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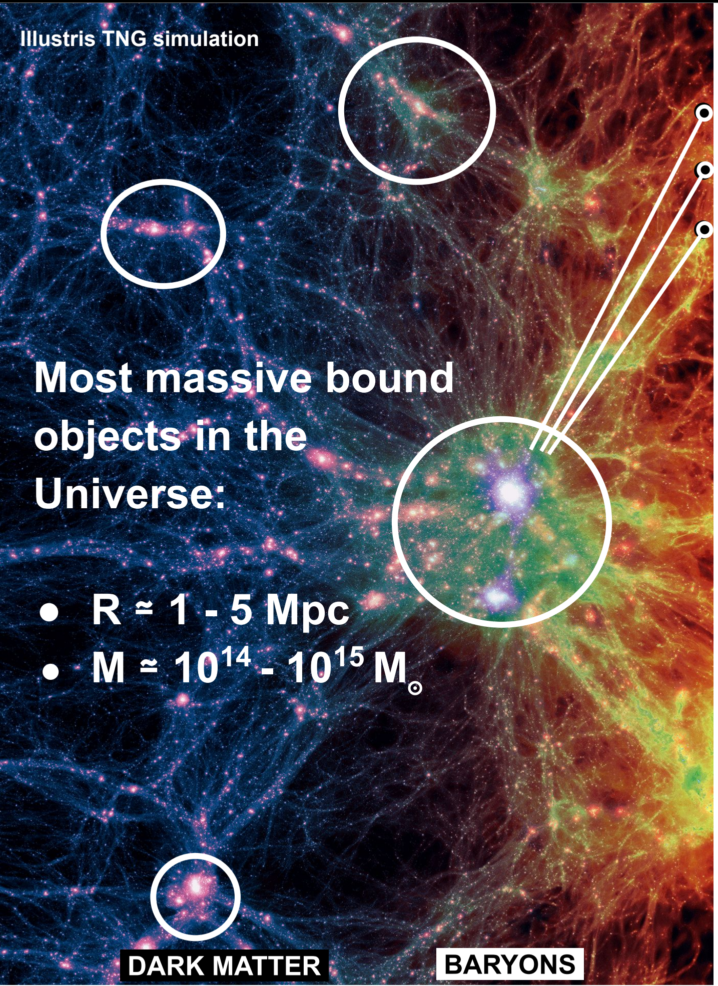
NextGenerationEU

DARK ENERGY SURVEY

CLUSTER COSMOLOGY: A MULTIWAVELENGTH VIEW

September 2024 | Matteo Costanzi - University of Trieste / INAF

GALAXY CLUSTERS



Most massive bound objects in the Universe:

- $R \simeq 1 - 5$ Mpc
- $M \simeq 10^{14} - 10^{15}\, M_\odot$

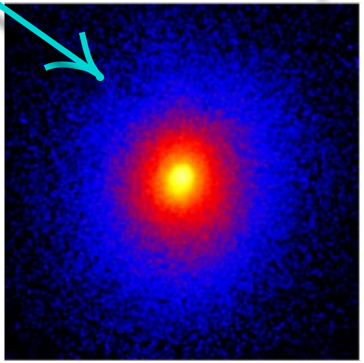
Multi-component systems:

- Galaxies and stars (~5%)
- ICM (~15%)
- DM (~80%)

OPTICAL

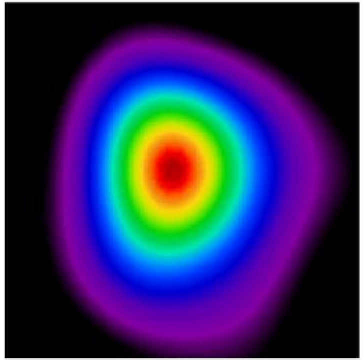
RICHNESS, LENSING EFFECTS

X-RAYS



LUMINOUS AND EXTENDED X-RAY SOURCES

MICROWAVES

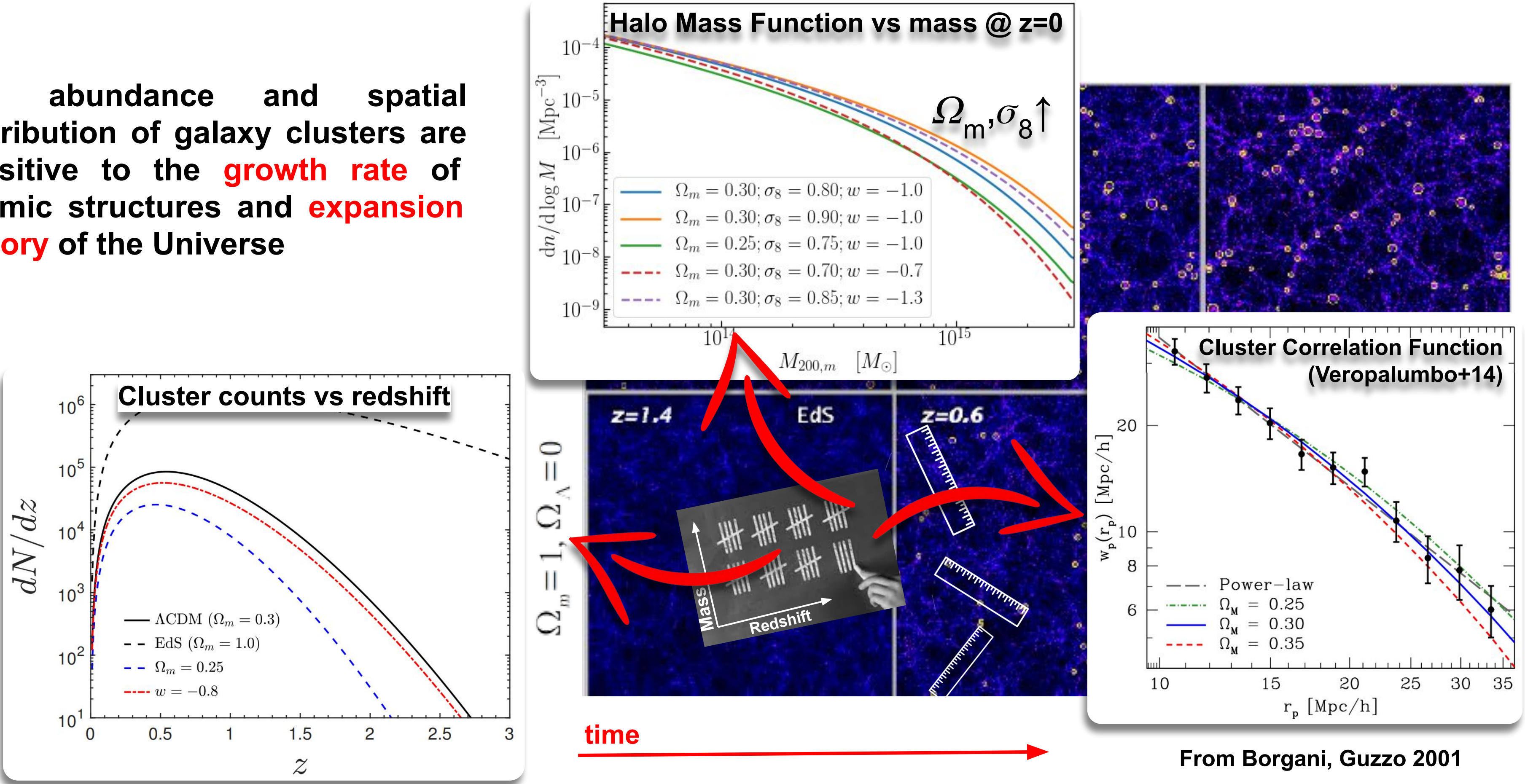


SUNYAEV-ZEL'DOVICH EFFECT

Credit: Allen+11

CLUSTER COSMOLOGY IN A NUTSHELL

The abundance and spatial distribution of galaxy clusters are sensitive to the growth rate of cosmic structures and expansion history of the Universe



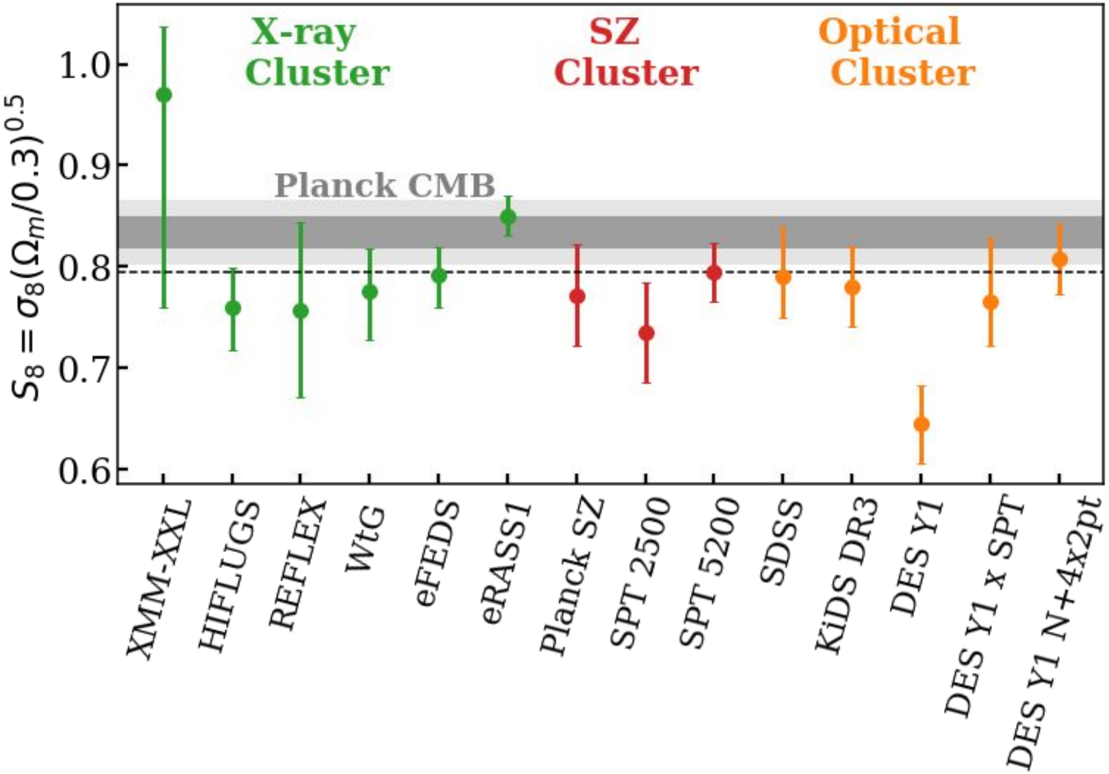
From Borgani, Guzzo 2001

CLUSTER COSMOLOGY IN A NUTSHELL

The abundance and spatial distribution of galaxy clusters are sensitive to the growth rate of cosmic structures and expansion history of the Universe

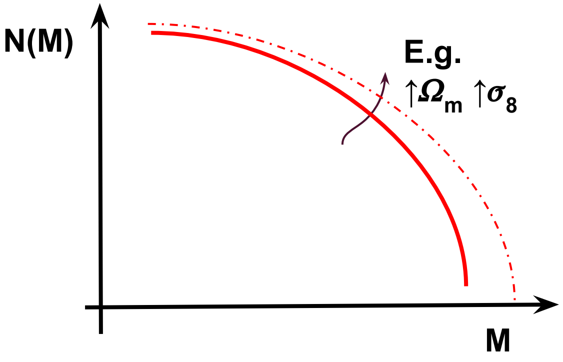
- Amplitude of matter fluctuations, σ_8
- Total matter density, Ω_m
- Dark energy equation of state parameter w
- Total neutrino mass, Σm_ν
- Modified gravity models

...

