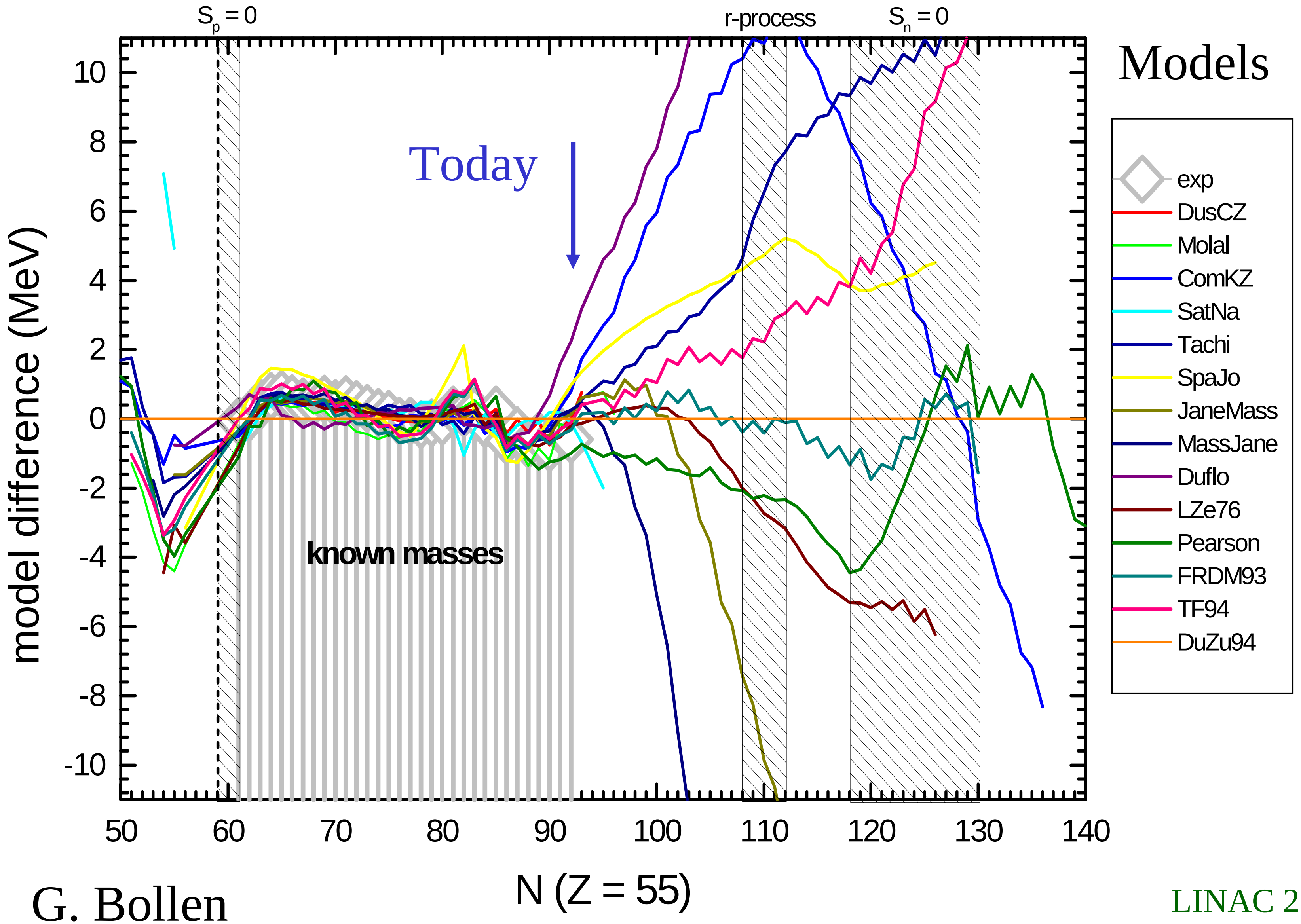
The Science of RIA

Brad Sherrill

Why build a high-power, heavy-ion LINAC?

- Introduction
- The intellectual challenges addressed by RIA (Nuclei, Chemical History of the Universe, Fundamental Symmetries)
- Production of rare isotopes – options and considerations
- What does SRF technology and the RIA concept make possible?
- Summary

We don’t know nuclei that well – Binding Energies

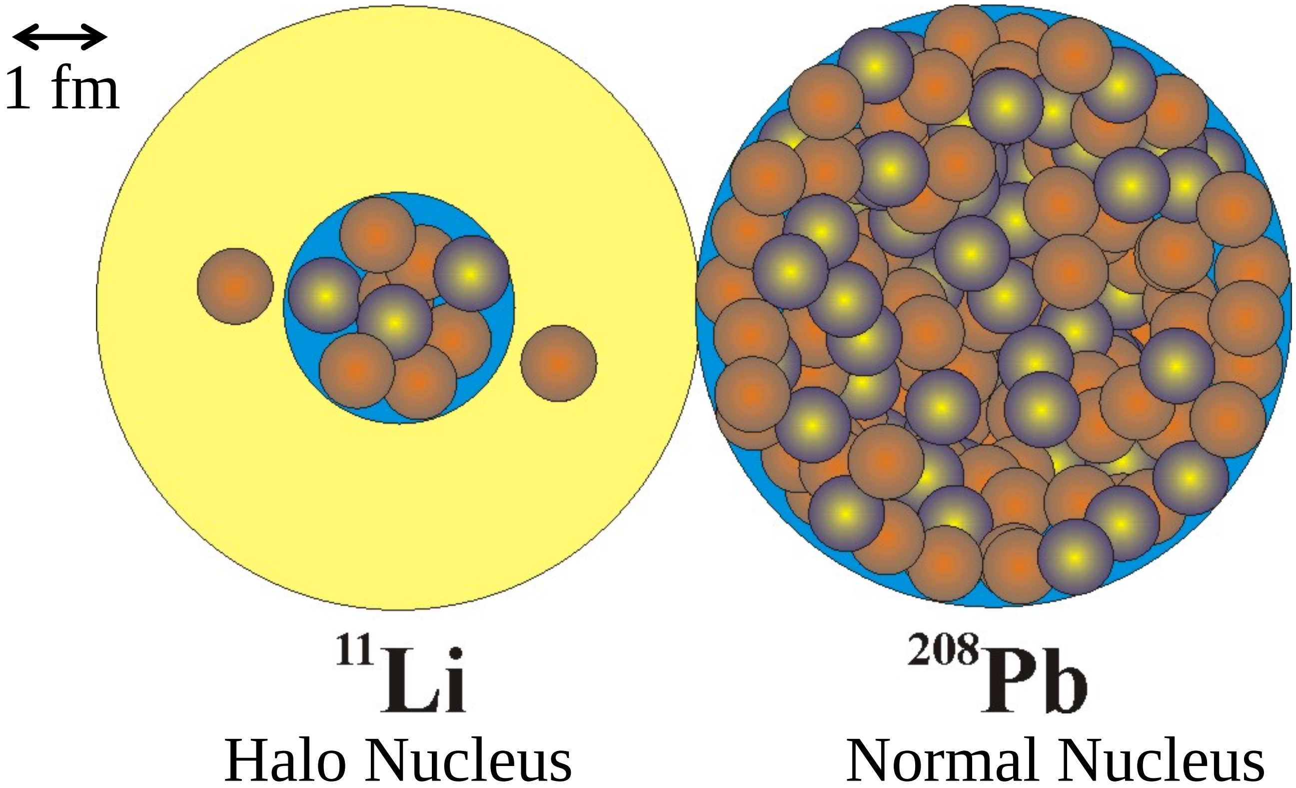


G. Bollen

LINAC 2004

An Example of a Nuclear Halo

A scaled cartoon



Two effects : QM penetration (halo) and a difference in proton and neutron Fermi levels (skins)

NRC Report: Connecting Quarks to the Cosmos

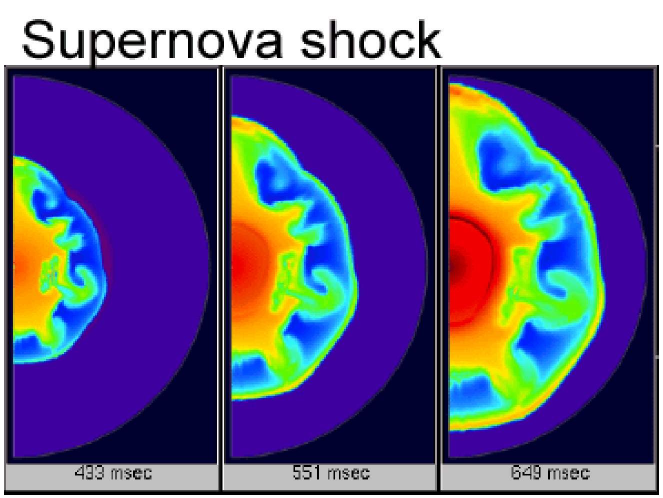
Eleven Science Questions for the New Century (2003) – National Academy Study, *M. Turner Chair*

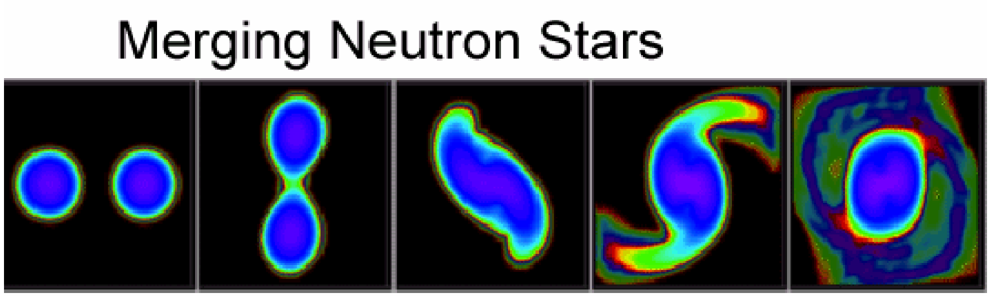
- What is dark matter?
- What is the nature of the dark energy?
- How did the Universe begin?
- Did Einstein have the last word on gravity?
- What are the masses of the neutrinos and how have they shaped the evolution of the universe?
- How do cosmic accelerators work and what are they accelerating?
- Are protons unstable?
- Are there new states of matter at exceedingly high density and temperature?
- Are there additional space-time dimensions?
- ✓ How were the heavy elements from iron to uranium made?
- Is a new theory of matter and light needed at the highest energies?

NEW: US Interagency Task Force stated that Underground Lab, RIA, RHIC II are needed to meet these goals. http://www.ostp.gov/

Rapid Neutron Capture Process (r-process)

How were the heavy elements from iron to uranium made?
Two possibilities (there are others):



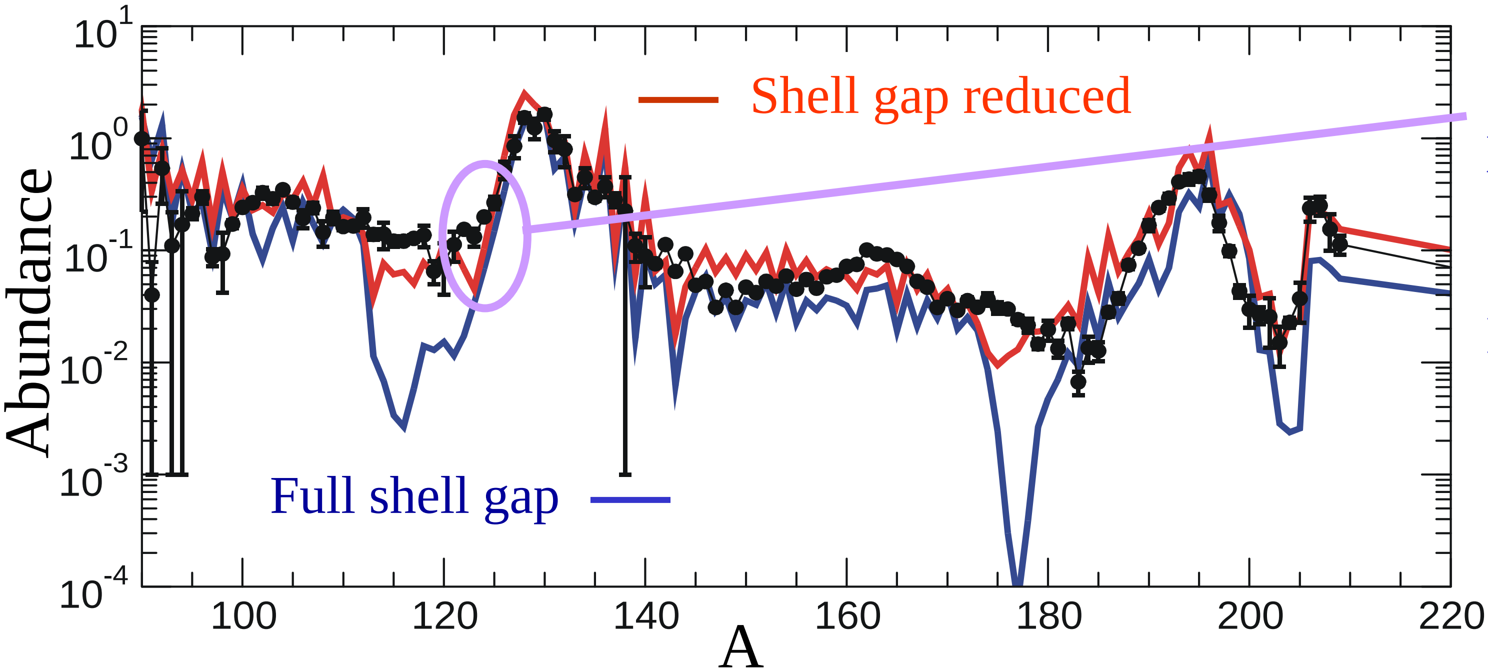


Woosley …

Thieleman …

Importance of Nuclear Physics in the r-process

In r-process model calculations nuclear shell structure is important.



