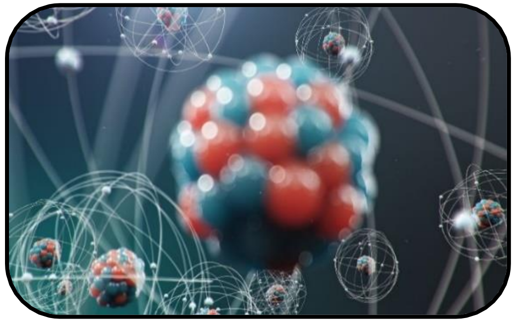
Nuclear Physics
Discovering, Exploring, Understanding All Forms of Nuclear Matter

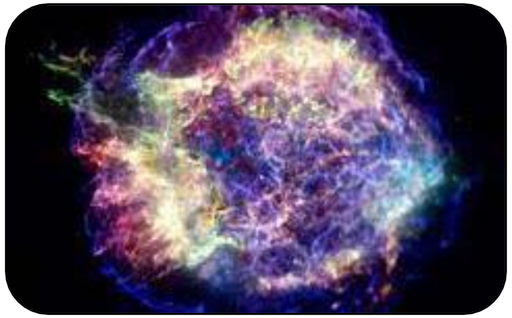
- Ground-breaking research and discoveries
    - First observation of the direction production of matter from energy; discovery that natural radiation frustrates quantum coherence time essential for quantum computing
- Safe and highly efficient operation of four world-leading national user facilities to maintain U.S. world leadership in Nuclear Physics
- The construction of new tools (e.g. the Electron-Ion Collider) to maintain U.S. dominance in nuclear physics and a trained nuclear/accelerator physics workforce
- Pioneering programs in RENEW, FAIR, EPSCOR to ensure the future NP workforce is fully capable of leveraging the entirety of diverse intellectual capital in the United States
- Applications critical for national needs through Nuclear Data, QIS, AI/ML, and Microelectronics

The Primary Deliverable: Nuclear Physics R&D Breakthroughs

- **Discovering and understanding new forms of nuclear matter**
  - Quark-Gluon Plasma at RHIC
  - Four new Super-Heavy Nuclei (Nihonium 113, Moscovium 115, Tennessine 117, Oganesson 118; search is starting for 120 at LBNL)
- **New discoveries**
  - World's best limit on the neutrino mass (800 → 300 milli-eV)
  - Neutron skins exist on heavy nuclei (e.g., ^{208}Pb) limiting the radii of neutrons stars (~ 12 Kilometers for solar masses of 1.4 – 2.0 M_0)
- **New technology important for national needs**
  - First ever demonstration of accelerator bunched-beam cooling
  - FEL ERL development for the Navy using LERF
- **Nuclear data & knowledge for a suite of applications**
  - ☆ Space exploration
  - ☆ Fission and fusion reactor design
  - ☆ Nuclear forensics / Nonproliferation



The Structure of the Atomic Nucleus



The Birth of Nuclei in Astronomical Processes

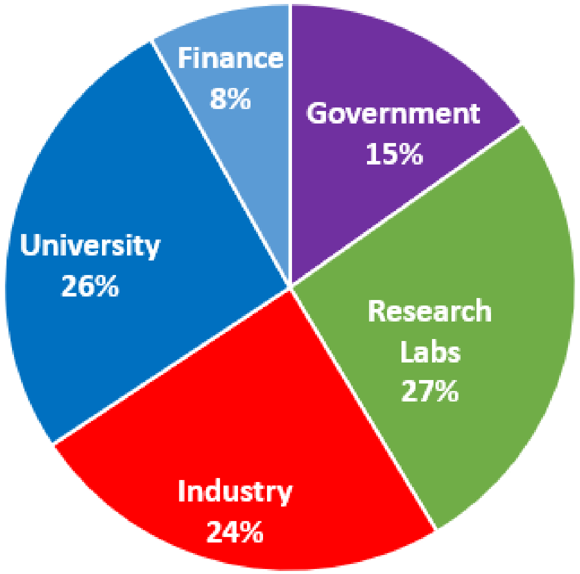
Probing Universal Laws in Nuclear Decays

A Second Very High Priority: Training in Nuclear Science

- Highly Specialized Technical skills
- Creative problem analysis/solving ability
- Scientific communication skills
- Resilience/perseverance despite set-backs
- Self confidence
- Time management ability
- Project planning skills
- Ability to work within a large collaboration
- Leadership development

The result is an essential national core competency useful not only for "things nuclear", but for a variety of other challenging pursuits as well

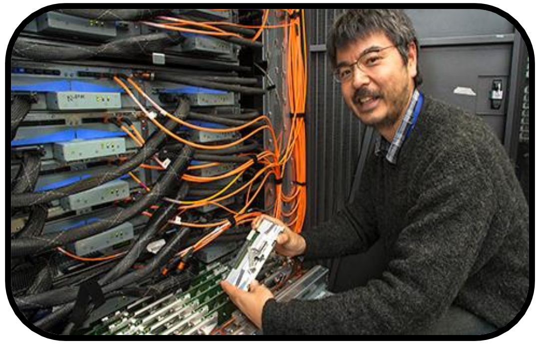
Where NP PhDs go



U.S. science, commerce, medicine, defense –all benefit, in part, from a stable level of sustained competence, capability, capacity, and leadership in nuclear physics;

Beyond Assertion: How NP Trained Workforce Benefits the Nation

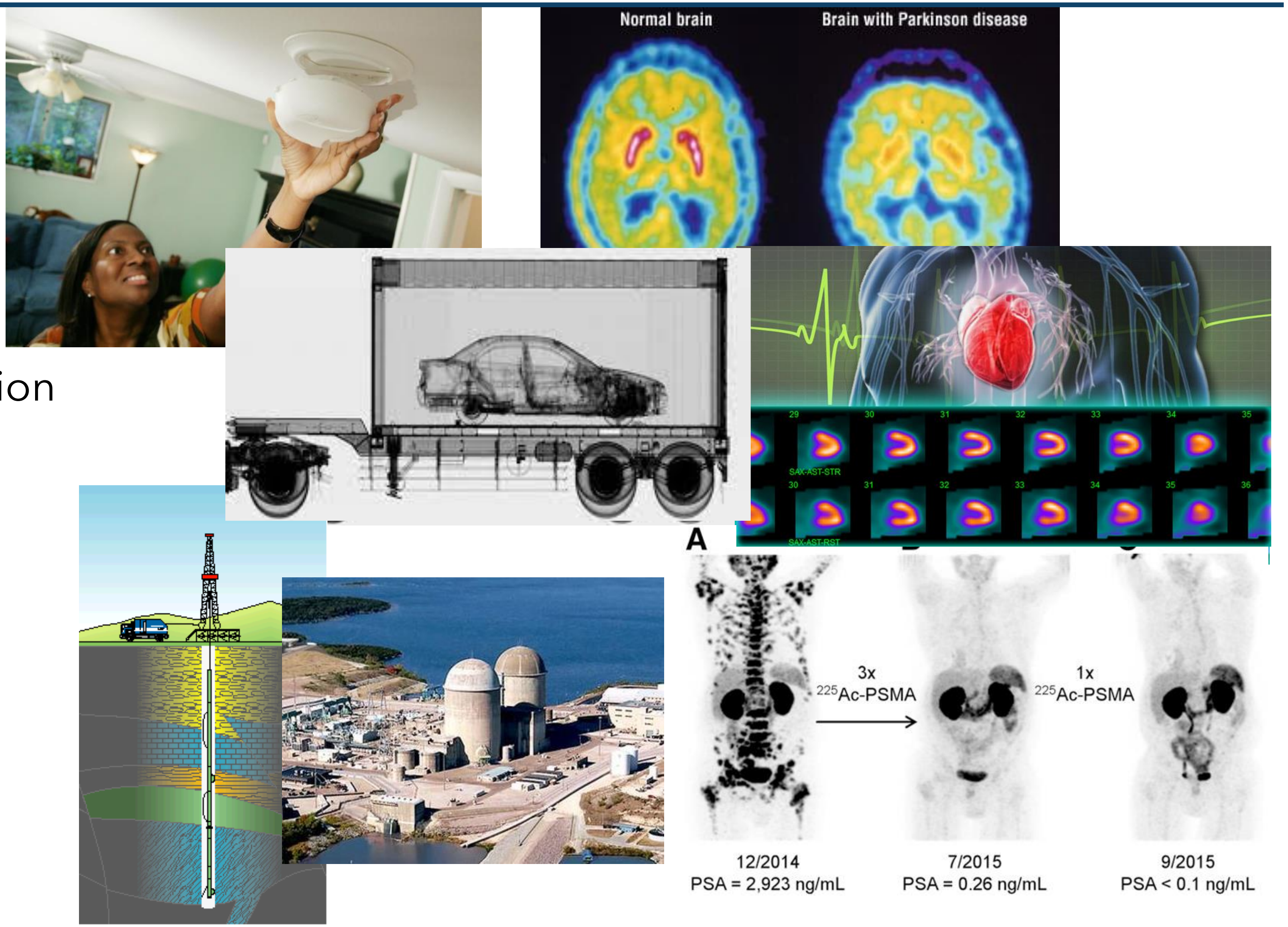
Sample of Non-Defense Roles Based on Breakthrough Prize Questionnaire



- Sr. Chemist at a mining company
- Sr. Research Scientist at a Fotune-100 conglomerate
- Head of bioinformatics at a molecular therapy company
- Director of Radiological Product Development of a global healthcare technology company
- Vice President of Engineering of a software application development company
- Chief Researcher at an international industrial research lab
- Director of Innovation at a popular data science platform company
- Senior Manager at an EU-listed company providing micro structuring equipment to the semiconductor industry.
- Accelerator and materials technical lead at the radiation effects laboratory of a major Fortune-50 aerospace company.
- Owner of a private technology/consulting company
- President of a high-tech company that provides geotechnical monitoring solutions and instrumentation to mining and industry
- CTO of a web design and software design company
- Principal Scientist (Global Research and Technology) of a major international healthcare company
- CEO of an international water purification technology company
- Principal Scientist (electronics and software development) at a company that provides radiation and explosive solutions to homeland security and industry
- Owner of a nuclear electronics, instrumentation and data analysis company
- Manager of the R&D department of a FTSE-100 detection and screening technology company
- Sr. Radiation Physicist, health science company that provides gamma technologies and medical isotopes
- Sr. Scientific Director (R&D) at a radiation analytic company

A Third Priority: Better Living Through Apps of Nuclear Physics

- Fire safety in your house
- Heart Health
- Food safety
- Medical Diagnosis
- Carbon free electricity generation
- Port of entry security
- Metastasized cancer treatment
- Oil and gas prospecting
- Deep space exploration
- Lasting joint replacements
- National Security



The Basic Nuclear Physics Research Portfolio That DOE NP Supports

People

NP Workforce

- ~852 Faculty & Lab Res Staff
- ~391 Post-docs
- ~630 Graduate Students
- ~900 Lab technical/admin
- ~150 Undergraduate Students

Research Groups

- 9 National Laboratories
- 100+ Universities

Approximately 3000-4000 scientists (0.001% of the U.S. population) are trained and working in nuclear science, providing highly specialized skills and knowledge to support medicine, commerce, national and homeland defense, and basic research.

