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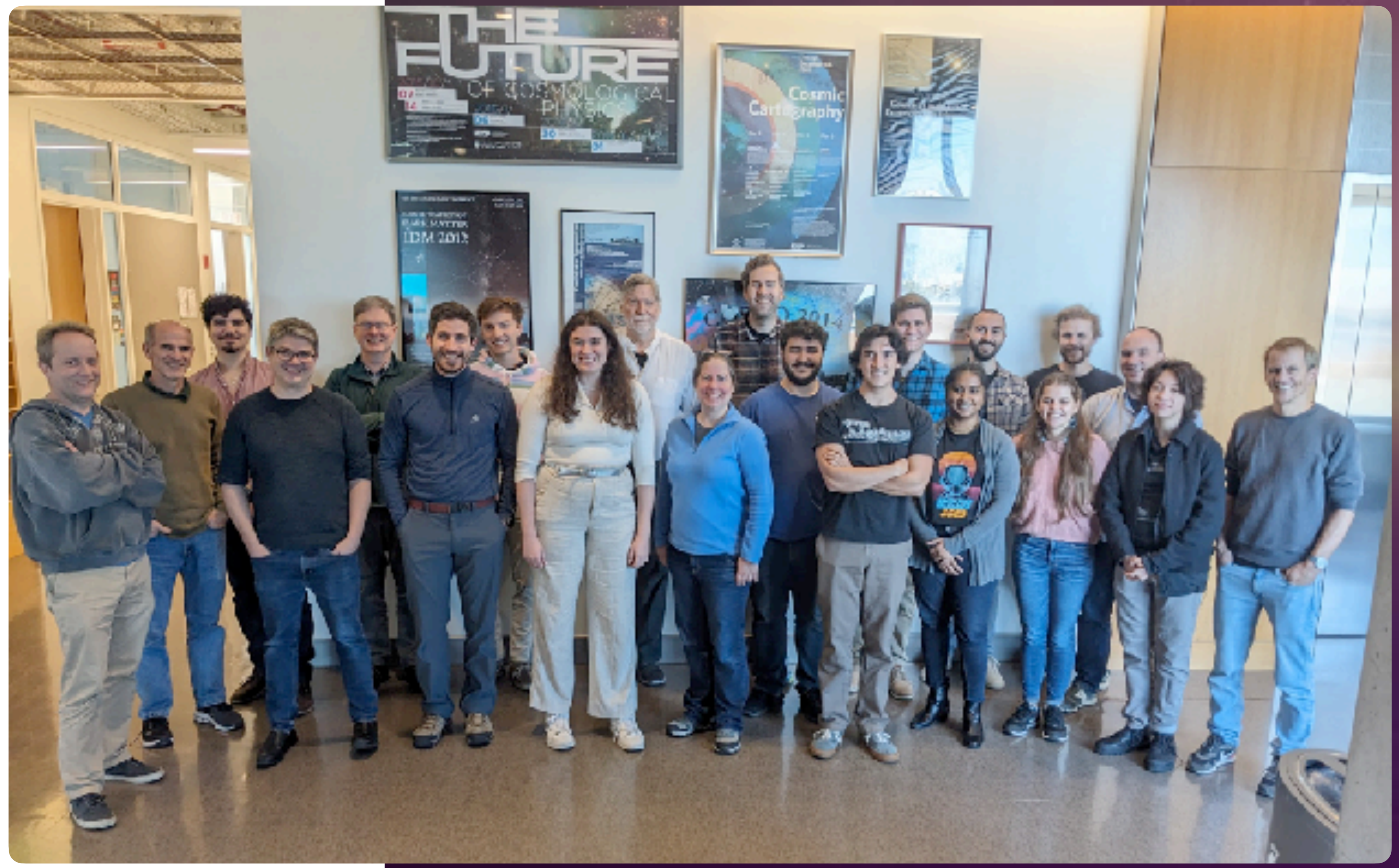
Cosmology with South Pole Telescope Selected Clusters

Sebastian Bocquet (LMU München)

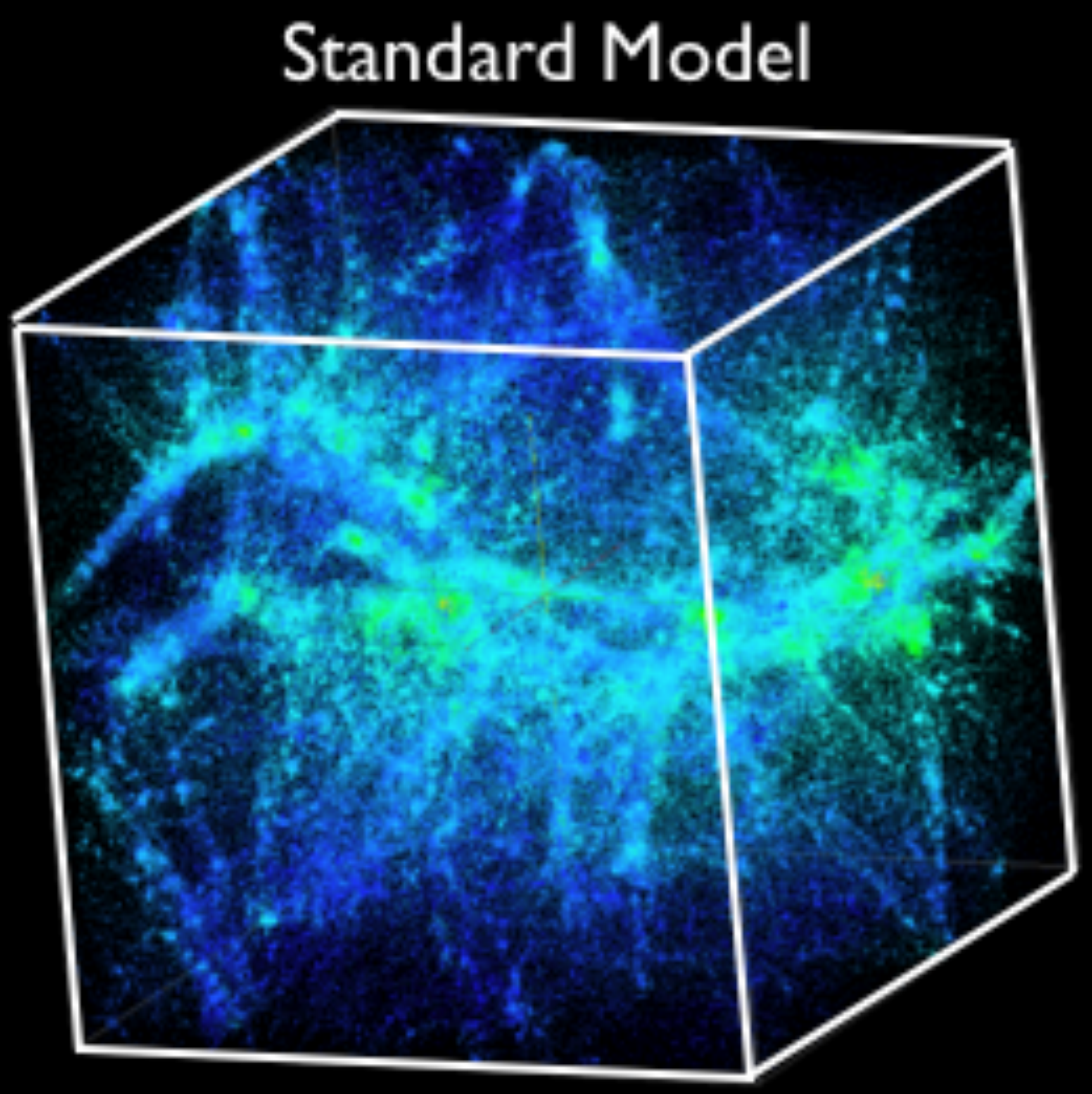
and the SPT cluster working group



SPT Cluster Working Group (2023)

Image credit: SPT 2024 winter-overs Josh + Kevin

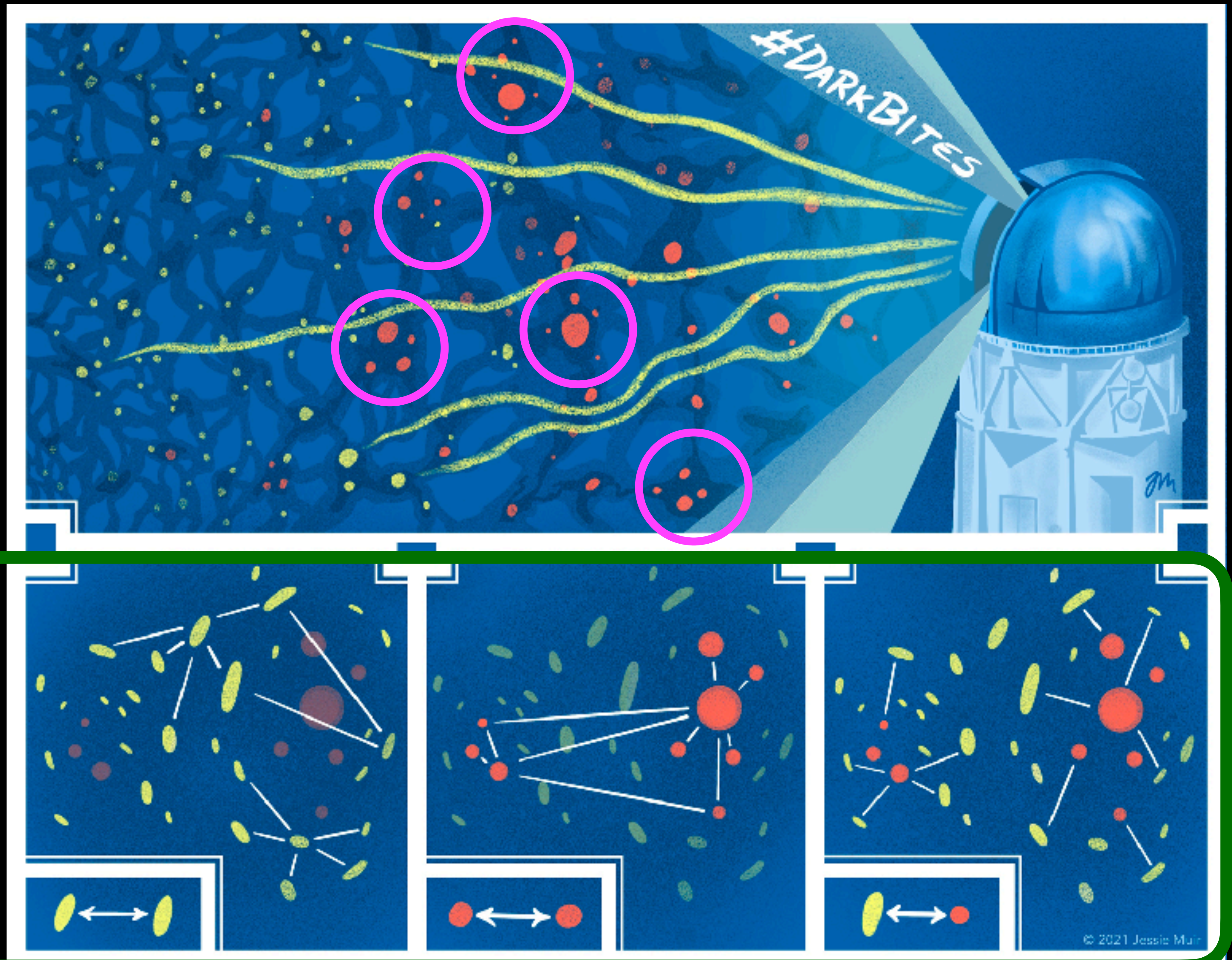
Cosmology and the Large-Scale Structure



Credit: Katrin Heitmann

Cosmology from the Large-Scale Structure

3x2pt and abundance of galaxy clusters



Credit: Jessie Muir (https://www.jessiemuir.com/)

gravitational lensing

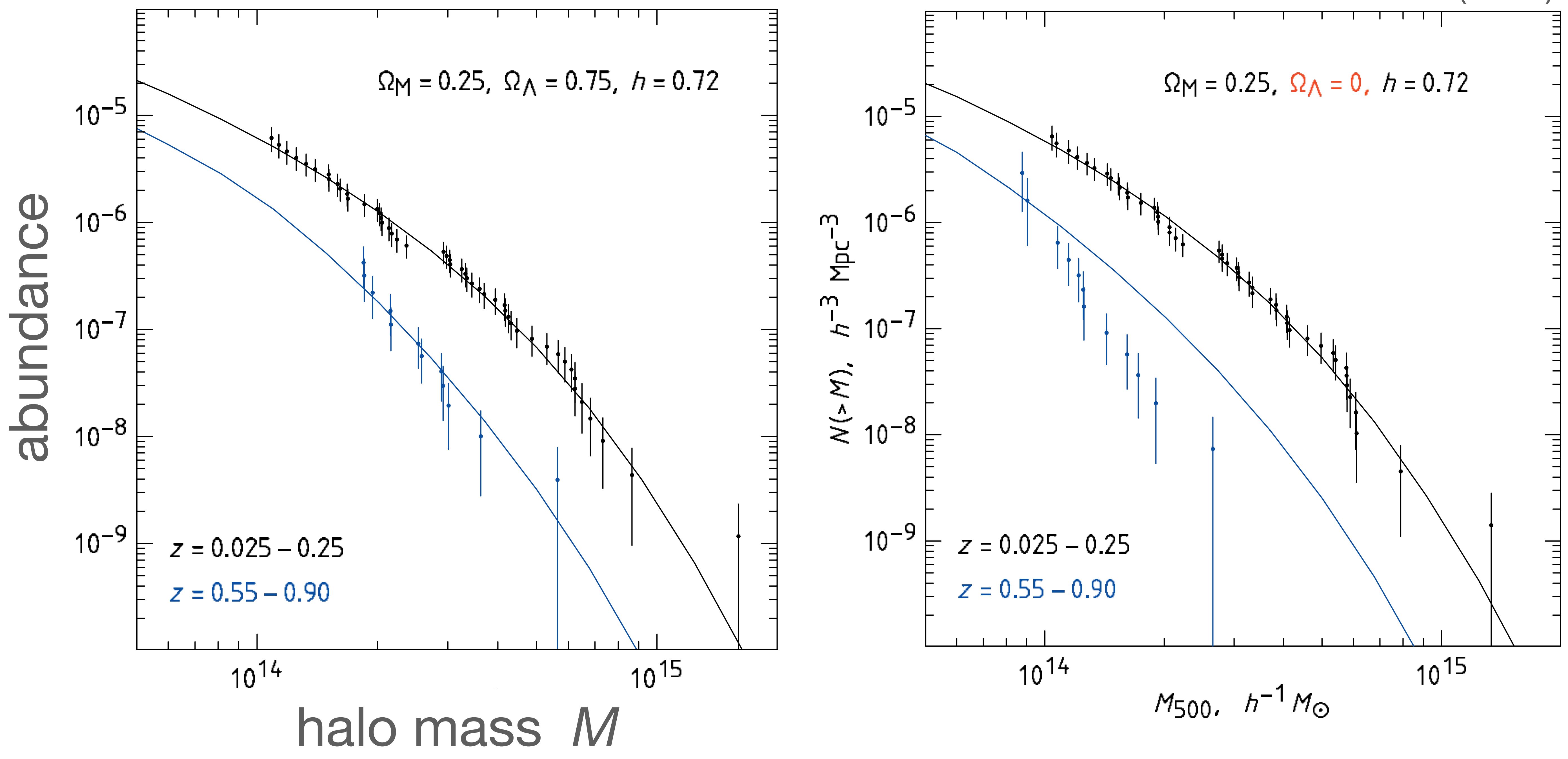
galaxy positions

Three
two-point correlation
functions
→ so-called *3x2pt*

Abundance of
massive halos

Cluster Abundance Cosmology

Vikhlinin et al. (2009)



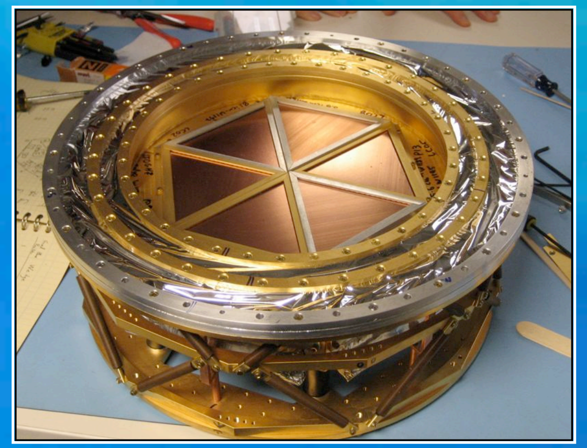
- Halo abundance is predicted using the halo mass function $dN(z)/dM$
- Compare observed with predicted number

The South Pole Telescope (SPT)

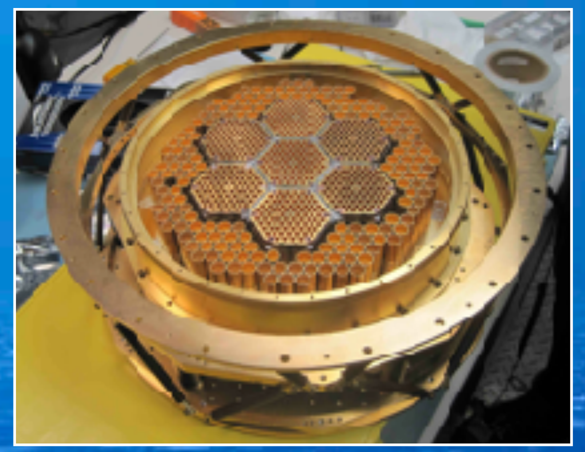
10-meter sub-mm quality wavelength telescope

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

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



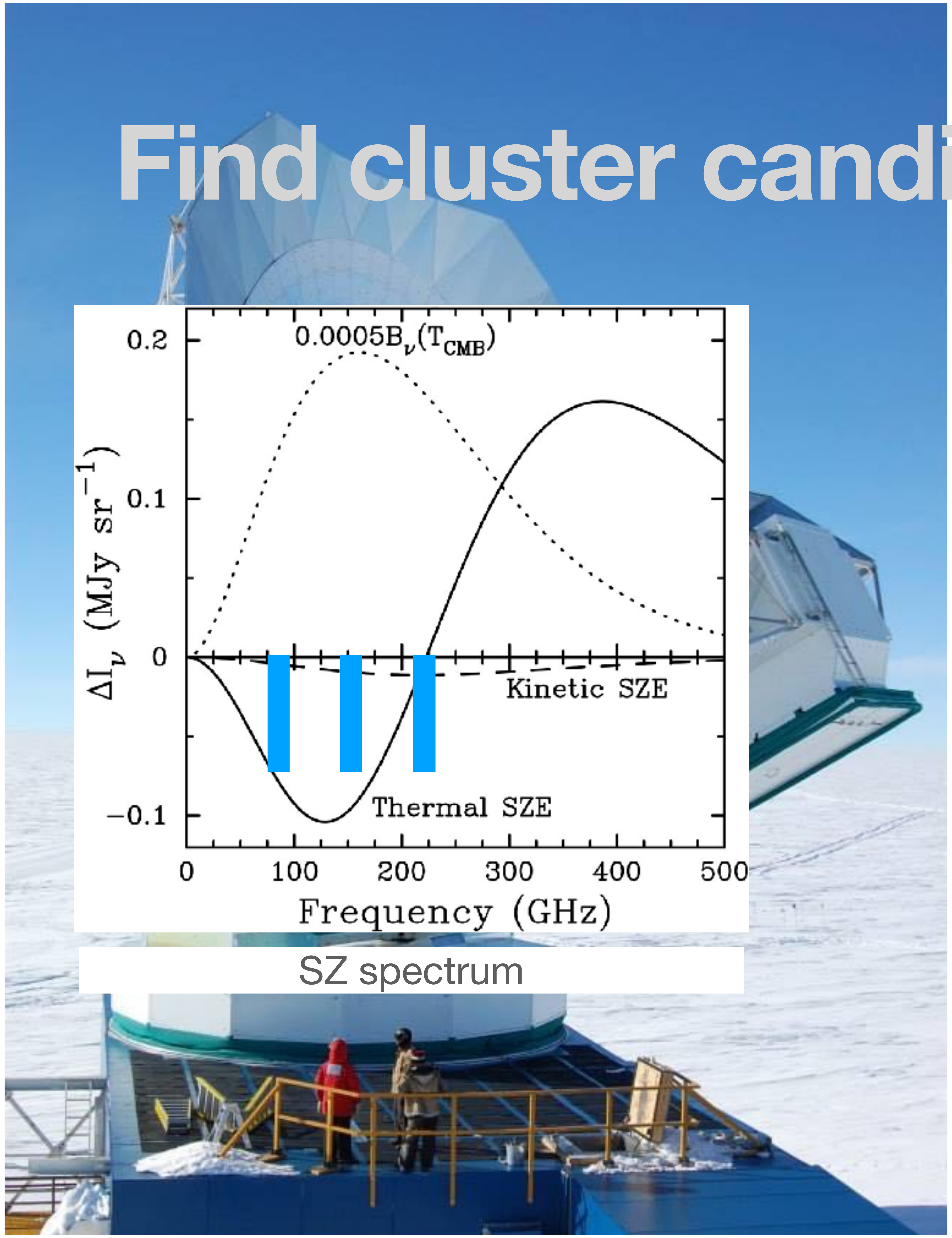
2012: SPTpol
1600 detectors
95,150 GHz
+Polarization



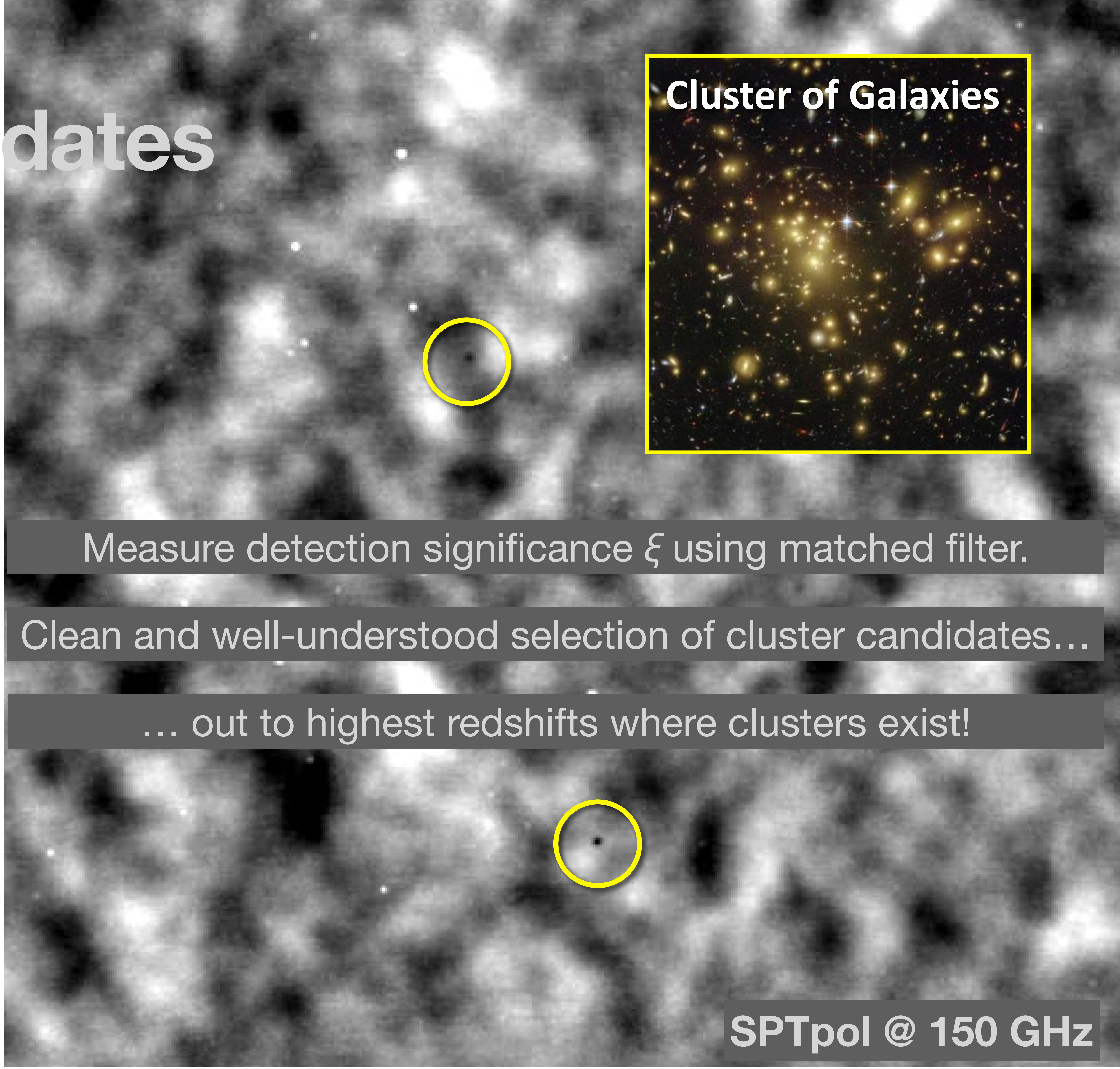
2017: SPT-3G
~15,200 detectors
95,150,220 GHz
+Polarization

U.S. DEPARTMENT of ENERGY

Find cluster candidates



SZ spectrum



Measure detection significance ξ using matched filter.

Clean and well-understood selection of cluster candidates…

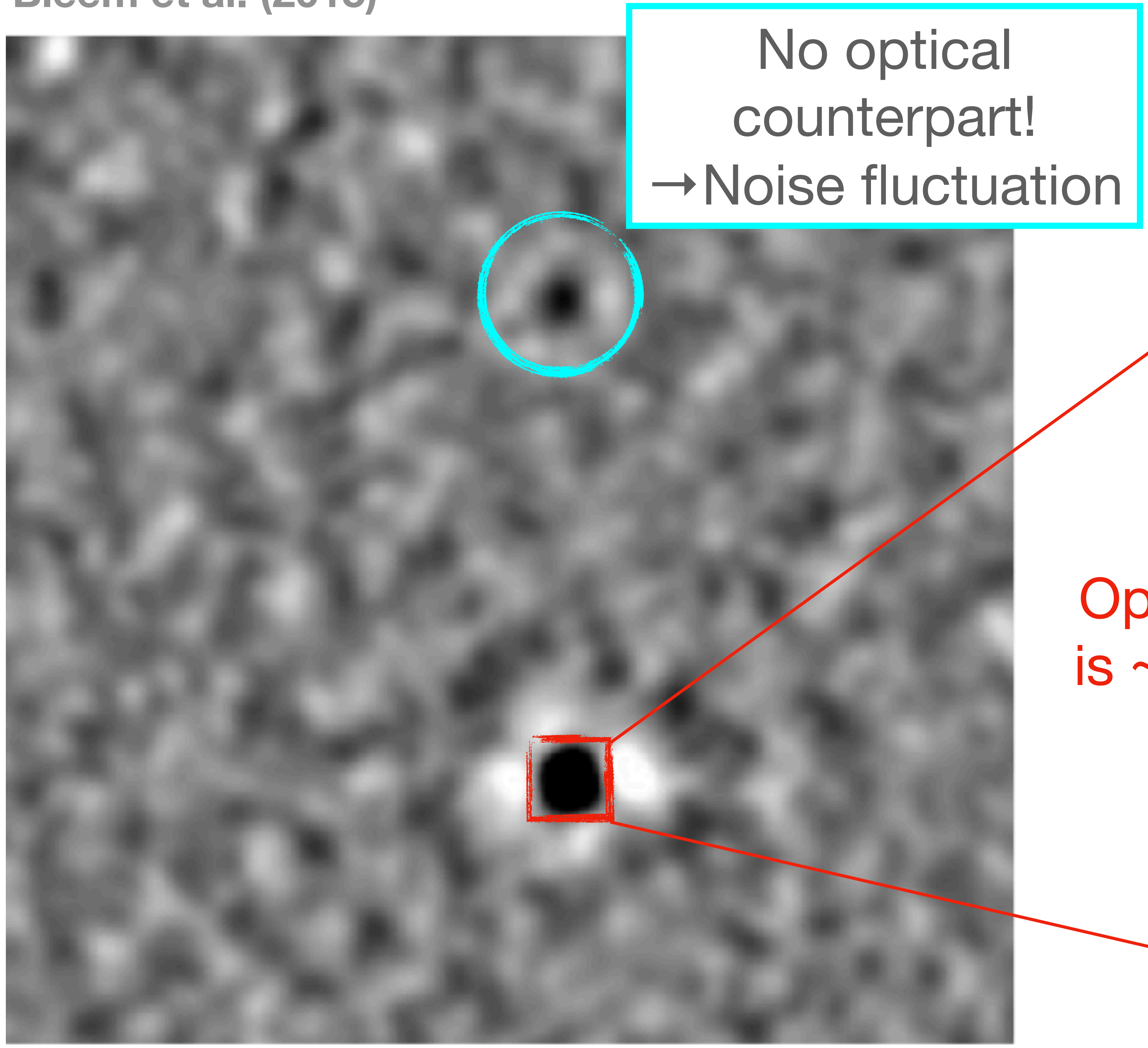
… out to highest redshifts where clusters exist!

