Cosmologic Insights from Galaxy Cluster and Weak Lensing Analyses

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in collaboration with DES and SPT

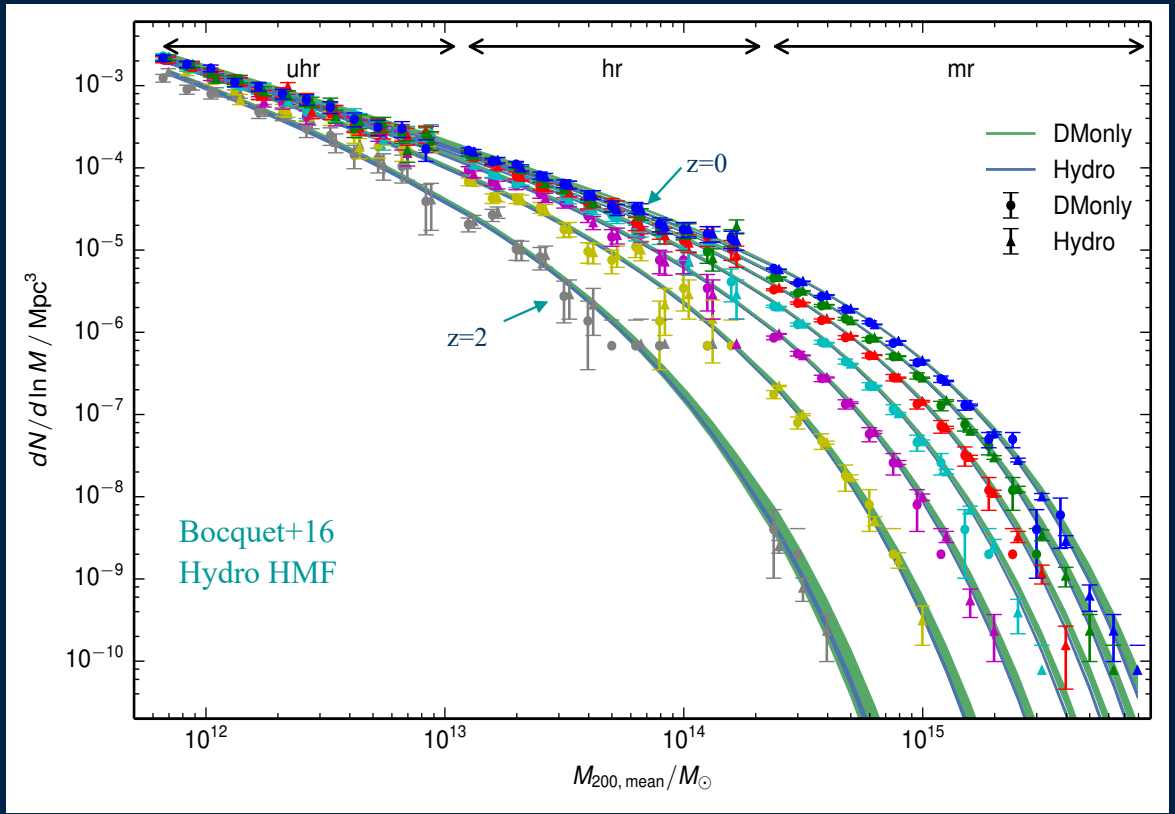
Unsolved Problems: dark energy, GR or modification
early probe vs late time probe tensions

Halo Mass Functions as a Cosmological Probe

- Abundance of collapsed halos increases over time and is sensitive to the growth rate of density perturbations
- Baryonic effects are present, because feedback redistributes mass and alters the HMF
- A survey of halos is also sensitive to the volume-redshift relation

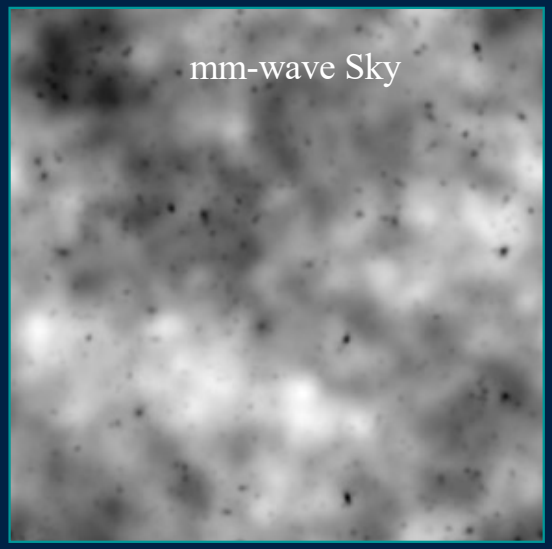
$$\frac{dN}{dz}(z)=\frac{dV}{dz}(z)\int_{M_{min}} dM'\frac{dn}{dM}(M',z)$$

