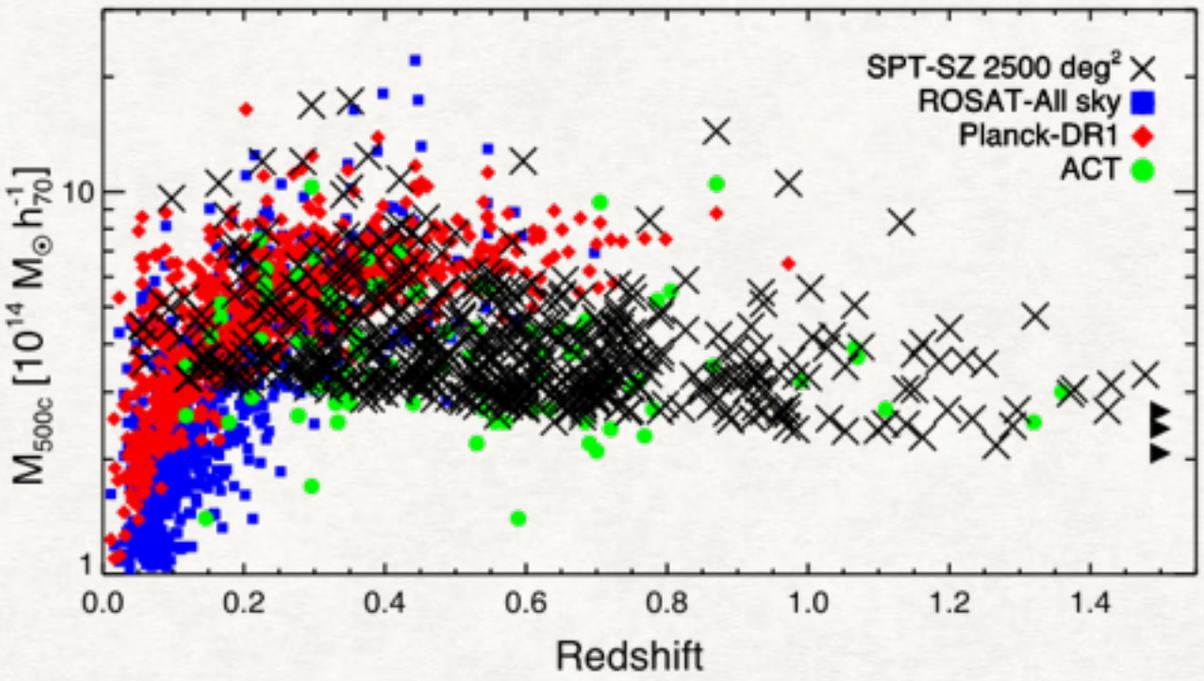
Galaxy Cluster Cosmology

South Pole Telescope SPT-SZ Survey
Weak Lensing & X-ray Follow-Up

Sebastian Bocquet

Argonne National Laboratory & KICP/UChicago

SPT-SZ 2500 deg2 survey sample - Bleem+15



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

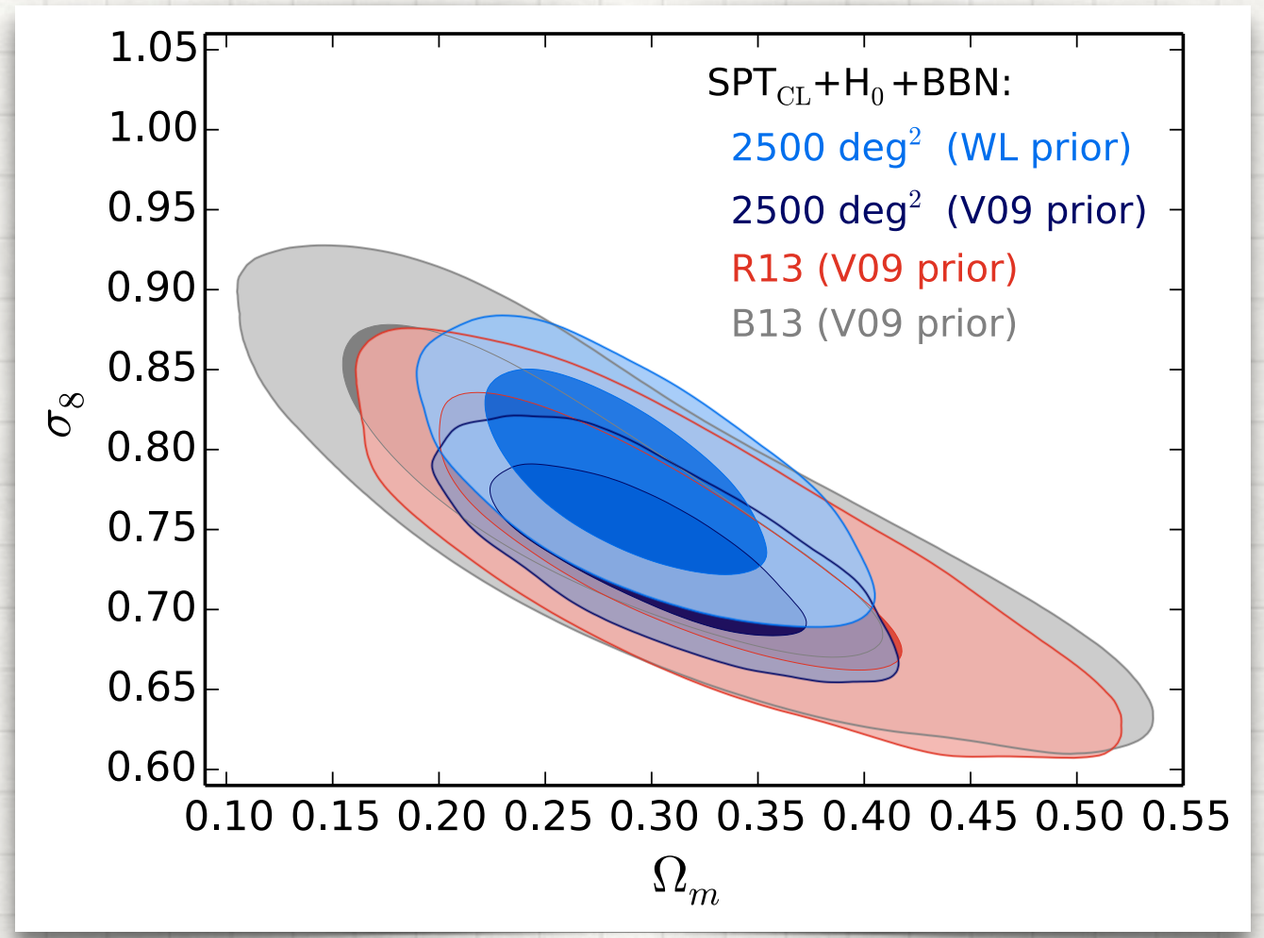
$\xi > 5$ — $z > 0.25$

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 deg^2: 18 clusters w/ 14 X-ray Y_X
  (hydrostatic Y_X-mass relation)
- 720 deg^2: 100 clusters w/ 14 X-ray Y_X
  (hydrostatic Y_X-mass relation, simulation-calibrated velocity dispersion-mass relation)
- 2500 deg^2: 377 clusters w/ 82 X-ray Y_X
  (normalization of Y_X-mass relation from external WL study (Hoekstra+ 15))

