NSAC Long Range Plan Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics

14-16 November 2022

Argonne National Laboratory

Co-conveners: Alex Gade, Sofia Quaglioni, Grigory Rogachev, Rebecca Surman

Local scientific organizing committee: Michael Carpenter (chair), Ben Kay (co-chair)

Melina Avila, Jason Clark, Calem Hoffman, Filip Kondev, Toben Lauristen, Claus Mueller-Gatermann, Peter Mueller, David Potterveld, Walter Reviol, Guy Savard, Daniel Santiago, Darek Seweryniak, Marco Scilliano

Argonne NATIONAL LABORATORY

NSF

U.S. DEPARTMENT OF ENERGY | Office of Science

APS physics

Our community is engaged and excited about what we accomplished since the last LRP and our bright future

This Town Meeting brought together 578 members of the Nuclear Science community

- 216 in-person participants
- 362 remote participants

They provided input to 12 Working Groups:

- We would like to gather all contributions and link them to the website. **Please, make sure the Points of Contact have a copy!**

The product of this Town Meeting is a Whitepaper

- WG POCs have been provided with instructions, a word template including citation preference, deadlines, and page limits - will also be posted on town meeting website
  - Frame the challenges for topic, lay out progress since last LRP, and envision the opportunities in the next 5-10 years & impact and needs to realize them
  - Less than 10-12 pages each for the core topics
  - Less than 5-6 pages for each the cross-cutting and intersecting WGs
  - The shorter the better! Include compelling graphics (with appropriate permissions)
  - Executive summary around resolutions will pull it all together based on the WG topical sections which provide more details, examples, and graphics
  - Deadline: Drafts to the conveners by 18 Dec 2022

NSAC Long Range Plan Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics

Plenary Session 5
Chairs: Alexandra Gade (FRIB), Grigory Rogachev (TAMU), Rebecca Surman (Notre Dame), Sofia Quaglioni (LLNL)
Held in the APS Conference Center (Bldg. 402) Auditorium
Please note a dedicated Zoom link for this session will be emailed to registered stakeholders

Time (CST)	Presentation	Speaker	Duration
08:05-08:10	Logistics		5
08:10-09:10	5-minute summaries of each of the 12 WGs	WG POCs	60
09:10-09:35	Discussion of the summaries, explore possible cross connections, gaps		25
09:35-10:00	Coffee break		25
10:00-12:00	Resolutions (until done but not later than noon)		120

Diplomacy can be complicated – what our field has been doing: Consensus

- Take the United Nations as example (hundreds of member countries with diverse opinions … sounds like us?)
  - Oppenheimer’s international Law: “it is the long-established practice of the General Assembly and its Main Committees to strive for consensus wherever possible”
- Consensus
  - Consensus “is understood as the absence of objection rather than a particular majority”
- Why?
  - Example of U.N.: Consensus is reached when all Member States agree on a text, but it does not mean that they all agree on every single element of a draft document. They can agree to adopt a draft resolution without vote, but still have reservations about certain parts of the text. They explain their position to improve the text to strive to reach the widest possible agreement among the States.
  - Constructive compromise for the greater good

Nuclear Structure and Reaction Theory

Thomas Papenbrock, Daniel Phillips, Maria Piarulli, Gregory Potel, Nicolas Schunck, Ingo Tews, Alexander Volya

Nuclear Structure and Reaction Theory

29 presentations

80+ minutes of discussion

2+ hours of finding the best words

Working group: Papenbrock, Phillips, Piarulli, Potel, Schunck, Tews, Volya

+ Fossez, Hebborn, Koenig

- **Continuum physics:** Exploration of the drip lines: driver behind theoretical, experimental, and technical advances; has led to several important discoveries. Full treatment requires accurate inclusion of continuum physics
- **Emergent features:** Explain emergent features: approximate few-body dynamics, appearance of a mean-field, emergence of symmetries and symmetry breaking in the form of deformation, clustering, & pairing, etc. that play an important role across the nuclear chart, from microscopic perspective
- **Strongly-correlated many-fermion systems:** Nuclei are an example of strongly-correlated many-fermion systems. This means there are interesting connections to cold atomic gases & conformal field theories. Provides a novel way to understand halo nuclei, low-energy neutron spectra. Where else can this connection be useful?
- **Connection to QCD:** Few-nucleon systems remain a place where we have exquisite theoretical control. We support experiments and theory efforts that elucidate the connection of QCD and nuclear structure. This is one avenue that will improve nuclear forces
- **Electroweak physics:** *Ab initio* calculations of electroweak observables at finite momentum and energy transfer will continue to get better. Important for neutrino scattering from nuclei, connects us to supernova simulations, DUNE, and JLab

- **Reactions are awesome:** Reactions are the best window into the structure and dynamics of nuclei, and address data needed for other fields. Full UQ and reaction-theory modeling crucial
- **Ab initio approach to reactions:** There has been & will continue to be progress in unified *ab initio* calculations of structure and reactions for light-ion processes based on modern interactions
- **How to make progress for bigger nuclei:** Unifying structure and reactions for medium-mass & heavy nuclei requires reaction theory that can connect to multiple approaches to structure, and continued work on incorporating microscopic information into optical potentials
- **Predictive EoS:** Extend χEFT + *ab initio* calculations of infinite matter to finite temperature and arbitrary proton fraction. At what density does χEFT break down? Confront wealth of multi-messenger data from astrophysical events. Test of our understanding of strongly-interacting dense matter
- **Heavy Ion Collisions for the EoS:** FRIB & FRIB-400 provide a golden opportunity to probe the nuclear EoS at 1.5-2ρ_0. But to do that we need sufficiently accurate transport theory. Continued development of hadronic transport codes is needed. Concerns about loss of expertise

- **Predictive energy functionals :** Quality energy density functionals provide the opportunity for quantitative understanding of heavy nuclei: masses, radii, shape coexistence…. Essential for predictive theory of super-heavy elements.
- **Theories for nuclear spectroscopy:** Multi-reference methods: configuration mixing, projection. Connections with ab initio theories.
- **Fission and Fusion:** Fusion is very sensitive to nucleon transfer and collective excitations, while fission is one of the most complex and least understood processes in nuclear theory.
- **Real-time Dynamics:** Time-dependent dynamics enables microscopic calculations of fission & fusion. Production of superheavy elements. Connections and quantum computing.

The base program is at the heart of everything we do

- Many important ideas—things that were unplanned—originate here
- Healthy funding of PI time and work-force enables full realization of investment in experimental & computing facilities
- Also enables continued flow of innovative theory research
- Longer grant cycles allow for more strategy, potentially disruptive research

FRIB Theory Alliance is a success story that must continue & evolve

Collaborative nuclear theory grants accelerate progress on key nuclear-physics problems

- Many work best when they build on existing theory insights from base program
- Bring theorists with different expertise & skill sets together

Collaborative and single-PI grants explore & exploit synergies with other fields

- SciDAC DOE (physics + computer science + applied math) and Cyberinfrastructure frameworks NSF (physics + applied math + statistics) and JINA-CEE have been great successes demonstrating the benefits of collaboration with other fields.
- Can this model be extended to collaboration with cross-cutting areas, other sub-fields of physics and working with experimental colleagues?

INT has greatly benefited theory community and nuclear physics

Nuclear Structure and Reactions Experiments

Mike Carpenter, Robert Charity, **Heather Crawford,** Kate Jones, Sean Liddick, Andy Rogers, Nick Scielzo

Nuclear Structure and Reactions Experiment Working Group

- **Conveners:** *Mike Carpenter (ANL), Bob Charity (WashU), Heather Crawford (LBNL), Kate Jones (UTK), Sean Liddick (FRIB), Andrew Rogers (UMass Lowell), Nick Scielzo (LLNL)*
- 2.5 working group sessions yesterday afternoon
- 7 invited talks giving overviews on “Decay Spectroscopy”, “In-beam Spectroscopy”, “Direct Reactions”, “Heavy Element Science”, “Equation of State”, “Precision Measurements” and “Unbound Systems” + 20 community contributions – 190+ slides
- Physics discussed ran the gamut from the lightest nuclei (e.g. 4n) to the superheavy elements, and highlighted results from **facilities the across the community**

What are the overarching scientific challenges?

- The challenges have been stated in different ways over the years, far more eloquently than I can…

National Research Council Report - 2013

- How did visible matter come into being and how does it evolve?
- How does subatomic matter organize itself and what phenomena emerge?
- Are the fundamental interactions that are basic to the structure of matter fully understood?
- How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

NSAC 2015 Long Range Plan: Nuclear Structure, Reactions, and Astrophysics

- **The origin and evolution of nuclei**
    - Where do nuclei and elements come from?
    - What combinations of neutrons and protons can form a bound nucleus?
- **The origin of nuclear patterns**
    - How are nuclei organized?
        - Emergent phenomena in complex systems

What progress has been made since the last LRP?

- Completion of FRIB and beginning of scientific operations.
- Determination of the neutron dripline up to Z=10, and progress in studying the structure of nuclei at and beyond the driplines.
- Precision targeted measurements utilizing the unique capabilities of the ARUNA facilities – e.g. Hoyle state, resonance in ^{11}B, Coulex with CLARION2 + TRINITY.
- Use of direct reactions to elucidate structure information across beam energy regimes
- Measurements of mirror systems and isospin multiplets to quantify the degree of isospin symmetry breaking in the NN interaction into the *fp* shell
- First hint of superallowed α decay in ^{108}Xe and implications for cluster structure near ^{100}Sn
- Direct mass determination of ^{288}Mc
- …

What are the most compelling scientific opportunities over the next decade & their potential scientific impact?

To progress to a predictive and comprehensive model of the atomic nucleus

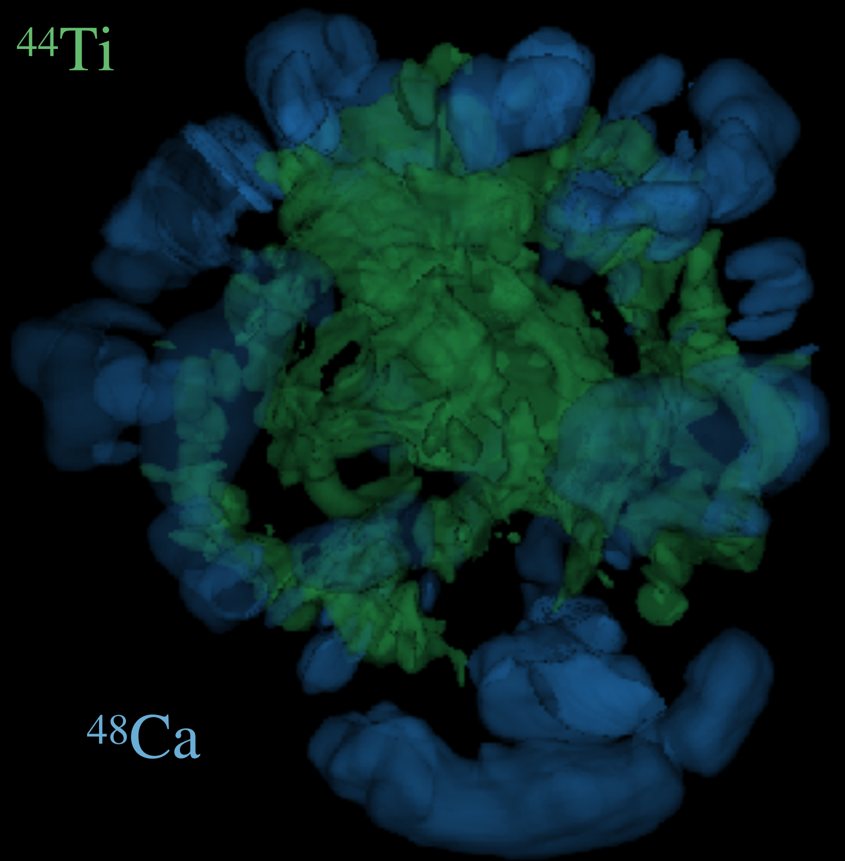
- Map the driplines (and beyond) as far as possible on both sides of stability – ^{42}Mg, Ca isotopic chain, 6p decay?,...
- Determine the single particle structure in (and around) ^{100}Sn, ^{60}Ca,...
- Elucidate the structure of the heaviest elements - limits of existence in *A* and *Z* – spectroscopy above *Z*=104, fission studies, a new element?,...
- Establish the structure of key nuclei relevant to the synthesis of the elements – decay properties, masses in the rare-earth, *N*=126,...

