DESC CWP 01/2025

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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*if anyone has been missed, please claim authorship in PubDB

Cosmology with cluster counts

The abundance of galaxy clusters

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

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

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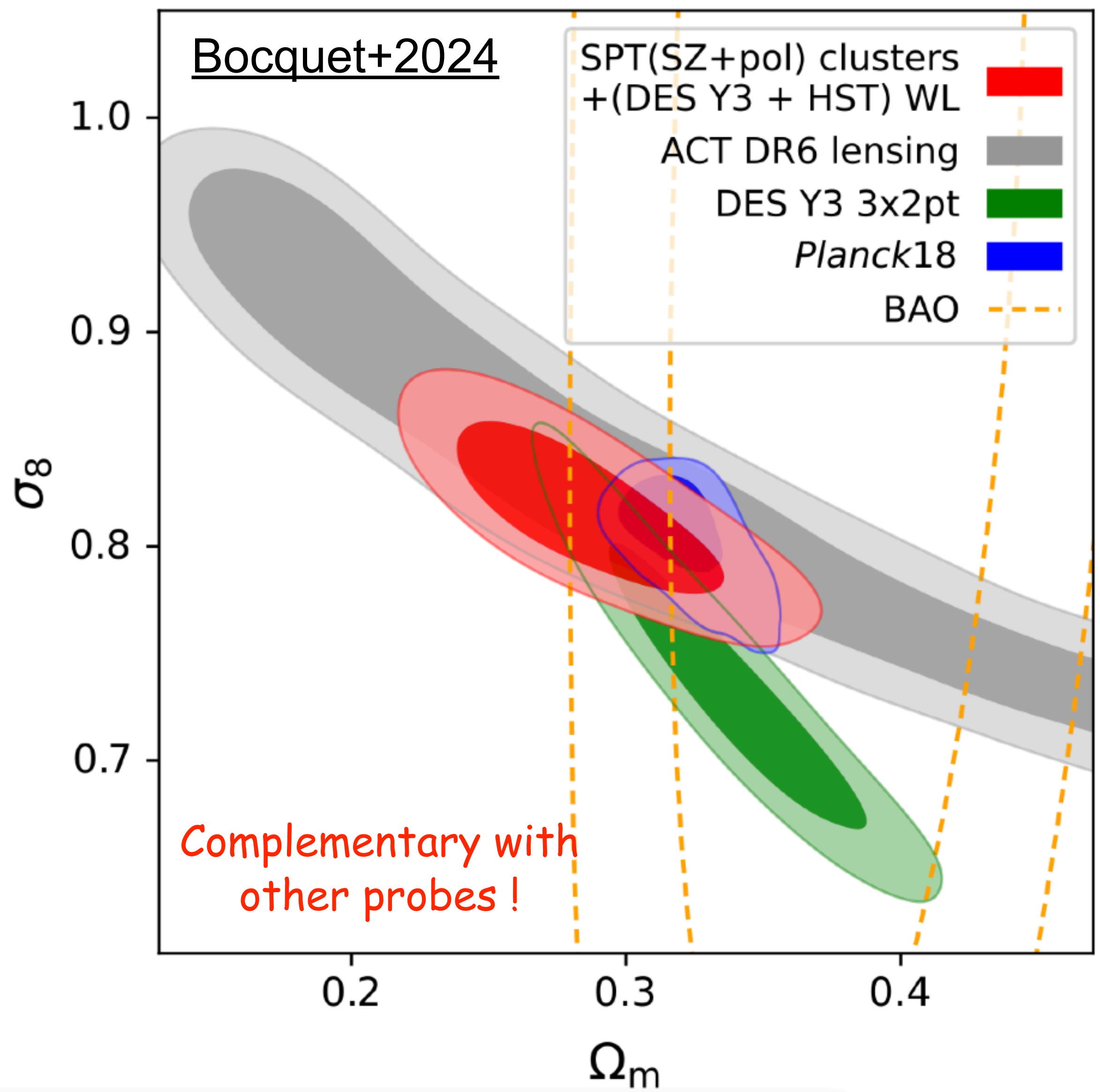
- Privileged probes for structure formation and geometry in ΛCDM (i.e. Ω_m, S_8) + beyond
- Current constraining power: determined by uncertainties on the scaling relation
- Stage IV catalogs (LSST, Euclid, SO) $\sim$ 100,000 clusters (x10 current datasets)
- Requires robust modeling of observables,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



Weak lensing by galaxy clusters

Weak lensing by galaxy clusters

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

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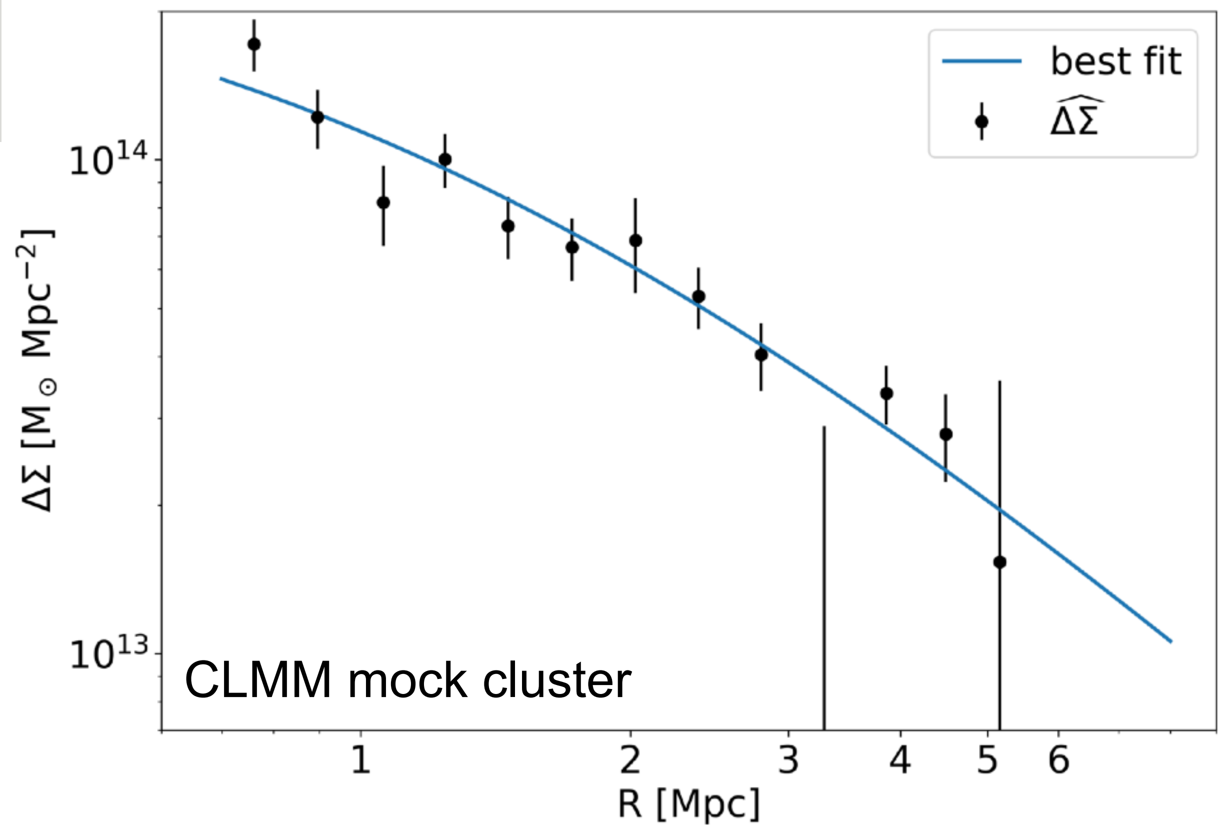

In practice: excess surface density estimator

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

Critical surface mass density

« tangential »

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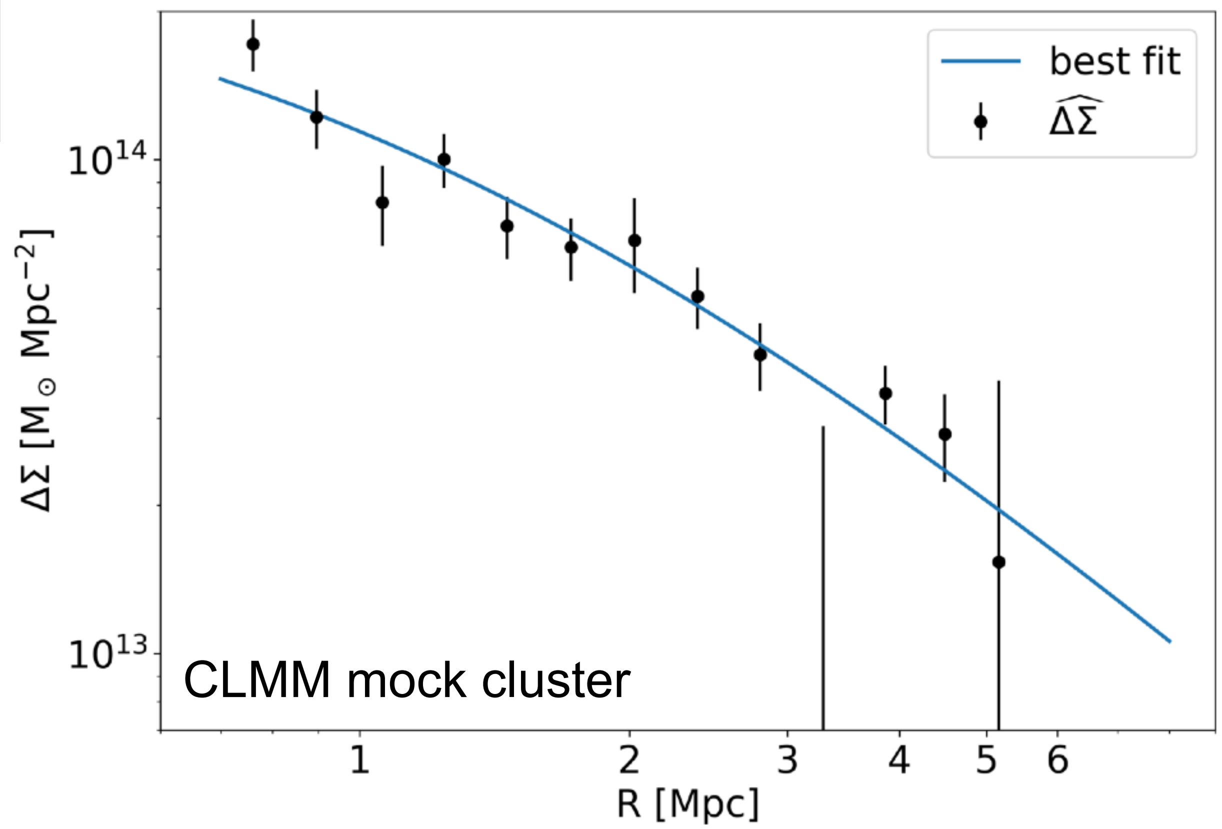

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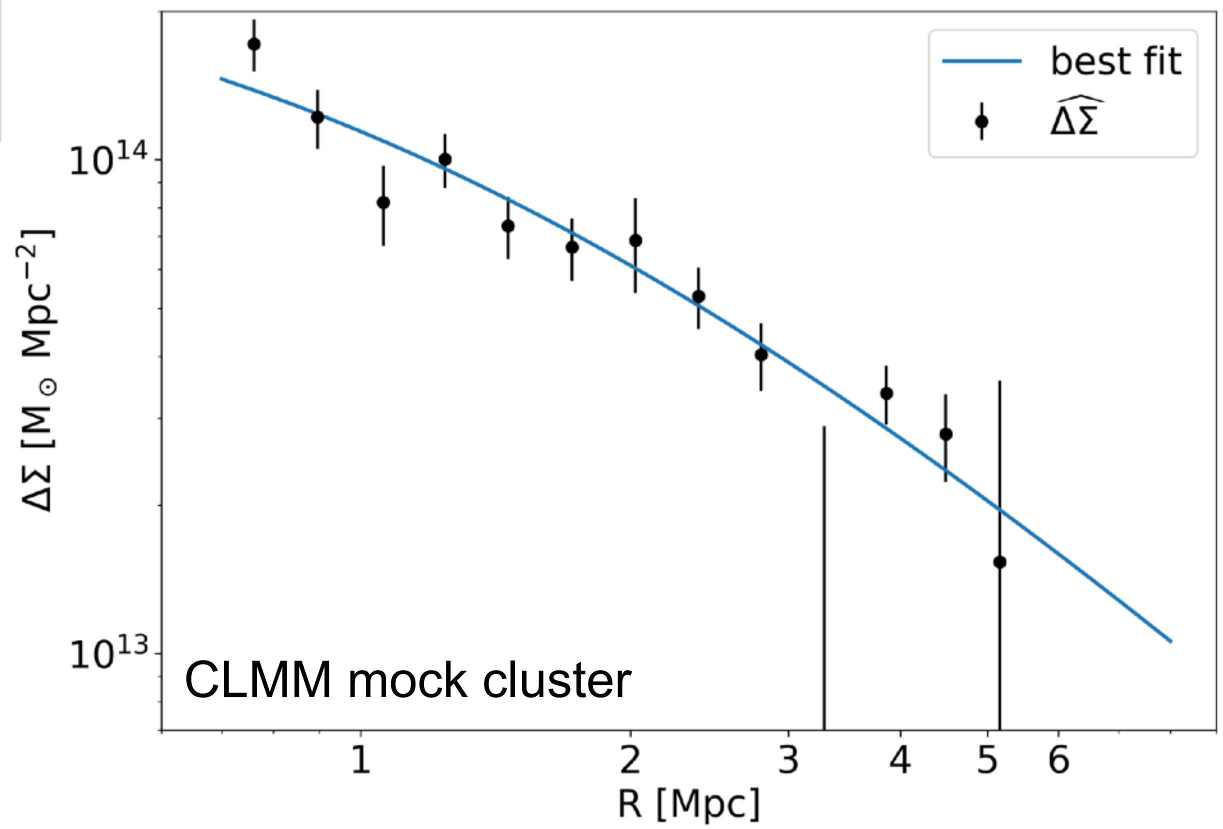
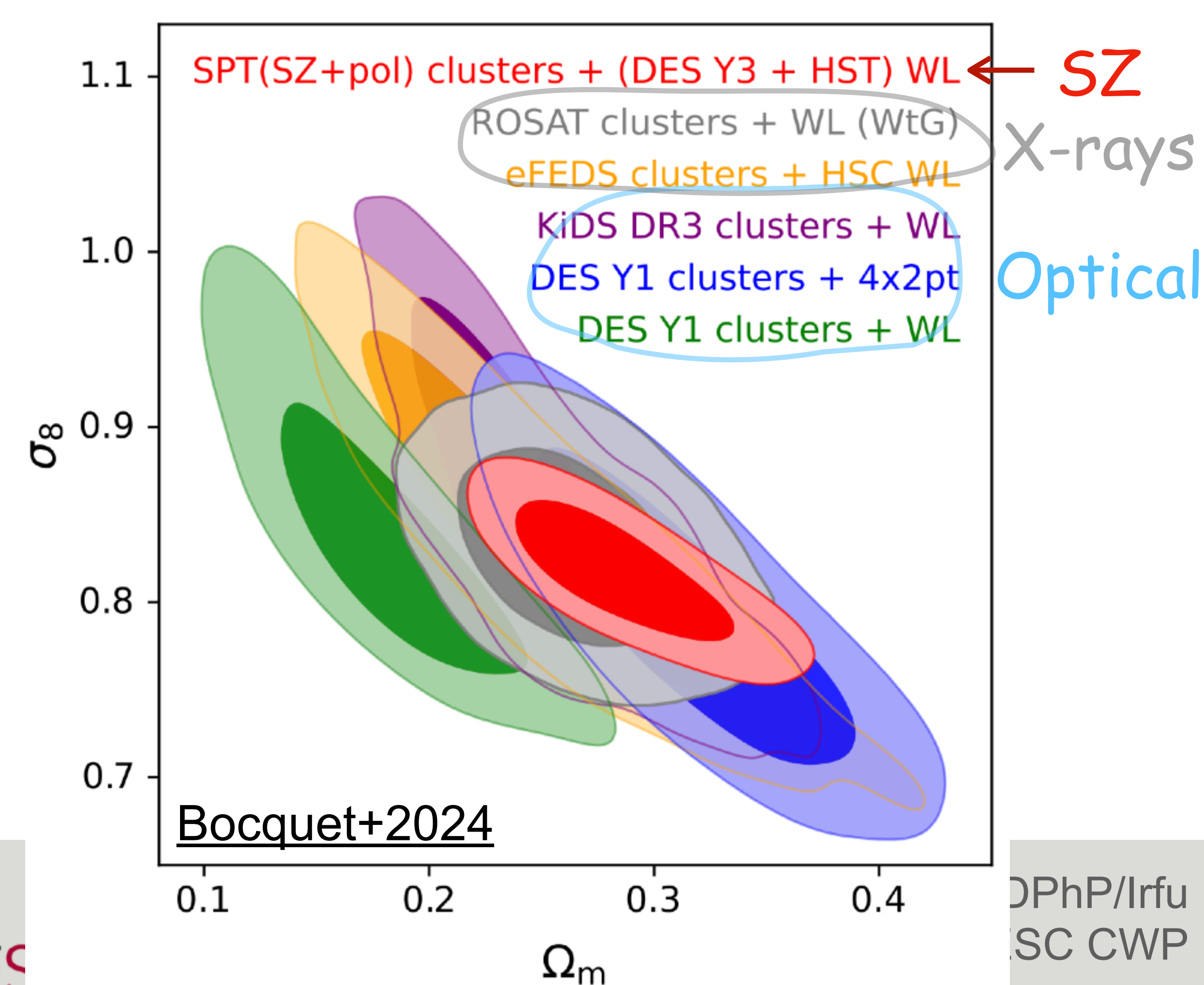
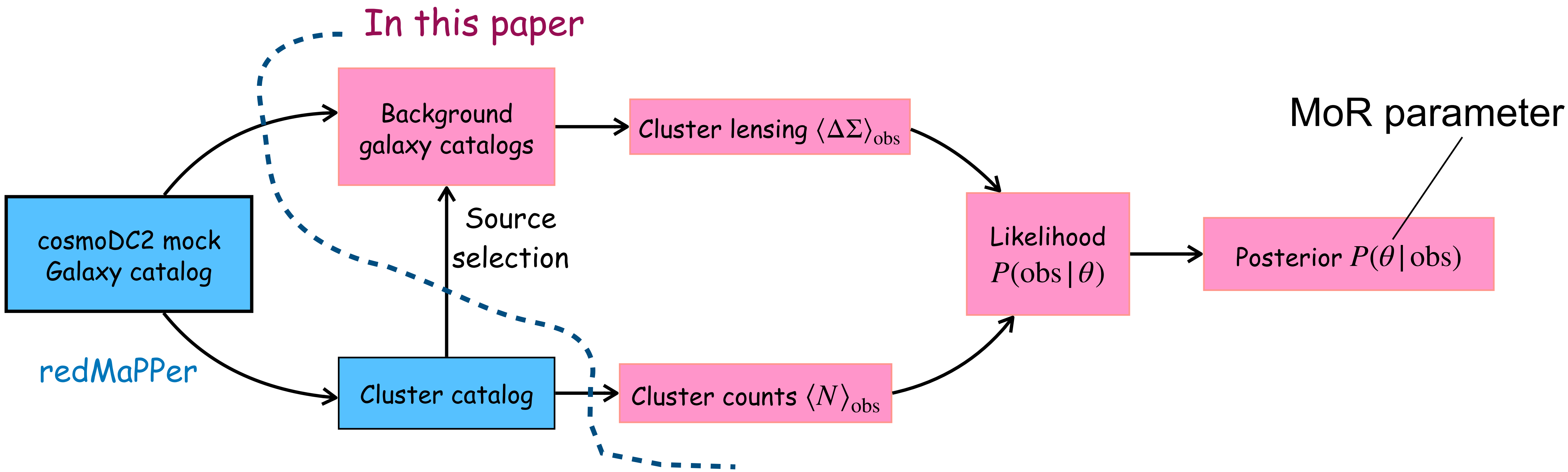
$\boxed{\text{Fit } \Delta\Sigma(R) \rightarrow M_{\rm cluster}}$ Mass-proxy relation !





