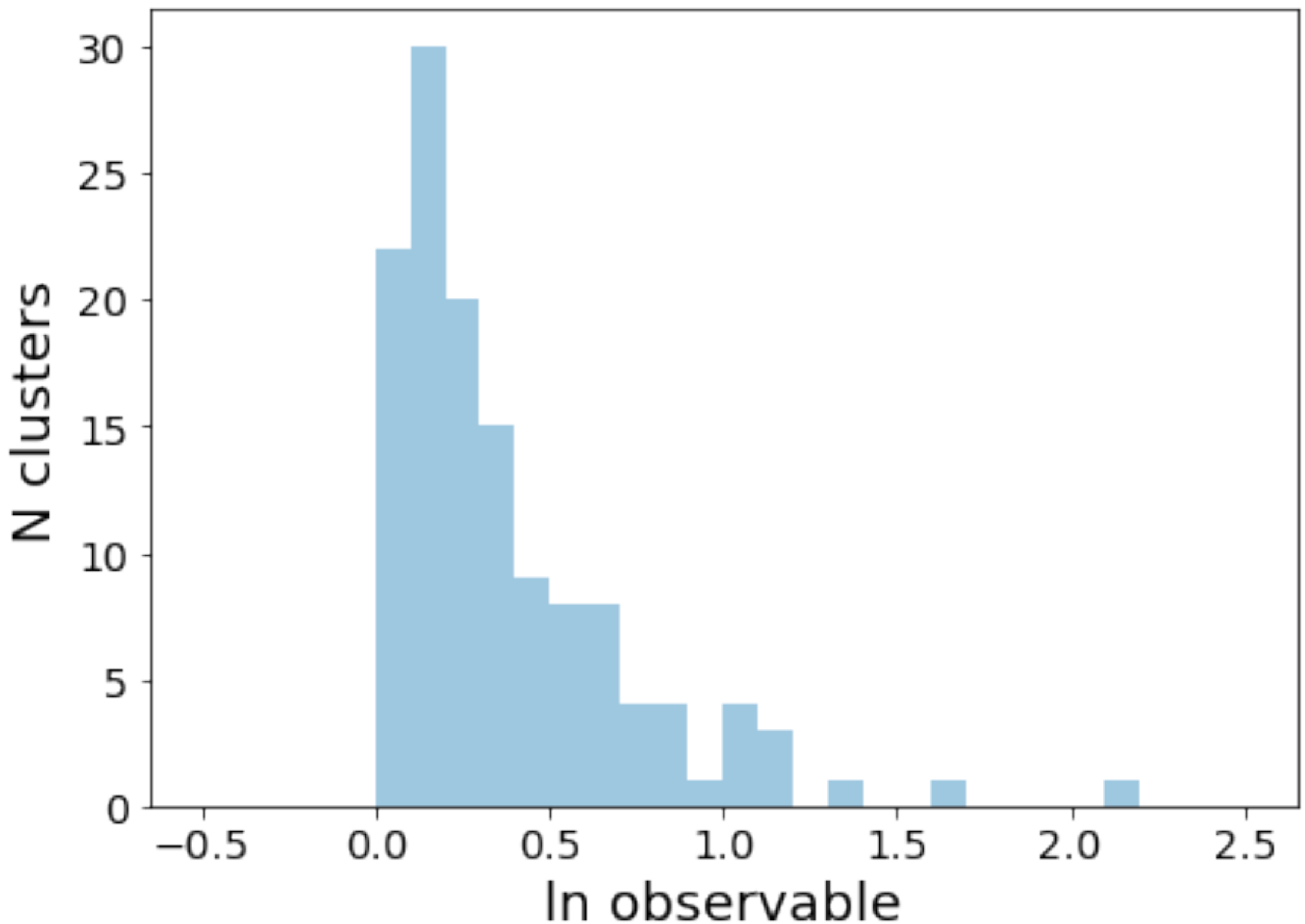
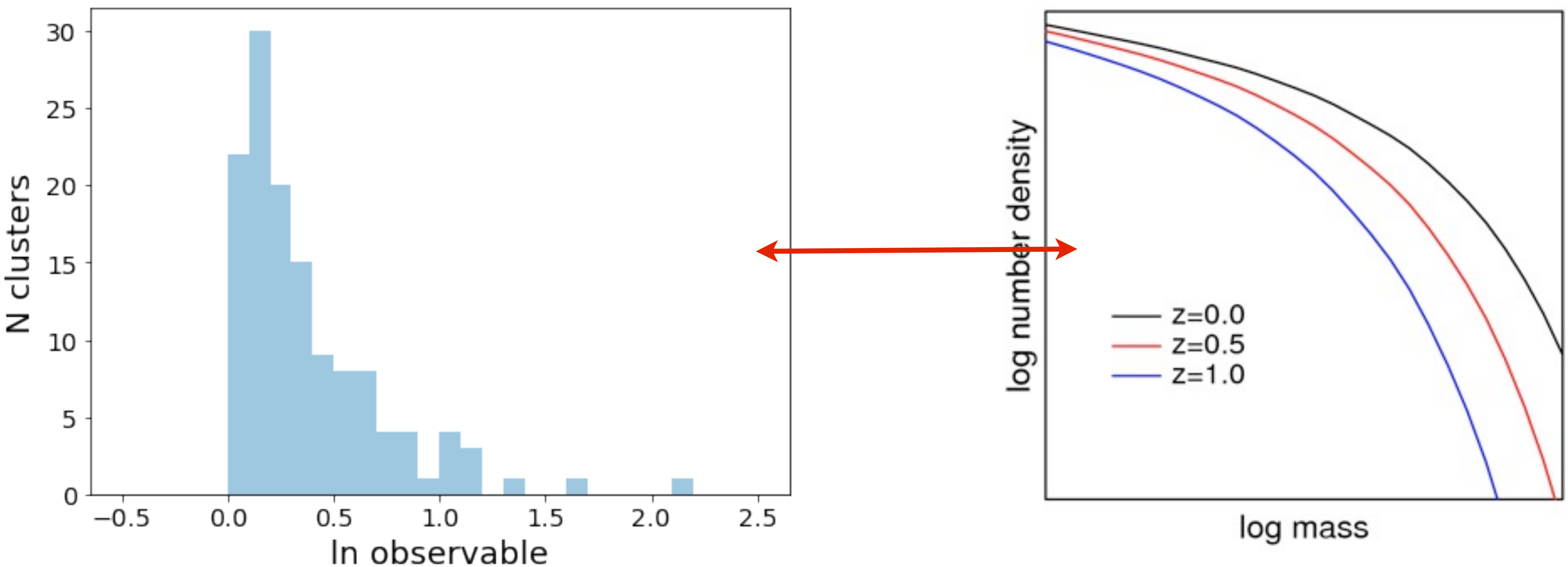
... but we can't tell from the survey data alone



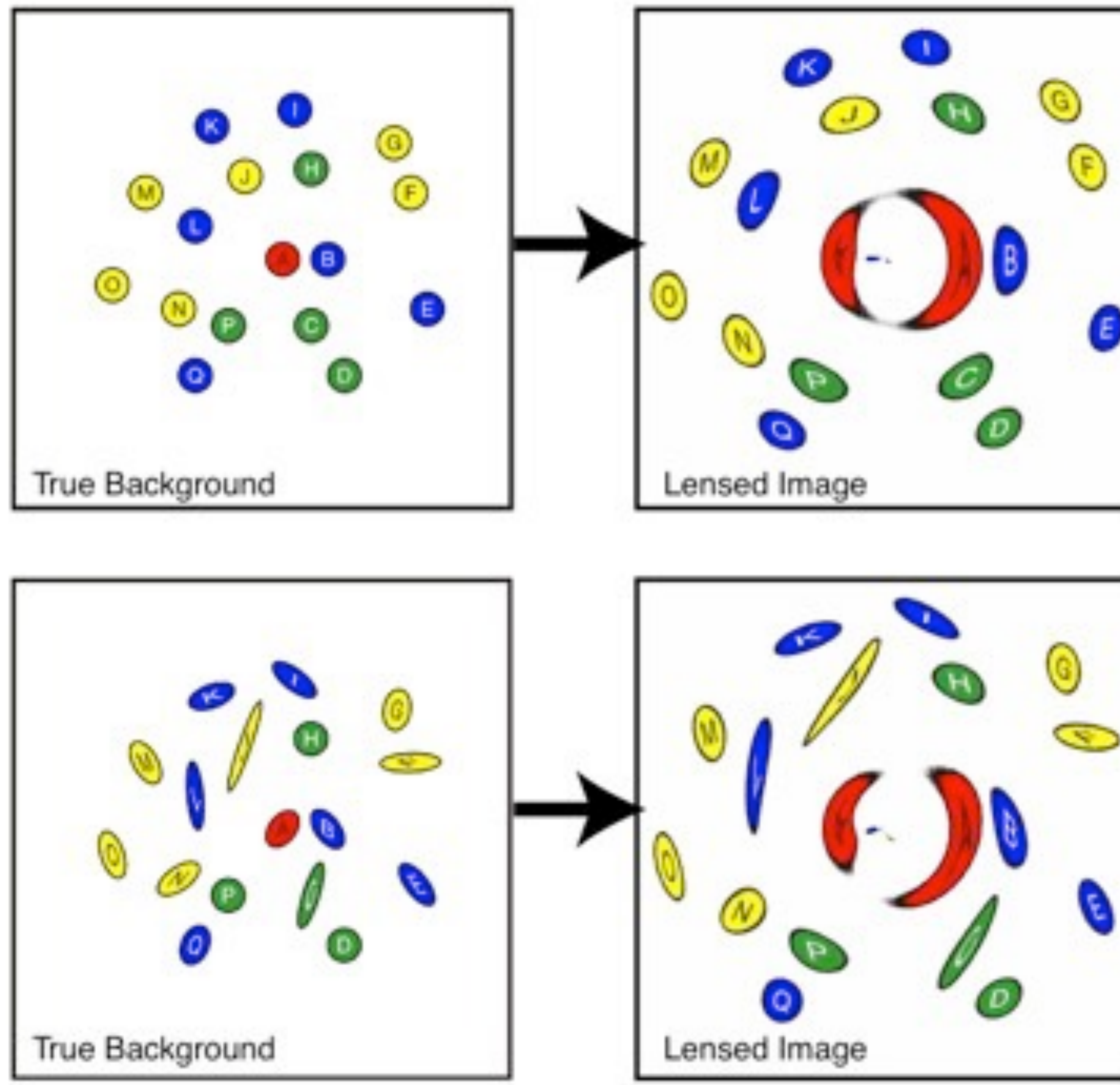
we need to connect the number of observed clusters (with some observable property such as richness) to the halo mass function