Places

University Centers of Excellence

- CENPA (U. of Wash)
- INT (U. of Wash.)
- TAMU (Texas A&M)
- TUNL (Duke)
- REC (MIT)

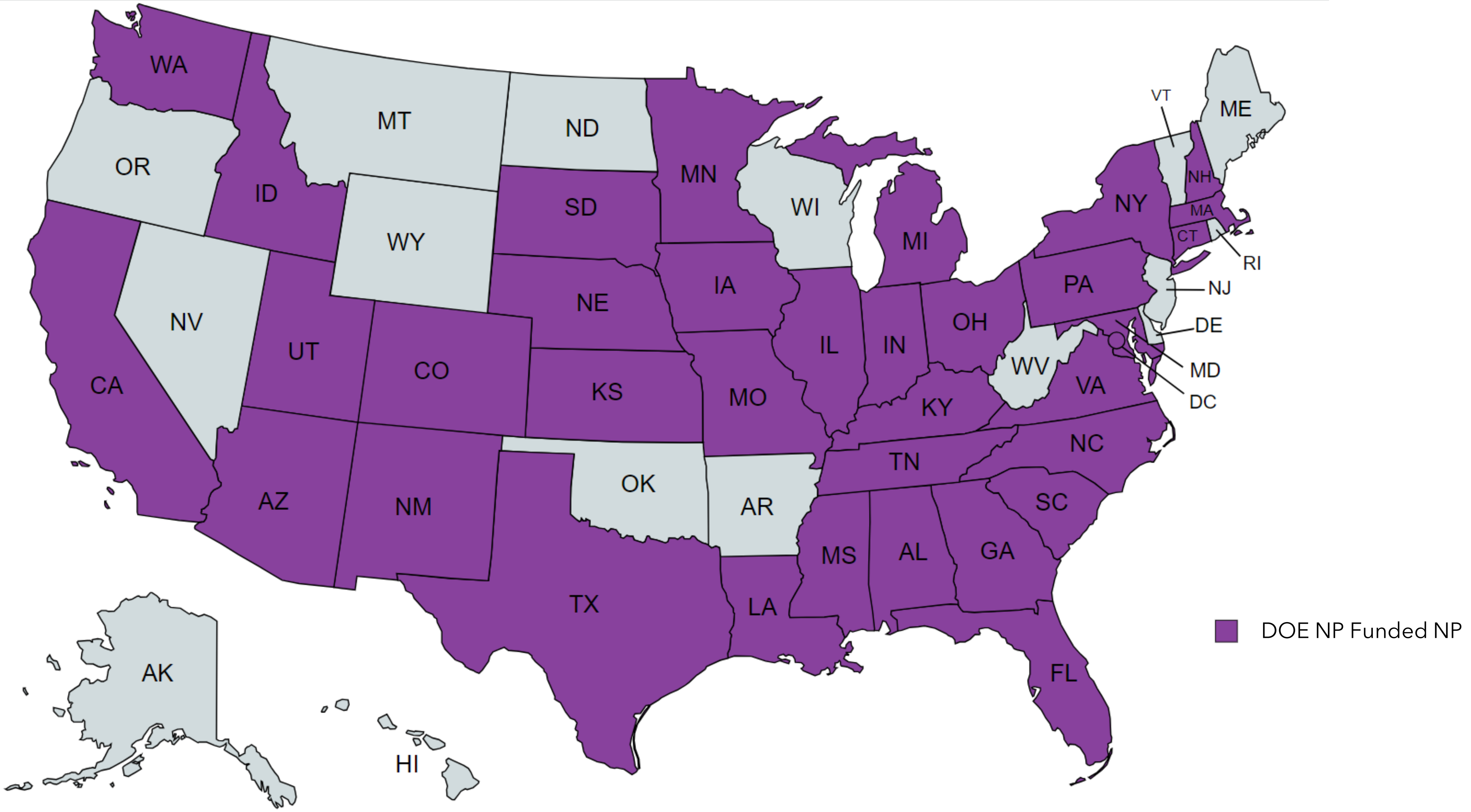
Scientific User Facilities ~6500 users

- RHIC (BNL)
- CEBAF (TJNAF)
- ATLAS (ANL)
- FRIB (MSU)

Other Lab. Facilities

- 88-Inch Cyclotron (LBNL)
- 200 MeV BNL Proton Linac (BNL)

States With DOE NP Supported Researchers



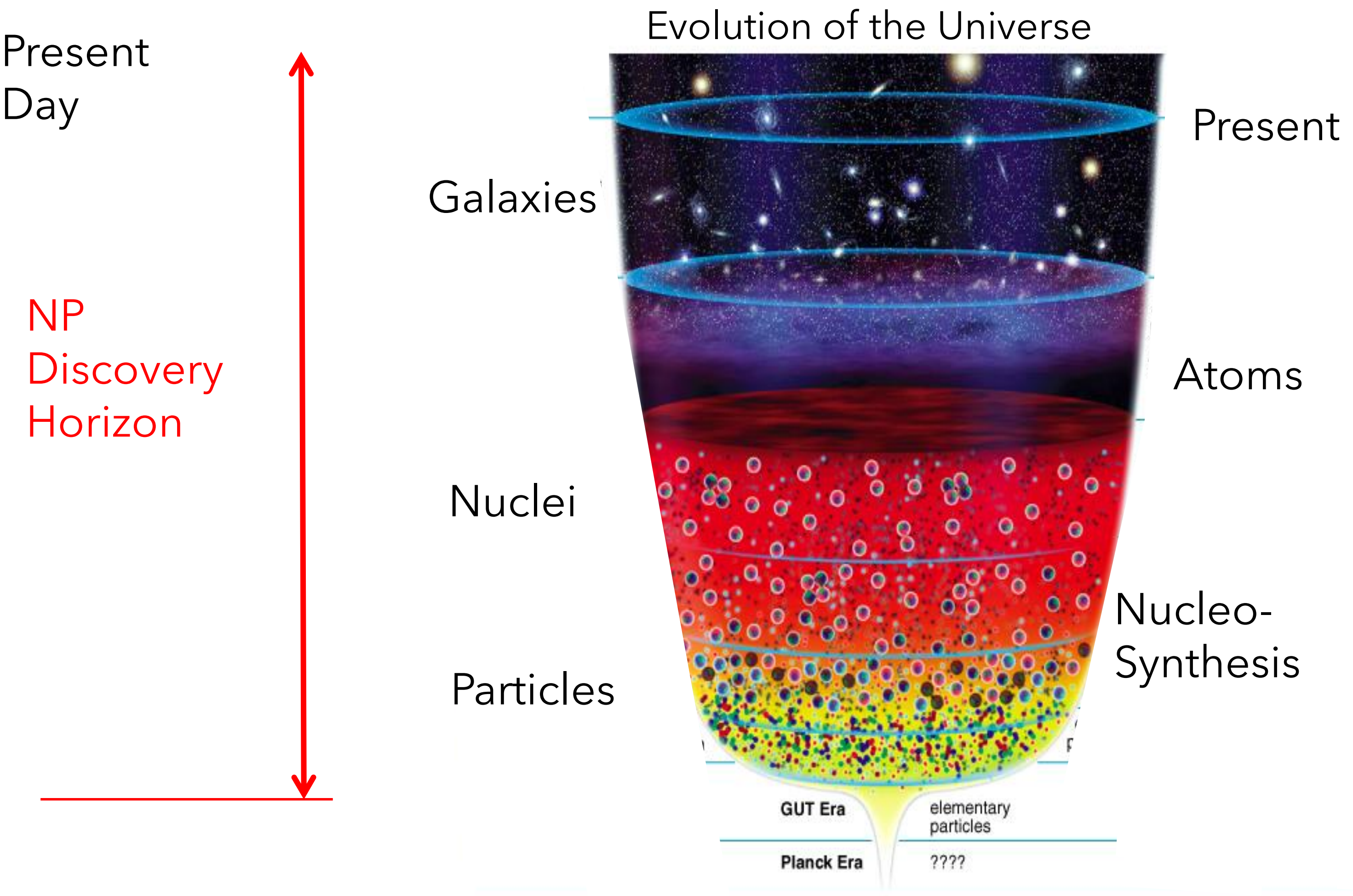
Alignment With Future Administration Priorities

- Advanced AI systems
- Microelectronics, QIS, HPC
- Cancer moonshot
- Regional workforce development
- Rigorous evaluation and data sharing
- Applied research, expt development, and pre-commercialization
- Support new R&D performers and emerging research institutions

Signified by ★ throughout this talk

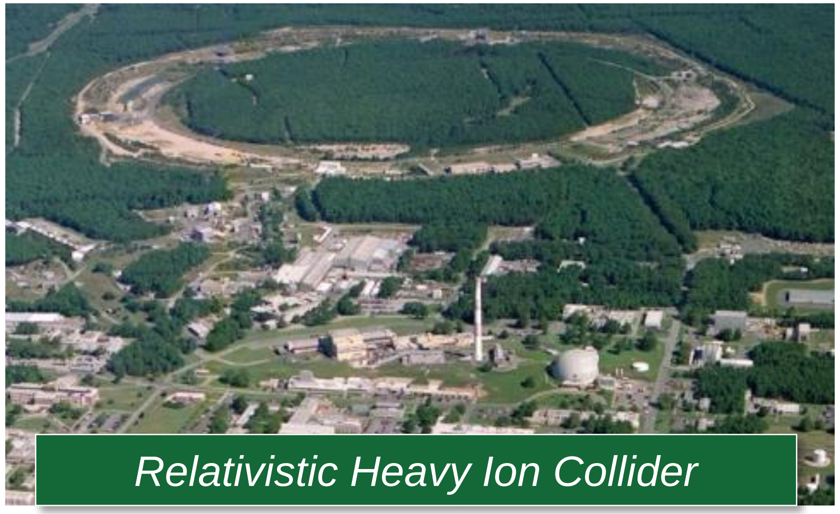
- 25% of NP funding awarded in FY 2023 went to HBCUs
- 20% of NP funding awards in FY 2023 went to emerging research institutions

The Reach of NP Scientific Research

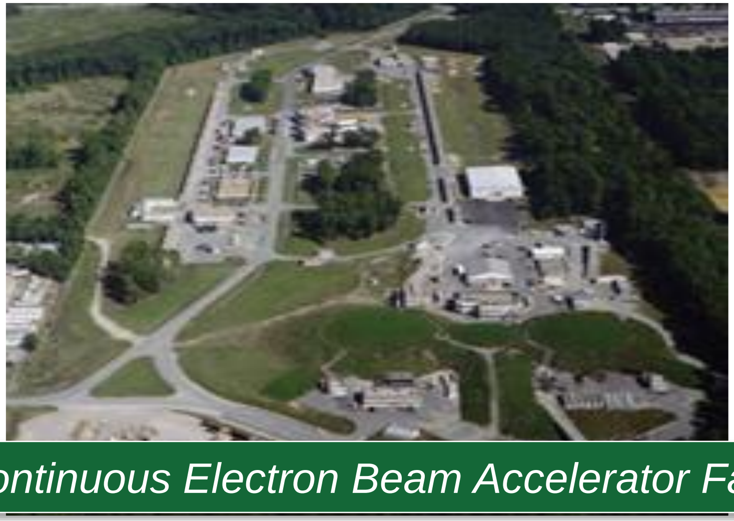


The vast range of time (μsec to 13.8B years) and physical scales (quarks to galaxies) requires "microscopes" of varying, complementary resolving "powers"

