GALAXY CLUSTER COSMOLOGY

SOUTH POLE TELESCOPE SPT-SZ SURVEY

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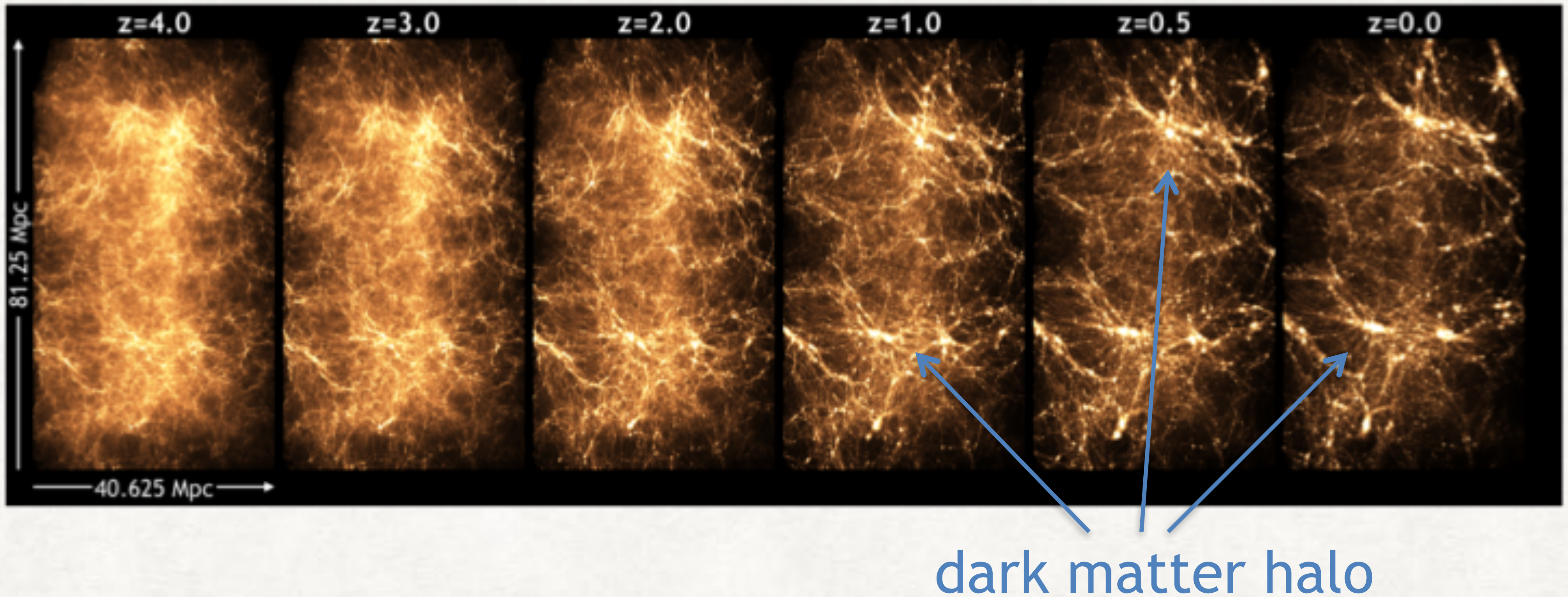
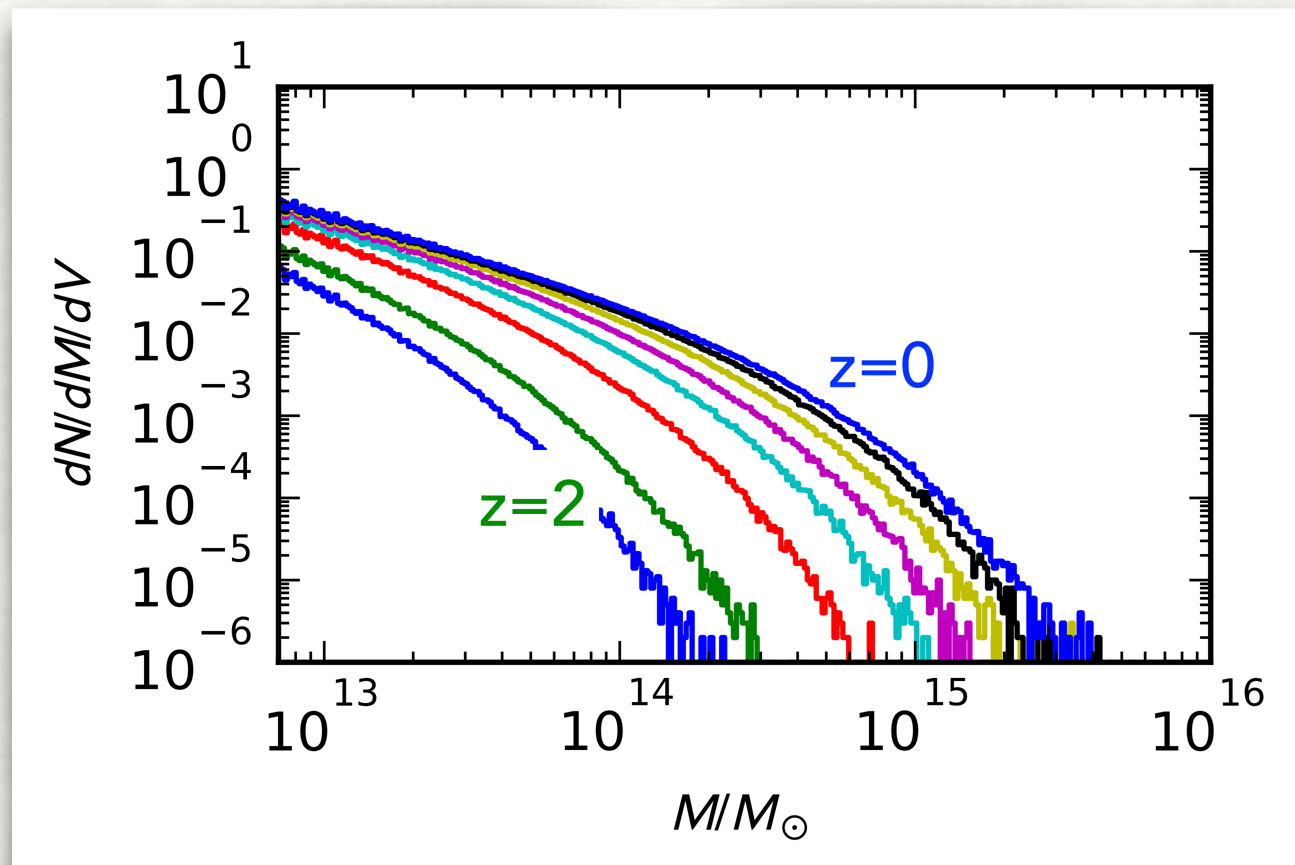
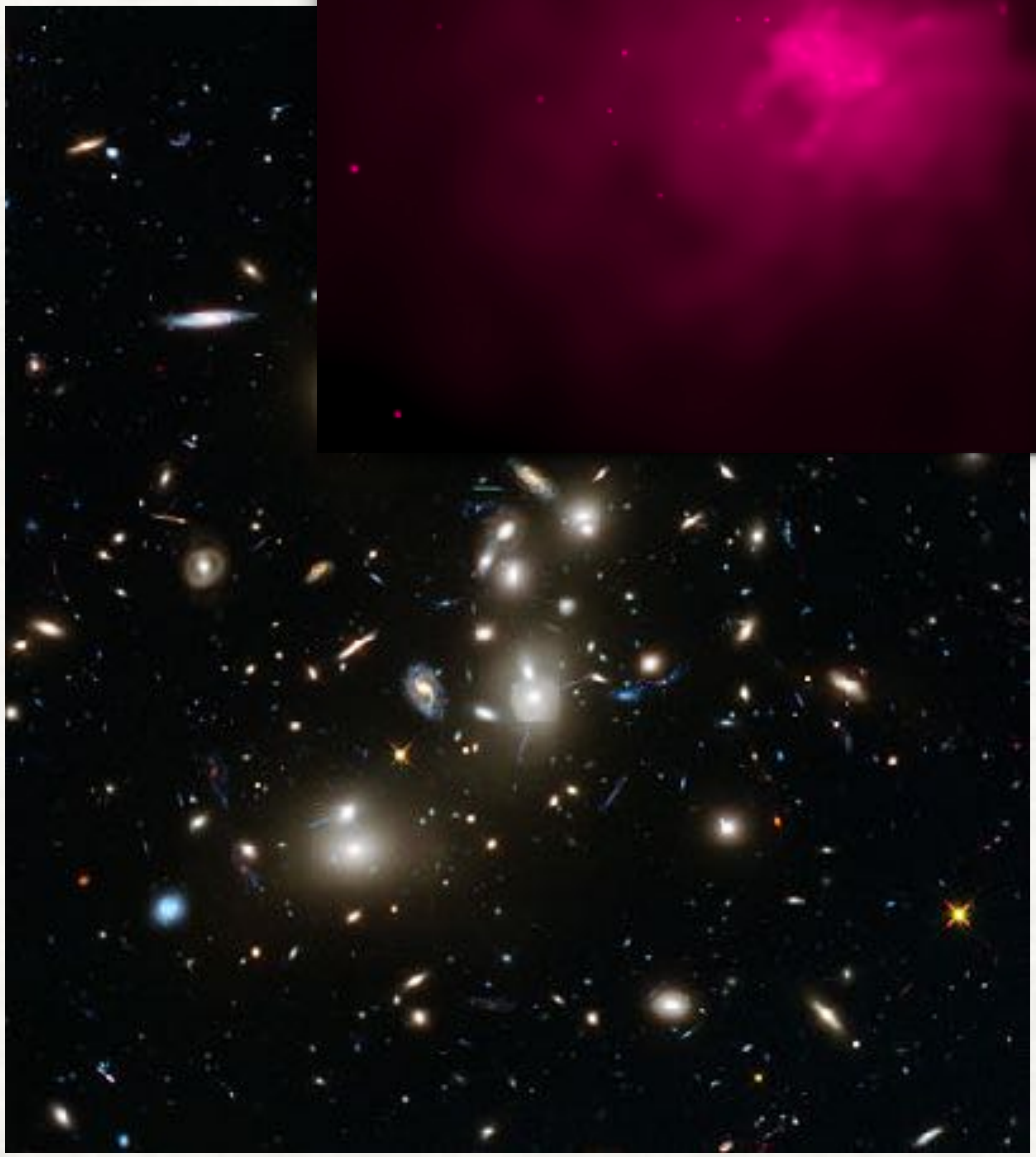
The Q Continuum Simulation: Heitmann et al., 2015 (arXiv:1411.3396)





1. Predict abundance of halos as a function of cosmology using numerical simulations
2. Measure number of galaxy clusters in a given survey as a function of mass and redshift
3. Learn about cosmology

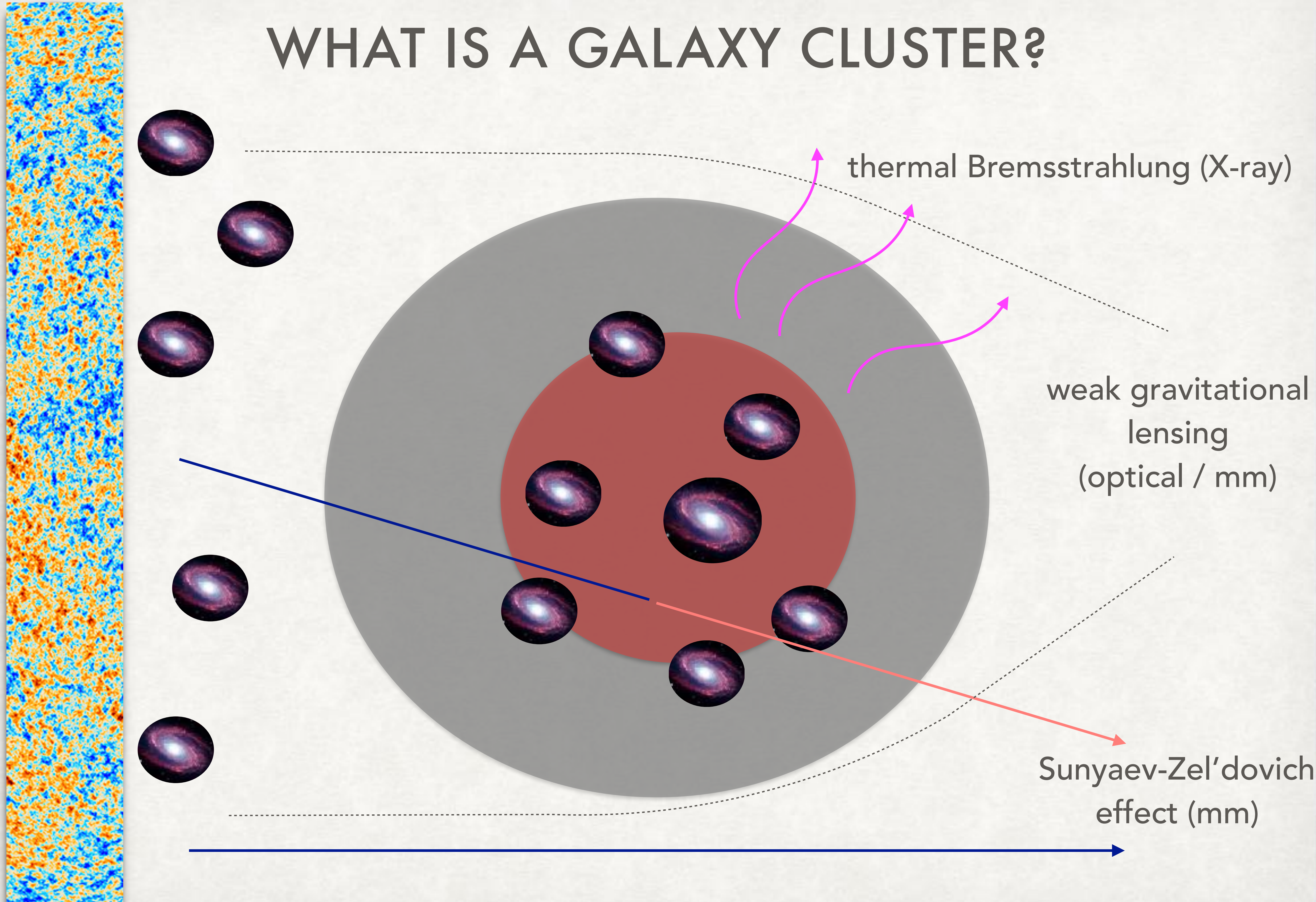
BACK TO REALITY...