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)

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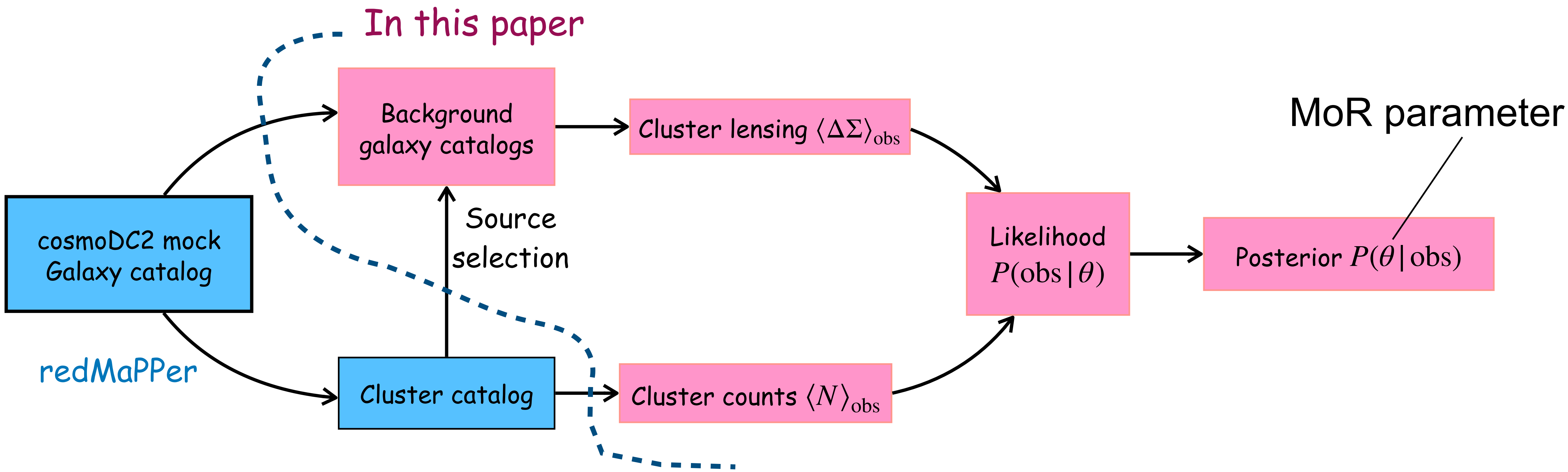

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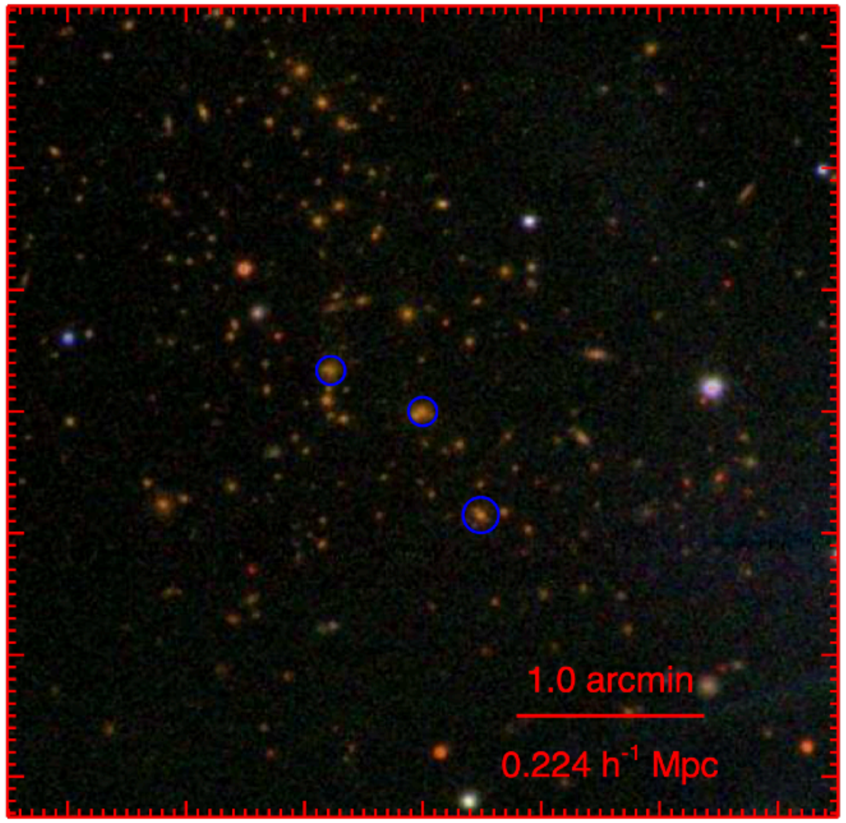
Study the MoR relation in DESC DC2 data
- DC2: Large simulation over 440 deg2
- cosmoDC2*:* extra-galactic (truth) catalog+*PZ add-ons*
- Cluster catalog: redMaPPer (Rykoff+13)
- CLCosmo_Sim_database: data vectors (only DESC members)

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, $\lambda < 300$, $z < 1.15$
- Other cluster catalogs on DC2 (AMICO, YOLO-CL, WAZP)

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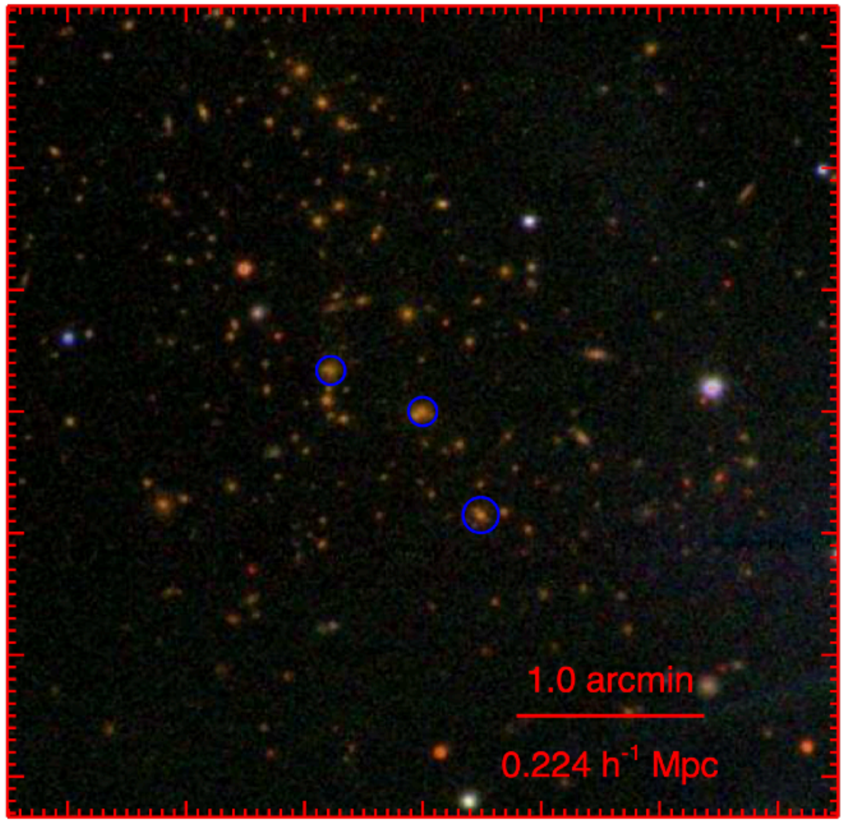

