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A Brief Survey of Nuclear Physics for the SNOWMASS Audience

Paul Sorensen
Program Manager for Fundamental Symmetries
Nuclear Physics, DOE-SC

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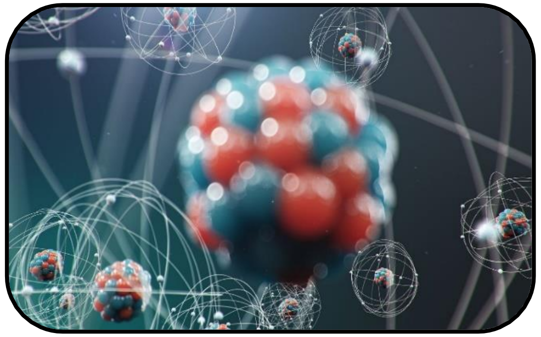
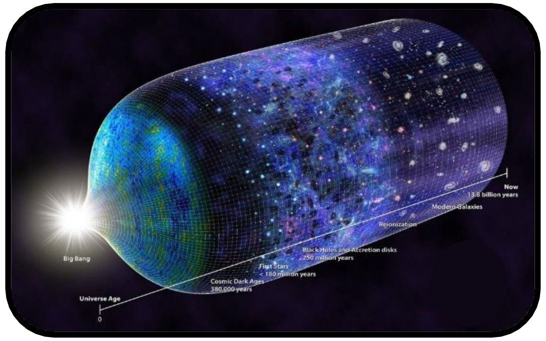
Why Nuclear Physics

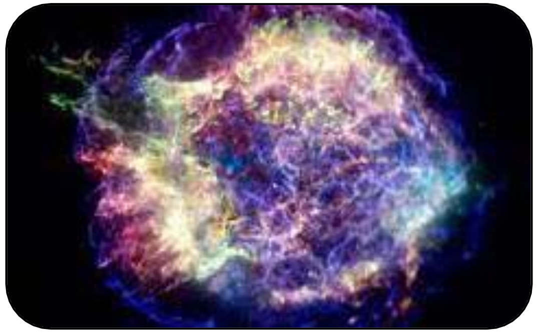
- The nucleus is the densest object we can “put our hands on”. Nuclei
  - enable searches into higher energy or higher density regions of physics
  - provide a window on the strong and weak forces, and are exceptional probes for the symmetries of nature
  - play a central role in the evolution of the universe, in stellar evolution, and in our origin story
  - make up most of the visible mass of the universe and are many-body, open quantum systems, fascinating in their own right
  - are important tools for quantum information science, medicine, industry, and defense
- The knowledge and skills required for this field provide ample opportunities for cooperation between HEP and NP: *examples include DEI and workforce training practices and programs, Lattice QCD, EFT, ultra-clean/low-background experiments and techniques, accelerator development, nuclear data, QIS sensors, detector development, neutrino scattering, etc.*



The Structure of the Atomic Nucleus



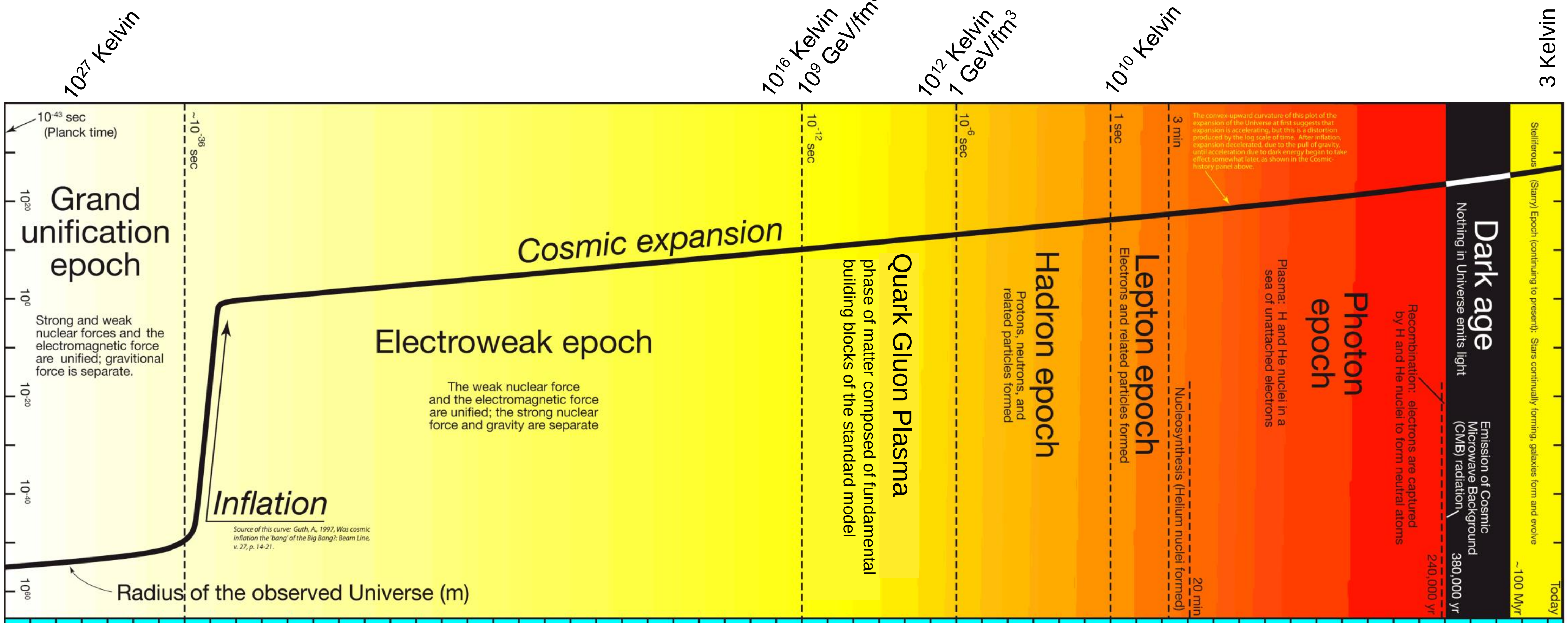
Probing the Matter in the Infant Universe



Birth of Nuclei in Astronomical Processes

Probing Universal Laws in Nuclear Decays

Nuclear physics touches many epochs of cosmic history: sometimes interleaving with HEP topics



Fundamental Symmetries

Heavy Ions at RHIC/LHC

Hadronic Properties

Nuclear Structure
Nuclear Astro

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The Office of Nuclear Physics Subprograms

Fundamental Symmetries: Uses nuclei, their decays, and properties to probe the symmetries of nature. Includes $0\nu\beta\beta$, EDM searches, cold neutrons, β-decay and electron capture studies to probe CKM unitarity, neutrino mass, & sterile neutrinos.