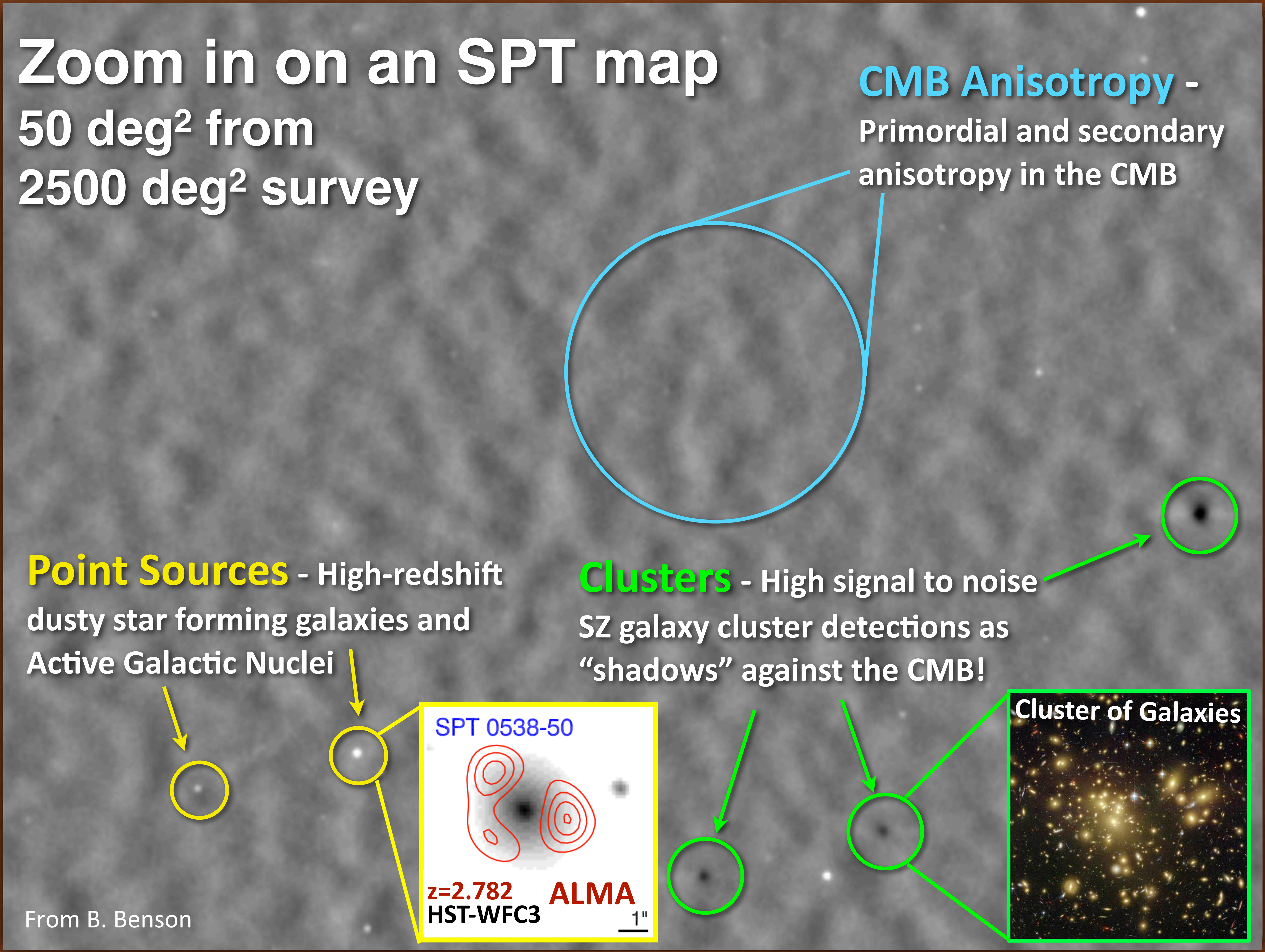


Credit: NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI) http://www.spacetelescope.org/images/heic1401a/

Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), J. Blakeslee (NRC Herzberg Astrophysics Program, Dominion Astrophysical Observatory), and H. Ford (JHU) http://www.spacetelescope.org/images/heic1317a

WHAT IS A GALAXY CLUSTER?




Zoom in on an SPT map
- 50 deg² from
2500 deg² survey
CMB Anisotropy -
Primordial and secondary
anisotropy in the CMB
Point Sources - High-redshift
dusty star forming galaxies and
Active Galactic Nuclei
Clusters - High signal to noise
SZ galaxy cluster detections as
“shadows” against the CMB!
SPT 0538-50
z=2.782
HST-WFC3
ALMA
1"
Cluster of Galaxies
From B. Benson

LIKELIHOOD FUNCTION (CMB-CENTRIC)

Abundance

$$\mathcal{P}_{\rm bin}(n_{\rm events}|n_{\rm model}) = \frac{\exp(-n_{\rm model})n_{\rm model}^{n_{\rm events}}}{n_{\rm events}!}$$

$$dn_{\rm model} = \frac{dN(\mathcal{O},z,\vec{p})}{d\mathcal{O}dz} = \int dM P(\mathcal{O}|M,z,\vec{p}) \frac{dN(M,z,\vec{p})}{dMdz}$$

$$\ln\mathcal{L}(\vec{p}) = \sum_i \frac{dN(\mathcal{O},z,\vec{p})}{d\mathcal{O}dz} - \int d\mathcal{O}dz\Theta_{\rm survey}\frac{dN(\mathcal{O},z,\vec{p})}{d\mathcal{O}dz}$$

SZ sample:

- Weak redshift dependence
- Low scatter
- Clean survey selection

$$\ln\mathcal{L} = \sum_j \ln\mathcal{P}(\vec{\mathcal{O}}'|\mathcal{O}_j,z_j,\vec{p}) = \sum_j \ln\left(\int dMd\mathcal{O}P(\vec{\mathcal{O}}',\mathcal{O}|M,z_j,\vec{p})P(M|z_j,\vec{p})\right)|_{\mathcal{O}_j}$$

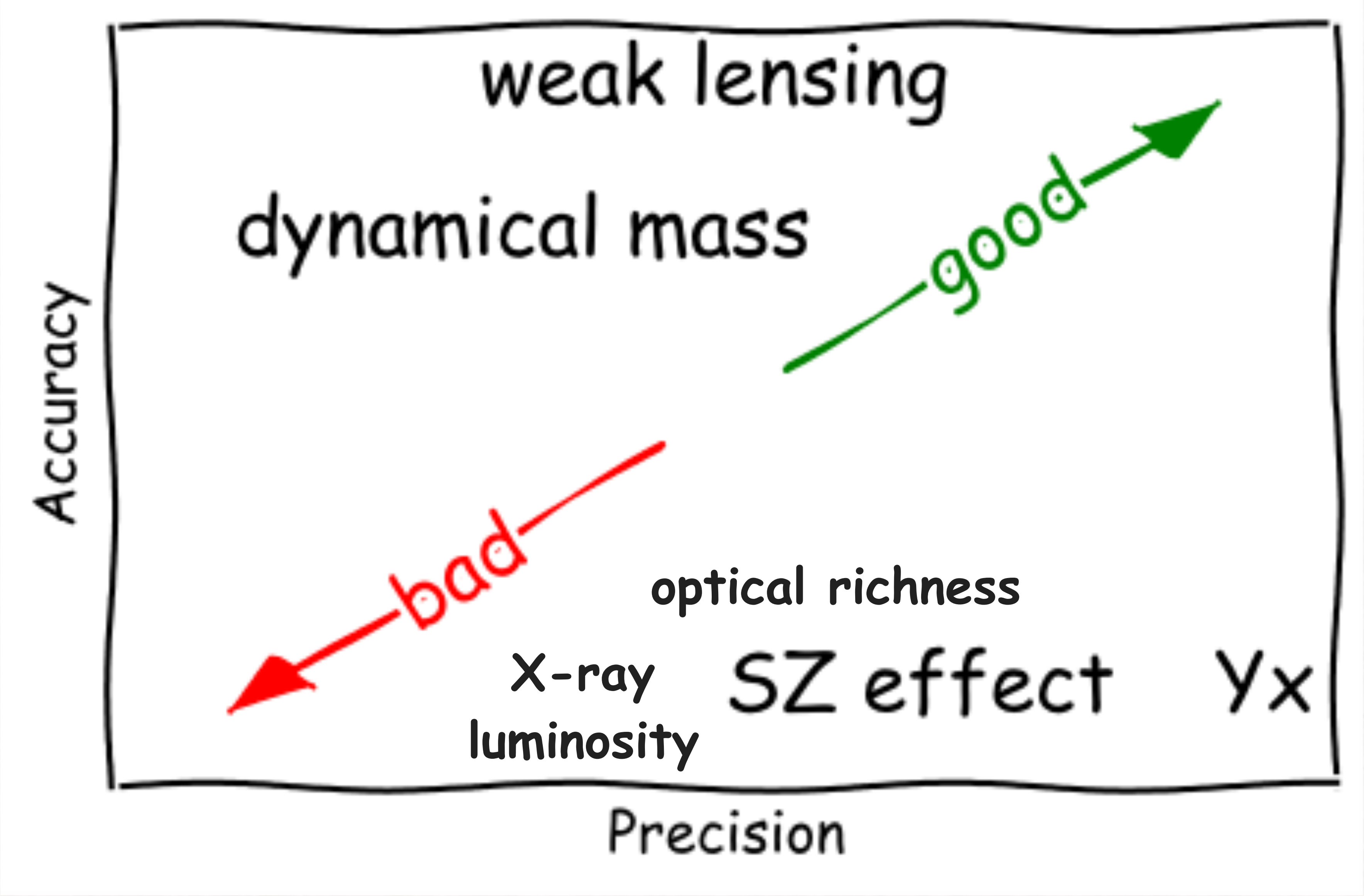
CMB lensing follow-up:

- Low systematics
- Out to high redshift *z*>1

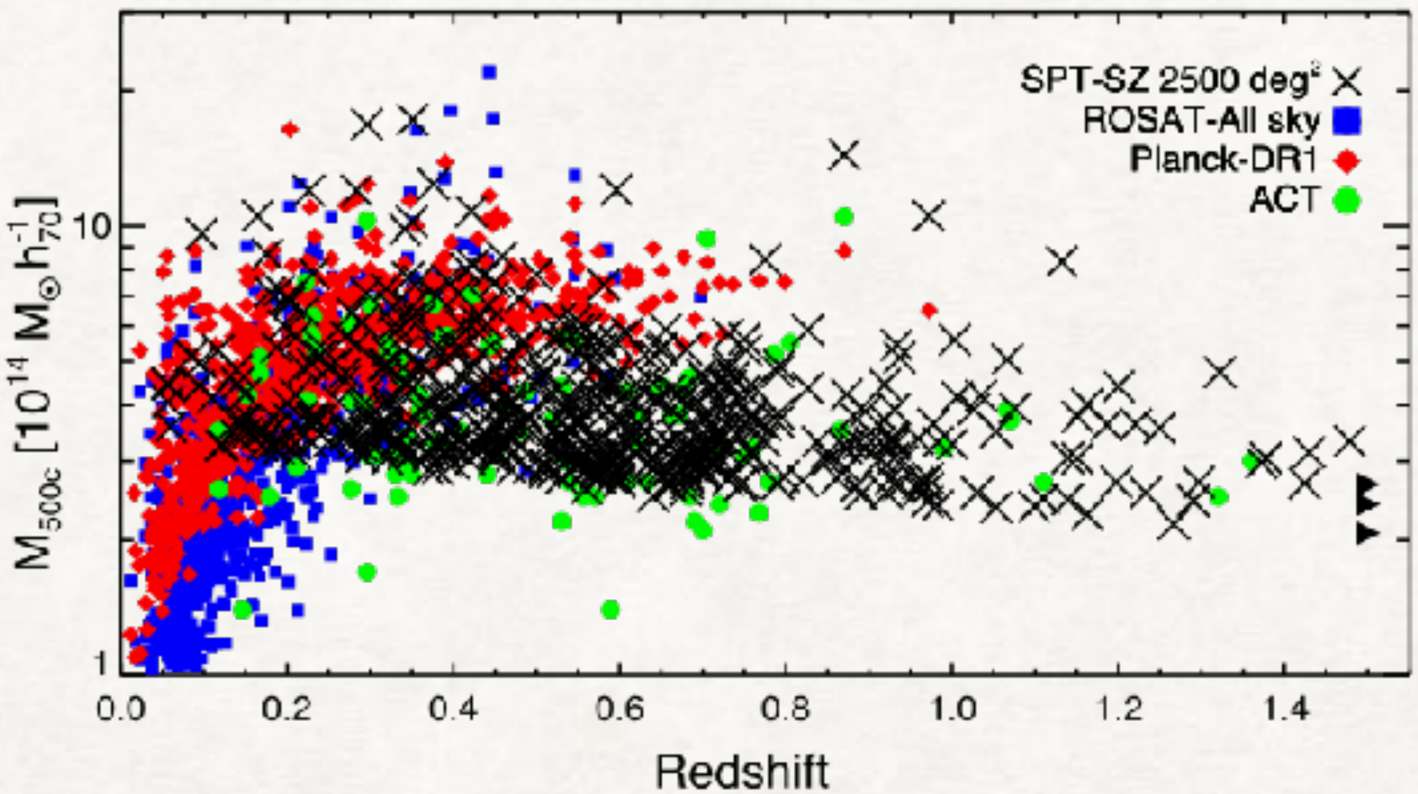
Mass calibration

MASS-OBSERVABLE RELATIONS

COMBINE TO INCREASE CONSTRAINING POWER



SPT-SZ 2500 DEG^2 SURVEY SAMPLE



Bleem et al. 2015

SPT SZ observable ξ (ξ):

maximum signal-to-noise in matched-filtered 95 and 150 GHz maps

Complete optical follow-up ξ > 4.5

confirmation and redshift measurement

Well-defined survey selection function

$\xi > 5$ — $z > 0.25$

measured purity 95%, simulation expectation 95%

SPT CLUSTER COSMOLOGY TO DATE

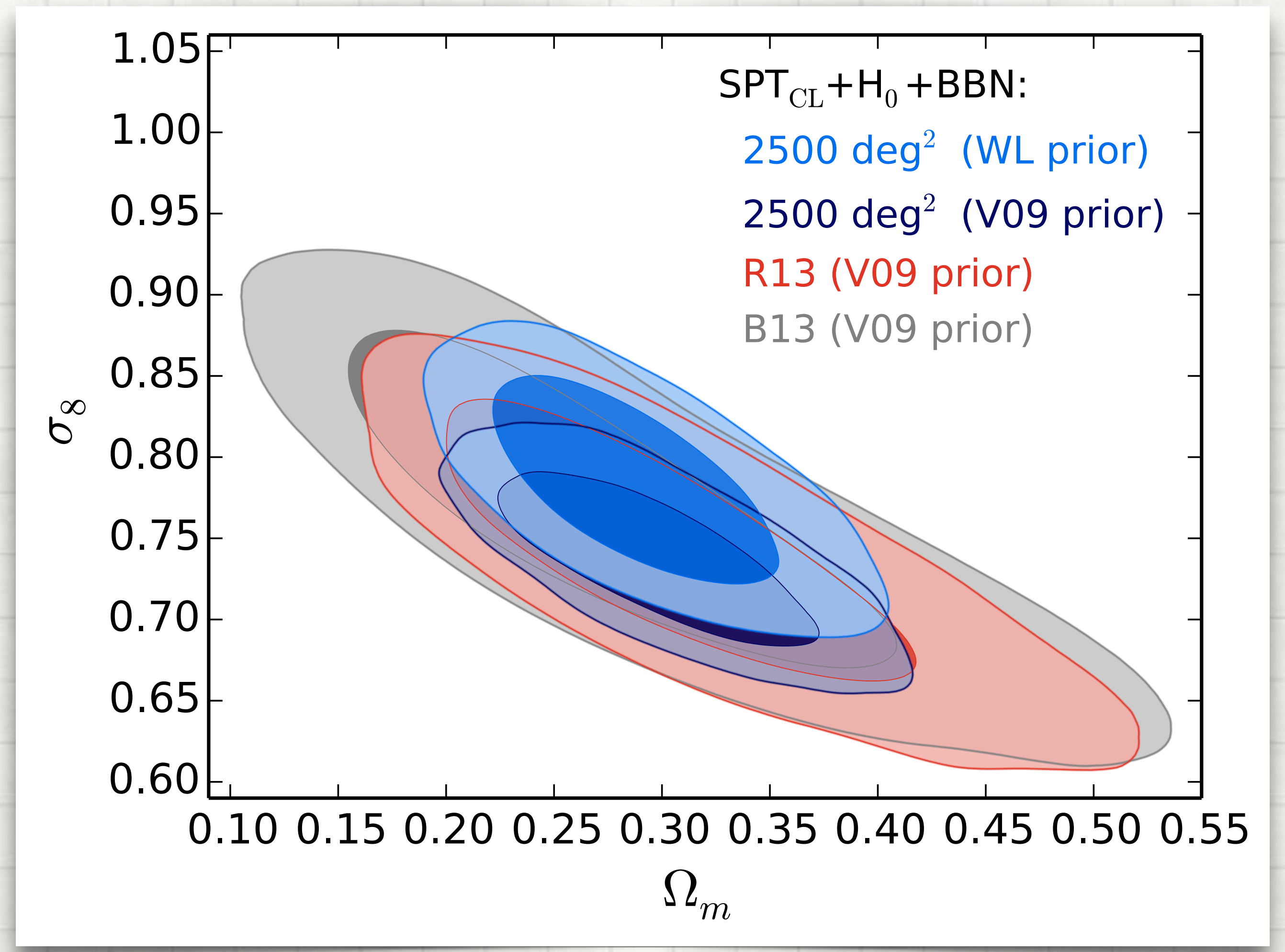
DATA SETS AND MASS CALIBRATION SCHEMES

- First 21 clusters
  (sim-calibrated SZ SNR-mass relation)

- 178 deg²: 18 clusters w/ 14 X-ray Y_X
  (hydrostatic Y_X-mass relation)

- 720 deg²: 100 clusters w/ 14 X-ray Y_X
  (hydrostatic Y_X-mass relation, simulation-calibrated velocity dispersion-mass relation)

- 2500 deg²: 377 clusters w/ 82 X-ray Y_X
  (normalization of Y_X-mass relation from external WL study (Hoekstra+ 15))
  e.g., w = -1.28 +/- 0.31 (SPTclusters only)

