Nuclear Data Opportunities and Needs at FRIB

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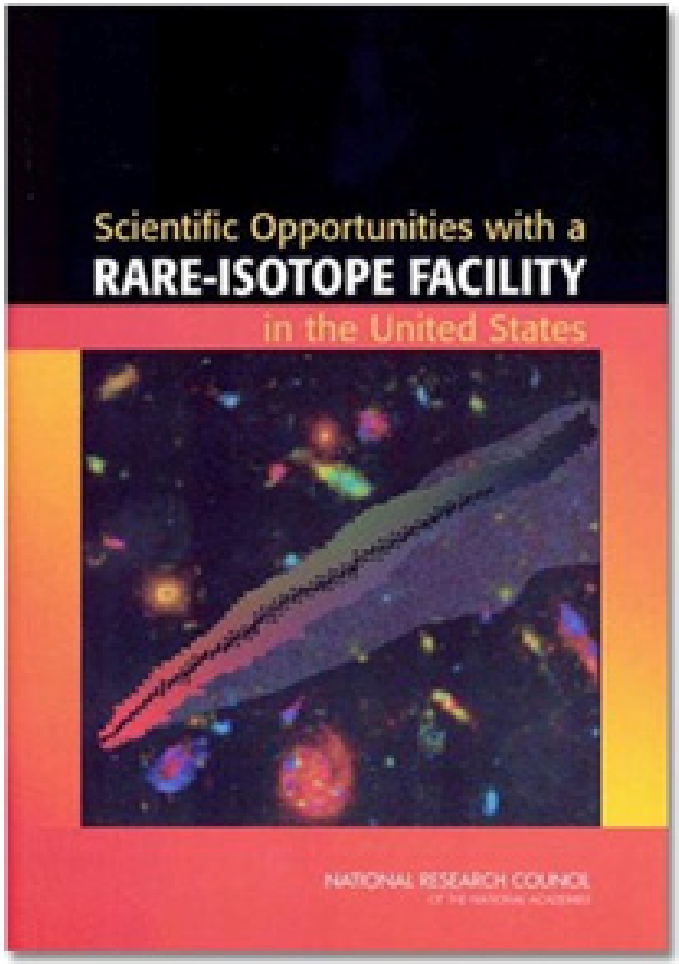
U.S. DEPARTMENT OF ENERGY
Office of Science

NRC Rare Isotope Science Assessment Committee, RISAC, on Study of Nuclei

"The committee concludes that the science addressed by a rare-isotope facility, most likely based on a heavy ion linac driver, should be a high priority for the United States."



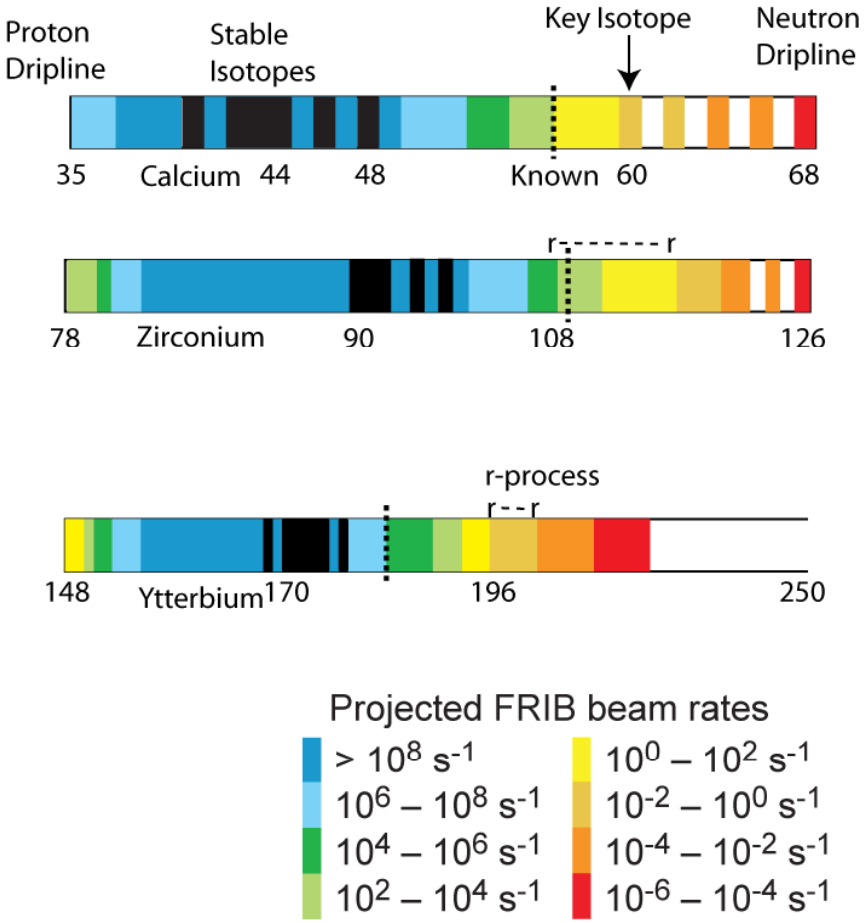
> The committee concludes that nuclear structure and nuclear astrophysics constitute a vital component of the nuclear science portfolio in the United States. Moreover, nuclear structure-related research provides the scientific basis for important advances in medical research, national security, energy production, and industrial processing."

> The Gathering Storm report argued that strong public support of basic research can help fuel the national economic engine… While it is nearly impossible to argue that any one specific investment is critically necessary to maintain the future health of the enterprise, the committee does recognize the value of a U.S. FRIB as one element of a much broader portfolio in the physical sciences."

—Scientific Opportunites with a Rare Isotope Facility, December 2006

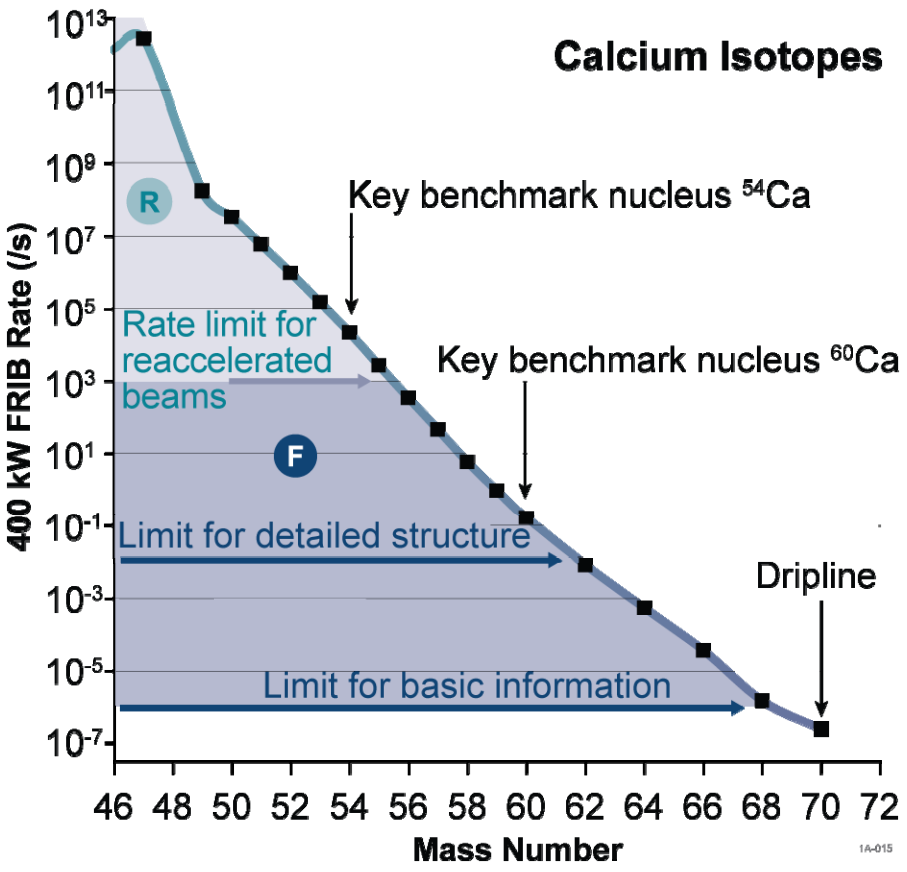
RISAC Science Drivers

- Nuclear Structure
  - Explore the limits of existence and study new phenomena
  - Possibility of a broadly applicable model of nuclei
  - Probing neutron skins
  - Synthesis of superheavy elements
- Nuclear Astrophysics
  - The origin of the heavy elements
  - Explosive nucleosynthesis
  - Composition of neutron star crusts
- Fundamental Symmetries
  - Tests of fundamental symmetries
- Other Scientific Applications
  - Stockpile stewardship, materials, medical, reactors



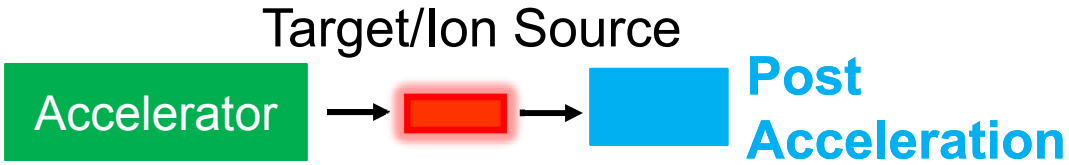
Examples of Scientific Goals of FRIB that Drive Specifications

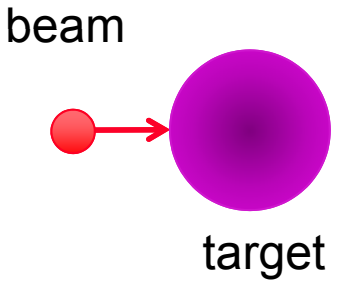
- Produce and study nuclei along the drip lines at A≈100
- Produce and study nuclei in the r-process including at N=126
- Provide reaccelerated beams capabilities (fusion, transfer, COULEX, etc.)
- Superheavy element studies and fundamental symmetries experiments require that ISOL production by 600 MeV protons be an option
- Example: FRIB intensity will allow the key benchmark nuclei ^{54}Ca (reaccelerated beams) and ^{60}Ca (fast beams) to be studied



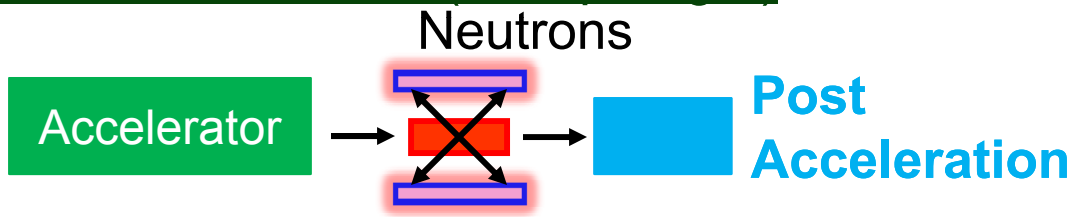
Rare Isotope Production Mechanisms

- Reacceleration by target spallation and fragmentation

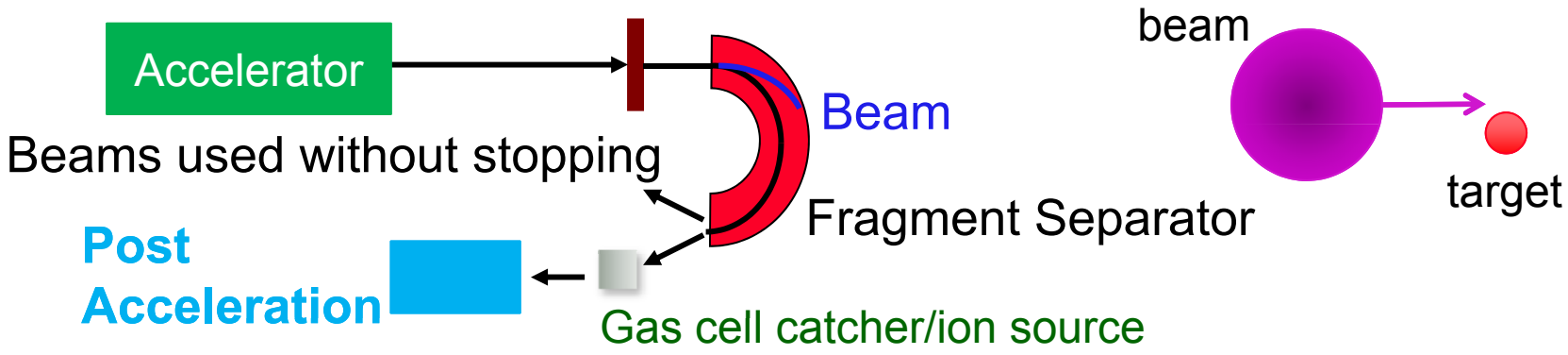




- Neutron induced fission (2-step target)

