DARK ENERGY SURVEY

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DARK ENERGY

Through Friedmann equations, which are Einstein equation $(G_{\mu\nu} = 8\pi G T_{\mu\nu})$ in FRWL metric $(ds^2 = -dt^2 + a^2(t)[dr^2/(1-kr^2) + r^2(d\theta^2 + sin^2\theta d\phi^2)])$, we find:

$$\Omega_K + \Omega_\Lambda + \Omega_M + \Omega_R = 1 \quad (1)$$

$$q = \frac{\Omega}{2}(1 + 3\omega) \quad (2)$$

where $\Omega_K = -\frac{k}{a^2 H^2}$, $\Omega_i = \frac{\rho_i}{\rho_{crit}}$, $\rho_{crit} = \frac{3H^2}{8\pi G}$, $p = \omega\rho$, $q = -\frac{\ddot{a}}{aH^2}$, $H = \frac{\dot{a}}{a}$

Notice that $q < 0$ if $\omega < -1/3$

High redshift $(1 + z = \frac{a(t_0)}{a(t_s)})$ measurements can say if the Universe expansion is accelerated or not *(Hubble law at 2nd order:* $H_0 d_L = z + \frac{1}{2}(1 - q_0)z^2$*)*

Observations say that we are in an accelerated Universe!

So what is going on?

THE NATURE OF DARK ENERGY

- Beyond Standard Model: new kind of matter *(scalar fields with vacuum energy* $\neq 0$ *and with* $\omega < -1/3$*. For example* $\mathcal{L} = \frac{1}{2}\partial_\mu Q \partial^\mu Q + V(Q)$*, if* $\dot{Q} << V(Q)$ *then* $\omega \sim -1$*)*

- Modified General Relativity:
  - $S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}F(\phi)R$
  - gravitons mass $\neq 0$

ΛCDM COSMOLOGICAL MODEL

In ΛCDM cosmological model $\omega = -1$ and $\rho_\Lambda = \frac{\Lambda}{8\pi G} \sim const$, *where* Λ *is the cosmological term.* The model parameters are: $\Omega_\Lambda \simeq 0.7$ $\Omega_M \simeq 0.3$ $\Omega_B \simeq 0.05$ $\Omega_R \simeq \Omega_K \simeq 0$; the difference between Ω_M and Ω_B is attributed to dark matter

There are different possible explanations to the "dark matter problem", e.g.: 1)PARTICLES, of which the classic ones are WIMP; 2) MACHOS, almost planetary compact objects; 3) MOND, $F = ma$ *for* $a > a_0$ *and* $F = ma^2/a_0$ *for* $a < a_0$ *with* $a_0 \simeq 10^{-10}ms^{-1}$*; 4)WAVE-LIKE, axions are the classical candidates.*

THE DARK ENERGY SURVEY

DES is a six-year survey that mapped 5000 deg^2 of the southern sky in five broadband filters using 570 megapixel Dark Energy Camera. The optically-selected catalog is built using redMaPPer algorithm

GOAL: testing the ΛCDM model and studying the nature of dark energy

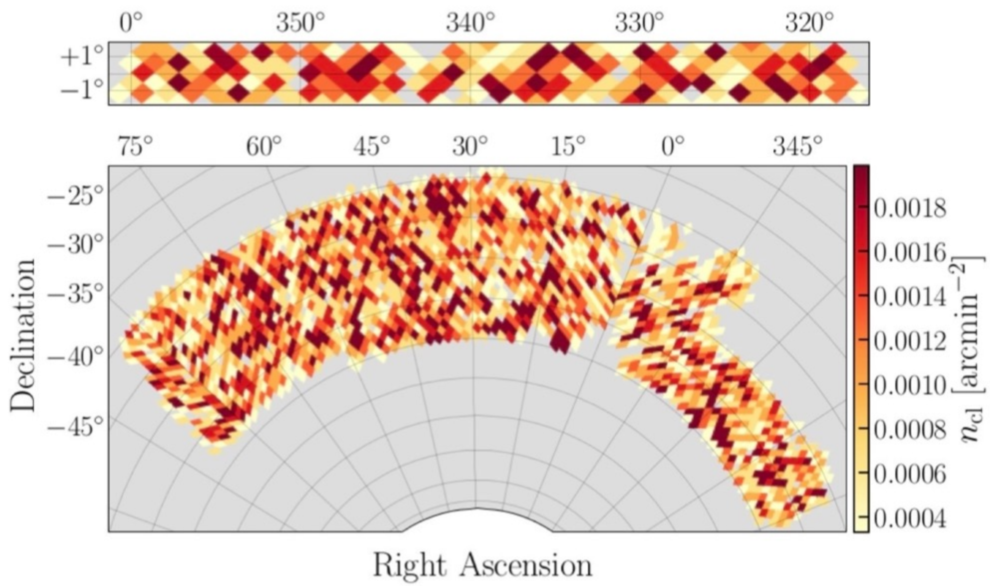

FIG. 1. The DES Y1 redMaPPer cluster density over the two non-contiguous regions of the Y1 footprint: the Stripe 82 region (116 deg^2; *upper* panel) and the SPT region (1321 deg^2; *lower* panel).

GRAVITATIONAL LENSING

Galaxy Cluster: SMACS 0723

Image credit: NASA, ESA, CSA, and STScI, James Webb Space Telescope, 2022 (infrared)

Galaxy Cluster: Abell 370

Image Credit: NASA, ESA, Hubble, 2019 (visible)

DES Y1 DATA

1. THE NUMBER OF GALAXY CLUSTERS in bins of richness and redshift
2. THE AVERAGE MASS OF THE GALAXY CLUSTERS in said bins

TABLE I. Number of galaxy clusters in the DES Y1 redMaPPer catalog for each richness and redshift bin. Each entry takes the form $N(N) \pm \Delta N$ stat $\pm \Delta N$ sys. The numbers between parenthesis correspond to the number counts corrected for the miscentering bias factors (see section III A). The first error bar corresponds to the statistical uncertainty in the number of galaxy clusters in that bin, and is the sum of a Poisson and a sample variance term. The systematic error is due to miscentering errors in the redMaPPer catalog (see text for details).

