Nuclear Physics Beyond the JLab (and QCD) Borders

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February, 2008

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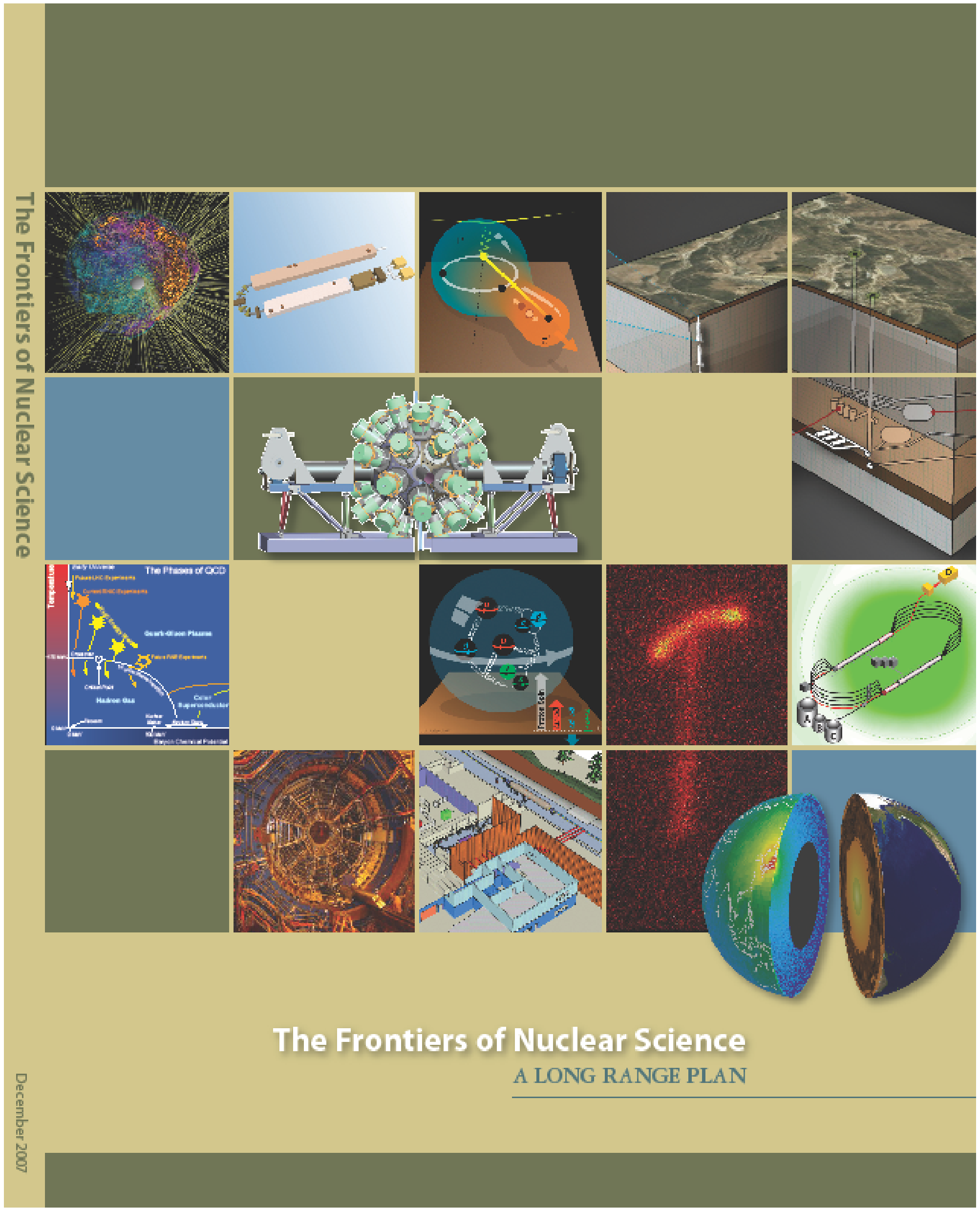
The Context



'Guidance' provided by the recent **Long Range Plan: The Frontiers of Nuclear Science**

LRP focus is on new science opportunities for **nuclear physics**

Requires **upgrading** facilities, **constructing** new facilities and detectors

U.S. Nuclear Science

[Today and for the Next Decade]

General goal:
Explain the origin, evolution, and structure of the visible matter of the universe—the matter that makes up stars, planets, and human life itself.

Frontiers:

- Quantum Chromodynamics (QCD)
- Physics of Nuclei and Astrophysics
- Fundamental Symmetries and Neutrinos

The Science – QCD

- What are the phases of strongly interacting matter and what roles do they play in the cosmos?
- What is the internal landscape of the nucleons?
- What governs the transition of quarks and gluons into pions and nucleons?
- What is the role of gluons in nucleons and nuclei and where do their self-interactions dominate?
- What does QCD predict for the properties of strongly interacting matter?
- What determines the key features of QCD and what is their relation to the nature of gravity and spacetime?

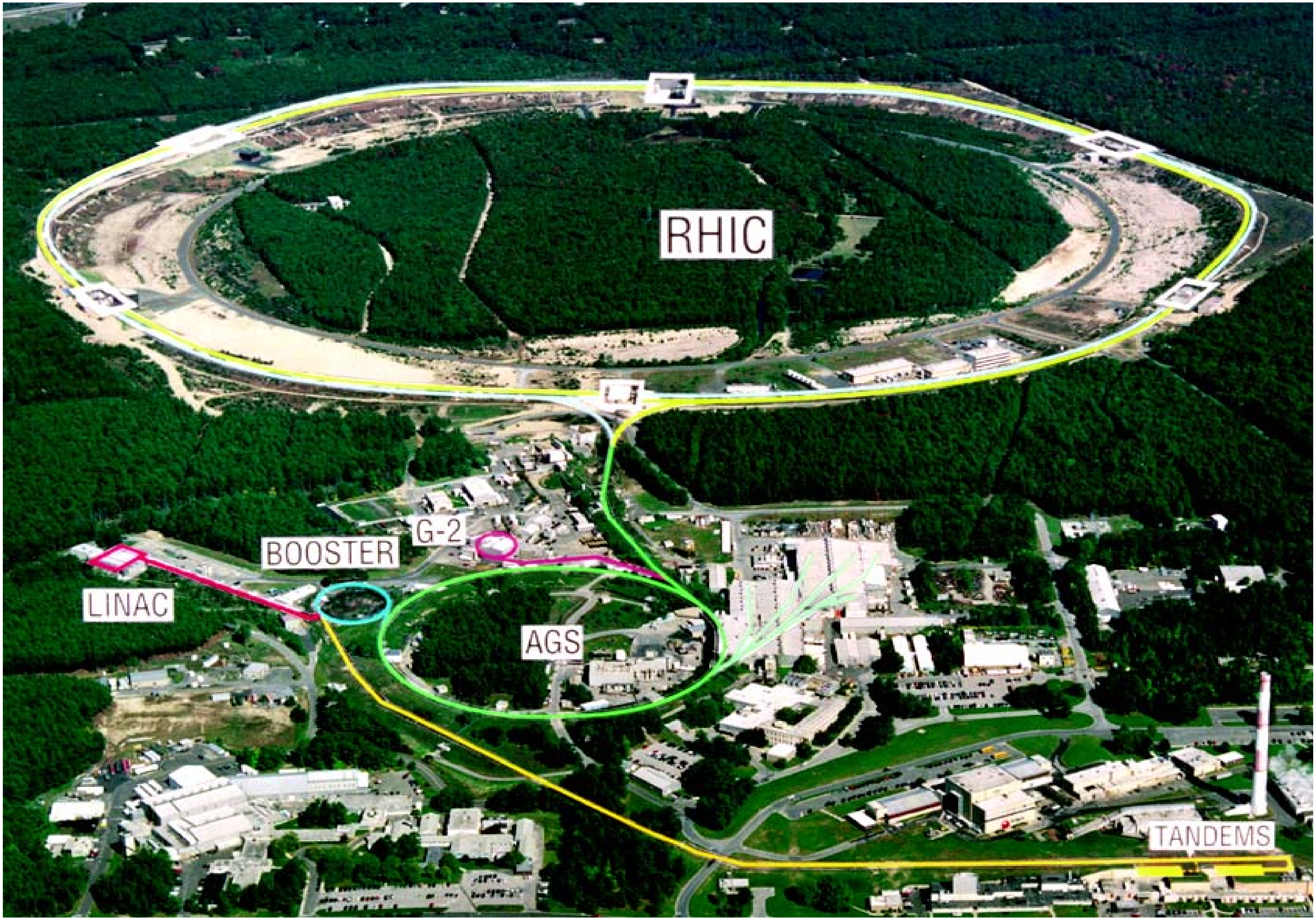
The Science – QCD

- Theory
- U.S. facilities

  &

- Recent Results

RHIC: the Relativistic Heavy Ion Collider

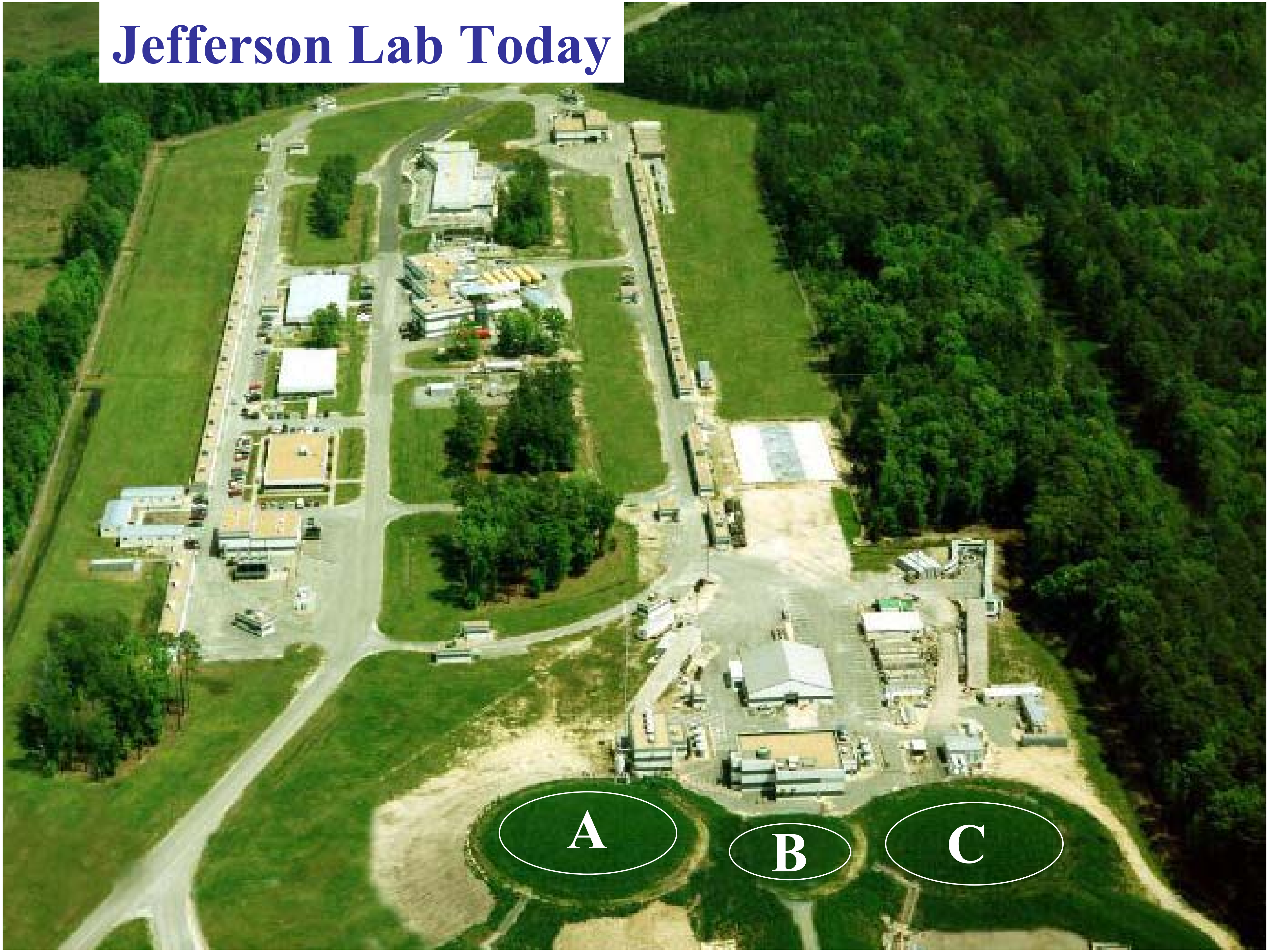


Hot QCD

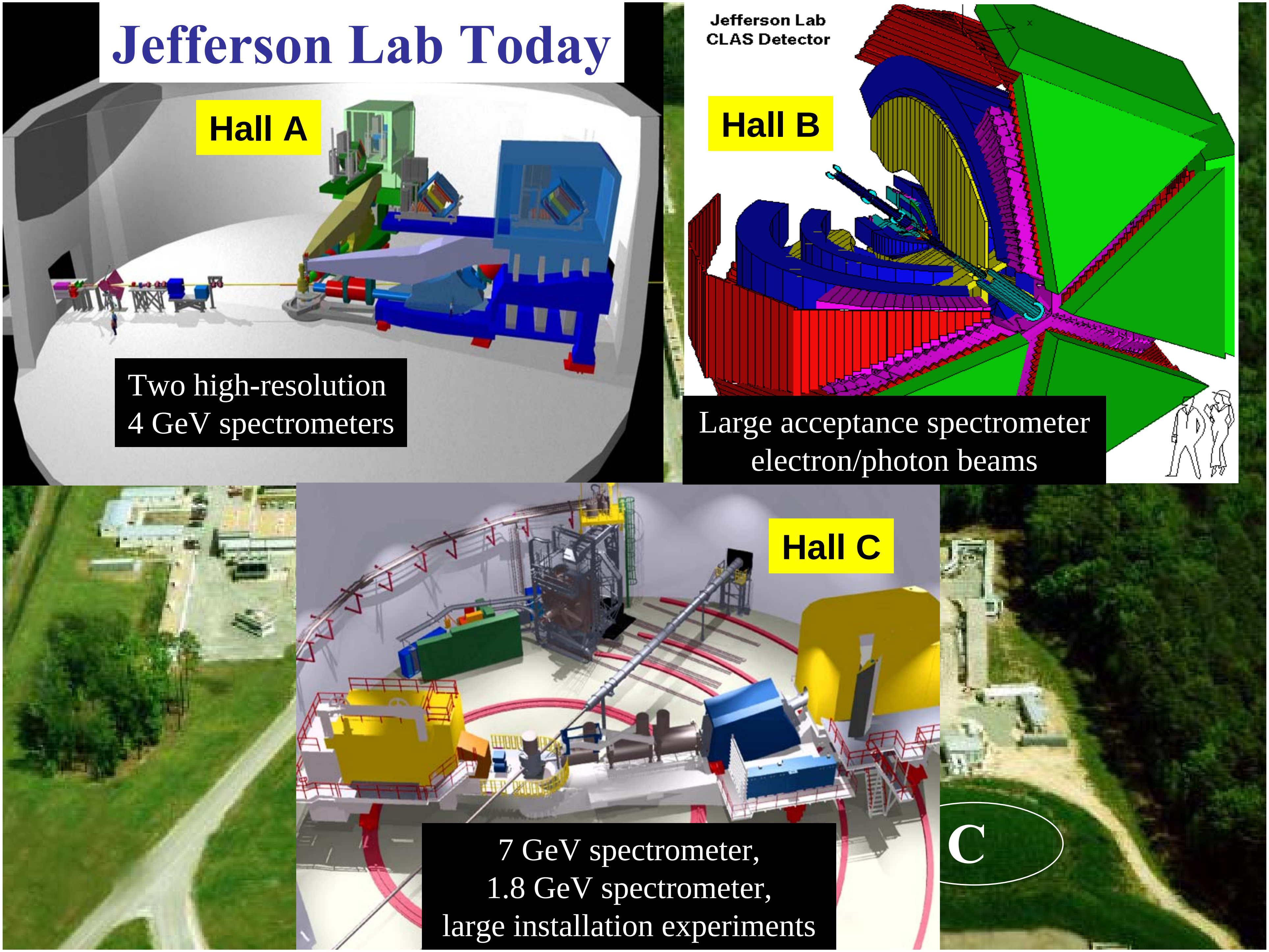
Recent Successes:

- Discovery of a **Near Perfect Fluid** – enormous collective motion found in the (QGP) medium
- **Jet Quenching** – large energy loss that shows up as shock wave
- **Novel Hadronization** (unexpected baryon/meson ratio appears to follow constituent quark scaling)
- **Novel phenomena at high parton density** (particle yields in central Au-Au collisions smaller than expected – saturation effects?)