SPTpol @ 150 GHz

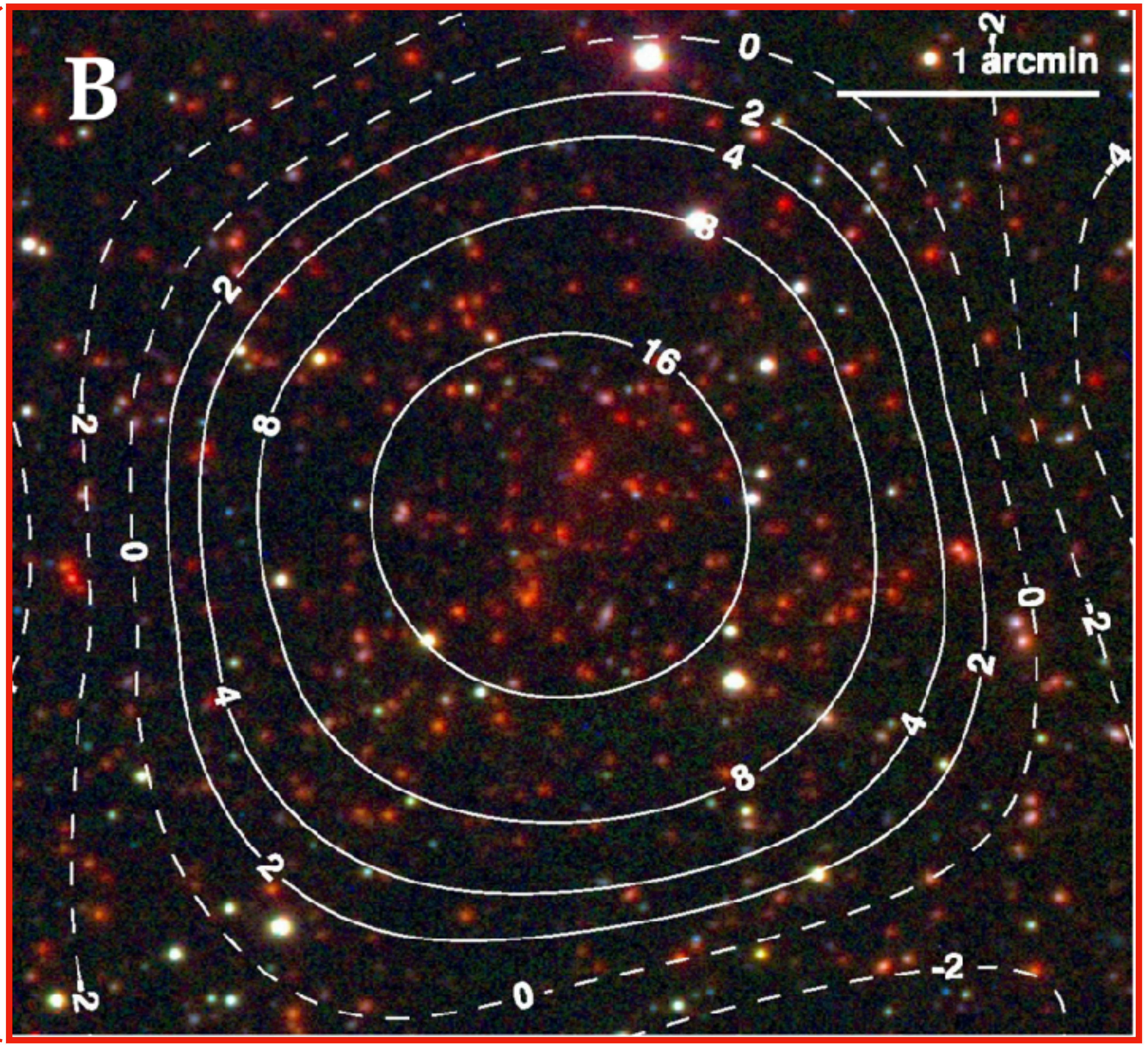
Cluster confirmation by eye

Optical / near-IR data to confirm the cluster and measure redshift *z*

Bleem et al. (2015)



Optical richness λ is ~ number of red galaxies

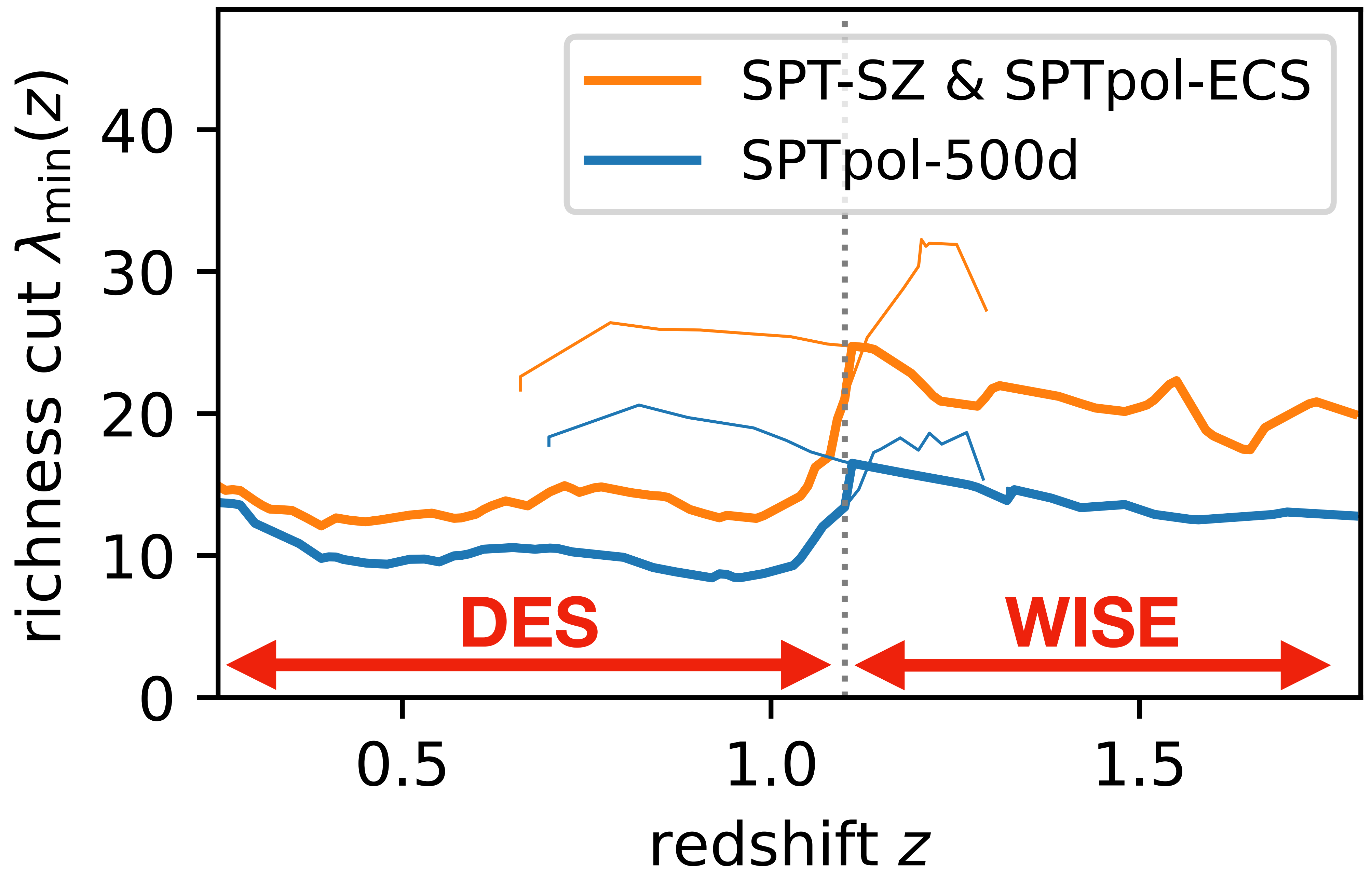


Systematic cluster confirmation

Construct clean and deep cluster catalogs

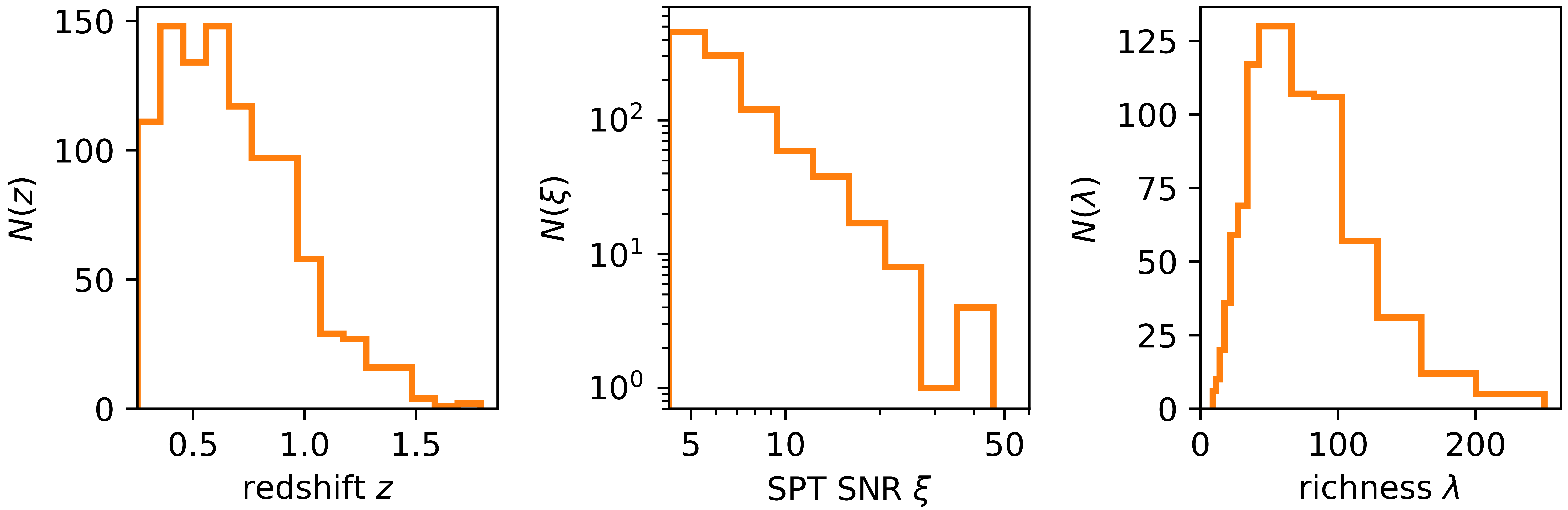
Bocquet et al. (2024a)

- MCMF machinery (Klein et al. 2018, 2024; Bleem et al. 2024)
  - Confirm SPT cluster candidates by measuring photo-*z* and optical richness λ
  - Get rid of chance associations (with SPT noise fluctuation) statistically
    - Calibrate probability of chance association by measuring (λ, *z*) at random locations
    - **Establish $\lambda_{\mathrm{min}}(z)$ to achieve target purity (> 98%)**
- For the experts:
  - SPT detection significance $\xi > 4.25$ (SPTpol 500d), $\xi > 4.5$ (SPT-SZ)
  - Outside DES footprint: $\xi > 5$
- **See Matthias Klein's talk this afternoon!**



SPT(SZ+pol) Cluster Sample

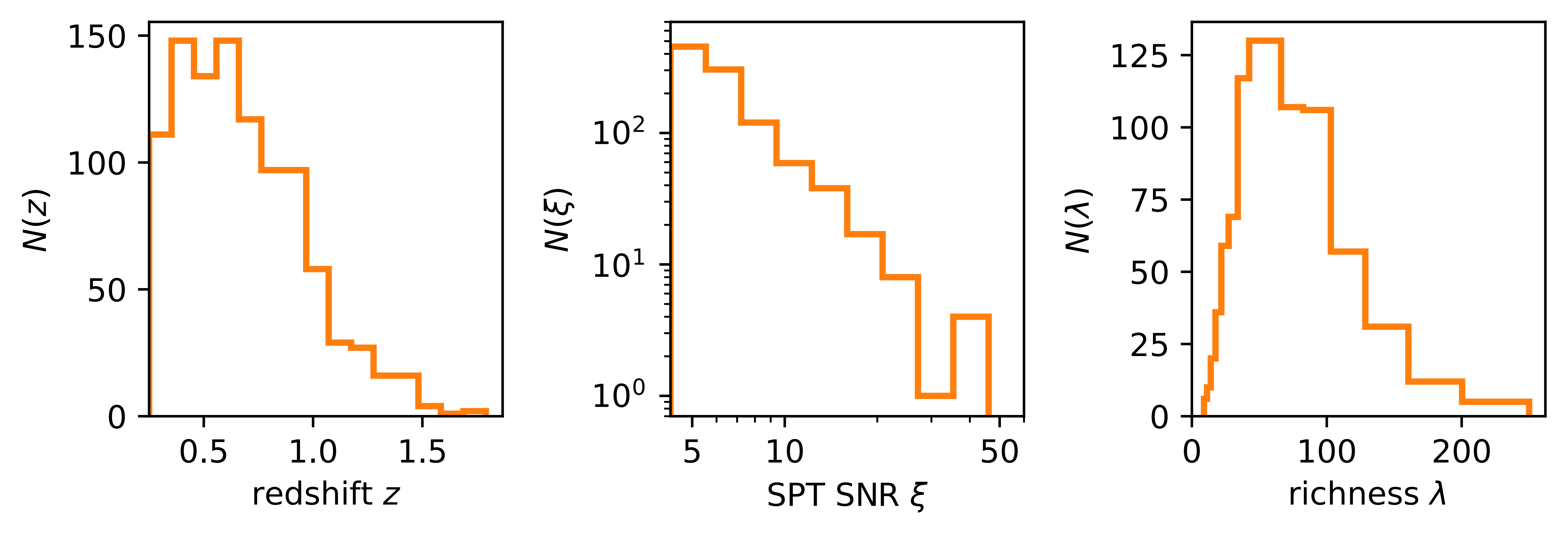
1,005 confirmed clusters above z > 0.25 over 5,200 deg²



SPT cluster catalogs: Bleem et al. (2015, 2020, 2024), Klein et al. 2024

Cluster Cosmology

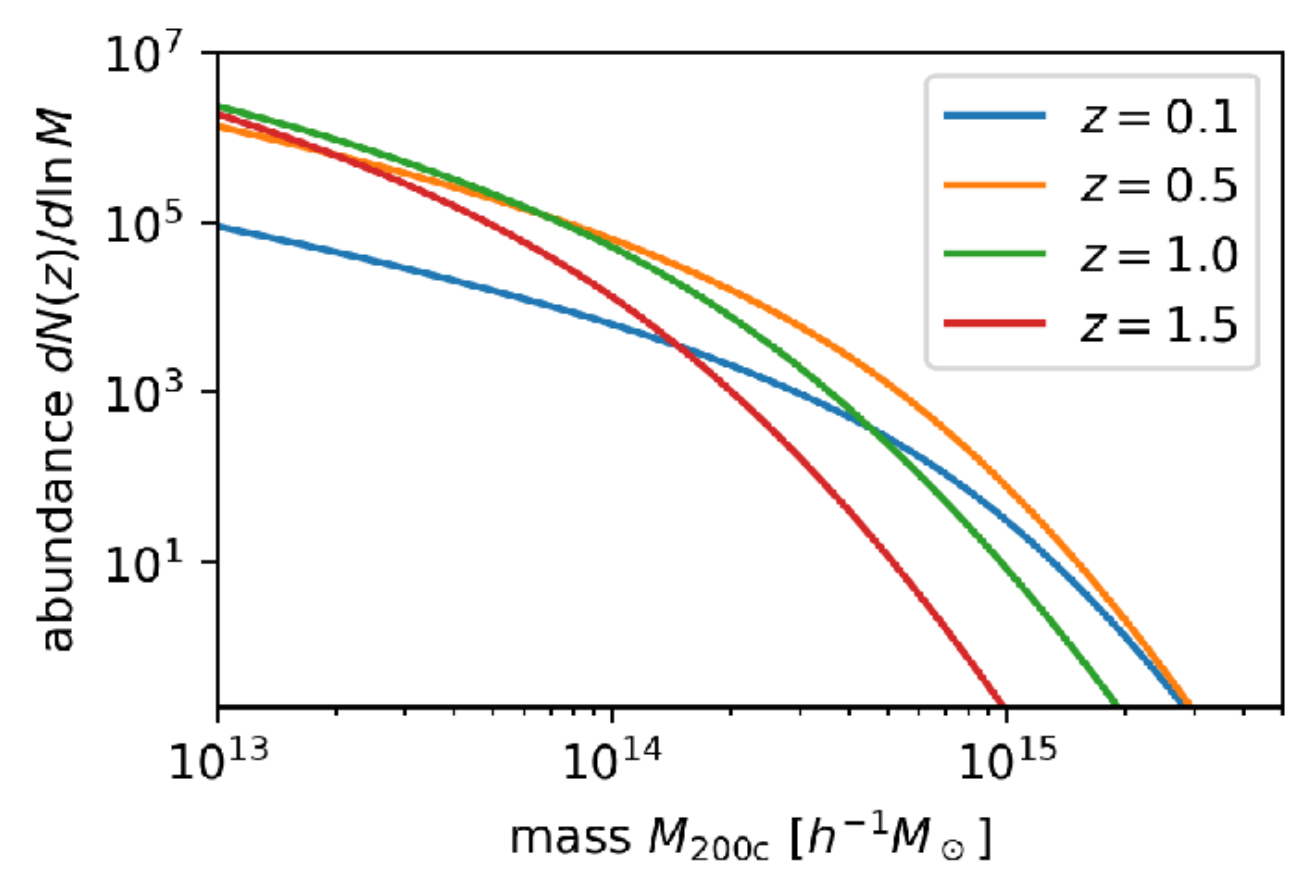
halo observable function



observations: clusters

theory: halos

halo mass function



Calibrate observable–mass relation:
mass calibration

observable–mass relation

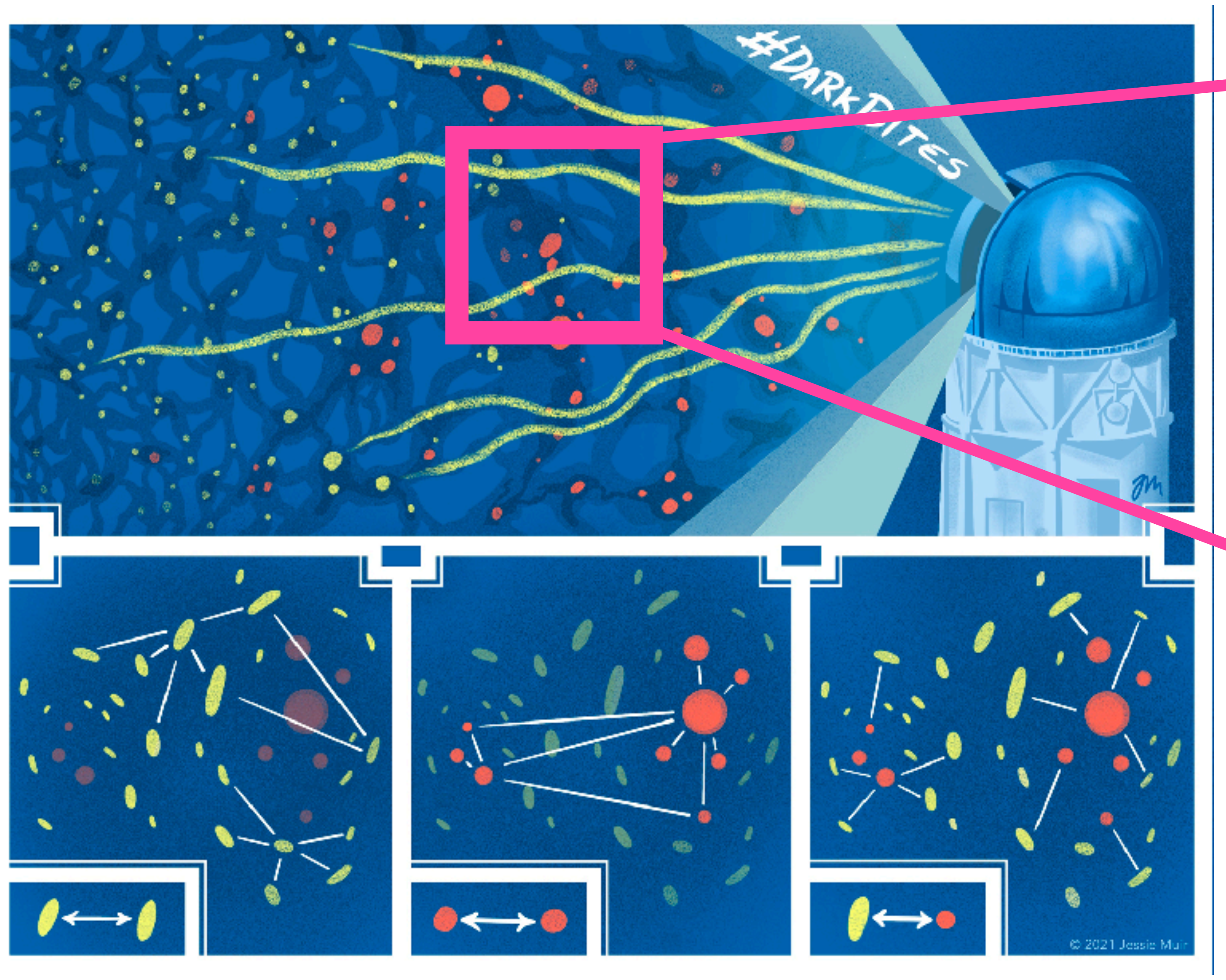
$$\frac{dN}{d\mathrm{obs}} = \int dM \, \boxed{P(\mathrm{obs}\,|\,M)} \, \boxed{\frac{dN}{dM}}$$

halo mass function

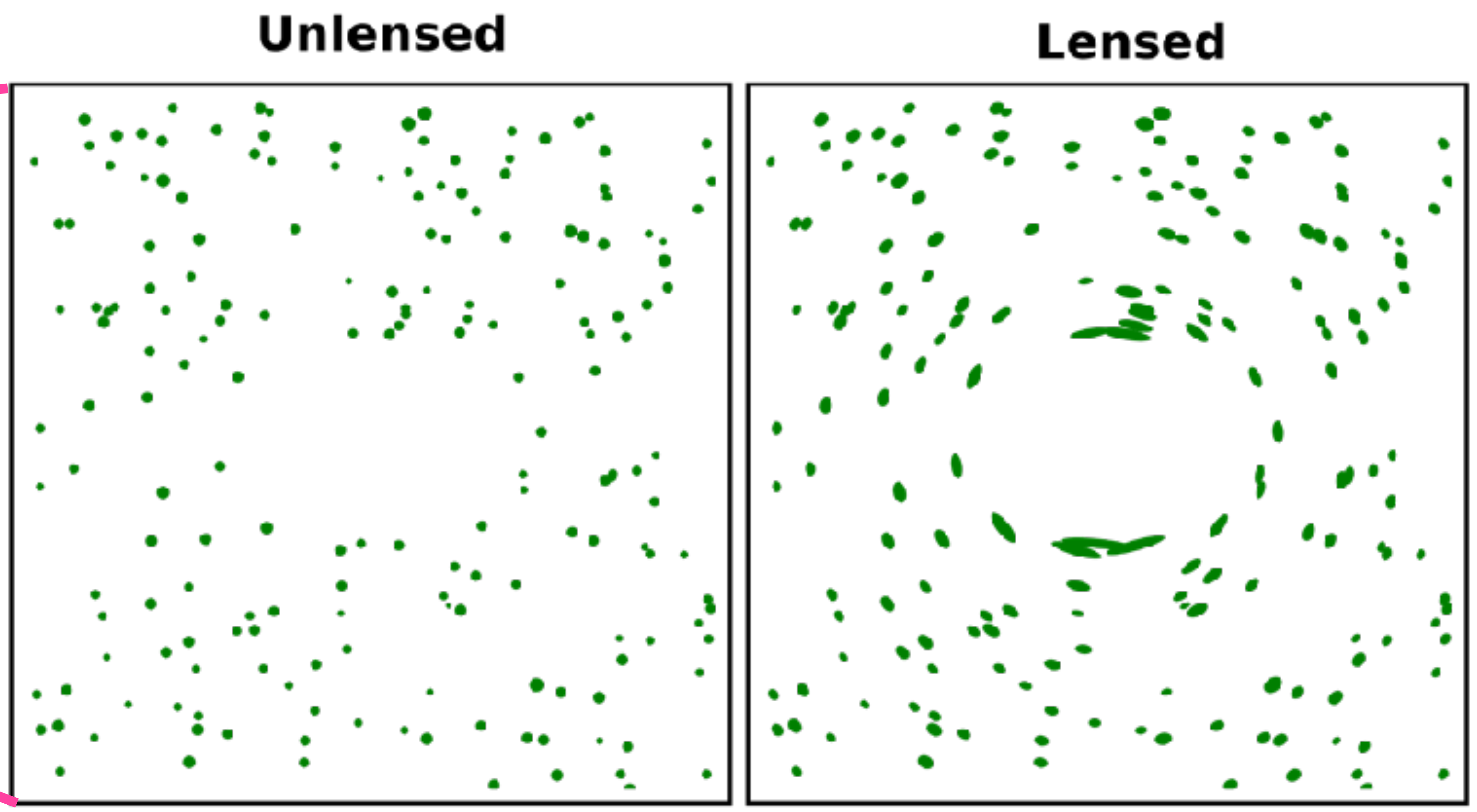
Mass Calibration

- ~~First principles / Hydrostatic equilibrium~~ No, because of non-thermal pressure support.
- ~~SZ–mass relation from hydrodynamic simulation~~ No(t yet), because of uncertain calibration of sub-resolution model.
- **Weak gravitational lensing is faithful tracer of (total) mass.**

  ➡ Empirically calibrate all other observable–mass relations.

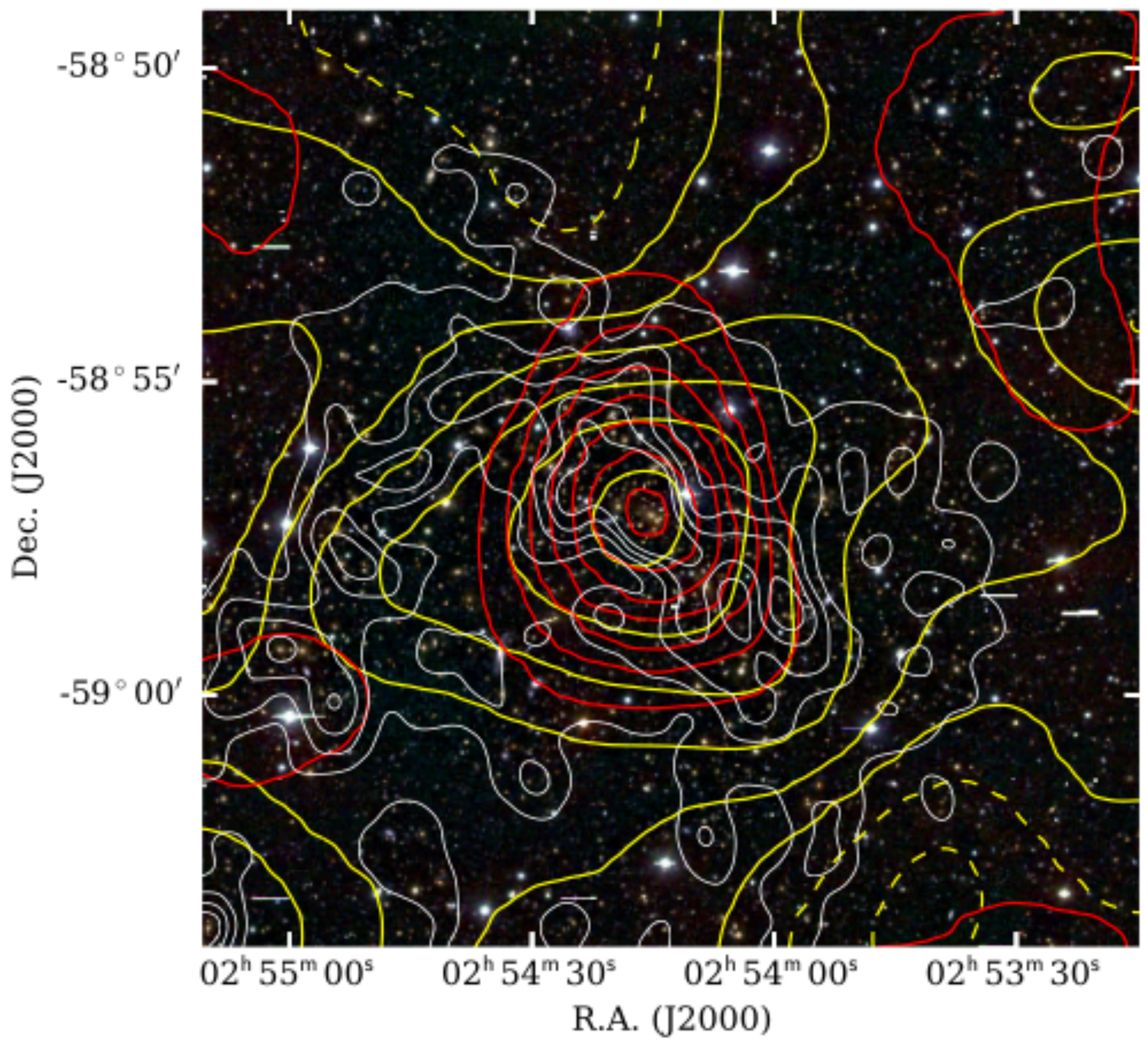


Credit: Jessie Muir (https://www.jessiemuir.com/)



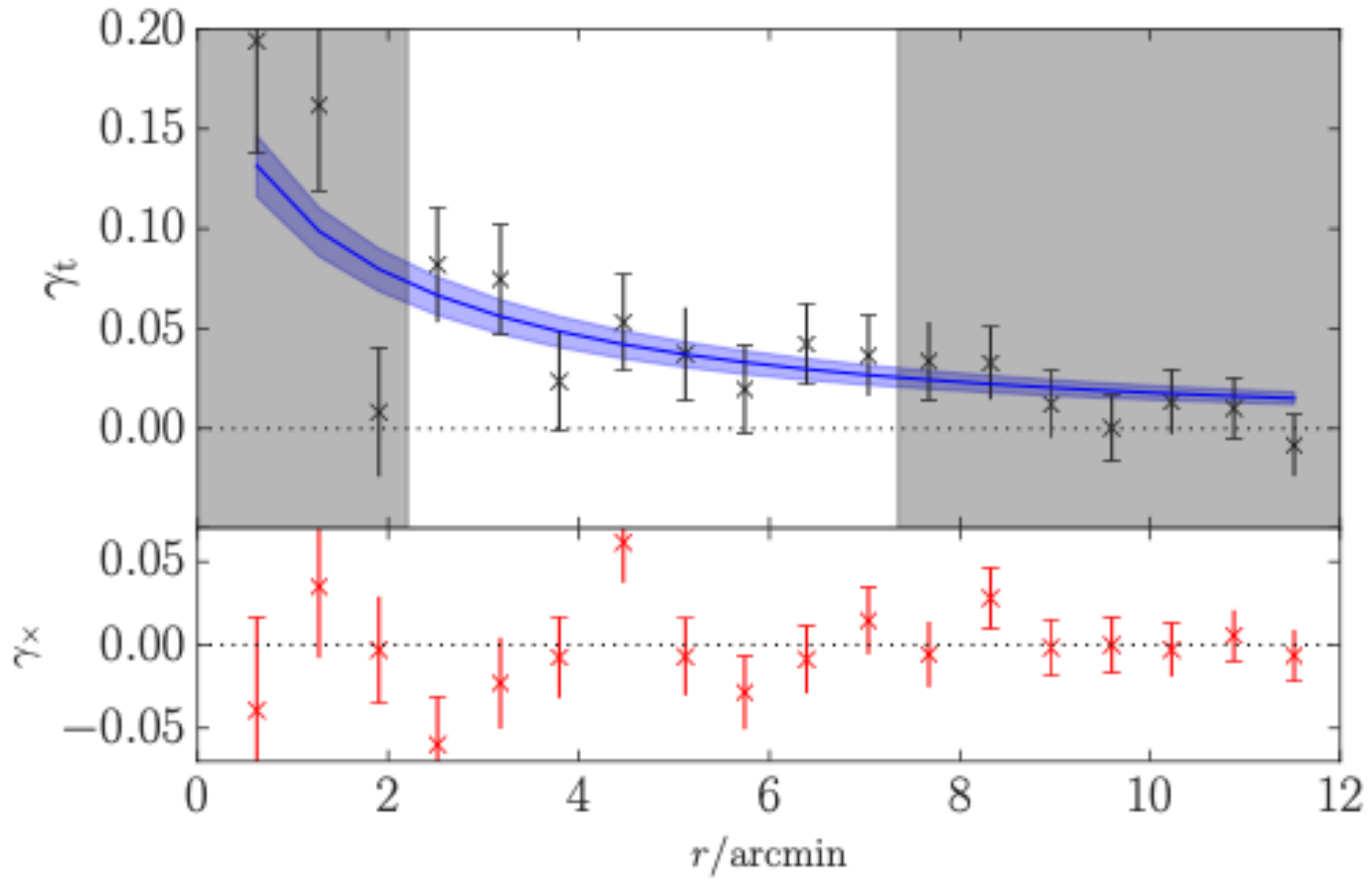
Weak Gravitational Lensing by Massive Halos

- Red: SZ effect
- Yellow: lensing



(a) Surface mass density of SPT-CL J0254−5857.

