USA Nuclear Science Advisory Committee

Long Range Plan Report

June 15, 2022

Gail Dodge, NSAC Chair

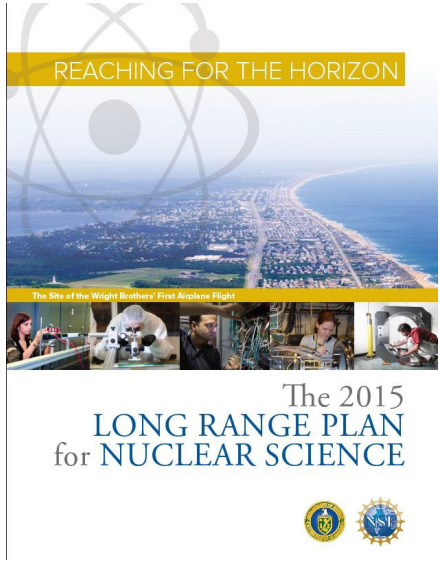
OLD DOMINION
UNIVERSITY

2015 Long Range Plan

1. Capitalize on investments made under guidance of the 2007 LRP
   - Run the program made possible with the CEBAF 12-GeV upgrade
   - Complete FRIB and initiate its scientific program
   - Undertake targeted program of fundamental symmetries and neutrino research
   - Use the upgraded RHIC
2. Develop and deploy a ton-scale neutrinoless double beta decay experiment
3. Pursue the EIC as the highest priority for new facility 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.

To support the above, invest in (a) theoretical and computational nuclear physics, and (b) detector and accelerator research and development

"A workforce trained in cutting-edge nuclear science is a vital resource for the Nation."



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Mainz

Paulo Bedaque
University of Maryland

Lee Bernstein
LBNL

Gail Dodge (Chair)
Old Dominion University

Romualdo deSouza
Indiana University

Evangeline Downie
George Washington University

Vicki Greene
Vanderbilt University
(APS ex-Officio)

Oliver Kester
TRIUMF

Joshua Klein
University of Pennsylvania

Cecilia Lunardini
Arizona State University

Rosi Reed
Lehigh University

Nathalie Wall
University of Florida
(ACS ex-Officio)

Fred Wietfeldt
Tulane University

LRP Recommendation #1

Jefferson Lab Overview

- CEBAF at Jefferson Lab: the world's highest intensity and highest precision multi-GeV electron beam.
- 12 GeV program in full swing in 4 experimental halls. A new era to:
  - Image nucleon and nuclei at their deepest level
  - Search for physics Beyond the Standard Model.
- Two initiatives have emerged from the user community which would significantly enhance the 12 GeV research capabilities: the MOLLER and SoLID projects.

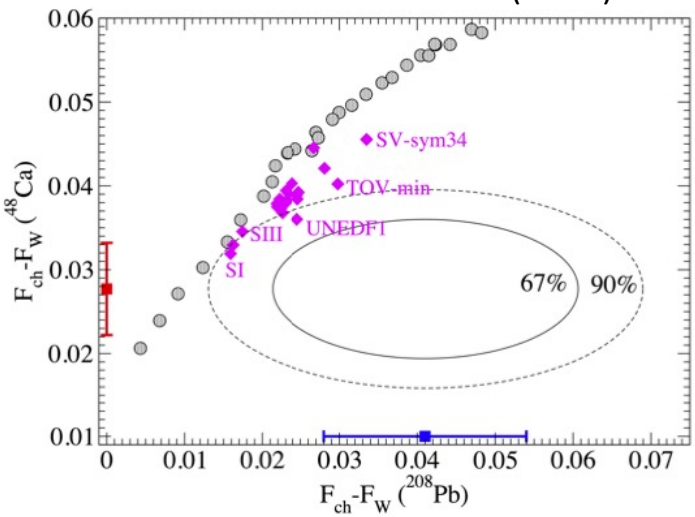
- 85 experiments approved (so far), ~1/3 completed. More than a decade of experimental program to run.
- Nuclear experiments at ultra-high luminosities, up to 10^{39} electrons-nucleons /cm^2/s ➞ a facility at "luminosity frontier," with unique scientific capabilities even in the era of the Electron-Ion Collider operation (a factor of 10^5 higher in luminosity).
- JLab is a major partner in the development, construction, and scientific utilization of the Electron-Ion Collider.