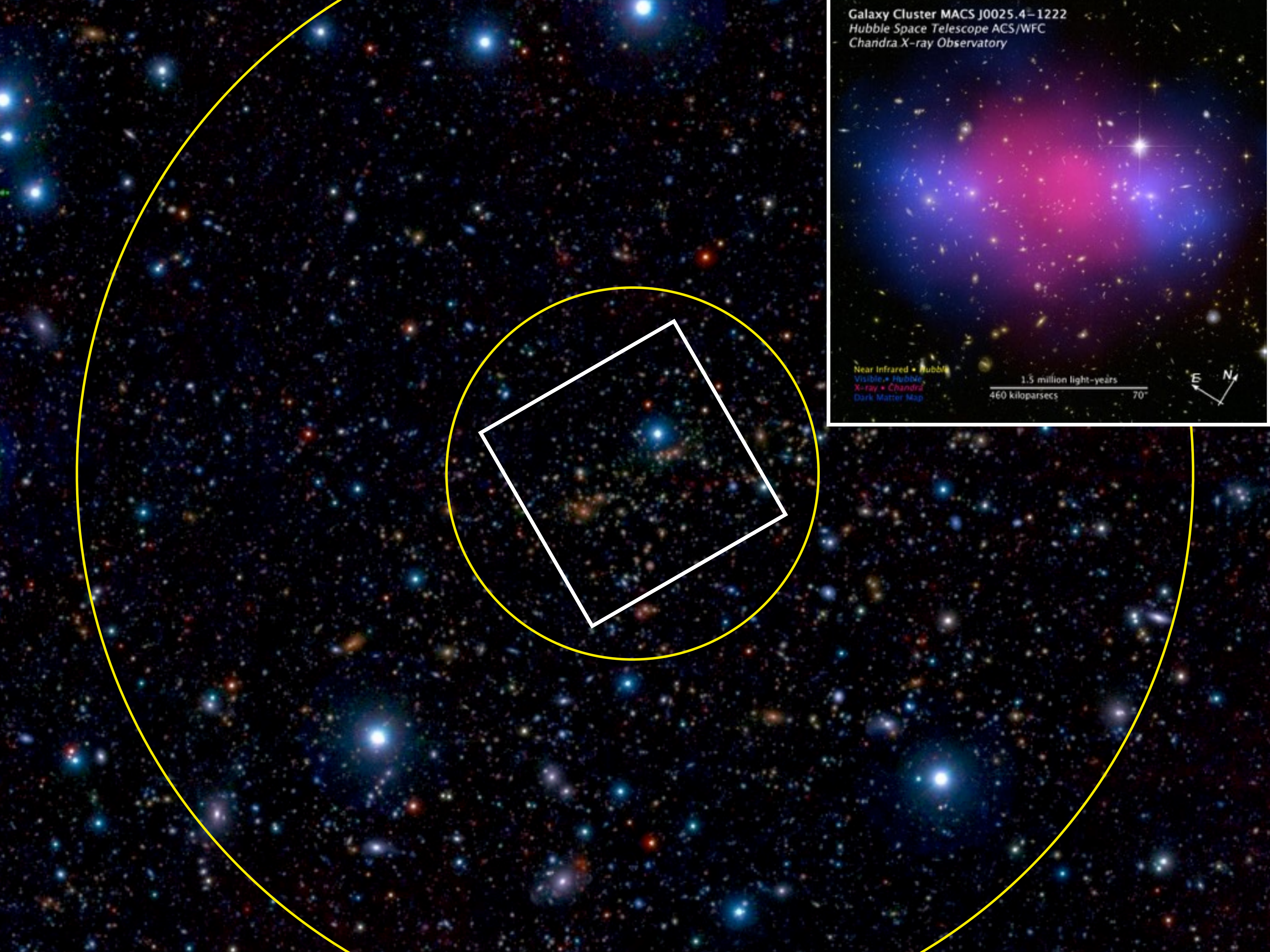


Cluster Weak Lensing

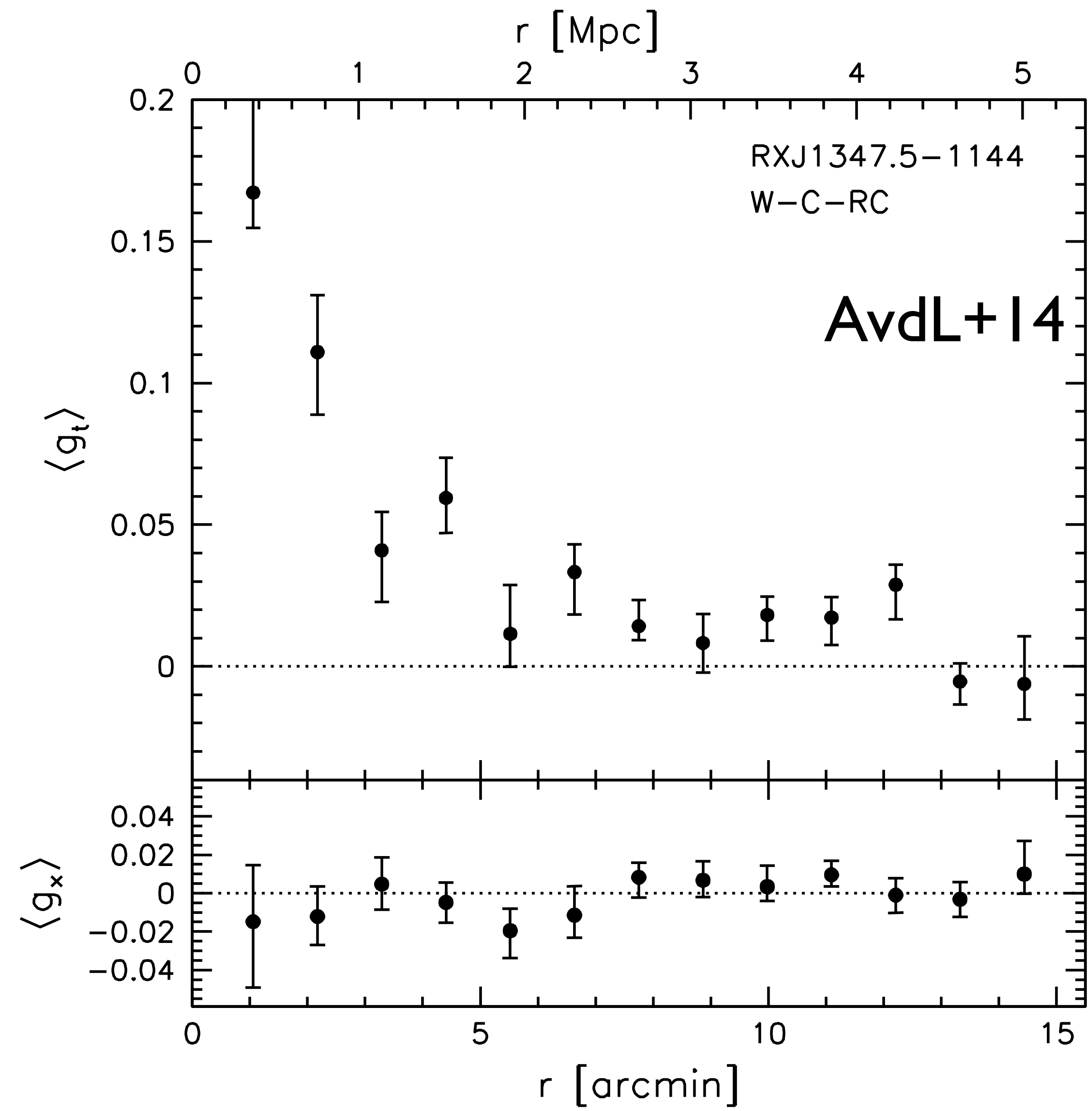
LSST is being built to excel at weak lensing

→ we can use cluster weak lensing to measure cluster masses



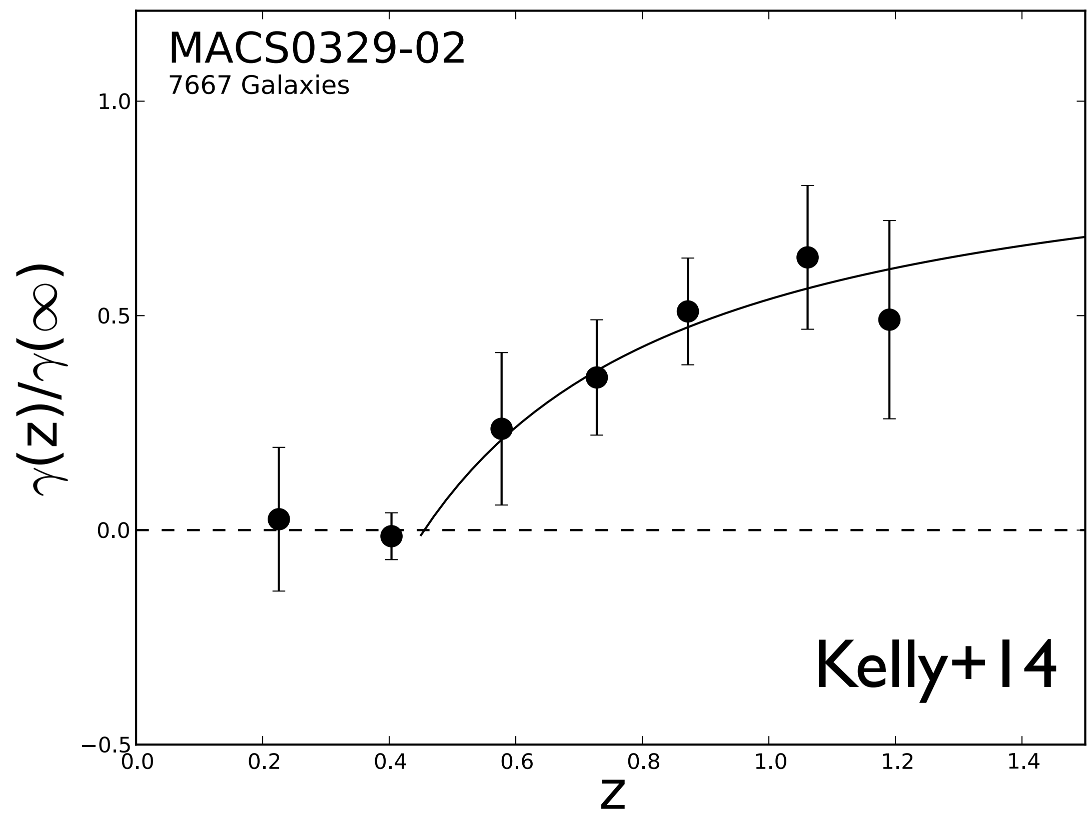

Galaxy Cluster MACS J0025.4−1222
Hubble Space Telescope ACS/WFC
Chandra X-ray Observatory
Near Infrared • Hubble
Visible • Hubble
X-ray • Chandra
Dark Matter Map
1.5 million light-years
460 kiloparsecs
70"
E
N

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

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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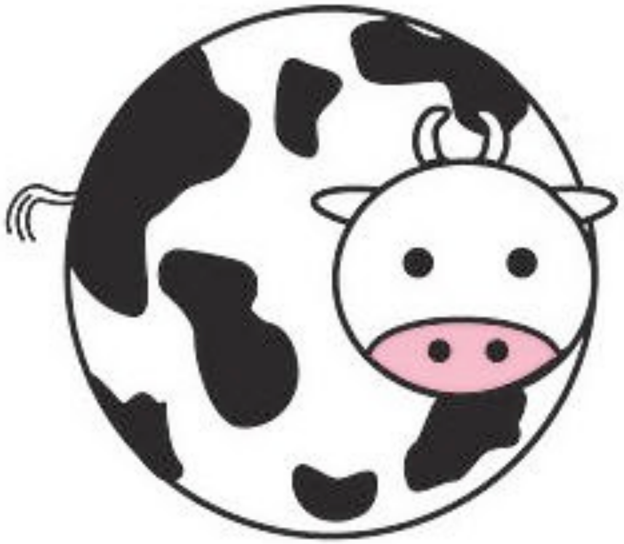

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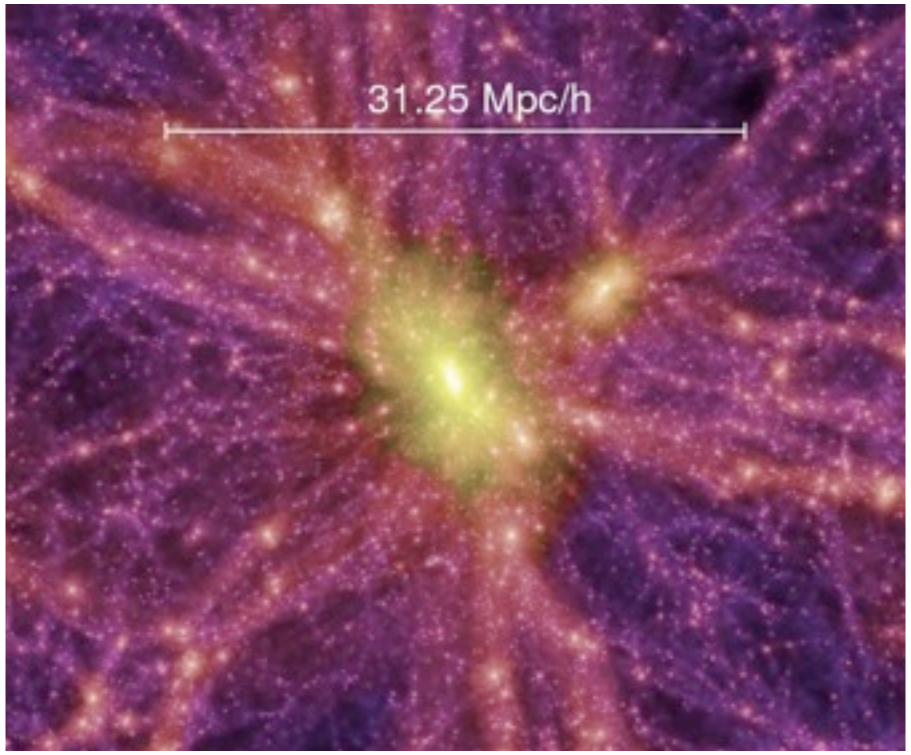
e.g. Meneghetti et al. 2010, Hoekstra 2003, 2011



