The Frontiers of Nuclear Physics In The 21st Century

Ani Aprahamian
University of Notre Dame

Thunderstorms and Elementary Particle Acceleration (TEPA-2014)

September 22-26, 2014

Byurakan, Armenia

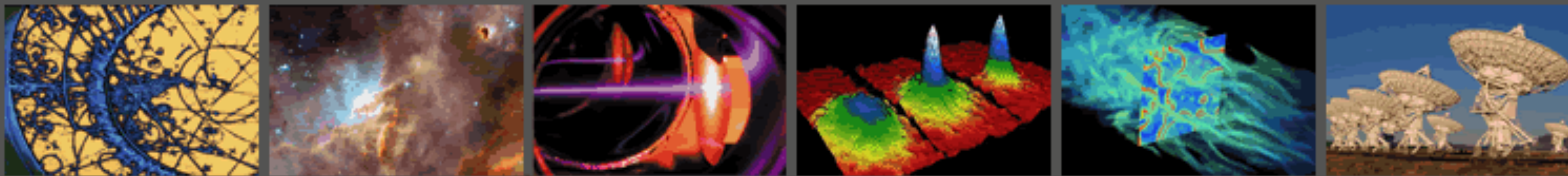
Decadal Reviews of Nuclear Physics

Long Range Planning in Nuclear Physics

The frontiers of
Nuclear Physics in the 21st century

BOARD ON PHYSICS AND ASTRONOMY

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

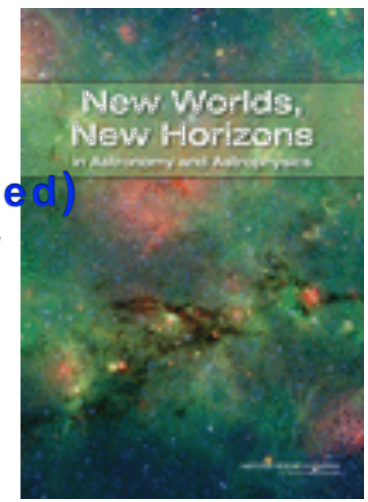


Science Academies of the USA
Decadal Survey of Nuclear Physics
NP 2010: An Assessment and Outlook for Nuclear Physics

Stuart Freedman (Chair: deceased)
University of California Berkeley

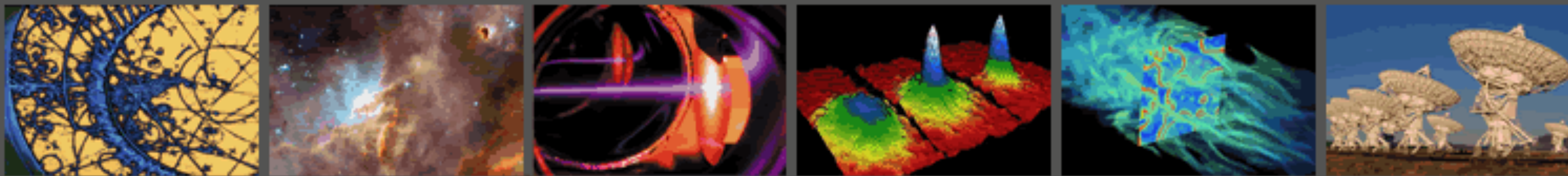
Ani Aprahamian (Vice-chair)
University of Notre Dame

2010



2007

2006



Membership of NP 2010

R. Alarcon
Arizona State University

A. Aprahamian (Vice-Chair)
University of Notre Dame

G. Baym
University of Illinois at Urbana-Champaign

E. Beise
University of Maryland

R. F. Casten
Yale University

J.A. Cizewski
Rutgers University

S. Freedman (Chair)
University of California Berkeley

A. Hayes
Los Alamos National Laboratory

R. Holt
Argonne National Laboratory

K. H. Langanke
GSI Helmholtz Zentrum Darmstadt and TU Darmstadt

C. Murray
Harvard University

W. Nazarewicz
University of Tennessee, Knoxville

Konstantinos Orginos
College of William and Mary

K. Rajagopal
Masschusetts Institute of Technology

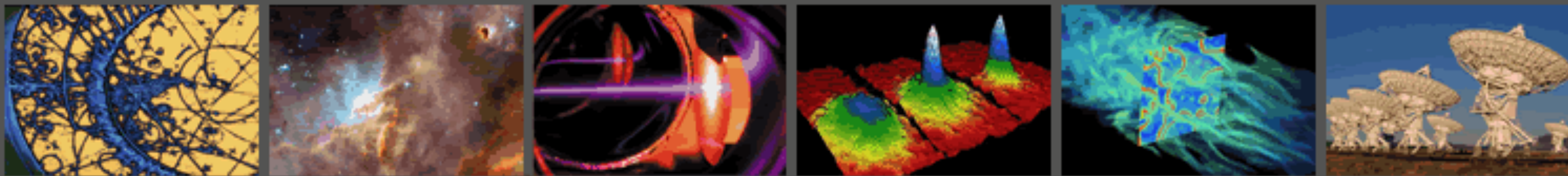
R.G. H. Robertson
Washington University

T. Ruth
Triumf

H. Schatz
Michigan State University

R. Tribble
Texas A&M University

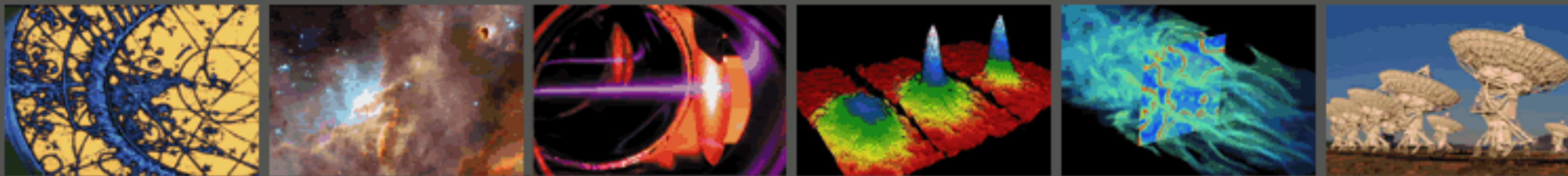
W. Zajc
Columbia University



NP 2010: 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.



NP 2010: Statement of Task

Phase 1:

Why should US support Nuclear Science?

Balance of the field, new opportunities?

Phase 2:

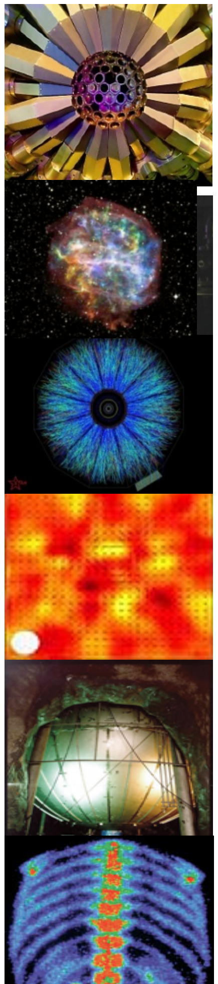
Sustainability of the field? Balance between facilities and science

What about the planning processes for new projects of our field? Why so slow?

Are we doing the best science/dollar?

International context? Do we coordinate, duplicate, orthogonalize?

Exploring the Heart of Matter



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

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.

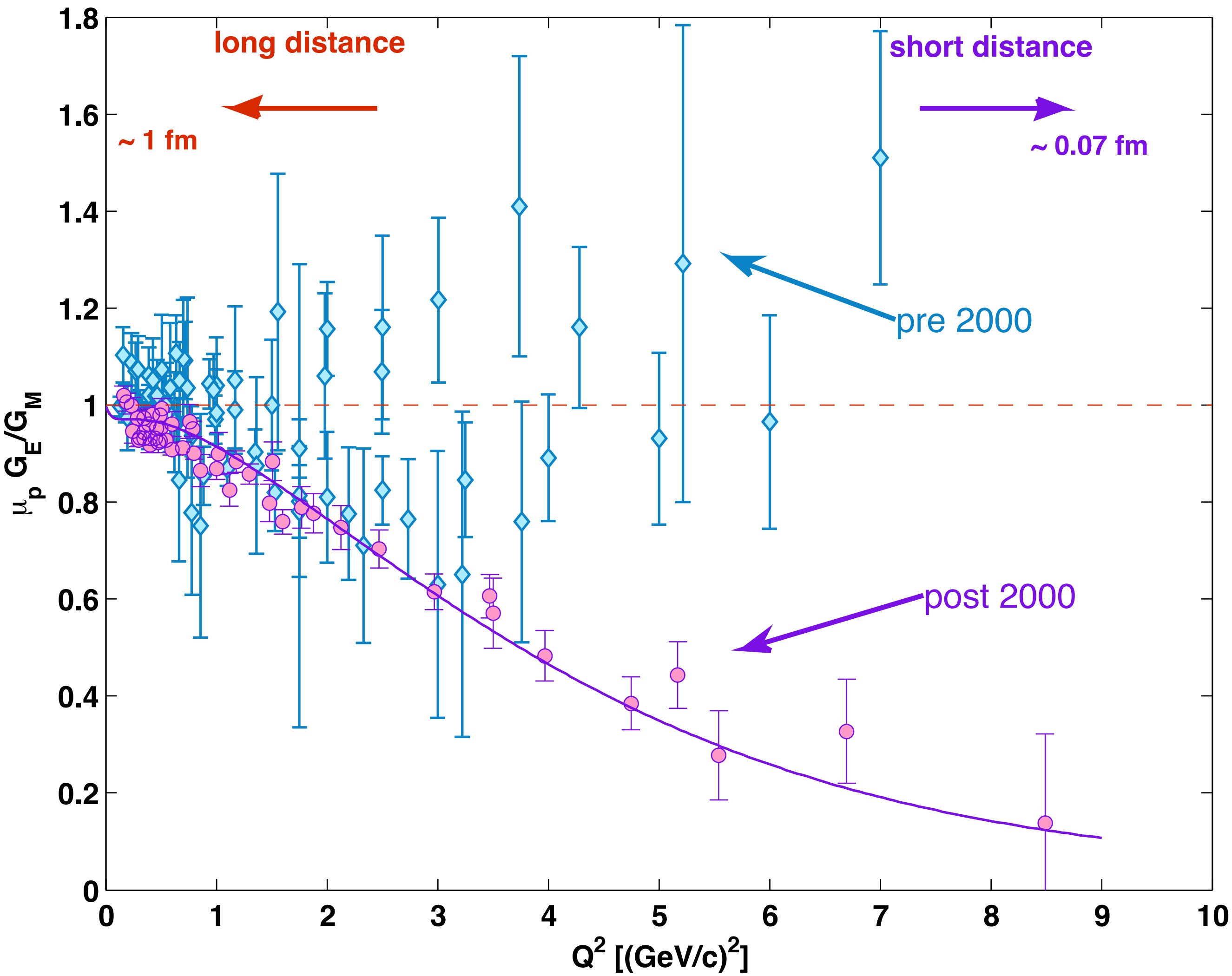
- Place the near term goals of **the 2007 LRP** in a broader national context.
- Discuss the strategy to optimize the partnership between facilities and universities.
- Address the role of international collaboration in leveraging future US investments.

Major Accomplishments in the last decade

- Discovery of a near perfect fluid in relativistic heavy-ion collisions at RHIC

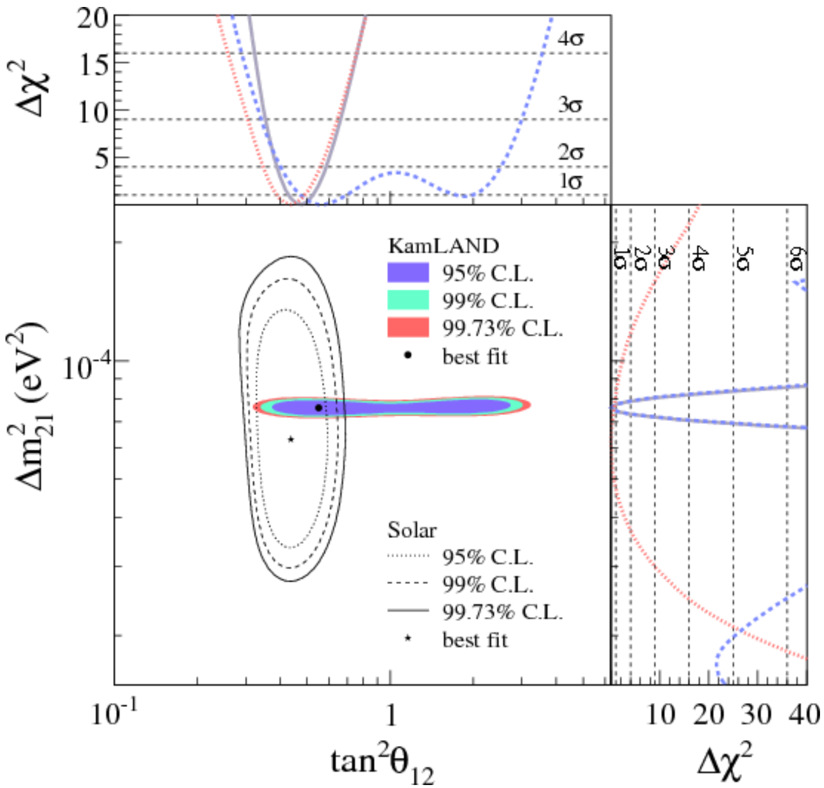
- Precision determination of the electric an magnetic form factors of the proton and neutron at Jlab

- Final resolution of the Solar Neutrino Problem and direct evidence for neutrino oscillations with SNO and KamLAND

