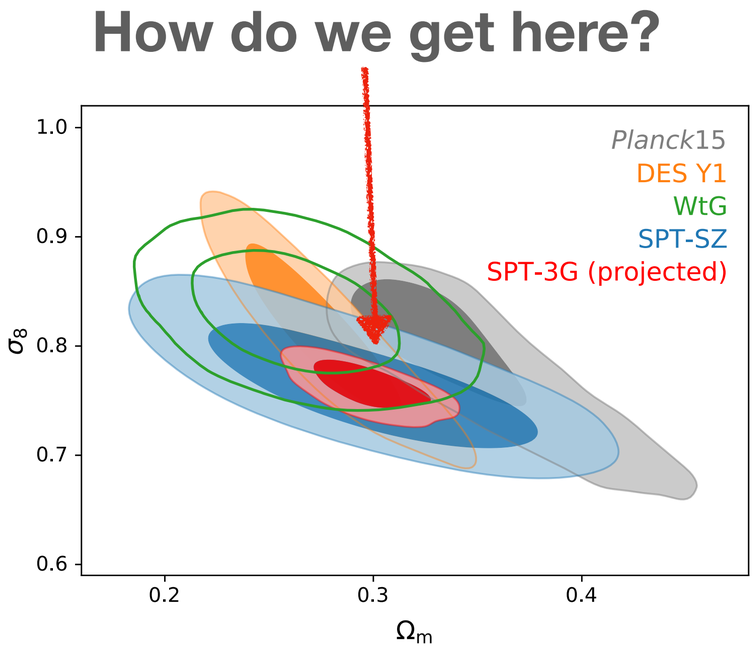
LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

# 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 — mm Universe @NIKA2 Conference

# Abundance of SPT clusters

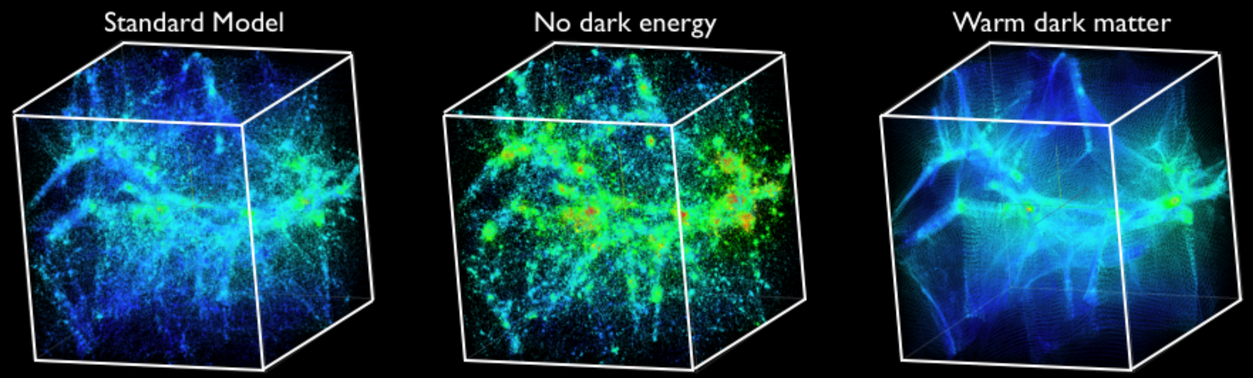



**SPT-SZ clusters + weak-lensing (19 Megacam, 13 HST) (Bocquet et al. 2019)**
**SPT-3G clusters + LSST weak-lensing (Projection by Prakut Chaubal)**