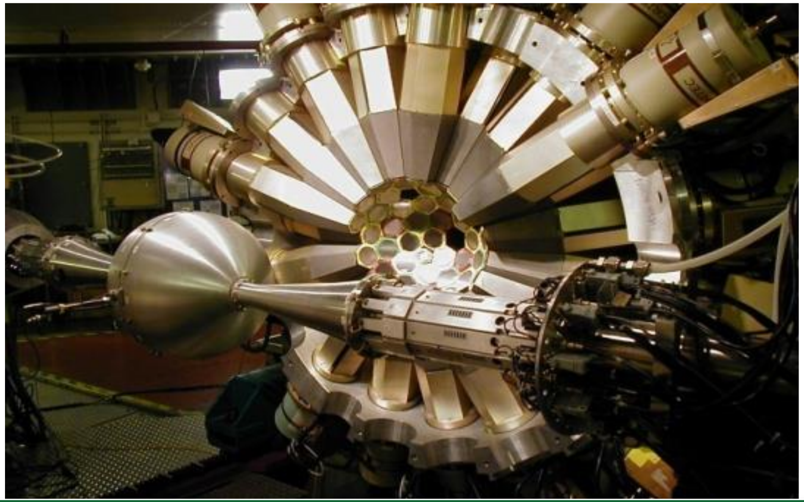
Four World-Leading National User Facilities Driving Advances



Relativistic Heavy Ion Collider



Continuous Electron Beam Accelerator Facility

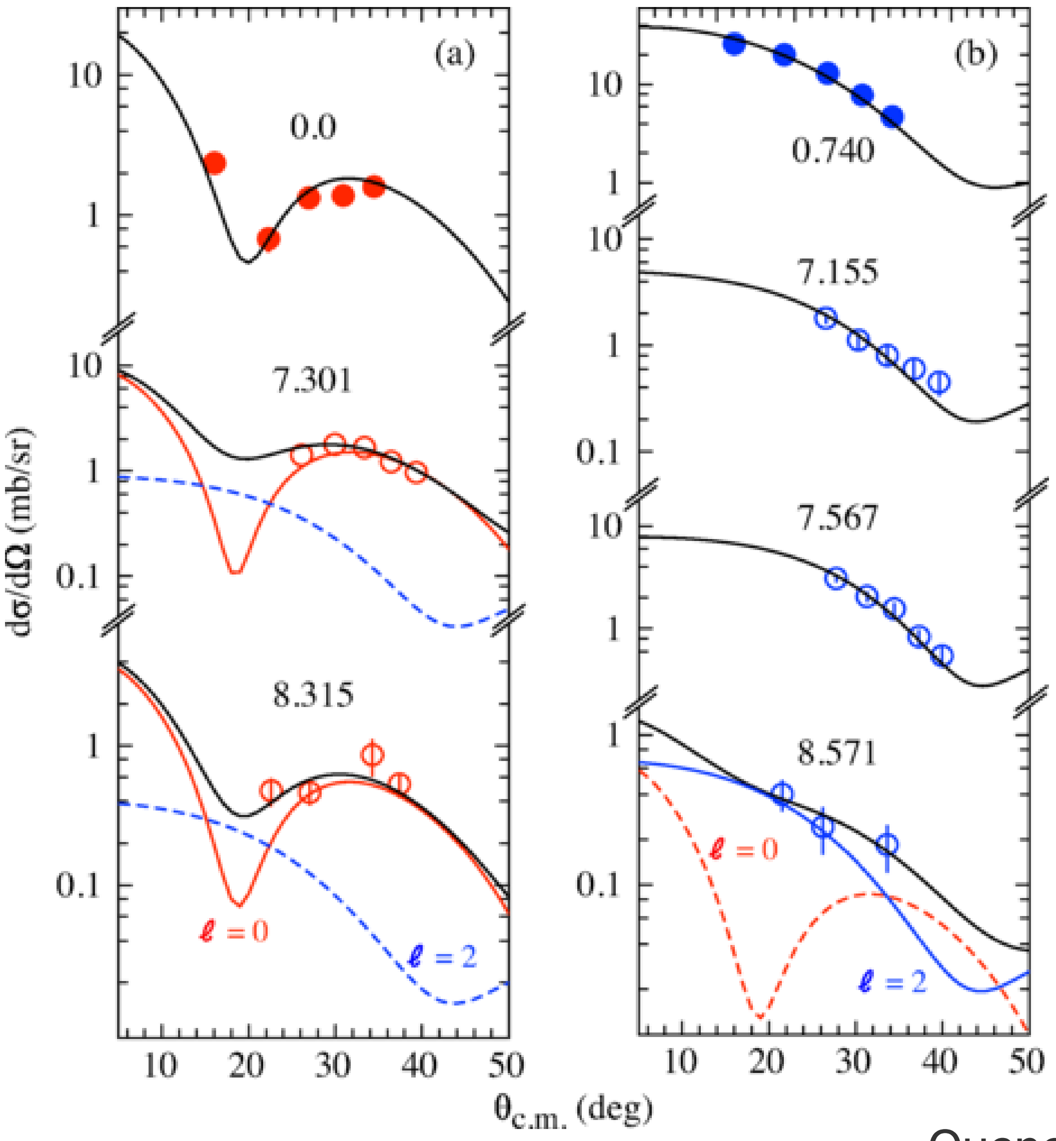


Argonne Tandem Linac Accelerator System

Facility for Rare Isotope Beams

Are "Microscopes" with Complementary Resolving Power

HELIOS @ ATLAS: (d,p) Reactions



Argonne NATIONAL LABORATORY

MANCHESTER 1824 The University of Manchester

OAK RIDGE National Laboratory

FLORIDA STATE UNIVERSITY 1851

THE AUSTRALIAN NATIONAL UNIVERSITY

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Lawrence Berkeley National Laboratory

Quenching of Single-Particle Strength in A=15 Nuclei, B. P. Kay, et al. Phys. Rev. Lett. **129**, 152501 – Published 3 October 2022

The Newest SC User Facility: the Facility for Rare Isotope Beams

Facility for Rare Isotope Beams

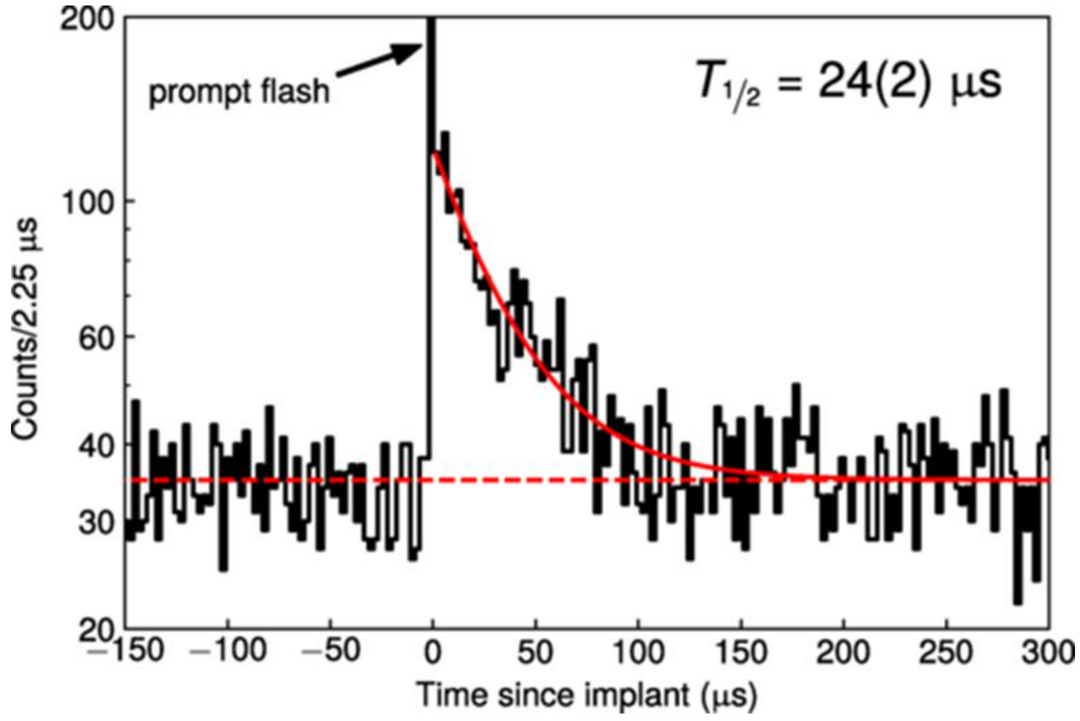
- FRIB construction started in 2013 and finished in 2022, on cost and ahead of schedule
- FRIB was constructed by DOE ($635M) and Michigan State University ($94.5M) under a unique Cooperative Agreement
- Now complete, FRIB provides access to 80% of all isotopes predicted to exist in nature

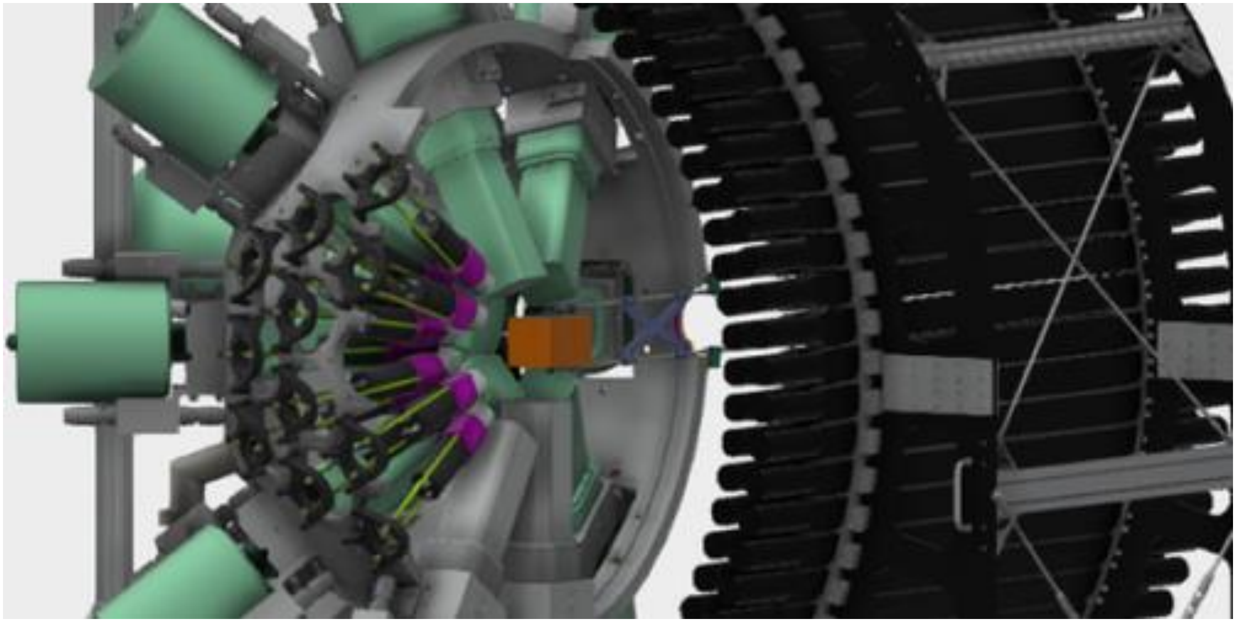
At this lab, the secrets of the atom — and the universe — are being discovered