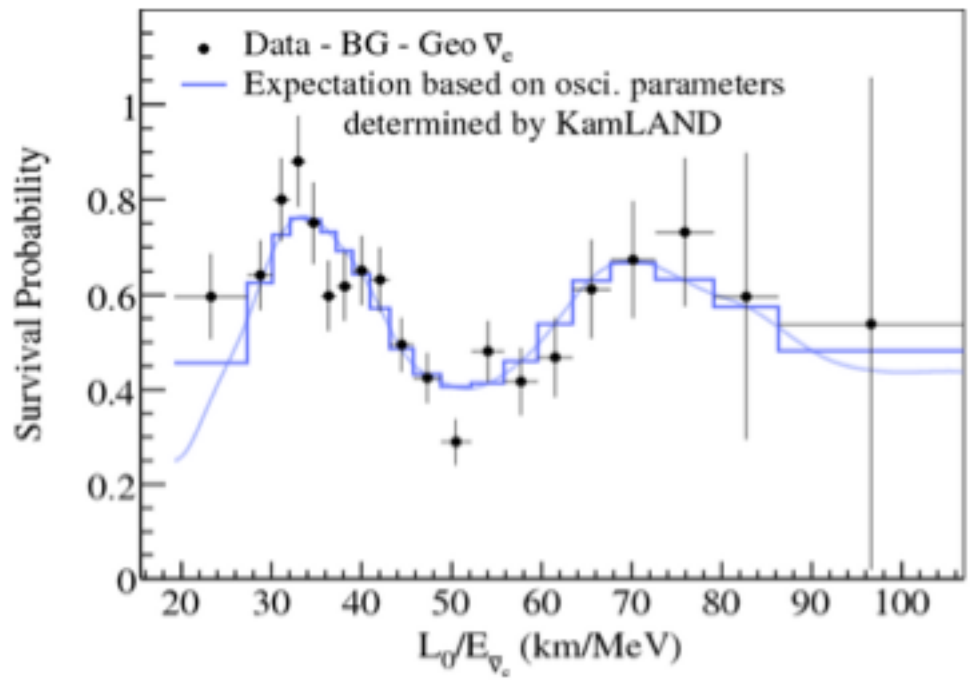


Magnetic and Electric distribution of charge is different in the proton

Solar Neutrino Problem Solved
Neutrino Oscillations Established

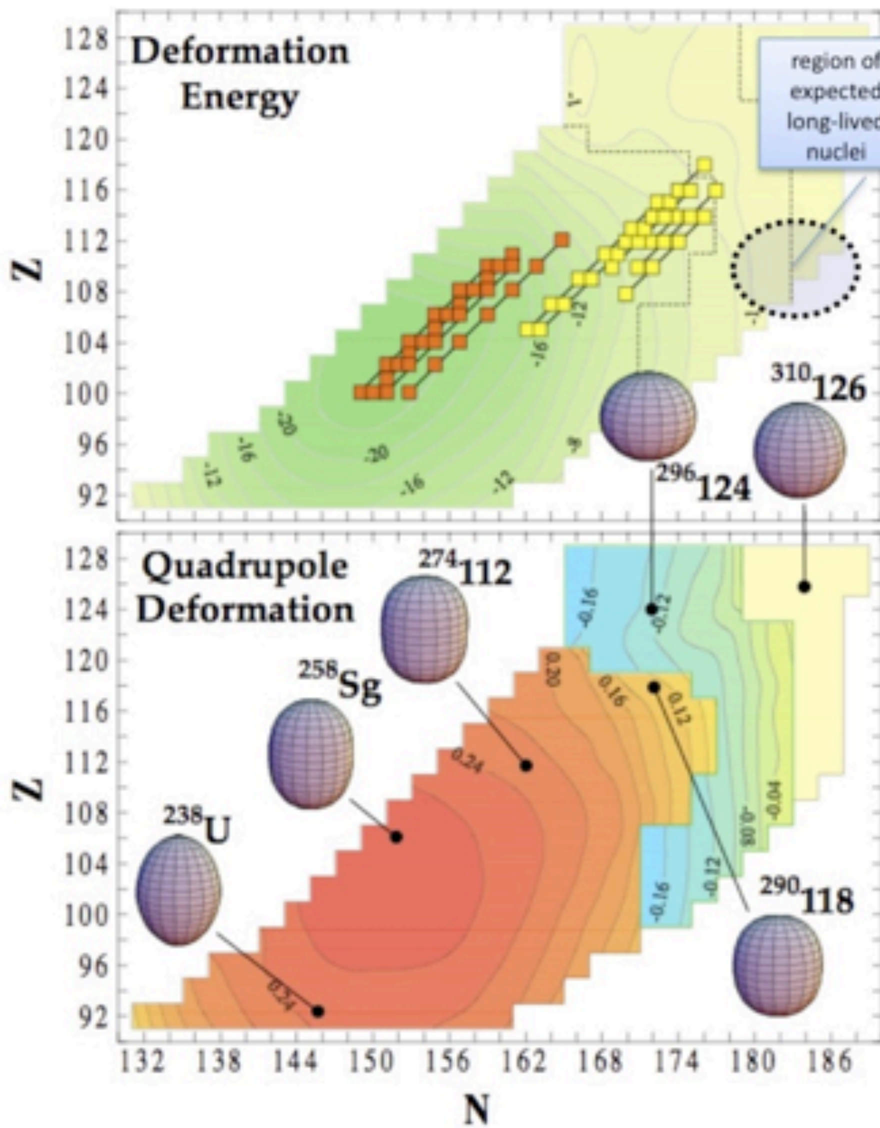


Constraints on neutrino oscillation parameters from SNO and KamLAND

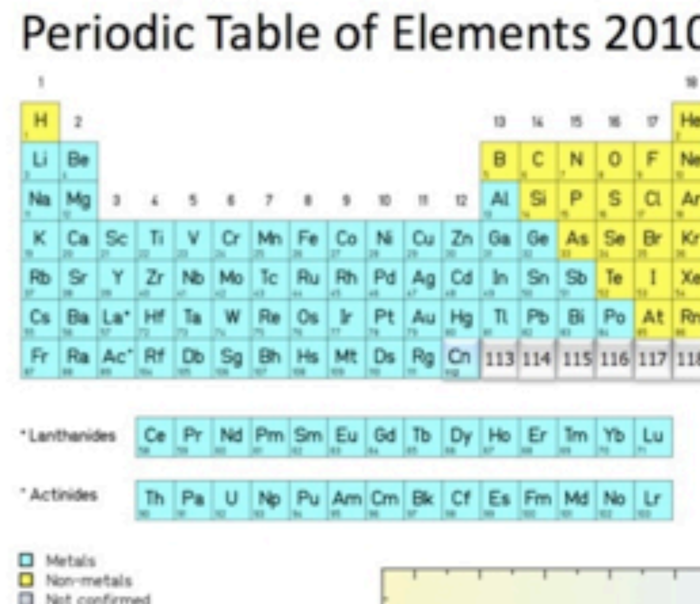


"Direct" observation of neutrino oscillations from KamLAND

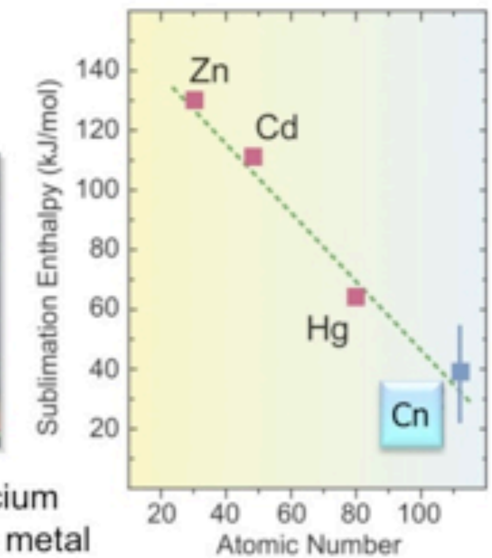
Physics of Superheavy Elements



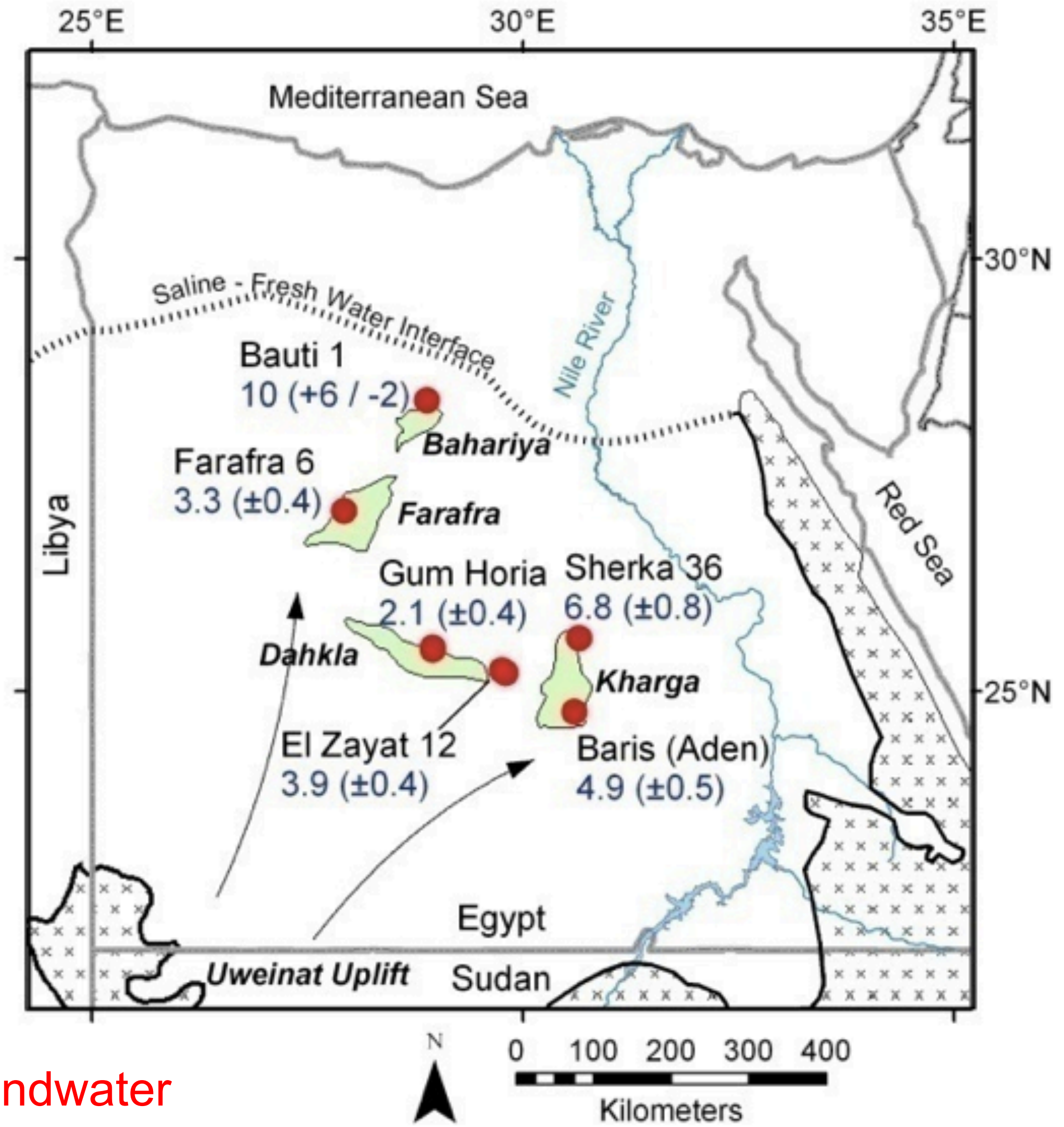
Chemistry of Superheavy Elements



Z=112: Copernicium
very volatile noble metal

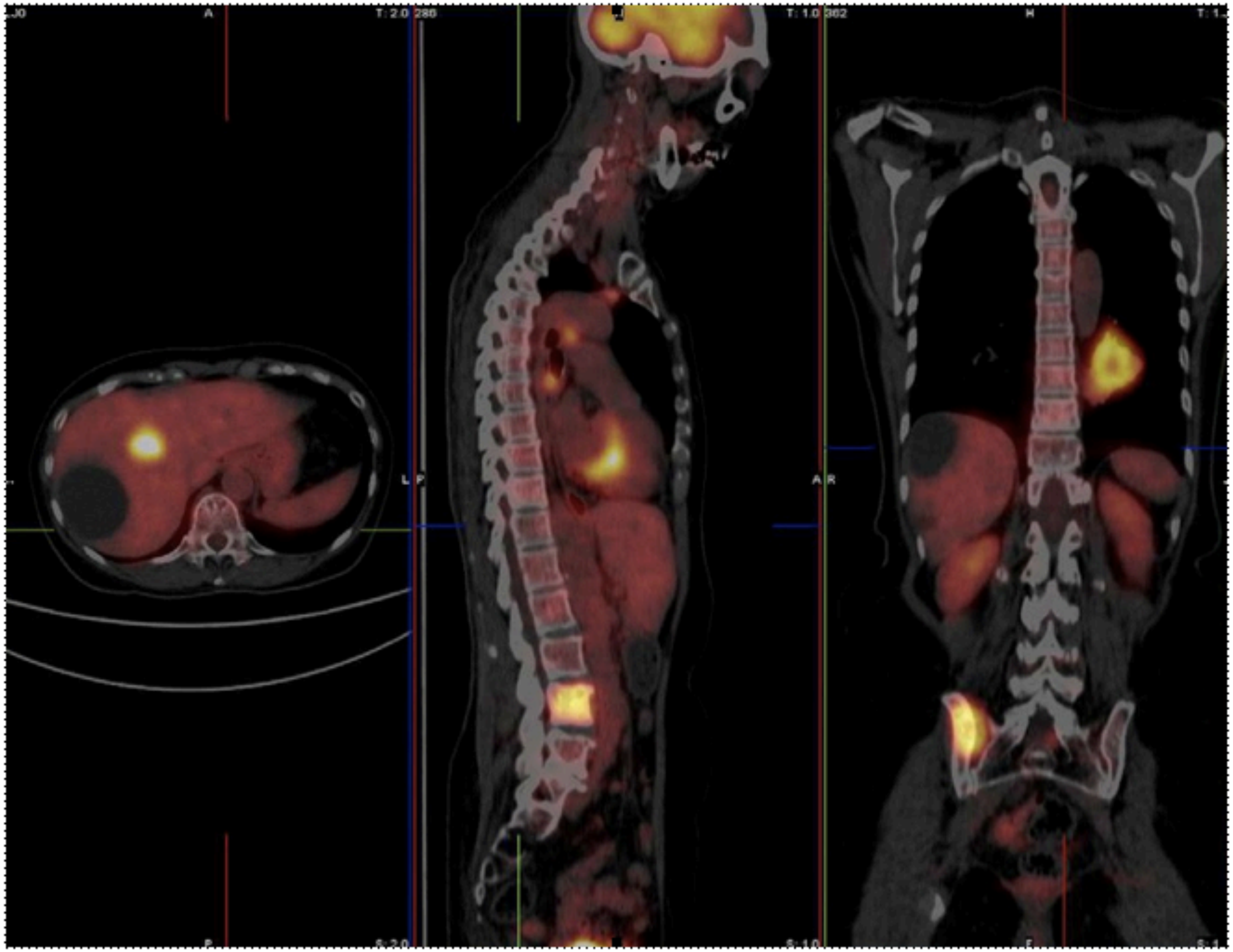


New techniques for trace element analysis with single trapped atoms



^{81}Kr activity in groundwater

New and improved imaging techniques



DOE Nuclear Physics Program in the U.S.

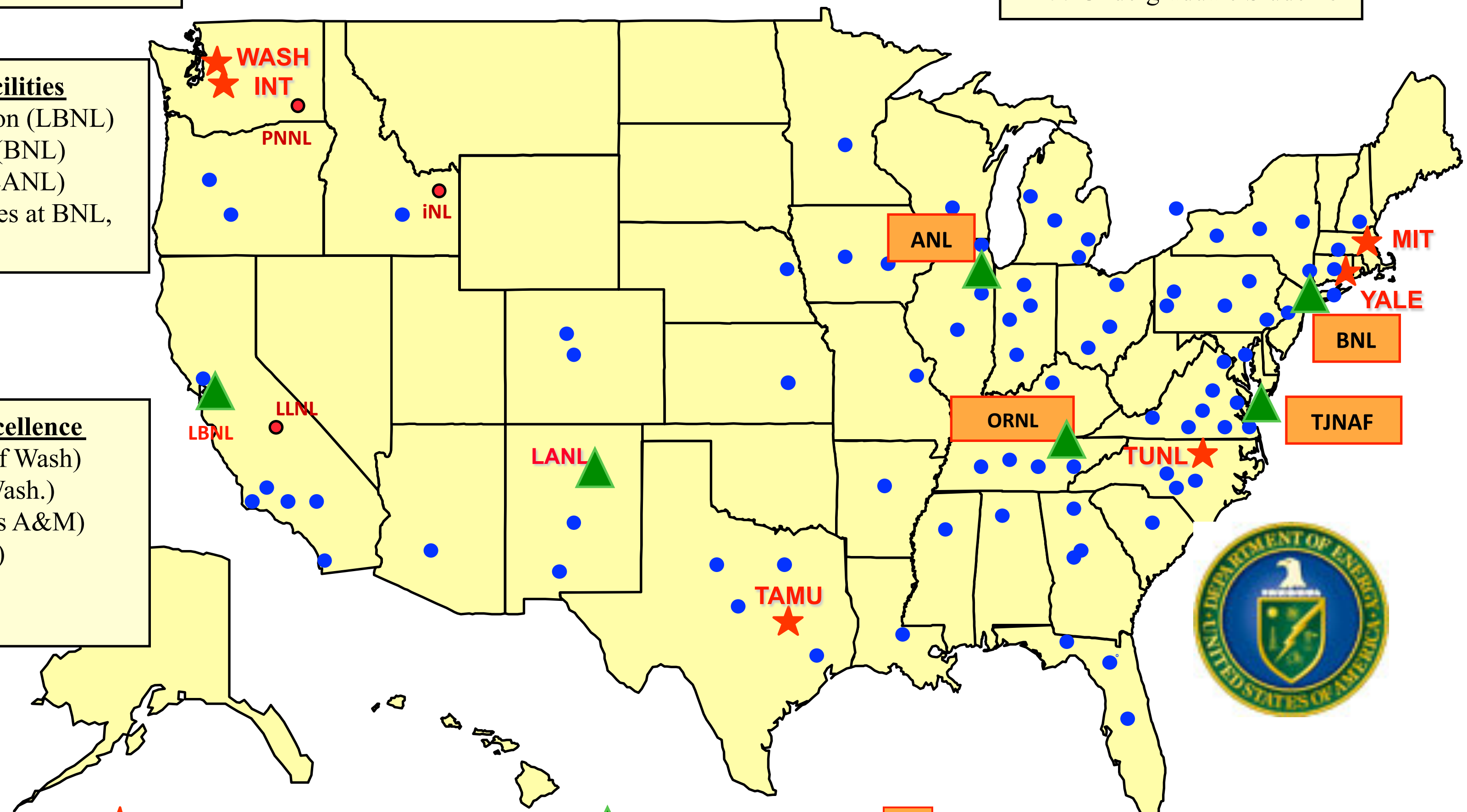
National User Facilities
- RHIC (BNL)
- CEBAF (TJNAF)
- ATLAS (ANL)
- HRIBF (ORNL)

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

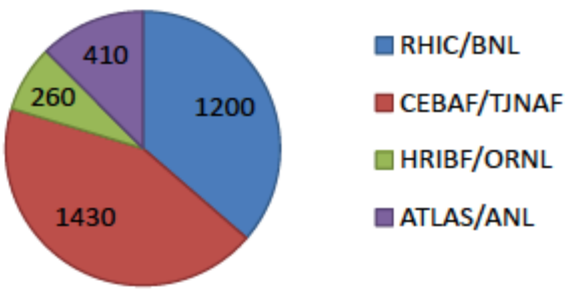
Centers of Excellence
- CENPA (U. of Wash)
- INT (U. of Wash.)
- TAMU (Texas A&M)
- TUNL (Duke)
- REC (MIT)
- WNSL (Yale)



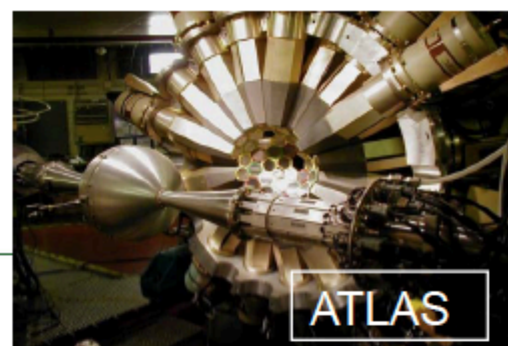
University Facility/Center of Excellence
Laboratory Facility
Laboratory
User Facility
University

Facilities

Users of NP Facilities



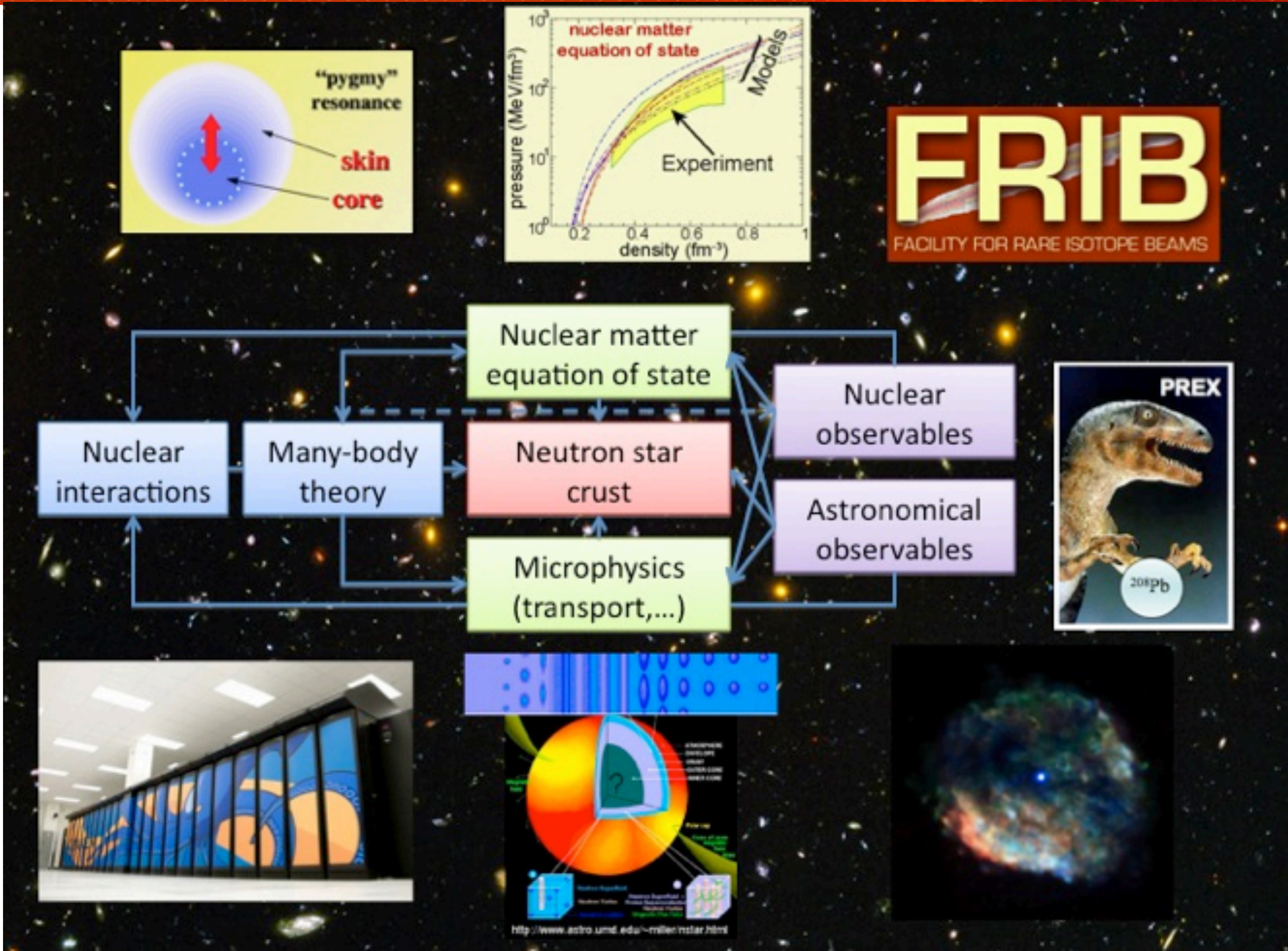
- Four National User Facilities
- Approximately 40% of users are from foreign institutions
- FRIB, when complete, will also be a National User Facility



