Associated to: Project 380 + PubDB 180

Analysis of the weak lensing mass-richness relation of redMaPPer clusters in the LSST DESC DC2 simulations

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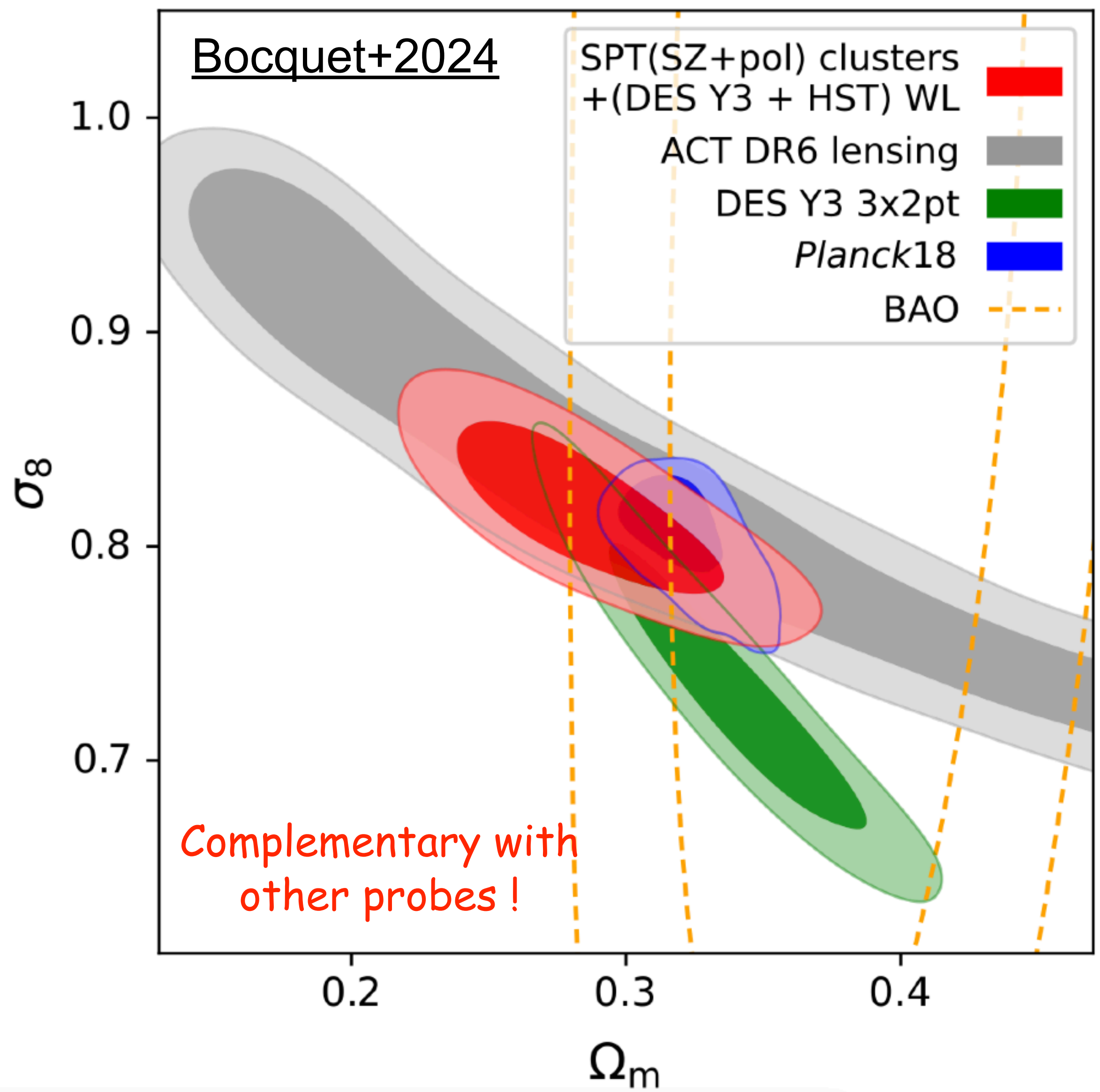
Cosmology with cluster counts

The abundance of galaxy clusters

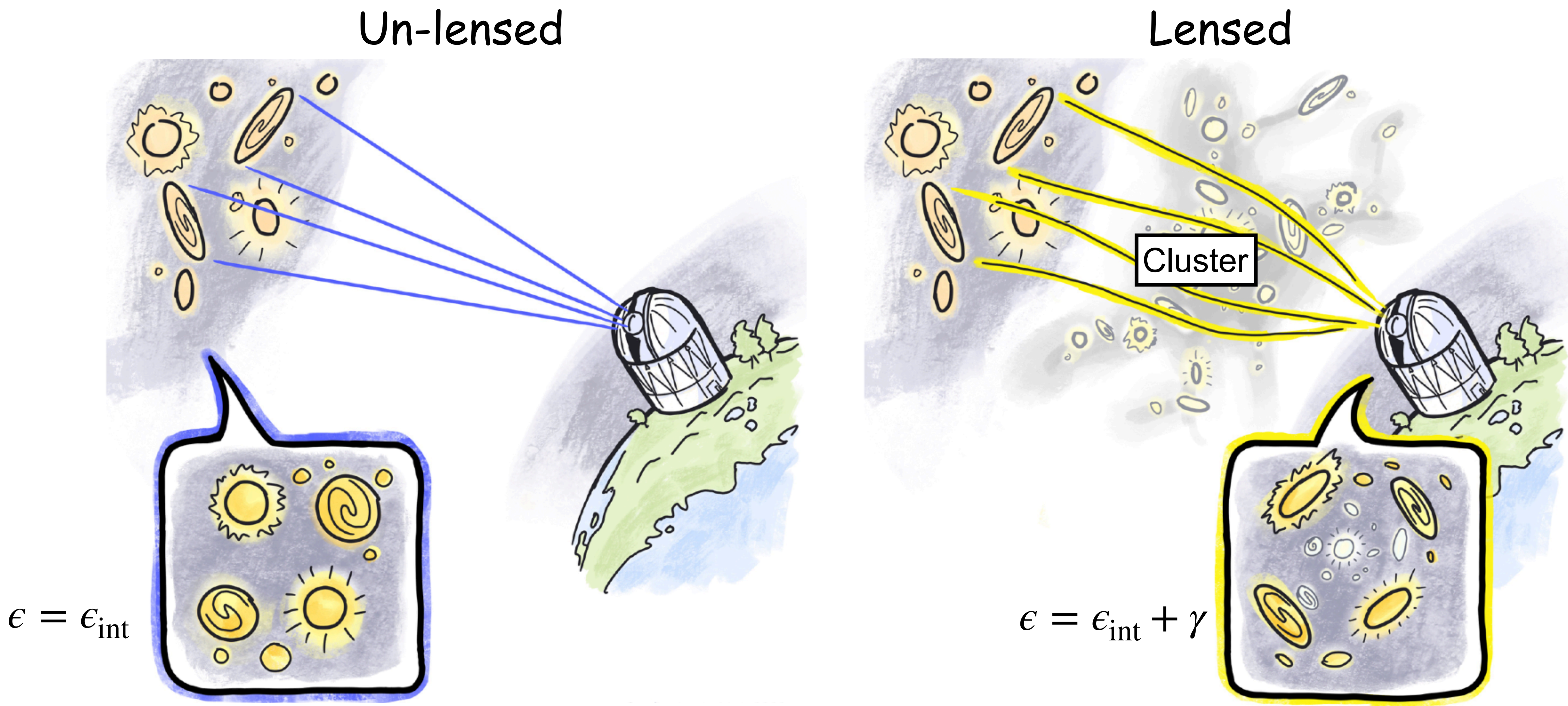
- Massive bound systems $M > 10^{14}\ M_\odot$ and detected in X-rays, mm, optical
- Connects proxy-cluster counts to cosmology via a scaling relation:

$$\frac{\partial^2 N_{\rm obs}^{\rm clusters}}{\partial \mathcal{O} \partial z} \propto \int dm \frac{\partial^2 N_{\rm th}^{\rm halo}(m,z)}{\partial m \partial z} P(\mathcal{O}\,|\,m,z)\Phi$$

- Privileged probes for structure formation and geometry in ΛCDM (i.e. Ω_m, S_8) + beyond
- Current constraining power: determined by uncertainties on the scaling relation (MoR)
- Stage IV catalogs (LSST, Euclid, SO) $\sim$ 100,000 clusters (x10 current datasets)
- Requires robust modeling of observables, better control of systematics in deriving MoR



Weak lensing by galaxy clusters

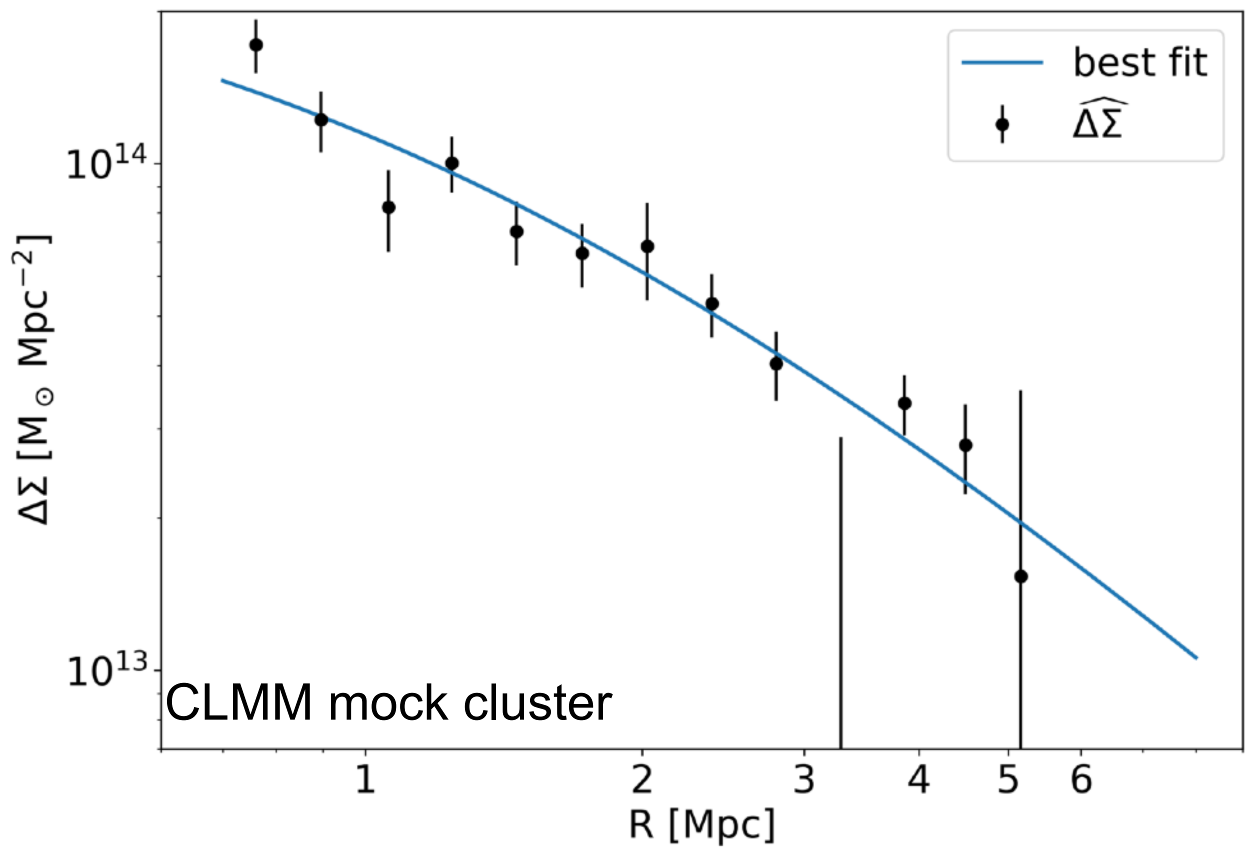


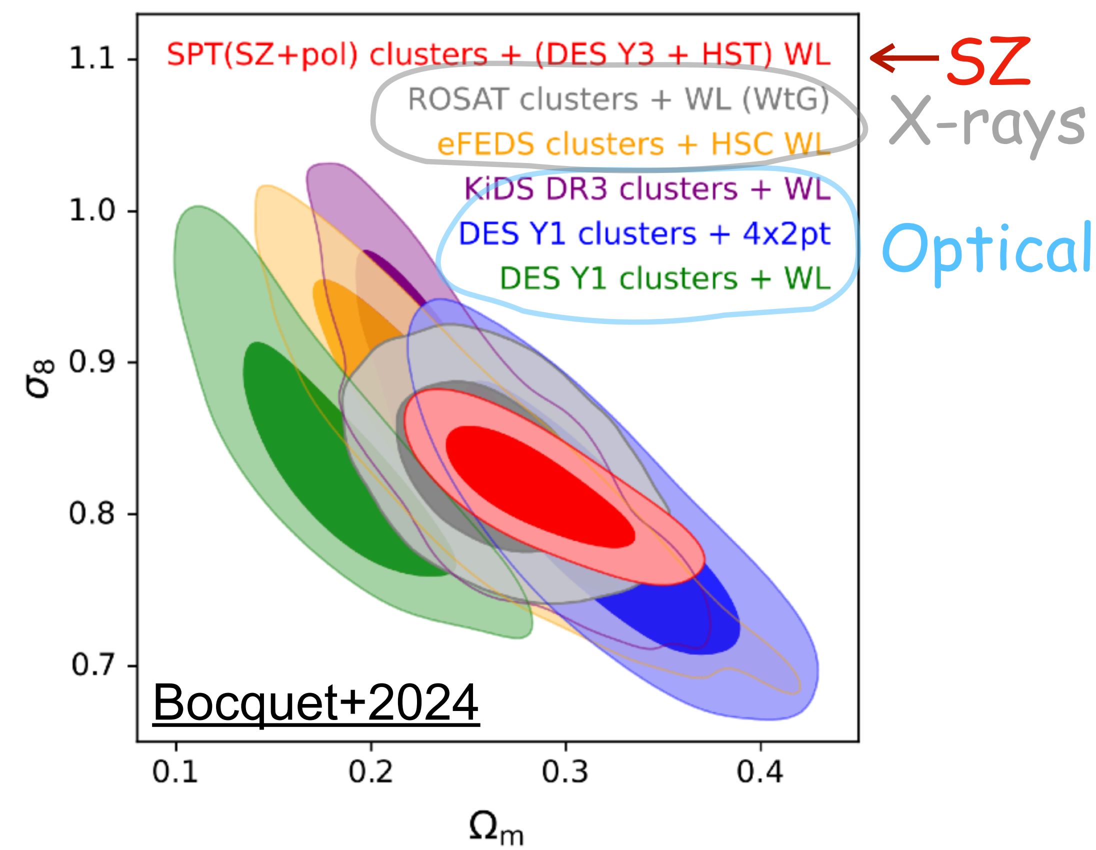
Credits: Jessie Muir 2020

Weak lensing by galaxy clusters

- Bending of light coming from distant galaxies by the gravitational potential of clusters
- Subtle deformation of galaxy shapes $\epsilon = \epsilon_{\rm int} + \gamma$
- Local average $\langle \epsilon \rangle = \gamma$
- Reveals the cluster mass density $\gamma = f(M_{\rm cluster})$

