Project Summary/Abstract

Probing Dark Energy with Precise and Accurate Weak Lensing from Joint Ground- and Space-Based Imaging

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Objectives and Merit. Understanding the physical origin of cosmic acceleration is one of the central open questions of the Cosmic Frontier. This single-investigator project (PI: Xiangchong Li, Brookhaven National Laboratory; no co-investigators) will deliver, for the first time at survey scale, a joint pixel-level weak-lensing (WL) analysis framework for ground- and space-based imaging from the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) and the Euclid space telescope, and apply it to sharpen LSST's constraints on whether dark energy is dynamical—whether its equation of state, $w(a) = w_0 + w_a(1-a)$, departs from a cosmological constant. The *scientific merit* is a substantial gain in WL constraining power: joint pixel-level detection raises the LSST WL effective galaxy number density by at least $\sim$50%, AI-based shape estimation reduces the per-galaxy shape noise by an additional 10–20%, and Euclid near-infrared photometry reduces the catastrophic photometric-redshift outlier rate by 25–40% at $z \gtrsim 1$—together conservatively delivering at least a 30% improvement in the LSST WL constraint on dynamical dark energy and an independent test of the recent DESI-motivated hint of time-evolving dark energy. The *technical merit* is a fast, analytical, AI-compatible shear-calibration framework that removes the dominant systematic bottleneck for joint multi-survey imaging.

Relevance to the Mission of the HEP Program. Probing the nature of dark energy and cosmic acceleration is a core science driver of the HEP Cosmic Frontier, and Stage-IV weak lensing was highlighted by the Snowmass and P5 processes as a top priority for the coming decade. This program takes advantage of the synergy between Rubin LSST—in which DOE has made a major investment, including LSSTCam—and the Euclid space mission, extracting substantially more dark-energy science from existing observational and computational resources at no additional hardware cost. The infrastructure developed here will help enable Rubin LSST to deliver the robust dark-energy constraints it was built to provide, and is designed to extend naturally to a joint LSST×Euclid×Roman analysis.

Appropriateness of the Proposed Method; Competency of Personnel and Adequacy of Resources. The program is organized around four coupled thrusts: (#1) a joint LSST×Euclid image-processing pipeline (joint detection, AI-based shear estimation with chromatic-PSF correction, and joint flux and photo-z); (#2) a Gaussian-prior field-level cosmology analysis pipeline; (#3) a DES×Euclid-DR1 pathfinder analysis on the $\sim$1,000 deg^2 overlap; and (#4) deployment on the $>$3,000 deg^2 LSST-DR1×Euclid-DR2 overlap, supported throughout by a dedicated overlapped ground–space image-simulation suite for sub-percent shear calibration. The approach is low risk: it extends the PI's mature, validated AnaCal analytical shear-calibration framework rather than building a new pipeline, and validates the full chain on a pathfinder dataset before production. The PI developed AnaCal from first principles, led the HSC Year-3 image-simulation campaign, shear catalog, and cosmic-shear analysis, and produced the LSST Commissioning Camera DP1 AnaCal shear catalog. Brookhaven National Laboratory provides the high-performance computing and the LSST Dark Energy Science Collaboration institutional context required, and Laboratory Directed Research and Development funding de-risks the AI components ahead of the program.

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PROJECT NARRATIVE

1 Background and Objectives

Dark Energy and Cosmic Acceleration

Understanding the physical origin of **cosmic acceleration** is one of the central open questions in modern cosmology. In the standard ΛCDM model, this acceleration is attributed to **dark energy** in the form of a cosmological constant, Λ, whose energy density remains constant as the Universe expands. A more general possibility is that dark energy is dynamical, with an equation of state that evolves with cosmic time. This evolution is commonly parameterized as [1]

$$w(a) = w_0 + w_a(1-a), \tag{1}$$

where a is the cosmic scale factor ($a = 1$ today), $w(a)$ is the ratio of dark-energy pressure to density, w_0 is its present-day value, and w_a describes its time evolution. A cosmological constant corresponds to $w_0 = -1$ and $w_a = 0$; a statistically significant departure would indicate physics beyond the standard cosmological model. The U.S. Department of Energy (DOE) has invested heavily in the Vera C. Rubin Observatory's Legacy Survey of Space and Time (**LSST**) [2] and the Dark Energy Spectroscopic Instrument (DESI) [3] to probe whether $w(a)$ deviates from a cosmological constant.

DESI is mapping tens of millions of galaxy and quasar redshifts over $\sim 14{,}000\ \mathrm{deg}^2$ to trace baryon acoustic oscillations (BAO) [4] and structure growth. The DESI Data Release 2 (DR2) BAO analysis provides the most precise BAO measurements to date [5, 6]; combined with cosmic microwave background (CMB) and Type Ia supernova datasets, they show 3–4σ evidence that dark energy may evolve with time [7]. Since this hint is driven by BAO distances combined with external CMB and supernova datasets, establishing whether dark energy truly evolves demands an independent probe with different parameter degeneracies and dominant systematics.

Weak gravitational lensing (WL) [8] is precisely such a probe: by measuring the coherent distortions of galaxy images caused by foreground matter, WL is sensitive not only to geometry but also to the structure growth, providing exactly the information needed to deliver an independent test of the DESI-motivated hint of dynamical dark energy. Delivering this test is one of the central dark-energy science goals of Rubin LSST.

A robust WL confirmation of a time-evolving dark-energy equation of state with the DOE's Rubin LSST would mark one of the most important breakthroughs in cosmology in more than a decade. **This proposal combines LSST and Euclid [9] imaging at the pixel level for the first time at survey scale**, via four coupled thrusts: (#1) a joint LSST×Euclid image-processing pipeline (joint detection, artificial-intelligence (AI) shear estimation with chromatic point-spread-function (PSF) correction, joint flux and photo-z); (#2) a Gaussian-prior field-level cosmology pipeline on the resulting catalog; (#3) a Dark Energy Survey (DES)×Euclid-DR1 pathfinder on the $\sim 1{,}000\ \mathrm{deg}^2$ overlap (FY27–FY28); and (#4) the first LSST-DR1×Euclid-DR2 joint WL dark-energy analysis on the $> 3{,}000\ \mathrm{deg}^2$ overlap (FY29–FY31). Joint pixel-level detection raises LSST WL n_{eff} by at least $\sim 50\%$ [10, 11]; AI-based shape estimation [12, 13] cuts per-galaxy shape noise by an additional 10–20%; and Euclid near-infrared (NIR) photometry reduces catastrophic photo-z outliers by 25–40% at $z \gtrsim 1$ [14, 15]. Together, these advances conservatively deliver at least a 30% improvement in the LSST WL constraint on dark energy, providing an independent test of the DESI-motivated hint.

Weak Gravitational Lensing with Stage-IV Surveys

The next five years will mark a golden age for weak-lensing cosmology. Data from the Stage-IV imaging surveys—Rubin LSST, Euclid, and the Nancy Grace Roman Space Telescope (Roman) [16]—are arriving in close succession, and **joint pixel-level processing** of Rubin LSST and Euclid is already recognized as an immediate priority for Stage-IV dark-energy science. The simultaneous rapid development of **artificial intelligence** technologies, together with the emergence of **field-level** weak-lensing inference that forward-models the survey footprint directly, further amplifies what a joint analysis of these surveys can deliver. Realizing this opportunity, however, hinges on a technical bottleneck in **shear calibration**: the complicated procedure required to meet the LSST Dark Energy Science Collaboration (DESC) sub-percent multiplicative-bias requirement, together with the large computational cost of the joint multi-survey image processing and the overlapped simulation campaigns needed to validate and calibrate it. To remove this bottleneck, in the next subsection we propose a fast and simple analytical shear-estimation framework that is compatible with AI by design.