Nuclear Structure/Nuclear Astrophysics: Understanding nuclei, their role in astrophysical processes, the origin of elements, and discovery of new elements.

Heavy Ions: Emergent properties, thermodynamics, and phases of hot and dense nuclear matter, QGP (the only early universe phase transition we can recreate in the lab).

Medium Energy/Hadronic Physics: Electron scattering, hadronic spectroscopy and properties, emergence of spin and hadron masses.

Nuclear Theory/Computing: EFT, Lattice QCD, Transport Models, ADS/QCD, Quantum computing and simulations.

Nuclear Data: applications to space exploration, nuclear reactors, medical physics, and neutrino physics. Well coordinated nationwide program with interagency collaboration and distributed activities.

Accelerator R&D: EIC, RHIC, CEBAF, FRIB, ATLAS. R&D on ion sources, SRF, and beam cooling.

QIS: NP work that advances QIS and vice-versa; e.g. radiation effects on q-bit coherence.

DOE NP User Facilities

RHIC

Relativistic Heavy Ion Collider

Recreates the QGP present one microsecond after the big bang to study its properties.

RHIC will finish its mission in the next several years after which an EIC (Electron-Ion Collider) will be installed in the RHIC tunnel to probe the origin of mass and spin, and to study dense gluonic matter.

CEBAF

Continuous Electron Beam Acc. Fac.

Uses electron scattering to probe the quark and gluon structure of nuclear matter.

Addresses nuclear, hadronic, and electroweak physics including nuclear femtography, hadron spectroscopy, quarks and gluons in nuclei, precision tests of the standard model, and dark sector searches.

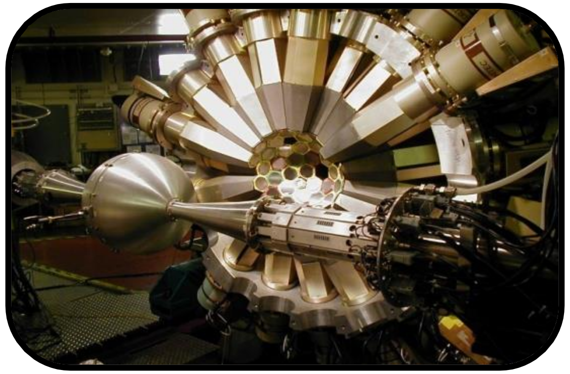
FRIB

Facility for Rare Isotope Beams

Began operations in May. It is the worlds most powerful heavy ion accelerator.

Investigates the properties of rare isotopes, nuclear astrophysics, fundamental symmetries. Applications for society, including in medicine, homeland security, and industry.

ATLAS



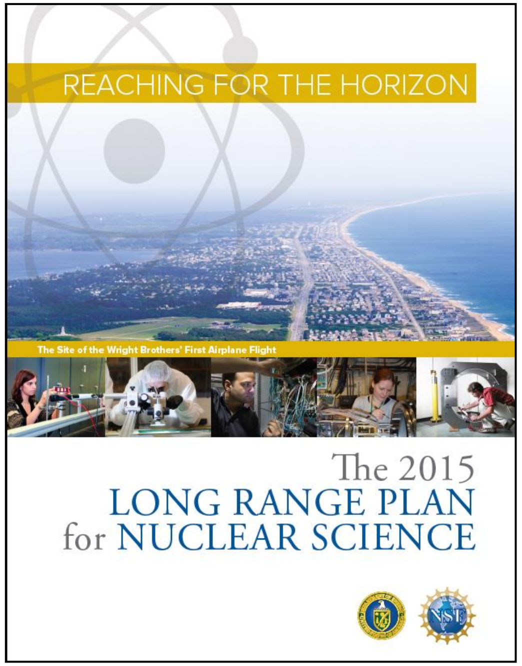
Argonne Tandem LINAC Accelerator

A superconducting linear accelerator for heavy ions at energies near the coulomb barrier, the energy domain best suited to study the properties of the nucleus.

Beams include neutron rich 252Cf fragments, in-flight radioactive beams, and a variety of stable beams.

+Many unique capabilities: UCNs and Neutron sources, Cyclotrons, Centers of Excellence

NSAC 2015 Long Range Plan (NPs P5)



2015 Recommendations:

1. Capitalize on investments made to maintain U.S. leadership in nuclear science.
2. Develop and deploy a U.S.-led ton-scale neutrino-less double beta decay experiment.
3. Construct a high-energy high-luminosity polarized electron-ion collider (EIC) as the highest priority for new construction following the completion of FRIB.
4. Increase investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

LRP process initiated in June

- Community meetings late 2022
- Report due October 2023

From the charge for the next LRP: *“The extent, benefits, impacts, and opportunities … involving different scientific disciplines should be specifically addressed and articulated in the report.”*

Progress Towards an Electron Ion Collider

Located at BNL with TJNAF as a major partner. Adds electron storage ring & electron cooling to existing RHIC assets

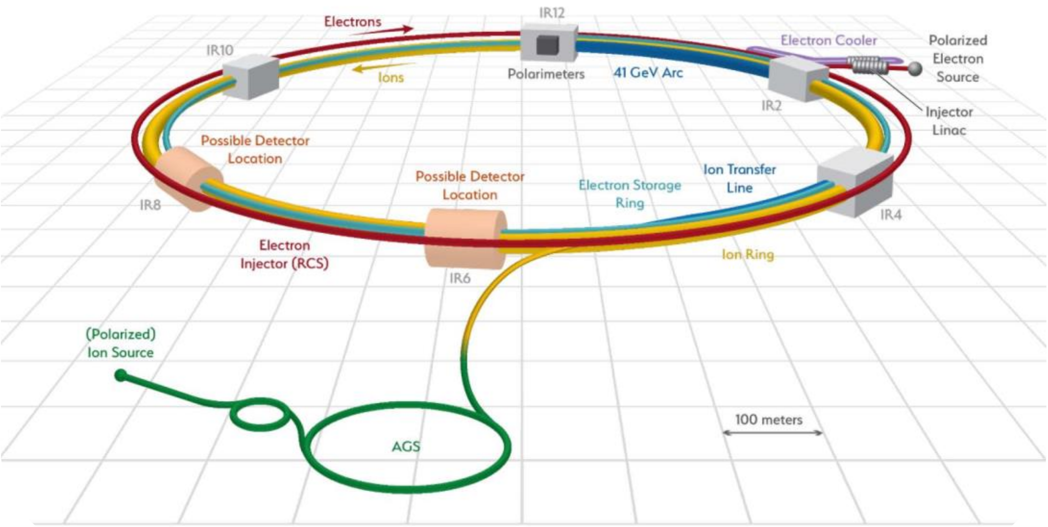
Variable CM energy 20-100 GeV with luminosity ~10^{34} cm^{-2} s^{-1}