J-PARC

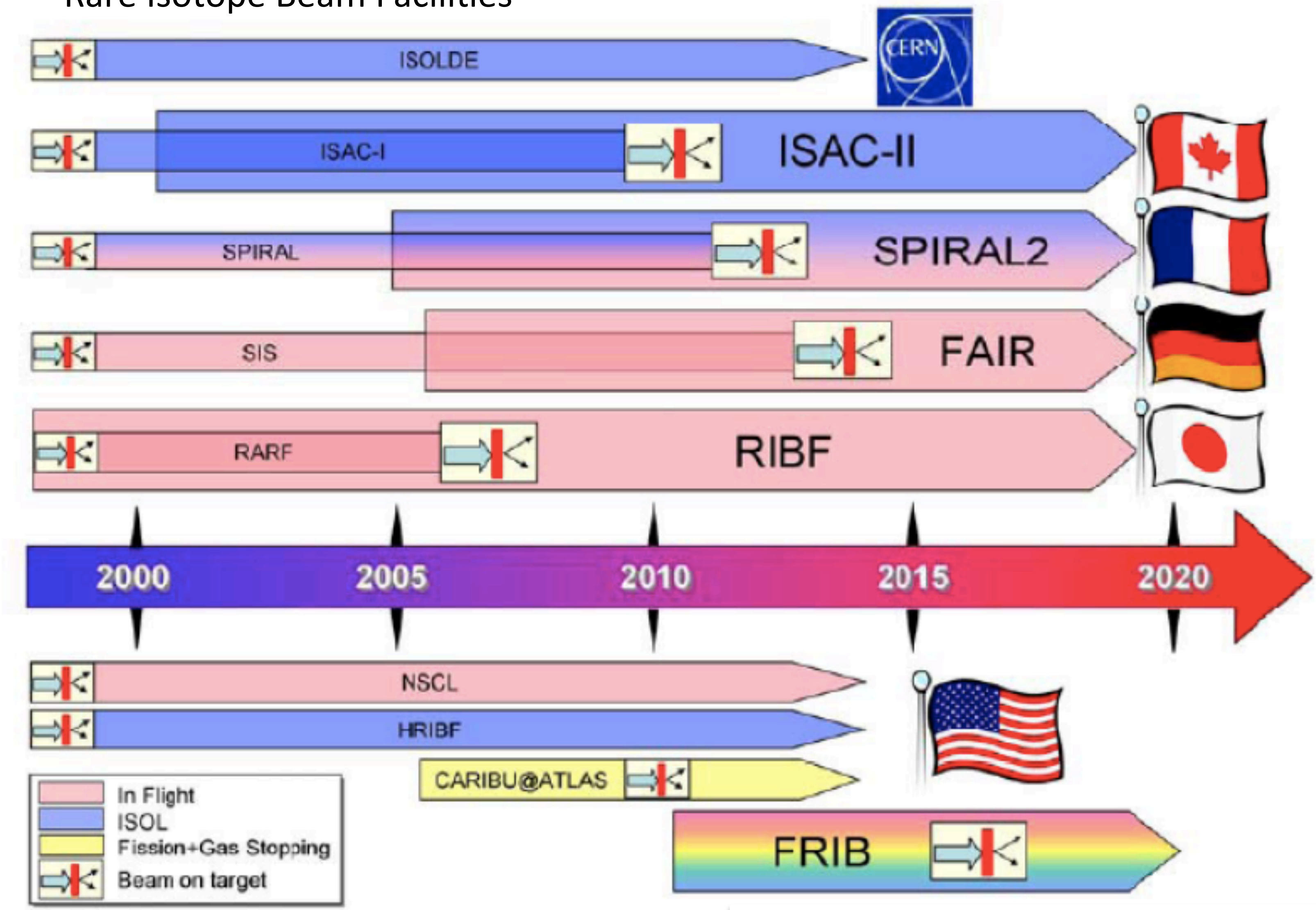
Major NP Accelerators in the World

Nagamiya


"pygmy" resonance
skin
core
nuclear matter equation of state
Models
Experiment
pressure (MeV/fm^3)
density (fm^{-3})
FRIB
FACILITY FOR RARE ISOTOPE BEAMS
Nuclear matter equation of state
Nuclear interactions
Many-body theory
Neutron star crust
Microphysics (transport,...)
Nuclear observables
Astronomical observables
PREX
^{208}Pb
http://www.astro.umd.edu/~miller/nstar.html

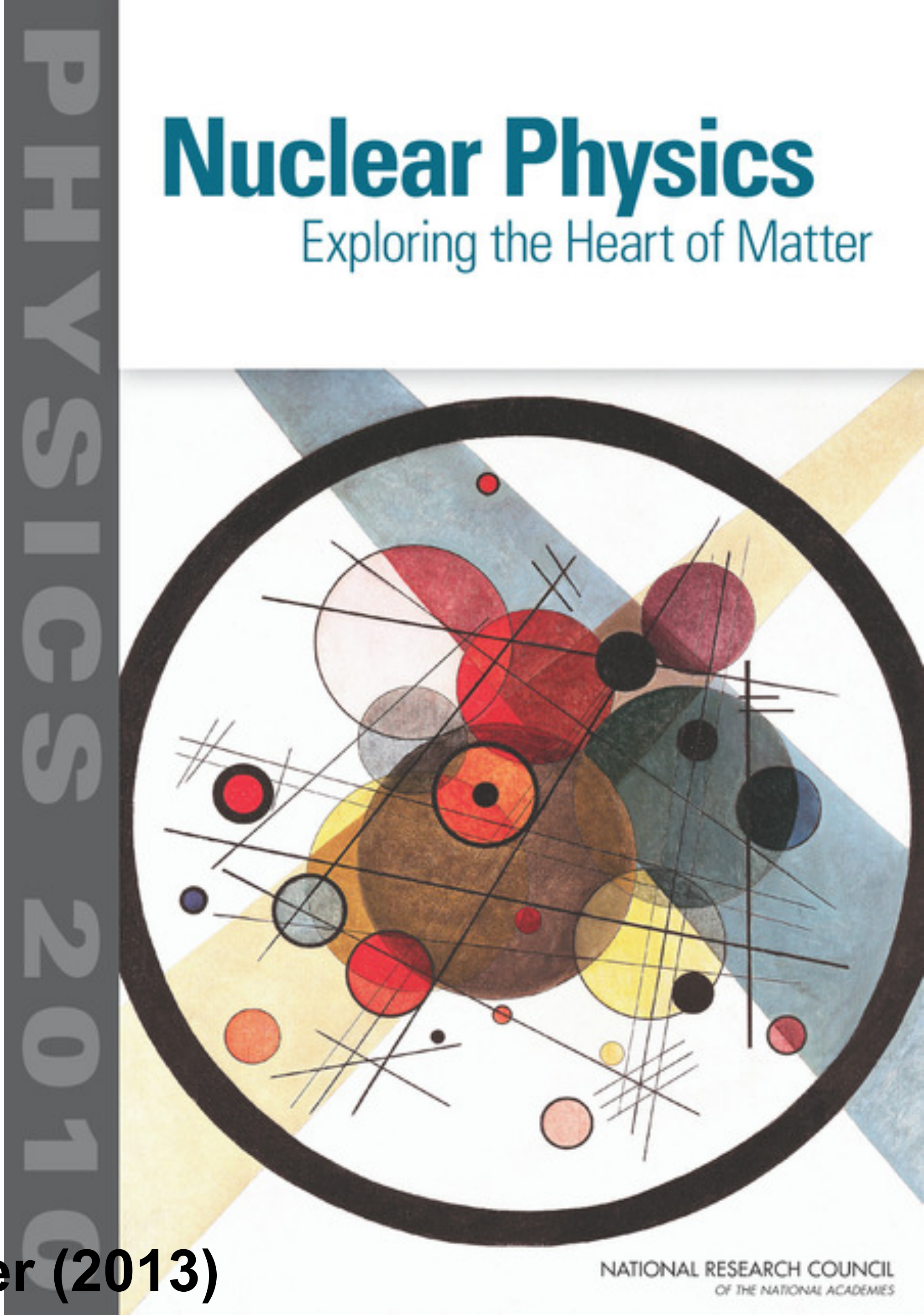
Rare Isotope Facilities

Rare Isotope Beam Facilities



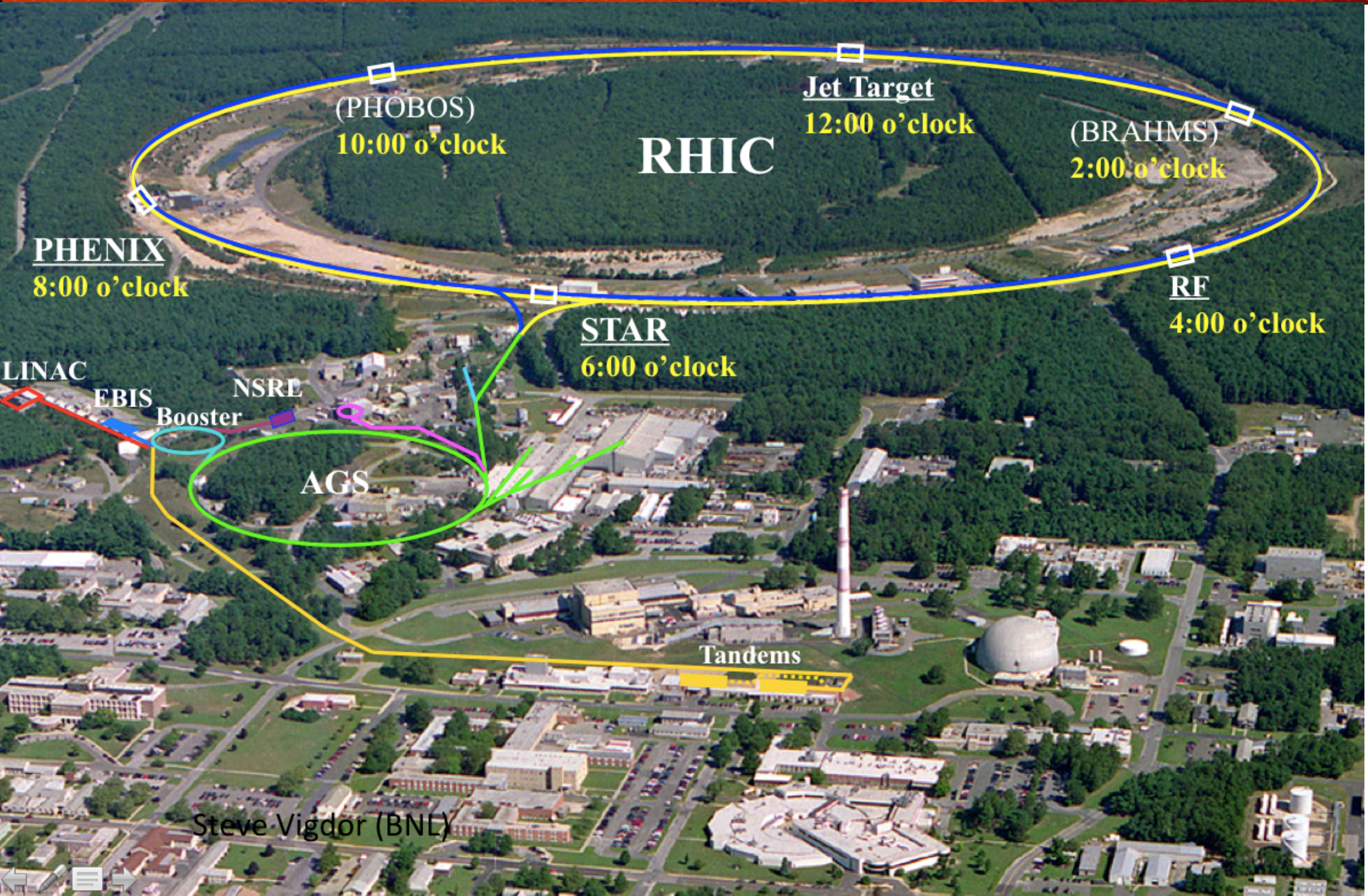
NAS Risac Report 2007

http://sites.nationalacademies.org/BPA/BPA_069589



Nuclear Physics:
Exploring the Heart of Matter (2013)

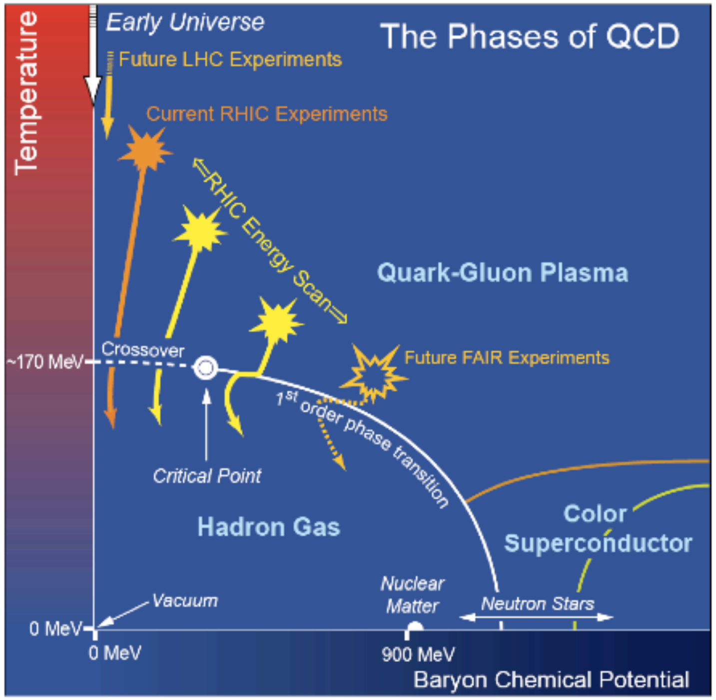
RHIC

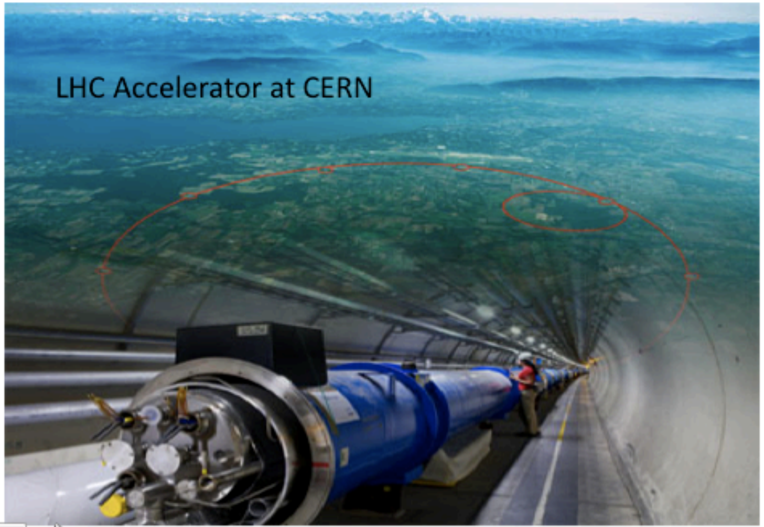


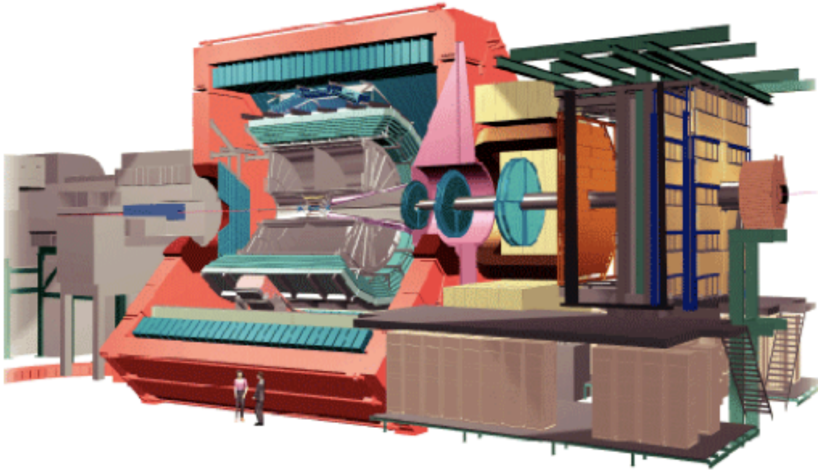
Steve Vigdor (BNL)

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







Jefferson Laboratory

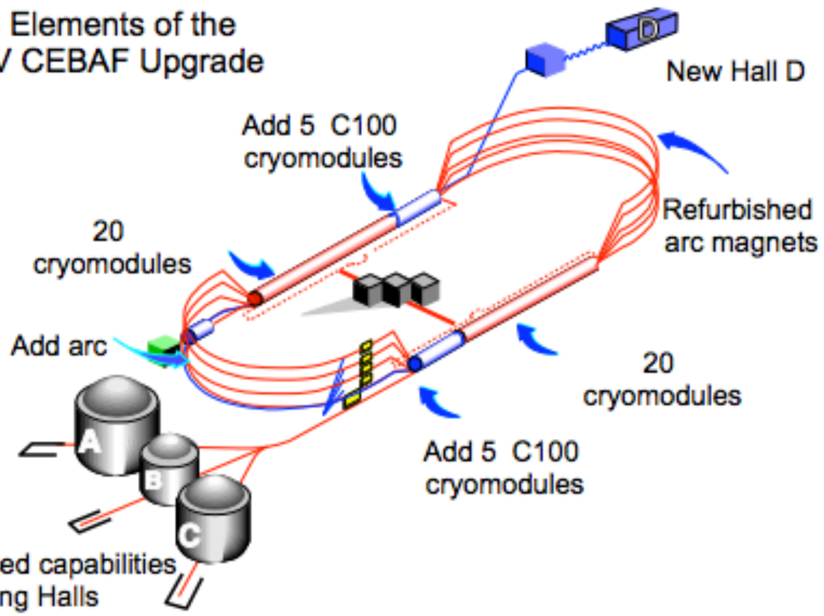
The JLaB 12 GeV Up-Grade

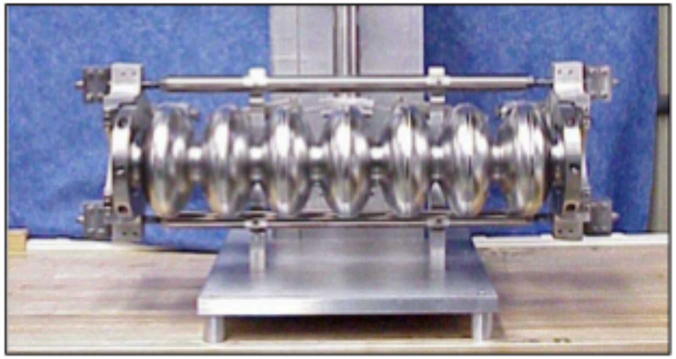
The 12 GeV CEBAF Upgrade at TJNAF is 60% Complete

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

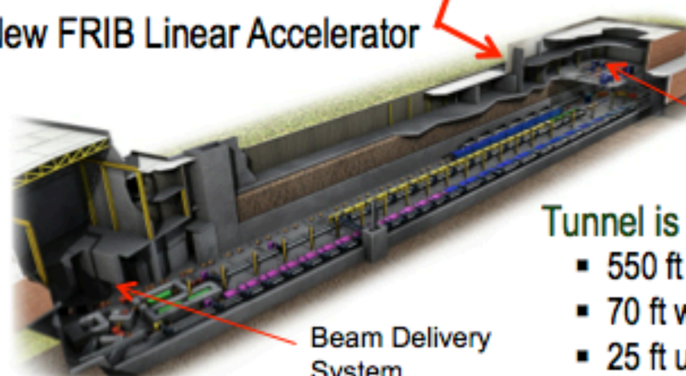
Finding: The Facility for Rare Isotope Beams is a major new strategic investment in nuclear science. It will have unique capabilities and offers opportunities to answer fundamental questions about the inner workings of the atomic nucleus, the formation of the elements in our universe, and the evolution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

New FRIB Linear Accelerator



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.

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 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.

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.

Nuclear physics and exascale computing

10^{18} operations /sec

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

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.

