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Early Career Award DE-SC0020247 Final Report

Elisabeth Krause, University of Arizona

1 Project Goals and Status

The principle projects of this award were

Project 1 joint 3×2pt+cluster CosmoLike analysis pipeline for DES Y3 & Y6 analyses, including multi-probe covariances and model validation.

Project 1 status The Arizona CosmologyLab's CosmoLike [1] and CosmoCov [2] codes uniquely provide the multi-probe covariances required for the DES 3×2pt key projects in Y1 through Y6. Furthermore, CosmoLike is one of the two DES likelihood codes providing crucial cross-validation; for the DES-Y3 key project the PI led the corresponding *code comparison* tasks. Within DES, the PI closely mentored student and postdoc projects that extended the theoretical modeling to smaller scales and new probes:

- Dr. Xiao Fang derived and implemented a numerical stable and efficient algorithm for the computation of cosmological covariances that is based on a 2D generalization of the FFTLog algorithm [CosmoCov, Product 16], improving the theoretical modeling for covariances of correlated observables from imaging surveys derived in **??**. The data covariance is the critical ingredient for the joint analysis of correlated observables. Different cosmological probes of structure formation, such as weak lensing, galaxy clustering and galaxy clusters, all trace the same underlying, unobservable matter density field, and are thus inherently correlated. The DES landmark analyses combine different two-point statistics; thus the data covariance, which encodes the inherent correlation of two different two-point measurements, is related to the four-point correlation function of the matter density field – a theoretically and numerically challenging computation. CosmoCov is a unique product: there are no other implementations of the necessary theoretical calculations required to enable the analysis of DES data as a whole. Indeed, this code is used to generate covariances for all DES analyses of two-point statistics (weak lensing, galaxy clustering, 3x2pt, etc.).
- Shivam Pandey validated a perturbative bias model [Product 15] for DES-Y3 and led one of the Y3-2×2pt analyses combining galaxy clustering and galaxy-galaxy lensing [Product 6].
- Lucas Secco led the astrophysical systematics modeling and analysis validation for the DES-Y3 cosmic shear analysis [Product 10], including enhancements in the intrinsic alignment model and scale cuts due to baryonic feedback contamination.

[1] https://github.com/CosmoLike

[2] https://github.com/CosmoLike/CosmoCov

- Chun-Hao To and the PI developed the first joint analysis of galaxy cluster abundance, weak lensing and galaxy clustering (6×2pt+N), obtaining stringent cosmology constraints on DES-Y1 *that are consistent with the DES-Y1 3×2pt key results* (Fig. 1, [Product 12]). This work extends previous Fourier-space based CosmoLike forecasts (Krause & Eifler, 2017) to include extended modeling of cluster observables, covariance validation and, crucially, calibration of projection effect modeling with simulations [Product 13]. This analysis provides an alternative to the DES-Y1 cluster abundance constraints, which rely on cluster mass calibration from small-scale cluster weak lensing (McClintock et al., 2019), are famously inconsistent not only with Planck, but also with other DES probes, most notably, the DES-Y1 3×2pt analysis (Abbott et al., 2020). Although much effort has been dedicated to accurate modeling of small-scale cluster lensing with optically selected clusters (Sunayama et al., 2020; Myles et al., 2021; Wu et al., 2022; Sunayama, 2023; Sunayama et al., 2023; Salcedo et al., 2024), the cosmological interpretation of the DES-Y1 cluster KP is yet to be resolved.

For DES-Y6, Dr. To leads the effort to refine the 6×2pt+N modeling to match the Y6 accuracy requirements (with Dr. Krause as second author). This analysis has been promoted to be part of the cluster key project ("large-scale analysis"). As the 6×2pt+N is unique to CosmoLike Dr. To and Dr. Krause are also extending the CosmoLike DES analysis pipeline to produce the DES-legacy combined probes cosmology results, combining DES measurements of BAO, clusters, galaxy clustering, supernovae and weak lensing.

