Cluster Cosmology with the South Pole Telescope
(and the Dark Energy Survey)

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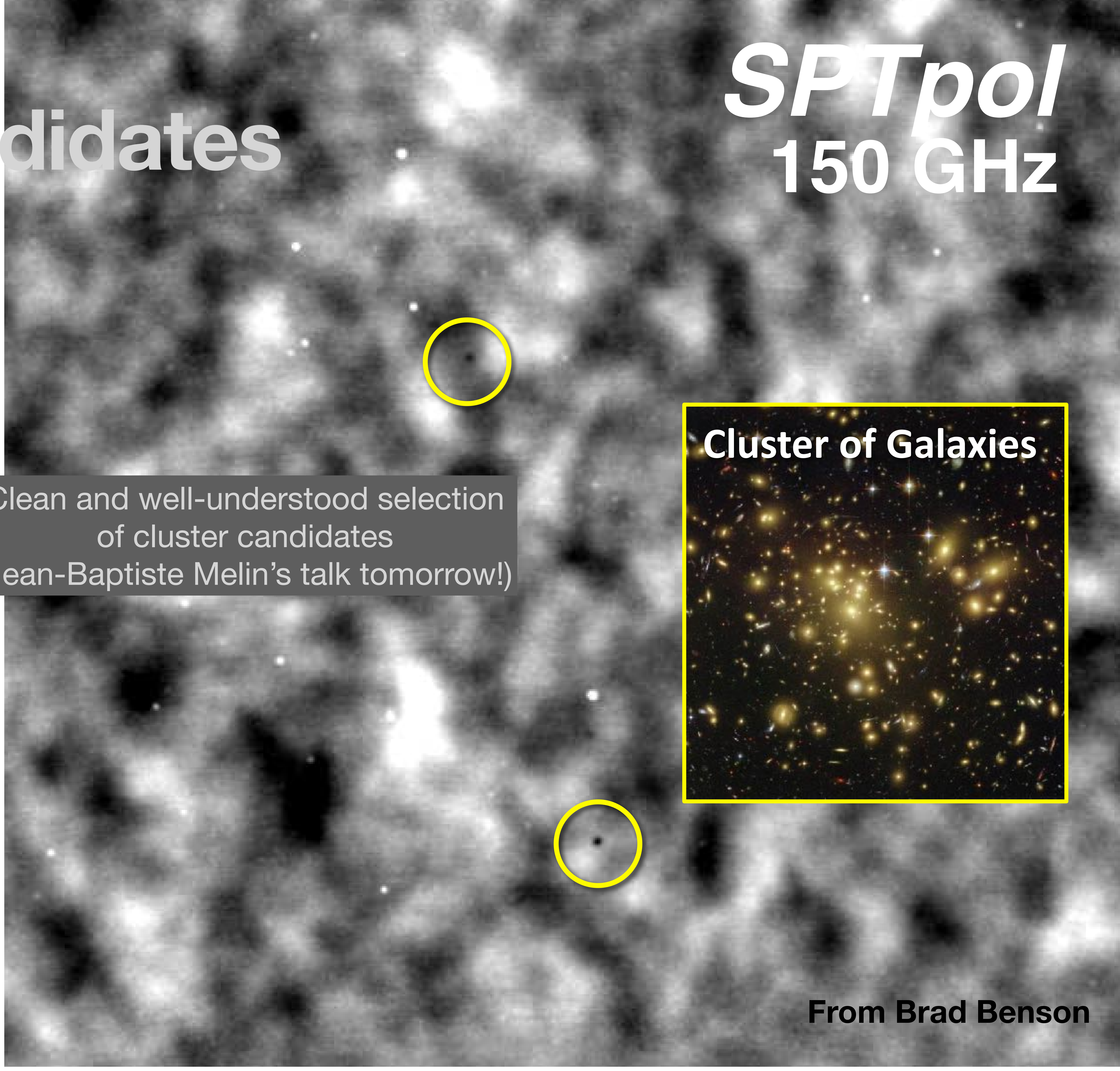
Image credit: SPT 2018 winter-overs Adam & Joshua

Overview
Topics to be covered

- Why the South Pole Telescope
- The role of weak-lensing data
- The role of numerical simulations
- Select results and work in preparation
- (Ask me about the role of X-ray data later, it’s interesting!)

Let’s do a cosmological analysis!

I. Find cluster candidates



Clean and well-understood selection of cluster candidates (Jean-Baptiste Melin's talk tomorrow!)

II. Multi-observable dataset

as of 2019

- SPT: detection significance, filter scale, RA, DEC
  selection: *ξ > 5, z > 0.25*
  Bleem+15, but also Planck, Atacama Cosmology Telescope (ACT)

- Optical/NIR/spectroscopy: cluster confirmation, redshift
  Bleem+15, Bayliss+17, Khullar+19, many more

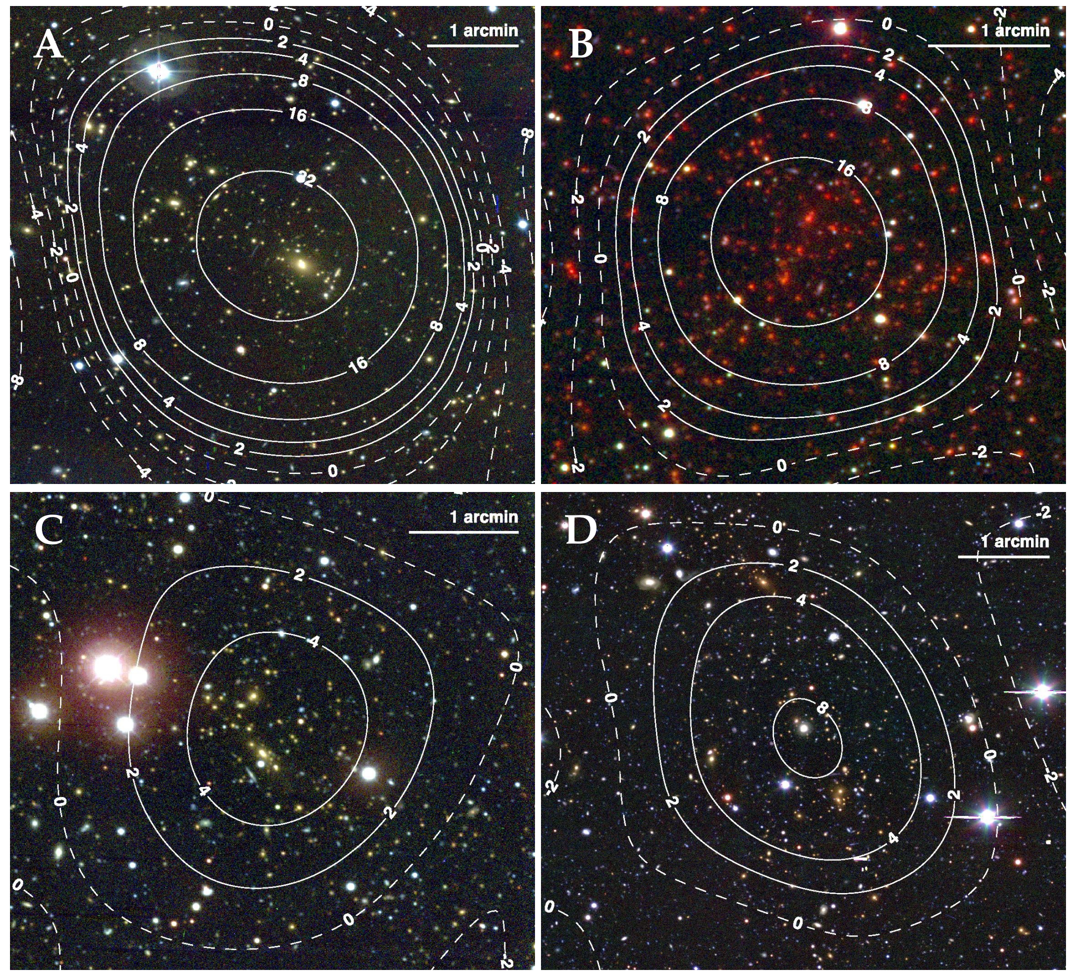
- X-ray: gas mass profiles, $Y_X(r)$ (gas mass x temperature) using *Chandra*
  McDonald+13,17

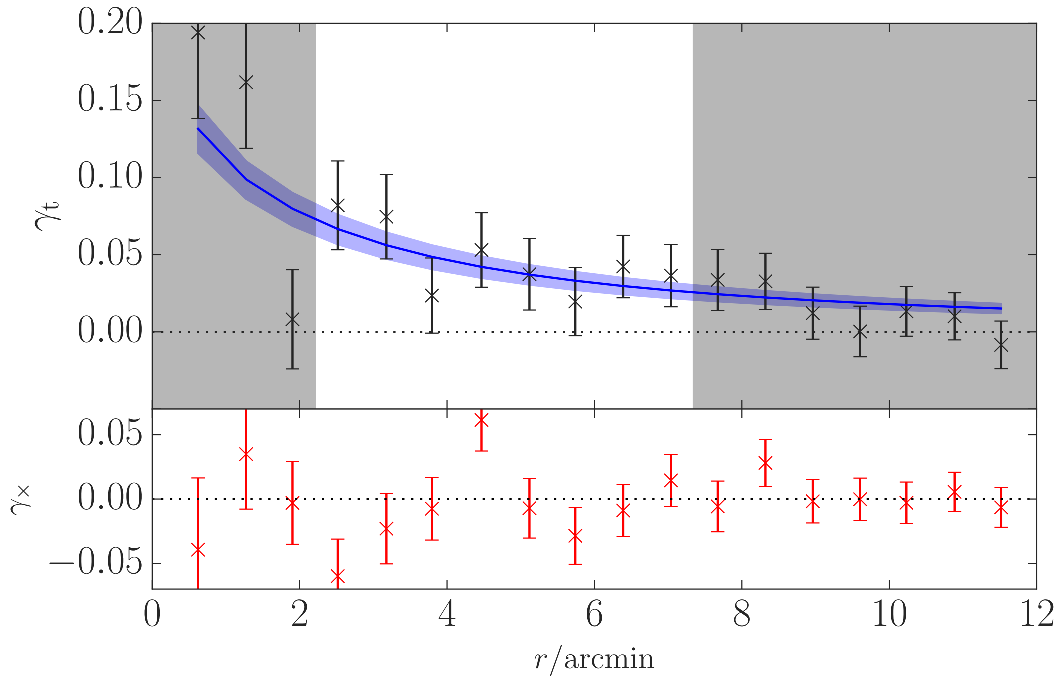
  A NEW ROBUST LOW-SCATTER X-RAY MASS INDICATOR FOR CLUSTERS OF GALAXIES

  Andrey V. Kravtsov[1,2], Alexey Vikhlinin[3,4], Daisuke Nagai[5]