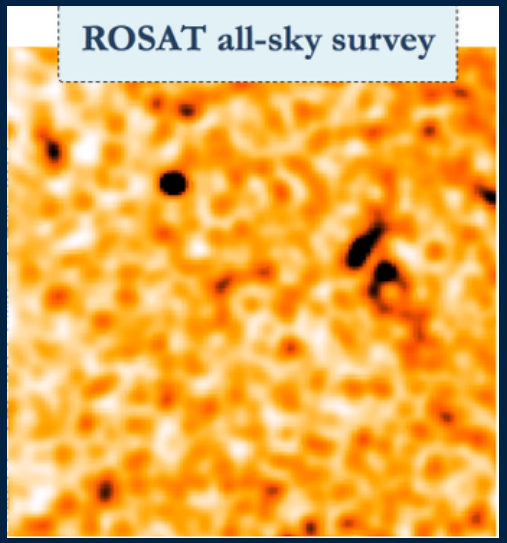
- Halo mass constraints crucial



Galaxy Cluster Observables and Selection

- Cluster finding: SZE, X-ray and Optical





In all cases, use cluster Red Sequence galaxies to estimate redshift

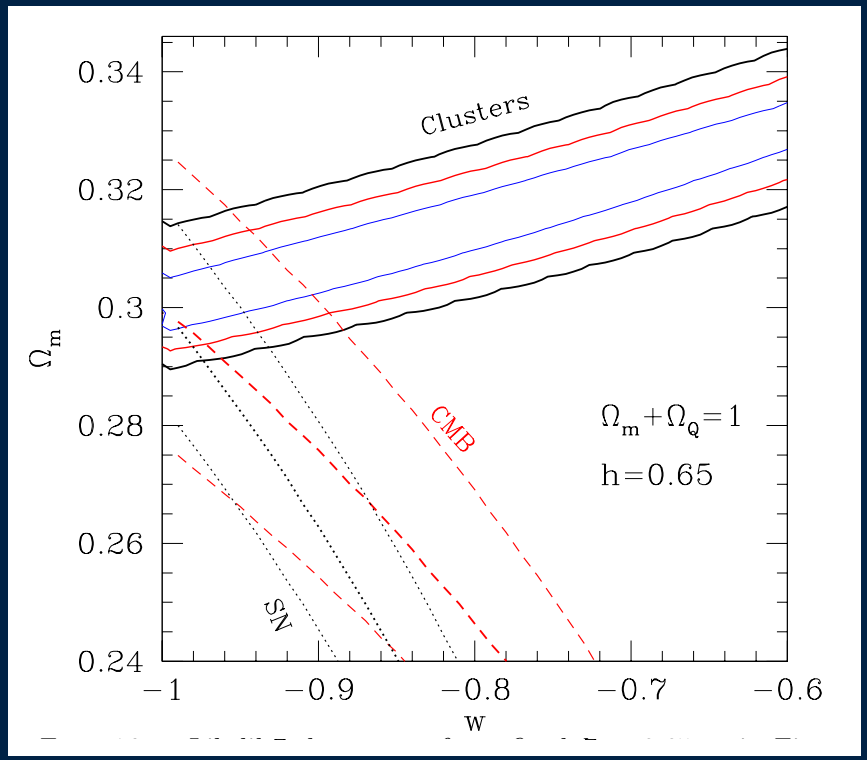
Cluster Mass Function as Cosmological Probe

- Galaxy Clusters are the most massive collapsed halos
  - Baryonic effects less important
  - Relatively easily observable: X-ray, SZE, optical richness. WL shear
- Select by “observable“ rather than mass
  - Power-law mass-observable scaling relations exist
  - Connect Observations to HMF through these scaling relations
  - Account for selection effects in modeling
- Science Driver for large, multi-wavelength surveys
  - e.g., SPT, DES and later eROSITA
- Weak lensing to calibrate cluster masses is essential

CONSTRAINTS ON COSMOLOGICAL PARAMETERS FROM FUTURE GALAXY CLUSTER SURVEYS

Zoltán Haiman[1,2,3], Joseph J. Mohr[4,5,6] & Gilbert P. Holder[6]

