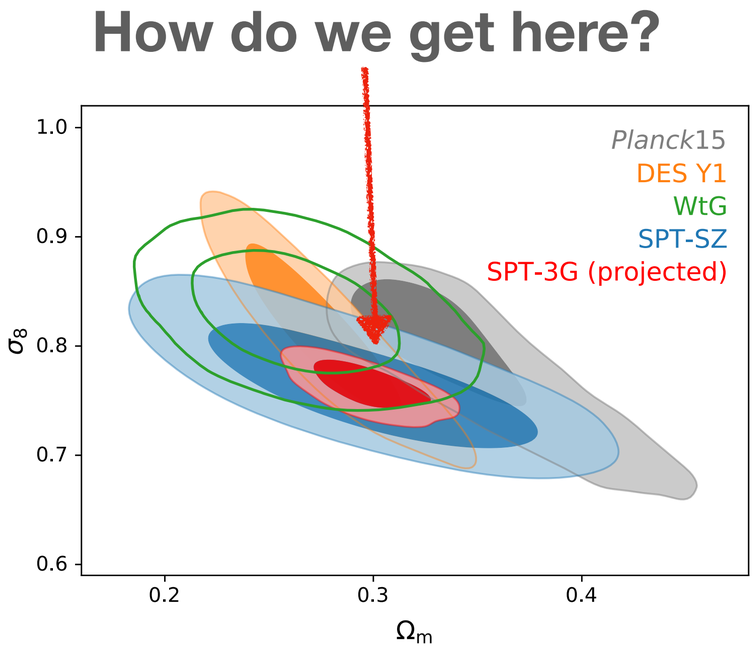
LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Multi-wavelength Galaxy Cluster Cosmology with the South Pole Telescope and the Dark Energy Survey

In collaboration with members of the South Pole Telescope and Dark Energy Survey collaborations

Sebastian Bocquet — Cosmology from Home 2021

Abundance of SPT clusters

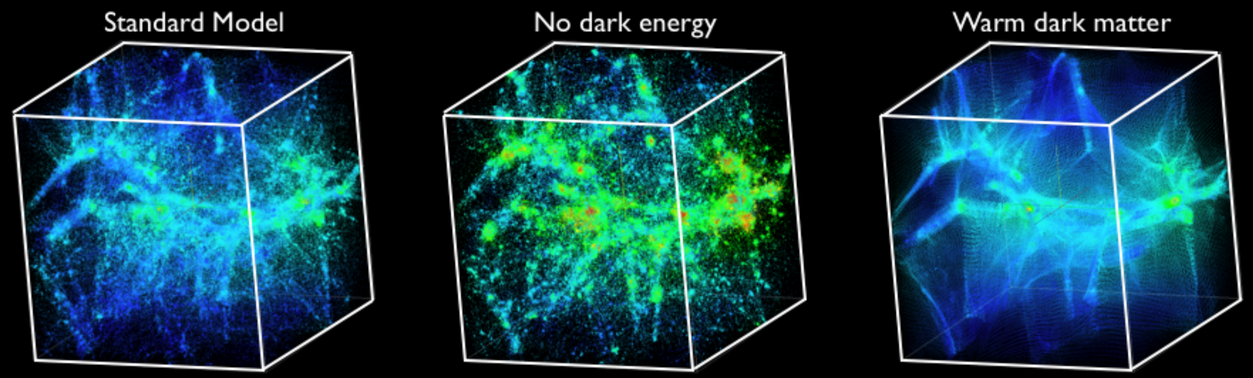


SPT-SZ clusters + weak-lensing (19 Megacam, 13 HST) (Bocquet et al. 2019)
SPT-3G clusters + LSST weak-lensing (Projection by Prakut Chaubal)

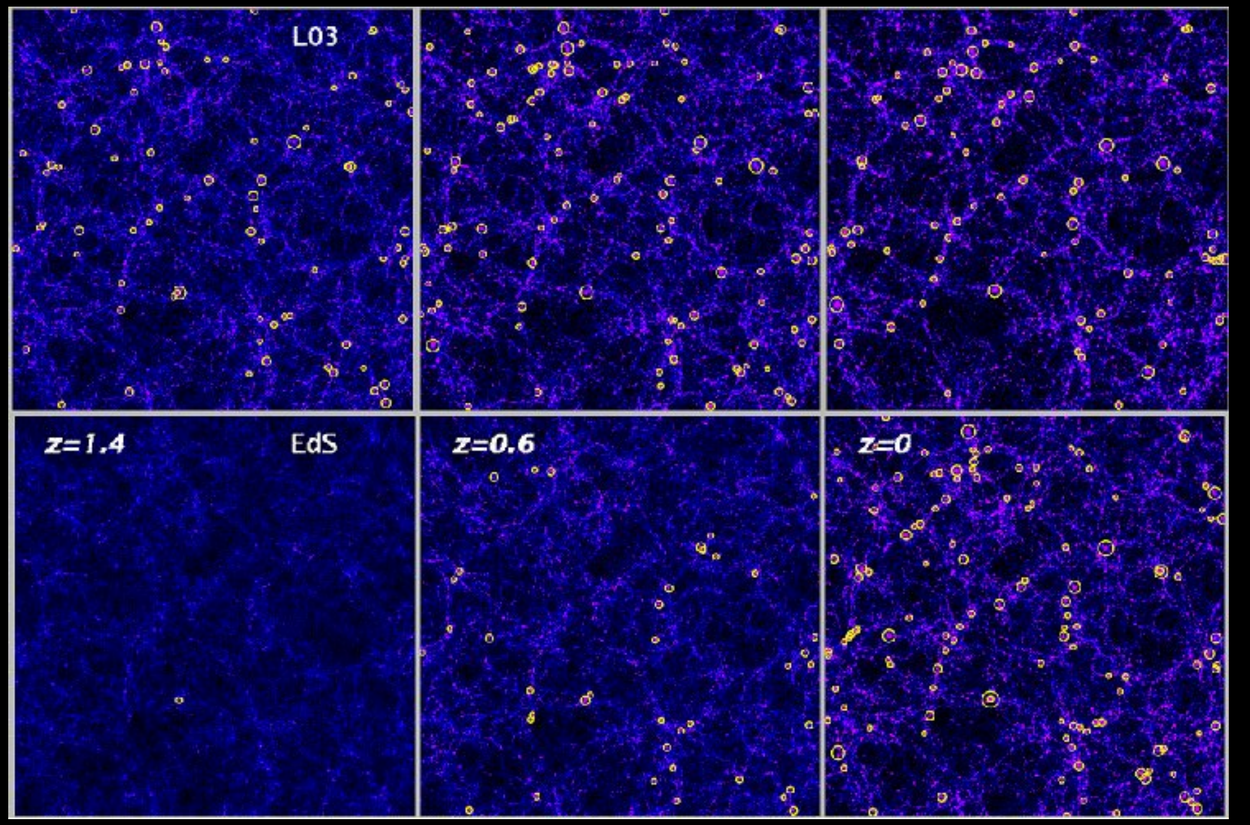
Overview

- Cluster cosmology in a nutshell
- Status of (published) SPT cluster cosmology
- SPT abundance + DES weak-lensing (ongoing analysis)
- Summary