A ν post-processing signature ? Qian, Haxton

Dobaczewski, Nazarewicz, Kratz, …

Question: Is this difference due to shell quenching for neutron-rich nuclei, or a problem with astrophysical model?

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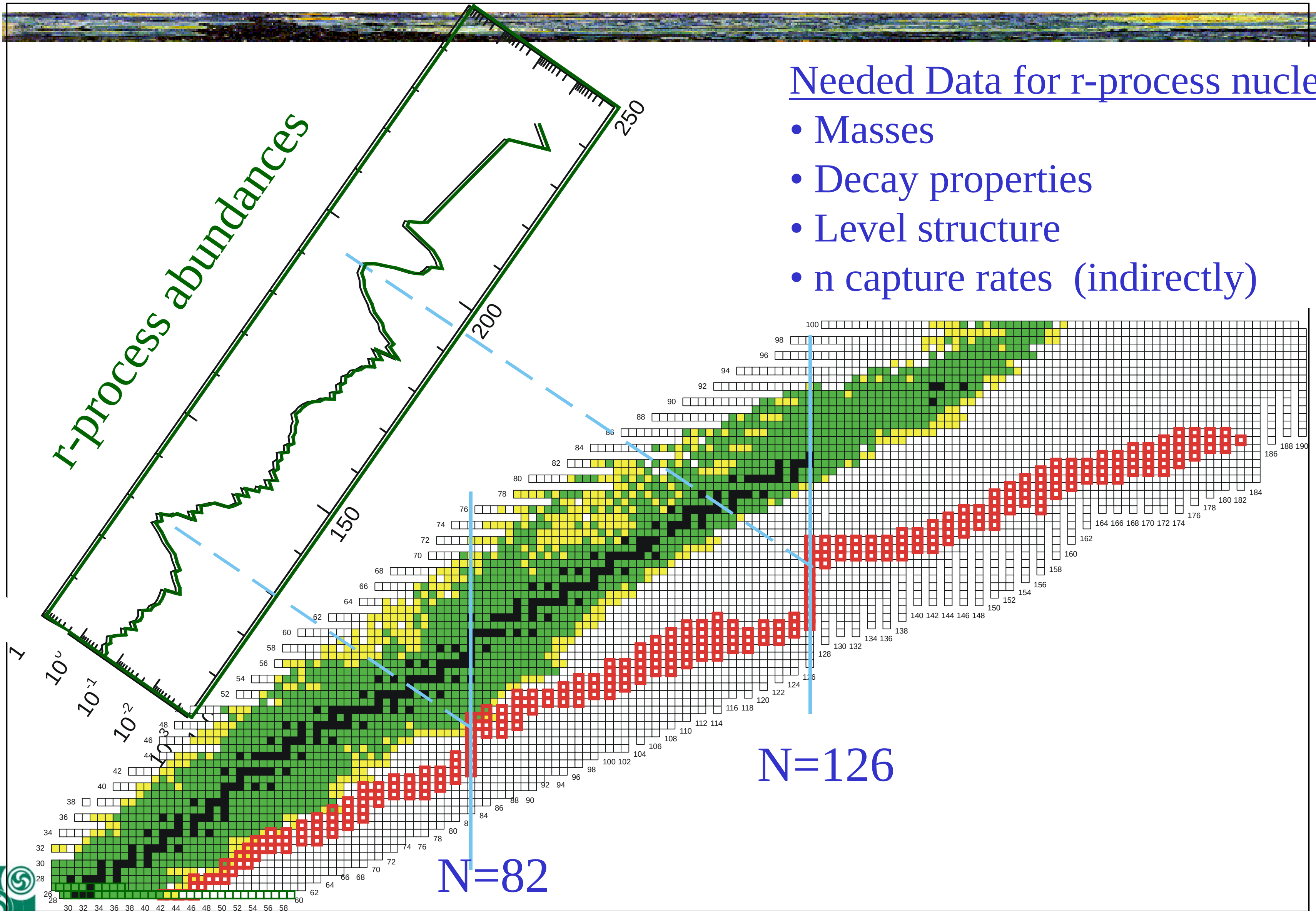
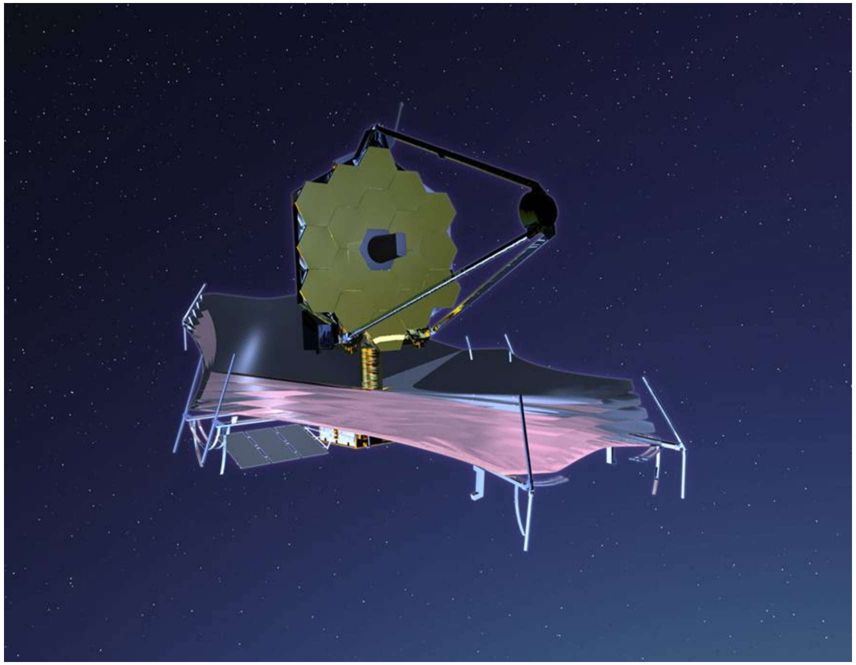
Possibilities to study r-process nuclei



Needed Data for r-process nuclei:

- Masses
- Decay properties
- Level structure
- n capture rates (indirectly)

Summary of the scientific justification for JWST



James Webb Space Telescope

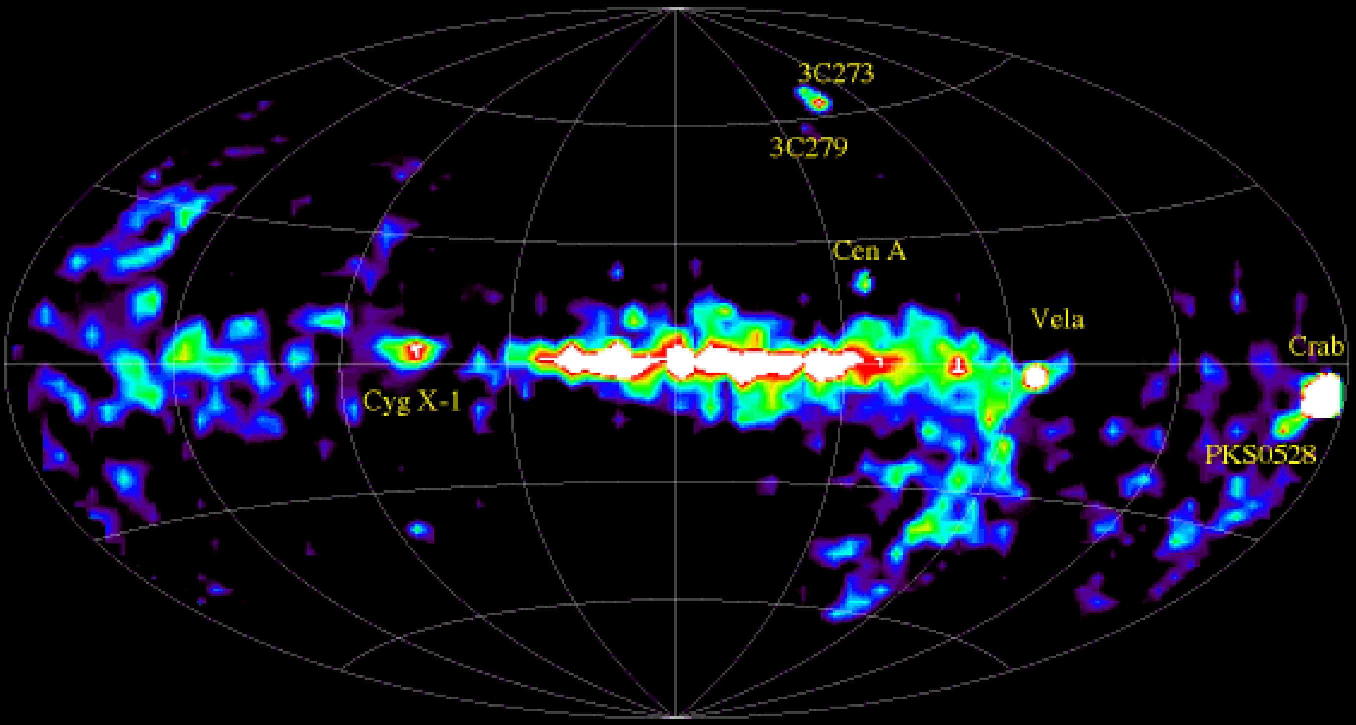
NASA/EESC/CSA

- What is the shape of the Universe?
- How do galaxies evolve?
- How do stars and planetary systems form and interact?
- How did the Universe build up it present elemental/chemical composition?
- What is dark matter?