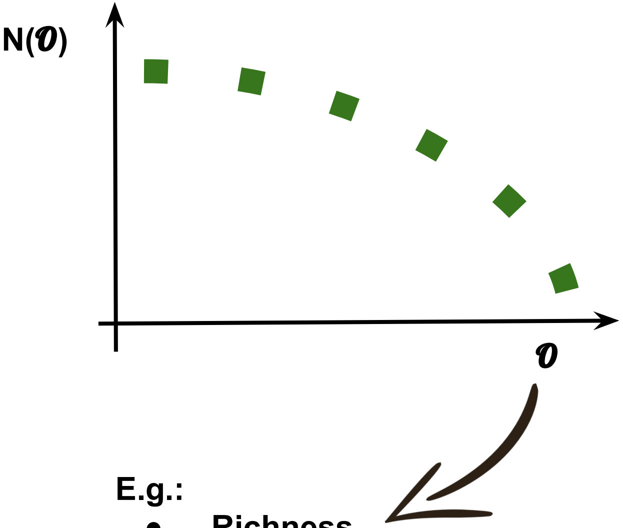


FROM OBSERVATION TO COSMOLOGICAL CONSTRAINTS

Theoretical prediction



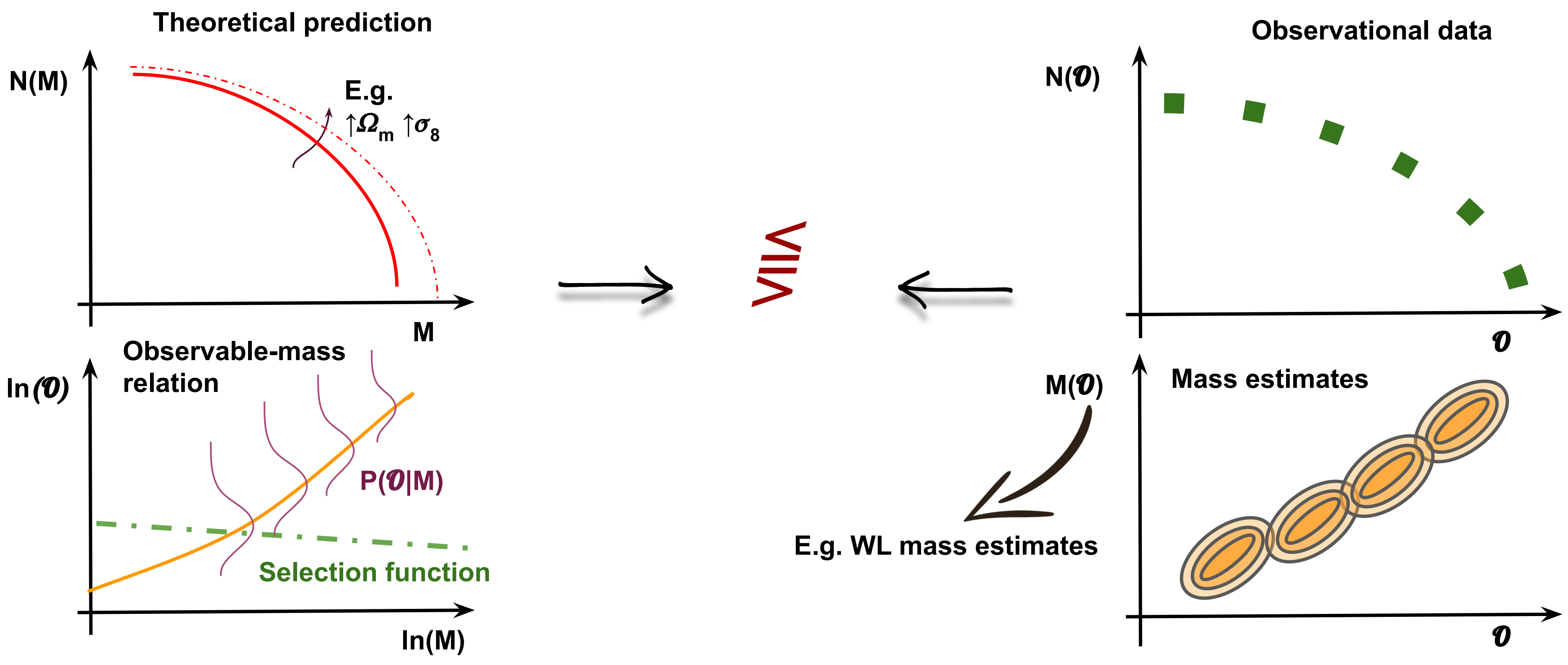
Observational data



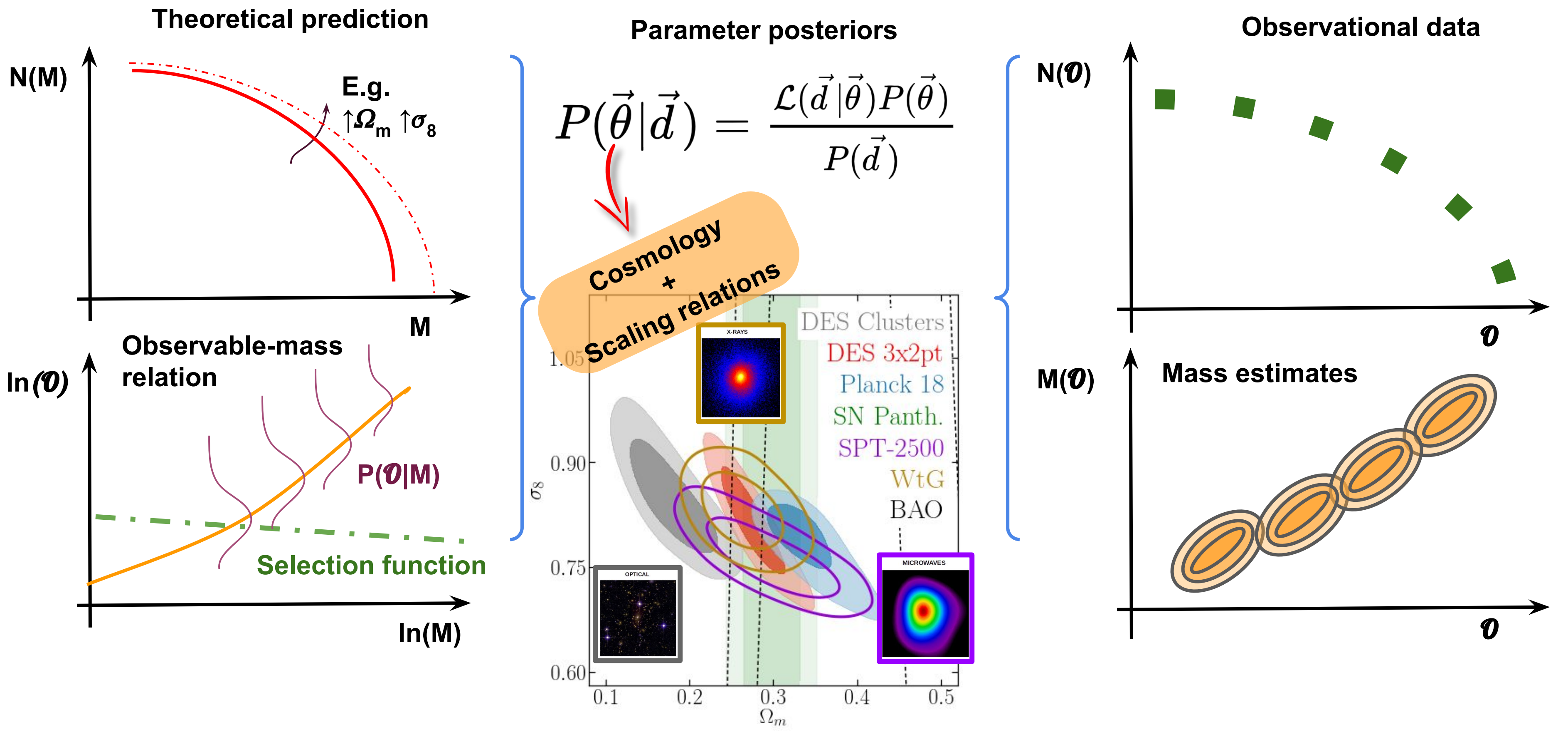
E.g.:

- Richness
- X-ray luminosity or photon counts
- SZ signal

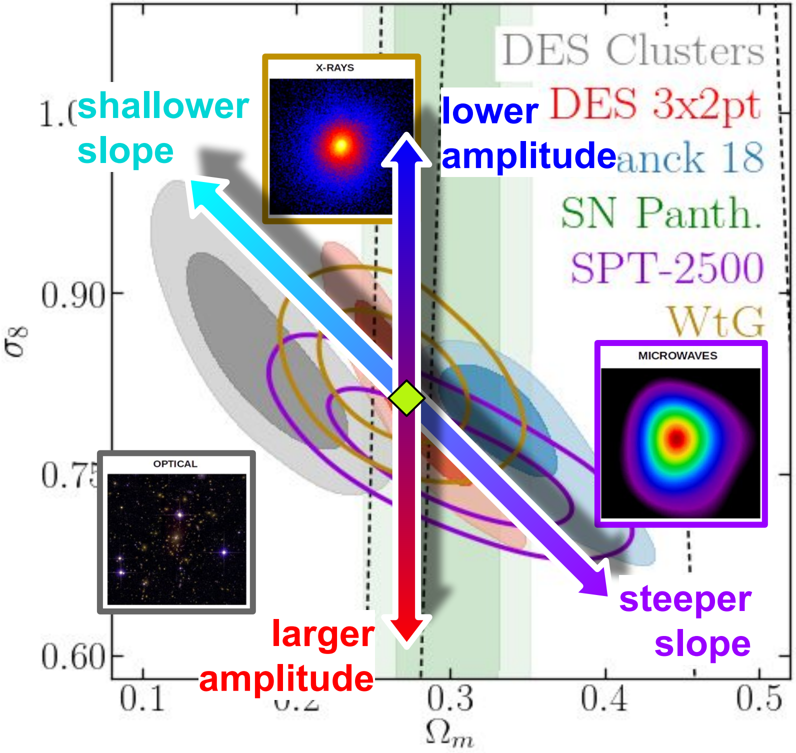
FROM OBSERVATION TO COSMOLOGICAL CONSTRAINTS