Weak lensing by galaxy clusters: in practice





Excess surface density estimator

Data: $\widehat{\Delta\Sigma}(R) = \langle \Sigma_{\rm crit}(z_{\rm cl}, z_{\rm gal})\ \epsilon_+^{\rm obs} \rangle$

Critical surface mass density

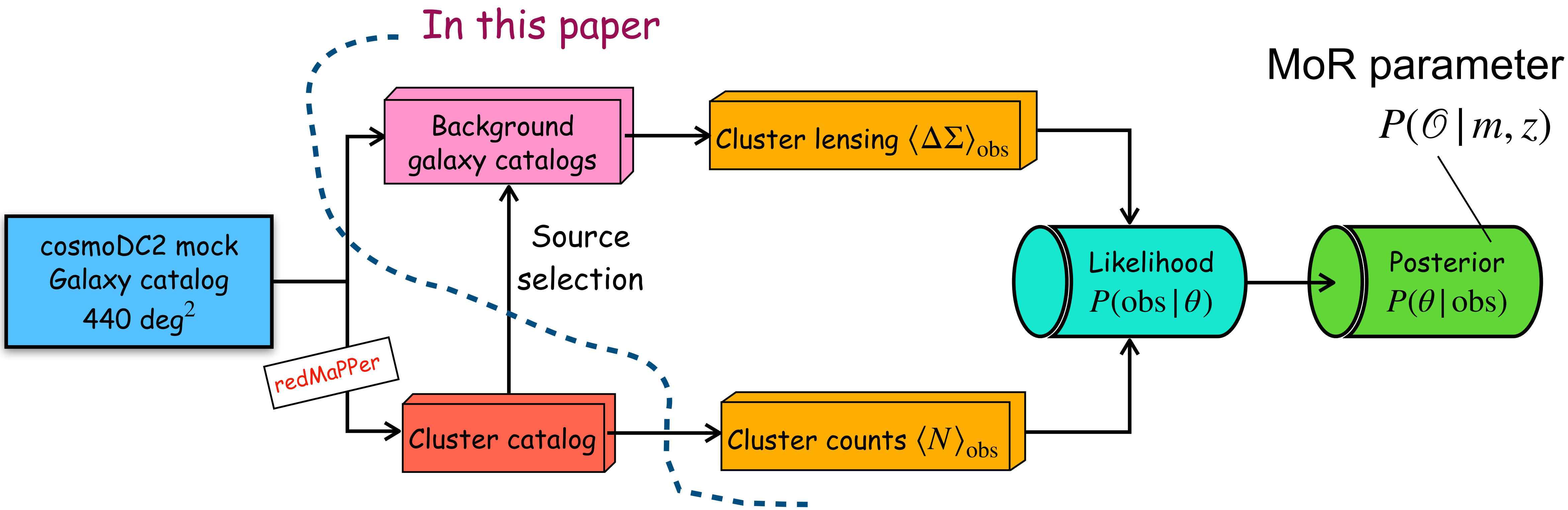
« tangential »

Model: $\Delta\Sigma(R) \to \Sigma(R) = \int d\mathrm{LOS}\ \rho_{3d}(r)$

$\boxed{\text{Fit } \Delta\Sigma(R) \to M_{\rm cluster}}$

Used to calibrate cluster mass-proxy relation !

Paper's objectives



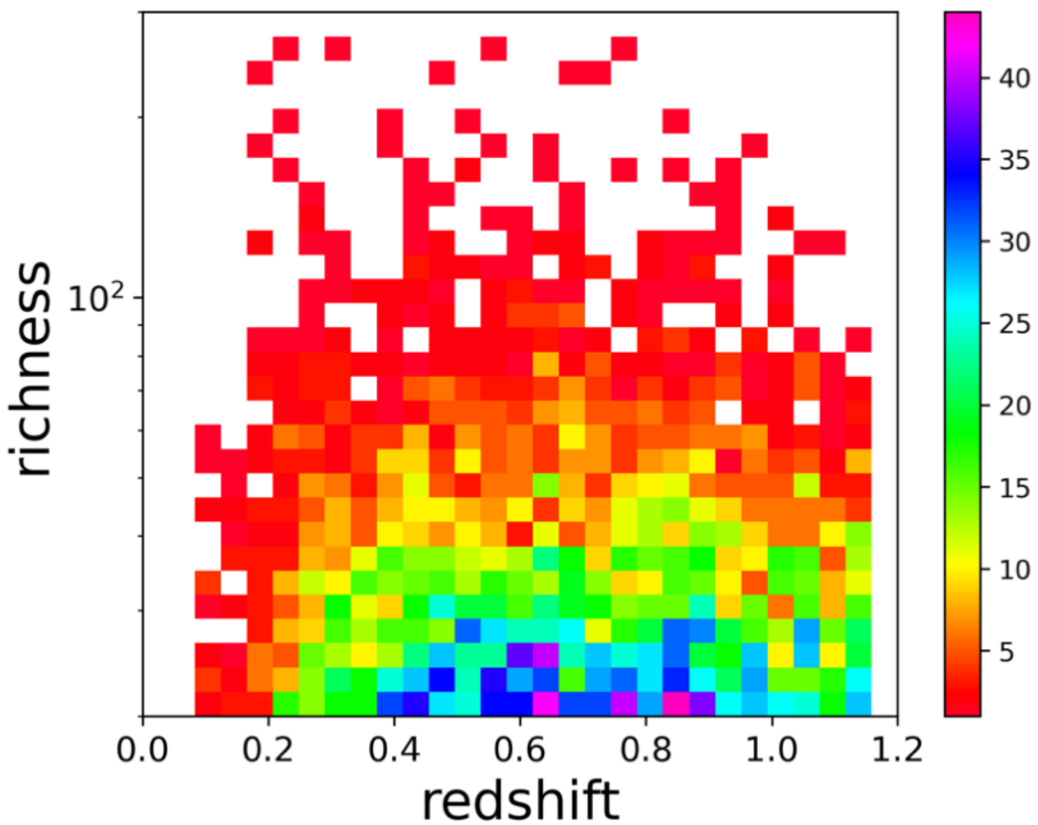
« Early » DESC CL end-to-end pipeline

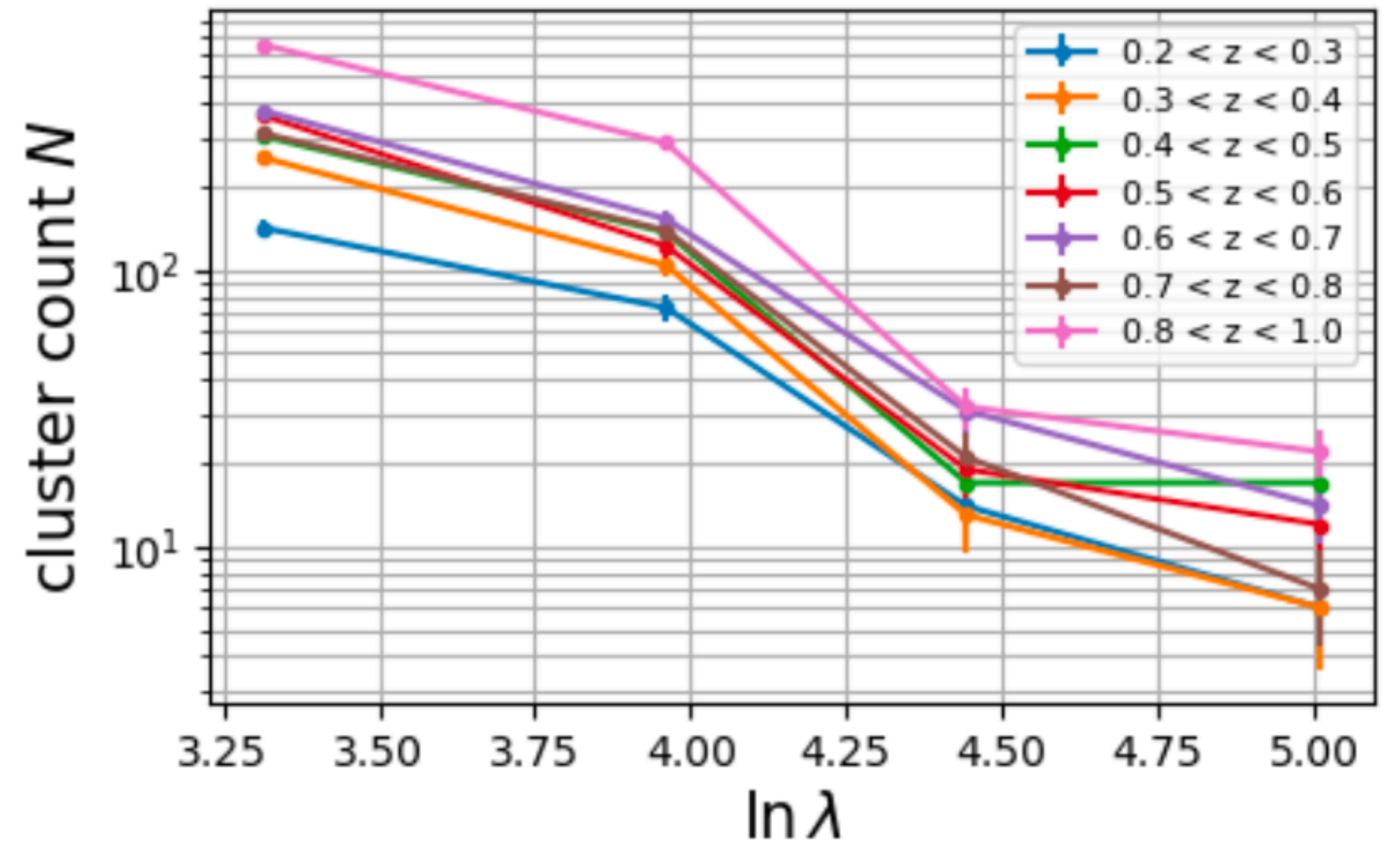
- From galaxies to params.
- With DESC tools (CLMM, CCL, ClEvaR)
- On DESC products (cosmoDC2)
- Combining CC + WL
- Help the design of the Firecrown likelihood
- CLCosmo_Sim: CC+WL pipeline (public)

Study the MoR relation in DESC DC2 data

- DC2: Large simulation over 440 deg2
- cosmoDC2*:* extra-galactic (truth) catalog+*PZ add-ons*
- Cluster catalog: redMaPPer (Rykoff+13)
- CLCosmo_Sim_database: data vectors (only DESC members)

CC Data: LSST DESC DC2 simulations





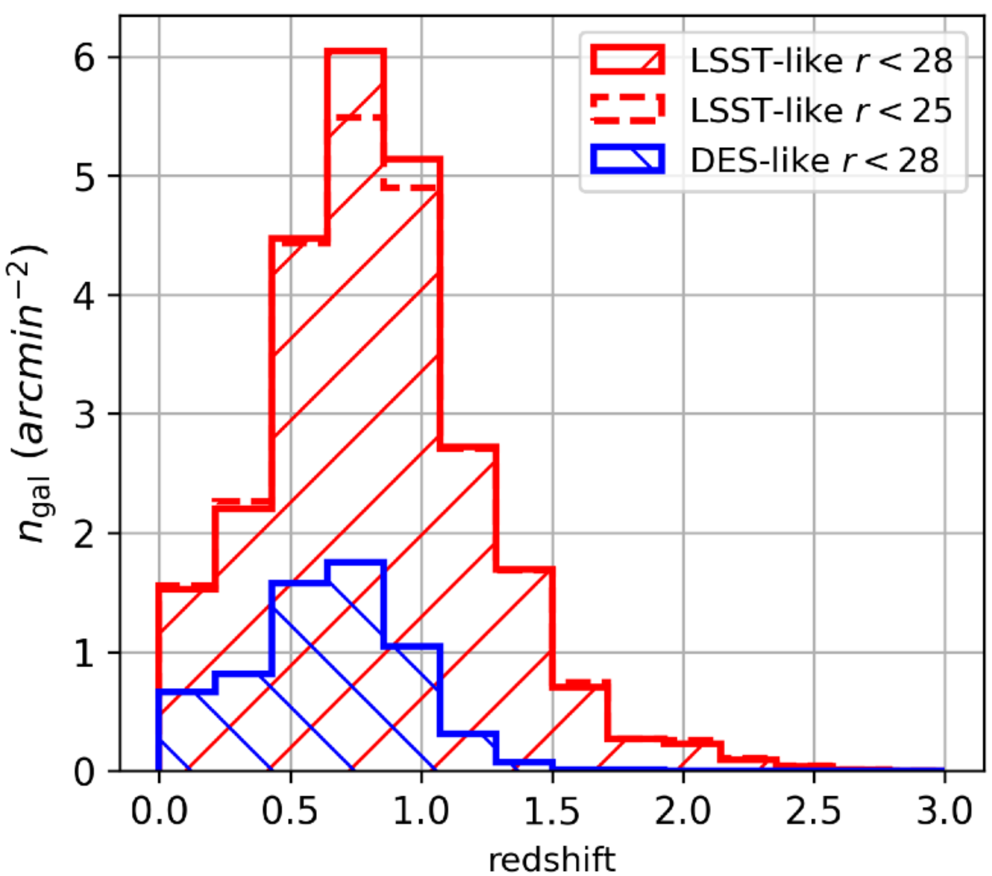
Cluster catalog: redMaPPer (Rykoff+13)

