overview

Lecture 1:

- basic concepts and language
- big science questions
- connection to astrophysics
- limits of stability (halos and exotic decays)
- production of the exotic stuff
- what is FRIB?

Lecture 2

- connection to QCD
- the many-body problem
- what is the state of the art

Lecture 3

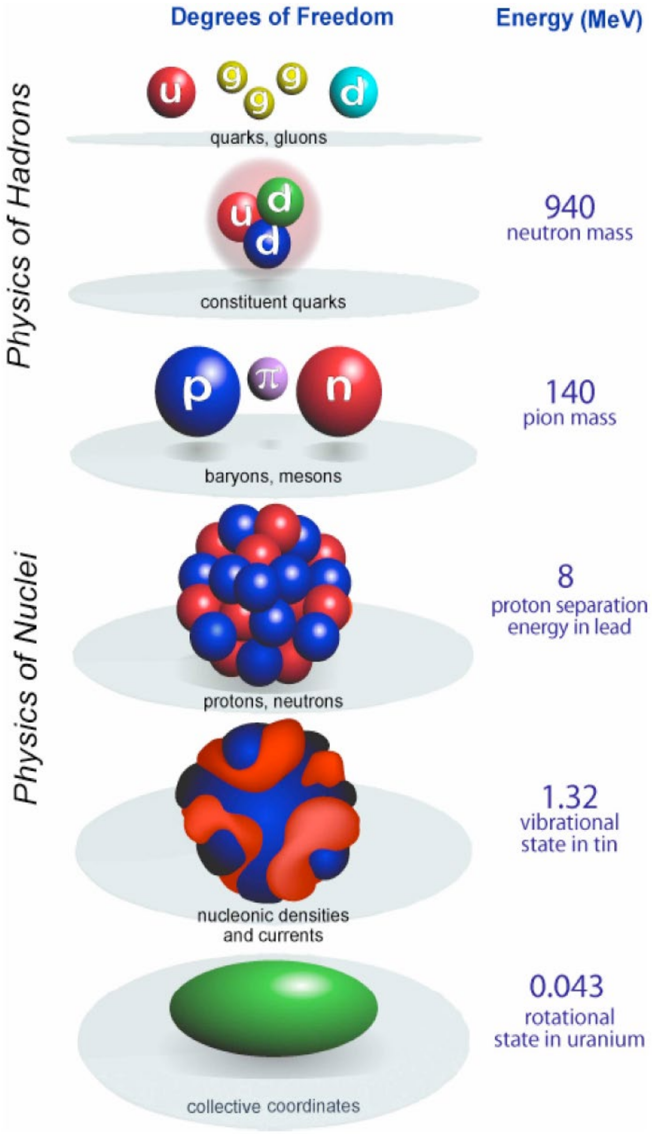
- nuclear reactions as a tool
- basics concepts in nuclear reactions
- some examples from my research

FRIB science (lecture 1)

Filomena Nunes

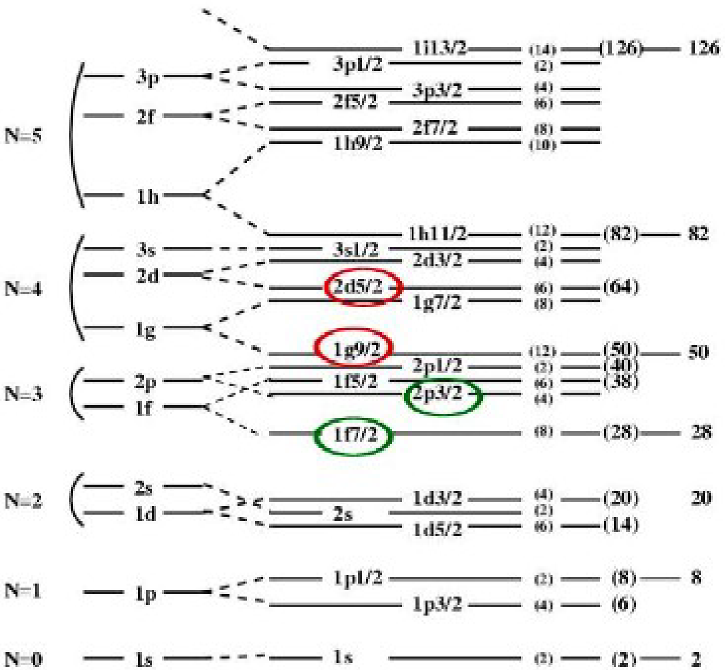
Michigan State University

relevant scales for nuclei

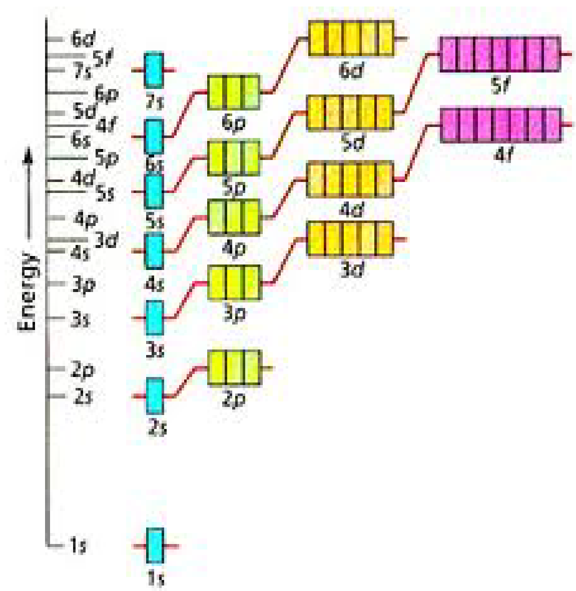


understanding nuclei

nuclear shell model



electronic shells



understanding nuclei

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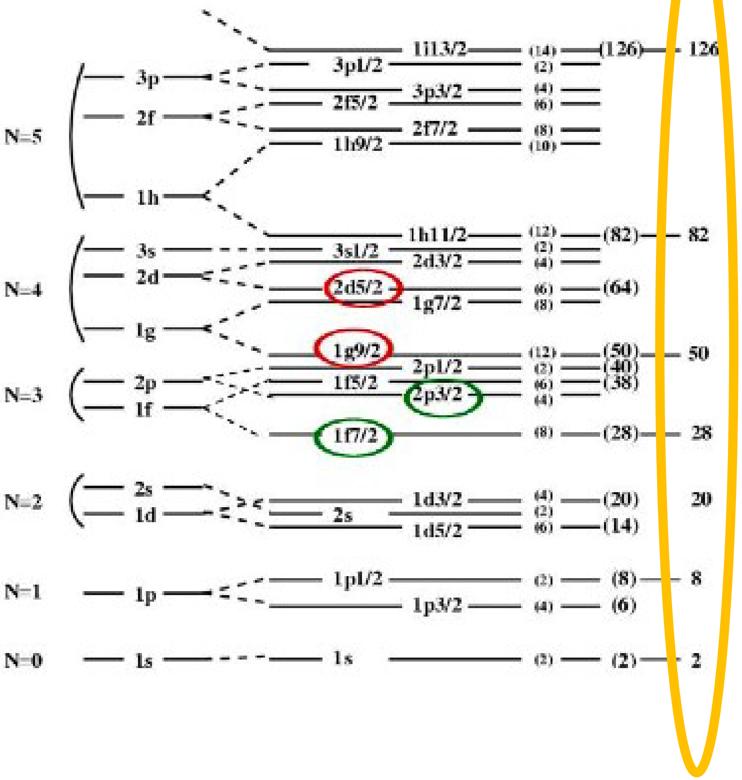


magic numbers

^{208}Pb

^{100}Sn, ^{132}Sn

^{56}Ni, ^{78}Ni

^{40}Ca, ^{48}Ca

^{16}O

Traditional shell model: single particle basis

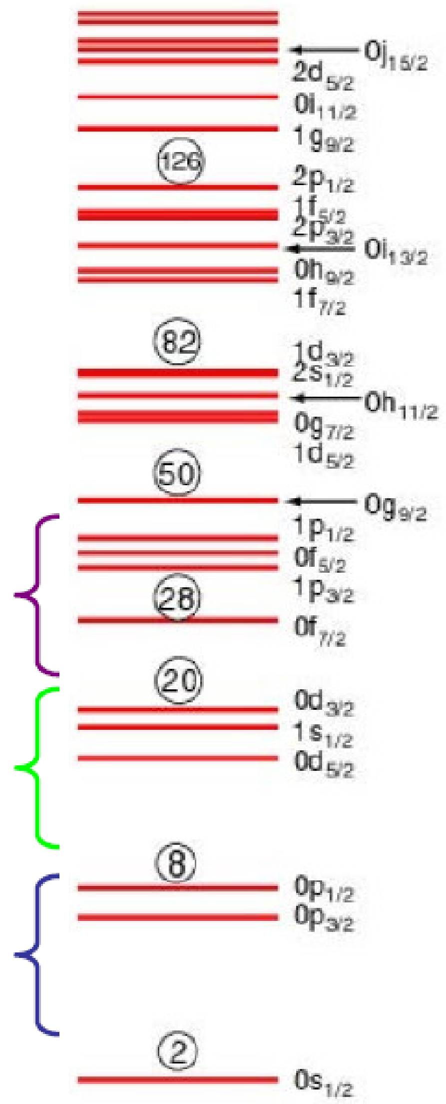
From Thomas Papenbrock's lecture slides

Main idea: Use shell gaps as a truncation of the model space.

- Nucleus (N,Z) = Double magic nucleus (N^*, Z^*)
  + valence nucleons ($N-N^*$, $Z-Z^*$)

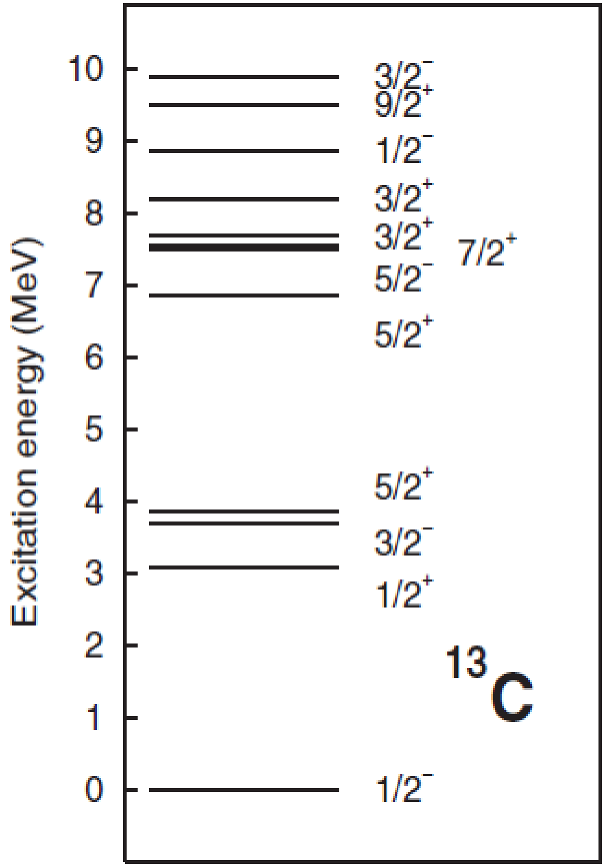
- Restrict excitation of valence nuclons to one oscillator shell.
  - Problematic: Intruder states and core excitations not contained in model space.

- Examples:
  - pf-shell nuclei: ^{40}Ca is doubly magic
  - sd-shell nuclei: ^{16}O is doubly magic
  - p-shell nuclei: ^{4}He is doubly magic



Based on these ideas, what is the expected spectrum for ^{13}C?

nuclear states: example



nuclear bulk properties: liquid-drop model

$$E_B = a_V A - a_S A^{2/3} - a_A \frac{(A-2Z)^2}{A^{1/3}} - a_C \frac{Z(Z-1)}{A^{1/3}} + \delta(A,Z)$$

Volume term

Surface term

Asymmetry term

Coulomb term

Pairing term

For pairing term:

$$\delta(A,Z) = \begin{cases} +\delta_o & \text{A, Z even} \\ 0 & \text{A odd} \\ -\delta_o & \text{A, Z odd} \end{cases}$$

where

$$\delta_o = \frac{a_P}{A^{1/2}}$$

Coefficients:

$a_V = 15.85$ MeV

$a_S = 18.34$ MeV

$a_A = 23.21$ MeV

$a_C = 0.714$ MeV

$a_P = 12.00$ MeV

nuclear stability

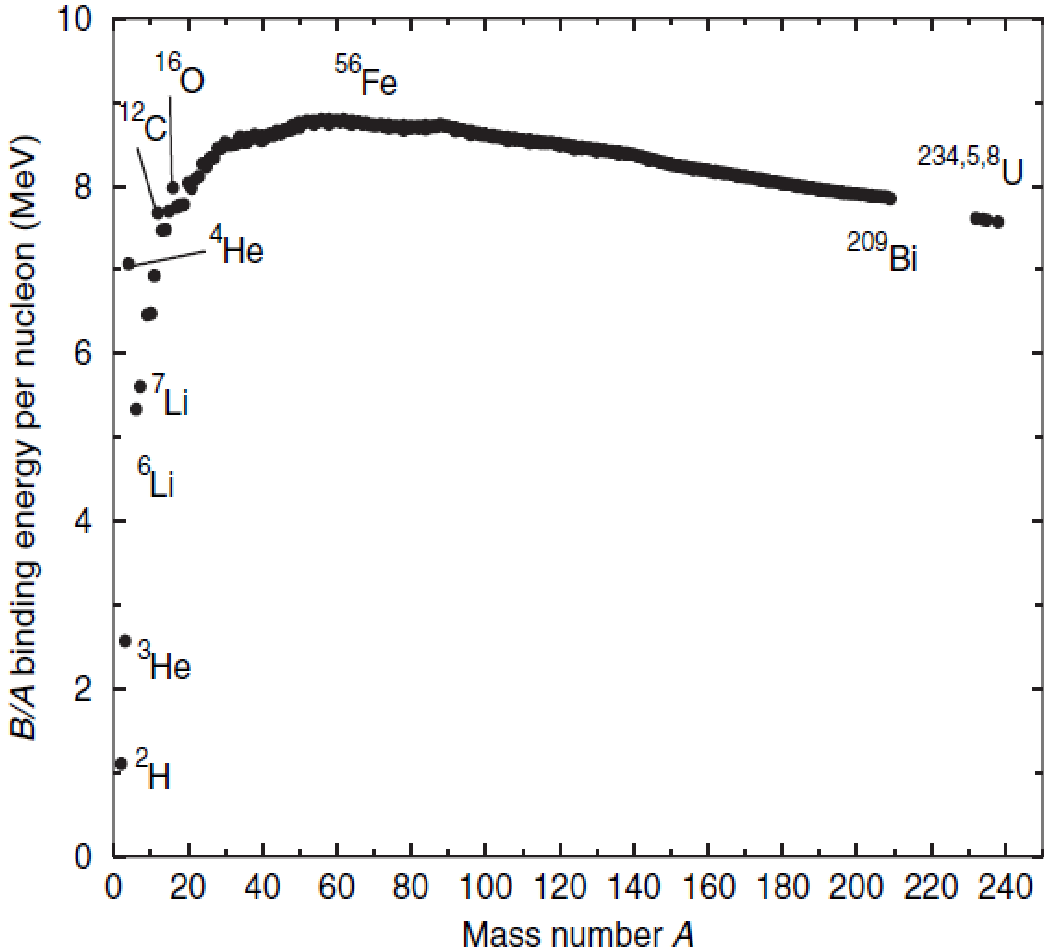


Fig. 1.1. Binding energies per nucleon, $B(A,Z)/A$, for all naturally occurring long-lived isotopes of A nucleons.

nuclear reactions and q-value

- projectile (A)
- target (B)
- residual nuclei (C+D)

- q-value of a reaction:

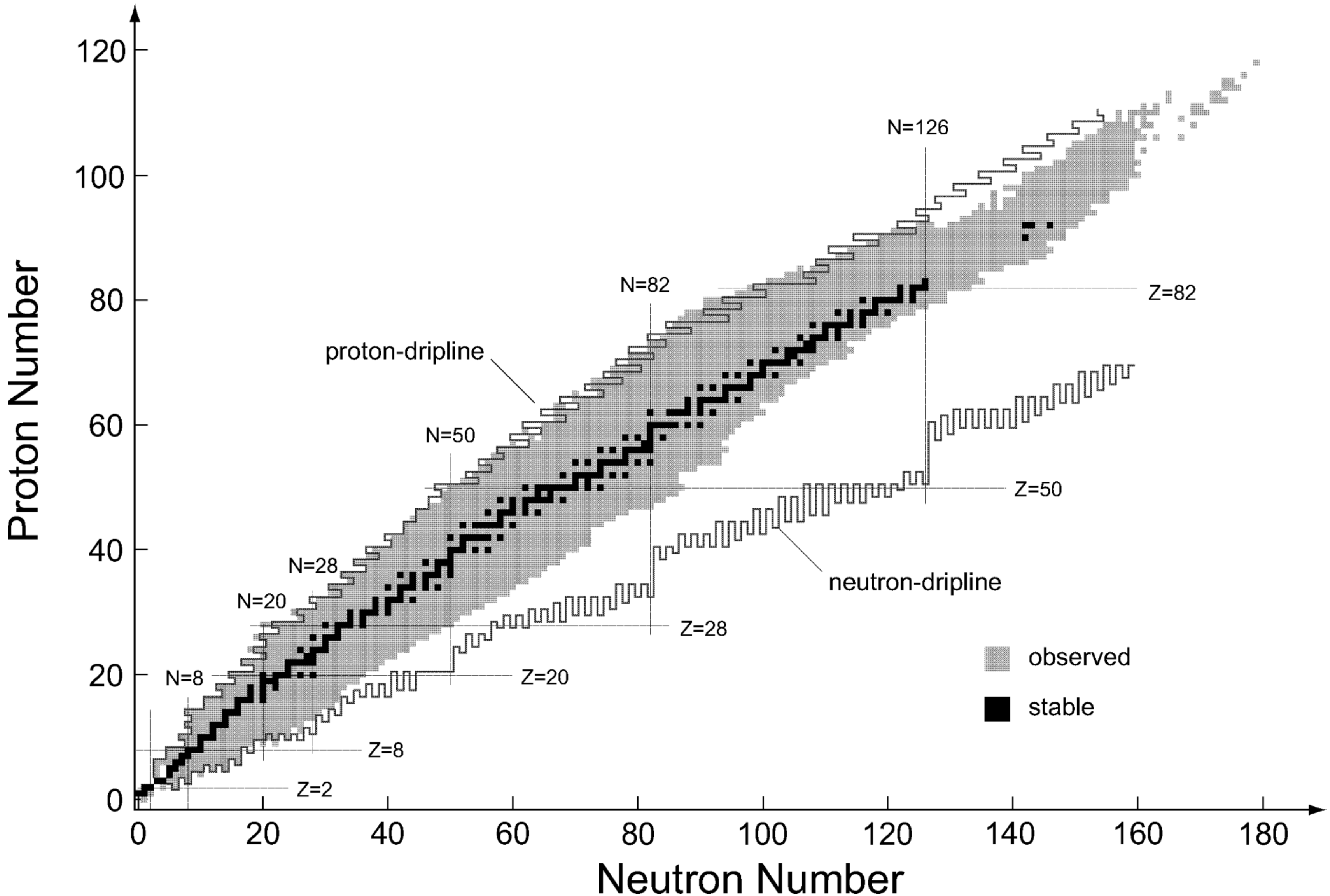
$$\boxed{Q = (m_\mathrm{A} + m_\mathrm{B} - m_\mathrm{C} - m_\mathrm{D})c^2}$$