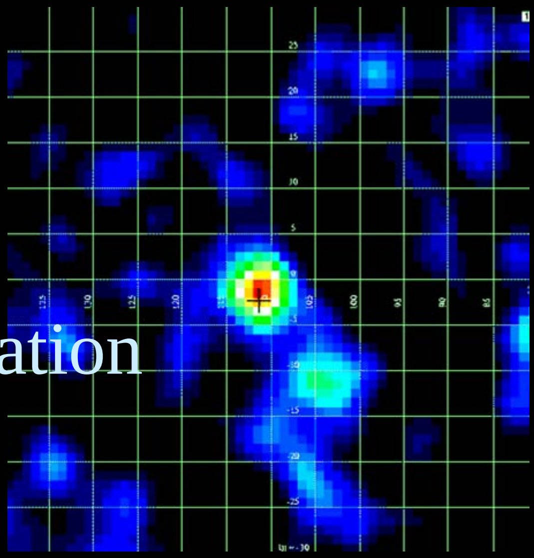
http://ngst.gsfc.nasa.gov/science/ScienceGoals.htm

The Active Universe- Gamma Ray Astronomy

M.Wiescher



(^{26}Al Half life: 700,0000 years)



^{44}Ti in Supernova Cas-A Location
1.157 MeV γ-radiation
(Half life: 60 years)

Observation of ^{26}Al Demonstrates Nucleosynthesis

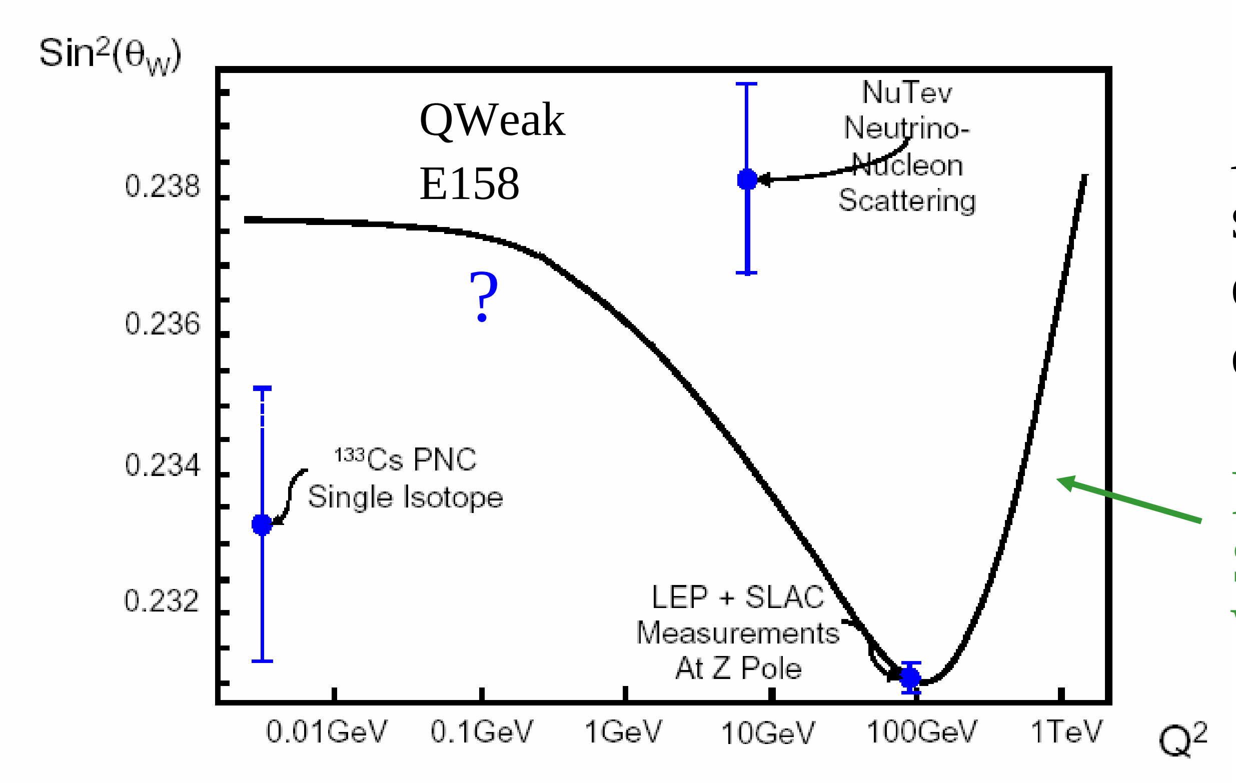
N. Prantzos, Astonomy & Astro **420** (2004)

The observation indicates 2 solar masses of ^{26}Al produced per My (1.5×10^{42} atoms/s). How?

- Type II Supernovae
  - ^{60}Fe/^{26}Al ratio is a problem
  - measured by RHESSI to be 0.16 (predicted >0.4)
  - ^{59}Fe(n,γ) is critical but ^{59}Fe is radioactive
- Novae
- Wolf-Rayet Stars

Needed: Better observations and better nucleosynthesis calculations

Rare Isotopes and Fundamental Symmetries



G. Sprouce

An example of the so called running of fundamental constants.

Prediction of the Standard Electro-Weak Theory

Rare-isotope facilities provide a credible path to necessary improvements on parity non-conservation in atoms.

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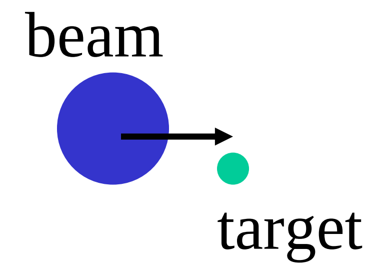
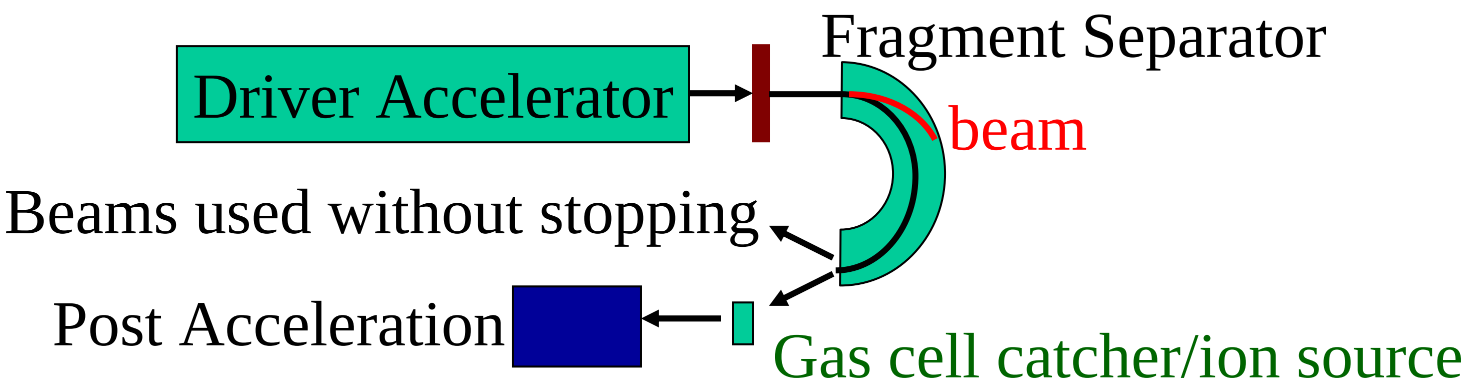
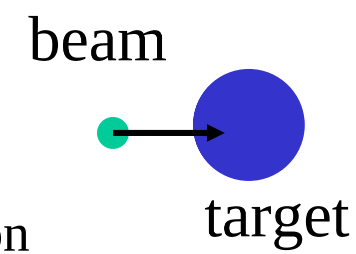
Radioactive Beam Production Mechanisms

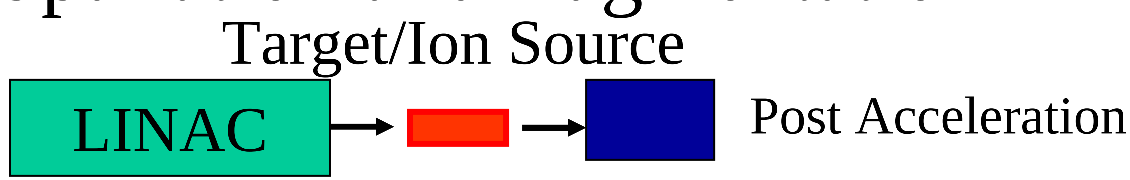
- Projectile Fragmentation/Fission



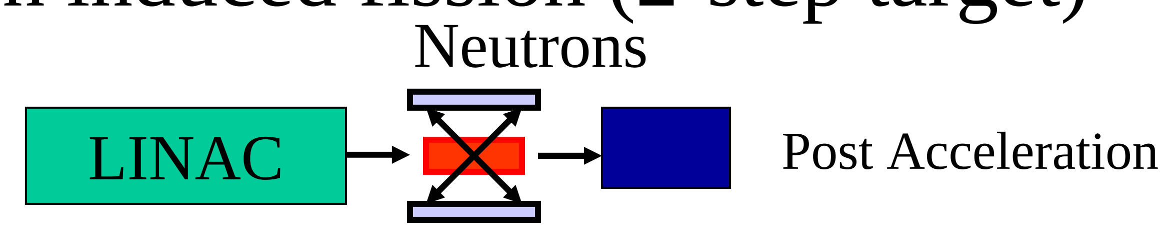


- Target Spallation and fragmentation





- Neutron induced fission (2-step target)



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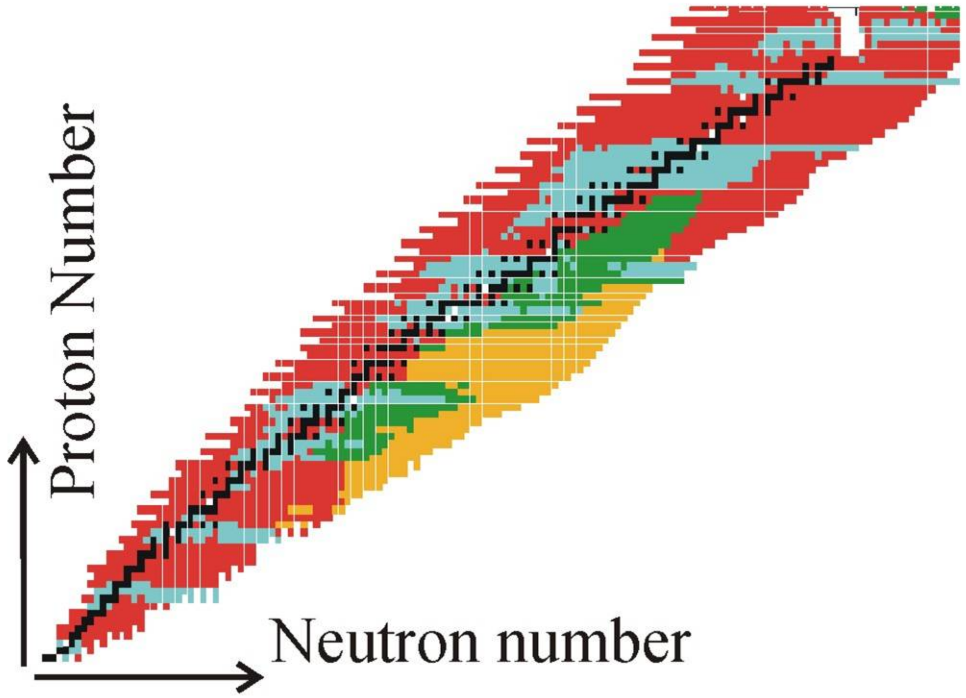
Optimum Mechanism for each Isotope

Optimum production method for low-energy beams

- Standard ISOL technique
- Two-step fission
- In-flight fission + gas cell
- Fragmentation + gas cell



Most facilities use only one production method.

Requirements

- Production cross sections for the interesting nuclei at the limits of stability are low (fb), thus as high as possible primary beam intensities are needed. Uranium Luminosity = 1 $pb^{-1}s^{-1}$
- There is no overall optimum production mechanism – we would like have access to all.
- Secondary beams from 60 kV to 1 GeV/u are needed to extract the science.

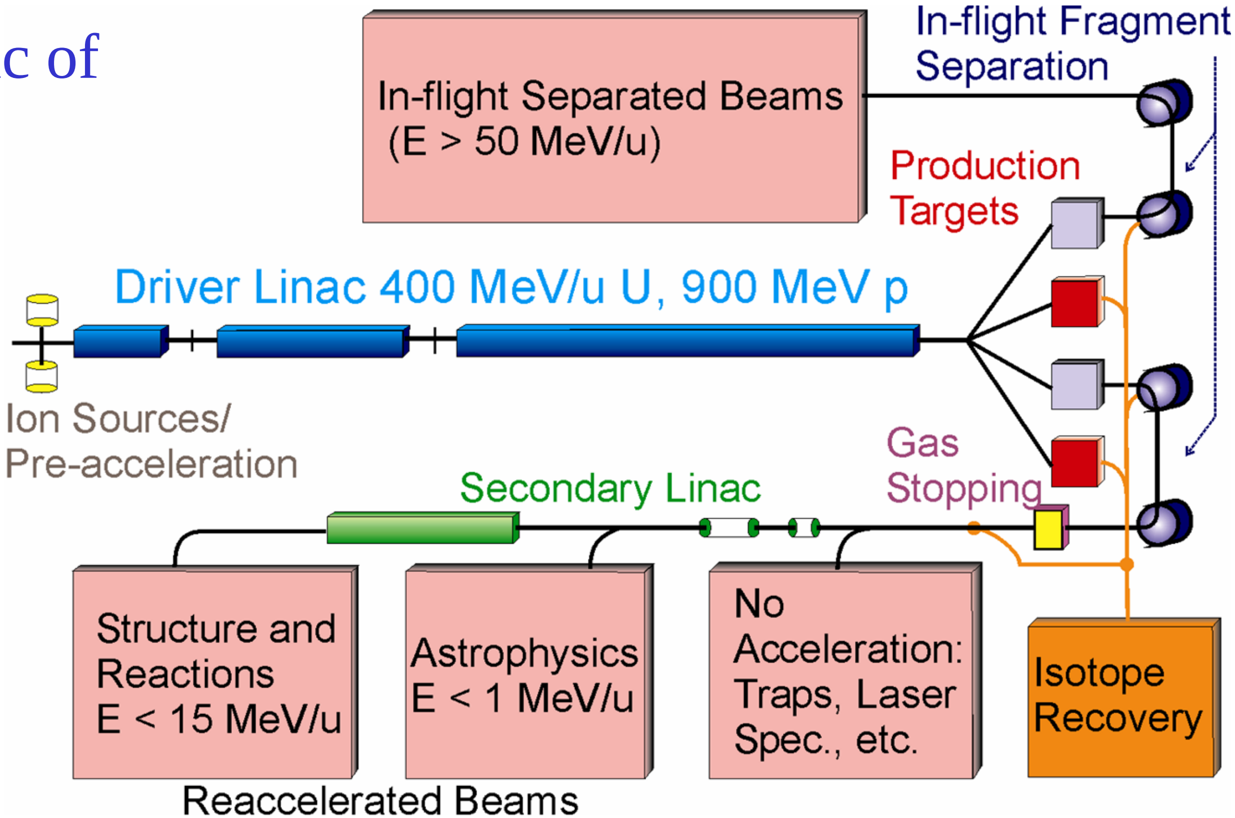
Solution:

SRF technology – Primary, high intensity, linear accelerator and efficient secondary accelerator

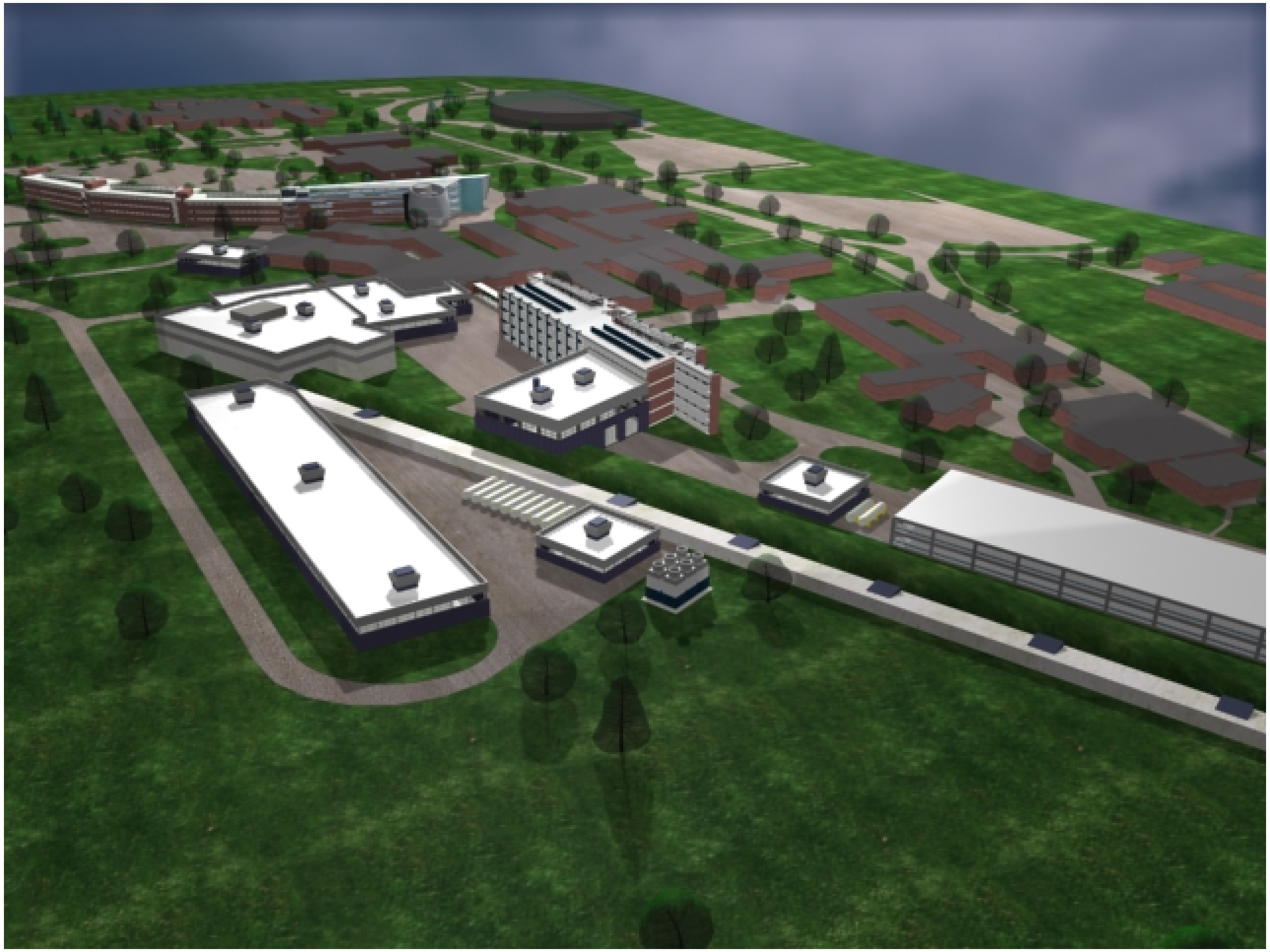
Rare Isotope Accelerator - RIA

- **Efficient acceleration** of elements up to uranium at 2.4×10^{13}/s and E > 400 MeV/nucleon. Beam power of 400 kW.
- Possibility to **optimize the production method** for a given nuclide.
- Secondary beams at energies from 60 kV to 400 MeV/u .

