BROOKHAVEN NATIONAL LABORATORY
LABORATORY DIRECTED RESEARCH AND DEVELOPMENT PROGRAM
LDRD TYPE B – PROPOSAL INFORMATION QUESTIONAIRE

	Submission Date	2025/02/10
TITLE OF PROPOSAL - LDRD TYPE B	**Illuminate the Invisible Universe with joint analysis of ground- and space-based imaging**	
PRINCIPAL INVESTIGATOR (PI)	**Xiangchong Li**	
DEPARTMENT/DIVISION	**Physics Dept in NPP**	
OTHER INVESTIGATORS	**Erin Sheldon (BNL), Rachel Mandelbaum (CMU)**	
PROPOSAL TERM (month/year)	FROM: **October 1st, 2025**	
	THROUGH: **September 30th, 2027**	
EARLY CAREER ELIGIBLE: **YES**		

SUMMARY OF PROPOSAL

Description of Project:

The mid-2020s mark an exciting era for cosmology, particularly in weak gravitational lensing. Stage-IV surveys, led by the Vera Rubin Observatory's Legacy Survey of Space and Time (**LSST**), the **Roman Space Telescope**, and the **Euclid Mission**, will map dark matter and probe dark energy by precisely measuring cosmic shear from galaxy images. The synergy between LSST's ground-based imaging and space-based data from Roman and Euclid offers unprecedented precision, enabling transformative cosmological insights. This joint-survey weak lensing analysis **could enhance cosmology precision by over 25%—equivalent to a 50% increase in LSST's integrated exposure time.** The potential for joint analysis is emphasized in the 2023 P5 report (Section 4.2.3), highlighting the power of combining LSST with space-based datasets. Despite this promise, progress in developing a shear estimation pipeline that meets LSST's stringent requirements has been limited. Existing methods are computationally intensive. This proposal aims to address these challenges with a fast, robust shear measurement algorithm that reduces computational demands while maintaining strict control over systematics below the LSST's requirements. **Our approach will, for the first time, enable joint pixel-level shear estimation from both ground- and space-based imaging in a computationally feasible manner.** This is an extension of our analytical shear estimation formalism, proven on LSST-only simulations to meet LSST's requirements and operate two orders of magnitude faster than existing methods.

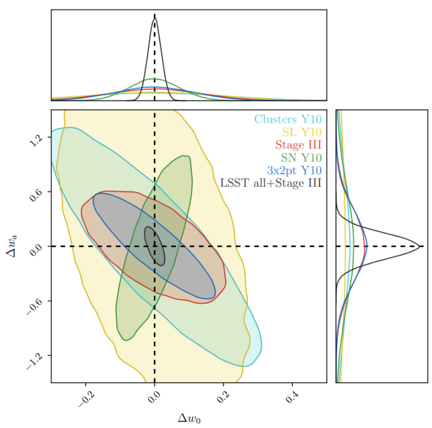
Expected Results:

(FY26) This proposal aims to develop a fast and accurate joint image processing pipeline for galaxy shape and photometry measurements. (FY27) This proposal will create realistic joint simulations of LSST and Roman images and use them to test the pipeline and quantify reductions in statistical uncertainties. In FY27, we will produce an initial joint-survey shear catalog in a small sky region. Beyond this project, the shear measurement pipeline and image simulations will serve as key tools for future research, supporting weak lensing cosmology analyses based on joint-survey shape catalogs and enable a competitive Early Career proposal focused on joint-survey dark energy research.

PROPOSAL

Weak Lensing (WL) and Dark Energy Physics. Weak gravitational lensing refers to the phenomenon that matter along the line of sight subtly distorts the shapes of background galaxies in observed images of the night sky. This slight lensing shear distortion is typically over an order of magnitude smaller than the intrinsic galaxy shape variations. Since WL is a coherent effect across large scales, it affects a large number of galaxies behind the same matter fluctuations. Therefore, we can statistically extract the signal by spatially correlating galaxy shapes across the sky. These correlation functions allow us to measure this coherent shear distortion and use it to probe **Dark Energy**. Dark Energy has a significant impact on WL correlation functions. It alters the expansion history of the Universe, which in turn affects the WL kernel—a geometric efficiency function that determines the amplitude of WL signals. Additionally, it shapes the growth of cosmic structure by influencing how matter over-densities evolve under gravity. A Universe with more Dark Energy experiences slower late-time structure formation, leading to smaller over-densities and a weaker WL signal [1].