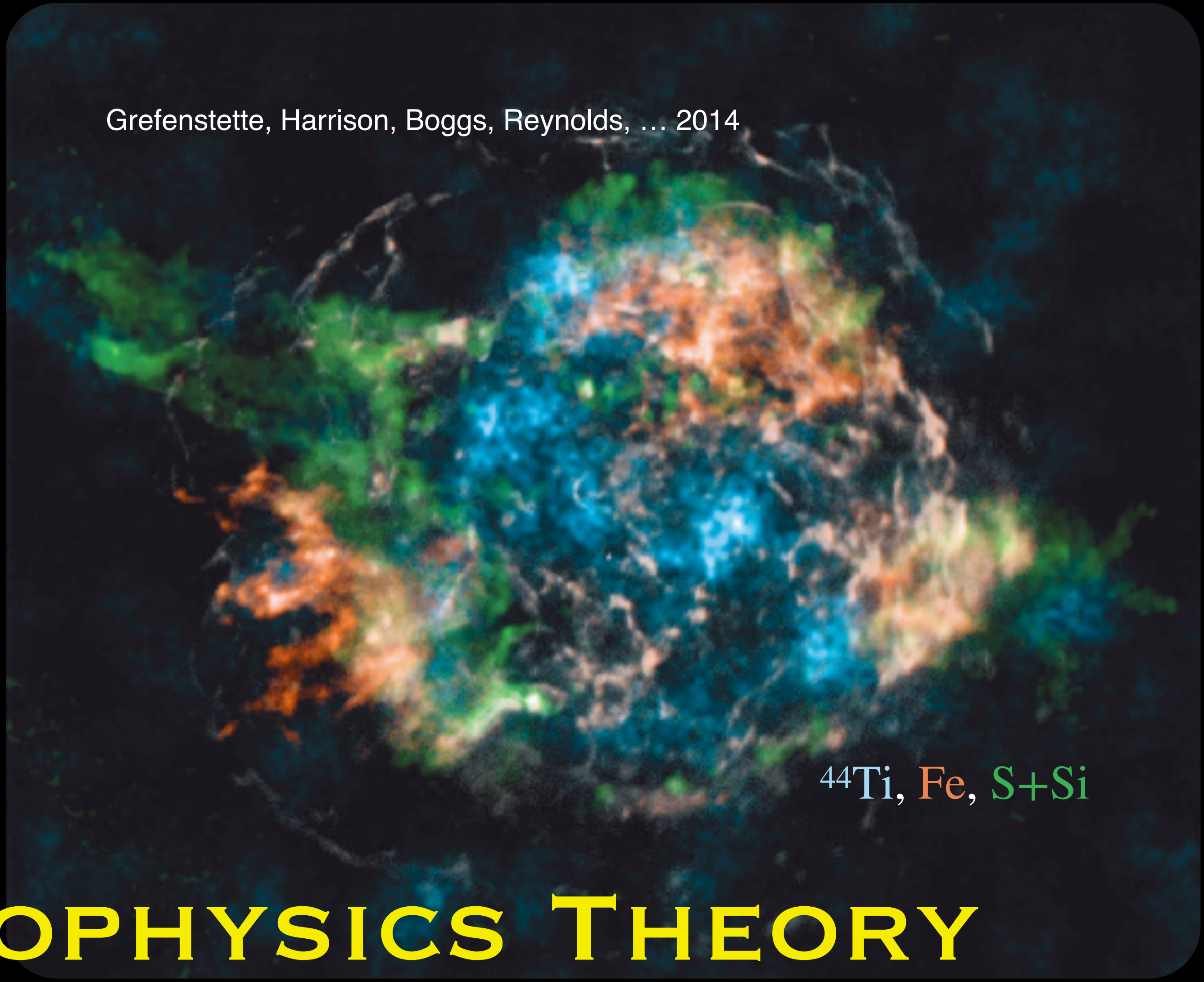
- The science enabled by the unique capabilities of ARUNA and lab-based facilities was highlighted across the sessions
- The physics enabled by FRIB 400MeV upgrade was front and center – adds capability to essentially **all aspects** of FRIB physics
- Expanding the capabilities at ATLAS and the AMUU is a direct value-add to our community
- There was a consistent message on the need to have sufficient support and funds for “small-scale” instrumentation

Nuclear Astrophysics – Modeling/Theory

Jutta Escher, Chris Fryer, **Raph Hix**, Amy Lovell, Gail McLaughlin, David Radice, Sanjay Reddy

Opportunities & Needs for



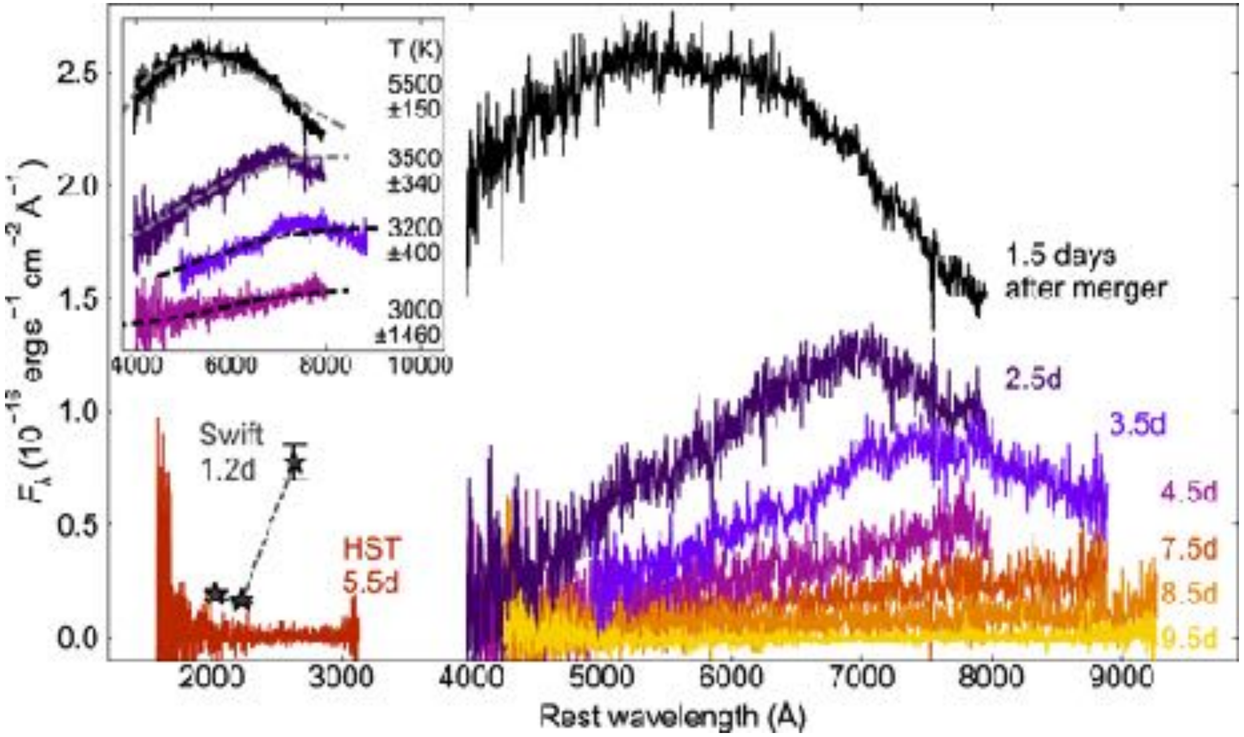


Nuclear Astrophysics Theory

William Raphael Hix (ORNL/U. Tennessee)

Past decade

GRB170817a/GW170817/AT 2017gfo revealed two component (blue/red) ejecta from binary neutron star merger including confirmation of r-process matter in the ejecta.



Multi-dimensional models of ignition in novae revealed the mechanism for mixing of white dwarf material into the accreted envelope by convective dredge-up.

Models for the neutrino reheating mechanism in core-collapse supernovae with spectral transport, general relativity and extended durations match the observed ranges in explosion energy and 56Ni ejecta as well as trends with stellar mass.

Multi-dimensional models of late stellar evolution revealed extensive anisotropy in the convective shells of massive stars, which accelerates the development of the subsequent supernova explosion.

Observations confirm both helium-ignited (via Gaia hypervelocity white dwarves) and Chandrasekhar mass (from 3C 397 remnant) mechanisms for thermonuclear supernovae.

Observational Bonanza

Next decade will see the accumulation of much larger set of gravitational wave data from LIGO for neutron star mergers (dozens of confident detections) and potentially for rotating neutron stars and starquakes.

For ~10 of these, kilonova counterparts will also be observed by UVOIR telescopes.

New neutrino observatories like Hyper-Kamiokade, DUNE & JUNO, will offer the potential to detect core-collapse supernovae throughout the Local Group with tens of thousands of counts for a galactic supernovae.

Within a decade, the Compton Spectrometer and Imager (COSI) γ-ray telescope will reveal ^{56}Ni in supernovae in the Local Group, ^{44}Ti in Galactic Supernova Remnants and potentially identify local kilonova remnants. Advanced Telescope for High Energy Astrophysics (Athena) will likewise improve our X-ray vision.

Vera Rubin Telescope and other Time-Domain surveys will find millions of nuclear-powered optical transients, some of which are likely to have previously unknown mechanisms.

Next Decade

To match this wealth of new data, a program of improved simulations is needed.

Models of neutron star mergers with improved neutrino transport and neutrino-matter interactions are needed to accurately capture the neutronization of the ejecta and hence its r-process content, to help ascertain the role of mergers as the r-process source.

Extended models of core-collapse supernovae with improvements to the neutrino transport and treatment of the ejecta composition are needed to match detailed photon observations.

Simulations of neutrino oscillations in supernovae and mergers are needed to determine the impact on these problems and lead to suitable approximations for use in these models.

Multidimensional models of X-ray bursts to track the ignition of the burst from the flame spreading across the surface of the entire star.

Improved models of thermonuclear supernovae identify progenitors through comparison to early light curves and detailed spectra as well as ^{44}Ti detection in galactic SNe Ia SNRs.

Models of the full menagerie of massive stellar deaths; supernovae associated with Long GRBs, supernovae that form Magnetars, Electron-Capture supernovae, Super-luminous supernovae.

Needs

Nuclear data for the r-process, νp-process, rp-process and other heavy element producing process that FRIB (and hopefully FRIB400) can provide.

Improved nuclear data for stellar/solar burning to address remaining uncertainties.

Upgraded theory for nuclear structure/reactions and nuclear matter to cover experimental gaps.

Community support for modeling of explosion mechanisms and resulting nucleosynthesis as a core nuclear physics activities.

End-to-end simulations for all objects of interest, to connect explosions and the formation of new elements to the appearance of these newly-made elements in the photospheric, nebular and remnant phases.

Support for multi-disciplinary collaborations, spanning the range of nuclear and neutrino physics at work in these events, but also reaching to the gravitational physics, particle physics and astronomy communities in order to maximize the impact of nuclear physics research.

Access to capability and capacity computing resources to complete the needed simulations and support for ongoing code improvements and adaptations to new hardware architectures, machine learning, etc.

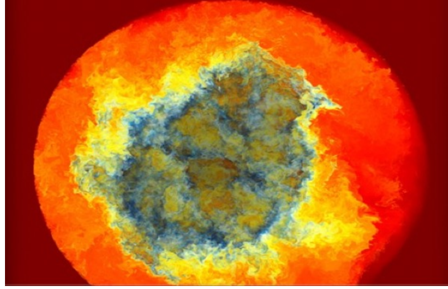
Connecting Nuclei to the Cosmos

Melina Avila, Dan Bardayan, Kelly Chipps, Aaron Couture, Catherine Deibel, Chuck Horowitz, Richard Longland, Alan McIntosh, **Hendrik Schatz**, Frank Strieder

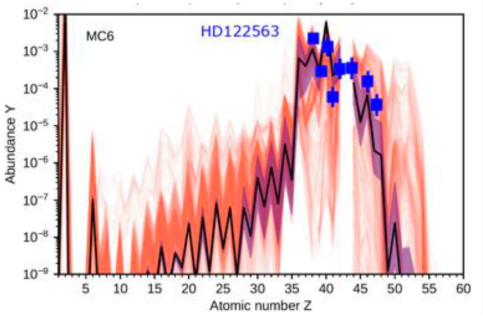
Working Group on Experimental Nuclear Astrophysics aka Connecting Nuclei with the Cosmos

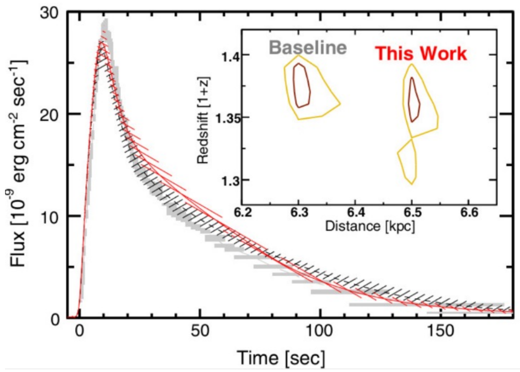
- Conveners: Melina Avila, Dan Bardayan, Kelly Chipps, Aaron Couture, Catherine Deibel, Chuck Horowitz, Richard Longland , Alan McIntosh, Hendrik Schatz, Frank Strieder
- Two sessions
- Four invited talks covering the overarching scientific challenges, 22 Contributed Talks, plus summary talk from Astro Theory
- About 80 participants, about half online
- Input:
  - White Paper: Horizons: Nuclear Astrophysics in the 2020s and beyond arXiv 2205.07996
  - Presentations
  - Online form
  - Google doc with all free to comment/suggest
  - Drive folder with information collected so far
- Will keep online form and google doc open for continued input

What progress has been made since the last LRP?

