FRIB

Nuclear Physics Perspectives with Next-Generation RIB Facilities

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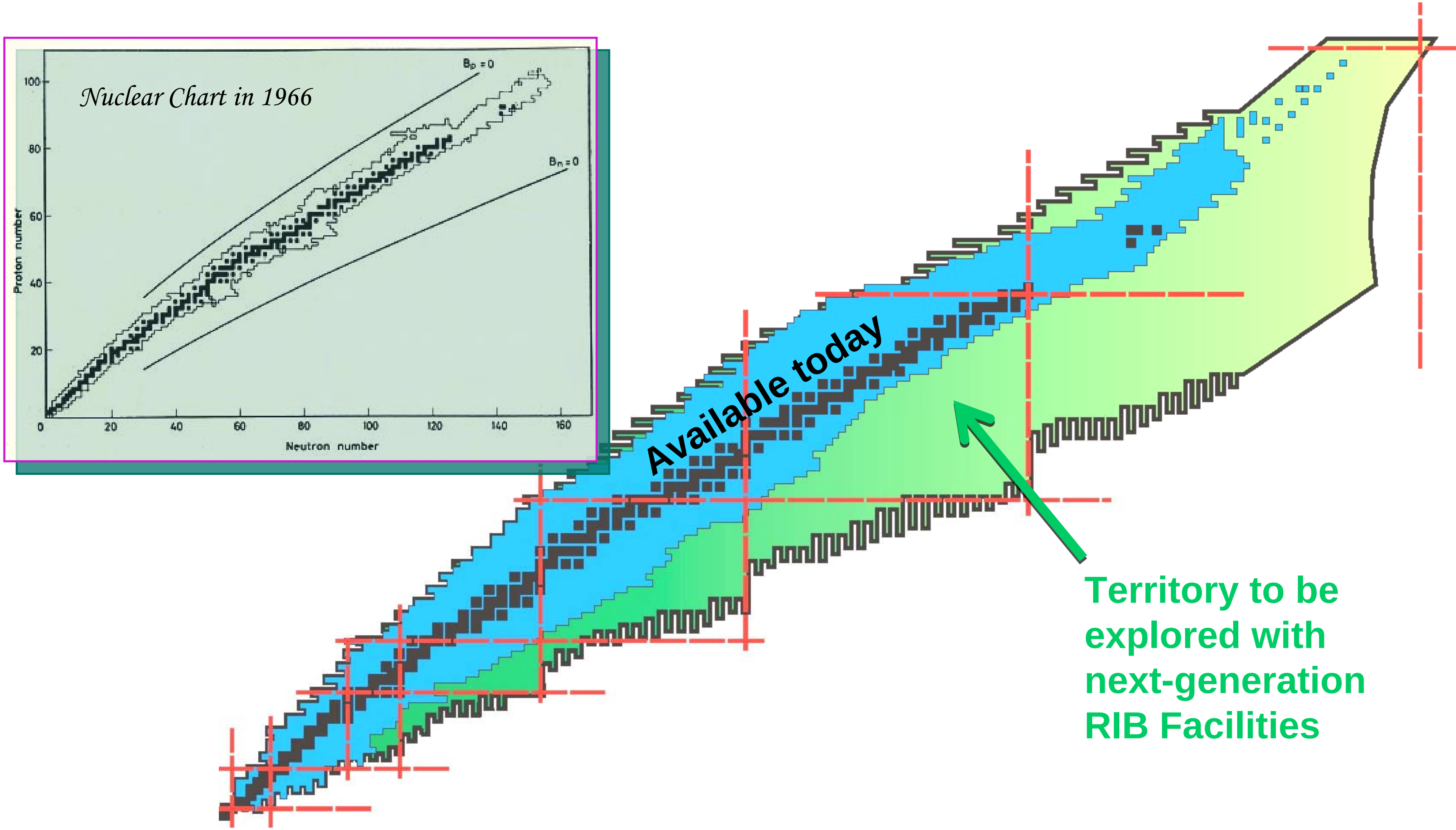
U.S. DEPARTMENT OF ENERGY
Office of Science

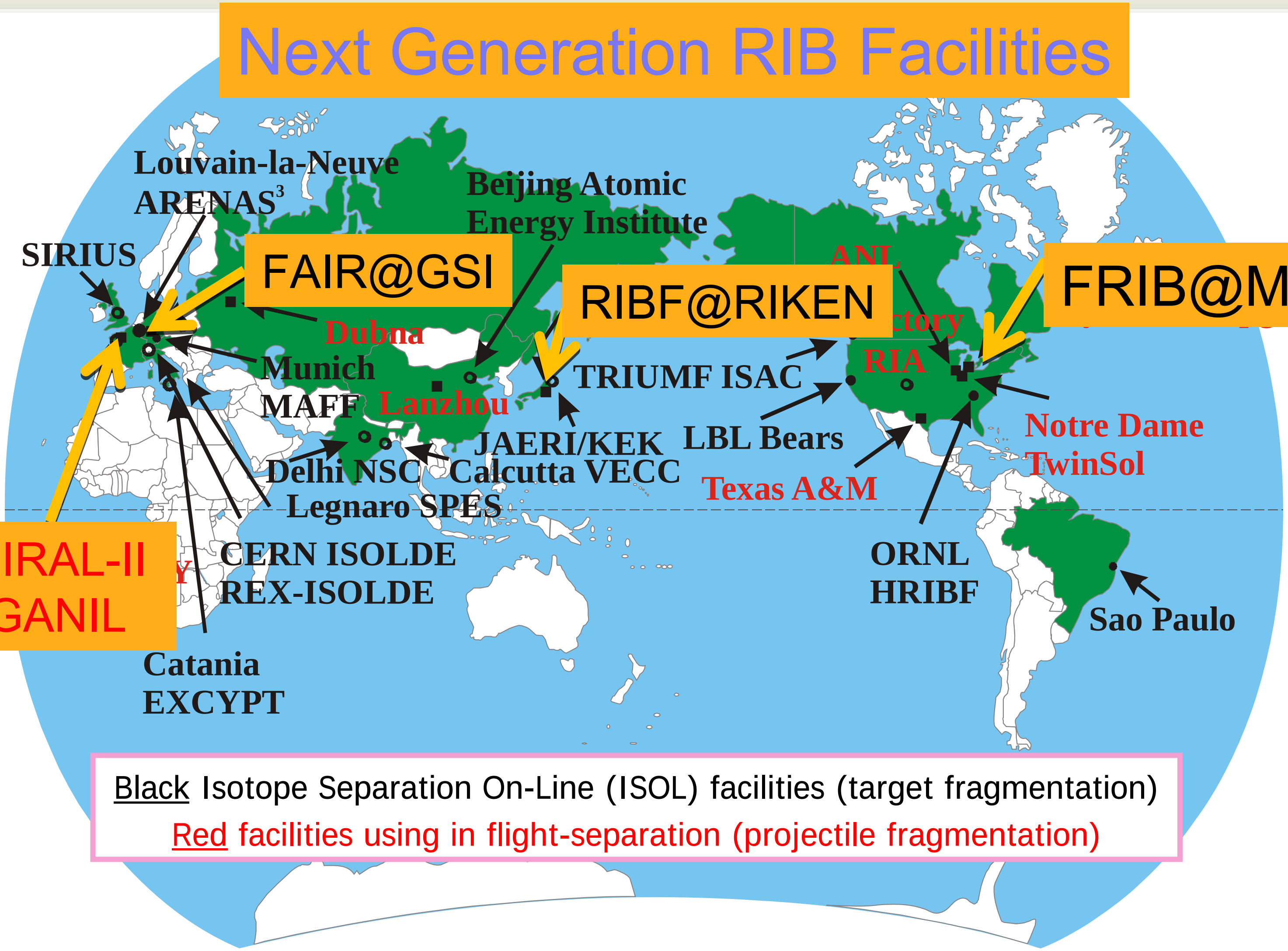
Need for rare isotope beams



Territory to be explored with next-generation RIB Facilities

World Wide Effort in Rare Isotope Science

Next Generation RIB Facilities



FAIR@GSI

RIBF@RIKEN

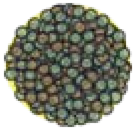
FRIB@MSU

SPIRAL-II
@GANIL

Black Isotope Separation On-Line (ISOL) facilities (target fragmentation)

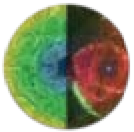
Red facilities using in flight-separation (projectile fragmentation)

The Science with Rare Isotope Beams



Properties of nucleonic matter

- Classical domain of nuclear science
- Many-body quantum problem: intellectual overlap to mesoscopic science – how to understand the world from simple building blocks



Nuclear processes in the universe

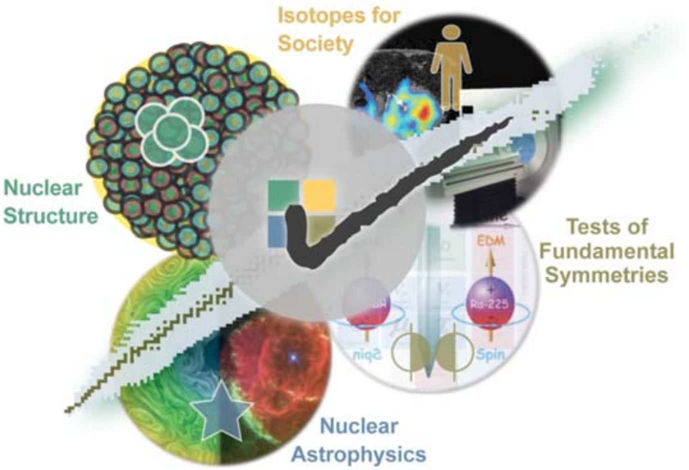
- Energy generation in stars, (explosive) nucleo-synthesis
- Properties of neutron stars, EOS of asymmetric nuclear matter

Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei

Societal applications and benefits

- Bio-medicine, energy, material sciences, national security



High beam rates are needed to do the science

Next-generation high-power (>100 kW) RIB facilities are the key

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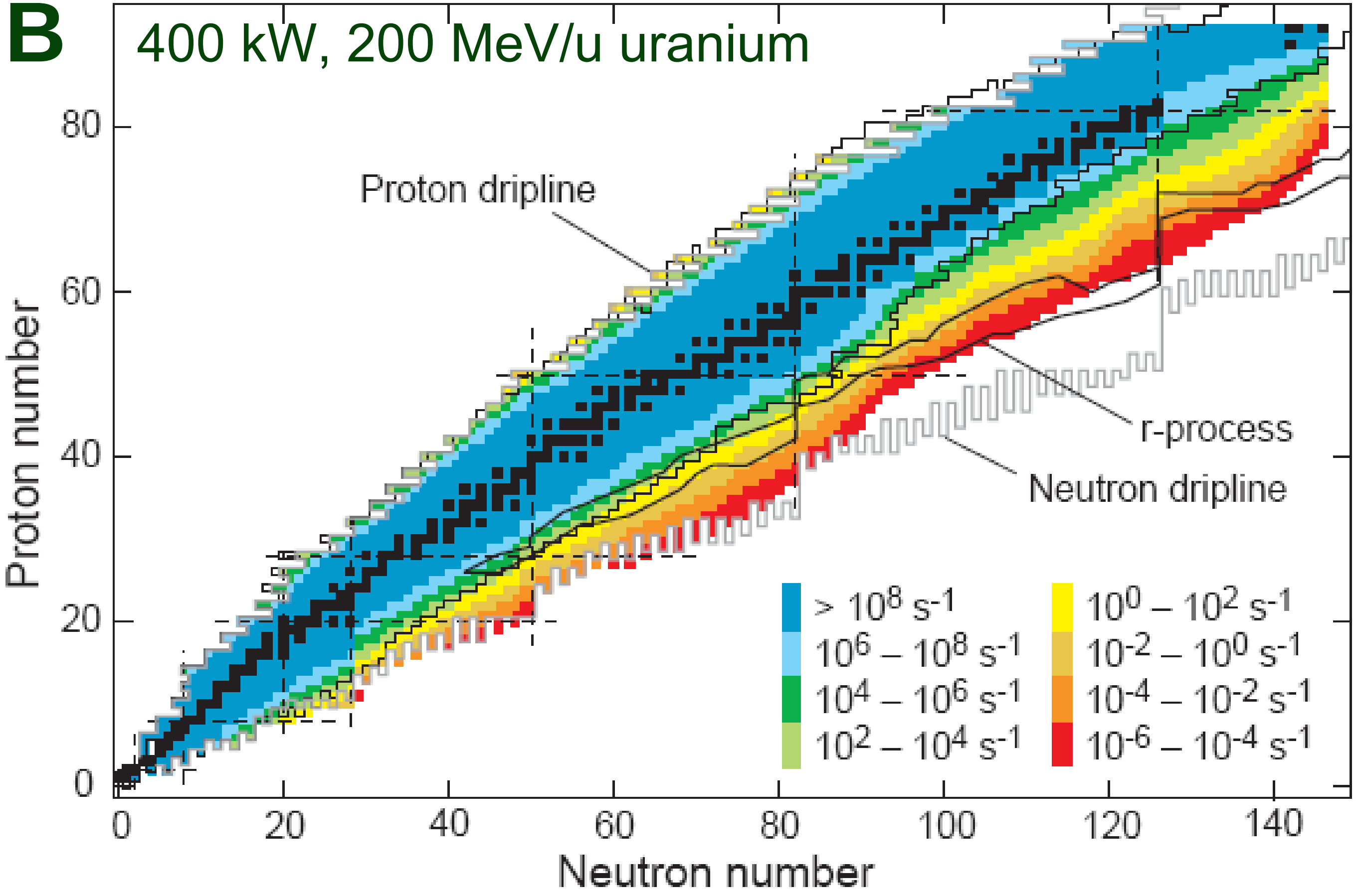
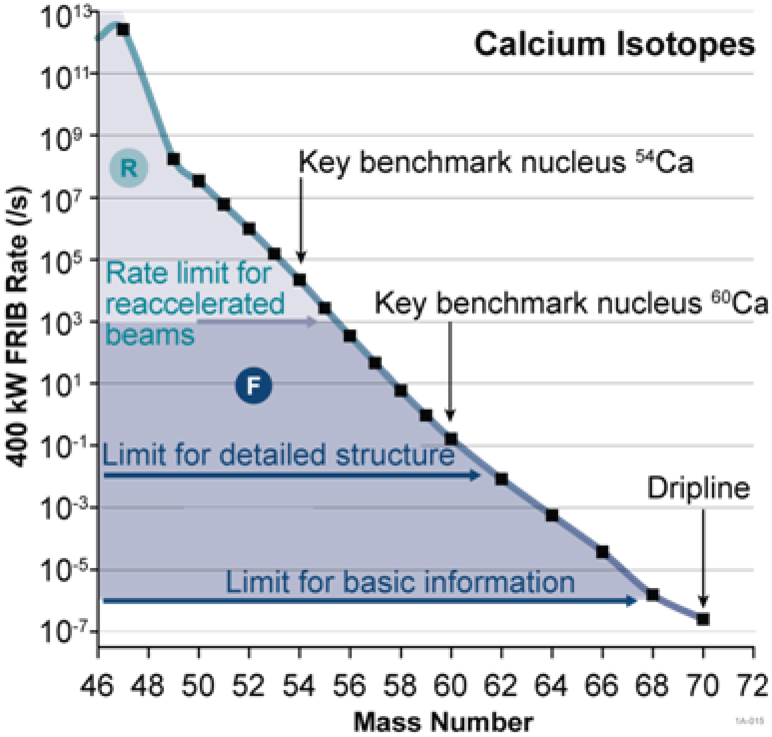


400 kW, 200 MeV/u uranium

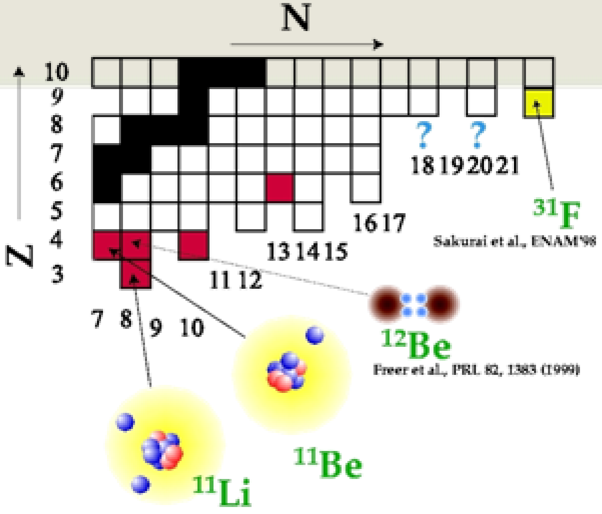
Gain factors of 10-10000 over operational facilities

Fast, stopped, and reaccelerated beams are needed to do the science

- Fast beams (>100 MeV/u)
  - Farthest reach from stability, nuclear structure, limits of existence, EOS of nuclear matter
- Stopped beams (0-100 keV)
  - Precision experiments – masses, moments, symmetries
- Reaccelerated beams (0.2-20 MeV/u)
  - Detailed nuclear structure studies, high-spin studies
  - Astrophysical reaction rates

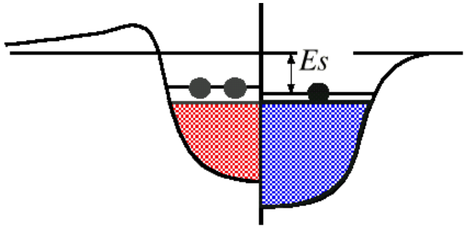


Properties of nucleonic matter

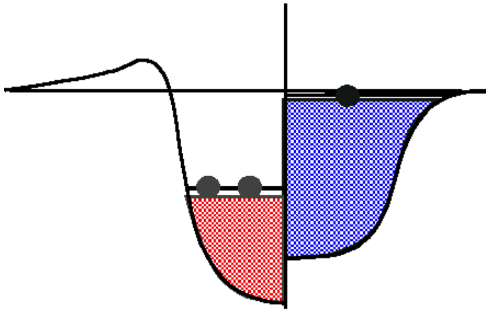


- Studies of rare isotopes are crucial for developing reliable models of nuclei and their reactions
  - – Link to mesoscopic science – deriving the properties of complex systems from their simple building blocks

- Stable nuclei: N/Z ≈ 1 - 1.5, $S_p \approx S_n \approx$ 6 - 8 MeV
  - – Homogeneous admixture of protons and neutrons
  - – Good mean-field description & “single-particle” picture
  - – Large gaps between major shells (magic numbers)
  - – Empirical shell-model interactions

