New Constraints from the Abundance of South Pole Telescope-selected Clusters and the Large-Scale Structure

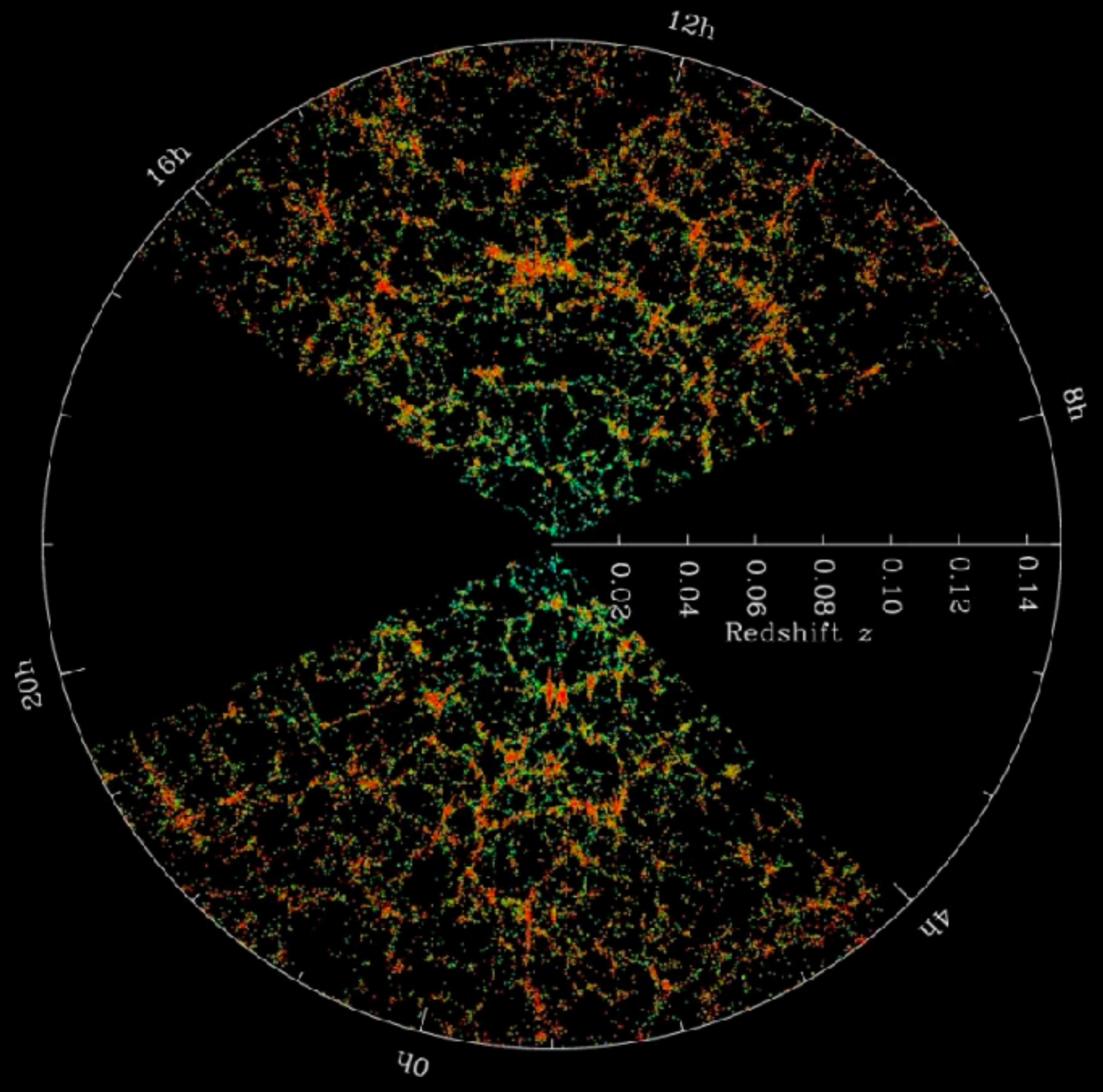
Sebastian Bocquet, LMU Munich

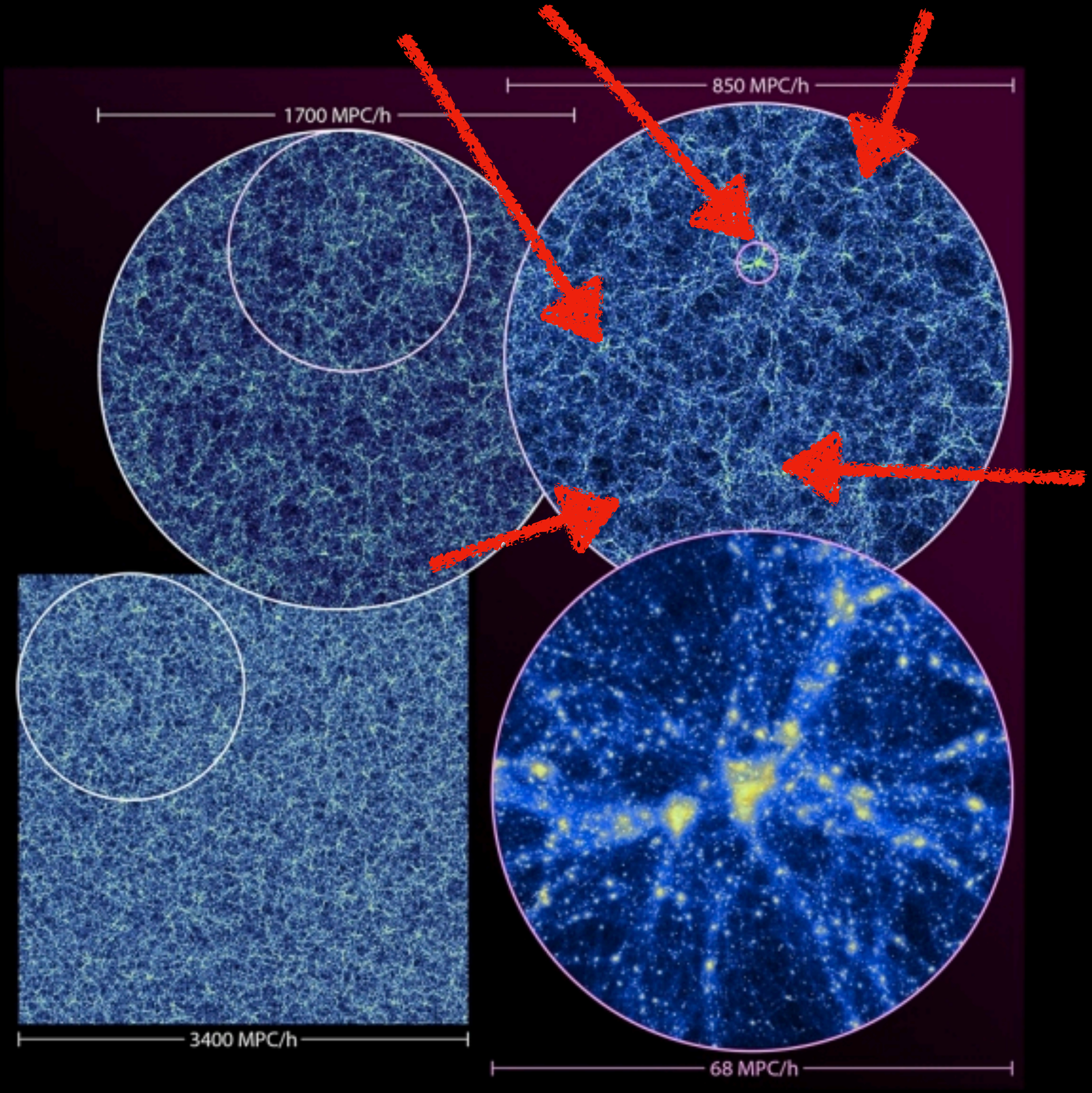
with Sebastian Grandis, Lindsey Bleem, Matthias Klein, Joe Mohr, Tim Schrabback, Elisabeth Krause, Chun-Hao To,
and the *South Pole Telescope* (SPT) and *Dark Energy Survey* (DES) collaborations

Image credit: SPT 2024 winter-overs Josh + Kevin

Massive Halos ≳ 10^{14} Msun

… trace the large-scale structure

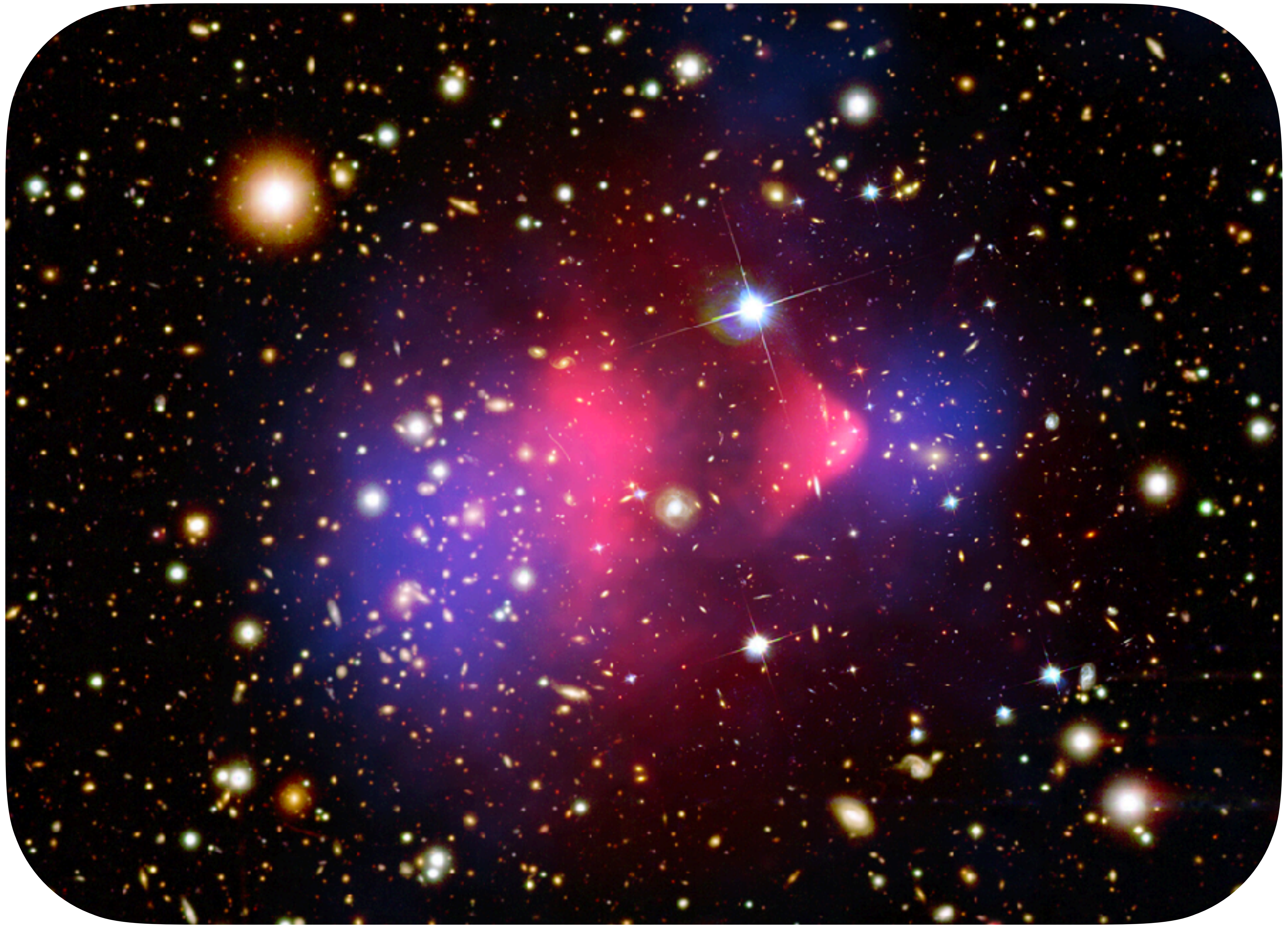




Last Journey (on Mira supercomputer) (Heitmann+)

Cluster Cosmology

The most massive collapsed objects $\gtrsim 10^{14}\ M_\odot$

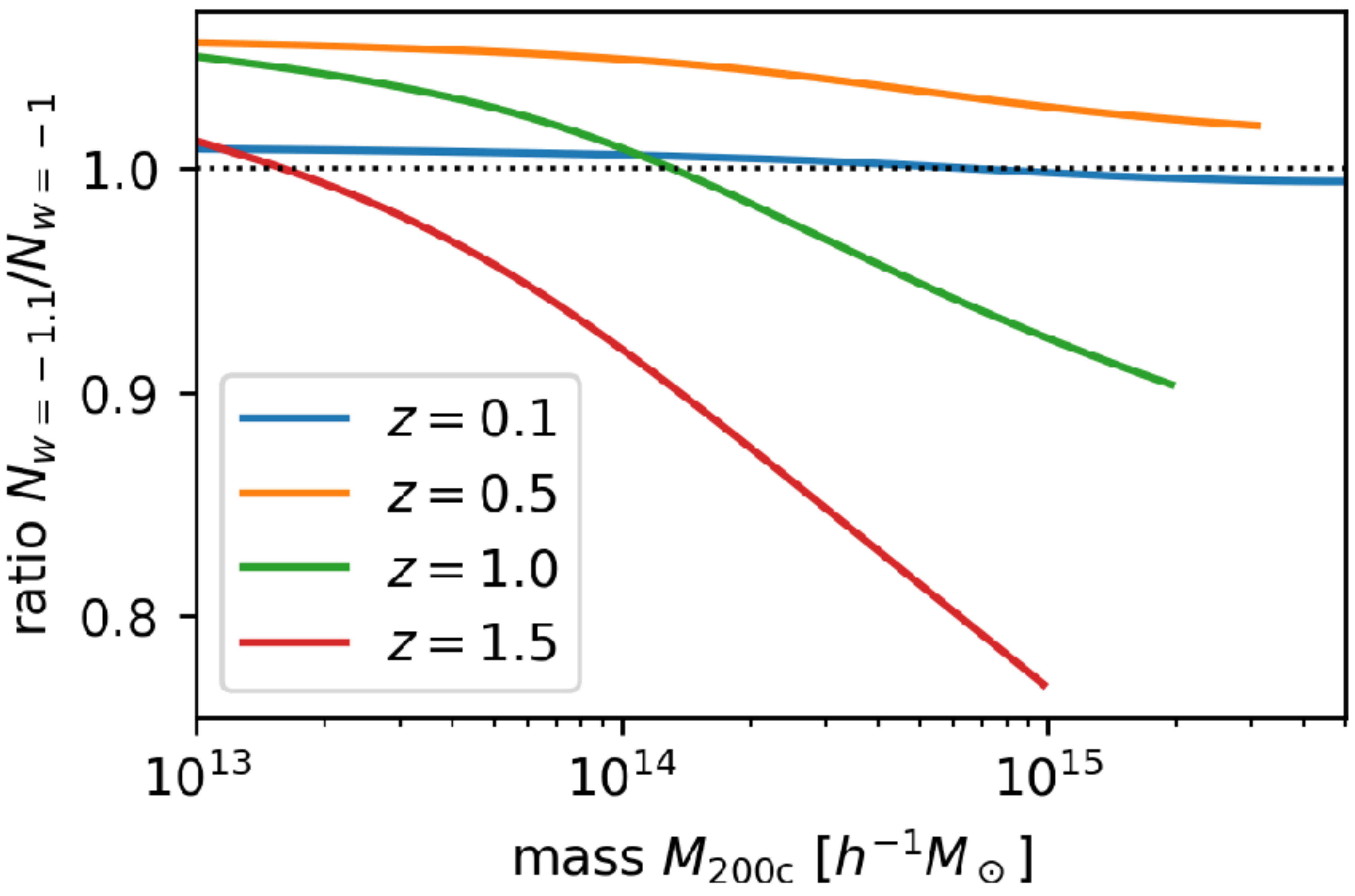


Bullet Cluster. X-ray: NASA/CXC/CfA/M.Markevitch, Optical and lensing map: NASA/STScI, Magellan/U.Arizona/D.Clowe, Lensing map: ESO WFI

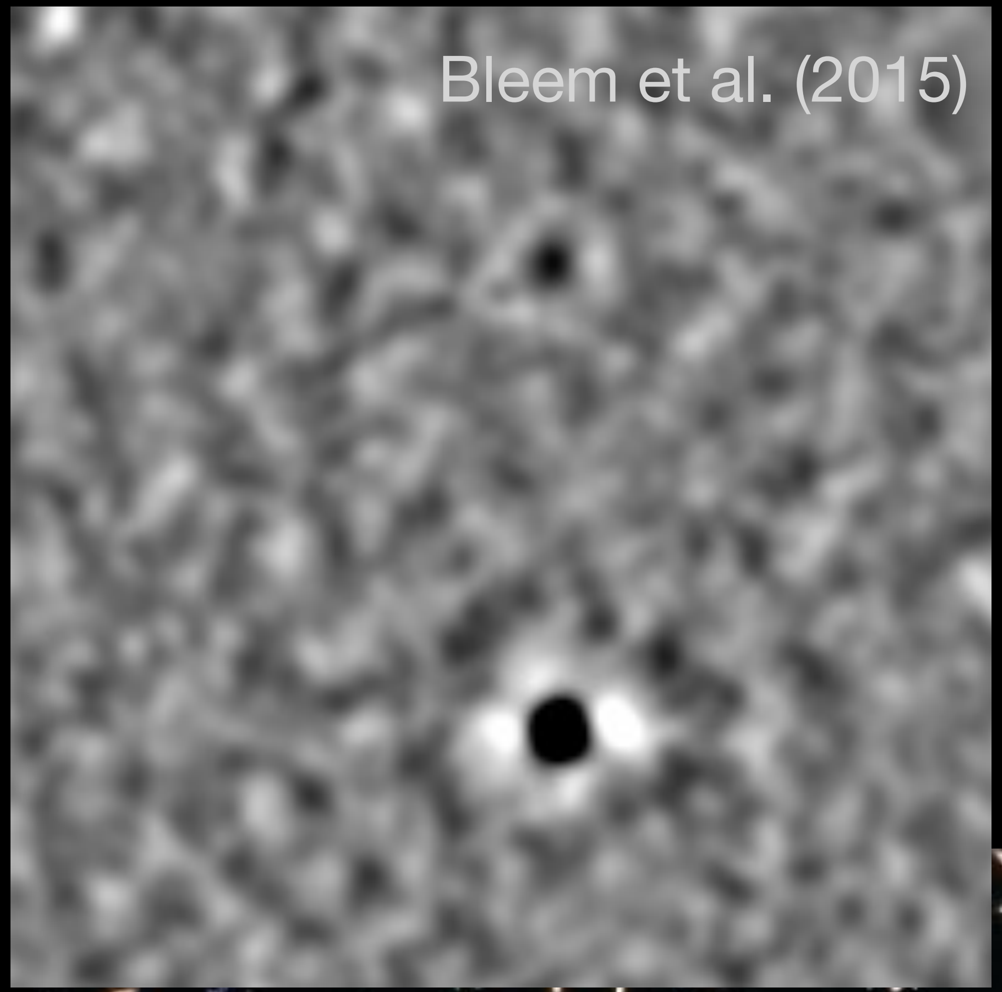
- Composition
  - 85—90% dark matter
  - 10—15% ordinary matter, of which
    - ~ 75% (gravitationally heated) gas
    - ~ 25% galaxies/stars
- Somewhat arbitrary (but useful) definition
  - Halo ≡ *entire* thing
  - Cluster ≡ galaxies & gas (what we see)