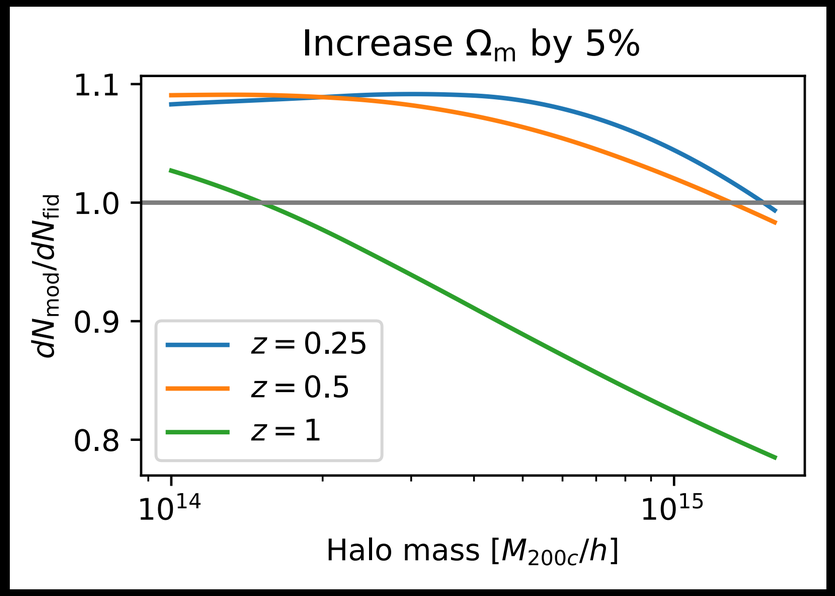
Cluster cosmology



Formation of highest peaks is highly sensitive to cosmological model (Figure: Katrin Heitmann)



Evolution of halo abundance over time allows to constrain dark energy (Figure: Borgani & Kravtsov 2011)



Halo abundance is highly sensitive to cosmological parameters: Omega_m, sigma_8, w

Cluster cosmology

dN/dM/dz/dV

dN/dobs/dz = dN/dM/dz/dV x dM/dobs x dV(z)

Pairs (obs, z)

Halo mass function

Exponential cosmological sensitivity

Calibrated using numerical simulations

Few-percent level accuracy

Observable—mass relation

Volume element (expansion history)

Measurement

Gold standard: mass calibration based on weak-lensing data

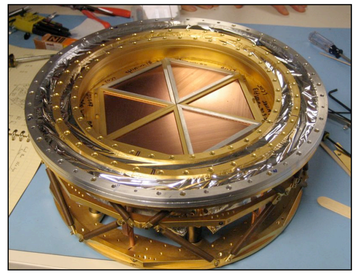
- Lensing traces total mass
- No assumption about hydrostatic state
- Accurate predictions/modeling using numerical simulations

The South Pole Telescope (SPT)

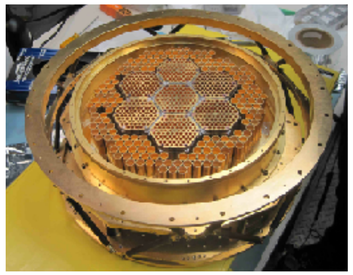
10-meter sub-mm quality wavelength telescope

95, 150, 220 GHz and
1.6, 1.2, 1.0 arcmin resolution

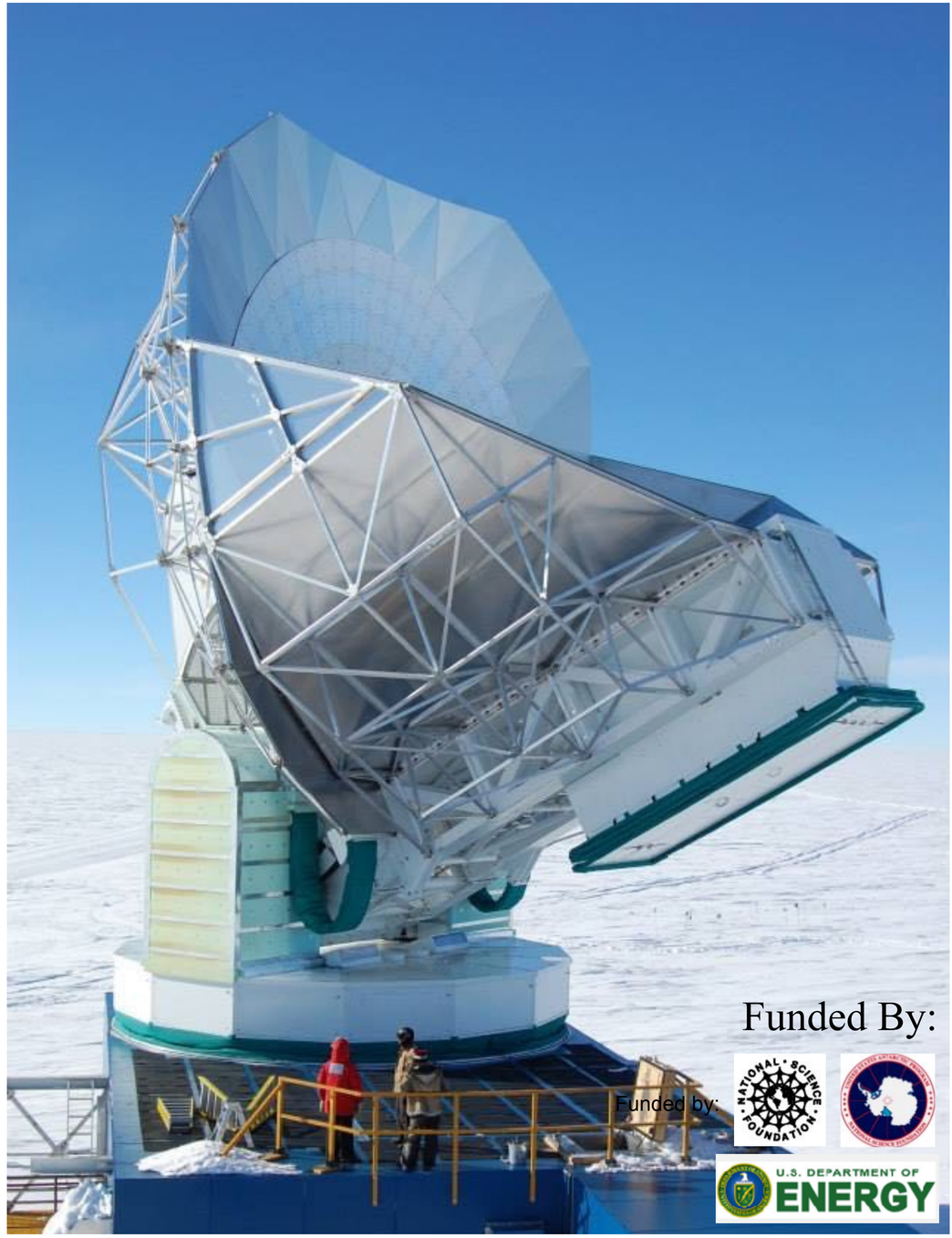
2007: SPT-SZ
960 detectors
95,150,220 GHz



