DARK ENERGY SURVEY

European Commission

erc

IASF Seminar:

COSMOLOGY WITH OPTICALLY SELECTED CLUSTERS

UNIVERSITAS STVDIORVM TERGESTVM MCMXXIV

OSSERVATORIO ASTRONOMICO DI TRIESTE
INAF ISTITUTO NAZIONALE DI ASTROFISICA

16 March 2022 | Matteo Costanzi - University of Trieste / INAF

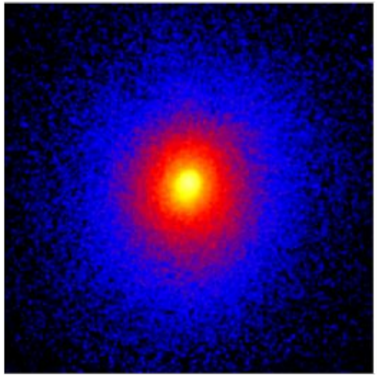
GALAXY CLUSTERS

- **Most massive bound objects in the Universe**:
  $M \simeq 10^{13} - 10^{15}\ M_\odot$ and $R \simeq 1 - 5$ Mpc
- **Multi-component systems**:
  Galaxies and stars (~5%), ICM (~15%), DM (~80%)

OPTICAL

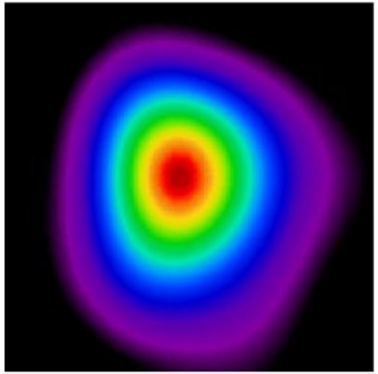
RICHNESS, LENSING EFFECTS

X-RAYS

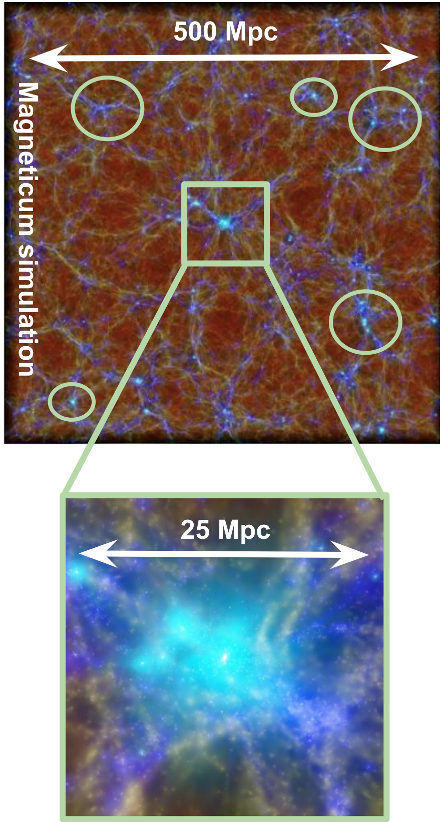


LUMINOUS AND EXTENDED X-RAY SOURCES

MICROWAVES



SUNYAEV-ZEL'DOVICH EFFECT



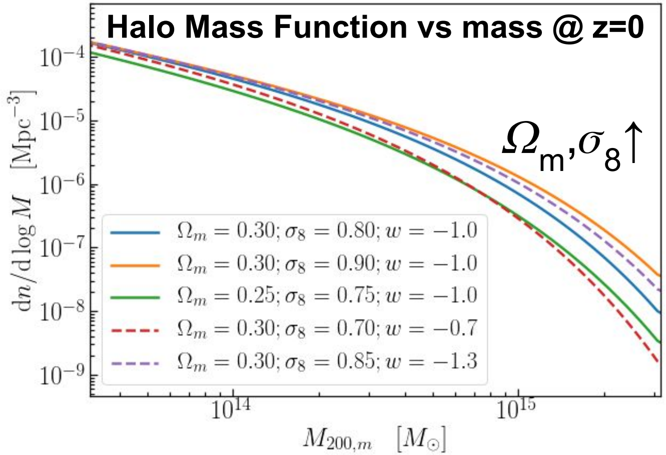
From Hirschmann+2014

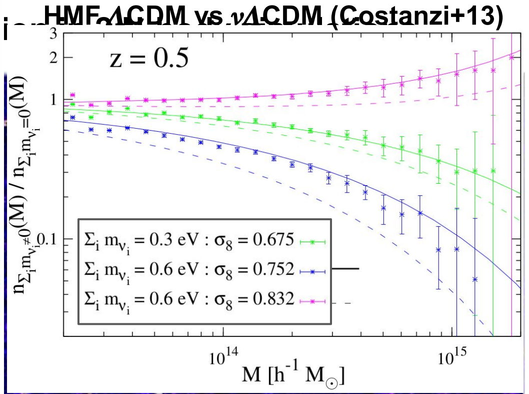
CLUSTER COSMOLOGY IN A NUTSHELL

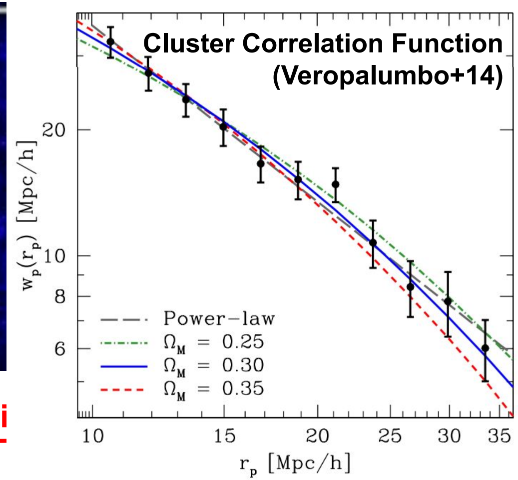
The abundance and spatial distribution of galaxy clusters are sensitive to the growth rate of cosmic structures and expansion history of the Universe

- **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**

...







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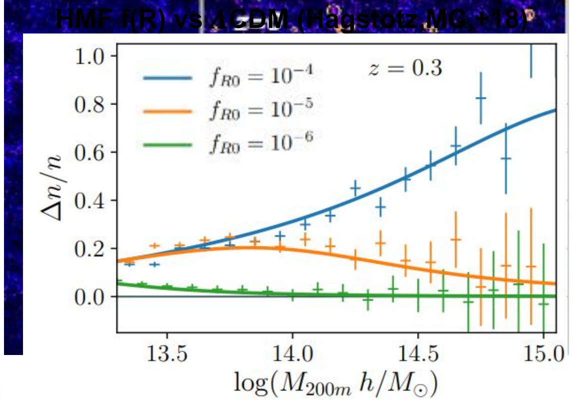
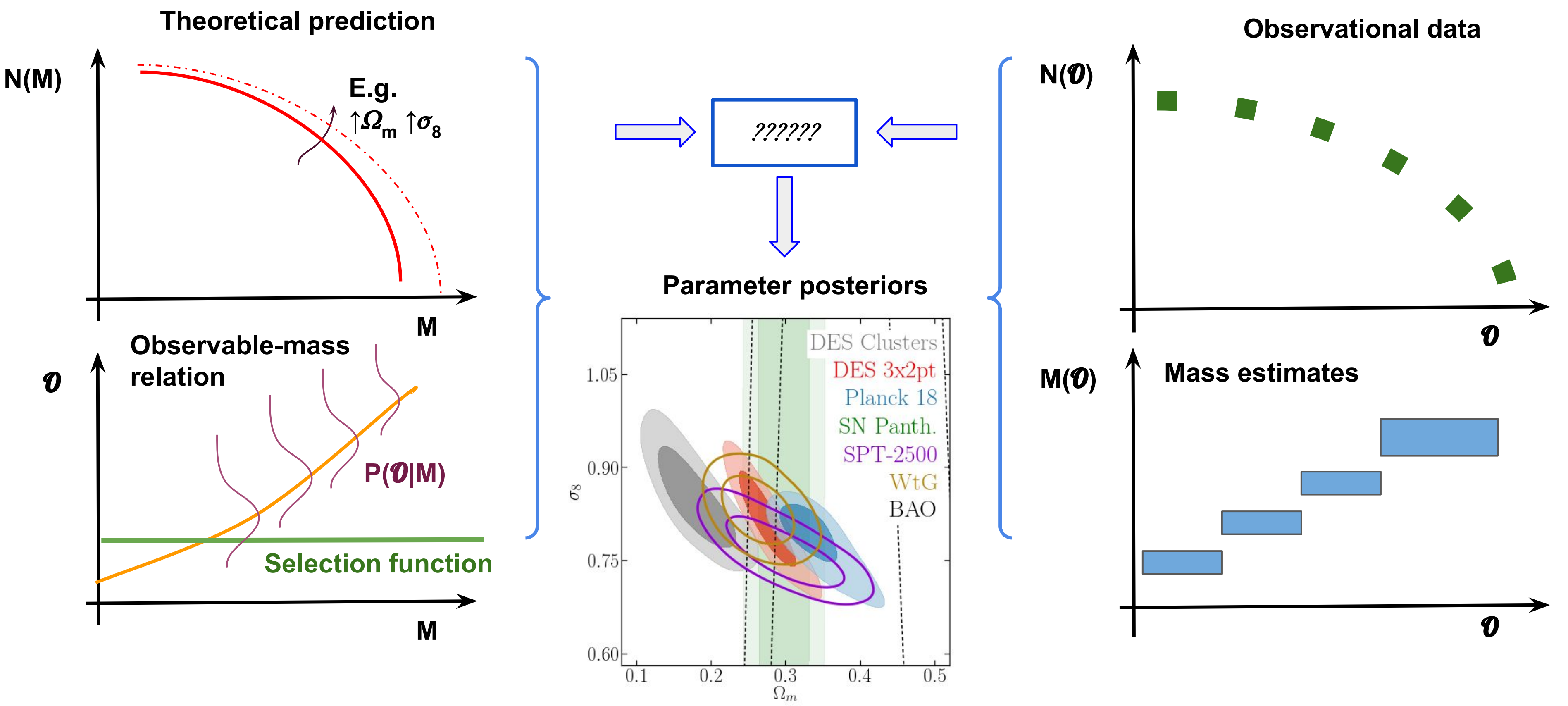


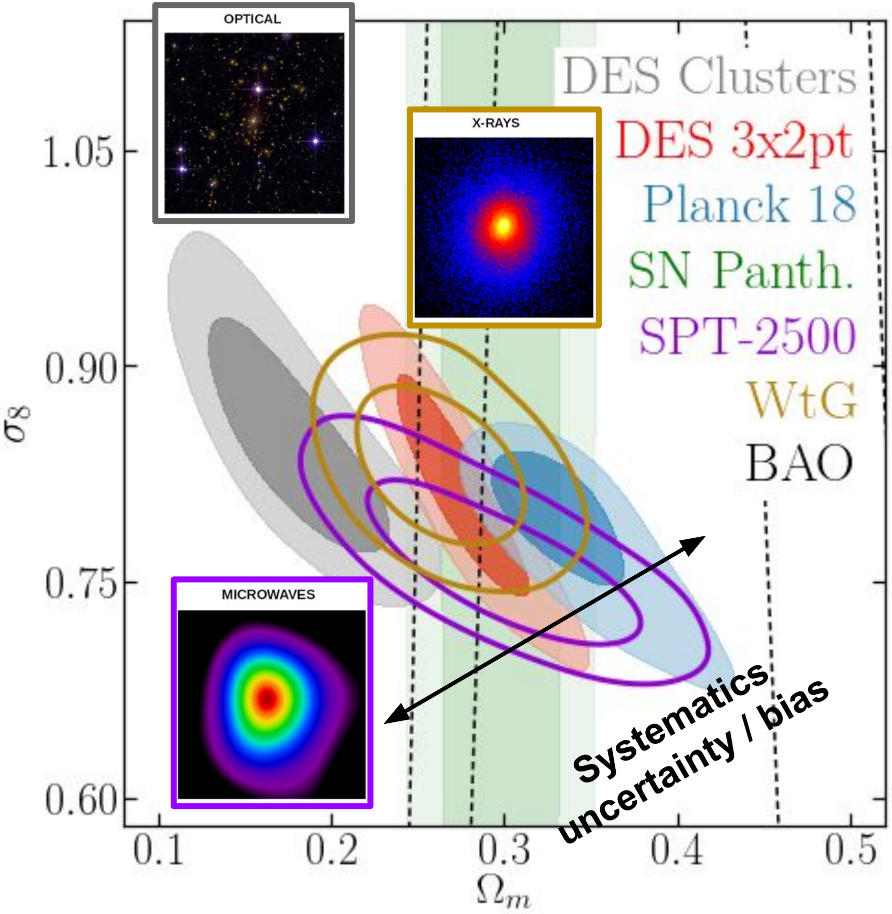
From Borgani, Guzzo 2001

FROM OBSERVATION TO COSMOLOGICAL CONSTRAINTS



GALAXY CLUSTERS AT DIFFERENT WAVELENGTHS

Different detection techniques imply different selection functions, mass proxies, mass calibration data and systematics:



DES Collaboration 2020 + Allen+ 2011

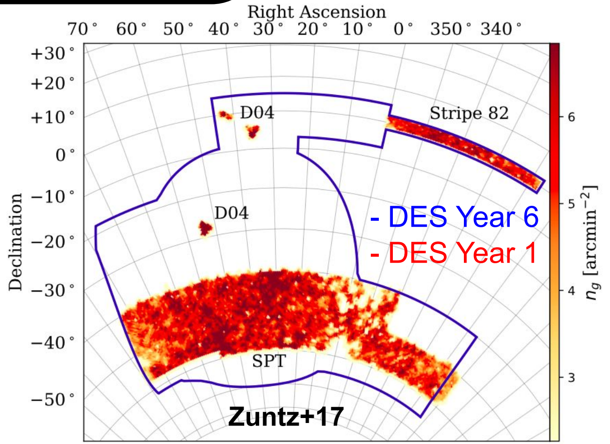
- **DES Survey:**
  - ~5000 deg^2 of southern sky
  - *g*,*r*,*i*,*z*,(Y) bands
  - 10 visits per pointing to reach *i*~24

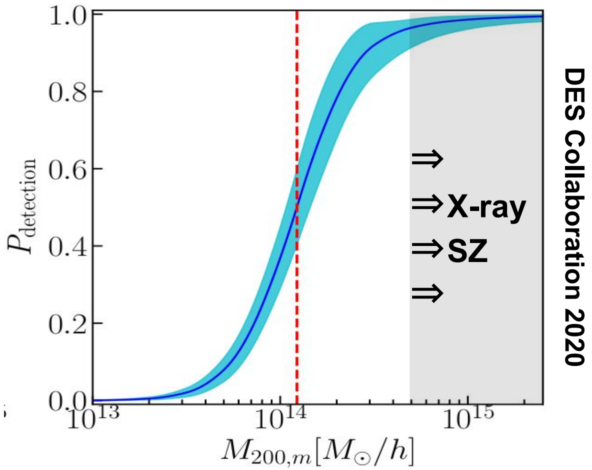
- **DES Year 1 redMaPPer :**

red-sequence **Ma**tched-filter **P**robabilistic **Per**colation cluster finding algorithm (Rykoff+14)

Mass Proxy: $$\lambda^{\rm ob} = \sum_{R<R_\lambda} p_{mem}$$

Area [deg^2]	Redshift range	# of clusters λ>20	σ_z/(1+z)	$n_{\rm eff}$ [arcmin^{-2}]
1470	0.2<z<0.65	~6540	0.006	6.3

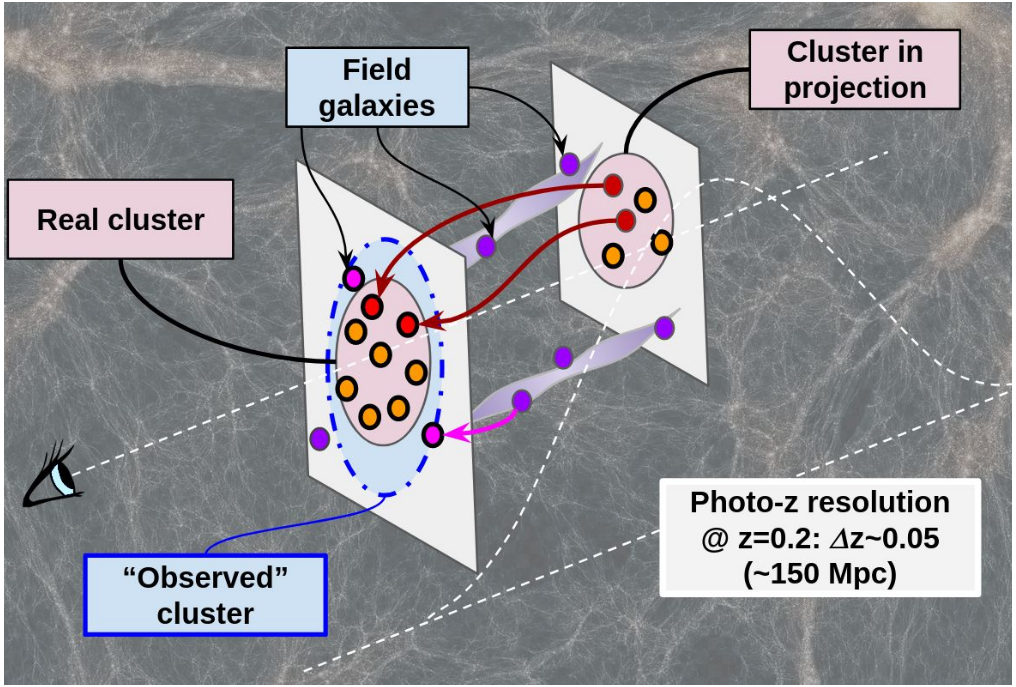




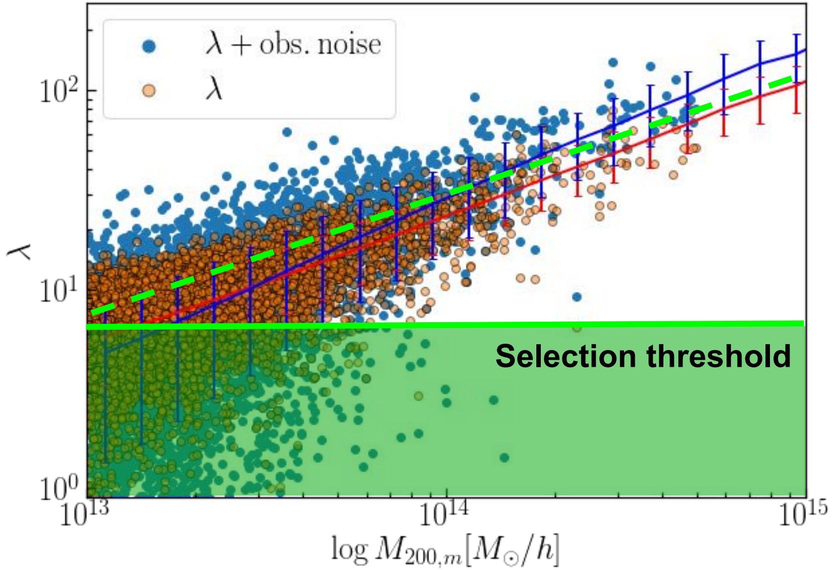
CLUSTER COUNTS: MODELING AND SYSTEMATICS

- **Halo mass function and halo bias calibration (~5% uncertainty within $\nu\Lambda$CDM)**
- **Modeling of the observable-mass relation(s)**
- **Modeling of the covariance matrix (e.g. Fumagalli et al 2021)**
- **Selection function:**
  - **Observational noise on richness estimates:**
    - **projection/masking effects and background subtraction noise**
    - **Orientation / Triaxiality effects (<1% uncertainty; Zhang+22)**
    - **Miscentering effects (<1% uncertainty; Zhang+19)**
  - **Variation of the survey depth/masking effects (<1% uncertainty)**
  - **Photometric redshift uncertainty (<1% uncertainty)**

OBSERVATIONAL NOISE ON RICHNESS ESTIMATES



$$\lambda^{ob} = \lambda^{true}(M) + \Delta\lambda^{obs\text{-}noise}$$

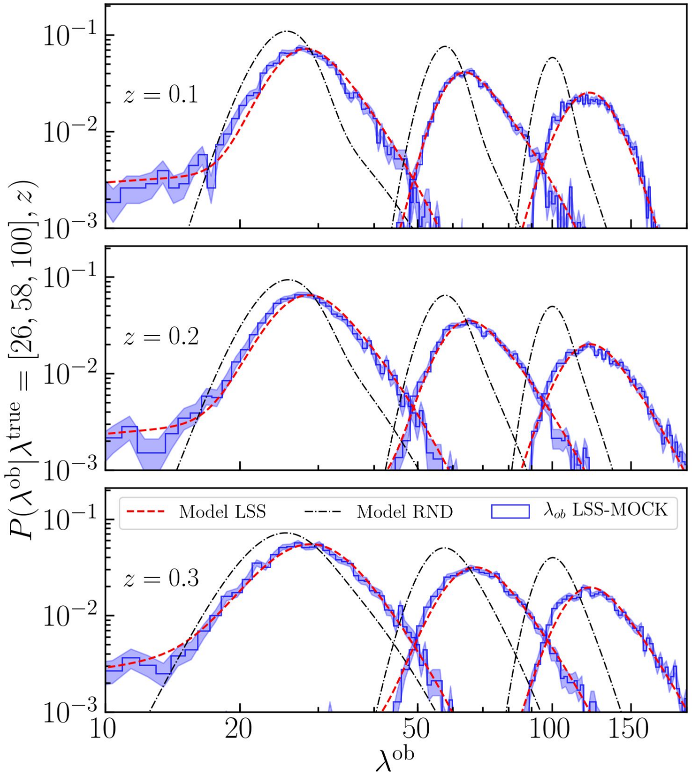


OBSERVATIONAL NOISE ON RICHNESS ESTIMATES

$$\lambda^{ob} = \lambda^{true}(M) + \Delta\lambda^{obs\text{-}noise}$$

- Using data: e.g. injecting synthetic clusters in the images; randomizing the member galaxy properties
- From simulations: e.g. running the cluster finder on mock data
- Using multi-wavelength data: e.g. spec-z follow-up of putative member galaxies

Scatter between true and observed richness



Costanzi+ 19

Dash-dotted line: Neglecting the scatter due to correlated structures

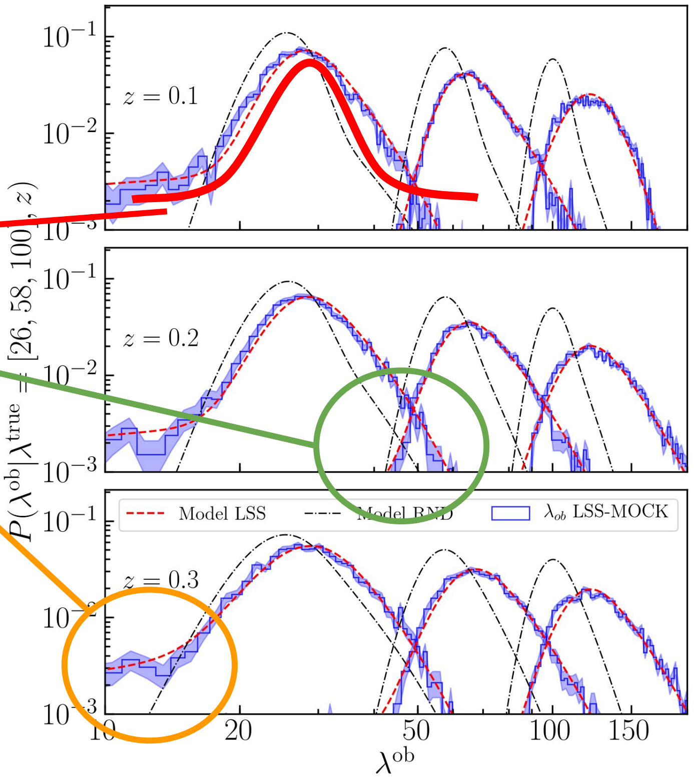
OBSERVATIONAL NOISE ON RICHNESS ESTIMATES

$$\lambda^{ob} = \lambda^{true}(M) + \Delta\lambda^{obs\text{-}noise}$$

- **From Background contamination → Gaussian kernel**
- **From projection effects → high richness tail**
- **From percolation/masking effects → low richness tail**

Calibration currently limited by lack of multi-wavelengths data (especially at low λ and high-z) and reliability of simulated data in reproducing galaxy properties in dense environments

Scatter between true and observed richness



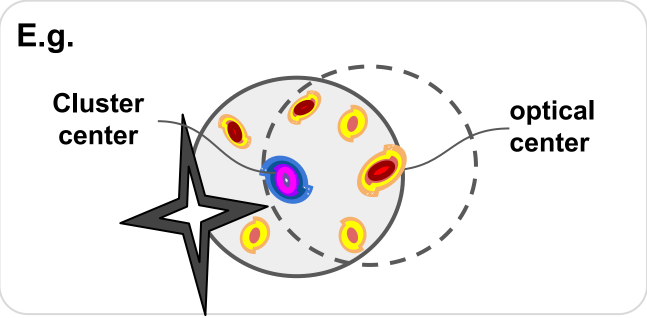
Dash-dotted line: Neglecting the scatter due to correlated structures

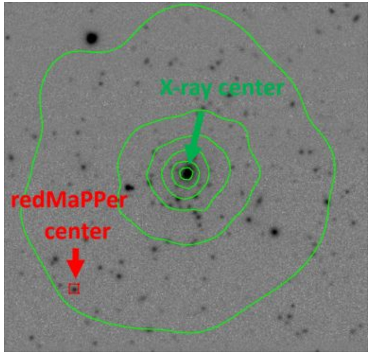
CLUSTER MISCENTERING

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

Miscenterd clusters tend to have low (observed) richness and biased lensing profile

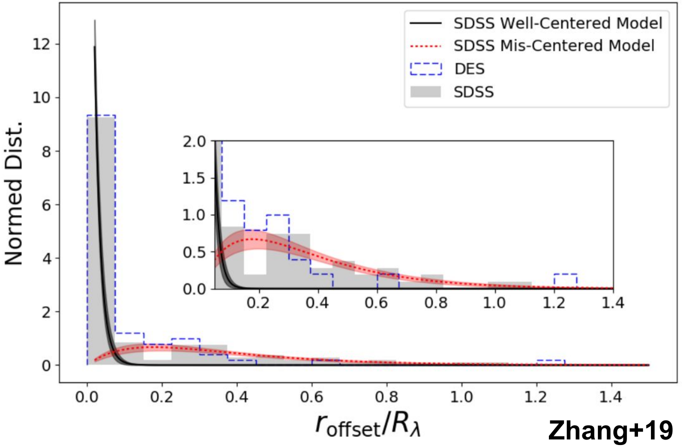
Miscentering effects are modeled calibrating:





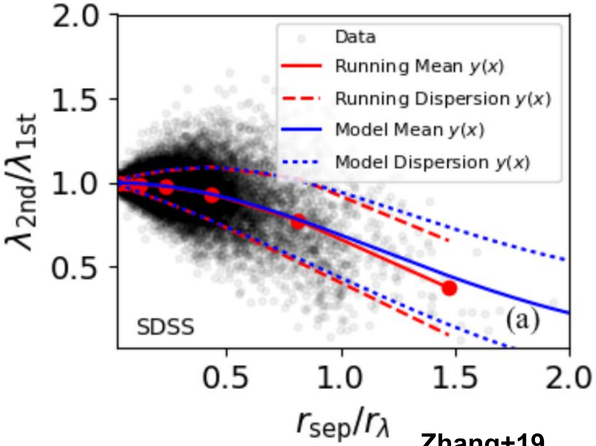
Credit: T. Jeltema

Radial offset distribution (X-ray vs optical center)



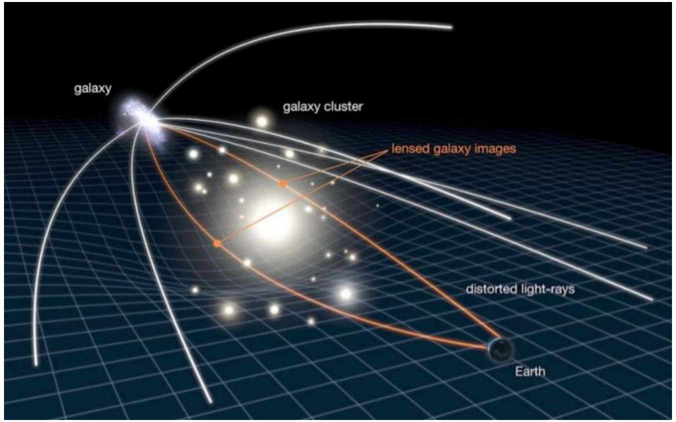
Zhang+19

Richness perturbation as a function of the offset distribution

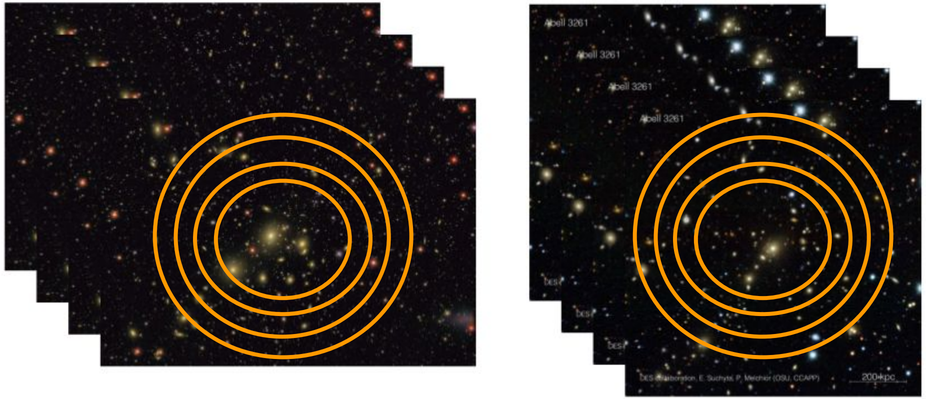


Zhang+19

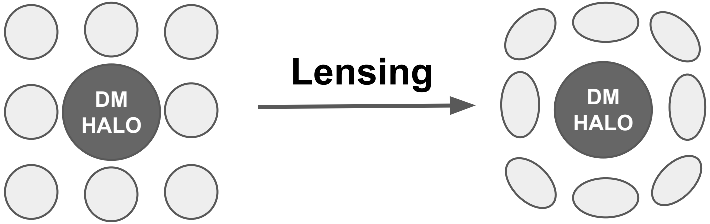
(STACKED) WEAK LENSING MASS ESTIMATES



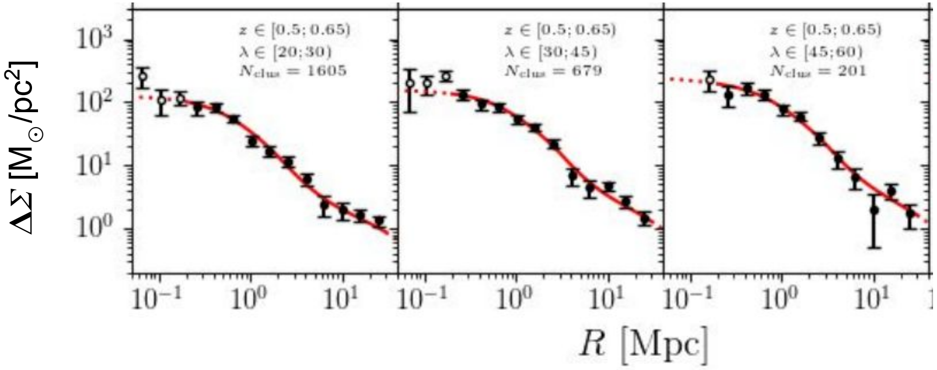
Stack clusters in bin of λ/z and measure mean tangential shear



Tangential shear ∝ Cluster surface mass density



Compute the surface mass density profile and fit for the mean masses



McClintock & Varga+19

WL MASS ESTIMATES: MODELING AND SYSTEMATICS

- **WL mass calibration (McClintock & Varga+19):**

Source of systematic	Y1 Amplitude Uncertainty
Shear measurement	1.7%
Photometric redshifts	2.6%
Modeling systematics	0.73% (*)
Membership dilution + miscentering	0.78% **(Varga+19, Zhang+19)**
Total Systematics	4.3%
Total Statistical	2.4%

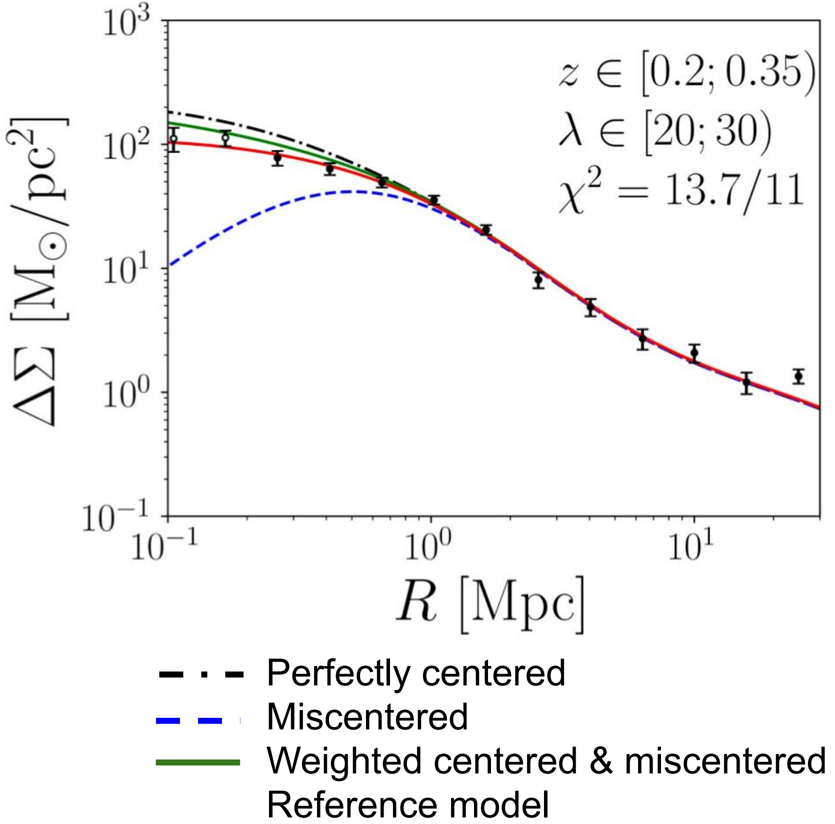
✚

Modeling of the cosmological dependence of the WL mass estimates (<1% uncertainty)

✚

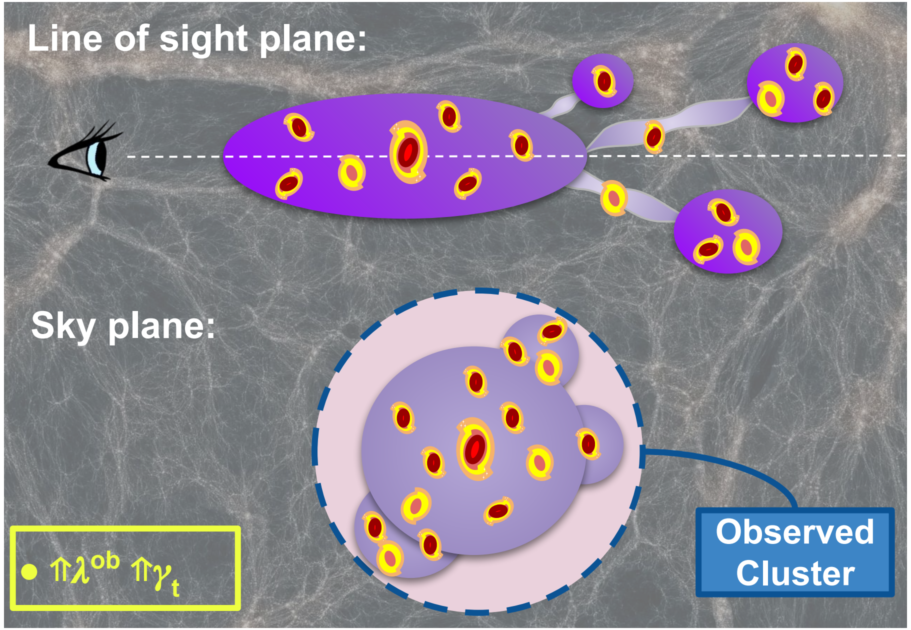
(*) **Selection effect bias (~15% uncertainty on mass)**

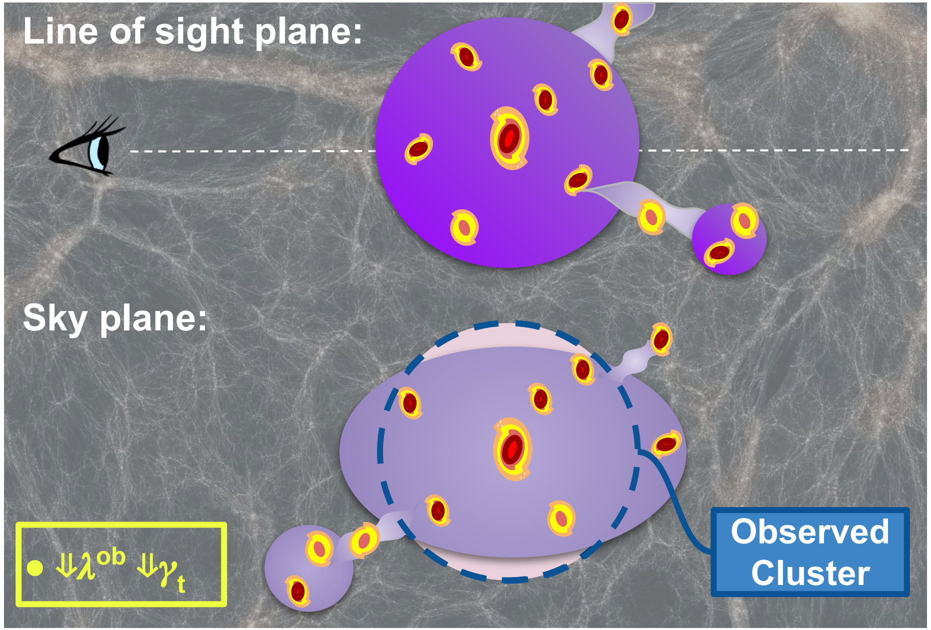
Effect of different systematics on the model prediction



SELECTION EFFECT BIAS

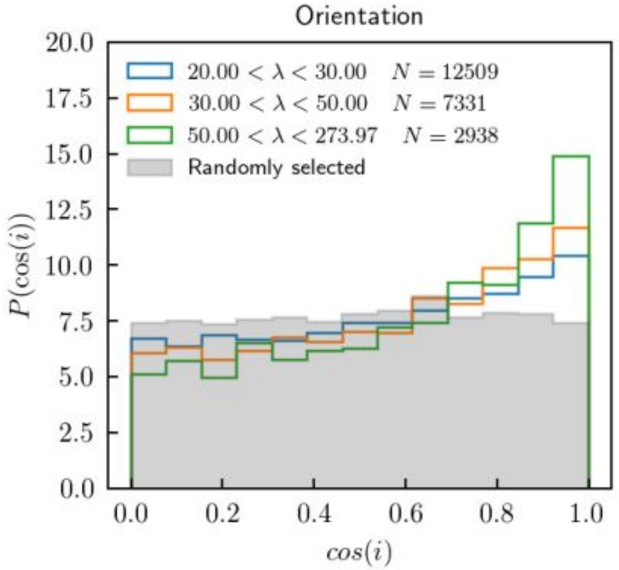
The cluster finder select preferentially clusters with properties (e.g. halos elongated along the l.o.s. and/or with structures in projection) which correlate with the mass proxy (i.e. richness and WL signal)