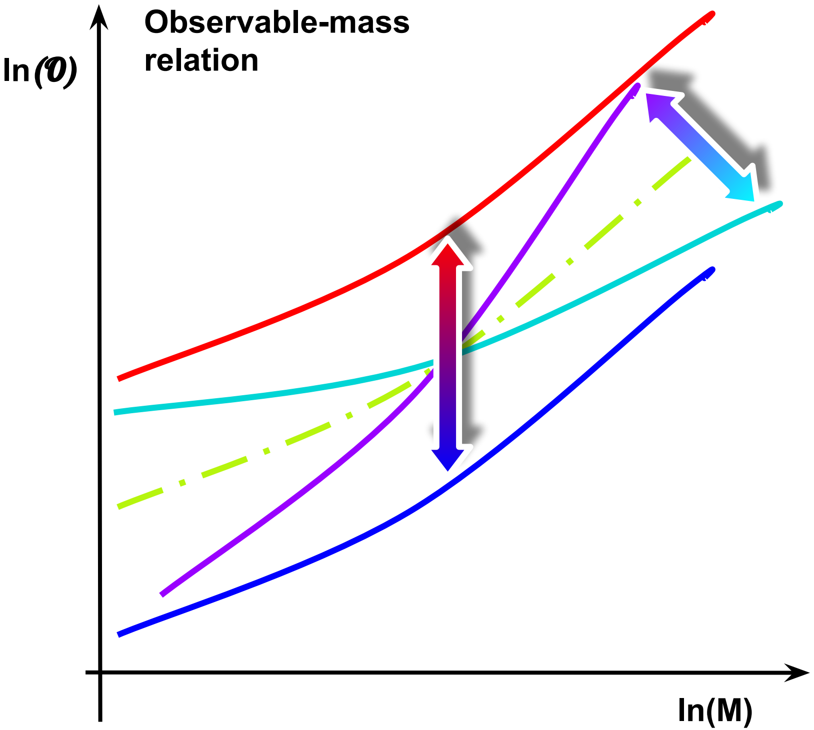


FROM OBSERVATION TO COSMOLOGICAL CONSTRAINTS

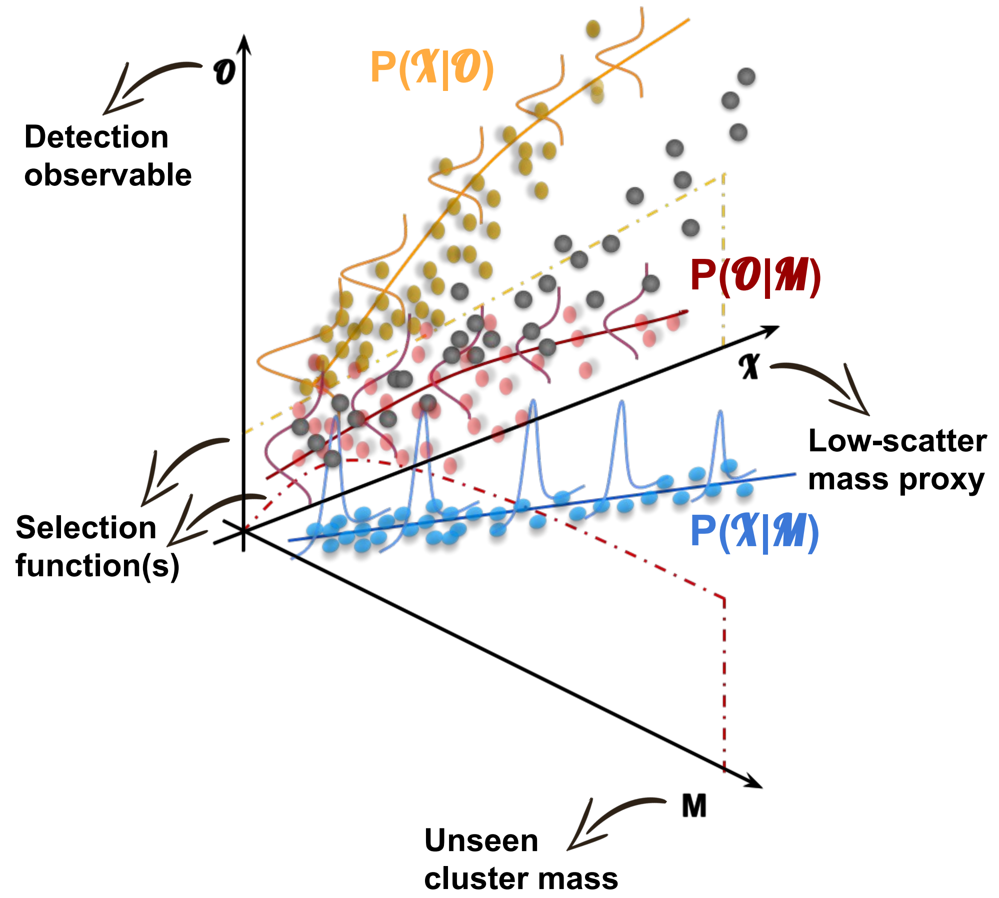


MASS CALIBRATION AND COSMOLOGICAL POSTERIORS





SELECTION FUNCTION AND MASS CALIBRATION



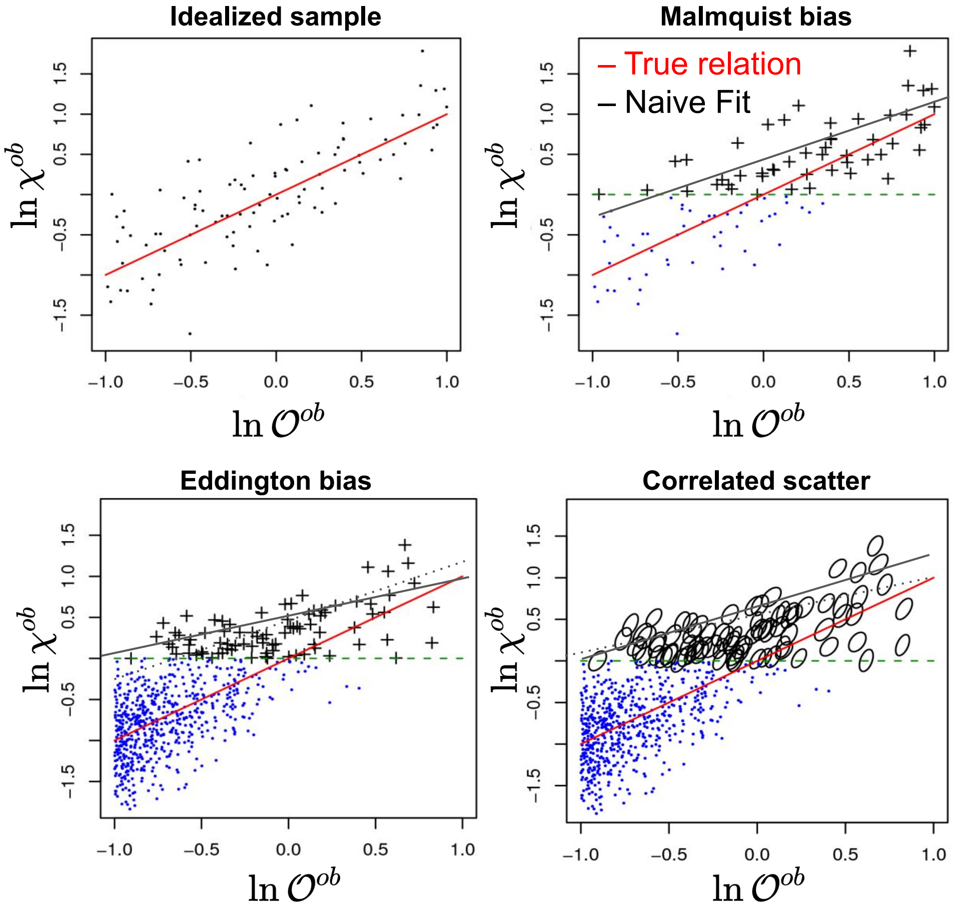
Different detection techniques imply different mass proxies, mass calibration data and systematics.

The calibration of the observable-mass relation(s) requires:

- **Well defined selection function(s)**
- **A model to describe the parent distribution as a function of mass (halo mass function)**
- **A model to describe the PDF of the multivariate observable space: P(𝒳,𝒪|ℳ)**

Credit A. Mantz

SELECTION FUNCTION AND MASS CALIBRATION



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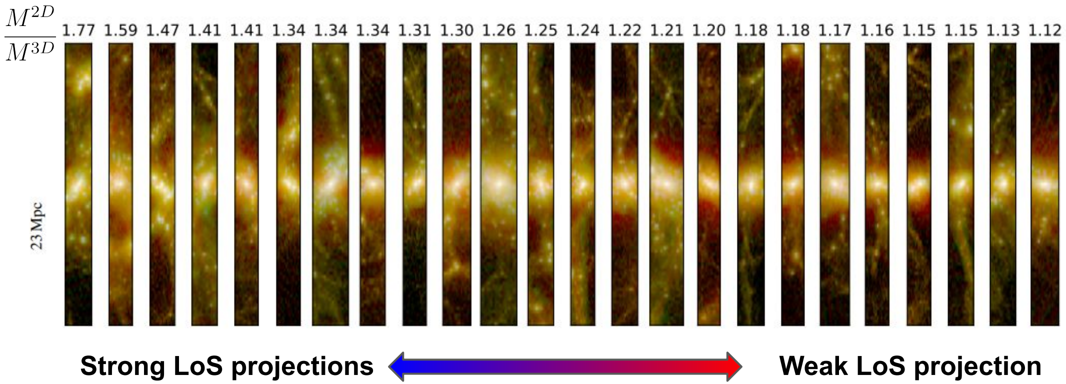
CORRELATION BETWEEN MULTI-λ OBSERVABLES

- Observationally, we only have access to projected quantities.

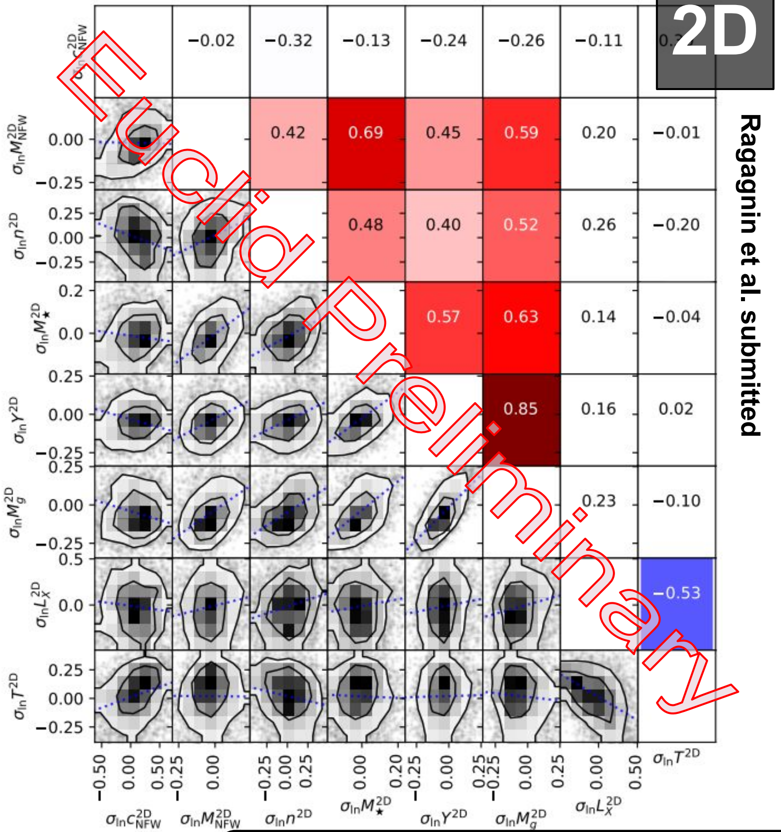
Projected cluster mass maps along a cylinder of length 23 Mpc



- Line-of-sigh projections increase the scatter and skewness of the Obs-Mass relations and introduce correlations between observables measured at different wavelengths

See also e.g. Farahi et al 2019

Correlation coefficients matrix (upper-right triangle) and scatter plot (bottom-left triangle) of log-residual for different 2D observables



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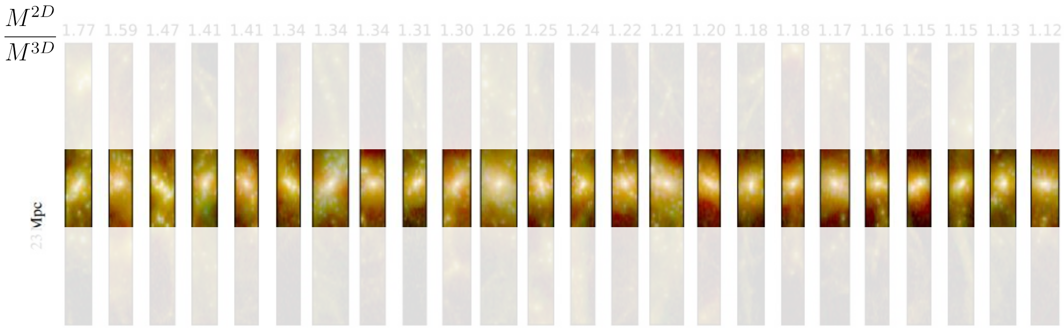
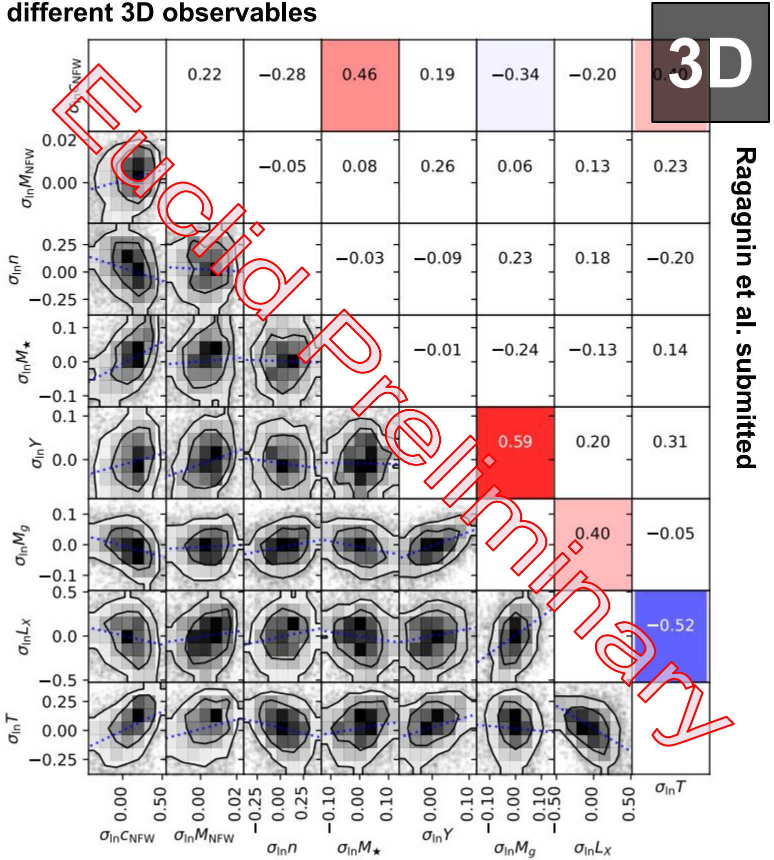


