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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

2010 Decadal Review of Nuclear Physics

An Assessment and Outlook for Nuclear Physics

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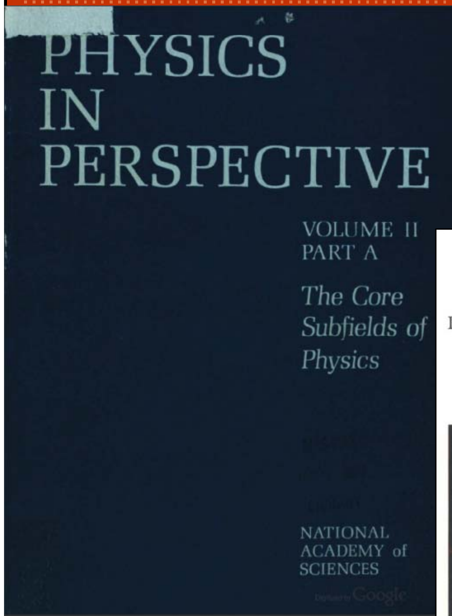
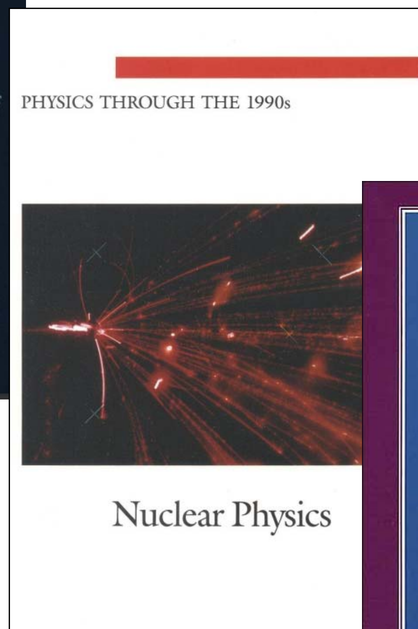
Thomas J. Ruth, TRIUMF
Hendrik Schatz, National Superconducting Cyclotron Laboratory
Robert E. Tribble, Texas A&M University
William A. Zajc, Columbia University

Latest in the Series



1972



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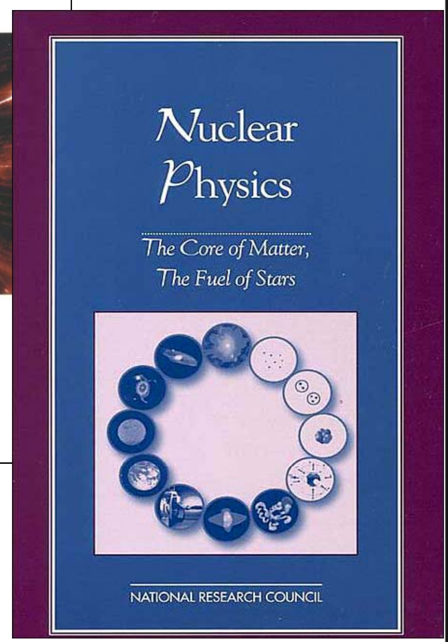
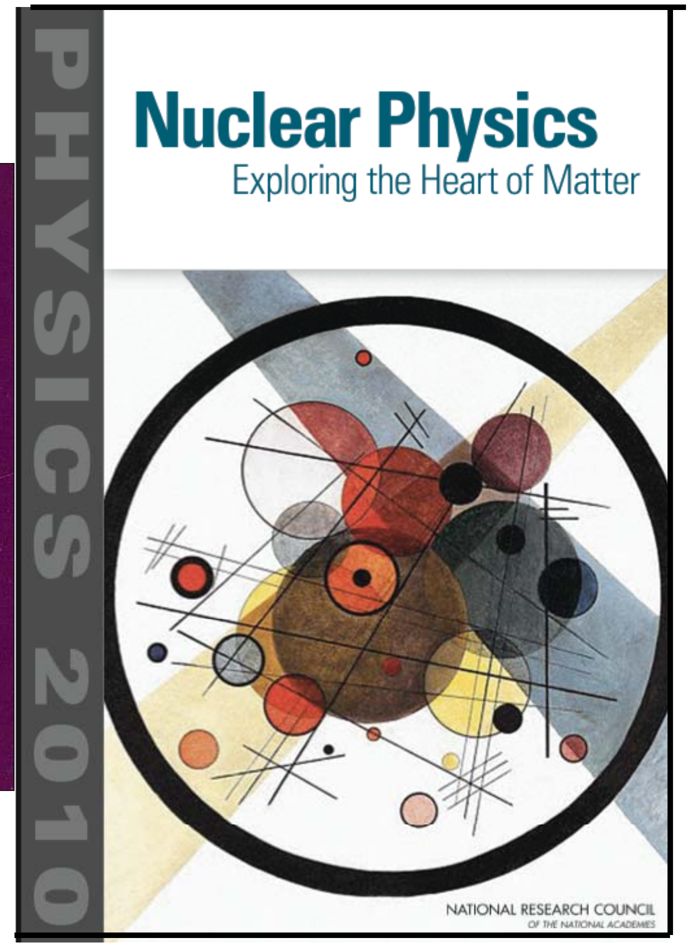


1999



2012

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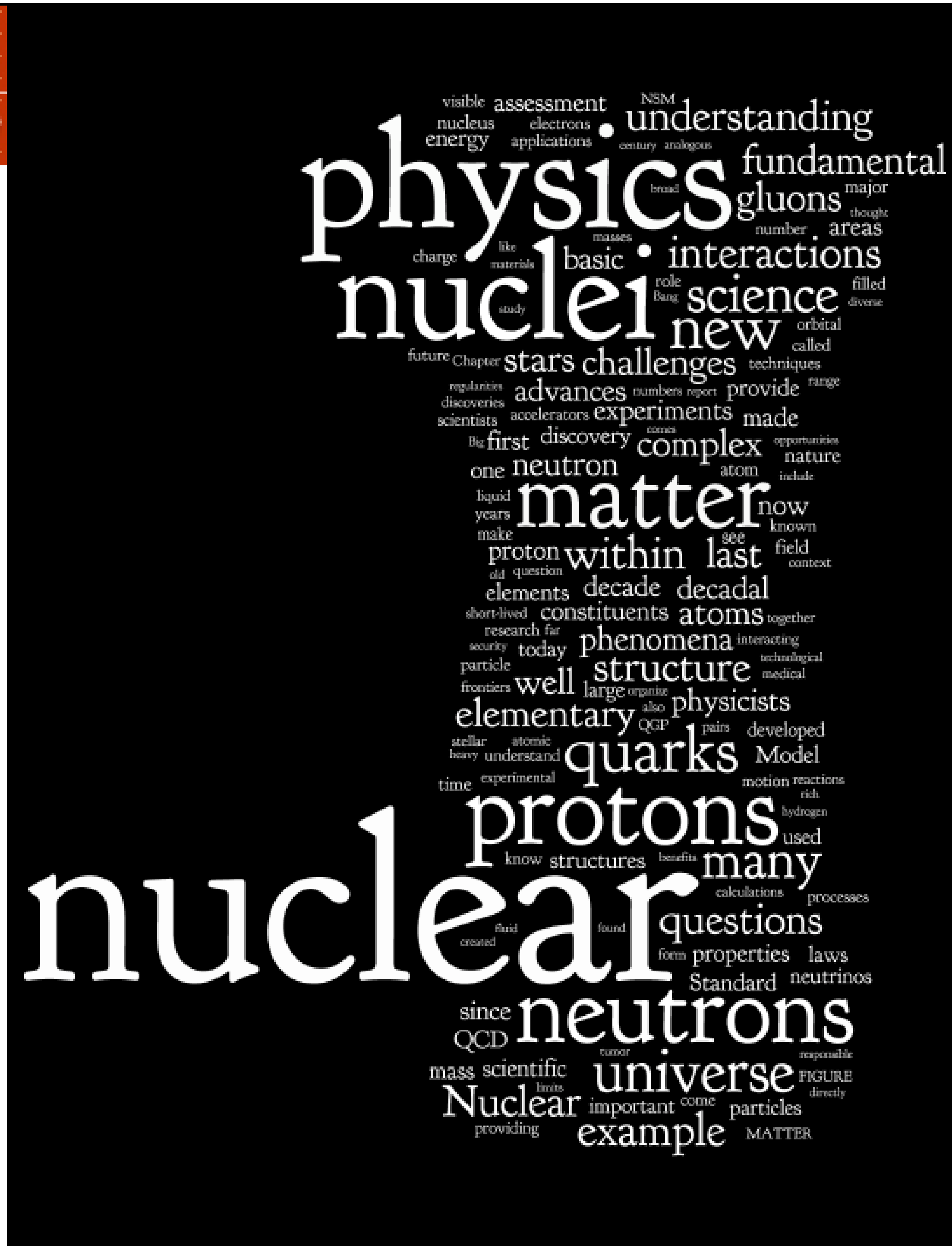
ne future



NP2010 Statement of Task

Statement of Task:

The new 2010 NRC decadal report will prepare an assessment and outlook for nuclear physics research in the United States in the international context. The first phase of the study will focus on developing a clear and compelling articulation of the scientific rationale and objectives of nuclear physics. This phase would build on the 2007 NSAC Long-range Plan Report, placing the near-term goals of that report in a broader national context.

The second phase will put the long-term priorities for the field (in terms of major facilities, research infrastructure, and scientific manpower) into a global context and develop a strategy that can serve as a framework for progress in U.S. nuclear physics through 2020 and beyond. It will discuss opportunities to optimize the partnership between major facilities and the universities in areas such as research productivity and the recruitment of young researchers. It will address the role of international collaboration in leveraging future U.S. investments in nuclear science. The strategy will address means to balance the various objectives of the field in a sustainable manner over the long term.

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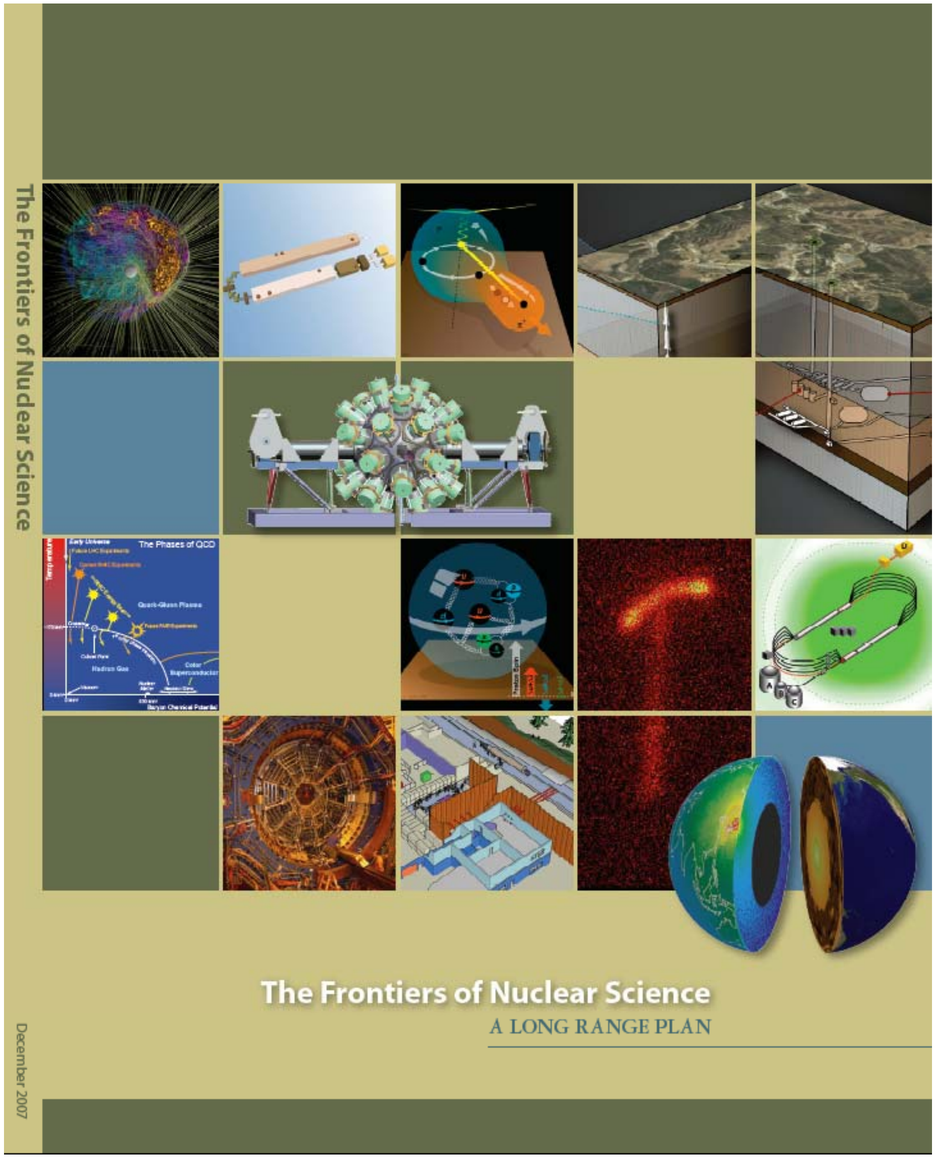
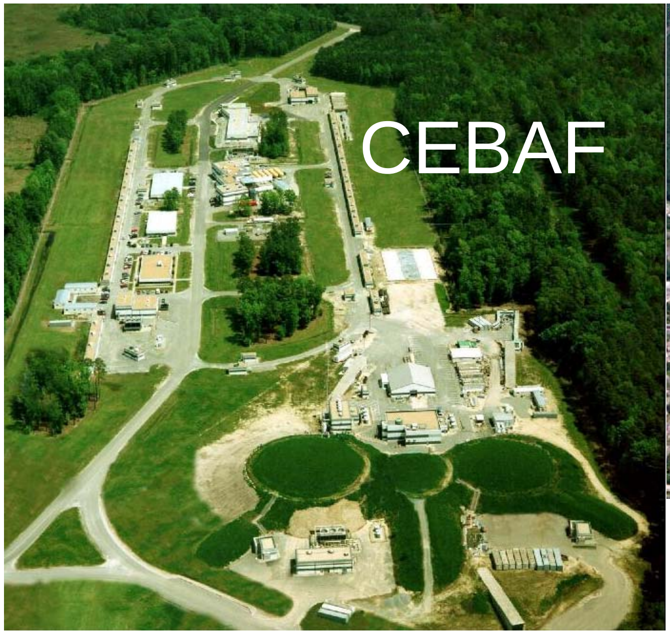
2007 NSAC Long Range Plan