Halo Mass Function

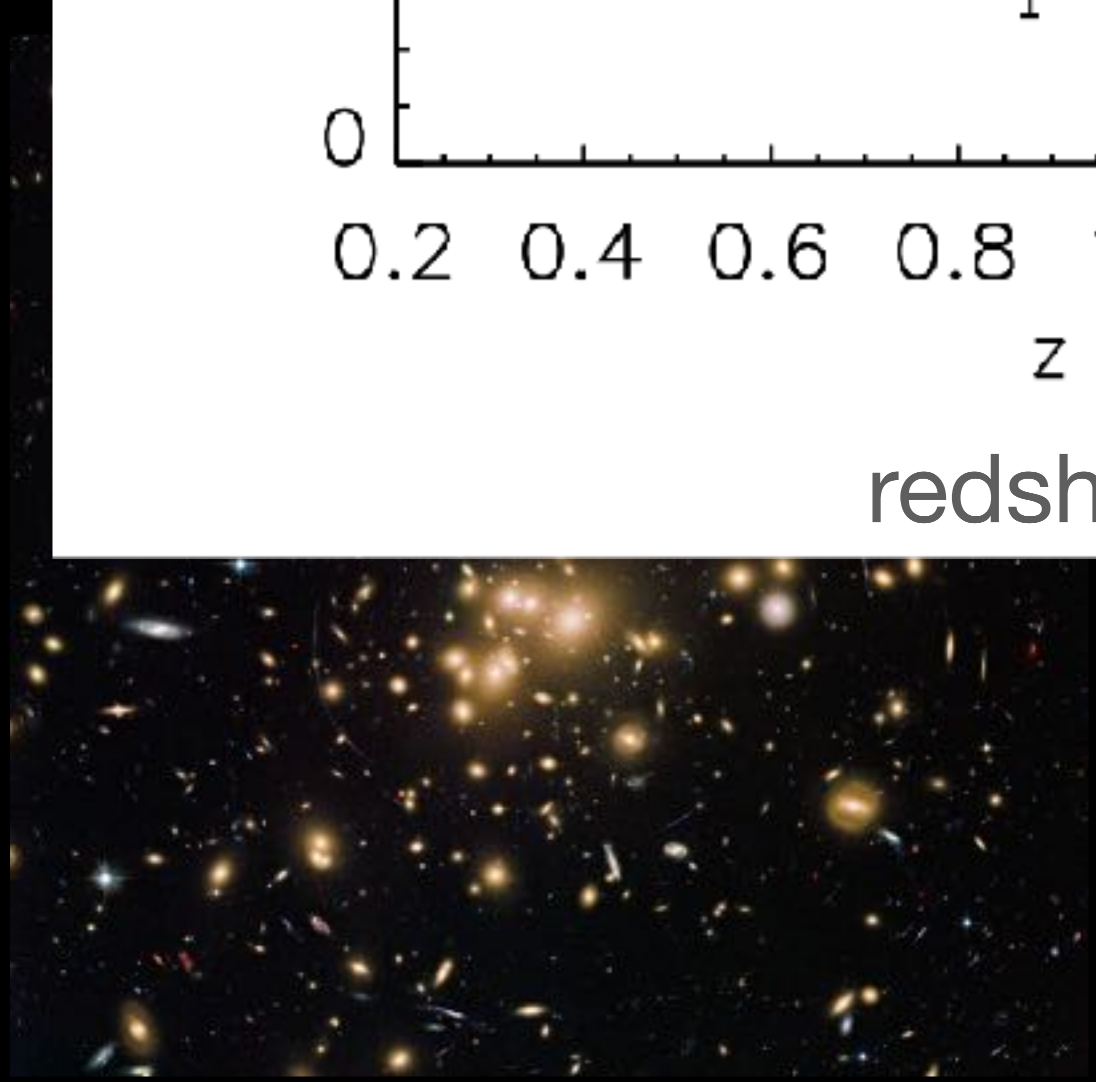
Impact of changing dark energy equation of state parameter by 0.1



Back to reality

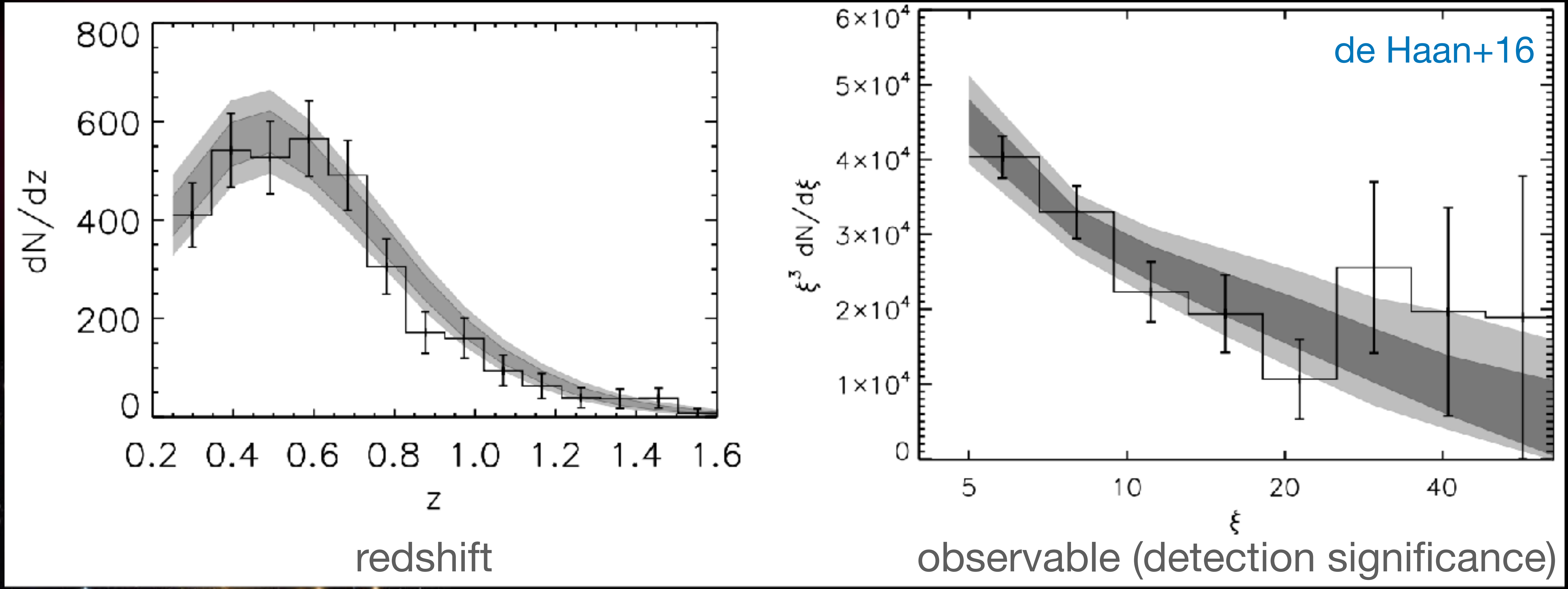


Credit: NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI) http://www.spacetelescope.org/images/heic1401a/



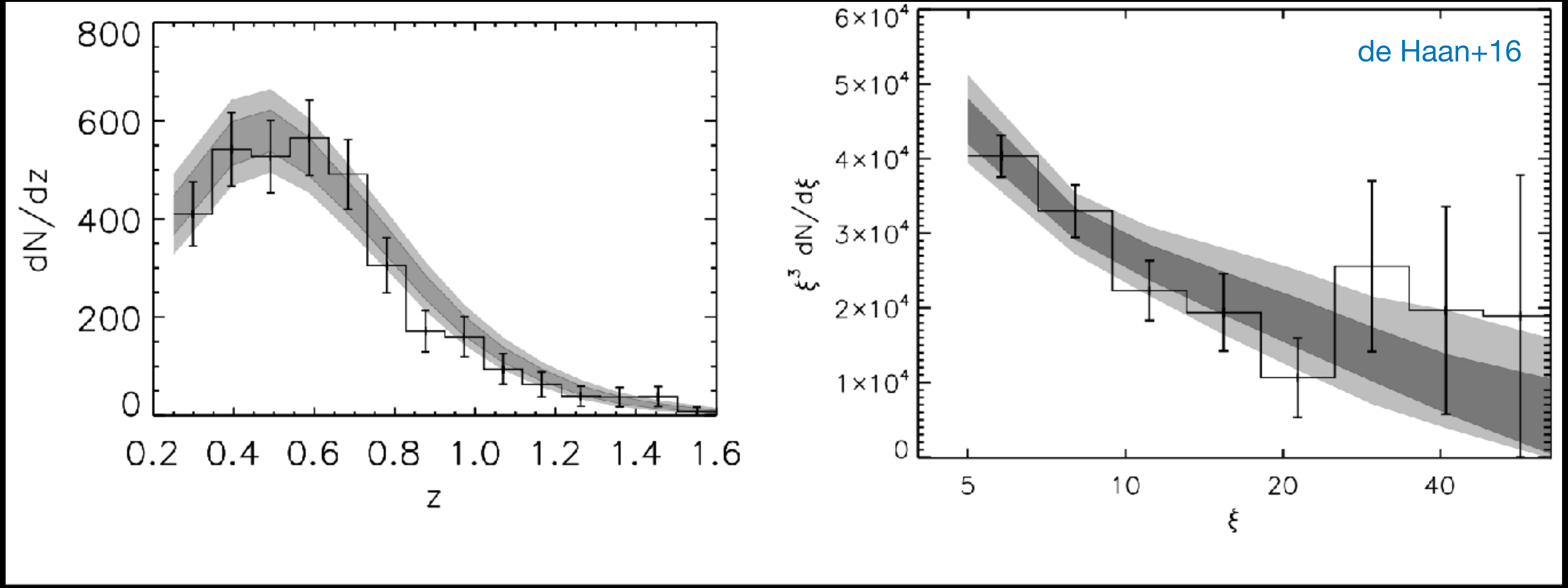
Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), J. Blakeslee (NRC Herzberg Astrophysics Program, Dominion Astrophysical Observatory), and H. Ford (JHU) http://www.spacetelescope.org/images/heic1317a

"Halo Observable Function"



Observable vs. Mass

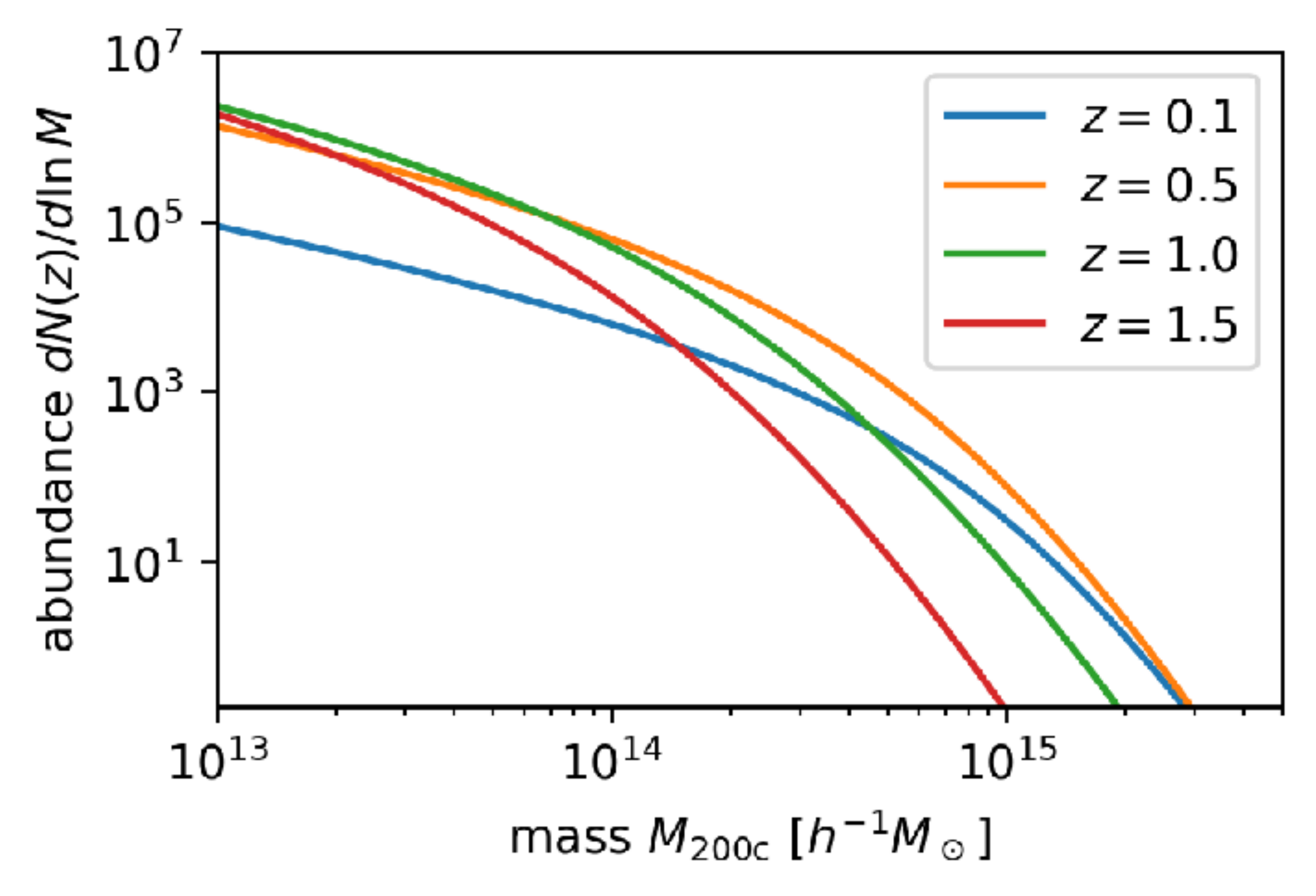
halo observable function



clusters

halos

halo mass function



observable—mass relation

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

halo mass function

cluster cosmology = cluster selection + mass calibration

SPT Clusters with DES and HST Weak Lensing. I. Cluster Lensing and Bayesian Population Modeling of Multi-Wavelength Cluster Datasets
Bocquet, Grandis, Bleem, Klein, Mohr, DES, SPT
(arXiv:2310:12213 — Phys. Rev. D 2024, 110, 083509)

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(arXiv:2310:12213 — Phys. Rev. D 2024, 110, 083510)

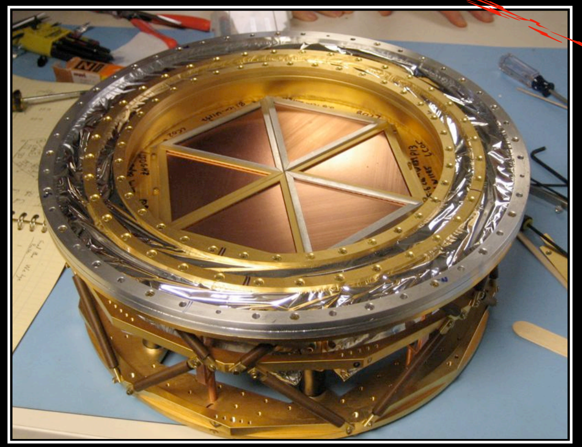
Image credit: SPT 2018 winter-overs Adam & Joshua

The South Pole Telescope (SPT)

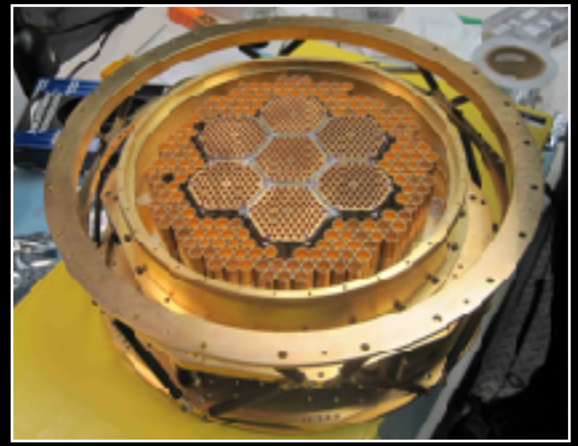
10-meter sub-mm quality wavelength telescope