WL is the small, coherent distortion ("shear") of distant galaxy images by the intervening matter distribution along the line of sight [17, 18, 19, 20], and is measured statistically across very large galaxy populations because the per-galaxy signal is more than an order of magnitude smaller than the intrinsic shape variation. Dark energy affects WL both by altering the distance–redshift relation that sets lensing efficiency and by suppressing the late-time growth of cosmic structure that sets the amplitude of WL correlations, so WL surveys probe cosmic geometry and structure growth simultaneously, complementing the BAO distance ladder of DESI. Equally important, the dominant WL systematics—shear estimation bias, PSF modeling, galaxy blending, intrinsic alignments, and photometric-redshift errors—are largely orthogonal to those of spectroscopic BAO, making WL the decisive independent probe with which to test the DESI-motivated hint of dynamical dark energy. The pioneering Stage-III imaging surveys—DES [21], Hyper Suprime-Cam (HSC) [22], and the Kilo-Degree Survey (KiDS) [23]—have established the modern cosmic-shear methodology and produced precise measurements of the structure-growth amplitude

$$S_8 \equiv \sigma_8 \sqrt{\Omega_\mathrm{m}/0.3}, \tag{2}$$

finding values 0.5–2.5σ below the *Planck* CMB [24] value under ΛCDM. With substantially larger area, greater depth, improved redshift information, and tighter control of shear systematics, the Stage-IV imaging surveys—now operating or coming online over the next few years (Figure 1)—will transform this emerging "S_8 tension" into a high-precision measurement of structure growth and an independent test of the DESI-motivated hint of dynamical dark energy. Among the LSST cosmological probes, WL 3×2pt is forecast to deliver the tightest single-probe constraint on the dark-energy equation-of-state parameters w_0 and w_a (Figure 2).

The scientific case for joint LSST–Euclid weak-lensing analysis is well established. Catalog-level forecasts show that combining LSST and Euclid shape measurements of the same galaxies increases the effective galaxy number density n_eff of the LSST WL sample by $\sim 50\%$ [10], and pixel-level joint detection and shape measurement—the approach pursued here—is expected to deliver still larger gains, as identified by the 2020 Joint Survey Processing Study Group [11]. Physics-informed AI shape estimators (D_4-equivariant convolutional neural networks [CNNs] trained with denoising score matching) [12, 13] further reduce the per-galaxy shape noise by an additional 10–20% on top of this joint-detection n_eff gain. Joint processing also tightens the photometric redshifts that underpin tomographic WL: adding Euclid NIR photometry to LSST *ugrizy* imaging reduces the catastrophic-outlier rate by 25–40%, especially at $z \gtrsim 1$, where 4000 Å-break/Lyman-break confusion makes optical colors degenerate [14, 15]. Both gains arise from the same complementarity—LSST contributes optical depth and multi-band sampling, Euclid contributes space-based

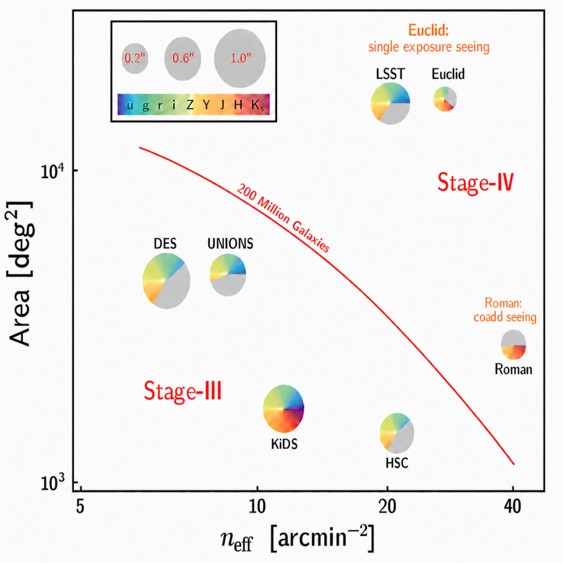

Figure 1: The Stage-III and Stage-IV imaging surveys. The diameter of each disk represents the size of the point-spread function (PSF) of the corresponding survey, and the color encodes its wavelength coverage from the ultraviolet (u band) to the near-infrared (K band).

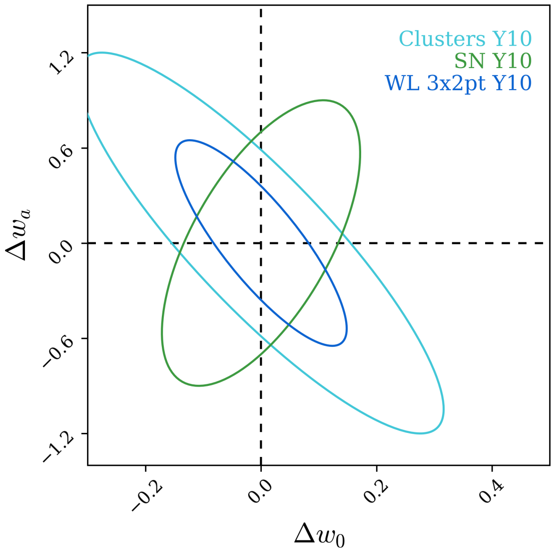

Figure 2: Forecast LSST ten-year 68% constraints on Δw_0, Δw_a from WL 3×2pt (blue), Type Ia SNe (green), and clusters (cyan). WL gives the tightest individual constraint and is the focus of this proposal. Adapted from Fig. G2 of the LSST DESC Science Requirements Document [25].

resolution and NIR coverage—and pixel-level forced photometry across the two surveys yields consistent u-through-H flux measurements for the same sources, avoiding catalog-matching ambiguities that limit existing multi-survey combinations and enabling consistent detection bias correction in shear estimation. Figure 3 illustrates this multi-band, multi-resolution complementarity in joint imaging of an eRASS1 galaxy cluster across Rubin, DES, and Euclid. These gains make pixel-level LSST–Euclid joint processing an immediate priority for Stage-IV dark-energy science, also recognized by the Astro2020 Decadal Survey white paper [26], and the pipeline developed here will extend naturally to Roman once Roman coadd imaging products are released.

A further driver is the recent emergence of *field-level* weak-lensing inference [28, 29], which forward-models the observed shear and density maps directly rather than compressing them into two-point summary statistics. Field-level analysis is particularly natural for joint LSST×Euclid data: traditional cosmic-shear analyses implicitly assume statistical homogeneity across the survey, but the LSST–Euclid overlap, LSST-only, and Euclid-only regions differ markedly in depth, PSF, wavelength coverage, selection, and photo-z performance. Forward-modeling these spatially varying survey properties lets the calibrated overlap anchor coherent inference across the larger non-overlapping footprints, extracting the maximum cosmological information from the full Stage-IV mosaic.

Realizing this opportunity, however, hinges on meeting the LSST DESC sub-percent shear-calibration requirement [25] at survey scale on heterogeneous survey data. Classic high-accuracy shear calibration approaches apply small artificial shears to the observed images and rerun detection, shape and flux measurement, photo-z estimation, and tomographic binning on each sheared realization to capture detection and selection biases at the sub-percent level. This calibration chain is technically intricate to validate and computationally demanding for joint-survey analysis, and remains the principal obstacle to turning the long-recognized promise of joint ground–space weak-lensing analysis into an operational survey-scale pipeline.

AnaCal: Robust and Efficient Self Calibration for Shear Estimation

> This proposal develops a survey-scale joint-imaging shear estimator for combined ground- and space-based data, closing the gap identified above: the absence of a method that can meet the LSST DESC sub-percent shear-calibration requirement at affordable cost. The work extends the PI's **AnaCal** [30, 31] framework into a joint ground–space pipeline for Stage-IV weak lensing. AnaCal computes the shear response in closed form and propagates it by automatic differentiation, eliminating counterfactual image shearing and running two orders of magnitude faster than artificial-shearing methods. The same differentiable construction makes AnaCal AI-compatible by design, supporting model-fitting features and symmetry-equivariant neural feature extractors within a single self-calibrated pipeline.

