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

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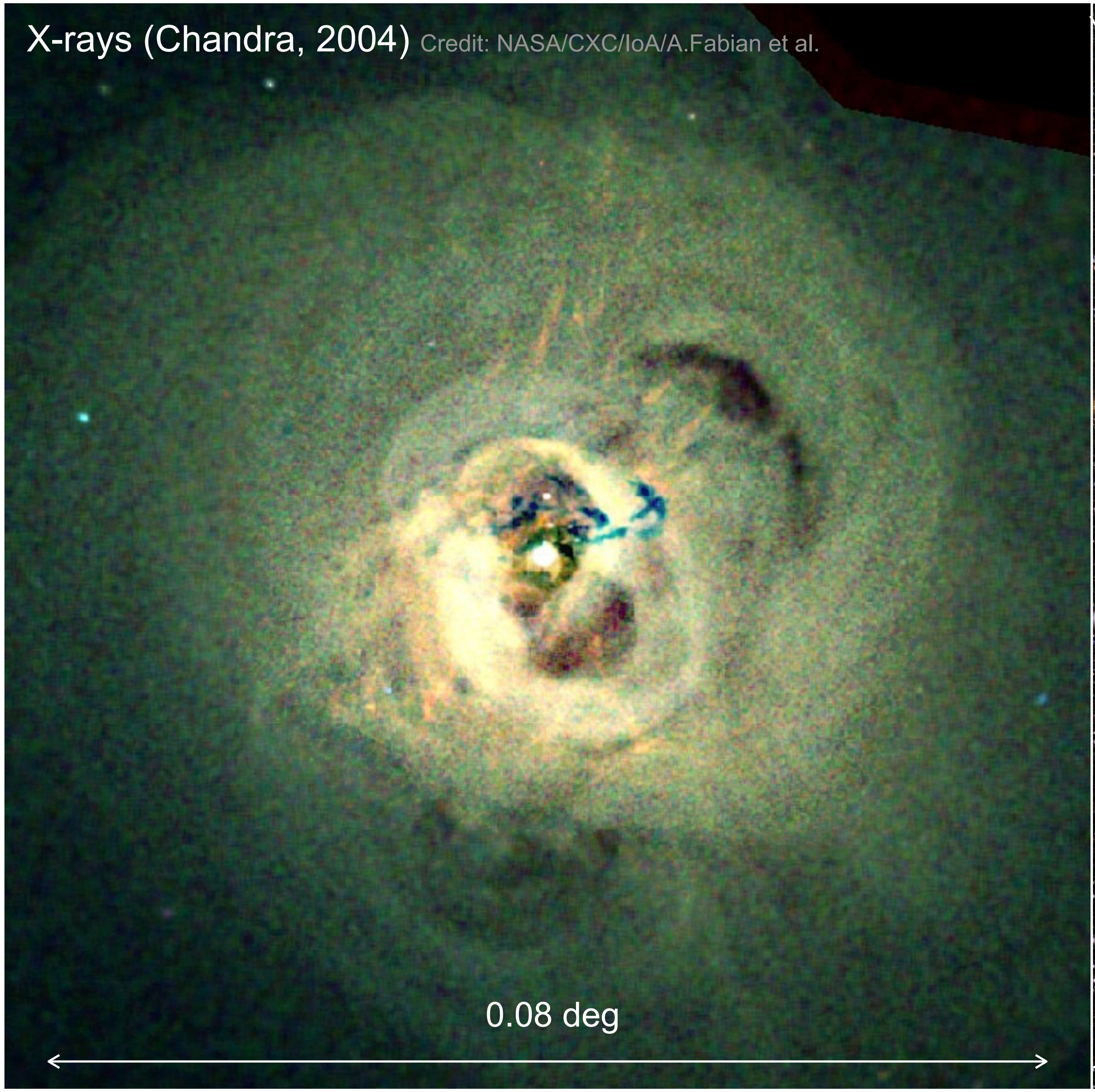
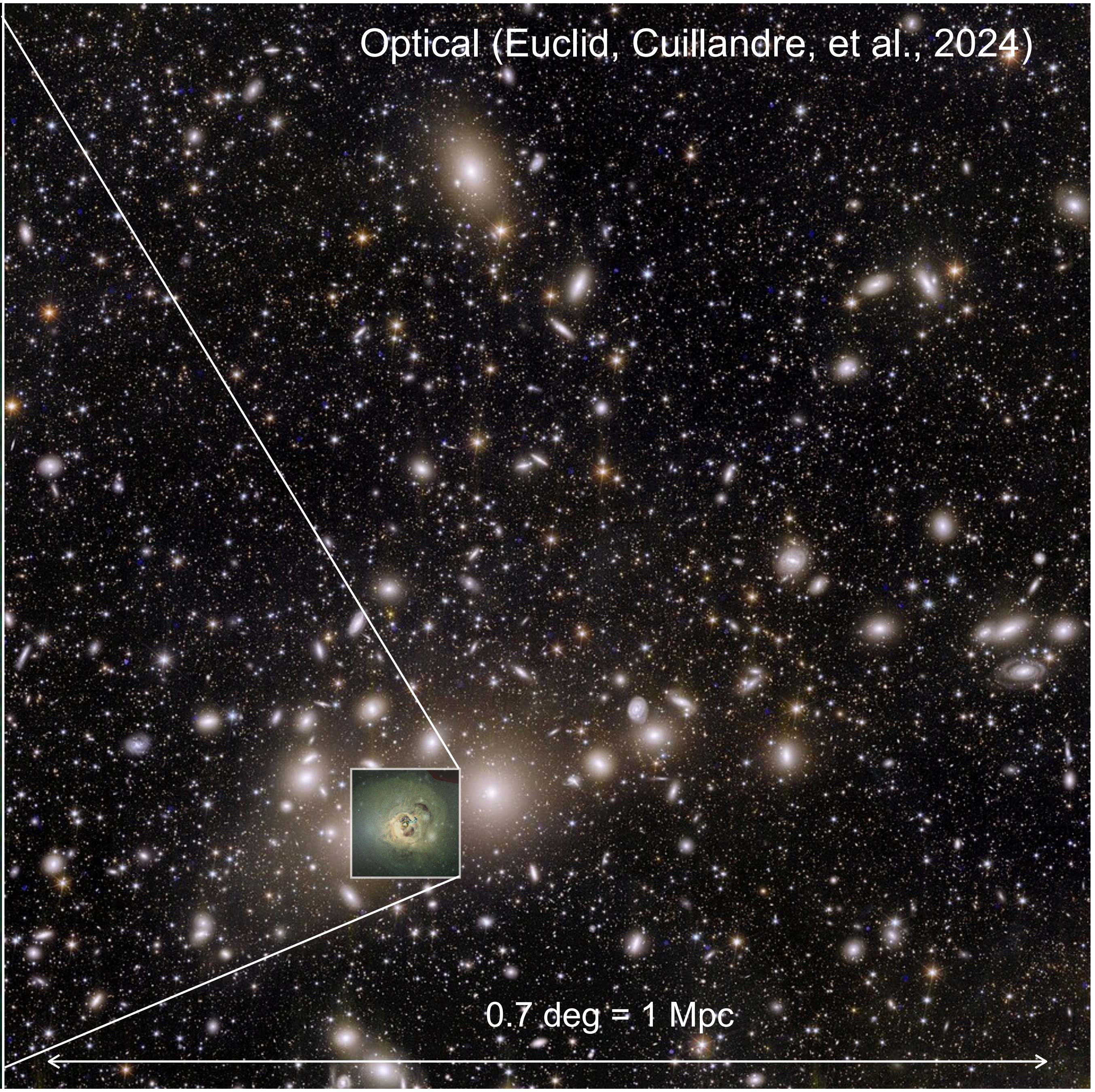
Galaxy clusters

