Exploring nuclear structure with the Facility for Rare-Ion Beams

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David J. Morrissey

Michigan State University

MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY

Office of Science

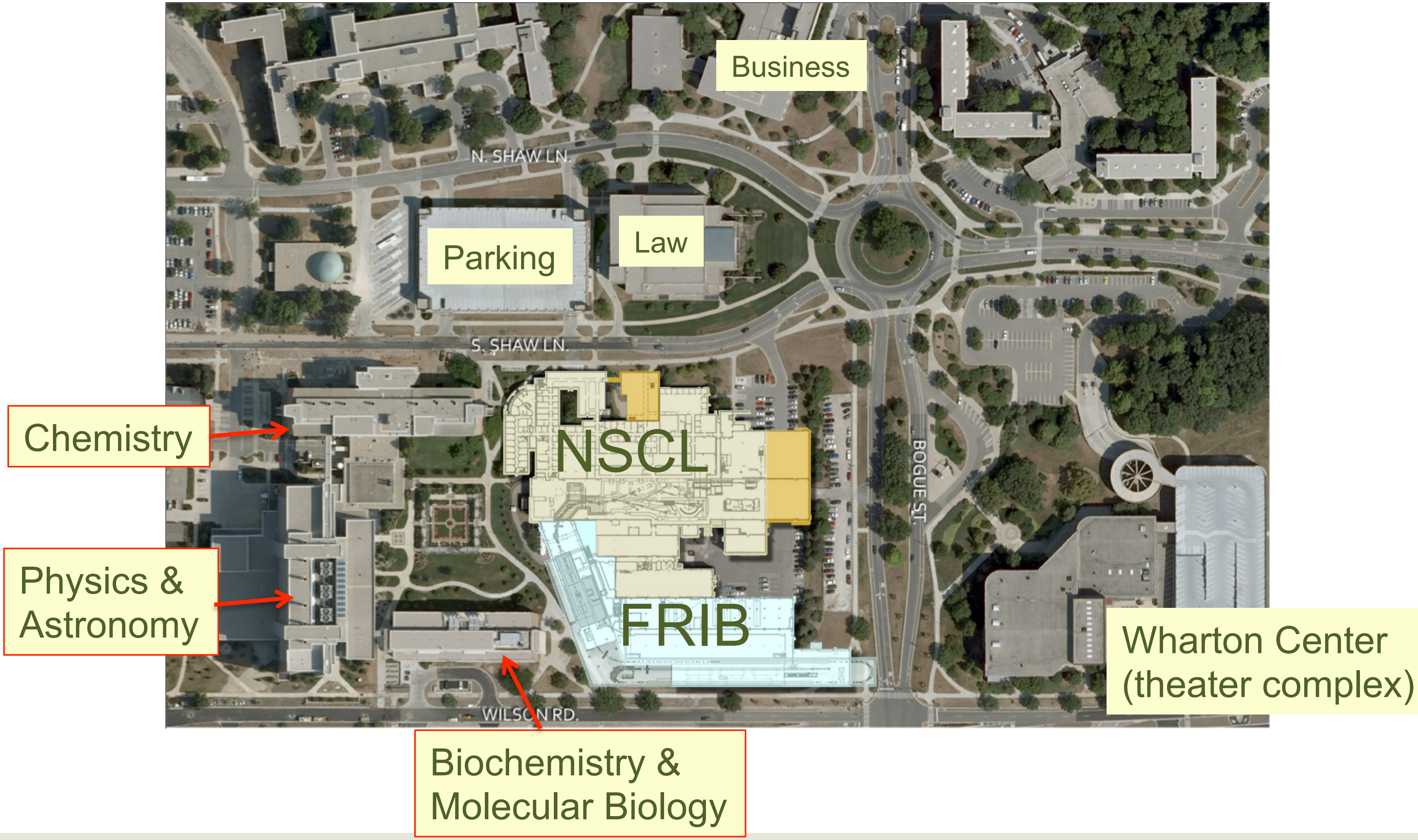
Outline

- Next major step in the exploration of nuclei in the US: FRIB
- Science Program for FRIB
  - Establishing the limits of neutron-rich nuclei
  - Modeling the chemical history of the universe, r-process, …
  - Providing nuclei for tests of nature's symmetries
  - Isotopes for other applications

I only have time to concentrate on the first and a little on the second topics.

Facility for Rare Isotope Beams

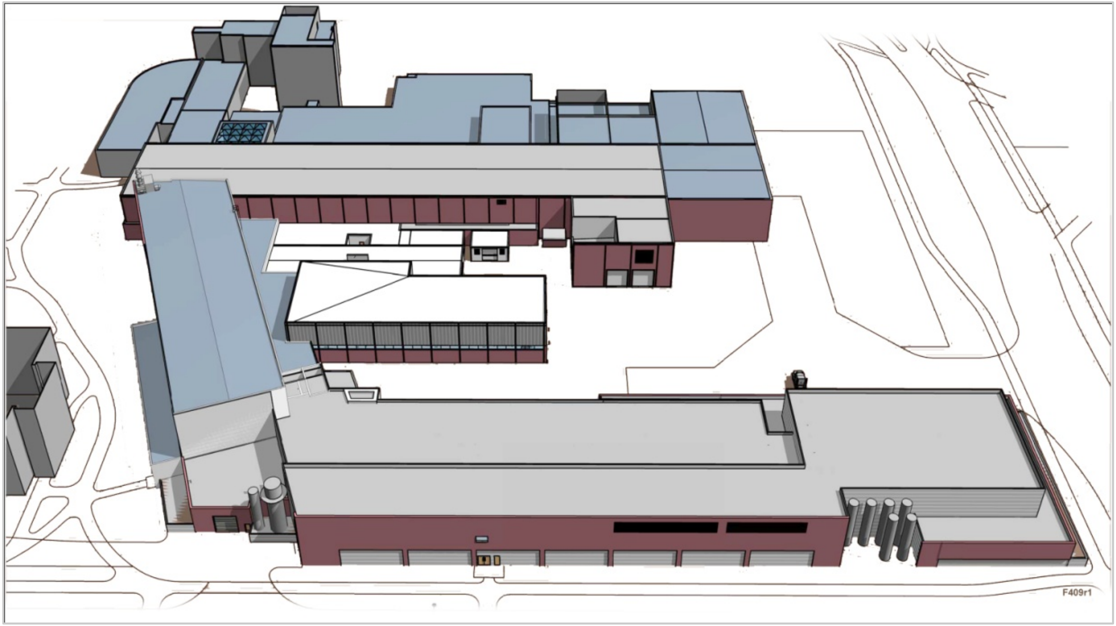
Part of a science complex on Michigan State University Campus



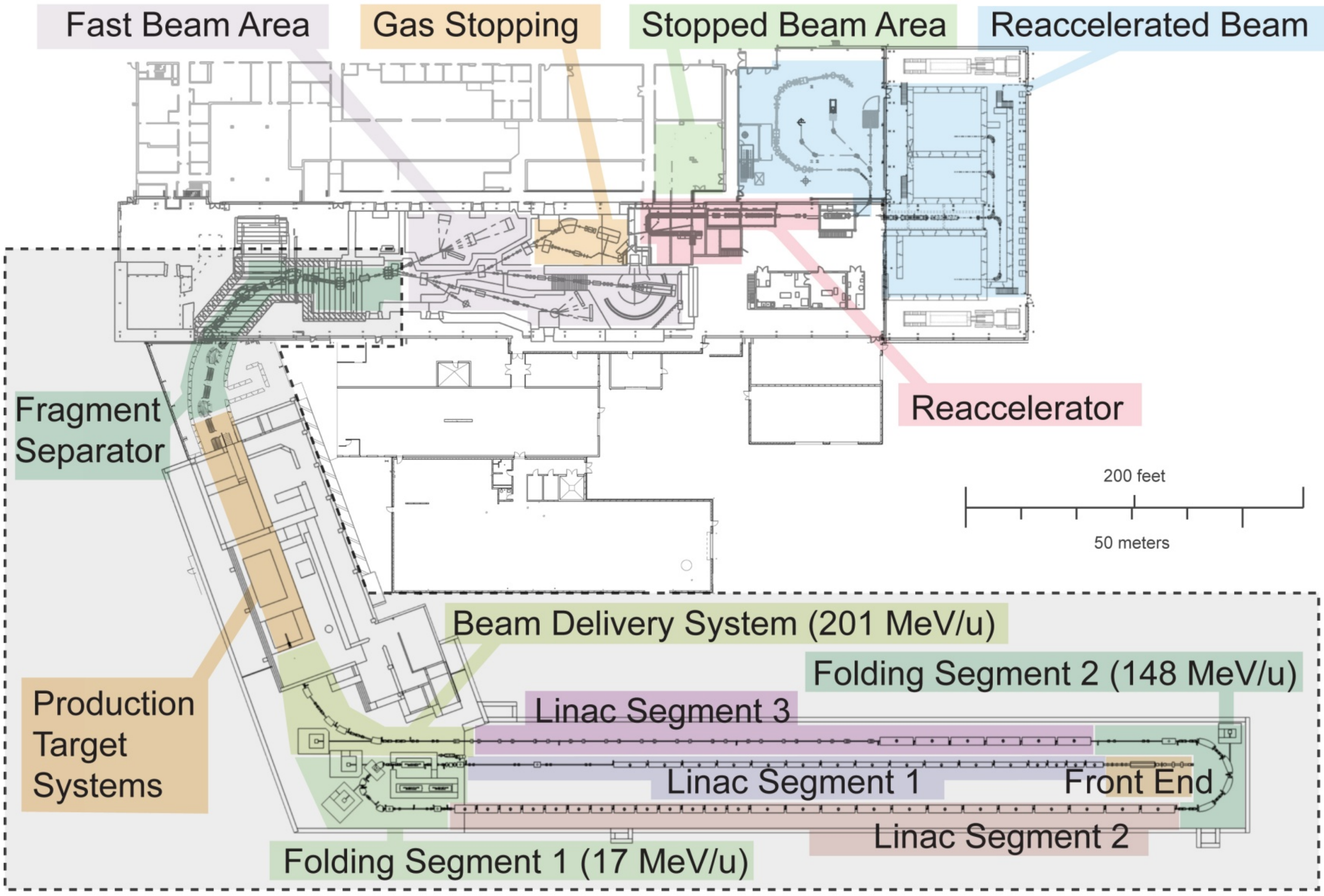
US community's major new initiative – Facility for Rare Isotope Beams

- Laboratory Director Konrad Gelbke,
  Project Director Thomas Glasmacher
- Estimate of TPC $614.5M
- Project completion in 2o20,
  early completion in 2o18
  (CD2/3A Review in April 2o12)
- Key features (unique)
  - Folded linear accelerator
  - 400 kW heavy ion beams
  - Separated fast nuclear beams
  - Buffer-gas thermalized and
    reaccelerated beams
- Space for later programs:
  - Reaccelerated beams,
  - "uranium" up to 12 (15) MeV/u
  - Isotope harvesting

FRIB

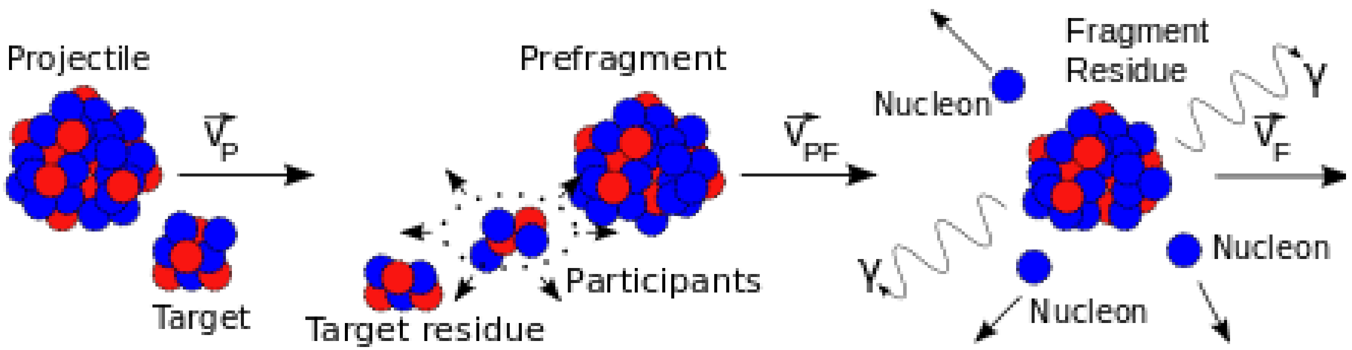


FRIB schematic layout
couples onto existing experimental facility



Production of rare isotopes by projectile fragmentation or proj. fission

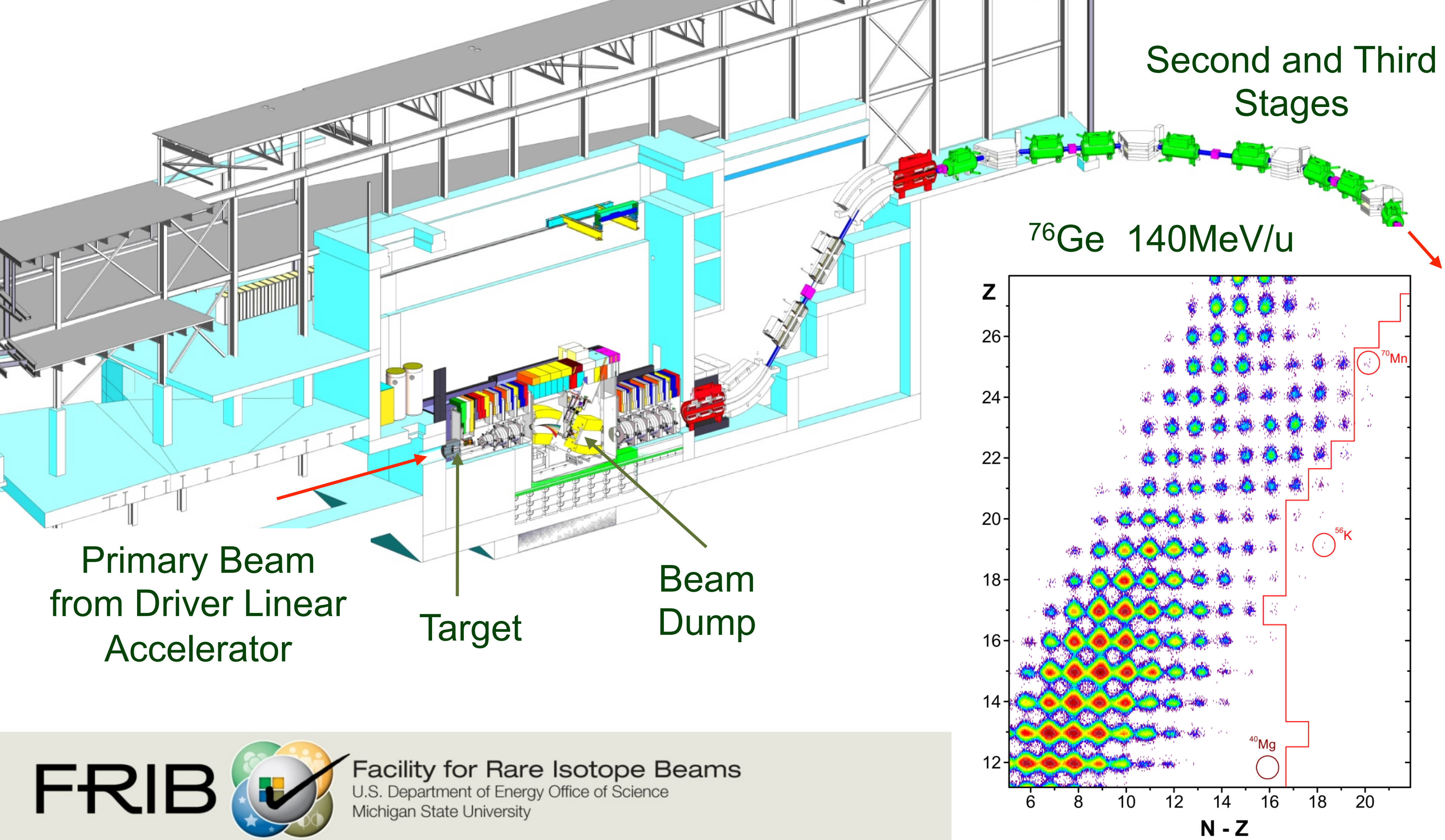
- Cartoon of the production process – projectile fragmentation (or fission)



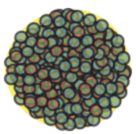
- The production cross section for an interesting nucleus like $^{122}Zr_{82}$ from $^{136}Xe_{82}$ is estimated to be 2×10^{-18} b (2 attobarns, 2×10^{-42} cm^2)
- Given $^{136}Xe \cong 8\times10^{13}$ ion/s (400 kW at 200 MeV/u & a high efficiency separator) a few atoms per week can be made and studied
- For comparison:
  - Element 117 production cross section was 1.3 (+1.5 -0.6) pb [Oganessian, et al. Phy. Rev. Lett. 104 (2010) 142502, thin target]
  - A few $\times10^{-42}$ cm^2 is on the order of the neutrino-electron elastic scattering cross sections at 100 MeV

FRIB tandem fragment separator

M Hausmann, B.M. Sherrill, et al.
G. Bollen, Head of Exp. Sys.

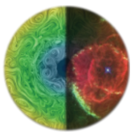


FRIB will provide rare isotopes for a broad scientific program



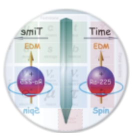
Properties of nuclei

- Develop a predictive model of nuclei and their interactions
- Understand the origins of the nuclear force in terms of QCD
- Many-body quantum science: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.