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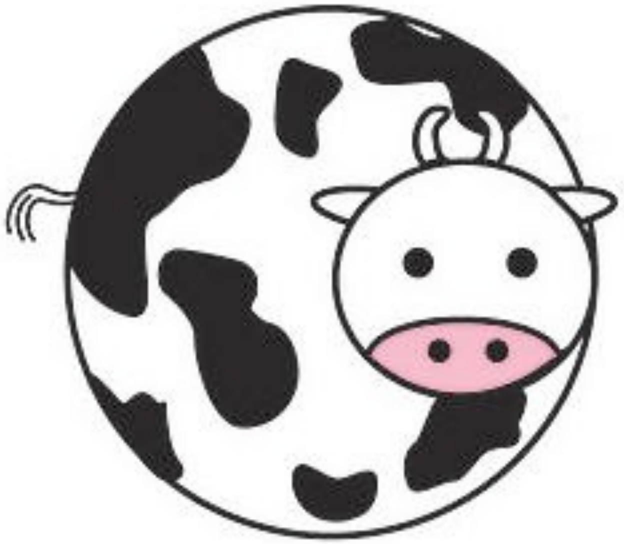

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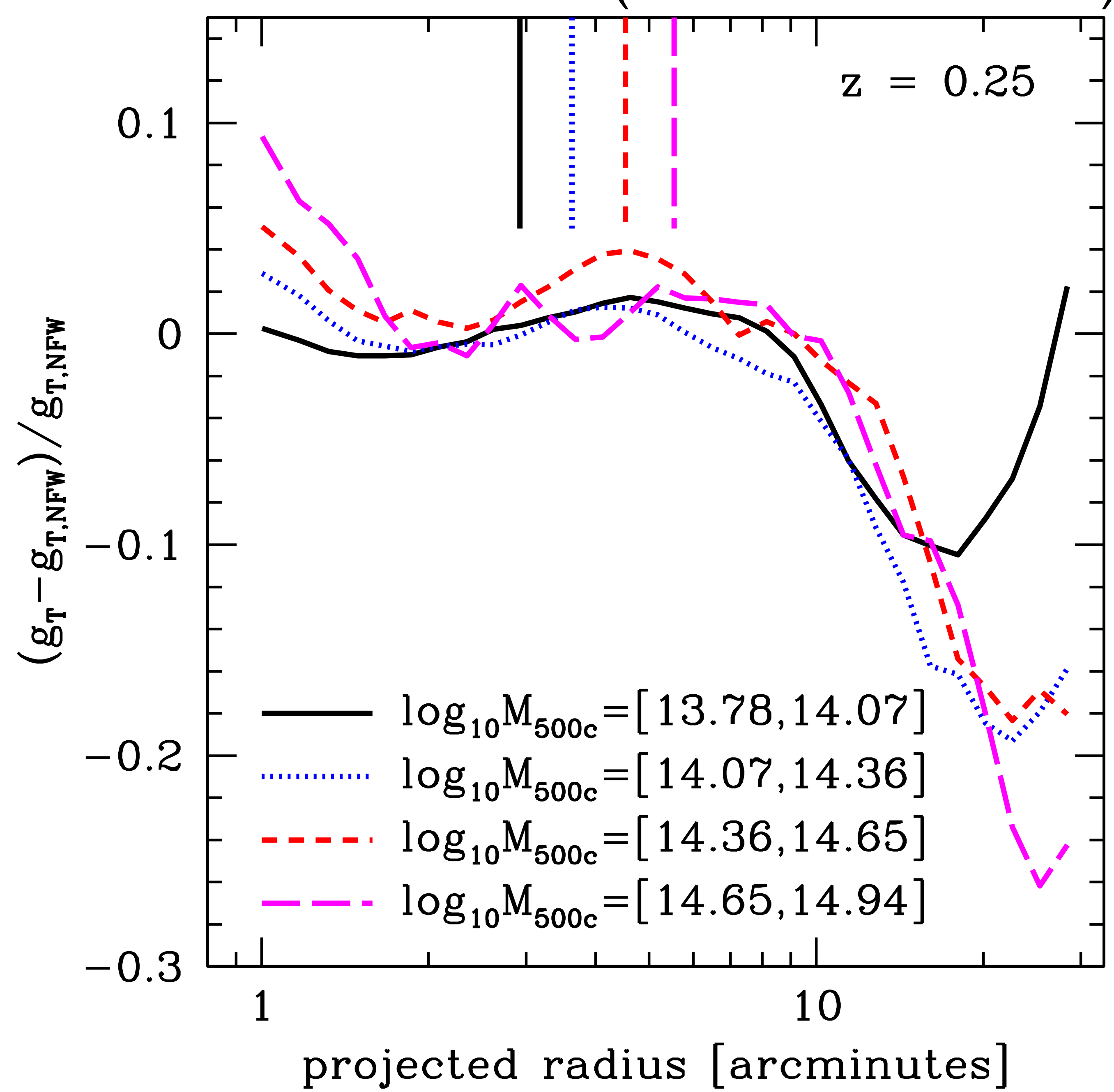
- (3D) lensing masses have **intrinsic, irreducible scatter** of $\gtrsim$20%
(ground-based: scatter from shape noise also ~20% ⇒ total scatter: ~30%)

(e.g. Becker & Kravtsov 2011)

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

- *methodology can be well tested on simulations*
- NFW profile good description only to virial radius

(Becker&Kravtsov 11)



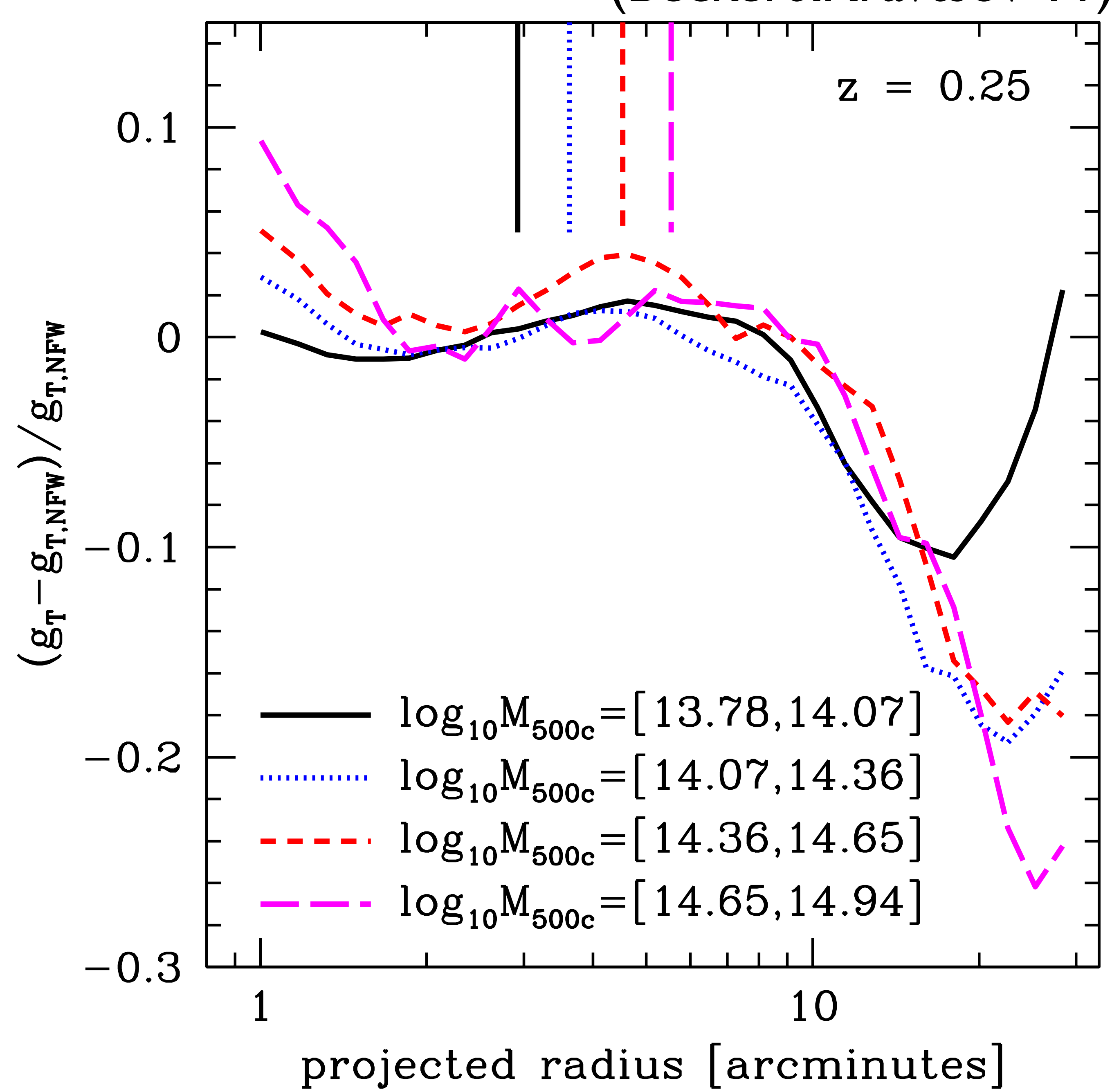
LSST DESC Dark Energy Science Collaboration

- mass bias small (a few percent), but needs to be accurately calibrated for cluster cosmology

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

- *methodology can be well tested on simulations*
- NFW profile good description only to virial radius
- need to quantify mass bias as function of mass, radius, redshift, fitting method, miscentering, cosmology, ... and include baryons

(Becker&Kravtsov 11)



LSST DESC Dark Energy Science Collaboration

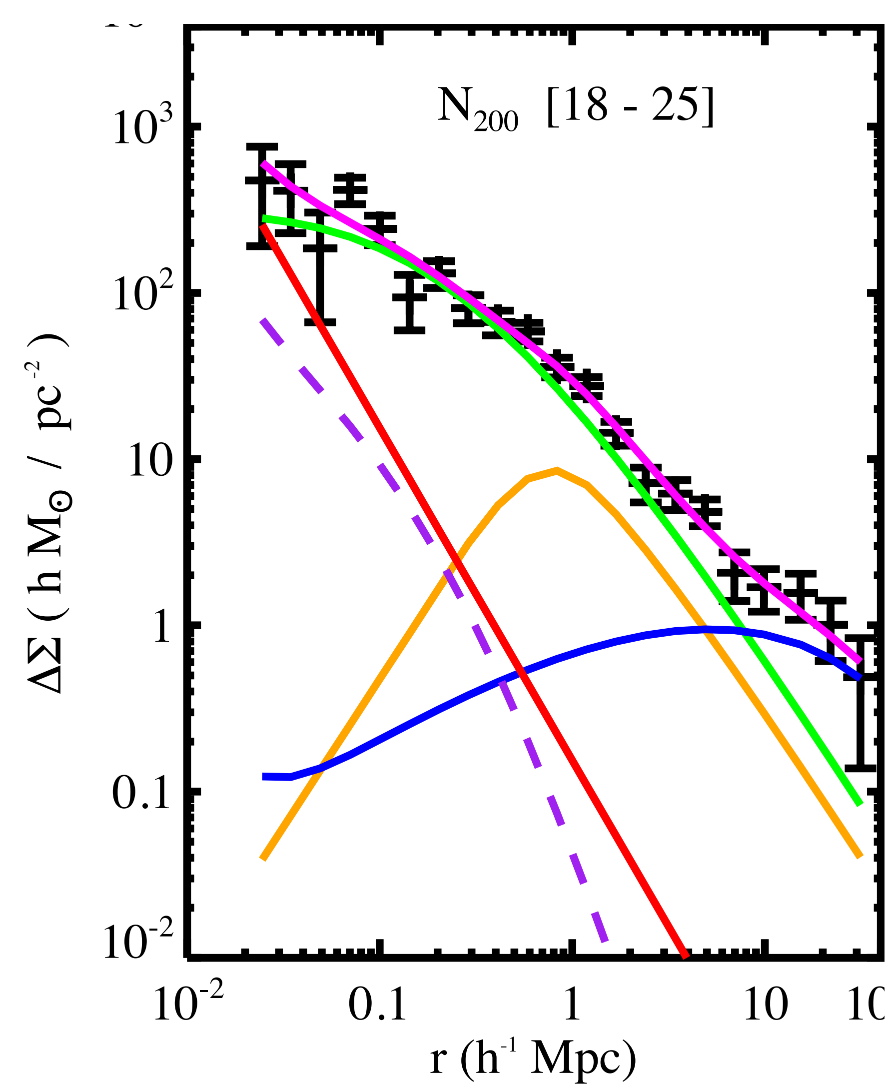
- mass bias small (a few percent), but needs to be accurately calibrated for cluster cosmology *average lensing mass (nearly) unbiased, but scatter of $\gtrsim$30%*