Submitted to ApJ, Feb. 17, 200; Resubmitted, Nov. 28, 2000



Haiman+2001

SPT SZE-selected Cluster Cosmology

Sebastian Bocquet

- Dataset:
  - 343 SZE selected clusters (ξ is SZE observable, and ξ>5, Bleem+2015)
  - Weak lensing (WL) data on 32 clusters
- SZE-mass-redshift power law scaling relation with scatter (4 params)
- Bayesian analysis w/ Poisson likelihood for counts and χ^2 likelihood for WL shear profile

$$\ln \mathcal{L}(\boldsymbol{p}) = \sum_i \ln \frac{dN(\xi, z|\boldsymbol{p})}{d\xi dz}\Big|_{\xi_i, z_i} - \int_{z_{\rm cut}}^{\infty} dz \int_{\xi_{\rm cut}}^{\infty} d\xi \frac{dN(\xi, z|\boldsymbol{p})}{d\xi dz}$$

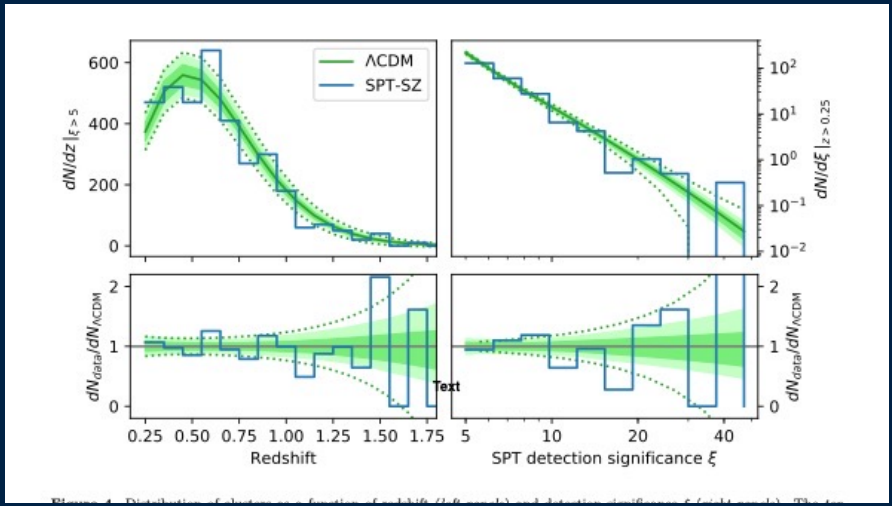
  - Model accounts for selection biases (Eddington, Malmquist)

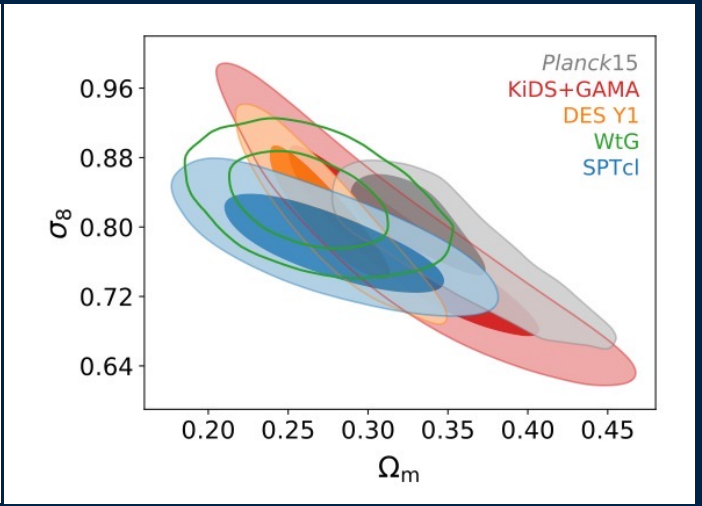
$$\frac{dN(\xi, z|\,\boldsymbol{p}\,)}{d\xi dz} = \int dM' P(\xi|M', z, \boldsymbol{p}) \frac{dN}{dMdz}(M', z|\boldsymbol{p})$$

SPT Cluster Cosmology Results 2019

Sebastian Bocquet

- Takeaways:
  - Cluster dataset well described by our model
  - Constraints in good agreement with other probes
  - Comparable uncertainties to other probes