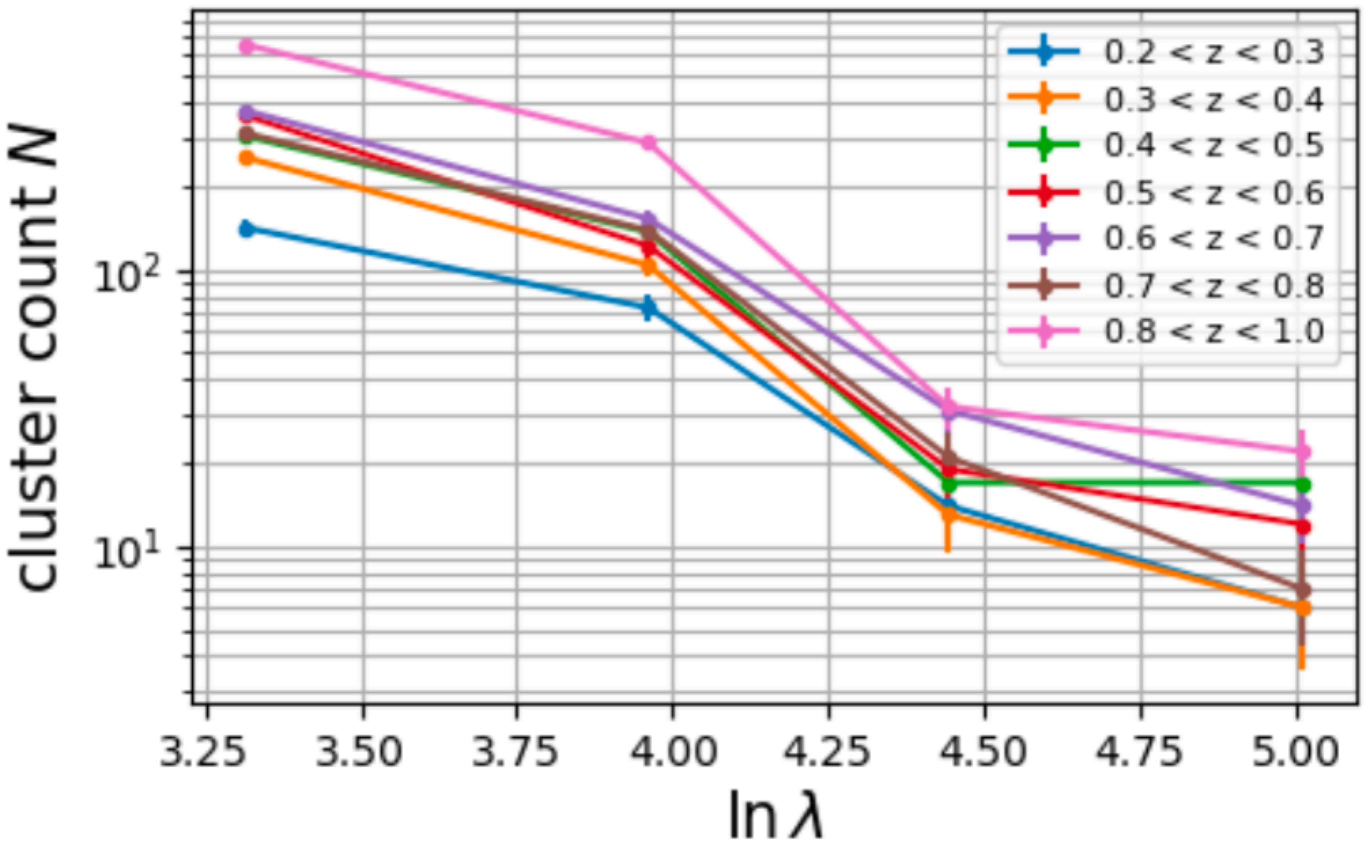

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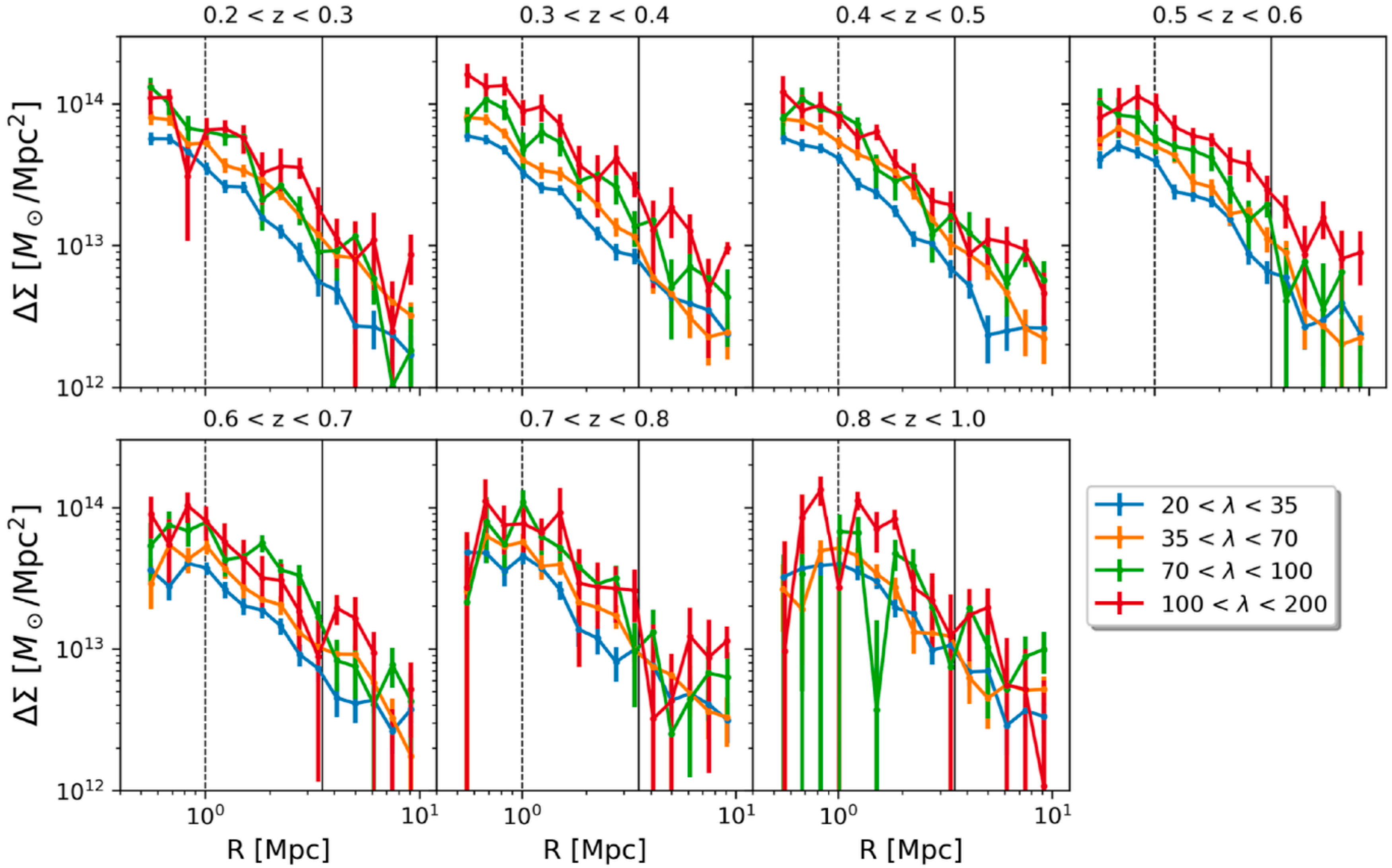
Summary statistics in this analysis
- 4x7 redshift-richness bins
- $20 < \lambda < 200$ + $0.2 < z < 1$
- Log-spaced for richness
- => 3,600 clusters on 440 deg2
- Study the mass-redshift dependency of the MoR

Data: LSST DESC DC2 simulations



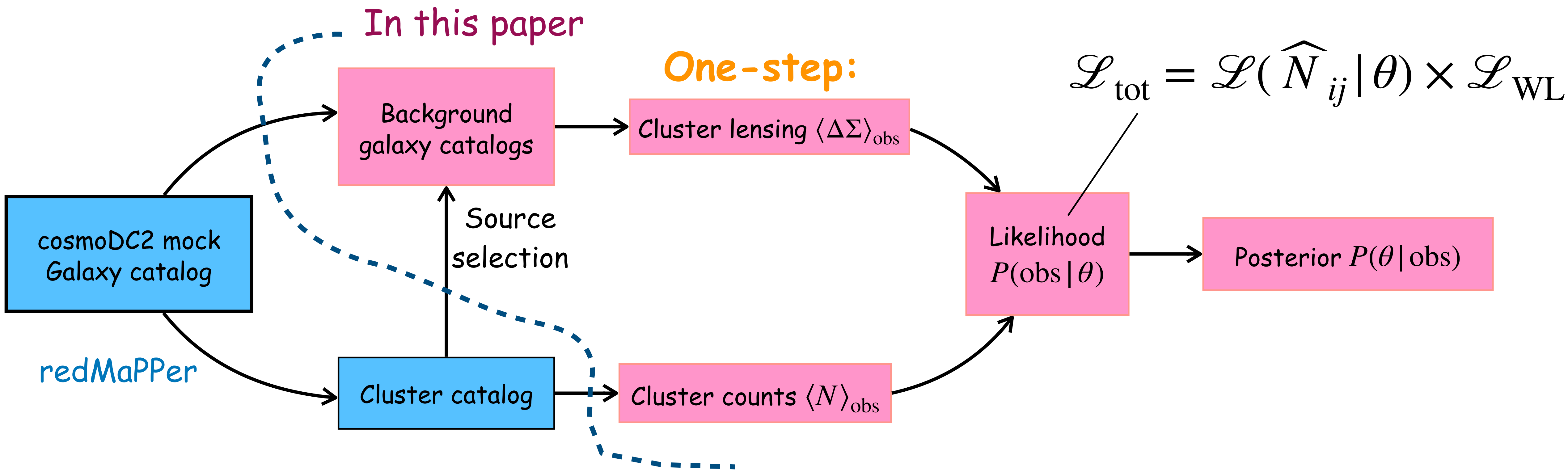
Source selection

- $i < 24.25 + r < 28$
- LSST-like density: 25 gal.arcmin-2
- Behind clusters: $z_{\rm gal} > z_{\rm cl} + 0.2$
- Baseline: true redshifts

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)
- Baseline: intrinsic shapes+local shear
- $\sigma_{\rm SN} = 0.25 + \sigma_{\rm meas} = 0$

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.

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

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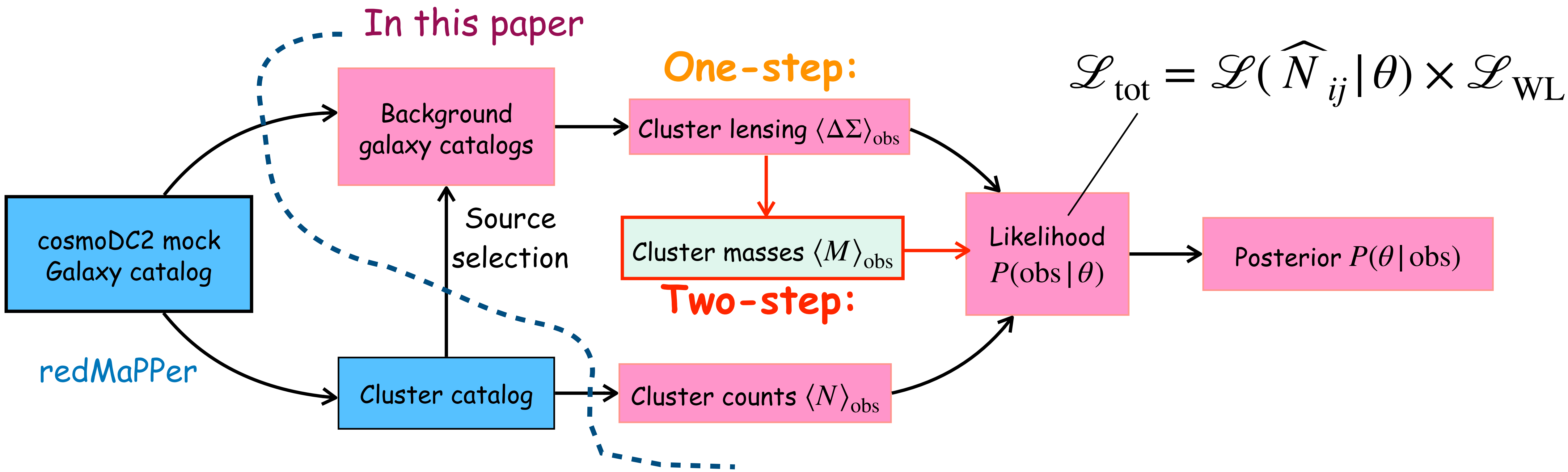

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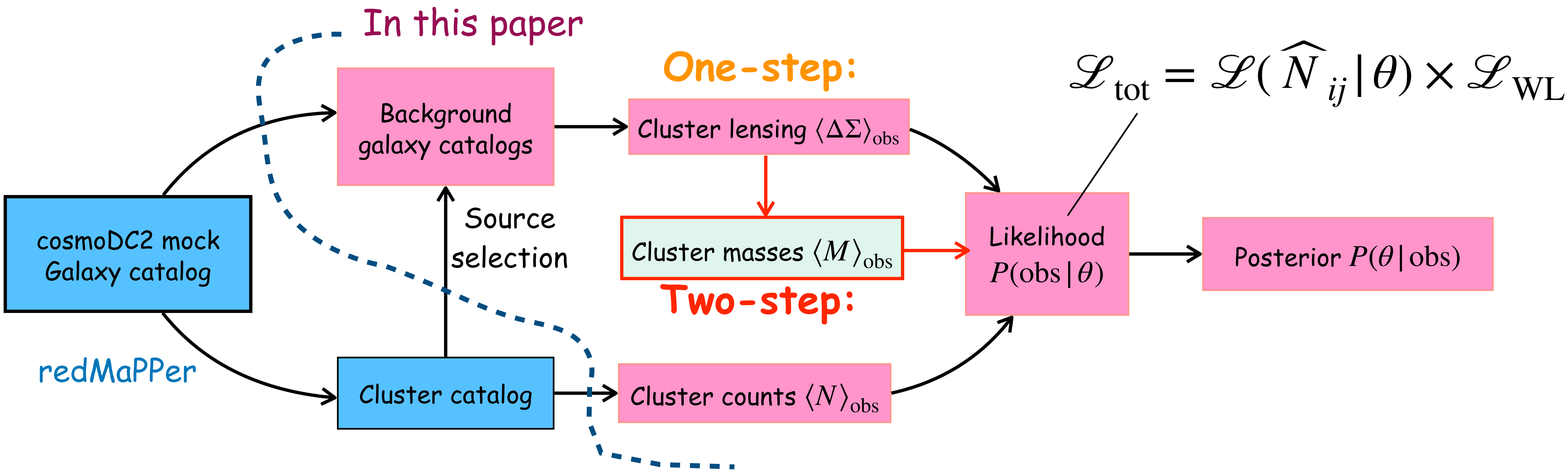
- **Two-step: First fit the mean mass**
  - spitting the problem ! Simplifies integrals and computational times

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

Or

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

Inference from CC+WL



$$\mathscr{L}_{\rm tot} = \mathscr{L}(\widehat{N}_{ij}\,|\,\theta) \times \mathscr{L}_{\rm WL}$$

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We can now discuss the modeling …

Modeling for the mass-richness relation

Mean

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

Log-normal distribution

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

Variance

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

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 $R < [1,3.5]$ Mpc

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

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Constrain MoR

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

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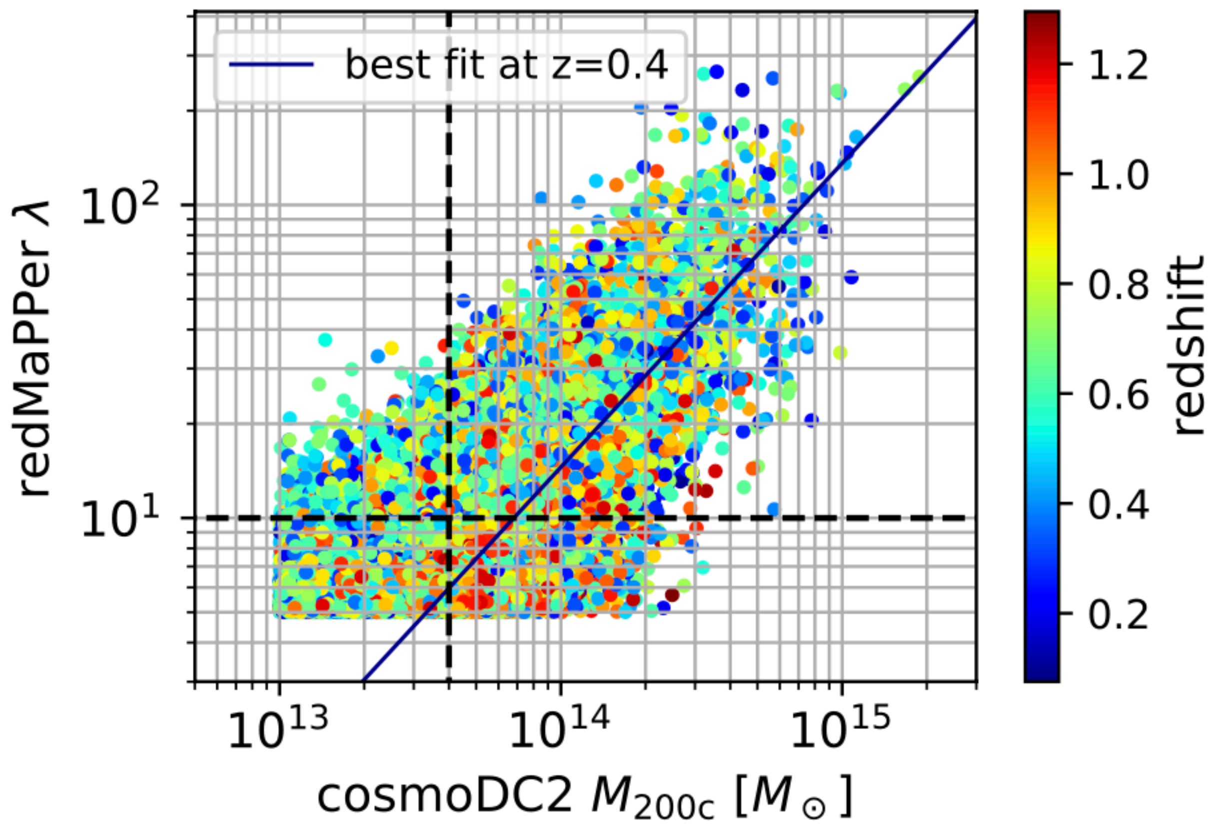
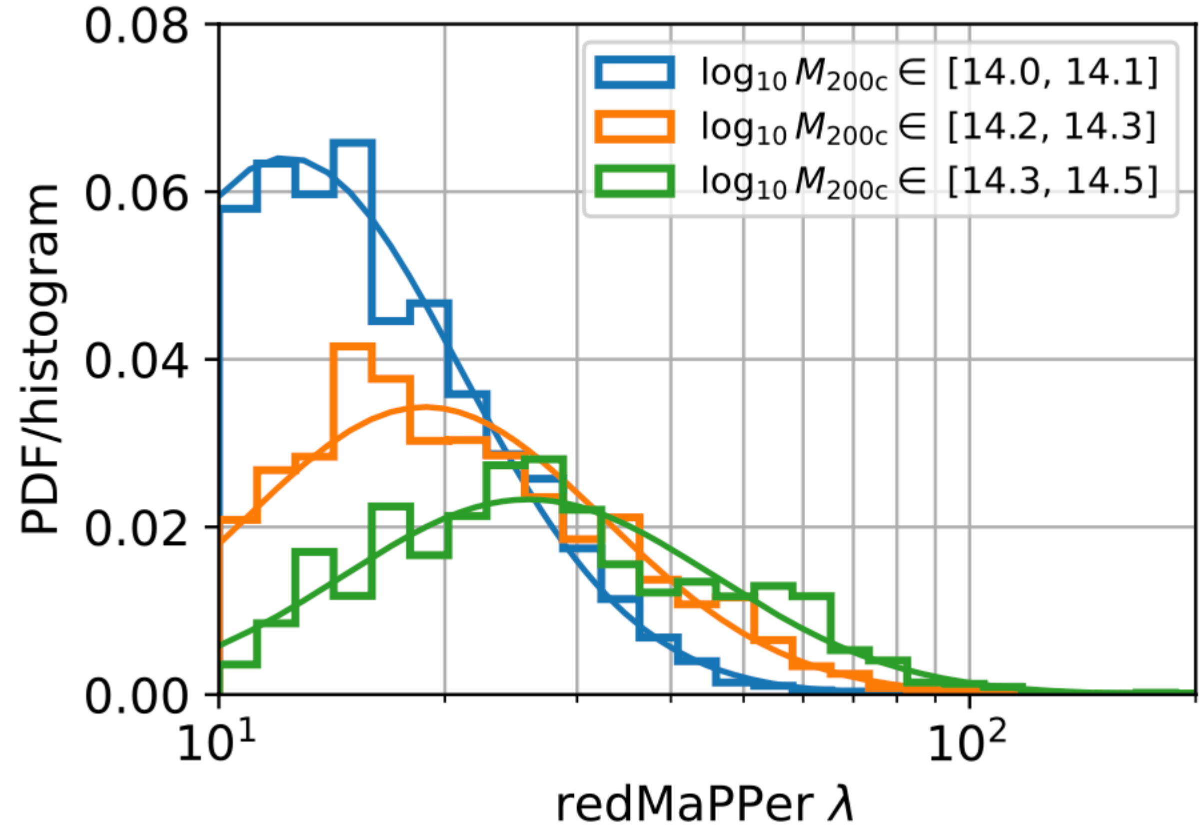
Weak Lensing