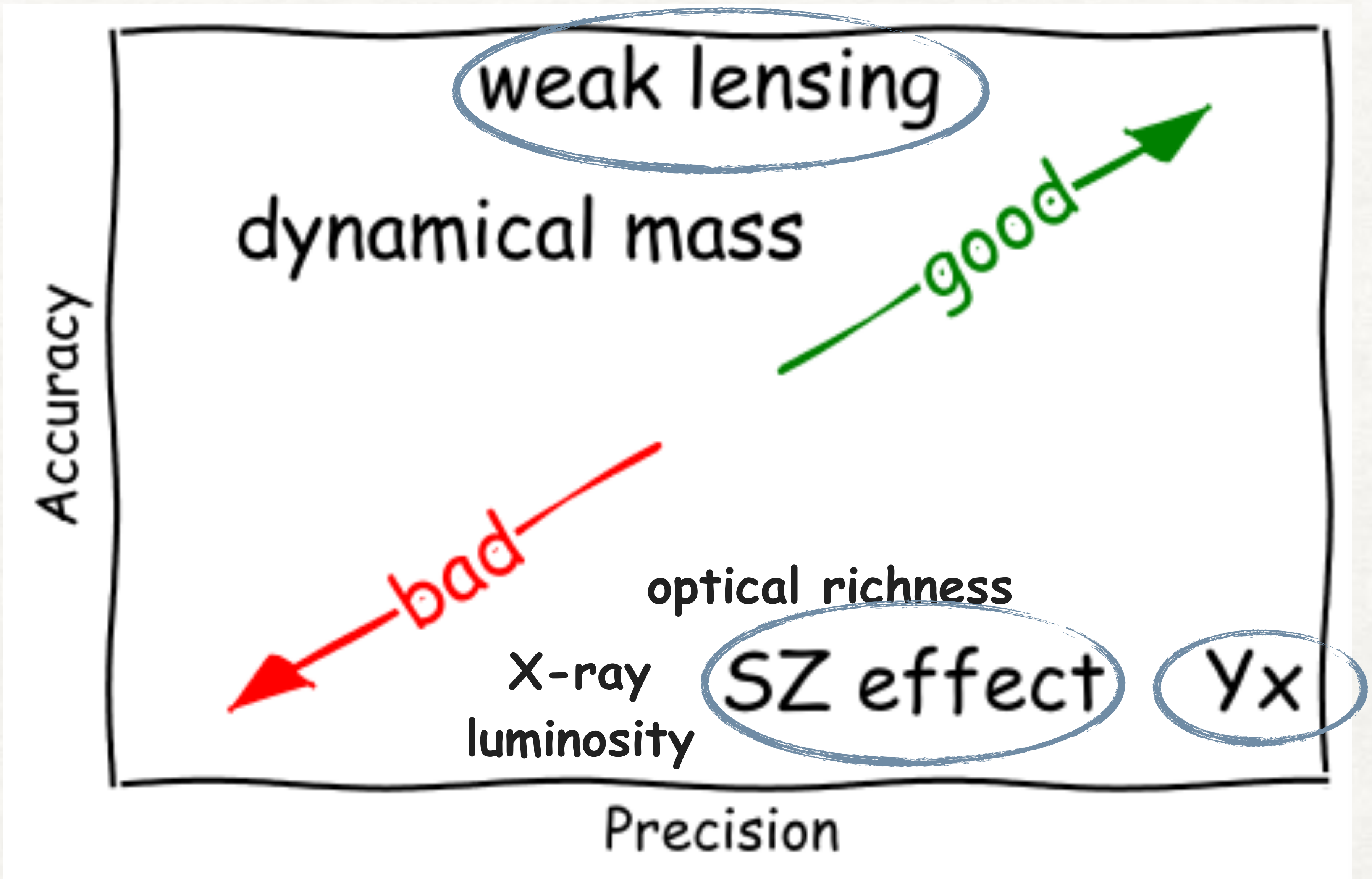


de Haan+ 2016

Vanderlinde+ 2010, Benson+ 2013, Reichardt+ 2013, SB+ 2015, de Haan+ 2016

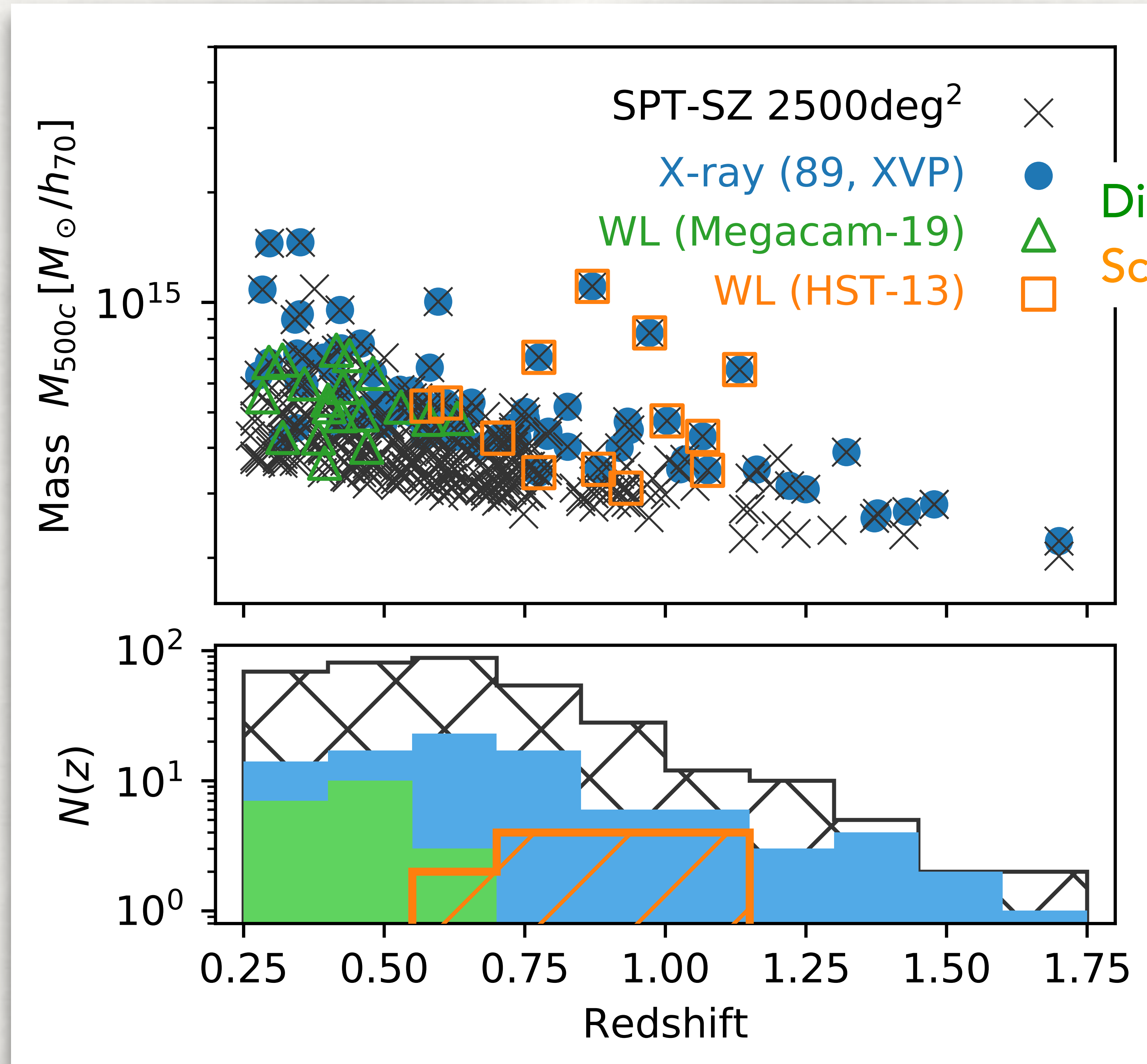
WHAT'S NEXT: ADD WEAK-LENSING DATA

FOR FULLY SELF-CONSISTENT ANALYSIS



SPT-SZ 2500 DEG² SURVEY COSMO SAMPLE (377)

X-RAY & WEAK LENSING FOLLOW-UP (89 AND 32 CLUSTERS)

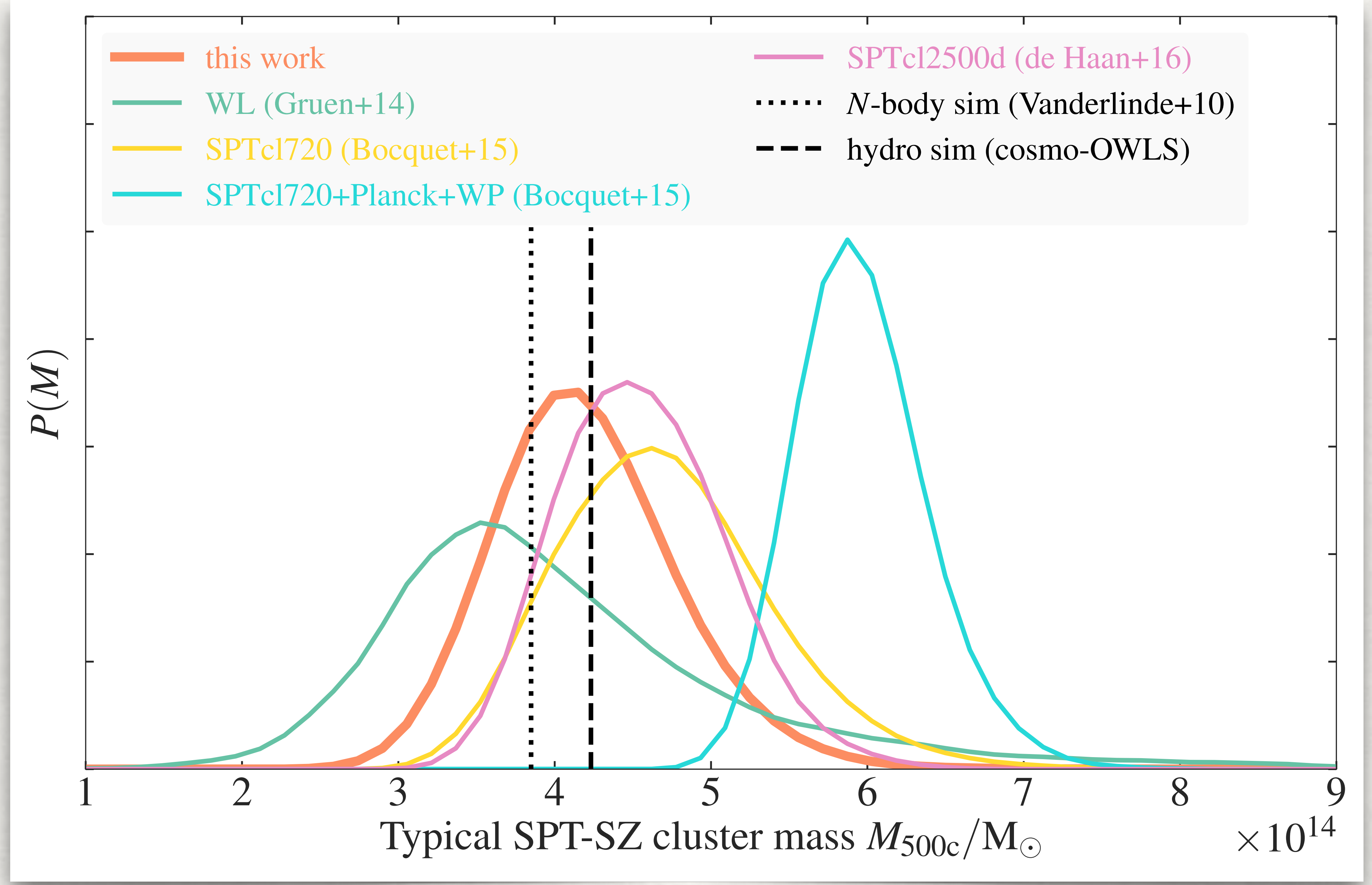


Dietrich, SB+ 2017

Schrabback+ 2016

SPT CLUSTER MASS SCALE

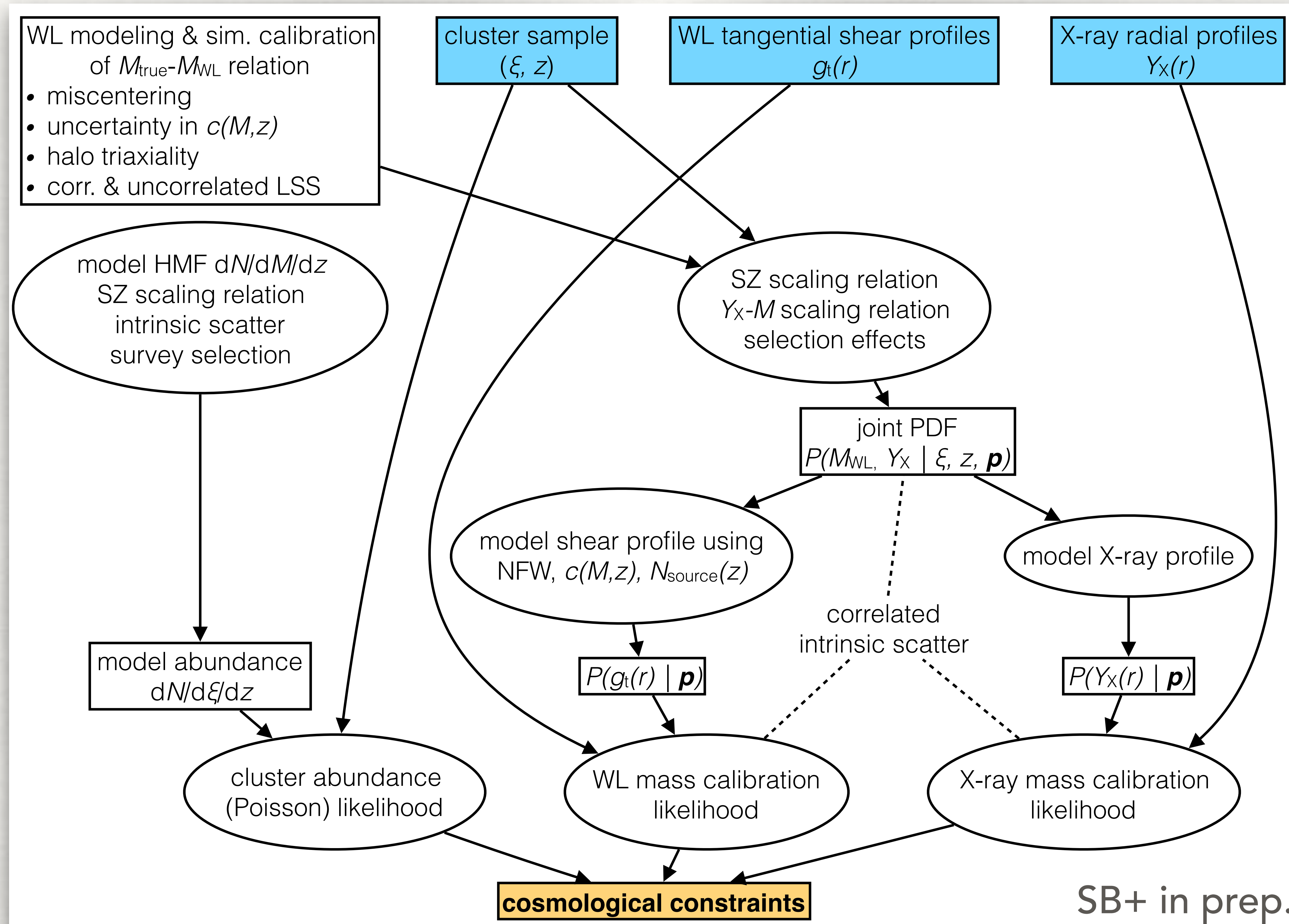
INFORMED BY GRAVITATIONAL WEAK LENSING



Dietrich, SB, et al., 2017

ANALYSIS PIPELINE

CLUSTER COUNTS & MULTI-WAVELENGTH MASS CALIBRATION



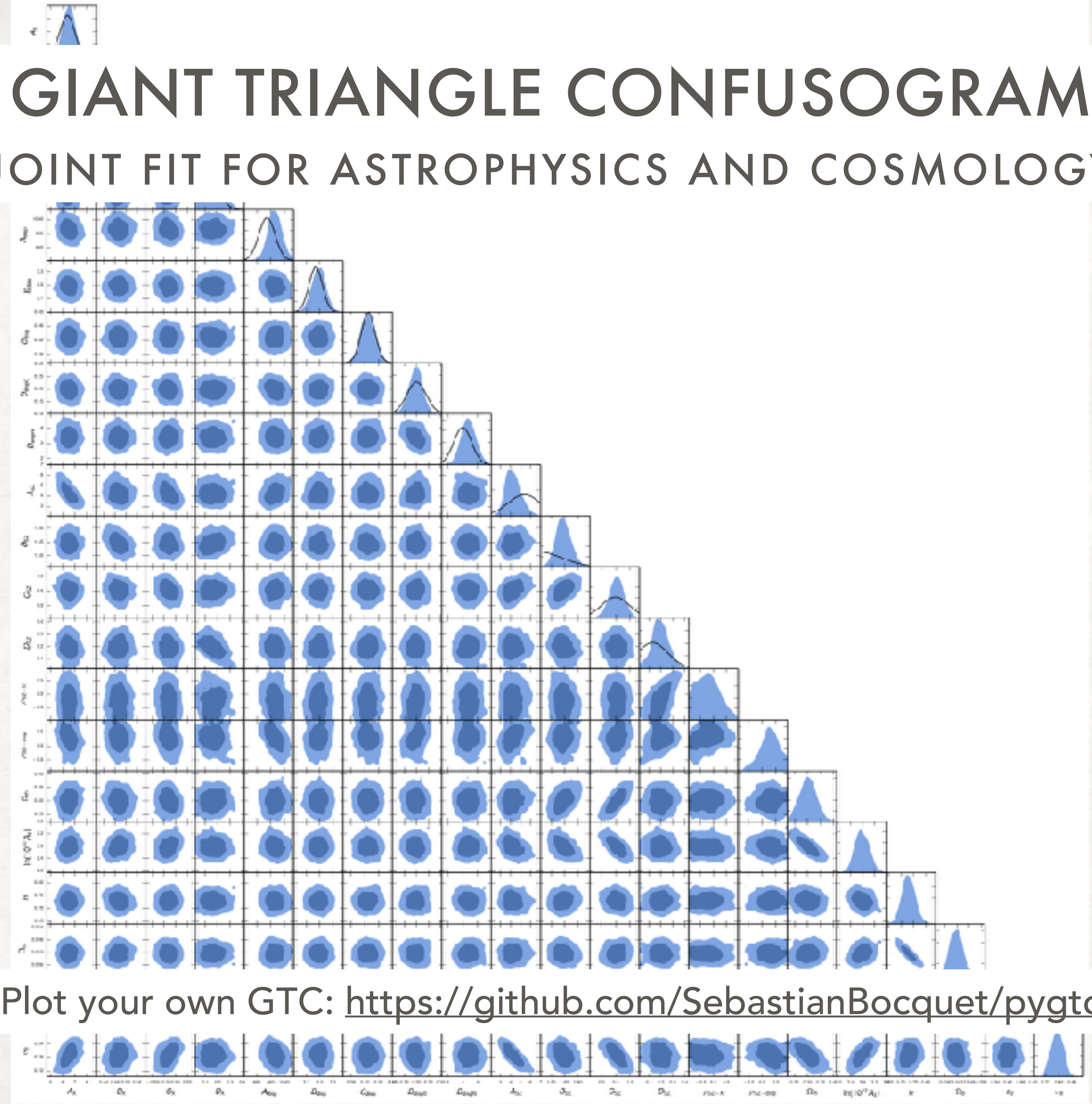
COSMOLOGY ANALYSIS

GENERAL PHILOSOPHY

- Rely on as few parameter priors as possible:
  - no priors on mass-slope and redshift evolution of the SZ and X-ray mass-observable relations
  - prior on intrinsic X-ray scatter (or intrinsic SZ scatter)
  - Simulation calibration of weak-lensing signal-to-true mass relation
- Self-consistent forward modelling analysis framework (SB+ 2015, Dietrich, SB+2017, SB+ in prep.; see also Mantz+ 2015)