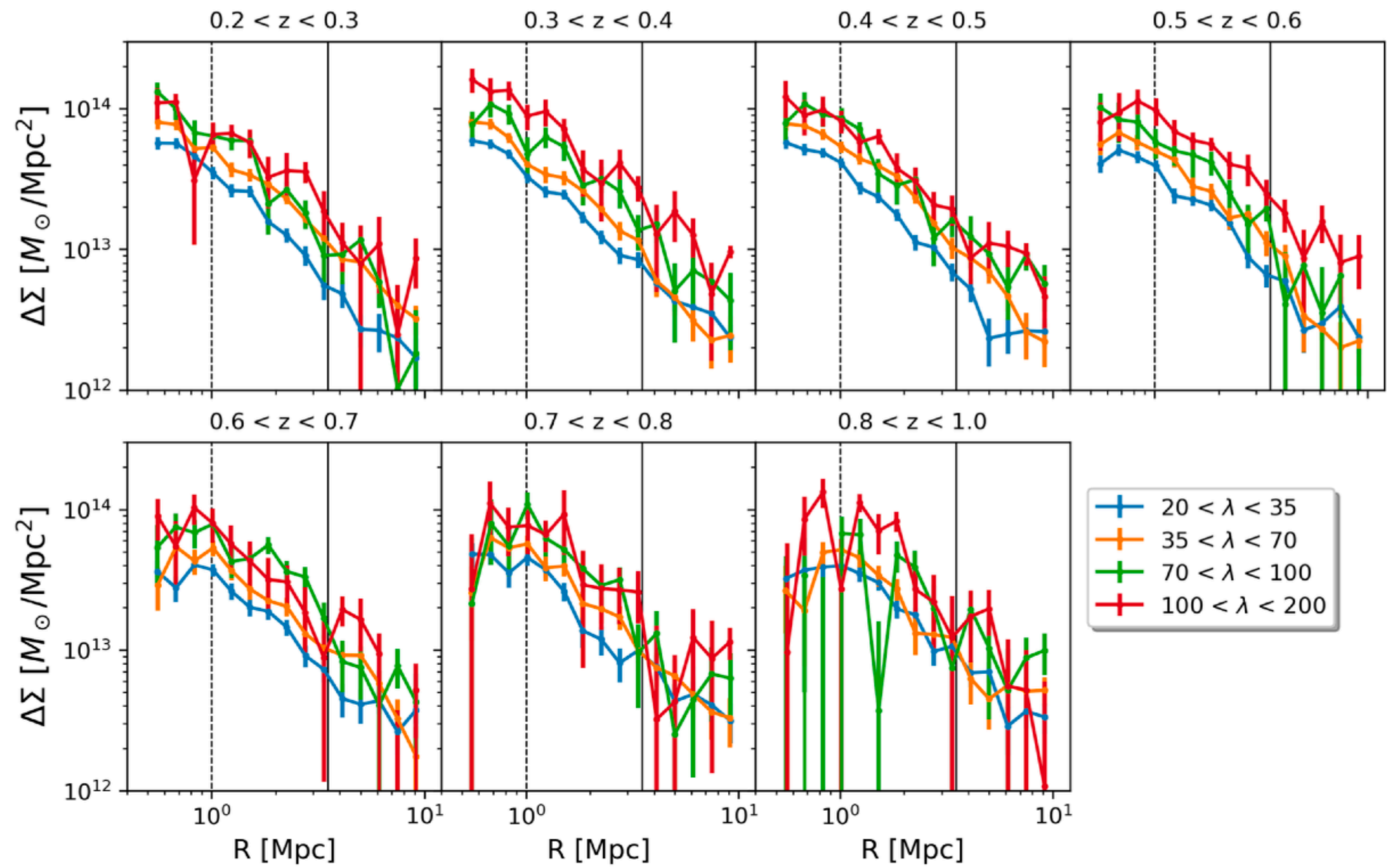
- detect over densities of red-sequence galaxies
- For each redMaPPer selected clusters:
  - Assign richness $\lambda \sim$ # of member galaxies
  - Cluster redshift
- $\sim$ 880,000 clusters with $\lambda < 300$, $z < 1.15$
- Other cluster catalogs on DC2 (AMICO, YOLO-CL, WAZP)

Summary statistics in this analysis

- 4x7 redshift-richness bins
- $20 < \lambda < 200$ + $0.2 < z < 1$
- Log-spaced for richness
- => 3,600 clusters on 440 deg2
- Study the mass-redshift dependency of the MoR

WL Data: LSST DESC DC2 simulations





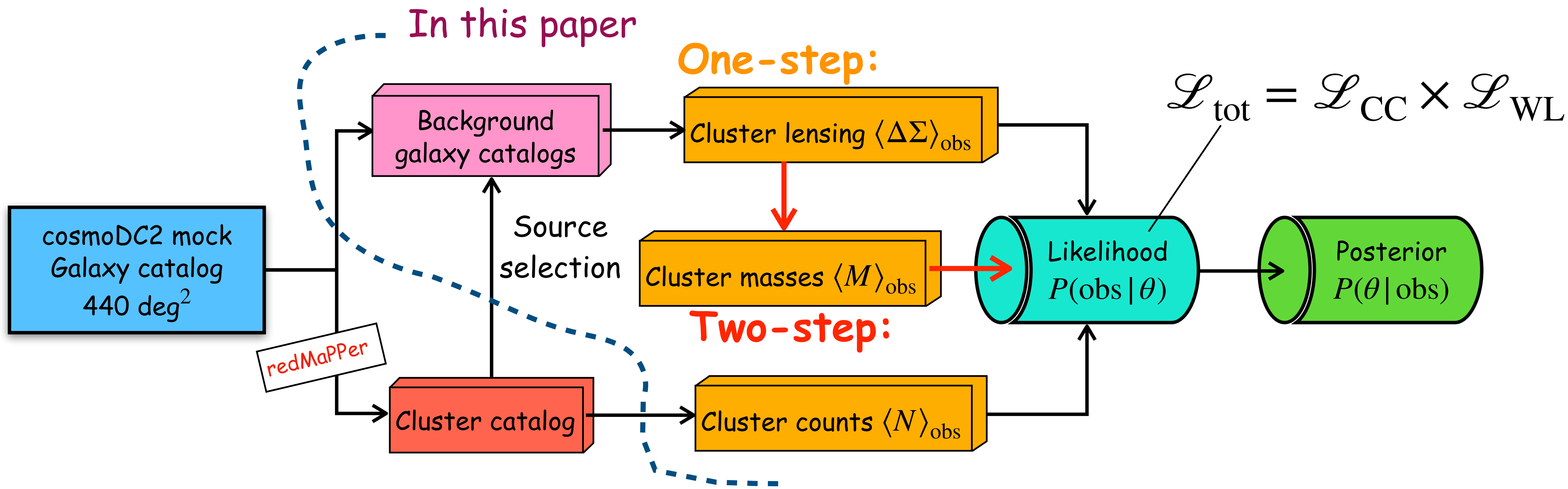
Source selection

- $r < 28$, adjust $i < 24.25$
- LSST-like density: 25 gal.arcmin-2
- Behind: $z_{\rm cosmoDC2} > z_{\rm cl} + 0.2$
- (PZ in the next slides)
- Baseline: $\epsilon_{\rm int}$ and $\gamma_{\rm cosmoDC2}$
- $\sigma_{\rm SN} = 0.25$ & $\sigma_{\rm meas} = 0$

Stacked cluster lensing profiles

- In richness-redshift bins
- 15 radial bins from 0.7 to 10 Mpc
- R > 1 Mpc (ray-tracing resolution, Kovacs+21)
- We focus on the one-halo regime
  - 1 < R[Mpc] < 3.5

Inference from CC+WL



Two alternatives for WL

- **One-step: use stacked profiles directly**
  - flexibility to incorporate several systematic effects (mis-centering, selection biases) *forward* modeling the raw observables.
- **Two-step: First fit the mean mass**
  - spitting the problem ! Simplifies integrals and computational times

$$\mathscr{L}_{\rm WL} = \mathscr{L}(\widehat{\Delta\Sigma}(R)\,|\,\theta)$$

Or

$$\mathscr{L}_{\rm WL} = \mathscr{L}(\widehat{M}\,|\,\theta)$$

We can now discuss the modeling …

Modeling for the mass-richness relation

Log-normal distribution

$$P(\ln\lambda\,|\,m,z) \propto \exp\left\{-\frac{[\ln\lambda - \langle \ln\lambda\,|\,m,z\rangle]^2}{2\sigma^2_{\ln\lambda|m,z}}\right\}$$

Mean

$$\underline{\ln\lambda_0} + \underline{\mu_z}\log\left(\frac{1+z}{1+z_0}\right) + \underline{\mu_m}\log_{10}\left(\frac{m}{m_0}\right)$$

Variance

$$\underline{\sigma_{\ln\lambda_0}} + \underline{\sigma_z}\log\left(\frac{1+z}{1+z_0}\right) + \underline{\sigma_m}\log_{10}\left(\frac{m}{m_0}\right)$$

Modeling choices

- « Forward » modeling $P(\ln\lambda\,|\,m,z)$, parametrization from [Murata+18]
- Easier to implement in CC analyses than $P(\ln M\,|\,\lambda,z)$
- Log-normal relation, 6 free params.
- $z_0 = 0.5$ and $\log_{10}(m_0/M_\odot) = 14.3$
- Possible redshift evolution μ_z and σ_z

Modeling for cluster count and lensing

Modeling choices

- Fixed **Despali+15** halo mass function (fiducial cosmoDC2 cosmology)
- Selection function $\Phi(m, \lambda, z)$:
    - redMaPPer performance (false detection, incompleteness)
    - Calibrated by matching with DM halos
    - Details in Ricci et al. in prep.
- Mass-richness relation
- WL baseline: one-halo regime modeled by a NFW profile, **Duffy+08** concentration-mass relation, consider only $R \in [1,3.5]$ Mpc

Constrain MoR

- Combine likelihoods CC+WL (Gaussian)
- CC: SSC theoretical prediction using PySSC
- WL profiles: data-driven bootstrap covariance
- Masses: errors from mass measurement

Cluster count

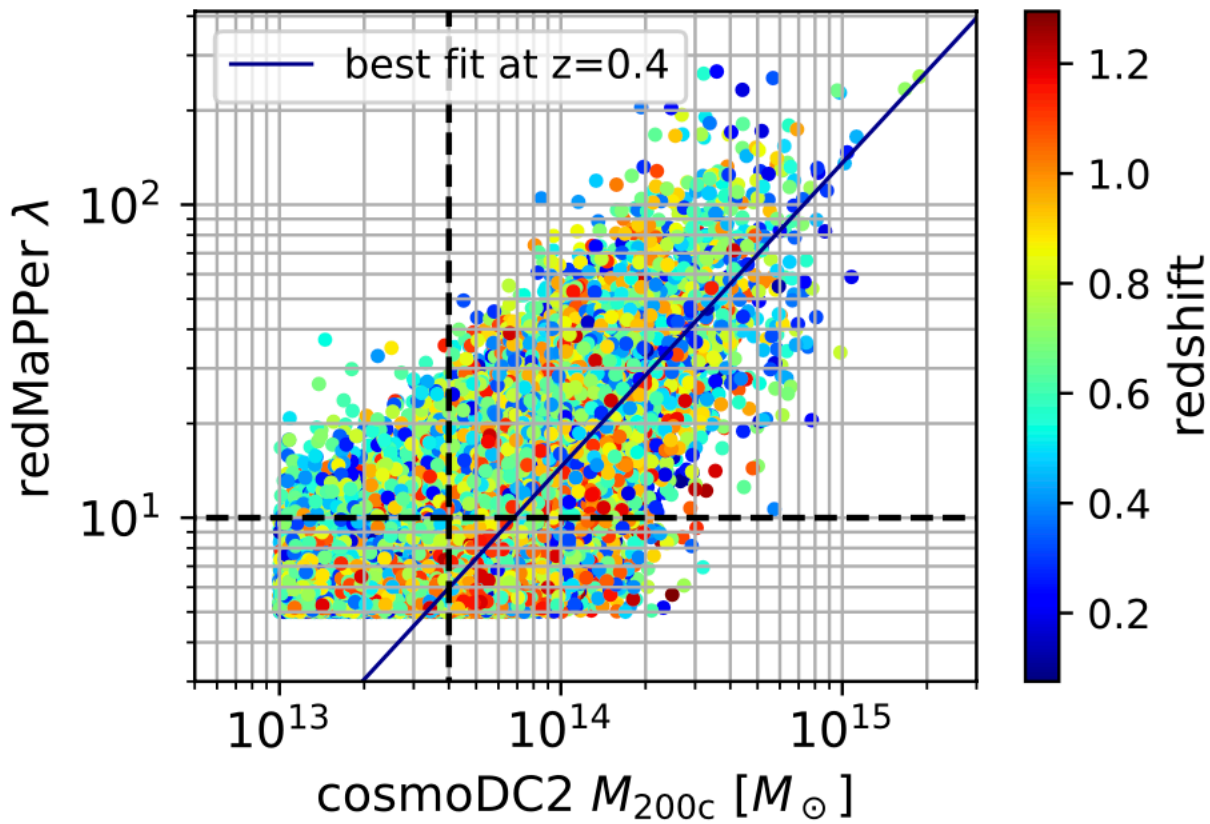
$$N_{ij}^{\rm th}(\theta) = \int_{z_i}^{z_{i+1}} dz \int_{\lambda_j}^{\lambda_{j+1}} d\lambda \int_{m_{\min}}^{+\infty} dm \times \underbrace{\frac{d^2N(m,z)}{dmdz}}_{\text{HMF}} \underbrace{\Phi(m,\lambda,z)}_{\text{selection function}} \underbrace{P(\lambda\,|\,m,z)}_{\text{Mass-richness relation}}$$

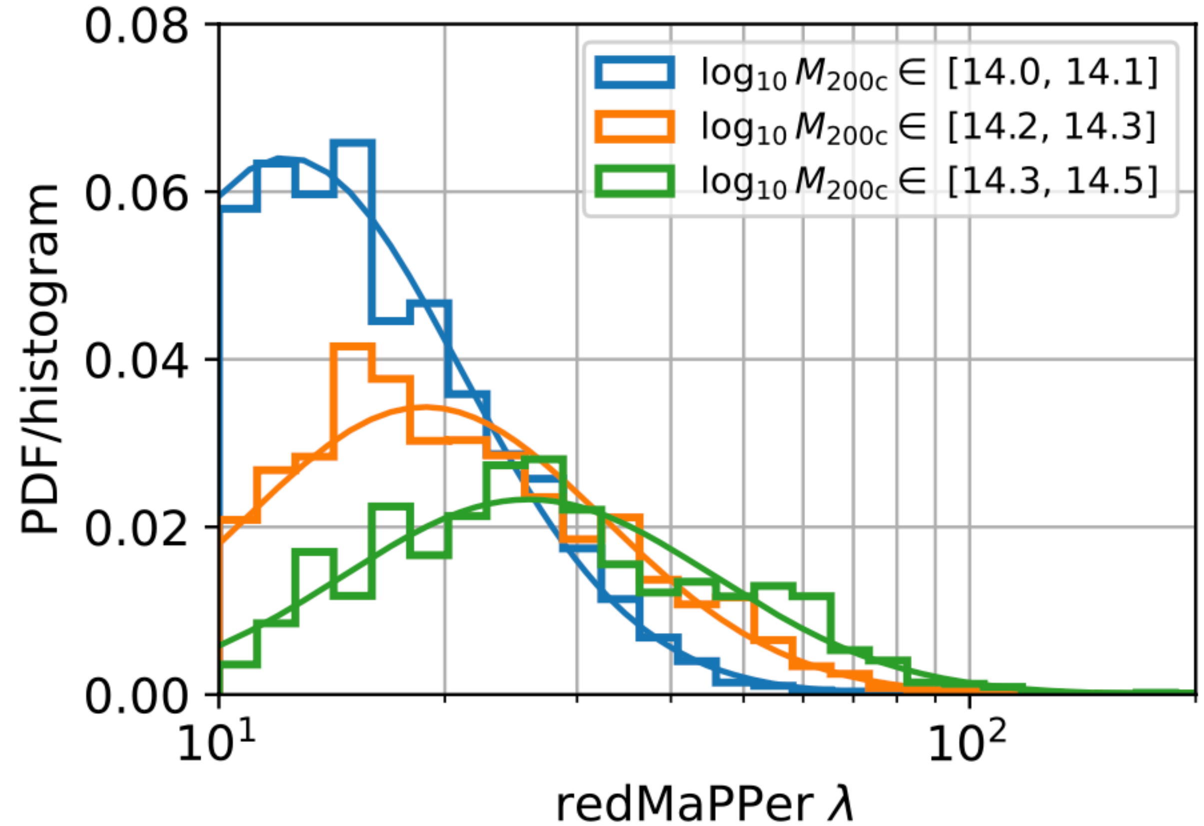
Weak Lensing

$\Delta\Sigma_{ij}^{\rm th}(\vec{\theta})$ or $M_{ij}^{\rm th}(\vec{\theta})$

$$\mathcal{L}_{\rm tot} = \underbrace{\mathcal{L}_{\rm CC}}_{\text{Shot noise + SSC}} \times \underbrace{\mathcal{L}_{\rm WL}}_{\text{Data-driven cov.}}$$

Fiducial scaling relation?