Keith Matheny
USA TODAY

Since the start of operations, a little over a year ago, the Facility for Rare Isotope Beams has made more than 210 rare-isotope beams for experiments involving 180 institutions representing 50 countries

Excited Na-32 With a Spherical Wave Function





FRIB | Oak Ridge National Laboratory | Lawrence Berkeley National Laboratory | Lawrence Livermore National Laboratory | GSI | Technische Universität Darmstadt | Georgia Tech

LSU | NNDC | Los Alamos National Laboratory | Argonne National Laboratory | The University of Tennessee Knoxville | State | TRIUMF | Florida State University | The Australian National University

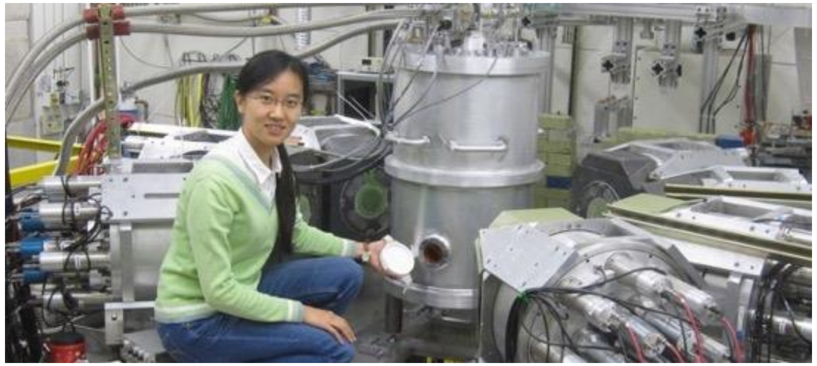
Microsecond Isomer at the N=20 Island of Shape Inversion Observed at FRIB

T. J. Gray *et al.* Phys. Rev. Lett. **130**, 242501 – Published 13 June 2023

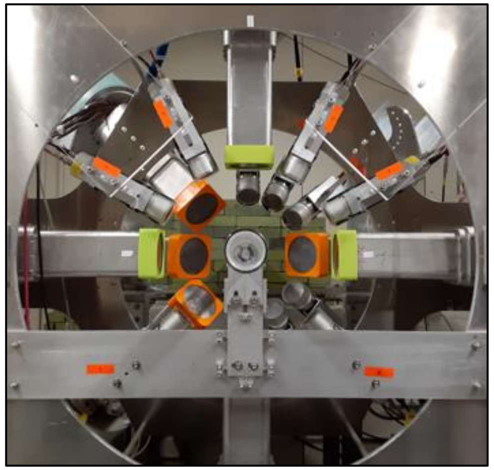
TUNL's Decadal Vision: Strong Research Programs at the Frontiers of the Field

Comissioning summer 2023

Nuclear Astrophysics: LENA Upgrade, New 2-MV single-tron accelerator with terminal ECR source and chopper/buncher for research on globular clusters, classical novae, astrophysical s-process, grains



Medium Energy: Low-Energy QCD research at HIγS on Compton scattering on H, D and ^{3,4}He to determine nucleon polarizabilities with high precision; develop HIγS beams t toward pion threshold



Nuclear Structure: New γ-ray Array at HIγS:

- Identify in stable nuclei new excitation modes found in n-rich systems
- Properties of states important for nucleo synthesis
- Strength functions

Fundamental Symmetries: $0\nu\beta\beta$

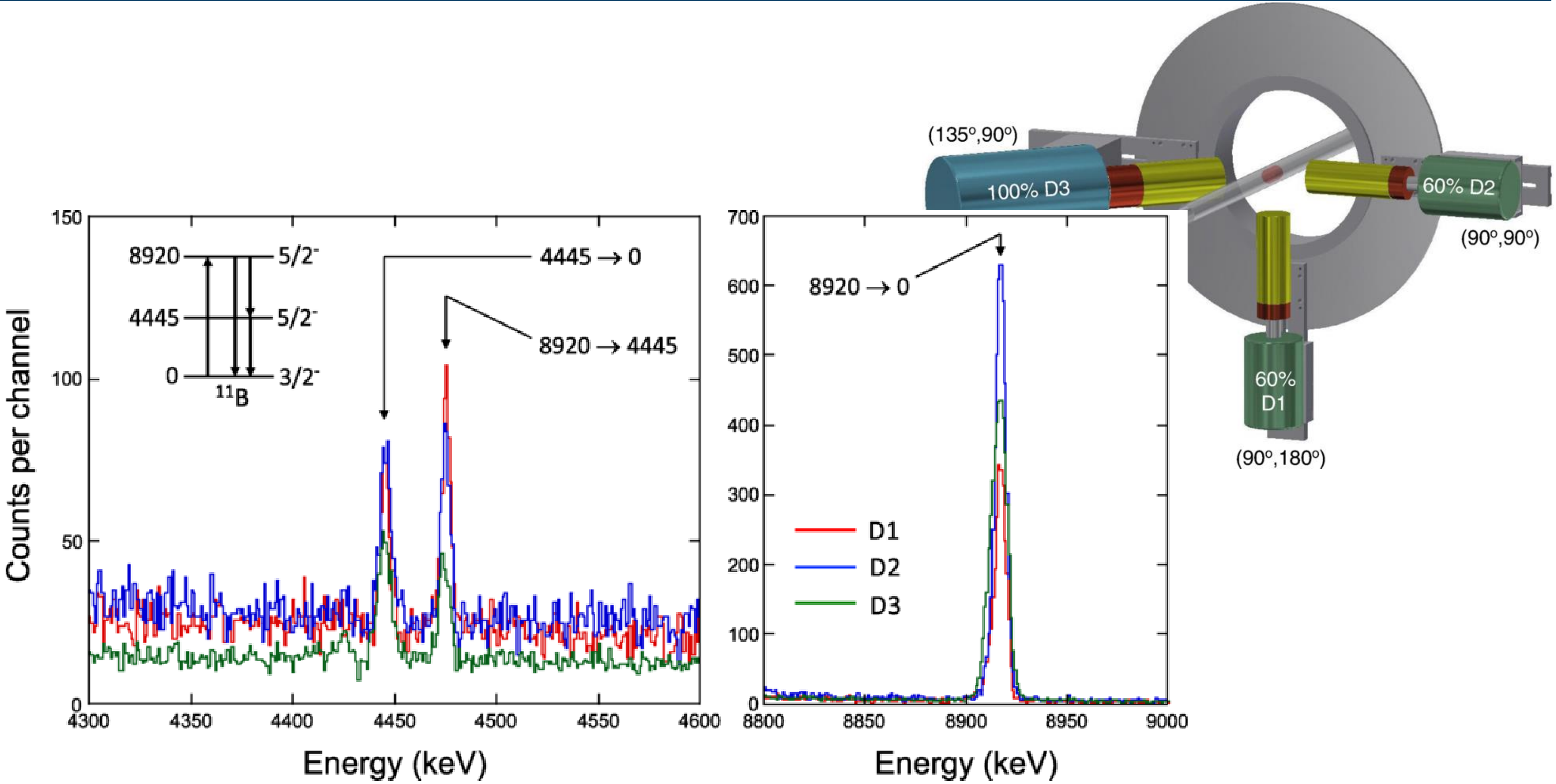
- Analysis of Majorana Demonstrator data
- Commission LEGEND-200
- Prepare for LEGEND-1000

Neutron EDM

- Systematics with polarized UCN and ^{3}He
- Neutron cell development and UCN storage time determination

Nuclear Resonance Fluorescence @ HIγS

Globular Cluster Tuc 47 image courtesy of NASA/Hubble



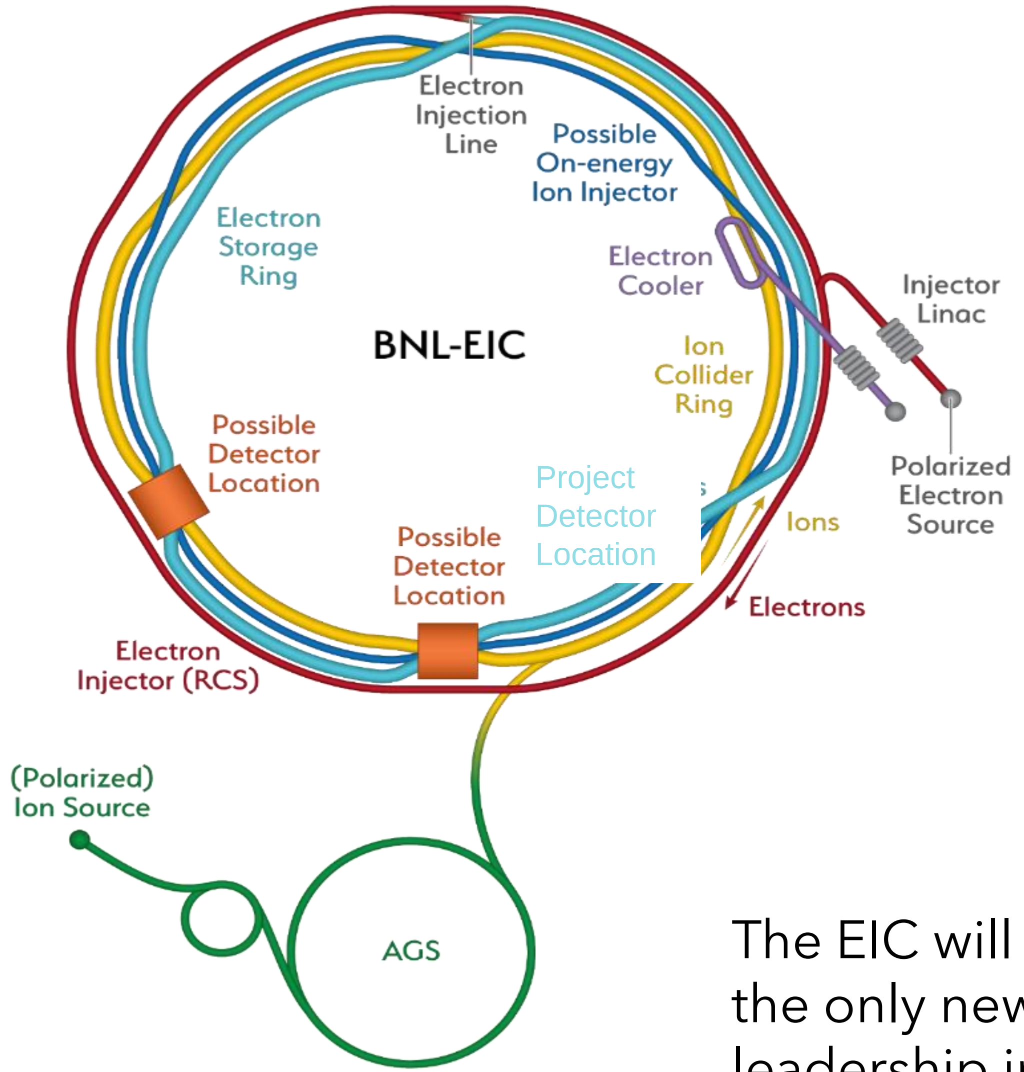
Investigation of 11B and 40Ca levels at 8–9 MeV by nuclear resonance fluorescence, D. Gribble, C. Iliadis, R. V. F. Janssens, U. Friman-Gayer, Krishichayan, and S. Finch, Phys. Rev. C **106**, 014308 – Published 14 July 2022

International Partnership Enabling Scientific Discovery: Success Stories in July 2023

- FRIB-CNRS International Research Laboratory
  - Collaborative effort in nuclear physics
  - MoU signed July 18, 2023.