Shear-estimation accuracy is summarized by $g_{\mathrm{obs}} = (1+m)g_{\mathrm{true}} + c$ [32, 33], where m is the multiplicative bias and c the additive bias; the LSST DESC SRD requires $|m| < 0.3\%$ across redshift bins [25]. *Perturbative* self-calibrating estimators (Metadetection and AnaCal) already achieve this target even on heavily blended images by expanding the measured ellipticity e to first order in the applied shear g and exploiting the spin-2 symmetry of weak lensing:

$$\langle e \rangle = \cancelto{0}{\langle e_0 \rangle} + g \left\langle \frac{\partial e}{\partial g} \right\rangle + g^2 \cancelto{0}{\left\langle \frac{\partial^2 e}{2\partial g^2} \right\rangle} + \mathcal{O}(g^3)\,. \tag{3}$$

Under isotropically distributed galaxy orientations, both $\langle e_0 \rangle$ (spin-2) and the second-order contribution (spin-2 plus spin-6) vanish, leaving only the spin-0 mean shear response $\langle \partial e / \partial g \rangle$. **Metacalibration** [34,

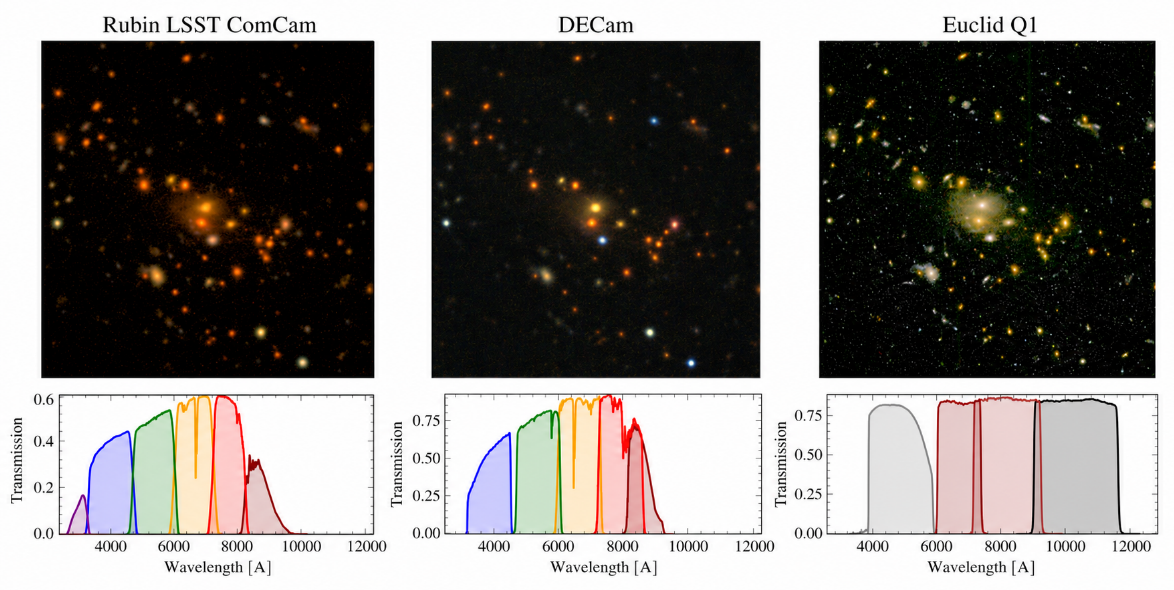

Figure 3: *Top:* Rubin Commissioning Camera Data Preview 1 (DP1), DES, and Euclid Quick Release 1 imaging of the same eRASS1 galaxy cluster [27] ($z = 0.69$, EDF-S). *Bottom:* corresponding filter transmission curves: Rubin *ugrizy*, DES *grizy*, and Euclid Visible Imager (VIS) plus Near-Infrared Spectrometer and Photometer (NISP; Y, J, H). The three surveys differ in depth, resolution, and wavelength coverage; joint pixel-level analysis across them underpins this proposal.

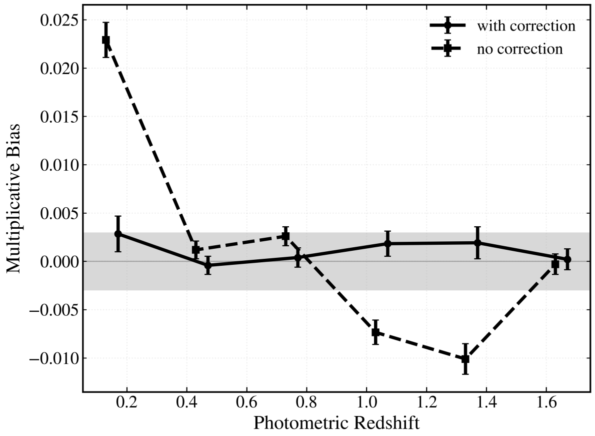

Figure 4: Multiplicative shear bias m as a function of `FlexZBoost` photometric redshift on LSST ten-year-like image simulations with blending. The *solid* line includes the analytical self-calibration for the selection bias induced by binning galaxies into tomographic redshift bins; the *dashed* line is without that correction. The *grey* band marks the LSST DESC requirement [25].

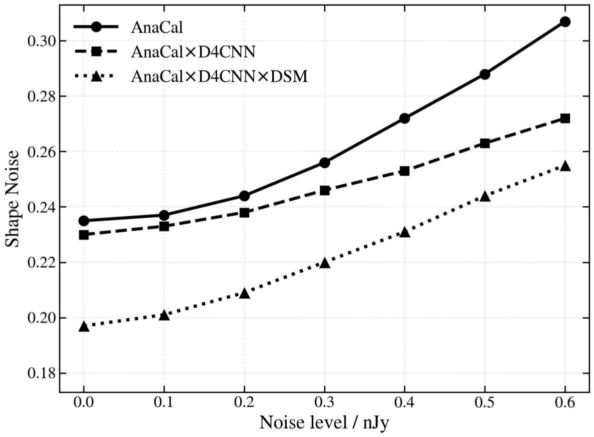

Figure 5: Per-component galaxy shape noise as a function of pixel-noise standard deviation σ_{noise} on LSST-like image simulations. *Solid:* AnaCal alone; *dashed:* AnaCal combined with a D_4-equivariant CNN [40]; *dotted:* AnaCal + D_4CNN further optimized with denoising-score matching. The expected LSST Year-10 i-band noise level is $\sigma_{\mathrm{noise}} = 0.59$.

Survey	**Method**	**Area [deg^2]**	n_{eff} **[arcmin^{-2}]**	z **range**	$\sigma(S_8)$
DES Y6	Metadetection	$\sim 4{,}200$	~ 8.2	0.3–1.5	~ 0.015
HSC Y6	AnaCal	~ 800	~ 15	0.3–1.5	~ 0.019

Table 1: Footprint, effective source density, source-redshift range, and measured uncertainty on S_8 for the Stage-III cosmic-shear analyses. The DES Y6 entry is the forecast for the final DES analysis. HSC Y6 refers to the HSC-SSP collaboration's internal Year-6 dataset (*not* unblinded and published yet); the corresponding cosmic-shear analysis is currently unpublished and blinded, and final published values may differ slightly from those quoted here.

35] and **Metadetection** [36] estimate this response *numerically*, by finite-differencing measured shapes across image realizations with small artificial shears applied. This approach delivers part-per-thousand accuracy and underpins the DES Y6 shear catalog ($|m| < 0.3\%$), but at the cost of additional computational complexity: four extra sheared image realizations must be generated and processed.