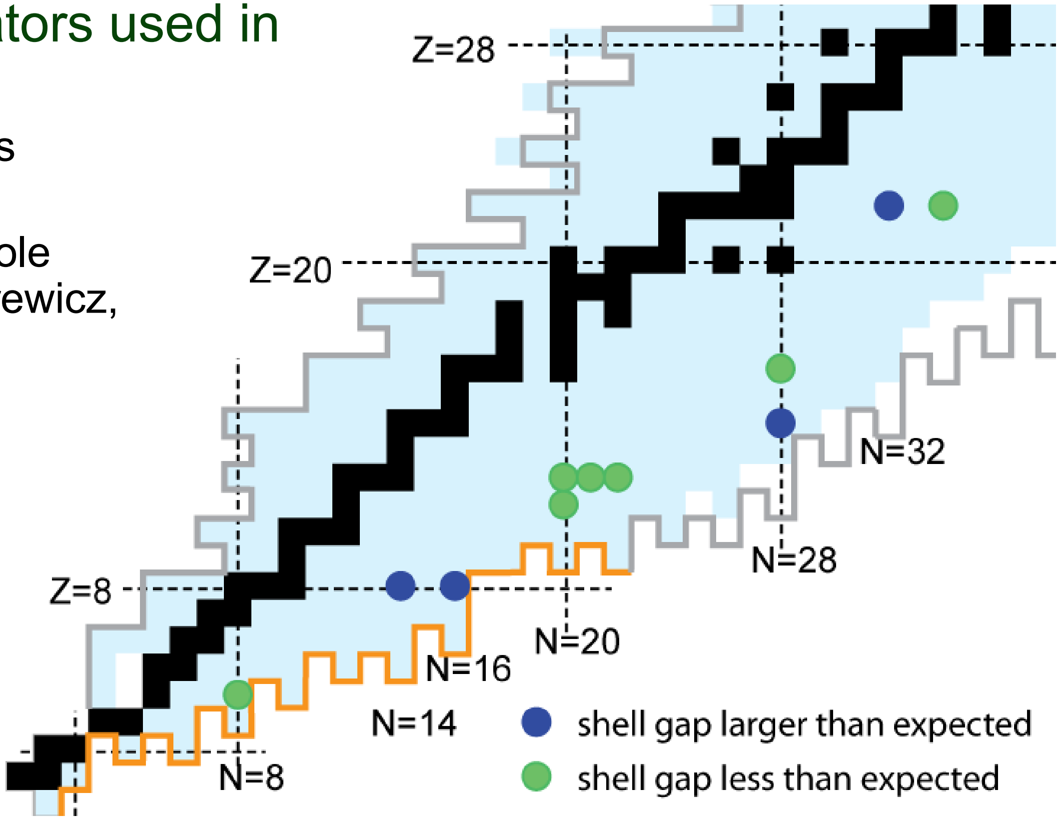


- Very neutron-rich nuclei: N/Z ≈ 2 - 2.5, S_n << 1 MeV
  - – Extended neutron distributions – neutron skins & halos
  - – Proximity of the Fermi surface – coupling to the continuum
  - – Redefinition of magic numbers
  - – Unknown shell-model interactions



Example: Evolution of Shell Structure

- Improved understanding of the nature of the effective interactions and operators used in nuclear structure models
  - Insight into tensor and 3-body forces in nuclei (e.g., Otsuka, et al.)
  - The continuum plays an important role in weakly bound nuclei (e.g., Nazarewicz, Zelevinsky, et al.)
- Needed: excitation energies, B(E2) gamma decay strength, spectroscopic factors, nuclear moments, masses, ...
- Further surprises are to be expected



Search for new nuclear “magic” numbers

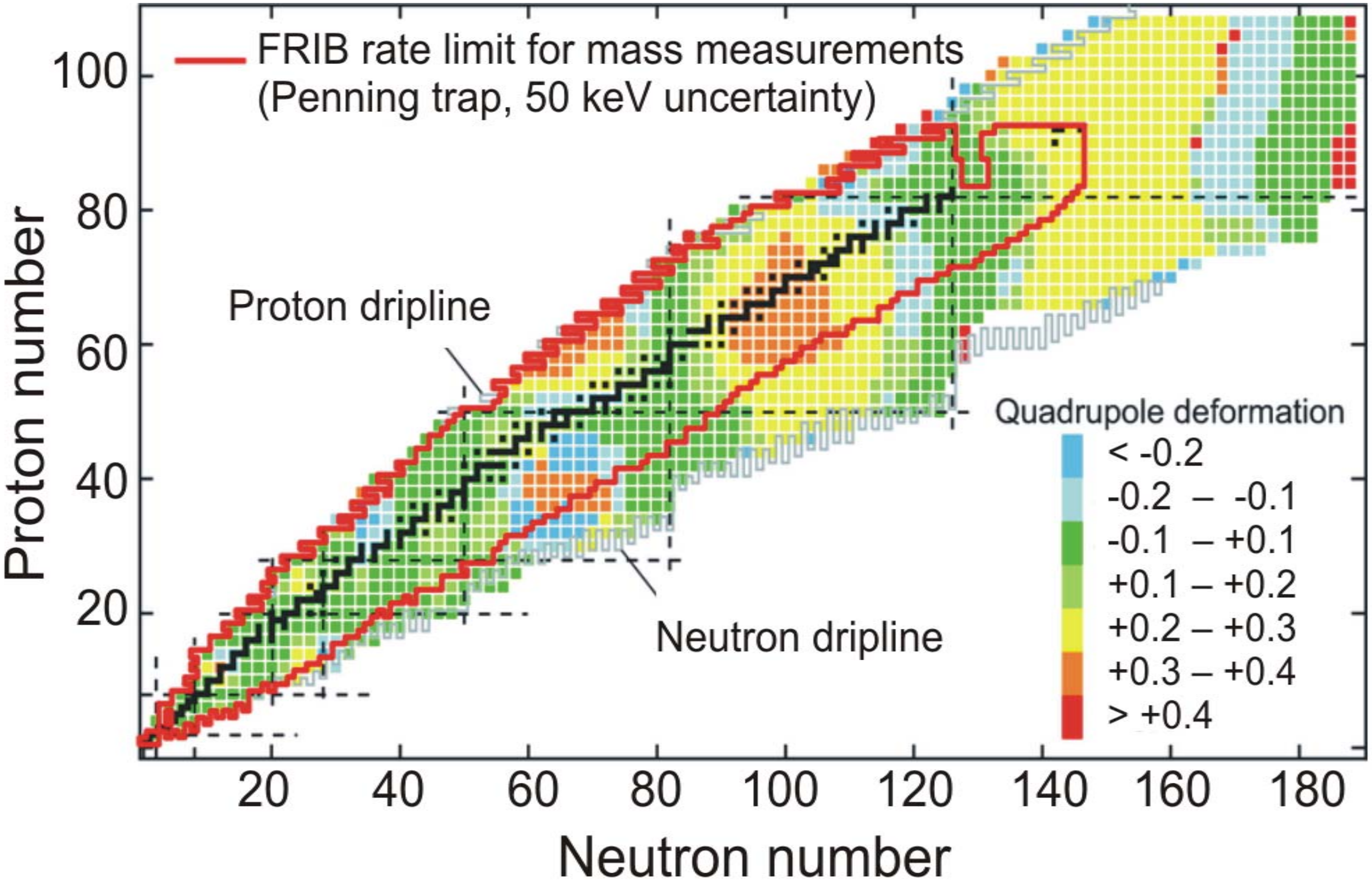
Broad View of Nuclear Properties

Measurements of

- masses
- moments
- deformations
- transition rates
- single particle strengths
- $2^+/4^+$ systematics
- fission barriers
- etc.

produce a more complete picture of the nuclear landscape

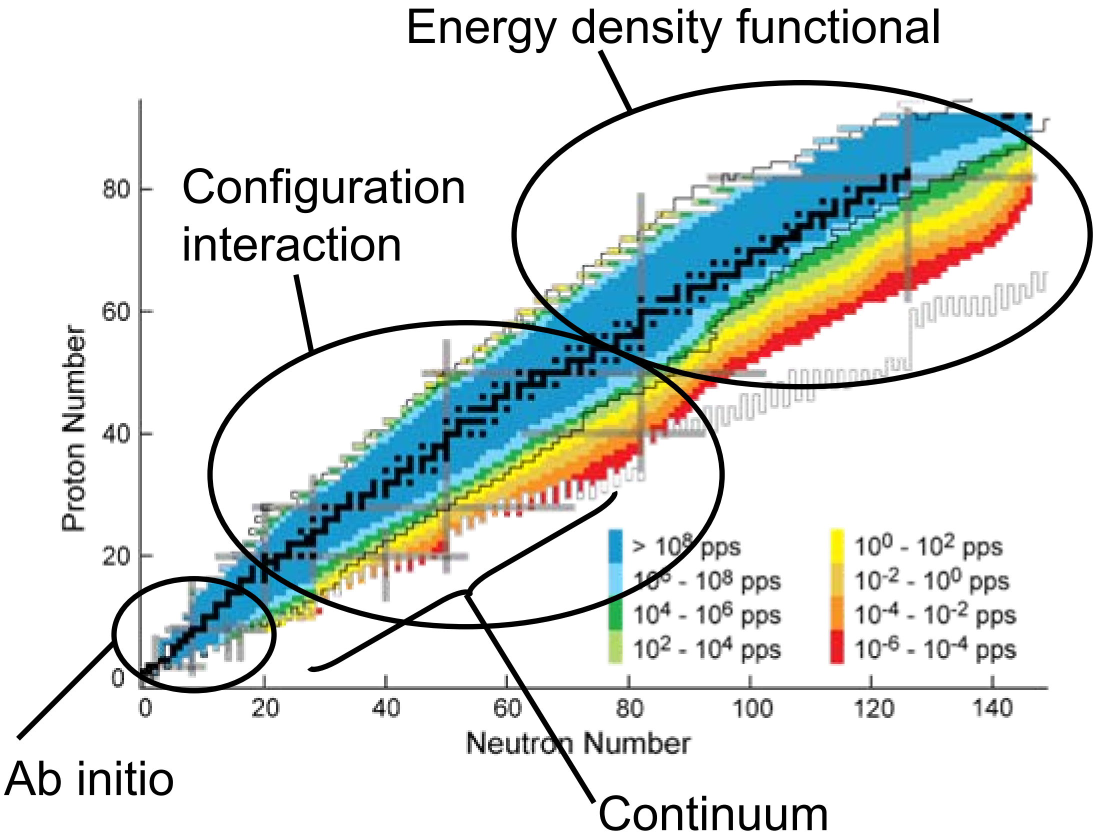
Ground state deformation from global mass calculations