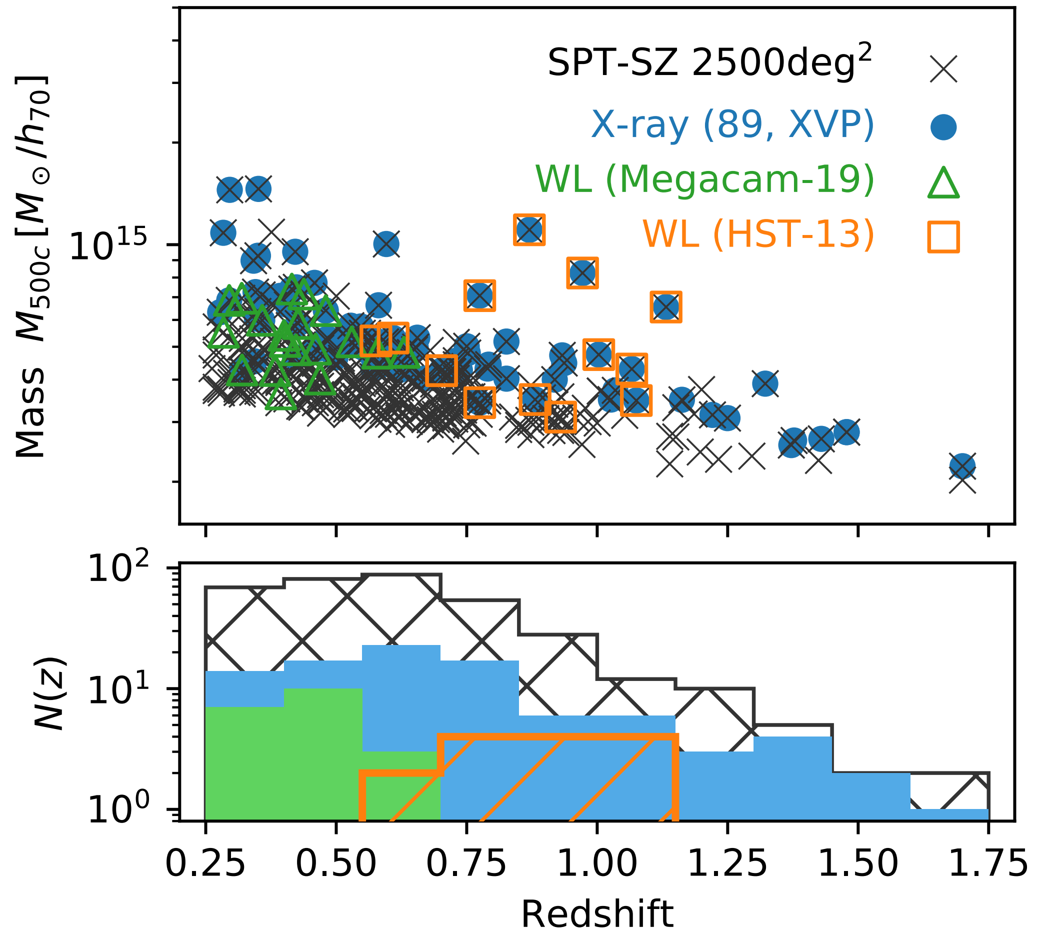
- Weak lensing: shear profiles, source redshift distribution using Magellan and *Hubble*
  Schrabback…Bocquet…+18, Dietrich,Bocquet+19

- All these are observables. I did NOT say “we measured masses”





(b) Tangential shear profile of SPT-CL J0254−5857.



III. Analysis and modeling strategy

- Framework for observable—mass relation P(obs | *M,z*)
  - the bigger a halo, the stronger its SZ, X-ray, and lensing signature will be (also add redshift evolution)
  - There is intrinsic scatter in observable—mass relation (no two clusters are the same)
  - The scatter among different observables could be correlated (due to, e.g, triaxiality, AGN activity, star formation)
- Likelihood function for the cluster sample and its follow-up data

$$\ln \mathcal{L}(\boldsymbol{p}) = \sum_i \ln \frac{dN(\xi, z|\boldsymbol{p})}{d\xi dz}\Big|_{\xi_i, z_i} - \int_{z_{\mathrm{cut}}}^{\infty} dz \int_{\xi_{\mathrm{cut}}}^{\infty} d\xi \frac{dN(\xi, z|\boldsymbol{p})}{d\xi dz} + \sum_j \ln P(Y_{\mathrm{X}}, g_{\mathrm{t}}|\xi_j, z_j, \boldsymbol{p})|_{Y_{\mathrm{X}_j}, g_{\mathrm{t}_j}}$$

$$\frac{dN(\xi, z|\boldsymbol{p})}{d\xi dz} = \iint dM\, d\zeta [P(\xi|\zeta) P(\zeta|M, z, \boldsymbol{p}) \times \frac{dN(M, z|\boldsymbol{p})}{dMdz} \Omega(z, \boldsymbol{p})],$$

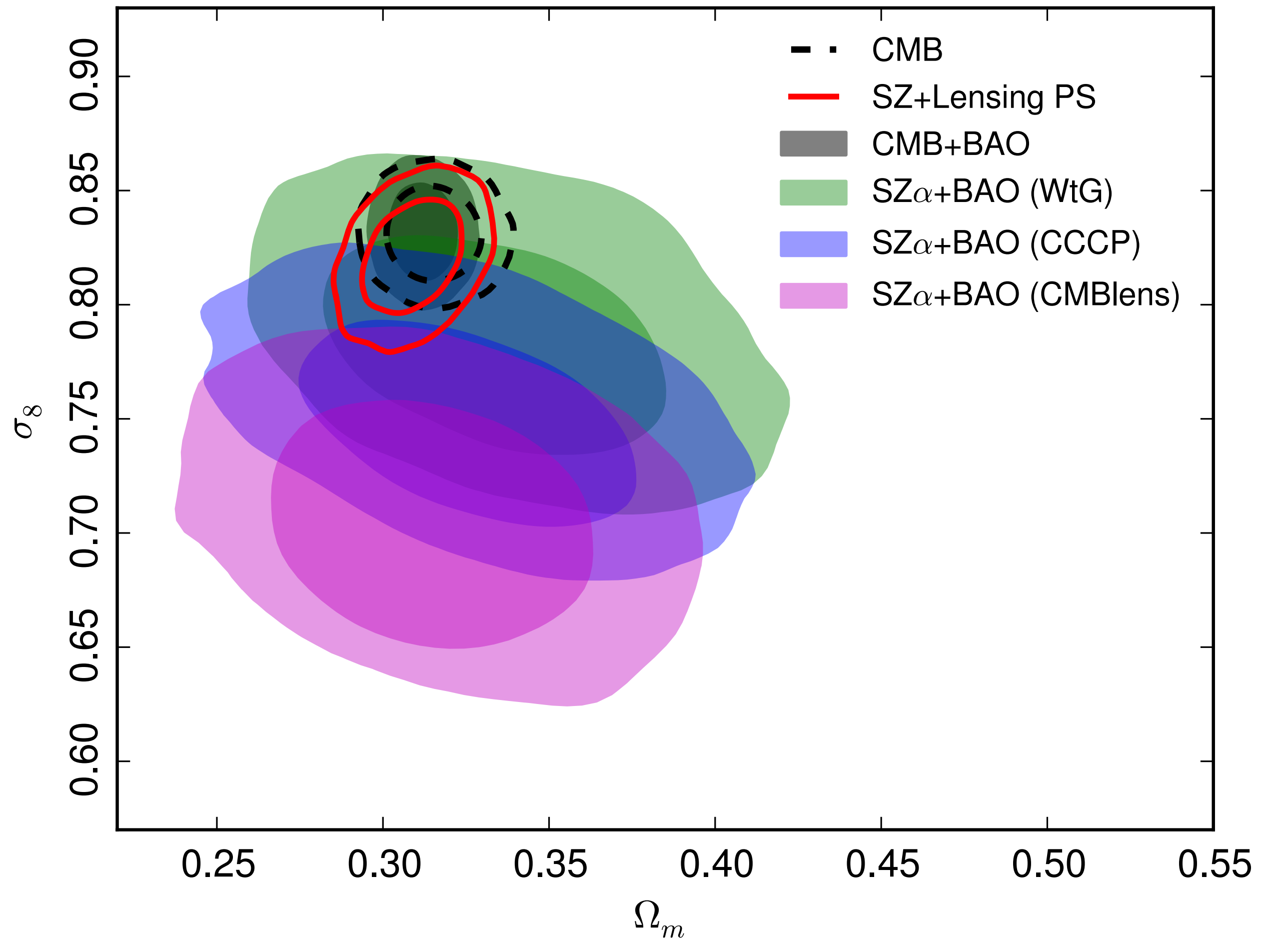
$$P(Y_{\mathrm{X}}^{\mathrm{obs}}, g_{\mathrm{t}}^{\mathrm{obs}}|\xi, z, \boldsymbol{p}) = \iiiint dM\, d\zeta\, dY_{\mathrm{X}} dM_{\mathrm{WL}} \times [P(Y_{\mathrm{X}}^{\mathrm{obs}}|Y_{\mathrm{X}}) P(g_{\mathrm{t}}^{\mathrm{obs}}|M_{\mathrm{WL}}) P(\xi|\zeta) \times P(\zeta, Y_{\mathrm{X}}, M_{\mathrm{WL}}|M, z, \boldsymbol{p}) P(M|z, \boldsymbol{p})],$$

- Nota bene: We are not measuring a halo mass. We are modeling observables.
- In fact, the variable *M* is marginalized over.

IV. Add information

- We just defined a statistical model with unknown parameters in the observable—mass relations.
- The cluster mass scale is degenerate with the cosmology we are after.
  Conversely, no mass information, no cosmology!
- We *could* use predictions of the SZ—mass (or X-ray—mass) relation from first principles or numerical simulations
  - Systematically limited by uncertain astrophysics
- Weak-lensing-to-mass relation is much less affected by astrophysics
  - We can accurately model the cluster lensing signal (within some uncertainty) using numerical simulations