λ	$z \in [0.2, 0.35)$	$z \in [0.35, 0.5)$	$z \in [0.5, 0.65)$
$[20, 30)$	762 (785.1) $\pm$ 54.9 $\pm$ 8.2	1549 (1596.0) $\pm$ 68.2 $\pm$ 16.6	1612 (1660.9) $\pm$ 67.4 $\pm$ 17.3
$[30, 45)$	376 (388.3) $\pm$ 32.1 $\pm$ 4.5	672 (694.0) $\pm$ 38.2 $\pm$ 8.0	687 (709.5) $\pm$ 36.9 $\pm$ 8.1
$[45, 60)$	123 (127.2) $\pm$ 15.2 $\pm$ 1.6	187 (193.4) $\pm$ 17.8 $\pm$ 2.4	205 (212.0) $\pm$ 17.1 $\pm$ 2.7
$[60, \infty)$	91 (93.9) $\pm$ 14.0 $\pm$ 1.3	148 (151.7) $\pm$ 15.7 $\pm$ 2.2	92 (94.9) $\pm$ 14.2 $\pm$ 1.4

TABLE II. Mean mass estimates for DES Y1 redMaPPer galaxy clusters in each redshift bin. The reported quantities are $\log_{10}(\mathrm{M})$ where masses are defined using a 200-mean overdensity criterion ($M_{200\mathrm{m}}$). The masses are measured in $h^{-1}\mathrm{M}_\odot$ and include the selection effect correction discussed in Appendix D. The first error bar refers to the statistical error in the recovered mass, while the second error bar corresponds to the systematic uncertainty.

λ	$z \in [0.2, 0.35)$	$z \in [0.35, 0.5)$	$z \in [0.5, 0.65)$
$[20, 30)$	14.036 $\pm$ 0.032 $\pm$ 0.045	14.007 $\pm$ 0.033 $\pm$ 0.056	13.929 $\pm$ 0.048 $\pm$ 0.072
$[30, 45)$	14.323 $\pm$ 0.031 $\pm$ 0.051	14.291 $\pm$ 0.031 $\pm$ 0.061	14.301 $\pm$ 0.041 $\pm$ 0.086
$[45, 60)$	14.454 $\pm$ 0.044 $\pm$ 0.050	14.488 $\pm$ 0.044 $\pm$ 0.065	14.493 $\pm$ 0.056 $\pm$ 0.068
$[60, \infty)$	14.758 $\pm$ 0.038 $\pm$ 0.052	14.744 $\pm$ 0.038 $\pm$ 0.052	14.724 $\pm$ 0.061 $\pm$ 0.069

SYSTEMATIC UNCERTAINTIES IN CLUSTER MASS CALIBRATION

Source of systematic	Y1 Amplitude Uncertainty
Shear measurement	1.7%
Photometric redshifts	2.6%
Modeling systematics	0.73%
Cluster triaxiality	2.0%
Line-of-sight projections	2.0%
Membership dilution + miscentering	0.78%
Total Systematics	4.3%
Total Statistical	2.4%
Total	5.0%

SYSTEMATIC UNCERTAINTIES IN CLUSTER COUNTS

The covariance matrix of cluster counts is due to Poisson noise, sample variance and cluster miscentering

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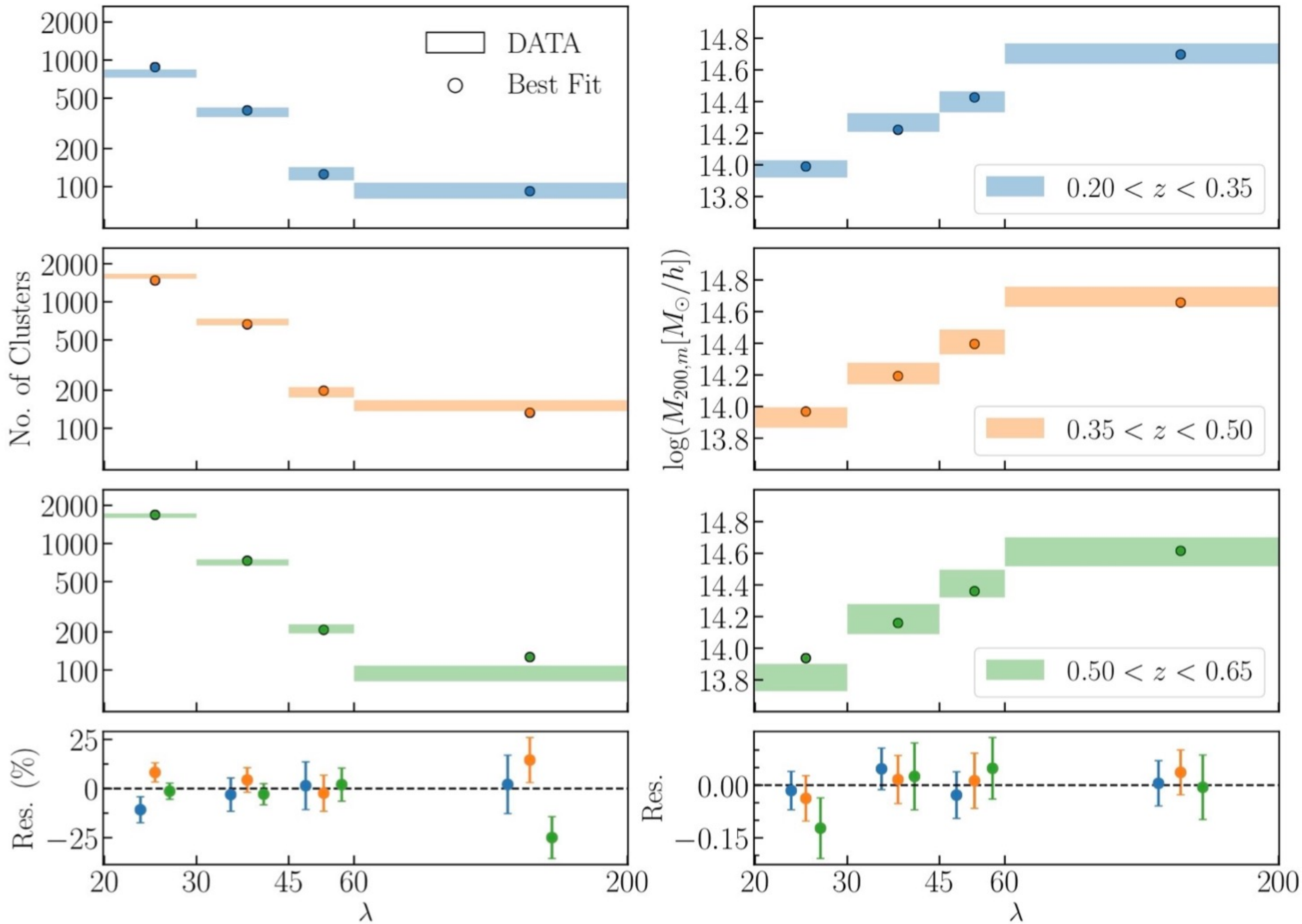
RESULTS