Worlds first e-p collider w control of the polarization (~70%) of the electron and proton

Studies precision, non-perturbative QCD to address three overarching questions:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?"

CD-1 was attained in June 2021 ($1.7-2.8 B)



The international community is highly engaged with 1110 collaborators, from 32 countries, and 235 institutions actively working on EIC development.

Many synergies with HEP on physics, detector development, and accelerator development.

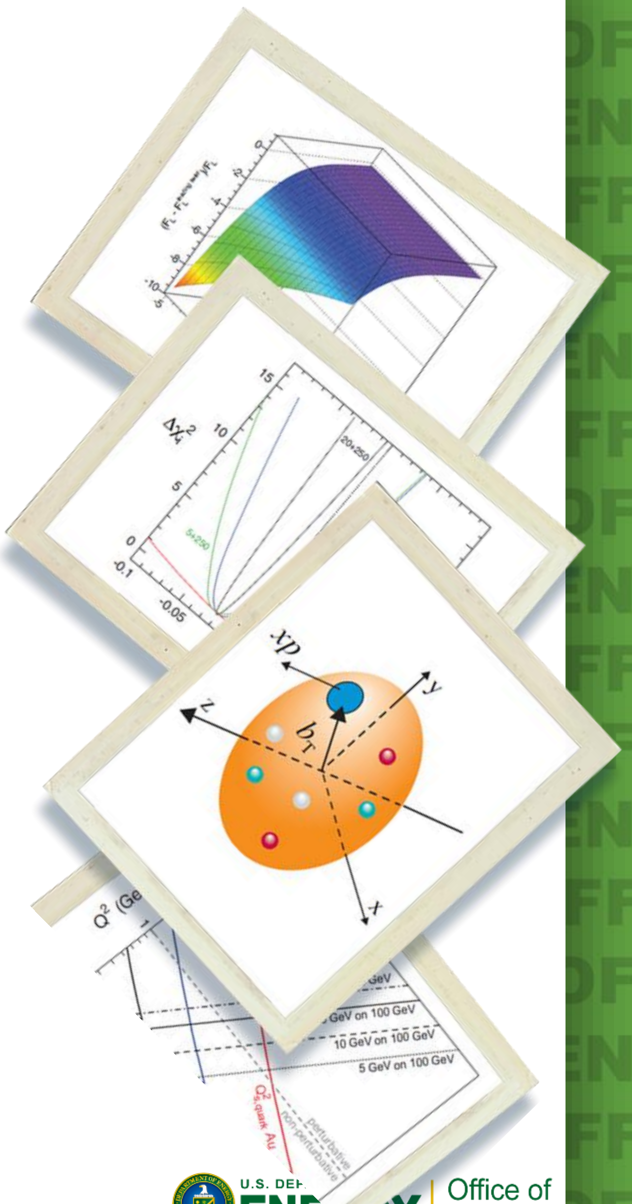
The project remains on a stable path toward the next DOE gateway, CD-2.

$ ~90M anticipated detector in-kind (~30%)
$ ~50M anticipated accelerator in-kind (~5%)
$100M grant from New York State

EIC Impacts on HEP-Related Physics

Precision, non-perturbative QCD studies at the EIC will impact HEP Frontiers including electroweak BSM physics, neutrino physics, and collider/energy-frontier physics:

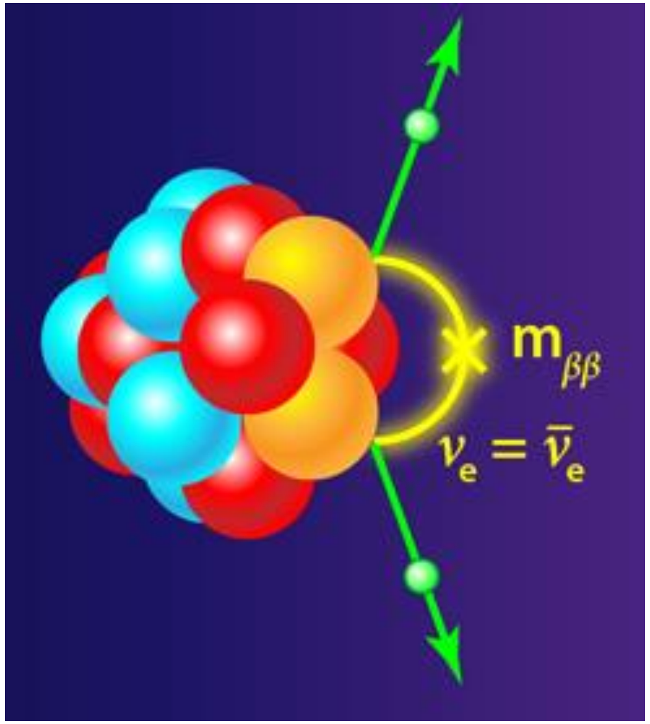
- Measurements of the weak mixing angle $\sin^2\theta_W$
- Charged lepton tests of ν-nucleus cross-sections (already explored at JLAB by CLAS & e4v: [Electron-beam energy reconstruction for neutrino oscillation measurements | Nature](#))
- Improved limits on Charged Lepton Flavor Violation
- 5-100 GeV scale sterile neutrinos through e+p->N+X
- Complimentary limits on charged current chiral structure
- Improvements in PDF precision; measurements of the QCD coupling and heavy-quark masses;
- Gluonic structure of the proton affecting Higgs phenomenology at the HL-LHC;
- TMDs for precision electroweak physics, including determination of the W boson mass at the LHC;
- In-depth studies of formation and structure of hadronic jets, and of scattering processes with heavy-quark states;
- Improved resolution of nuclear structure and nuclear-medium effects, with connections to phenomena like ultra-peripheral photonuclear collisions at hadron colliders;
- Accurate measurements of unpolarized and polarized parton distributions with large momentum fractions that can be confronted with predictions from lattice QCD.