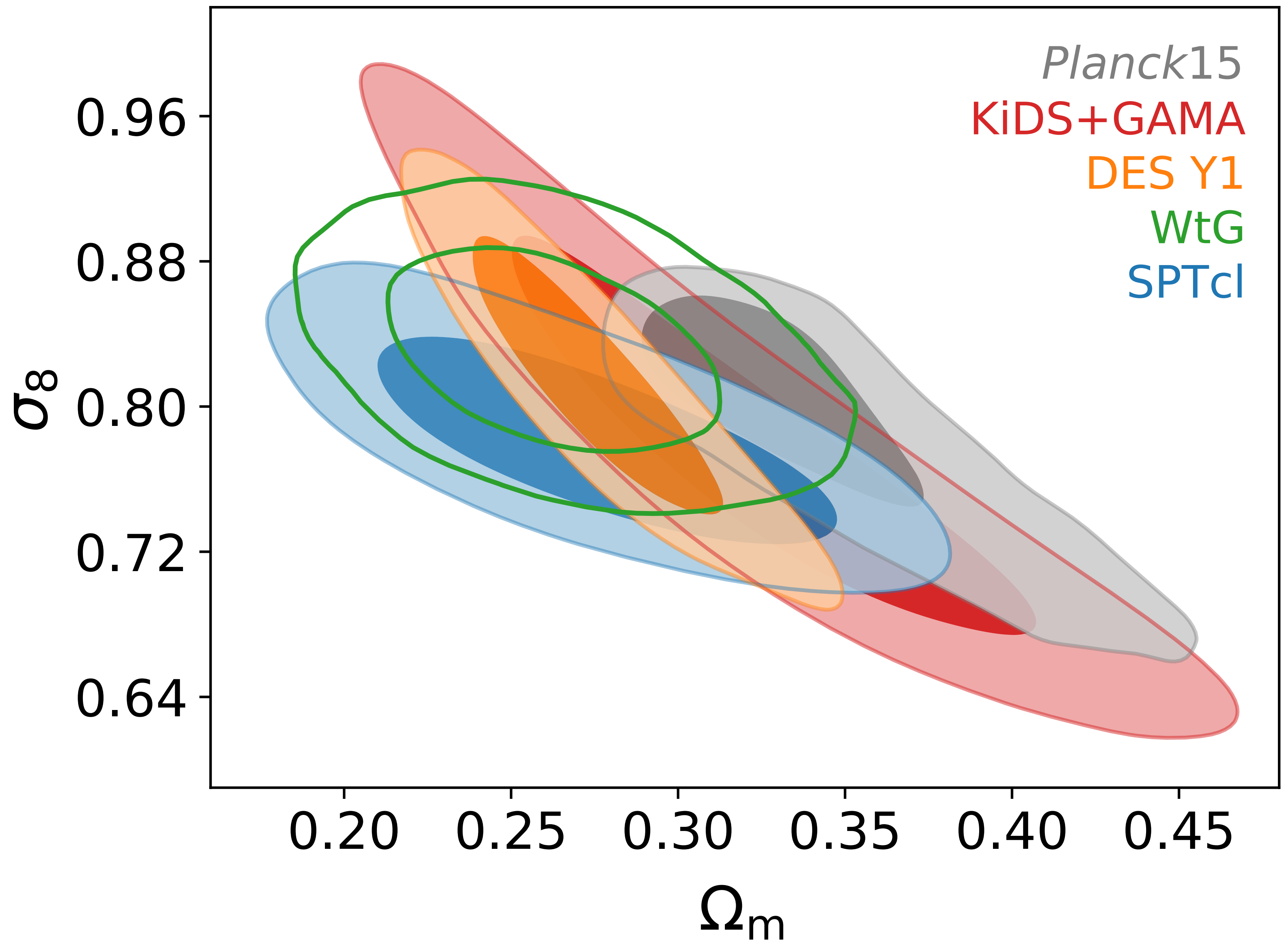
Planck 2015



V. Cosmological constraints from SPT-SZ

LCDM constraints (w/ massive neutrinos)

- 343 clusters, of which 32 w/ weak lensing and 89 w/ X-ray data
- 6—9% systematic uncertainty in weak-lensing systematics (not saturated by the small sample size)
- $\Omega_m = 0.276 \pm 0.047$, $\sigma_8 = 0.781 \pm 0.037$



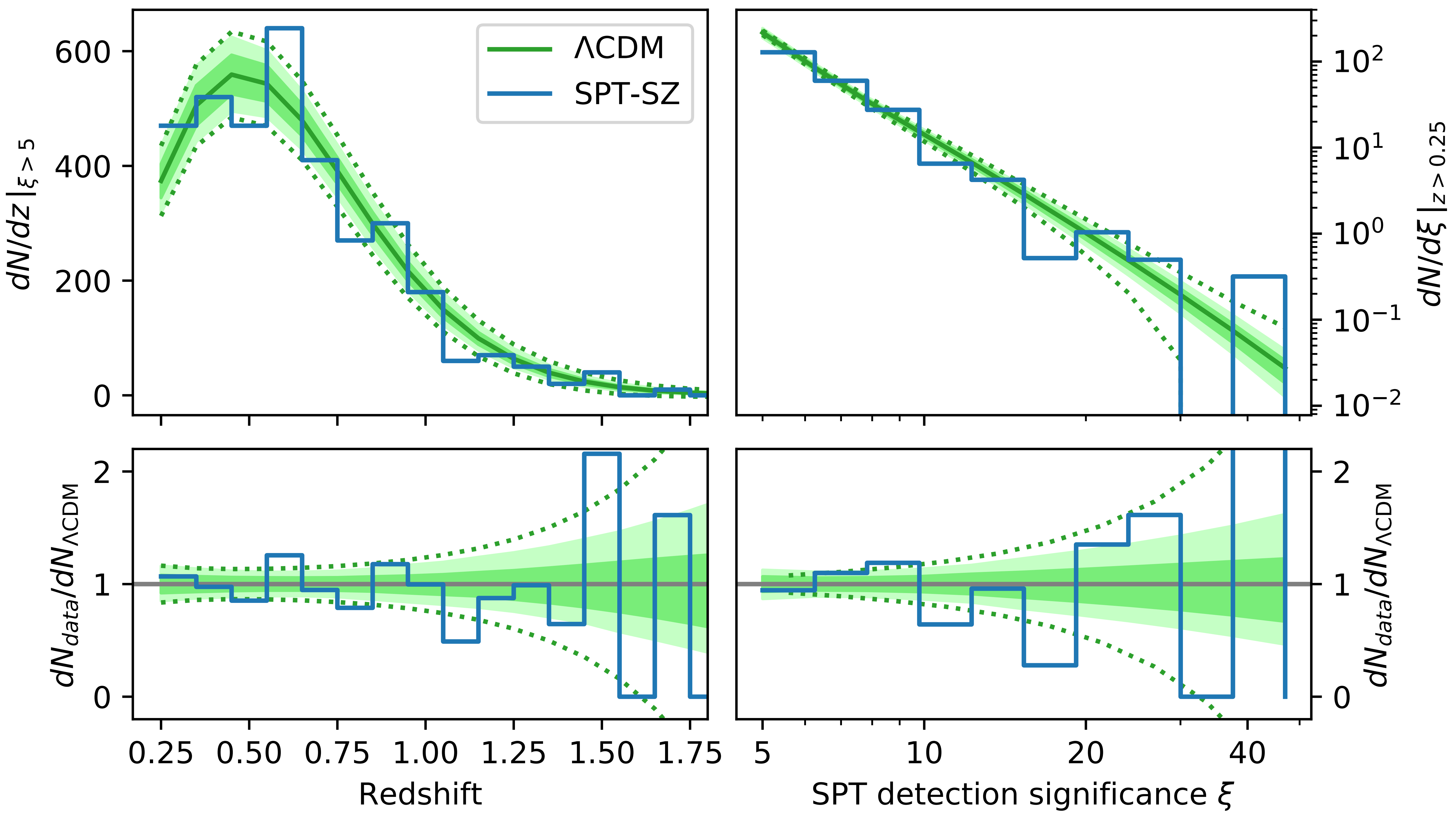
Bocquet+19

Parameter	Prior
Cosmological	
Ω_m	$\mathcal{U}(0.05, 0.6)$, $\Omega_m(z > 0.25) > 0.156$
$\Omega_b h^2$	$\mathcal{U}(0.020, 0.024)$
$\Omega_\nu h^2$	$\mathcal{U}(0, 0.01)$
Ω_k	fixed (0)
A_s	$\mathcal{U}(10^{-10}, 10^{-8})$
h	$\mathcal{U}(0.55, 0.9)$
n_s	$\mathcal{U}(0.94, 1.00)$
w	fixed (-1) or $\mathcal{U}(-2.5, -0.33)$
Optical depth to reionization	
τ	fixed or $\mathcal{U}(0.02, 0.14)$
SZ scaling relation	
A_{SZ}	$\mathcal{U}(1, 10)$
B_{SZ}	$\mathcal{U}(1, 2.5)$
C_{SZ}	$\mathcal{U}(-1, 2)$
$\sigma_{\ln \zeta}$	$\mathcal{U}(0.01, 0.5)$ $(\times \mathcal{N}(0.13, 0.13^2))$
X-ray Y_X scaling relation	
A_{Y_X}	$\mathcal{U}(3, 10)$
B_{Y_X}	$\mathcal{U}(0.3, 0.9)$
C_{Y_X}	$\mathcal{U}(-1, 0.5)$
$\sigma_{\ln Y_X}$	$\mathcal{U}(0.01, 0.5)$
$d\ln M_g / d\ln r$	$\mathcal{U}(0.4, 1.8) \times \mathcal{N}(1.12, 0.23^2)$
WL modeling	
$\delta_{WL,bias}$	$\mathcal{U}(-3, 3) \times \mathcal{N}(0, 1)$
$\delta_{Megacam}$	$\mathcal{U}(-3, 3) \times \mathcal{N}(0, 1)$
δ_{HST}	$\mathcal{U}(-3, 3) \times \mathcal{N}(0, 1)$
$\delta_{WL,scatter}$	$\mathcal{U}(-3, 3) \times \mathcal{N}(0, 1)$
$\delta_{WL,LSS_{Megacam}}$	$\mathcal{U}(-3, 3) \times \mathcal{N}(0, 1)$
$\delta_{WL,LSS_{HST}}$	$\mathcal{U}(-3, 3) \times \mathcal{N}(0, 1)$
Correlated scatter	
ρ_{SZ-WL}	$\mathcal{U}(-1, 1)$
ρ_{SZ-X}	$\mathcal{U}(-1, 1)$
ρ_{X-WL}	$\mathcal{U}(-1, 1)$
	$\det(\mathbf{\Sigma}_{multi\text{-}obs}) > 0$

V.a Goodness of fit

In observable space: redshift and SPT detection significance

Bocquet+19

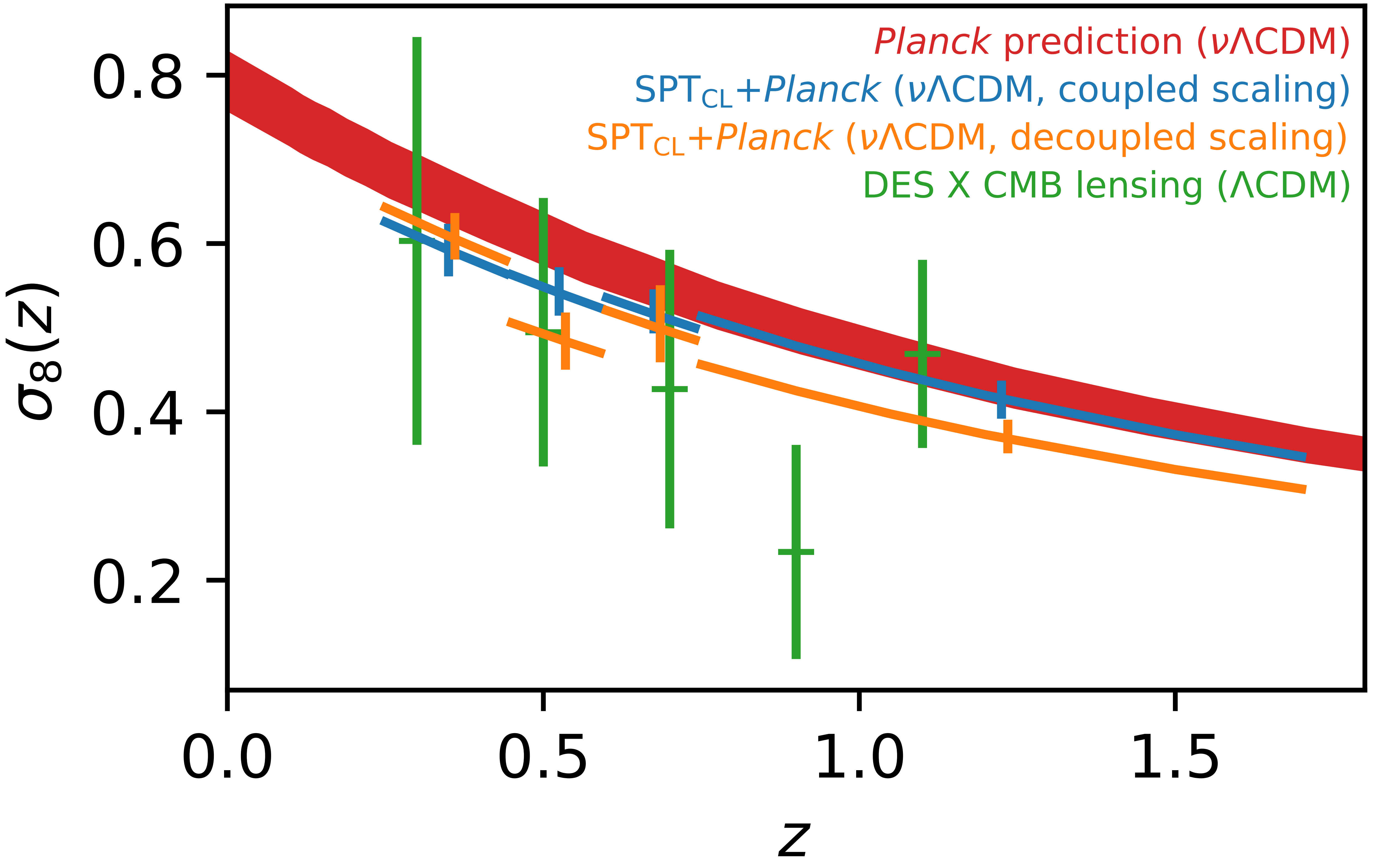


V.b Cosmological constraints from SPT-SZ

Growth of Structure

- Planck CMB fixes evolution history
- Use SPT clusters to constrain growth history
- Blue points: single SZ scaling relation
- Orange points: separate SZ amplitudes in each bin