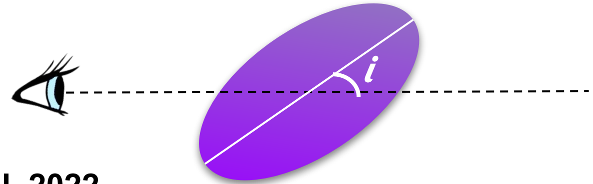


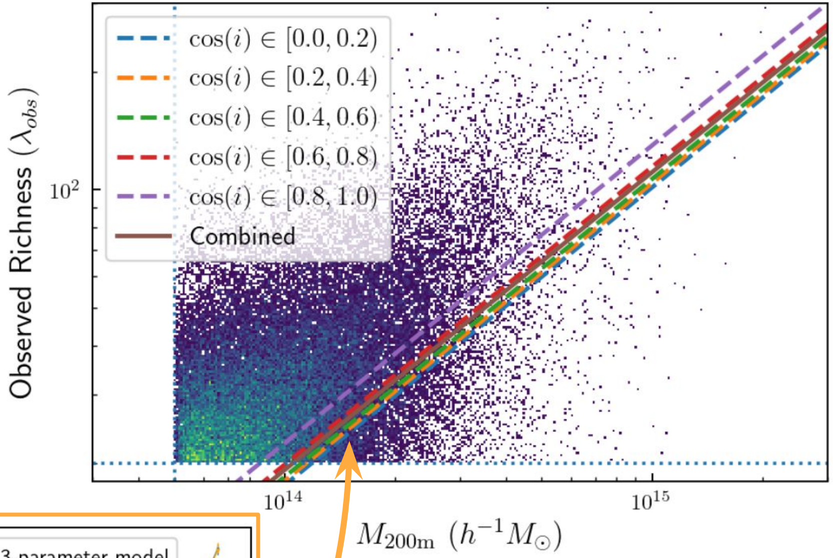


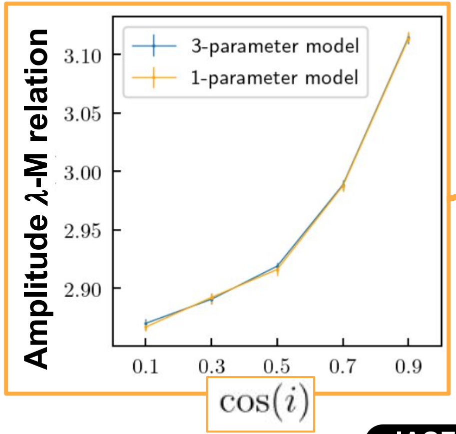
ORIENTATION & TRIAXIALITY EFFECTS ON λ

The cluster finder preferentially select clusters with the major axis align to the line of sight:





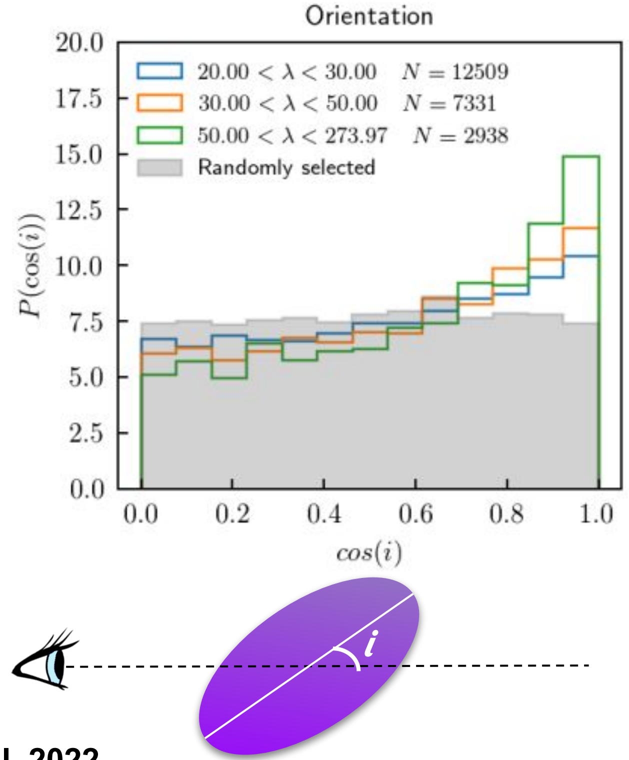




Zhang et al. 2022

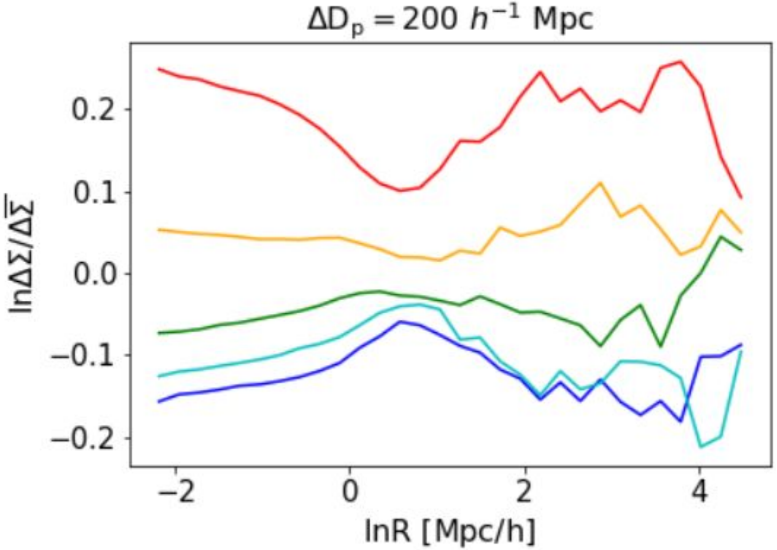
ORIENTATION & TRIAXIALITY EFFECTS ON WL

The cluster finder preferentially select clusters with the major axis align to the line of sight:



Zhang et al. 2022

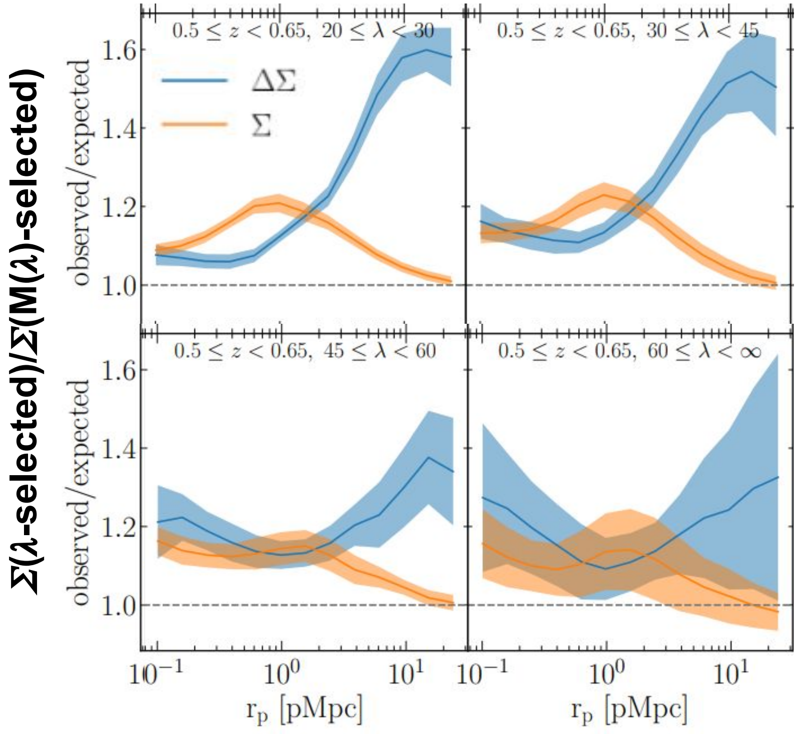
Excess surface density profile bias for different halo orientation



0.0<cos(i)<0.2 0.2<cos(i)<0.4
0.4<cos(i)<0.6 0.6<cos(i)<0.8
0.8<cos(i)<1.0 $M \in [10^{14}\text{-}5 \cdot 10^{14}]$

SELECTION EFFECT BIAS ON WL

Selection effects bias on WL profile from mock redMaPPer catalogs



Wu et al. 2022

Selection bias term

Ca

$$\langle \ln\Sigma | \ln\lambda, M \rangle = \langle \ln\Sigma | M \rangle + \boxed{r\, \sigma_{\ln\Sigma} \frac{(\ln\lambda - \langle \ln\lambda | M \rangle)}{\sigma_{\ln\lambda}}}$$

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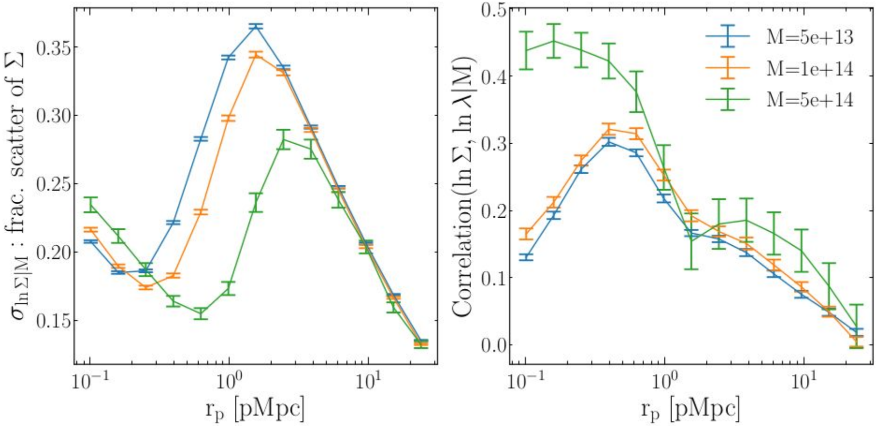
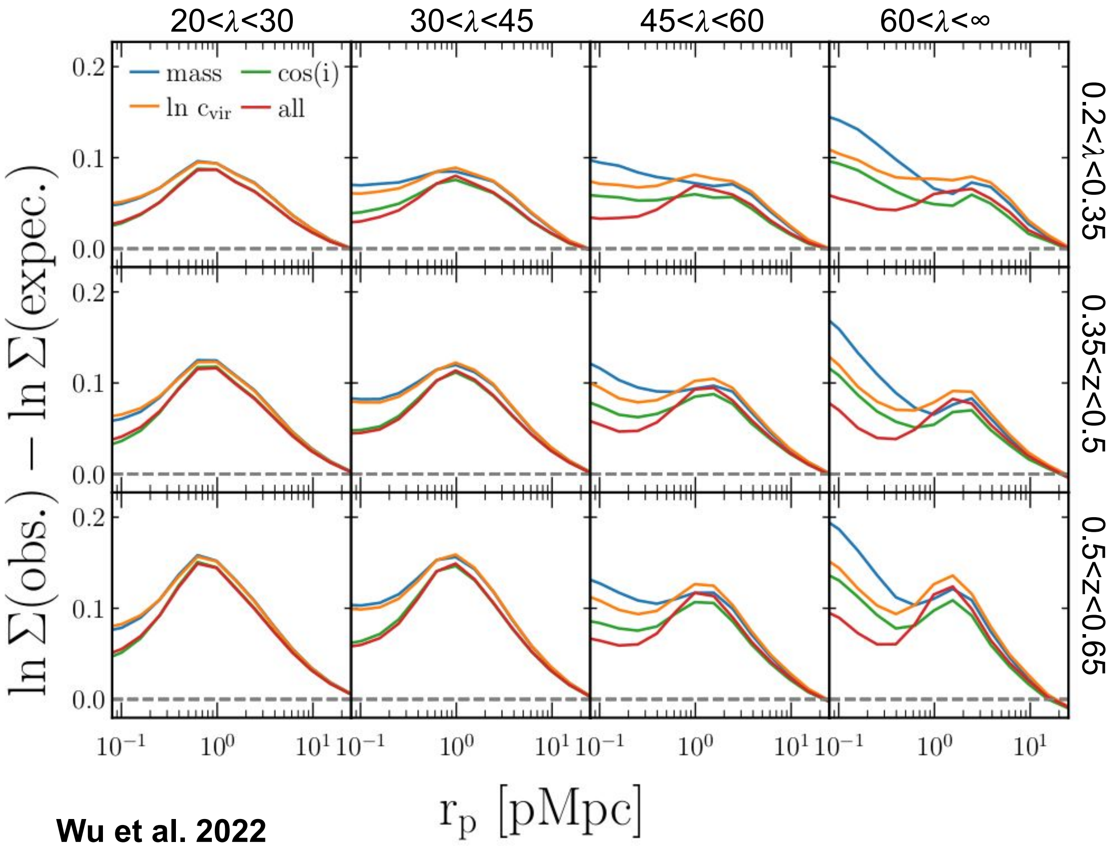
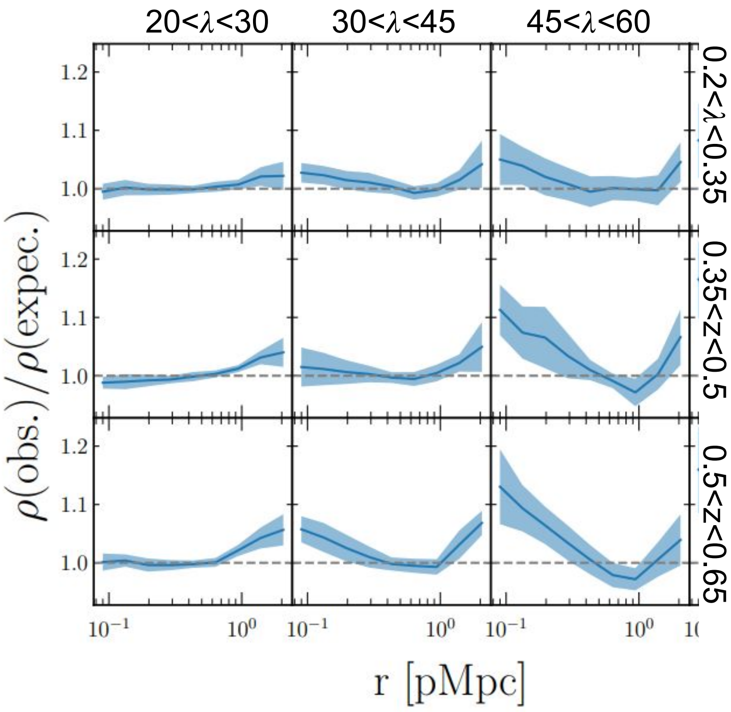