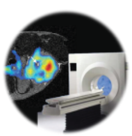
Astrophysical processes

- Establish chemical history of the universe; use this for stellar archaeology
- Model explosive environments
- Properties of neutron stars, EOS of asymmetric nuclear matter



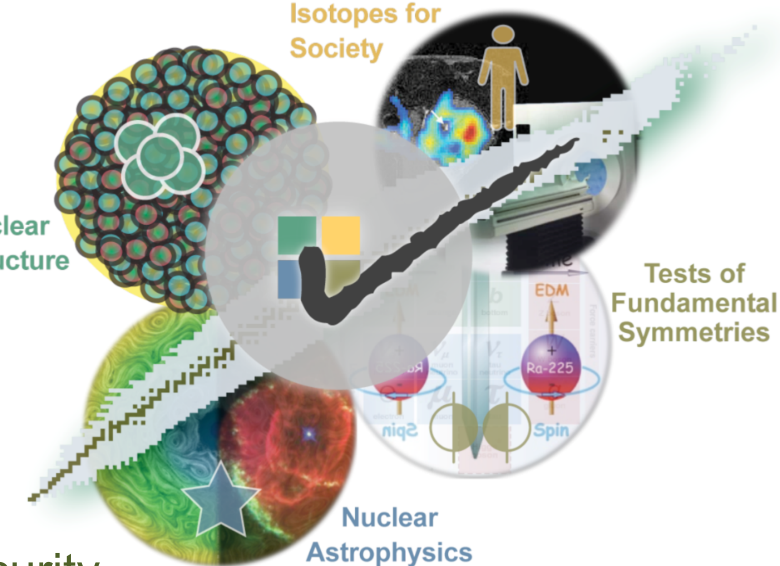
Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei



Societal applications and benefits

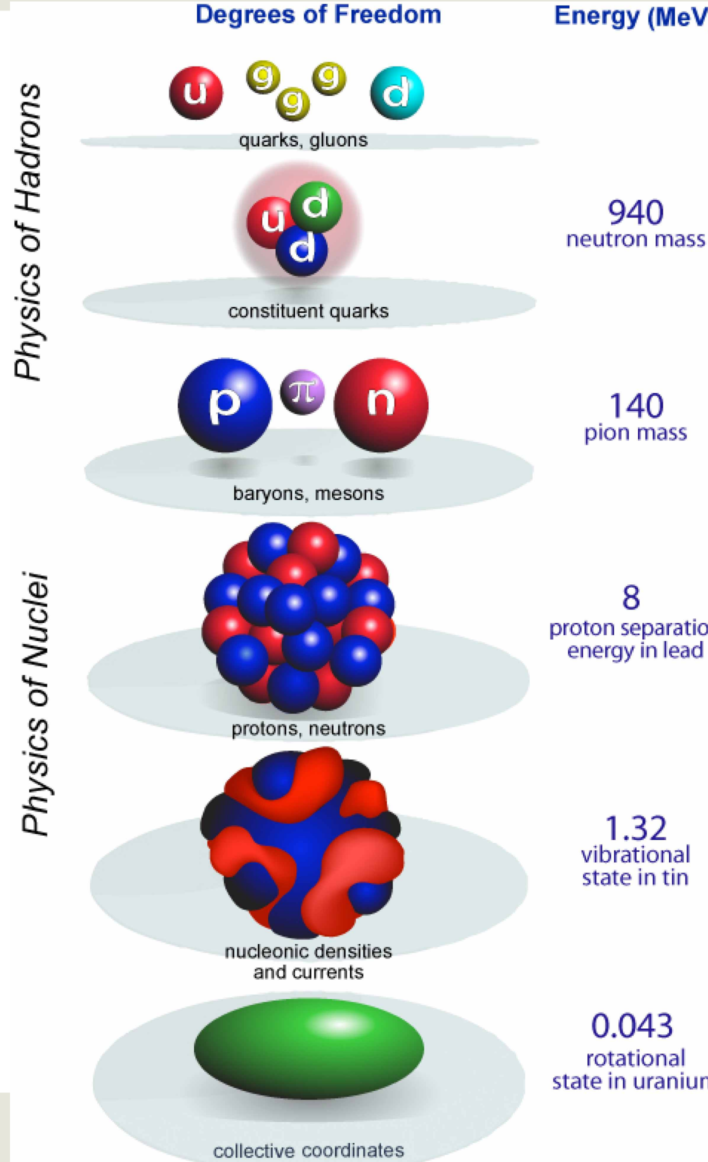
- Novel isotopes for biology, medicine, energy, material sciences, national security



Contemporary challenge(s) for nuclear science

- Model physical phenomena that result from the strong force
- This includes understanding atomic nuclei, hadrons, QGP, …
- Remarkable progress has been made in modeling hadrons – e.g., 2004 Nobel Prize: Gross, Politzer, Wilczek ; LQCD calculation of nucleon and meson masses (Dürr, Fodor, Lippert et al., Science 322 (2008))
- There is room for significant progress in understanding atomic nuclei

[Illustration from David Dean]



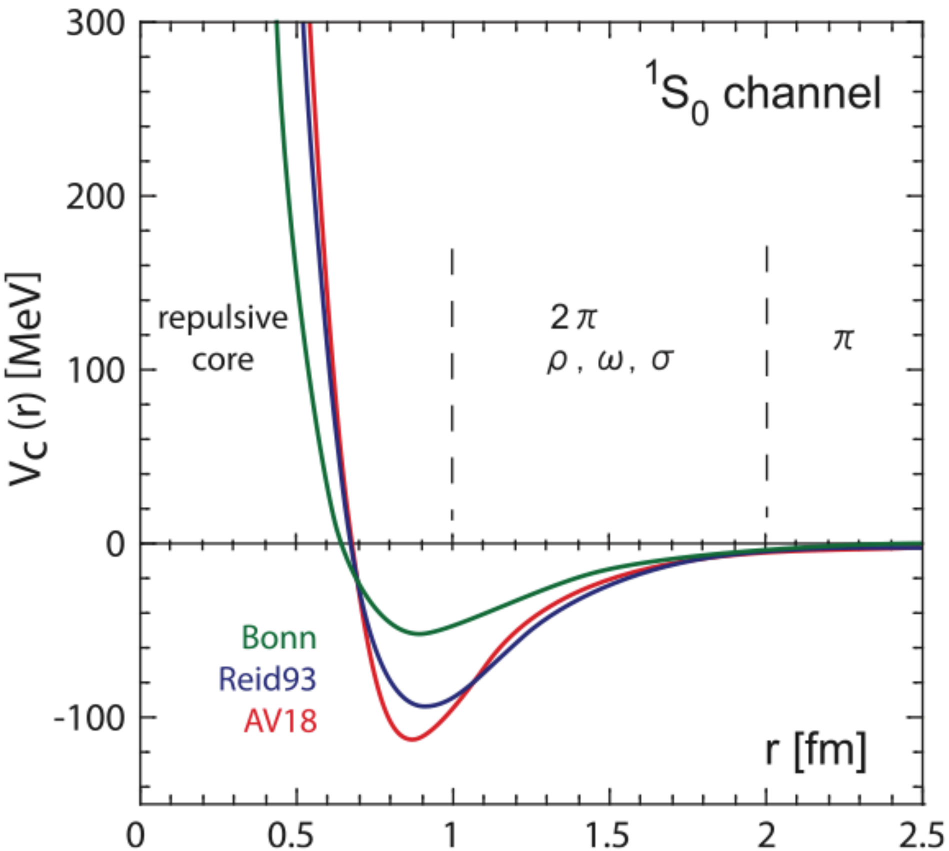
FNL
JLAB

FRIB

How should we model nuclei? Fundamental approach, start with NN forces

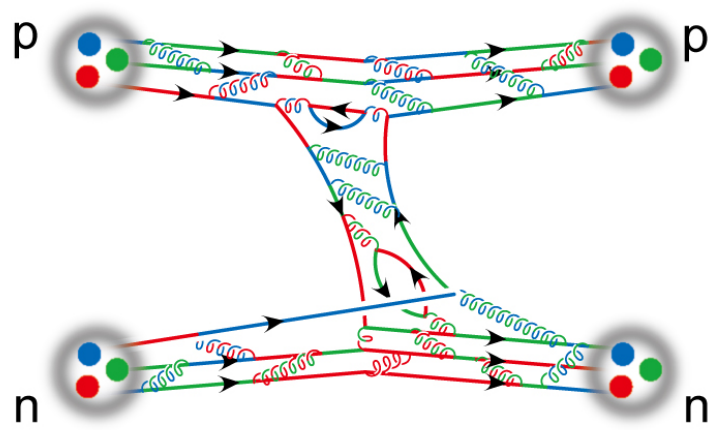
- Construct NN potentials based on neutron and proton scattering data and properties of light nuclei (Bonn, Reid, Illinois AV18, Nijmegen, etc.) example shown by Ishii et al.

- More recently construct the potentials some more fundamental theory
  - QCD Inspired Effective Field Theory
  - String Theory Inspired
    - » Hashimoto, et al., Prog, Theor. Phys. 122 (2009) 427
  - Lattice QCD – Ishii, et al.
    - » And talks later today

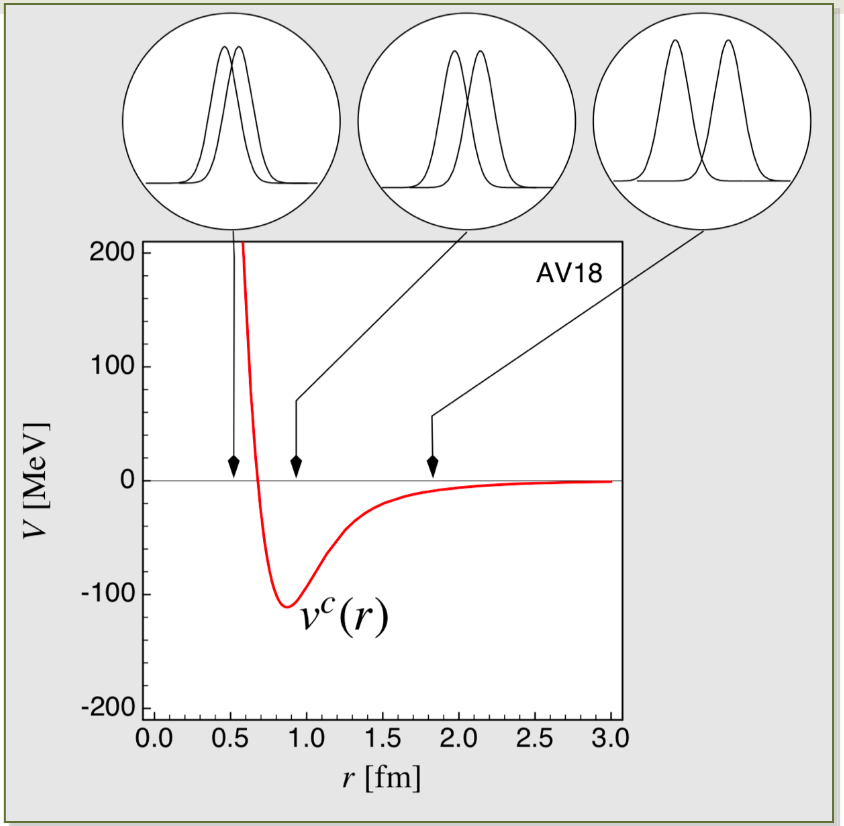


N. Ishii, S. Aoki, and T. Hatsuda, Phys. Rev. Lett. **99** (2007) 022001

Nuclear distances and the nucleon-nucleon force



N. Ishii, S. Aoki, T. Hatsuda,
Phys. Rev. Lett. **99 (2007)** 022001



- In nuclei even more complications since nucleons have structure and are in contact with one-another so many-body forces are also very important (three-, four-body, …)
- How are nucleon properties modified in medium from their free structure?

The big picture: Modeling nuclei & reactions

Goal: Model and accurately describe nuclei and their reactions. For example, the ability to calculate reactions like $^{7}Be(p,\gamma)^{8}B$ (responsible for neutrinos from the core of the Sun) from first principles is thought to be transformational.

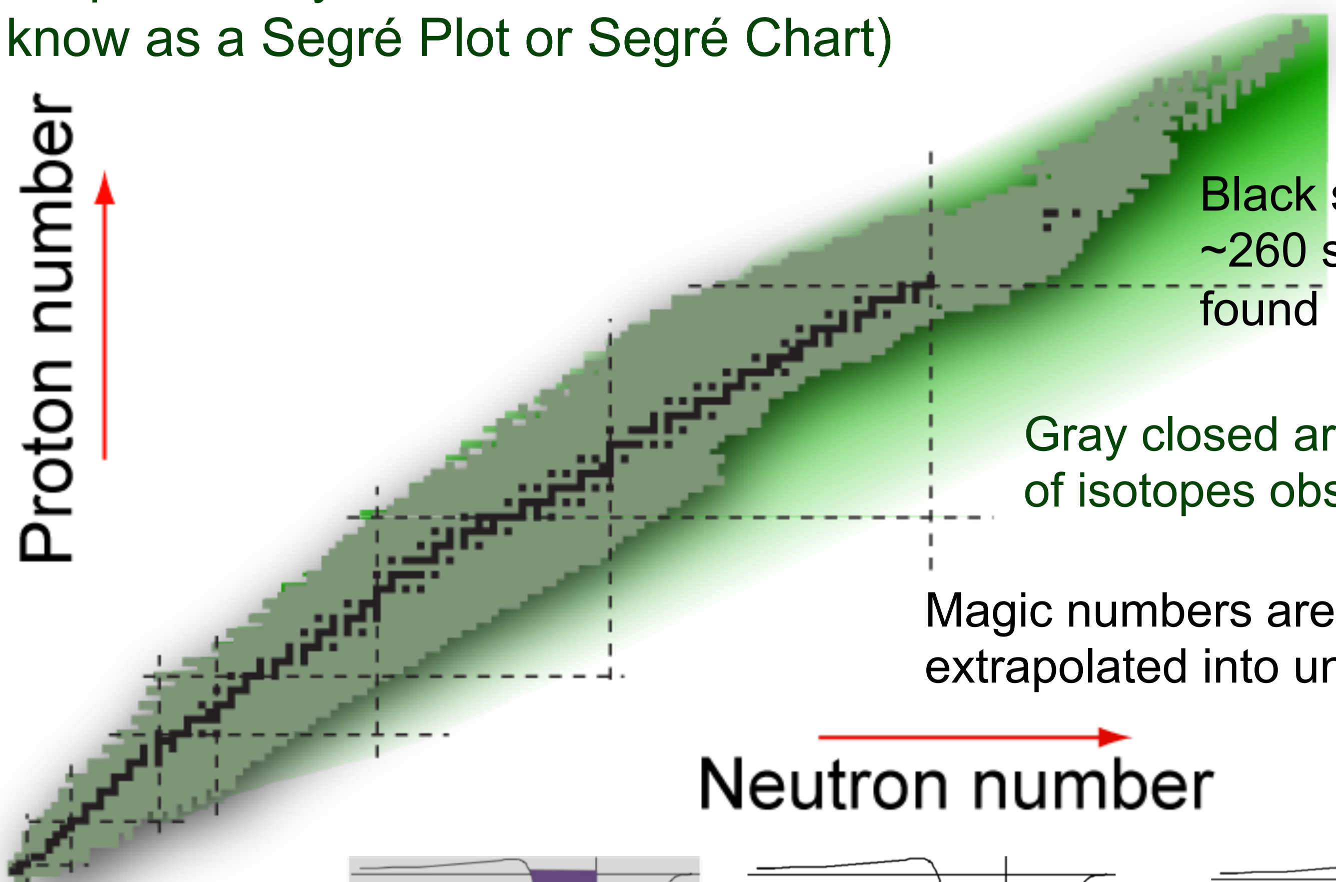
Theory Roadmap – 2007 NSAC Long Range Plan

- Step 1: Use *ab initio* theory and study of exotic nuclei to determine the interactions of nucleons in light nuclei and connect these to QCD by comparison to lattice calculations of NN and NNN forces [most of the test case nuclei are known].
- Step 2: For mid-mass nuclei use configuration space models [aka shell models]. The degrees of freedom and interactions must be determined from observations of the properties of exotic nuclei.
- Step 3: Use density functional theory to connect to heavy nuclei. Exotic nuclei be used to test the form and parameters of the DFT.

Thus, still in the regime that large amount of data is needed to constrain theory.

The nuclear landscape

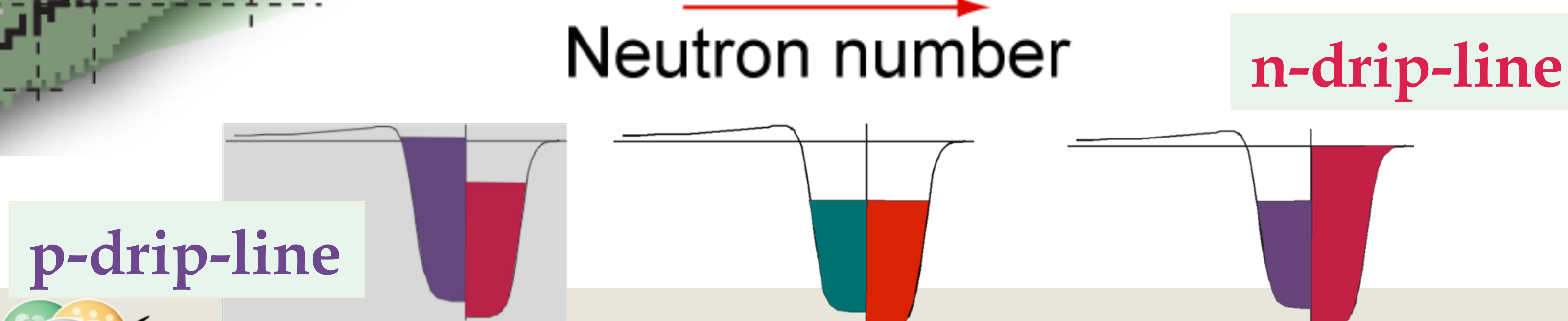
Roadmap for study: Chart of Nuclides
(first know as a Segré Plot or Segré Chart)



Black squares are the ~260 stable isotopes found in nature (> 1 Gy)

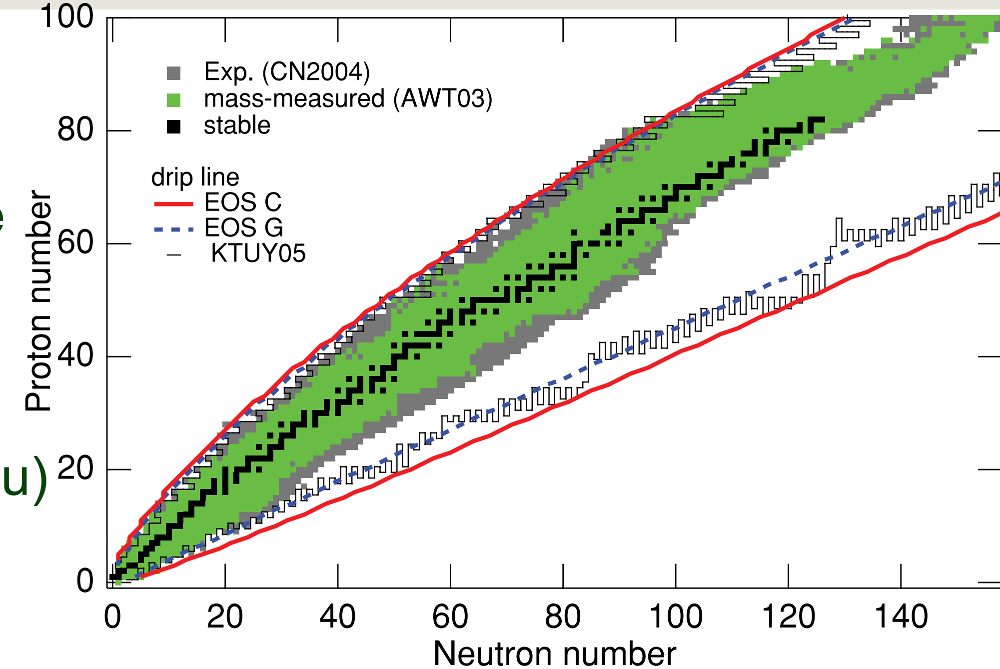
Gray closed area is the region of isotopes observed so far.

Magic numbers are glibly extrapolated into unknown



Why are the limits of nuclear binding interesting?

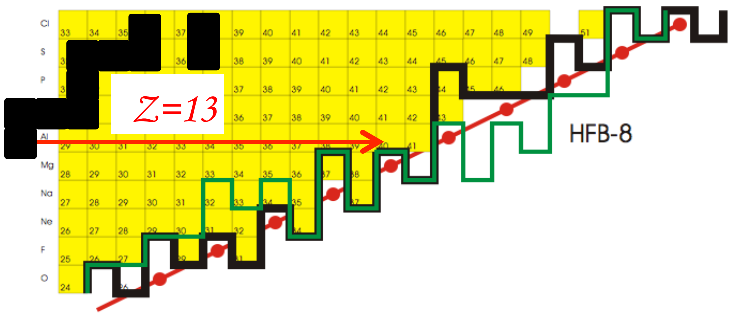
- Benchmark that all nuclear models can be measured against
- Along the neutron limit (drip line) the structure of nuclei is qualitatively different than that of stable nuclei
- Sensitive to aspects of the nuclear force (e.g., see figure from Oyamatsu)
- Interesting Physics: New types of clustering, enhanced pairing, importance of the continuum (and relation to scattering), novel quantum states (Efimov states), study of nuclear interactions in a low density environment, etc.