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

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

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 (truncated gaussians)

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

→ **Used to validate our results !**

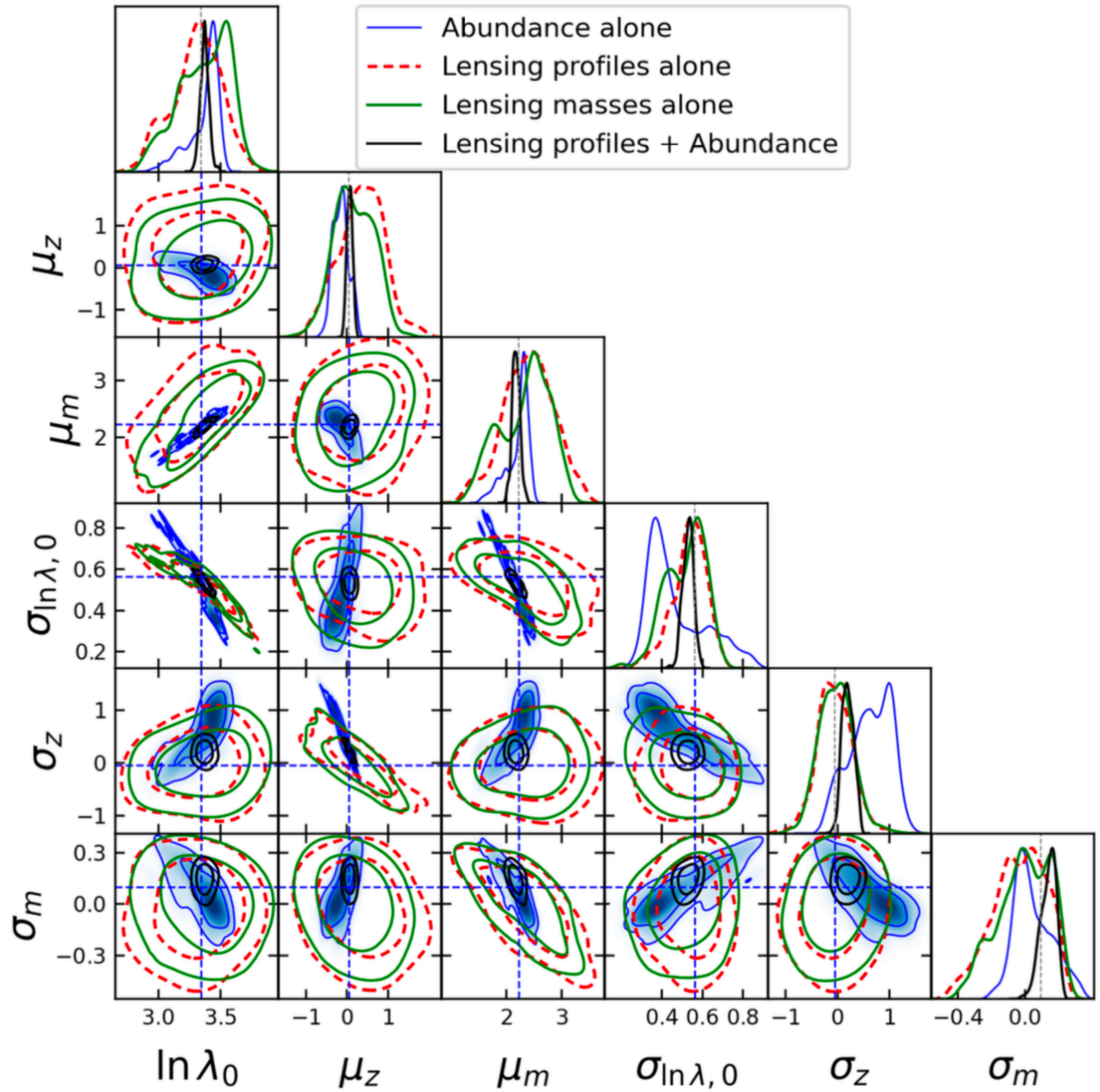
Baseline analysis

Separate Count and lensing

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

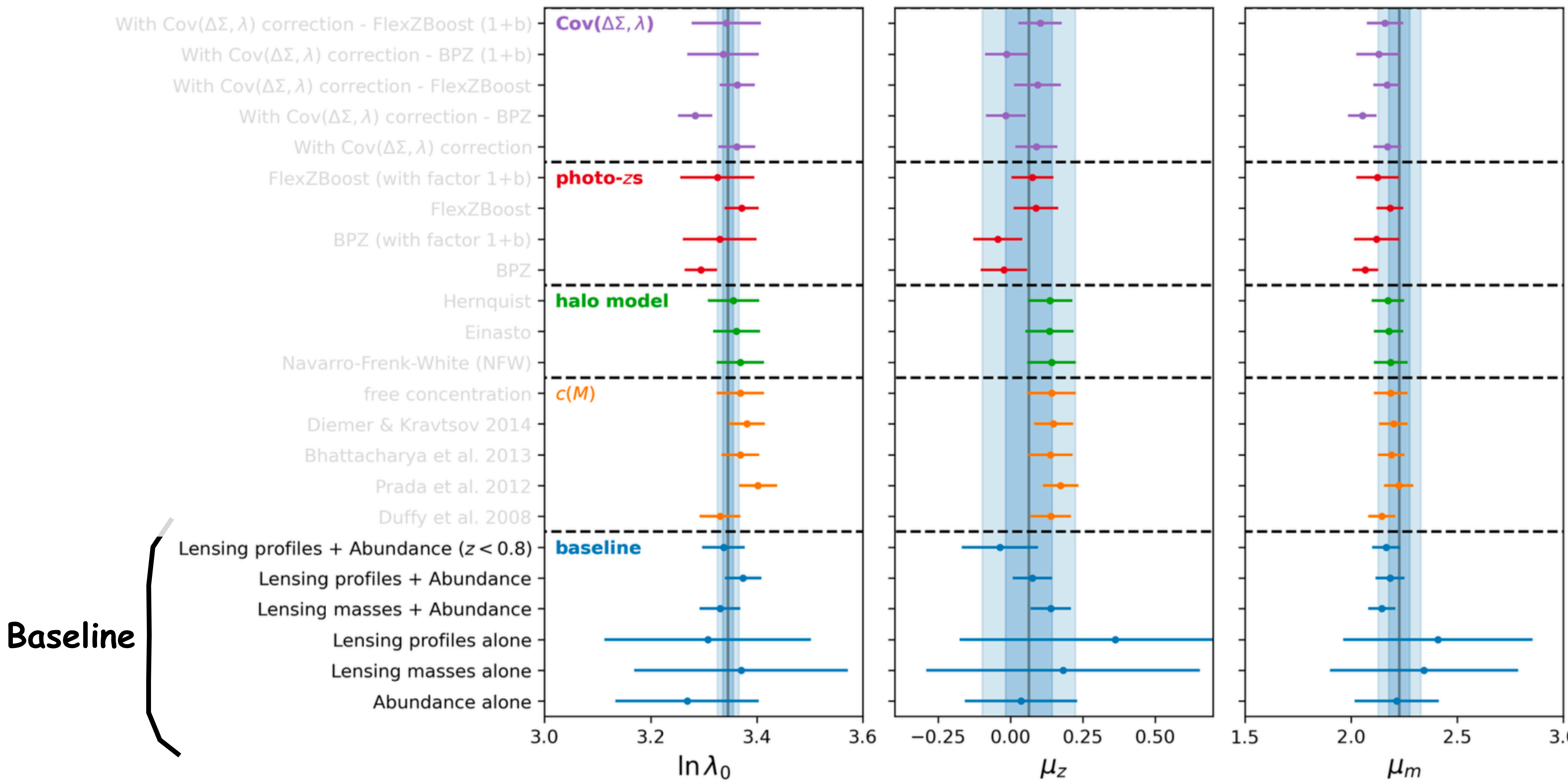
Joint analysis

- 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



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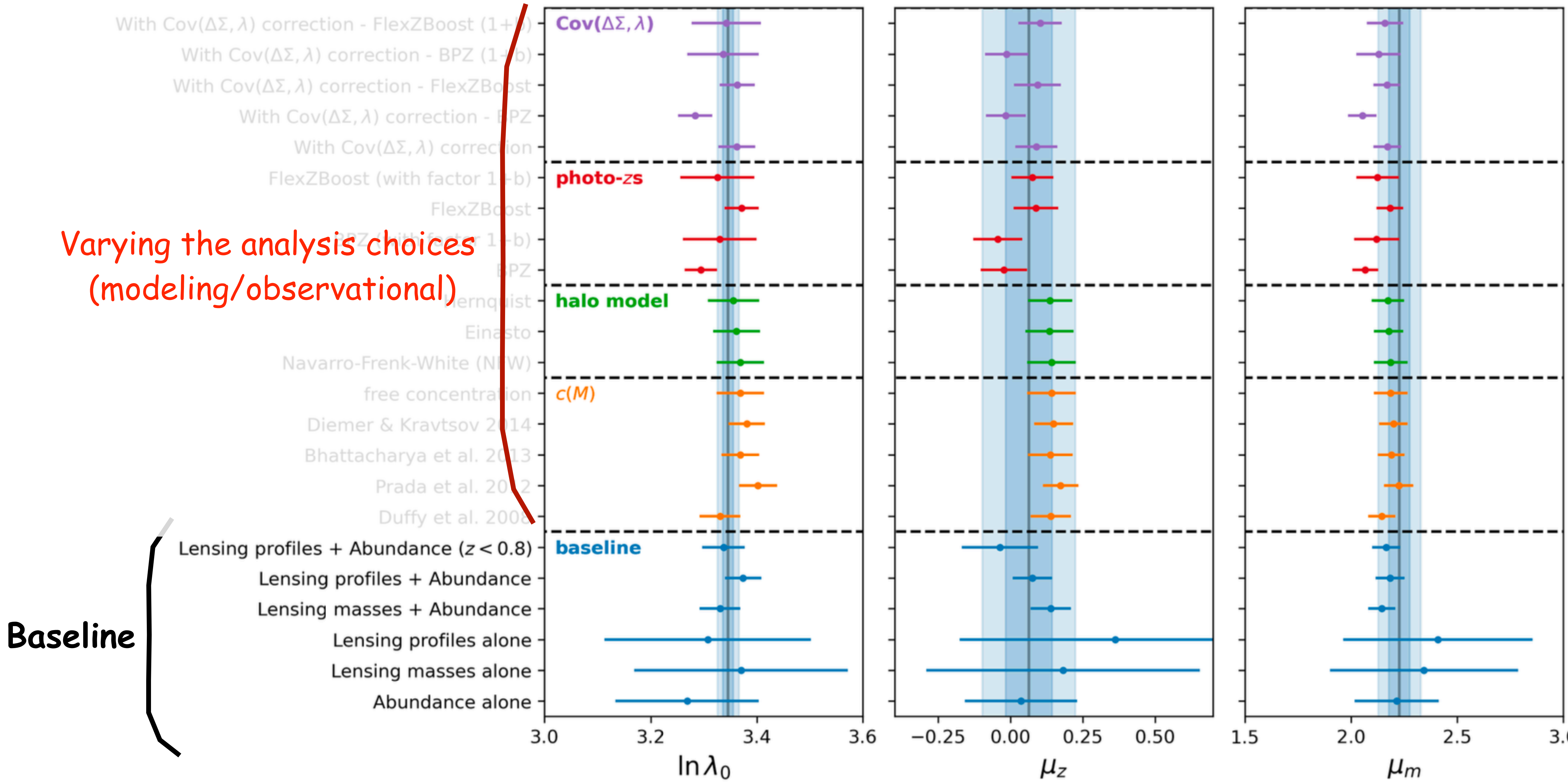

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- For stage-IV surveys: LSST-like precision of lensing data + large cluster samples, controlling these systematics uncertainties are a big concern

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Modeling choices: Cluster density

- Different $\rho_{3\mathrm{d}}$ exist in the literature (NFW, Einasto, Hernquist)
- Params.: 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

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

Modelling

Robustness of MoR in LSST DESC DC2

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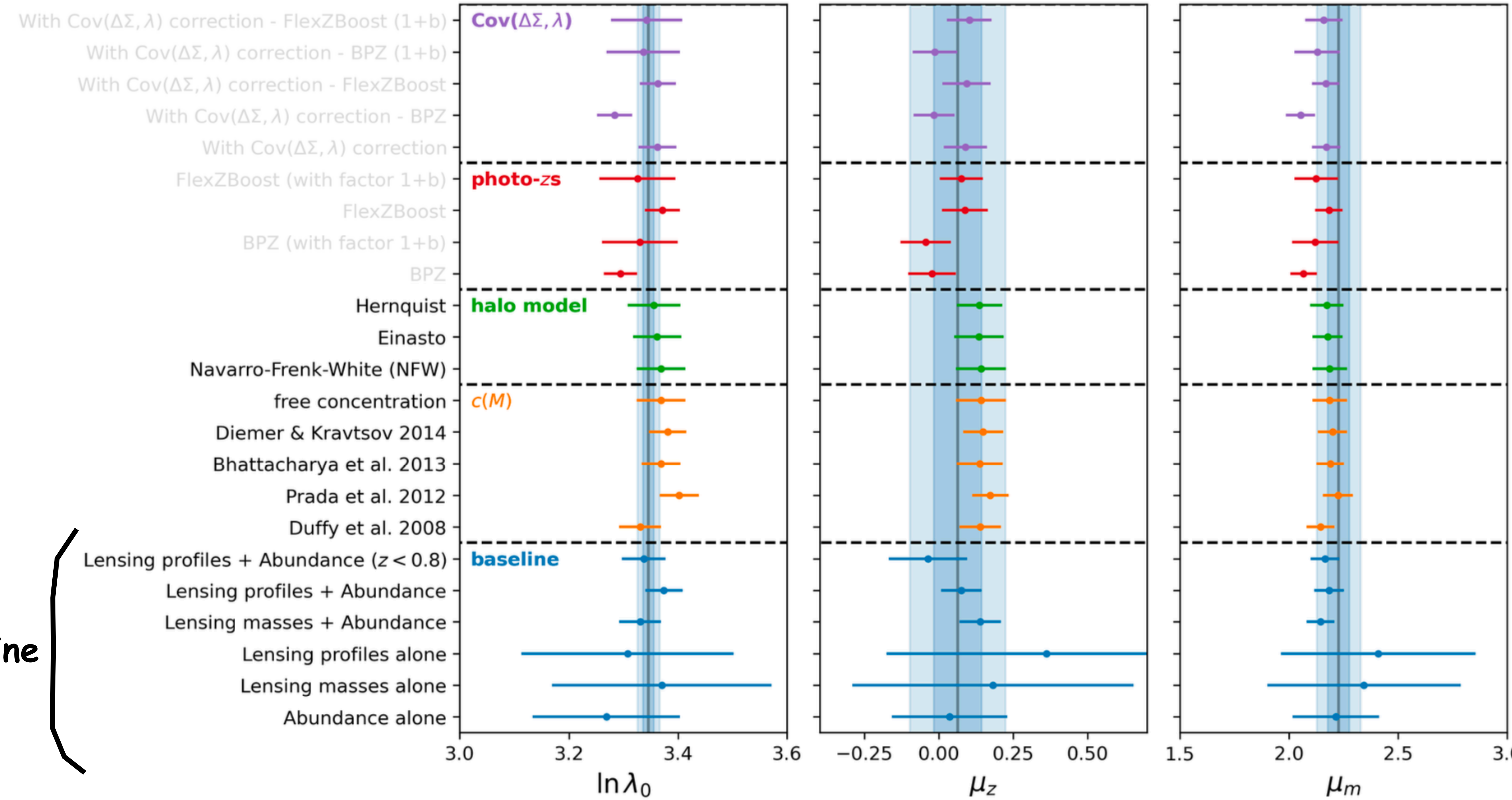
Baseline