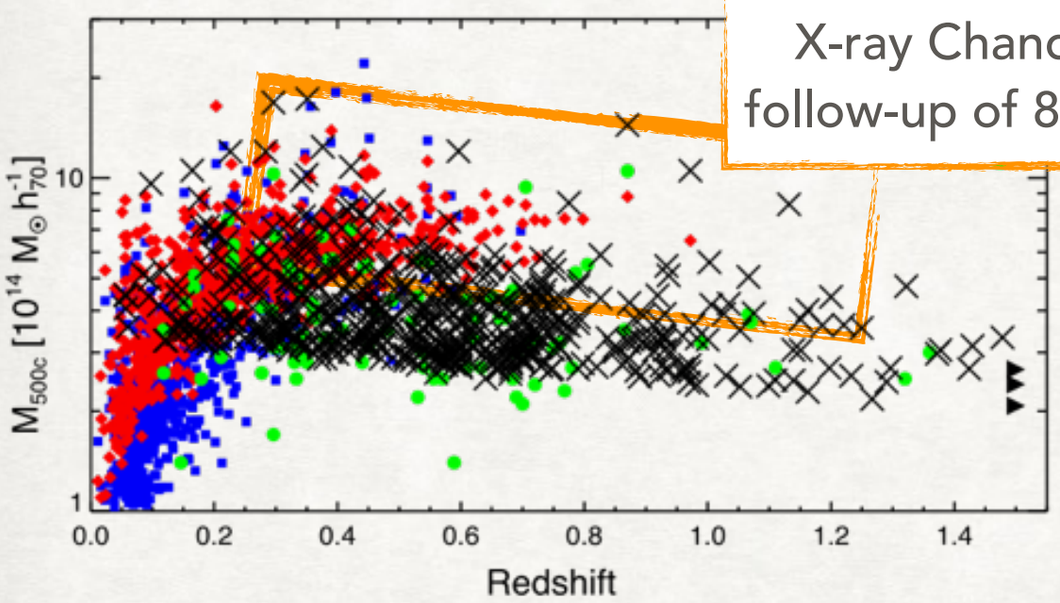


SPT collaboration: de Haan+ 2016

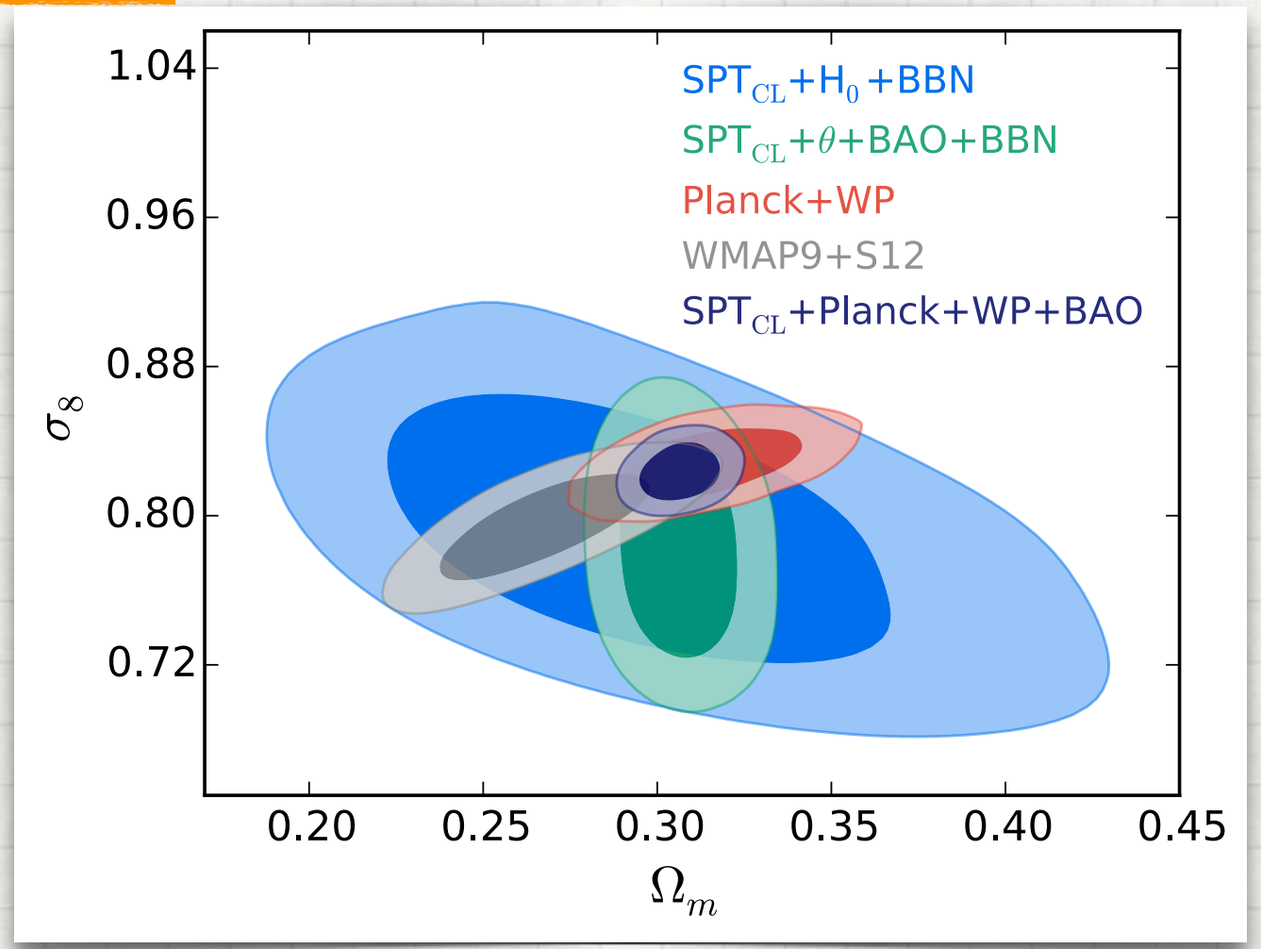
Vanderlinde+ 2010, Benson+ 2013, Reichardt+ 2013, SB+ 2015, de Haan+ 2016

Flat LCDM cosmology

SPT collab.: de Haan et al. (with SB), 2016



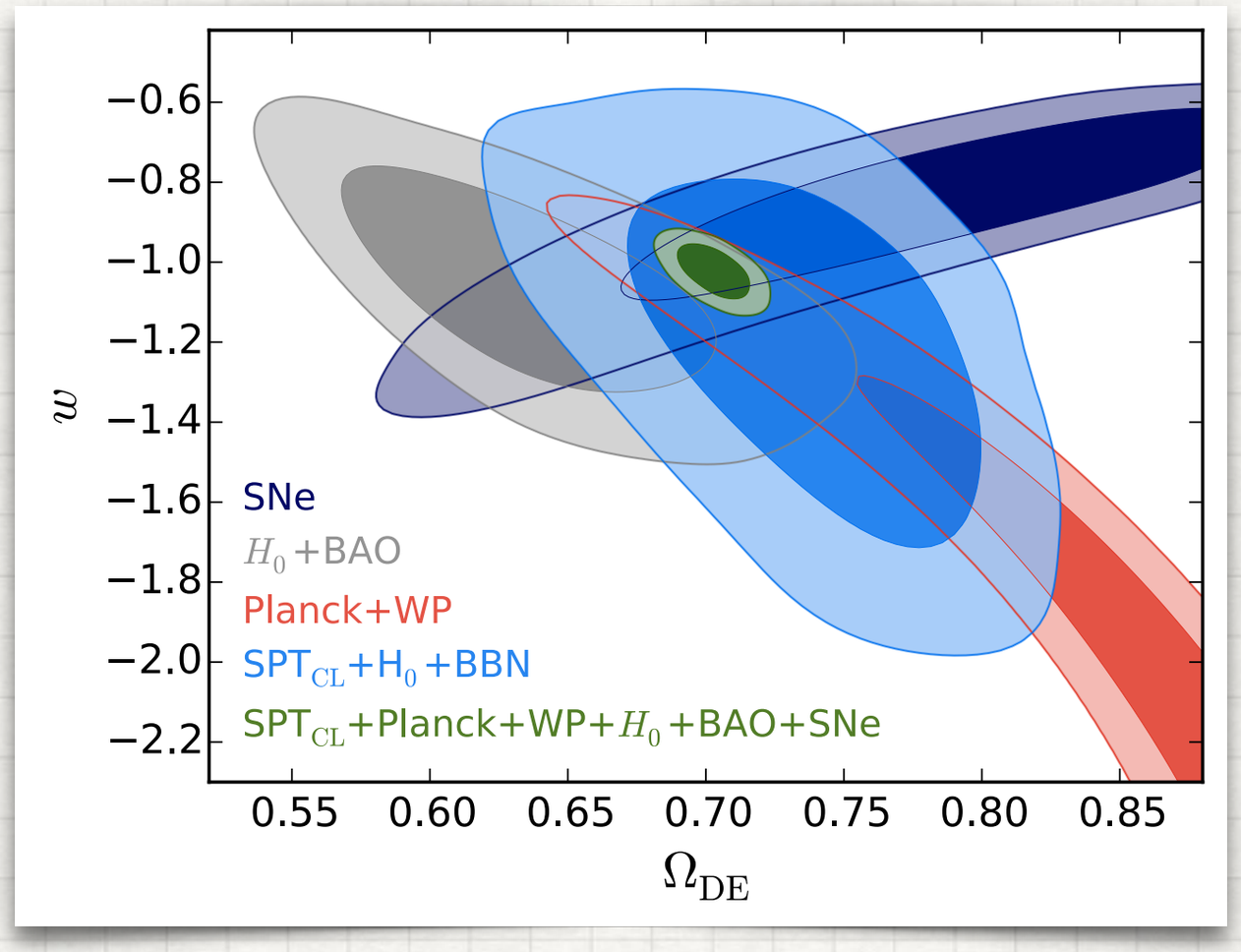
- Clusters + BBN + H_0:
  - Ω_m = 0.289 +/- 0.042
  - σ_8 = 0.784 +/- 0.039
- Consistent with primary CMB