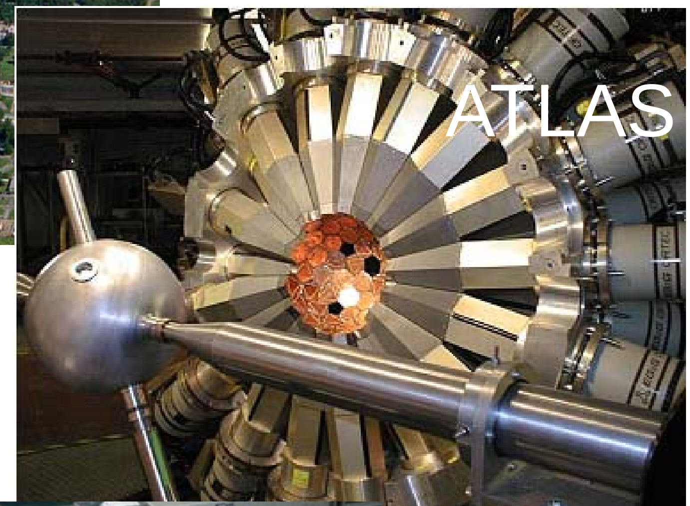


A five year plan organized and formulated by the community through NSAC, advising DOE & NSF on science & development priorities in Nuclear Physics!

- ❑ Selecting organizing & writing committees
- ❑ Town meetings for sub-communities
- ❑ NSAC meeting for entire community
- ❑ Write-up of report
- ❑ Presentation of report to NSAC
- ❑ Presentation of report to agencies

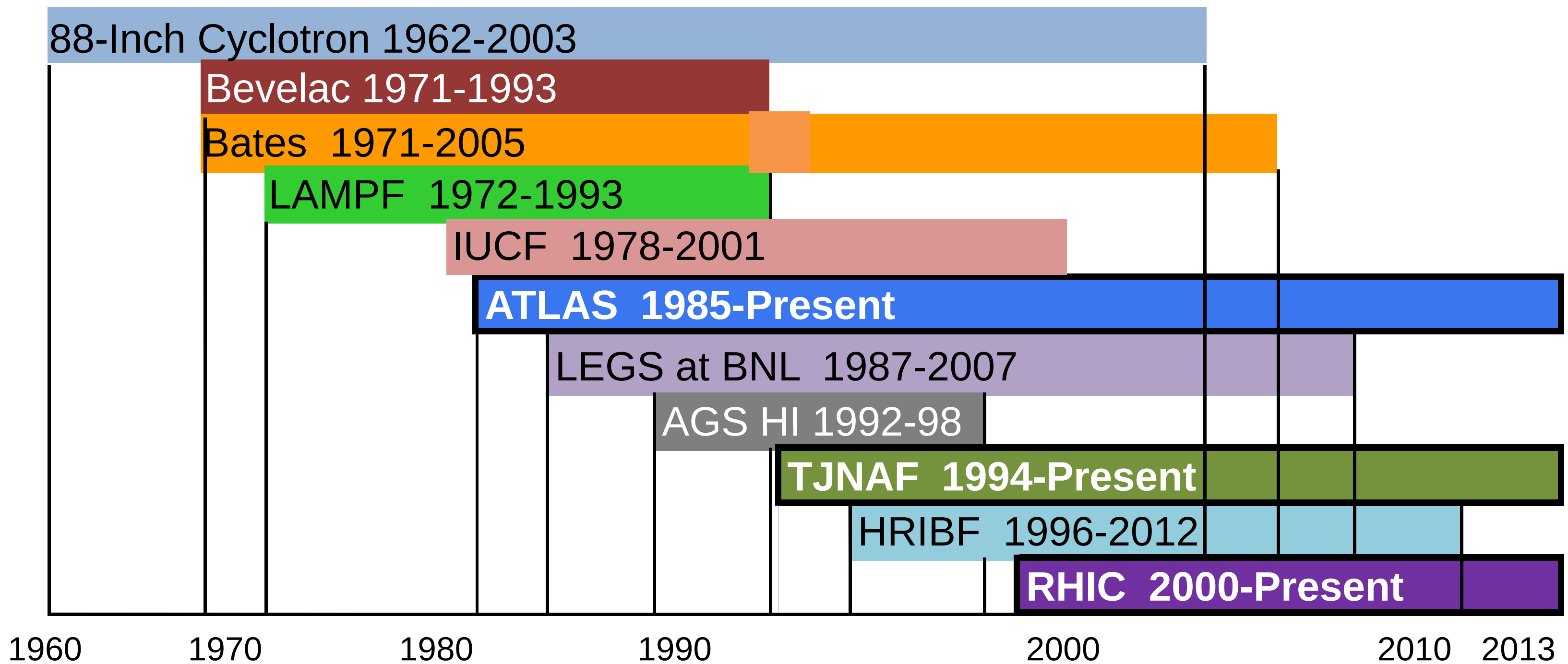
User Facilities





- 4 National User Facilities
- Approximately 40% of users are from foreign institutions
- After completion FRIB will be a major National User Facility

Timeline of Nuclear Physics Facilities



NSCL (NSF)which is still operating is not included in the figure
Other opportunities passed over due to prioritization in the field are not shown: e.g.,LAMPF2, KAON, LISS, ORLAND

The community has envisioned a Facility for Rare Isotope Beams beginning operation near the end of this decade

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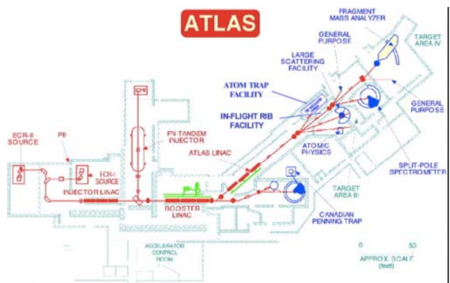
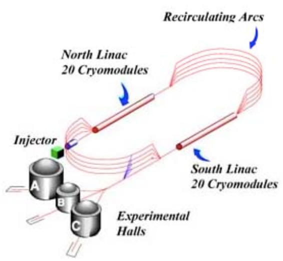
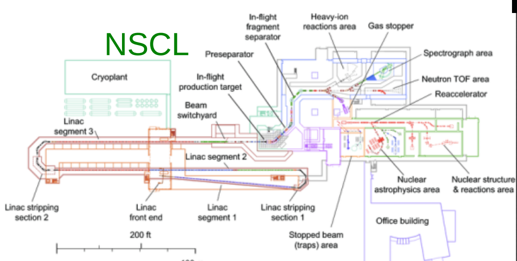
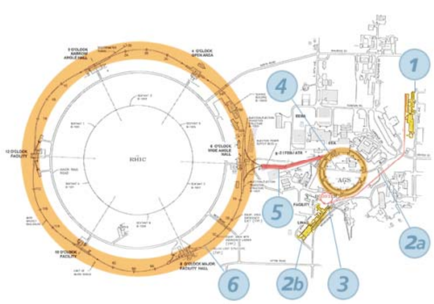


CEBAF



NSCL



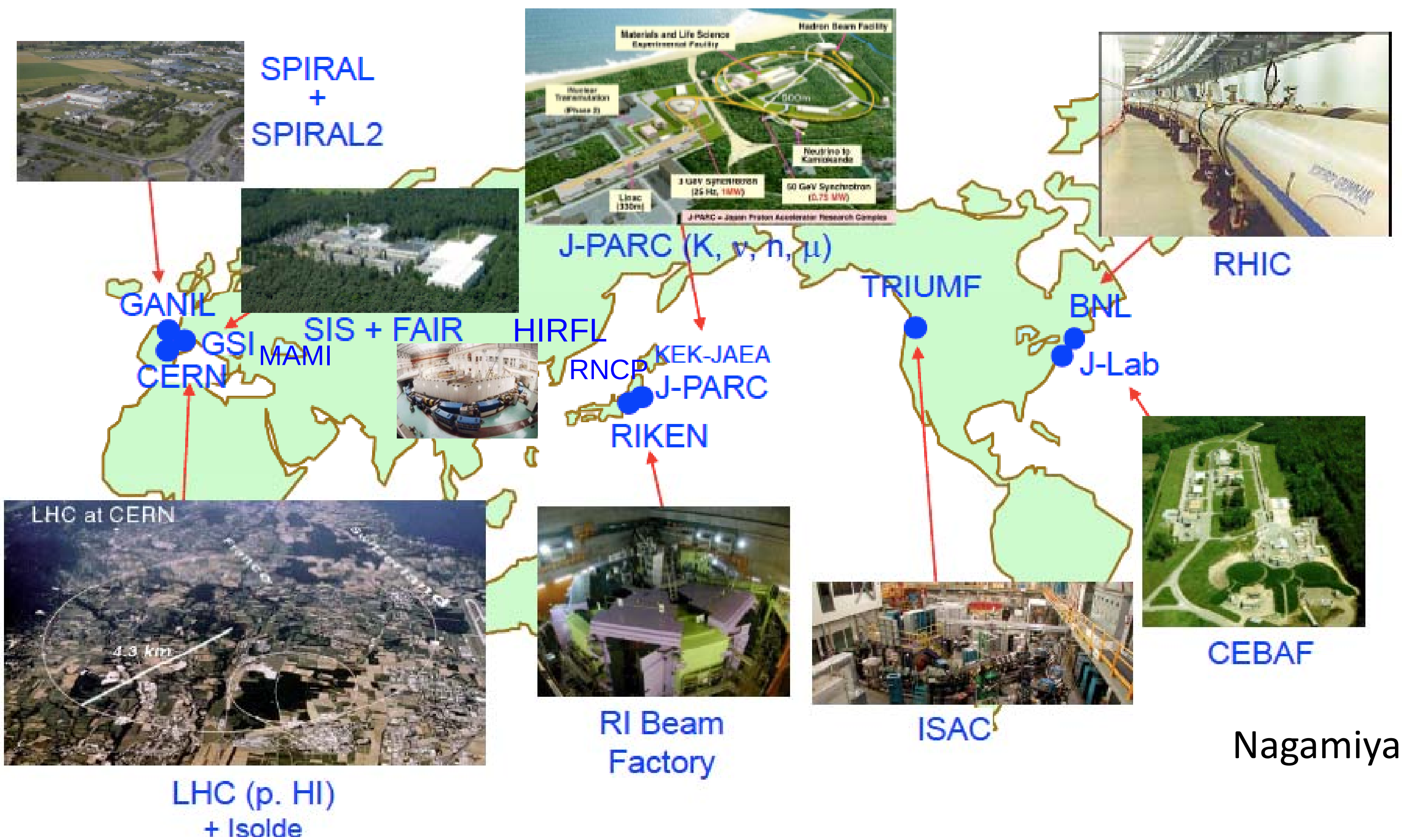


RHIC

Domestic Nuclear Physics Facilities

	Beam Characteristics				
Facility	Species	Energies	Research Areas	Number of Users Per Annum	Future Upgrades
Argonne National Laboratory (ANL) - Argonne Tandem Linear Accelerator System (ATLAS) Argonne, IL	Protons, Heavy Ions $(1 \leq A \leq 238)$, some rare isotope beams	<18 A MeV	Study of atomic nuclei near and far of stability and at high spin, nuclear astrophysics, and fundamental symmetries with stable and radioactive beams. Accelerator Physics.	411	CARIBU facility for stopped and reaccelerated fission products.
Thomas Jefferson National Accelerator Facility (JLab) - Continuous Electron Beam Accelerator Facility (CEBAF) Newport News, VA	Electrons Free-electron laser	1-6 GeV 10kW (IR)	Probe the nucleus to understand quark matter Superconducting radiofrequency (RF) accelerator development	1285	Energy range increase to 12 GeV for better quark matter research Free-electron laser upgrade to 1 kW in the UV range
Michigan State University (MSU) - National Superconducting Cyclotron Laboratory (NSCL) East Lansing, MI	Protons, Heavy Ions $(1 \leq A \leq 238)$, wide range of rare isotope beams	<200 A MeV	Study of atomic nuclei very far from stability, nuclear matter, nuclear astrophysics, and fundamental symmetries with radioactive beams, Accelerator physics.	718	ReA3 and ReA12 facilities for gas stopping and reacceleration of radioactive beams to 3 A MeV and 12 A MeV, respectively. Recoil separators,
Brookhaven National Laboratory - Relativistic Heavy Ion Collider (RHIC) Upton, NY	Heavy Ion collider $(d \leq A \leq Au)$ Proton collider	(maxima) 100 + 100 A GeV (equivalent to fixed target collisions at 21000 A GeV) 250 + 250 GeV	Create, explore and understand matter at extreme temperatures and energy densities governed by QCD. Analyze behavior of gluons, quarks and antiquarks in protons.	922	Increasing RHIC's luminosity. Detector upgrades

Major NP Accelerators in the World



Nagamiya +

Nuclear Physics Program in the U.S.