- RIKEN-BNL 25th Anniversary
  - Japanese collaboration enables scientific collaboration
  - Celebration on June 22, 2023

NP Is Constructing Capability to Maintain World Leadership Throughout The Century: the Future Electron-Ion Collider

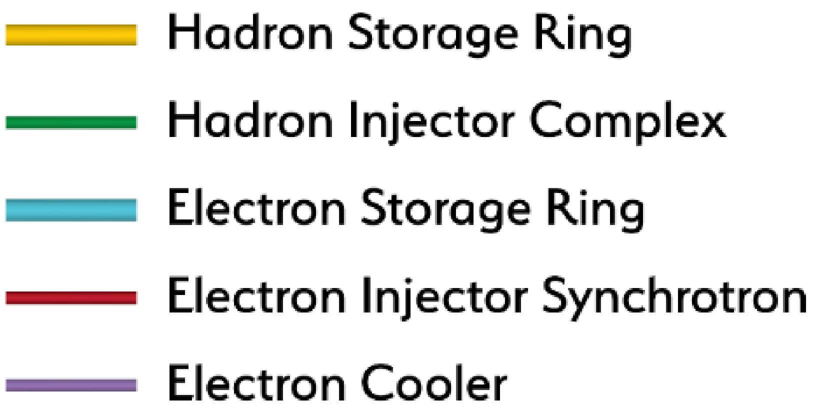


Recent Progress

Successful OPA Progress Review 1/ 2023

Significant Project staffing increases via IRA

Pursuing Long Lead (CD-3a) followed by CD-2



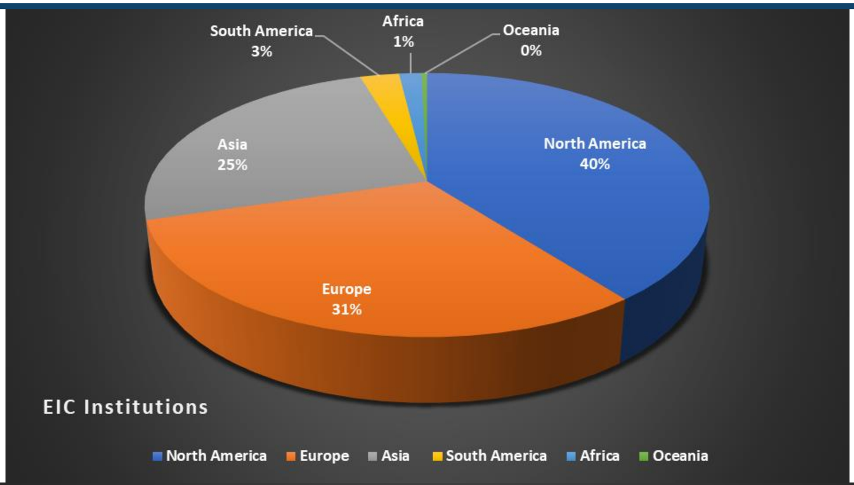
The EIC will be the most advanced accelerator in the world and the only new collider built for decades. It will maintain US leadership in accelerator physics.

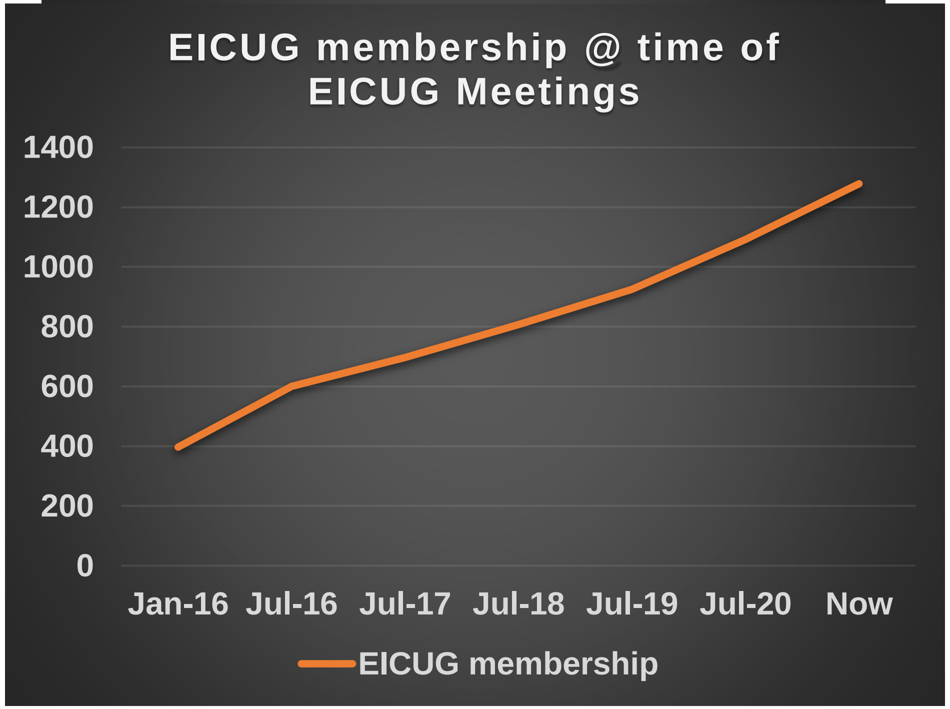
The EIC is International At Its Core

EIC Users Group Formed in 2016
EICUG.ORG

Status August 2023:

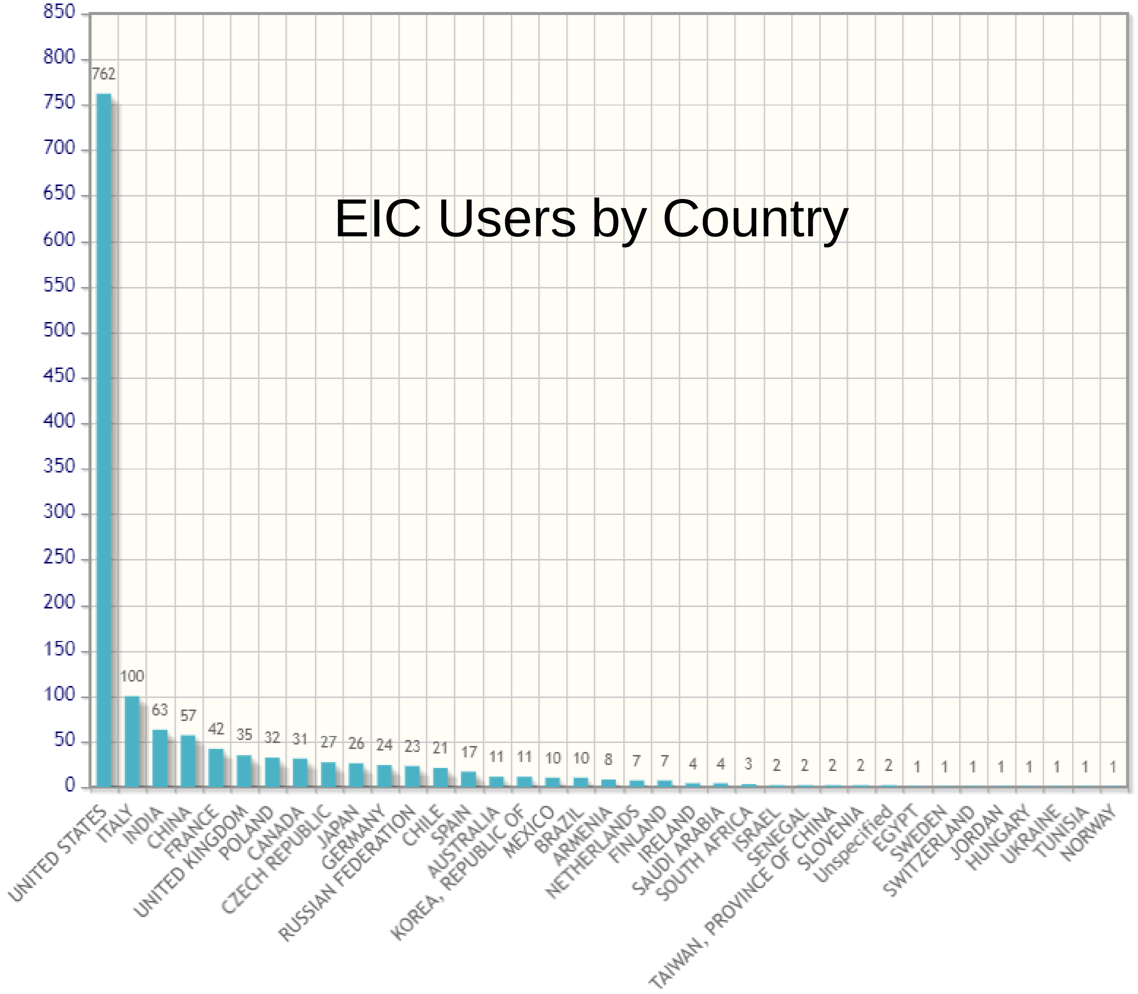
- Collaborators **1407**
- Institutions **281**
- Countries **37**