Notations for the reaction

B(A,C)D

A+B ⇨C+D

properties of nuclei: chart of nuclei



Big science questions

1) *How did matter come into being and how does it evolve?*
2) *How does subatomic matter organize itself and what phenomena emerge?*
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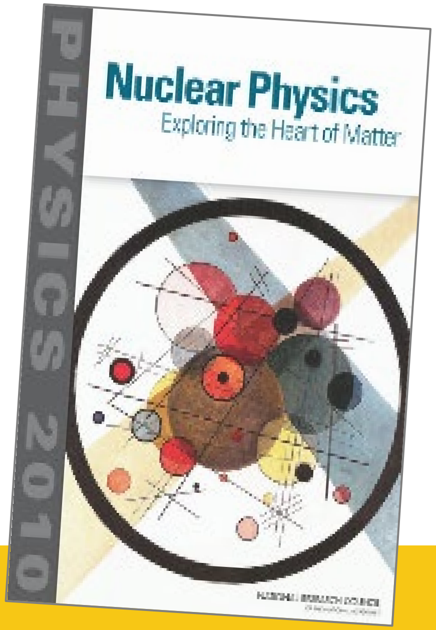
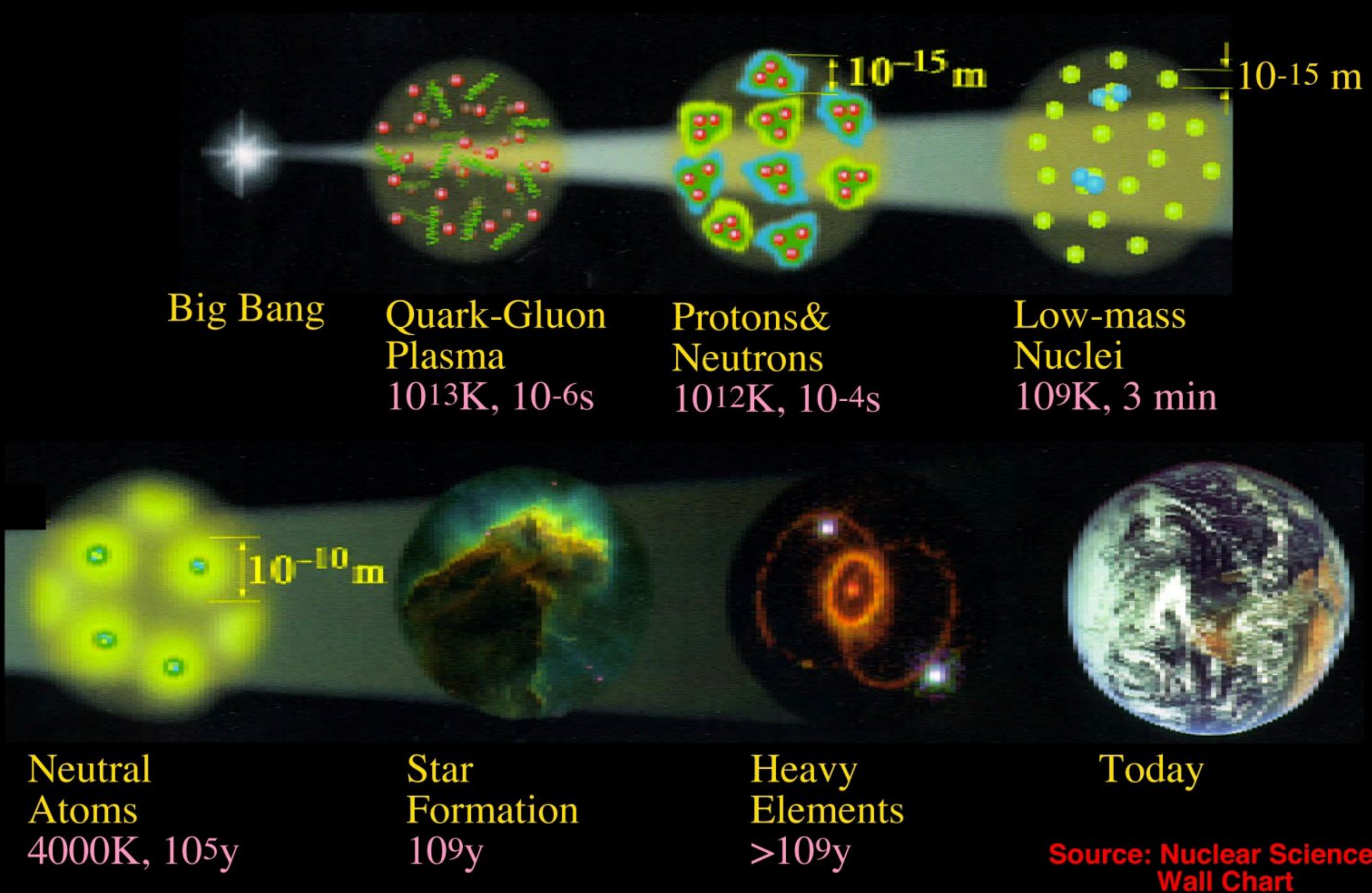


FRIB theory manifesto, Balantekin et al, MPLA 2014 (arXiv:1401.6435)

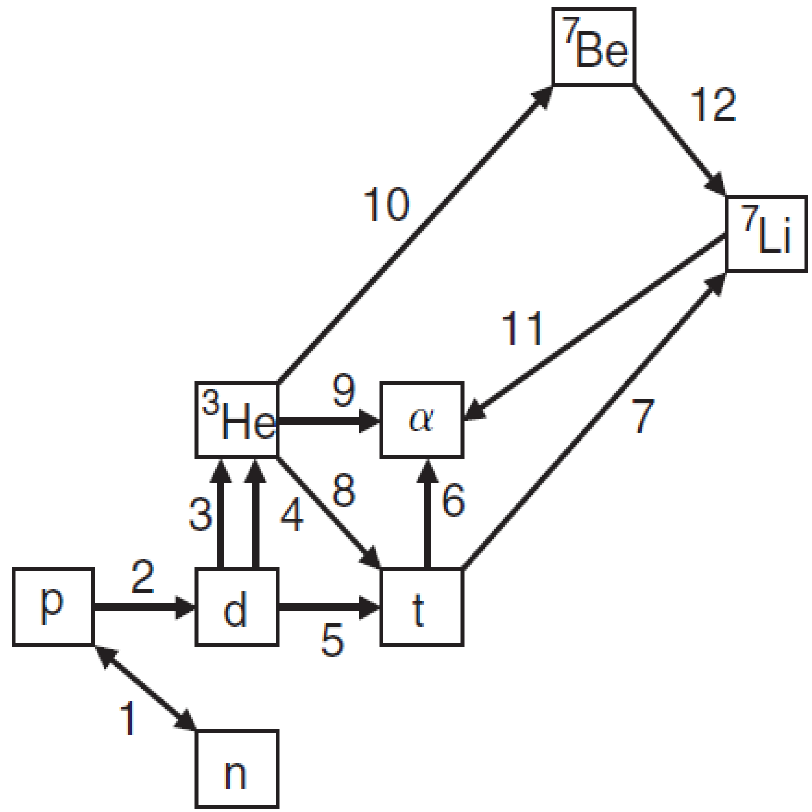
Big science questions: our history



Nuclei play a role in our whole history, starting around 3 min after the BB to now!

primordial nucleosynthesis

1: $n \leftrightarrow p$
2: $p(n,\gamma)d$
3: $d(p,\gamma)^3He$
4: $d(d,n)^3He$
5: $d(d,p)t$
6: $t(d,n)\alpha$
7: $t(\alpha,\gamma)^7Li$
8: $^3He(n,p)t$
9: $^3He(d,p)^4He$
10: $^3He(\alpha,\gamma)^7Be$
11: $^7Li(p,\alpha)^4He$
12: $^7Be(n,p)^7Li$



Q-value for p(n,g)d 2.26 MeV

T(universe to cool down to E=2.26)=7 min

slightly less than T(free neutron decay)

reactions in light stars

$$p + p \rightarrow d + e^+ + \nu$$

$$p + d \rightarrow {}^3He + \gamma$$

86%

14%

$${}^3He + {}^3He \rightarrow {}^4He + 2p$$

Chain I

$Q_{ret} = 26.20$ MeV

$${}^3He + {}^4He \rightarrow {}^7Be + \gamma$$

99.7%

0.3%

Solar neutrino problem

$${}^7Be + e^- \rightarrow {}^7Li + \nu$$

$${}^7Li + p \rightarrow 2\,{}^4He$$

Chain II

$Q_{ret} = 25.66$ MeV

$${}^7Be + p \rightarrow {}^8B + \gamma$$

$${}^8B \rightarrow {}^8Be + e^+ + \nu$$

$$\downarrow$$

$$2\,{}^4He$$

Chain III

$Q_{ret} = 19.17$ MeV

Overall result: $4p \rightarrow {}^4He + 2e^+ + 2\nu + Q_{ret}$

Coulomb effects in reactions

$$\sigma(E) = \frac{1}{E} e^{-2\pi\eta} S(E)$$

Astrophysical S-factor

$$\eta = Z_1 Z_2 e^2 / (\hbar v)$$

Sommerfeld parameter

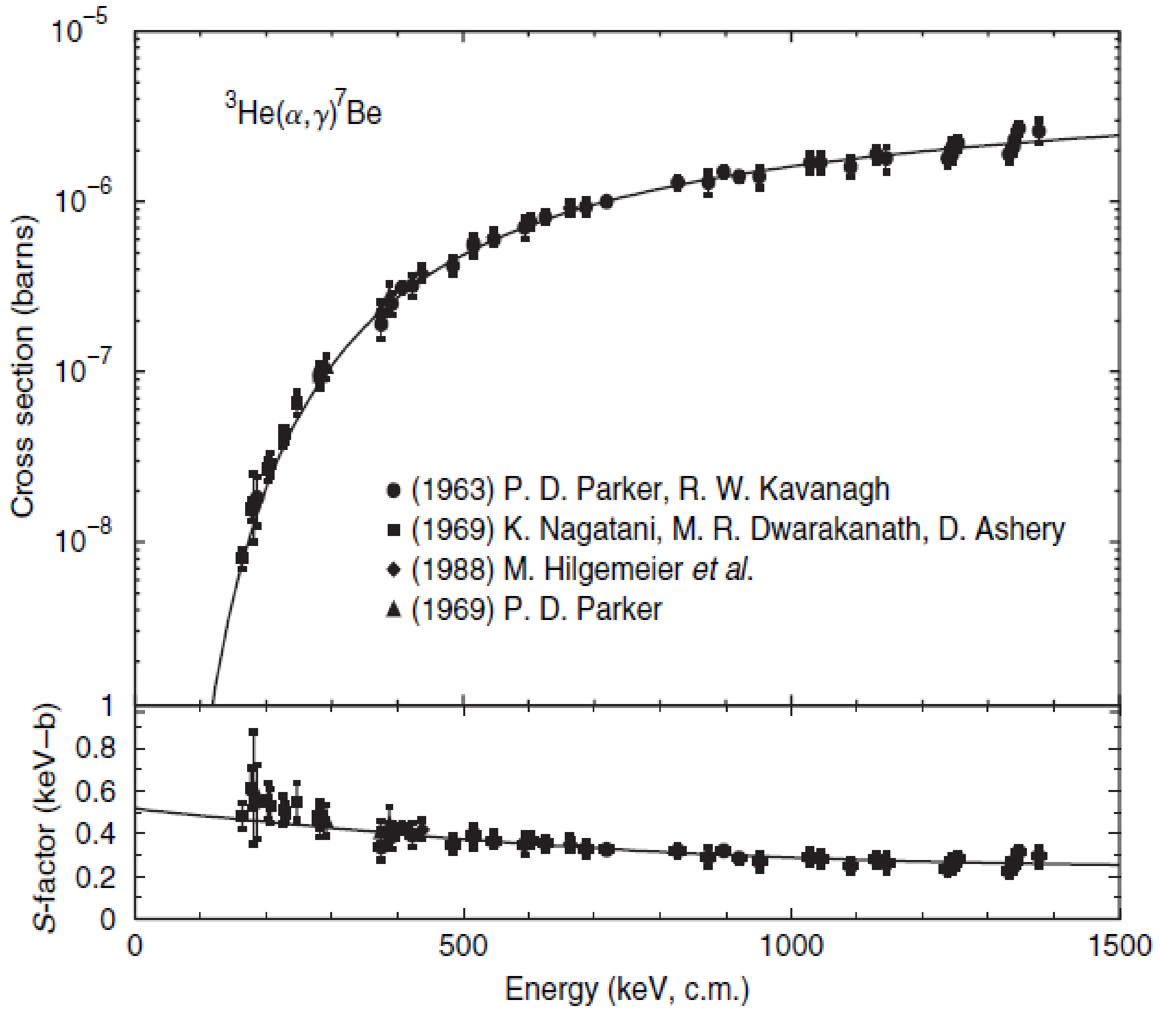


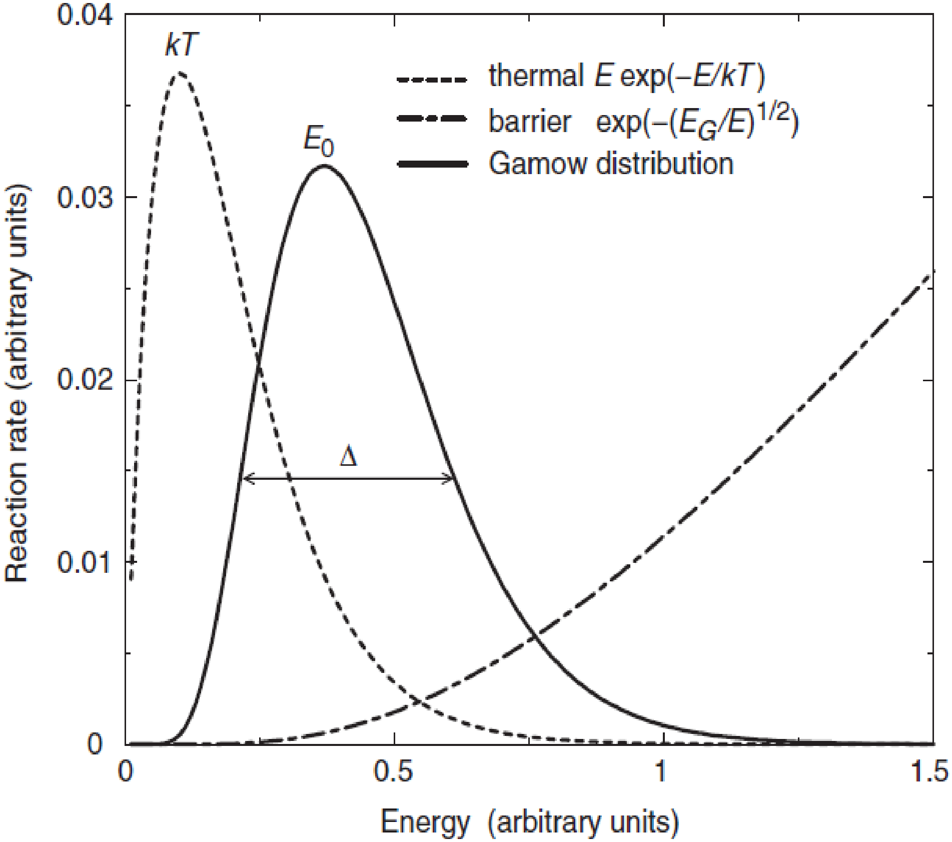
Fig. 1.4. Dependence of cross section and $S(E)$ on energy, for the reaction ^{3}He$(\alpha, \gamma)^7$Be. The solid curve is a calculation to be discussed in Appendix B.

reaction rates and the Gamow peak

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi \mu_{12} (k_B T)^3}} \int_0^\infty S(E) \exp\left(-\frac{E}{k_B T} - \sqrt{\frac{E_G}{E}} \right) \mathrm{d}E.$$

$$E_G = 4\pi^2 \eta^2 E = 2\mu_{12} (\pi Z_1 Z_2 e^2)^2 / \hbar^2$$

$$E_0 = \left(\frac{E_G k_B^2 T^2}{4} \right)^{\frac{1}{3}}$$



Univ Colorado

solar neutrino puzzle

status in the nineties:
measured solar neutrino flux << predicted flux

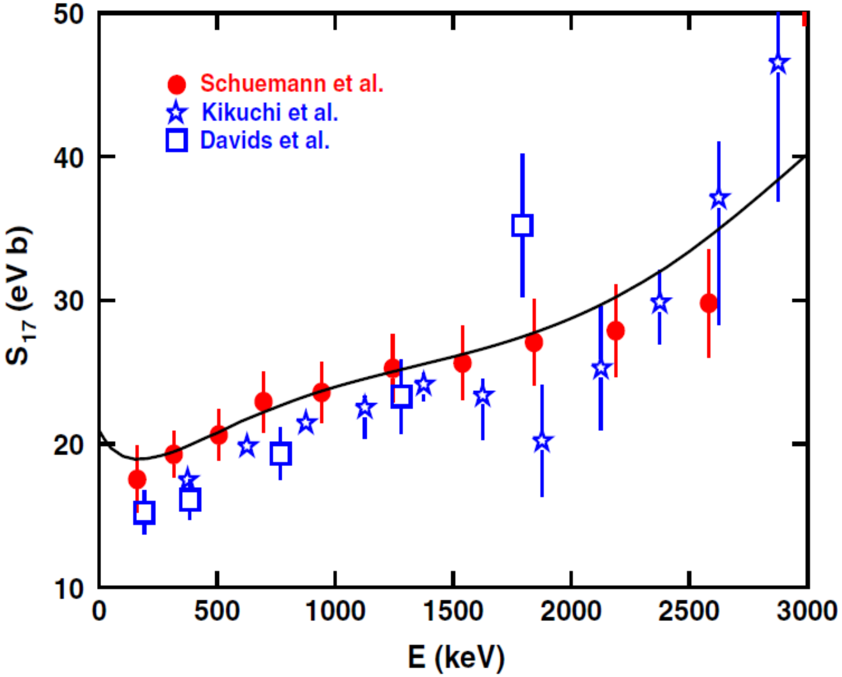


FIG. 8 (color online). S_{17} values from CD experiments. Full circles: latest analysis of the GSI CD experiment (Schümann *et al.*, 2006); open stars: Kikuchi *et al.* (1998) analyzed in first-order perturbation theory; open squares: Davids and Typel (2003). The error bars include statistical and estimated systematic errors. The curve is taken from the cluster-model theory of Descouvemont *et al.* (2004), normalized to $S_{17}(0) = 20.8$ eV b.