No « input » mass-richness relation in DC2

- Can be calibrated by matching halos to redMaPPer clusters (ClEVaR)
- Membership matching => m_k, λ_k, z_k
- We use the unbinned likelihood

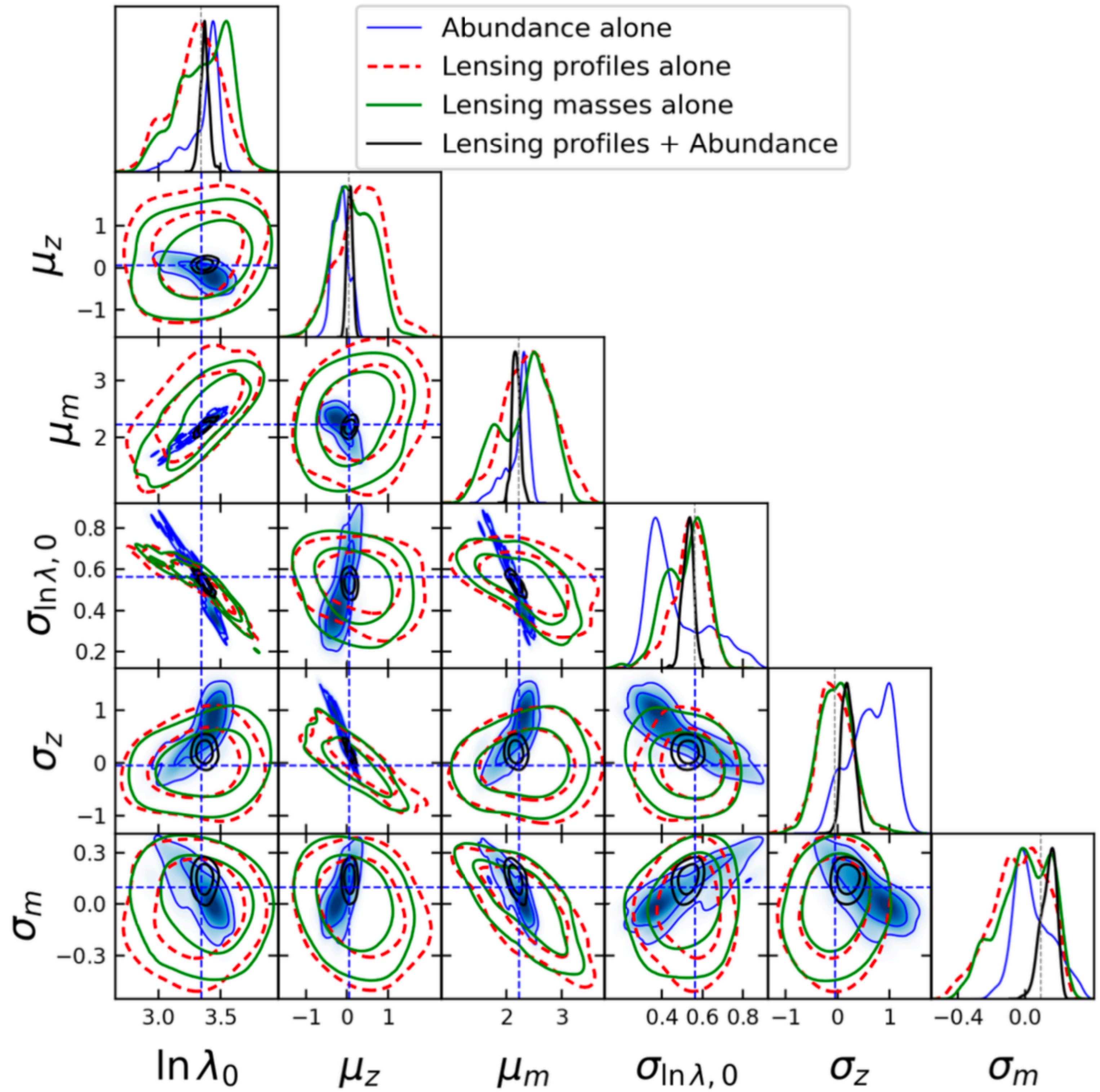
→ **Used to validate our results !**

$$\mathscr{L}_{\rm fid}({\rm MoR}\,|\,{\rm data}) = \prod_{k}^{N_{\rm match}} P(\ln \lambda_k\,|\,m_k, z_k)$$

Baseline analysis

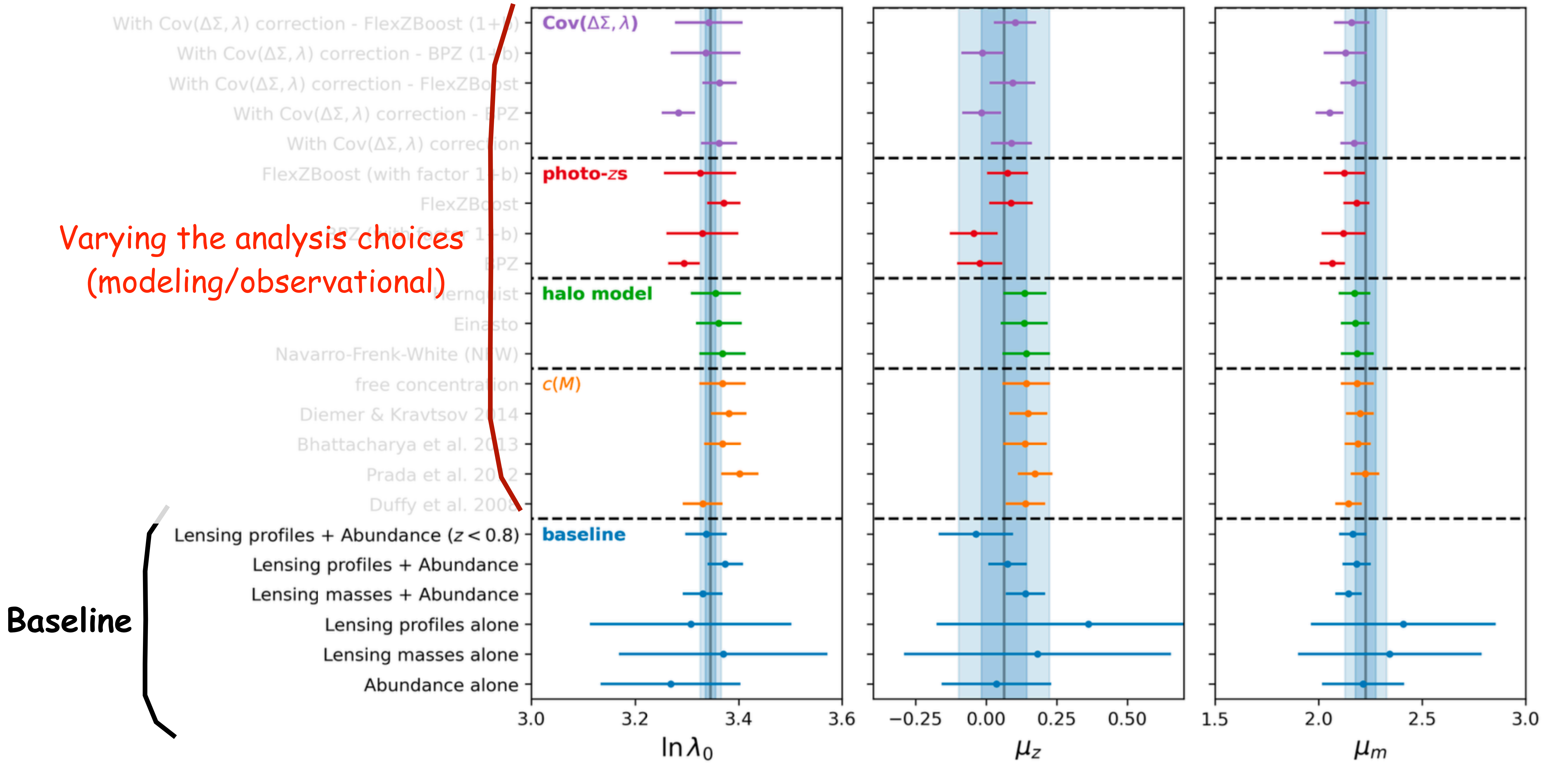
Separate Count and lensing
- Different correlations and error
- Compatible constraints at 1σ
- Compatible with « fiducial » relation (using the cluster-halo matched catalog)

Joint analysis
- Combination breaks degeneracy between params.
- Increase precision significantly
- Recovered fiducial at < 2σ
- First CC+WL constraints of redMaPPer MoR in DESC DC2 !



Robustness of MoR in LSST DESC DC2

Goal 2: Test its robustness to modeling choices and observational systematics



Robustness of MoR in LSST DESC DC2

$$\Delta\Sigma(R) \text{ depends on } \int_{-\infty}^{+\infty} dz\, \boxed{\rho_{3\mathrm{d}}(r)}$$

Modelling

Goal 2: Test its robustness to modeling choices and observational systematics

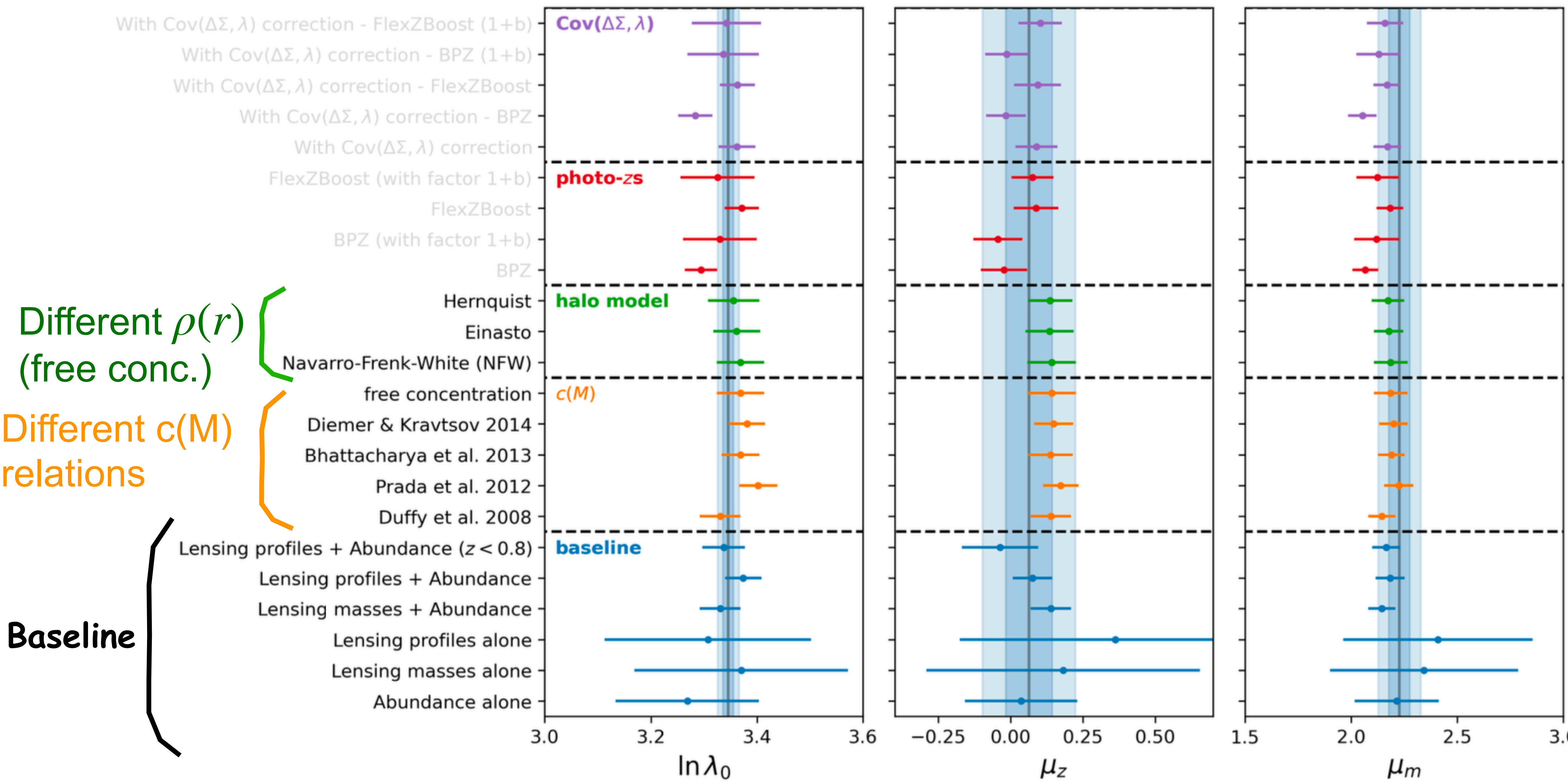
- WL impacted by several systematics (modeling choices, observational systematics)
- For stage-IV surveys: LSST-like precision of lensing data + large cluster samples, controlling these systematics uncertainties are a big concern

Modeling choices: Cluster mass density

- Different ρ_{3d} exist in the literature (NFW, Einasto, Hernquist)
- mass M and the concentration c
- M and c appear be correlated in simulations
- c can be set apriori via a $c(M, z)$ relation
- Instead of fitting it jointly with M !
- Again, some $c(M, z)$ exist in the literature

Robustness of MoR in LSST DESC DC2

Goal 2: Test its robustness to modeling choices and observational systematics



1. c(M): consistent with free c, low impact due to R > 1 Mpc
2. Density profile: perfect agreement

Conclusion: 1 < R < 3.5, one-halo regime, MoR stable !