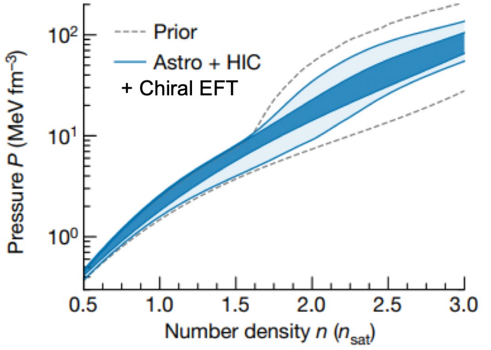


- **Dynamic Stars:** New successful measurements of key stellar nuclear reactions had broad impact on first star, solar neutrino interpretation, heavy element nucleosynthesis, supernova neutrino signals, white dwarf seismology, LIGO black hole mass distribution (all messengers)
- **Heavy Elements**: Discovered that a much broader range of processes is needed to explain the origin of the heavy elements, including within NS mergers - experiments and theory enabled first constraints on these processes
- **Thermonuclear Transients:** Identified and characterized important nuclear physics in novae, X-ray bursts, and neutron star crusts
- **Dense Matter:** Unprecedented combined constraints on EOS from GW Waves, X-ray pulsars (NICER), electron scattering, nuclear properties, heavy ion collisions, theory
- **Major instrument and facility developments:** FRIB + ReA3/6 FDSi SECAR, ANL ATLAS, St.George (ND), LENA II (TUNL), CASPAR (SURF), Spectrographs (TUNL, FSU), Radioactive targets



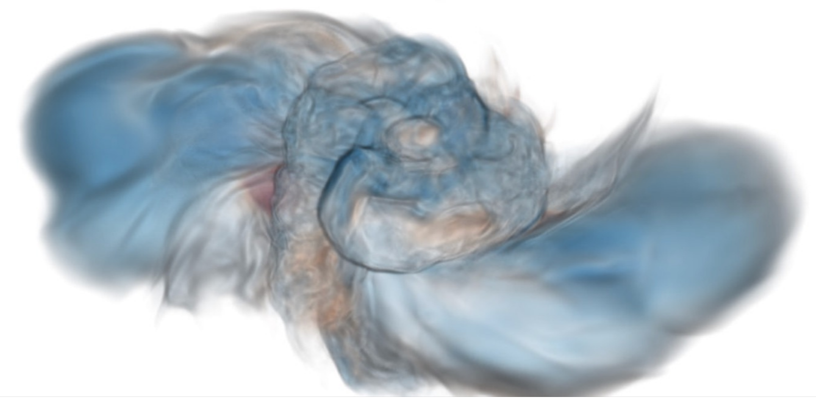


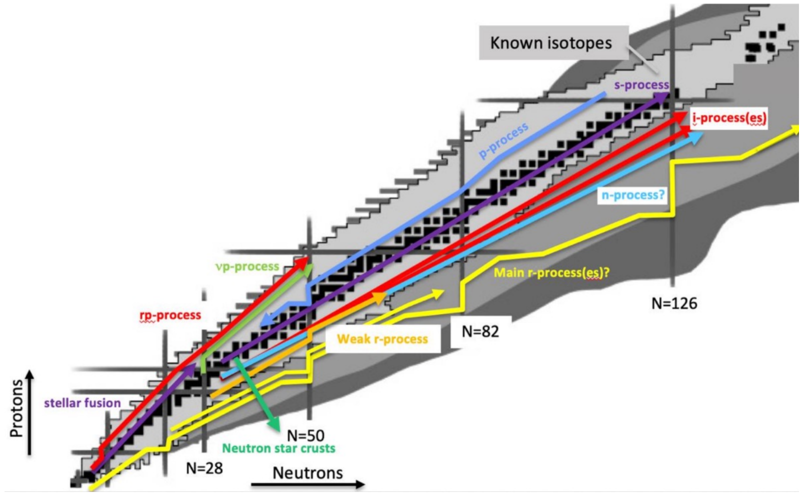
Huth, Pang et al., Nature 606, 279 (2022)

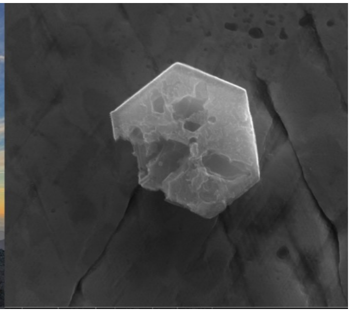


Most compelling scientific opportunities

- **Determine the nucleosynthesis contributions of neutron star mergers** [need whole chain from EOS over FRIB/ANL data to kilonova atomic physics FRIB FDS, 400, ANL nuCARIBU N=126, neutron target/strorage ring]
- **Unravel the origin of heavy elements:** Characterize the multitude of sources and processes producing the heavy elements based on experiments at a broad range of facilities [FRIB FDS, ANL nuCARIBU/N=126, stable beam facilities above and underground, ReA12/ISLA, neutron beams, gamma beams, neutron target/strorage ring, isotope harvesting, targets]
- **Advance fundamental understanding of low energy nuclear reactions** through novel experiments and renewed reaction theory efforts [stable beam facilities above and underground, gamma beams, plasma reactions/NIF, targets]
- **Map and understand the nuclear powered transient sky in unprecedented detail** (including its nucleosynthertic, radioactive, and stardust fingerprints) through experiments at broad range of facilities and novel techniques, direct and indirect techniques, and isomeric beams [stable beam facilities, FRIB intense beams + SECAR, ISLA, ReA12, GRETA, HRS, FRIB400, isotope harvesting, targets]
- **A golden era of neutron stars:** Global EOS from low to high density, crust to core, especially push to higher densities relevant for neutron stars - combine new HICs with LIGO O4, O5 runs, advances in theory, measurement of extremely neutron rich nuclei [FRIB 400]
- **Connection to neutrino physics, use nucleosynthesis as a tool**







International, Interdisciplinary, and Cross Cutting Aspects

- Broad community buy-in and a concerted effort to put DEIA goals on equal footing with scientific goals – nuclear astrophysics can make important contributions
- Strong support for research groups at broad range of facilities and institutions
- Need a center that connects experiment, nuclear and astrophysics theory, and observations for the multi-messenger era. Nuclear astrophysics is inherently interdisciplinary.
- Take advantage of international capabilities
- Reaction theory advances are needed
- Software tools to facilitate interdisciplinary work and exchange

Computing (HPC, Quantum, AI/ML)

Gaute Hagen, Calvin Johnson, Michelle Kuchera, **Dean Lee**, Pieter Maris, Kyle Wendt

Computing working group

- Session on High Performance Computing (HPC):
  - Introduction (5 mins) followed by four 15 minutes talks and a short 5 minute presentation. At the end we had a 20 minutes discussion

- Session on New Computing Technologies (QC, AI/ML):
  - Divided into two smaller sessions, one on quantum computing (QC) and one on Artificial Intelligence/Machine Learning (ML). Both QC and AI/ML started with an overview talk (15 mins) followed by 5 mins presentations (9 in total). The end of each session was followed by a 20 mins discussion

What progress has been made since the last LRP?

See talks on Monday:

- Thomas Papenbrock: “Predictive theory of nuclei and their interactions”
- Gail McLaughlin: “Theory for nuclear astrophysics”
- Dean Lee: “Quantum computing and simulations for nuclear physics”
- Joe Carlson: “Report from the Computation/AI/ML Workshop”

Overarching scientific challenges in HPC

- Need resources to aid in migration to GPUs
- Strengthen collaborations between applied mathematicians, computer scientists, and nuclear physicists in order to efficiently utilize leadership-class computing resources
- Better articulate ‘best practices’ for data and code management
- Codes continually need to be ported to new architectures
- Computing is becoming more heterogeneous
- Learning curve for new students is increasing greatly
- We all need more computer time
- Training opportunities for NP students will become even more important over the next decade as computing technologies explode

Overarching scientific challenges in QC and AI/ML

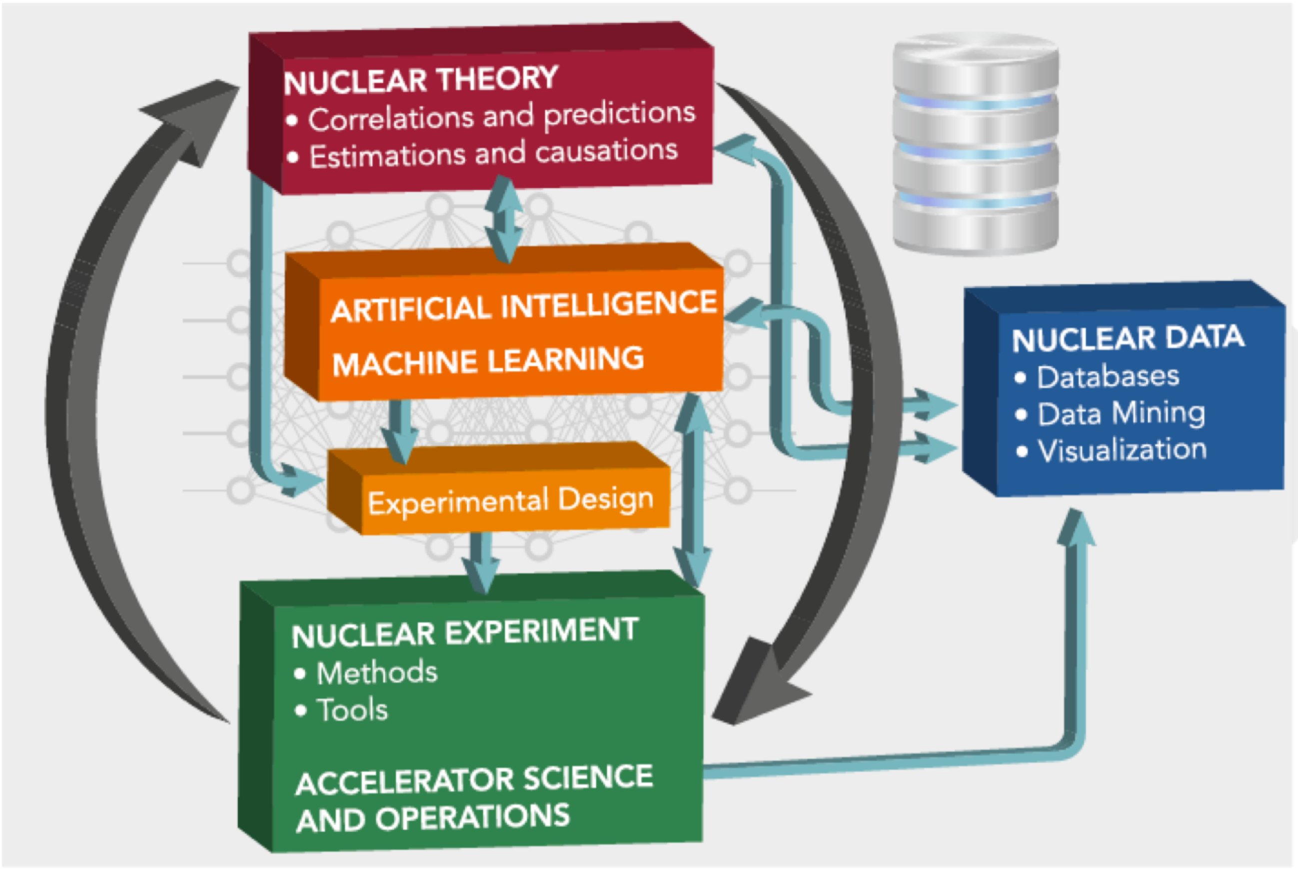
- (QC) Real nuclear physics calculations will require a large number qubits and low error rates
- (QC) Current devices are still quite noisy and have limited numbers of qubits
- (QC) It is not easy to prepare energy eigenstates for large quantum systems

- (AI/ML) Understanding model biases for deep learning is not always straightforward
- (AI/ML) There can be a trade off between efficiency and interpretability
- (AI/ML) In applications such as accelerator science, need to account for time variability
- (AI/ML) Need more open access, data sharing, and data standards

What are the most compelling scientific opportunities over the next decade & their potential scientific impact?

- Development of emulators, AI/ML and Bayesian methods:
  - Opens up entirely new ways to make predictions and quantify uncertainties
  - Experimental design: which measurements will help constrain/inform theoretical models (maximize the success of an experiment)

Experimental design: Emulators, built using ML and HPC, could enable real-time analysis of experiments



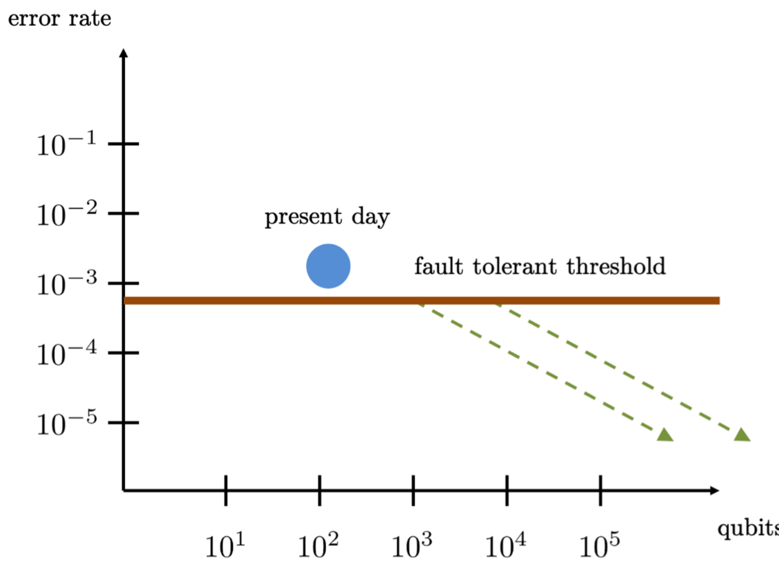
What are the most compelling scientific opportunities over the next decade & their potential scientific impact?