DATA
Best Fit
No. of Clusters
Res. (%)
$\log(M_{200,m}[M_\odot/h])$
Res.
$0.20 < z < 0.35$
$0.35 < z < 0.50$
$0.50 < z < 0.65$
λ

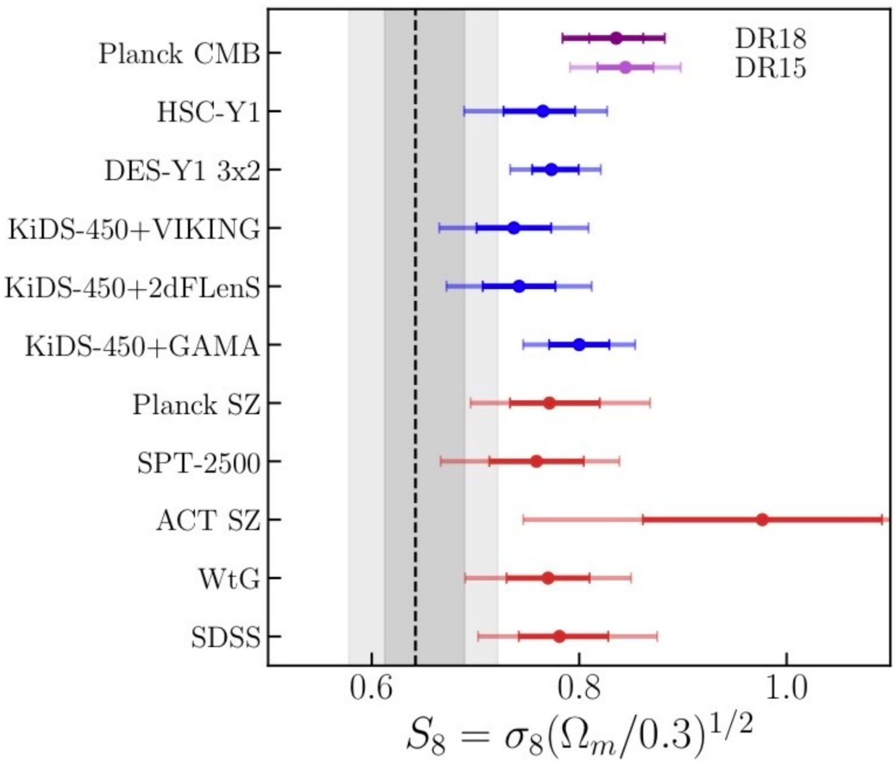
COSMOLOGICAL CONSTRAINTS

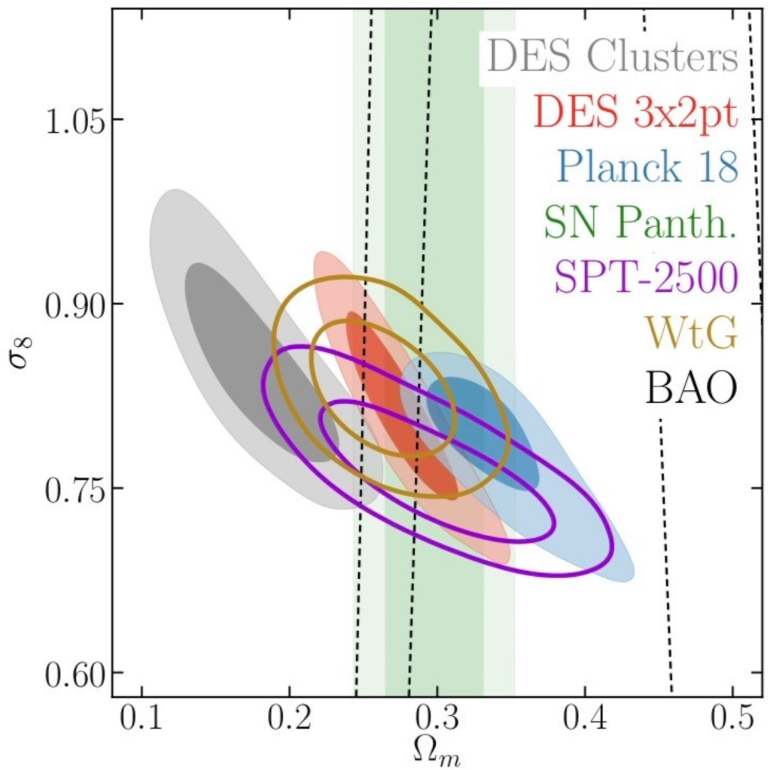
TABLE III. Model parameters and parameter constraints from the joint analysis of redMaPPer DES Y1 cluster abundance and weak-lensing mass estimates. In the third column we report our model priors: a range indicates a top-hat prior, while $\mathcal{N}(\mu, \sigma)$ stands for a Gaussian prior with mean μ and variance σ^2. The fourth column lists the modes of the 1-d marginalized posterior along with the 1-σ errors. Parameters without a quoted value are those for which the marginalized posterior distribution is the same as their prior.