AnaCal, by contrast, computes the analytical shear response for each smoothed image pixel and propagates it forward through detection, deblending, and measurement to the final observables [37], while noise-induced bias is corrected analytically using the symmetry of the noise field. Automatic differentiation through this construction yields a fully differentiable estimator that enforces the spin-2 symmetry of weak lensing, suppresses the leading second-order bias terms (Equation (3)), and achieves $|m| < 0.3\%$ across all redshift bins. Figure 4 demonstrates this on LSST Y10 image simulations, with photo-z estimated using `FlexZBoost` [38] in the `RAIL` [39] framework: the solid curve includes AnaCal's analytical self-calibration for tomographic-binning selection effects (without external simulations) and lies safely within the LSST DESC SRD band.

Avoiding the artificial-shearing step makes AnaCal $\sim 100\times$ faster than Metadetection: processing the full

LSST *ugrizy* coadd at survey scale requires only $\sim 10^4$ CPU hours (a few hundred node-hours on the National Energy Research Scientific Computing Center [NERSC] Perlmutter). The same differentiable construction extends naturally to physics-informed AI shear estimation, propagating the shear response through machine-learned D_4-equivariant representations of galaxy images [40] while preserving analytical self-calibration.

AnaCal is already deployed at survey scale: it is the shear pipeline for the ongoing HSC Year-6 cosmology analysis (PI is a core contributor), has been run on LSST Commissioning Camera DP1 [41], is being extended to LSST Data Preview 2 (DP2), and has been validated for the chromatic-PSF effects [42] relevant to joint Rubin–Roman weak lensing [43, 44]. Table 1 compares the resulting HSC Y6 cosmic-shear analysis with DES Y6 in survey area, source density, redshift range, and S_8 uncertainty (Equation (2)).

Toward Physics-Informed AI Shear Estimation with AnaCal

The fast, AI-compatible AnaCal pipeline is the natural foundation on which to build the next generation of shear estimators. Deep neural networks learn flexible pixel-level representations relevant to shape measurement, deblending, and multi-band galaxy morphology, going beyond hand-crafted moment features. **Physics-informed AI shear estimators**—neural networks acting as the feature extractor while the shear response is analytically propagated and calibrated through AnaCal—are therefore a natural extension: they reduce the per-galaxy shape noise by an additional 10–20% on top of the perturbative AnaCal baseline, while preserving the self-calibration needed for sub-percent shear-bias control.

The central technical challenge is that black-box ML shear estimators are not, on their own, calibratable to the LSST DESC sub-percent requirement [45, 46]: blindly trained networks introduce shape-dependent multiplicative bias at the 10^{-2} level, and simulation-based recalibration is prohibitive at survey scale. Two ingredients remove this obstacle:

(i) **AnaCal.** The analytical AnaCal calibration is applied to the network outputs by forward-propagating the analytical pixel-to-feature shear response through the trained network via automatic differentiation. This solves the shear-bias perturbation problem consistently through second order in g (Equation (3)).

(ii) D_4**-equivariant network.** The network [47] embeds the D_4 group of 90° rotations and reflections into the network weights, so the predicted ellipticity transforms exactly as a spin-2 quantity under image rotations. This eliminates orientation-dependent biases and cuts the parameter count by $\sim 8\times$, yielding a $\sim 10\times$ training-data-efficiency gain at no accuracy cost.

A first realization of this $\mathrm{D}_4\mathrm{CNN} \times \mathrm{AnaCal}$ architecture [12], demonstrated on isolated galaxies in LSST-like single-band simulations, achieves $|m| < 0.1\%$ **across all tested noise levels, PSF sizes and ellipticities, and magnitude cuts (most at the $\sim 10^{-4}$ level)**, while delivering $\sim 10\%$ lower shape noise than the moment-based estimator in the high-noise regime—equivalent to a $\sim 20\%$ gain in effective galaxy number density. A complementary advance, *denoising score matching* [13], trains the equivariant feature extractor to align with the analytical score function of the image likelihood (provably the minimum-variance unbiased shear estimator), reducing the per-component shape noise by another $\sim 10\%$ at LSST Y10 noise levels (Figure 5) while preserving $|m| < 0.1\%$ calibration.

Field-Level Inference for Joint Stage-IV Imaging

The second methodological pillar of this proposal is enabling *field-level* weak-lensing inference on joint LSST×Euclid data. Traditional two-point cosmic-shear analyses implicitly assume statistical homogeneity across the survey footprint, an assumption already violated within a single survey by depth and observing-condition variations [48], and broken much more severely when LSST-only, Euclid-only, and LSST–Euclid overlap regions are combined: these regions differ in depth, PSF, wavelength coverage, selection, and photo-z performance. Field-level inference forward-models these spatially varying survey properties directly, letting the calibrated overlap anchor coherent inference across the larger non-overlapping footprints [28, 29, 49, 50, 51].

Catalog-level cosmic-shear pipelines either restrict analyses to nominally homogeneous patches—losing the area-driven statistical power of the joint mosaic—or absorb survey-property variations into approximate mode-coupling matrices, leaving residual inhomogeneity systematics that threaten to become a dominant systematic floor at Stage-IV precision [48]. The field-level analysis pipeline `Miko`, developed by a student co-supervised by the PI [28], has demonstrated on HSC Year-3-like mocks that a forward-modeled, pixel-space treatment of analysis systematics (aliasing, boundary effects, mode coupling, density-induced shape noise) yields *unbiased* tomographic power-spectrum amplitudes when a Gaussian field-level prior is used, whereas a non-Gaussian log-normal prior introduces significant bias from prior misspecification. Building on this finding, the proposed program adopts the Gaussian-prior `Miko` backbone for unbiased field-level inference, which is the natural framework into which the LSST/Euclid survey inhomogeneities can be absorbed via the forward model. Extending this framework to the joint LSST×Euclid mosaic requires precisely the calibrated, co-registered, multi-resolution shear and photo-z catalogs developed here as its data layer: each sub-region (LSST-only and LSST-Euclid overlap) enters the field-level likelihood with its own shape noise, number density and photometric redshifts. By producing this calibrated anchor in the LSST–Euclid overlap, the proposed pipeline opens the door to field-level dark-energy analyses that coherently exploit the full Stage-IV footprint, rather than only its homogeneous subsets. Gradient-based posterior sampling over cosmological and nuisance parameters at field-level resolution is made tractable by coupling the pipeline to differentiable cosmological emulators: `CosmoPower`-like frameworks [52, 53] accelerate the mapping from cosmological parameters to linear and nonlinear power spectra inside the forward model, providing analytic gradients that integrate seamlessly with the AnaCal autodiff calibration layer. The same calibrated catalog will also feed downstream pipelines that target the *non-Gaussian* information in the cosmic shear field, which is inaccessible to two-point statistics: log-normal and N-body-prior field-level inference [49, 50, 51, 54], and simulation-based / deep-learning cosmology analyses based on higher-order summaries (scattering transforms, wavelet harmonics, mass-map moments, or learned features) [55, 56, 57]. This breaks the Gaussian-prior ceiling of two-point and Gaussian field-level analyses and broadens the scientific reach of the joint LSST×Euclid catalog beyond any single inference framework.

2 Scientific and Technical Merit

The overarching goal of this project is to deliver, for the first time at survey scale, a joint pixel-level weak-lensing analysis framework for ground- and space-based imaging from Rubin LSST and Euclid, and to use it to sharpen Rubin LSST's constraints on dynamical dark energy. The program is organized around four coupled thrusts (see Section 3 for details): (#1) the joint LSST×Euclid image-processing pipeline (joint detection, joint shape measurement including AI shear estimation and chromatic-PSF correction, and joint flux and photo-z); (#2) Gaussian-prior field-level cosmology analysis on the resulting calibrated catalog; (#3) the DES×Euclid-DR1 pathfinder analysis on the $\sim$ 1,000 deg^2 overlap; and (#4) the LSST-

DR1×Euclid-DR2 analysis on the $> 3{,}000$ deg^2 overlap. The resulting infrastructure is designed as a foundation for next-generation AI-based image-to-cosmology inference and is built to extend naturally to a joint LSST×Euclid×Roman analysis once Roman coadd data become available.