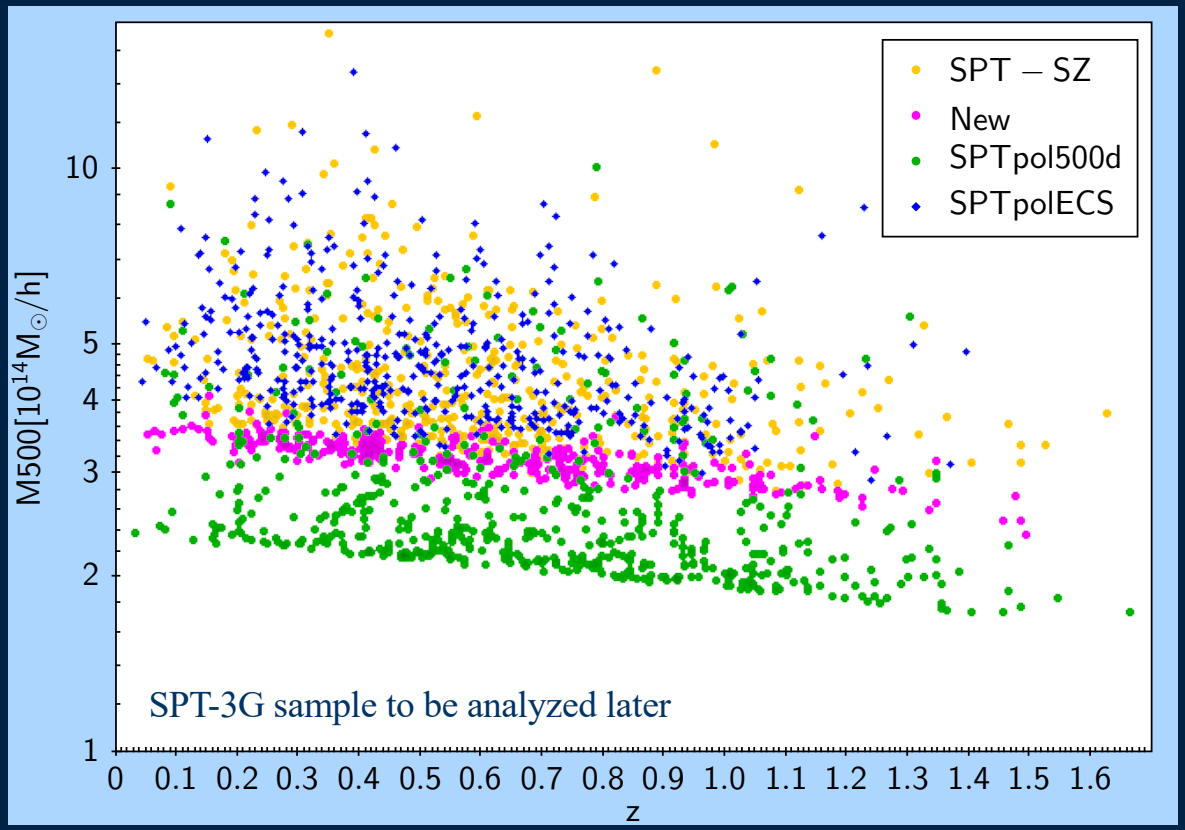
Bocquet+2019

Next step is SPTxDES analysis

- Since then we have been preparing a more sensitive analysis:
  - Enlarging sample through more SPT data and improved techniques (3x clusters)
  - Combining cluster counts with DES WL constraints (650 clusters)
  - Expanding toolkit to constrain cluster masses with WL shear profiles
  - Developing a framework for incorporating WL mass systematics
  - Running a fully blinded analysis

Expanded SPT SZE-selected Sample

- SPT summer fields and 500d added
- Optical followup tool MCMF (Klein+18,19) applied
  - employs existence of optical cluster associated with SZE candidate to expand and clean the SPT sample
- Low contamination (<2%), excellent photo-z's (RMS$\left[\frac{\delta z}{(1+z)}\right] \approx 0.005$)
- Current cosmo sample: **1009** clusters