On the modelling side

$\Delta\Sigma(R)$ depends on $\int_{-\infty}^{+\infty} dz\ \rho_{3d}(r)$

Modelling

On the data side

$$\widehat{\Delta\Sigma}(R, z_l) = \langle \Sigma_{crit}(z_{gal}, z_l)\ \epsilon_+^{obs} \rangle$$

1. Measured redshift

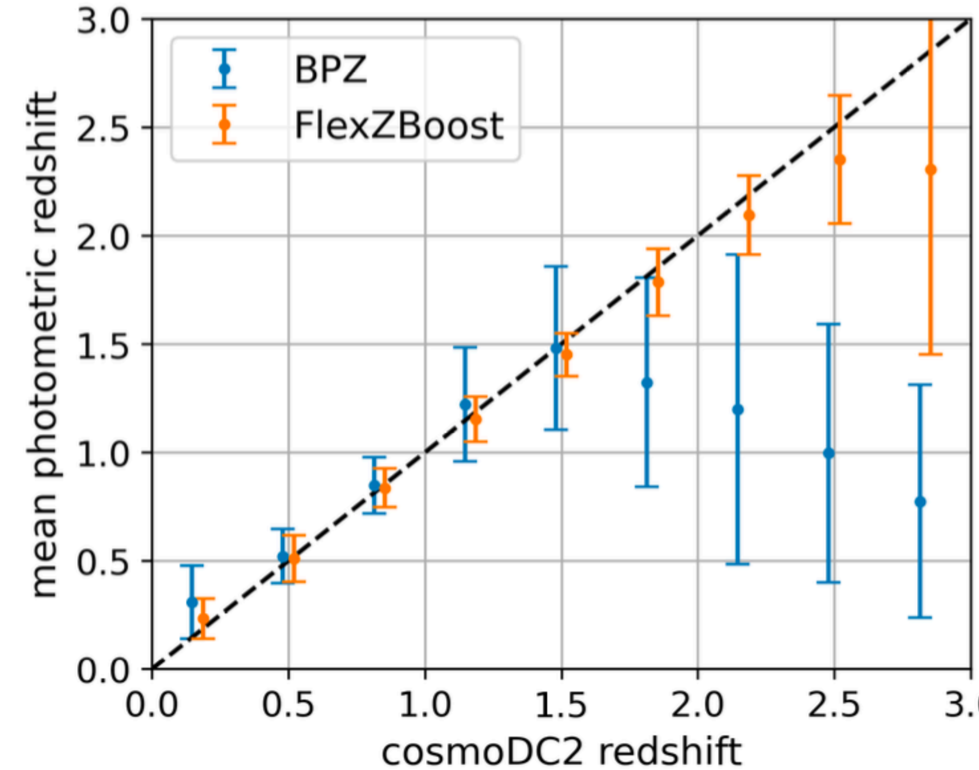
Measured shapes

2. Selection biases in cluster finder algorithms

Photometric redshifts of source galaxies

PZ runs in cosmoDC2

- FlexZBoost: ML-based, will work with deep spectro. datasets => $p(z\,|\,m)$
- BPZ: SED template + galaxy type
- We use the first released version
  - Flex:« optimistic » trained with i < 25 galaxies
  - BPZ: « discreteness » in the color-redshift space of cosmoDC2 galaxies => pessimistic
  - No quality cuts applied ! Worst case scenario
- How does it impact WL meas. ?

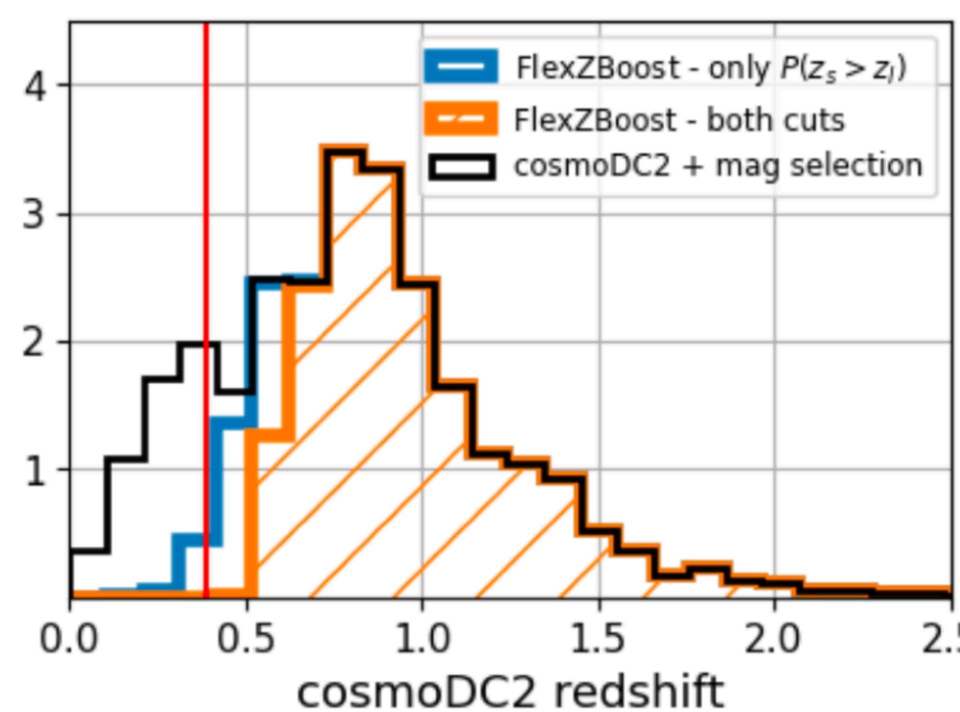


1. Source selection →

$$\langle z_{\rm gal}\rangle > z_{\rm cl} + \text{offset}$$
$$P(z_{\rm gal} > z_{\rm cl}) > \text{offset}'$$

2. WL lens-source weights

$$w_{ls}^{1/2} \propto \int_{z_l}^{+\infty} dz_s\ p(z_s)\Sigma_{\rm crit}(z_s, z_l)^{-1}$$
$$\Sigma_{\rm crit}(z_s, z_l)^{-1} \propto \frac{D_{ls}}{D_s D_l}$$



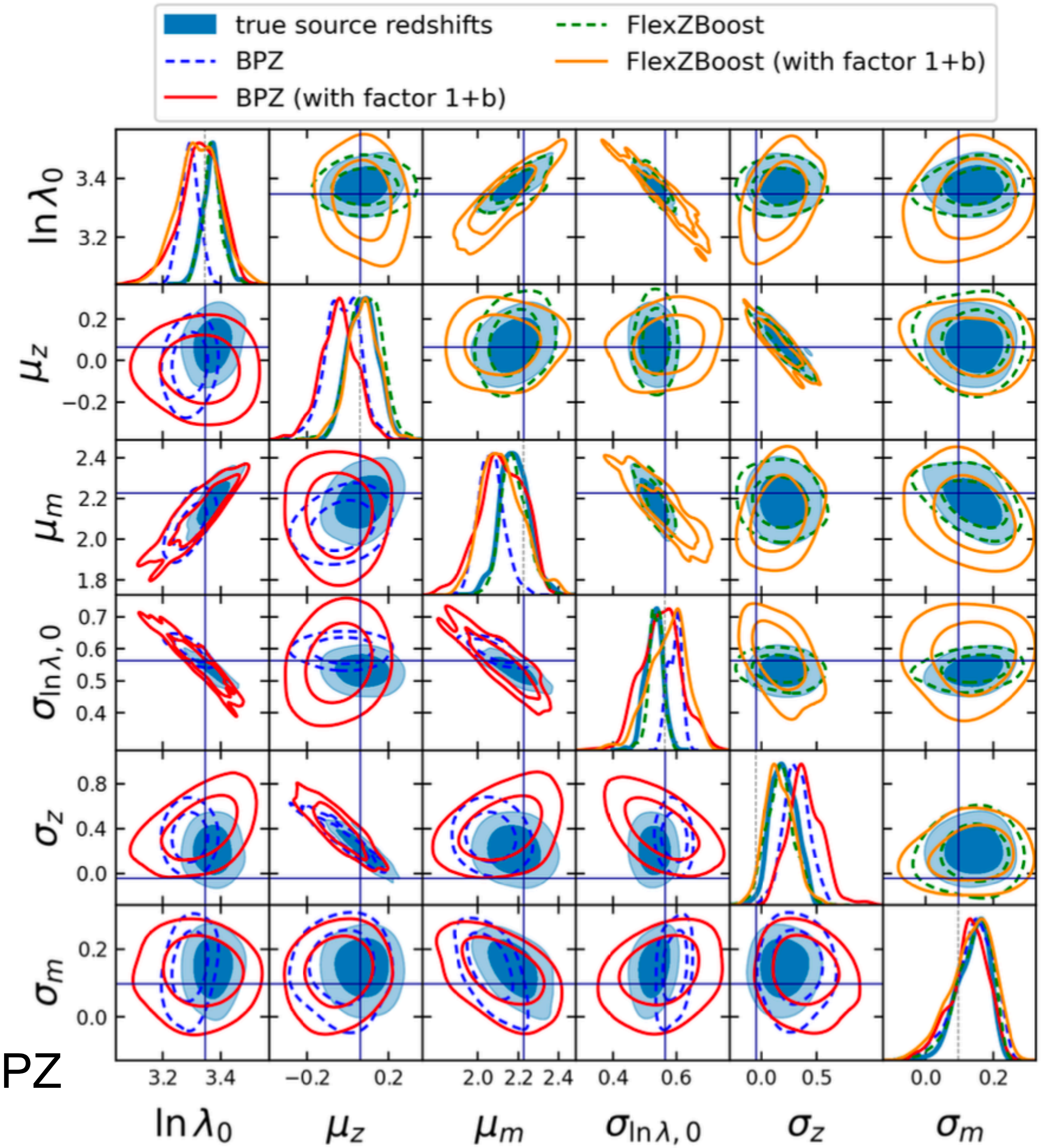
Results

- FlexZBoost: perfect agreement with true redshift case (baseline)
- BPZ: negative bias, 1σ in the normalization $\ln \lambda_0$+mass dependence
- We can correct the model for possible systematic PZ bias 1+b (Simet+16)
- And use CC+WL to calibrate this bias

$$\Delta\Sigma_{ij}^{\rm corr} = (1+\underbrace{b}_{\text{Uncorrected PZ systematics}})\Delta\Sigma_{ij}$$

$$b_{\rm flex} = 0.02 \pm 0.03 \quad b_{\rm bpz} = -0.02 \pm 0.03$$

- Increase the error bar for both cases
- b compatible with 0 in both cases
- Increase compatibility with baseline for BPZ



On the data side

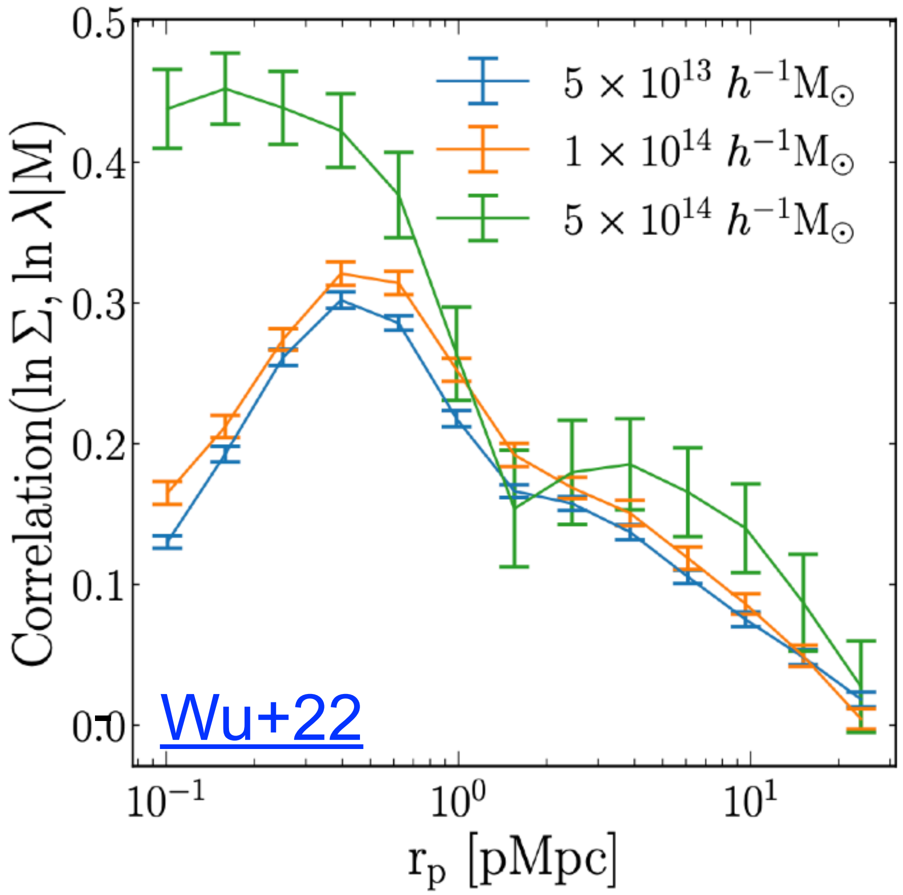
$$\widehat{\Delta\Sigma}(R, z_l) = \langle \Sigma_{\rm crit}(z_{\rm gal}, z_l)\ \epsilon_+^{\rm obs} \rangle$$

1. Measured redshift

Measured shapes

2. Selection biases in cluster finder algorithms

Shear-richness covariance in CL analyses



$$\Delta\Sigma_{ij}^{\rm corr} = \underbrace{\Delta\Sigma_{ij}}_{\text{« standard » prediction}} + \frac{\overbrace{[\beta_1]_{ij}}^{\text{HMF mass slope}}}{\underbrace{\mu_m}_{\text{MoR mass slope}}}\underbrace{\langle {\rm Cov}(\Delta\Sigma, \ln\lambda\,|\,m, z)\rangle_{ij}}_{\text{Shear-richness covariance}}$$