Jefferson Lab Today



Jefferson Lab Today



QCD and Hadron Structure

Recent Achievements:

- New era - **precision predictions of QCD** from the lattice
- New **constraints on the origin of the nucleon spin**
- PV electron scattering – **strange quark contribution to electric and magnetic properties** of the proton
- Mapping of **charge distribution of neutron**
- Observation of **three-nucleon short range correlations** in nuclei
- Initial constraints on **Generalized Parton Distributions**
- Proton **quark distributions** are modified by **spin orbit correlations**

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The Science – Fundamental Symmetries and Neutrinos

- **What is the nature of the neutrinos, what are their masses, and how have they shaped the evolution of the universe?**
- **Why is there now more matter than antimatter in the universe?**
- **What are the unseen forces that were present at the dawn of the universe but disappeared from view as it evolved?**

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The Science – Fundamental Symmetries and Neutrinos

- **Uses wide range of facilities**

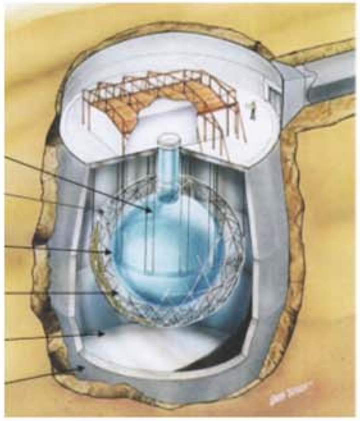
- **Many recent successes**

Activities in the field (accelerators)

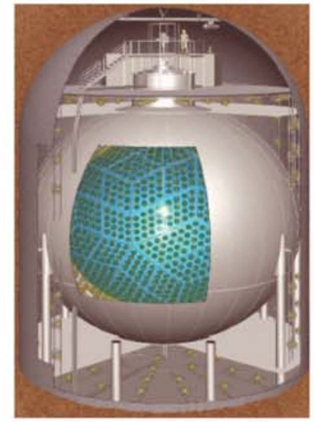
Neutrons	NIST LANSCE SNS FnPB	nEDM	BSM, BAU, CP …
		Lifetime Asymmetries	g_A, (λ), V_{ud}, BSM CKM Unitarity,
PVES	JLab SLAC	G0,Happex	s-quark; QCD
		Qweak	
		Möller ee	α running; BSM
		PVDIS	
Muons	PSI TRIUMF BNL FNAL ?	Michel parm	$\rho, \delta, \eta, P_\mu\xi$ (÷10)
		Lifetime	G_F (1 ppm)
		μ^-p capture	Λ_S -> g_P
		μ^-d capture	L1A; SNO ν connect
		g-2	SUSY, BSM
		μA->eA	LFV, BSM

DoE Division of Nuclear Physics

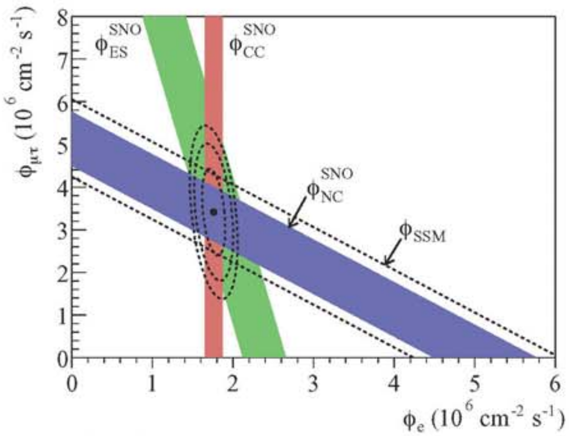
Returns from investments in Neutrino Physics



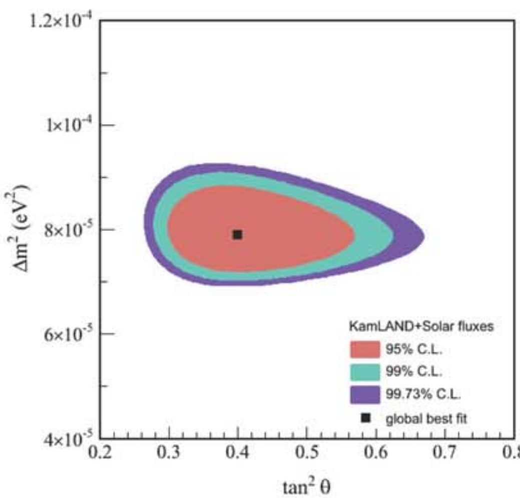
SNO



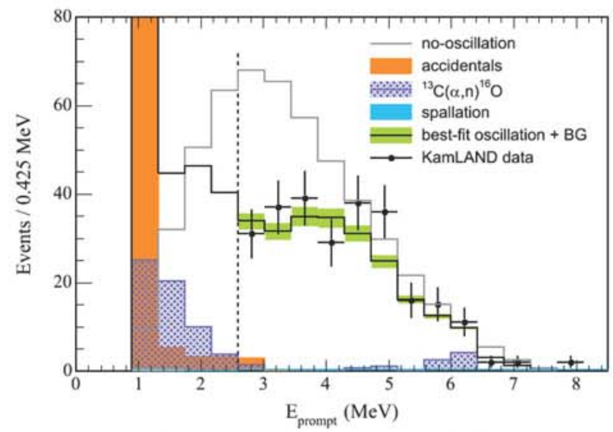
KamLAND



Solar neutrino problem resolved



Precise values of mass and mixing



LMA solution of the Solar Neutrino problem established

Open Questions

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

$\theta_{23} = (45 \pm 7)^\circ$

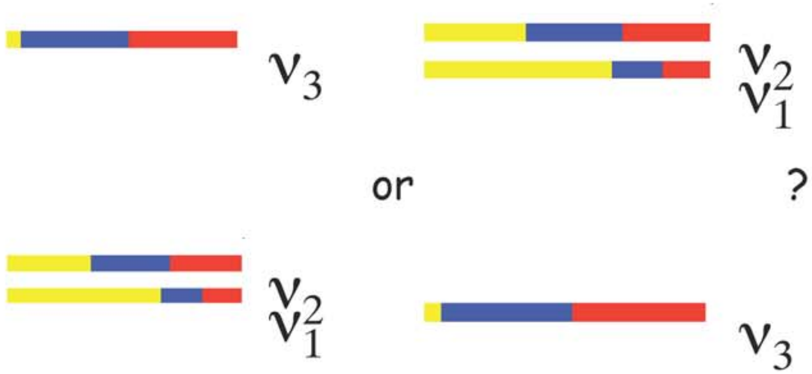
$\theta_{13} < 13^\circ$

$\delta = ?$

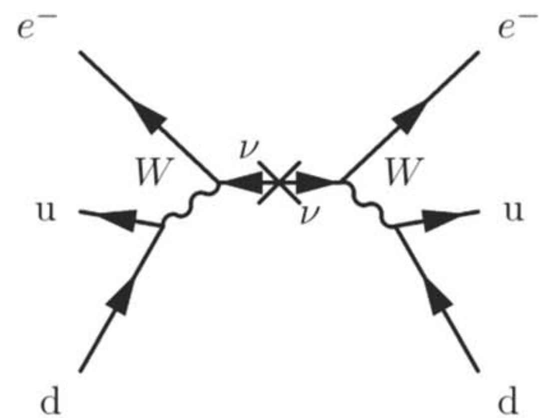
$\theta_{12} = (33.9^{+2.4}_{-2.2})^\circ$

$\alpha = ?$

$\beta = ?$



Normal or Inverted?



Majorana or Dirac?

Fundamental Symmetries and Neutrinos – **the Future**

- **$\beta\beta$ decay**
- θ_{13} (Daya Bay with HEP)
- **CP violation** – neutron EDM (β decay)
- new solar neutrino detector
- muon (g-2)
- . . .

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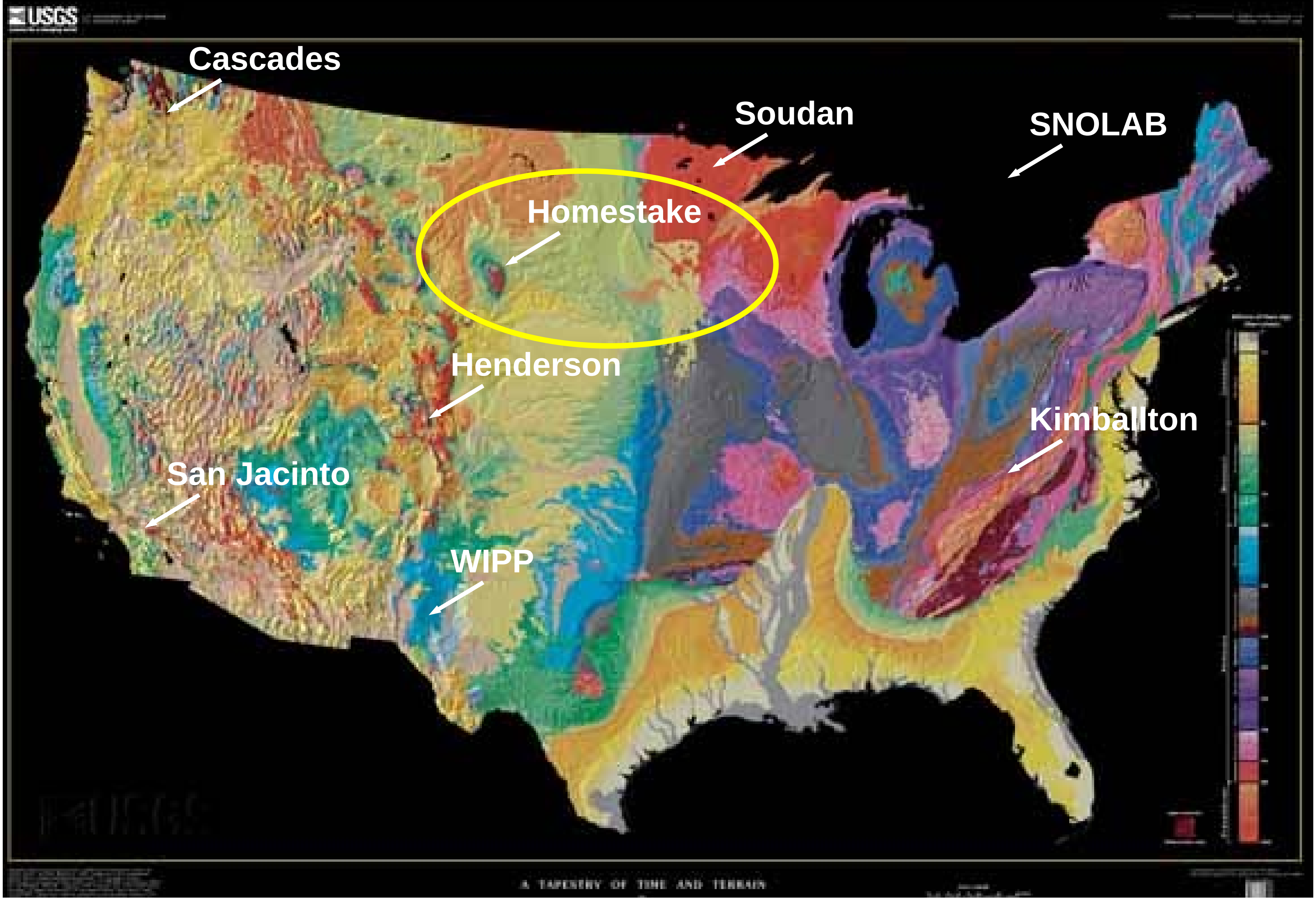
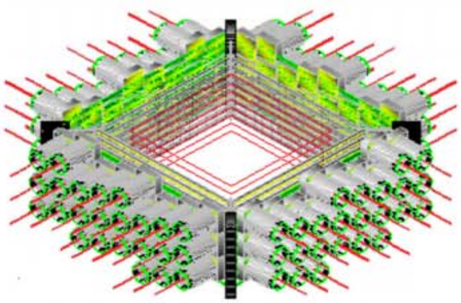
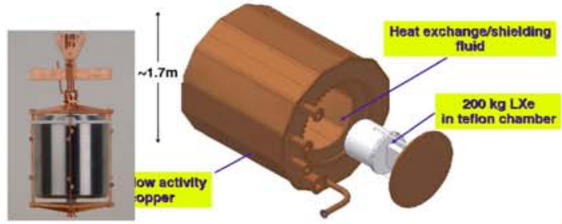
DUSEL Site Selection



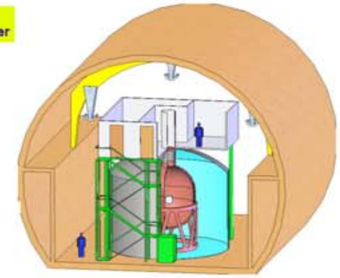


MOON

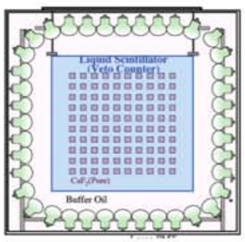


EXO

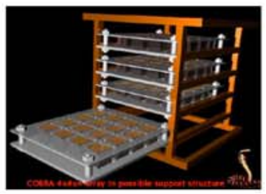
NEMO



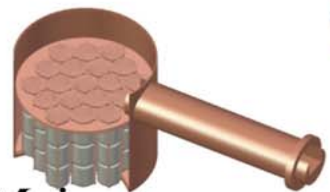
GERDA



Candles



Cobra



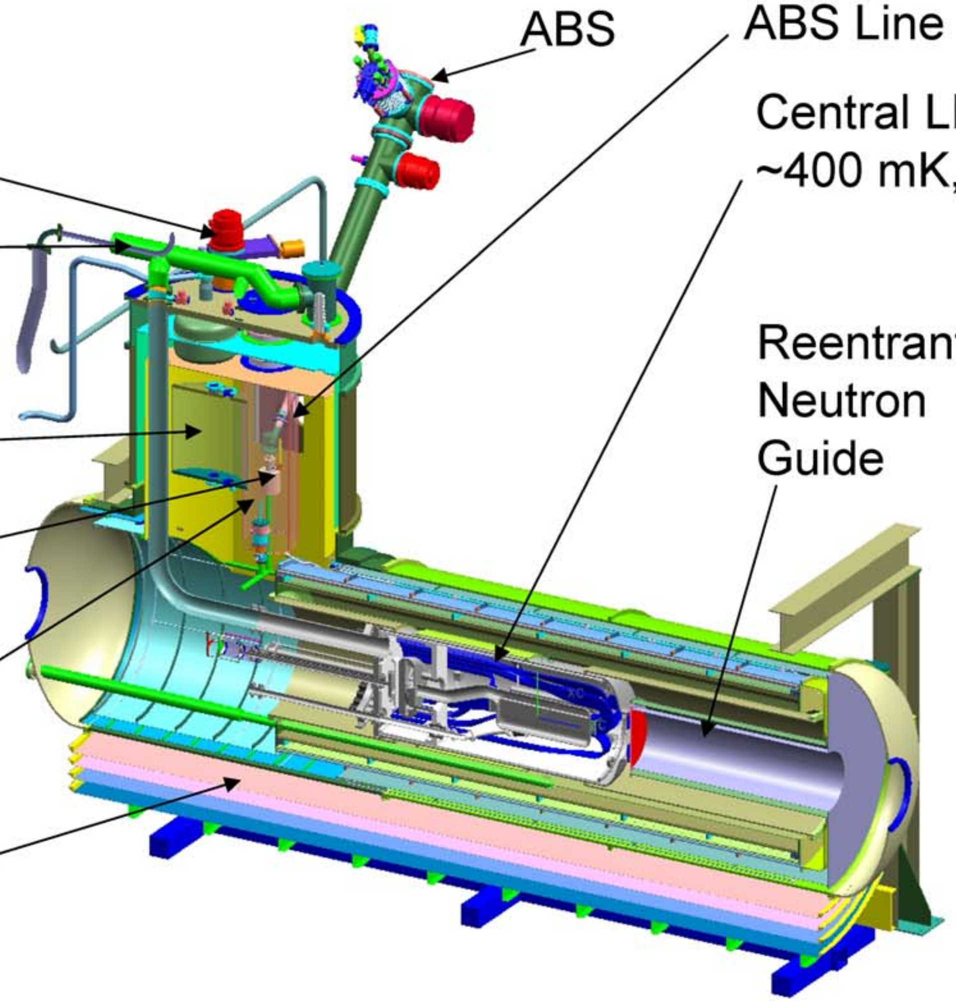
Majorana

CUORE

Double Beta Decay

As a result of the review-panel recommendations, DOE has approved CD-0, a statement of mission need, for a generic double-beta-decay program. The EXO ^{136}Xe double beta decay experiment is under construction at the 200-kg level. CUORE is a European double-beta-decay experiments with substantial US involvement; US capital for CUORE is in the FY08 Presidential Budget. The COBRA CdTe double-beta decay experiment is receiving R&D support. A European ^{76}Ge experiment, GERDA, is moving ahead towards a 45-kg enriched isotope array. In the US, the Majorana collaboration is now requesting support for a 60-kg enriched array in an aggressive R&D program aimed at a future 1-ton Ge experiment. In Japan, the MOON and CANDLES double beta decay experiments (^{100}Mo and ^{48}Ca respectively) are under construction at the several-Kg scale.