90, 150, 220 GHz and
1.6, 1.2, 1.0 arcmin resolution

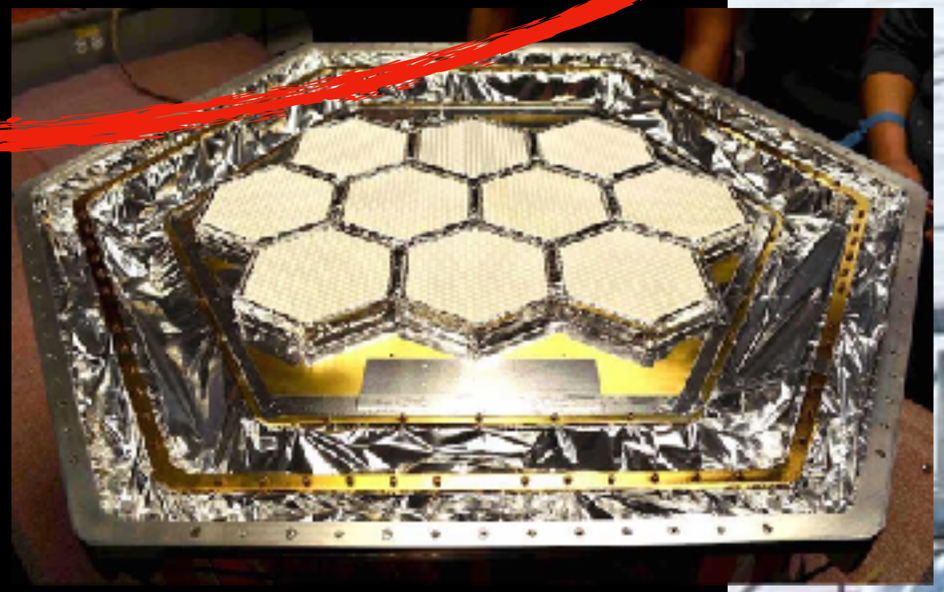
2007: SPT-SZ
960 detectors
90,150,220 GHz



2012: SPTpol
1600 detectors
90,150 GHz
+Polarization

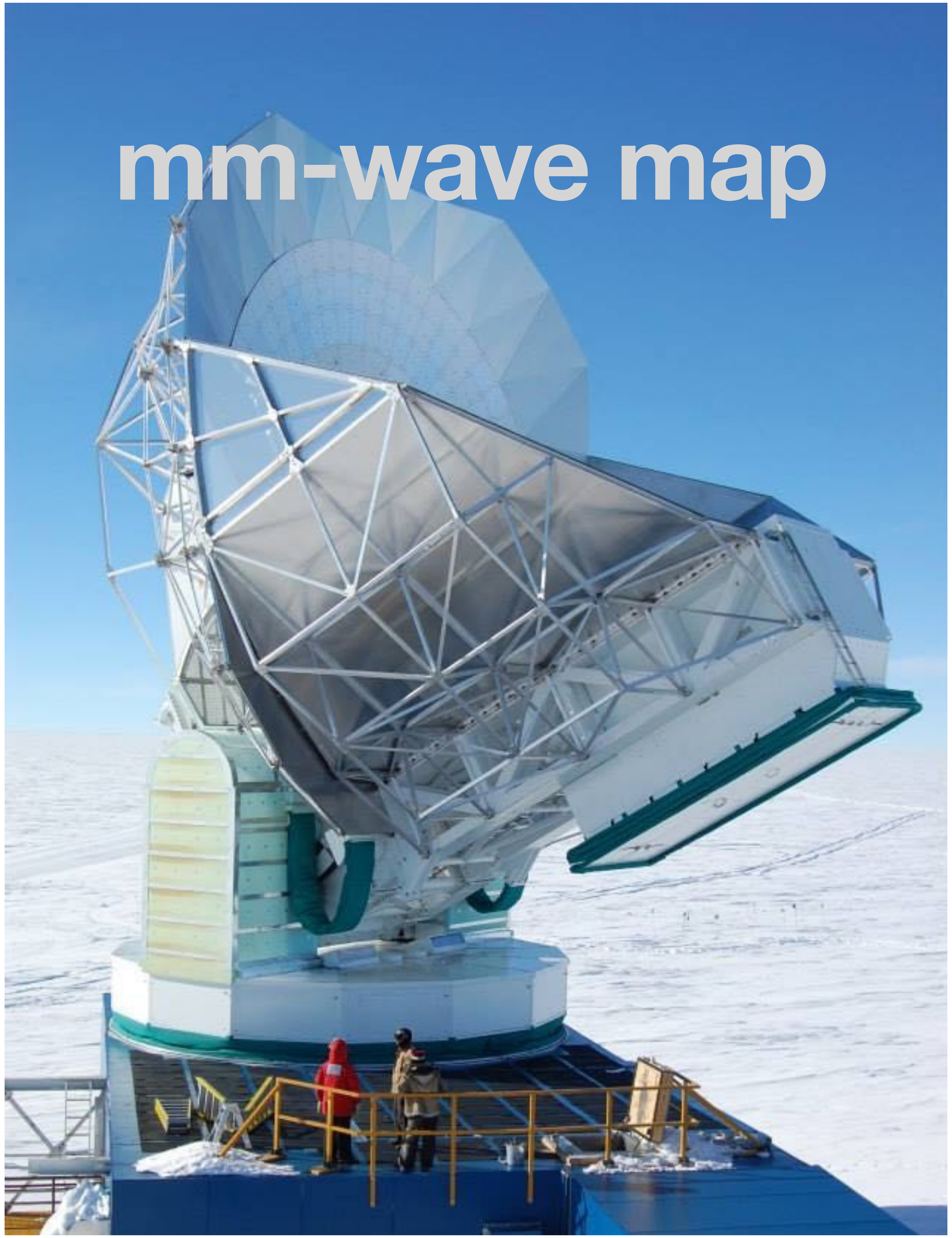


2017: SPT-3G
~15,200 detectors
90,150,220 GHz
+Polarization

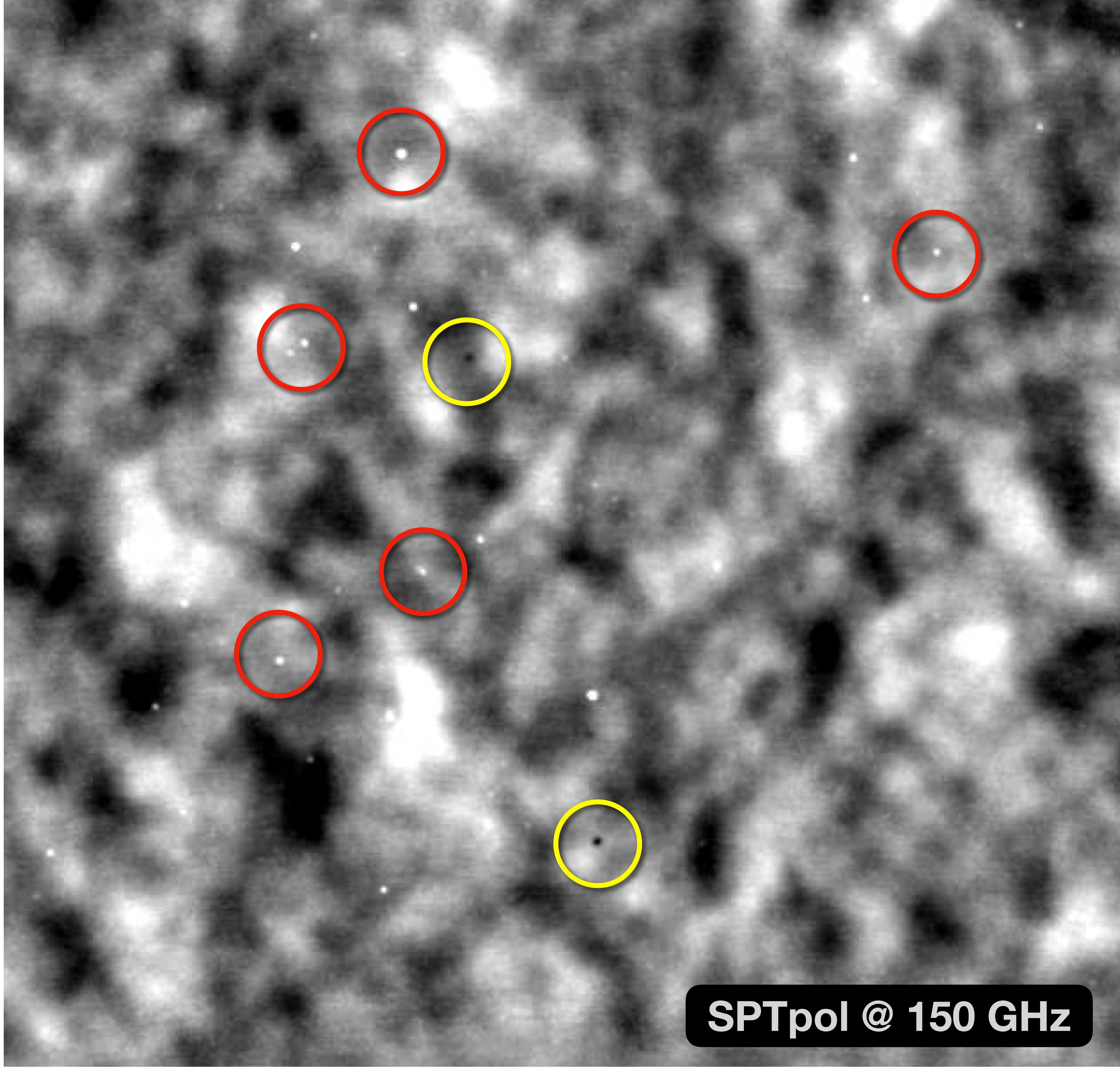


Funded By:

U.S. DEPARTMENT OF ENERGY

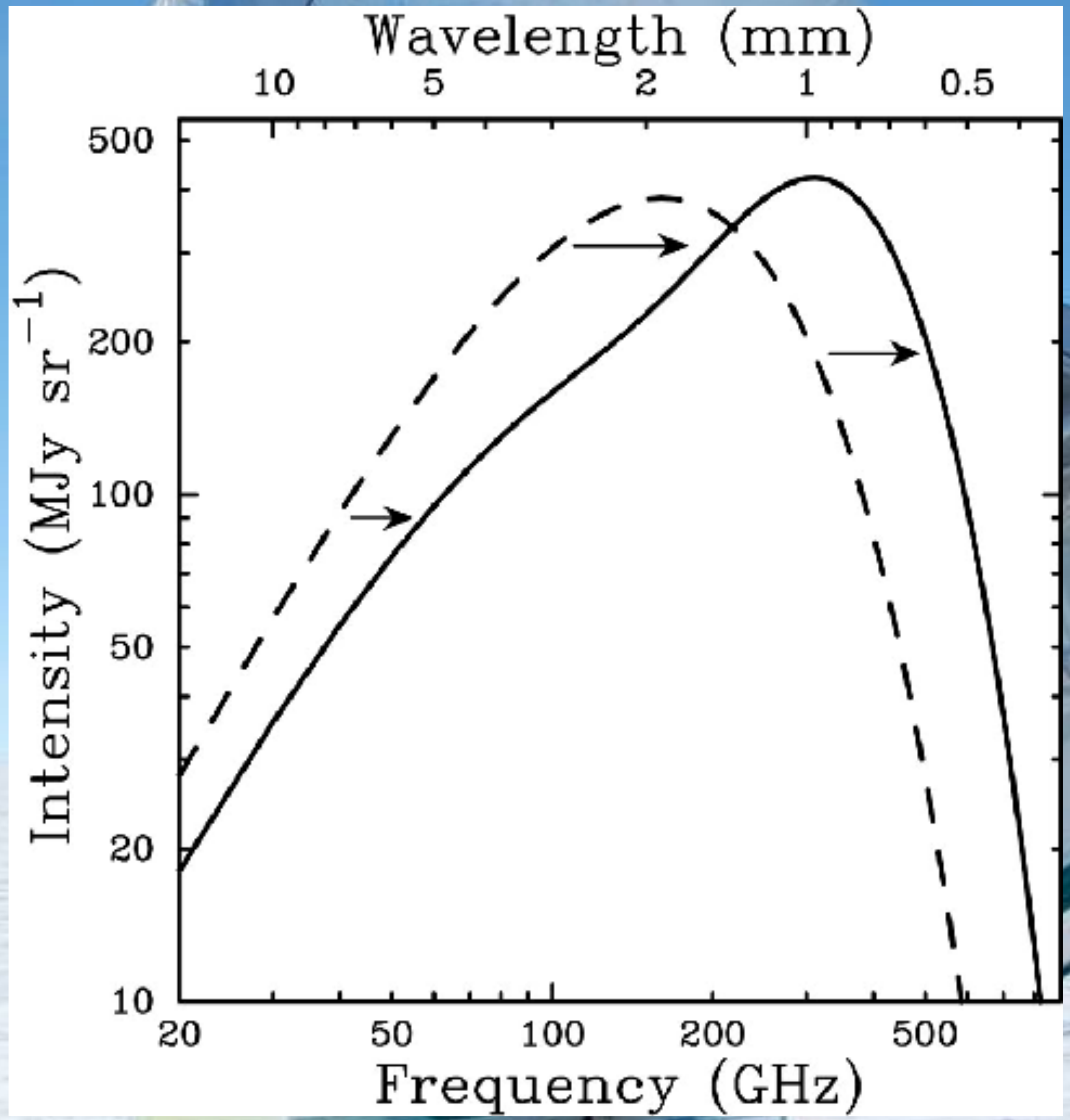


AstroParticle Symposium 2024

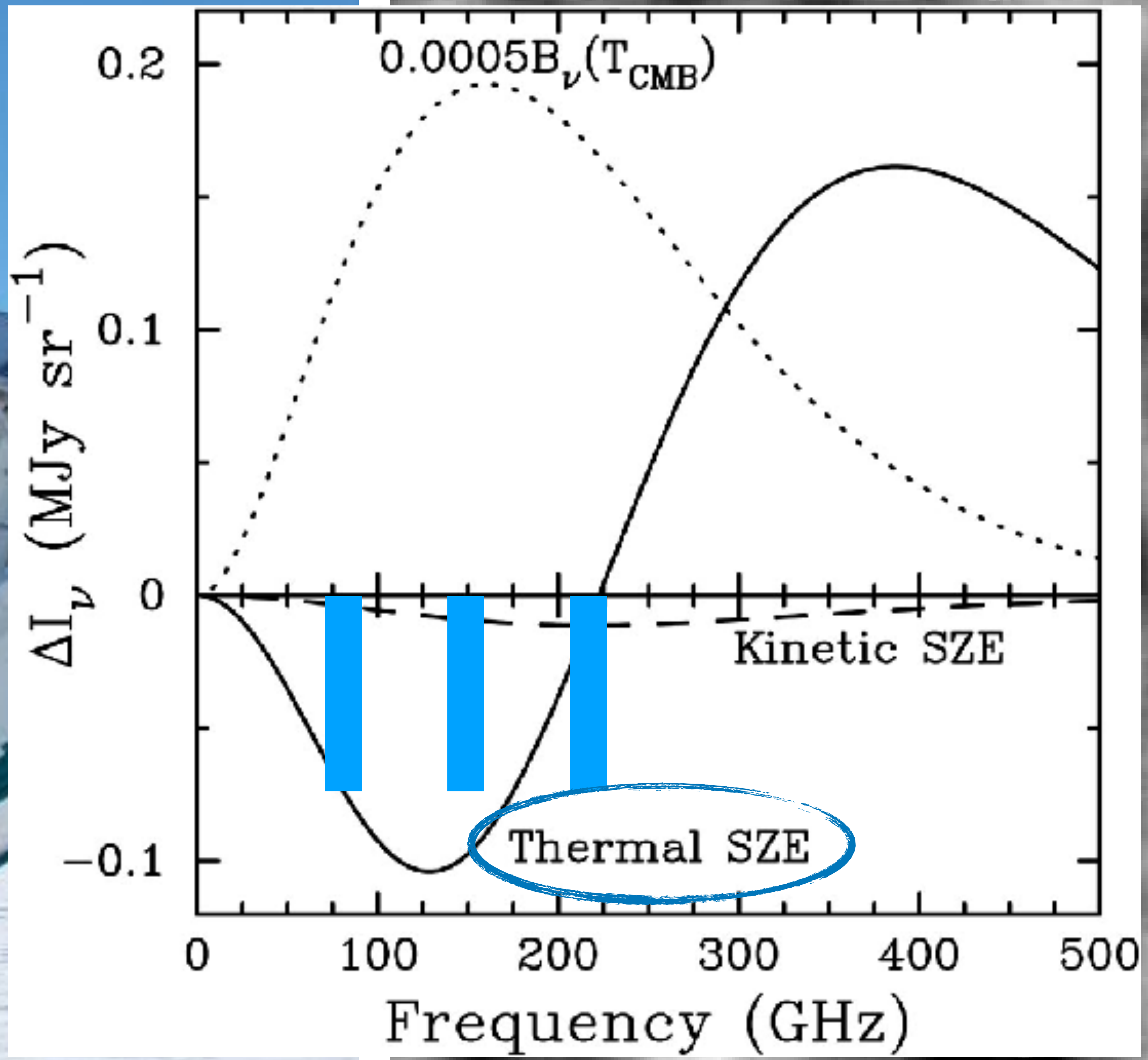


Find clusters

Sunyaev-Zel'dovich (SZ) Effect



CMB spectrum

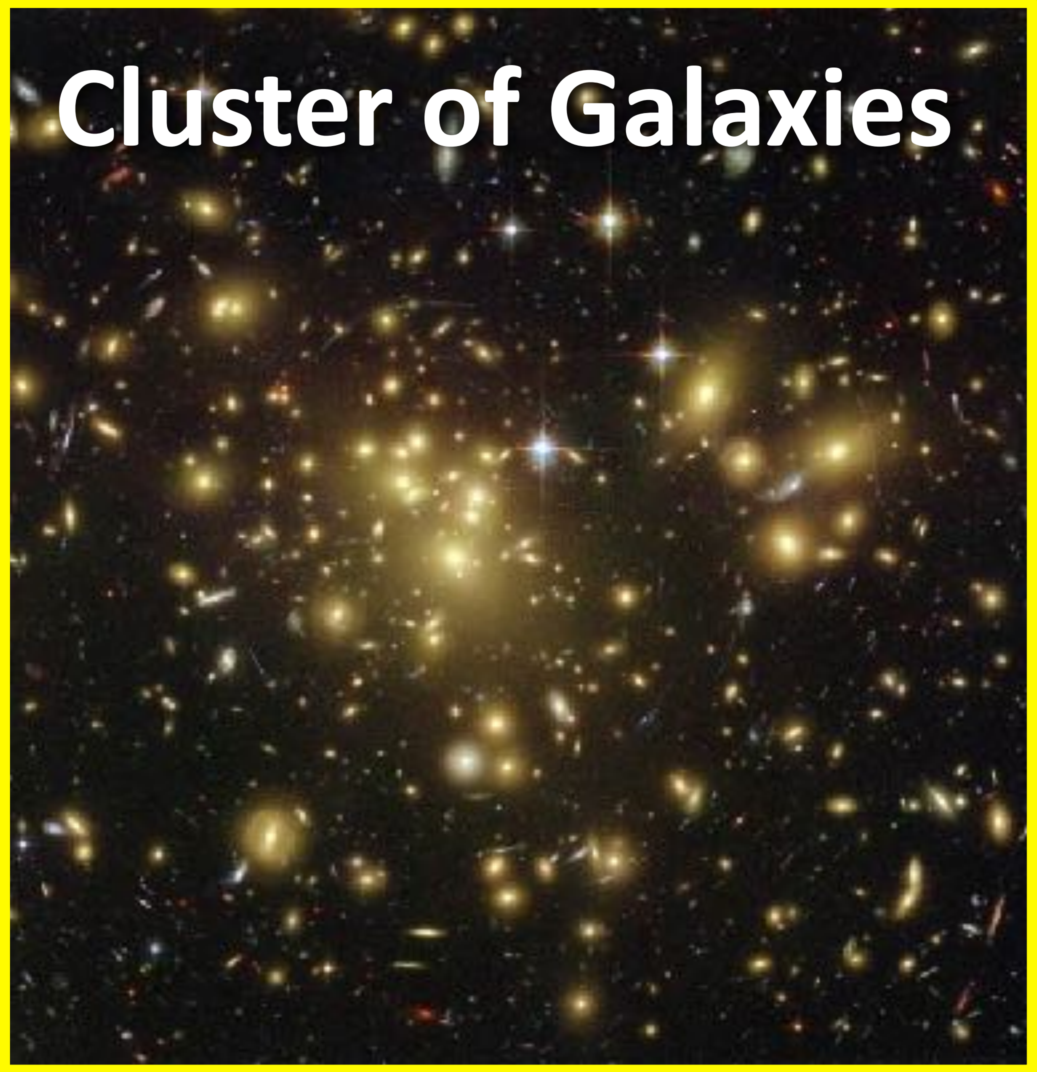


SZ spectrum

Clean and well-understood selection of cluster candidates

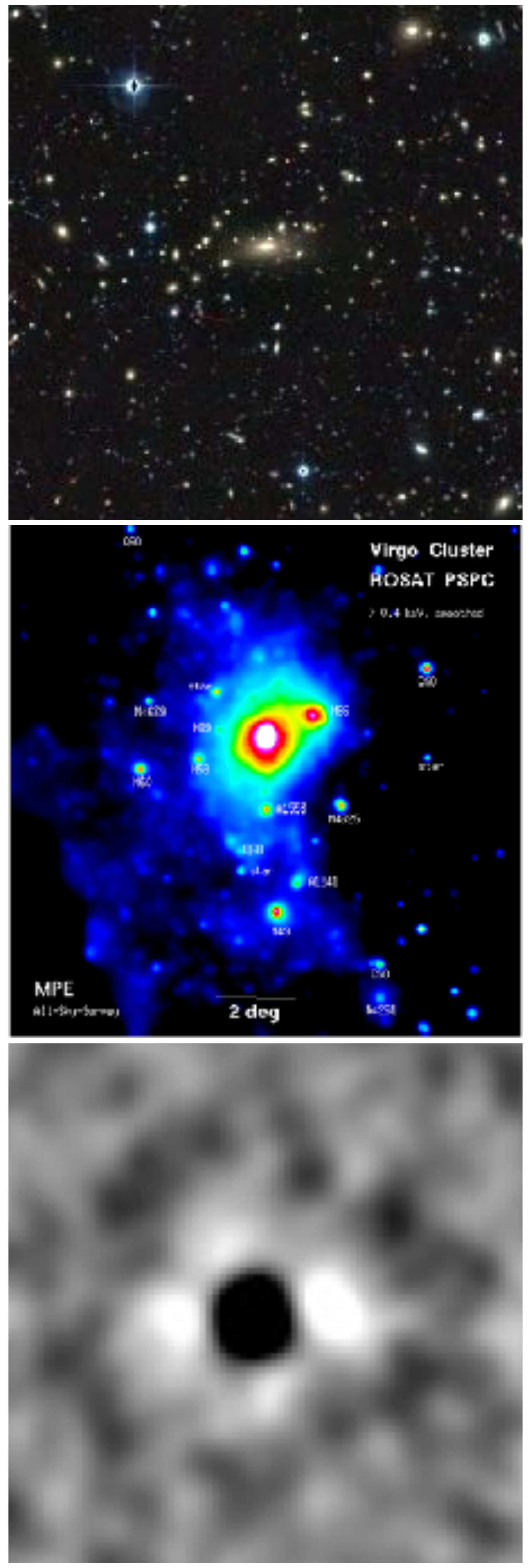
Out to highest redshifts where clusters exist!

SPTpol @ 150 GHz

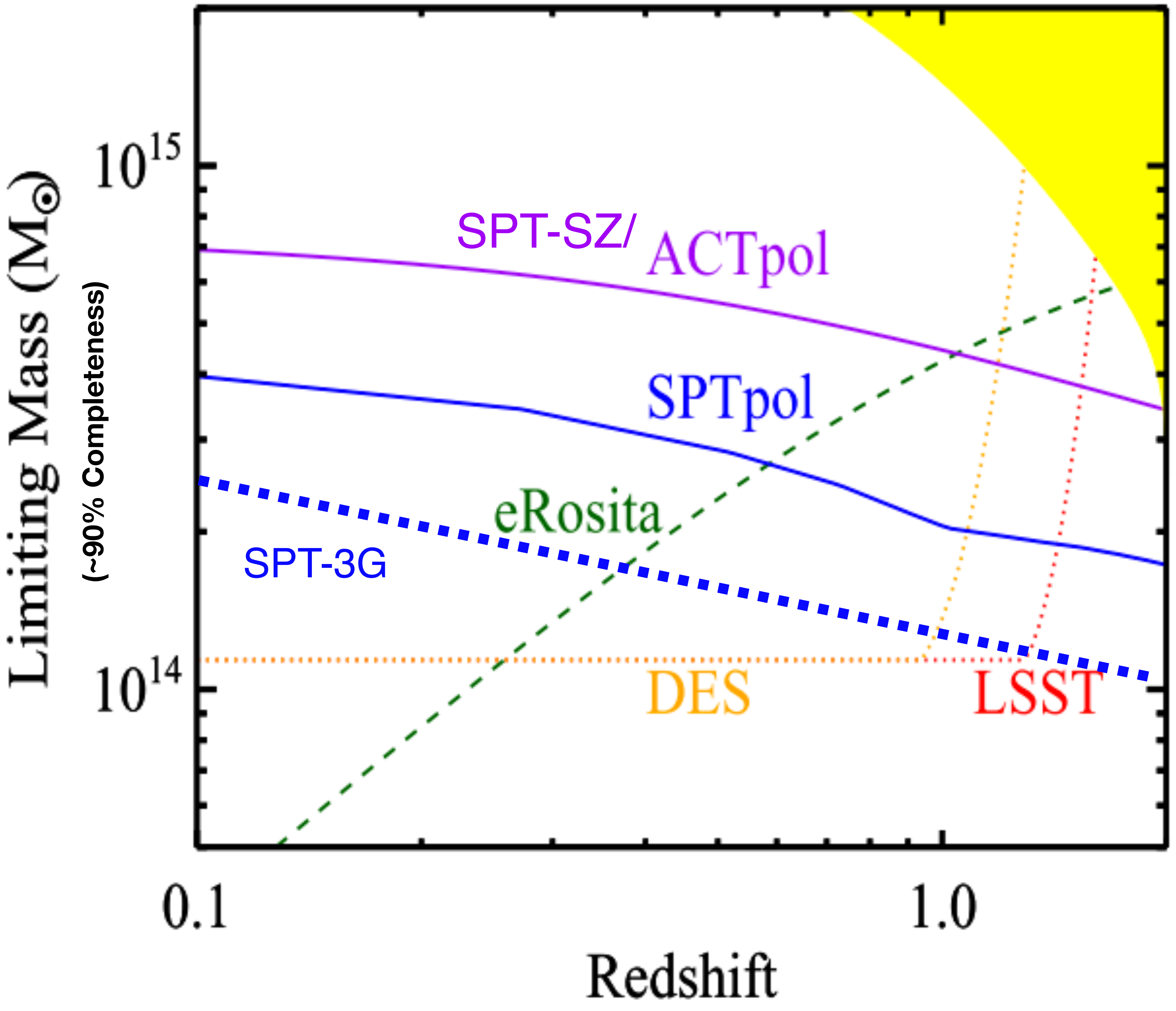


Why use SZ-selected clusters?