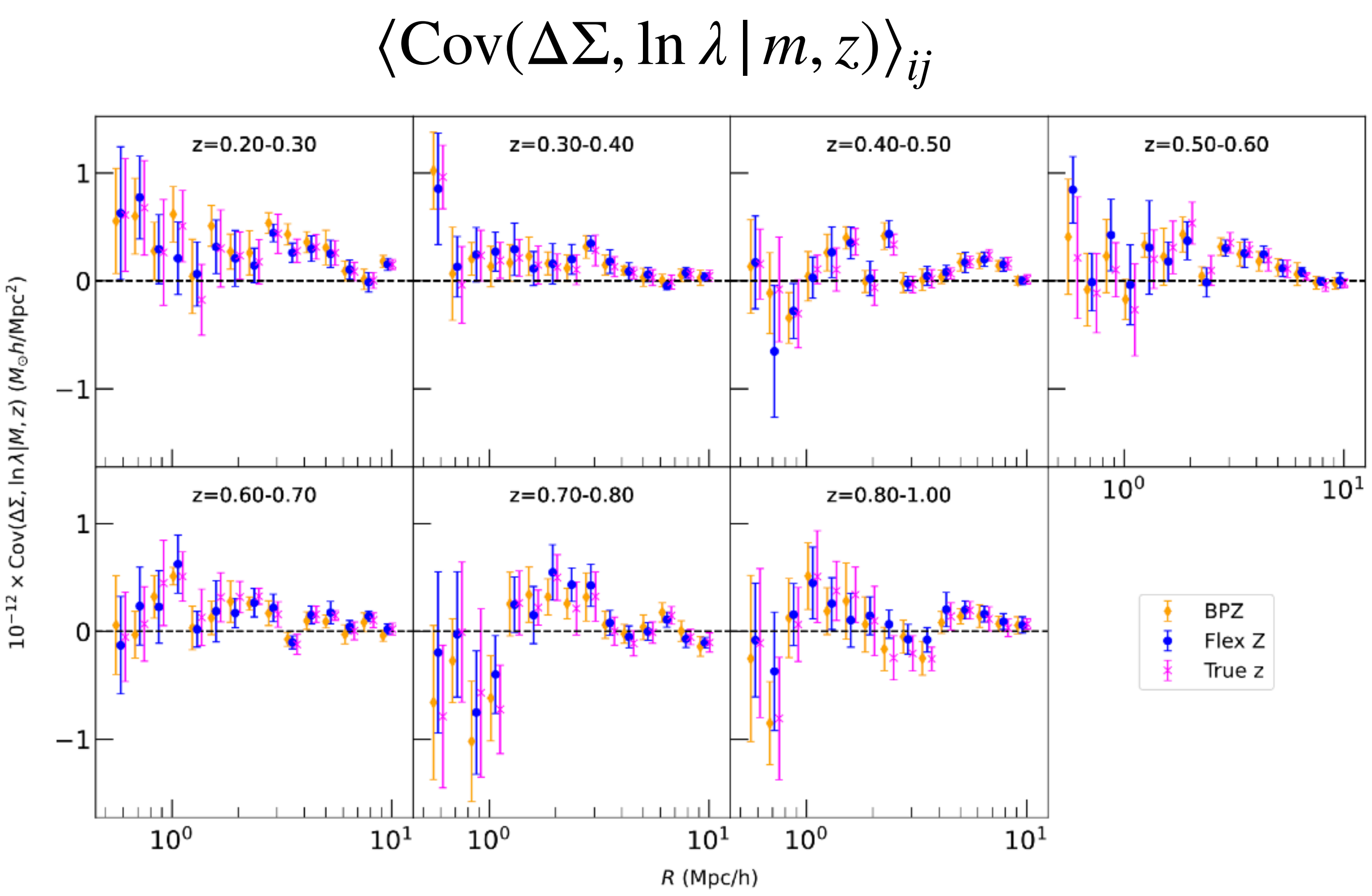
Shear-richness covariance

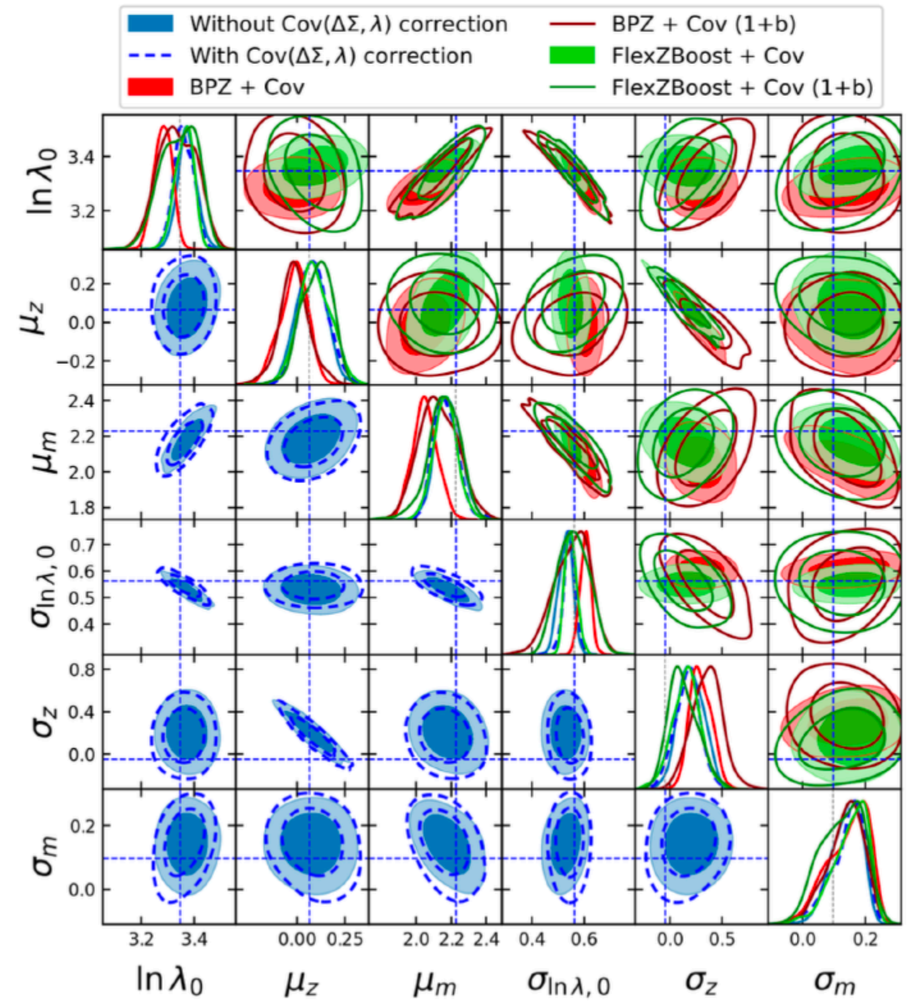
- Corr($\Delta\Sigma, \ln\lambda$) arises from halo formation+baryonic physics Zhang+24: property covariance < 0
- +from optically-detected clusters > 0 (e.g. projection effects, Wu+22)
- Plays an increasing role with LSST (see e.g. DES CL Y1)

Implementation in CL pipeline

- Need to add $P(\Delta\Sigma, \ln\lambda\,|\,M)$ relation (see appendix D)
- $\Delta\Sigma$ correcting factor depending on the mass slope of MoR+ « binned » HMF log-slope β_1

Shear-richness covariance in cosmoDC2





In DC2 data

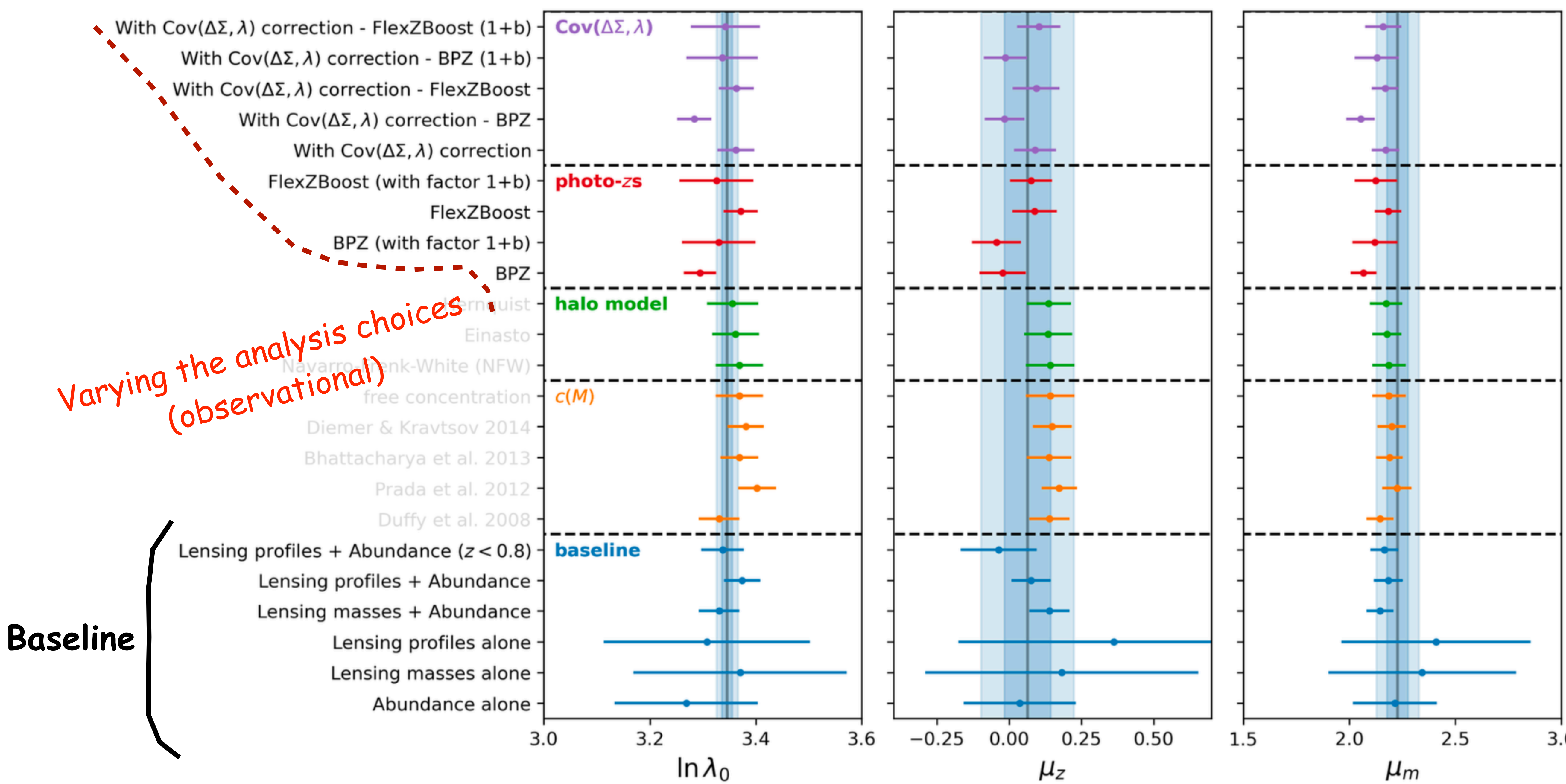
- Using the matched cluster-halo catalog and individual profiles
- Measure the total (intrinsic+extrinsic) cov
- Low amplitude: 0.1-0.01 × standard profile
- Expected: HOD model for cosmoDC2 halos, idealistic run for redMaPPer (true magnitudes)

Impact on MoR

- Small impact < 1\sigma, as expected
- Assess PZ+shear-richness covariance by using PZ data vectors, and (1+b) factor

Robustness of MoR in LSST DESC DC2

Goal 2: Test its robustness to modeling choices and observational systematics



Summary

Context

- Clusters are important cosmological probes of the Universe formation history
- Well-calibrated MoR are crucial for cluster-based analyses
- WL probes the mass distribution around clusters, asset to constrain MoR

This work

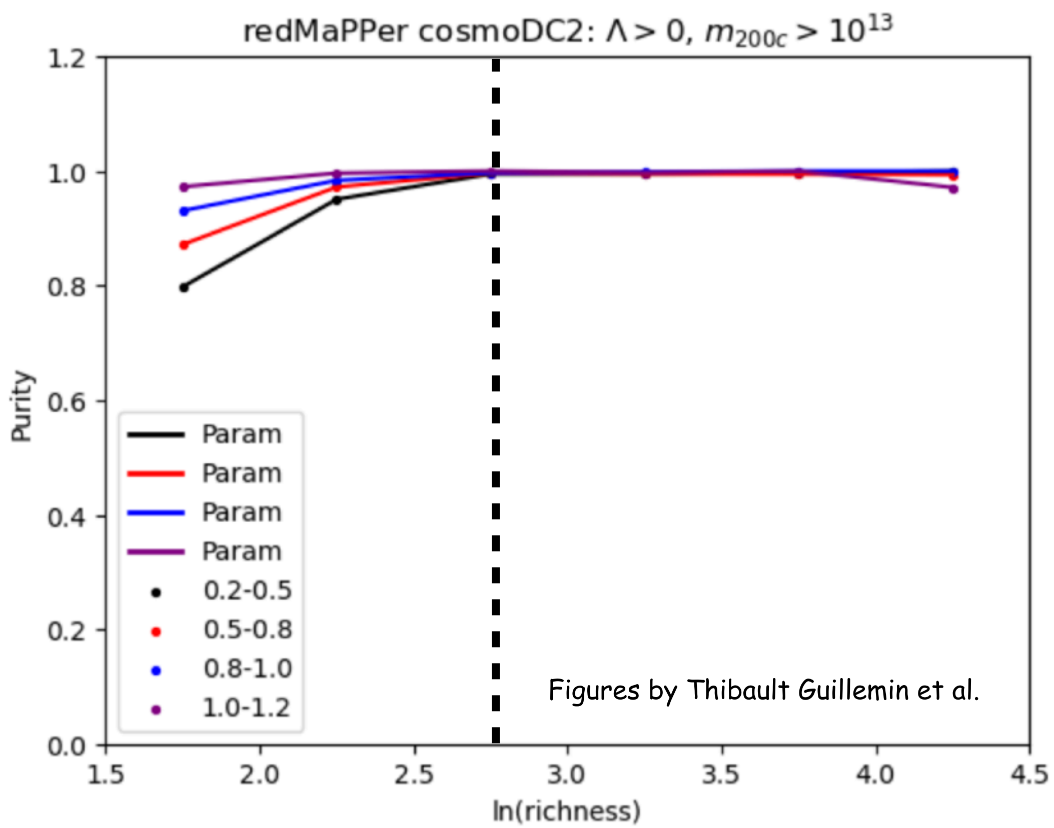
- Build « Early » DESC CL pipeline with DESC tools (CLMM, CCL, CIEVAR)
- Analysis of the redMaPPer MoR
    - CC+WL MoR, improve the precision when combining probes
    - Account for redMaPPer selection function
    - Robustness tests (non exhaustive list) wrt to modeling choices
    - Wrt to observational systematics: PZ, shear-richness covariance
    - Compatible with the baseline choices and fiducial constraints
- Contribues to the analysis/validation of the cosmoDC2 dataset for CL studies

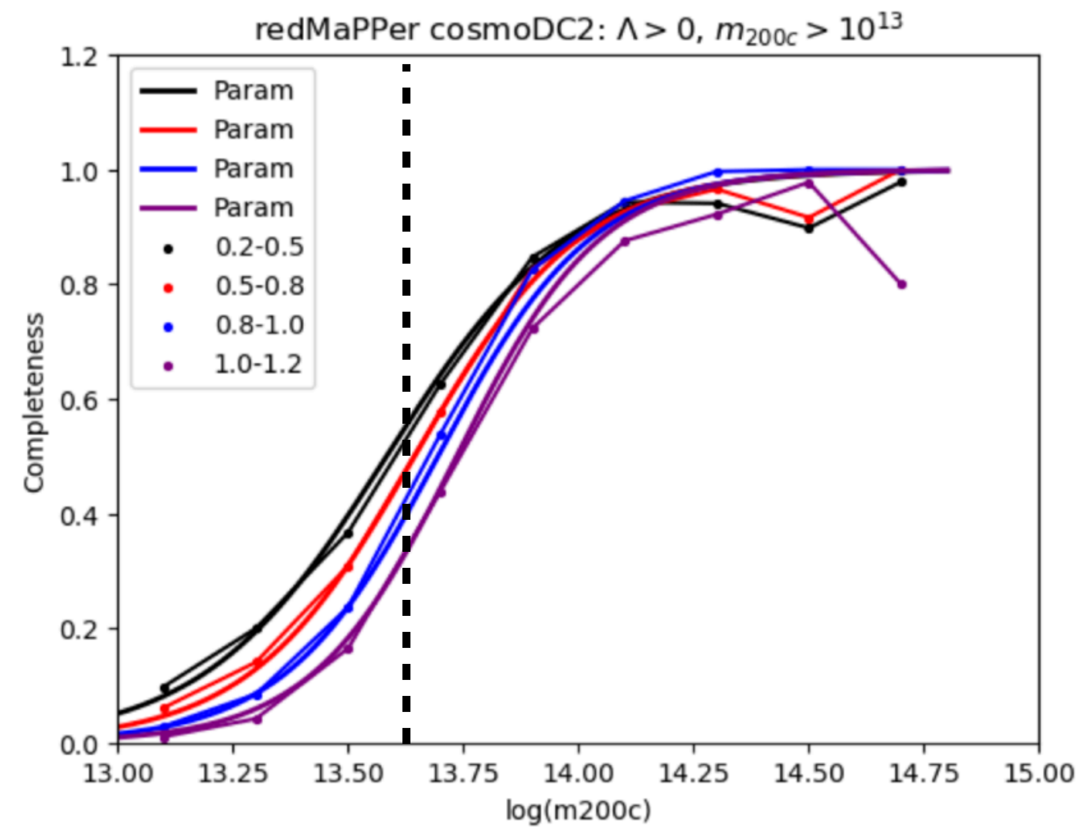
Plan for analyzing the LSST

- Hope it paves the way for the LSST CL DESC pipeline ! Active discussions in prep. of ComCam data
- **Precision** $\times\sqrt{\Omega_{\rm LSST}/\Omega_{\rm DC2}} = 6.4$ **with « idealistic » LSST** (e.g. true mag./ shapes), work is needed to estimate the budget of shape measurement error.