SELECTION EFFECT BIAS ON WL

Selection bias dependency on secondary halo properties:



Selection bias in 3D density profile:

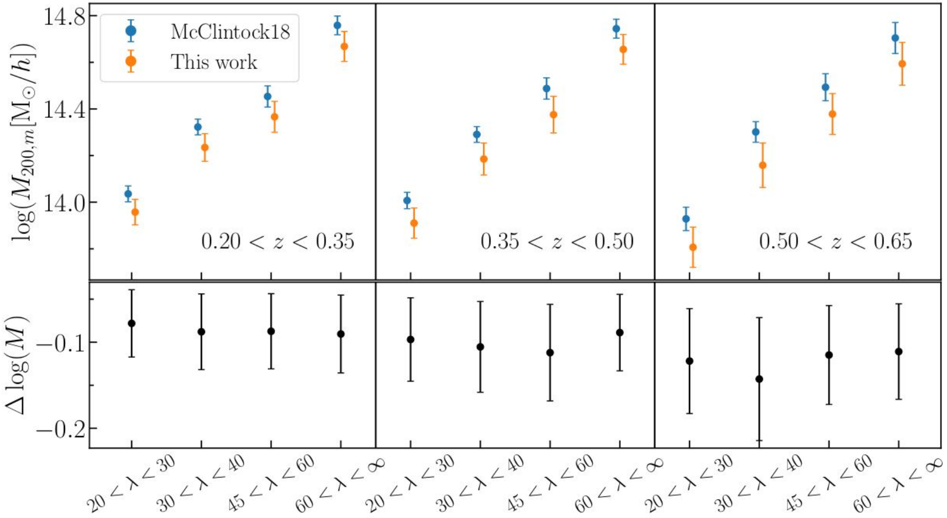


Wu et al. 2022

SELECTION EFFECT BIAS ON WL

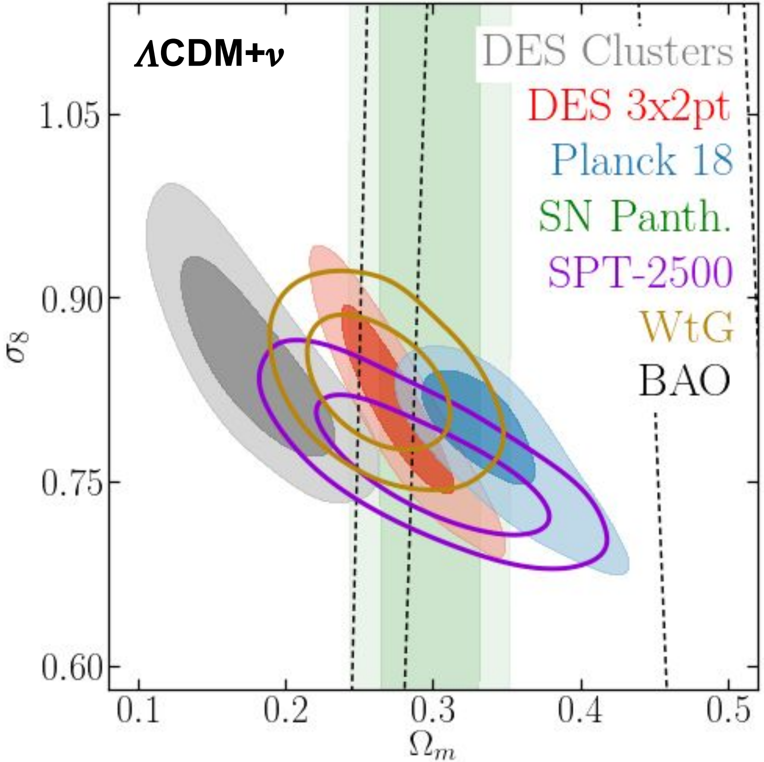
Selection effect bias:

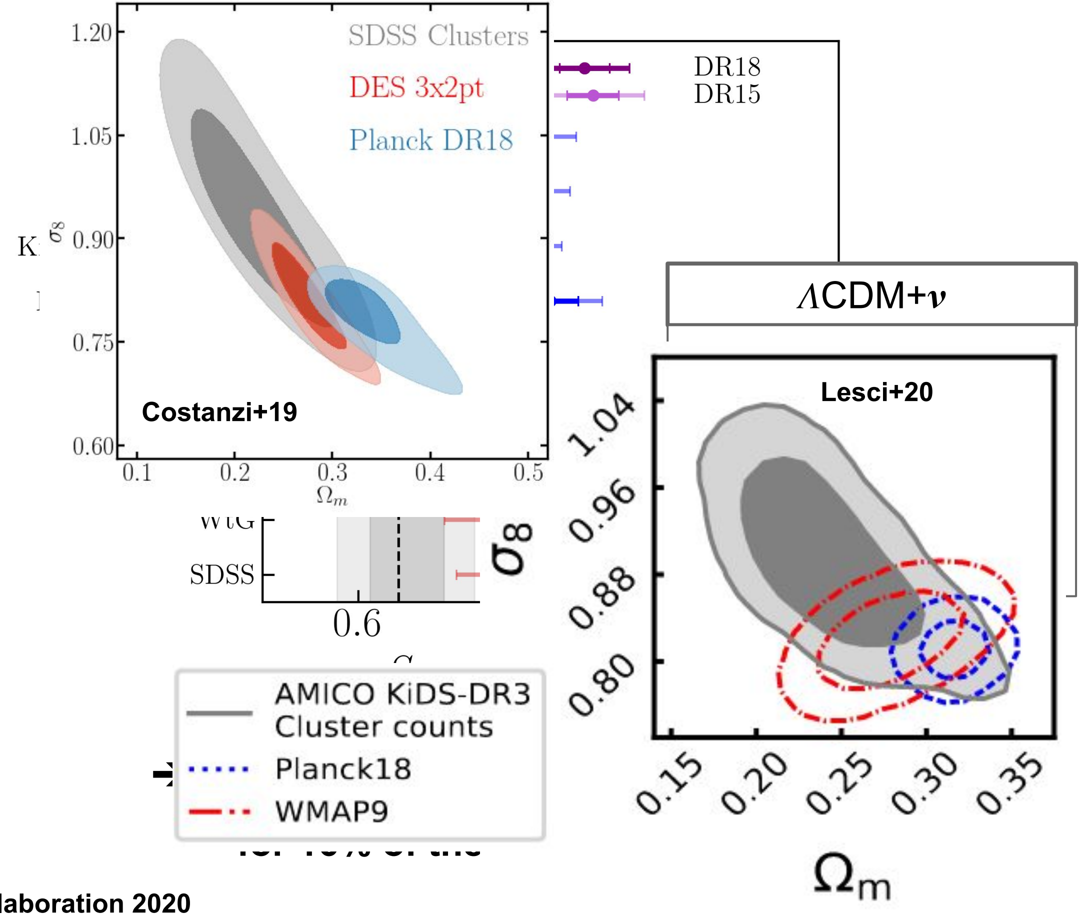
- **Tend to boost the WL signal (and thus M_{WL})**
- **Mostly explained by projection effects, and partially by halo orientation/concentration**
- **A low fraction (~20/30%) of systems strongly affected by projections is responsible for most of the bias (Sunayama et al 2020)**
- **Systematic uncertainty dominating the total error budget in DES Y1 analysis (DES Collaboration 2020)**



Mean % error budget for DES Y1	
σ^{tot}/ M	18%
σ^{stat}/ M	10%
σ^{syst}/ M	15%

COSMOLOGICAL CONSTRAINTS DES Y1





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

DES Collaboration 2020

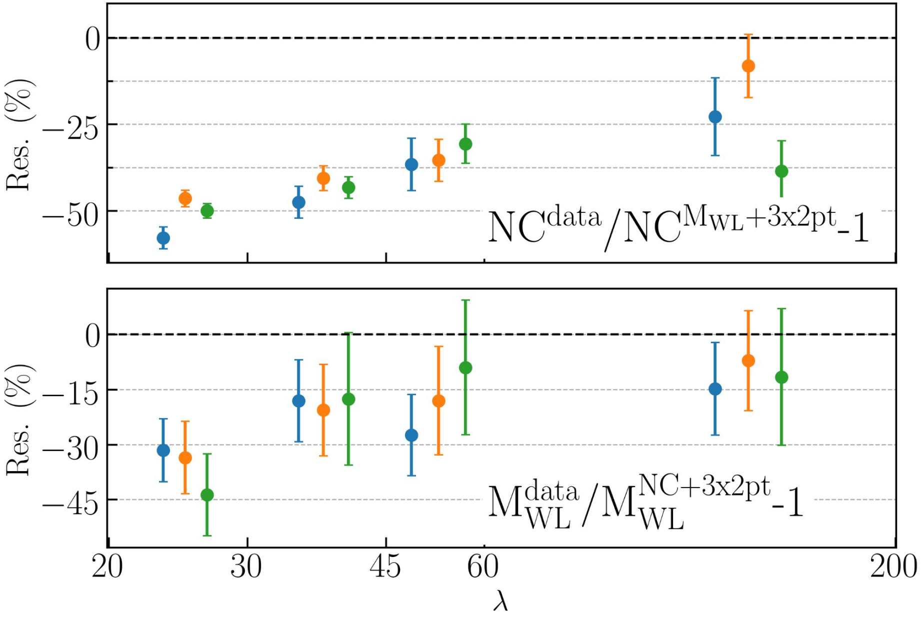
WHAT DRIVES THE TENSION WITH OTHER PROBES?

The large tension with multiple cosmological probes implies that either:

- **The cosmological model is wrong (ΛCDM+ν)**
- **There are unmodeled systematics, either in the NC or M_{WL} data (or both)**

- **If M_{WL} estimates are correct: redMaPPer should be incomplete at ~50% at low λ and ~25% at high λ**
- **If NC data are correct: M_{WL} should be biased low by ~30% at low λ and ~10% at high λ**

Prediction from NC or M_{WL} @ DES 3x2pt Cosmology vs. Data

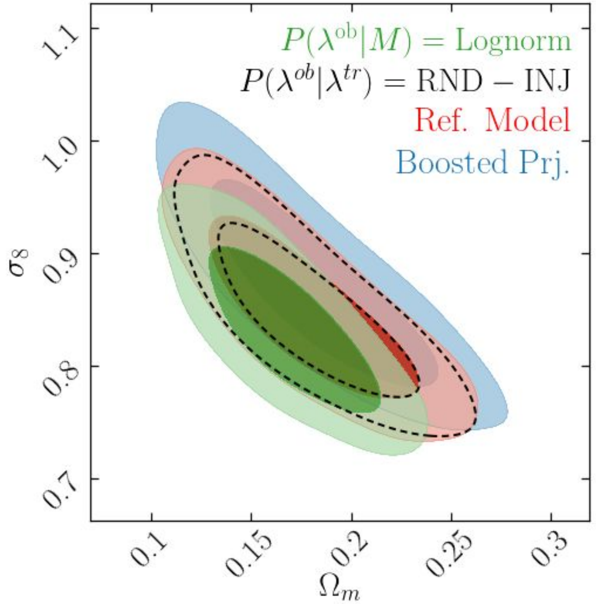


●0.2<z<0.35 ●0.35<z<0.5 ●0.5<z<0.65

NOT VIABLE SOLUTIONS . . .