EDM Experiment - Vertical Section View

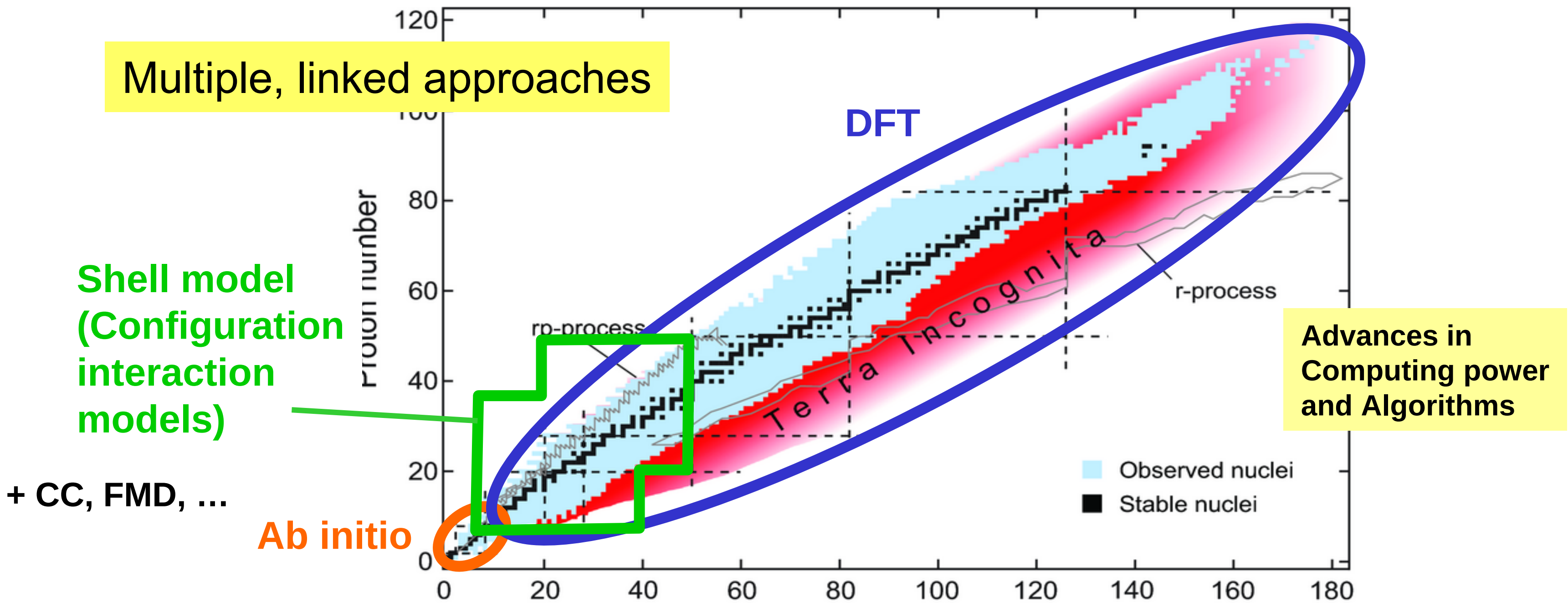


The Science – Physics of Nuclei and Nuclear Astrophysics

- **What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?**
- **What is the origin of simple patterns in complex nuclei?**
- **What is the nature of neutron stars and dense nuclear matter?**
- **What is the origin of the elements in the cosmos?**
- **What are the nuclear reactions that drive stars and stellar explosions?**

What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?

Goal: describe all nuclei with interactions rooted in QCD: major progress within reach!
Connect with reaction theory (example: ab initio calculations of $^7Be(p,\gamma)$ …)

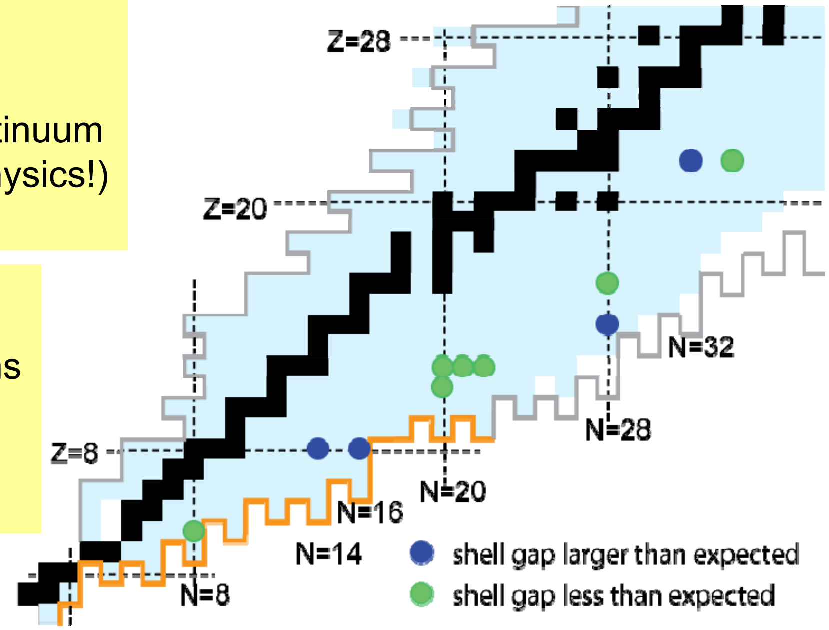


Need experimental data to

- to assess validity of theoretical approximations
- to test validity of extrapolations - data need to span significant area on chart
- to understand nature of inter-nucleon interactions by revealing and isolating aspects of it in nuclear properties and phenomena

Examples of new phenomena that reveal aspects of the nuclear force in new ways

- shell structure changes with neutron excess
  - accomplished: major changes occur, correlations, role of tensor interaction, impact of continuum
  - future : heavier shells far from stability (astrophysics!) incl. precision mass measurements



- neutron skins and halos
  - accomplished: precision measurements in light systems
  - future : halos: search in heavier nuclei <A~100 find the most extreme skins PREX at JLAB

- location of n-drip line
  - accomplished: up to O
  - future : up to ~Zr with FRIB

- new radioactive decay modes: 2p decay
  - accomplished: discovered several cases
  - now underway: measure correlations->pairing

- weakening of spin-orbit force with n-excess?
  - accomplished: hints from a few isolated cases
  - future : broader picture, find microscopic origin

→ Vast majority of these far from stability – that's the frontier
→ but just at the beginning: great discovery potential for the future

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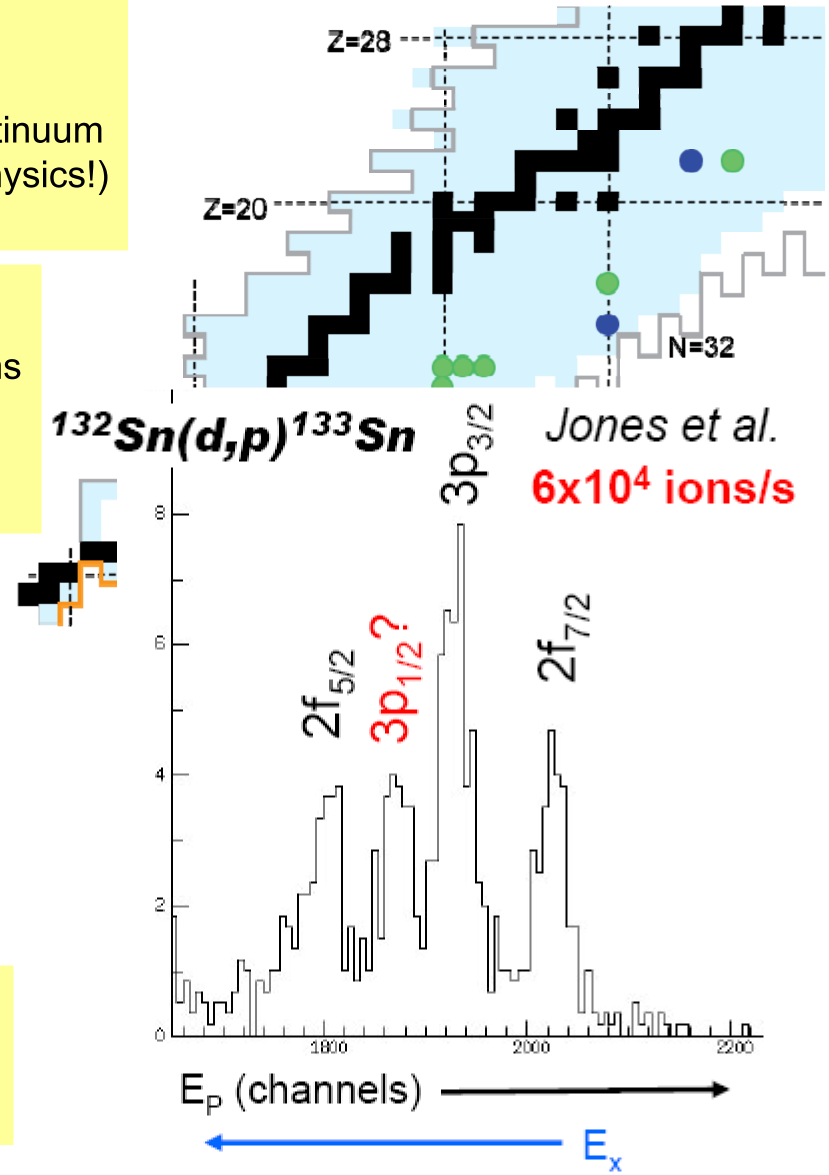

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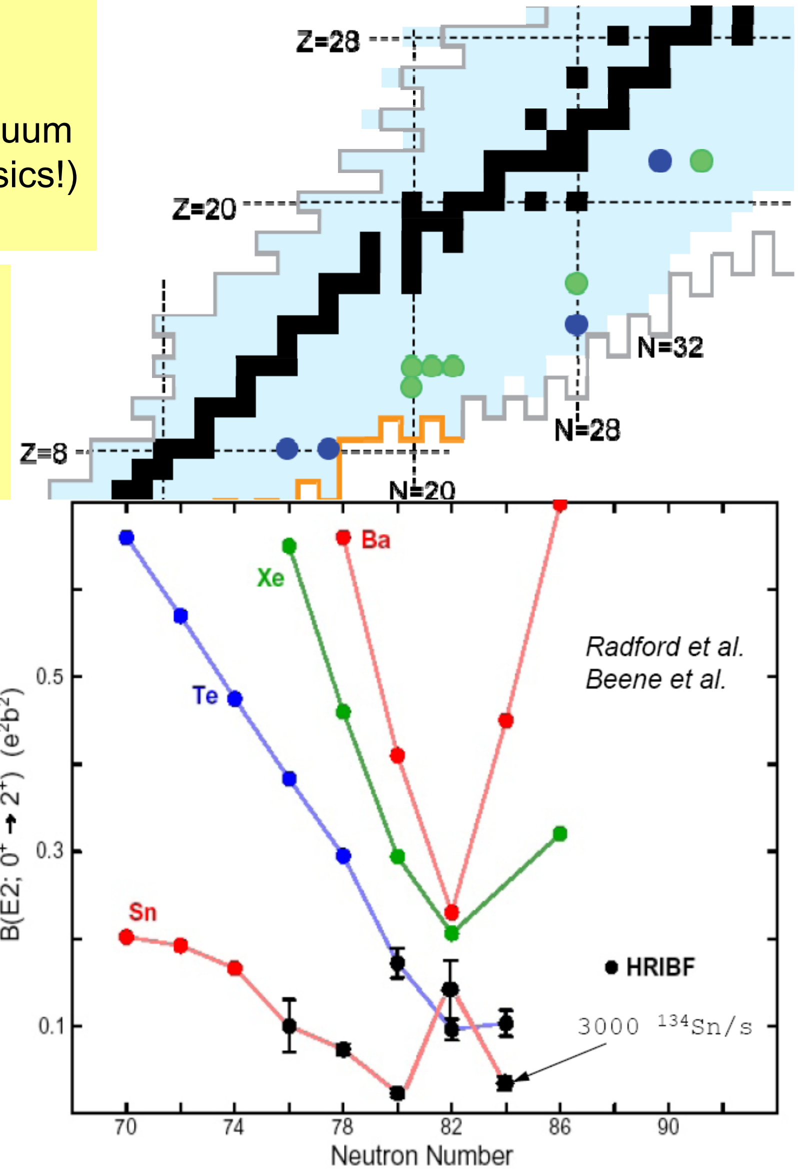

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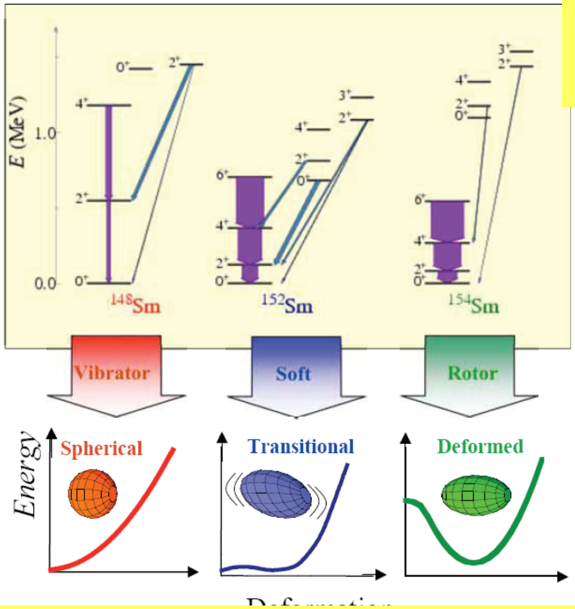
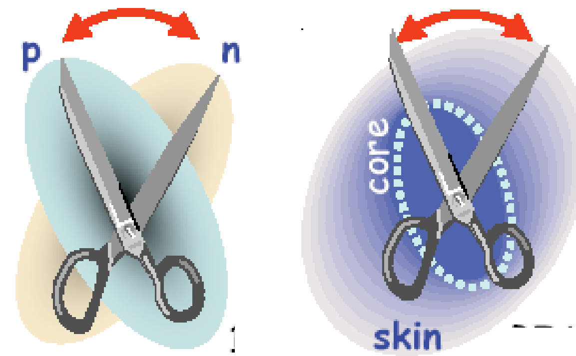
What is the origin of simple patterns in complex nuclei ?

Shape evolution with N,Z

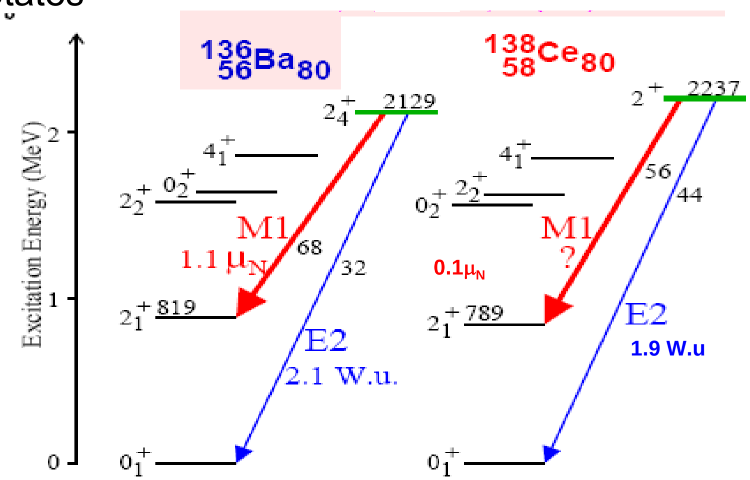


Described as phase transition
Can understand behavior at critical
Point with X(5) symmetry

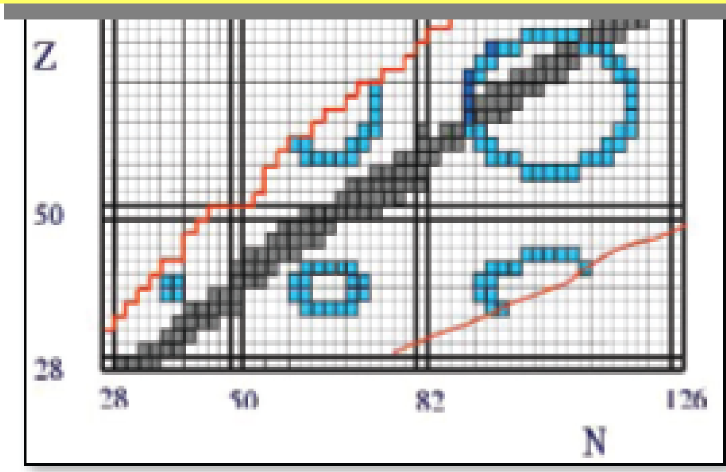
New collective modes



Mixed-Symmetry States

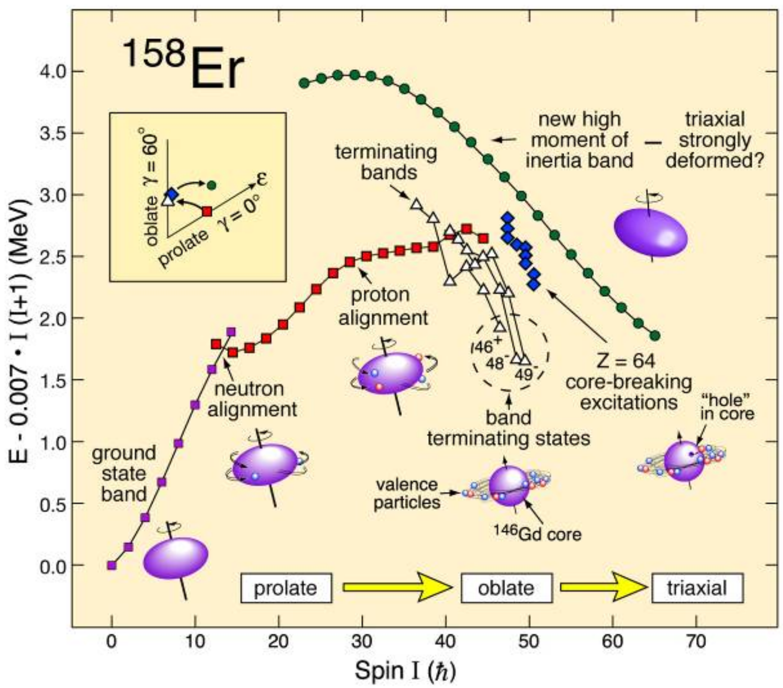


Future: systematic study → far from stability
impact of n/p ratio on phase transitions



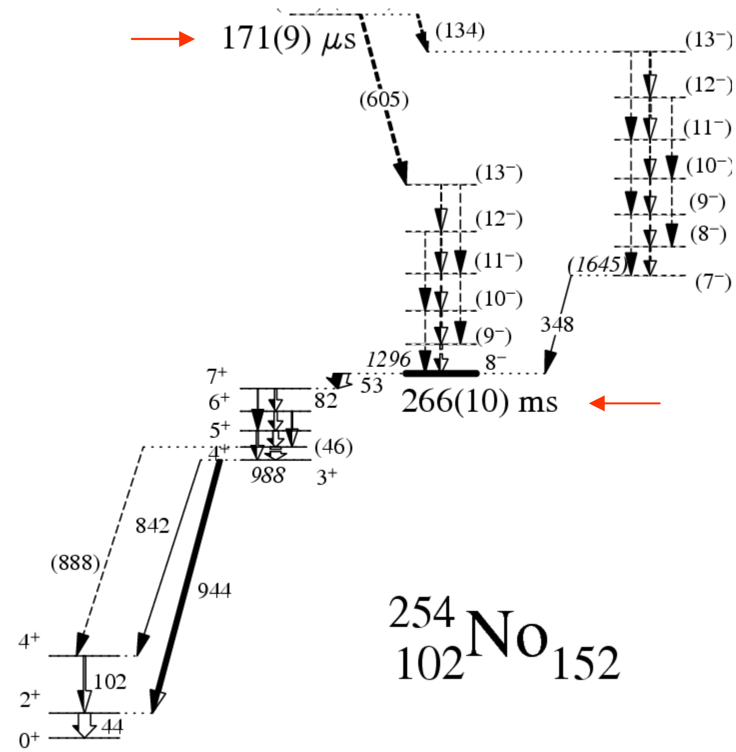
Future: signature at large N?
decoupling of n & p deformations?
new symmetry or breakdown of algebraic picture (fragmentation)

Shape evolution at high spins



Return of collectivity at the highest spins, in a regime where it had been thought to be destroyed
→ Triaxial shapes

Use collectivity as a probe for shell structure in heaviest nuclei



K-isomers in very heavy nuclei:
→Direct proof of axial symmetry
→Information on E_{sp} → gaps and spacings
→ shell stabilization → SHN

What is the nature of neutron stars and dense nuclear matter?