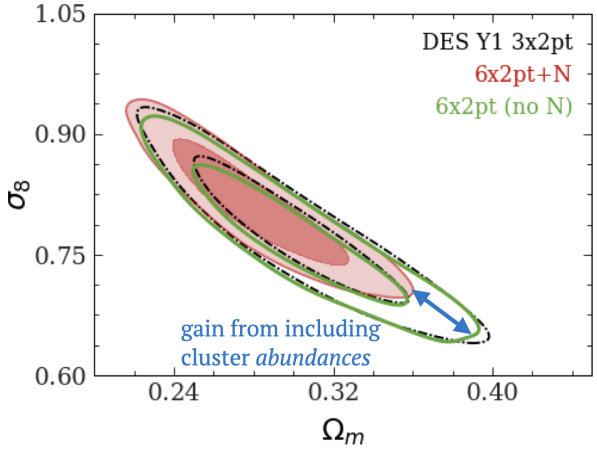

Figure 1: DES-Y1 cosmology constraints from the 3x2pt key project (Abbott et al., 2018, **black**), and an analysis incorporating galaxy clusters (enabled by this award): the **green** contour incorporates galaxy clusters as density field tracers, resulting in six different 2pt statistics; the **red** contour further includes cluster abundances (6x2pt+N), with cluster masses self-calibrated from large-scale cluster-2pt statistics. Adapted from [Product 12].

Project 2 contribute to implementation of consistent multi-probe systematics modeling in the LSST-DESC cosmology likelihood, TJPCosmo, in the fireCrown code.

Project 2 status The theoretical modeling development in CosmoLike and the analysis of DES data serve as critical pathfinders for LSST-DESC software, and this award has directly supported the integration of algorithms developed in CosmoLike into LSST-DESC software: [Product 18] developed a fast but accurate calculations of non-Limber integrals in CosmoLike with initial applications in DES-Y3 analyses. Subsequently, Dr. Fang participated in the DESC challenge "Non-Limber Integration for LSST Cosmology" (Leonard

et al., 2023) and his algorithm was considered the most efficient across all submissions. Supported by this award, the Arizona CosmologyLab team then implemented the FKEM non-Limber algorithm as the `nonlimber_FKEM` module for LSST-DESC Core Cosmology Library `CCL.v3` and also implemented related routines for generalized integrals over Bessel functions in `CCL`.

Arizona CosmologyLab graduate student Paul Rogozenski, supported by this award, continuously contributed to the development of DESC pipelines `CCL` and `fireCrown`, in particular the non-Limber integration and nonlinear systematics modeling modules. He provided expertise in 3x2pt modeling, the physics on non-linear systematic effects, and pipeline comparisons between previous DESC-SRD forecasts (obtained with CosmoLike) and the present pipeline. He also provided expertise as a `CCL` developer in running simulated analyses and interfacing the Fisher forecasting framework, `AUGUR`. Paul also serves as Forecasting Topical Team Co-Lead for LSST Year 1-10, where his efforts include updating the Science Requirements Document, determining initial modeling choices and their implementation in DESC tools, and providing community forecasts of the combined probes constraining power with the most recent survey choices.

2 Other Scientific Accomplishments

The broader research program supported by this award develops the theoretical language and computational framework to combine and consistently interpret different cosmological probes. Combining multiple probes improves cosmological constraints not only (1) by increasing the total signal-to-noise (S/N) included in the analysis, but also (2) by improving the marginalized constraining power per S/N through self-calibration of systematics, enabled by the different degeneracy directions of different observables (cf. Fig. 2 for an illustration in the context of joint analyses of LSST and Simons Observatory data). Such joint analyses require consistent signal modeling of all probes and accurate (cross-)covariances to avoid overcounting information in inherently correlated data. This award supported several small research projects synthesizing rigorous cosmological and astrophysical modeling, incorporating information from cross-correlations including Cosmic Microwave Background (CMB) surveys, to unlock the cosmological constraining power of correlated probes.

- A series of papers developed the covariance framework and theoretical modeling to consistently include CMB lensing and thermal Sunyaev-Zeldovich (tSZ) effect cross-correlations in simulated LSST galaxy clustering and weak lensings analyses, and explored their potential for constraining contamination from photometric redshift outliers and self-calibration of baryonic feedback [Products 7, 3].

- The blue vertical bar in Fig. 2 illustrates the out-sized impact of priors halo properties on cosmological constraining power, as this unlocks information in small-scale weak lensing which is otherwise dominated by uncertainties in baryonic feedback modeling. [Product 1] demonstrates that the relevant feedback parameters can be calibrated from the cluster weak lensing mass – cluster tSZ decrement relation. The 6×2pt+N analysis