Perseus Cluster redshift=0.01





Massive bound systems $M > 10^{14}\ M_{\odot}$ and detected in X-rays, mm, optical

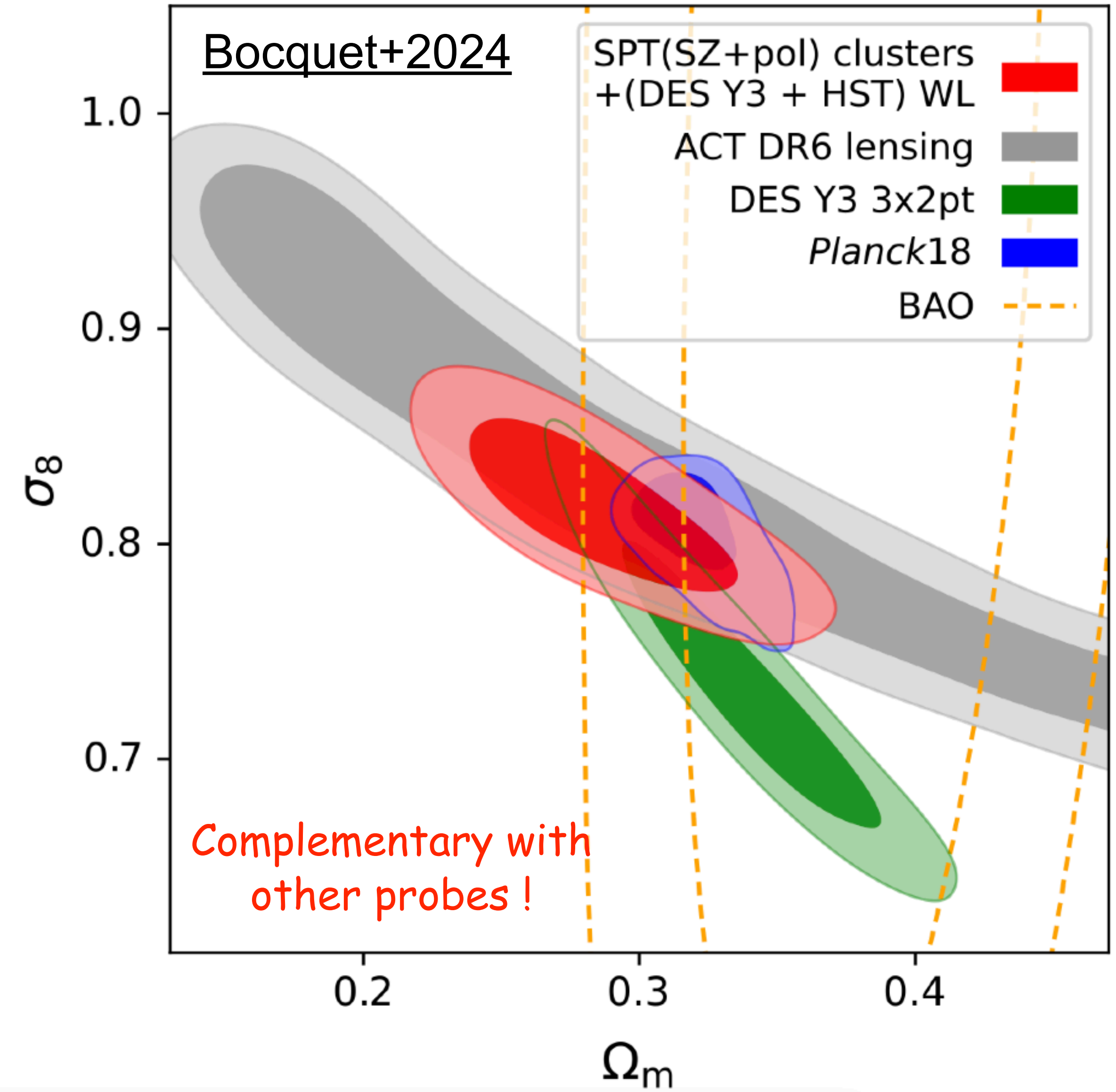
Cosmology with cluster counts

The abundance of galaxy clusters

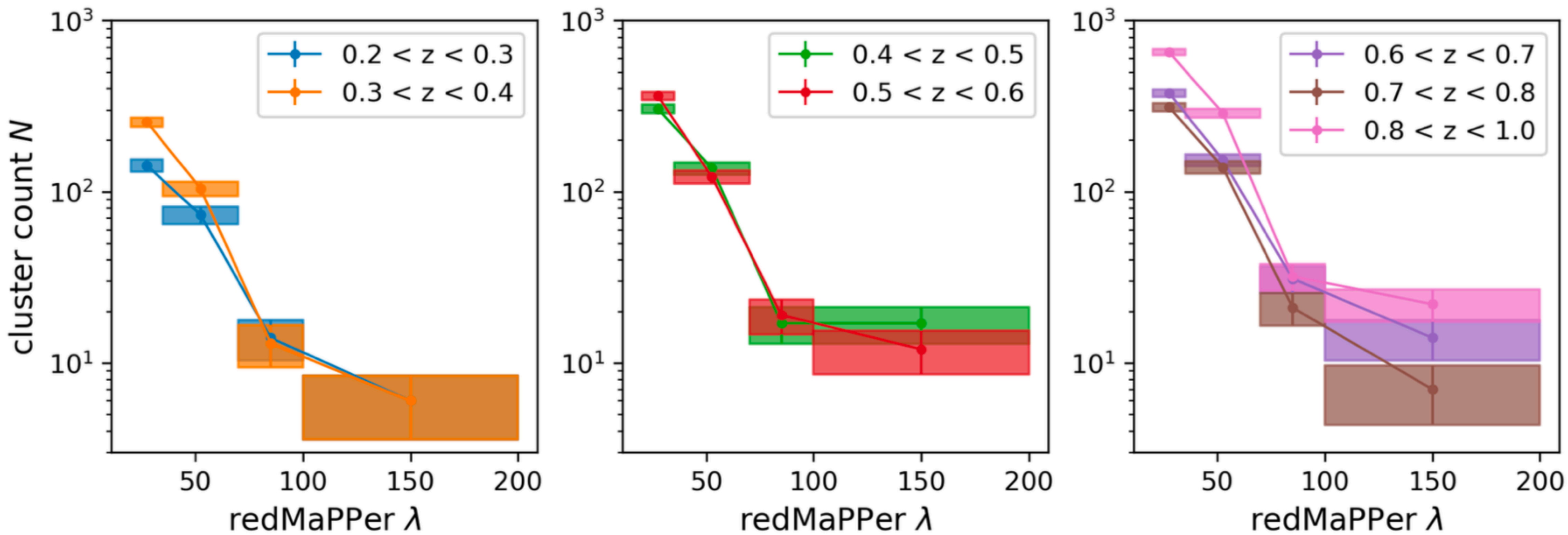
- Connects proxy-cluster counts to cosmology via a scaling relation:

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

- 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 (LSST, Euclid, SO) $\sim$ 100,000 clusters (x10 current datasets)
- Requires robust modeling of observables, better control of systematics in deriving MoR



CC Data: LSST DESC DC2 simulations



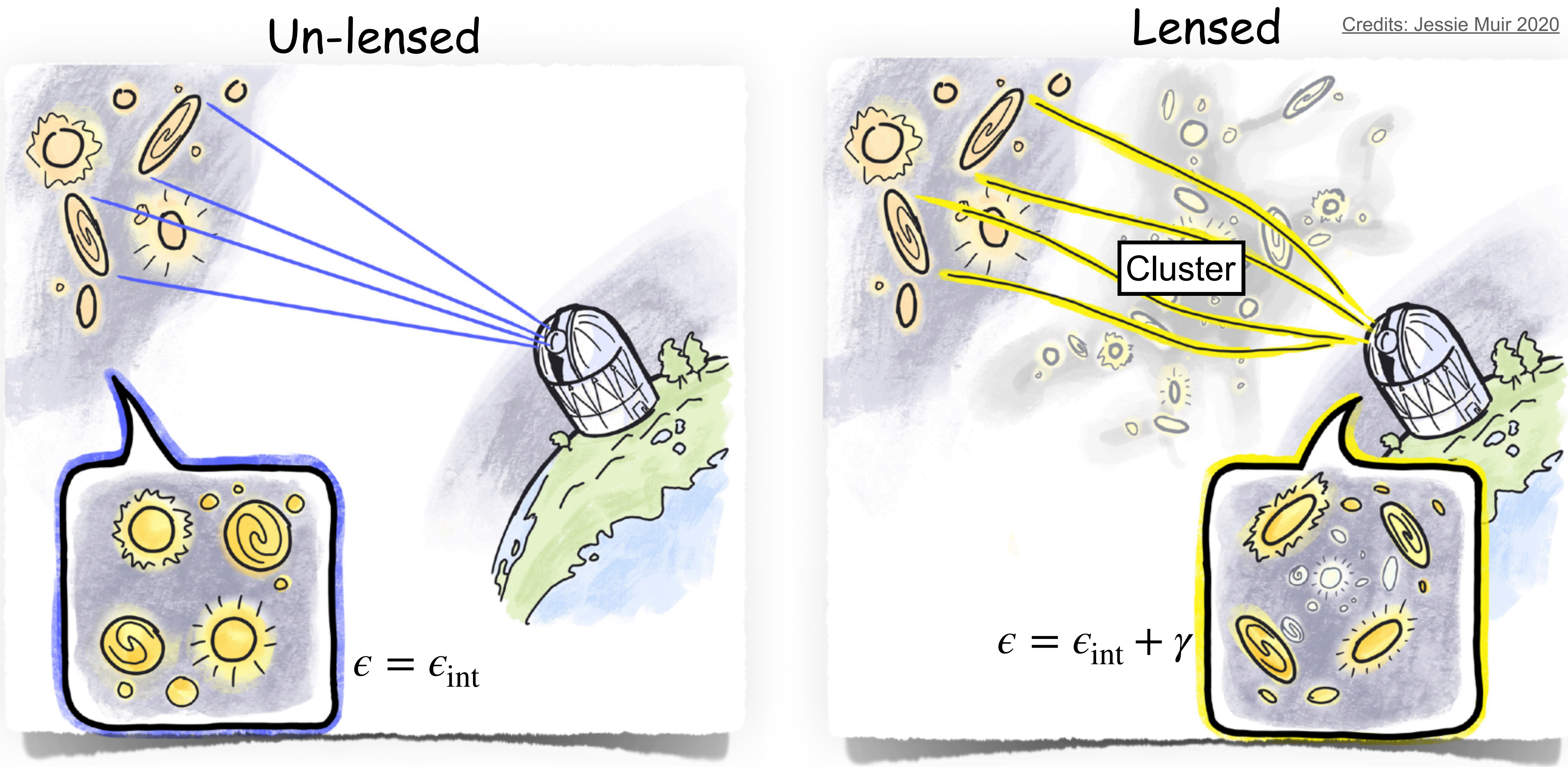
Cluster catalog: redMaPPer

- detect over densities of red-sequence galaxies
- For each redMaPPer selected clusters:
  - Assign richness $\lambda \sim$ # of member galaxies
  - Cluster redshift
- cosmoDC2: $\sim$ 880,000 clusters with $\lambda < 300$ and $z < 1.15$