Scientific Merit

The scientific case for this program rests on four cosmological deliverables, each of which directly addresses one of the outstanding open questions in late-Universe cosmology and feeds into the LSST DESC dark-energy science program.

(1) An independent weak-lensing test of the DESI-motivated hint of dynamical dark energy. The combined gain from joint $n_{\rm eff}$, AI shape noise, and joint photo-z improves the LSST WL constraint on w_0–w_a by at least $\sim 30\%$ relative to single-survey LSST, and a Gaussian-prior field-level analysis on the joint footprint provides a complementary, inhomogeneity-aware route to extract this signal. Together these advances accelerate the survey epoch at which Rubin LSST delivers an independent weak-lensing test of the 3–4σ hint for time-evolving $w(a)$ reported by DESI DR2 with external probes [7]. The key advance is independence: weak lensing probes geometry and late-time growth, with degeneracies and systematics distinct from BAO, supernovae, and CMB. A consistent result would provide independent evidence for dynamical dark energy; an inconsistent one would point to statistical fluctuation, probe-combination effects, or residual systematics in the current evidence.

(2) Sub-percent measurement of S_8 to resolve the S_8 tension. Stage-III cosmic-shear surveys (DES, HSC, KiDS) consistently report values of S_8 that lie 0.5–2.5σ below the *Planck* CMB value under ΛCDM (Equation (2)) [58], but lack the statistical reach to discriminate *statistical fluctuation*, *residual systematics*, and *new physics*. Stage-IV surveys provide that reach only if the accompanying systematics budget—shear calibration, cross-redshift blending, photo-z, intrinsic alignments, baryons, and small-scale modeling—is brought under matching sub-percent control. This proposal is built around that requirement: AnaCal delivers sub-percent shear bias on joint imaging, joint pixel-level detection plus AI shape estimation raise $n_{\rm eff}$ by $\sim 50\%$ and reduce per-galaxy shape noise by a further 10–20%, joint photo-z cuts catastrophic outliers by 30–40% at $z \gtrsim 1$, and the analytical magnitude-response correction removes selection-induced multiplicative bias from tomographic binning. Together with the LSST-DR1×Euclid-DR2 statistical reach, these advances deliver $\sigma(S_8) \lesssim 0.003$, sufficient by construction to classify the S_8 tension.

(3) A validated joint shear catalog for LSST DESC strong-lensing dark-energy and H_0 cosmology. The joint LSST×Euclid shear catalog produced by this program will anchor the LSST DESC strong-lensing program by tightening the constraint on the *mass-sheet degeneracy* (MSD) [59], which currently limits both time-delay H_0 measurements [60, 61] and tomographic strong-lensing constraints on dark energy [62]. Breaking the MSD requires extending the galaxy–galaxy WL shear profile around strong-lens deflectors down to small angular scales—a projected radius of ~ 0.04 Mpc, corresponding to only a few arcseconds at typical lens redshifts $z \sim 0.5$, just beyond the Einstein radius [63]. The proposed program is well matched to this requirement: joint LSST×Euclid pixel-level detection plus AI-based shape estimation together raise the small-scale signal-to-noise on the deflector shear profile by combining a higher source density with a lower per-galaxy shape noise. The resulting tightening of the stacked galaxy–galaxy WL constraint on the MSD reaches $\sim 30\%$ relative to LSST-only WL [63], supporting a percent-level H_0 from time-delay cosmography and a tomographic strong-lensing measurement of $w(z)$ to better than 0.1 out to $z \sim 3$, both independent of the CMB and the local distance ladder [62].

(4) A late-time growth anchor for the cosmological neutrino-mass measurement. The proposed joint LSST×Euclid WL constraint also provides a precise, low-redshift growth anchor for the cosmological sum of neutrino masses $\sum m_\nu$, which suppresses small-scale structure growth in a scale- and redshift-dependent way. Joint analyses of LSST WL + clustering with future CMB-Stage-IV data forecast $\sigma(\sum m_\nu) \sim 30$ meV even in beyond-ΛCDM extensions that vary curvature and the dark-energy equation of state [64], breaking the degeneracies that limit CMB-only constraints and supporting a robust 3σ detection of the minimal ~ 60 meV normal-hierarchy mass once improved CMB optical-depth information is available. The sub-percent-calibrated, joint-imaging shear catalog produced by this program directly enables this neutrino science by ensuring that the neutrino-mass signal in the late-time growth measurement is not absorbed by shear-calibration, photo-z, or survey-inhomogeneity nuisance parameters.

Technical Merit

To deliver the scientific outputs above, the program develops four coupled technical contributions that together form an end-to-end, differentiable, analytically calibrated pipeline running from raw multi-survey pixels to LSST DESC-ready cosmology likelihoods, all at realistic computational and implementation cost.

(1) A joint Rubin × Euclid image-to-shear pipeline with sub-percent bias control and a drop-in interface for AI shear estimators. Building on AnaCal [65, 30, 31], the pipeline replaces image re-rendering in Metadetection with analytical, autodiff-based shear responses propagated consistently across Rubin and Euclid pixel data, controlling $|m| < 0.3\%$ at survey scale at $\sim 100\times$ lower calibration cost than Metadetection. Joint pixel-level detection across the deep multi-band Rubin and the high-resolution stable-PSF Euclid imaging raises the LSST WL n_{eff} by at least $\sim$50% at the catalog level [10], with image-level processing expected to deliver more [11]. The pipeline's modular, differentiable structure also serves as a drop-in backbone for AI shear estimators: the D_4-equivariant-CNN [12] and denoising-score-matching extensions [13] inherit AnaCal's analytical calibration through automatic differentiation and cut shape noise by another 10–20%, and the same interface extends to **DeepDISC** [66, 67, 68] and to foundation models such as **AION-1** [69]. Combined with the photo-z improvement from Euclid NIR, this yields $>30\%$ improvement in the LSST WL constraint on dark energy.

(2) A joint LSST+Euclid photometric-redshift pipeline. Pixel-level forced photometry on LSST *ugrizy* + Euclid NIR delivers consistent u-through-H fluxes for the same sources, avoiding catalog matching ambiguities. Ingested into the LSST DESC RAIL [39, 38] estimators, the joint photometry cuts the catastrophic-outlier rate by 30–40% at $z \gtrsim 1$ [14, 15] and de-biases the tomographic $n(z)$. The same differentiable framework also propagates analytical *magnitude* responses to shear through the tomographic binning step, correcting the selection-induced multiplicative bias that leaks into $n(z)$—to our knowledge the first end-to-end propagation of the magnitude–shear response in a Stage-IV WL pipeline, and essential for keeping the total selection-induced bias sub-percent.

(3) End-to-end validation and reusable LSST DESC data products. $|m| < 0.3\%$ validation at survey scale requires controlled simulations of blending, anisotropic and chromatic PSFs [42, 43, 44], and detection systematics. The pipeline will be exercised on a continuous-integration basis against the PI-codeveloped `descwl-shear-sims` (the established LSST DESC shear-bias-validation tool) wired into the LSST `imSim` [70, 71, 72] framework, sharing identical inputs with Rubin Operations and DESC validation runs. The validated outputs—coadded multi-survey image stacks of the Rubin Deep Drilling Fields (DDFs) and overlapping Euclid/Roman deep fields, plus object catalogs, photo-z training sets, and shear responses—are packaged as a reusable LSST DESC data product leveraged by the cosmic-shear, cluster, photo-z, and strong-lensing working groups.