- Shear and photo-z systematics would affect the DES 3x2pt results even more strongly. They would not lead to a λ-dependent bias
- Miscentering model validated with 2 X-ray samples
- Cross-match with SZ (Planck, SPT) and X-ray (XCS) samples exclude large incompleteness at $\lambda \gtrsim 40$
- Cross-match with *Swift* X-ray sample disfavour large contamination at $\lambda \simeq 30$. Also, a large contamination fraction would require a large incompleteness fraction to accommodate simultaneously the abundance and WL data.
- NC modeling/systematics do not have large impact on the posteriors
- Baryonic effects cannot account for 30% mass depletion in ~10^{14} $M_\odot$ halos (e.g. Cui+14, Velliscig+14,Henson+17,Springel+17,)
- Too aggressive percolation scheme: decreasing the redMaPPer percolation radius by 20% change the cluster counts by less than 1%

Effects on σ_8 and Ω_m of different model assumptions

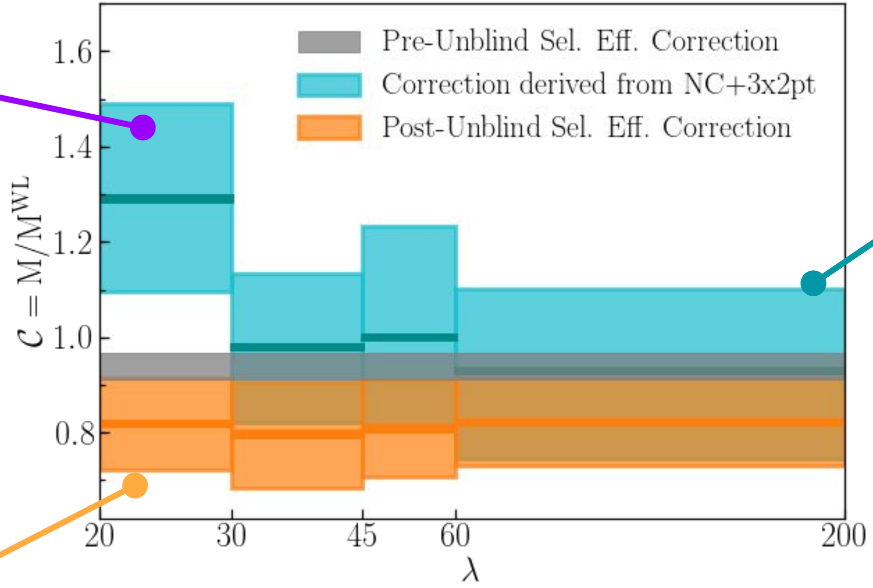


POSSIBLE SOLUTIONS . . .

- **Selection effects bias on M_{WL} might be overestimated at $\lambda \gtrsim 30$ ...**

WL signal around λ~20 systems is lower than expected

Connection with "lensing-is-low" of BOSS galaxies? (see e.g. Leauthaud+17; Leauthaud+22)



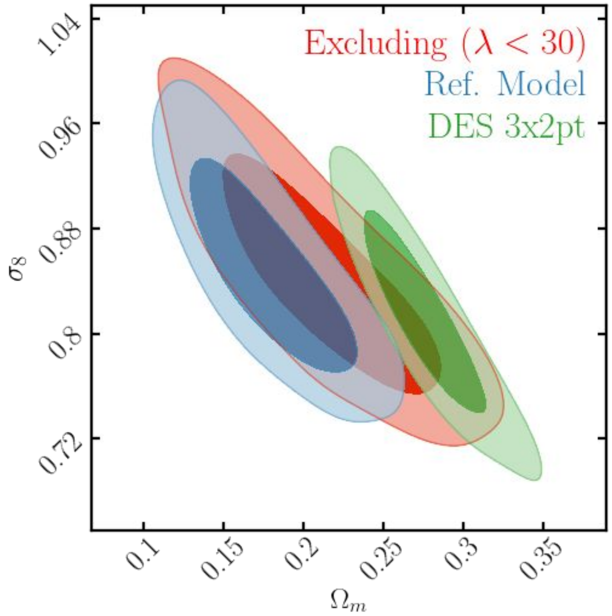
WL Mass bias needed to recover DES 3x2pt cosmology

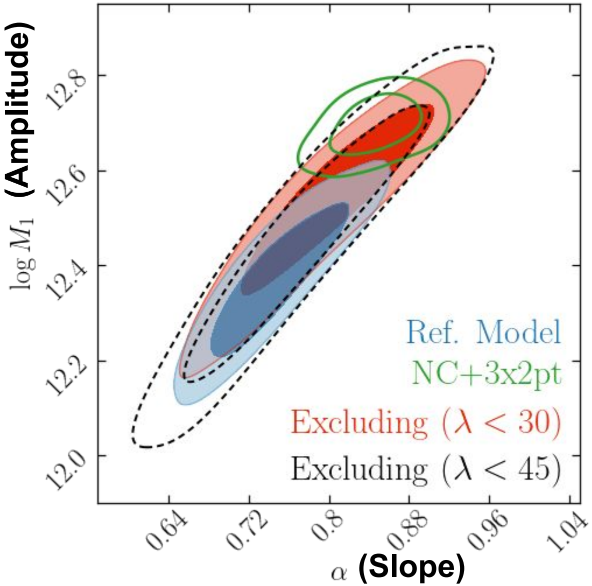
Selection effect bias calibration from simulations

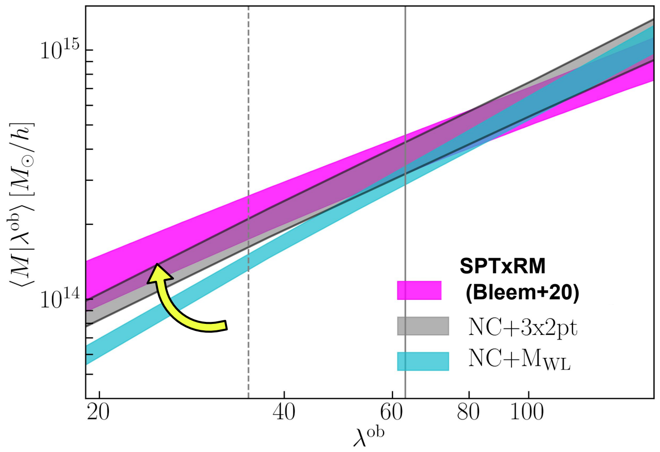
… but cannot explain the sign of the correction needed in lowest λ-bin

POSSIBLE SOLUTIONS . . .

- **Unmodeled systematic at λ<30 ⇒ Removing the lowest λ-bins reduces the tension with DES 3x2pt cosmology steepening the λ-M relation, but the error on S_8 increase by 18%**







DES Collaboration 2020

CURRENT DIRECTIONS OF IMPROVEMENT

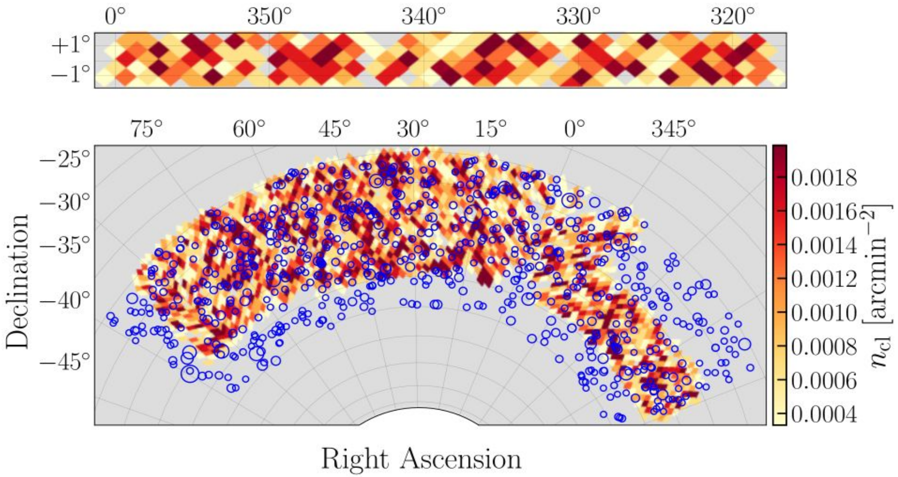
- Is the current modeling of the observational scatter and selection effect sufficient to describe to whole mass and redshift ranges probed by optical cluster surveys?
- Is the lower-than-expected lensing signal of λ<30 clusters due to systematics affecting optically selected clusters or it has a physical origin?

- Improve mass calibration with multi-wavelength data (Costanzi+21)
- Combine cluster abundance with auto/cross 2pt. statistics (To+21)
- Use spectroscopic data to calibrate projection effects (Myles+21)
- Cross-match with SZ and X-ray catalogs to assess completeness (e.g. Grandis+21) and test selection effects on WL signal
- Improve reliability of simulated data, especially galaxy color and clustering models in dense environments, to improve our understanding of selection effects (Black+ in prep)

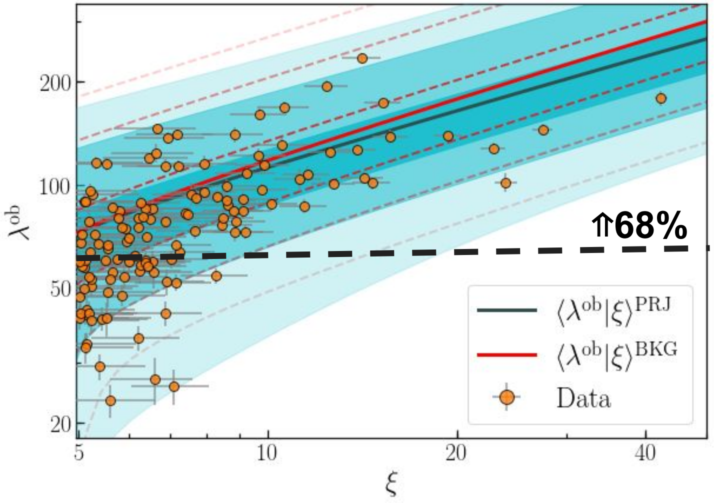
DES NC x SPT MULTI-λ DATA

- Cross match redMaPPer DES Y1 with SPT-SZ 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

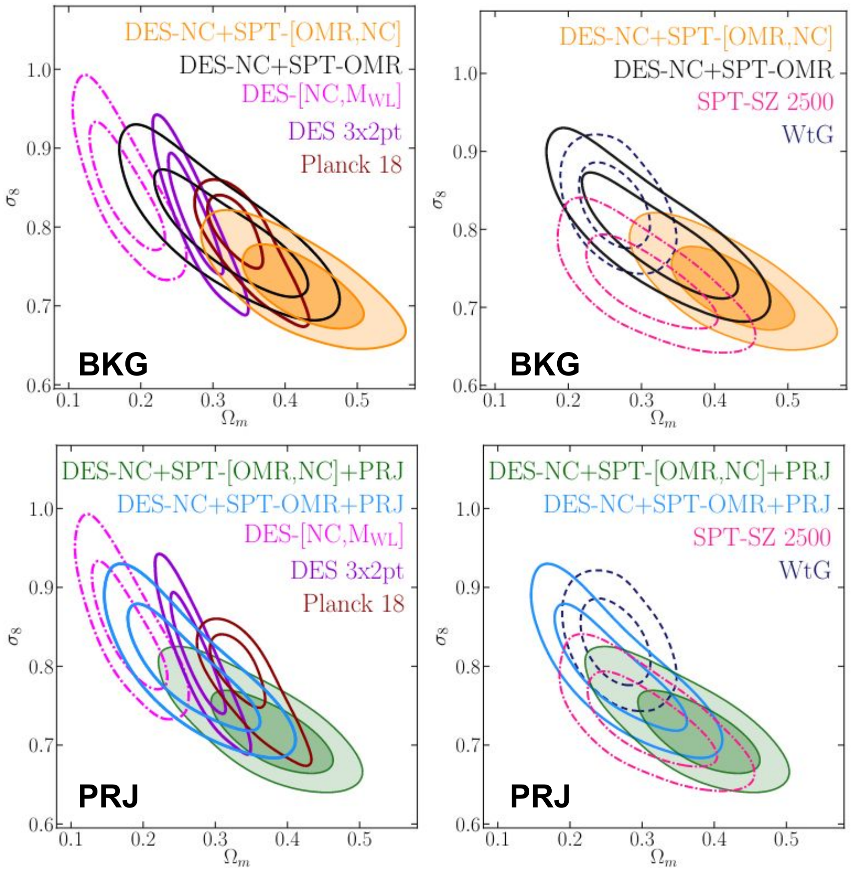


Costanzi+21

DES NC x SPT MULTI-λ DATA

- **DES-NC+SPT-OMR yields results consistent with multipole cosmological probes, for both scatter models (BKG, PRJ).**

- **Inclusion of SPT-NC (BKG, PRJ) improves Ω_m/σ_8 constraints by 20/30% but shift contours toward higher/lower Ω_m-σ_8 values (still consistent within 2σ with other probes)**

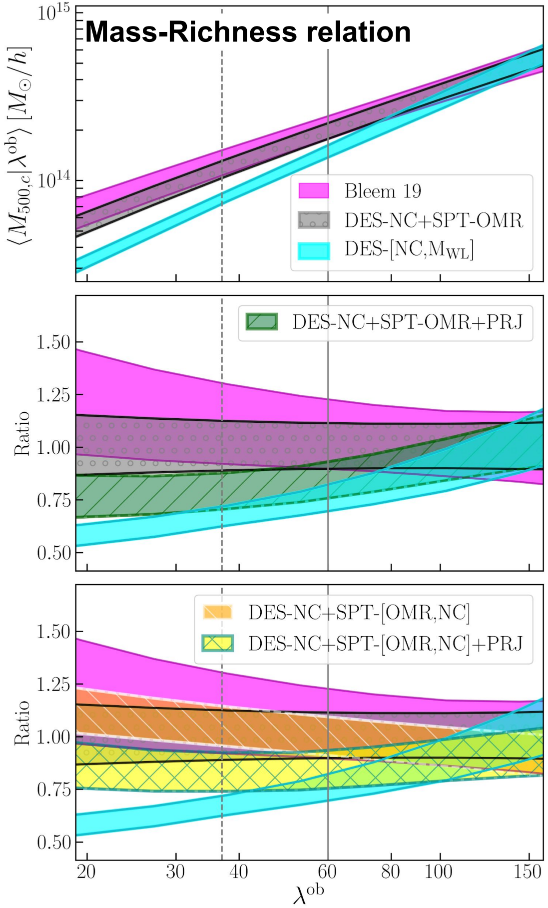


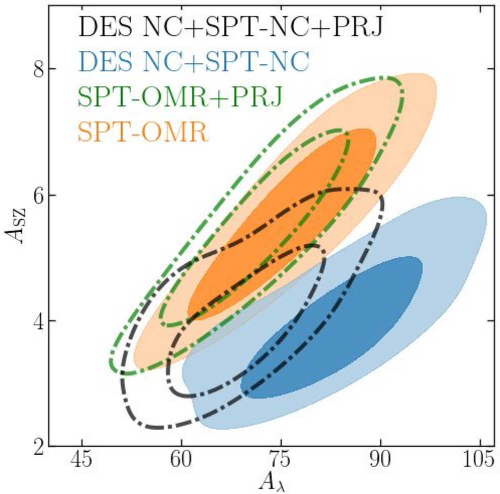
NC = Number Counts data
OMR = Observable Mass Relation data
BKG = Scatter model which account only for background subtraction noise
PRJ = Scatter model which account also for projection effects