from Patrizia Rossi

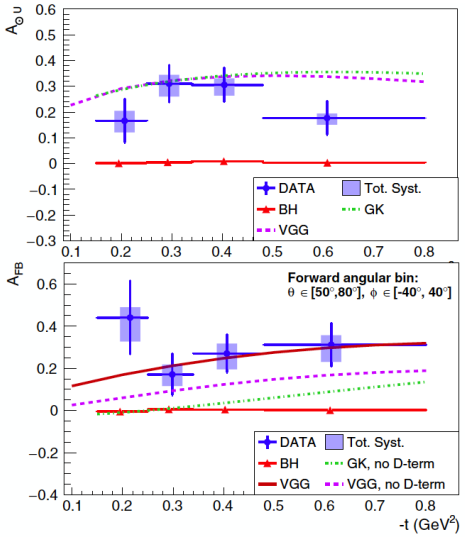
12 GeV Science

- **Hall A:**
  - Tritium family of experiments – all 4 complete!
  - PREX-II published in PRL, CREX complete
  - Two exp. with SBS - G_M^n & two-photon exchange - completed
- **Hall B:**
  - First phase of CLAS12 Run Groups A & B complete
  - PRad results published in Nature
  - Bonus experiment completed phase 1
  - RG-M (electrons for neutrinos) completed
  - Start Run Group C with longitudinally polarized target
- **Hall C:**
  - Deuteron electrodisintegration published - PRL
  - Color Transparency published - PRL
  - Search for LHCb pentaquark complete
  - A_1^n running complete, d_2^n partially completed
  - Pion form factor and pion production experiments partially completed
- **Hall D:**
  - GlueX phase I complete
  - Threshold J/y published in PRL
  - PrimeX-eta experiment partially completed
  - Short-Range Correlation and Color Transparency experiments completed
  - Search for dark sector particles submitted

arXiv:2205.11593 (CREX)



A narrow range of models are consistent with a "thick" skin in ^{208}Pb and "thin" skin in ^{48}Ca



First measurement of Timelike Compton Scattering (time-reversal symmetric process of DVCS) with CLAS12

PRL 127 (2021) 262501

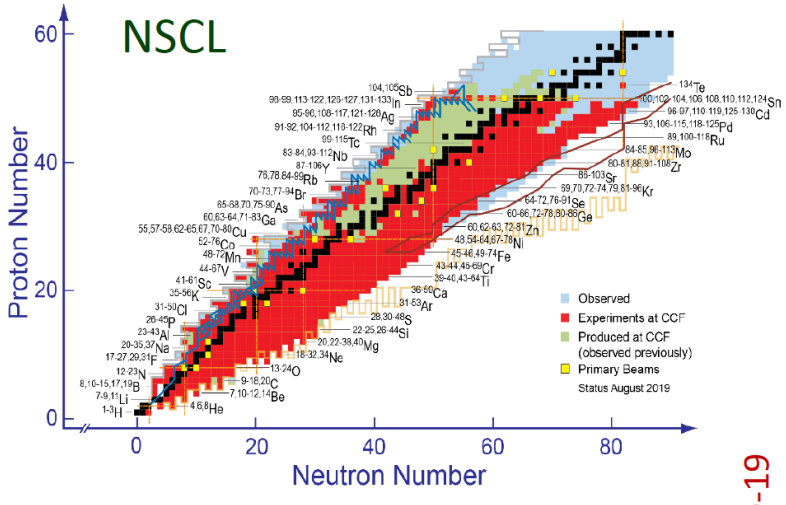
from Patrizia Rossi

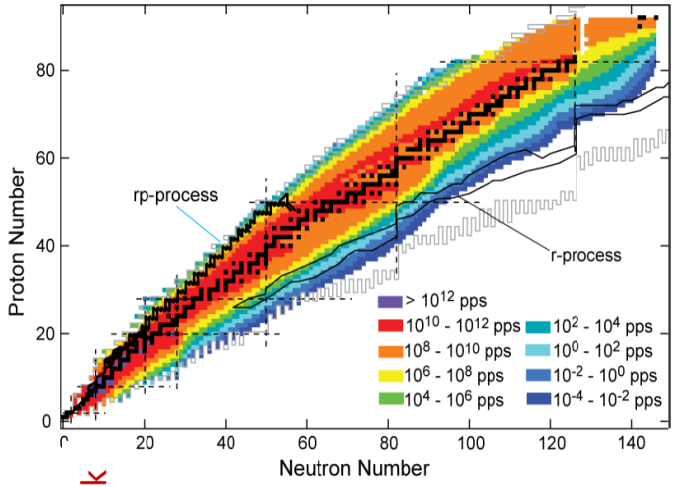
LRP Recommendation #1

Facility for Rare Isotope Beams (FRIB)

NSCL / FRIB Transition

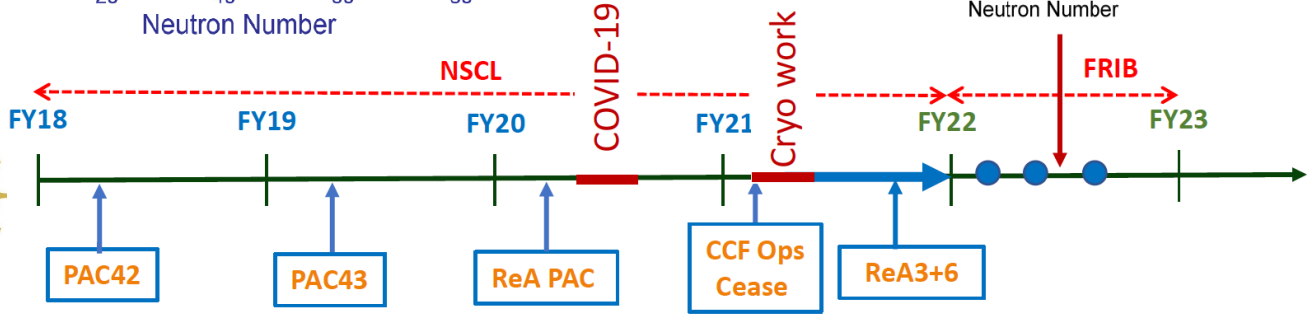
Smooth & close coordination → exciting opportunities