- Large Neutron-Rich Nuclei:
  - masses and decays
  - Confronting FRIB, ATLAS data, ...
  - Input to important new experiments
- Connections to Astro and Fundamental Symmetries
  - Double Beta Decay and beta decay for BSM, nuclear EDM
  - Neutron Skins and Neutron Star Matter
  - Improved EOS (higher densities, finite T, ...)
  - Neutrinos in astrophysical environments
- Nuclear Dynamics:
  - Electron and Neutrino Inclusive Scattering
  - Reactions at low energies (resonances, ...)
  - Reactions at higher energy in ab initio
  - Coexistence phenomenon and Large amplitude collective motion in fission and fusion

Adapted from J. Carlson's talk on Monday

What are the most compelling scientific opportunities over the next decade & their potential scientific impact?

- (QC) Calculate real time dynamics and spectral functions
- (QC) Nuclear physics problems are nearly ideal for quantum computing due to short range interactions
- (QC) Opportunity to design new quantum algorithms with potentially widespread applications
- (QC) New talent considering nuclear physics through opportunities in quantum computing
- (QC) Interdisciplinary partnerships with quantum information scientists, including DOE Quantum Testbed researchers



Facilities, Instruments, and Upgrades

Georg Bollen, Manoel Couder, Paul Fallon, **Robert Janssens**,
Steve Pain, Guy Savard, Ingo Wiedenhoever

WG on FACILITIES, UPGRADES, INSTRUMENTS

- How many sessions? ← 2 sessions of 2 hours each
- How many contributions and/or invited talks? ←

→ Session 1: User facilities (3), ARUNA accelerators (10), 88 Inch (1)
Targets (1)

→ Session 2: Community Detectors (5), Other initiatives (11)

- How did you organize yourself? ← Conveners discussions & call to the community

- Anything else you think is relevant ← Impossible to summarize!!

TAKE AWAYS:

- FRIB is a reality and first experiments have taken place
- ATLAS continues to serve a large community while upgrading its capabilities to meet demand
- ARUNA facilities complement the user facilities while providing unique additional capabilities (types of beams, beam time, detectors)
- The community continues to develop first rate instrumentation and ideas to expand the reach of our science

- → **FULL STEAM AHEAD**

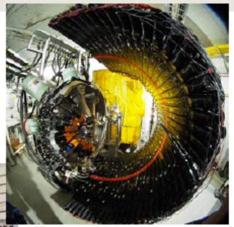
Experimental Instruments Integrated

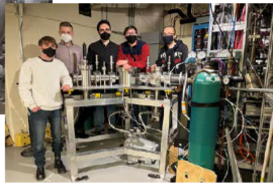
- Roadmap for scientific instruments and experimental areas supports 5 year science strategy and 10 year perspective
- Experimental areas accommodate lab-supported and user-provided instruments
  - https://frib.msu.edu/users/instruments/index.html

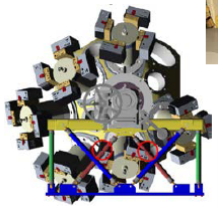
HRS PRIORITY

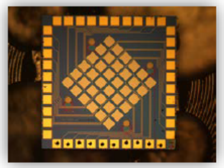
New Scientific Instrumentation Realization with Community Engagement and Leadership

- **FRIB Decay Station initiator (FDSi)** - led by ORNL
  - Phase 1 completed, 2 FRIB experiments successful
- **SOLARIS**: SOLenoid spectrometer Apparatus for ReactIon Studies – led by ANL
  - Intermediate phase completed and first experiments at ReA6 successful
  - FSU collaborates on DAQ system
- **RiSE**: Collinear laser Resonance Ionization Spectroscopy at BECOLA – led by MIT
  - Beam line installed and stable beam test performed
- **GRETA detectors at S800** - Gretina frame modification in collaboration with LBNL
- **SALER** – Superconducting Array for Low-Energy Radiation
  - New project led by Colorado School of Mines
- **EOS-TPC:** EOS active target time projection chamber under discussion







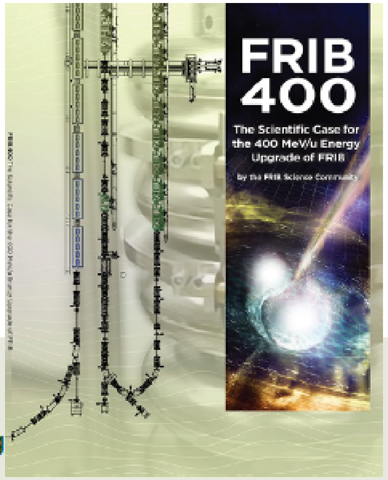


Expect the community to have new ideas, small and large. Space is available and FRIB is open to new initiates.

Staged implementation possible without interrupting user operations

- Modest cost – see Thomas’ plenary talk for details
- Technically ready: R&D ongoing, technology being demonstrated, prototype cavities tested, and team is in place
- Staged implementation possible during scheduled shutdowns
  - First shutdown would have to be a longer one to implement the cryo infrastructure (we will have those during the power ramp up)
  - Cryomodules can be put in one-by-one as they become ready during regular shorter maintenance shutdowns
- Every gain in energy is a gain in intensity – a benefit at every step

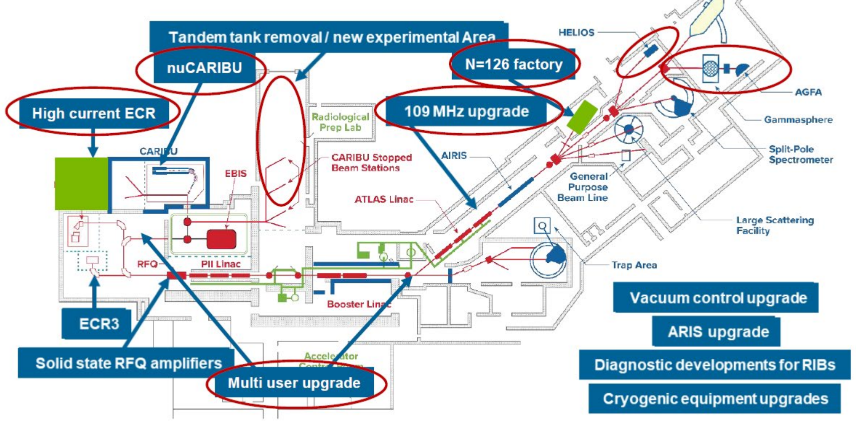
See the Whitepaper and presentations during the meeting for the science opportunities!



STATUS

- ATLAS is constantly evolving to better fulfill the needs of its users.

Recently completed / ongoing / planned



- Needs are:
  - More intense stable, CARIBU and RAISOR beams
  - More beamtime
  - Higher sensitivity and rate capability for the instruments
  - Access to new regions

- Currently being addressed by:
  - New ECR source, 109 MHz cryostat upgrade, nuCARIBU, and better targets
  - ATLAS Multi-User Upgrade
  - Gammasphere upgrade, AT-TPC at HELIOS, MUSIC2, PI-ICR at CPT, …
  - N=126 facility

- Need sustained R&D to keep ATLAS, and facilities in our field in general, at the forefront

- ARUNA facilities:

  FSU: **I. Wiedenhoever**

  ND: **D. Bardayan**

  JMU: **A. Banu**

  UK: **B. Crider**

  Ohio U: **C. Brune**

  Texas A &M: **Ph. Adsley**

  TUNL **C. Howell**

  UMass Lowell: **A. Rogers**

  CENPA **A. Garcia**

  Underground facilities: **M.Wiescher**

ARUNA Labs have upgraded their capabilities as well and need to be able to continue to do so

- Accelerator upgrades at ND, TUNL, Ohio, TAMU (for example)

- Case of FSU: Scenario for energy increase: old technology or..

FSU Linac upgrade project

The current FSU linac has 12 accelerating resonators with β=0.1 natural vel.

The original design already anticipated an upgrade to 20 resonators, including 4 with β=0.07 and 16 with β=0.1

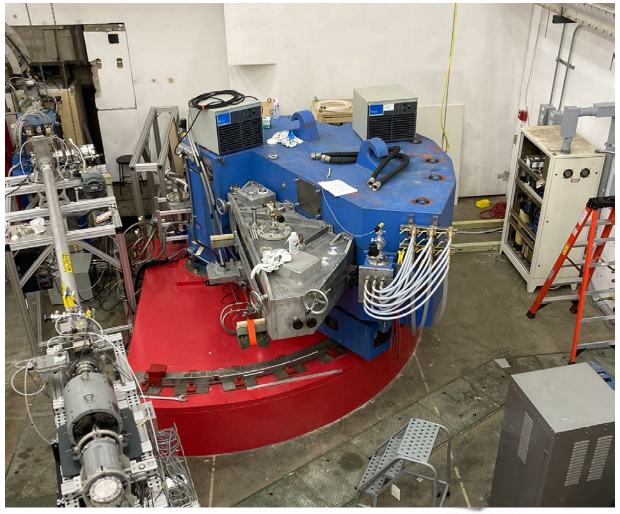
Plan A: We already acquired the missing resonators and electronics from Kansas State and Resonators from ANL => Need to build cryostats

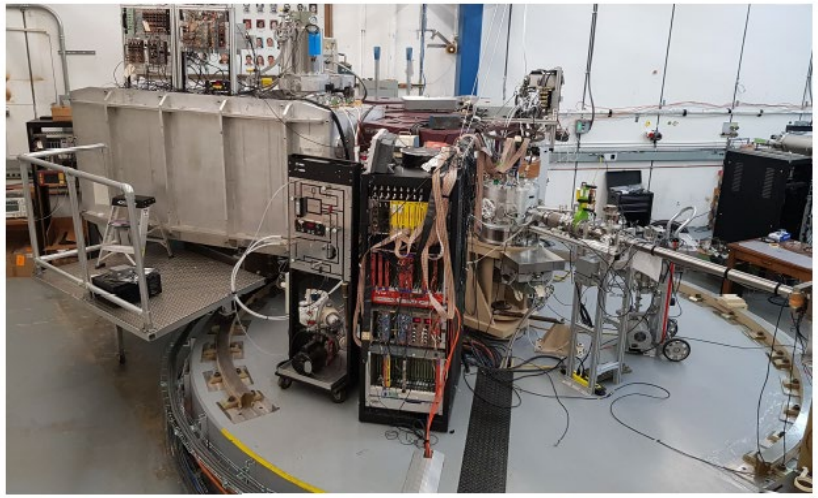
The upgraded linac will easily support RESOLUT operations up to mass 40

MeV/u	Energy Tandem	Current Linac	Complete Upgrade
^{16}O	3.9	8.0	9.9
^{24}Mg after prod. target	2.9	6.6 5.7	8.6 7.8
^{32}S after prod. target	2.5	5.8 4.6	7.9 6.9
^{40}Ca after prod. target	2.2	4.7	6.8 5.6

→ Can we find a way to benefit from the experience available at the laboratories in a model that would not require full cost recovery

→ Improved instrumentation: Split-pole spectrographs available at FSU, TUNL and soon at ND, gamma-ray arrays shared (CLARION, Clovershare…), & instr. Moving between labs ← sharing of knowledge & expertise while educating the next generation

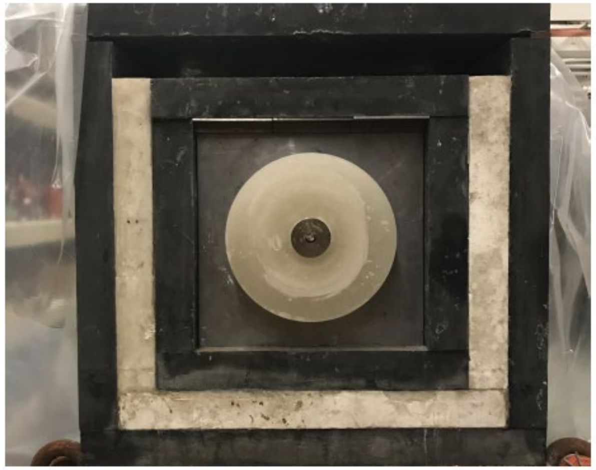




ND, FSU,TUNL

DAPPER – TAMU

U Mass-Lowell

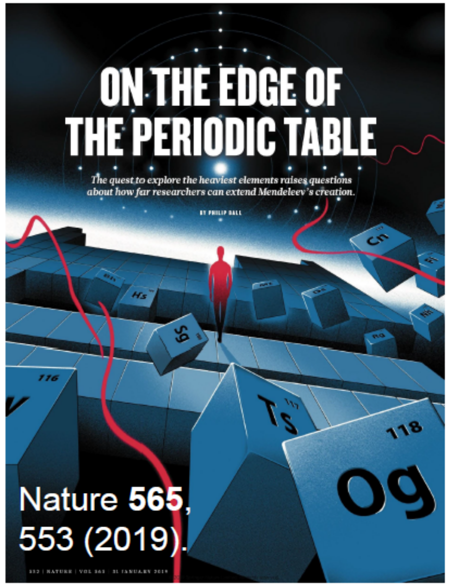


FAST n Facility
Ohio U.

