Low Energy Nuclear Experiments

Ben Kay, Argonne National Laboratory

National Nuclear Physics Summer School, 8-19 July 2019

Overview, part 1 *(general properties of nuclei, mostly macroscopic)*

What can experimentalists determine about a nuclear system in the lab?

- *History … the isotopes, the facilities we use*
- *What can we measure/is observable?*
- *Questions to ask about the nucleus*
  - *How much do they weigh?*
  - *What size are they?*
  - *What shape are they?*

Attempt to use many accessible examples from recent literature, leaning towards the study of exotic nuclei where possible

Overview, part 2 *(mostly direct reactions, not so exotic, <u>microscopic</u>)*

The connection between direction reactions and nuclear structure

- *History*
- *Reactions, reaction types, direct reactions*
- *Observables*
- *Energies, momentum*
- *Spectroscopic factors, occupancies (in context of 'modern' [but stable-beam] examples)*
- *Other reactions (pairing, cluster, charge exchange)*

Attempt to steer clear of reactions for reaction's sake, rather using them as a meaningful tool to gain insights into topical nuclear structure properties

Overview, part 3 *(mostly direct reactions, quite exotic, microscopic)*

The connection between direction reactions and nuclear structure

- *History*
- *Exotic beams*
- *Kinematics*
- *Spectrometers (with a focus on solenoidal spectrometers)*
- *A few examples from the last few years (2014, 2017, 2017, 2019) (what drove them, reaction choices, results, commentary)*

Reading

- Slides from past schools (NNPSS [Heather Crawford's are exemplary], EBSS) are impressive (next slide for references)
- Books are good, but often dense and not always transparent (on direct reactions, my personal favorites are N. K. Glendenning's *Direct Nuclear Reactions*, and C. A. Bertulani and P. Danielewicz's *Introduction to Nuclear Reactions*.
- Great papers (some of the older ones can be wonderfully pedagogical, others far less so). I will attempt to highlight some as I go through.

Past schools … slides on reactions

2002 (ORNL 1st), 2003 (NSCL 2nd), 2004 (ANL 3rd), 2005 (LBNL 4th) 2006 (ORNL 5th), 2007 (NSCL 6th), 2008 (ANL 7th), 2009 (LBNL 8th) 2010 (ORNL 9th)

https://people.nscl.msu.edu/~zegers/ebss2011/cizewski.pdf (J. Cizewski of Rutgers, NSCL 2011) …10th in EBSS series

http://www.phy.anl.gov/atlas/EBSS2012/NuclearReactions-ExperimentI.pptx (L. Trache of Texas A&M, ANL 2012) … 11th
http://www.phy.anl.gov/atlas/EBSS2012/NuclearReactions-ExperimentII.pptx

http://fribusers.org/documents/2013/ebssLectures/reactions1.pdf (Grigory Rogachev of FSU, LBNL 2013) … 12th
http://fribusers.org/documents/2013/ebssLectures/reactions2.pdf
http://fribusers.org/documents/2013/ebssLectures/reactions3.pdf

http://fribusers.org/documents/2014/ebssLectures/hoffman_1.pdf (Calem Hoffman of Argonne, ORNL 2014) … 13th
http://fribusers.org/documents/2014/ebssLectures/hoffman_2.pdf

http://aruna.physics.fsu.edu/ebss_lectures/F_Lecture2.pdf (Ben Kay of Argonne, FSU 2015) … 14th

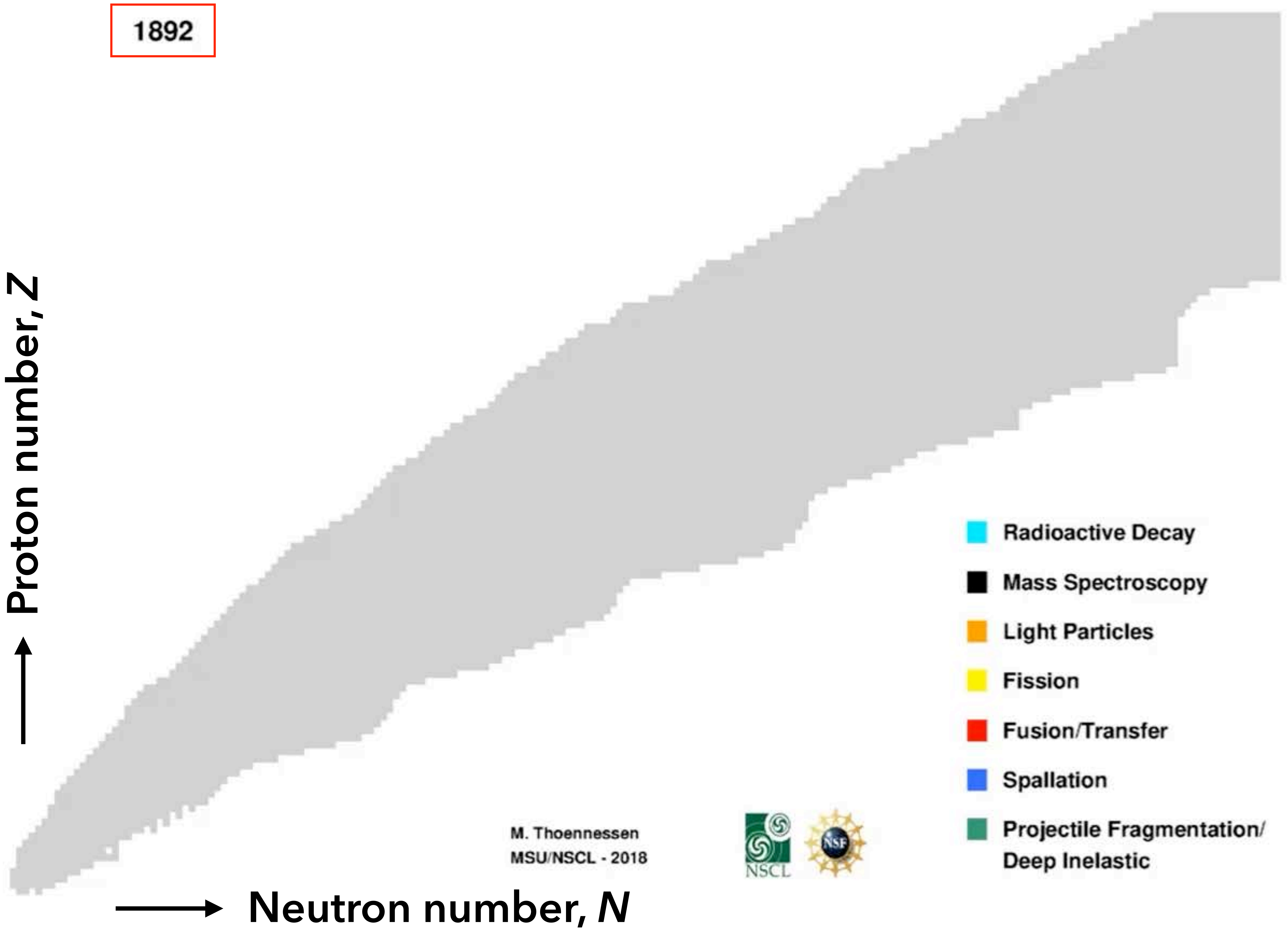
https://people.nscl.msu.edu/~iwasaki/EBSS2016/reaction_1.pdf (Alan Wuosmaa of UConn, NSCL 2016) … 15th
https://people.nscl.msu.edu/~iwasaki/EBSS2016/reaction_2.pdf
https://people.nscl.msu.edu/~iwasaki/EBSS2016/reaction_3.pdf

http://www.phy.anl.gov/ebss2017/ebss-2017-zegers.pdf (Remco Zegers of NSCL, ANL 2017) … 16th

And soon, these slides … 17th

Part 1: General overview
Isotopes, masses, sizes, shapes

Isotopes



https://people.nscl.msu.edu/~thoennes/isotopes/

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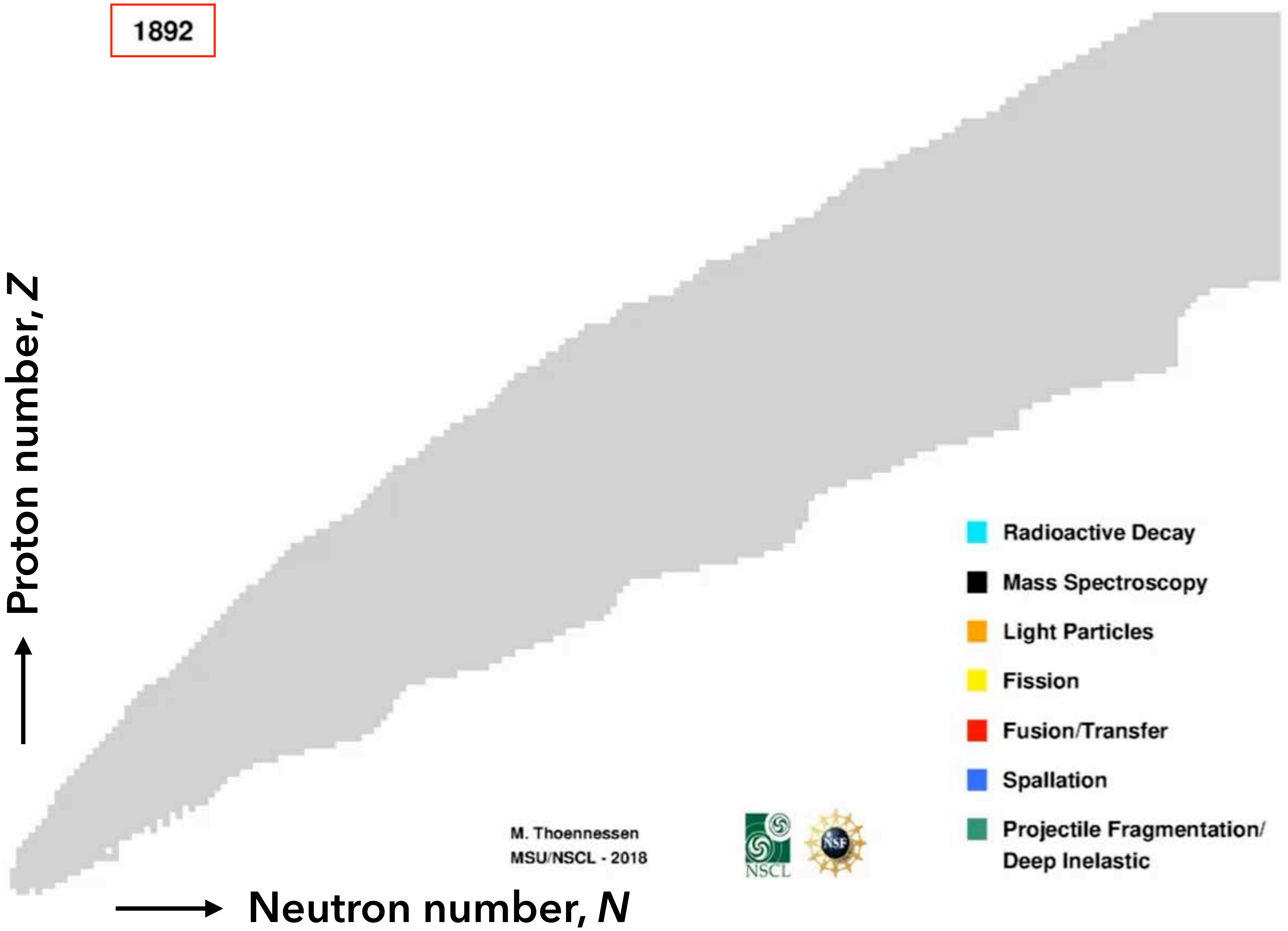
Isotopes



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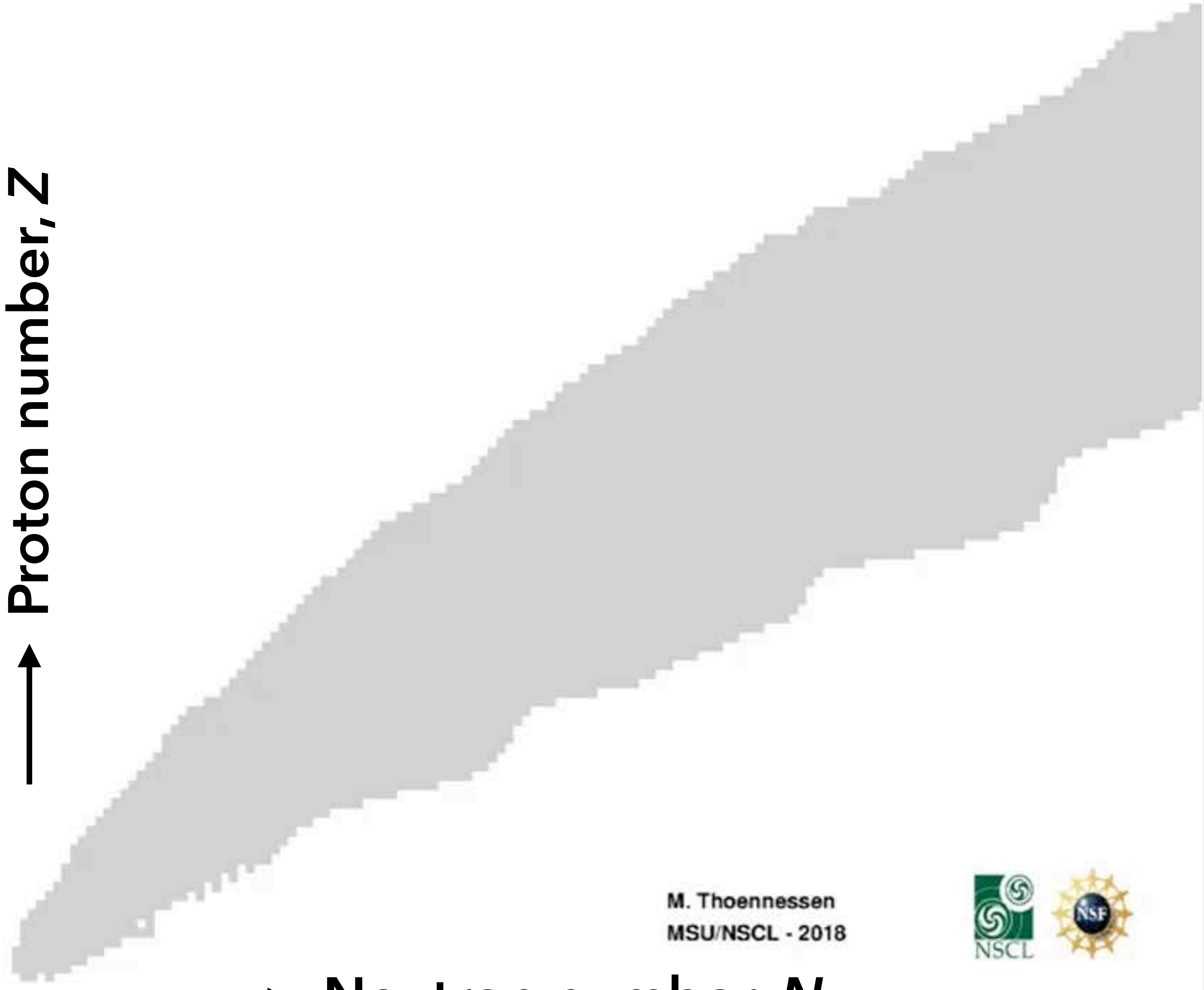
Isotopes

1892



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Physics Letters B 795 (2019) 266–270

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Discovery of ^{68}Br in secondary reactions of radioactive beams

K. Wimmer [a,b,*], P. Doornenbal [b], W. Korten [c], P. Aguilera [d], A. Algora [e,f], T. Ando [a], T. Arici [g,h], H. Baba [b], B. Blank [i], A. Boso [j], S. Chen [b], A. Corsi [c], P. Davies [k], G. de Angelis [l], G. de France [m], D.T. Doherty [c], J. Gerl [g], R. Gernhäuser [n], D.G. Jenkins [k], S. Koyama [a], T. Motobayashi [b], S. Nagamine [a], M. Niikura [a], A. Obertelli [c,b], D. Lubos [n], B. Rubio [e], E. Sahin [o], T.Y. Saito [a], H. Sakurai [a,b], L. Sinclair [k], D. Steppenbeck [b], R. Taniuchi [a], R. Wadsworth [k], M. Zielinska [c]

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ARTICLE INFO

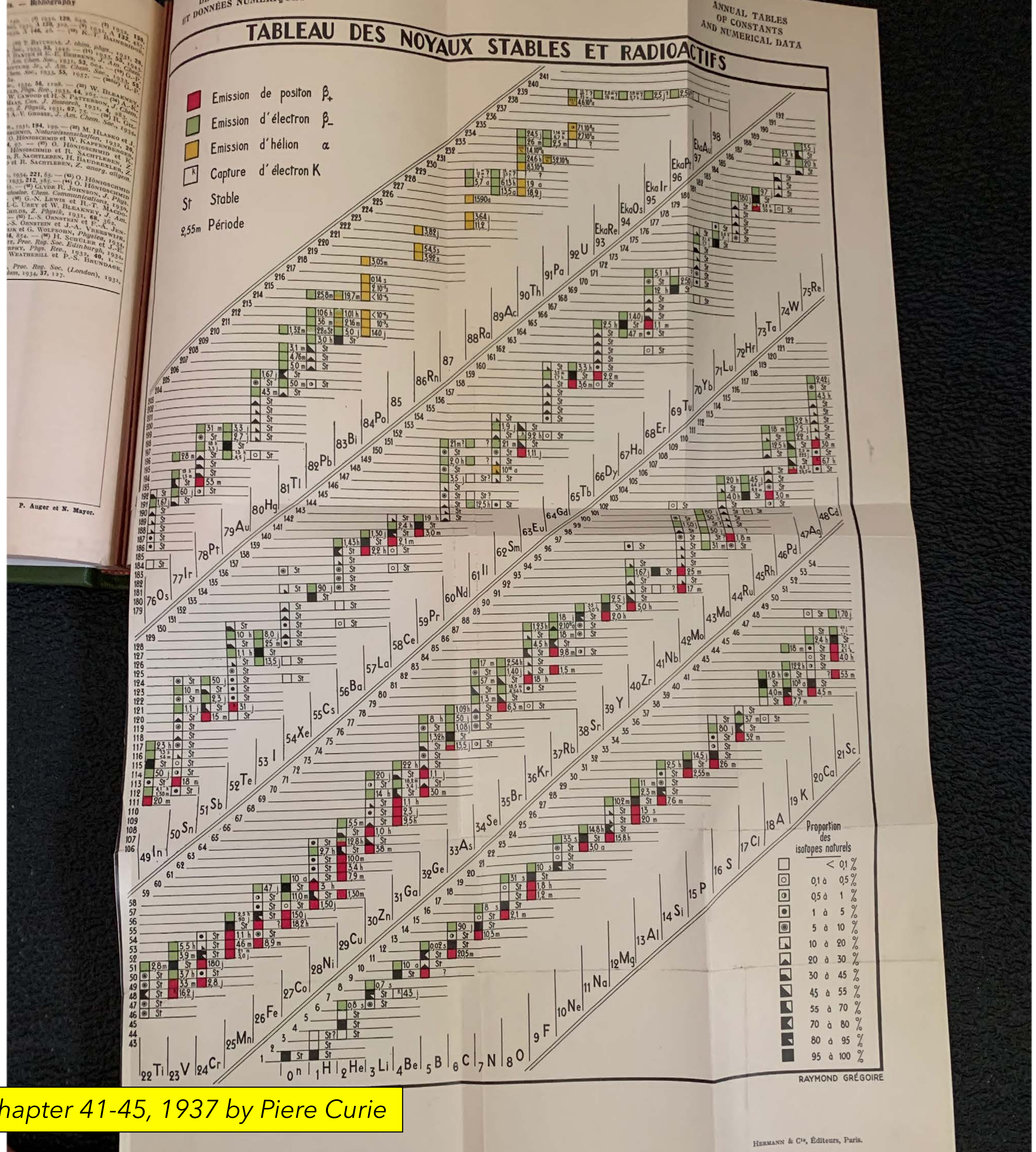
Article history:
Received 15 May 2019
Received in revised form 10 June 2019
Accepted 10 June 2019
Available online 12 June 2019
Editor: D.F. Geesaman

Keywords:
Radioactive beams
New isotope
Direct reaction

ABSTRACT

The proton-rich isotope ^{68}Br was discovered in secondary fragmentation reactions of fast radioactive beams. Proton-rich secondary beams of ^{70,71,72}Kr and ^{70}Br, produced at the RIKEN Nishina Center and identified by the BigRIPS fragment separator, impinged on a secondary ^{9}Be target. Unambiguous particle identification behind the secondary target was achieved with the ZeroDegree spectrometer. Based on the expected direct production cross sections from neighboring isotopes, the lifetime of the ground or long-lived isomeric state of ^{68}Br was estimated. The results suggest that secondary fragmentation reactions, where relatively few nucleons are removed from the projectile, offer an alternative way to search for new isotopes, as these reactions populate preferentially low-lying states.

1937

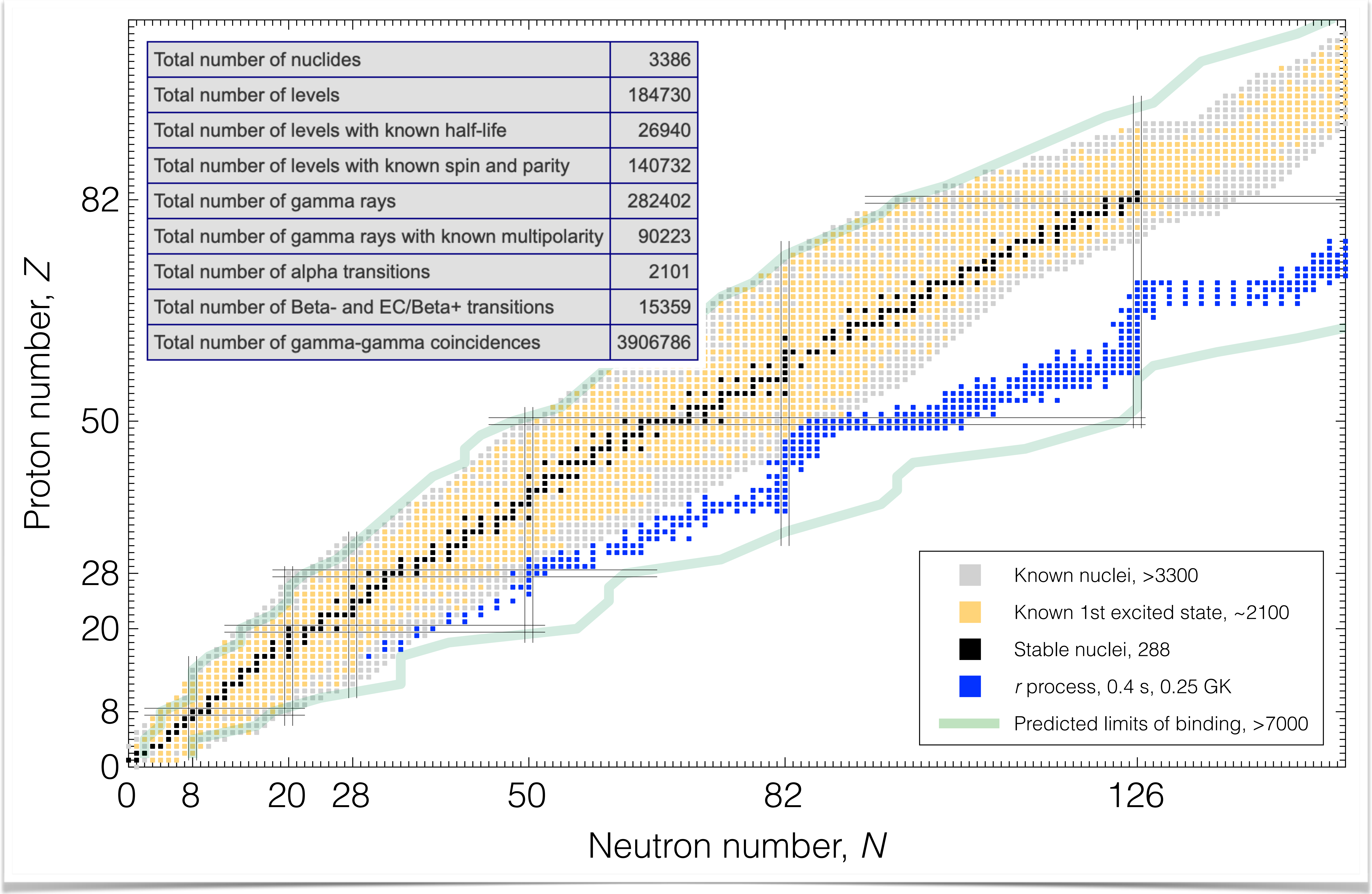


World pop: 2.3 B
Gas: 16 cents/gal.

From Table Annuelles Volume XI, Chapter 41-45, 1937 by Piere Curie

Today ...

World pop: 7.53 B
Gas: 250 cents/gal.



Total number of nuclides	3386
Total number of levels	184730
Total number of levels with known half-life	26940
Total number of levels with known spin and parity	140732
Total number of gamma rays	282402
Total number of gamma rays with known multipolarity	90223
Total number of alpha transitions	2101
Total number of Beta- and EC/Beta+ transitions	15359
Total number of gamma-gamma coincidences	3906786

*Limits from Erler et al., Nature **486**, 509 (**2012**), other information from https://www.nndc.bnl.gov/nudat2/help/index.jsp*

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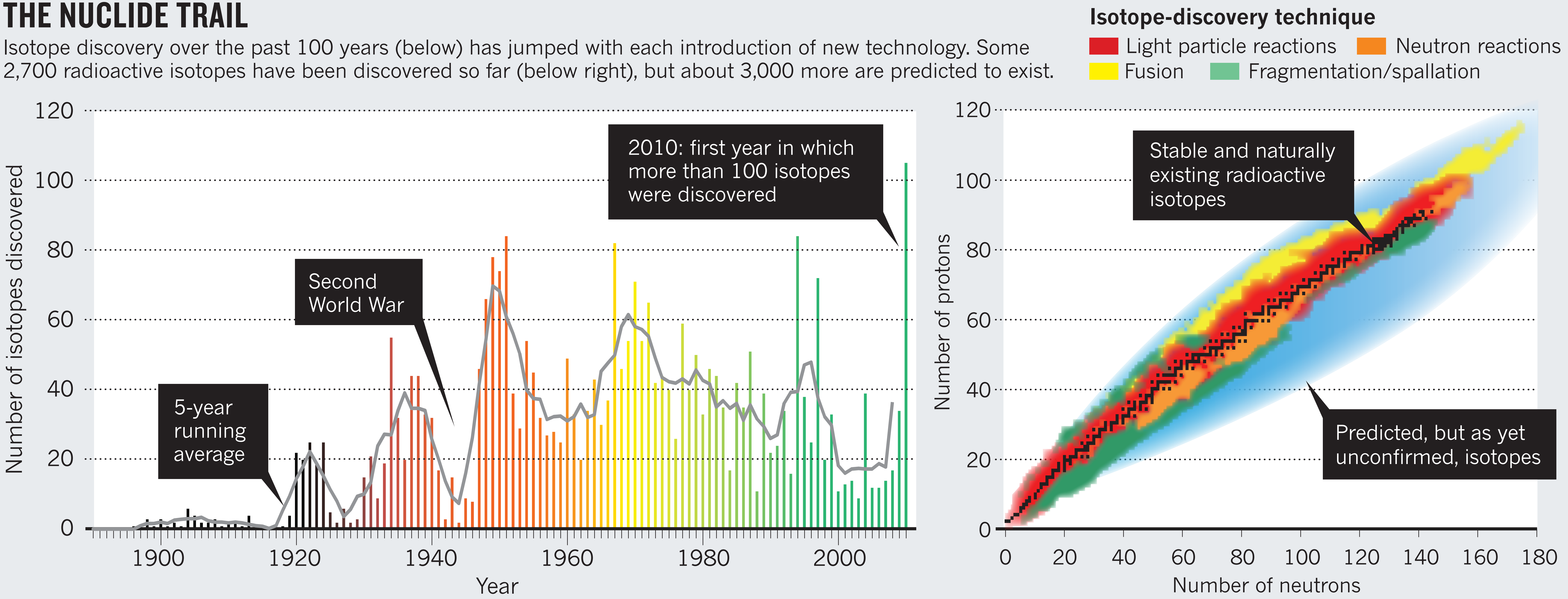
Isotopes

THE NUCLIDE TRAIL

Isotope discovery over the past 100 years (below) has jumped with each introduction of new technology. Some 2,700 radioactive isotopes have been discovered so far (below right), but about 3,000 more are predicted to exist.



*M. Thoennessen and B. Sherrill, Nature **473**, 25 (**2011**)*

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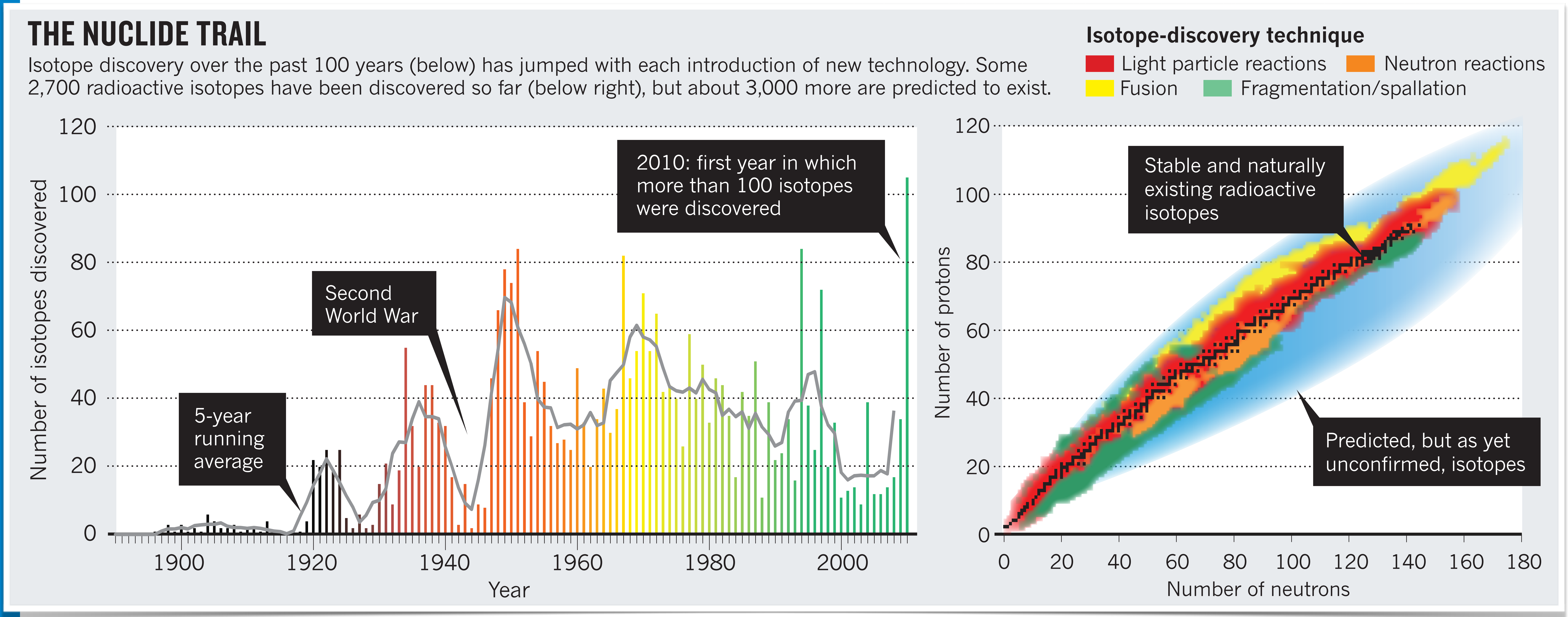
Isotopes



^{12}O	^{13}O	^{14}O	^{15}O	^{16}O	^{17}O	^{18}O	^{19}O	^{20}O	^{21}O	^{22}O	^{23}O	^{24}O	^{25}O	^{26}O	^{27}O	^{28}O

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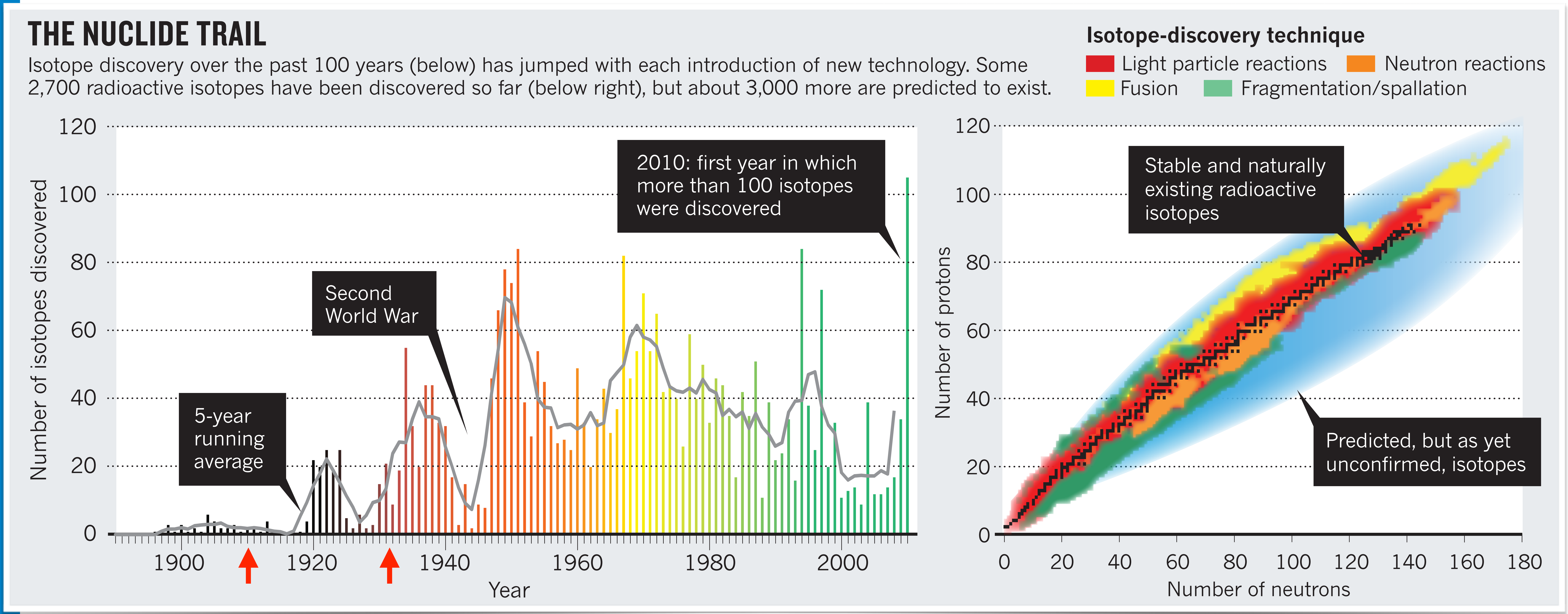
Isotopes



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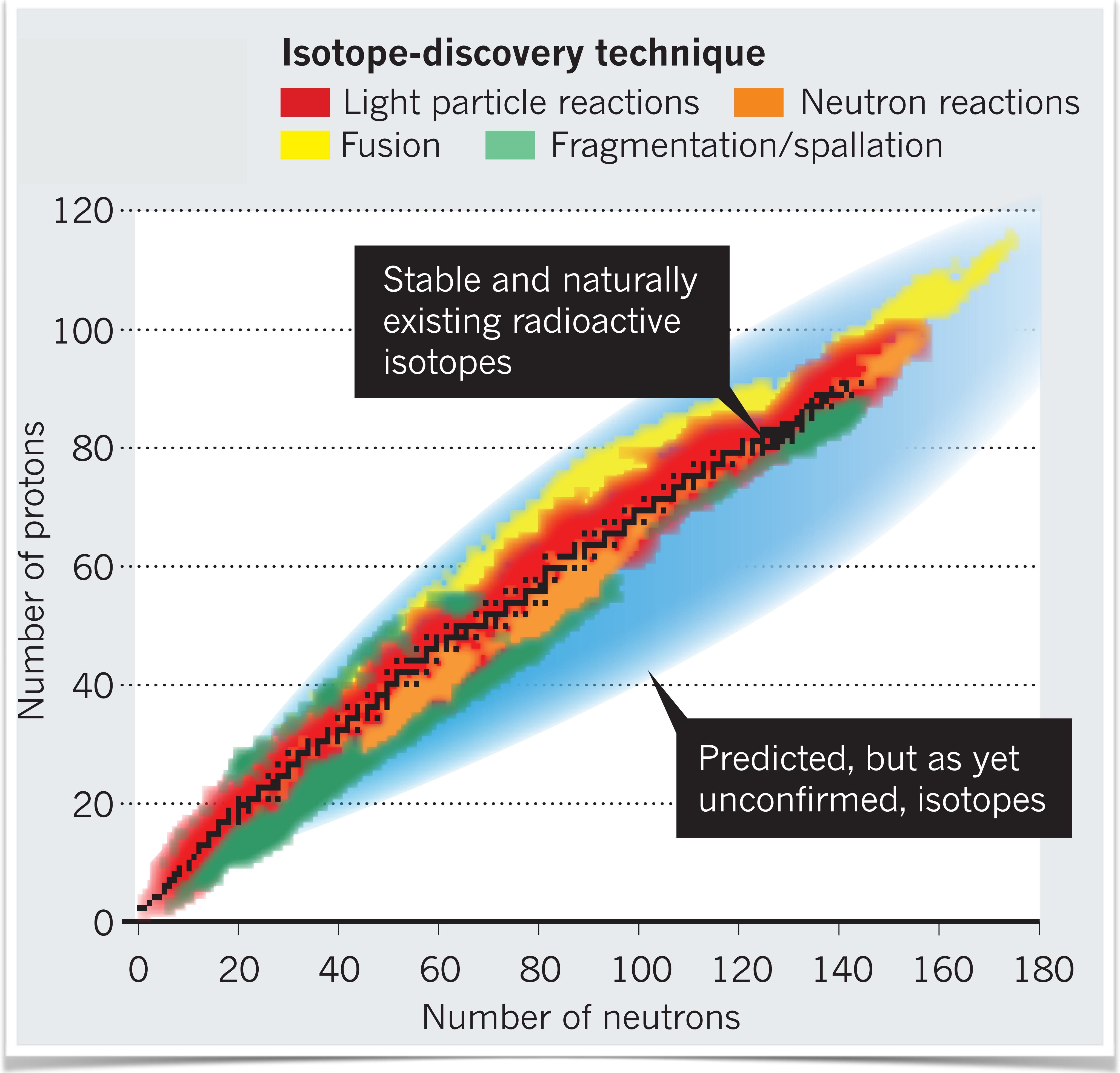
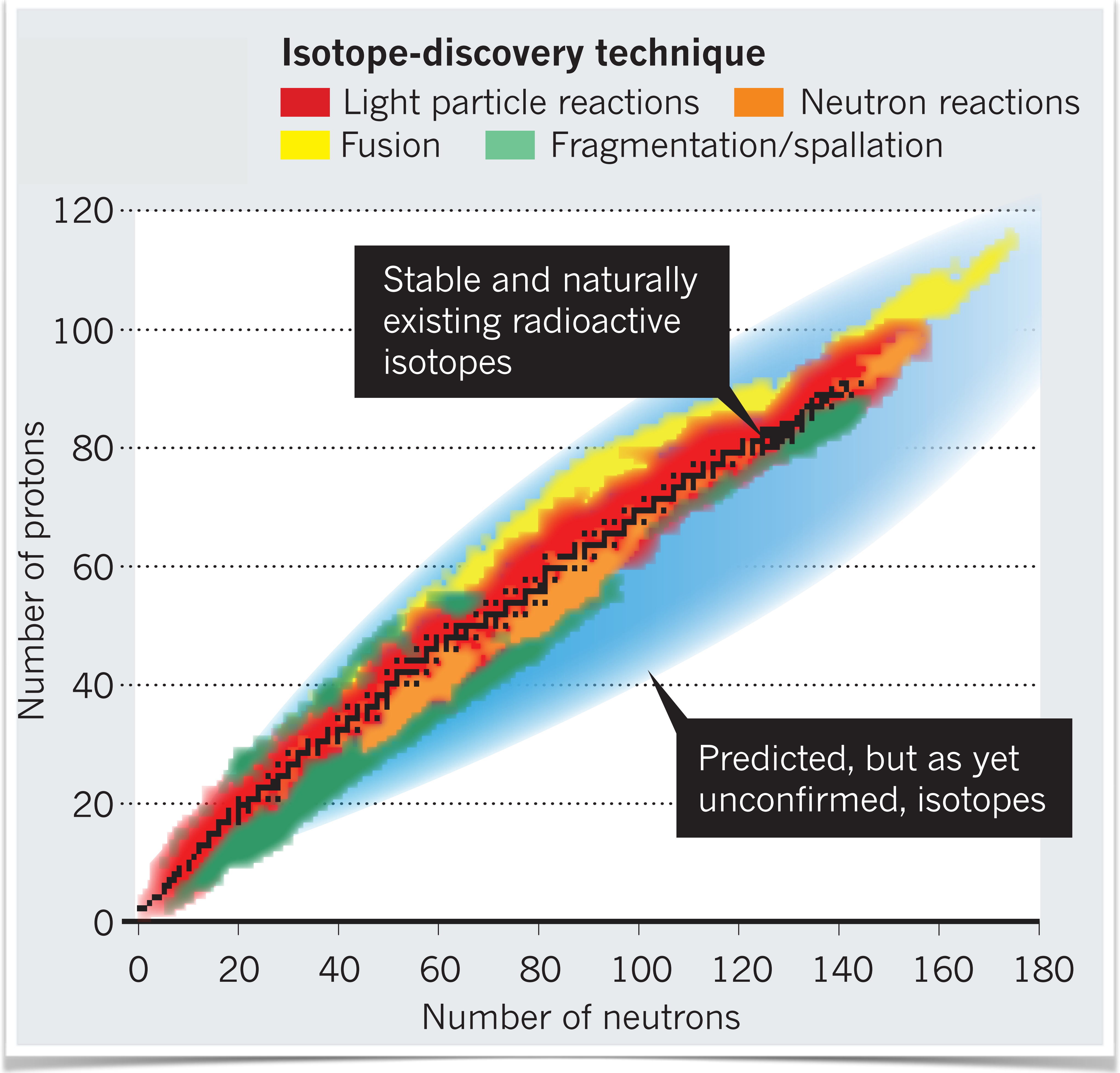
Isotopes

First challenge for an experimentalist is to make/probe the nucleus you want to study …



Isotopes

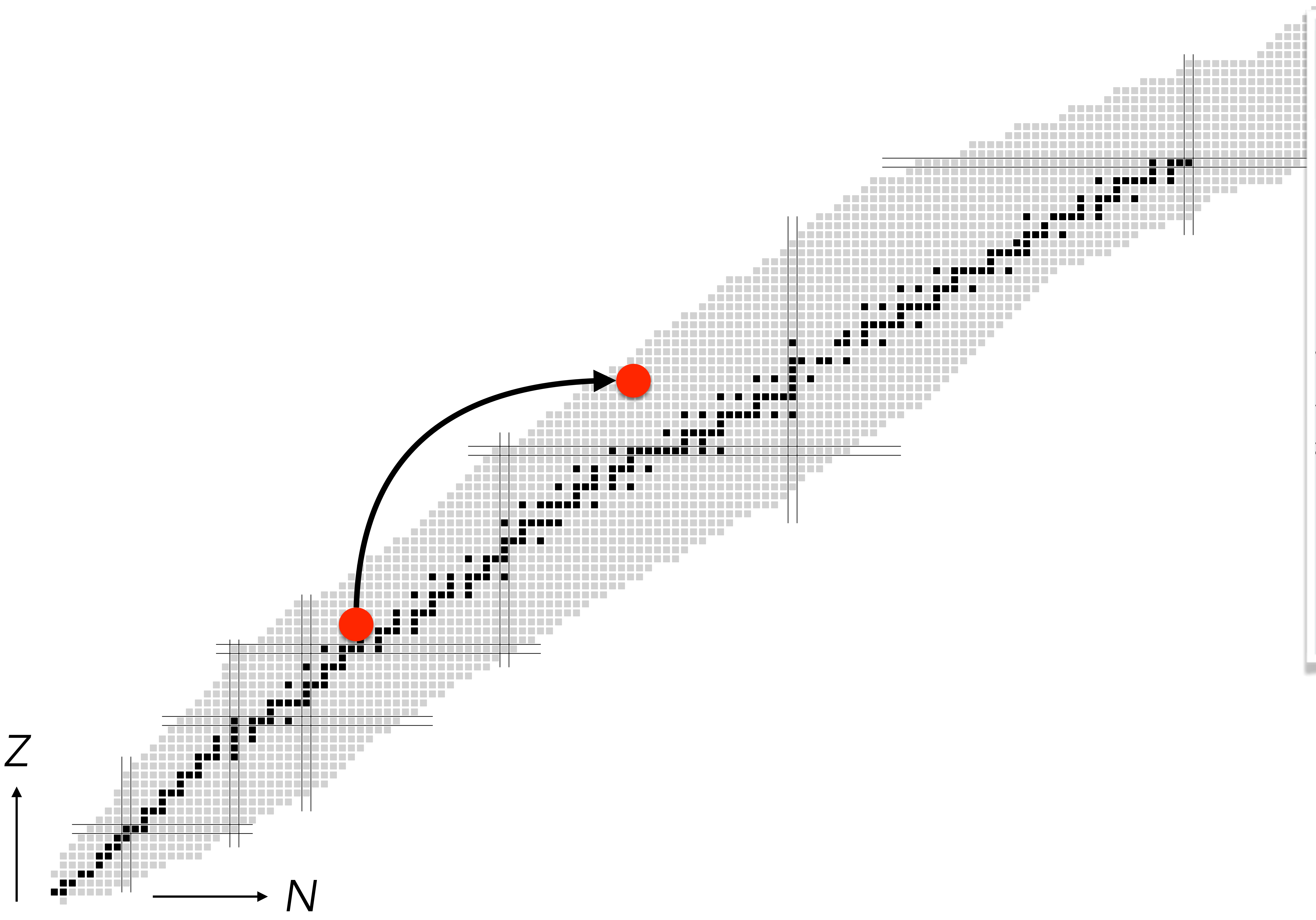
First challenge for an experimentalist is to make/probe the nucleus you want to study …

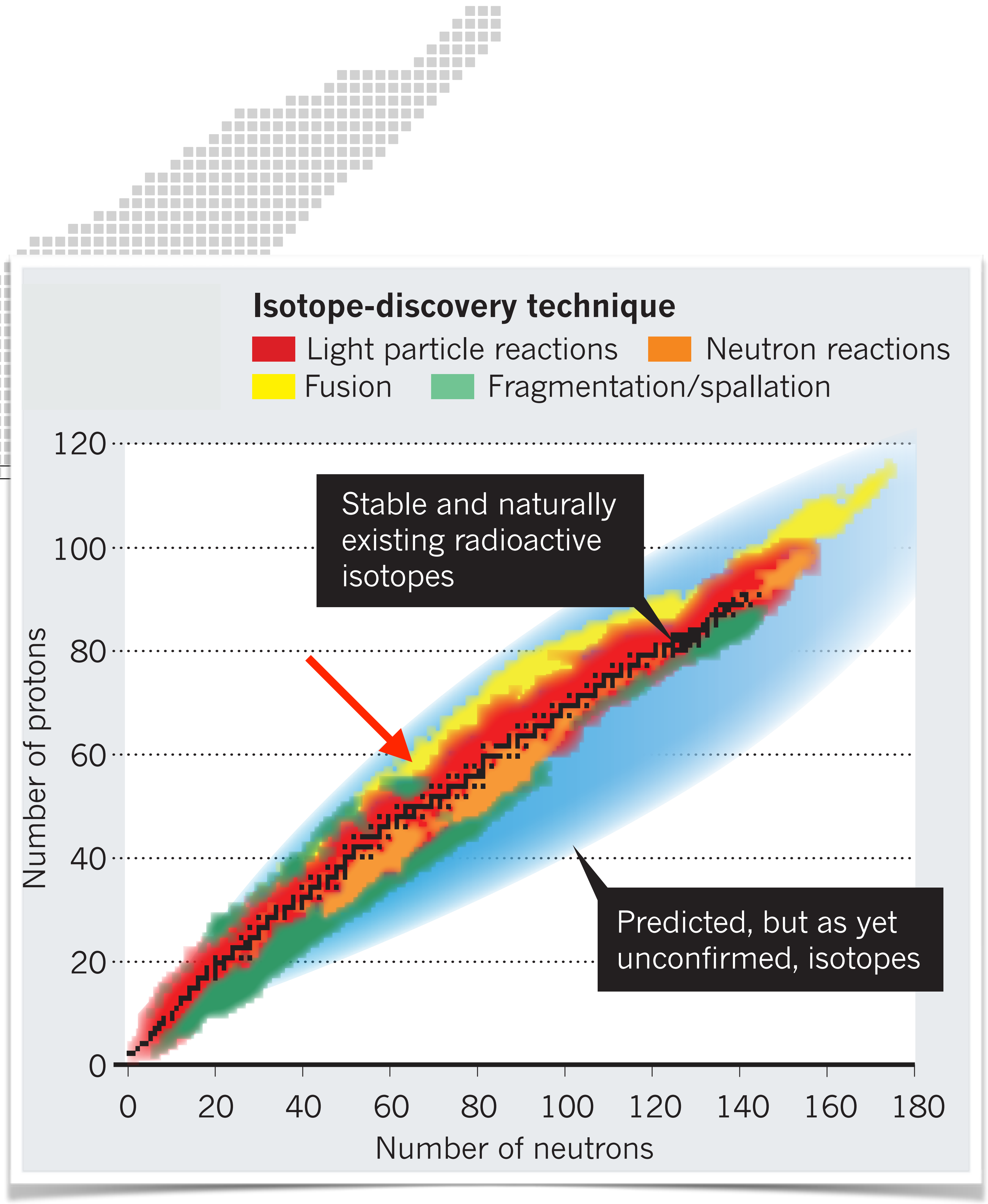


$^{12}\mathrm{O}$	$^{13}\mathrm{O}$	$^{14}\mathrm{O}$	$^{15}\mathrm{O}$	$^{16}\mathrm{O}$	$^{17}\mathrm{O}$	$^{18}\mathrm{O}$	$^{19}\mathrm{O}$	$^{20}\mathrm{O}$	$^{21}\mathrm{O}$	$^{22}\mathrm{O}$	$^{23}\mathrm{O}$	$^{24}\mathrm{O}$	$^{25}\mathrm{O}$	$^{26}\mathrm{O}$	$^{27}\mathrm{O}$	$^{28}\mathrm{O}$

E.g. fusion(-evaporation)

^{122}Ce discovered via ^{64}Zn + ^{64}Zn → ^{122}Ce + α + 2n





*J. F. Smith et al. PLB **625**, 203 (**2005**), Bark et al., Nucl. Phys. A **514**, 503 (**1990**) (and A. N. Deacon's thesis, Manchester **2006**)*

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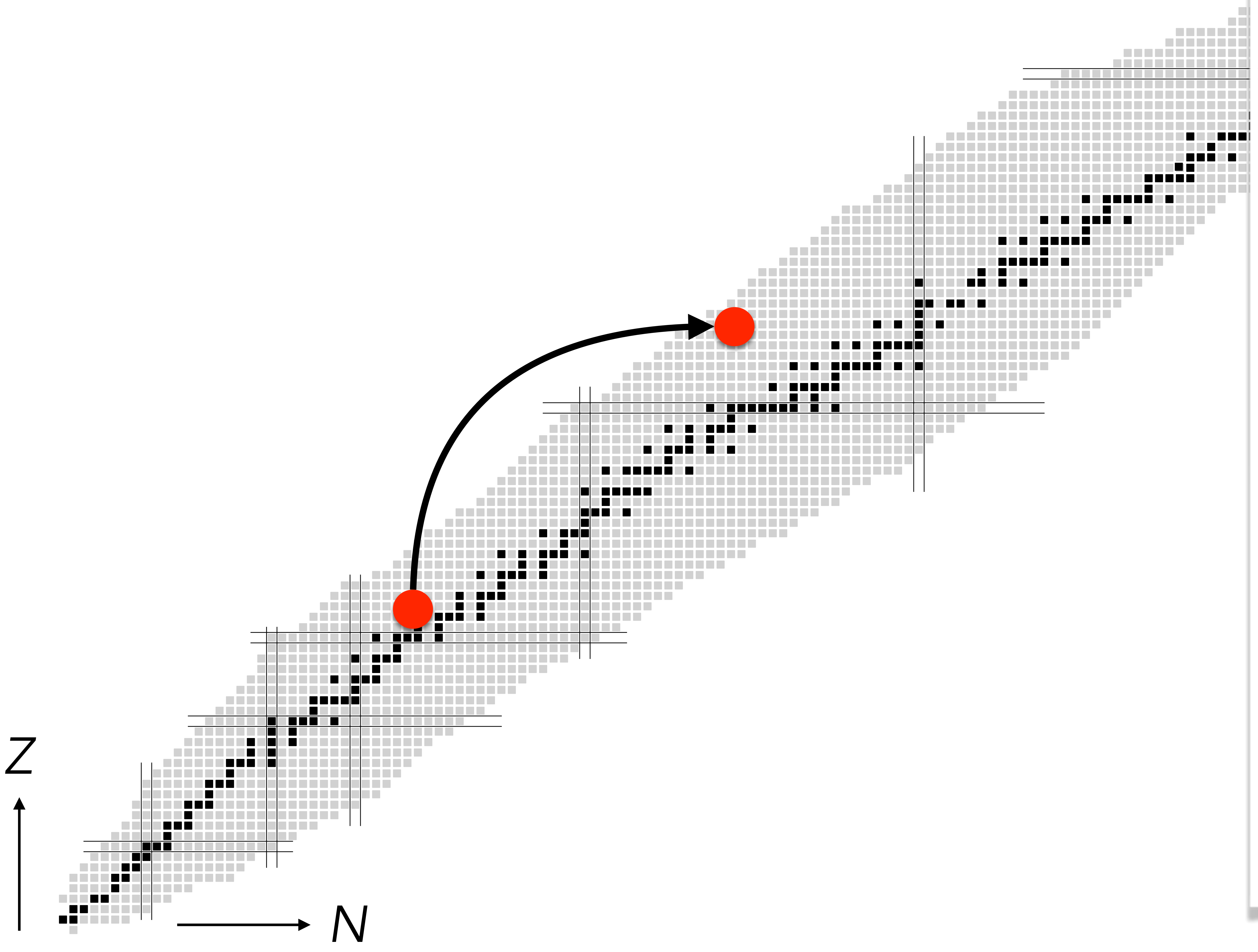

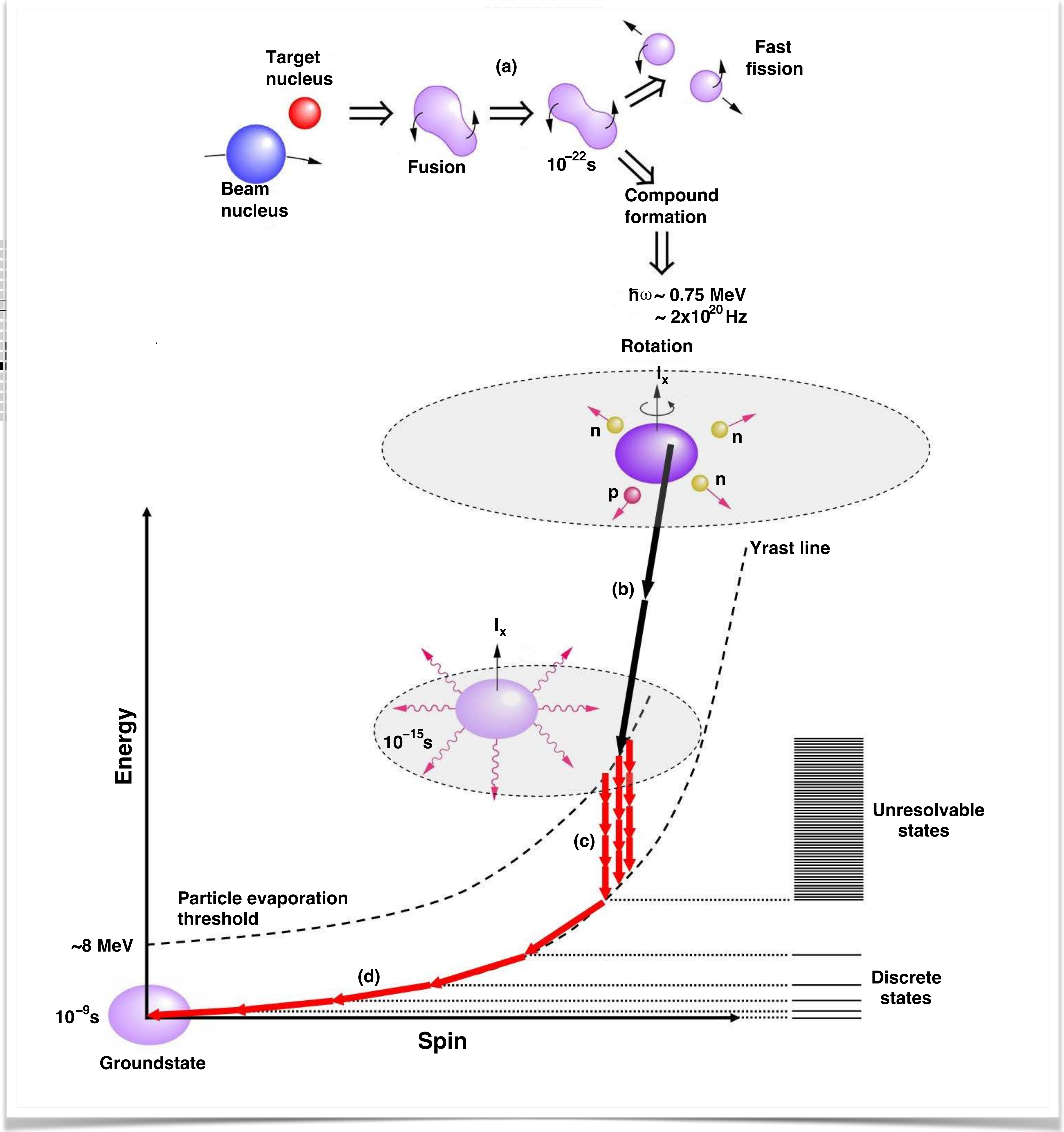

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E.g. fusion(-ev

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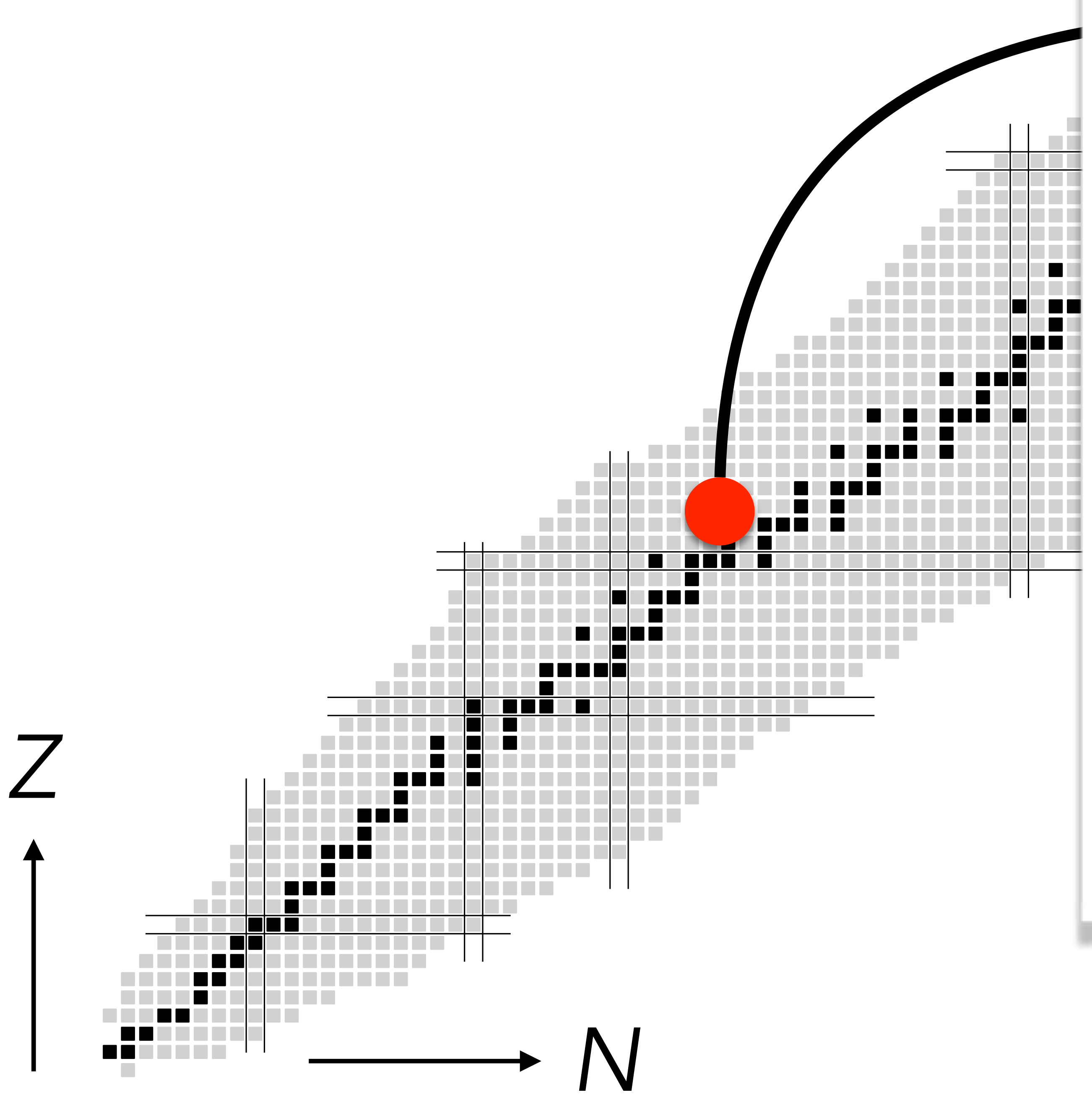

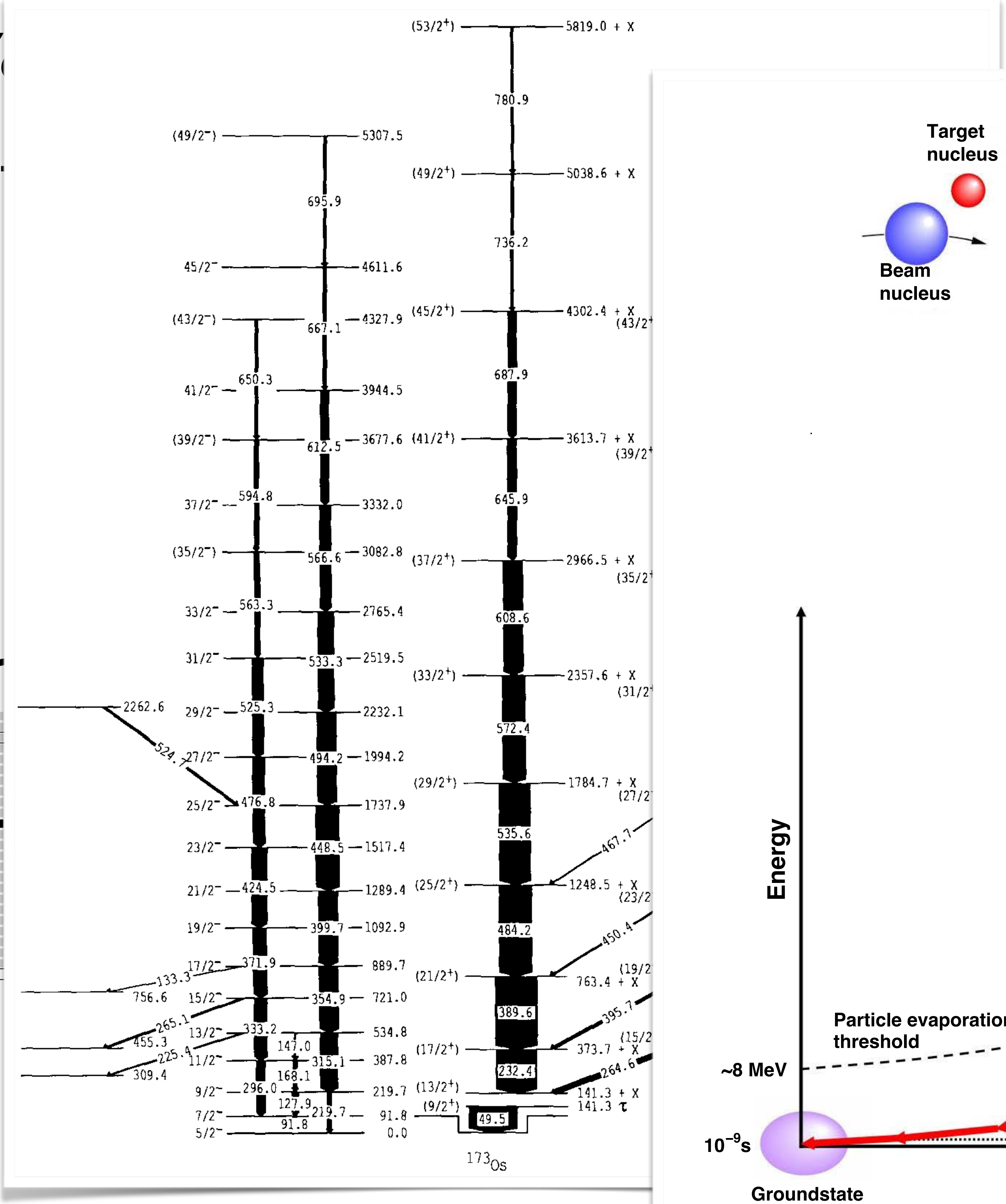

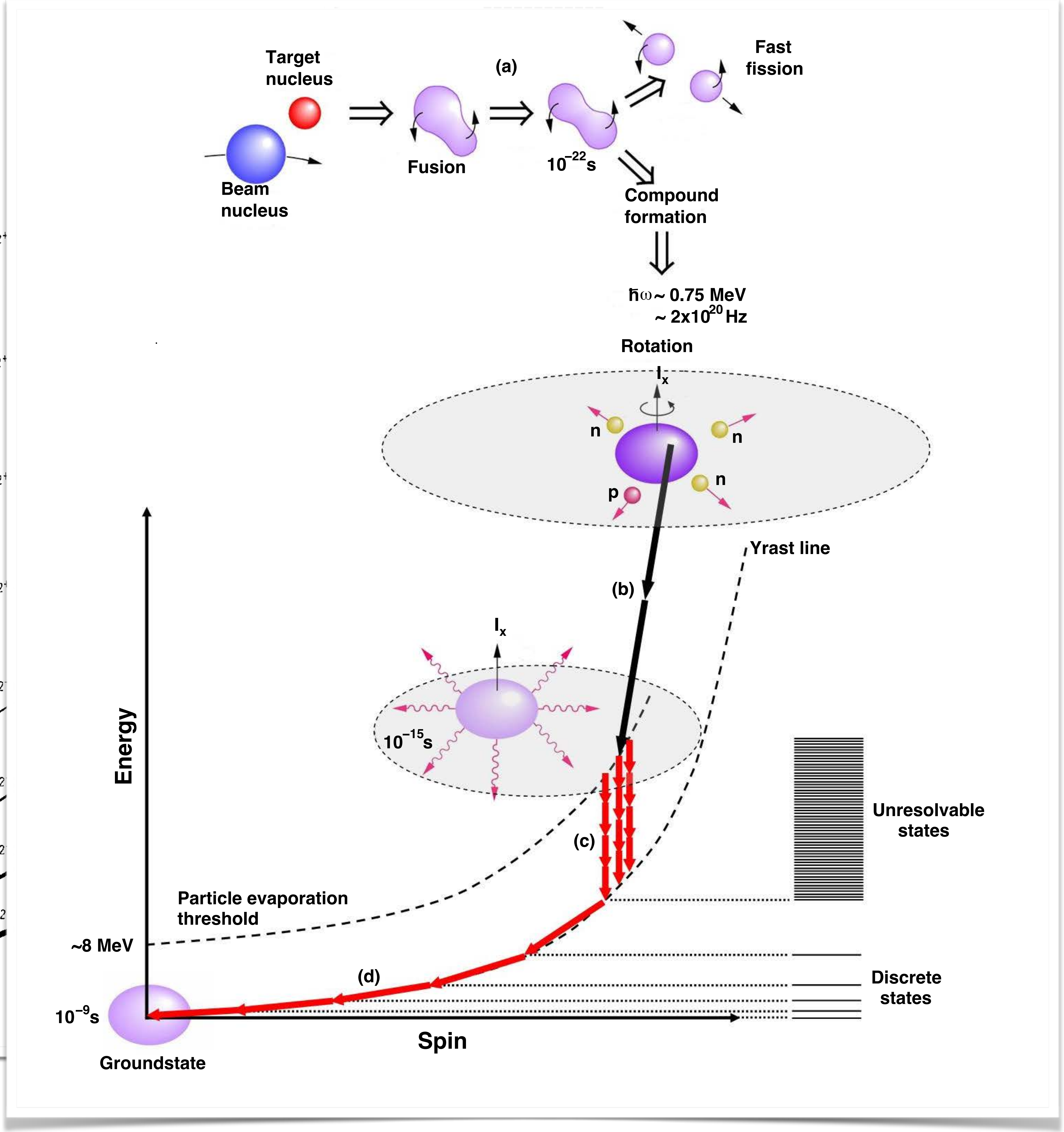

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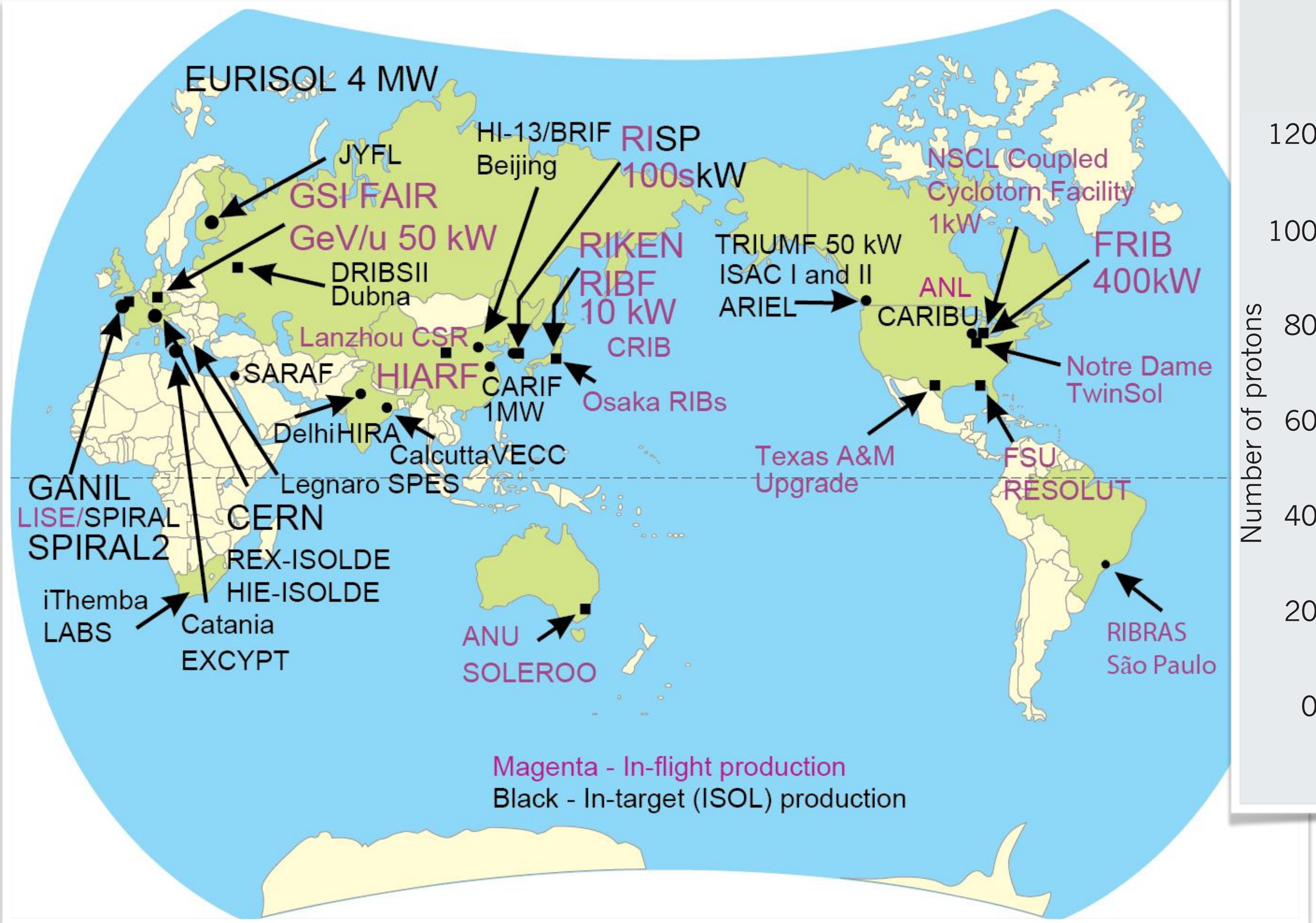
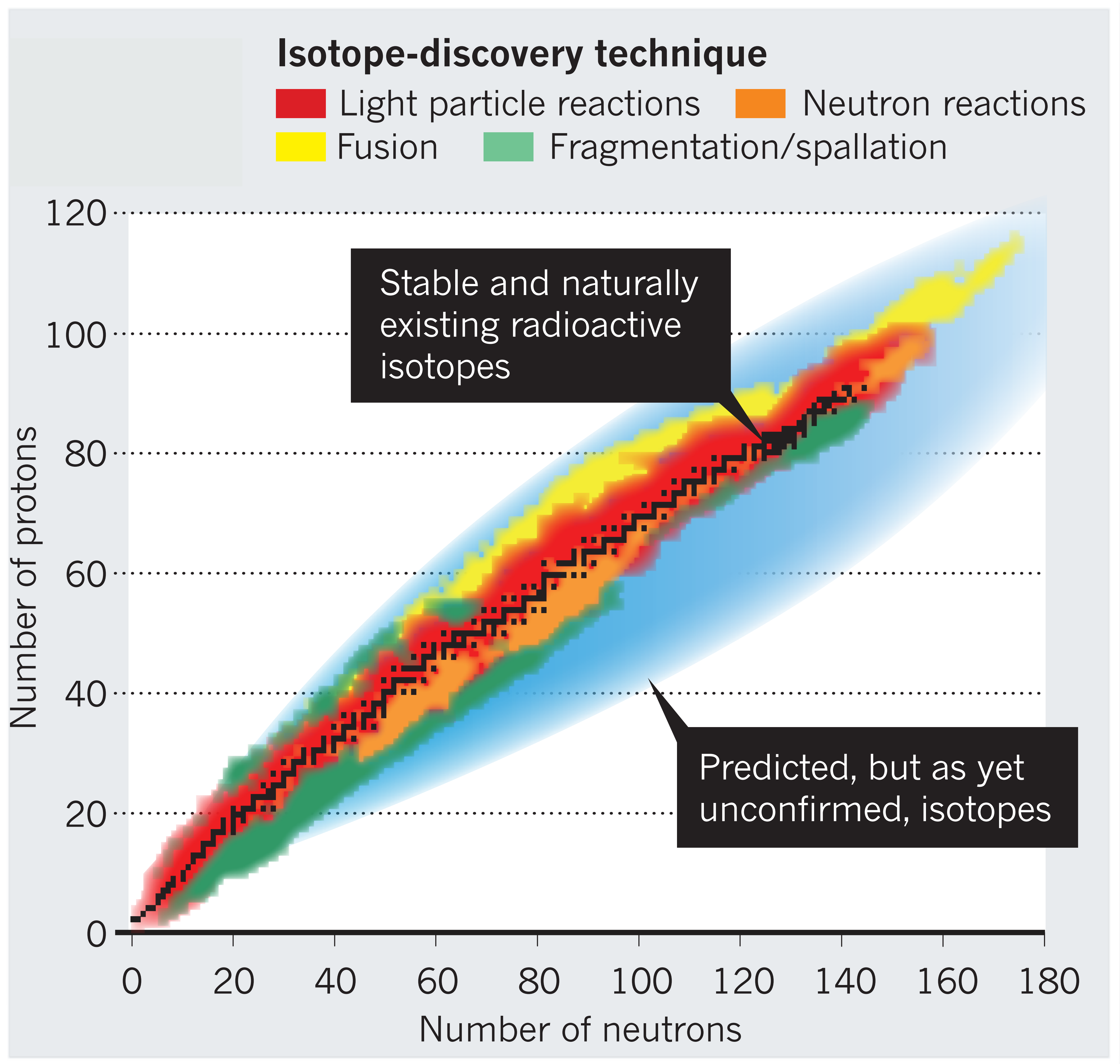
Radioactive ion beam facilities