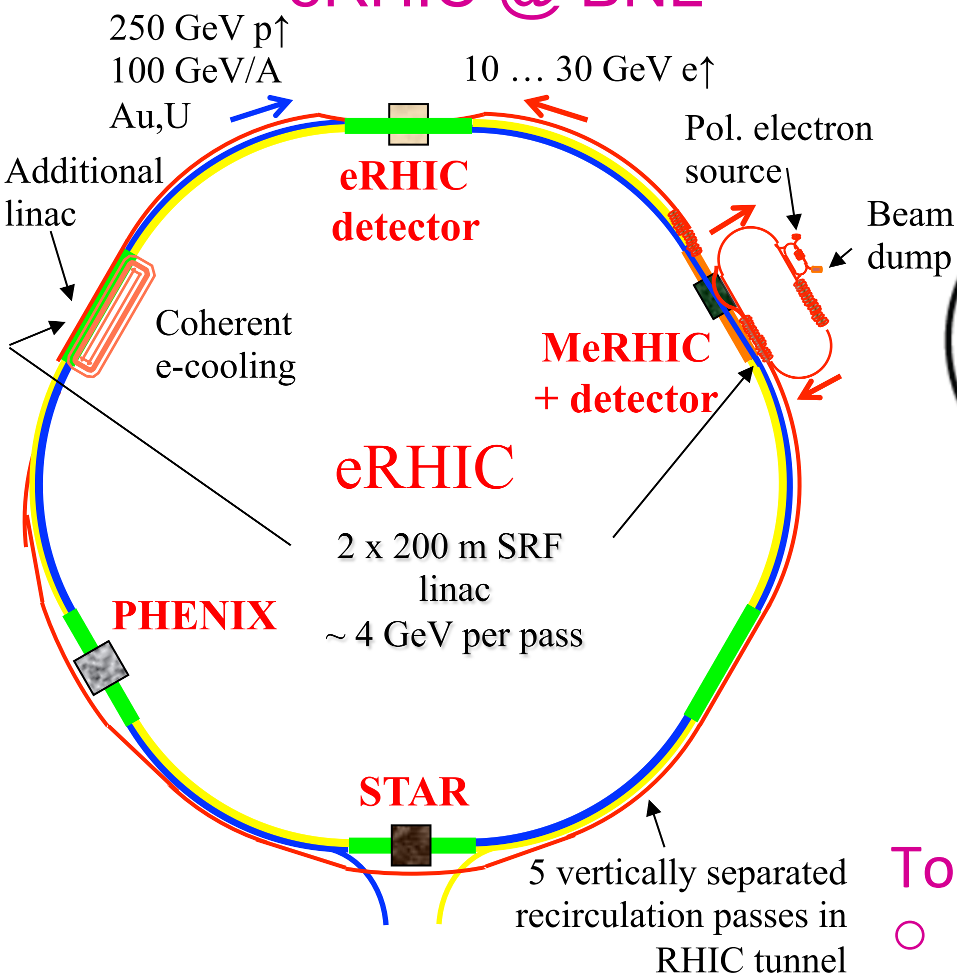
The prospects of an electron-ion collider

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

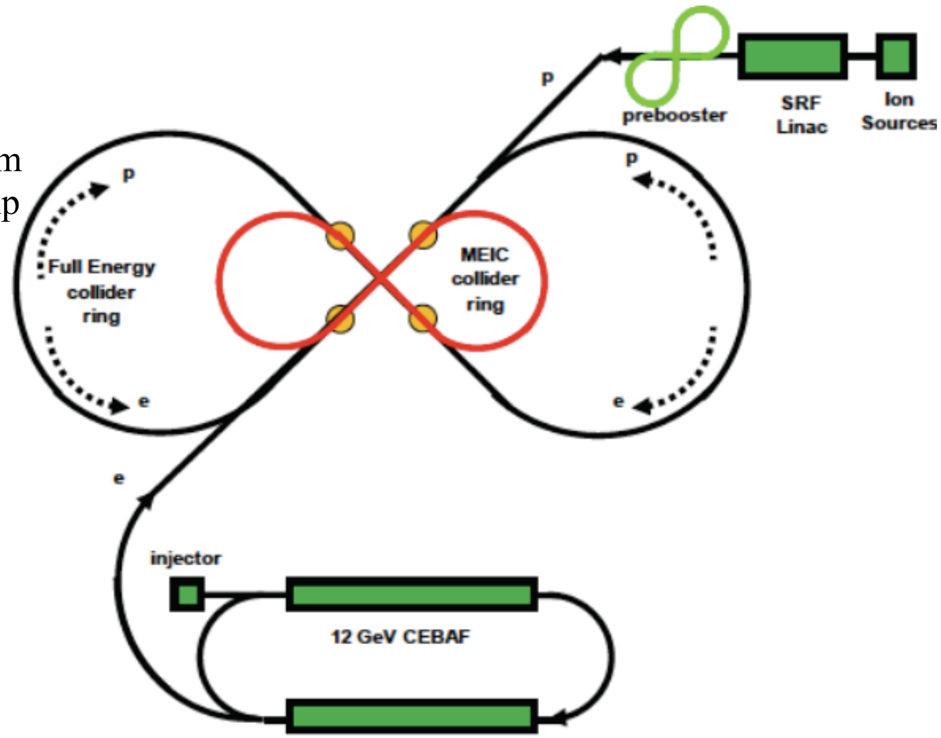
Recommendation: Investment in accelerator and detector research and development for an electron-ion collider should continue. The science opportunities and the requirements for such a facility should be carefully evaluated in the next Nuclear Science Long Range Plan.

Future Facilities

MeRHIC and eRHIC @ BNL



MEIC and EIC @ JLab



To Investigate:

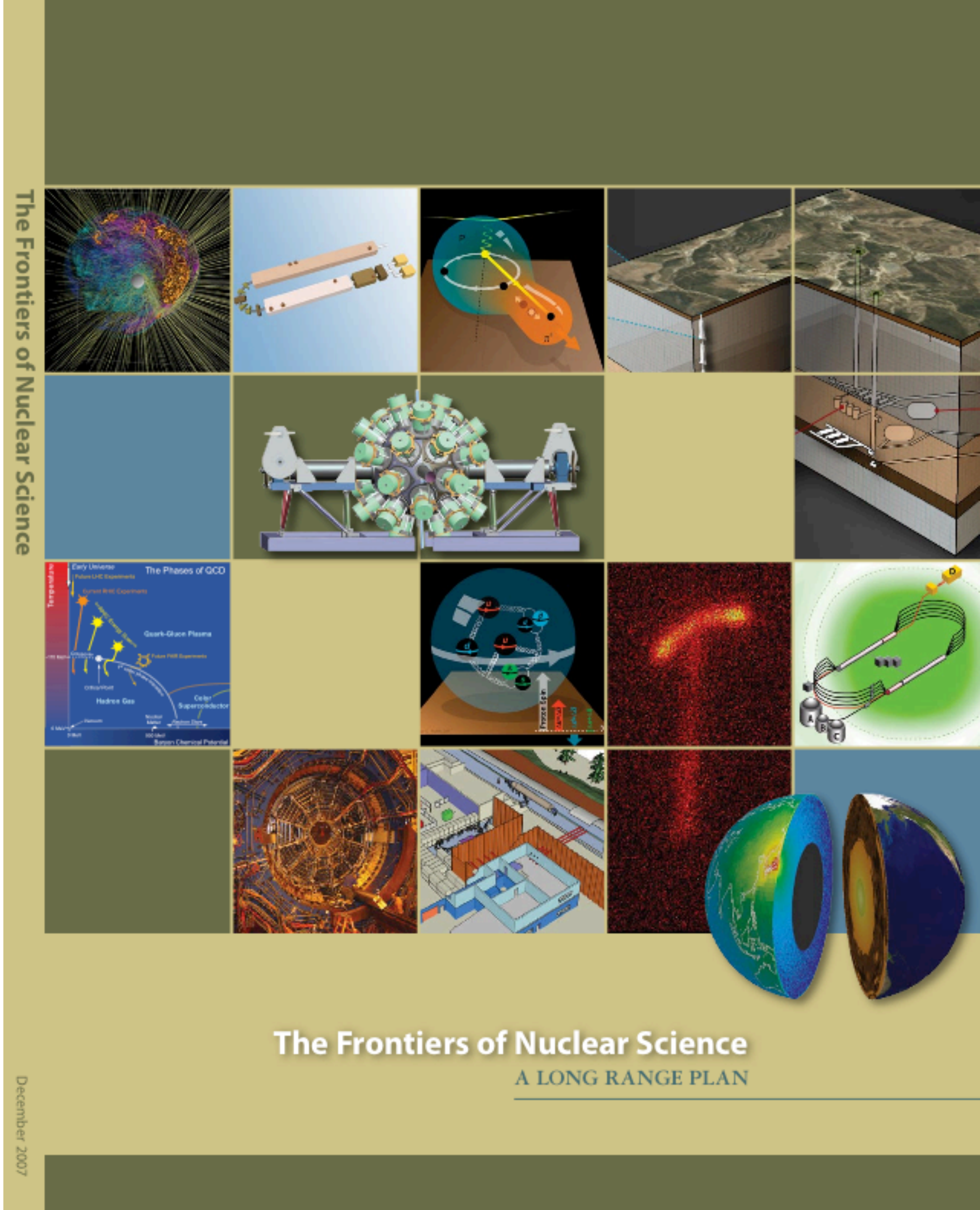
- The gluon structure of matter
- The 3D structure of hadrons
- Physics beyond the Standard Model

video

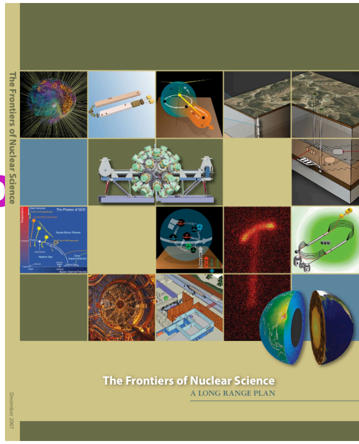
http://sites.nationalacademies.org/BPA/BPA_069589

2007 Long Range Plan for US Nuclear Science

- Process
- Recommendations
- Science

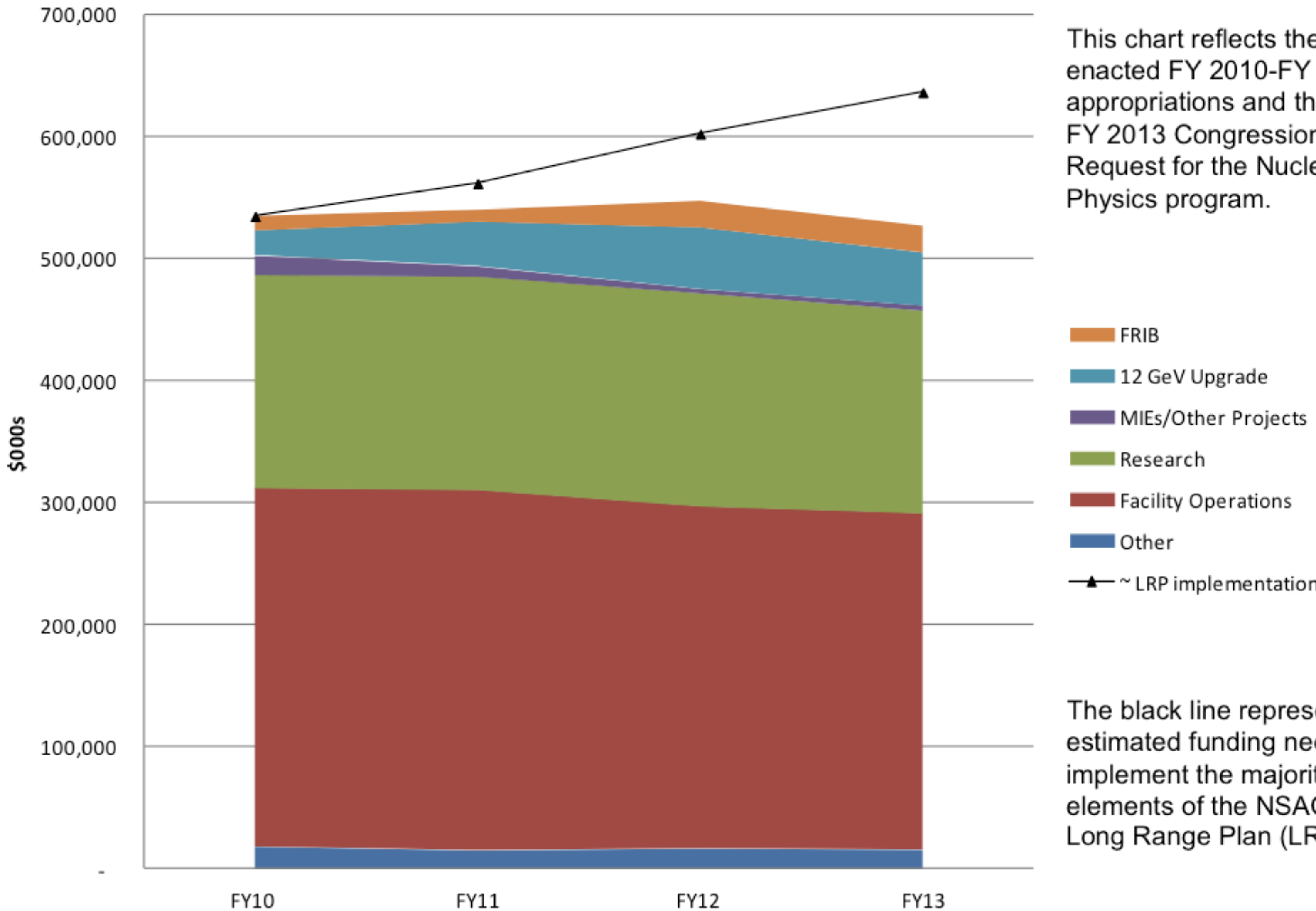


Recommendations…in order of priority (4)



- Completion of the 12 GeV upgrade at **Jefferson Lab**
- Construction of **FRIB**…
- 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 **DUSEL** is vital to US leadership in core aspects of this initiative.
- Implementation of the **RHIC II** luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.

Office of Nuclear Physics FY 2013 Congressional Request



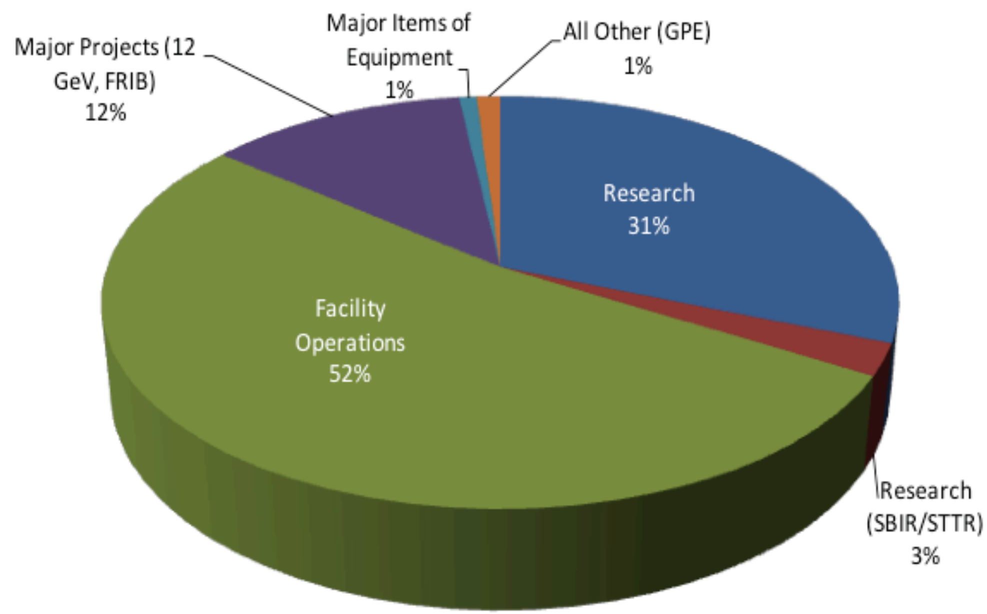
This chart reflects the enacted FY 2010-FY 2012 appropriations and the FY 2013 Congressional Request for the Nuclear Physics program.

The black line represents estimated funding needed to implement the majority of elements of the NSAC 2007 Long Range Plan (LRP).

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

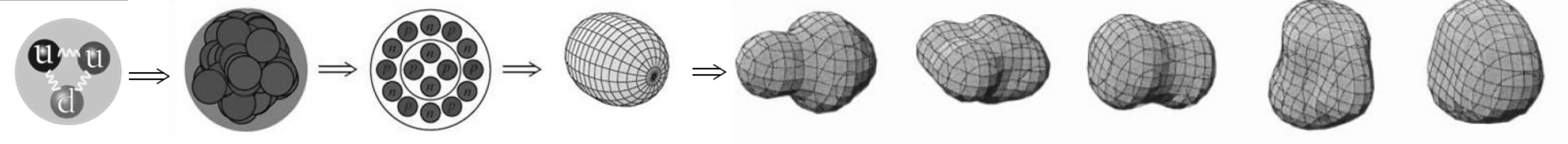


FY 2013 Congressional Request
Total = $526.9M

2014 LRP: Community Input

- **5 Town meetings sponsored by APS-DNP**
- **White papers to be produced from meetings**
    - Phases of QCD Matter
    - QCD and Hadron Physics
    - Nuclear Structure
    - Nuclear Astrophysics
    - Neutrinos and Fundamental Symmetries

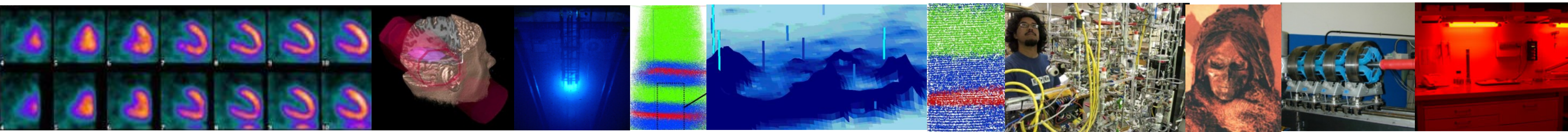
Deadlines: April 2014 Charge to community
March 2015 Recommendations
October 2015 Report

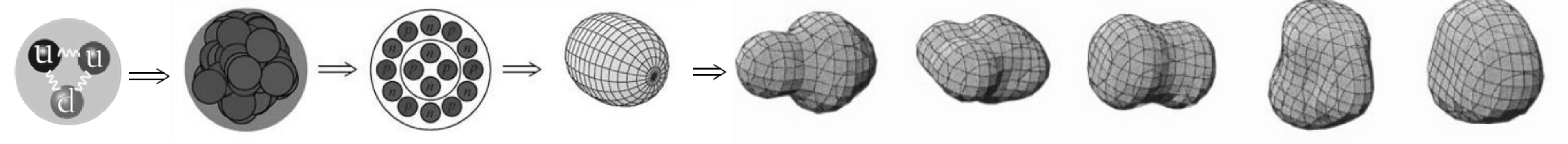


Nuclear Physics at the frontiers

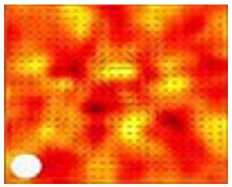
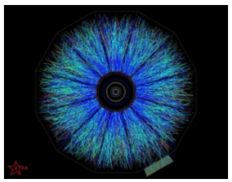
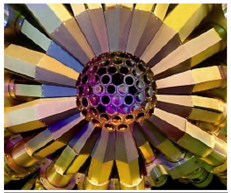
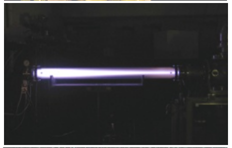
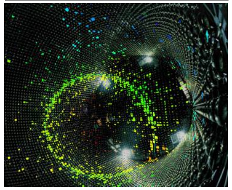
Questions, Directions, Applications

- Science Questions & Goals of Nuclear Physics
- Implications of Nuclear Physics to other sciences
- Applications of Nuclear Physics in other Fields





Science Goals in Nuclear Physics

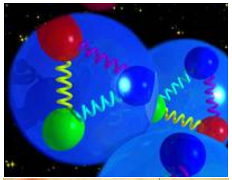
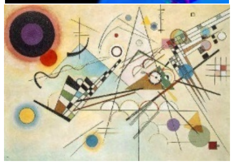
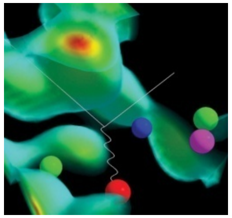
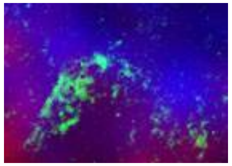
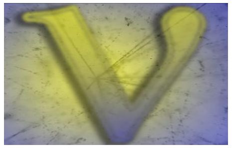
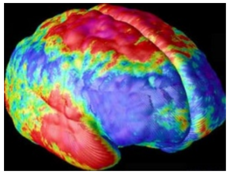