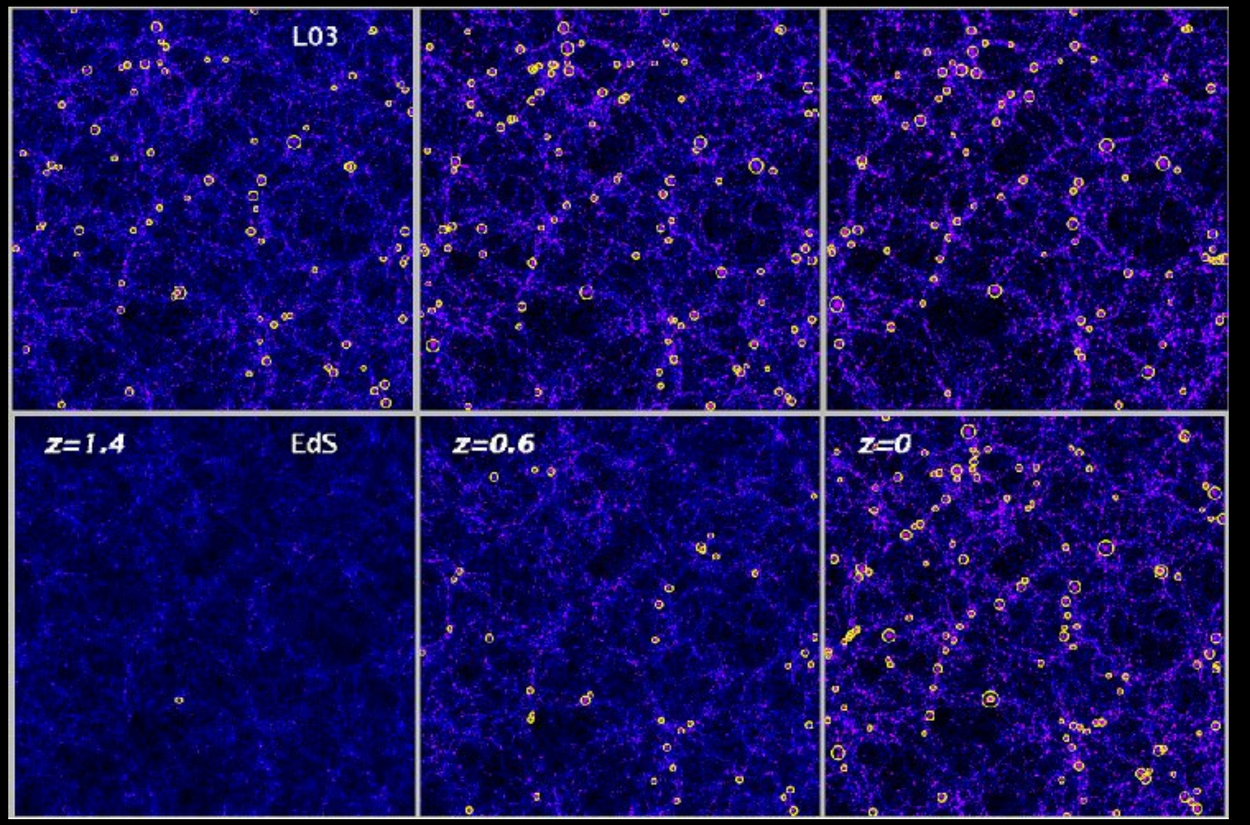
# Overview

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

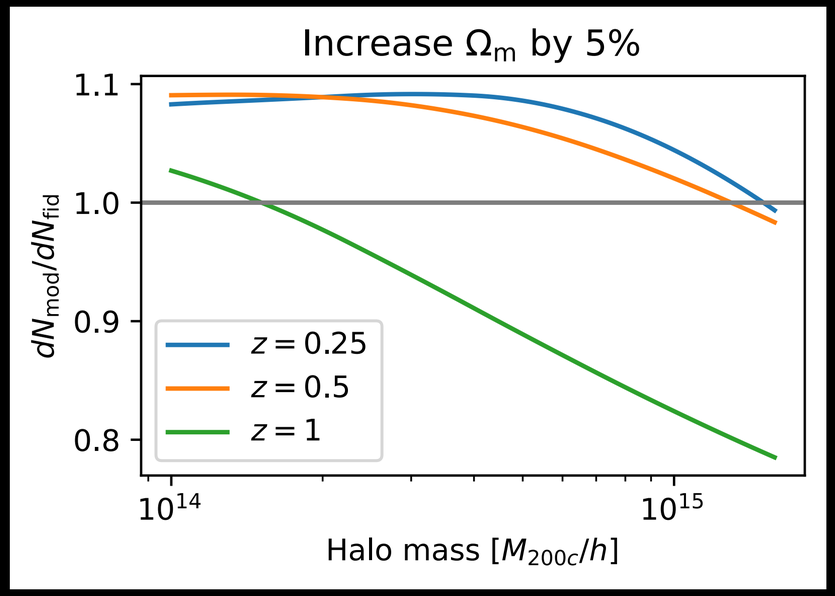
# Cluster cosmology




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

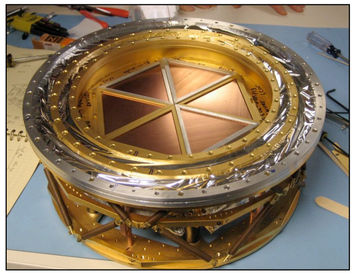
- Lensing traces total mass
- No assumption about hydrostatic state
- Accurate predictions/modeling using numerical simulations

# The South Pole Telescope (SPT)

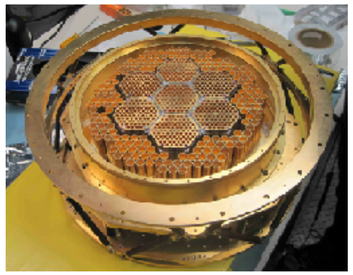
10-meter sub-mm quality wavelength telescope

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

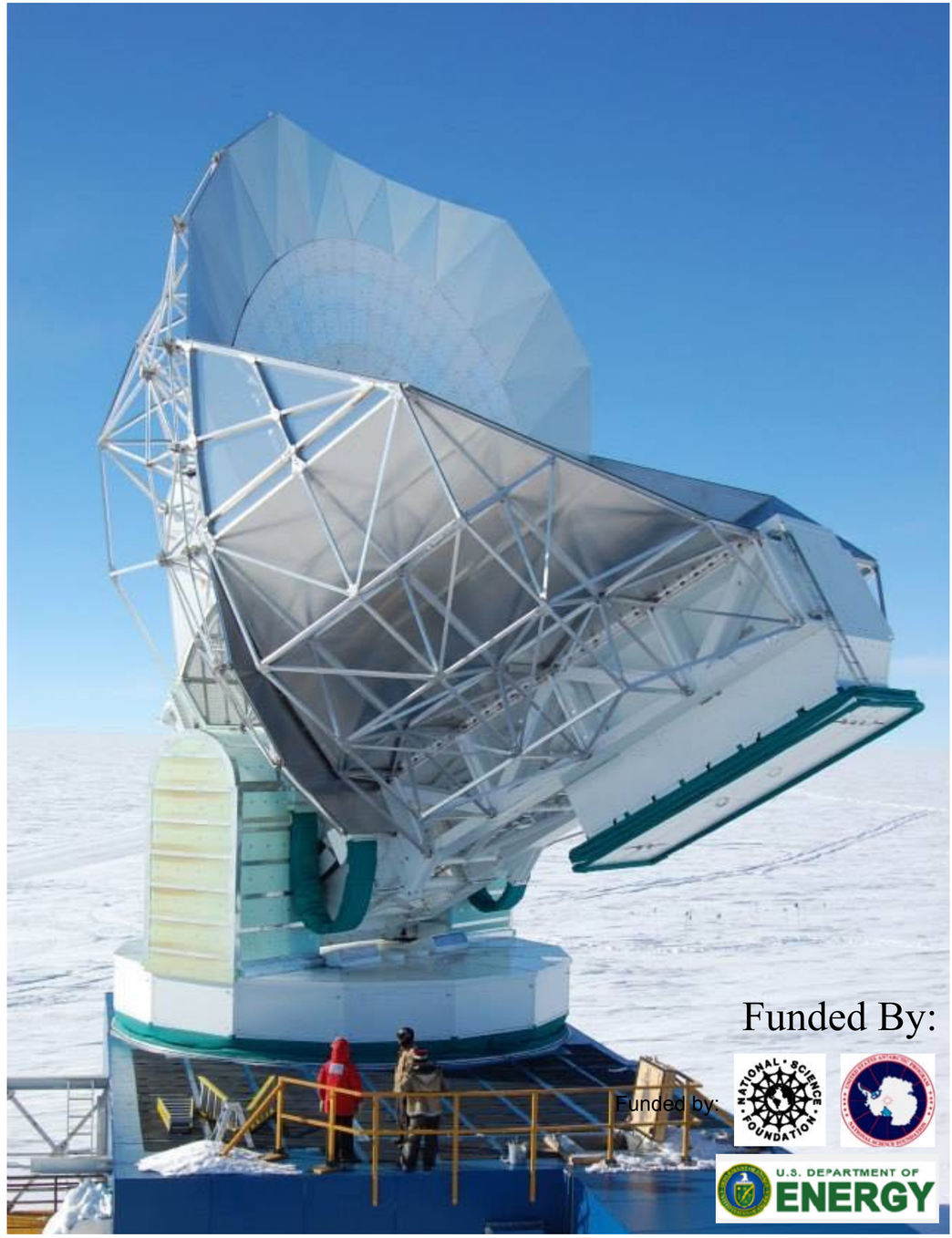
**2007: SPT-SZ**
960 detectors
95,150,220 GHz