Theory Road Map and Nuclear Structure

Realize a comprehensive and coherent description of atomic nuclei

- Theory Road Map – comprehensive description of the atomic nucleus
  - – Ab initio models – study of neutron-rich, light nuclei helps determine the force to use in models
  - – Configuration-interaction theory; study of shell and effective interactions
  - – The universal energy density functional (DFT) – determine parameters
- Measurements are needed to quantitatively constrain theory



Energy density functional

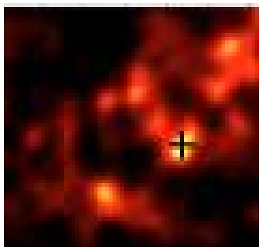
Configuration interaction

Ab initio

Continuum

Nuclear processes in the universe

Important scientific questions



- What is the origin of the elements in the cosmos
  - Synthesis of neutron-rich nuclei heavier than iron: r-process
  - Gamma-ray emitters in supernovae
  - Isotope harvesting for s-process studies

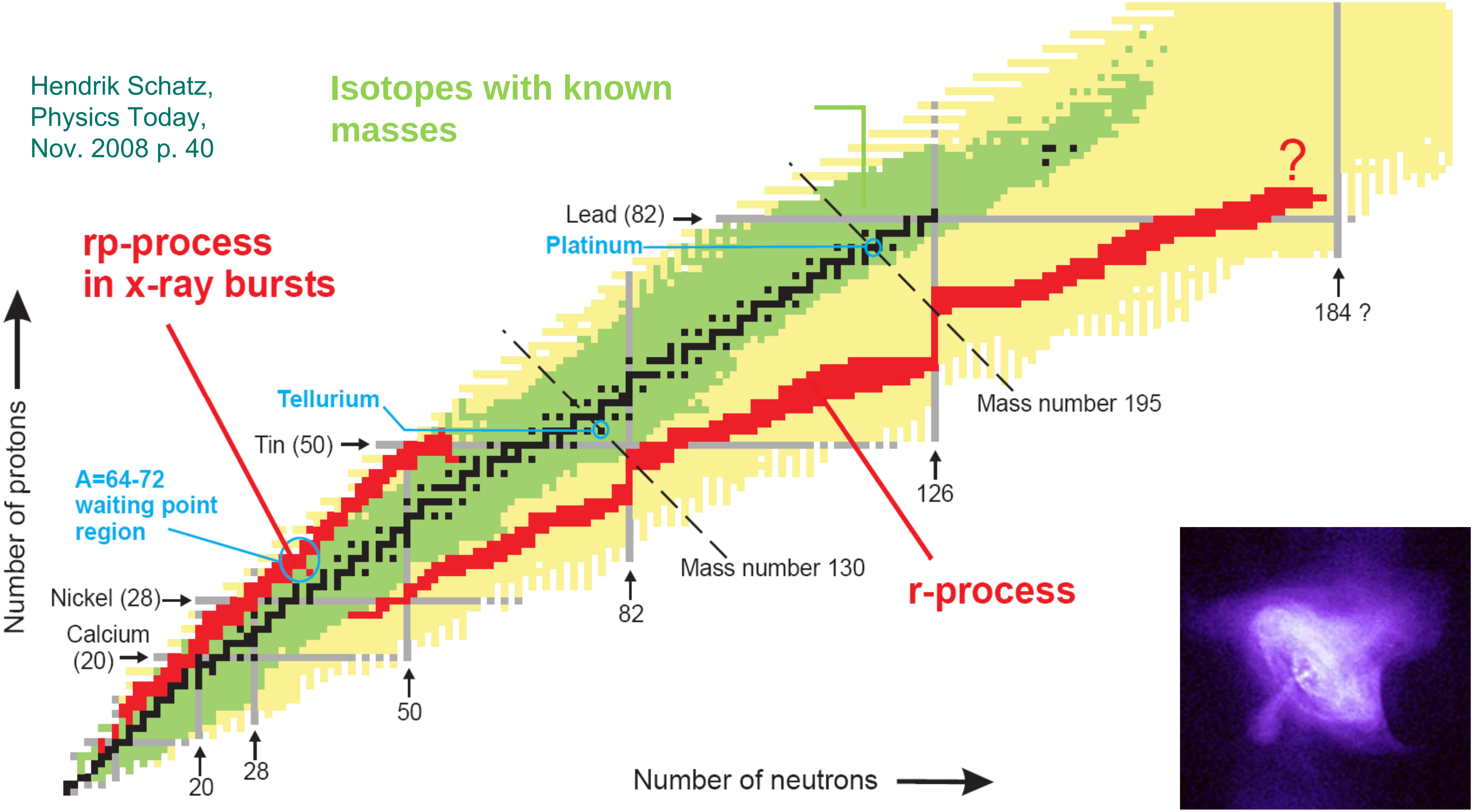
- What are the nuclear reactions that drive stellar explosions
  - Synthesis of proton-rich nuclei: rp-process
  - Weak interactions in supernovae

- What is the nature of neutron stars and dense nuclear matter
  - Nuclear processes in the crusts of neutron stars
  - Symmetry energy term of equation of state of nuclear matter

Explosive Nucleo-Synthesis Paths

r and rp-processes

Hendrik Schatz,
Physics Today,
Nov. 2008 p. 40

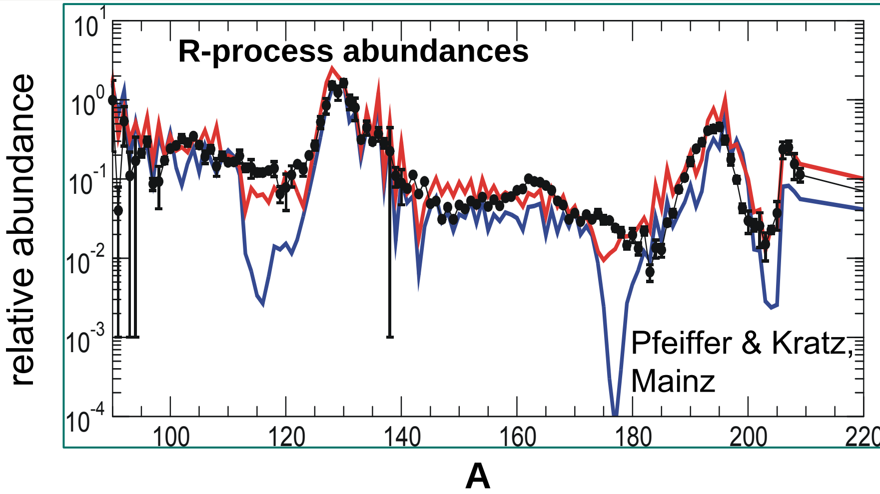


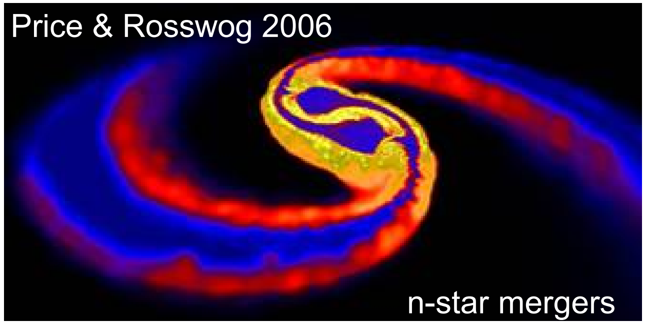
FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

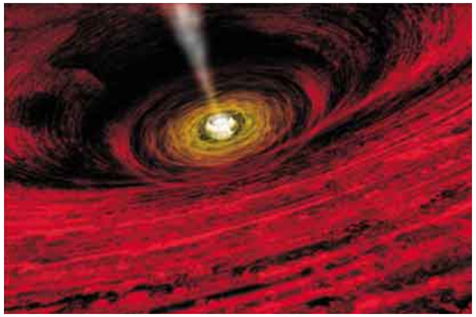
The Rapid Neutron Capture Process

Occurs at T > 10^9 K, $\rho_{neutron} > 10^{20}\ cm^{-3}$

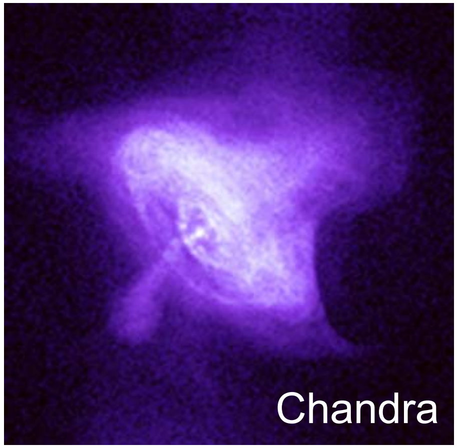
- Open questions:
  - Where does nature produce about half of the heavy elements beyond Fe?
  - What does the abundance pattern tell us about the astrophysical environment?
- Needed: Data
  - FRIB: Nuclear experimental data (masses, half-lives) plus improved nuclear theory
  - Precision observations of abundance patterns produced by the r-process in nature







Nucleosynthesis in gamma ray burst accretion disks?