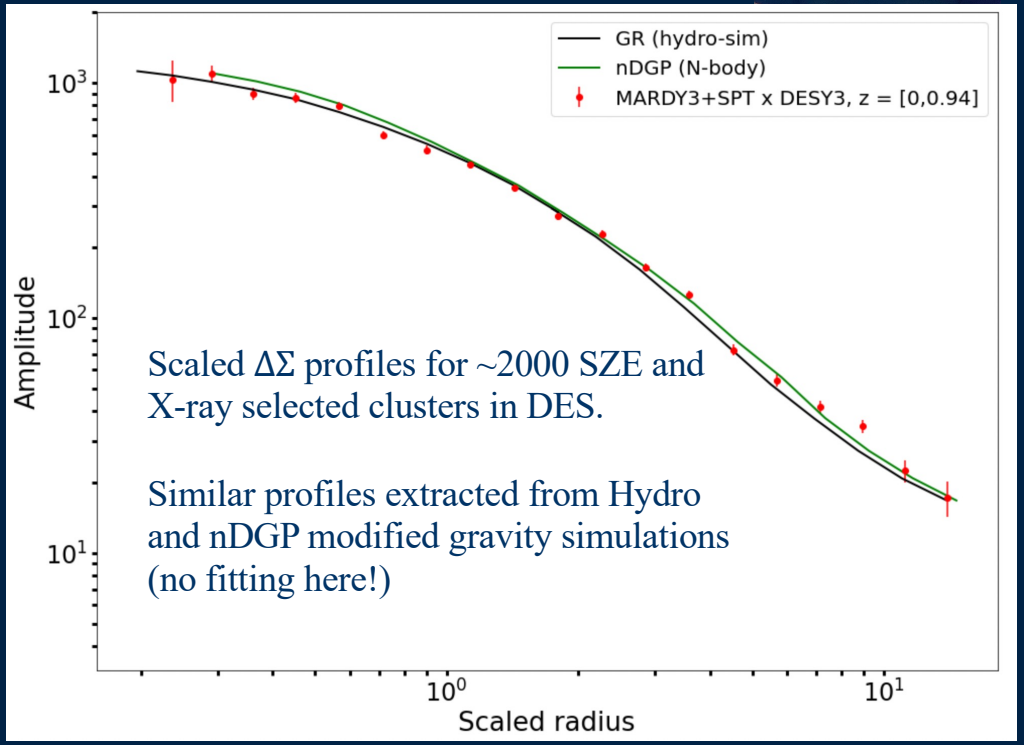


Matthias Klein

Weak Lensing Mass Constraints from DES

Aditya Singh

- The DES Shear and Photo-z catalogs have been prepared primarily to support 3x2pt cosmology
  - Extensive characterization of systematics
- Cluster specific improvements required:
  - Cluster member contamination modeling
  - Cluster mis-centering modeling
- DES contains a tremendous amount of cluster mass information
  - See stacked Delta-Sigma profiles for ~2000 SZE and X-ray selected clusters



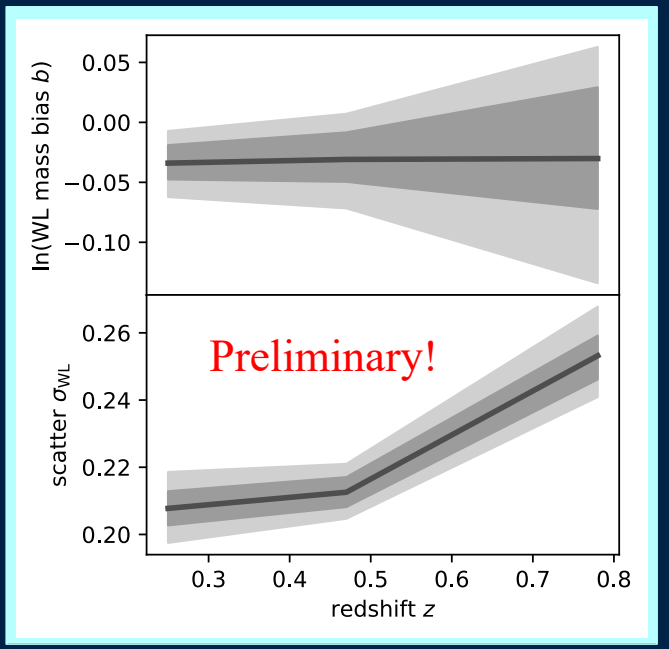
Characterizing WL Mass Systematics

Common framework for all weak-lensing modeling ingredients (Grandis, Bocquet et al. 2021)

- Mass modeling (halo profiles, miscentering, uncorrelated LSS)
- Shear modeling (shear and photo-z calibration, cluster member contamination)
- Relate hydro 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)
- Estimate Impact of baryonic effects: compare Magneticum and Illustris TNG hydrodynamical simulations: 2% difference in mass

- Characterize M_{WL}-M_{halo} relation as f(M,z)
  - **Total systematic weak-lensing uncertainty in DES Year 3: 3 — 6 % as function of cluster redshift**