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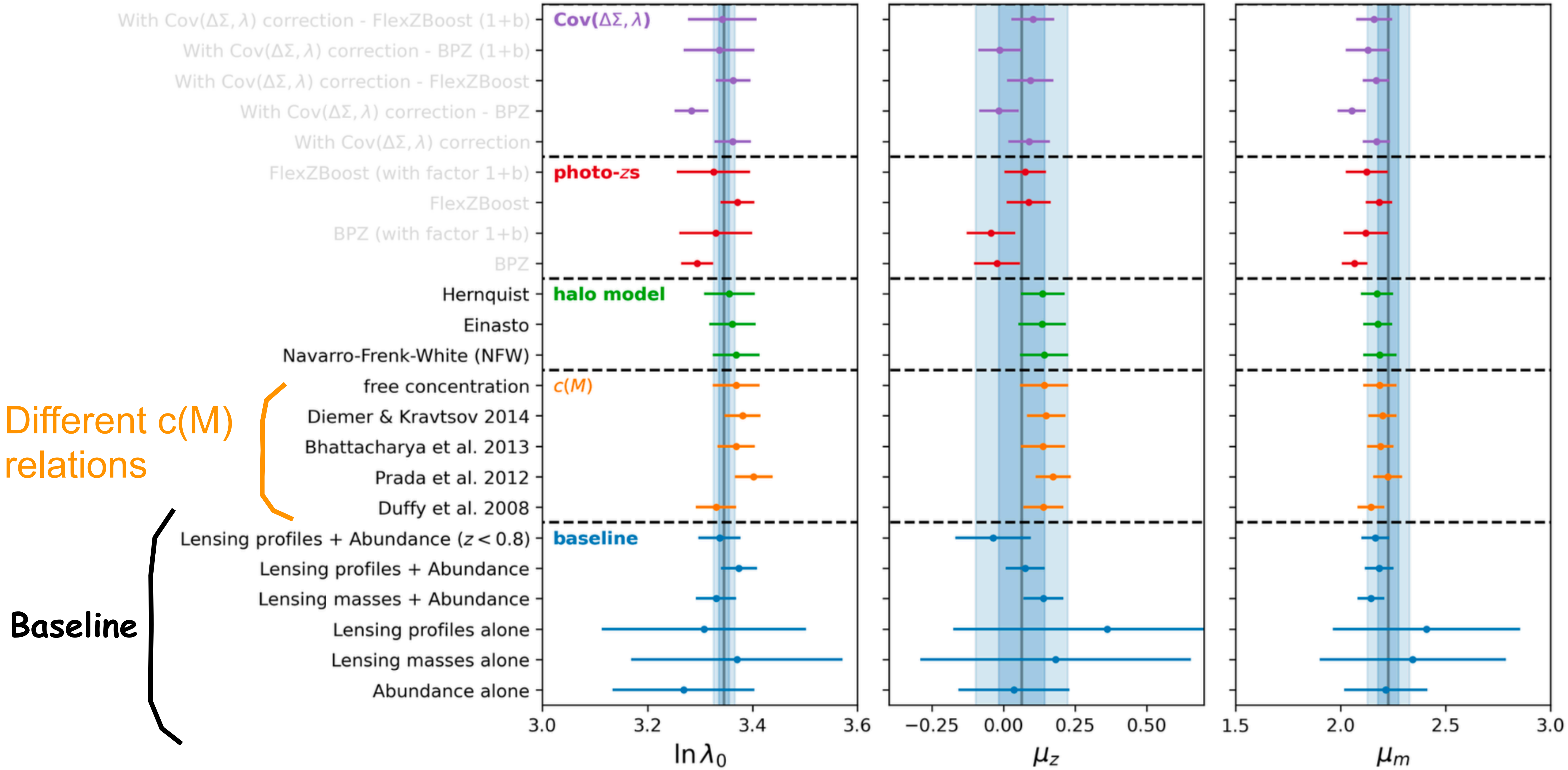

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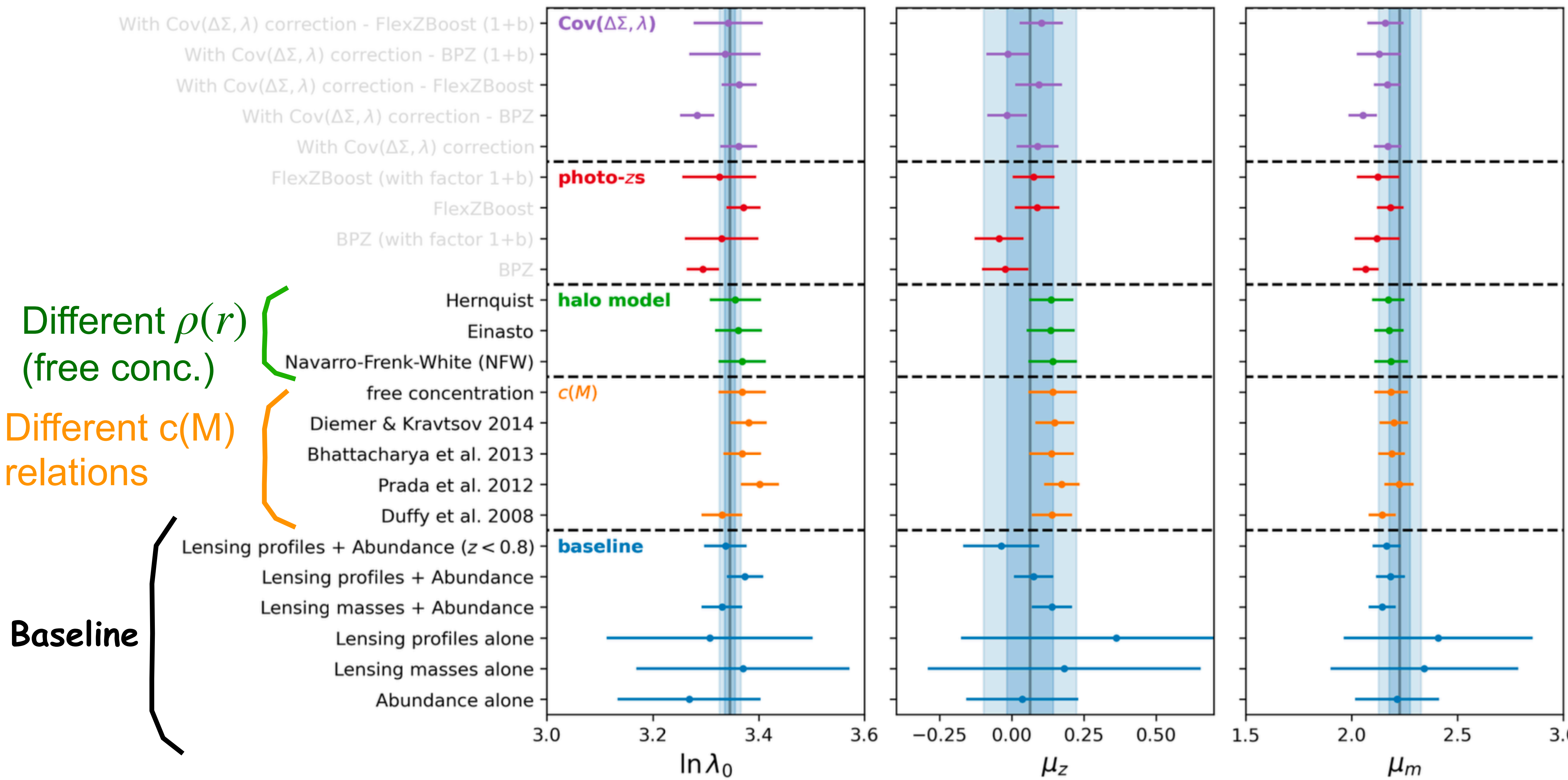

On the modelling side

$\Delta\Sigma(R)$ 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

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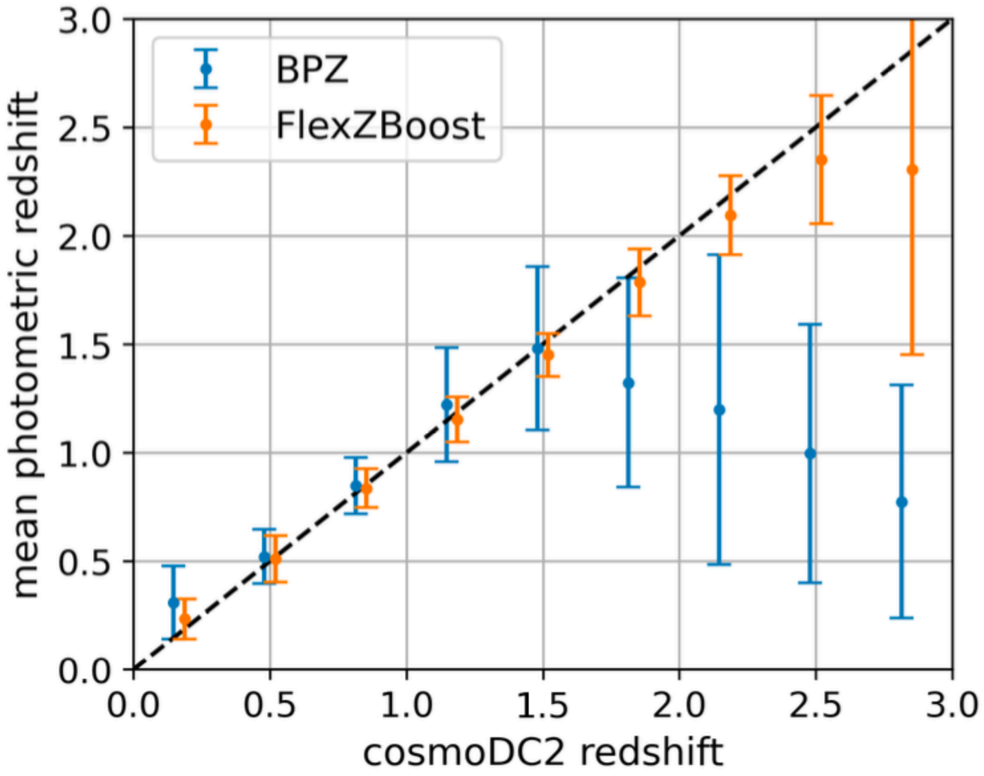
Photometric redshifts of source galaxies

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. ?



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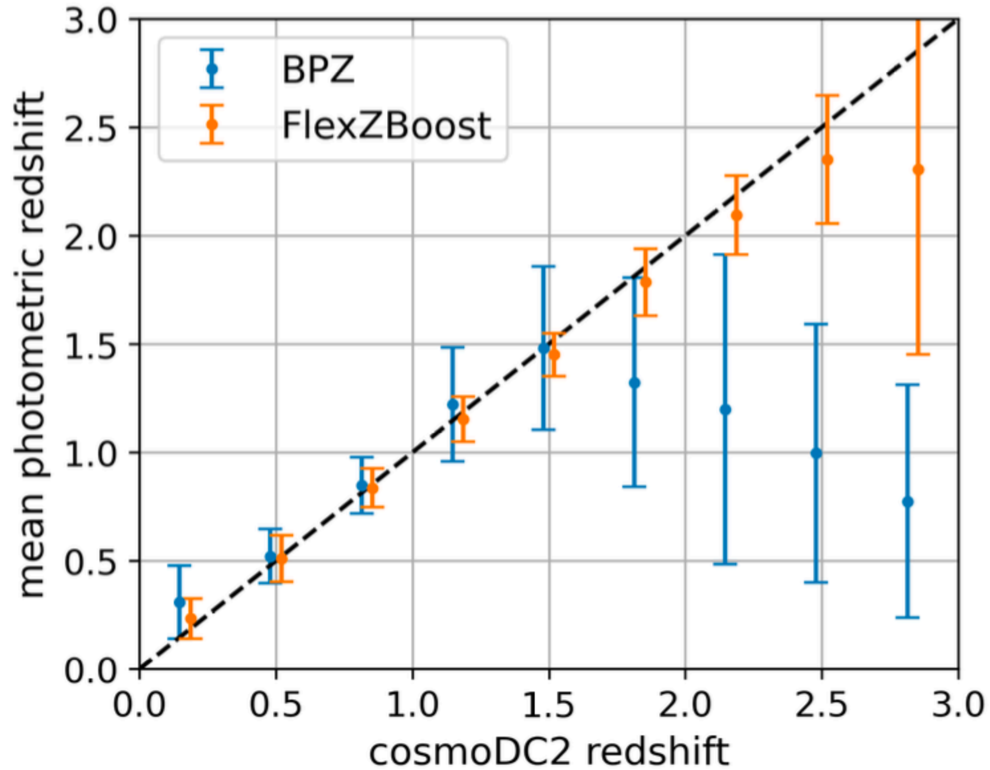
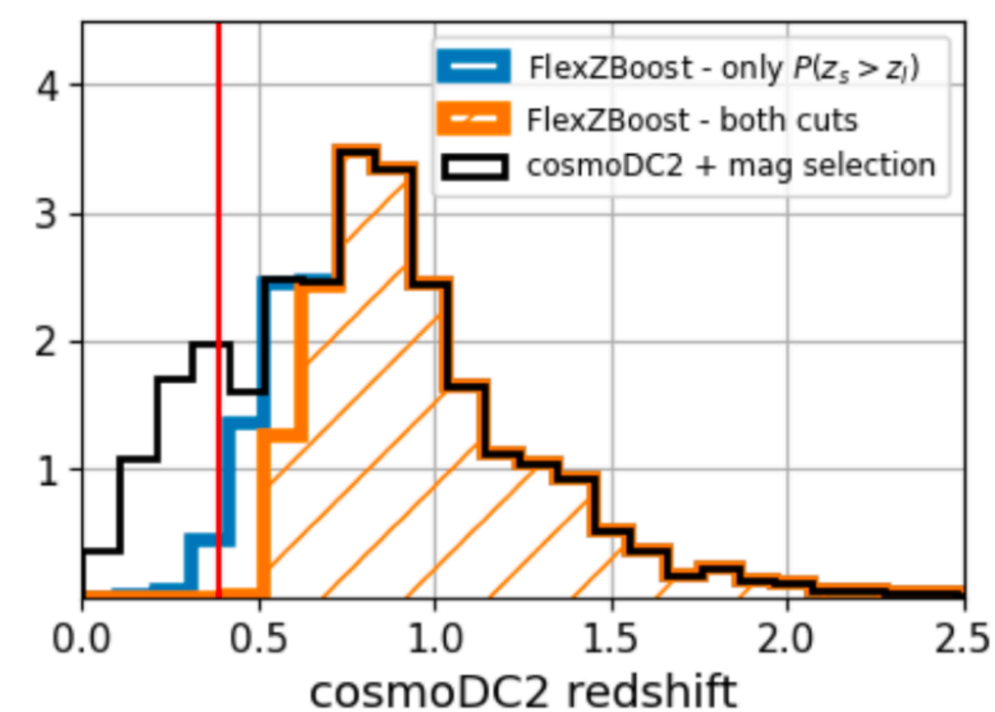


