European Commission

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DARK ENERGY SURVEY

CLUSTER COSMOLOGY IN THE DARK ENERGY SURVEY

M. Costanzi, DES Galaxy Clusters & Weak Lensing working groups

https://zoom.us/j/596761139

Modeling of the Selection Function: Costanzi+ 18a (arXiv:1807.07072)
Methodology paper - SDSS Cluster Cosmology: Costanzi+ 18b (arXiv:1810.09456)
DESY1 WL mass calibration: McClintock+ 18 (arXiv:1805.00039)
Modeling of Miscentering Effects: Zhang+ 19 (arXiv:1901.07119)
Modeling of Membership Dilution: Varga+ 18 (arXiv:1812.05116)
Prior on observable-mass relation scatter: Farahi+ 19 (arXiv:1903.08042)
DES Y1 Cluster Cosmology: DES Collaboration 19, in prep.

OSSERVATORIO ASTRONOMICO DI TRIESTE · INAF ISTITUTO NAZIONALE DI ASTROFISICA

LIneA webinar - Oct 2019 | Matteo Costanzi

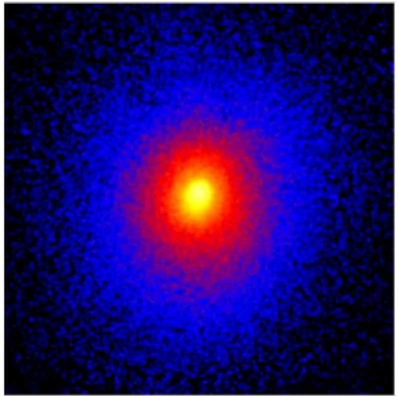
GALAXY CLUSTERS

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

OPTICAL

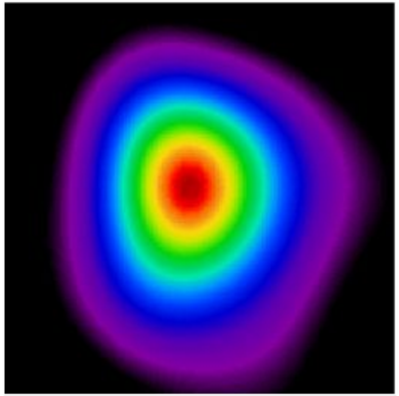
RICHNESS, LENSING EFFECTS

X-RAYS



LUMINOUS AND EXTENDED X-RAY SOURCES

MICROWAVES

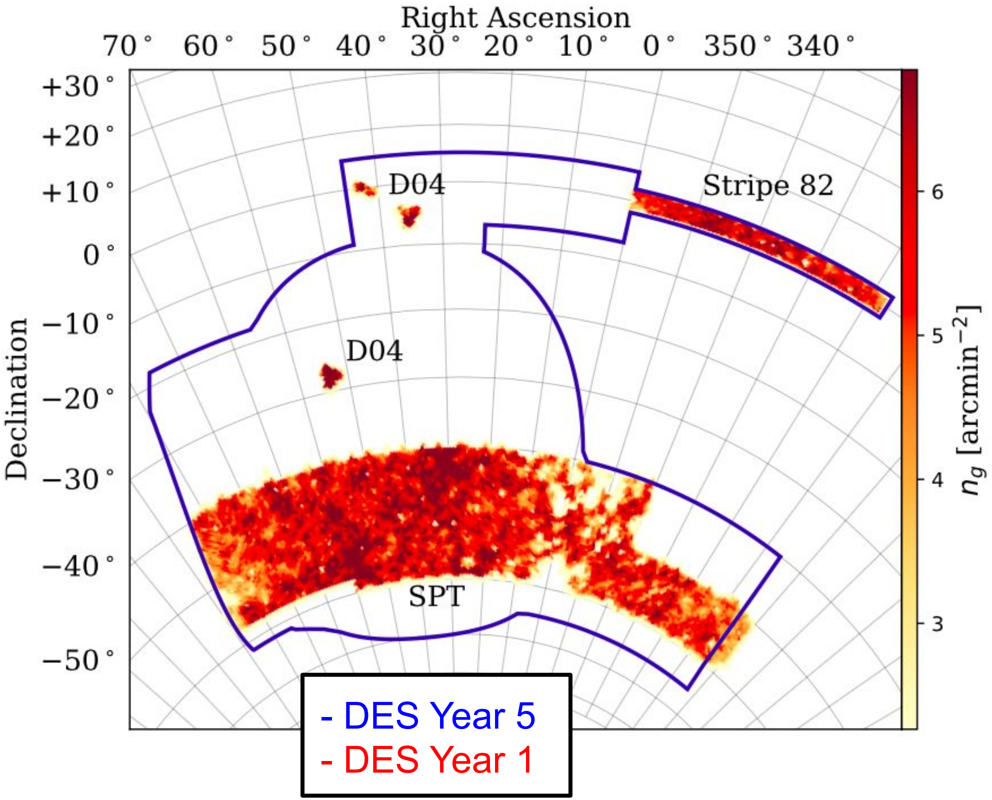


SUNYAEV-ZEL'DOVICH EFFECT

THE DARK ENERGY SURVEY

- **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:**
  - ~1500 deg^2 with 10σ depth *i*~22.9
  - N_{eff}~6.3 $arcmin^{-2}$ (34M source glxs)



From Zuntz+ 17

redMaPPer CLUSTER CATALOGS

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

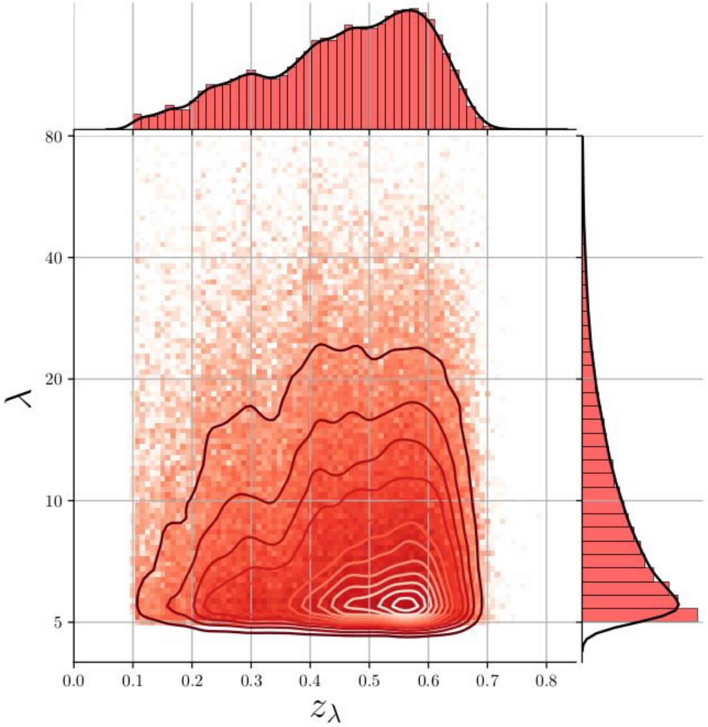
Detect overdensities of red-sequence galaxies and assign a membership probability, p_{mem}, to each cluster member candidate

$$\lambda^{ob} = \sum_{R<R_\lambda} p_{mem}$$

$$z^{ob}$$

Area [deg^2]	Redshift range	# of clusters (λ>20)	σ_z/(1+z)
1470	0.2<z<0.65	~6540	0.006

z-λ distribution of redMaPPer clusters in DES Y1



From McClintock+18

COSMOLOGY WITH CLUSTER NUMBER COUNTS

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

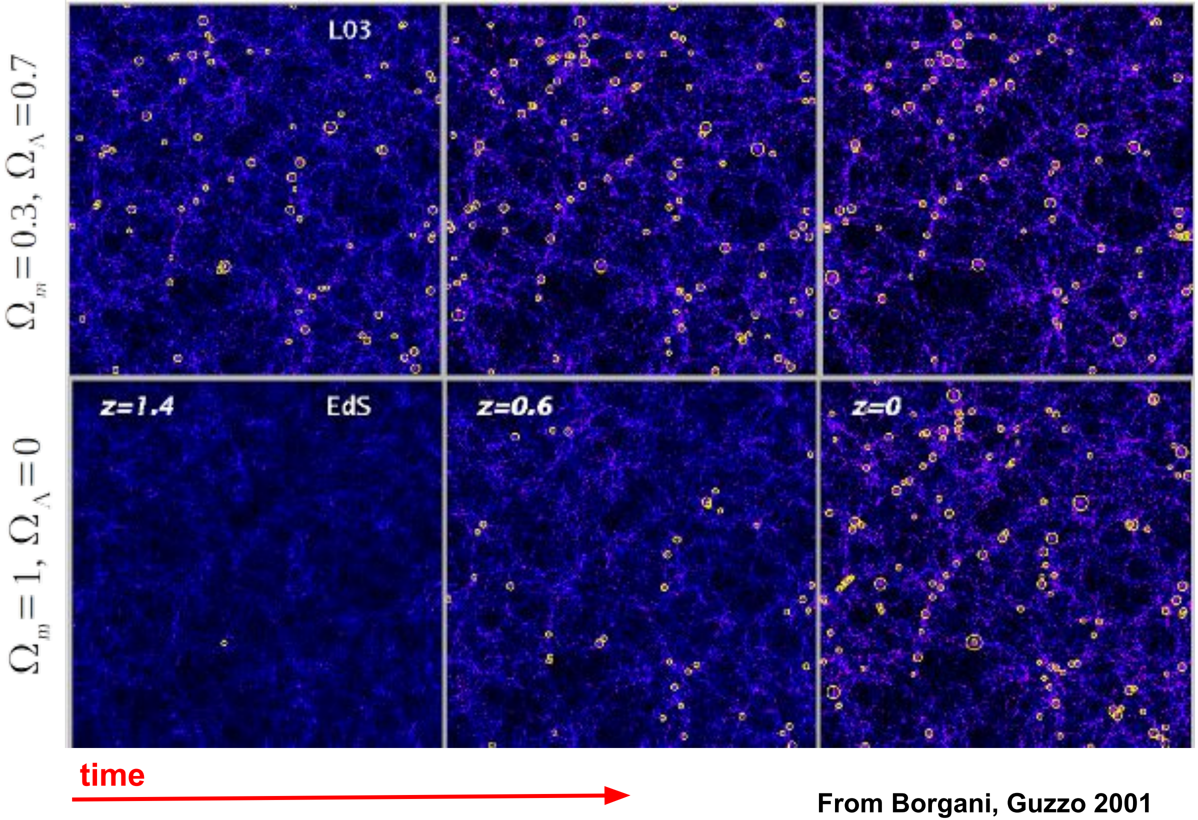
σ_8: Amplitude of the matter power spectrum

Ω_m: Present-day total matter density

$$S_8 = \sigma_8 (\Omega_m / 0.3)^{0.5}$$

Dark energy equation of state parameter
Total neutrino mass
Deviation from GR
....