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

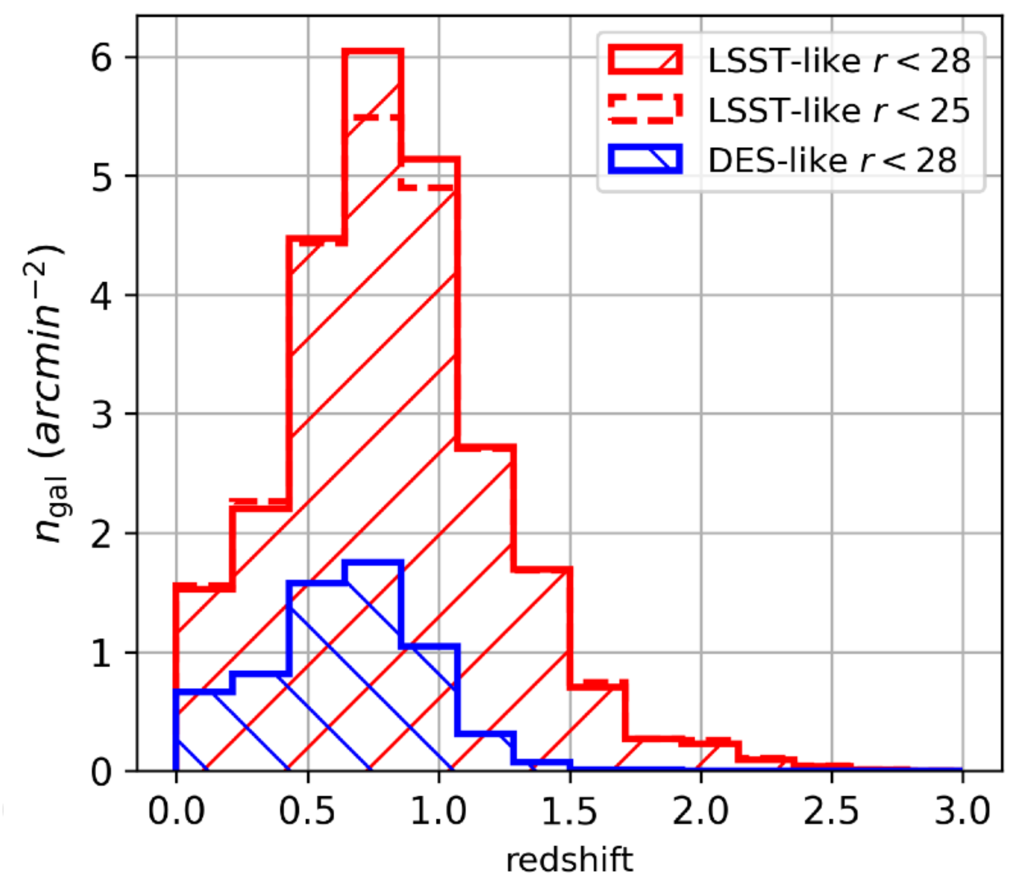
Weak lensing by galaxy clusters

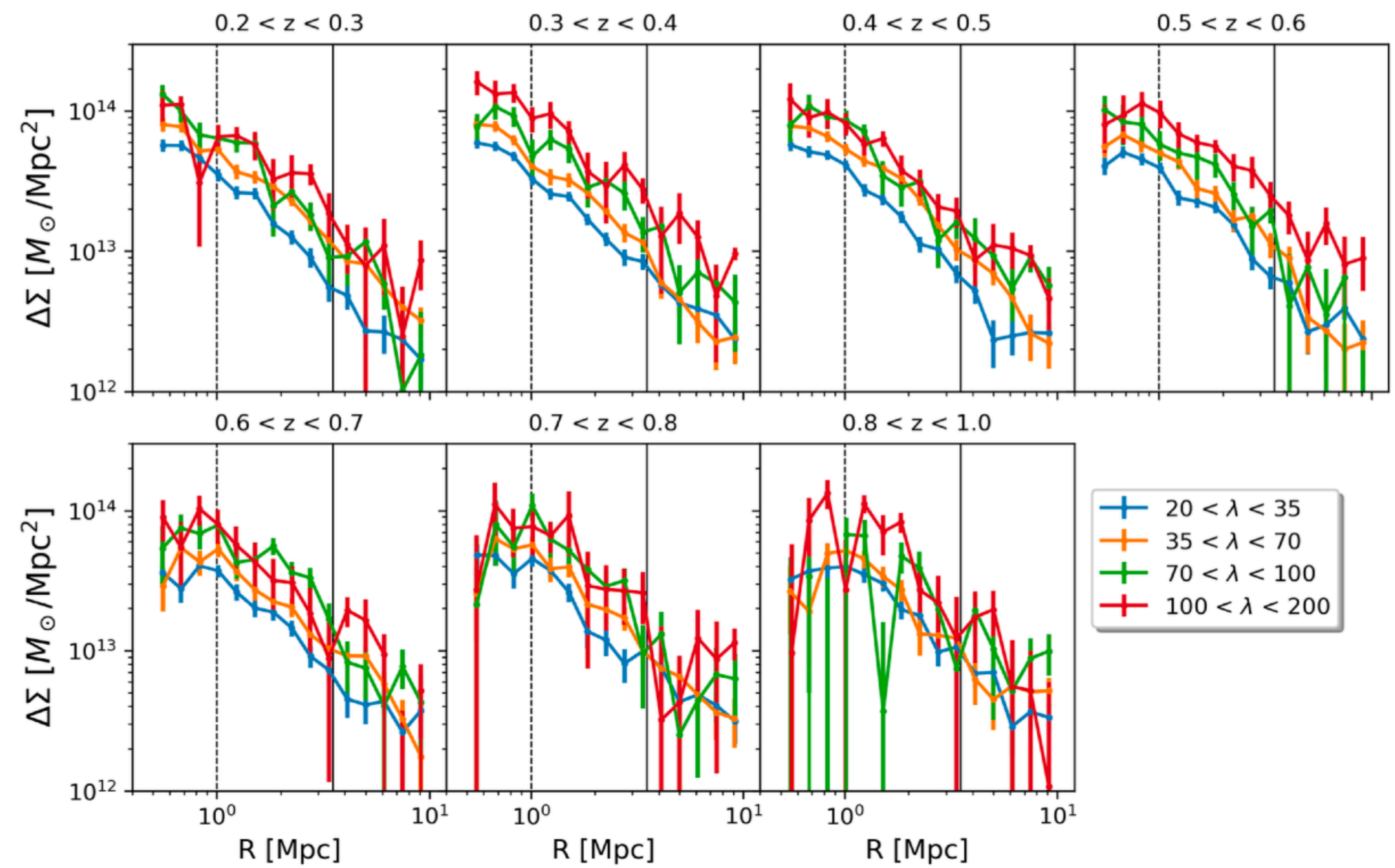


Weak lensing by galaxy clusters

- 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 $\gamma = f(M_{\rm cluster})$

WL Data: cosmoDC2 + add-ons





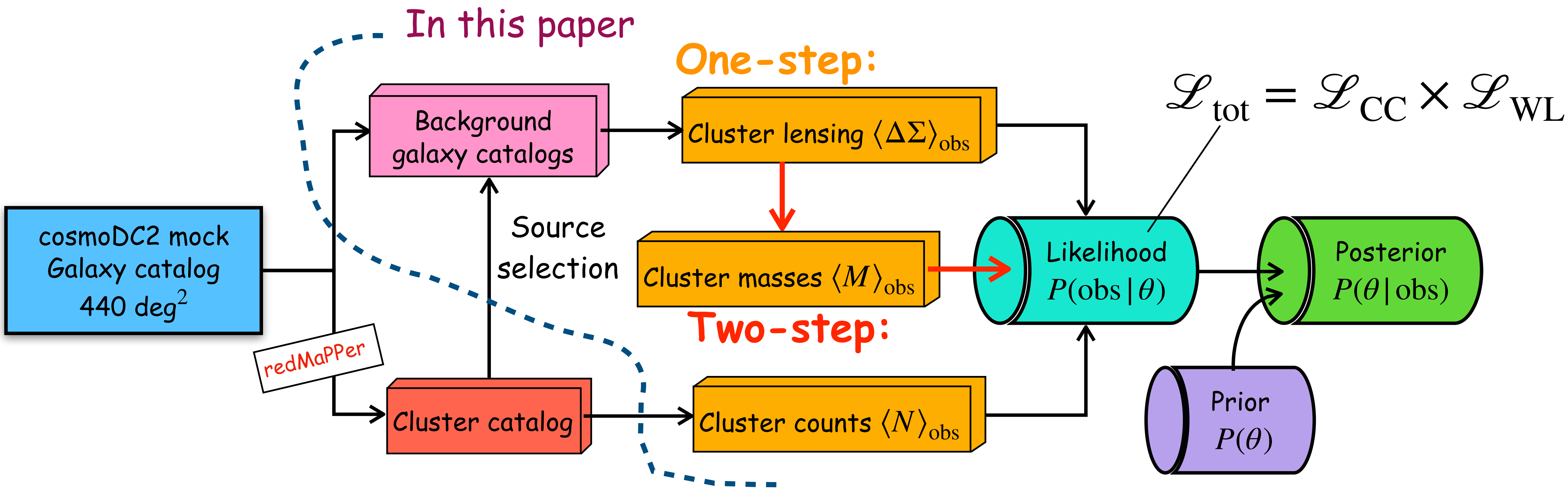
Source selection

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

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 1-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.