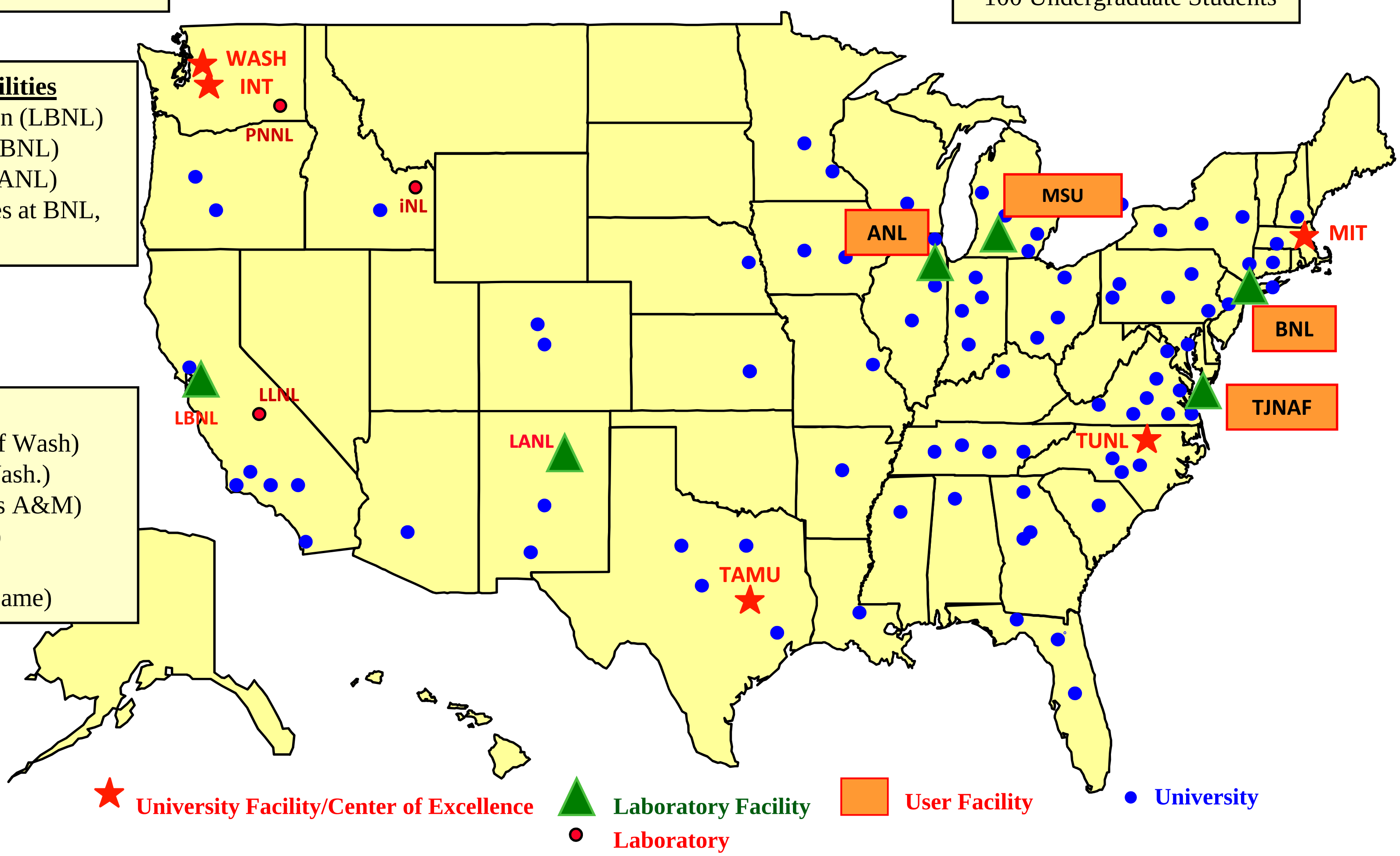
National User Facilities
- RHIC (BNL) - DOE
- CEBAF (TJNAF) - DOE
- ATLAS (ANL) - DOE
- NSCL (MSU) - NSF

Research Groups
- 9 National Laboratories
- 85 Universities

NP Workforce
~720 Faculty & Lab Res Staff
~400 Post-docs
~500 Graduate Students
~100 Undergraduate Students

Other Lab. Facilities
- 88-Inch Cyclotron (LBNL)
- 200 MeV BLIP (BNL)
- 100 MeV IPF (LANL)
- Hot Cell Facilities at BNL, LANL, ORNL

Centers
- CENPA (U. of Wash)
- INT (U. of Wash.)
- TAMU (Texas A&M)
- TUNL (Duke)
- REC (MIT)
- JINA (Notre Dame) (NSF)



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US University Laboratories

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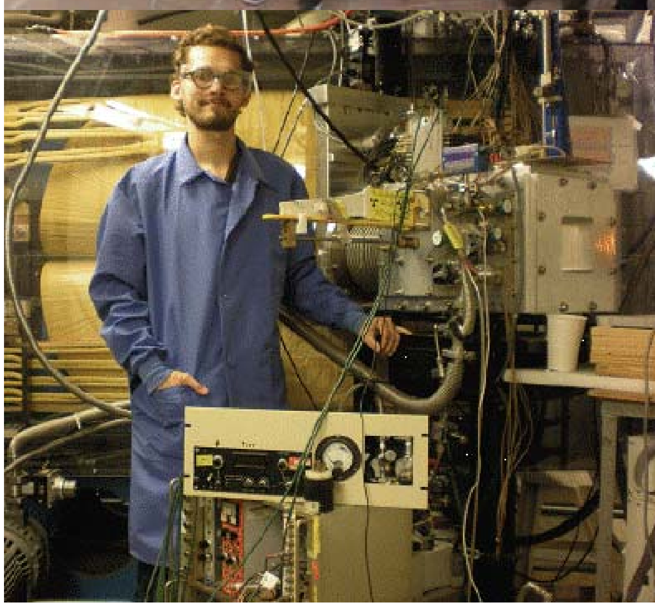
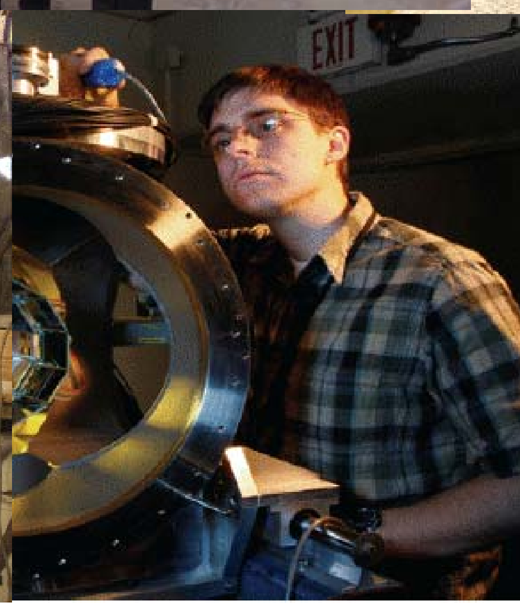
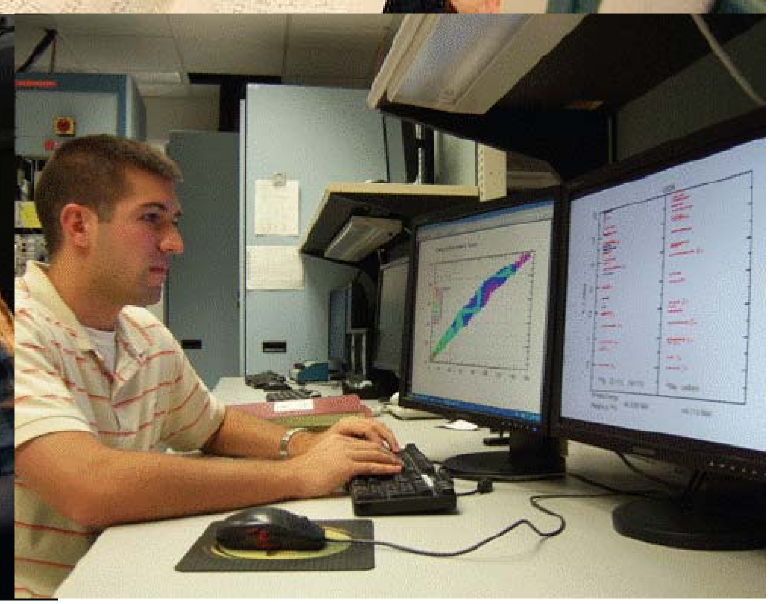
Building the next generation of Nuclear Physicists