➡ need large cluster samples

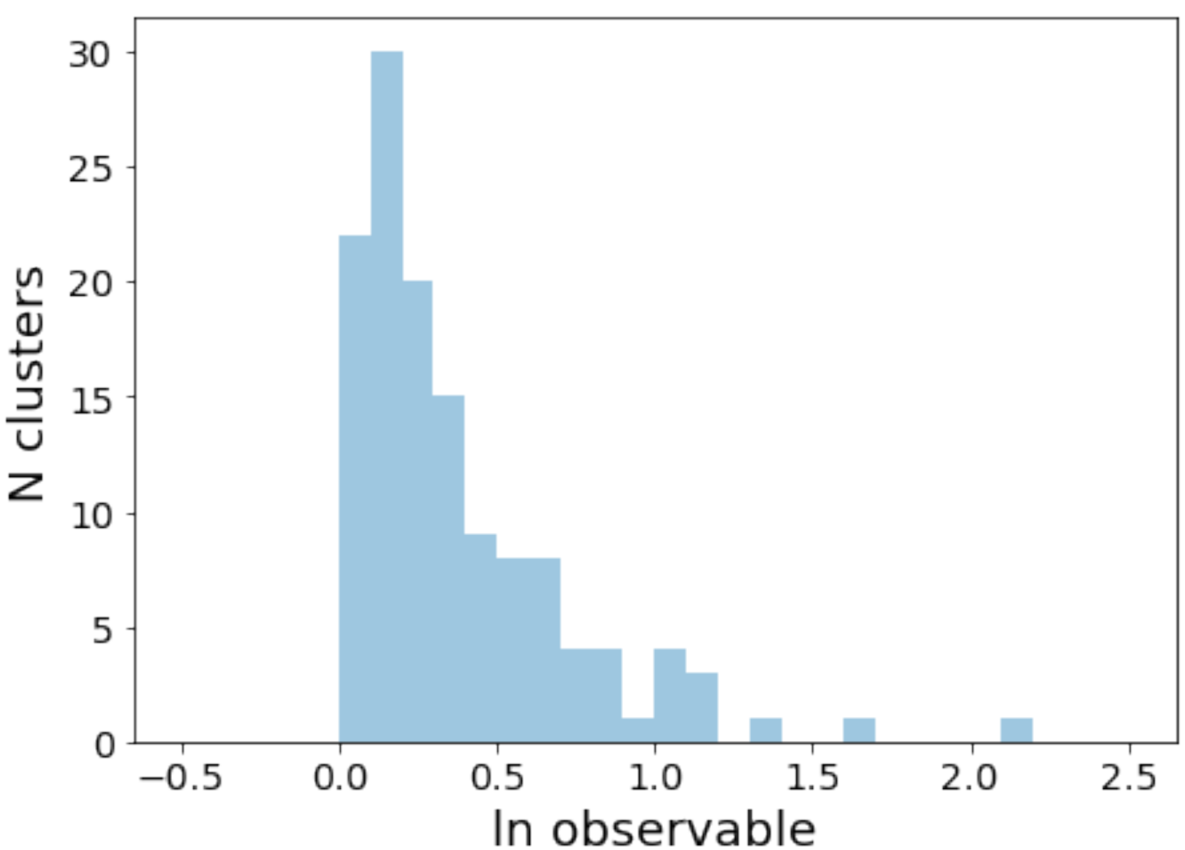
(Johnston et al. 2007)

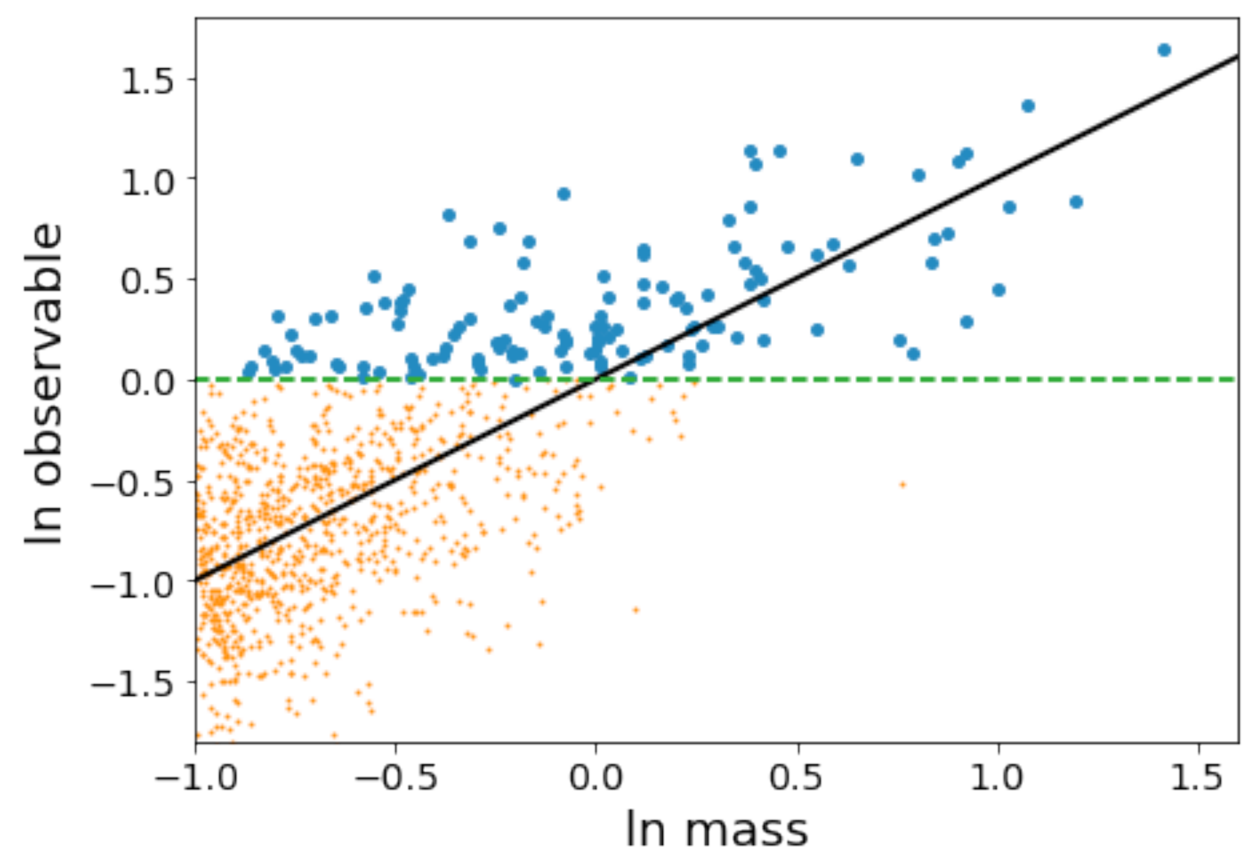
individual masses are constrained only for massive clusters;

especially for lower mass clusters: use stacked weak lensing to get the mean mass (or joint analyses, Lieu et al. 2017)

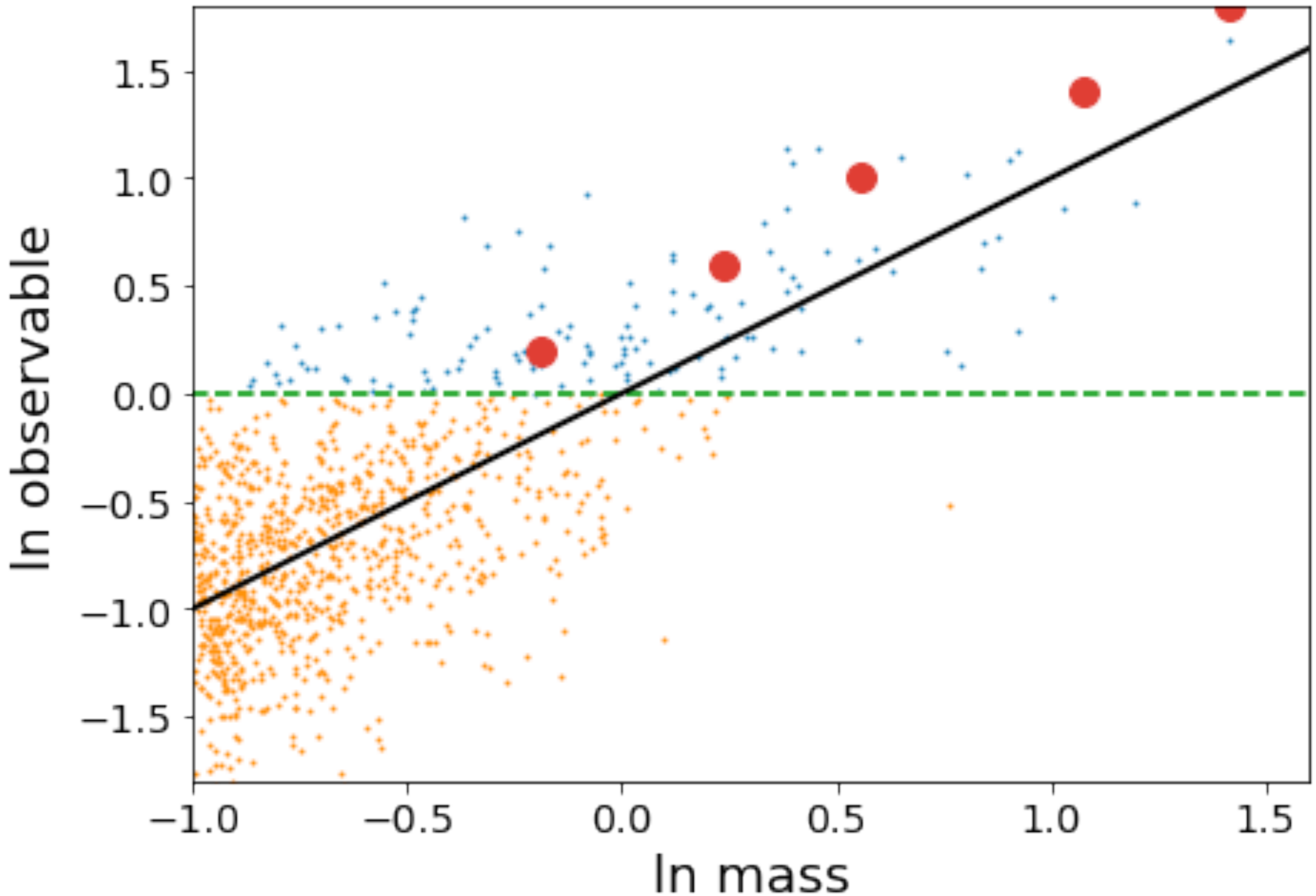


5. Perform a stacked weak lensing analysis for your mock MOR, i.e. "measure" the mean mass in bins of the observable
6. Draw your measurements onto the MOR. Can you reconstruct the true MOR?