Parameter	Description	Prior	Posterior
Ω_m	Mean matter density	$[0.0, 1.0]$	$0.179^{+0.031}_{-0.038}$
$\ln(10^{10} A_s)$	Amplitude of the primordial curvature perturbations	$[-3.0, 7.0]$	4.21 ± 0.51
σ_8	Amplitude of the matter power spectrum	–	$0.85^{+0.04}_{-0.06}$
$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$	Cluster normalization condition	–	$0.65^{+0.04}_{-0.04}$
$\log M_{min}[\mathrm{M}_\odot/h]$	Minimum halo mass to form a central galaxy	$(10.0, 14.0)$	11.13 ± 0.18
$\log M_1[\mathrm{M}_\odot/h]$	Characteristic halo mass to acquire one satellite galaxy	$\log(M_1/M_{\mathrm{min}}) \in [\log(10), \log(30)]$	12.37 ± 0.11
α	Power-law index of the richness–mass relation	$[0.4, 1.2]$	0.748 ± 0.045
ϵ	Power-law index of the redshift evolution of the richness–mass relation	$[-5.0, 5.0]$	-0.07 ± 0.28
σ_{intr}	Intrinsic scatter of the richness–mass relation	$[0.1, 0.5]$	< 0.325
s	Slope correction to the halo mass function	$\mathcal{N}(0.047, 0.021)$	–
q	Amplitude correction to the halo mass function	$\mathcal{N}(1.027, 0.035)$	–
h	Hubble rate	$\mathcal{N}(0.7, 0.1)$	0.744 ± 0.075
$\Omega_b h^2$	Baryon density	$\mathcal{N}(0.02208, 0.00052)$	–
$\Omega_\nu h^2$	Energy density in massive neutrinos	$[0.0006, 0.01]$	–
n_s	Spectral index	$[0.87, 1.07]$	–