1. Source selection →

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



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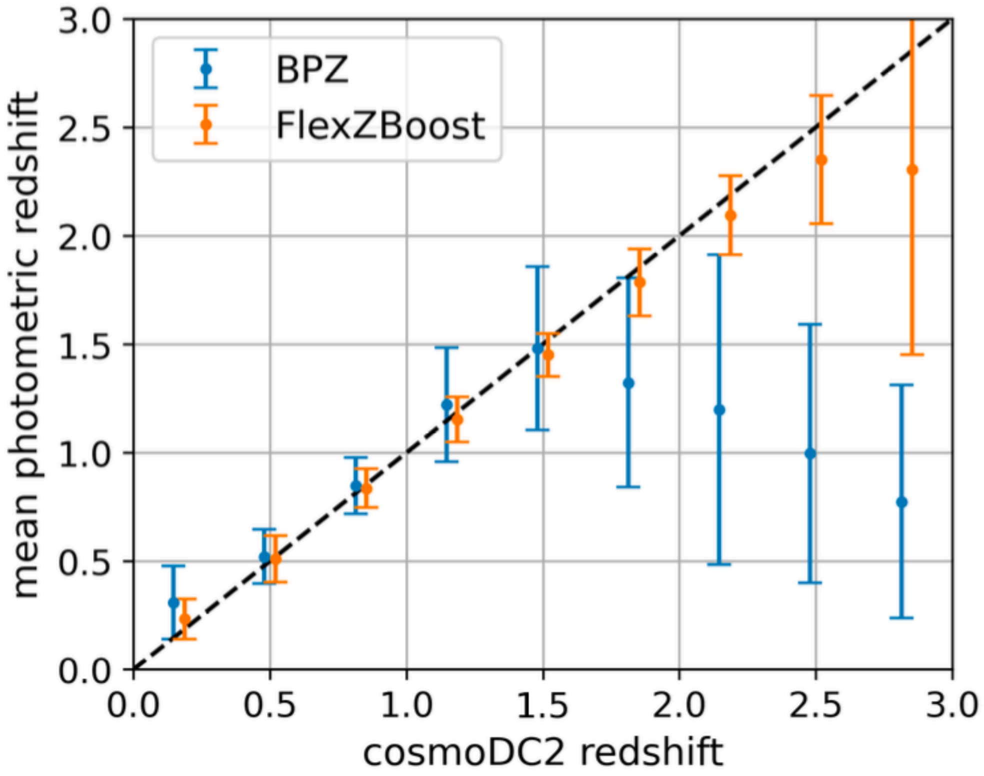

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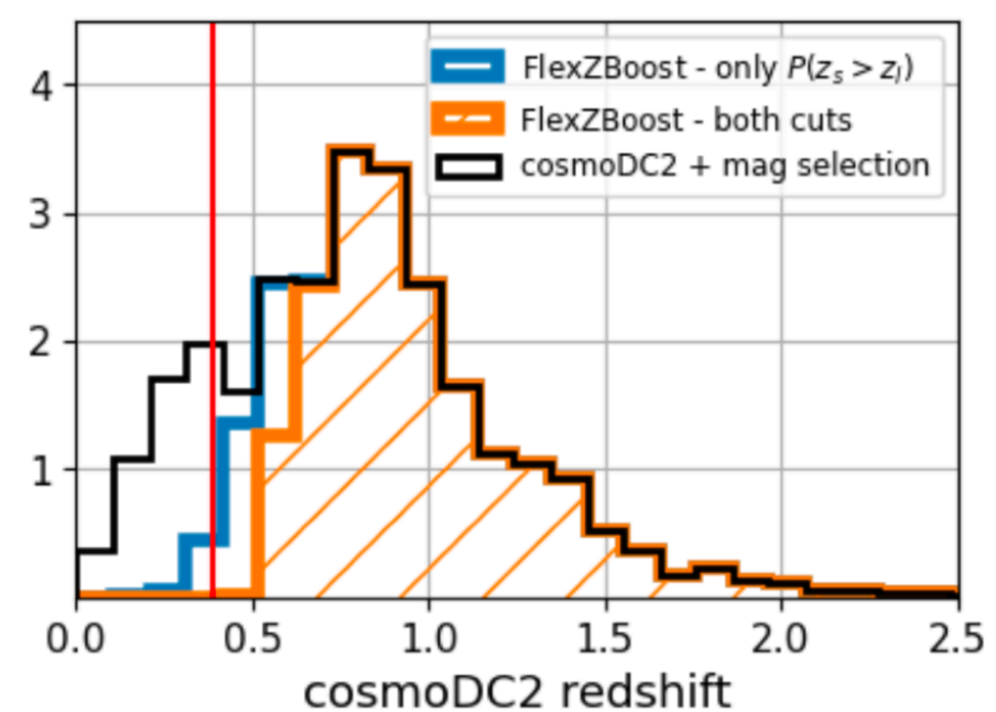
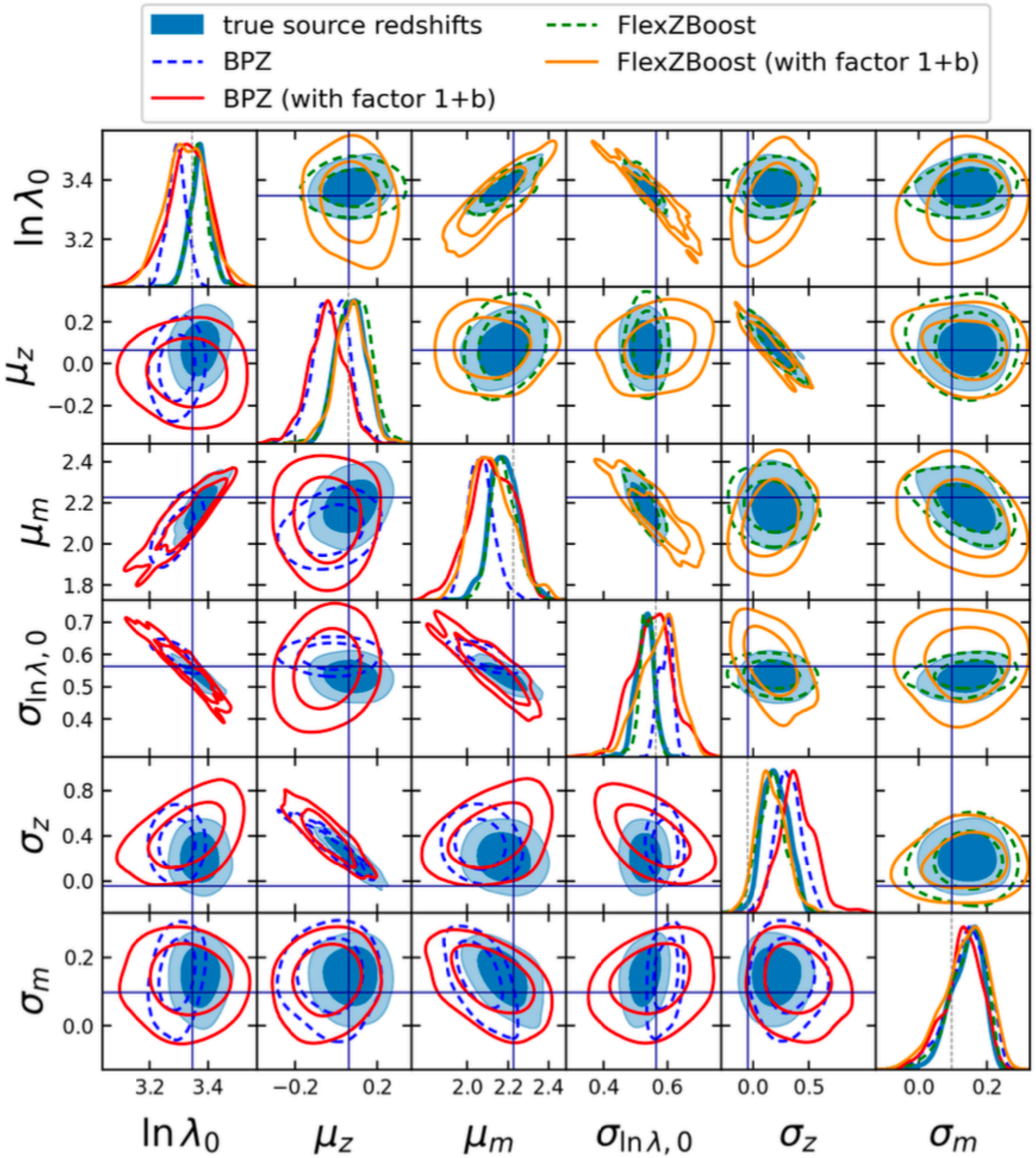
2. WL lens-source weights

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



Results

- FLexZBoost: perfect agreement with true redshift case (baseline)
- BPZ: shift at most 1σ in the normalization $\ln \lambda_0$



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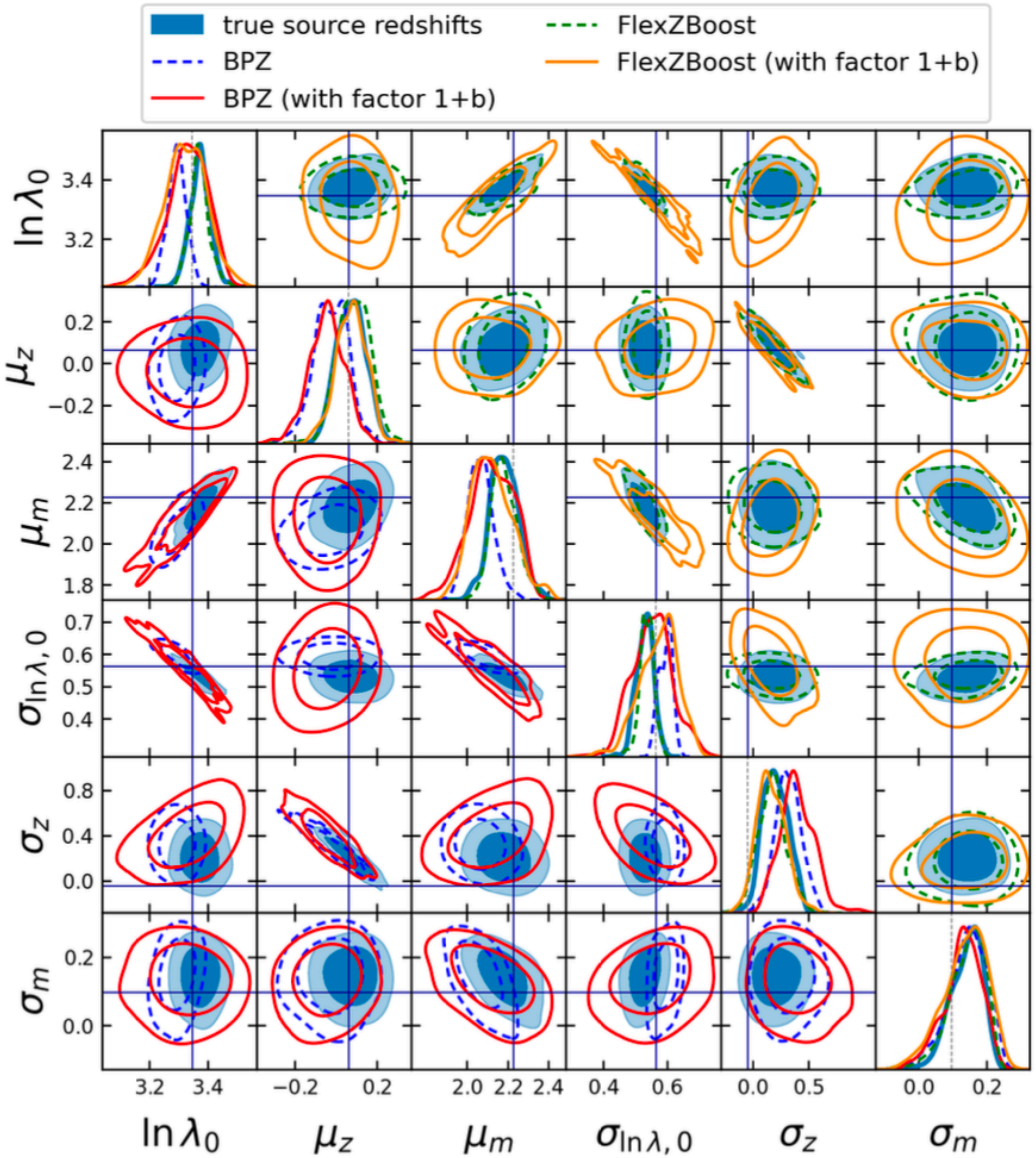
$$\Delta\Sigma_{ij}^{\rm corr} = (1+b)\Delta\Sigma_{ij}$$

Uncorrected PZ systematics



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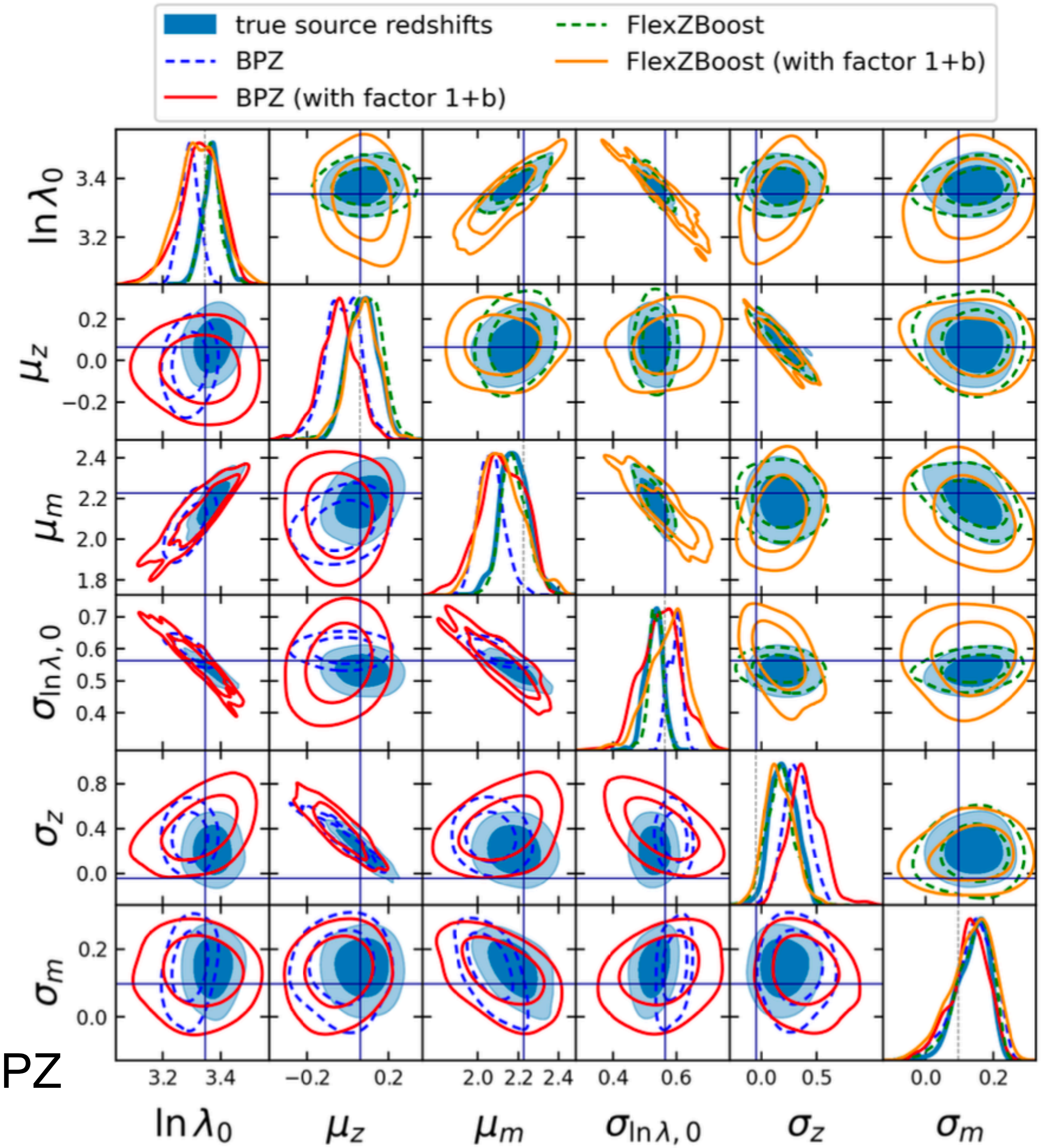
Uncorrected PZ systematics