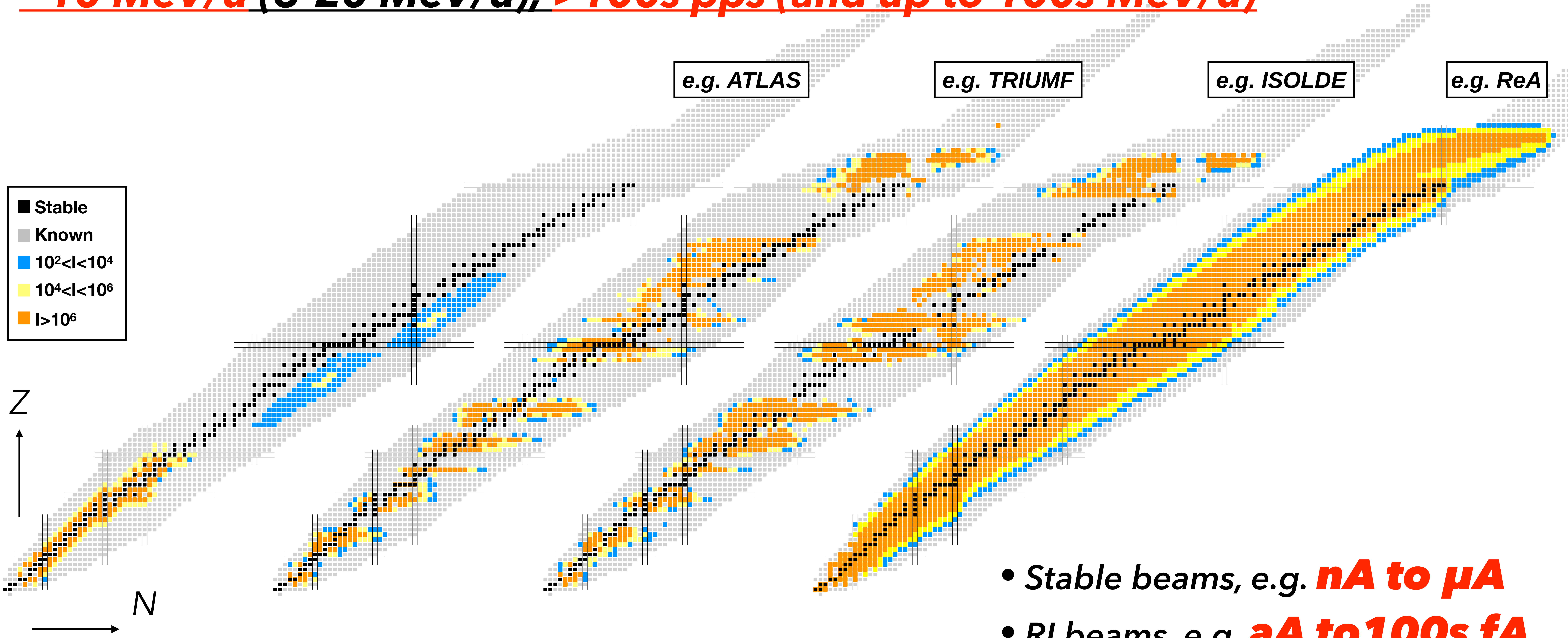




(Left) Original source unsure (perhaps Brad Sherrill)

… RI beams

~10 MeV/u (3-20 MeV/u), >100s pps (and up to 100s MeV/u)



- *Stable beams, e.g.* ***nA to μA***
- *RI beams, e.g.* ***aA to100s fA***

(Beam rates are very crude estimates from various sources, illustrative, likely ~1-2 orders of mag. off

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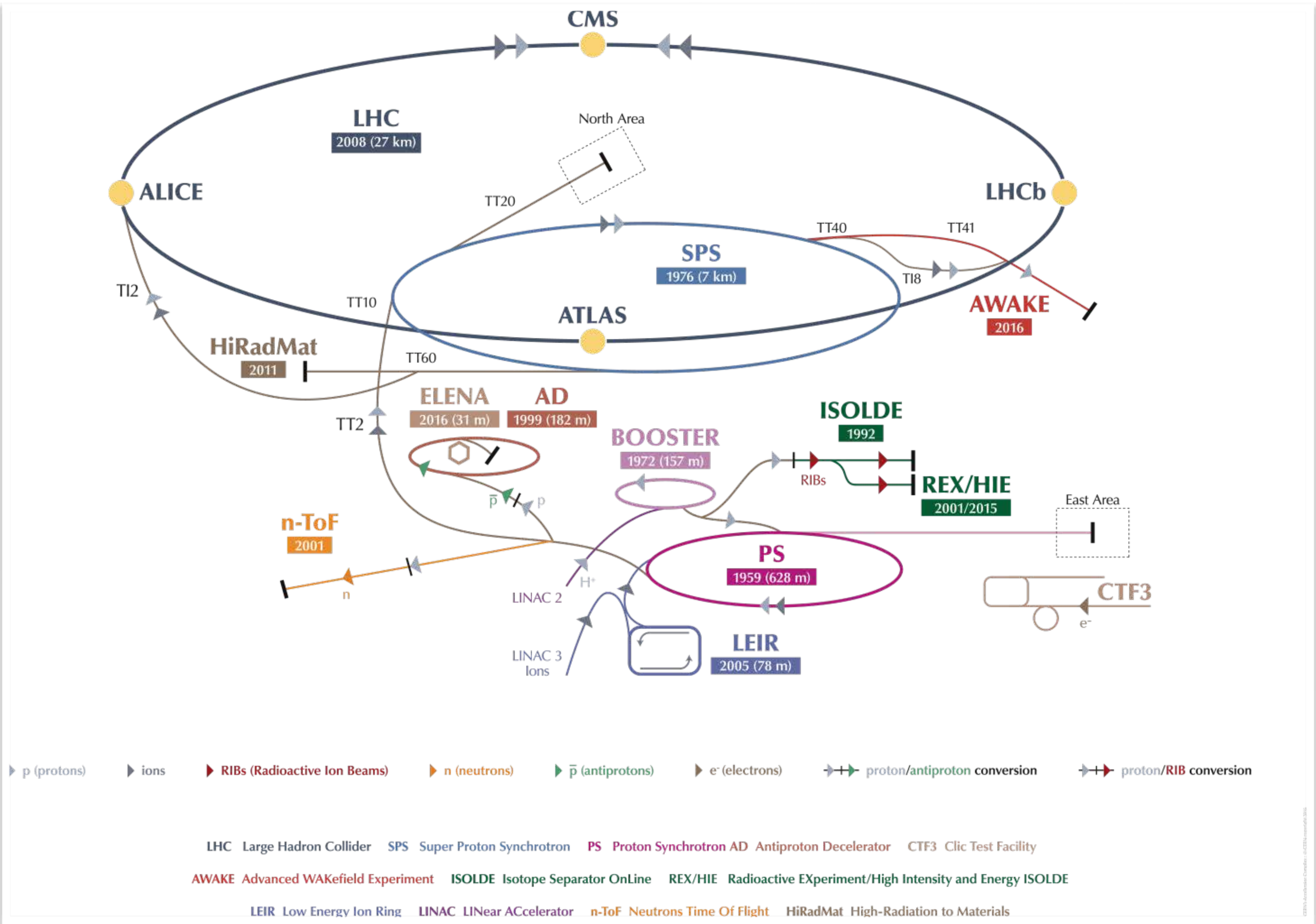
RIB facilities, ISOL at e.g. CERN, TRIUMF, …



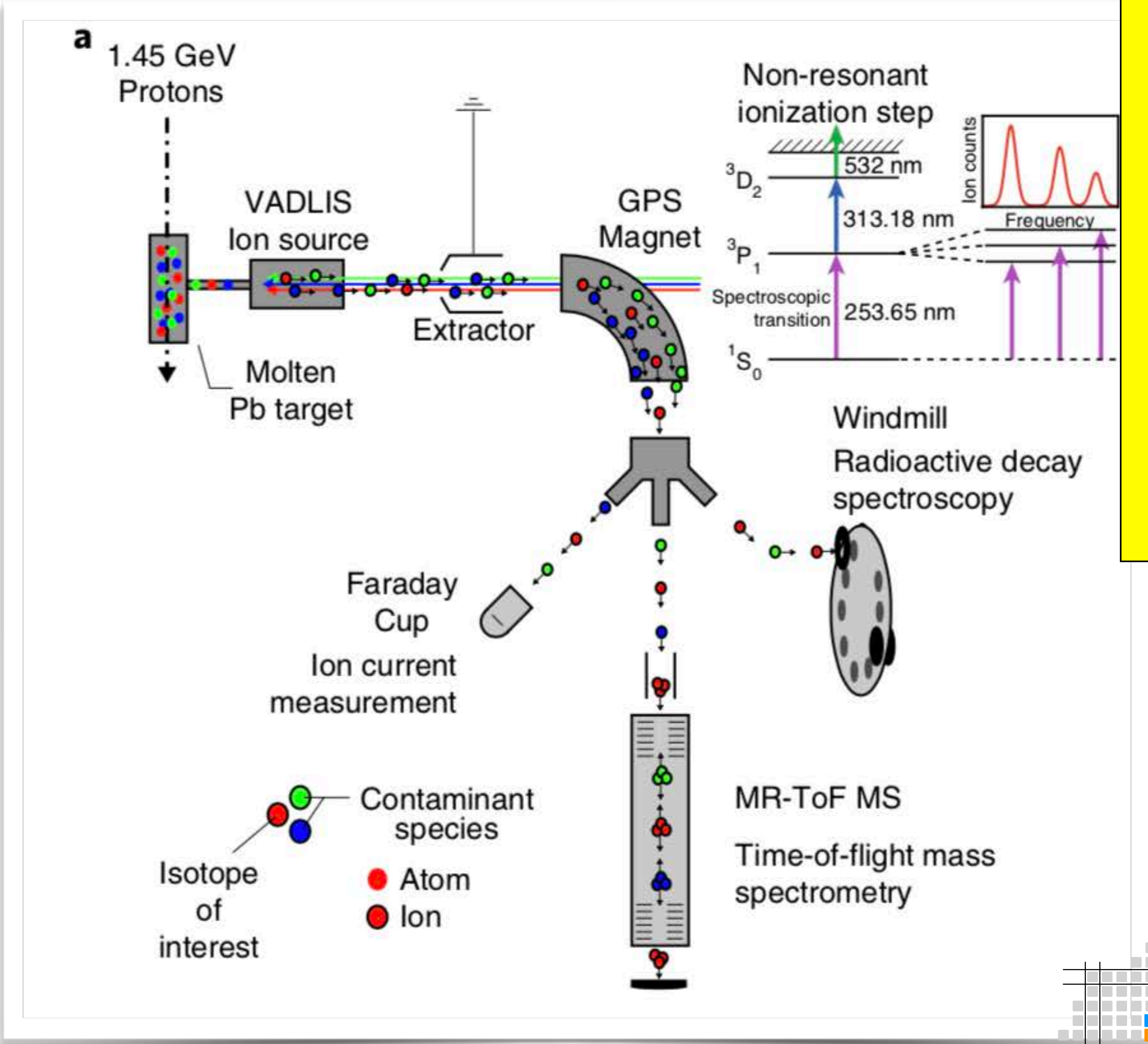
Examples of ISOL facilities:
TRIUMF (Canada)
SPIRAL/SPIRAL2 (France)
REX-ISOLDE/HIE-ISOLDE (CERN)
iTHEMBA - future radioactive-beam facility (South Africa)
JYFL (Finland) - IGISOL

Typically:

- *Light, energetic ion*
- *Thick, hot target*
- *Ion source*
- *Separator*
- *Post acceleration*
- *Lower beam energies*

CERN website

RIB facilities, ISOL at e.g. CERN, TRIUMF, …



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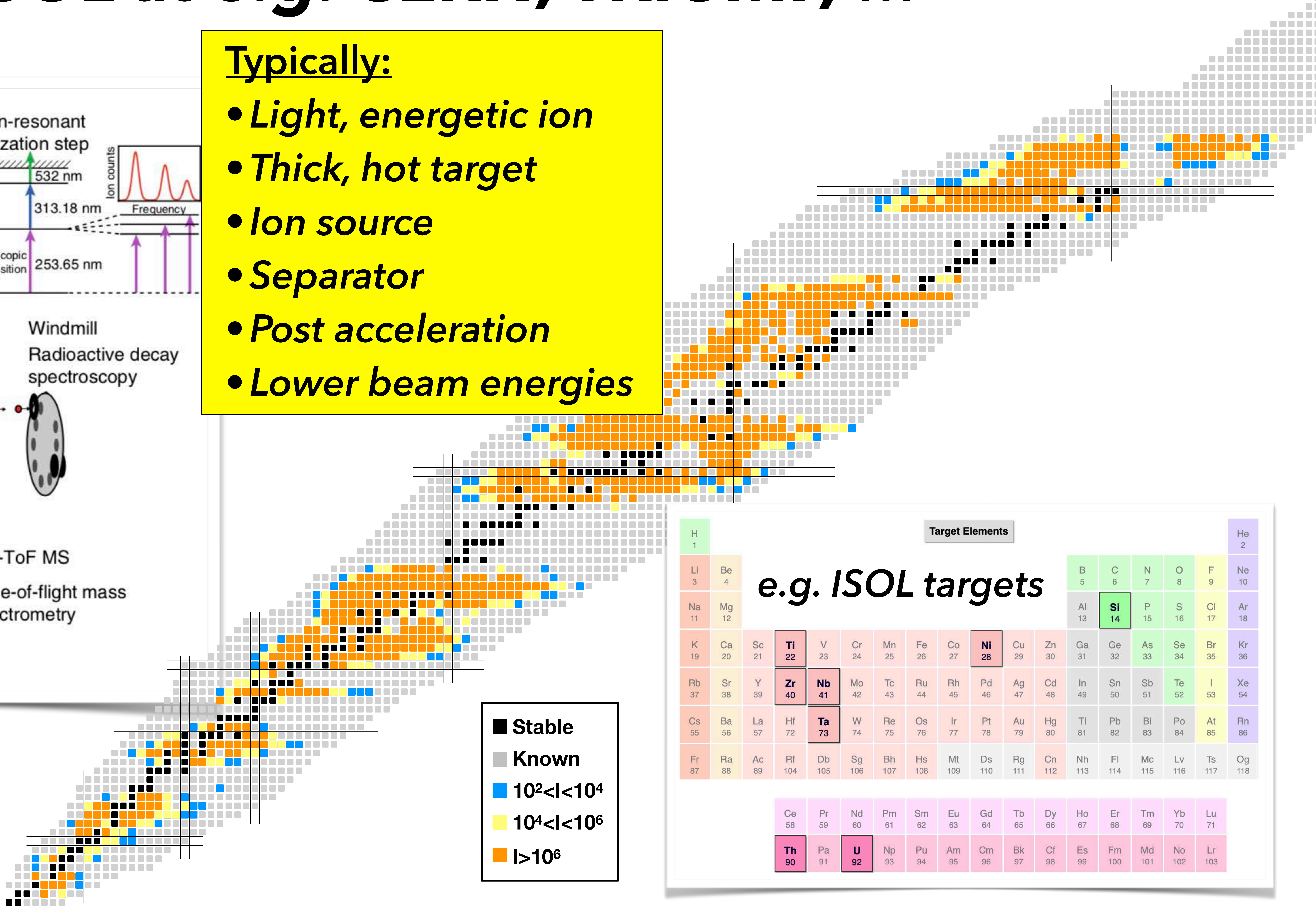

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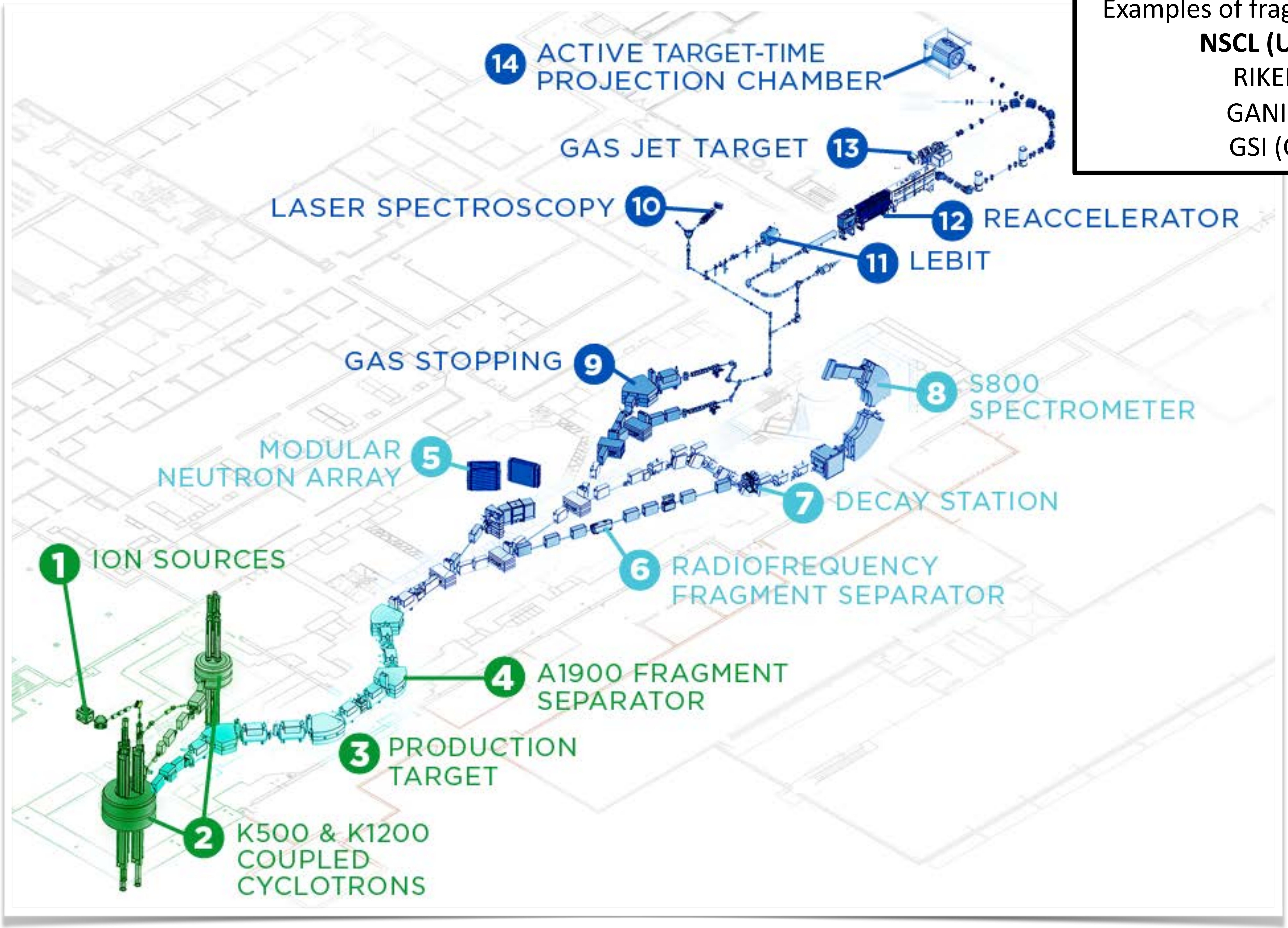
In-flight / fragmentation at e.g. NSCL



Examples of fragmentation facilities:
NSCL (USA) → FRIB
RIKEN (Japan)
GANIL (France)
GSI (Germany)

Typically:

- *Ion source*
- *heavy, energetic ion*
- *Thin, light target*
- *Separator*
- *Higher beam energies*

https://www.nscl.msu.edu/public/virtual-tour.html

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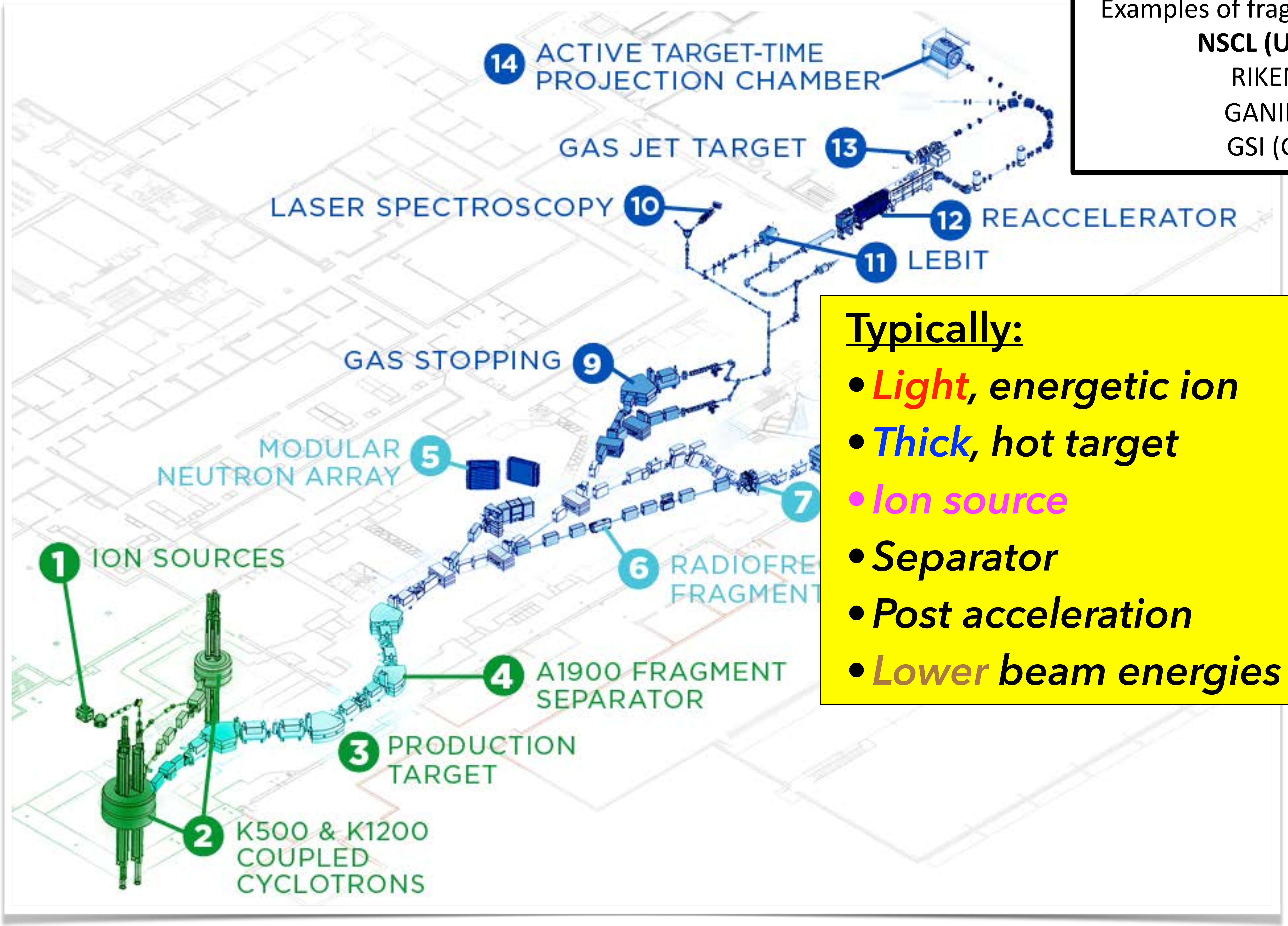

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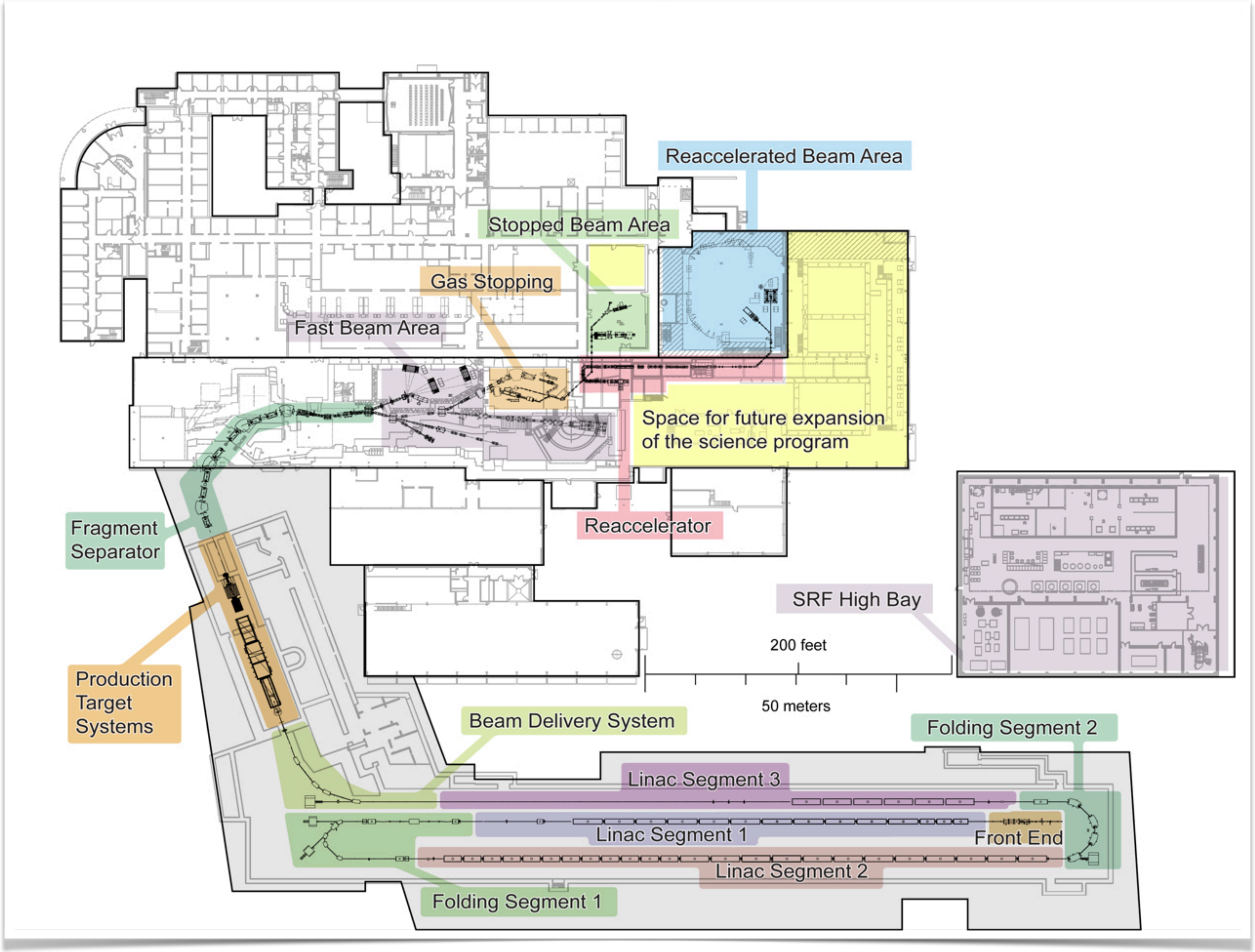
In-flight / fragmentation at e.g. NSCL → FRIB



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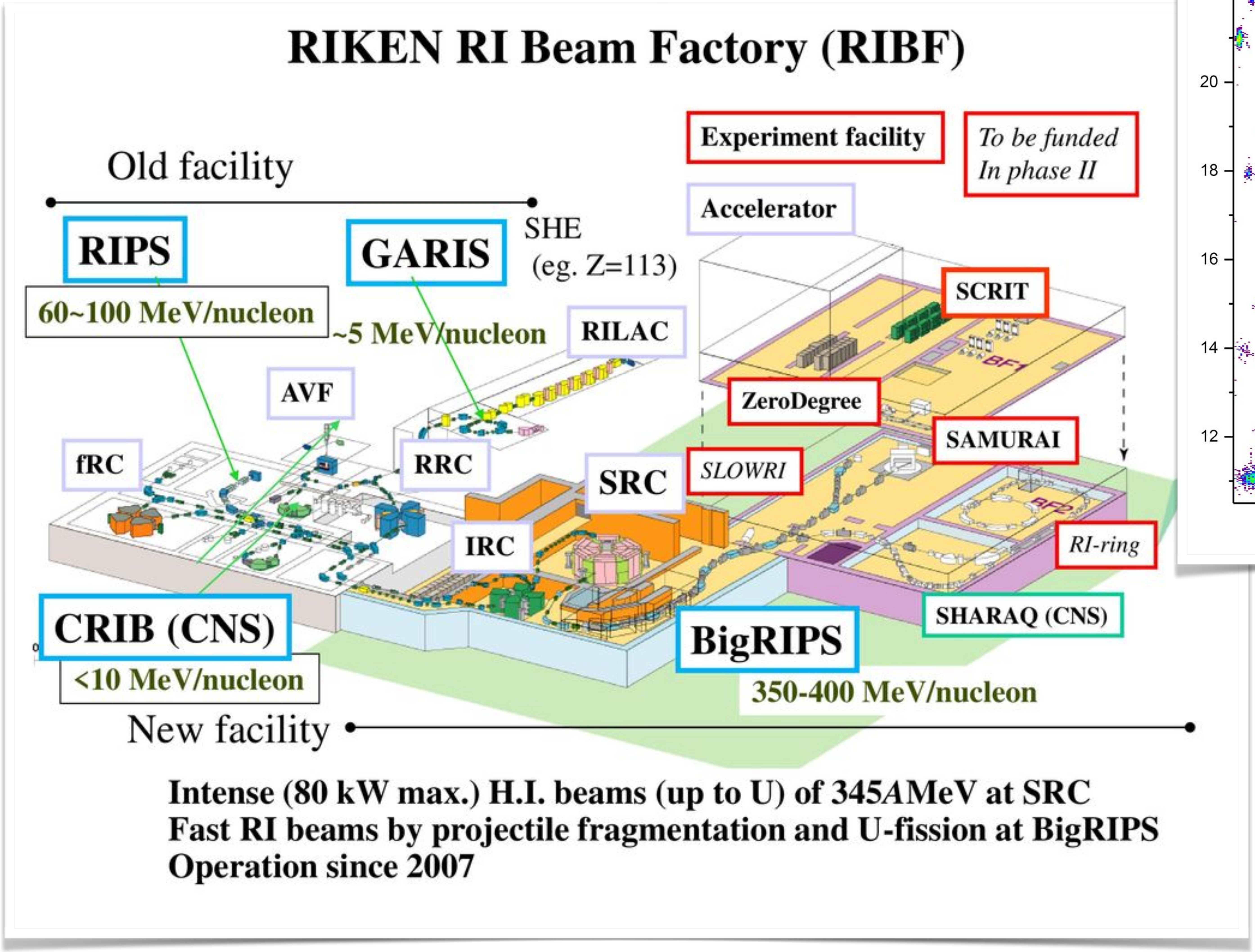
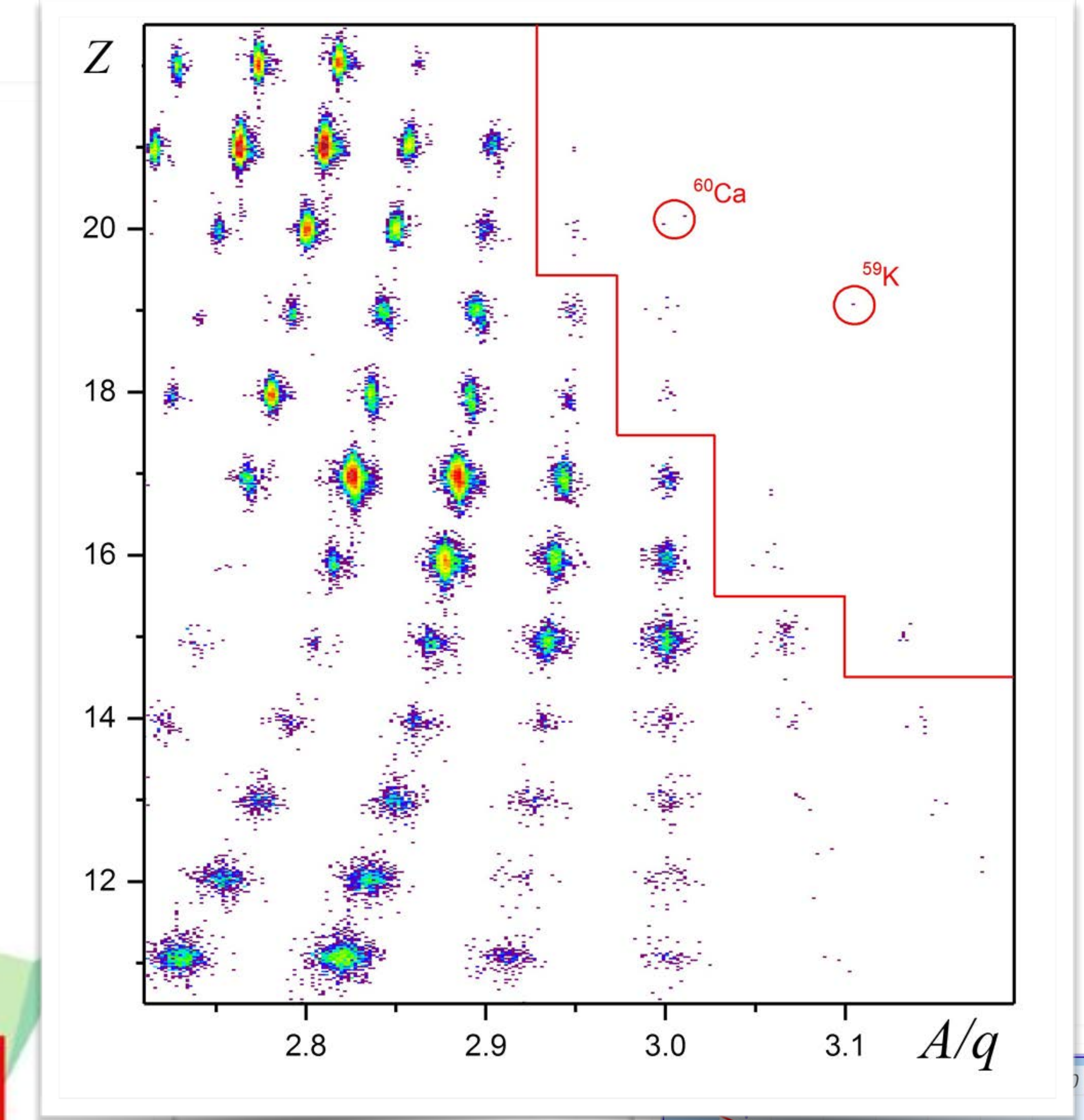
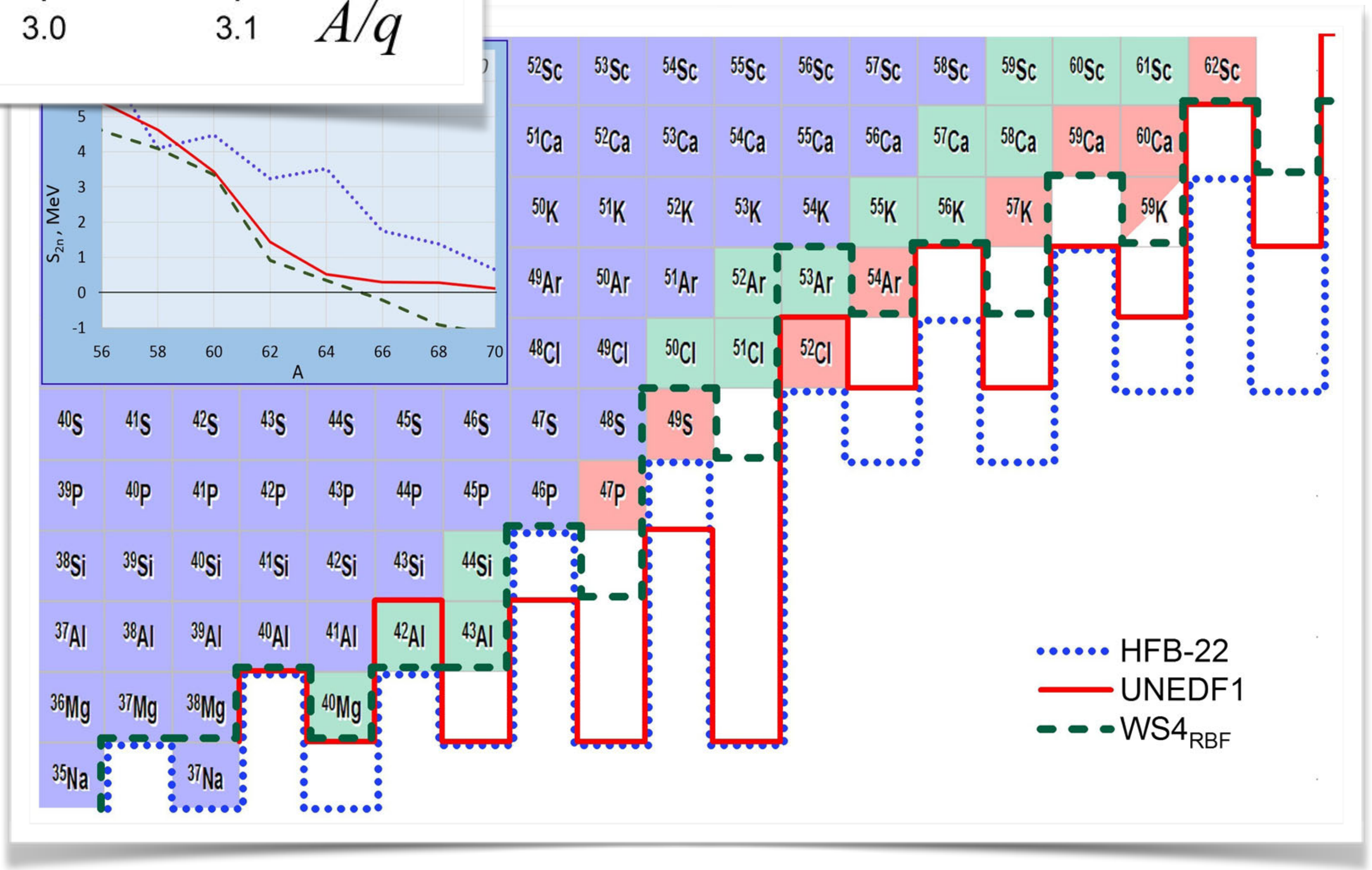
In-flight / fragmentation at e.g. RIBF, RIKEN







http://www.nishina.riken.jp/RIBF/ and O. Tarasov et al., Phys. Rev. Lett. **121**, 022501 (**2018**)

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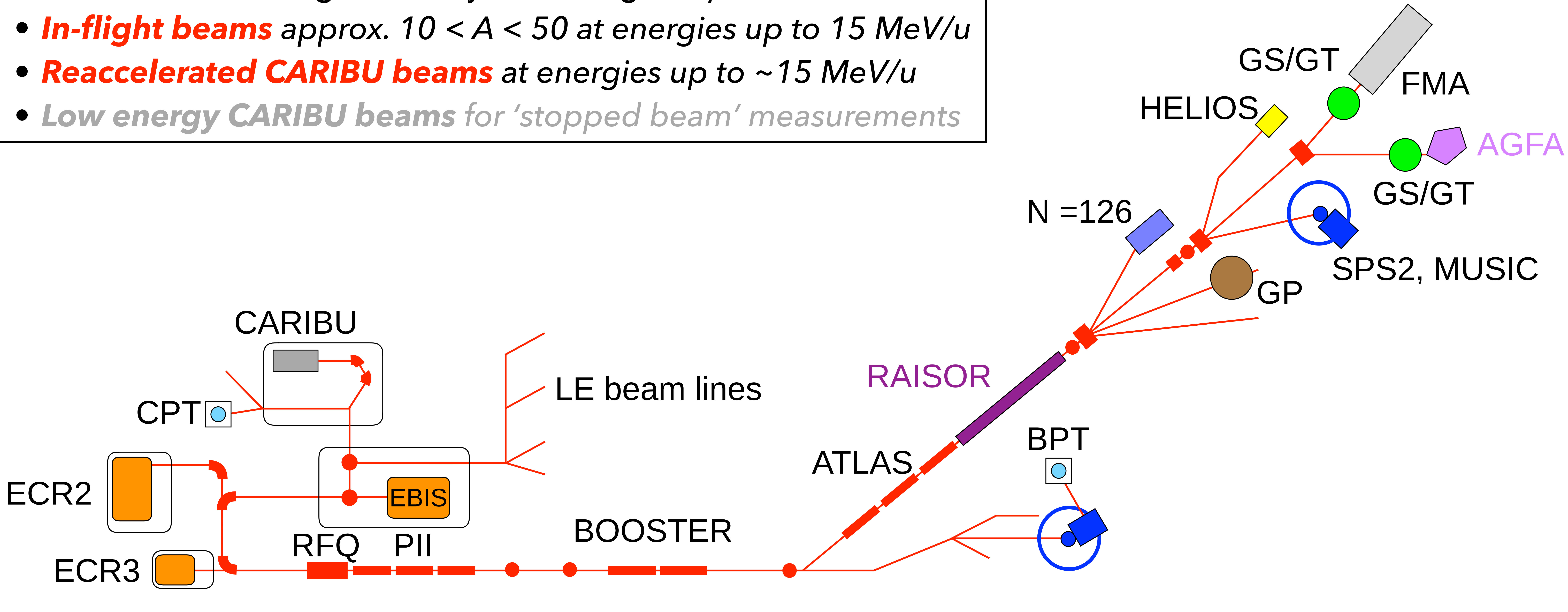
E.g. "ISOL" and in-flight at Argonne

An unrivaled combination for direct reaction studies

- ***Stable beams*** *at high intensity and energies up to 18 MeV/u*
- ***In-flight beams*** *approx. 10 < A < 50 at energies up to 15 MeV/u*
- ***Reaccelerated CARIBU beams*** *at energies up to ~15 MeV/u*
- ***Low energy CARIBU beams*** *for 'stopped beam' measurements*



www.anl.gov/atlas

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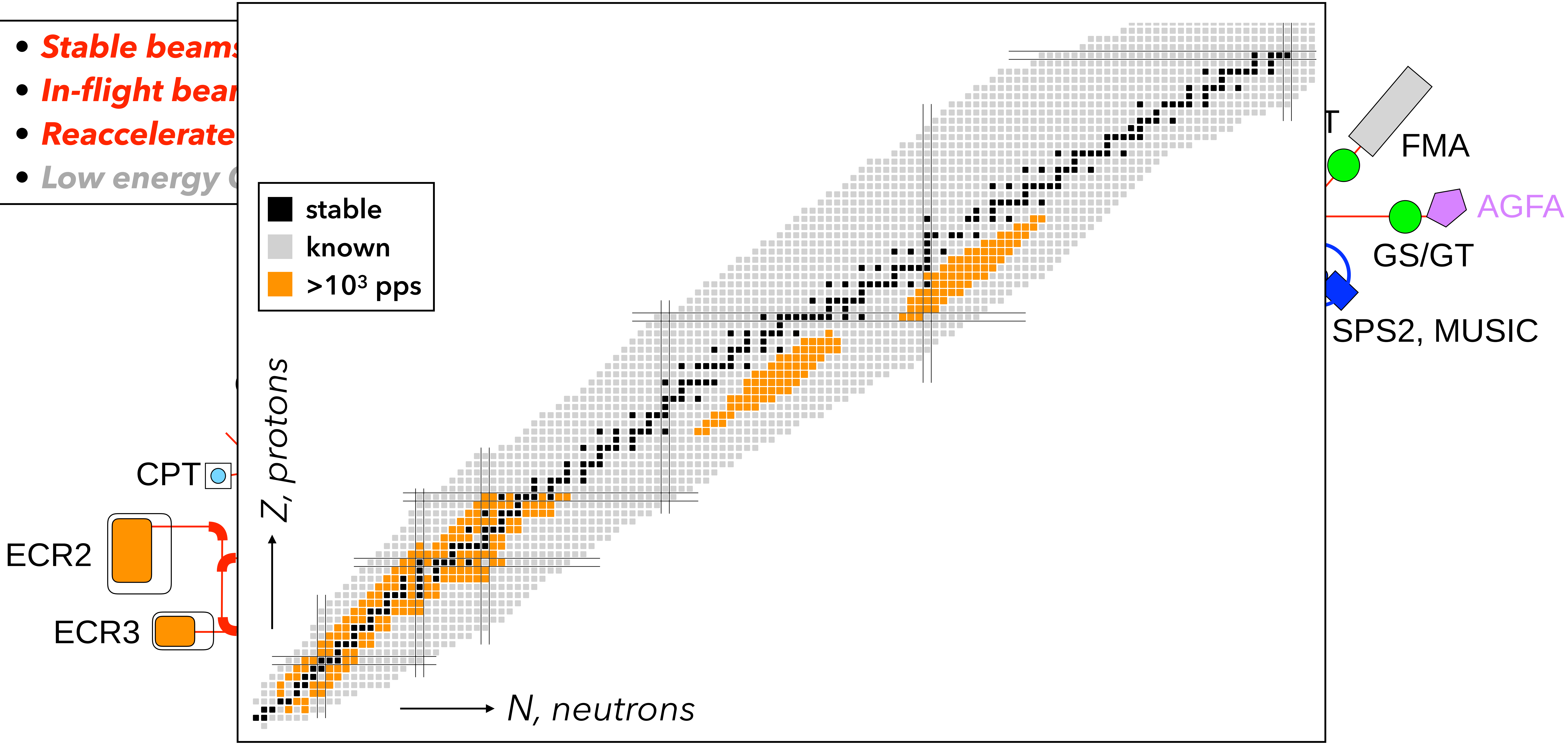
E.g. "ISOL" and in-flight at Argonne

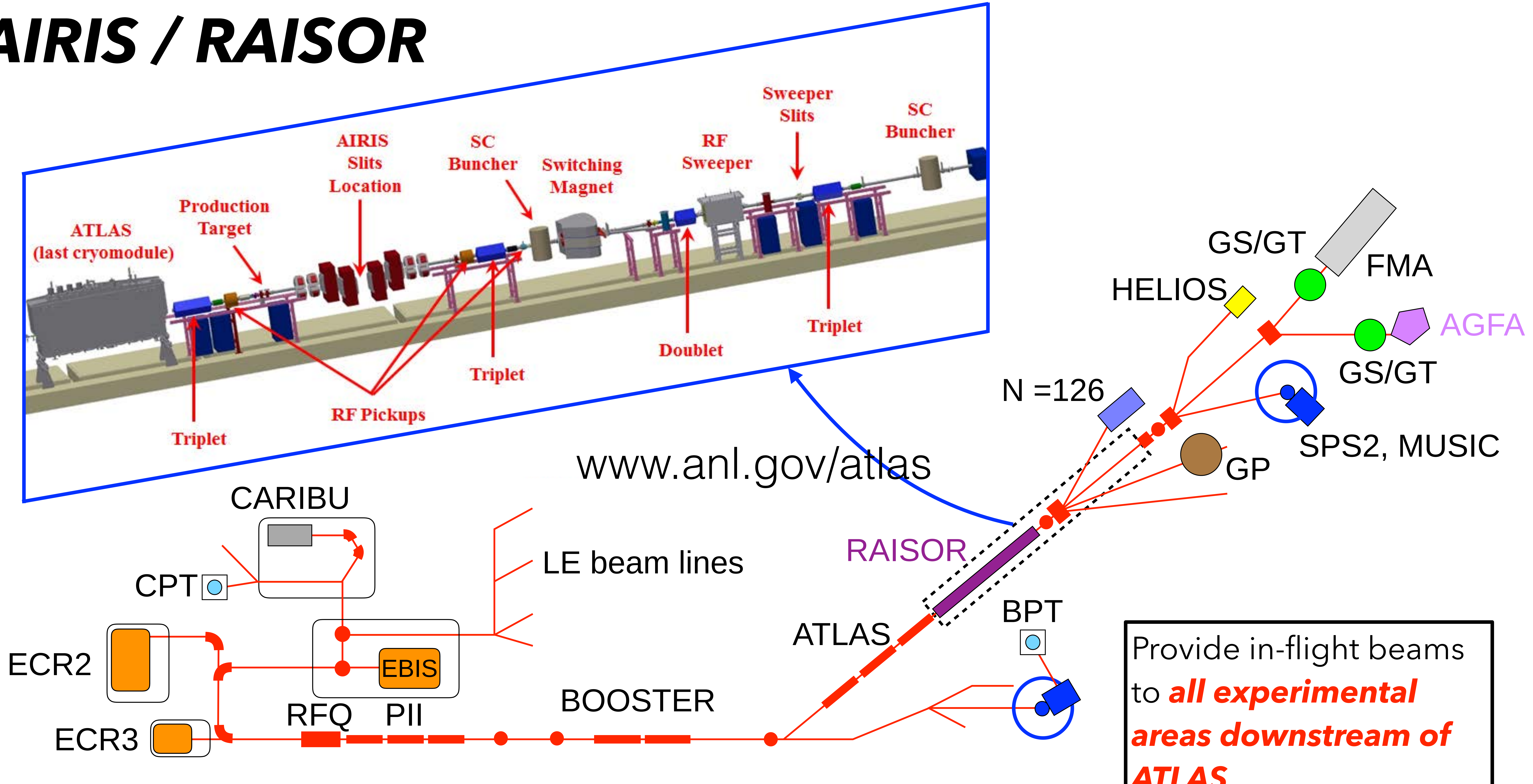
An unrivaled combination for direct reaction studies

- ***Stable beams***
- ***In-flight bea***
- ***Reaccelerate***
- ***Low energy (***



www.anl.gov/atlas

AIRIS / RAISOR



Provide in-flight beams to ***all experimental areas downstream of ATLAS***

Primary beam from ATLAS, a few to 20 MeV/u, <few pμA

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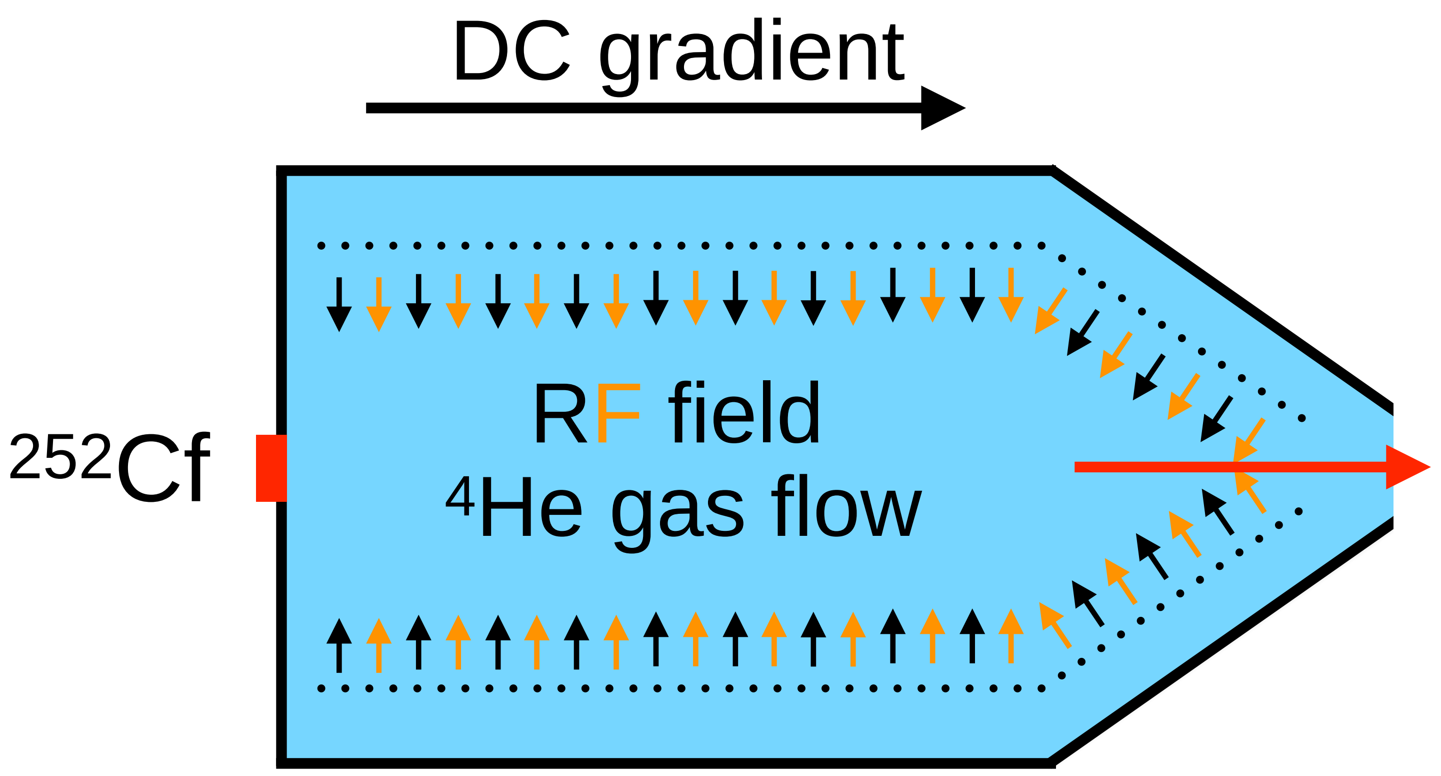
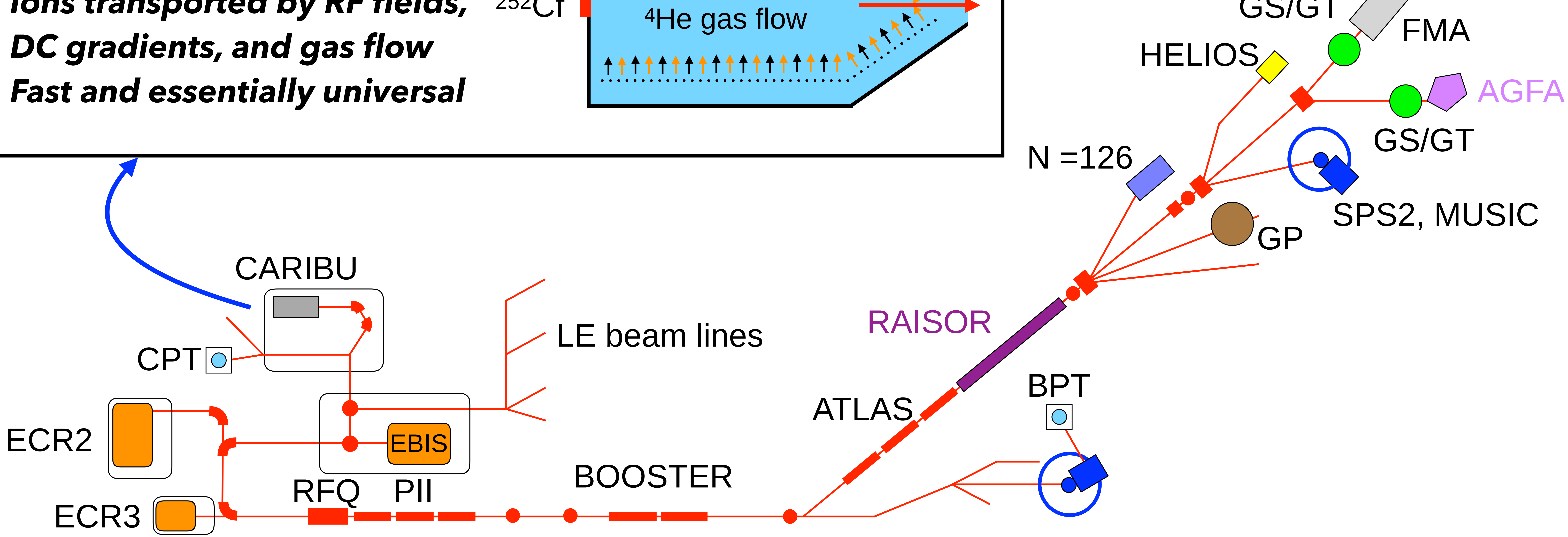
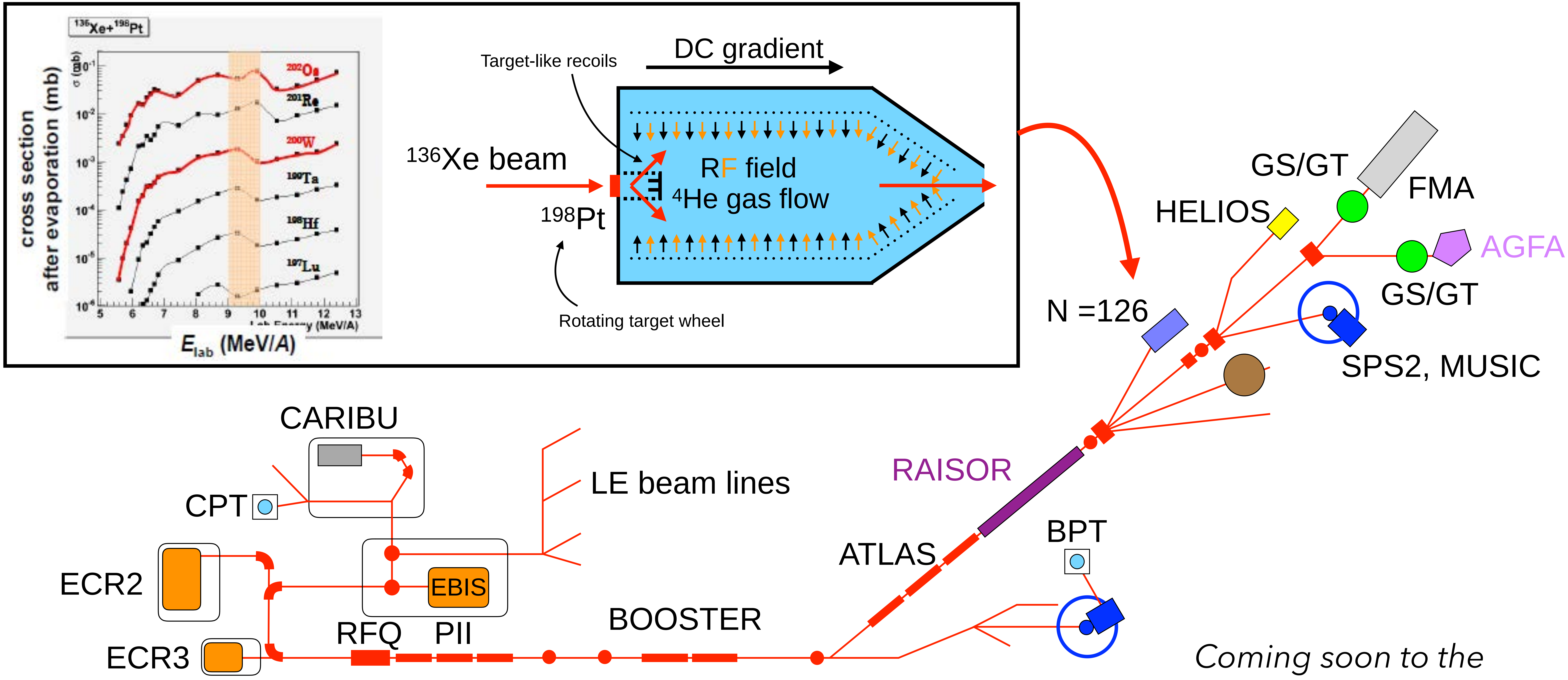
CARIBU

- ***Fission fragments stopped in high purity He***
- ***Ions transported by RF fields, DC gradients, and gas flow***
- ***Fast and essentially universal***





Production of N = 126 nuclei



Coming soon to the "BGO" area ...

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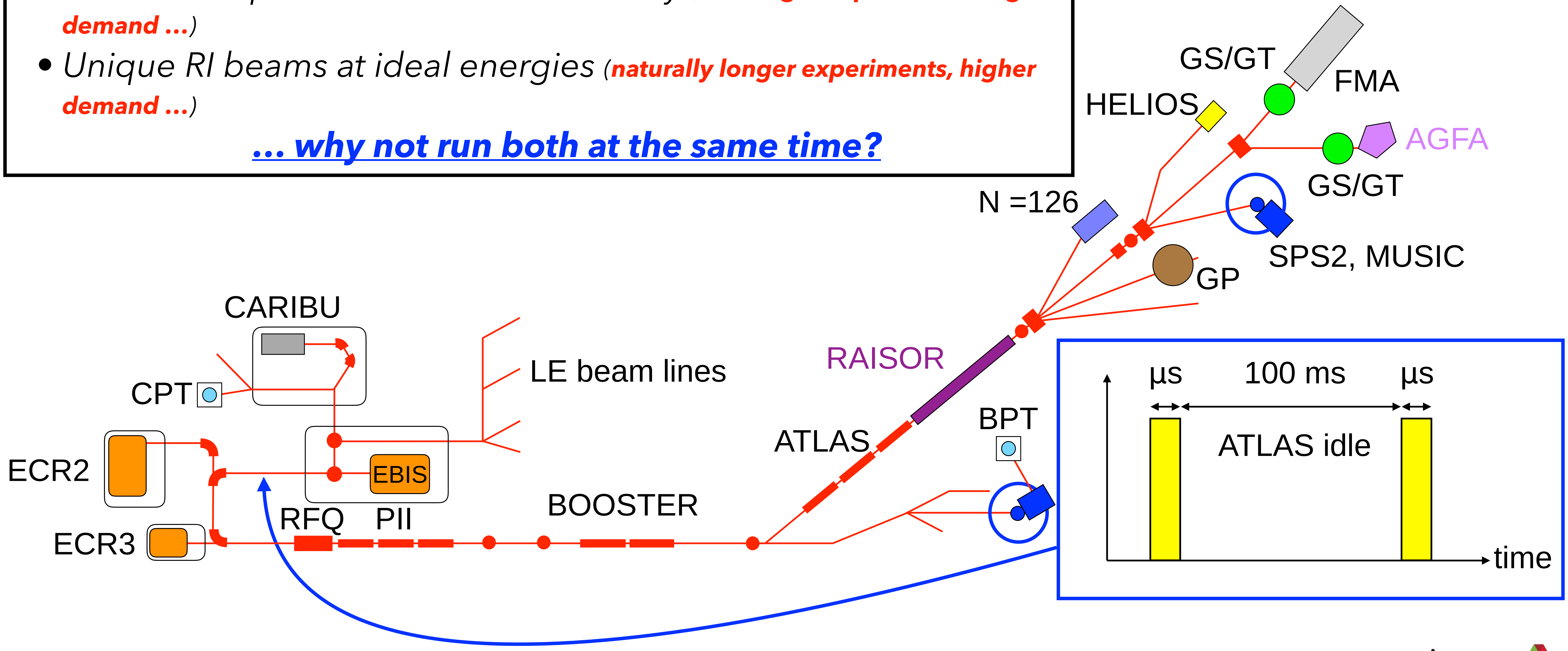
More than one beam!?

Higher demand for ATLAS beam time resolved …

- *The nations premier stable beam facility (**but longer experiments, higher demand …**)*
- *Unique RI beams at ideal energies (**naturally longer experiments, higher demand …**)*

… why not run both at the same time?