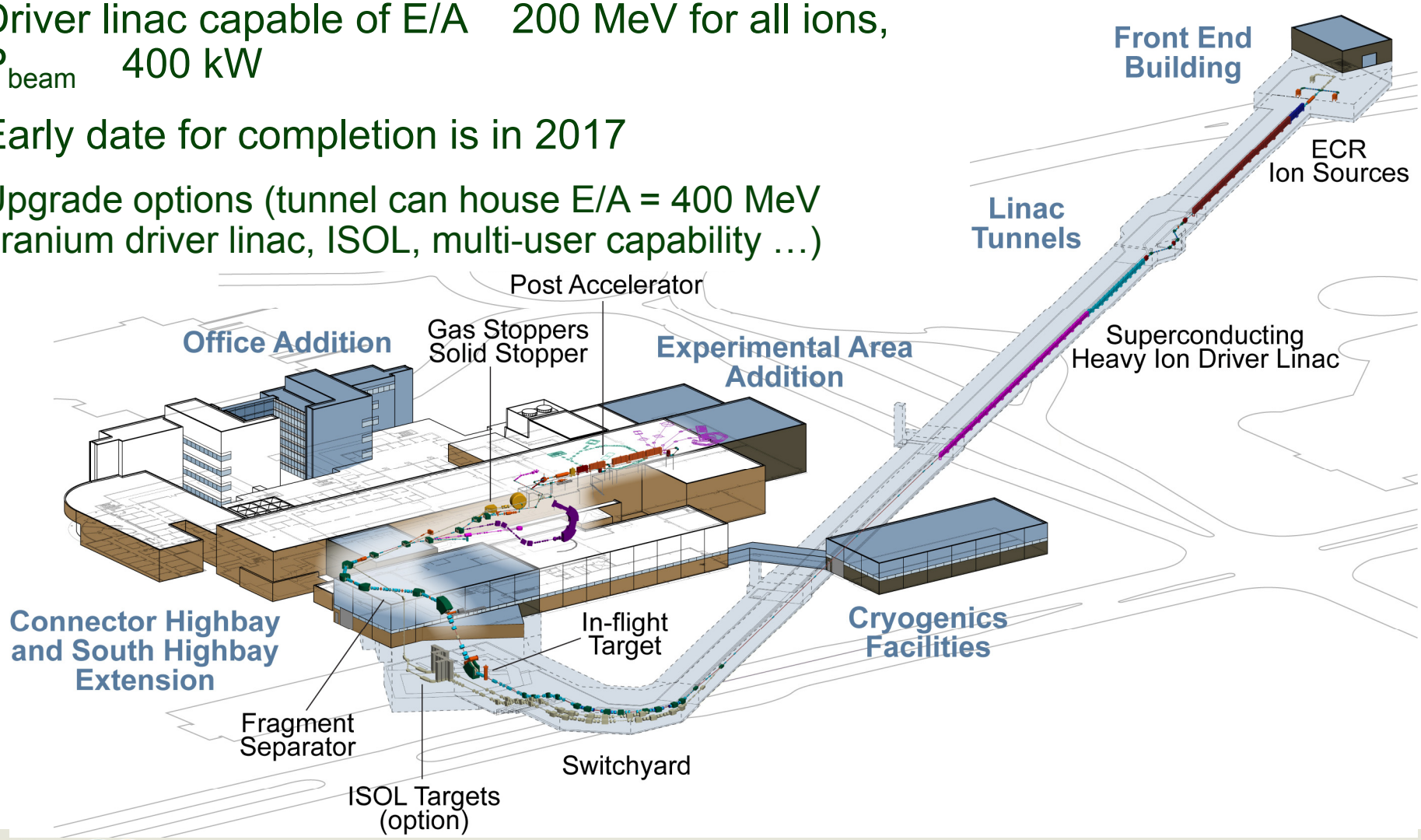


- NEW: In-flight Separation following projectile fragmentation/fission



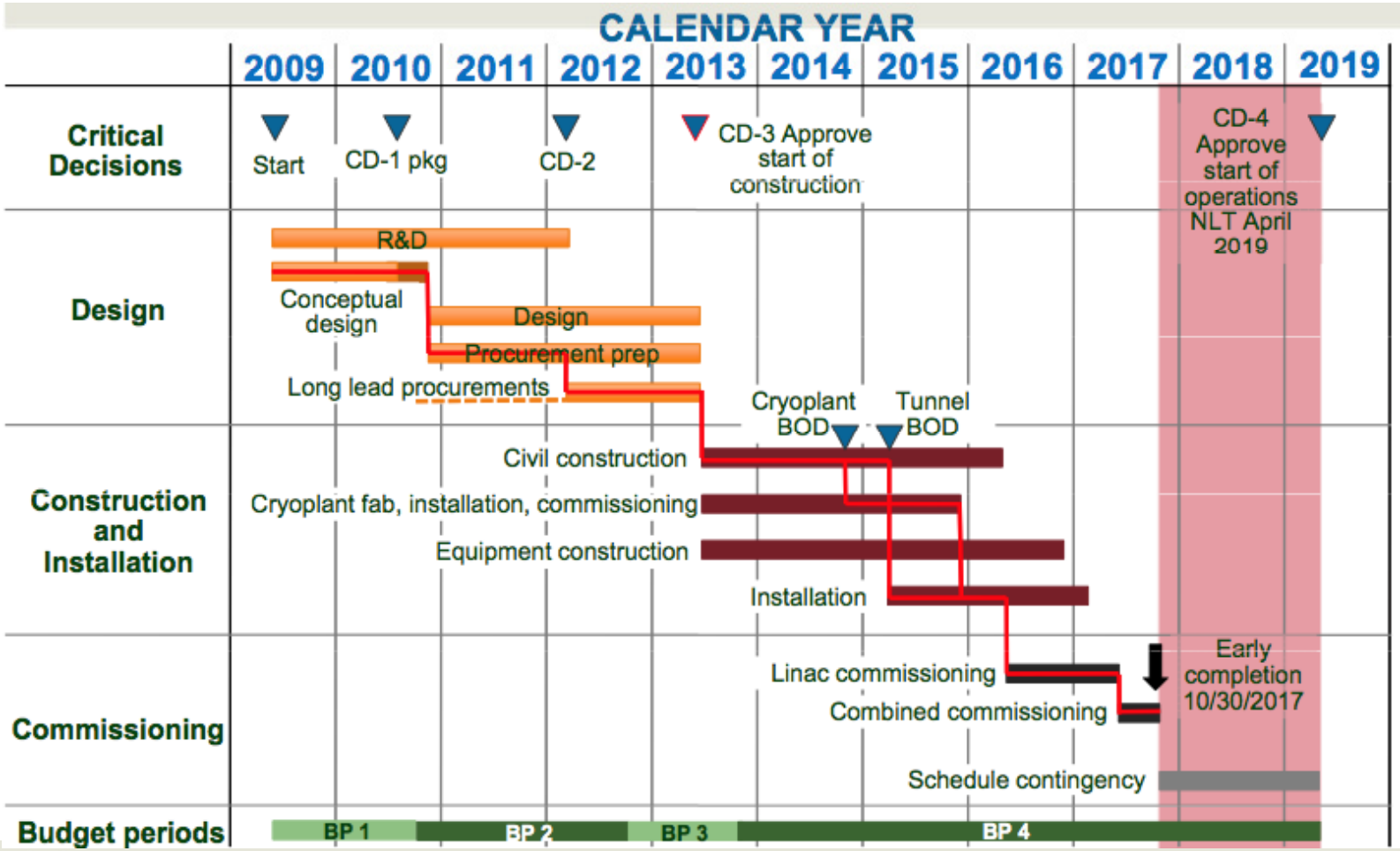
Facility for Rare Isotope Beams, FRIB Broad Overview

- Driver linac capable of E/A 200 MeV for all ions, P_{beam} 400 kW
- Early date for completion is in 2017
- Upgrade options (tunnel can house E/A = 400 MeV uranium driver linac, ISOL, multi-user capability …)