See the EIC Yellow Report (https://doi.org/10.5281/zenodo.6423305)

Searching for the Wellspring of Matter

Neutrinoless Double Beta Decay (0vBB) is sensitive to lepton number violation at any scale; the creation of matter without anti-matter. Majorana nature of neutrinos is foundational to leptogenesis.



Observation of 0vBB would at once

- Demonstrate lepton number violation
- Provide a natural explanation for the origin of the matter vs anti-matter asymmetry of our universe (lepto-genesis)
- Confirm Majorana's prediction that neutral fermions can be their own antiparticles
- Illuminate by what mechanism neutrinos get their mass
- Determine an absolute mass scale for neutrinos

Searches for these rare decays require excellent energy resolution, extreme radiopurity, and accumulation of specific enriched isotopes (~ton for 10^{28} years sensitivity)

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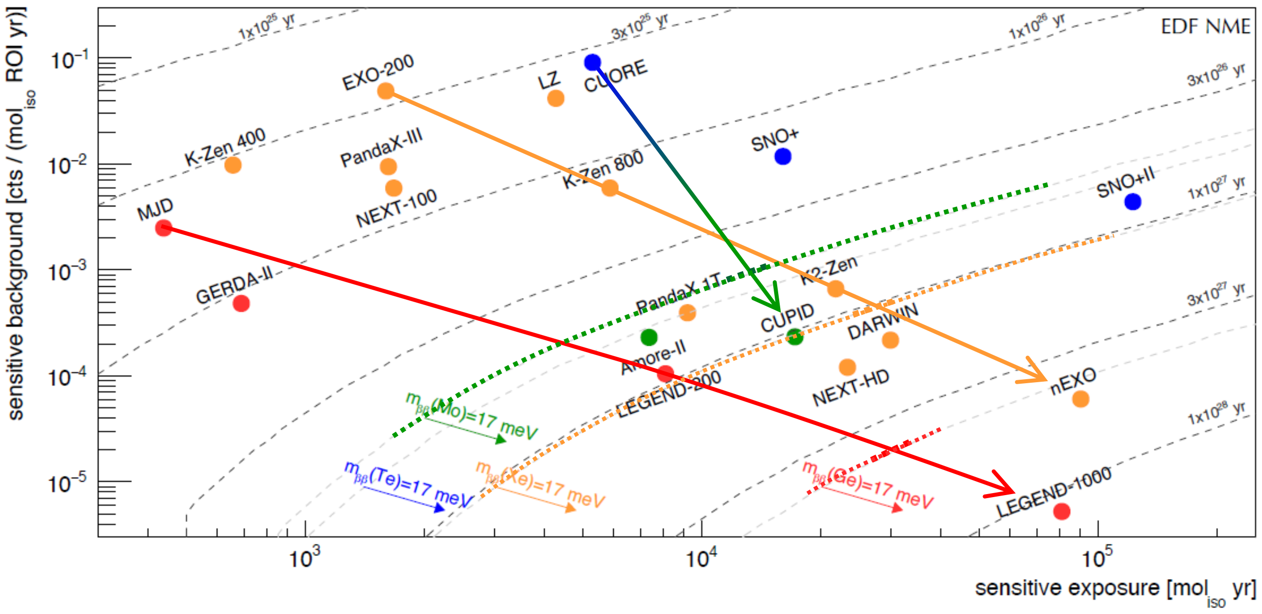
The Ton-Scale Strategy and Beyond

	$T_{1/2}$ (10^{28} years)		$m_{\beta\beta}$ (meV) 3σ Discovery	
	Excl. Sens.	3σ Disc	Median	Range
CUPID Mo	0.14	0.10	15	12 to 20
LEGEND Ge	1.60	1.30	12	9 to 21
nEXO Xe	1.35	0.74	11	7 to 32



Each experiment is world leading in its isotope. Each provides unique benefits. Portfolio review (July 2021) put highest priority on LEGEND-1000.

International stakeholders endorsed the goal of creating a consortium to support a multi-experiment campaign with a large experiment in Europe and in North America

DOE envisions construction funding in FY 2024 (Oct 2023) and continued support toward CD-1 with program funds in FY23.

This is a world-wide, multi-stage campaign requiring at least one more leap in sensitivity beyond ton-scale. Investments in R&D remain an important component of the Fundamental Symmetries portfolio

NP Facilities and Interdisciplinary Efforts

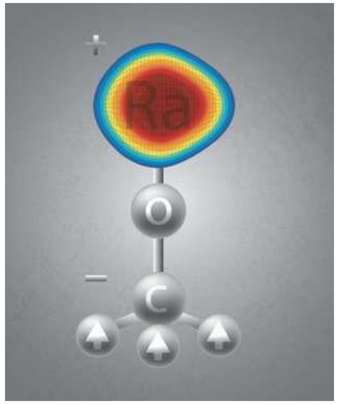
Quantum Sensors, AMO techniques, and Radioactive Beams: FRIB and ATLAS provide access to radioactive beams including heavy deformed nuclei that when combined with AMO techniques and Quantum Sensors enable new opportunities to probe BSM physics.

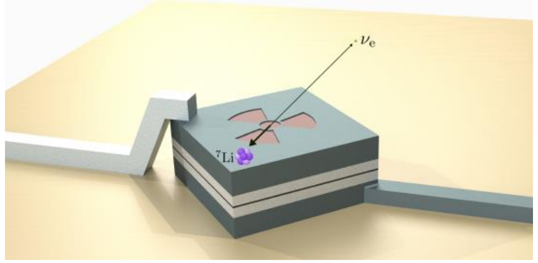
Diverse opportunities and observables: EDMs, Vud and CKM unitarity, magnetic quadrupole moments, nuclear recoil spectroscopy to search for scalar and vector currents, sterile neutrinos, etc.