- Quark Structure of Nucleon
- Quark gluon plasma
- Nuclear Structure

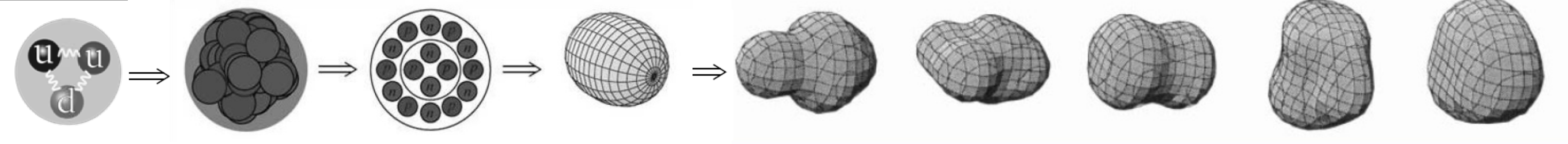
NP Science

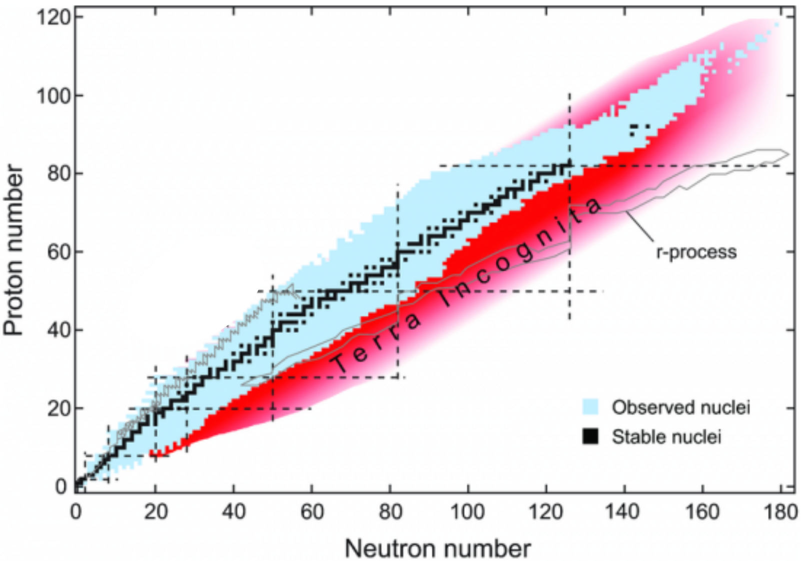
- Nuclear Astrophysics
- Fundamental Studies

NP Implications

- Nuclear Physics Applications

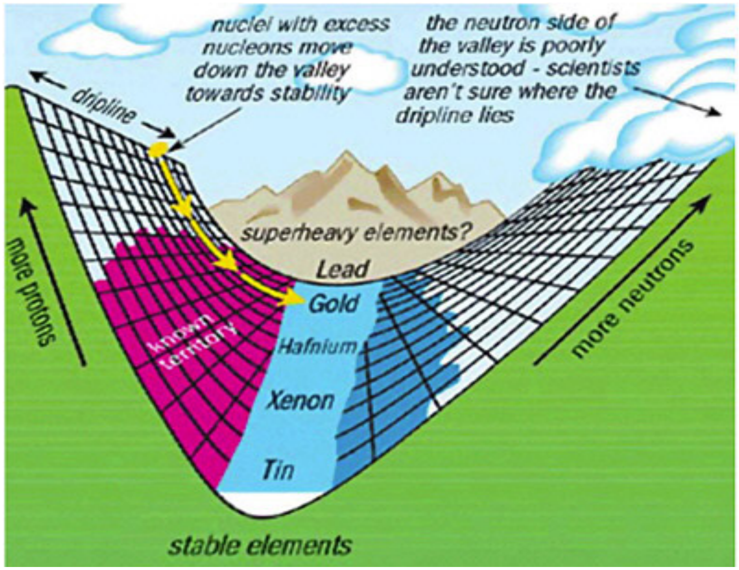







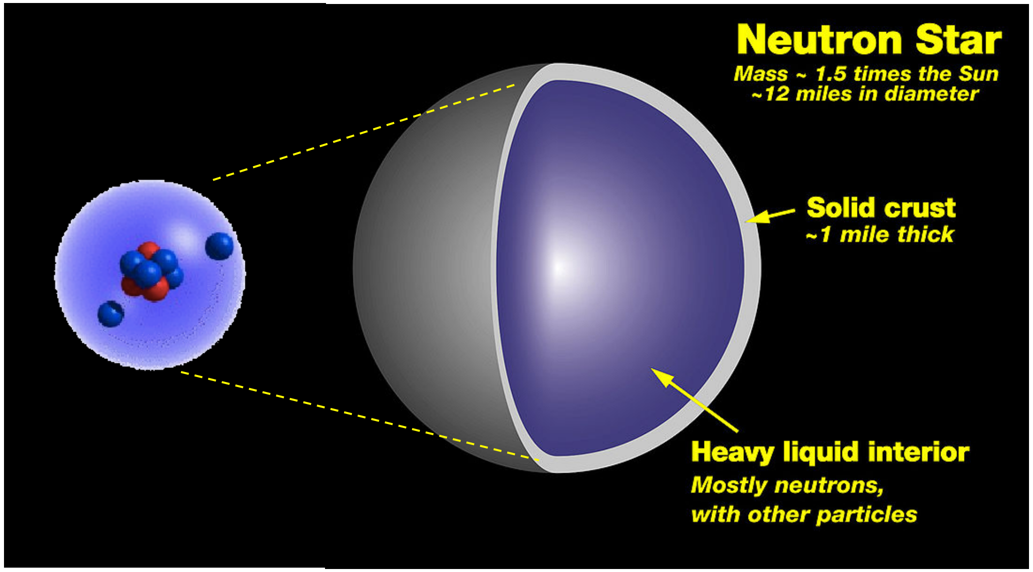


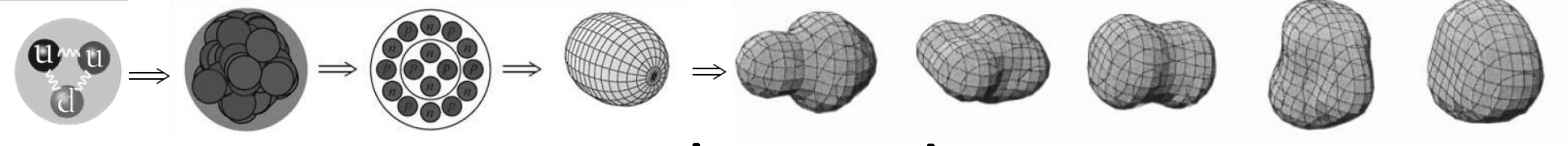


Goals….far off Stability

- Nuclear Masses & decay properties
- Neutron halos
- Disappearance of shell structure
- Emergence of new shapes
- New collective modes of excitation
- Mapping the driplines
- Islands of stability

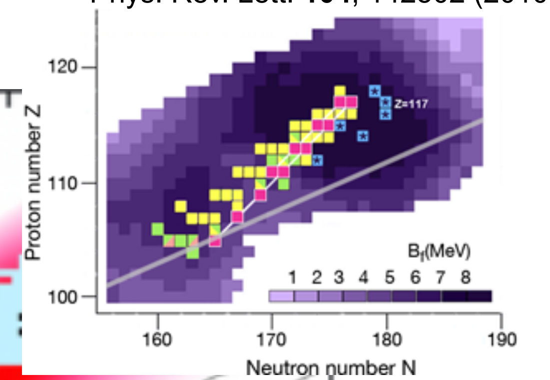


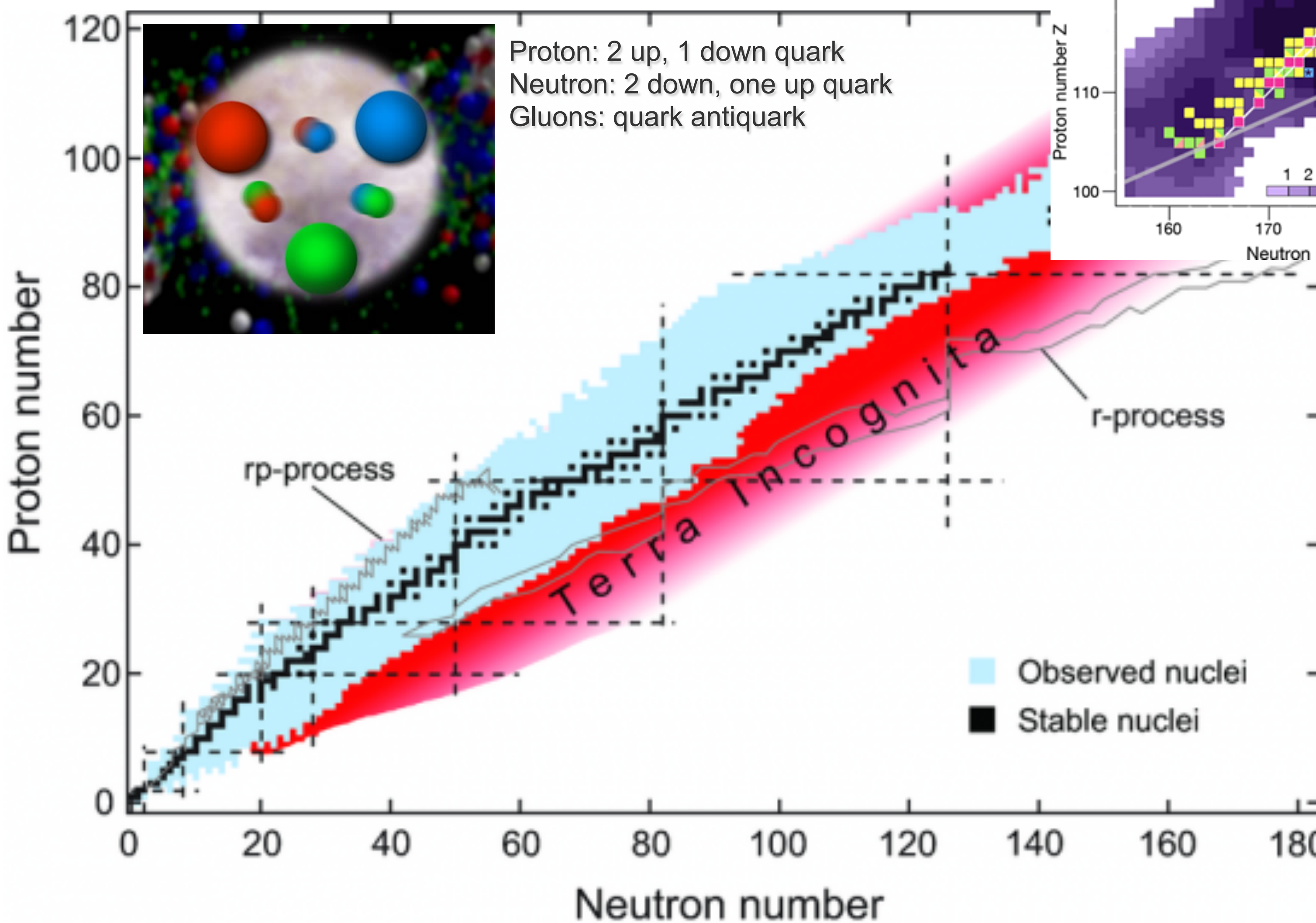


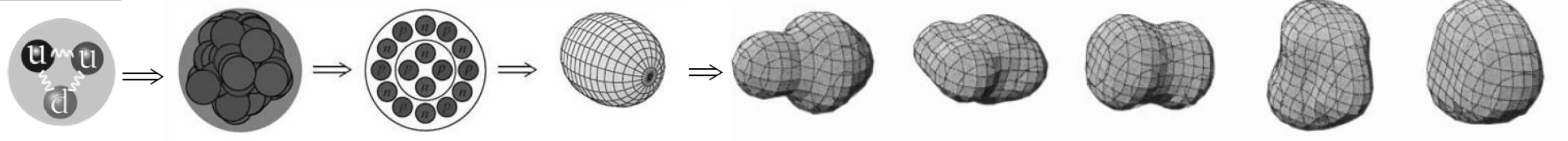


The Nuclear Chart

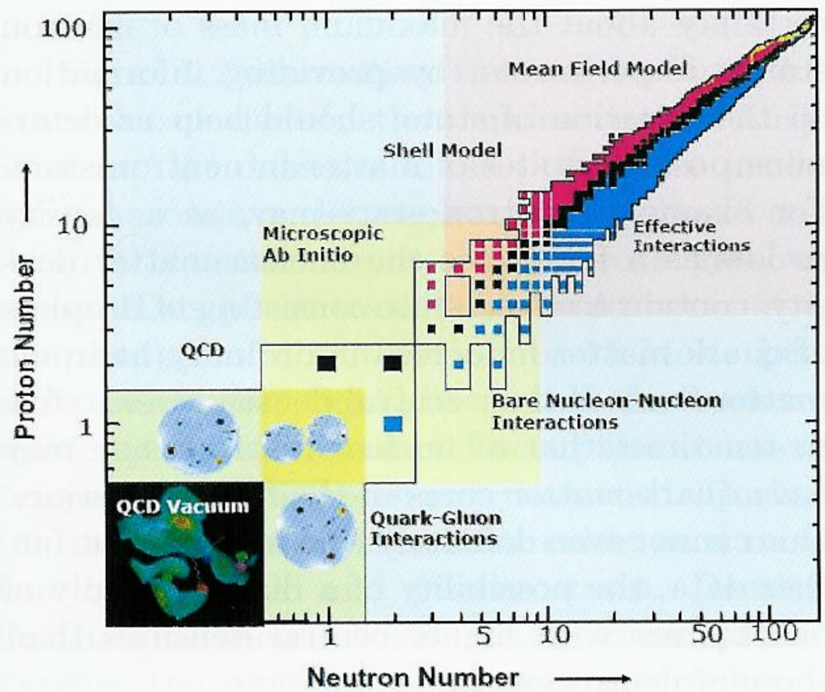
Yu. Ts. Oganessian et al.
Phys. Rev. Lett. **104**, 142502 (2010

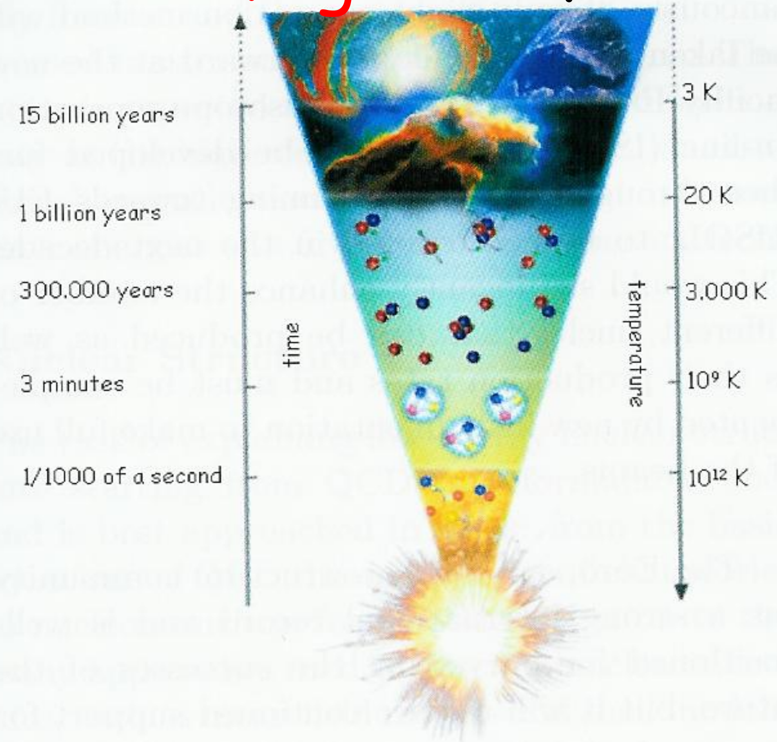






Nucleus as few body system, interacting through the strong, weak, and electromagnetic forces!

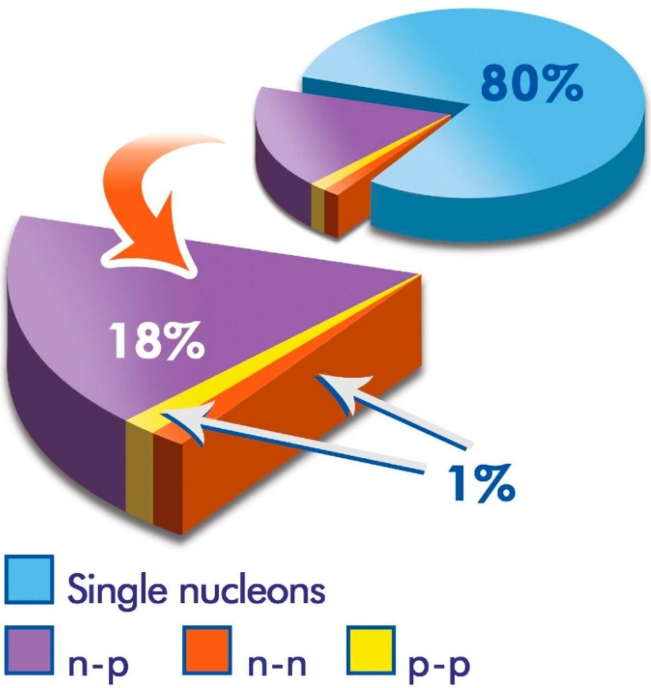


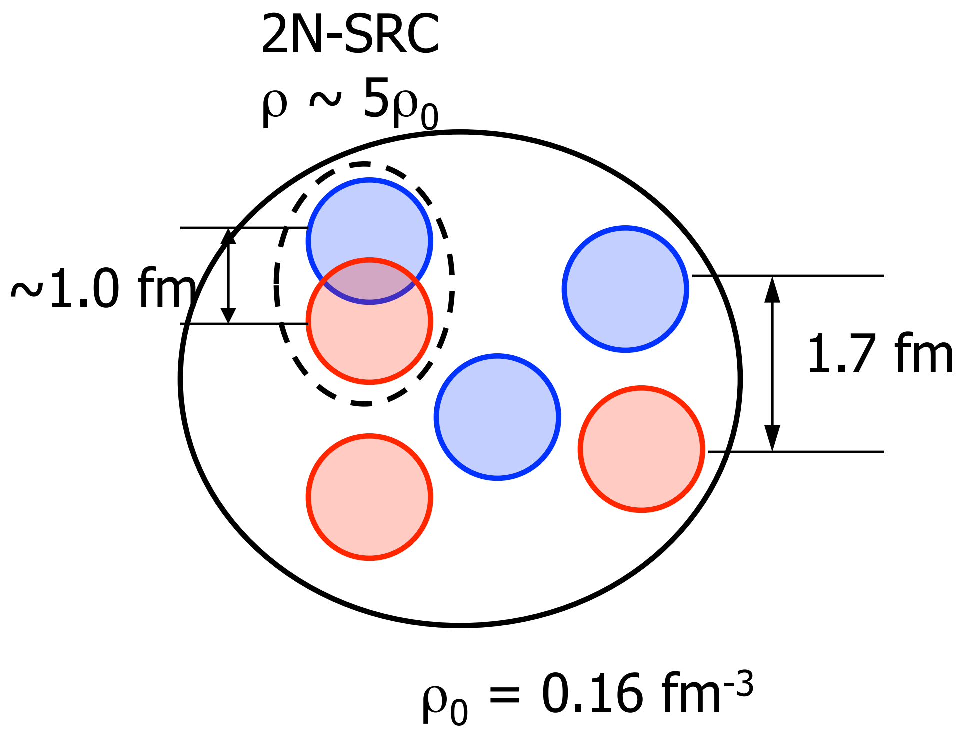


Implications for: Astrophysics, Particle physics, Mesoscopic physics, Condensed matter physics