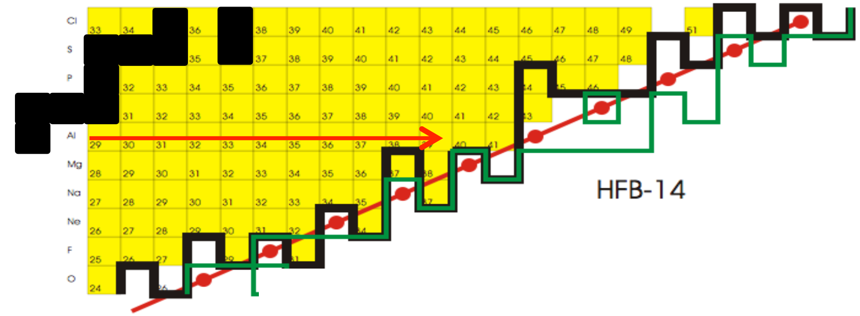


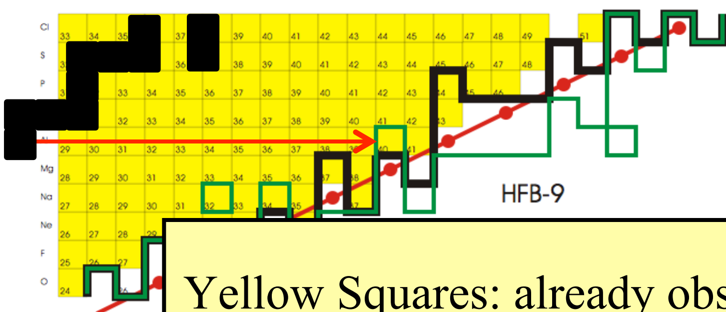
K Oyamatsu, K Iida, H Koura, Phy Rev C 82 (2010) 027301

Two Equations of State (EOS) used to explore the density dependence of the asymmetry term through a macroscopic calculation of drip lines.

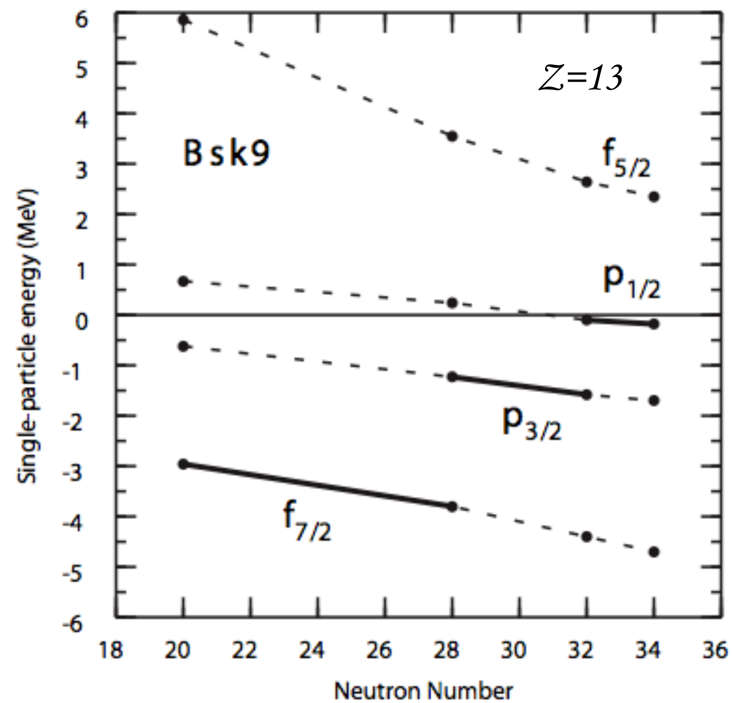
Where is the neutron drip line in theory?







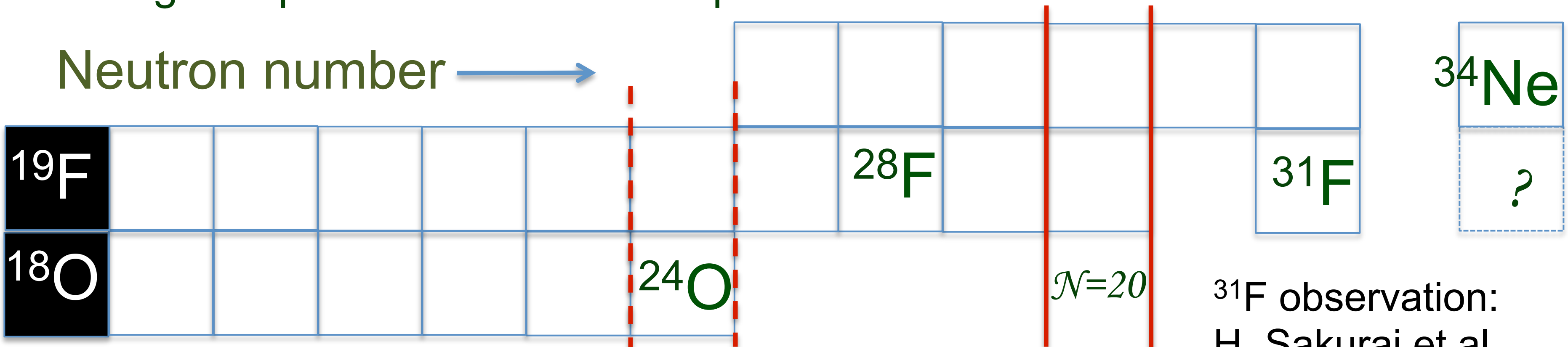
Yellow Squares: already observed
Black Line: Finite-Range Liquid-Drop
Moeller, et al. ADNDT 59 (1995) 185
Greeen Lines: Hartree-Foch-Bogoliubov
Goriely, et al. Nucl.Phys. A750 (2oo5)425
http://www-astro.ulb.ac.be/Html/hfb14.html



Shell Model Calculation by B. Alex Brown (MSU)

Extent of Oxygen and Fluorine Isotopes

- The last bound isotope of Oxygen is $^{24}O_{16}$; $^{25\text{-}28\ldots}O_{17\text{-}20\ldots}$ are unbound
- Adding one proton extends the drip line to at least ^{31}F



^{31}F observation:
H. Sakurai et al.,
PLB 448 (1999) 189

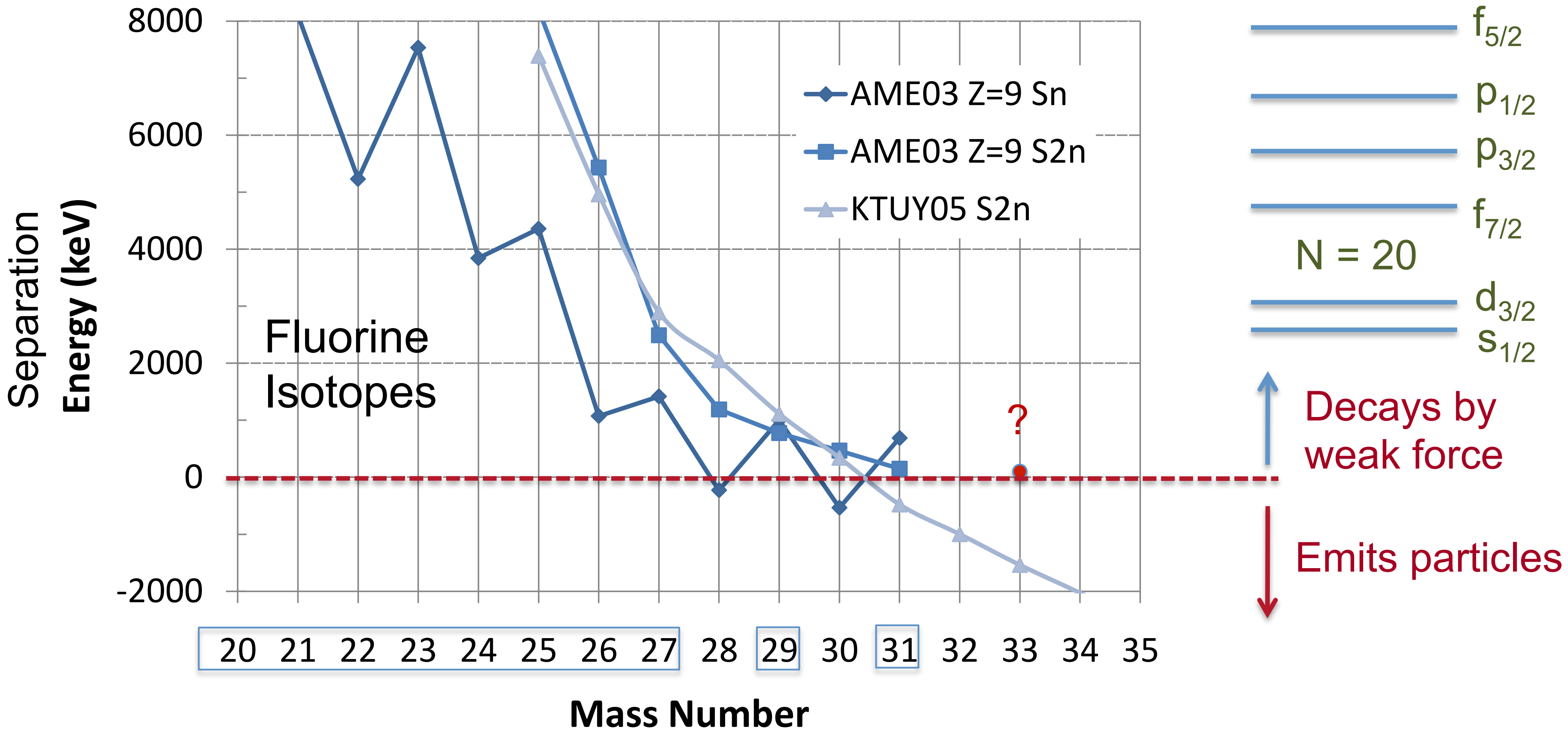
^{26}O unstable (first evidence of problems):
D. Guillemaud-Mueller et al., PRC 41 (1990) 937

^{24}O extra-stable (evidence of new subshell):
C.R. Hoffmann, et al., PLB 672 (2009) 17
R.V.F. Janssens, News and Views, Nature 459 (2009) 1069

- Surprise was that ^{24}O has a larger than expected shell-gap and heavier oxygen nuclei are less stable than expected.

Systematics of Separation Energies: Fluorine

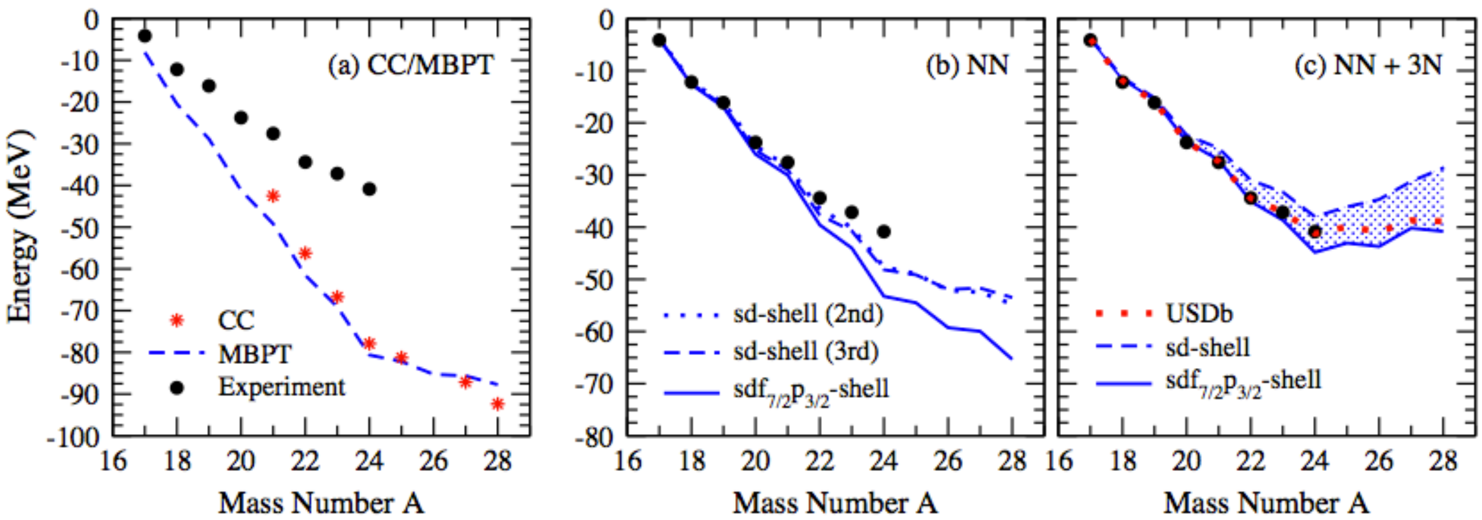
Separation energy is the energy required to remove 1 neutron (S_n) or 2 neutrons (S_{2n}) – negative numbers say the neutron(s) is unbound



KTUY05 - Koura-Tachibana-Uno-Yamada, Prog. Theor. Phys. 113 (2005) 305

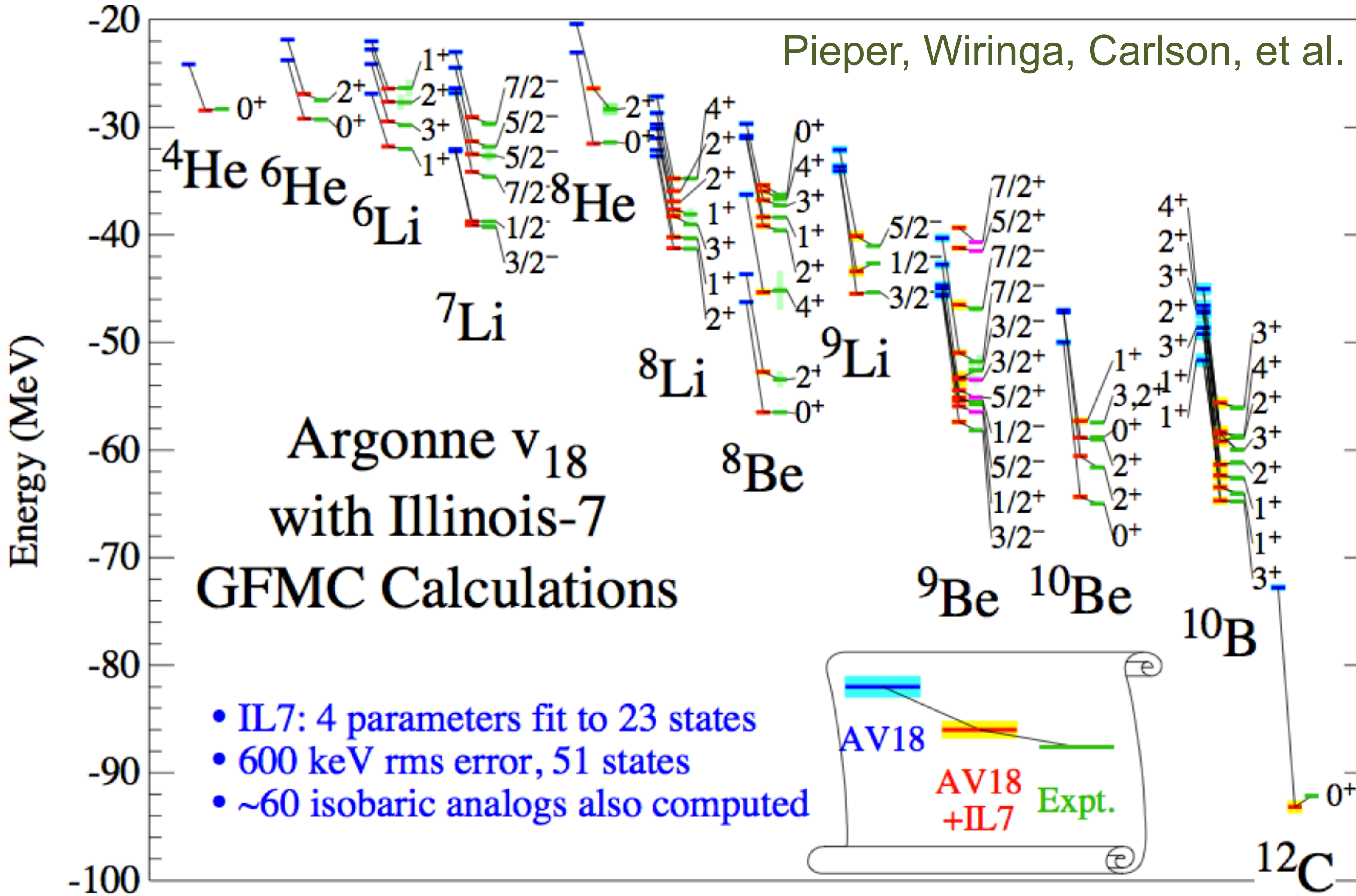
Three-body forces determined from exotic isotopes

- Holt, Menendez, and Schwenk arXiv:1108.2680
- Theories based on NN interaction generally predict ^{28}O to be particle bound (stable to the decay by the strong force)
- Three body forces tend to be repulsive and reduce the strength of the NN potentials



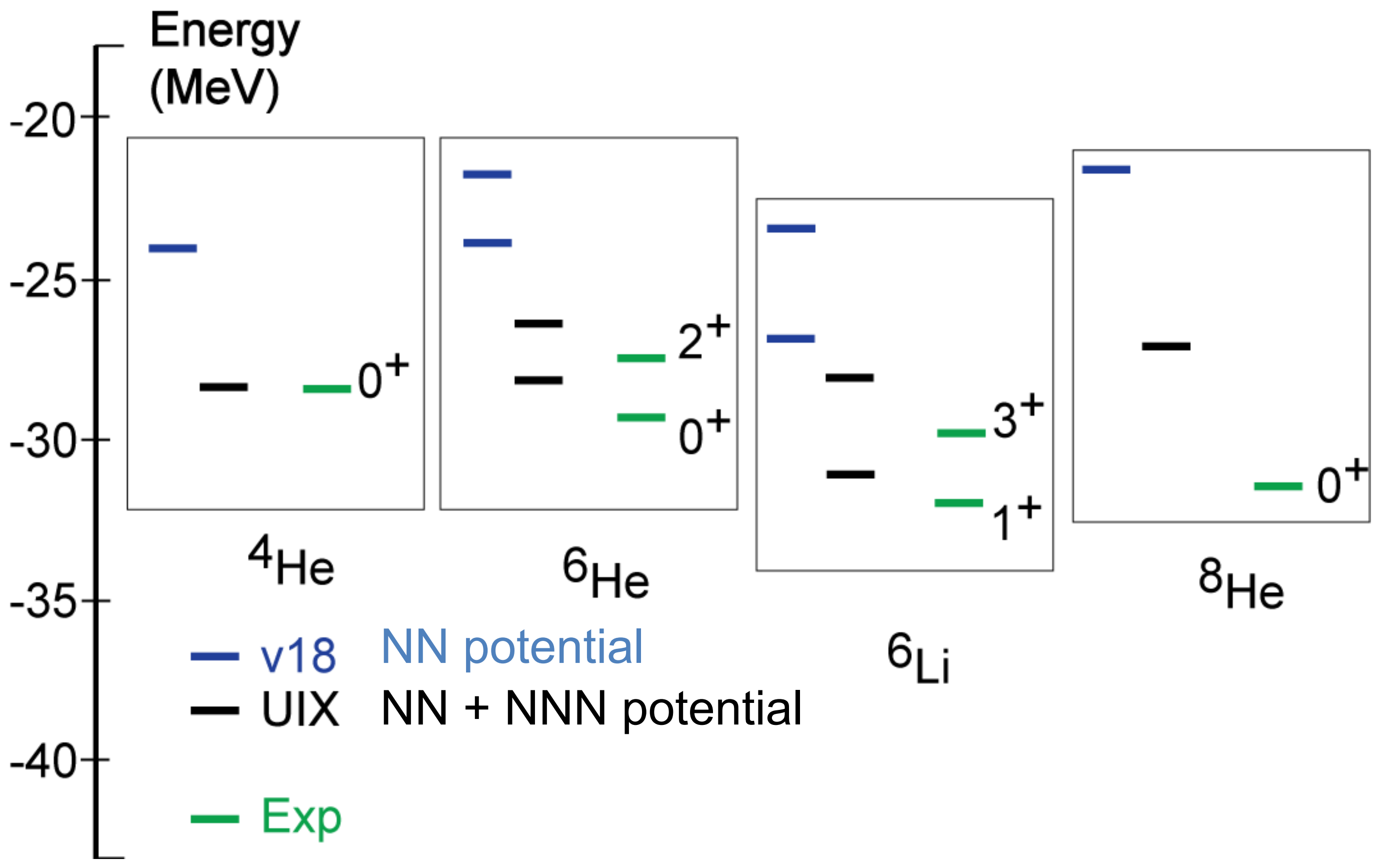
- CC – coupled cluster, sets SinglePartEnergies; MBPT – ManyBodyPertTheory
- The heaviest Oxygen isotopes provide insight to the 3N forces in nuclei