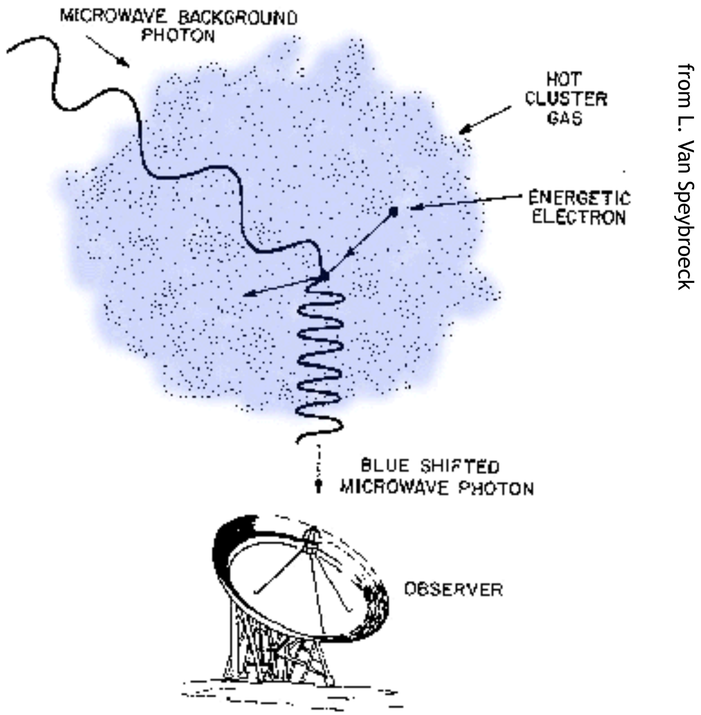
2012: SPTpol
1600 detectors
90,150 GHz
+Polarization



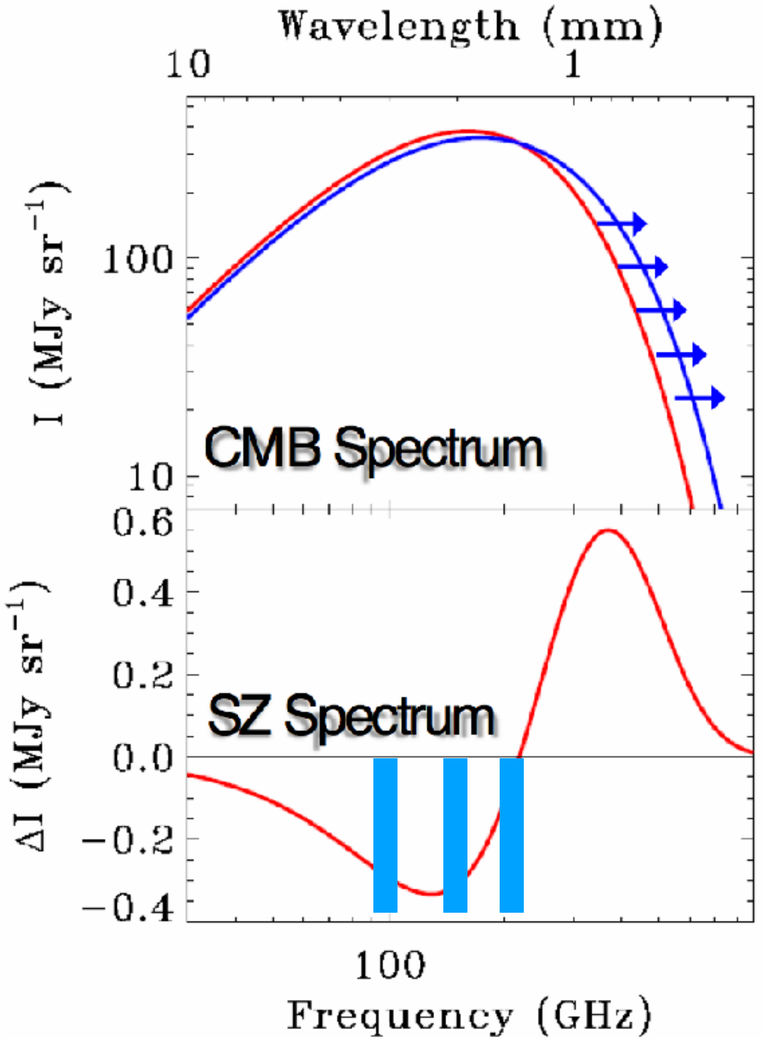
2017: SPT-3G
~15,200
detectors
95,150, 225 GHz
+Polarization