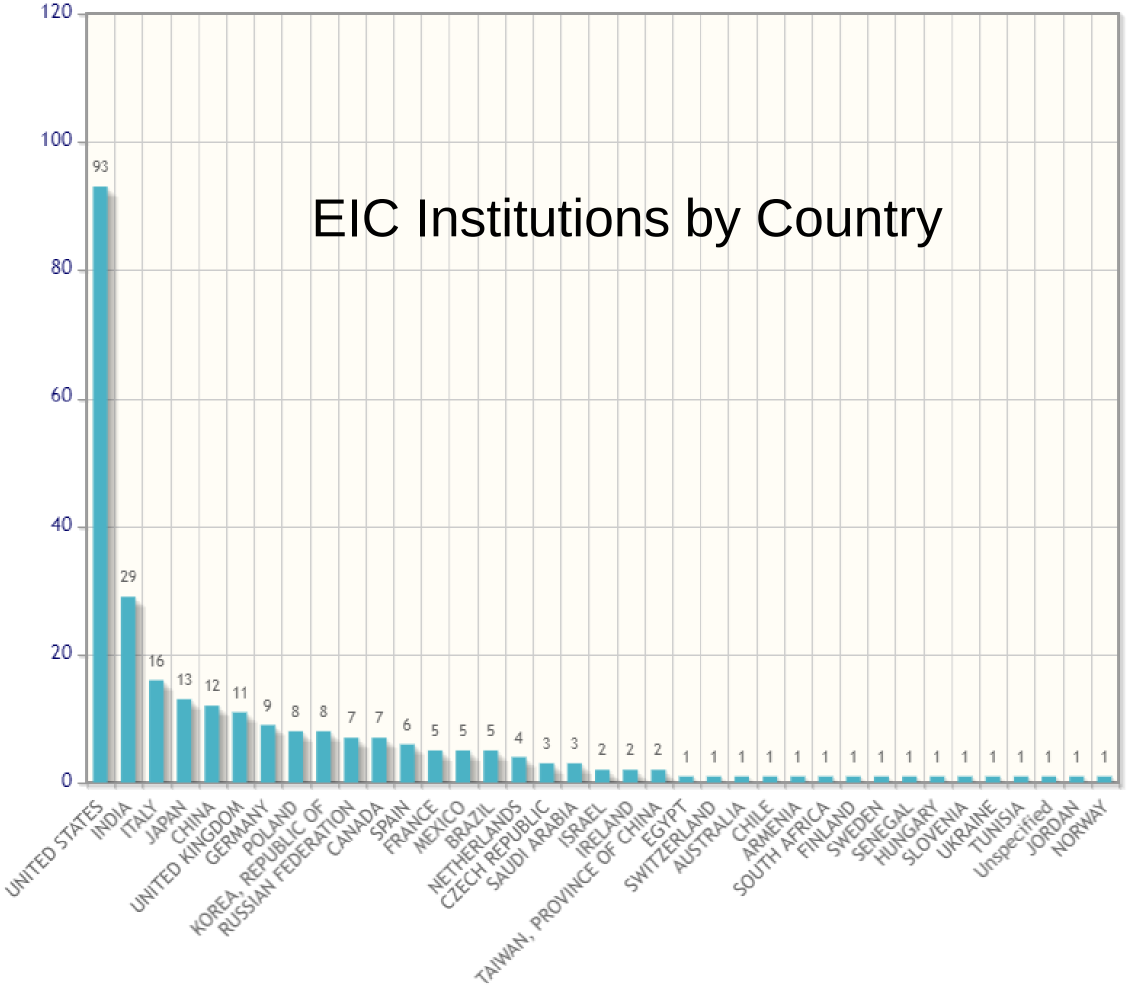




The EIC User Group

Over 1400 EIC Highly Active Users from 281 Institutions in 37 countries





International Contributions to the Electron-Ion Collider

- The EIC Project is envisioning international contributions to the EIC detector of approximately $100M, and contributions to the accelerator of approximately $50M
  - About half of these contributions have already been notionally identified by international collaborators
- The body being established to coordinate such contributions in analogy with the way this is handled at CERN is an EIC Resource Review Board (RRB)

The Next EIC RRB Will Be in Washington D.C. 12/2023

Name	Affiliation	Country	Funding Agency/PI
Hayotsyan, Sargis	State Science Committee of Armenia	Armenia	Funding Agency
Samson, Claire	Canada Foundation for Innovation (CFI)	Canada	Funding Agency
Vyšinka ,Marek	Ministry of Education, Youth and Sports	Czech Republic	Funding Agency
Sabatie, Franck	Institut de Recherche sur les Lois Fondamentales de l’Univers (Irfu-SPhN), CEA-Saclay	France	Funding Agency
Grasso, Marcella	IN2P3/CNRS	France	Funding Agency
Lucotte, Arnaud	IN2P3/CNRS	France	Funding Agency
Bettoni, Diego	Instituto Nazionale de Fisica Nucleare (INFN)	Italy	Funding Agency
Nania, Rosario	Instituto Nazionale de Fisica Nucleare (INFN)	Italy	Funding Agency
Moon, Young Kun	Research Promotion Division at the Ministry of Science and ICT	Korea	Funding Agency
Gaczyński, Mateusz	Department of Innovation and Development, Ministry of Science and Higher Education	Poland	Funding Agency
Ka, Oumar	Cheikh Anta Diop University	Senegal	N/A
Nxomani, Clifford	National Research Foundation	South Africa	Funding Agency
Blaire, Grahme	UK Science and Technology Facilities Council (STFC)	United Kingdom	Funding Agency
Hiscock, Jenny	UK Science and Technology Facilities Council (STFC)	United Kingdom	Funding Agency
Hallman, Timothy	DOE Office of Nuclear Physics	United States	Funding Agency

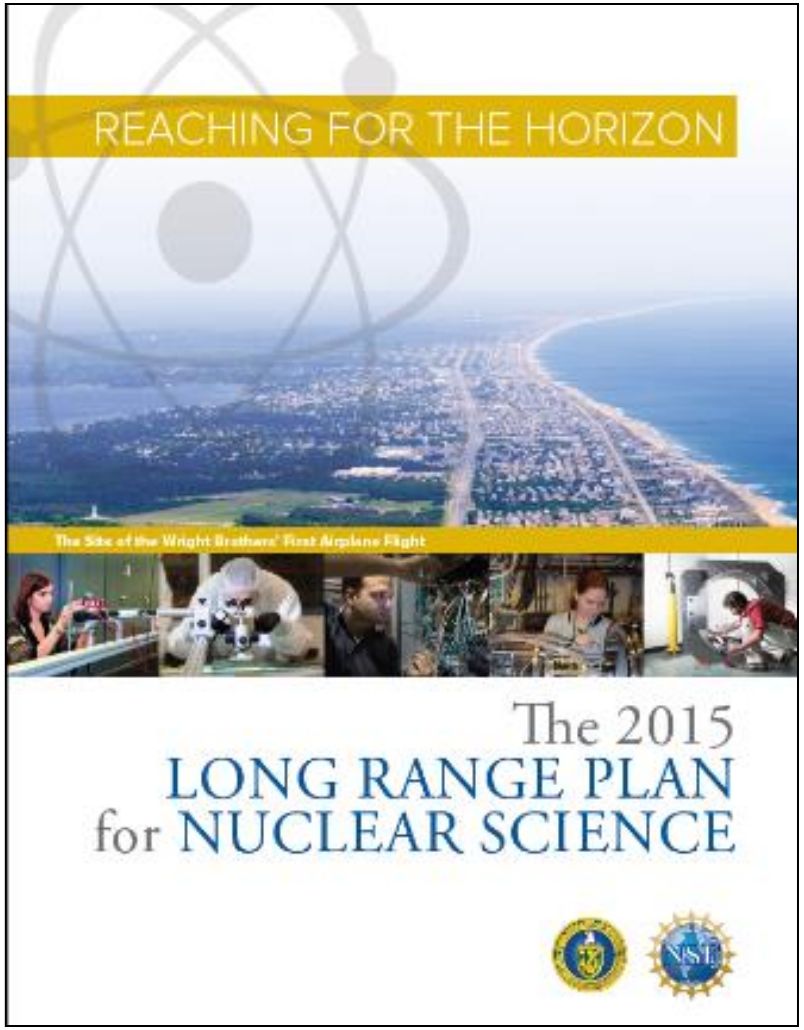
The High-Level NP Work Plan – Up Until Now

1. Operate and get science out from the Relativistic Heavy Ion Collider (RHIC),the Continuous Electron Beam Accelerator Facility (CEBAF), the Argonne Tandem Linac Accelerator System (ATLAS) and the Facility for Rare Isotope Beams (FRIB)

2. Make progress on a U.S.-led ton-scale neutrino-less double beta decay experiment.

3. Start construction of a high-energy high-luminosity polarized electron-ion collider (EIC)

4. Implement smaller scale instrumentation to take advantage of facility capabilities



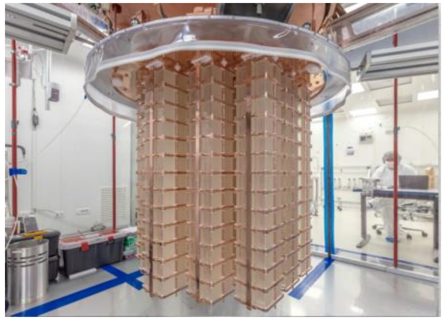
The work plan centers on NP’s mission to understand all forms of nuclear matter to benefit energy, commerce, medicine, and national security. A new Long Range Plan is in development by NSAC.

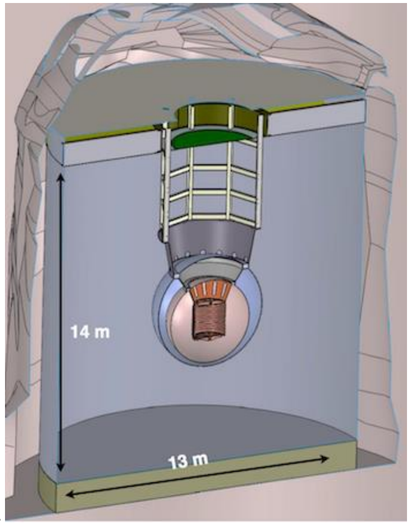
The Other Top Priority of the 2015 Long Range Plan for Nuclear Science: Neutrinoless Double Beta Decay

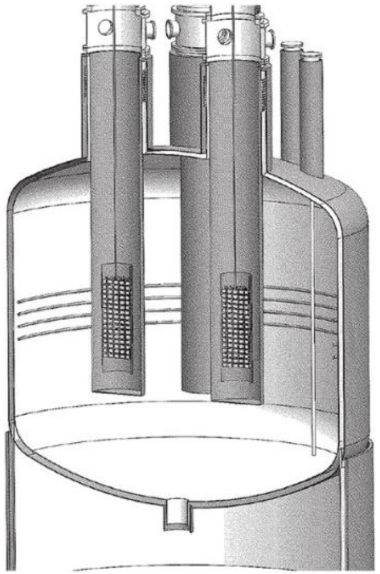
- Between IRA funding and NP Program Funding, approximately \$12.8 M allocated to the three technologies being explored LEGEND 1000, nEXO, and CUPID since FY 2020.
- Additional resources provided by international partners
- Inability to procure isotopes from Russia is having a severe impact
- The 2^{nd} DBD international summit occurred on April 27, 2023 at SNOLab in Canada. A Virtual Global DBD Observatory is being established.