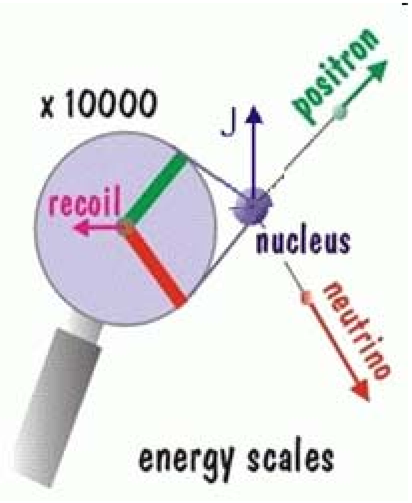


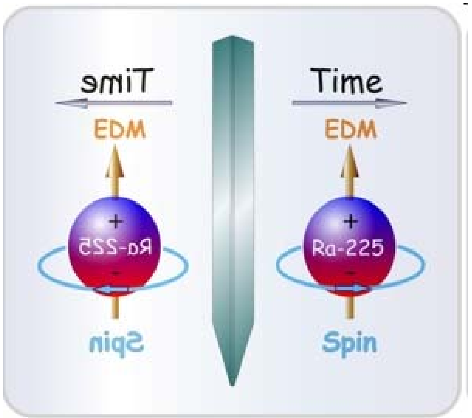
Supernovae: Neutrino-driven wind?
Prompt explosions?
Shocked O-Ne-Mg cores?

Tests of fundamental symmetries

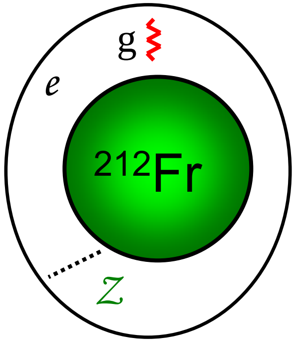
Why is there more matter than antimatter in the universe?

- Angular correlations in β-decay and search for scalar currents
  - Mass scale for new particle comparable with LHC
- Electric Dipole Moments
  - ^{225}Ra, ^{223}Rn, ^{229}Pa
- Parity Non-Conservation in atoms
  - weak charge in the nucleus (francium isotopes)
- Unitarity of CKM matrix
  - V_{ud} by superallowed Fermi decay
  - Probe the validity of nuclear corrections

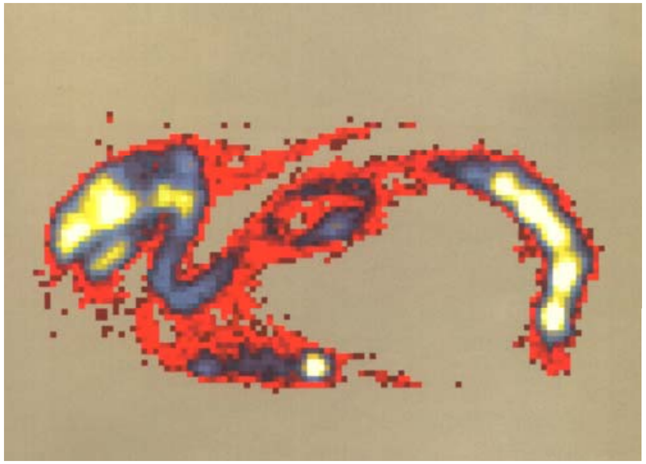




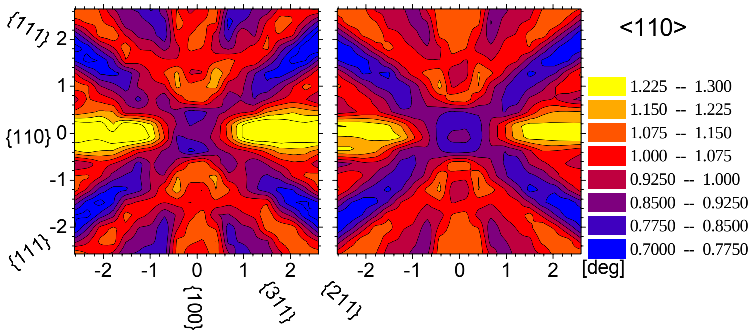
$$\begin{vmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix}$$



Applications of rare isotopes



- Cross sections for evaluation of new nuclear technologies such as transmutation of nuclear waste.
- New radioisotopes for medicine – targeted cancer therapy, diagnostics.
- Tracers for various studies.
- Soft doping of semiconductors.
- …
- Stockpile stewardship – allow measurements of necessary cross sections to insure the reliability of simulations.



Long-lived isotopes via harvesting

Facility for Rare Isotope Beams (FRIB)

Historical background:

1999: ISOL Task Force Report – proposes RIA concept

2003: RIA ranks 3rd in DOE 20-year Science Facility Plan

2005: DOE cancels draft of RIA-RFP (request for proposal)

- DOE and NSF charge Rare Isotope Science Assessment Committee (RISAC) of the Academies to assess science case for Rare -Isotope Facility

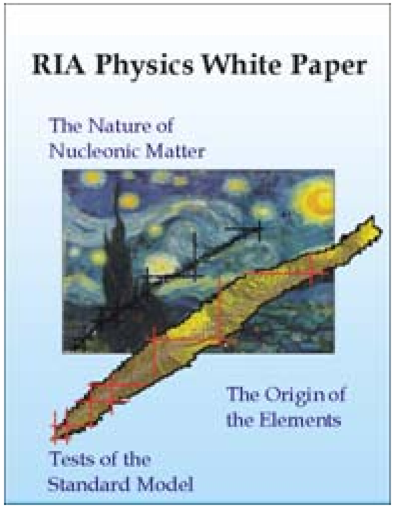
2006: DOE cancels RIA and pursues a lower cost option

- RISAC endorses construction of a Rare-Isotope Facility

2007: NSAC makes FRIB the 2nd highest priority for nuclear science

2008: DOE issues a Funding Opportunity Announcement for FRIB.
ANL and MSU submit applications.
DOE selects the MSU application following a merit review and evaluation process (Dec. 11)