Sunyaev-Zel'dovich (SZ) effect



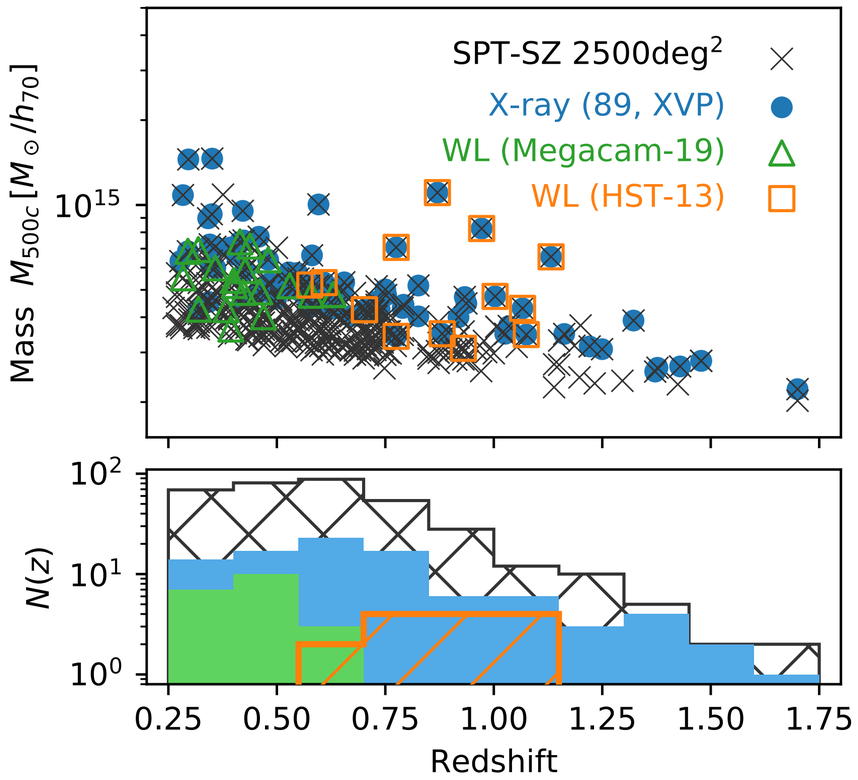
from L. Van Speybroeck



- About 1% of CMB photons scatter
- SZE flux proportional to total thermal energy in the electron population
- SZE surface brightness is independent of redshift

SPT-SZ cluster cosmology

History and dataset



Precursor analyses based on X-ray mass calibration: Benson+13, Reichardt+13, Bocquet+15, de Haan+16

SPT-SZ cluster sample: 343 SZ-selected clusters above detection SNR 5 and $z > 0.25$

X-ray follow-up data: McDonald+13,17

Weak-lensing follow-up data:
HST-13 (Schrabback+18)
Megacam-19 (Dietrich,Bocquet+19)

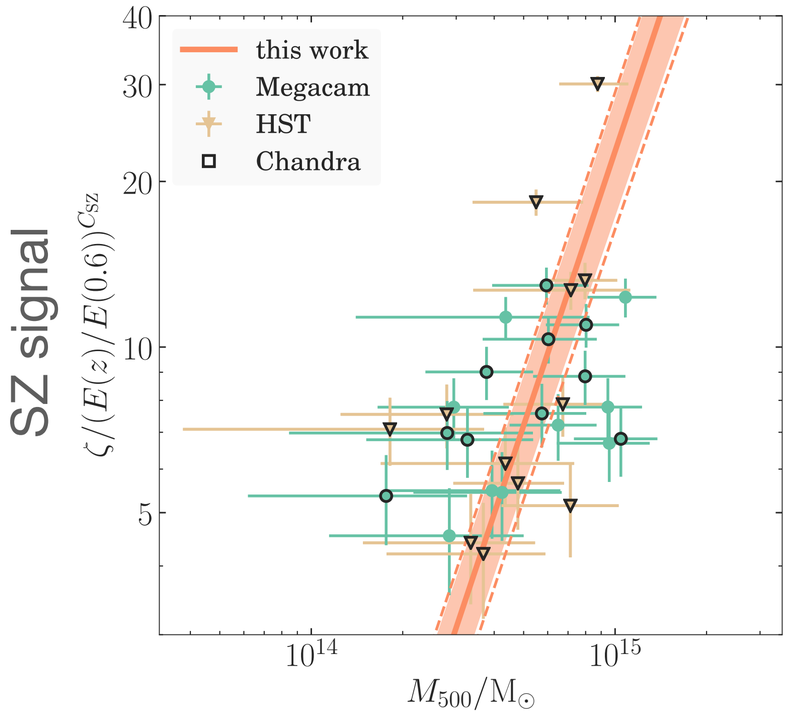
SPT-SZ cluster cosmology

Analysis strategy

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

Abundance likelihood:
distribution of clusters in SZ signal—redshift space
Poisson likelihood (sample variance is negligible)

Mass calibration likelihood:
Measurement of follow-up observables (weak lensing, X-ray)