Flat wCDM cosmology

SPT collab.: de Haan et al. (with SB), 2016

- SPT-SZ clusters:
  - w = -1.28 +/- 0.31
- SPT clusters + Planck +WP + BAO + SNIa:
  - w = -1.023 +/- 0.042
  - 14% tighter than same data combination without clusters



SPT CLUSTER COSMOLOGY TO DATE

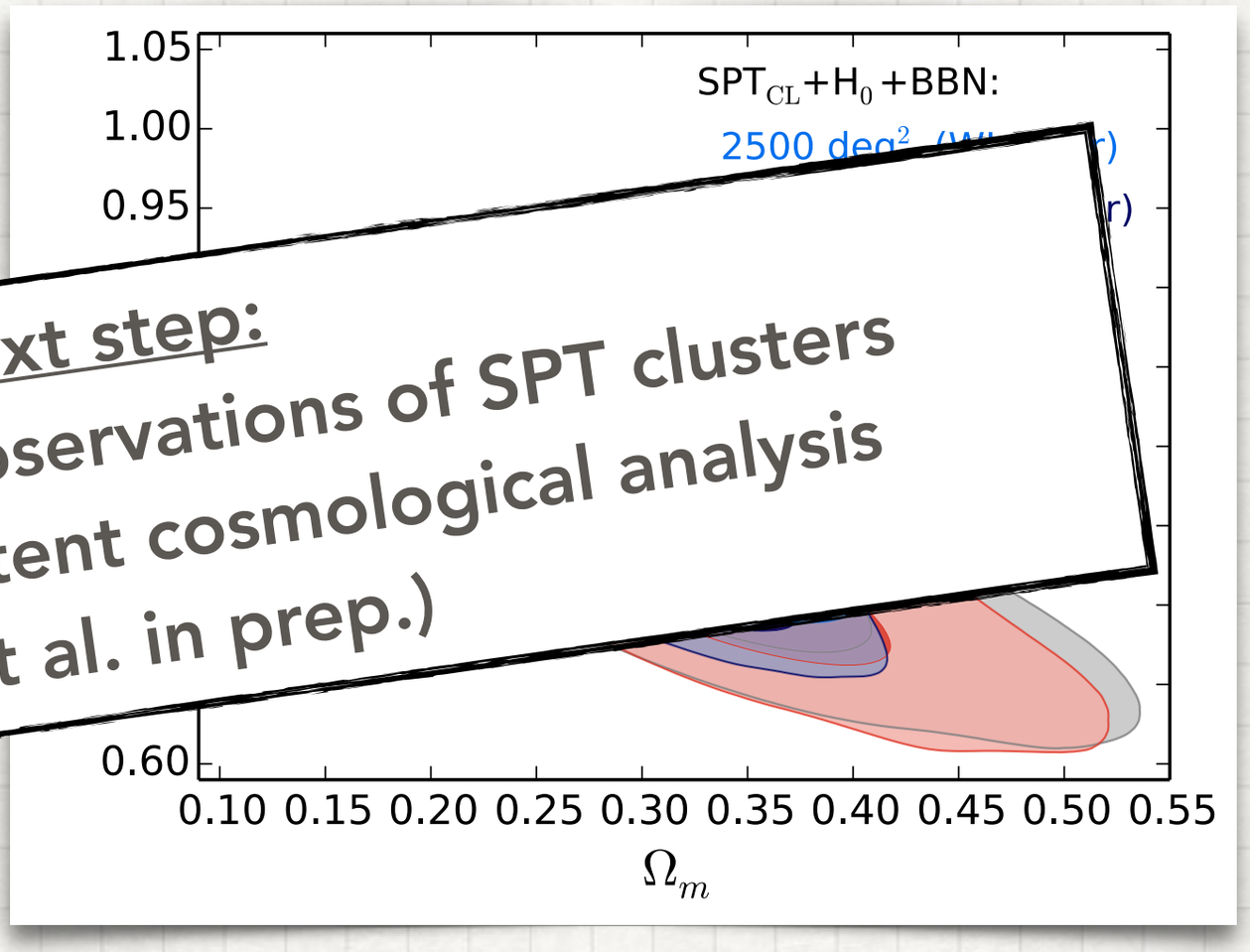
DATA SET AND MASS CALIBRATION SCHEMES

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

- 178 deg^2: 18 clusters w/ 14 X-ray Y_X
  hydrostatic Y_X-mass relation

- 720 d
  hydr
  simul
  dispe

- 2500 d 377 clusters w/ 82 X-ray Y_X
  normalization of Y_X-mass relation from
  external WL study (Hoekstra+ 15)



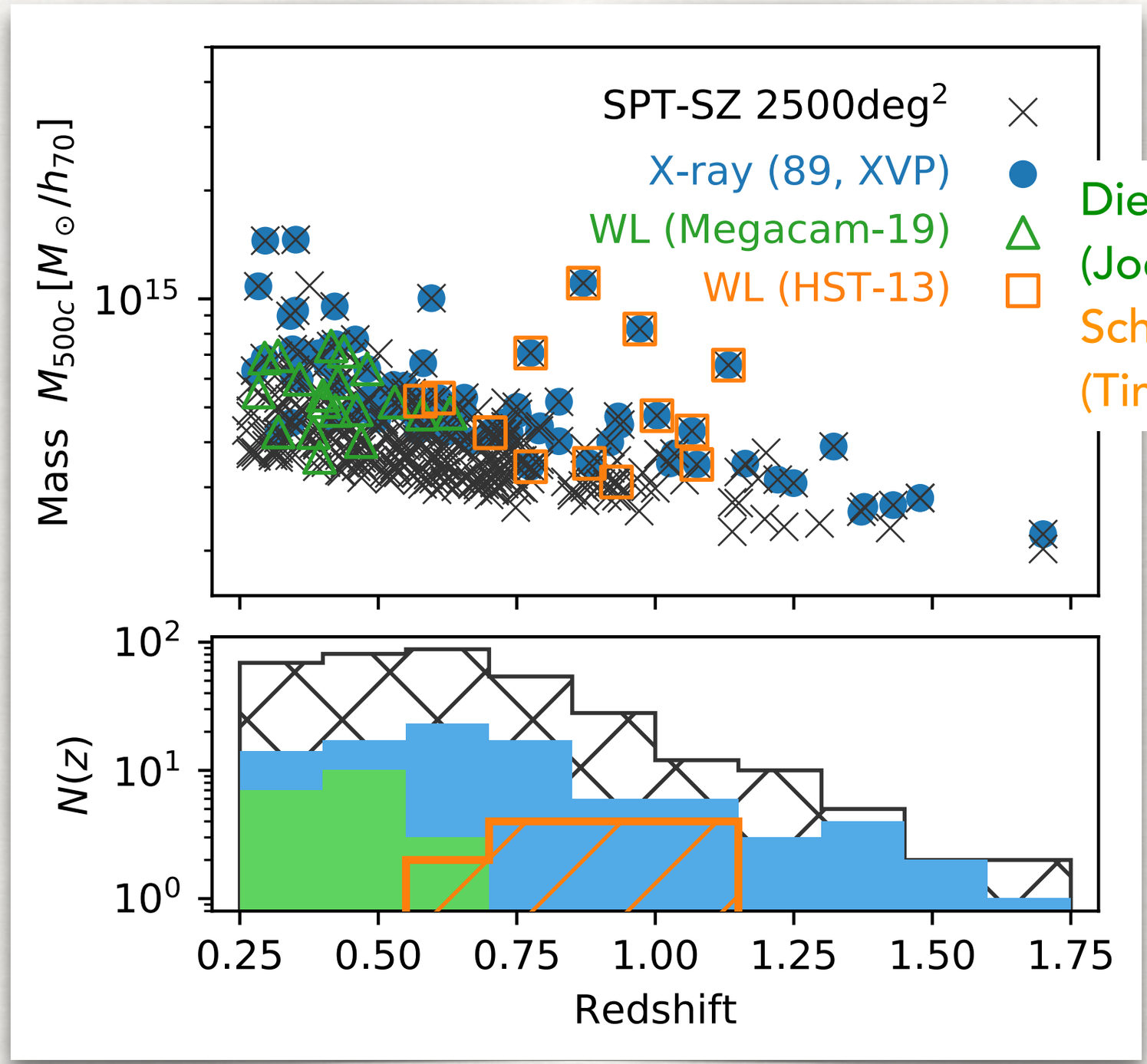
Next step:
Use weak lensing observations of SPT clusters for fully self-consistent cosmological analysis (SB et al. in prep.)