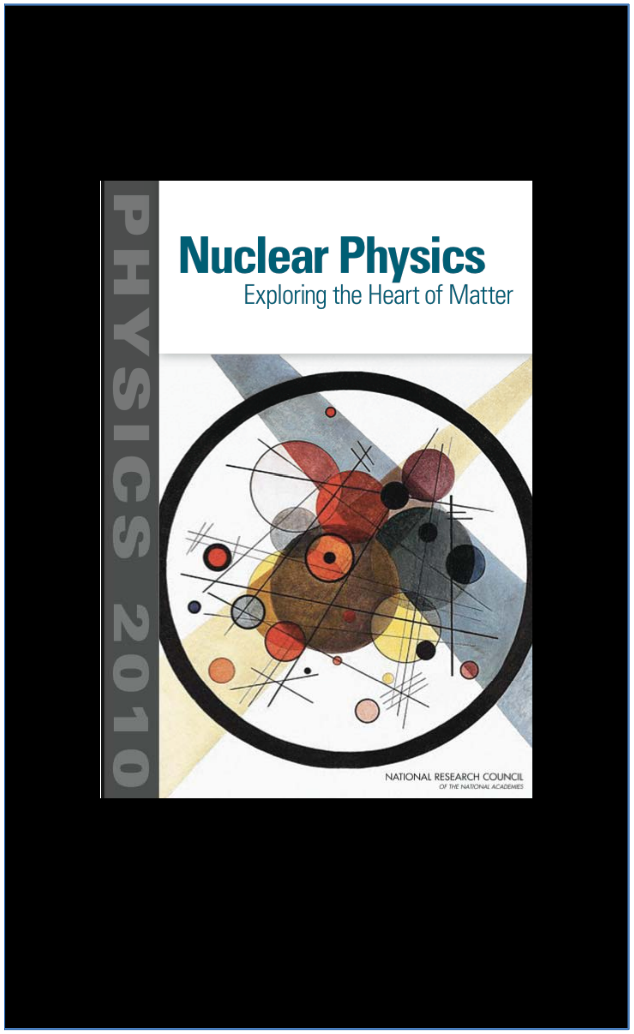


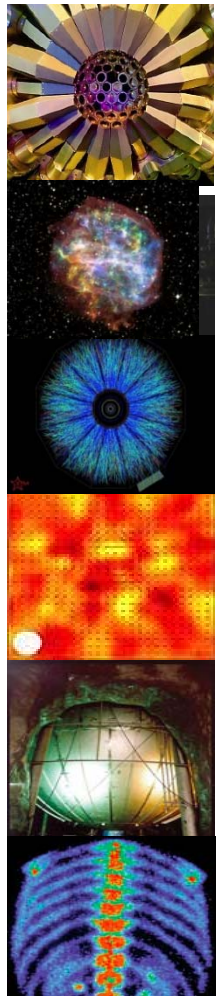




Chapter 2, Science Topics

Exploring the Heart of Matter



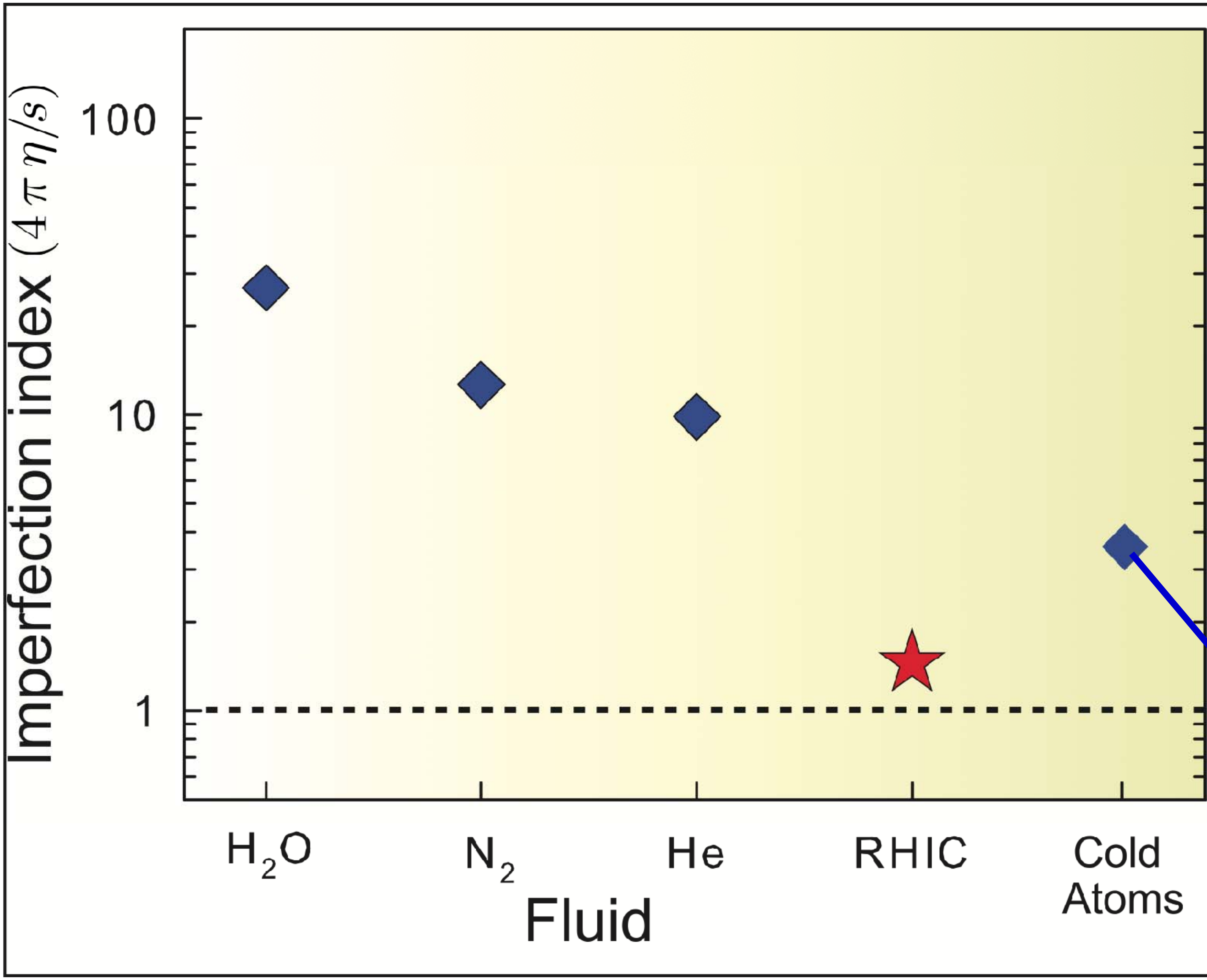


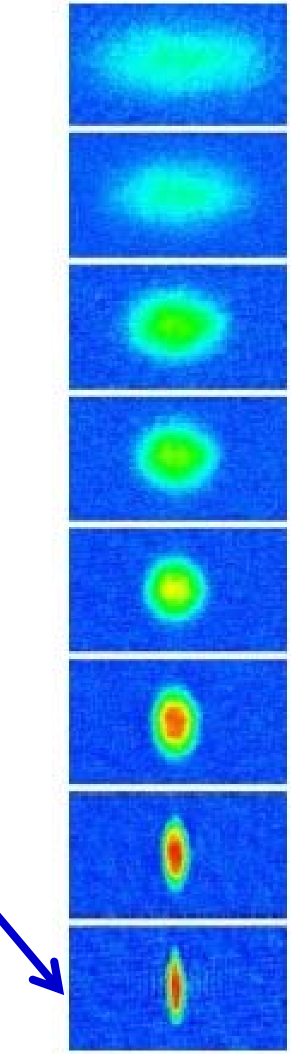
- Structure of Atomic Nuclei
- Nuclear Astrophysics
- Quark Gluon Plasma
- Quark Structure of the Nucleon
- Fundamental Symmetries
- Nuclear Physics Applications

Major Accomplishments Since 1999

- Discovery of a near perfect fluid in relativistic heavy-ion collisions at RHIC
- Precision determination of the electric and magnetic form factors of the proton and neutron at Jlab
- Final resolution of the Solar Neutrino Problem, Neutrino Mass and Mixing

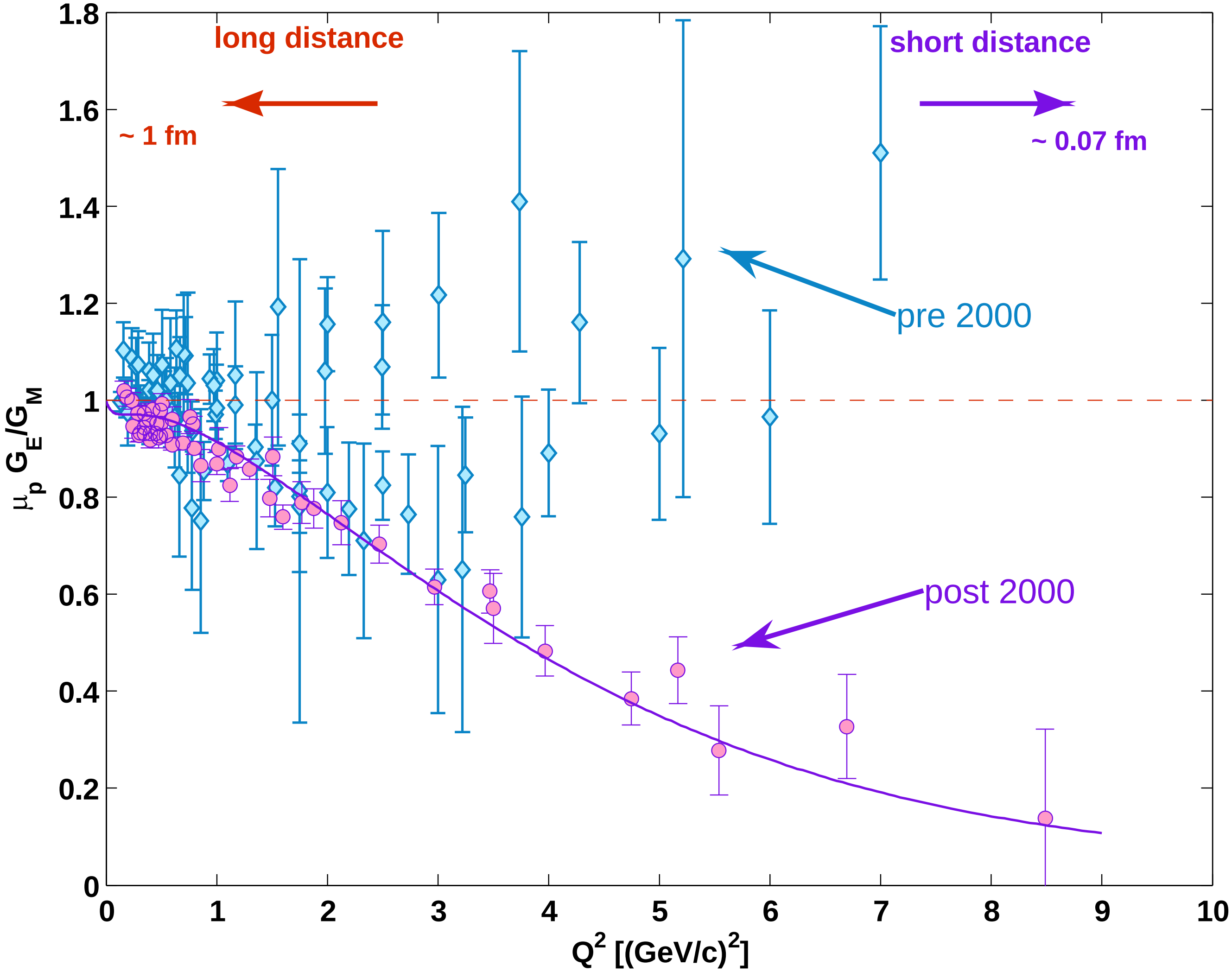
Quantifying Perfection





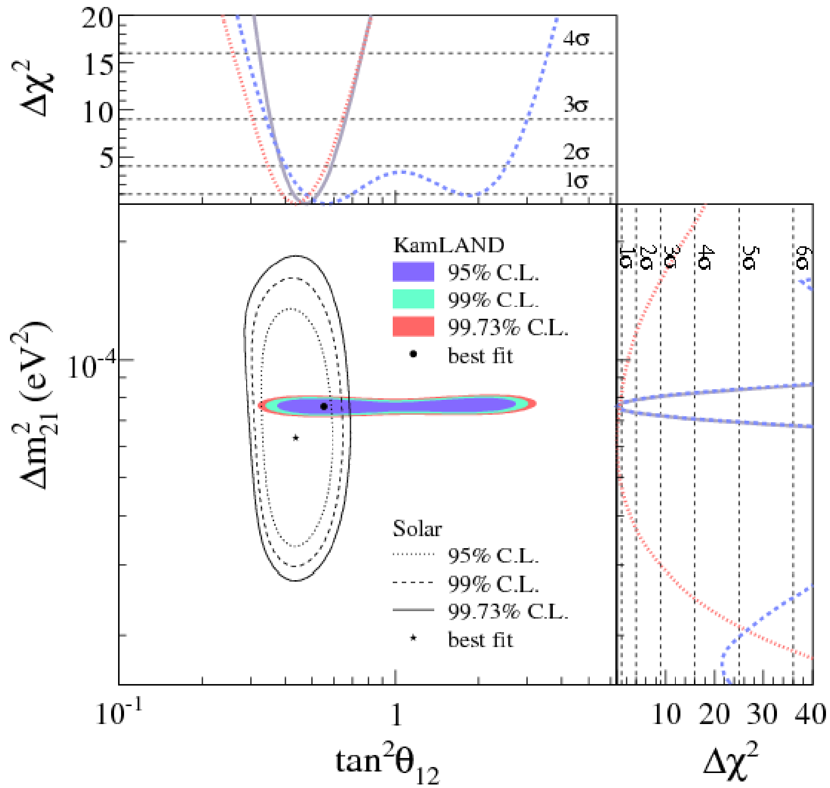
Bill Zajc

NP2010 Committee

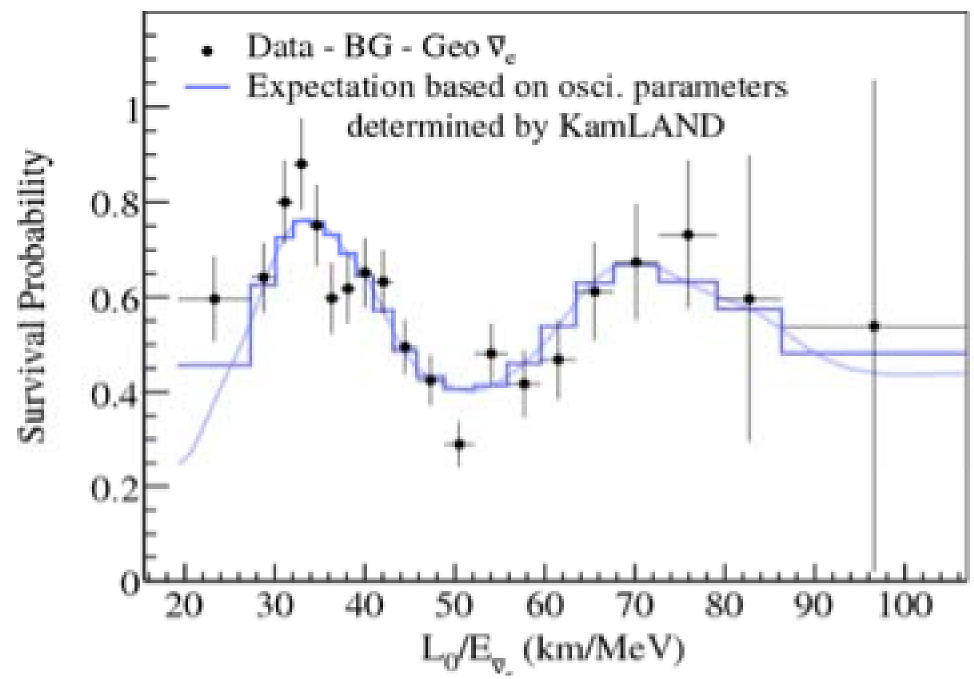


Magnetic and Electric distribution of charge is different in the proton

Solar Neutrino Problem Solved
Neutrino Oscillations Established



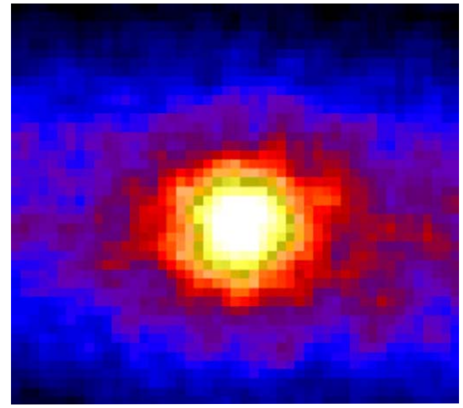
Constraints on neutrino oscillation parameters from SNO and KamLAND