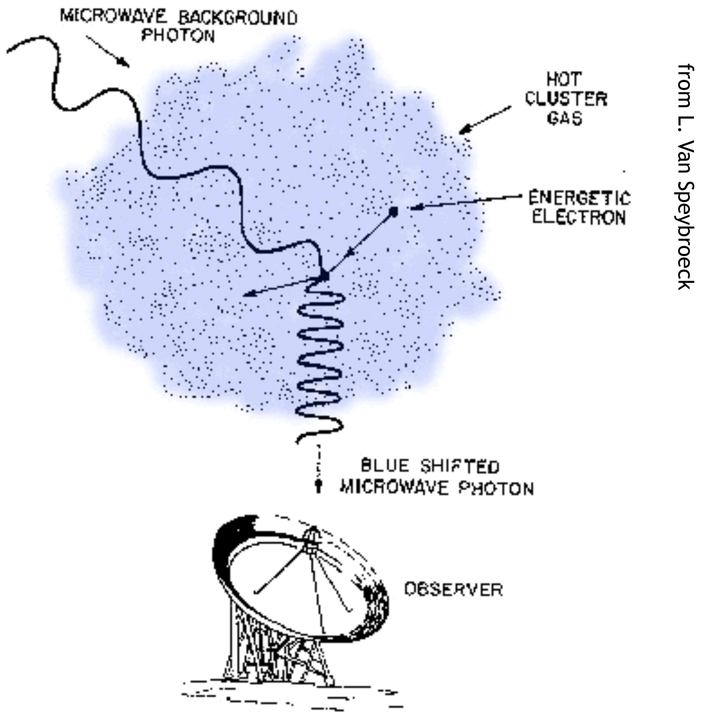
**2012: SPTpol**
1600 detectors
90,150 GHz
***+Polarization***



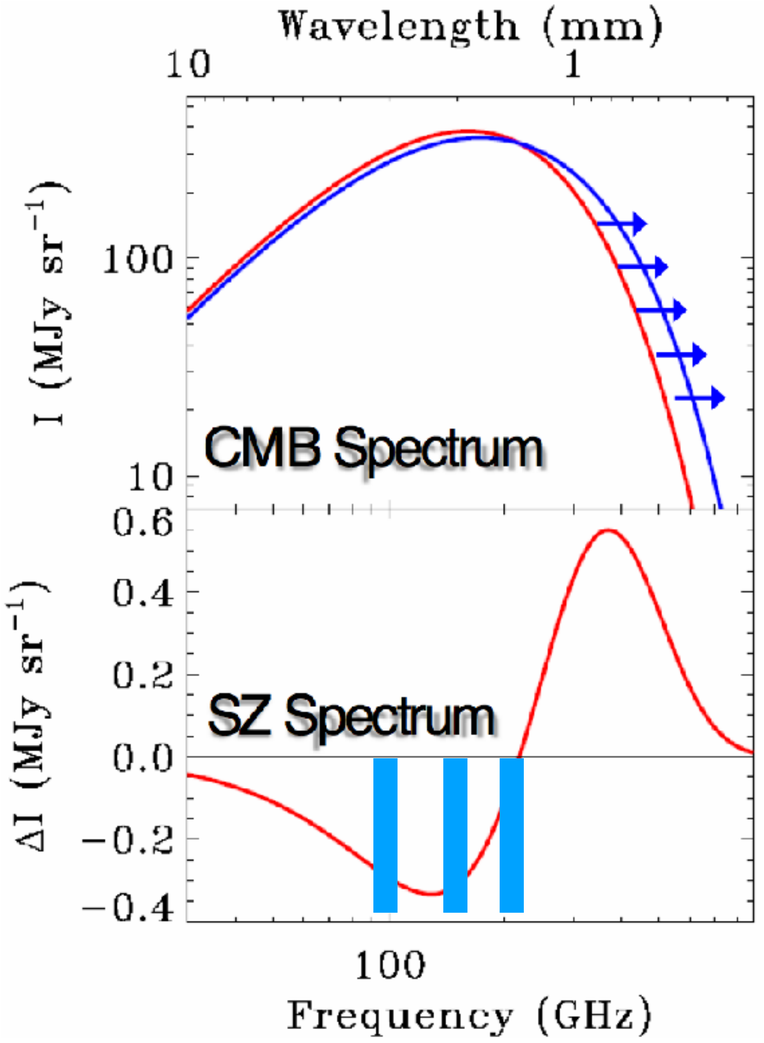
**2017: SPT-3G**
~15,200
detectors
95,150, 225 GHz
***+Polarization***