SPT collaboration: de Haan+ 2016

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

SPT-SZ 2500 DEG^2 SURVEY COSMO SAMPLE (377)

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



Dietrich, SB+ in prep.
(Joerg's talk Friday)
Schrabback+ 2016
(Tims' talk Tuesday)

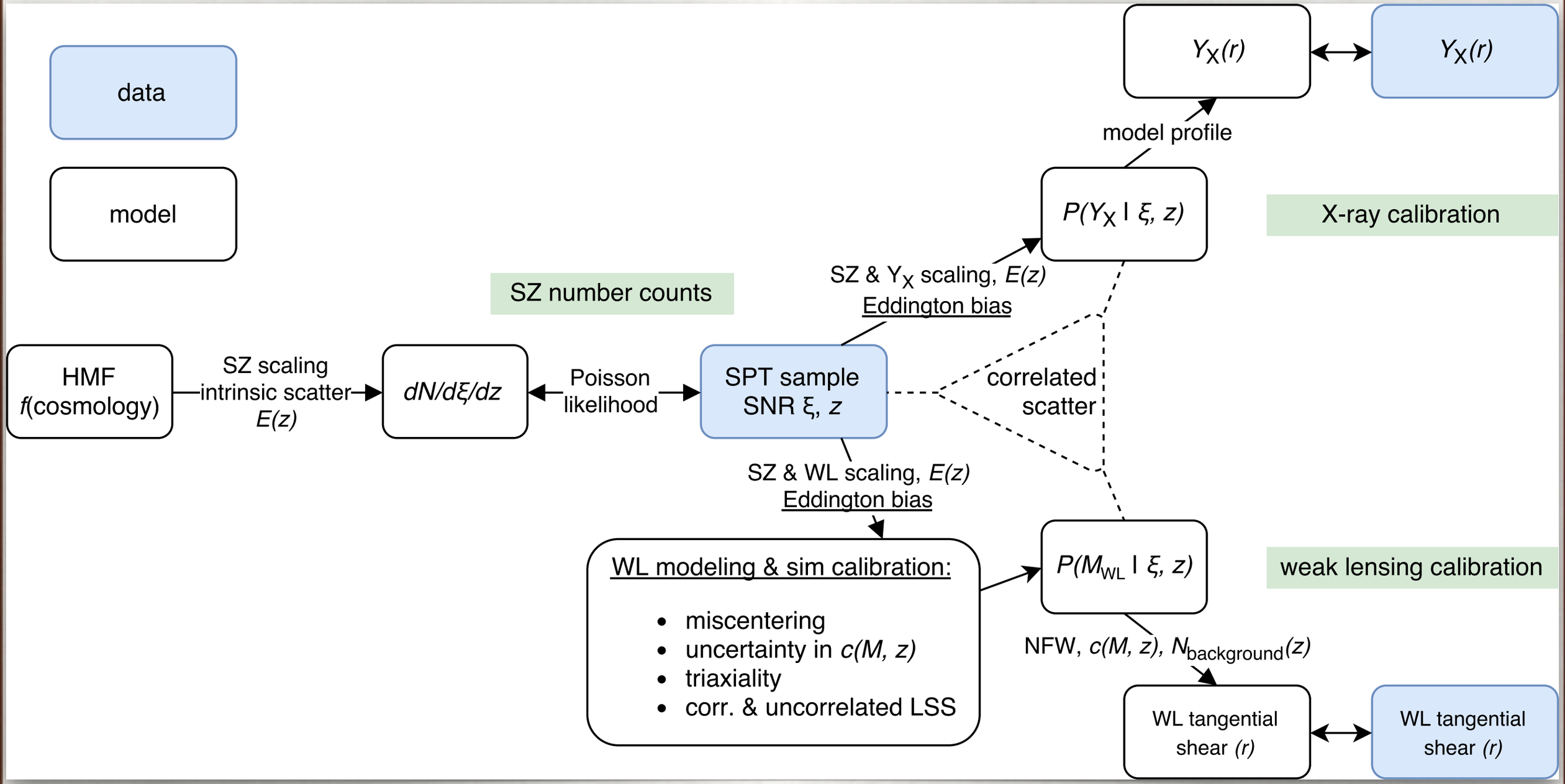
Analysis framework

Cluster counts & multi-wavelength mass calibration

- Halo mass function (Tinker+08)
- Mass-observable relations
  - SZ: SNR ~ $Asz\ M^{Bsz}\ E(z)^{Csz}$; log-normal scatter Dsz
  - X-ray: M ~ $Ax\ Y_X^{Bx}\ E(z)^{Cx}$; log-normal scatter D_X
  - WL: $M_{WL} = b\ M$; log-normal scatter D_{WL}
  - correlated scatter: $\rho_{SZ\text{-}X}$, $\rho_{SZ\text{-}WL}$, $\rho_{WL\text{-}X}$
  - WL bias and scatter calibrated against numerical simulations (Applegate+ in prep.)