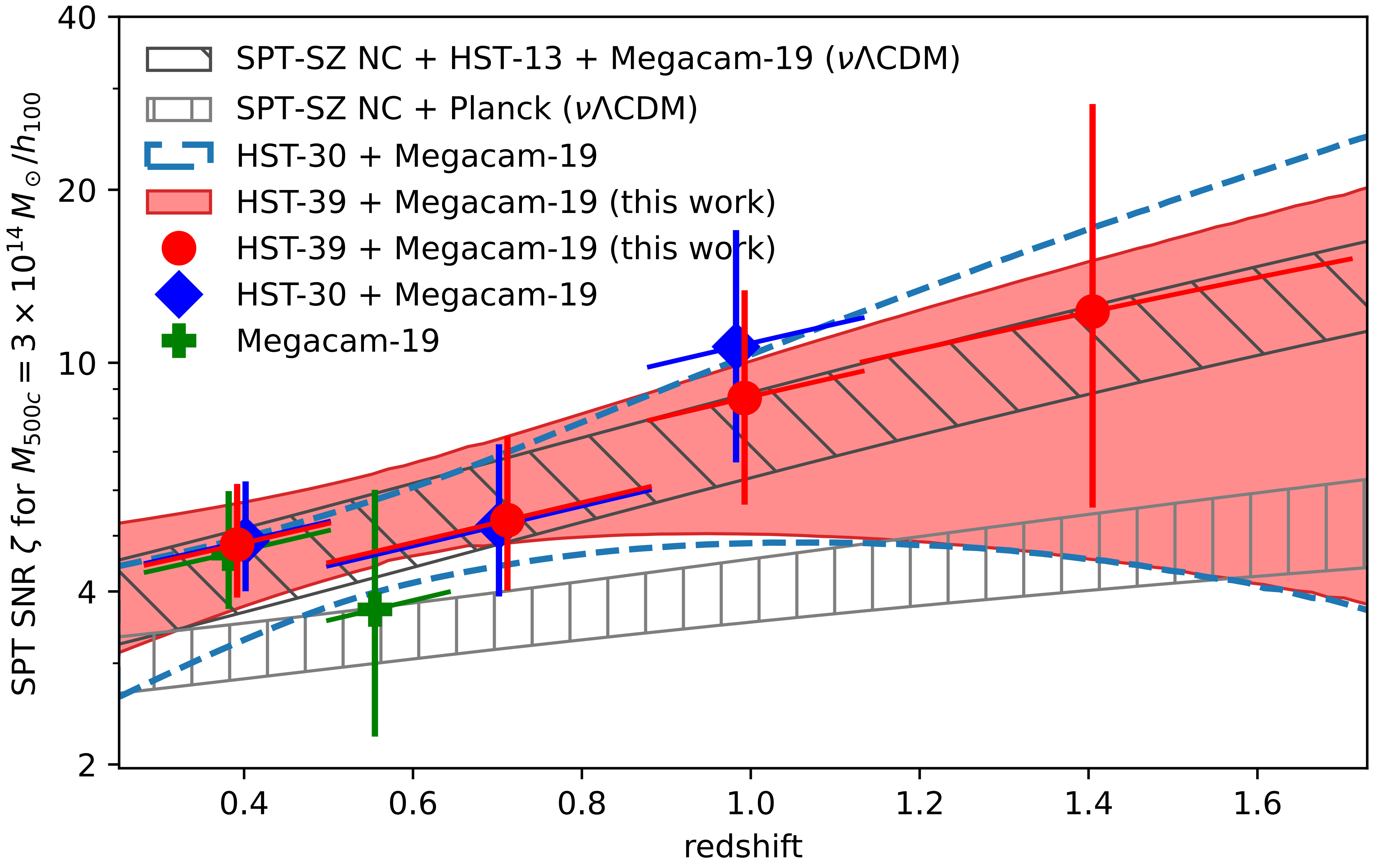
Bocquet+19



Select recent highlights

High-Redshift Cluster Lensing using Hubble

Lensing measurements beyond cluster redshift z > 1

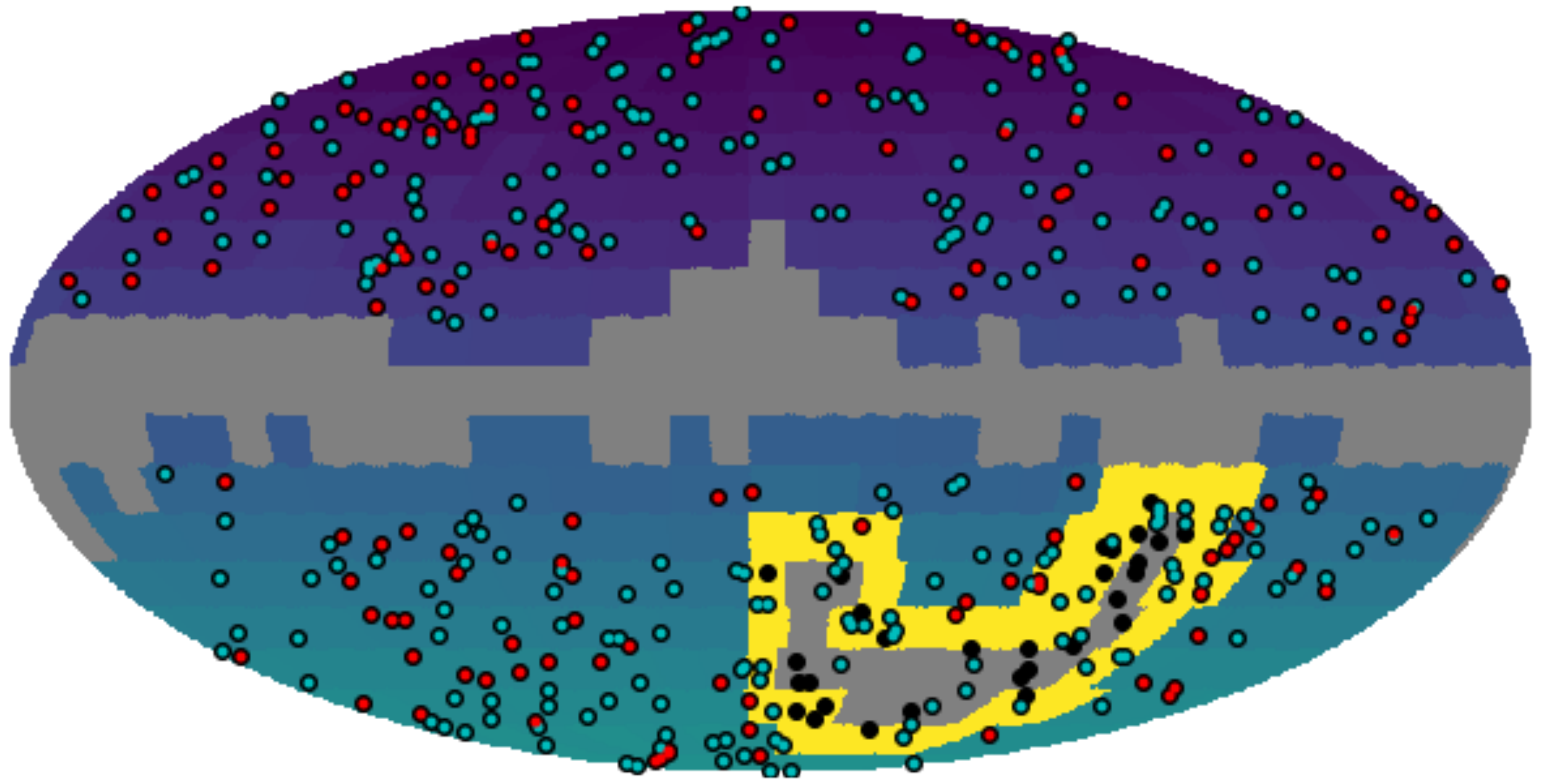


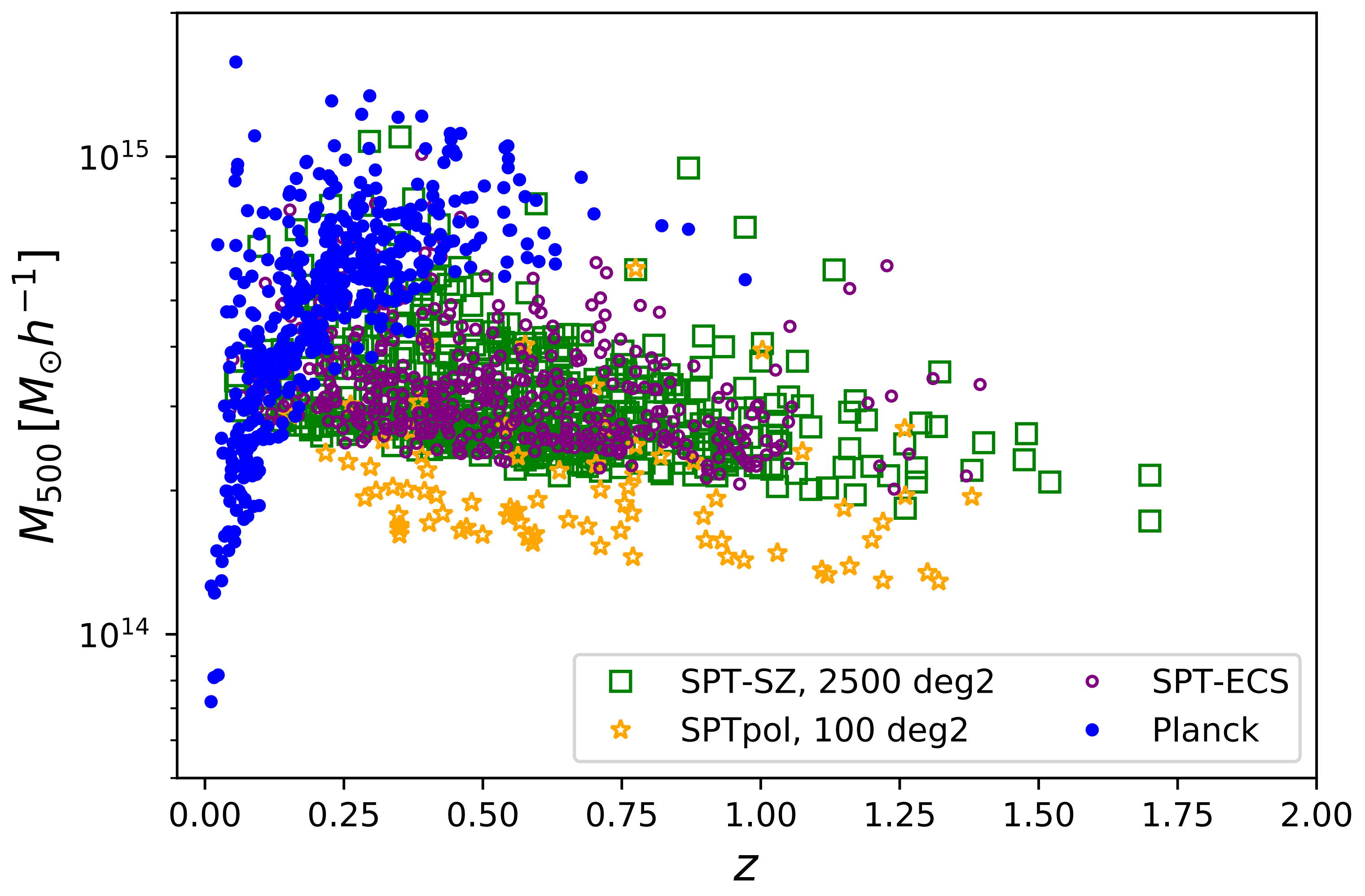
High-z lensing dataset expanded from 13 to 30 HST clusters (Schrabback, Bocquet et al. 2021)