→ Collaborations between ARUNA labs and between ARUNAL Labs and user facilities serve the community as a whole

The 88” Cyclotron science opportunities

Super heavy elements



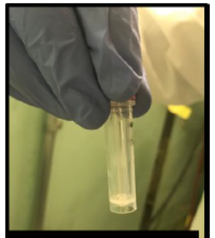
Nature **565**, 553 (2019).

Nuclear Data (experimental needs)

Finding the sweet spot:

therapeutic radionuclide

^{225}Ac via ^{226}Ra(n,2n)

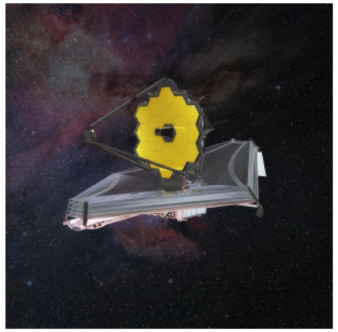


^{226}RaNO$_3$ (1 mg)

A 43 g ^{226}Ra target with a 40 MeV deuteron beam would outproduce BNL-BLIP

- Chemical separation efficiency: 91.4 %
- Production rate: 2.1 mCi/mAh/g
- No fission fragments in separated ^{225}Ac.
- No measurable ^{227}Ac (t½=21.8 y)

BASE, SEE testing



- Nearly all American spacecraft have had one or more parts tested at the 88-Inch Cyclotron BASE Facility.

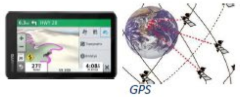
BASE

NP Community: Contributions to Space Exploration*

Solar Terrestrial Relations Observatory (STEREO)
Genesis (Solar Wind Sample Return)
Messenger (Mercury)
Parker Solar Probe
Pioneer Venus
Van Allen Probes
IMAGE/Explorer 78
Solar Dynamics Observatory (SDO)
Landsat
GPS
Mars Pathfinder
Mars Polar Lander
Orion Crew Vehicle
Mars Climate Orbiter

Parker

SDO



GPS

Orion

Mars Exploration Rover (MER) / Spirit & Opportunity
Mars Science Laboratory (MSL) / Curiosity Rover
Mars Atmosphere & Volatile Evolution (MAVEN)
Mars Odyssey
Phoenix (Mars)
ExoMars
Mars 2020 (Perseverance & Ingenuity)
InSight (Mars) Lander
Dawn (Asteroid Belt)
Juno (Jupiter)
Galileo (Jupiter)
Cassini-Huygens (Saturn)
Europa Clipper (Jupiter)
Voyager (Jupiter, Saturn, Uranus, Neptune)
New Horizons (Pluto)

Ingenuity

Juno

Europa

Space Shuttle
Lunar Reconnaissance Orbiter
International Space Station (ISS)
James Webb Space Telescope
Spitzer Infrared Telescope Facility
Swift Gamma-Ray Burst Mission
Stardust (Comet Sample Return)
Deep Space 1
xEMU Space Suit
Atlas Launch Vehicles
Delta Launch Vehicles

James Webb

xEMU

*Tested at the 88” Cyclotron

- COMMUNITY DETECTORS

GRETA: **P. Fallon**

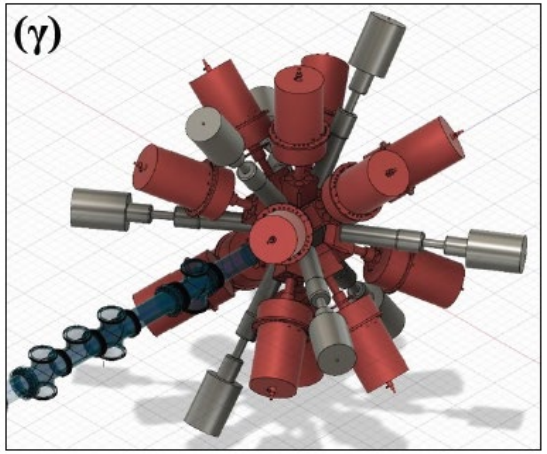
GAMMASPHERE: **M. Carpenter**

FDS: **M. Allmond**

GODDESS/ORRUBA **S. Pain**

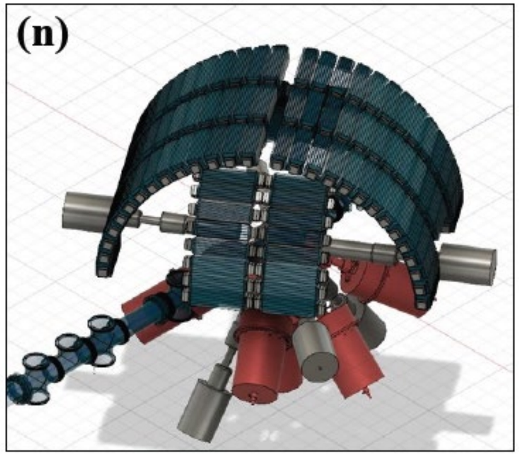
ISLA: **D. Bazin**

DEGA (HPGe for gammas)

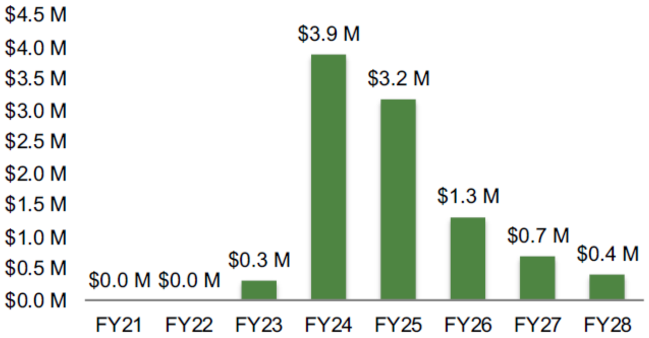


$10-12M

NEXT (neutrons)

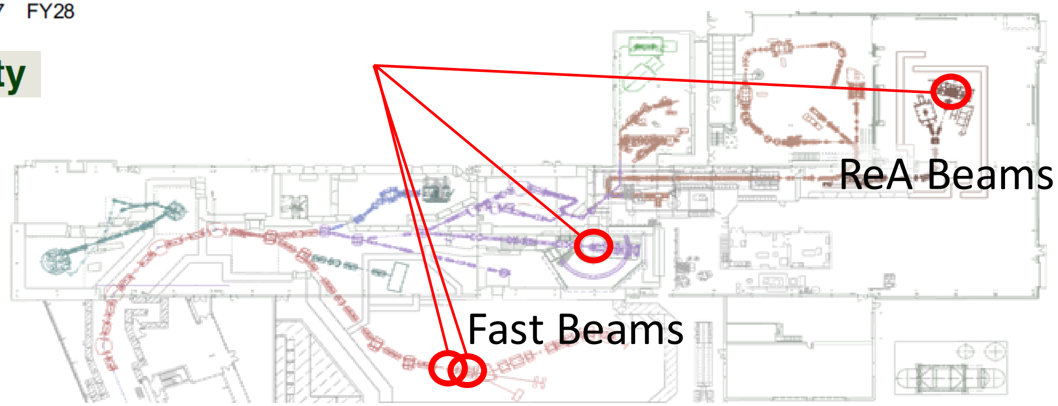


$8-12M



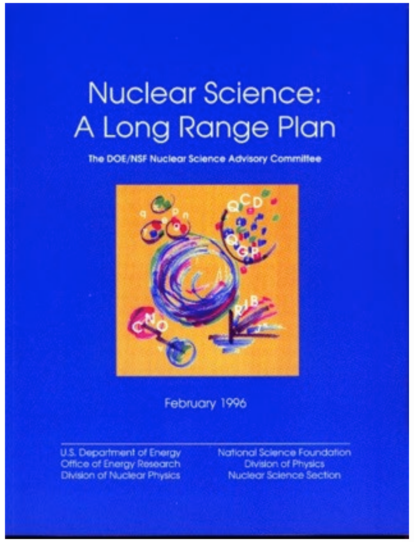
Cost and funding opportunity

GRETA Initial Operations (starting 2025)



LRP key to initiating new Major Instruments – science based

‘96

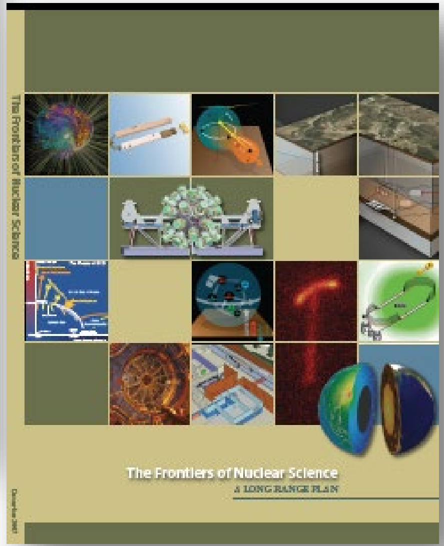


GRETA first discussed in the 1996 NSAC LRP

‘02

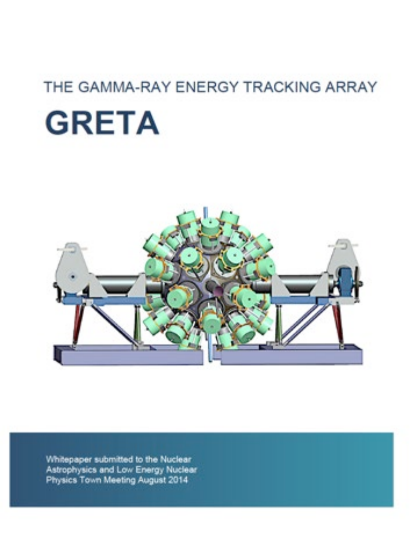
2002 NSAC LRP *“The detection of γ-ray emissions from excited nuclei plays a vital and ubiquitous role in nuclear science ..”*

‘07

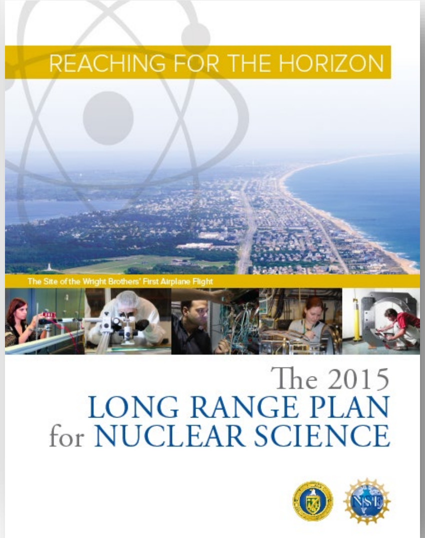


2007 NSAC LRP *“Construction of GRETA should begin immediately upon successful completion of the GRETINA array”*

‘14



‘15



Concept endorsed – GRETA identified as a key instrument for FRIB

Extended Proton Tracking Target for In-Beam Spectroscopy **Heather Crawford**

A Neutron Source at FRIB **Michael Smith**

A Time Projection Chamber for the measurement of lifetimes of excited states following alpha decay **David O'Donnell**

Measurements at the Intensity Frontiers with Improved AT-TPC **Moshe Gai**

Reaction Studies at the Los Alamos Neutron Science Center **Aaron Couture**

An Infrastructure for Integrating Experimental Facilities with HPC Facilities **Mario Cromaz**

A New Targetry Lab at SJSU **Nicholas Esker**

Towards a Neutron Target and Radioactive Ion Beam Storage Ring Facility at LANSCE **Andrew Cooper**

New solenoidal spectrometer development at Los Alamos Neutron Science Center (LANSCE) **Hye Young Lee**

LSTAR: an isotope separator for a new 3He-LIG system at the Cyclotron Institute **Dan Melconian**

"Bromide-share" – network for a dedicated lifetime array for inbeam and decay work **Walter Reviol**

Education

Mark Caprio, Paul Cottle, Ben Kay, **Shelly Lesher**, Andrew Ratkiewicz, Remco Zegers

Scientific & Technical Workforce Development

- 2 sessions + 1 discussion session with DEIB
- We asked the community for 5 min contributions on education, outreach and workforce.

1. Summer schools / online course resources
2. Engaging the public & outreach
3. Undergraduate, graduate education, and national lab needs

What are the overarching challenges?
What progress has been made since the last LRP?

- Challenges:
  - How do we recruit, retain, and expand the next generations of scientists and technical workforce to ensure the needed workforce for academia, research laboratories, and industry
  - How do we diversify the workforce and ensure that nuclear science benefits from the talent in groups that are presently underrepresented?

- Progress?
  - Educational initiatives - Summer school series & course development
  - Continued and new support from NSF and DOE in workforce development with investments that support diversification (schools, summer programs, REU, CEU, traineeships)

What are the most compelling scientific opportunities over the next decade & their potential scientific impact?