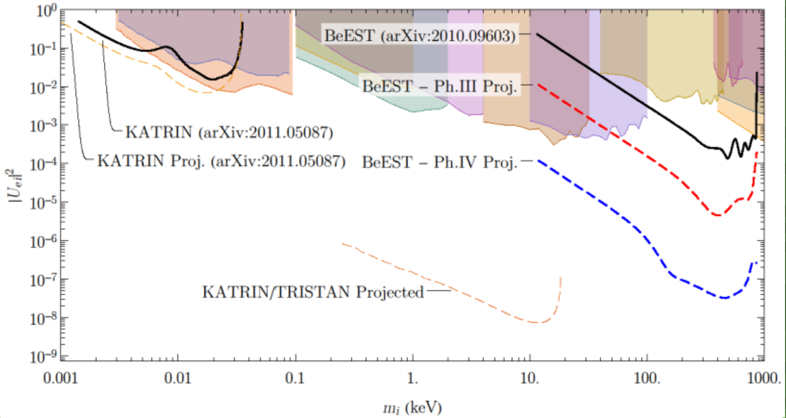
Workshop held at MIT: “New Opportunities for Fundamental Physics Research with Radioactive Molecules” June 28 - July 2, 2021

Formation of a community organization SLAM – Short Lived Atoms and Molecules is a positive step towards organizing the community to make best use of NP facilities and cross-disciplinary expertise.

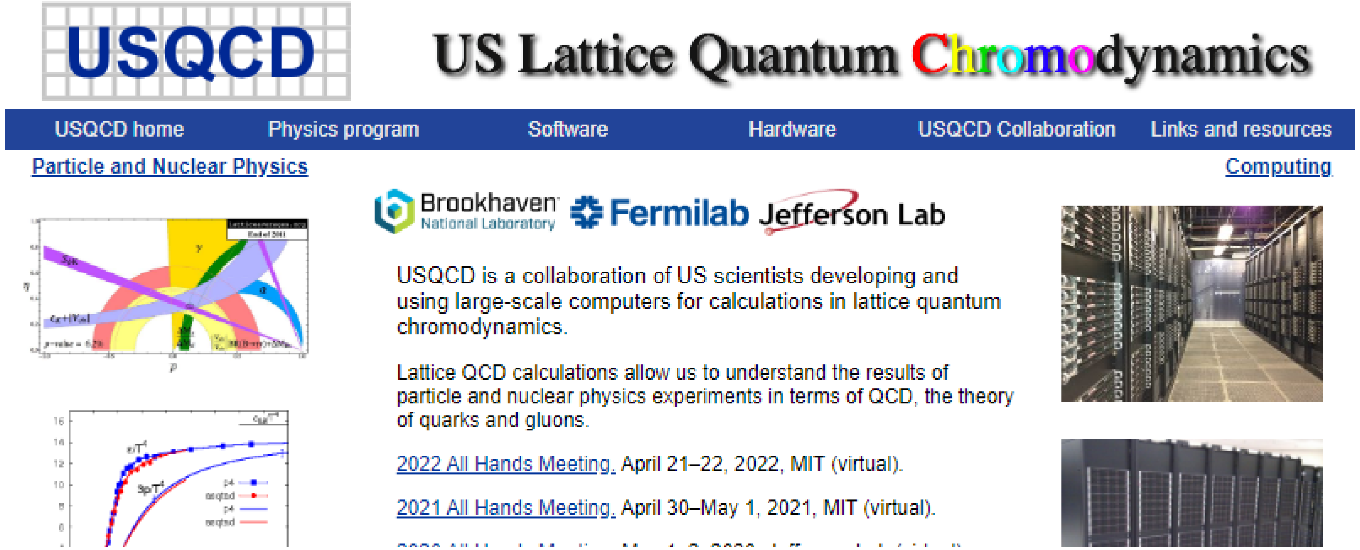
This physics complements other NP searches like nEDM, NAB, He6-CRES, UCNtau and probes very high scales with relatively small investment and with potentially rapid progress.







Lattice: BNL, FNAL, JLAB (Joint HEP/NP funding)



Objectives

1) Calculate the effects of the strong interactions on weak interaction processes to the accuracy needed to make precise tests of the Standard Model and to search for evidence of BSM physics;
2) Determine the properties of strongly interacting matter under extreme conditions such as those that existed in the very early development of the universe;
3) Calculate the masses of strongly interacting particles and obtain a quantitative understanding of their internal structure; and
4) Lay the foundations for investigations of strongly interacting sectors of new physics which may be discovered at the LHC.

NP Strategy on DEI

In 2021, NP released an FOA focused on creating **extended duration traineeships** to provide financial and mentoring support to undergraduates from underrepresented groups.

The program was designed to leverage existing infrastructure; enable and encourage research groups from National Labs and Universities to partner with MSI faculty and provide training and **mentorship for undergraduates** to

- Increase a **sense of belonging**
- Facilitate the development of a **physics identity**, and
- Provide support to **help students advance academically while earning money**