FRIB provides
- Fast beams
- Stopped beams
- Reaccelerated beams

Capable of producing ~5000 isotopes to study:
- Nuclear structure
- Nuclear astrophysics
- Fundamental symmetries



from Allena Opper

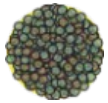
FRIB Science Program Started in May 2022

- FRIB is a Department of Energy Office of Science (DOE-SC) user facility for rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC
- Superconducting radio-frequency heavy ion accelerator capable of accelerating any stable ion to 200 MeV/nucleon and up to 400 kW of beam power (10^{13} uranium ions/sec)
- FRIB Project started in 2008, concluded on budget and ahead of schedule. FRIB Project was funded by DOE-SC, Michigan State University, and the State of Michigan
- Ribbon cutting and first experiments started in May 2022
- FRIB enables scientists to make discoveries about the properties of these rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society

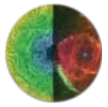
First science experiment studied the beta-decay of ^{48}Ca fragments

from Thomas Glasmacher

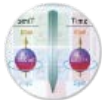
Discovery Science at FRIB



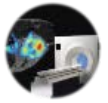
- Properties of atomic nuclei
  - Develop a predictive model of nuclei and their interactions
  - Many-body quantum problem: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.



- Astrophysics: What happens inside stars?
  - Origin of the elements in the cosmos
  - Explosive environments: novae, supernovae, X-ray bursts…
  - Properties of neutron stars



- Tests of laws of nature
  - Effects of symmetry violations are amplified in certain nuclei



- Societal applications and benefits
  - Medicine, energy, material sciences, national security

Science is aligned with priorities articulated by

- Nuclear Science Advisory Committee to DOE and NSF *Long Range Plan for Nuclear Science* (2015)
- National Research Council *Decadal Survey of Nuclear Physics* (2012)
- National Research Council *Rare Isotope Science Assessment* report (2006)

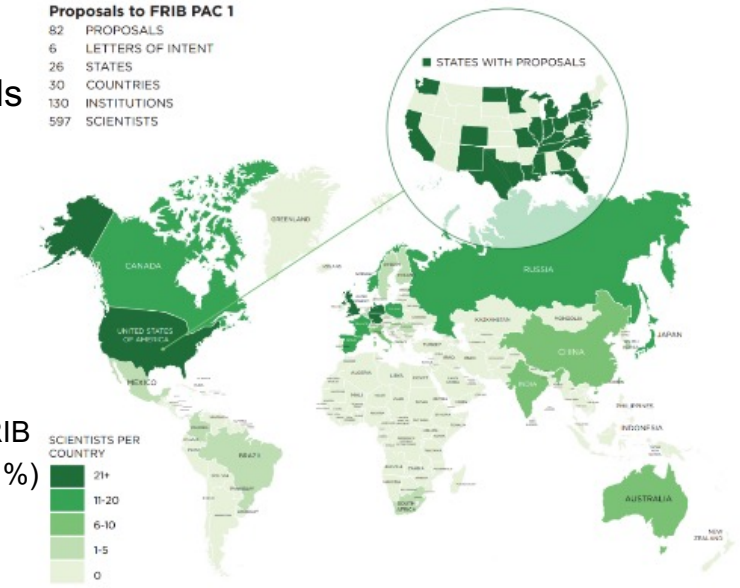
Opportunities articulated in

- Nuclear Science Advisory Committee SC *2015 Long Range Plan for the DOE-NP Isotope Program*

First PAC approves experiments addressing 13 of the 15 National Academies benchmarks

First PAC-Recommended Experiments Promise Balanced, Exciting Science Program

- February 2021: Strong response to first FRIB call for proposals
  - 82 proposals and 6 letters of intent received representing
  - 597 scientists
  - 9,784 science hours requested (12,412 hours facility use)
  - 30 countries
  - 130 institutions
- August 2021: FRIB Program Advisory Committee (PAC1) reviews, ranks proposals PAC-recommended experiments represent
  - 34 out of 82 experiments proposed
  - 401 out of 597 scientists
  - 4,122 hours out of 12,412 hours facility-use hours requested
  - 25 out of 30 countries
  - 88 institutions
  - 15 of 17 National Academies benchmarks for FRIB
  - 31 of 34 approved experiments outside MSU (91%)
- May 2022: First user experiments



from Thomas Glasmacher

LRP Recommendation #1

Fundamental Symmetries

- $0\nu\beta\beta$ (Majorana Demonstrator/LEGEND-200, CUORE, SNO+, KamLAND-Zen, EXO-200, NEXT and R&D on Ton-scale $0\nu\beta\beta$)
- Neutrino mass and sterile neutrinos (KATRIN, BeEST, Project-8 R&D)
- Neutron EDM (SNS and LANL)
- Neutron lifetime (beam and trap)
- Beta Decay (Nab, He6 fierz, TAMUTrap, Hadronic parity violation, UCNA)
- EDM (electron, positron, nuclei, molecular)
- Coherent elastic neutrino-nucleus scattering (COHERENT, CEνENS)
- Moller Experiment (JLab – Parity Violating Electron Scattering)
- g – 2 (Fermilab)

Lots of investment!