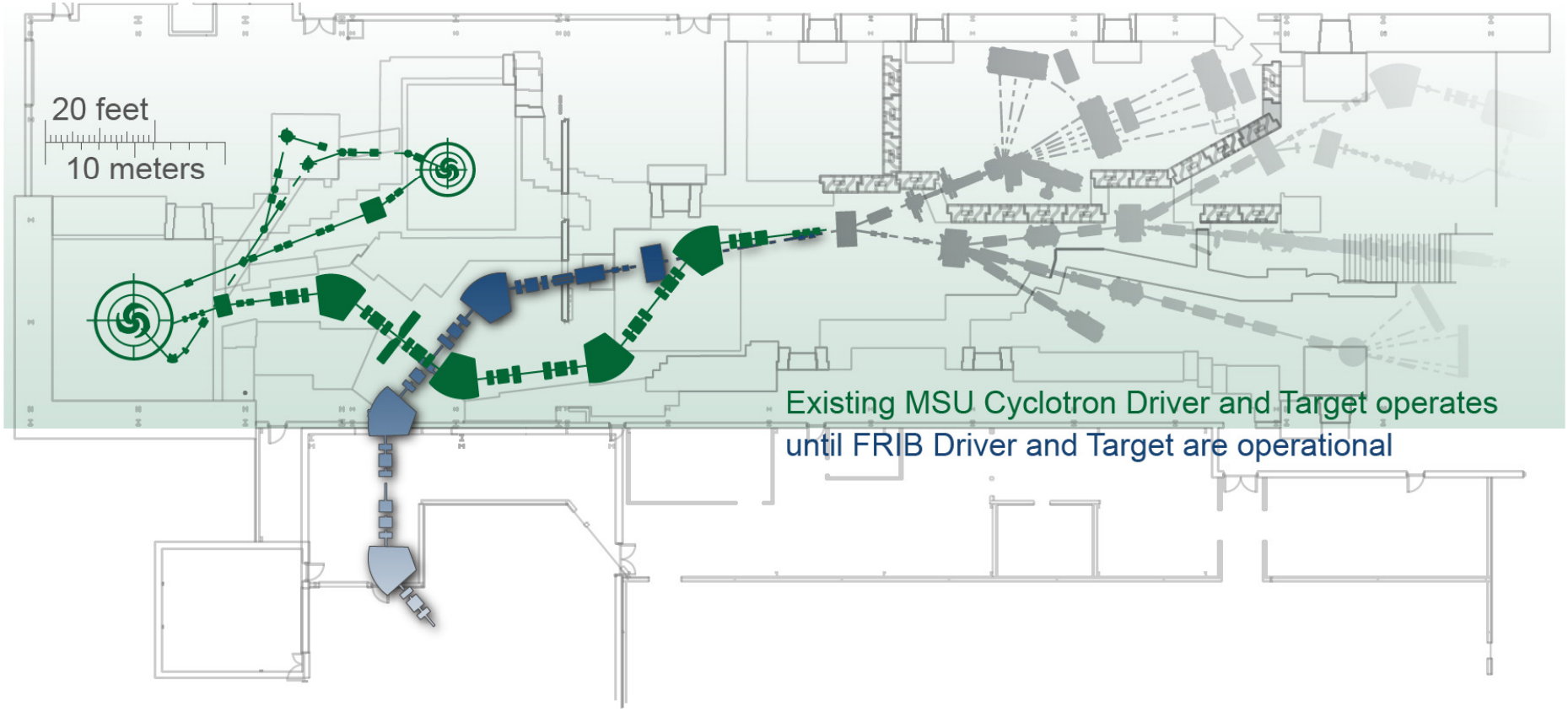
Timeline for Establishment of FRIB

- The timeline for FRIB is dependent on funding by congress and approval by DOE



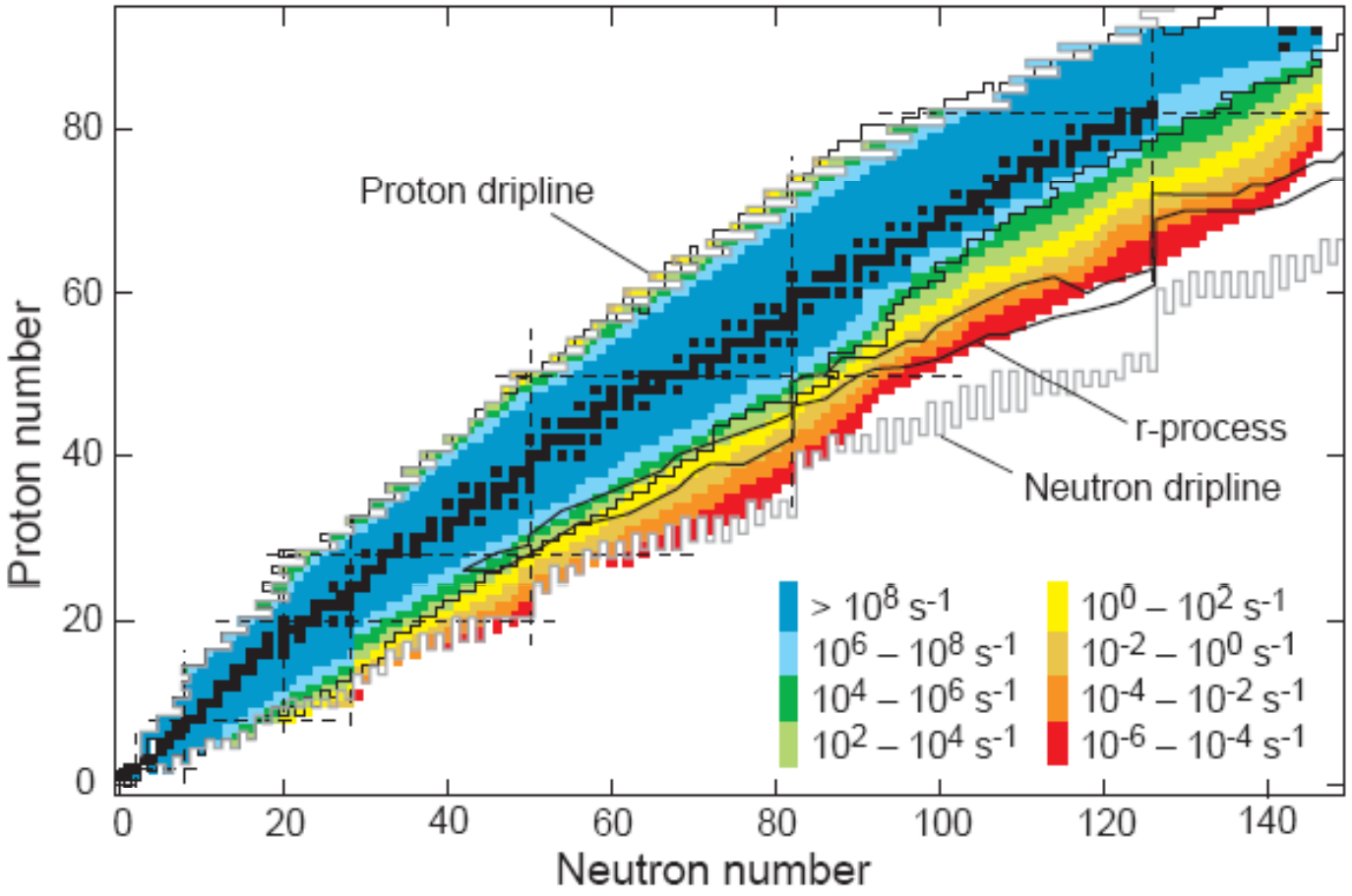
Transition from NSCL to FRIB Operations

- Minimal perturbation of the experimental area when transitioning from CCF to FRIB operations (goal is six months down time)



What New Nuclides Will FRIB Produce?

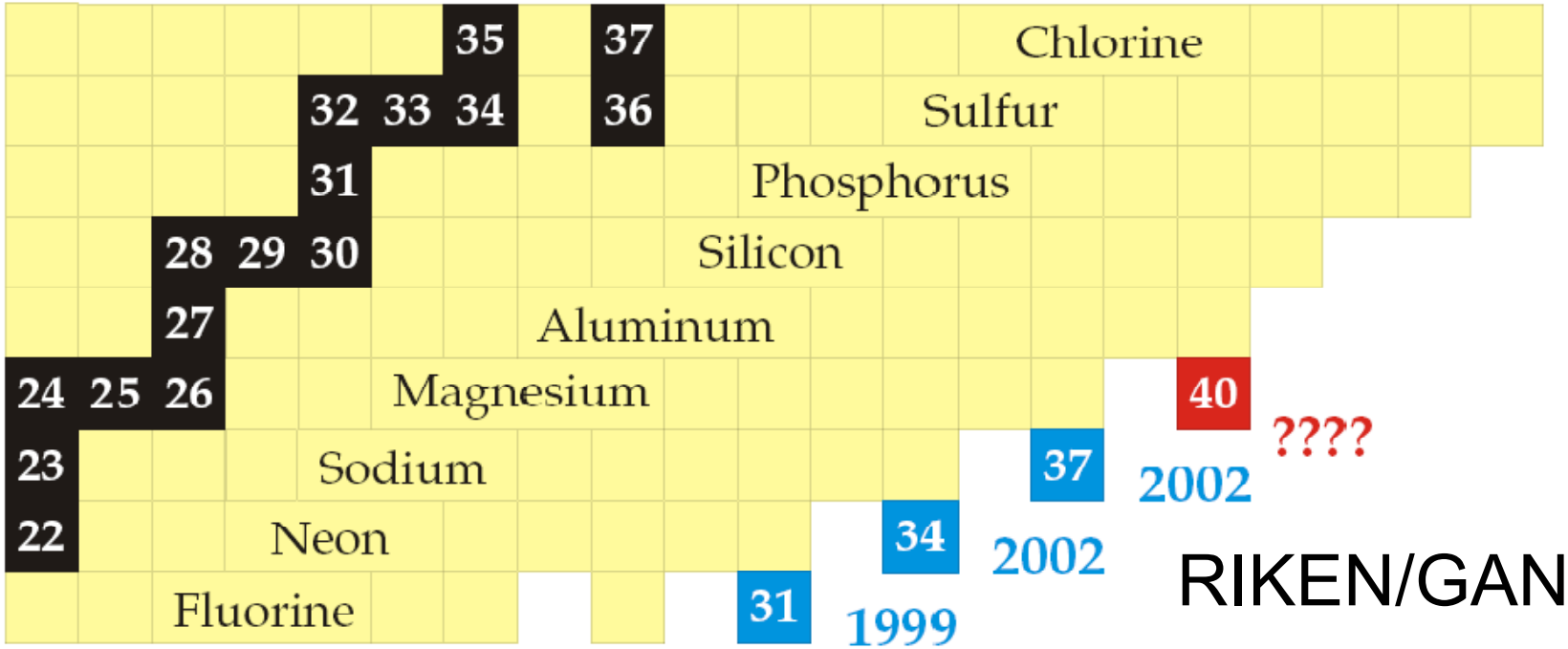
- FRIB will produce more than 1000 NEW isotopes at a useful rate
- Cross section data is needed
- The limits of stability are a benchmark for nuclear models and have an influence on astronomical phenomena.
- What are the prospects for defining the limits?



Rates are available at http://groups.nscl.msu.edu/frib/rates/

Status of Drip Line Search < 2007

- 2009 DOE Milestone: Determine the limit of stability up to = 11



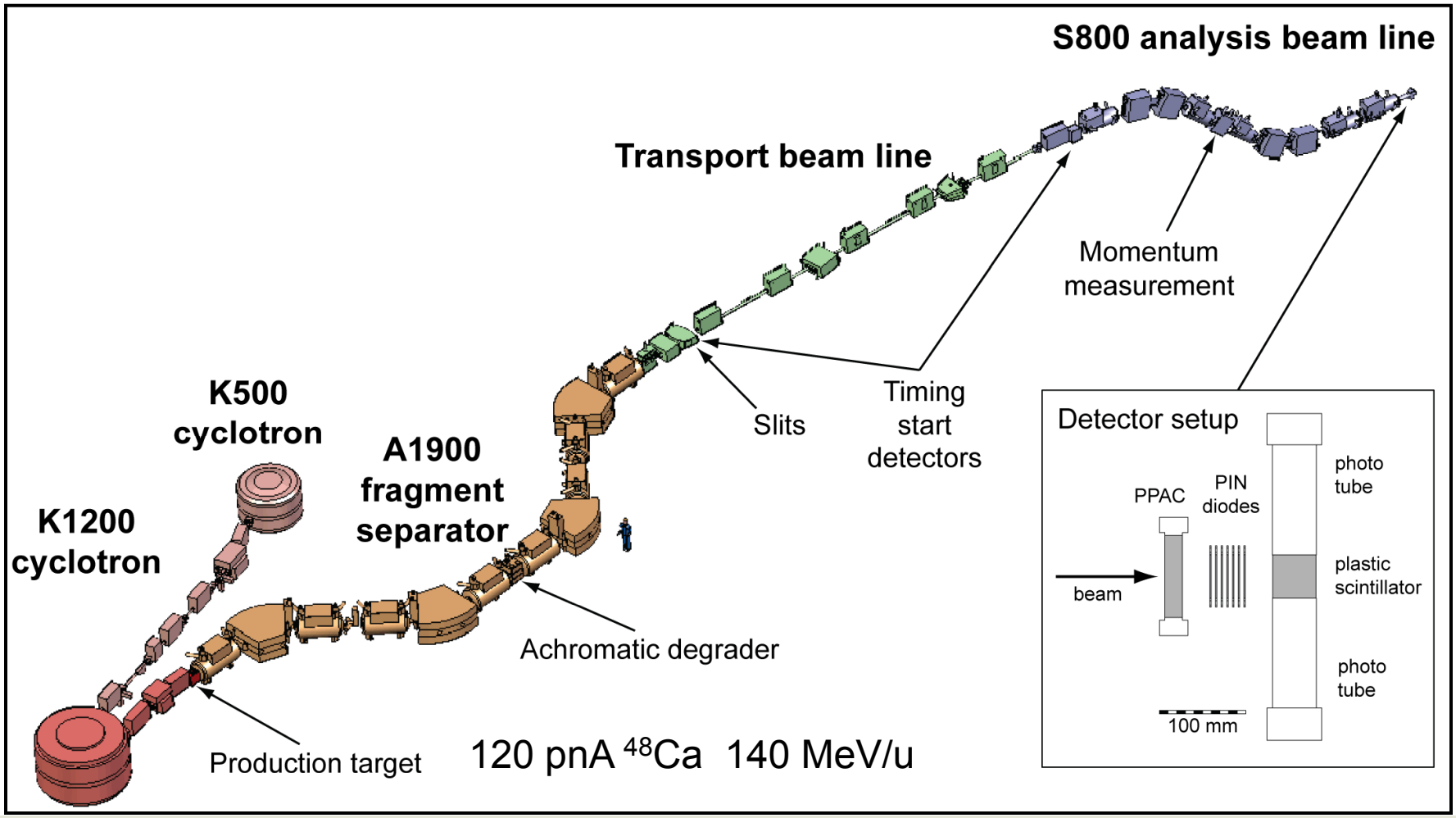
H. Sakurai et al., PLB 448 (1999) 180

M. Notani et al., PLB 542 (2002) 49

S.M. Lukyanov et al., JPG 28 (2002) L41

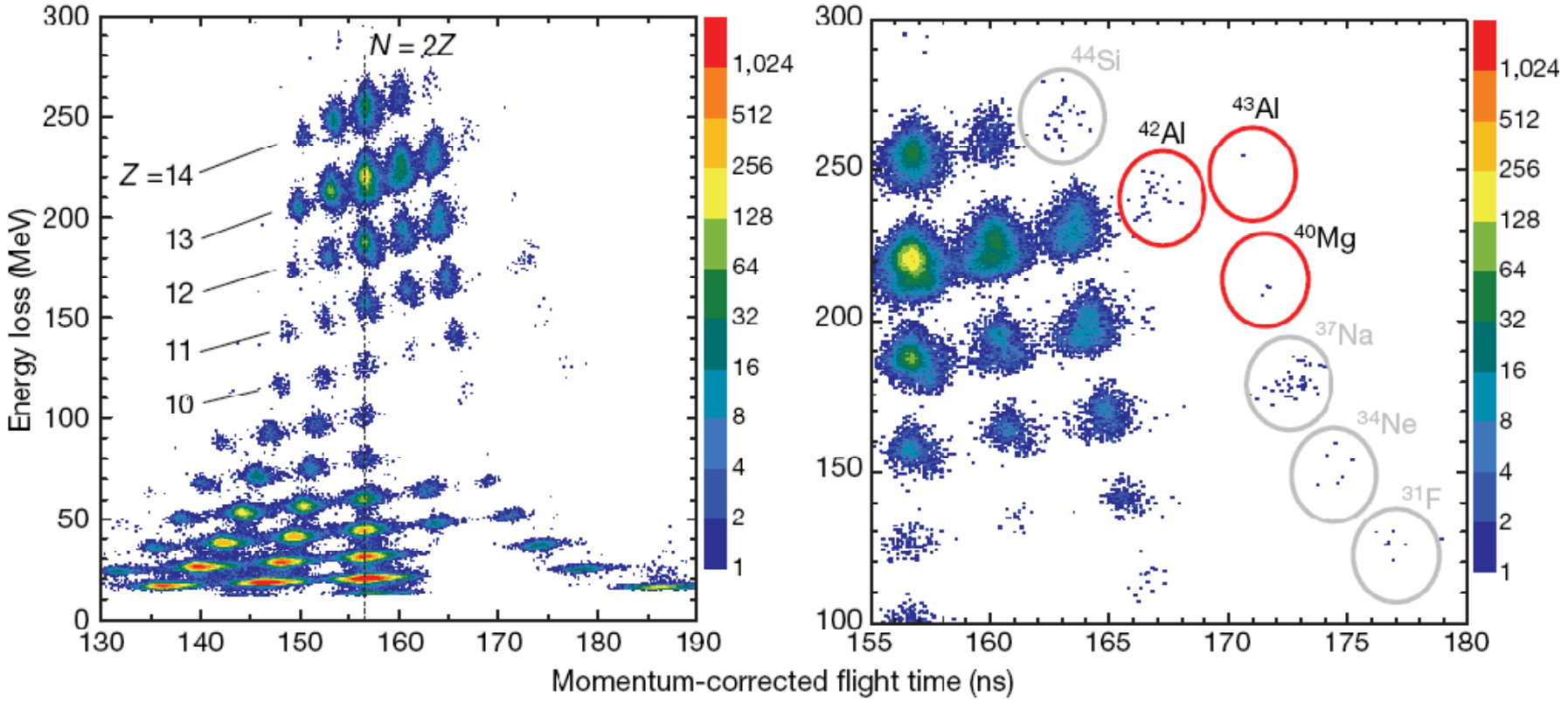
New Experiments at NSCL Using A1900+S800