GIANT TRIANGLE CONFUSOGRAM

JOINT FIT FOR ASTROPHYSICS AND COSMOLOGY

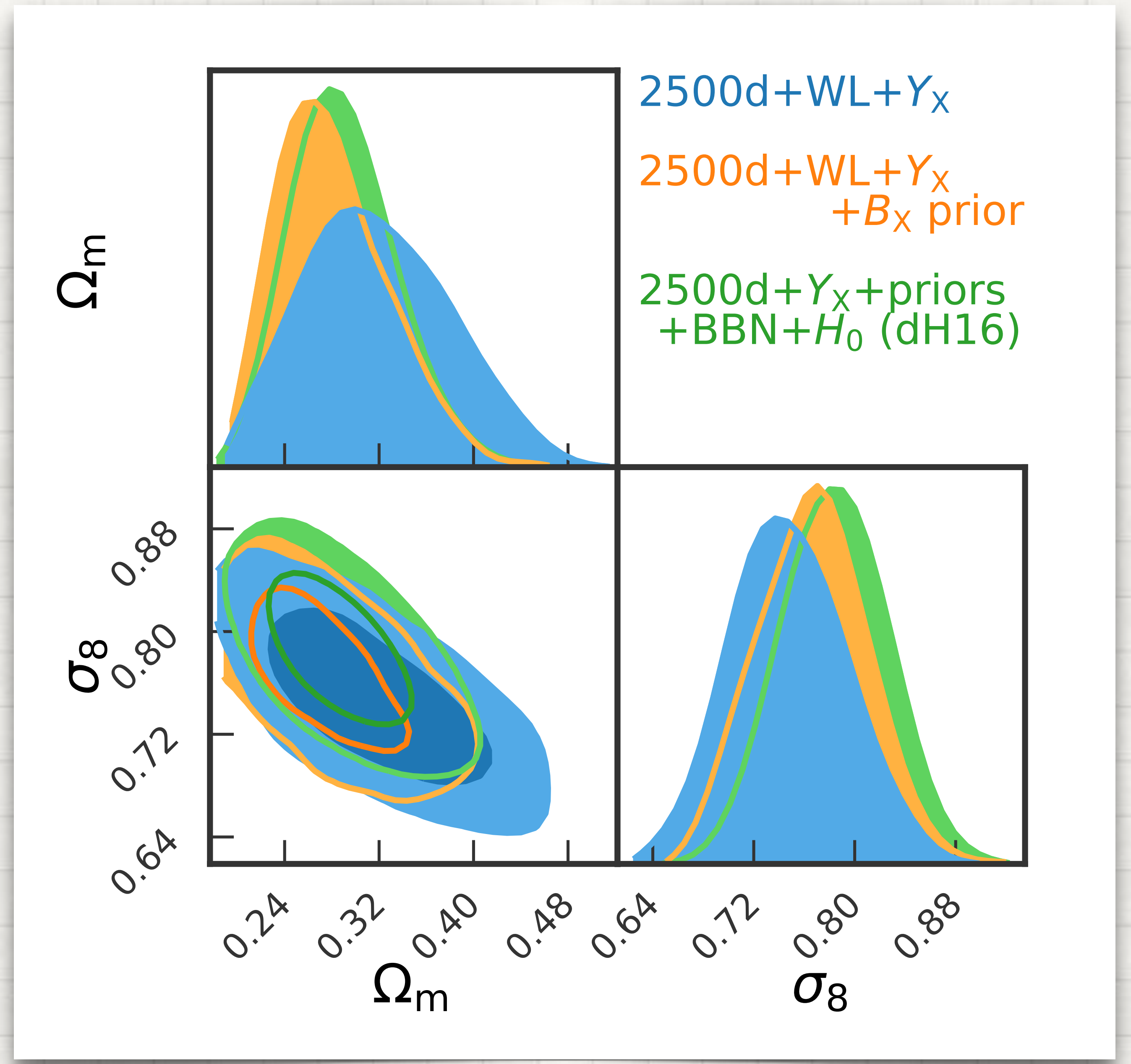


Plot your own GTC: https://github.com/SebastianBocquet/pygtc

SPT CLUSTER COSMO WITH WEAK LENSING CALIBRATION

Assuming LCDM:

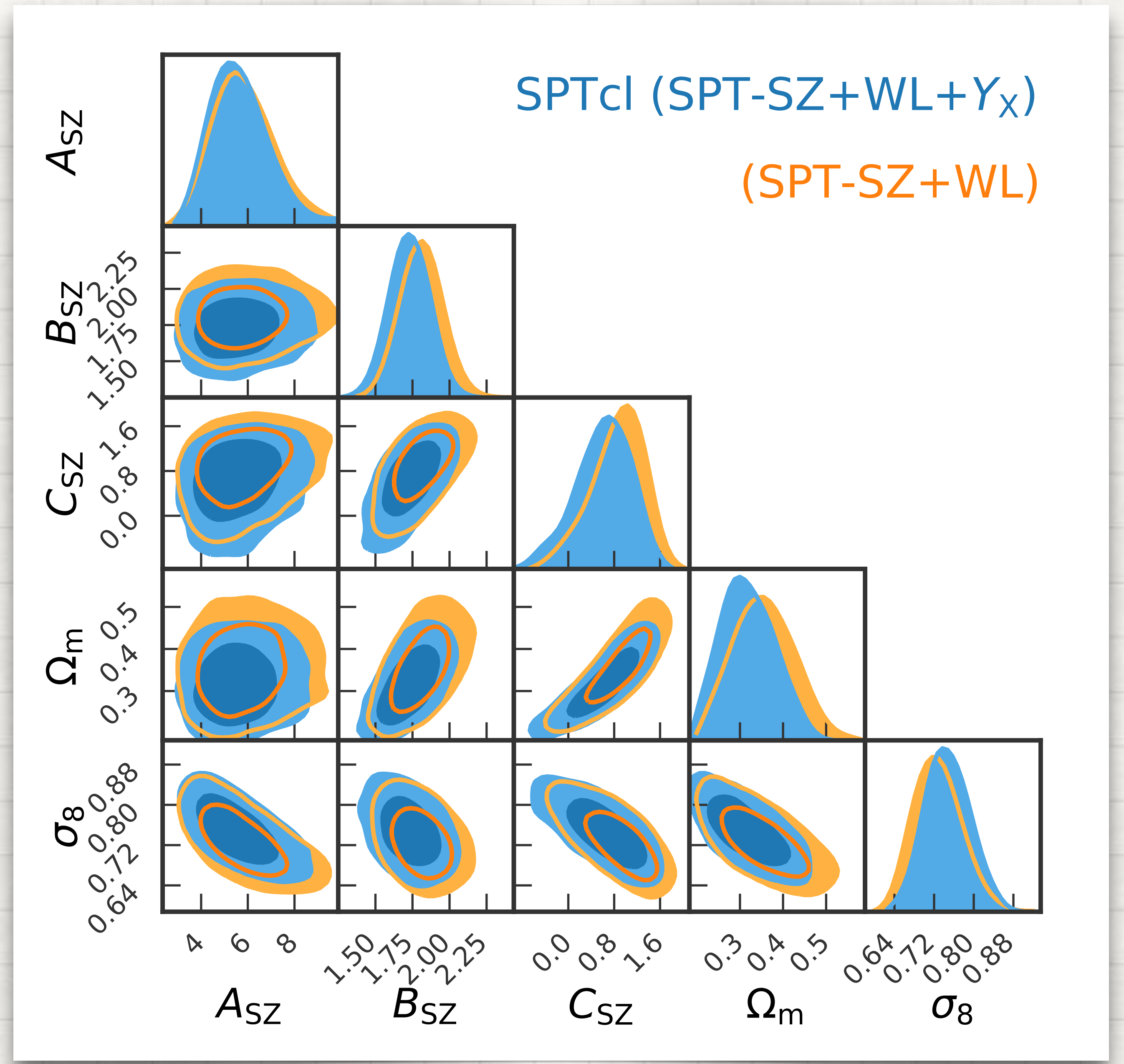
- Priors: simulation calibrated WL observable, X-ray scatter
- Ω_m = 0.31 +/- 0.06
  $\boldsymbol{\sigma}_8$ = 0.75 +/- 0.05
- Consistent with previous SPT analysis (de Haan+16), which used prior on Y_X-mass normalization (Hoekstra+ 15)



SB+ in prep.

ANALYSIS W/ AND W/O X-RAY DATA

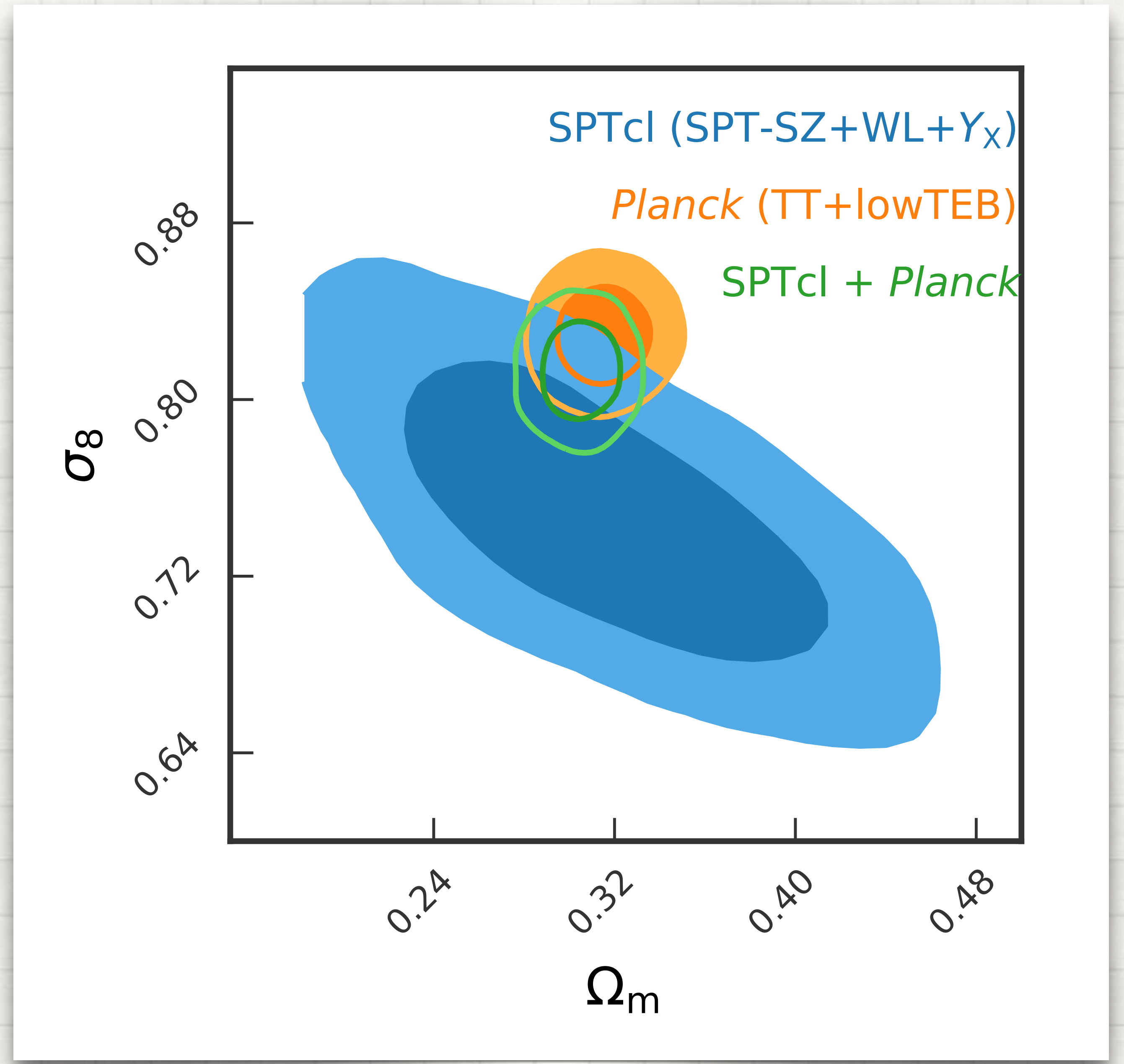
- Apply prior on X-ray scatter or SZ scatter
- Very similar constraints



SB+ in prep.