Example SPT cluster with Megacam lensing (Dietrich, Bocquet et al. 2019)



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

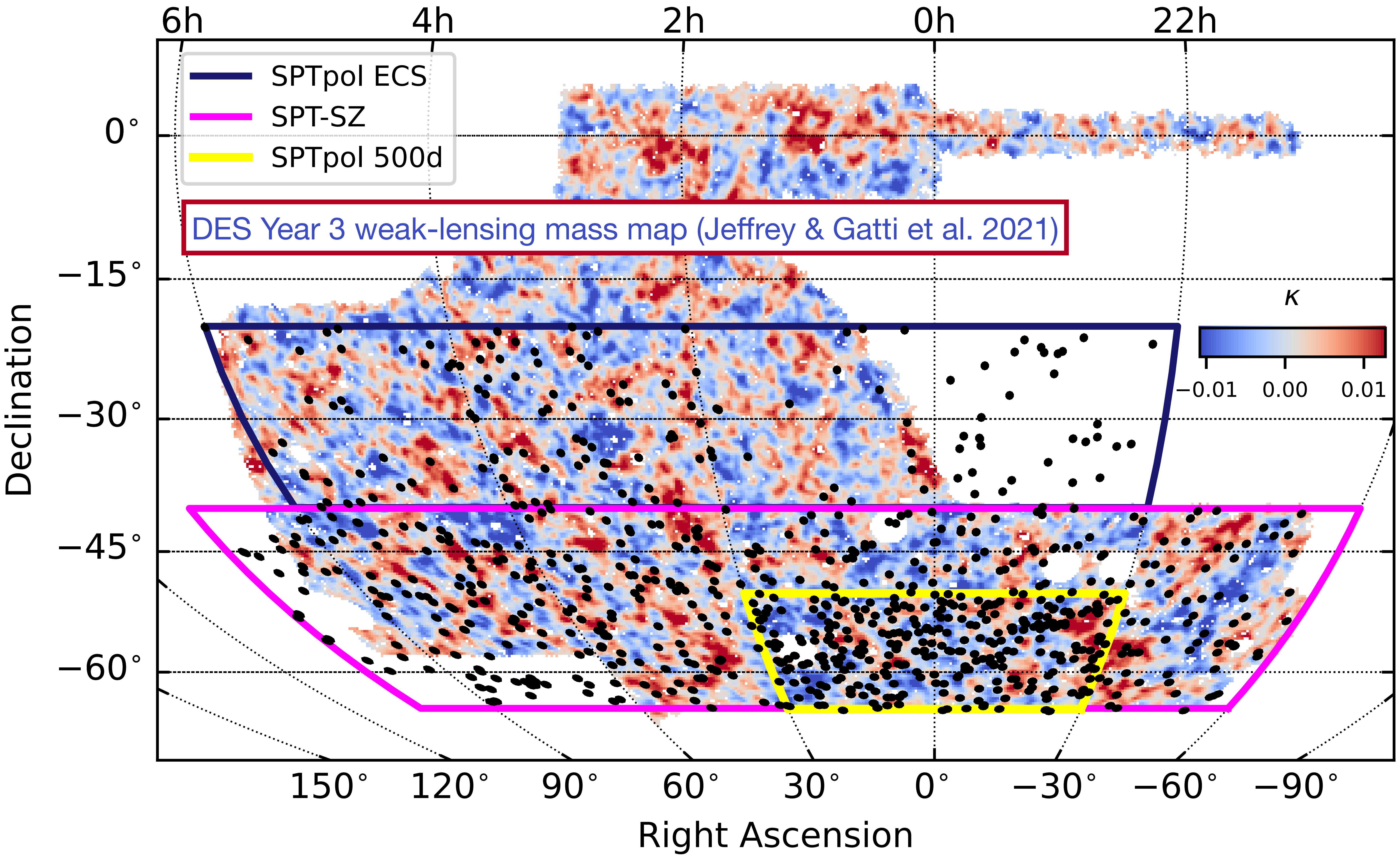
Now let's use a big lensing dataset!

5,200 deg² (13% of full sky) SPT Cluster Surveys

3,600 deg² overlap with Dark Energy Survey

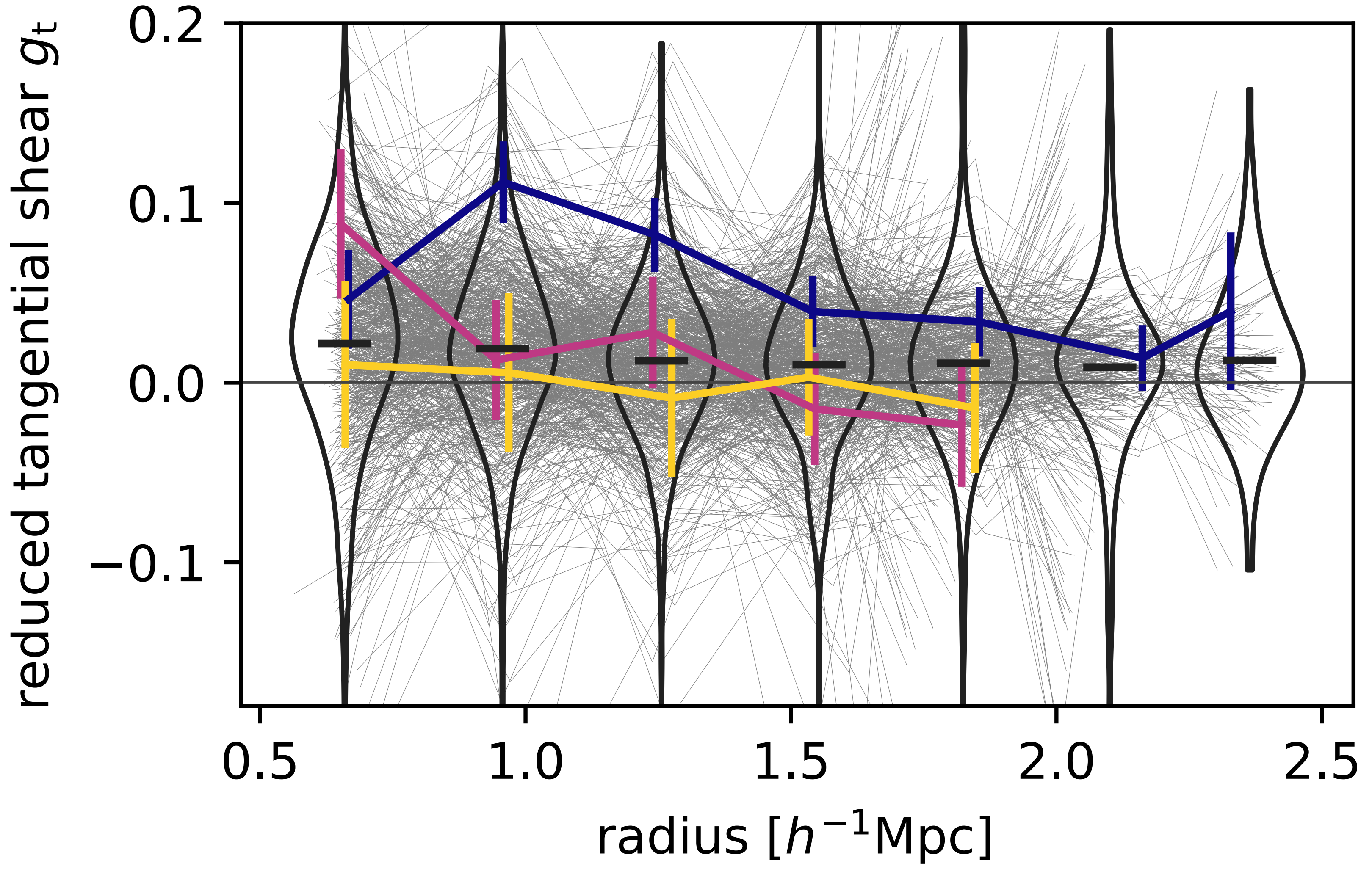
CTIO Blanco Telescope

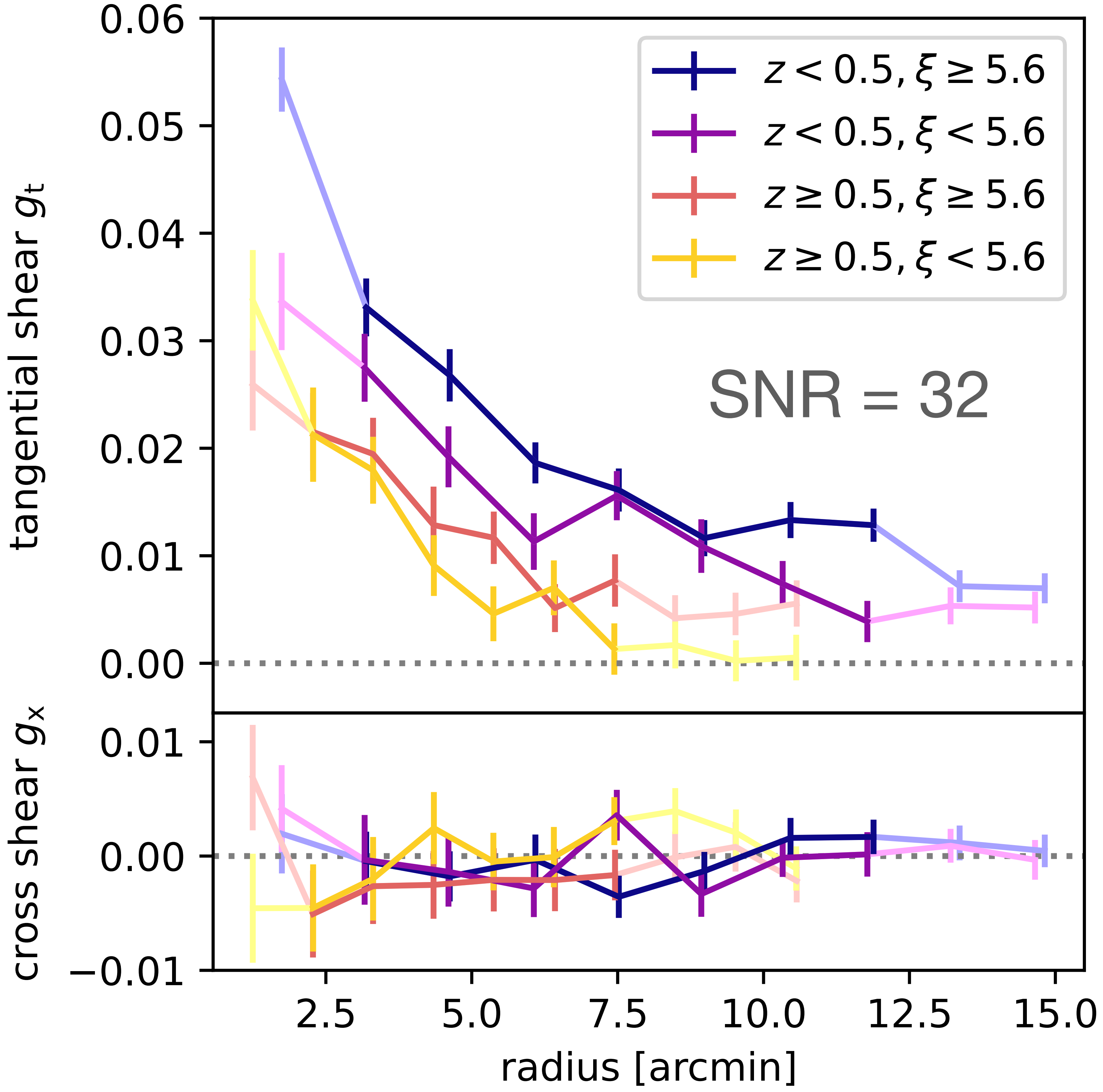
by Jessie Muir
https://www.jessiemuir.com/2019-09-03-markerblanco/



Cluster lensing analysis
Shear profiles

- 688 SPT clusters with DES Y3 shear
  (Bocquet et al. 2024a)
  - Analysis uses individual cluster shear profiles
  - Stacked for visualization purposes
  - For the experts: Same source selection as in DES Y3 3x2pt
    - Same photo-*z* and shear calibrations
- 39 high-redshift clusters with HST lensing
  (Schrabback et al. 2018; Schrabback, Bocquet et al. 2021; Zohren, Schrabback, Bocquet et al. 2022)





Bocquet et al. (2024a)

Cluster Lensing Model

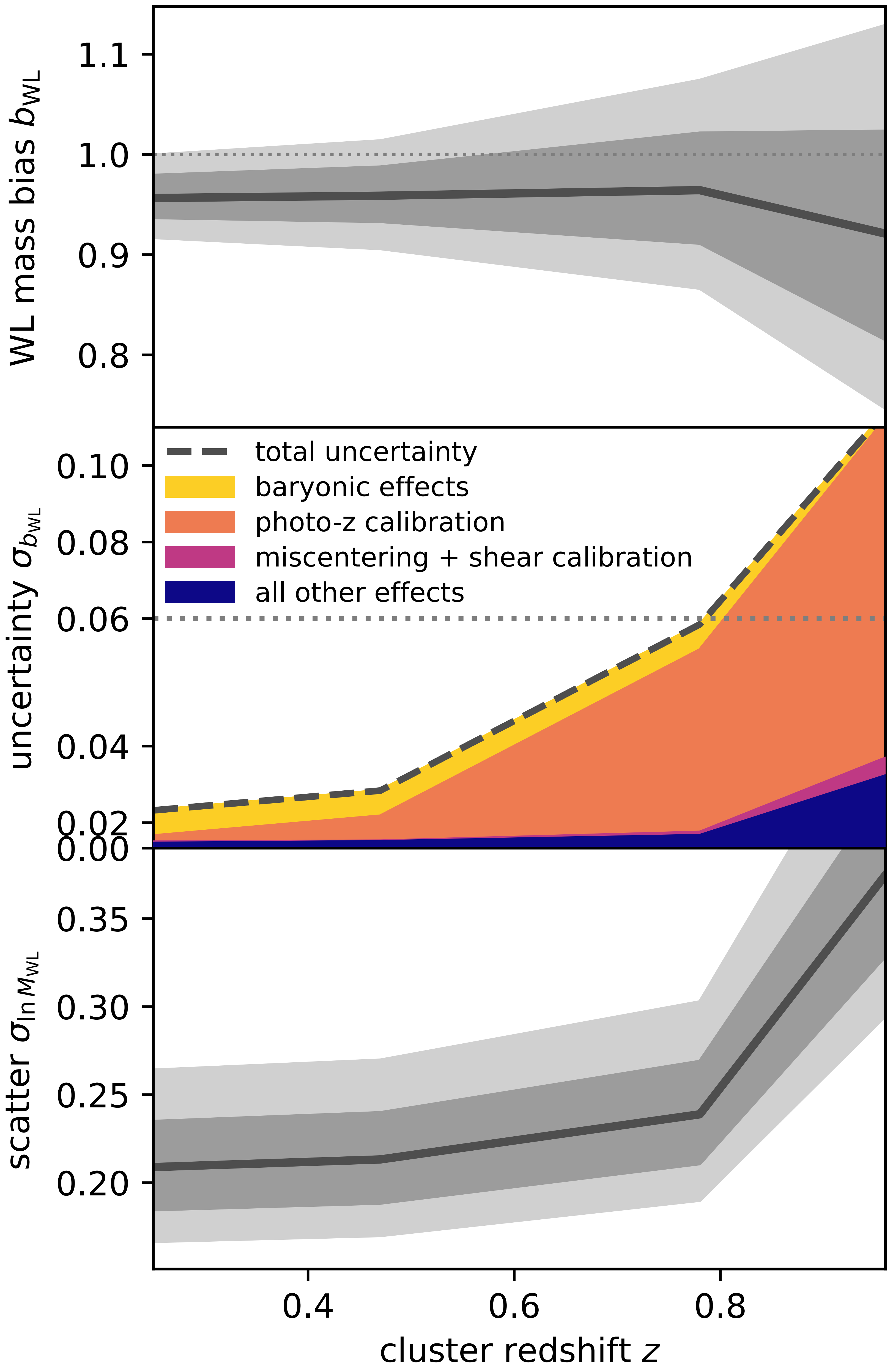
Grandis, Bocquet et al. (2021)

- Radial range: $0.5 < r\ [h^{-1}\mathrm{Mpc}] < 3.2\ /\ (1 + z)$
  (avoid cluster centers and stay in 1-halo term regime)

- Simple model based on modified Navarro-Frenk-White profile

- Incorporation of all biases and stochastic and systematic uncertainties in cluster lensing measurements
  - ✓ Model mismatch (real cluster not pure NFW)
  - ✓ photo-z and shear bias and uncertainty
  - ✓ Miscentering
  - ✓ Cluster member contamination
  - ✓ Baryonic effects (~2% impact on mass)

- < 10 % overall systematic uncertainty



Likelihood Function I

Let us generate a cluster dataset!

cosmological

halo mass function

astrophysical

observable–mass relation

observational

telescope, detector, atmosphere, etc.

$$\frac{d^2N(\boldsymbol{p})}{dM\,dz}\,\frac{d^2V(z,\boldsymbol{p})}{dz\,d\Omega_\mathrm{s}} \xrightarrow{\text{Poisson draw}} \{M,z\} \xrightarrow{\text{OMR + scatter}} \{\zeta,\lambda,M_\mathrm{WL},z\} \xrightarrow{\text{measurement noise}} \{\xi,\lambda,\boldsymbol{g}_\mathrm{t},z\}$$

Differential multi-observable cluster abundance

$$\boxed{\frac{d^4N(\boldsymbol{p})}{d\xi\,d\lambda\,d\boldsymbol{g}_\mathrm{t}\,dz}} = \boxed{\int\ldots\int dM\,d\zeta\,d\tilde{\lambda}\,dM_\mathrm{WL}}\,d\Omega_\mathrm{s}\,\boxed{P(\xi\,|\,\zeta)P(\lambda\,|\,\tilde{\lambda})P(\boldsymbol{g}_\mathrm{t}\,|\,M_\mathrm{WL})}\,\boxed{P(\zeta,\lambda,M_\mathrm{WL}\,|\,M,z,\boldsymbol{p})}\,\boxed{\frac{d^2N(\boldsymbol{p})}{dM\,dV}\,\frac{d^2V(z,\boldsymbol{p})}{dz\,d\Omega_\mathrm{s}}}$$

marginalize over

latent variables

Likelihood Function II

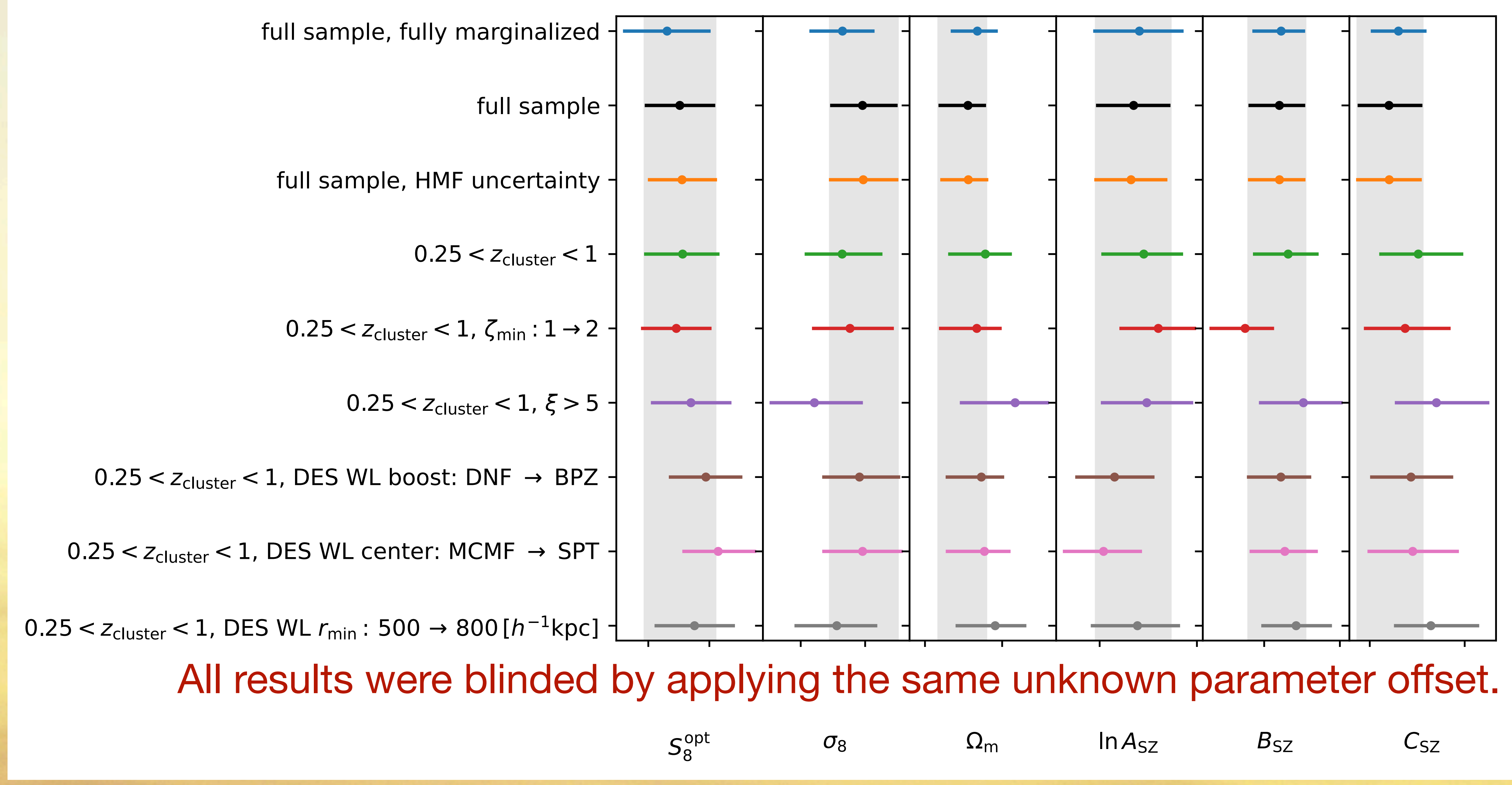
Poisson likelihood function: $\mathscr{L}(k\,\textbf{events}\,|\,\textbf{rate}\,\mu) \propto \mu^k e^{-\mu} \Rightarrow \ln\mathscr{L} = k\ln(\mu) - \mu$

Likelihood function

$$\ln\mathscr{L}(\boldsymbol{p}) = \sum_i \ln \boxed{\frac{d^4N(\boldsymbol{p})}{d\xi\, d\lambda\, d\boldsymbol{g}_\mathrm{t}\, dz}}\Bigg|_{\xi_i,\lambda_i,g_{\mathrm{t},i},z_i} - \int \ldots \int d\xi\, d\lambda\, d\boldsymbol{g}_\mathrm{t}\, dz \boxed{\frac{d^4N(\boldsymbol{p})}{d\xi\, d\lambda\, d\boldsymbol{g}_\mathrm{t}\, dz}} \Theta_\mathrm{s}(\xi,\lambda,z) + \mathrm{const}\,.$$

Differential multi-observable cluster abundance

$$\frac{d^4N(\boldsymbol{p})}{d\xi\, d\lambda\, d\boldsymbol{g}_\mathrm{t}\, dz} = \int \ldots \int dM\, d\zeta\, d\tilde{\lambda}\, dM_\mathrm{WL}\, d\Omega_\mathrm{s}\, P(\xi\,|\,\zeta) P(\lambda\,|\,\tilde{\lambda}) P(\boldsymbol{g}_\mathrm{t}\,|\,M_\mathrm{WL}) P(\zeta,\lambda,M_\mathrm{WL}\,|\,M,z,\boldsymbol{p}) \frac{d^2N(\boldsymbol{p})}{dM\, dV} \frac{d^2V(z,\boldsymbol{p})}{dz\, d\Omega_\mathrm{s}}$$



All results were blinded by applying the same unknown parameter offset.

Pipeline verification using mock catalogs

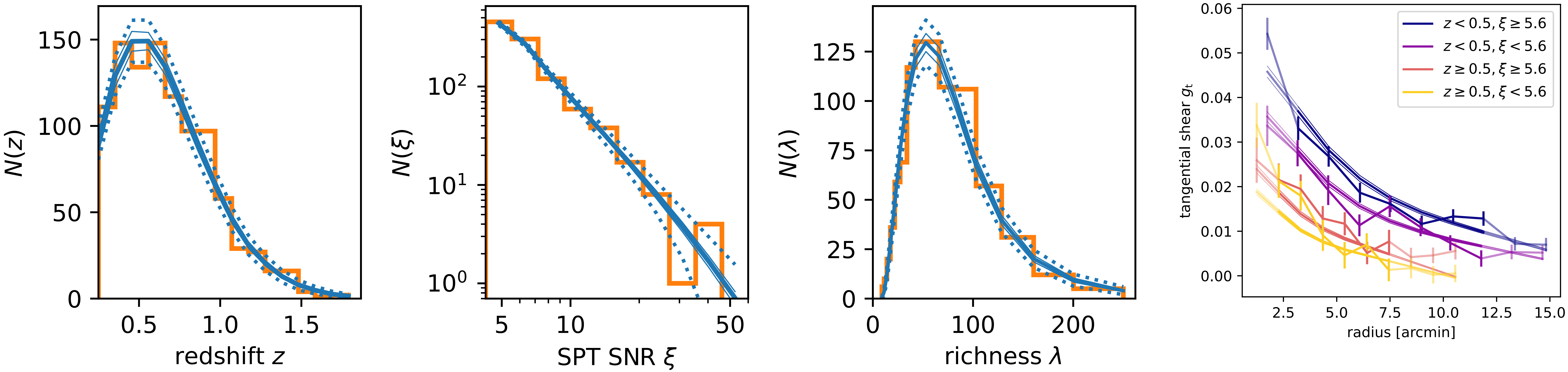
Blind analysis: Check our biggest worries blindly

No changes after unblinding!

Does the model describe the data?

Binned and stacked data for visualization

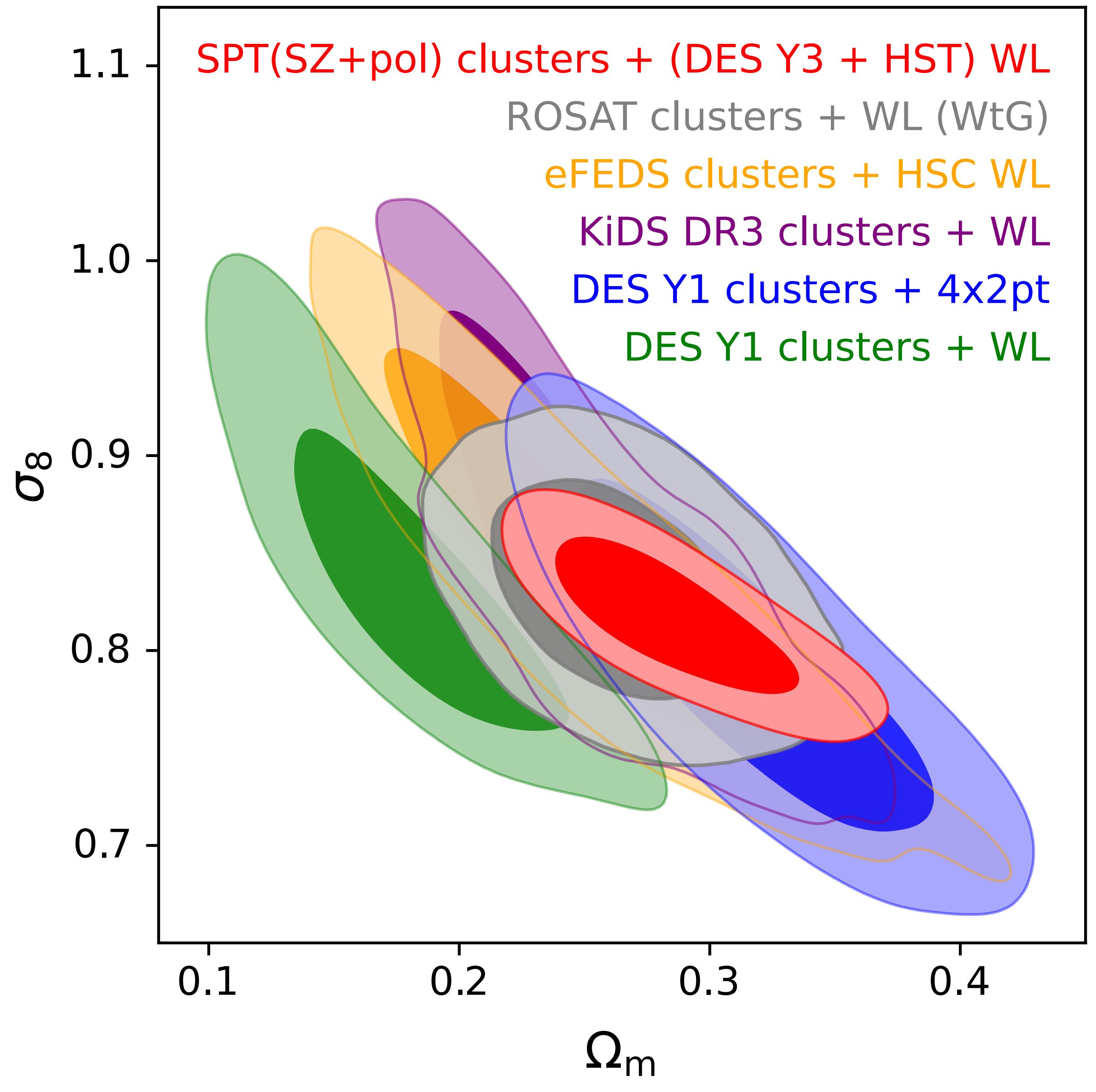
Bocquet et al. (2024b)