6/2009: Cooperative Agreement between MSU and DOE will be signed

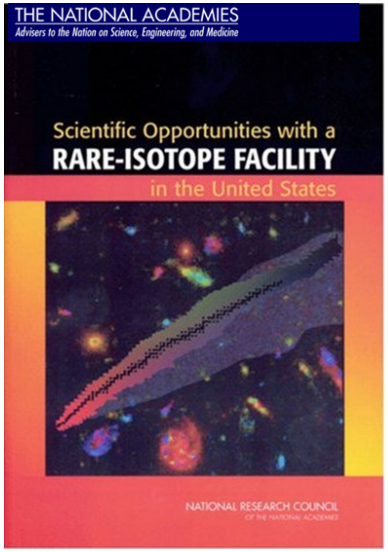


RIA Physics White Paper

The Nature of Nucleonic Matter

The Origin of the Elements

Tests of the Standard Model



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

Scientific Opportunities with a
RARE-ISOTOPE FACILITY
in the United States

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

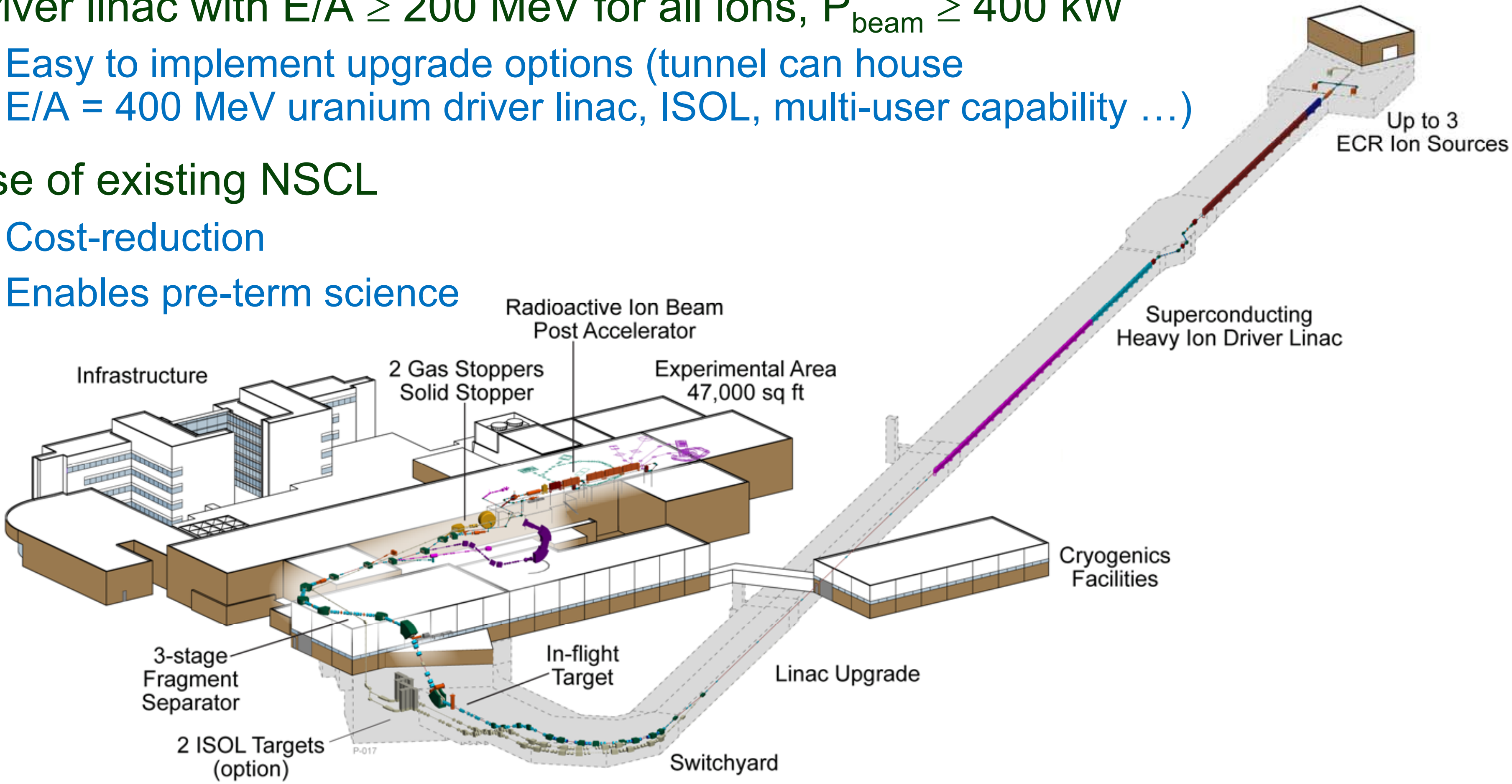
FRIB Specifications (DOE)

- 200 MeV/u, 400 kW superconducting heavy-ion driver linac
- initial capabilities should include fragmentation of fast heavy-ion beams combined with gas stopping and reacceleration
- capable of world-class scientific research program at start of operation
- designed, built and commissioned for a total project cost of ≤ 550 M$

FRIB

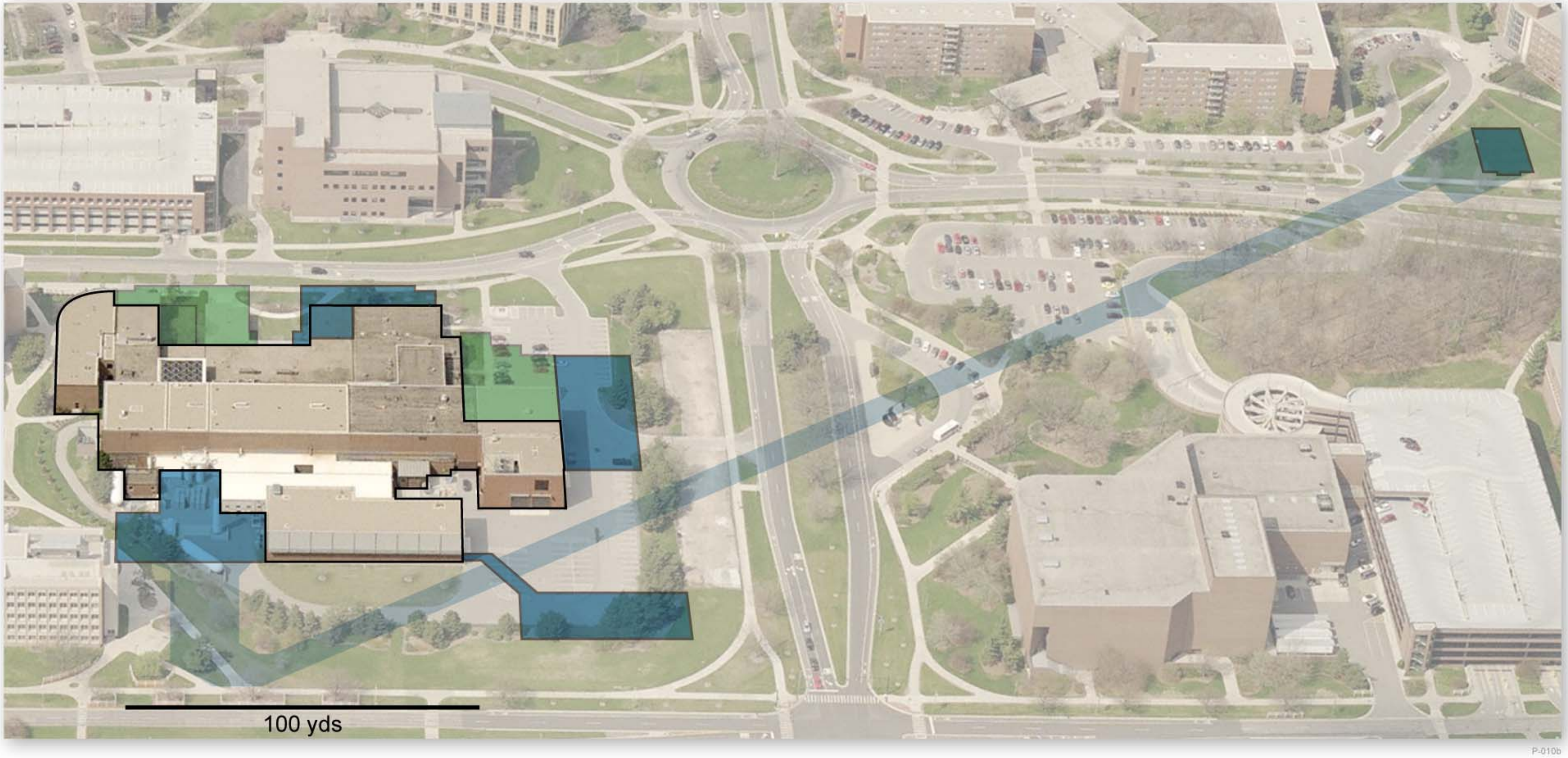
MSU-Proposed FRIB

- Driver linac with E/A ≥ 200 MeV for all ions, $P_{beam} \geq$ 400 kW
  - Easy to implement upgrade options (tunnel can house E/A = 400 MeV uranium driver linac, ISOL, multi-user capability …)
- Use of existing NSCL
  - Cost-reduction
  - Enables pre-term science