Strong LoS projections ⟷ **Weak LoS projection**

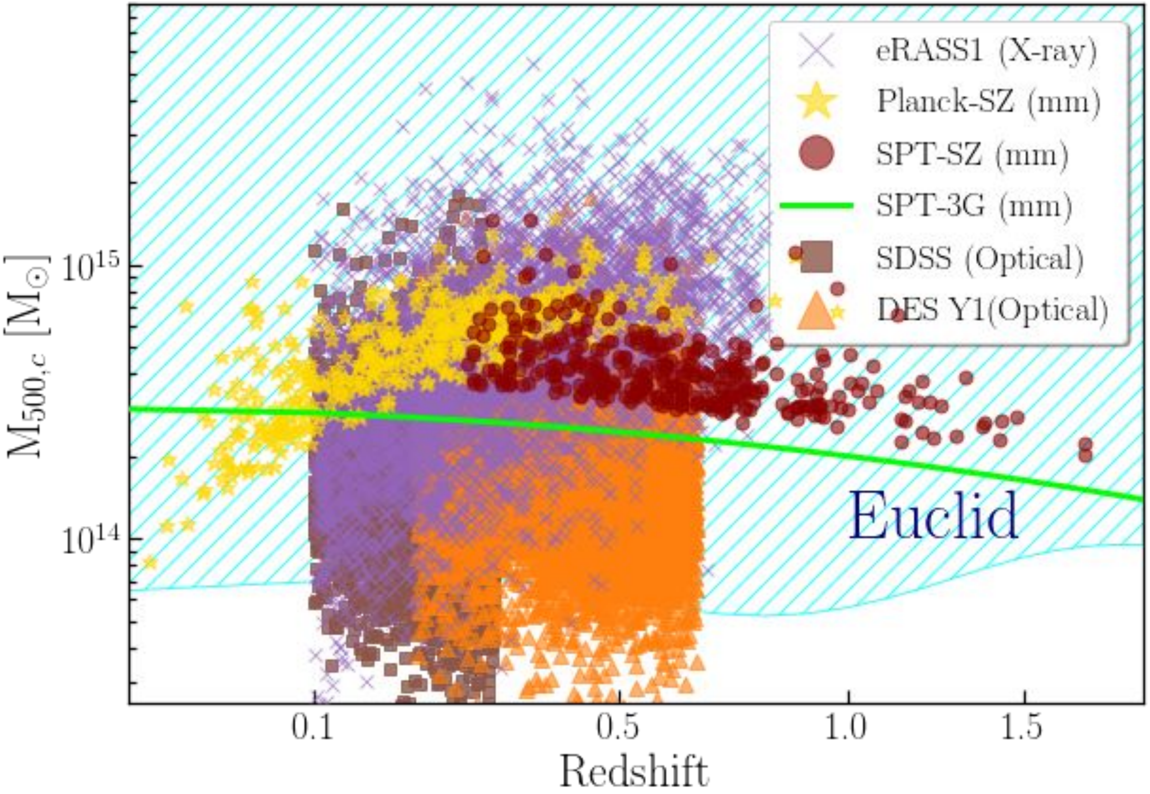
- **Line-of-sigh projections increase the scatter and skewness of the Obs-Mass relations and introduce correlations between observables measured at different wavelengths**

See also e.g. Farahi et al 2019

Correlation coefficients matrix (upper-right triangle) and scatter plot (bottom-left triangle) of log-residual for different 3D observables



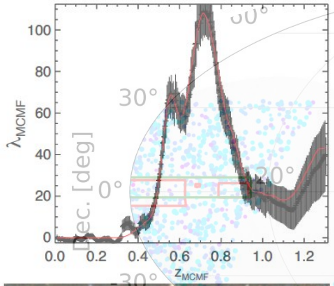
CLUSTER CATALOGUES AT DIFFERENT λs

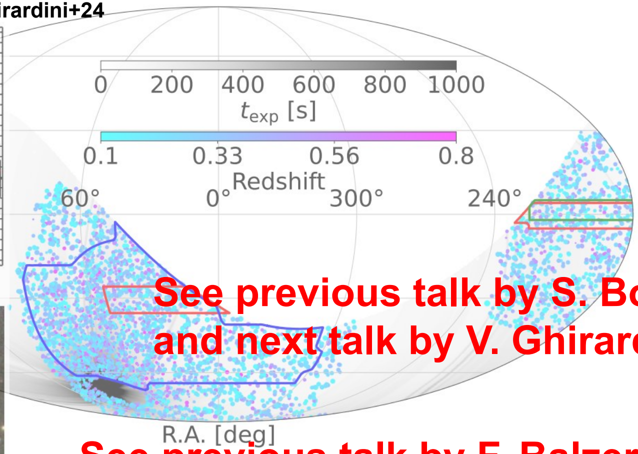


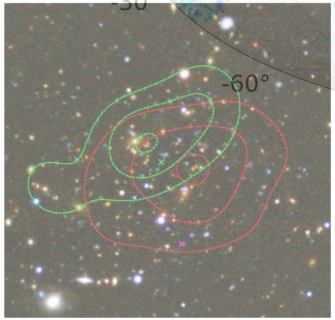
- **X-ray, SZ:**
  - **Mass limit M~2 · 10^{14} $M_\odot$**
  - **Clean selection function (SZ signal independent of redshift!)**
  - **Need optical follow-up for confirmation, redshift and WL data**
- **Optical:**
  - **Lower mass limit M~5 · 10^{13} $M_\odot$ (x10 sample size)**
  - **Selection function hard to model**
  - **WL and photo-z data readily available**

CLUSTER CATALOGUES AT DIFFERENT λs

Ghirardini+24



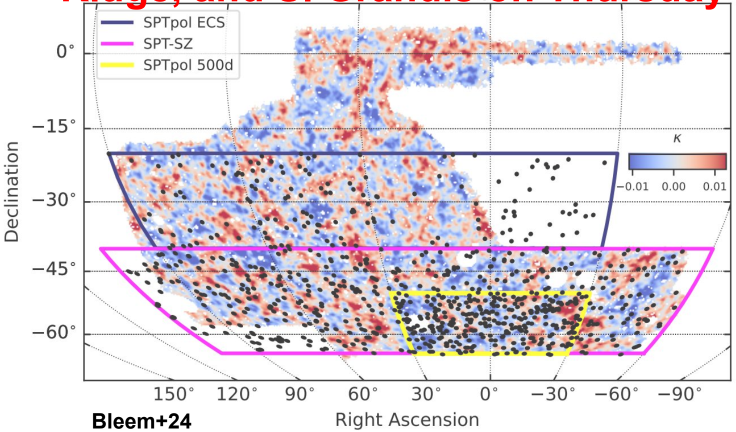




Klein+19

See previous talk by S. Bocquet and next talk by V. Ghirardini

See previous talk by F. Balzer and M. Kluge, and S. Grandis on Thursday



Bleem+24

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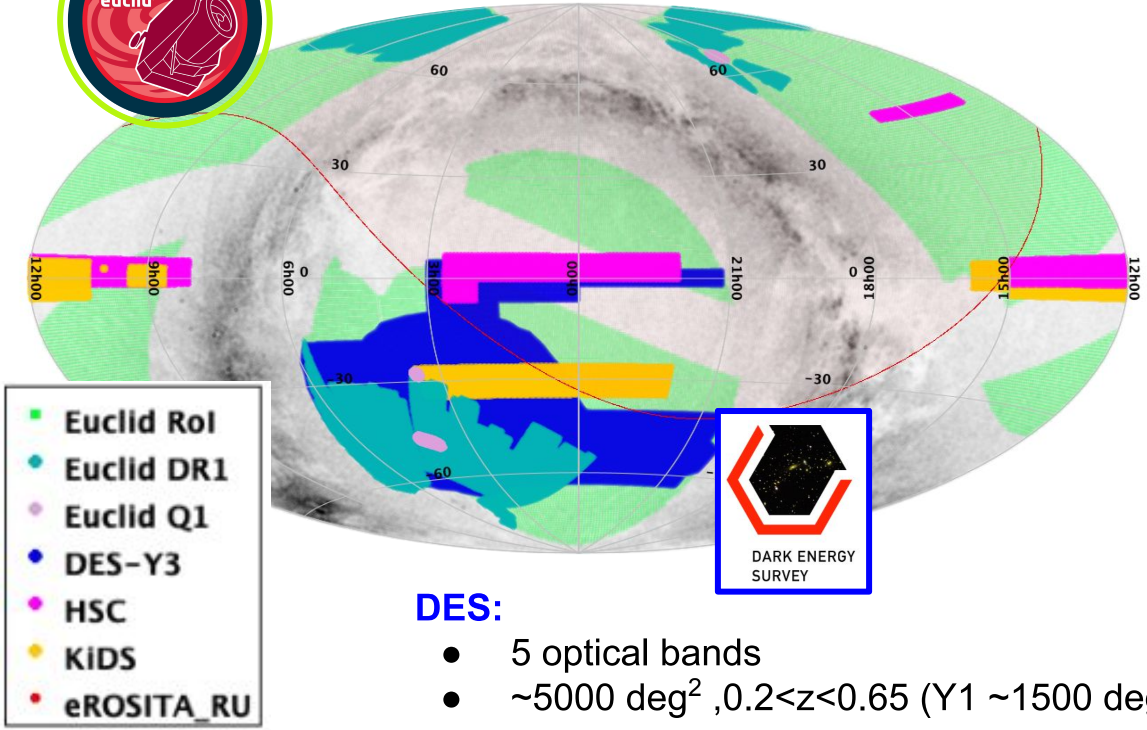
CLUSTER CATALOGUES AT DIFFERENT λs

Euclid:

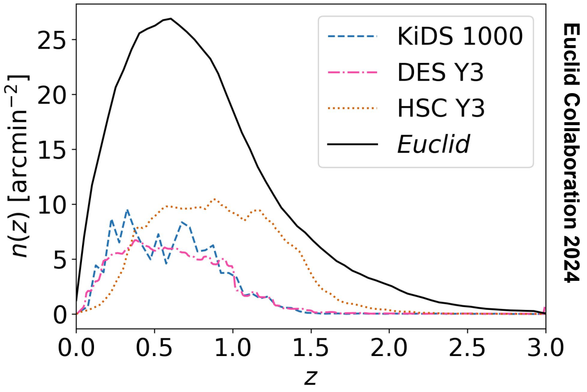
- Optical and IR bands + slitless spectroscopy
- ~15000 deg^2 ,0.2<z<2.0 (DR1 ~1700 deg^2)



DES:

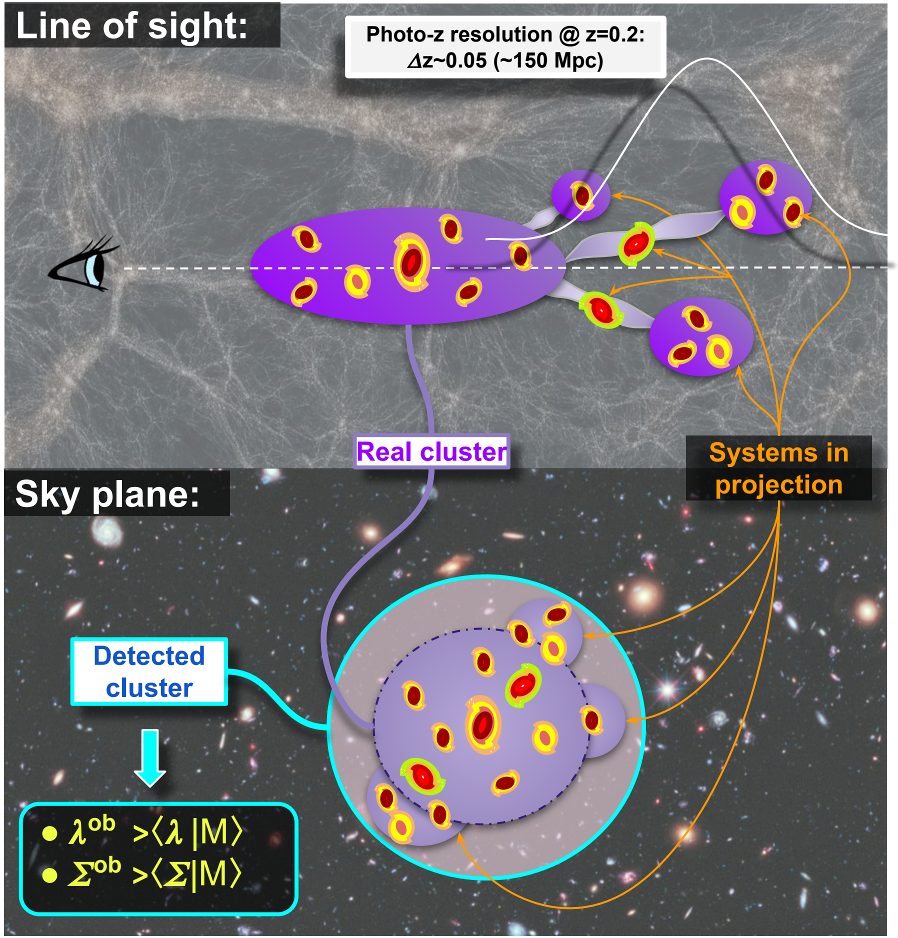
- 5 optical bands
- ~5000 deg^2 ,0.2<z<0.65 (Y1 ~1500 deg^2)