Status of ab-initio calculations for light nuclei



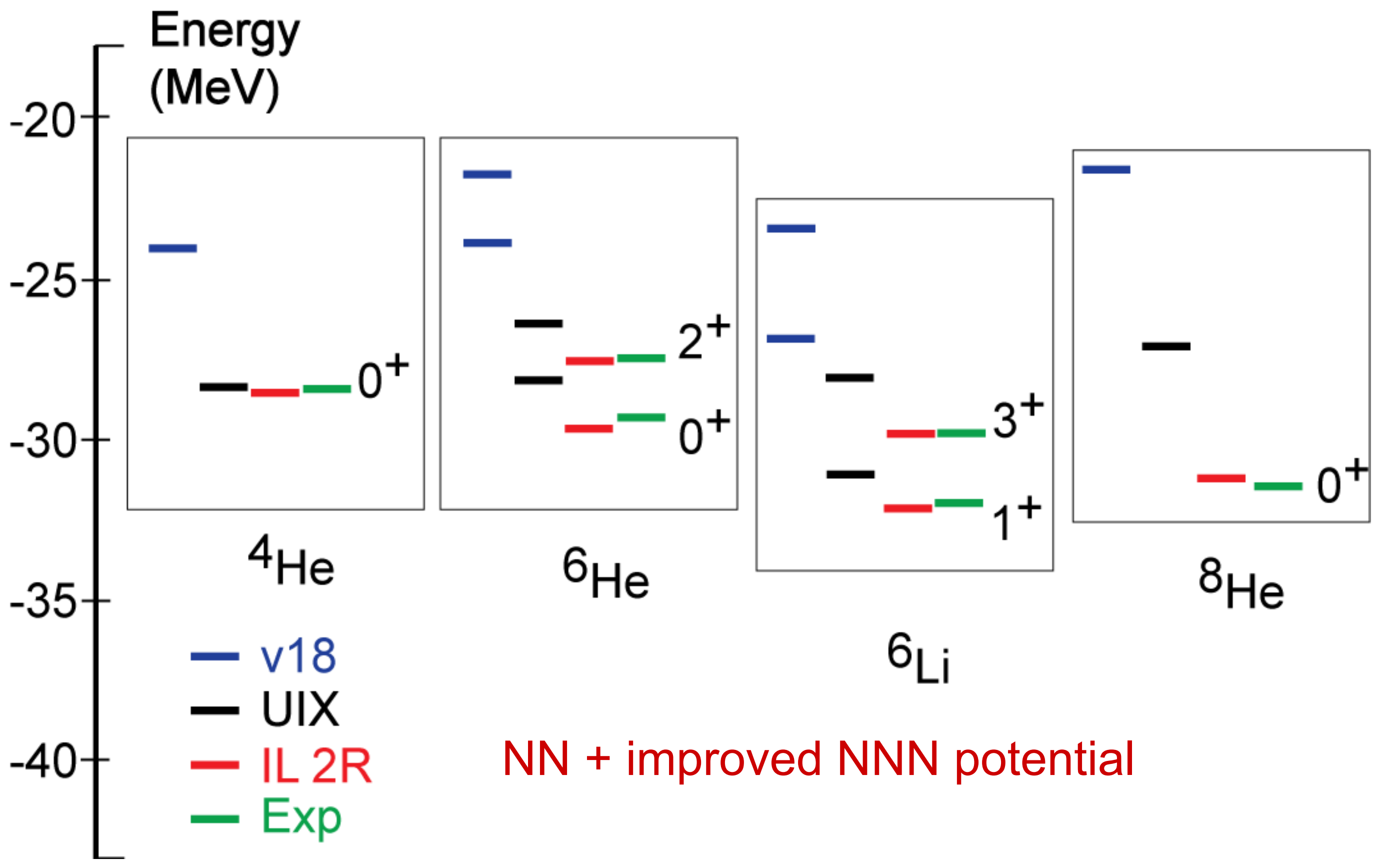
Comparison of calculated and measured binding energies with ab-initio calculation

- Greens Function Monte Carlo techniques provide calculations up to mass number 12
- NN 2-body forces from V_{18}
- S. Pieper, *et al.*



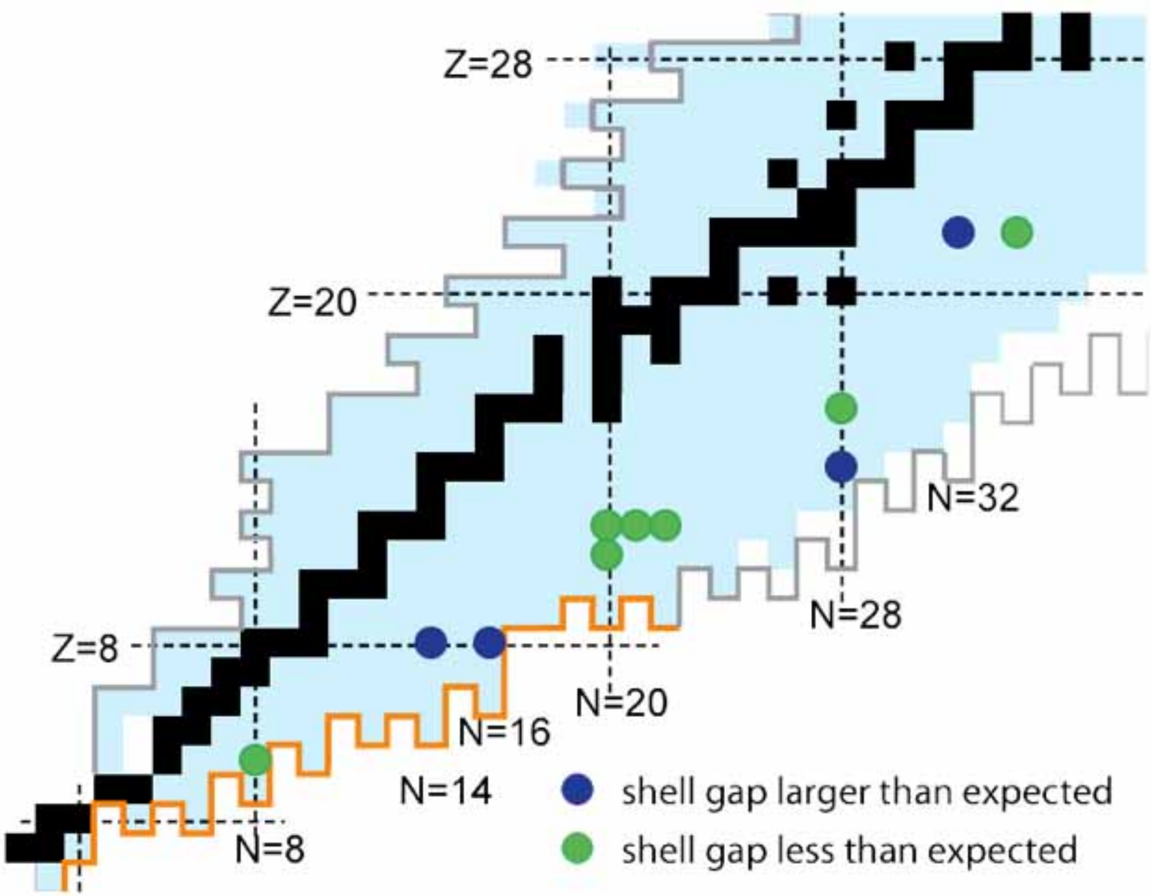
New information from most exotic isotopes

- Neutron rich nuclei were key in determining the isospin dependence of 3-body forces and the development of IL-2R from UIX
- New data on exotic nuclei continues to lead to refinements in the interactions
- S. Pieper, *et al.*

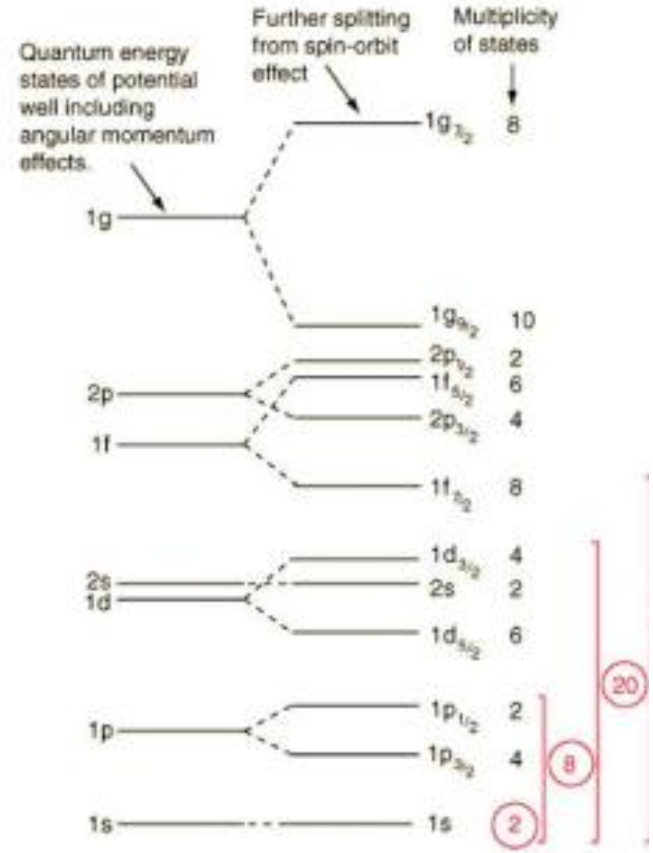


Properties of exotic isotopes are essential in determining NN and NNN potentials

Changing shell structure – the traditional nuclear shell model is incomplete



Textbook Shell Picture



Exotic nuclei provide new tests (failures) - Weak binding, tensor force, three-body force, …

2) Nuclear astrophysics community

- Understand the origin and history of nuclei/atoms in the Universe
  - Model the chemical history of the Milky Way
  - Trace the chemical history of the Universe back to the first stars
  - Learn about the early Universe from material produced in the Big Bang
- Use the chemical nature of a star, cluster or galaxy to infer something about its origin and history
- Provide accurate modeling of astrophysical objects and allow observations to be used to infer conditions at the site
  - For example, using the light as a function of time (called a light curve) of an X-ray burst to determine the size of emitting region.
  - Use observations to tell us about extreme environments in the universe; neutron stars, supernovae, novae, black holes, the Big Bang, etc.

Hubble Space Telescope image of the face-on spiral galaxy Messier 101 (M101)

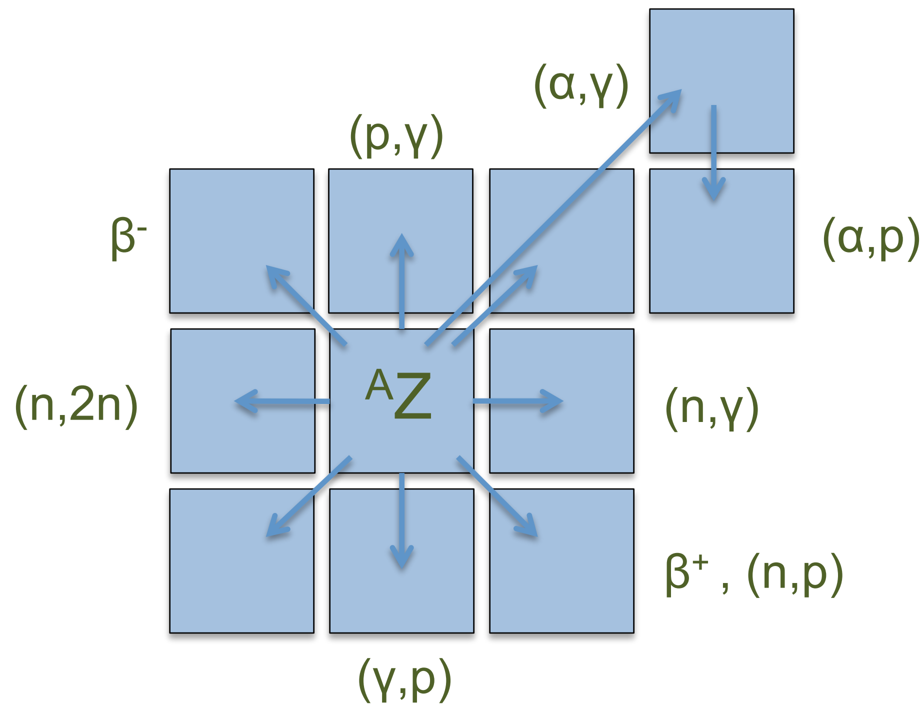
There are a number of nucleosynthesis processes involving rare isotopes

- Big Bang Nucleosynthesis
- pp-chain
- CNO cycle
- Helium, C, O, Ne, Si burning
- s-process
- r-process
- rp-process
- νp – process
- p – process
- α - process
- fission recycling
- Cosmic ray spallation
- pycnonuclear fusion

\+ probably others

Fission of exotics

Sample reaction paths

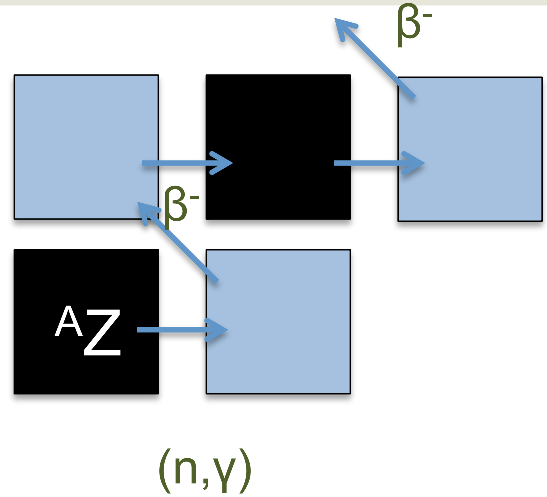


Can the community measure and model the relevant nuclear reactions?

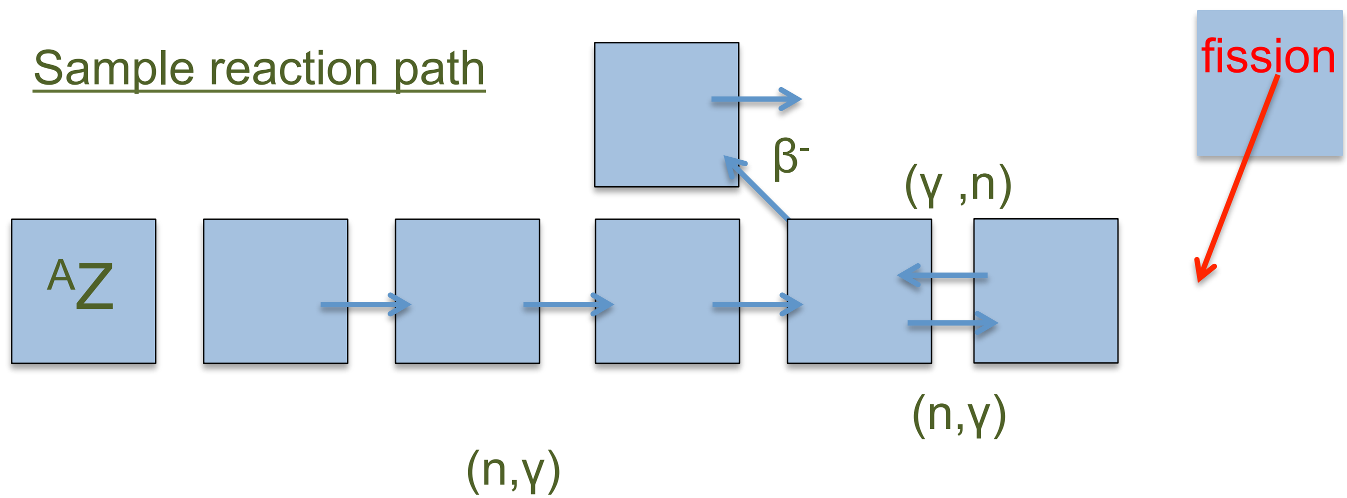
- No, not now, but the trick is to identify and measure the important ones, develop theoretical tools to calculate the rest.
- Develop a comprehensive model of nuclear properties and reactions
- Produce many of the rare isotopes that are important for modeling and measure their properties/reactions
- Develop capabilities for intense stable beam accelerators and low backgrounds [not FRIB]

Neutron-capture processes leading to elements heavier than iron

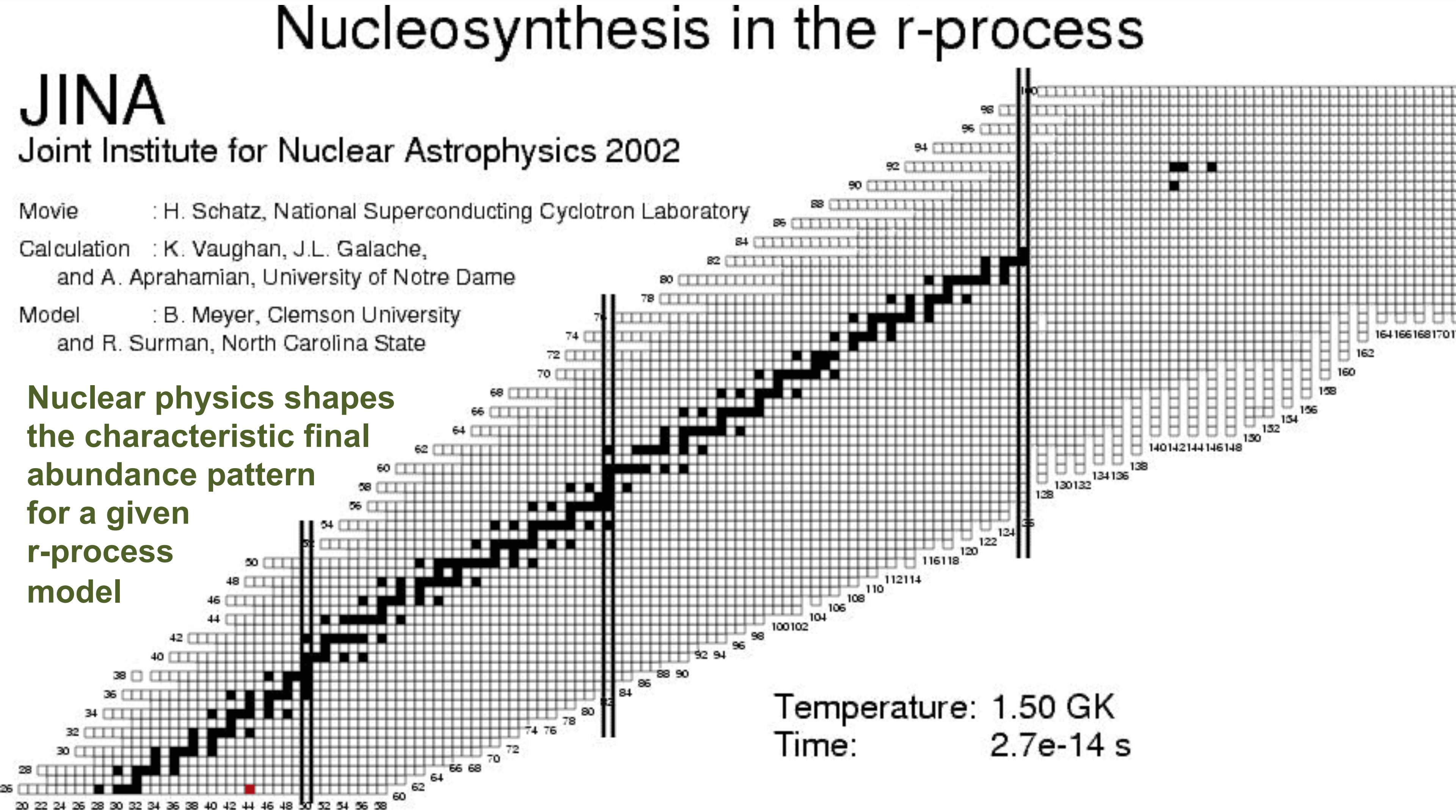
- s-process
  - Occurs over a time of hundreds of thousands of years
  - Technetium observed in red giant stars
  - Occurs in AGB Stars (C,O core; He and H fusion shells)