Three approaches: X-ray, Optical, SZ



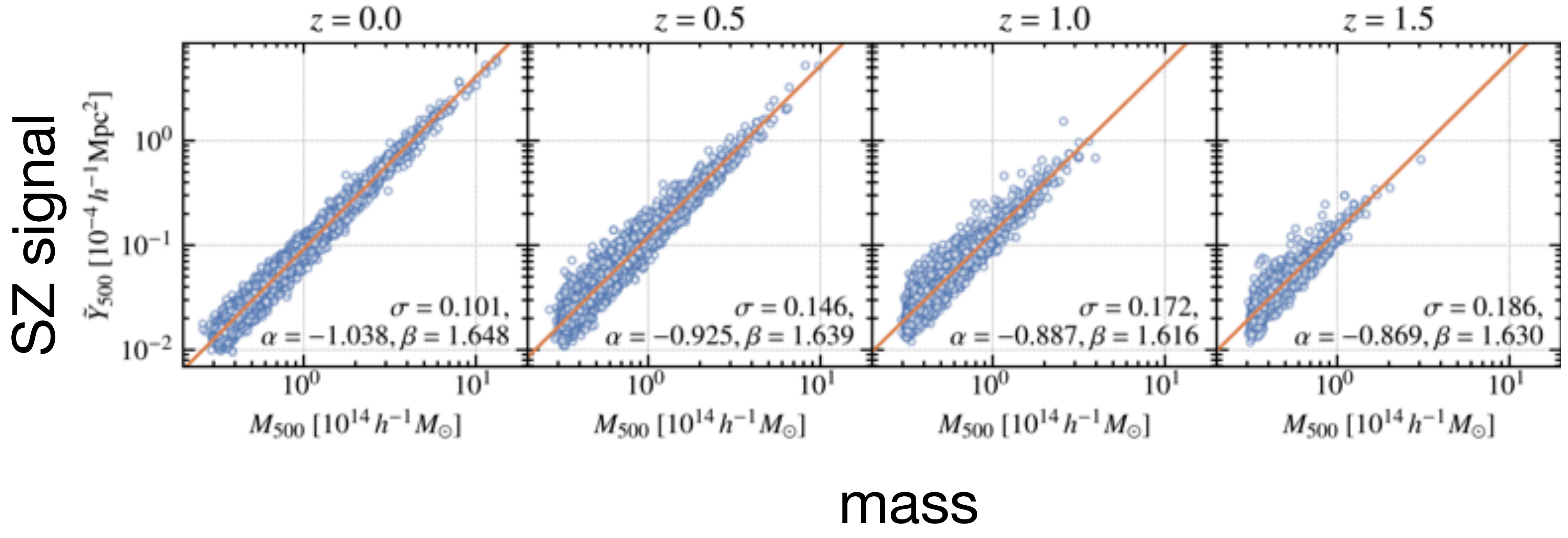
Weinberg et al. 2013

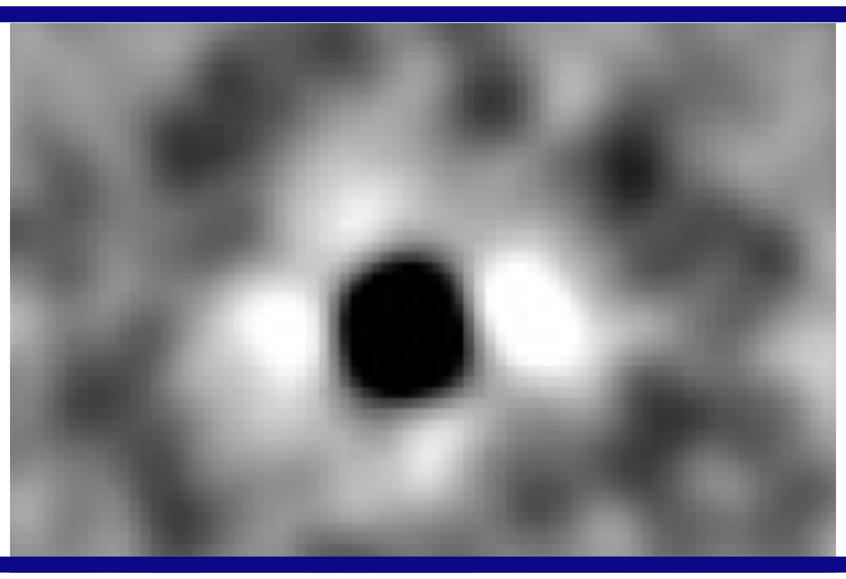


SZ: clean, well-understood selection

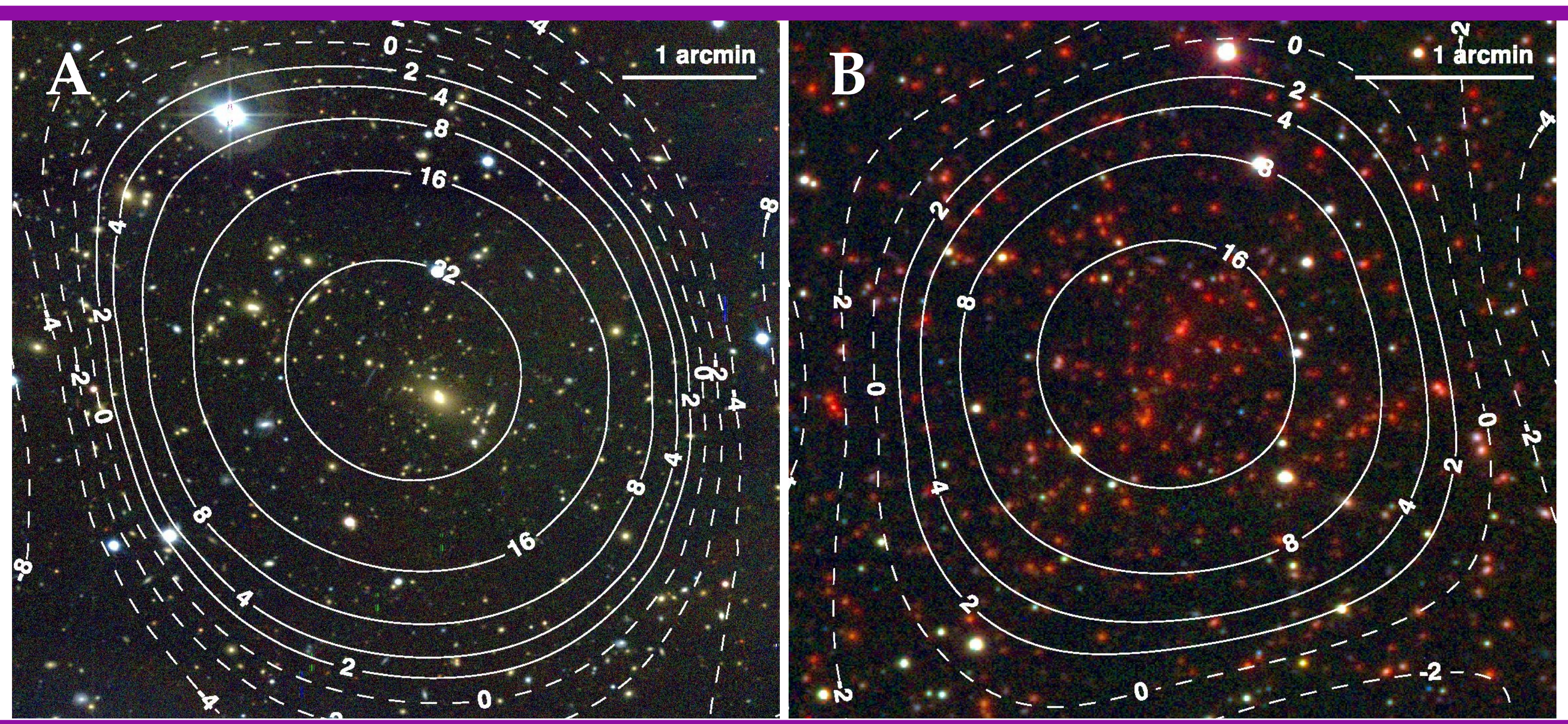
Complementarity with other methods

Kéruzoré et al. 2023

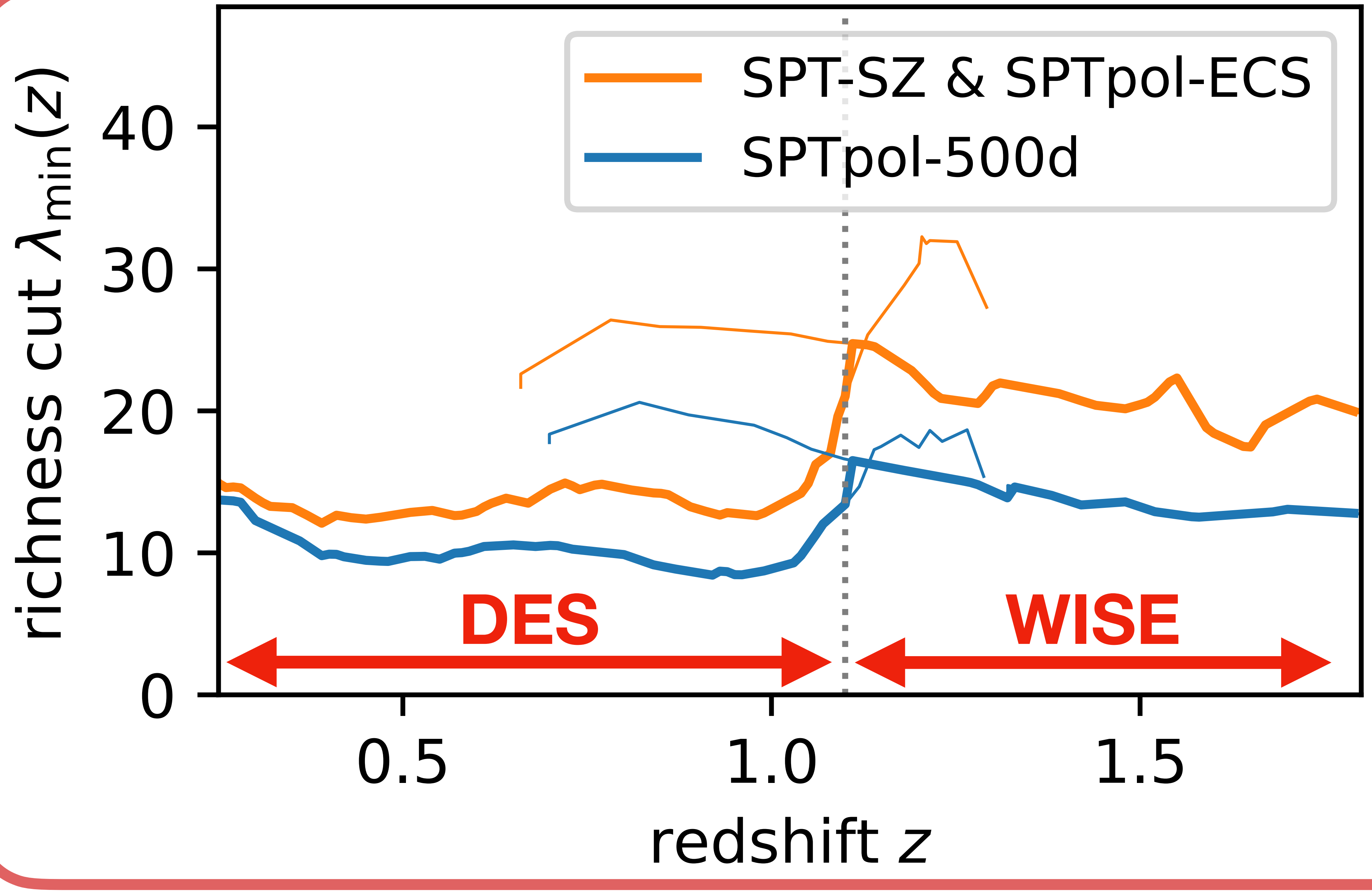




How to confirm SZ candidates?



Measure richness (≅number of cluster member galaxies) and redshift



Get rid of chance associations (with SPT noise fluctuation)

Calibrate probability of chance association by measuring (λ, z) at random locations

Establish $\lambda_{min}(z)$ to achieve target purity (> 98%)

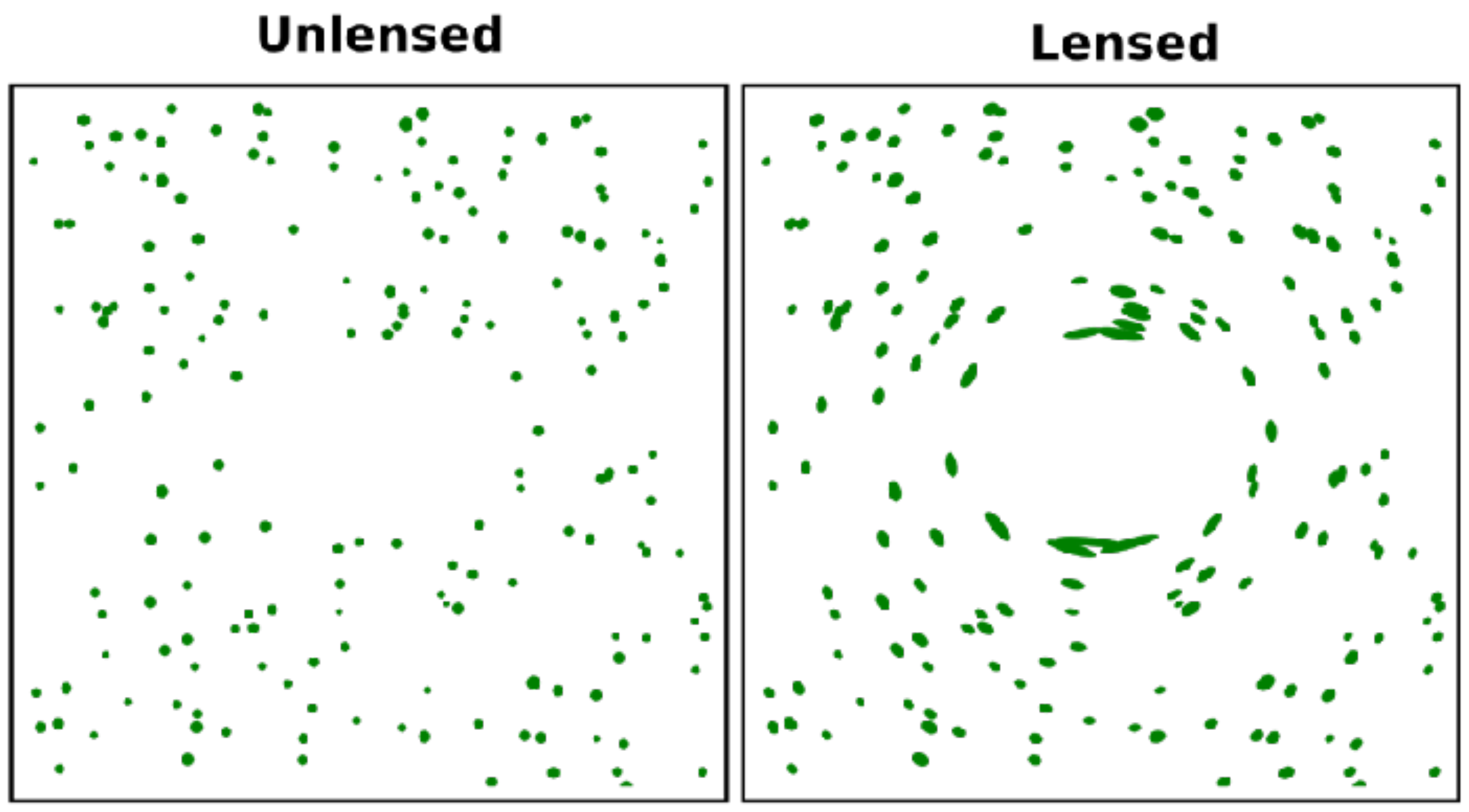
(Klein+18,24; Bleem+24)

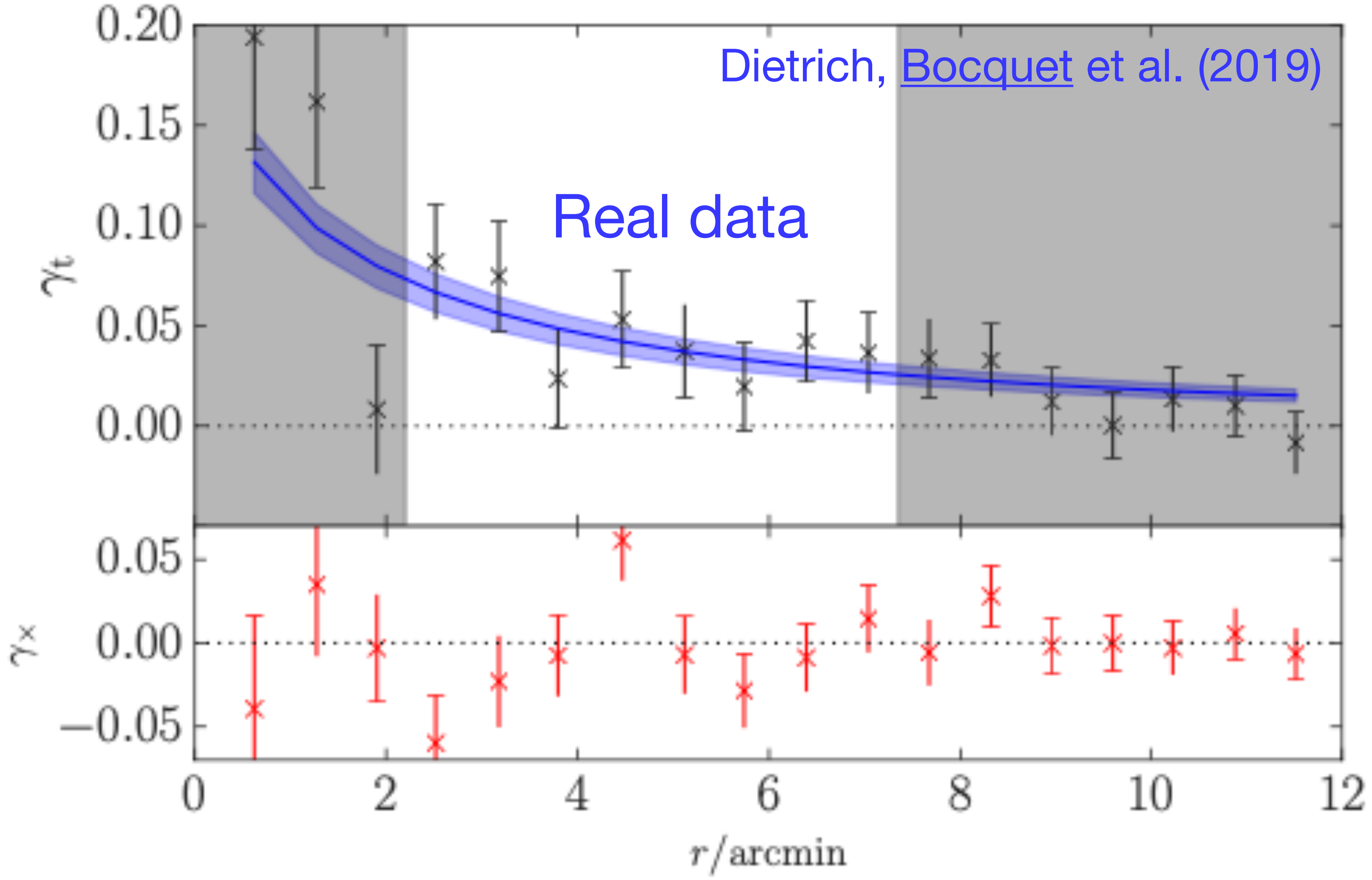
Mass Calibration I

How do the observables relate to halo mass?

- We *could* use predictions from first principles (e.g., hydrostatic equilibrium) or numerical simulations
    - Systematically limited by uncertain astrophysics
- Weak-lensing-to-mass relation is known within few percents

Idealized (exaggerated) situation





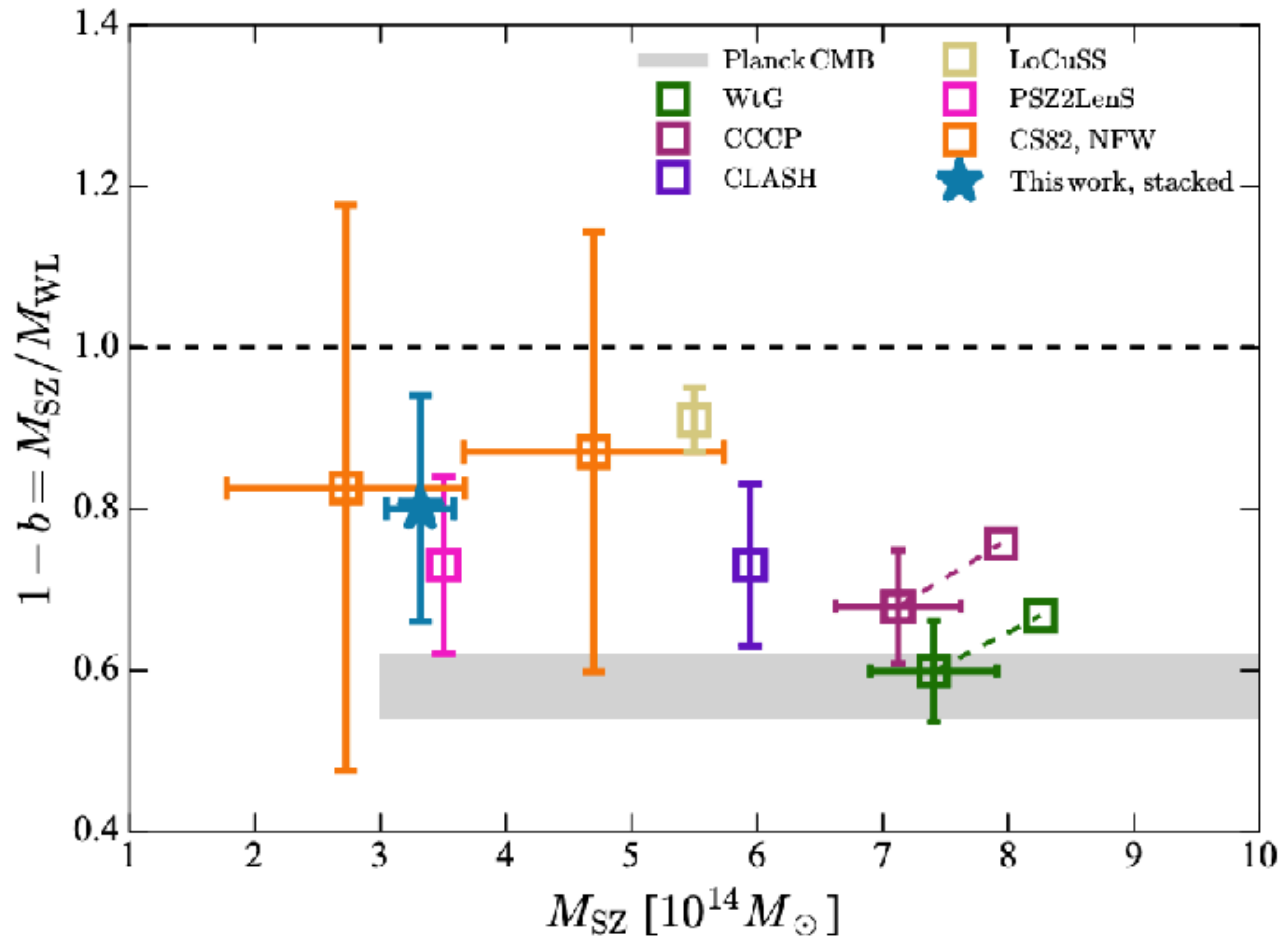
(b) Tangential shear profile of SPT-CL J0254−5857.