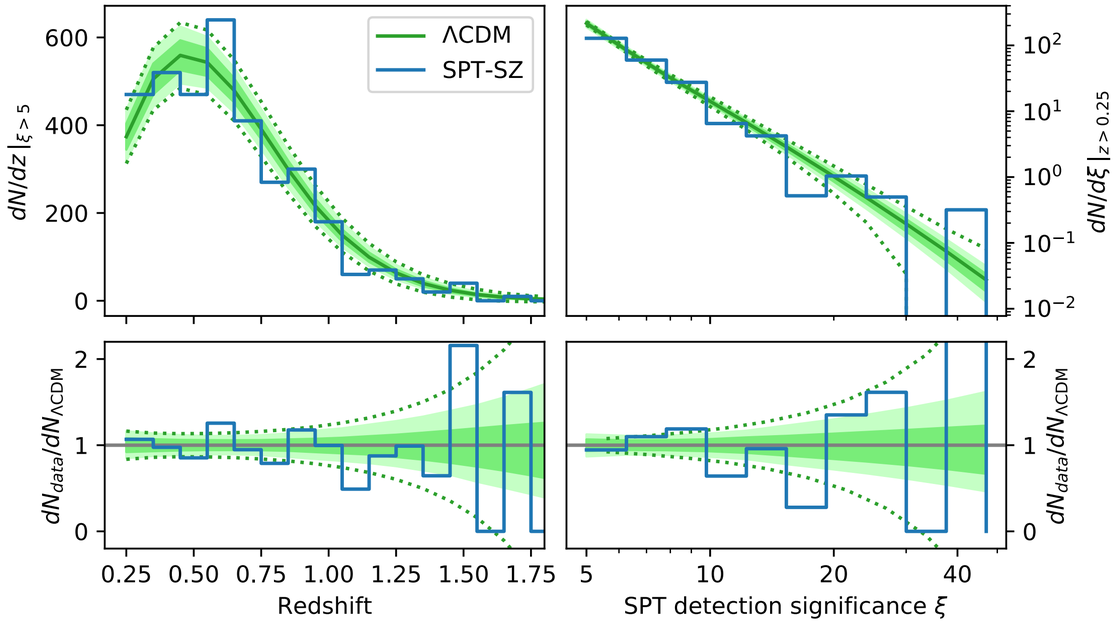


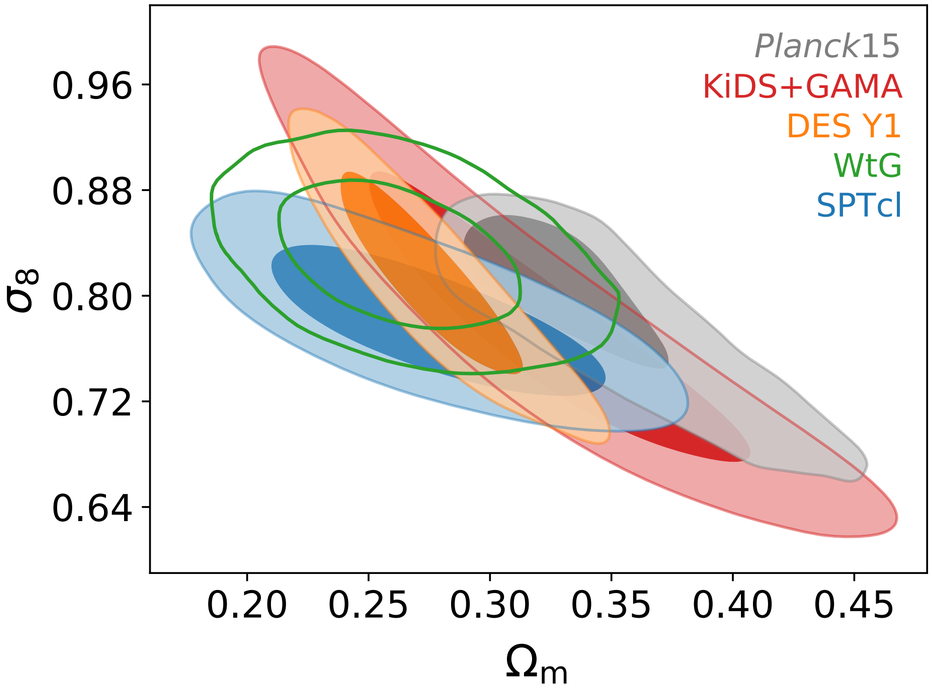
Use known Mwl—Mhalo relation to calibrate SZ—mass relation (Dietrich,Bocquet+19)

SPT-SZ cluster cosmology

LCDM constraints (w/ massive neutrinos) Bocquet+19

- Wide flat priors on SZ scaling relation parameters fully encompass posterior
- Cluster constraint statistically limited by mass calibration: need more (weak lensing) data! (currently 32 clusters)
- 1.5 σ agreement with *Planck*15 TT+lowTEB

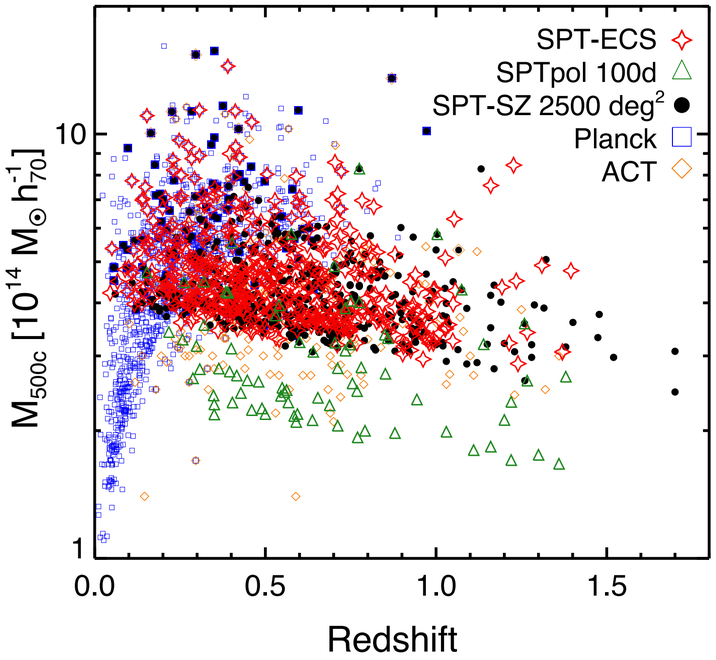


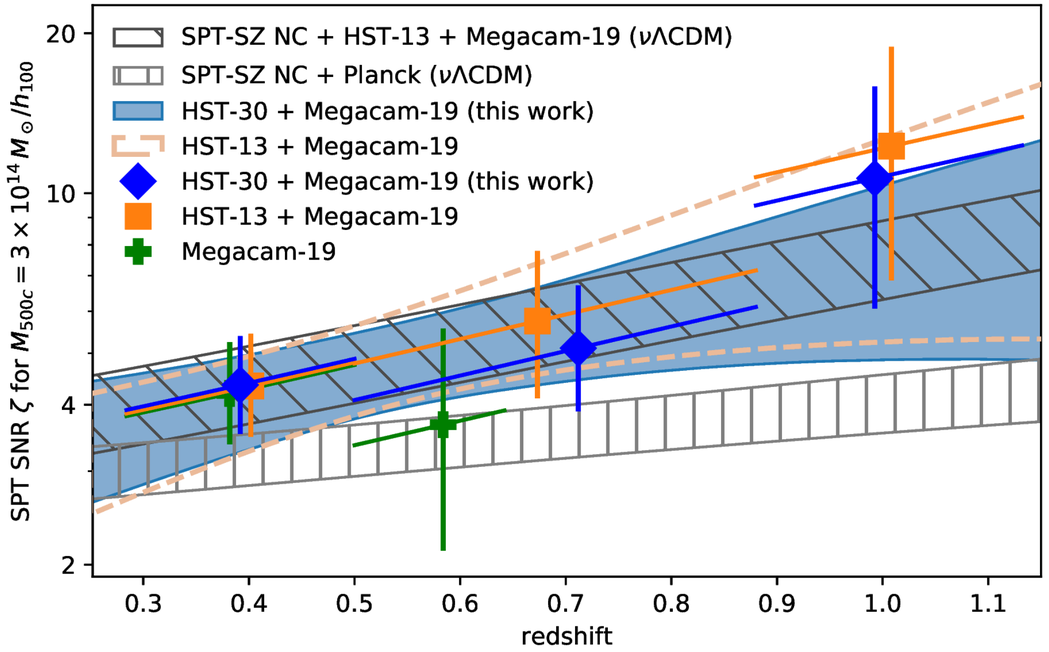


How to improve?