LRP Recommendation #1

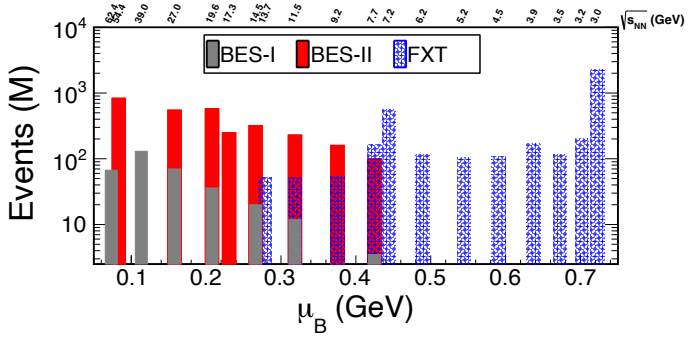
RHIC in the 2015 NSAC Long Range Plan

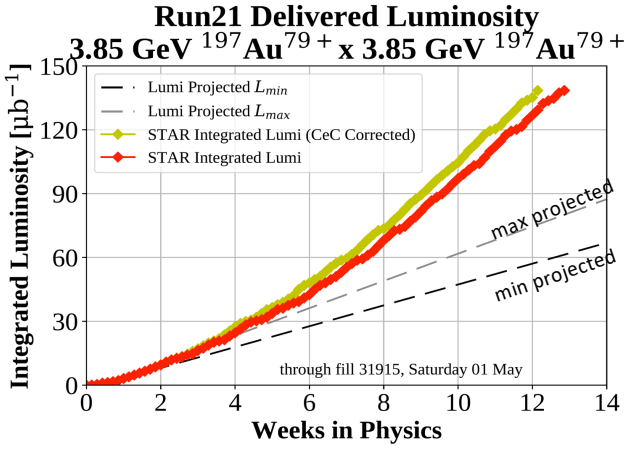
"There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC:

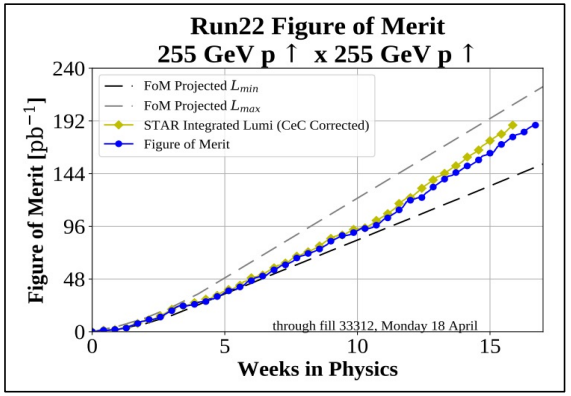
(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX.

(2) Map the phase diagram of QCD with experiments planned at RHIC."

Completed multi-year beam energy scan II program in Run 2021; Run 2022 with transversely polarized proton-proton collisions and STAR forward upgrade was successful



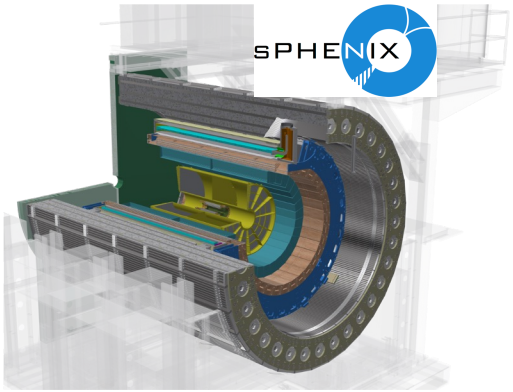




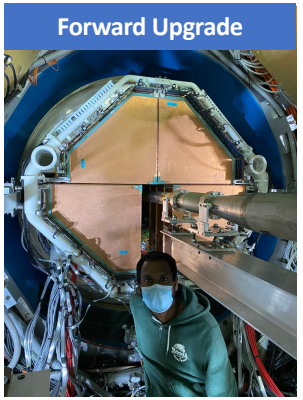
from Haiyan Gao

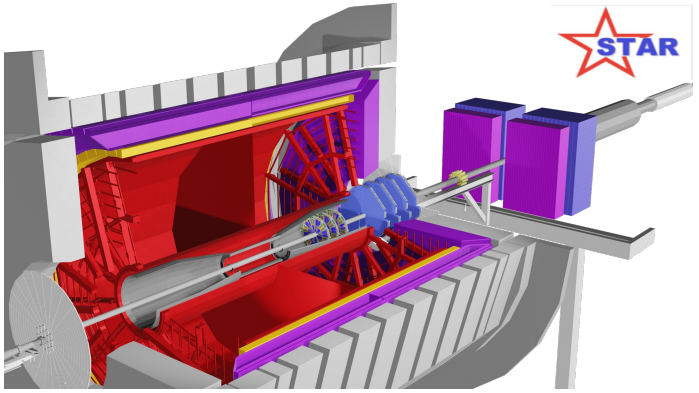
Completing the RHIC Mission with sPHENIX and STAR