Projected Magneticum Halo

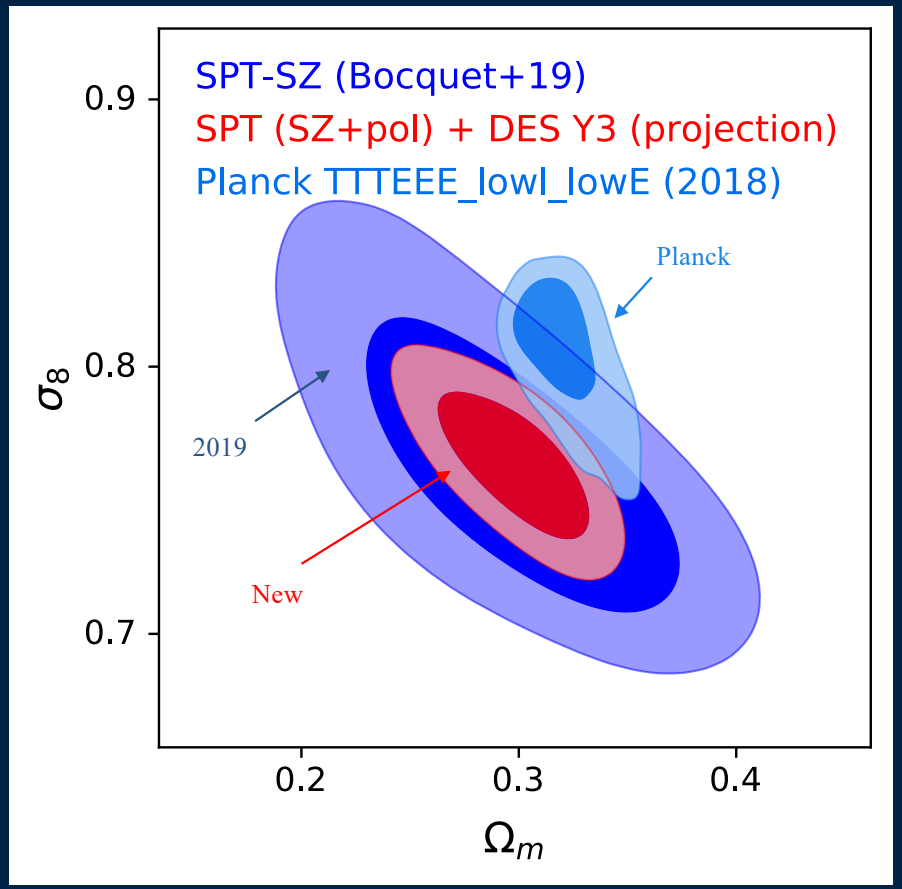


Sebastian Grandis

Bocquet+22(or 23?) Status

- Analysis strategy:
  - Similar Poisson likelihood for abundance
  - Cluster by cluster WL shear profile likelihood
  - SZE-mass, optical richness-mass, M_{WL}-mass scaling relations
    - 10 params + correlated scatter (SZE, WL, λ)
- Validation on mocks, Blinded tests on data ongoing
- Mocks indicate this will be best chance yet to test S8 tension with clusters...

Sebastian Bocquet



Recent Results on eROSITA Cluster Cosmology

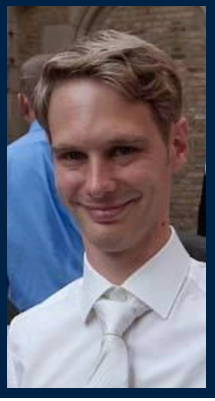
Chiu, Klein, Mohr, Bocquet 2022, MNRAS submitted (https://arxiv.org/pdf/2207.12429.pdf)

I-Non Chiu

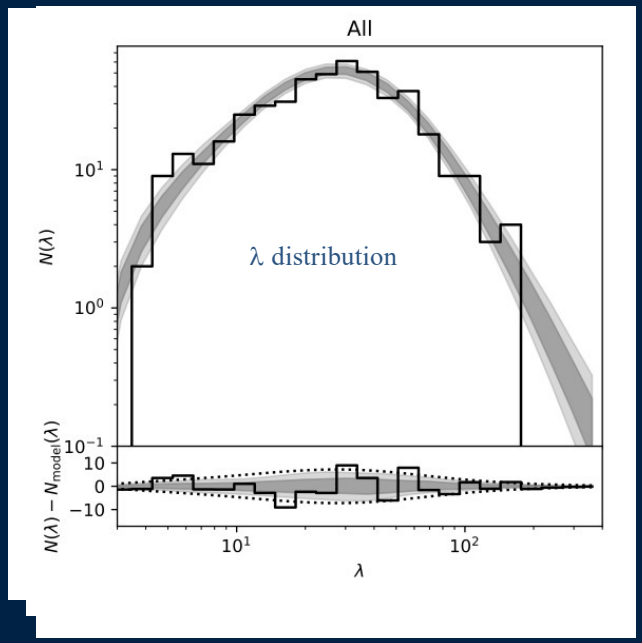
- We recently carried out the first cosmological analysis of the eROSITA cluster sample using a public eFEDS survey (140 deg^2) dataset using public HSC weak lensing
  - 455 clusters after optical cleaning with MCMF, 177 with WL data
  - Expected contamination of 6% (20% contamination in original eFEDS sample)
- Similar approach as SPTxDES but for X-ray selected sample we have:
  - X-ray count rate-mass-redshift relation (η is count rate; 5 params)
  - Optical richness-mass-redshift relation, too (5 params)
- Complication: analyzed eFEDS „extent“ selected sample, and therefore had to model incompleteness in η selected sample introduced by extent selection
  - Used MCMF to identify ALL clusters (including in unresolved sample)