(4) A differentiable, emulator-accelerated field-level inference backbone. The calibrated, co-registered shear and photo-z catalog feeds the Gaussian-prior `Miko` [28] engine, with each LSST-only / Euclid-only / overlap region entering the forward model with its own number density, shape noise, and $n(z)$ so that survey inhomogeneity is absorbed by construction. Gradient-based posterior sampling at field-level resolution is made tractable by coupling `Miko` to the differentiable `CosmoPower` [52, 53] emulators, which provide analytic gradients of the linear and nonlinear power spectra and integrate seamlessly with the AnaCal autodiff calibration layer—yielding an end-to-end-differentiable stack from raw pixels to the cosmological posterior.

The proposed work will be carried out within the LSST DESC, primarily in the *Pixel-to-Object (PO)* and *Photometric Redshift (PZ)* working groups, with the resulting joint catalogs and simulations delivered to the large-scale-structure, cluster, and strong-lensing working groups for downstream cosmological analysis. The staged approach is built on PI-developed, validated foundations—AnaCal in HSC-Y6, and LSST DP1; and PI-codeveloped `descwl-shear-sims`—reducing the technical risk of the proposal.

3 Proposed Research and Methods

The proposed methodology is organized into four coupled thrusts that together deliver an end-to-end, differentiable joint LSST×Euclid weak-lensing analysis: (#1) the joint image-processing pipeline (joint detection, joint shape measurement with chromatic-PSF correction, and joint flux and photo-z); (#2) Gaussian-prior field-level cosmology analysis on the resulting calibrated catalog; (#3) the DES×Euclid-DR1 pathfinder analysis; and (#4) the LSST-DR1×Euclid-DR2 analysis. For each thrust we describe the method and why it is appropriate and timely for the LSST-DR1 / Euclid-DR2 schedule.

Thrust #1: Joint LSST×Euclid image processing pipeline

Method. The joint pipeline ingests overlapping LSST and Euclid imaging and delivers a co-registered shear and photometric-redshift catalog through three chained AnaCal modules in which the analytical pixel-level shear response is propagated by automatic differentiation end-to-end: (i) *joint detection* on a combined log-likelihood map built from Euclid VIS and LSST imaging oversampled onto the Euclid pixel grid, so the analytical detection-bias correction [30] propagates through the joint map by construction; (ii) *joint shape measurement* on the joint pixel data using three complementary AnaCal-calibrated estimators—Fourier moments [65], galaxy model fitting [37], and physics-informed D_4-equivariant CNN feature extractors [12] optionally augmented with denoising score matching [13]—with chromatic-PSF corrections [43, 44] for the Euclid VIS and NISP bands constrained by overlapping LSST *ugrizy* and Roman NIR imaging; (iii) *joint flux and photometric-redshift estimation* in all LSST *ugrizy* and Euclid VIS + NISP bands using fixed-aperture photometry feeding the LSST DESC RAIL/FlexZBoost [39, 38] estimator, with the analytical shear response propagated through to the photometric redshift itself.

Appropriate. AnaCal delivers sub-percent multiplicative-bias control on the moment-based, model-fitting, and AI feature families [31, 37, 12], while joint LSST–Euclid pixel-level detection and shape measurement raises the effective galaxy number density and reduces the shape noise on the LSST WL sample relative to LSST-only processing [10, 11]. Adding Euclid NIR photometry to LSST *ugrizy* further reduces the catastrophic photo-z outlier rate by 30–40% at $z \gtrsim 1$ [14, 15], and propagating the shear response analytically all the way to the photo-z estimate corrects the magnitude-cut selection bias in closed form—a step that has not previously been implemented end-to-end in any Stage-IV WL pipeline. Validation is performed in `descwl-shear-sims/imSim` [70, 71, 72] with controlled truth shear distortions.

Timely. The AnaCal + RAIL backbone is already deployed at survey scale on HSC-Y6 and LSST DP1, and is currently being applied to LSST DP2 [31, 41]—providing a validated single-survey baseline on which the joint extension is a small delta. The physics-informed AI shear estimators [12, 13] and the chromatic-PSF correction methodology [43, 44] have both been developed in the past two years and are ready to be ingested into the joint-imaging pipeline. The required LSST+Euclid overlap becomes available with Euclid-DR1 and the DES–Euclid-DR1 pathfinder fields at the start of FY27, and the Roman overlap needed for LSST-Y1-

precision chromatic-PSF correction follows in the FY29–FY30 window, exactly aligned with Thrusts #3 and #4.

Thrust #2: Field-level cosmology analysis pipeline

Method. The calibrated, co-registered shear and photo-z catalog from Thrust #1 is fed into the Gaussian-prior `Miko` [28] field-level inference engine. The forward model partitions the survey footprint into LSST-only, Euclid-only, and LSST–Euclid overlap subregions, and assigns each subregion its own depth, shape-noise level, source number density, PSF, blending, and photo-z model, so that survey inhomogeneity is absorbed into the likelihood by construction. Posterior sampling over cosmological and nuisance parameters at field-level resolution is made tractable by coupling `Miko` to the differentiable cosmological emulators `CosmoPower` [52] and `CosmoPower-JAX` [53], which provide analytical gradients of the linear and nonlinear matter power spectra with respect to the cosmological parameters. These gradients integrate seamlessly with the AnaCal autodiff calibration layer of Thrust #1, yielding an end-to-end-differentiable stack from raw pixels to the cosmological posterior.

Appropriate. A Gaussian-prior field-level analysis has been demonstrated to recover *unbiased* tomographic power-spectrum amplitudes on HSC Year-3-like mocks [28], in contrast to log-normal field-level priors that introduce significant prior misspecification bias [49, 50]. The forward-model treatment of survey inhomogeneity is the natural way to combine LSST-only, Euclid-only, and LSST–Euclid overlap regions coherently, avoiding the residual inhomogeneity systematics that limit catalog-level cosmic-shear analyses at Stage-IV precision [48].

Timely. The `Miko` pipeline and the `CosmoPower-JAX` emulators are publicly released and already validated, so the field-level analysis can be deployed immediately on the joint LSST-DR1 / Euclid-DR2 catalog produced by Thrust #1 in the FY29–FY30 window. Downstream, the same calibrated catalog will also feed log-normal and N-body-prior field-level inference [49, 50, 51, 54] and simulation-based / deep-learning cosmology analyses based on higher-order summaries [55, 56, 57], broadening the scientific reach beyond the Gaussian-prior baseline.

Thrust #3: DES×Euclid-DR1 pathfinder analysis

Method. We apply the Thrust #1 joint pipeline to the $\sim 1{,}000\ \mathrm{deg}^2$ DES×Euclid-DR1 overlap to produce a joint shear and photo-z catalog; carry out null tests of PSF modeling, shear estimation, and star–galaxy correlations using the LSST DESC `TXPipe` [73] framework; and feed the catalog into the Thrust #2 field-level cosmology pipeline. The DES Y6 shear catalog is used over the non-overlapping DES footprint to extend the cosmic-shear constraint beyond the DES×Euclid-DR1 overlap.

Appropriate. The DES×Euclid-DR1 overlap is the first ground×space WL dataset at a depth comparable to LSST-Y1, and is therefore the natural proving ground for the joint image-processing pipeline before it is brought into production on the LSST-DR1×Euclid overlap. `TXPipe` is the mature LSST DESC null-test infrastructure, and the DES Y6 shear catalog provides a benchmark against which the joint-imaging cosmic-shear constraint can be cross-validated.

Timely. Euclid-DR1 is released at the start of FY27, exactly aligned with the start of this proposal; `TXPipe` is publicly available; and the DES Y6 shear catalog will be released during the pathfinder window.