- r-process
  - Fast, few s
  - 10^{20-28} n/cm^3
  - Runs out to where (n,γ) and (γ,n) are similar in rate
  - Adds 30-40 neutrons
  - Site unknown



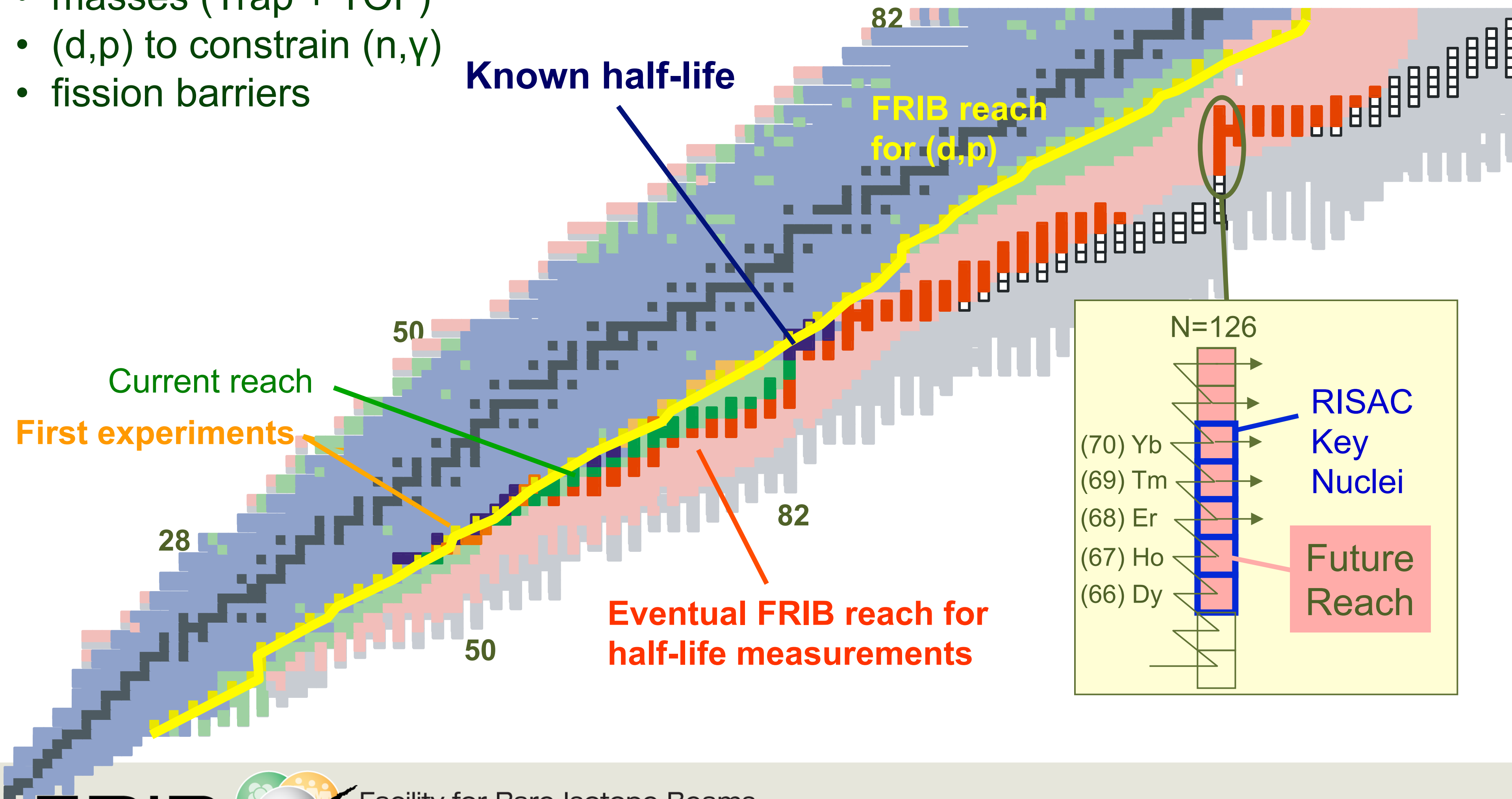
About half of heavier isotopes must be made in an r-Process



Nuclear physics shapes the characteristic final abundance pattern for a given r-process model

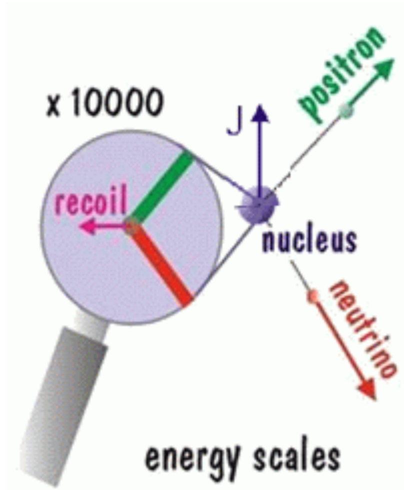
Isotopic reach of FRIB beams to provide data for modeling the r-process

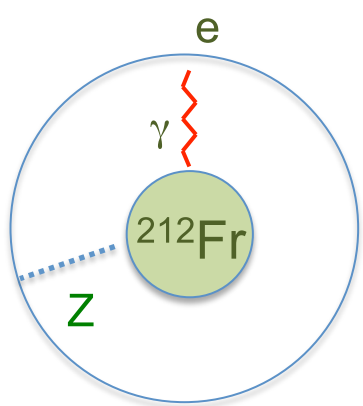
- β-decay properties
- masses (Trap + TOF)
- (d,p) to constrain (n,γ)
- fission barriers

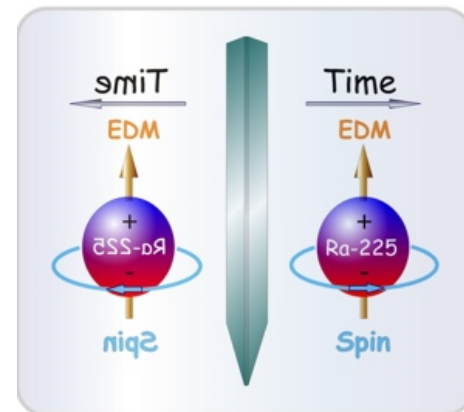


3) Tests of nature's fundamental symmetries

- Angular correlations in β-decay and search for scalar currents
  - Mass scale for new particle comparable with LHC
  - ^{6}He and ^{18}Ne at 10^{12}/s
- Electric Dipole Moments
  - ^{225}Ac, ^{223}Rn, ^{229}Pa (30,000x more sensitive than ^{199}Hg; $^{229}Pa > 10^{10}$/s)
- Parity Non-Conservation in atoms
  - weak charge in the nucleus (francium isotopes; 10^{9}/s)
- Unitarity of CKM matrix
  - V_{ud} by super allowed Fermi decay
  - Probe the validity of nuclear corrections



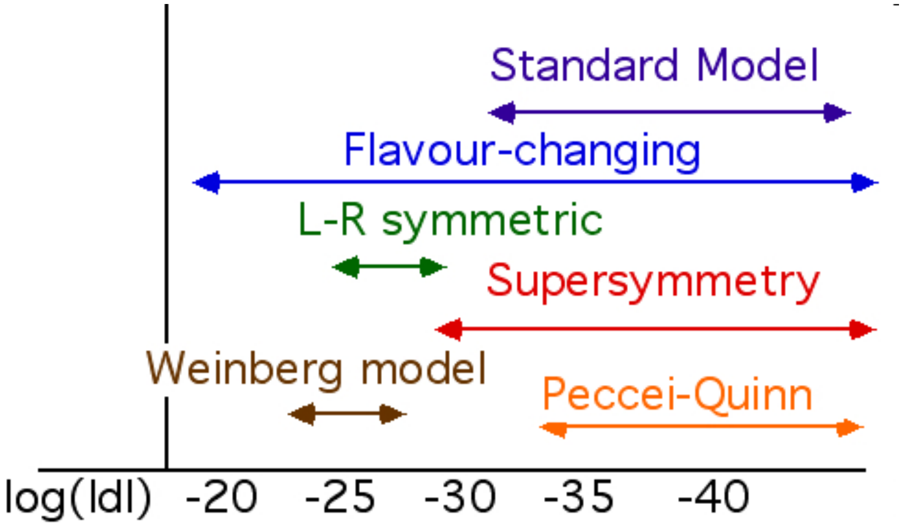




$$\begin{vmatrix} \mathbf{V_{ud}} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix}$$

Atomic Electric Dipole Moment

- EDM violates time reversal symmetry
- Improving EDM limit is an important constraint on models
- Neutron EDM
  - Present < 3.0 x 10^{-23} e-cm
  - SNS goal 10^{-28} e-cm
- ^{199}Hg EDM
  - Present < 3 x 10^{-29} e-cm
- ^{223}Rn proposed to have 20x greater sensitivity to EDM
- ^{229}Pa may have 10,000x greater sensitivity



Lu, Mueller, ANL
Chupp, U of Michigan
Swenson, Guelp

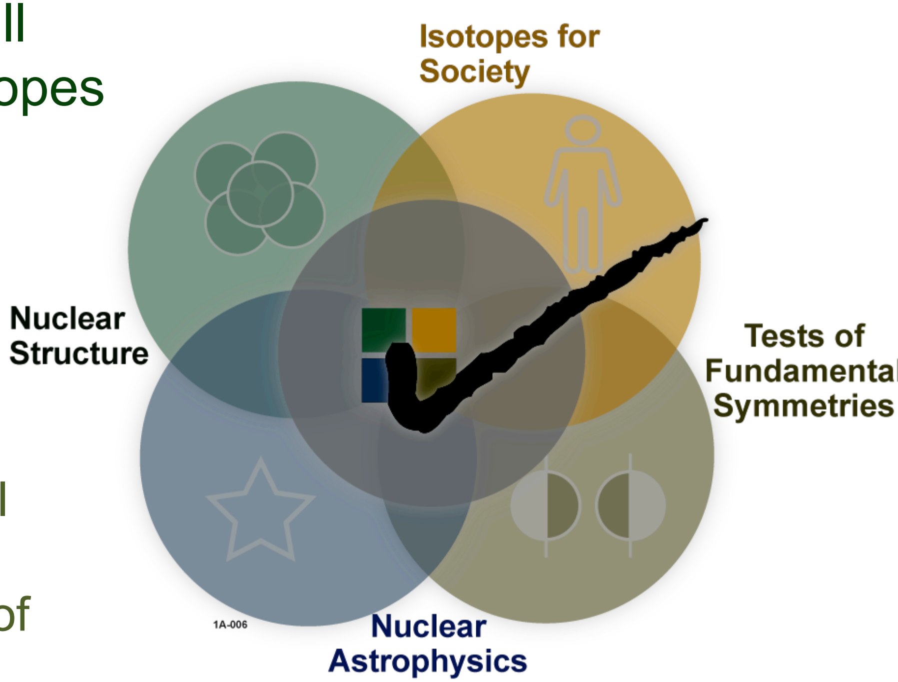
4) Sample of "interesting" isotopes from FRIB and uses

- 2010 Santa Fe Workshop on Applications of Isotopes from FRIB

Nuclide	Half-life	Use
^{32}Si	153 y	Oceanographic studies; climate change
^{221}Rn	25 m	Targeted alpha therapy
$^{225}Ra/^{229}Po$	15 d	EDM search in atomic systems
^{85}Kr	11 y	High specific activity ^{85}Kr for nuclear reaction network studies, e.g., s-process
^{44}Ti	60 y	Target and ion-source material
^{67}Cu	62 h	Imaging and therapy for hypoxic tumors

Summary

- We are in an age of designer atomic nuclei – new tool for science
- Current and next generation facilities will allow production of a wide range of isotopes not presently available:
  - Necessary for the next steps in accurate modeling of atomic nuclei
  - Necessary for progress in astronomy (chemical history, mechanisms of stellar explosions)
  - Opportunities for the tests of fundamental symmetries
  - Important source for research quantities of exotic isotopes
- To be sure there are likely to be many surprises along the way



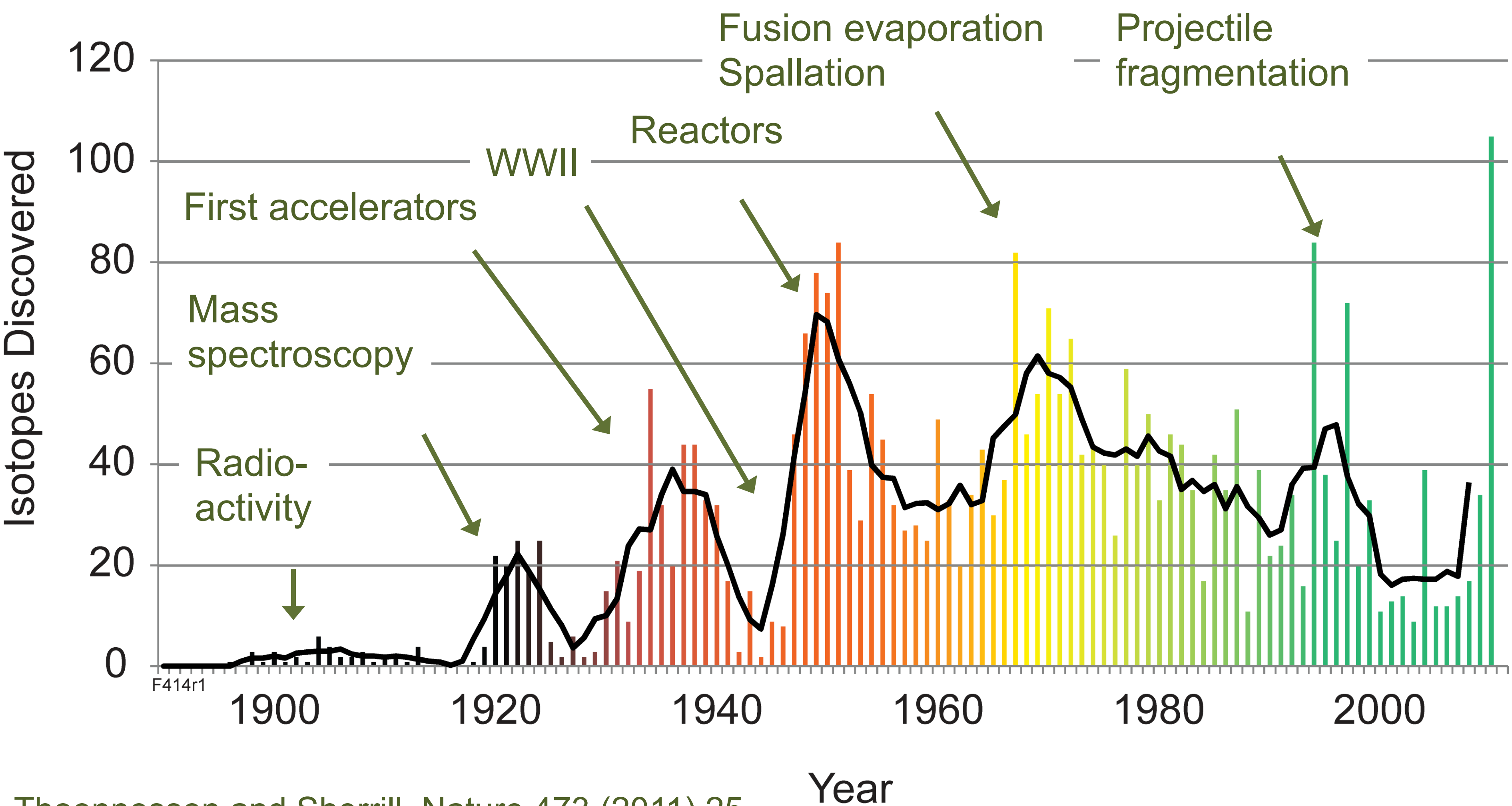
Thank you for your attention

and

Thanks to the organizers for the invitation to this charming location

Backup

Historical view of "isotope identification"

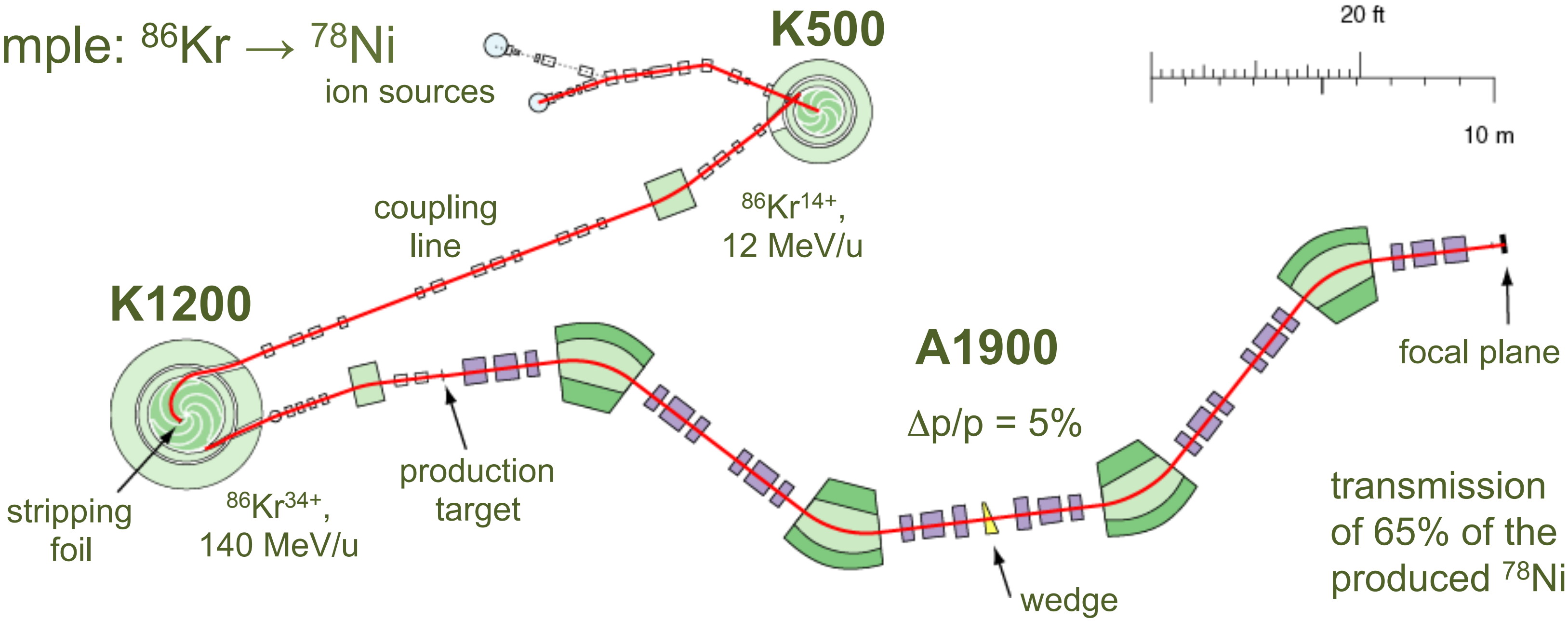


Thoennessen and Sherrill, Nature 473 (2011) 25

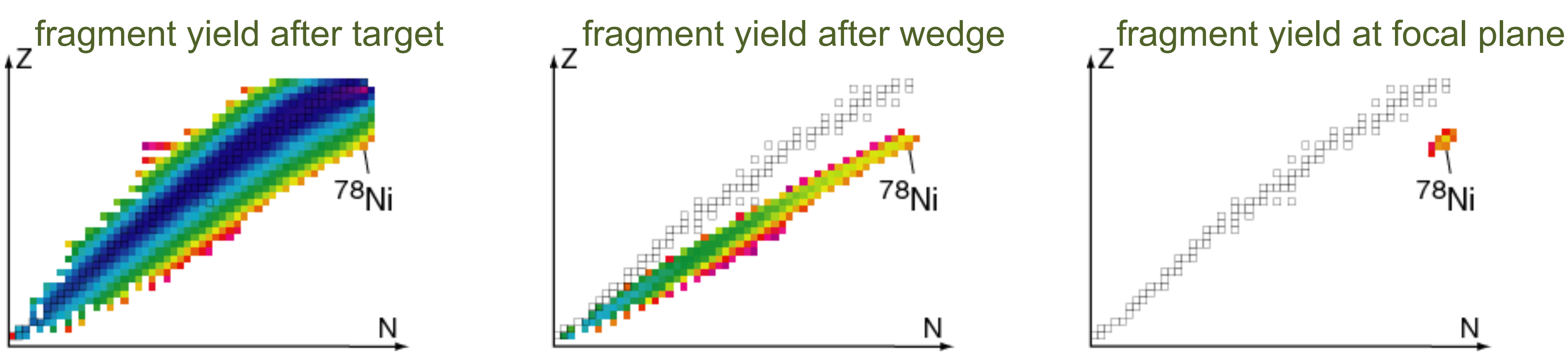
In-Flight Production Example: NSCL's CCF

D.J. Morrissey, B.M. Sherrill, Philos. Trans. R. Soc. Lond. Ser. A. Math. Phys. Eng. Sci. 356 (1998) 1985.