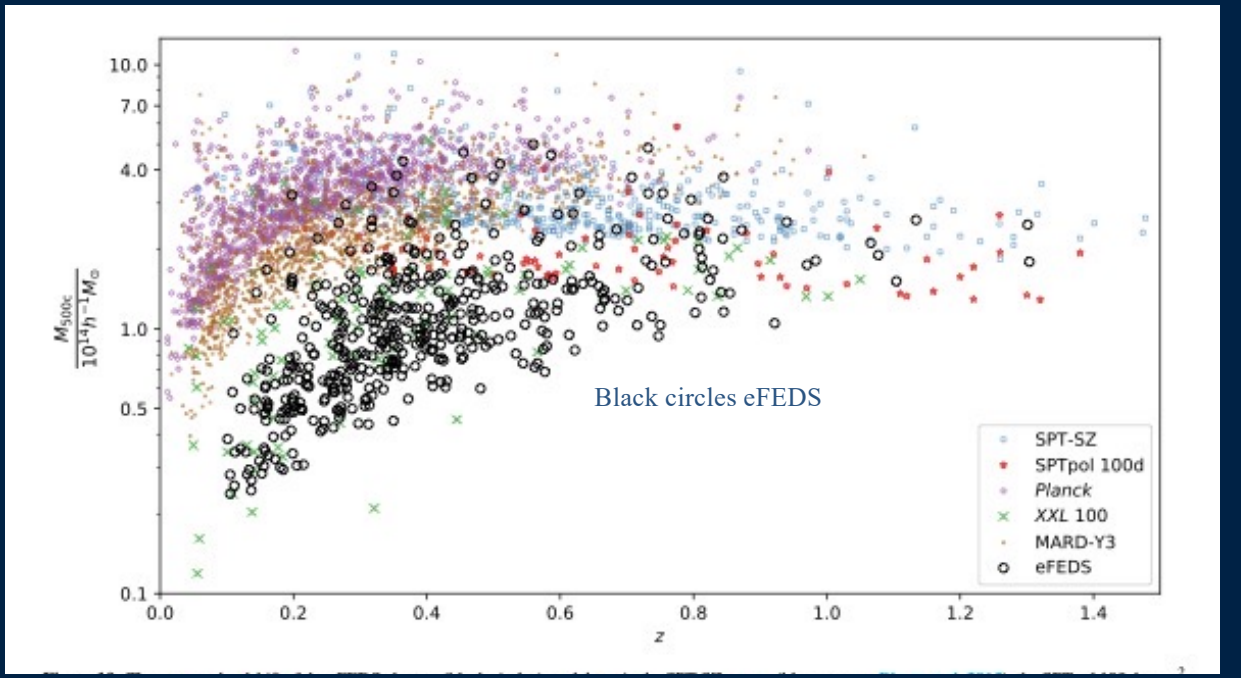
The eFEDSxMCMF sample

- eFEDS clusters are lower mass and span broad redshift range
- HSC WL shear profiles used in similar manner (M_{WL}-M_{halo})
- Model consistency with data is encouraging