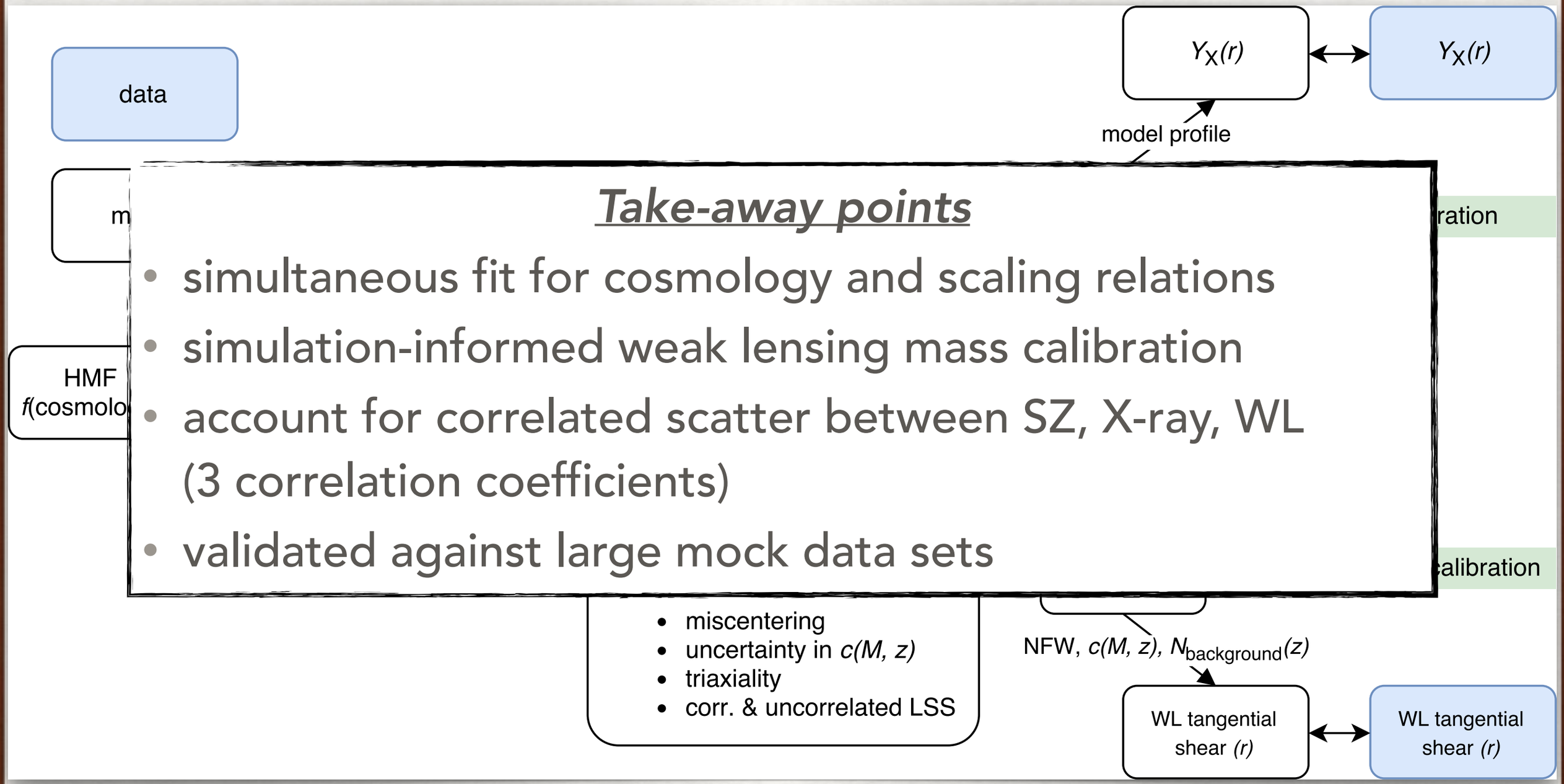
Analysis pipeline

Cluster counts & multi-wavelength mass calibration



Analysis pipeline

Cluster counts & multi-wavelength mass calibration

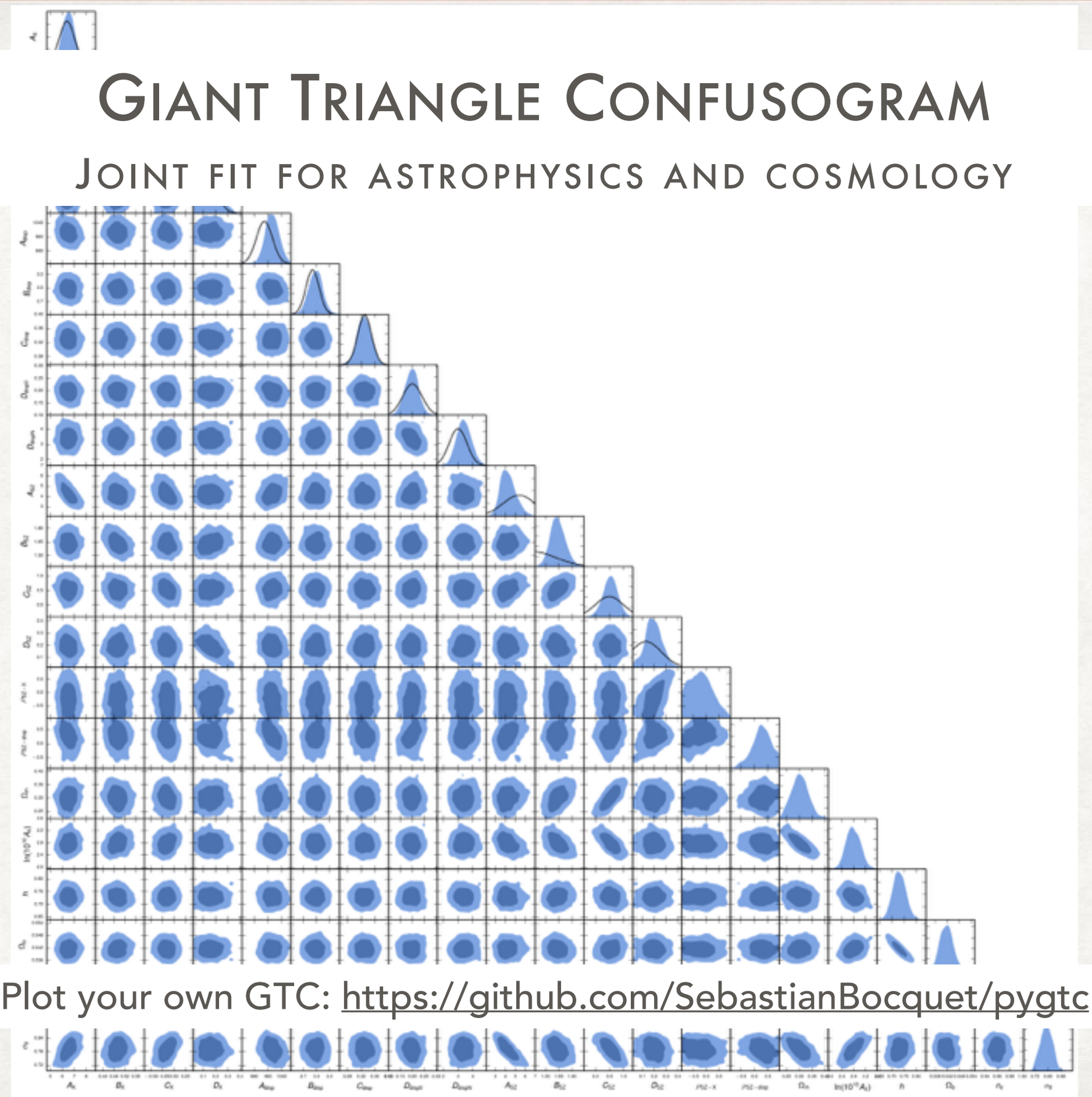


Take-away points

- simultaneous fit for cosmology and scaling relations
- simulation-informed weak lensing mass calibration
- account for correlated scatter between SZ, X-ray, WL (3 correlation coefficients)
- validated against large mock data sets