Thrust #4: LSST-DR1×Euclid-DR2 analysis

Method. Building on the Thrust #3 pathfinder result, we run the Thrust #1 joint pipeline on the $> 3{,}000$ deg^2 LSST-DR1×Euclid-DR2 overlap to deliver a calibrated joint shear and photo-z catalog, perform `TXPipe` null tests, and feed the catalog into the Thrust #2 field-level cosmology pipeline to deliver the first joint-imaging WL constraint on w_0–w_a. The shear catalog is validated against the LSST DESC SRD shear-bias requirement using an LSST-Y1-scale `descwl-shear-sims/imSim` [70, 71, 72] simulation campaign.

Appropriate. LSST-DR1×Euclid-DR2 is the first joint ground×space WL dataset that reaches LSST-Y1 depth and the LSST DESC SRD systematic-error requirements, making it the dataset on which the joint pipeline produces its primary cosmological deliverable.

Timely. LSST-DR1 is released in June 2028 and Euclid-DR2 in March 2029, so the $> 3{,}000$ deg^2 overlap becomes available in the middle of FY29. By that time the joint pipeline has been validated end-to-end on the Thrust #3 DES×Euclid-DR1 pathfinder, allowing immediate deployment.

4 Timetable of Activities

The proposed program is organized into a five-year plan that is tightly synchronized with the Stage-IV imaging-survey data-release schedule: Euclid-DR1 (21 October 2026), Roman launch (by May 2027), LSST-DR1 (June 2028), Euclid-DR2 (March 2029), and LSST-DR2 (anticipated 2030). Each year couples a methodology deliverable to a real-data deliverable, with built-in risk-buffer fallbacks that keep the program productive if any single survey schedule slips, as illustrated in Figure 6. **Each year requires 50% full-time equivalent (FTE) of the PI and 100% FTE of one postdoctoral researcher (PD).**

The first two and a half years build and validate the joint image-processing pipeline (Thrust #1) and the field-level cosmology backbone (Thrust #2) through the DES×Euclid-DR1 pathfinder analysis (Thrust #3) on the $\sim 1{,}000$ deg^2 DES×Euclid-DR1 overlap, which is comparable in depth to LSST-Y1. The remaining two and a half years carry the validated pipeline into production on the $> 3{,}000$ deg^2 LSST-DR1×Euclid-DR2 overlap (Thrust #4), fully coordinated with the LSST DESC DR1 analysis. The LSST-DP2 footprint does not provide sufficient overlap with Euclid to support a joint shear analysis, so no intermediate LSST-DP2 deployment is attempted.

Year 1 (FY26–FY27): Build the joint image-processing pipeline (Thrust #1). Extend AnaCal [31] from single-survey to multi-resolution, multi-survey joint imaging: joint detection with analytical detection-bias propagation; moment-based, model-fitting, and physics-informed D_4-equivariant CNN shape estimators; and joint flux + RAIL photo-z with the analytical shear response carried through to the photometric redshift. Build the overlapped ground–space image-simulation suite within `descwl-shear-sims/imSim` [70, 71, 72], with controlled truth shear, realistic PSFs and pixel scales, and survey-specific noise. **Deliverables:** a public release of the joint-imaging AnaCal pipeline; the overlapped ground–space image-simulation suite; and a journal paper documenting the pipeline and its simulation tests.

Year 2 (FY27–FY28): From images to pathfinder catalogs (Thrusts #1/#3). Apply the pipeline to the DES×Euclid-DR1 overlap. Carry out `TXPipe` [73] null tests of PSF modeling, shear estimation, and star–galaxy shape correlations, and compare WL cluster mass estimates against the DES Y6 baseline. Calibrate the joint photometric redshifts against the rich spectroscopic sample in the Extended Chandra Deep Field–South (ECDFS), processed end-to-end in the LSST DESC `RAIL` [39] framework, to anchor the joint $n(z)$ tomography with a spectroscopic-quality redshift truth set. **Deliverables:** a public DES×Euclid-DR1 joint shear catalog with joint photo-z estimates covering the overlapping $\sim 1{,}000$ deg^2; one journal paper presenting the shear catalog and its null tests, and a companion paper presenting the photo-z catalog with its

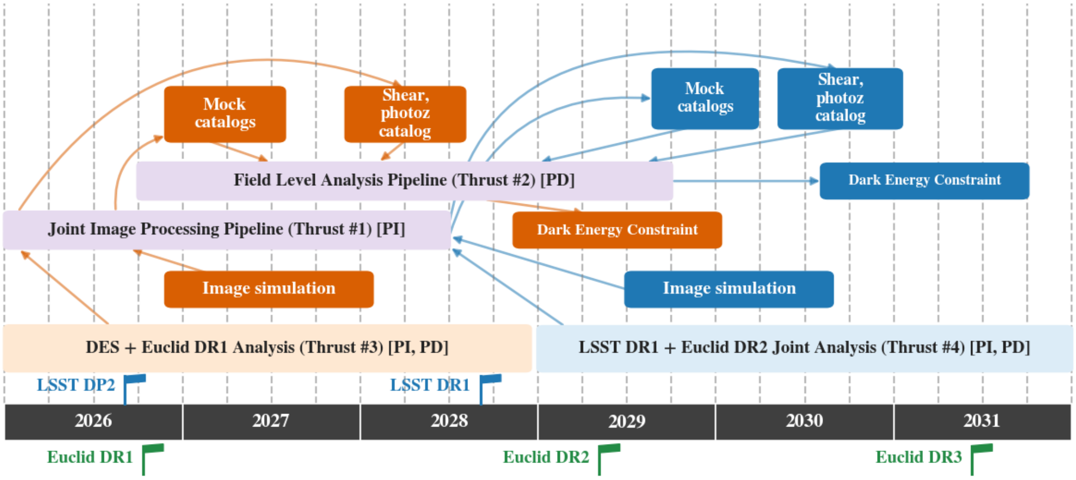

Figure 6: Five-year timeline of the proposed program, aligned with the Stage-IV imaging-survey data-release schedule (LSST-DP2, Euclid-DR1, LSST-DR1, Euclid-DR2, Euclid-DR3). Transparent boxes mark the four program thrusts—purple for the methodology backbones (Thrust #1 joint image-processing pipeline, Thrust #2 field-level analysis pipeline), orange for Thrust #3 (DES×Euclid-DR1 pathfinder), and blue for Thrust #4 (LSST-DR1×Euclid-DR2 joint analysis)—with their horizontal extent indicating the active period on the timeline. Solid orange and blue boxes are the per-thrust deliverables (image simulations, mock catalogs, shear+photo-z catalogs, and dark-energy constraints), positioned at the time they are produced. Arrows show data and product flow between deliverables and pipelines.

standard validation.

Year 3 (FY28–FY29): Pathfinder cosmology and chromatic-PSF deployment (Thrusts #1/#2/#3). Complete the DES×Euclid-DR1 pathfinder program with a Gaussian-prior field-level cosmology analysis on the joint shear and photo-z catalogs above, using the `Miko` [28] engine coupled to the differentiable `CosmoPower` [52, 53] emulators, with a self-consistent forward-model treatment of shear bias, intrinsic alignments, photo-z uncertainty, and survey inhomogeneity, and extend the cosmic-shear constraint beyond the overlap using the DES Y6 shear catalog. The result will be benchmarked against the DES Y6 cosmic-shear baseline. In parallel, deploy the chromatic-PSF correction component of Thrust #1 at LSST-Y1 systematics precision using the LSST-DR1 + Roman overlap that becomes available in this window [43, 44]. **Deliverables:** cosmological parameter posteriors from the DES×Euclid-DR1 joint analysis; a journal paper reporting the cosmic-shear cosmology analysis; and updated chromatic-PSF models for the Euclid VIS and NISP bands with their PSF-systematics tests.