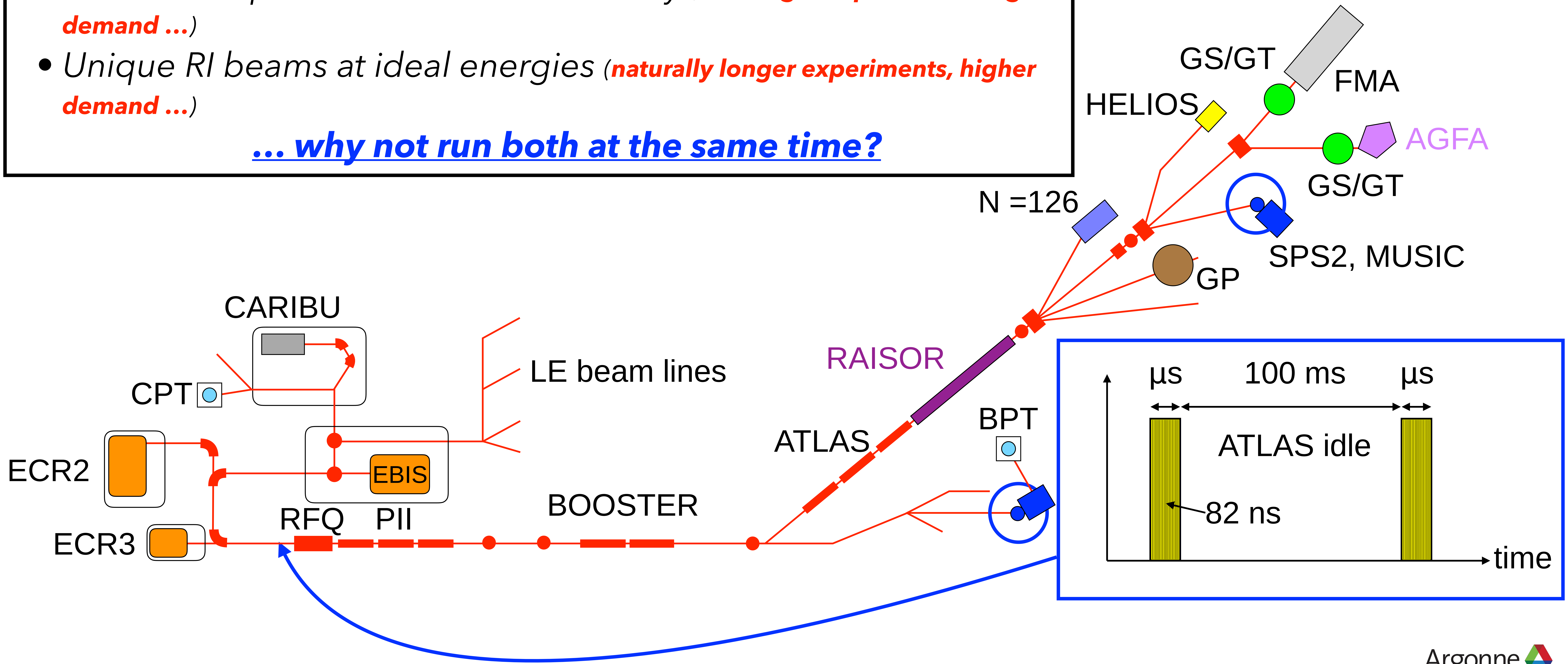


"Multi-user" facility

Higher demand for ATLAS beam time resolved …

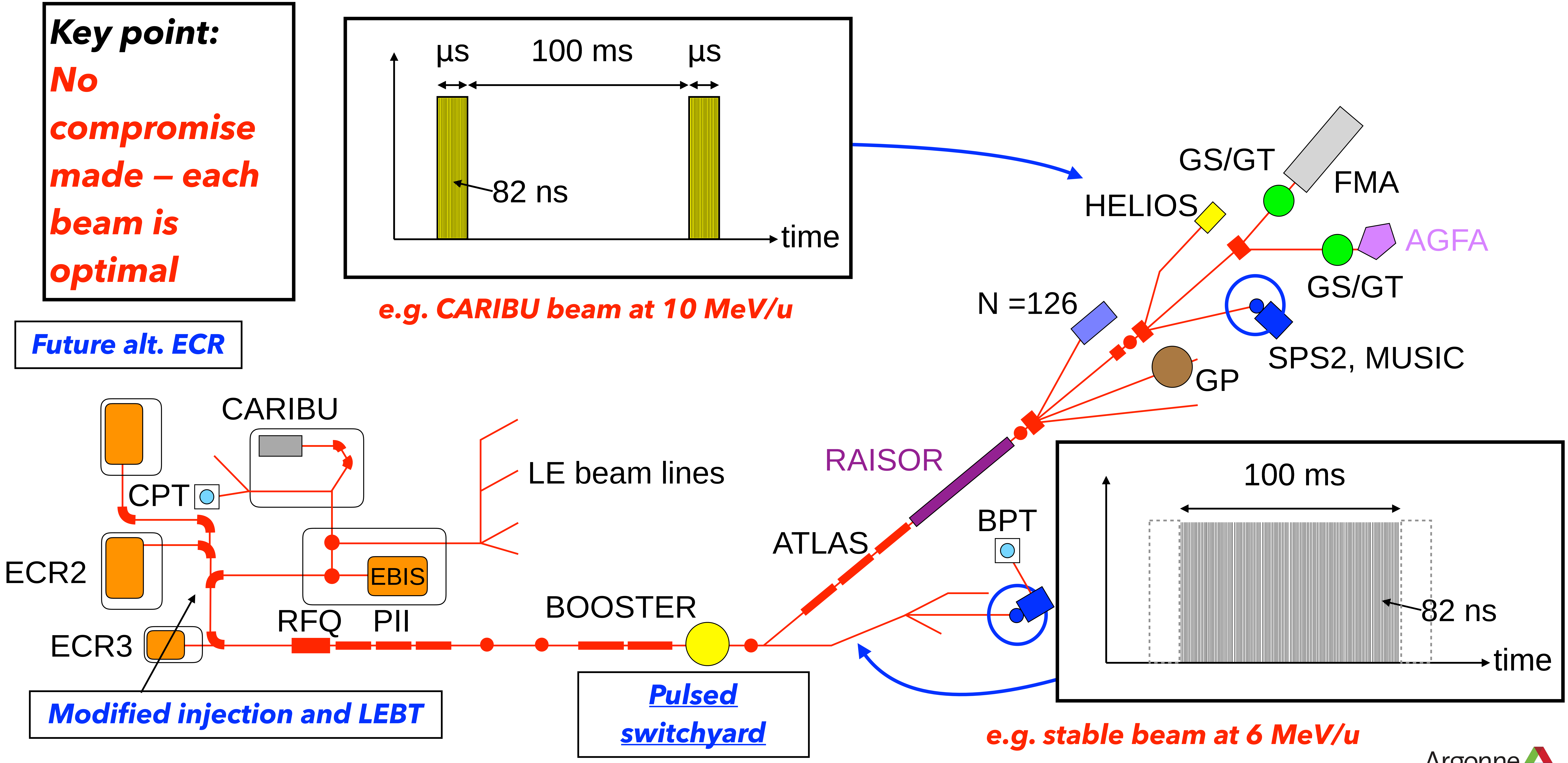
- *The nations premier stable beam facility* (**but longer experiments, higher demand …**)
- *Unique RI beams at ideal energies* (**naturally longer experiments, higher demand …**)

… why not run both at the same time?

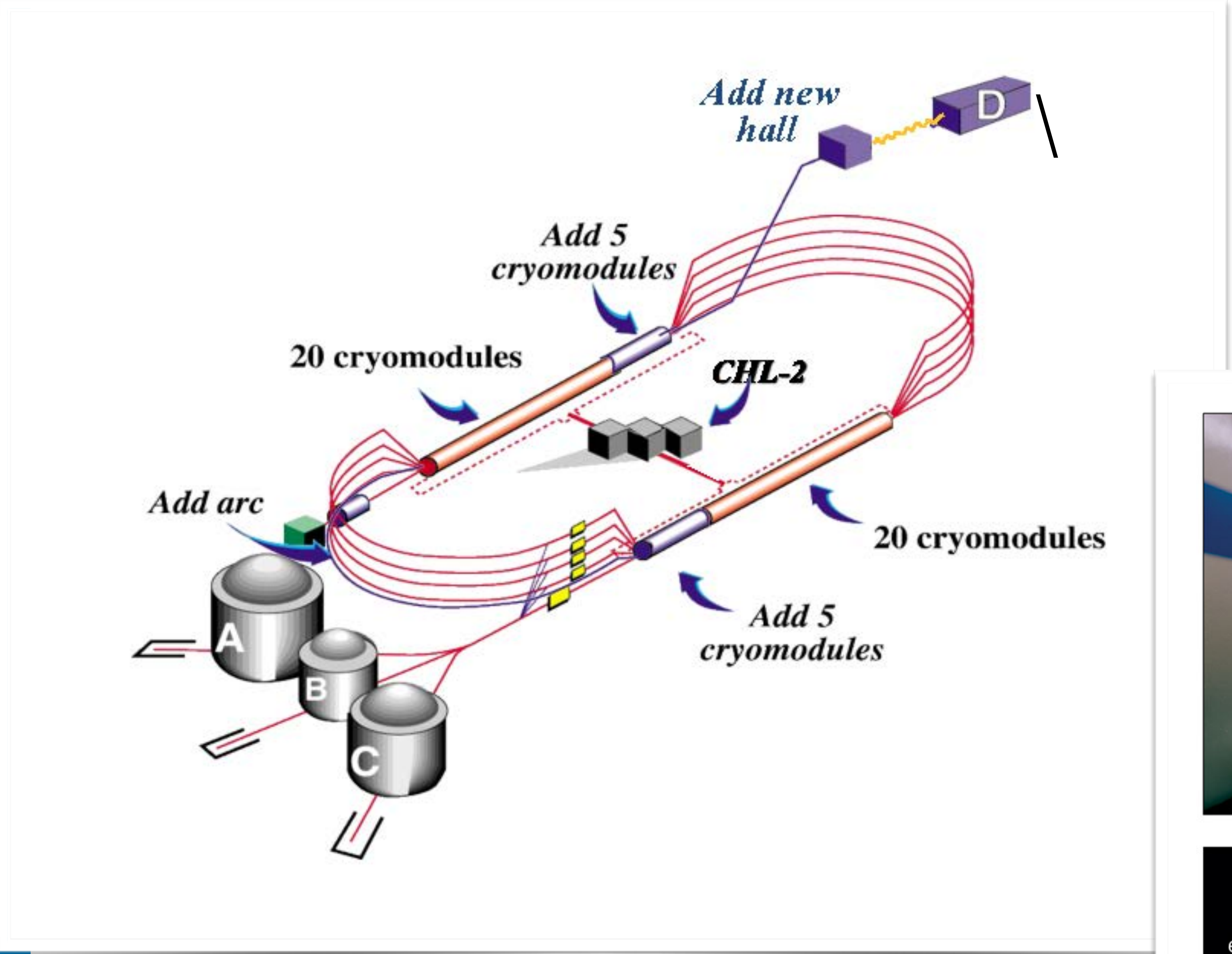


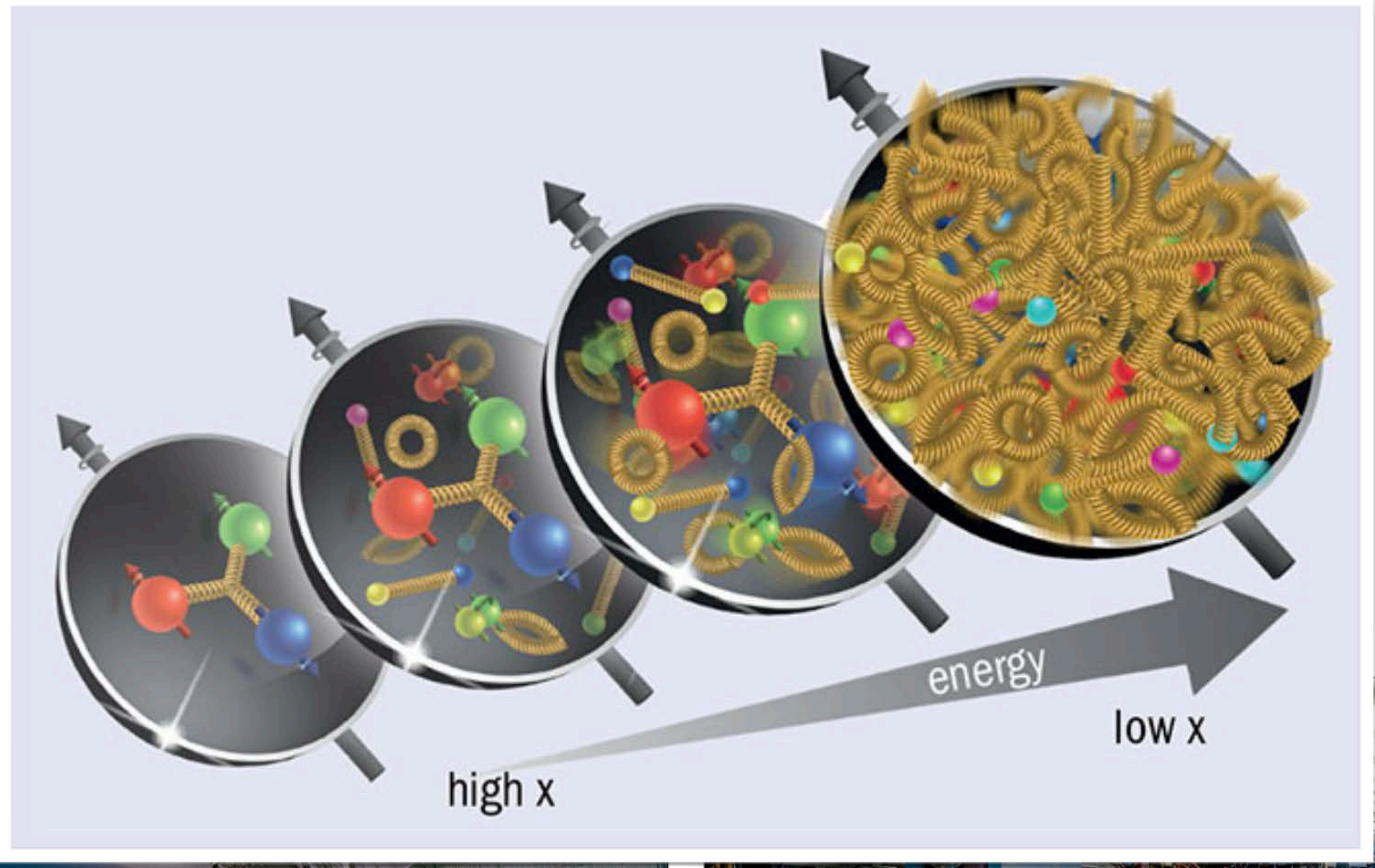
… AMUU

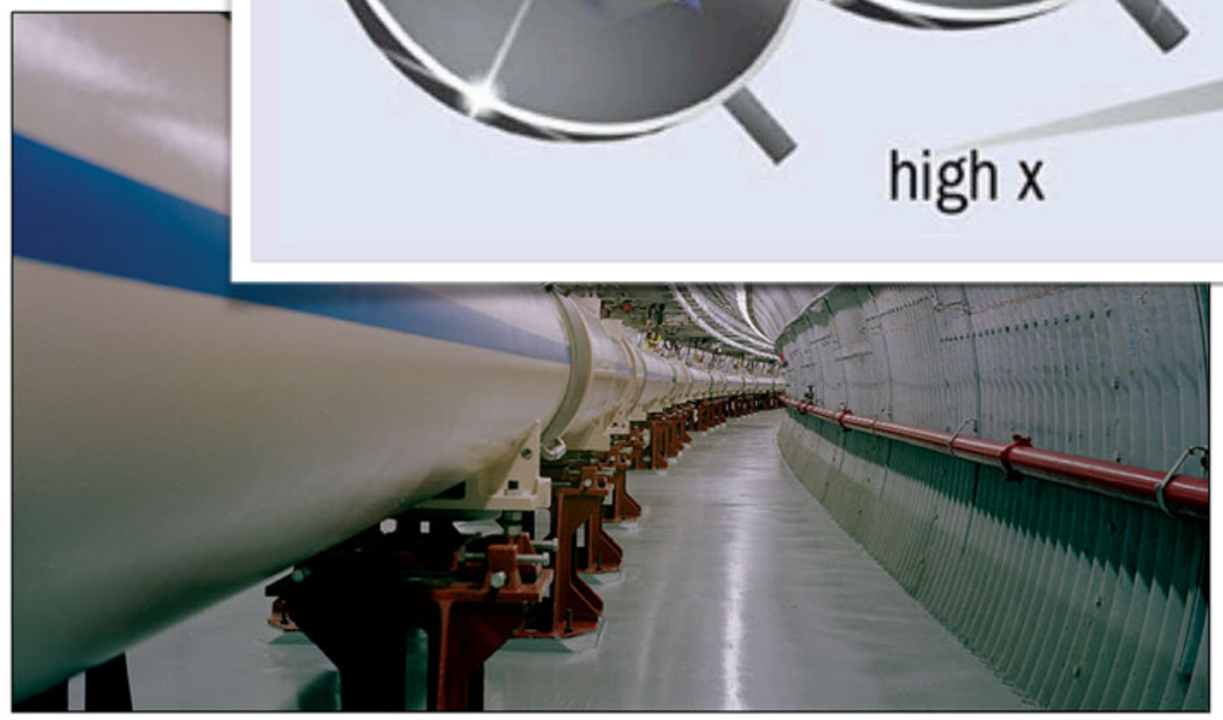
Key point:
No compromise made – each beam is optimal

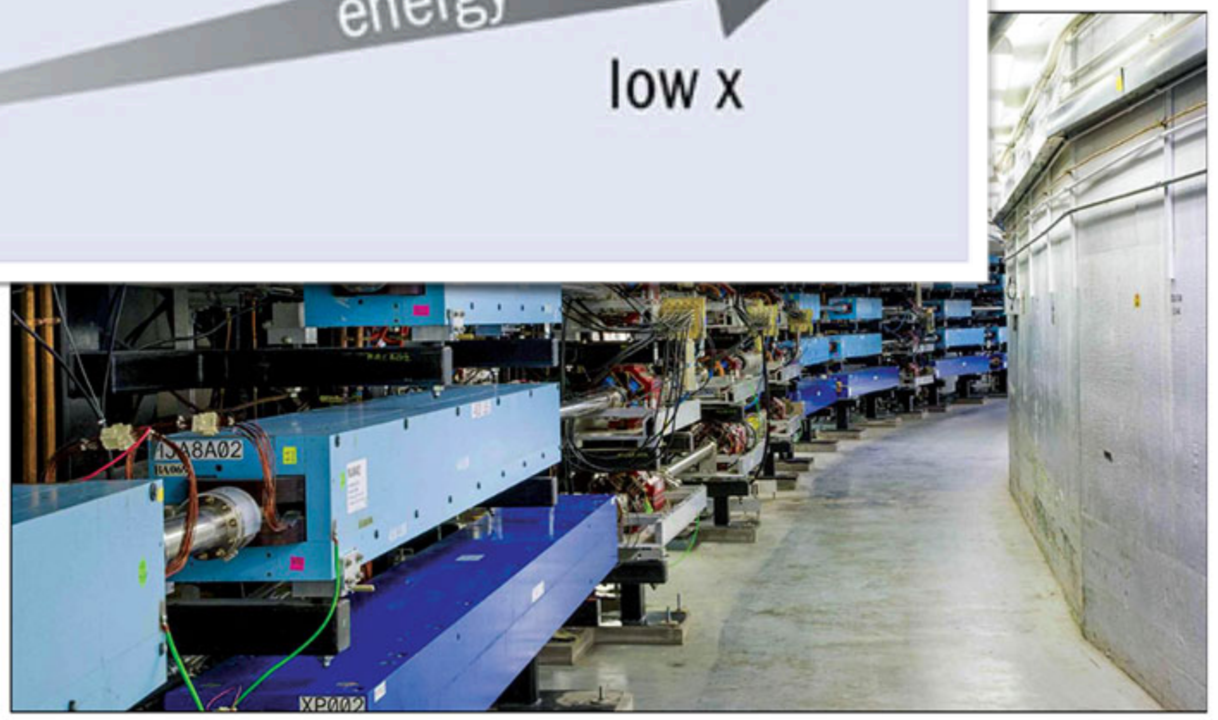


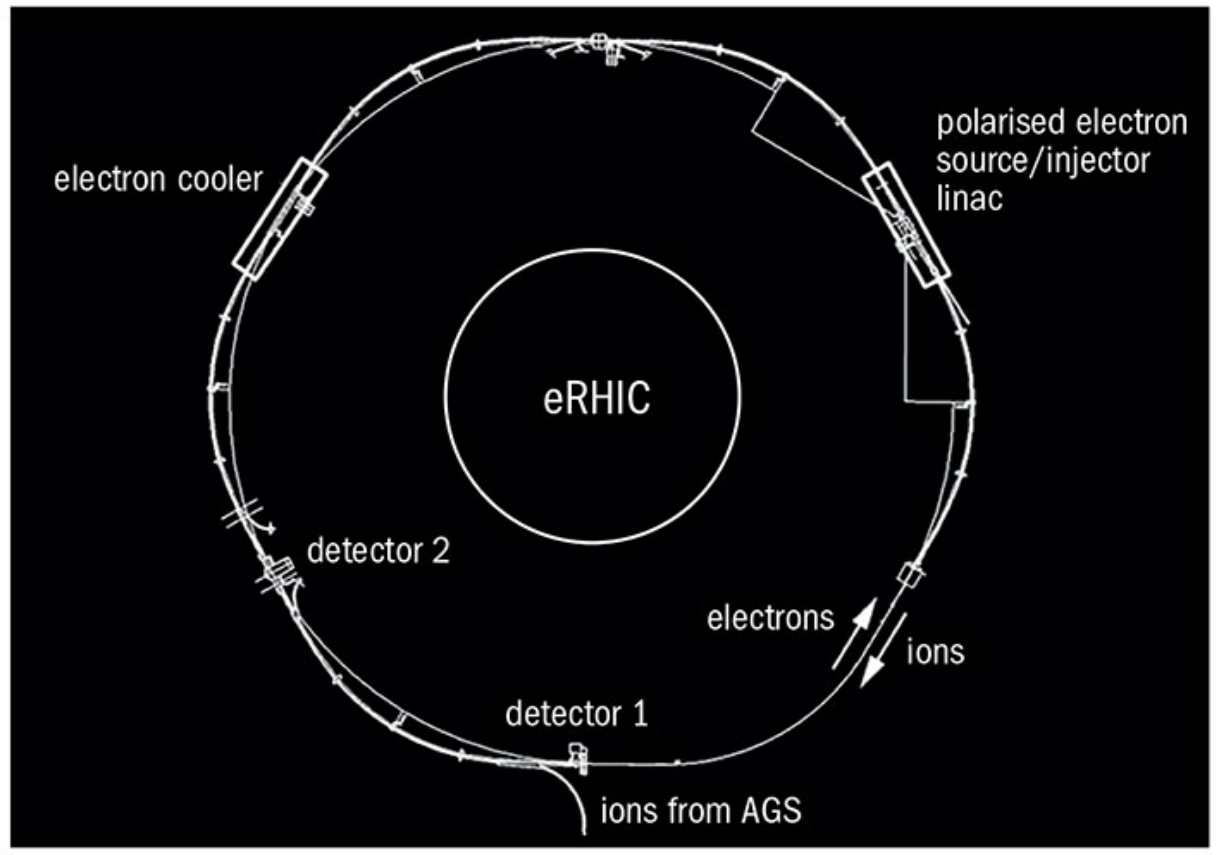
Non-hadronic probes …

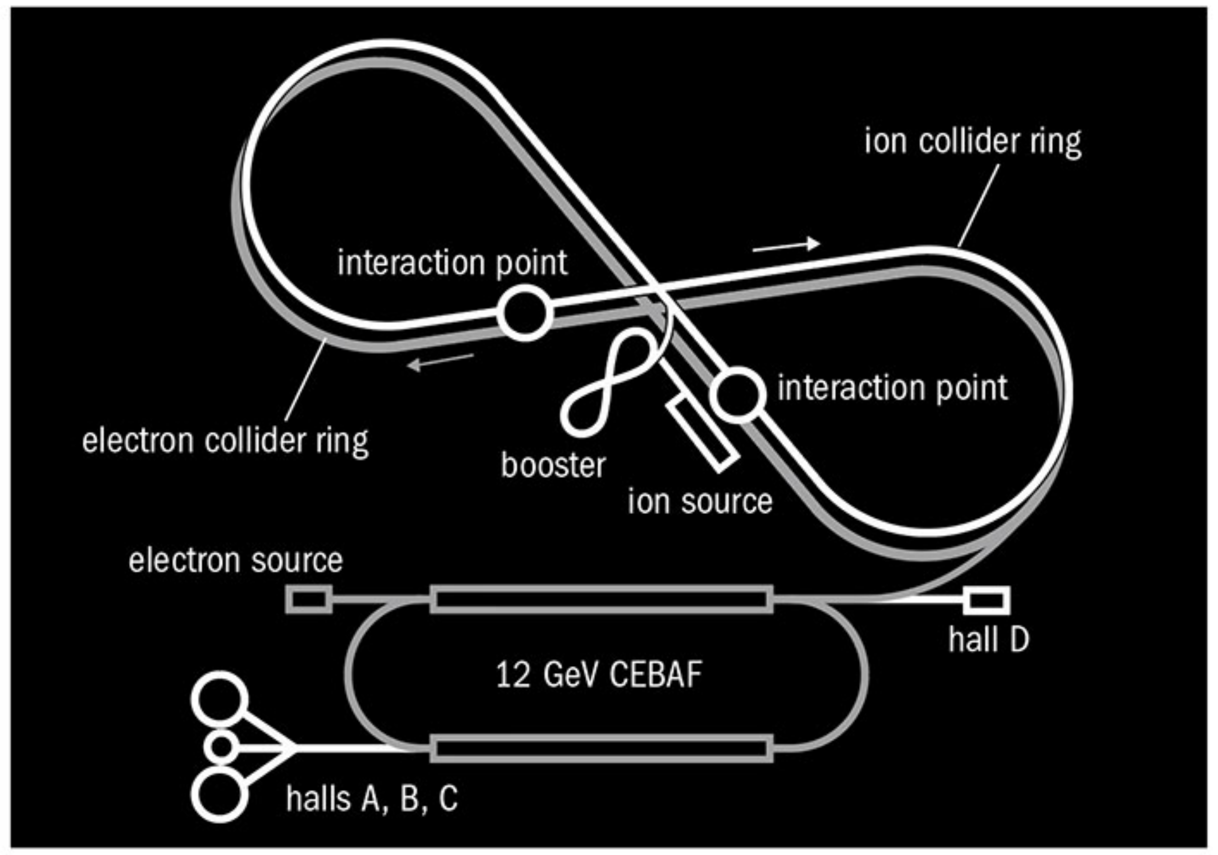












https://cerncourier.com/electron-ion-collider-on-the-horizon/

Nuclear cartography

PAPER

Phys. Educ. **52** (2017) 064002 (9pp) iopscience.org/ped

Nuclear cartography: patterns in binding energies and subatomic structure

E C Simpson[1] and M Shelley[2]

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[2] Department of Physics, University of York, York YO10 5DD, United Kingdom

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CrossMark

Abstract

Nuclear masses and binding energies are some of the first nuclear properties met in high school physics, and can be used to introduce radioactive decays, fusion, and fission. With relatively little extension, they can also illustrate fundamental concepts in nuclear physics, such as shell structure and pairing, and to discuss how the elements around us were formed in stars. One way of visualising these nuclear properties is through the nuclide chart, which maps all nuclides as a function of their proton and neutron numbers. Here we use the nuclide chart to illustrate various aspects of nuclear physics, and present 3D visualisations of it produced as part of the binding blocks project.

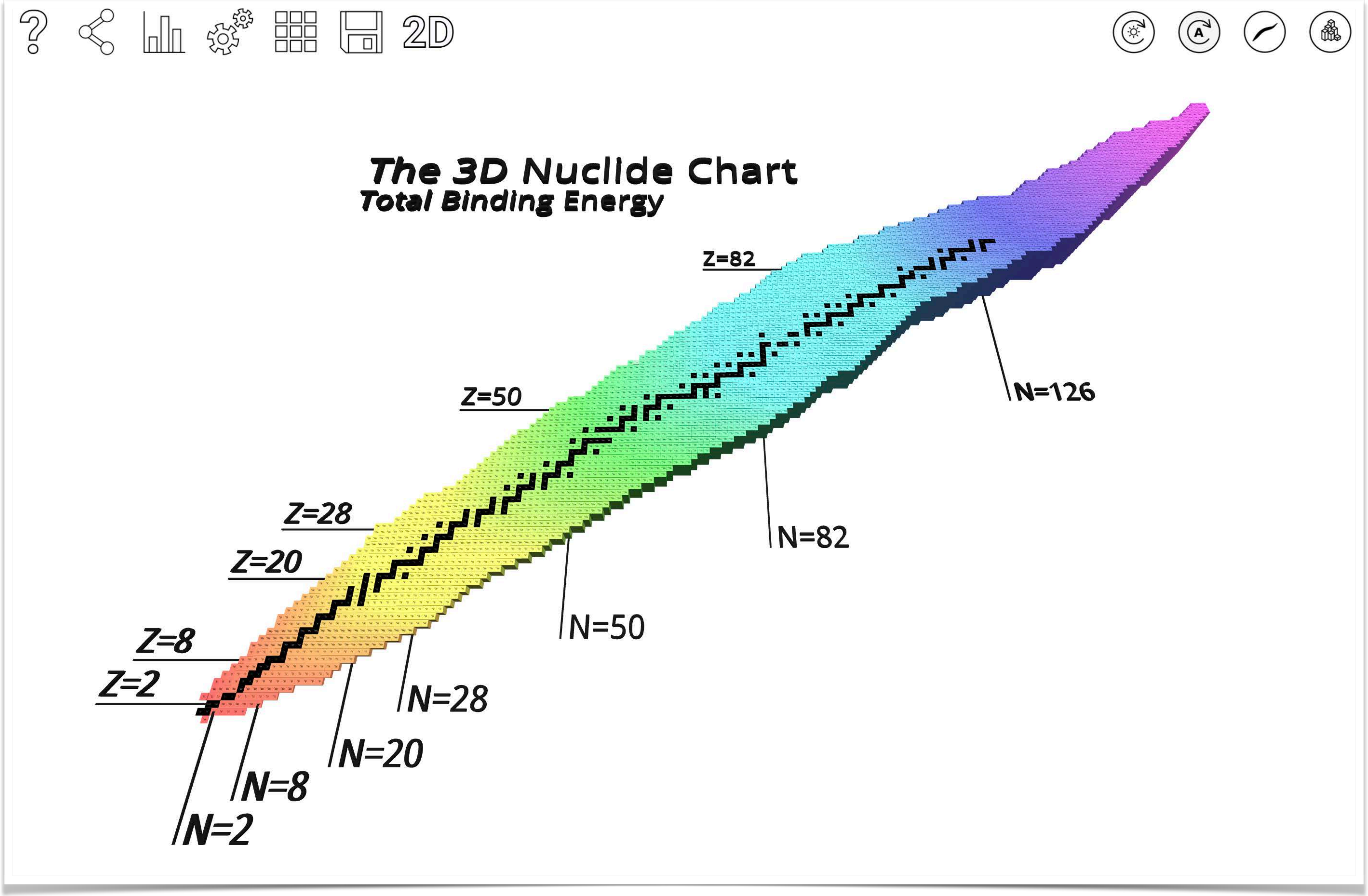
The 3D Nuclide Chart

Putting the joy back into nuclear data.

WARNING: support for touch devices is currently experimental!

E. C. Simpson and M. Shelley, Phys. Educ. ***52****, 064002 (****2017****)*

Nuclear playground



https://people.physics.anu.edu.au/~ecs103/chart3d/

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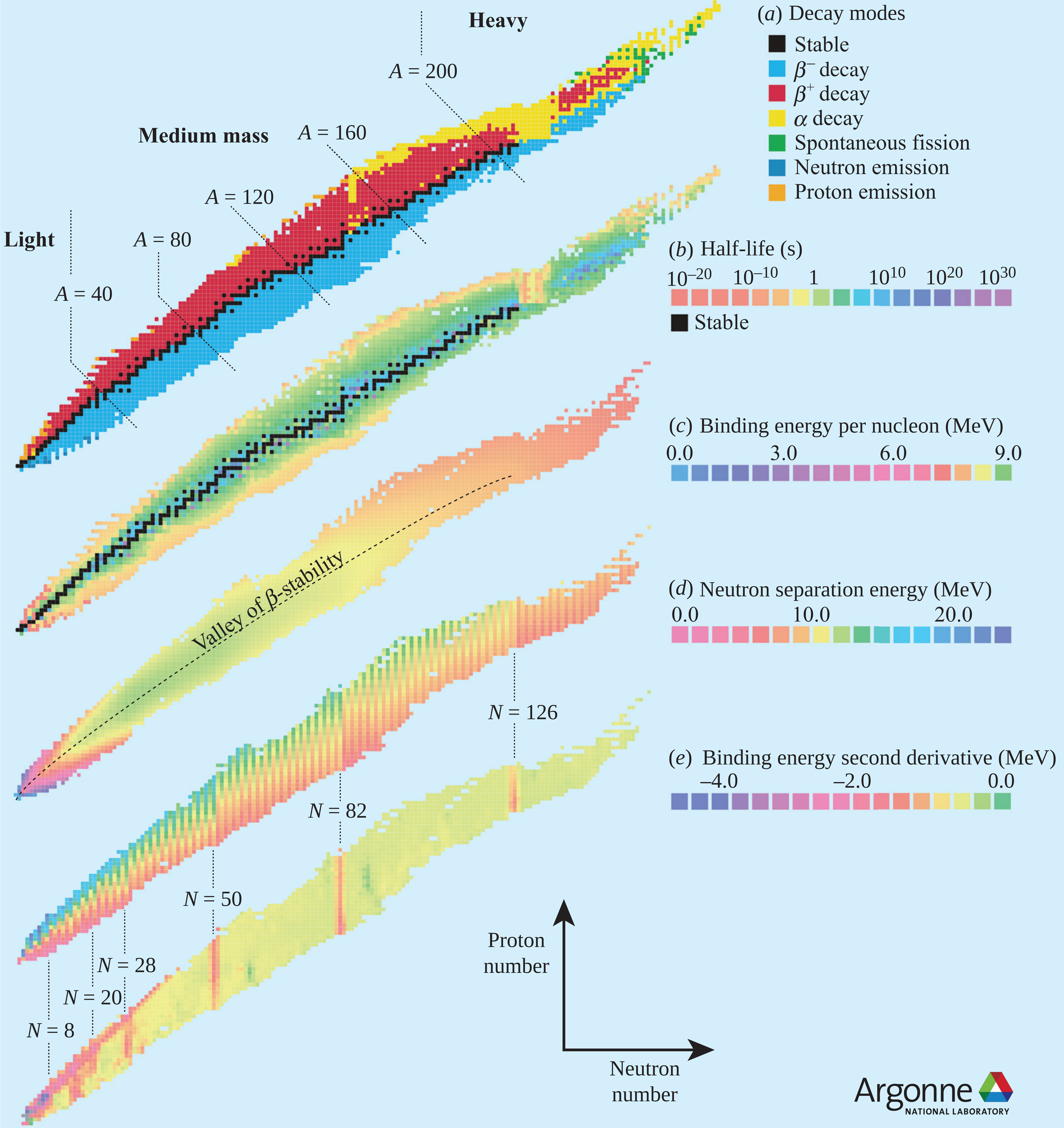
Nuclear playground

As experimentalists we can:

- *Determine the decay mode*
- *Determine the half life*
- *Determine the mass, binding*
- *Reaction cross sections*
- *Moments*
- *Transition rates / energies*



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E. C. Simpson and M. Shelley, Phys. Educ. **52**, 064002 (**2017**)

What can one observe, why is it tough?

- As you will have heard over the work shop, there are only a handful of physical properties of nuclei one can probe and link to models

- For a low-energy experimentalists the challenges are many … as we've just seen only about 4% of the nuclei predicted to be bound are stable, the rest we have to make …

- The best probes are typically nuclei themselves …

- Then there is the connection to theory and understanding, what we measure are not always instructive without model-dependent conversions (plenty of discussions in lectures 2 and 3)

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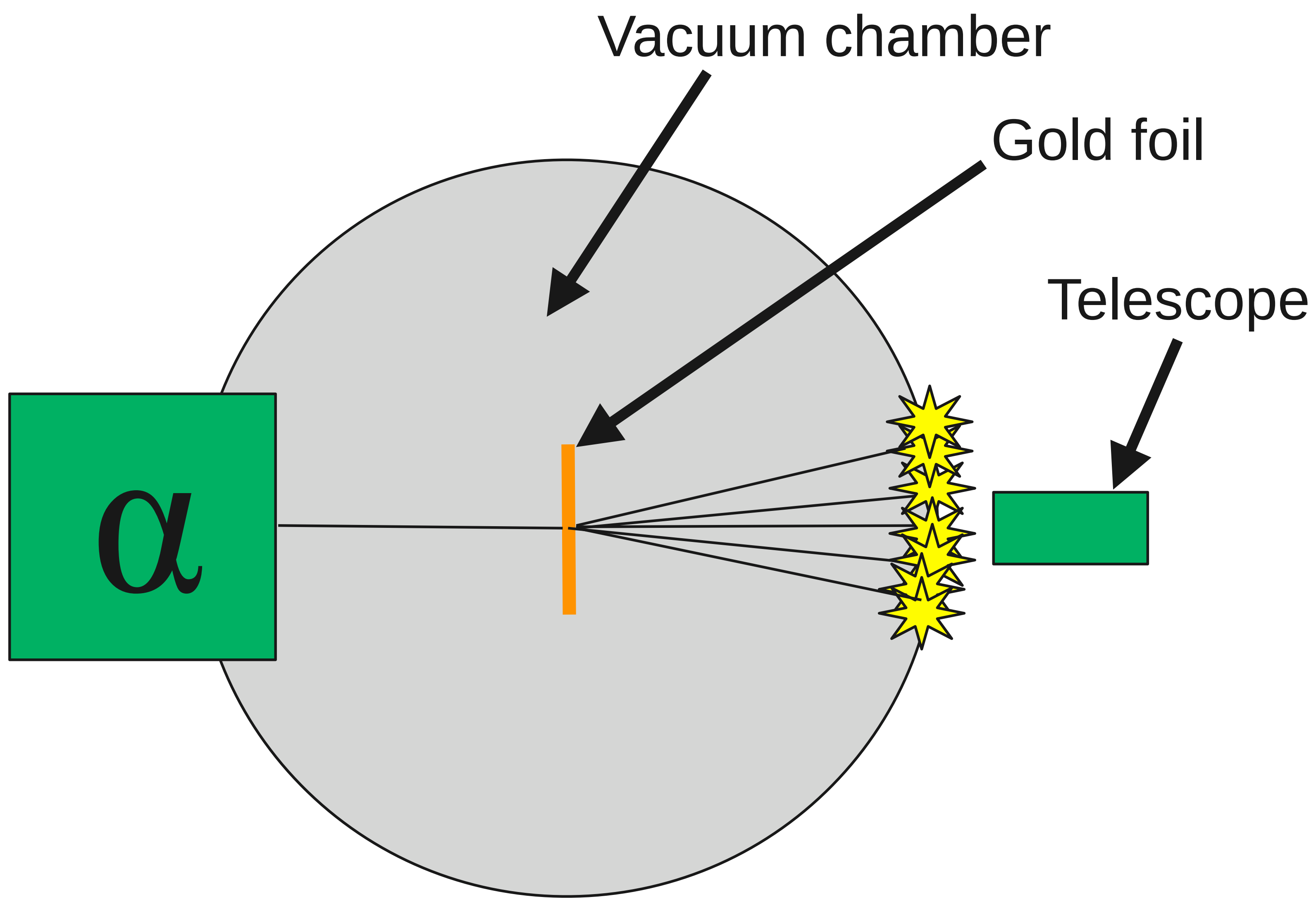
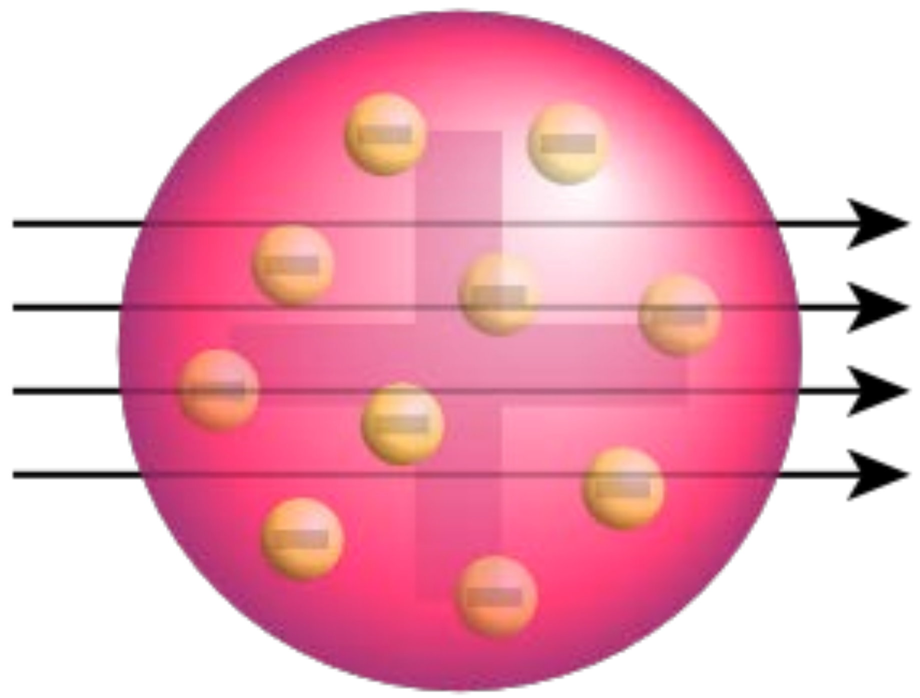
To begin at the beginning …

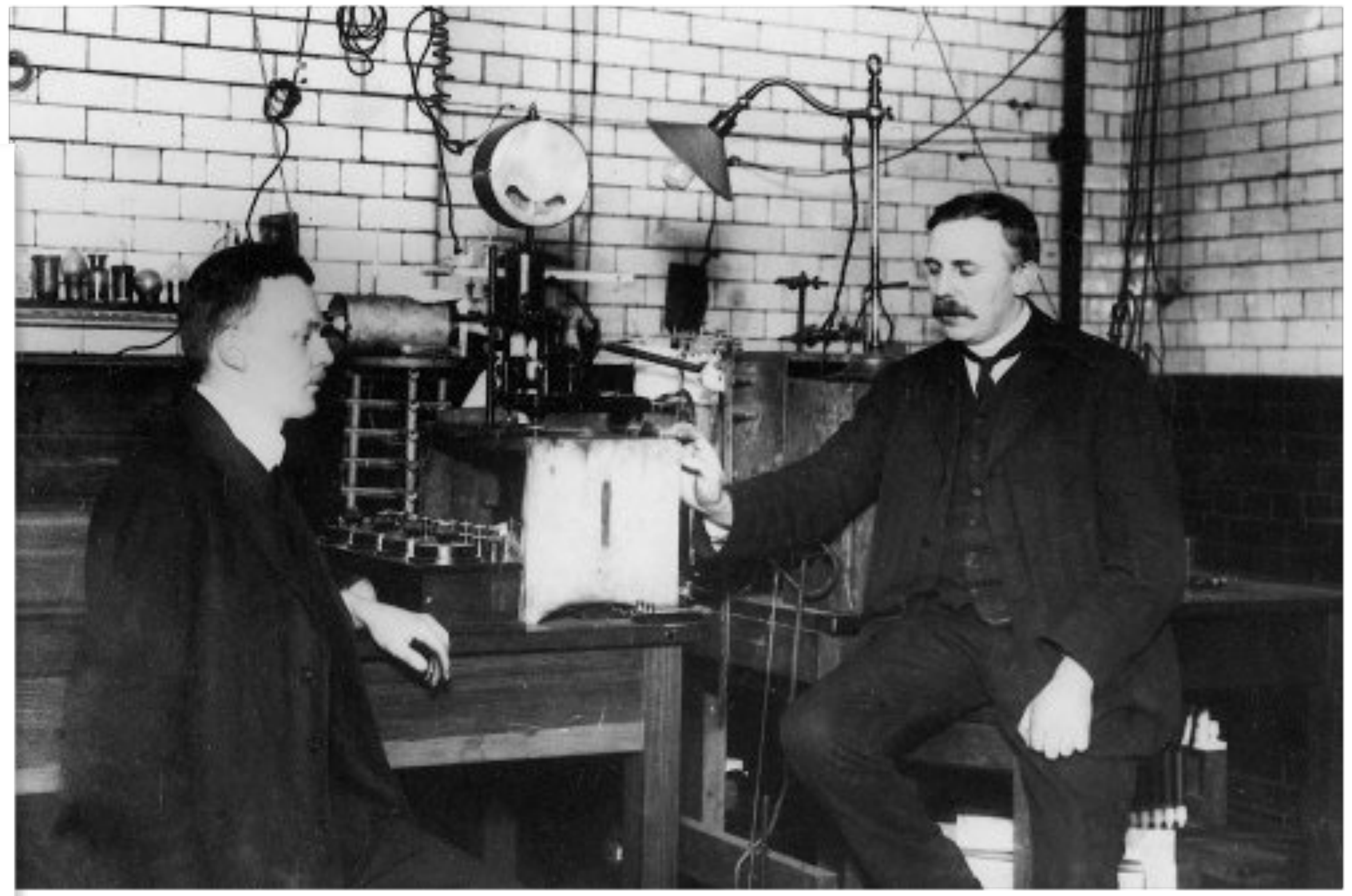
The Geiger-Marsden experiment



The plum-pudding idea seemed reasonable: this result would fit expectations



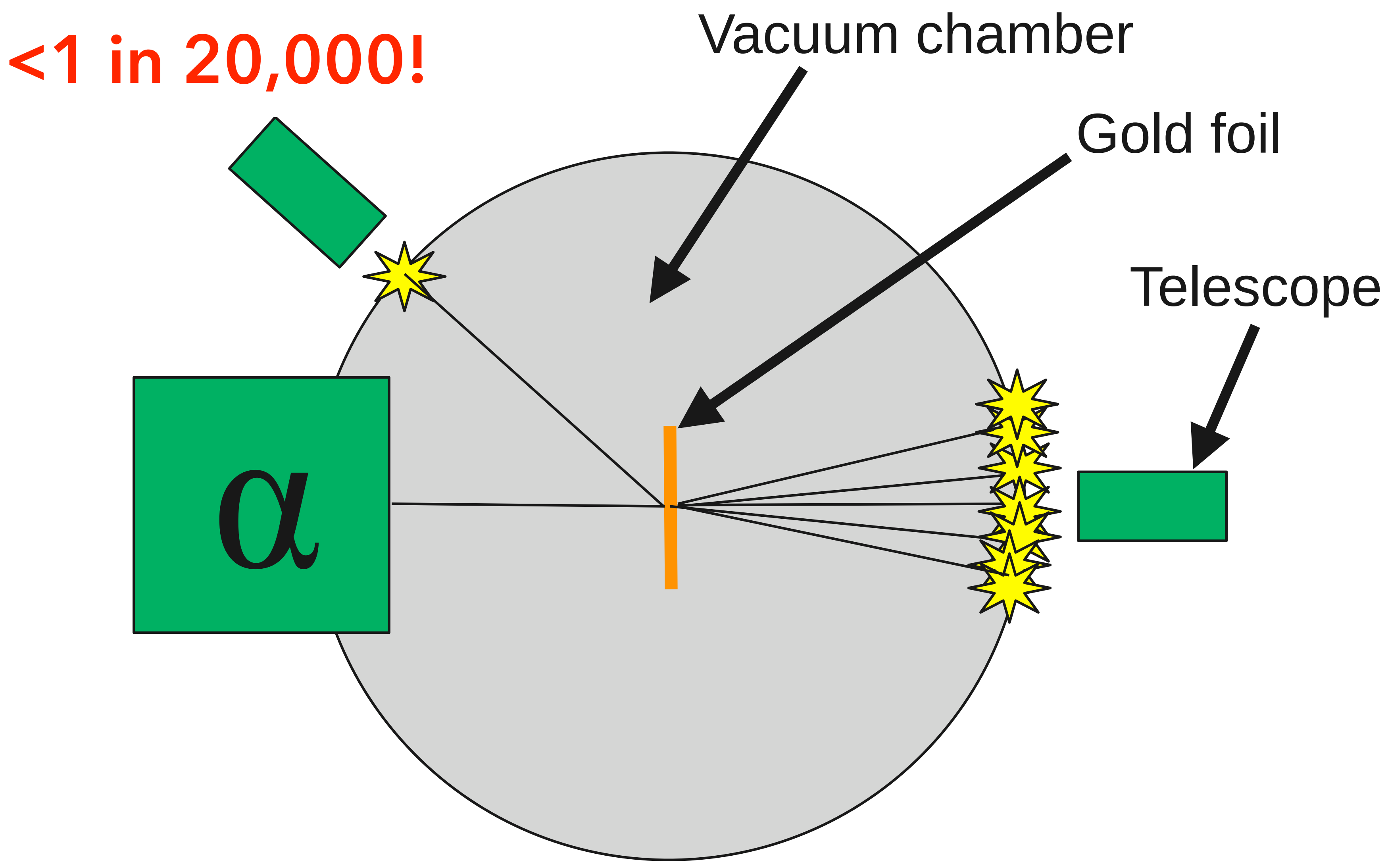
- A 0.1 Ci radium source
- ~10^{10} α particles per second (~ 1nA of ^{4}He)
- α particles of 7.7 MeV (~1.9 MeV/u)
- A gold foil of 0.00004 cm thick (~0.8 mg/cm^2)
- A telescope was used to look at flashes of light on a zinc sulphide screen

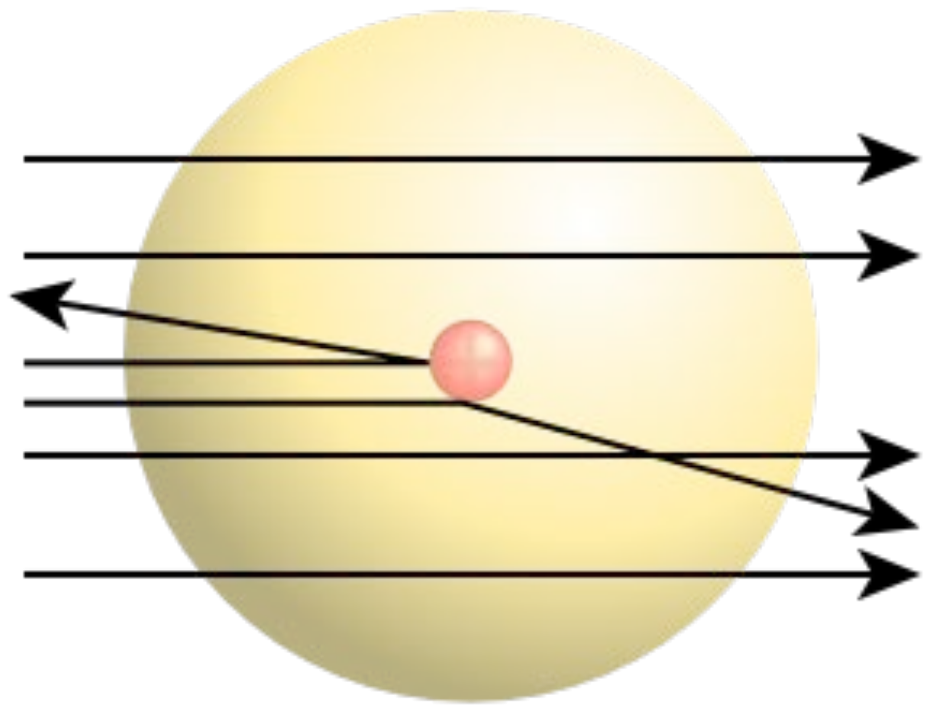


E. Rutherford, Philosophical Magazine ***21****, 669 (****1911****)*

Reaction … information

The Geiger-Marsden experiment





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- A gold foil of 0.00004 cm thick (~0.8 mg/cm^2)
- A telescope was used to look at flashes of light on a zinc sulphide screen

"It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." – E. Rutherford.

This has *all the same* ingredients a modern nuclear reaction experiment:

- A beam
- A target
- A chamber
- Reaction products
- A detector
- *… deduce something about the gold … its* ***SIZE, that's it's bound,…***

E. Rutherford, *Philosophical Magazine* **21**, 669 (**1911**)

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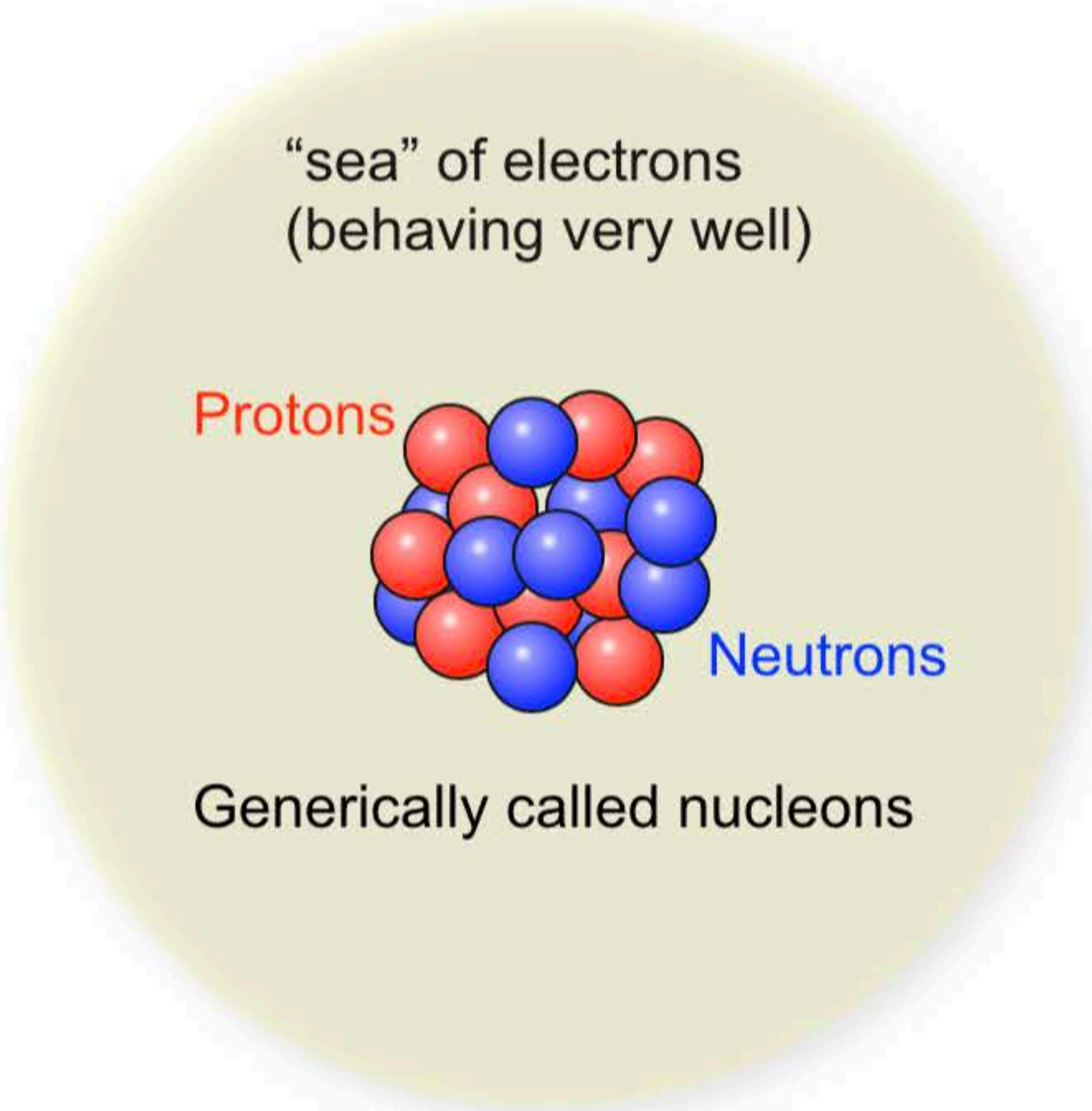
Neutrons, strong force, shell structure

Still not quite the nucleus … what's missing

- What is the positive charge? Protons (Rutherford)
- What else is in there? Neutrons (Chadwick)
- How does it stick together? (A strong nuclear potential)

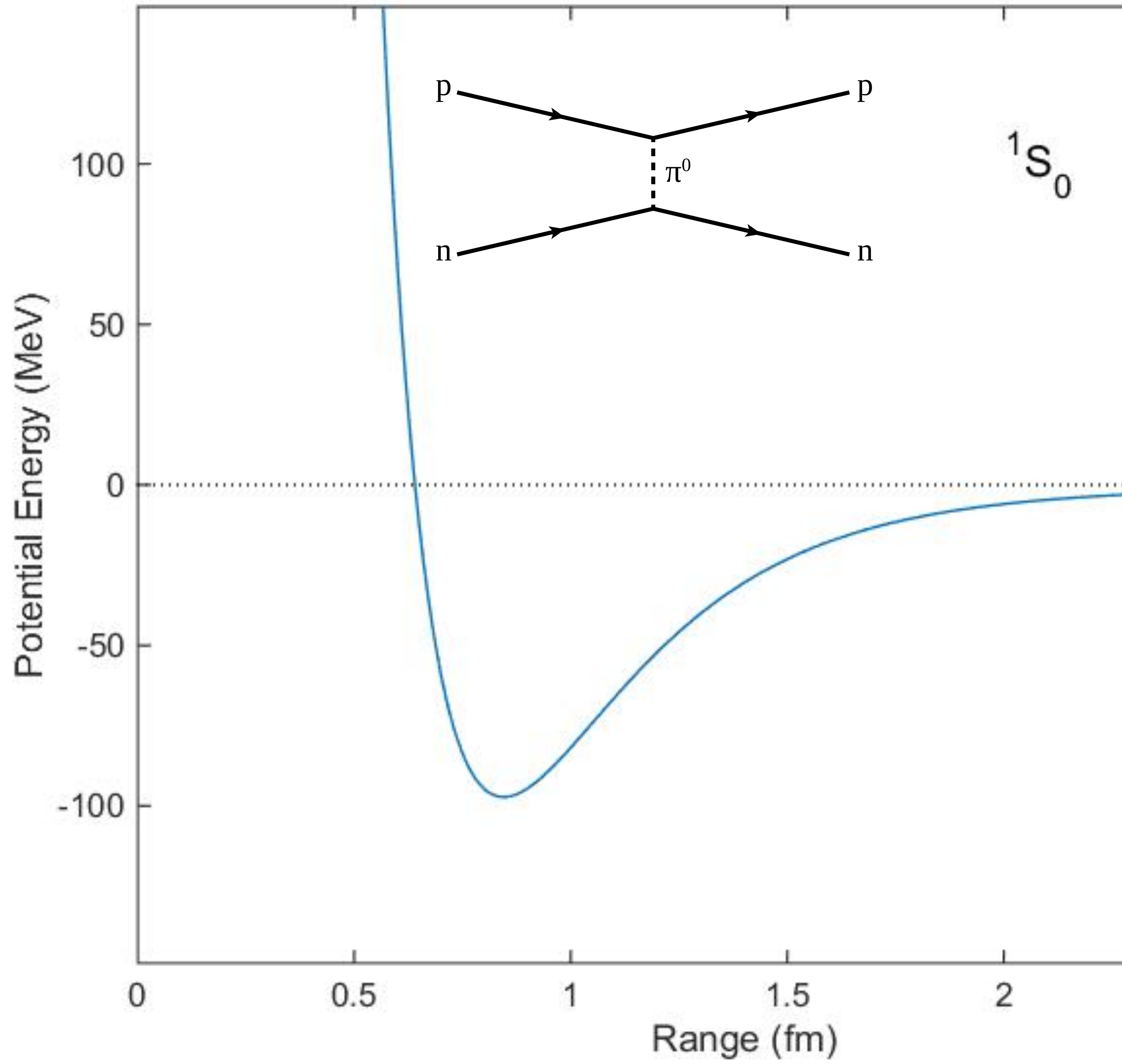
Neils Bohr, Atomic theory

James Chadwick, neutrons



Hideki Yukawa, potential

Hugely exaggerated cartoon on the atom. On this scale the nucleus would be a tiny period at the center.



An old talk I gave 10 years ago …

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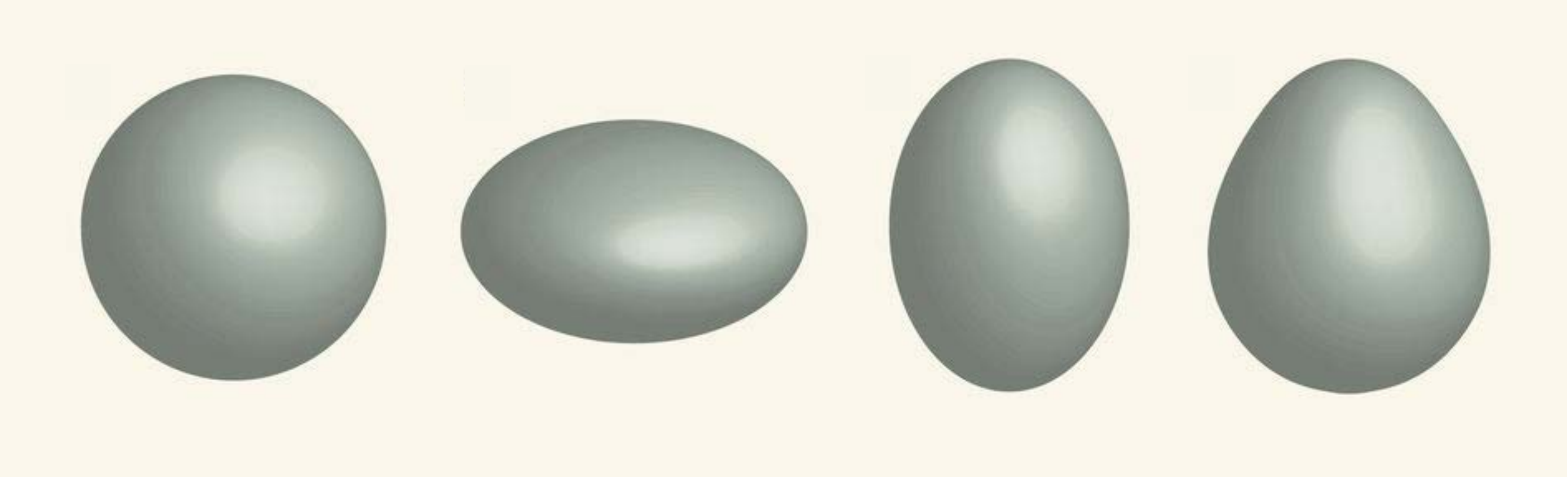
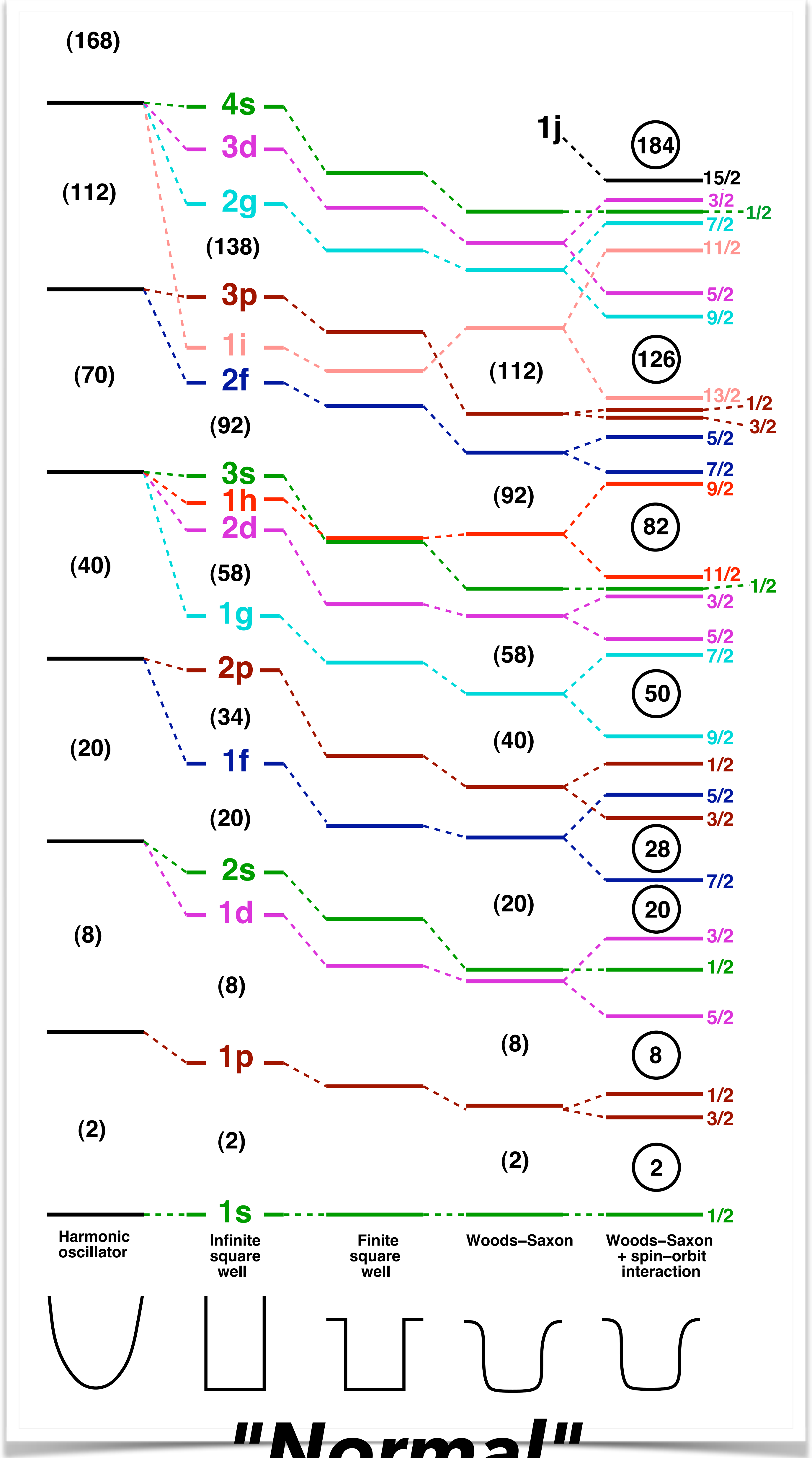
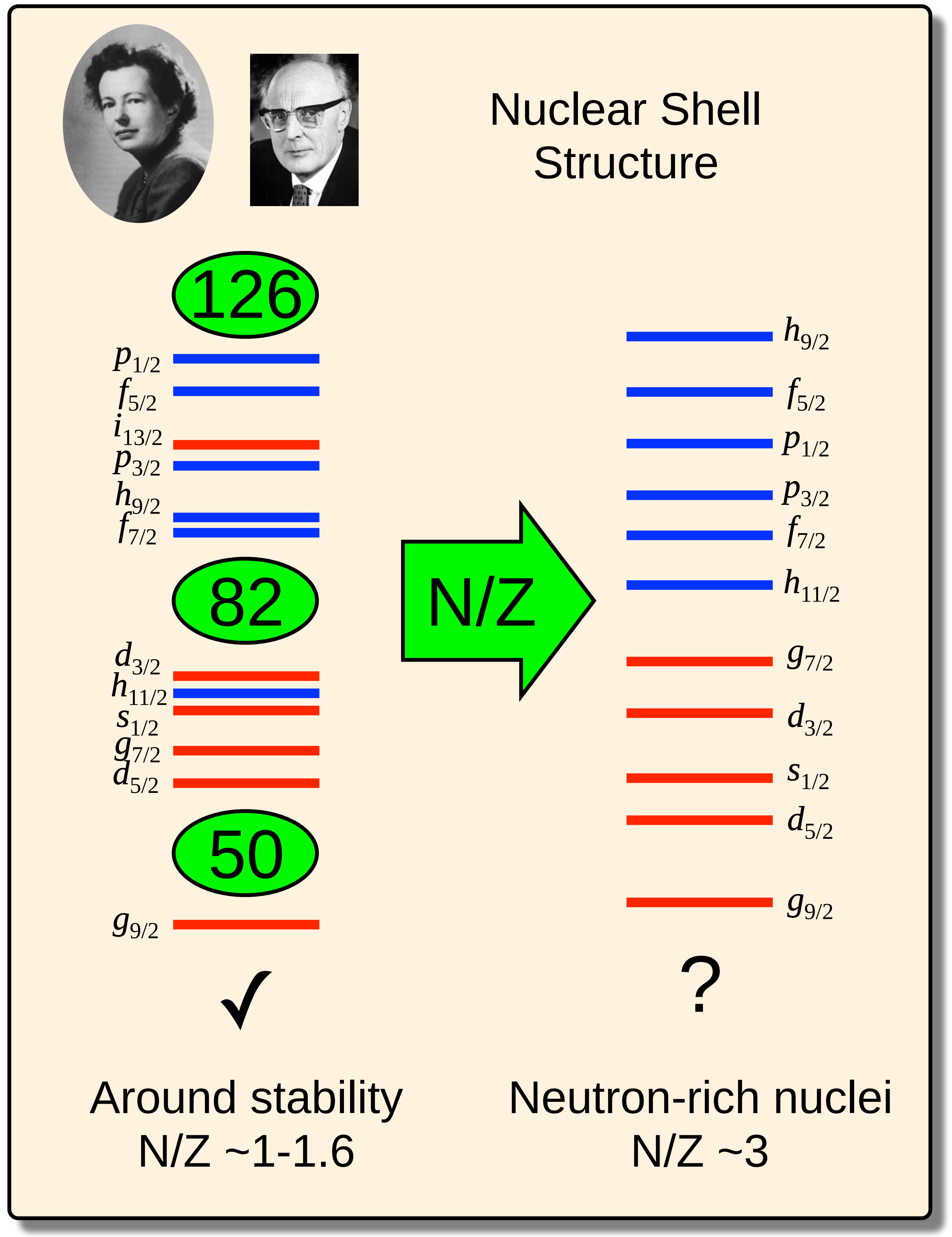
Neutrons, strong force, shell structure, shapes

- ***Shapes** (all nucleons, collective)*
- ***Single-particle** (inert cores, valence nucleons)*





"Normal"



"Exotic"

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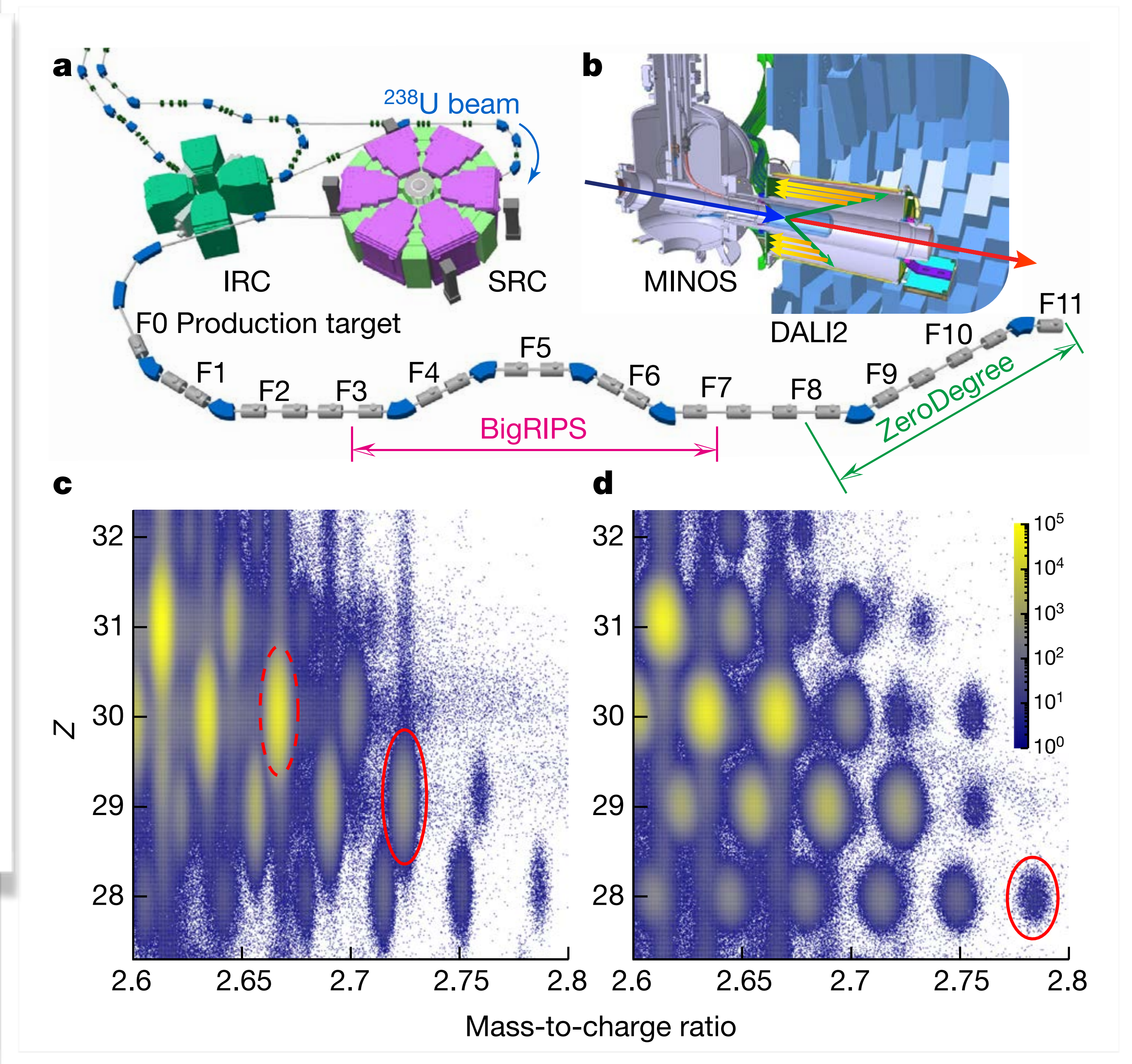
Magic systems still the pillars of our understanding