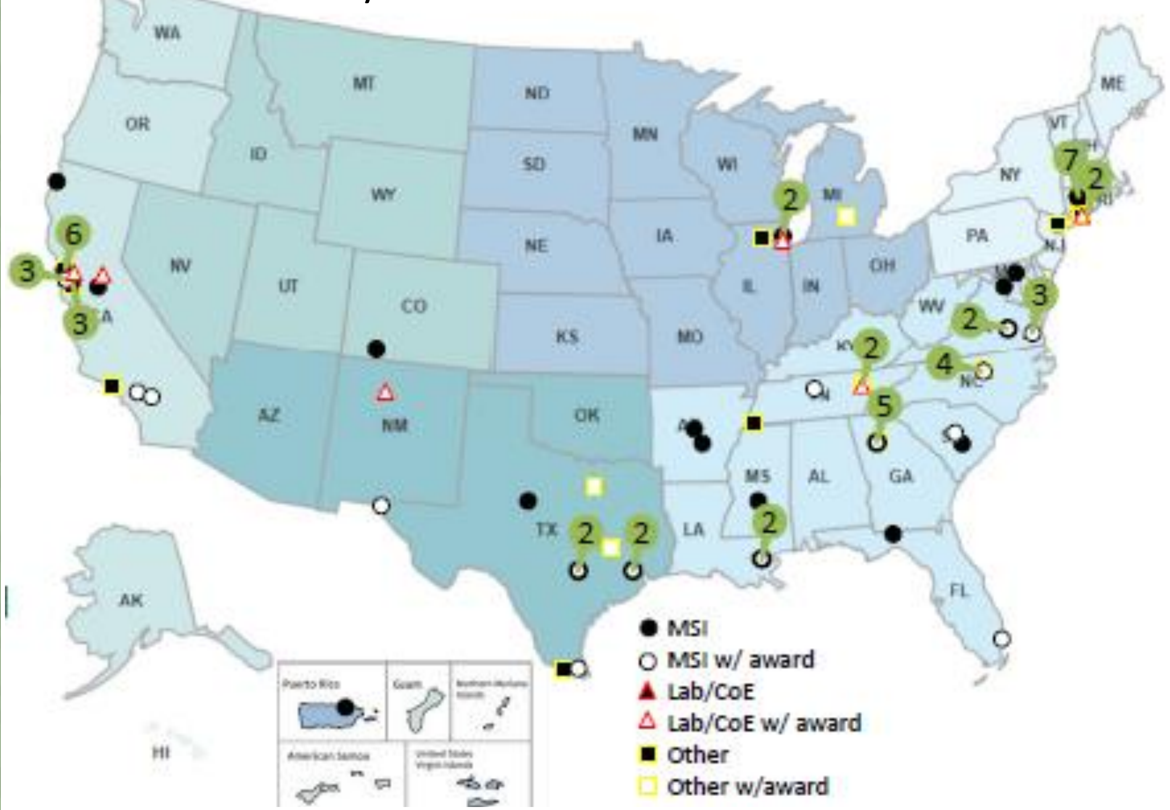
In it's first two years, with collaboration from HEP, the NP program will support 110 trainees. If half go on to receive a Nuclear Physics Ph.D., that will completely erase underrepresentation of Blacks and Hispanics within that class.

In the next FOA, NP plans to focus on 1) bolstering retention, 2) continuing to build partnerships, 3) investing in research (people and equipment) at MSIs.

Current NP Traineeship/RENEW Activities

Program funds 110 Trainees who are building familiarity with our field and community:

- 40% identify as Hispanic
- 40% identify as Black or African American
- 10% identify as White
- 10% identify as other



NP traineeship award recipients include:

- 18 MSIs,
- 10 other colleges/universities,
- 5 DOE laboratories

MSI award recipient distinctions:

- 9 Hispanic Serving Institutions (HSIs),
- 8 HBCUs,
- 5 Asian American, Native American, and Pacific Islander Serving Institutions (AANAPISI),
- 1 Predominantly Black Institution (PBI)

All other institutions on the map are involved in the traineeship program as recruitment sites (38), Co-Is (9), members of INSIGHT (8), and/or hosts (7)

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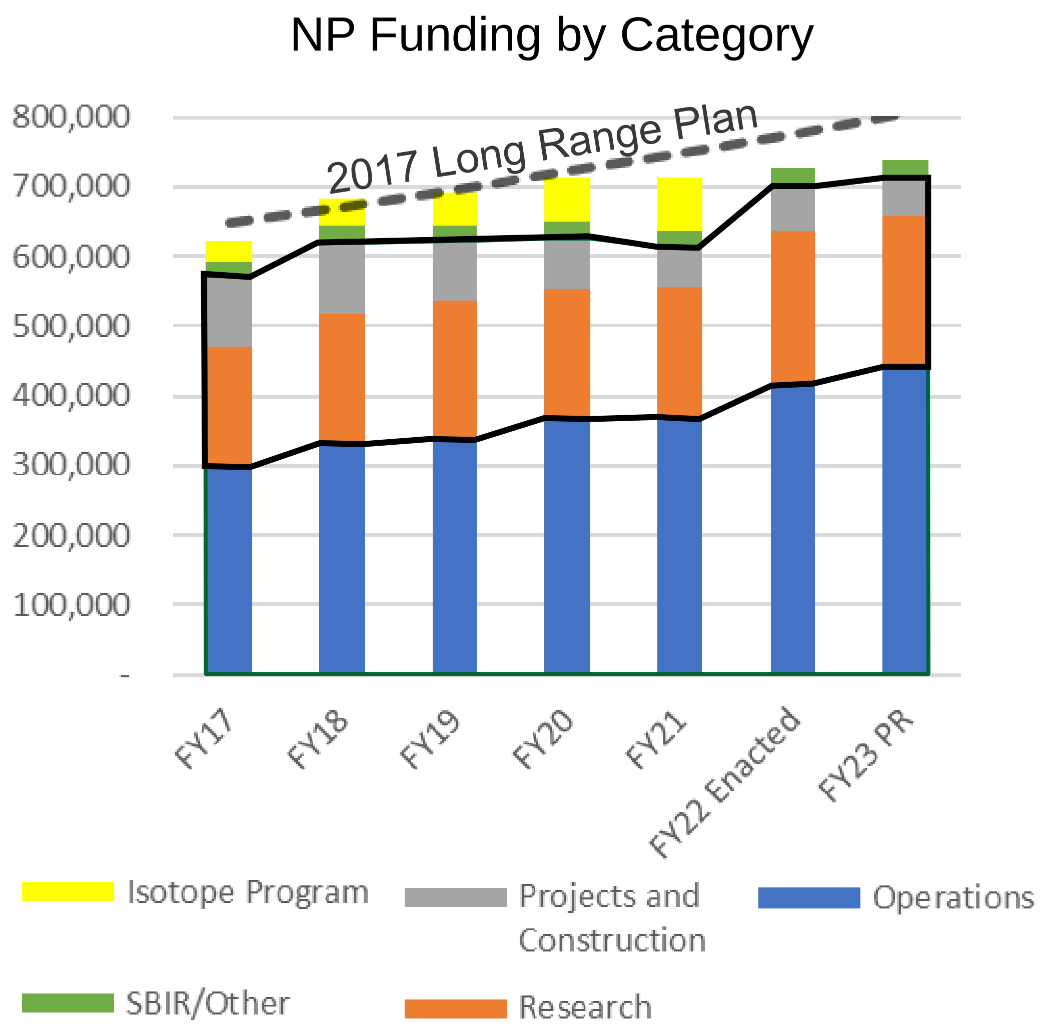
Thank you

Budget



Operations enable our programs: EDMs with radioactive molecules, parity violating electron scattering, nuclear astrophysics, probing the quark-gluon to hadron phase transition, etc.