— Larger cluster sample
— More weak-lensing data

Recent progress





New cluster catalogs:

- Deep 100 square-degree SPTpol-100d survey (Huang+20)
- Wide 2700 square-degree SPTpol-ECS survey (Bleem,Bocquet+20)

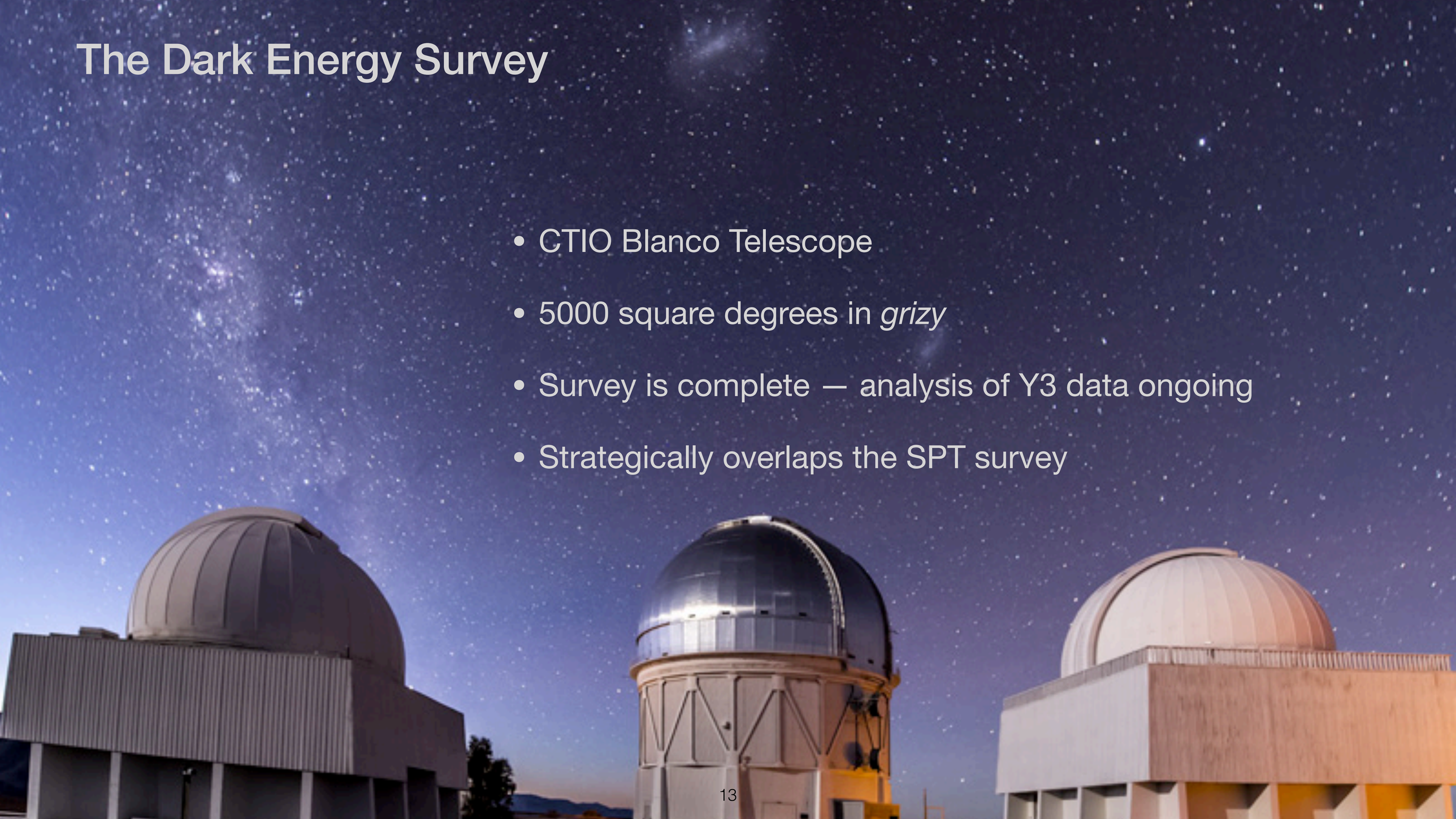
~1000 clusters above detection SNR 4.5

Redshifts/optical confirmation mainly from Dark Energy Survey

High-redshift cluster weak-lensing using Hubble Space Telescope

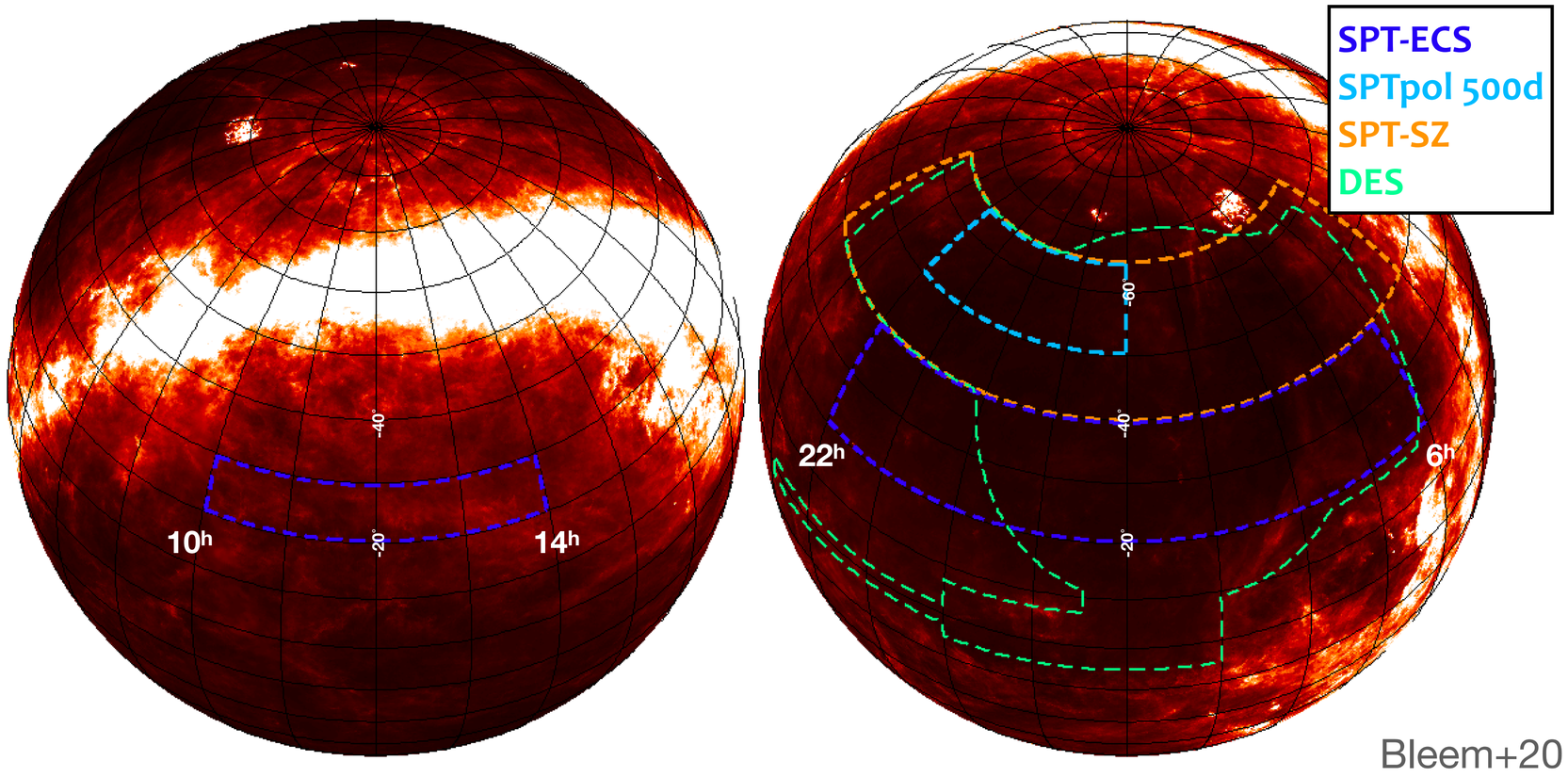
High-z dataset now comprises 30 HST clusters (Schrabback,Bocquet+21)