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

Or

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

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

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 « backward » $P(\ln M\,|\,\lambda,z)$
- 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

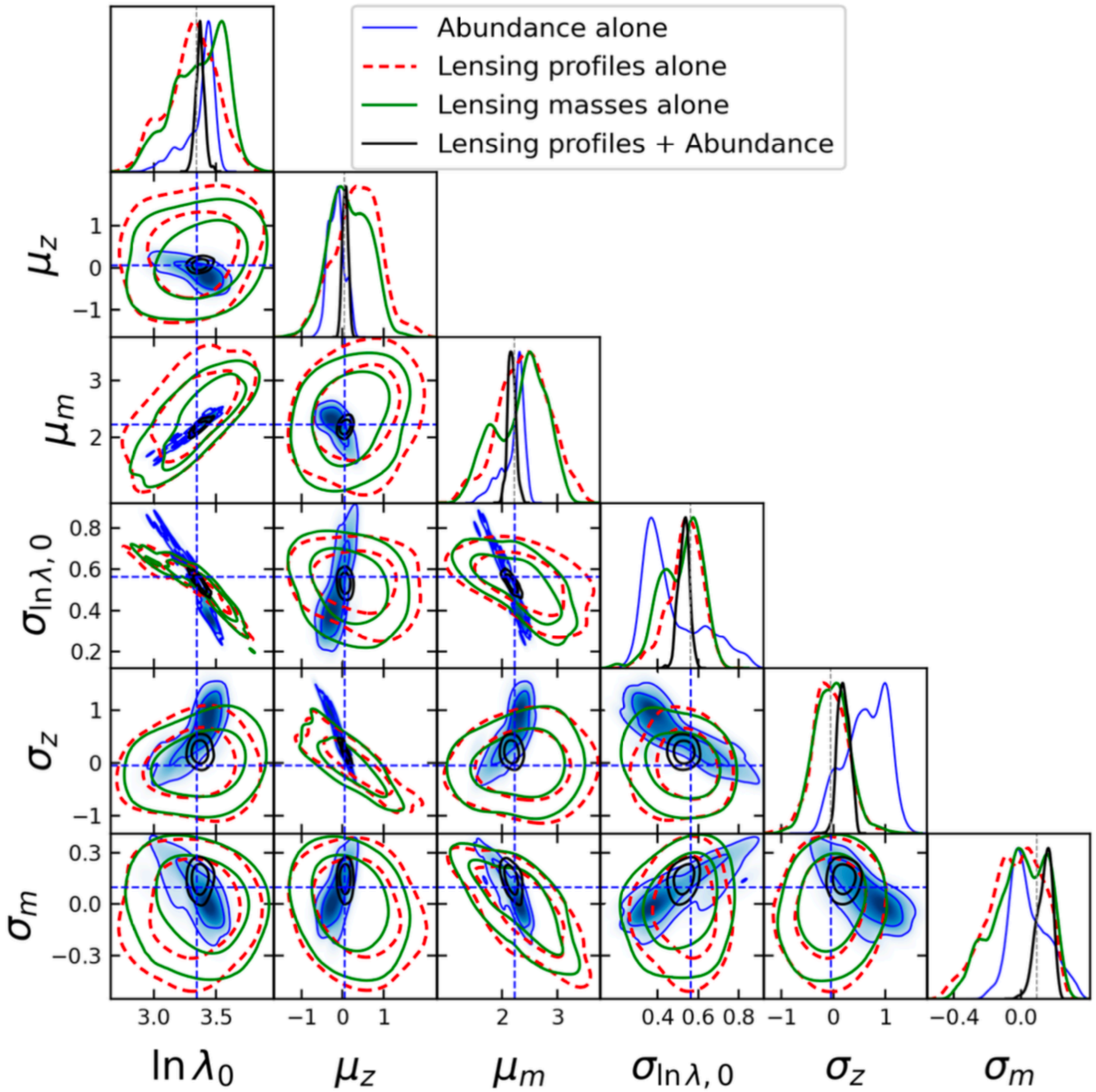
Baseline analysis

Separate Count and lensing

- Different correlations and error
- Compatible constraints at 1σ
- Compatible with « fiducial » relation:
    1. cluster-halo matched catalog
    2. => set of $\{M_i;\ \lambda_i;\ z_i\}$
    3. Inferred at the catalog level

Joint analysis

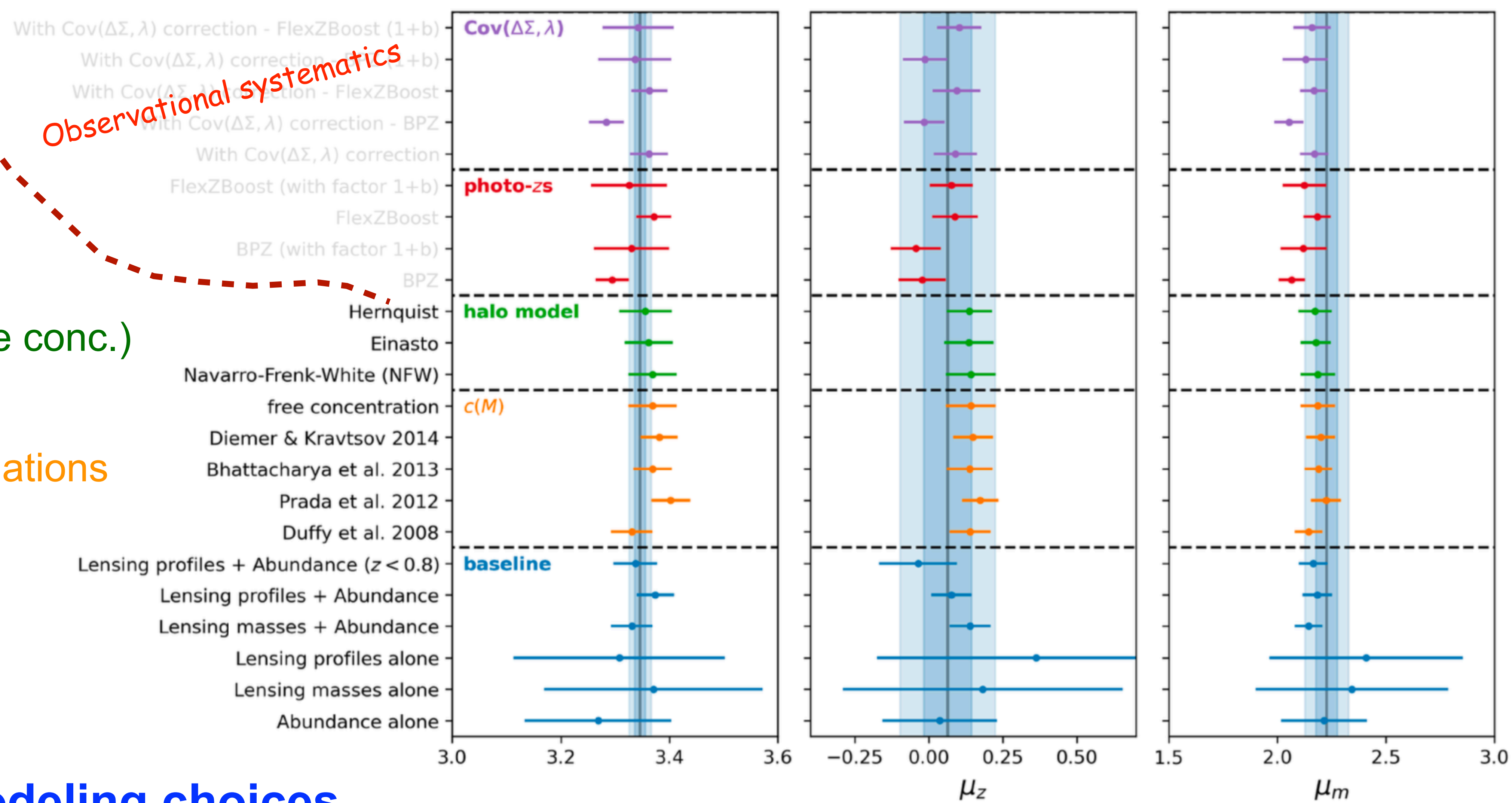
- Combination breaks degeneracy between params.
- Increase precision significantly
- Recovered fiducial at < 2σ
- Consistency between the 2-steps and 1-step approaches!