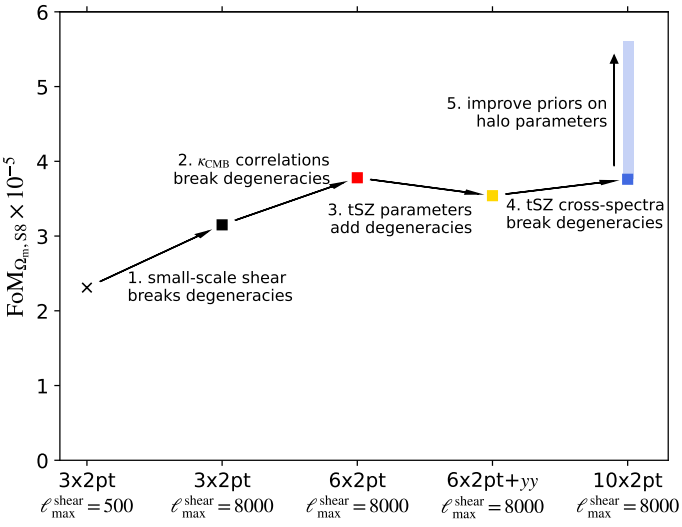

Figure 2: Gain in cosmological constraining power (FoM) for hypothetical *signal-to-noise matched analyses* of LSST (3×2pt, **black** symbols) and Simons Observatory (SO) data (6×2pt = LSST × SO CMB lensing, **red**; 10×2pt = LSST × SO CMB lensing and tSZ, **blue**). Including small-scale information and cross-correlation with CMB experiments improves the self-calibration of baryonic physics and improves FoM *per unit S/N*. The **blue vertical bar** illustrates the transformative gain from improved priors on halo properties. From [Product 3].

provides the natural statistical framework to enable such feedback self-calibration in a consistent multi-probe analysis.

- Products [19,14,11] develop the analytic formalism to mitigate small-scale modeling uncertainties (from non-local contributions to cluster/galaxy-galaxy lensing, or residual baryon feedback model misspecification) at the covariance level, with direct application to DES and LSST analyses.

- Arizona CosmologyLab postdocs Dr. Andres Salcedo and Dr. Tomomi Sunayama are advancing the characterization of cluster projection effects and small-scale selection biases of optically selected clusters and developed a simulation-based forward model. Initial results of this approach (at fixed cosmology) are promising (Salcedo et al., 2024, *Consistency of Dark Energy Survey Year 1 Galaxy Clusters with Planck*, PRL 133,221002) and may unlock the constraining power of small-scale cluster lensing in future DES and LSST analyses.

3 Scientific Leadership and Service

The PI served as co-coordinator of the DES Theory & Combined Probes working group (2016-2019) and co-chaired the DES Science Committee during the DES-Y3 analysis (10/2018-05/2021). As DESC Theory & Joint Probes (TJP, now Modeling & Combined Probes) working group co-convener (2015-2018), the PI conceived the original TJP project and pipeline structure for the DESC Science Roadmap, designed and co-led (2015-2019) the Core Cosmology Library software project (Chisari et al., 2019), iniated the `TJPCosmo/fireCrown` pipeline, for which she was project lead until 2020. Dr. Krause served on the DESC Spokesperson Nominating Committees for the 2019, 2021 and 2023 elections, and currently serves on the DESC speaker bureau.

4 Products

During the award period, the PI and group members supported by this award were principal authors of following 18 publications on combined probes analyses with DES and LSST:

1. To, C.-H., Pandey, S., Krause, E., Dalal, N., Anbajagane, D. & Weinberg, D., *Deciphering baryonic feedback with galaxy clusters*, Journal of Cosmology and Astrophysics 07, 037 (2024)

2. Rogozenski, P., Krause, E. & Miranda, V., *Modeling Neutrino-Induced Scale-Dependent Galaxy Clustering for Photometric Galaxy Surveys*, Journal of Cosmology and Astrophysics 04, 076 (2024)

3. Fang, X, Krause, E., Eifler, T., Ferraro, S., Benabed, K. et al.: *Cosmology from weak lensing, galaxy clustering, CMB lensing and tSZ: I. 10x2pt Modelling Methodology*, Monthly Notices of the Royal Astronomical Society 527 4, 9581 (2024)

4. Secco, L. F., Karwal, T., Hu, W., & Krause, E., *The Role of the Hubble Scale in the Weak Lensing vs. CMB Tension*, Physical Review D 107 8,083623, (2023)

5. To, C.-H., Rozo, E., Krause, E., Wu, H.-Y., Wechsler, R. H., & Salcedo, A. N., *LINNA: Likelihood Inference Neural Network Accelerator*, Journal of Cosmology and Astrophysics 01, 016 (2023)