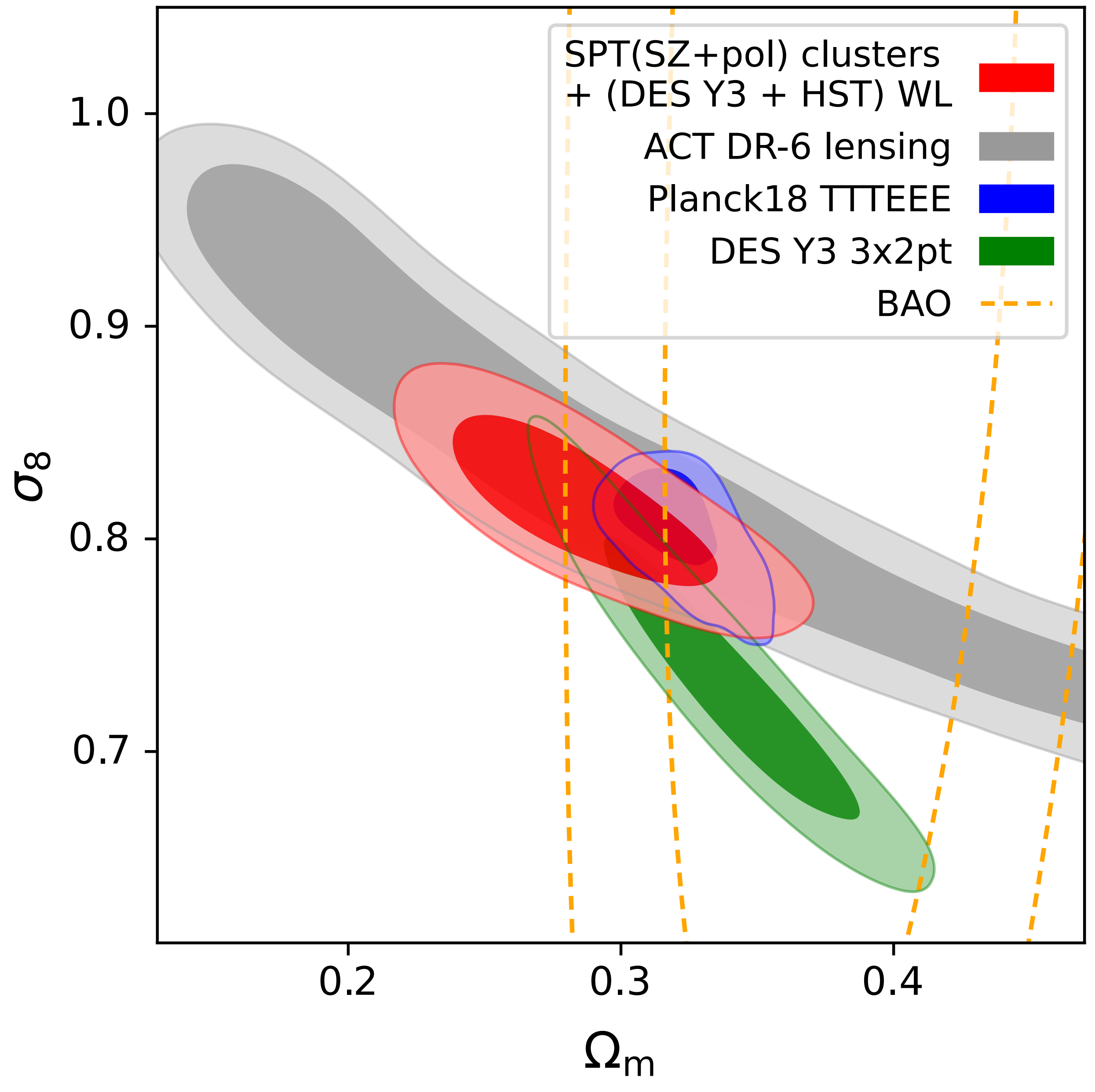


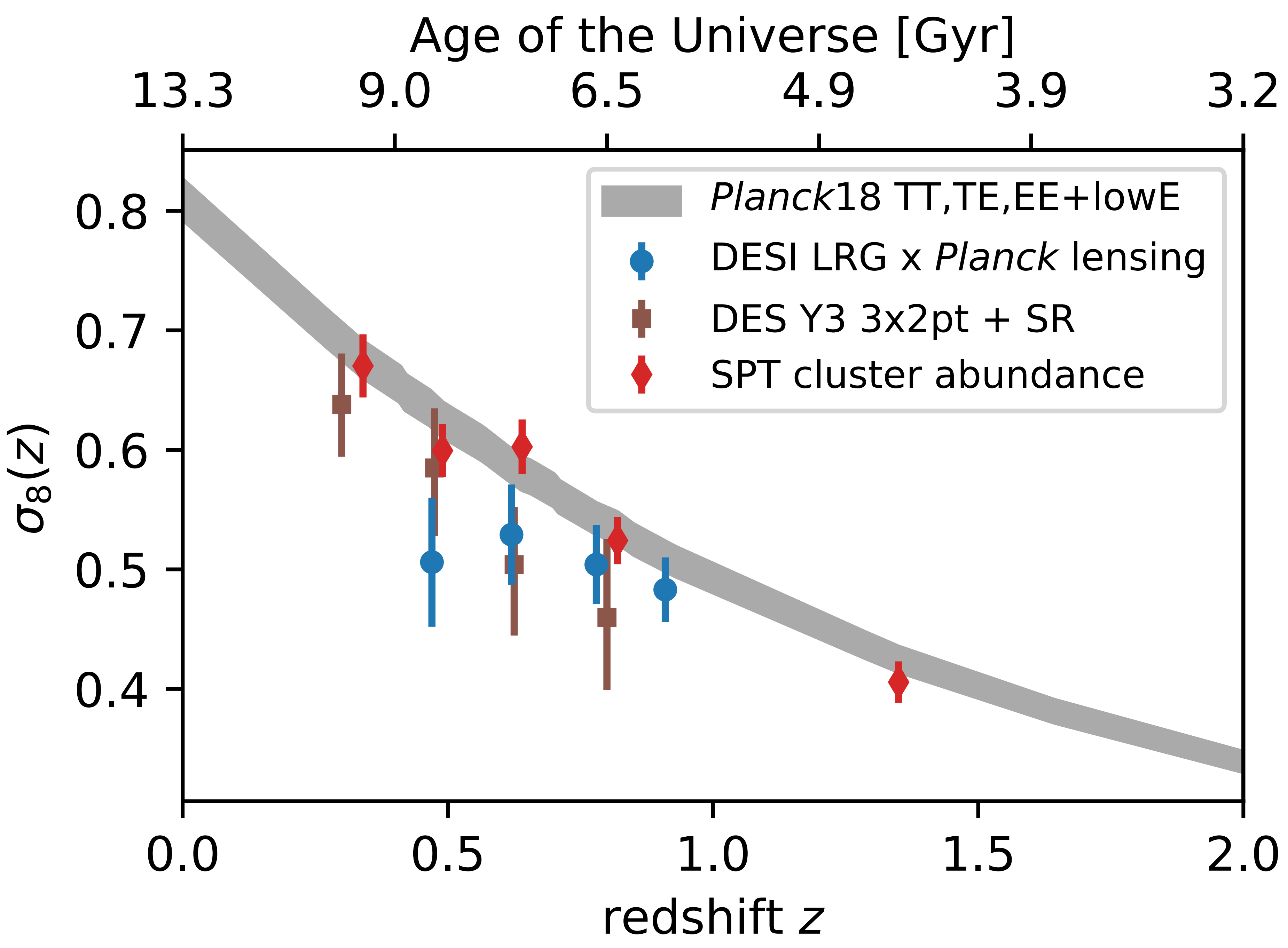
Mean recovered model (and uncertainties) from full analysis.
No significant signs of problems.

SPT clusters: ΛCDM with massive neutrinos

Bocquet et al. (2024b)





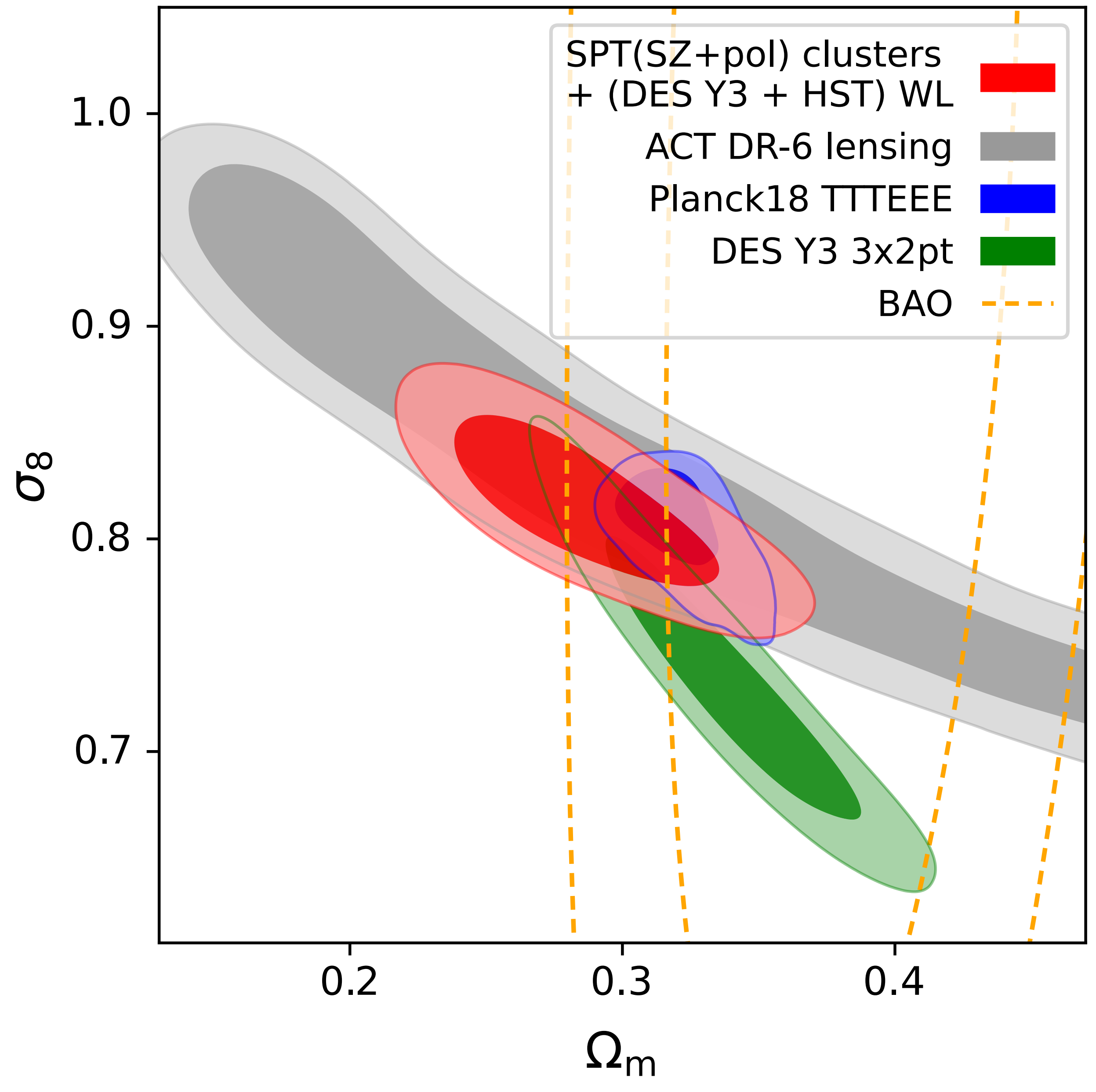


Competitive constraints, especially on $S_8^{\rm opt} \equiv \sigma_8 \left(\Omega_{\rm m}/0.3\right)^{0.25}$

No evidence for S_8 tension with *Planck* (1.1 σ)

See Esra Bulbul's talk for comparison with eROSITA eRASS1 (after coffee break)

SPT clusters: Where does the information come from?



$$\frac{dN}{d\mathrm{obs}} = \int dM\, P(\mathrm{obs}\,|\,M)\,\frac{dN}{dM}$$

Halo mass function d$N(z)$/dM from numerical simulations (Tinker et al. 2008)
Clear path forward with emulators.

Observable–mass relations

SZ-to-mass modeled as power law with unknown parameters
(amplitude, mass trend, redshift evolution)
and unknown lognormal scatter

Lensing-to-mass from numerical simulations, only small corrections due to uncertain baryonic effects

~~Assumption about hydrostatic equilibrium~~
Empirical lensing-based mass calibration absorbs all first-order biases in the SZ–mass relation

Baryons
"Someone should worry about the impact of baryons on cluster abundance cosmology" (M. Schaller, yesterday)
→ We did. We link the observables to the "gravity-only" halo mass and we include the baryon-induced uncertainties in the weak-lensing-to-mass model.
In other words, we solve the "baryon impact on halo mass function" problem by accounting for the baryon impact on lensing measurements, which is where we get the mass information from.

Selection Function of Clusters in Dark Energy Survey Year 3 Data

from Cross-Matching with South Pole Telescope Detections (Grandis et al. 2021, 2025)

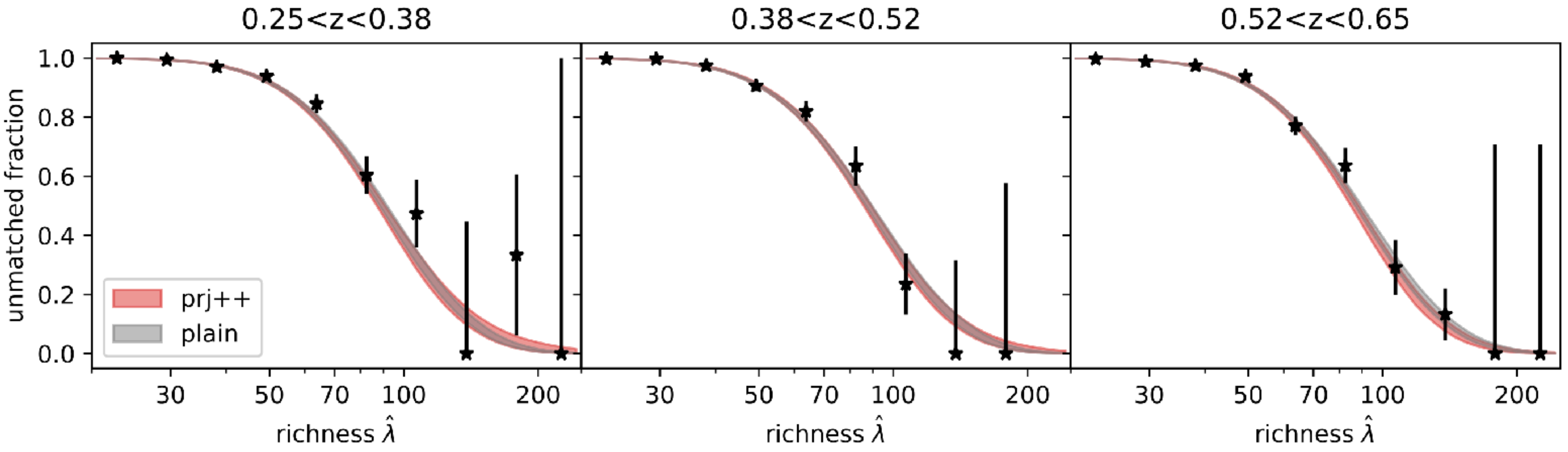


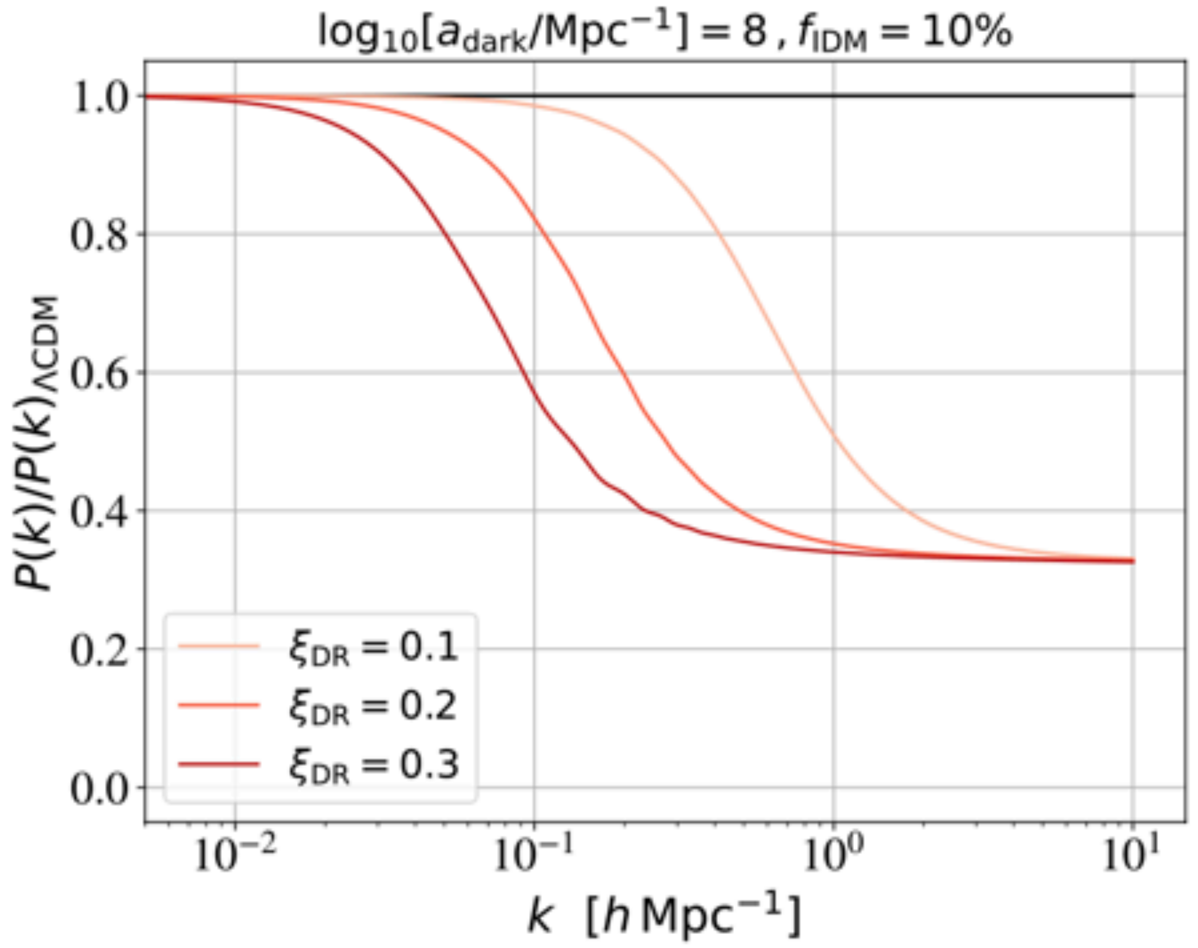
Fig. 8. Unmatched fraction of `redMaPPer` objects as a function of redshift bins. As black points, we show the empirical estimate for the fraction of `redMaPPer` objects not detected by SPT in redshift panels (columns) and richness bins. We show the posterior predictive distribution of the fraction of unmatched objects in the best-fit model ('prj++', red), and the worst-fitting model ("plain", grey). The filled area encompasses the 16th and 84th percentile.

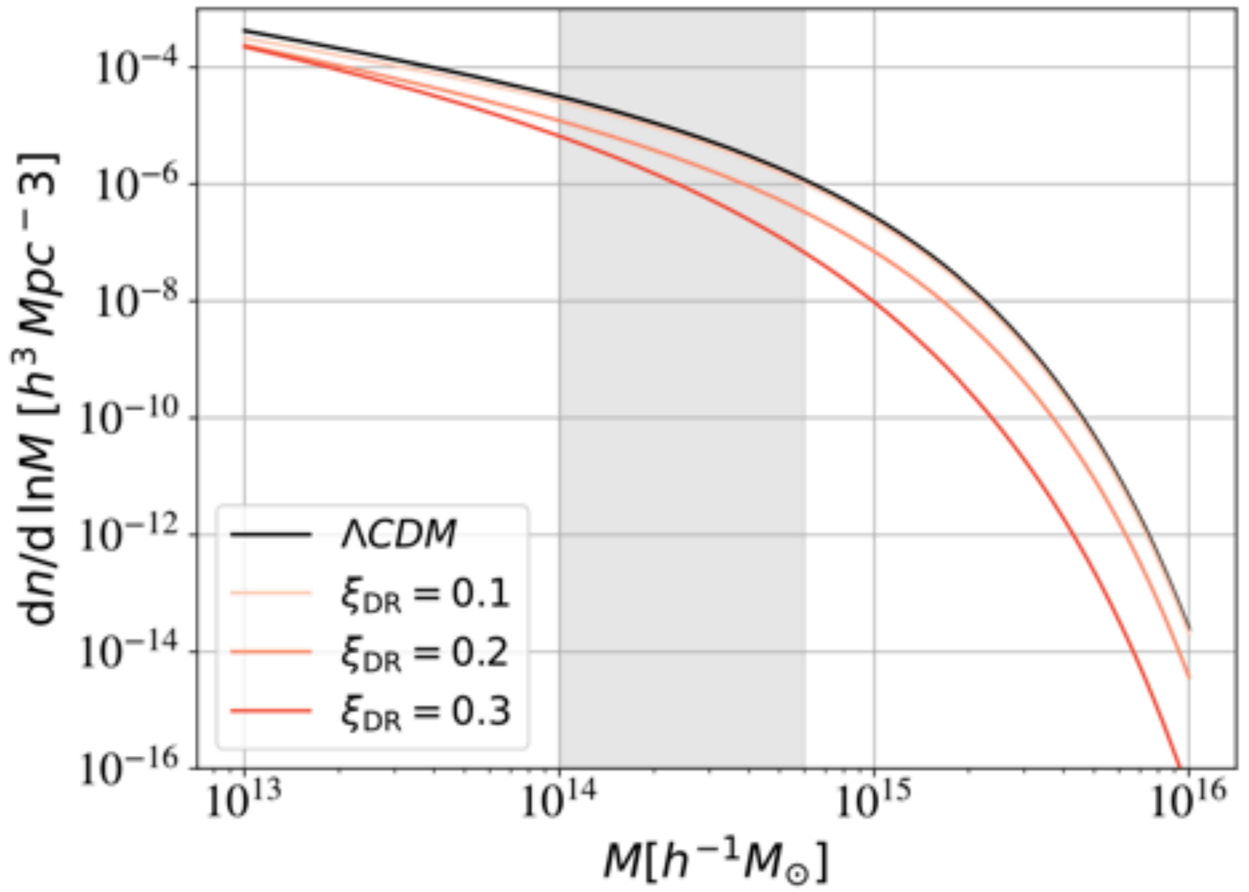
Beyond the standard model
Interacting dark matter dark radiation model

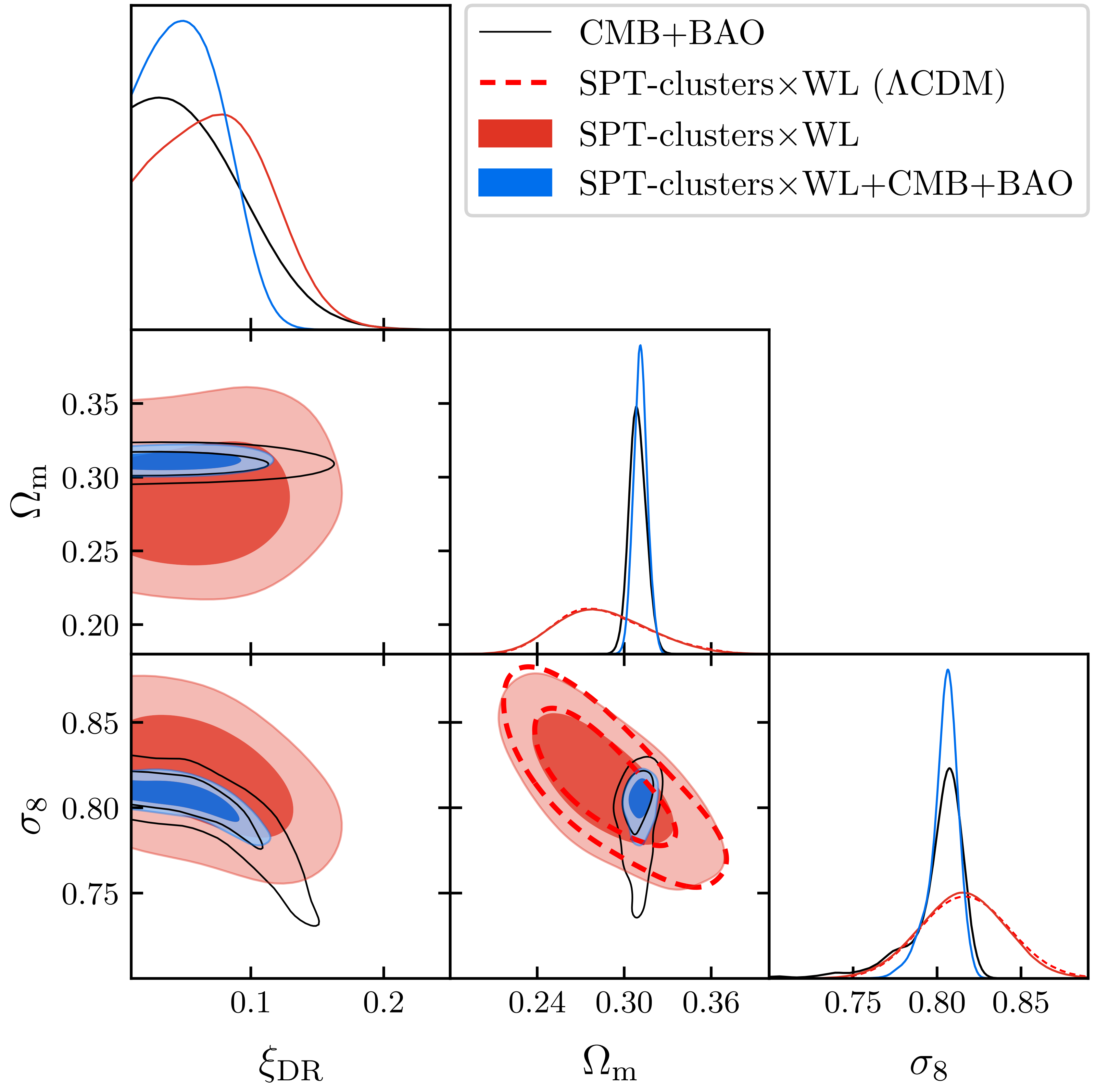
ξ_{DR} temperature ratio dark radiation / CMB

Asmaa Mazoun

Mazoun, Bocquet, Garny, Mohr, Rubira, Vogt (2024)
Mazoun, Bocquet, Mohr, Garny, Rubira et al. [SPT and DES] (2025)







Beyond the standard model
Modified gravity

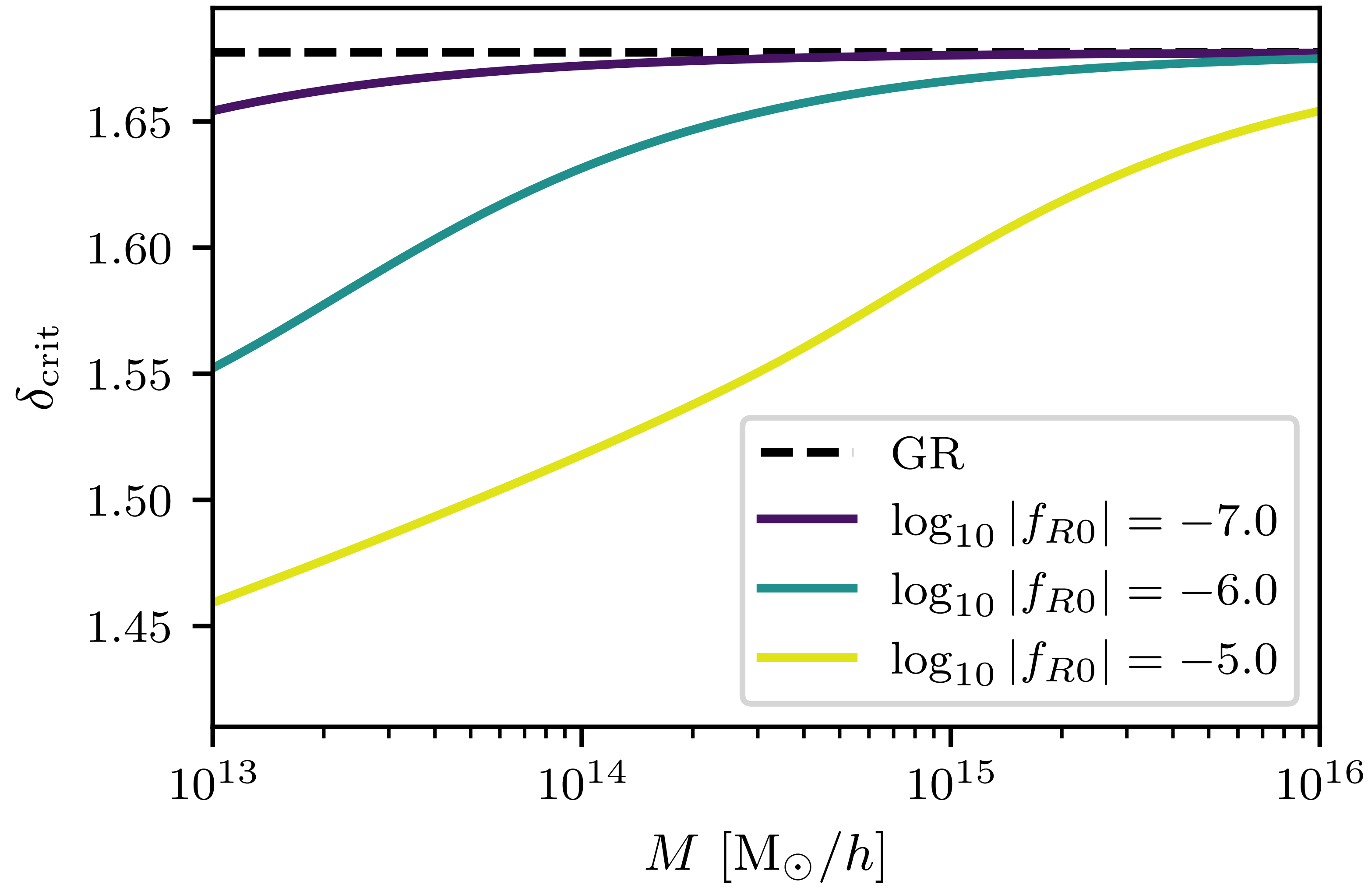
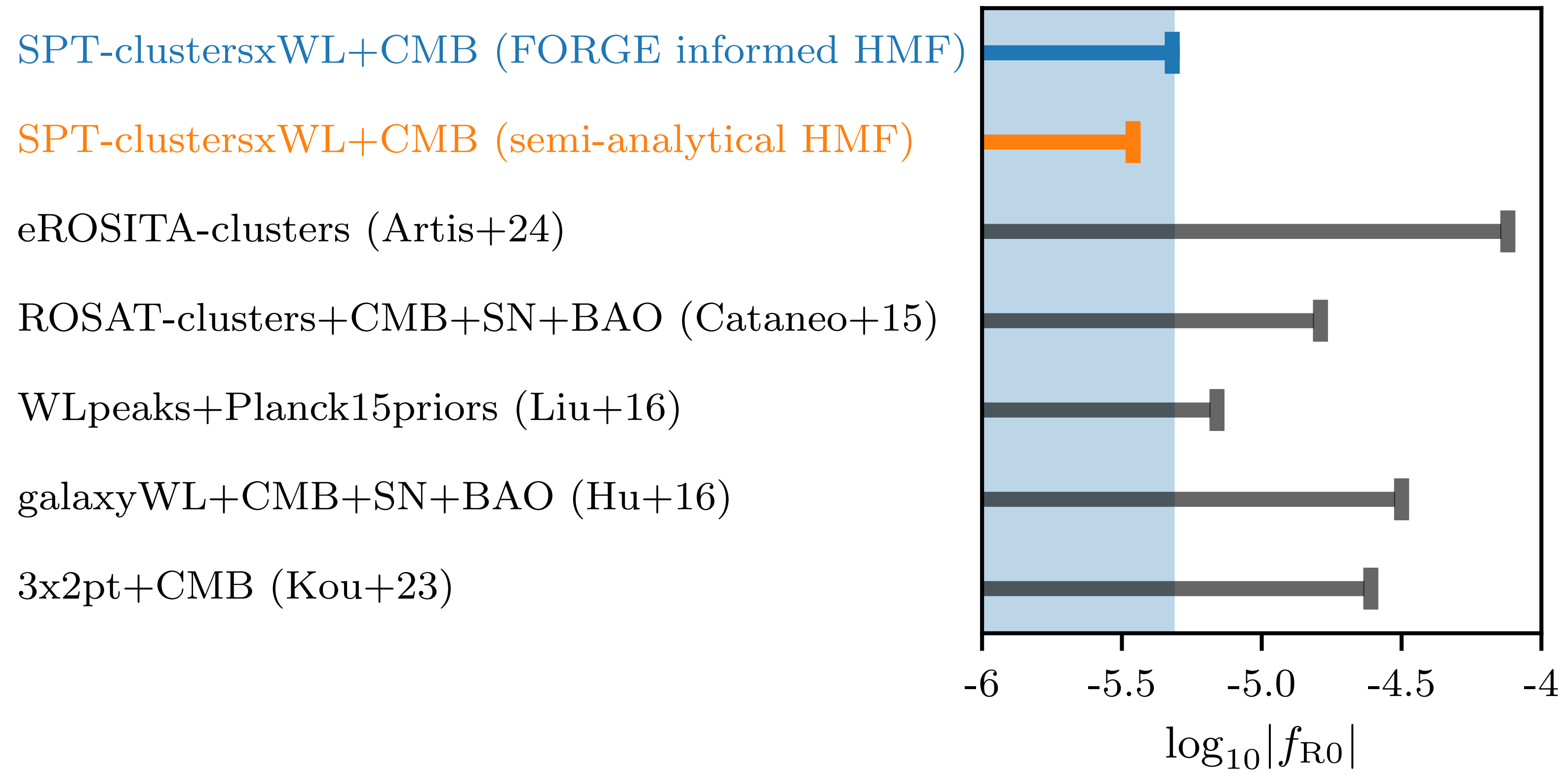


FIG. 1. The critical overdensity $\delta_{\rm crit}$ for spherical collapse in $f(R)$ gravity (Eq. (12)) for different values of $\log_{10}|f_{R0}|$ at collapse redshift $z_c = 0$ in colored solid lines. The dashed black line represents $\delta_{\rm crit}$ in a corresponding GR cosmology (Eq. (13)).