But limitations in funding for research and projects continues to hinder progress on efforts like ton-scale 0vBB, next-generation neutrino mass (project-8), PVES, etc.

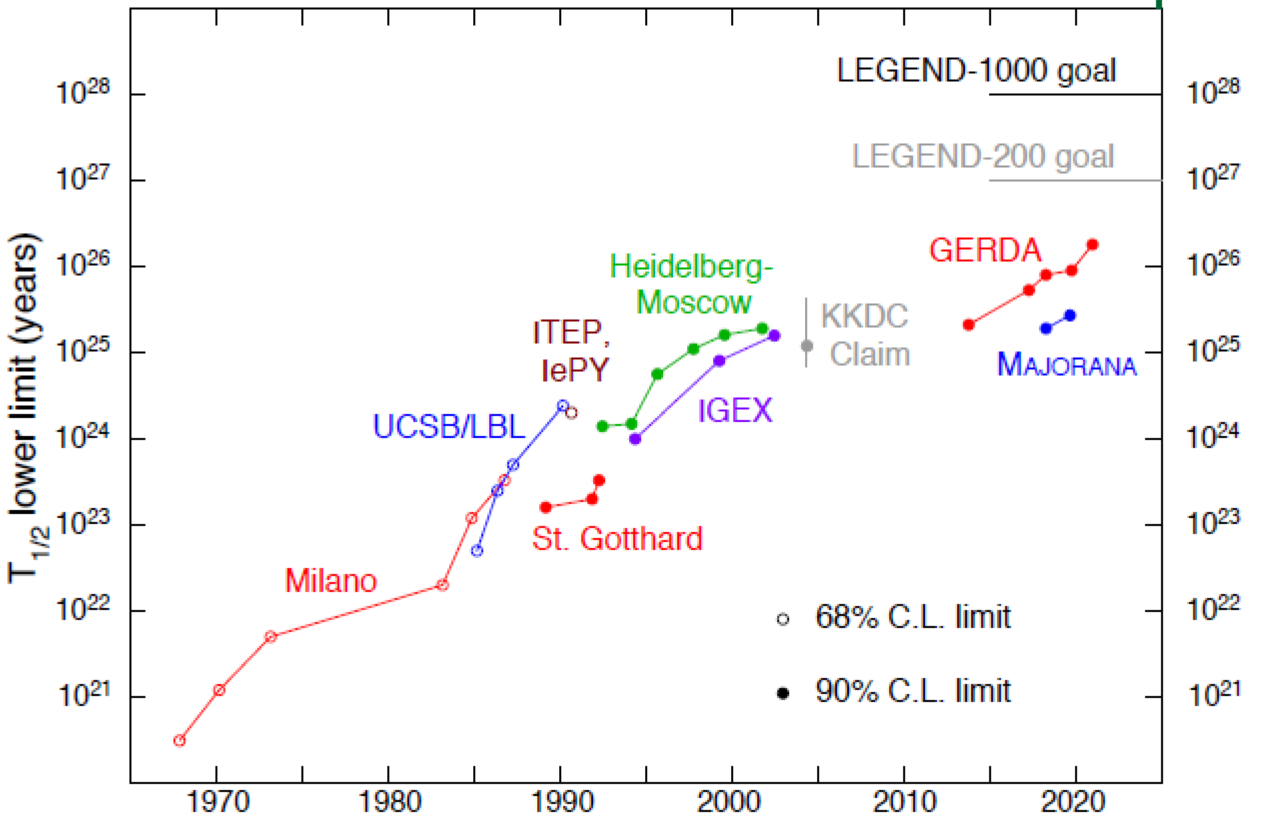
In the FY23 PR, dedicated funding for initiatives consumed all increases plus more, representing a reduction in the base portfolio.

NP Projects

Project	Lead/Site	Cost	Status	CD-4 Date
FRIB	MSU	$730M	Complete	2022
EIC	BNL	$1.7-2.8B	CD-1	2033
GRETA	LBNL	$58M	CD-2/3	2028
sPHENIX	BNL	$27M	PD-3	2022
MOLLER	TJNAF	$46-57M	CD-1	2027
HRS	MSU	$85-111M	CD-1	2029
Ton-Scale 0vBB	TBD	$215-250M	CD-0	TBD

Ambitious goals for the proposed Ton-scale experiments push well beyond past experiments. This example shows progress in high purity Germanium Crystals

normal hierarchy region excluded



Building on Decades of Improvement

← Ton-scale goal, about 2 orders of magnitude higher than current limit; inverted hierarchy region excluded

← Slowest process ever observed
$2x10^{22}$ years (Xenon-124 double electron capture)

There is an end-point to this line of exploration visible within the technology horzion

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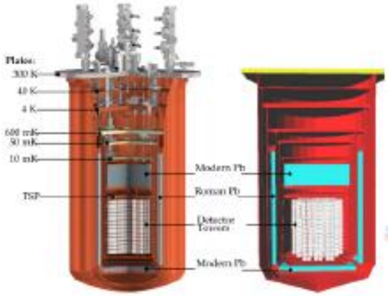
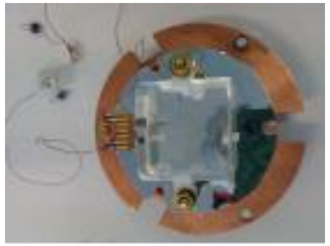
The Ton-Scale Candidates As Proposed

Numbers are in $K

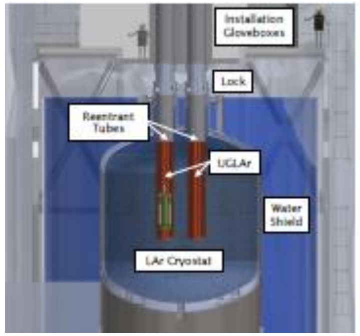
	CUPID	LEGEND-1000	nEXO
Full Project TPC	63,903	442,350	406,169
DOE Only TPC	34,703	257,347	349,531
Non DOE TPC	29,200	185,003	56,638
DOE/Non %	55/45	60/40	85/15
Proj. Complete	2028-2030	2030-2033	2028-2030
Site	LNGS	SNOLab or LNGS	SNOLab