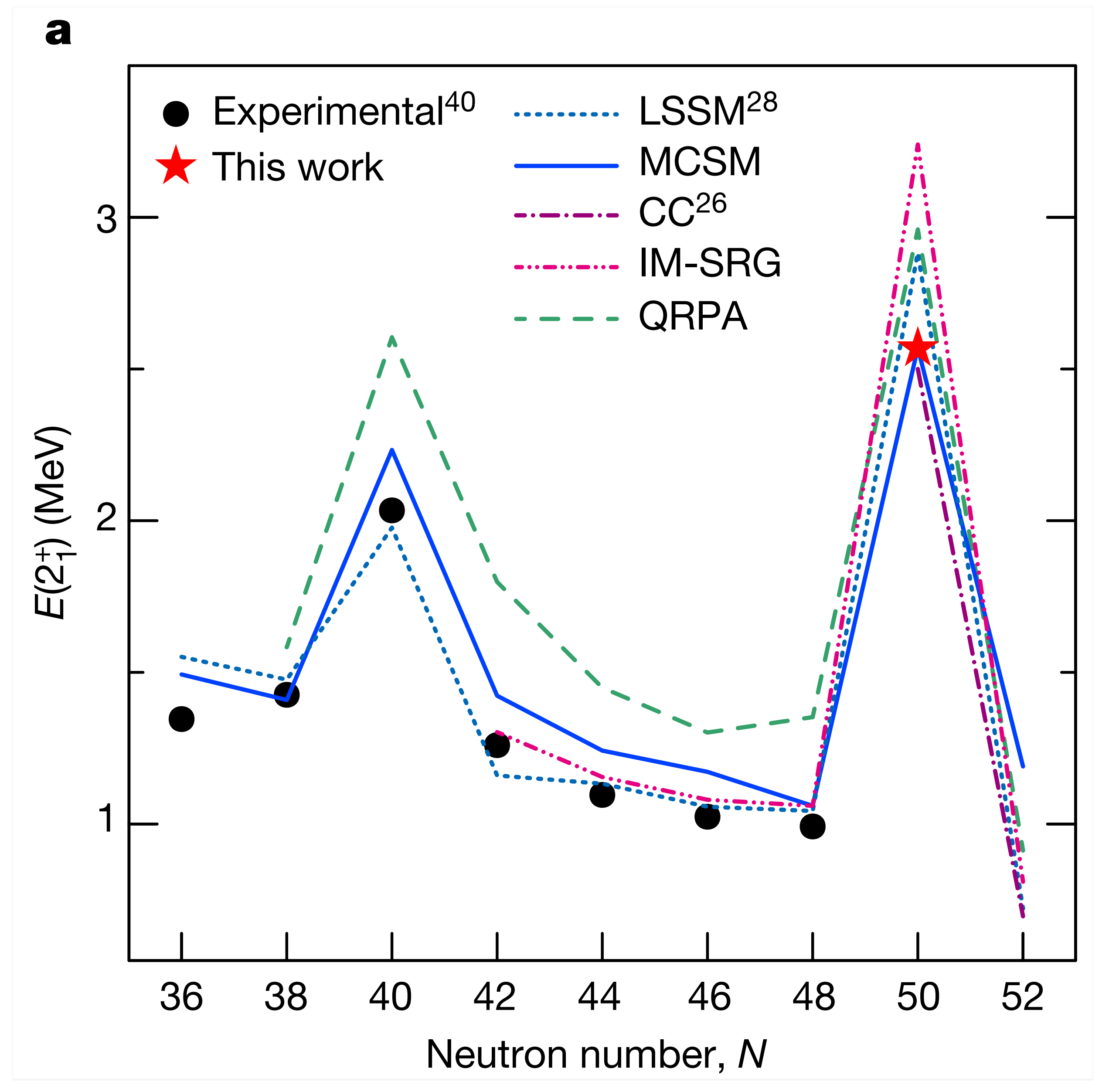
ARTICLE

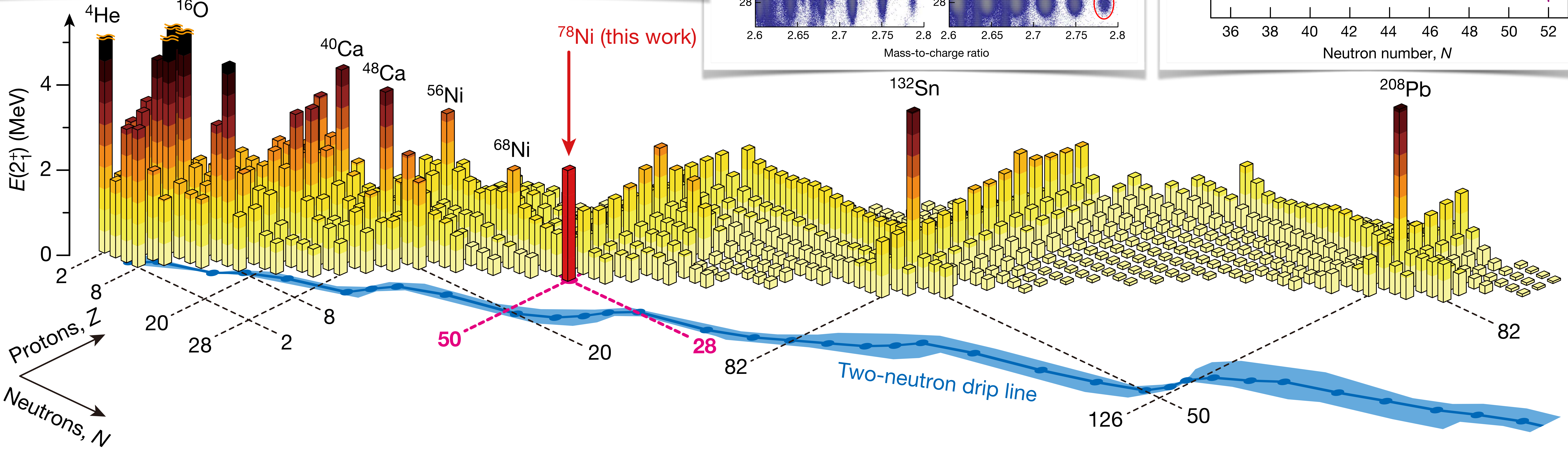
https://doi.org/10.1038/s41586-019-1155-x

^{78}Ni revealed as a doubly magic stronghold against nuclear deformation

R. Taniuchi[1,2], C. Santamaria[2,3], P. Doornenbal[2]*, A. Obertelli[2,3,4], K. Yoneda[2], G. Authelet[3], H. Baba[2], D. Calvet[3], F. Château[3], A. Corsi[3], A. Delbart[3], J.-M. Gheller[3], A. Gillibert[3], J. D. Holt[5], T. Isobe[2], V. Lapoux[3], M. Matsushita[6], J. Menéndez[6], S. Momiyama[1,2], T. Motobayashi[2], M. Niikura[1], F. Nowacki[7], K. Ogata[8,9], H. Otsu[2], T. Otsuka[1,2,6], C. Péron[3], S. Péru[10], A. Peyaud[3], E. C. Pollacco[3], A. Poves[11], J.-Y. Roussé[3], H. Sakurai[1,2], A. Schwenk[4,12,13], Y. Shiga[2,14], J. Simonis[4,12,15], S. R. Stroberg[5,16], S. Takeuchi[2], Y. Tsunoda[6], T. Uesaka[2], H. Wang[2], F. Browne[17], L. X. Chung[18], Z. Dombradi[19], S. Franchoo[20], F. Giacoppo[21], A. Gottardo[20], K. Hadyńska-Klęk[21], Z. Korkulu[19], S. Koyama[1,2], Y. Kubota[2,6], J. Lee[22], M. Lettmann[4], C. Louchart[4], R. Lozeva[7,23], K. Matsui[1,2], T. Miyazaki[1,2], S. Nishimura[2], L. Olivier[20], S. Ota[6], Z. Patel[24], E. Şahin[21], C. Shand[24], P.-A. Söderström[2], I. Stefan[20], D. Steppenbeck[6], T. Sumikama[25], D. Suzuki[20], Z. Vajta[19], V. Werner[4], J. Wu[2,26] & Z. Y. Xu[22]



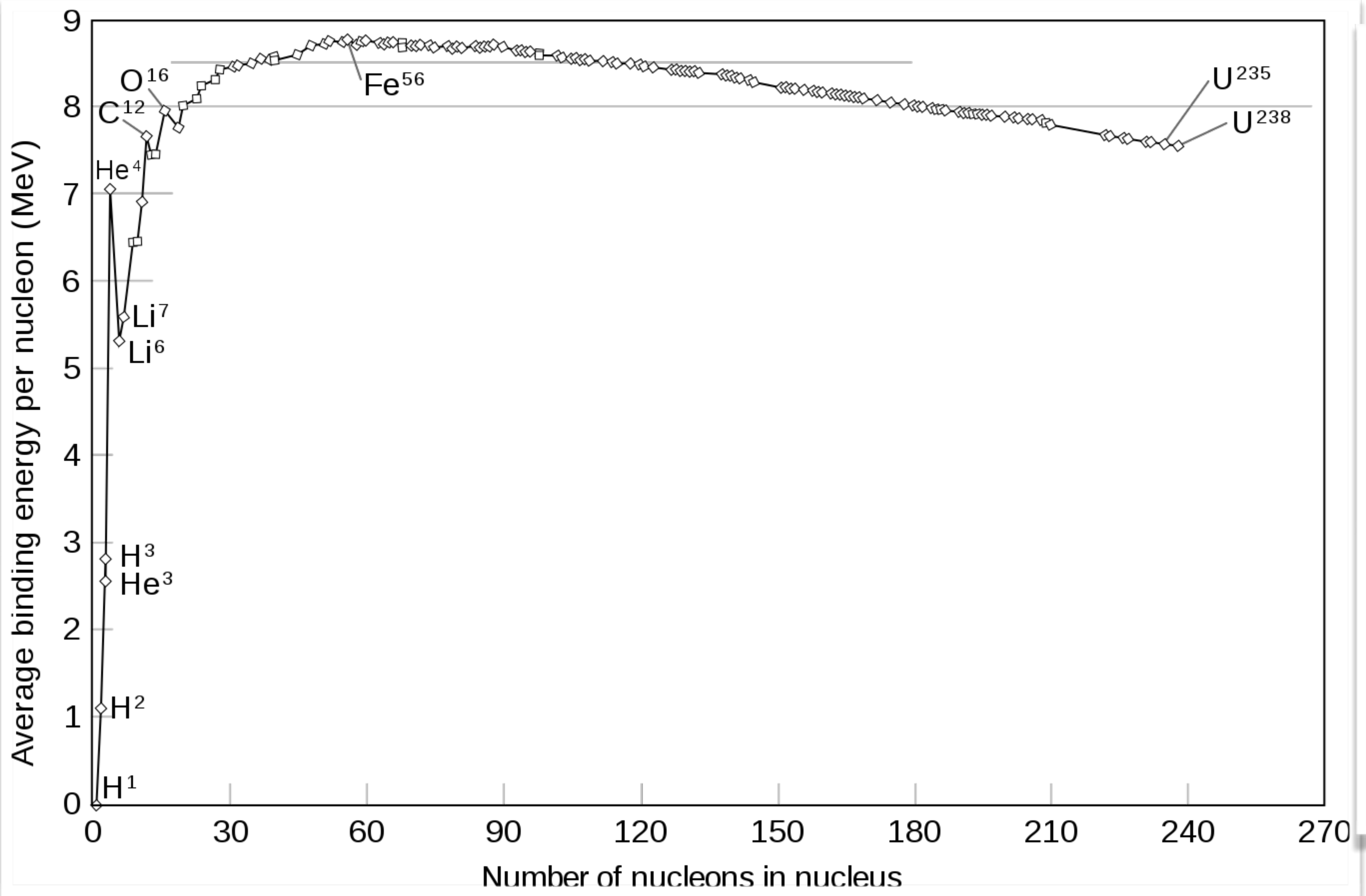


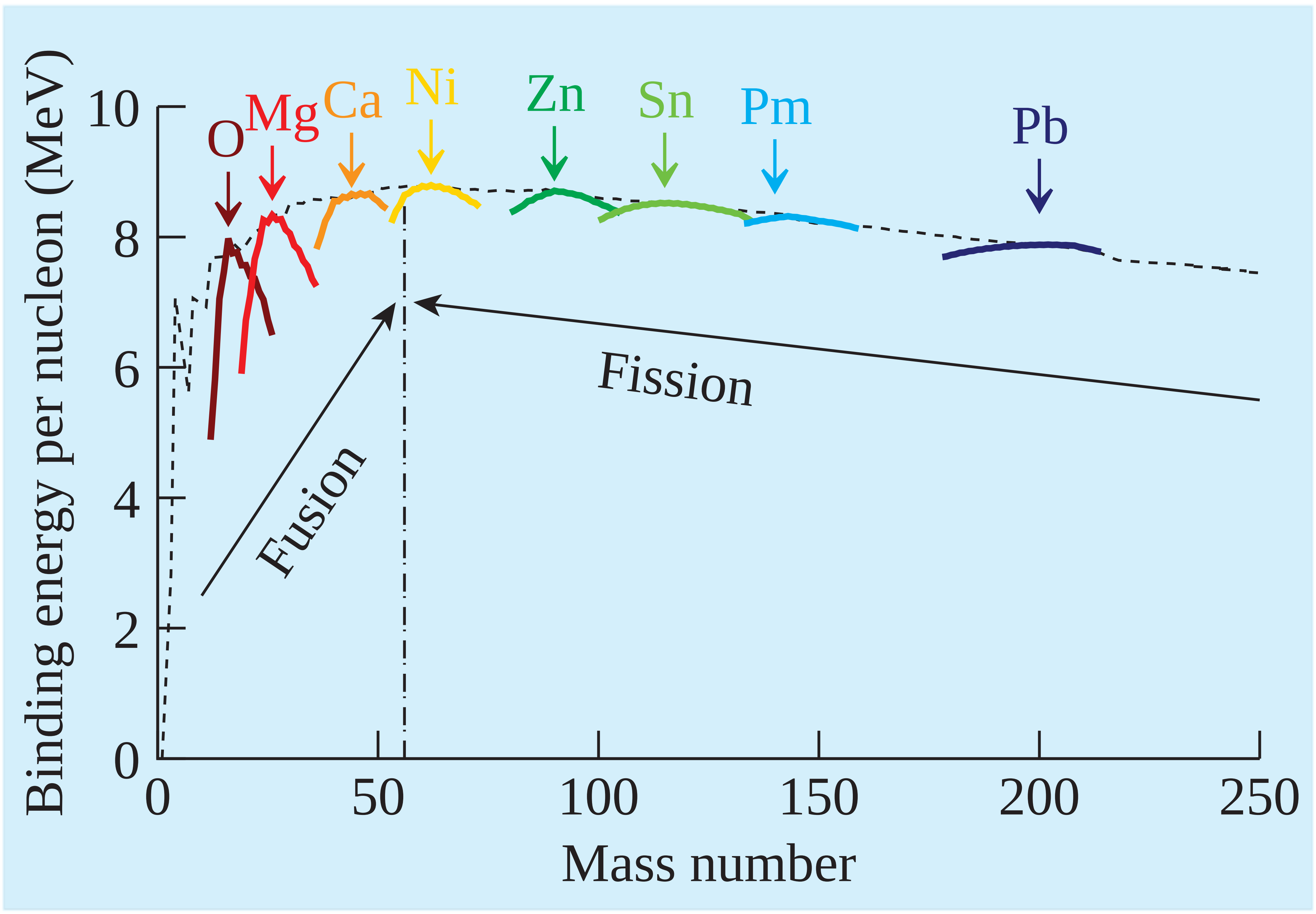


May 2019 … Taniuchi et al., Nature **569**, 53 (**2019**)

Masses

Binding energy

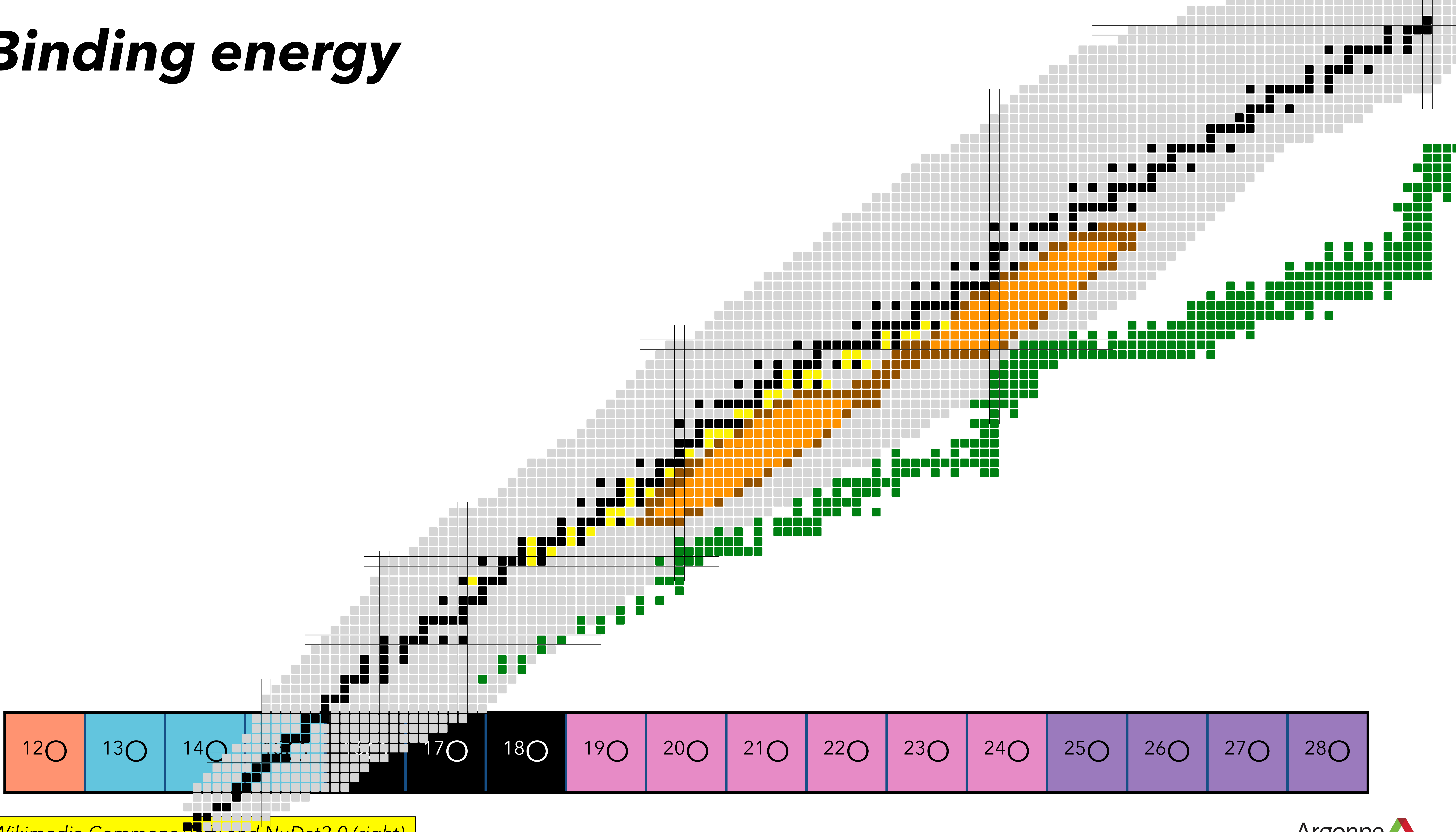




12O	13O	14O	15O	16O	17O	18O	19O	20O	21O	22O	23O	24O	25O	26O	27O	28O

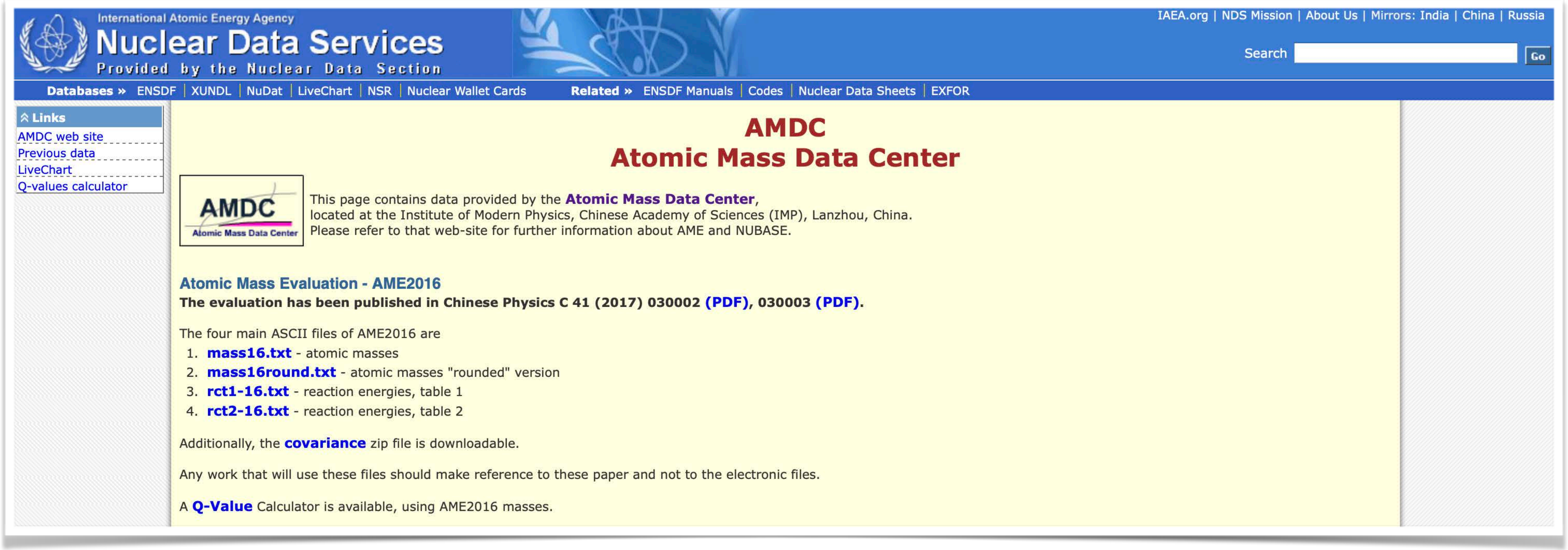
Wikimedia Commons (left) and NuDat2.0 (right)

Binding energy



Wikimedia Commons (left) and NuDat2.0 (right)

Terms and data



Nuclear mass: *m(Z,N)*

Binding energy per nucleon

Mass excess: $\{Zm_p + Nm_n - m(Z,N)\}c^2$

Separation energies, S_p and S_n (S_{2p} + S_{2n})

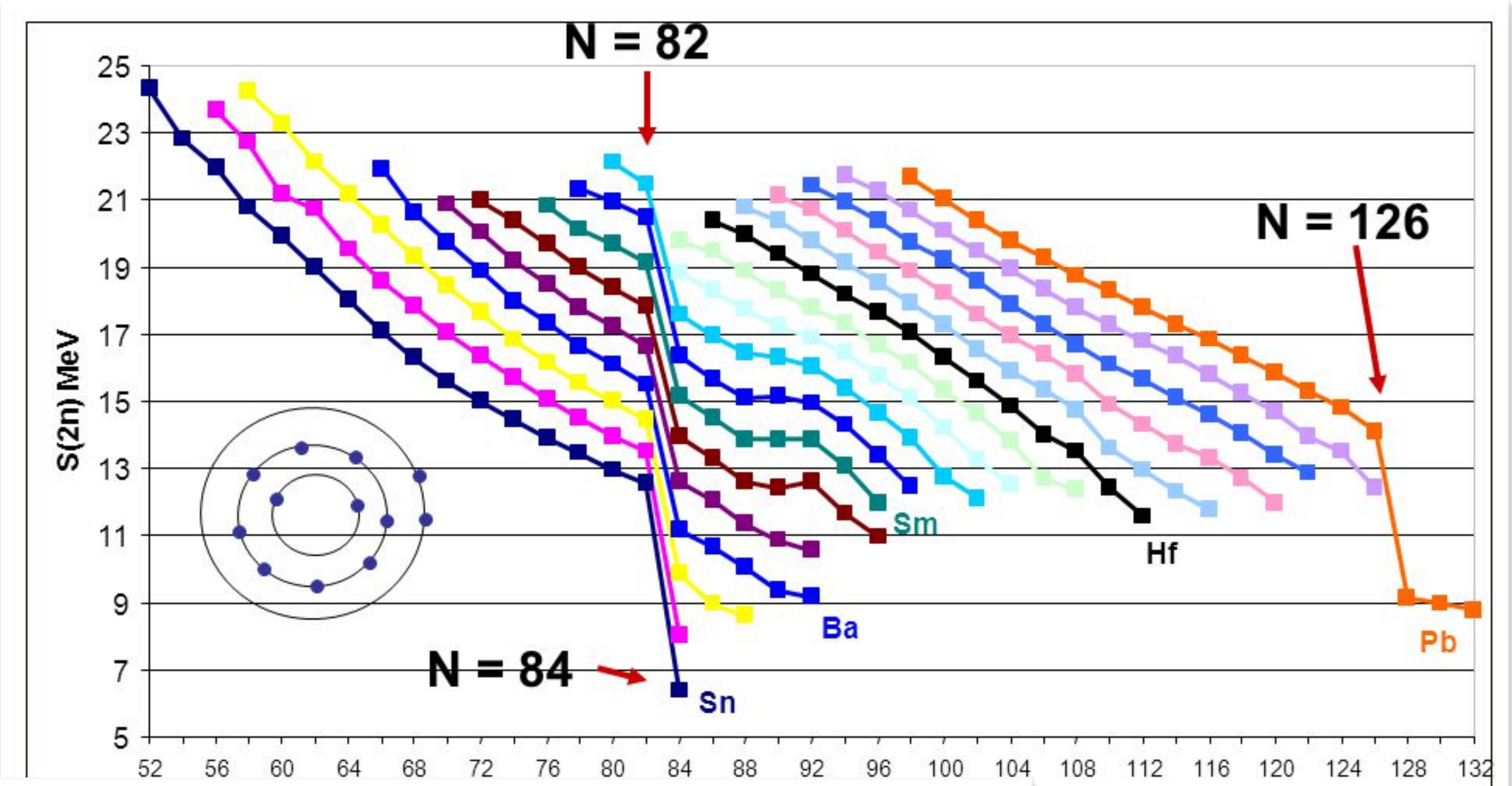
[difference in binding energies e.g. $S_n = \{m(Z,N-1) + m_n - m(Z,N)\}c^2 = B(Z,N) - B(Z,N-1)$]

Atomic mass unit (mass of nucleon): $931.49410242(28)$ MeV/c^2

Mass databases compile these …

e.g. https://www-nds.iaea.org/amdc/

Terms and data




```
                                  MASS LIST
                                for analysis

1N-Z    N    Z   A  EL    O    MASS EXCESS        BINDING ENERGY/A        BETA-DECAY ENERGY        ATOMIC MASS        V/S
                                  (keV)                (keV)                  (keV)              (micro-u)
0  1    1    0    1  n        8071.31714   0.00046      0.0       0.0   B-    782.347    0.000   1 008664.91585    0.00049
  -1    0    1    1 H         7288.97059   0.00009      0.0       0.0   B-      *                 1 007825.03223    0.00009
0  0    1    1    2 H        13135.72174   0.00011   1112.283   0.000 B-      *                 2 014101.77812    0.00012
```

```
                                    LINEAR COMBINATIONS

0                                        ADAM STYLE(1)
                                         for analysis

1 A  elt  Z        S(2n)              S(2p)             Q(a)              Q(2B-)            Q(ep)             Q(B- n)
0  1  n   0          *                  *                 *                 *                 *                 *
   1 H    1          *                  *                 *                 *                 *                 *
0  2 H    1          *                  *                 *                 *                 *                 *
0  3 H    1    8481.80     0.00         *                 *           -13717#   2000#         *                 *
```

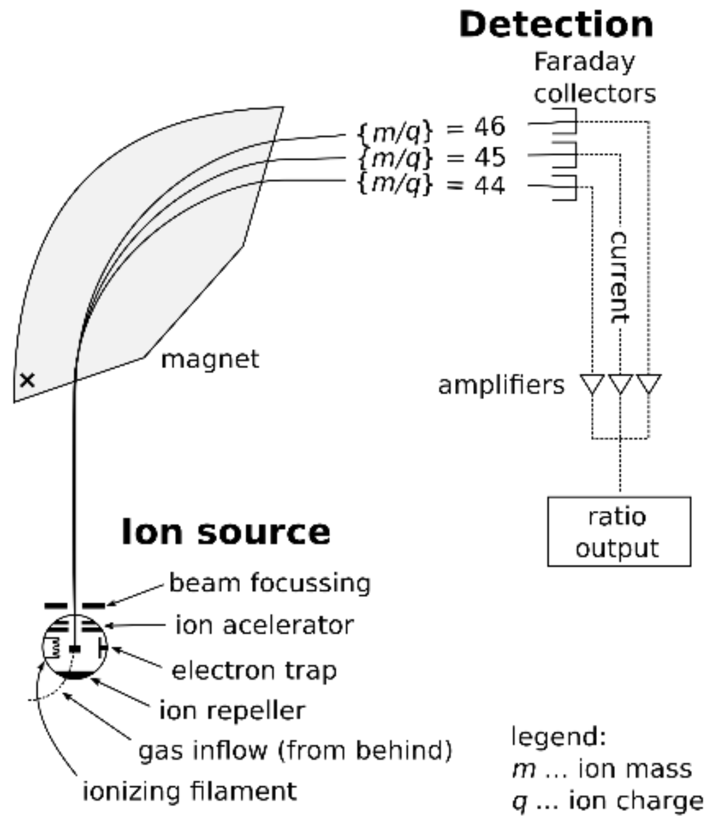
e.g. https://www-nds.iaea.org/amdc/, the 2016 mass evaluation

Various techniques to determine mass

- ***Q*-values**
  - Decays
  - Kinematics

$$Q = \Sigma m_i - \Sigma m_f$$

- **Dispersion**
  - Spectrograph



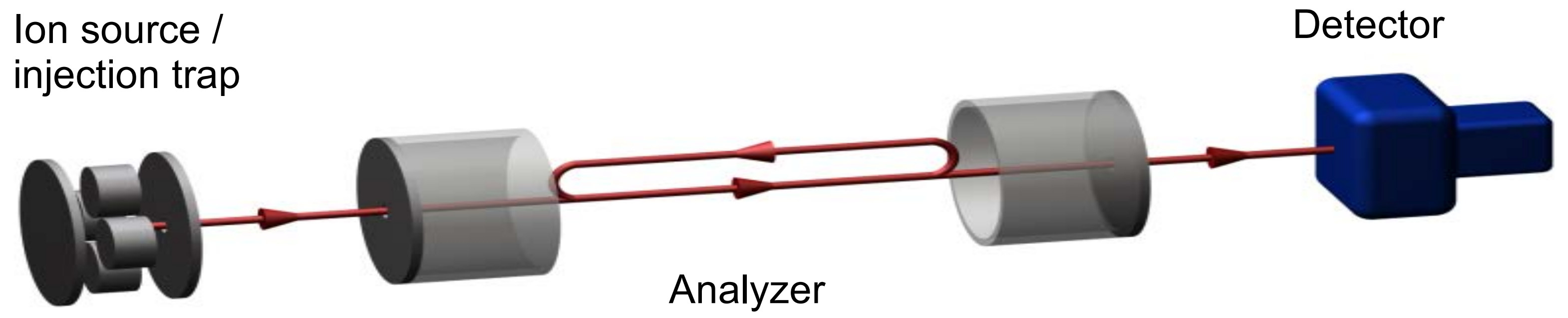
- **ToF**
  - Spectrograph

$$qvB = \frac{(\gamma m_0)(L_{path}/ToF)^2}{\rho}$$

$$\Rightarrow m_0 = \frac{ToF}{L_{path}} \frac{qB\rho}{\gamma}$$

  - Multi-reflection (MR-TOF)

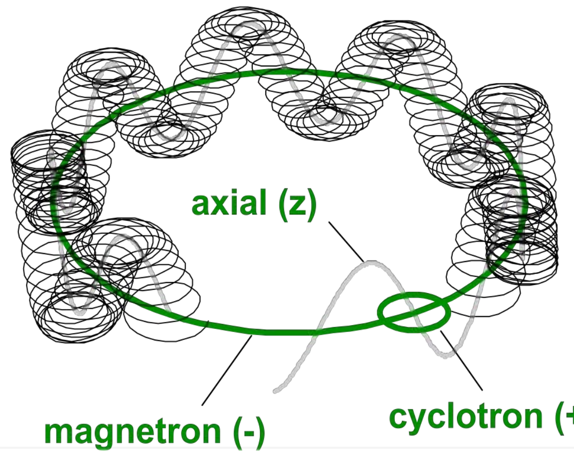
$$E = \frac{1}{2}mv^2 = qeU \quad \Rightarrow \quad \frac{m}{q} \propto t^2$$

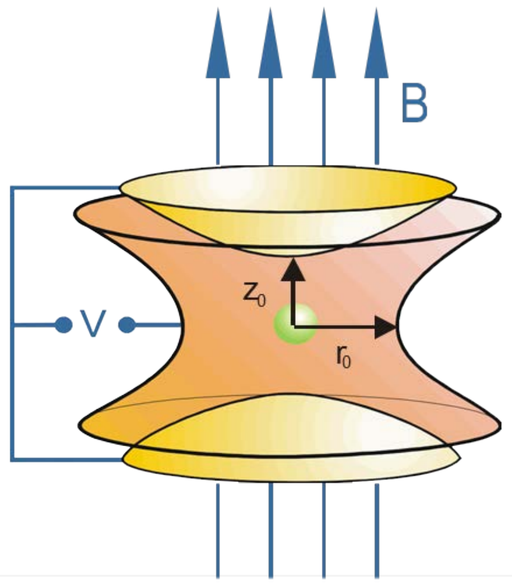


- **Frequency**
  - Penning trap
  - Storage rings

Cyclotron Frequency

$$\omega_c = \frac{1}{2\pi}\frac{q}{m}B$$



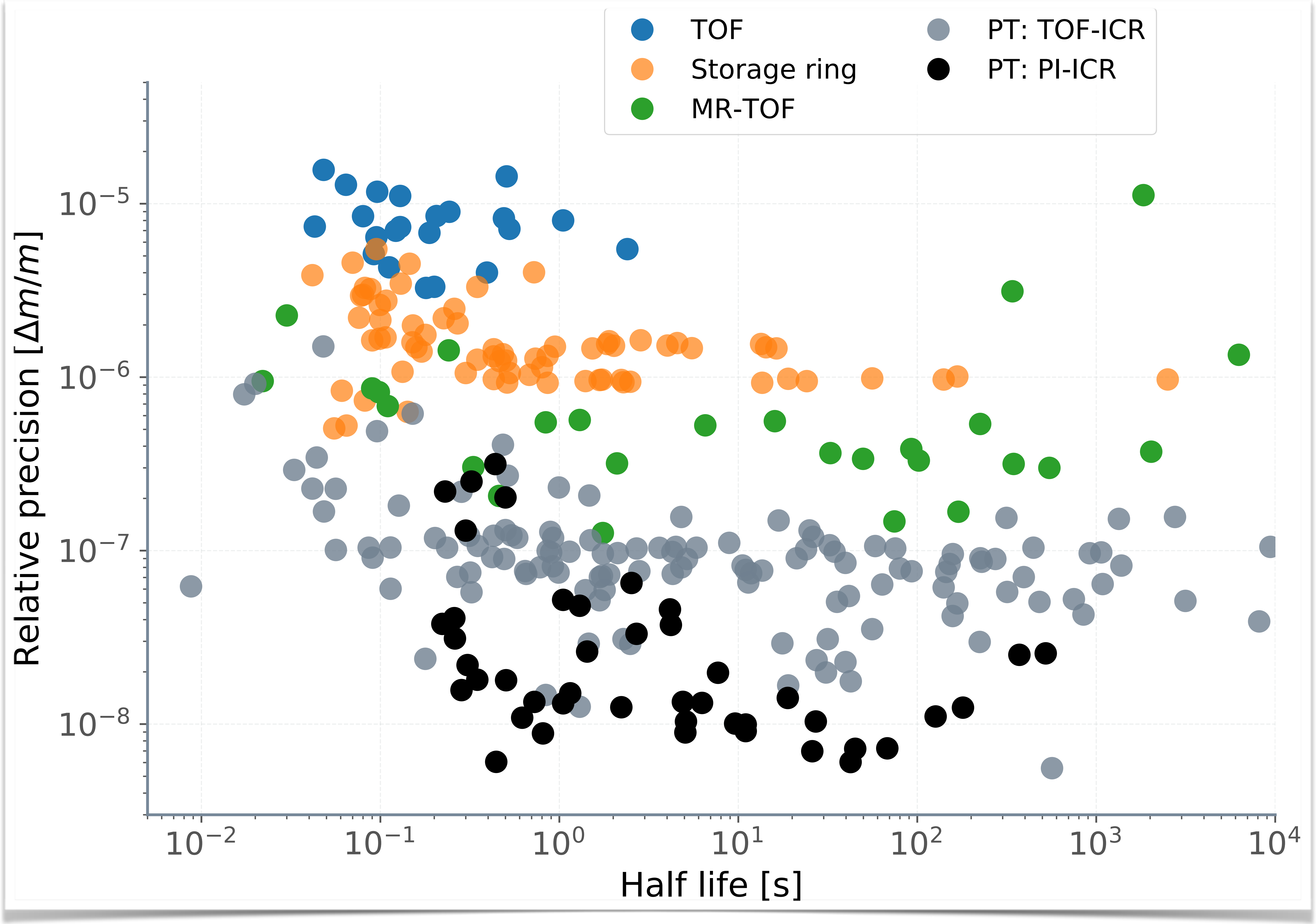


Slide stolen from Chris Chiara, ARL, who was inspired by others …

Precision, time, resolution

Modern techniques:

- *TOF (fast, low precision)*
- *Storage rings (fast, many measurements at once)*
- *MR-TOFs (fast, high resolution)*
- *Penning traps ("slow", high resolution, high precision)*



Plot from Rodney Orford, LBNL and proud Canadian

Argonne NATIONAL LABORATORY

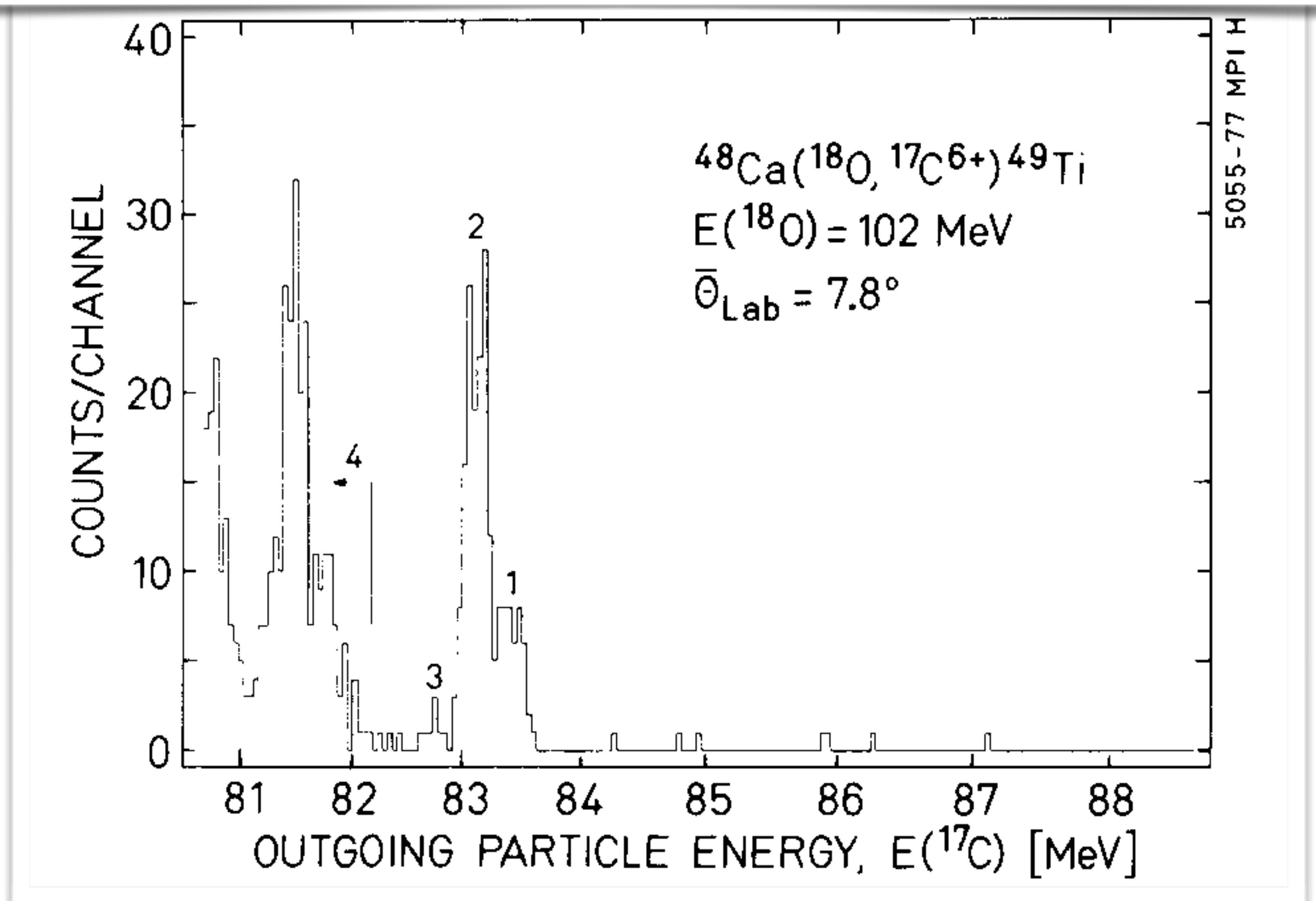
e.g. Q value

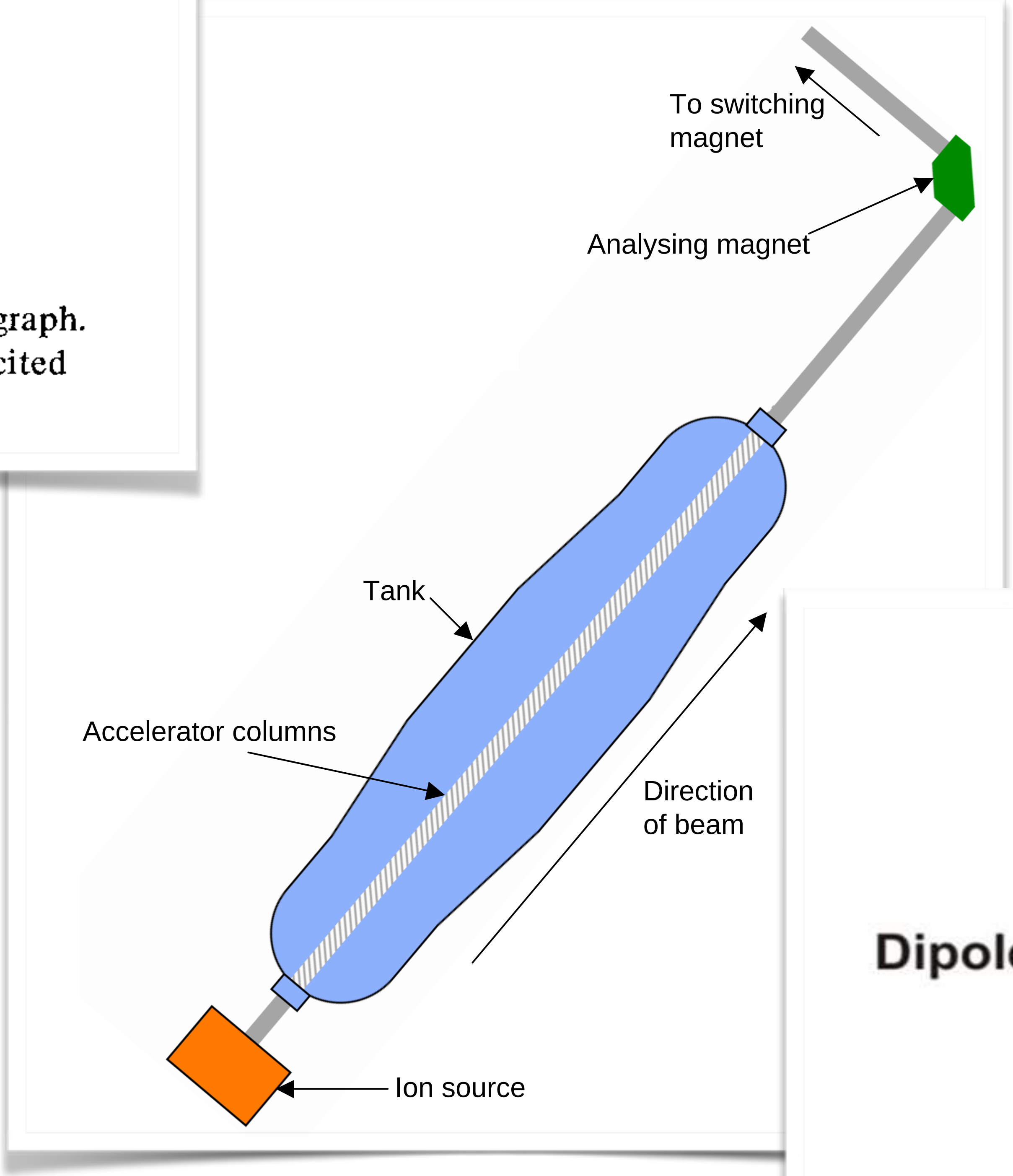
THE MASS AND LOW-LYING LEVEL STRUCTURE OF ^{17}C

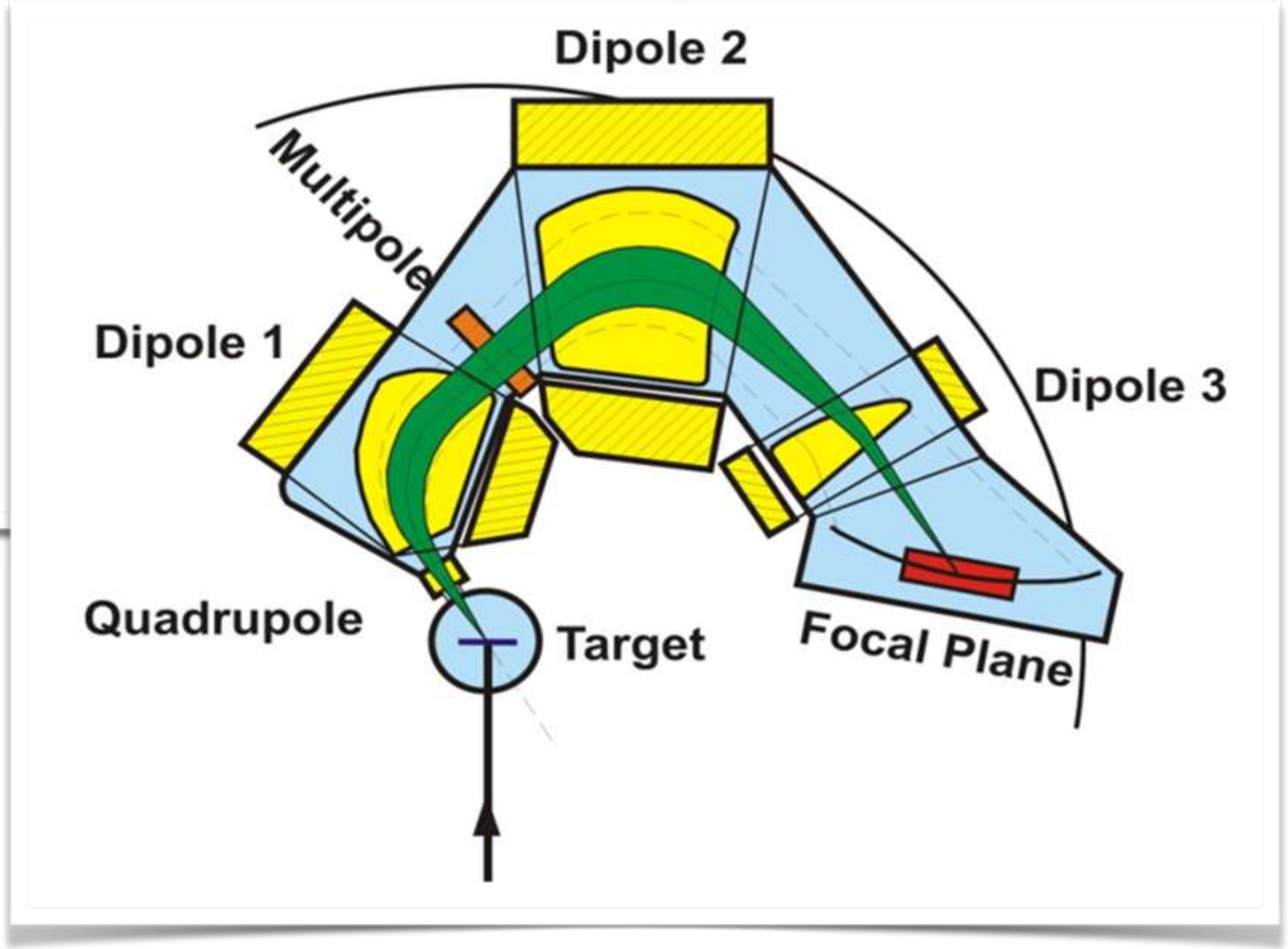
J.A. NOLEN[1], T.S. BHATIA[2], H. HAFNER[3], P. DOLL[4],
C.A. WIEDNER and G.J. WAGNER
Max-Planck-Insitut für Kernphysik, Heidelberg, Germany

Received 14 September 1977

Spectra of ^{17}C ions from the ^{48}Ca(^{18}O, ^{17}C) ^{49}Ti reaction at 102 MeV were recorded with a Q3D spectrograph. The lowest state observed, assumed to be the ground state of ^{17}C, has a mass excess of 21023 ± 35 keV. An excited state of ^{17}C was also observed at an excitation energy of 292 ± 20 keV.





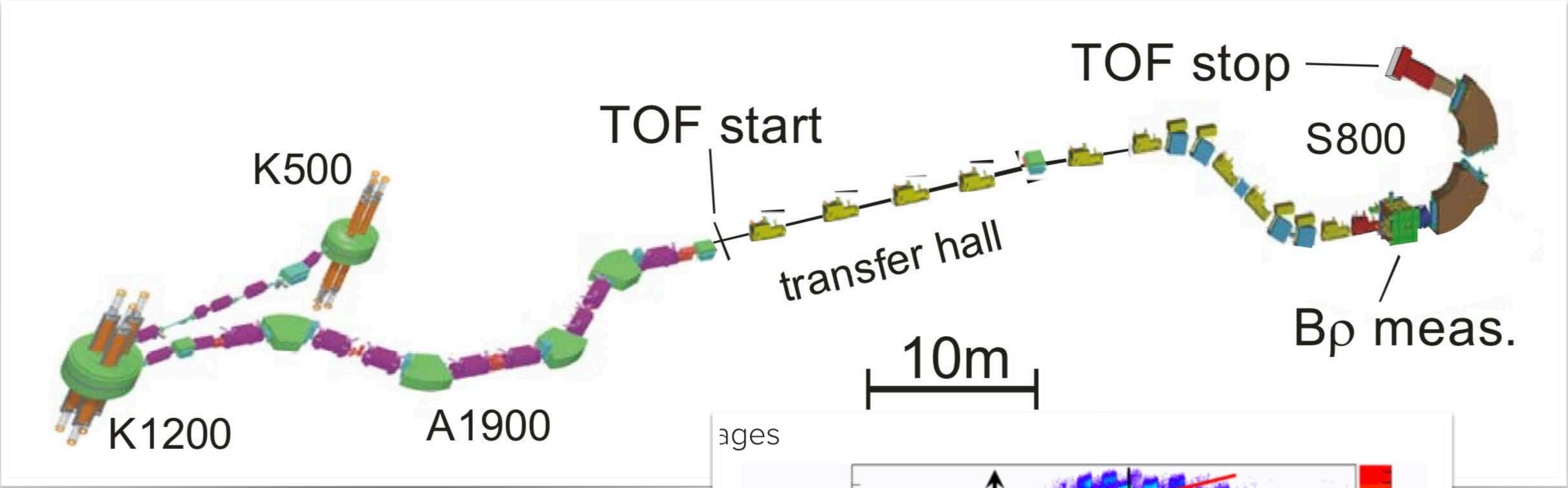


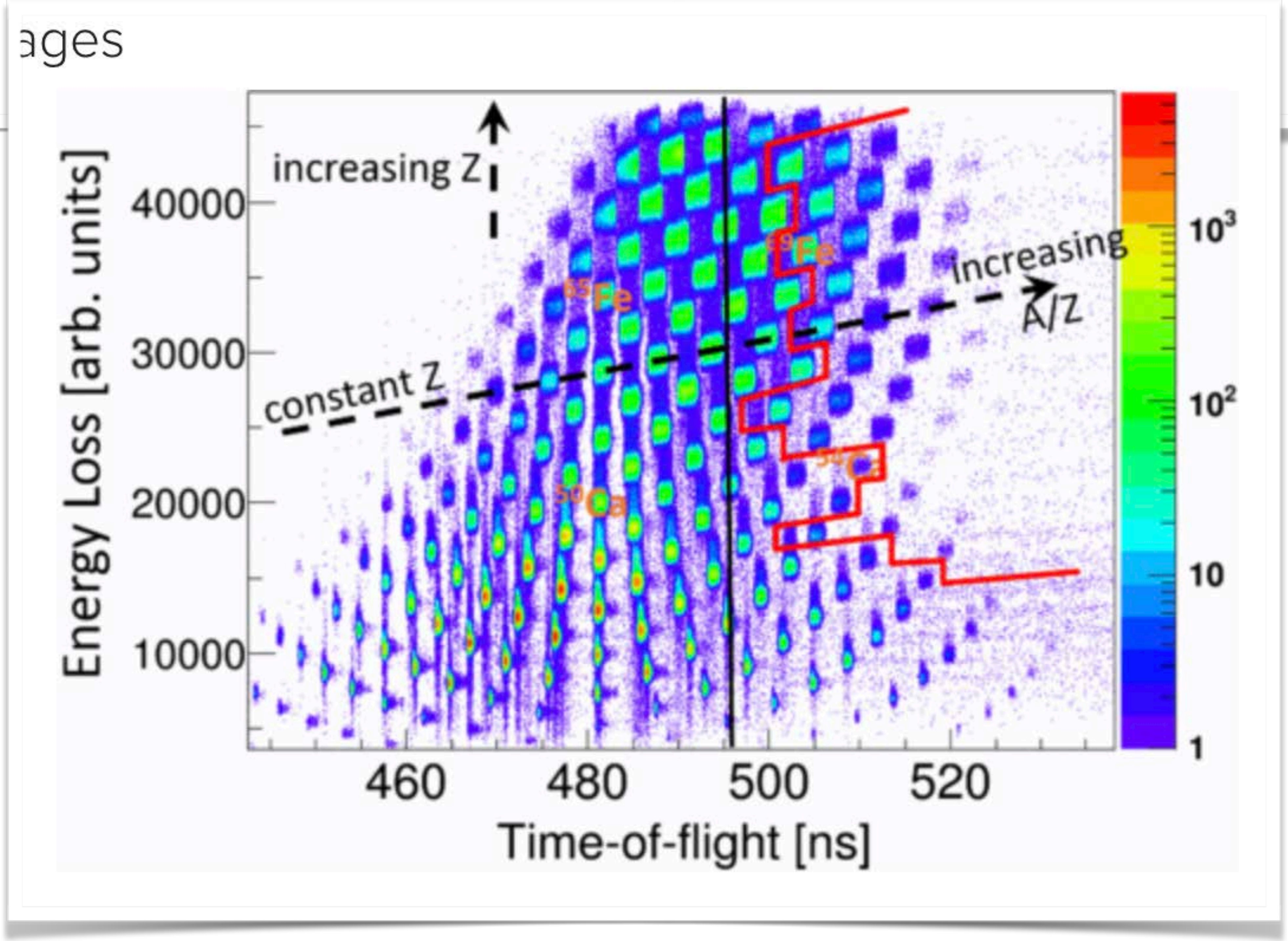
$$S_n = \{m(Z,N-1) + m_n - m(Z,N)\}c^2 = B(Z,N) - B(Z,N-1)] = Q$$

(with knowledge of other masses and beam energies)

J. A. Nolen et al., Phys. Lett. B **71**, 314 (1977)

e.g. TOF (and magnetic spectrograph)

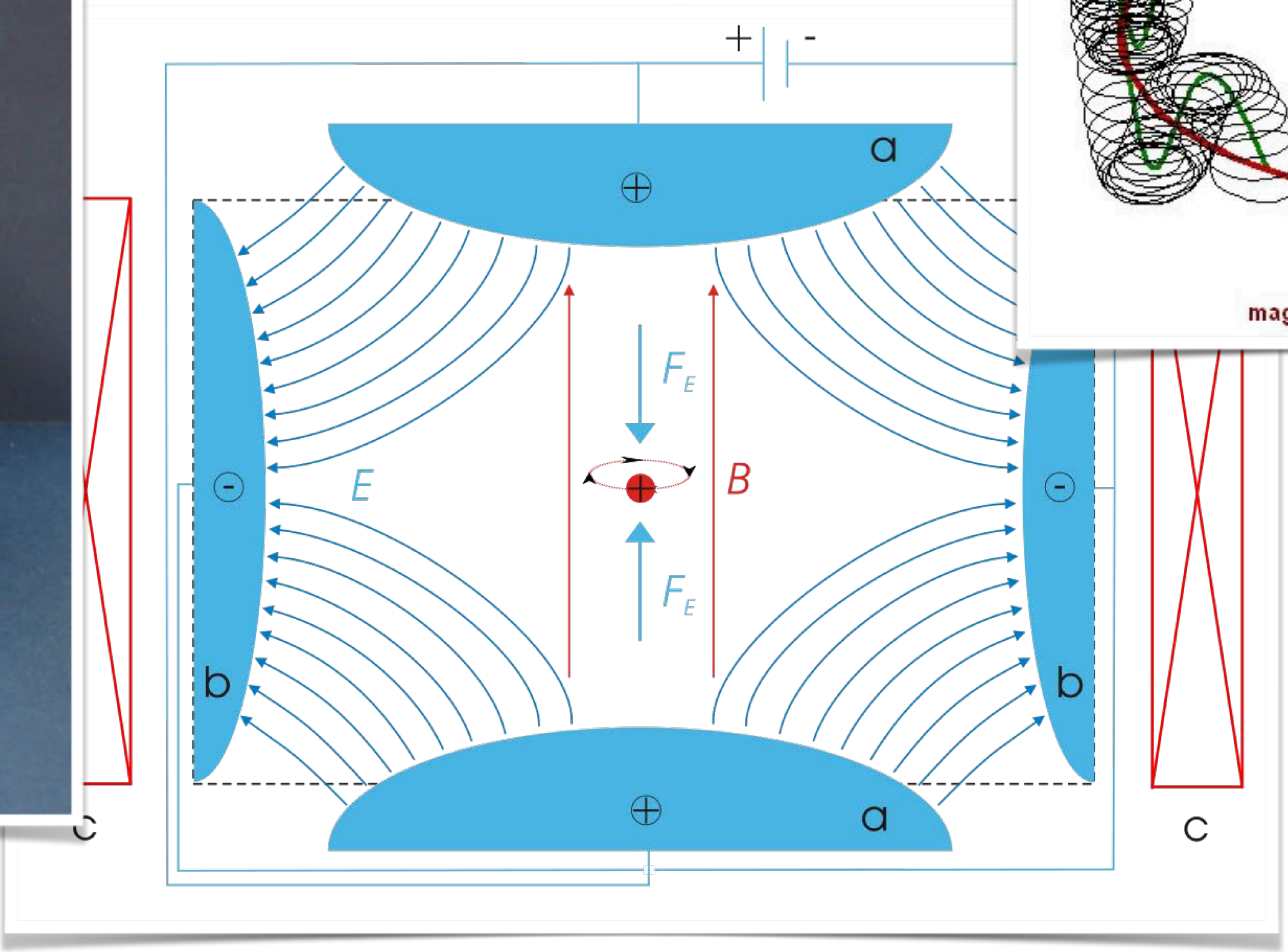


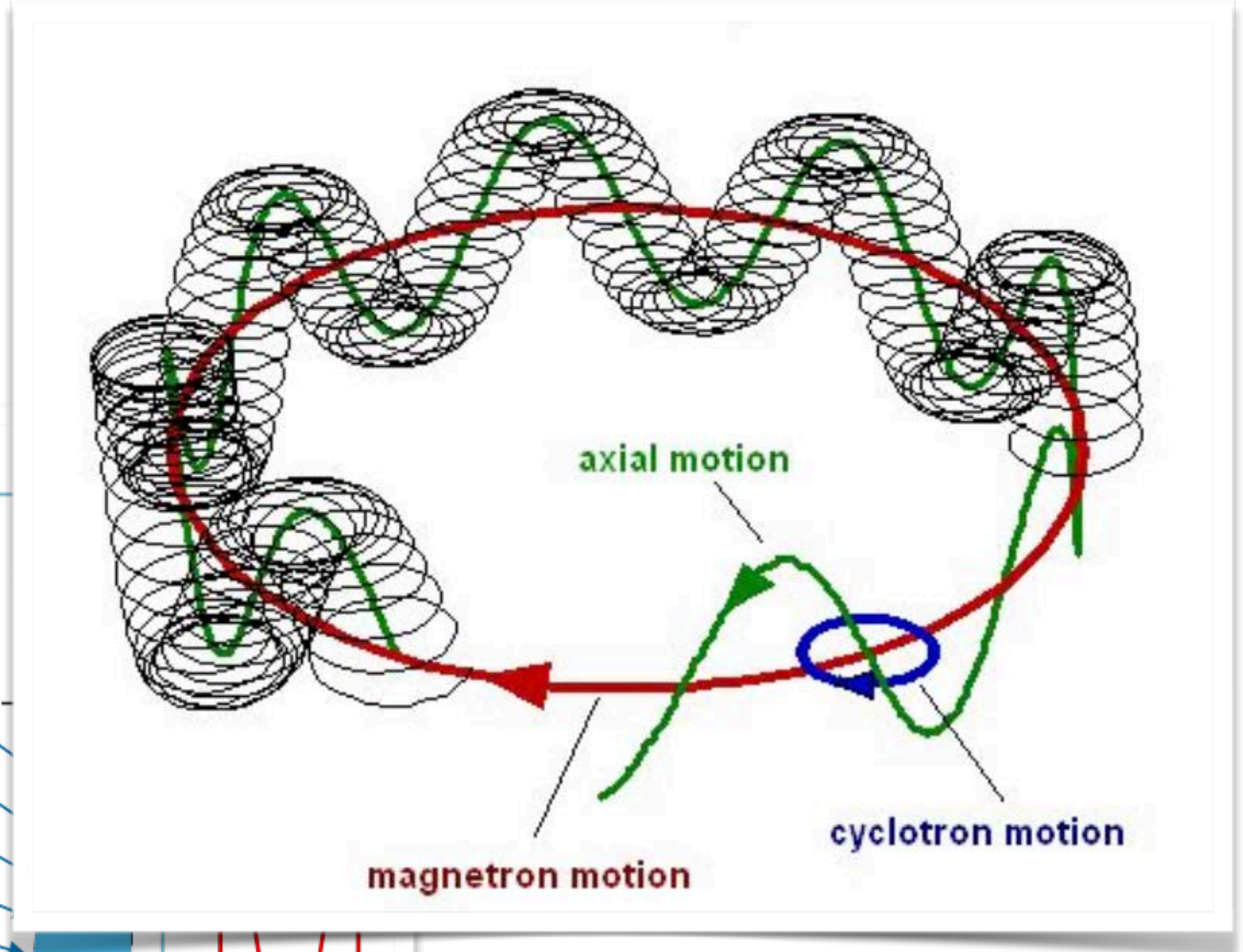


e.g. Z. Meisel, Phys. Rev. C ***93****, 035805 (****2016****)*

e.g. Penning traps

A somewhat de-facto approach for 30+ years



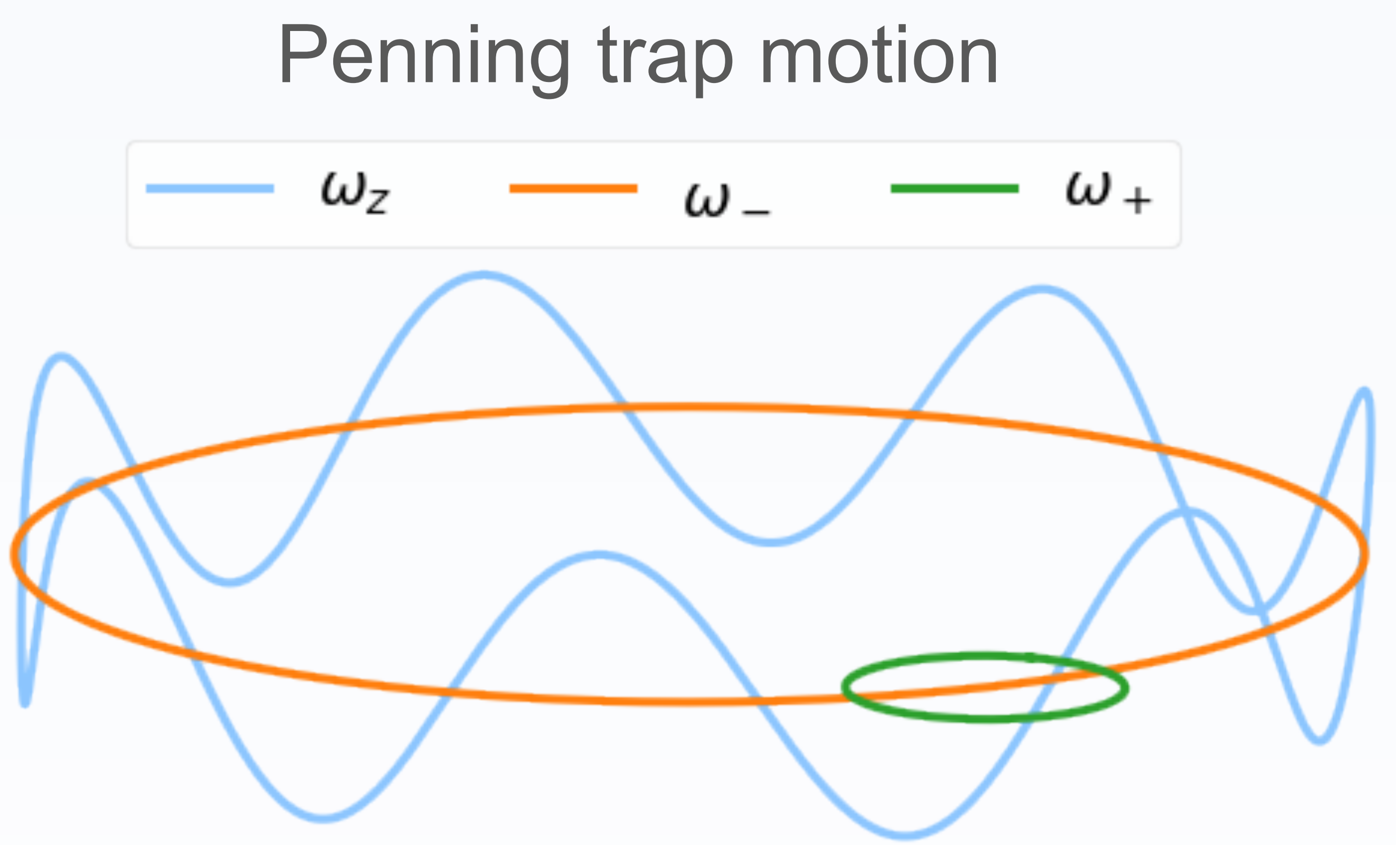


$$\omega_c = \frac{qB}{m_{ion}}$$

Ion confined in strong B field (radial confinement), with electrodes providing a potential for axial confinement and manipulation

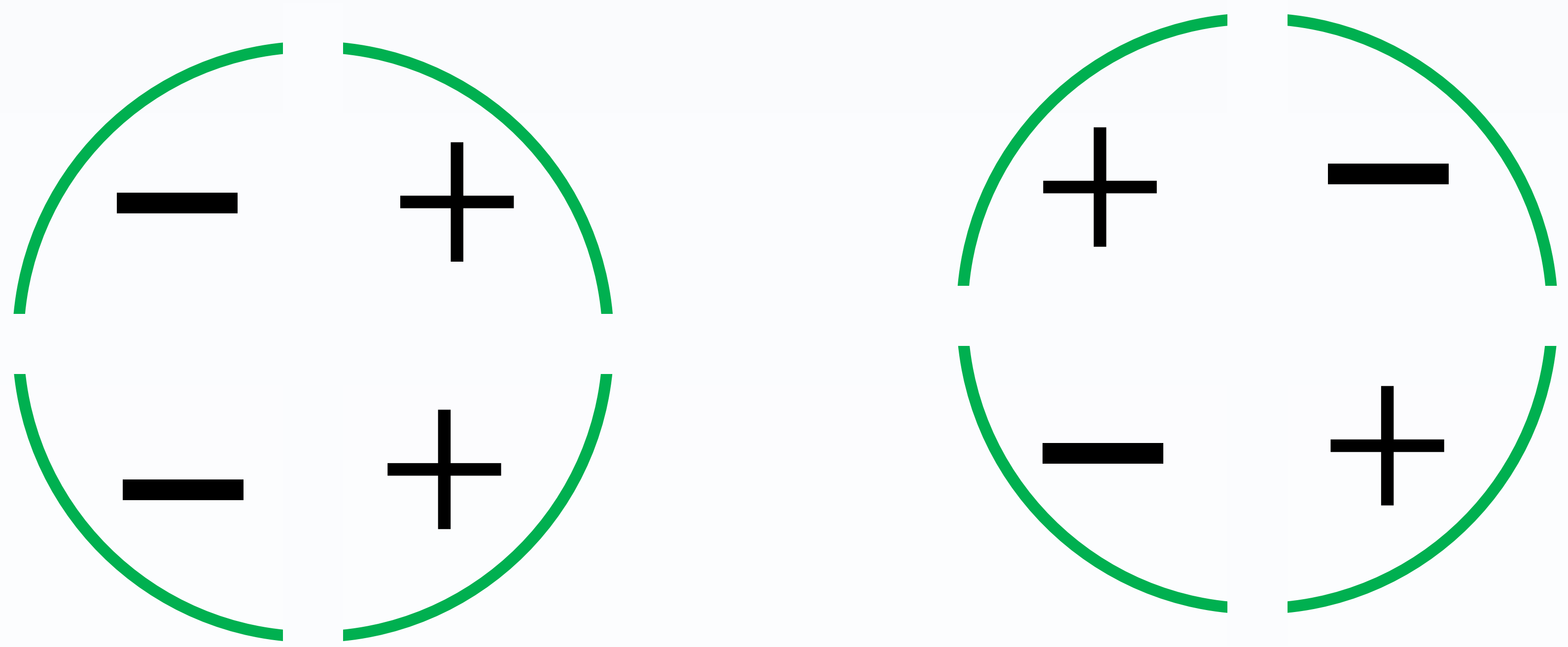
Images and suggestions from Rodney Orford (LBNL) and Jason Clark (ANL)

Ion motion in Penning trap



Segmented Ring electrode allows for:

1. Driving of orbital motions through a dipole excitation
2. Interconversion of orbital motions through a quadrupole excitation at ω_c