SPTCLUSTERS VS. PLANCK PRIMARY CMB

- Cluster constraint is lower in this parameter space
- 1.95 σ difference (PTE 0.05)

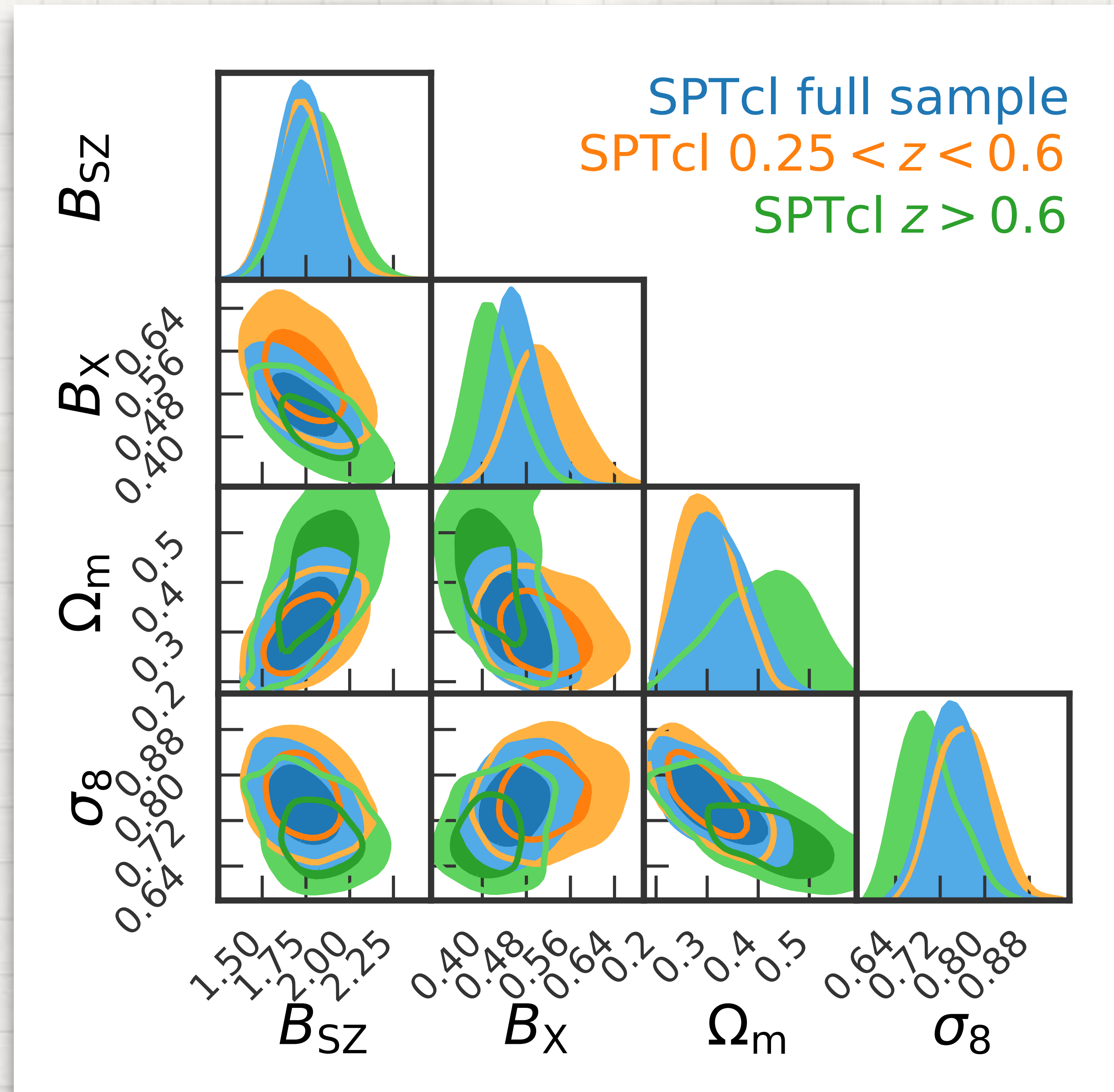


SB+ in prep.

LOW- VS. HIGH-REDSHIFT HALVES OF OUR SAMPLE

LEVERAGING SPT'S REDSHIFT COVERAGE

- Split at $z = 0.6$ (!)
- SZ mass-slope *Bsz*: no change
- X-ray mass slope *Bx* (evolution with mass): ~self-similar at low *z* significantly steeper at high *z*
- High Ω_m at high redshift
- **σ_8** ~consistent

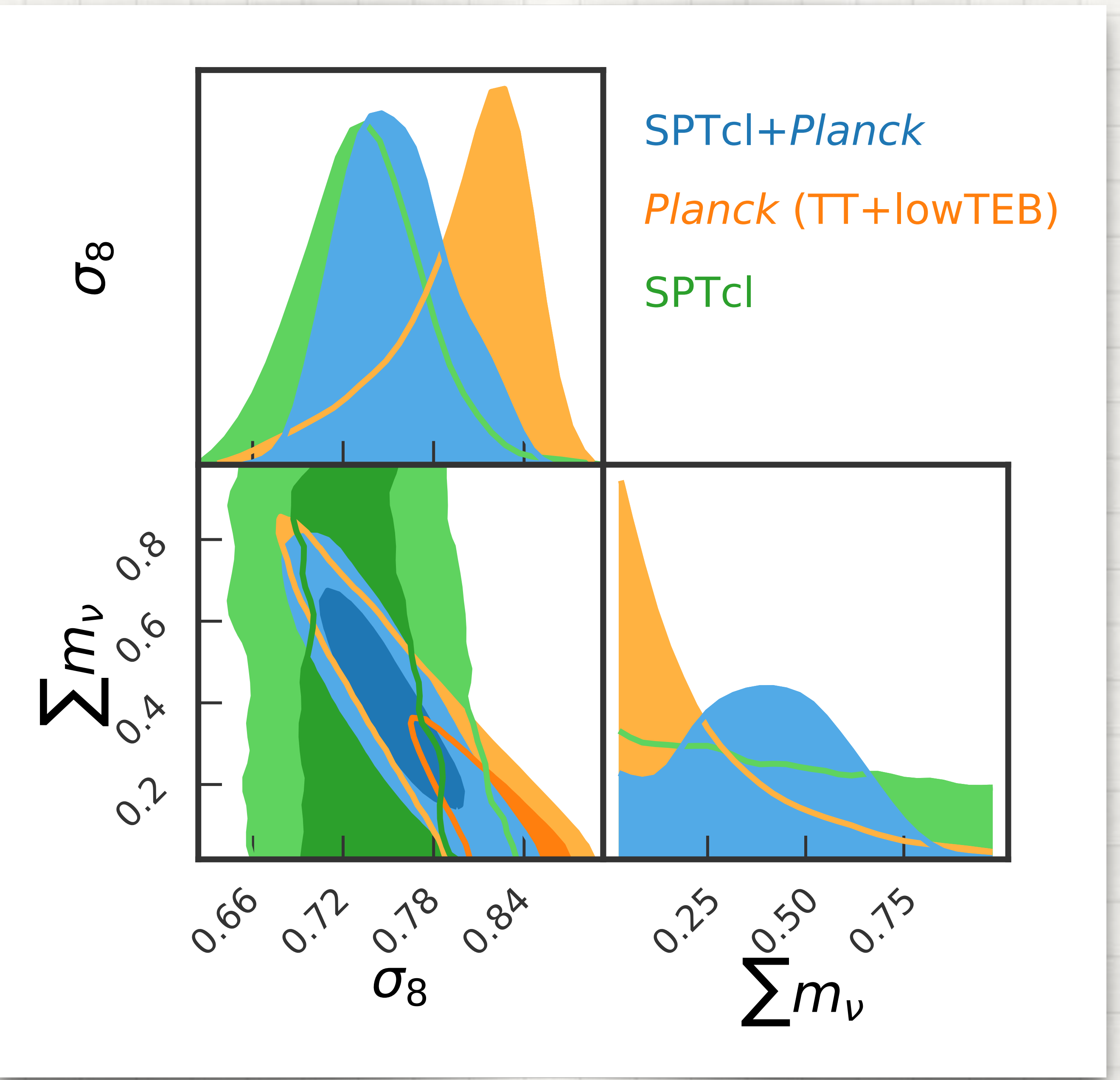


SB+ in prep.

CONSTRAINTS ON THE SUM OF NEUTRINO MASSES

COMBINE CLUSTERS AND PRIMARY CMB

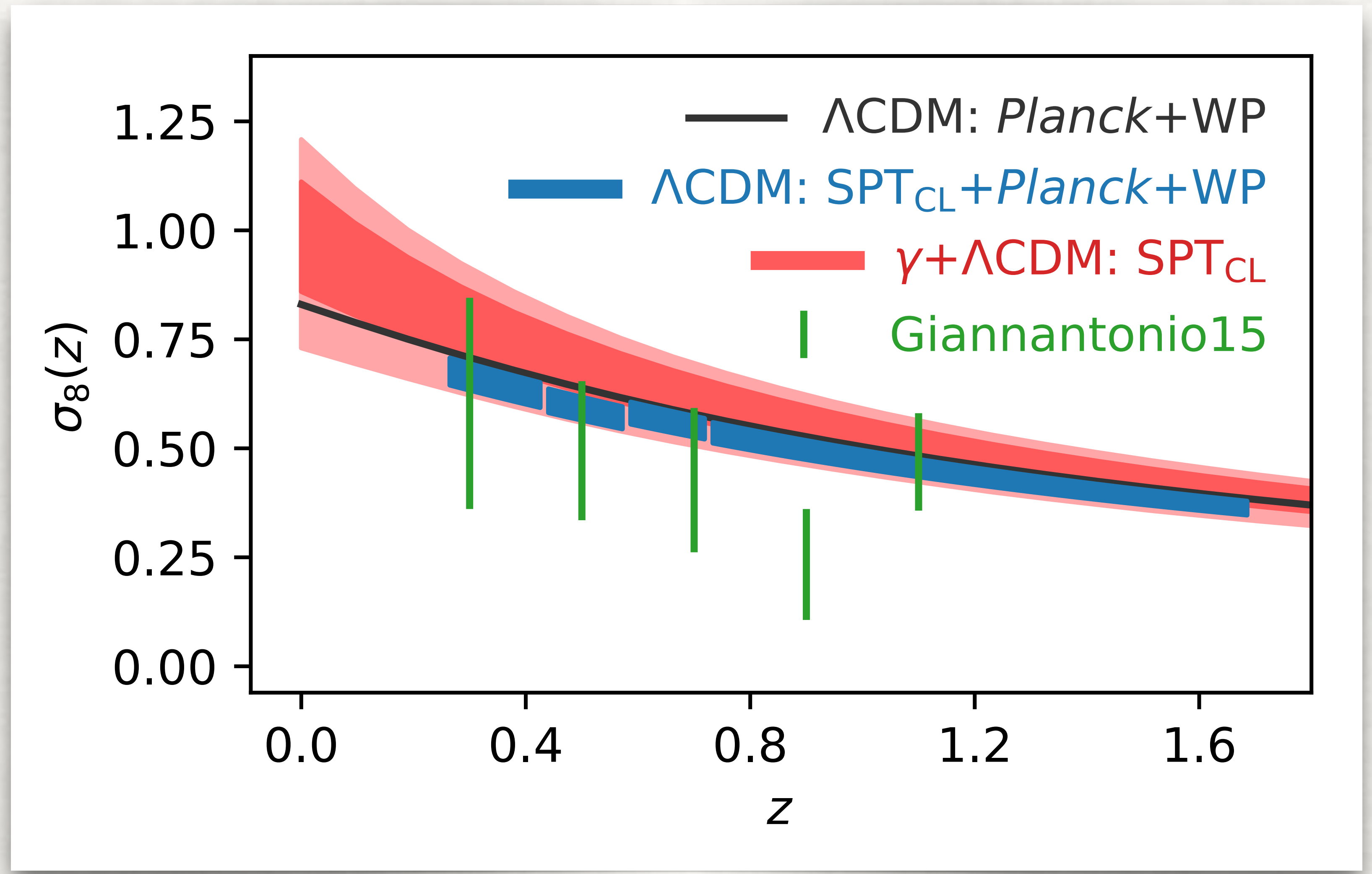
- Clusters alone cannot constrain neutrino mass
- Primary CMB alone shows strong degeneracy with σ_8
- Combine both data sets!
- $\Sigma m_\nu = 0.4 \pm 0.2$ eV
- Better mass calibration will lead to tighter constraints!