The Dark Energy Survey



- CTIO Blanco Telescope
- 5000 square degrees in *grizy*
- Survey is complete — analysis of Y3 data ongoing
- Strategically overlaps the SPT survey

SPT cluster mass calibration using DES weak-lensing data



Bleem+20

Dark Energy Survey Year 3: *griz*, 4143 deg2, > 300e6 objects

SPT-SZ + SPTpol-ECS: 5200 deg2
(deeper pol-100d and pol-500d are within SPT-SZ)

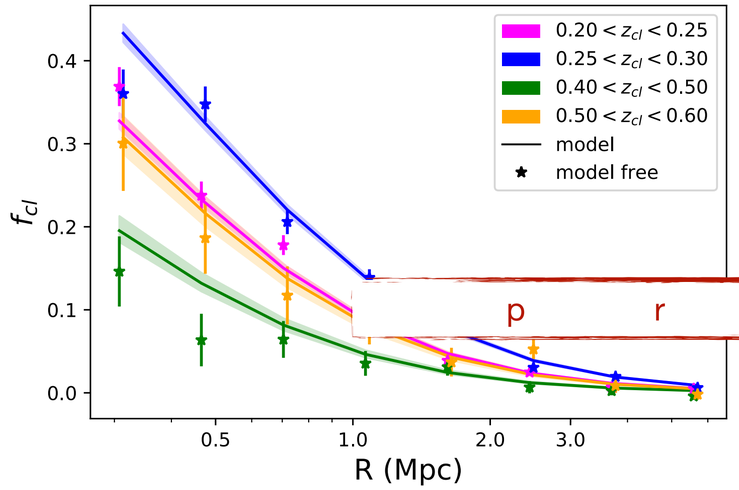
Paper series “SPT Clusters with DES and HST Weak Lensing”

with Sebastian Grandis, Matthias Klein, Joe Mohr, Lindsey Bleem, Tim Schrabback, DES, SPT

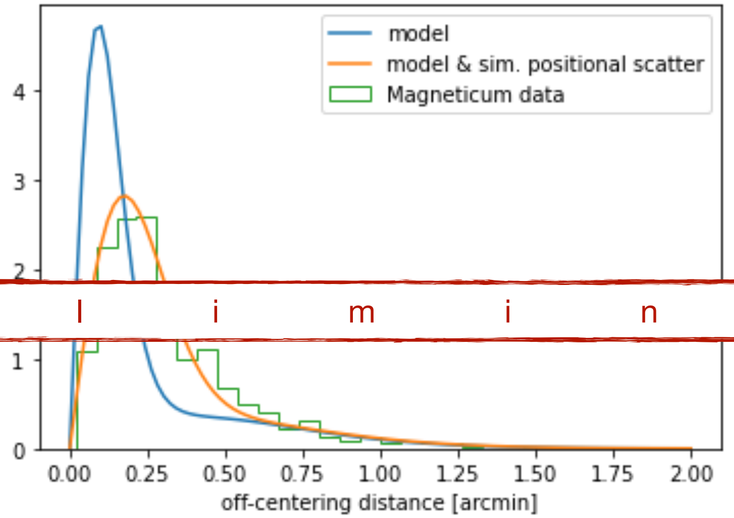
First papers in 2021

SPT cluster mass calibration using DES weak-lensing data

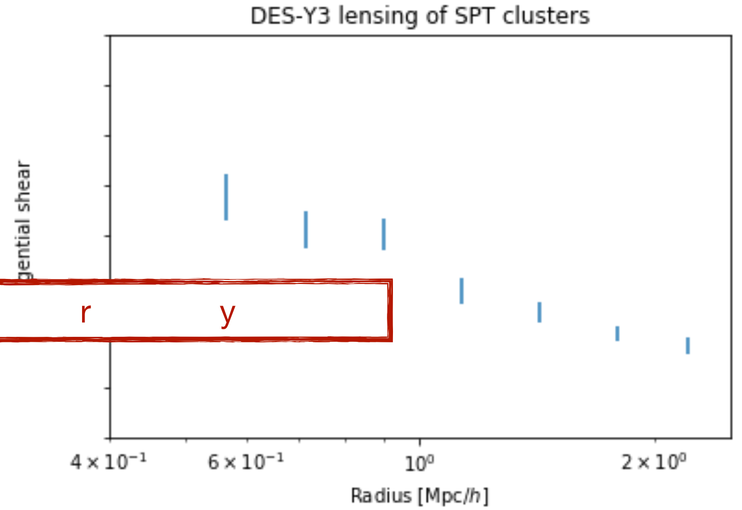
Cluster member contamination a.k.a. boost factors