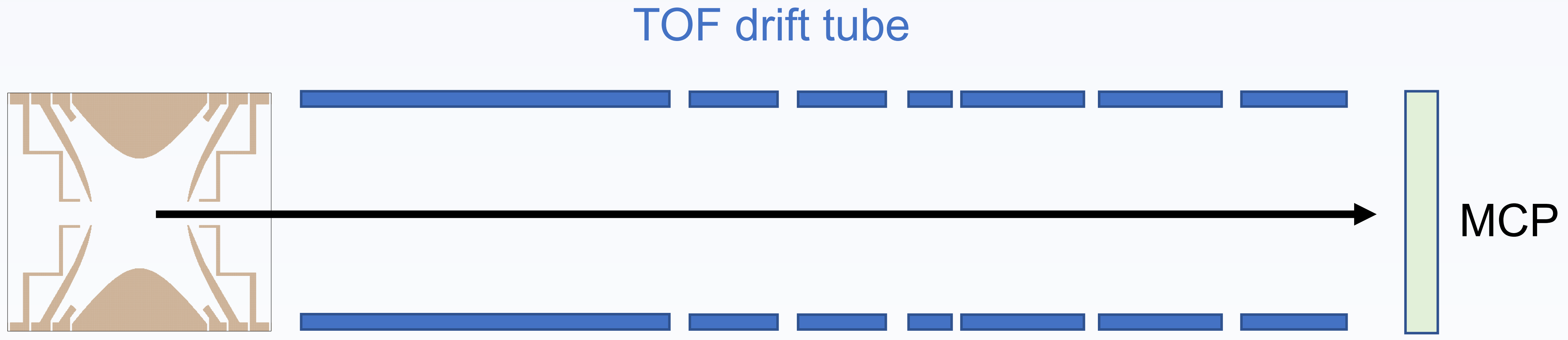
$$\omega_c = \omega_- + \omega_+$$

ω_- ~1.6 kHz
Mass independent

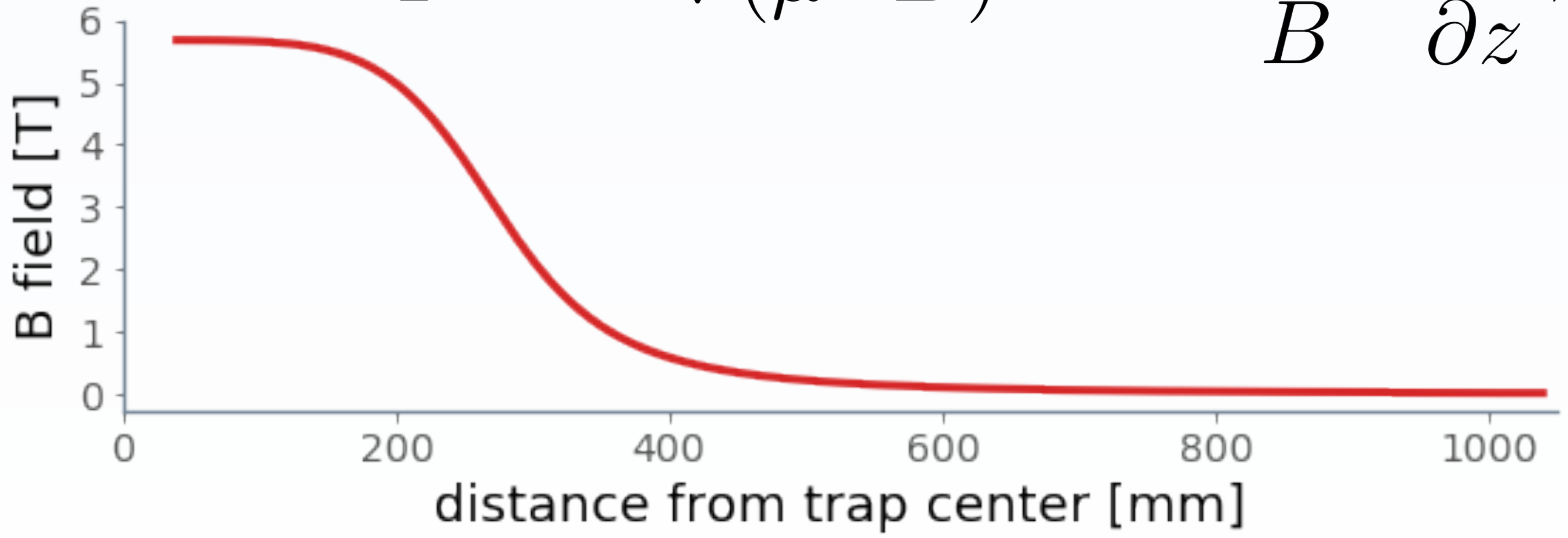
ω_+ ~1 MHz
Mass dependent

Images and suggestions from Rodney Orford (LBNL) and Jason Clark (ANL)

Penning trap mass measurements



$$\vec{F} = -\nabla(\mu \cdot \vec{B}) = -\frac{E_{rad}}{B}\frac{\partial B}{\partial z}\hat{z}$$

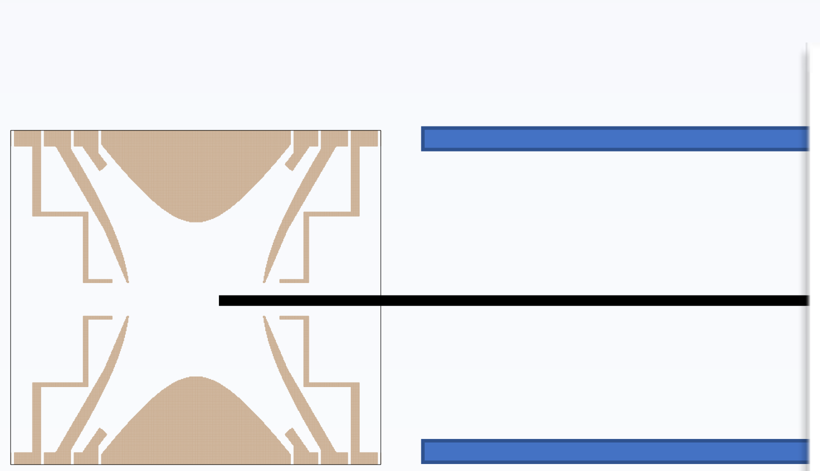


$$\omega_+ >> \omega_-$$

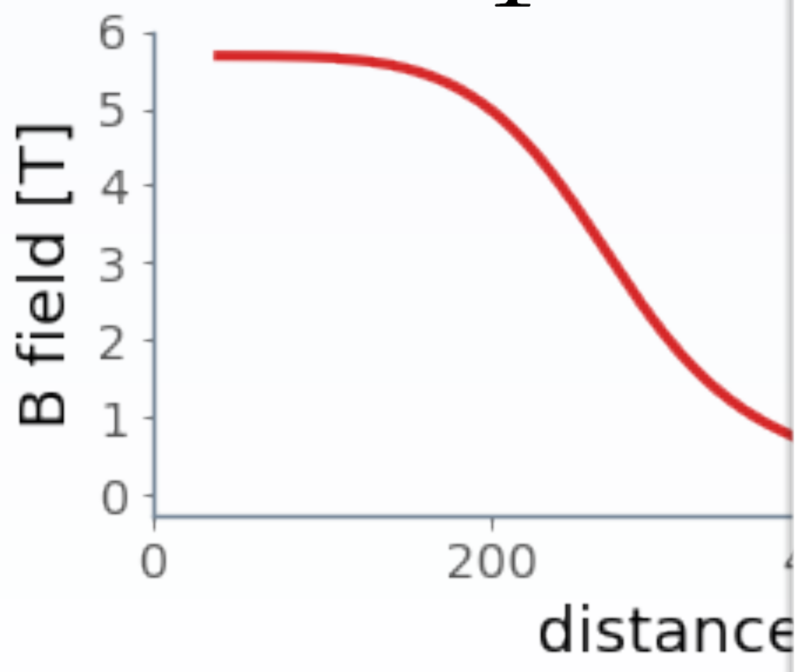
Leads to Time-Of-Flight Ion-Cyclotron-Resonance (TOF-ICR) method of mass measurements

Images and suggestions from Rodney Orford (LBNL) and Jason Clark (ANL)

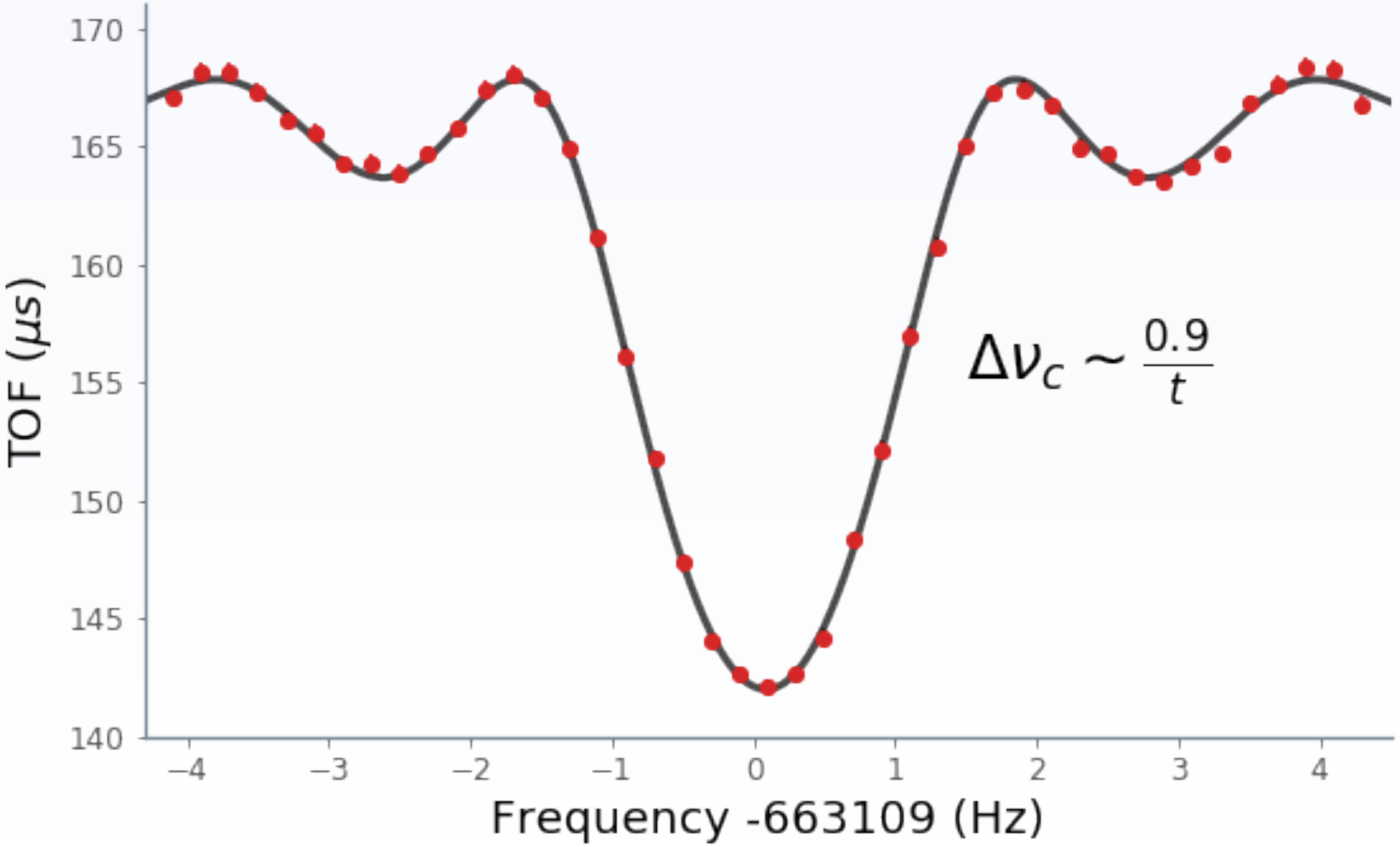
Penning trap mass measurements



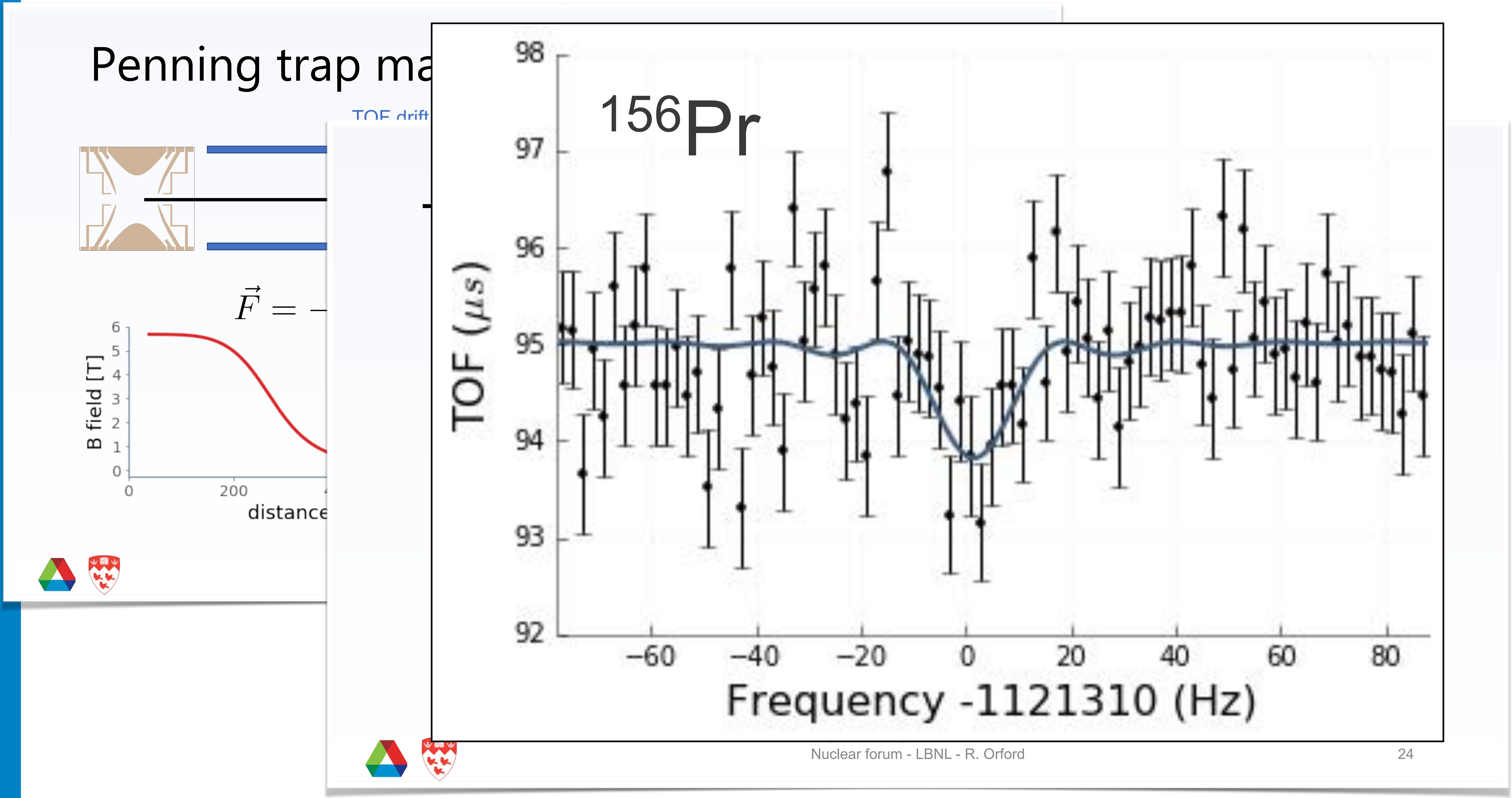
$\vec{F} = -$



TOF-ICR Method

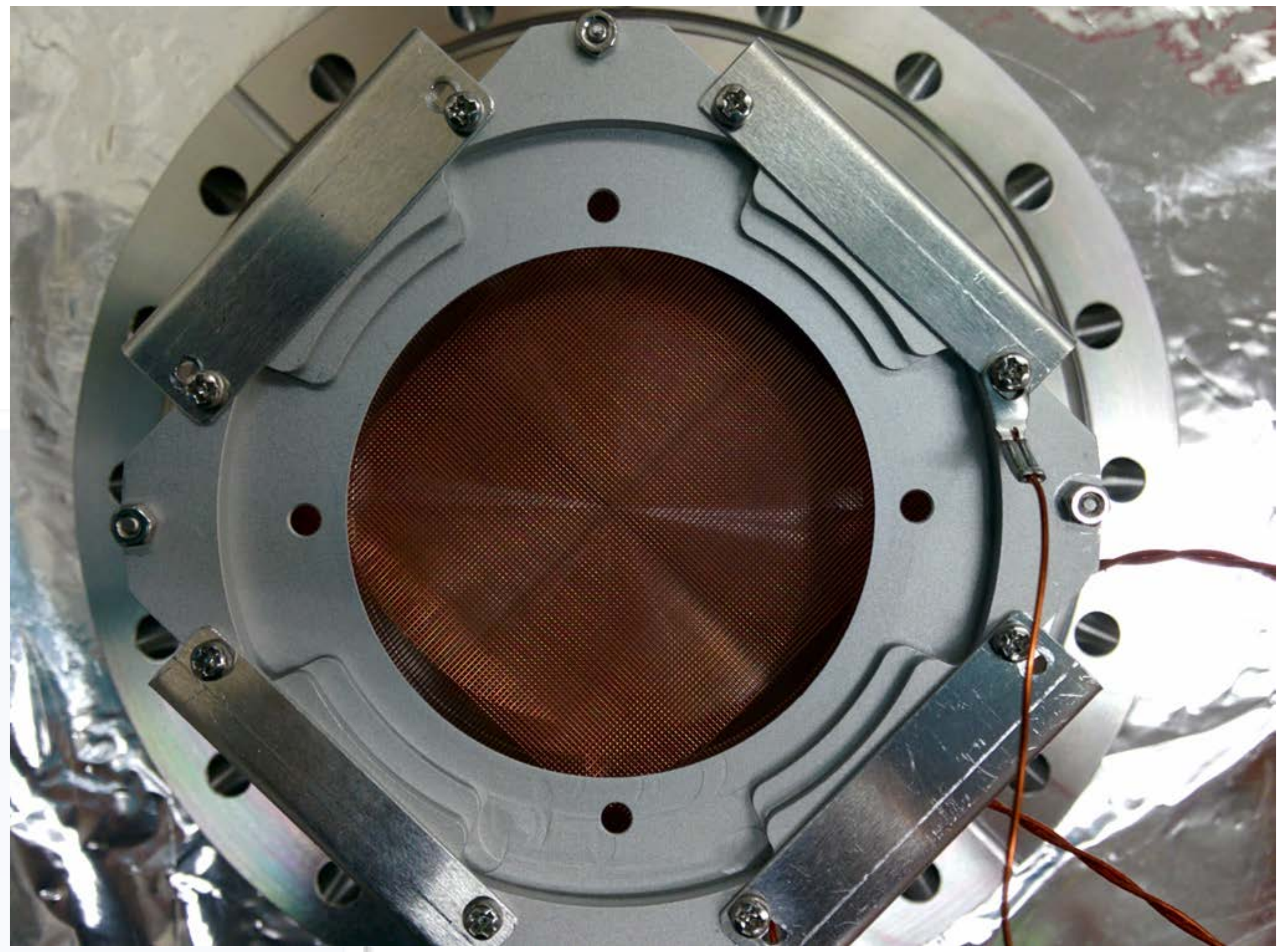


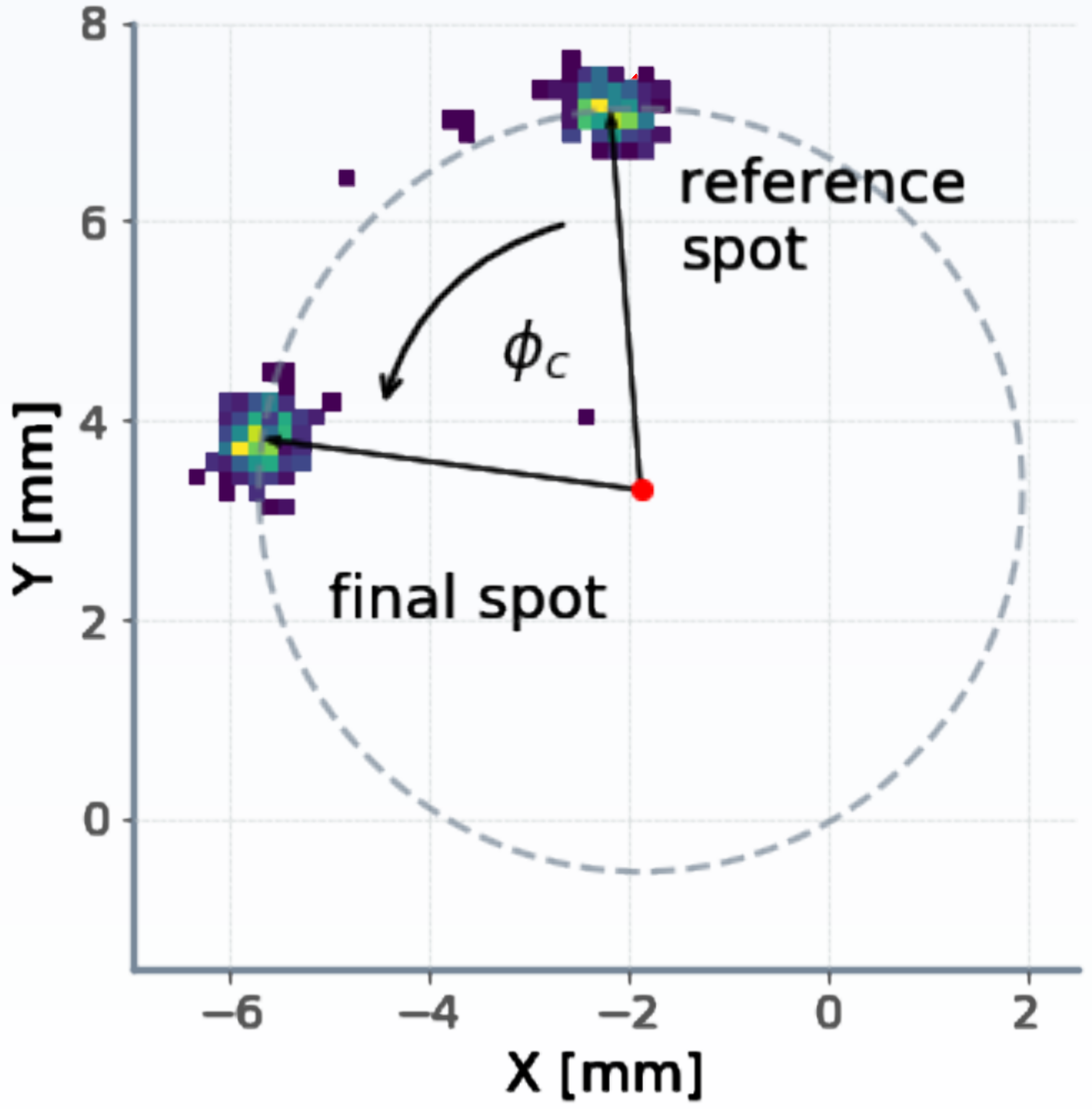
Images and suggestions from Rodney Orford (LBNL) and Jason Clark (ANL)



Images and suggestions from Rodney Orford (LBNL) and Jason Clark (ANL)

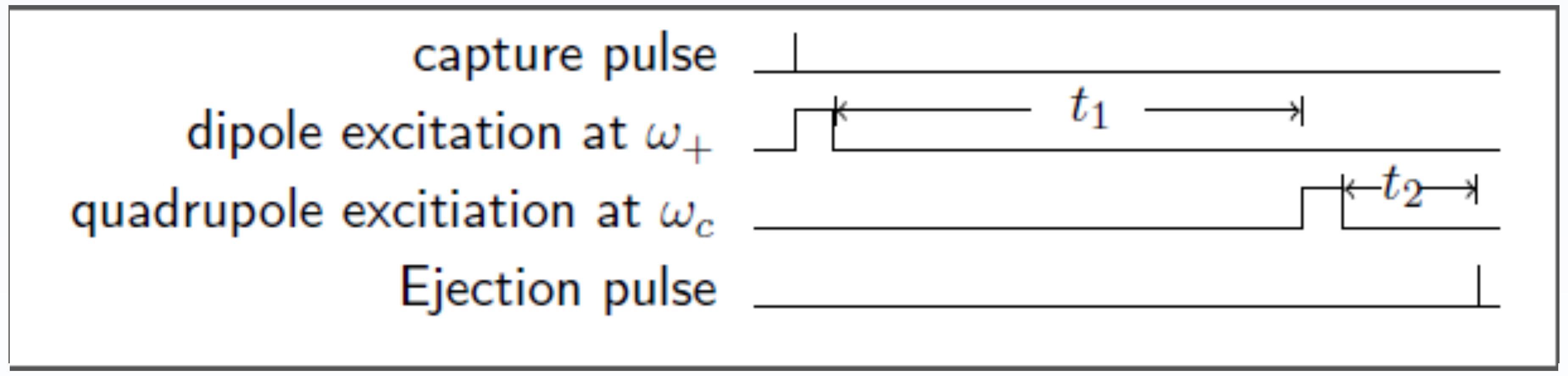
PI-ICR technique





General concept: Determine the cyclotron frequency of trapped ions by measuring the phase advance of ions over a period excitation free motion

- Use a position-sensitive detector to determine ion position

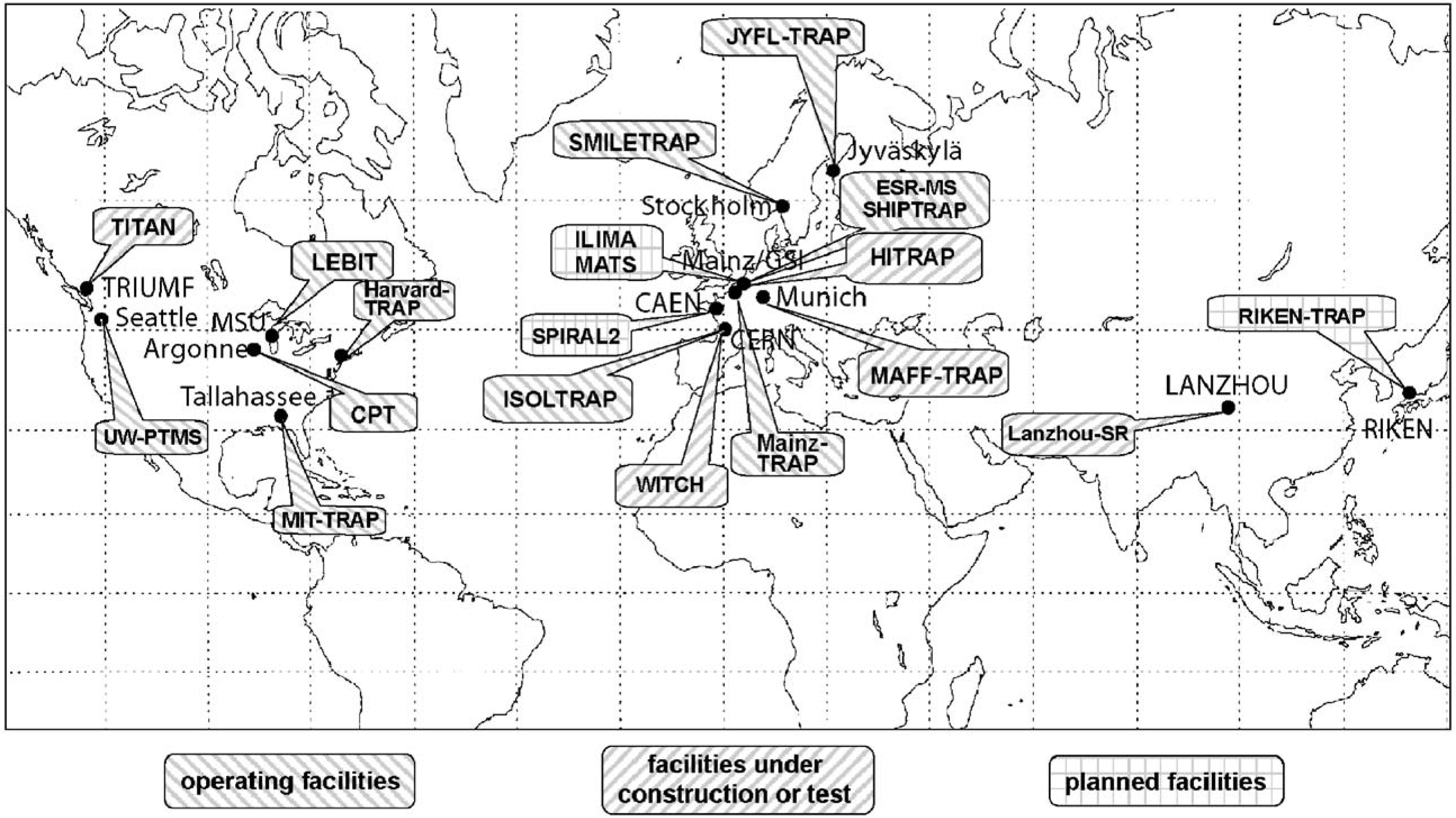


$$\omega_c = \frac{qB}{m_{ion}} = \frac{\phi_c + 2\pi N}{t_1}$$

Images and suggestions from Rodney Orford (LBNL) and Jason Clark (ANL)

e.g. Penning traps

WORLDWIDE EXPLOSION OF PENNING TRAP PROJECTS



K. Blaum, Phys. Rep. ***425****, 1 (****2006****)*

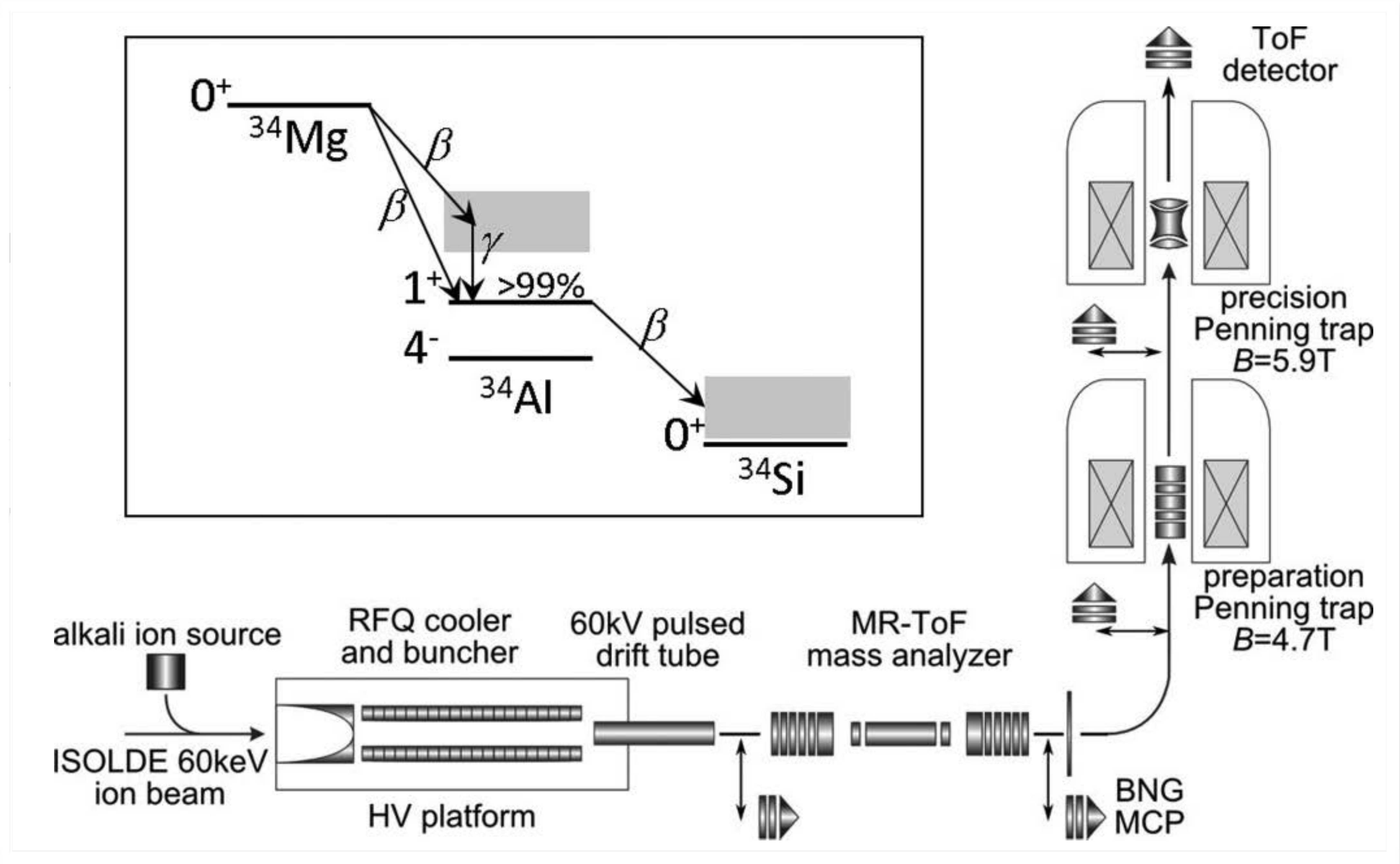
Penning traps … popular? *(last 10 days)*

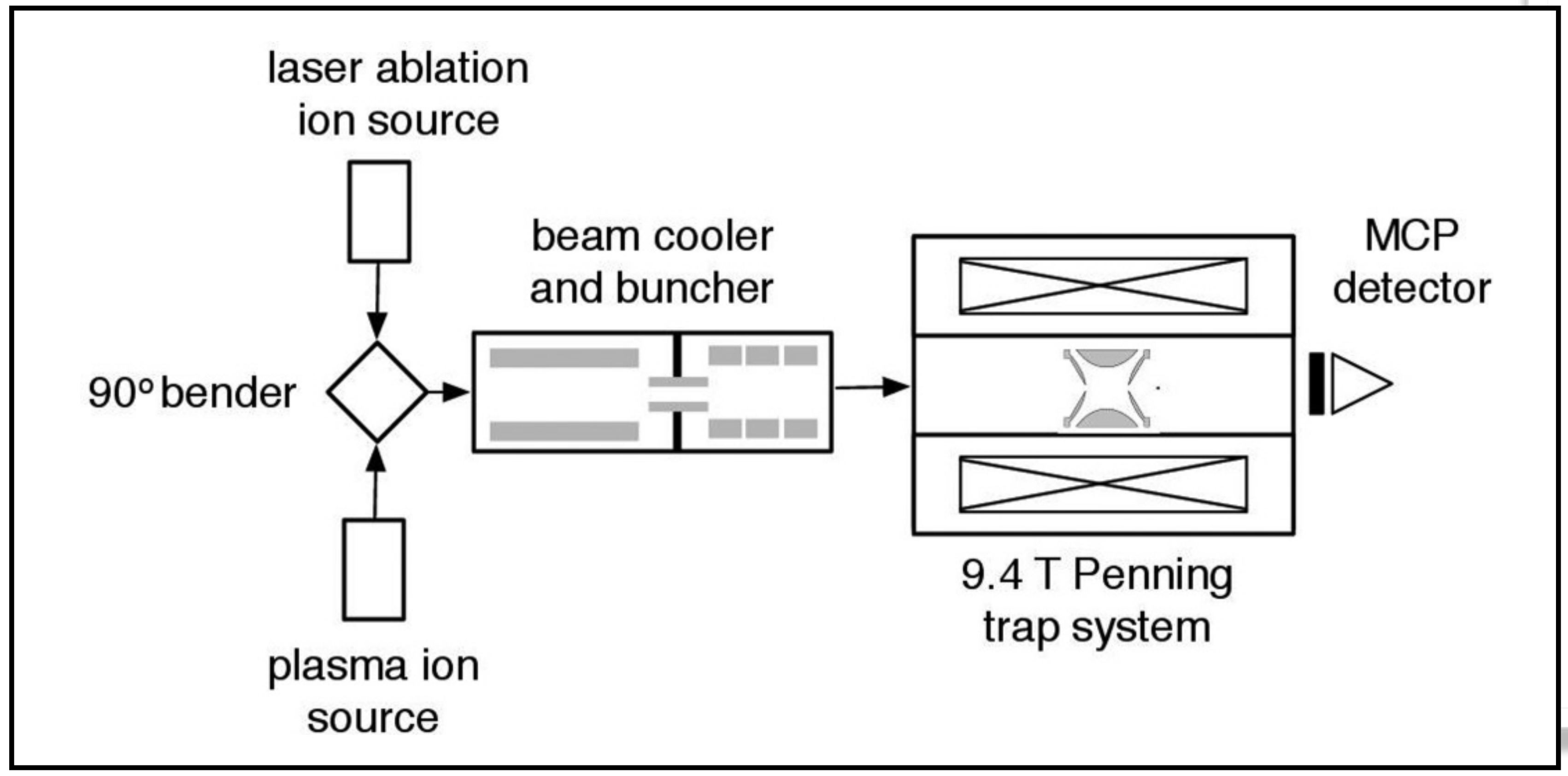
PHYSICAL REVIEW C **100**, 014304 (2019)

**Mass measurements of neutron-rich isotopes near $N = 20$ by in-trap d
with the ISOLTRAP spectrometer**

P. Ascher,[1,*] N. Althubiti,[2,3] D. Atanasov,[4,†] K. Blaum,[4] R. B. Cakirli,[5] S. Grévy,[1] F. Herfurth,[6] S. K
V. Manea,[8,†] D. Neidherr,[6] M. Rosenbusch,[9] L. Schweikhard,[10] A. Welker,[11] F. Wienholtz,[10] R. N. Wo
[1]*Centre d'Études Nucléaires de Bordeaux-Gradignan, Gradignan, France*
[2]*School of Physics and Astronomy, The University of Manchester, Manchester, United Kingdo*
[3]*Physics Department, Faculty of Science, Jouf University, Aljouf, Saudi Arabia*
[4]*Max-Planck-Institut für Kernphysik, Heidelberg, Germany*
[5]*University of Istanbul, Department of Physics 34134, Istanbul, Turkey*
[6]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany*
[7]*CSNSM-IN2P3-CNRS, Université de Paris Sud, Orsay, France*
[8]*Experimental Physics Department, CERN, Geneva, Switzerland*
[9]*RIKEN Nishina Center, Wako, Saitama 351-0198, Japan*
[10]*Institut für Physik, Universität Greifswald, 17487 Greifswald, Germany*
[11]*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Germany*

(Received 28 February 2019; revised manuscript received 21 May 2019; published 8 July 2019)





PHYSICAL REVIEW C **100**, 014308 (2019)

Direct determination of the ^{138}La β-decay Q value using Penning trap mass spectrometry

R. Sandler,[1,2,*] G. Bollen,[2,3,4] J. Dissanayake,[1] M. Eibach,[2,5] K. Gulyuz,[1] A. Hamaker,[2,4] C. Izzo,[2,4] X. Mougeot,[6]
D. Puentes,[2,4] F. G. A. Quarati,[7,8] M. Redshaw,[2,1] R. Ringle,[2] and I. Yandow[2,4]
[1]*Department of Physics, Central Michigan University, Mount Pleasant, Michigan 48859, USA*
[2]*National Superconducting Cyclotron Laboratory, East Lansing, Michigan 48824, USA*
[3]*Facility for Rare Isotope Beams, East Lansing, Michigan 48824, USA*
[4]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[5]*Institut für Physik, Universität Greifswald, 17487 Greifswald, Germany*
[6]*CEA, LIST, Laboratoire National Henri Becquerel (LNE-LNHB), Bât. 602 PC111, CEA-Saclay 91191 Gif-sur-Yvette Cedex, France*
[7]*AS, RST, LM, Delft University of Technology, Mekelweg 15, 2629JB Delft, The Netherlands*
[8]*Gonitec BV, Johannes Bildersstraat 60, 259EJ Den Haag, The Netherlands*

(Received 29 April 2019; published 11 July 2019)

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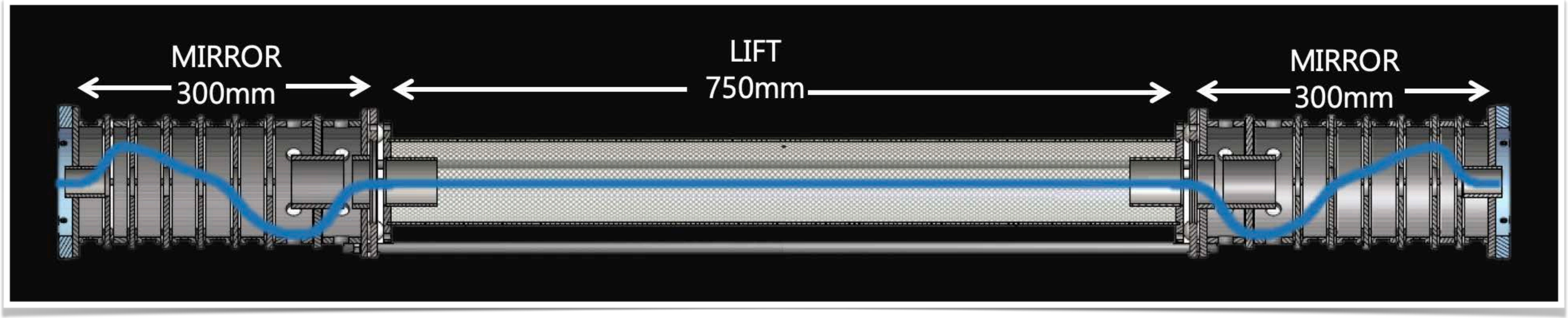
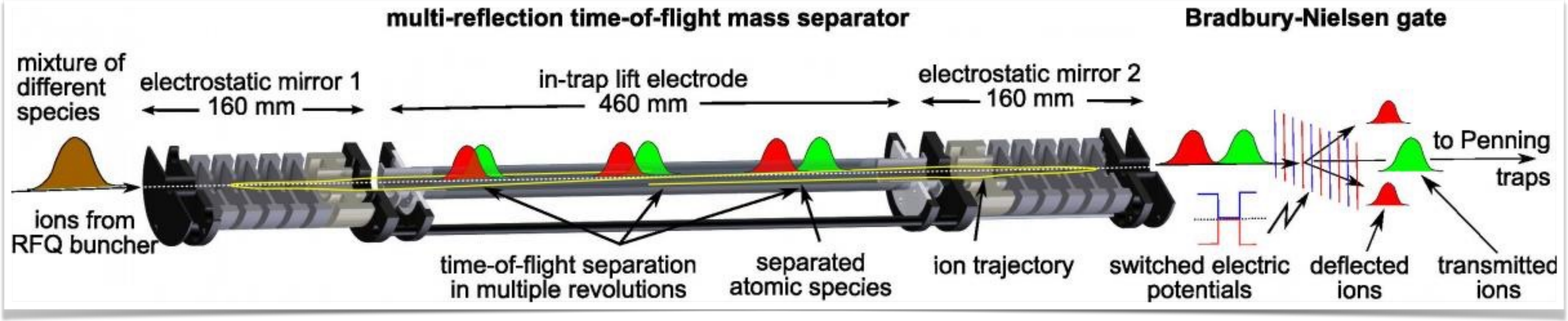
MR-TOF



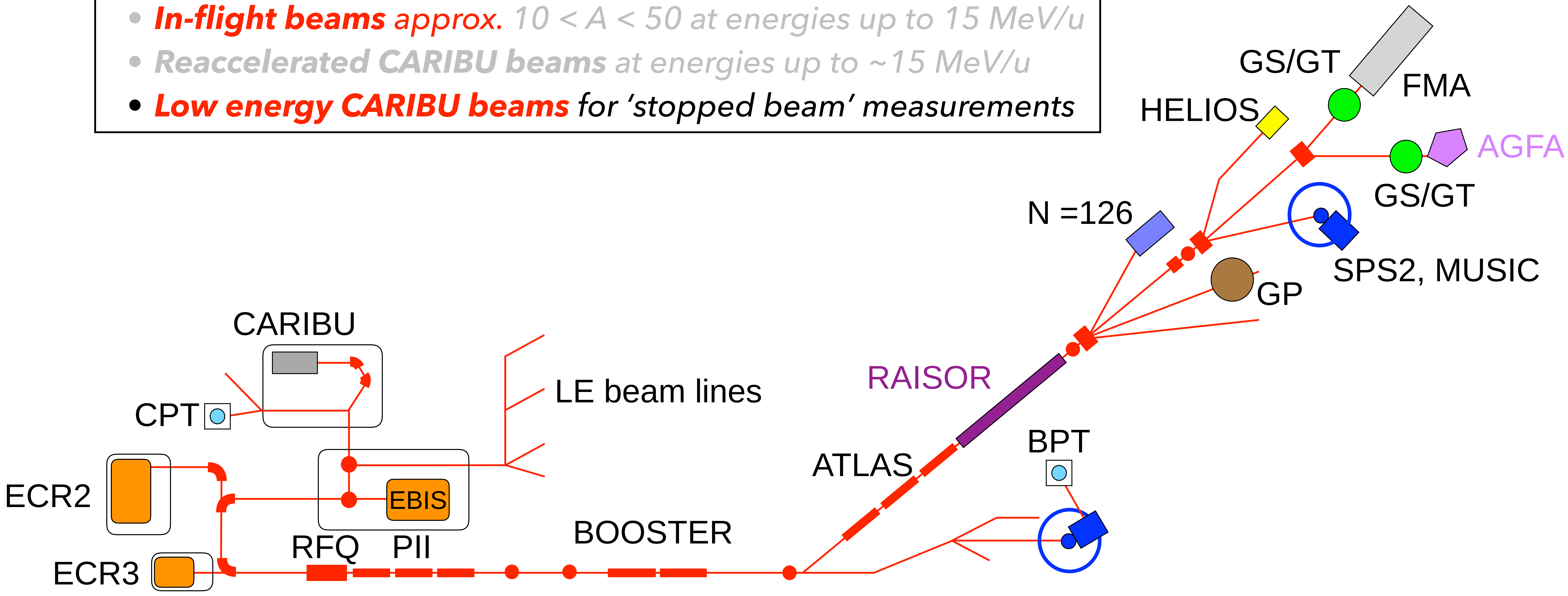


Ions cycle back and forth. A time separation occurs such that $t \sim \sqrt{m/q}$. Fast. High resolution.

Images and suggestions from Rodney Orford (LBNL) and Jason Clark (ANL)

ATLAS

- **Stable beams** at high intensity and energies up to 18 MeV/u
- **In-flight beams** approx. 10 < A < 50 at energies up to 15 MeV/u
- **Reaccelerated CARIBU beams** at energies up to ~15 MeV/u
- **Low energy CARIBU beams** for 'stopped beam' measurements



https://www.anl.gov/atlas

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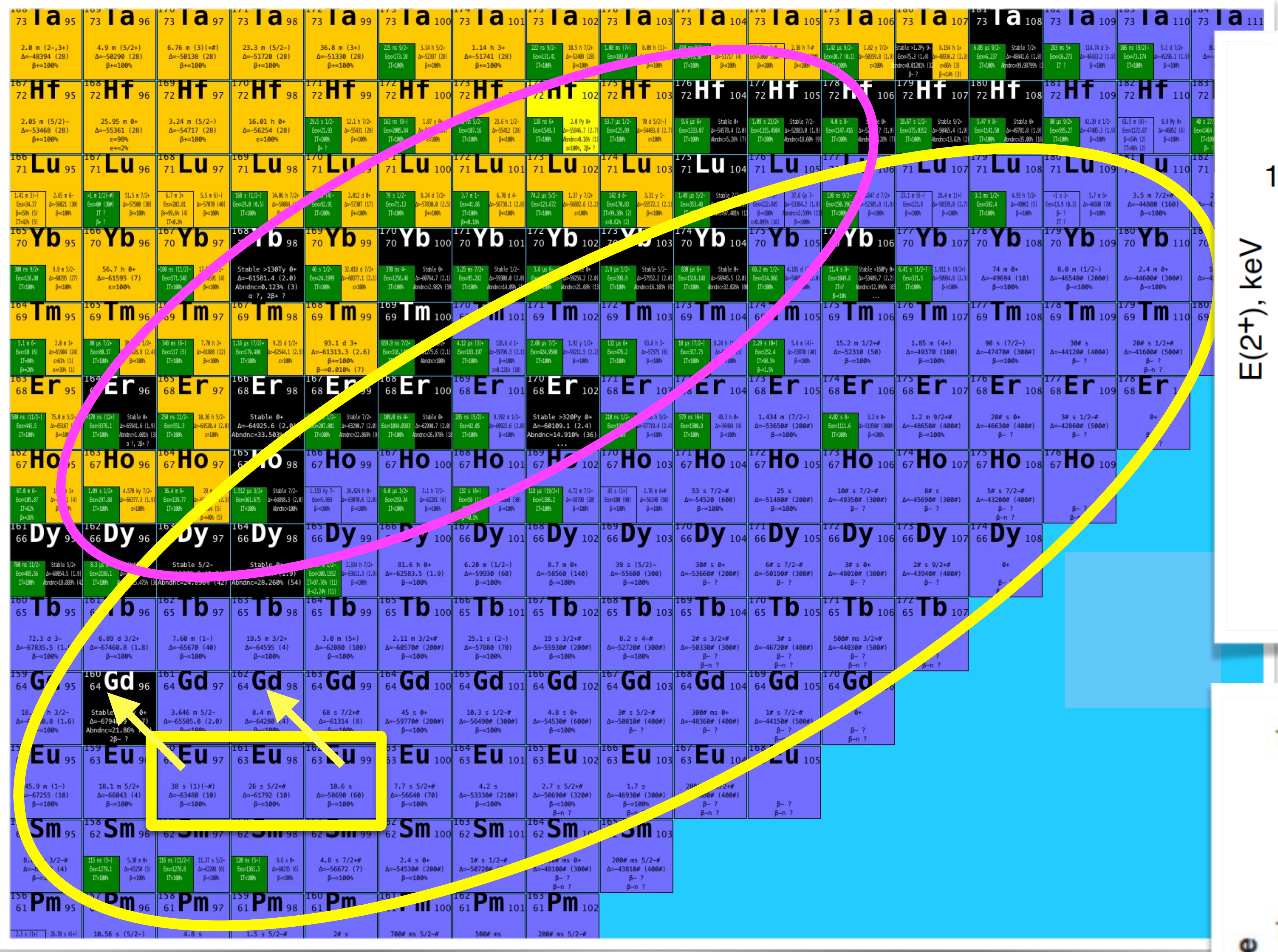
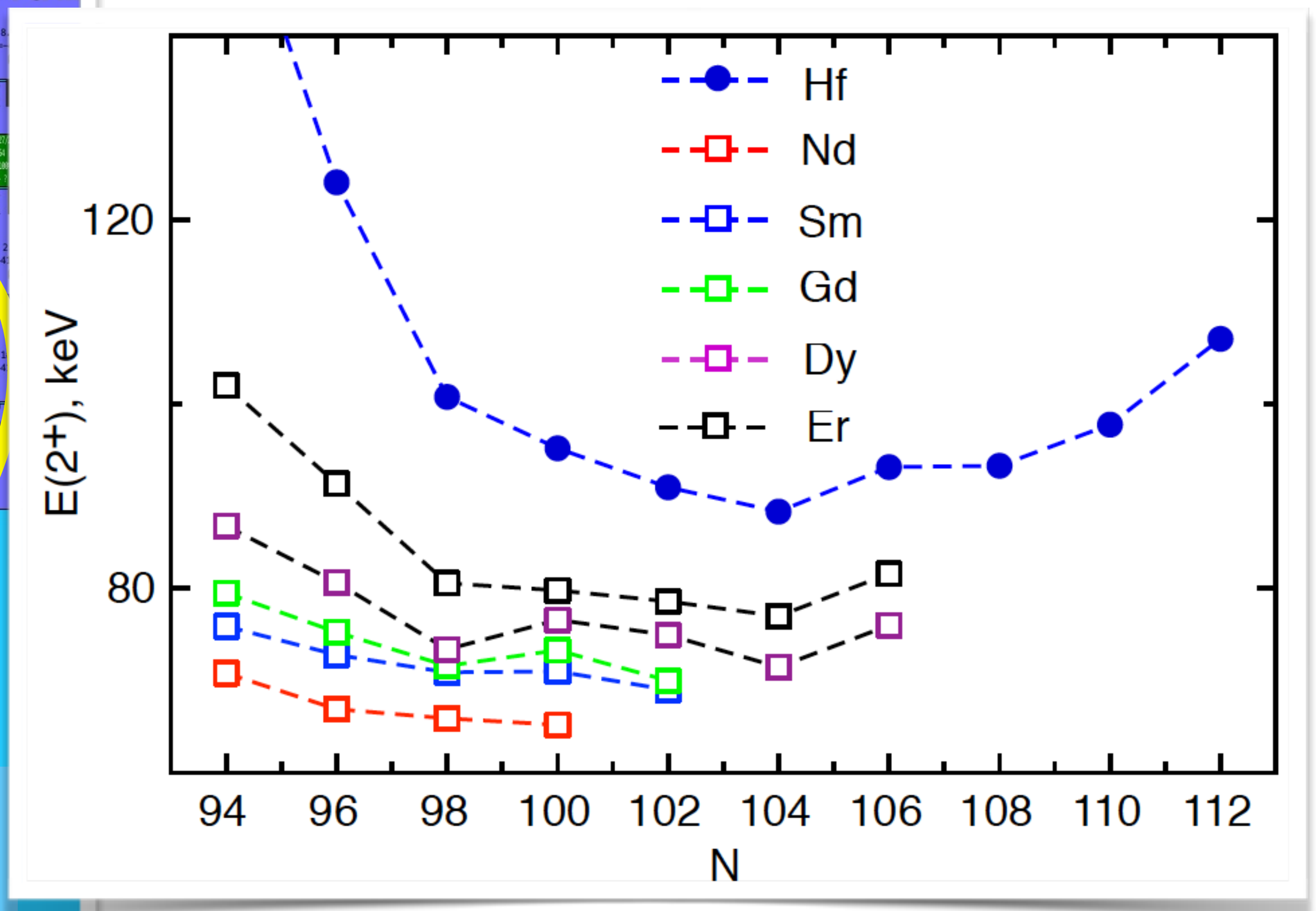
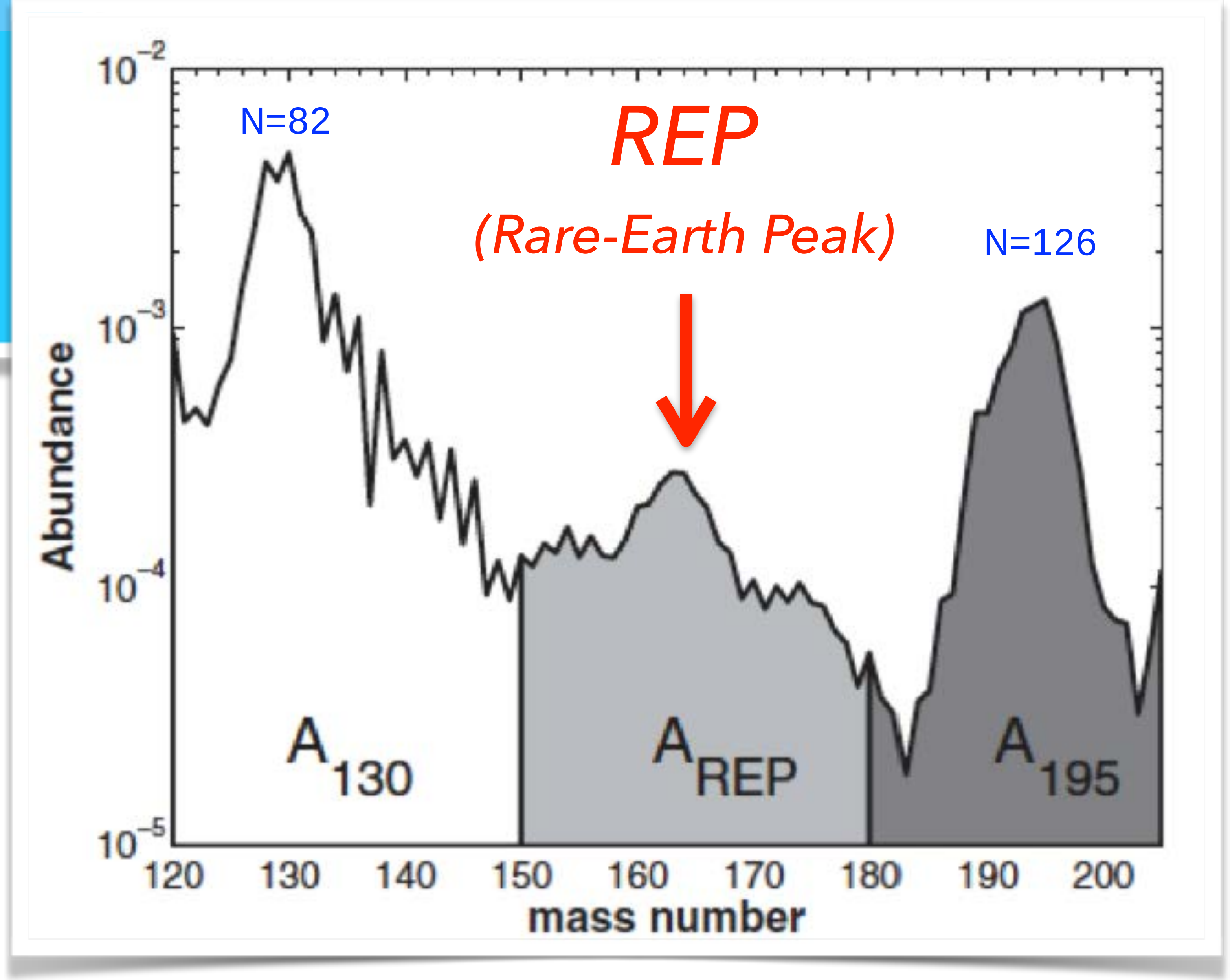
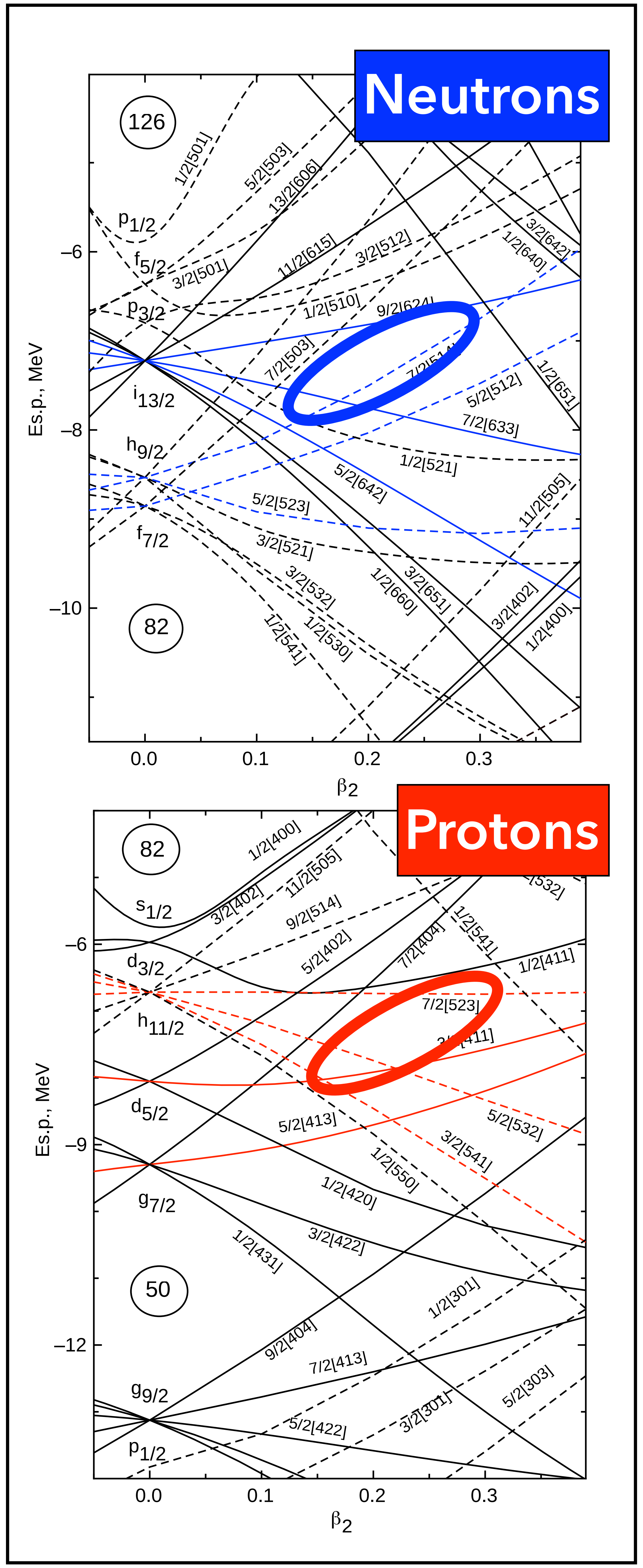
Deformed, neutron-rich nuclei



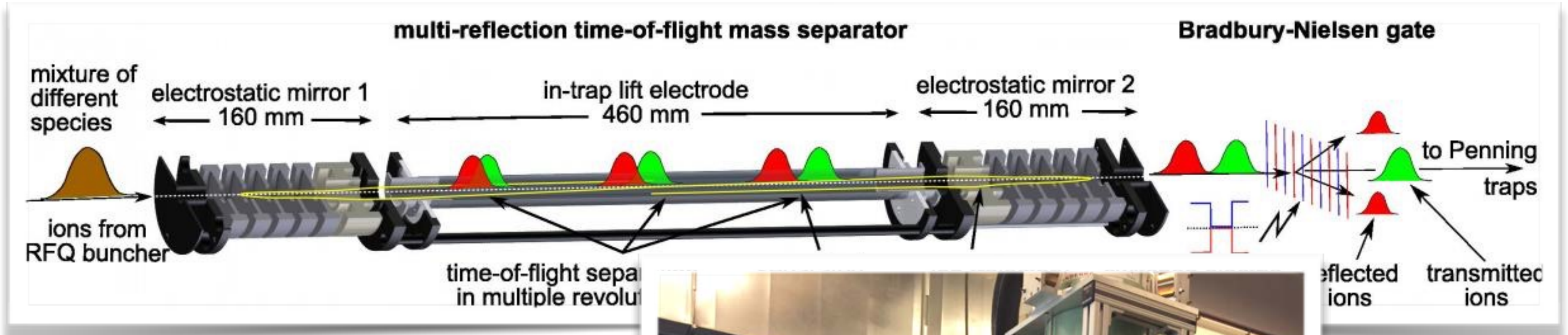


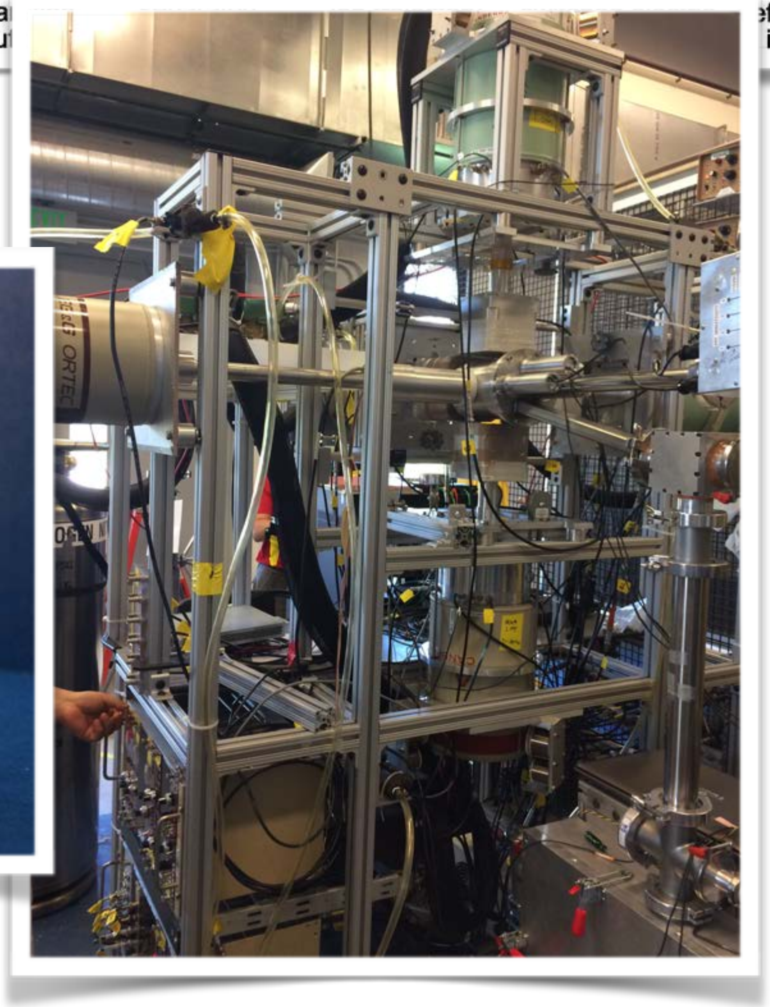




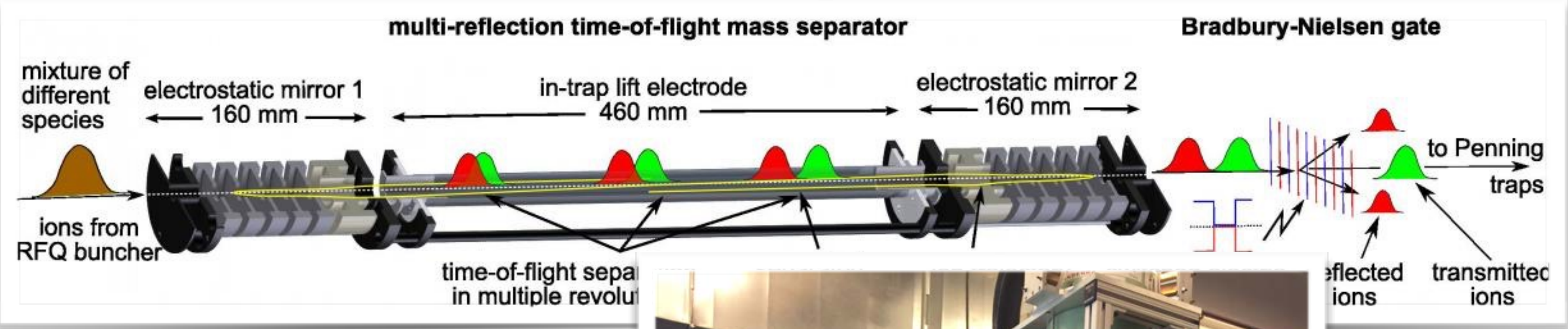
CARIBU allows access to terra incognita: What stabilizes these deformed shapes? What role does the structure of these nuclei have on the r-process abundance?

