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Dark Energy Survey Year 1 Results: Cosmological Constraints from Cluster Abundances, Weak Lensing, and Galaxy Correlations

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We present the first joint analysis of cluster abundances and auto/cross correlations of three cosmic tracer fields: galaxy density, weak gravitational lensing shear, and cluster density split by optical richness. From a joint analysis (4×2pt+N) of cluster abundances, three cluster cross-correlations, and the auto correlations of the galaxy density measured from the first year data of the Dark Energy Survey, we obtain $\Omega_{\rm m} = 0.305^{+0.055}_{-0.038}$ and $\sigma_8 = 0.783^{+0.064}_{-0.054}$. This result is consistent with constraints from the DES-Y1 galaxy clustering and weak lensing two-point correlation functions for the flat $\nu\Lambda$CDM model. **Consequently, we** combine cluster abundances and all two-point correlations from **across all** three cosmic tracer fields (6×2pt+N) and find improved constraints on cosmological parameters as well as on the cluster observable–mass scaling relation. This analysis is an important advance in both optical cluster cosmology and multi-probe analyses of upcoming wide imaging surveys.

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Introduction. — The standard flat ΛCDM model has been remarkably successful at describing a broad range of cosmological observations across the history of the universe. However, a fundamental physics explanation of the two main constituents of this model — dark matter and dark energy — is still missing. This has inspired ambitious cosmic surveys that are testing the ΛCDM model with increasingly precise measurements of complementary cosmological probes [1].

Wide-field imaging surveys, such as the Dark Energy Survey (DES[1]), the Hyper-Suprime Cam Subaru Strategic Program (HSC[2]), and the Kilo Degree Survey (KiDS[3]), are one class of these cosmic surveys, which map the spatial distribution, shapes, and colors of millions of galaxies. These data sets enable a wide range of cosmological measurements [2–8]. Two of the most established cosmological probes are galaxy clustering and weak gravitational lensing. Analyses that include the auto-correlation of these two tracer fields as well as their cross correlation, galaxy–galaxy lensing, are referred to as 3×2pt analyses and are emerging as a competitive cosmological test.

The abundances and spatial distribution of galaxy clusters provide another powerful probe of cosmic structure formation and expansion history [9]. **The principal obstacle to robust cosmological inference from cluster abundances is an accurate calibration of the relation between cluster observables and cluster mass [10–14].** In this work, we combine three cluster related cross-correlations with galaxy clustering to calibrate this relation. **We note that despite the use of galaxy clustering, the cosmological information in our combined analysis is driven by the the cluster abundance data, with galaxy clustering breaking degeneracies between cosmology and the cluster observable–mass relation.**

In this *letter*, we first demonstrate the consistency between our cluster cosmology analysis (4×2pt+N), the 3×2pt analysis, and other cluster cosmology analyses, in the context of the ΛCDM model with massive neutrinos ($\nu\Lambda$CDM). We then present the first *joint* analysis, referred to as 6×2pt+N, of galaxy clusters abundances and clustering, galaxy clustering, and weak gravitational lensing. In Fig. 1, we summarize the different components of the analysis. Our analysis uses the same set of systematics modeling, calibration procedures, and analysis pipeline across all probes, and properly accounts for the covariance between the probes. We demonstrate that combining galaxy clusters and the 3×2pt analysis improves both cosmological and cluster mass–observable relation constraints, compared to these individual analyses.

Data and Measurement. — We measure galaxy density fields, weak gravitational lensing shear fields, and cluster density fields from the 1321 deg^2 of imaging data taken in the first season of the Dark Energy Survey [15] (DESY1). The measurement is based on procedures described in [16] using the DESY1 public catalogs[4]. These include the redMaGiC galaxy catalog [17] for the galaxy density field; the METACALIBRATION shape catalog [18] and BPZ photometric redshift (photo-z) catalog [19] for the weak gravitational lensing shear field; and the redMaPPer cluster catalog [20] for the cluster density field. To construct the galaxy density field, $\sim 650,000$ redMaGiC galaxies over the redshift range $0.15 < z < 0.9$ are split into five redshift bins based on their photo-z estimations. The weak gravitational lensing shear field is constructed based on ~ 26 million galaxies spanning the redshift range $0.2 < z < 1.3$, split into four redshift bins based on BPZ photo-z estimation. For the cluster density fields, 4794 redMaPPer clusters are split into three redshift bins spanning **the** range $0.2 < z < 0.6$. **The** clusters are further split into four bins based on their richness (λ), a cluster mass proxy defined as a weighted sum of the cluster red-sequence member galaxies. The clusters span the richness range $20 < \lambda < 235$.