Giant Triangle Confusogram

Joint fit for astrophysics and cosmology



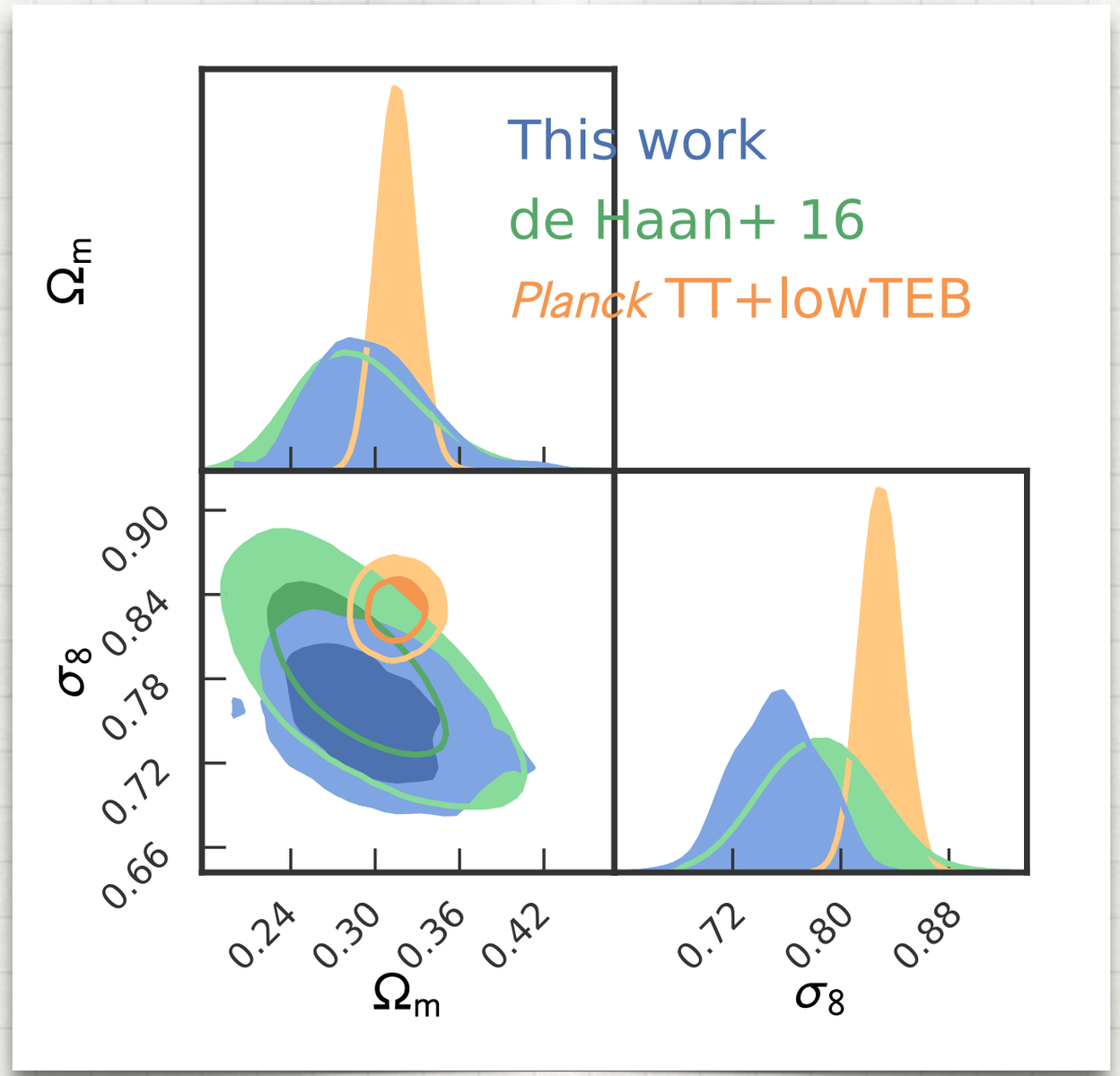
Plot your own GTC: https://github.com/SebastianBocquet/pygtc

SPT CLUSTER COSMO WITH WEAK LENSING CALIBRATION

SB+ IN PREP.

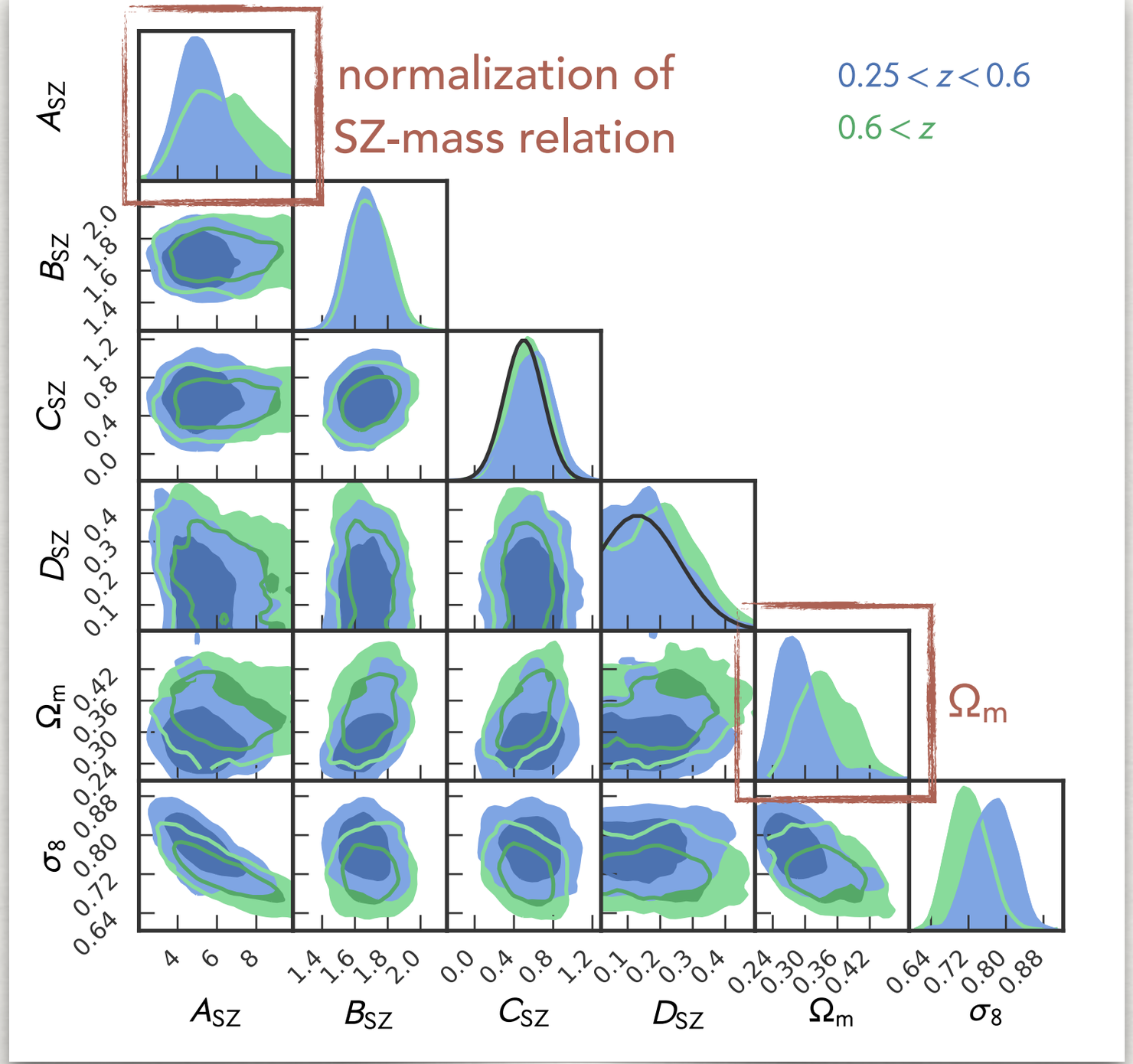
Assuming LCDM:

- Consistent with previous SPT analysis (de Haan+16), which used prior on Y_X-mass normalization (Hoekstra+ 15)
- Important cross-check of different mass calibration techniques and data sets
- Slight difference wrt *Planck*15