Robustness of MoR in LSST DESC DC2

Different $\rho(r)$ (free conc.)

Different c(M) relations



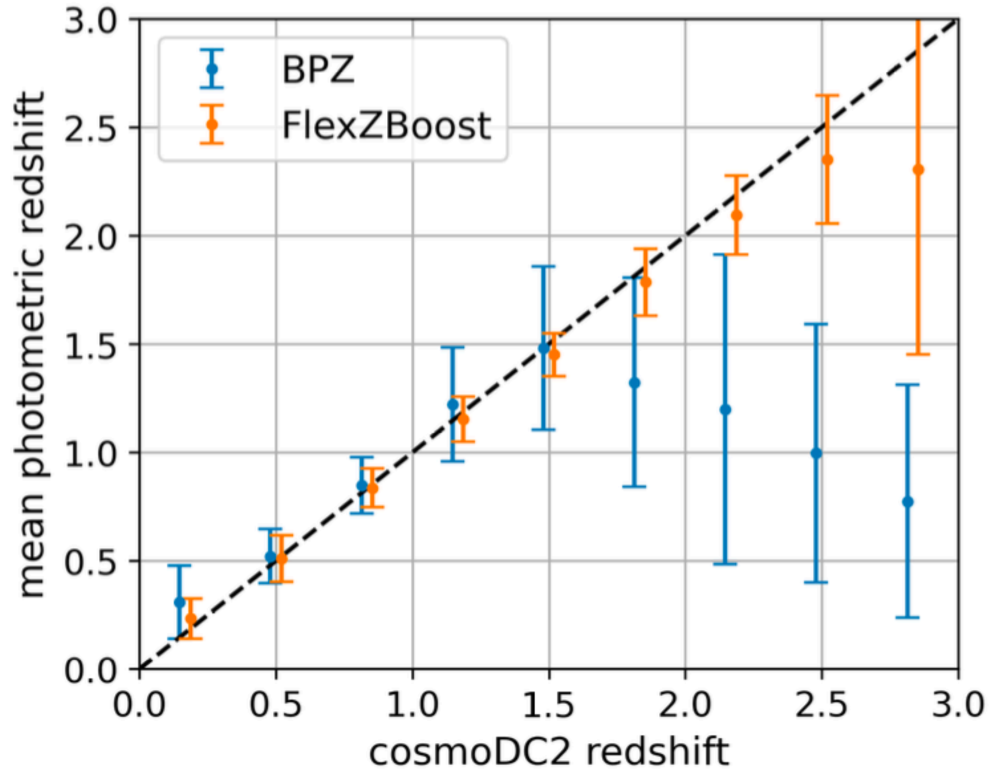
Impact of modeling choices

- c(M): consistent with free c, low impact due to R > 1 Mpc
- Density profile: perfect agreement
- Conclusion: 1 < R < 3.5, one-halo regime, MoR stable !

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. ?