- sPHENIX will use energetic probes (jets, heavy quarks) to study quark-gluon plasma on different length scales with unprecedented precision
  - How the structureless "perfect" fluid emerges from the underlying interactions of quarks and gluons at high temperature
- State-of-the-art collider detector using technology developed for LHC by ONP and OHEP
- sPHENIX magnet and its hadron calorimeter will be part of the EIC project detector



- STAR with forward upgraded detectors
  - 3-D tomography of the nucleon uncovers new information
  - STAR exploits such 3-D parton dynamics in ways complementary to the EIC, where precision tomography of the nucleon and nuclei will be carried out





RHIC data taking scheduled for 2023–2025

sPHENIX upgrade and STAR with forward upgrade will fully utilize the enhanced (~50 times Au+Au design) luminosity of RHIC

from Haiyan Gao

ATLAS

ATLAS is the DOE low-energy nuclear physics stable beam national user facility

It provides:

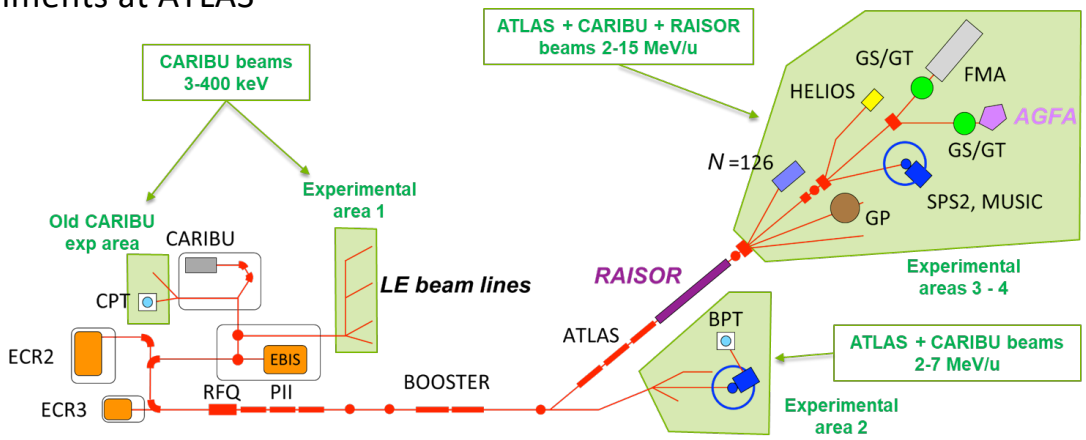
- Stable beams from protons to Uranium at high intensity and energy up to 10-20 MeV/u
- Light in-flight radioactive beams with RAISOR
- World unique heavy neutron-rich beams from CARIBU at energies up to 10-15 MeV/u
- State-of-the-art instrumentation for Coulomb barrier and low-energy experiments

Operating ~ 6000 hrs/yr (+ 2000 hrs/yr CARIBU stand alone) at about 93% efficiency

- Common PAC for ATLAS and CARIBU …. oversubscribed by a factor of ~ 3
- 300-400 "single users" per year performing experiments at ATLAS

Continuously adding new capabilities for our users:

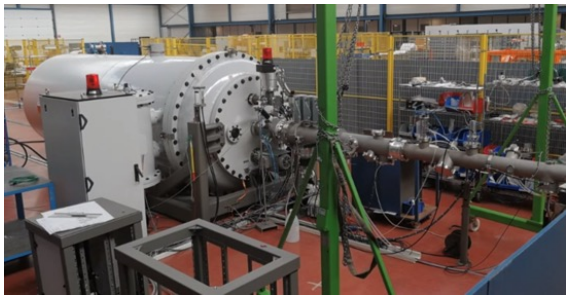
- N=126 factory -> use multi-nucleon transfer reactions to access new regions of the nuclear chart
- nuCARIBU -> increase intensity for CARIBU beams from neutron-induced fission
- Multi-user upgrade -> increase available beamtime by delivering two independent beams to two experiments simultaneously



from Guy Savard

TUNL's vision for the decade

Strong Research Programs at the Frontiers of the Field in:

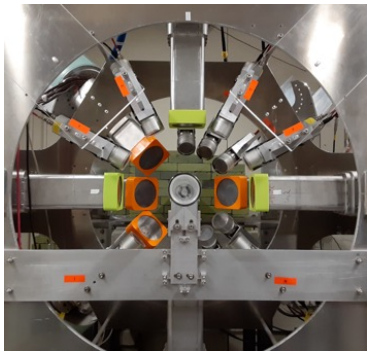


Delivery summer 2022

Nuclear Astrophysics:
LENA Upgrade

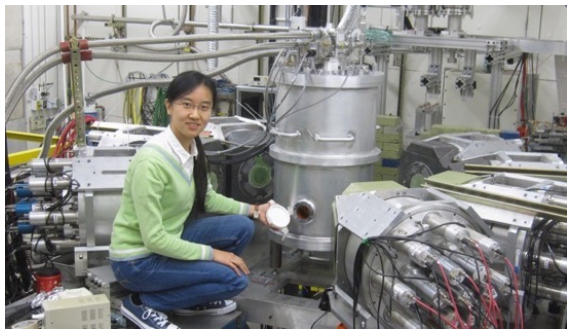
New 2-MV Singletron accelerator with terminal ECR source and chopper/buncher