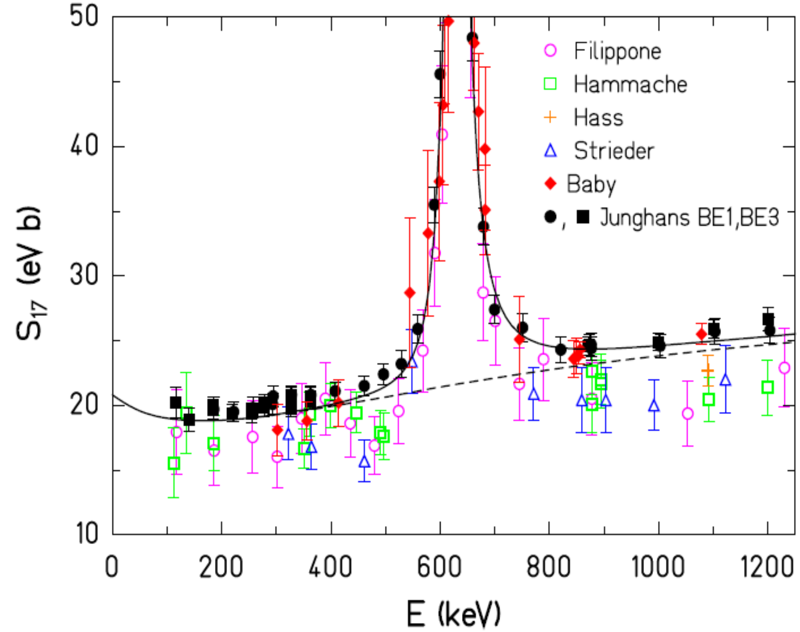
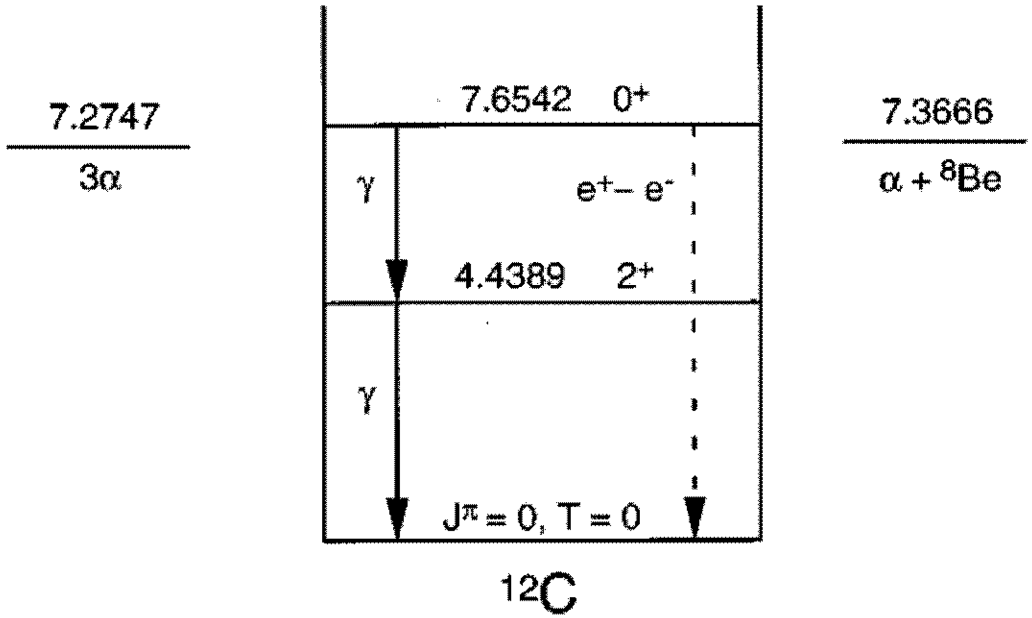
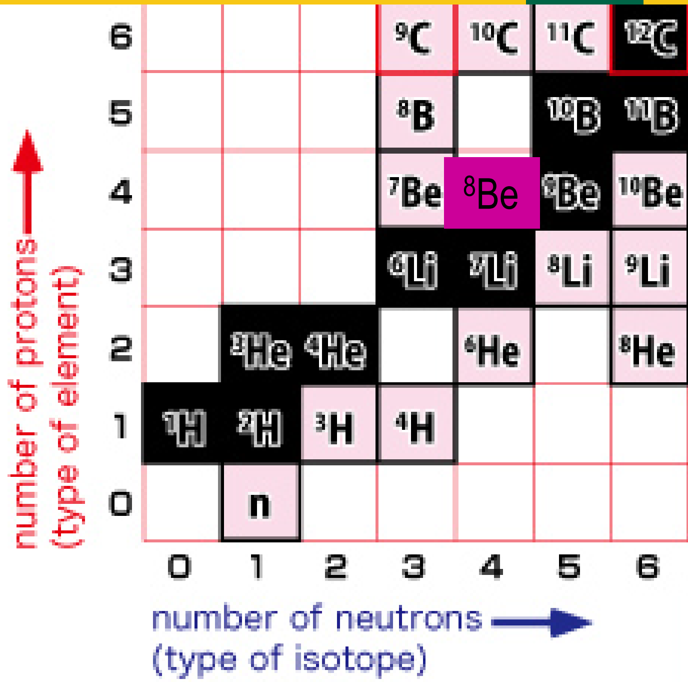


FIG. 9 (color online). $S_{17}(E)$ vs center-of-mass energy E, for $E \leq 1250$ keV. Data points are shown with total errors, including systematic errors. Dashed line: scaled Descouvemont (2004) curve with $S_{17}(0) = 20.8$ eV b; solid line: including a fitted 1^+ resonance shape.

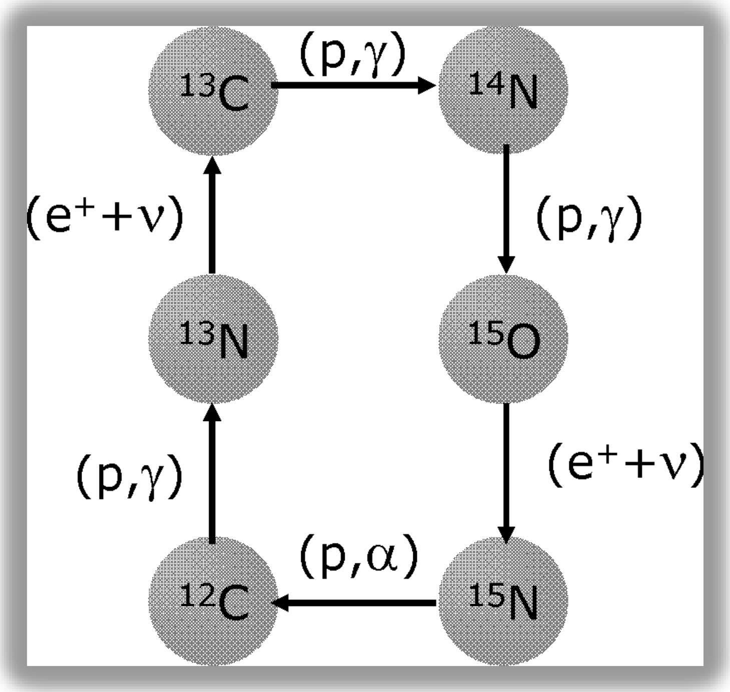
REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 2011

triple-alpha reaction and Hoyle state

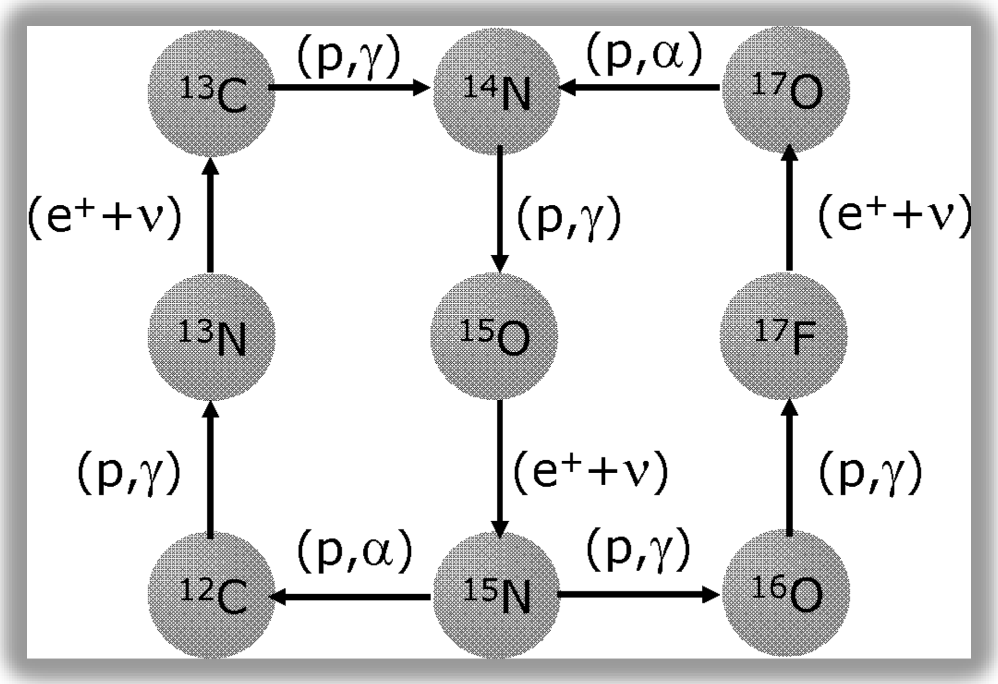




CNO cycles



^{13}C
(p,γ)
^{14}N
(e$^+$+ν)
(p,γ)
^{13}N
^{15}O
(p,γ)
(e$^+$+ν)
^{12}C
(p,α)
^{15}N

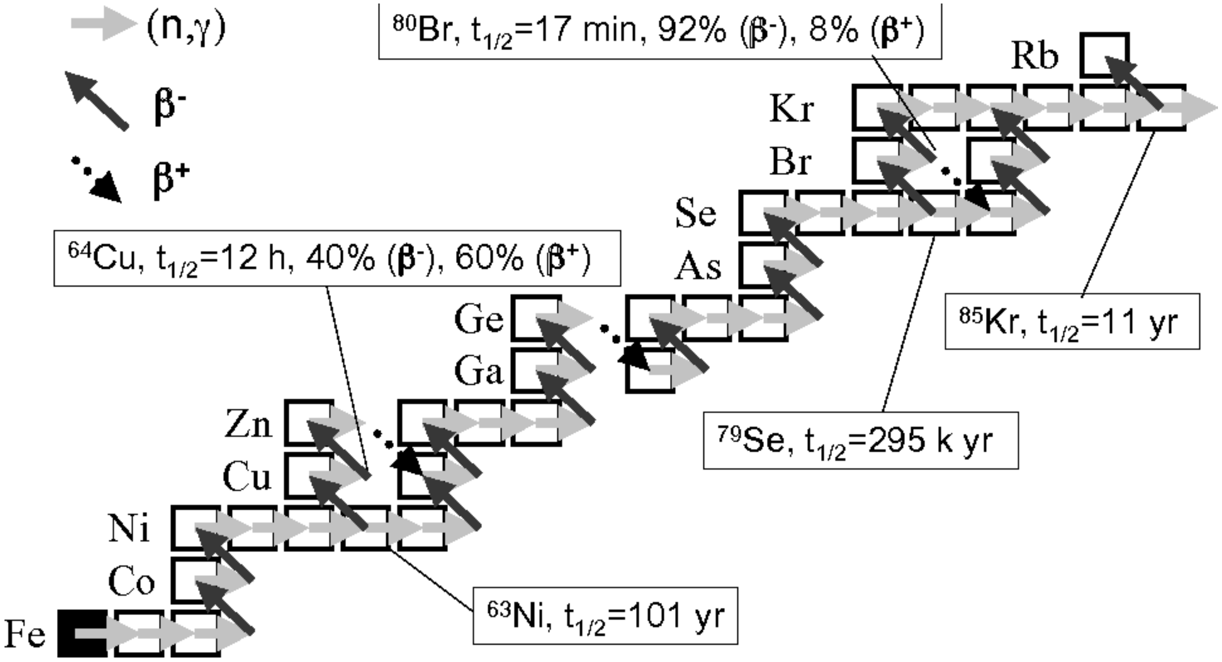


^{13}C
(p,γ)
^{14}N
(p,α)
^{17}O
(e$^+$+ν)
(p,γ)
(e$^+$+ν)
^{13}N
^{15}O
^{17}F
(p,γ)
(e$^+$+ν)
(p,γ)
^{12}C
(p,α)
^{15}N
(p,γ)
^{16}O

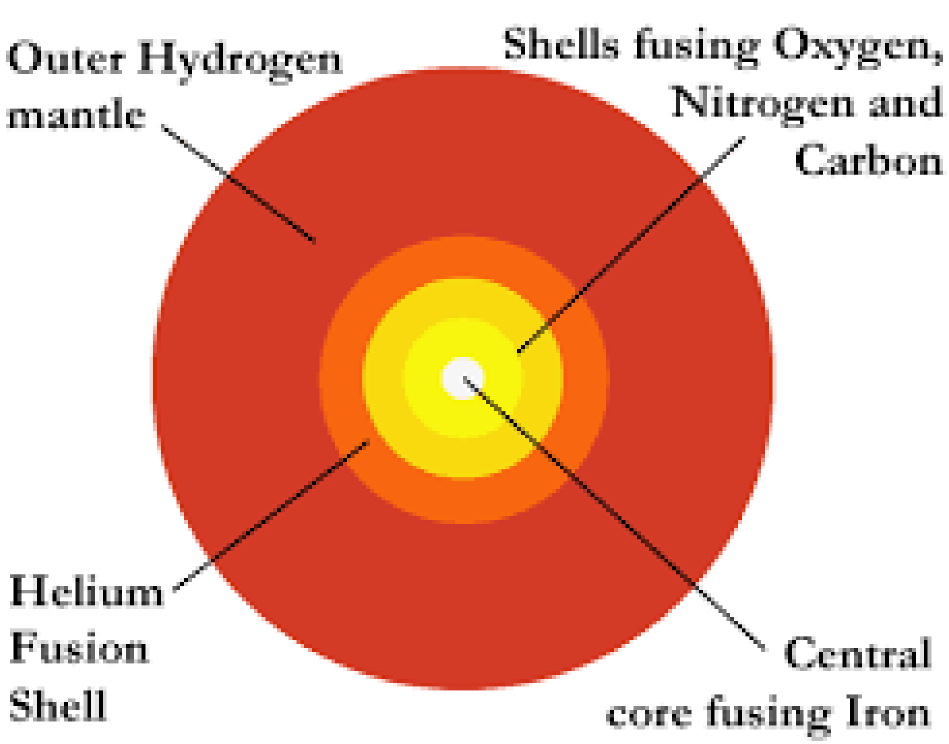
heavier elements

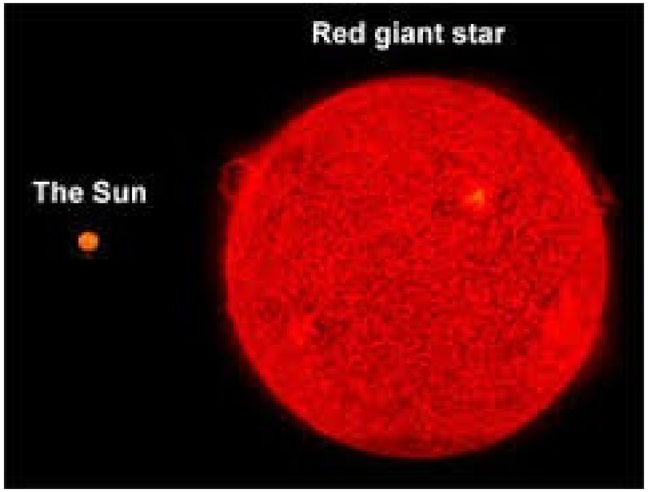
Big bang: neutrons, protons
Solar type stars: alphas, C, O
How about Ca?
How about Iron?
How about Lead?
How about Uranium?