Stage-IV WL Surveys. Stage-IV WL surveys, starting in the mid-2020s, include both **ground-based** (e.g., Rubin Observatory LSST) and **space-based** (e.g., Euclid Mission, Nancy Grace Roman Space Telescope) observations across optical to infrared wavelengths. These surveys will map thousands of square degrees in the next ten years, measuring the shapes of billions of galaxies up to redshift 1.5. Combining LSST with space-based imaging has the potential to improve precision by more than 25% [3], equivalent to increasing LSST's integrated exposure time by 50%.

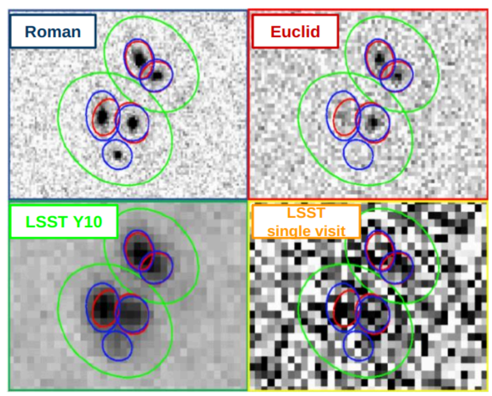


Department of Energy (DOE) Investment in the Rubin LSST. The exceptional sensitivity of weak gravitational lensing to the nature of Dark Energy, coupled with its prioritization by the scientific community, has driven the DOE to invest in the Rubin LSST (P5 report, section 4 [8]). The Rubin Observatory's 6.4-meter telescope will image 10,000 square degrees over 10 years, supporting Dark Energy research. The figure on the right reproduced from the LSST DESC Science Requirements Document [2], illustrates the projected constraining power WL surveys. These constraints are expressed in terms of the $w_a - w_0$ parameters from the $w(a) = w_0 + w_a(1 - a)$ parameterization of Dark Energy's equation of state [2]. The figure also highlights the contributions of current Stage-III lensing surveys, which combine WL with other probes such as galaxy clusters, baryon acoustic oscillations etc. We propose to enhance LSST WL constraints through a joint-survey analysis, **enabling us to effectively distinguish between competing theoretical frameworks that aim to explain cosmic acceleration.**

Synergy between Rubin LSST and Space-based Observations. The Roman and the Euclid are two major space-based observations designed for wide-field cosmological surveys. Roman, led by NASA, features a 2.4-meter mirror and is optimized for infrared observations. It will survey approximately 2,000 square degrees, mapping billions of galaxies to study dark energy. Its Wide Field Instrument (WFI) provides a field of view 100 times larger than that of the Hubble Space Telescope, enabling highly efficient surveys. Euclid, led by the European Space Agency (ESA), has a 1.2-meter mirror and observes in both optical (VIS) and near-infrared (NISP) bands. It will map 15,000 square degrees of the extragalactic sky, covering galaxies up to redshift $z \approx 1.5$. Both missions complement LSST, offering high-resolution images to improve shape measurement and deeper infrared coverage. Table 1 summarizes the timeline of the Stage-IV surveys and our proposal plan.

	FY26Q1	FY26Q2	FY26Q3	FY26Q4	FY27Q1	FY27Q2	FY27Q3	FY27Q4
LSST Commissioning								
LSST Data Release 1 (DR1)								
LSST Data Release 2 (DR2, first year catalog)								
Roman Launch								
Euclid Data Release 1								
Part I-A: Develop Joint-survey pipeline								
Part I-B: Validation on simple simulations								
Part II: Prepare Realistic Image simulation								
Part III: Preparing Initial Catalog Construction								

Table 1: Timeline of Objectives. This chart illustrates key milestones of Rubin LSST, Roman, and Euclid relevant to this proposal (top) alongside the proposal's components (bottom). Part I happens during the LSST commissioning, while Parts II and III coincide with LSST DR1 and DR2 (Y1) data releases, as well as the availability of Euclid and Roman images.



Joint pixel level processing. Results from different surveys can be combined at multiple levels: either at the level of cosmological constraints (once fraction of shared sky is taken into account), at the level of galaxy catalogs or at the level of pixels in individual surveys. The latest offers the biggest benefits, but is technically the most demanding [9]. **DOE and NASA have tasked the *Joint Survey Processing Study Group* (JSPSG)**[1] to study the feasibility of the joint processing and their final report has been released in 2020 [4]. On the right we show the image taken from this report which illustrates the potential gains. Five objects are barely measured in a single r-band exposure and even after 10 year integration suffer from significant blending and might be detected as two extended objects. The space-based data allows a clear identification of individual objects and offers deep-infrared data, but suffers from a fewer independent bands. Only using joint analysis at the pixel level can this information be profitably extracted.