6. Pandey, S., Krause, E., DeRose, J., MacCrann, N., Jain, B., Crocce, M., et al., *Dark Energy Survey year 3 results: Constraints on cosmological parameters and galaxy-bias models from galaxy clustering and galaxy-galaxy lensing using the redMaGiC sample*, Physical Review D, 106, 043520 (2022)

7. Fang, X., Eifler, T., Schaan, E., Huang, H.-J., Krause, E., & Ferraro, S., *Cosmology from clustering, cosmic shear, CMB lensing, and cross correlations: combining Rubin observatory and Simons Observatory*, Monthly Notices of the Royal Astronomical Society, 509, 5721 (2022)

8. Miranda, V., Rogozenski, P., & Krause, E., *Interpreting internal consistency of DES measurements*, Monthly Notices of the Royal Astronomical Society, 509, 5218 (2022)

9. DES Collaboration (Abbott, T. M. C., et al.), *Dark Energy Survey Year 3 results: Cosmological constraints from galaxy clustering and weak lensing*, Physical Review D, 105, 023520 (2022)

10. Secco, L. F., Samuroff, S., Krause, E., Jain, B., Blazek, J., Raveri, M., et al., *Dark Energy Survey Year 3 results: Cosmology from cosmic shear and robustness to modeling uncertainty*, Physical Review D, 105, 023515 (2022)

11. Moreira, M. G., Andrade-Oliveira, F., Fang, X., Huang, H.-J., Krause, E., Miranda, V., et al., *Mitigating baryonic effects with a theoretical error covariance*, Monthly Notices of the Royal Astronomical Society, 507, 5592 (2021)

12. To, C.-H., Krause, E., Rozo, E., Wu, H., Gruen, D., Wechsler, R. H., et al., *Dark Energy Survey Year 1 Results: Cosmological Constraints from Cluster Abundances, Weak Lensing, and Galaxy Correlations*, Physical Review Letters, 126, 141301 (2021)

13. To, C.-H., Krause, E., Rozo, E., Wu, H.-Y., Gruen, D., DeRose, J., et al., *Combination of cluster number counts and two-point correlations: validation on mock Dark Energy Survey*, Monthly Notices of the Royal Astronomical Society, 502, 4093 (2021)

14. Park, Y., Rozo, E., & Krause, E., *Localizing Transformations of the Galaxy-Galaxy Lensing Observable*, Physical Review Letters, 126, 021301 (2021)

15. Pandey, S., Krause, E., Jain, B., MacCrann, N., Blazek, J., Crocce, M., et al., *Perturbation theory for modeling galaxy bias: Validation with simulations of the Dark Energy Survey*, Physical Review D, 102, 123522 (2020)

16. Fang, X., Eifler, T., & Krause, E., *2D-FFTLog: efficient computation of real-space covariance matrices for galaxy clustering and weak lensing*, Monthly Notices of the Royal Astronomical Society, 497, 2699 (2020)

17. Muir, J., Bernstein, G. M., Huterer, D., Elsner, F., Krause, E., Roodman, A., et al., *Blinding multiprobe cosmological experiments*, Monthly Notices of the Royal Astronomical Society, 494, 4454 (2020)

18. Fang, X., Krause, E., Eifler, T., & MacCrann, N., *Beyond Limber: efficient computation of angular power spectra for galaxy clustering and weak lensing*, Journal of Cosmology and Astroparticle Physics, 2020, 010 (2020)

19. MacCrann, N., Blazek, J., Jain, B., & Krause, E., *Controlling and leveraging small-scale information in tomographic galaxy-galaxy lensing*, Monthly Notices of the Royal Astronomical Society, 491, 5498 (2020)

Furthermore, the PI gave over 60 invited talks on work supported by this award, including plenary talks at the 234^{th} AAS meeting, the Texas Symposium on Relativistic Astrophysics (2019), Phenomenology (2021), Cosmo'21, and the Dark Energy Overview at the Cosmic Frontier DOE P5 Town Hall (2023).

5 Training and Professional Development

This award supported the scientific training and professional development of junior researchers:

- Paul Rogozenski (graduate student, 2019-2024; now cosmology postdoc with with Prof. Mandelbaum at Carnegie Mellon University) contributed to DES-Y3 extended cosmology analyses (Abbott et al., 2023), in particular neutrino modeling [Product 2], and DESC `CCL/fireCrown` development, in particular 3x2pt systematics. Paul also served as Forecasting Topical Team Co-Lead.

- Dr. Xiao Fang (postdoc, 2019-2021; moved to Berkeley BCCP postdoc fellowship) developed critical infrastructure for DES-Y3 analysis (non-Limber modeling, covariance implementation), contributed to several multi-probe systematics modeling projects with DES and LSST applications.