# Sunyaev-Zel'dovich (SZ) effect



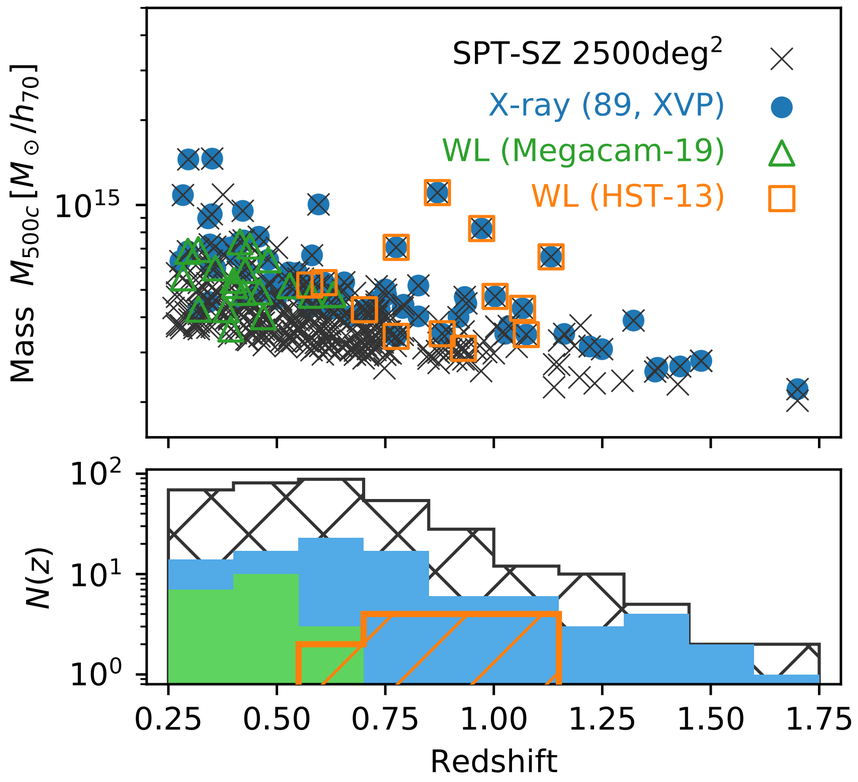

from L. Van Speybroeck




- 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)