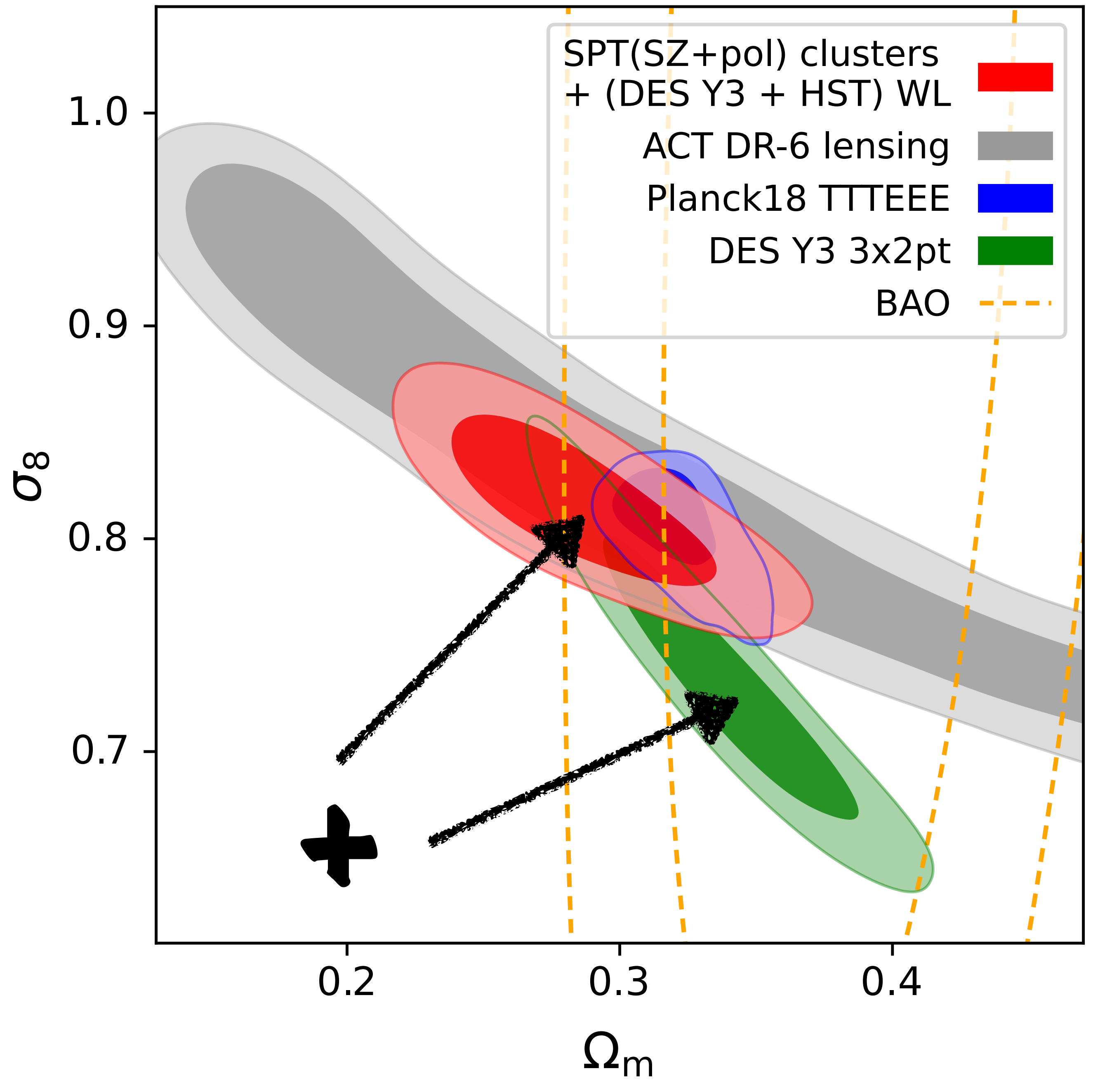
SPT clusters + DES cluster lensing



Sophie Vogt

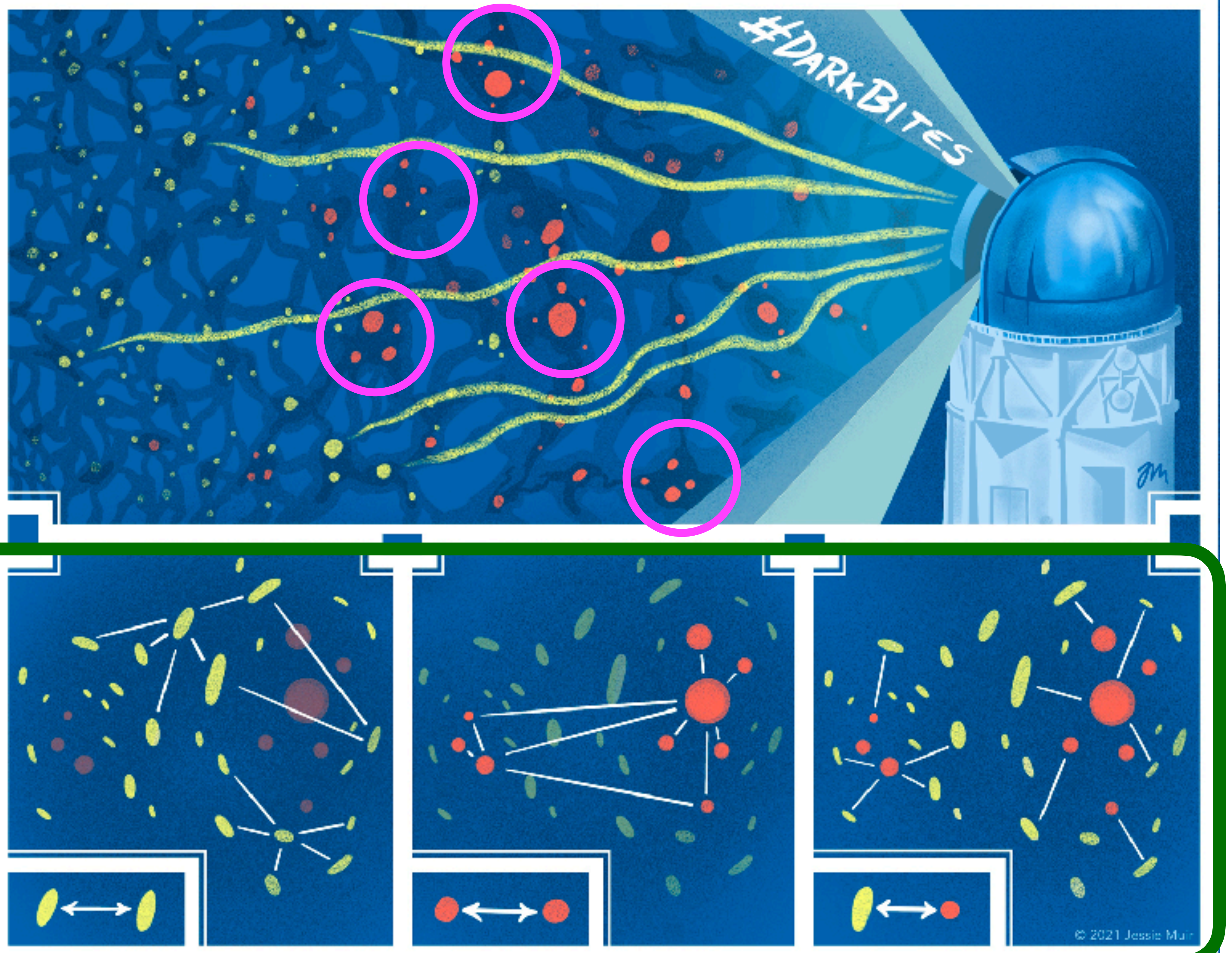
Vogt, Bocquet, Davies, Mohr, Schmidt (2024)
Vogt, Bocquet, Davies, Mohr, Schmidt, Ruan, Li et al. [SPT and DES] (2025)

nDGP analysis in progress!



Cosmology from the Large-Scale Structure

3x2pt and abundance of galaxy clusters

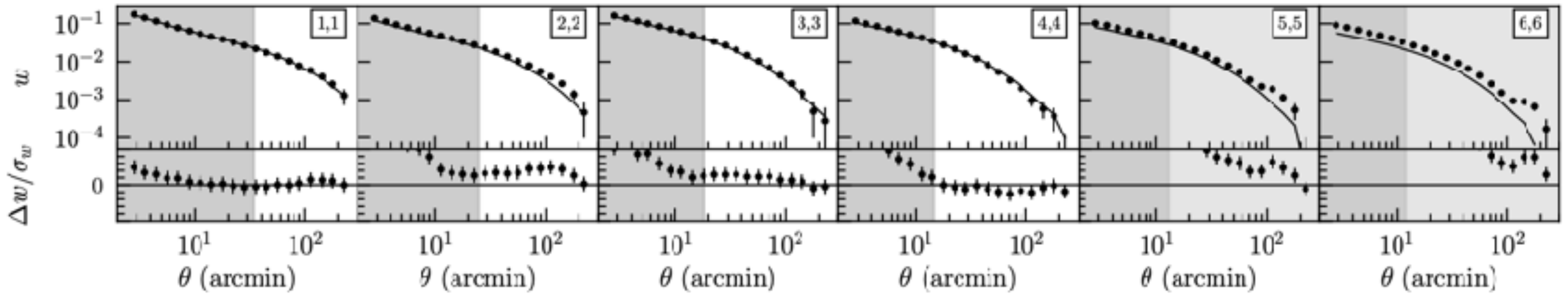


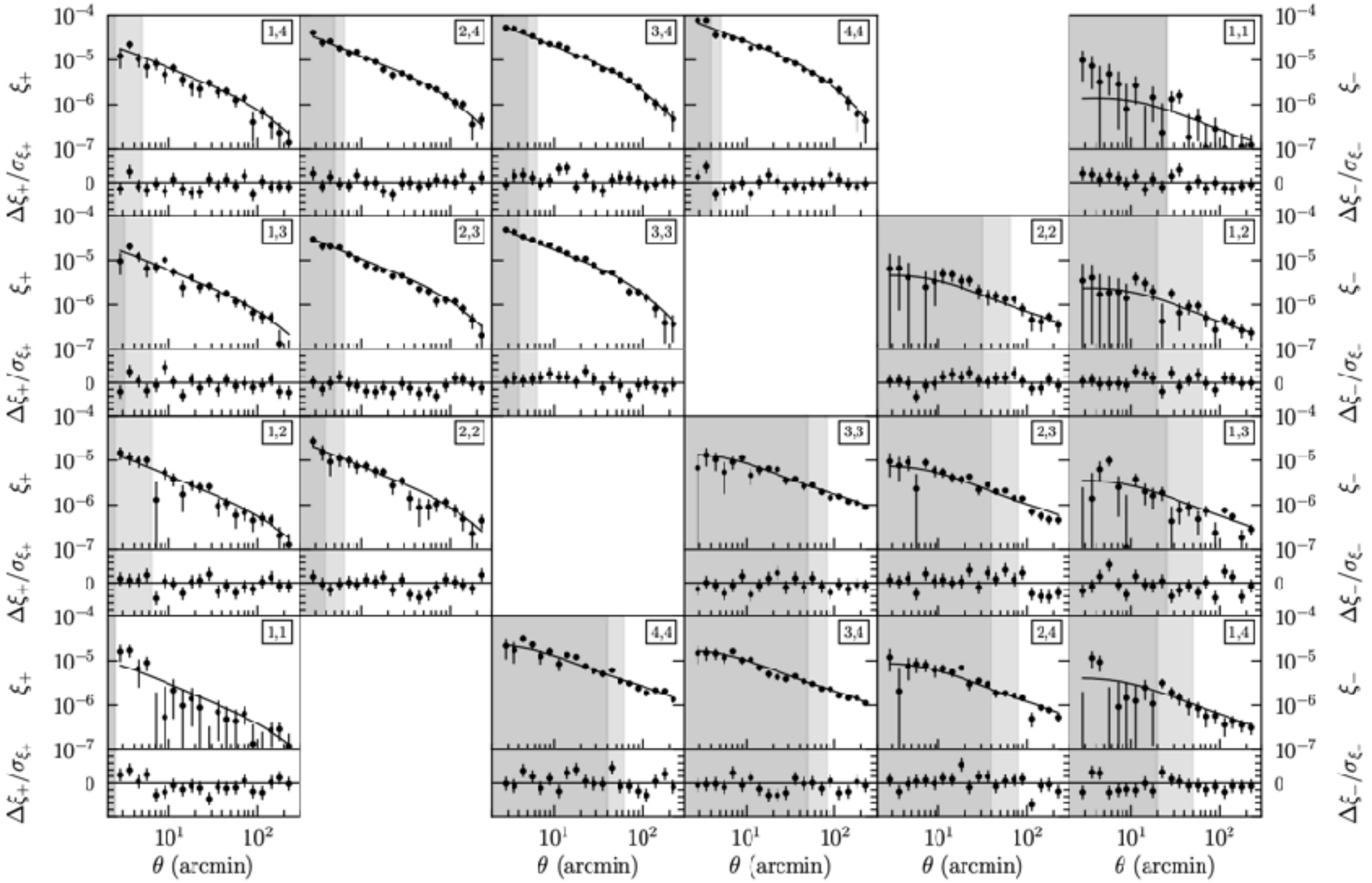
Three
two-point correlation
functions
–> 3x2pt

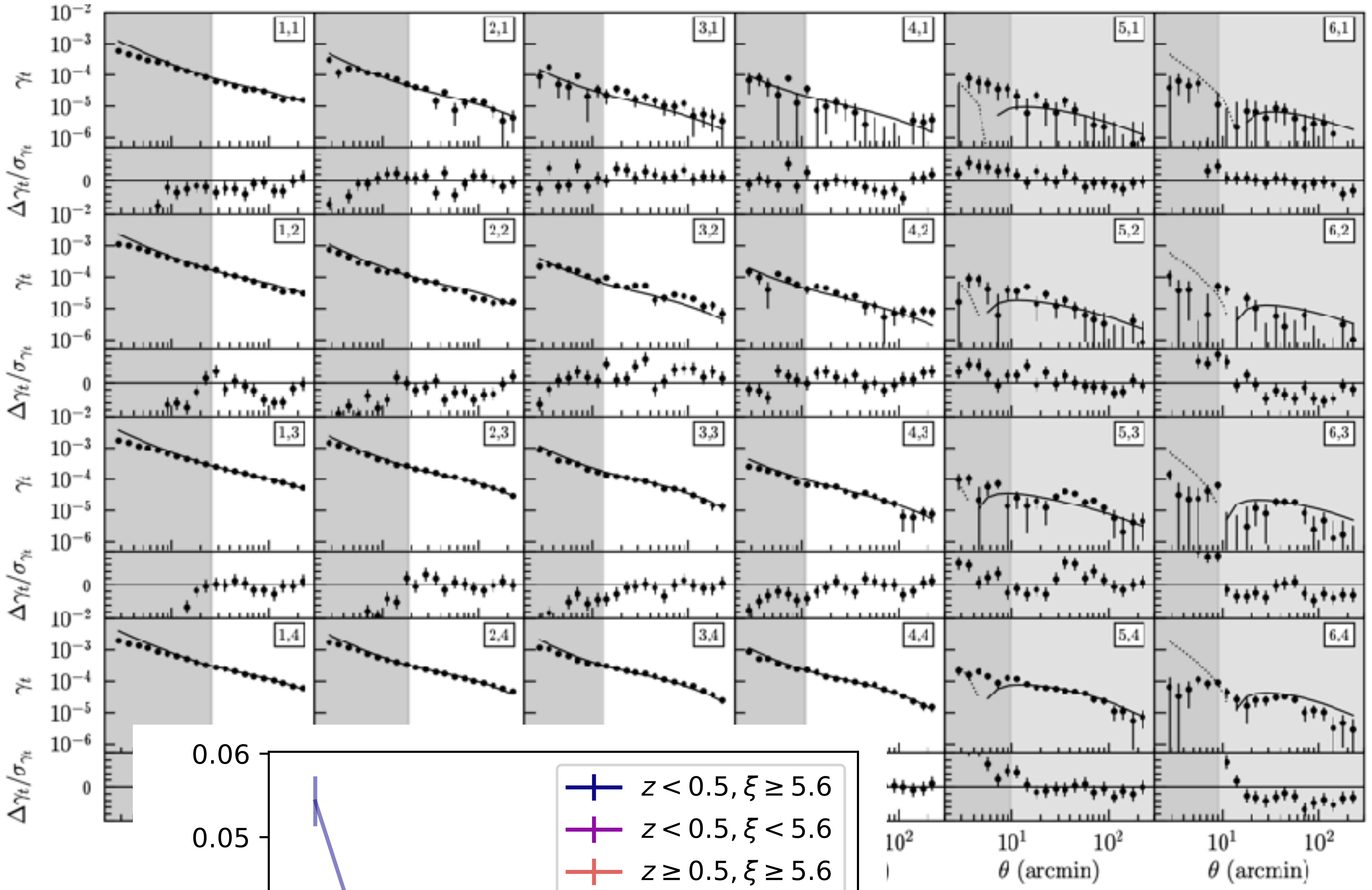
Abundance of
massive halos

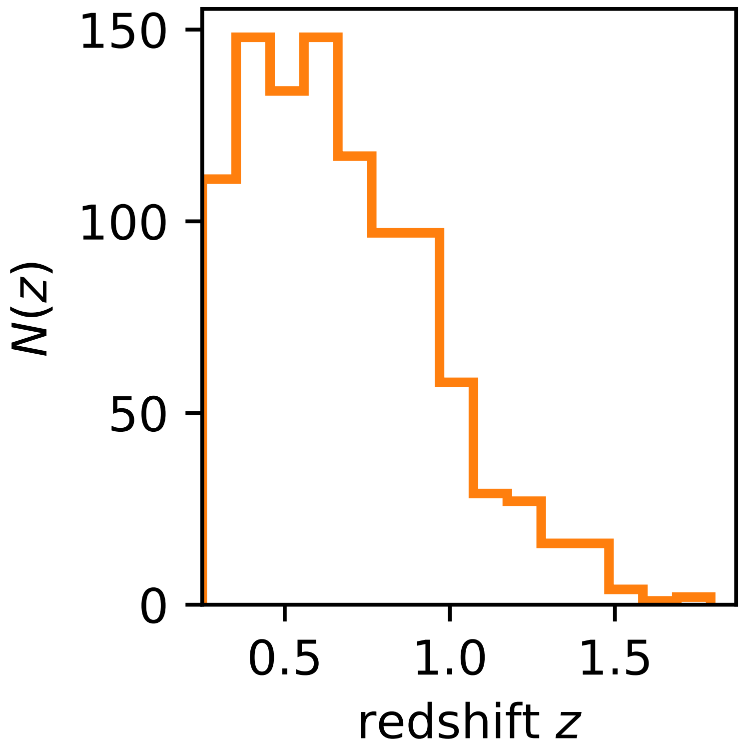
Credit: Jessie Muir (https://www.jessiemuir.com/)

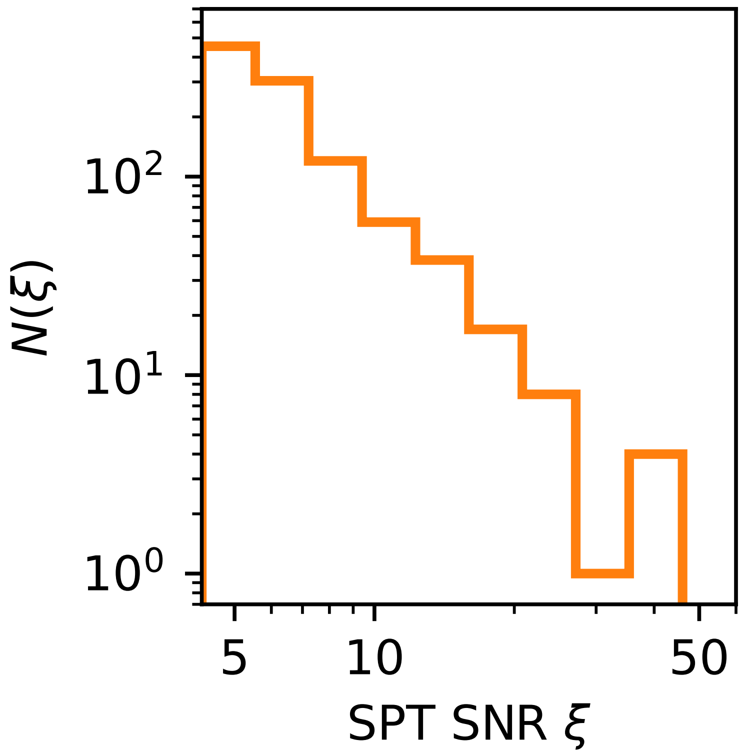
DES+SPT Dataset

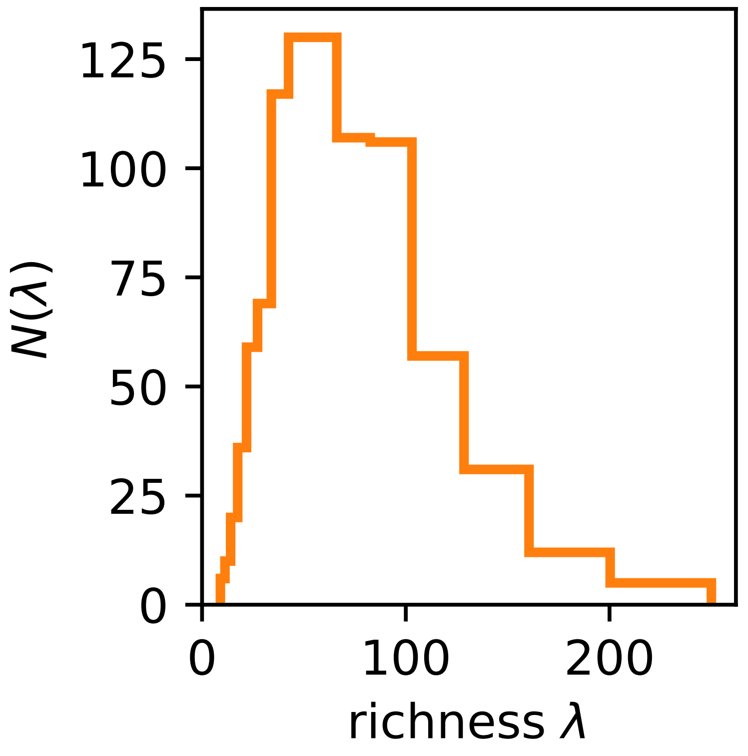


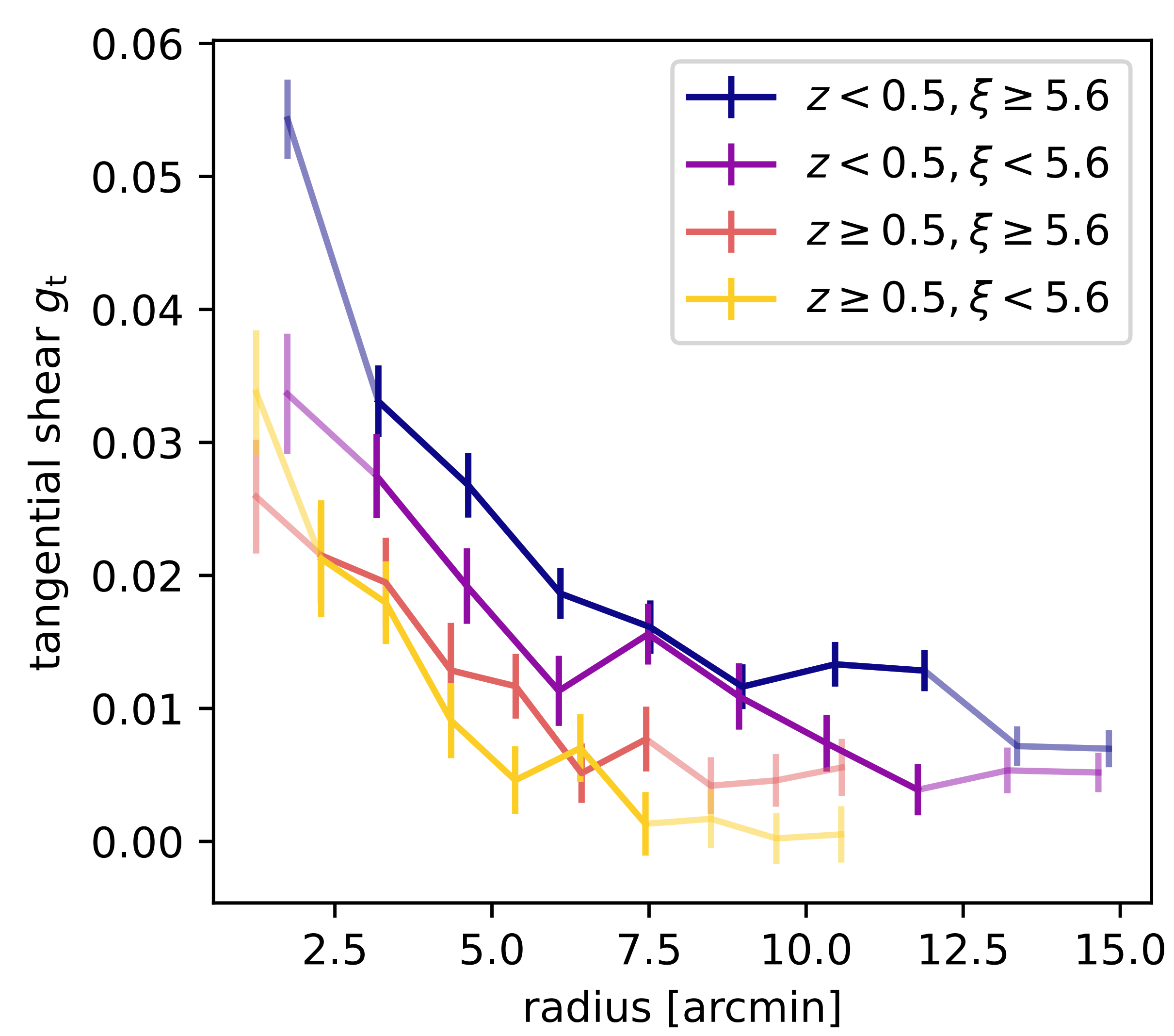




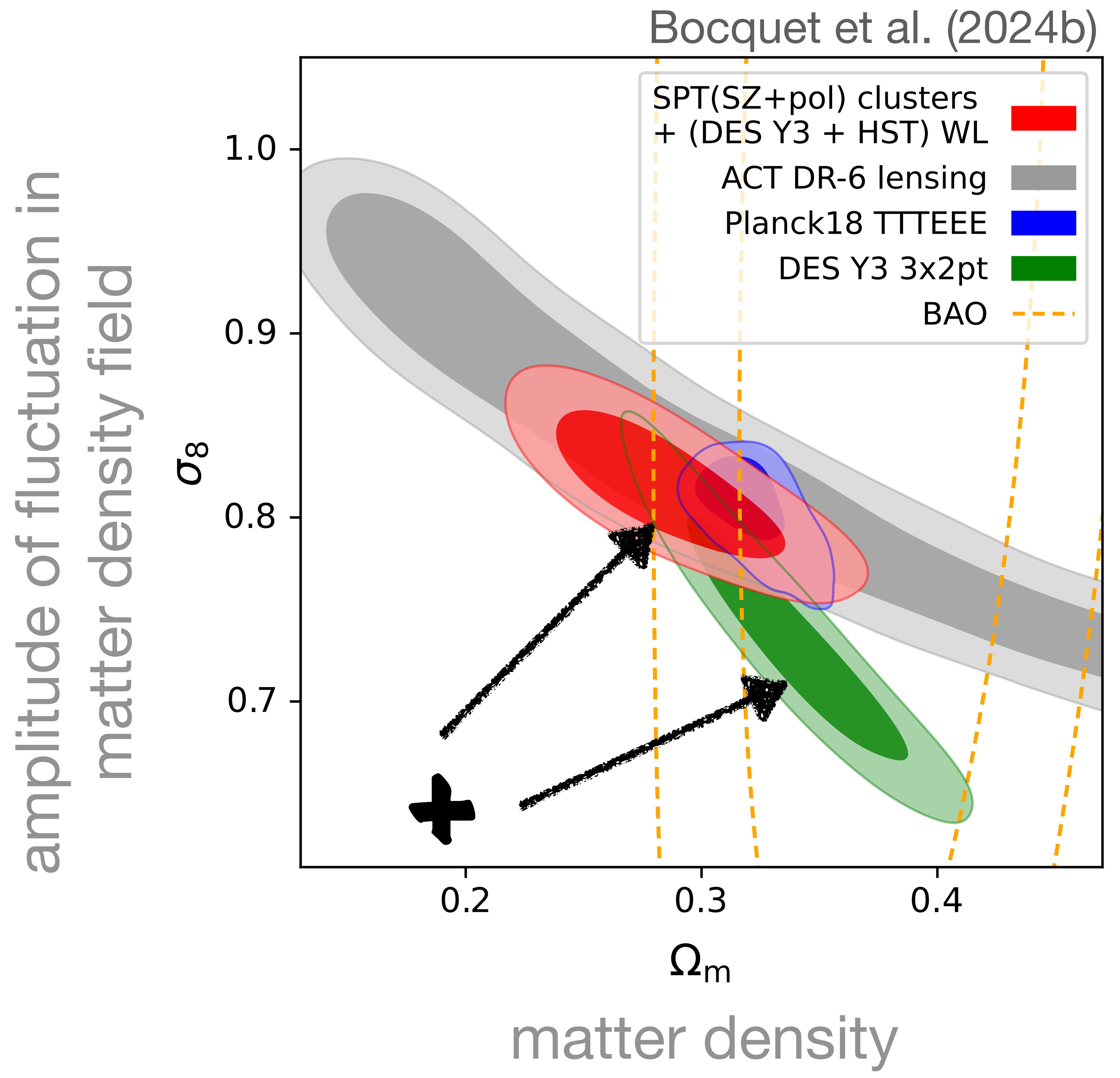








SPT Cluster Abundance + DES 3x2 pt = Multiprobe Cosmology



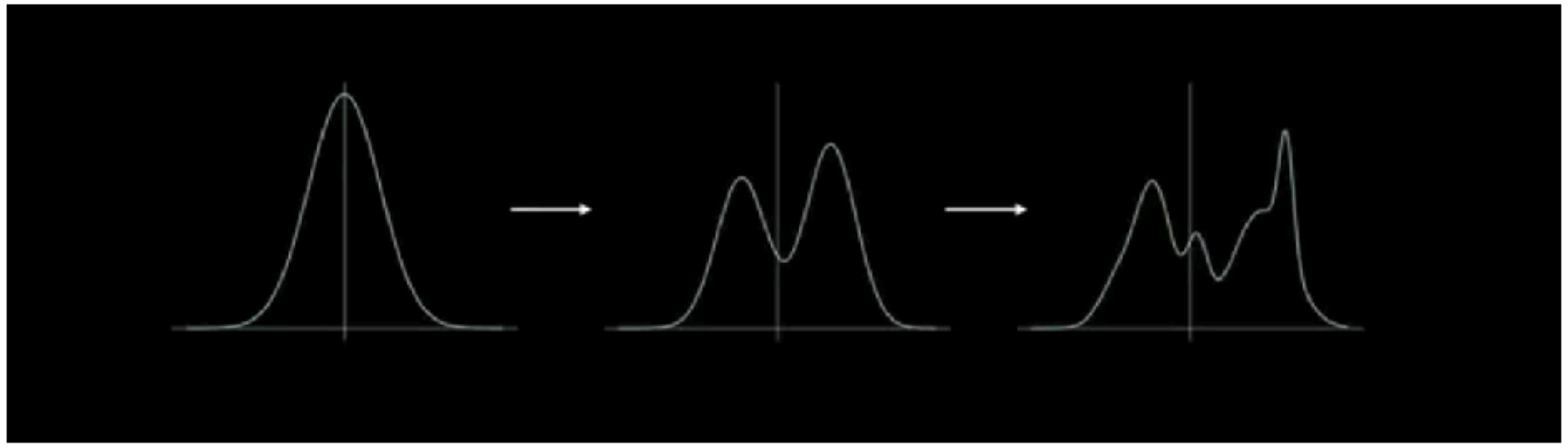
- Multiprobe analysis (w/ Chun-Hao To, Elisabeth Krause, Sebastian Grandis)
  - Cosmological covariance
    - SPT cluster abundance is dominated by shot noise
    - SPT cluster mass calibration limited by lensing shape noise
    - For simulated dataset, the difference in SNR between analysis with full covariance and independent analysis is 0.05%
    - Covariance is negligible! We can use the existing analysis pipelines.
  - Expect shared systematics such as calibration of DES lensing source photo-z