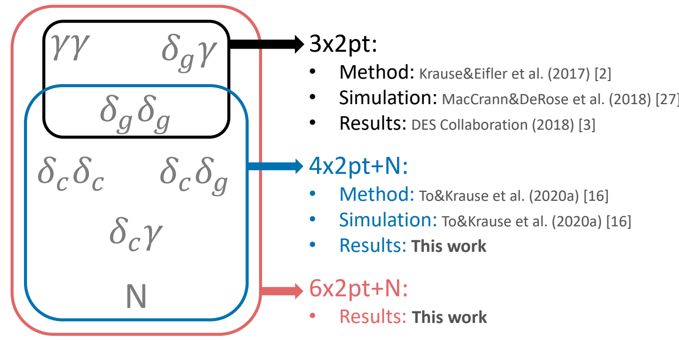

FIG. 1. Summary of the different components in this analysis and a non-exhaustive list of papers describing and validating our methodology. **A more comprehensive list of relevant references can be found in** [3, 14, and references therein]. The data in this paper consist of cluster abundances (N) and six two-point correlation functions derived from three cosmic tracer fields, namely galaxy density (δ_g), weak gravitational lensing shear (γ), and cluster density (δ_c). The correlation functions include cosmic shear ($\gamma\gamma$), galaxy–galaxy lensing ($\delta_g\gamma$), galaxy clustering ($\delta_g\delta_g$), cluster–galaxy cross-correlation ($\delta_c\delta_g$), cluster auto-correlation ($\delta_c\delta_c$), and cluster lensing ($\delta_c\gamma$).

We measure six two-point correlations from the three cosmic tracer fields, as described in Fig. 1. The 3×2pt correlations are the DESY1 public 3×2pt data vector[5]. The cluster (cross-)correlations and cluster abundances are measured following procedures described in [16].

Modeling + Inference. — **We assume a Gaussian likelihood function as detailed below.**

Covariance and Model — The covariance matrix [21] is derived based on halo models [22, 23] and is validated in

[1] https://www.darkenergysurvey.org/
[2] http://www.naoj.org/Projects/HSC/HSCProject.html
[3] http://www.astro-wise.org/projects/KIDS/
[4] https://des.ncsa.illinois.edu/releases/y1a1/key-catalogs
[5] https://des.ncsa.illinois.edu/releases/y1a1/key-products

[2, 16]. The derivation and construction procedures are detailed in [16]. **We** relate the abundances of galaxy clusters to the halo mass function [24] assuming a power-law relation with log-normal scatter between the halo mass and cluster richness [16]. The three cosmic tracer fields are assumed to be linearly **related** to the matter density field, **whose power spectrum is modeled** using CLASS [25] and HALOFIT [26]. The model of cosmic shear and galaxy–galaxy lensing is described and validated in [2, 27], while the model of 4×2pt+N is described and validated in [16] with modifications to the modeling of the effect of massive neutrinos [21]. Both the covariance matrix derivation and the model prediction are implemented in COSMOLIKE [23]

Analysis Choices — **We have designed our analysis to ensure robustness of the inferred result.** Key analysis choices are summarized below.

(*i*) *Only large scale information is used.* Due to uncertainties of modeling baryonic effects, non-linear relations between cosmic tracer fields and matter density fields, and random fluctuations of sparse tracers on small scales, we adopt conservative angular scale cuts on the two-point correlation functions. The scale cuts of 3×2pt data vectors are defined and validated in [2]; the scale cuts of 4×2pt+N are defined and validated in [16].