Mass Calibration II. Weak Lensing

Robust observable—mass relations

- We *could* use predictions from first principles (e.g., hydrostatic equilibrium) or numerical simulations
  - Systematically limited by uncertain astrophysics
- Weak-lensing-to-mass relation is known within few percents
  - Used to demonstrate that **hydrostatic mass ≠ halo mass**
  - **With lensing** measurements of sample clusters, ***we empirically* calibrate the observable—mass relations**

Medezinski+ 18



The Dark Energy Survey

5000 deg^2 galaxies & weak lensing

Catalog of SPT-selected cluster candidates needs

- Confirmation
- Cluster redshifts
- Weak-lensing (mass) measurement

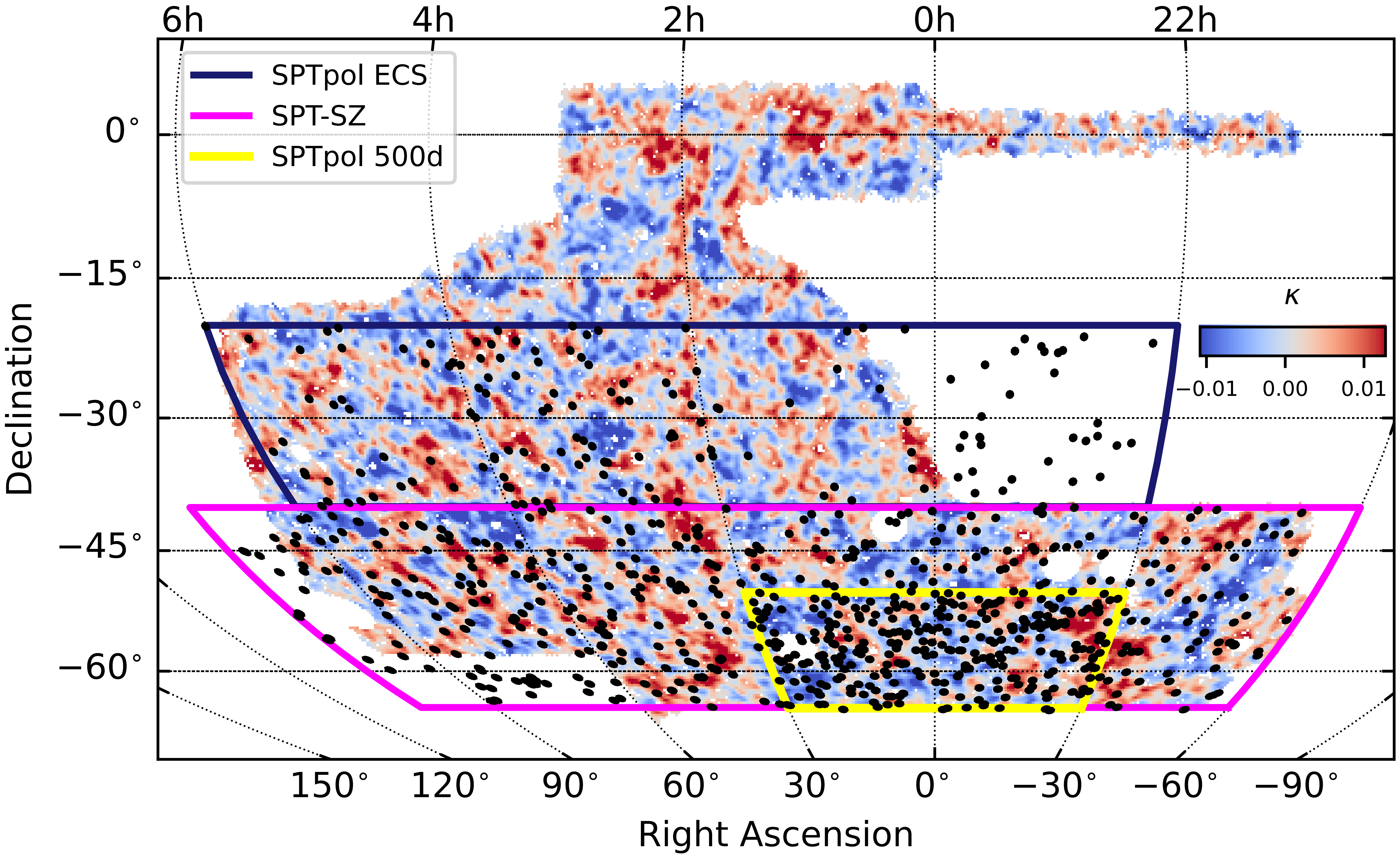
all of which DES was designed for

(here we use DES Year 3 data = Y3)

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

SPT Clusters and the Dark Energy Survey

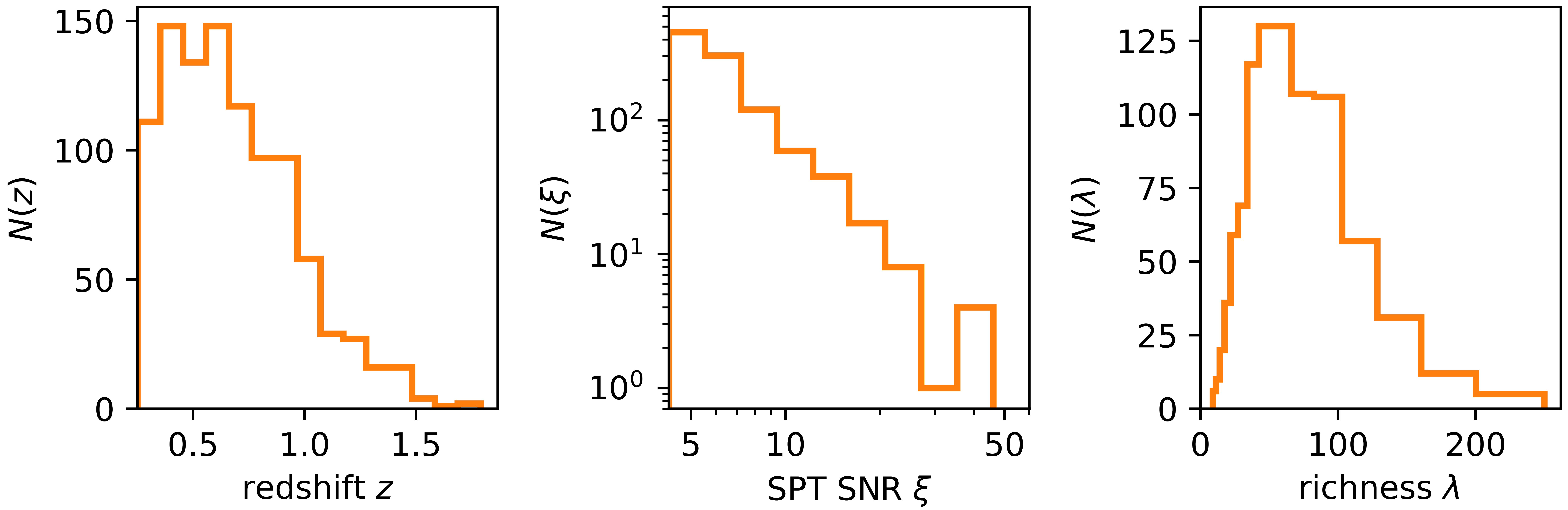
3,600 deg² overlap



Bleem+15,20,24
Klein+24
Bocquet+24II

SPT(SZ+pol) Cluster Sample

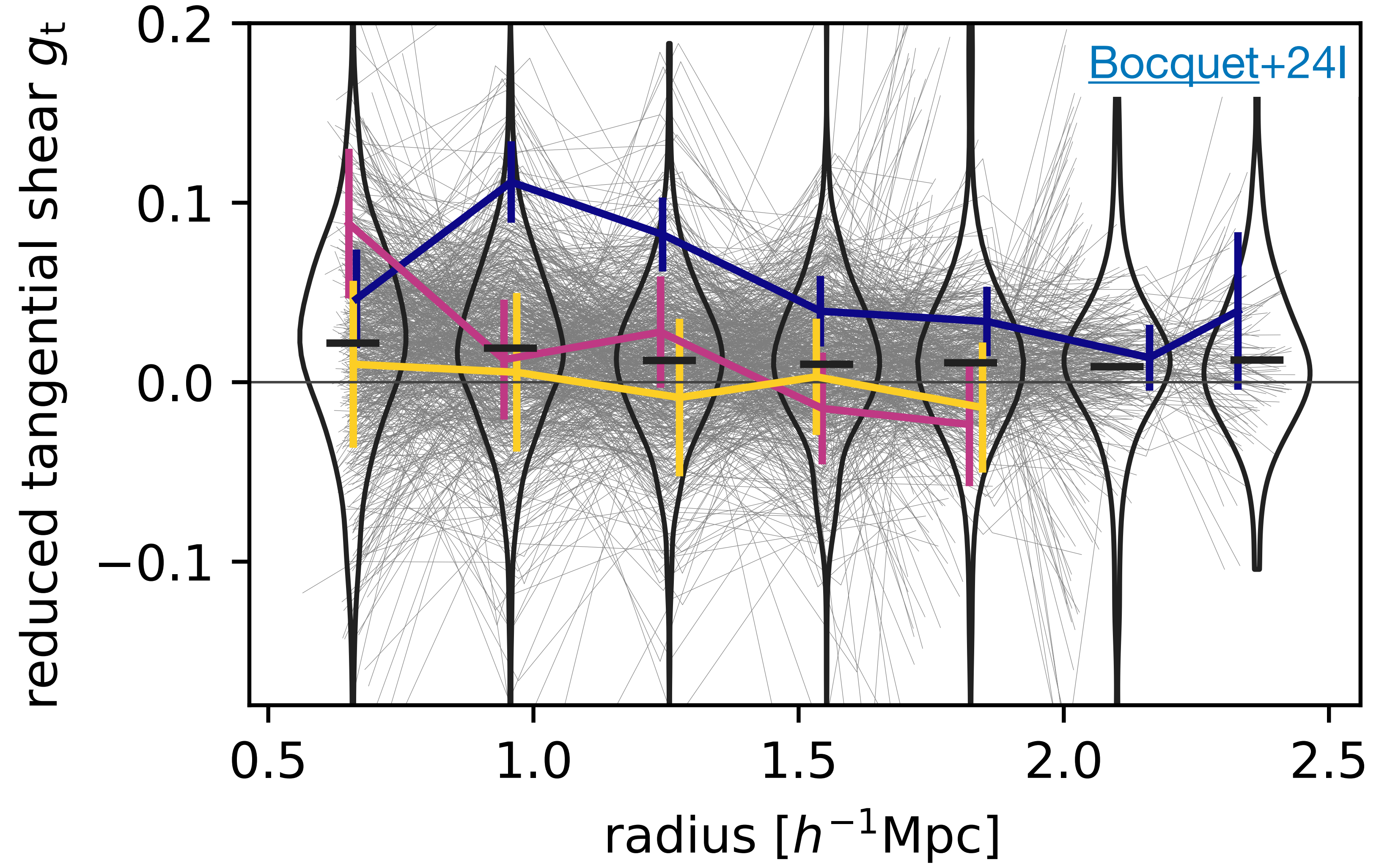
1,005 confirmed clusters above $z > 0.25$ over 5,200 deg²

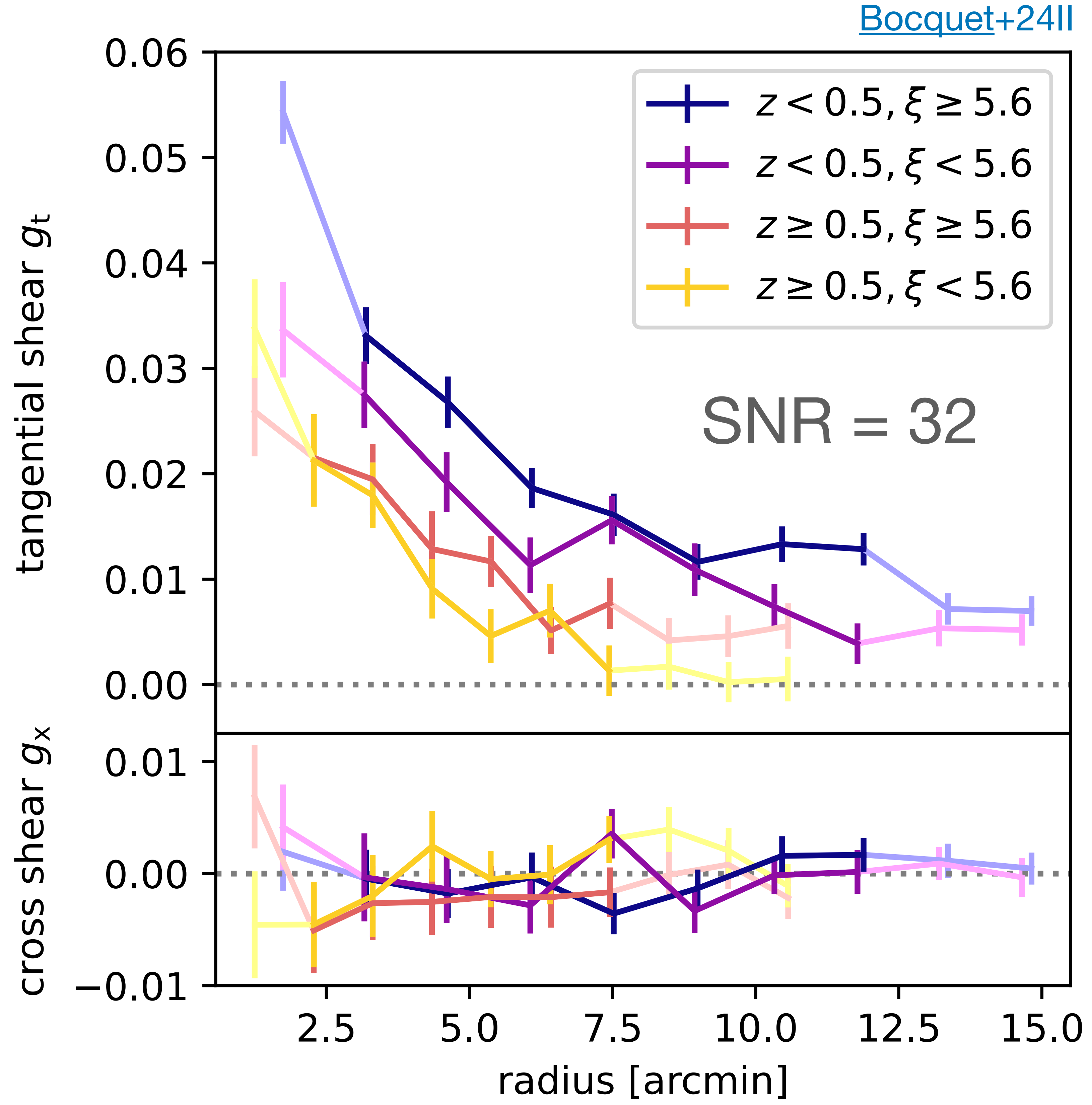


Cluster lensing analysis

Shear profiles

- Almost 700 SPT clusters (redshift 0.25—0.95) with DES Y3 shear
  - For the experts:
    - Analysis uses individual cluster shear profiles (Stacks are shown for visualization purposes)
    - Same source selection as in DES Y3 3x2pt
      - Same photo-z and shear calibrations
    - Radial range: $0.5 < r\ [h^{-1}\mathrm{Mpc}] < 3.2 / (1 + z)$ (avoid cluster centers, stay in 1-halo term regime)
- 39 high-redshift clusters (redshift 0.6—1.7) with the Hubble Space Telescope
  Schrabback+18, Schrabback,Bocquet+21, Zohren,Schrabback,Bocquet+22





Likelihood Function I

Bayesian Population Modeling

Let us generate a cluster dataset!

cosmological — halo mass function

astrophysical — observable—mass relation

observational — telescope, detector, atmosphere, etc.

$$\frac{d^3N(\boldsymbol{p})}{dM\,dz\,dV}\frac{dV(z,\boldsymbol{p})}{d\Omega_\mathrm{s}} \xrightarrow{\text{Poisson draw}} \{M, z\} \xrightarrow{\text{OMR + scatter}} \{\zeta, \lambda, M_\mathrm{WL}, z\} \xrightarrow{\text{measurement noise}} \{\xi, \lambda, \boldsymbol{g}_\mathrm{t}, z\}$$

Differential multi-observable cluster abundance

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

marginalize over latent variables

Likelihood Function II

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

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

Likelihood Function II

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

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

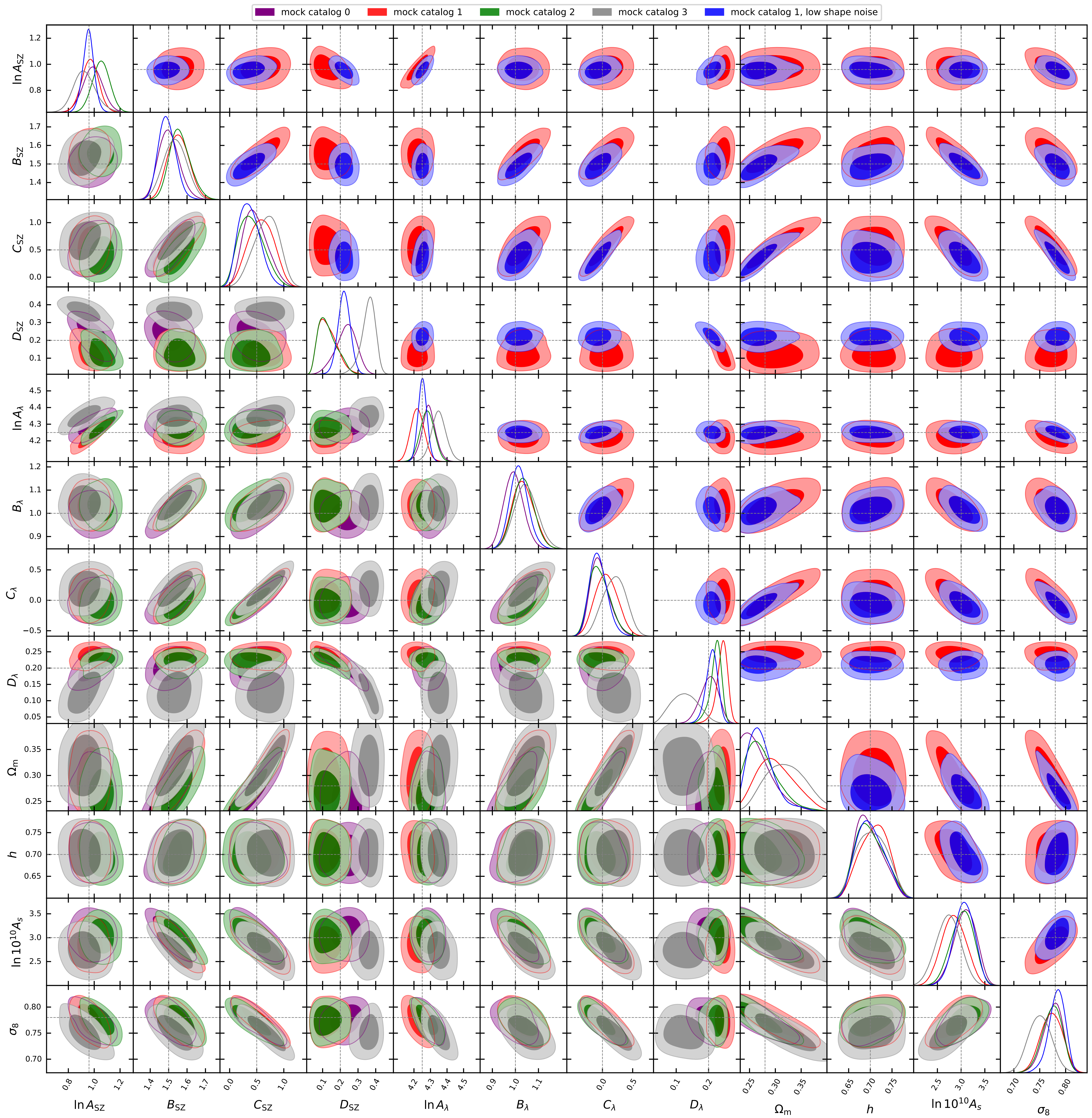
can be re-written as

$$\ln \mathscr{L}(\boldsymbol{p}) = \sum_i \ln \int_{\lambda_\mathrm{cut}}^{\infty} d\lambda \left.\frac{d^3 N(\boldsymbol{p})}{d\xi\, d\lambda\, dz}\right|_{\xi_i, z_i} - \int_{z_\mathrm{cut}}^{\infty} dz \int_{\xi_\mathrm{cut}}^{\infty} d\xi \int_{\lambda_\mathrm{cut}}^{\infty} d\lambda \frac{d^3 N(\boldsymbol{p})}{d\xi\, d\lambda\, dz} + \sum_i \ln \frac{\left.\frac{d^4 N(\boldsymbol{p})}{d\xi\, d\lambda\, d\boldsymbol{g}_\mathrm{t}\, dz}\right|_{\xi_i, \lambda_i, \boldsymbol{g}_{\mathrm{t},i}, z_i}}{\int_{\lambda_\mathrm{cut}}^{\infty} d\lambda \left.\frac{d^3 N(\boldsymbol{p})}{d\xi\, d\lambda\, dz}\right|_{\xi_i, z_i}} + \mathrm{const}\,.$$

cluster abundance likelihood

$$\frac{\frac{d^4 N(\boldsymbol{p})}{d\xi\, d\lambda\, d\boldsymbol{g}_\mathrm{t}\, dz}}{\int_{\lambda_\mathrm{cut}}^{\infty} d\lambda \frac{d^3 N(\boldsymbol{p})}{d\xi\, d\lambda\, dz}} = \frac{P(\lambda, \boldsymbol{g}_\mathrm{t}, \xi, z\,|\,\boldsymbol{p})}{P(\lambda > \lambda_\mathrm{cut}, \xi, z\,|\,\boldsymbol{p})} \equiv P(\lambda, \boldsymbol{g}_\mathrm{t}\,|\,\lambda > \lambda_\mathrm{cut}, \xi, z, \boldsymbol{p})$$

conditional “mass calibration likelihood”