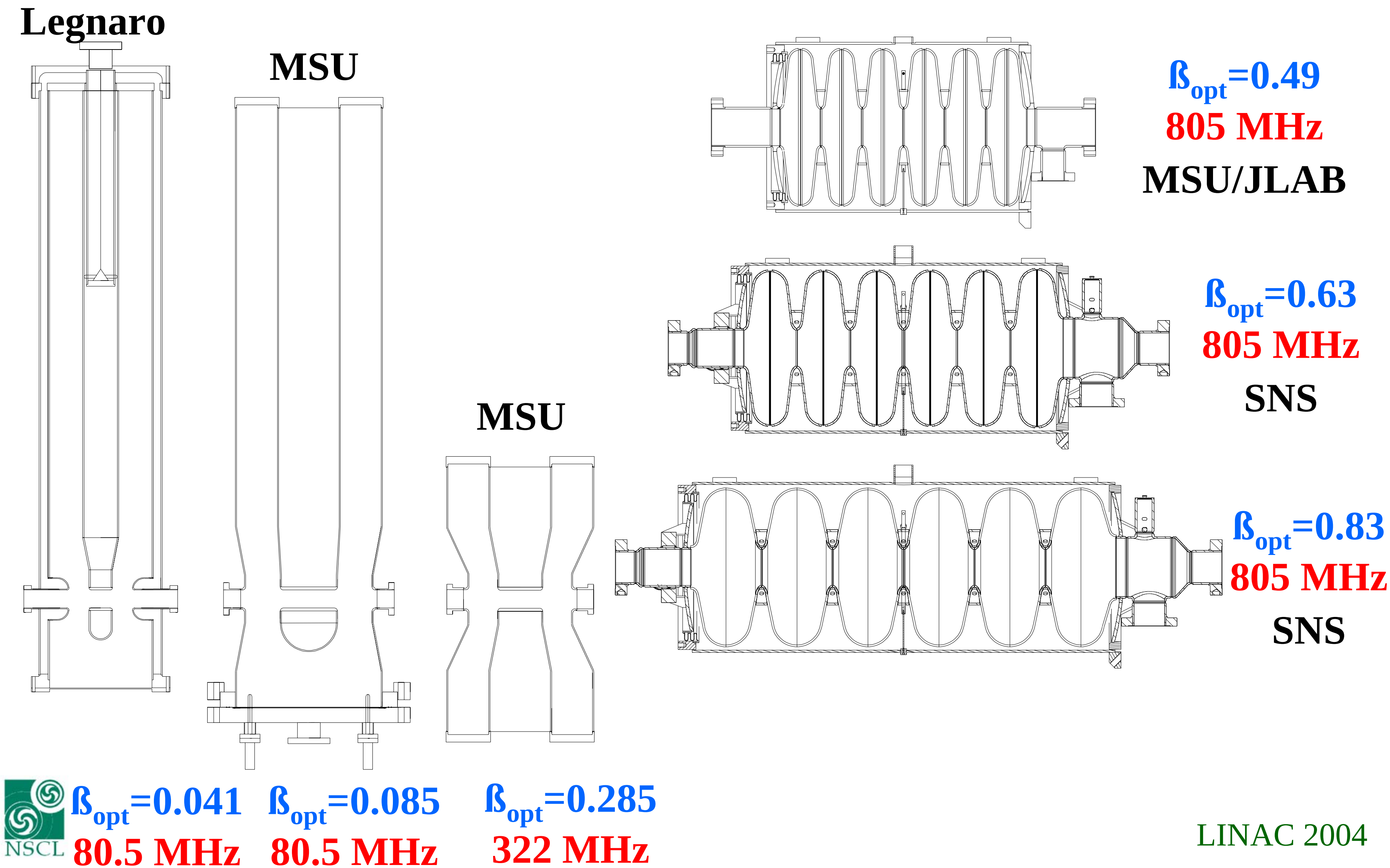
Schematic of the RIA Concept



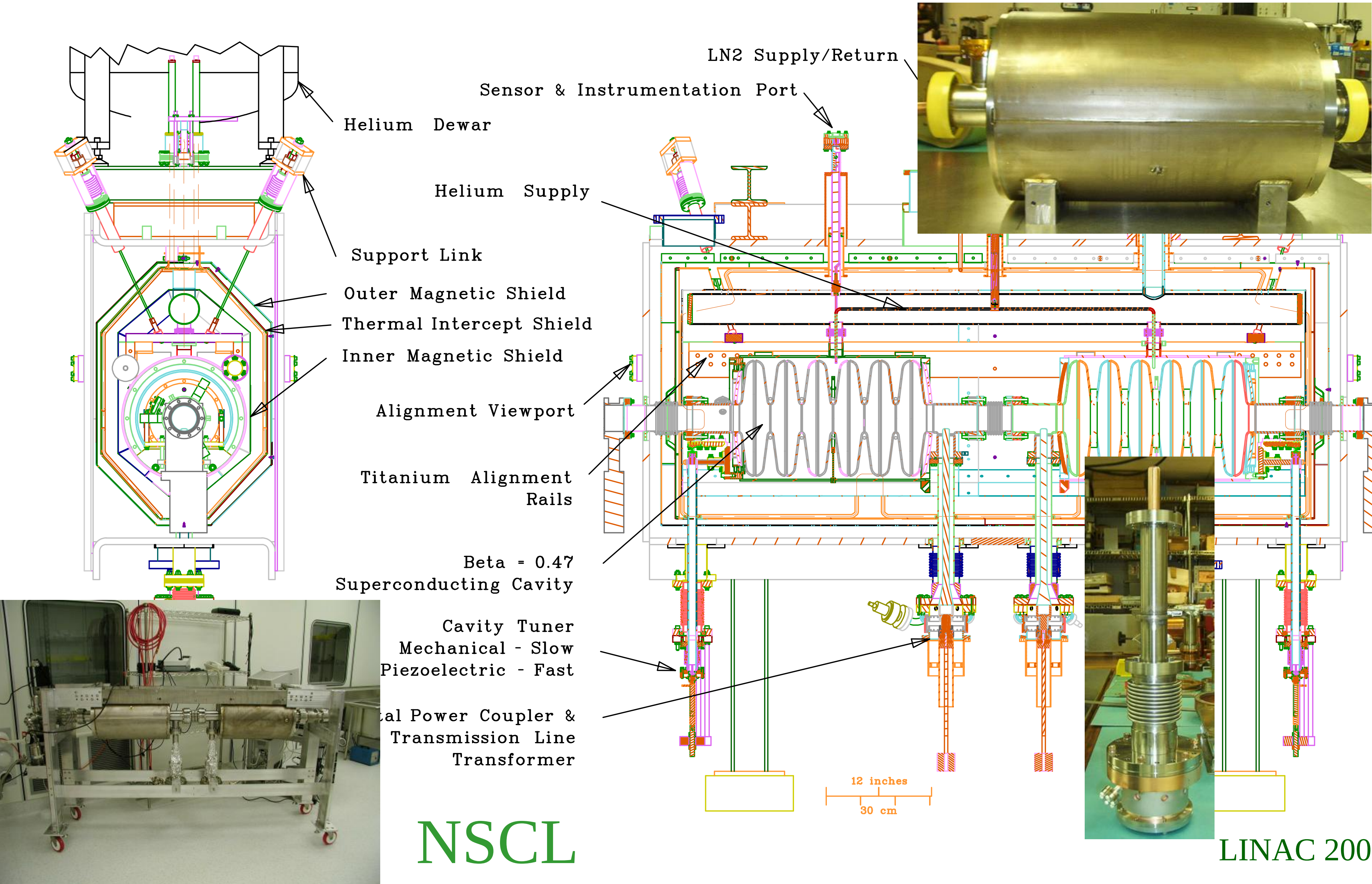
Artist's Conception of RIA at ANL



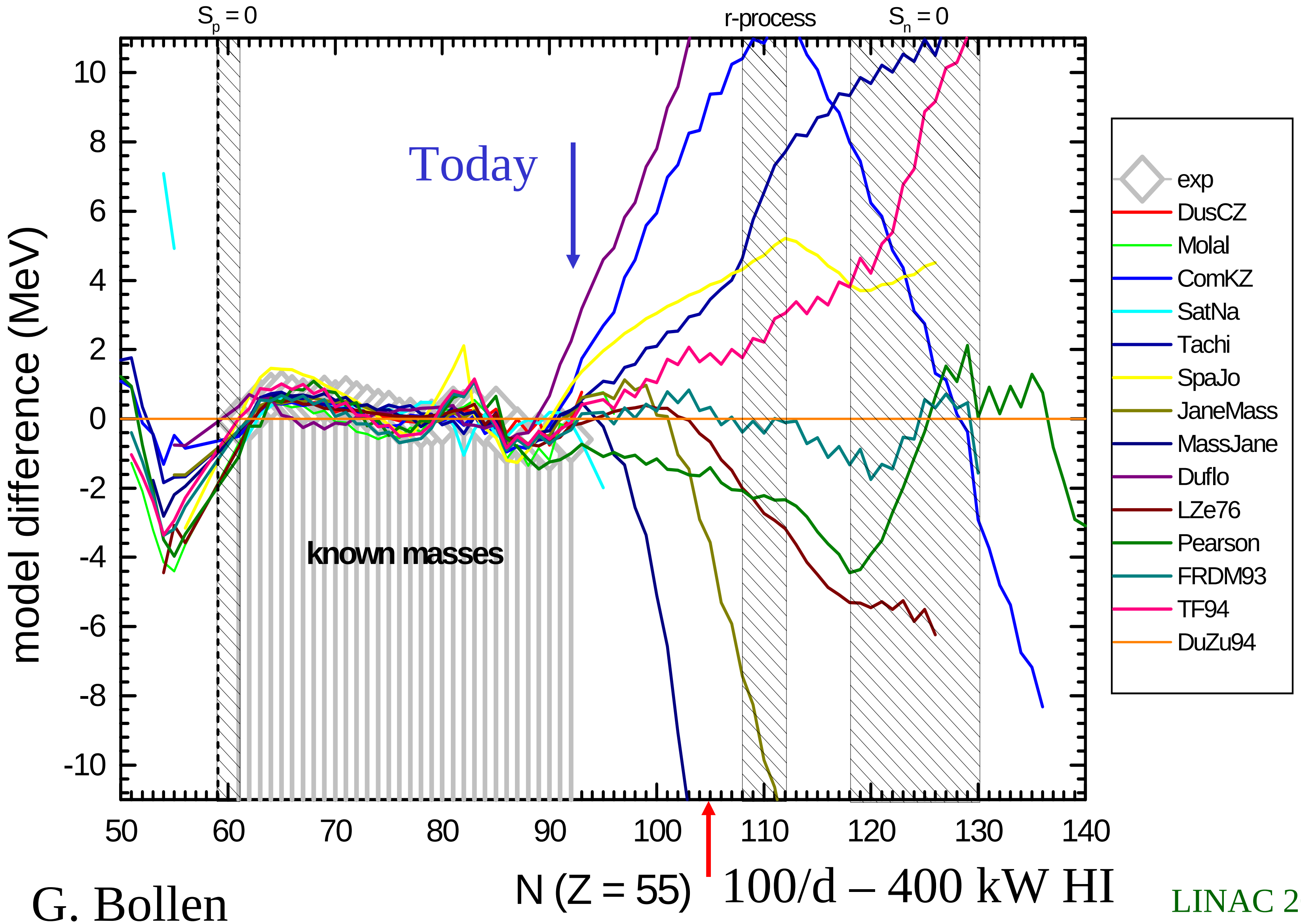
RIA SRF Cavities – All Tested by 2003



β=0.49 Cryomodule Prototype (THP70)

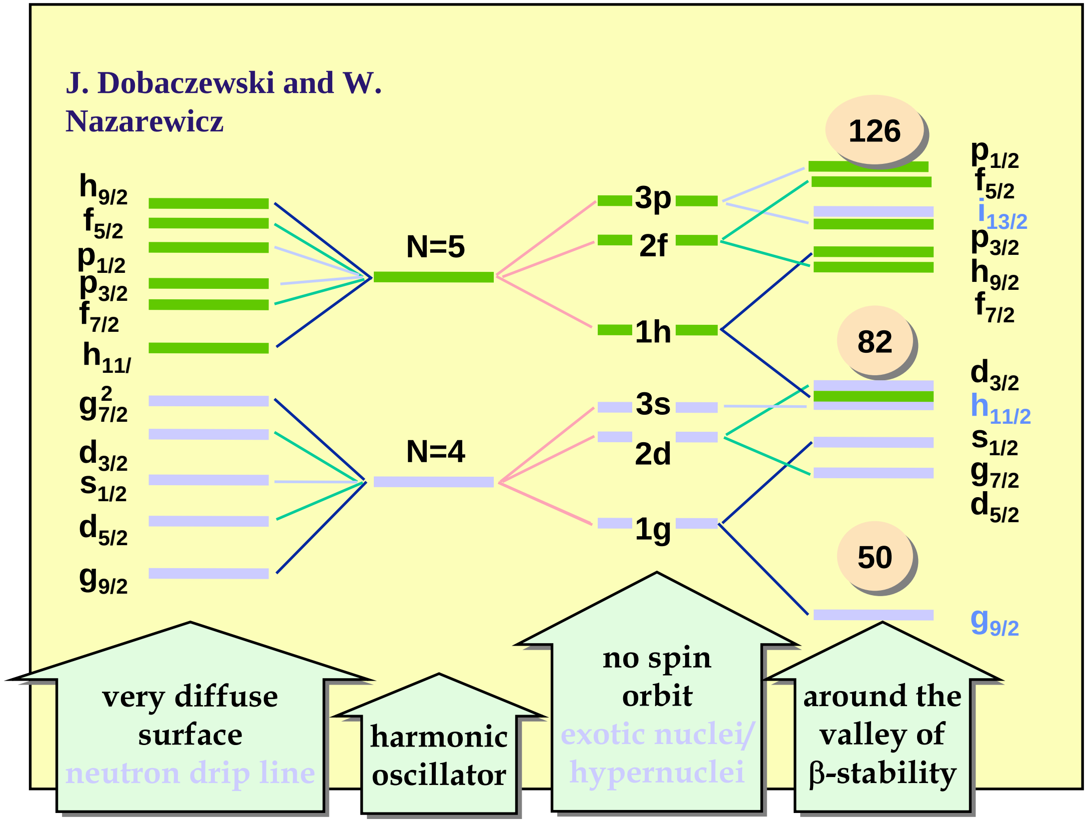


Tests of Nuclear Models – Binding Energies



G. Bollen

Changes in nuclear shell structure for n-rich nuclei



Phil. Trans. R. Soc. Lond. A 356, 2007 (1998)

The nuclear mean field potential is dependent on the number and type of nucleons present in the nucleus.

Shell structure for very asymmetric nuclear matter will be different than for normal $N=Z$ nuclear material.

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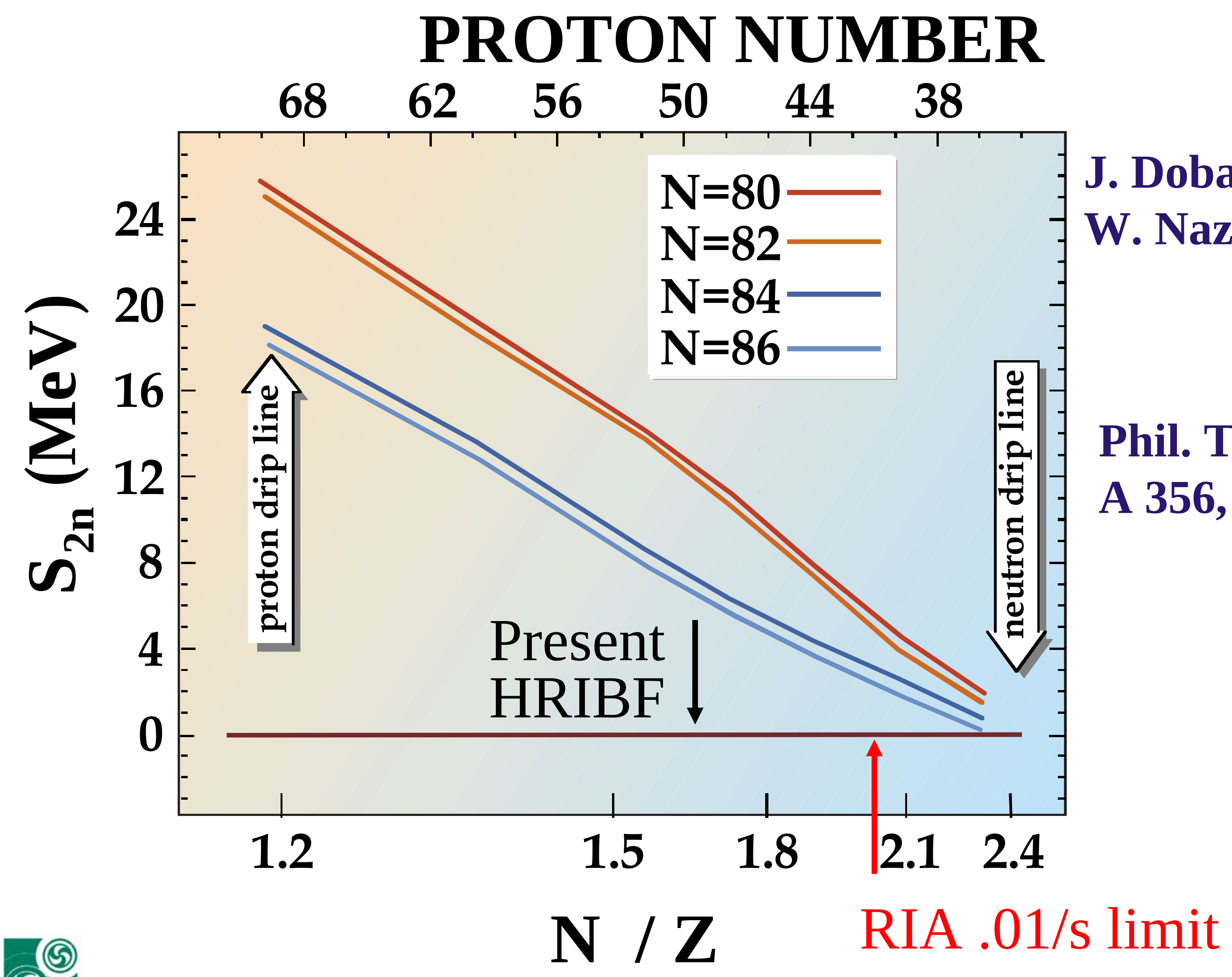
Weakening of Shell Structure in Exotic Nuclei