heavy elements and the s-process

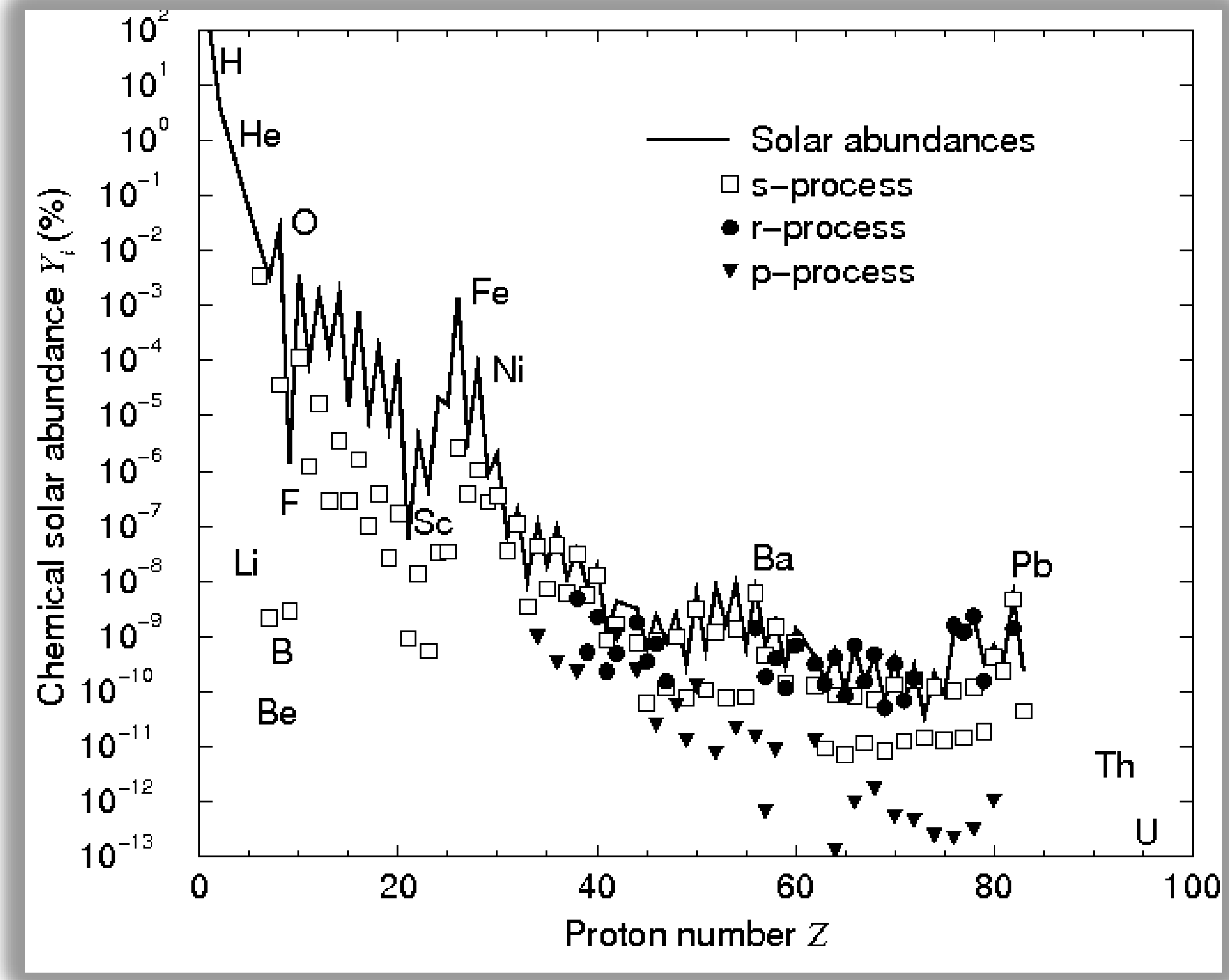


medium mass elements and red giants

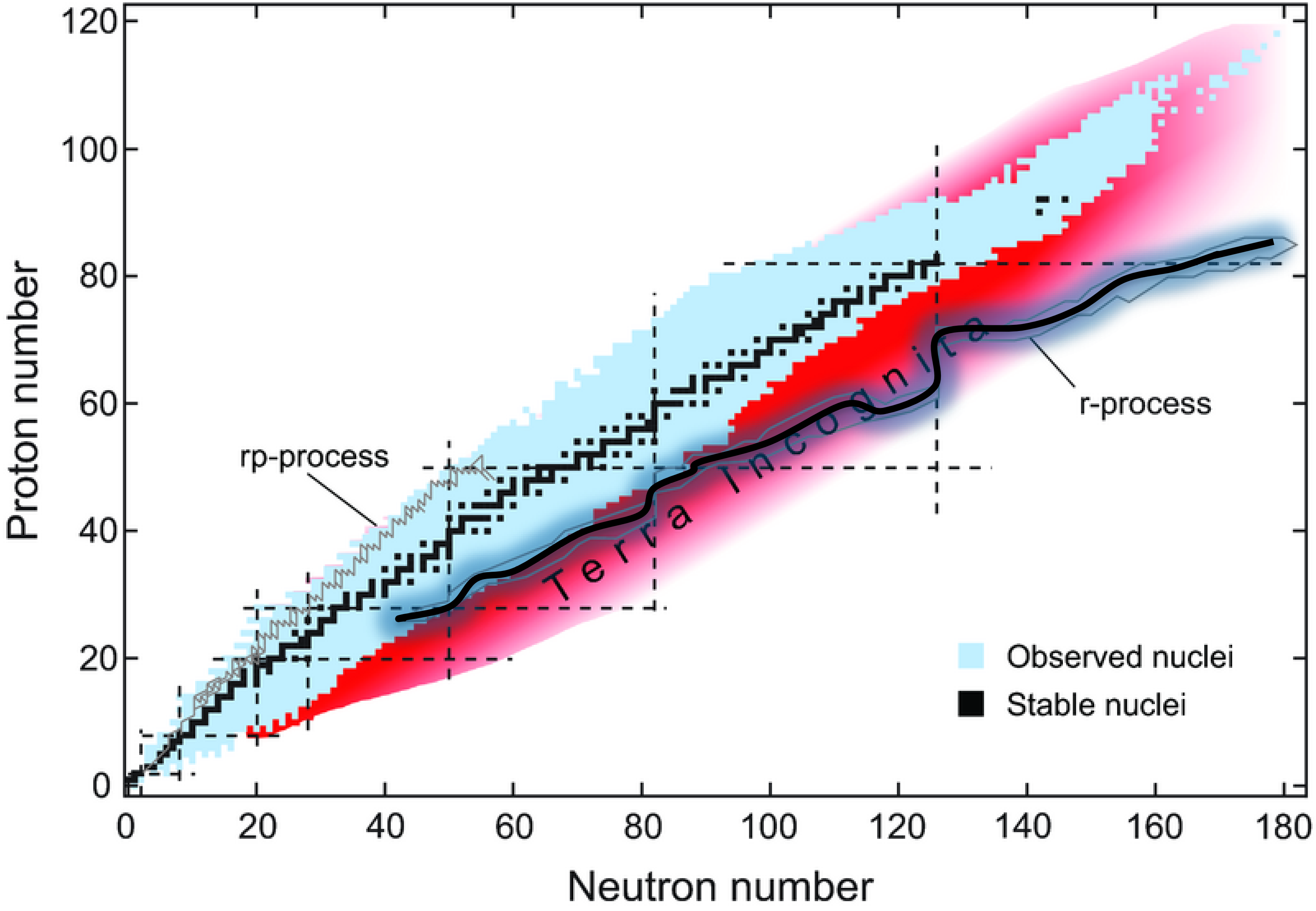




heavy elements: elemental abundancies

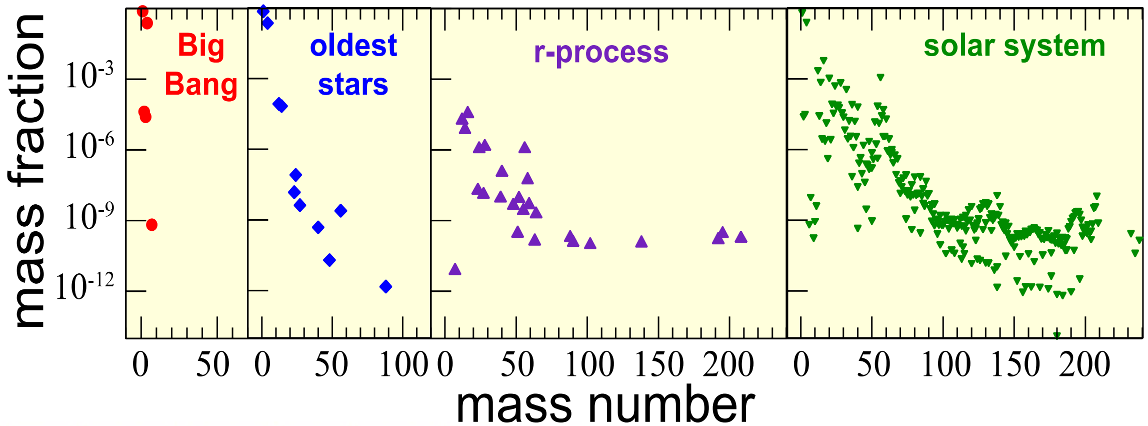


heavy elements: r-process in the chart



Big science questions

1) How did matter come into being and how does it evolve?



Understanding the observed sequence of abundance enrichment of nuclides is a current challenge.

FRIB theory manifesto, Balantekin et al, MPLA 2014 (arXiv:1401.6435)

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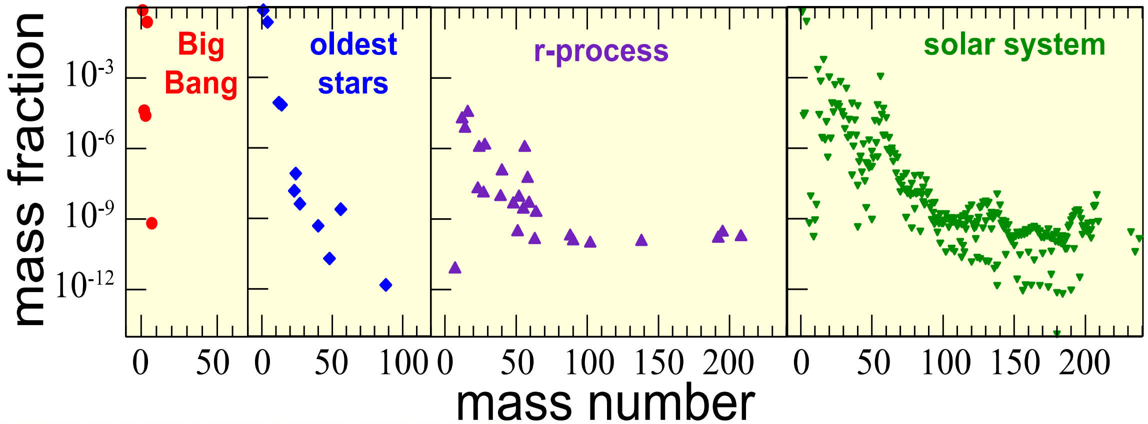
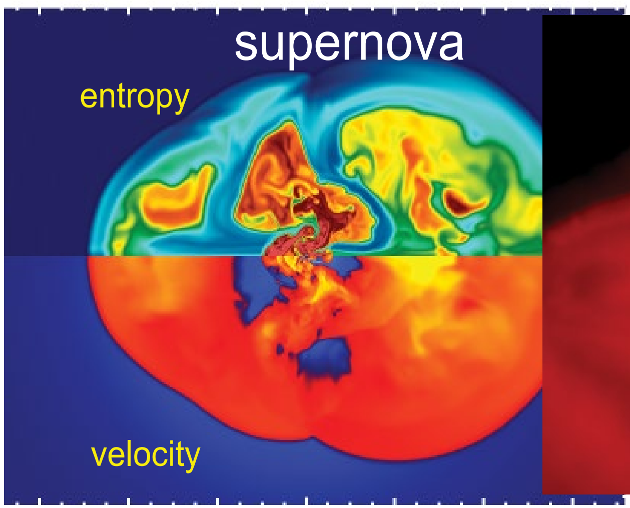
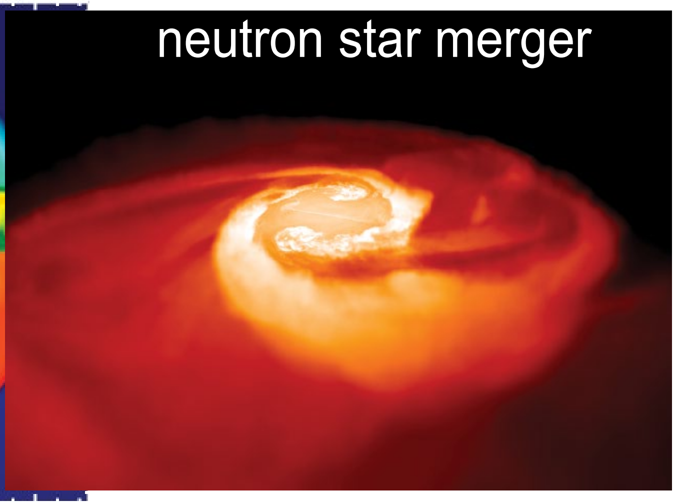






Understanding the observed sequence of abundance enrichment of nuclides is a current challenge. Bottom: Advanced simulations of supernova (left) and neutron star mergers (right) - possible r-process sites.

FRIB theory manifesto, Balantekin et al, MPLA 2014 (arXiv:1401.6435)

Big science questions

1) How did matter come into being and how does it evolve?

Strong interplay of various subfields:

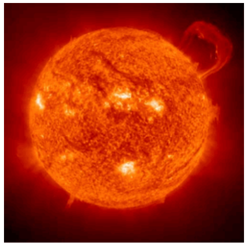
- Nuclear Data (experiments)
- Nuclear theory input complements those data
- Observations (astronomy) that provide additional constraints
- Astrophysics simulations

FRIB theory manifesto, Balantekin et al, MPLA 2014 (arXiv:1401.6435)

Big science questions: origin of the elements

- The stability of matter is closely related to its origin.
- Our field explores the likely series of nuclear reactions and decays that have led to the synthesis of the elements and their isotopes.

- Experimentally the study of the origin of matter has two parts
  - Nuclear astrophysics with intense stable beams studies the reactions of stable isotopes in stars – role for stable beam facilities and an underground accelerator
  - the key role unstable isotopes play in astrophysical processes (radioactive beam facilities)



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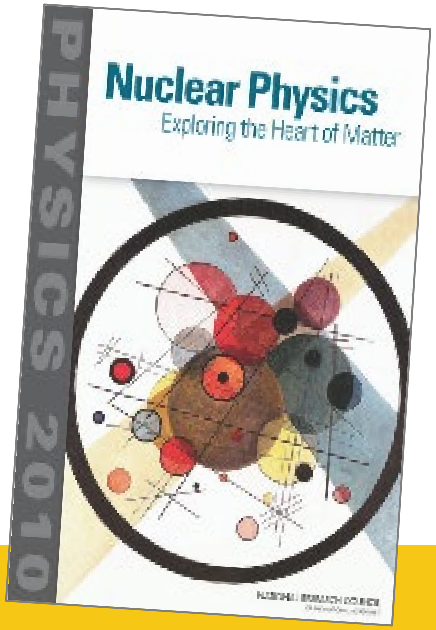
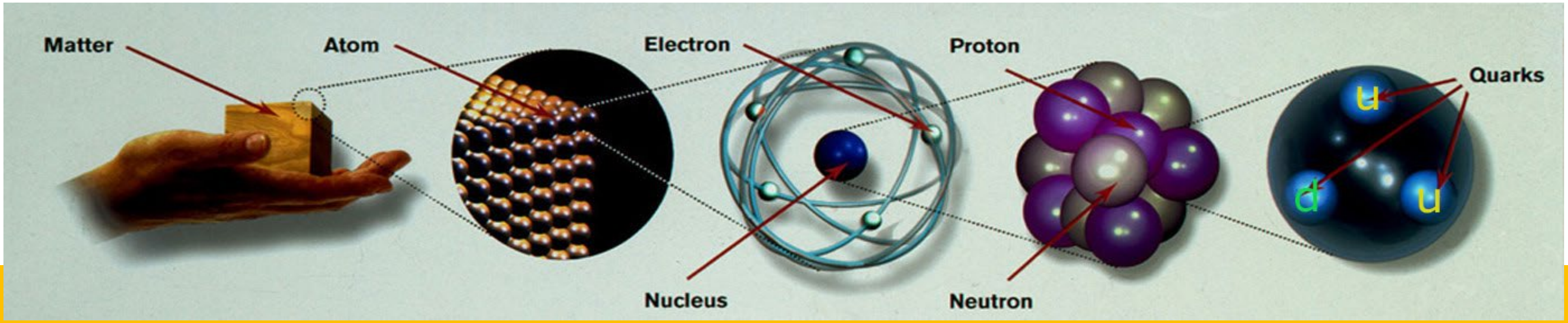


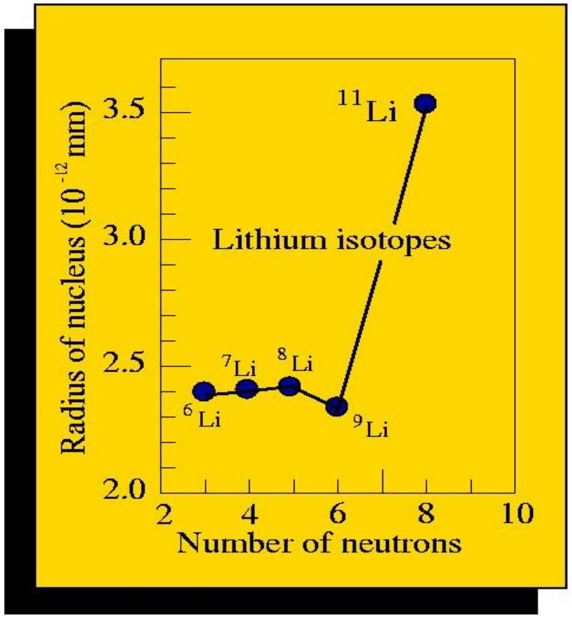
FRIB theory manifesto, Balantekin et al, MPLA 2014 (arXiv:1401.6435)

Big science questions: why is matter stable?

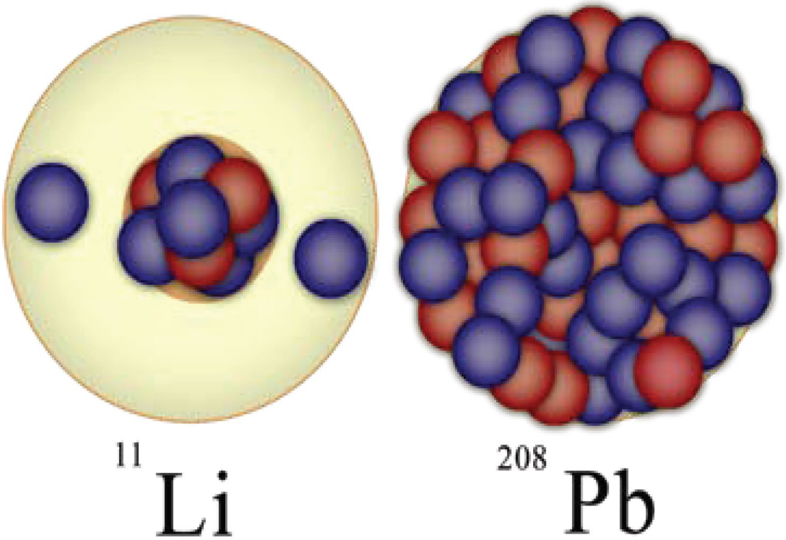
- We want to understand the stability of finite nuclei and extended nuclear matter.
  - What makes the nuclei of atoms possible?
  - what are the limits of stability?
  - How and why do they decay?
  - What is the nature of neutron star matter?