Source density vs redshift



- **Optical:**
  - **Lower mass limit M~5 · 10^{13} M$_\odot$ (x10 sample size)**
  - **Selection function hard to model**
  - **WL and photo-z data readily available**

SELECTION EFFECTS IN OPTICAL CATALOGS



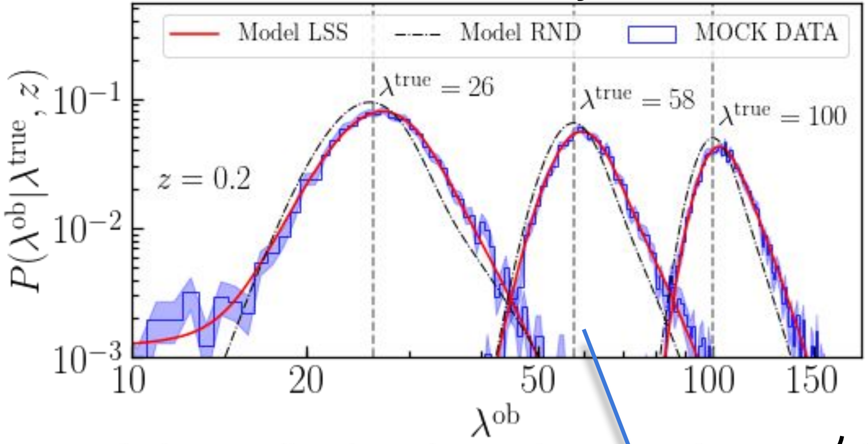
$$\lambda^{ob} = \lambda^{true}(M) + \delta\lambda(\lambda^{true}, \ldots)$$

$$\Sigma^{ob} = \Sigma(M) + \delta\Sigma(\lambda^{ob}, \ldots)$$

Optical selection bias introduce a correlation between richness and WL signal which needs to be properly modeled to recover unbiased mass estimates

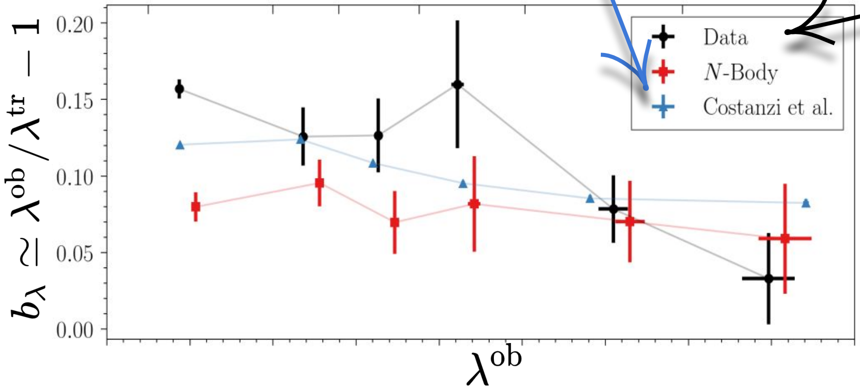
$\delta\lambda$ CALIBRATION: SPEC-Z DATA

Scatter between true and observed richness calibrated via mock/data analysis



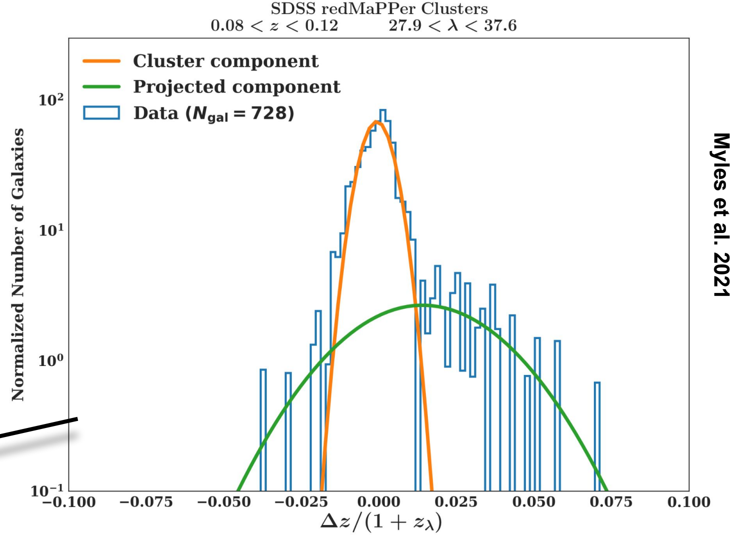
Costanzi et al. 2019

Richness contamination



Myles et al. 2021

Richness contamination from stacked spec-z data

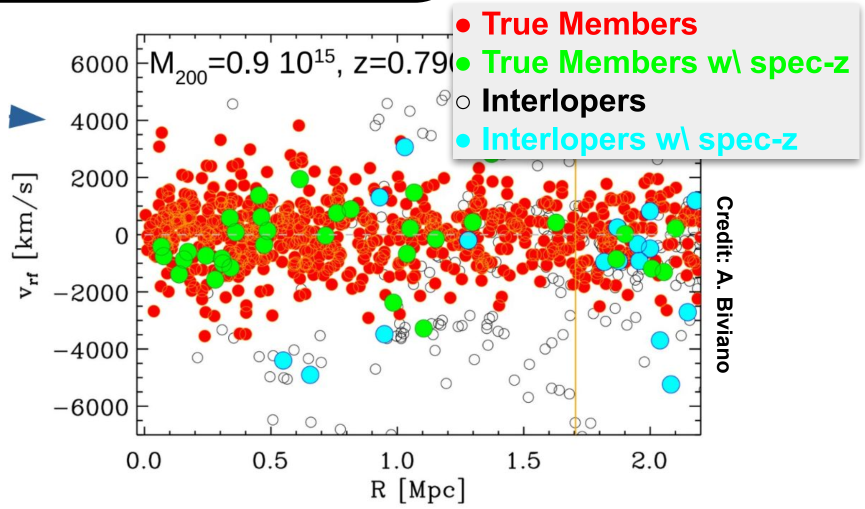


Myles et al. 2021

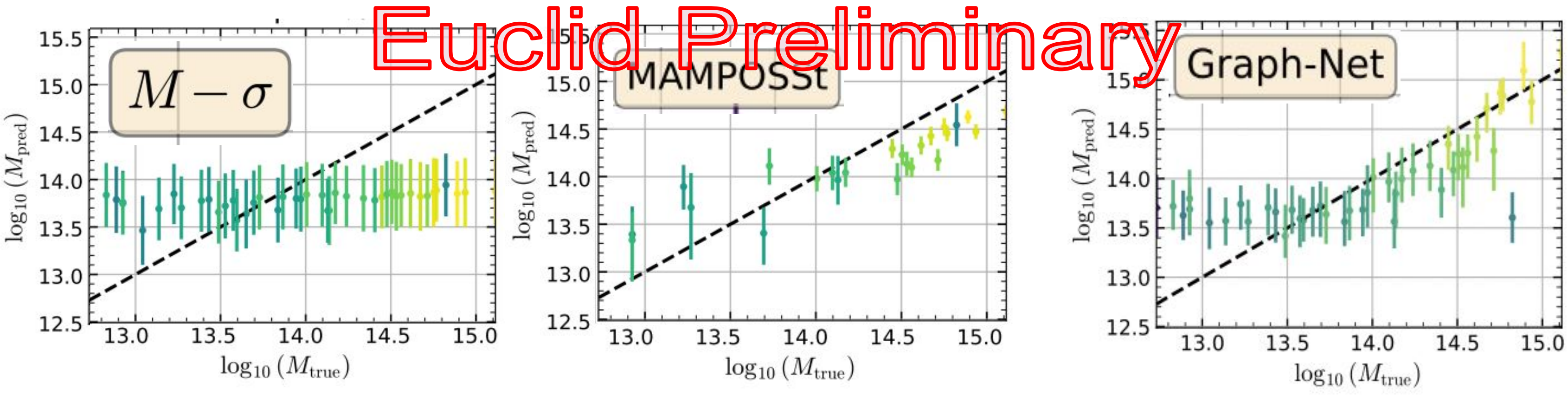
- **Spectroscopic data of putative cluster members allow to distinguish between a population of true cluster galaxies and projected interlopers**

MASS CALIBRATION WITH SPEC-Z

- **Euclid slitless spectroscopic data can be used to improve redshift estimates, and calibrate cluster masses in the redshift range 0.9<z<1.8.**
- **Low completeness and biased population of tracers prevent the use of traditional methods to derive dynamical masses**

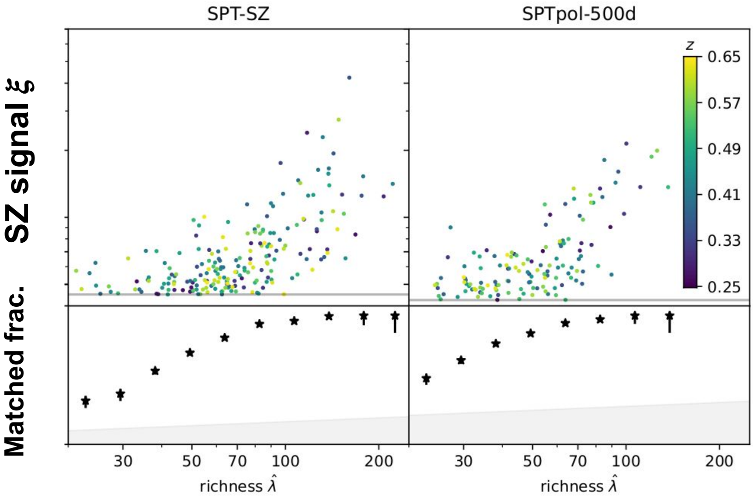


Machine Learning based estimates (Ho et al in prep.)