Recently: 9 additional 1 < z < 1.7 clusters (Zohren, Schrabback, Bocquet et al. 2022)

Joint Analysis of Planck and SPT Clusters

- Combine shallow all-sky survey from Planck with the deeper SPT-SZ survey
  (Salvati, Saro, Bocquet, Costanzi et al. 2021)
- Compared to SPT alone, Planck adds the most massive clusters in the z < 0.6 universe
- Weak-lensing mass calibration from SPT program (Magellan, *Hubble*)



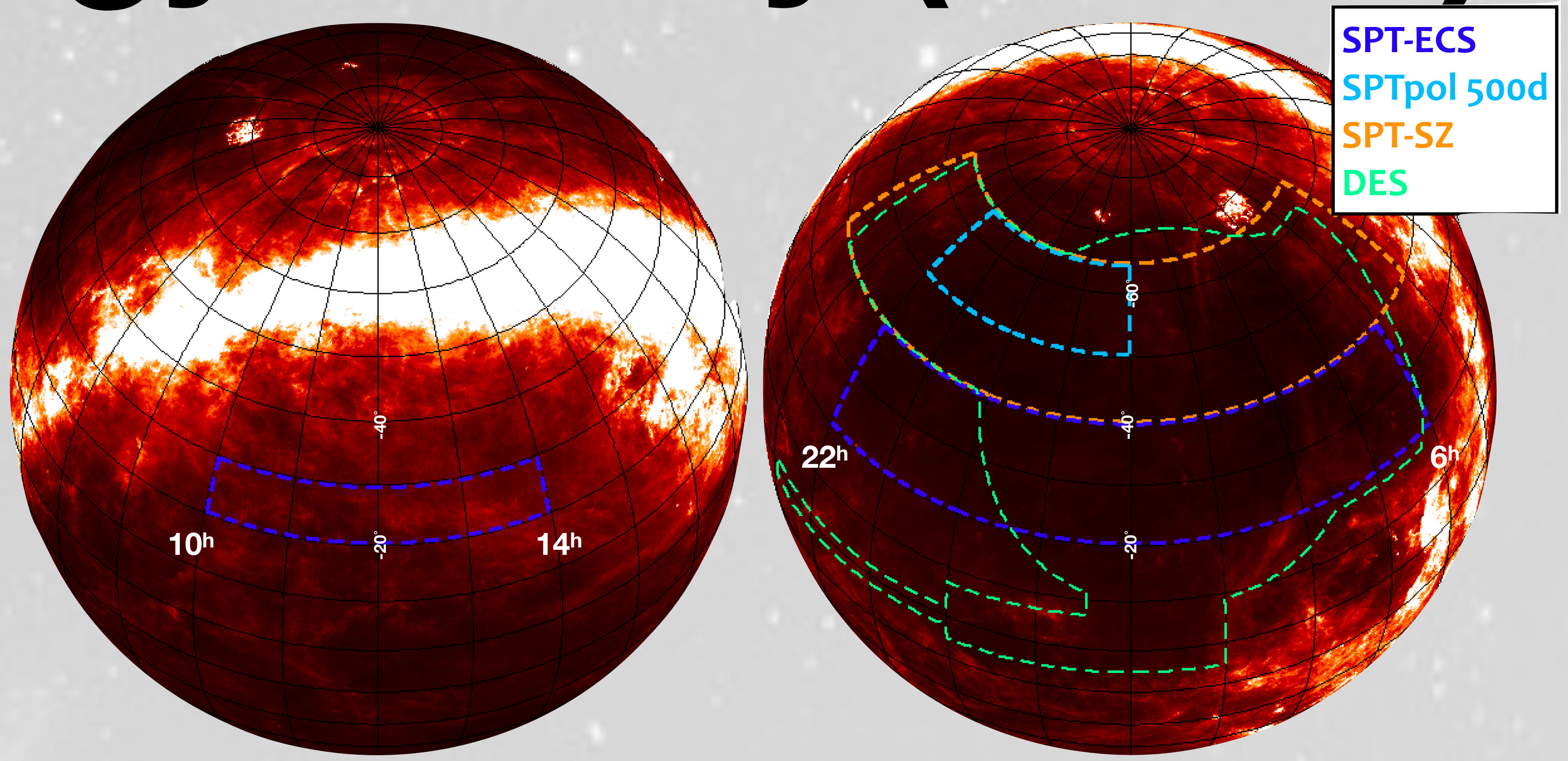



CTIO Blanco Telescope
(Dark Energy Survey)

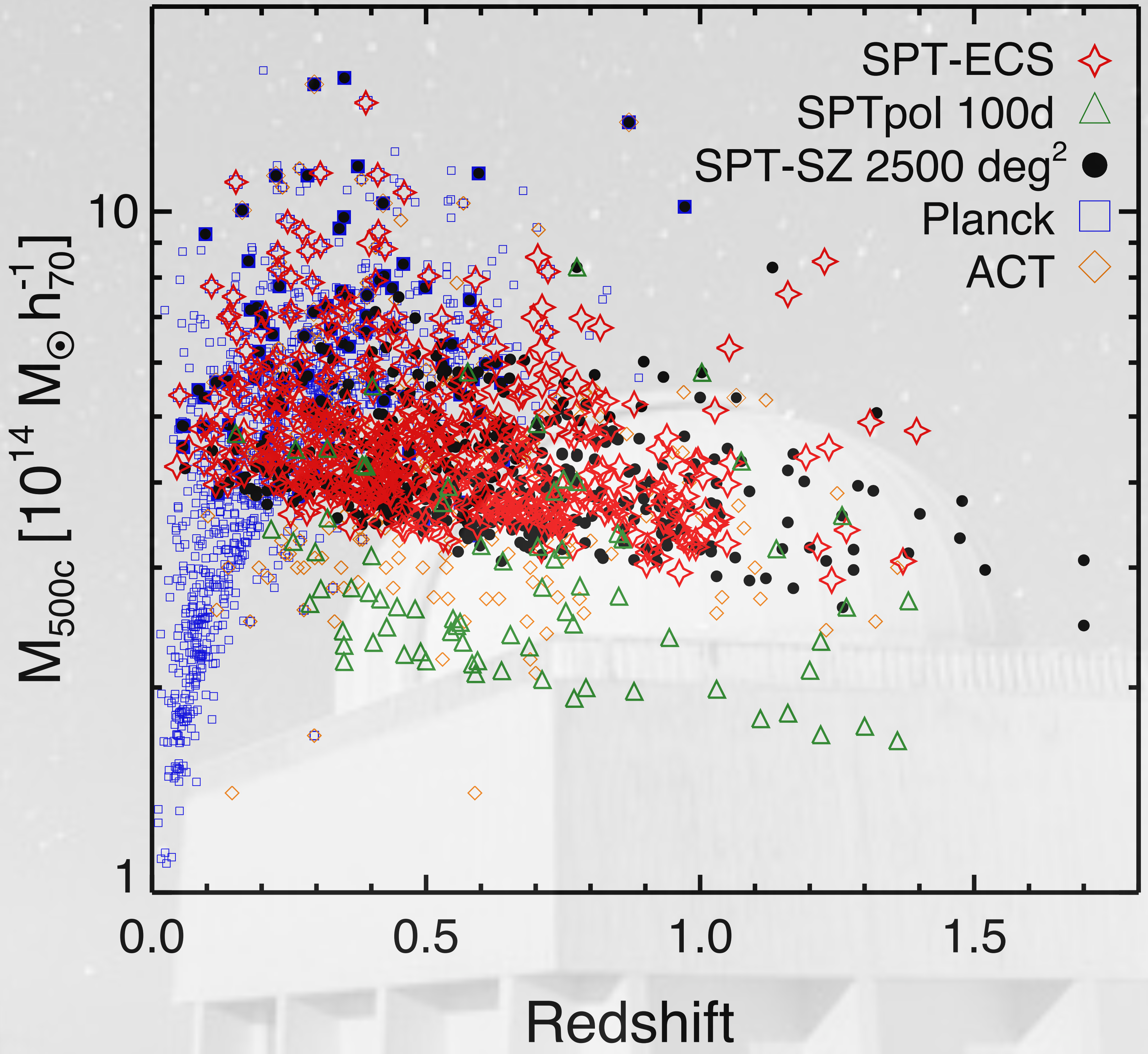
South Pole Telescope and Dark Energy Survey (Year 3)

5200 deg2 of SPT, of which 58% with DES (lensing) data

- South Pole Telescope surveys
  - 2500 square-degree SPT-SZ (Bleem et al. 2015)
  - SPTpol
    - ultra-deep 100 square-degree SPTpol-100d (Huang…Bocquet et al. 2020)
    - Wide 2700 square-degree SPTpol-ECS (Bleem,Bocquet et al. 2020)
    - Deep 500 square-degree SPTpol-500d (Bleem et al., in prep.)
  - SPT-3G data being processed (Sobrin et al., in prep.)
- Dark Energy Survey Year 3
  - 1e8 lensing sources over ~4000 square-degrees (Gatti+21)
  - 650 SPT cluster with DES lensing data (Bocquet+ in prep.)