Parameter inference

Importance sampling using normalizing flows (FLOWJAX)

- 6 cosmology parameters
  + 29 3x2pt parameters
  + 23 cluster parameters
- Joint sampling really hard (curse of dimensionality)

  But: the analyses are almost independent!
- Learn the posteriors, so that one
  - Can draw large number of samples for one probe
  - Evaluate likelihood of other probe at that point quickly
- Use samples from fiducial DES Y3 3x2pt analysis
- Re-run SPTcluster analysis using the same cosmology priors as DES Y3 3x2pt

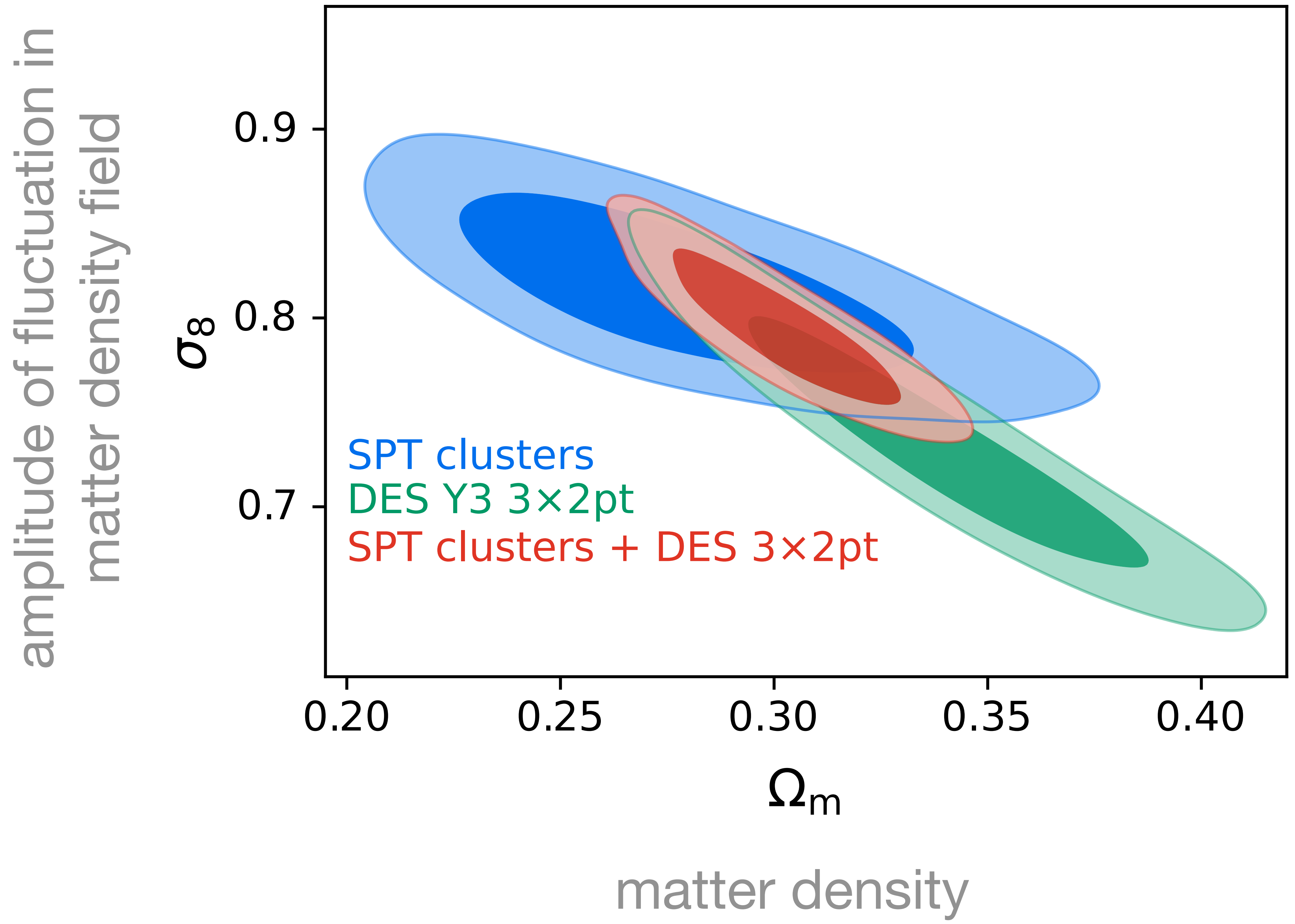


Transforming simple distribution to a complex one by a series of bijective and differentiable functions

ΛCDM with massive neutrinos

SPT clusters + DES 3x2pt

Bocquet et al. (2025)



Ratio of areas of 95% credible regions

SPT clusters : DES 3x2pt : joint analysis

3.3 : 2.1 : 1

$\Omega_m = 0.300 \pm 0.017$

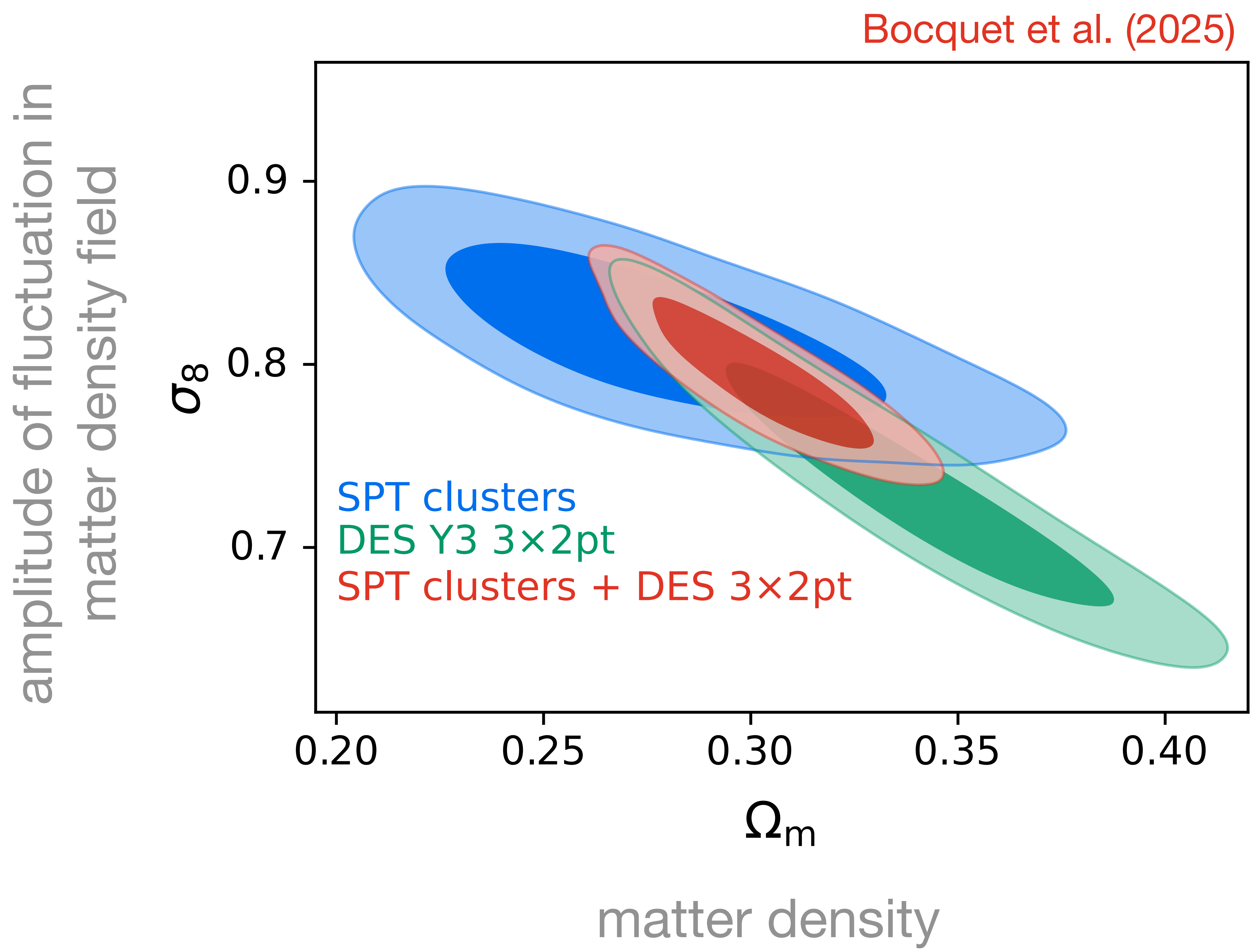
$\sigma_8 = 0.797 \pm 0.026$

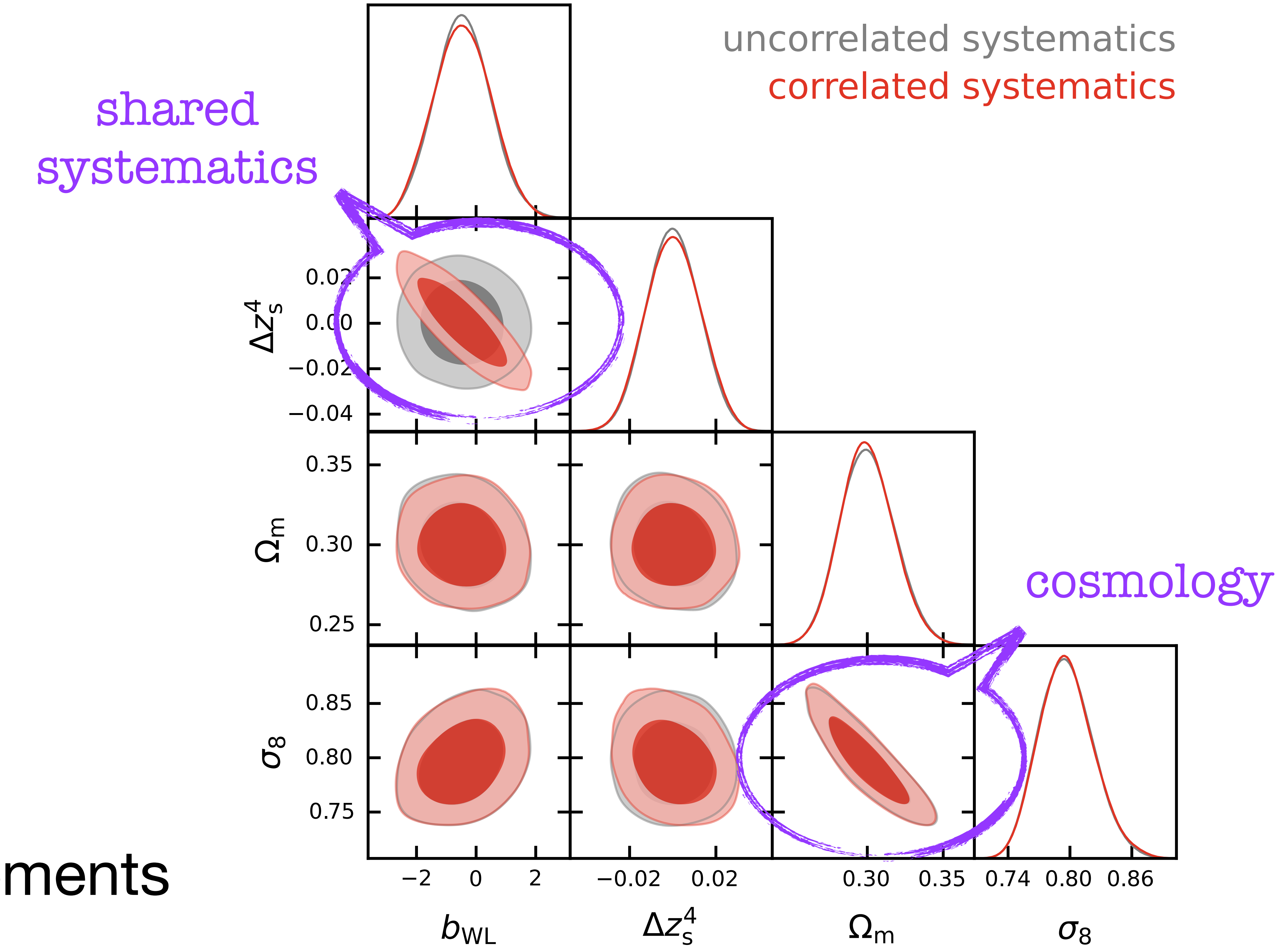
$S_8 \equiv \sigma_8\,(\Omega_m/0.3)^{0.5} = 0.796 \pm 0.013$

$H_0 = 73 \pm 7$ km/s/Mpc

ΛCDM with massive neutrinos

SPT clusters + DES 3x2pt



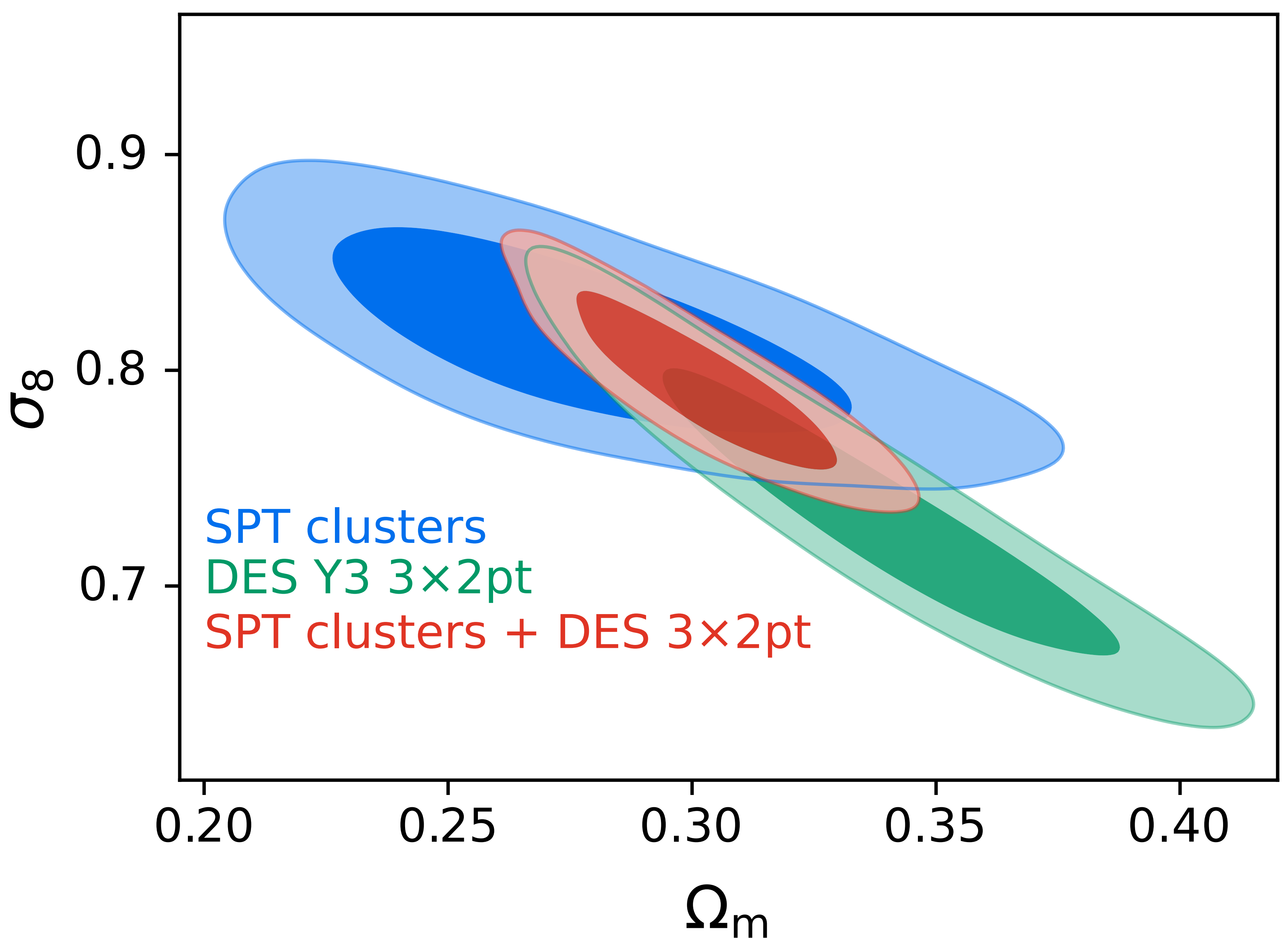


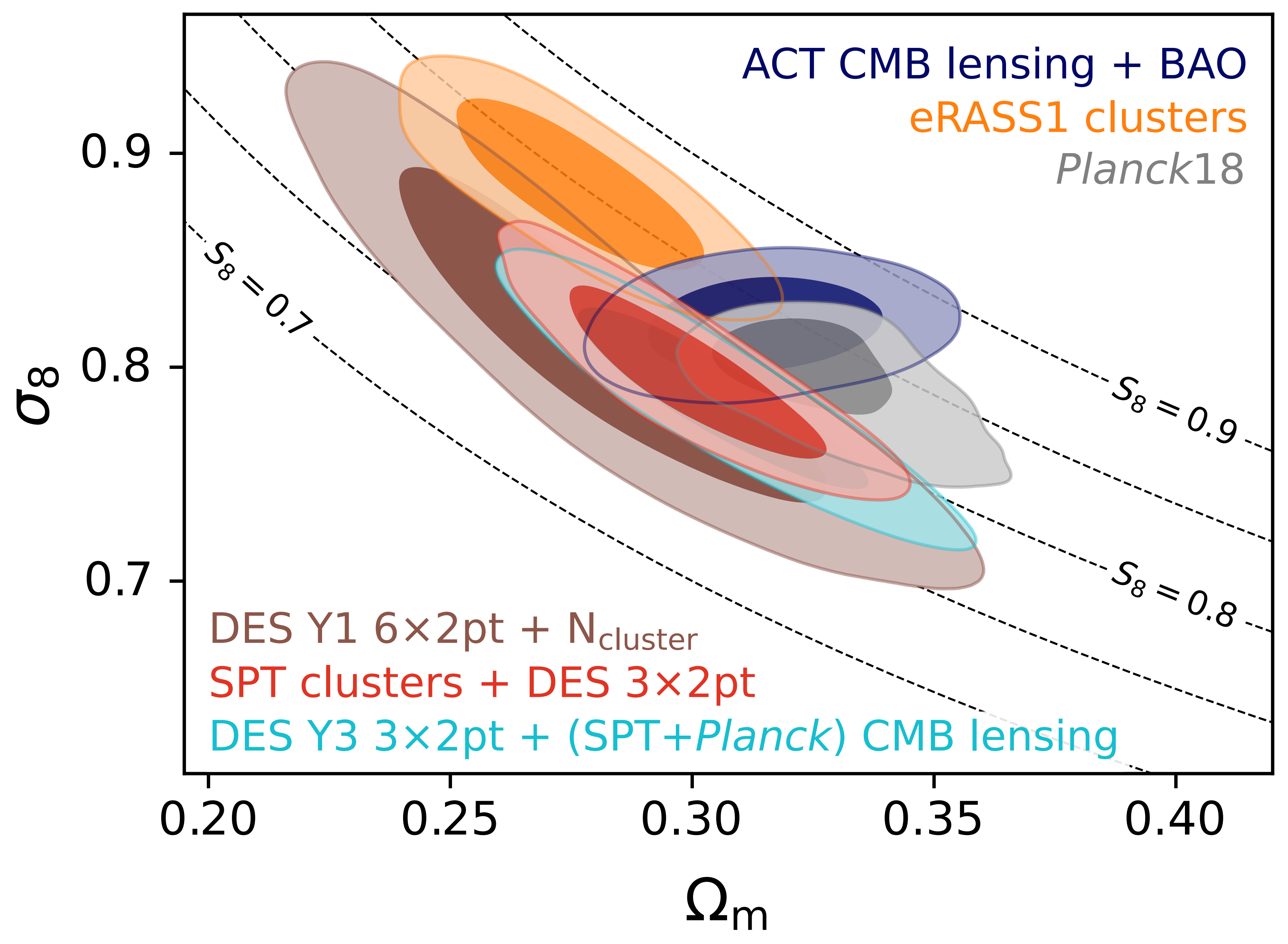
Impact of shared systematics in lensing measurements on final cosmology results is negligible.

ΛCDM with massive neutrinos

SPT clusters + DES 3x2pt

Bocquet et al. (2025)





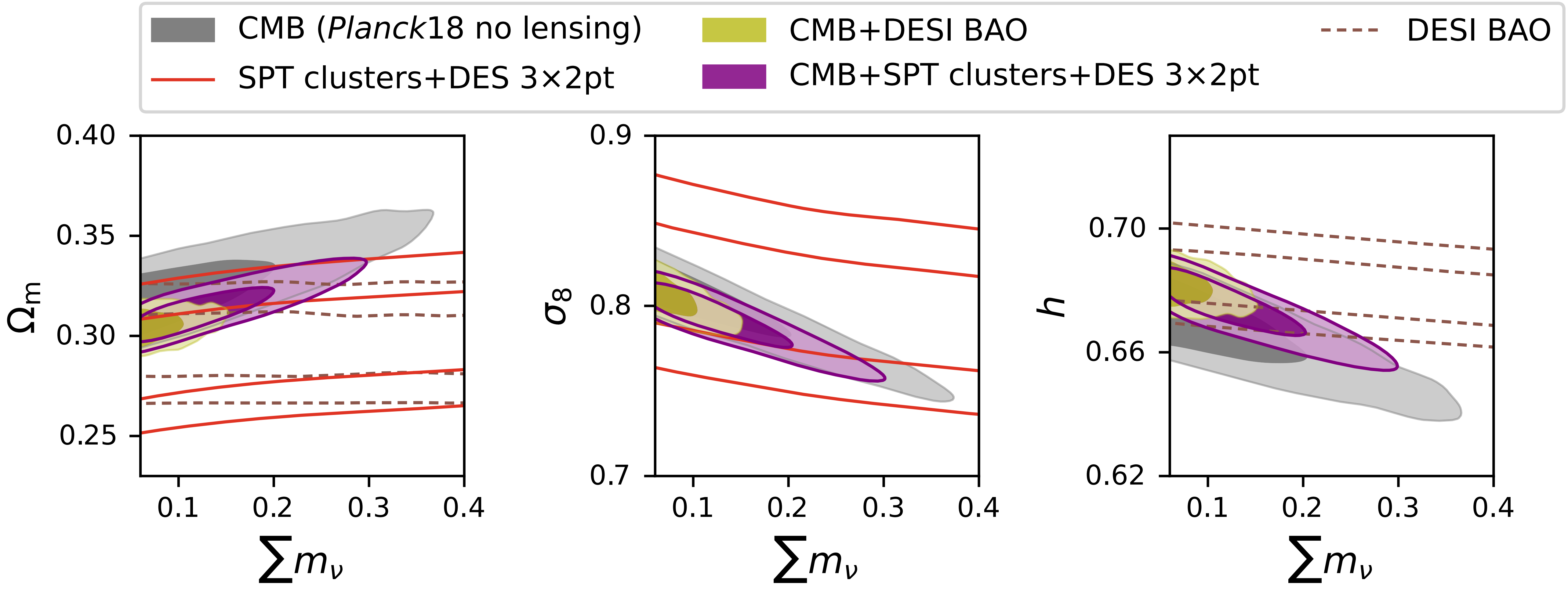
Contours are only 15% wider than *Planck* 2018 TT,TE,EE

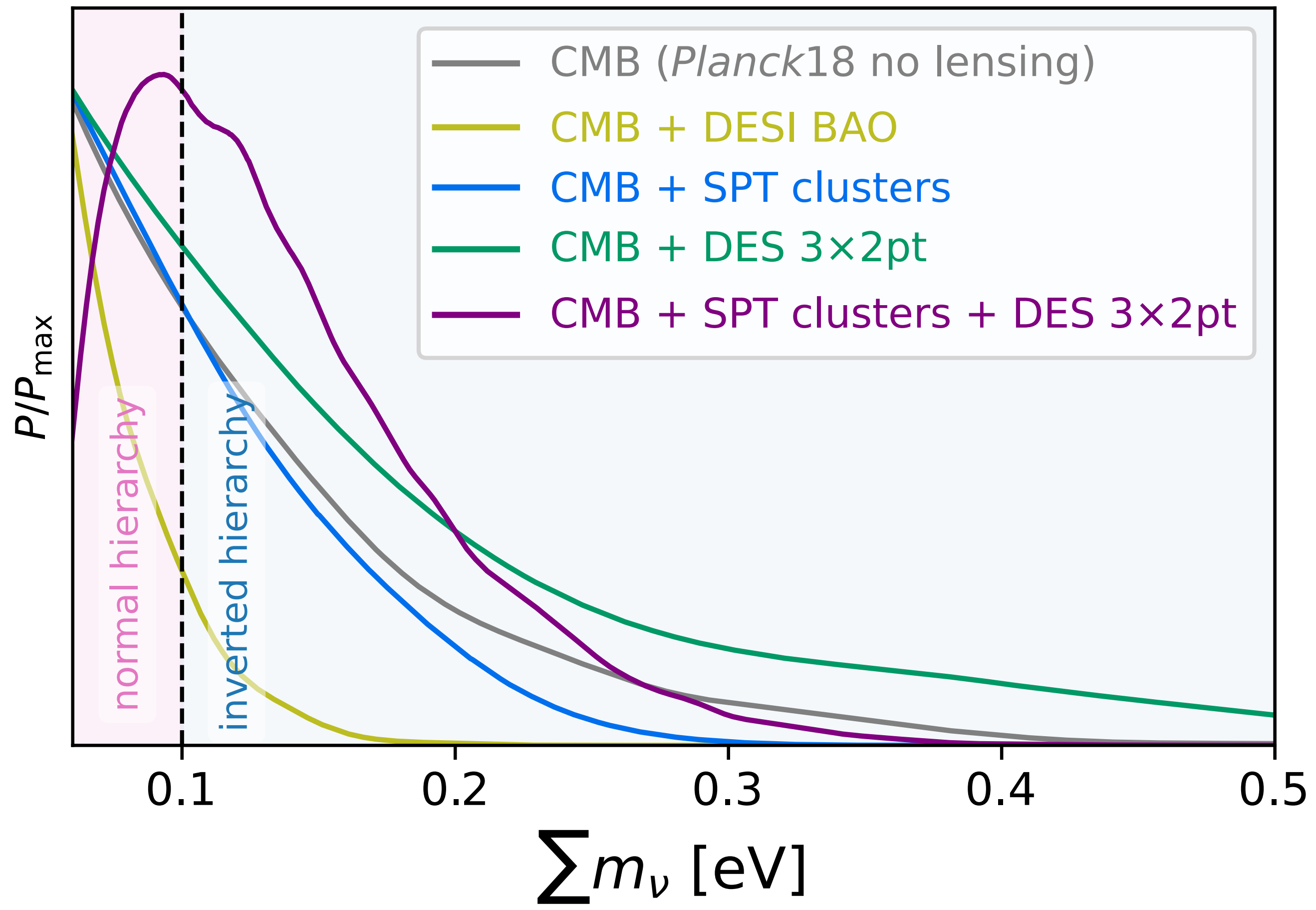
No strong suggestion for S_8 tension (1.6 σ difference with *Planck*)

See Chun-Hao To's talk for DES clusters + DES 3x2pt (after coffee break)

ΛCDM with massive neutrinos

Bocquet et al. (2025)