Looking for 1 event from 10^{18} beam particles - Baumann et al. Nature 449 (2007) 1022



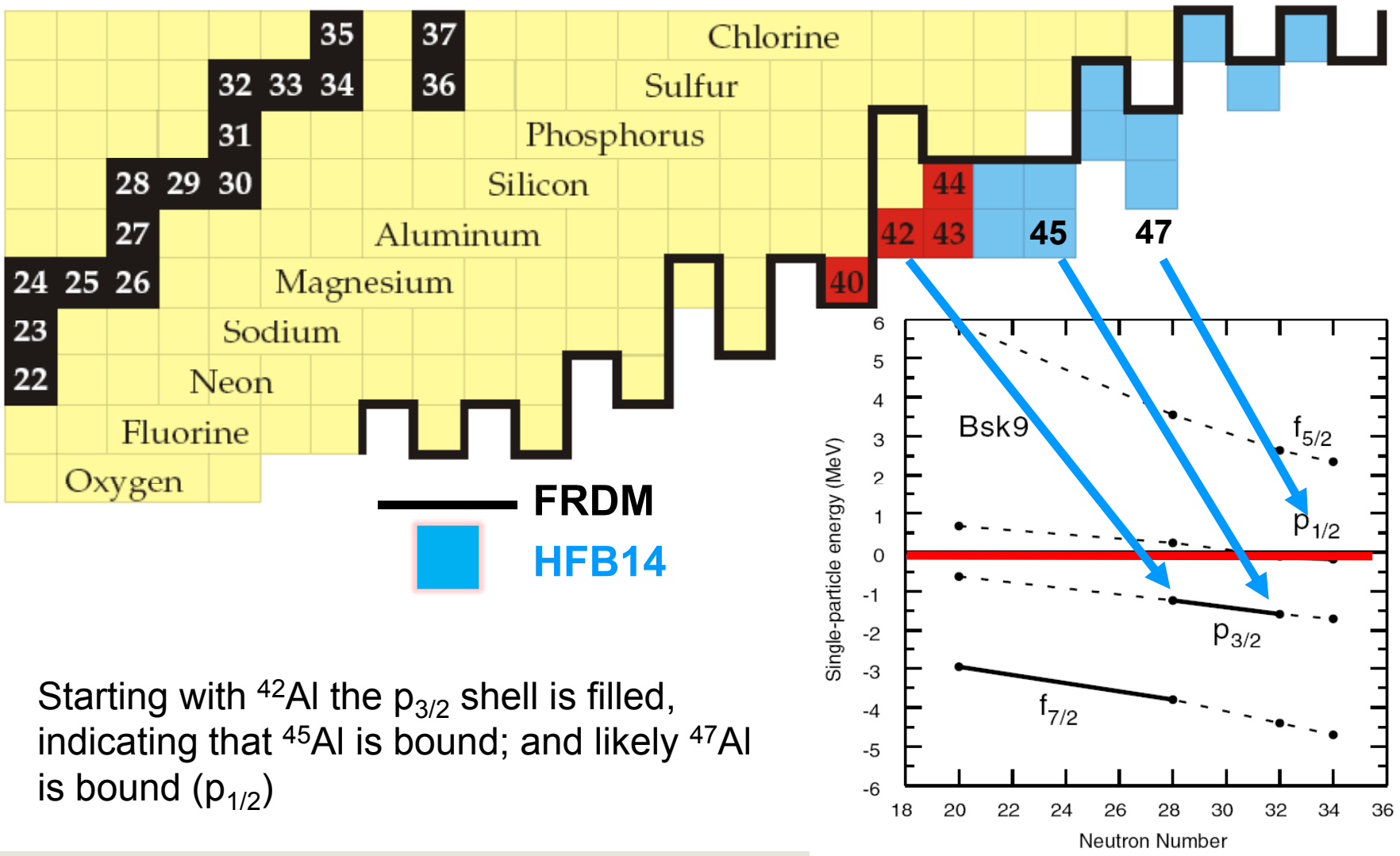
First Observation of ^{40}Mg

- 3 Events of ^{40}Mg observed in 10 days



T. Baumann *et al.*, Nature **449**, 1022 (2007)

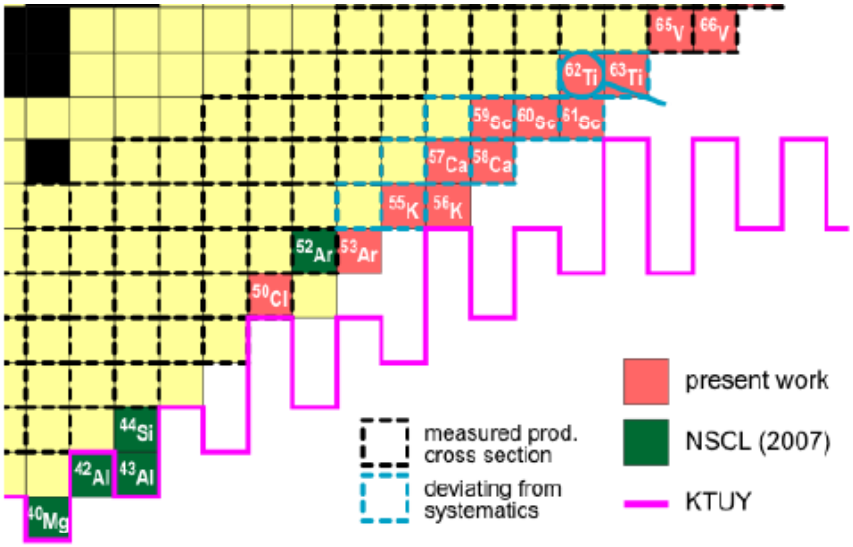
Drip Line Extends Farther Than Believed

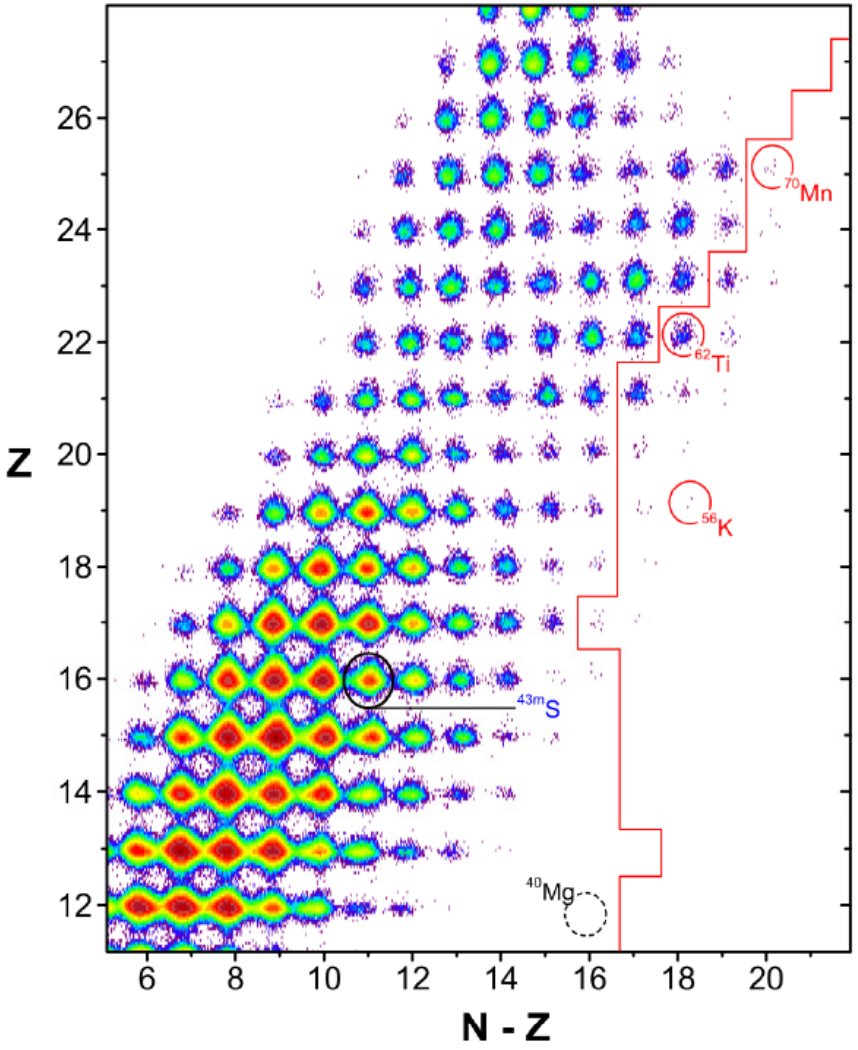


Starting with ^{42}Al the $p_{3/2}$ shell is filled, indicating that ^{45}Al is bound; and likely ^{47}Al is bound ($p_{1/2}$)

Drip line search extended

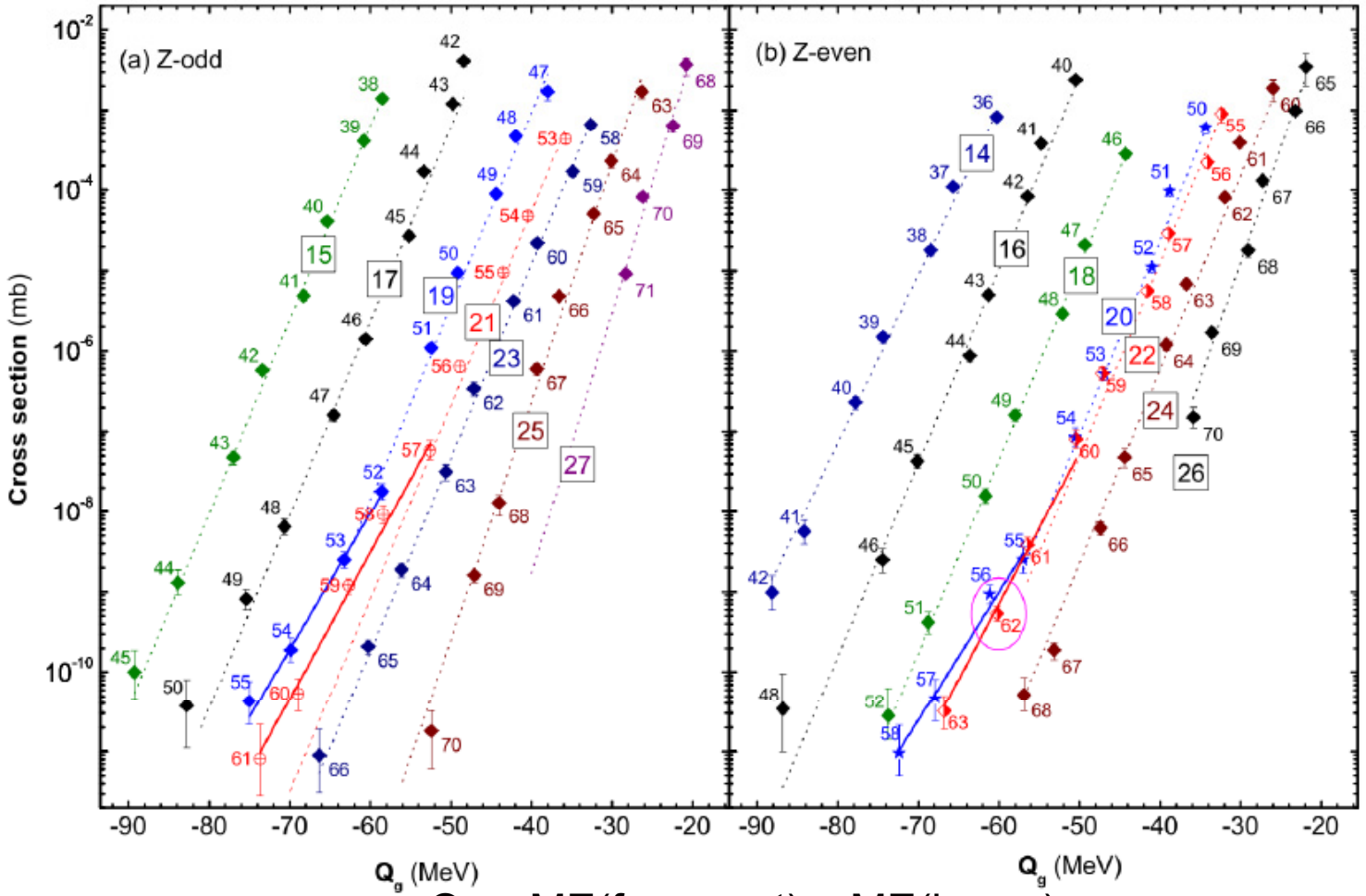
- The next step in the search used ^{76}Ge, 100 pnA, 130 MeV/u
- Momentum distributions and production cross sections measured by changing the target thickness
- Tarasov et al. Phys. Rev. Lett. 102, 142501 (2009):