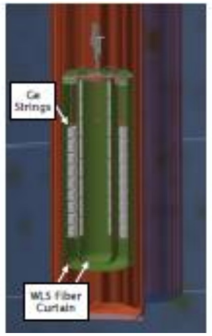
CUPID: Scintillating Crystal Bolometer



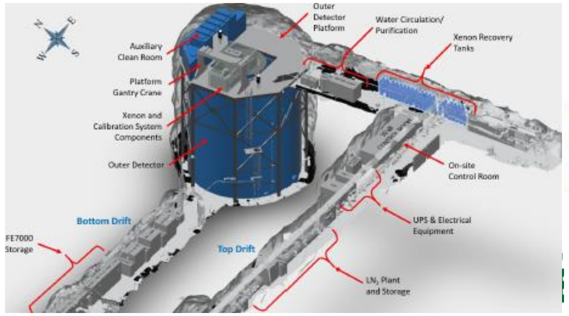


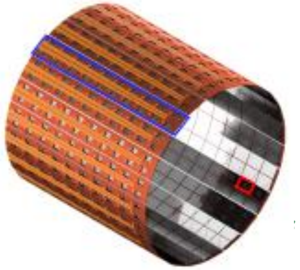
LEGEND: High Purity Ge Crystals





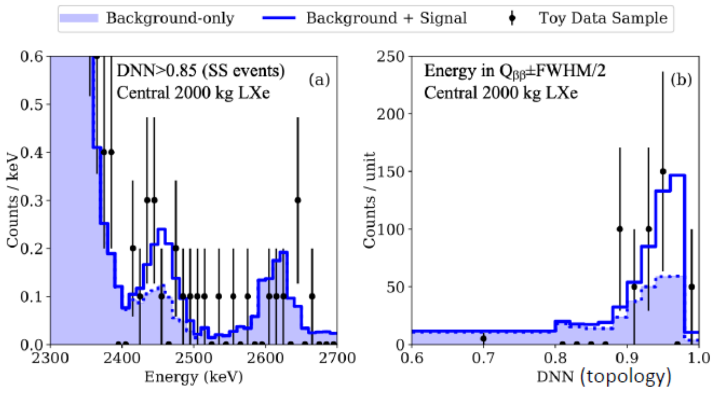
nEXO: Liquid Xe Time Projection Chamber



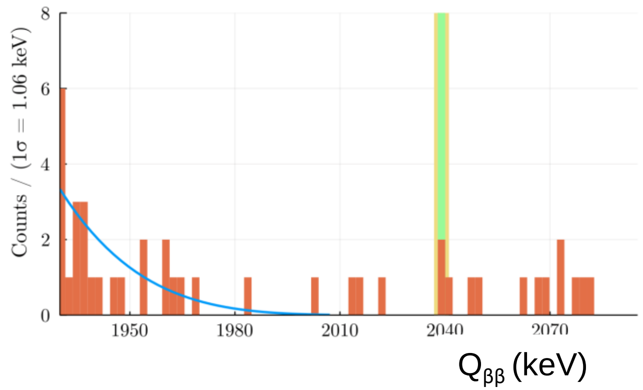


Distinct Approaches: limits of sensitivity

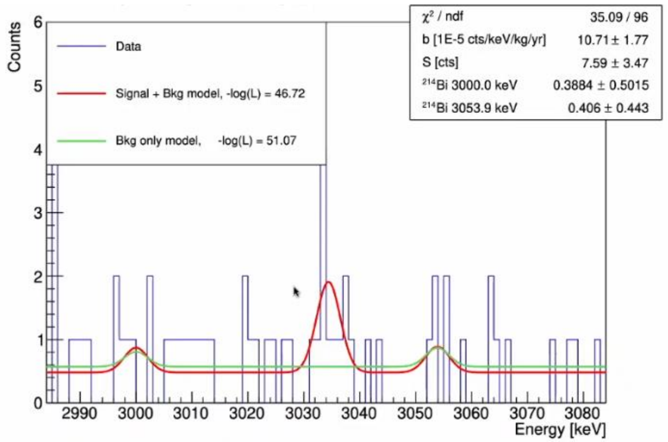
nEXO: Liquid Xe TPC



LEGEND-1000: High Purity Ge



CUPID: Scintillating Bolometer



About 10 counts expected at sensitivity limit

- Monolithic with differential information
- Powerful multiparameter statistical analysis
- Unique control experiment is possible

Several counts expected at sensitivity limit

- Segmented and scalable
- Excellent energy resolution (narrow ROI)
- Excellent background suppression

Several counts expected at sensitivity limit

- Advantageous properties of Mo provide boost to sensitivity and room for growth
- Excellent energy resolution
- Upgrade within existing cryostat.

Confirmation may be crucial for such an important and challenging measurements

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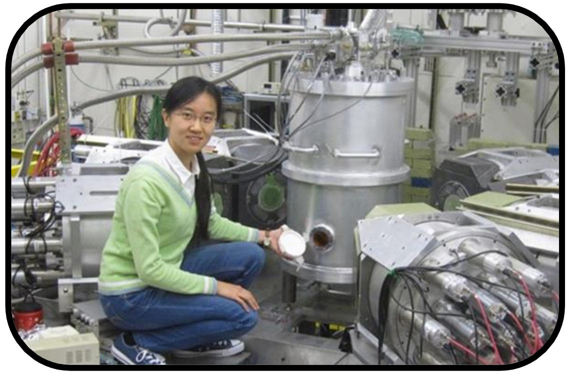
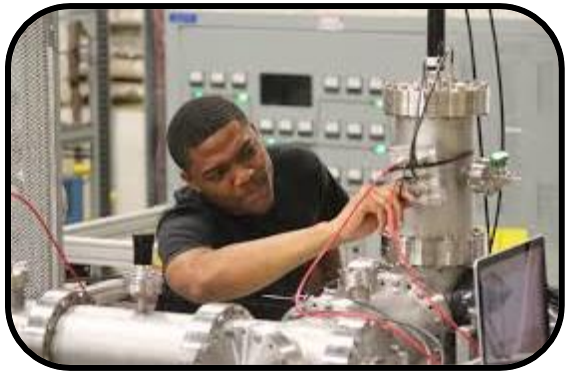
Nuclear Physics: Centers-of-Excellence

Center for Experimental Nuclear Physics and Astrophysics

Institute for Nuclear Theory



Triangle Universities Nuclear Laboratory



Texas A&M Cyclotron Institute

MIT-BATES Research and Engineering Center

Exceptional capabilities in a university setting
Provides access to training and hands-on work for students to gain expertise with accelerators, instrument building.