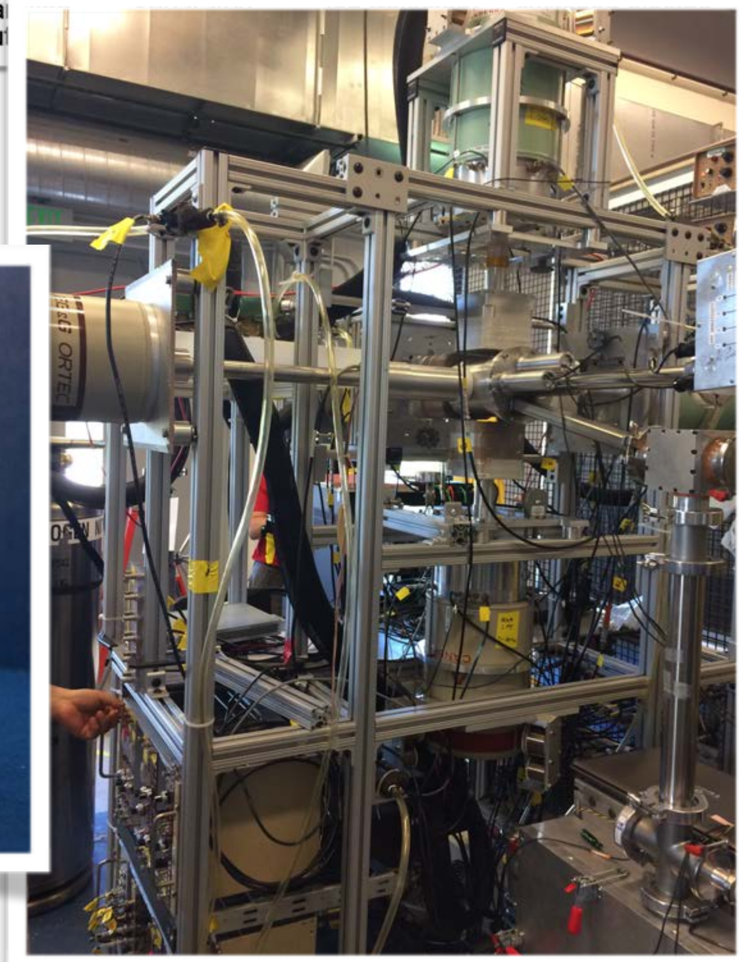
Detailed spectroscopy

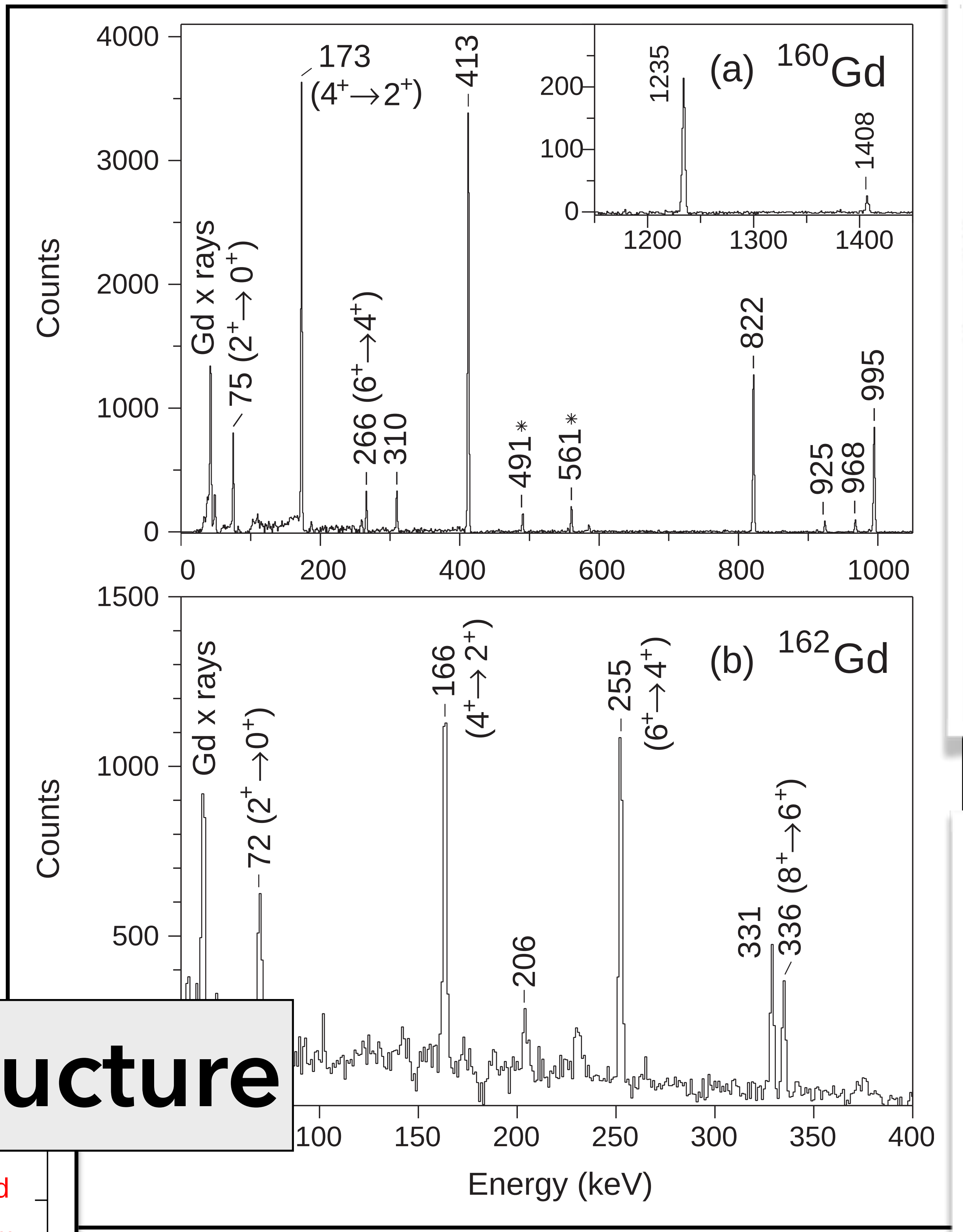




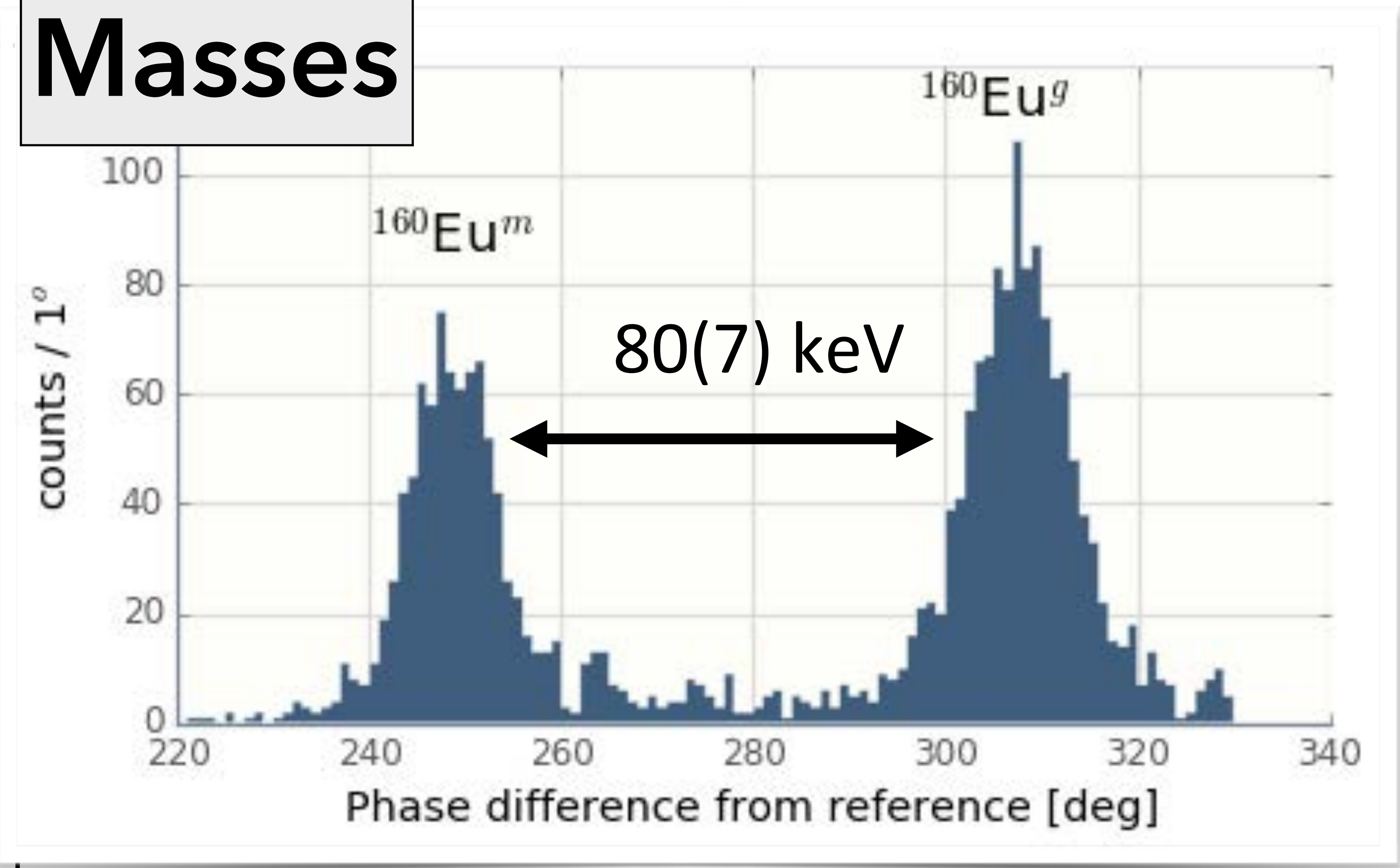
Detailed spectroscopy



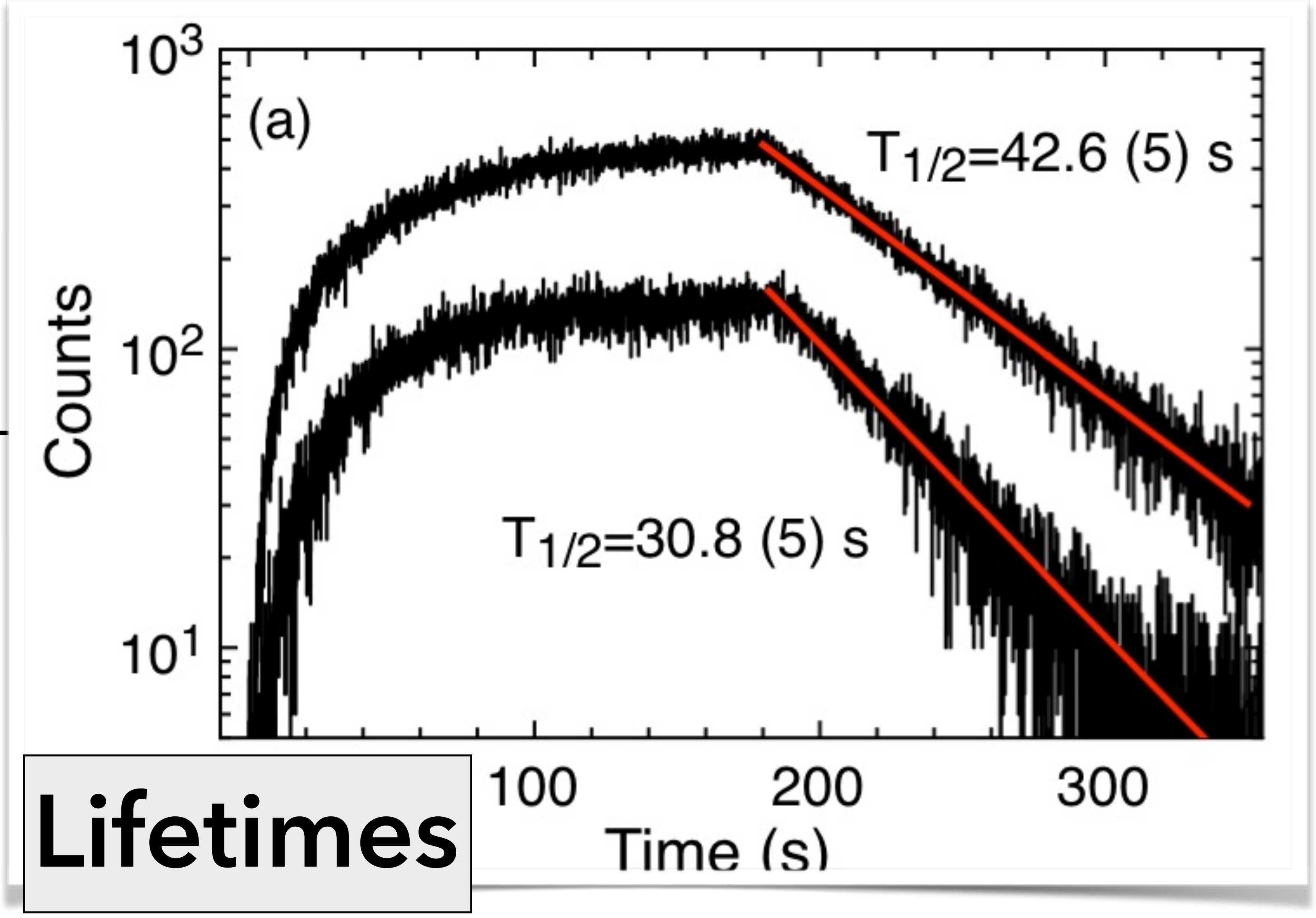




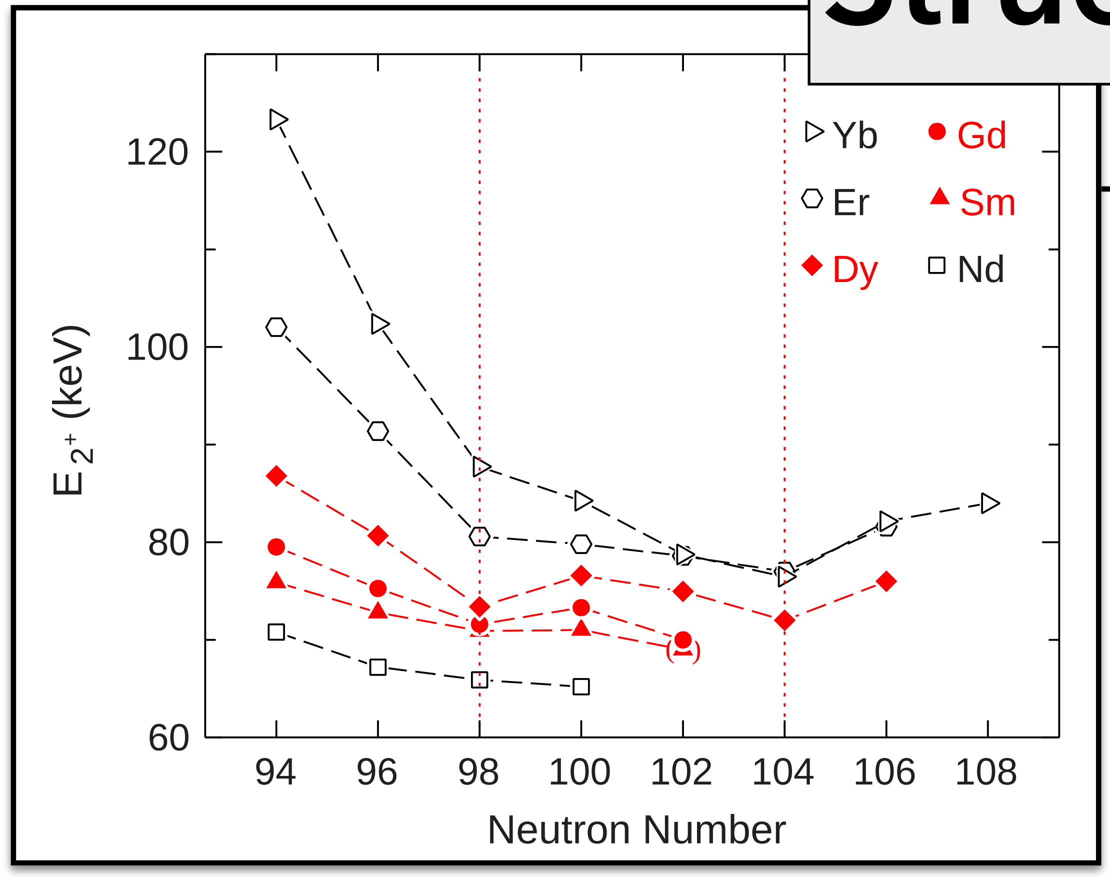
Structure



Masses

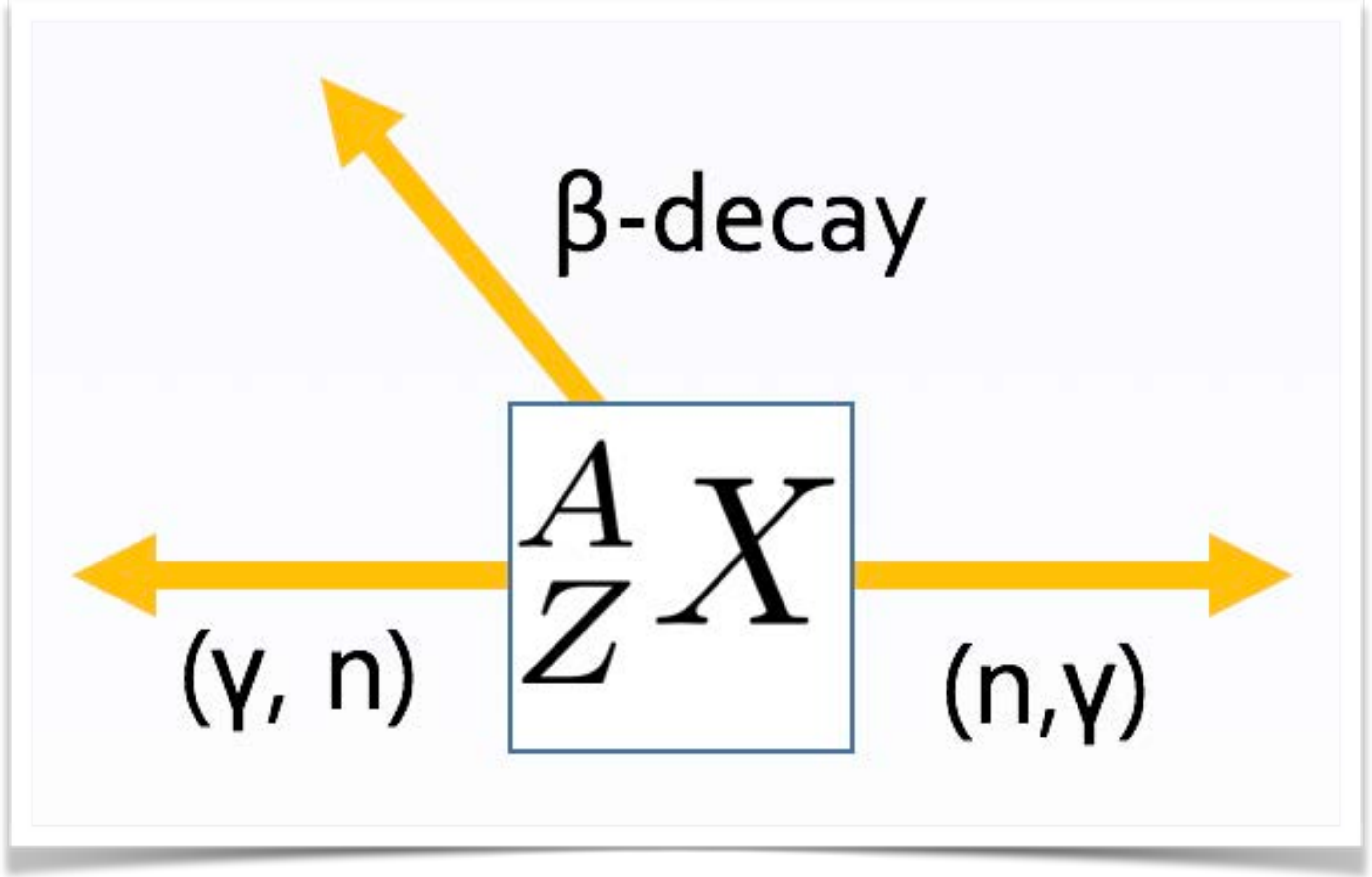


Lifetimes



D. J. Hartley et al., Phys. Rev. Lett. ***120****, 182502 (****2018****)*

Understanding REP formation

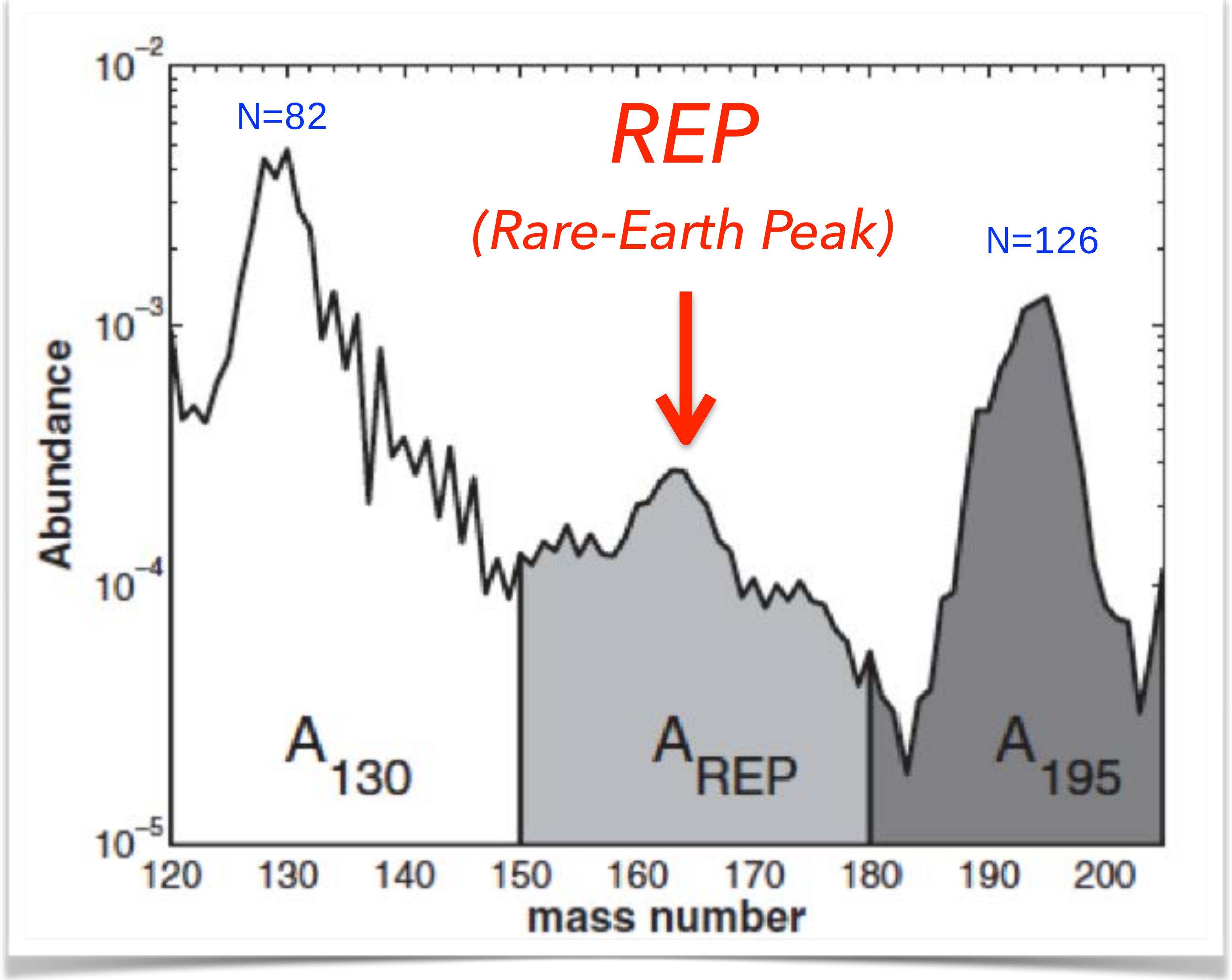


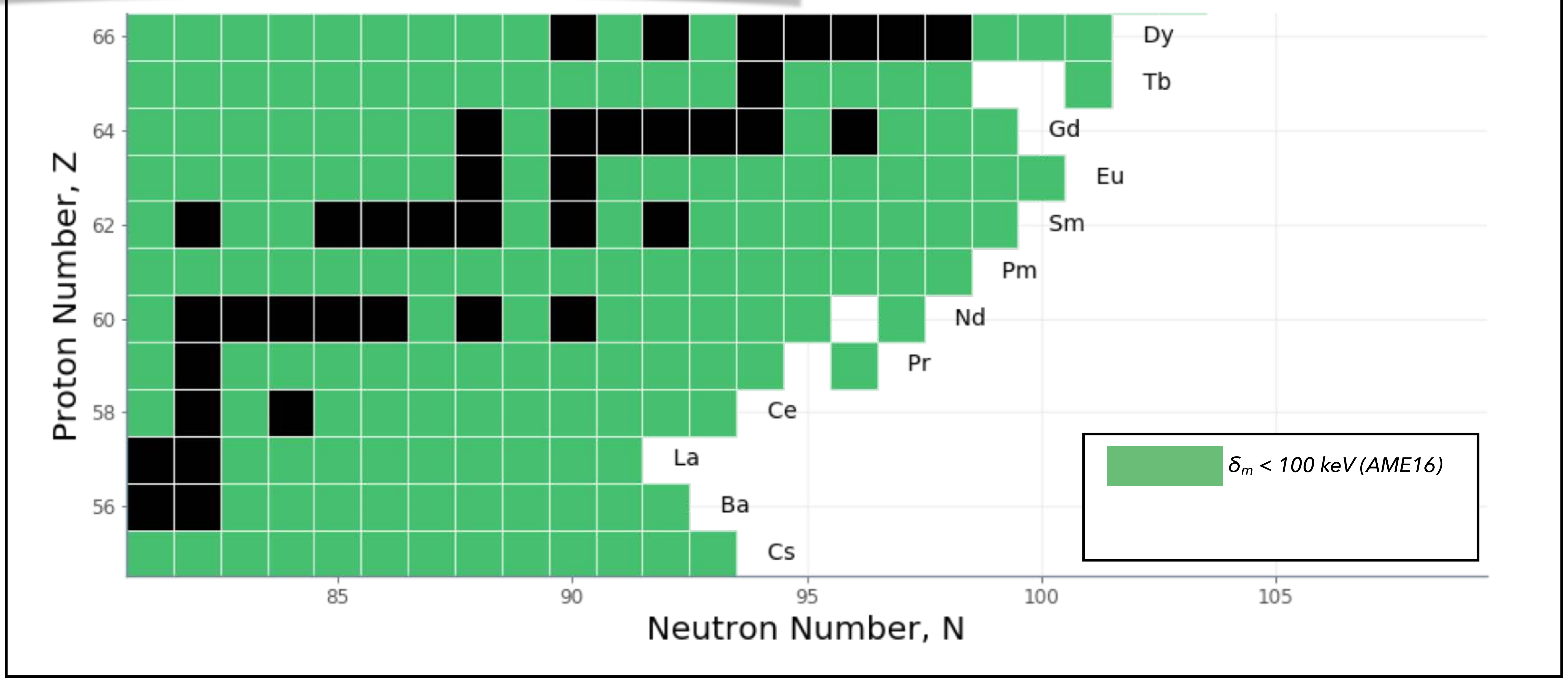
General classification:

Hot : $(n, \gamma) \rightleftharpoons (\gamma, n)$

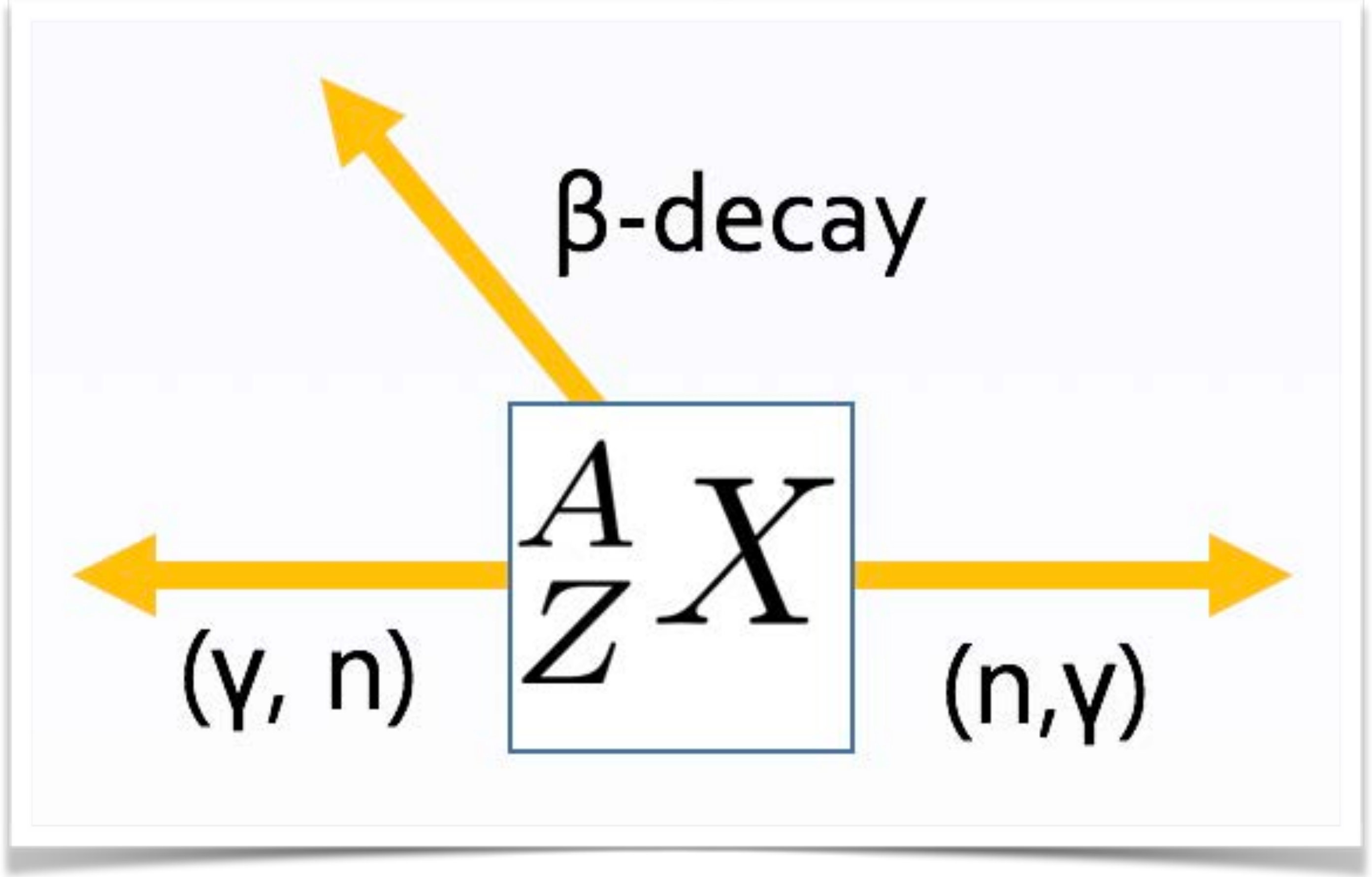
Cold: no equilibrium, competition between decay and neutron-capture

Masses measurements necessary to gain insights into what ***environment produces the observed abundance*** *peaks*





Understanding REP formation



General classification:

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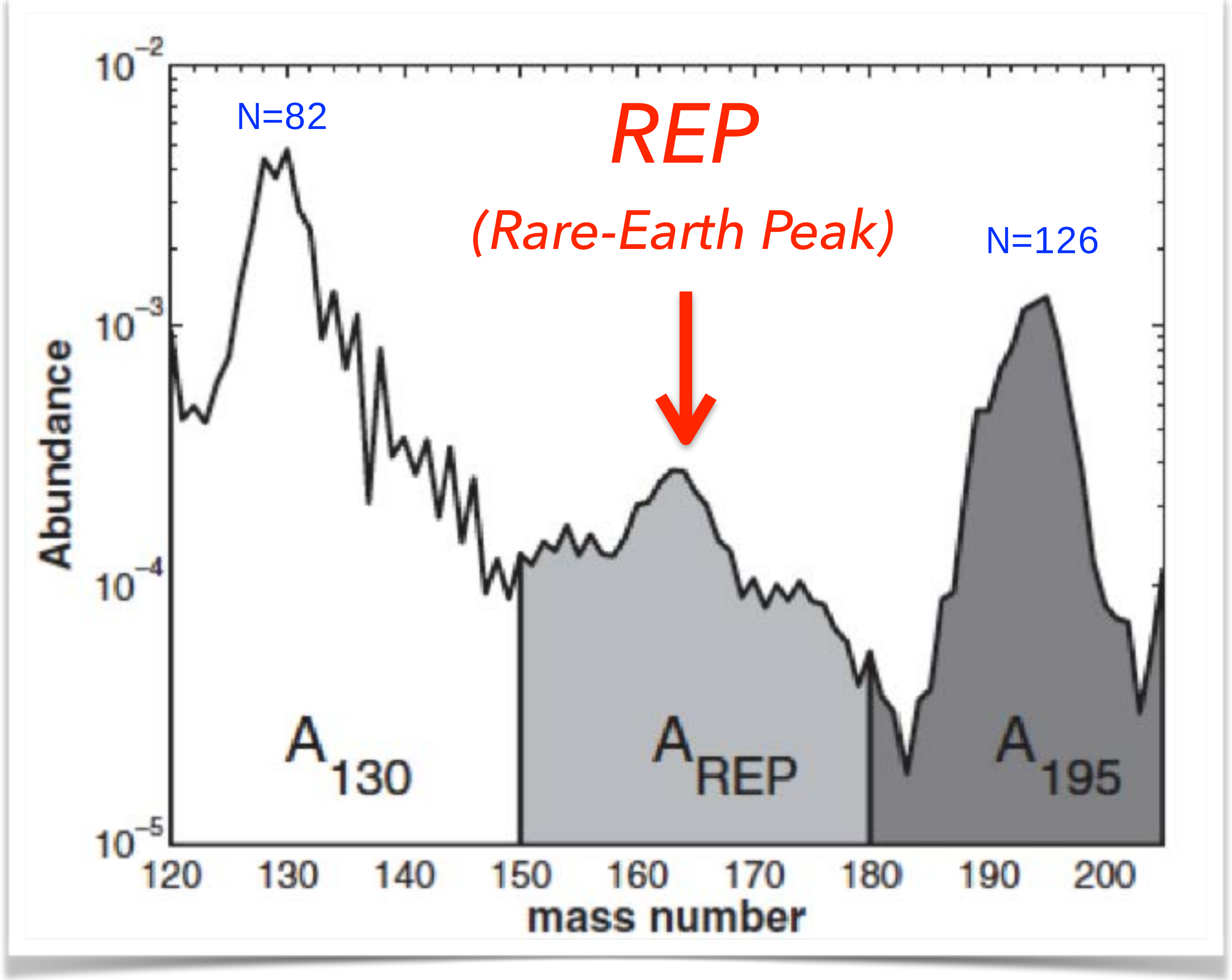
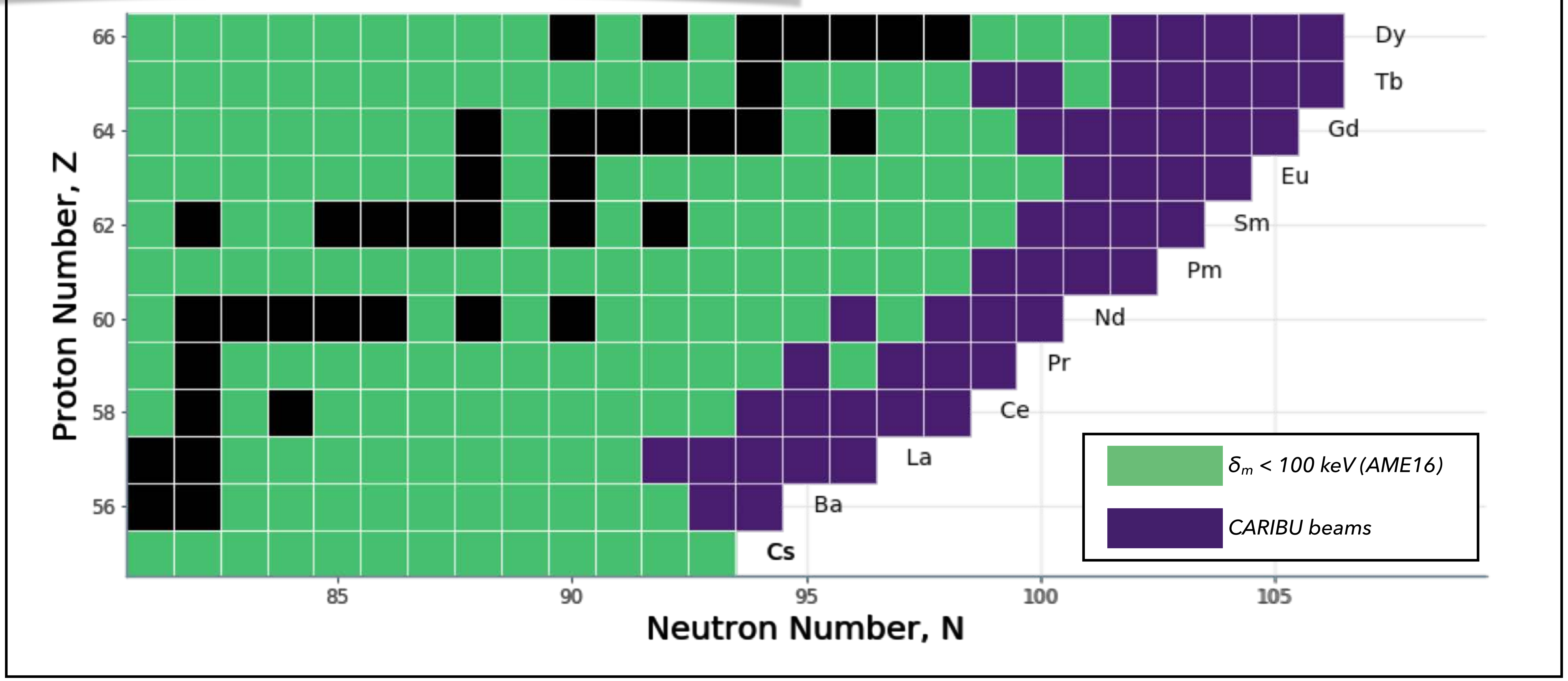
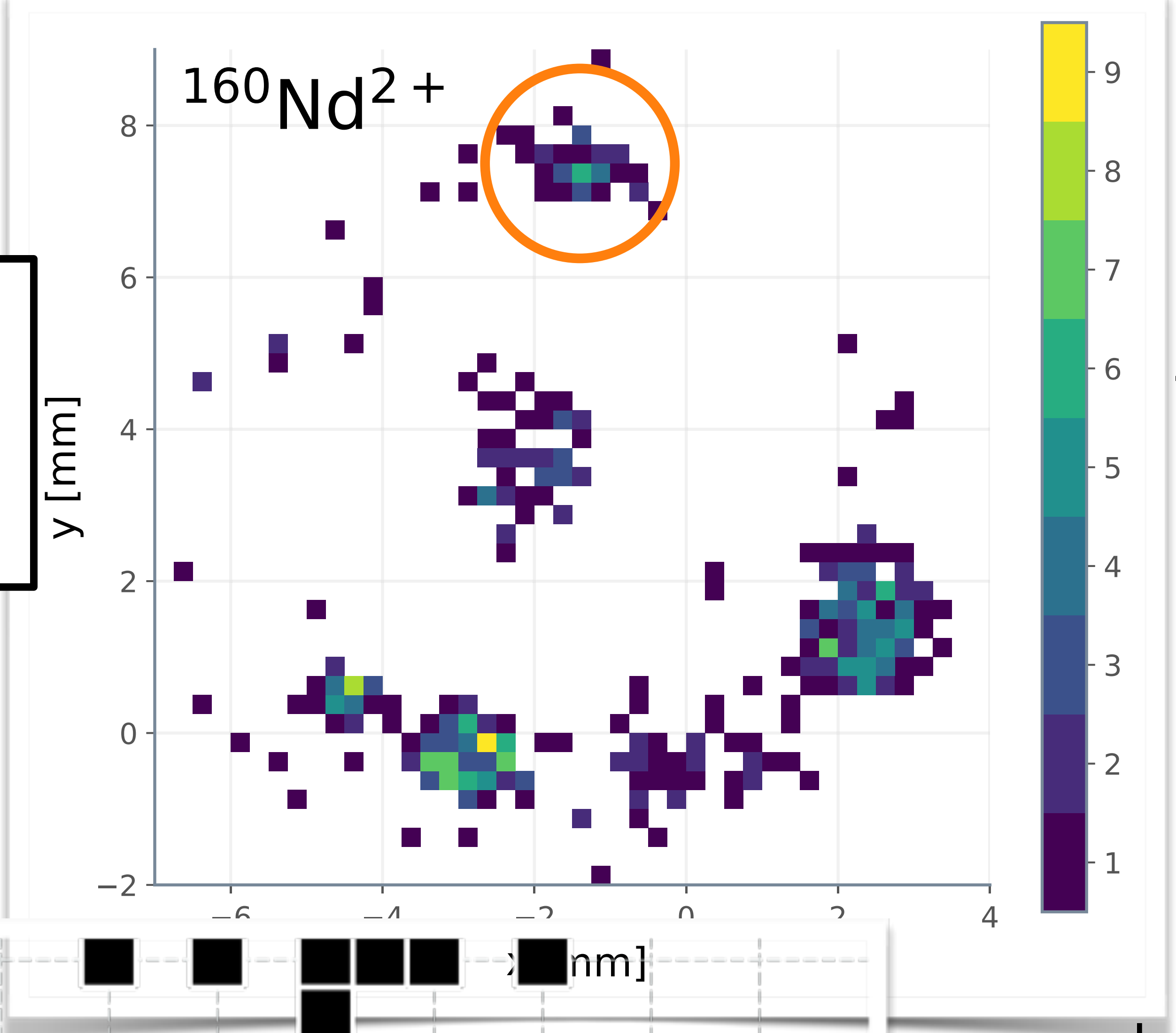
*Masses measurements necessary to gain insights into what **environment produces the observed abundance** peaks*

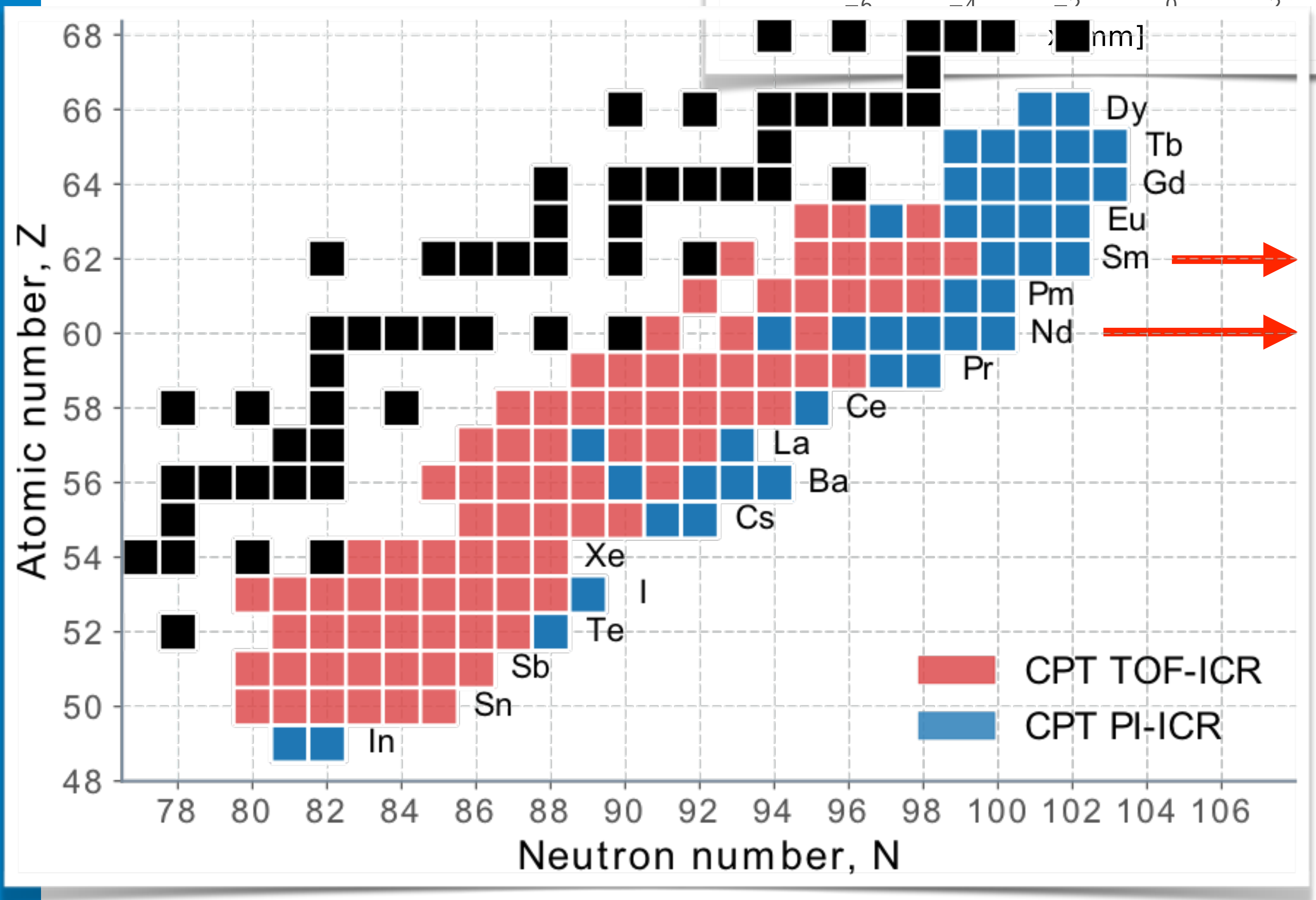




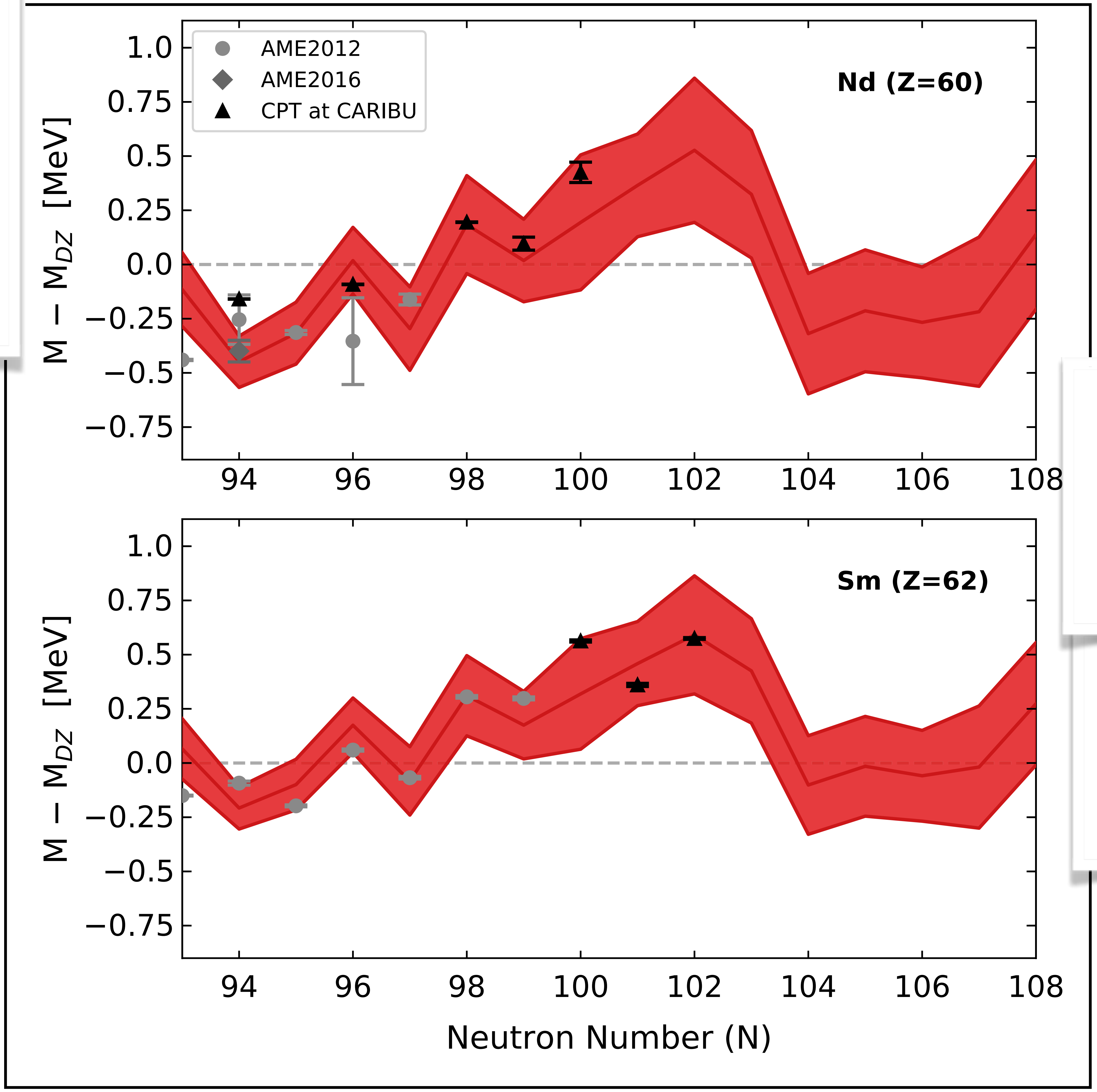
Masses, mass models

TOF: **T**ime **O**f **F**light
PI: **P**hase **I**maging
ICR: **I**on-**C**yclotron **R**esonance





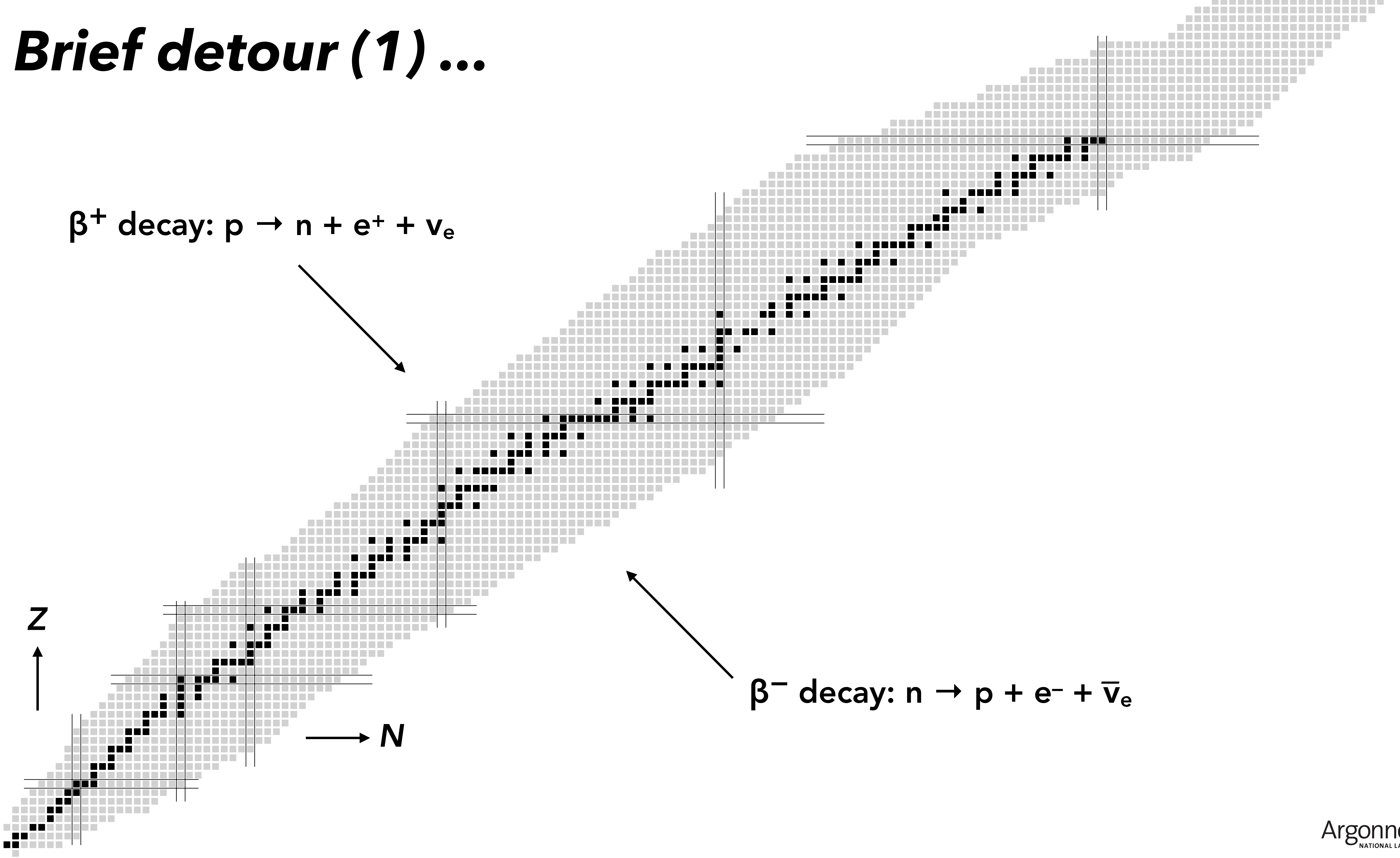
Monte Carlo Mass Corrections (MCMC):
"reverse engineering" the masses



R. Orford et al., Phys. Rev. Lett. ***120****, 262702 (****2018****)*

Brief detour (1) ...

β⁺ decay: $p \rightarrow n + e^+ + \nu_e$



β⁻ decay: $n \rightarrow p + e^- + \bar{\nu}_e$

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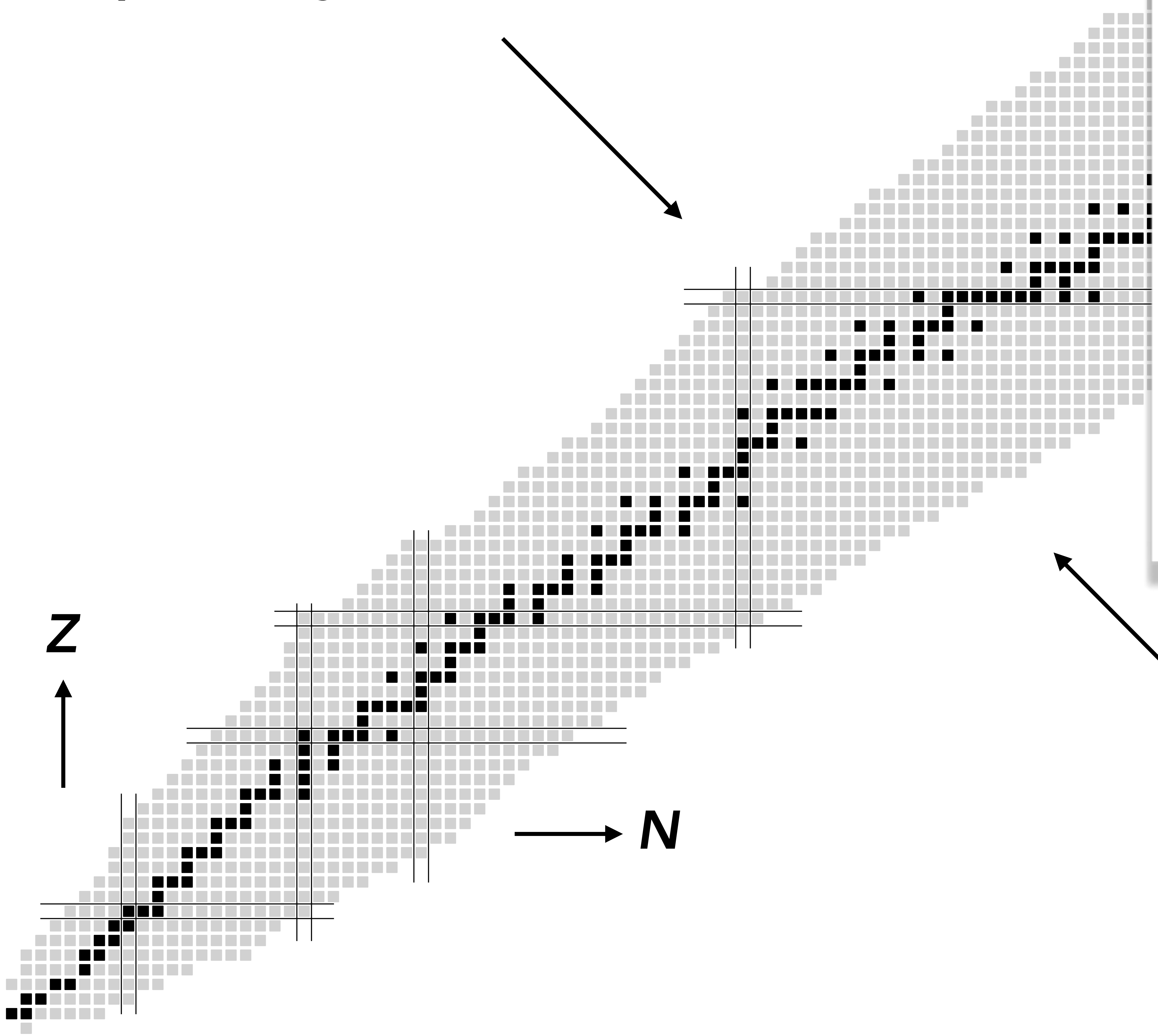
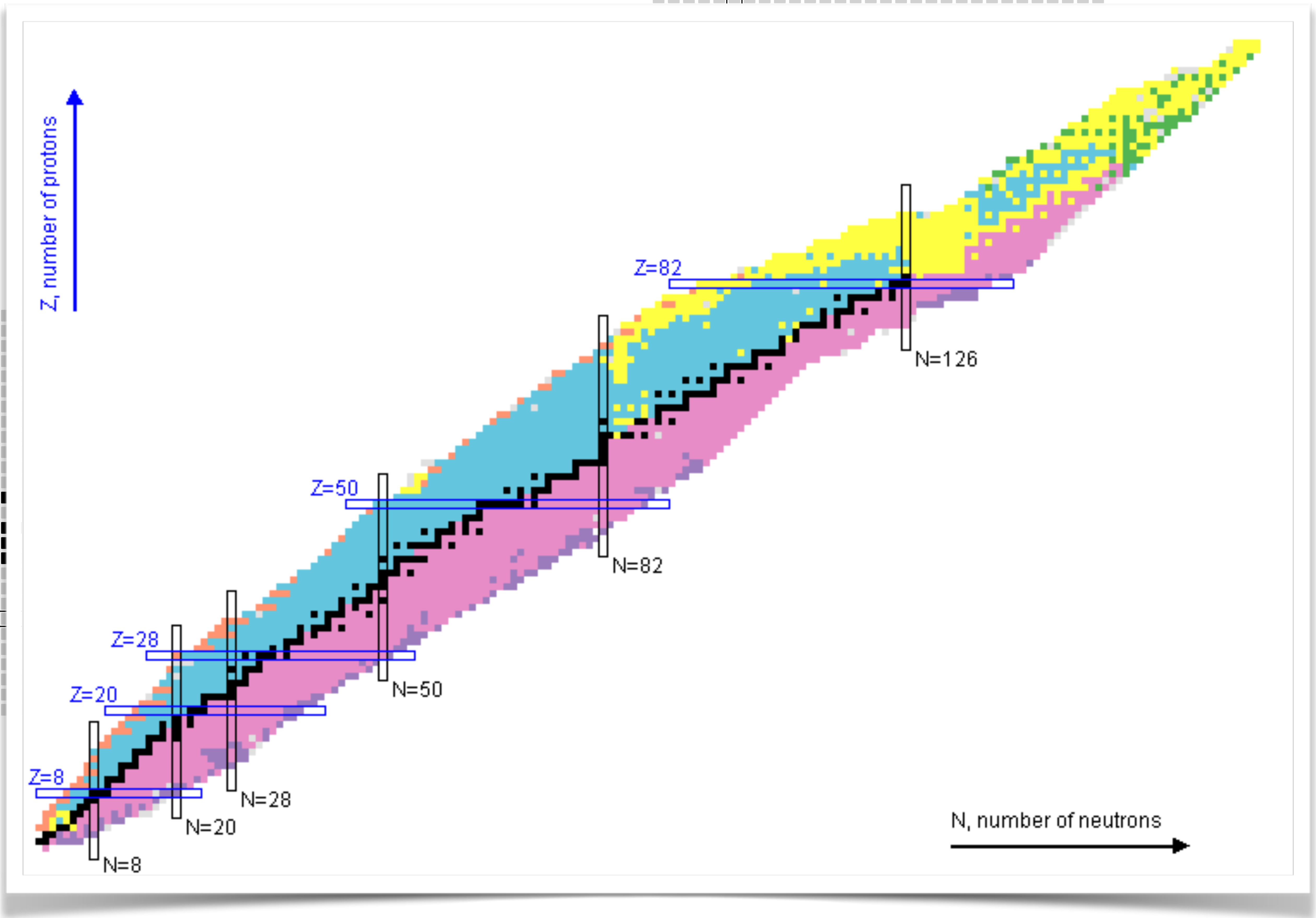
Brief detour (1) ...

β^+ decay: $p \rightarrow n + e^+ + \nu_e$





β^- decay: $n \rightarrow p + e^- + \bar{\nu}_e$

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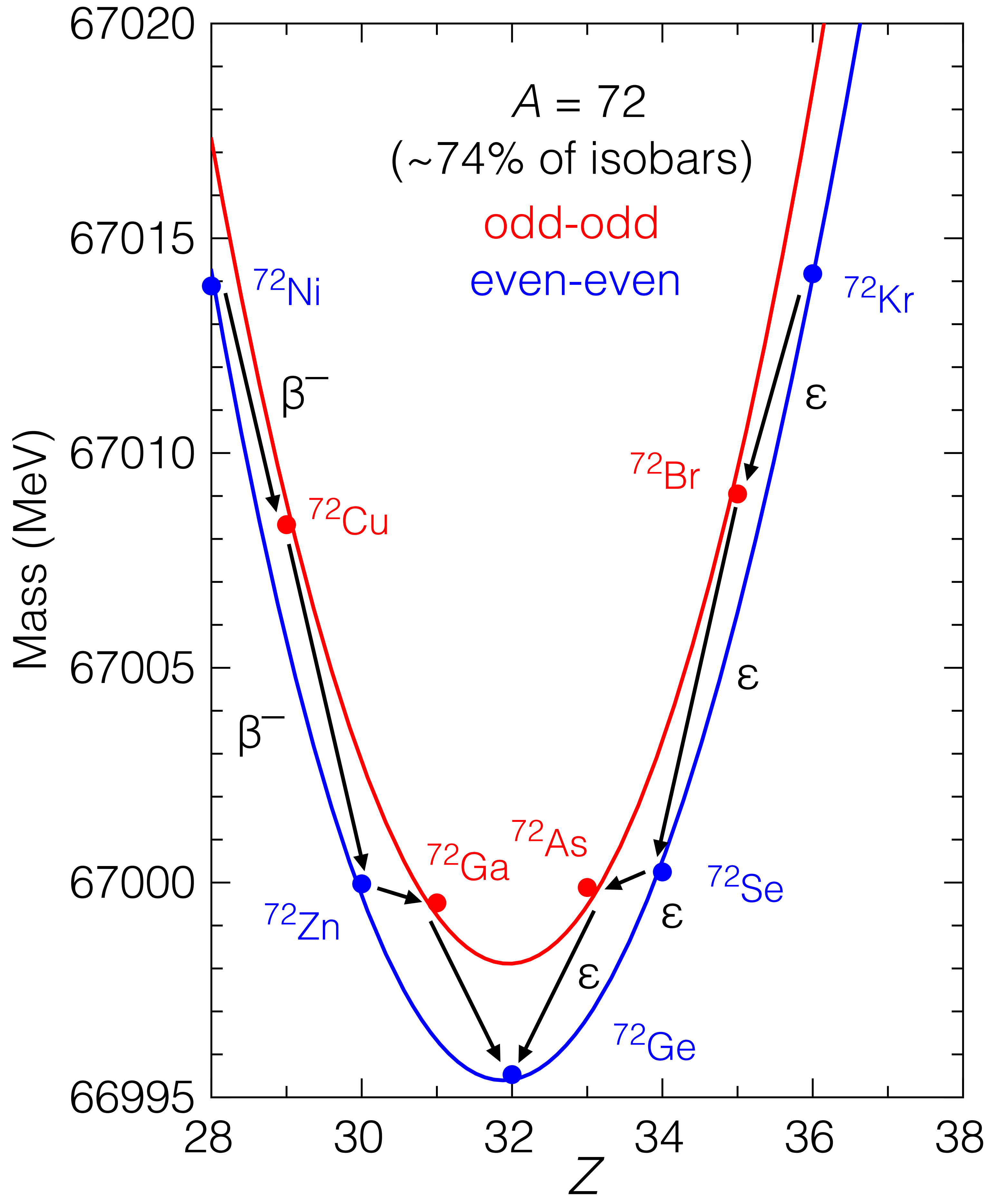
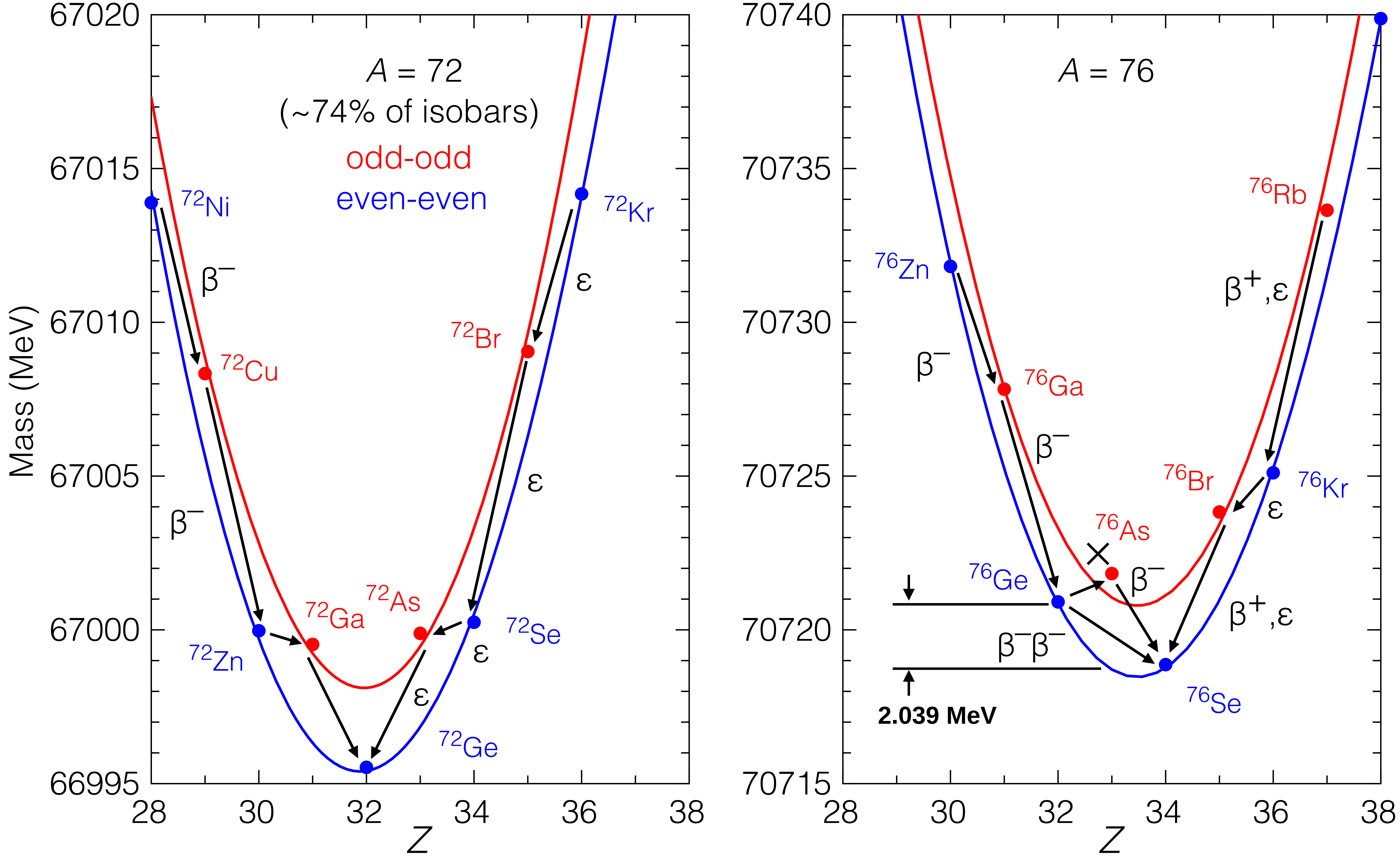
Beta decay, double beta decay …



Pairing in nuclei results in a displacement of even-even and odd-odd mass parabolas for given isobars. Data from AME 2012.

Beta decay, double beta decay ...