SB+ in prep.

TOWARD NON-PARAMETRIC GROWTH

Blue error bands: Combined analysis with primary CMB from *Planck*, but fit for σ_8 in four redshift bins using cluster data only. This way, *Planck* only constrains the geometry of the Universe, but not growth.

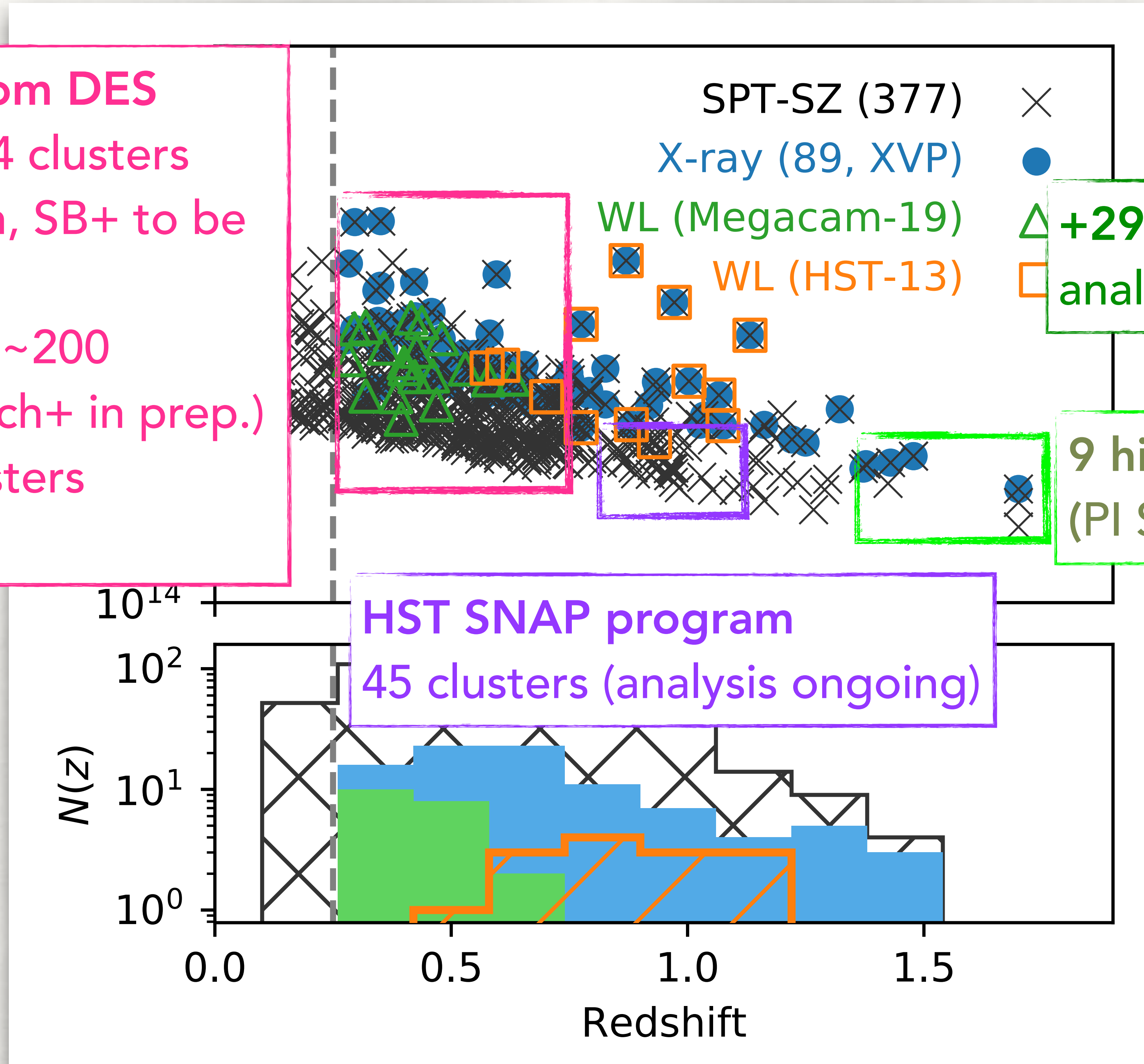


SB+ in prep.

OUTLOOK: ONGOING (OPTICAL) WEAK LENSING FOLLOW-UP

WL calibration from DES

1. SV 200deg^2: 34 clusters (Stern, Dietrich, SB+ to be submitted)
2. Y1 1500 deg^2: ~200 clusters (Dietrich+ in prep.)
3. Y3: all SPT clusters @ z < ~0.7



HST SNAP program

45 clusters (analysis ongoing)

+29 Megacam clusters

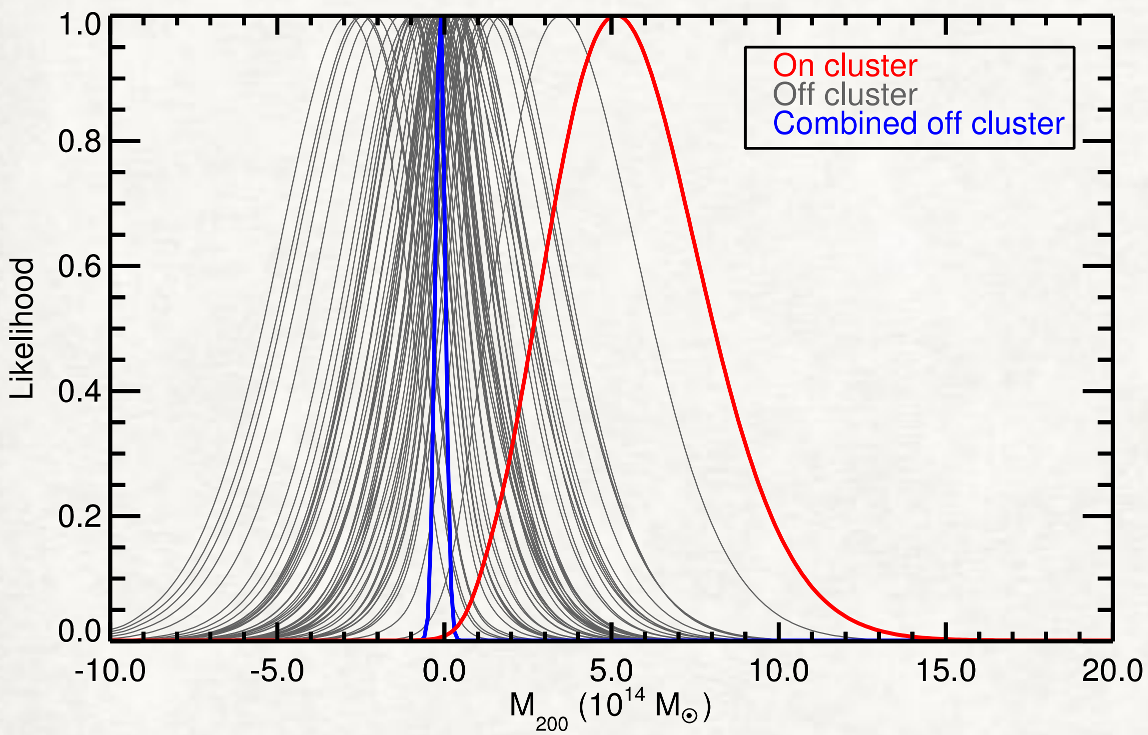
analysis ongoing

9 high-z clusters (HST)

(PI Schrabback)

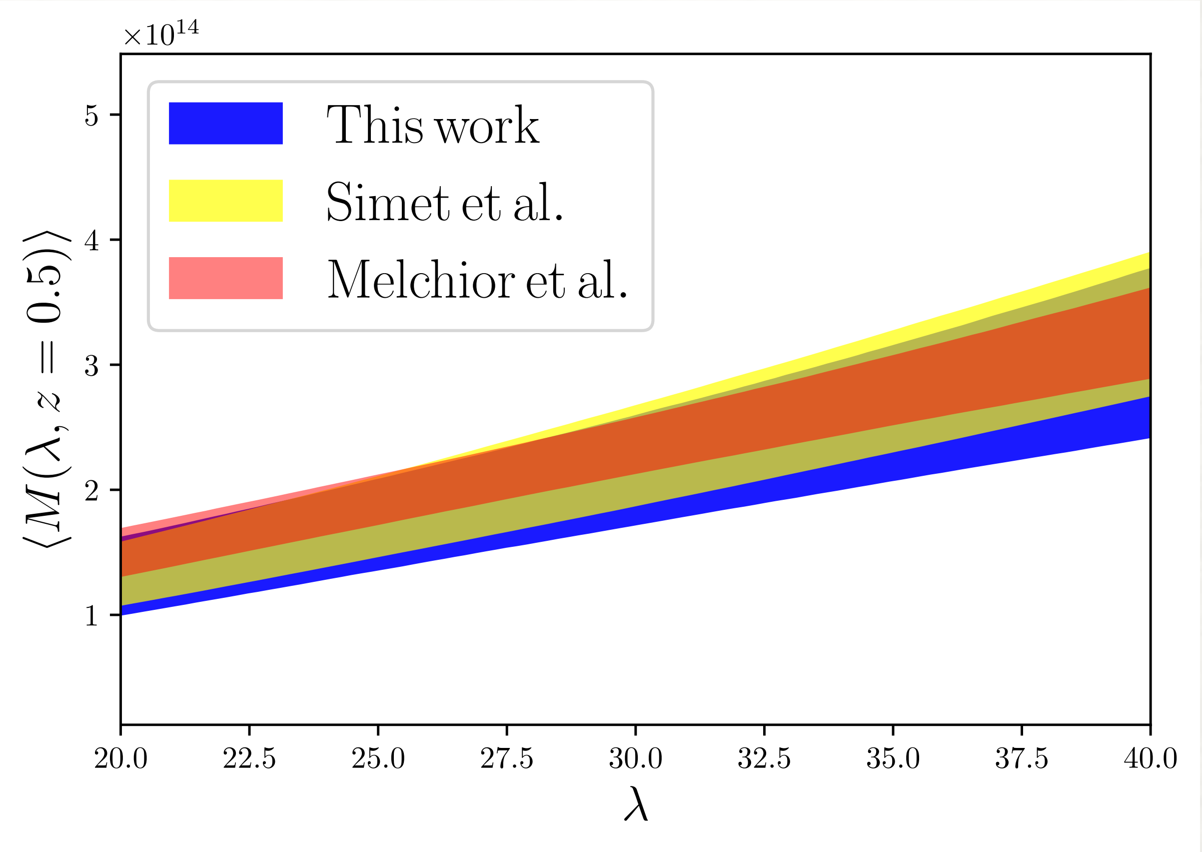
CMB CLUSTER LENSING

WITH SPT-SZ



Mass

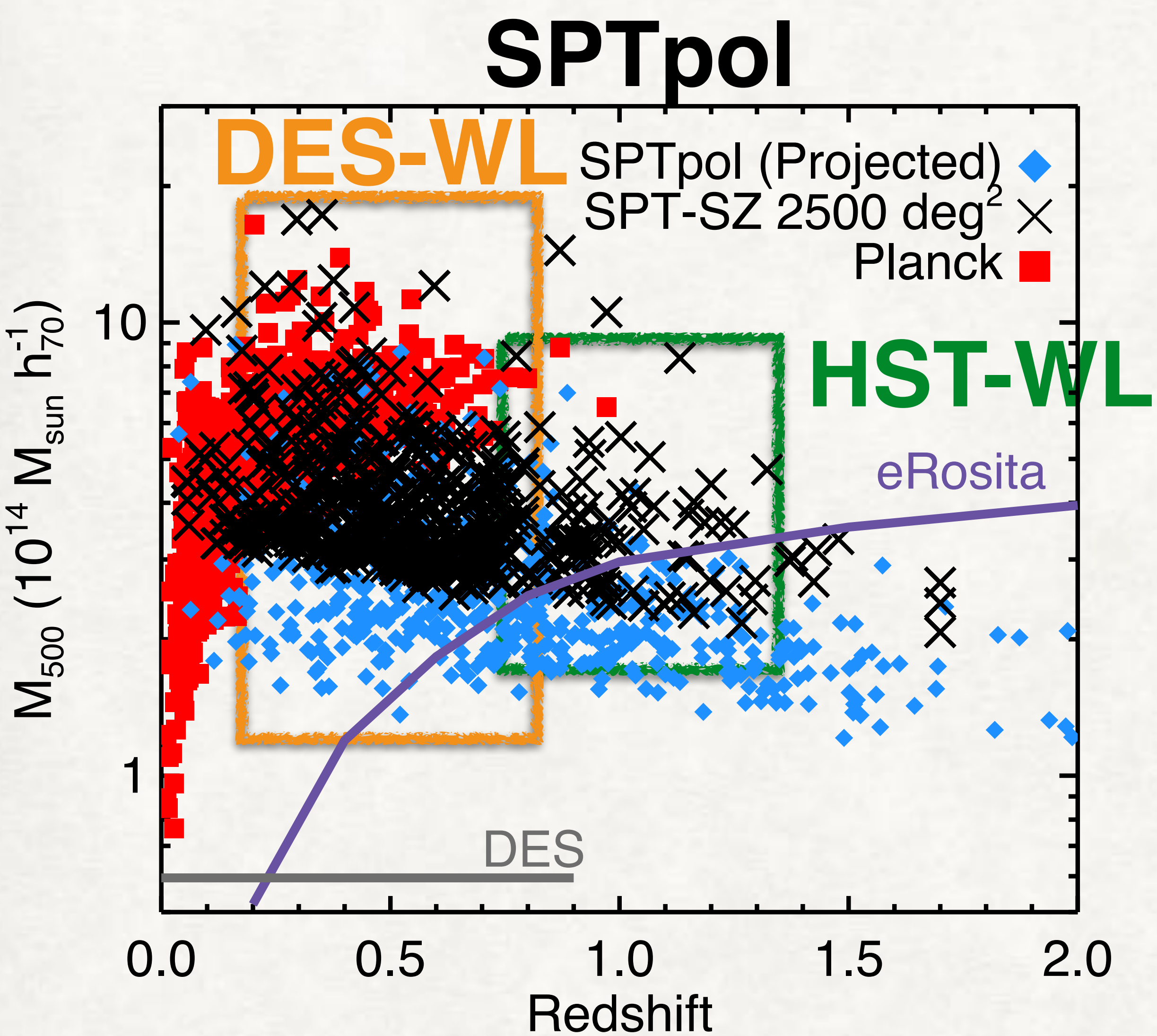
513 SPT-SZ clusters
3.1 **σ** detection of lensing
(Baxter et al. 2015)