Costanzi+21

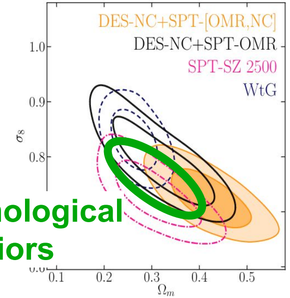
DES NC x SPT MULTI-λ DATA

- **DES-NC+SPT-OMR (▩) and DES-NC+SPT-[OMR,NC] (▨): M-λ relation consistent with SPT-NC (Bleem+20; ■) and in tension with DES Y1 weak lensing (■) mass at low λ.**
- **Amplitudes of SZ and λ scaling relations derived from DES and SPT NC assuming BKG (■) are in tension with those derived from SPT multi-λ data (■).**
- **“Projection effect model” alleviate the tension between the abundance (□) and mass-calibration data (□), as well as with Y1 M_{WL} estimates (▨, ▨).**





Amplitudes of SZ and λ scaling relations from abundance and multi-λ data including or not PRJ model(*)



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COMBINATION WITH OTHER LSS PROBES

- ❑ **4x2pt+N: Combination of DES Y1 cluster counts with 2pt auto and cross correlation functions from different cosmic tracers: $\delta_c\delta_c$, $\delta_g\delta_g$, $\delta_c\delta_g$, $\delta_c\gamma$**
- ❑ **Used only large scale information (>8Mpc; i.e. no 1-halo term)**

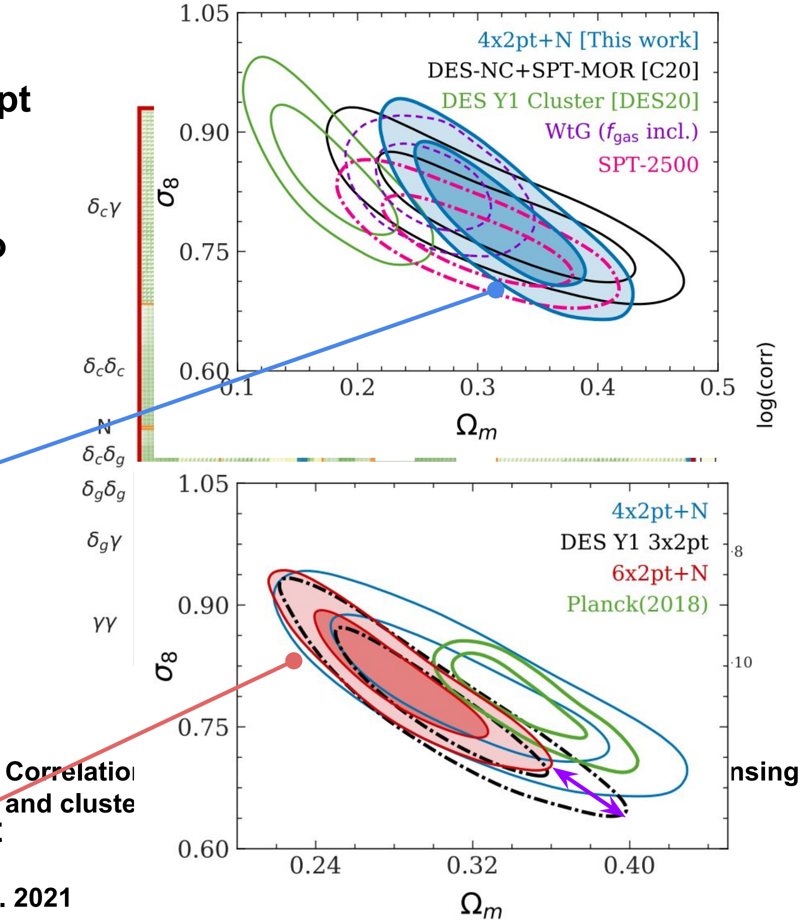
- **Main results:**

- **Cosmological posteriors consistent with DES 3x2pt and other cluster abundance studies**

- **Constraints on (large-scale) selection bias:**

$$b_{\rm sel} = w_{\rm cg}[\lambda]/w_{\rm cg}[M] \simeq 1.2$$

- **When combined with other probes, cluster data provide 20% improvement on Ω_m constraint over 3x2pt analysis**



To & Krause et al. 2021

TAKEAWAY FROM CURRENT ANALYSES

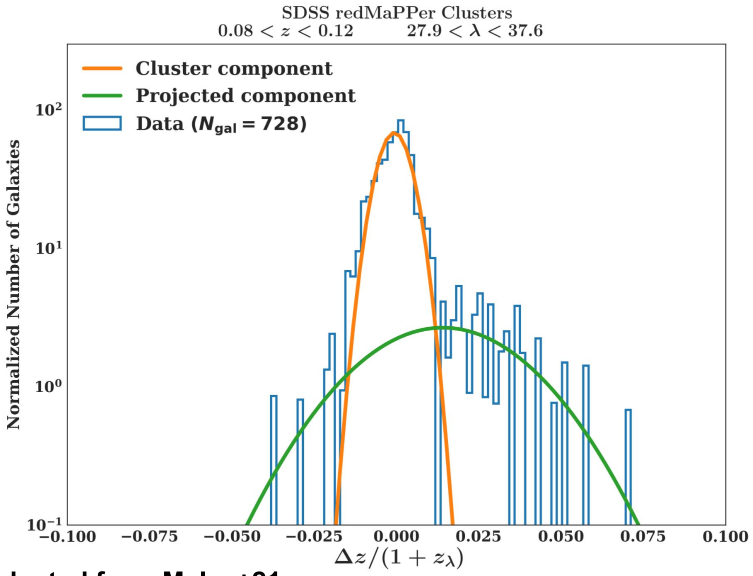
- **If we replace the stacked WL mass estimates with follow-up data (λ>40) or exclude the WL signal below ~8Mpc the DES NC provide cosmological constraints consistent with other probes**

- **The NC+4x2pt analysis suggests that the tension in Y1 analysis is due to a flawed modeling of the stacked WL signal of optically selected clusters in the one-halo regime**

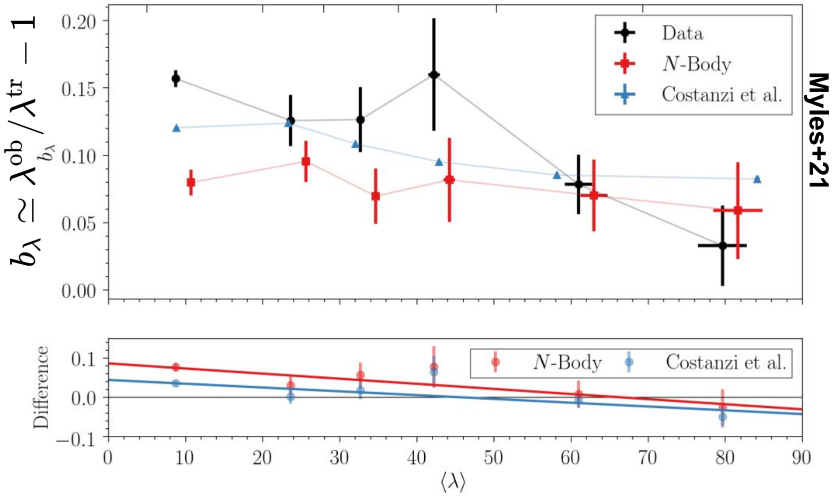
- **Multi-λ follow-up data and/or combination with 2pt statistics allow to effectively calibrate the systematics affecting optically selected clusters**

CALIBRATION WITH SPECTROSCOPIC DATA

- **Spectroscopic follow-ups of putative cluster members allow us to recognize misclassified member galaxies …**



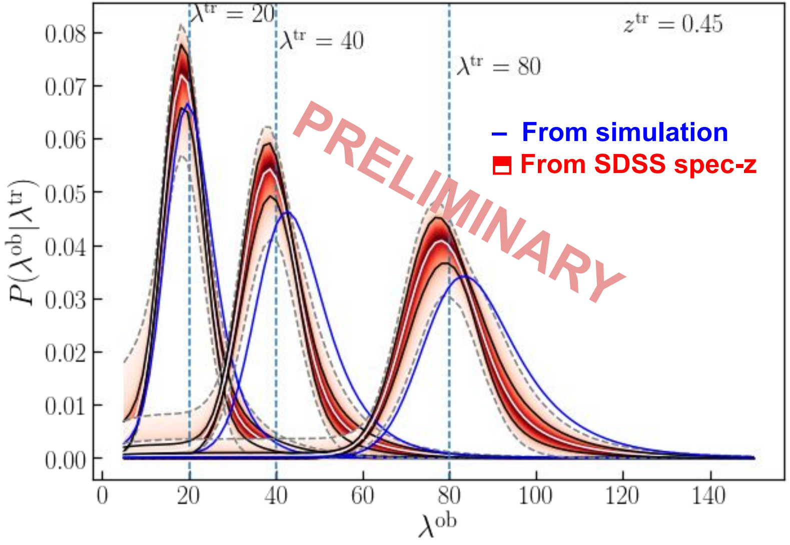
Adapted from Myles+21

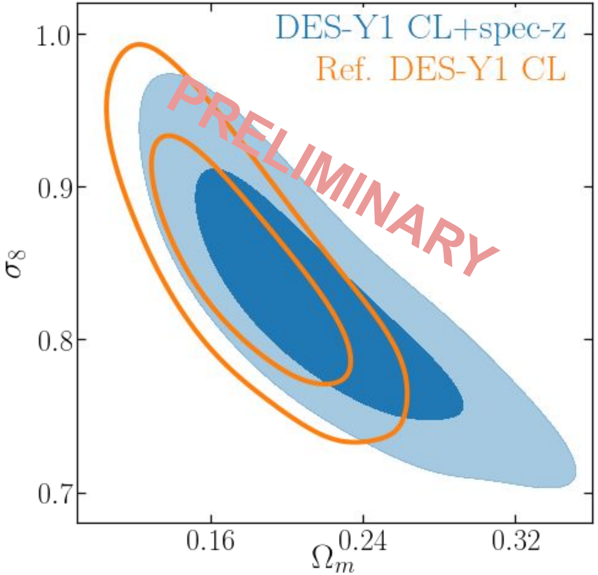


… and thus empirically calibrate projection effects on richness estimates.

CALIBRATION WITH SPECTROSCOPIC DATA

… this in turn can be used to place priors on the projection effect parameters entering P(λ^{ob} | λ^{true}) …

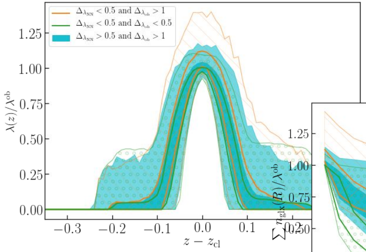


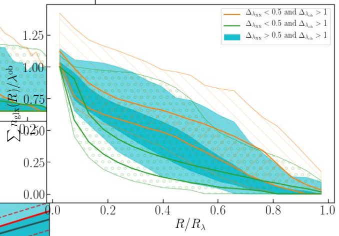


… allowing a "self-calibration" of the remaining parameters controlling the observational noise on λ.