Towards the driplines



nuclear halos

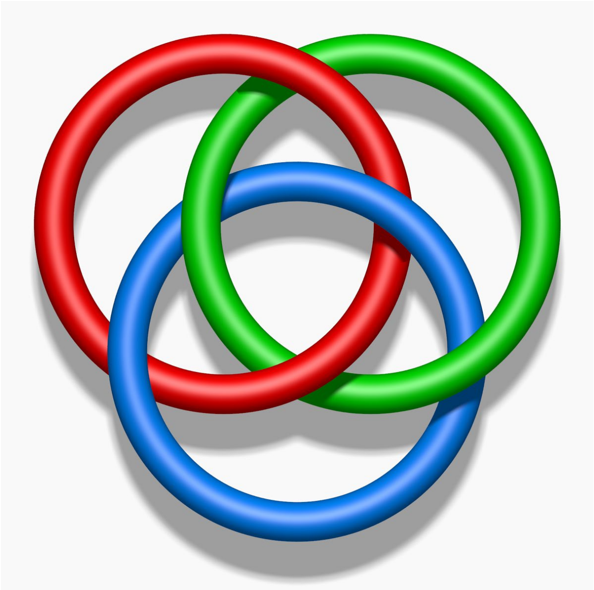


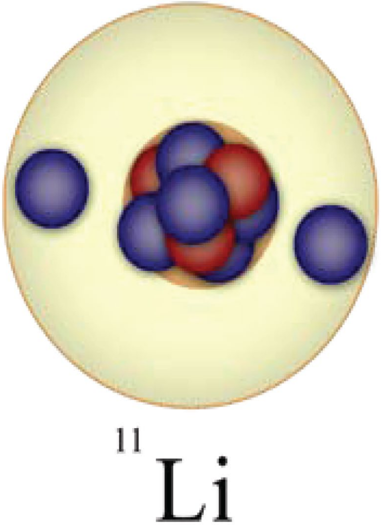
Very large spatial extension:

correct asymptotic behaviour needed

finite range effects crucial

weakly bound systems: halo nuclei

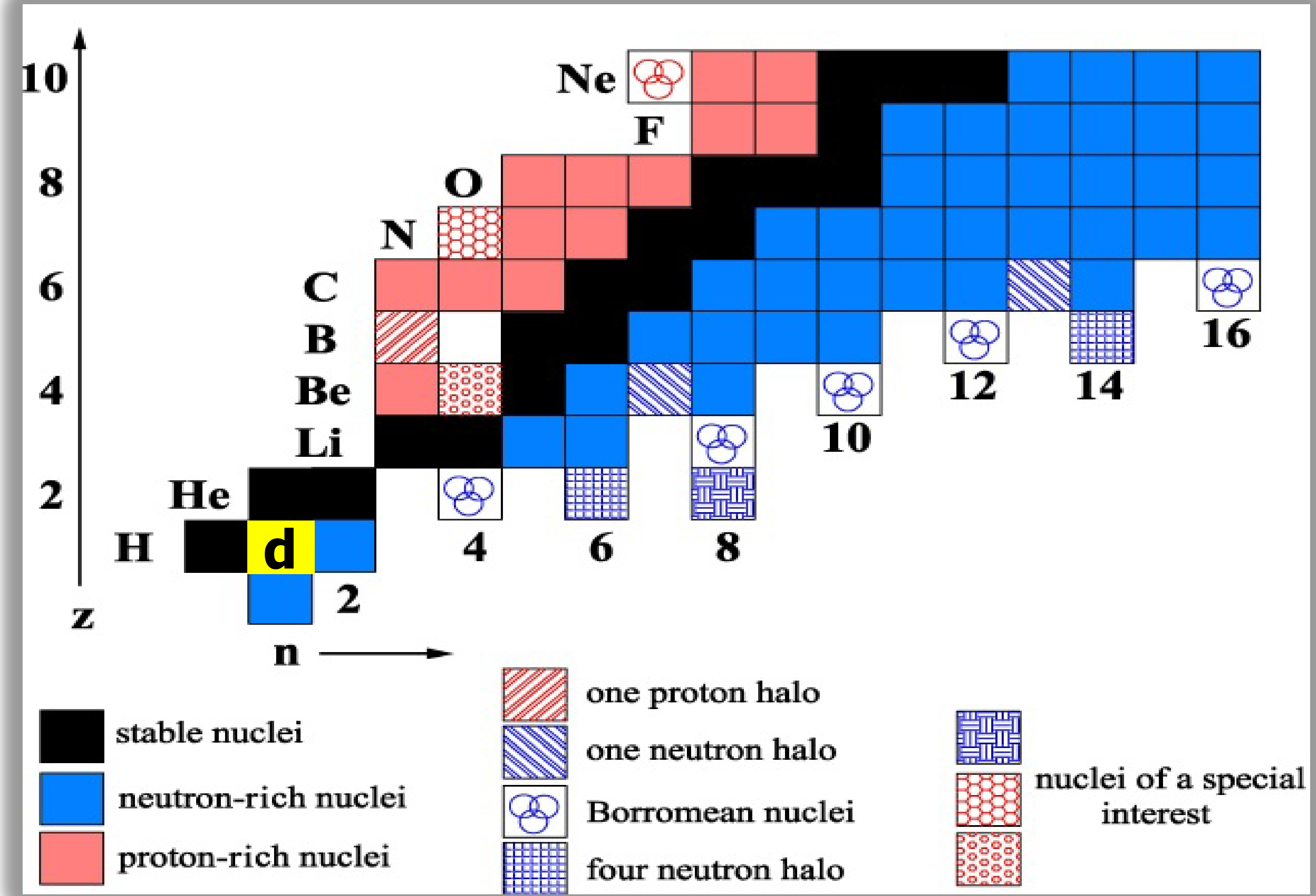




What's so cool about 2n halo nuclei?

Borromean systems

properties of nuclei: chart of nuclei



the heaviest halo so far

^{22}C

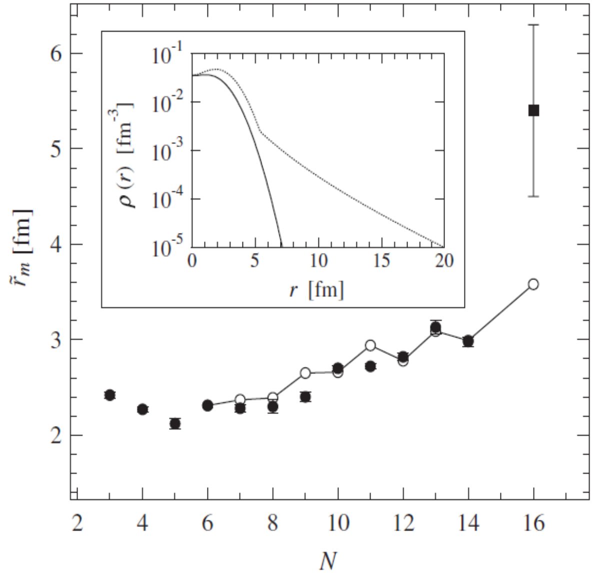


FIG. 2. The $\tilde{r}_m$ as a function of the neutron number of C isotopes. The filled square and circles show the present result and those determined at GSI [14], respectively, while open symbols are the result of the calculation [22]. The lines connect the open circles. The inset shows $\rho_p(r)$ (solid line) and $\rho_n(r)$ (dotted line) of ^{22}C for the determined parameter. See text.

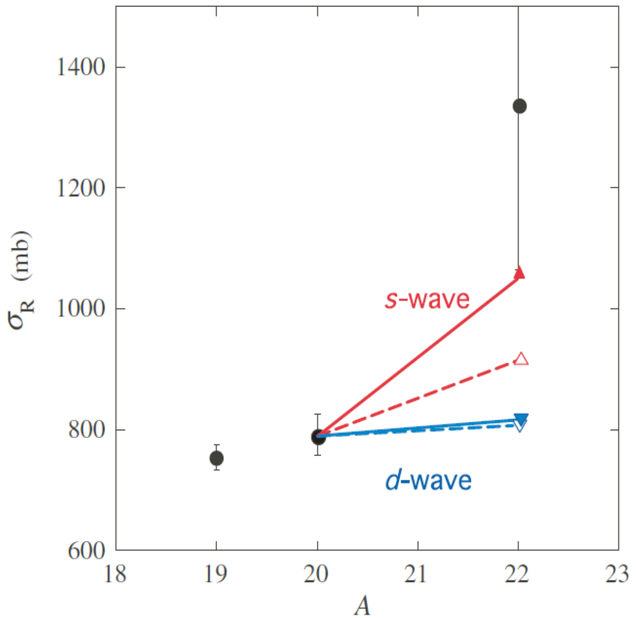
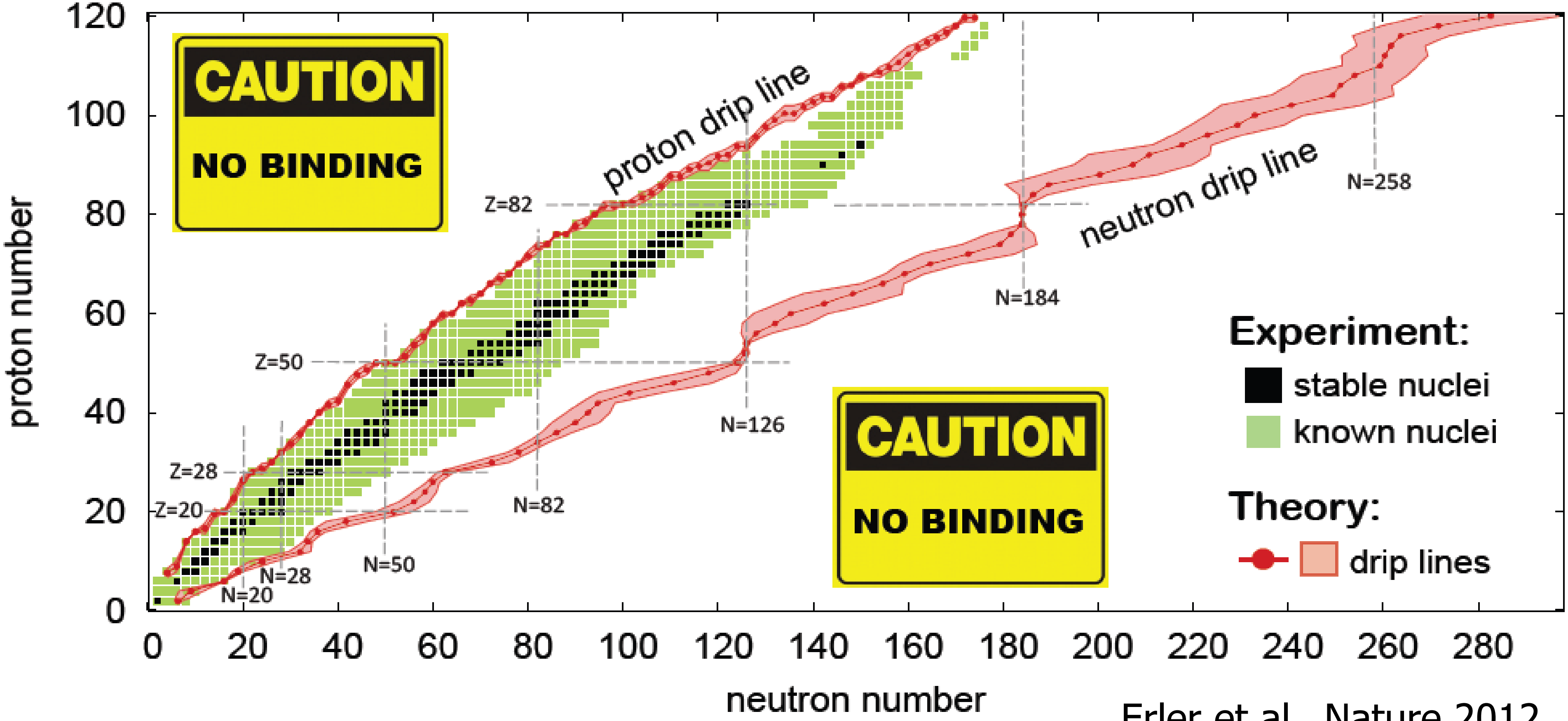


FIG. 3 (color). The σ_R for $f = 1.0$ (red triangles) and that for $f = 0.0$ (blue triangles), with $S_{2n} = 420$ keV (open symbols) and $S_{2n} = 10$ keV (closed symbols), respectively. The lines are to guide the eye. The experimental data (solid circles) as a function of the mass number of C isotopes are also plotted.

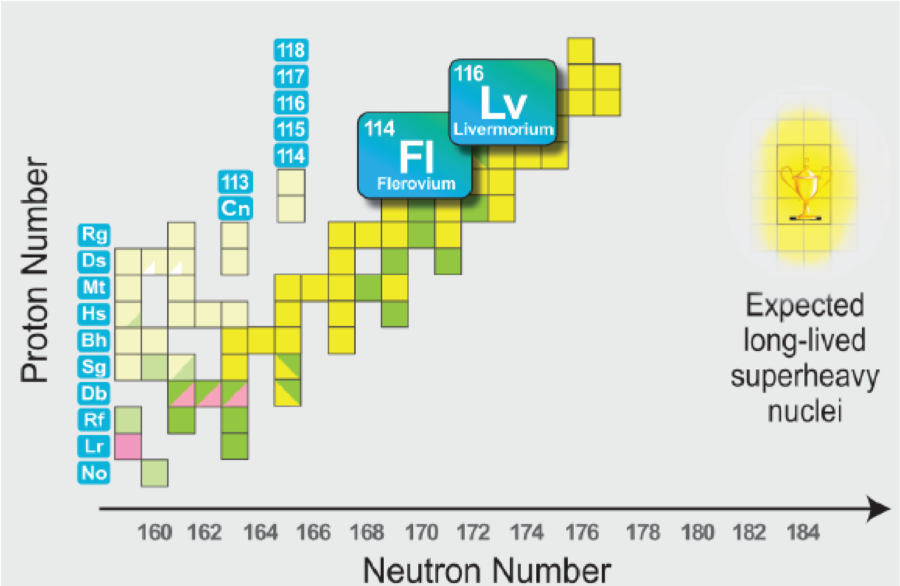
PRL **104,** 062701 (2010)

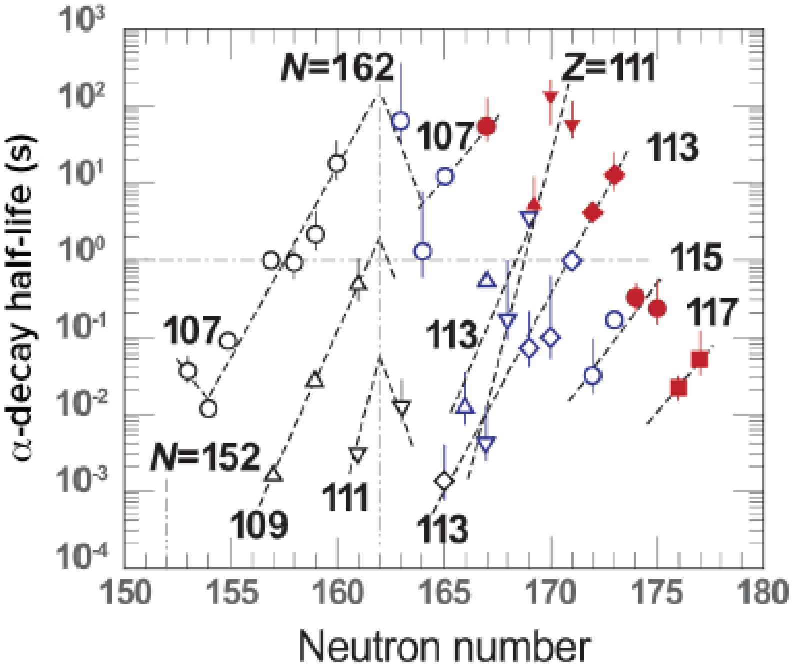
Limits of stability – terra incognita…



Erler et al., Nature 2012
NP Long range plan 2015

Superheavies

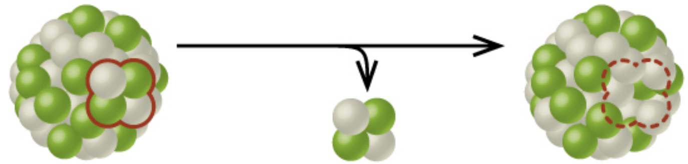
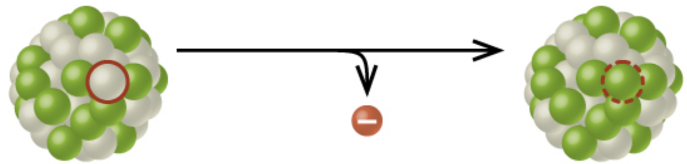
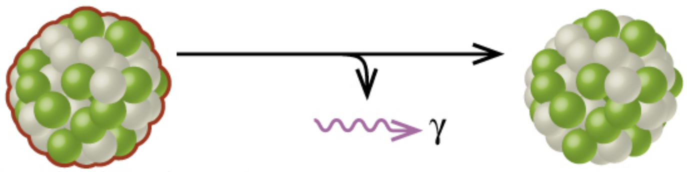
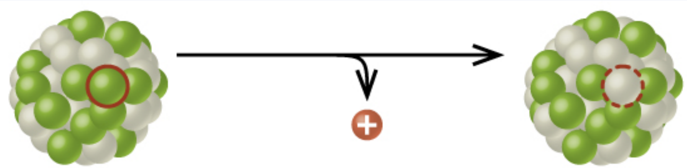
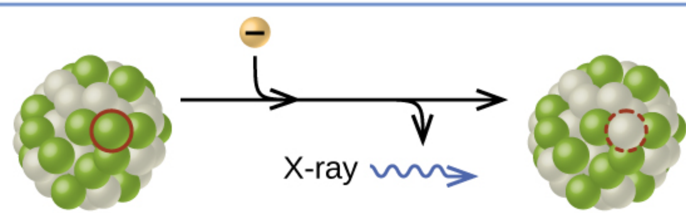




- Elements 113 and 115 were confirmed
- Flerovium (Z=114) and Livermorium (Z=116) joined the periodic table
- New chemical element 117 was discovered and experimentally confirmed