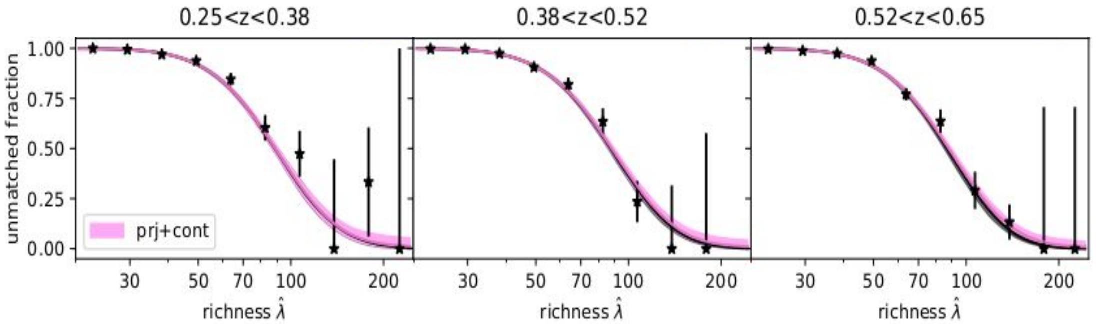


Ho et al. in prep

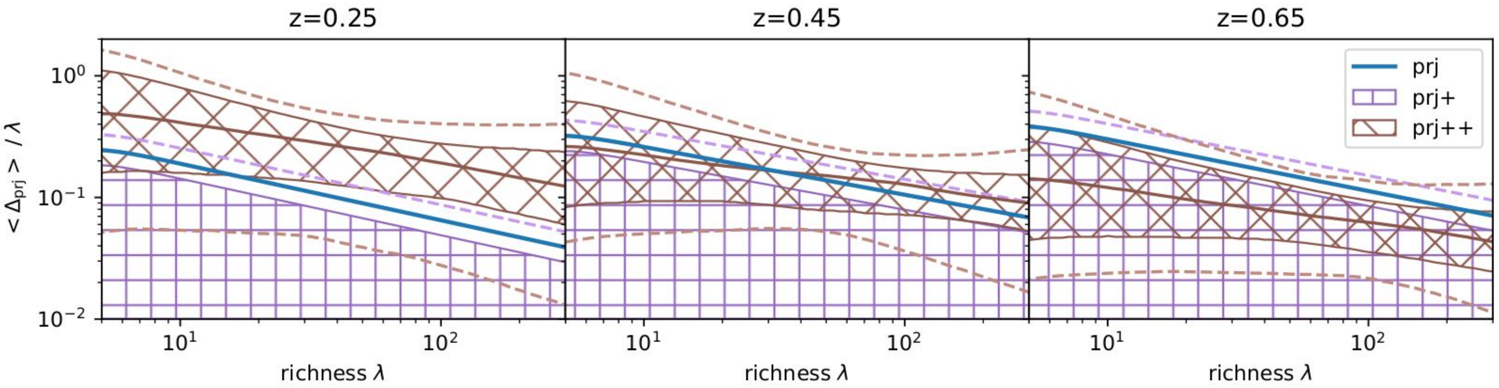
$\delta\lambda$ CALIBRATION: SZ DATA



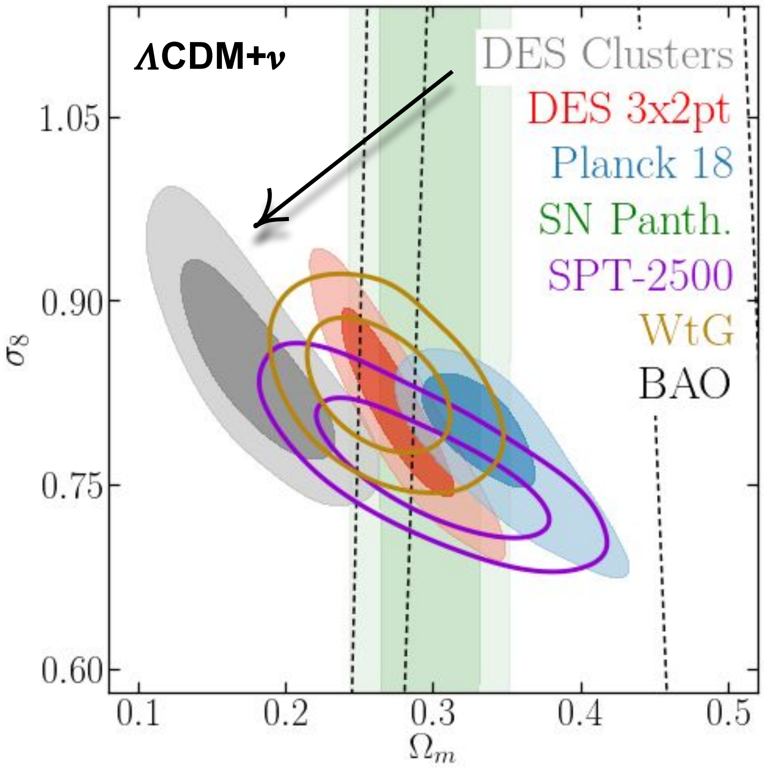
- **Use redMaPPer DES Y3 x SPT-SZ/500d/ECS matched and unmatched sample to calibrate projection effects: (Grandis et al in prep; see also Grandis+21)**

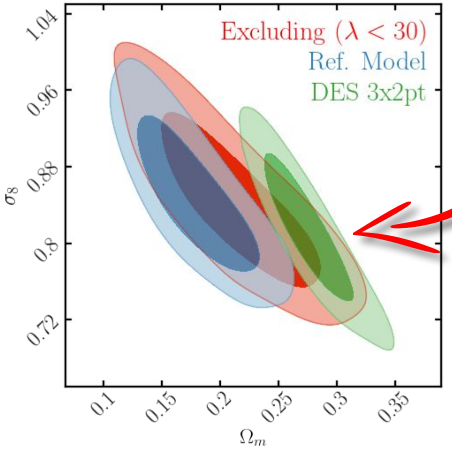


Calibration of richness contamination for different projection models

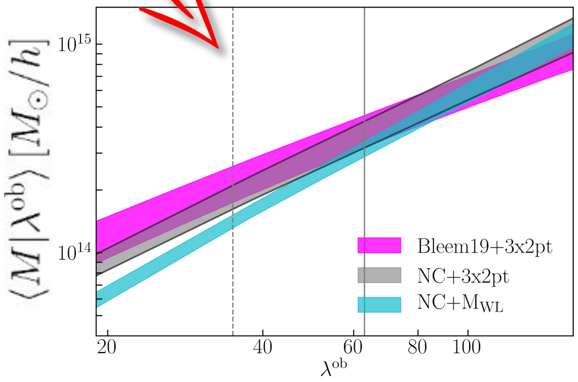


SELECTION EFFECT BIAS: LESSON FROM DES Y1





Flawed modeling of the stacked WL signal of λ<30: Removing the lowest richness bins reduces the tension with DES 3x2pt cosmology changing the slope of the λ-M relation

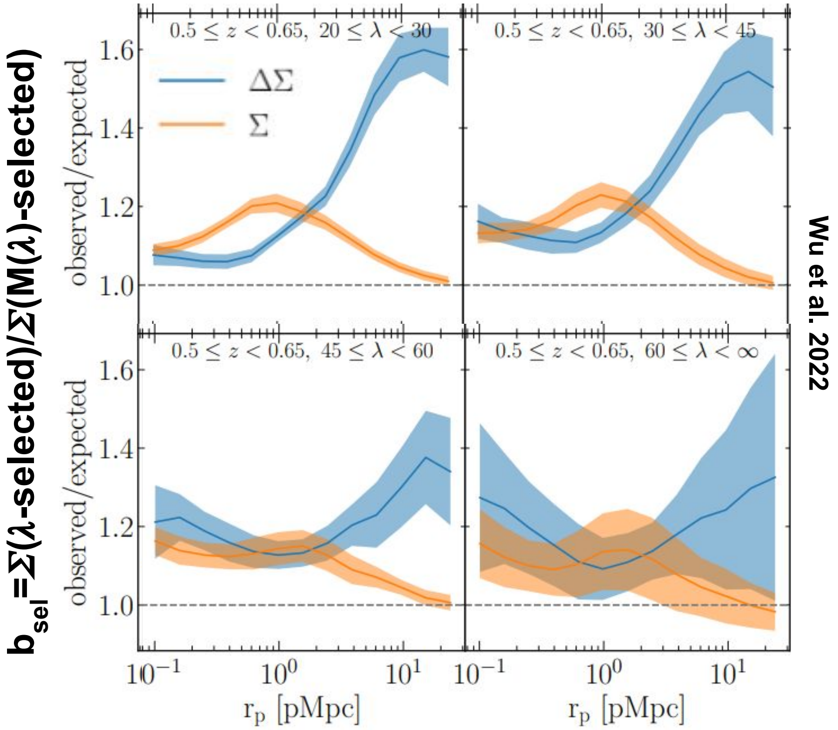


- **2.4σ tension with DES 3x2pt**
- **5.6σ tension with Planck 18**

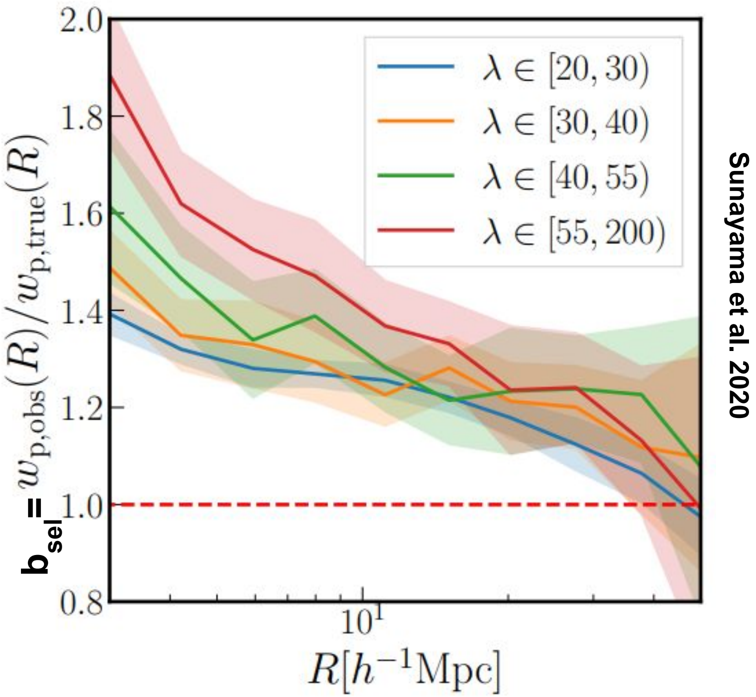
DES Collaboration 2020

SELECTION EFFECT BIAS ON WL AND CLUSTERING

Selection effects bias on WL profile from mock redMaPPer catalogs



Selection effects bias on projected 2-pt correlation function from mock redMaPPer catalogs

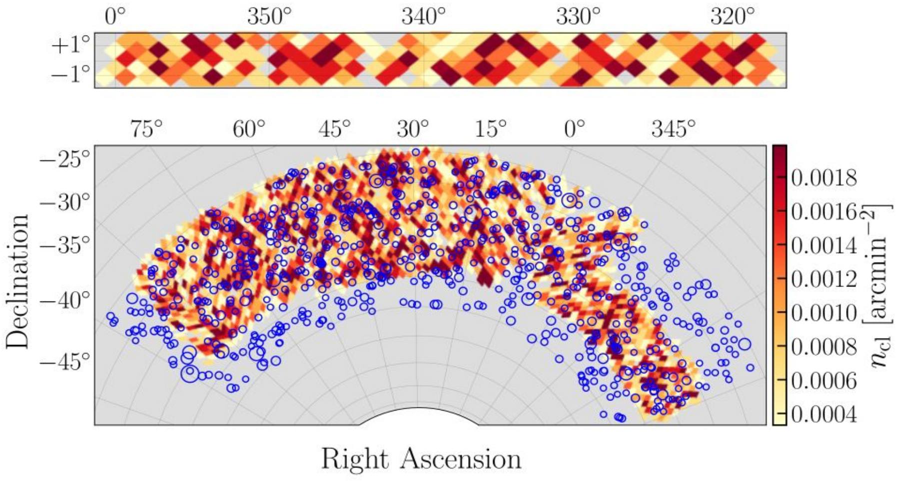


Also see To et al 2022, Zhang et al 2022, Zeng et al 2023

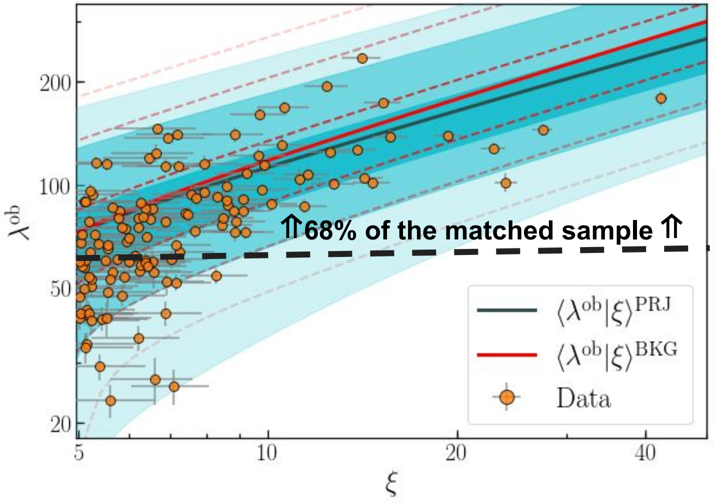
DES Y1 CLUSTER COUNTS x SPT MULTI-λ DATA

- Idea: Remove DES WL data and use SPT-SZ multi-wavelengths data (SZ, X-ray, WL) to constrain the richness–mass scaling relation
- Use DES Y1 Number Counts to constrain cosmology
- Add high-z SPT NC to test consistency between abundance and follow-up data sets and assess possible cosmological gain