- We need to make educational initiatives widely available and develop material for a variety of skill levels; share best practices, create impactful community-wide initiatives
- Engage the public in our work to gain buy-in and support for our field; recognize public engagement efforts in terms of career advancement
- Expand the effort to build relationships with middle and high school students from a wide range of backgrounds and engage their teachers in this effort.
- Educate students on career paths and opportunities in the field of nuclear science and how to translate their skills to a wide range of careers in and outside academia/research – recruit more students for the benefit of nuclear science research AND other careers

- Investing in our workforce is <u>essential</u> in enabling all of our scientific endeavors. Minor investments in support structures to advance wellness/mental health; socio-economic support; equity, inclusion, and belonging; effective administration are necessary for making real progress and meeting the workforce needs of the community and the nation.

Diversity, Equity, Inclusion, and Belonging

Daniel (Akaa) Ayangeakaa, Paul Gueye, Stephanie Lyons,
Warren Rogers, Alejandro Sonzogni, Vandana Tripathi

Diversity, Equity, Inclusion, and Belonging (DEIB) working group

- We met for 2 WG sessions + 1 joint session with Education.
- We heard from a total of 21 speakers.
- We met as a group via Zoom weekly, developed a strategy for our working group sessions, produced a list of invited speakers.
- Topics covered in talks included among others
    - DEIB efforts at DOE, NSF, AIP, APS, and the DNP;
    - Outreach efforts at national laboratories;
    - Student experience at MSIs;
    - DNP DEI committee efforts;
    - LGBTQ+ culture;
    - Summer outreach camps; and
    - Financial stress for graduate students.

What are the overarching scientific challenges? What progress has been made since the last LRP?

- The topic of DEI was not explicitly included in the 2015 LRP
- Nuclear Science thrives best when all members of its diverse community feels a sense of inclusiveness, belonging and respect.
- Nuclear Science will continue to lose talented scientists, especially those from under-represented and marginalized groups, as long as harassment continues to be tolerated, and the quality of its science will continue to greatly suffer.

What are the most compelling scientific opportunities over the next decade & their potential scientific impact?

- We recommend that all physics collaborations be required to adopt Community Agreements, which include expectations for community members' behavior, a process for enforcement and fact-finding, and enforcement of consequences for misconduct that are unbiased, transparent, and just.
- We recommend the expansion of the DNP Allies Program at Spring APS meetings and the promotion of its adoption in other APS units; as well as bystander trainings be provided at APS meetings.
- We recommend that DEI plans be integrated into all grant proposals with grants renewal re-assessed based on DEIB performances.
- We recommend that community climates be measured annually through anonymous surveys to assess and improve on the impact of DEIB efforts.
- We recommend more funding to support hiring of outreach coordinators, especially at MSIs and PUIs.
- We recommend the establishment of an undergraduate focused summer school that would complement the NS3 and include a combination of lectures and hands-on activities guided by the USPAS and MSU/EMP3 approaches.
- We recommend the establishment of more students and teachers programs at the pre-college level across all communities but especially for under-represented and marginalized groups.
- We recommend more funding that will foster international collaboration and international students, especially from African and Hispanic countries (the latter guided by the traineeship program at FIU).
- We recommend the strong support of programs that would include technical and community colleges and foster collaborations with national labs and users facilities.

Accelerator Science, Applications, and Broader Impacts

Mike Kelly, Graham Peaslee, **Brad Sherrill**

Introduction to the working group

- How many sessions?
  - 2 afternoon sessions from 1:30 pm – 6:40 pm
- How many contributions and/or invited talks?
  - 5 Overview talks
  - 28 Brief presentations
- How did you organize yourself?
  - Speakers solicited in a broadly disseminated email (user groups, collaborators in industry and academia)
  - Invited overview talks were selected to represent a few of the major themes
  - Everyone who requested a time slot presented
- Anything else you think is relevant
  - Very broad discussion over several areas: accelerator science (for which our field contributes significant advances), NP facilities, applications of NP accelerators, applications of nuclear techniques

What are the overarching scientific challenges? What progress has been made since the last LRP?

- Overarching Challenges in Accelerator Physics
  - Advancing key technologies in SRF, ion sources, and magnets
  - Transfer of technology and expertise for facilities and applications
  - Meeting the needs of the applied users for accelerator technology and generated data
  - Advancing nuclear techniques for homeland security and medical applications
  - Application of ML and AI to improve operations
- Main take aways
  - Our field makes major contributions to accelerator science; forefront developments are underway that will impact many fields of science
  - Core expertise and training at NP facilities supports a significant accelerator and accelerator-related technological industrial base in the US and offers the opportunity for US industrial growth
  - Nuclear Physics Accelerators provide critical infrastructure for testing electronics for space applications, identifying hazardous trace elements and chemicals. Nuclear techniques are essential components in identification of illicit nuclear materials, in medicine, and other societal applications
  - Continued broad support for the core activities at NP supported facilities is important to carry forward advancements in applied science and the associated societal benefits

Challenge: Training the Needed Accelerator Workforce

- Examples below
- Our field contributes a large fraction of trained accelerator science and cryogenic engineers to the US workforce

Ostroumov

ASET Traineeship @ Michigan State University

Staff	20+ Academic Faculty: in Physics & Astronomy Dept + Engineering Dept. 30+ PhD Scientists & Engineers: Available for Supervisory Roles
Focus	Primarily PhD, Recently Extended to MS Thesis projects and advisory teams formed to fit student interest/aptitude Regular Student Meetings & Lab Accelerator Seminar Series
Lab Part.	ANL, BNL, Fermilab, FRIB, LANL, LBNL, SNL, Trane
Applicat.	Integrated with MSU Physics & Astronomy and Engineering Dept. Fall Admit Cycle for PhD Candidates, MS Any Time
Oversight	Yearly Accelerator Traineeship Advisory Panel (S. Nagaitsev, J. Byrd, M. Bai), Reviews & Guides the Program
Accel Courses	Accel Systems; Accel Technology; RF Power Engineering; Accel Physics; Cryogenic Engineering (via MSU Cryo Initiative); Accelerator Certificate: Available (9 credits); USPAS Encouraged
ASE Cert	To-date, 16 students received AS&E Certificate
Nat. Labs	Currently 8 students are supported by National Laboratories (BNL, LANL, LBNL, SLAC, FNAL)

Knudsen

Cryogenic Initiative

- The cost, efficiency, and reliability of superconducting accelerators is heavily influenced by the same factors of the cryogenic system
- Are helium cryogenic systems an ‘established’ technology like ‘conventional’ facilities?
  - Cryogenic engineering is a specialized engineering discipline
  - These systems are largely one-of-a-kind due to the experimental nature of the science they support, and the long project timespans (e.g., 14 years for FRIB; 2008 to 2022)
  - *The low volume production, one-of-a-kind design/application, and long project time-span aspects are limiting industry from sustaining any R&D effort for equipment, systems, and technology needed*
  - Consequently, much of the equipment is adapted from other industries, such as oil and gas and commercial refrigeration
    - But the adaptation is usually inefficient and lacking reliability and robustness
    - Often manufacturers will not even want to supply their equipment for others to adapt it for cryogenic system application!

Nuclear Data

Christian Illiadis, John Kelley, **Filip Kondev**, Libby McCutchan, Matt Mumpower, Artemis Spyrou

Nuclear Data WG

Introduction to the Nuclear Data working group

- NDWG co-organizers - put together by the NSAC LRP Town hall conveners
  - C. Iliadis (UNC), J. Kelley (NC State & TUNL), F.G. Kondev-POC (ANL), E. McCutchan (BNL), M. Mumpower (LANL) & A. Spyrou (MSU)

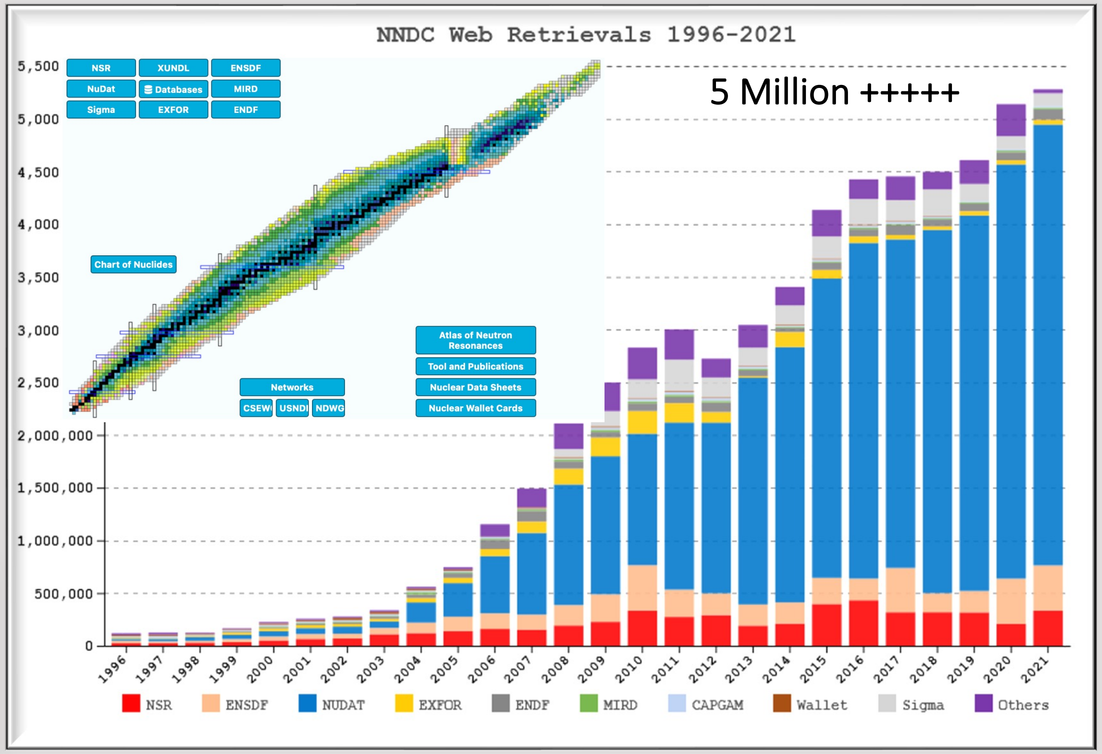
- Several ZOOM meetings prior the Town hall meeting - solicited input from broader community - FRIB, ATLAS and NNDC mailing lists

- Two WG sessions on Tuesday, November 15 – attended by ~25 in person and ~30 virtually
  - 4 overview talks (20+5 min)
    - *Nuclear Structure* – M. Carpenter (ANL)
    - *Nuclear Reactions* – A. Couture (LANL)
    - *Nuclear Astrophysics* – C. Iliadis (UNC)
    - *Nuclear Data & Society* – J. Ressler (LLNL)
  - 23 contributed talks (5+1 min) – intersections between the four main areas

What are the overarching scientific challenges? What progress has been made since the last LRP?

Libby McCutchan (BNL) talk

- increased connections with users – nuclear databases are part of the everyday life of a nuclear scientist
  - ☞ preparation of experiments -> during the experiments -> data analysis & simulations publication (reviews)
  - ☞ important ENSDF format upgrade is underway!



PHYSICAL REVIEW RESEARCH **4**, 021001 (2022)

Perspective

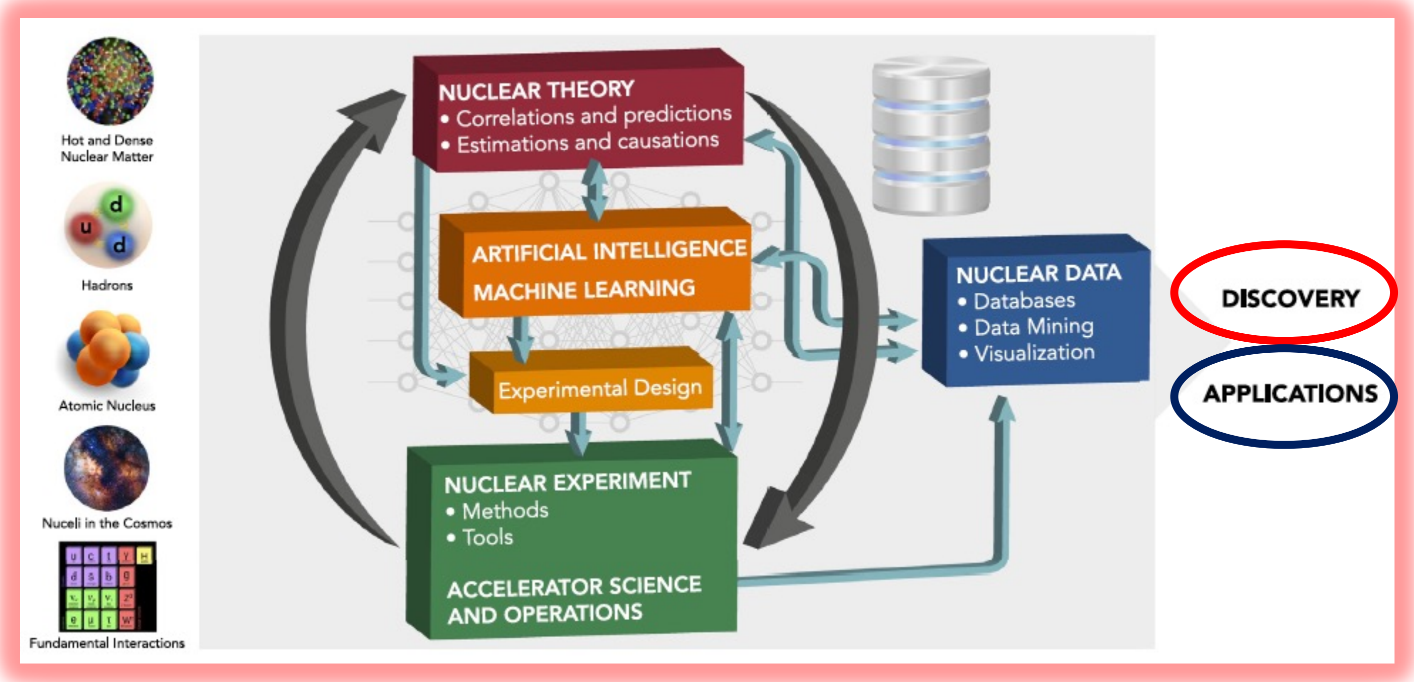
Current nuclear data needs for applications