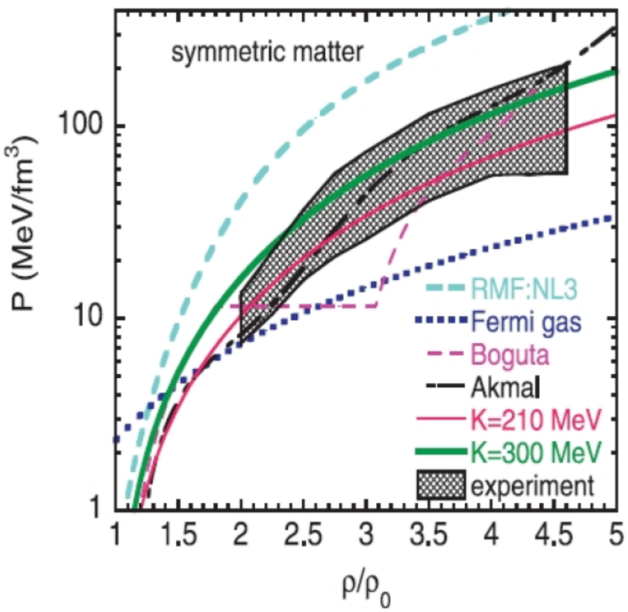
- **What is the maximum mass of a neutron star?**
- **What is the mass-radius relationship?**
- **How do neutron stars cool?**
- **What is the core made of?**
- **What is the origin of transient phenomena?**
  (bursts, superbursts, transient cooling)
- **What is the EOS of nuclear matter**
  in particular the density dependence of asymmetry?

→These are as much nuclear physics questions
as they are astrophysical questions

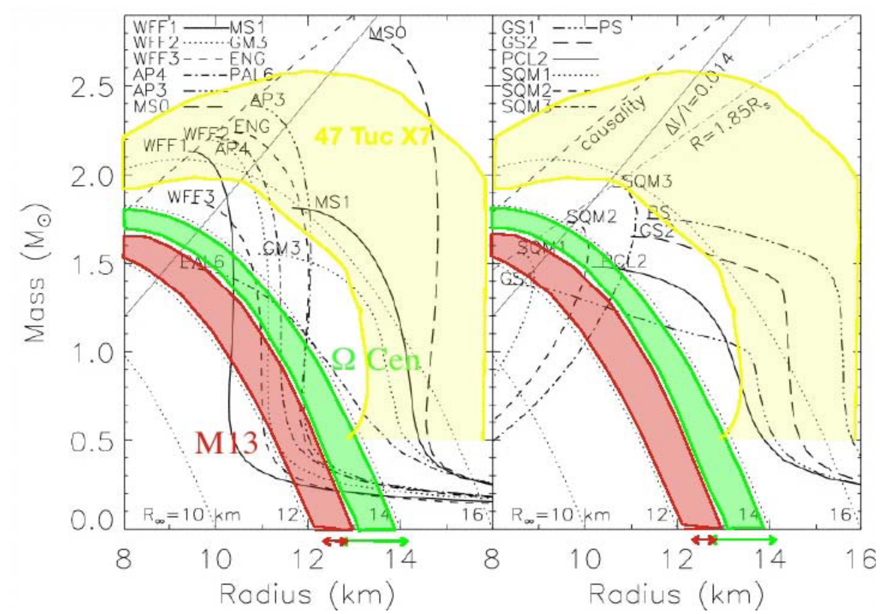
Recent accomplishments:

- first NS seismology
- massive (>1.4 solar masses) neutron stars discovered
- first hints for non-standard cooling
- ground state at extreme densities: color superconductor with CFL phase
- consistent values for compressibility from Giant Resonances and HI collisions
  K = 230 +/- 10 MeV (Giant Resonance Studies)
  K = 233 +/- 39 MeV (Multi-Fragm. HI collisions)

EOS constraints from experiments



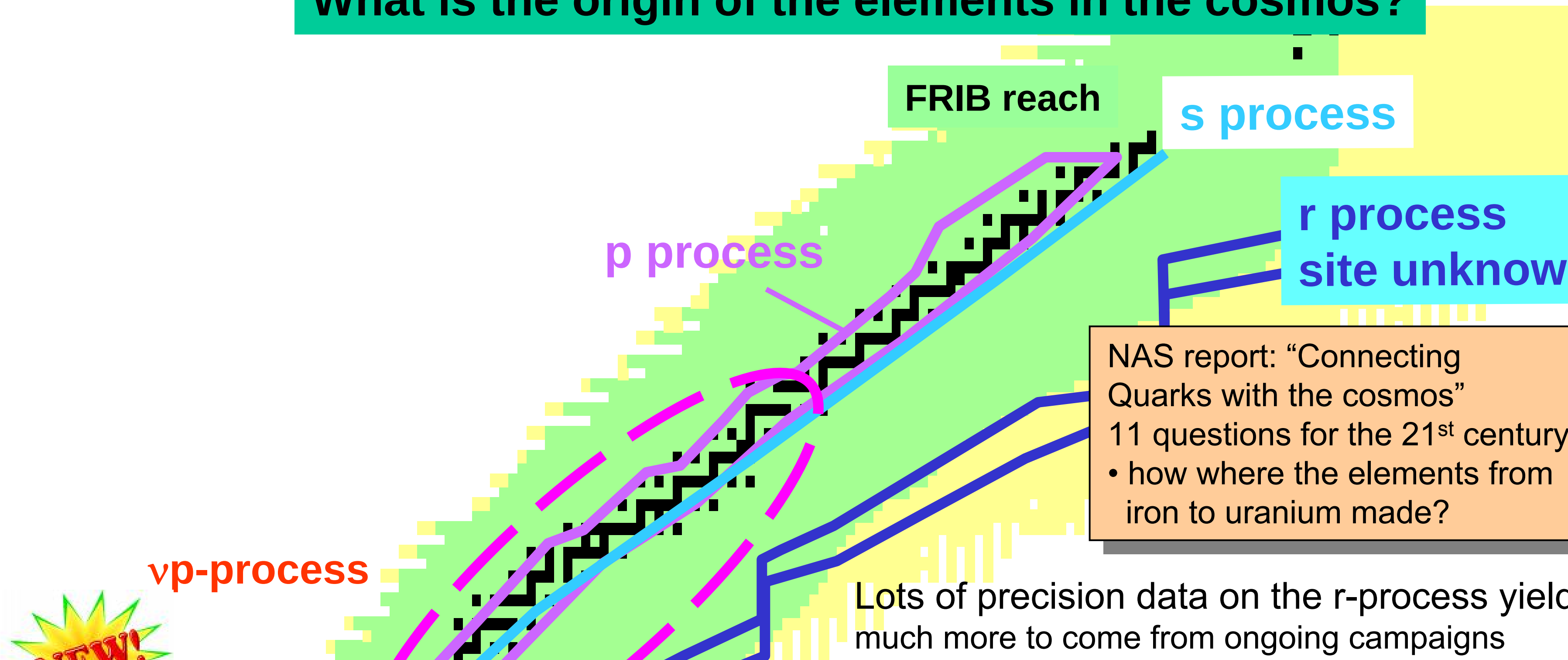
EOS constraints from observations



But: long way to go …

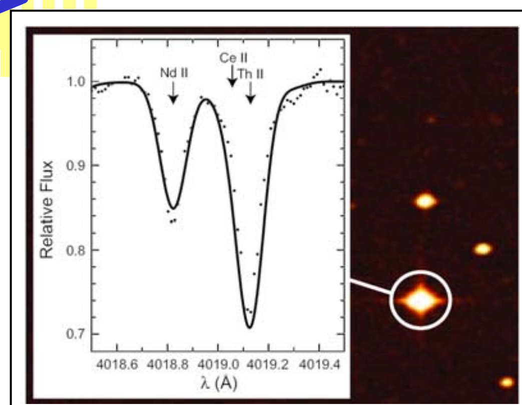
Better theory (interpolation from finite nuclei to nuclear matter) Better observations, Neutron skin measurements (PREX), HI collisions with large asymmetry (FRIB)…

What is the origin of the elements in the cosmos?



NAS report: "Connecting Quarks with the cosmos"
11 questions for the 21st century
- how where the elements from iron to uranium made?

Lots of precision data on the r-process yields:
much more to come from ongoing campaigns



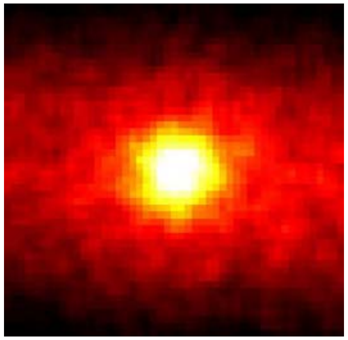
→ **Experimental data needed to interpret astronomy data and to test various r-process models against data**

(~20 r-process nuclei have been reached by experiments incl ^{78}Ni)

Goals: • understand the origin of all the elements – chemical history of the Galaxy
• use nucleosynthesis processes as diagnostics for other physics

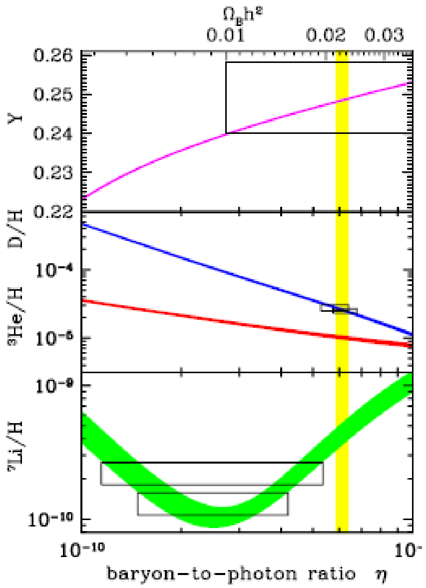
Owing to decades of experimental work this has been accomplished for some processes involving stable nuclei or nuclei close to stability:

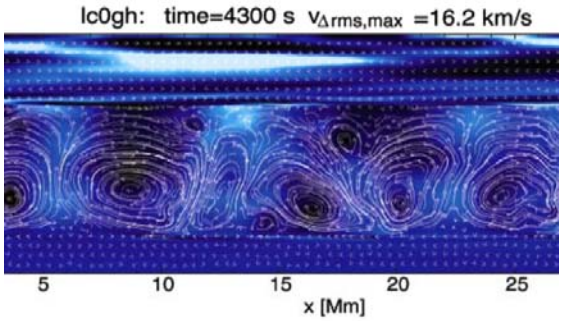
→ Still lots of work to be done – need stable and neutron beam facilities
→ Vision for the future: achieve same for processes with unstable nuclei



Fusion reactions in the sun:
constrains neutrino physics

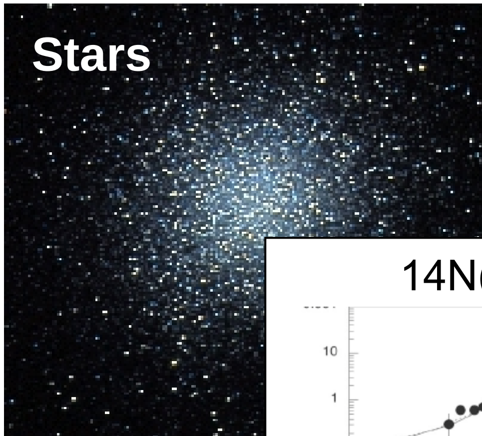
Big Bang nucleosynthesis:
determined baryon contents
of the universe





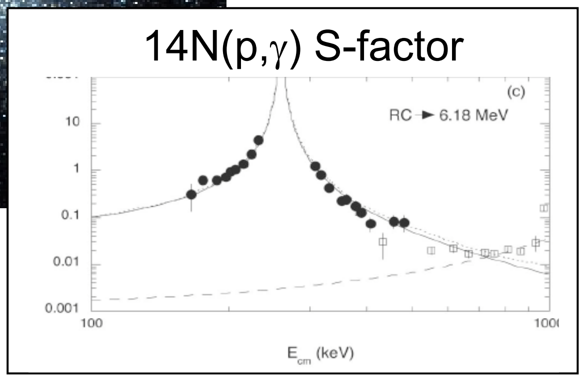
s-process:
constrains mixing processes
in AGB stars

What are the nuclear reactions that drive stars and stellar explosions?



M13

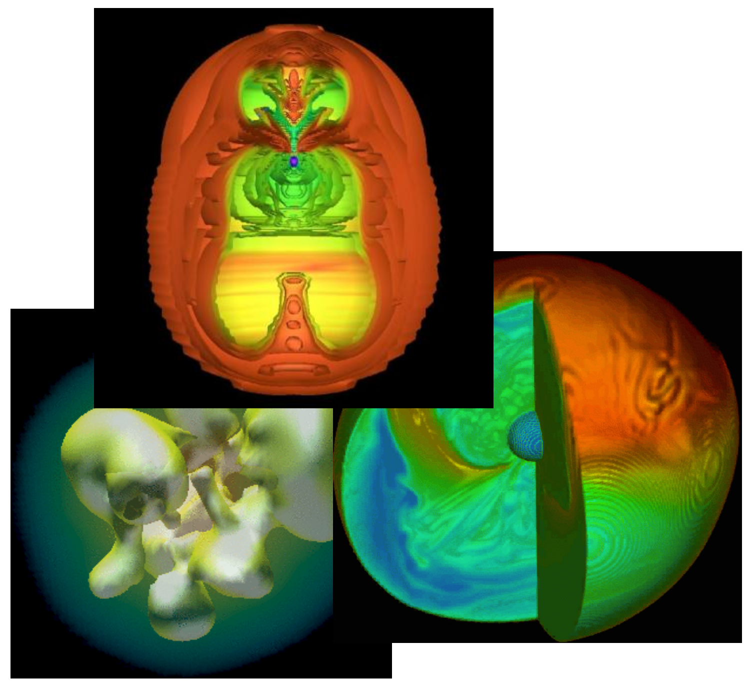
Accomplishment: new measurements of $^{14}N(p,\gamma)$ rate show rate is x2 smaller
→ Globular cluster ages increase by ~1 Gyr



R-matrix with ANC

Future: many challenges, for example $^{12}C(\alpha,\gamma)$ → need stable beam facilities

Supernovae:
Accomplishments: major progress in modeling (though explosion mechanism is still unknown)
identified critical weak interactions



Need EC rates on unstable nuclei

ν-physics is also critical

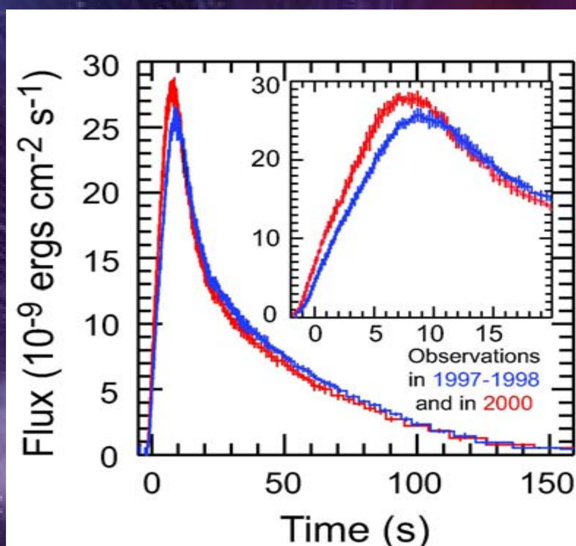
X-ray bursts (and Novae)