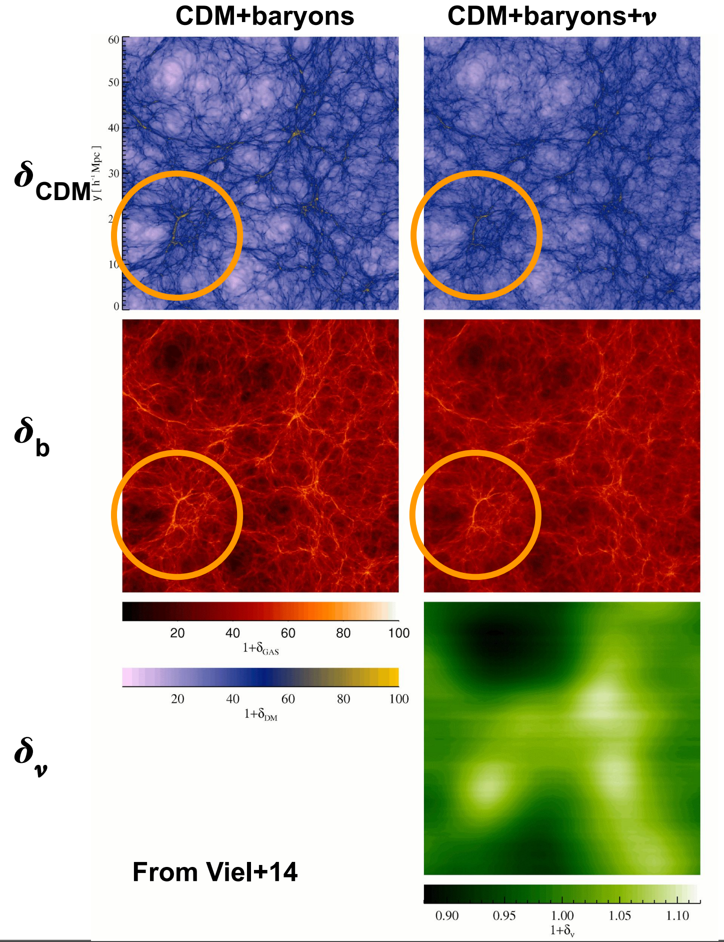
Evolution of the clusters population in 2 N-body simulations



See e.g. Allen+2011 or Kravtsov+2012 for a review

From Borgani, Guzzo 2001

COSMOLOGY WITH CLUSTER NUMBER COUNTS

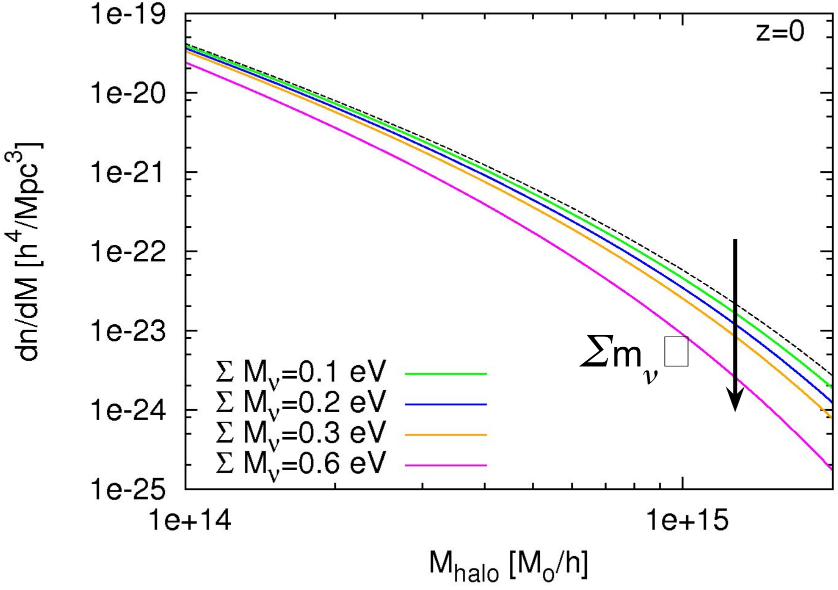


From Viel+14

Massive neutrinos:

- Dealy the epoch of matter-radiation equality
- Suppress the growth of density fluctuation on scale smaller than the free-streaming length

Effects on the number density of halos as a function of mass

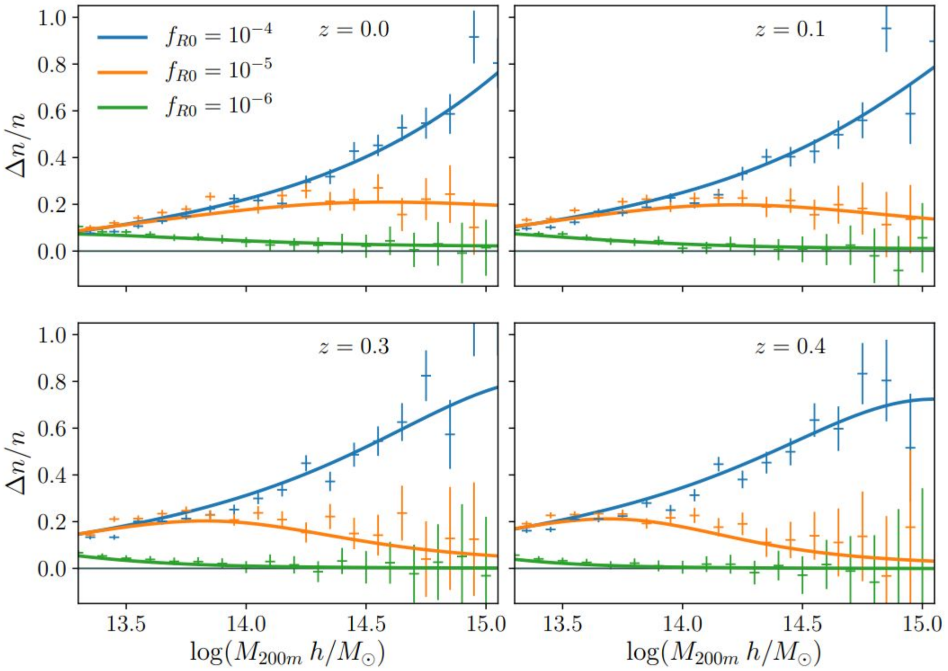


COSMOLOGY WITH CLUSTER NUMBER COUNTS

Modified gravity models, e.g. *f*(R):

- Give rise to accelerated expansion and enhance gravity
- Introduce screening mechanism that restores GR in high density environments

Relative effect on the Halo Mass Function compared to ΛCDM

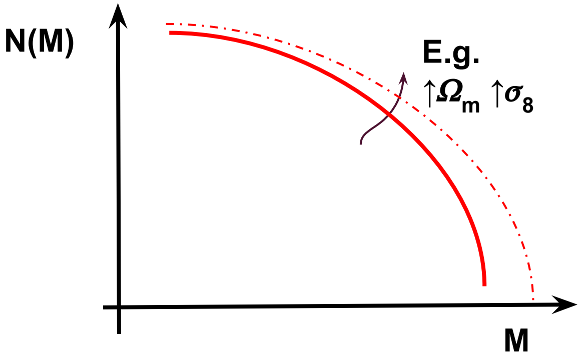


From Hagstotz+18

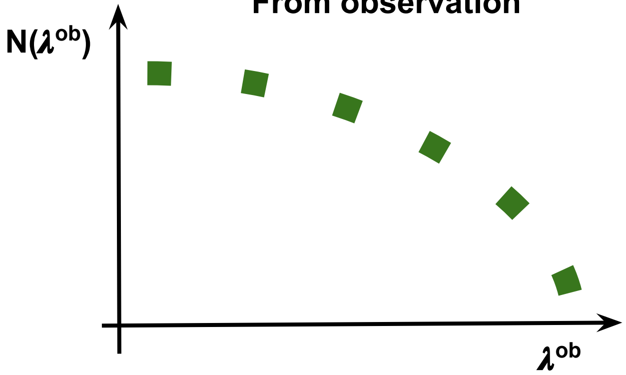
COSMOLOGY WITH CLUSTER NUMBER COUNTS

- **From theory to observation**

From theory



From observation

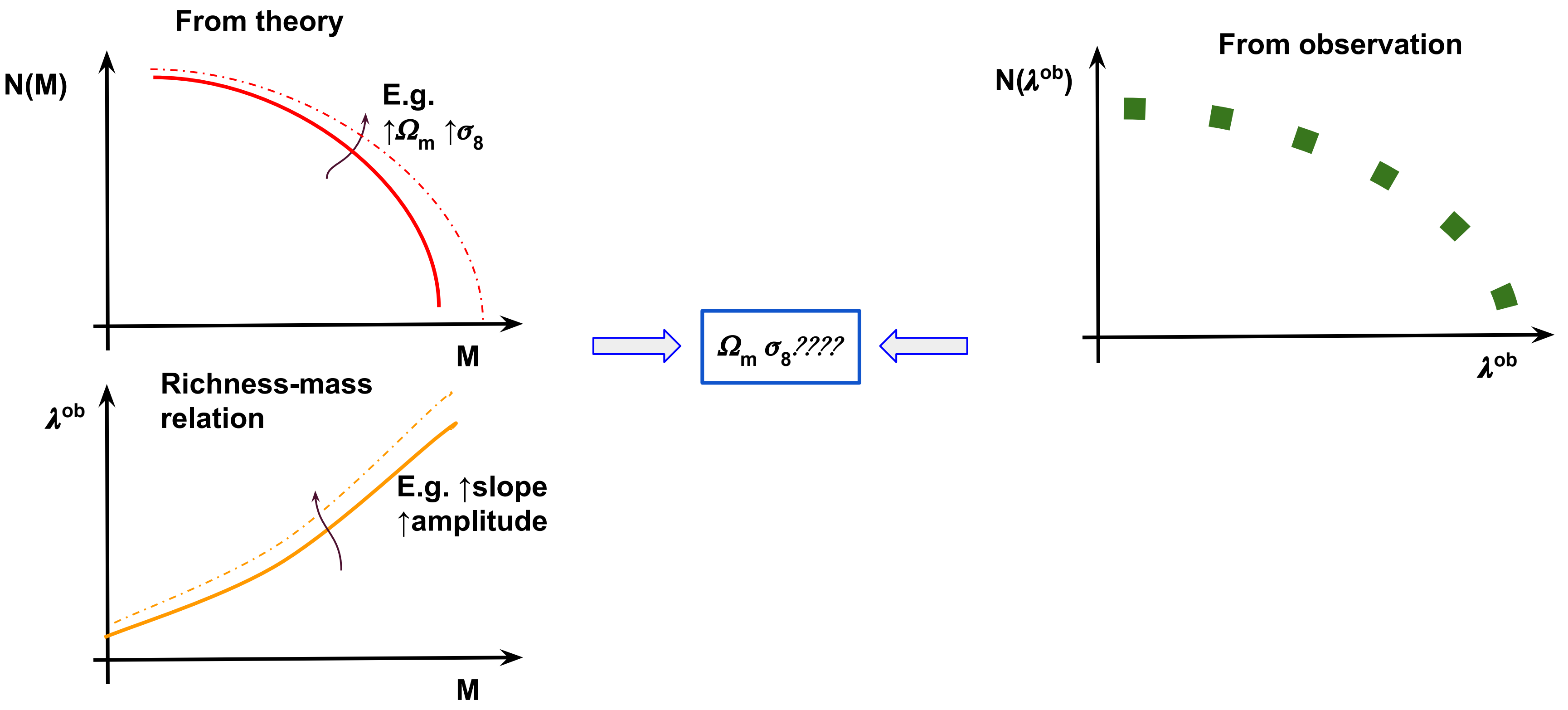


For optically-selected clusters:

λ=richness~ # member galaxies

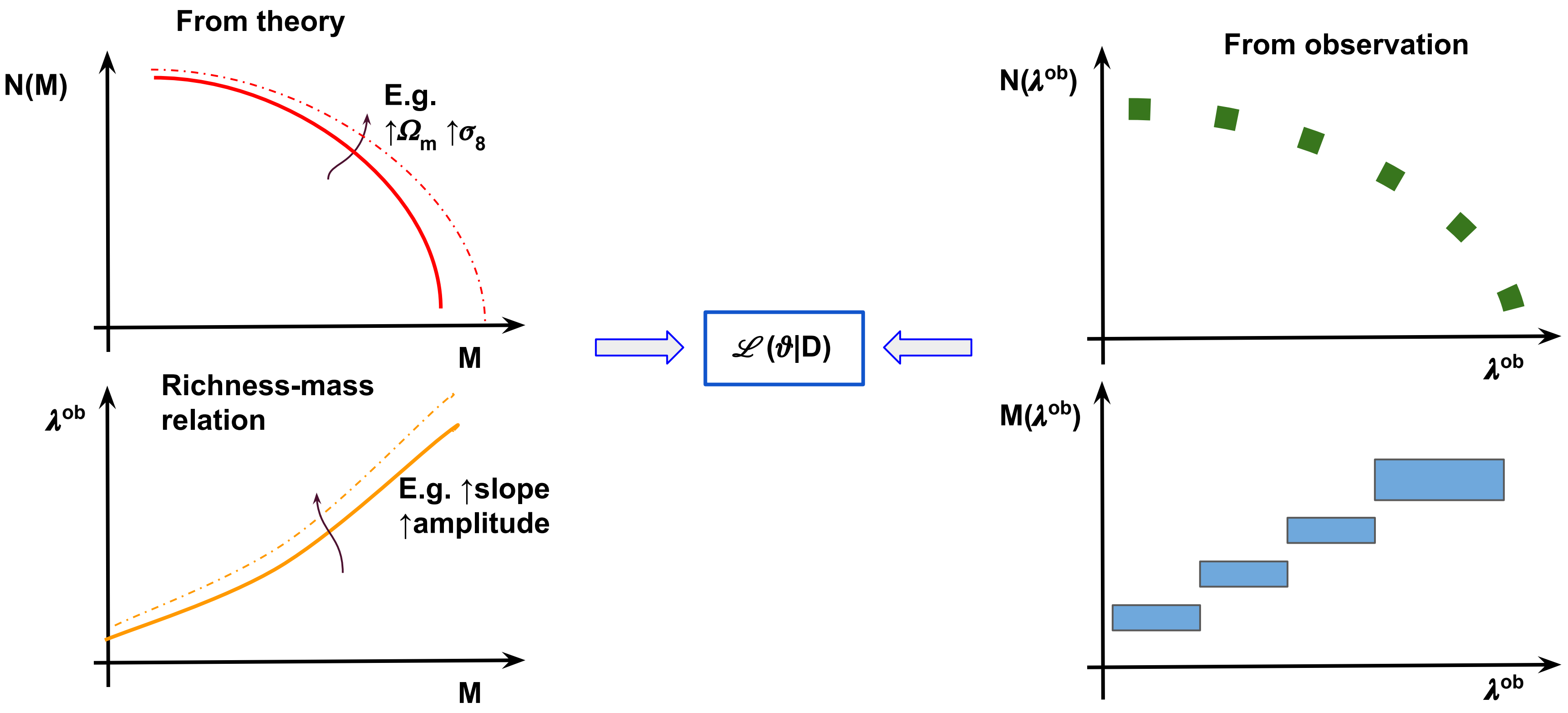
COSMOLOGY WITH CLUSTER NUMBER COUNTS

- **From theory to observation**



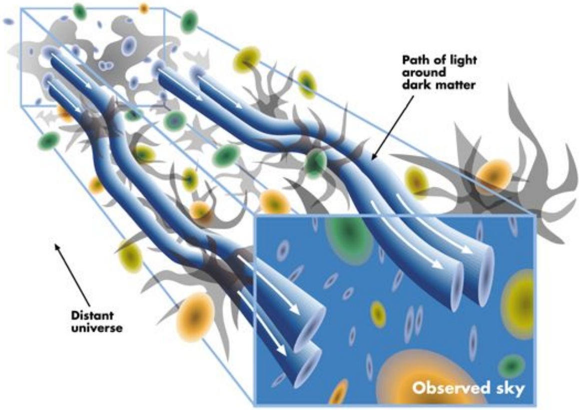
COSMOLOGY WITH CLUSTER NUMBER COUNTS

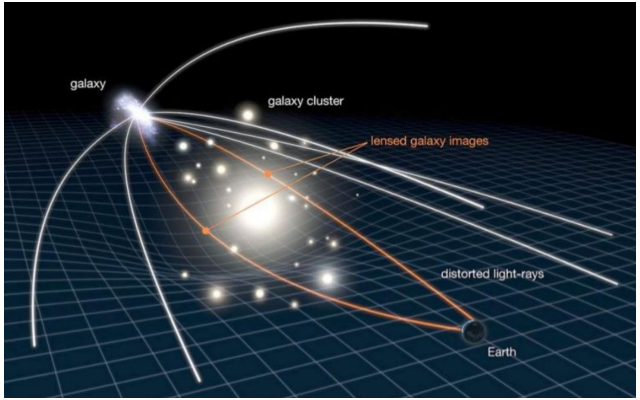
- **Combine cluster abundance and cluster mass estimates to simultaneously constrain cosmology and the richness-mass relation**



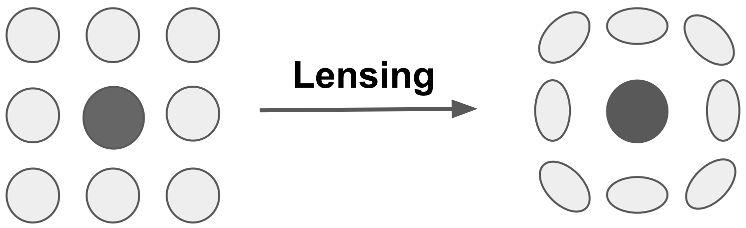
WEAK LENSING MASS ESTIMATES

Gravitational lensing:





Tangential shear: the tangential alignment of background galaxies around foreground clusters due to gravitational lensing

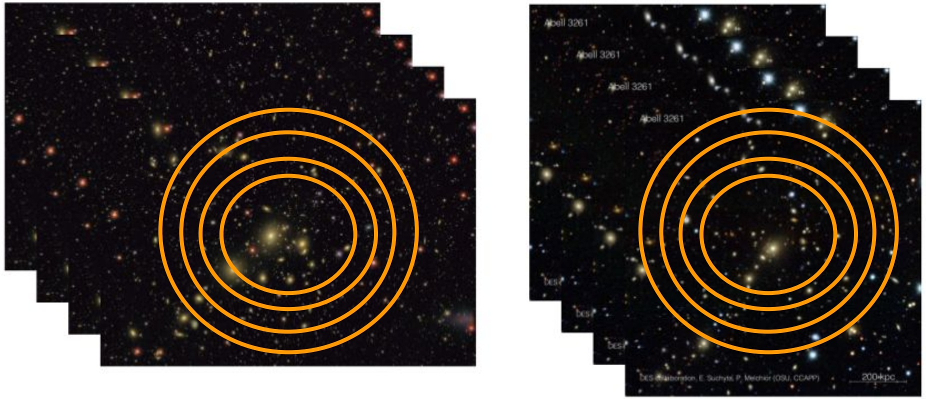


Tangential shear ∝ Surface mass density of the cluster

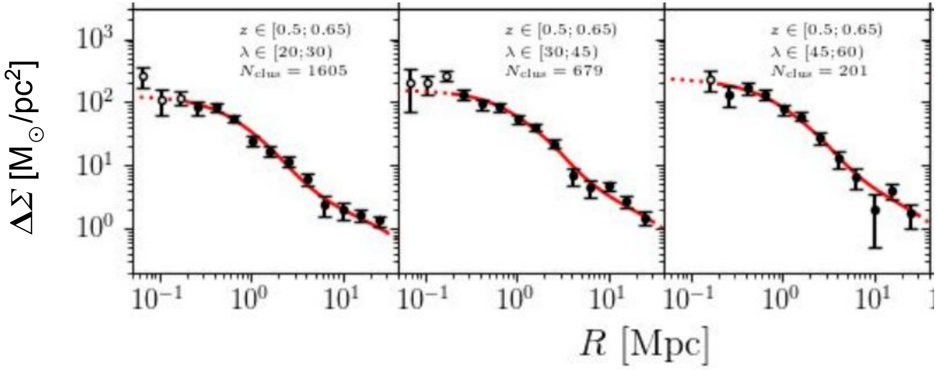
WEAK LENSING MASS ESTIMATES

Mass estimates in DES Y1:

- **Stack clusters in bin of richness and redshift**
- **Measure the mean tangential shear of background galaxies in radial bin around the cluster center**
- **Compute the (excess) surface mass density profile $\Delta\Sigma$**
- **Fit for the mean mass of the λ/z bin**



Surface mass density profile from stacked lensing analysis



McClintock+18

WL MASS ESTIMATES MODELING AND SYSTEMATICS

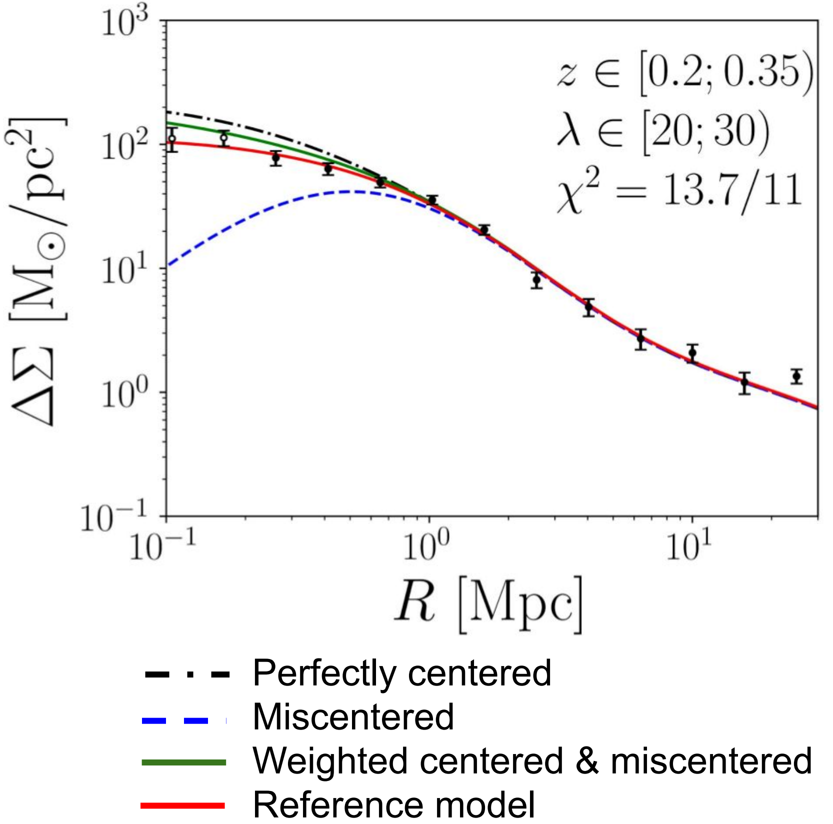
Source of systematic	Y1 Amplitude Uncertainty
Shear measurement	1.7%
Photometric redshifts	2.6%
Modeling systematics	0.73%
Membership dilution + miscentering	0.78% **(Varga+19, Zhang+19)**

From McClintock+18 (WL mass calibration of redMaPPer DESY1)

+

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

Effect of different systematics on the model prediction

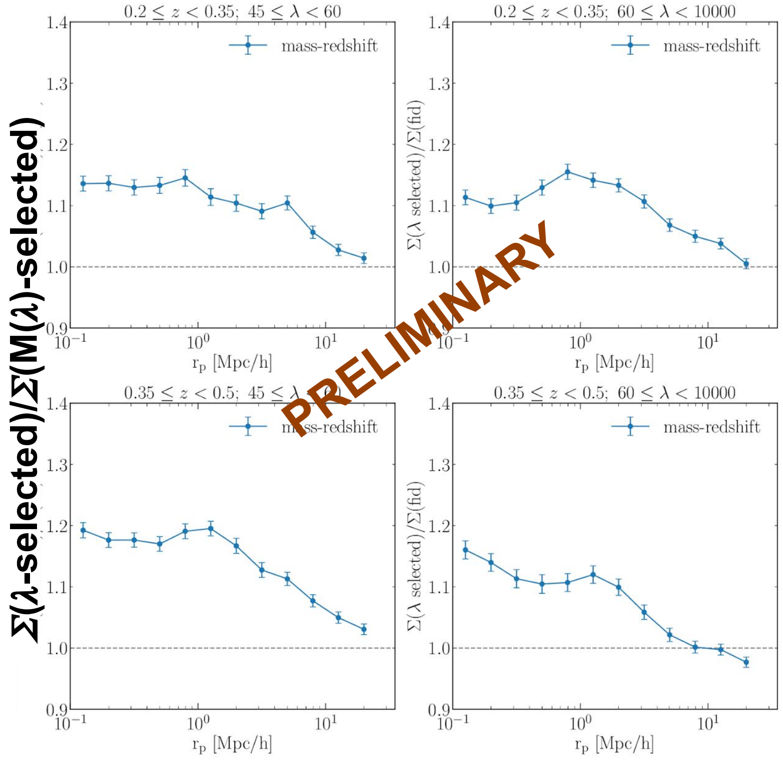


The cluster finder might select preferentially clusters with some properties which correlate with WL signal (e.g. elongated along the l.o.s.)