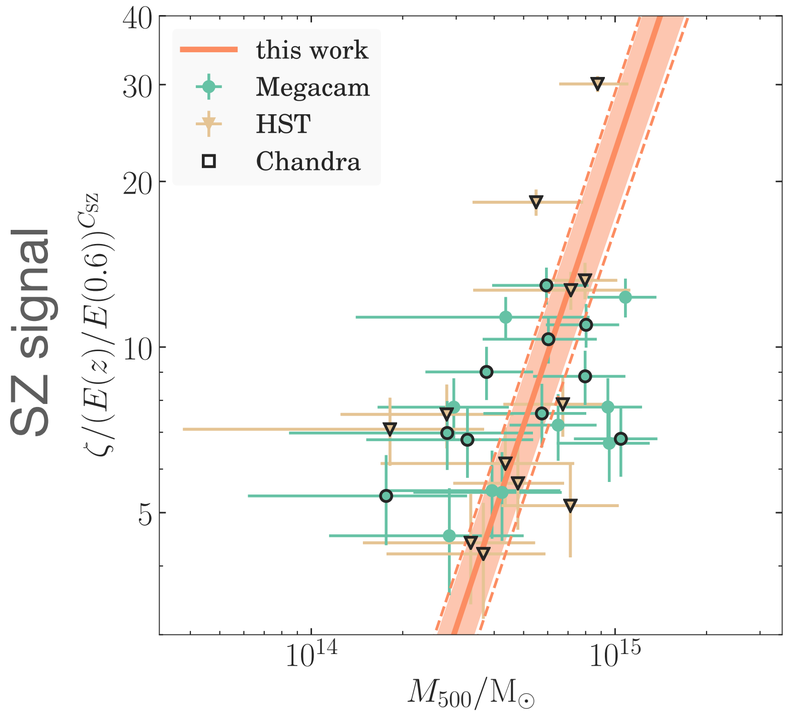
# SPT-SZ cluster cosmology

## 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)

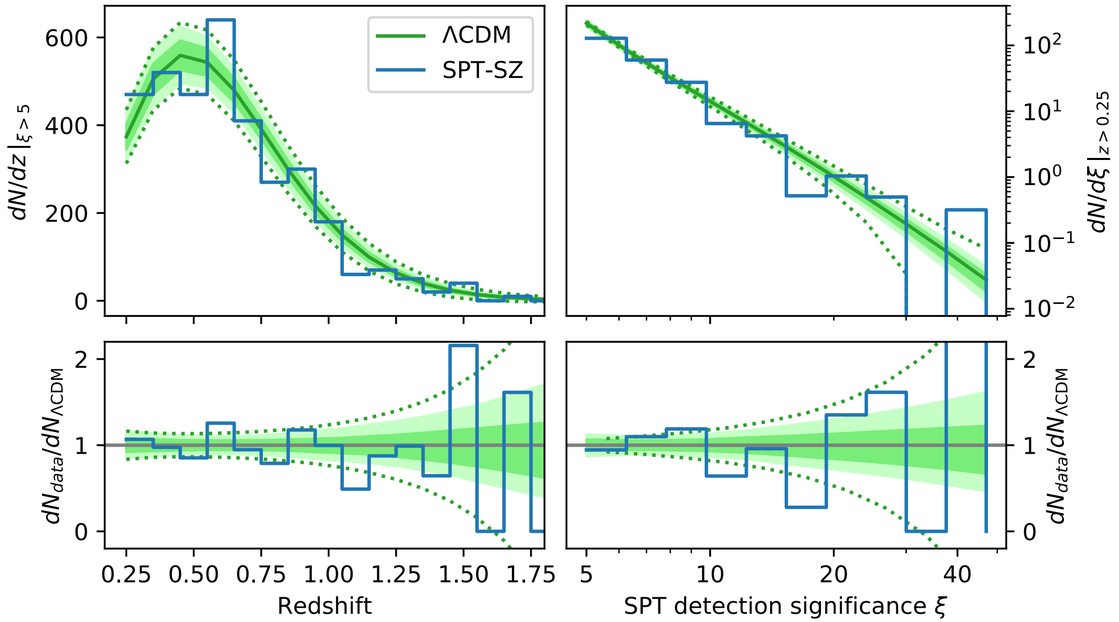


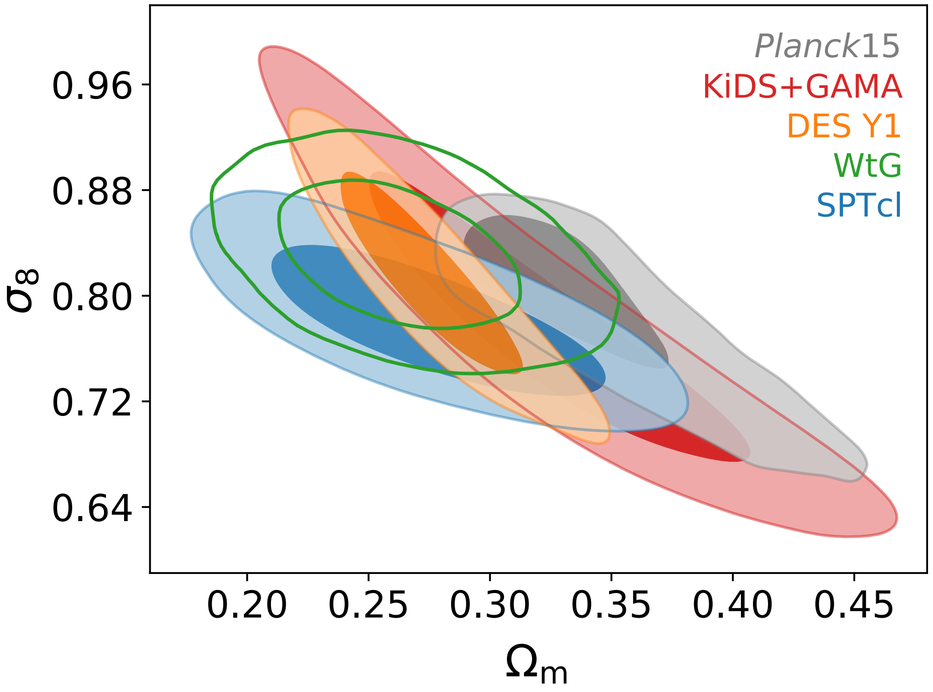

Use known Mwl—Mhalo relation to calibrate SZ—mass relation (Dietrich,Bocquet+19)

# 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 $\sigma$ agreement with *Planck*15 TT+lowTEB

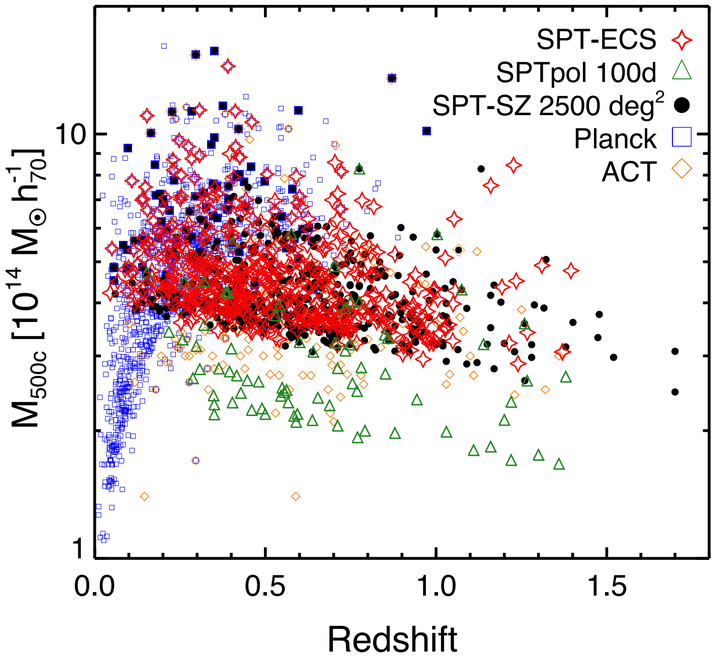


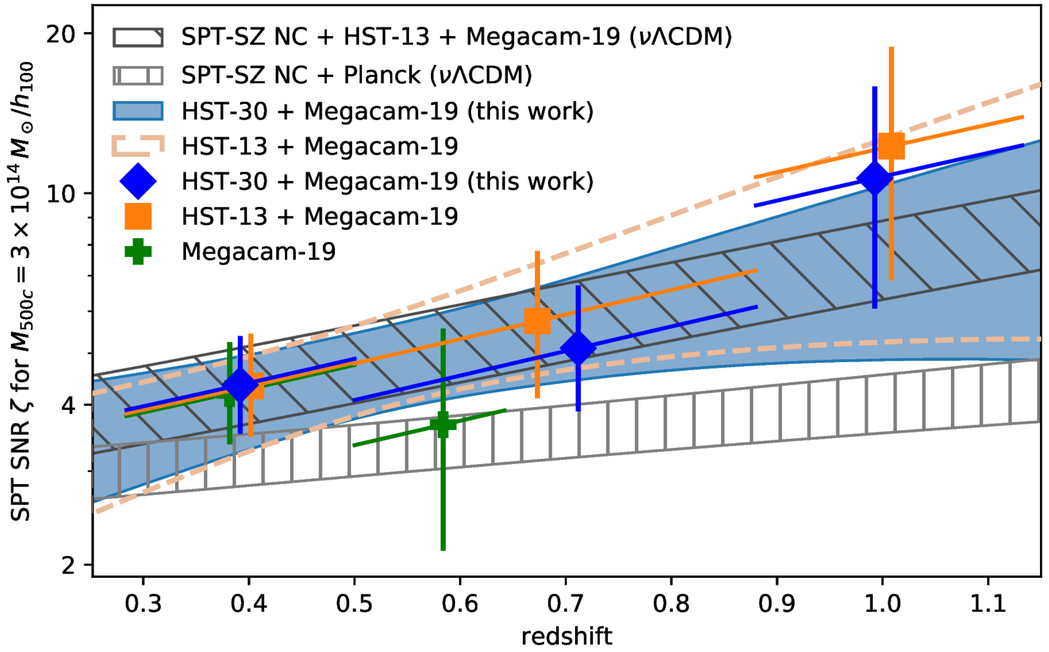



# How to improve?

— 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)