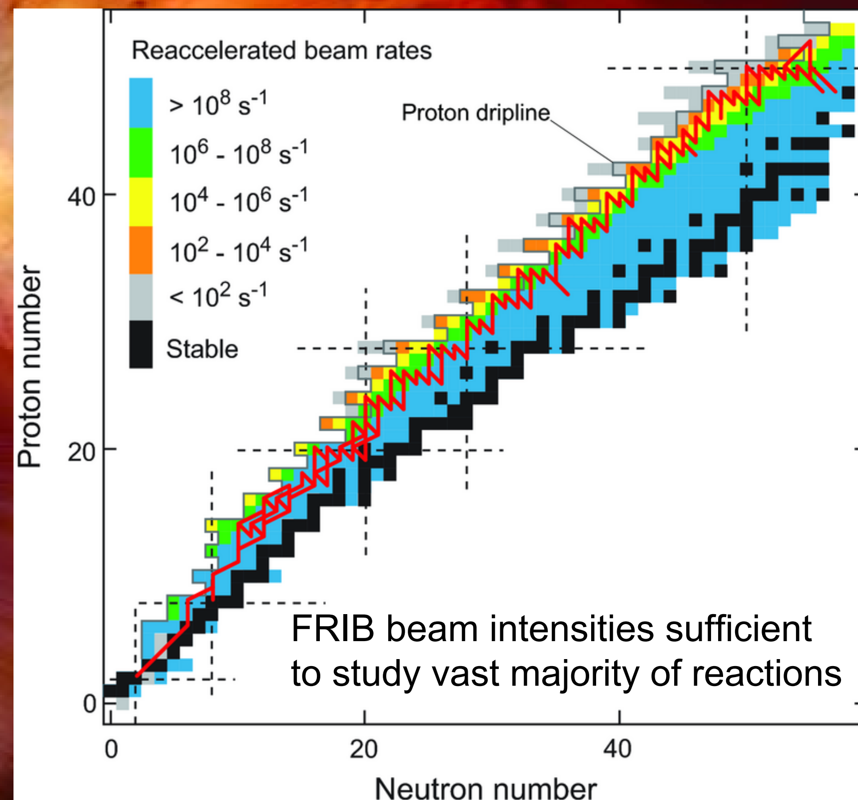
Many open questions from X-ray observations:
superbursts, constraints on neutron star, ejected composition, …

Accomplishments:

- **use indirect techniques to obtain first constraints on many rates**
- **pioneered techniques to directly measure reaction rates with rare isotope beams**

many exciting results but field is strongly limited by selection of available beams and beam intensities





Future:
FRIB will have sufficient beam intensities to apply techniques to most reactions (need stopped, reaccelerated, and fast beam capabilities)

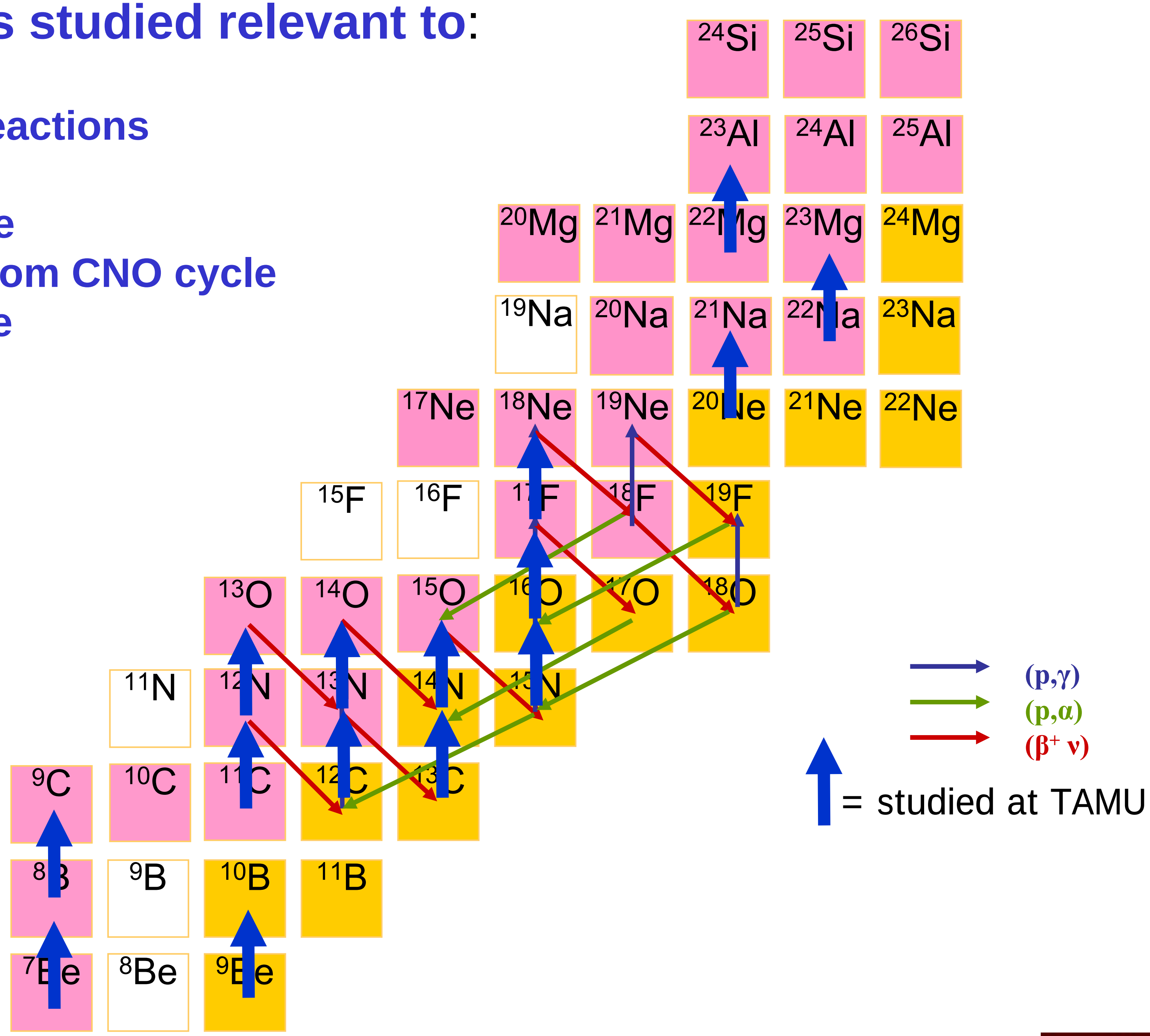
A Digression

Direct and **Indirect** Techniques to get N.A. reaction rates

- **Direct measurements**:
  - stable beam and targets ‘going underground’
- **Widths** (γ and ‘p’) of resonance rates
  - populate resonance state and measure decay
  - now extending to radioactive beams
- **Resonance energies** – determine E_R
- **Coulomb dissociation**
- **Trojan Horse Method**
  - unique way to understand screening
- **Asymptotic Normalization Coefficients**
  - use with stable and radioactive beams

Reactions studied relevant to:

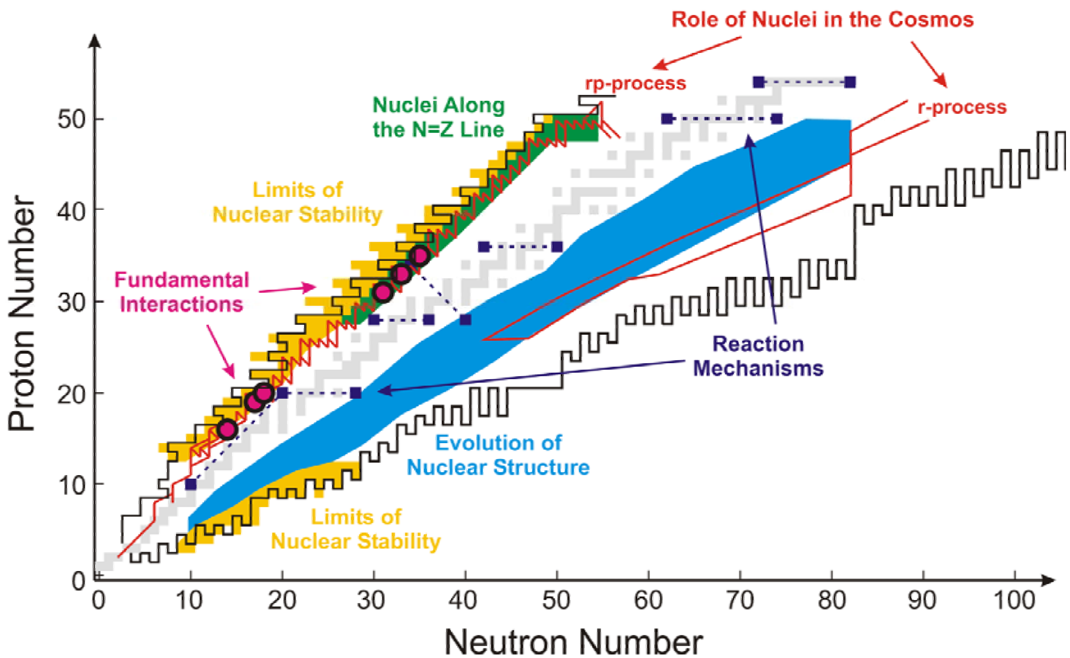
p-p chain
rapid α-p reactions
CNO cycle
HCNO cycle
Breakout from CNO cycle
Ne-Na cycle



The Science – Physics of Nuclei and Nuclear Astrophysics

- U.S. facilities

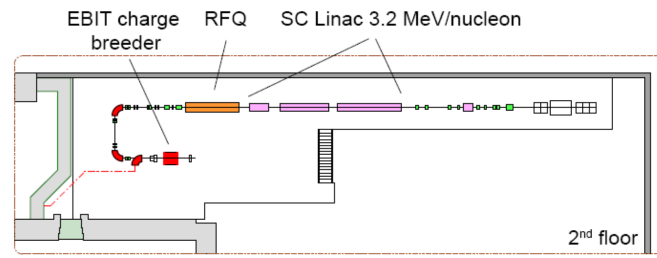
NSCL Coupled Cyclotron Facility (CCF)

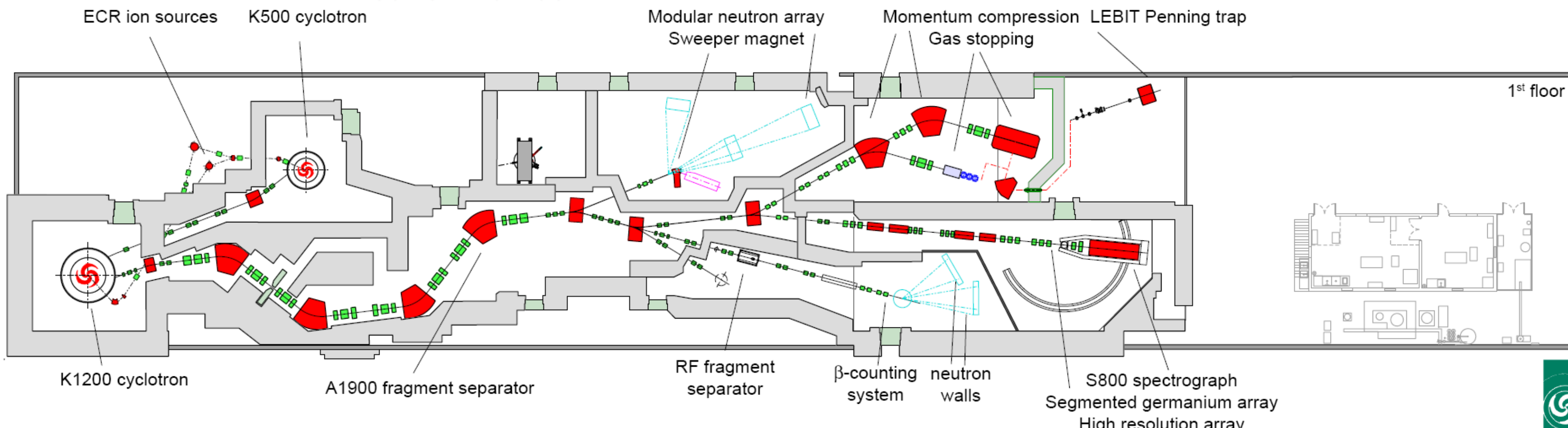


Primary beams (He–U): E/A ≤ 200 MeV

Fast and stopped rare isotopes beams

Reaccelerated beams in 2010





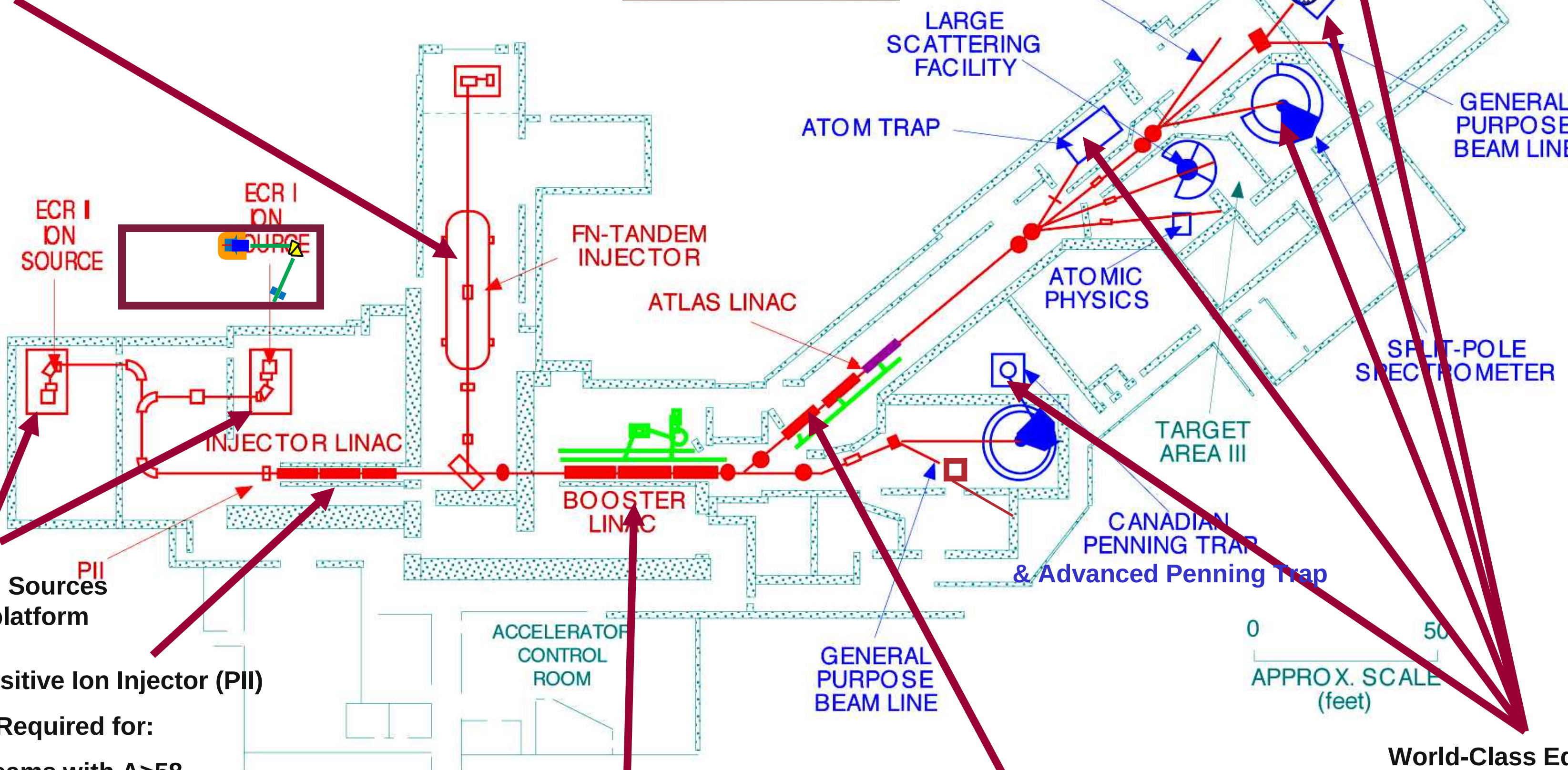
The ATLAS Facility Today

8.5-MV Tandem Injector

Important for:

Beams of A<58

Long-lived RIB's



2 ECR Ion Sources on HV platform

12-MV Positive Ion Injector (PII)

Required for:

Beams with A>58

Noble gases

High current

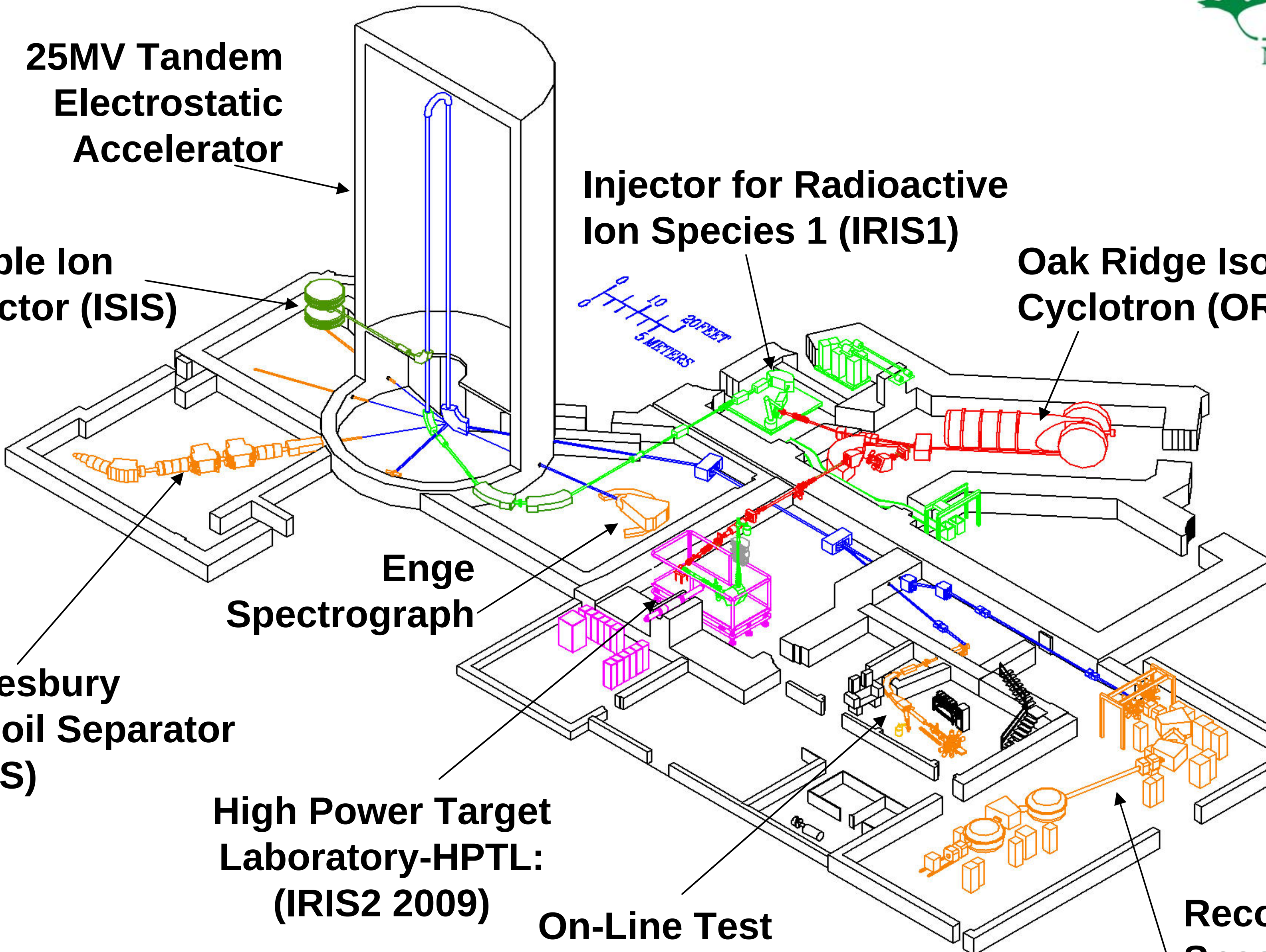
18 Quarter-wave SC resonators

24-Resonator Booster

19-Resonator ATLAS

World-Class Equipment

HRIBF



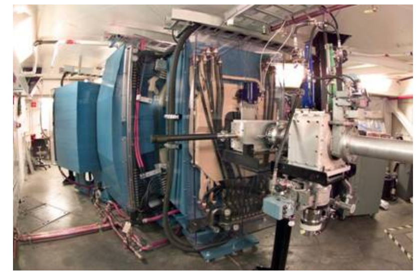
25MV Tandem Electrostatic Accelerator
Stable Ion Injector (ISIS)
Injector for Radioactive Ion Species 1 (IRIS1)
Oak Ridge Isochronous Cyclotron (ORIC)
Enge Spectrograph
Daresbury Recoil Separator (DRS)
High Power Target Laboratory-HPTL: (IRIS2 2009)
On-Line Test Facility (OLTF)
Recoil Mass Spectrometer (RMS)

88-Inch Cyclotron- Facilities

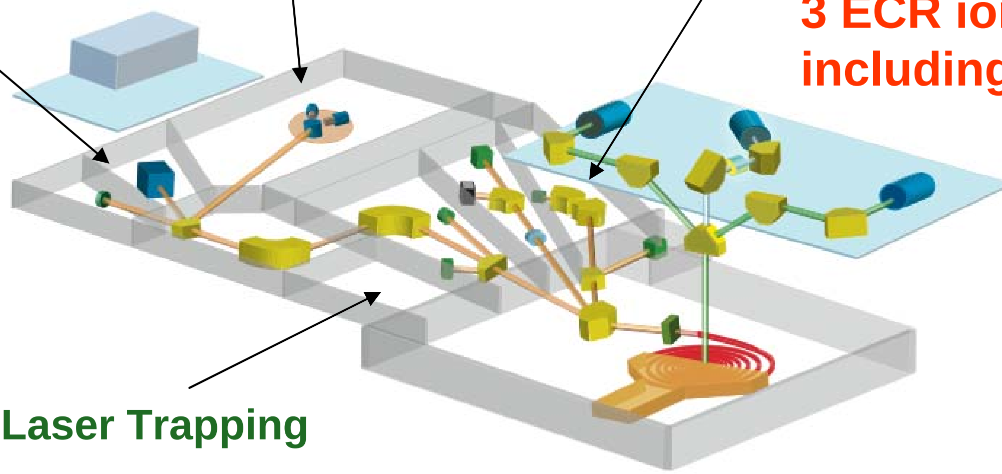
BASE Facility
Space radiation effects

LIBERACE

Berkeley Gas-filled Separator



3 ECR ion sources including VENUS



Laser Trapping

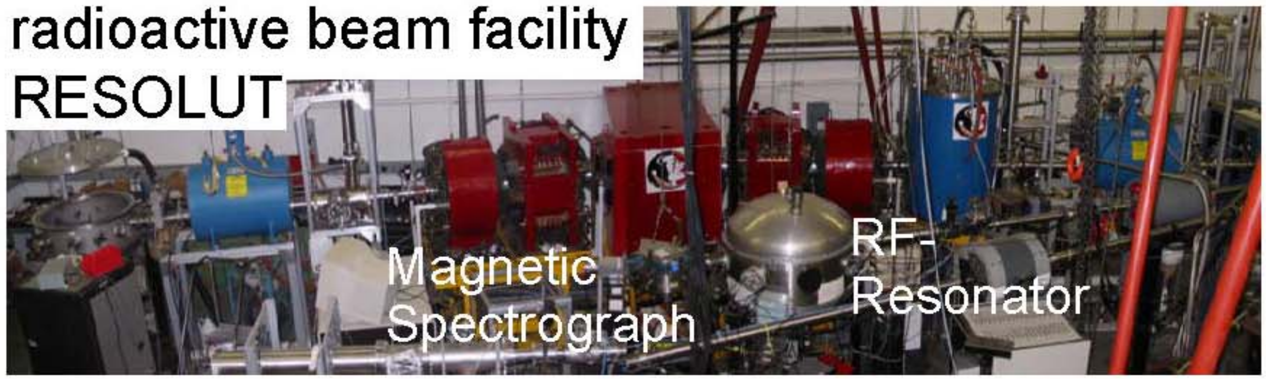
K-140 separated sector cyclotron
High intensity light and heavy ions

Proton	55 MeV
Alpha	130 MeV
Li to S	32 MeV/A
Kr	20 MeV/A
Xe	14 MeV/A
U	5 MeV/A

US Mid-Size Nuclear Physics Facilities

FN Tandem in low and high energy
LINAC post-acceleration mode

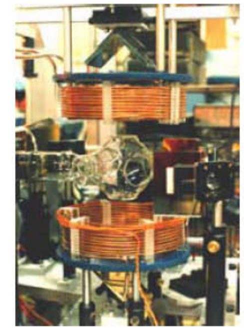
FN Tandem with LINAC post-acceleration
radioactive beam facility
RESOLUT



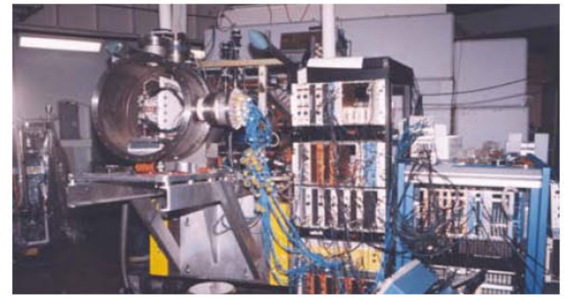
FN Tandem, KN & JN single ended accelerators
radioactive beam facility TWINSOL
AMS facility with gas
filled spectrometer

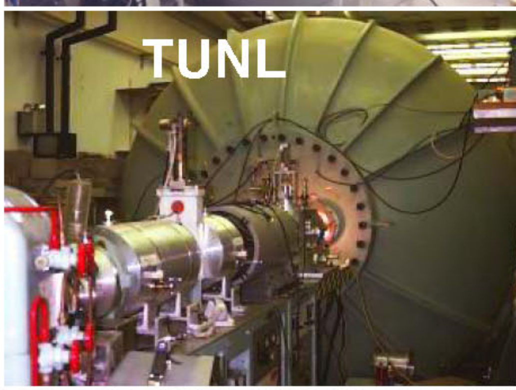
FN Tandem with LINAC post-acceleration

Francium trap

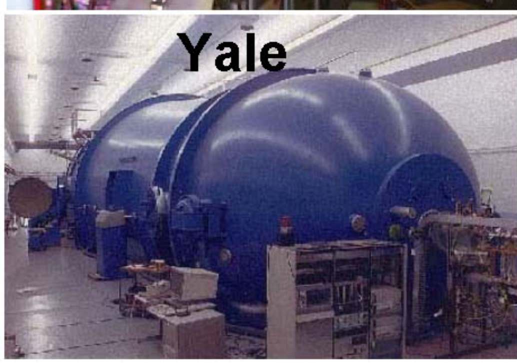


K-500 cyclotron
radioactive beam facility MARS





FN Tandem, neutron beam facility
LENA laboratory, JN single ended machine
HIGS photon beam facility

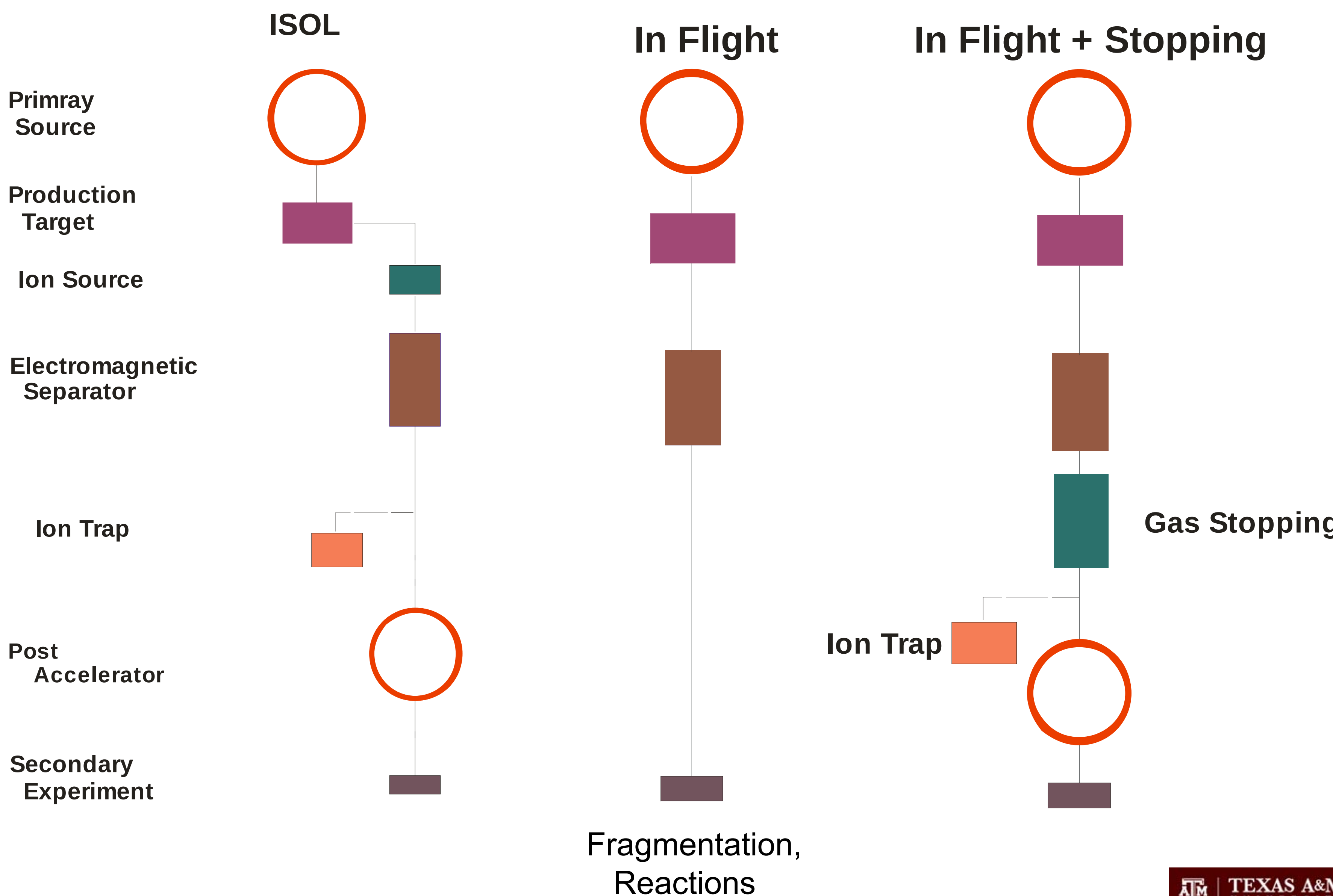


MP Tandem
Sassyer Separator
Yrast Ball,

Present *and* **Future Direction** in **Physics of Nuclei and Nuclear Astrophysics**

Rare Isotope Beams

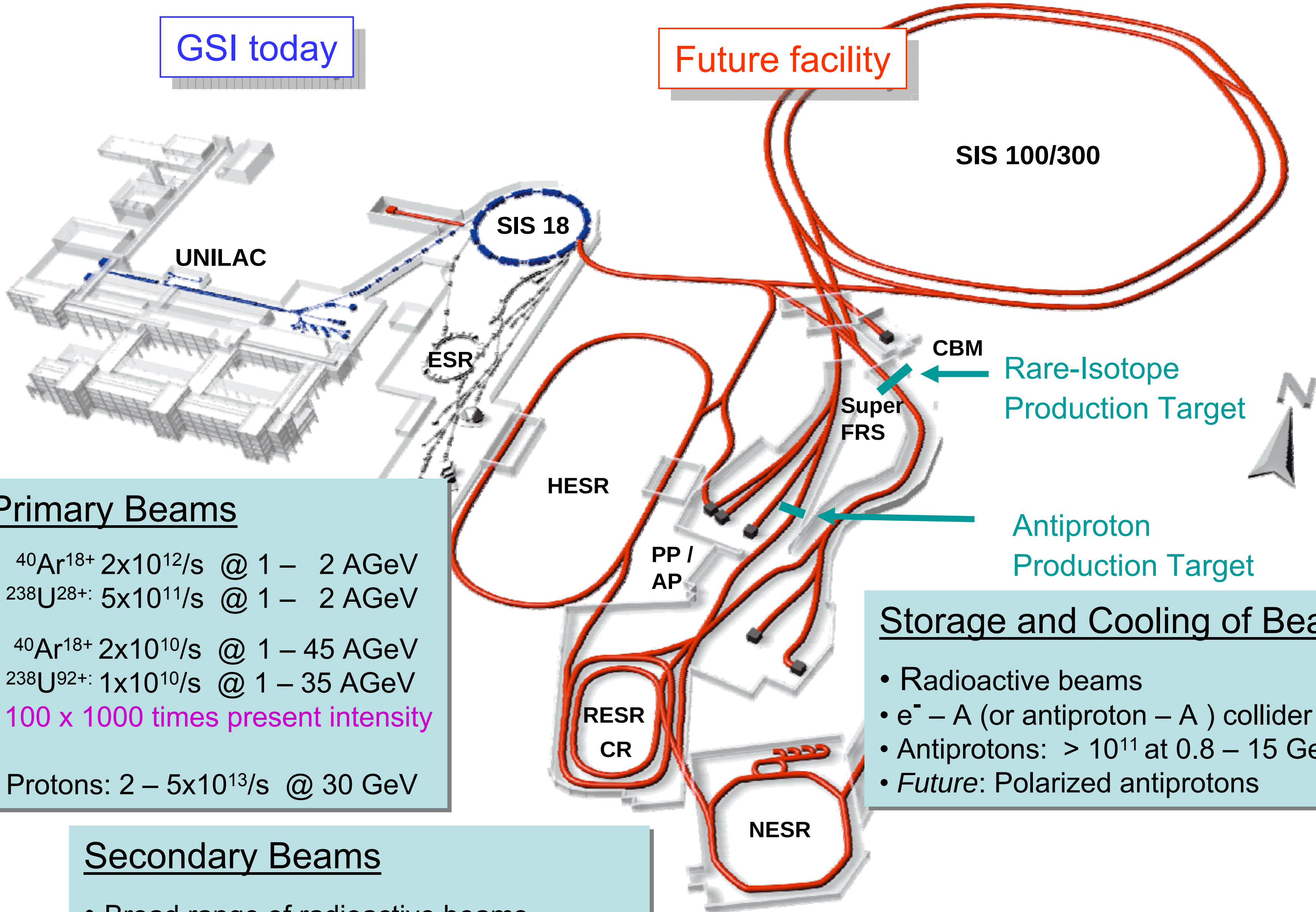
Basic Techniques for Producing RIBs



RIB Facilities

(Operating or Under Construction)