- Dr. Vivian Miranda (postdoc, 2019-2021; now junior faculty at YITP, SUNY Stony Brook) contributed to DES theoretical modeling and inference characterization [Product 8]. Dr. Miranda also served as DESC pipeline scientist for `fireCrown` inference infrastructure.

- Dr. Tomomi Sunayama (postdoc, 2023-2024; now junior faculty ASIAA, Taiwan) contributed to cluster projection effect modeling in LSST-DESC, and also served as DESC pipeline scientist for the CL working group.

- Dr. Andres Salcedo (postdoc, 2022-2024; current Arizona postdoc) developed models for the small-scale cluster selection bias in DES (Salcedo et al., 2024), which has the potential to enable accurate cluster cosmology including small-scale information with optically selected clusters. If successful, this analysis would have transformative impact on the constraining power of DES and DESC cluster analyses.

Furthermore, the PI gave invited lectures at two international cosmology summer schools:

- 2023 ICTS School "Largest Cosmological Surveys and Big Data Science" – invited lecturer for week-long lectures and hand-on tutorials on machine learning-accelerated cosmology inference, ICTS Bengaluru, India; May 2023

- 2024 ICTP Cosmology Summer School – invited lecturer for week-long lectures on cosmic structure formation, ICTP Trieste, Italy; June 2024

6 Awards

During this Early Career Award, the PI's scientific contributions and leadership in the Dark Energy Survey have been recognized by the following awards:

- **2022 Early Career Award, Universities Research Association** One award annually, *For developing crucial theoretical tools for multi-probe cosmology analyses and providing scientific leadership to the Dark Energy Survey (DES) collaboration.*

- **2022 Curie Award, University of Arizona** Up to three awards annually to *junior faculty, whose innovative work is not only advancing science, but also adding to the diversity within the scientific community.*
- **2021 Sloan Research Fellowship**, Alfred P. Sloan Foundation
- **2020 Packard Fellowship**, David and Lucile Packard Foundation
- **2020 Maria Goeppert-Mayer Award, American Physical Society** One award annually, *For contributions to theoretical cosmology and astrophysics, in particular, pioneering approaches to modeling key observables and extracting cosmological constraints from large galaxy surveys.*
- (awarded 10/2019) **2018 Young Scientist Award, International Union of Pure and Applied Physics (IUPAP)**, Commission on Astrophysics One award annually, *For pioneering contributions to the extraction of cosmological insights from large galaxy surveys, including modeling key observables, covariance matrix estimation, and the development of cosmological analysis tools, which have ushered in a new era of multi-probe cosmology and set a new standard for forthcoming experiments.*

References

Abbott, T. M. C., Abdalla, F. B., Alarcon, A., et al. 2018, , 98, 043526, doi: 10.1103/PhysRevD.98.043526

Abbott, T. M. C., Aguena, M., Alarcon, A., et al. 2020, , 102, 023509, doi: 10.1103/PhysRevD.102.023509

—. 2023, , 107, 083504, doi: 10.1103/PhysRevD.107.083504

Chisari, N. E., Alonso, D., Krause, E., et al. 2019, , 242, 2, doi: 10.3847/1538-4365/ab1658

Krause, E., & Eifler, T. 2017, , 470, 2100, doi: 10.1093/mnras/stx1261

Leonard, C. D., Ferreira, T., Fang, X., et al. 2023, The Open Journal of Astrophysics, 6, 8, doi: 10.21105/astro.2212.04291

McClintock, T., Varga, T. N., Gruen, D., et al. 2019, , 482, 1352, doi: 10.1093/mnras/sty2711

Myles, J., Gruen, D., Mantz, A. B., et al. 2021, , 505, 33, doi: 10.1093/mnras/stab1243

Salcedo, A. N., Wu, H.-Y., Rozo, E., et al. 2024, , 133, 221002, doi: 10.1103/PhysRevLett.133.221002

Sunayama, T. 2023, , 521, 5064, doi: 10.1093/mnras/stad786

Sunayama, T., Park, Y., Takada, M., et al. 2020, , 496, 4468, doi: 10.1093/mnras/staa1646

Sunayama, T., Miyatake, H., Sugiyama, S., et al. 2023, arXiv e-prints, arXiv:2309.13025, doi: 10.48550/arXiv.2309.13025

Wu, H.-Y., Costanzi, M., To, C.-H., et al. 2022, , 515, 4471, doi: 10.1093/mnras/stac2048