[Bocquet+24I](#)

Pipeline Verification

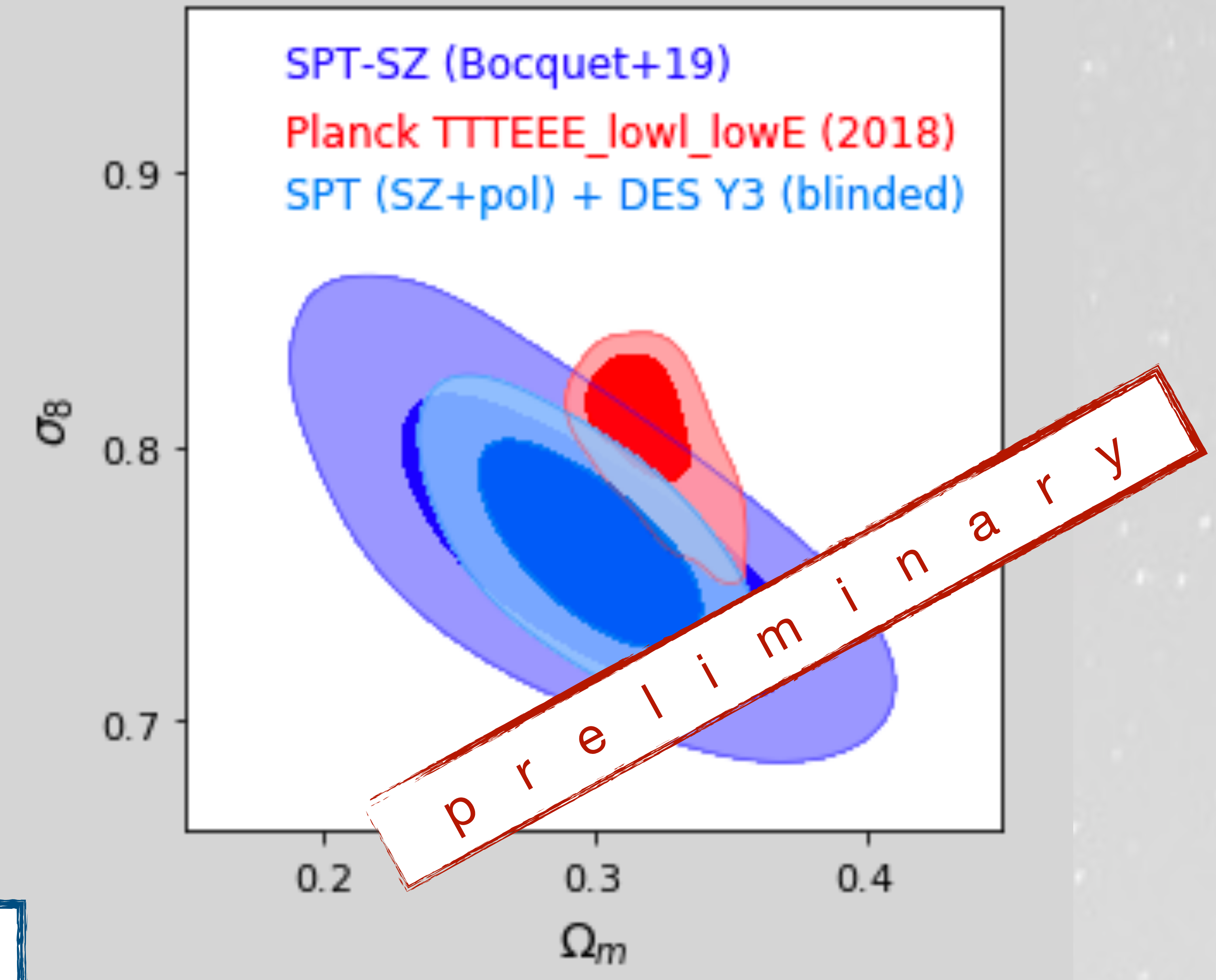
using mock datasets created from the model

- Create synthetic clusters from the halo mass function using observable—mass relations
- Analyze several statistically independent mock realizations
- Pipeline recovers input values
- We correctly implemented the analysis framework!

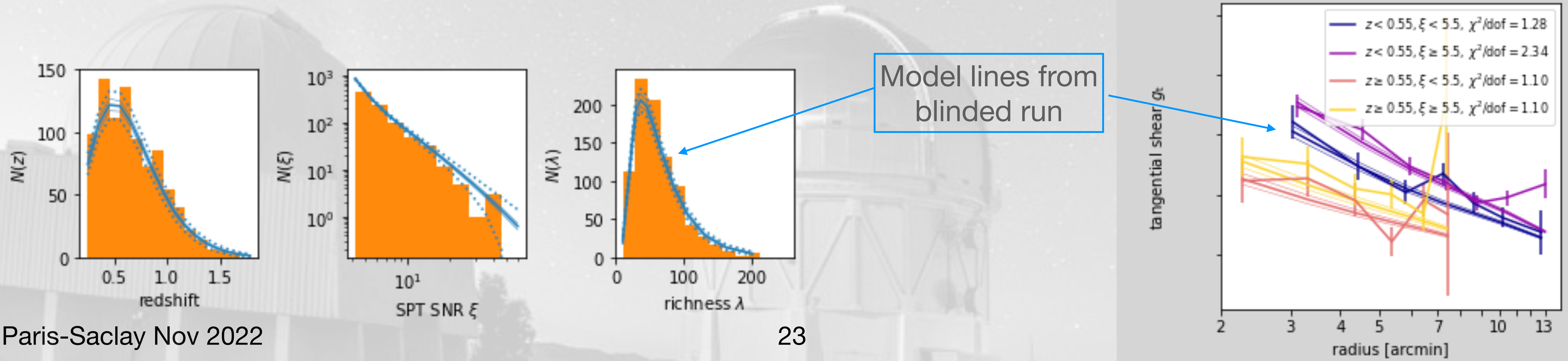
SPT-SZ + SPTpol + DES Year 3 Weak Lensing

Update on blinded results

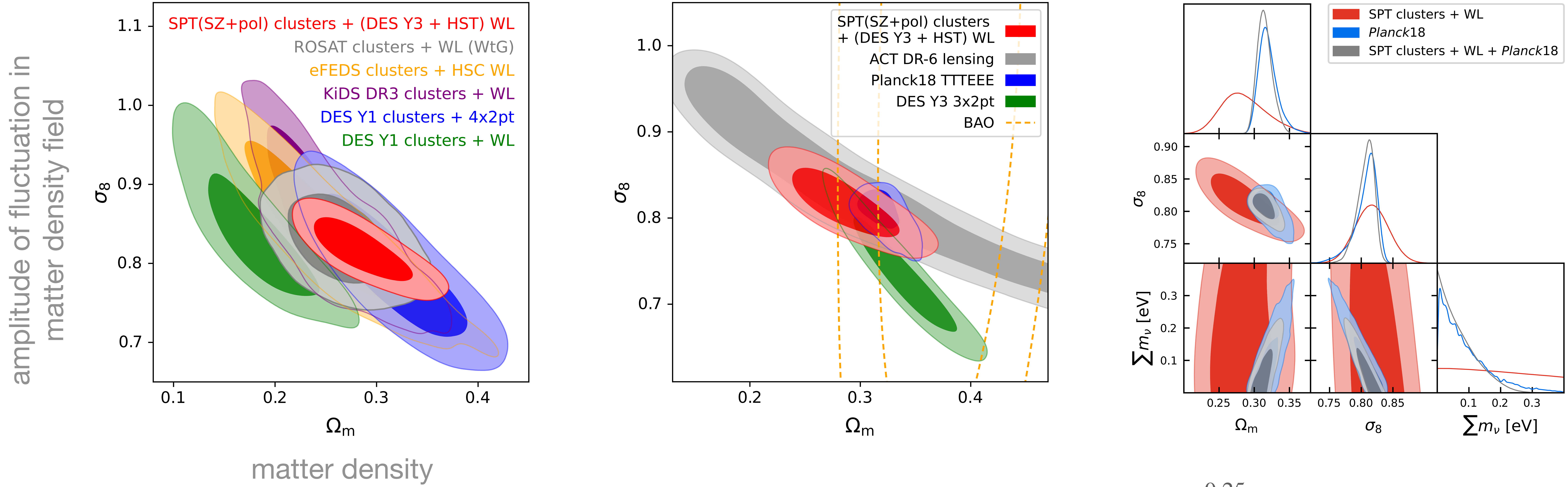
- Confirm robustness of lensing modeling blindly (centering, boost factors, radial cuts)
- Model is a good description of the data
- No roadblock toward unblinding!



Slide from AstroParticle Symposium 2022!



ΛCDM with massive neutrinos

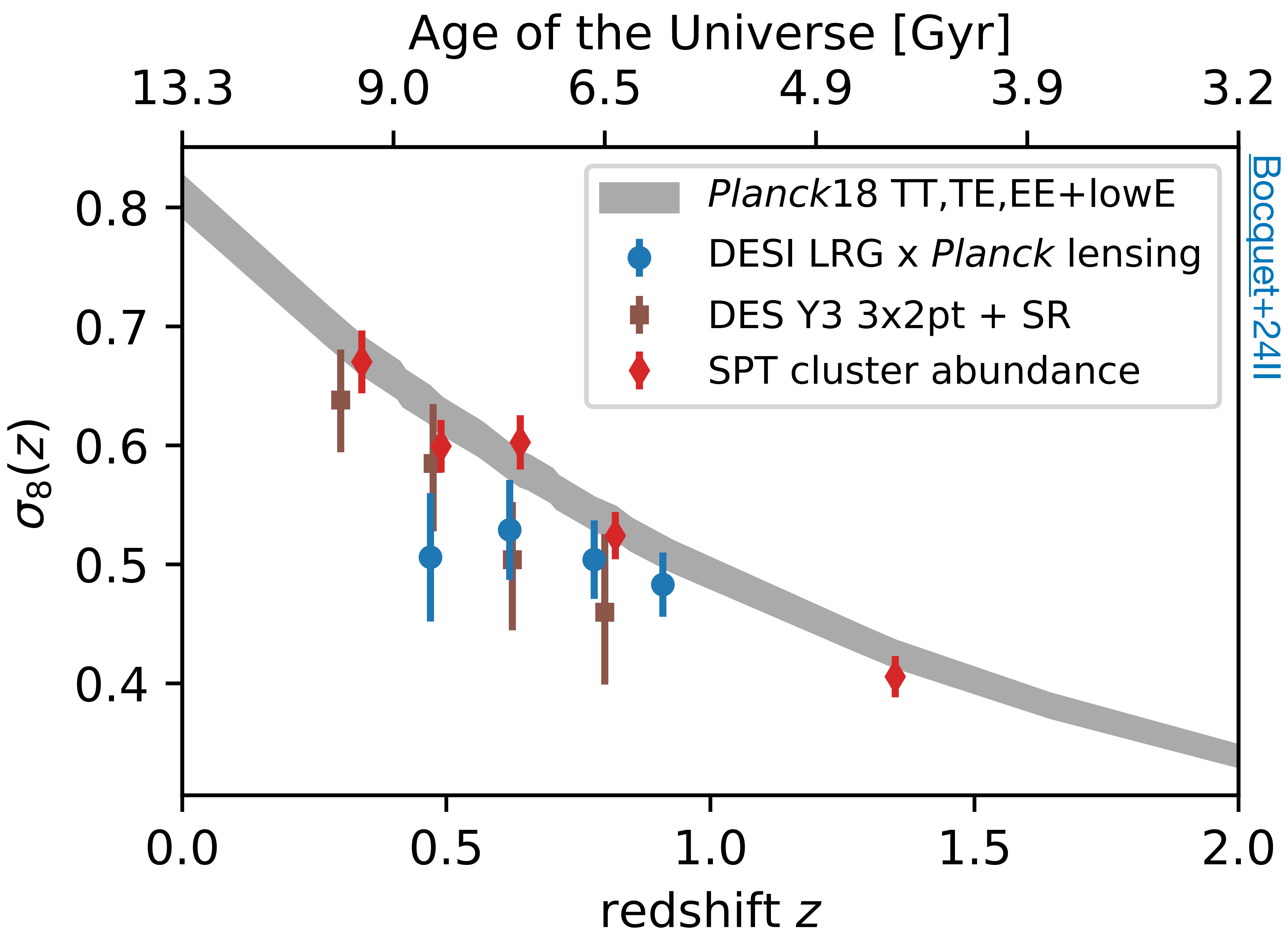


- Competitive constraints, especially on $S_8^{\mathrm{opt}} \equiv \sigma_8 \left(\Omega_\mathrm{m}/0.3\right)^{0.25}$
- No evidence for S_8 tension (difference with Planck 1.1 σ)
- In combination with Planck $\sum m_\nu < 0.18\,\mathrm{eV}\ (95\,\%\,\mathrm{C.L.})$

Tracing the Growth of Structure

Phenomenological test

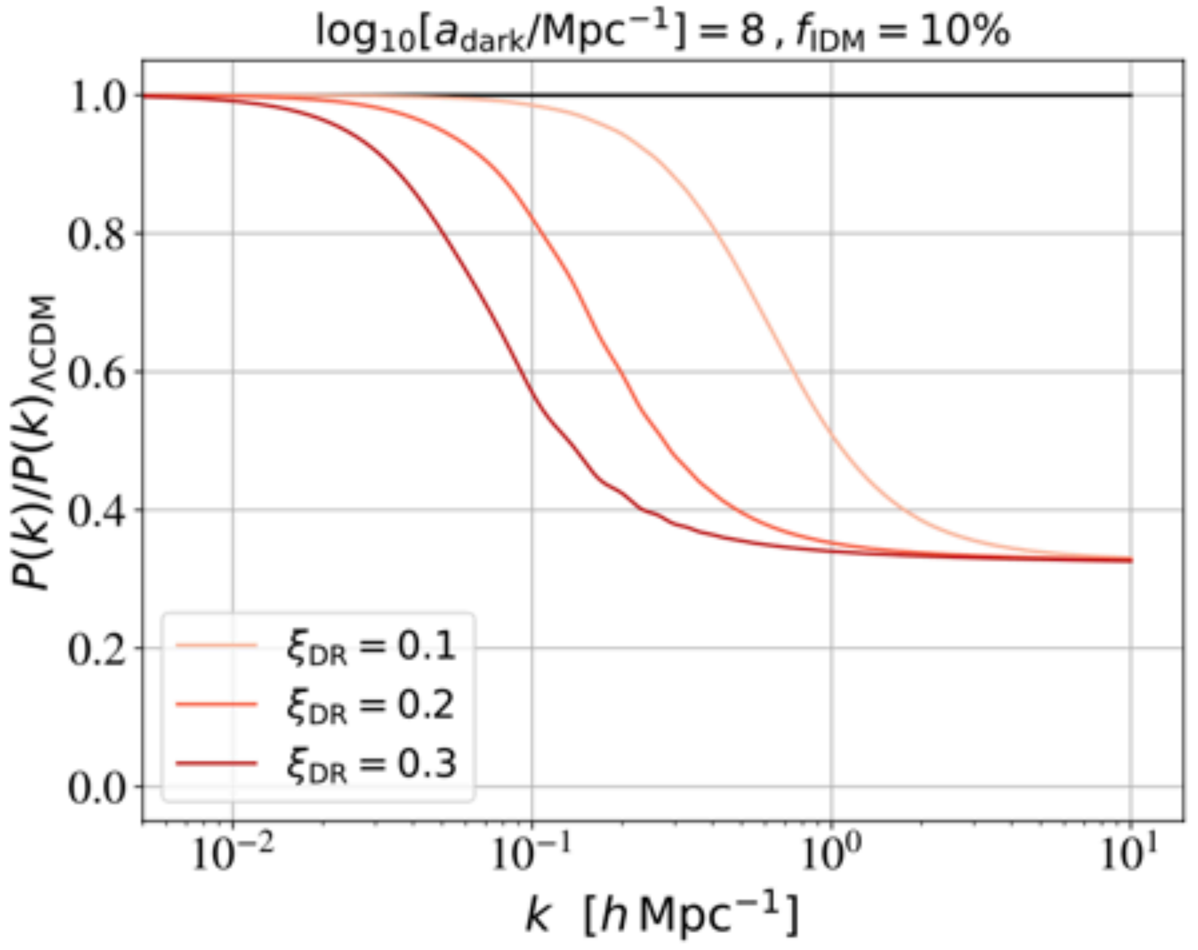
- Five bins in redshift with equal number of clusters
- Fit for independent amplitudes $\sigma_8(z)$
- With loose prior on Ω_m from the sound horizon at recombination θ_*
- Good agreement with ΛCDM model and *Planck* parameters from $z = 0.25$ to $z = 1.8$