Calibrate selection effects with simulations:

- **Run redMaPPer on simulations**
- **Select clusters in λ/z bins**
- **Select clusters with the same mass/z distribution as the λ/z selected sample**
- **Compare the stacked Σ(R) profiles of the two samples**

Selection effects systematics on WL profile

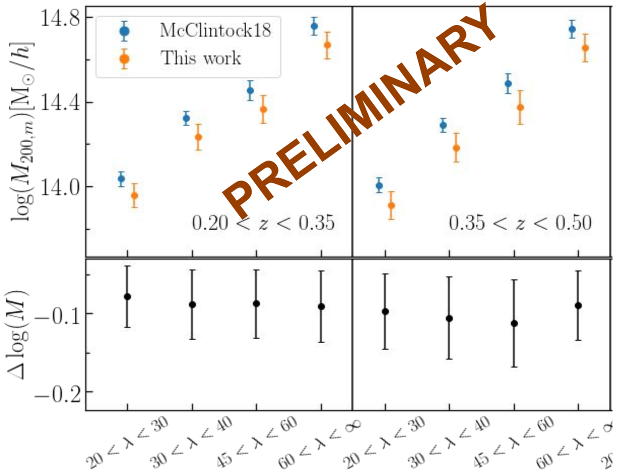


Wu et al. (in prep.)

WL MASS ESTIMATES: SELECTION EFFECT SYSTEMATICS

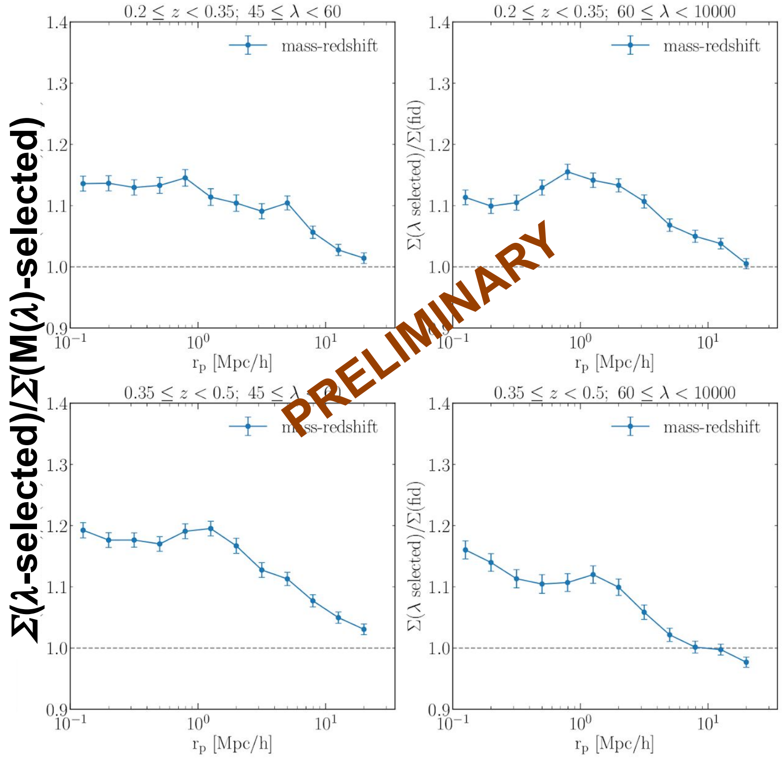
Selection effect bias:

- **Mostly explained by projection and triaxility effects**
- **Lowers mass estimates by ~20%-30% in all richness and redshift bins**
- **Increases the error on WL mass estimates by a factor of 2 (main source of uncertainty for Y1!)**



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

Selection effects systematics on WL profile



Wu et al. (in prep.)

CLUSTER NUMBER COUNTS ANALYSIS

- **Bayesian approach**

  Likelihood model:

$$\mathcal{L}(\boldsymbol{d}|\boldsymbol{\theta}) \propto \frac{\exp\left[-\frac{1}{2}\left(\boldsymbol{d}-\boldsymbol{m}(\boldsymbol{\theta})\right)^{T} \boldsymbol{C}^{-1}\left(\boldsymbol{d}-\boldsymbol{m}(\boldsymbol{\theta})\right)\right]}{\sqrt{(2\pi)^{M} det(C)}}$$

  - *d*: data $\{NC(\lambda^{ob},z^{ob}),M_{WL}(\lambda^{ob},z^{ob})\}$
  - *m(ϑ)*: expectation values for $NC(\lambda^{ob},z^{ob}),M_{WL}(\lambda^{ob},z^{ob})$ as a function of the parameters ϑ
  - *C*: covariance matrix (C_{NC} , C_{WL})

LIKELIHOOD MODELING: ⟨N⟩

- **Expectation value NC (Forward modeling):**

Effective Survey Area

$$\langle N(\Delta\lambda_i^{ob}, \Delta z_j^{ob})\rangle = \int_0^\infty \mathrm{d}z^{true} \Delta\Omega_{mask}(z^{true}) \frac{\mathrm{d}V}{\mathrm{d}z^{true}\mathrm{d}\Omega} \langle n(\Delta\lambda_i^{ob}, z^{true})\rangle \int_{\Delta z_j^{ob}} \mathrm{d}z^{ob} P(z^{ob}|z^{true}),$$

Photo-z error

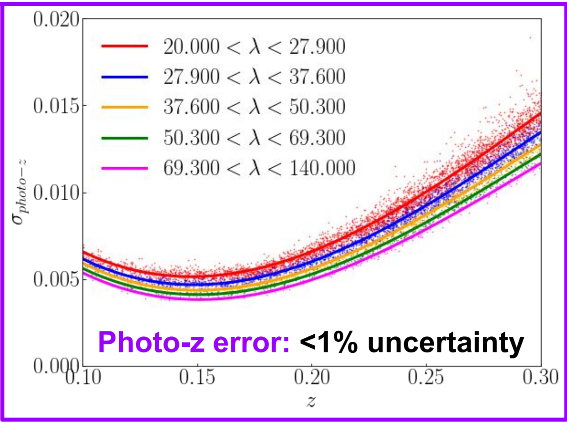
HMF

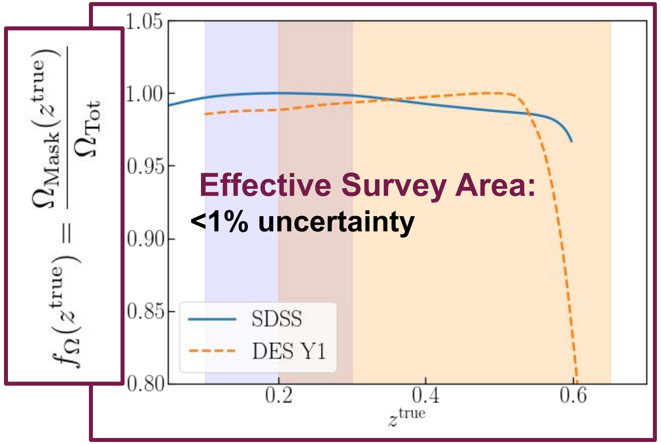
$$\langle n(\Delta\lambda_i^{ob}, z^{true})\rangle = \int_0^\infty \mathrm{d}M\, n(M, z^{true}) \int_{\Delta\lambda_i^{ob}} \mathrm{d}\lambda^{ob} P(\lambda^{ob}|M, z^{true})$$

Observed Richness-mass relation
(a.k.a selection function)

EFFECTIVE SURVEY AREA and HMF / PHOTO-Z UNCERTAINTY

$$P(z^{\rm ob}|z^{\rm true}) = \mathcal{N}(z^{\rm true}, \sigma_z(z^{\rm true}))$$

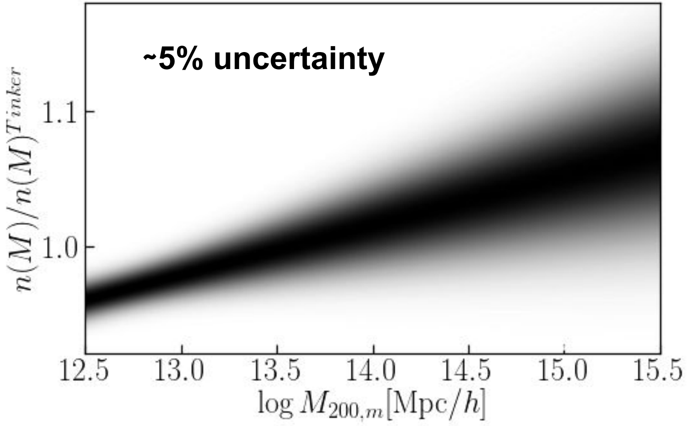




Uncertainty HMF

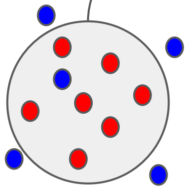
$$n(M,z) = n(M,z)^{\rm Tinker}\left(s\log(M/M^*) + q\right)$$

Priors on s & q calibrated with 40 N-body simulations spanning a range of cosmologies.



MODELING OBSERVABLE-MASS RELATION

- **Observed richness-mass relation:**



$$\lambda^{ob} = \lambda^{true}(M,z) + \Delta\lambda(\lambda^{true},z)$$

$P(\lambda^{ob}|M,z)$:= Probability to observe a cluster of mass "M" and redshift "z" with richness "λ^{ob}"

$$P(\lambda^{ob}|M,z) = \int_0^\infty \mathrm{d}\lambda^{true} P(\lambda^{ob}|\lambda^{true}) P(\lambda^{true}|M,z)$$

Richness estimate error introduced by the cluster finder ($P(\lambda^{ob}|\lambda^{true})$)

"Intrinsic" Richness-mass relation ($P(\lambda^{true}|M,z)$)

MODELING P(λ^{true}|M,z)

- λ^{true} : **cluster richness in absence of errors introduced by the cluster finder (e.g. error in the background subtraction, projection effects)**

HOD-like Model:

Central galaxy

$<\lambda^{tr}(M)> = \Theta(M-M_{min})\,[\,1 + <\lambda^{sat}(M)>]$

$<\lambda^{sat}(M)> = [(M-M_{min})/(M_1-M_{min})]^{\alpha}$

M_{min} : Minimum mass to form a CG

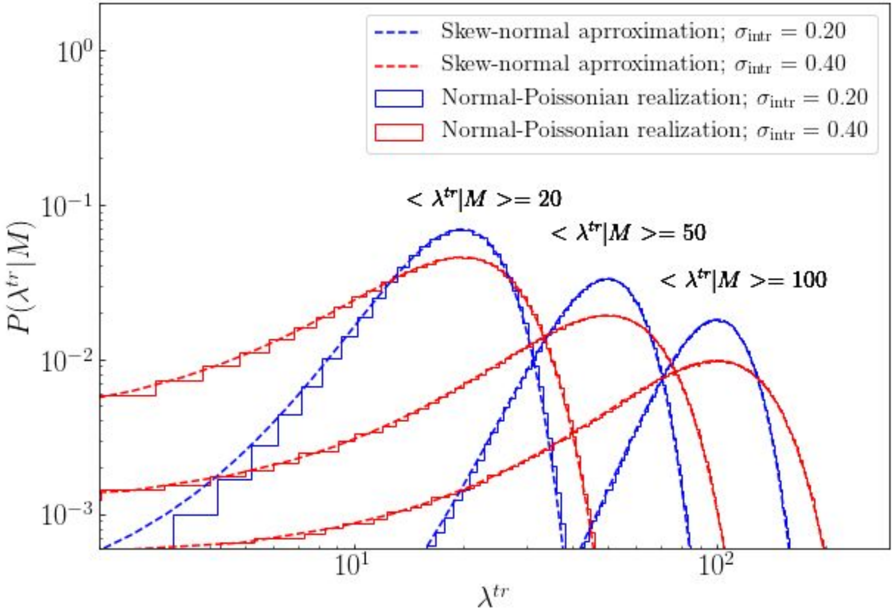
M_1 : Characteristic mass to acquire 1 Sat. Glx.