Pairing in nuclei results in a displacement of even-even and odd-odd mass parabolas for given isobars. Data from AME 2012. ***Precise masses ⇒ precise Q value.***

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REACHING FOR THE HORIZON

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

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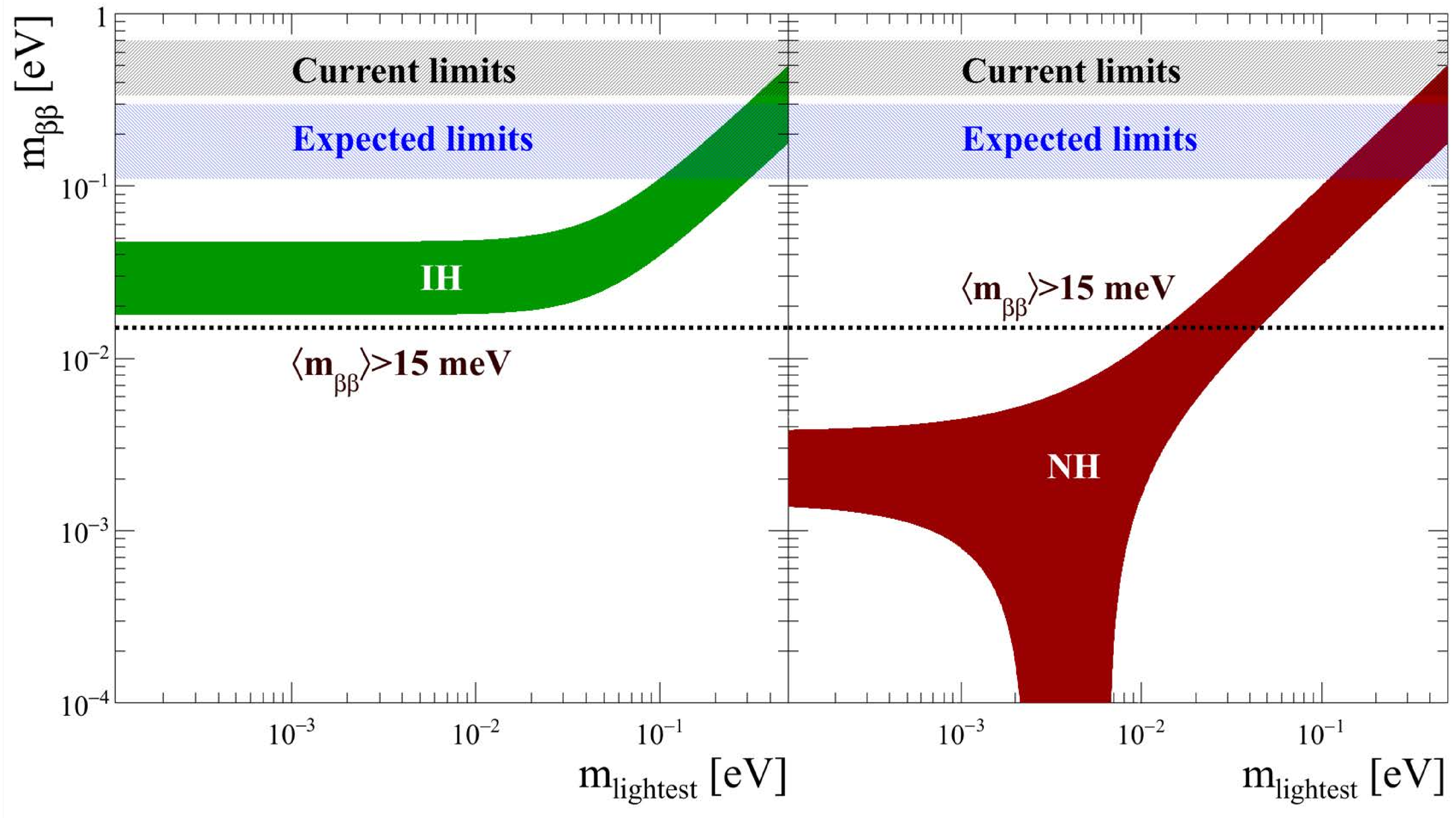
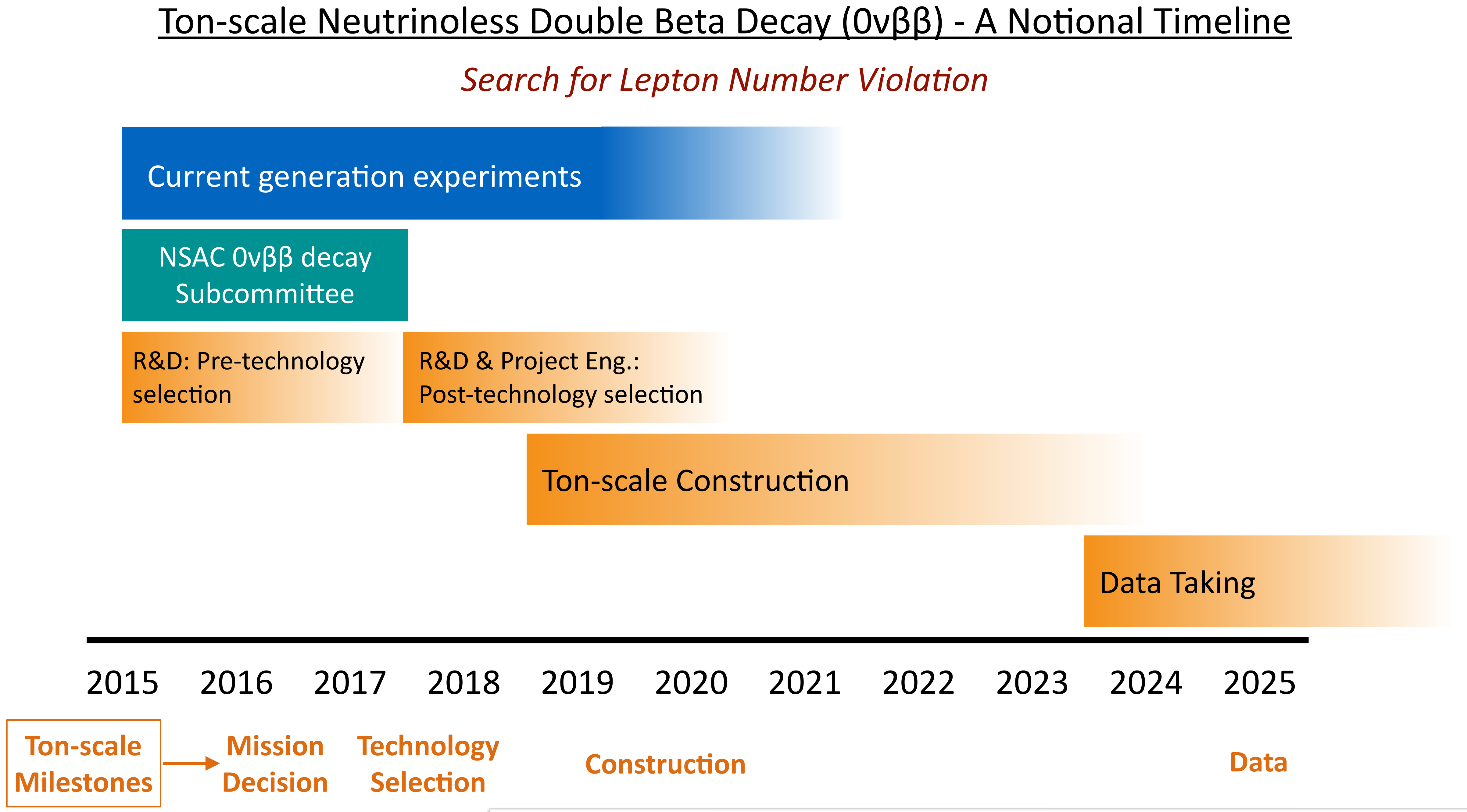


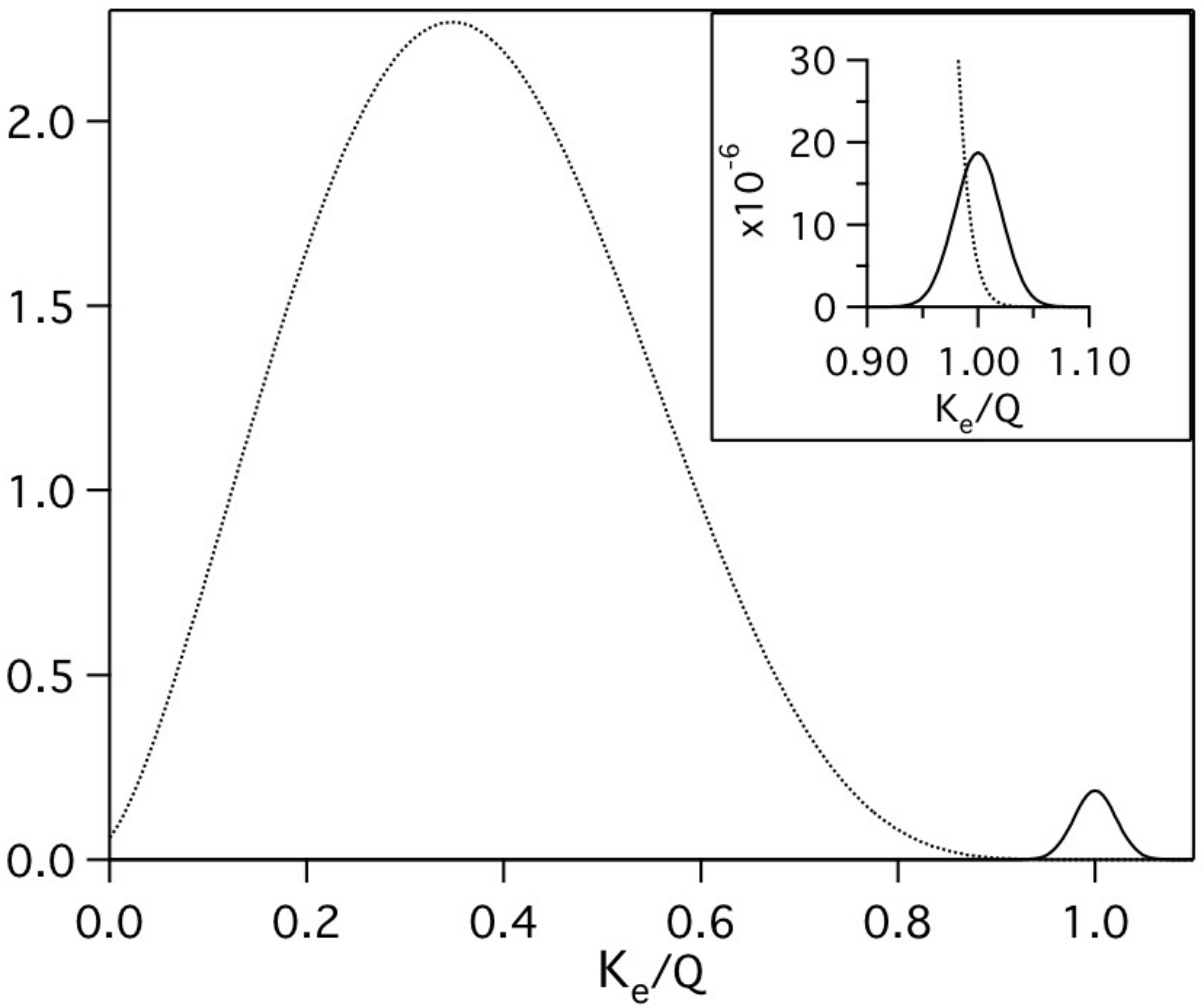


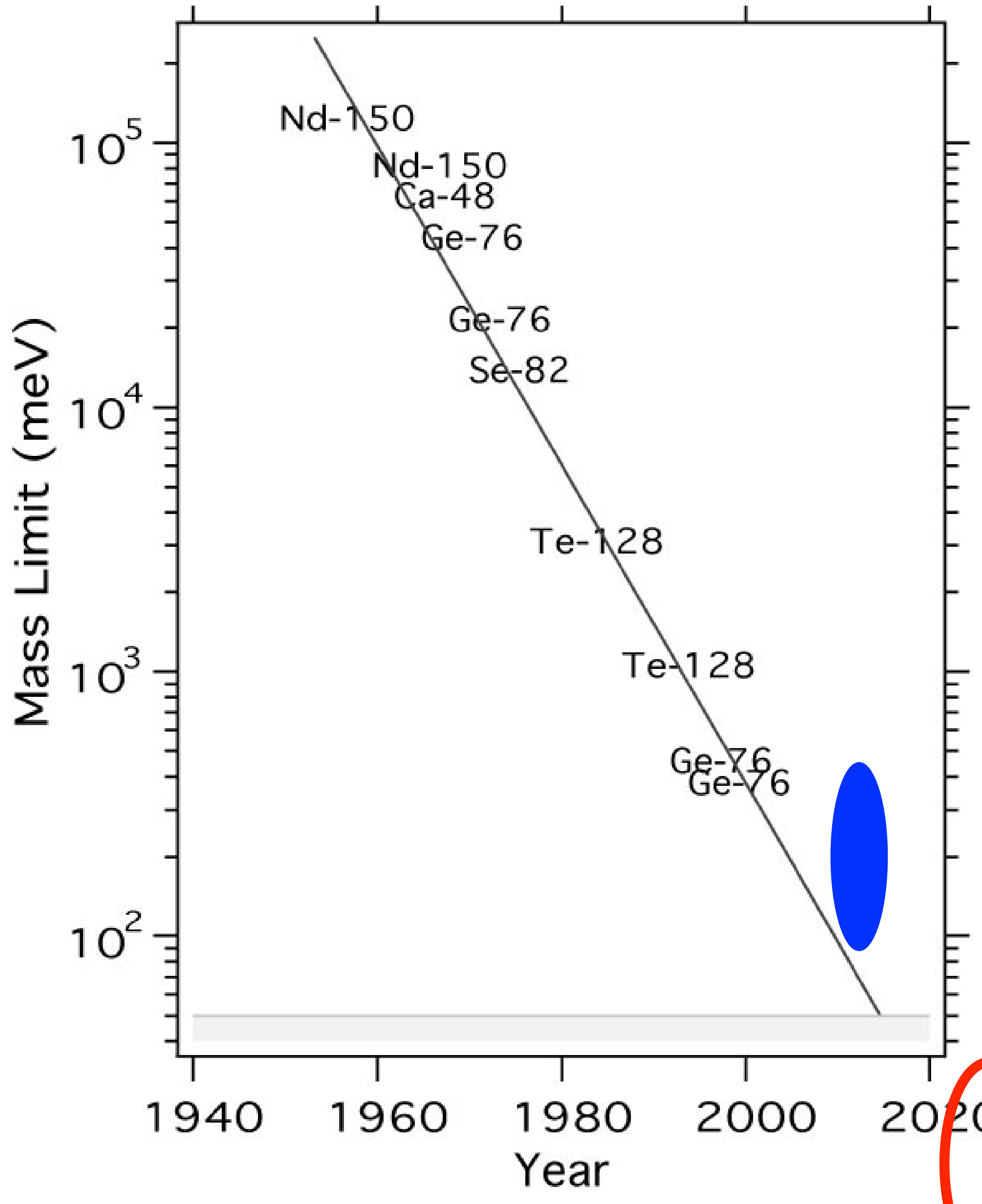
*"The **second recommendation** specifically targets the development and deployment of a ton-scale neutrino- less double beta decay experiment. **Demonstration experiments at the scale of 100 kg are currently underway** to identify the requirements and candidate technologies for a larger, next-generation experiment, which is needed to be sensitive to postulated new physics. **An ongoing NSAC subcommittee is helping to guide the process of the down-select, from several current options to one U.S.-led ton-scale experiment**."*

"Construction of this flagship experiment is expected to require five years, with capital investment peaking at about $50M/year during this period."

*"Since neutrinoless double beta decay measurements use the atomic nucleus as a laboratory, **nuclear theory is critical in connecting experimental results to the underlying lepton-number violating interactions and parameters through nuclear matrix elements**, which account for the strong interactions of neutrons and protons. Currently, **there exists about a factor of two uncertainty in the relevant matrix elements**, but by the time a ton-scale experiment is ready to take data, we expect reduced uncertainties as a result of the application to this problem of improved methods to solve the nuclear many-body physics."*

(Neutrino-less) double beta decay





EXO-200: ***200-400 meV***
KamLAND-Zen: ***61-165 meV***
(~1 year ago)
GERDA: ***200-400 meV***.

Next Gen. >15 meV

The search is on … what does the future hold?

Q^5

$$[T^{0\nu}_{1/2}]^{-1} = (\text{Phase Space Factor}) \times |\text{Nuclear Matrix Element}|^2 \times |\langle m_{\beta\beta} \rangle|^2$$

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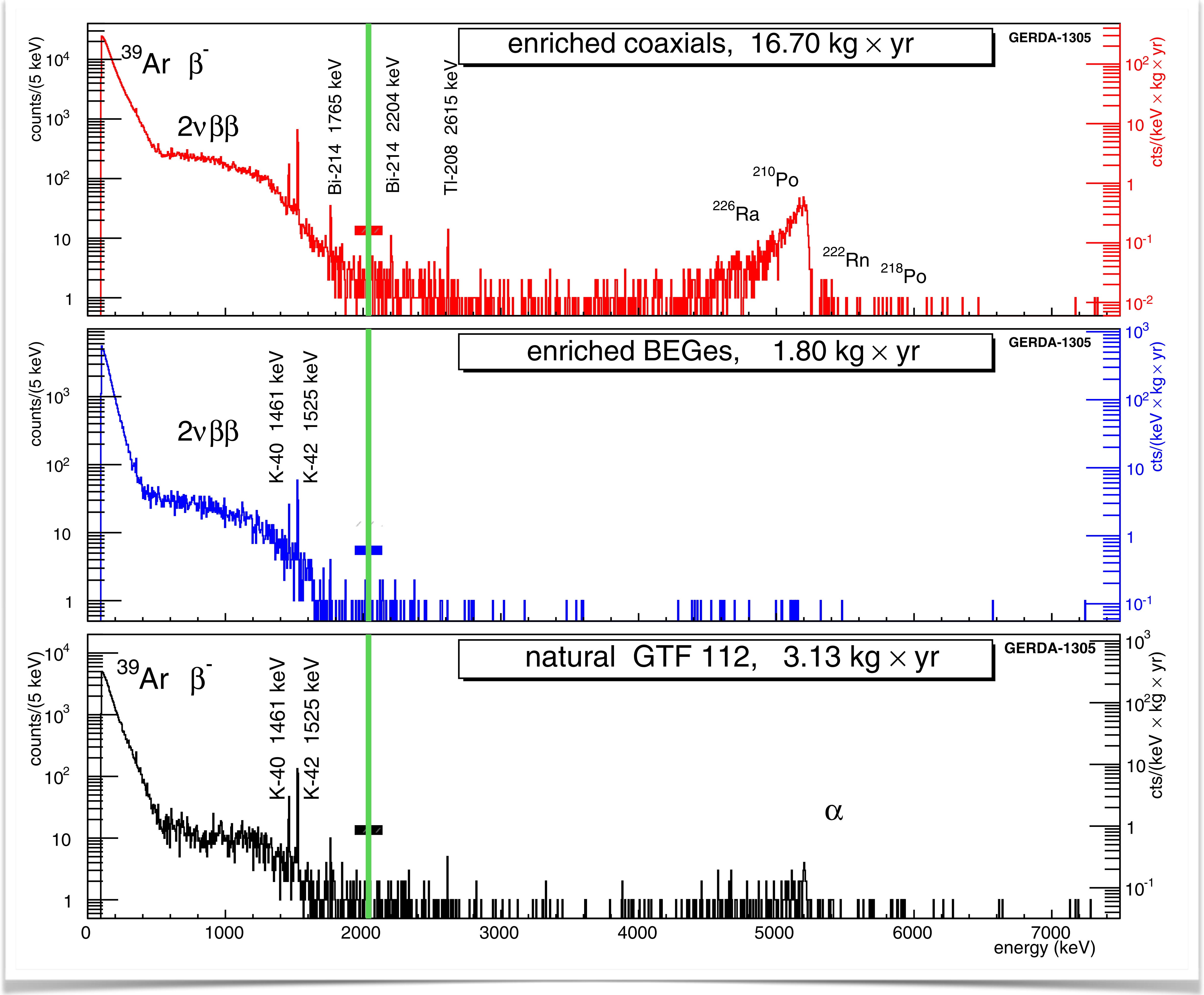
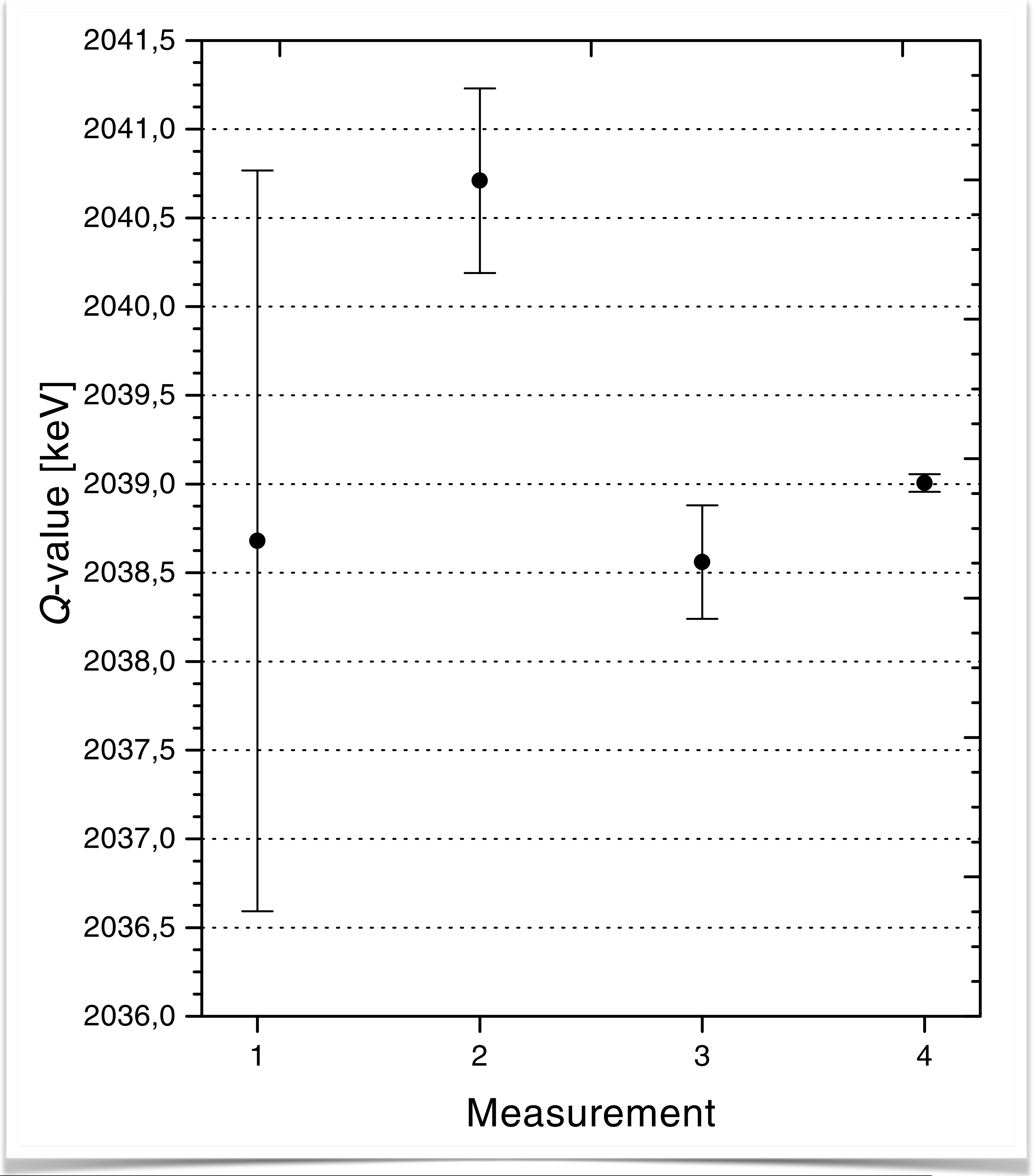
Knowing the Q value is essential





Q5!

$$[T^{0\nu}_{1/2}]^{-1} = (\text{Phase Space Factor}) \times |\text{Nuclear Matrix Element}|^2 \times |\langle m_{\beta\beta}\rangle|^2$$

M. Agostini et al., Eur. Phys. J. C ***74****, 2764 (****2014****) and G. Douysset et al., Phys. Rev. Lett.* ***86****, 4289 (****2001****)*

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Sizes

Sizes

ARTICLES

PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3529

nature physics

Neutron and weak-charge distributions of the ^{48}Ca nucleus

G. Hagen[1,2★], A. Ekström[1,2], C. Forssén[1,2,3], G. R. Jansen[1,2], W. Nazarewicz[1,4,5], T. Papenbrock[1,2], K. A. Wendt[1,2], S. Bacca[6,7], N. Barnea[8], B. Carlsson[3], C. Drischler[9,10], K. Hebeler[9,10], M. Hjorth-Jensen[4,11], M. Miorelli[6,12], G. Orlandini[13,14], A. Schwenk[9,10] and J. Simonis[9,10]

What is the size of the atomic nucleus? This deceivably simple question is difficult to answer. Although the electric charge distributions in atomic nuclei were measured accurately already half a century ago, our knowledge of the distribution of neutrons is still deficient. In addition to constraining the size of atomic nuclei, the neutron distribution also impacts the number of nuclei that can exist and the size of neutron stars. We present an *ab initio* calculation of the neutron distribution of the neutron-rich nucleus ^{48}Ca. We show that the neutron skin (difference between the radii of the neutron and proton distributions) is significantly smaller than previously thought. We also make predictions for the electric dipole polarizability and the weak form factor; both quantities that are at present targeted by precision measurements. Based on *ab initio* results for ^{48}Ca, we provide a constraint on the size of a neutron star.

G. Hagen et al., Nat. Phys. **12**, 186 (**2015**)

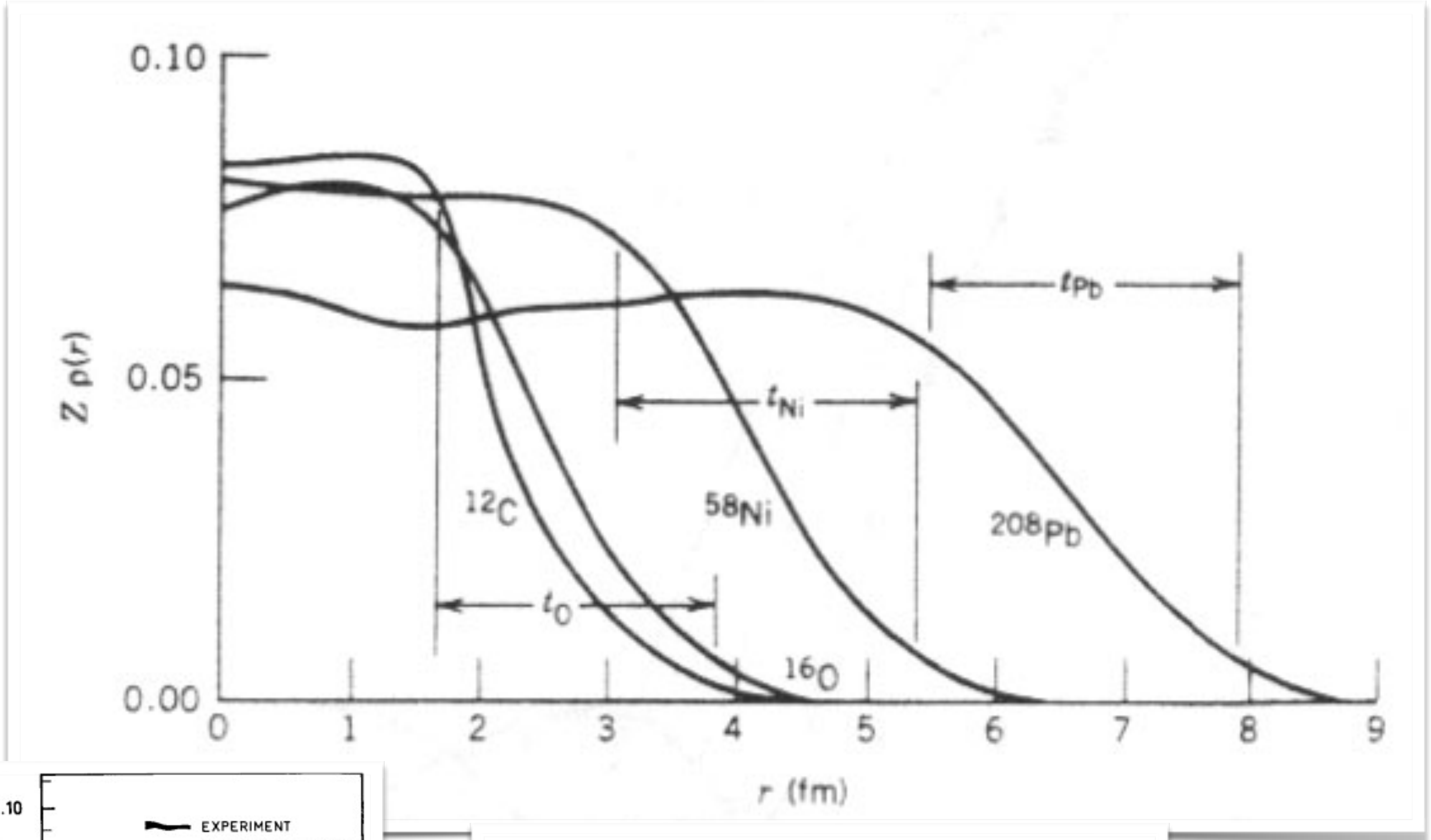
Sizes

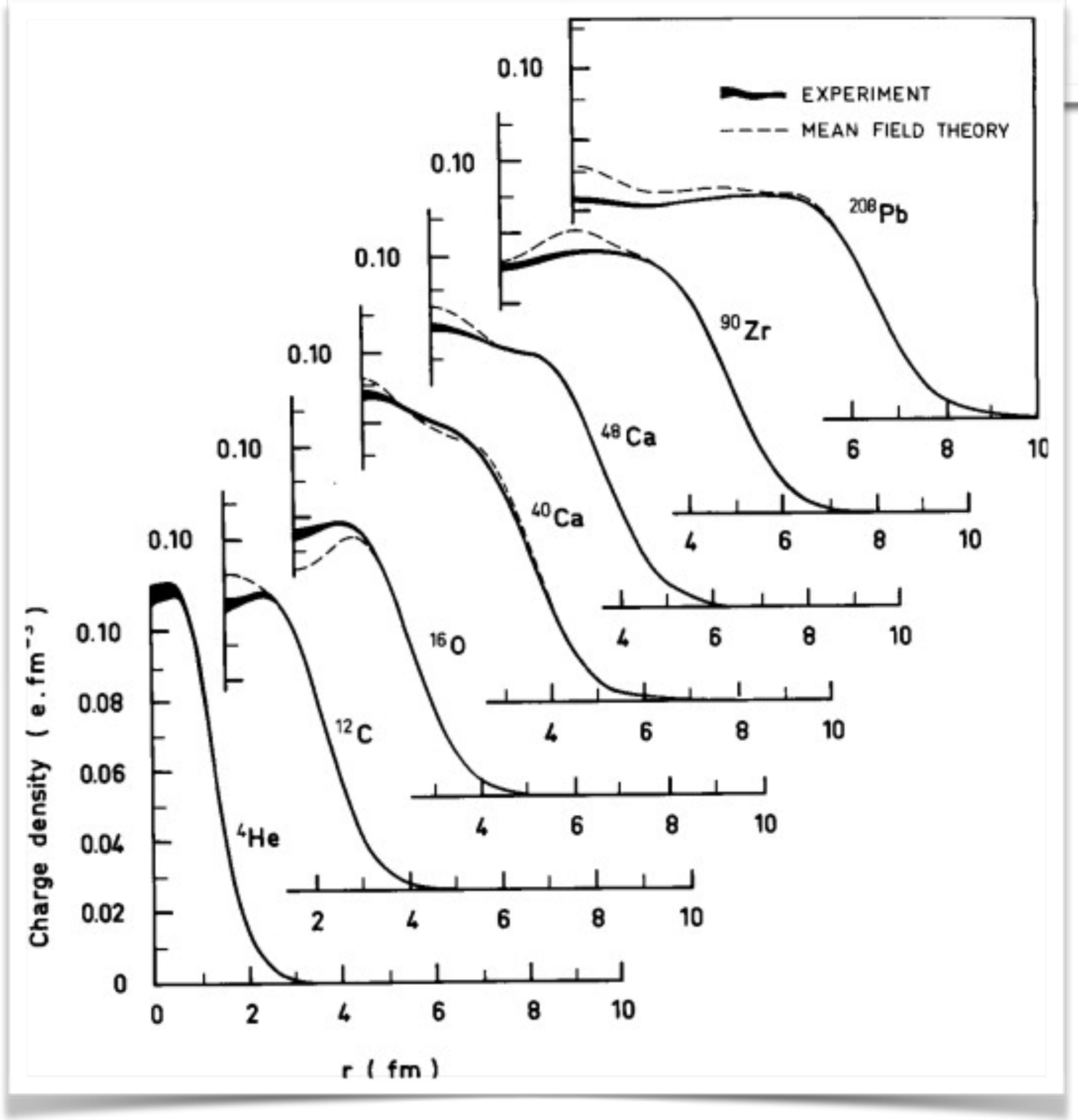
- Sizes of nuclei along with their mass (binding) is a fundamental property of the nucleus
- Radius links to size of the nuclear potential
- Matter and charge radii are similar for most nuclei, but dramatic differences seen in exotic systems
- Neutron skins
- Matter radii, neutron structure, can modify charge radius (or center-of-mass motion)?
- Shapes of nuclei can result in changes in charge radii
- ..... a series of examples ... via dramatic examples

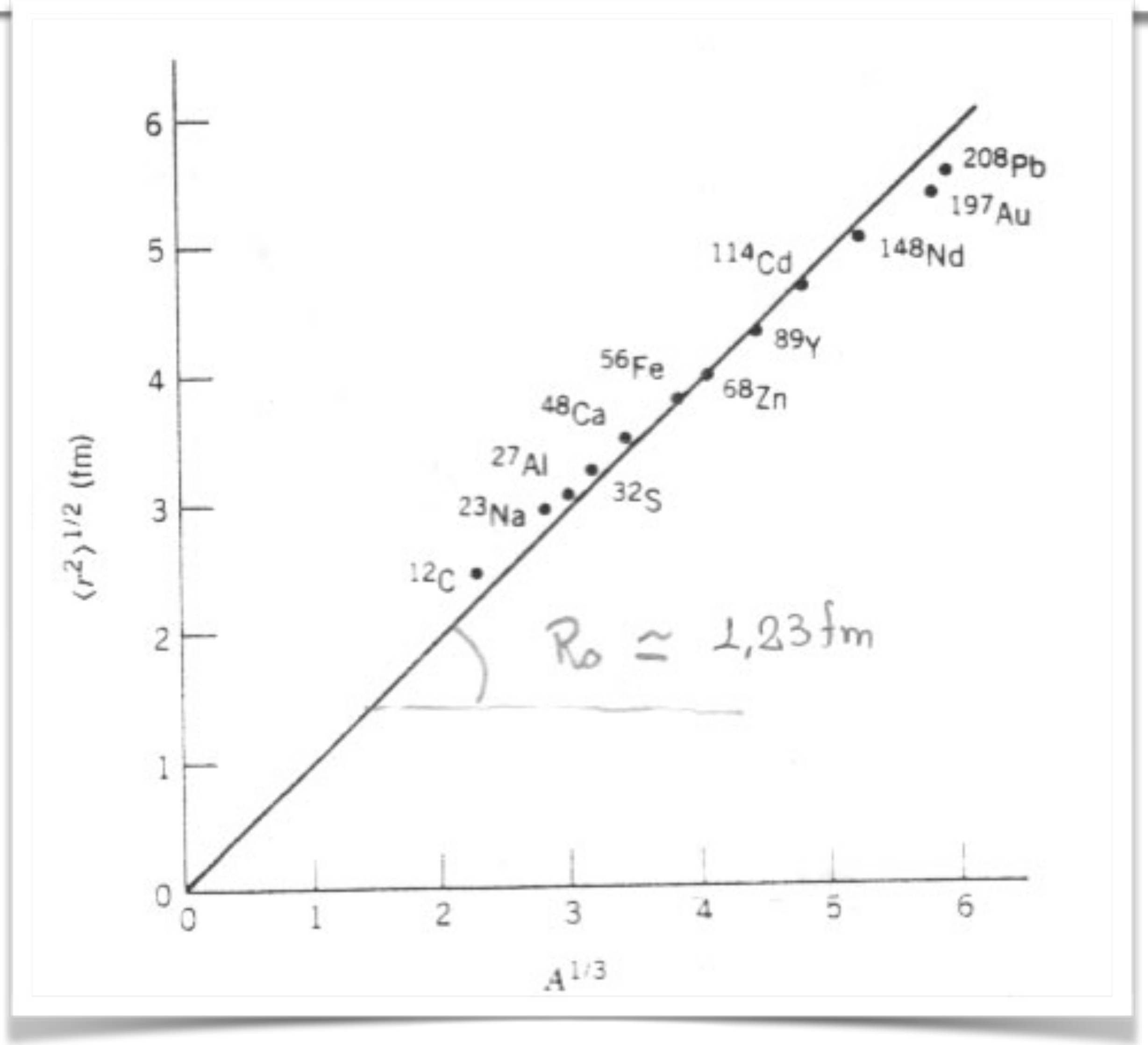
Proton, neutron, matter

$$r_c^2 = \frac{1}{Z} \int \rho_c(r) r^2 d^3 r$$

- Can be probed via elastic scattering, isotope shifts (precise)
- Matter distributions (radii) through interaction cross sections, or hadronic scattering reactions (less precise)
- A global picture of something like $r = r_0 A^{1/3}$ emerges (r_0 ~ 1.15-3 fm)







Krane's text book … Rolf's slides from this school

Proton, neutron, r

$$r_c^2 = \frac{1}{Z}\int \rho_c(r$$

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- A global
  something
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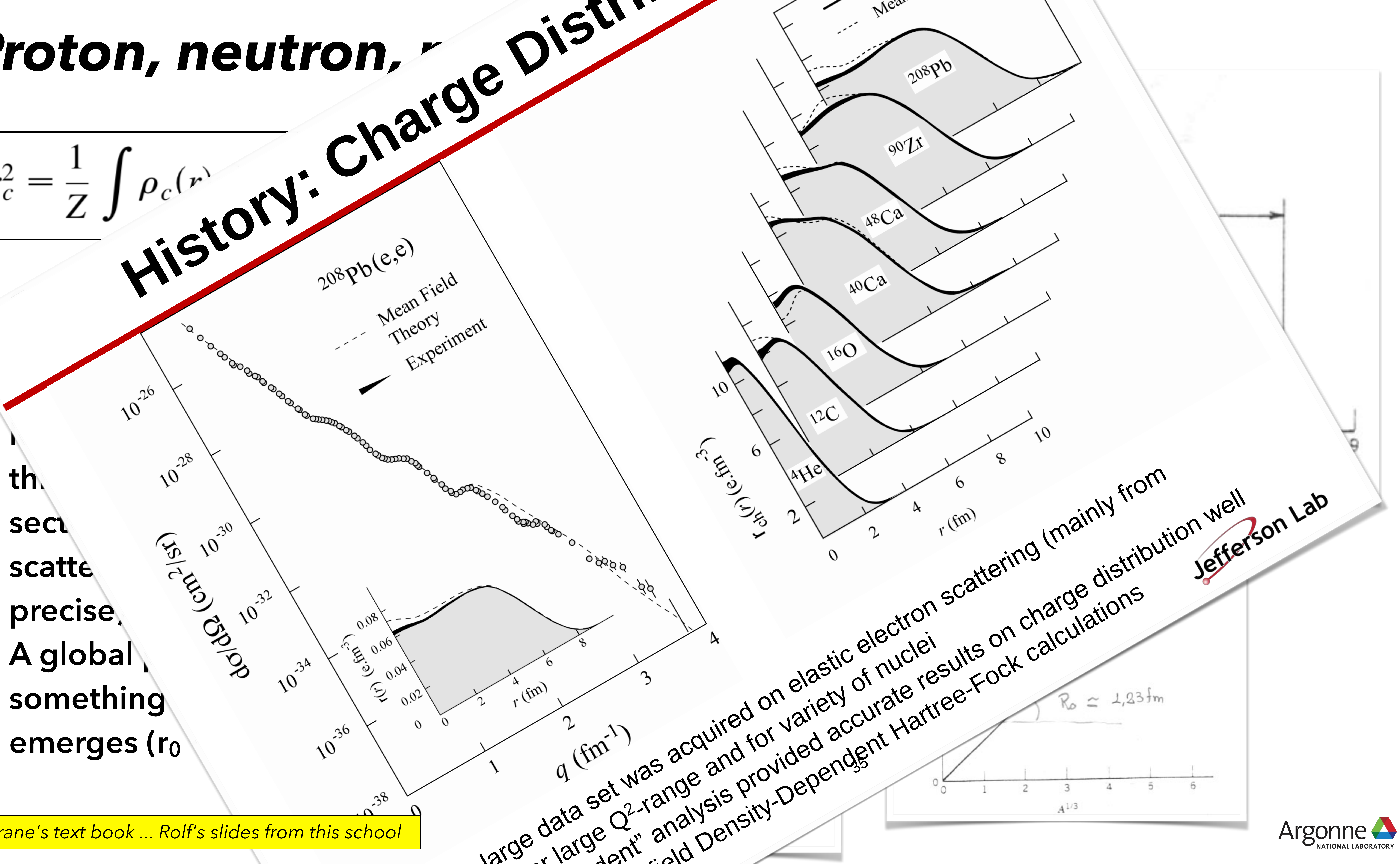

Krane's text book ... Rolf's slides from this school

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FORM FACTORS OF NUCLEI AT LOW ENERGY

Elastic scattering → $W^2 = M^2$ → $Q^2 = 2M(E-E')$ → Q^2 and ν are correlated

$$d\sigma/d\Omega \;\; \text{(and not } d\sigma/d\Omega dE) = \sigma_M F_0^2(q)$$

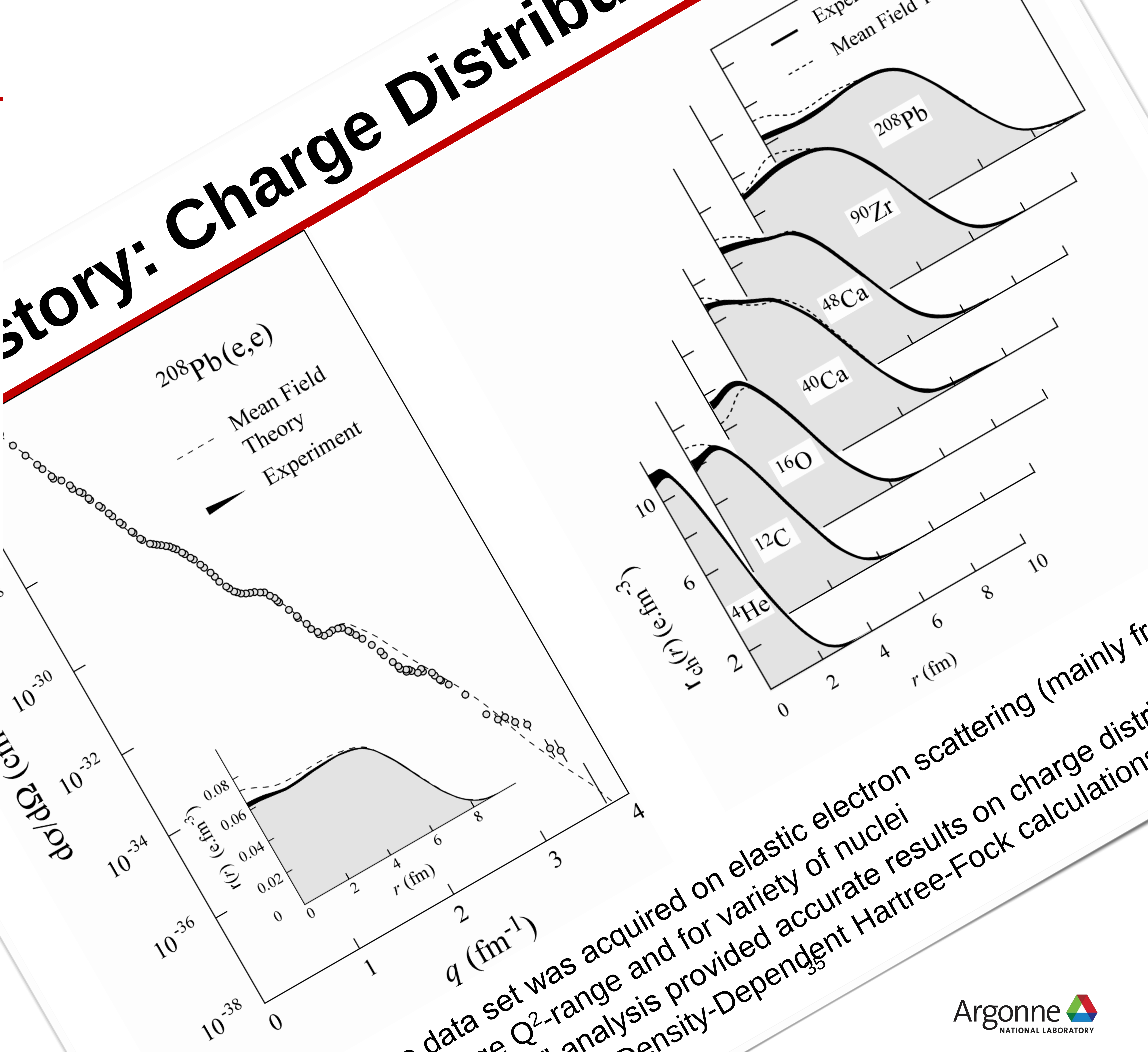
- For a point charge with charge Z one has $F_0(q) = Z$.
- For a charge with a finite size $F_0(q)$ will be smaller than Z, because different parts of $\rho(r)$ will give destructive contributions in the integral that constitutes $F_0(q)$.
- Often one includes the factor Z in σ_M and not in F_0, such that $F_0(0) = 1$.

$$F(q) = \frac{4\pi}{Zq}\int \rho(r)\sin(qr)rdr$$

Scatter from uniform sphere with radius R at low q: $\sin(qr) = qr - (1/6)(qr)^3$

1st term disappears (charge normalization)
2nd term gives direct R_{RMS} measurement (for q low enough)
At higher q pattern looks like slit scattering with radius R

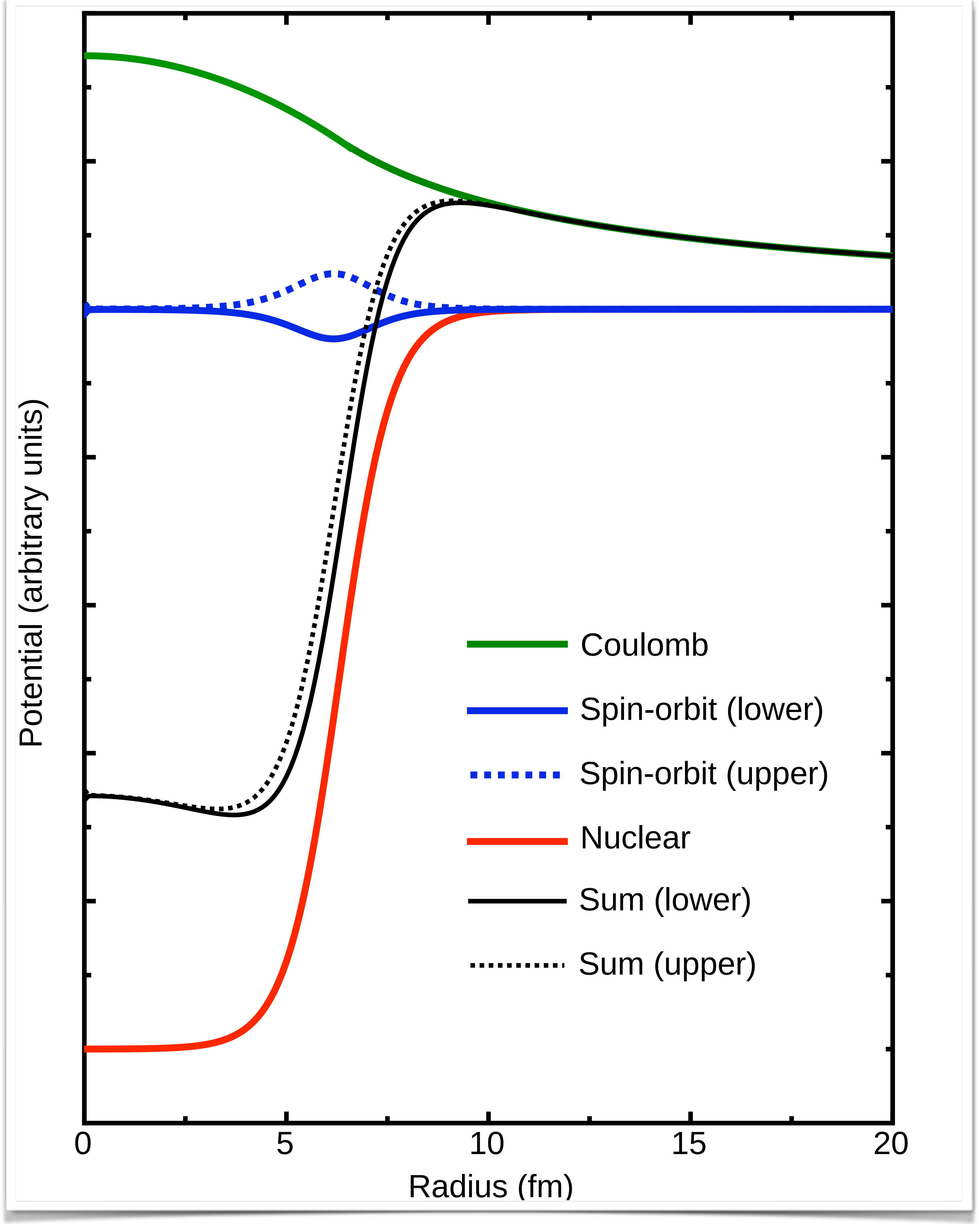
Jefferson Lab



Krane's text book … Rolf's slides from this school

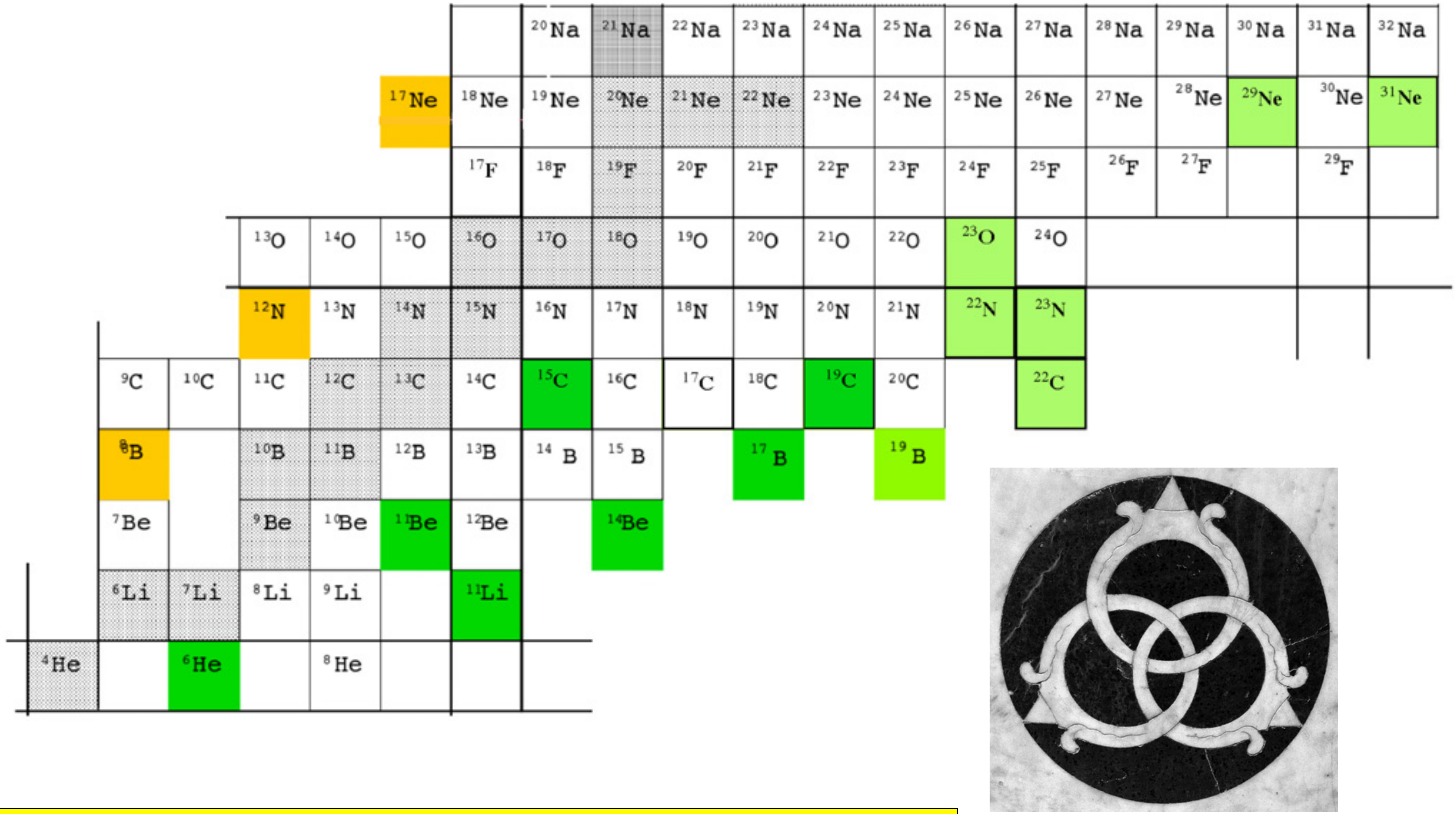
Charge radii

Target nucleus	E_x [MeV]	J^π	S (e,e′p)	r_0 [fm]	S (d,^{3}He) literature	S (d,^{3}He) reanalysis
^{12}C	0.000	3/2$^-$	1.72(11) [43]	1.35(2)	2.98 [44]	1.72
	2.125	1/2$^-$	0.26(2)	1.65(2)	0.69	0.27
	5.020	3/2$^-$	0.20(2)	1.51(2)	0.31	0.11
^{16}O	0.000	1/2$^-$	1.27(13) [45]	1.37(3)	2.30 [46]	1.02
	6.320	3/2$^-$	2.25(22)	1.28(2)	3.64	1.94
^{31}P	0.000	0$^+$	0.40(3) [47]	1.27(2)	0.62 [48]	0.36
	2.239	2$^+$	0.60(5)	1.18(3)	0.72	0.49
	3.498	2$^+$	0.28(2)	1.12(3)	0.30	0.19
^{40}Ca	0.000	3/2$^+$	2.58(19) [49,50]	1.30(5)	3.70 [51]	2.30
	2.522	1/2$^+$	1.03(7)	1.28(6)	1.65	1.03
^{51}V	0.000	7/2$^-$	0.37(3) [3]	1.30(3)	0.73 [52]	0.30 [5]
	1.554	7/2$^-$	0.16(2)	1.31(4)	0.39	0.15
	2.675	7/2$^-$	0.33(3)	1.32(3)	0.64	0.26
	3.199	7/2$^-$	0.49(4)	1.34(3)	1.05	0.39
	4.410	1/2$^+$	0.28(3)	1.22(3)	0.63	0.22
	6.045	1/2$^+$	0.35(3)	1.27(4)	1.10	0.30
^{90}Zr	0.000	1/2$^-$	0.72(7) [3]	1.32(3)	1.80 [53]	0.60 [54]
	0.909	9/2$^+$	0.54(5)	1.31(2)	1.25	0.30
	1.507	3/2$^-$	1.86(14)	1.27(2)	3.90	1.20
	1.745	5/2$^-$	2.77(19)	1.30(2)	8.90	2.40
^{142}Nd	0.000	5/2$^+$	1.39(23) [55]	1.29(9)	2.53 [56]	1.25
	0.145	7/2$^+$	3.14(43)	1.26(8)	6.28	3.79
	1.118	11/2$^-$	0.56(7)	1.28(8)	0.74	0.36
	1.300	1/2$^+$	0.05(1)	1.26(9)	0.11	0.07
^{206}Pb	0.000	1/2$^+$	0.68(6) [57]	1.23(9)	1.15 [58]	1.03
	0.203	3/2$^+$	1.10(9)	1.27(9)	1.77	0.99
	0.616	5/2$^+$	0.32(3)	1.23(8)	0.52	0.44
	1.151	3/2$^+$	0.52(5)	1.28(9)	0.66	0.37
	1.479	11/2$^-$	3.58(32)	1.25(9)	6.94	5.21
^{208}Pb	0.000	1/2$^+$	0.98(9) [57]	1.25(8)	1.8 [59]	1.5
	0.350	3/2$^+$	2.31(22)	1.23(8)	3.8	2.2
	1.350	11/2$^-$	6.85(68)	1.16(9)	7.7	5.4
	1.670	5/2$^+$	2.93(28)	1.19(8)	3.5	3.1
	3.470	7/2$^+$	2.06(20)	1.15(9)	3.5	2.9



Kramer, Blok, Lapikás, Nucl. Phys. A ***679****, 267 (****2001****)*

He isotopes



Z.-T. Lu et al., Rev. Mod. Phys. ***85****, 1385 (****2013****), Tanihata et al., Prog. Part. Nucl. Phys.* ***68****, 215 (****2013****)*

He isotopes

Which is larger charge radius? ^{4}He, ^{6}He, ^{8}He?

Which is larger matter radius? ^{4}He, ^{6}He, ^{8}He?

... *and how were they determined?*

Z.-T. Lu et al., Rev. Mod. Phys. ***85****, 1385 (****2013****)*

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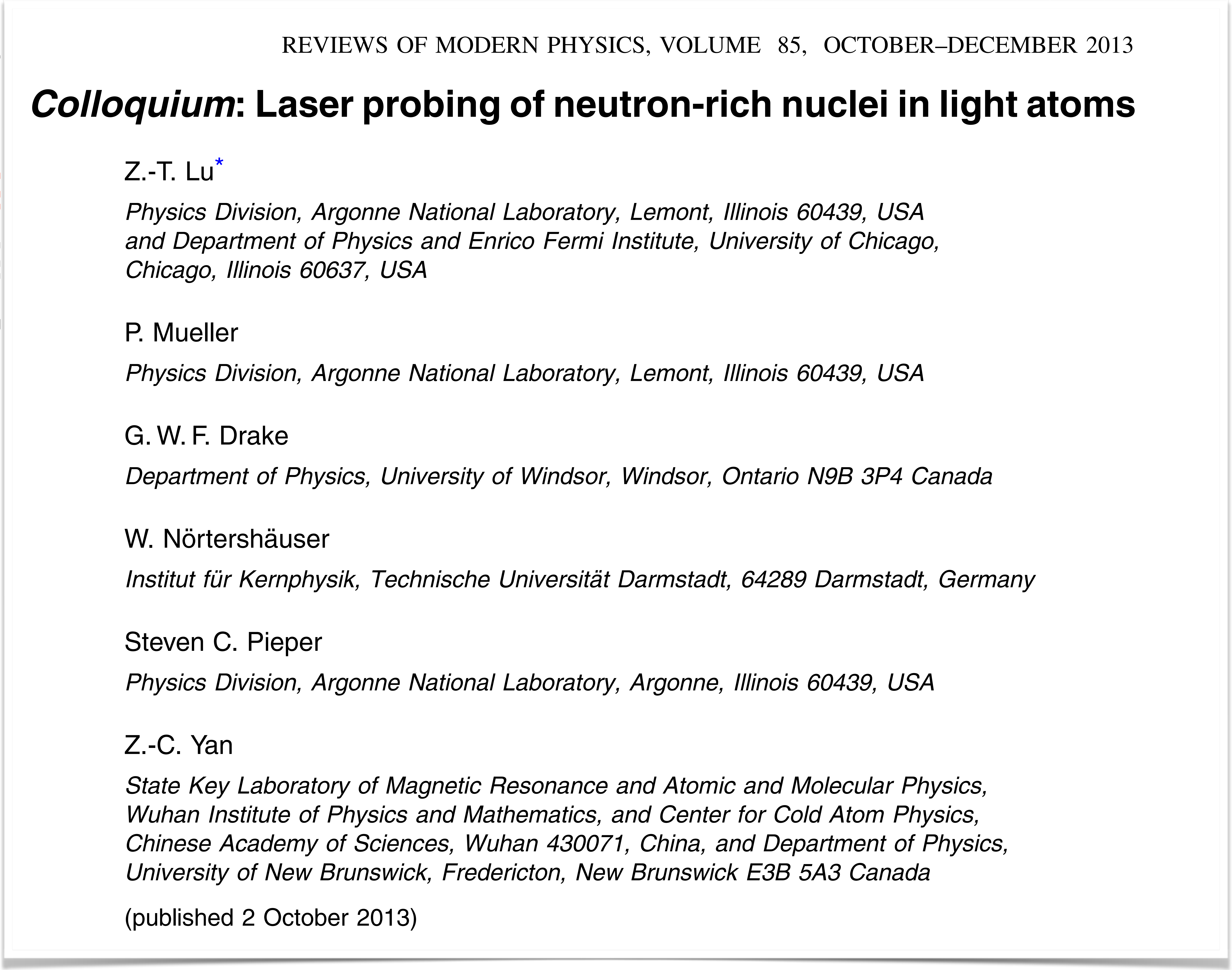
REVIEWS OF MODERN PHYSICS, VOLUME 85, OCTOBER–DECEMBER 2013

Colloquium: Laser probing of neutron-rich nuclei in light atoms

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State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, and Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China, and Department of Physics, University of New Brunswick, Fredericton, New Brunswick E3B 5A3 Canada

(published 2 October 2013)

Z.-T. Lu et al., Rev. Mod. Phys. ***85****, 1385 (****2013****)*

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He isotopes

Which is larger charge radius? ^{4}He, ^{6}He, ^{8}He?

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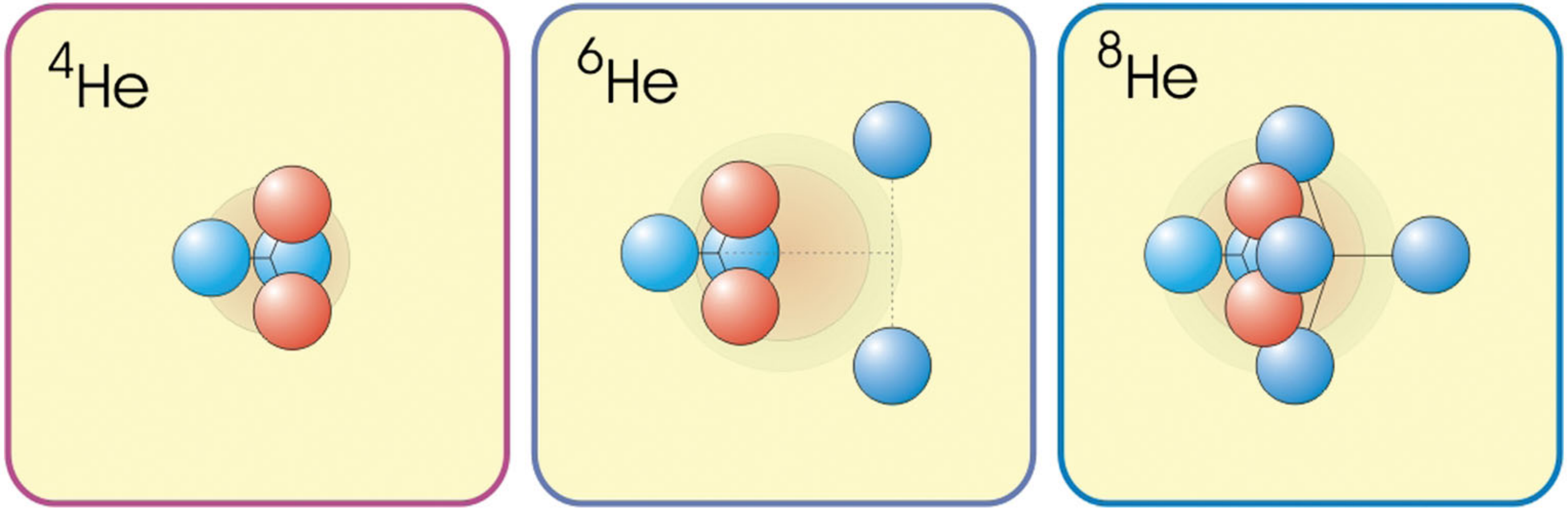
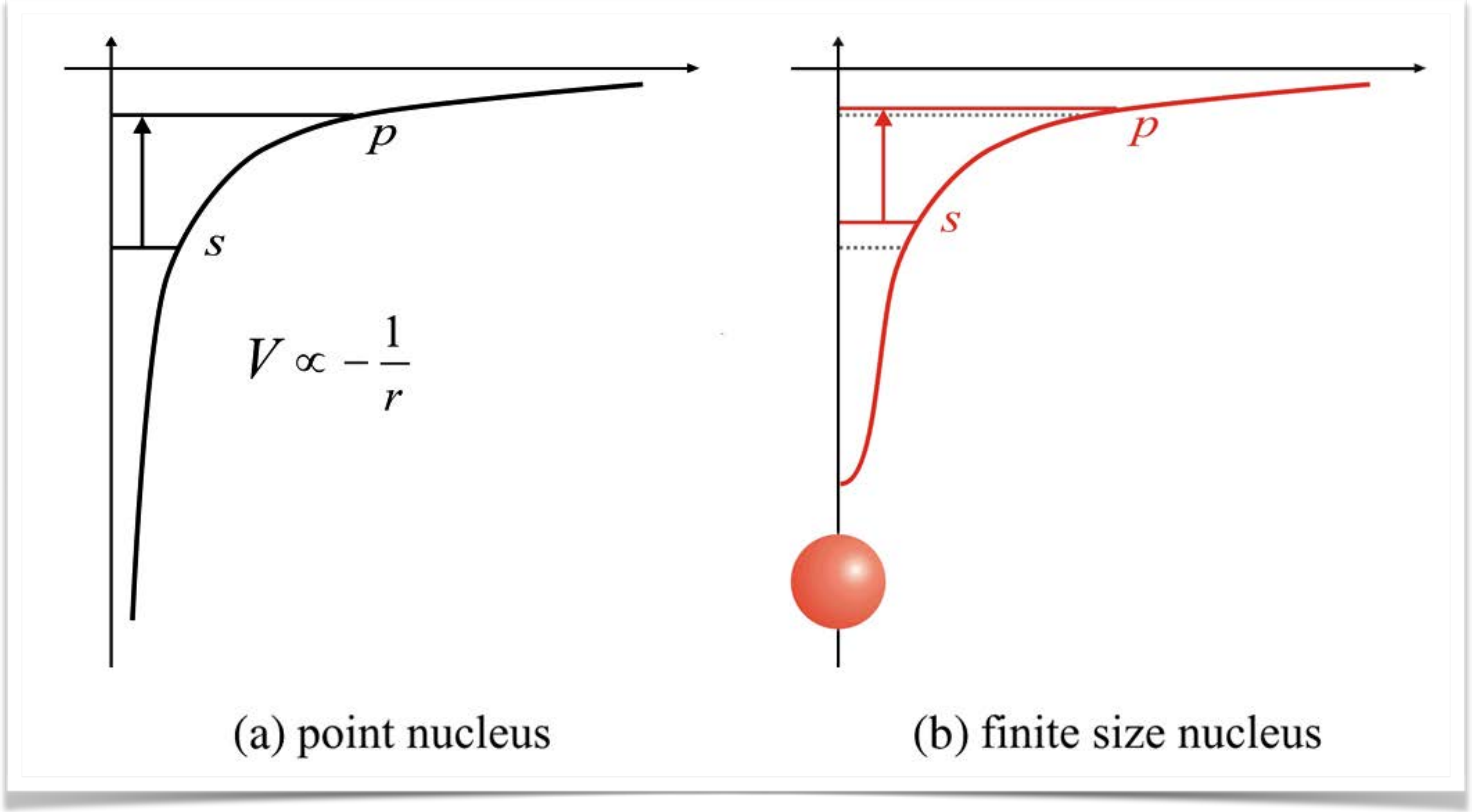
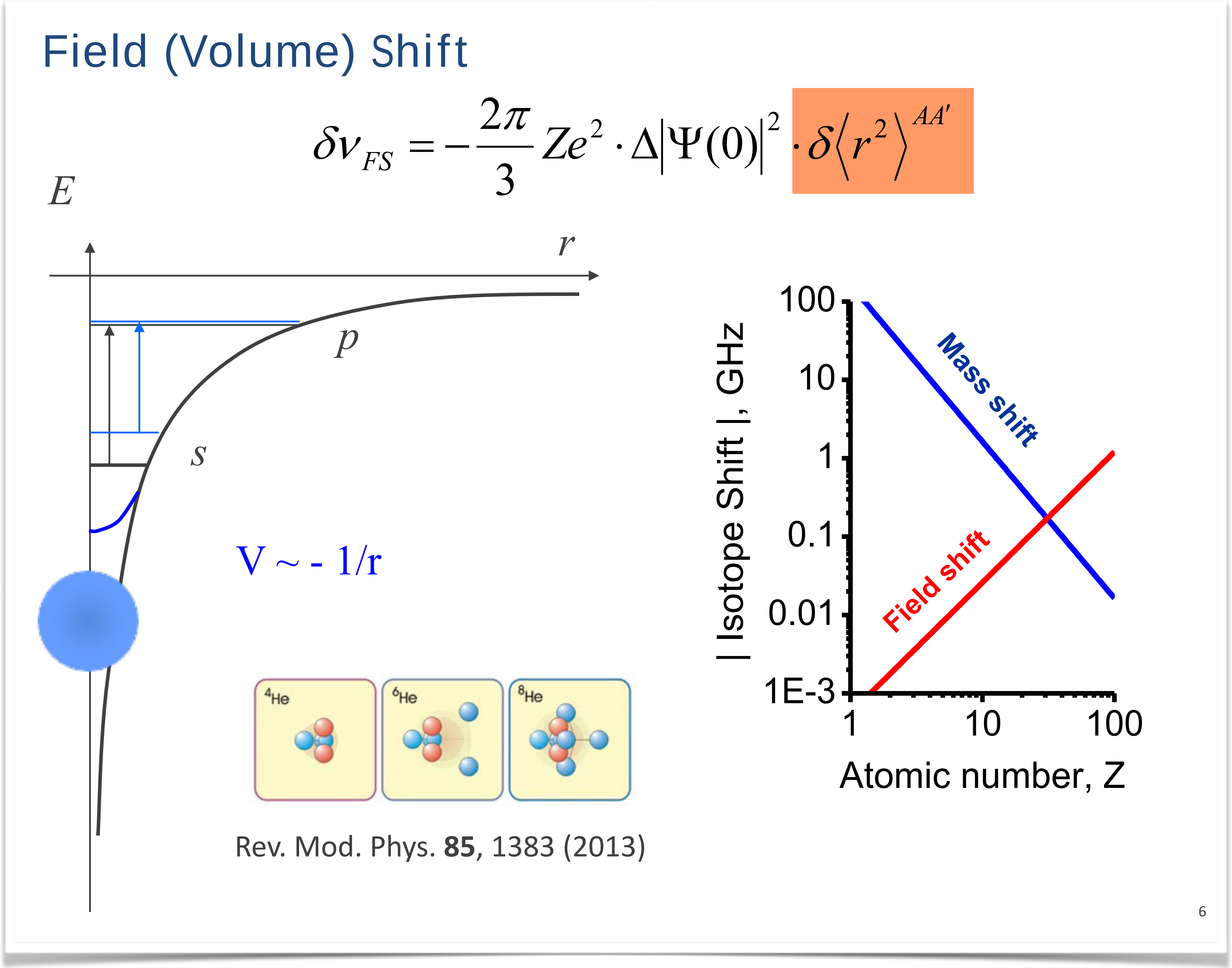


Z.-T. Lu et al., Rev. Mod. Phys. **85**, *1385 (**2013**), Tanihata et al., Prog. Part. Nucl. Phys.* **68**, *215 (**2013**)*

Charge radii, isotope shift

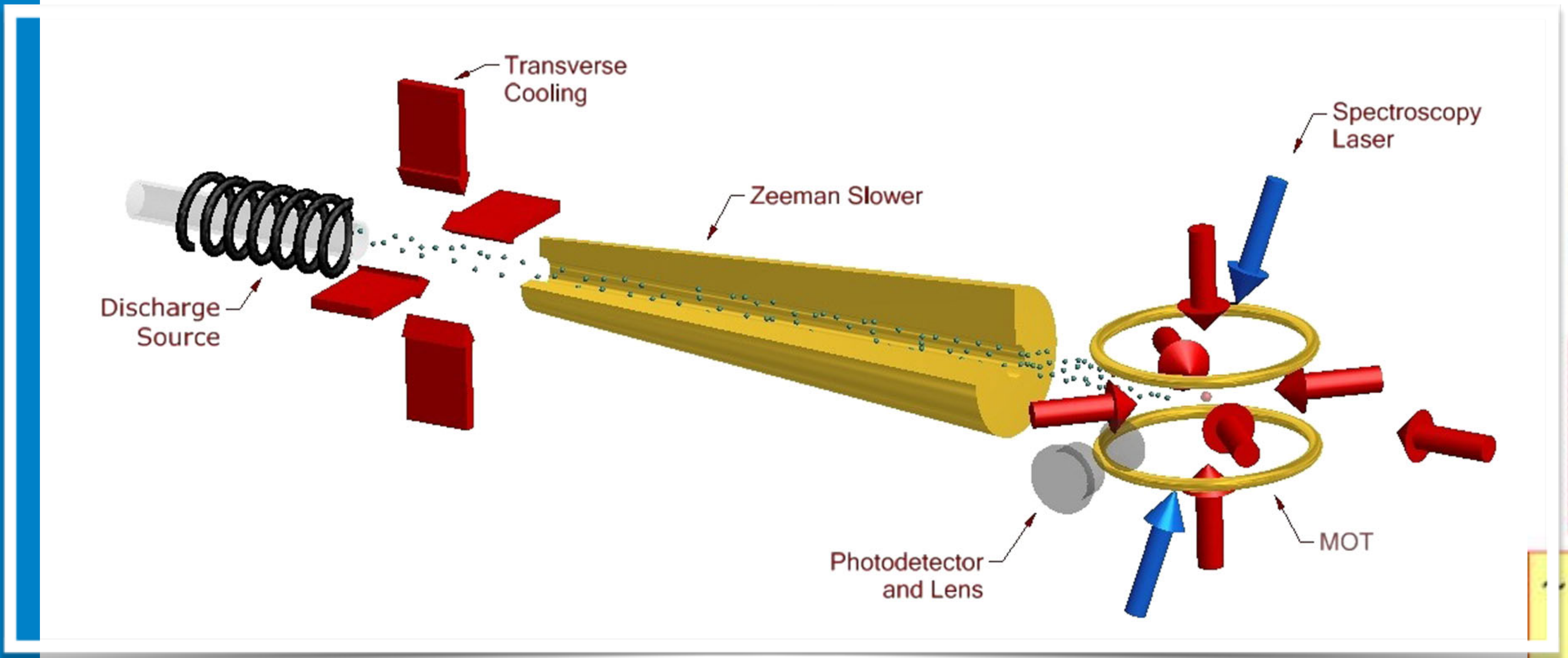


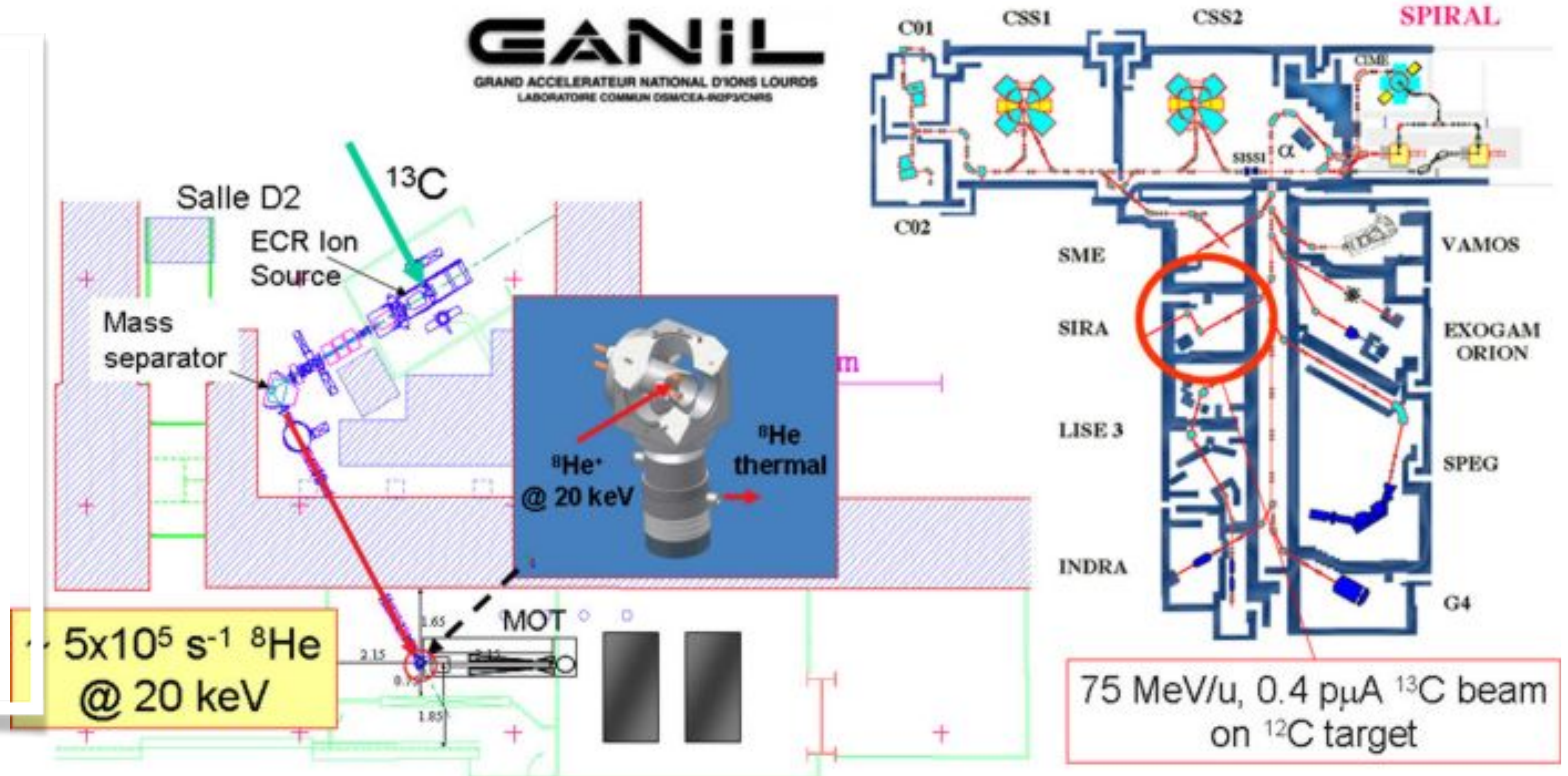


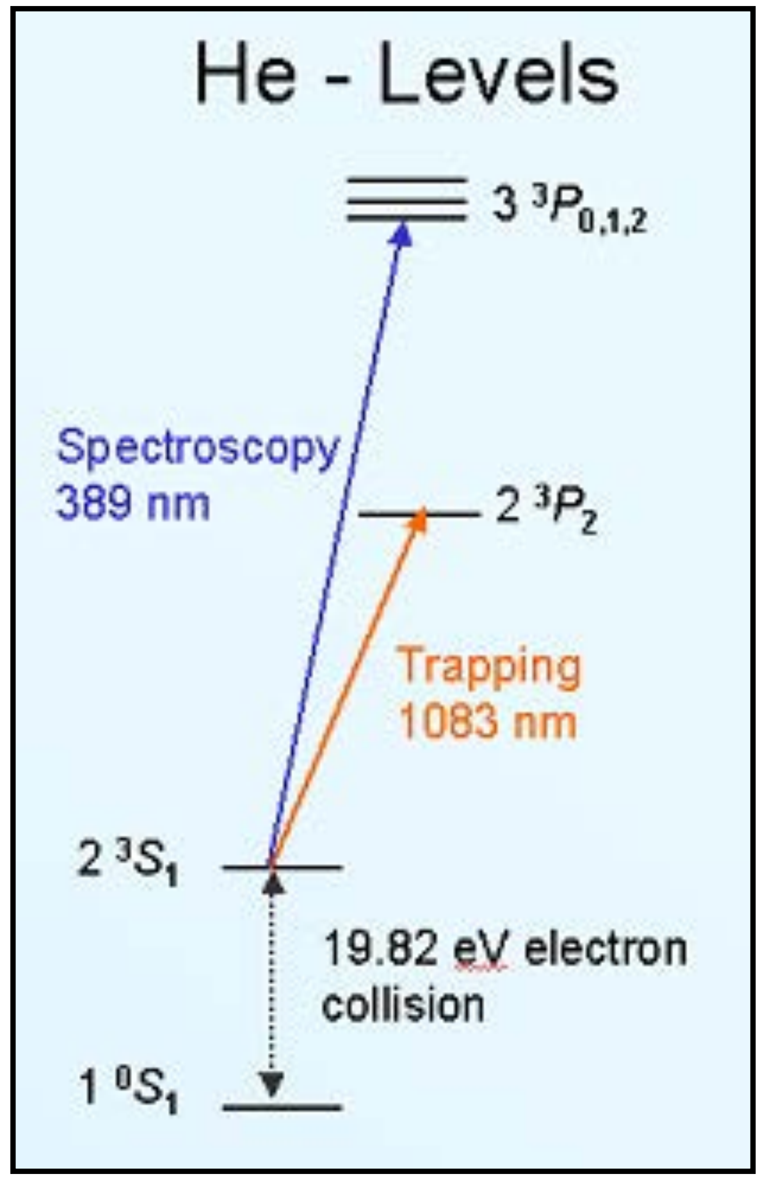
- **Field shift, mass shift, and radius**