- globular clusters, classical novae, astrophysical s-process, grains



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 nucleosynthesis
- Strength functions



Medium Energy:
Low-Energy QCD at HIgS

- Compton scattering on H, D and ^{3,4}He to determine nucleon polarizabilities with high precision
- Develop HIgS beams toward pion threshold

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

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

Neutron EDM

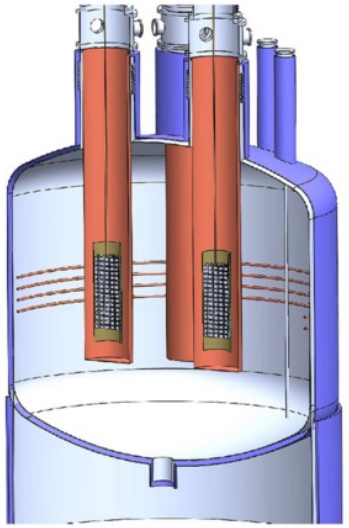
- Systematics with polarized UCN and ^{3}He
- Neutron cell development and UCN storage time determination

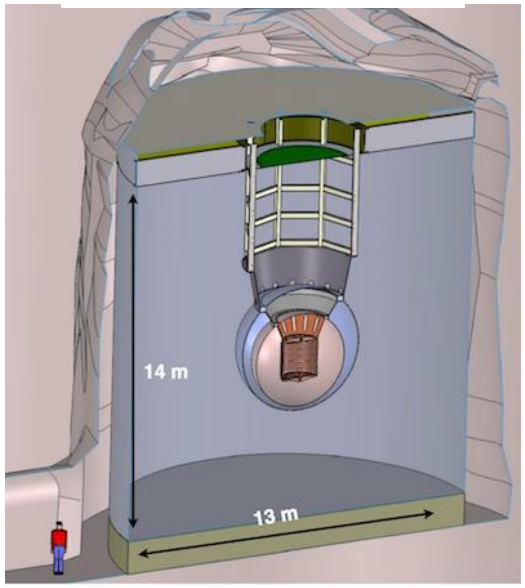
from Art Champagne

LRP Recommendation #2

Ton-Scale Neutrinoless Double Beta Decay (NLDBD)

- Three Front–Runner Technologies
  - LEGEND-1000 (Large Enriched Germanium Experiment for 0nbb)
    - Building on LEGEND-200 (GERDA and Majorana Demonstrator)
  - CUPID (CUORE Upgrade with Particle Identification)
    - ^{100}Mo enriched Li_2MoO_4 crystals for scintillating bolometry (detect heat and light)
  - nEXO (liquid Xe TPC)
    - Submerged in water (active shielding); SiPMs
- Background constraints: <1 count/ton of material/year
- Possible Experiment Location
  - SURF (South Dakota)
  - SnoLab (Canada)
  - Gran Sasso (Italy)





from Tim Hallman, DOE

LRP Recommendation #2

Ton-Scale Neutrinoless Double Beta Decay

- DBD Portfolio Review was held July 13-16, 2021 to inform US investment strategy.
- North American – European Summit was held Sept. 29 to Oct. 1, 2021. Common ground exists for an international approach to DBD investment and the mounting of two ton-scale experiments, in North America and Europe respectively.
- Funding for ton-scale $0\nu\beta\beta$ is going to be challenging

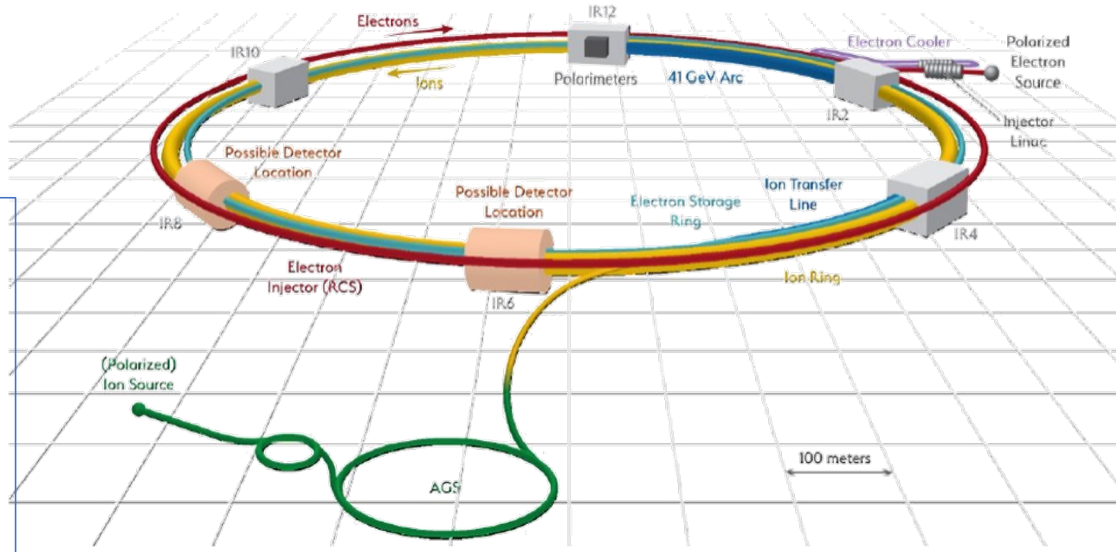
from Tim Hallman, DOE

LRP Recommendation #3

The Electron-Ion Collider

Project Design Goals

- High Luminosity: L= 10^{33}–10^{34}cm^{-2}sec^{-1}, 10–100 fb^{-1}/year
- Highly Polarized Beams: ~70%
- Large Center of Mass Energy Range: E_{cm} = 20 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)
- Conceptual design scope and expected performance meet or exceed NSAC Long Range Plan (2015) and the EIC White Paper requirements endorsed by NAS (2018)