Matthias Klein

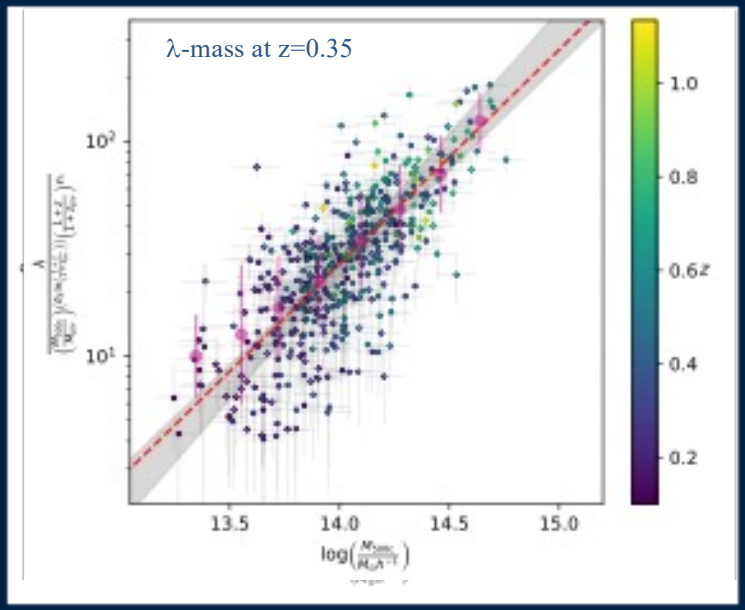


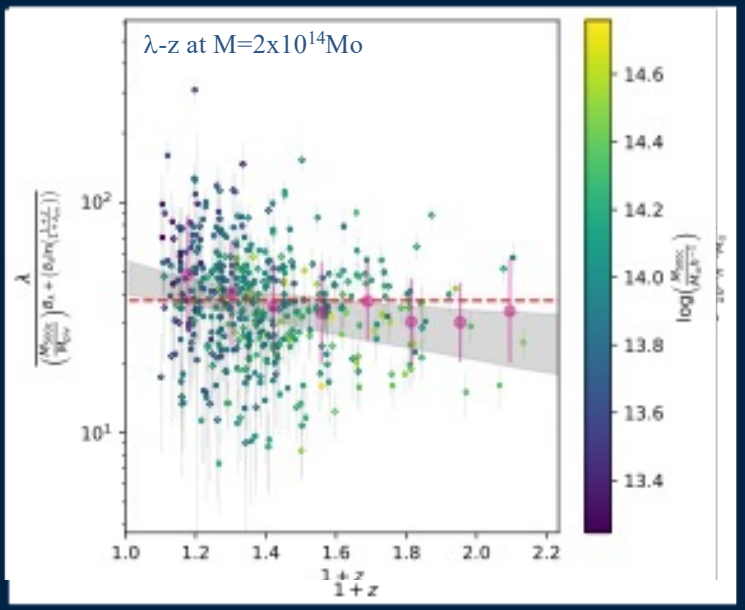


Scaling Relation Constraints

- The data follow the scaling relations well
  - 5 param power law rel'ns (plus correlated scatter) adequate

I-Non Chiu

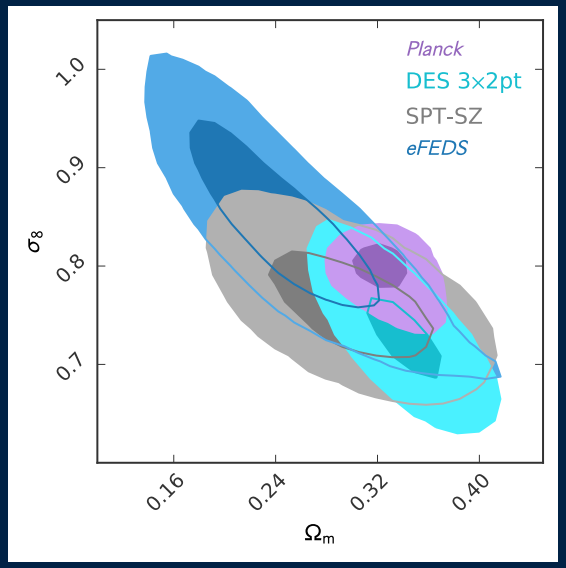


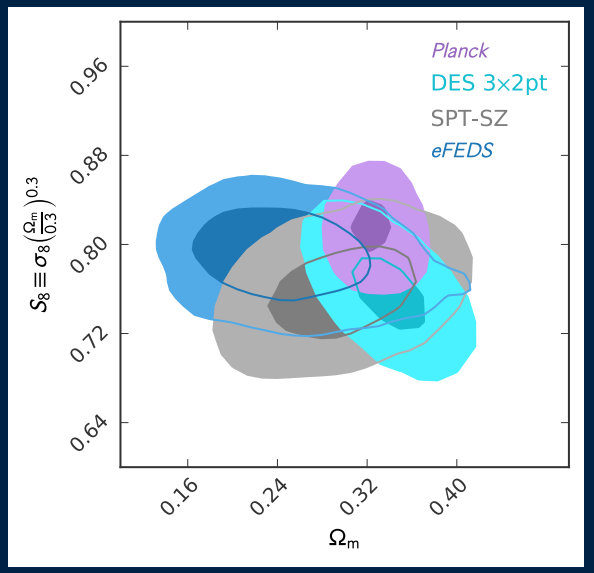


eROSITA Cosmological Constraints

- Fully blinded analysis
- Constraints in good agreement with other probes (no tension with Planck)

I-Non Chiu





ıre 18. The comparisons of the cosmological parameters assuming the ΛCDM cosmology between the eFEDS clusters (blue) and the external re

Summary

- Bayesian analysis framework to handle multi-wavelength cluster samples and incorporate systematic uncertainties has been demonstrated
- SPT and eROSITA cluster samples supported by weak lensing mass constraints are promising cosmological probes
- Larger SZE and X-ray selected samples on the horizon
- Dramatic improvements in WL data expected from Euclid and Rubin
- Such samples provide leverage to address many Unsolved Problems

  DE, DM, modified gravity, neutrino masses, etc