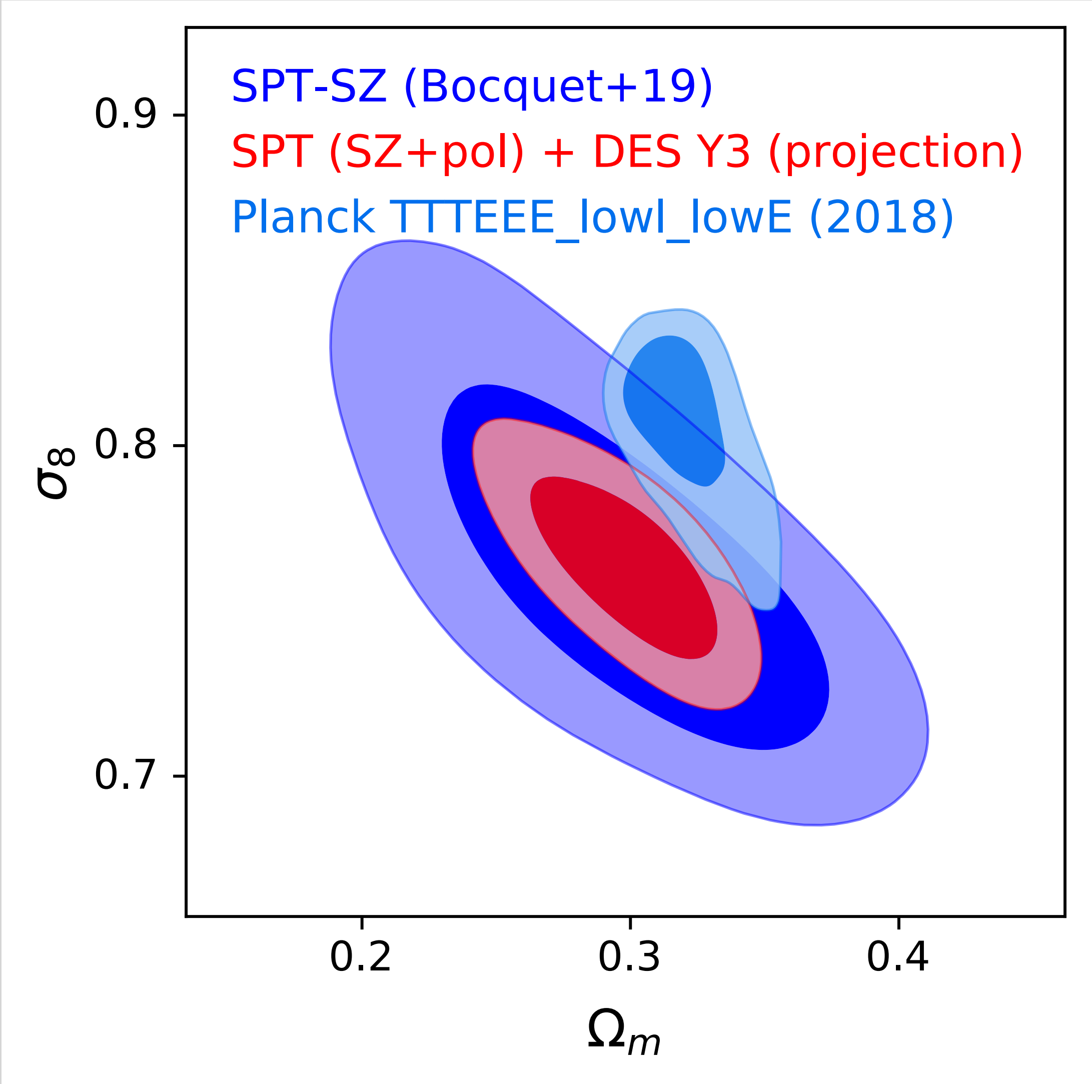
Bleem,Bocquet+20

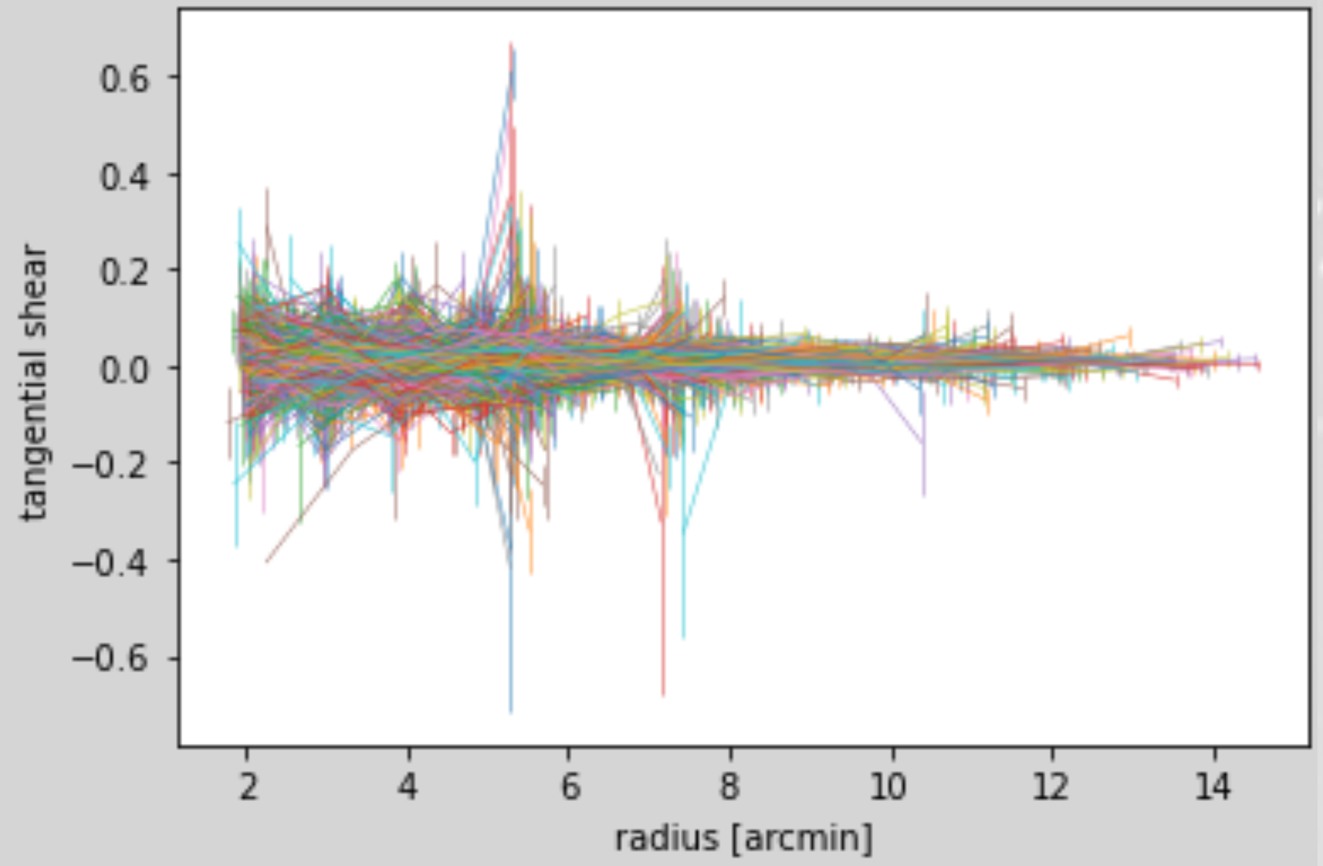


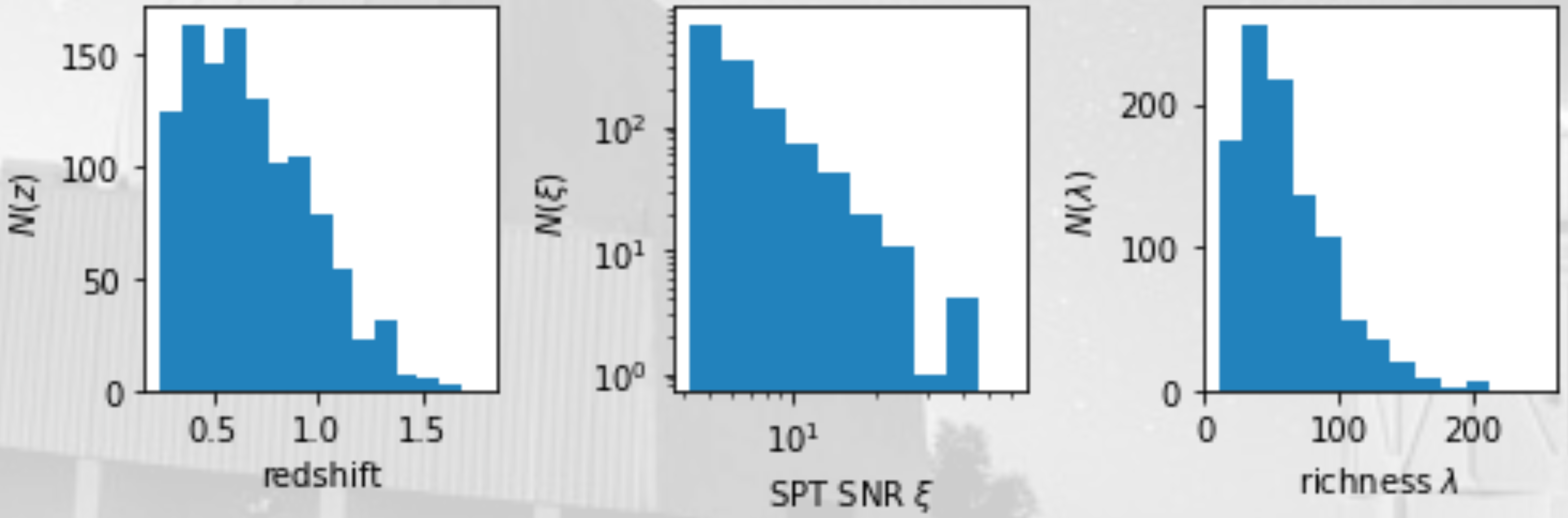
SPT-SZ + SPTpol + DES Year 3 Weak Lensing