Example: $^{86}Kr \rightarrow {}^{78}Ni$

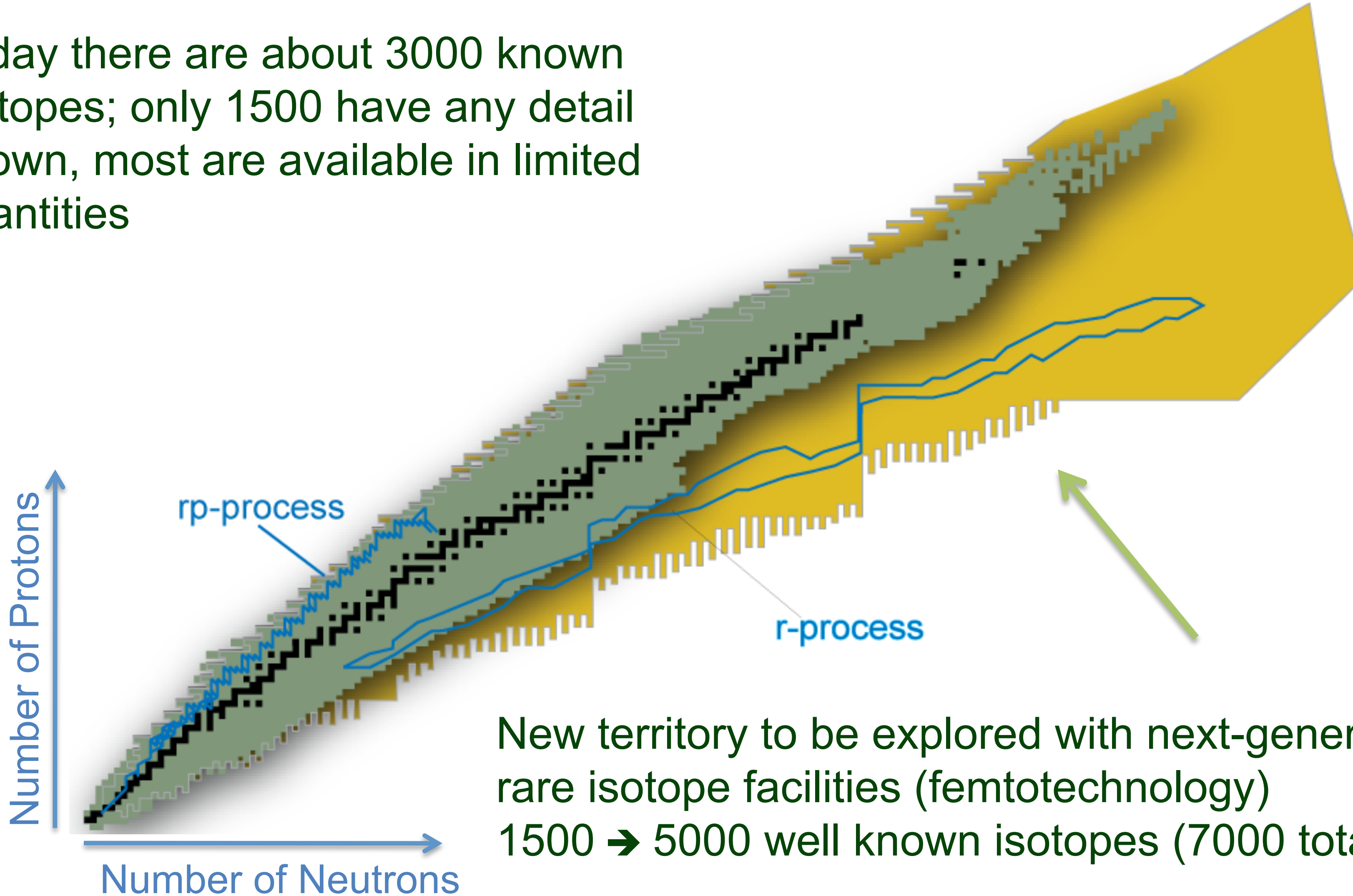


transmission of 65% of the produced ^{78}Ni



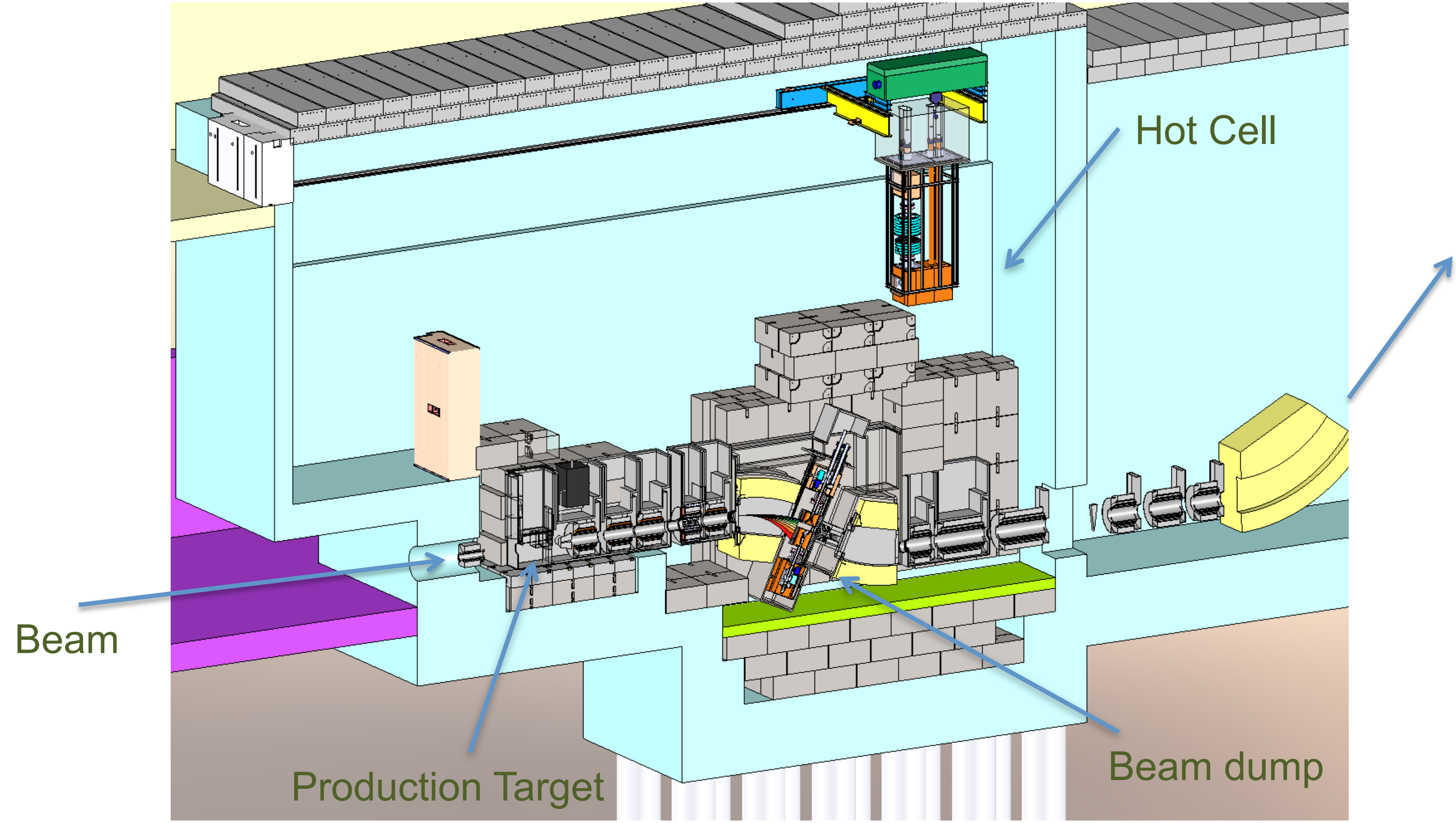
Goal: arbitrary combination of neutrons and protons requested by researchers

Today there are about 3000 known isotopes; only 1500 have any detail known, most are available in limited quantities

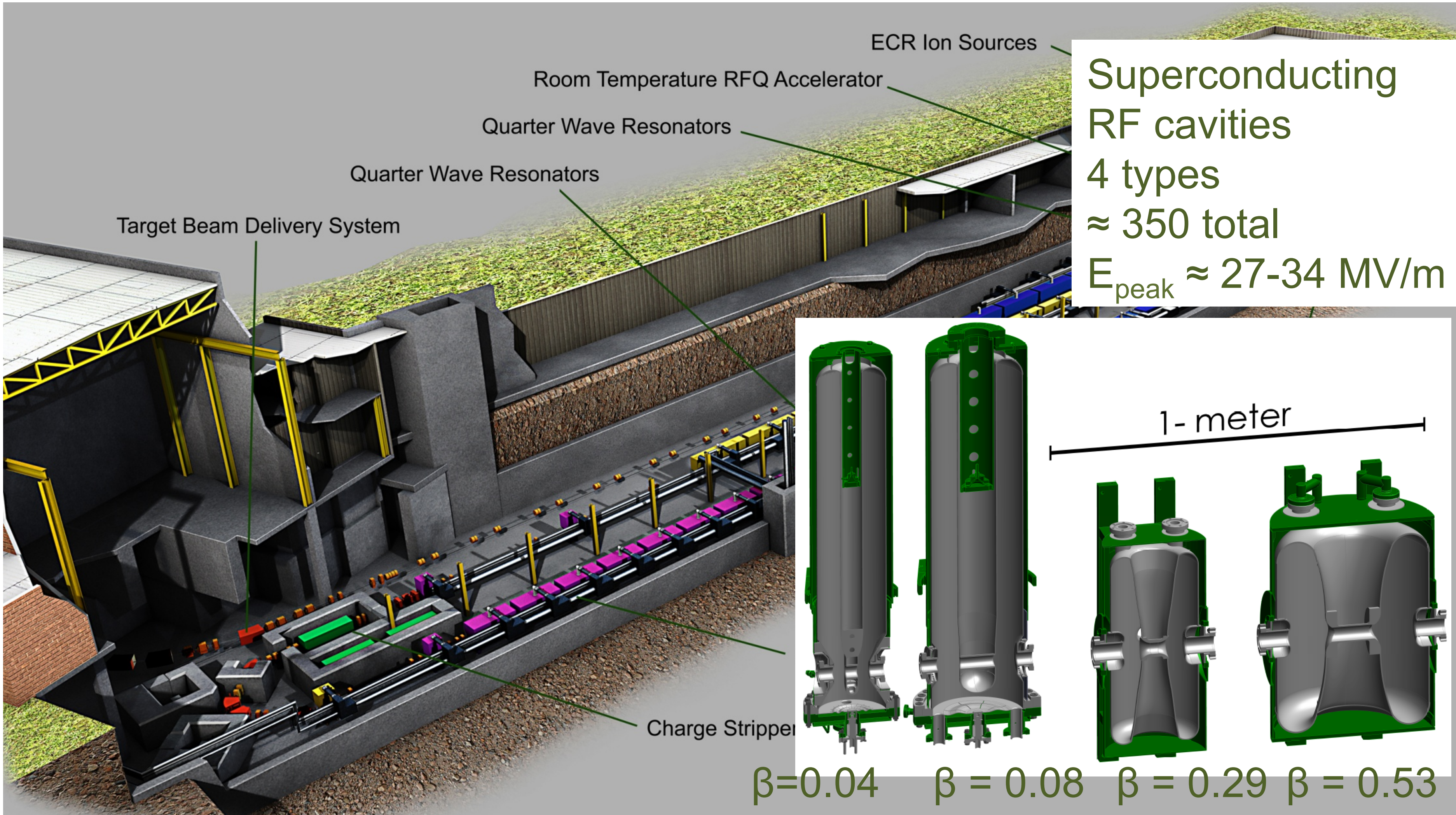


New territory to be explored with next-generation rare isotope facilities (femtotechnology)
1500 ➔ 5000 well known isotopes (7000 total?)

Production target and beam dump hot-cell



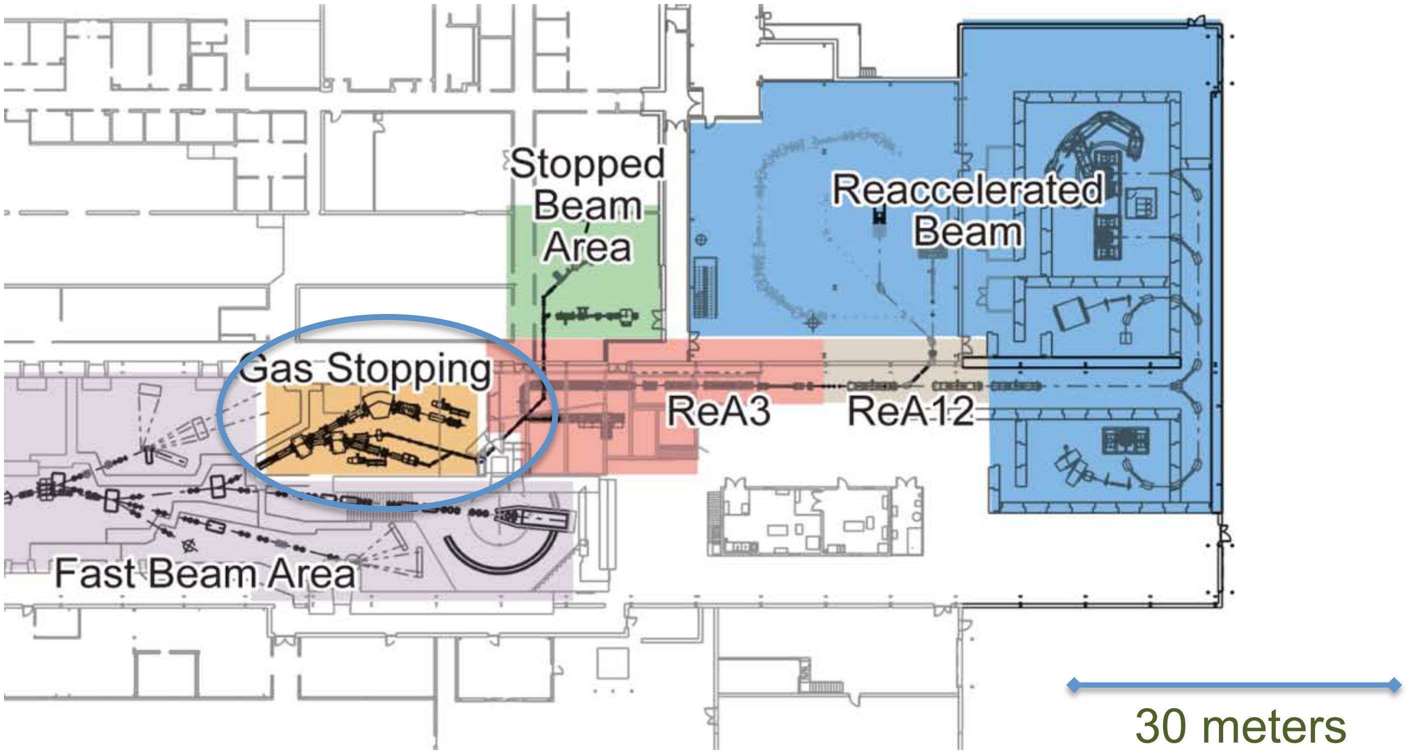
FRIB Driver: SRF linear accelerator



Superconducting RF cavities
4 types
≈ 350 total
E_{peak} ≈ 27-34 MV/m

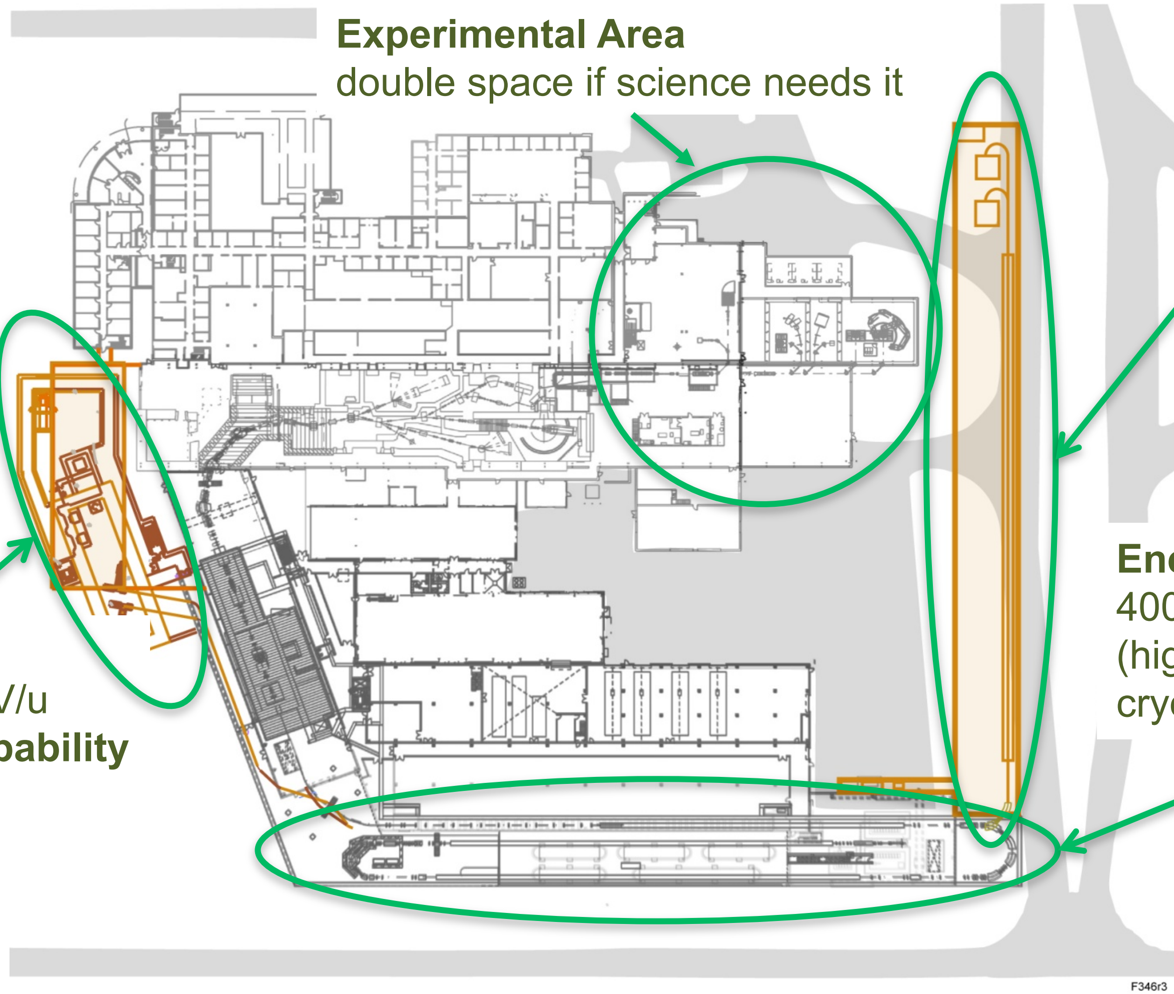
Overview of FRIB reaccelerators and experimental stations