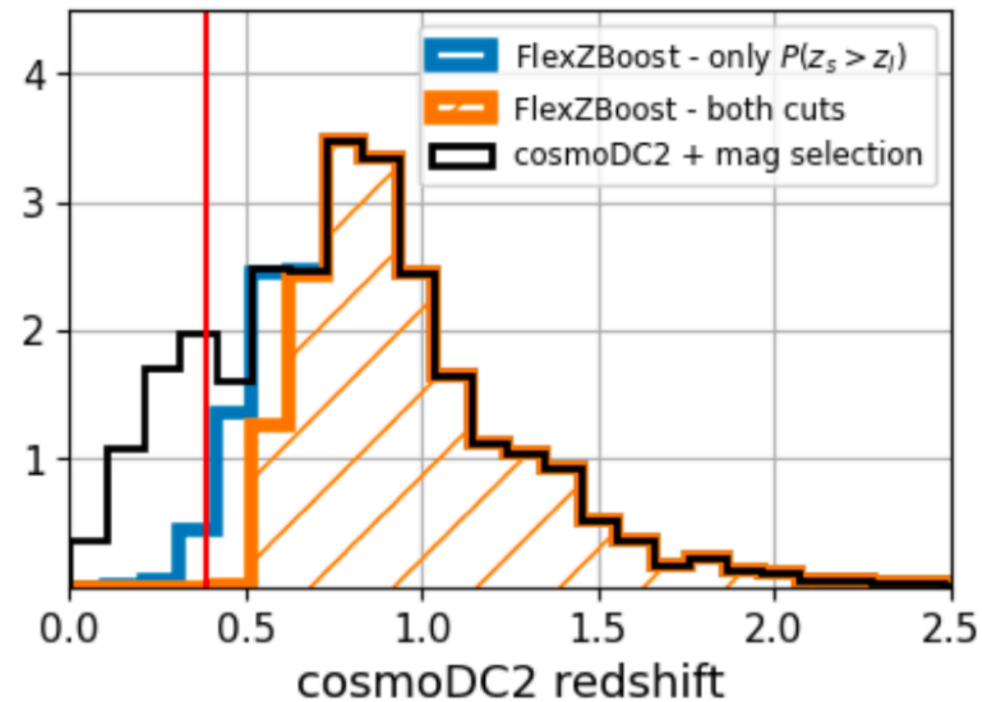
1. Source selection →

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

2. WL lens-source weights

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

$$\propto \frac{D_{ls}}{D_s D_l}$$



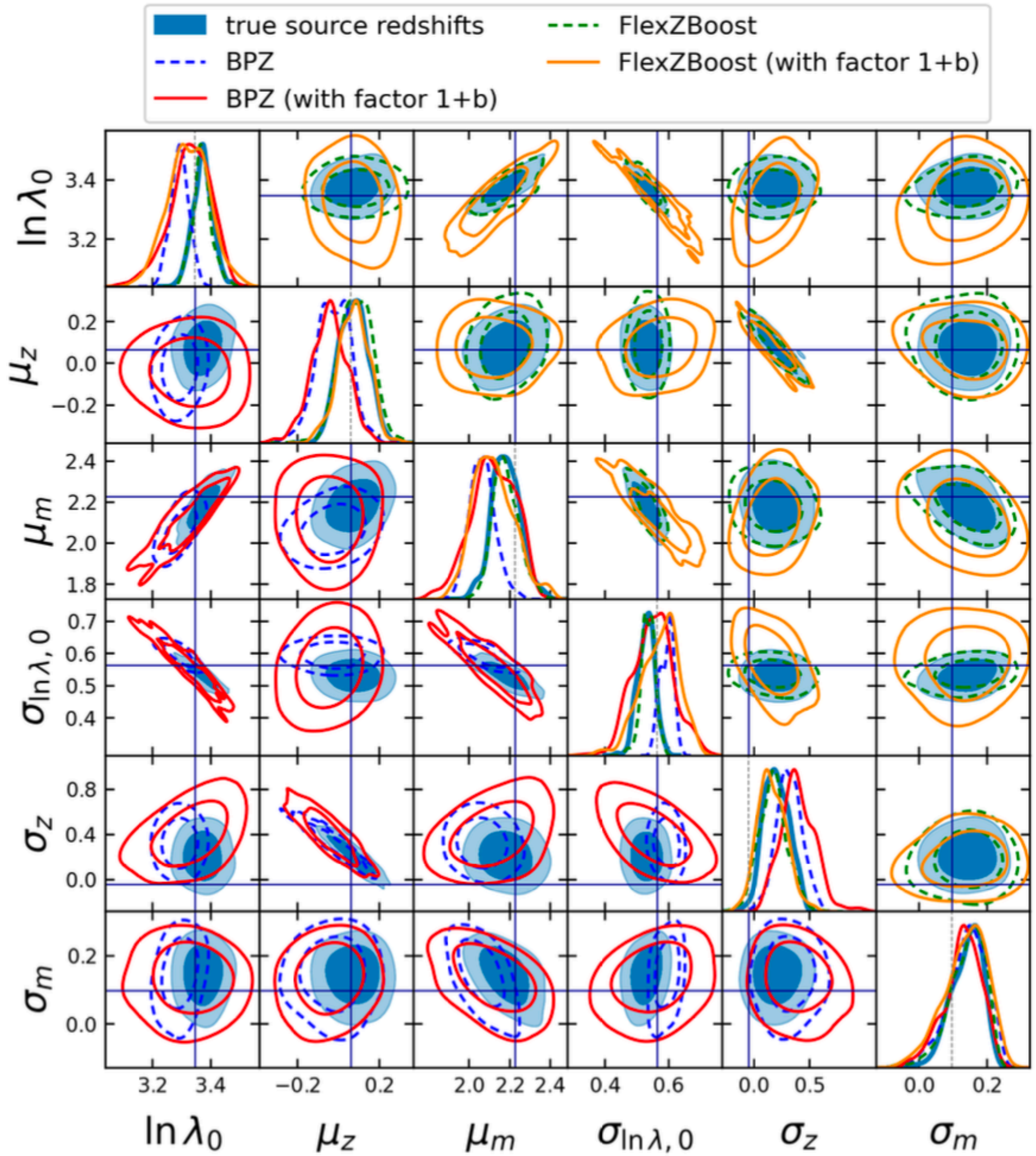
Results

- 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
- And use CC+WL to calibrate this bias

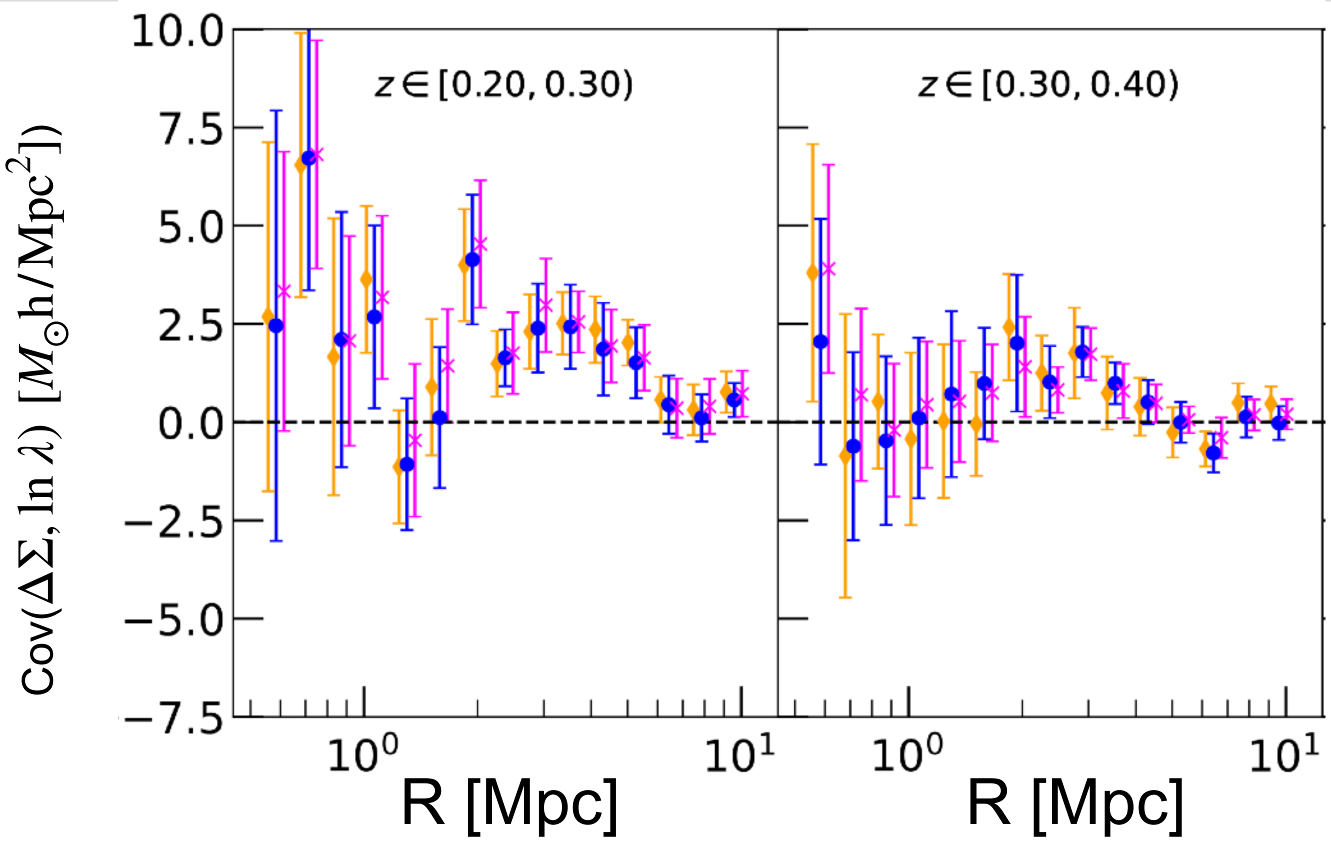
$$\Delta\Sigma_{ij}^{\rm corr} = \underbrace{(1+b)}_{\text{Uncorrected PZ systematics}}\Delta\Sigma_{ij}$$