α : Slope

$\lambda^{sat}(M) = \Delta^{Pois} + \Delta^{Gauss}$

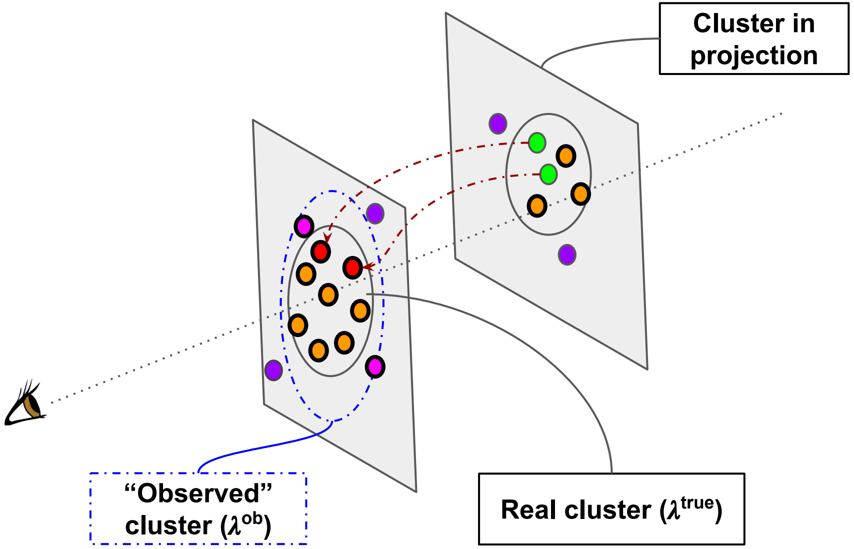
PDF(Δ^{Pois})= Poisson(mean=$<\lambda^{sat}(M)>$)
PDF(Δ^{Gauss})= Normal(mean=0,std=$<\lambda^{sat}(M)>\sigma_{intr}$)

P(λ^{true}|M,z)= Poisson*Normal ≃ Skew-Normal distribution



MODELING OBSERVATIONAL NOISE

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

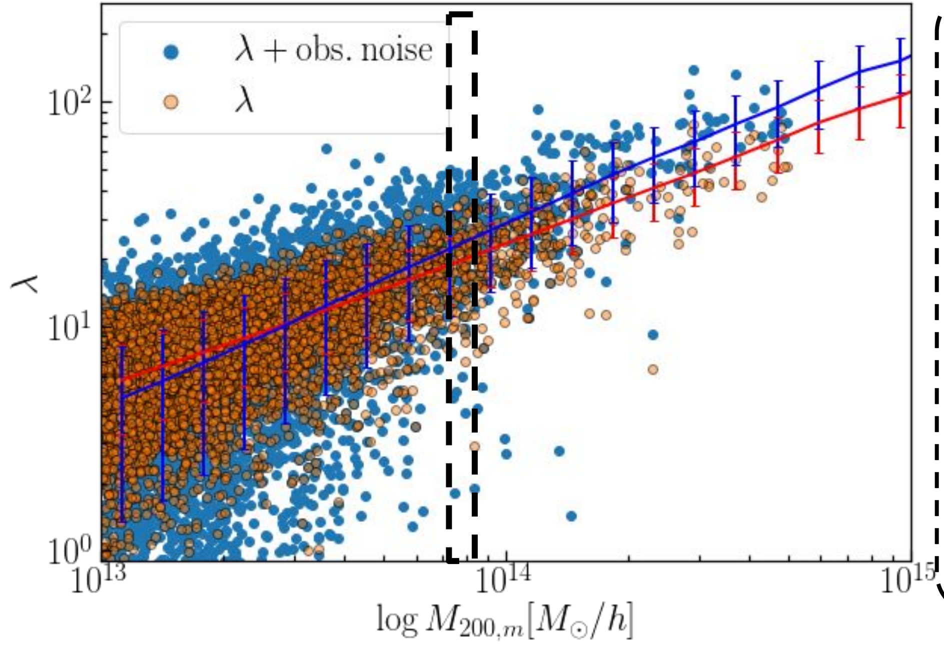


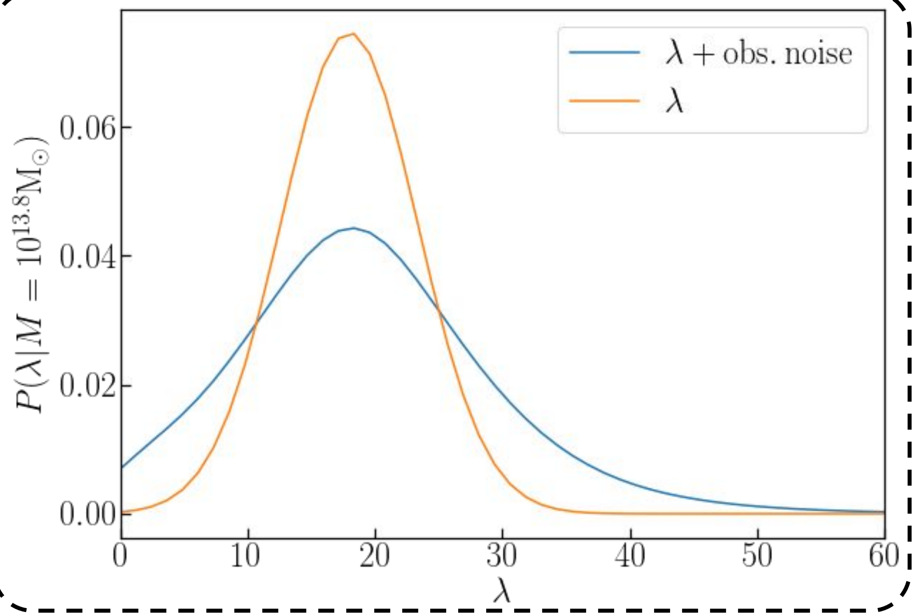
- Cluster members (λ^{true})
- Main sources of scatter in richness estimates:
  - Uncertainties in the background subtraction
  - Projection effects
  - Percolation (loss of member galaxies due to projection effects)

MODELING OBSERVATIONAL NOISE

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

Richness-mass relation with and without obs. noise





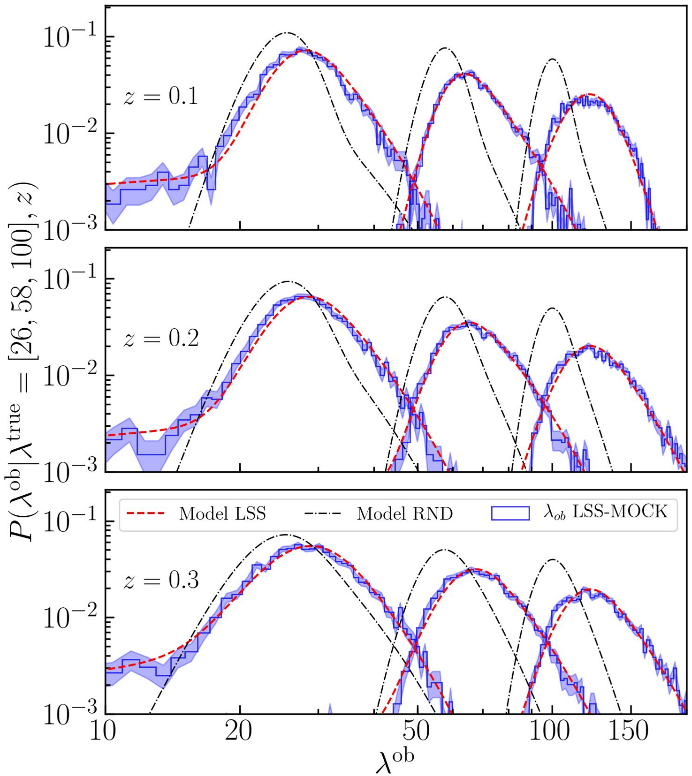
MODELING OBSERVATIONAL NOISE

- **From DATA, we can determine:**
  - **How background sources/photo-z noise contaminate λ^{true}**
  - **The magnitude of projection effects for two clusters aligned along the same line of sight**

- **From SIMULATIONS, we can determine:**
  - **How correlated structures (i.e. clusters in projection) contaminate λ^{true}**

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

Scatter between true and observed richness



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

Costanzi+ 18a (arXiv:1807.07072)

MISCENTERING CORRECTION NUMBER COUNTS

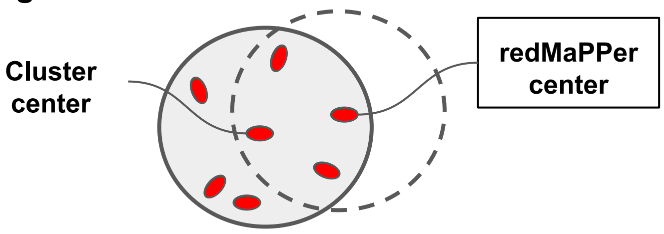
Miscenterd clusters tend to have low (observed) richness:

We correct the NC data for miscentering effect:

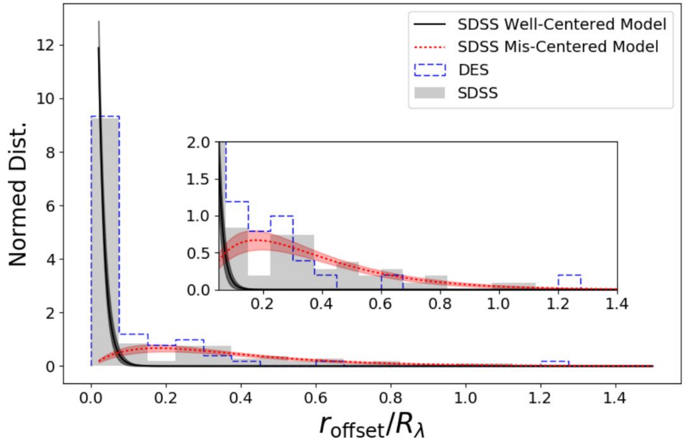
$$NC^{w\backslash o\ Misc} = NC^{Obs}\ \gamma^{cen}\ (\simeq 1.03 \pm 0.01)$$

γ^{cen} derived by modeling (Zhang+19):

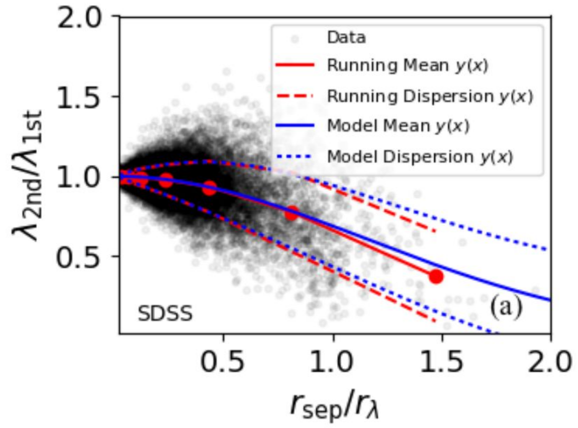
E.g.