Production Cross Sections Measured in the Experiment

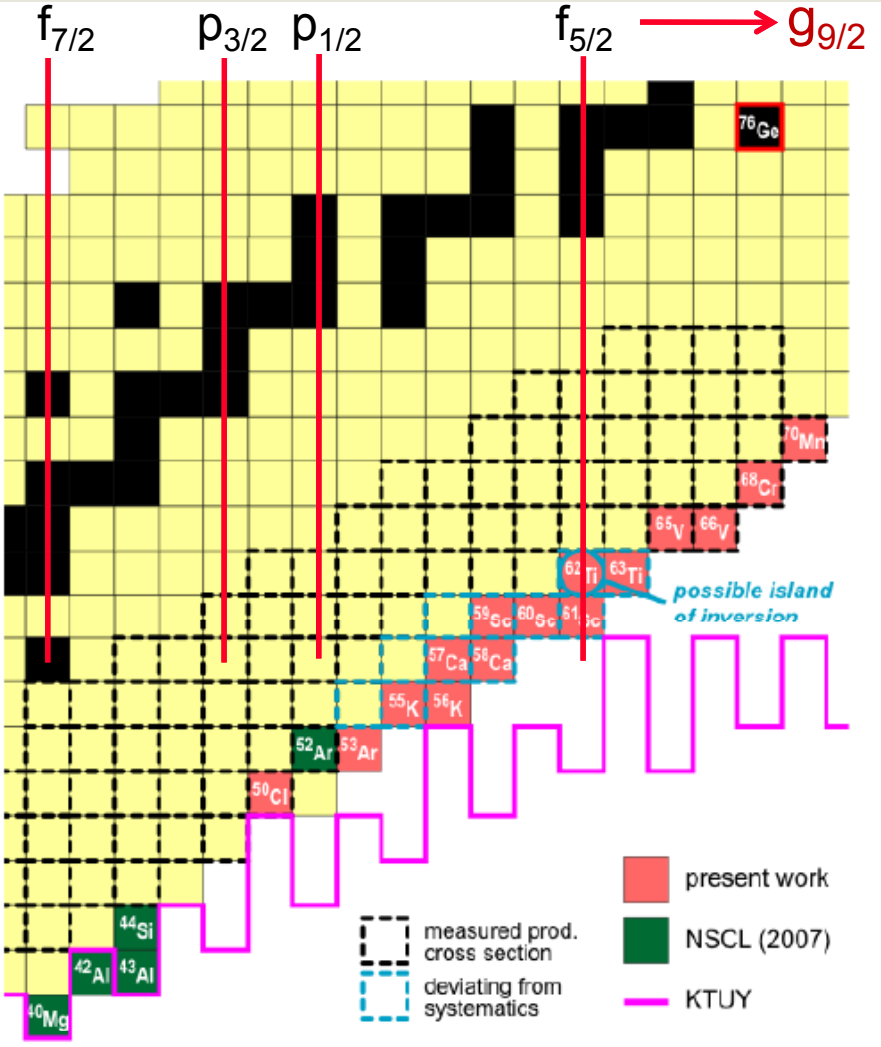
Cross section logarithmic with Q_g (Tarasov PRC75)



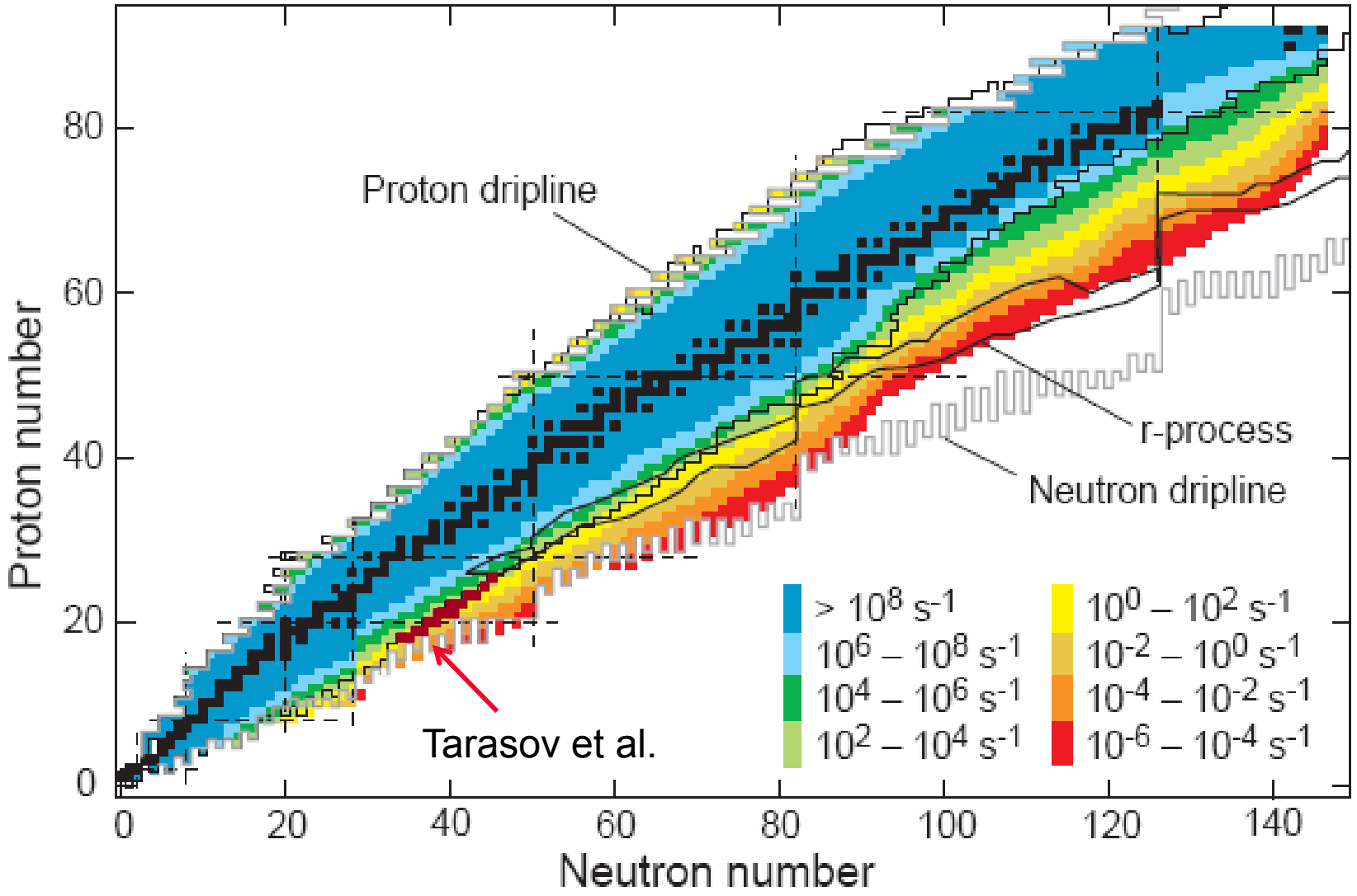
Q_g = ME(fragment) – ME(beam)

New Island of Inversion

- Evidence for enhanced production cross sections could be interpreted as enhanced stability in these nuclei
- A new “island of inversion” was predicted by BA Brown centered on ^{62}Ti
- The new “island” corresponds to the filled f-shell with a near-by g-shell
- Similar to the filled s-d shells and the proximity of the $f_{7/2}$ orbit

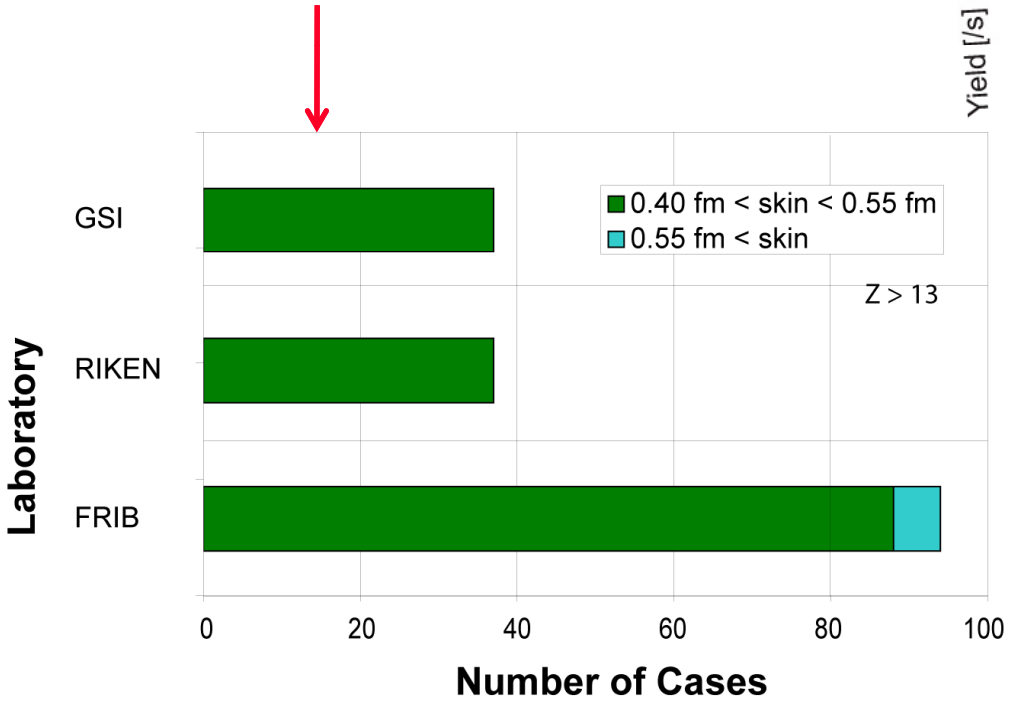


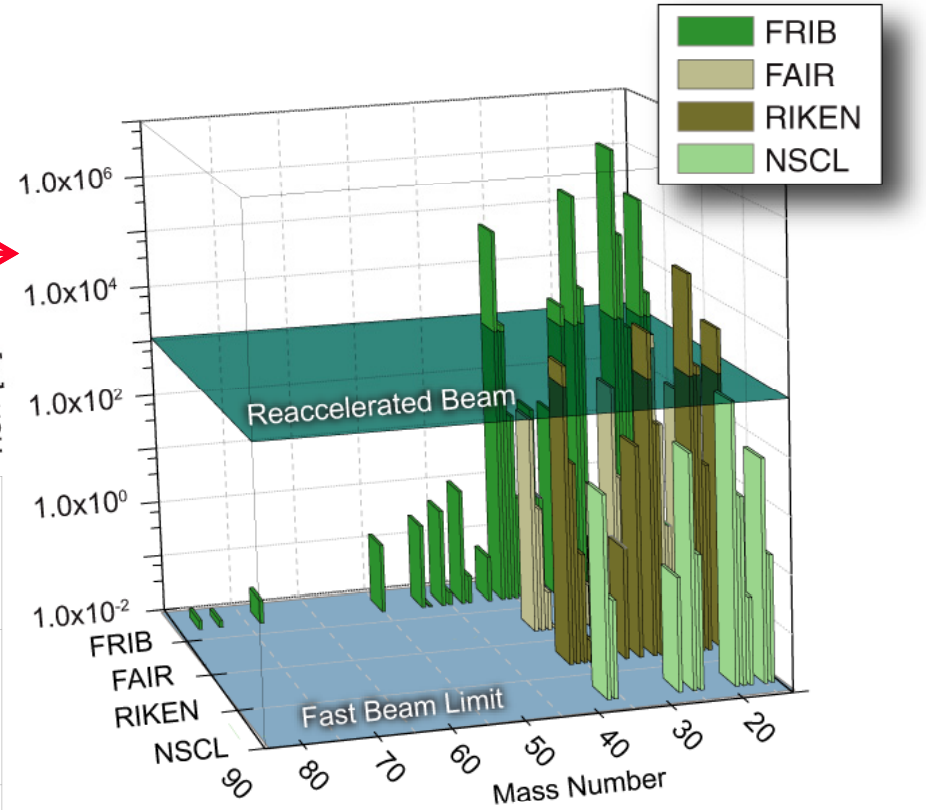
How Far Will FRIB Extend the Drip Lines?