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

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



On the 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

On the modelling side

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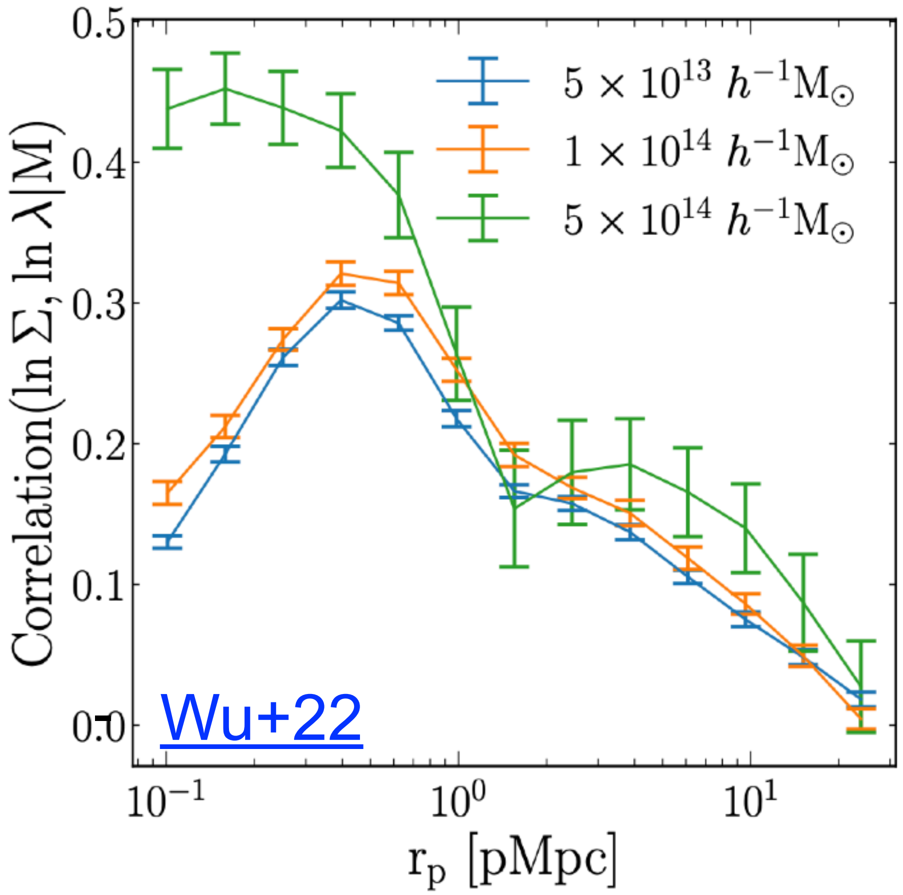
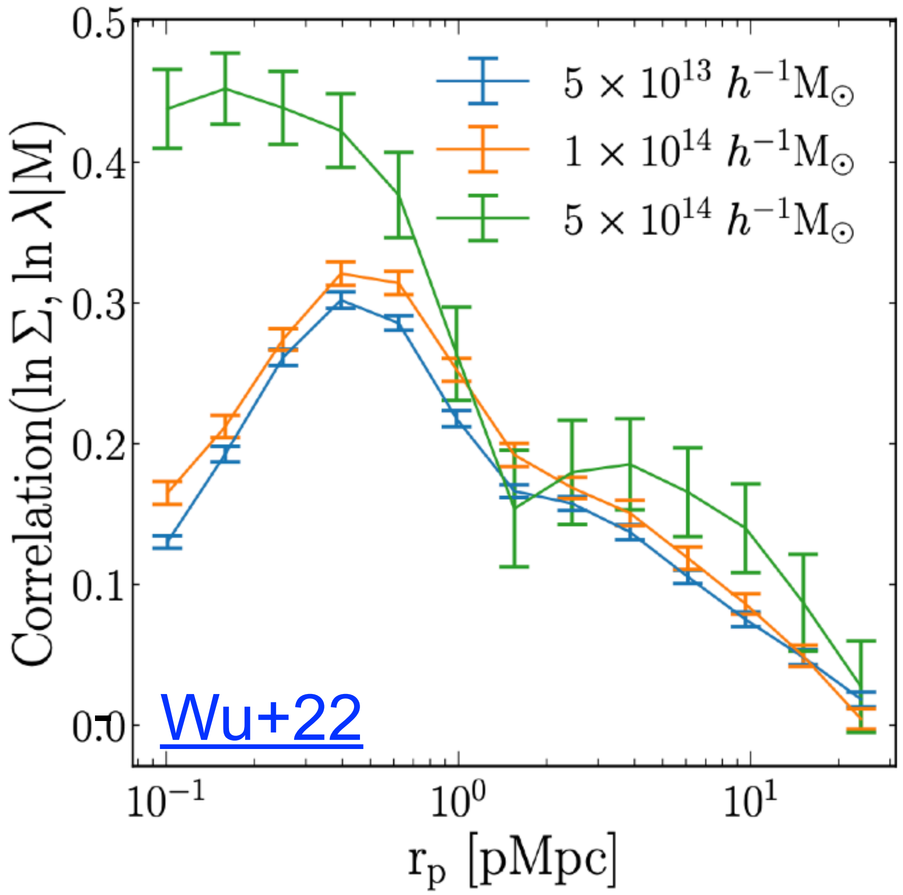
Shear-richness covariance in CL analyses



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)

Shear-richness covariance in CL analyses



$$\Delta\Sigma_{ij}^{\rm corr} = \Delta\Sigma_{ij} + \frac{[\beta_1]_{ij}}{\mu_m}\langle \mathrm{Cov}(\Delta\Sigma, \ln\lambda\,|\,m, z)\rangle_{ij}$$

HMF mass slope

« standard » prediction

MoR mass slope

Shear-richness covariance

Shear-richness covariance

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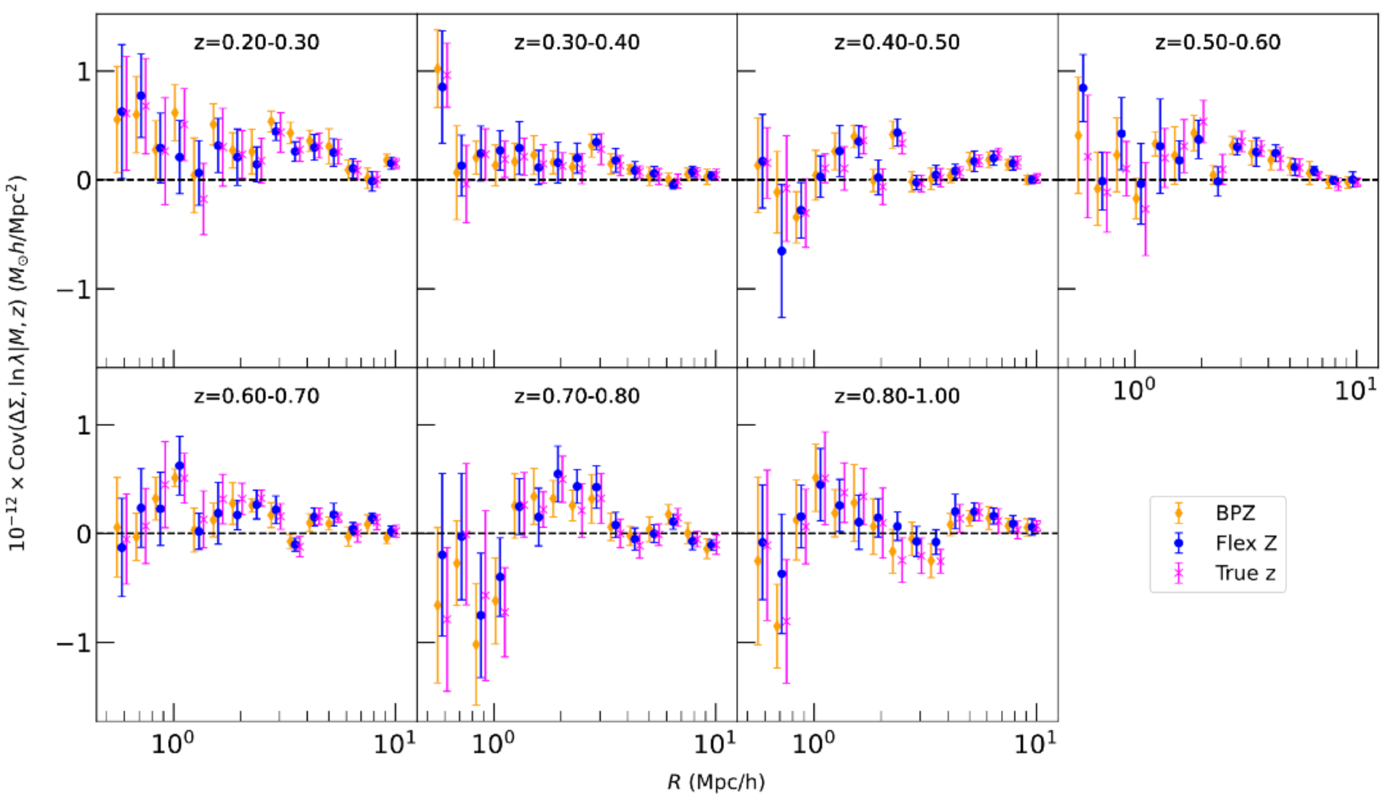
Implementation in CL pipeline

- 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

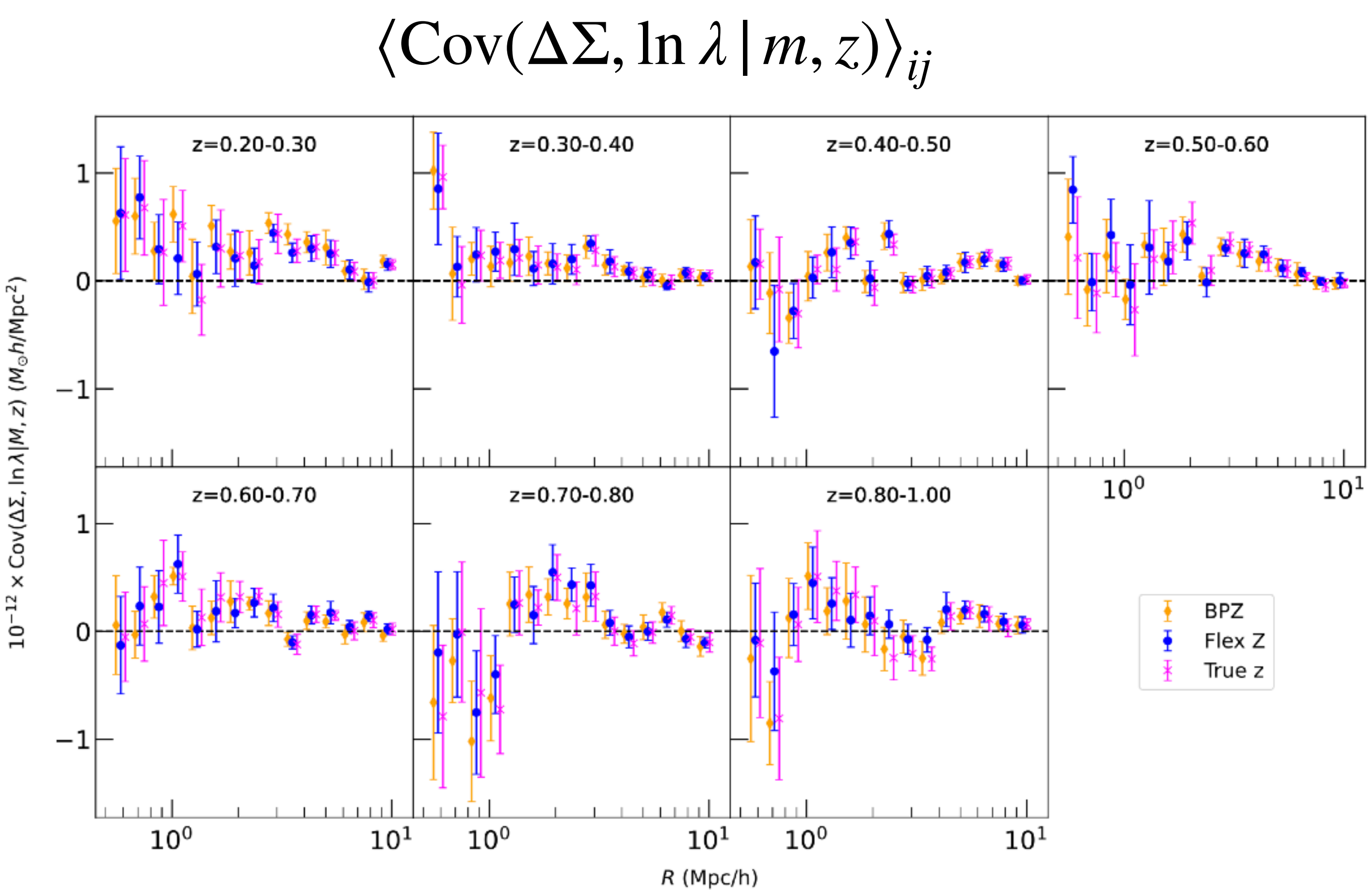
$$\langle \mathrm{Cov}(\Delta\Sigma, \ln\lambda \,|\, m, z)\rangle_{ij}$$

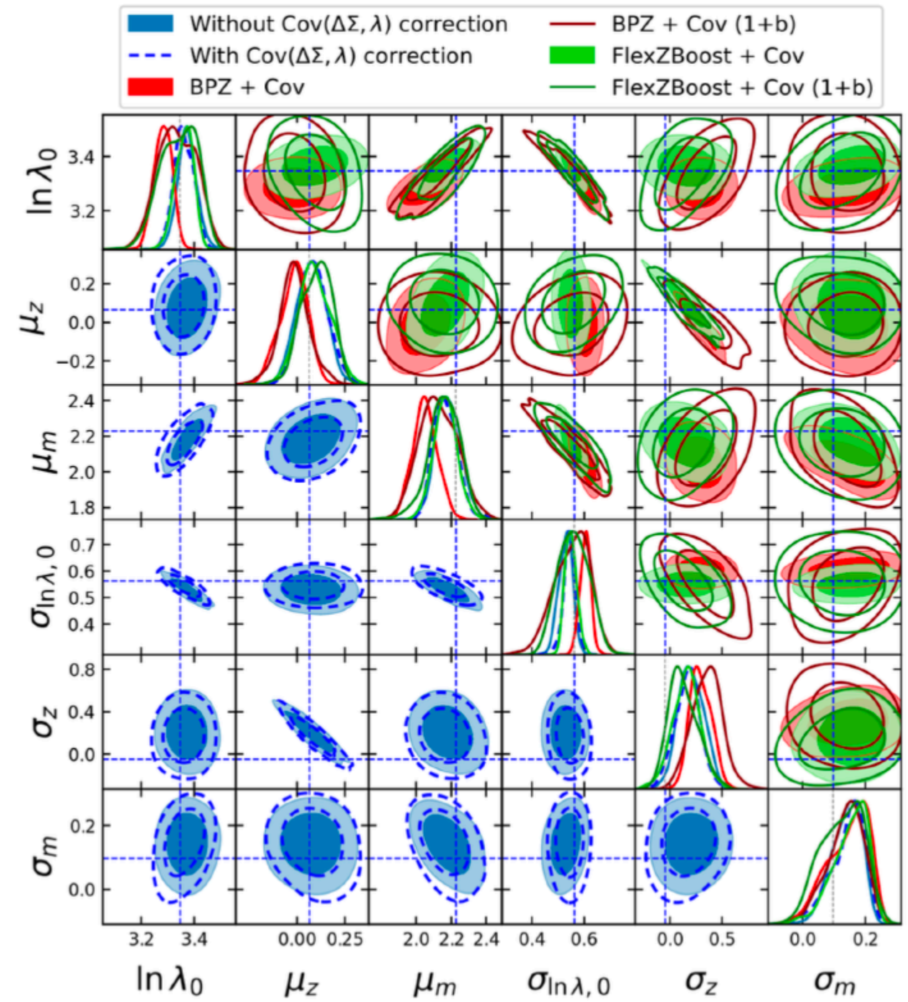


In DC2 data

- 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)