Karolina Kolos,[1] Vladimir Sobes,[2] Ramona Vogt,[1,3] Catherine E. Romano,[4] Michael S. Smith,[5] Lee A. Bernstein,[6,7] David A. Brown,[8] Mary T. Burkey,[9] Yaron Danon,[10] Mohamed A. Elsawi,[11,12] Bethany L. Goldblum,[6,7] Lawrence H. Heilbronn,[2] Susan L. Hogle,[13] Jesson Hutchinson,[14] Ben Loer,[11] Elizabeth A. McCutchan,[7] Matthew R. Mumpower,[15] Ellen M. O'Brien,[16] Catherine Percher,[17] Patrick N. Peplowski,[18] Jennifer J. Ressler,[9] Nicolas Schunck,[1] Nicholas W. Thompson,[14] Andrew S. Voyles,[6,7] William Wieselquist,[19] and Michael Zerkle[20]

- collaborations within broader ND community in cross-cutting areas - **WANDA** – Workshop for Applied Nuclear Data Activities - yearly meeting since 2018 - input to NDIAWG DOE FOA's

What are the most compelling scientific opportunities over the next decade & their potential scientific impact?

- **Discovery Science:** enhancement of the currency and quality of recommended nuclear data by building a diverse and inclusive workforce **->** propel scientific progress in Nuclear Structure, Reactions and Astrophysics and in other fundamental physics research programs
- **Applications of Nuclear Science:** interagency supported crosscutting opportunities that enrich the utility of nuclear data in both science and society



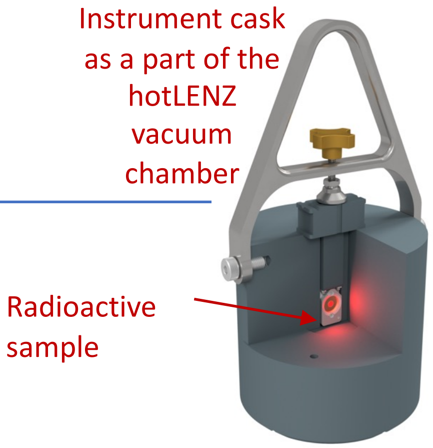
Rev. Mod. Phys. 94 (2022) 031003

Isotope Science

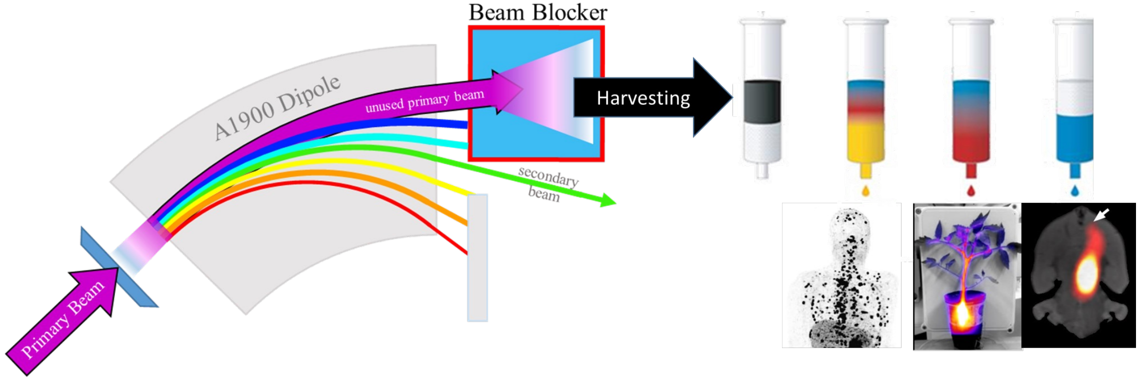
Ani Aprahamian, Jonathan Engle, Jerry Nolen, Greg Severin, Jennifer Shusterman, Etienne Vermeulen, **Sherry Yennello**

Isotope Science

- One session - Six formal presentations and robust discussion
- Similar issues are being faced in Europe
- Inavailability of Russian isotopes

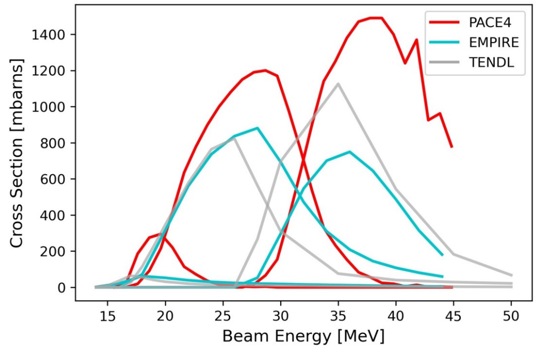


- Isotope Program not part of Nuclear Physics
- Success of Ac-225 for cancer treatment (impact on EDM experiments)
- Production of high specific activity target for NP expt at LANL
- Fabrication of actinide targets @ND
- Isotope Harvesting at NSCL/FRIB
- University Isotope Network

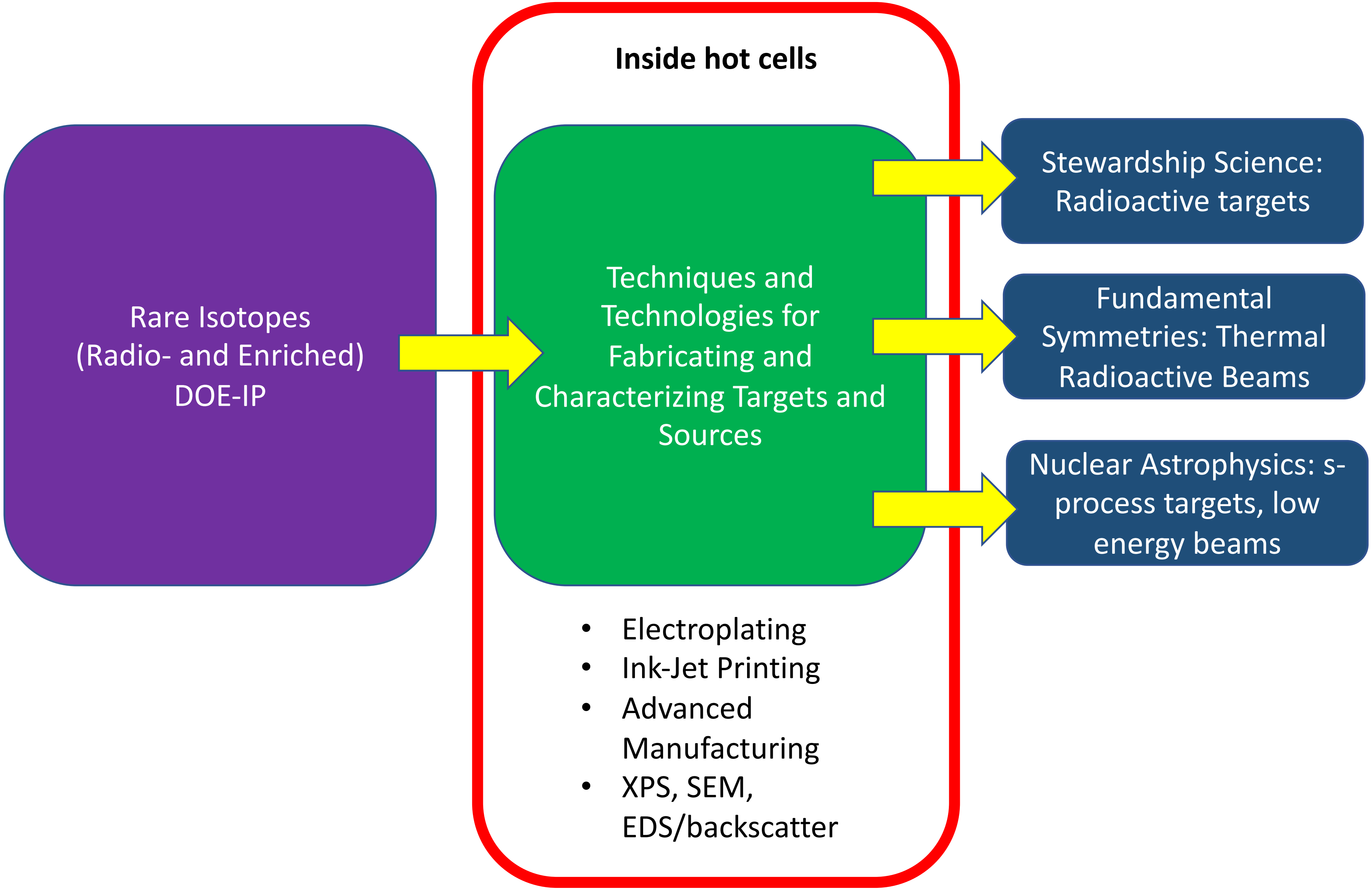


Isotopes enable science ←→ science enables isotopes

- New enabling technologies are needed to be able to provide the isotopes, isotopic beams and isotopic targets for the nuclear physics enterprise



- Improvement of nuclear reaction models
- Workforce development (not just Nuclear Physics PhDs)
- Opportunity for cooperative engagement with other programs that have similar – or overlapping - interests. Isotope Program; NNSA
- Opportunity for cooperation with European colleagues


Inside hot cells
Rare Isotopes
(Radio- and Enriched)
DOE-IP
Techniques and
Technologies for
Fabricating and
Characterizing Targets and
Sources
Electroplating
Ink-Jet Printing
Advanced
Manufacturing
XPS, SEM,
EDS/backscatter
Stewardship Science:
Radioactive targets
Fundamental
Symmetries: Thermal
Radioactive Beams
Nuclear Astrophysics: s-
process targets, low
energy beams

Intersections of low-energy nuclear physics and fundamental symmetries

Max Brodeur, Vincenzo Cirigliano, Alejandro Garcia, **Kyle Leach**, Dan Melconian, Peter Mueller, Saori Pastore, Jaideep Singh, Ragnar Stroberg

Intersections with Fundamental Symmetries

- 1 session – Tuesday morning at 10:30 – 12:30
- 5 invited talks – no contributed (reserved for December Town Hall)
- We were asked to convene a WG session by the NS/NS Town Hall organizers as an interface with the FS community
- Conveners: Max Brodeur (Notre Dame), Vincenzo Cirigliano (UW), Alejandro Garcia (UW), Kyle Leach (Mines/FRIB), Dan Melconian (TAMU), Peter Mueller (ANL), Saori Pastore (Washington U.), Jaideep Singh (FRIB/MSU), Ragnar Stroberg (Notre Dame)
- 35 people attended (18 in-person, 17 online)

What are the overarching scientific challenges? What progress has been made since the last LRP?