Shear Estimation Technique. Historically, weak gravitational lensing shear measurements have been subject to numerous biases arising from various sources, including atmospheric effects, CCD physics, object detection biases etc. The parameter characterizing the performance of shear estimation is multiplicative bias m. $g_{meas} = (1 + m)g_{true} + c$. Table 2 shows the community has developed two techniques that meet Rubin LSST requirements (|m| less than 0.3%) in the presence of blending. However, the community lacks **an accurate shear estimation technique that integrates space- and ground-based images with different resolutions.** Developing a joint shear estimation pipeline is essential to fully harness all the Stage-IV survey data for constraining Dark Energy. Among existing shear estimation methods, AnaCal [5, 6]—developed by the PI—stands out for its strong analytical foundation,

Techniques	Multiplicative bias	Relative Precision
AnaCal Joint Shear Estimation	<1 1e-3	>1.25
AnaCal [5, 6]	<1 1e-3	1
MetaDetection [7]	<1 1e-3	1

Table 2. The proposed (top row) and current (other rows) shear estimation techniques.

[1] https://jsp.ipac.caltech.edu/

achieving sub-percent level accuracy while being **nearly two orders of magnitude faster than the other algorithm** [5]**.** This novel algorithm analytically derives the shear response (which quantifies how pixel value response to the underlying shear perturbation) of each image pixel and forward propagates them to derive the shear response of other observables (**inspired by auto-differentiation in Machine Learning and AI**). We will extend AnaCal's mathematical framework for joint-survey shear estimation. The code[2] is implemented in low-level C++ and seamlessly integrated with Python, enabling efficient GPU resource utilization and providing a clear path for future CUDA integration.

Project Objectives and Timeline. We propose to develop a joint-survey shear estimation algorithm leveraging AnaCal's mathematical framework and validate it with realistic joint image simulation between LSST and Roman or Euclid, and prepare for the joint-survey shear catalog construction. The objective is broken into three parts. Table 1 provides an overview of the timeline.

Part I: Algorithm development and validation on simple image simulations. The first phase of this project will focus on developing the algorithm, integrating it into the LSST DM pipeline, and testing it with image simulations. The primary objective is to ensure the algorithm remains unbiased within LSST's requirements while achieving the expected gain in precision. By the end of part I, we will have 1~2 paper publication on shear measurement algorithms in a reputable, peer-reviewed journal.

Part II: Realistic image simulation and validation. The second phase begins once data from LSST and space-based observations become available. Our team will generate realistic galaxy image simulations that closely match real observations, providing a crucial resource for validating shear estimation and calibrating redshift distribution estimates. This work will also **contribute to the image simulations needed for LSST's first-year shear catalog** validation and redshift calibration. By the end of part II, we will have one paper publication for the image simulation and validation.

Part III: Initial Joint-survey catalog production. Building on the algorithms developed in Part I and Part II, we will take the next steps to prepare for constructing an initial series of joint-survey catalogs using LSST Data Release 1 along with available data from Roman and Euclid. We will present our results at an Astronomy conference in early 2028.

Competency of Applicant's Personnel. The PI has delivered innovative shear measurement results in LSST DESC over the past two years [5, 6]. The proposed technique extends the AnaCal shear estimation algorithm, developed by the PI. Additionally, the PI played a key role in Hyper Suprime-Cam's WL cosmology, leading shear catalog production [10] and cosmic shear analysis [11]. Erin Sheldon's expertise in joint photometry fitting with the Dark Energy Survey and Hubble is vital for advancing shear estimation across multiple surveys. Collaborating with Rachel Mandelbaum, key contributor to Roman and Euclid, will help align our work with these space-based missions and broaden the impact of this proposal beyond LSST.

Future work and Return on Investment. So far, there exist only two techniques for shear estimation that satisfy the LSST requirements. **Both of those techniques were developed by BNL staff members.** Supporting this proposal will enable BNL to maintain the lead in this crucial analysis for LSST in the next ten years. Starting in 2027, Euclid and Roman will publicly release their data. The proposed work empowers researchers at BNL to enhance LSST's constraints on dark energy in a very cost efficient manner by using advanced analysis methods employed on public images from space-based telescopes. By advancing the technical foundations necessary for joint-survey analysis, this program will provide crucial support for the PI's **Early Career Award application**. Its success will demonstrate the expertise required to integrate multi-survey data, positioning the PI for a strong early career in this field.