Low vs. high redshift half samples

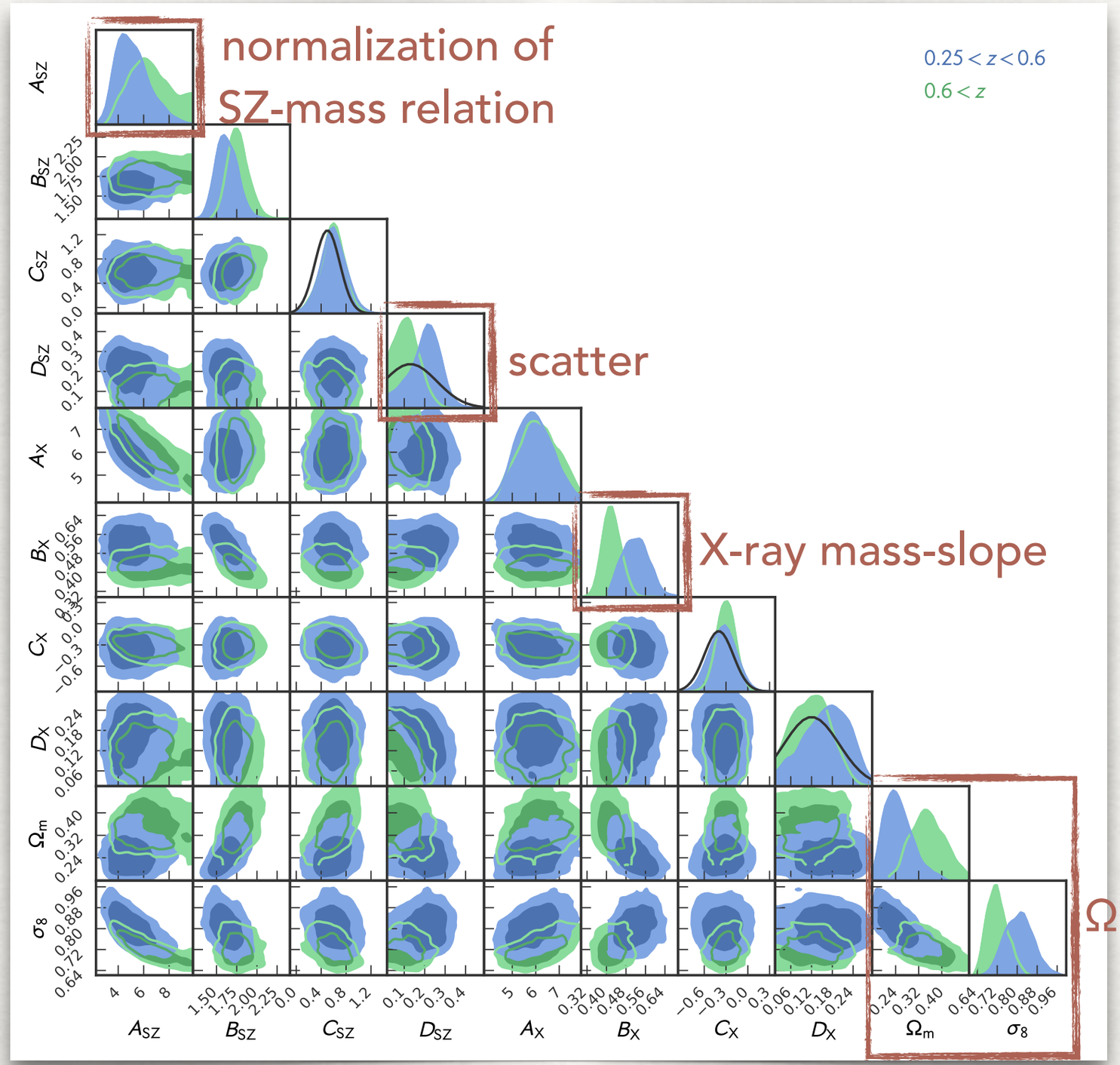
Split sample at z = 0.6, use SZ and WL data (no X-ray)



- high-z mass calibration is weaker
- Ω_m from high-z slightly higher
- This is awesome!

Low vs. high redshift half samples

Split sample at z = 0.6, use SZ + WL + X-ray data

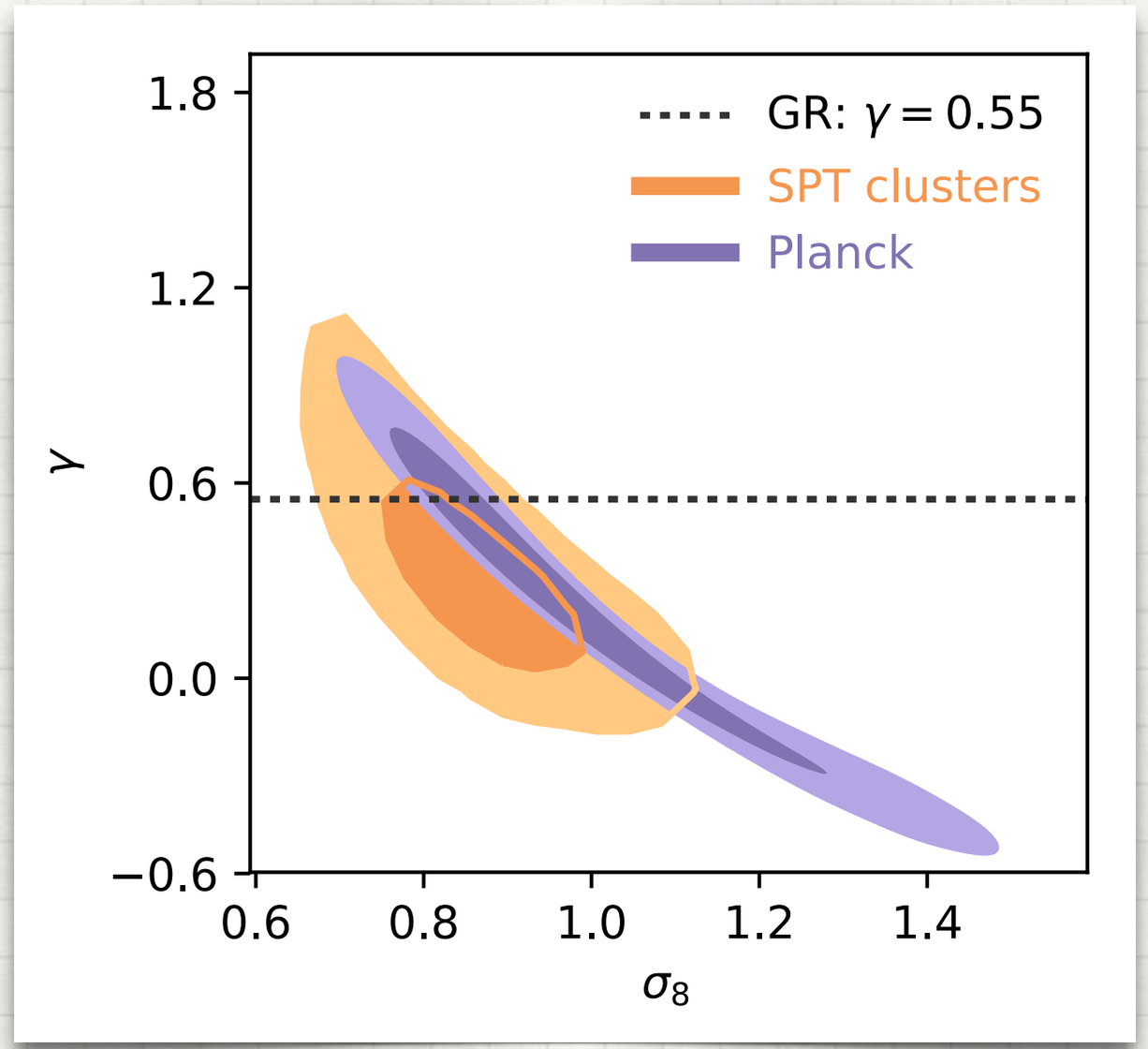


- z-dependence of scatter between SZ - X-ray?
- z-dependence of X-ray mass-slope?
- X-ray slope enhances difference in Ω_m — σ_8
- Remember the *M*gas-*M* plots our simulator friends showed, suggesting non-power-law slopes
- This is interesting!

GROWTH INDEX FROM SPT-SZ CLUSTERS

SB+ IN PREP.