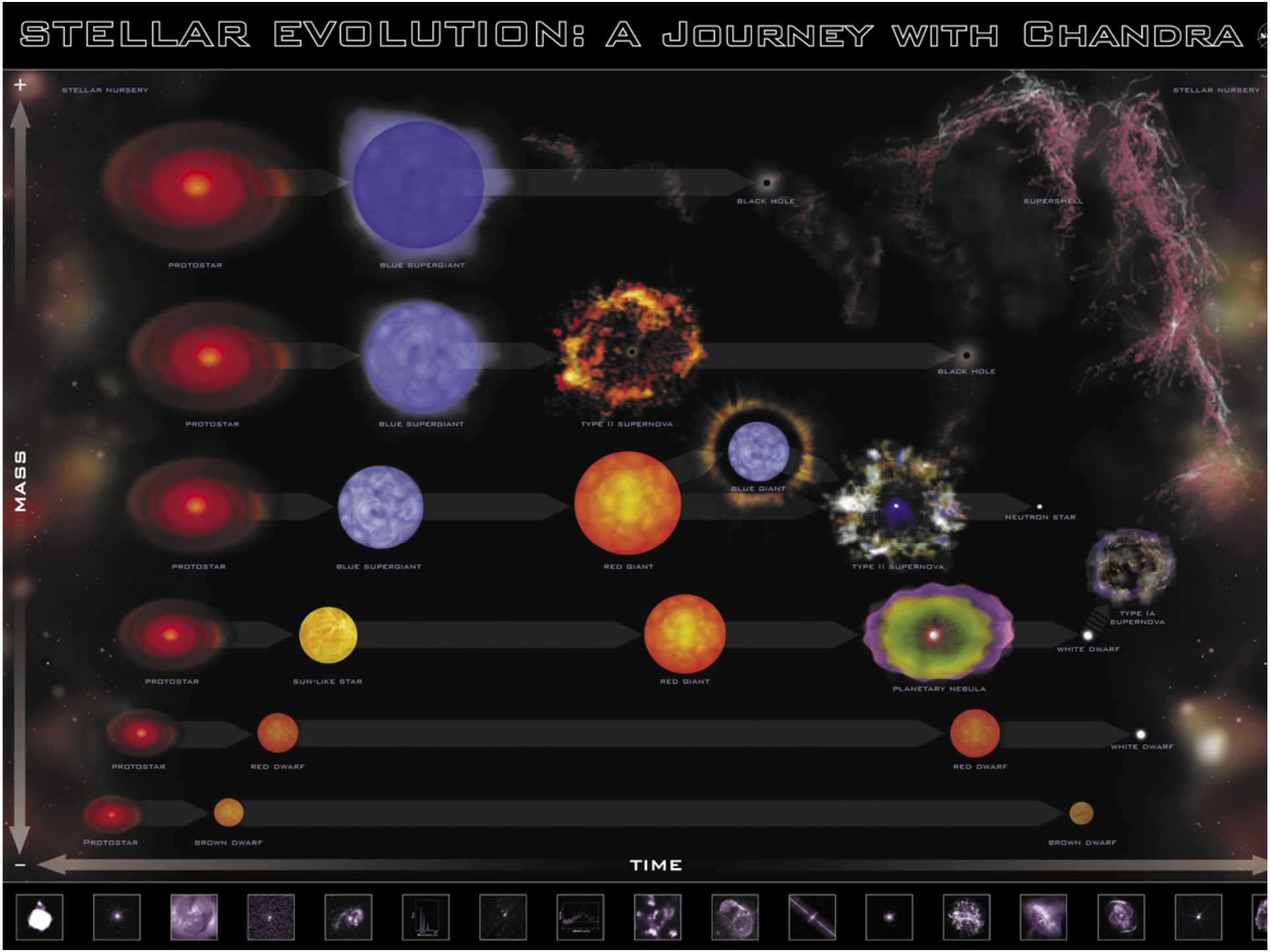


Studies Near the Drip Lines

- FRIB will be one of the best places to study nuclei at and near the drip lines
  - Extreme Halo Nuclei
  - Nuclei with large neutron skins

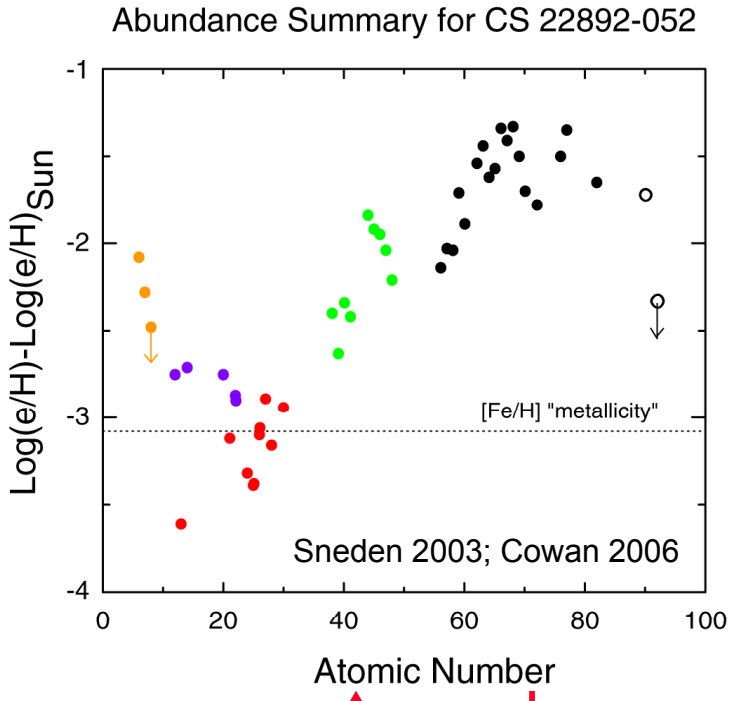


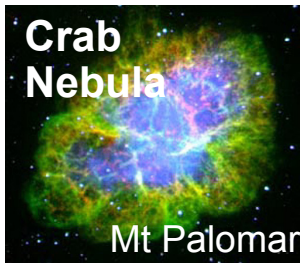



STELLAR EVOLUTION: A JOURNEY WITH CHANDRA
STELLAR NURSERY
STELLAR NURSERY
+
MASS
−
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
BLUE GIANT
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE Ia SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF
TIME

Goal: Understanding of Astrophysical Environments

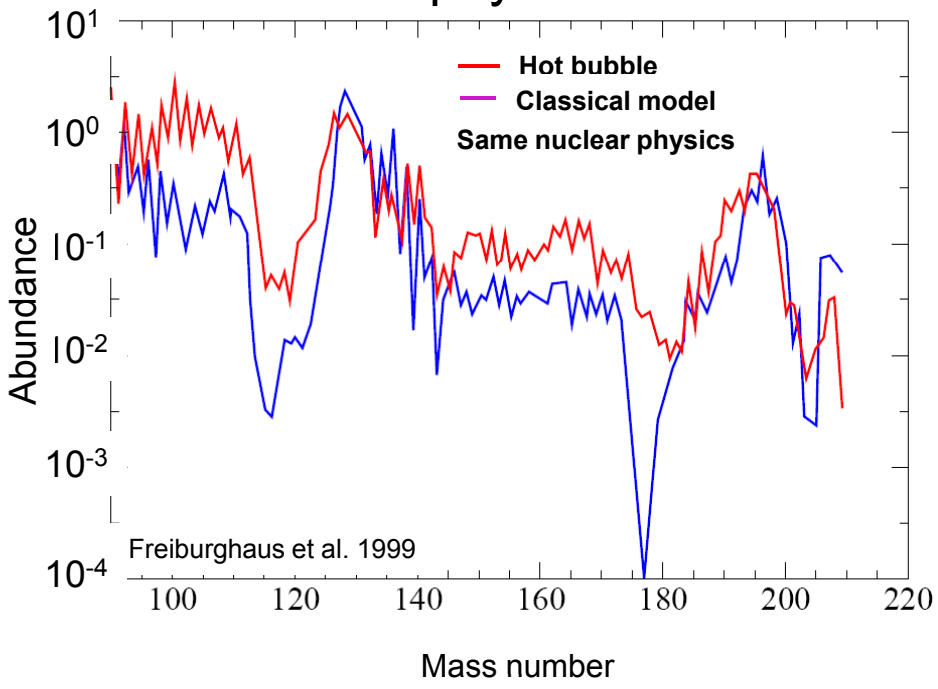
- Use observational data to infer conditions at the site
- Accurate modeling requires
  - that we make the same isotopes that participate in astrophysical environments
  - reproduce the nuclear reactions that occur in those environments
- The hard part is that nature produces isotopes in environments like the r-process with $T > 10^9$ K, $_{neutron} \approx 10^{20\text{-}28}$ cm^{-3}