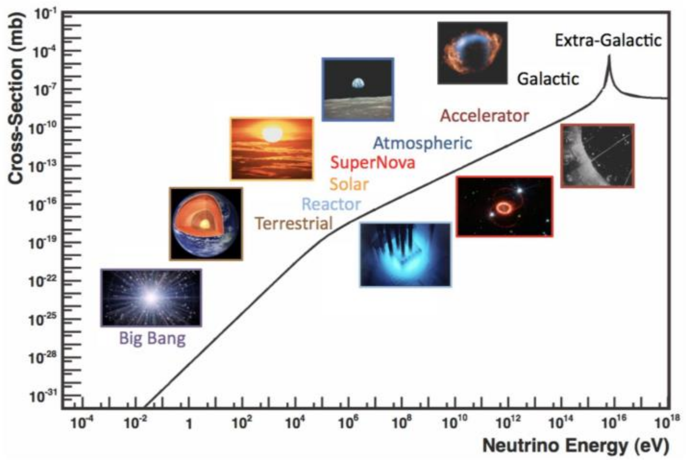
- Largely, this group searches for physics beyond the standard model by testing the underlying assumptions of the fundamental interactions
- Since the last LRP (relevant to the structure community):
  1. Nuclear theory related to FS has made MAJOR strides in several areas including $0\nu\beta\beta$ decay NMEs, neutrino-nucleus scattering, corrections to beta decay in the extraction of Vud (both nuclear and radiative) - especially UQs. (Talks by: *Heiko Hergert and Joe Carlson*)
  2. Atomic and Nuclear structure work towards EDM measurements with atoms and molecules (Talk by: *Ronald Garcia-Ruiz*)
  3. Significant extension of mirror nuclear decay data set and improvement of tensor limits from *A=8* decay (Talk by: *Leendert Hayen*)
  4. Development and implementation of new measurement techniques including CRES, decay ion traps, and superconducting sensors (Talk by: *Dan Melconian*)

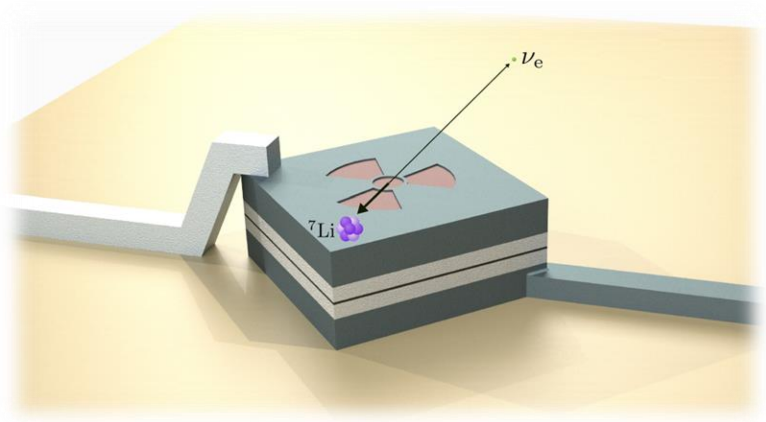
What are the most compelling scientific opportunities over the next decade & their potential scientific impact?

Neutrinos as a gateway to the dark sector

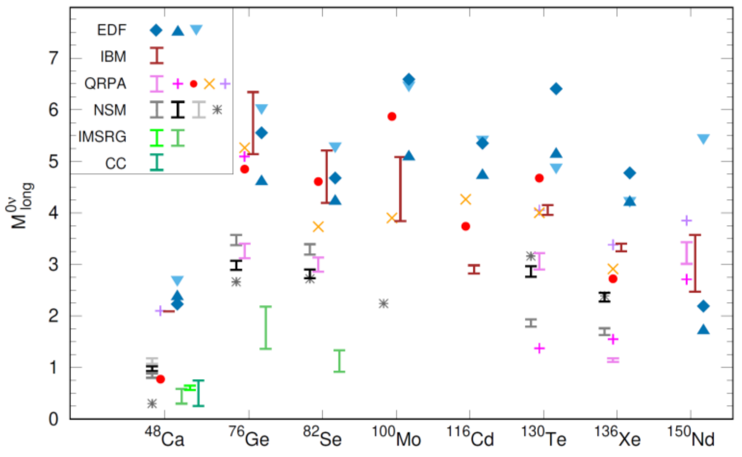
Experiment and Theory

- Direct neutrino mass measurement – ^{3}H (KATRIN, Project-8) and ^{163}Ho (ECHo, HOLMES) decay
- Search for sterile neutrino dark matter – ^{3}H (KATRIN/TRISTAN), ^{7}Be (BeEST), ^{131}Cs (HUNTER), ^{241}Pu (Magneto-ν)
- Tonne-scale neutrinoless double beta decay – ^{76}Ge (LEGEND-1000), ^{100}Mo (CUPID), ^{136}Xe (nEXO)
- Neutrino-nucleus interactions – CP violation, mass hierarchy, astrophysical, CEvNS





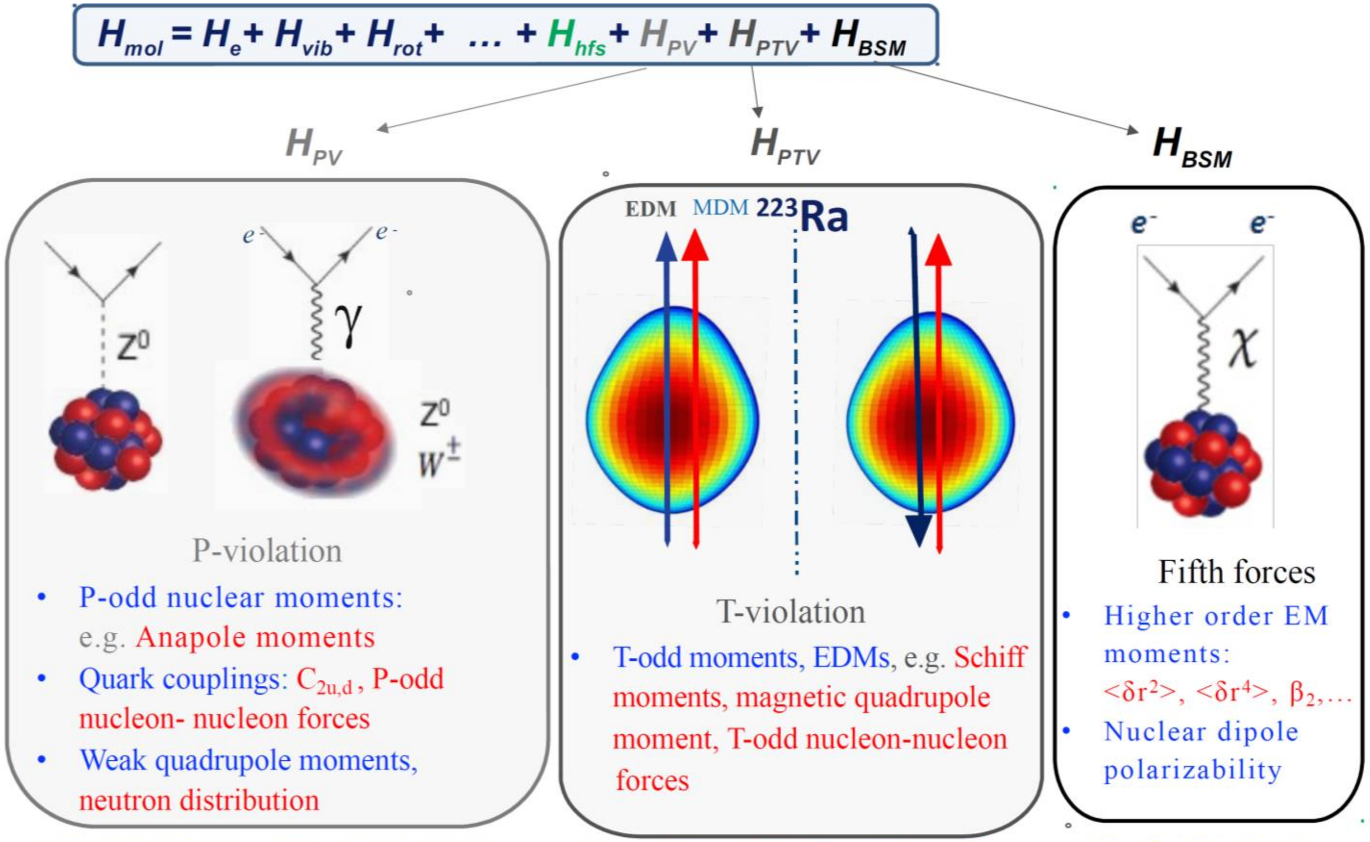
M. Agostini et al., to appear in RMP, arXiv: 2202.01787



What are the most compelling scientific opportunities over the next decade & their potential scientific impact?

Search for EDM and other new physics in heavy atoms and molecules

Nuclear structure experiment & theory provide critical input



Current and planned experiments:

^{29}Si, ^{18,19}F, ^{133}Cs, ^{137}Br, ^{171}Yb, ^{205}Tl, ^{209,210}Fr, ^{223,225}Ra

^{129}Xe, ^{199}Hg, ^{171,173}Yb, ^{205}Tl, ^{181}Ta, ^{223}Fr, ^{223}Rn, ^{223,225}Ra, ^{229}Th, ^{229}Pa

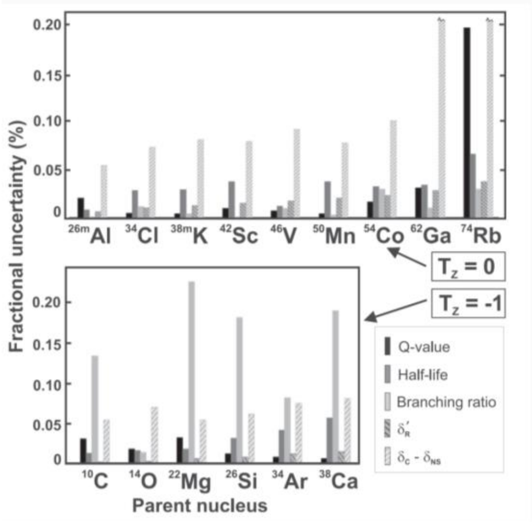
Ca, Sr, Cd, Yb, Ra, …

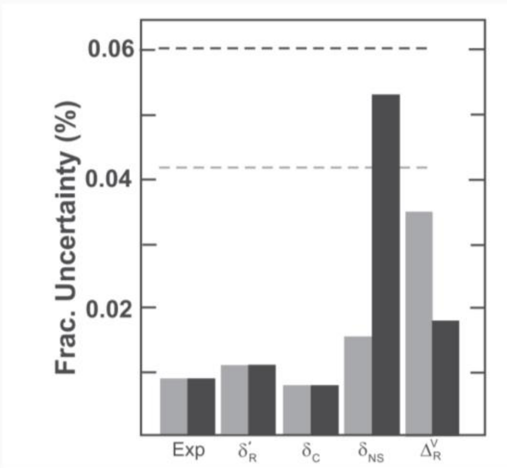
What are the most compelling scientific opportunities over the next decade & their potential scientific impact?

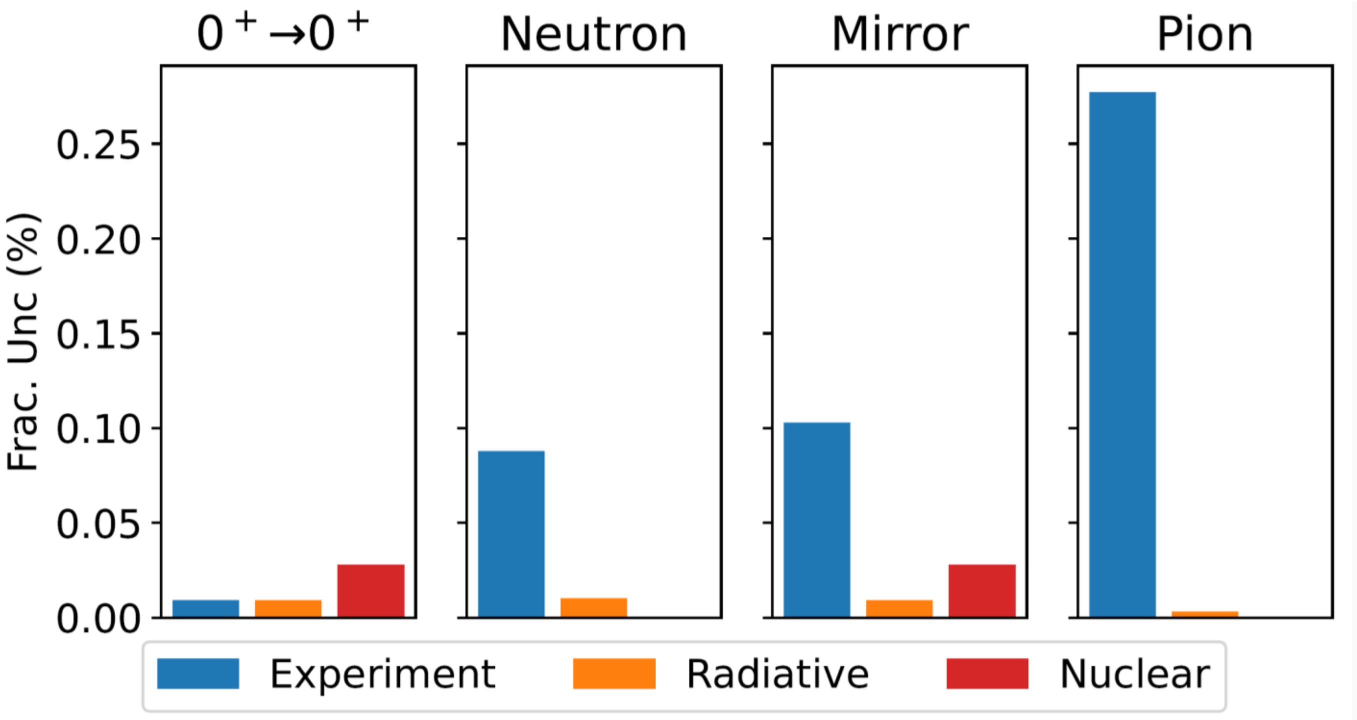
Top-row CKM Unitarity

Experiment and Theory

- Currently a 2-3σ deviation from unity, with higher precision
- Major structure concerns:
  - Isospin symmetry breaking
  - Other nuclear structure corrections
  - ^{10}C and ^{14}O BR measurements







What are the most compelling scientific opportunities over the next decade & their potential scientific impact?

Search for Exotic Weak Currents

Experiment and Theory

New experimental techniques
- CRES
- Superconducting Sensors
- Ion Traps