Completion foreseen in 2017

FRIB Location on the MSU Campus



Superconducting RF Driver LINAC
400 kW, 200 MeV/u uranium, 610 MeV protons

Venus (LBNL) type ECR ion sources + LEBT

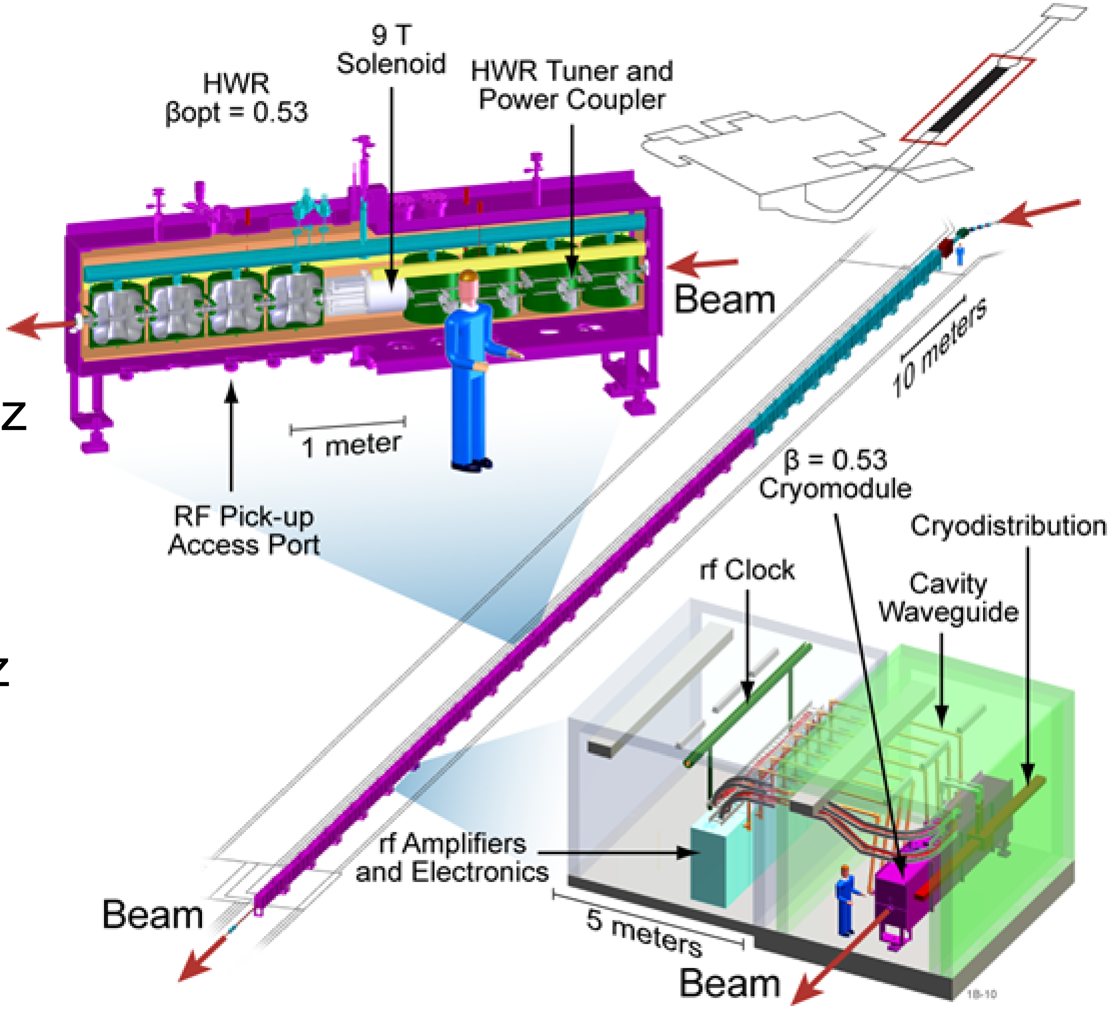
<u>SRF LINAC:</u>

Two types of quarter-wave Resonators (QWRs) at 80.5 MHz

One stripping station

Two types of Half-wave Resonators (HWRs) at 322 MHz

Multi-charge state acceleration

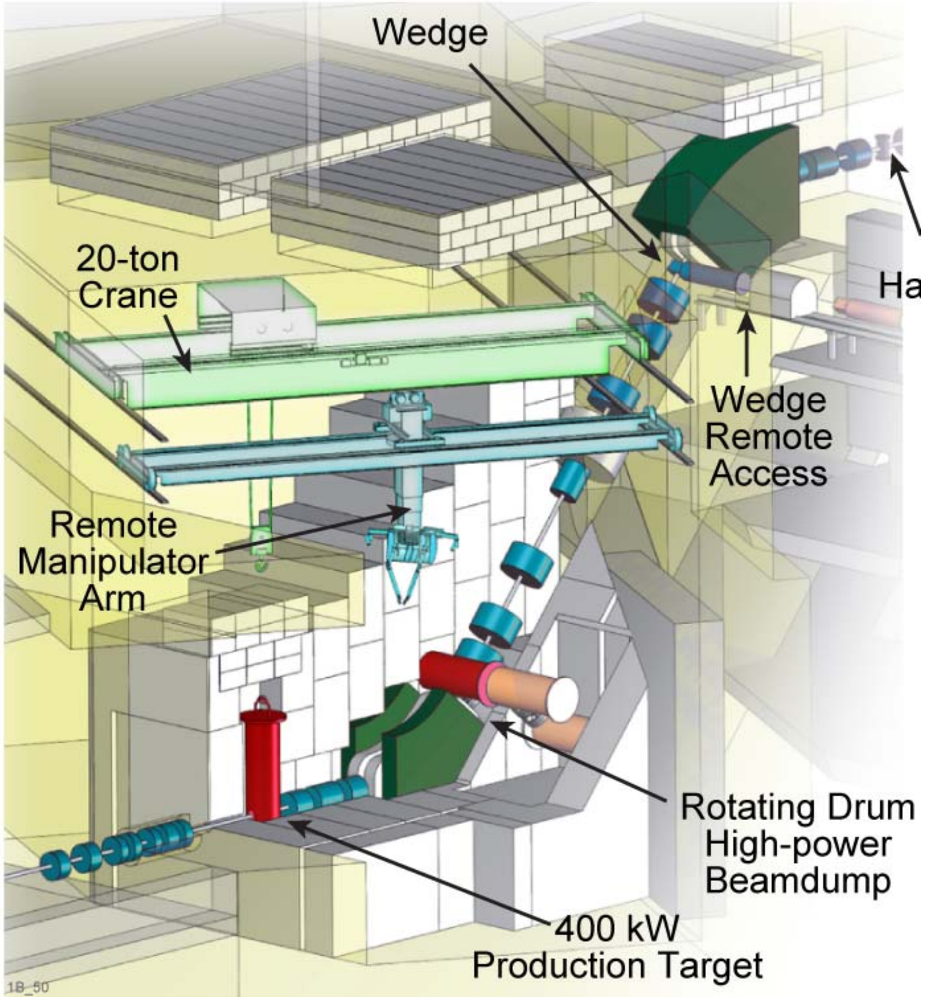


Production Target Facilities

Baseline: projectile fragmentation with in-flight separation

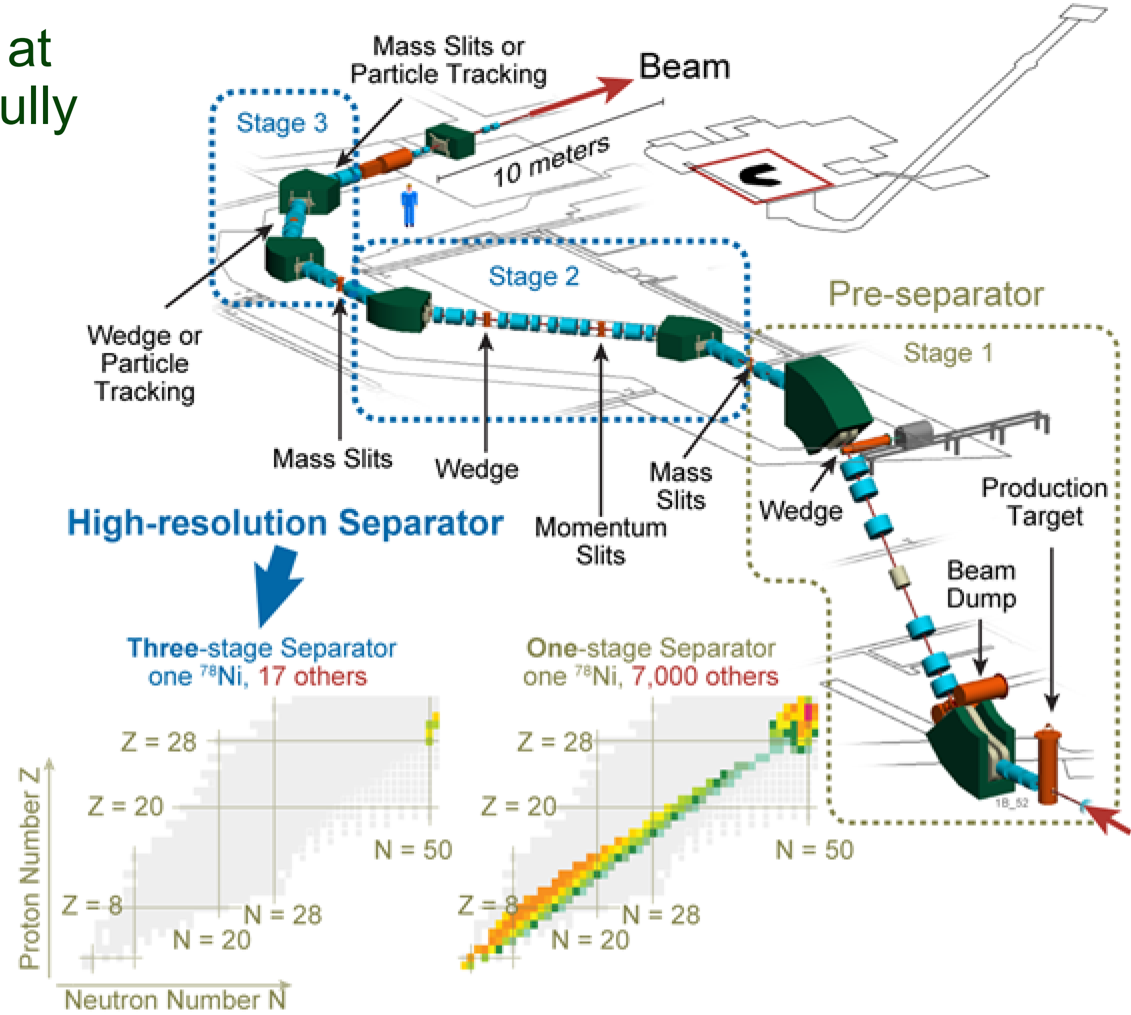
- Self-contained target building to keep most-activated and contaminated components in one spot
- State-of-the-art full remote-handling to maximize efficiency
- Target applicable to light and heavy beams
  - Rotating solid graphite target foreseen
  - Liquid Li target (optional) for use with uranium beams
- Upgrade options
  - Two ISOL stations or 2nd fragment separator

R&D on high-power density, high radiation issues needed



In-Flight Fragment Separation

- Heavy rare isotopes produced at 200 MeV per nucleon are not fully stripped
- Beam purity can be critical for new discoveries
- Beam purity important for gas stopping
- 3-stage separation to provide optimal purity