Radial offset distribution (comparing X-ray vs redMaPPer center)



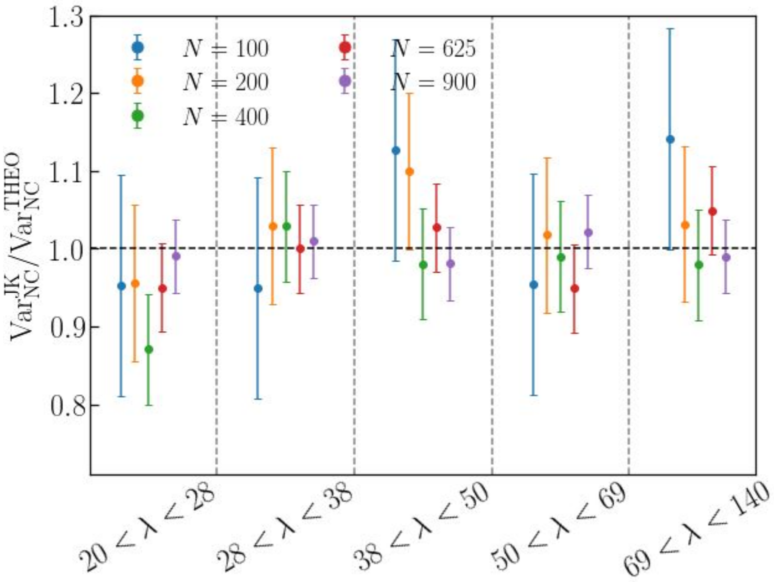
Richness perturbation as a function of the offset distribution



COVARIANCE MATRIX FOR NC

- $C^{NC} = C^{Poisson} + C^{SampVar} + C^{Misc}$
  - $C^{Poisson}$: Contribution due to the Poisson fluctuations in the number of halos at given mass in the survey volume
  - $C^{SampVar}$: Sample variance contribution due to the fluctuation of the density field in the survey volume
  - C^{Misc} : Contribution due to uncertainty in the miscentering corrections

Covariance matrix validated using mock catalog



LIKELIHOOD MODELING: ⟨*M*⟩

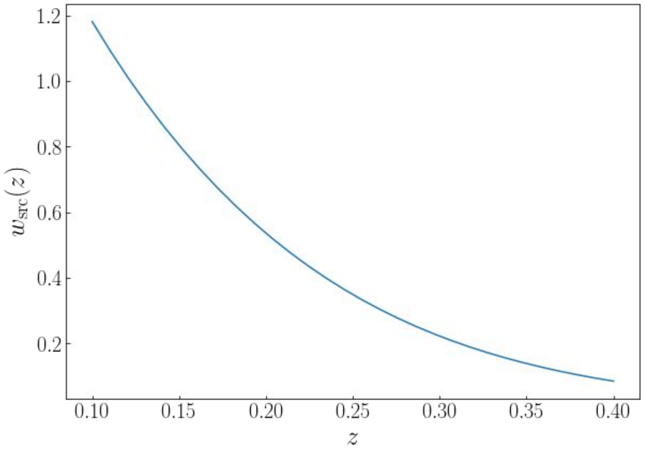
- **Expectation value for the mean mass:**

$$\log\langle \bar{M}(\Delta\lambda_i^{ob}, \Delta z_j^{ob})\rangle = \log \frac{\langle M^{tot}(\Delta\lambda_i^{ob}, \Delta z_j^{ob})\rangle}{\langle N(\Delta\lambda_i^{ob}, \Delta z_j^{ob}) w_{src}(z^{ob})\rangle}$$

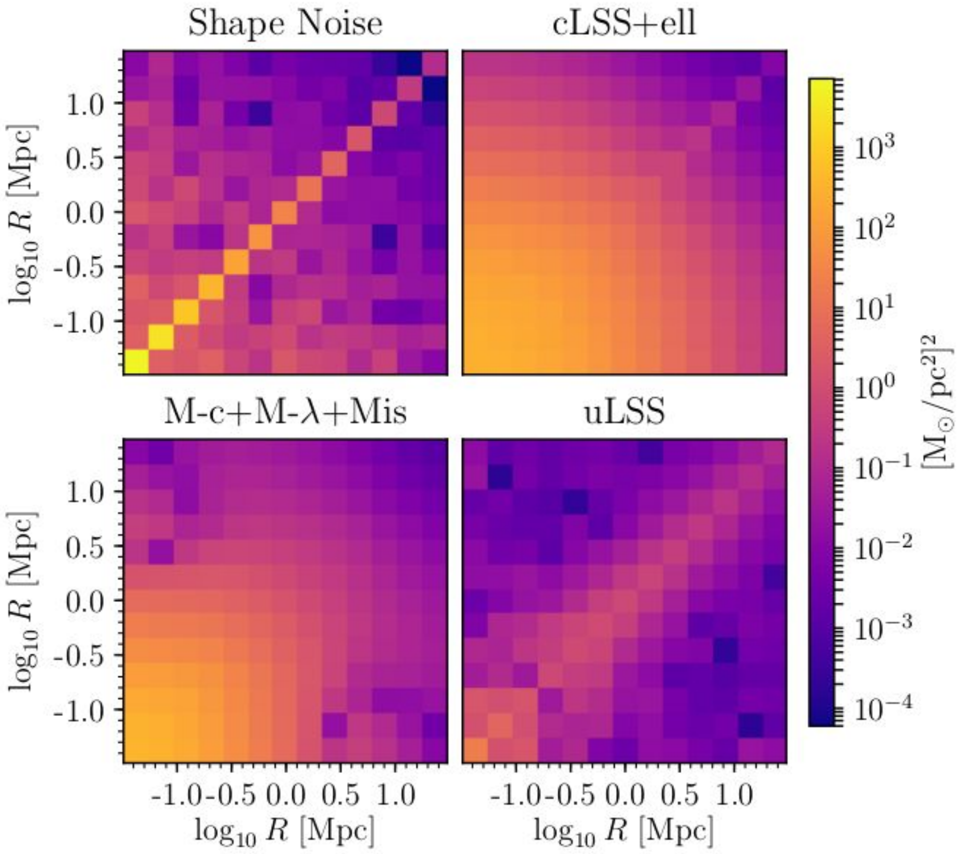
$$\langle M^{tot}(\Delta\lambda_i^{ob}, \Delta z_j^{ob})\rangle = \int_0^\infty \mathrm{d}\, z^{true}\, \Omega_{mask} \frac{\mathrm{d}V}{\mathrm{d}z^{true}\mathrm{d}\Omega}(z^{true}) \langle nM(\Delta\lambda_i^{ob}, z^{true})\rangle \int_{\Delta z_j^{ob}} \mathrm{d}z^{ob}\; P(z^{ob}|z^{true}) w_{src}(z^{ob})$$

$$\langle nM(\Delta\lambda_i^{ob}, z^{true})\rangle = \int_0^\infty \mathrm{d}M\; M n(M, z^{true}) \int_{\Delta\lambda_i^{ob}} \mathrm{d}\lambda^{ob}\; P(\lambda^{ob}|M, z^{true})$$

Lensing weight



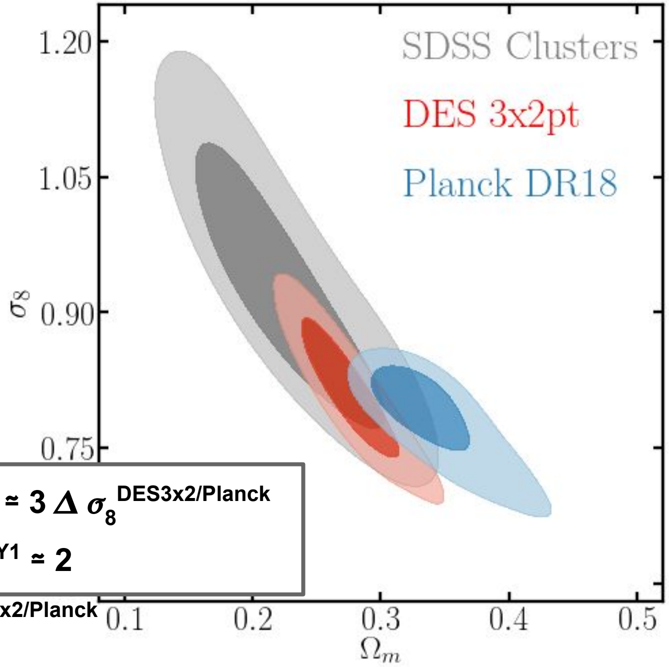
COVARIANCE MATRIX FOR M_{WL}



✚ **Selection Effect Uncertainty**

TESTING THE PIPELINE WITH redMaPPer SDSS

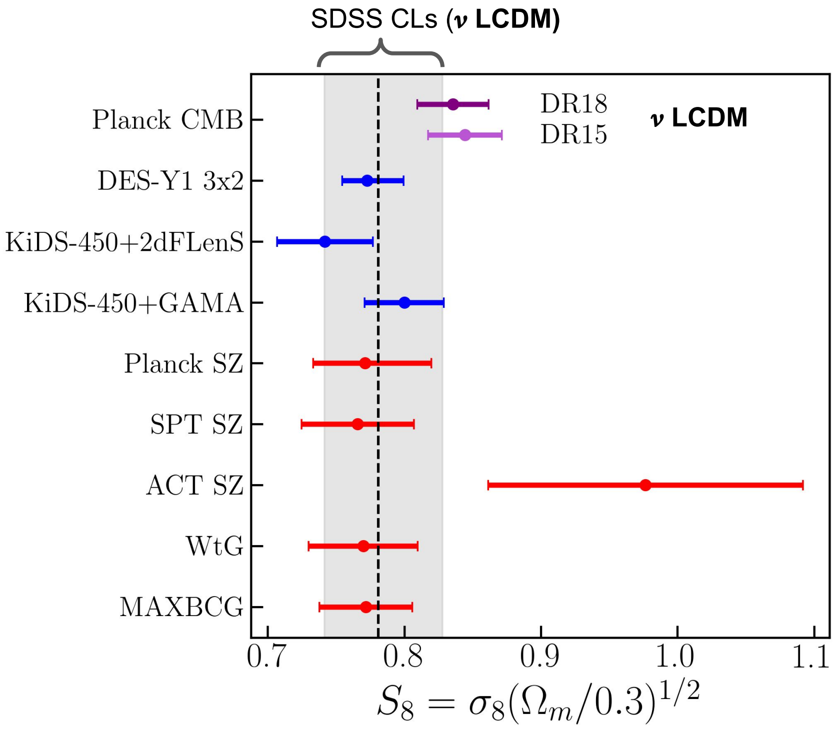
Costanzi+ 18b (arXiv:1810.09456)



$\Delta\sigma_8^{SDSS} \simeq 3\, \Delta\, \sigma_8^{DES3x2/Planck}$

$\Delta\Omega_m^{DESY1} \simeq 2$

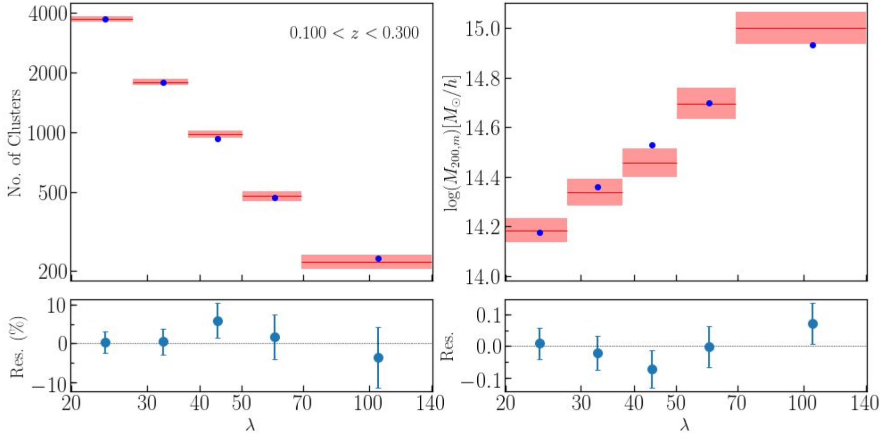
$\Delta\Omega_8^{DES3x2/Planck}$

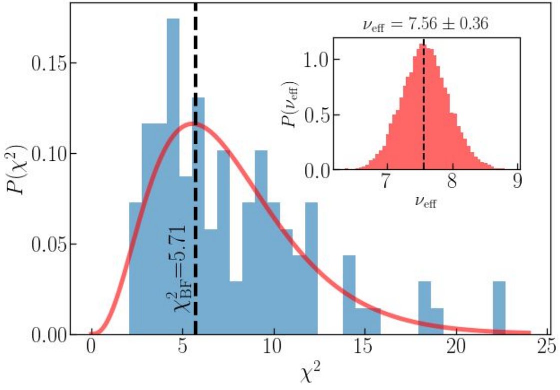


Catalog	Redshift range	Area [deg^2]	# of clusters (λ^{ob}>20)	WL analysis	σ_{Mass}
SDSS DR8	0.1<z<0.30	10.000	~6964	Simet+17	13%