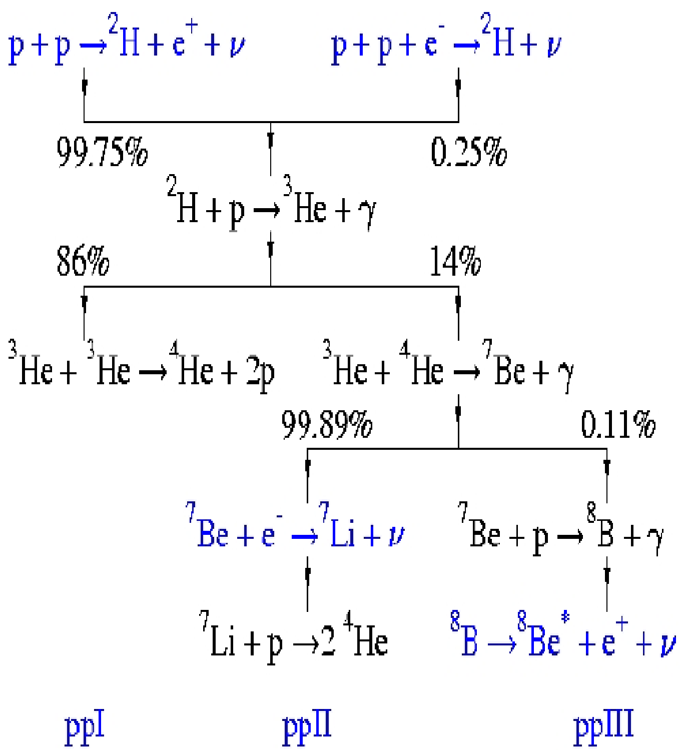


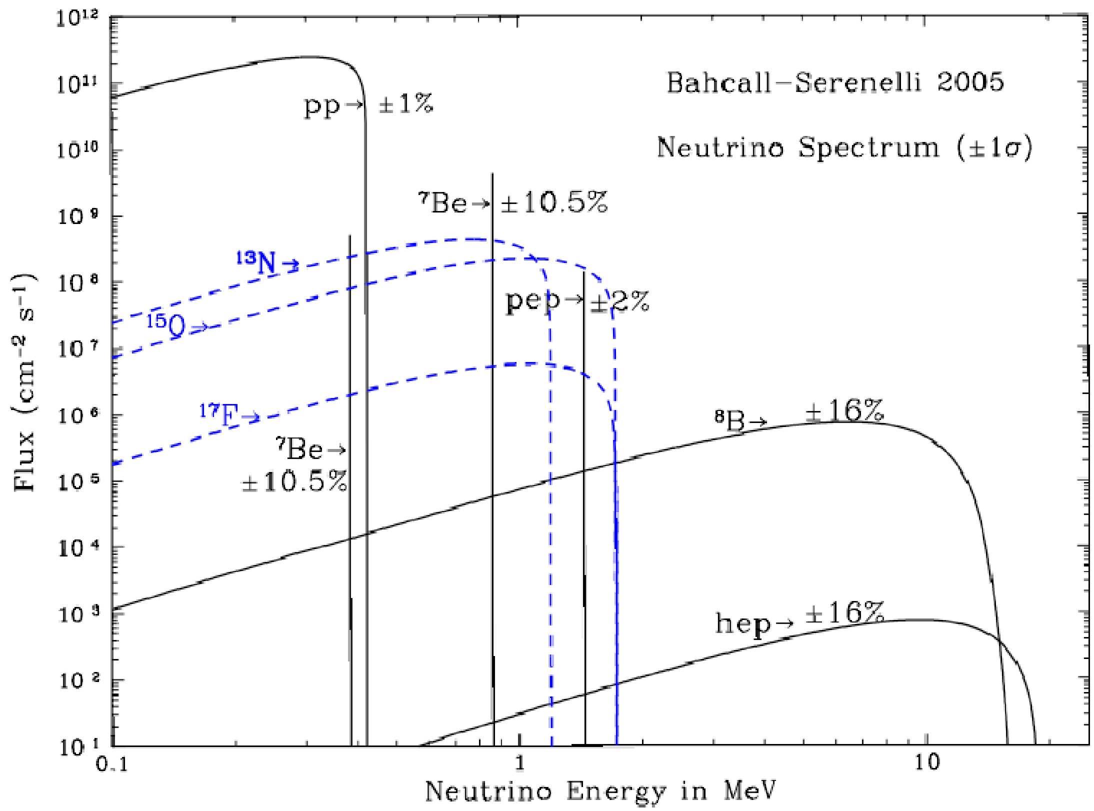
“Direct” observation of neutrino oscillations from KamLAND

Understanding Solar Neutrinos

Major Accomplishment of
Nuclear Astrophysics

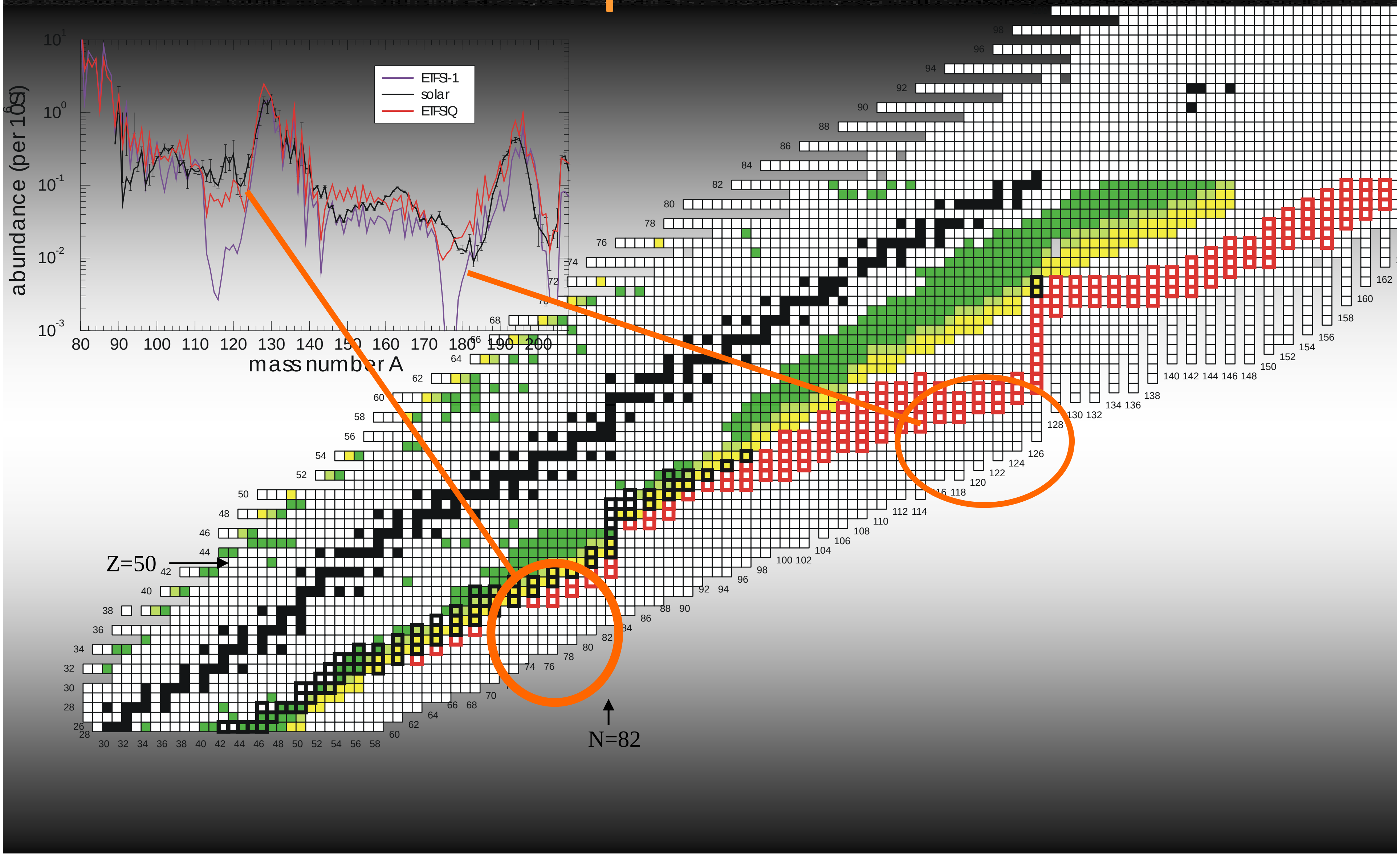






Progress in Nuclear Structure and Nuclear Astrophsics toward Understanding the Origin of the Elements

r-process



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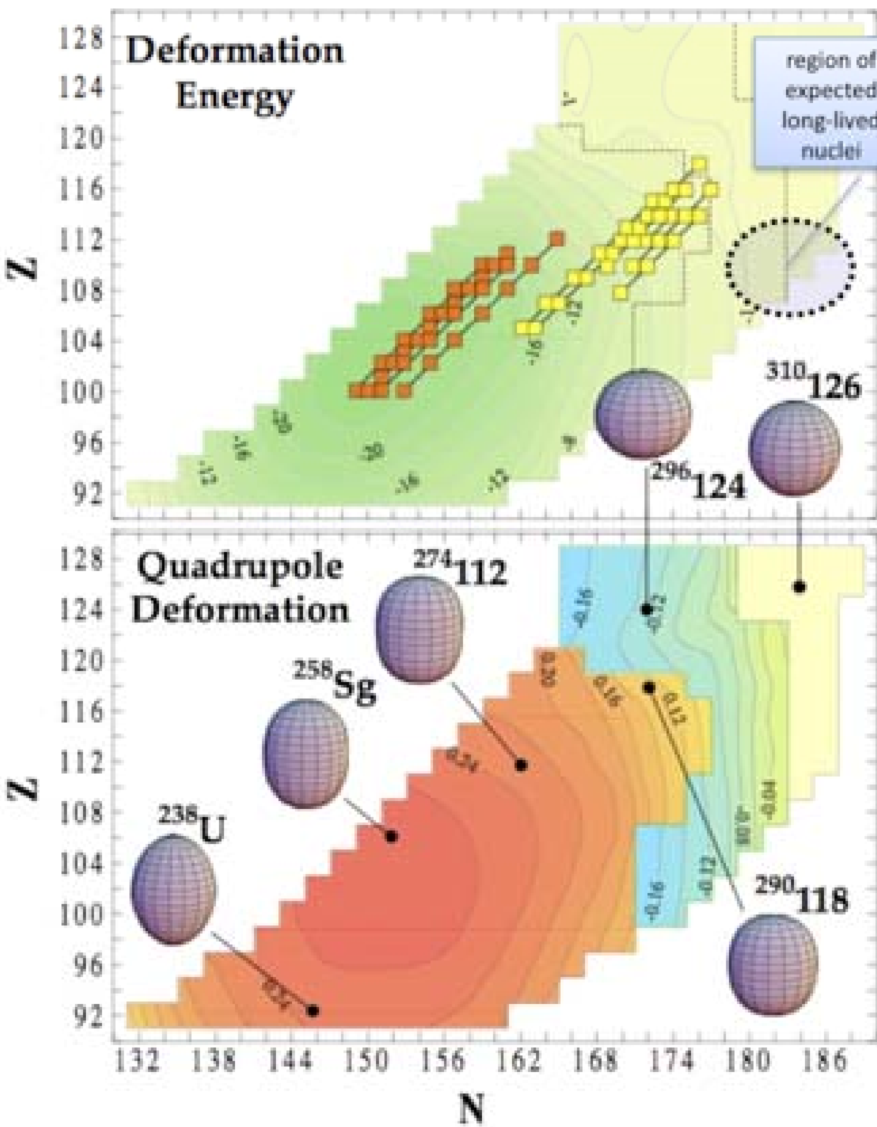
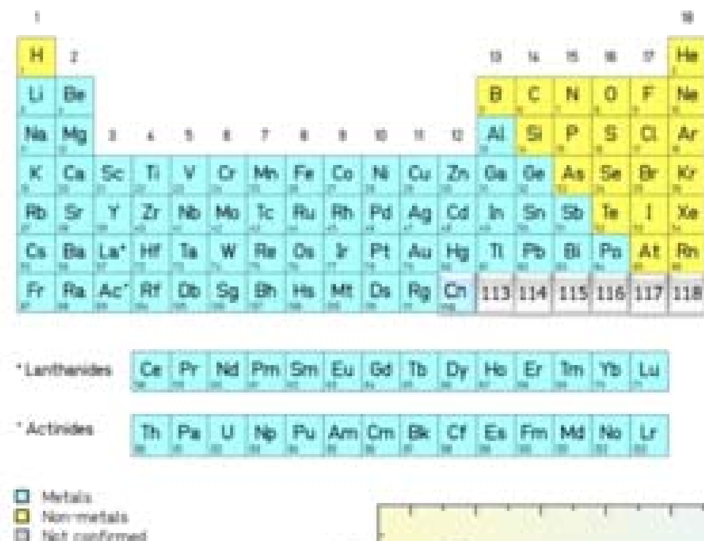
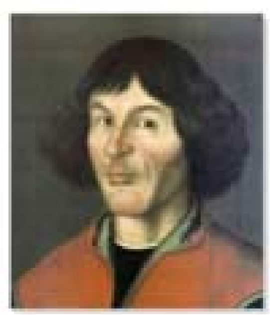
Physics of Superheavy Elements