$$\Omega_m = 0.179^{+0.031}_{-0.038} \neq 0.3. \text{ Why?}$$

COMPARISON WITH OTHER CONSTRAINTS FROM THE LITERATURE

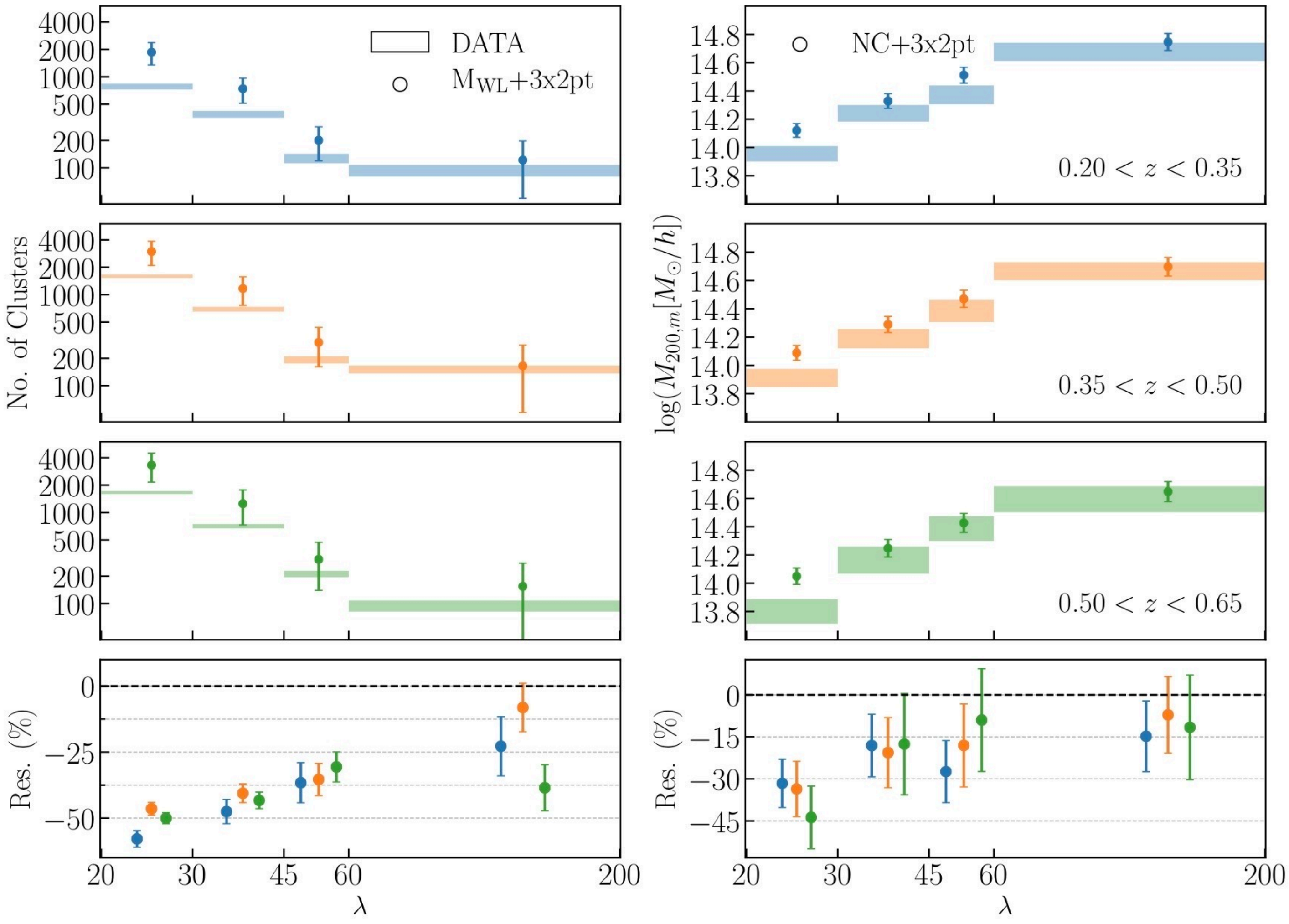




What is wrong with cluster analysis?

SELECTION EFFECT BIAS

It induces correlation between lensing signal and cluster richness at fixed mass



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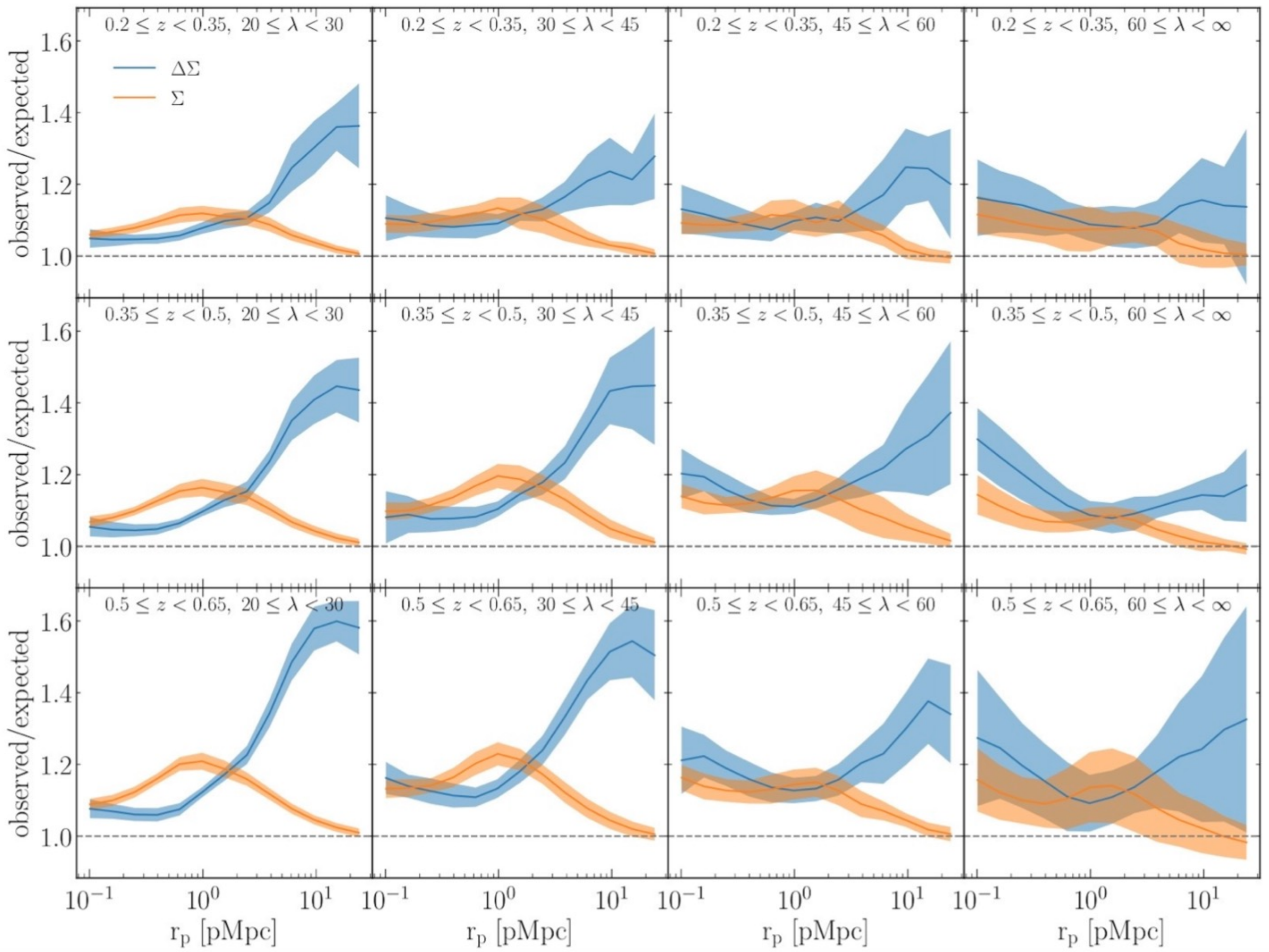
SURFACE DENSITY AND EXCESS SURFACE DENSITY

$$\Sigma(R) = \Omega_m \rho_{crit} \int_{-\infty}^{\infty} dz\, \xi_{hm}(\sqrt{R^2 + z^2}) \quad (3)$$

$$\Delta\Sigma(R) = \langle\Sigma\rangle(< R) - \Sigma(R) = \frac{2}{R^2} \int_0^R dR'\, R'\, \Sigma(R') - \Sigma(R) \quad (4)$$