[2] https://github.com/mr-superonion/AnaCal

Reference:

[1] M. Chevallier and D. Polarski. Accelerating Universes with Scaling Dark Matter. International Journal of Modern Physics D, 10(2):213–223, Jan. 2001.

[2] The LSST Dark Energy Science Collaboration. The LSST Dark Energy Science Collaboration (DESC) Science Requirements Document. arXiv:1809.01669, Sept. 2018.

[3] R. Schuhmann, C. Heymans, J. Zuntz. Galaxy shape measurement synergies between LSST and Euclid. arXiv:1901.08586, Jan 2019

[4] R. Chary et. al., Joint Survey Processing of Euclid, Rubin and Roman: Final Report. arXiv:2008.10663, Aug 2020

[5] **X. Li** and R. Mandelbaum. Analytical weak-lensing shear responses of galaxy properties and galaxy detection. Monthly Notices of the Royal Astronomical Society, Volume 521, Issue 4, June 2023, Pages 4904–4926

[6] **X. Li** and R. Mandelbaum , and The LSST Dark Energy Science Collaboration. Analytical noise bias correction for precise weak lensing shear inference. Monthly Notices of the Royal Astronomical Society, Volume 536, Issue 4, February 2025, Pages 3663–3676

[7] E. Sheldon, B. Matthew, J. Michael, A. Robert, and LSST Dark Energy Science Collaboration, Metadetection Weak Lensing for the Vera C. Rubin Observatory. The Open Journal of Astrophysics

[8] S. Asai, Exploring the Quantum Universe: Pathways to Innovation and Discovery in Particle Physics. arXiv:2407.19176, July, 2024

[9] J. Rhodes et. al. Scientific Synergy between LSST and Euclid. The Astrophysical Journal Supplement Series, Volume 233, Number 2

[10] **X. Li** et. al, The three-year shear catalog of the Subaru Hyper Suprime-Cam SSP Survey. Publications of the Astronomical Society of Japan, Volume 74, Issue 2, April 2022, Pages 421–459

[11] **X. Li** et. al, Hyper Suprime-Cam Year 3 results: Cosmology from cosmic shear two-point correlation functions. Phys. Rev. D 108, 123518

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website: https://idark.ipmu.jp/~xiangchong.li/me/

Education

Ph.D. in Physics	University of Tokyo	2021
M.S. in Physics	University of Tokyo	2018
B.S. in Physics	Shanghai Jiao-Tong University	2015

Appointments

Assistant Staff Scientist	Brookhaven National Laboratory	since October, 2024
Postdoctoral Research Associate	Carnegie Mellon University	2021 – 2024

Honors and Awards

- Japan Society for the Promotion of Science (JSPS) Doctoral Course (DC1) Fellowships (2019 – 2021).
- Global Science Graduate Course (GSGC) (2016 – 2019)

Professional Experience

- Author of 42 peer-reviewed journal papers, including 10 as first author.
- Developer of Analytical Shear Estimation (AnaCal) techniques.
- Member of HSC, LSST, Roman and Euclid Surveys.
- Leader of HSC year 3 shape catalog production and cosmic shear cosmology analysis.
- Reviewer for A&A, ApJ, MNRAS Journals.
- Convenor of HSC weak lensing working group

Computer Skills

C++, python, fortran, shell script

1. ALIGNMENT WITH THE LABORATORY MISSION AND VISION

This proposal aligns with the **lab's priority 4.1 — Understanding the Building Blocks of the Universe**: **Dark Energy and the Universe.**

- **BNL has played a pivotal role in LSST development**, supplying the LSST Camera sensors and readout electronics. As a leading LSST analysis institution, BNL staff have developed the only algorithms capable of measuring cosmic shear with the precision required by LSST, even in the presence of blending.
- **The importance of joint analysis has been recognized** by both the DOE and NASA, as highlighted in the JSPSG report, and by the broader scientific community in the 2023 P5 report.

In addition, this proposal aligns with the **lab's priority 4.3 — Developing the next generation of information science and technologies**.

- **Developing a next-generation image processing framework** for joint-survey shear estimation, achieving second-order shear accuracy while meeting LSST requirements.
- **Leveraging AI techniques** for computational acceleration (e.g., auto-diff for shear response propagation) and enhanced precision (e.g., normalizing flows to learn priors for galaxy model fitting).
- **Building a GPU-based image processing framework** optimized for weak lensing cosmology.
- **Exploring future advancements** in quantum computing for astronomical image processing.