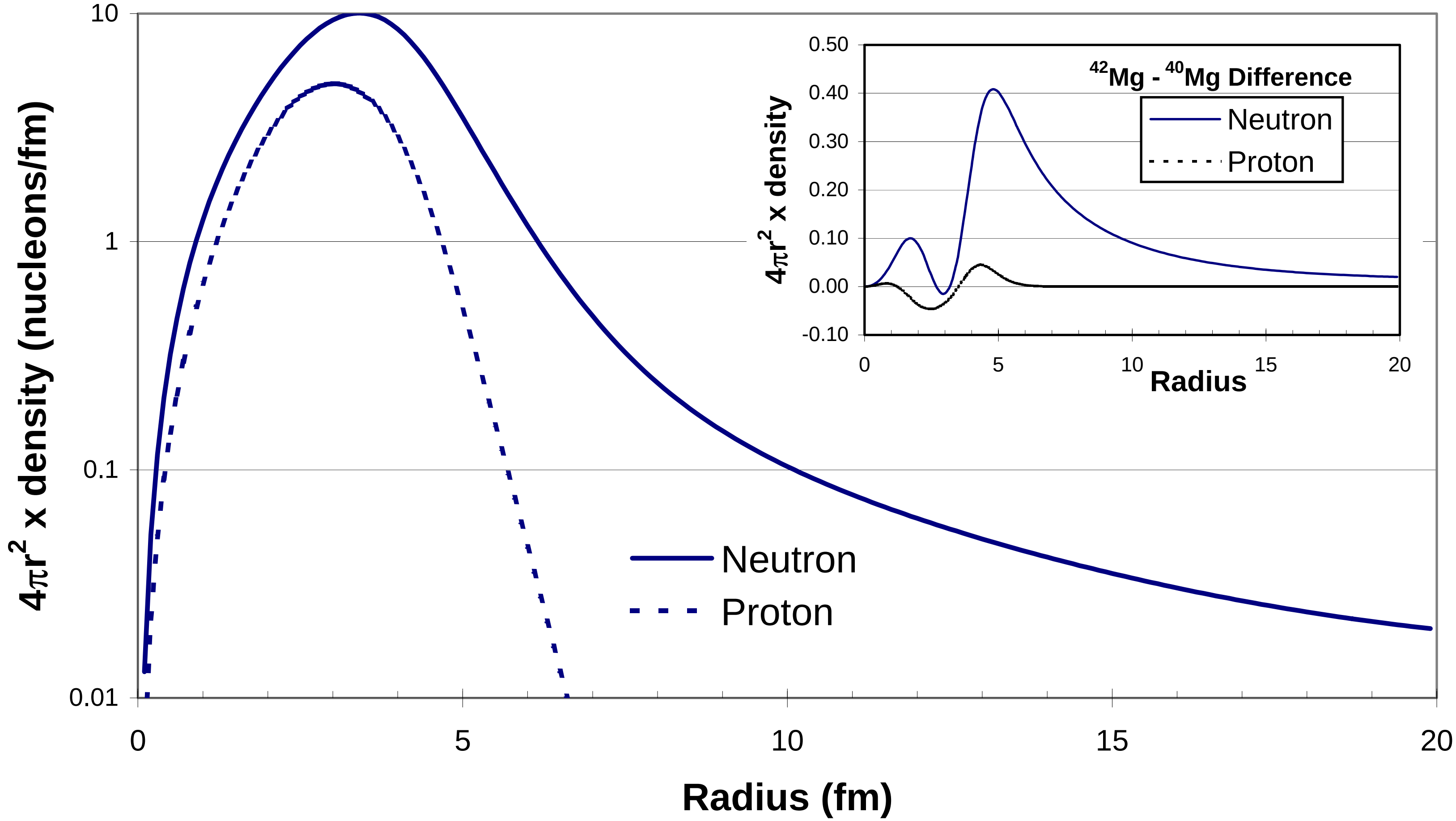


J. Dobaczewski and W. Nazarewicz

Phil. Trans. R. Soc. Lond. A 356, 2007 (1998)

Extreme Halos Reachable at RIA

Example: ^{42}Mg   Theory BA Brown

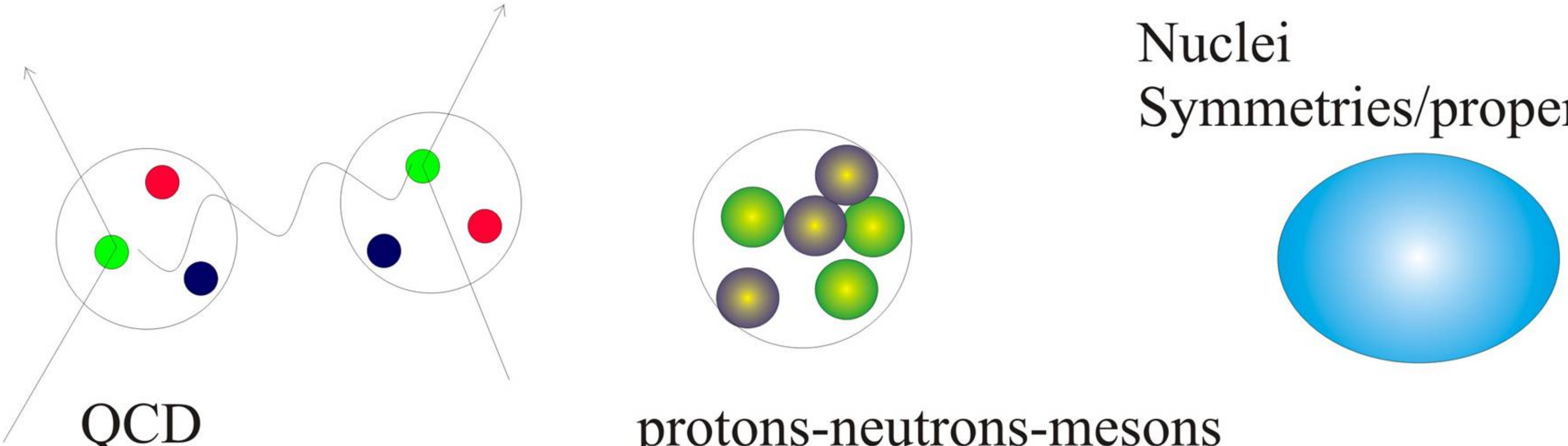


<u>Science:</u> Pairing in low-density material - Interaction with continuum states - Efimov States - Reactions

Nuclear Science needs to study n/p degree of freedom

Approach

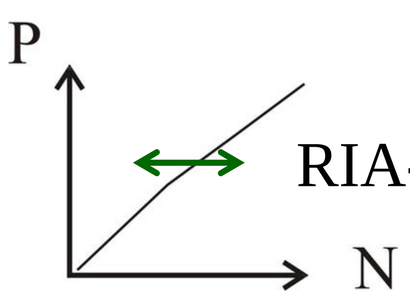
Nuclei
Symmetries/properties



QCD
Quarks-Gluons

protons-neutrons-mesons
Effective Theory

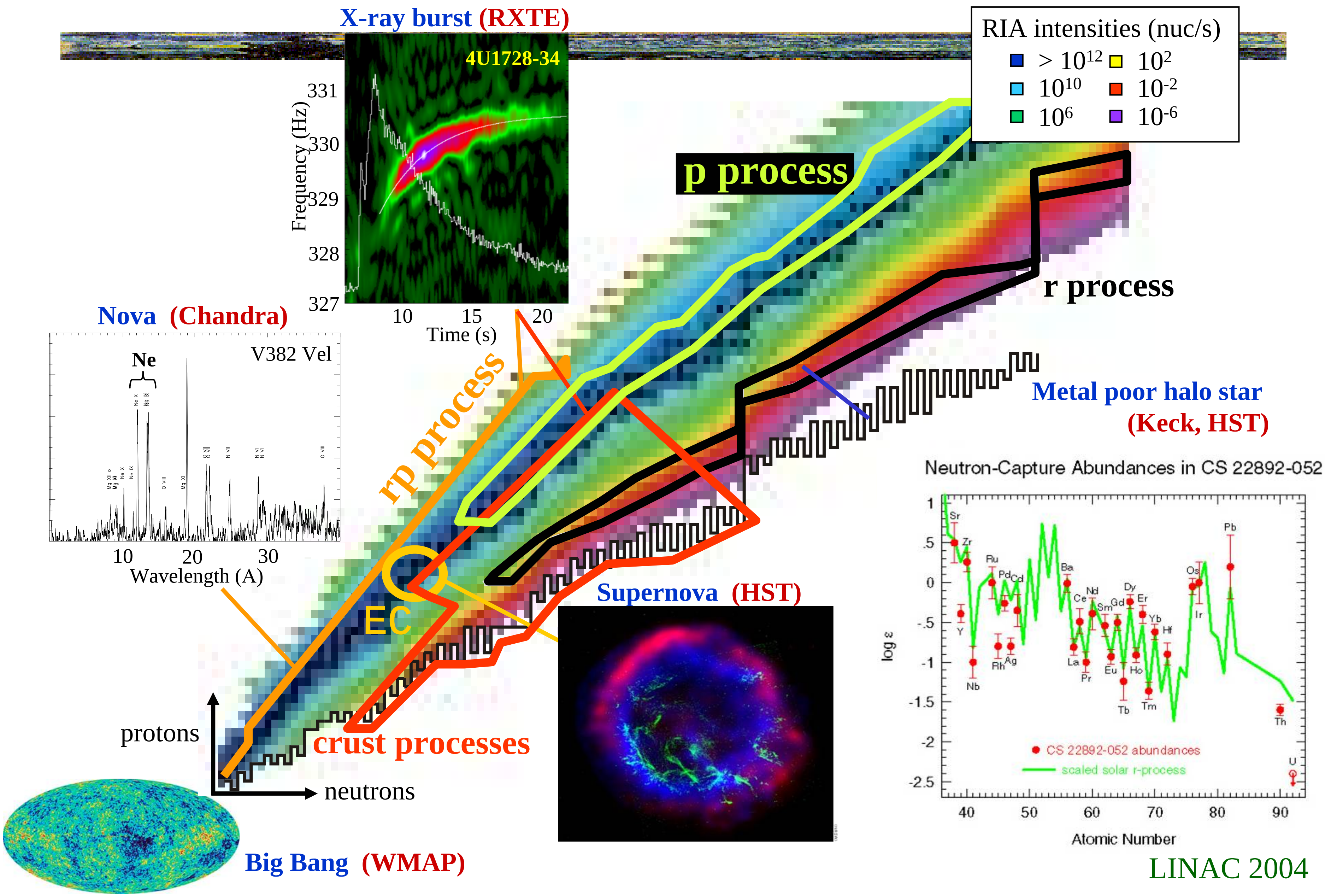
Very hard



RIA-Fair-ISAC

Necessary to know what effective interactions operate in nuclei

Nuclear Microphysics of the Universe



What is Unique about the RIA linac?

- Possibility to optimize the production method
- Multiple charge state acceleration
  - 400kW beam power
  - highest efficiency for rare stable isotope acceleration, e.g., ^{48}Ca, ^{124}Sn (this can yield gains of 100 to 1000)
- Intense Uranium Beams at 400 MeV/u and 400 kW
- Liquid Li production target + fragment separator + gas catcher system
  - Ability to handle 400 kW beams
  - Precision reaccelerated beams without chemical or half-life dependence
  - Same setup for all elements with short development times
- 2.1 GeV ^{3}He (1 GeV protons) at 400 kW intensity for ISOL targets

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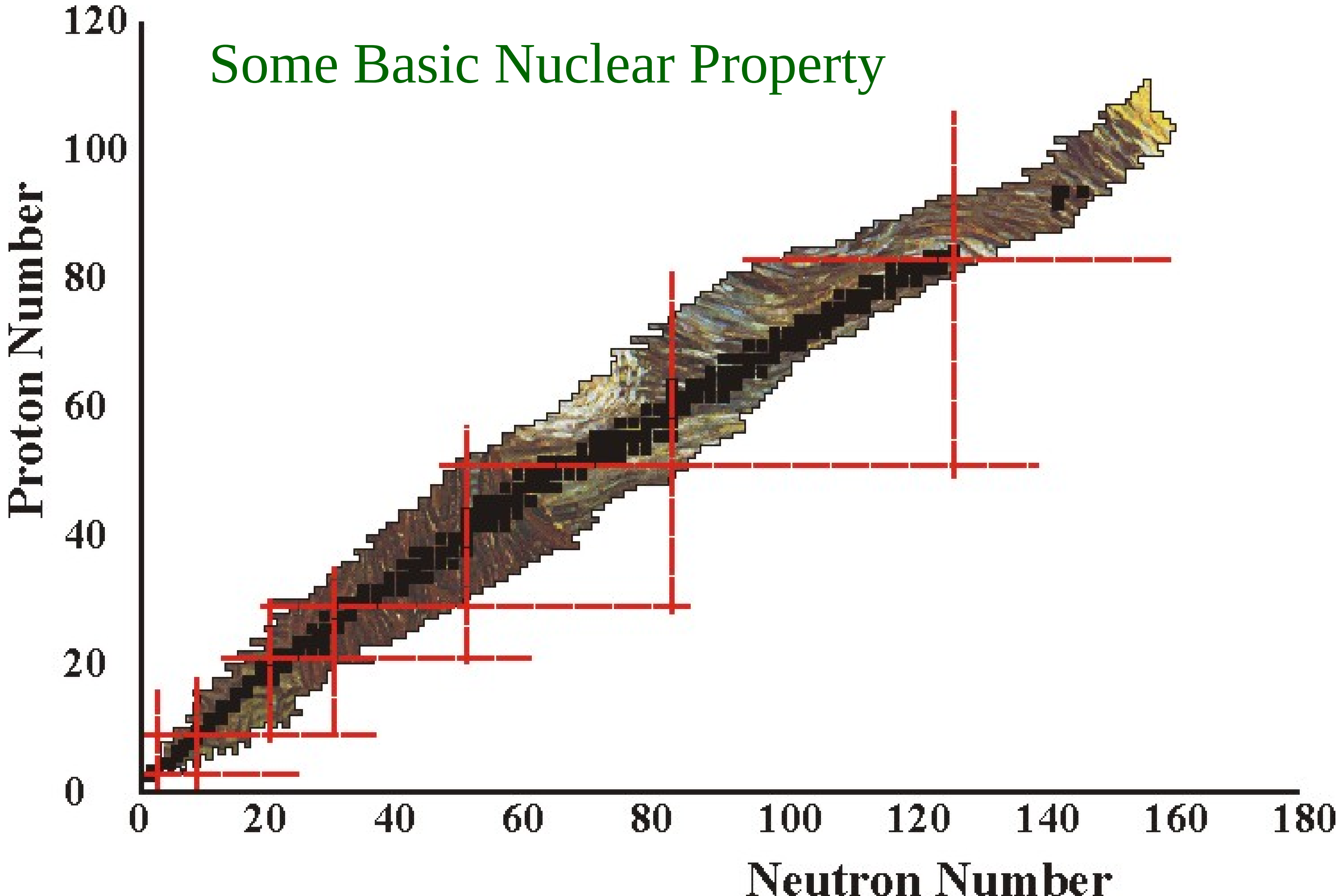
Summary