Thank you!

redMaPPer selection function





Principle

- Geometrical match between RM clusters to DC2 halos (ClEvaR)
- Membership matching
- Selection function

$$\Phi(m, \lambda, z) = \frac{c(m, z)}{p(\lambda, z)}$$

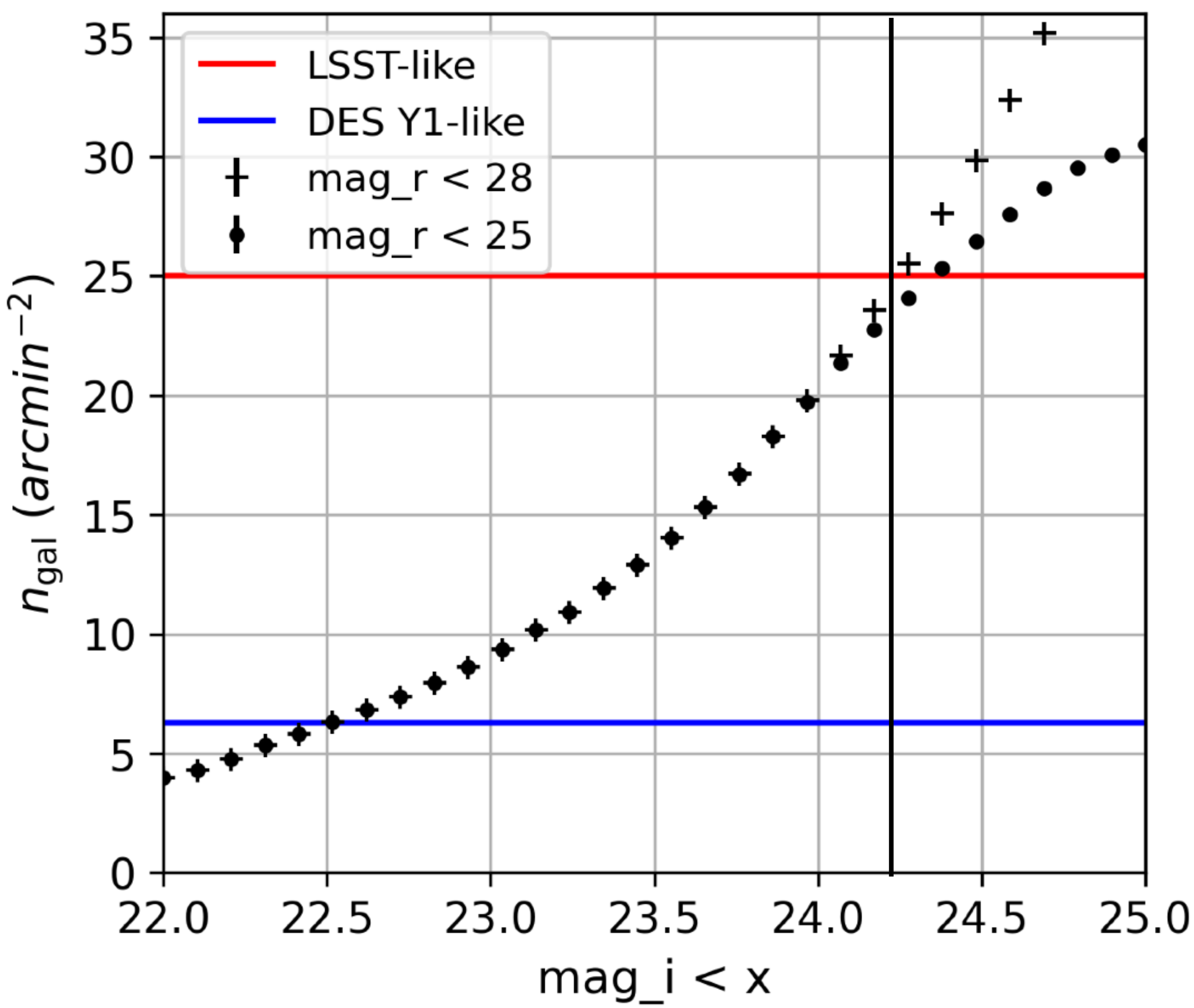
Completeness

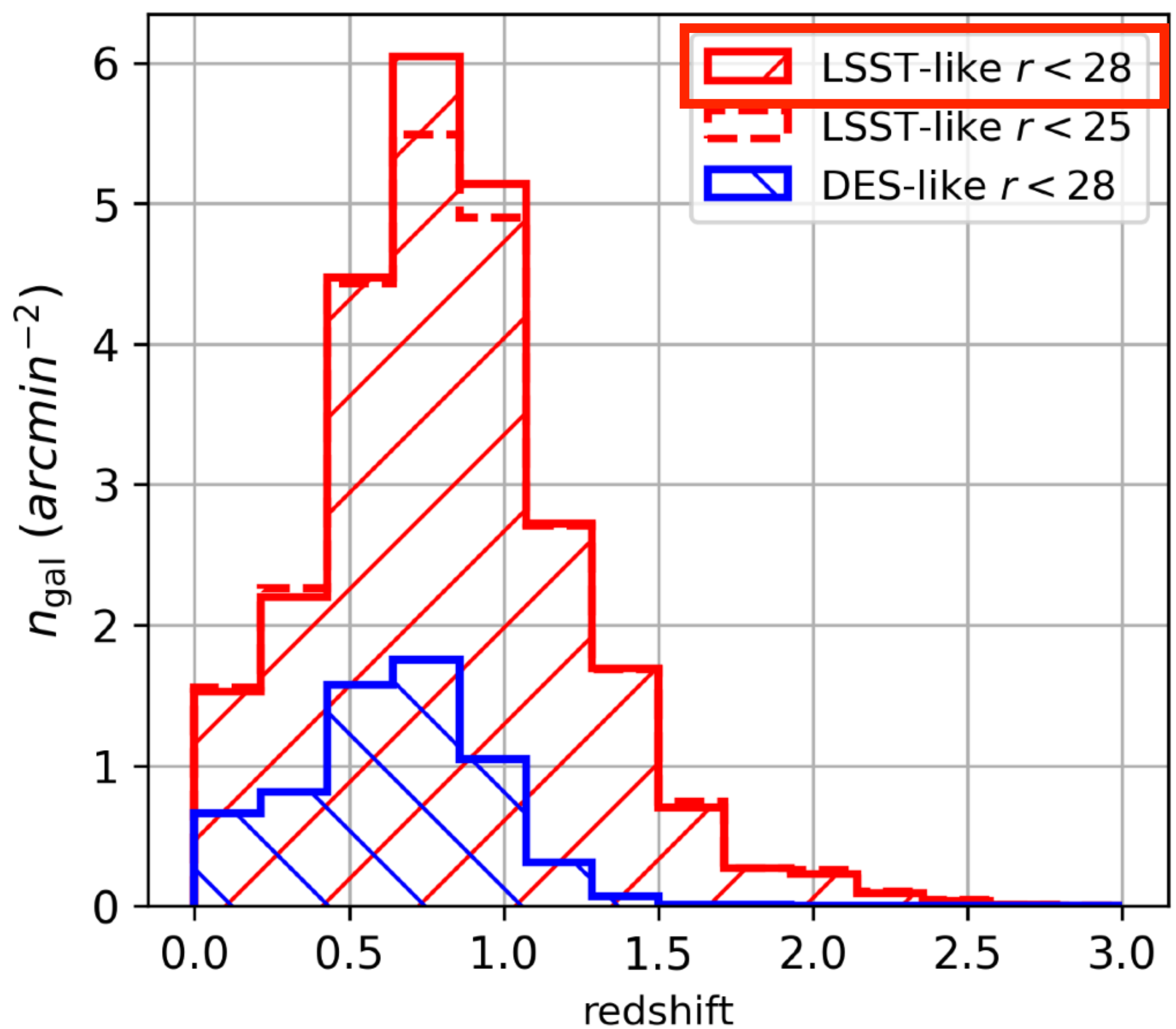
Purity

Results

- RM cat. is pure for $\lambda \geq 20$ is pure
- RM cat. is > 80% complete for $M \geq 10^{14} M_\odot$
- We fit « smooth » functions to be used in the CL+WL prediction modules

Source selection

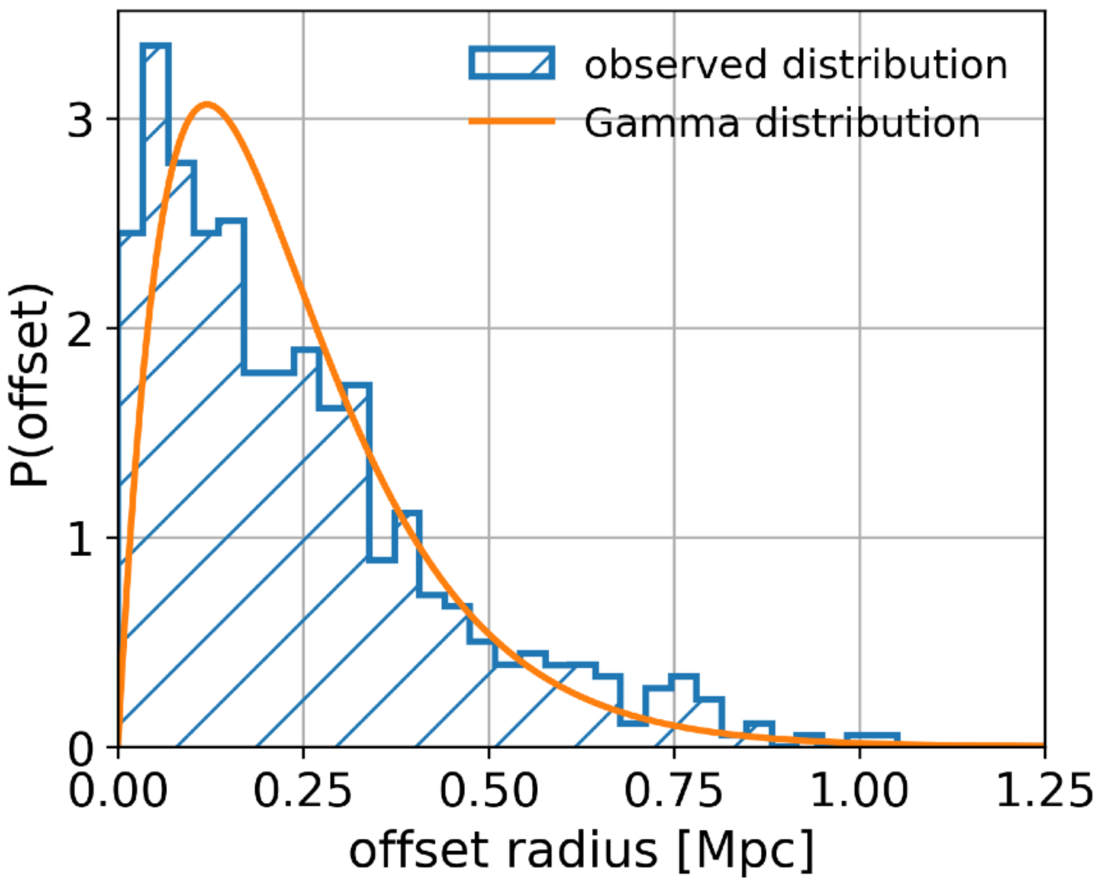


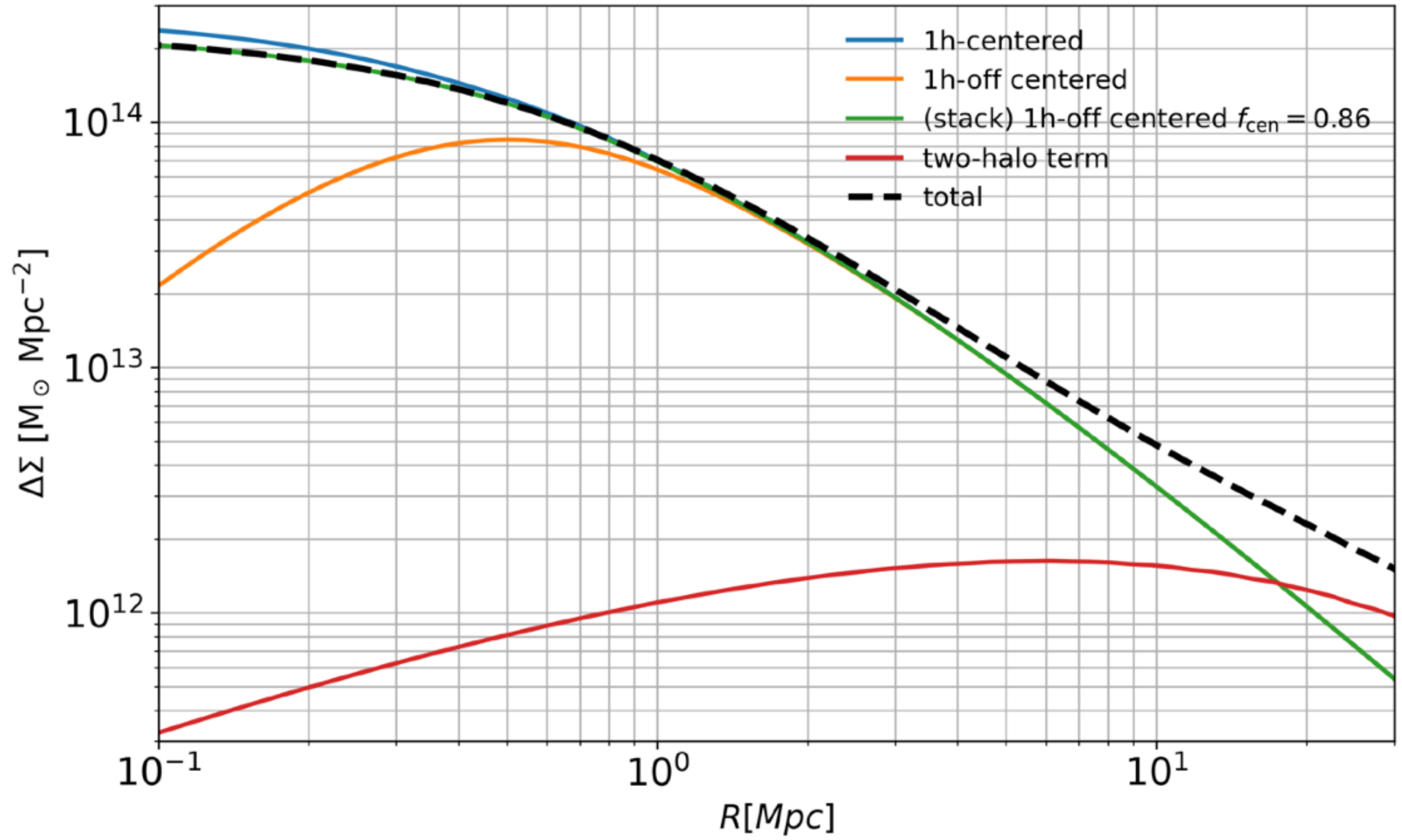


Choices:

- $r < 28$ + adapt i-band cut to match desired source density
- **LSST-like 25 gal.armin-2:** $i < 24.25$
- DES-like 6 gal.armin-2: $i < 22.5$

Modeling - Miscentering





Offset distribution

- Matching redMaPPer clusters-cosmoDC2 halos
- Considering the cosmoDC2 center to be the true one (f_mis=0.15)
- Offset distribution = Gamma distrib.
- Injected into modeling of $\Delta\Sigma$
- < 1% bias at R > 1 Mpc wrt. perfect centered profile

$$\Sigma_{\rm mis}(R, R_{\rm mis}) = \frac{1}{2\pi}\int_0^{2\pi} d\theta\ \Sigma\left(\sqrt{R^2 + R_{\rm mis}^2 + 2RR_{\rm mis}\cos\theta}\right)$$

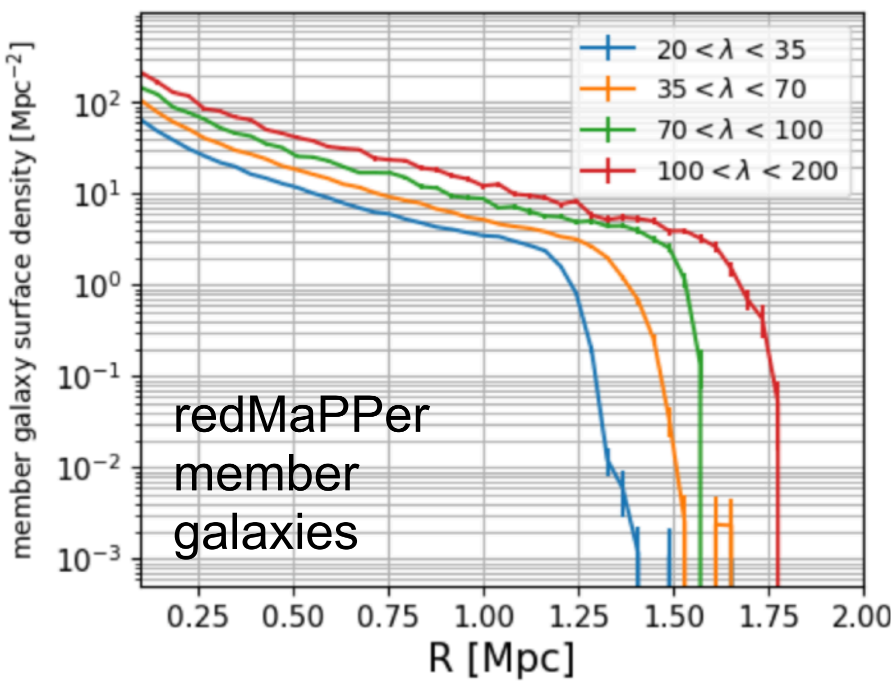
$$\downarrow$$

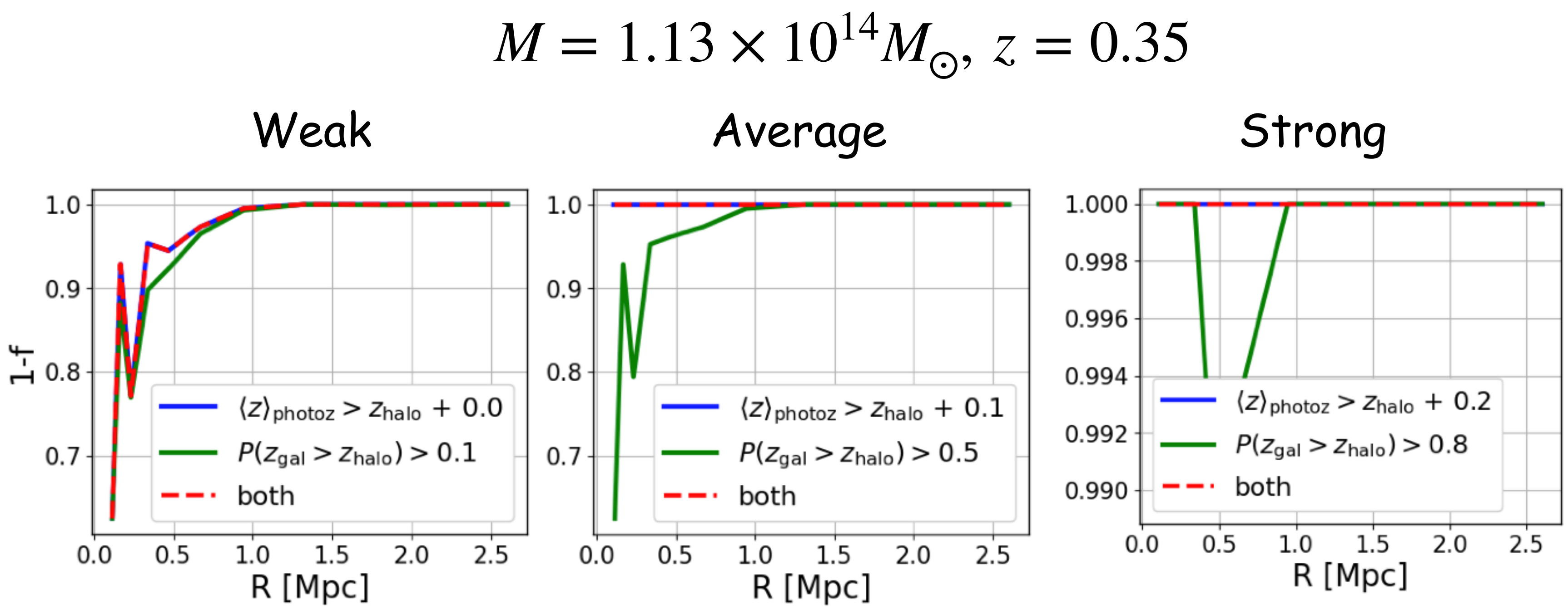
$$\Sigma_{\rm mis}^{\rm stack}(R) = \frac{1}{2\pi}\int_0^{2\pi} dR_{\rm mis}\ \boxed{P(R_{\rm mis})}\ \Sigma_{\rm mis}(R, R_{\rm mis})$$

$$\downarrow$$

$$\Delta\Sigma_{\rm 1h}(R) = f_{\rm mis}\Delta\Sigma_{\rm 1h,mis}(R) + (1 - f_{\rm mis})\Delta\Sigma_{\rm 1h,cen}(R)\,.$$

Modeling - Boost factor





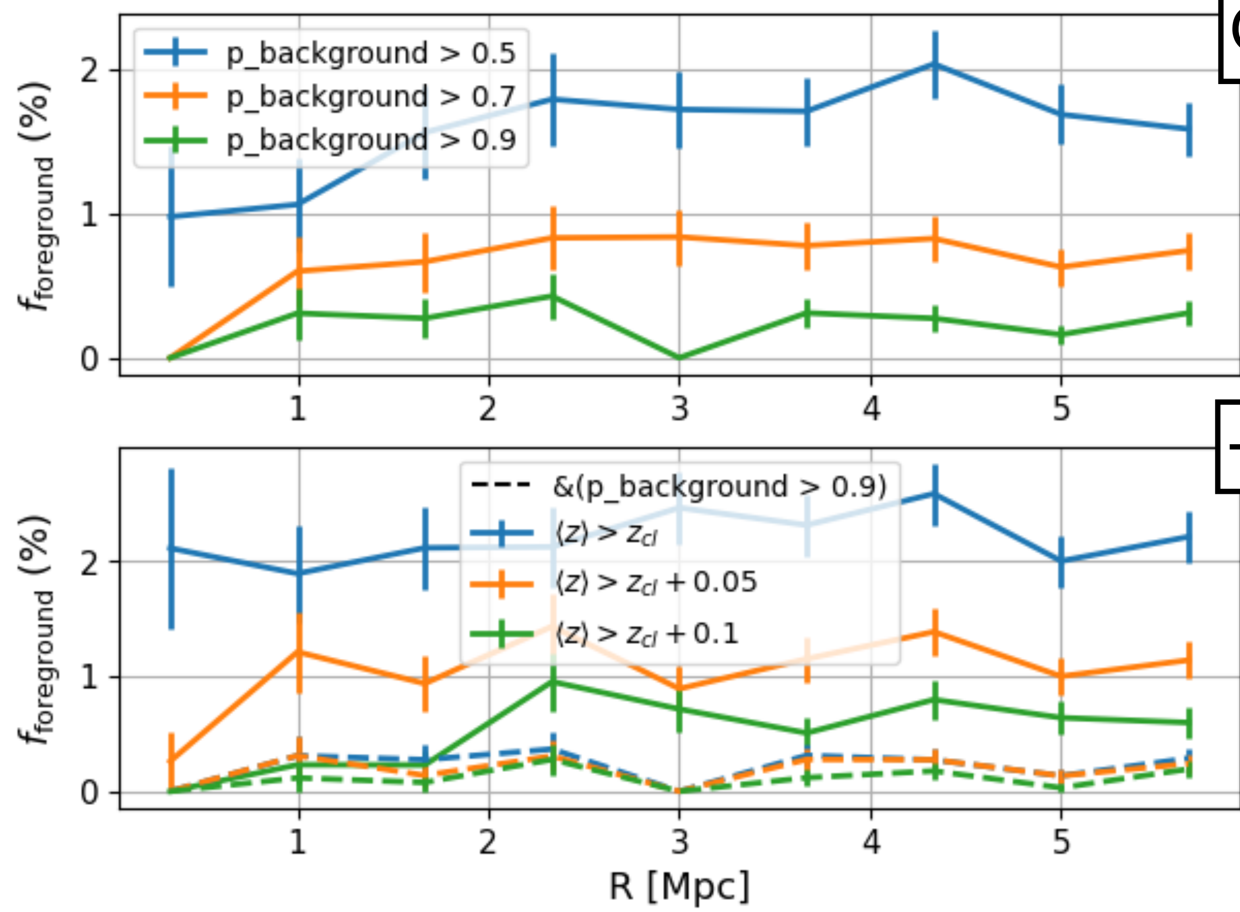
Contamination by member galaxies

- Member galaxies can be misidentified as source galaxies
- Dilute the signal $\Delta\Sigma_{ij}^{\rm cont}(R) = [1 - f_{\rm cl}(R)]\Delta\Sigma_{ij}(R)$
- $f_{\rm cl}(R)$ = fraction of member galaxies in the source sample

With cosmoDC2 halos

- (We use cosmoDC2 halos instead of redMaPPer clusters)
- (i) Apply PZ source selection
- (ii) We know the « member galaxies » in halos (DC2 flag 'halo_id')
- (iii) Compute the fraction of members in the source sample wrt to radius
- Our cuts are sufficient to remove members

Impact of foreground galaxies



Only $P(z_s > z_l)$ cut

$z = 0.35$

+ mean redshift cut

Contamination by foreground galaxies

- As for member galaxies, foreground galaxies (not associated to halos) can be misidentified as source galaxies
- Dilute the signal 1-$f_{\rm foreground}$, rather stable across radius, contrary to member galaxies which depends on R.

With cosmoDC2 halos

- (i) Apply PZ source selection
- (ii) We know the « foreground galaxies » in halos (z_gal < z_halo)
- (iii) Compute the fraction of foregrounds in the source sample wrt to radius
- Our cuts: $f_{\rm foreground} < 0.5\ \%$

Experimental landscape

Analysis < June 2024 Payerne+24

Survey	Analysis	Ω_S (deg^2)	$z_{\min}$ - $z_{\max}$	$N_{\rm tot}$
ROSAT	WtG, Mantz et al. (2015)	400	0–0.5	224
XMM	XXV, Pacaud et al. (2018)	50	0.05–1	178
	XLVI, Garrel et al. (2022)	47.36	0.05–1	178
eROSITA	eFEDS, Chiu et al. (2023)	140	0.1–1.2	455
	eRASS1, Ghirardini et al. (2024)	12 791	0.1–0.8	5259
ACT	S11, Sehgal et al. (2011)	455	0.16–1	9
	H13, Hasselfield et al. (2013)	504	0.15–0.8	15
Planck	XX, Ade et al. (2014)	26 000	0–1	189
	XXIV, Ade et al. (2016)	26 000	0–1	439
	S18, Salvati, Douspis & Aghanim (2018)	26 000	0–1	439
	Z19, Zubeldia & Challinor (2019)	26 000	0–1	439
	×SPT, Salvati et al. (2022)	(26 000)×(2500)	0–1	782
	×*Chandra*, Aymerich et al. (2024)	26 000	0–1	439
	×ACT, Lee, Battye & Bolliet (2024)	(26 000)×(987.5)	0–1.4	439
SPT	B15, Bocquet et al. (2015)	720	$z > 0.3$	100
	H16, de Haan et al. (2016)	2500	0.25–1.7	377
	B19, Bocquet et al. (2019)	2500	0.25–1.75	343
	C22, Chaubal et al. (2022)	2500	0.25–1.75	343
	B24, Bocquet et al. (2024)	5200	0.25–1.75	1005
SDSS	R10, Rozo et al. (2010)	7398	0.1–0.3	10 810
	M13, Mana et al. (2013)	7500	0.1–0.3	13 823
	C19, Costanzi et al. (2019)	11 000	0.1–0.3	7000
	A20, Abdullah, Klypin & Wilson (2020)	11 000	0.045–0.125	756
	P23, Park et al. (2023)	11 000	0.1–0.33	8379
	S23, Sunayama et al. (2023)	11 000	0.1–0.33	8379
	F23, Fumagalli et al. (2023)	11 000	0.1–0.3	6964
DES	Y1, Abbott et al. (2020)	1800	0.2–0.65	7000
	T21, To et al. (2021)	1321	0.2–0.6	4794
	×SPT, Costanzi et al. (2021)	(1800)×(2500)	$z > 0.2$	7000
KiDS	DR3, Lesci et al. (2022)	377	0.1–0.6	3652

X-rays: ~100 to 5,000* cl.
*thanks eROSITA !

SZ: 100 to 1000 cl.

Optical: 1000 to 10,000 cl.