Applications in: Medicine, Material Science, Art and Archaeology, Geology and Climatology, Energy Production, Defense, Nuclear Forensics

Two nucleon short range correlations (NN-SRC)

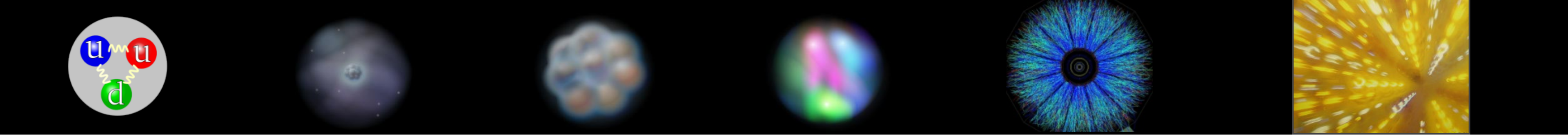




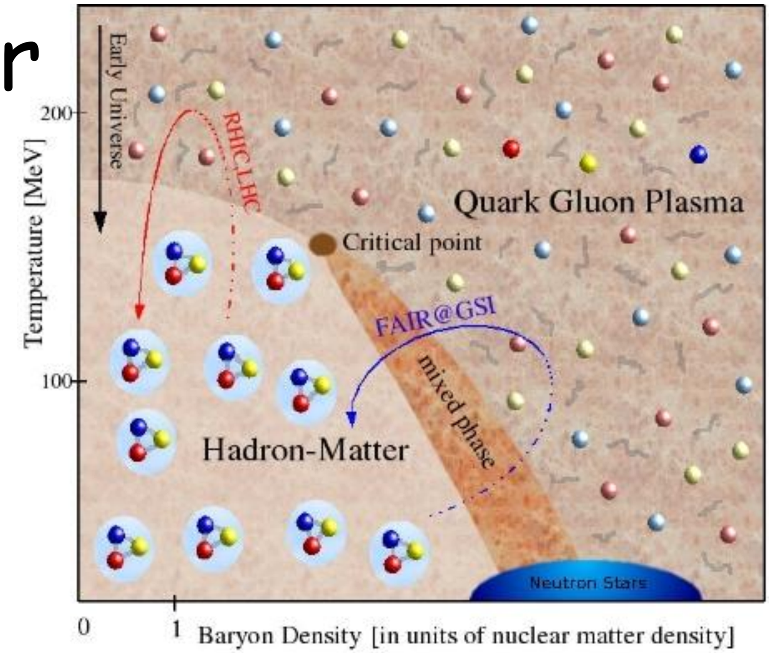
Studying NN-SRC concerns:

- High momentum part of the nuclear wave function
- Short distance behavior of nucleons - overlapping??
- EMC Effect
- Neutron Stars

K.S. Egiyan, N.B. Dashyan, M.M Sargsian, et al.
Phys. Rev. Lett. 96, 082501 (2006)

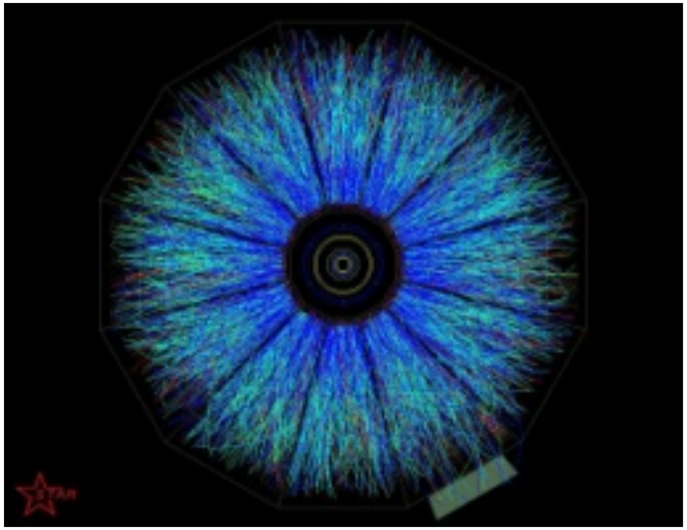


Phases of Nuclear Matter

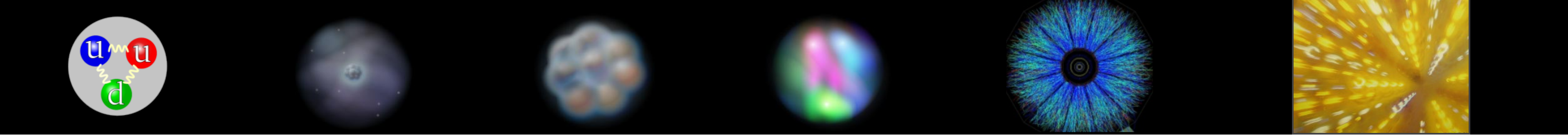


QCD phase transitions in nuclear matter from quark structure of nuclei to quark gluon plasma. (from quark gluon liquid to quark gluon gas)

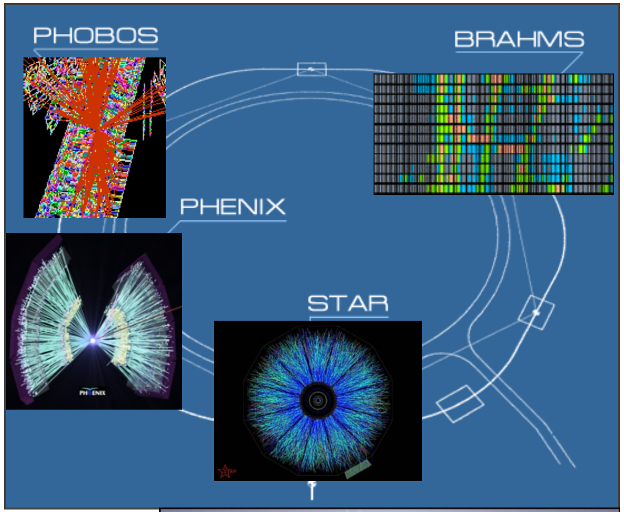
Measurements performed by the study of Relativistic Heavy Ion Collisions: RHIC



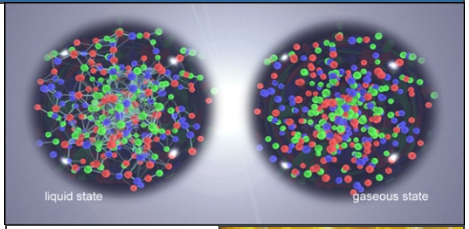
Collision creates the conditions of the early universe in a split second!



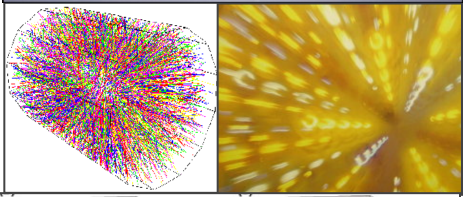
Accomplishments in Quark Gluon Plasmas



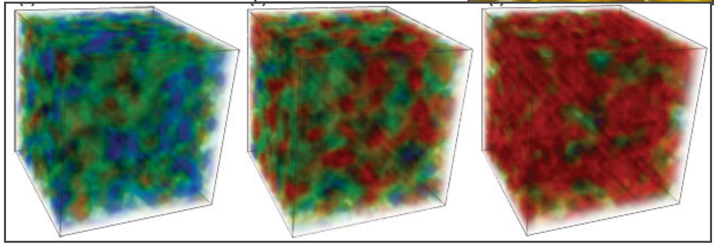
Starting the Relativistic Heavy Ion Collider program with BRAHMS, PHENIX, PHOBOS, and STAR



The quark gluon liquid or quark-gluon glass

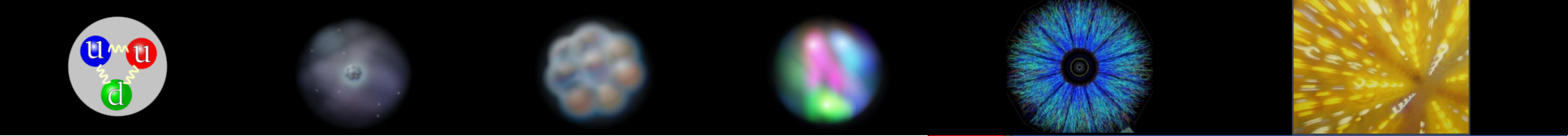


Jet production in collision experiments



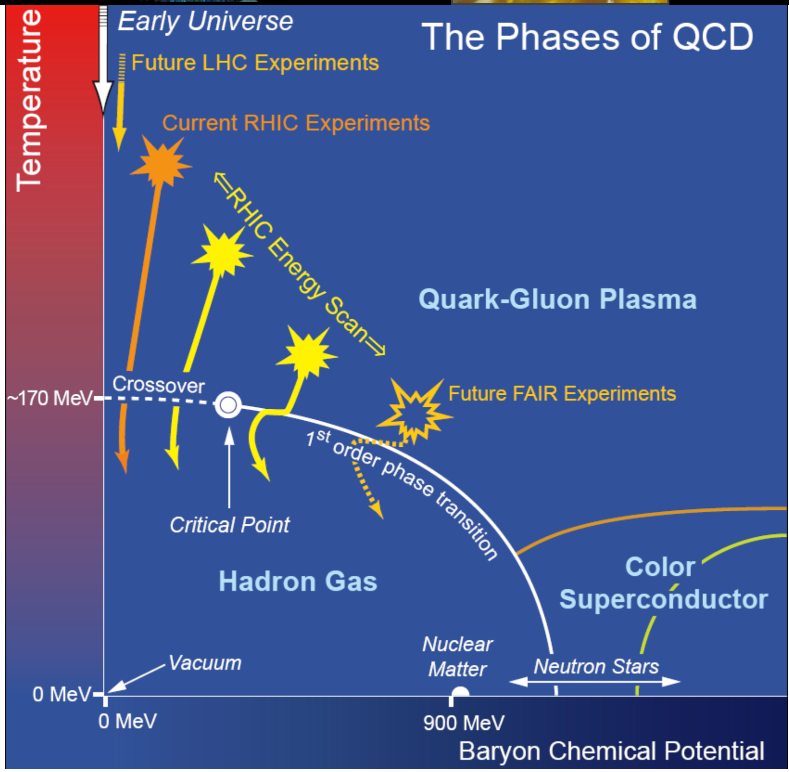
Lattice QCD calculations for QCD matter

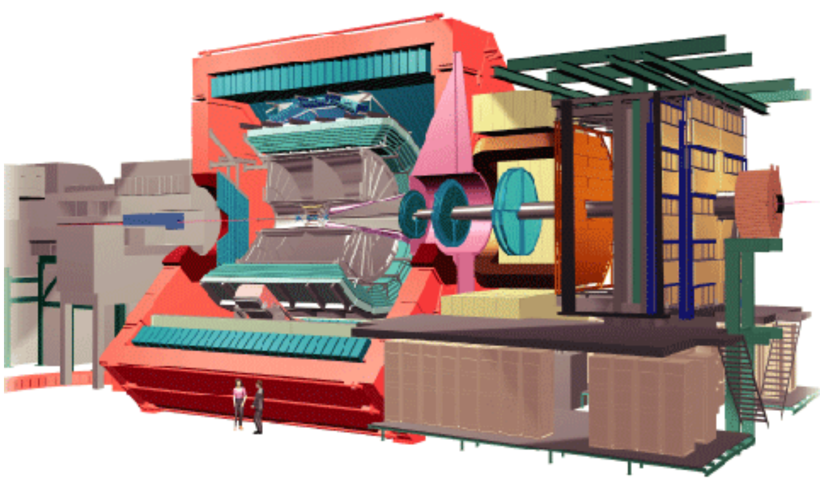
nucleons ⇒ quarks

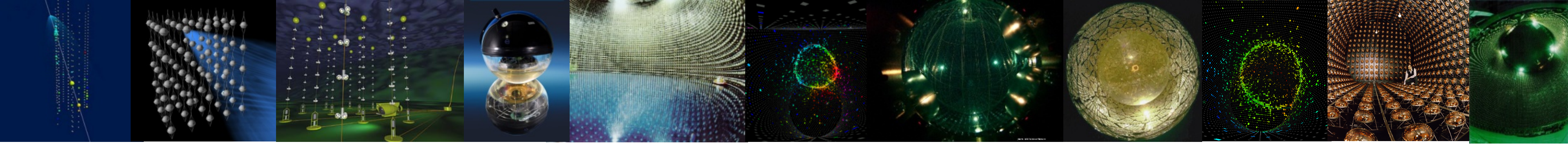


Future Goals & Efforts

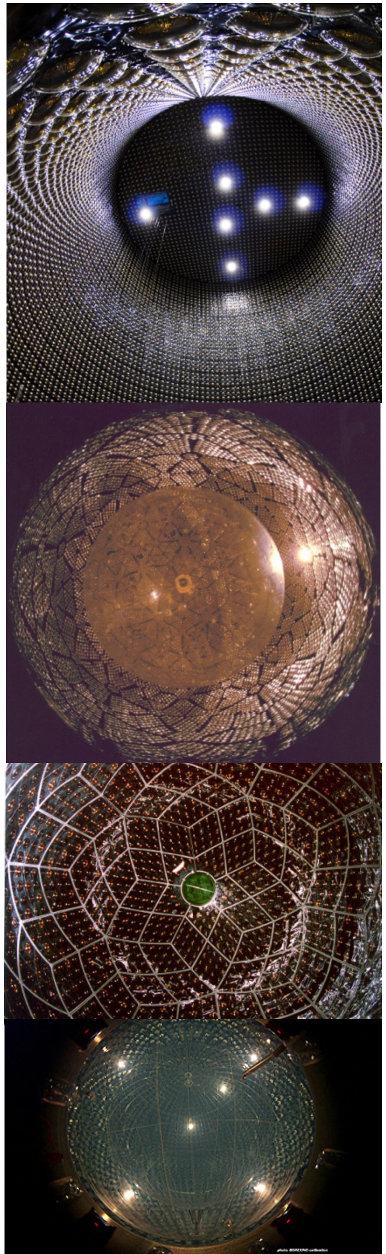
- Up-grade of PHENIX & STAR
- Increase of RHIC luminosity
- US participation in heavy ion program at LHC at CERN with the detectors ALICE
- Relativistic heavy ion beam experiments at the HADES detector at FAIR/GSI







Neutrino Physics Accomplishments



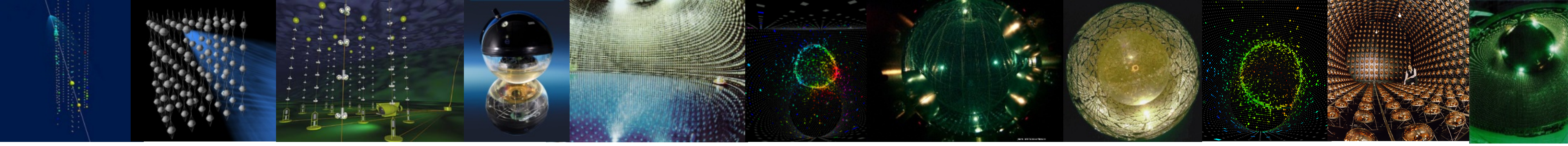
Last decade opened new era of nuclear physics, the study of low energy neutrinos from sun and supernova and in laboratory decay

1998 Super Kamiokande (light water Cherenkov detector) announces evidence for neutrino oscillations which indicates that neutrinos have mass (0.05 – 0.18 eV)

2001 SNO (heavy water Cherenkov detector) confirmed neutrino oscillations and solves solar neutrino problem by detecting neutrinos consistent with predicted decay rate of ^{8}B in the 3rd pp-chain

2003 KamLAND (liquid scintillator detector) confirmed neutrino oscillation from terrestrial neutrino source (reactor) and showed oscillation pattern

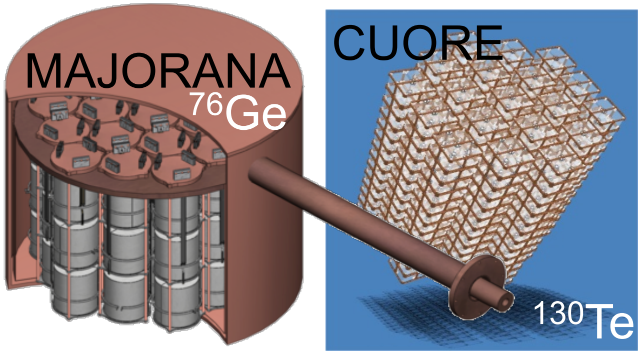
2007 Borexino (liquid scintillator detector) at Gran Sasso detects low energy solar neutrinos consistent with the predicted electron capture rate of ^{7}Be in 2nd pp chain.



Fundamental Symmetries

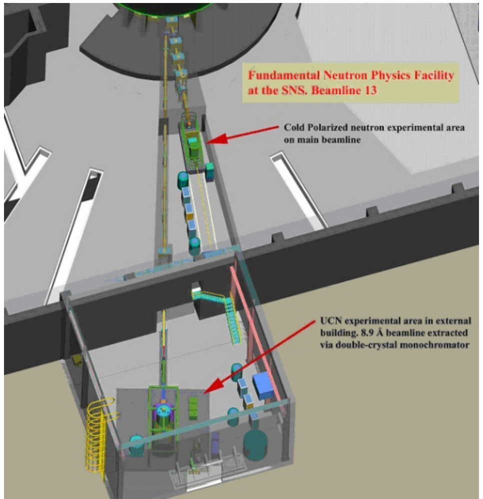
Standard Model Initiative

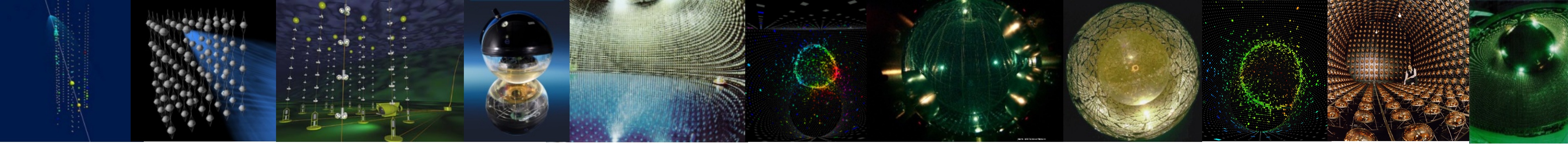
What are the neutrino masses?
Tritium decay measurements with KATRIN



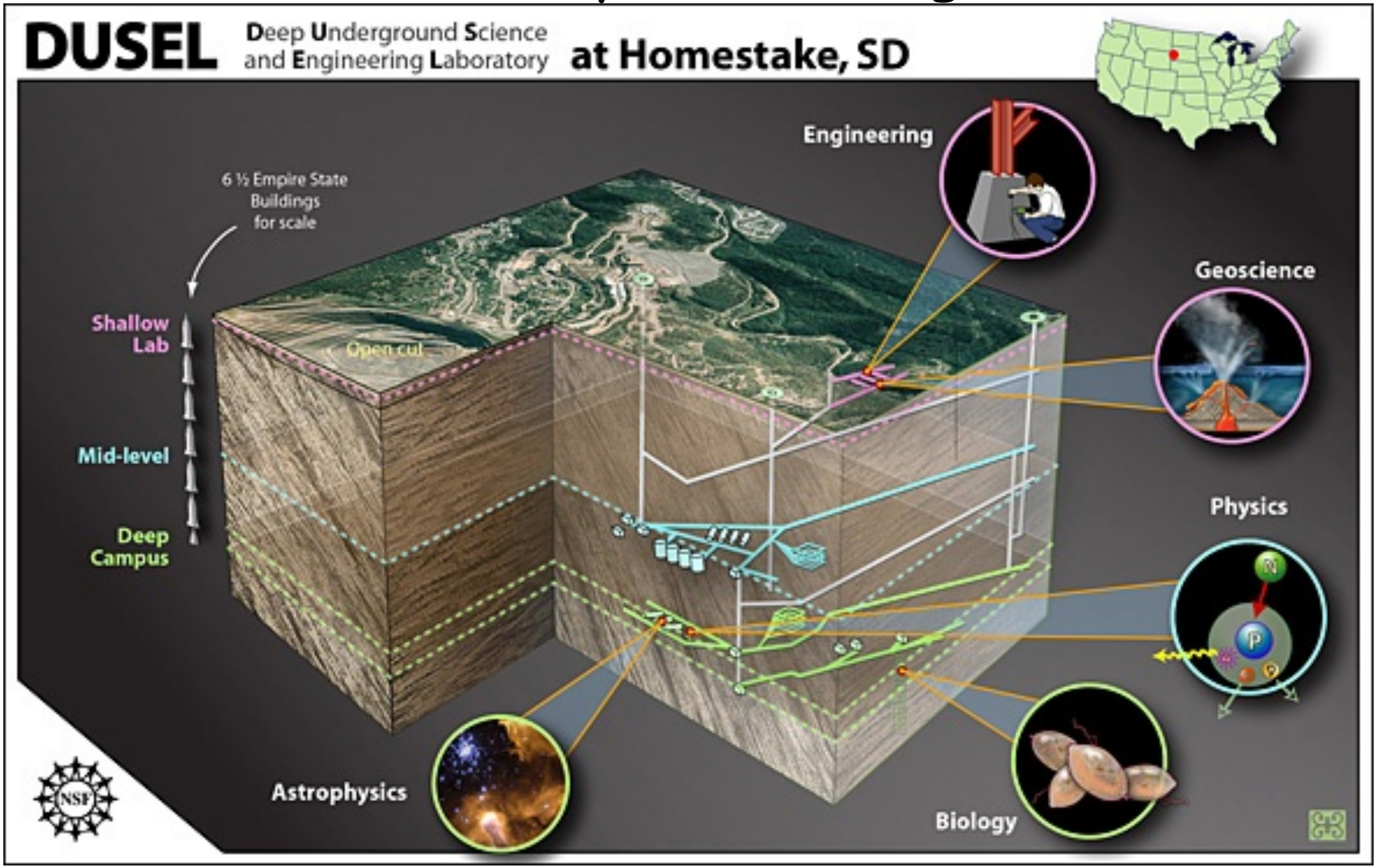
Are neutrinos their own antiparticles?
Neutrino less double beta decay measurements
In background free underground environments
(Gran Sasso, SNO, WIPP, ...)