- Fast, stopped, and reaccelerated beam capabilities (unique)
- ReA12 experimental hall is ready for occupancy in (October 2011)
- ReA12 is not fully funded, well reviewed by NSF, MSU will move forward with ReA6



Science-driven upgrade options remain

Experimental Area
double space if science needs it



Light ion injector upgrade
$^{3}He^{+}$, 195 MeV/u

Energy upgrade to ≥ 400 MeV/u for all ions (high performance λ/2 cryomodules)

ISOL targets
^{3}He, 400 MeV/u
Multiuser capability with light ion injector

FRIB Users Organization

- Potential users register as members of the independent FRIB Users Organization, FRIBUO
  - Chartered organization with an elected executive committee (Chair is Michael Smith, ORNL; members – Aprahamian, Blackmon, Casten, Gade, Macchiavelli, Savard, Wiedenhoever, Wuosmaa)
  - 15 January 2010 began registration
  - 16 August had 870 members (51 countries) ; we anticipate 1500 closer to CD4
  - The FRIBUO has 21 equipment working groups
- NSCL and FRIB Users organizations are in the process of merging
- FRIB Theory Organization will merge with the FRIBUO

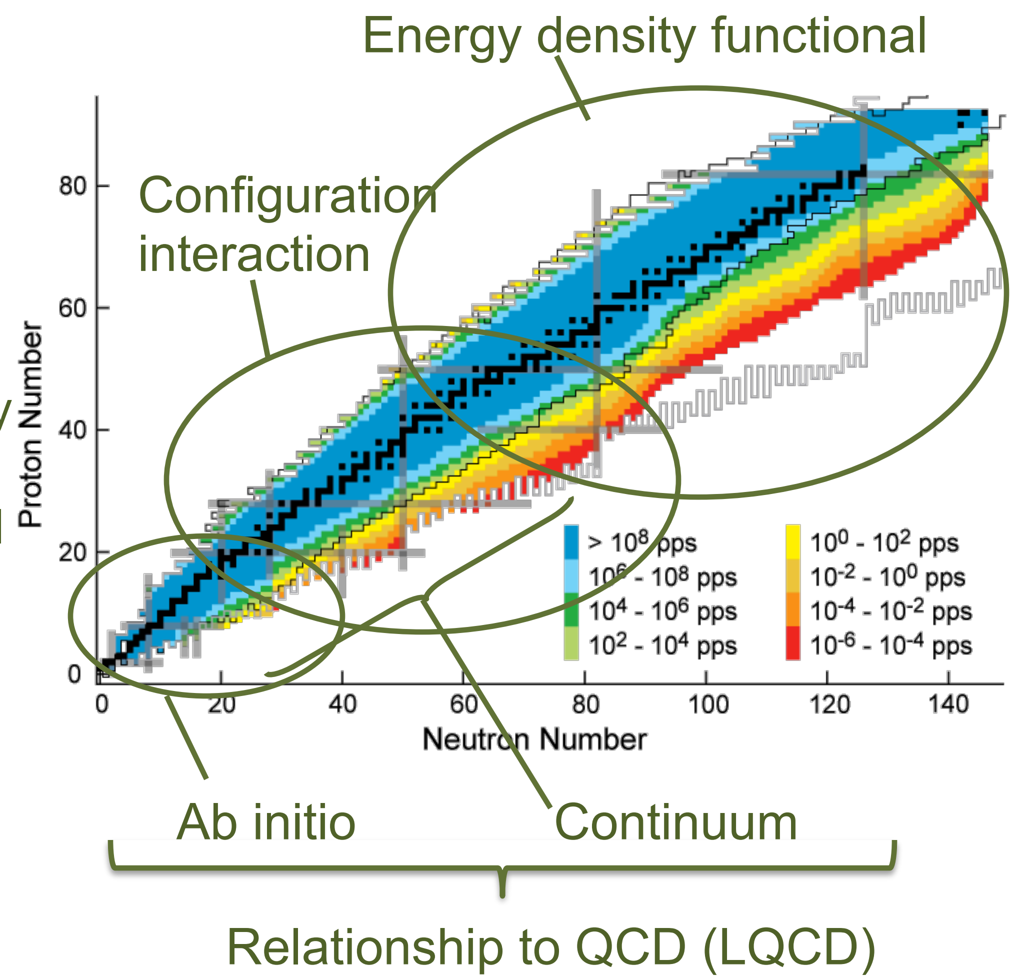
FRIB Users Organization
FACILITY FOR RARE ISOTOPE BEAMS

http://fribusers.org/

Feb 2010 FRIB equipment workshop

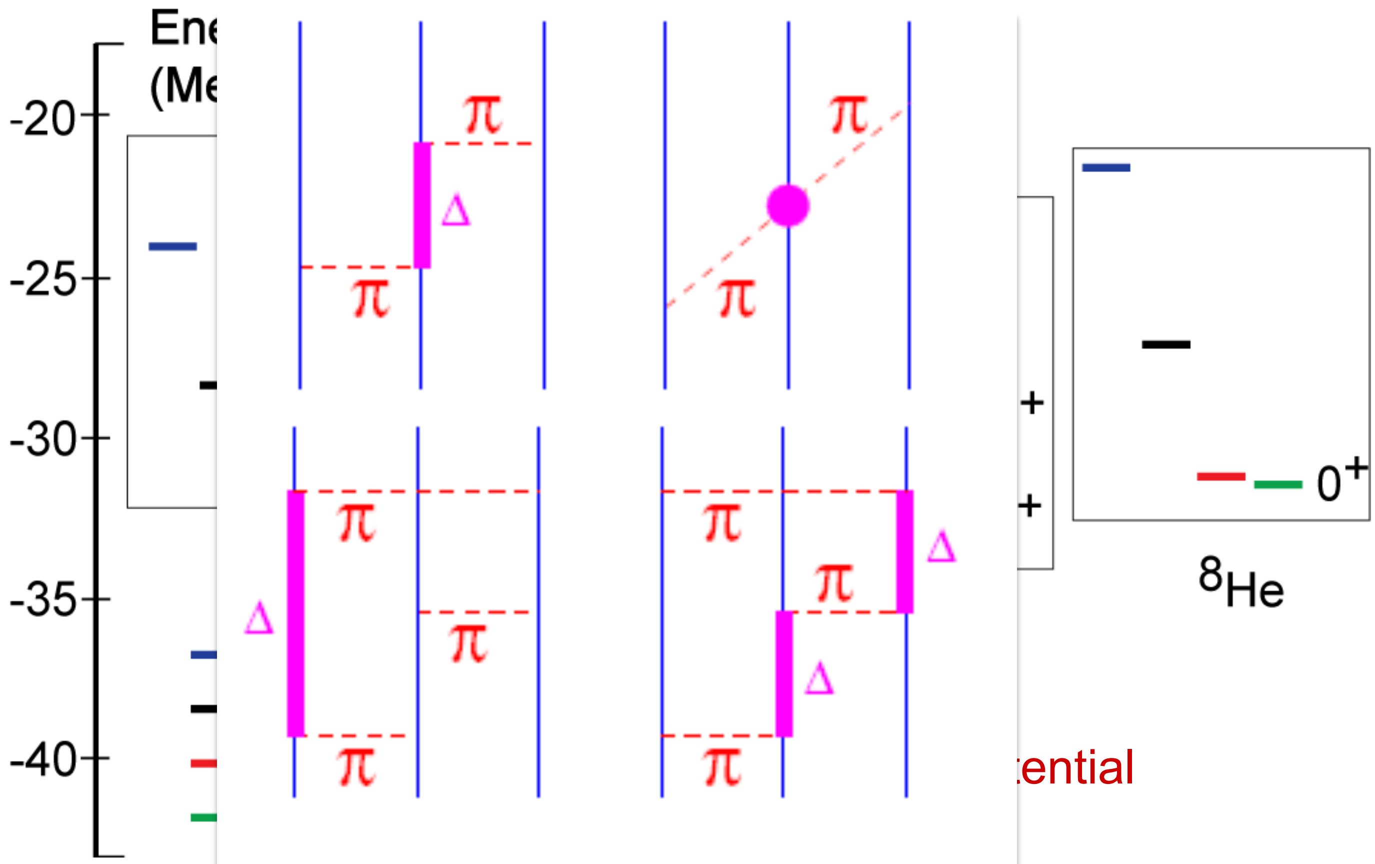
Theory Road Map: Comprehensive model of nuclear structure and reactions

- 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 (measurement of sensitive properties for N=14, 16 nuclei)
  - Configuration-interaction theory; study of shell and effective interactions (study of key nuclei such as ^{54}Ca, ^{60}Ca, ^{122}Zr)
  - The universal energy density functional (DFT) – determine parameters (broad view of mass surface, BE(2)s, BE(4)s, fission barrier surface, etc.)
  - The role of the continuum and reactions and decays of nuclei (halo studies up to A ~100)



New information from most exotic isotopes

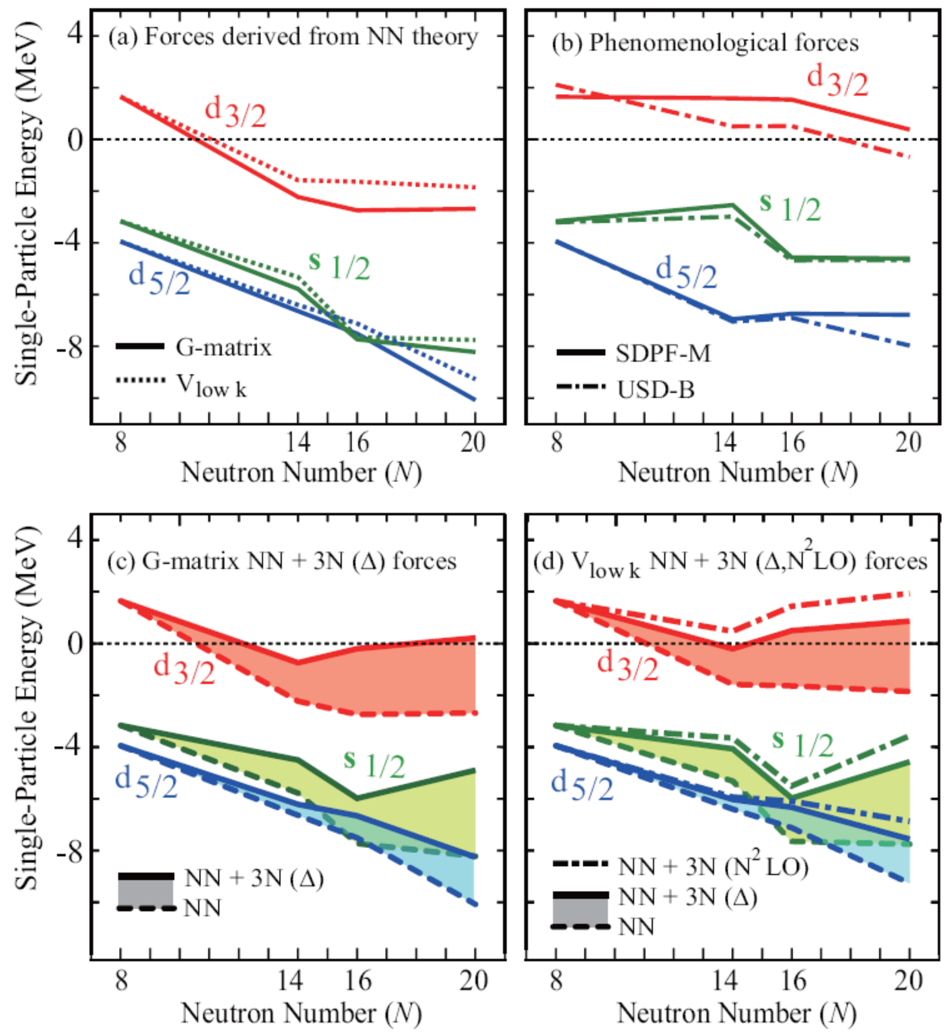
- Neutron rich nuclei were key in determining the isospin dependence of 3-body forces and the development of IL-2R from UIX
- New data on exotic nuclei continues to lead to refinements in the interactions
- S. Pieper B.Wiringa, *et al.*



Properties of exotic isotopes are essential in determining NN and NNN potentials

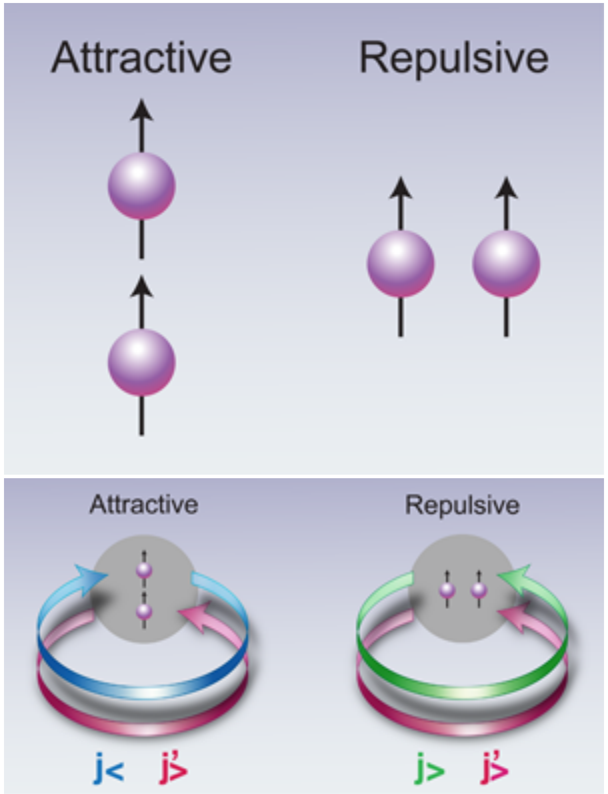
Other Evidence for Three Body Forces – Evidence for QCD

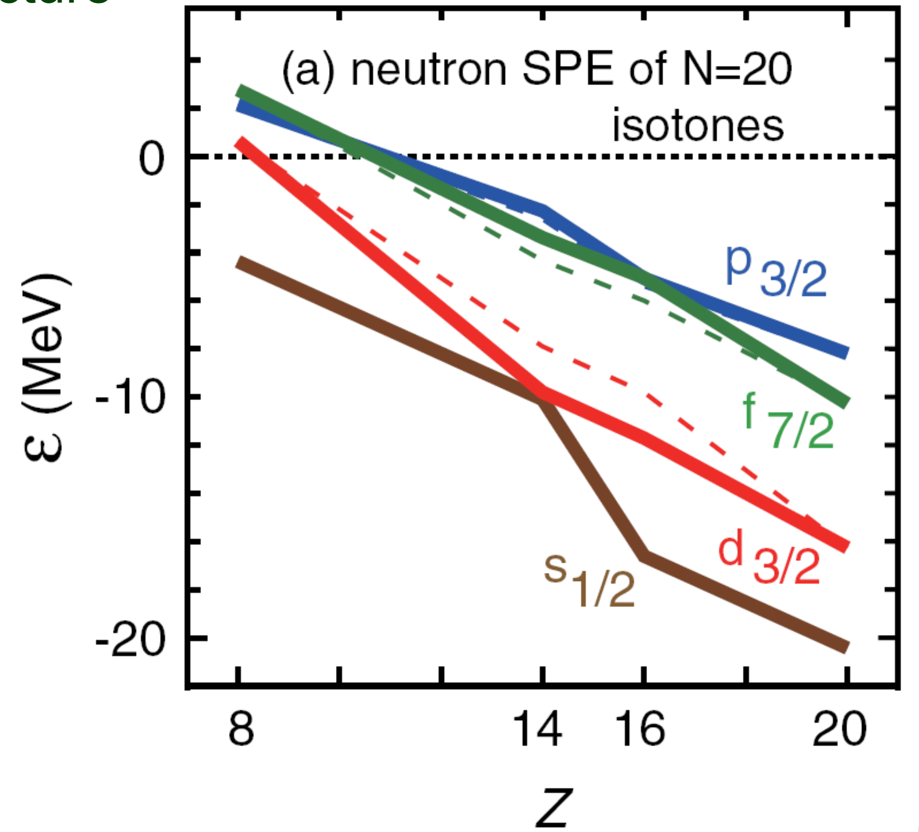
- T. Otsuka *et al.* PRL 2010: NNN force may be the solution to understanding the Oxygen drip line
- Lattice QCD may be able to provide the isospin dependence of the NNN force needed to understand nuclei
- Comparison of this dependence to rare isotope data allows a test of lattice QCD in nuclei