2. POTENTIAL FUNDING

This LDRD-B funding is essential for supporting the work required to develop a competitive Early Career Award proposal for the DOE Office of Science, High Energy Physics, which the Principal Investigator (PI) will apply for in 2027 (see next section for details).

This proposal initializes the development of the next generation astronomical image processing pipeline and it can support the application to **DOE Frontiers in Artificial Intelligence for Science, Security and Technology (FASST) Call** shown as below:

Next-Generation Image Processing Pipeline for Weak-Lensing Cosmology

- Development of an image processing pipeline capable of automatically deriving observable responses to coordinate perturbations.
- AI-driven acceleration for both image processing and simulation.

3. POTENTIAL EARLY CAREER AWARD INVESTIGATORS (if applicable)

The PI will submit an Early Career Award application in 2027 (the PI got the Ph.D. degree in 2019). The Early Career Award (ECA) proposal will leverage the pipeline developed by this LDRD-B to measure shear from all available data from LSST, Euclid, and Roman. In addition, the ECA will leverage the simulation package developed by this LDRD-B project to make realistic image simulation to validate the image processing pipeline. Validation tests will be conducted on real observations, and this will enable analysis of the cosmic shear, galaxy-galaxy lensing, and cluster abundance to constrain dark energy.

4. BUDGET JUSTIFICATION

FY2026:

1. **0.24 FTE** to support Xiangchong Li (PI) to work on algorithm development for joint galaxy model fitting from images with different resolutions.
2. **0.5 FTE** to support one postdoc (new hire) to work on joint-survey image simulation, shear estimation code validation, and preparing initial joint-survey shear catalog. The new hire starts from April 2026 to September 2027. In addition, **$6,000 Reallocation** supports the reallocation of the postdoc**.**
3. Supporting students and postdocs to visit BNL to prepare for the image simulation and data analysis of Euclid and Roman images:
   a. **$10,000 housing**
   b. perdiem paid to visitor: **$10,000 various small contract**
   c. Car Rental: **$5,000 Various Small Contract**
4. Supporting Xiangchong Li (PI) to visit collaborators and conference: **$6,000 Domestic Travel**
5. Desktop Server with GPU to develop next generation shear estimation pipeline: **Various Purchases**
6. SDCC disk space **Various Punches**
7. Paper Publication fee: **Various Punches**

FY2027:

1. Supporting one postdoc (hired in FY2026) to work on joint-survey image simulation, shear estimation code validation, and preparing initial joint-survey shear catalog. Depending on the performance, the postdoc may be supported with astronomy and cosmology group's core funding after FY2027.
   a. **1 FTE**
   b. **$4000 International travel**
   c. **$4000 Domestic Travel**
2. **0.08 FTE** for Xiangchong Li (PI) to lead the project and help on image simulation and initial shear catalog production.
3. Supporting students and postdocs to visit BNL to prepare for the image simulation and data analysis of Euclid and Roman images:
   a. **$5,000 housing**
   b. Perdiem: **$4,000 Various Small Contract**
   c. Car rental: **$1,000 Various Small Contract**
4. Supporting Xiangchong Li (PI) to visit collaborators and conference
   a. **$4,000 Domestic Travel**
   b. **$4,000 International Travel**
5. Paper Publication fee: **Various Punches**

5. NAME(S) OF SUGGESTED BNL REVIEWERS

Provide the name of (4) four BNL subject matter experts (SMEs). Two of the SMEs may be contacted as potential reviewers of your proposal. Their reviews will be in addition to those conducted by two members of the Research Staff, not associated with the research.

Name 1: Hooman Davoudiasl _
Name 2: _Paul O'Connor _
Name 3: _Chao Zhang _
Name 4: _Raju Venugopalan___

6. EQUIPMENT (reference: DOE Order 413.2C Chg. 1 (Min Chg) for guidance on equipment restrictions)
Will LDRD funding be used to purchase equipment?
Yes

If **yes**, provide cost and description of equipment

Year 1 - $_____28,000_____

Year 2 - $_______0________

Year 3 - $_______0________

Description: $20,000 will be allocated for purchasing a high-performance computing server for code development. $8,000 will cover SDCC server disk usage.