(*ii*) *The same set of parameters and priors are used in 3×2pt, 4×2pt+N, and 6×2pt+N analyses.* In addition to the six cosmological parameters in the $\nu\Lambda$CDM model, we simultaneously sample over 26 nuisance parameters [21]. These include galaxy bias parameters (5), lens and source galaxy photo-z biases (9), multiplicative shear biases (4), intrinsic alignment parameters (2), parameters describing the richness–mass relation (4), and parameters describing selection bias for clusters (2). For detailed descriptions of these nuisance parameters and the associated priors, we refer the readers to [2, 16, 21]. We note that we do not account for intrinsic alignments in the cluster lensing analysis. The effect is expected to be small [28] and was not included in the previous weak lensing analysis of the same sample [29]. In addition, in the cluster lensing model, we exclude bins where the maximum redshift of galaxy clusters is larger than the mean redshift of source galaxies.

(*iii*) *The analysis was done blindly.* Cosmological parameters were blinded by random shifts before the analysis choices were determined. We detail our blinding procedure in [21].

We use Multinest [30] to generate Monte Carlo Markov Chain (MCMC) samples from the posterior. We find consistent results when using emcee [31].

Results and Discussions — Table I presents the cosmological parameter constraints from 3×2pt, 4×2pt+N, and 6×2pt+N.

Parameter	3×2pt	4×2pt+N	6×2pt+N	Flat Prior
$\Omega_{\rm m}$	0.297 ± 0.036	$0.305^{+0.055}_{-0.038}$	$0.276^{+0.033}_{-0.026}$	[0.1,0.9]
A_s ($\times 10^9$)	$2.15^{+0.38}_{-0.34}$	$2.27^{+0.57}_{-0.41}$	$2.08^{+0.41}_{-0.31}$	[0.5, 5]
n_s	-	-	-	[0.87, 1.07]
$\Omega_{\rm b}$	-	-	-	[0.03,0.07]
$\Sigma m_\nu [eV]$	-	-	-	[0.047, 0.931]
h	-	-	-	[0.55, 0.91]
σ_8	$0.771^{+0.064}_{-0.054}$	$0.783^{+0.064}_{-0.054}$	$0.802^{+0.056}_{-0.048}$	Derived
χ^2 (d.o.f)	512 (444)	610 (567)	1054 (992)	
p-value	0.014	0.103	0.084	

TABLE I. Summary of cosmological parameter constraints in the $\nu\Lambda CDM$ model from three combinations of data vectors, as described in Fig. 1 The number reported is the 1D peak of the posterior and the asymmetric 68% confidence interval. Cells with no entries correspond to posteriors dominated by the priors. The last two rows summarize the goodness of fit for each data vector computed at the best-fit model.

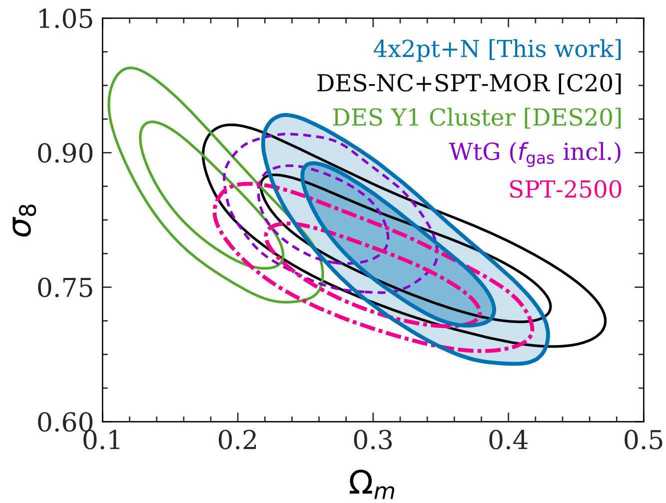

FIG. 2. Comparison of $\nu\Lambda$CDM constraints on $\Omega_{\rm m}$ and σ_8 derived from 4×2pt+N (blue) and other cluster cosmology analyses in the literature: DES-Y1 joint analysis of cluster abundances and weak lensing mass estimates from [14] (green); a joint analysis of DES cluster abundances and SPT-SZ multiwavelength data from [32] (black); the Weighing the Giants study from [11] (purple); the SPT-2500 analysis from [12] (pink). Contours show 68% and 95% confidence levels.