Three Proposed Technologies

- Scintillating bolometry (**CUPID**, ^{100}Mo enriched Li_2Mo_4 crystals)
- Enriched ^{76}Ge crystals (**LEGEND-1000**, drifted charge, point contact detectors)
- Liquid Xenon TPC (**nEXO**, light via SiPM, drifted ionization)

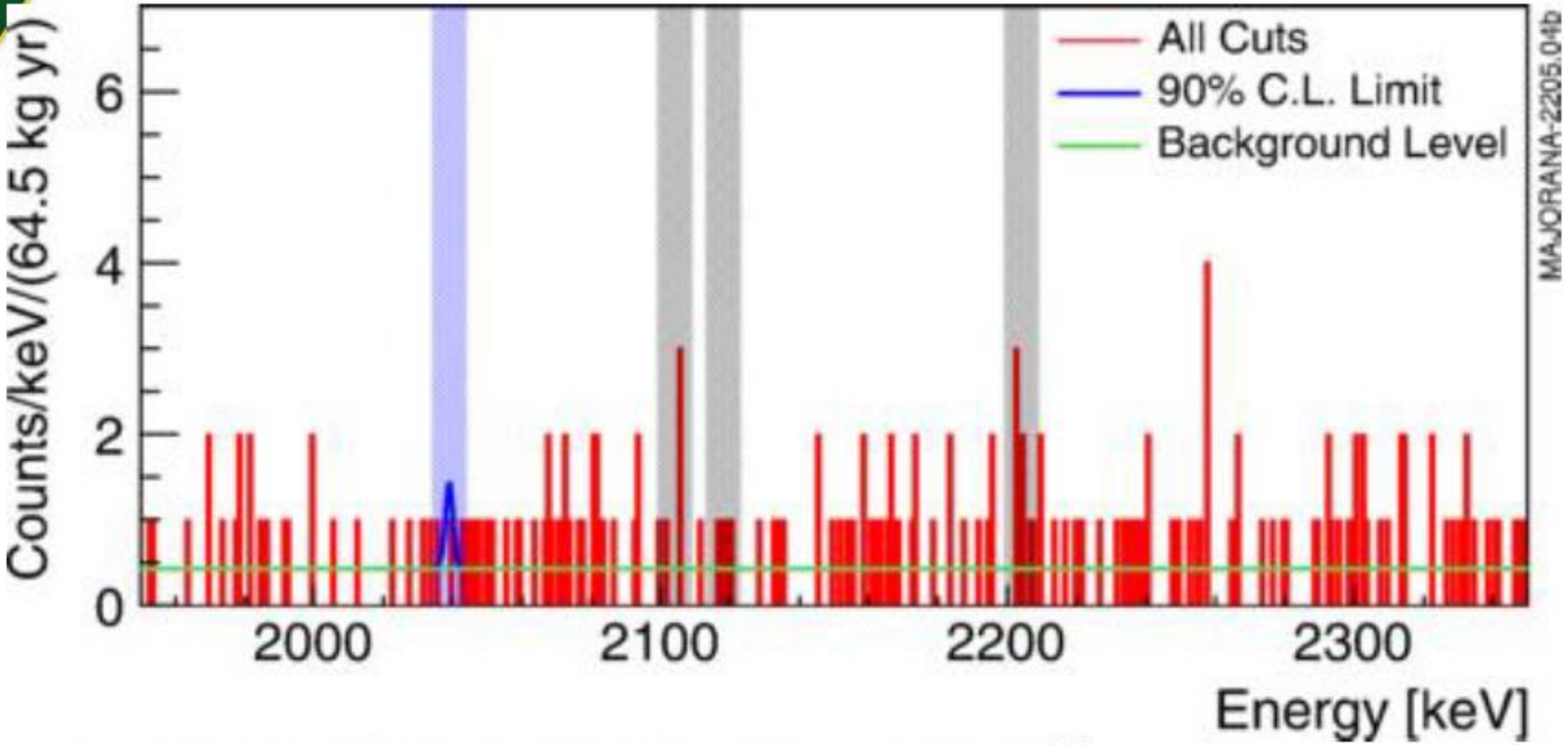






Early Potential Partners:
Italy, Canada, and Germany

Final Result of the MAJORANA DEMONSTRATOR Experiment



lower limit on the half-life of the decay at 8.3x10^{25} years

Final Result of the MAJORANA DEMONSTRATOR's Search for Neutrinoless Double-β Decay in 76Ge, Arnquist I.J., et al. (MAJORANA Collaboration), Phys. Rev. Lett. 130, 062501 – Published February 10, 2023

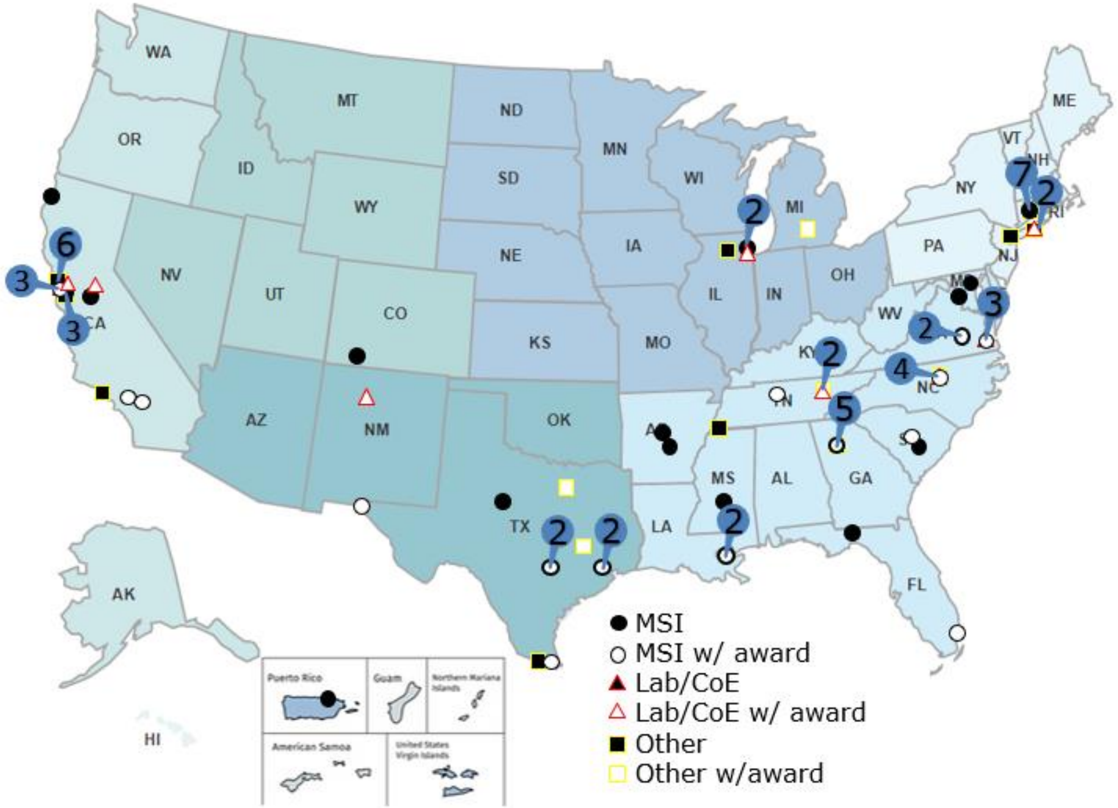
Comparable nEXO200 limit: 0νββ half-life of 3.5×10^{25} yr at 90% confidence

Future NP Research Horizons ?

- Search for anomalous atomic electric-dipole moments at FRIB as a signal of new physics using laser trapped isotopes
- Search for anomalous parity violation in electron scattering as a signal of new physics using MOLLER at JLAB
- ☆ Search for the next superheavy nucleus (Z = 120) at the LBNL 88-Inch cyclotron
- Understanding the equation of state of the quark-gluon plasma using sPHENIX at RHIC
- Expanding the boundary of present knowledge of how heavy elements are produced in the cosmos via never-before-produced heavy neutron-rich nuclei at FRIB
- Discovering ways to suppress the effects of natural radiation on quantum coherence times
- ☆ Quantum step improvement in rare search capability via AI/ML pattern recognition software
- ☆ Significantly advancing imaging technology for the physical sciences.

NP Helped Pioneer An Early Initiative Leading Toward RENEW

- 110 NP traineeship award recipients include:
  - 18 MSIs,
  - 10 other colleges/universities,
  - 5 DOE laboratories
- MSI award recipients include:
  - 9 Hispanic Serving Institutions (HSIs),
  - 8 HBCUs,
  - 5 Asian/Native American, and Pacific Islander Serving Institutions (AANAPISI),
  - 1 Predominantly Black Institution (PBI)

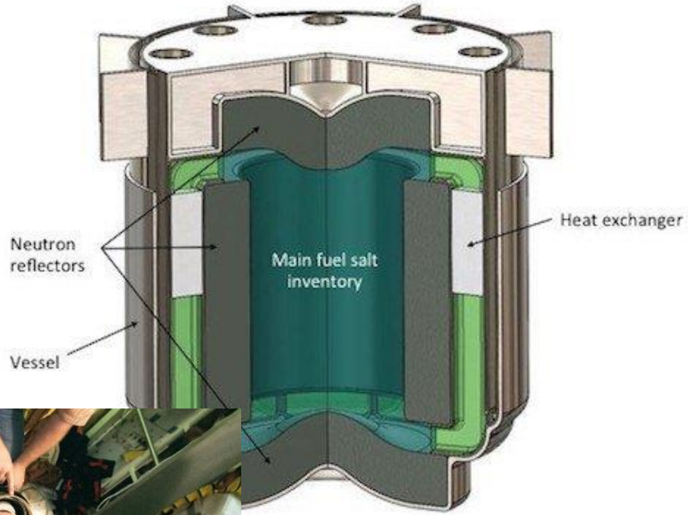


Other institutions on the map are involved in the traineeship program as recruitment sites (38), Co-Is (9), and/or hosts (7).

Of the funds awarded, ~ 70% went to MSIs, MSI faculty, or MSI students. About 50% of trainees awarded continued on to Graduate Programs in Science or Engineering

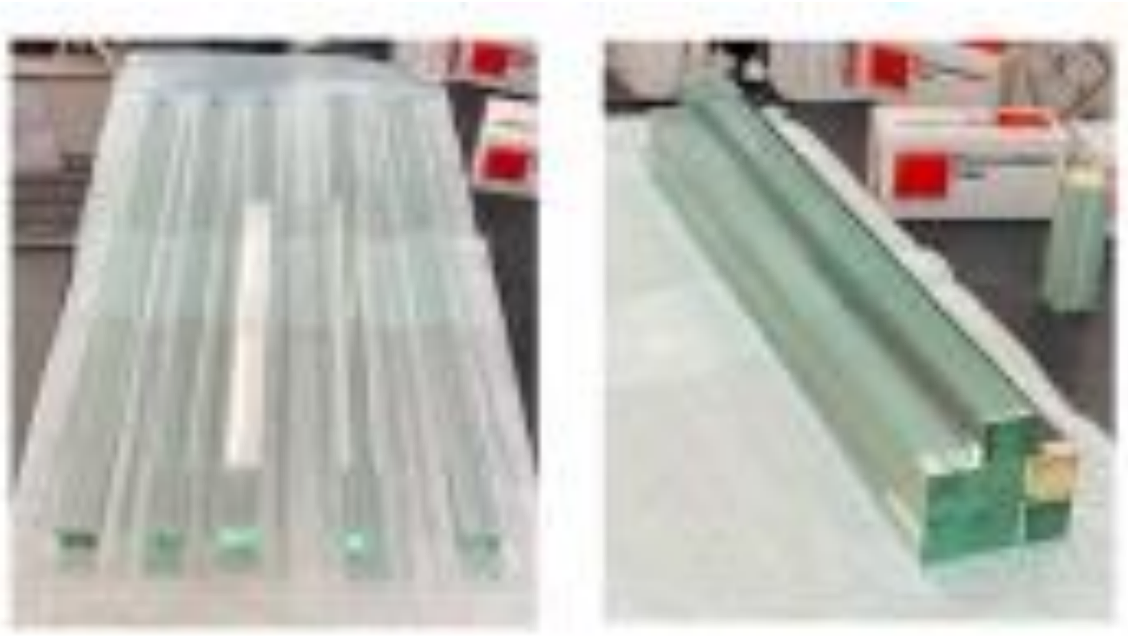
NP Broader Impacts & Apps For Other Missions: Nuclear Data

- NP is providing new and updated nuclear data to existing customers
  - Working to identify impactful nuclear data needs and leverage resources
    - ★ Ex: Data for next generation molten salt reactors with DOE/NE, ARPA-E
- NP is reaching out to new nuclear data application customers
  - ★ Electronics protection (NASA, Missile Defense Agency, Federal Aviation Administration)
  - ★ Human safety (NASA [spaceflight], NIH [ion beam therapy])
  - ★ Advanced reactors (ARPA-E, NASA) and fusion energy



SBIR Value Added: NP Phase II Example: Lead-glass Scintillator for Nuclear Physics Detectors

- STTR award to Scintilex/Catholic University of America
- New material is being developed due to the expense and difficulty in obtaining the $PbWO_4$ often used in electromagnetic calorimeters, a component of current and future NP detectors
- Currently crystals come from the Czech Republic; LHC is buying up all material for next few years
- "SciGlass" will be ~ 5x cheaper in volume than $PbWO_4$. This development is essential for the Electron-Ion Collider (EIC)
- The Company received a Phase IIA award to finish R&D and scale up production.