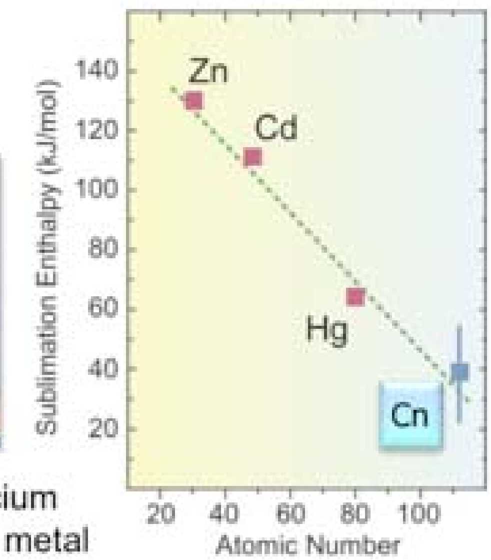
Chemistry of Superheavy Elements

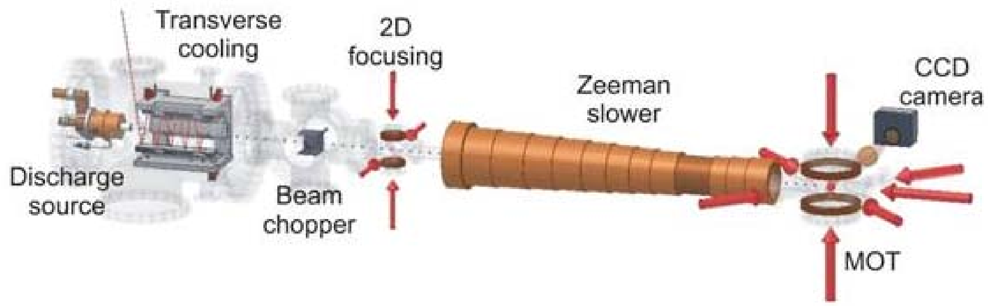
Periodic Table of Elements 2010



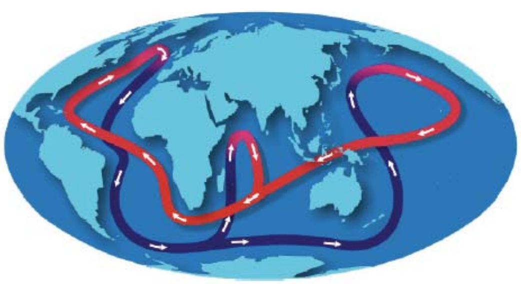


Z=112: Copernicium
very volatile noble metal

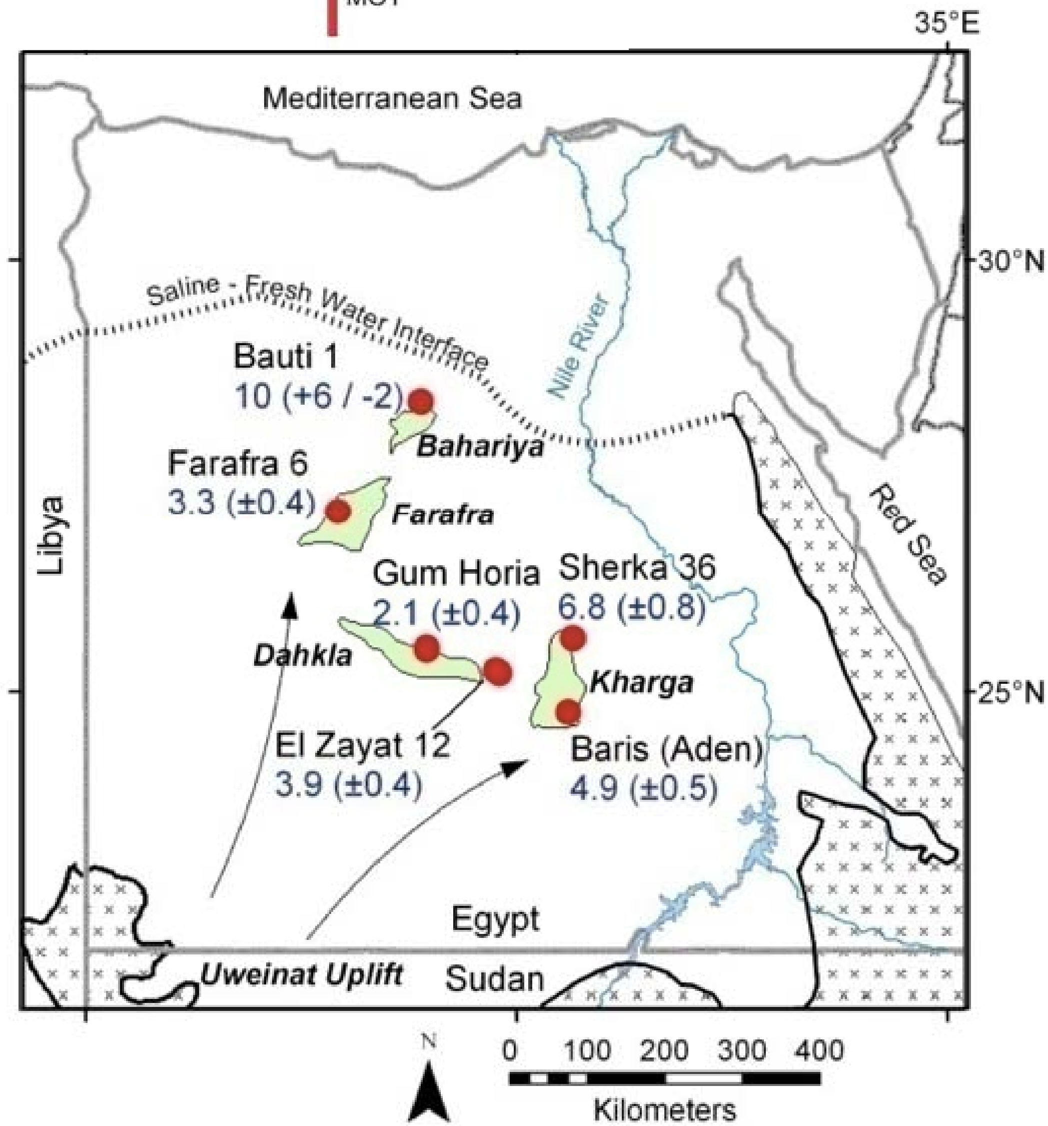




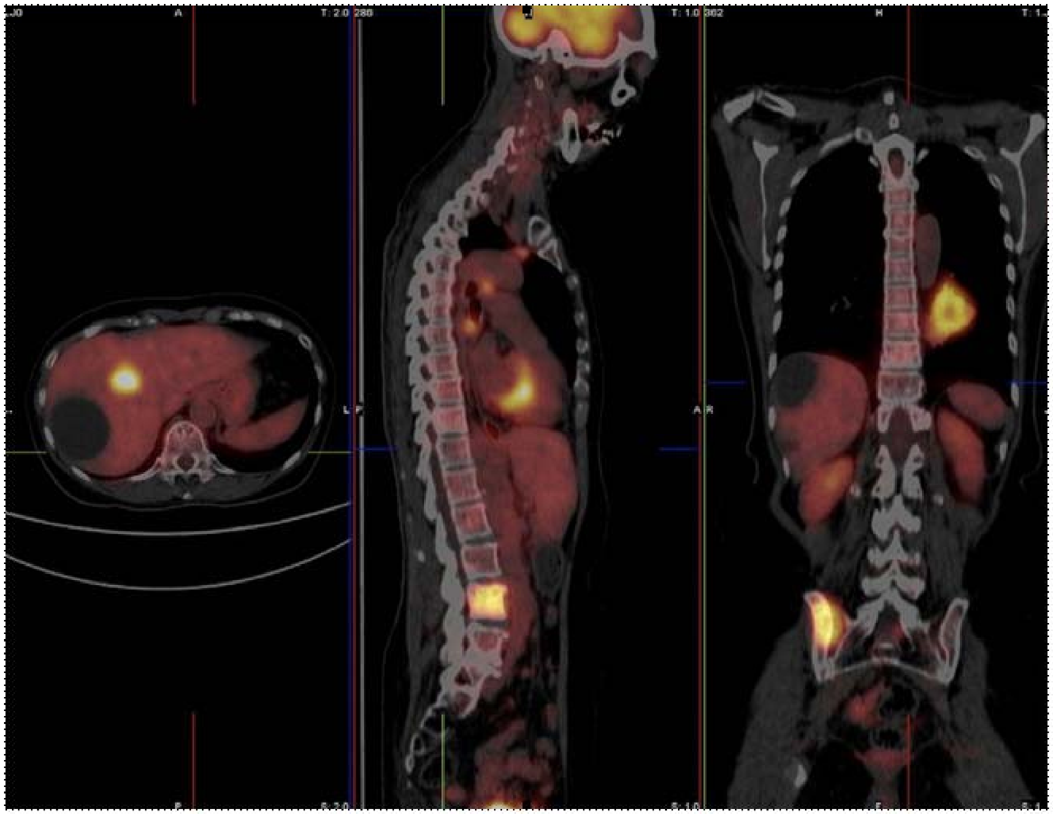
New techniques for trace element analysis with single trapped atoms

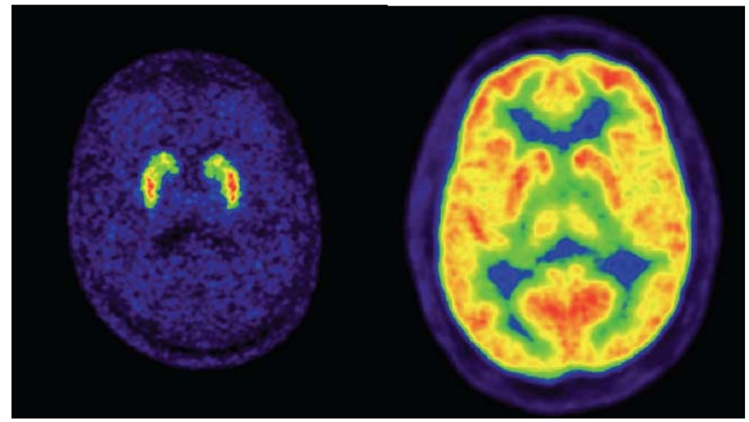


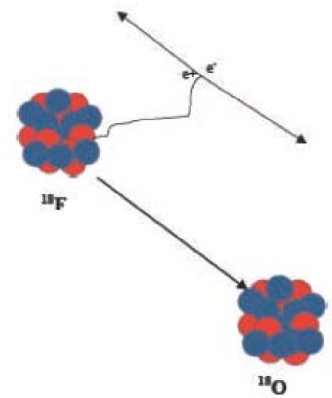
^{39}Ar



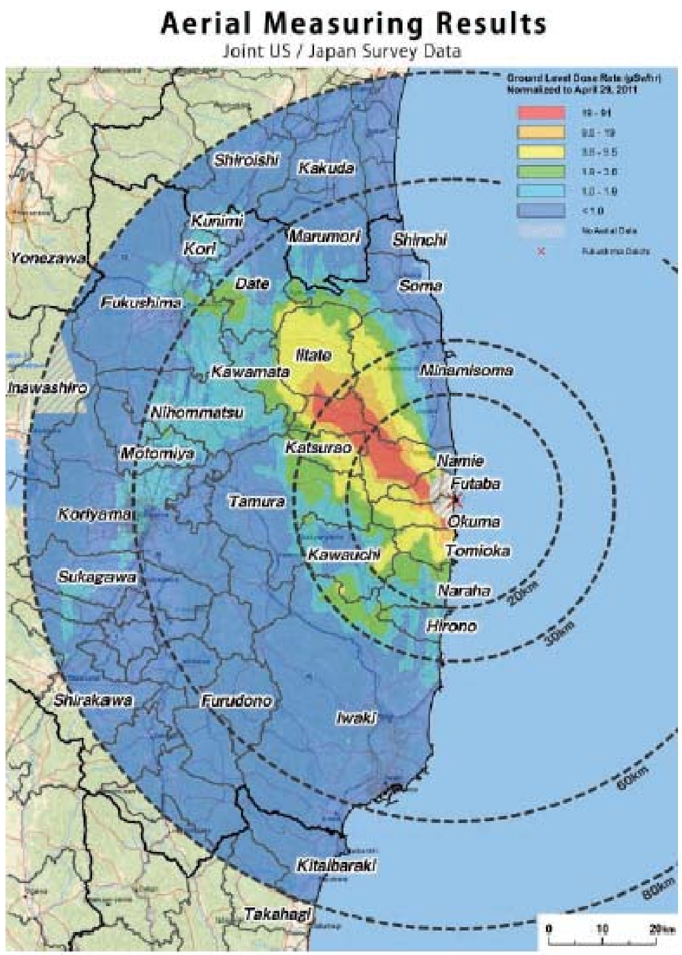
New and improved imagining techniques

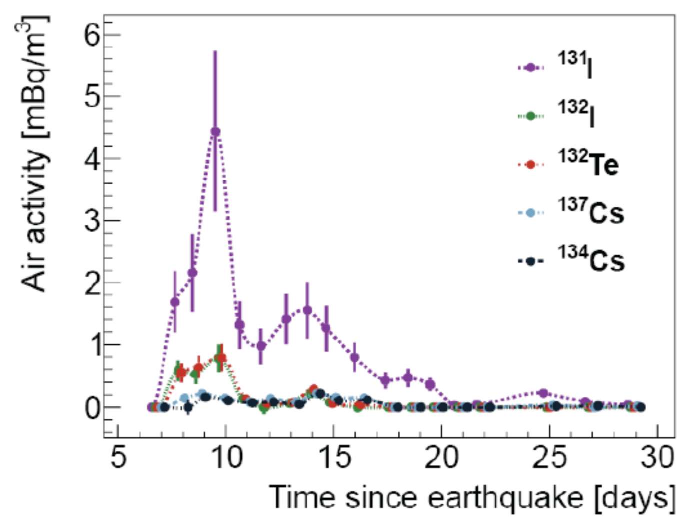






Capabilities in Place to Respond to International Emergencies





Statement of Task

- **What are the scientific rationale and objectives of nuclear physics?**

- **Develop a long term strategy for US nuclear physics into 2020 in the global context.**

    - Place the near term goals of the 2007 LRP in a broader national context.
    - Discuss the strategy to optimize the partnership between facilities and universities.
    - Address the role of international collaboration in leveraging future US investments.

2007 Long Range Plan

RECOMMENDATION I

We recommend completion of the 12 GeV CEBAF Upgrade at Jefferson Lab. The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of nuclei, and the nature of confinement.

RECOMMENDATION II

We recommend construction of the Facility for Rare Isotope Beams (FRIB), a world-leading facility for the study of nuclear structure, reactions, and astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, provide an understanding of matter in the crust of neutron stars, and establish the scientific foundation for innovative applications of nuclear science to society.

RECOMMENDATION III

We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet-unseen violations of time-reversal symmetry, and other key ingredients of the New Standard Model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to U.S. leadership in core aspects of this initiative.