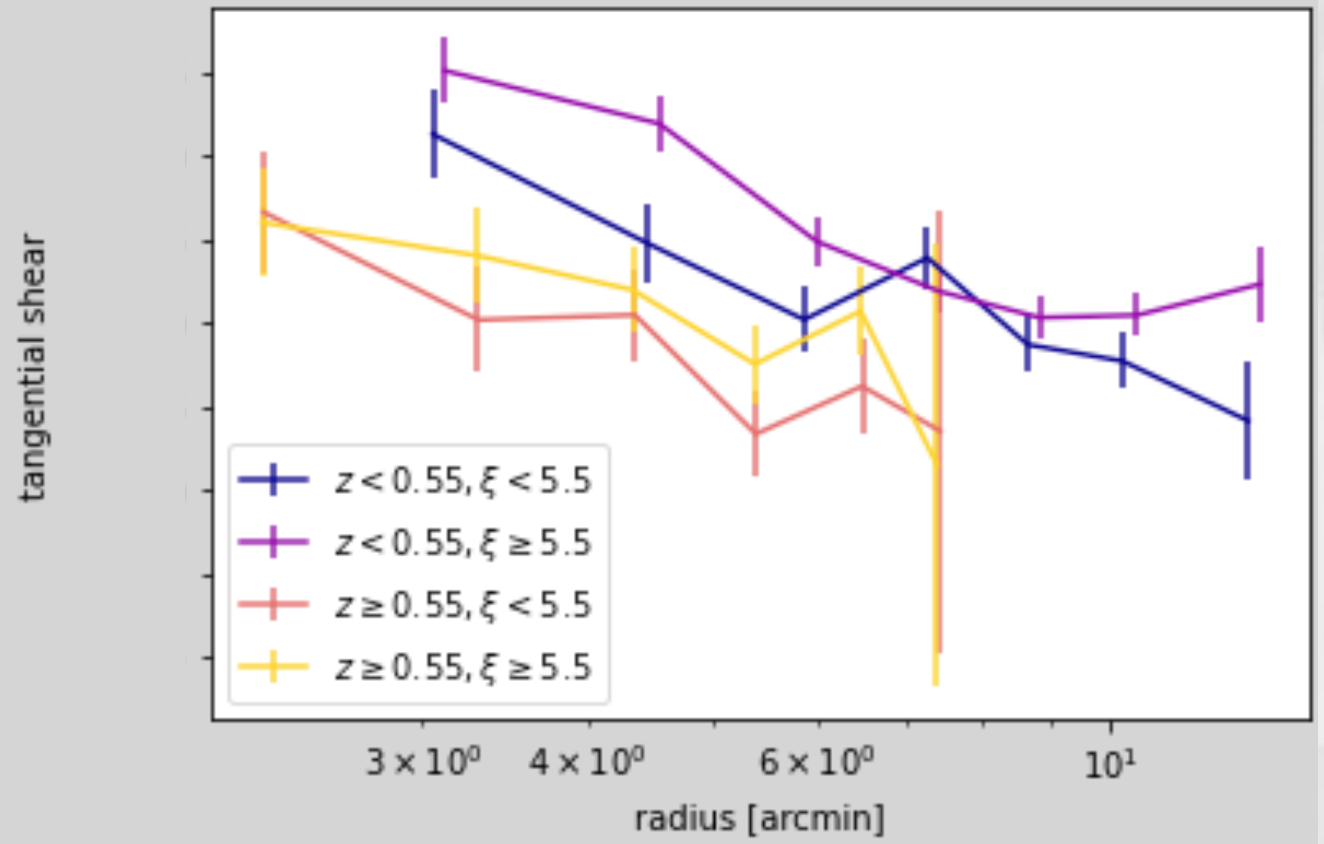
Data Overview

- SPT SZ candidates over 5200 deg^2
  (SPT-SZ + SPTpol-ECS + SPTpol-500d, Bleem+15,20,22)
- Cluster confirmation and redshifts from DES and WISE (Matthias Klein @ LMU) and targeted programs (Lindsey Bleem, SPT collaboration)
- 1009 confirmed clusters with $z > 0.25$
- Expanded HST lensing sample up to z~1.7 (Schrabback,Bocquet+21; Zohren,Schrabback,Bocquet+22)
- DES weak-lensing mass calibration up to z~0.94 (~650 clusters) (Bocquet+ in prep.)
- Thorough pipeline validation using synthetic datasets

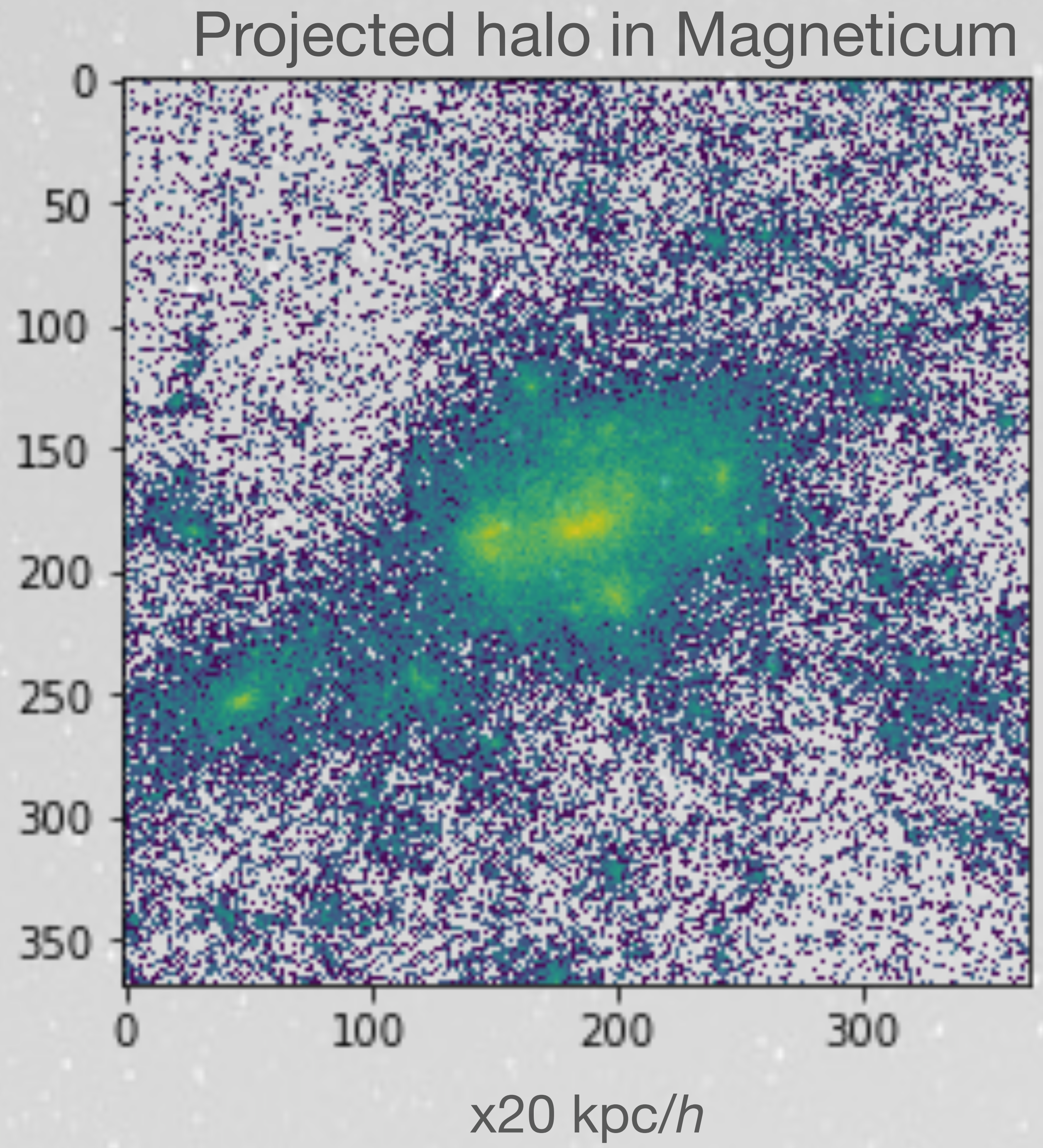








Cluster Weak-Lensing Model

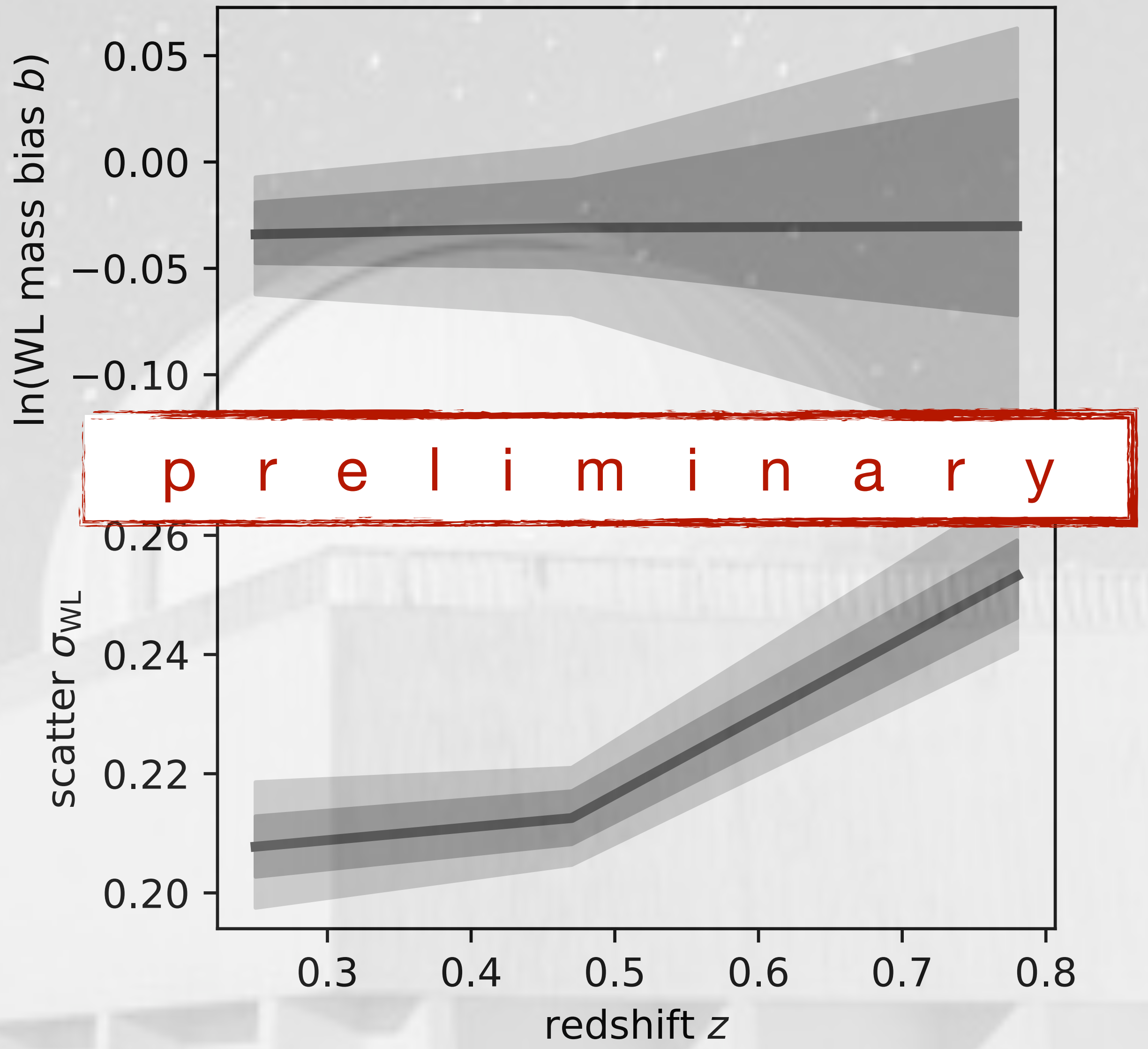


Combine all weak-lensing modeling ingredients into common framework (Grandis, Bocquet et al. 2021):

- Mass modeling (halo profiles, miscentering, uncorrelated LSS)
- Shear modeling (shear and photo-z calibration, cluster member contamination)
- Relate full-physics halo profiles to gravity-only halo mass function
- Calibrate mis-match between NFW model and realistic synthetic lensing data ((z, M)-dependent bias & (z, M)-dependent scatter)

Impact of baryonic effects on halo profiles by comparing Magneticum and Illustris TNG hydrodynamical simulations: 2% difference in mass