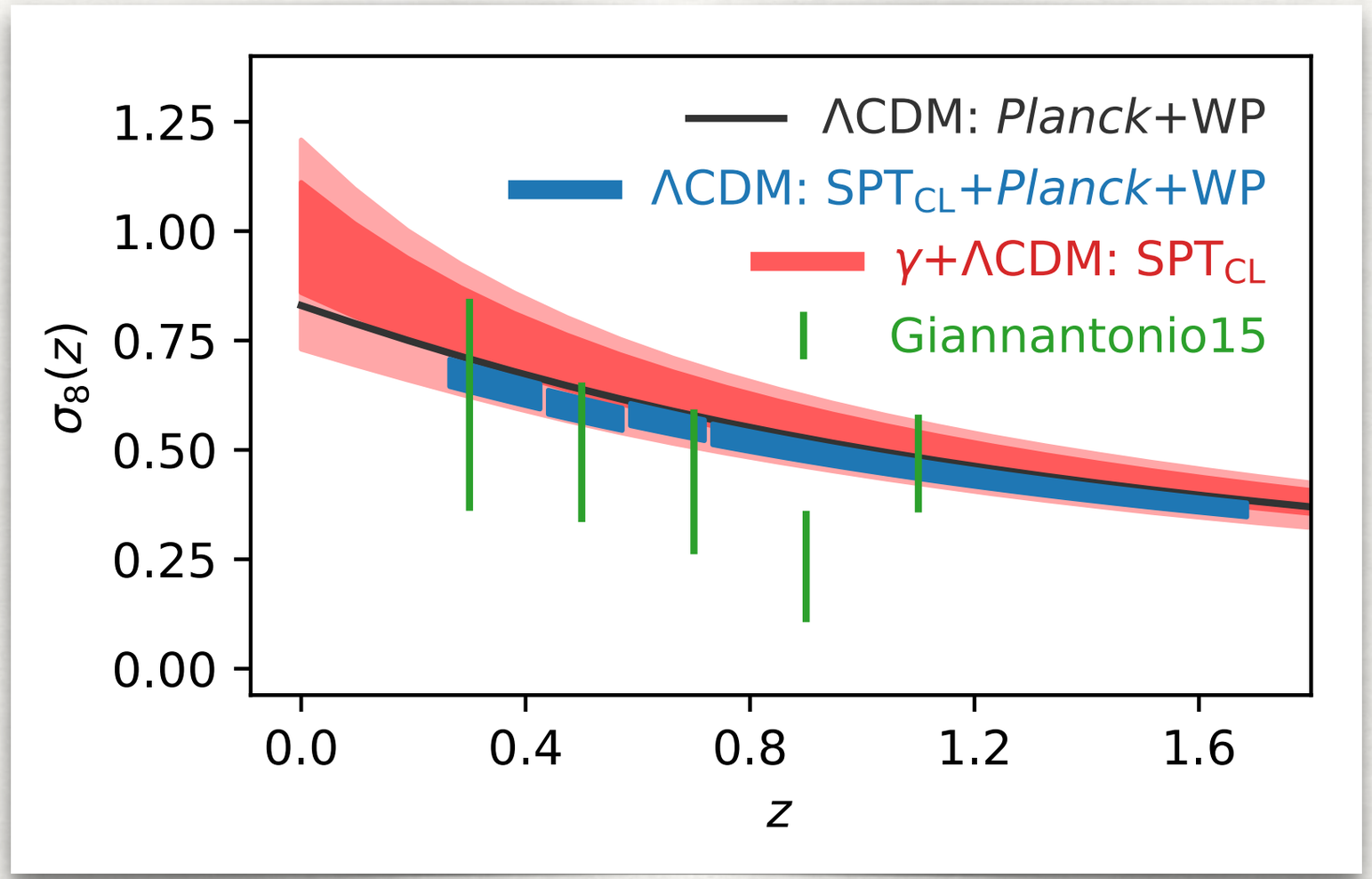
- Parametrized growth of structure as a consistency test for LCDM
- $f(a) \equiv d\ln \delta / d\ln a = \Omega_m(a)^{\gamma}$
- SPT clusters favor slightly low values of γ
- Primary CMB has some constraining power due to ISW effect



Toward non-parametric growth

SB+ in prep.

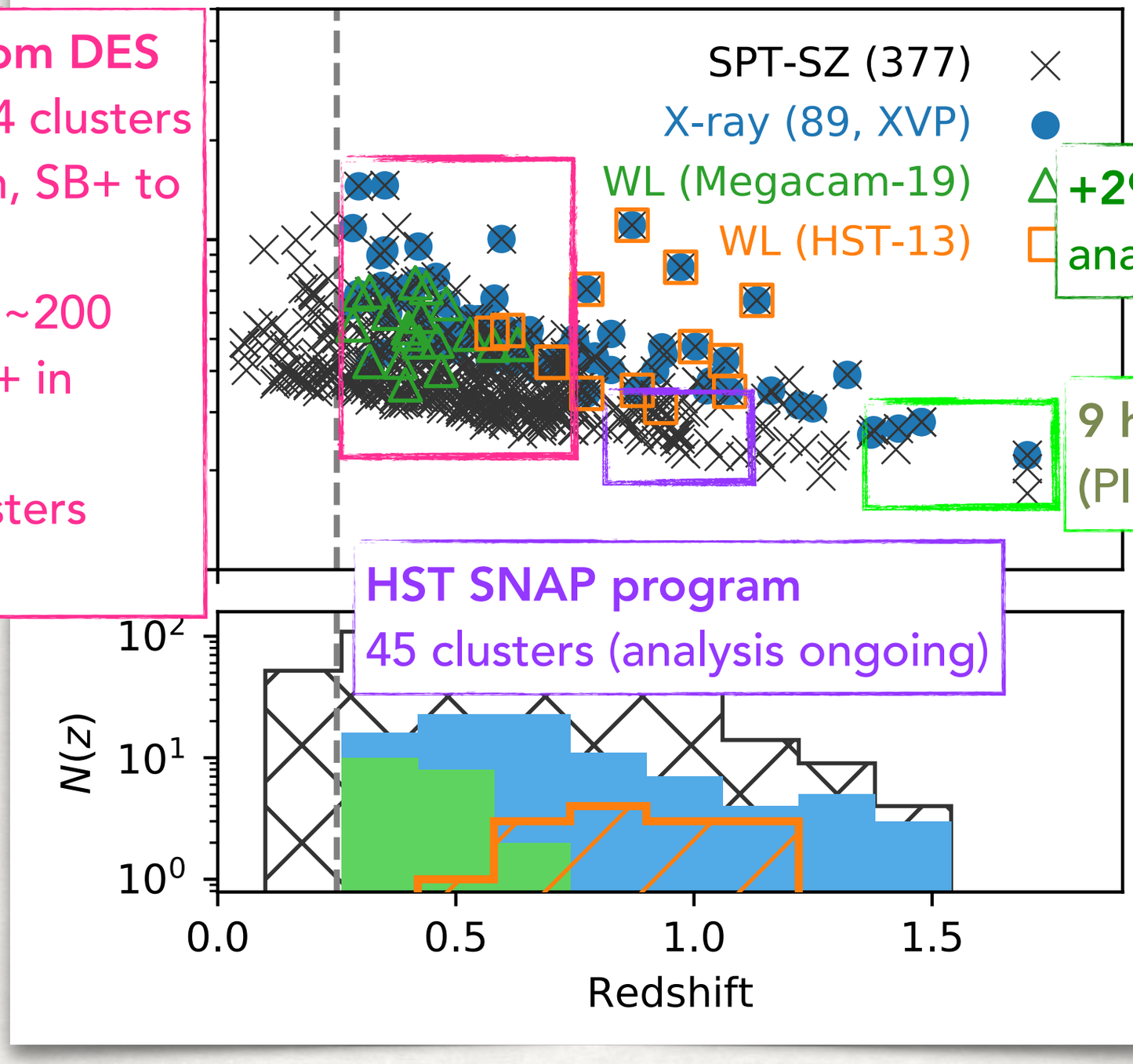
Blue error bands: Combined analysis with primary CMB from *Planck*, but fit for σ_8 in four redshift bins using cluster data only. This way, *Planck* only constrains the geometry of the Universe, but not growth.



OUTLOOK: ONGOING 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 (Stern+ in prep.)
3. Y3: all SPT clusters @ z < ~0.7



+29 Megacam clusters analysis ongoing

9 high-z clusters (HST) (PI Schrabback)

Summary

Stay tuned for:

- WL-calibrated cosmology from SPT clusters
  - first constraints from high-*z* cluster sample
  - growth of structure
- SPTpol cluster sample: deep fields and wide fields extend the sample's mass and redshift range
- Ongoing WL observations:
  - targeted high-*z* with HST
  - all clusters @ $z < 0.7$ from Dark Energy Survey
  - targeted high S/N measurements from Magellan/Megacam