Double Ring Design Based on Existing RHIC Facility

$1.7 to 2.8 Billion

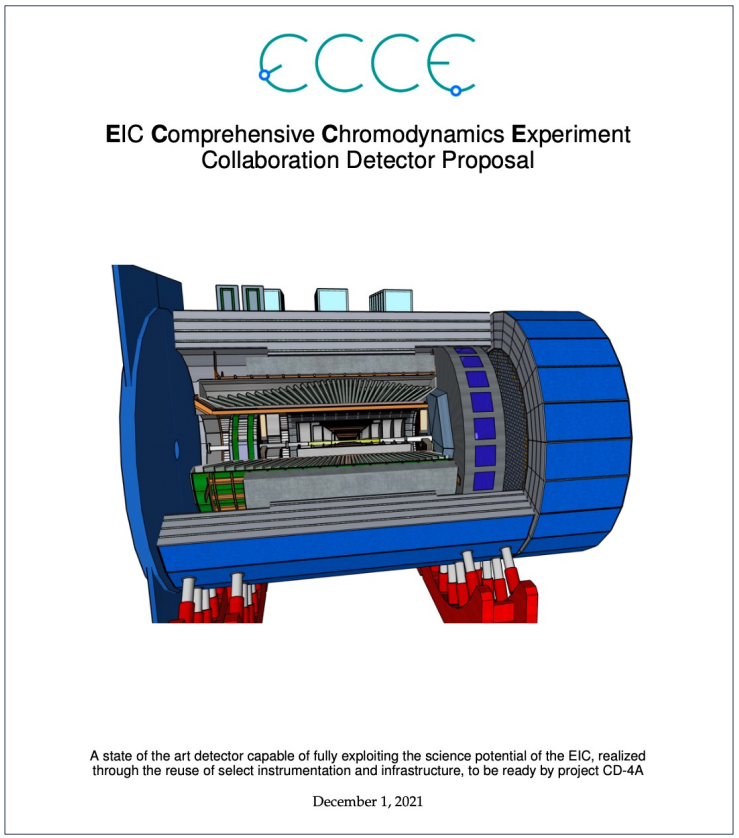
Major milestones:

- CD-0 December 2019
- DOE EIC site selection on Jan 9, 2020
- CD-1 June 2021
- EIC project detector reference design selected in March 2022

from Haiyan Gao

LRP Recommendation #3

The EIC Project Detector



Three EIC Proto-collaboration Proposals Submitted

A scientific-technical committee of renowned and independent experts, jointly appointed by BNL and JLab, evaluated the proposals (ATHENA, CORE, ECCE)

- "…unanimously recommends ECCE as Detector 1…urged to accept additional collaborators and quickly consolidate its design so that the Project Detector can advance to CD-2/3a in a timely way."
- "…supports the case for a second EIC detector…a decision on Detector 2 should be delayed until the resources and schedule for Detector 1 are more fully realized."

The EIC project detector collaboration is being formed, including all proto-collaborations

from Haiyan Gao

EIC Users Group

Established in July of 2016 *"… with the goal of giving the future users community a stronger and more visible role in the process leading to the realization of the EIC."*

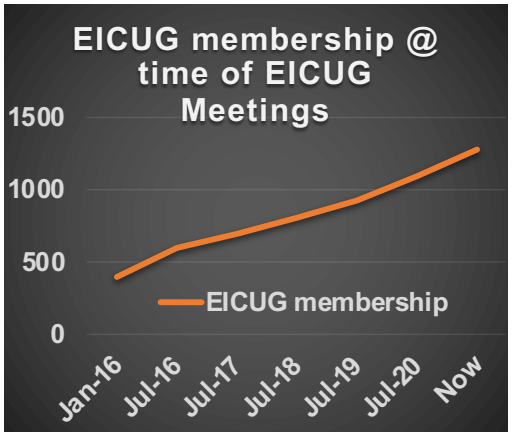
Composed of :

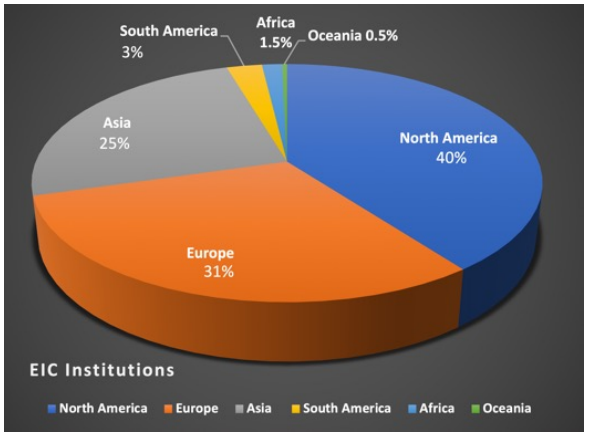
- 1331 members / 266 institutions from 36 countries
- 62% Experimental / 25% Theoretical / 12% Accelerator Physicists / 1% Other

Advocates for support from U.S. Congress for current and future facilities during Nuclear Physics Fly-In days.