TEXAS A&M UNIVERSITY



Primary Beams

- $^{40}Ar^{18+}$ 2x10^{12}/s @ 1 – 2 AGeV
- $^{238}U^{28+}$: 5x10^{11}/s @ 1 – 2 AGeV
- $^{40}Ar^{18+}$ 2x10^{10}/s @ 1 – 45 AGeV
- $^{238}U^{92+}$: 1x10^{10}/s @ 1 – 35 AGeV

100 x 1000 times present intensity

- Protons: 2 – 5x10^{13}/s @ 30 GeV

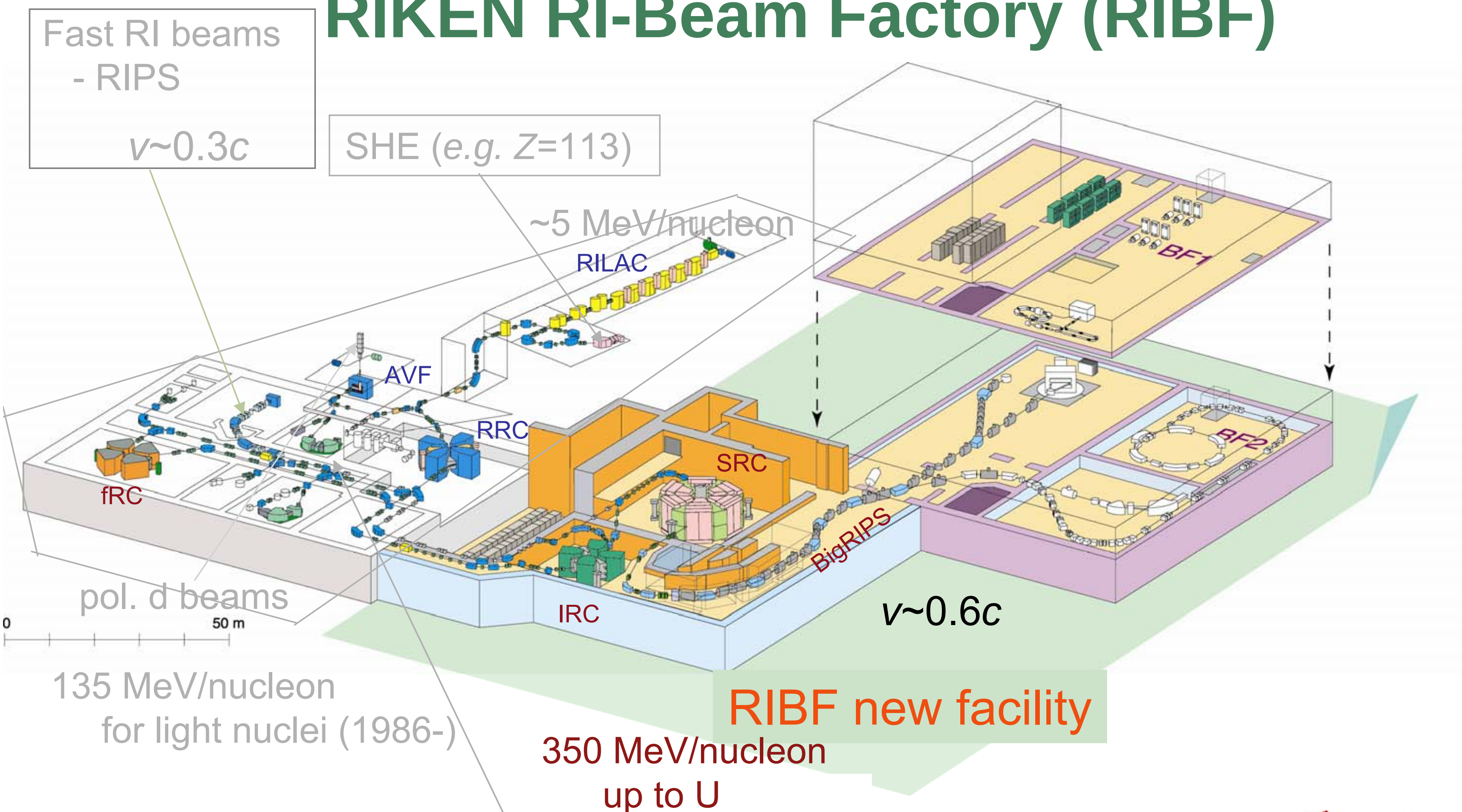
Secondary Beams

- Broad range of radioactive beams up to 1 – 2 AGeV
- RI- Intensities up to 10 000 over present
- Antiprotons

Storage and Cooling of Beams

- Radioactive beams
- e^- – A (or antiproton – A) collider
- Antiprotons: > 10^{11} at 0.8 – 15 GeV/c
- *Future*: Polarized antiprotons

RIKEN RI-Beam Factory (RIBF)



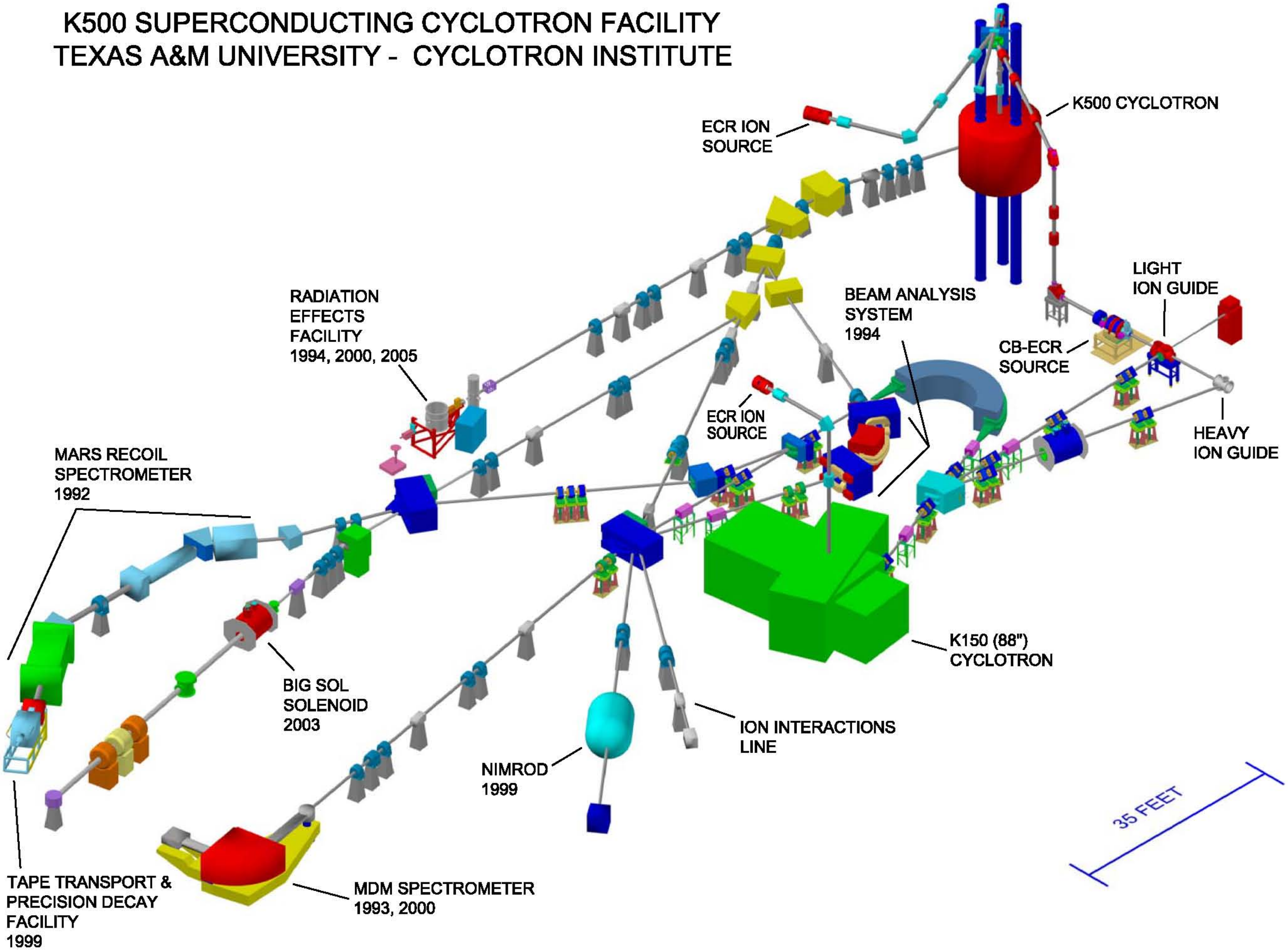
1st beam in Dec. 2006
U beam in Mar. 2007
1st new isotope (^{125}Pd): May 2007

June 2008

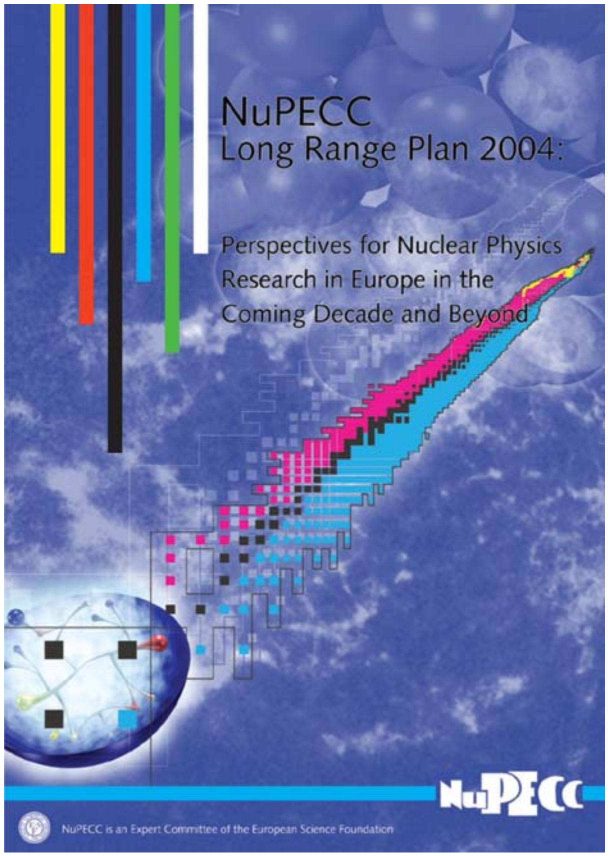
RIKEN NISHINA CENTER

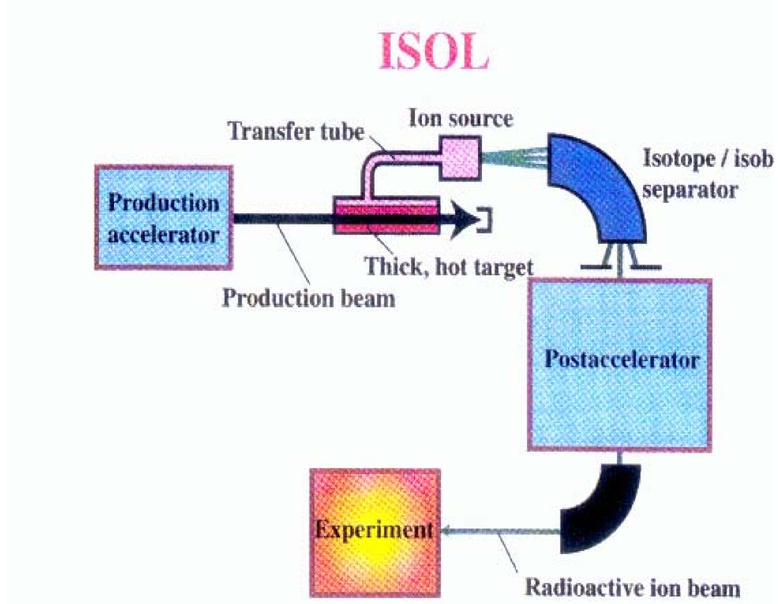
A(nother) Digression

K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE



The European ISOL Road Map





- Vigorous exploitation of current ISOL facilities : EXCYT, REX/ISOLDE, SPIRAL
- Construction of intermediate generation facilities: SPIRAL2, HIE-ISOLDE, SPES
- Design and prototyping in the framework of EURISOL Design-Study (20 Labs, 14 Countries, 30M€)

The Science of FRIB

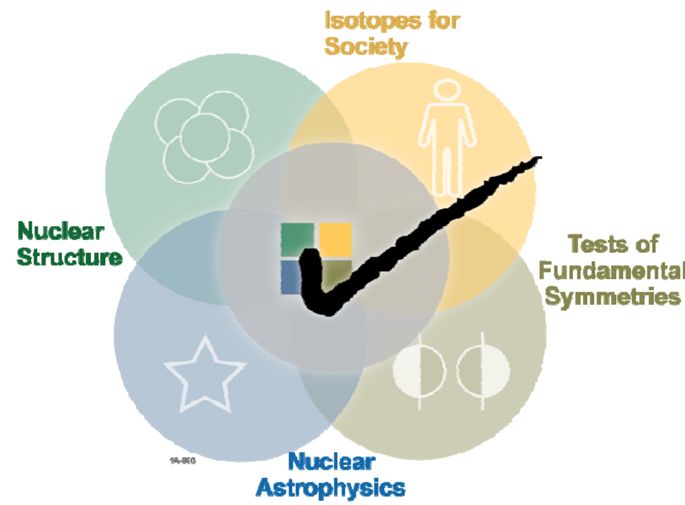
Overarching Goal: A predictive model of nuclei and their reactions.

SCIENCE OF THE SMALL: The atomic nucleus is a unique laboratory of interdisciplinary sciences related to quantum, many-body, open systems

UNDERSTANDING THE UNIVERSE: Nuclei determine the chemical history of the Universe and drive stellar explosions. Connection of models of novae, supernovae, X-ray bursts etc. to observations require rare isotopes.

TESTING SYMMETRIES IN NATURE: Rare isotopes provide complementary information to high-energy experiments at, e.g., LHC

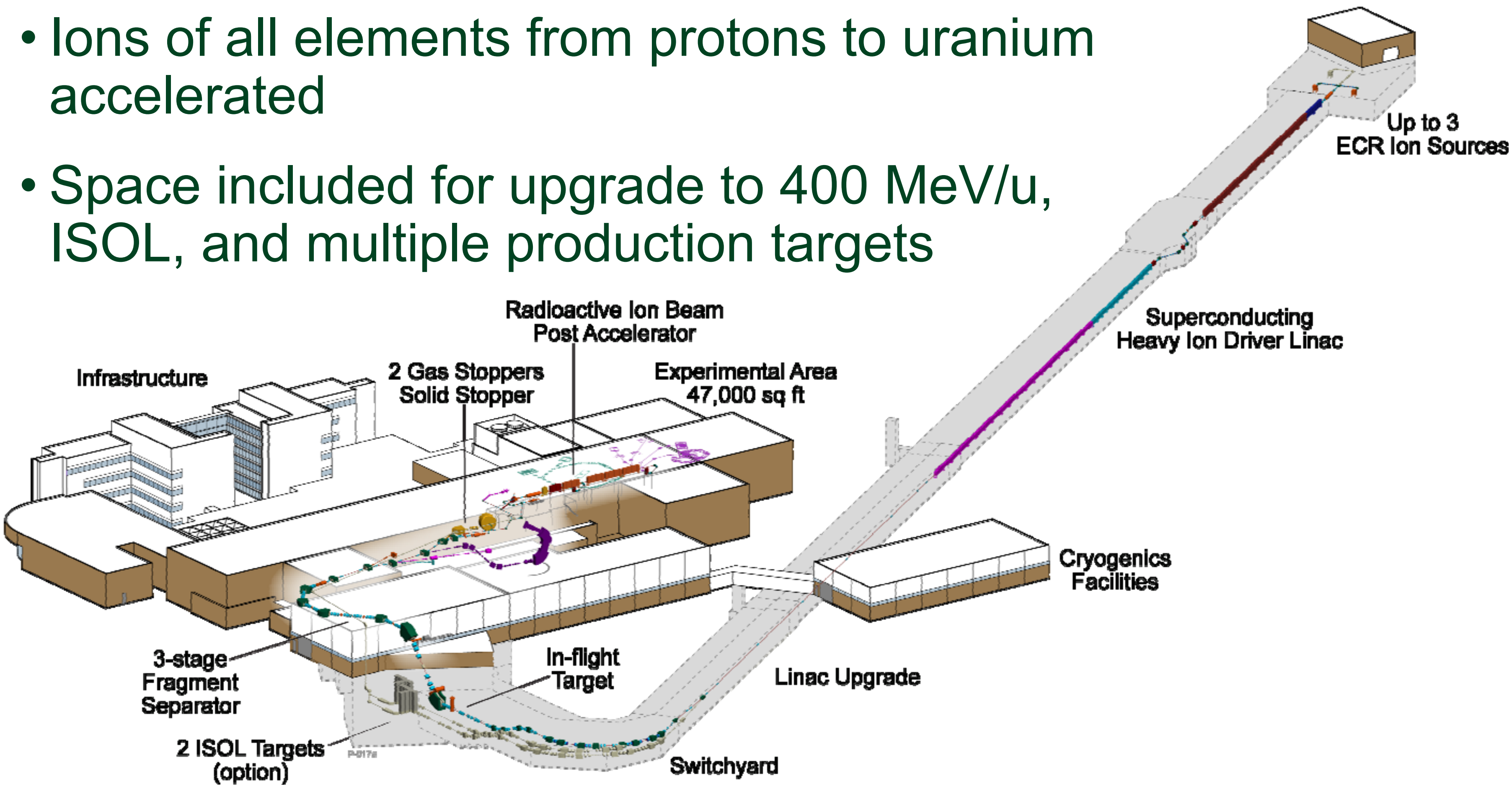
NUCLEI MATTER: Nuclei have applications to medicine, energy, industry, other sciences, and national security