Violation of CP symmetry (matter anti-matter balance) by neutrino oscillation experiments and neutron EDM measurements (ultra-cold neutrons at Los Alamos, SNS, PSI ...

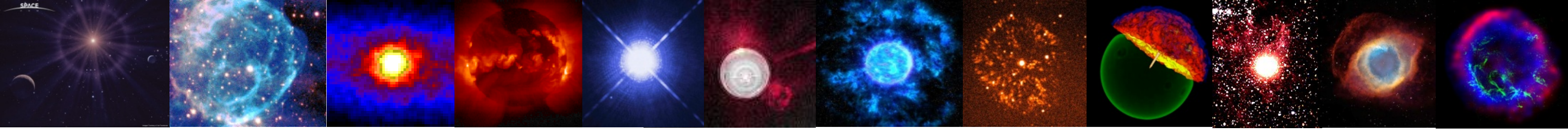




Neutrino Physics Underground



designed for experiments that require extremely low cosmogenic backgrounds: in particular, the search for neutrino-less double beta decay and relic dark matter.

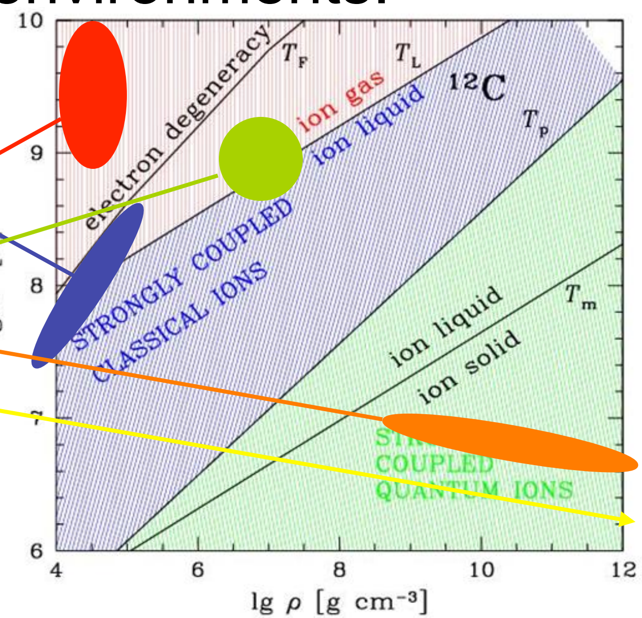


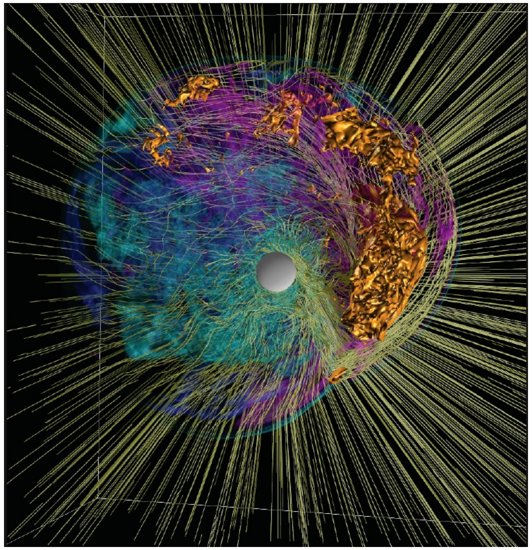
Nuclear Astrophysics

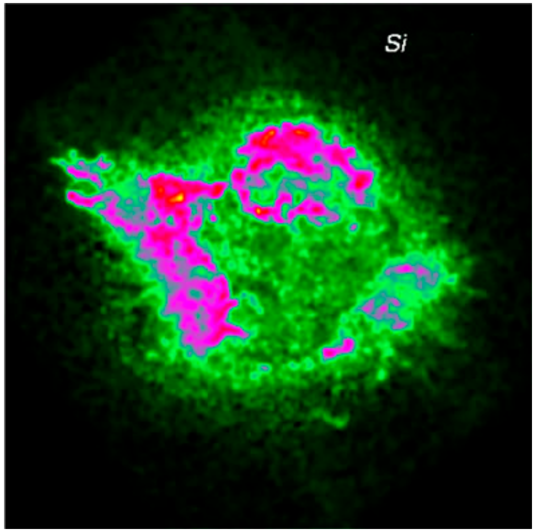
The Cosmic Laboratory

Understanding nuclear processes at the extreme temperature & density conditions of stellar environments!

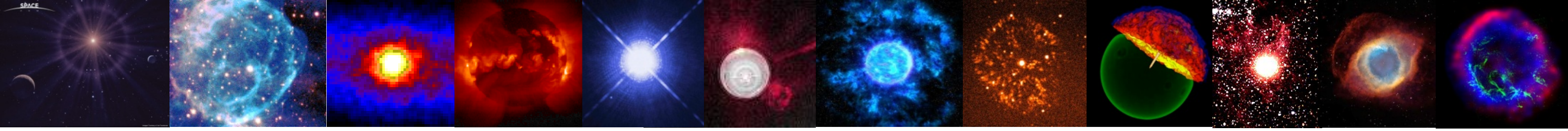
- Stellar matter
- Stellar explosions
- White Dwarf matter
- Neutron Star matter
- Quark Star matter





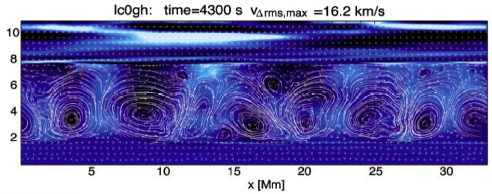


Field requires close communication between nuclear experimentalists, theorists, stellar modelers and stellar observers (astronomers)

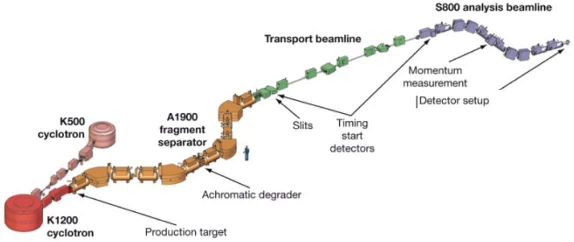


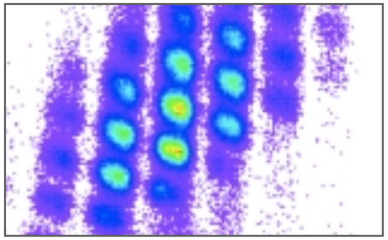
Measurements of solar reaction rates at LUNA, Gran Sasso within Gamow window of solar core temperature

Mapping the s-process at ORELA, LANSCE, n-ToF. Model simulations for AGB stars.

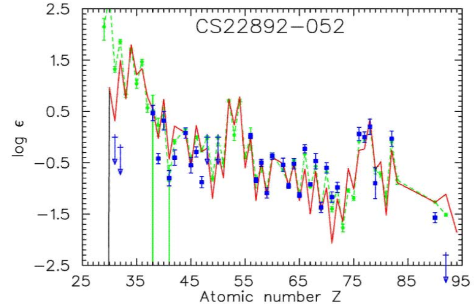


Probing reactions and decays far off stability for r- and rp-process at HRIBF and NSCL for supernovae and cataclysmic binaries.

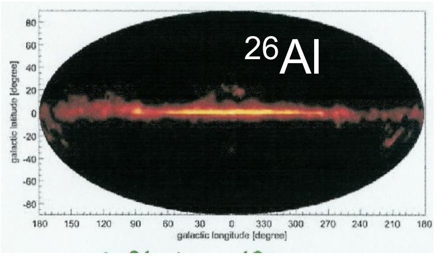


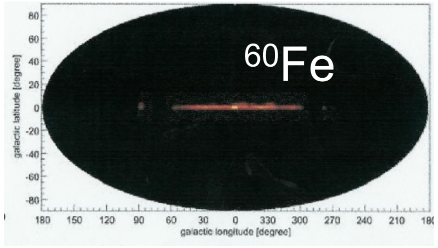


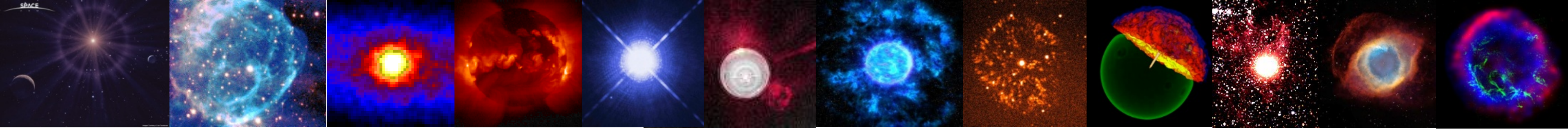
Observation of r-process signatures in metal poor (old) halo stars



Mapping Galactic Radioactivity with gamma ray satellites





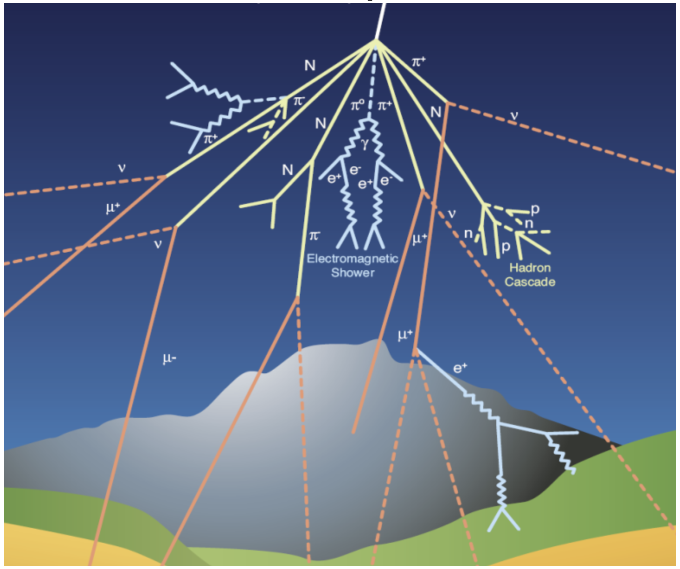


Astrophysics underground

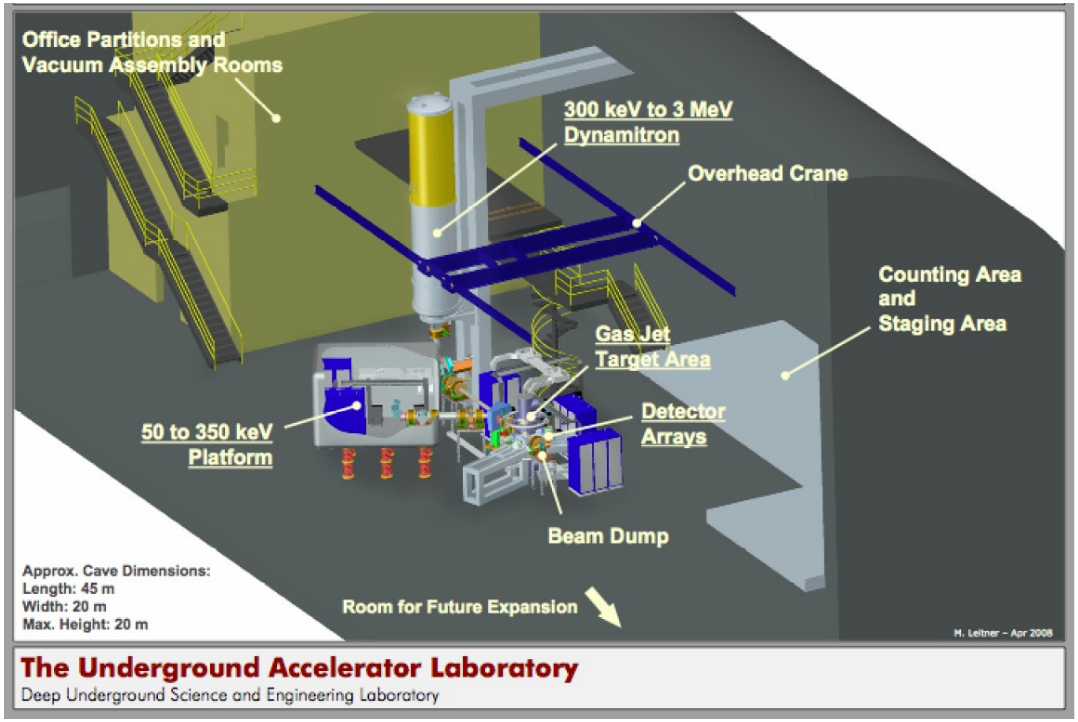
Nuclear Reactions at stellar temperatures

- Timescale of stellar evolution
- Stellar energy production
- Nucleosynthesis from He to Fe
- Seed production for explosive nucleosynthesis
- Neutron production for trans-Fe elements
- Solar neutrino production