GOODNESS OF FIT & ROBUSTNESS OF THE ANALYSIS

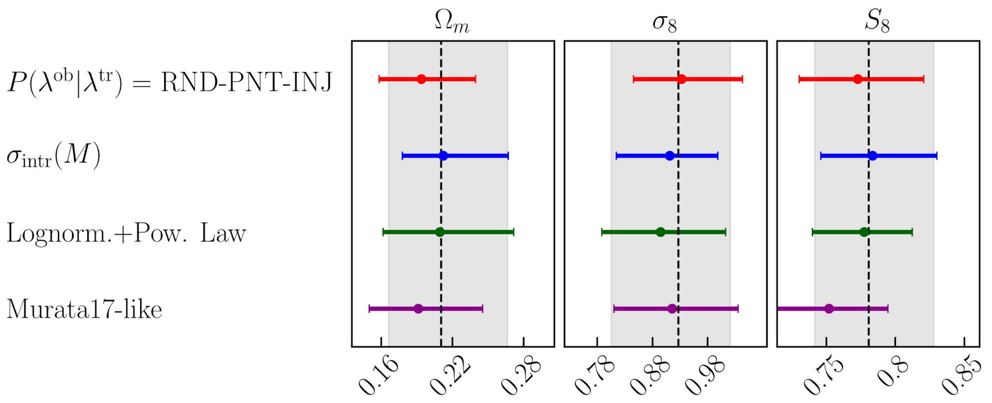
Goodness of fit





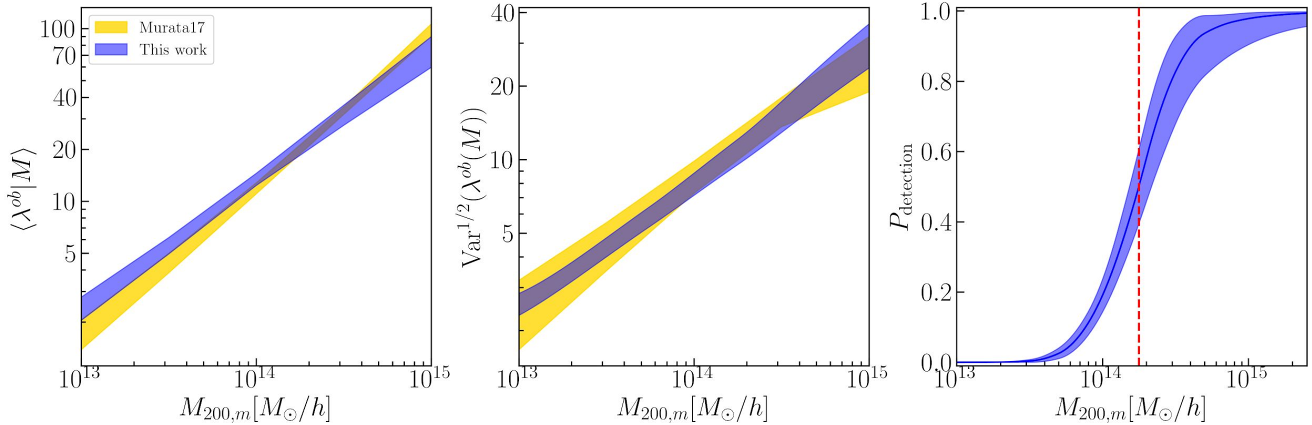
Expected χ^2

Robustness to model assumptions and systematics

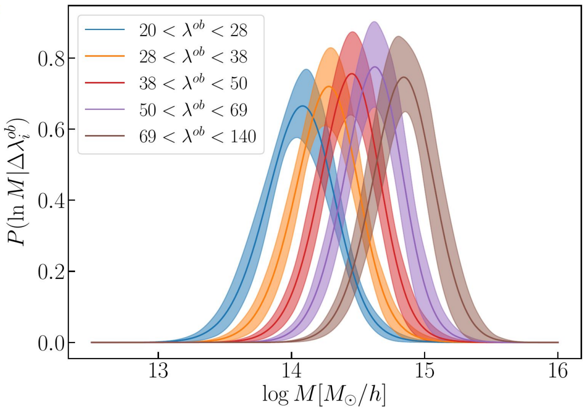


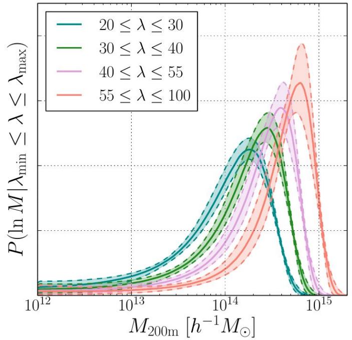
- Gray band: Reference Model
- RND-PNT-INJ: No contribution from correlated structures
- σ_{intr}(M) : Mass dependent scatter between λ^{true}-M
- P(λ^{true}|M)=Lognorm. & <λ^{true}|M>= Pow. Law
- P(λ^{ob}|M)=Lognorm. & <λ^{ob}|M>= Pow. Law & σ_{intr}(M)

RICHNESS-MASS RELATION FROM redMaPPer SDSS



Mass distribution inside the λ bins

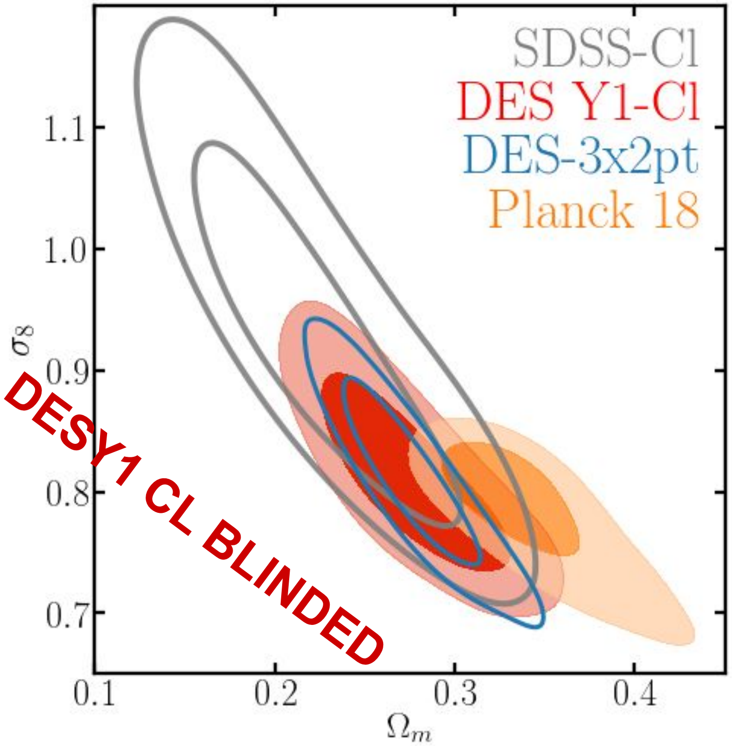




From Murata+17

COSMOLOGICAL CONSTRAINTS DESY1 ΛCDM+ν model

BLINDED



PRELIMINARY

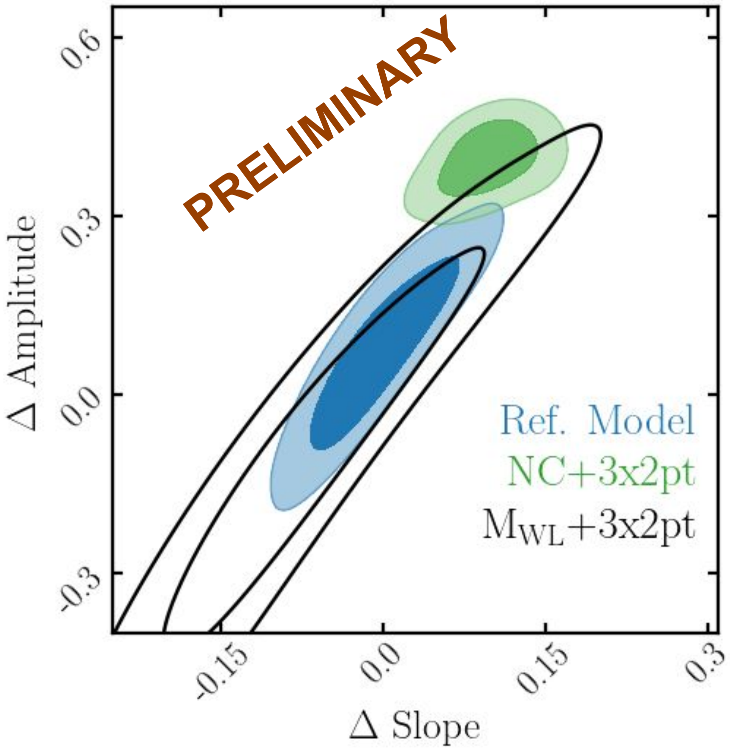
ΛCDM+ν
$\Delta S_8^{DESY1} \simeq 0.9\,\Delta S_8^{SDSS}$
$\Delta S_8^{DESY1} \simeq 0.8\,\Delta S_8^{SPT\text{-}SZ}$
$\Delta S_8^{DESY1} \simeq 1.7\,\Delta S_8^{DES3x2}$
$\Delta S_8^{DESY1} \simeq 1.8\,\Delta S_8^{Planck18}$

➔ **Selection effect uncertainty accounts for 16% of the total error budget on S_8**

DES Collaboration 19, in prep.

CONSISTENCY DES Y1 NC & M_{WL} DATA

Assume DESY1 3x2pt cosmology fit for the λ-M relation using only NC or M_{WL} data



DES Collaboration 19, in prep.