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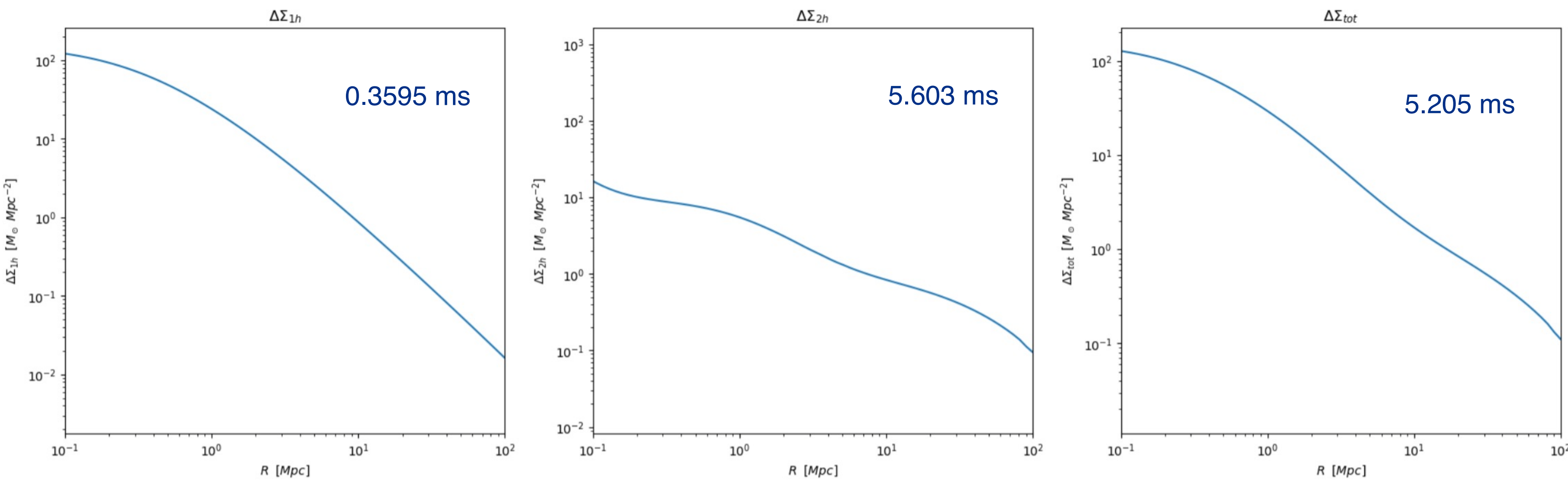
OUR WORK

❶ TIME

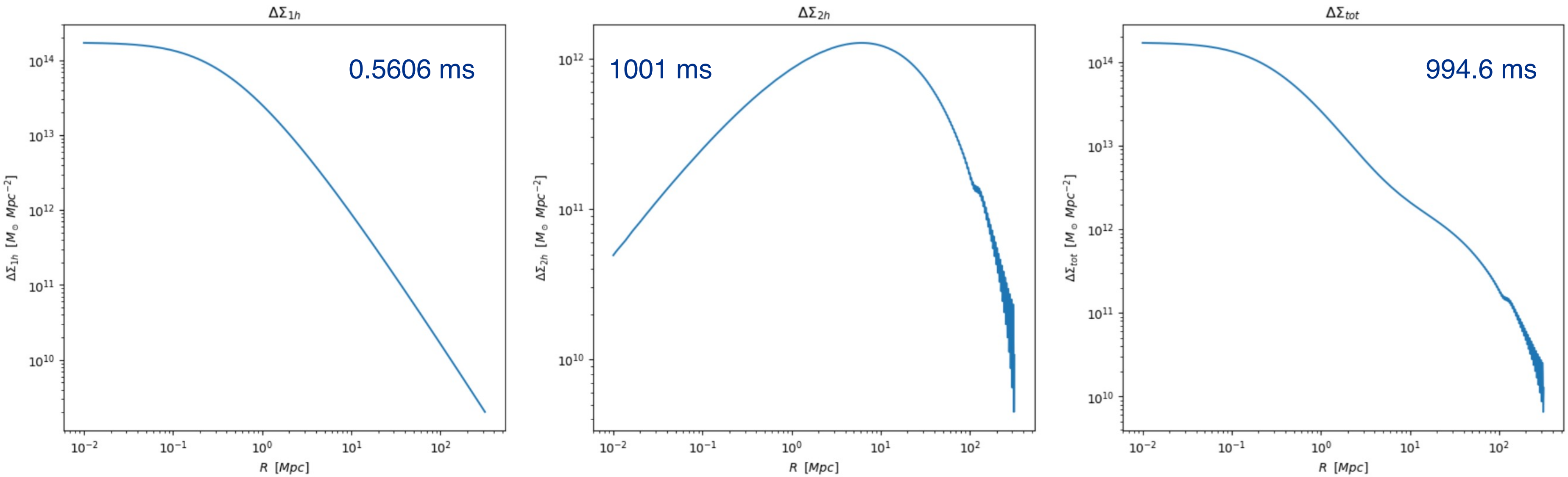
Compare the time needed to compute $\Delta\Sigma$ from cluster toolkit, CCL, CLMM
in order to find the fastest one

cluster toolkit:

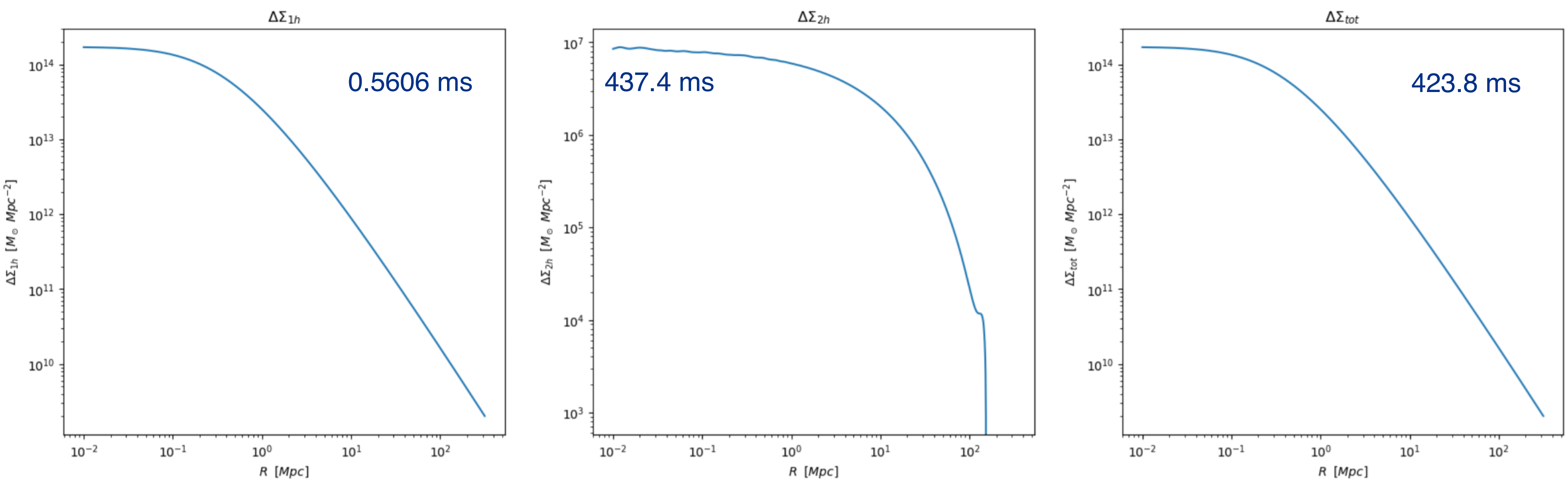


CLMM:

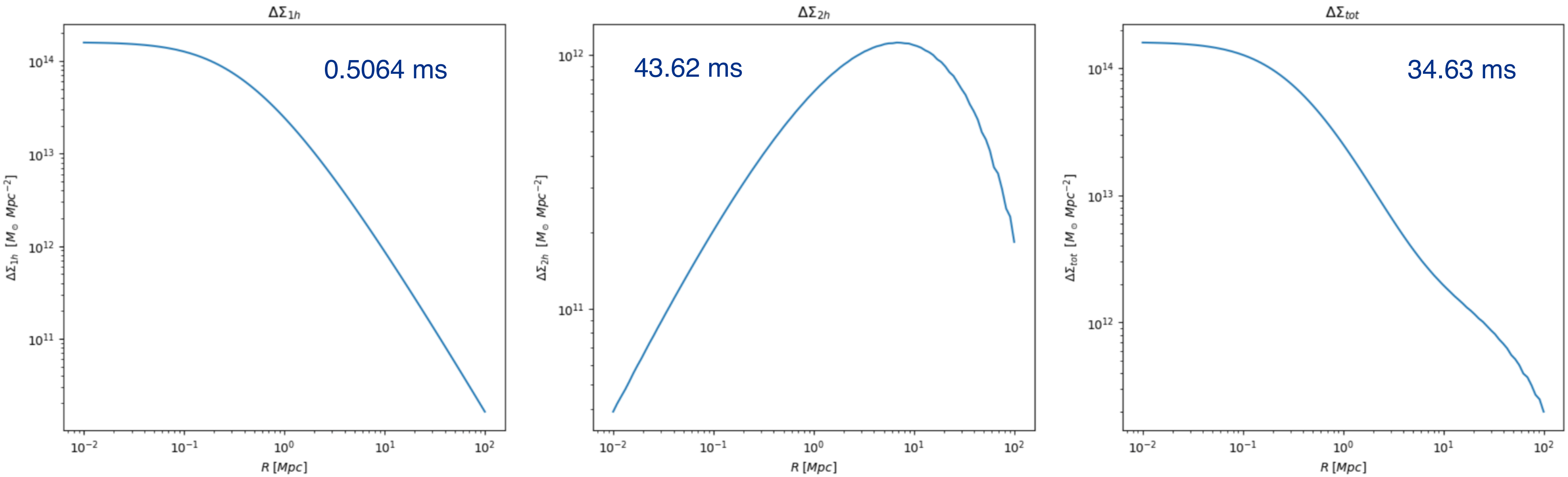
Simpson integration



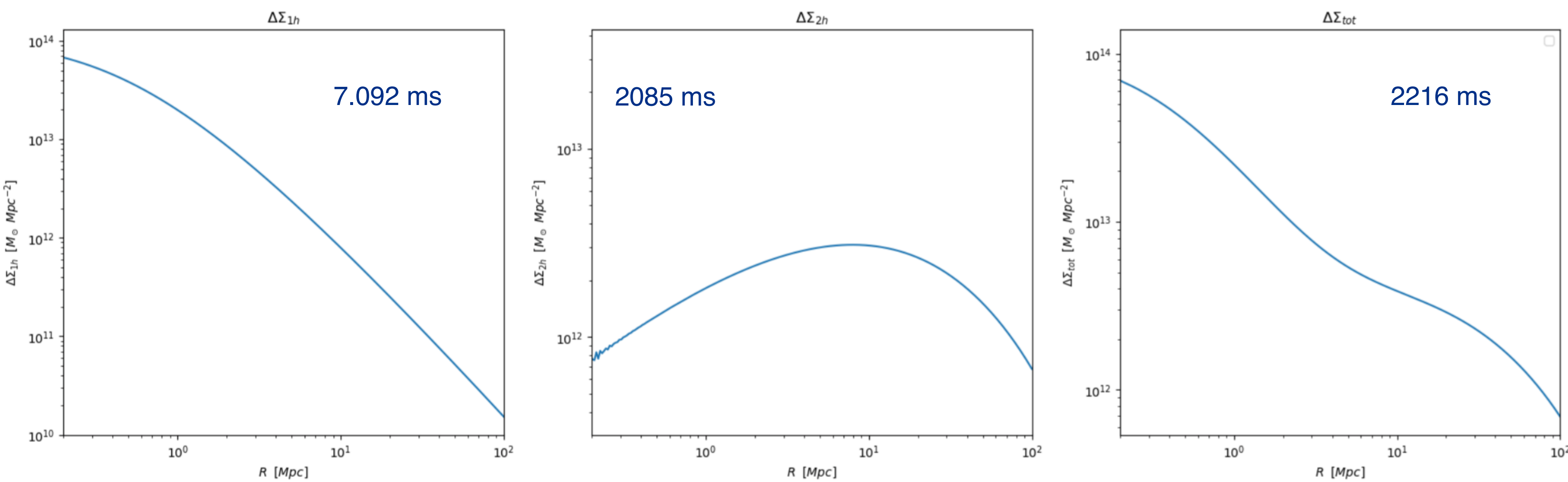
Hankel function



clmm functions



CCL:



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❷ MODEL

- Observed/expected Σ: $\Pi(R) = \begin{cases} \Pi_0 (R/R_0) & \text{for } R \leq R_0 \\ \Pi_0 + c \; ln(R/R_0) & \text{for } R > R_0 \end{cases}$

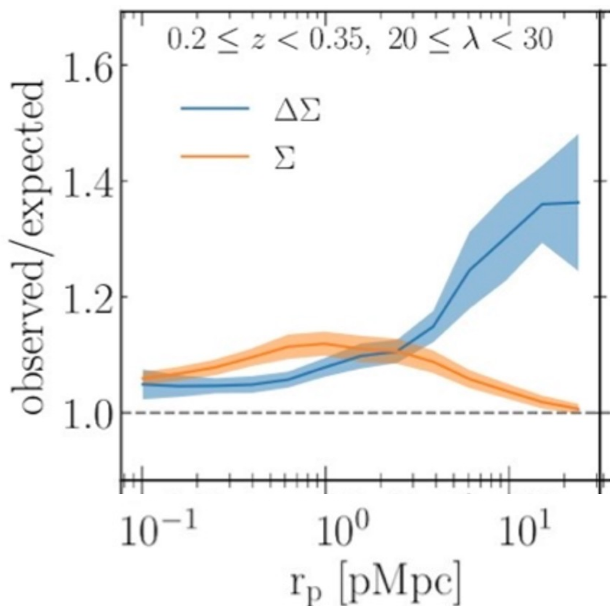
Π_0 and R_0 are defined for each richness bin, while c is shared across all richness bins

- Observed/expected $\Delta\Sigma$: $\Delta\Pi(R) = a \; ln(R)^2 + b \; ln(R) + c$

with $a = a_0 + (\lambda/30)^{\alpha_a} + ((1+z)/1.3)^{\beta_a}$,

$b = b_0 + (\lambda/30)^{\alpha_b} + ((1+z)/1.3)^{\beta_b}$ and $c = c_0 + (\lambda/30)^{\alpha_c} + ((1+z)/1.3)^{\beta_c}$

All the parameters are shared across the bins



❸ MODULE

Consider a simultaneous likelihood

↓

Write two new modules

↓

Include them into the pipeline

```
[pipeline]
modules = consistency camb mf_tinker deltasigma SigmaCentY1MortCUDAScalarIntegrand SigmaMiscentY1MortCUDAScalarIntegrand
 NCCentY1MortCUDAScalarIntegrand NCMiscentY1MortCUDAScalarIntegrand finish parabola SigmaMort_Like
; The file to get cosmological and nuisance parameters
; from.
values = ${Y3_CLUSTER_CPP_DIR}/y1_rerun/values_y1_analysis.ini
likelihoods = SigmaMort_Like
extra_output = cosmological_parameters/sigma_8
quiet=T
debug=T
timing=T
```

↓

Run the code using CosmoSIS

↓

New cosmological constraints will be obtained

❹ NEXT STEPS

- $\Omega_m^{new} \simeq 0.3$: try to find theoretical explanations to the selection effect model
- $\Omega_m^{new} \neq 0.3$: think about other possible systematics/effects and continue to consider the possibility that there could be some cluster physics which is still not known

BIBLIOGRAPHY

- Dark Energy Survey Year 1 Results: Cosmological Constraints from Cluster Abundance and Weak Lensing *arXiv:2002.11124*
- Cluster cosmology with anisotropic boosts: Validation of a novel forward modeling analysis and application on SDSS redMaPPer clusters *arXiv:2112.09059*
- Dark Energy Survey Year 1 results: weak lensing mass calibration of redMaPPer galaxy clusters *arXiv:1805.00039*
- Optical selection bias and projection effects in stacked galaxy cluster weak lensing *arXiv:2203.05416*
- Dark Energy Survey Year 3 Results: Cosmological constraints from galaxy clustering and weak lensing *arXiv:2105.13549*

THANK YOU FOR YOUR ATTENTION