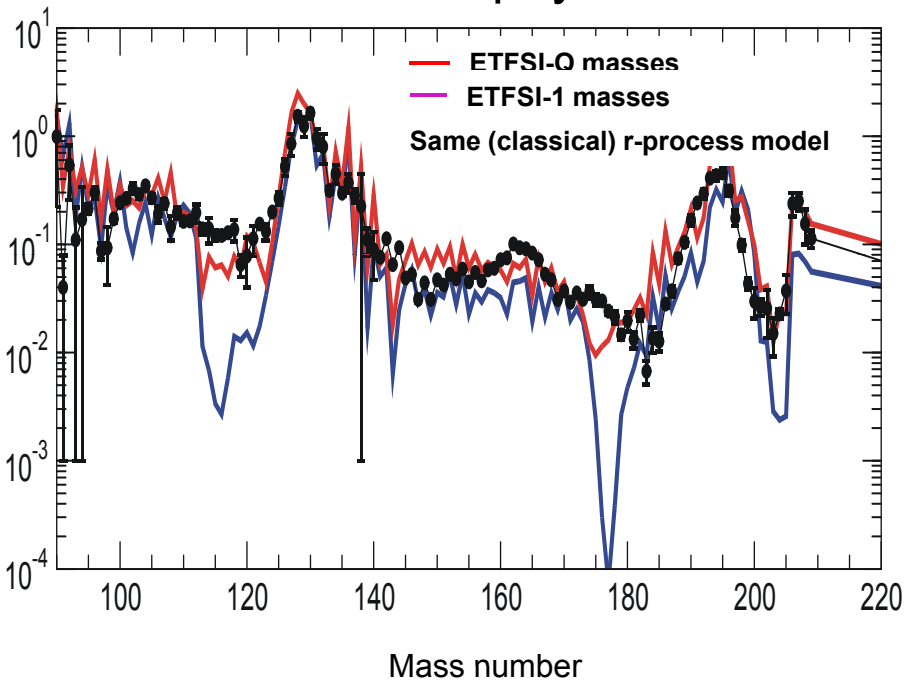


Uncertainty Between Models and Nuclear Properties

Astrophysics



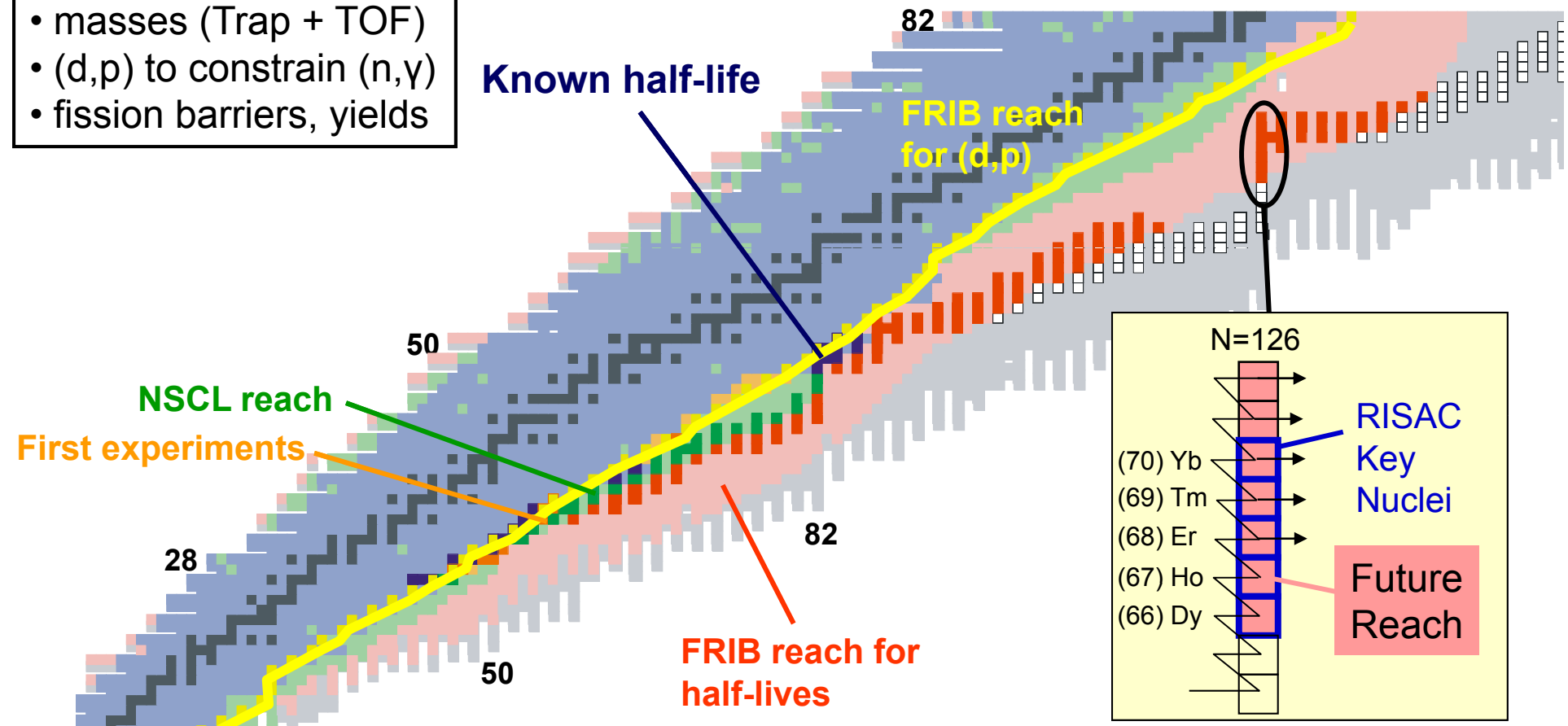
Nuclear physics



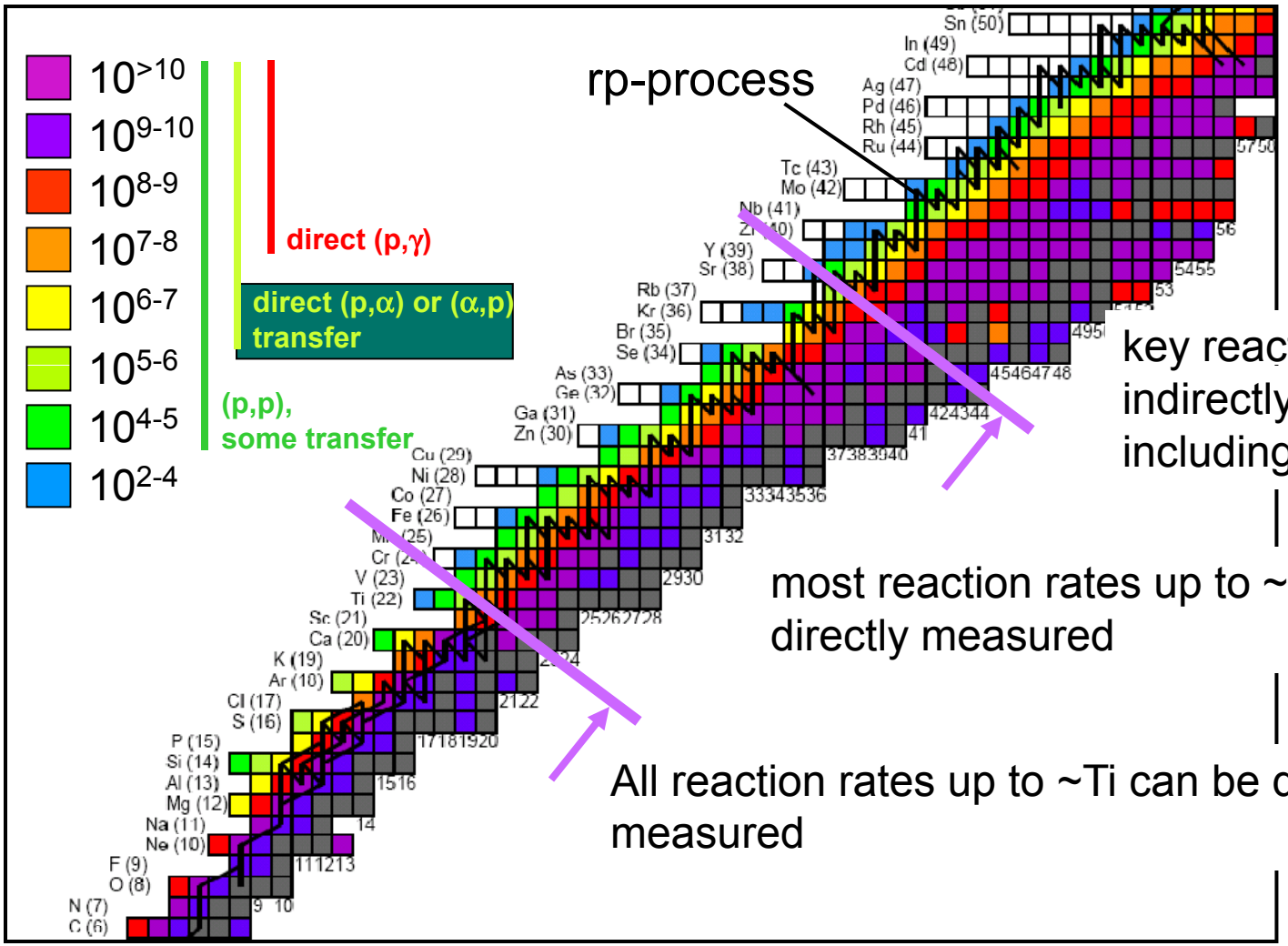
Hendrik Schatz

Reach of FRIB

- β decay properties
- masses (Trap + TOF)
- (d,p) to constrain (n,γ)
- fission barriers, yields



FRIB Reach for Novae and X-ray burst reaction rate studies



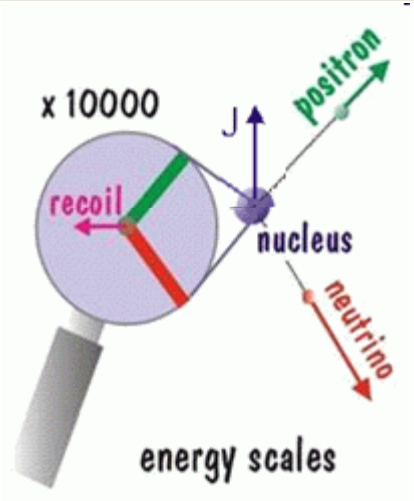
key reaction rates can be indirectly measured including ^{72}Kr waiting point

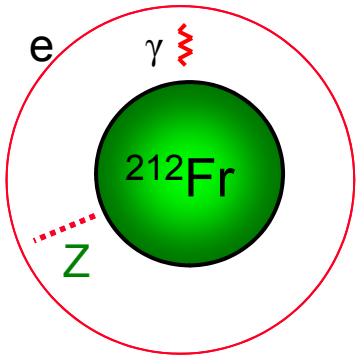
most reaction rates up to ~Sr can be directly measured

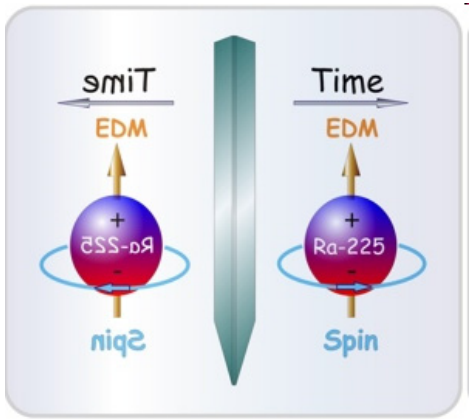
All reaction rates up to ~Ti can be directly measured

Tests of Nature's Fundamental Symmetries

- Angular correlations in β-decay and search for scalar currents
  - Mass scale for new particle comparable with LHC
- Electric Dipole Moments
  - ^{225}Ac, ^{223}Rn, ^{229}Pa (30,000 more sensitive than ^{199}Hg)
- Parity Non-Conservation in atoms
  - weak charge in the nucleus (francium isotopes)
- Unitarity of CKM matrix
  - V_{ud} by super allowed Fermi decay
  - Probe the validity of nuclear corrections





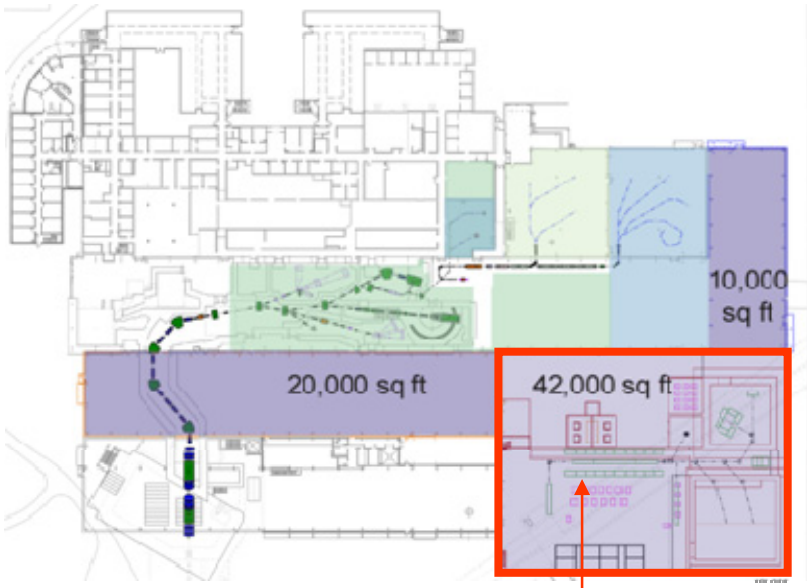


$$\begin{vmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix}$$

Rare Isotopes For Society

- Isotopes for medical research
  - Examples: ^{47}Sc, ^{62}Zn, ^{64}Cu, ^{67}Cu, ^{68}Ge, ^{149}Tb, ^{153}Gd, ^{168}Ho, ^{177}Lu, ^{188}Re, ^{211}At, ^{212}Bi, ^{213}Bi, ^{223}Ra (DOE Isotope Workshop)
  - -emitters ^{149}Tb, ^{211}At: potential treatment of metastatic cancer
- Reaction rates important for stockpile stewardship – non-classified research
  - Determination of extremely high neutron fluxes by activation analysis
  - Rare isotope samples for (n,γ), (n,n'), (n,2n), (n,f) e.g. ^{88,89}Zr
    - » Same technique important for astrophysics
  - More difficult cases studied via surrogate reactions (d,p), (^{3}He,α xn) …