DES Y1 cluster density and SPT-SZ clusters



DES Y1-SPT SZ cross matched sample

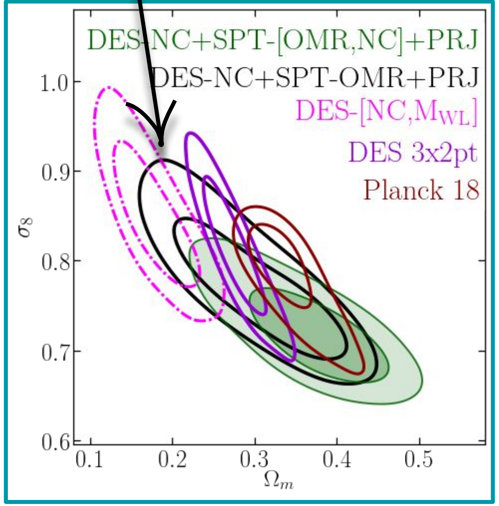


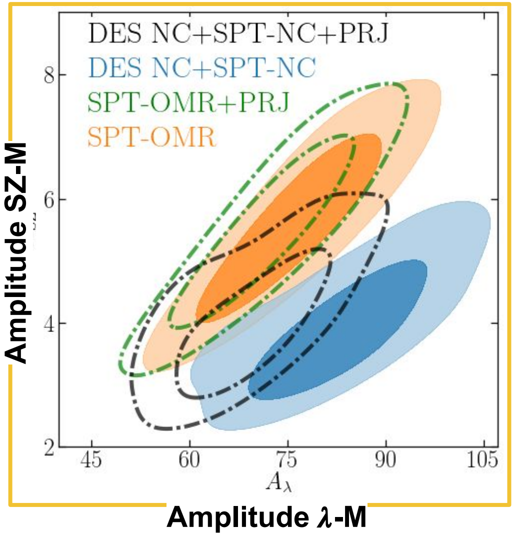
Costanzi+21

DES CLUSTER COUNTS x SPT MULTI-λ DATA

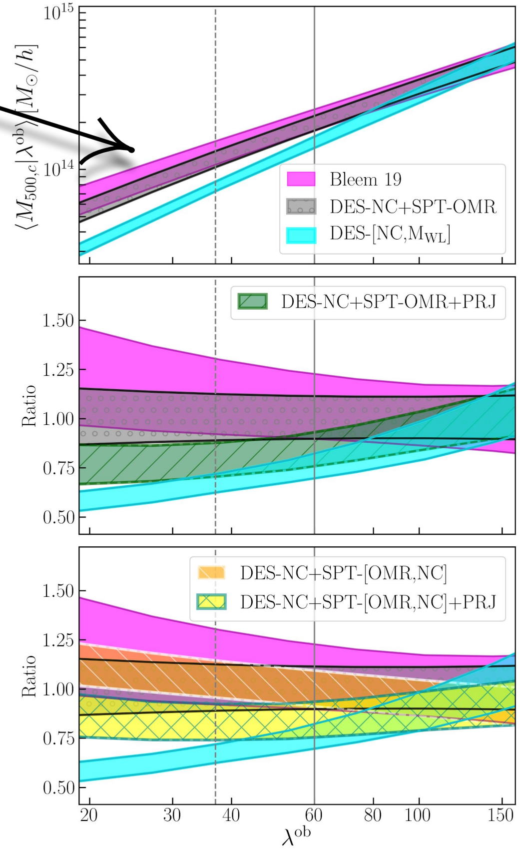
DES-NC x SPT-multi-λ yields results consistent with multiple cosmological probes.

Inclusion of high-redshift SPT NC data serves as a test of different scatter models for λ^{ob}





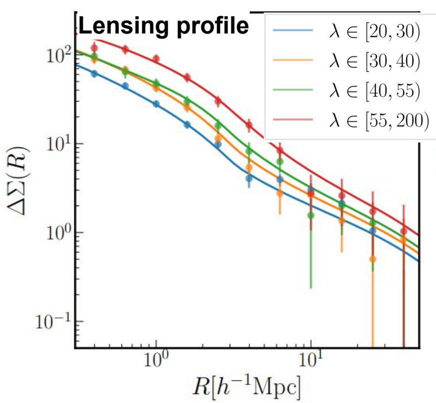
Mass-richness relations for different data combinations

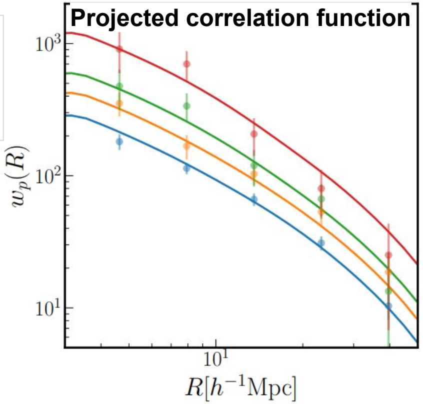


Costanzi+21

CALIBRATING SELECTION EFFECT BIAS

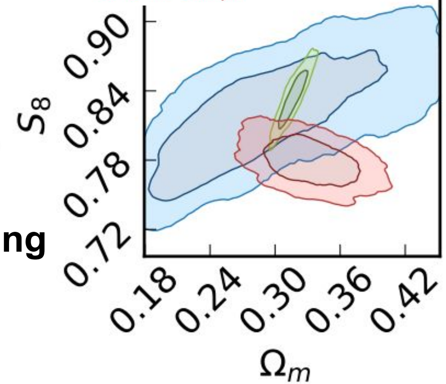
- **Self Calibration**





$$w_\mathrm{p}(R) = \Pi^2(R) w_\mathrm{p}^\mathrm{iso}(R),$$

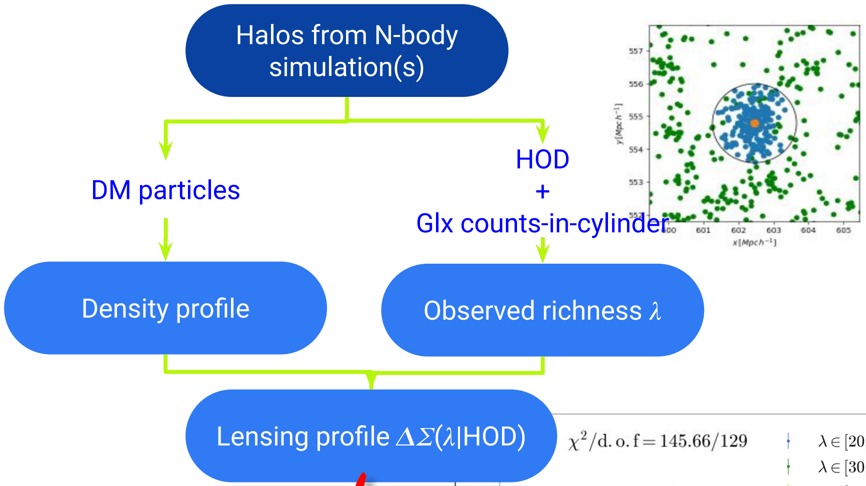
$$\Sigma(R) = \Pi(R)\Sigma^\mathrm{iso}(R).$$



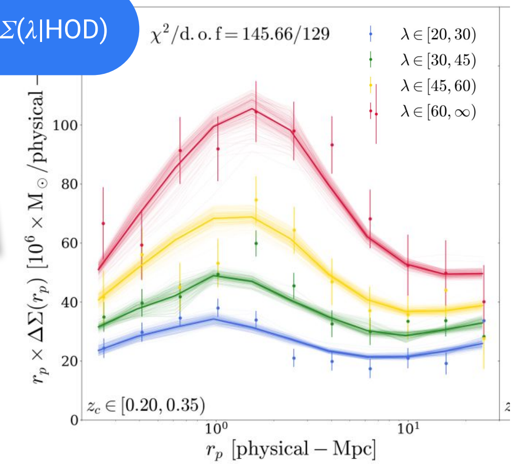
Selection bias fitted along with cosmological parameters

Sunayama et al. 2023

- **Simulation-based forward modeling**



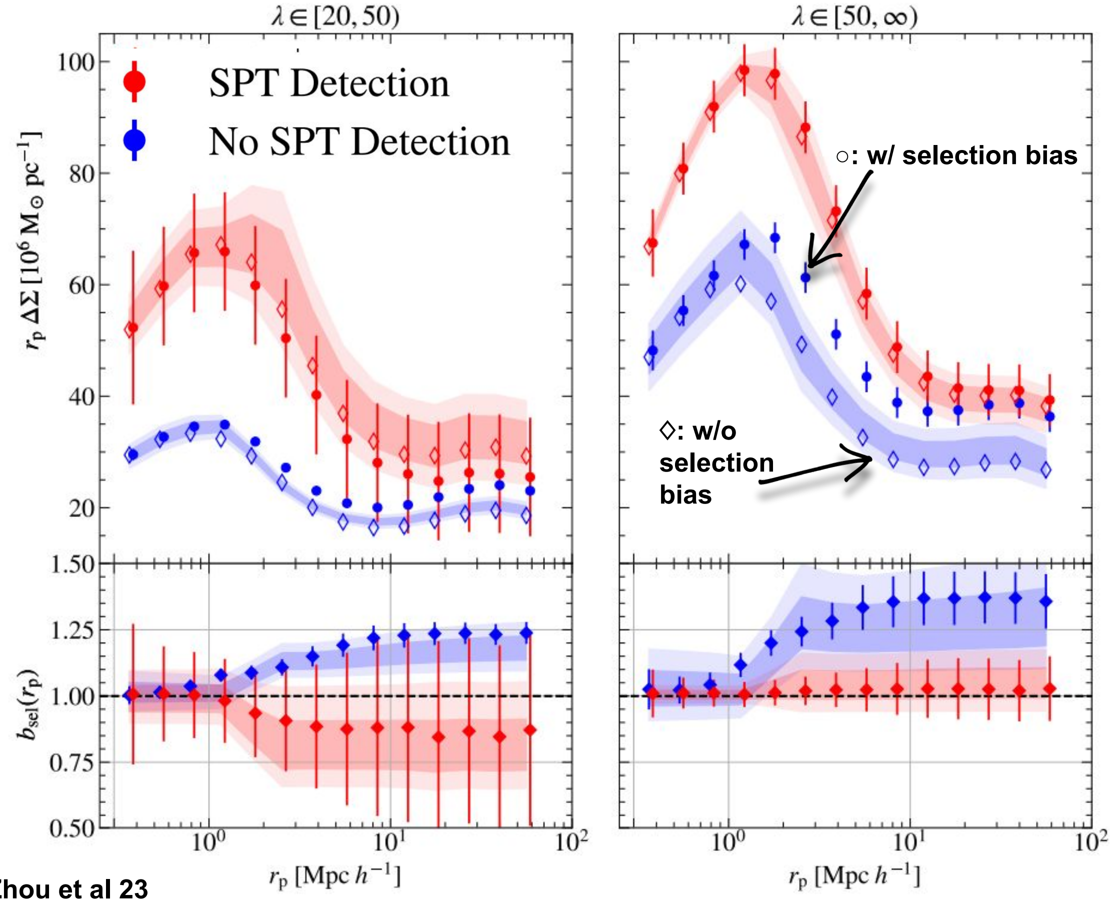
DES Y1 cluster lensing profiles vs Emulated lensing profiles



Salcedo et al. 2023

MULTI-λ SELECTION EFFECT BIAS CALIBRATION

Mock lensing profile of DES clusters matched and unmatched to SPT-SZ



Zhou et al 23

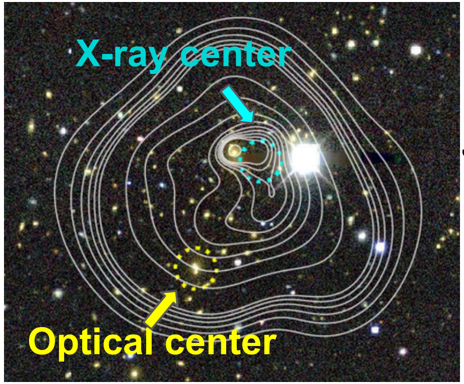
- **Cross match optical and SZ cluster samples and calibrate simultaneously the richness, SZ and WL - mass scaling relations, scatters and correlations**
- **The SZ signal, being less affected by projection effects, can be effectively used to calibrate the WL selection bias, b_{sel}.**

CLUSTER MISCENTERING: X-RAY CALIBRATION

Cluster miscentering caused by: masked data, merging/disturbed clusters, “blue” BCG

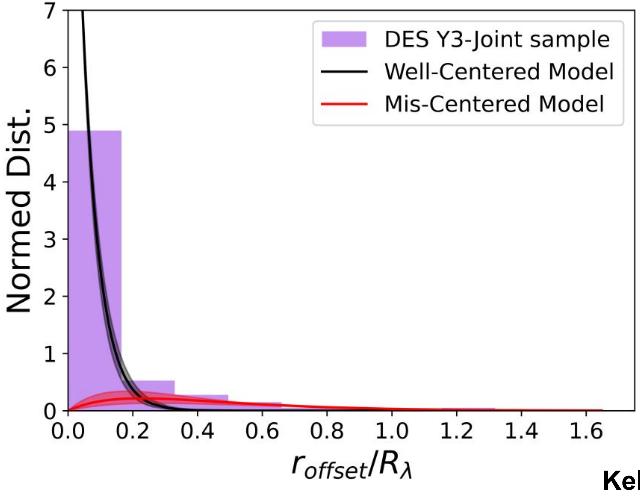
Miscentering tends to bias low the lensing signal and other cluster observables (e.g. richness)