Shear-richness covariance in cosmoDC2





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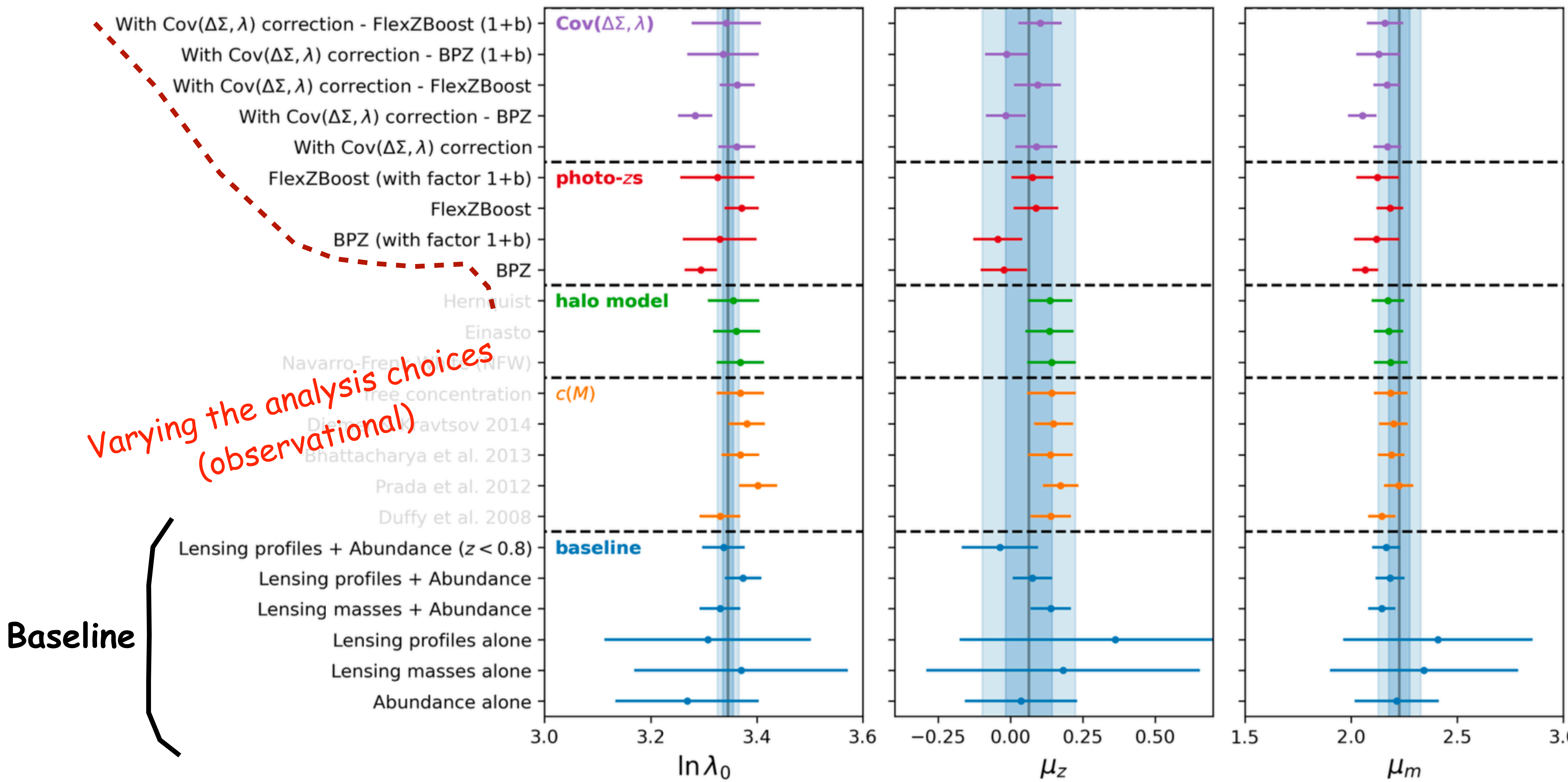
Impact on MoR

- 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

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- Build « Early » CL pipeline for DESC 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

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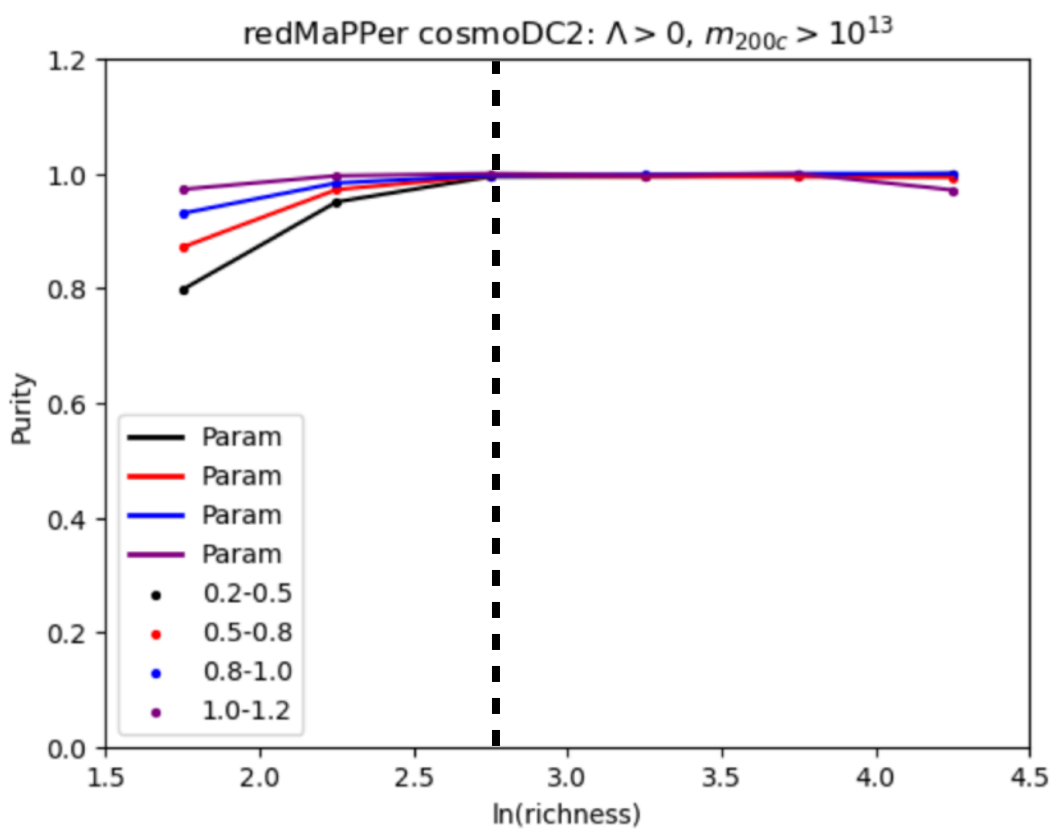
Plan for analyzing the LSST

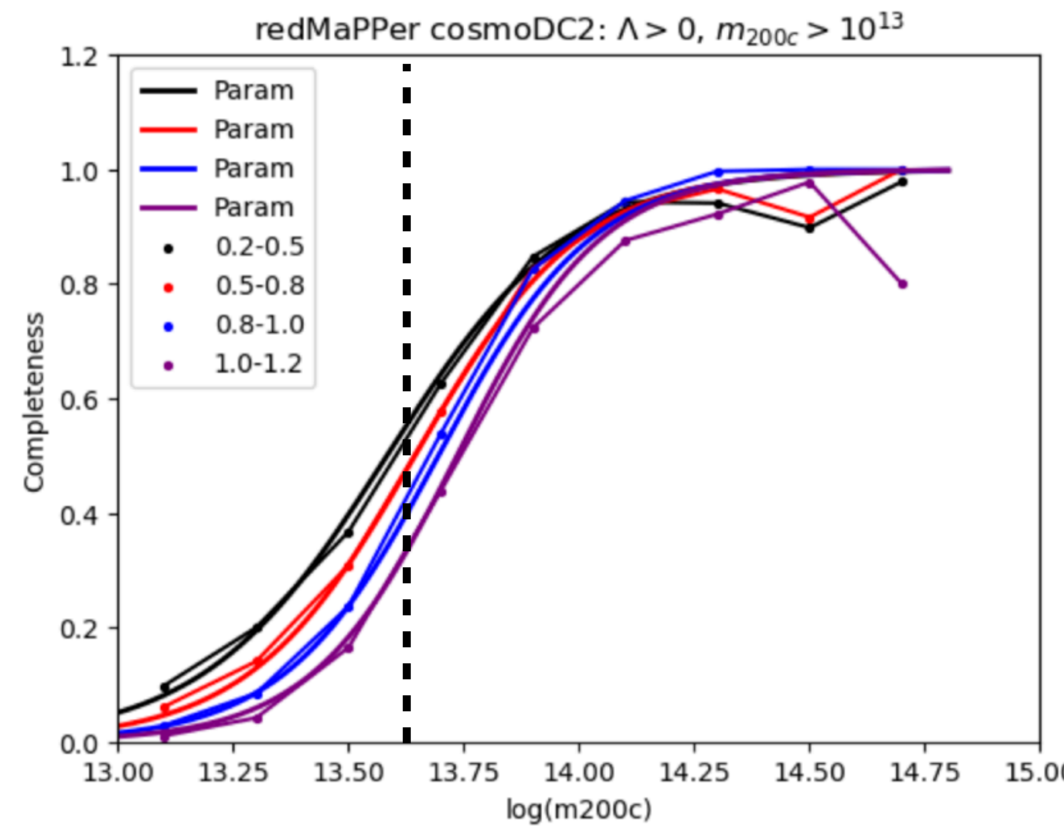
- Hope it paves the way for the LSST CL DESC pipeline ! Active discussions in prep. of ComCam data
- **Precision** $\times 6.4$ **with « idealistic » LSST** (e.g. true mag./shapes), work is needed to estimate the budget of shape measurement.


Thank you!

redMaPPer selection function

Figures by Thibault Guillemin et al.





Principle

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

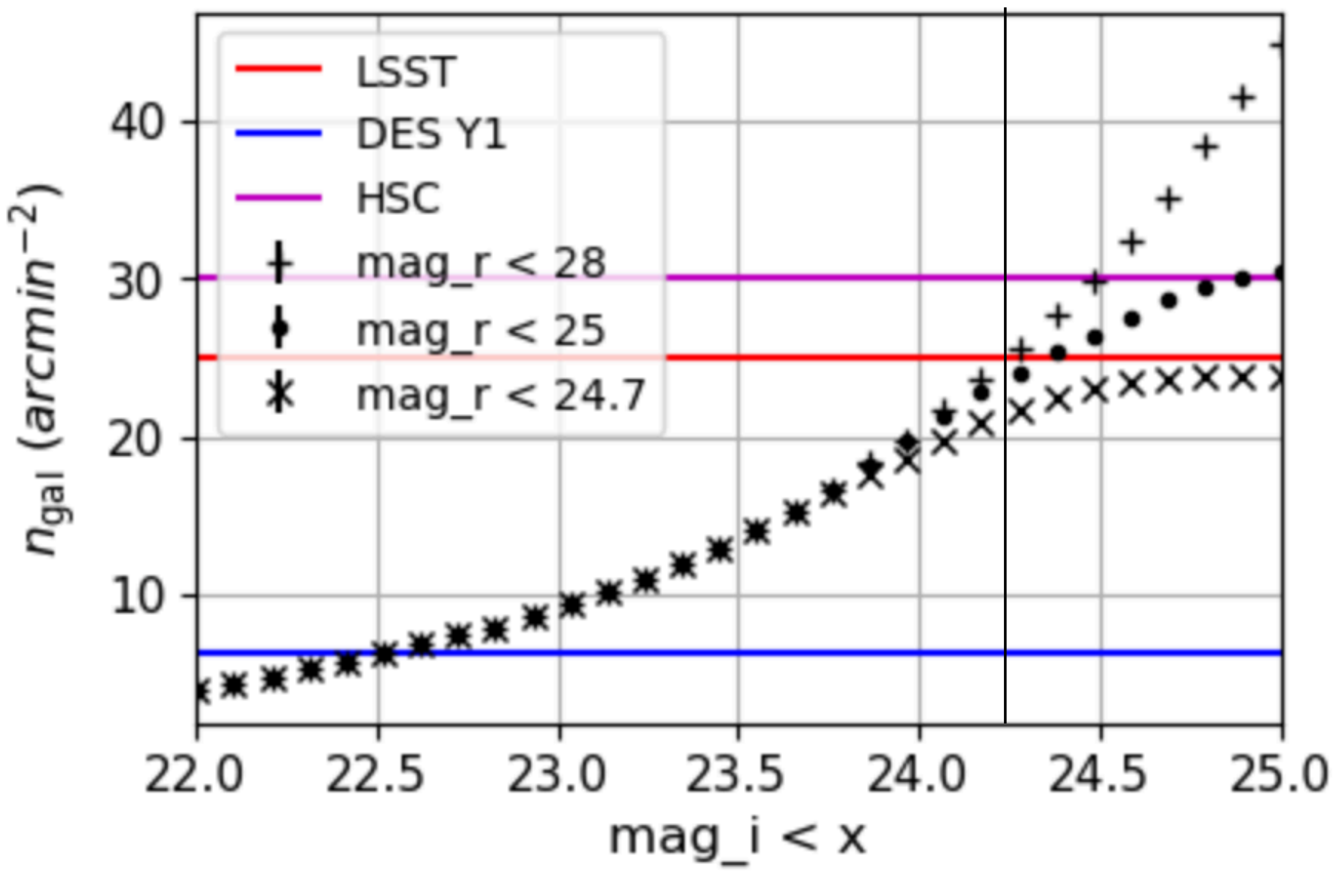
Completeness

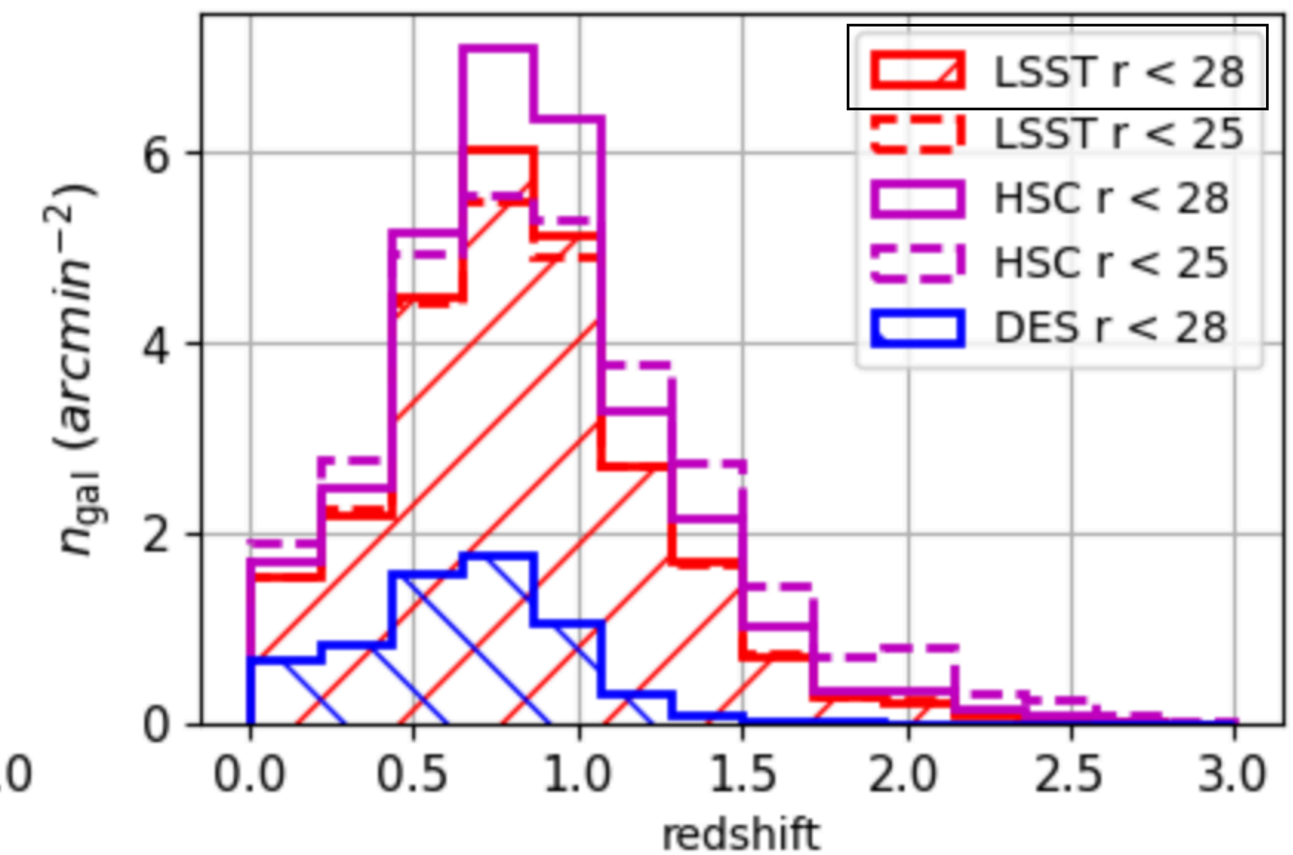
$$\Phi(m, \lambda, z) = \frac{c(m, z)}{p(\lambda, z)}$$

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





Choices:

- $i < 24.25$
- $r < 28$