Cluster cosmology — We first compare our cosmological constraints (4×2pt+N) with cluster analyses in the literature. The result is shown in Fig. 2. According to the $Q_{\rm DM}$ tension metric [33], the 4×2pt+N constraints **are consistent**[6] with most of the cluster cosmology analyses within 0.6σ, except for the constraints from

[6] Since no tension metric can guarantee consistency, we use the word ‘consistent‘ as a short expression of no significant inconsistency found by the tension metric throughout the paper.

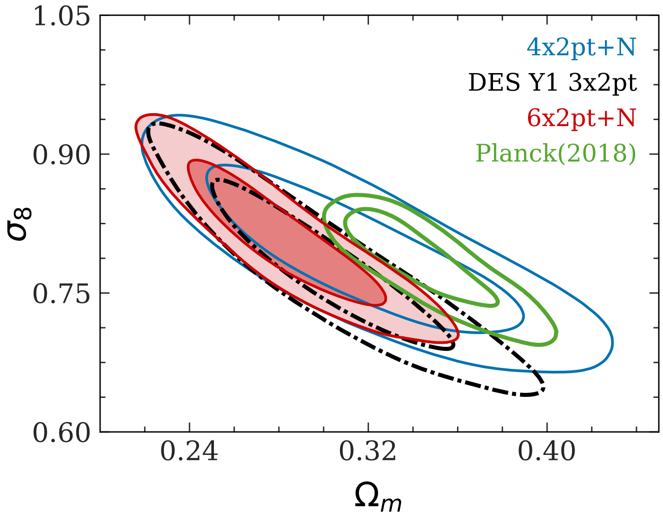

FIG. 3. $\nu\Lambda$CDM constraints on Ω_m and σ_8 from 3×2pt (black), 4×2pt+N (blue), and their combination (red). For comparison, the green contours show constraints from the CMB at high redshift (Planck without lensing). Contours show 68% and 95% confidence levels.

a joint analysis of cluster abundances and weak lensing mass estimates in the DES-Y1 data [14] (hereafter called DES20). DES20 is in 2.9σ tension with our 4×2pt+N analysis despite the fact that the two analyses share the same galaxy cluster and weak gravitational lensing shear catalogs. The main difference between 4×2pt+N and DES20 is that 4×2pt+N only uses large-scale information while the DES20 signal-to-noise is dominated by small-scale cluster lensing. We note that a similar tension has been found when comparing DES20 with a joint analysis of the DES cluster abundances and SPT-SZ multi-wavelength data [32] (hereafter called C20). In C20, the cluster mass–observable scaling relation is calibrated by cross-matching the redMaPPer and SPT-SZ catalog (mean $\lambda = 78$) and using the high-quality X-ray and weak lensing follow-up data available for 121 SPT-SZ clusters to constrain the scaling relation [34–39]. Comparison between DES20, C20, and 4×2pt+N suggests that the tension between the DES20 analysis and other cluster cosmology analyses is likely due to unmodeled systematic artifacts in the weak lensing data of the redMaPPer clusters at small scales. This is consistent with the interpretation advanced by DES20. **Alternatively,** the low lensing signal observed for redMaPPer clusters may be related to the lensing-is-low problem for massive galaxies in the SDSS [40]. Should these two lensing anomalies be related, it is interesting to note that this anomaly **disappears** at the high mass end of the mass function. The resolution to **the** lensing anomaly at small scales remains **unknown.**