→ **See P. Giles talk on Thursday**

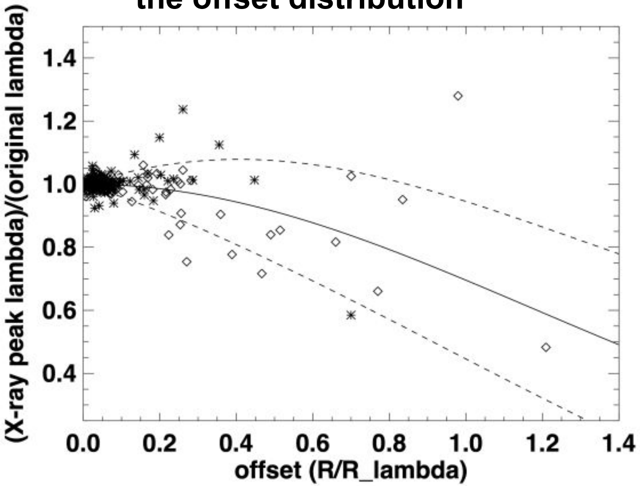


Kelly+24

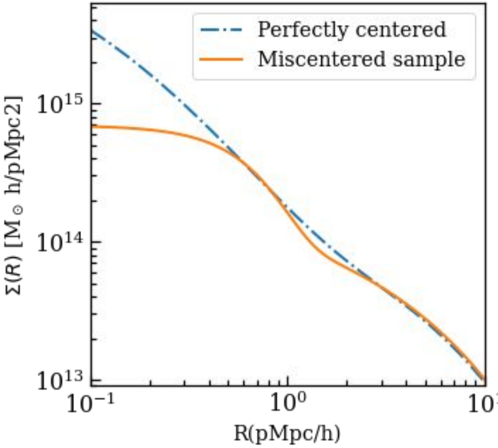
Radial offset distribution calibration using X-ray vs optical center



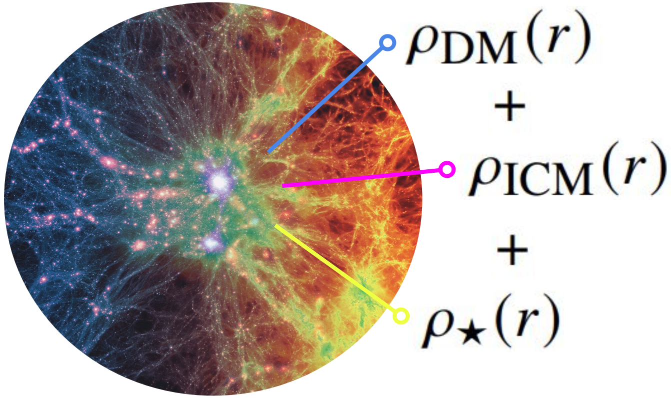
Richness perturbation as a function of the offset distribution



Kelly+24

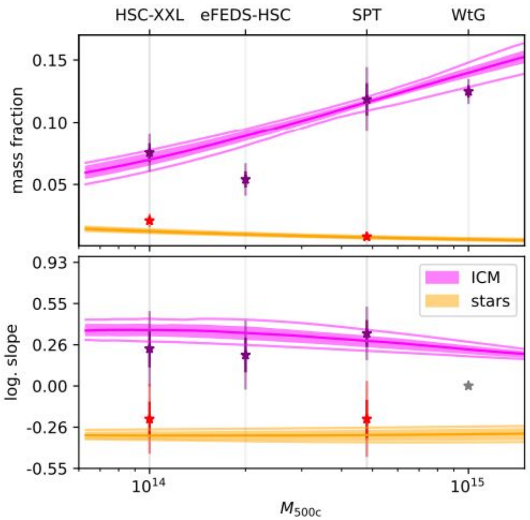


BARYONIC FEEDBACK CALIBRATION WITH GC MULTI-λ

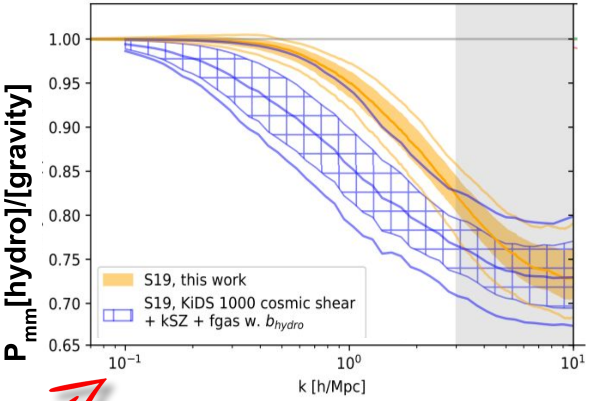


- **Multi-λ data provide a means to probe the gas (X-ray, SZ) and stellar (optical/IR) components of clusters**
- **Combining gas and stellar mass measurements with halo mass estimates (e.g. from WL) it is possible to constrain the modulation of the matter clustering due to baryonic feedbacks**

Stellar/ICM mass fraction measurements from X-ray and SZ surveys



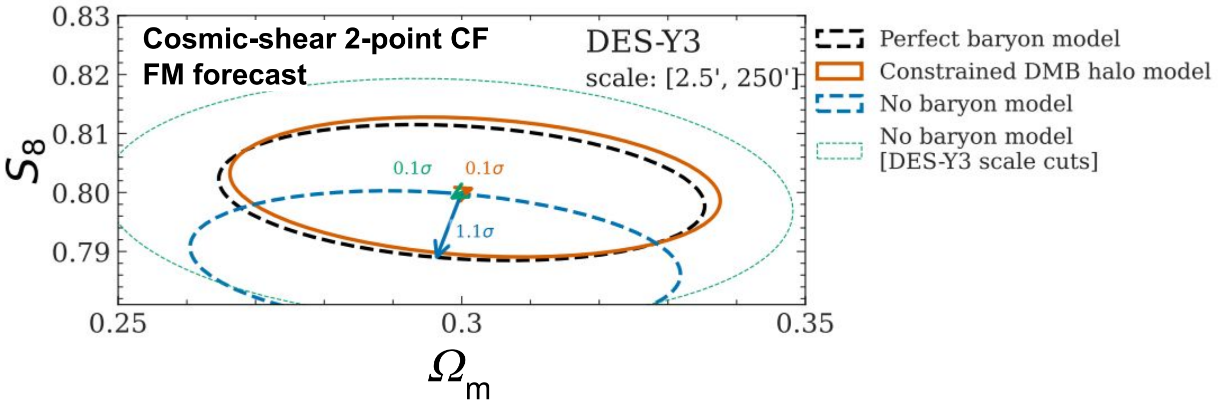
Matter power spectrum suppression due to baryonic feedbacks



Grandis+24

Also see Pandey+21, Troster+22 , Schneider+22, To+24

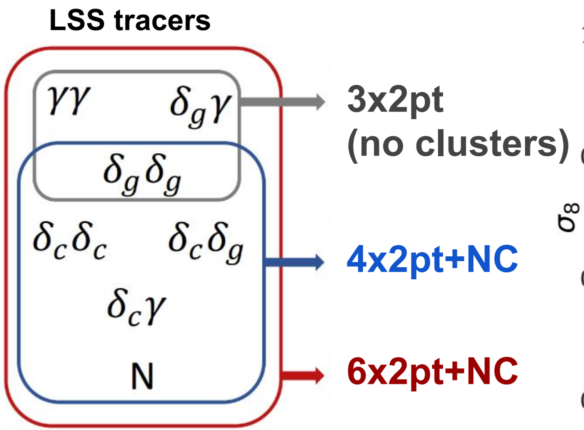
MULTI-PROBE COSMOLOGY WITH GCs

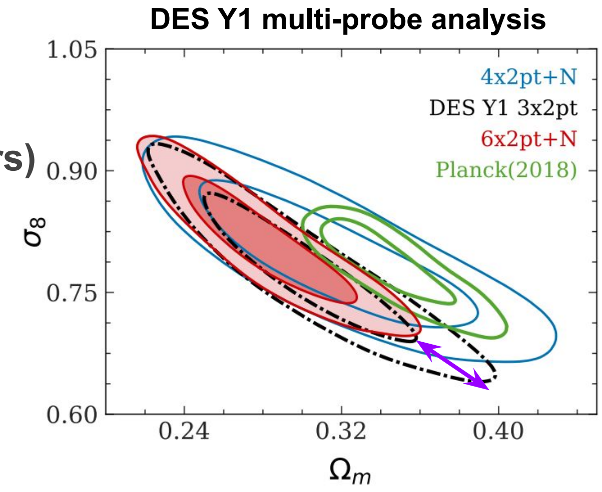


To+24

- A calibration of baryonic feedback on the matter power spectrum allows to push to smaller scale the cosmological analysis of other LSS probes

- When combined with other probes of the LSS, cluster data entail a sizeable improvement of the constraints in the σ_8 - Ω_m plane



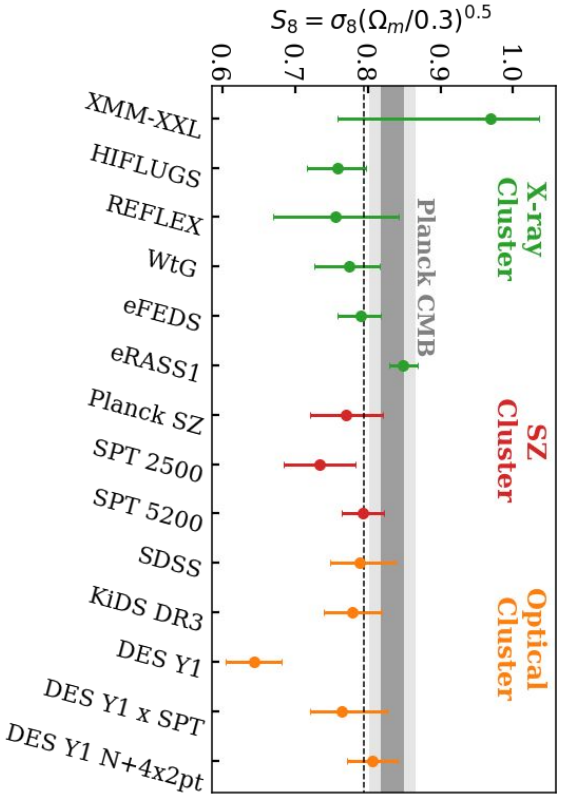


To & Krause et al. 2021

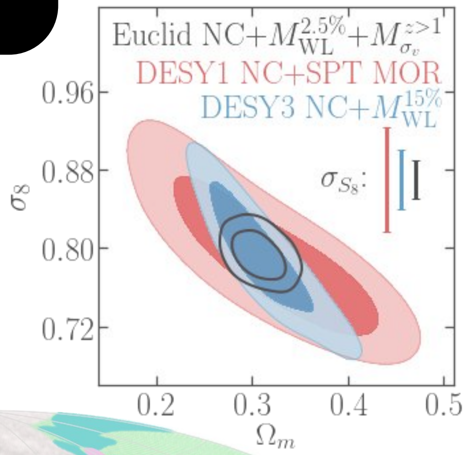
TAKEAWAY & FUTURE DIRECTIONS

- **Galaxy clusters, with their multi-component nature, offer a unique opportunity to study and characterize a cosmological probe across the electromagnetic spectrum.**

- **There is no such thing as “standalone” X-ray, mm or optical cluster cosmology: Cluster catalogs selected at all wavelengths require multi-wavelength data to derive competitive and unbiased cosmological constraints.**
    - **Recent cluster analysis results across different wavelengths are consistent among themselves and other probes, reinforcing the robustness of current multi-wavelength approaches.**
    - **The full potential of optical cluster catalogs is currently limited by the lack of multi-wavelength data, particularly at low richness and high redshift. However, this is set to improve with the increased sensitivity and depth of upcoming X-ray and SZ surveys (e.g. eROSITA 4.5y, SPT-3G, AdvACT).**



TAKEAWAY & FUTURE DIRECTIONS



- **Clusters have the potential to deliver the most precise single-probe cosmological constraints, provided that systematics in mass estimates can be accurately characterized (~2% level).**
  - **With the substantial overlap of ongoing and upcoming wide-field cluster surveys across X-ray, mm, and optical wavelengths, future cluster cosmology studies should aim to leverage the potential of a full multi-λ data combination.**

- **Galaxy clusters should be regarded as a key ingredient of multi-probe analyses: combined with other probes of the LSS, (multi-λ) cluster data is capable of constraining astrophysical parameters and breaking cosmological degeneracies greatly improving the overall constraining power.**