Engages and cultivates support from the international nuclear physics community.

Facilitates and supports user talks on EIC at International Workshops and Conferences





from Renee Fatemi

LRP Recommendation #4

Small-scale and midscale projects and initiatives

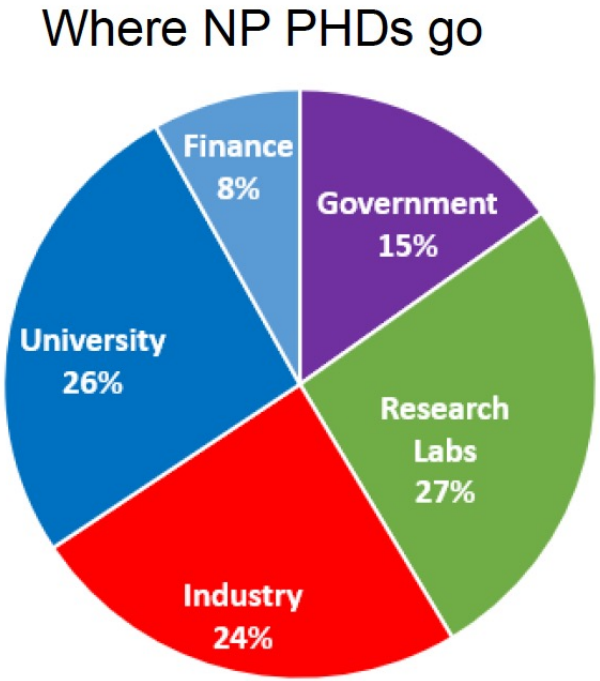
- MOLLER – parity violating Moller scattering (Jefferson Lab) $46 – 57 M
  - DOE CD-1 Dec 2020; Successful reviews Sept and Nov 2021; on track for CD-2/3
- GRETA – Gamma Ray Tracking Array (FRIB) $58.3 M
  - Under construction; FRIB science will start with GRETINA
- HRS – High Rigidity Spectrometer (FRIB) - for use with fast beams $85 - 111 M
  - Working on preliminary design; CD-1 approved
- MUSE – MUon proton Scattering Experiment to determine the proton radius
- SECAR – Separator for Capture Reactions at FRIB (for use with ReA to provide low energies needed for nuclear astrophysics)
- sPHENIX (RHIC) – Installation underway; will be ready for Run 2023 run $27 M
- STAR forward upgrade (RHIC) – complete; used with Run 2022
- nEDM@SNS; nEDM@LANL
- BL3 (instrumentation to measure the free neutron lifetime with the beam method to sub-second precision)
- SoLID – Semi-Inclusive Deep Inelastic Scattering; J/Ψ; Parity Violating DIS

Not a complete list!

Workforce, Diversity, Equity, and Inclusion

- DOE Research Traineeships to Broaden and Diversify Nuclear Physics
- DOE RENEW (Reaching a New Energy Sciences Workforce)
- NSF PHY: Growing a Strong, Diverse Workforce
- NSF LEAPS: Launching Early-Career Academic Pathways in MPS
- NSF ASCEND - Postdoctoral Research Fellowships

There is a very strong commitment to growing and diversifying the nuclear physics workforce



Nuclear Data

Nuclear data is critical to basic science and many applications.

- In April NSAC received a charge from DOE and NSF to assess challenges, opportunities, and priorities for effective stewardship of nuclear data.
- "Nuclear data" is data derived from observed properties of nuclei, their decays and decay products, and the interactions of both nuclei and their decay products with other nuclei, subatomic particles or in bulk matter. Data from theoretical models created for comparison with experimental nuclear data may also be considered for inclusion under this definition.
- NSAC is requested to develop a strategic plan with prioritized recommendations to guide federal investment in the U.S. Nuclear Data Program (USNDP).
  - Assess USNDP Status – interim report by Sept. 15, 2022
  - provide recommendations for maintaining effective stewardship of nuclear data by Jan. 30, 2023

Lee Bernstein (Lawrence Berkeley National Lab) will chair the subcommittee

Next Long Range Plan

- NSAC expects to receive a charge to develop a new long range plan at the July meeting.
- We will form a large committee that includes NSAC members
- The American Physical Society Division of Nuclear Physics will organize a series of community workshops.
- We will seek broad input.
- Our recommendations will have to be in the context of budget guidance from NSF and DOE.
- We expect the process to take approximately 18 months.

Summary

- Department of Energy and National Science Foundation have been aggressive in pursuing the priorities identified by the community in the 2015 Long Range Plan
- All of the recommendations have seen good progress.
- International collaboration has been critical to success so far and will continue to be vital to enable discovery science
- We look forward to a new long range planning process.

Thank you!

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