Miscentering

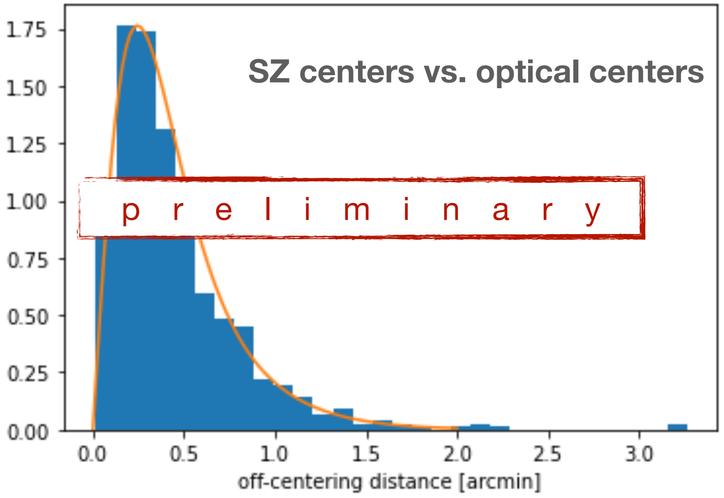


Lensing data



p r e l i m i n a r y

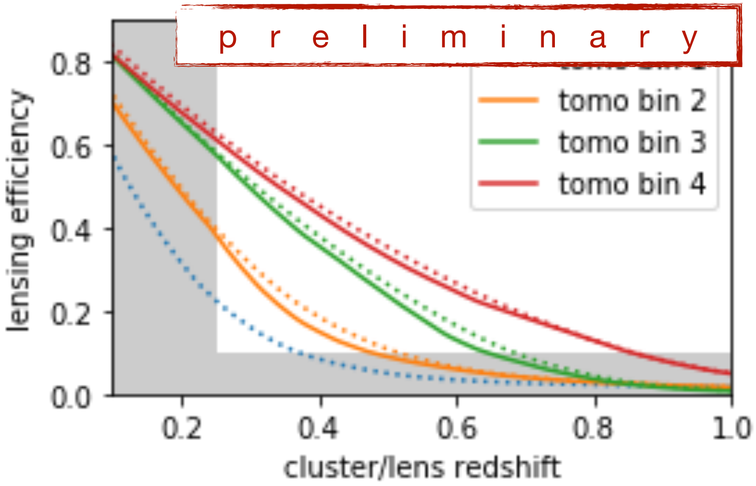
Cluster galaxies that appear in source sample
Correction using P(z) decomposition method (e.g., Gruen+15, Varga+19)
Figure: Application to individual-cluster lensing using DES Year 1 data (Paulus+ to be submitted)



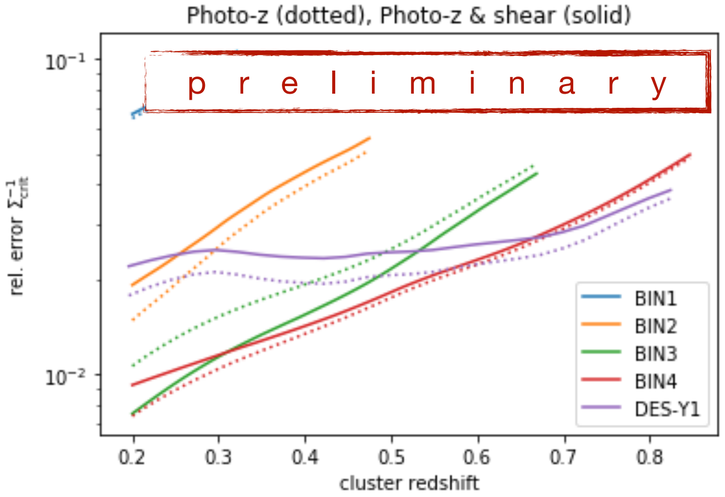
SPT SNR > 4.5 clusters
0.5 Mpc/h < r < 3.2 / (1+z) Mpc/h
Shear SNR ~80

Weak-lensing systematics

DES Y3 tomographic source selection



Weighting of tomographic bins as function of cluster redshift by lensing efficiency



Systematic uncertainty in inv(Sigma_crit)

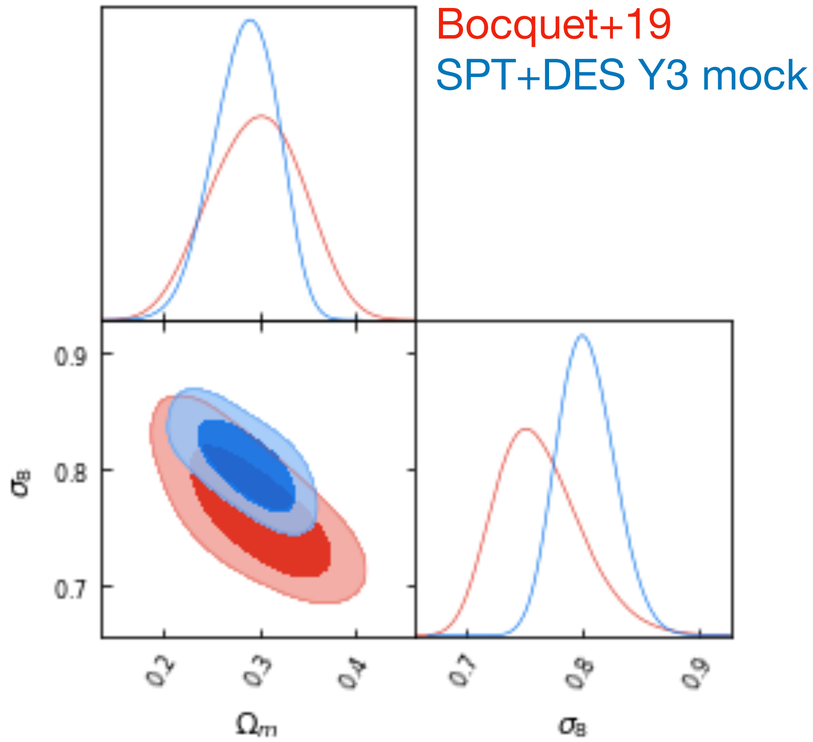
Significant improvement over DES Year 1

Weak-lensing mass modeling

- Real halos are messy
- Approach: fit NFW-inspired shear profile to the data
- Capture resulting mass bias and scatter in Mwl—Mhalo relation (e.g., Becker&Kravtsov11, Oguri&Hamana11, Bahé+12, Lee+18)
- Pushed it further in Grandis,Bocquet+21:
  - Also include other systematics: miscentering, boost factors, source photo-z and shear calibration, uncorrelated LSS
  - Restrict to 1-halo term regime: 0.5 Mpc/h < r < 3.2 / (1+z) Mpc/h
  - Use hydrodynamical simulations (Magneticum, Dolag+) to calibrate gravity-only halo mass to Mwl relationship
    - Allows to rely on state-of-the art mass function emulators based on N-body gravity-only simulations (McClintock+19, Nishimichi+19, Bocquet+20)
    - Compare to results recovered using Illustris TNG: 2% systematic uncertainty in lensing mass
- Applied to DES Y3 data: systematic uncertainty 3—6% as function of cluster redshift

SPT cluster abundance with DES weak-lensing mass calibration

- Code validation against mocks
- Analysis blinded at parameter level
- Start running blinded chains ~now



Summary

- Clear path forward for improved cosmology from SPT-selected clusters
- DES Year 3 weak-lensing data will play crucial role
- Stay tuned!