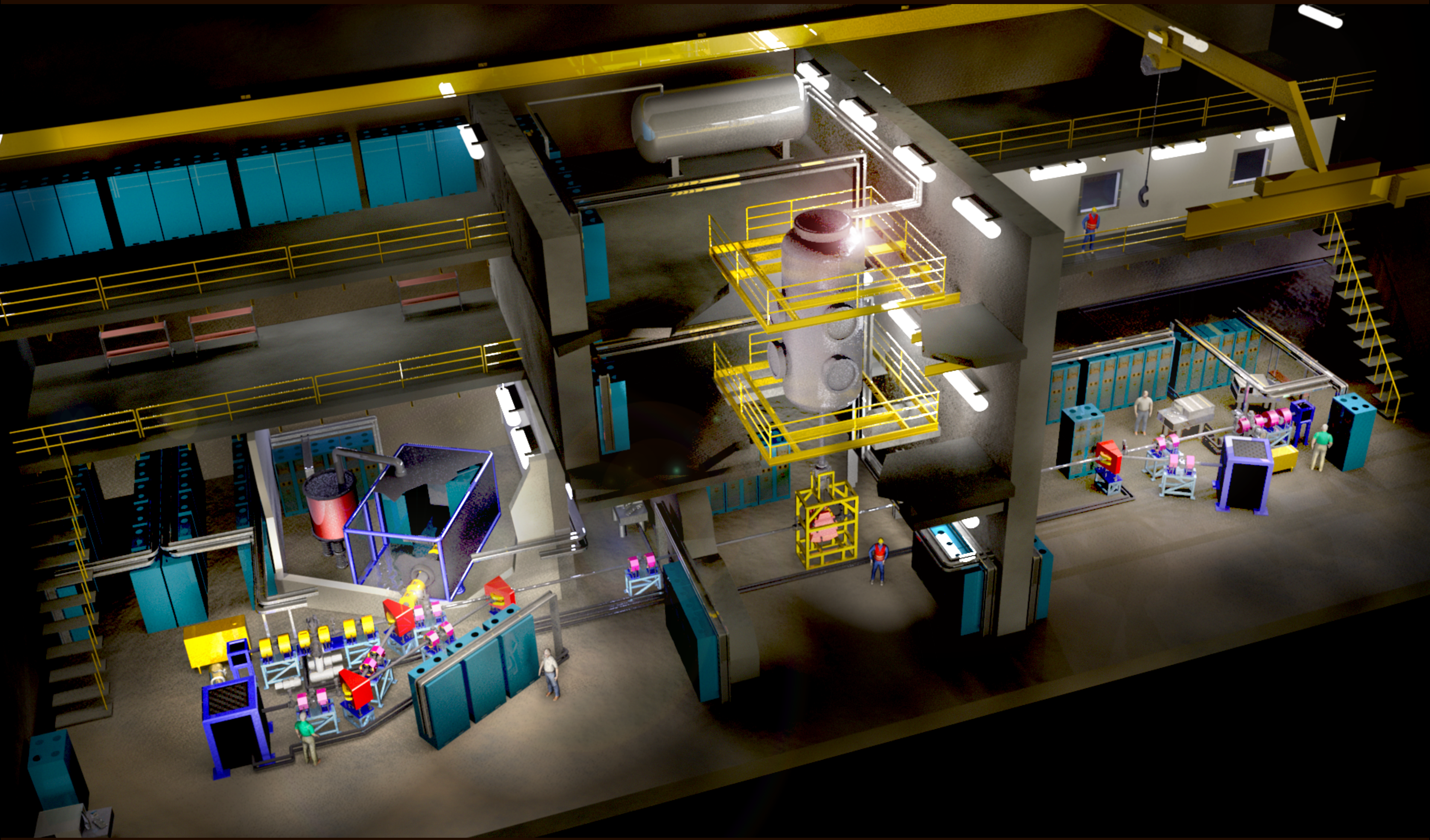
Two-Accelerator laboratory at DUSEL



Measurements handicapped by Cosmic Ray background

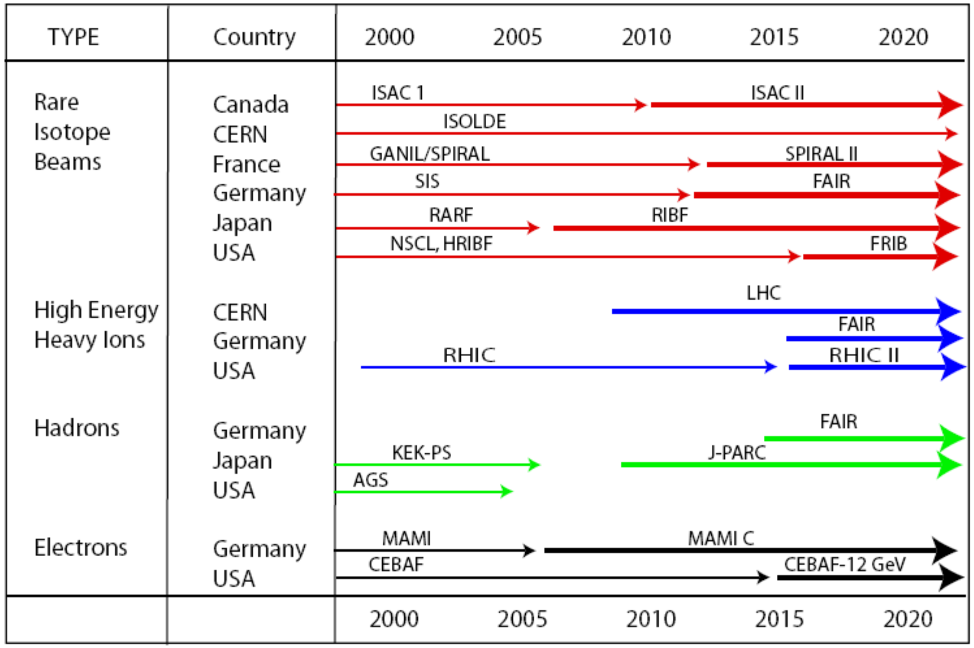


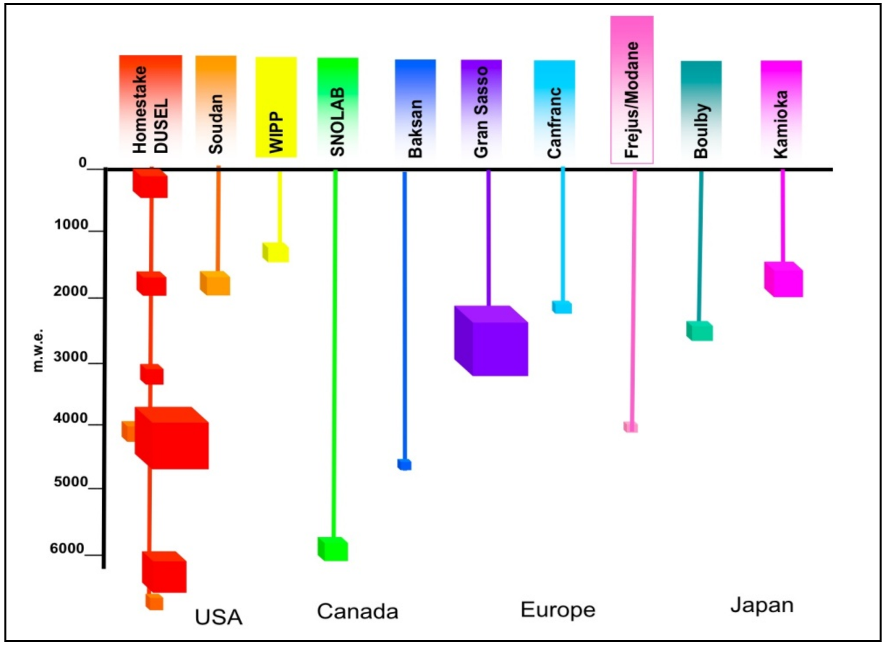
DIANA design

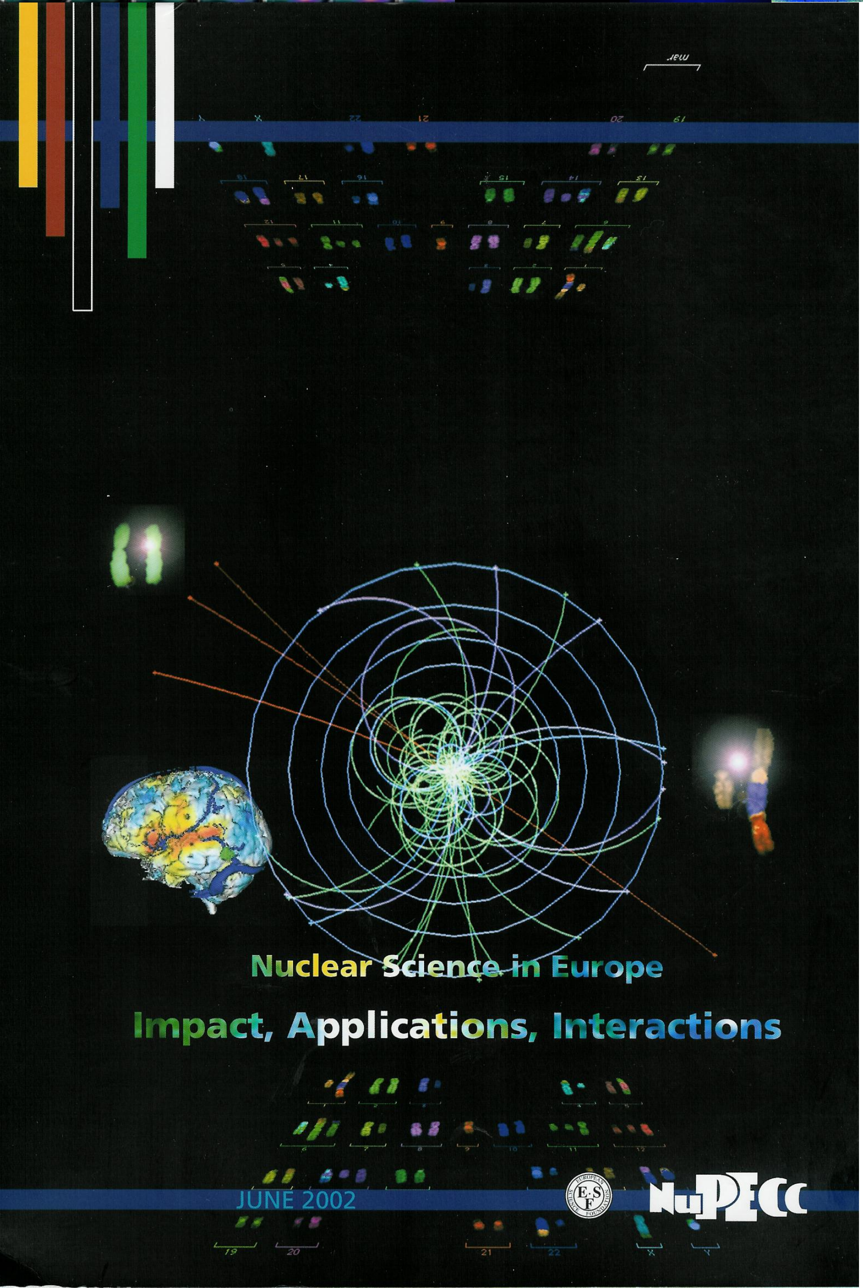


International Situation

Figure 4: Roadmap for existing and planned underground laboratories with the size of the box corresponding to the relative space for experiments at each depth. These facilities are typically shared or primarily funded by other disciplines such as particle astrophysics.







Nuclear Physics Applications

Energy
- ADS systems
- Fusion confinement
- Nuclear Waste
- Nuclear Data

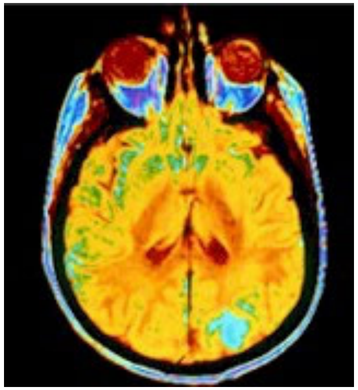
Nuclear Forensics
- Homeland Security
- Risk Assessments
- Nuclear Trafficking
- Proliferation

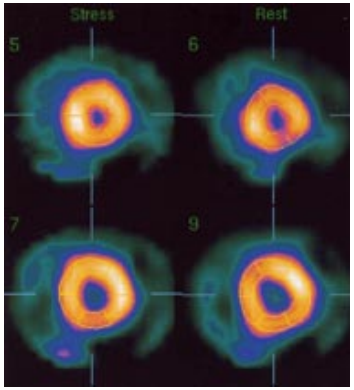
Life Sciences
- Medical Diagnostics
- Medical Therapy
- Radiobiology
- Biomedical tracers

Material Analysis
- Ion Implantation
- Material Structure
- Geology & Climate
- Environment
- Art & Archaeology

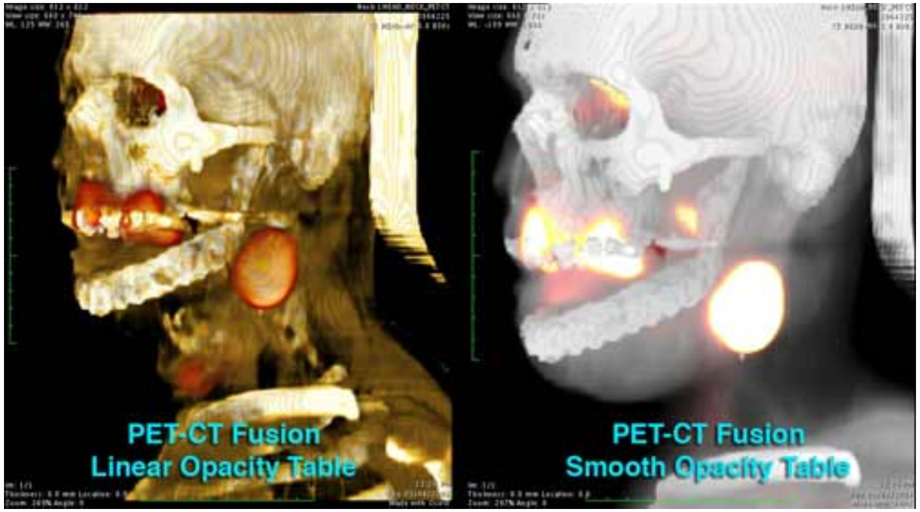
Nuclear Defense
- Weapon Analysis
- Functionality Simulation
- Long-Term Storage

Nuclear Imaging

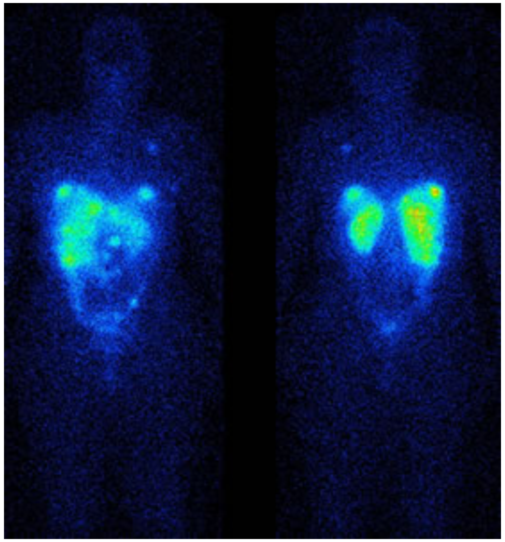




Blood flow with radiopharmaceuticals



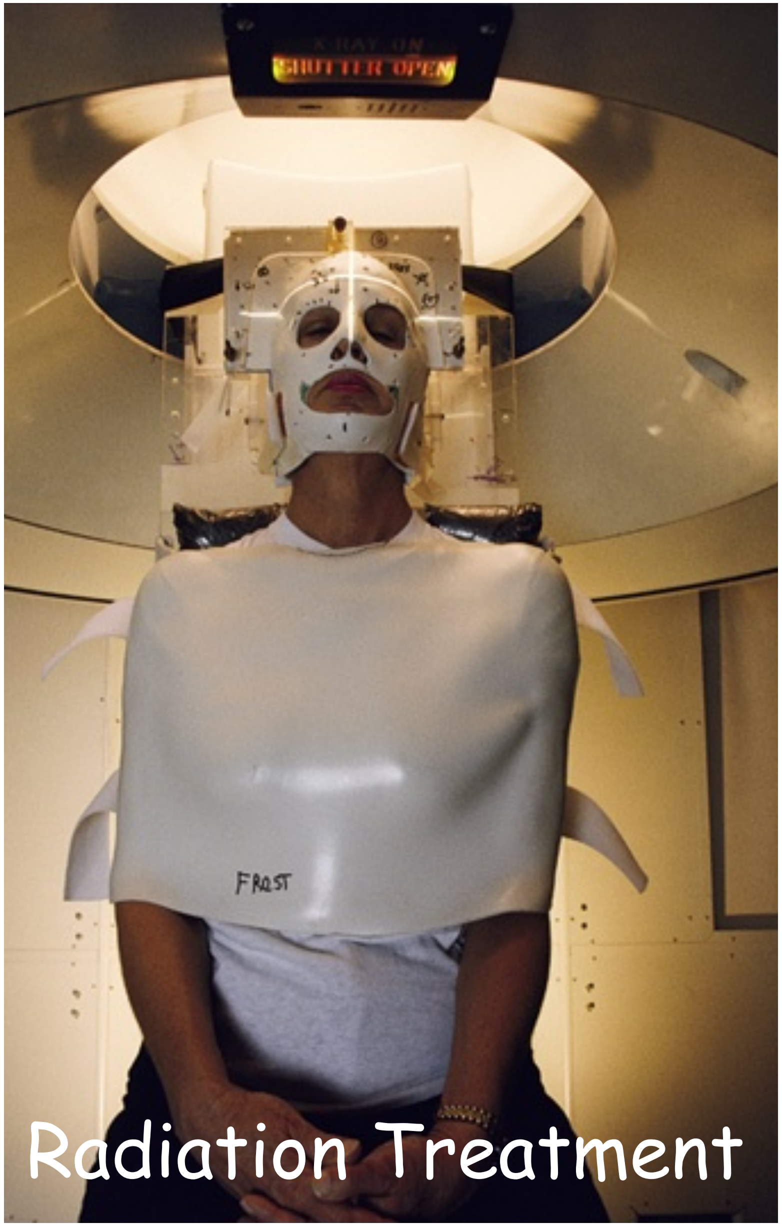
Imaging software and analysis

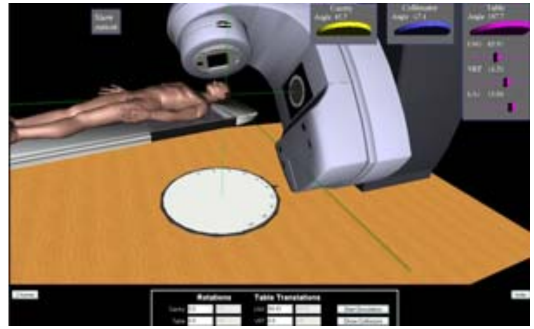


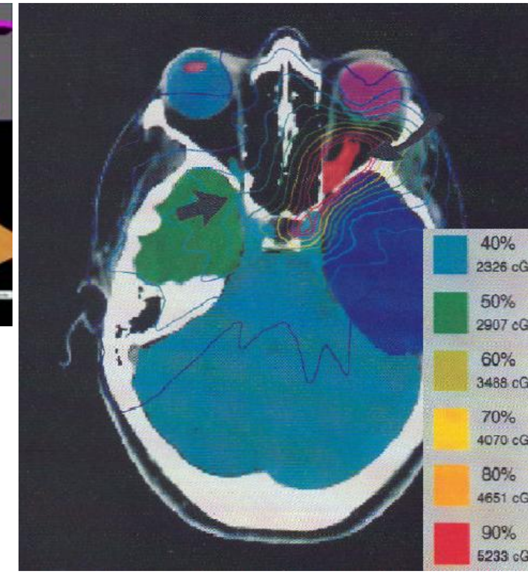
- Gamma Camera
- SPEC & PEP

Tumor mapping & visualization by radioactive isotope accumulation.

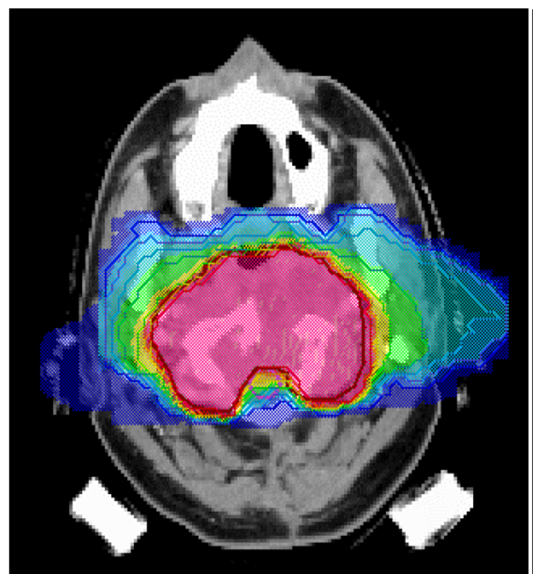
Imaging system development



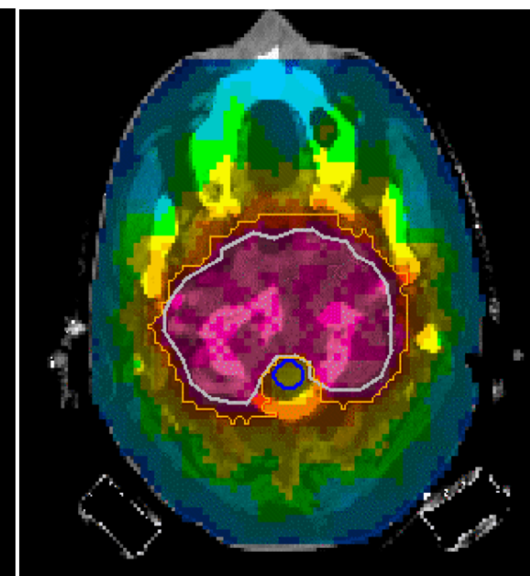




- Brachytherapy
- Gamma therapy
- Neutron therapy
- Heavy ion therapy

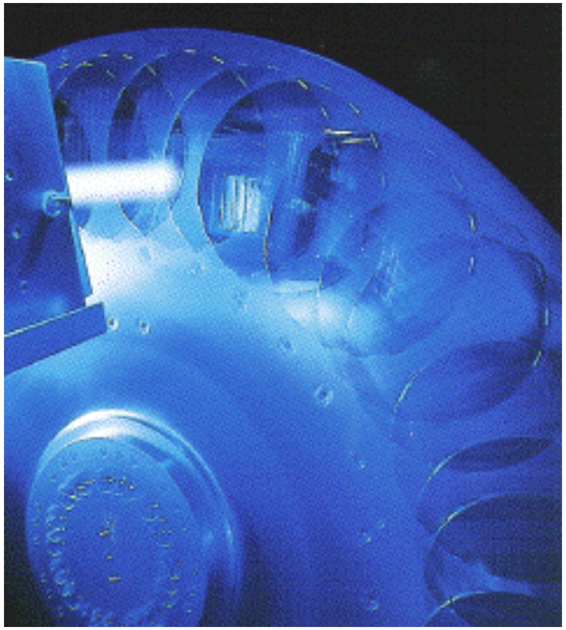


Treatment plan with 2 heavy ion fields



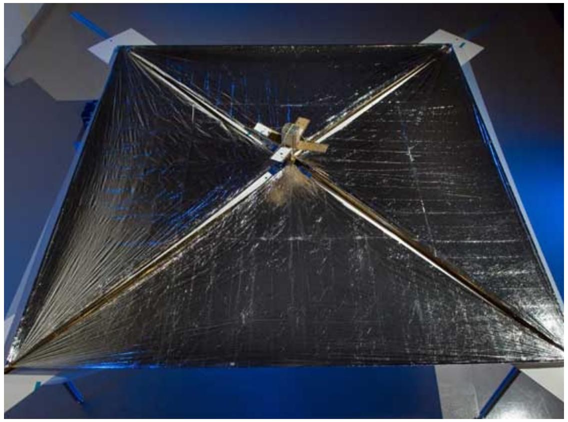
Treatment plan with 9 photon fields IMRT

Material Treatment and Analysis of Artifacts



Dating real and false mummies

Implantation and irradiation from silicon chips to solar sails



Conclusions:

Excitement about nuclear physics worldwide.

Can Open many doors to other areas of research.

Provide many exciting opportunities for applications.