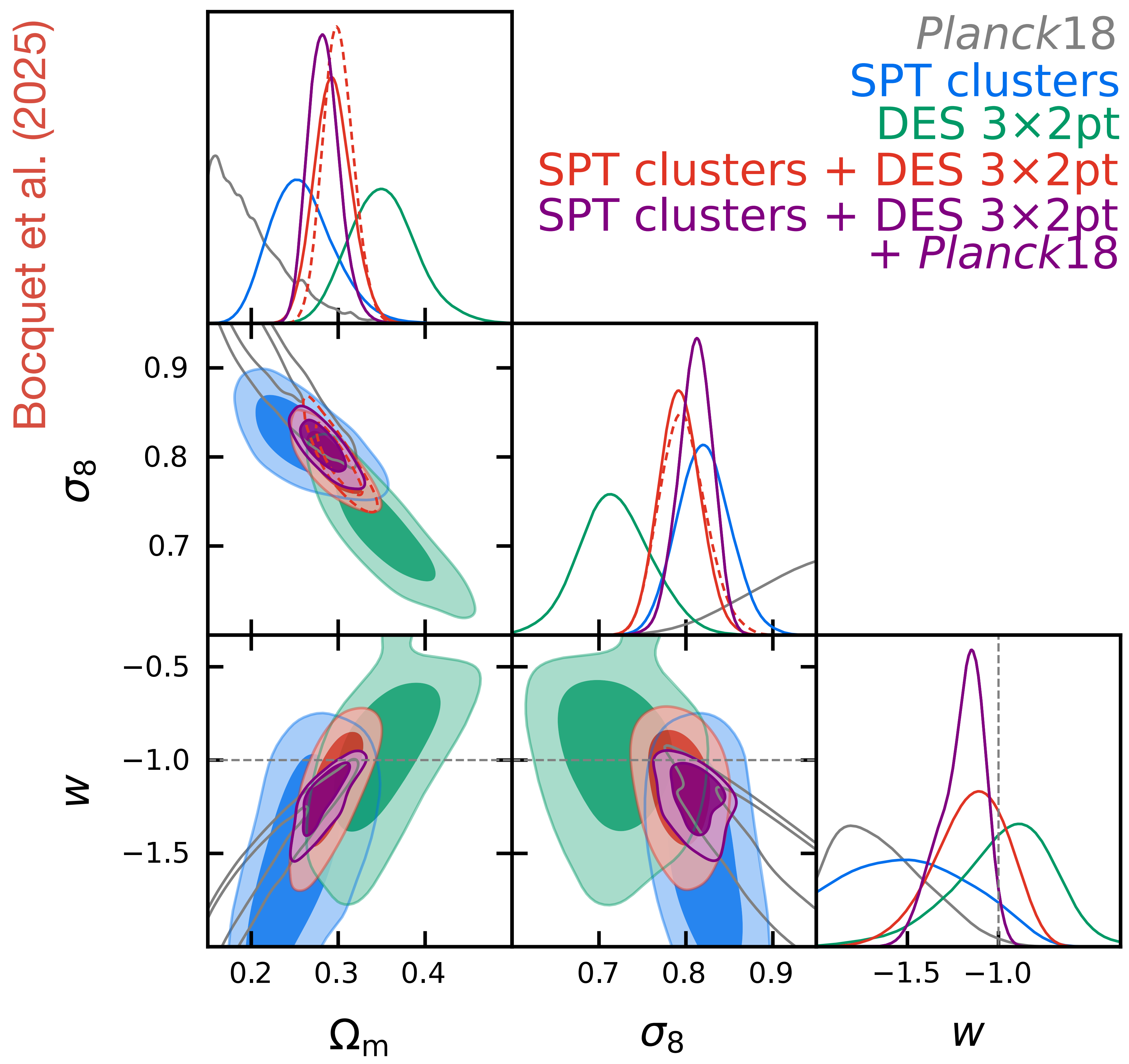




- CMB cannot constrain neutrino properties due to degeneracies
  - Add large-scale structure probe
- CMB + SPT clusters + DES 3x2pt: peak at 0.1 eV
  Measurement does not inform the neutrino hierarchy.
- Reminder
  - $\sum m_\nu > 0.06\,\mathrm{eV}$ (neutrino oscillations)
  - if $\sum m_\nu < 0.1\,\mathrm{eV}$ then normal hierarchy

    else inverted hierarchy

wCDM with massive neutrinos



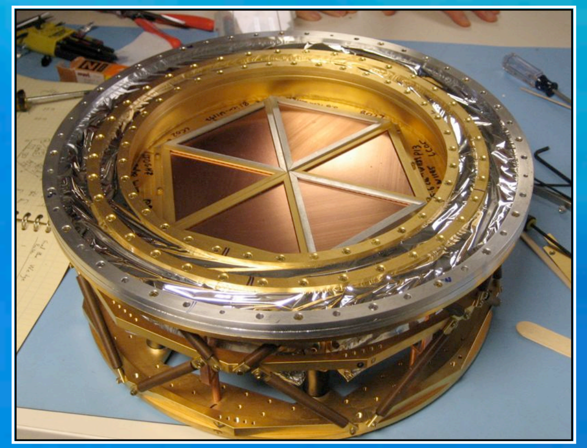
- SPT clusters + DES 3x2pt
  $w = -1.15^{+0.23}_{-0.17}$
- In combination with *Planck* CMB
  $w = -1.20^{+0.15}_{-0.09}$

The South Pole Telescope (SPT)

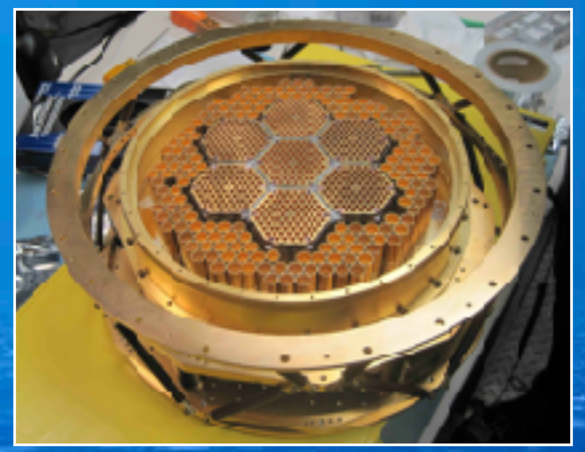
10-meter sub-mm quality wavelength telescope

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

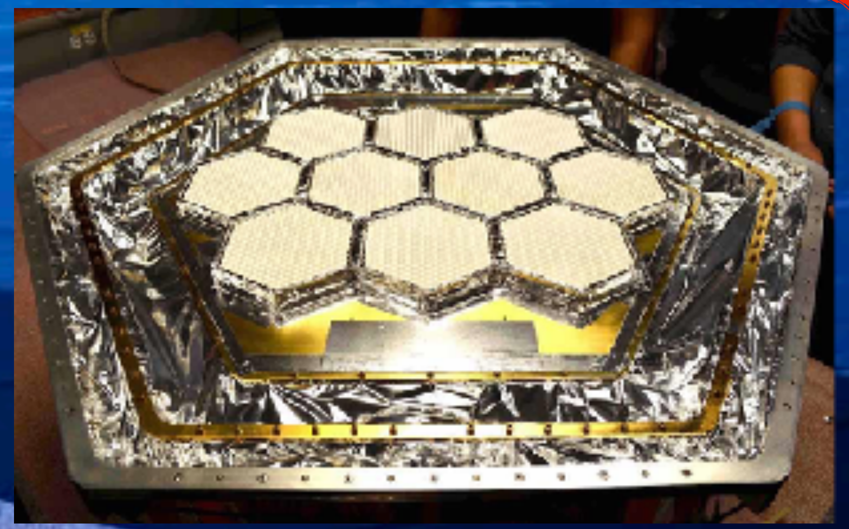
2007: SPT-SZ
960 detectors
95,150,220 GHz



2012: SPTpol
1600 detectors
95,150 GHz
+Polarization

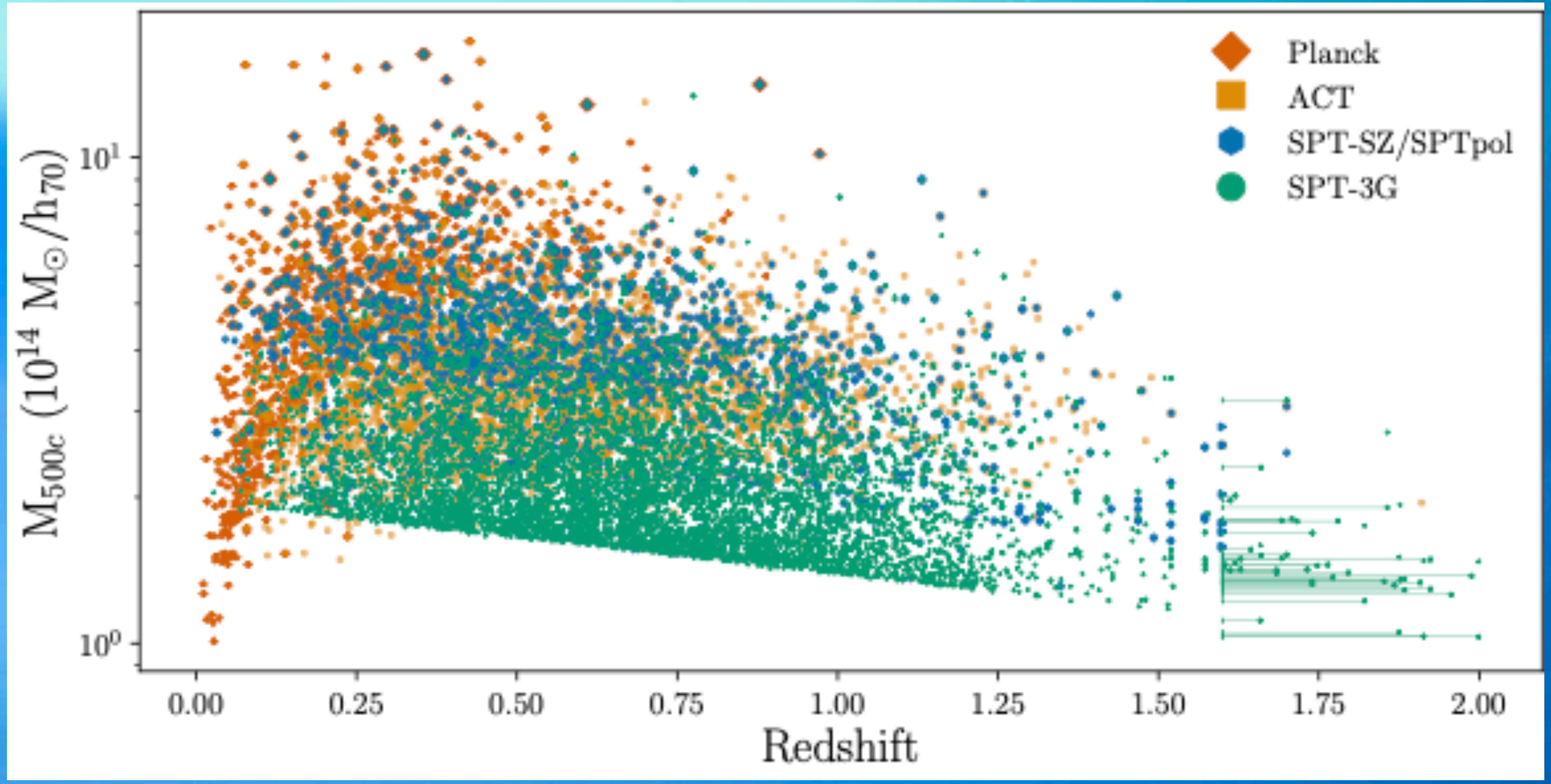


2017: SPT-3G
~15,200 detectors
95,150,220 GHz
+Polarization

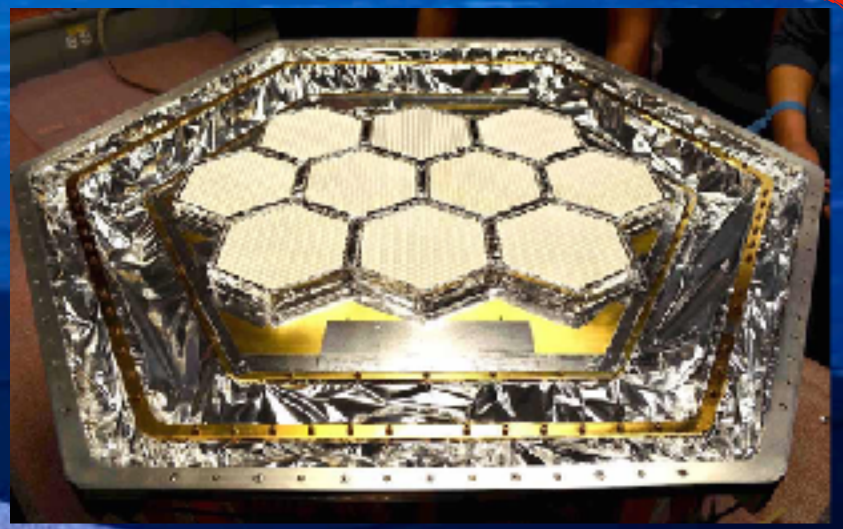


SPT-3G clusters

Bleem et al.



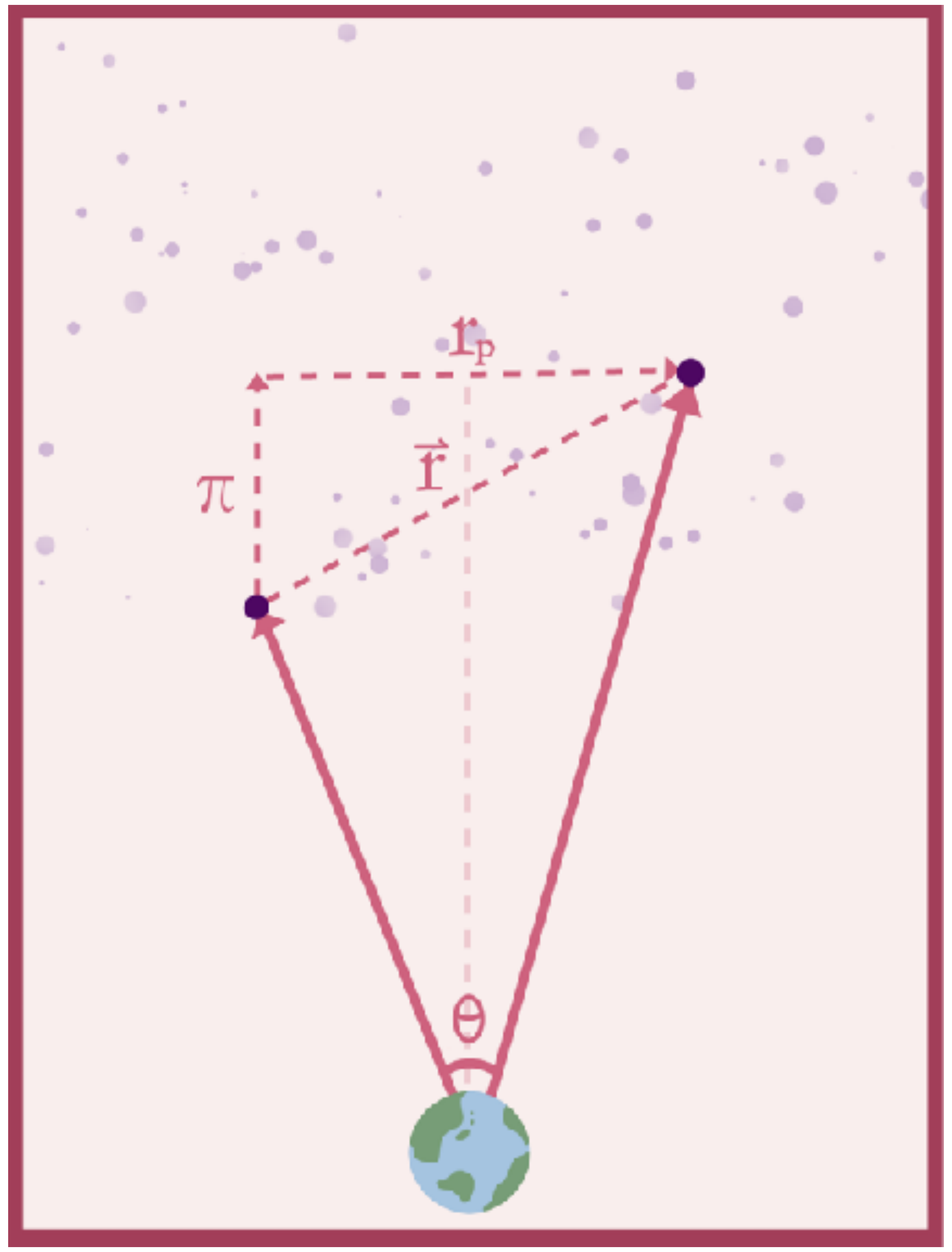
2017: SPT-3G
~15,200 detectors
95,150,220 GHz
+Polarization

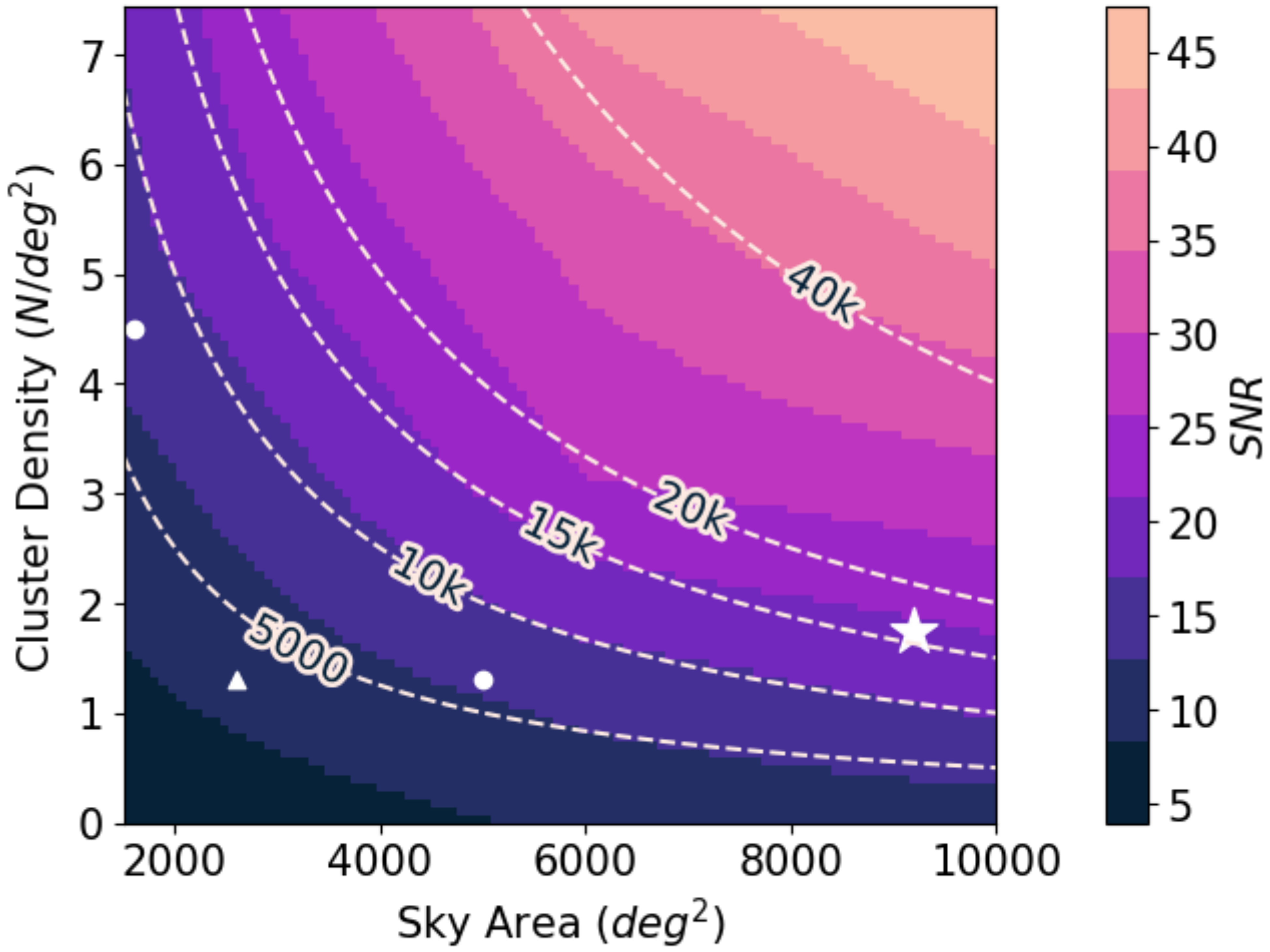


2pt Correlation of Galaxy Clusters

Emily Martsen et al. – Go see the poster!

SPT-3G cluster catalog large enough to measure the 2pt correlation of clusters with high significance.





2pt Correlation of Galaxy Clusters

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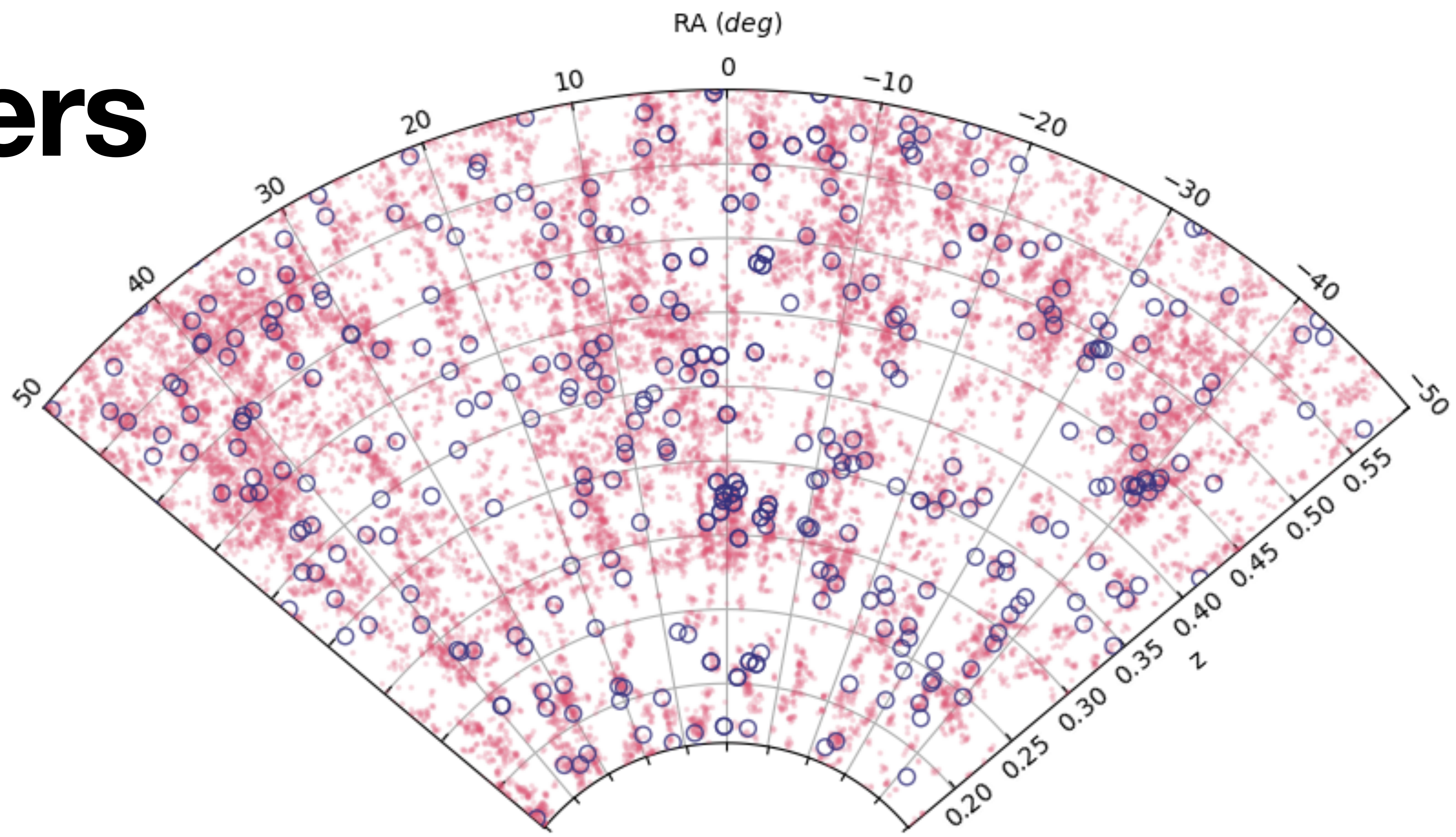
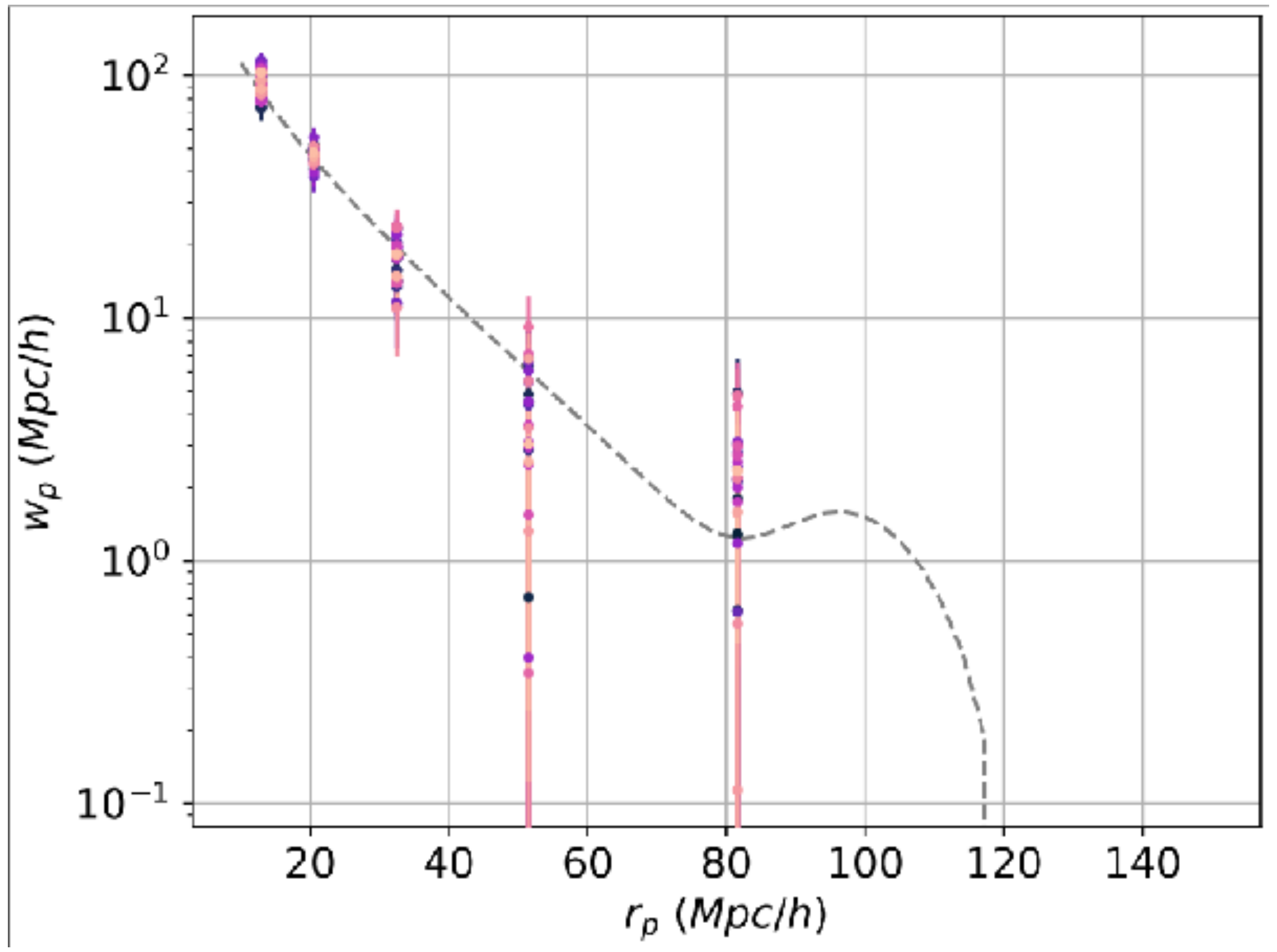
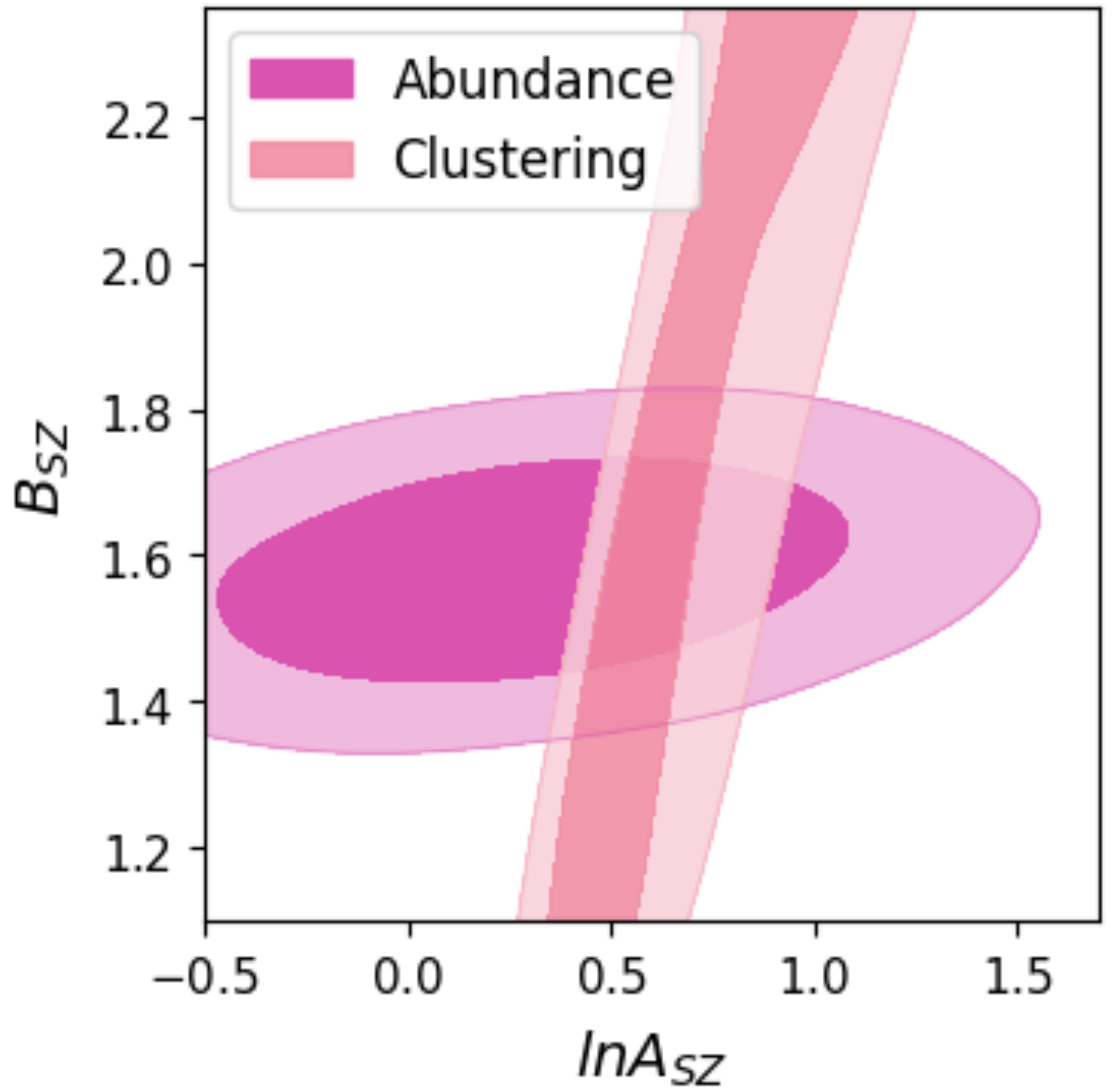


SPT-3G cluster catalog large enough to measure the 2pt correlation of clusters with high significance.