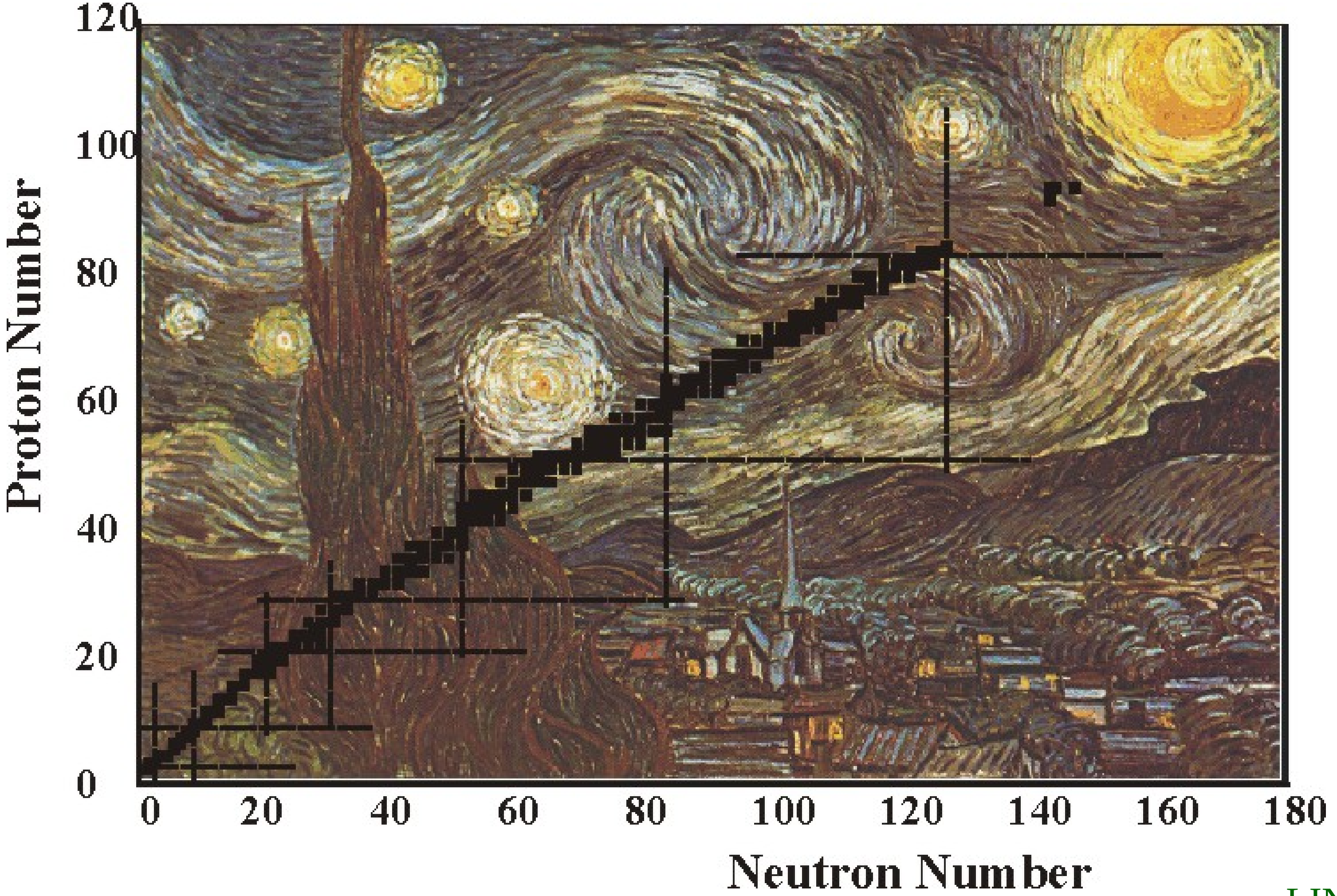
- The science of rare isotope facilities:
  - Nature of nucleonic matter – nuclei with special features (e.g. ^{78}Ni) and production of nuclei with sufficiently large N/Z ratios (1.5 now to 2.0)
  - Chemical evolution of the Universe (origin of the elements) – produce nuclei relevant to the various astrophysical processes
  - Test of symmetries – requires the production of Radon and Francium over a range of isotopes
- There a number of approaches. The two main categories are in-flight and ISOL
- RIA uses a superconducting LINAC to provide the most efficient acceleration of primary beams, access to all production mechanisms and a wide range of secondary beam energies.

At the moment we are limited in our view of the atomic nucleus

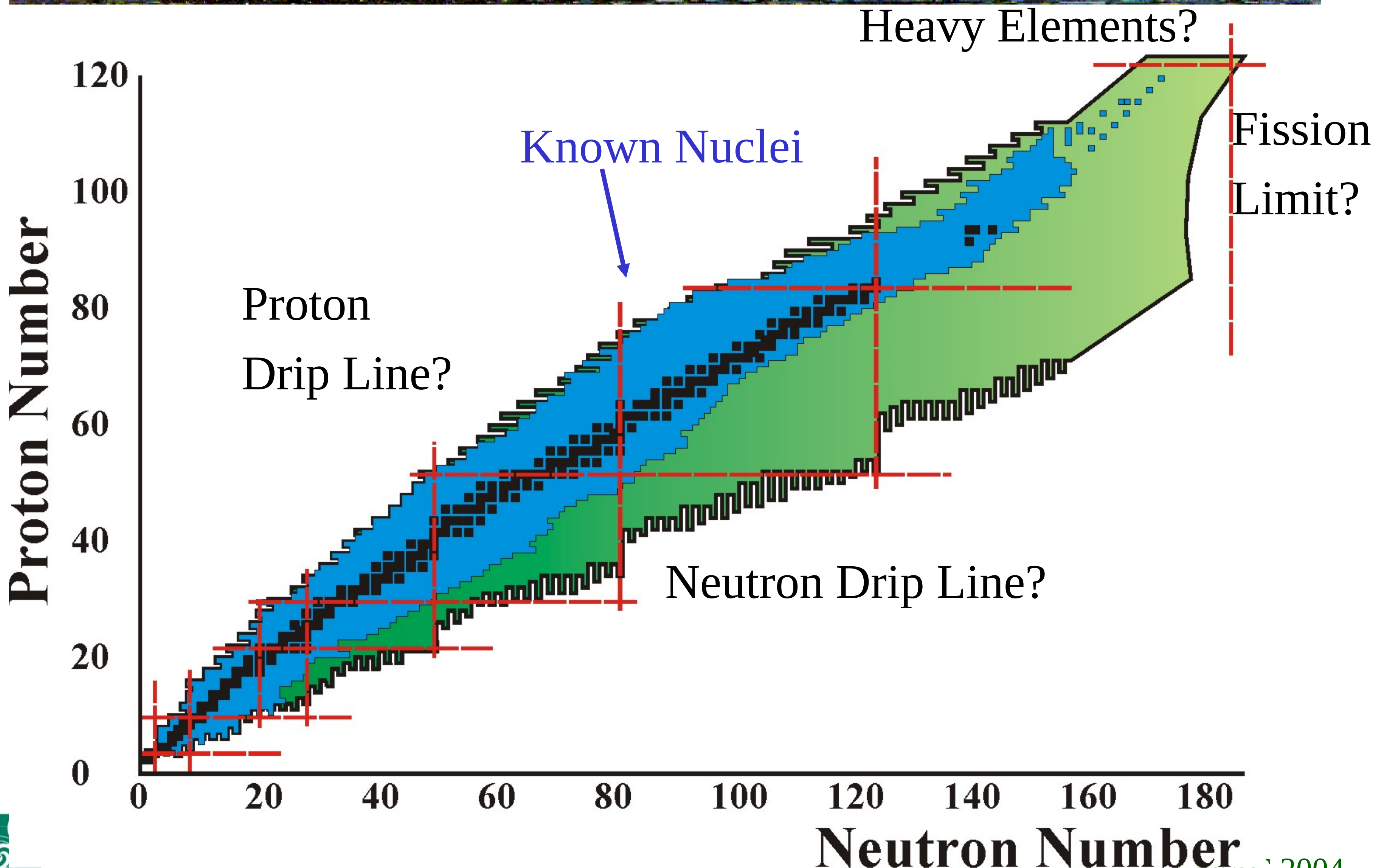


RIA Will Greatly Expand Our Horizons

Thank you LINAC technology.



The Chart of the Nuclides



Advantages/Disadvantages of ISOL/In-Flight

In-flight:

GSI
RIKEN
NSCL
GANIL
RIA

- Provides beams with energy near that of the primary beam
  - For experiments that use high energy reaction mechanisms
  - Thick secondary targets, kinematic focusing
  - Individual ions can be identified
- Efficient, Fast (100 ns), chemically independent separation
- Capture in storage rings
- Production target is relatively simple

ISOL:

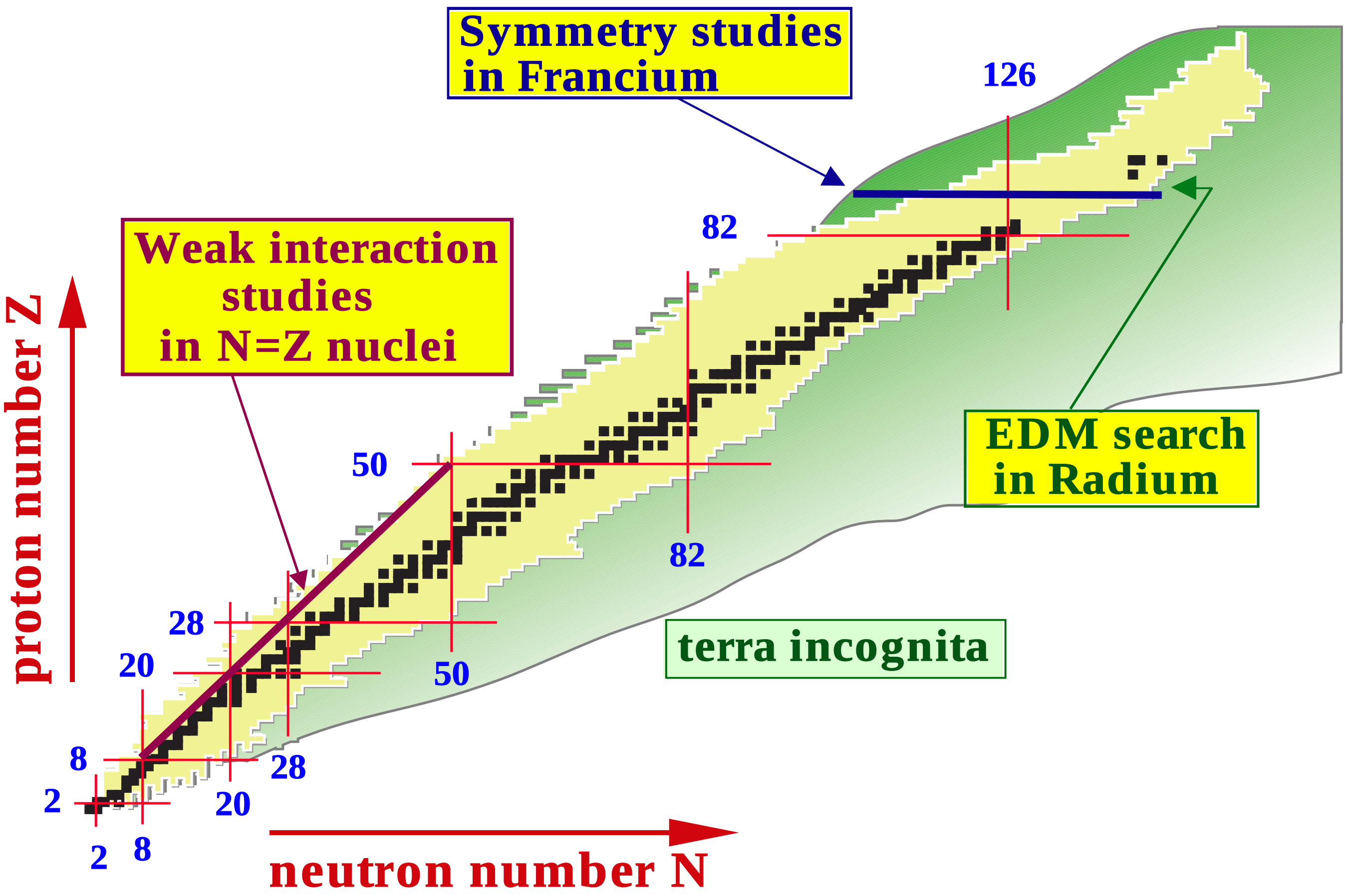
HRIBF
ISAC
SPIRAL
ISOLDE
EURISOL
RIA

- Good Beam quality (π mm-mr vs. 10s π mm-mr transverse)
- Small beam energy spread for fusion studies
- Can use chemistry to limit the elements released
- 2-step targets provide a path to 400kW targets
- High beam intensity leads to 100x gain in secondary ions

Summary of the key science requirements

- Production of benchmark nuclei: traditional closed shell nuclei ^{100}Sn, ^{132}Sn, ^{78}Ni and new magic nuclei ^{60}Ca
- Nuclei with large neutron skins (most extreme changes in structure)
- Production of very weakly bound nuclei such as ^{42}Mg. Nuclei along the neutron drip line as heavy as possible.
- Nuclei along the r-process path. Particularly important are the N=126 closed shell nuclei.
- Sufficient quantities of N=Z nuclei below ^{100}Sn to study proton capture reactions (often this requires 10^{10} ions/s) – novae, X-ray burst, X-ray sources, …
- Radon and Francium isotopes at (10^{11}/s) over a wide range

Tests of the Standard Model



Specific nuclei offer new opportunities for precision tests of:

- CP and P violation
- Unitarity of CKM matrix
- Physics beyond VA
- $\sin^2\Theta_W$ at low q

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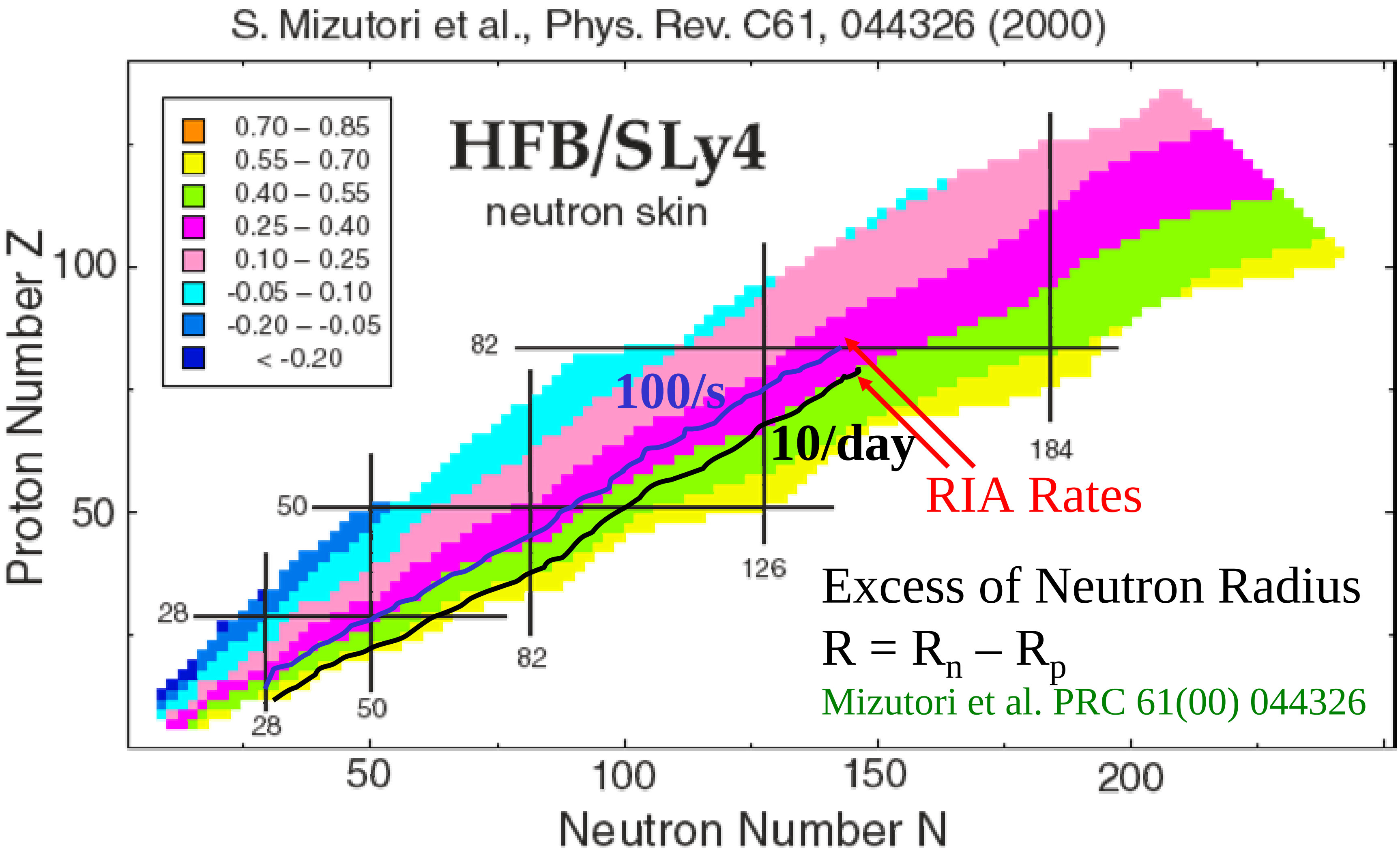
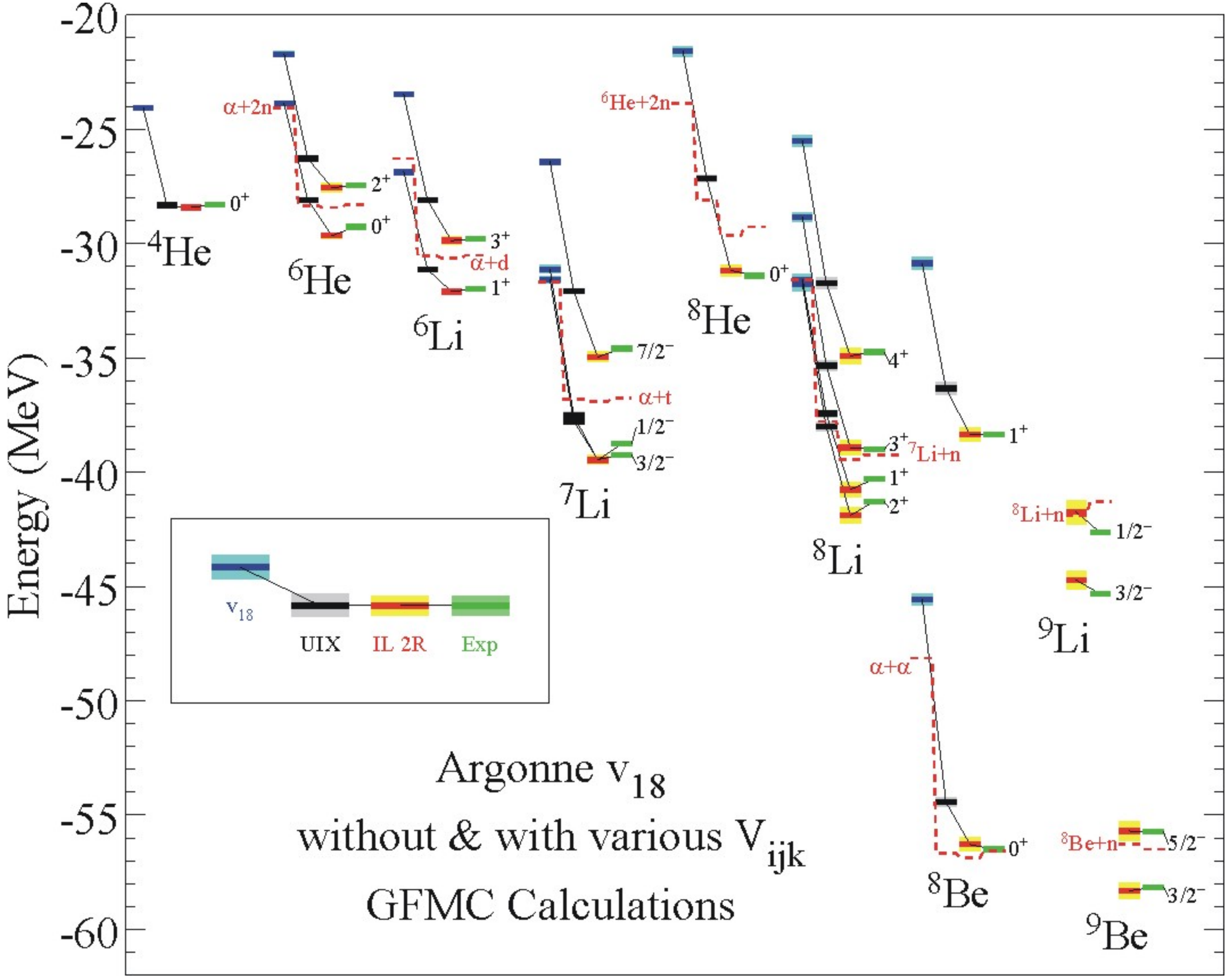
Availability of Neutron Skin Nuclei



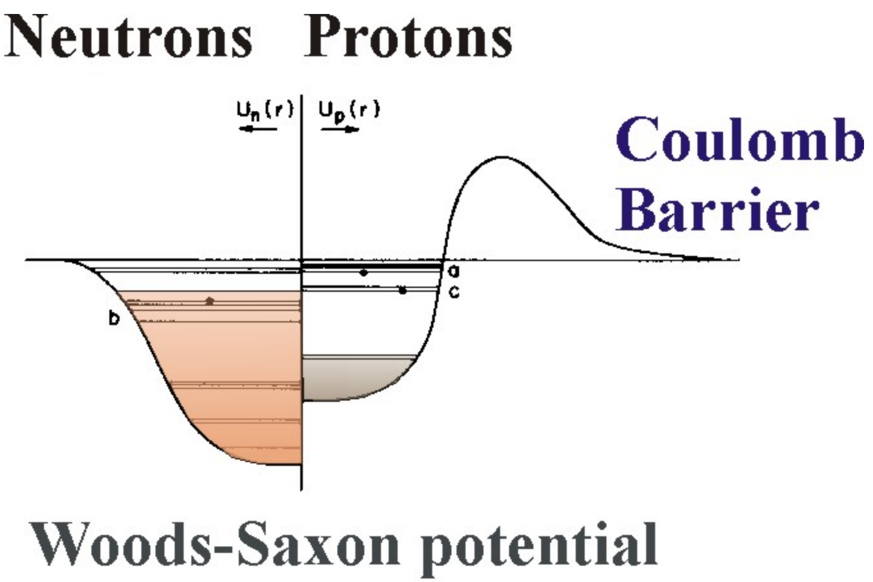
<u>Two problems:</u> (1) Make them (2) Study them

Systematic Studies are Essential for Nuclear Theory



S. Pieper, R. Wiringa, et al.

Difference in Fermi Levels Results in Skins*



$$U(r) = \frac{-V}{1 + e^{(r-R)/a}}$$

* the neutron EOS also plays a role and the size of the neutron skin is related to the volume symmetry energy.