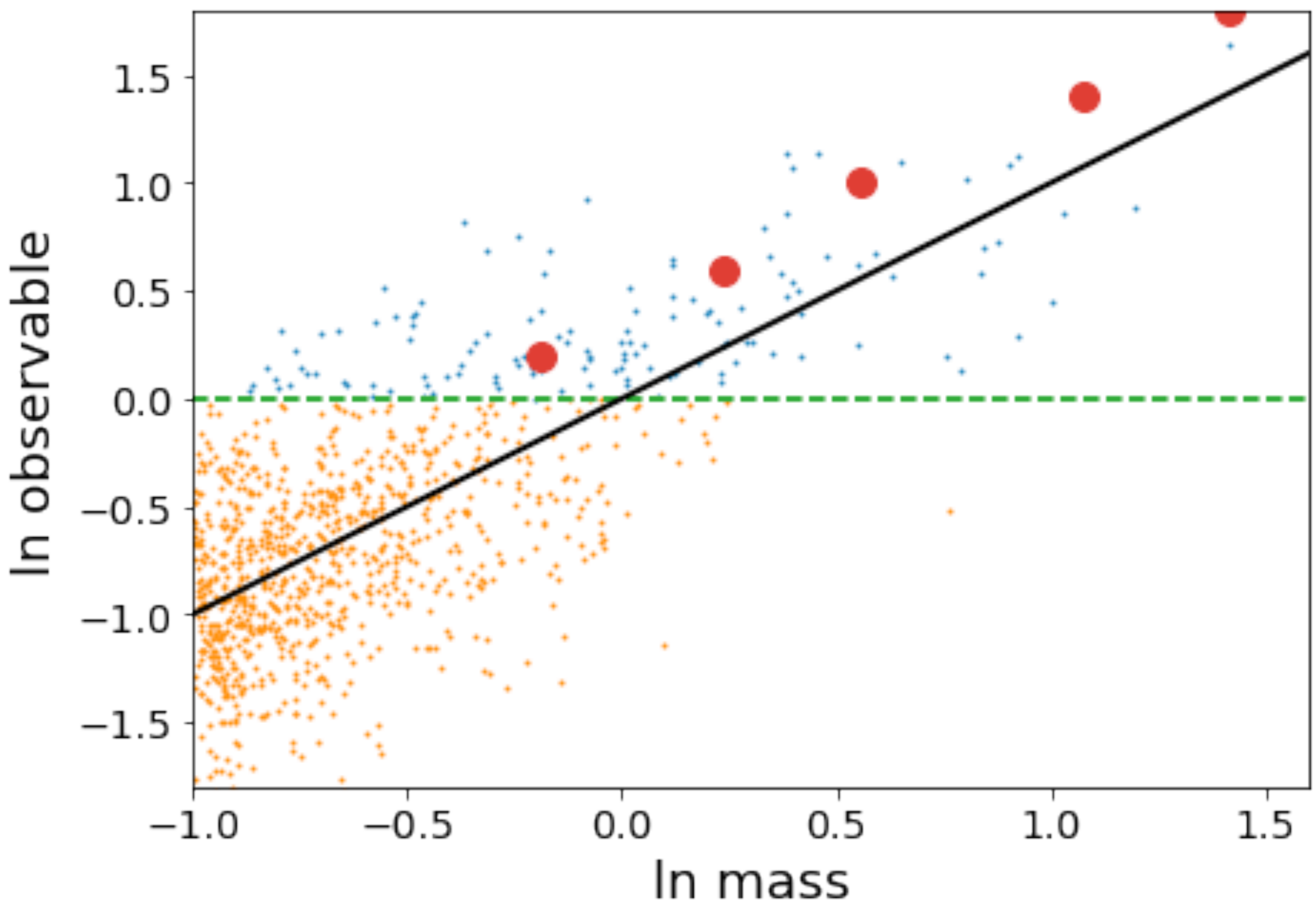


because of Eddington bias, the mean mass in each bin of ln(observable) does not lie on the mean MOR



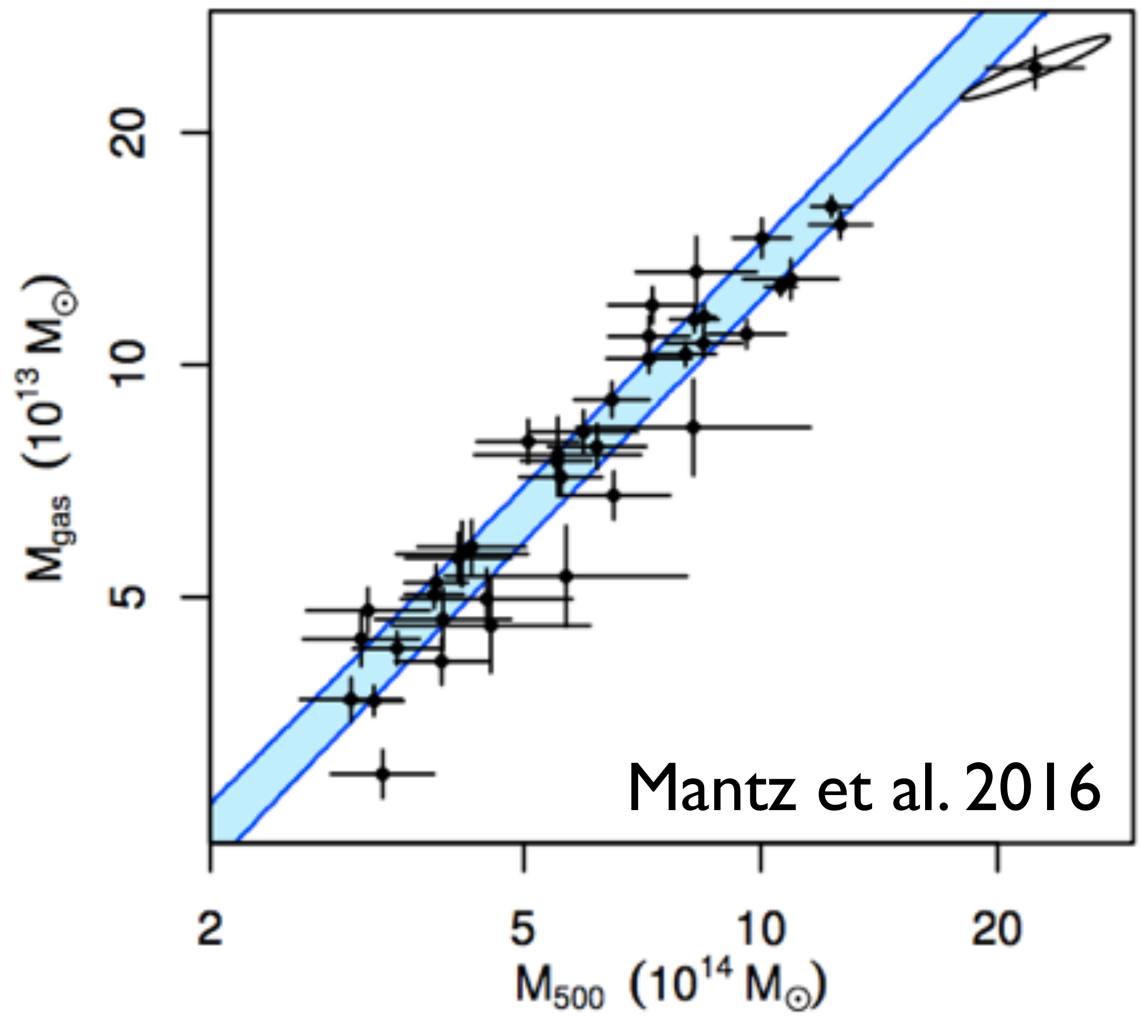
How to get the true MOR?

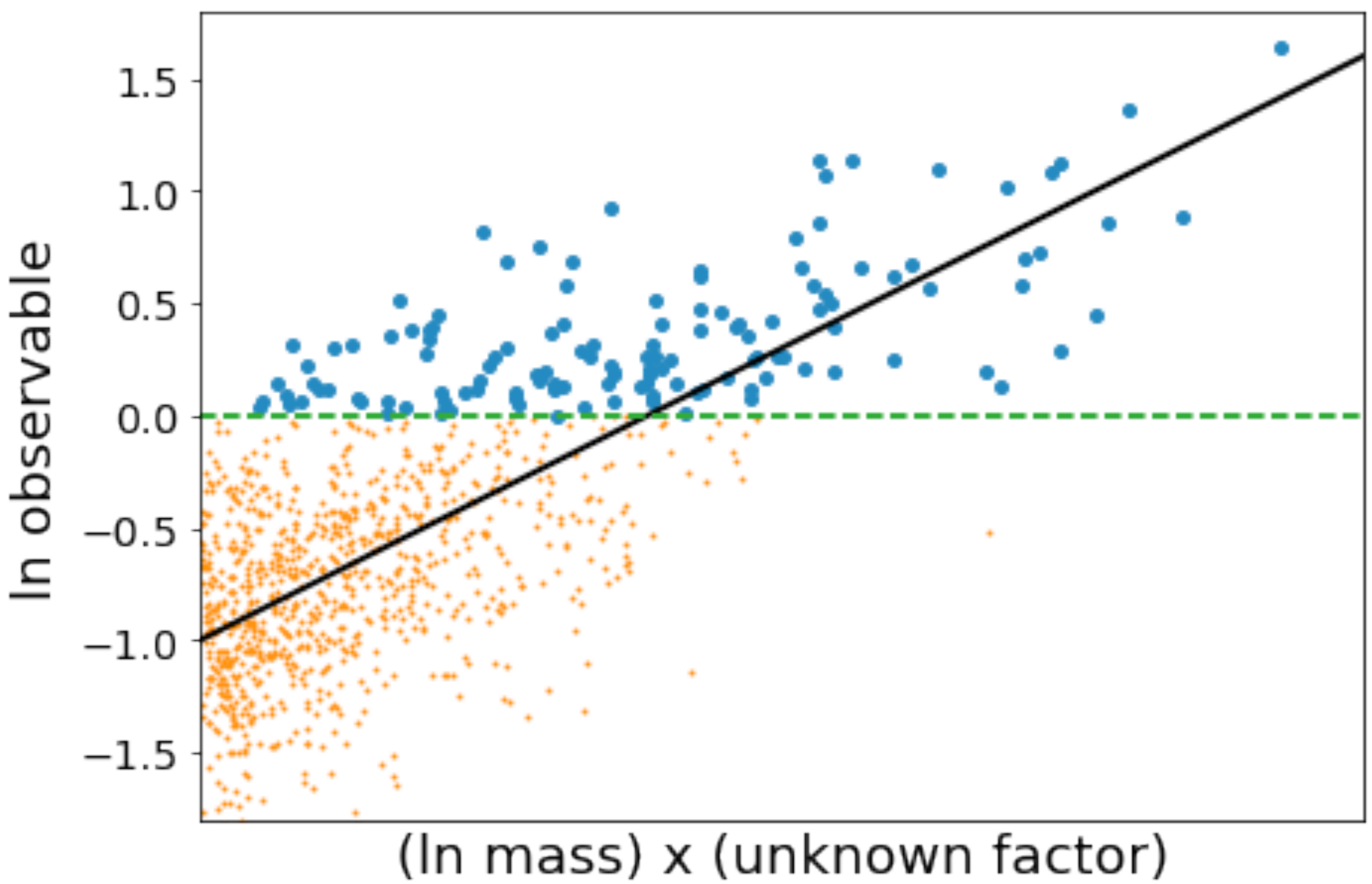
a) calibrate (the scatter) on simulations? → very difficult
b) additional follow-up observations



Low-scatter mass proxies

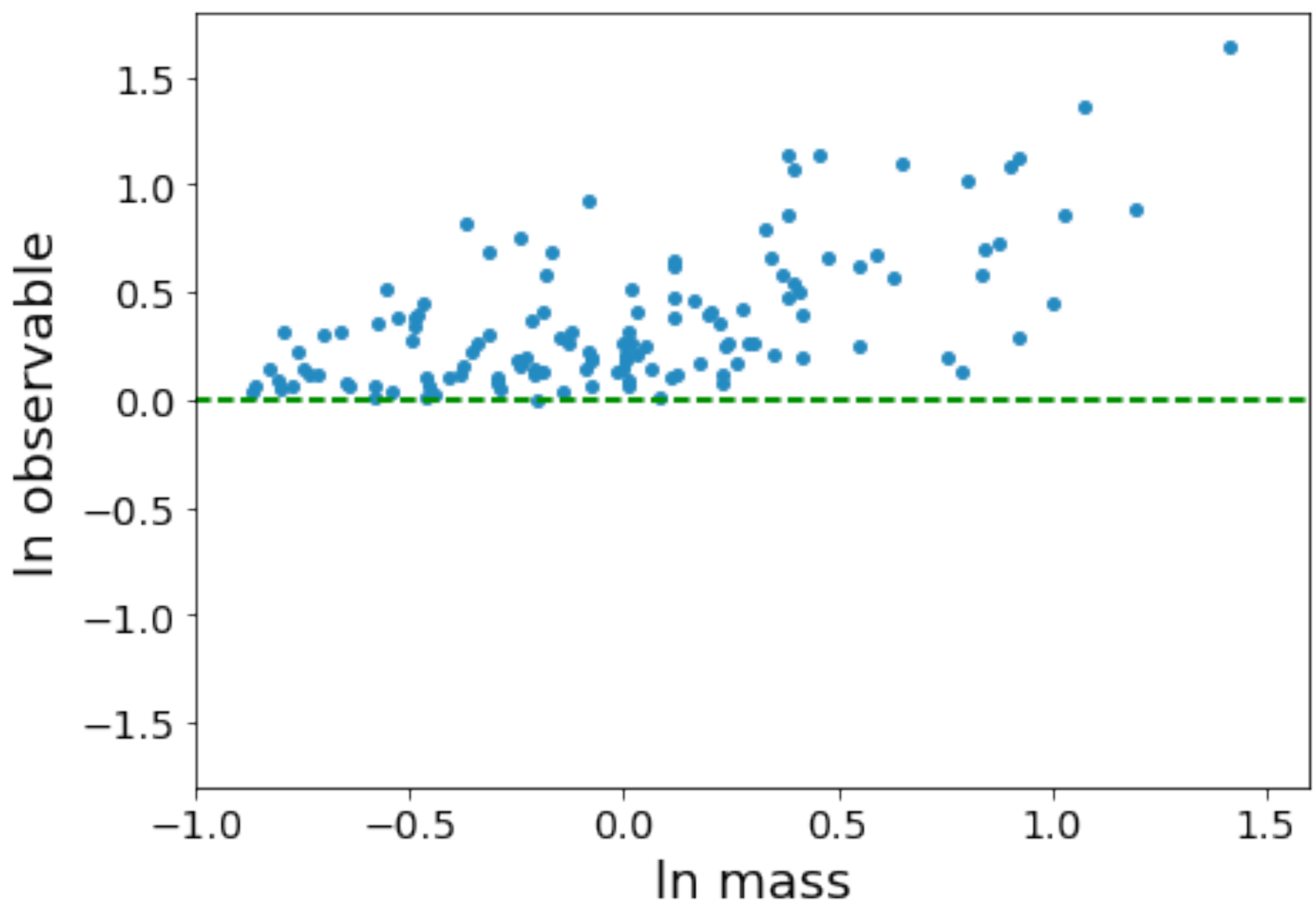
- follow-up X-ray observations can provide a number of low-scatter (≲10%) mass proxies:
  - ICM temperature T_X; gas mass M_{gas}; $Y_X = M_{gas} \times T_X$