Forecasts using mock catalogs from simulations show the ability to detect clustering in SPT-3G 5yr main with a detection S/N of >13.

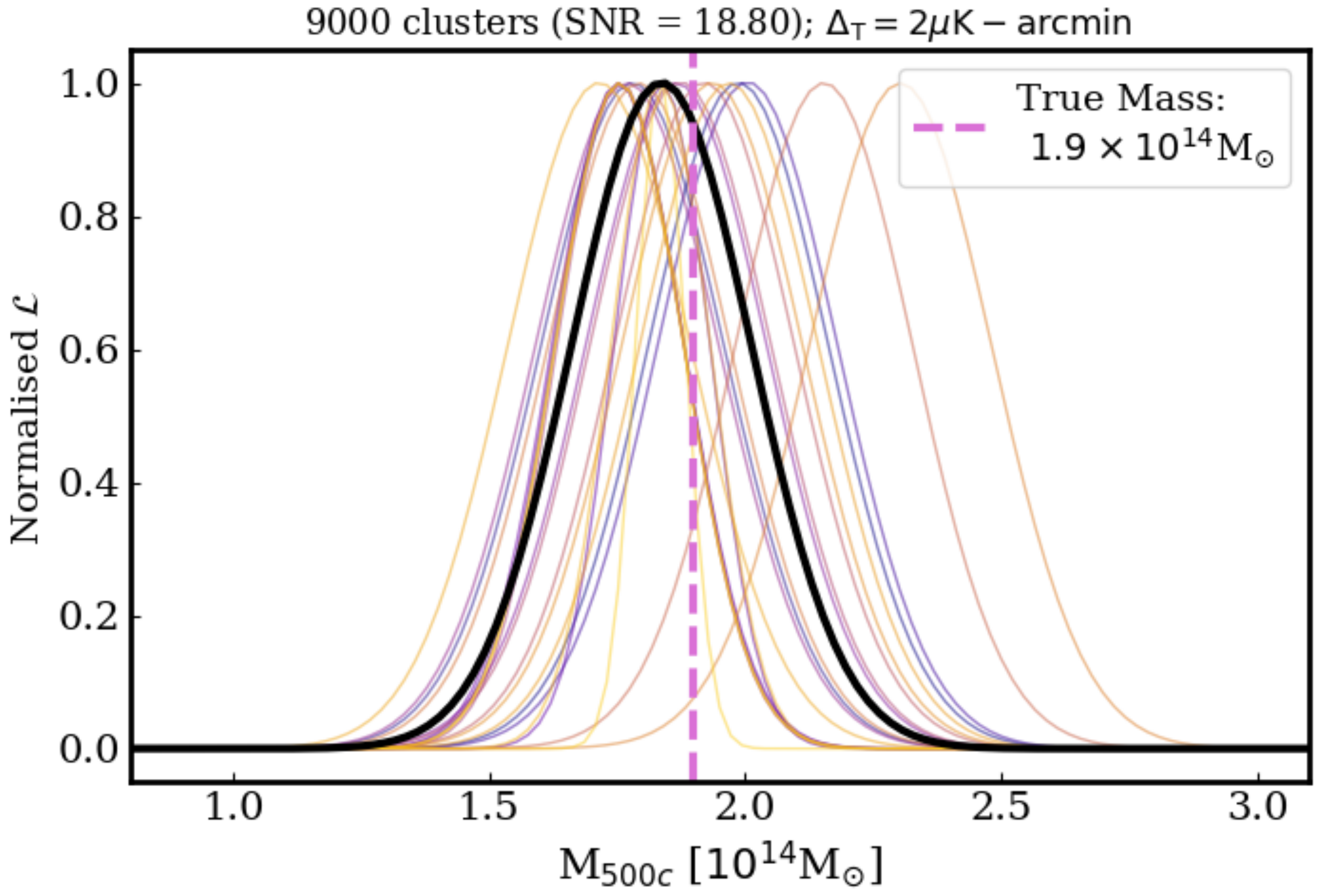
Complementary to abundance measurements.





Projected SPT-3G 1500d CMB Cluster Mass Calibration constraints

Kayla Kornoelje et al.



From an **SPT-3G-like cluster catalog:**

- ~9000 clusters
- $0.25 < z < 1.6$

$$M_{\mathrm{mean}} = 1.9 \times 10^{14} M_{500c}$$

We predict a constraint on the mean cluster mass of $\pm$ 0.22 at ~19 σ based on a set of 20 simulated SPT-3G like dipole signals

To come: additional constraints with SPT-3G polarization data

SPT-3G clusters with DES lensing

Higher lens density, higher source density, better calibration

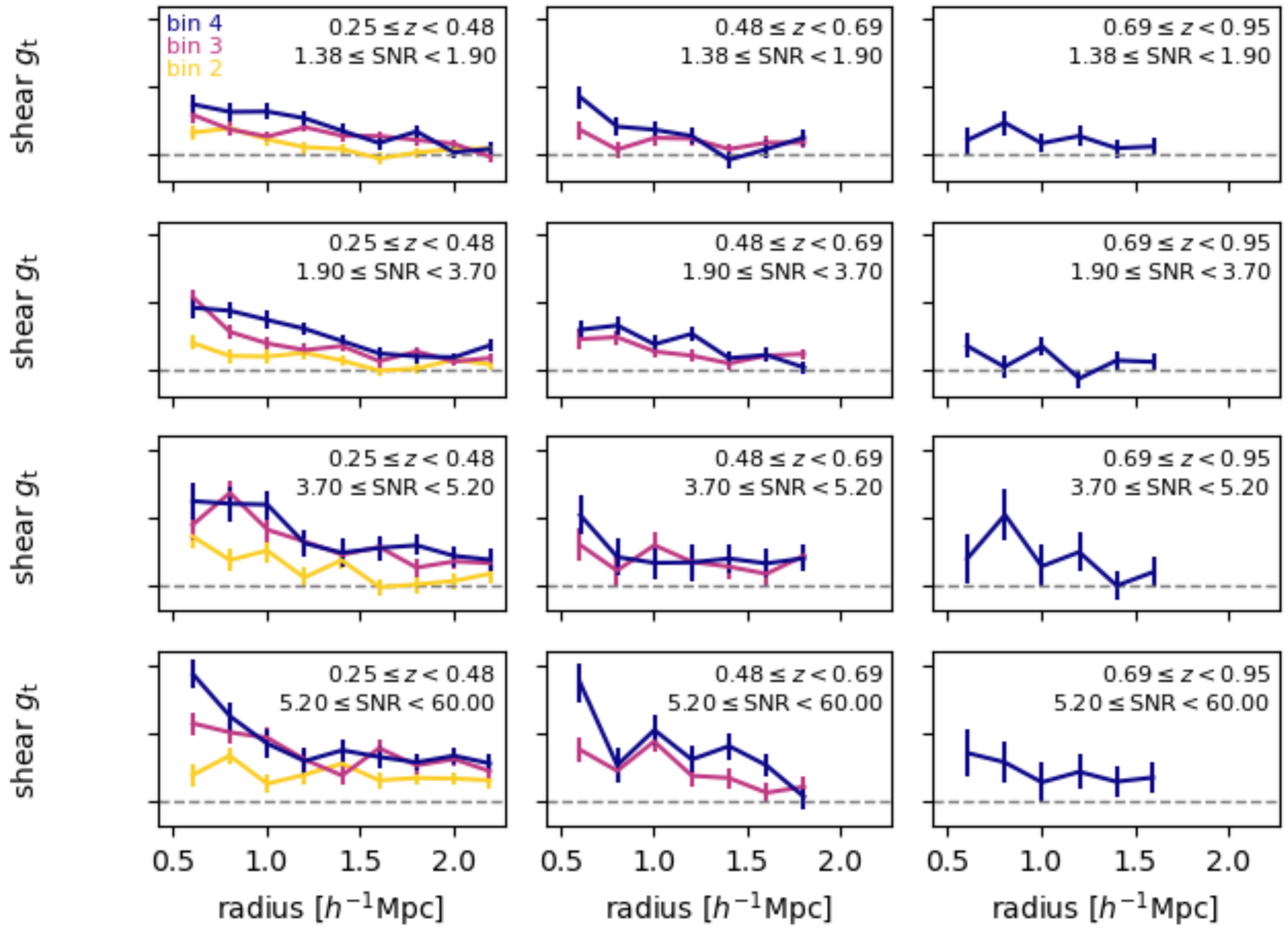
(SPTpol + SPT-SZ) x DES Y3

- lensing SNR = 32

(SPT-3G + SPT-SZ + SPTpol) x DES Y3

- 3 redshift bins, 4 SZ bins
- lensing SNR > 47 (preliminary!)

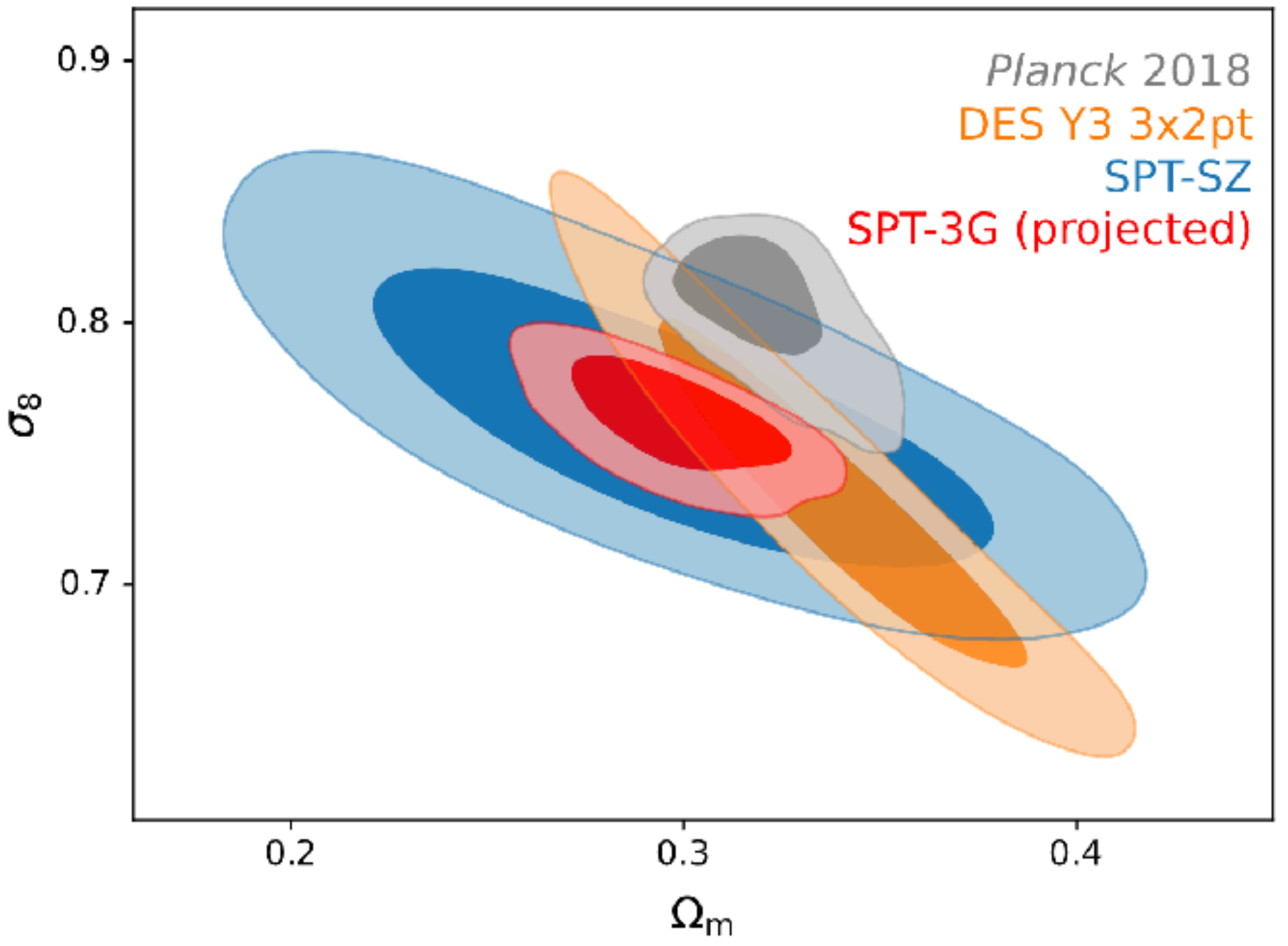
DES Year 6 lensing leads to further improvement over Year 3.



SPT-3G Cluster Cosmology

Cluster abundance – Forecasts

Chaubal…Bocquet et al. 2021



S.Bocquet + L. Bleem

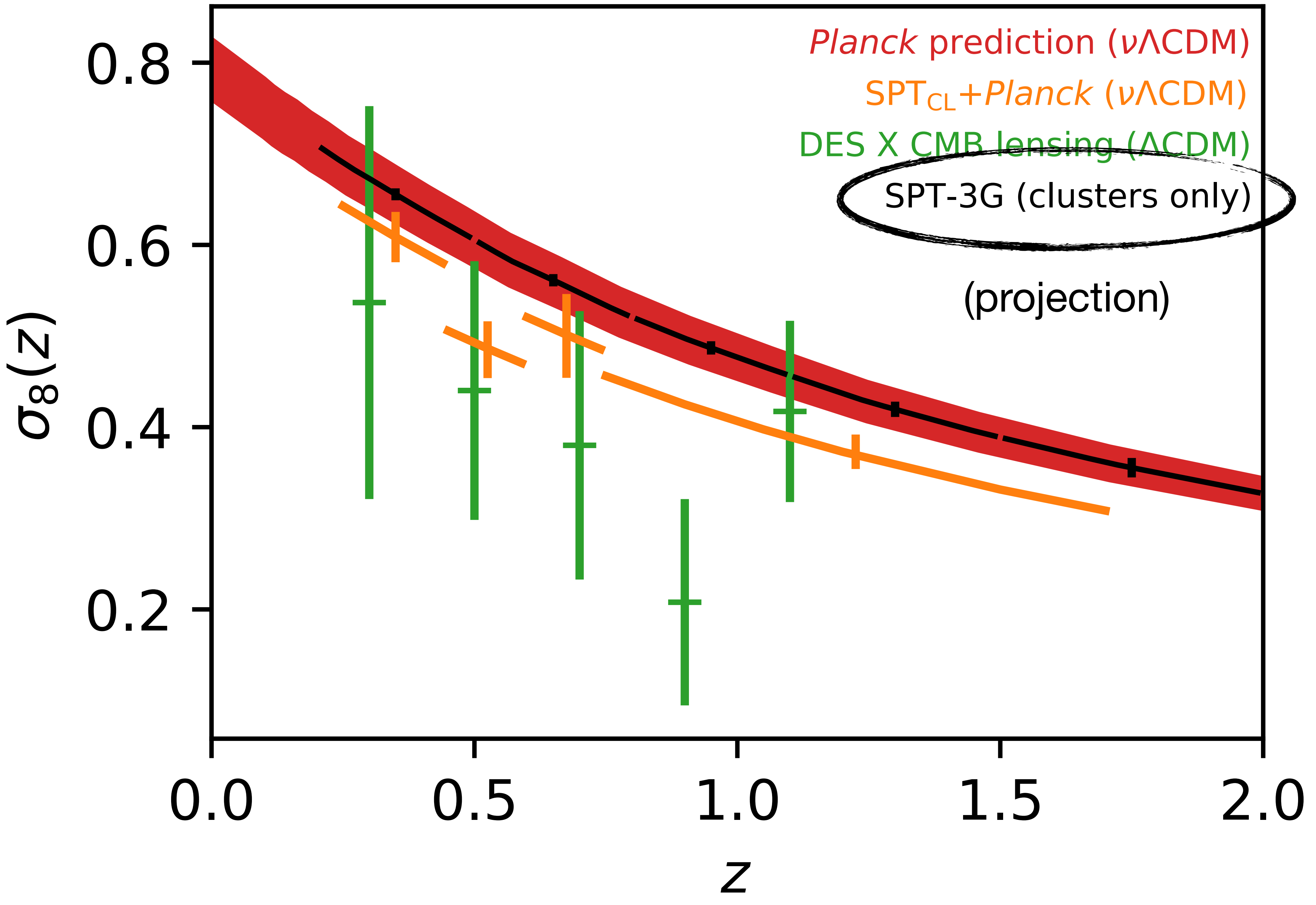


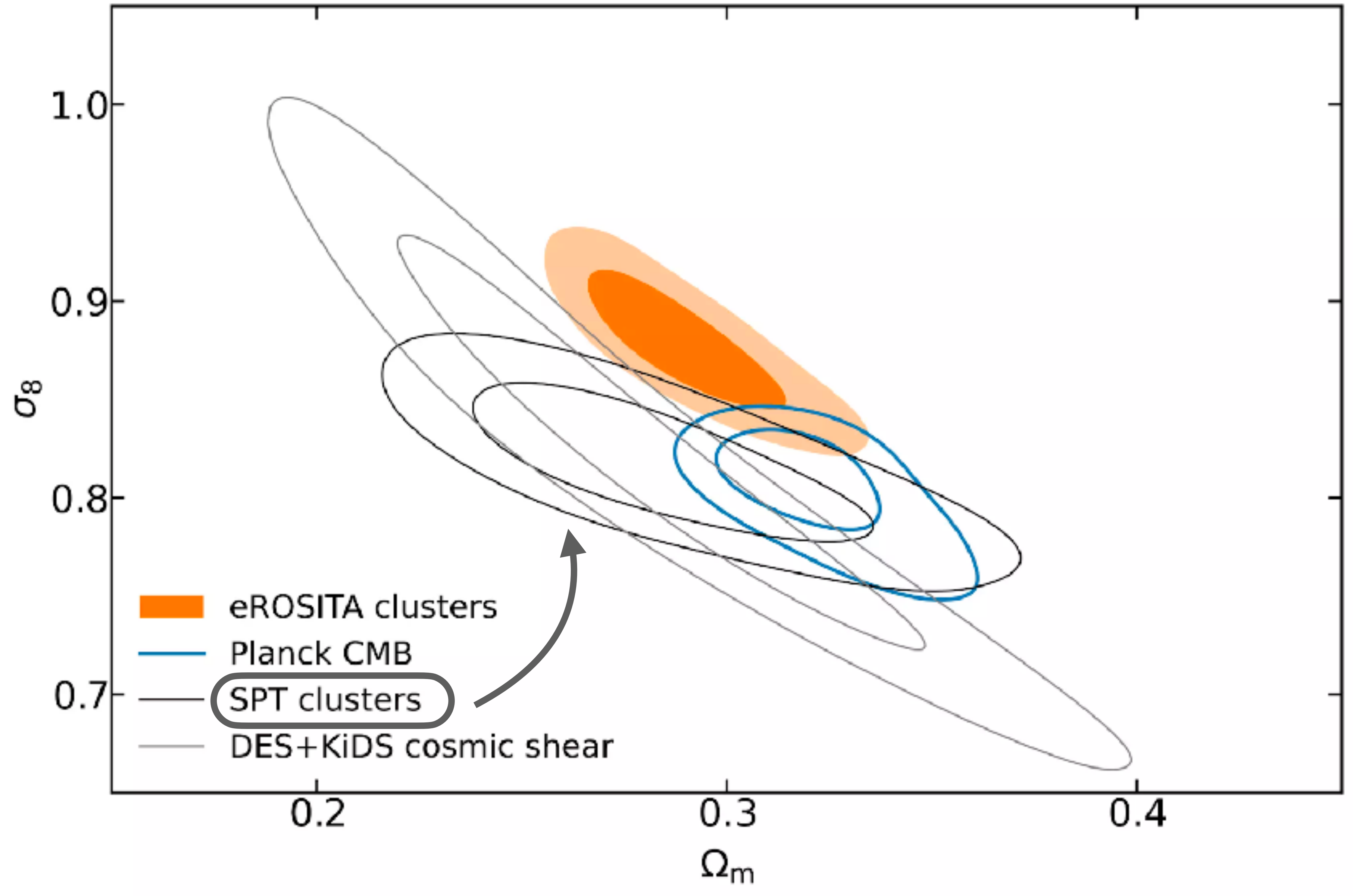
Image credit: Aman Chokshi

eRASS1 cluster abundance

>5,000 X-ray selected clusters

- Mass calibration driven by DES Year 3 lensing data (SNR 65) (Grandis, Ghirardini, Bocquet+24)
- eROSITA largely follows our approach
  - Individual cluster likelihoods
  - *M*wl–*M*halo relation
  - DES Year 3 lensing analysis
    (but they also use KiDS and HSC data)
- Simultaneous constraints on Ω_m, σ_8, w
- Cluster cosmology using ICM-selected clusters works!

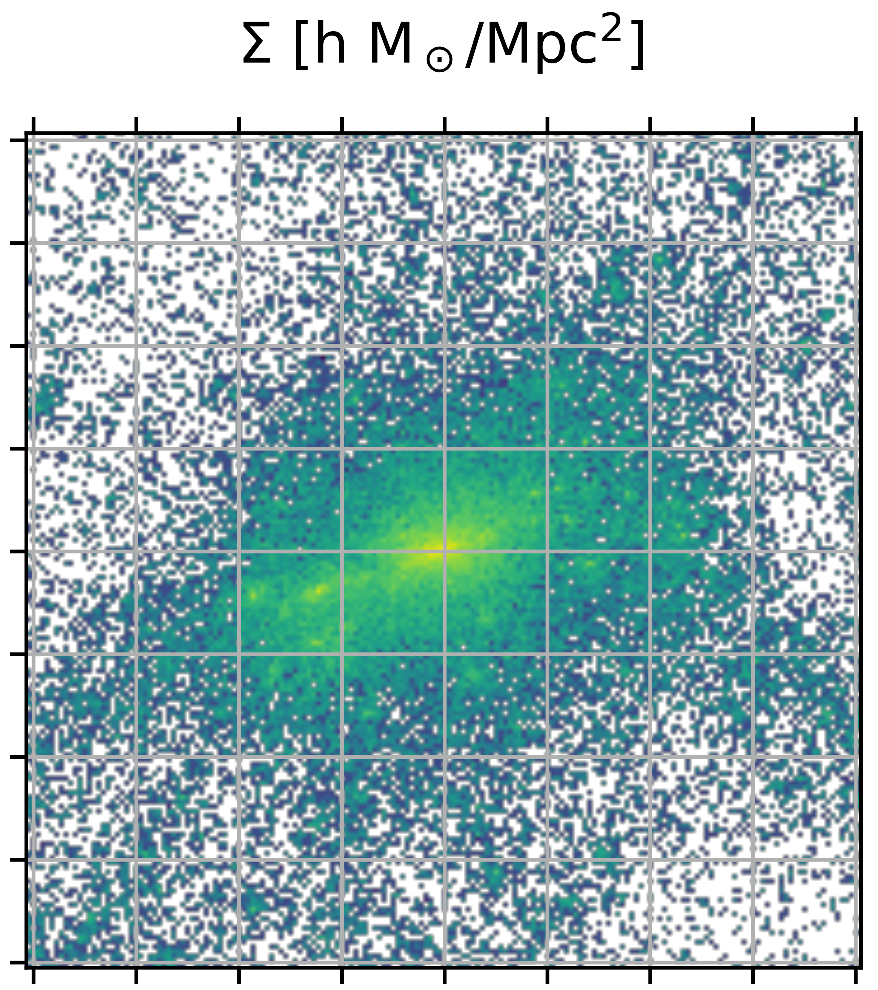
Ghirardini+24



Cluster Lensing Model

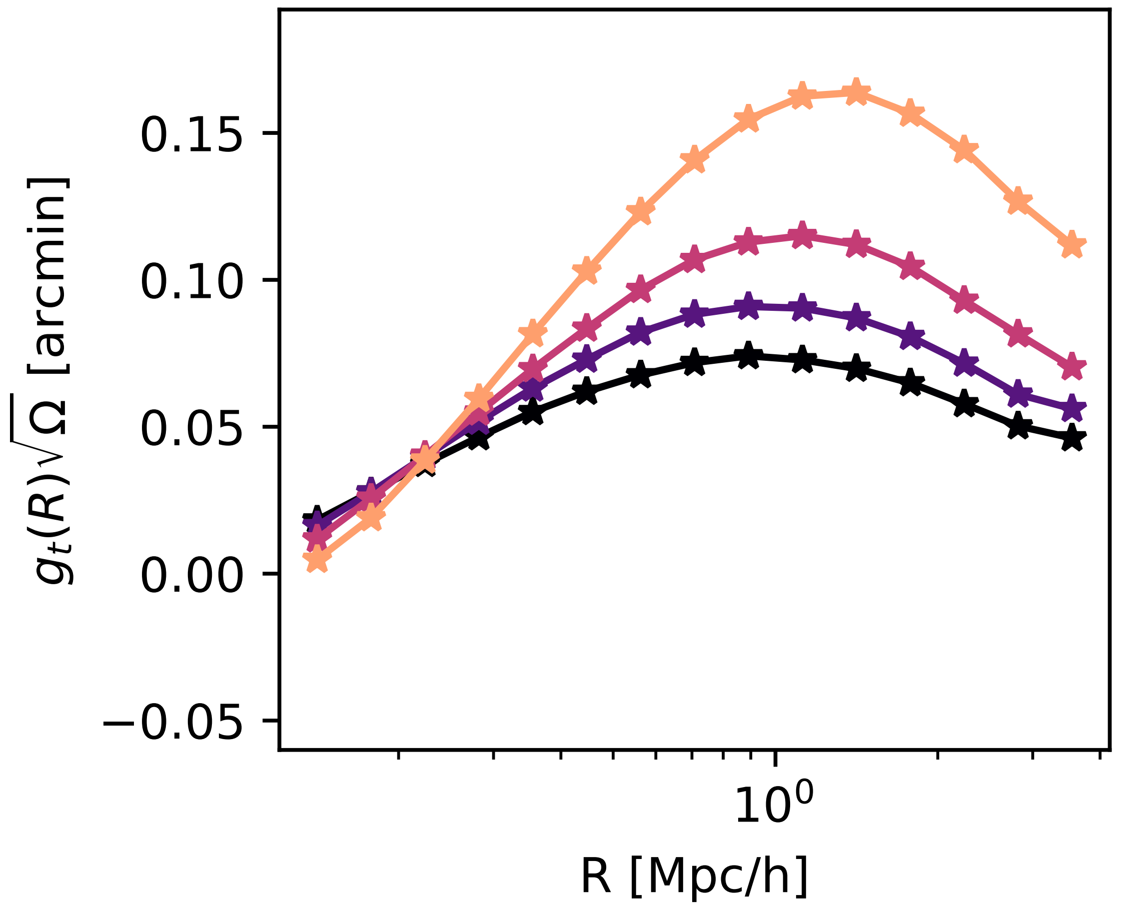
Grandis, Bocquet et al. (2021)

- Simple model shear(*Mass*) based on Navarro-Frenk-White (NFW) mass profile
- Biased and noisy estimator
  (e.g., Becker & Kravtsov 2011)
- Solution: Introduce latent variable $M_{\rm WL}$ and establish $M_{\rm WL}$–$M_{\rm halo}$ relation such that shear($M_{\rm WL}$) is unbiased
- establish $M_{\rm WL}$–$M_{\rm halo}$ relation using hydrodynamic simulations to capture baryonic effects



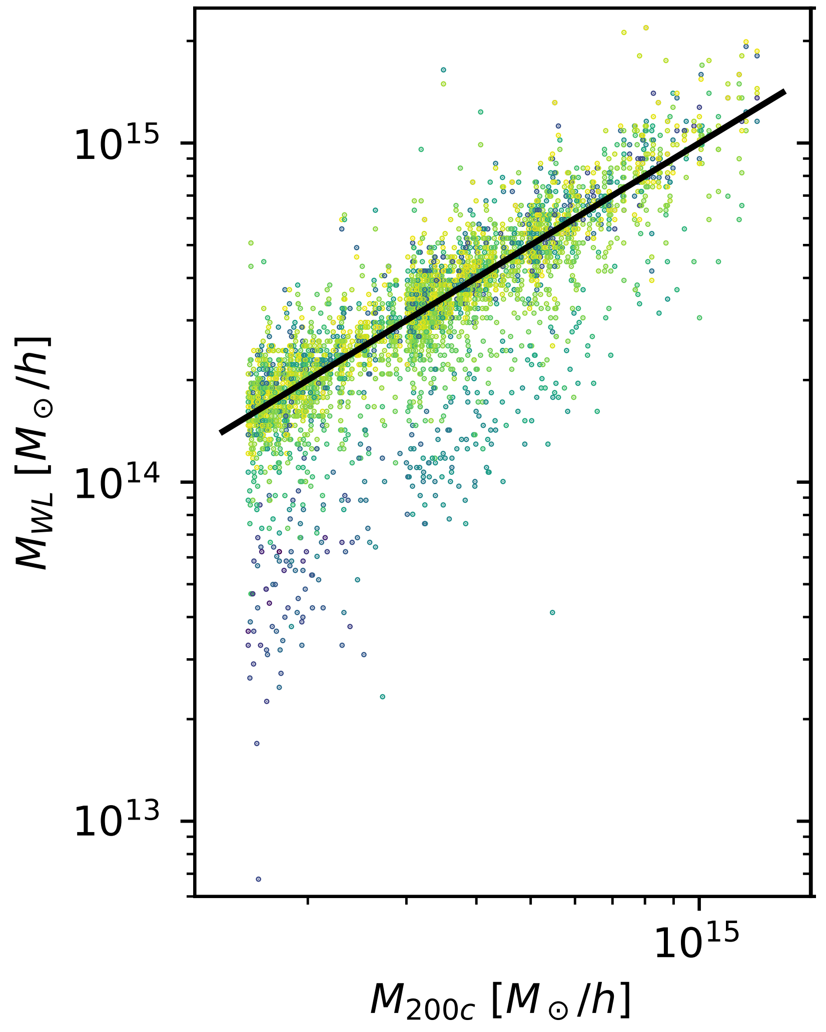
halo mass map from hydro simulation

synthetic shear profile



apply mass estimator

lensing mass



halo mass

Calibrate mean $M_{\rm WL}$–$M_{\rm halo}$ relation and intrinsic scatter

$$\left\langle \ln\left(\frac{M_{\rm WL}}{M_0}\right)\right\rangle = b_{\rm WL}(z) + b_M \ln\left(\frac{M_{200c}}{M_0}\right)$$

$$\ln \sigma_{\ln M_{\rm WL}} = \frac{1}{2}\left[s_{\rm WL}(z) + s_M \ln\left(\frac{M_{200c}}{M_0}\right)\right]$$