RECOMMENDATION IV

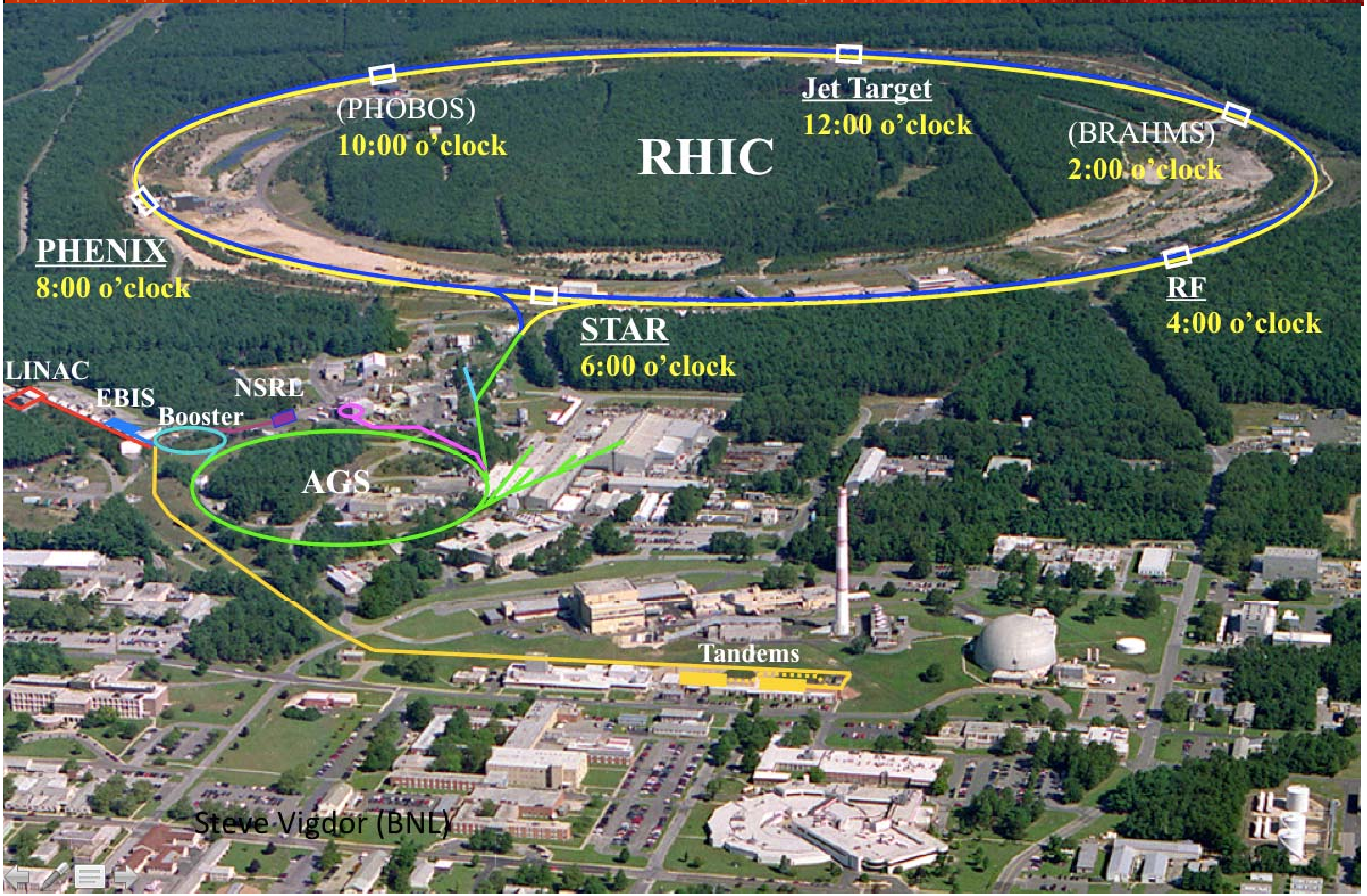
The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density—a quark-gluon plasma that exhibits unexpected, almost perfect liquid dynamical behavior. We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.

Exploitation of current opportunities

Finding: By capitalizing on strategic investments, including the ongoing upgrade of CEBAF and the recently completed upgrade of RHIC, as well as other upgrades to the research infrastructure, nuclear physicists will confront new opportunities to make fundamental discoveries and lay the groundwork for new applications.

Conclusion: Exploiting strategic investments should be an essential component of the U.S. nuclear science program in the coming decade.

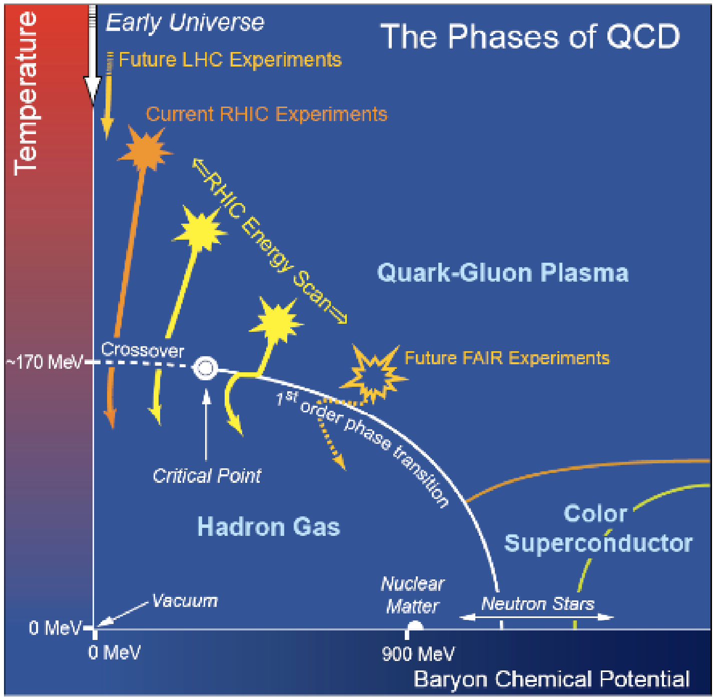
RHIC

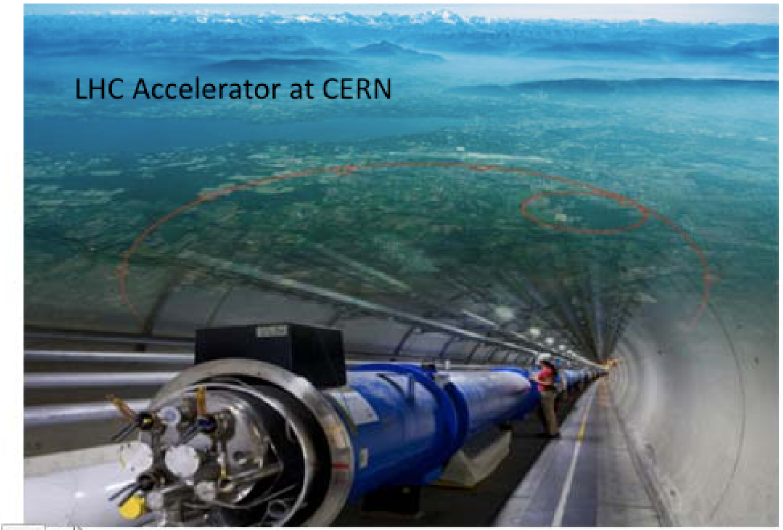


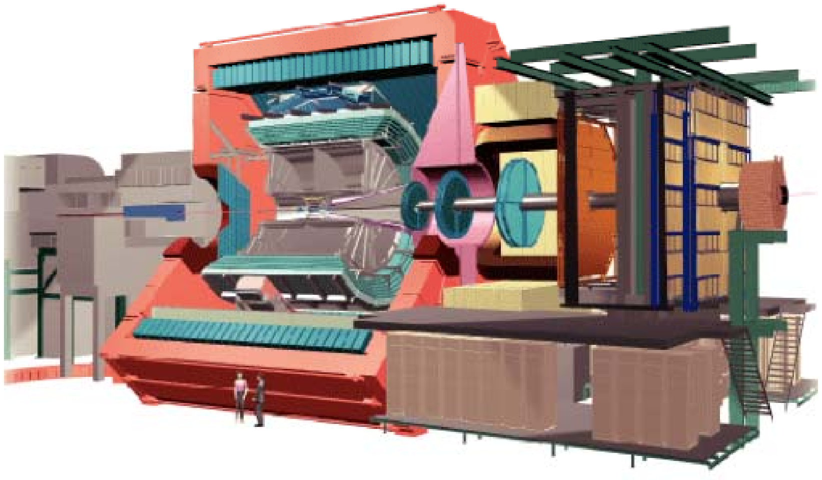
Steve Vigdor (BNL)

NP2010 Committee

- Up-grade of PHENIX & STAR
- Increase of RHIC luminosity
- US participation in heavy ion program at LHC at CERN with the detectors ALICE
- Relativistic heavy ion beam experiments at FAIR/GSI







Thomas Jefferson Laboratory

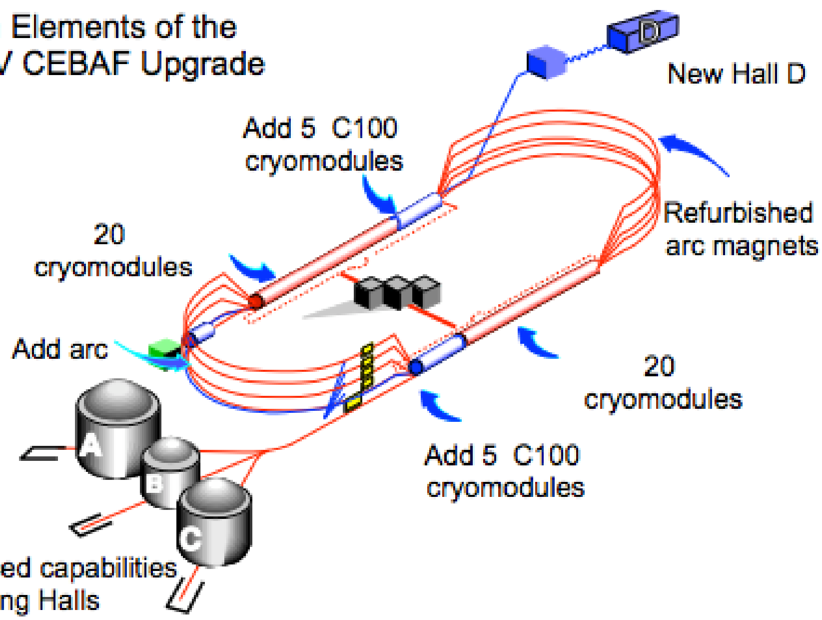
The JLaB 12 GeV Up-Grade

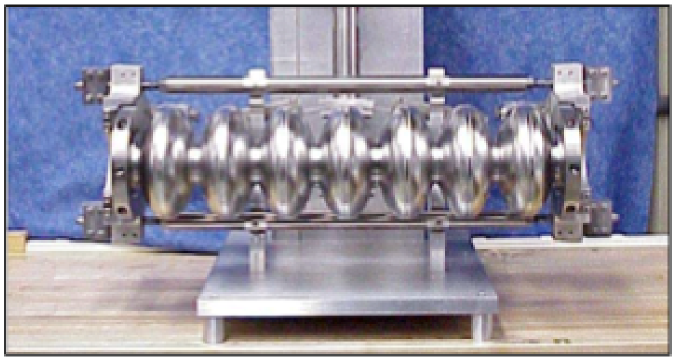
The 12 GeV CEBAF Upgrade at TJNAF is 60% Complete

The 12 GeV CEBAF Upgrade will enable world-leading research on:

- The search for exotic new quark-anti-quark particles to advance our understanding of the strong force
- Evidence of new physics from sensitive searches for violations of nature's fundamental symmetries
- A detailed microscopic understanding of the internal structure of the proton, including the origin of its spin, and how this structure is modified when the proton is inside a nucleus

Main Elements of the
12 GeV CEBAF Upgrade





A photograph of one of the superconducting radio frequency (SRF) cavities developed and constructed at Thomas Jefferson National Laboratory (TJNAF) to increase the energy of the CEBAF electron beam. There are eight such cavities in each of the ten C100 cyromodules installed as part of the 12 GeV CEBAF Upgrade (above schematic)

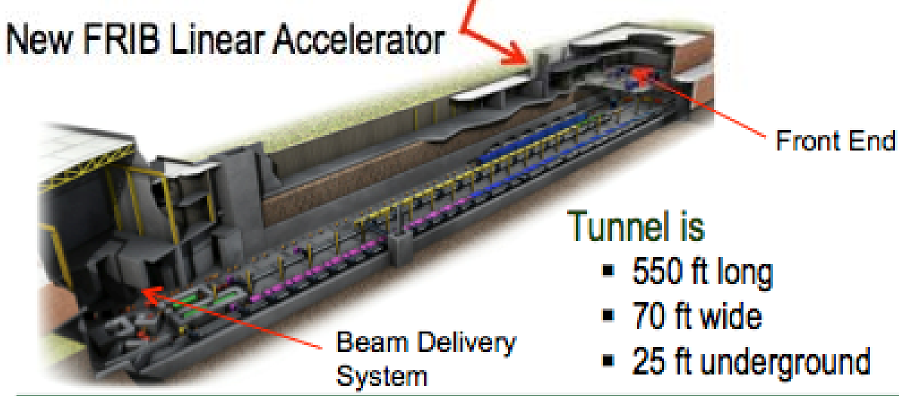
The Facility for Rare Isotope Beams

Finding: The Facility for Rare Isotope Beams is a major new strategic investment in nuclear science. It will have unique capabilities and offers opportunities to answer fundamental questions about the inner workings of the atomic nucleus, the formation of the elements in our universe, and the evolution of the cosmos.