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

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



Shear-richness covariance in CL analyses



Shear-richness covariance

- Correlation between lensing obs. and richness
  - arises from halo formation+baryonic physics (<0)
  - selection bias/projection effects (>0)
- Impact unexplored in the literature (when uncorrelated scatters are subdominant)
- Important for low-richness CL analyses with LSST (post-DES CL Y1 analysis)
- Corrected $\Delta\Sigma$ depending on $\beta_1 \mathrm{Cov}(\Delta\Sigma, \ln\lambda)/\mu_m)$

In cosmoDC2

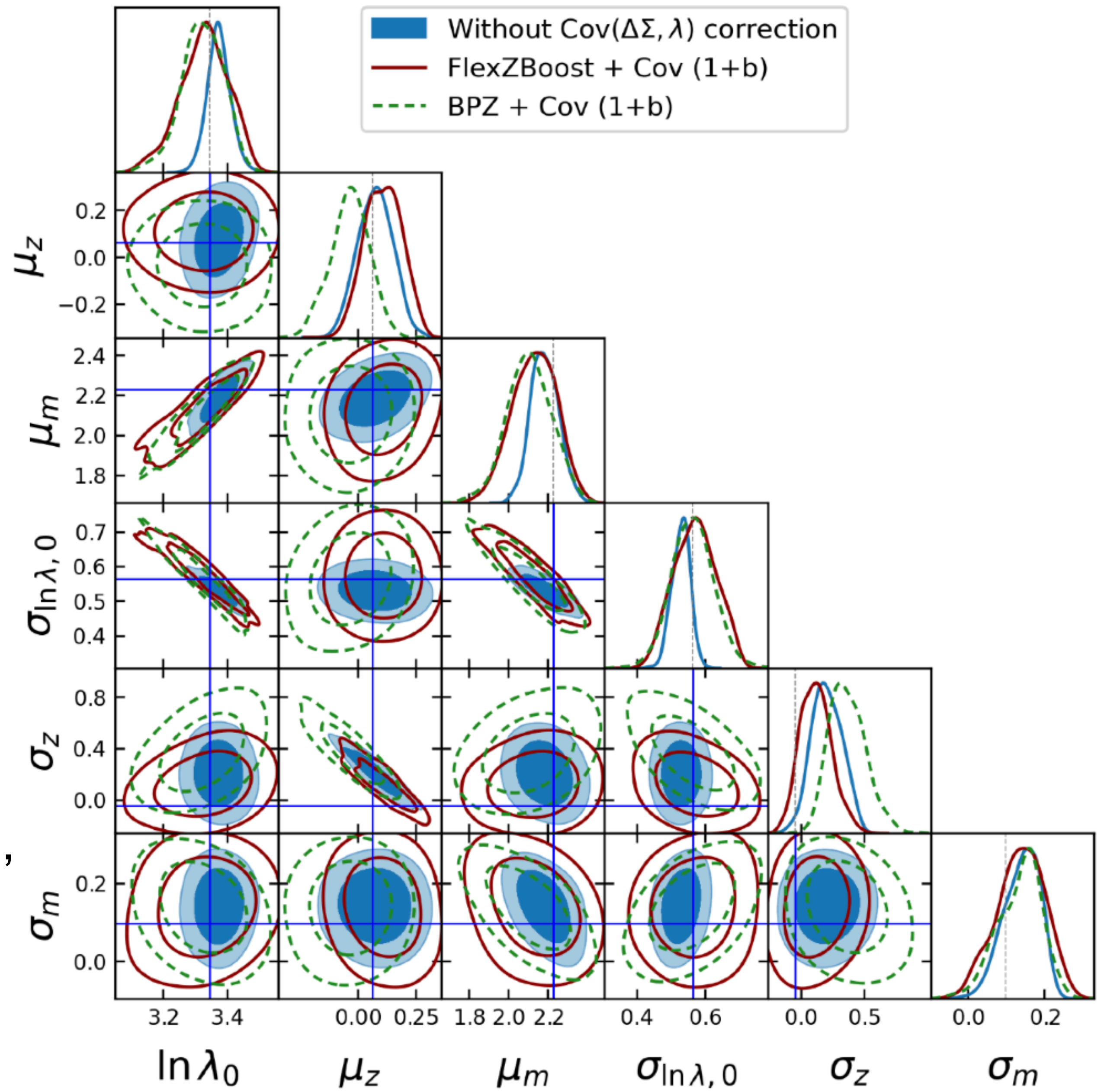
- cosmoDC2: 0.1% - 0.01% of standard profile
- Expected: HOD model for cosmoDC2 halos, idealistic run for redMaPPer (true ugrizy magnitudes)
- Shifts comparable to FleXZBoost-only fits

Recap

Impact on MoR

- **Modeling choices:**
  - Consistency between the one- and two-step approach (<$1\sigma_{\rm stat.}$)!
  - up to $1\sigma_{\rm stat.}$ shift due to cM relation
  - Stable wrt. halo model

- **Observational systematics:**
  - Shear-richness cov. alone < $1\sigma_{\rm stat.}$, as expected
  - Stronger impact from PZ (BPZ $\sim 1\sigma_{\rm stat.}$) => we can mitigate this effect
  - Shear-richness cov. alone: Small impact < $1\sigma_{\rm stat.}$, as expected
  - Combined Mean parameters errors: increase from 30% to 90%!



Long-term project

A bit of history

- Associated to: DESC Project 380
- First talk about this project at Rubin LSST France meeting in nov. 2020!
- 2 DESC internal notes, many contributors!
- Paper accepted for publication in *A&A* (arXiv:2502.08444) !

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Constantin Payerne,[1,2,⋆] Zhuowen Zhang,[3] Michel Aguena,[4,5] Céline Combet,[2] Thibault Guillemin,[6] Marina Ricci,[4] Nathan Amouroux,[6] Camille Avestruz,[7,8] Eduardo J. Barroso,[6] Arya Farahi,[9,10] Eve Kovacs,[11] Calum Murray,[4,12] Markus M. Rau,[13,14] Eli S. Rykoff,[15,16] Samuel J. Schmidt,[17] and the LSST Dark Energy Science Collaboration

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

- CLCosmo_Sim: « Early » CL pipeline with DESC tools (CLMM, CCL, ClEvaR)
- CLCosmo_Sim_database: cosmoDC2+add-ons data vectors (only DESC members)
- **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

More talks

1. Independent DESC analysis, to be compared with the official pipeline (Firecrown, TXPipe, under construction) - **see E. Barroso's talk**
2. Other cluster finders competing for LSST science - **see T. Vinh Phat's talk!**
3. **LSST: Precision** $\times\sqrt{\Omega_{\rm LSST}/\Omega_{\rm DC2}} = 6.4$, but huge work is needed to estimate the budget of shape measurement error - **see M. Ramel's talk!**


Thank you!