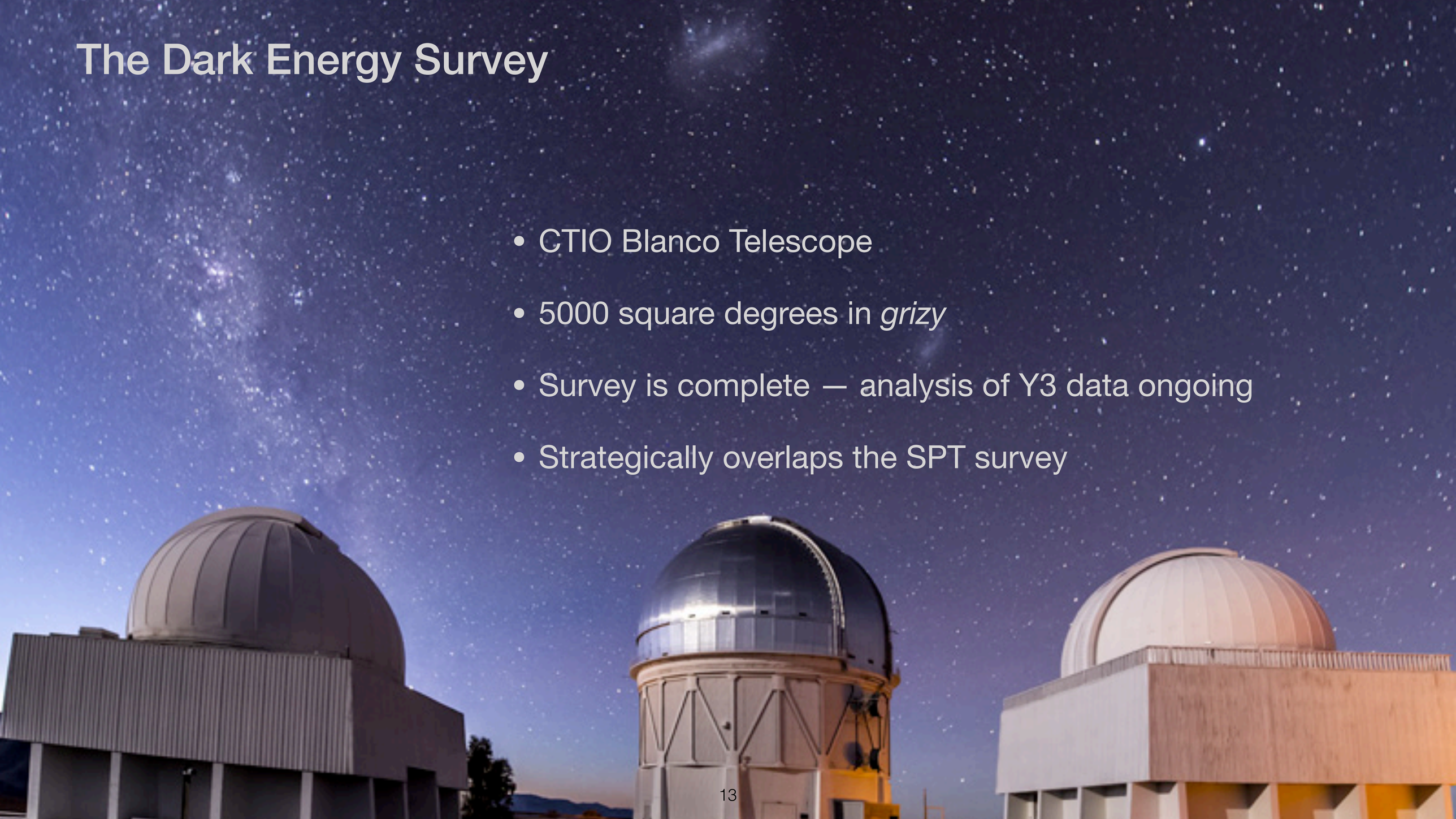
~1000 clusters above detection SNR 4.5

Redshifts/optical confirmation mainly from Dark Energy Survey

High-redshift cluster weak-lensing using Hubble Space Telescope

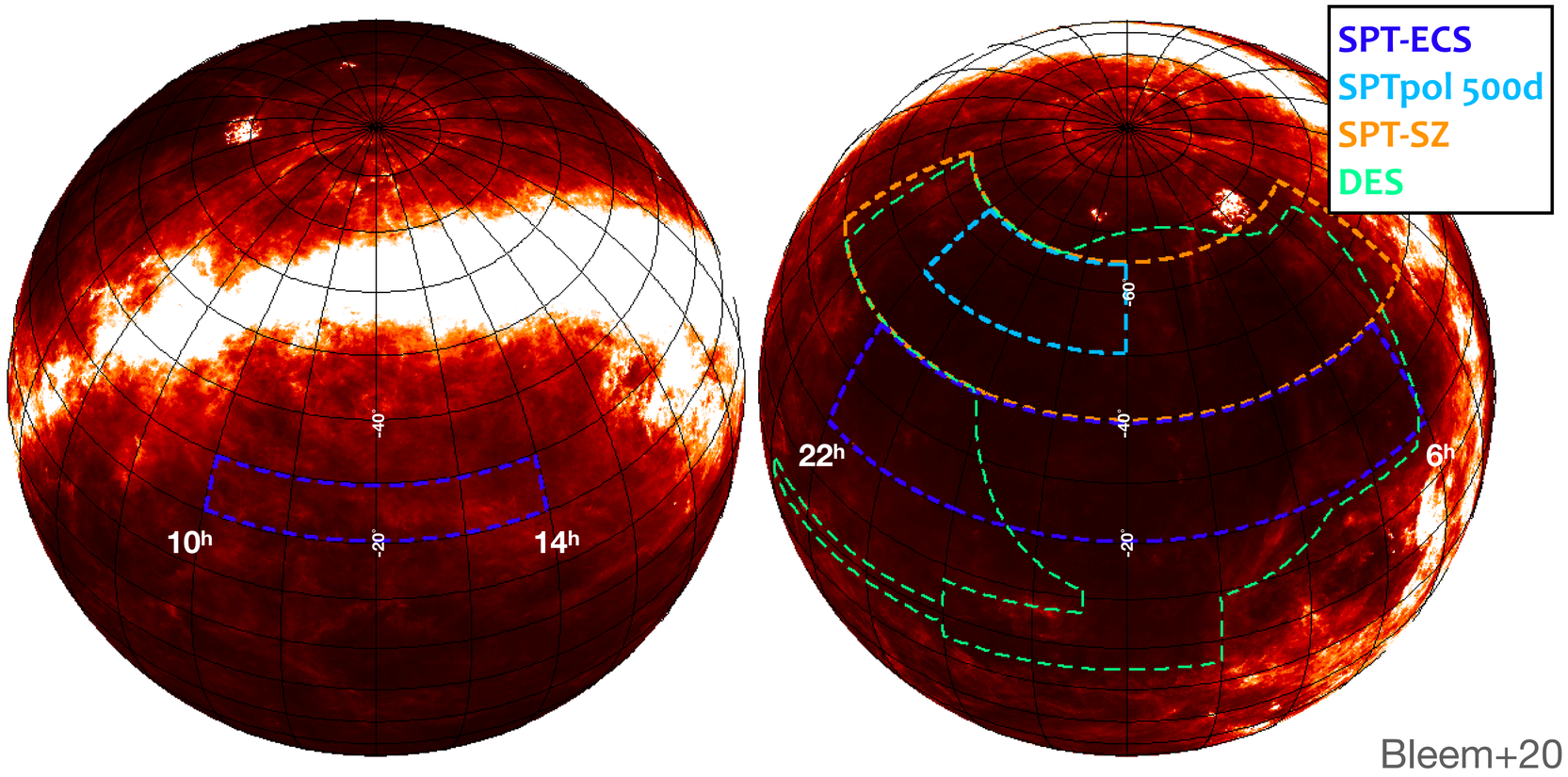
High-z dataset now comprises 30 HST clusters (Schrabback,Bocquet+21)

# 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)

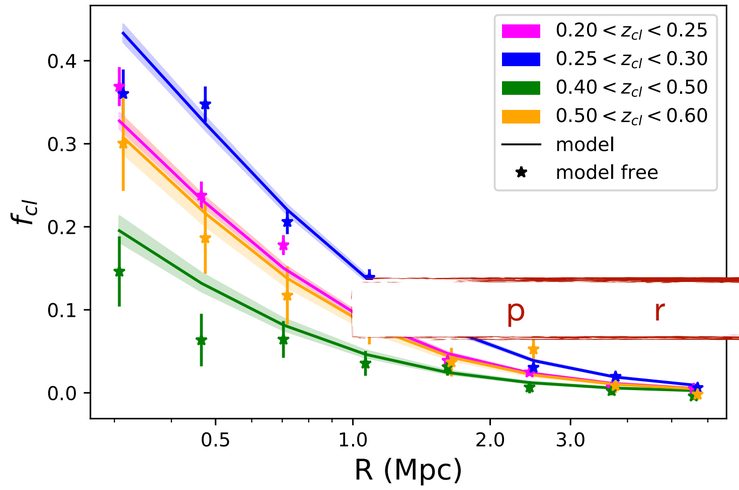