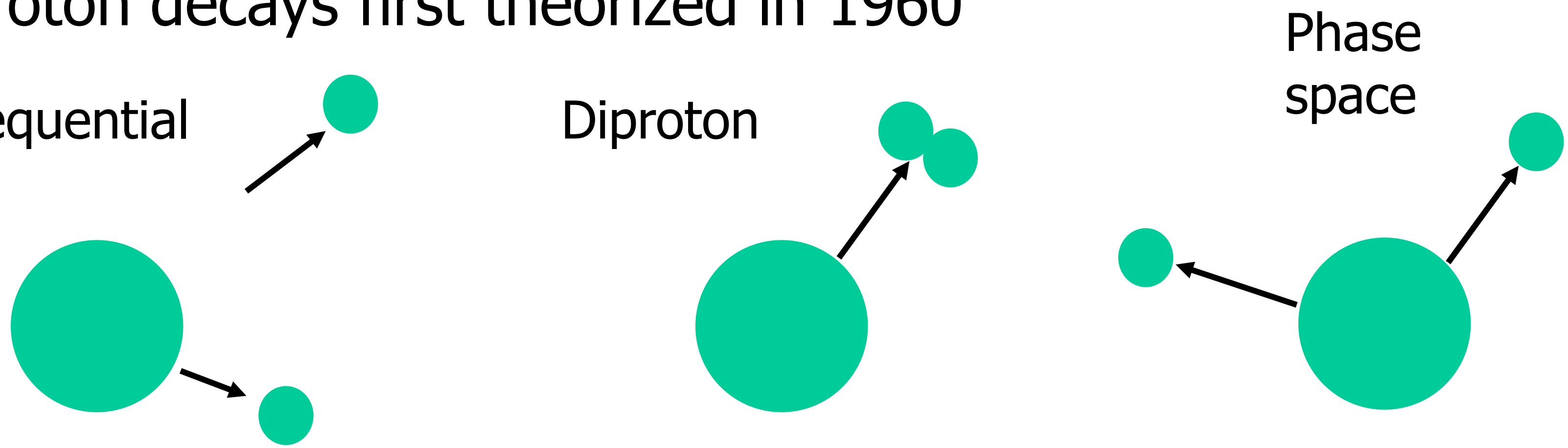
- Recently discovered nuclei (red and blue) show a trend of longer half-lives as the neutron number increases

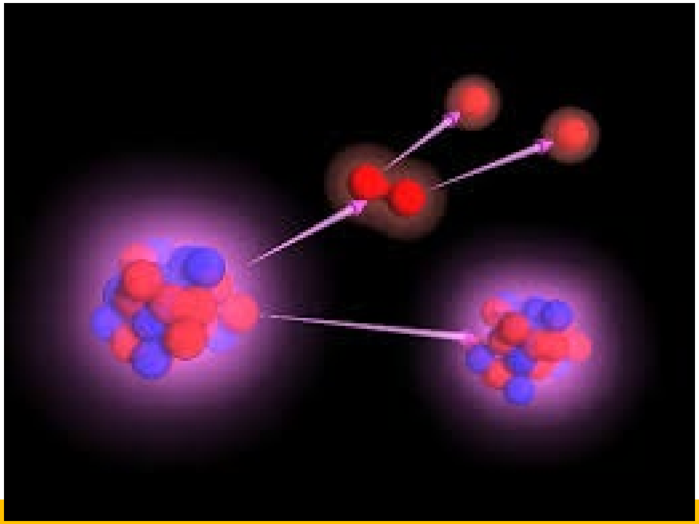
Nuclear decays and radioactivity

Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	$^{A}_{Z}X$ $\quad ^{4}_{2}He + ^{A-4}_{Z-2}Y$		A: decrease by 4 Z: decrease by 2
Beta decay	$^{A}_{Z}X$ $\quad ^{0}_{-1}e + {}^{A}_{Z+1}Y$		A: unchanged Z: increase by 1
Gamma decay	$^{A}_{Z}X$ $\quad ^{0}_{0}\gamma + ^{A}_{Z}Y$	 Excited nuclear state	A: unchanged Z: unchanged
Positron emission	$^{A}_{Z}X$ $\quad ^{0}_{+1}e + {}^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1
Electron capture	$^{A}_{Z}X$ $\quad ^{0}_{-1}e + {}^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1

Nuclear decays at the dripline (2p)

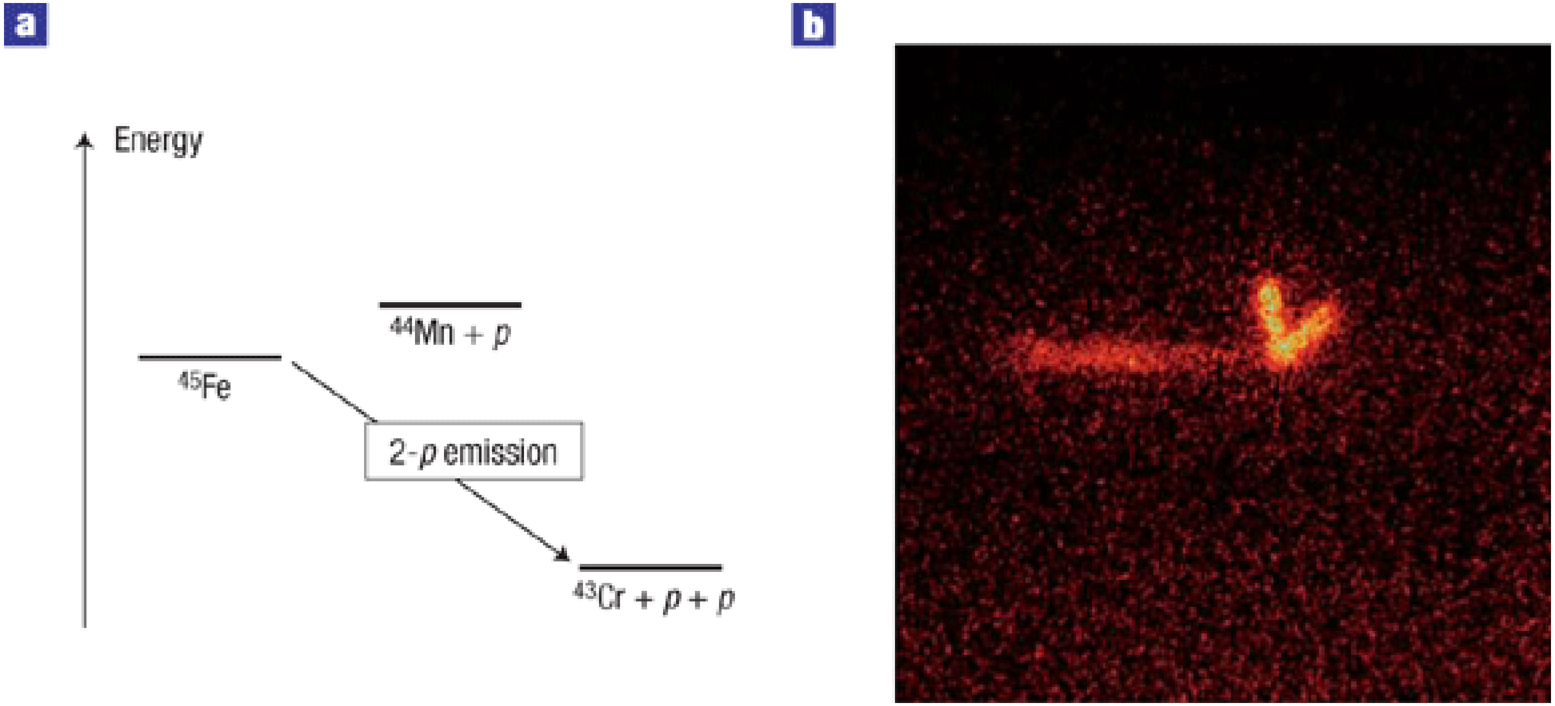
- Two-proton decays first theorized in 1960





Nuclear decays at the dripline: 2p radioactivity

Two-proton decays first experimentally observed in 2002 (^{45}Fe)

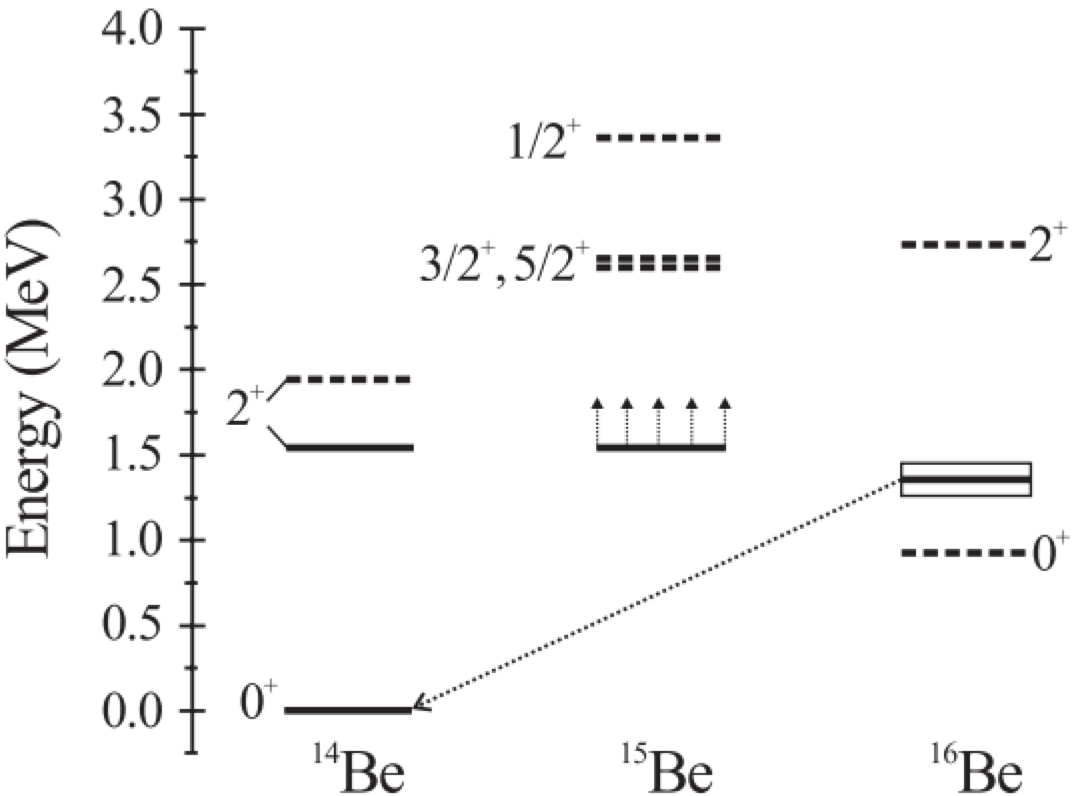


J. Giovinazzo, et. al., PRL **89** 102501 (2002)

M. Pfützner, et. al., Eur. Phys. J A **14** 279 (2002)

Nuclear decays at the driplines: 2n radioactivity

- A-1 nucleus (^{15}Be) should be energetically inaccessible to decay



Ground state of ^{16}Be measured to be **1.35 MeV** (2012)

A. Spyrou, et. al., PRL **108** 102501 (2012)

Lower bound on ground state of ^{15}Be at **1.54 MeV** (2011)

A. Spyrou, et. al., PRC **84** 044309 (2011)

d-wave in ^{15}Be measured at **1.8 MeV** (2013)

J. Snyder, et. al., PRC **88** 031303(R) (2013)

A. Spyrou, et. al., PRL **108** 102501 (2012)

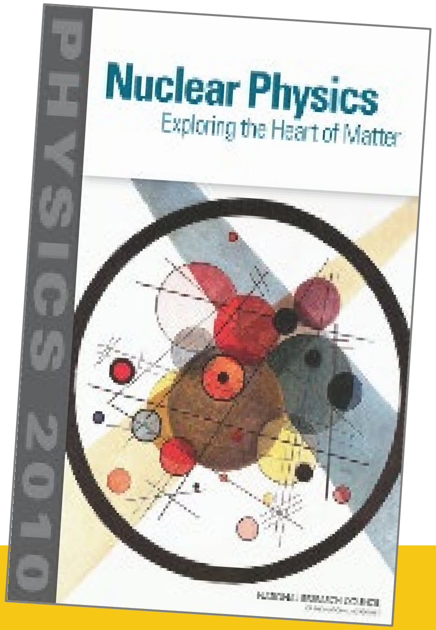
Big science questions

1) *How did matter come into being and how does it evolve?*

2) *How does subatomic matter organize itself and what phenomena emerge?*

3) *Are the fundamental interactions that are basic to the structure of matter fully understood?* and

4) *How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?*



FRIB theory manifesto, Balantekin et al, MPLA 2014 (arXiv:1401.6435)

Big science questions: fundamental symmetries

○ use of the decay of unstable nuclei to explore fundamental symmetries in physics.

○ Angular correlations in β-decay and search for scalar and tensor weak currents (mass scale for new particle comparable with LHC, possibly with ^{6}He and ^{18}Ne at 10^{12}/s)

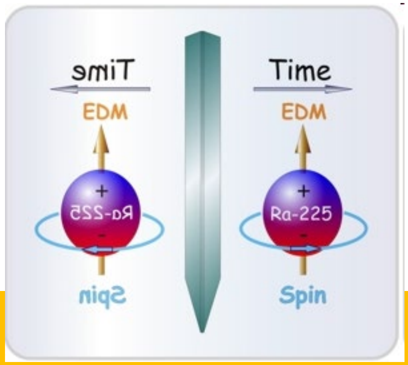
○ Testing time reversal with Electric Dipole Moments: ^{225}Ac, ^{223}Rn, ^{225}Ra, ^{229}Pa (~10,000x more sensitive than ^{199}Hg; ^{229}Pa > 10^{10}/s)

○ Parity non-conservation in atomic transitions: long chain of francium isotopes at >10[illegible]/s)

○ Unitarity of CKM matrix: V_{ud} by super-allowed Fermi decay, and probe the validity of nuclear corrections

○ Neutrinoless double-beta decay in nuclei and the majorana neutrinos

More on this later in the School



Big science questions: how can rare isotopes by used for societal benefit

Many sciences use isotopes as diagnostics for physical and biological process.

Need wide range of isotopes:

- What quantities of key isotopes can be used for targeted cancer therapy?
- Study relevant nuclear reactions needed for the US Forensics and Stewardship missions
- Separated samples of all actinides and allow their properties and fission products to be measured, in connection to energy generation.
- isotopes for study of climate change, biological catalyst pathways, production of advanced materials, etc.

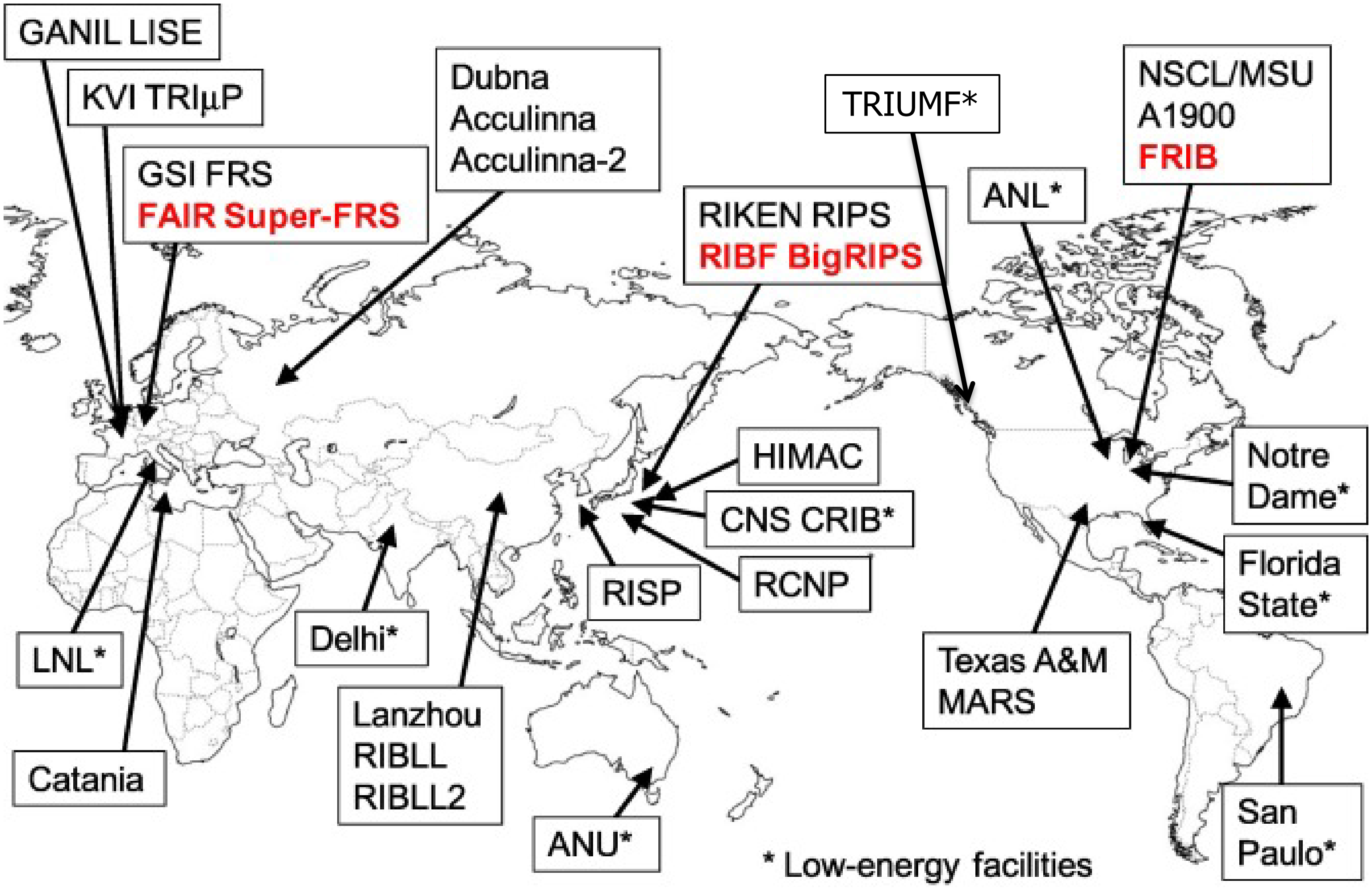
Nuclei matter to society

We are always discovering new ways in which isotopes can benefit society

- Nuclear medicine
- National Security
- Energy production
- Forensics
- Dating
- Etc, etc

How are rare isotopes produced?