Systematics of redMaPPer *clusters* — Photometrically selected galaxy clusters are subject to two important systematics: projection effects [14, 45, 46] and orientation biases [14, 47]. These two systematics bias the observed galaxy and matter overdensities of the selected galaxy clusters relative to randomly selected halos of the same mass. On large scales these two effects manifest as a **multiplicative** bias factor (b_sel) in the amplitude of the correlation functions, which can be sufficiently described by a power law in mass: $b_\mathrm{sel}(M) = b_{s0}(M/5\times10^{14}h^{-1}M_\odot)^{b_{s1}}$[16]. From the 6×2pt+N analysis, we obtain $b_{s0} = 1.15^{+0.11}_{-0.09}$ and $b_{s1} = -0.029^{+0.056}_{-0.062}$. **This result can be used to compare against future simulation-based estimates of these systematics.**

Comparison of different cosmological probes in the Dark Energy Survey — Fig. 3 shows a comparison between 3×2pt and 4×2pt+N. Here, before the analysis was unblinded, the tension metric was set to Q_UDM [33, 48], which compares the parameters from 3×2pt and from its combination with 4×2pt+N. According to Q_UDM, the tension between 3×2pt and 4×2pt+N is 0.024σ, indicating a strong consistency between galaxy clustering, weak gravitational lensing, and galaxy clusters in the context of the $\nu\Lambda CDM$ model. Given the demonstrated consistency between 3×2pt and 4×2pt+N, we proceed to perform a joint analysis of cluster abundances and all six two-point correlations derived from galaxy density fields, galaxy cluster density fields, and weak gravitational lensing shear fields. The constraints from this combination (6×2pt+N) are shown in Fig. 3. Our 6×2pt+N analysis leads to a $\sim 20\%$ improvement on the constraints of Ω_m **relative to the** 3×2pt **constraints**.

Since DES only measures the matter distribution when the universe is older than 10 billion years, it is interesting to compare our constraints **to those derived from the Early Universe as inferred from the Cosmic Microwave Background (CMB).** Specifically, we compare our result with the prediction from the joint TT, EE, BB, TE likelihood measured by the Plank satellite [49], reanalyzed using the DES analysis choice of marginalizing over the unknown sum of neutrino masses [3]. The comparison is shown in Fig. 3. Despite the visual offset between the Planck $\nu\Lambda$CDM prediction and 6×2pt+N, we find that the tension is at the level of 1.42σ, according to the tension metric [50]. The consistency between 6×2pt+N and Planck is strong confirmation of the validity of the $\nu\Lambda$CDM model. Built on many previous works [3, 14, and references therein], **Fig. 3 presents the first joint analysis of galaxy clustering, galaxy lensing, and galaxy cluster abundance and clustering. This is an important milestone in multi-probe analyses of imaging surveys.**

Mean mass of redMaPPer *clusters* — A precise measurement of cluster masses is important, for cosmological exploitation of cluster samples as well as for astrophysical studies involving galaxy clusters [e.g. 51–54]. From 4×2pt+N and 6×2pt+N analyses, we can derive the mean mass of the redMaPPer clusters and its de-