Internal tension between Y1 NC and M_{WL} data (@ DES 3x2pt cosmology) implies that either:

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

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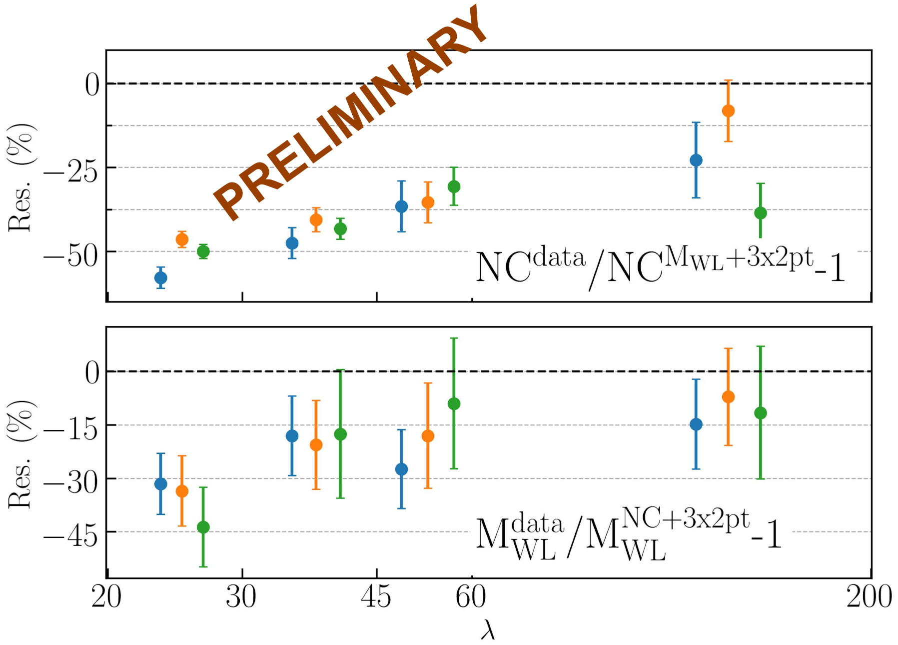


Internal tension between Y1 NC and M_{WL} data (@ DES 3x2pt cosmology) implies that either:

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

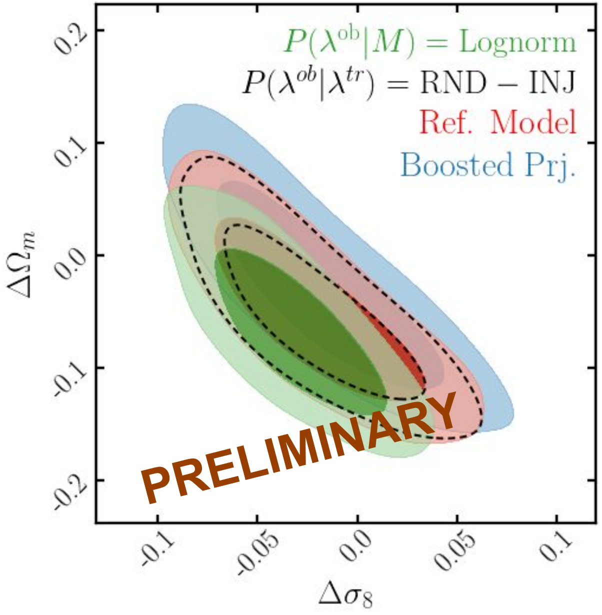
- **If M_{WL} estimates are correct: redMaPPer should be incomplete at ~50% at low λ and ~25% at high λ**
- **If NC data are correct: M_{WL} should be biased low by ~30% at low λ and ~10% at high λ**

DES Collaboration 19, in prep.

NOT VIABLE SOLUTIONS . . .

- Shear and photo-z systematics would affect the 3x2pt results even more strongly
- 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 exclude large contamination at $\lambda \approx 30$
- NC modeling/systematics does not have large impact on the posteriors
- Baryonic effects cannot account for 50% 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 NC by less than 1%

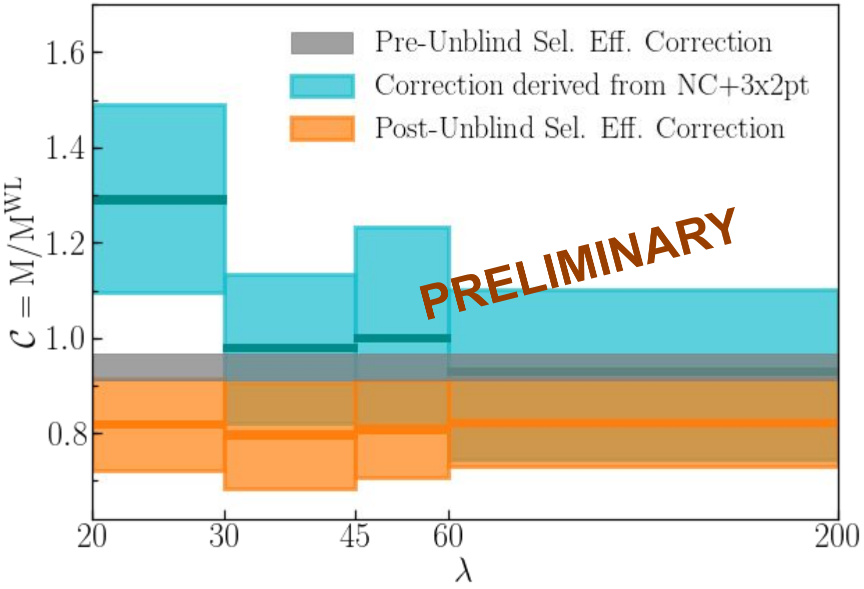
Effect on σ_8 and Ω_m of different model assumptions



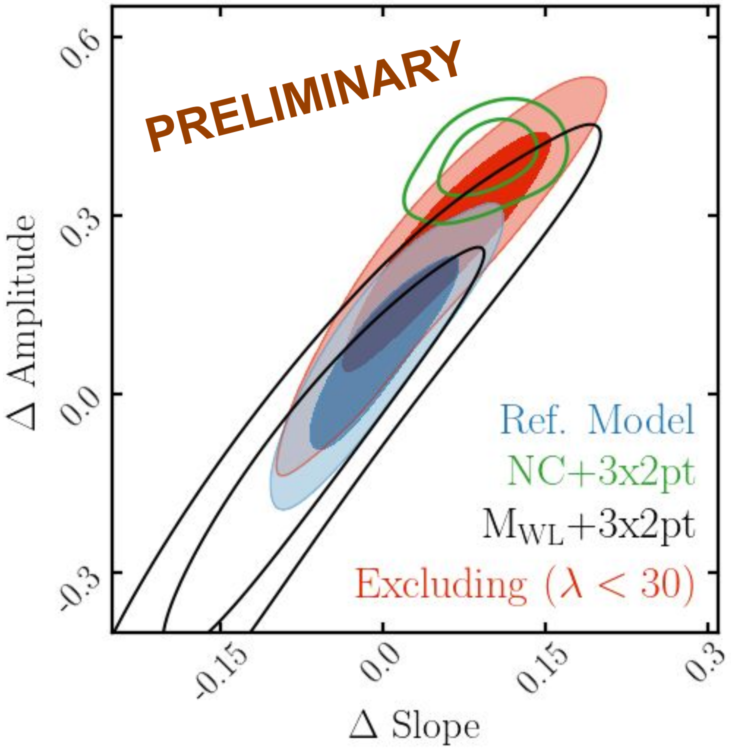
DES Collaboration 19, in prep.

POSSIBLE SOLUTIONS . . .

- Selection effects bias might be overestimated at $\lambda \gtrsim 30$, but cannot explain correction needed at lowest λ-bin



- Unmodeled systematic at λ<30 (contamination?)

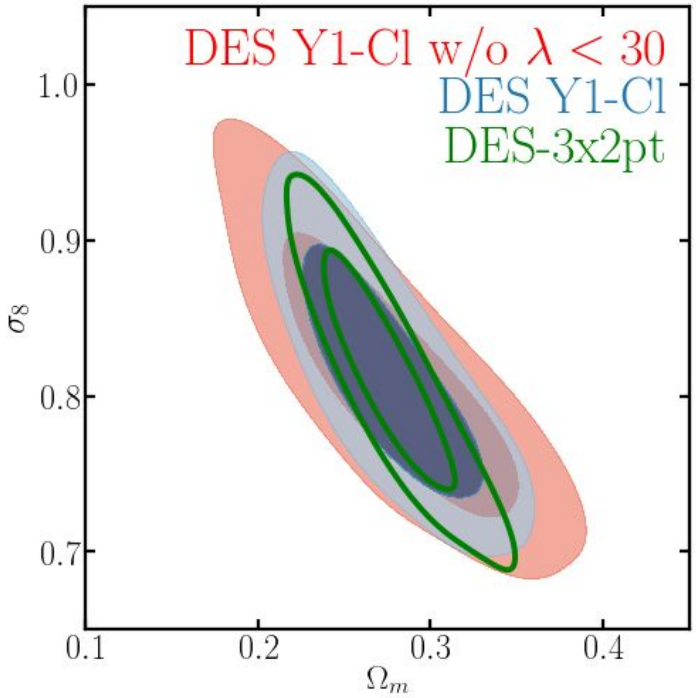


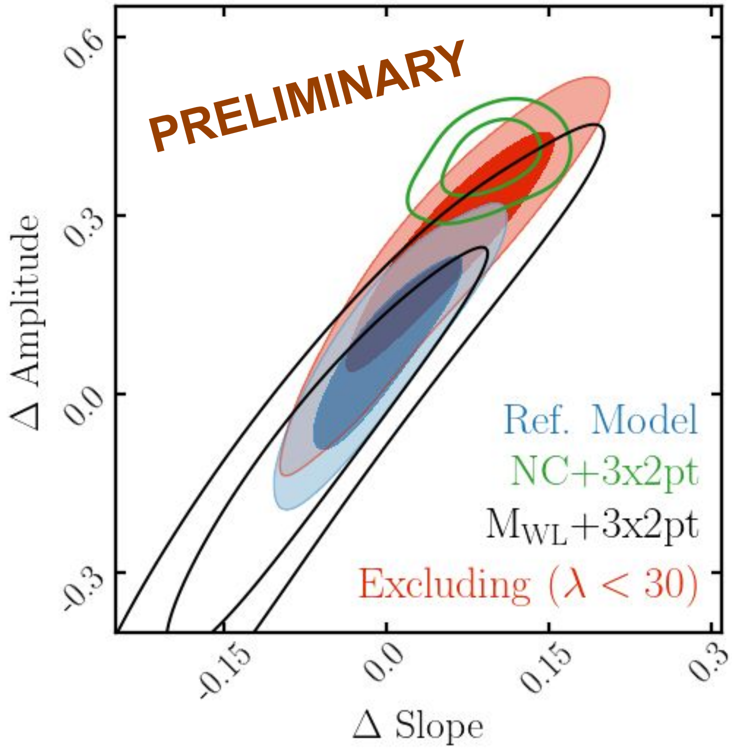
DES Collaboration 19, in prep.

POSSIBLE SOLUTIONS . . .

➔ **Dropping the lowest λ-bins remove the tension with DES3x2pt but the error on S_8 increase by 18%**

- **Unmodeled systematic at λ<30 (contamination?)**





DES Collaboration 19, in prep.

SUMMARY

- Cluster abundance can be a powerful cosmological probe, provided we are able to precisely characterise the relation between observable and underlying halo mass.

- DES Y1 cluster catalog can provide cosmological constraints which are independent and competitive with those obtained from other probes but . . .

- Numerical simulations suggest that selection effects severely impact the M_{WL} of redMaPPer clusters
  - Mass lowered by ~20% compared to previous estimates
  - Currently represent the main source of systematic uncertainty (~50% of the M_{WL} error budget)
- Internal tension between NC and M_{WL} pointed out unmodeled systematics (likely) in M_{WL} data, which:
  - has to be richness dependent
  - has to dilute the WL signal for λ<30
- Removing λ<30 data greatly reduce the tension, but at the expense of looser constraints

OUTLOOK FOR DES Y3 CLUSTER COSMOLOGY

- **redMaPPer DES Y3: 4600 deg^2 up to z=0.7 → ~3 times more clusters than redMaPPer DES Y1 !**

- **End-to-end simulations needed to calibrate selection effects and validate the modeling.**
  Main limitations: galaxy color and clustering model, resolution limit for shear measurements.
  Hydro sims to calibrate bias in WL estimates

- **Validation of selection effects with external data (especially at low λ):**
  - **Complete samples of spectroscopic data to validate projection effects**
  - **X-ray follow-up of complete samples to model miscentering and contamination and constrain the λ-M relation scatter**
  - **Cross-match with SZ and X-ray data to assess completeness (@ medium/high λ; SPT-3G and eROSITA might help also at low λ), test selection effects on WL signal (e.g. comparing WL signal of SZ and X-ray selected samples to redMaPPer)**

- **“Full” forward modeling of NC and WL signal (rather than passing through the mass calibration) to ensure consistency between the likelihoods and correctly account for cross correlations**