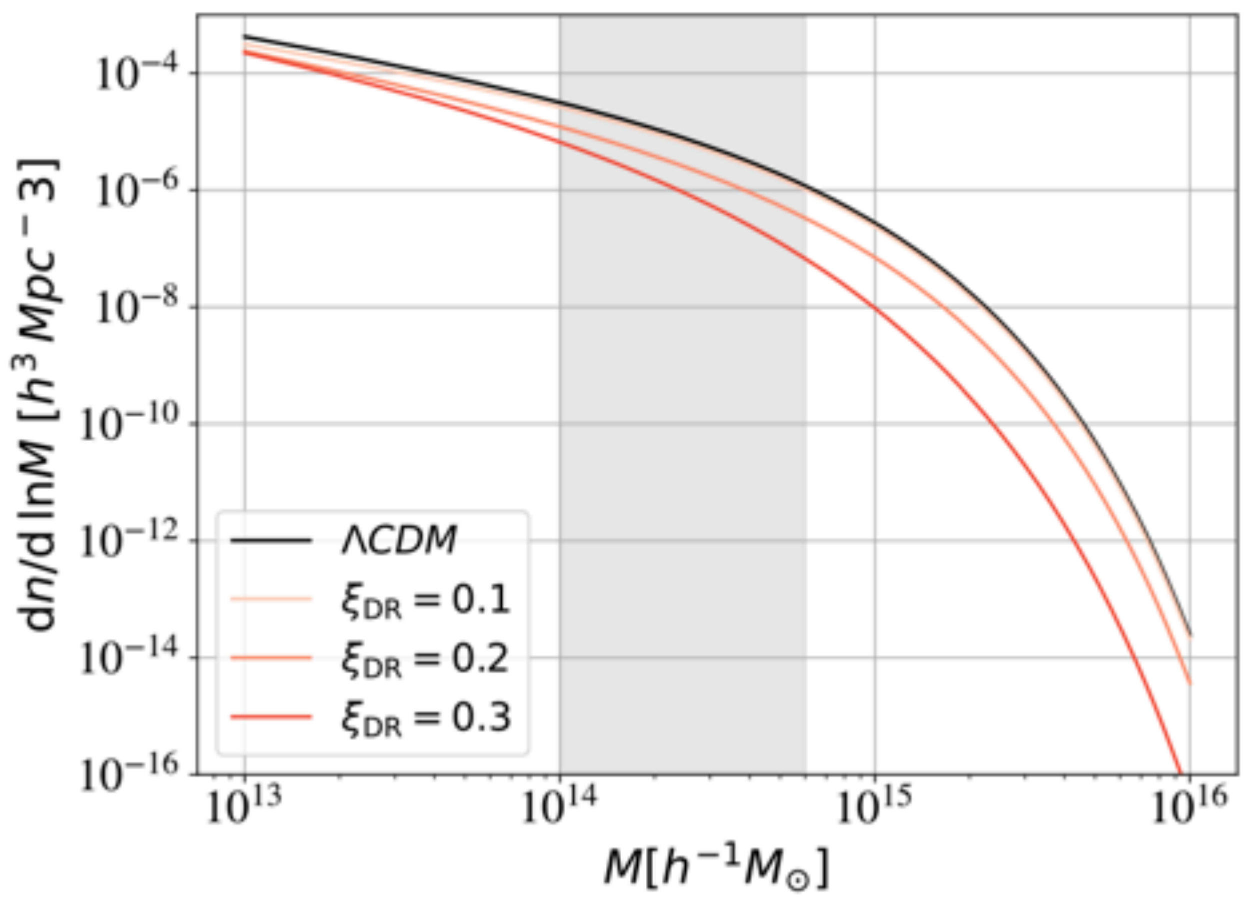


Bocquet+24II

Outlook
Select Work by PhD Students

Mazoun, Bocquet, Garny, Mohr, Rubira, Vogt 24
(arXiv:2312.17622)





Asmaa Mazoun

Interacting dark sector models

Analysis of SPT+DES dataset ongoing
(Mazoun+ in prep.)

Sophie Vogt

f(R) and nDGP models

Analysis of SPT+DES dataset done
(Vogt+ arXiv:2409.13556)

Vogt, Bocquet, Davies, Mohr, Schmidt 24
(arXiv:2401.09959)

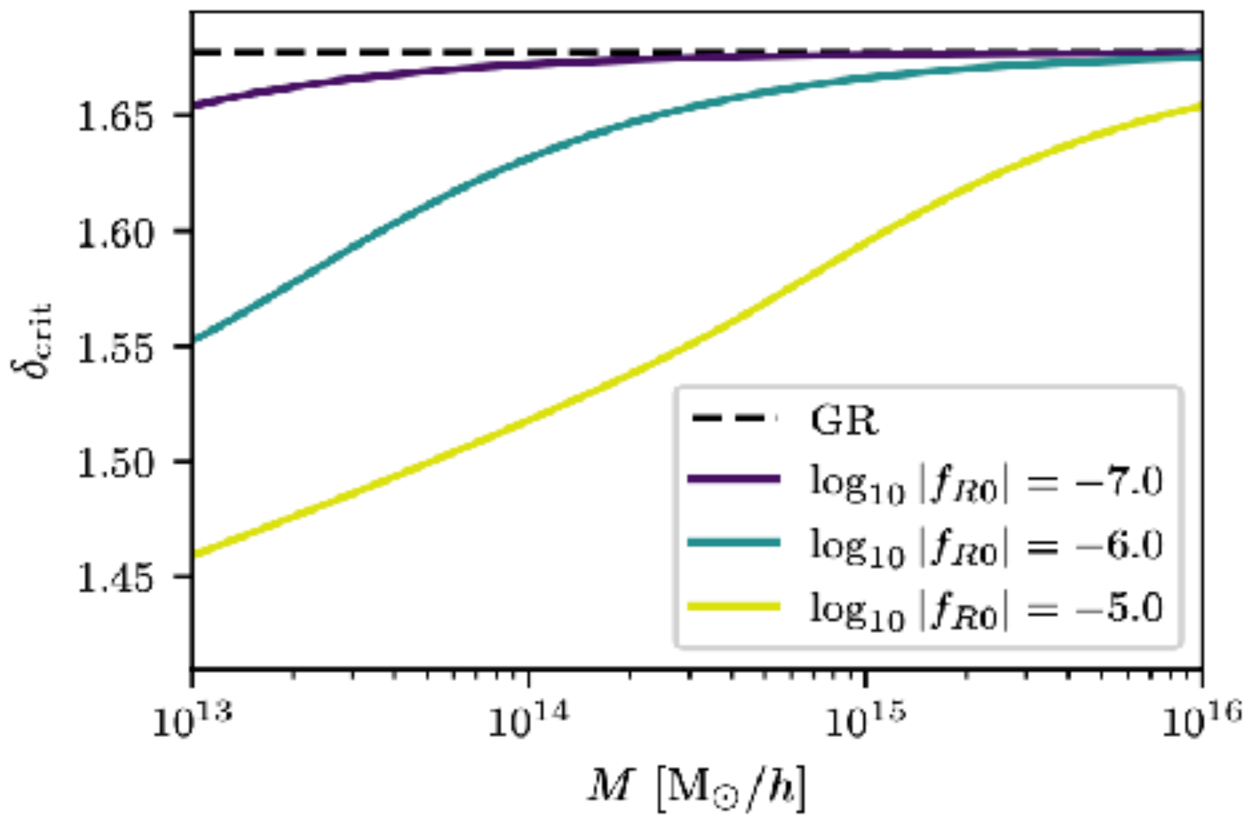


FIG. 1. The critical overdensity δ_{crit} for spherical collapse in $f(R)$ gravity (Eq. (12)) for different values of $\log_{10}|f_{R0}|$ at collapse redshift $z_c = 0$ in colored solid lines. The dashed black line represents δ_{crit} in a corresponding GR cosmology (Eq. (13)).

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(arXiv:2310:12213 — Phys. Rev. D 2024, 110, 083509)

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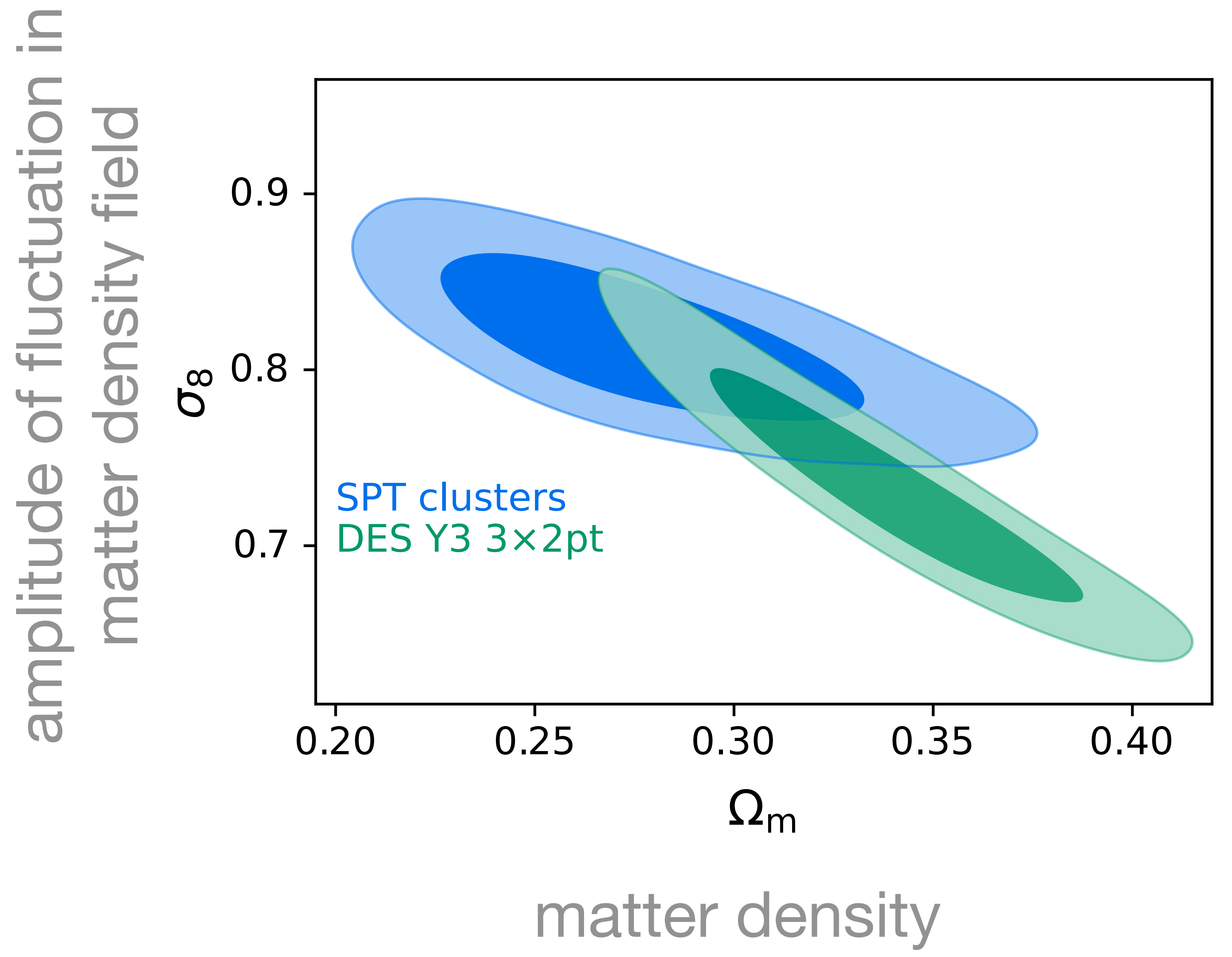
Bocquet, Grandis, Bleem, Klein, Mohr, Schrabback, SPT, DES
(arXiv:2401.02075 — Phys. Rev. D 2024, 110, 083510)

Multiprobe Cosmology from the Abundance of SPT Clusters and DES Galaxy Clustering and Weak Lensing
Bocquet, Grandis, Krause, To, SPT, DES
(to be submitted)

Image credit: SPT 2018 winter-overs Adam & Joshua

Outlook: Joint Constraints

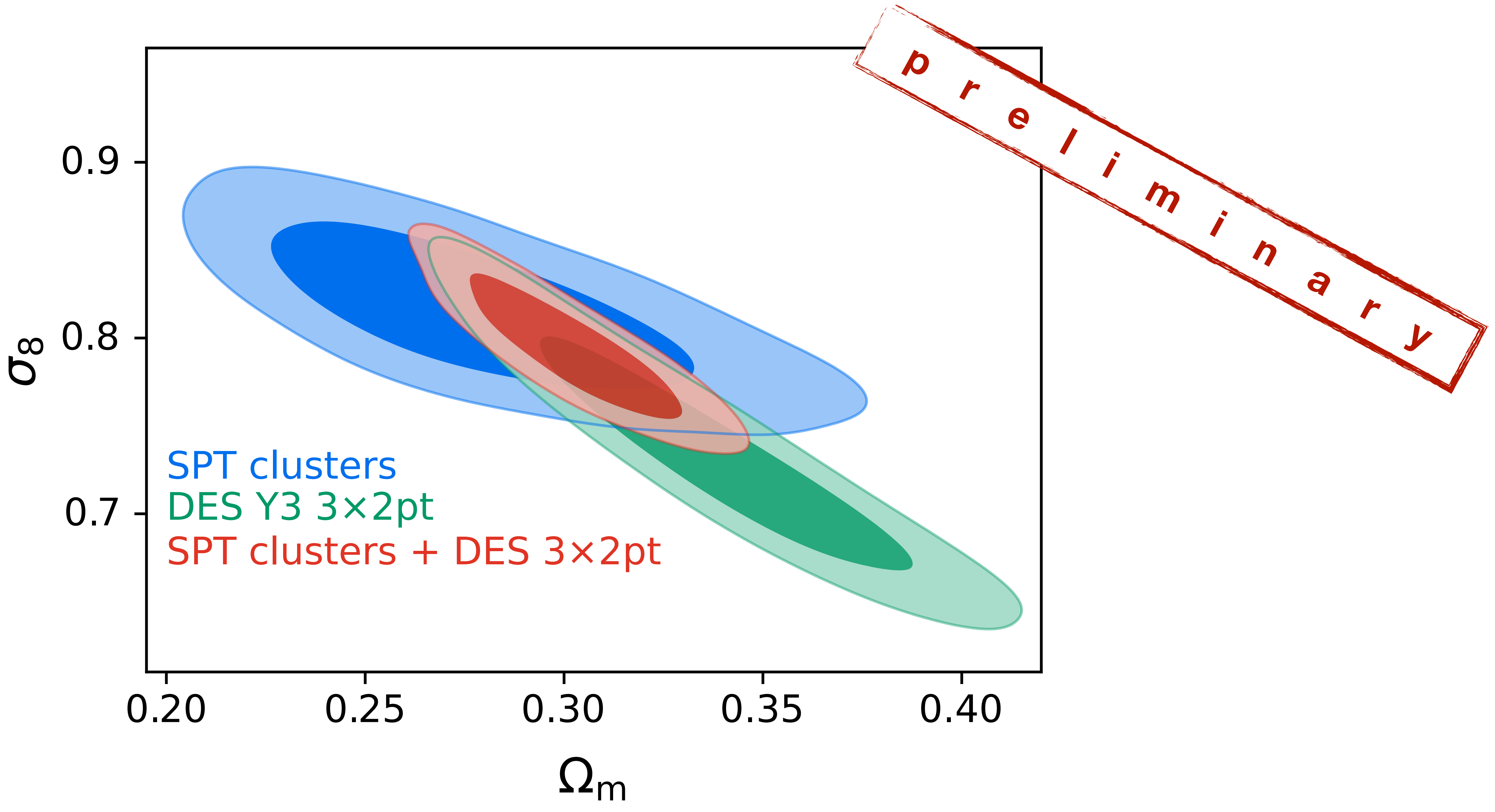
SPT Cluster Abundance + DES 3x2 pt = Multiprobe Cosmology



- Joint analysis (w/ Chun-Hao To, Elisabeth Krause, Sebastian Grandis)
    - Cosmological covariance (negligible)
        - SPT cluster abundance is dominated by shot noise
        - SPT cluster mass calibration limited by lensing shape noise
    - Shared systematics (same DES Y3 lensing data)
- Expect powerful constraints on $z < 2$ large-scale structure
- Ideal complement to high-redshift CMB measurements by *Planck*

ΛCDM with massive neutrinos

SPT clusters + DES 3x2pt



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

Independent constraint on Hubble parameter

No strong suggestion for S8 tension (1.7 σ difference with *Planck*)

Summary

Cluster abundance as a cosmological probe

SZ-selection + weak-lensing mass calibration = excellent control over systematics

Latest analysis of SPT (SZ+pol) clusters with DES Y3 + HST lensing is compatible with and complementary to other probes

Joint SPT clusters + DES 3x2pt analysis yields tight constraints

Image credit: Aman Chokshi

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