Paper series “SPT Clusters with DES and HST Weak Lensing”

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

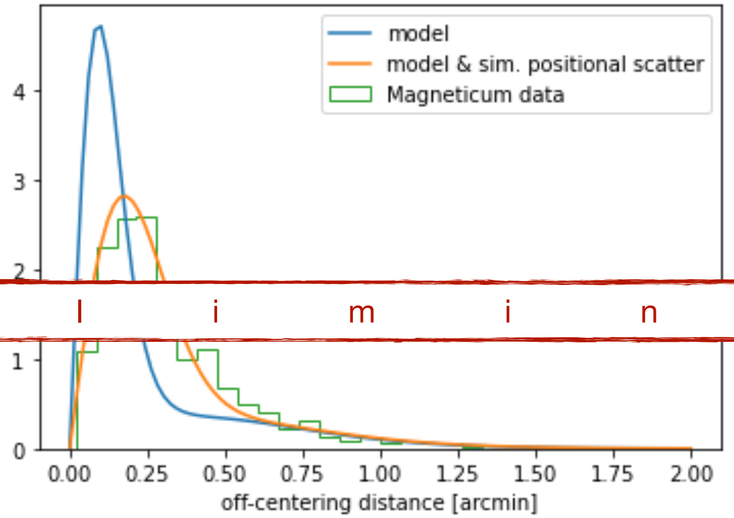
First papers in 2021

# SPT cluster mass calibration using DES weak-lensing data

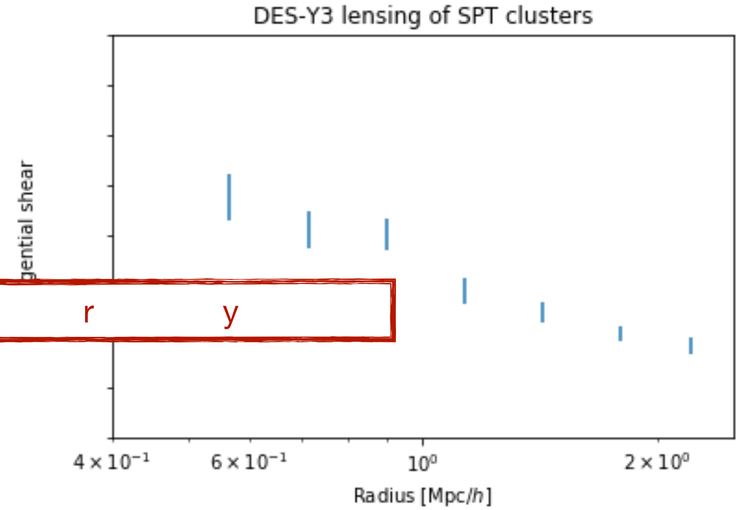
## Cluster member contamination a.k.a. boost factors