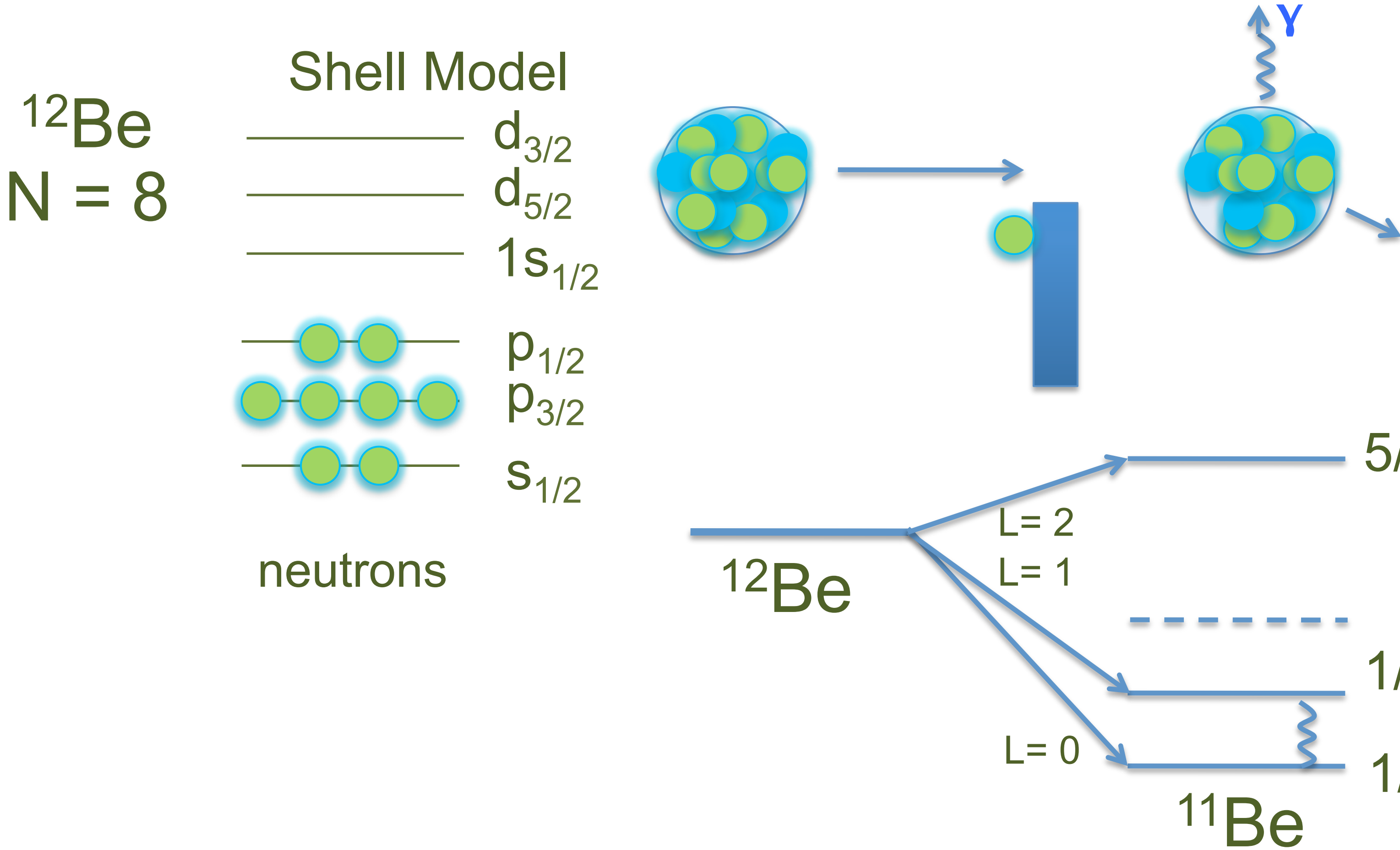
Tensor Force

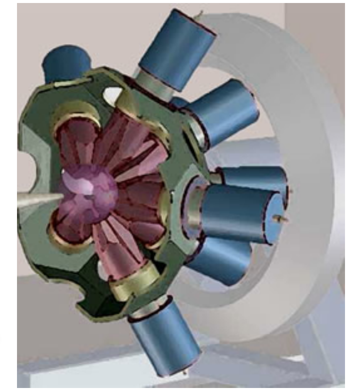
- Otsuka *et al.* has shown the importance of a monopole part of the tensor force in nuclei (Otsuka et al. PRL 2001, 2005, 2010)
- Related to single pion exchange (Yukawa 1935)
- This modifies the standard shell picture





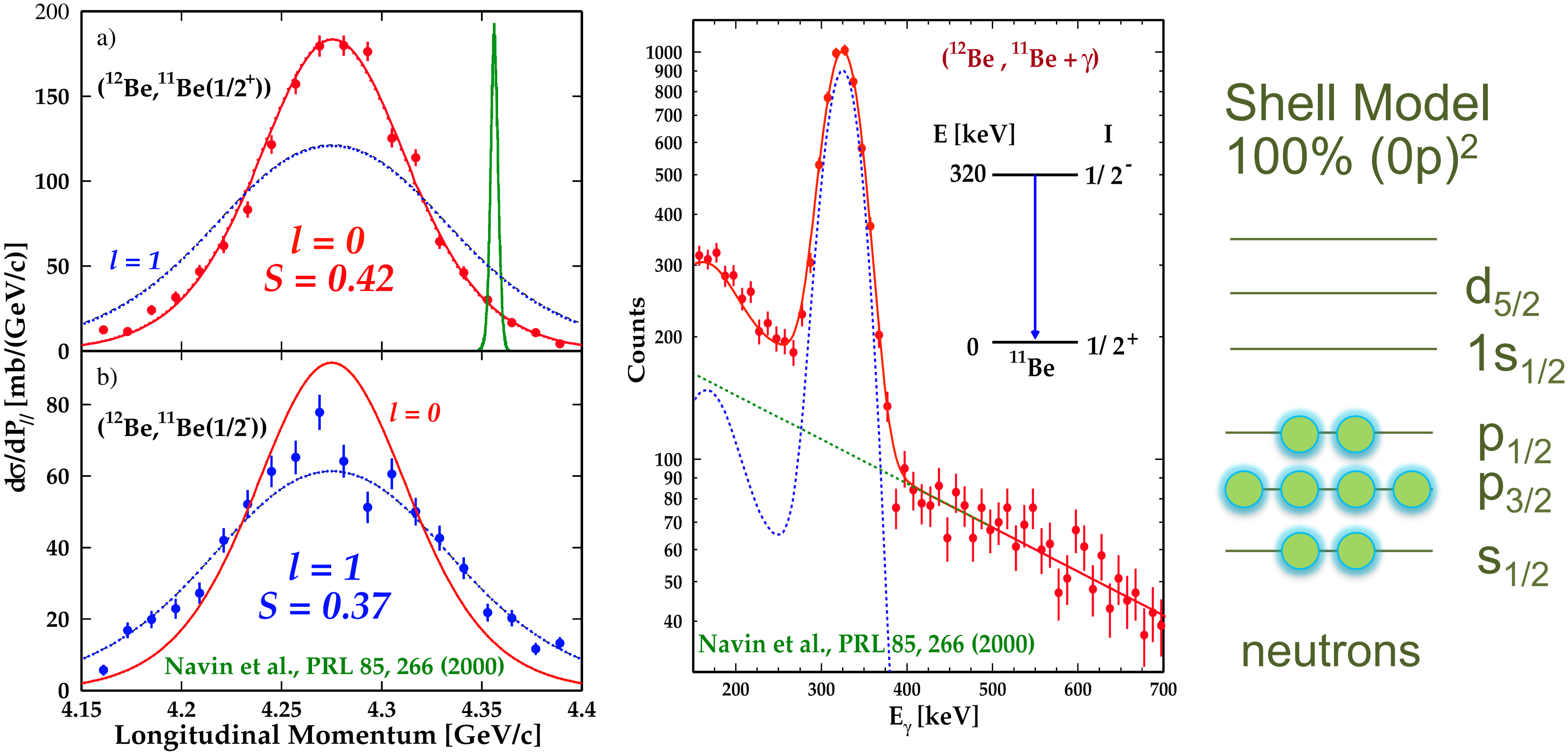
Nucleon knockout technique to measure wave functions





P. G. Hansen and J. A. Tostevin, Annu. Rev. Nucl. Part. Sci. 53, 219 (2003).

Recoil momentum shows which orbit the nucleons came from

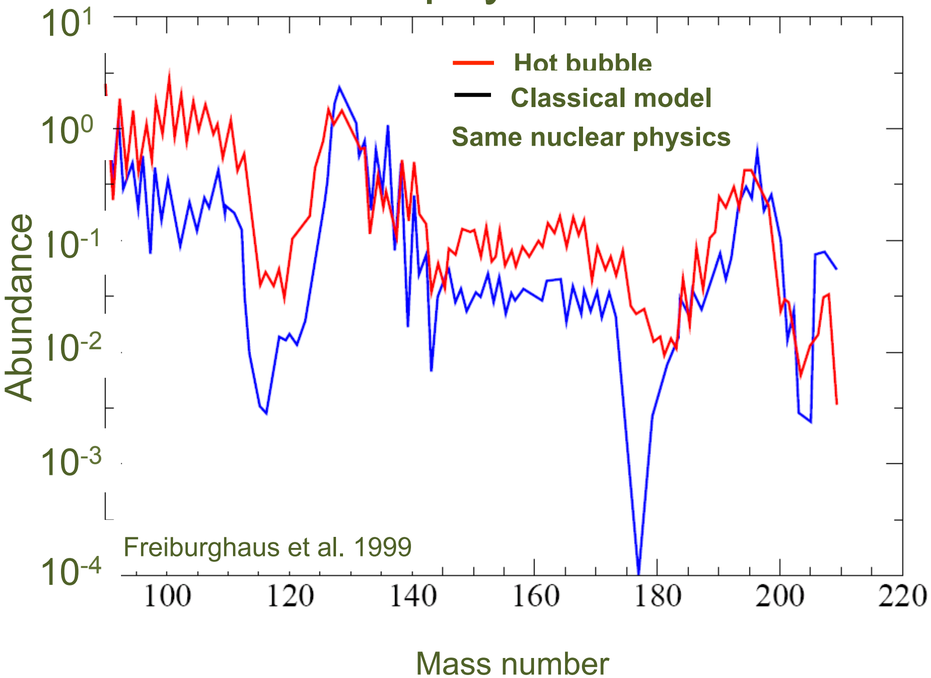


Shell Model
100% $(0p)^2$

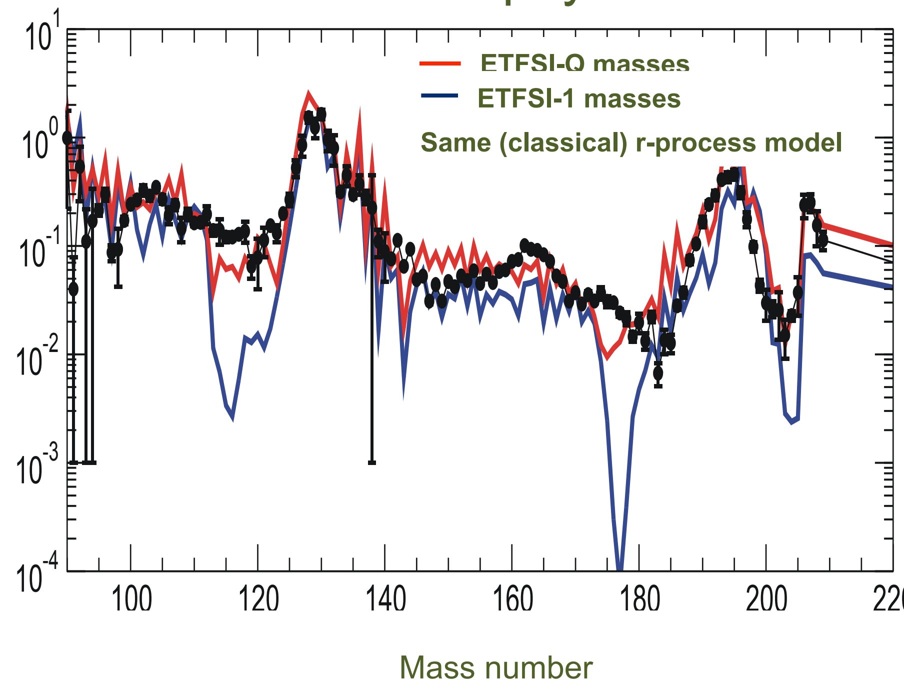
N=8 is not a shell closure in ^{12}Be: It is just about the opposite with the wave function of 32% $(0p)^8$, 34% $(1s)^2$, 34% $(0d)^2$

Uncertainty between models and nuclear properties

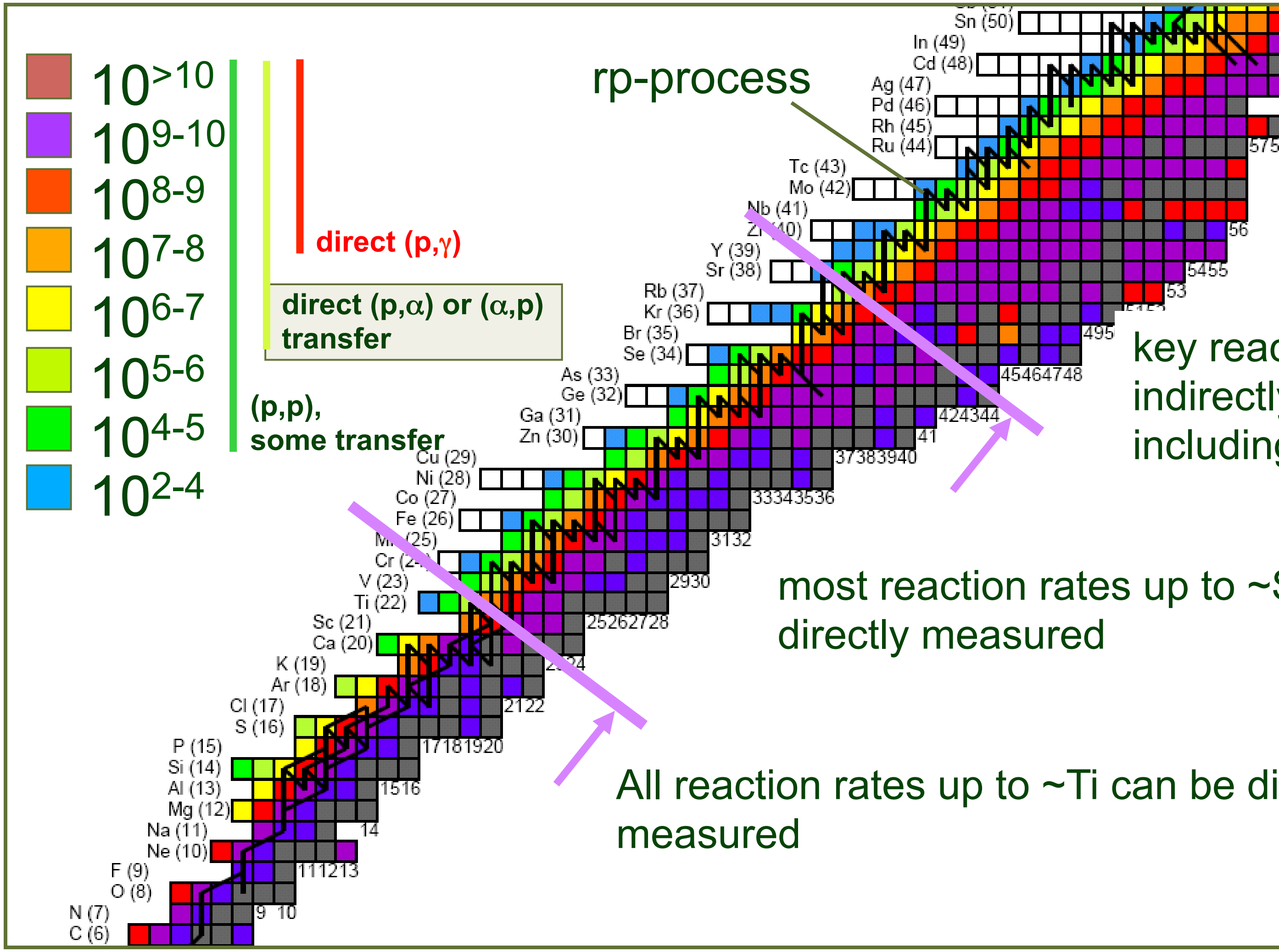
Astrophysics



Nuclear physics



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



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

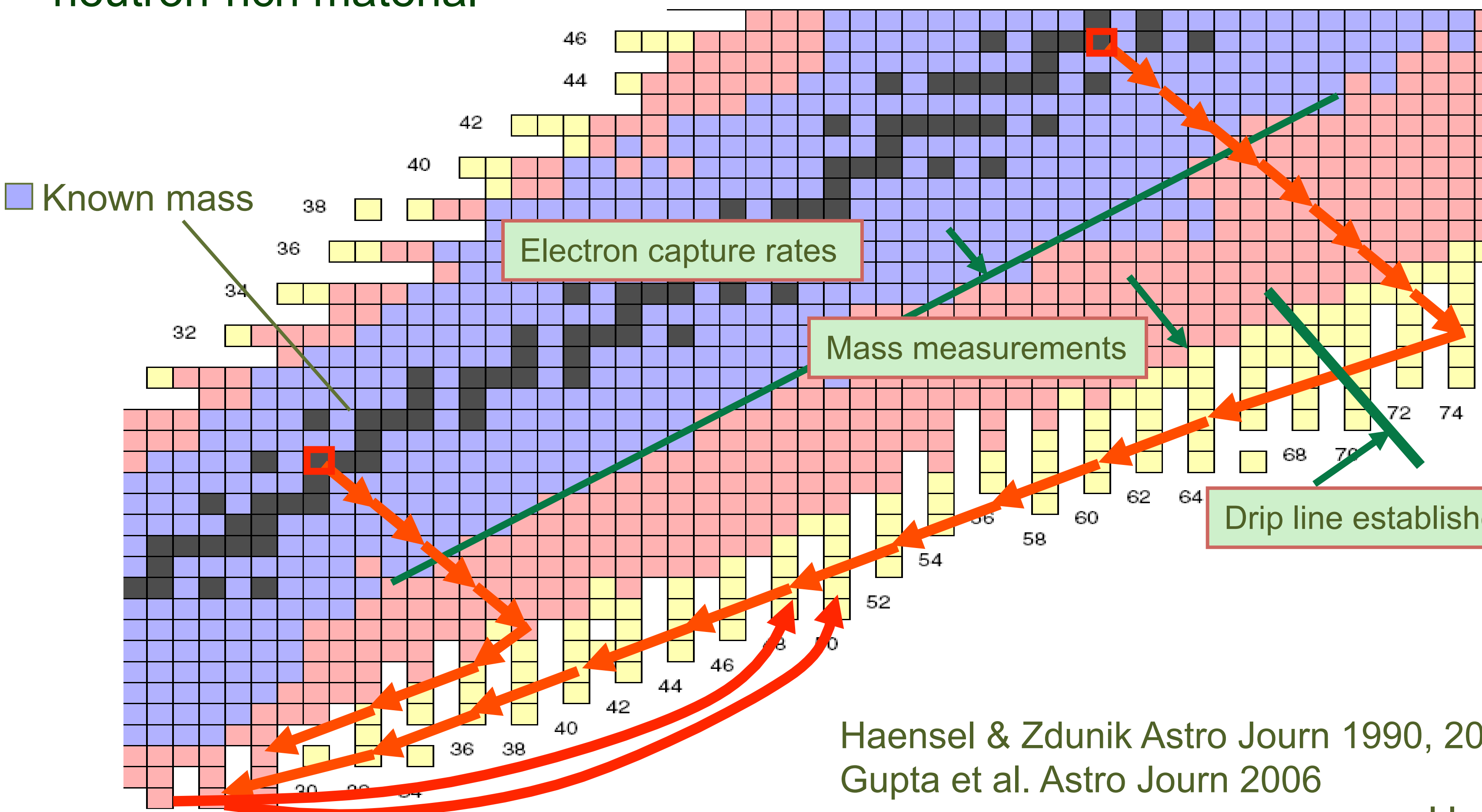
most reaction rates up to ~Sr can be directly measured

All reaction rates up to ~Ti can be directly measured

H. Schatz

FRIB Reach For Crust Processes

- Interesting set of reactions leading to proton-rich material converted to neutron-rich material



Haensel & Zdunik Astro Journ 1990, 2003, 2008
Gupta et al. Astro Journ 2006

H. Schatz