2×2×40 cm^3 bars – full scale $PbWO_4$ replacements

Sponsors

NIH NATIONAL CANCER INSTITUTE

NIH National Institute of Biomedical Imaging and Bioengineering

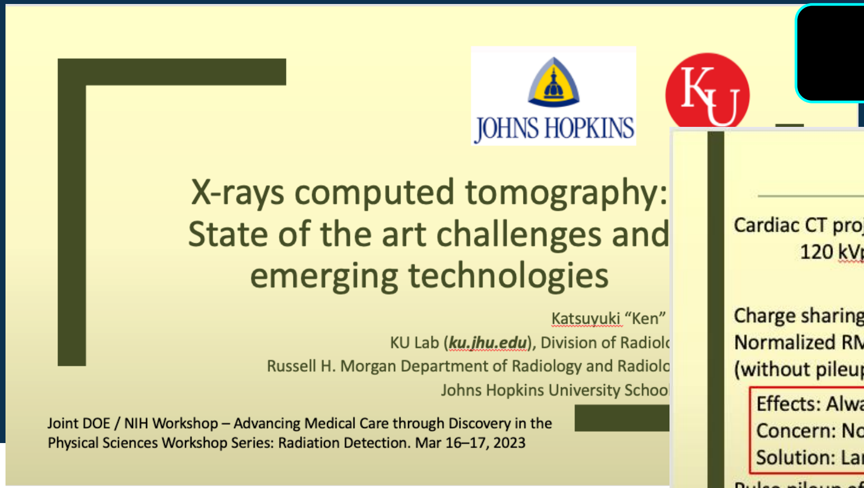
U.S. DEPARTMENT OF ENERGY Office of Science

Jefferson Lab

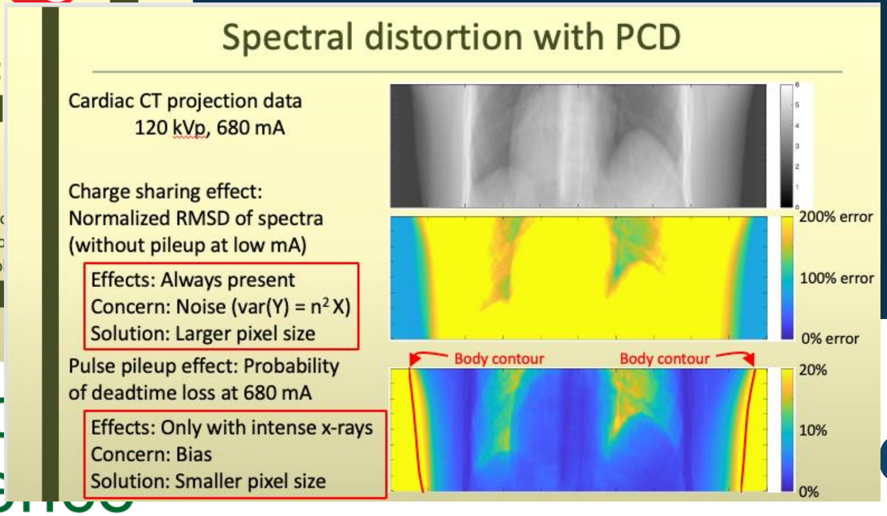
March 15, 2023 to March 17, 2023 at the Thomas Jefferson National Accelerator Facility

89 participants from DOE, NCI, NIBIB, universities, clinics

Second workshop (this time focused on radiation detection) in an ongoing series



Unmet goals: Small pixels, less noise, good spectral information



Unmet need: Address both charge sharing and pulse pileup

Ideas Consistent with Administration Priorities

- ☆ **Ultra-low Temperature Calorimetry Sensors for Discovery Science** Ultra-low temperature, superconducting sensors promise a critical, inherent, physics-based signal-to-noise advantage that may promote both high precision nuclear science as well as new biological discovery with medical implications.
- ☆ **The 10 ps Challenge:** Needed for high rate (such as the luminosity frontier at JLab) and high volume (such as the EIC) nuclear science experiments, the continued development of these techniques may also directly pave the path for addressing the 10 ps challenge in time-of-flight (TOF) PET.
- ☆ **Enabling Multi-institutional, Multi-agency Collaborations with Scalable Federated Learning**: Federated learning (FL) is a distributed machine learning method that allows a network of participants to collaboratively train a shared model without exchanging their data
- ☆ **Non-imaging and Imaging Detector Technologies for Enabling Nuclear Science and Customized Dosimetry-based Cancer Treatment Planning:** The goal of this topic is to develop and validate cost-effective, potentially small cross-section, detector technologies that will enable radiation monitoring for personnel, equipment, and/or personalization of radiation therapy treatment planning. It could be achieved by combining high-resolution, hyper-sensitive radiation detectors
- ☆ **Compton Scattering-based Detectors and Systems:** Compton scattering-based detectors can resolve much lower radiation emissions than standard sensors, and can do so more rapidly, as compared for example to PET or other sources and therefore offer great promise in medical and other applications

Snapshot of the Status of NP Projects

Project	Location	Status	Cost	CPI	SPI	CD-4	Operation cost plan
Construction Projects							
Facility for Rare Isotope Beams (FRIB) *	MSU	CD-4	$730M	1.00	1.00	6/2022	Included in NP budget formulation
Electron-Ion Collider (EIC)	BNL	CD-1	$1.7B to $2.8B			Q4 FY33	RHIC operations funds redirected to EIC project recovered for EIC operations
Major Items of Equipment							
Gamma Ray Energy Tracking Array (GRETA) [FF]	LBNL	CD-2/3	$58.3M	0.96	0.93	4/2028	Mostly covered by host laboratory operations experimental support
Super Pioneering High Energy Nuclear Interaction Experiment (sPHENIX) *	BNL	PD-4	$26.5M	1.00	1.00	12/2022	Covered by RHIC operations experimental support
Measurement of Lepton-Lepton Electroweak Reactions (MOLLER) [FF]	TJNAF	CD-3A	$45.8M to $56.6M			Q4 FY27	Covered by TJNAF operations experimental support
High Rigidity Spectrometer (HRS)	*MSU*	*CD-1*	*$85.0M to $111.4M*			*Q2 FY29*	*Covered by FRIB operations experimental support*
Ton Scale Neutrinoless Double Beta Decay (TS-NLDBD)	TBD	CD-0	$215M to $250M			TBD	TBD

Blue (*) indicates "Completed", green ([FF]) "Fully Funded", *and purple italic "Substantially Funded"*

Smaller NP Projects are being "cleared off the books"

NP Budget Overview

(B/A in thousands)

	FY 2022	FY 2022	FY 2023	FY 2024		
	Enacted	Enacted	Enacted	Request	HouseMark	SenateMark
	Regular	IRA Supp.	Regular	Regular	Regular	Regular
Nuclear Physics						
Medium Energy Physics	196,113	...	208,917	197,485	**201,724**	**198,985**
Heavy Ion Physics	255,461	10,000	248,236	226,499	**216,238**	**228,999**
Low Energy Physics	199,166	78,760	230,170	215,292	**227,396**	**218,292**
Nuclear Theory	57,260	...	67,873	77,142	**59,642**	**77,142**
Program Subtotal	**708,000**	88,760	**755,196**	**716,418**	**705,000**	**723,418**
20-SC-52, Electron Ion Collider EIC, BNL	20,000	128,240	50,000	95,000	**95,000**	**95,000**
Construction Subtotal	**20,000**	128,240	**50,000**	**95,000**	**95,000**	**95,000**
Total Nuclear Physics	**728,000**	**217,000**	**805,196**	**811,418**	**800,000**	**818,418**

Outlook

- NP continues stewardship of a world-leading program in nuclear physics that delivers new science, operates unique leadership user facilities, supports and enhances a diverse workforce, and delivers impactful applications

- The EIC Project is making steady progress, towards CD-3a (Long Lead Procurement), and the next DOE gateway CD-2 (Approve Performance Baseline). Although not yet baselined, increased support from annual appropriations is essential to enable timely progress and a smooth transition of workforce from the Relativistic Heavy Ion Collider.

- The FY 2024 Request is greatly appreciated, allowing NP National User Facilities to operate at or above 90% of optimal funding. That said, this level is not sufficient for adequate RHIC running

- NP Research funding allows for a compelling program of science but continues to be constrained due to the priority of increased funding for FRIB Operations and EIC construction

What To Do Now?

Key Points:

1) In turbulent, challenging times it is crucial to **Keep One's Eye On The Ball**—keep delivering the knowledge, discoveries and training that are valued outcomes for the U.S.
2) **Articulate the value of Nuclear Physics**
3) **Mutual Respect** among scientific sub-disciplines
4) **Commitment To The Greater Good** of nuclear science as a discipline
5) Meticulously **Level Playing Field** leading to respect for process and outcomes
6) The community **MUST REMAIN UNIFIED**

Staying united we can accomplish great things together

Division will setback the entire field and is the last thing needed right now

The Current Focus of NP Research

Understanding why matter takes on the specific forms observed in nature and how that knowledge can benefit energy, commerce, medicine, and national security, by:

- Mapping the quantum cosmos inside the proton using the future Electron-Ion Collider
- Discovering the properties of the novel quark-gluon plasma RHIC, LHC
- Exploring the mechanism underlying the confinement of quarks and gluons via CEBAF and RHIC
- Searching for new exotic particles and violations of nature’s symmetries at CEBAF, FRIB, ATLAS
- Determining the limits of nuclear existence and how are heavy elements made via FRIB and ATLAS
- Discovering if the neutrino its own anti-particle or if the neutron’s precise properties point to new physics Neutrino-less Double Beta Decay
- Exploring the strong force in many-body systems via SciDAC, Core Research, QIS/QC, AI/ML
- ☆ Advancing Nuclear Data for Space, Energy, and Research through Nuclear Data and AI/ML