## Miscentering

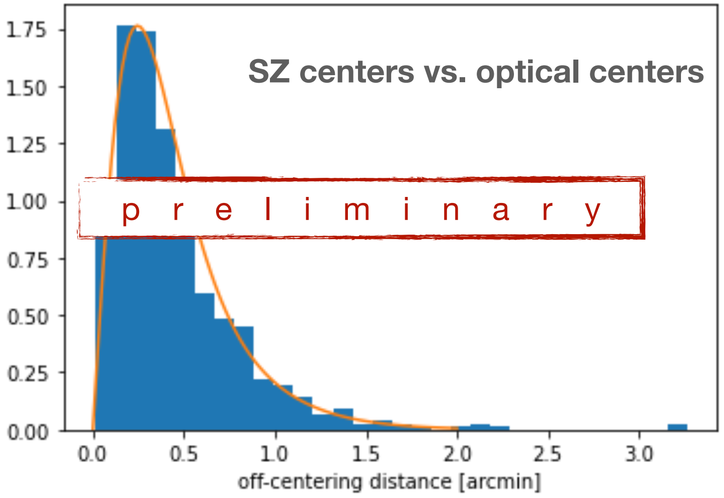



## Lensing data




p r e l i m i n a r y

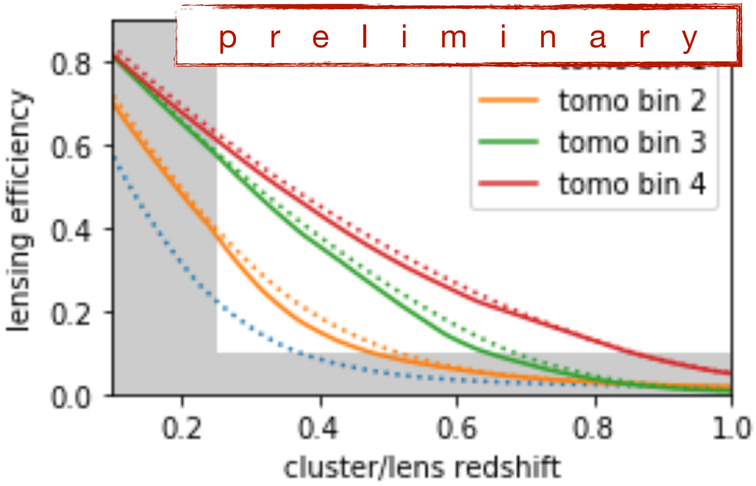
Cluster galaxies that appear in source sample
Correction using P(z) decomposition method (e.g., Gruen+15, Varga+19)
Figure: Application to individual-cluster lensing using DES Year 1 data (Paulus+ to be submitted)



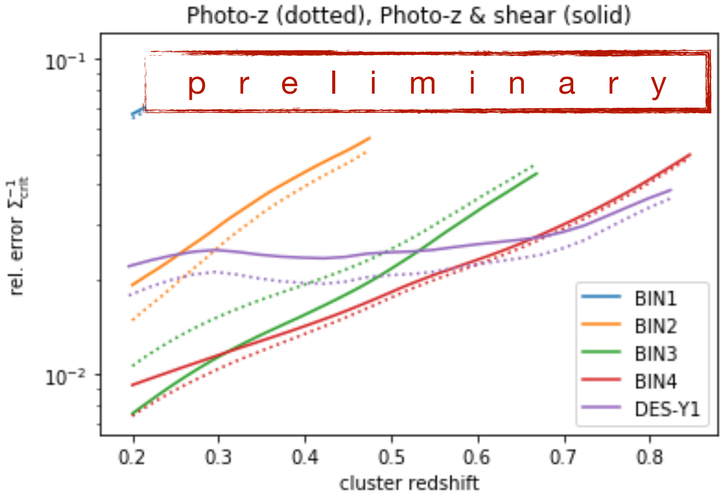

SPT SNR > 4.5 clusters
0.5 Mpc/h < r < 3.2 / (1+z) Mpc/h
Shear SNR ~80

# 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)

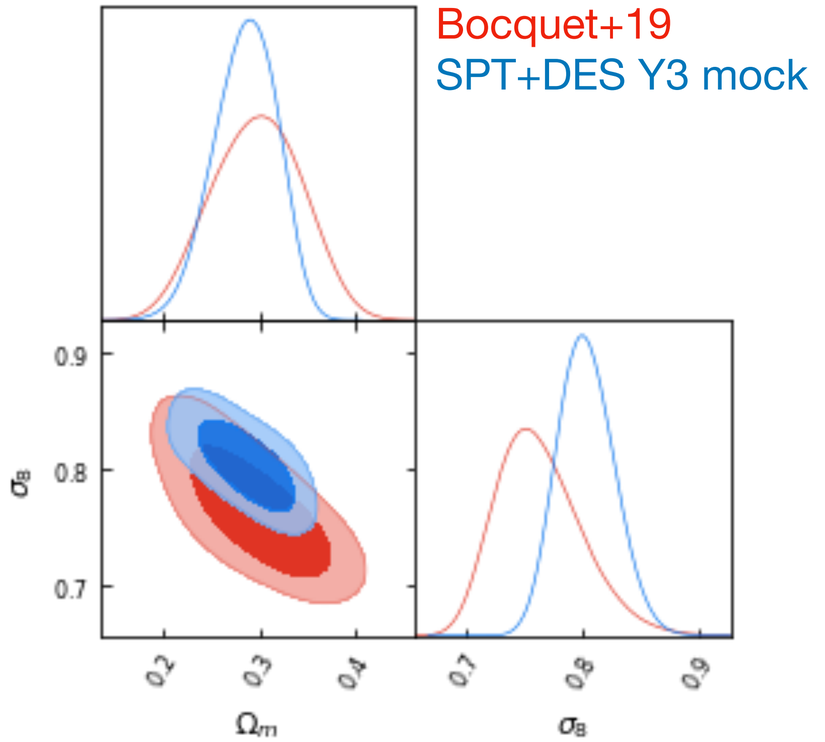
Significant improvement over DES Year 1

# 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!