rare isotope beams facilities worldwide



Kubo, NPA376 (2016)102

FRIB facility for rare isotope beams

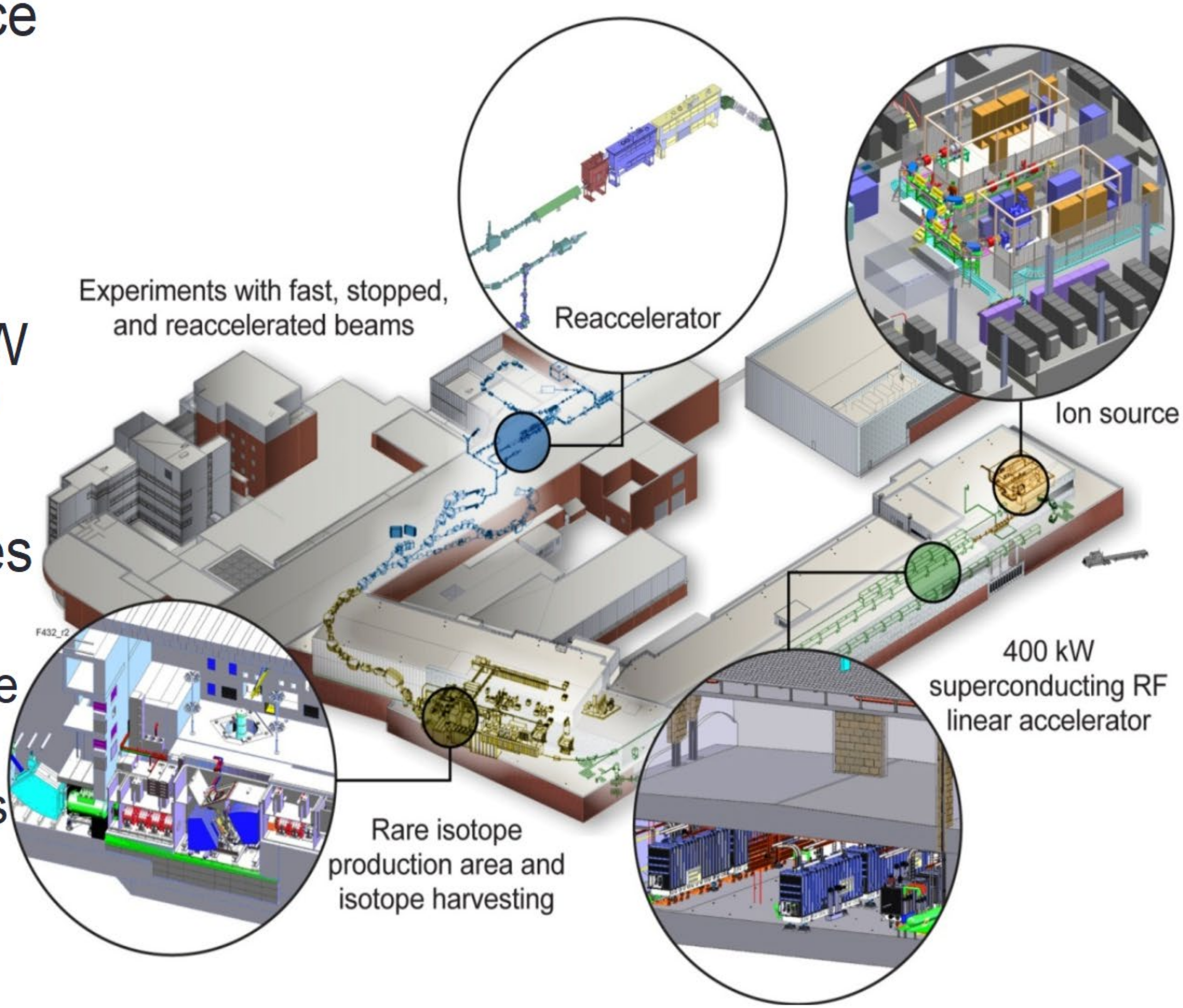
Google FRIB?

The Facility for Rare Isotope Beams (FRIB) will be a new national user facility for nuclear science that will provide intense beams of rare isotopes (that is, short-lived nuclei not normally found on Earth).

FRIB will enable scientists to make discoveries about the properties of these rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society.

Facility for Rare Isotope Beams (FRIB)

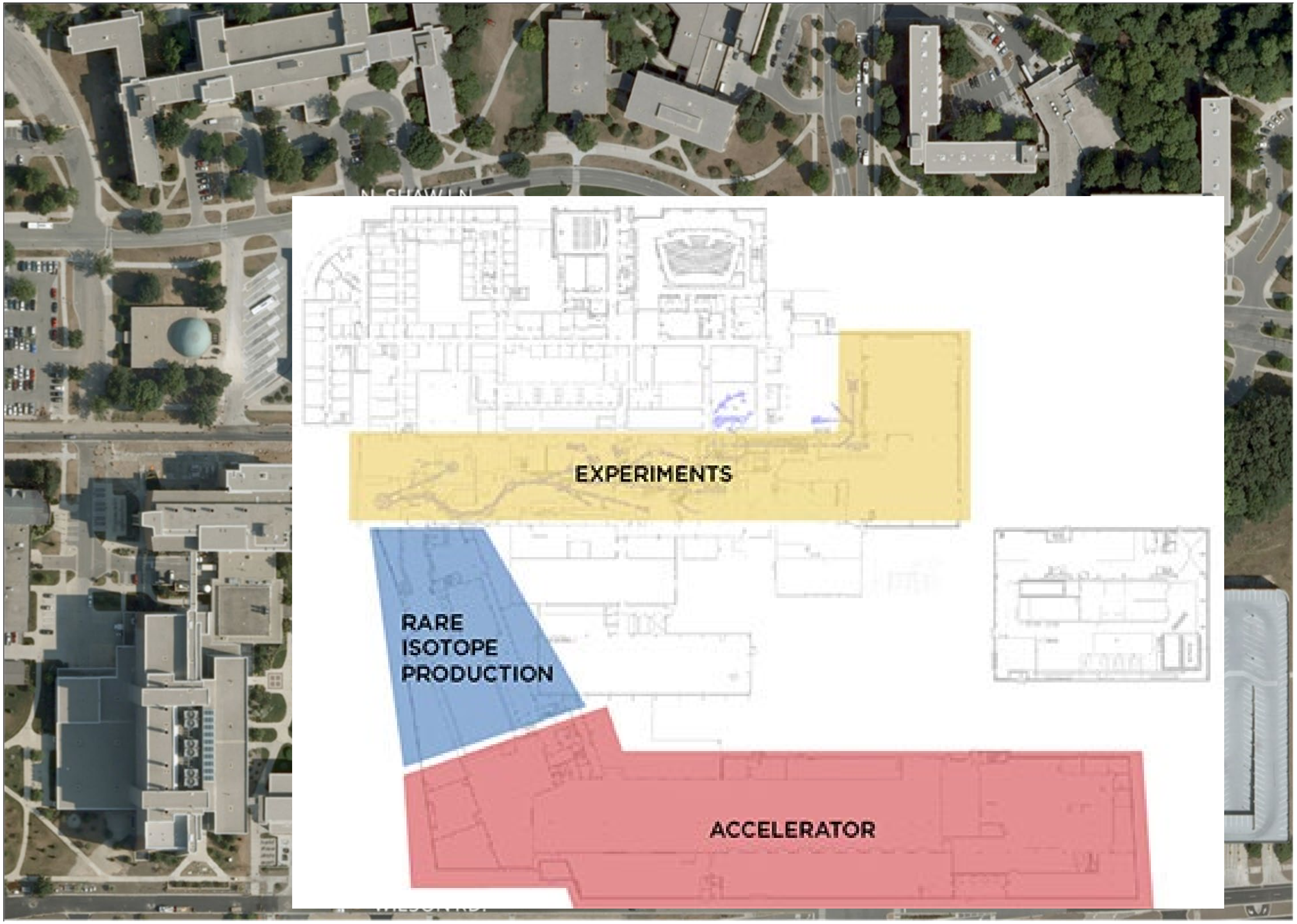
- Funded by DOE Office of Science Office of Nuclear Physics. T. Glasmacher, Project Director
- Key Feature is 400kW beam power (5 x10^{13} ^{238}U/s)
- Separation of isotopes in-flight
  - Fast development time for any isotope
  - Suited for all elements and short half-lives
  - Fast, stopped, and reaccelerated beams



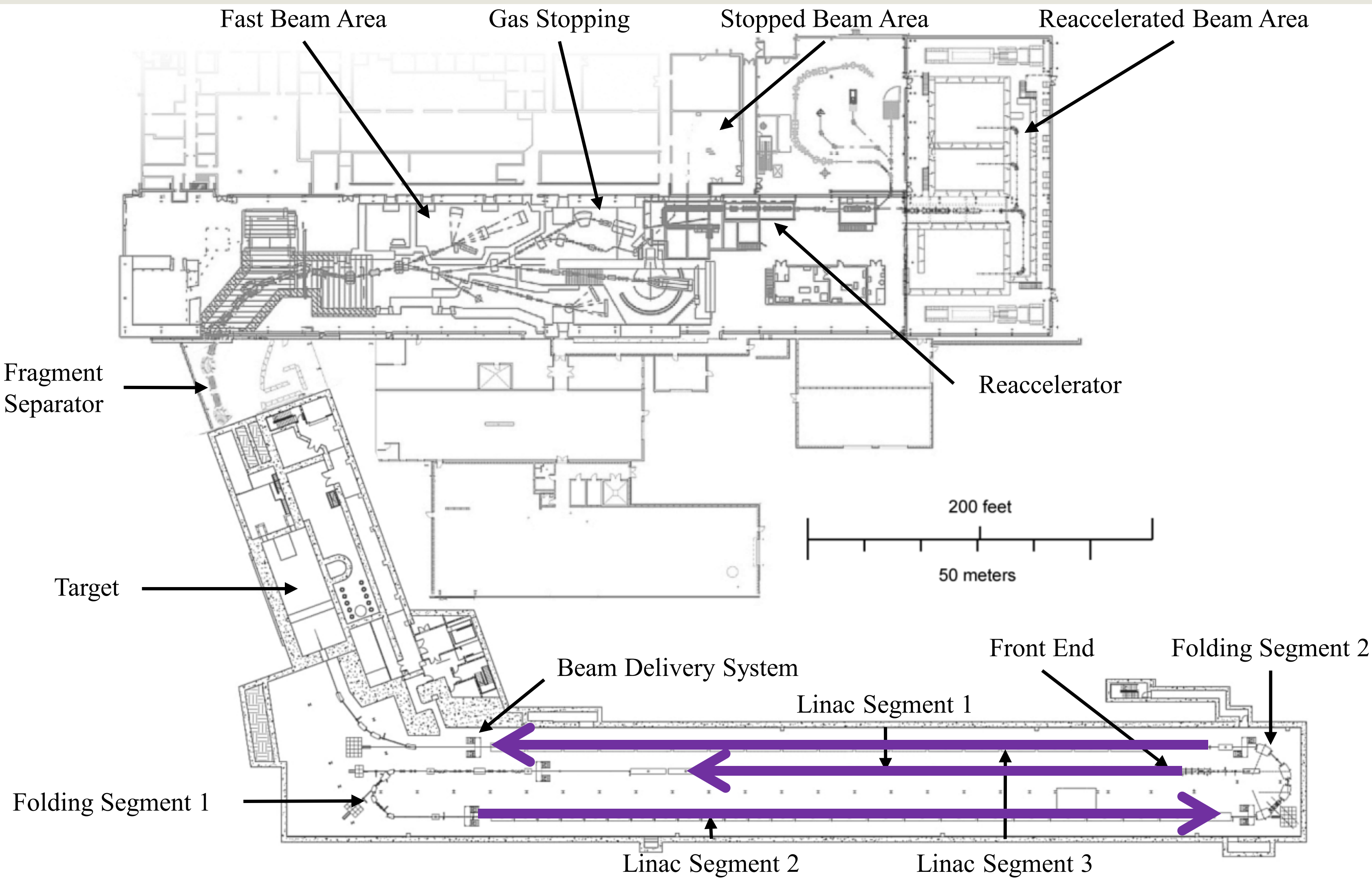
Features of FRIB

- Heavy ion, superconducting linear accelerator with 400 kW beam power at 200 MeV/u
- 400 kW corresponds to a ^{136}Xe beam of 8×10^{13} ion/s and a sensitivity to production cross sections as low as **2×10^{-6} pb**.
- ^{238}U intensity of 5×10^{13} ion/s
- FRIB laboratory will have beams of rare isotopes at a wide range of energies
  - Stopped beams for trapping, laser spectroscopy, etc.
  - Reaccelerated beams to 15 MeV/u (goal) with 15 – 22 MeV/u depending on A/Q)
  - Fast beams up to 250 MeV/u (used in-flight with no slowing)
- Limited multi-user capability through harvesting