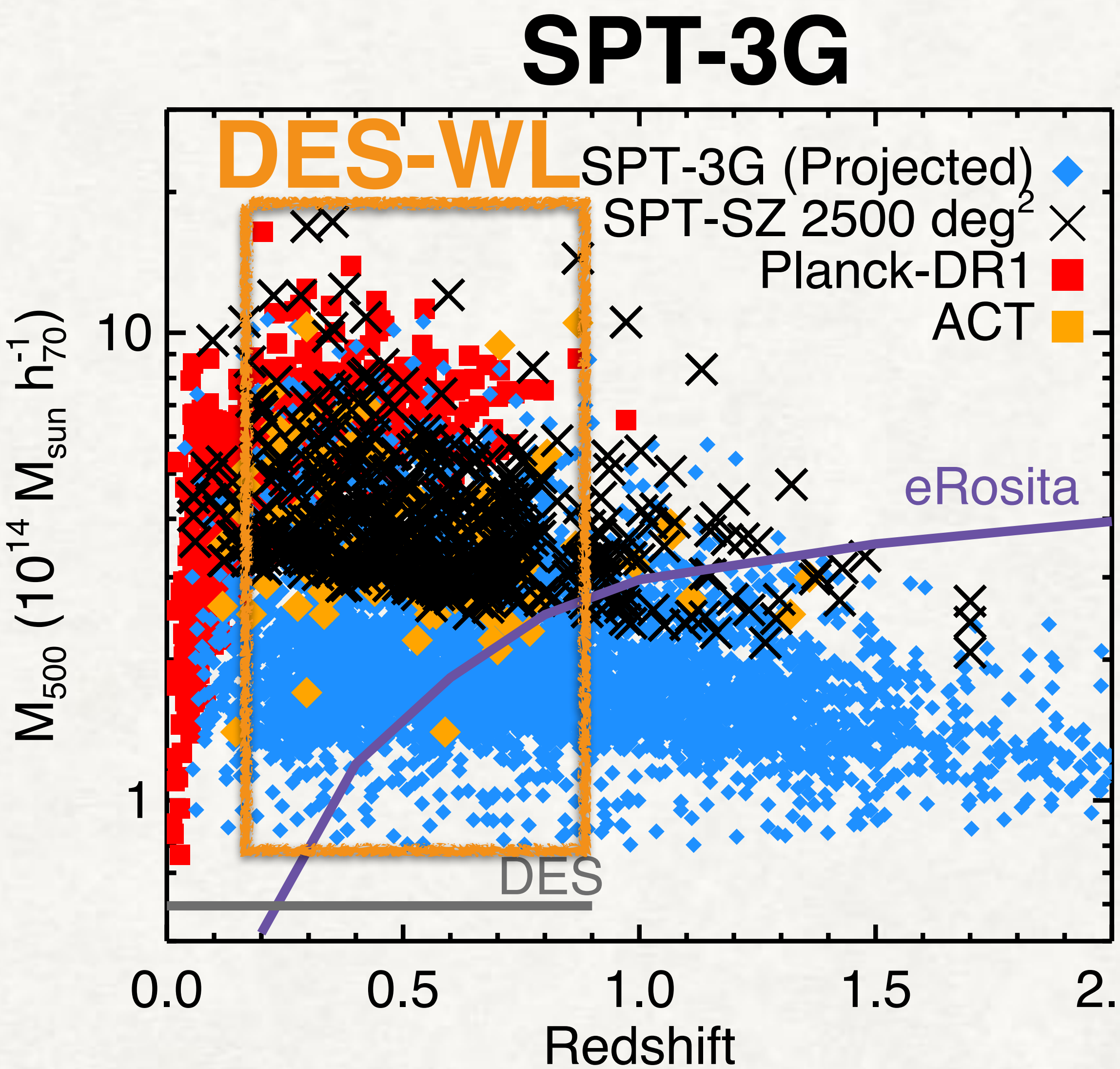


3700 DES Y1 clusters
8.1 **σ** detection of lensing
20% constraint on mass scale
(Baxter et al. 2018)

UPCOMING SPT CLUSTER SURVEYS

BOTH FULLY WITHIN DARK ENERGY SURVEY FOOTPRINT





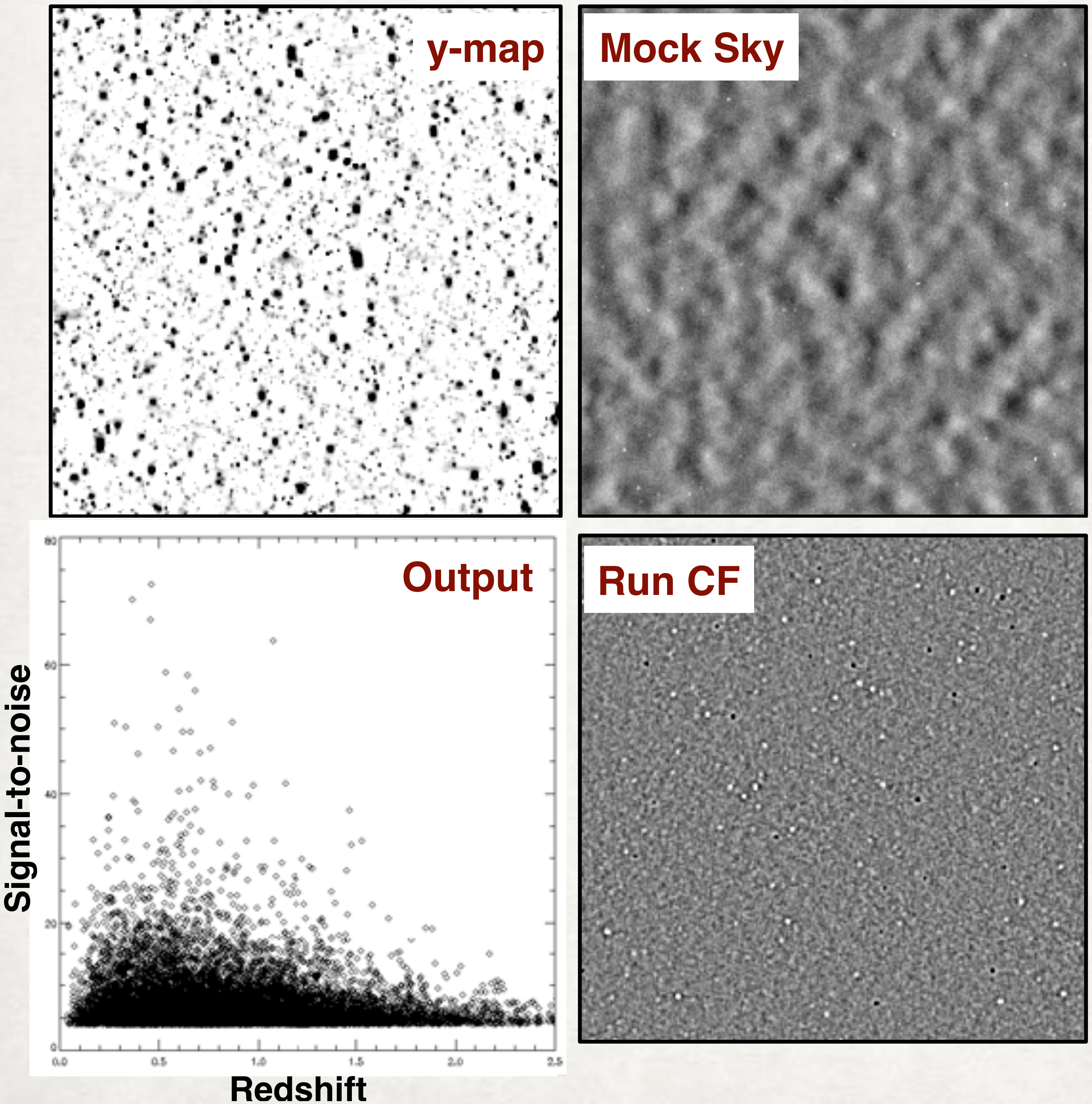
adds:

- deep 500 deg² ~300 clusters
- shallow 2500 deg² ~ 200 clusters

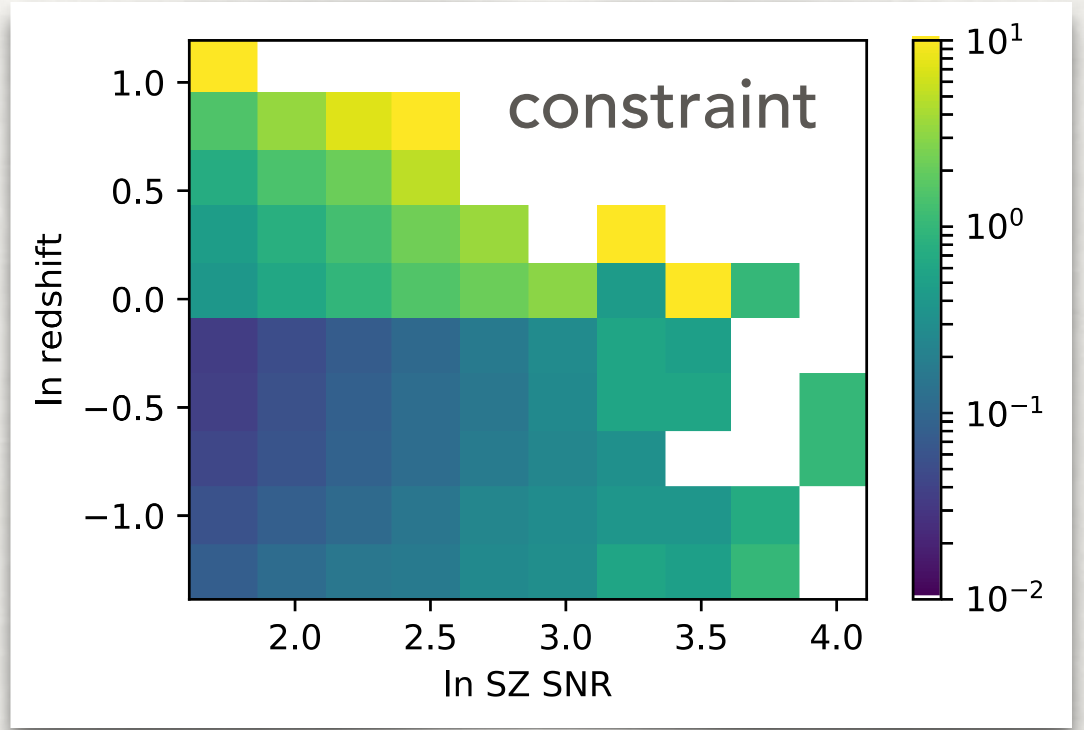
- very deep 1500 deg² ~ 2000 clusters

MAP-BASED CLUSTER FORECASTING CMB S≥3

INCLUDE ALL (KNOWN) SYSTEMATICS



- Start from simulation lightcone
- Include *mm*-wave background and foregrounds
- Assume stacked optical (DES, LSST) & CMB lensing for mass calibration



Lindsey Bleem & SB

CONCLUSIONS

STAY TUNED FOR:

- SZ cluster cosmology in general:
  - Clean survey selection
  - Probes the highest redshifts at which clusters exist
  - CMB cluster lensing coming up
- Specifically:
  - Cosmology with SPT-SZ cluster sample using optical weak-lensing mass calibration (Magellan & HST) (SB+ in prep.)
  - Joint analysis of SPT-SZ sample with DES weak-lensing (SB+ in prep.)