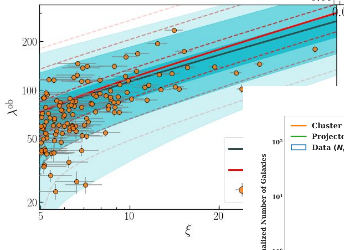
IMPROVING RICHNESS ESTIMATES WITH ML

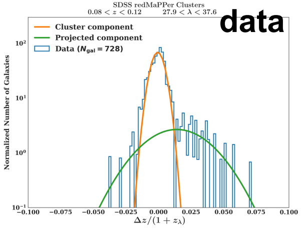
- **Machine learning algorithms can help exploiting the whole information carried by currently available photometric and/or follow-up data, allowing to refine the richness estimates and reduce the scatter of the mass proxy.**



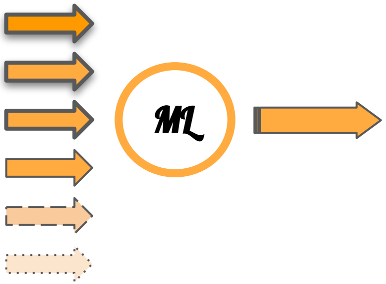


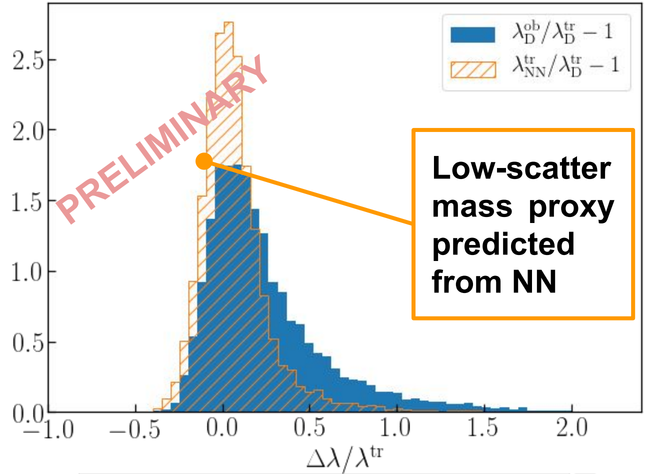
Photometric features

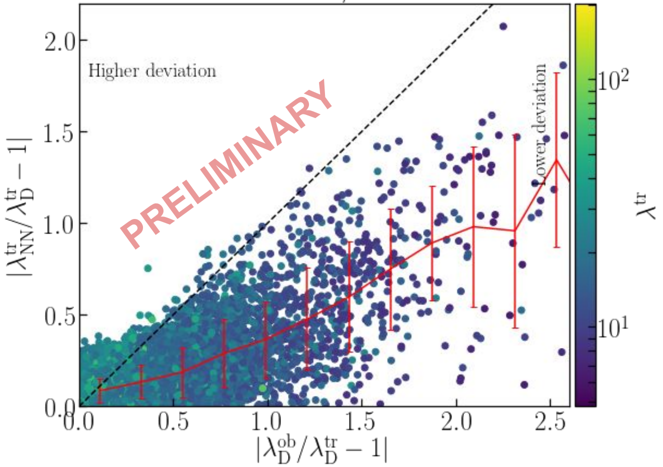




Follow-up data



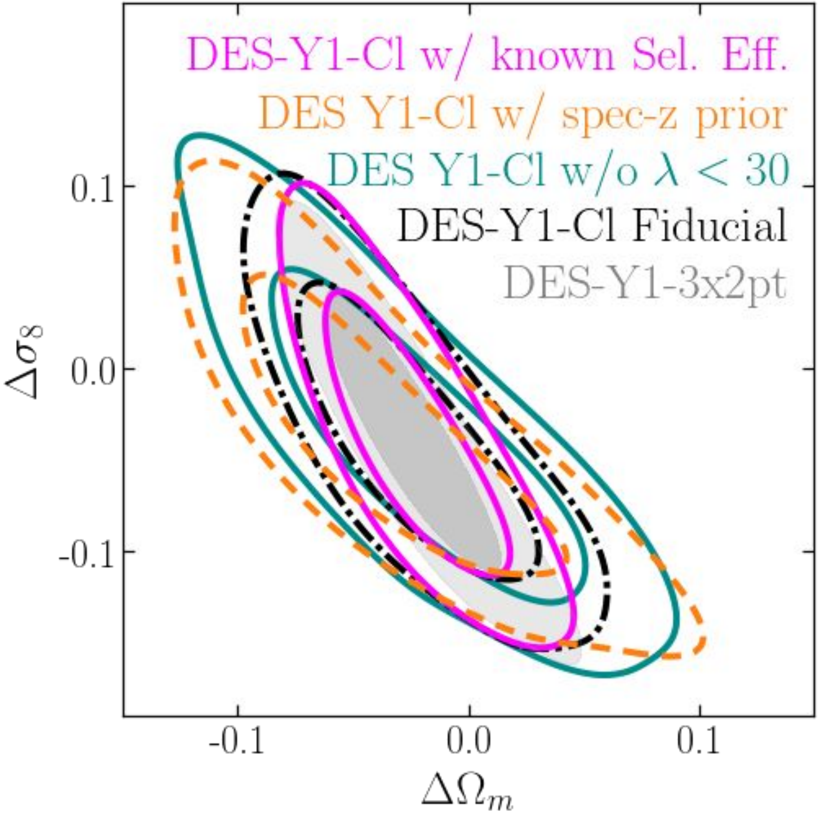




FUTURE DIRECTIONS OF IMPROVEMENTS

- **Multi-wavelength follow up data (X-ray, SZ, spec-z) of low-λ systems to solve the puzzle of the lower-than-expected stacked WL signal.**
- **Larger spec-z follow-up programs covering higher redshift range to improve priors on projection effect parameters.**
- **Improve calibration of selection effect bias on WL (and 2pt CF), either using multi-wavelength data (X-ray, SZ), or improving the reliability of mock galaxy catalogs.**

Impact of different systematics on DES Y1 cluster constraints



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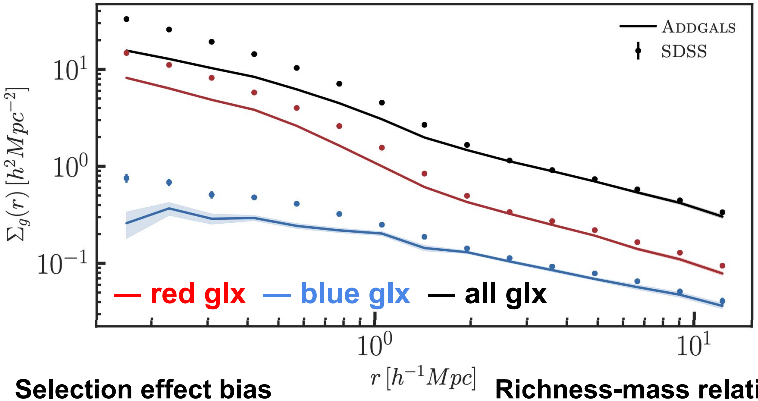
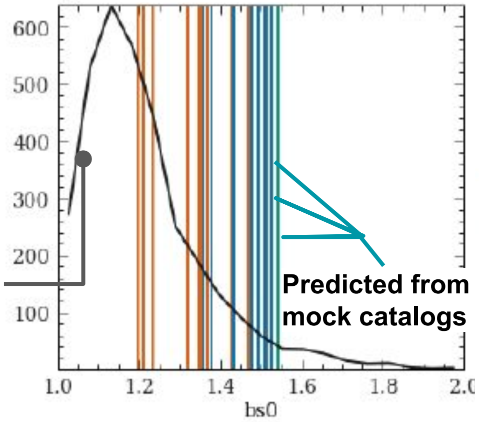
Projected galaxy profile around clusters



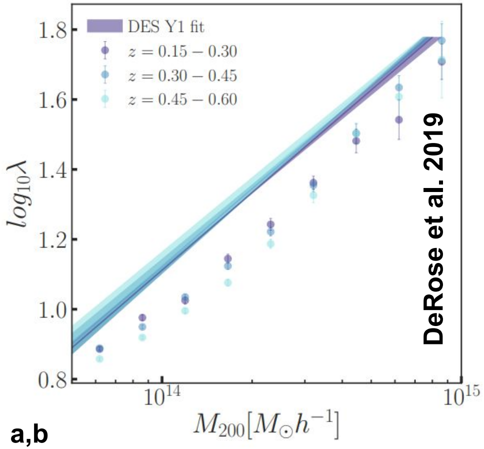
Wechsler & DeRose et al. 2021

Selection effect bias

Constraints from 6x2pt+N analysis



Richness-mass relation



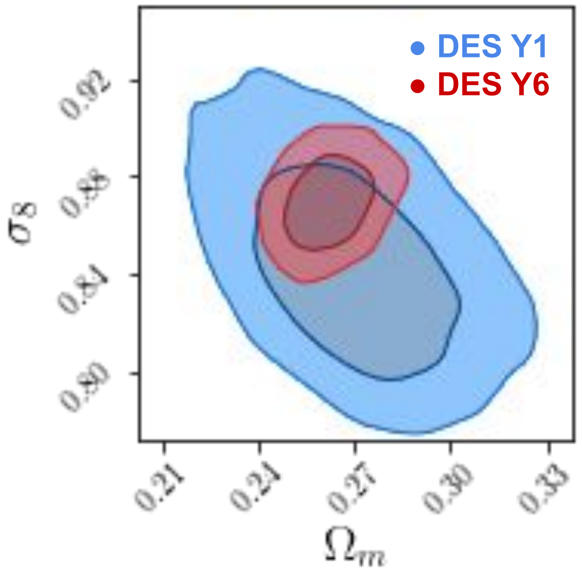
DeRose et al. 2019

Adapted from: To & Krause et al. 2021 a,b

FUTURE PERSPECTIVES

- **DES Y6: 3 times more clusters than DES Y1 → potentiality to provide the tightest single-probe constraints if we manage to characterize the low-λ systems**
- **Next generation cluster surveys will lower the mass limit and extend the redshift range probed →improved statistics, measure growth rate over cosmic time (w_0, w_a, GR test)**
- **Large overlap between survey footprints will allow multi-wavelength cluster cosmology → improved mass calibration and control of systematics.**
- **Combination with other LSS probes is expected to yield significant cosmological gain.**

Forecast DES Y6 NC+WL



Area [deg^2]	Redshift range	# of clusters	n_{eff} [arcmin^{-2}]
~5000	0.2<z<0.80	~16000 (λ>20)	~10

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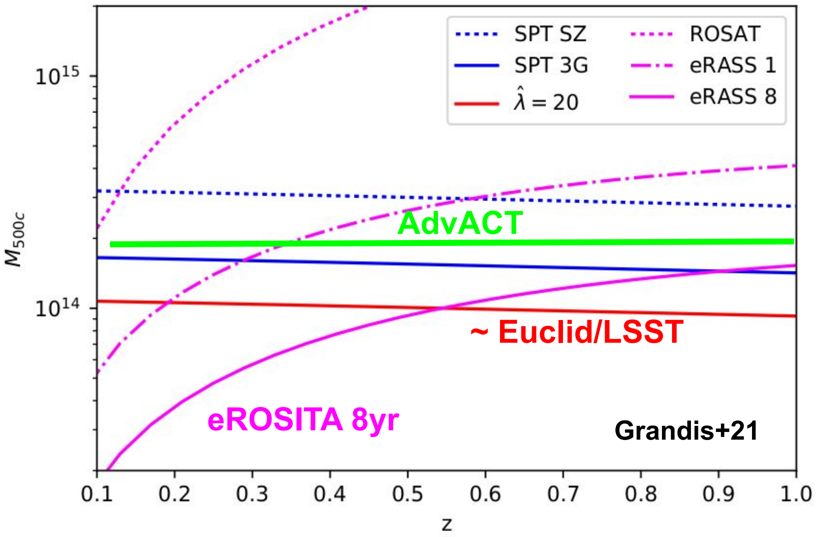
Mass limit vs redshift for different surveys



Forecasted constraining power for the combination of NC and 2pt statistic (Sartoris+15)

Constraints:	FoM	Δw_0	Δw_a	$\Delta\Omega_m$	$\Delta\sigma_8$	$\Delta\gamma$
NC+PS	73	0.037	0.38	0.0019	0.0032	0.023
NC+PS+known SR	291	0.034	0.16	0.0011	0.0014	0.020
NC+PS+known SR+Planck	802	0.017	0.074	0.0010	0.0012	0.015

SUMMARY AND CONCLUSIONS

- **Mass calibration and selection biases dominate the error budget of cluster cosmology studies (at all wavelengths). Optical cluster catalogs are particularly prone to projection and selection effects which hamper the calibration of the scaling relation and selection function.**
- **The DES Y1 analyses suggest a flawed interpretation of the stacked WL signal of low-λ systems (in the 1-halo regime). It is not clear yet whether the low-lensing signal around low-λ clusters is caused by systematic effects or it has a physical origin.**
- **Multi-wavelength and multi-probes analyses proved their capability to empirically calibrate systematics affecting optically selected clusters ⇒ Further follow-up data for complete samples of low-λ systems and improved simulations are needed to solve the current puzzle.**
- **Next generation cluster surveys, thanks to the different wavelengths covered, the wide area and overlapping footprints, will provide such opportunity.**
- **Larger statistics, lower mass limits and wider redshift ranges probes will allow to derive competitive and independent constraints on many key cosmological parameters.**

(SOME) REFERENCES

- **Modelling of miscentering effects: Zhang et al 2018 (arXiv:1901.07119)**
- **Modeling of membership dilution: Varga et al 2019 (arXiv:1812.05116)**
- **DES Y1 WL mass calibration: McClintock & Varga et al 2019 (arXiv:1805.00039)**
- **Modeling of the selection function: Costanzi et al 2019a (arXiv:1807.07072)**
- **SDSS Cluster Cosmology: Costanzi et al 2019b (arXiv:1810.09456)**
- **Prior on observable mass relation: Farahi et al 2019 (arXiv:1903.08042)**
- **DES Y1 results: DES Collaboration 2020 (arXiv:2002.11124)**
- **DES NC x SPT multi-λ: Costanzi et al 2021 (arXiv:2010.13800)**
- **DES Y1 N+4x2pt analysis: To & Krause et al 2021 (arXiv: 2010.01138)**
- **Calibration of projection effects with spec-z data: Myles et al 2021 (arXiv:2011.07070)**
- **DES-Y1 x SPT calibration of projection effects: Grandis et al 2021 (arXiv:2101.04984)**
- **On triaxiality and orientation selection bias: Zhang et al. 2022 (arXiv:2202.08211)**
- **Selection effect bias on stacked WL: Wu et al 2022 (arXiv:2203.05416)**