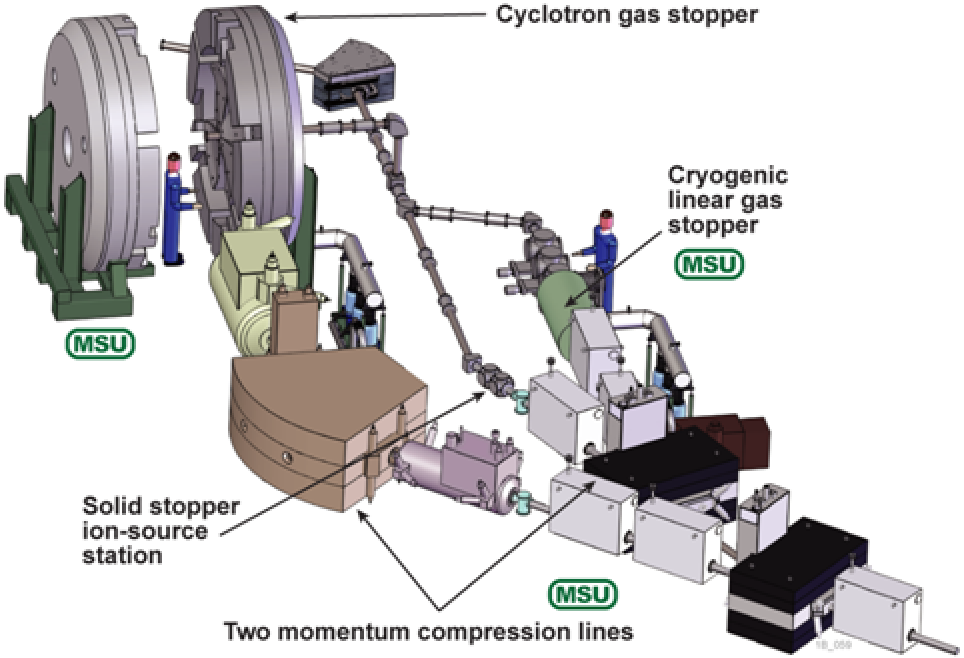
Beam Stopping

Beams for precision experiments at very low-energies or at rest

Penning trap mass measurements, fundamental interactions tests
with atom traps, radii and moments from laser spectroscopy

+ reacceleration of rare isotopes produced by projectile fragmentation

- Cyclotron gas stopper
  - Best for light and medium heavy isotopes
- Cryogenic linear gas stopper
  - Best for heavy isotopes
- Solid stopper
  - For special elements and very high beam rates
  - Example: ^{15}O, I >10^{10}/s

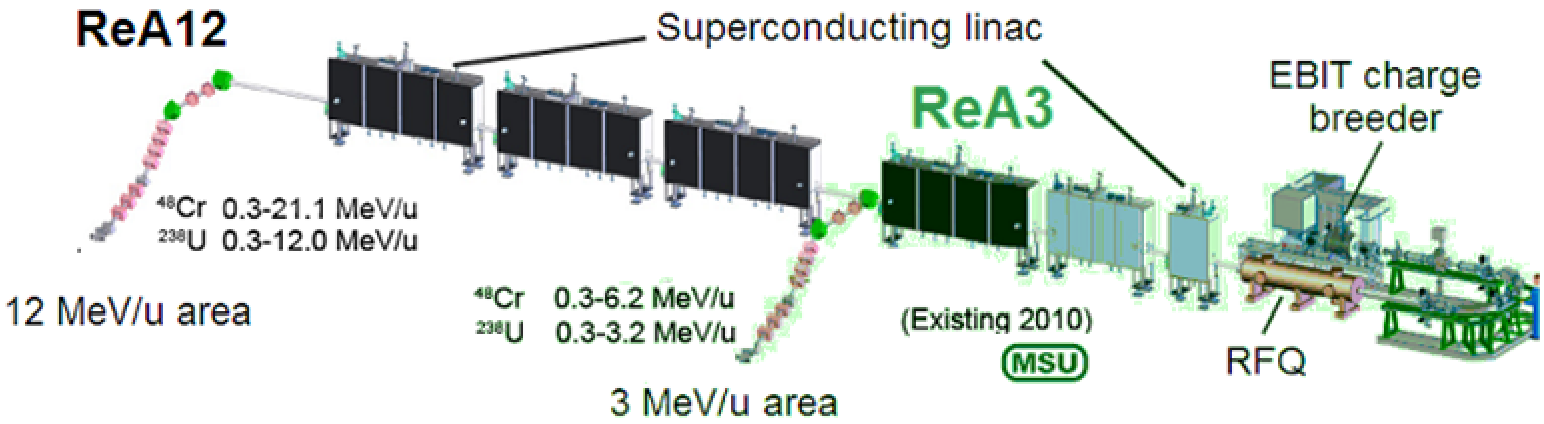


Reacceleration

Reaccelerated beams of rare isotopes from projectile fragmentation

Nuclear structure studies: Coulomb excitation, transfer reactions

Nuclear astrophysics: reaction rates critical to element synthesis processes



Advanced n+ reaccelerator with EBIT charge breeder

– High-intensity EBIT as $1^+ \rightarrow n^+$ charge breeder

– Modern linear accelerator – RT RFQ+ SRF linac

   » Energies 0.3-3 MeV/u and 0.3-12 MeV/u uranium

   » higher energies for lighter ions

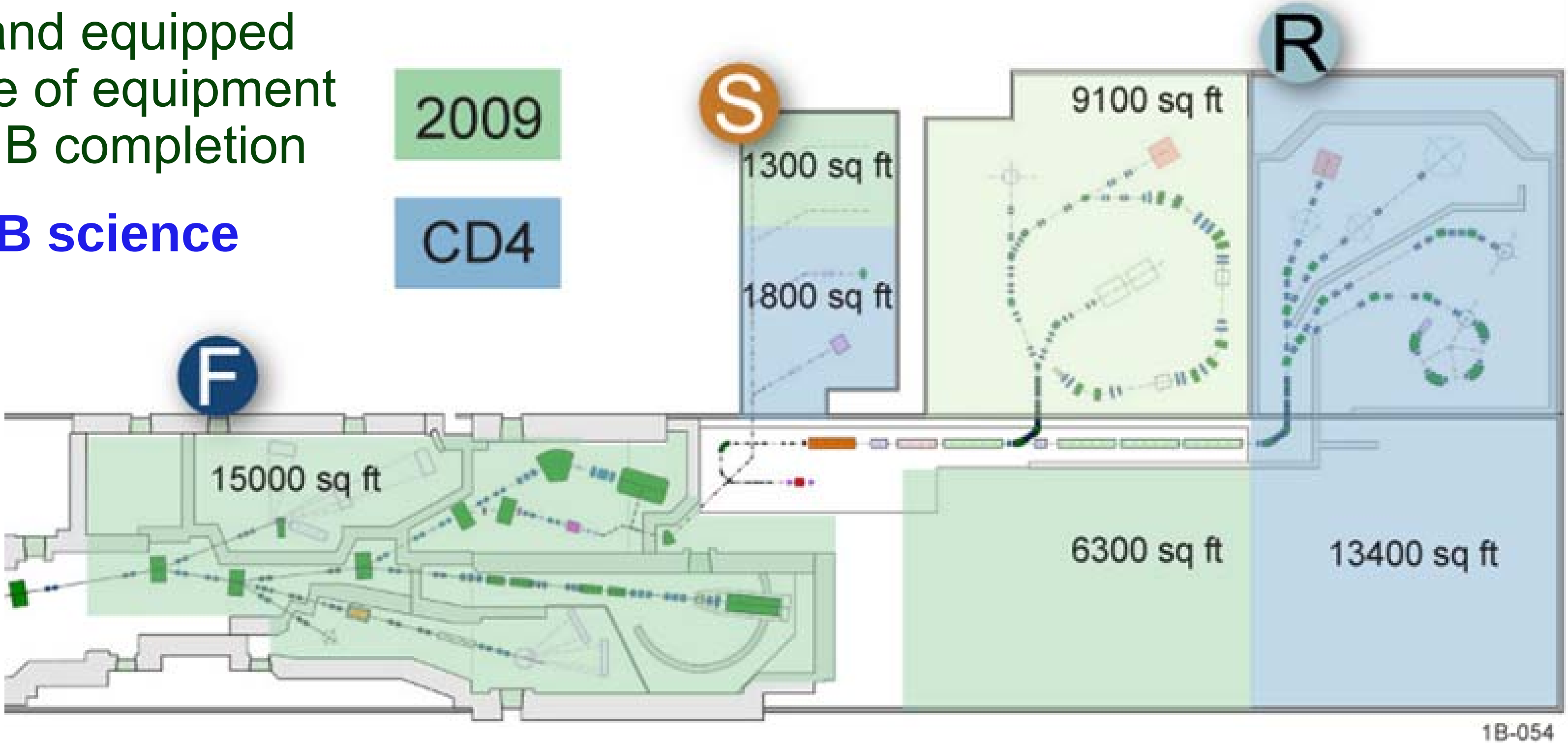
Talk by Marc Doleans on ReA3

Experimental Areas

Experimental areas for fast, stopped and reaccelerated beams

All types of areas available and equipped with a suite of equipment before FRIB completion

→**Pre-FRIB science**



47, 000 sq ft; Possibility for future science-driven area expansions

Summary and conclusions

- Next-generation high-power RIB facilities for new science opportunities with rare isotopes
  - –Properties of nucleonic matter
  - –Nuclear processes in the universe
  - –Tests of fundamental symmetries
  - –Societal applications and benefits
- FRIB in the US to become the world's next flagship facility for rare isotope science.

FRIB