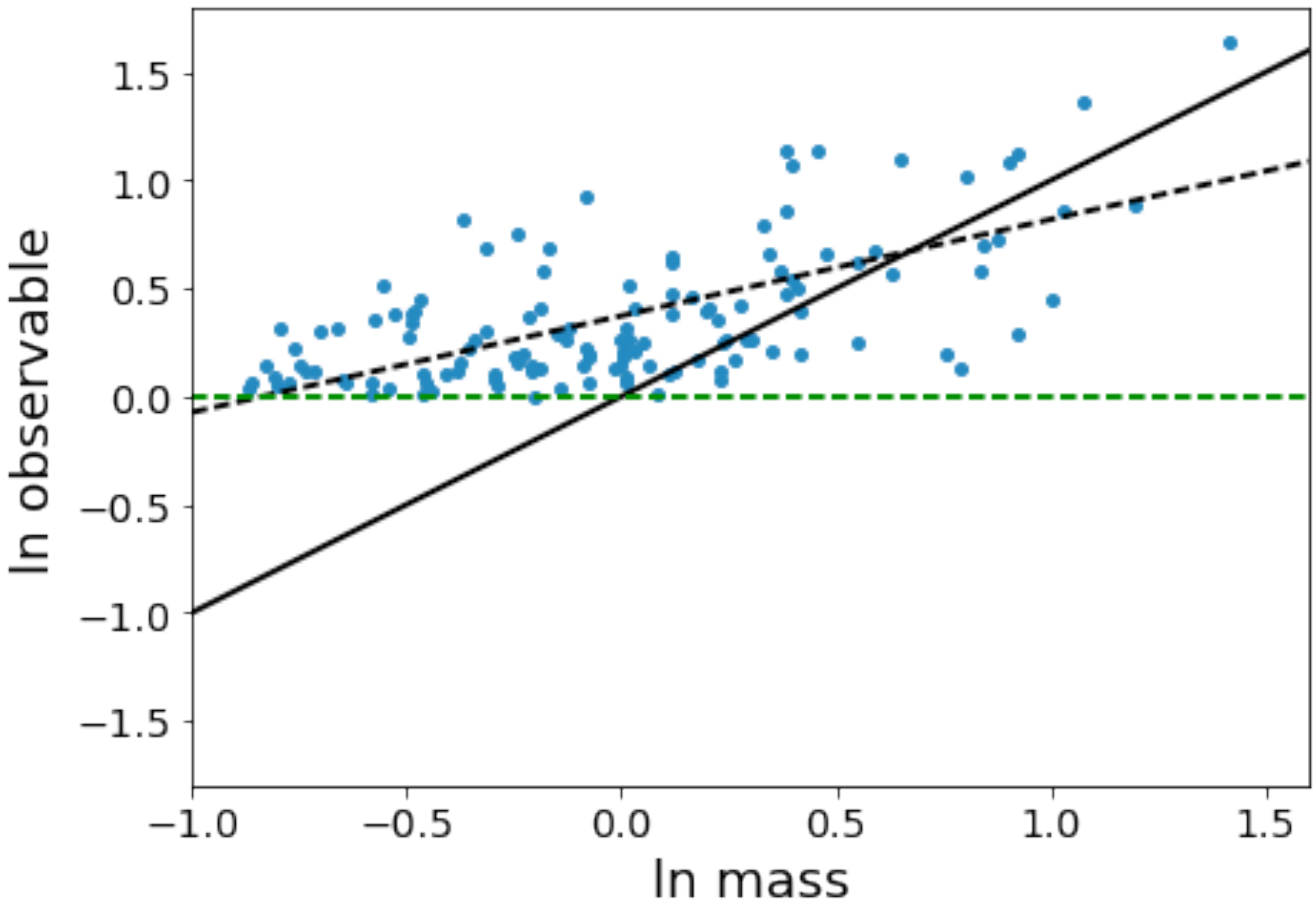


- essential for measuring shape and scatter of M-O relation
- do *not* provide absolute mass calibration → need WL

- with both weak-lensing mass estimates and low-scatter mass proxies, can reconstruct MOR <u>for detected clusters</u>



- this is now an inference problem with *truncated* data
- ordinary least-squares is not applicable!