Office of Science

FRIB General Features

- Driver linac with 400 kW and greater than 200 MeV/u for all ions
- Ions of all elements from protons to uranium accelerated
- Space included for upgrade to 400 MeV/u, ISOL, and multiple production targets

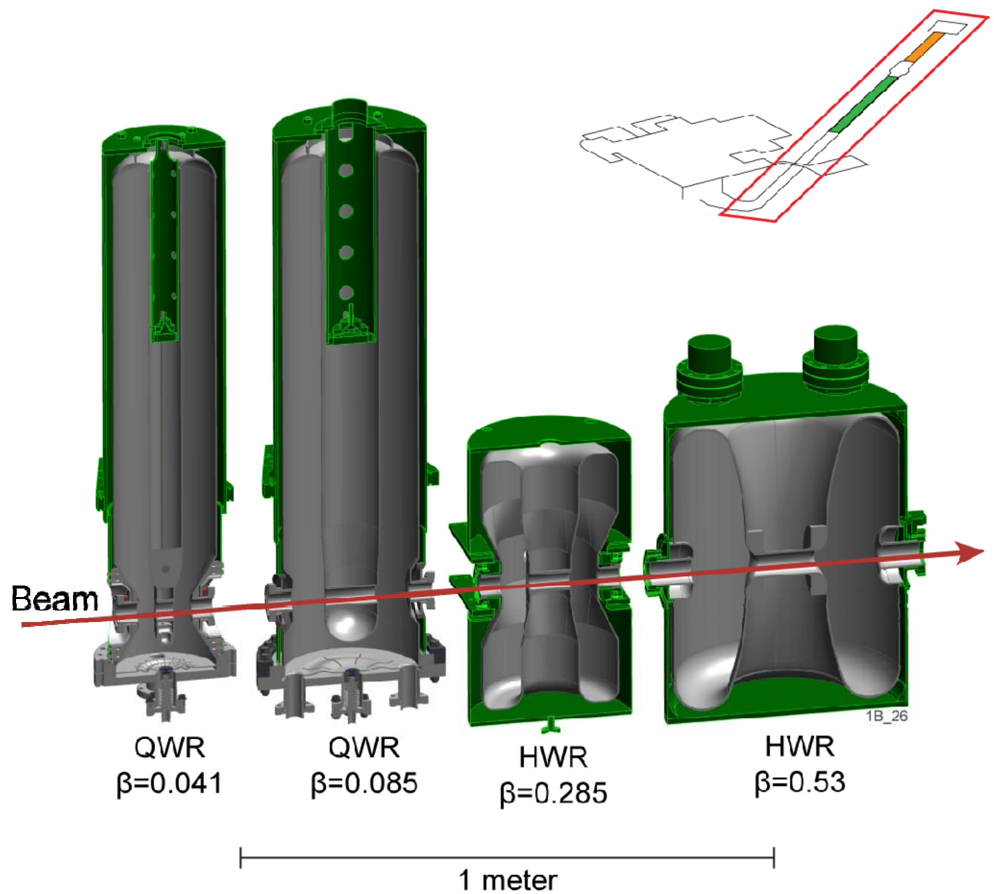


U.S. DEPARTMENT OF ENERGY
Office of Science

Superconducting Heavy Ion Driver Linac

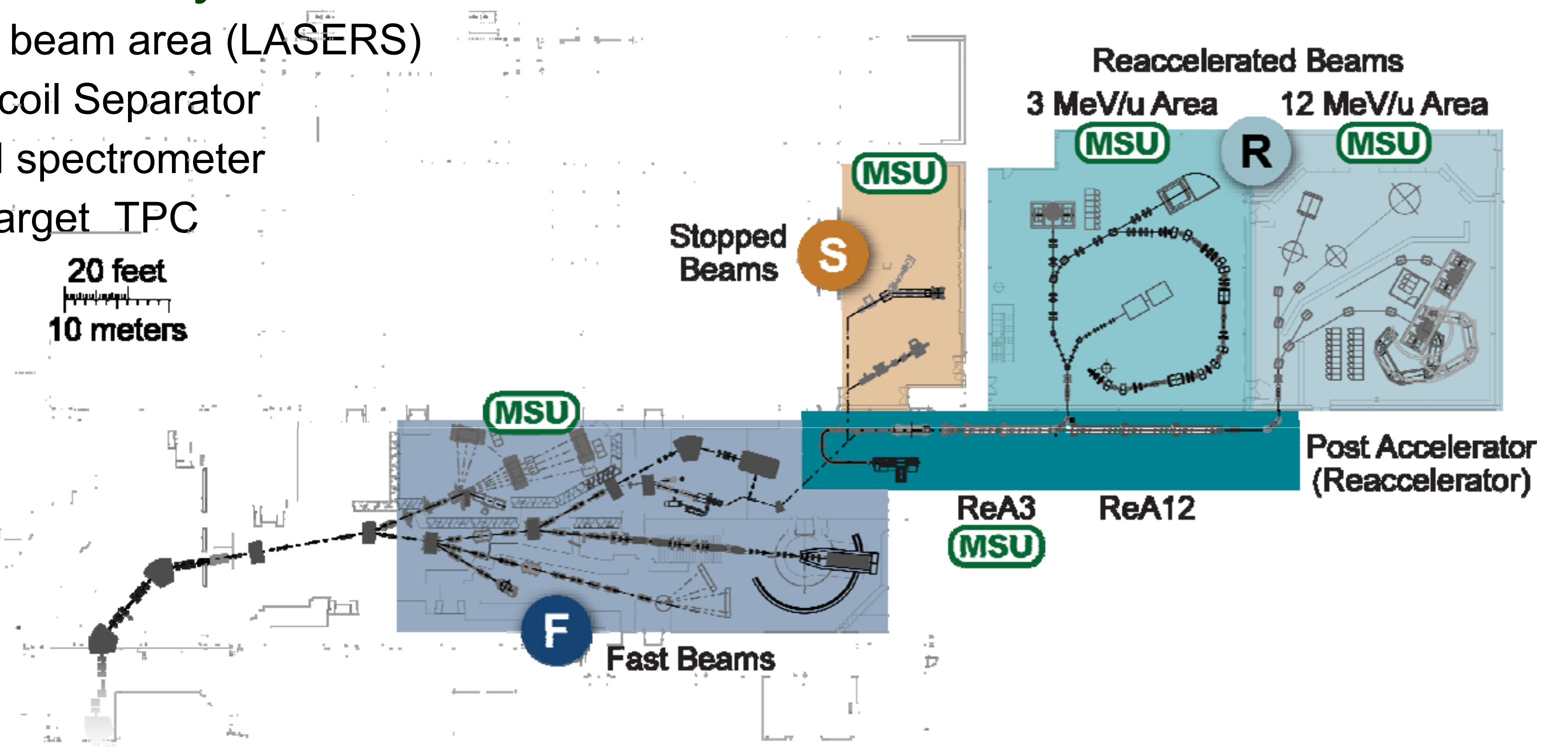
- 4 cavity types required
- Prototypes of all cavities except β = 0.53 complete
- Alternative analysis underway

Type	β	# per Cryomodule		# Cryomodules
		Cavities	Solenoids	
QWR	0.041	8	7	2
	0.085	8	3	12
HWR	0.285	6	1	12
	0.53	8	1	19
Totals		336	81	45



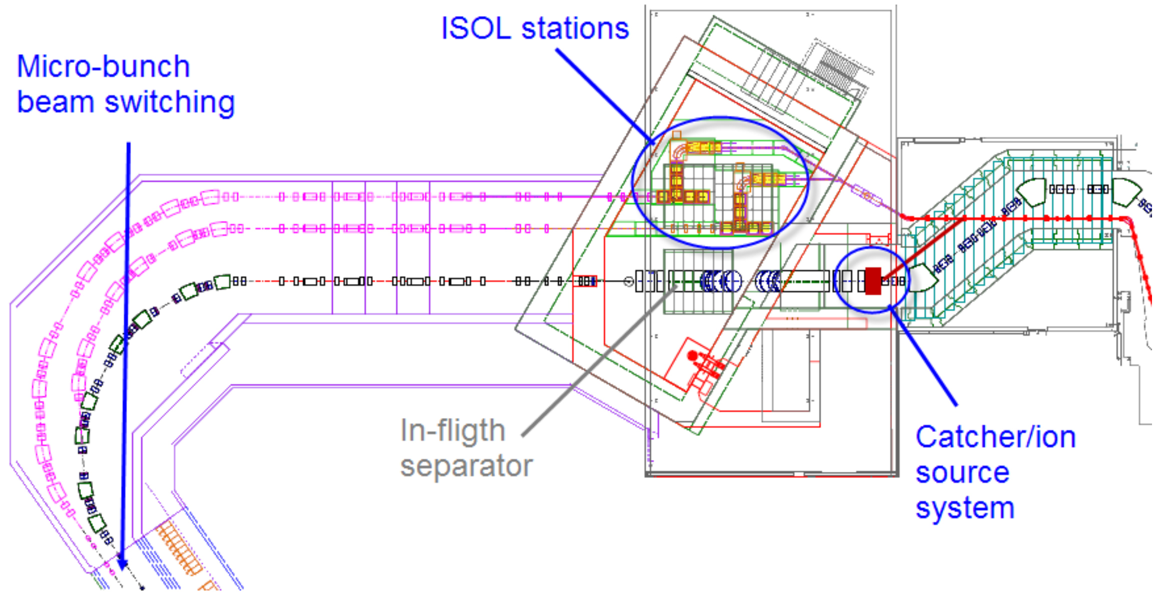
ReA12 and Experimental Areas

- A full suite of experimental equipment will be available for fast, stopped and reaccelerated beams
- New equipment developed in collaboration with users
- These will likely include
  - Stopped beam area (LASERS)
  - ISLA Recoil Separator
  - Solenoid spectrometer
  - Active Target TPC



ISOL and Multi-user Capability

- Harvesting for off-line use of isotopes in focal plane chambers
- Catcher/ion source system in focal plane
  - Low-energy ISOL-type beams
  - Stopped and reaccelerated beams simultaneous to fast beams for experiments



- Additional production stations could be added
  - 2 ISOL stations or 2nd fragment separator
  - Single-beam and multiple-beam option for primary beams

U.S. DEPARTMENT OF ENERGY
Office of Science

Isotope Production
– a new program for DOE NP

The FY09 budget request for DOE includes a transfer of the Isotope Production program from Office of Nuclear Energy to Office of Nuclear Physics in Office of Science

The budget line for this program is about $20 M

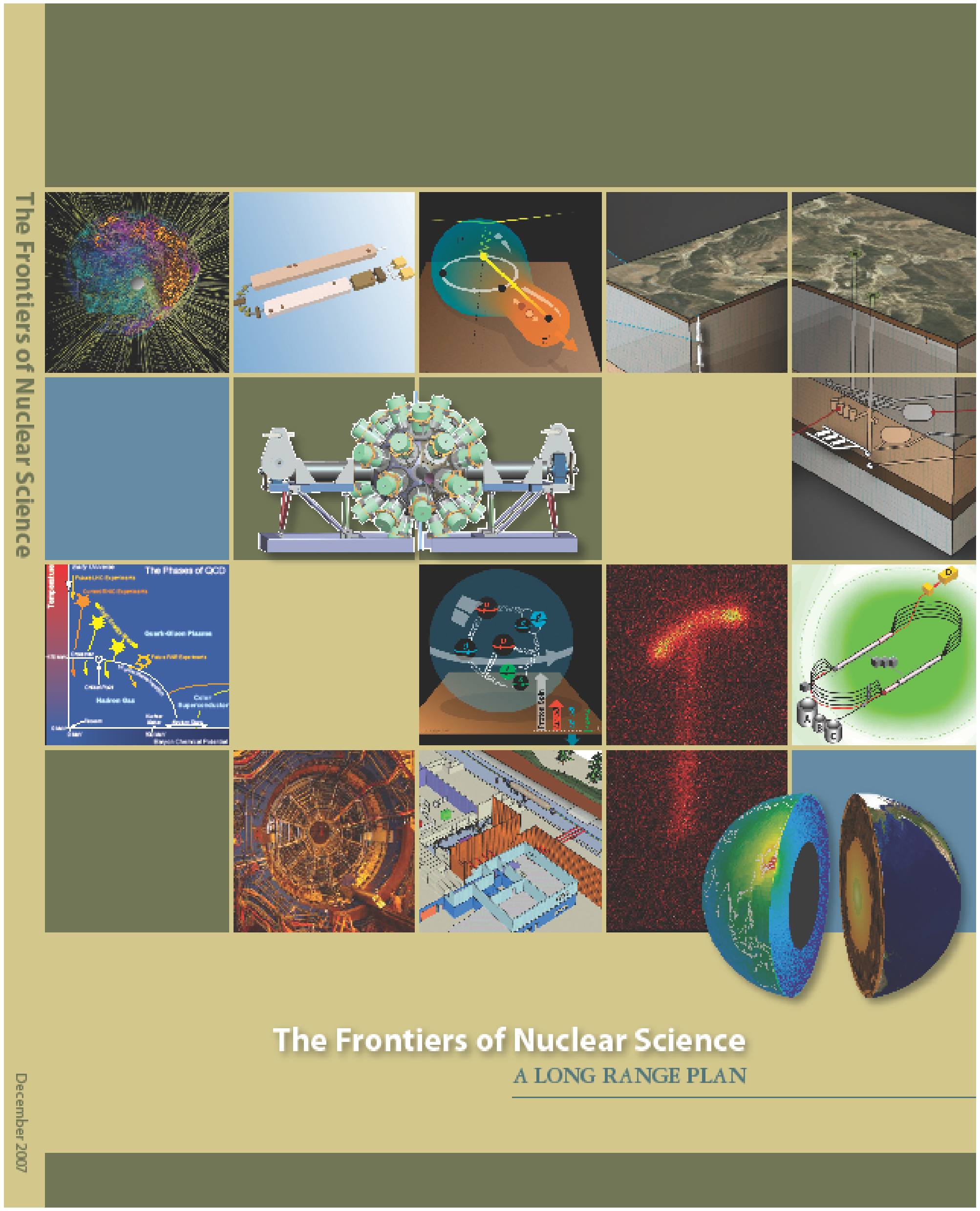
An additional $3 M R&D was added for new isotopes

Program also sells about $20 M of isotopes in a year – funds stay in the program to support production costs

Isotope Related Activities

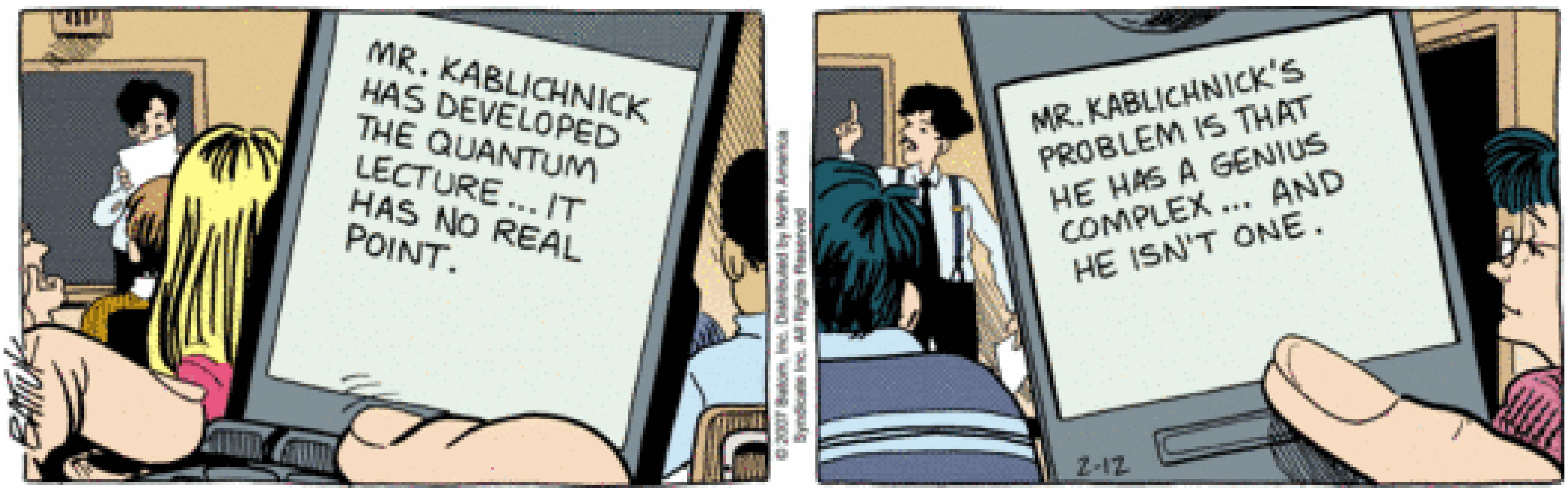
- Workshop on Nations Needs for Isotopes: Present and Future
- NSAC established NSACI subcommittee
  - Asked to prioritize how to spend R&D funding
  - Asked to develop an Isotopes Program LRP due in July, 2009

The U.S. Nuclear Science Program



DOE and NSF support a very diverse program in nuclear science that cover the three frontier areas

With funding profile endorsed by Congress to double science budgets, the program will flourish over the next decade


MR. KABLICHNICK HAS DEVELOPED THE QUANTUM LECTURE... IT HAS NO REAL POINT.
MR. KABLICHNICK'S PROBLEM IS THAT HE HAS A GENIUS COMPLEX ... AND HE ISN'T ONE.
2-12