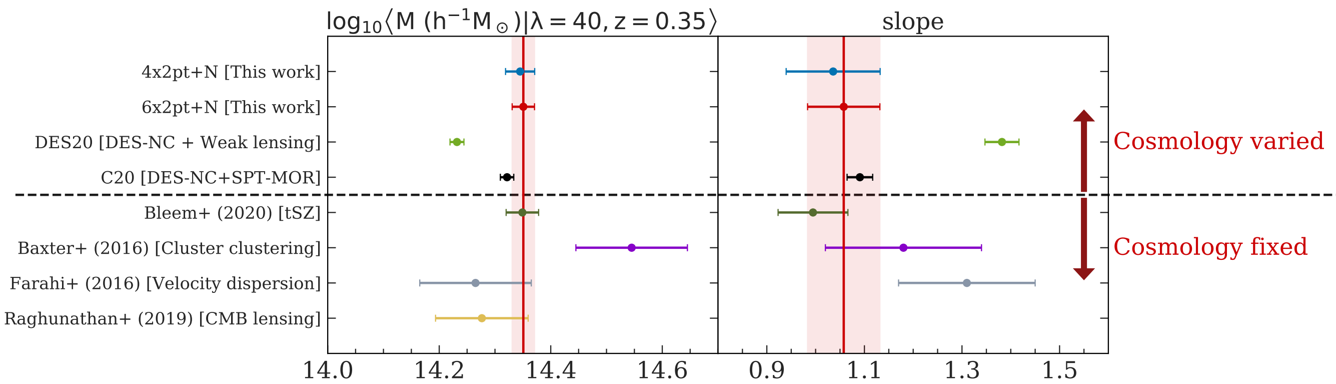

FIG. 4. Comparison of the predicted mean mass at richness $\lambda = 40$ and redshift $z = 0.35$ and the slope of the richness scaling relation from this *letter* (blue and red) with results in literature: a joint analysis of number counts and weak lensing mass estimates [14] (light green); a joint analysis of DES cluster abundances and SPT-SZ multi-wavelength data [32] (black); SZ scaling relation [41] (dark green); auto-correlations of galaxy clusters [42] (purple); velocity dispersion [43] (gray); and CMB lensing [44] (brown). Error bars show 68% confidence intervals. **The slope is unconstrained in [44]. We note that [14, 32] marginalize over cosmological parameters while [41–44] fix cosmological parameters.**

pendence on the richness. The result is shown in Fig. 4 and the calculation is detailed in [21]. **The 6×2pt+N analysis yields a $\sim 20\%$ improvement on the constraints of mean cluster masses and their richness dependency compared to 4×2pt+N.** From the 6×2pt+N analysis, the mean mass of redMaPPer clusters at $z = 0.35$ is constrained as

$$\langle M_{200\mathrm{m}}|\lambda\rangle = 10^{14.351\pm0.020}\left(\frac{\lambda}{40}\right)^{1.058\pm0.074} h^{-1}M_\odot,$$

where $M_{200\mathrm{m}}$ is the mass enclosed within a sphere in which the mean matter density is equal to 200 times the mean matter density of the universe. In Fig. 4, we compare our constraints with results in the literature and find that our constraints are competitive. **In terms of the consistency between different methods, we caution the reader that constraints on the mean mass and the slope of the mass–richness relation might change by up to 15% and 10% respectively due to assumptions about the modeling of projection effects [32]. Homogenization of projection-effect modeling is beyond the scope of this work.**

Conclusions and outlook — In this *letter*, we present the first joint analysis of cluster abundances and six two-point correlation functions derived from three cosmic tracer fields: galaxy density, weak gravitational lensing shear, and cluster density. Our findings can be summarized as follows:

(*i*) Despite the surprising results of the DES-Y1 cluster abundances analysis [14], our multi-probe cluster cosmology approach finds consistent results compared with other cluster cosmology analyses and other cosmological probes in DES. This is likely a consequence of our analysis being restricted to large scales only. This result, together with C20 [32], suggests that the modeling of small-scale cluster lensing for low mass optically selected clusters is **the likely culprit behind the surprising results in** [14].

(*ii*) We find that combining galaxy clusters with galaxy clustering and weak gravitational lensing improves both cosmological constraints and constraints on the mean mass of galaxy clusters by $\sim 20\%$, **compared to results from galaxy clustering and weak gravitational lensing.**

(*iii*) The combined cosmological constraint from DES is consistent with Planck at the 1.4σ level in the context of the $\nu\Lambda$CDM model.

(*iv*) Combining galaxy clusters with galaxy clustering and weak gravitational lensing provides a precise constraint on the mean mass of galaxy clusters and its richness dependence.

In the near future, we expect a $\sim 40\%$ improvement in cosmological constraints for 4×2pt+N from the analysis of the first three years of data from the Dark Energy Survey, mostly due to the increased survey area. This improvement will be followed by significant additional improvements from upcoming wide imaging surveys in the 2020s [55–57]. The analysis presented in this *letter* is an important step towards fully realizing the potential of these richer and larger datasets.

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