7. HUMAN SUBJECTS (Reference DOE Order 443.1C)
Are human subjects involved from BNL or a collaborating institution?

No

Human subjects are defined as "A living individual from whom an investigator obtains either (1) data about that individual through intervention or interaction with the individual, or (2) identifiable, private information about that individual".

If **yes**, attach a copy of the current Institutional Review Board Approval and Informed Consent Form from BNL and/or collaborating institution.

8. VERTEBRATE ANIMALS
Are live vertebrate animals involved?

No

If yes, attach a copy of approval from BNL's Institutional Animal Care and Use Committee.

9. NEPA REVIEW
Are the activities proposed similar to those now carried out in the Department/Division that have been previously reviewed for potential environmental impacts and compliance with federal, state, local rules, and regulations, and BNL's Environment, Safety, and Health Standards? (Therefore, if funded, proposed activities would require no additional environmental evaluation.)

Yes

If **no**, has a NEPA review been completed in accordance with the National Environmental Policy Act (NEPA) and Cultural Resources Evaluations Subject Area and the results documented?

☐ Yes or No ☐

(**Note:** If a NEPA review has not been completed, submit a copy of the work proposal to the BNL NEPA Coordinator for review. No work may commence until the review is completed and documented.

10. ESH CONSIDERATIONS

Does the proposal provide sufficient funding for appropriate decommissioning of the research space when the experiment is complete?

No

Is there an available waste disposal path for project waste throughout the course of the experiment?

No

Is funding available to properly dispose of project waste throughout the course of the experiment?

No

Are biohazards involved in the proposed work?

No

If **yes**, attach a current copy of approval from the Institutional Biosafety Committee.

Can the proposed work be carried out within the existing safety envelope of the facility (Facility Use Agreement, Nuclear Facility Authorization Agreement, Accelerator Safety Envelope, etc.) in which it will be performed?

Yes

If **no**, attach a statement indicating what has to be done and how modifications will be funded to prepare the facility to accept the work.

11. TYPE OF WORK

Select:

- ☑ Basic
- ☐ Applied
- ☐ Development

Title: Illuminate the Invisible Universe with Joint Analysis of ground - and space-based Imaging
PI: Xiangchong, Li

Resource Category	DESCRIPTION		FY26		FY27
050	Salary - Scientific		47,932		16,357
051	Salary - Research Assoc		53,517		110,781
050	Salary - Professional		0		0
050	Salary -Technical		0		0
050	Salary - Management & Admin.		0		0
150	Salary - Awards		0		0
	Total FTEs		**0.74**		**1.08**
TOTAL SALARY/WAGE & FRINGE			**101,450**		**127,139**
various	Contracts - Low Value		15,000		5,000
280	Foreign Travel				8,000
290	Domestic Travel		6,000		8,000
various	Purchases		35,000		5,000
TOTAL MSTC			**56,000**		**26,000**
170	Relocation Expense		6,000		0
240	Registration Fees		0		0
271	Communications		0		0
TOTAL COM/MISC			**6,000**		**0**
161	Housing		10,000		5,000
163	Pass Thru		0		0
TOTAL MODC			**10,000**		**5,000**
TOTAL DIRECT COSTS			**173,450**		**158,139**
251	Electric Distributed (Electric Power Burden)		1,014		1,271
700/701/481	Organizational Burden		12,073		15,129
TOTAL ORGANIZATIONAL BURDEN			**13,087**		**16,401**
745	Procurement (Material Handling)		3,920		1,820
735	G&A Burden		0		0
730	Common Institutional Support		59,543		73,641
722	Safeguards & Security Assess		0		0
TOTAL LABORATORY BURDEN			**63,463**		**75,461**
705	LDRD Burden		0		0
TOTAL PROGRAM COSTS			**250,000**		**250,000**
740	Full Cost Recovery		0		0
TOTAL PROGRAM COSTS			**250,000**		**250,000**

Labor Band	Name	FY26		FY27	
		FTE	Amount	FTE	Amount
RA1	Post Doc	0.50	53,517	1.00	110,781
SCI1	Xianchong Li	0.24	47,932	0.08	16,357

APPROVALS

James L. Desmond III

Business Operations Manager **Signature**

Hong Ma

Department Chair/Division Manager **Signature**

To the Department Chair/Division Manager:
Please indicate if this project is a sensitive technology under the S&T Risk Matrix. (**Note:** Red projects require an Access Management Plan.)

☐Green
☐Yellow
☐Red
☒Not Applicable

Cognizant Associate Lab Director **Signature**