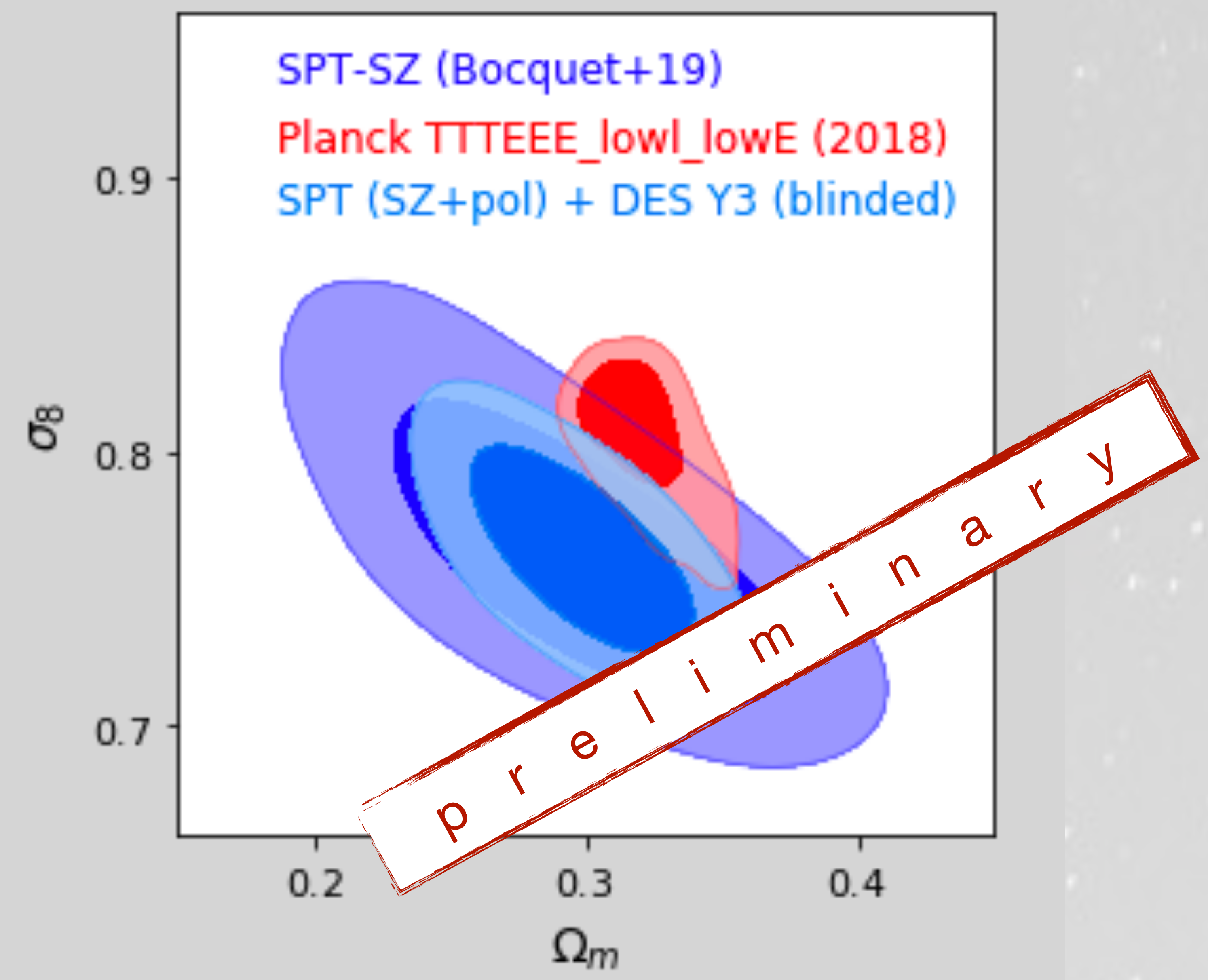
Total systematic weak-lensing uncertainty in DES Year 3:
3 — 6 % as function of cluster redshift

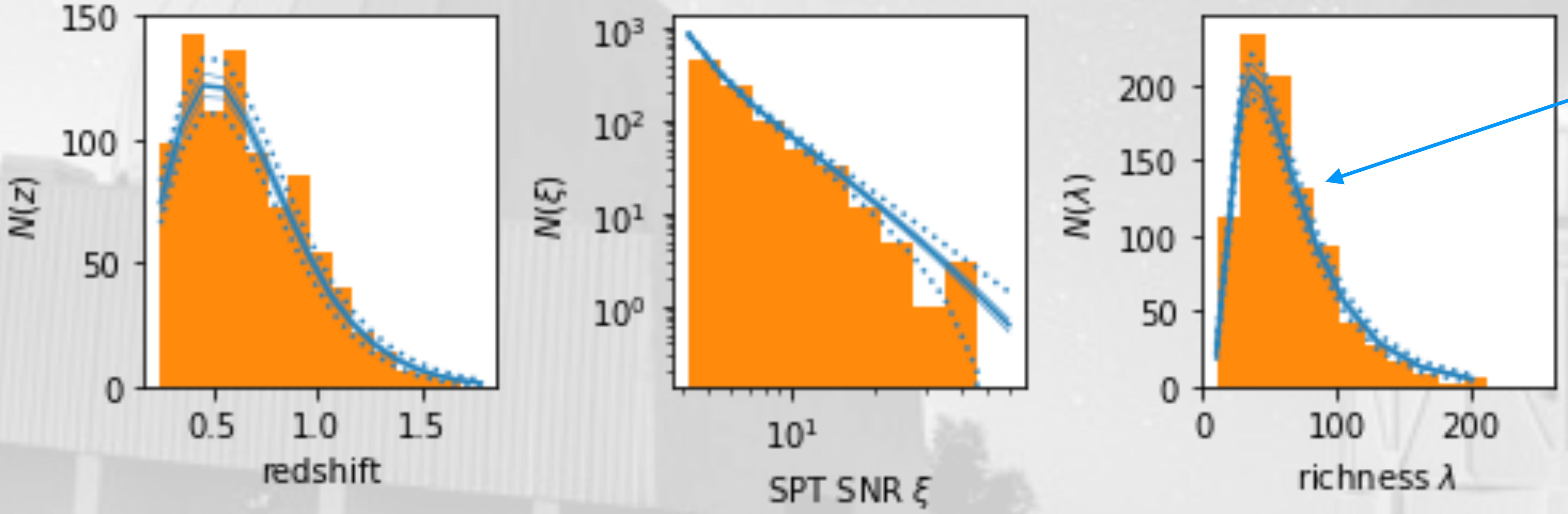


SPT-SZ + SPTpol + DES Year 3 Weak Lensing

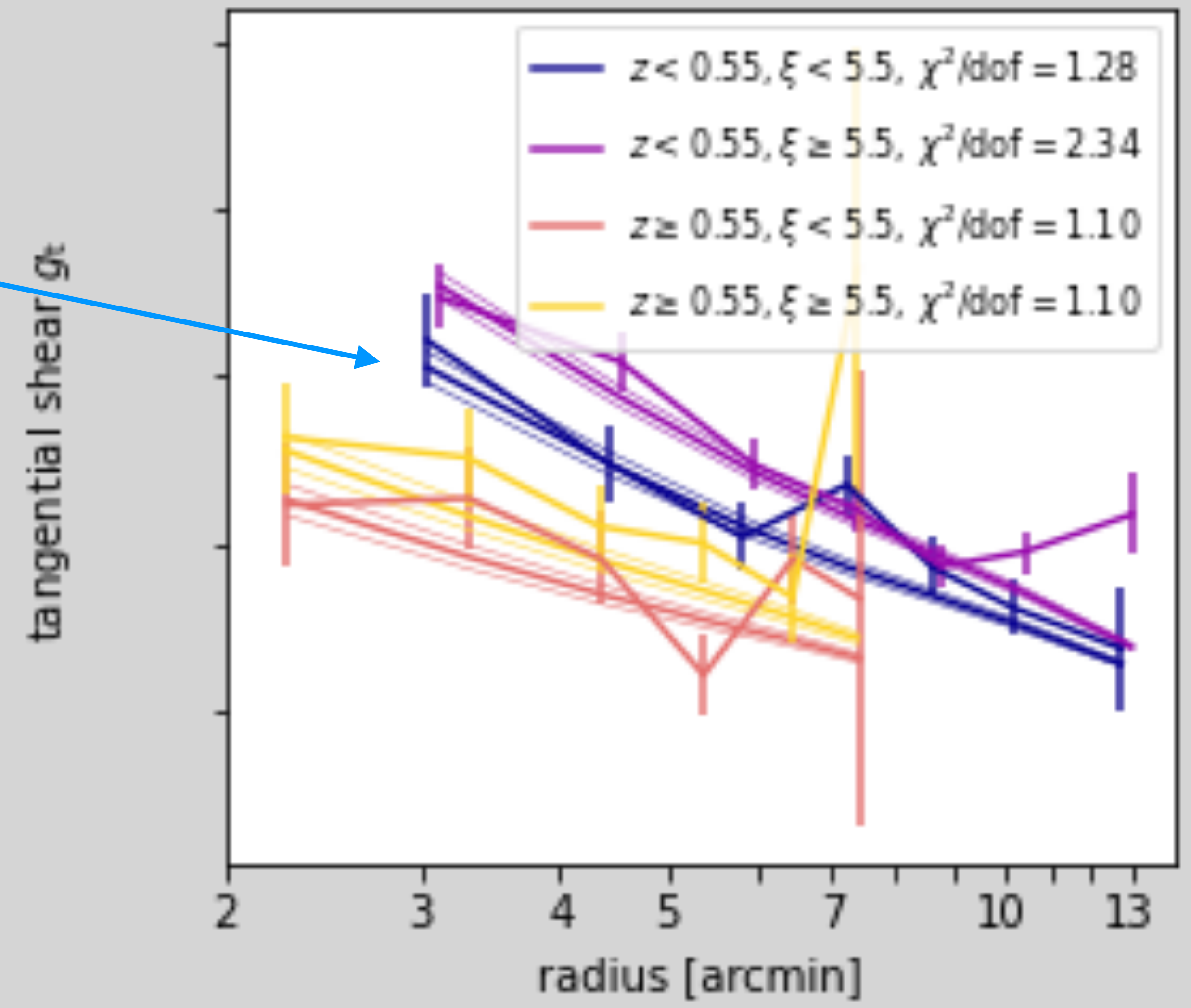
Update on blinded results

- Confirm robustness of lensing modeling blindly (centering, boost factors, radial cuts)
- Model is a good description of the data
- No roadblock toward unblinding!





Model lines from blinded run



The combination of the well-understood SZ-selected SPT cluster sample with optical data (redshifts and lensing) from DES is extremely powerful. Stay tuned for the unblinded results!

And of course, expect further cool results from other teams:
Dark Energy Survey (DES, Matteo’s talk)
Kilo Degree Survey (KiDS)
Hyper Suprime Cam (HSC)
Atacama Cosmology Telescope (ACT) + DES lensing
eROSITA: Performance Verification data + HSC lensing (Chiu+22)
eRASS:1 + DES+KiDS+HSC lensing
CMB lensing by SPT-3G, ACT, *Planck*

Image credit: Aman Chokshi

Image credit: CTIO/NOIRLab/NSF/AURA/D. Munizaga

V.c The role of the X-ray follow-up data

Astrophysics and constraints on intrinsic scatter

- Constraints on X-ray scaling relations as a *byproduct*
  - We find self-similar redshift evolution
  - Very similar story when using M_{gas} instead of Y_{X}
- Intrinsic scatter in X-ray shows tight degeneracy with scatter in SZ (bottom right panel)
  - W/o X-ray data, need to assume (broad) prior on SZ scatter, w/ X-ray data, the model self-calibrates

Bocquet+19