Recommendation: The Department of Energy's Office of Science, in conjunction with the State of Michigan and Michigan State University, should work toward the timely completion of the Facility for Rare Isotope Beams and the initiation of its physics program.

Preparations for Construction of Facility for Rare Isotope Beams

Existing National Superconducting Cyclotron Laboratory



Tunnel is
- 550 ft long
- 70 ft wide
- 25 ft underground

FRIB will increase the number of isotopes with known properties from ~2,000 observed over the last century to ~5,000 and will provide world-leading capabilities for research on:

Nuclear Structure

- The ultimate limits of existence for nuclei
- Nuclei which have neutron skins
- The synthesis of super heavy elements

Nuclear Astrophysics

- The origin of the heavy elements and explosive nucleo-synthesis
- Composition of neutron star crusts

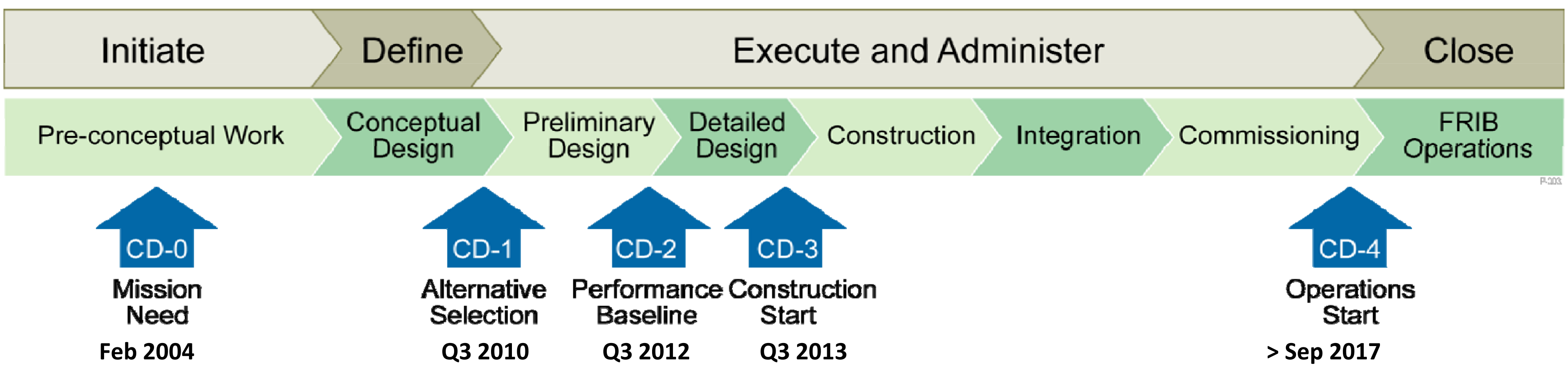
Fundamental Symmetries

- Tests of fundamental symmetries, Atomic EDMs, Weak Charge

This research will provide the basis for a model of nuclei and how they interact.

Schedule for FRIB

- Technical choices will be reexamined with science community input, peer review, DOE review and approval
  - CD-1 – Possible choices (a.k.a. alternatives) will be documented in a Conceptual Design Report (CDR) together with the preferred alternatives indicated. The CDR is subject to DOE approval
  - CD-2 – Following Preliminary Engineering and Design, FRIB will have performance baseline (scope, cost, schedule) defined. This baseline is subject to DOE approval.
  - CD-3 – After detailed design, project starts construction (subject to DOE approval)
  - CD-4 – Pre-operations after construction leads to project completion (subject to DOE approval)



Underground science in the United States

Recommendation: The Department of Energy, the National Science Foundation and other funding agencies where appropriate should develop and implement a targeted program of underground science, including important experiments on whether neutrinos differ from antineutrinos, what is dark matter, and nuclear reactions of astrophysical importance. Such a program would be substantially enabled by the realization of a deep underground laboratory in the United States.

Nuclear physics and exascale computing

Recommendation: A plan should be developed within the theoretical community and enabled by the appropriate sponsors that permits forefront-computing resources to be exploited by nuclear science researchers and establishes the infrastructure and collaborations needed to take advantage of exascale capabilities as they become available.

Nuclear Physics at Universities

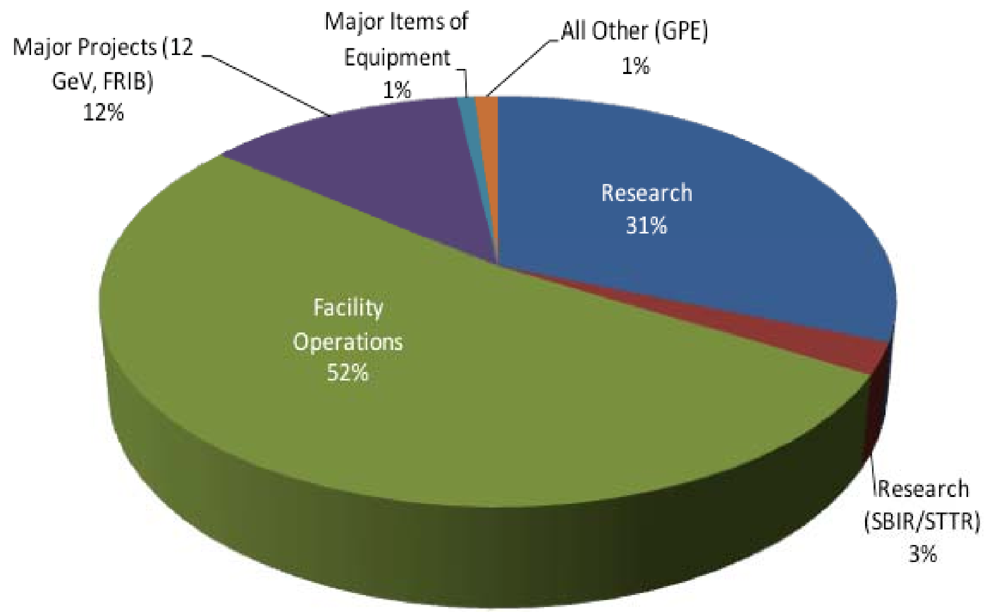
Finding: The dual roles of universities, education and research, are important in all aspects of nuclear physics including the operation of small, medium, and large scale facilities, as well as the design and execution of large experiments at national research laboratories. The vitality and sustainability of the U.S. nuclear physics program depend in an essential way on the intellectual environment and the workforce provided symbiotically by universities and national laboratories. The fraction of the nuclear science budget reserved for facilities operations cannot continue to grow at the expense of the resources available to support research without serious damage to the overall nuclear science program.

Conclusion: In order to ensure the long-term health of the field, it is critical to establish and maintain a balance between funding of major facilities operations and the needs of university-based programs.

FY 2013 Congressional Request
Nuclear Physics by Major Category

66% of the FY 2013 NP budget supports operations or construction of facilities & instrumentation

The percentage devoted to major projects is 12% in FY 2013



FY 2013 Congressional Request
Total = $526.9M

Nuclear Physics at Universities

Recommendation: The Department of Energy and the National Science Foundation should create and fund a national prize fellowship program for graduate students that will help recruit the best among the next generation into nuclear science along with a national prize postdoctoral fellowship to provide the best young nuclear scientists with support, independence, and visibility.

Keeping Nuclear Physics Vital at Universities

1. National Graduate Student Fellowship Program in Nuclear Physics
2. National Prize Fellowship for Postdoctoral Resarchers
3. Sustain Undergraduate REU and CEU programs in Nuclear Physics
4. Sustain CAREER and Early Career Awards to young faculty
5. Use Bridging support to maintain Nuclear Physics positions after retirements
6. Compeittive awards for shared research instrumentation at Universities
7. Fund Topical Collaborations in Nuclear Theory once success is demonstrated
8. Broadening the boundaries of nuclear physics should be encouraged (experimentalists using nuclear skillls to search for dark matter, theorists applying neuclear physics developed techniques to cold atoms)

Striving to be Competitive and Innovative

Finding: The scale of projects in nuclear physics covers a broad range, and sophisticated new tools and protocols have been developed for successful management of the largest of them. At the other end of the scale, nimbleness is essential if the United States is to remain competitive and innovative in a rapidly expanding international nuclear physics activity.

Recommendation: Streamlined and flexible procedures should be developed within the sponsoring agencies that are tailored for initiating and managing smaller scale nuclear science projects.

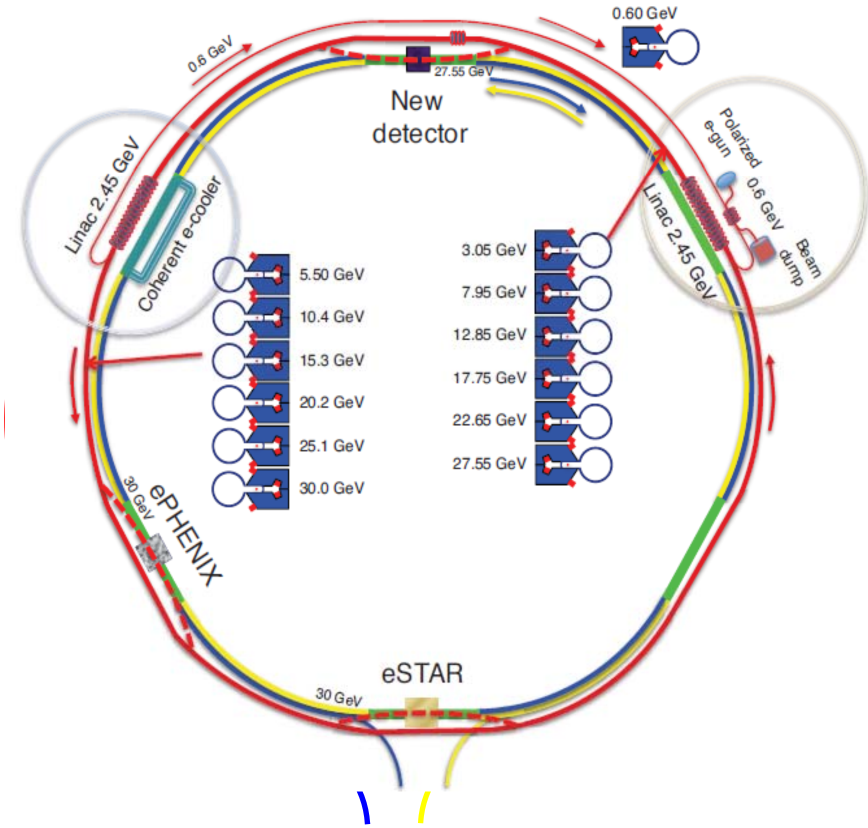
The prospects of an electron-ion collider

Finding: An upgrade to an existing accelerator facility providing the capability of colliding nuclei and electrons at forefront energies would be unique for studying new aspects of quantum chromodynamics and, in particular, would yield new information on the role of gluons in protons and nuclei. An electron-ion collider is currently a subject of study as a possible future facility

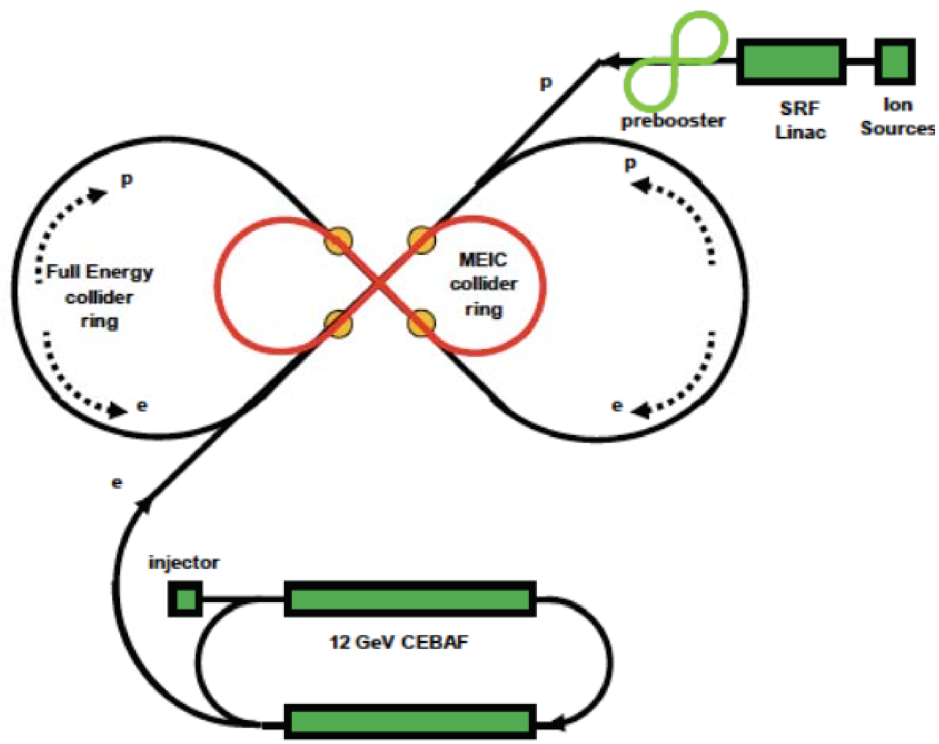
Recommendation: Investment in accelerator and detector research and development for an electron-ion collider should continue. The science opportunities and the requirements for such a facility should be carefully evaluated in the next Nuclear Science Long Range Plan.

Future Facilities

eRHIC



MEIC and EIC



Electron-Ion Collider

Nuclear Physics Funding Distribution
FY 2008 – FY 2013 (actual $)