NSCL/FRIB and the Michigan State campus

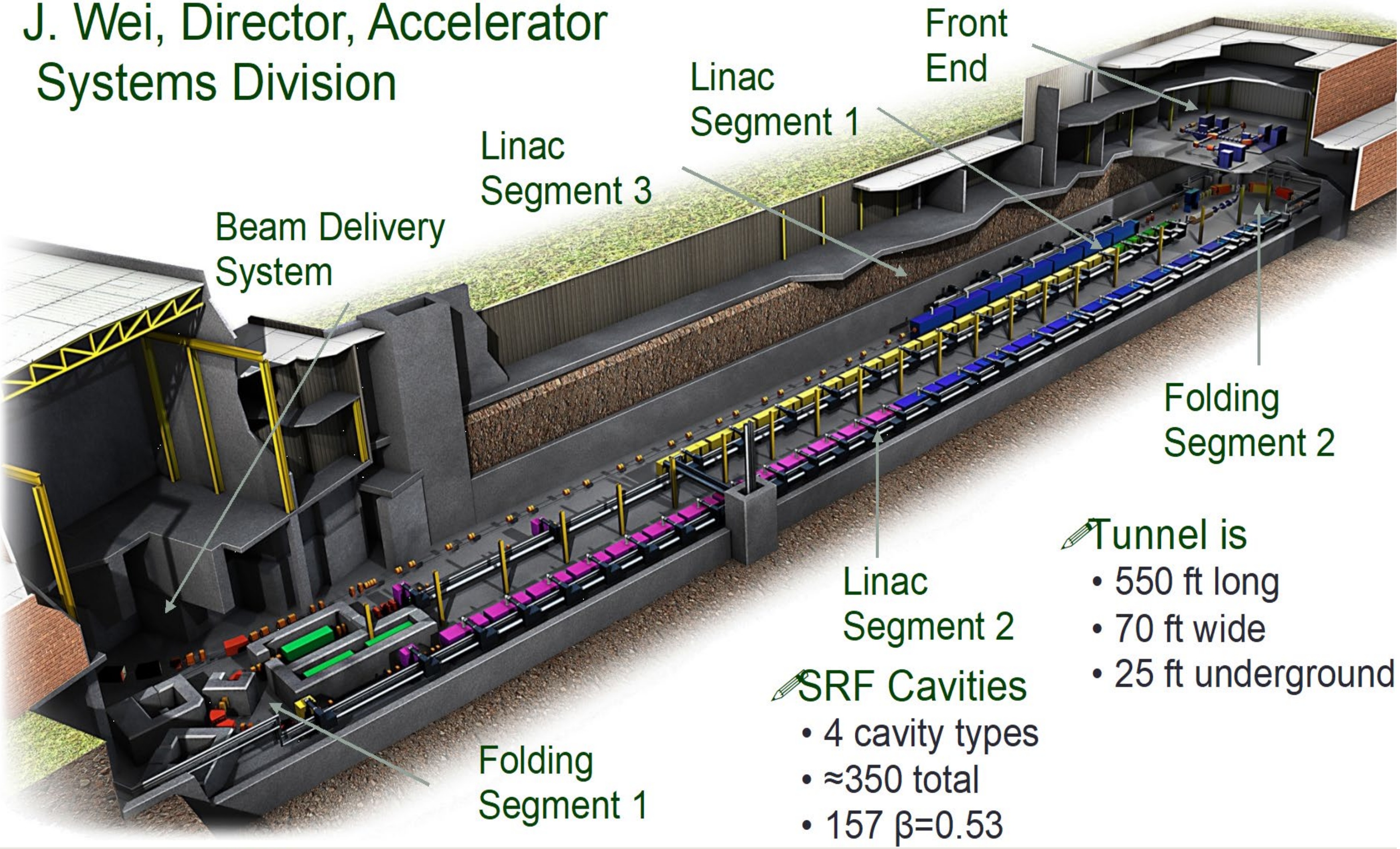


FRIB: Layout Frozen Since June 2011



FRIB driver linear accelerator

J. Wei, Director, Accelerator Systems Division

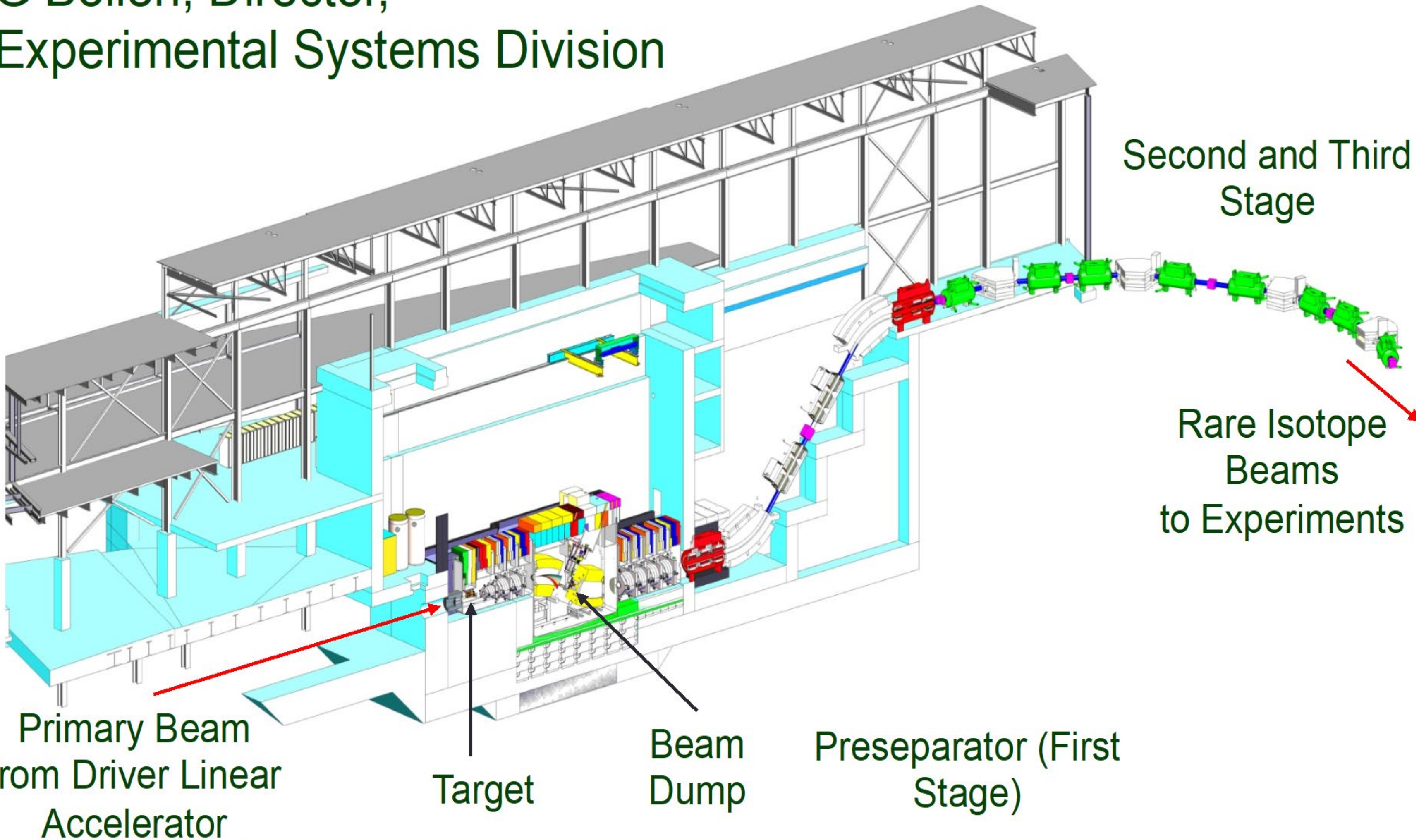


Tunnel is
- 550 ft long
- 70 ft wide
- 25 ft underground

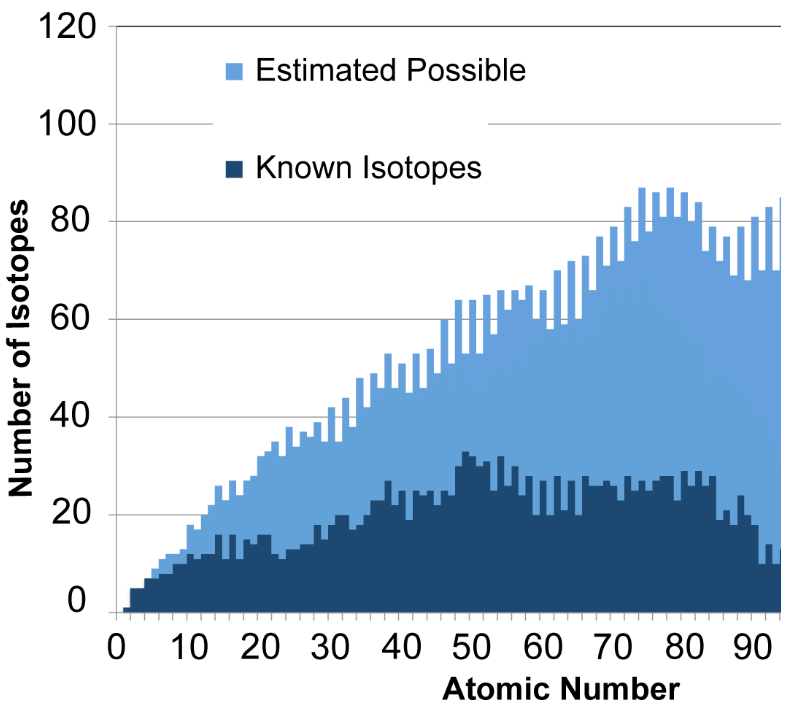
SRF Cavities
- 4 cavity types
- ≈350 total
- 157 β=0.53

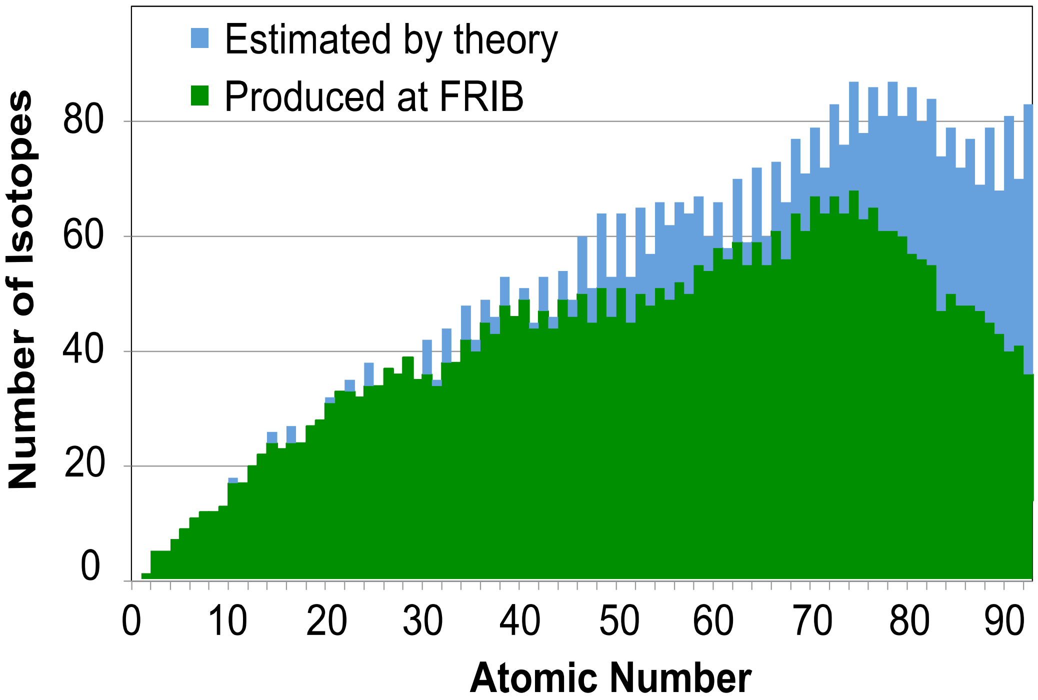
Isotope production area: target and fragment separator

G Bollen, Director,
Experimental Systems Division



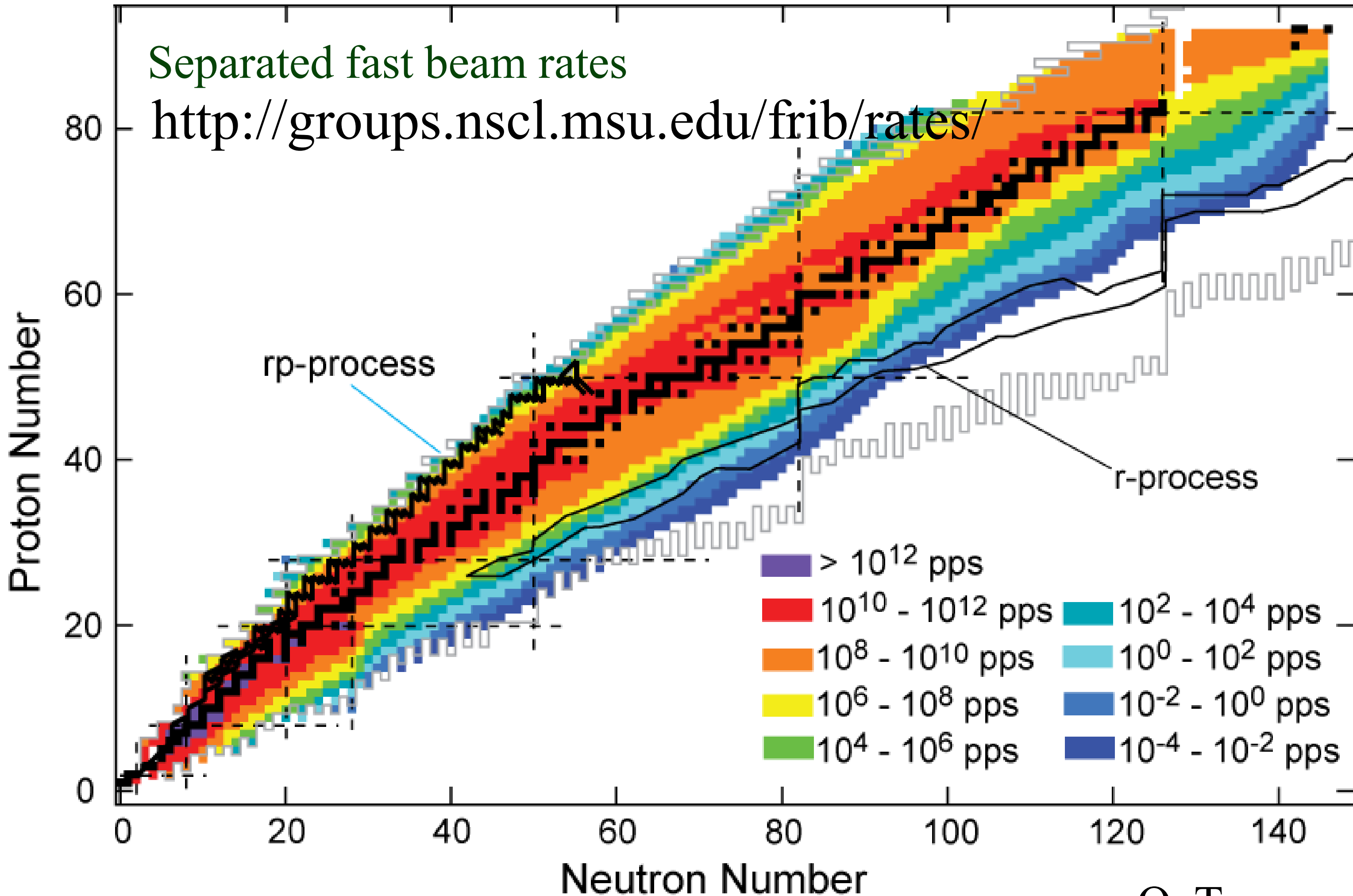
Our nucleus factory





Nearly 80% of all isotopes up to Uranium may be produced at FRIB

The Reach of FRIB – Designer Isotopes



O. Tarasov LISE++

FRIB construction

September 2015

June 2017

FRIB news

In December 2016, the radio frequency quadrupole (RFQ) was assembled and tuned in the Facility for Rare Isotope Beams linear accelerator tunnel, marking a significant technical milestone for the FRIB Project.

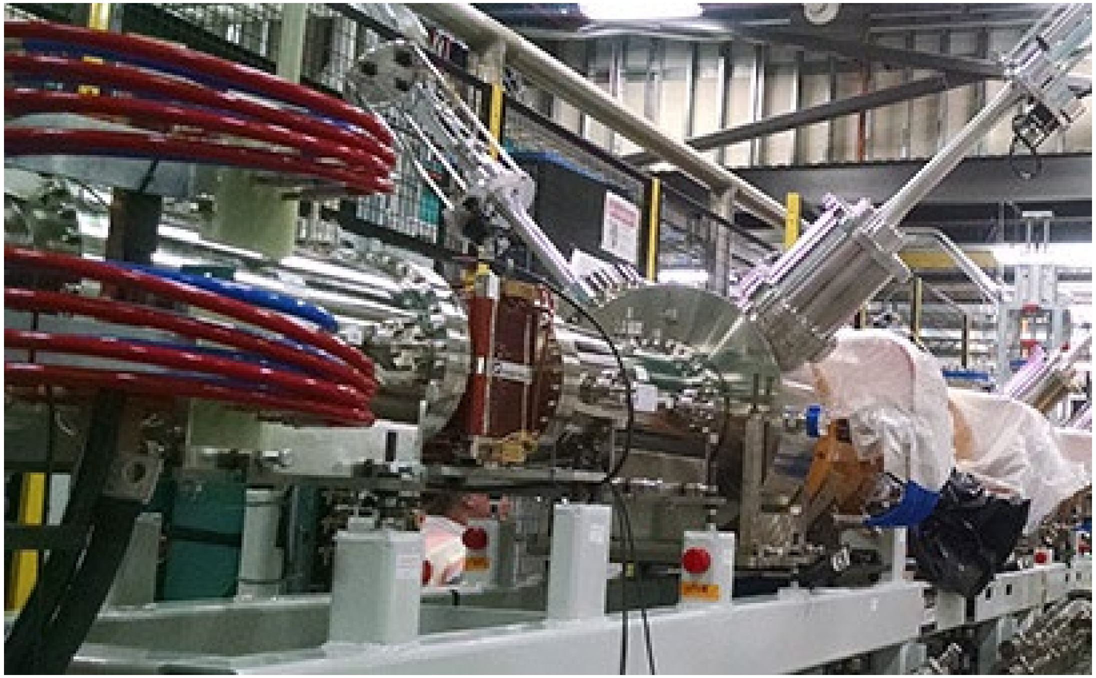
The RFQ is a critical system of the FRIB linear accelerator, required to run the beam. The energy of the beam produced by FRIB ion sources is too low for the injection into superconducting radio frequency cavities, so the RFQ increases the beam energy from 12 kiloelectron volt/atomic mass unit (keV/u) to 500 keV/u and prepares the beam for the injection into the superconducting linac.

The RFQ is a microwave cavity resonator that uses a high-frequency oscillating electromagnetic field to focus and accelerate a low-energy beam of ions.

FRIB news

The assembly and installation of all components and diagnostics for the upper Low Energy Beam Transport (LEBT) line was completed on 6 March. It was then connected to the Advanced Room-TEMperature Ion Source (ARTEMIS).

ARTEMIS was FRIB's first accelerator component to be installed, which took place last year. It is one of two electron cyclotron resonance (ECR) ion sources that FRIB will use to produce ions from elements.



QUESTION TIME

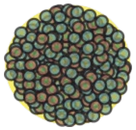
1. Consider the traditional shell model picture for the nucleus. Predict the spin and parity of the ground state of the nucleus ^{11}Be? Verify your conclusions with NNDC.

2. What are the neutron separation energies for ^{16}O, ^{17}O and ^{23}O.

3. Calculate the Q-value for $^{48}Ca(d,p)^{49}Ca(gs)$ and $^{132}Sn(d,p)^{133}Sn(gs)$ and discuss the differences in the final state.

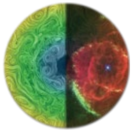
Questions

FRIB Scientific Program



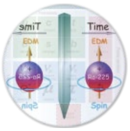
Properties of nuclei

- Develop a predictive model of nuclei and their interactions
- Many-body quantum problem: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.
- The limits of stability of elements and isotopes



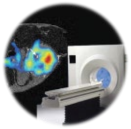
Astrophysical processes

- Stellar archeology
- Origin of the elements in the cosmos
- Explosive environments: novae, supernovae, X-ray bursts …
- Properties of neutron stars



Tests of fundamental symmetries

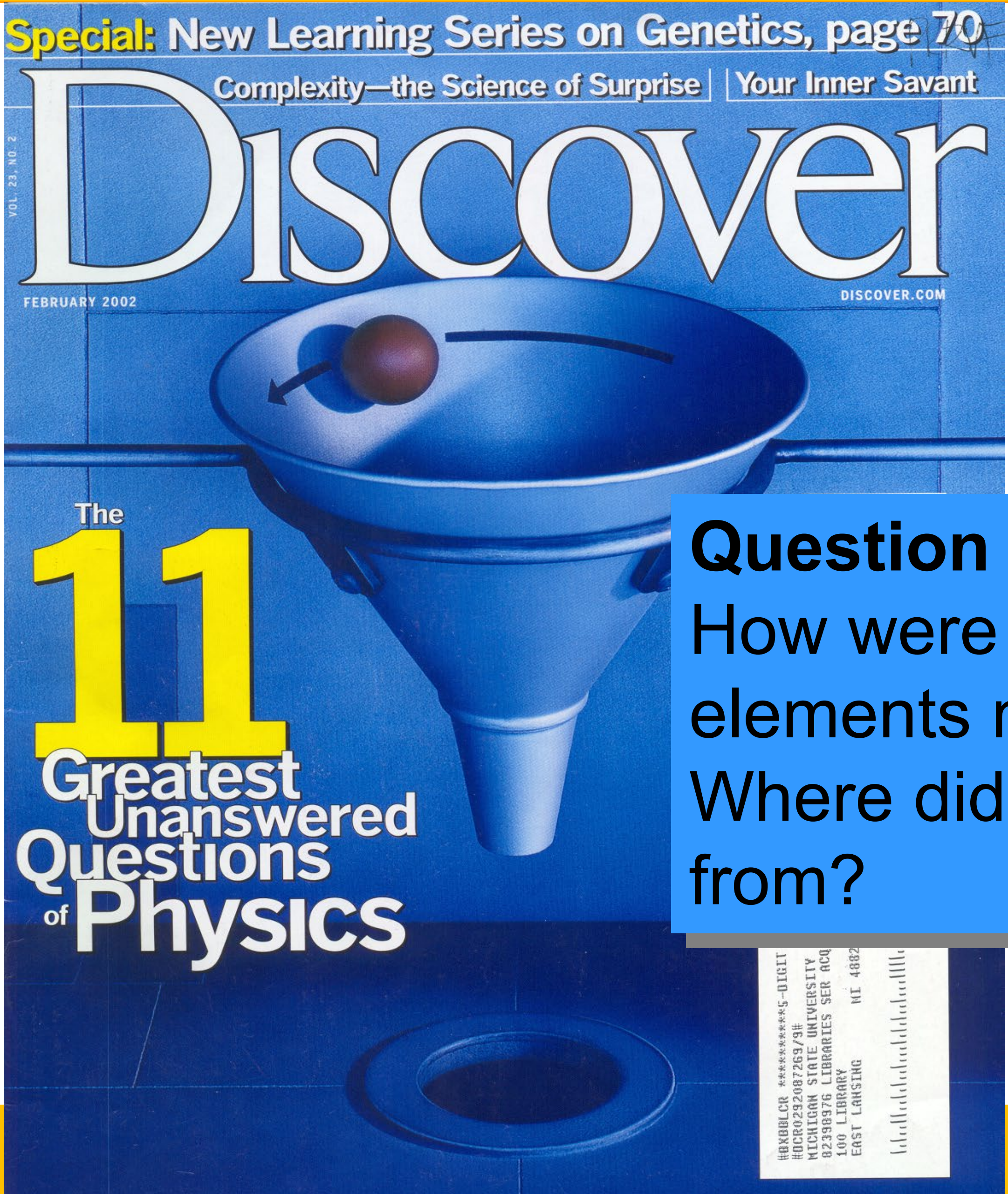
- Effects of symmetry violations are amplified in certain nuclei



Societal applications and benefits

- Biology, environment, energy, material sciences, national security

Big science questions: origin of the elements



Question 3
How were the heavy elements made? Where did it come from?