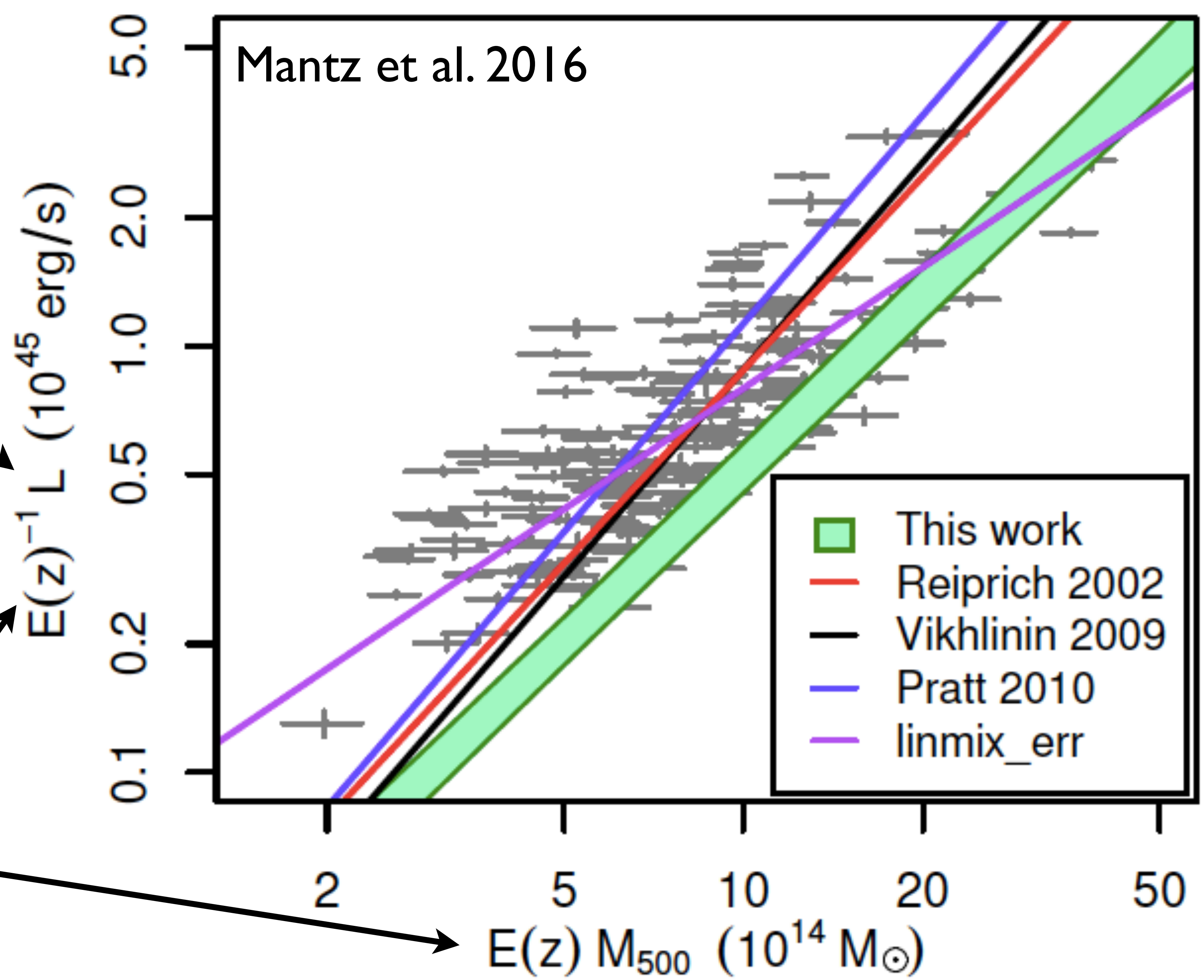
Real-world example

Weighing the Giants: X-ray selected clusters

- with individual weak-lensing masses
- and follow-up low-scatter mass proxies

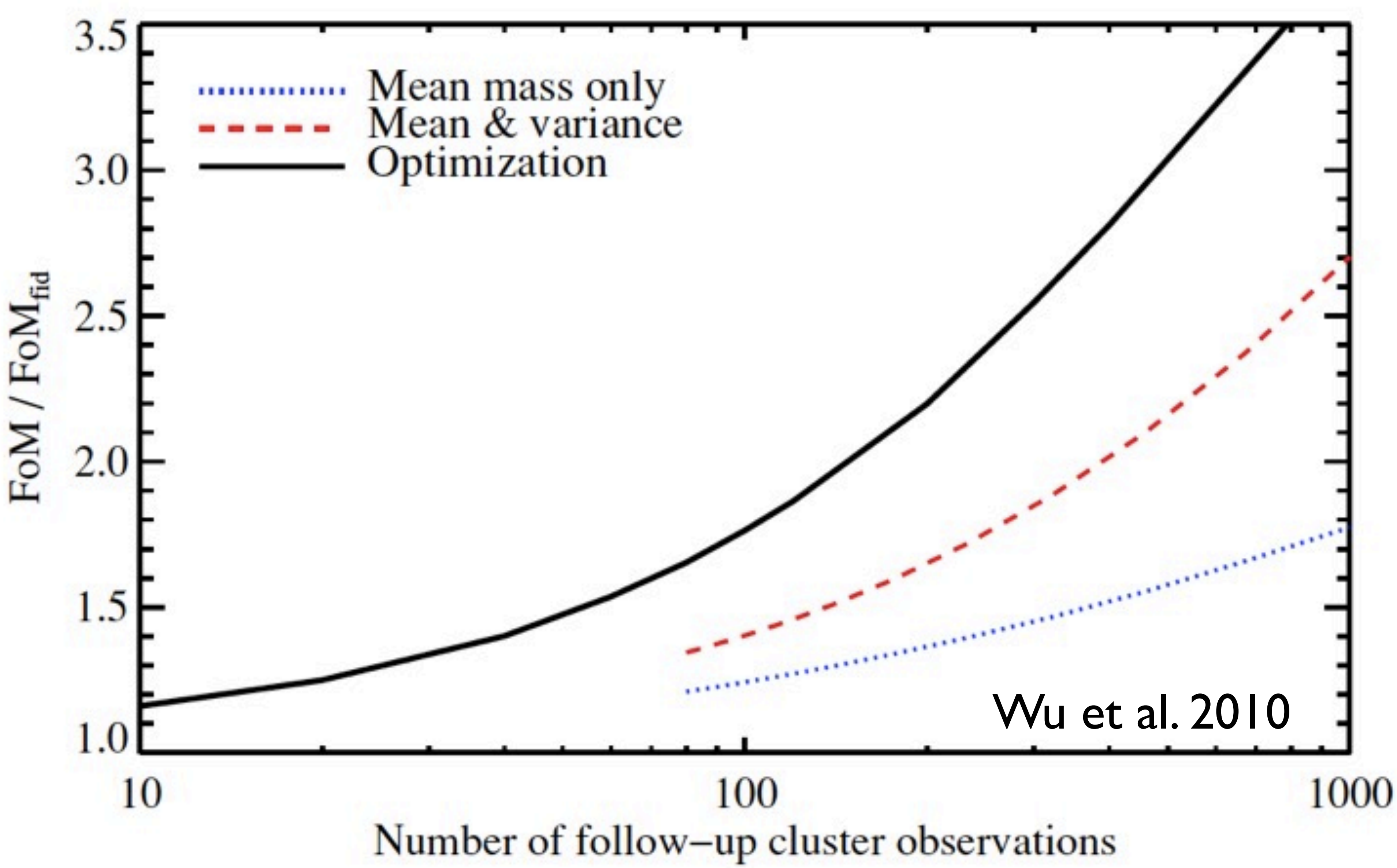
survey observable:
X-ray luminosity

$E(z) = H(z) / H_0$



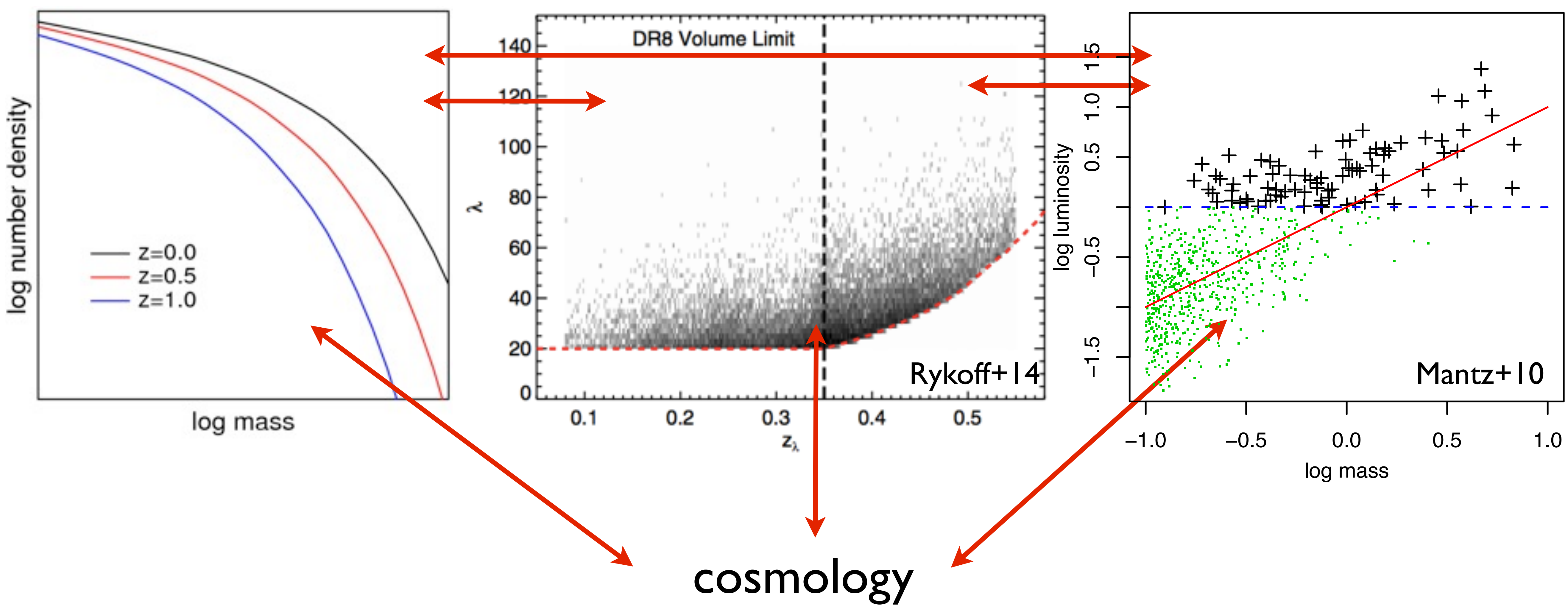
Low-scatter mass proxies

- essential for measuring shape and scatter of M-O relation
  - ➡ significant increase in constraining power



Cosmology + MOR

- generally, the quantities on the y- and x-axis of the MOR depend on cosmology
- e.g. weak lensing mass (angular diameter distances)
- e.g. X-ray luminosity (from X-ray flux and redshift)
- cannot determine MOR independently of cosmology!



Let's review our assumptions

- mean MOR follows a power-law
- shape of intrinsic scatter in MOR is log-normal
- size of intrinsic scatter in MOR is constant
- scatter in weak-lensing mass is independent of scatter in observable

How good are these assumptions?

Finding clusters

optical / NIR

✓ highest completeness, to low masses

- subject to projection effects
- some fraction of BCGs catastrophically miscentered

X-rays:

✓ in principle, very high purity and completeness (every extended extragalactic source is a cluster)

- in practice: limited angular resolution leads to impurity / incompleteness due to AGN confusion
- large scatter Lx - mass of ~40% due to cool cores

Sunyaev-Zeldovich effect:

✓ nearly redshift-independent mass selection threshold

✓ high purity and completeness

✓ relatively small scatter in SZ signal - mass of ~20%

- scatter mostly caused by triaxiality / orientation

Let's review our assumptions

- mean MOR follows a power-law
- shape of intrinsic scatter in MOR is log-normal
- size of intrinsic scatter in MOR is constant
- scatter in weak-lensing mass is independent of scatter in observable

Which of these assumptions could be broken for which cluster finder?

Some answers

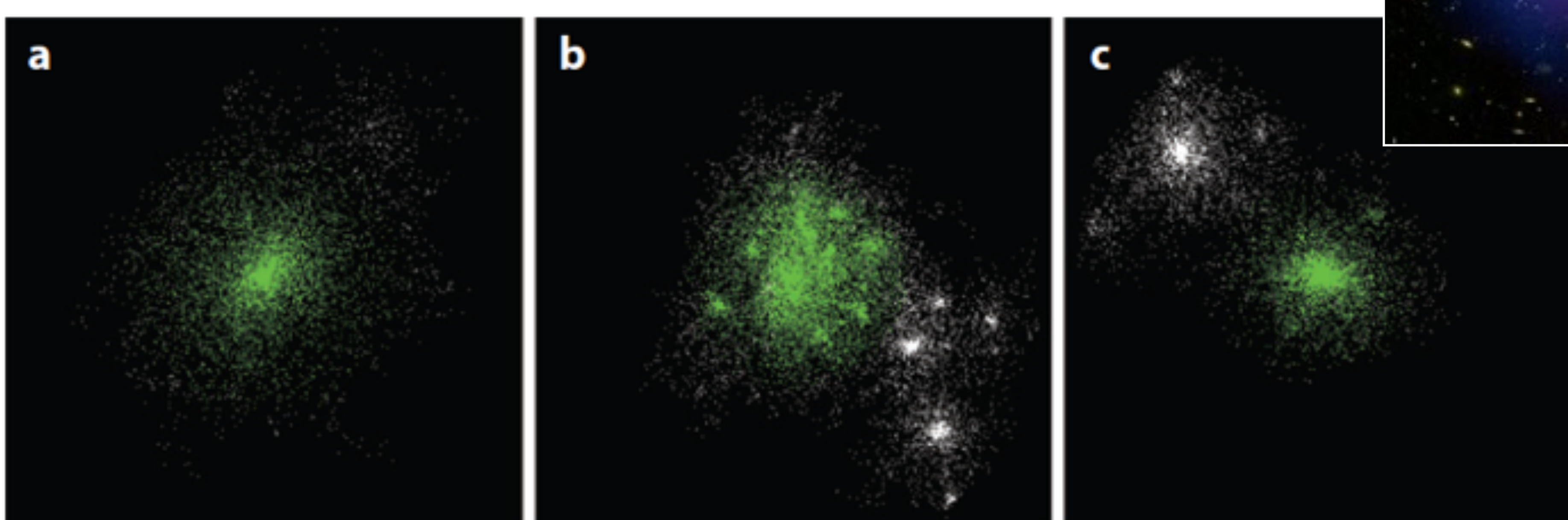
Which of the assumptions could be broken for which cluster finder?

- X-ray luminosity: is the intrinsic scatter bimodal (cool core Y/N)?
- optical and SZ: scatter caused by triaxiality / orientation, same as WL scatter
- projection effects: skewed scatter

Some answers

Which of the assumptions could be broken for which cluster finder?

- X-ray luminosity: is the intrinsic scatter bimodal (cool core Y/N)?
- optical and SZ: scatter caused by triaxiality / orientation, same as WL scatter
- projection effects: skewed scatter
- is it one cluster? two clusters? ... ?



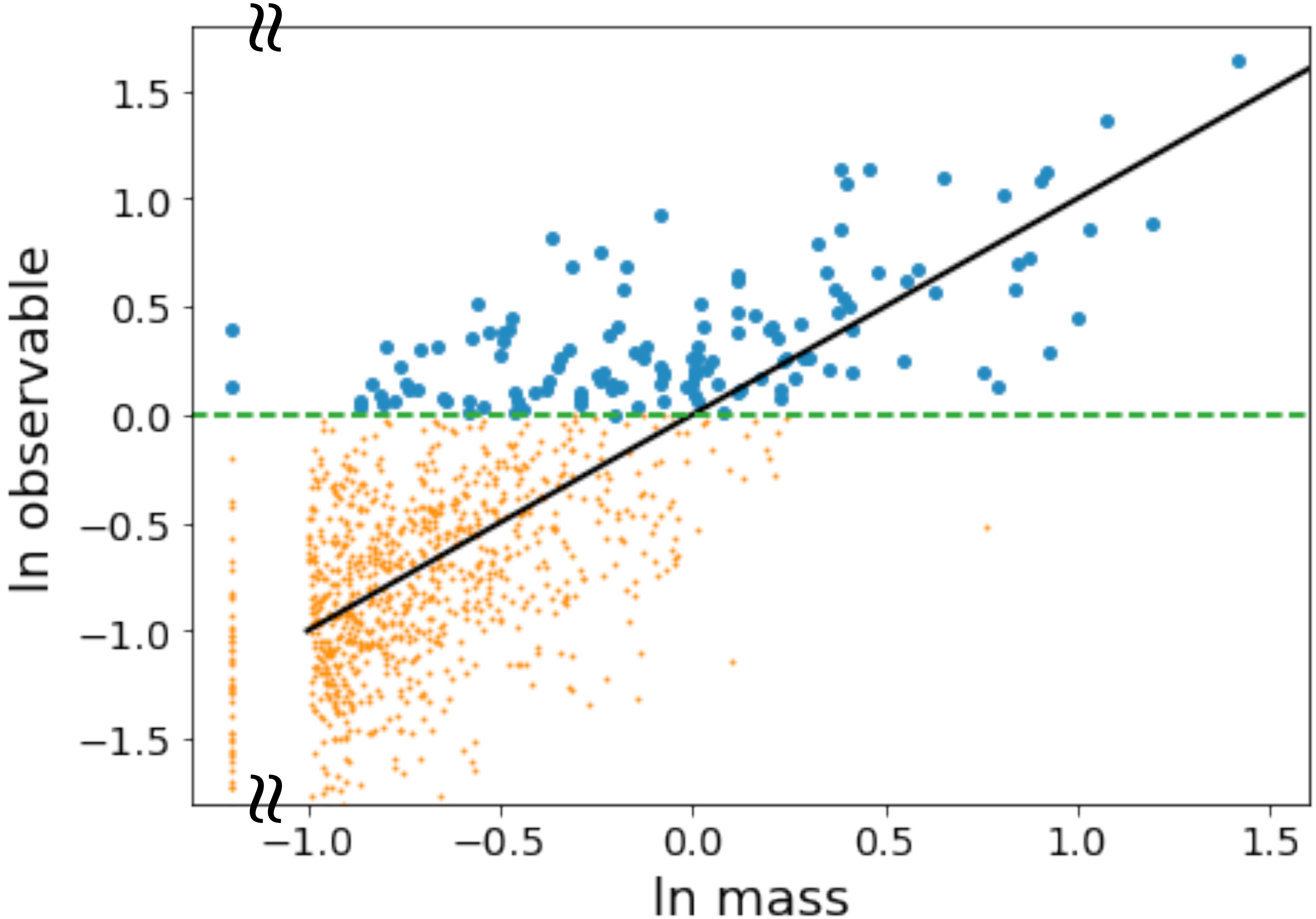
Complications (an incomplete list)

need to know the *survey selection function*:

completeness: what fraction of *real* clusters are detected?

purity: how many false positives are there?