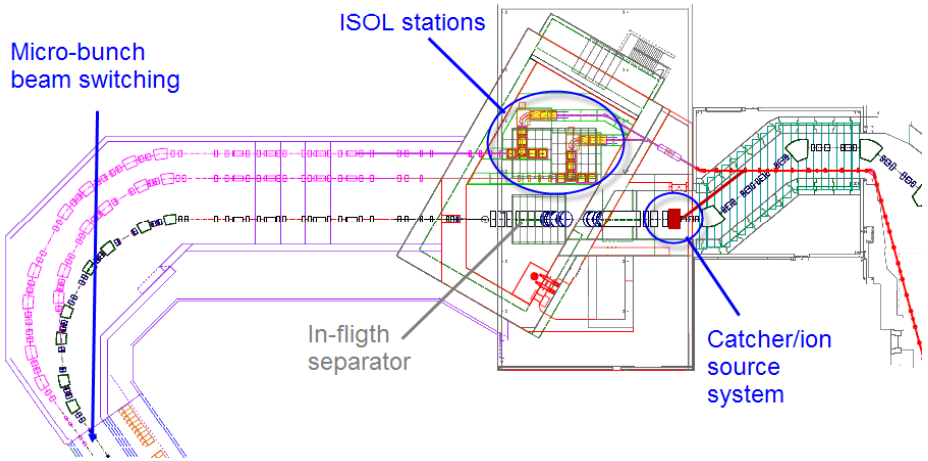
Expansion options (beyond FRIB scope)

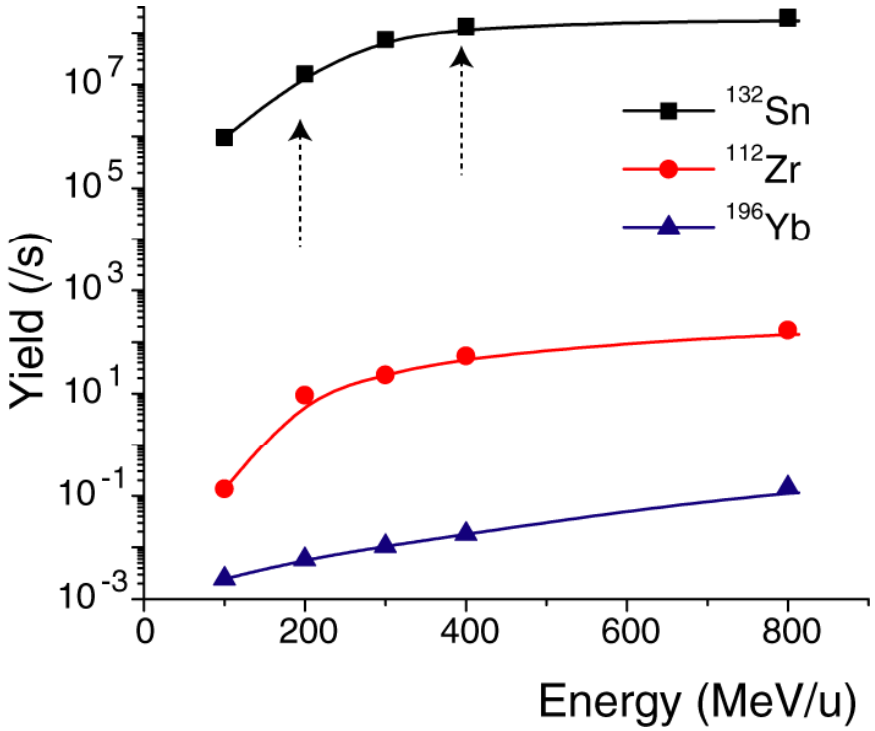


Example:
NNSA Neutron Facility as proposed by LLNL

Flexibility for Science Driven Upgrades

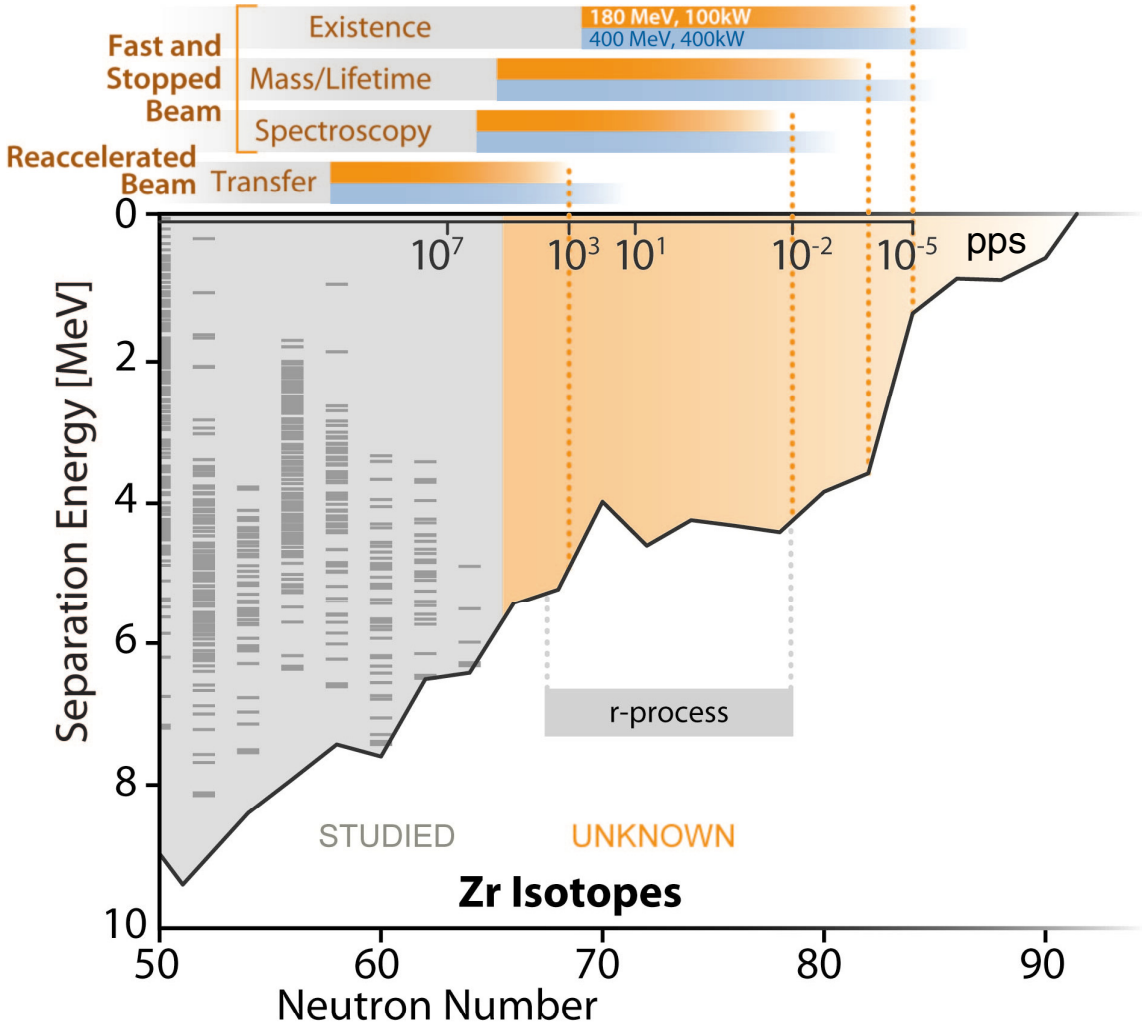
- Possible future expansion for FRIB
  - ISOL capability – full infrastructure is included in the design, targets could be added when appropriate
  - Upgrade of Heavy-ion Linac Driver to 400 MeV/u for Uranium – space in tunnel included
  - Reacceleration of Rare Isotopes to 200 MeV/u Using the Existing K1200 Cyclotron



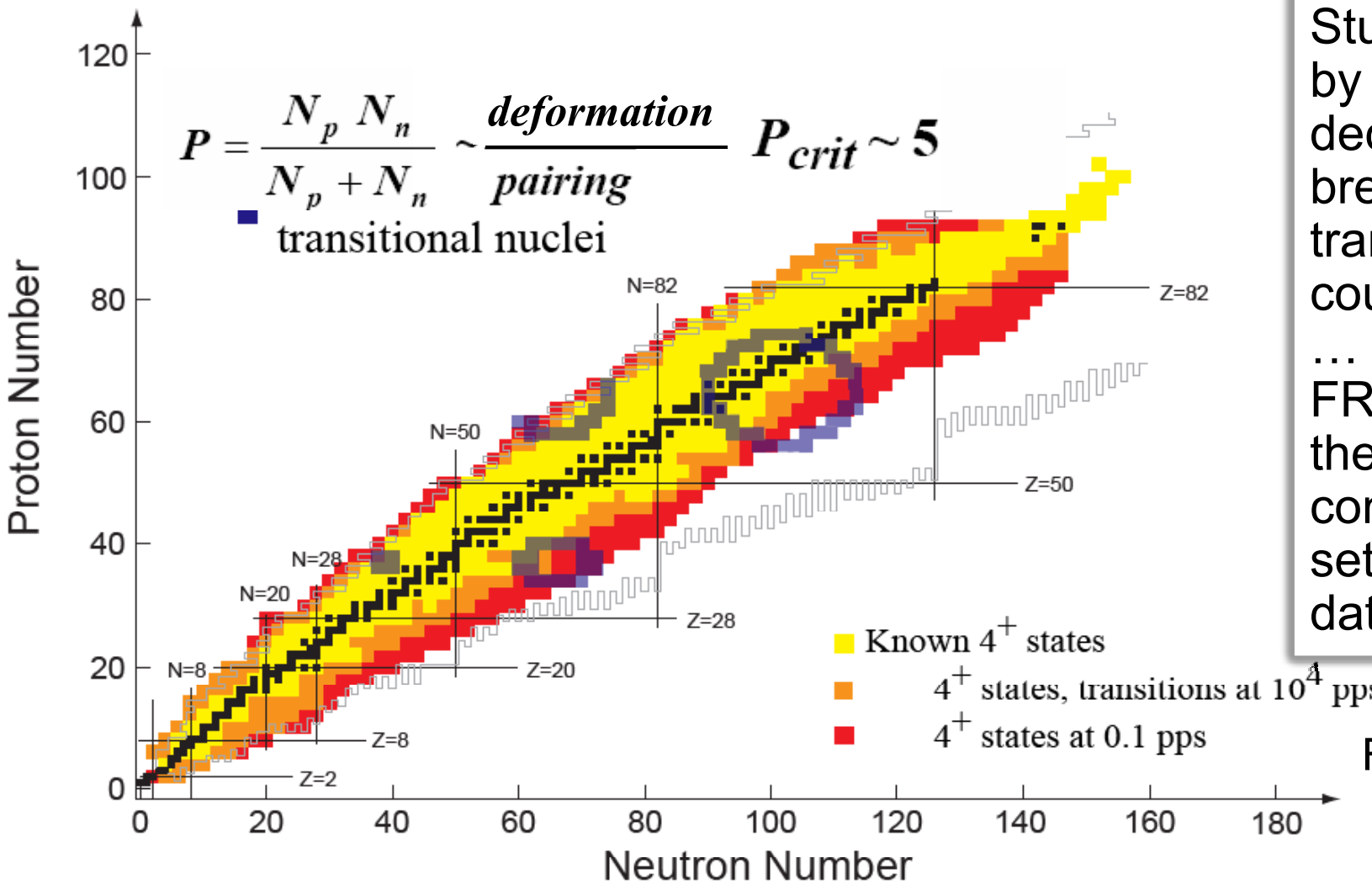


What to Learn and What to Do

- Nuclear properties over a wide range of new isotopes will be studied – one example for Zr illustrated on the right
- How do we publish/evaluate large amounts of new data?
- What is most interesting?
- How do we evaluate trends and extract interesting signals on the nature of the nuclear force?



Example of the Data Available From FRIB on Symmetry Phases in Nuclei



Studied by β-decay, breakup, transfer, coulex

…

FRIB give the most complete set of data

FRIB

Nuclear Data Requests

- Help in evaluating and publishing nuclear data.
  - How do we help users publish meaningful (with accurate error bars)
  - Proper evaluation techniques
  - Provide easy and accurate review of the literature (conference proceedings?)
- Specific requests for information to include in the compellations
  - Isospin be included in the compellations online
  - NSR distinction between theory and experimental papers
  - Quadrupole moments of excited states
  - Octupole moments of excited states
  - Magnetic moments of
  - B(E2)'s in units of e^2fm^2 or e^2b^2
  - "Make one table per nucleus that has level energy, spin, E_{gamma}, I_{gamma} - At present there is one table with E_{level}, spin, lifetime (no transitions at all) and one table with E_{level}, E_{gamma}, I_{gamma} (no spin info in there)"
- Nuclear data center participation in FRIB facility and equipment development.

Summary

- FRIB will allow production of a wide range of isotopes
  - Extend our searches for the limits to nuclear stability
  - Answer key questions on the nature of the universe (chemical history, mechanisms of ste explosions)
  - Significant opportunities for the tests of fundamental symmetries
  - Potential for important societal applications
- FRIB will greatly increase the available nuclear data. We must partner with the data evaluation effort
- Among the challenges are selecting the best measurements