Year 4 (FY29–FY30): From images to the LSST-DR1×Euclid-DR2 catalog (Thrusts #1/#4). Run the full joint pipeline on the $> 3{,}000$ deg^2 LSST-DR1×Euclid-DR2 overlap as Euclid-DR2 becomes available (March 2029), perform `TXPipe` null tests and cross-survey validation, and quantify residual shear and selection biases. In parallel, build the image-simulation suite at LSST-Y1 scale on top of `imSim` and use it to calibrate the joint shear catalog against the LSST DESC SRD shear-bias requirement. **Deliverables:** a public LSST-Y1 joint image-simulation suite; a calibrated LSST-DR1×Euclid-DR2 joint shear catalog; one journal paper documenting the image-simulation tests and shear-bias calibration; and a companion paper presenting the joint shear catalog and its null-test validation.

Year 5 (FY30–FY31): Joint LSST×Euclid field-level dark-energy analysis (Thrusts #2/#4). Use the validated joint catalog to perform a Gaussian-prior field-level cosmology analysis on the LSST-DR1×Euclid-DR2 overlap with `Miko` [28] coupled to `CosmoPower` [52, 53], delivering the first joint-imaging WL constraint on w_0–w_a. Combine with DESI BAO and *Planck* CMB priors to deliver an independent Stage-IV cross-check of the DESI dynamical-dark-energy hint, and establish the joint-pipeline foundation for the LSST-DR2 era by delivering tools and catalogs to the LSST DESC large-scale-structure (LSS) and cluster working groups for downstream WL science. **Deliverables:** cosmological parameter posteriors from the joint-imaging WL field-level analysis; a peer-reviewed publication of the dark-energy result; and a DESC-supported public release of the joint LSST×Euclid analysis pipeline and simulation infrastructure.

Contingencies and Risk Mitigation

Method maturity. The joint image-processing pipeline is an extension of AnaCal [31], a shear-calibration framework already derived, implemented, and validated at survey scale by the PI on HSC and on the LSST Commissioning Camera DP1. The proposed work extends this mature single-survey framework to multi-resolution, multi-survey joint imaging rather than building a new pipeline from scratch, which substantially lowers the technical risk of Thrust #1.

Euclid data availability. The schedule depends on the Euclid-DR1 (October 2026) and Euclid-DR2 (March 2029) releases. If Euclid-DR1 slips, the Thrust #3 pathfinder proceeds on the Euclid Quick Release (Q2) data over the same fields; if Euclid-DR2 slips, Thrust #4 begins on the Euclid-DR1 footprint. In both cases an earlier Euclid release is already in hand before the nominal date, so the program stays productive without waiting on the full release.

Algorithmic complexity. The AI components of the joint shear measurement start from a simple CNN baseline and add complexity (physics-informed D_4-equivariant architectures, denoising score matching) incrementally, only where it demonstrably improves performance, following a start-simple, integrate-first strategy. This effort is further de-risked by the Laboratory Directed Research and Development (LDRD) program at Brookhaven National Laboratory, which supports preparatory work on AI-based shear estimation before this program begins.

5 Competency of Applicant's Personnel and Adequacy of Proposed Resources

PI track record. The PI developed the AnaCal analytical shear-calibration framework from first principles—deriving the analytical pixel-level shear response, the analytical detection-bias correction [30], and the analytical noise-bias correction [31] that together constitute the AnaCal formalism—and wrote the entire AnaCal code base from scratch [37]. Building on this foundation, the PI has consistently delivered survey-scale weak-lensing shear catalogs and cosmic-shear analyses for the most demanding cosmology surveys of the past decade: led the HSC Y3 image-simulation campaign and shear catalog production [74] and the subsequent HSC Y3 cosmic-shear analysis [75], developed the HSC Y6 image-simulation suite for shear calibration, is leading the ongoing HSC Y6 shear catalog, produced the LSST Commissioning Camera DP1 AnaCal shear catalog [41], and is currently leading the LSST DP2 AnaCal shear catalog. The PI is also supervising graduate students applying AnaCal to calibrate AI-based shear estimators [12, 13], and has co-supervised the graduate student who developed the `Miko` field-level weak-lensing inference pipeline [28]—giving the PI direct training-the-trainer experience that maps onto both the AI-extension and field-level-inference thrusts of this proposal.

Host institution. The PI is employed at Brookhaven National Laboratory (BNL), which regularly attracts top-tier postdoctoral scholars to its Cosmology and Astrophysics group. BNL has a long tradition of leadership in weak-lensing shear measurement, catalog production, and cosmological analysis, dating back to the founding contributions of Erin Sheldon to the Sloan Digital Sky Survey (SDSS), DES, and LSST WL programs and continued through the PI's work on the HSC and LSST WL pipelines—providing exactly the institutional expertise required to deliver the joint Rubin×Euclid pipeline proposed here.

Scientific Computing and Data Facilities. The proposal also relies on world-class computational facilities through BNL's Scientific Data and Computing Center (SDCC), a DOE-recognized high-performance computing (HPC) and large-scale data-handling center supporting the LSST, ATLAS, DUNE, and DESI experiments, among others. SDCC provides petabyte-scale storage, GPU-equipped HPC nodes, and a direct, low-latency connection to NERSC and to the LSST/Rubin Data Management infrastructure. These resources are essential for the overlapped ground–space image simulations, joint-survey image processing, and end-to-end shear-pipeline validation that underpin the proposed work, and are already in routine use by the PI's group for LSST DP1/DP2 AnaCal shear analyses.

6 Potential For Leadership Within the Scientific Community

The PI is a recognized leader in weak-lensing shear measurement and catalog production for the leading optical imaging surveys of the past decade. The PI developed the AnaCal analytical shear-calibration framework from first principles—using a perturbative pixel-level formulation to derive the analytical shear response of the full image processing chain and validating it against image simulations at the LSST DESC sub-percent multiplicative-bias requirement.

Beyond methodology, the PI has consistently led the survey-scale catalog production efforts that turn shear estimators into cosmology deliverables: the PI led the HSC Year-3 image-simulation campaign and shear catalog [74] and the corresponding HSC Y3 cosmic-shear analysis [75], produced the LSST DP1 AnaCal shear catalog [41], is currently leading the LSST DP2 AnaCal shear catalog, and is the convener of the HSC weak-lensing working group. The PI is also co-supervising graduate students applying AnaCal to AI-based shear estimators [12, 13], positioning the analytical-calibration framework for the AI-driven era of WL methodology that is now rapidly emerging.

This proposal will consolidate and extend that leadership position along three axes. First, by bringing AnaCal into joint LSST×Euclid pixel-level processing, the program positions the PI as the methodological bridge between the U.S. DOE/NSF Rubin LSST effort and the ESA Euclid and NASA Roman missions, ensuring that the LSST-Y1 shear-and-photo-z cosmology analysis benefits directly from AnaCal-anchored systematic control. Second, by extending AnaCal to AI-based shear estimators within the LSST DESC analysis path, the program keeps the PI at the front of WL methodology through the next decade, in which physics-informed AI is expected to become the dominant analysis paradigm. Third, the proposal further strengthens BNL's role within LSST DESC by anchoring its WL pipeline contributions in the joint-imaging pixel-level layer, complementing BNL's long-standing leadership in shear-measurement methodology established by Erin Sheldon and ensuring that BNL realizes a strong return on its sustained investment in Rubin Observatory cosmology infrastructure.

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APPENDIX 2: Facilities & Other Resources

Facilities and other resources go here.

APPENDIX 3: Equipment

Equipment information goes here.

APPENDIX 4: Data Management Plan

Data management plan goes here.

APPENDIX 5: Synergistic Activities (optional)

Synergistic activities go here.

APPENDIX 6: Transparency of Foreign Connections

Transparency of foreign connections information goes here.

APPENDIX 7: Other Attachments

Other attachments go here.