→ need to know for number counts AND stacked lensing

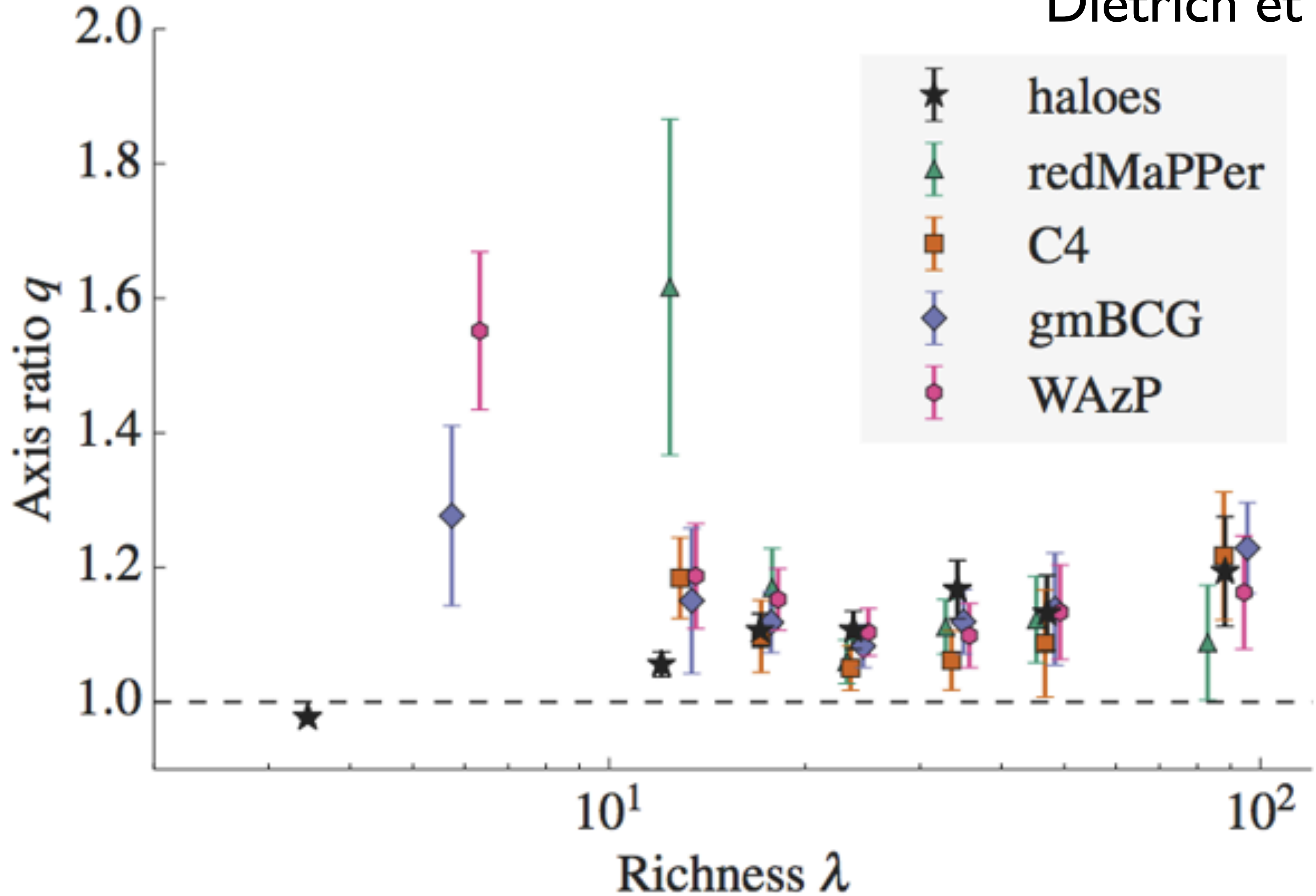


Complications (an incomplete list)

covariance in observable and lensing mass: prolate halos oriented along line-of-sight have:

- higher richness
- higher SZ signal
- higher lensing mass

Dietrich et al. 2014

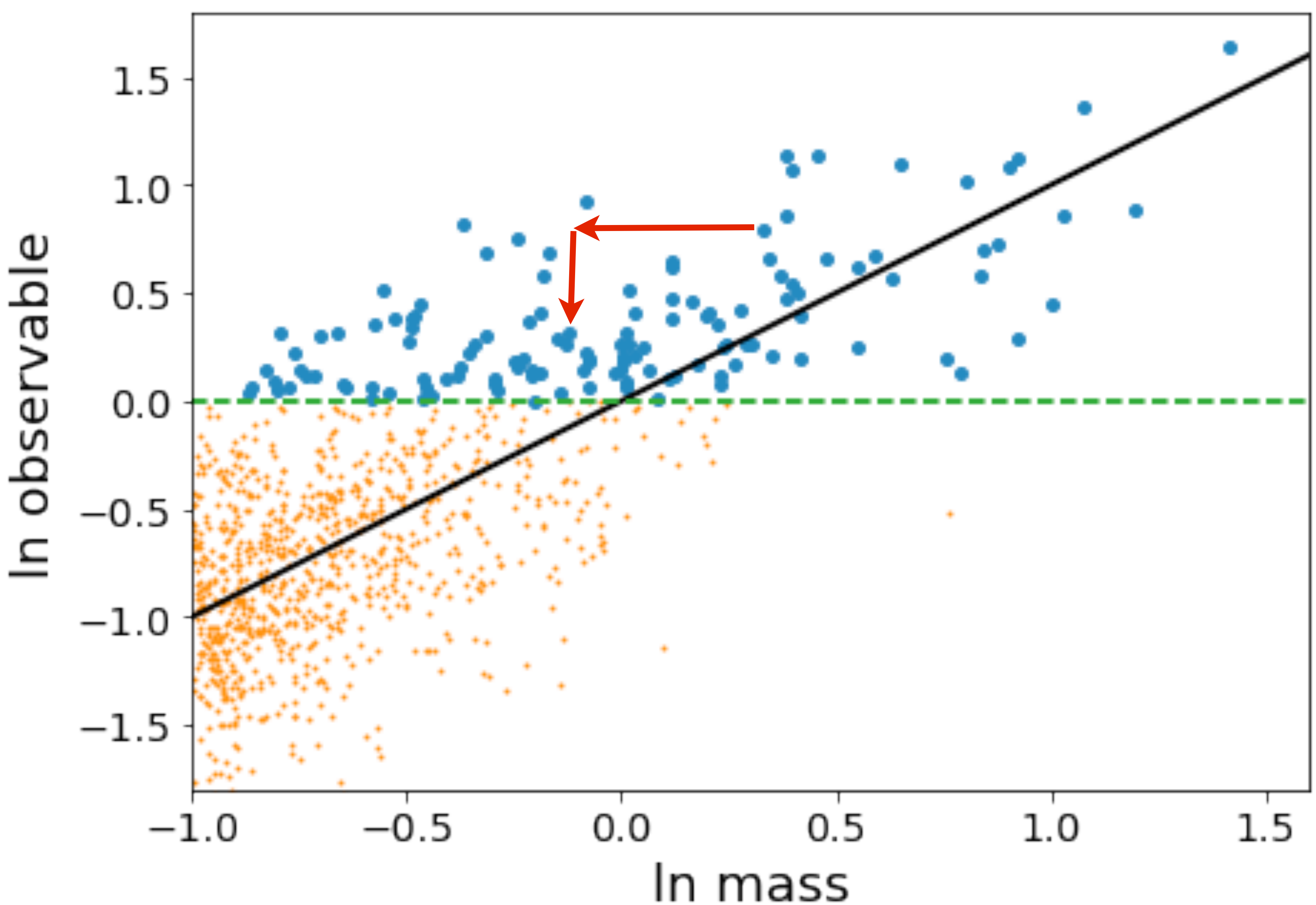


Complications (an incomplete list)

miscentering: “wrong” cluster center

→ observable underestimated

→ lensing mass underestimated



Multi-wavelength synergy

intrinsic scatter in different observables (optical, X-ray, SZ) due to different causes

combining cluster surveys can inform several issues:

- purity / completeness
- miscentering
- triaxiality
- ...

+ necessity for low-scatter mass proxies

→ best cosmology constraints come from multi-wavelength analyses

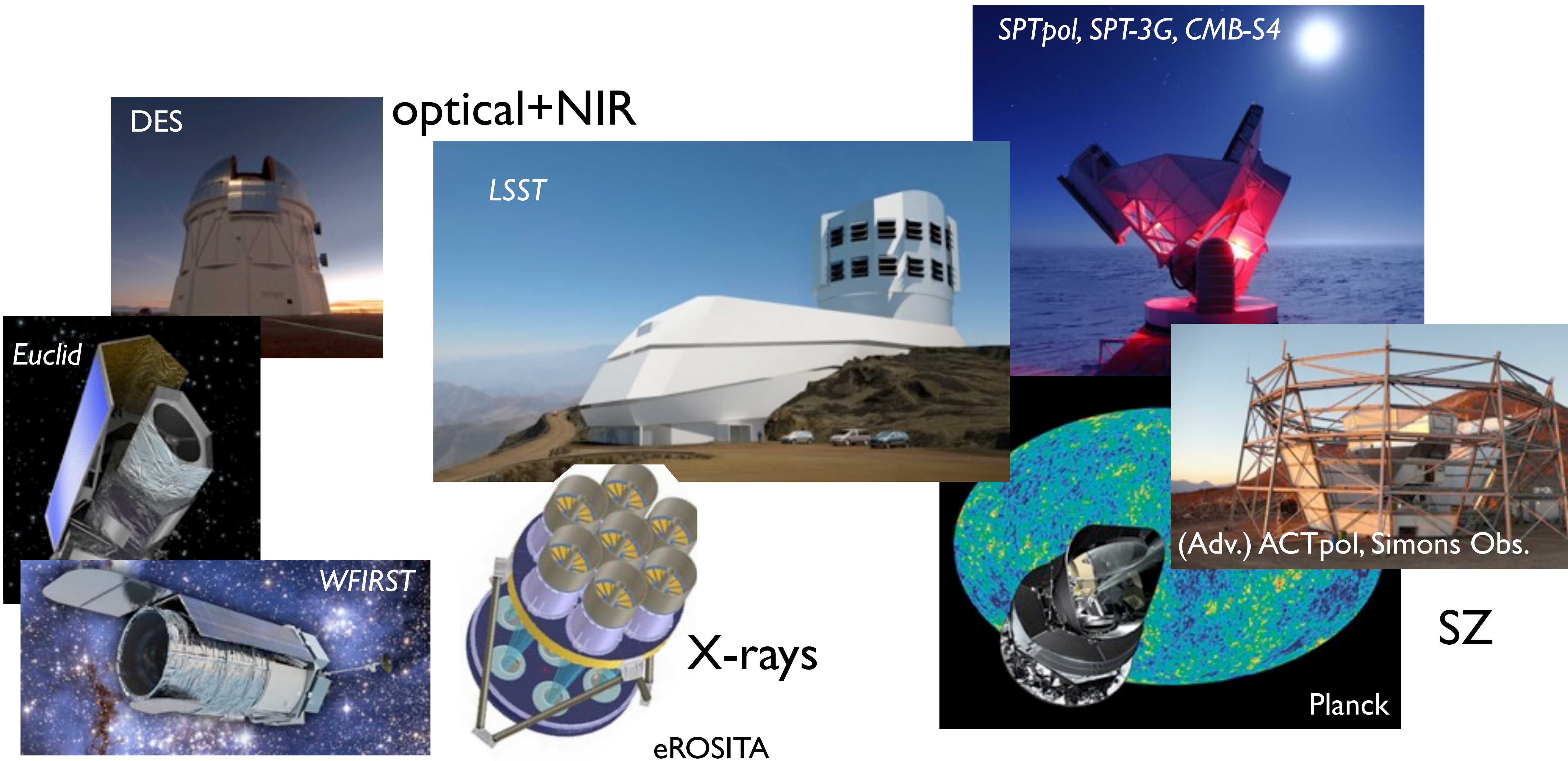
Cluster Cosmology in the LSST era

many surveys in optical, SZ, X-rays on-going, starting, or planned

→ great synergy prospects

→ key developments: mass calibration

→ *LSST cluster weak lensing will be essential for the mass calibration*



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