Z.-T. Lu et al., Rev. Mod. Phys. ***85****, 1385 (****2013****), Tanihata et al., Prog. Part. Nucl. Phys.* ***68****, 215 (****2013****)*

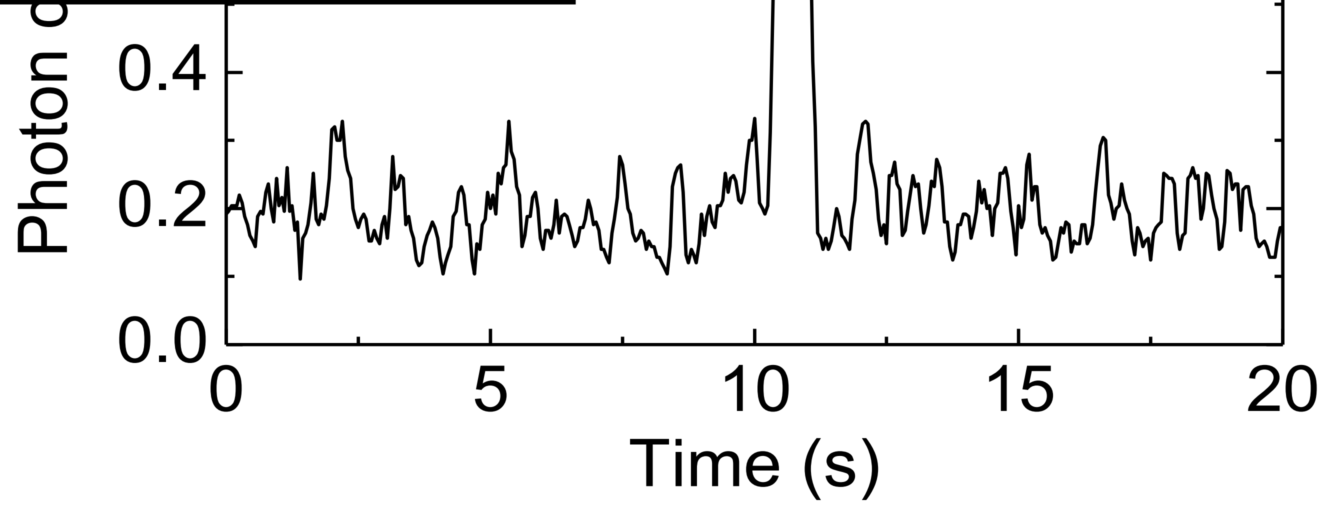
E.g. ^{8}He

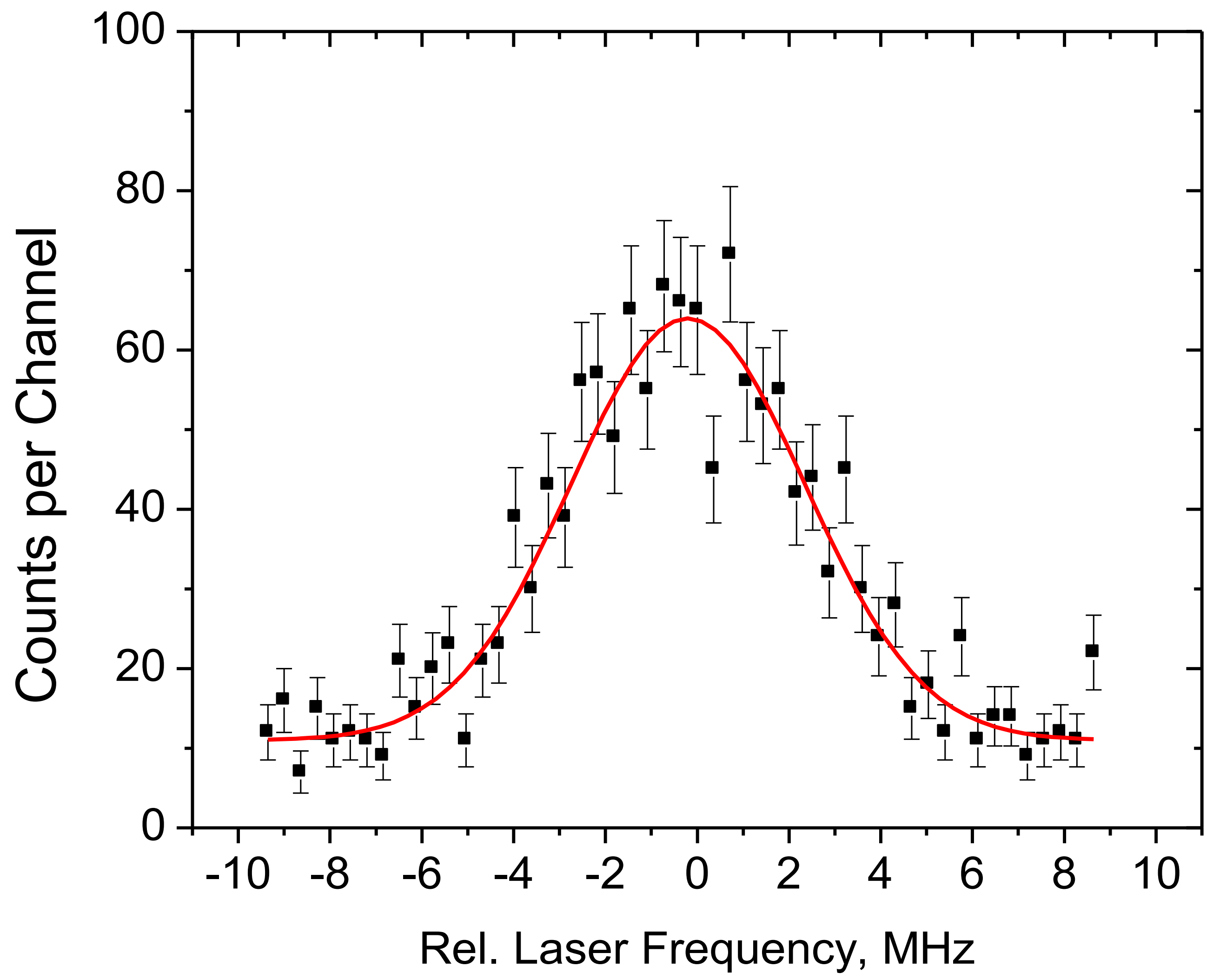






work, ^{6}He nuclei were produced in a hot (750 °C) graphite target via the ^{12}C(^{7}Li, ^{6}He)^{13}N reaction with a 100 pnA, 60 MeV beam of ^{7}Li from the ATLAS accelerator at Argonne National Laboratory. Neutral ^{6}He atoms diffused out of the target and were transferred in vacuum to the nearby atomic beam assembly in approximately 1 s. By detecting the characteristic β decay, we established that ^{6}He atoms were transferred to the atomic beam assembly at the rate of $\sim 1 \times 10^{6}$ s^{-1}. Details on the production and transfer of ^{6}He atoms are given in [11]. Our design of the atomic beam assembly is based on a type of MOT system widely used to trap various



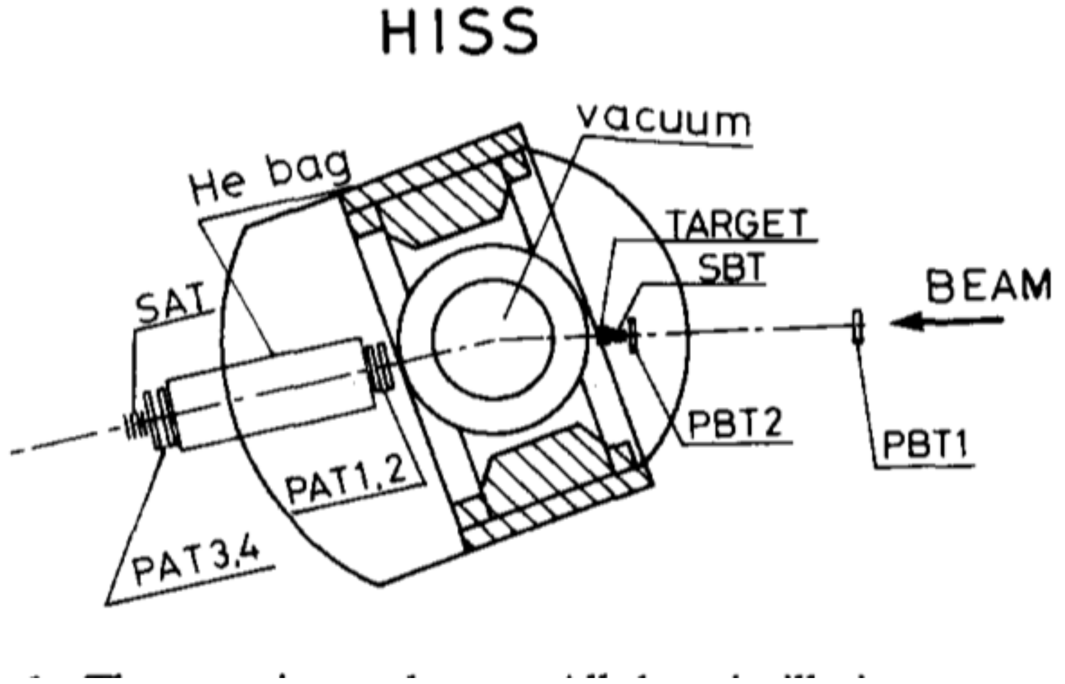


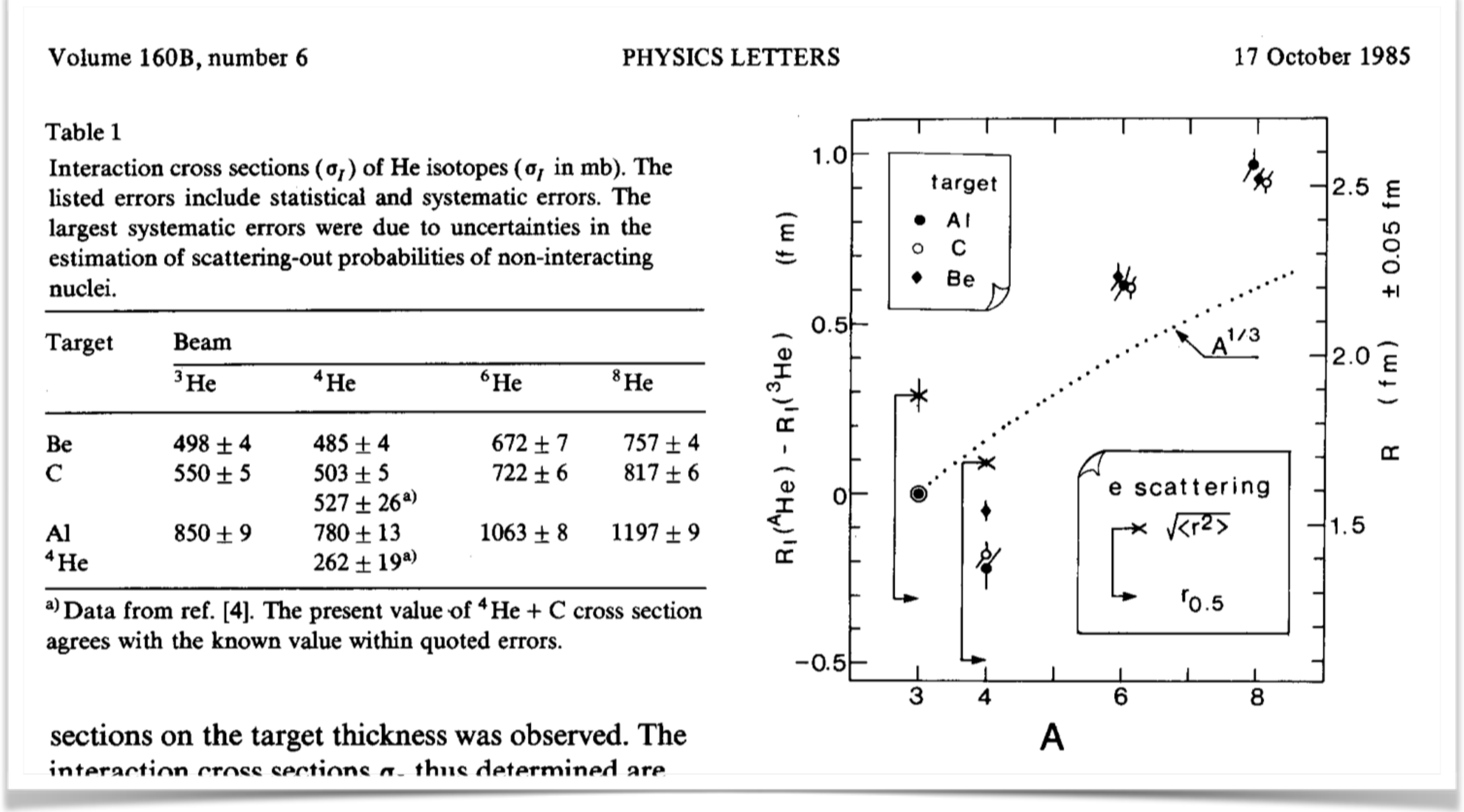
L.-B. Wang et al., Phys. Rev. Lett. ***93****, 142501 (****2004****), P. Mueller et al., Phys. Rev. Lett.* ***99****, 252501 (****2007****)*

Matter radii

- Matter radii can be determined from interaction cross sections

$$\sigma_I(p,t) = \pi\left[R_I(p) + R_I(t)\right]^2$$





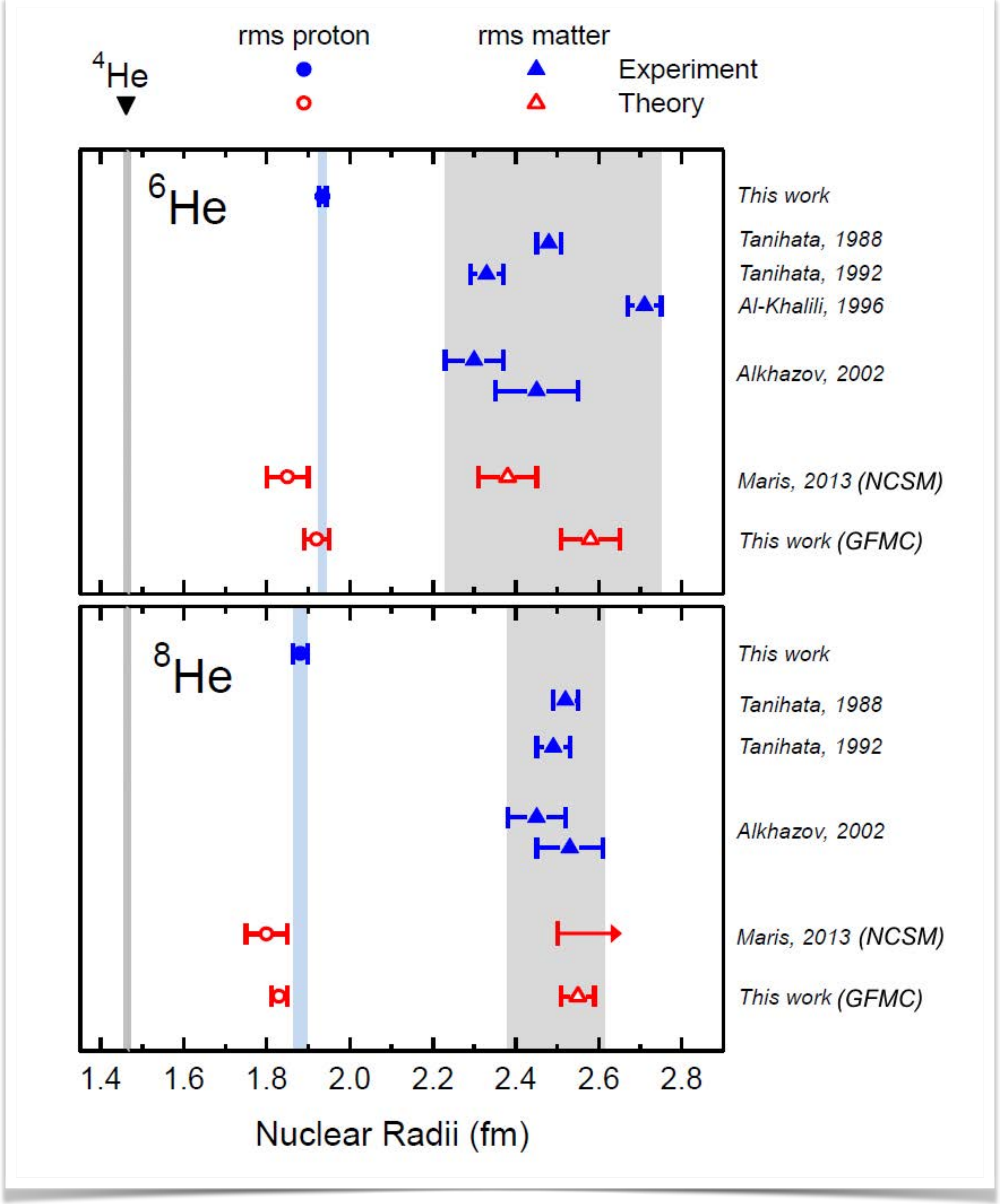
Volume 160B, number 6 PHYSICS LETTERS 17 October 1985

Table 1
Interaction cross sections (σ_I) of He isotopes (σ_I in mb). The listed errors include statistical and systematic errors. The largest systematic errors were due to uncertainties in the estimation of scattering-out probabilities of non-interacting nuclei.

Target	Beam ^{3}He	^{4}He	^{6}He	^{8}He
Be	498 ± 4	485 ± 4	672 ± 7	757 ± 4
C	550 ± 5	503 ± 5 527 ± 26 [a]	722 ± 6	817 ± 6
Al	850 ± 9	780 ± 13	1063 ± 8	1197 ± 9
^{4}He		262 ± 19 [a]		

[a] Data from ref. [4]. The present value of ^{4}He + C cross section agrees with the known value within quoted errors.

sections on the target thickness was observed. The interaction cross sections σ_I thus determined are



L.-B. Wang et al., Phys. Rev. Lett. **93**, 142501 (**2004**), P. Mueller et al., Phys. Rev. Lett. **99**, 252501 (**2007**)

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He isotopes

Which is larger charge radius? ^{4}He, ^{6}He, ^{8}He?

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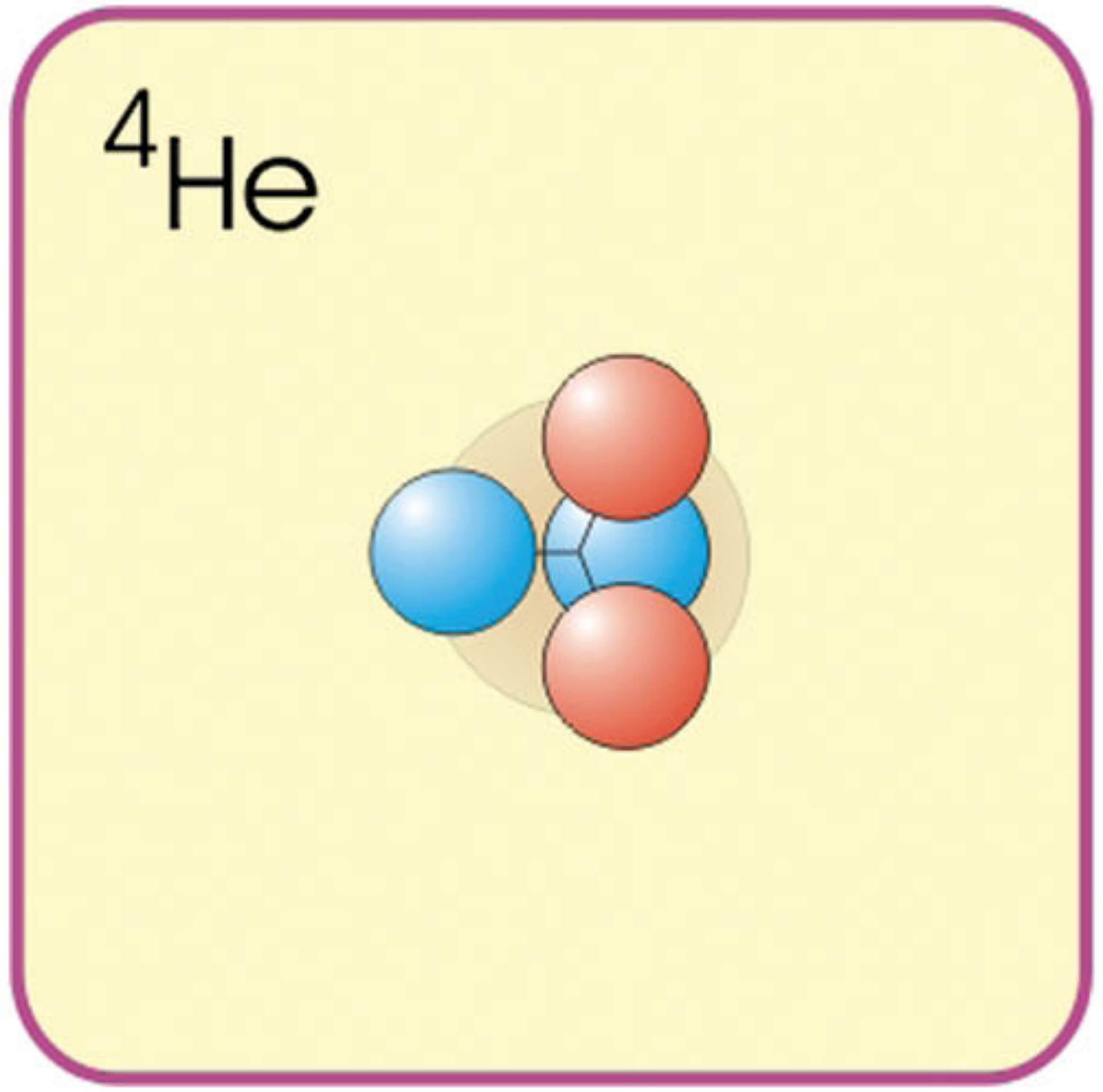
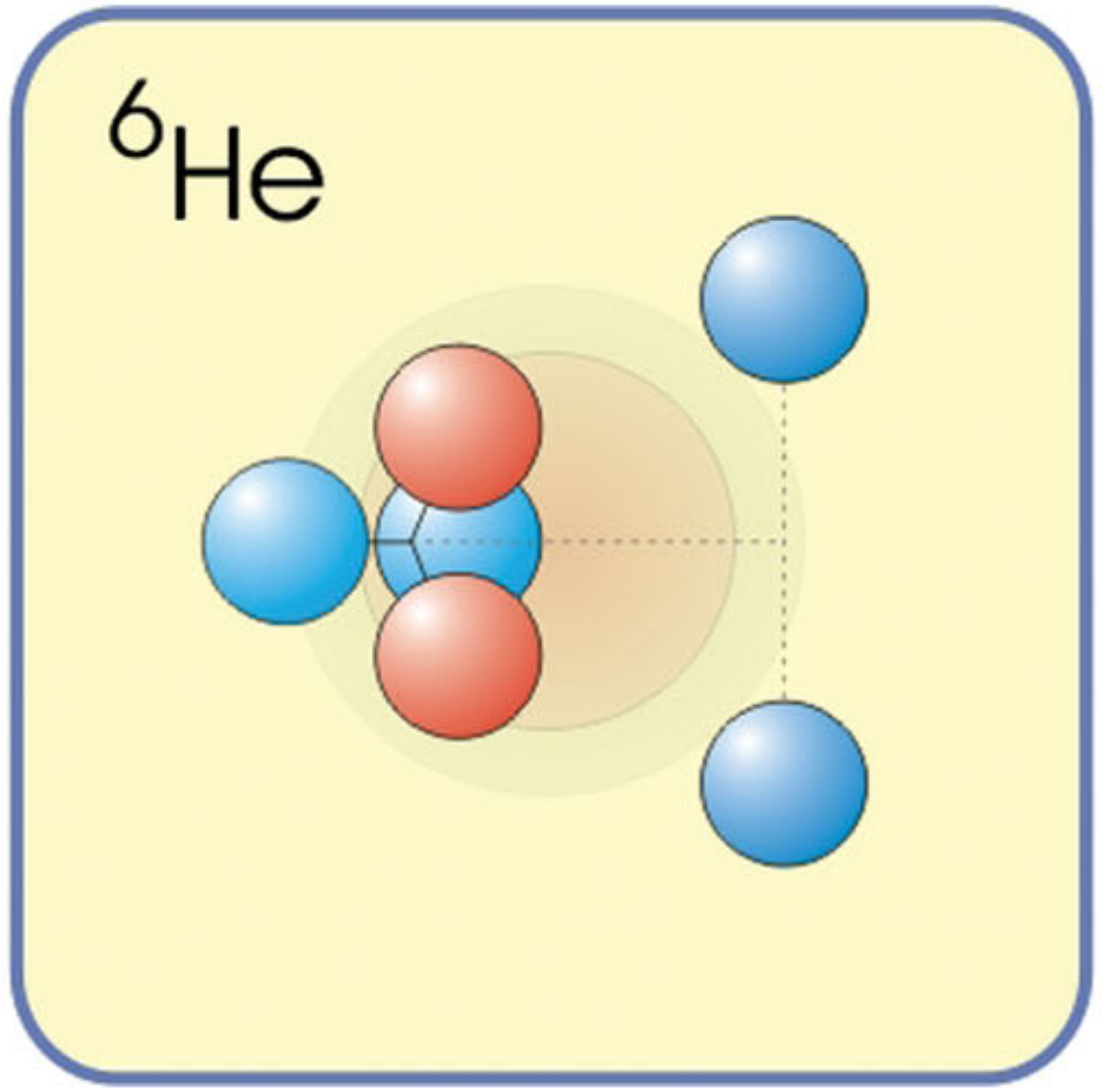
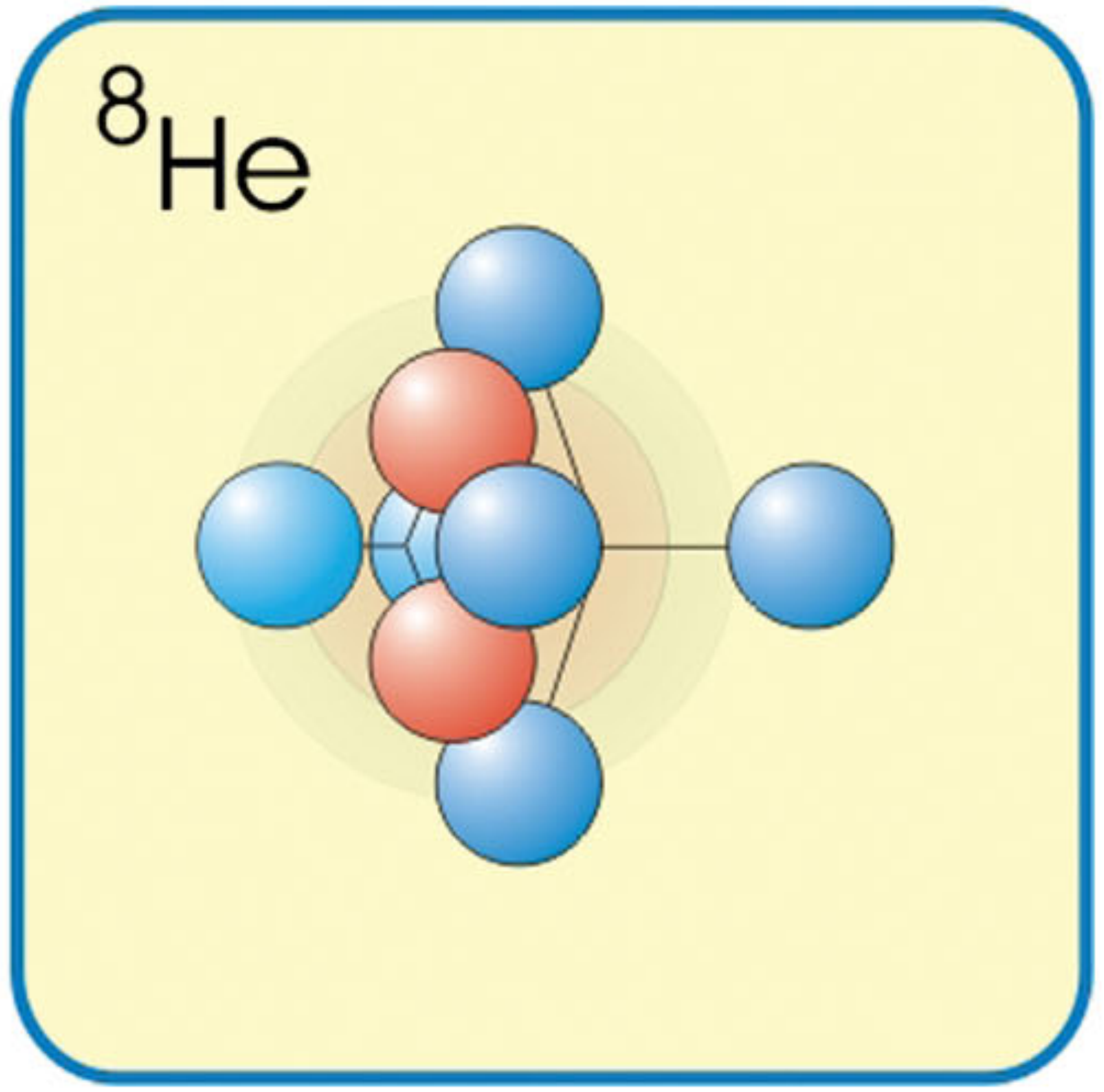




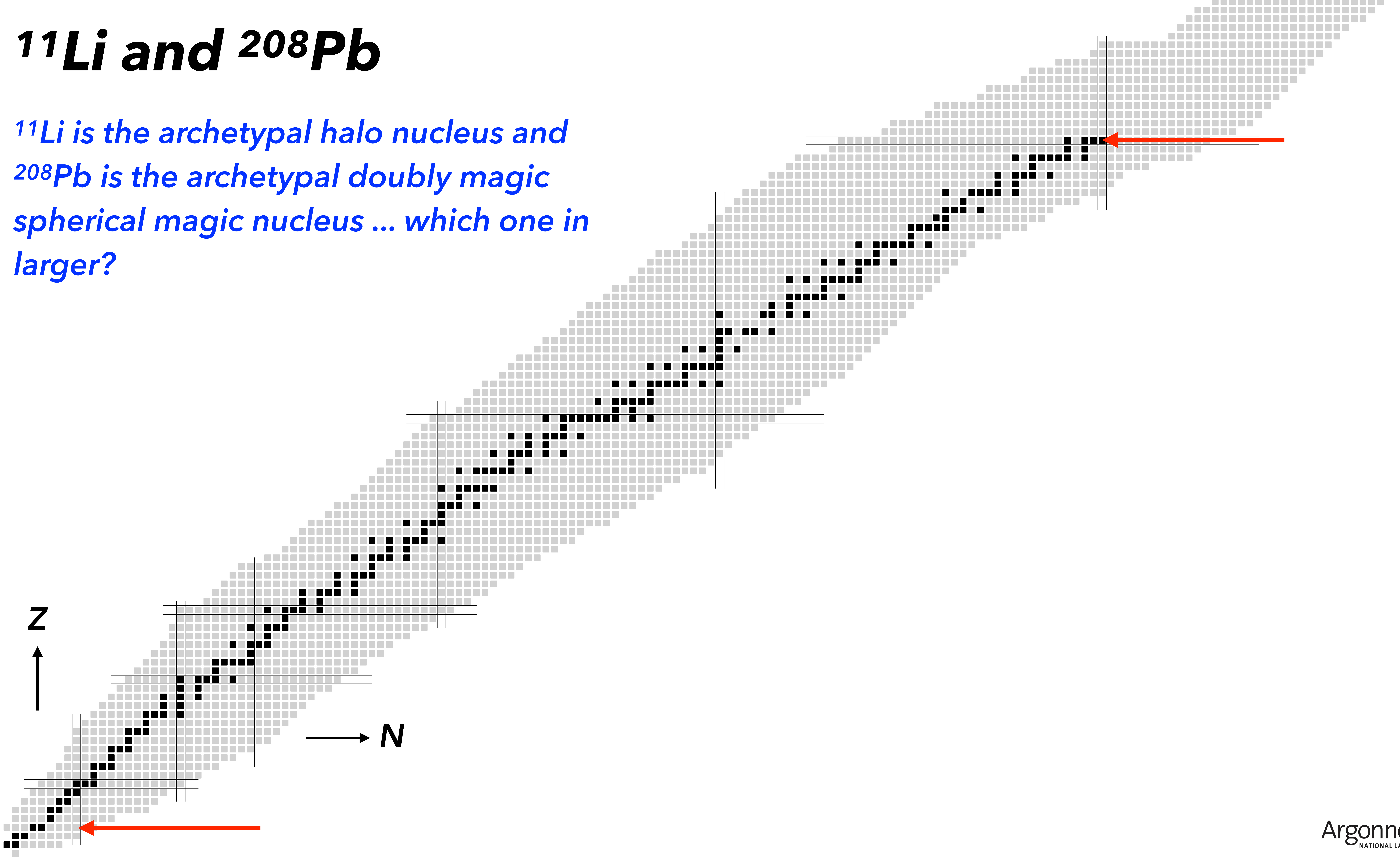


1.681(4) fm	2.060(8) fm	1.959(16) fm
1.63(3) fm	2.33(4) fm	2.49(4) fm

Z.-T. Lu et al., Rev. Mod. Phys. ***85****, 1385 (****2013****), Tanihata et al., Prog. Part. Nucl. Phys.* ***68****, 215 (****2013****)*

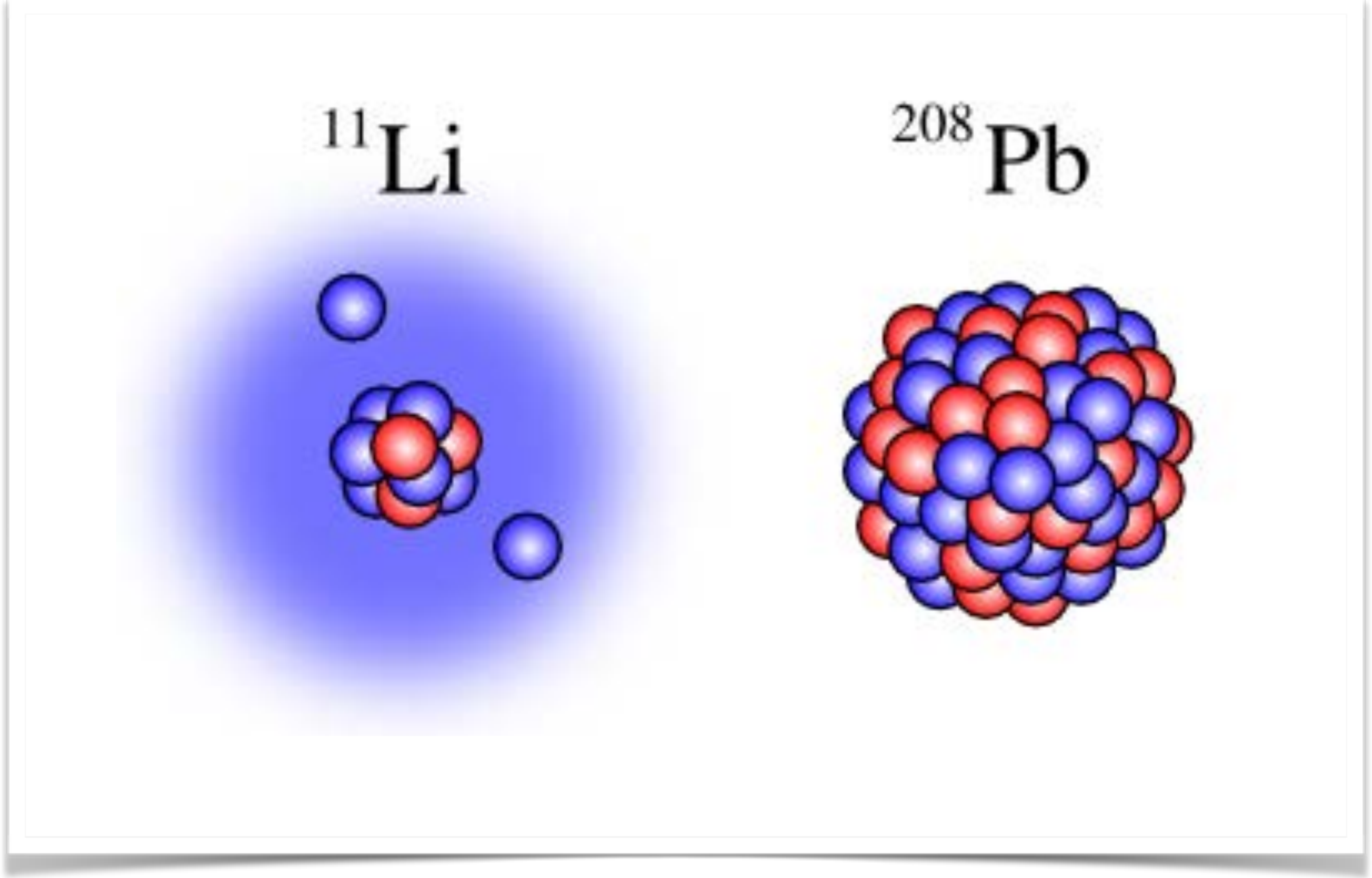
^{11}Li and ^{208}Pb

^{11}Li is the archetypal halo nucleus and ^{208}Pb is the archetypal doubly magic spherical magic nucleus … which one in larger?



^{11}Li and ^{208}Pb

^{11}Li is the archetypal halo nucleus and ^{208}Pb is the archetypal doubly magic spherical magic nucleus … which one in larger? About the same size!



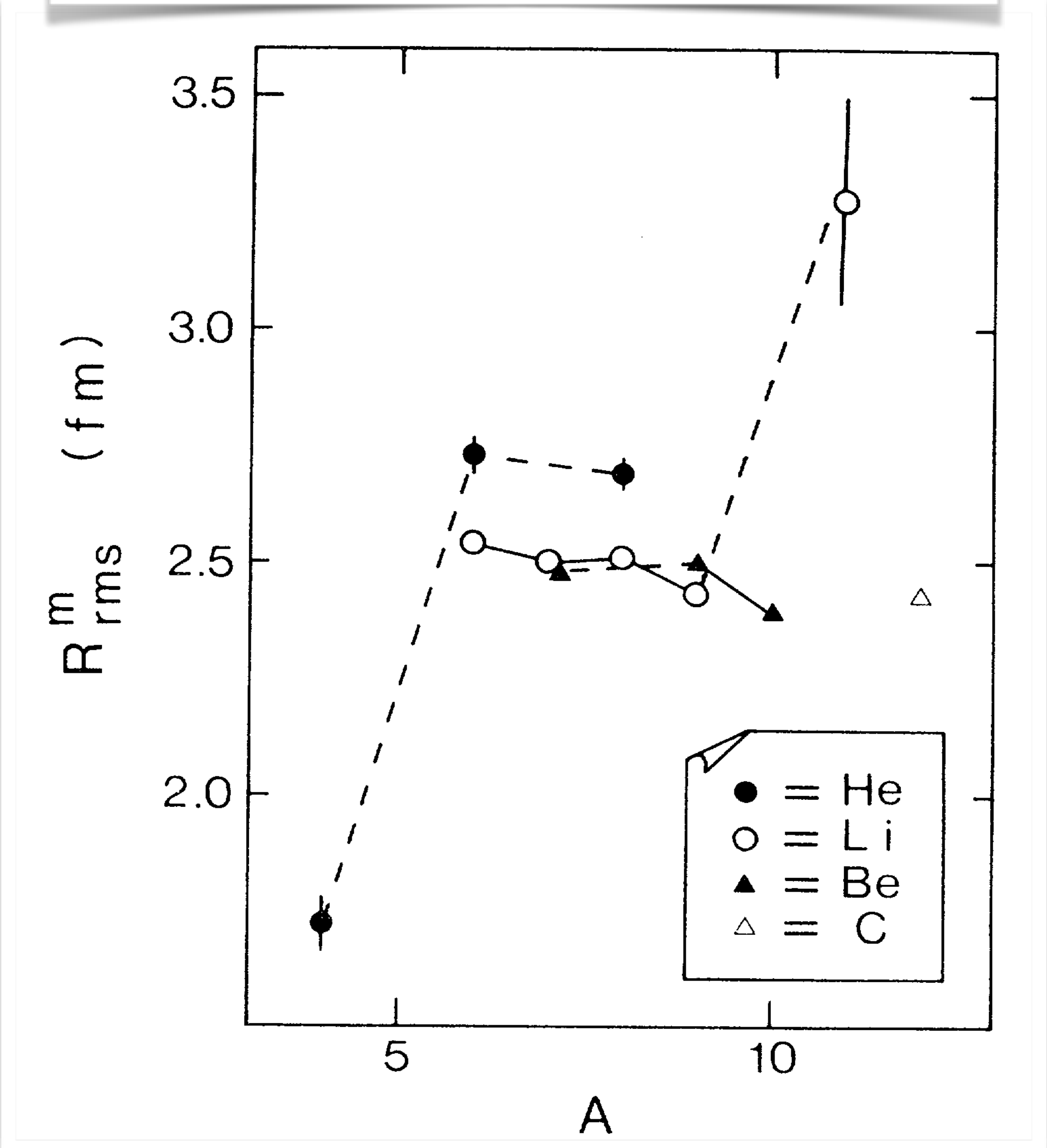
Recently, exotic-isotope beams, produced through the projectile-fragmentation process in high-energy heavy-ion reactions, were used to measure the interaction cross sections (σ_I) for all the known He isotopes.[1] This novel technique of using exotic nuclear beams makes it possible to study systematically properties of unstable nuclei. In the present paper, we report the σ_I for all the known Li isotopes (^{6}Li, ^{7}Li, ^{8}Li, ^{9}Li, and ^{11}Li) and ^{7}Be, ^{9}Be, and ^{10}Be on the target nuclei Be, C, and Al at 790 MeV/nucleon. A firm basis has been empirically established by use of a Glauber-type calculation to extract root mean square (rms) nuclear radii from the σ_I.

The Li isotopes, except ^{11}Li, and the Be isotopes were produced as secondary beams through projectile fragmentation of the 800-MeV/nucleon ^{11}B accelerated by the Bevalac at the Lawrence Berkeley Laboratory. The beam of ^{11}Li was produced from a ^{20}Ne primary beam. The isotopes produced in a production target of Be were separated by rigidity with the beam-line magnet system as described in previous papers.[1,2] The rigidity-separated isotopes were further identified before incidence on a reaction target by velocity [time-of-flight (TOF)] and by charge (pulse height in scintillation counters). No contamination more than 10^{-3} was observed in any selected isotope beam.

The interaction cross section (σ_I) was measured by a transmission experiment using the large-acceptance spectrometer as in the measurement of the He isotopes.[1] Here σ_I is defined as the total reaction cross section for the change of proton and/or neutron number in the incident nucleus. The obtained σ_I are listed in Table I. The largest systematic error on σ_I, up to about 0.3%, came from uncertainties in the estimation of the scattering-out probability of the nonin-

TABLE I. Interaction cross sections (σ_I) in millibarns.

Beam	Target: Be	Target: C	Target: Al
^{6}Li	651 ± 6	688 ± 10	1010 ± 11
^{7}Li	686 ± 4	736 ± 6	1071 ± 7
^{8}Li	727 ± 6	768 ± 9	1147 ± 14
^{9}Li	739 ± 5	796 ± 6	1135 ± 7
^{11}Li		1040 ± 60	
^{7}Be	682 ± 6	738 ± 9	1050 ± 17
^{9}Be	755 ± 6	806 ± 9	1174 ± 11
^{10}Be	755 ± 7	813 ± 10	1153 ± 16



I. Tanihata et al., Phys. Rev. Lett. **54**, 2676 (**1985**)

(Not sure who to credit for figure … found as image online …)

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Nuclei … neutron stars

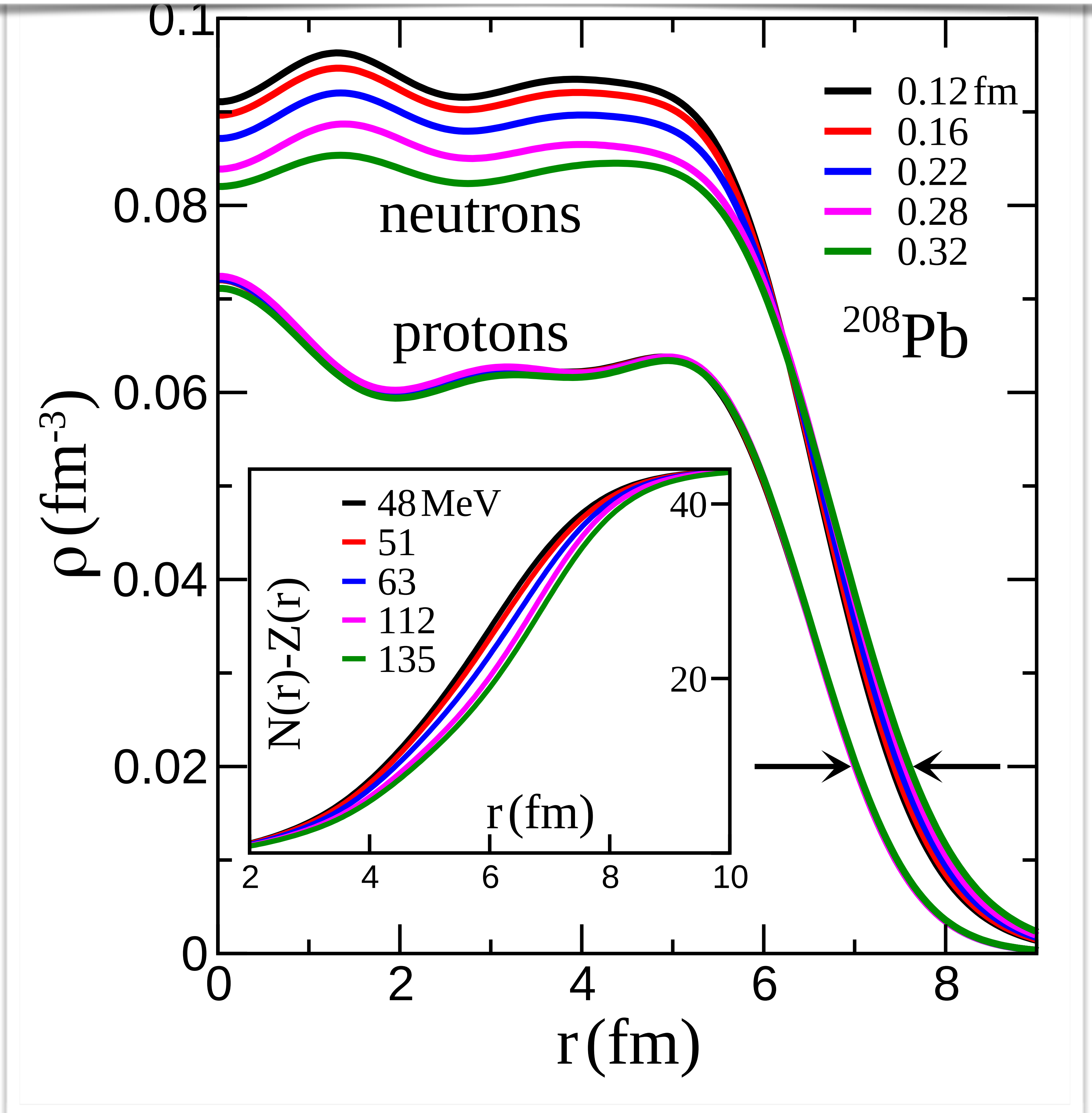
Neutron rich matter in heaven and on Earth

J. Piekarewicz[1,*] and F. J. Fattoyev[2,†]

[1] *Department of Physics, Florida State University, Tallahassee, FL 32306, USA*
[2] *Physics Department, Manhattan College, Riverdale, New York, NY, 10471, USA*

(Dated: July 8, 2019)

Despite a length-scale difference of 18 orders of magnitude, the internal structure of neutron stars and the spatial distribution of neutrons in atomic nuclei are profoundly connected.



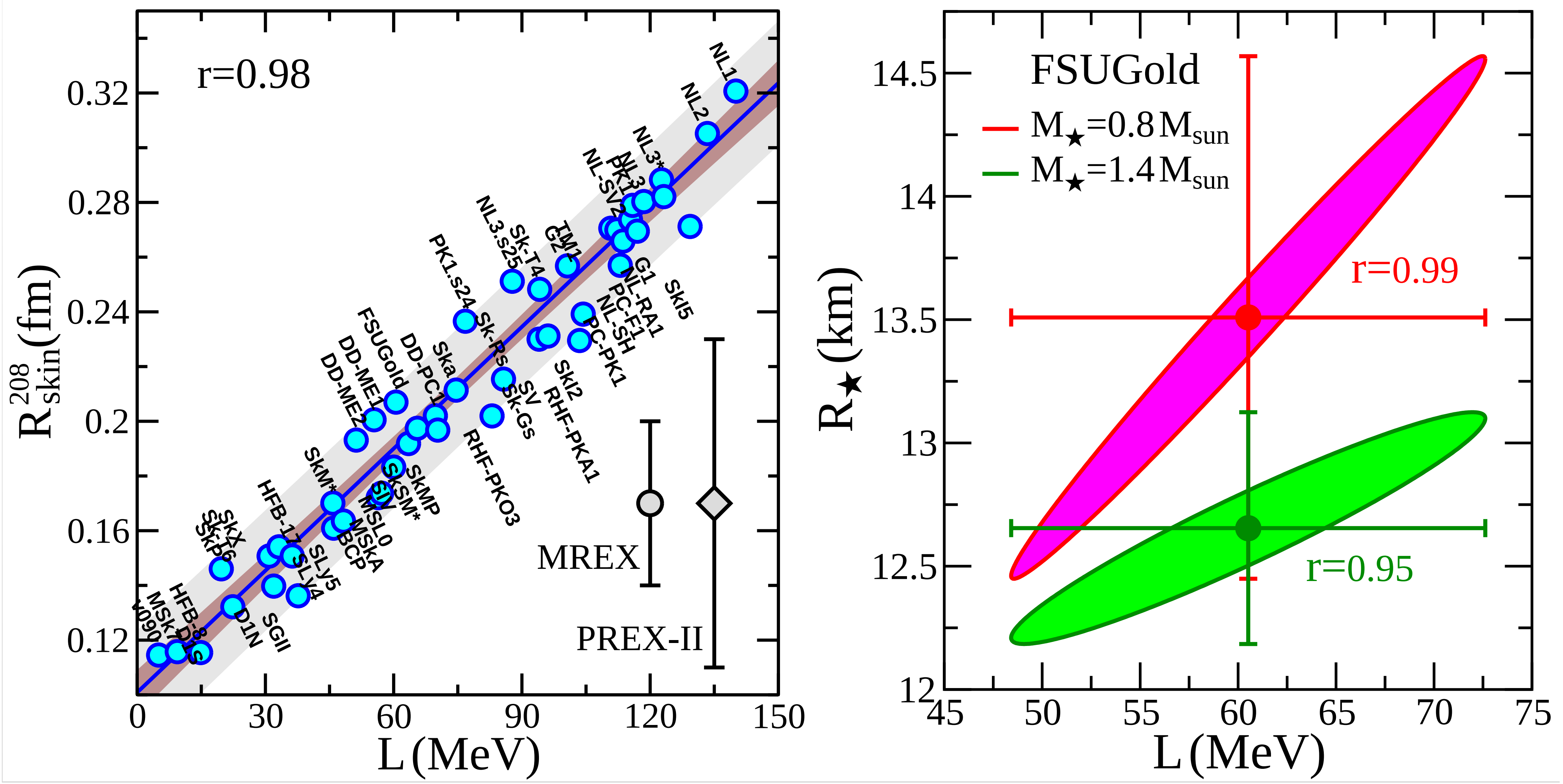


FIG. 3: **Connecting the very small to the very big.** Despite a difference in size of 18 orders of magnitude, the symmetry pressure L controls both the neutron skin thickness of ^{208}Pb as well as the radius of a neutron star. On the left hand panel a large set of highly successful models are used to illustrate the correlation between L and $R_{\rm skin}^{208}$; figure adapted from Ref. [5]. The right hand panel displays the correlation between L and neutron star radii for one of these models: "FSUGold" [6].

*Physics Today **72**, 30 (**2019**) [two weeks ago]*

Nuclei … neutron stars

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J. Piekarewicz[1,*] and F. J. Fattoyev[2,†]

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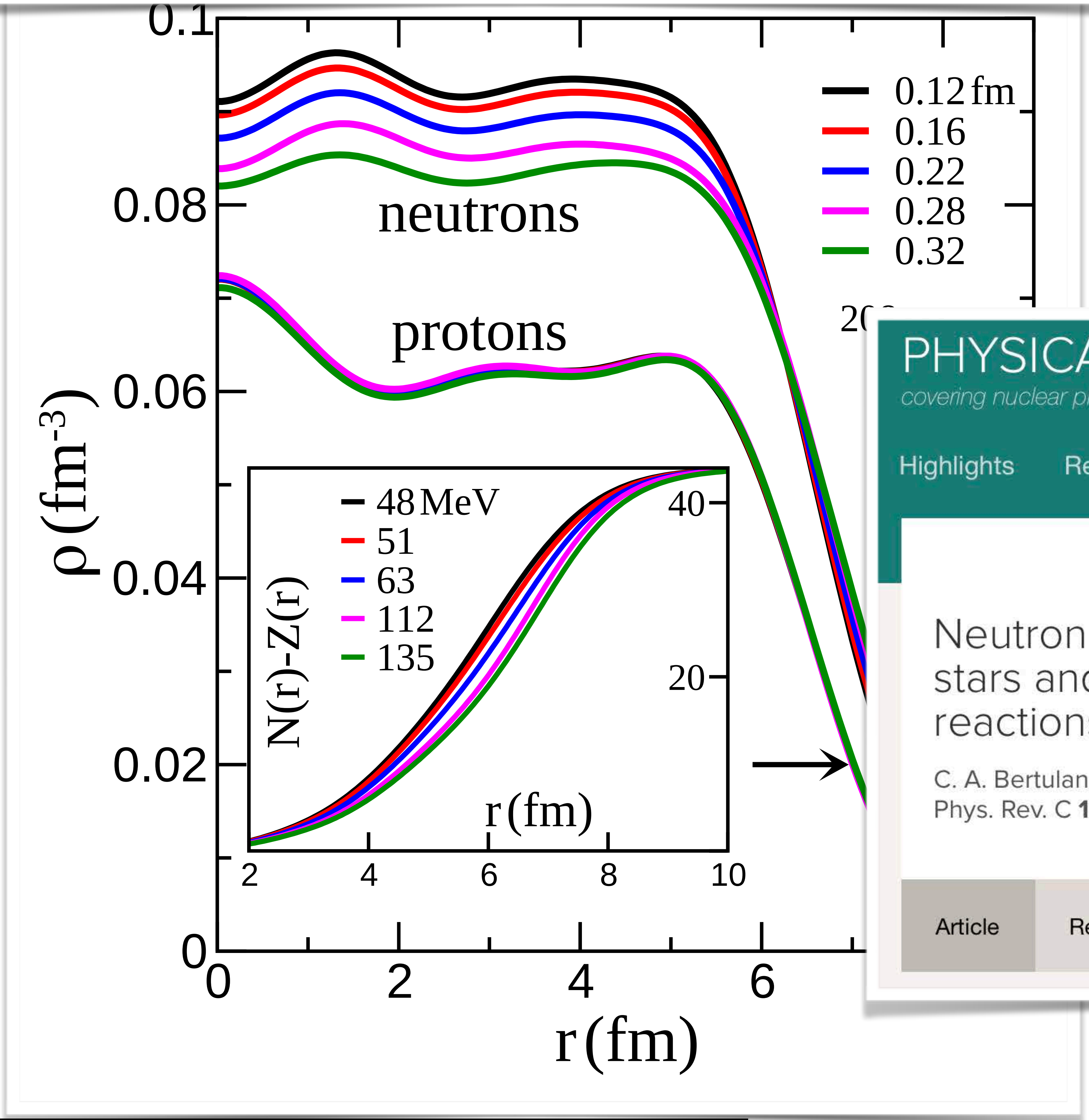

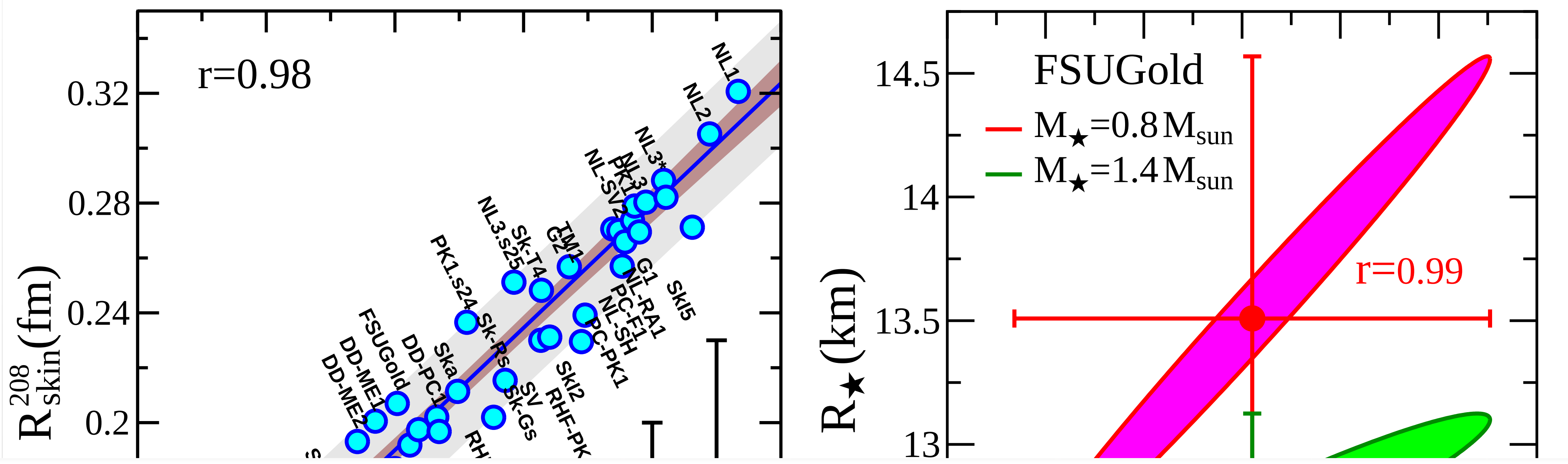

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covering nuclear physics

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Neutron skins as laboratory constraints on properties of neutron stars and on what we can learn from heavy ion fragmentation reactions

C. A. Bertulani and J. Valencia
Phys. Rev. C **100**, 015802 – Published 15 July 2019

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Physics Today ***72**, 30 (**2019**) [two weeks ago]*

Shapes (and sizes)

ISOLDE and Hg beams

nature physics

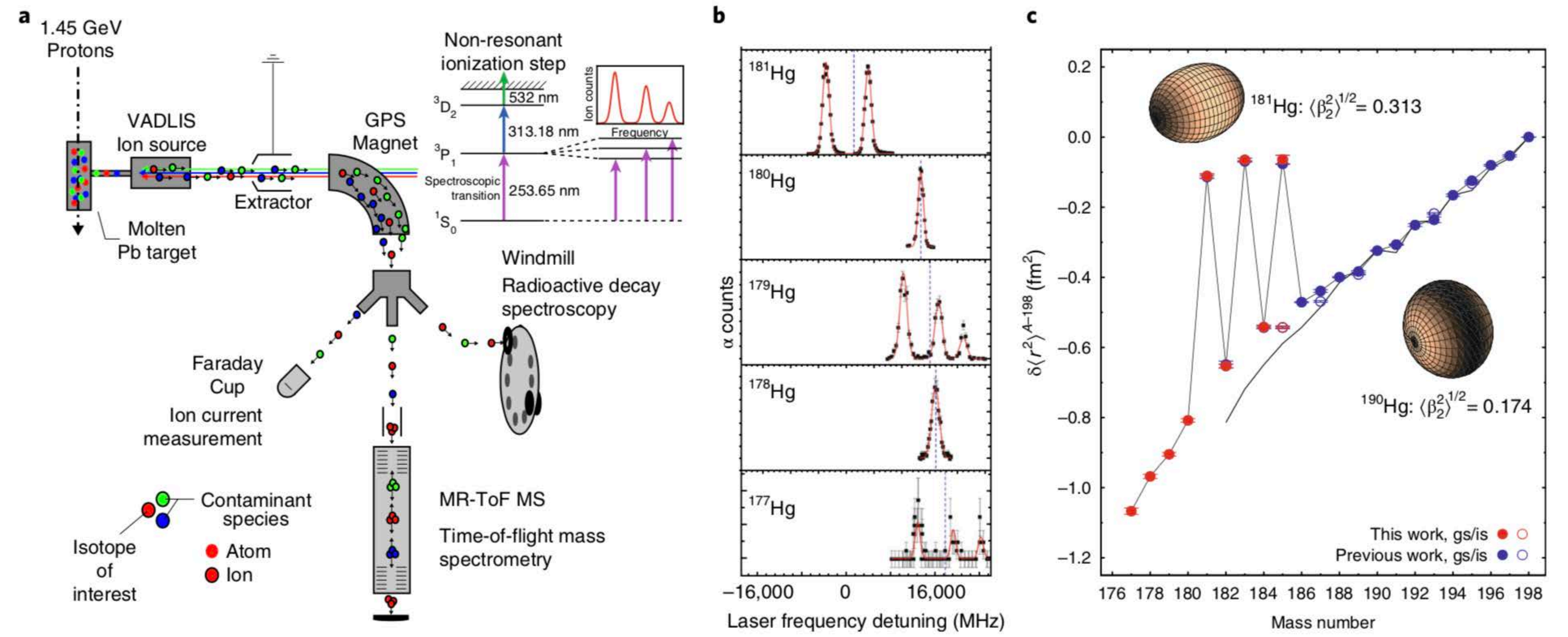
LETTERS

https://doi.org/10.1038/s41567-018-0292-8

Characterization of the shape-staggering effect in mercury nuclei

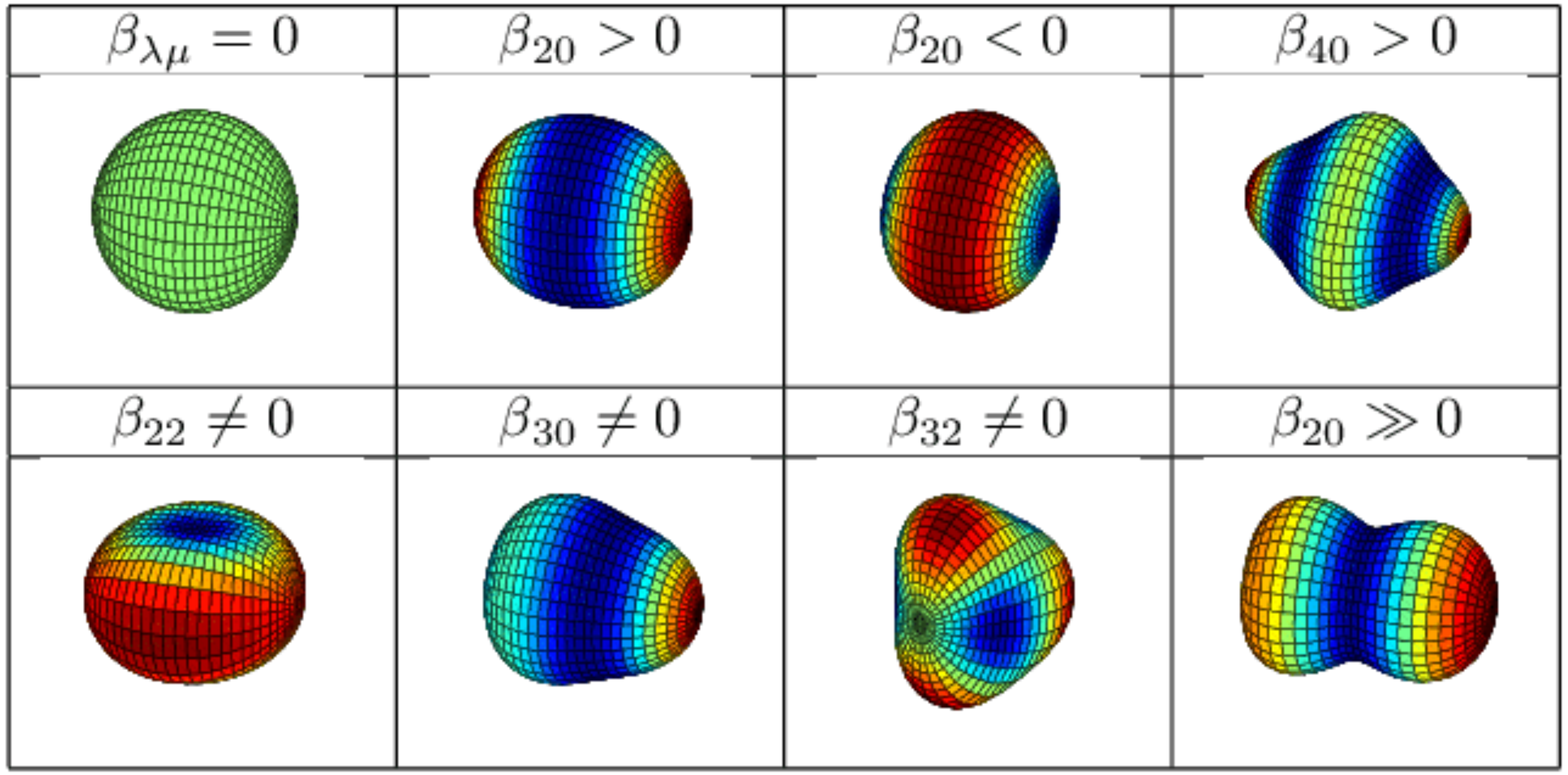
B. A. Marsh[1*], T. Day Goodacre
N. A. Althubiti[2], D. Atanasov[8], A.
J. Dobaczewski[6], G. J. Farooq-Sm
L. Ghys[3], M. Huyse[3], S. Kreim[8], D.
T. Otsuka[3,4,12,13,14], A. Pastore[6], M.
P. Spagnoletti[10], C. Van Beveren[3],
F. Wienholtz[15], R. N. Wolf[8], A. Zad

LETTERS NATURE PHYSICS



*Nature Physics, October 10, **2018***

Shapes



$$R(\theta, \phi) = c(\alpha_{\lambda\mu}) R_0 \left[1 + \sum_{\lambda=0}^{\infty} \sum_{\mu=-\lambda}^{\lambda} \alpha_{\lambda\mu} Y_{\lambda\mu}(\theta, \phi) \right]$$

Multipole order: 2^{λ}

2^0 = monopole - breathing mode
2^1 = dipole - centre of mass shift
2^2 = quadrupole - axial deformation
2^3 = octupole - asymmetric deformation
2^4 = hexadecapole - pinching

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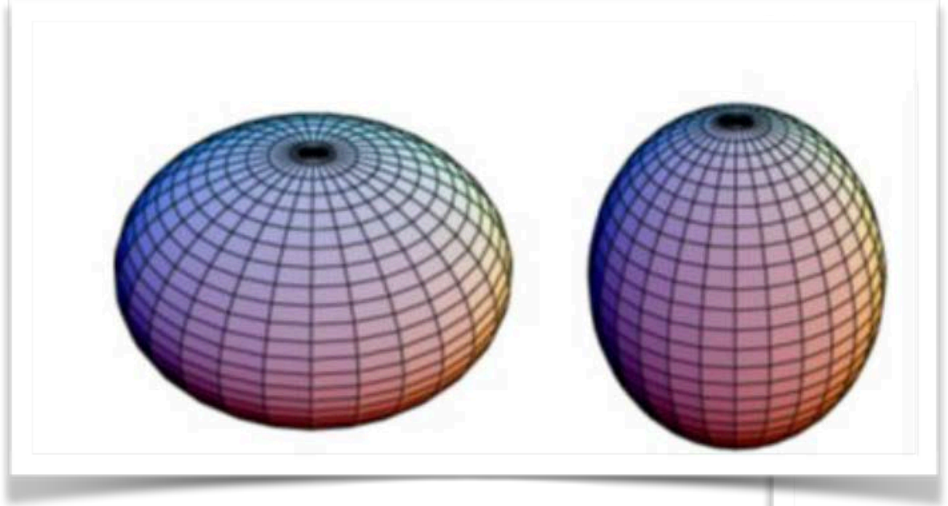
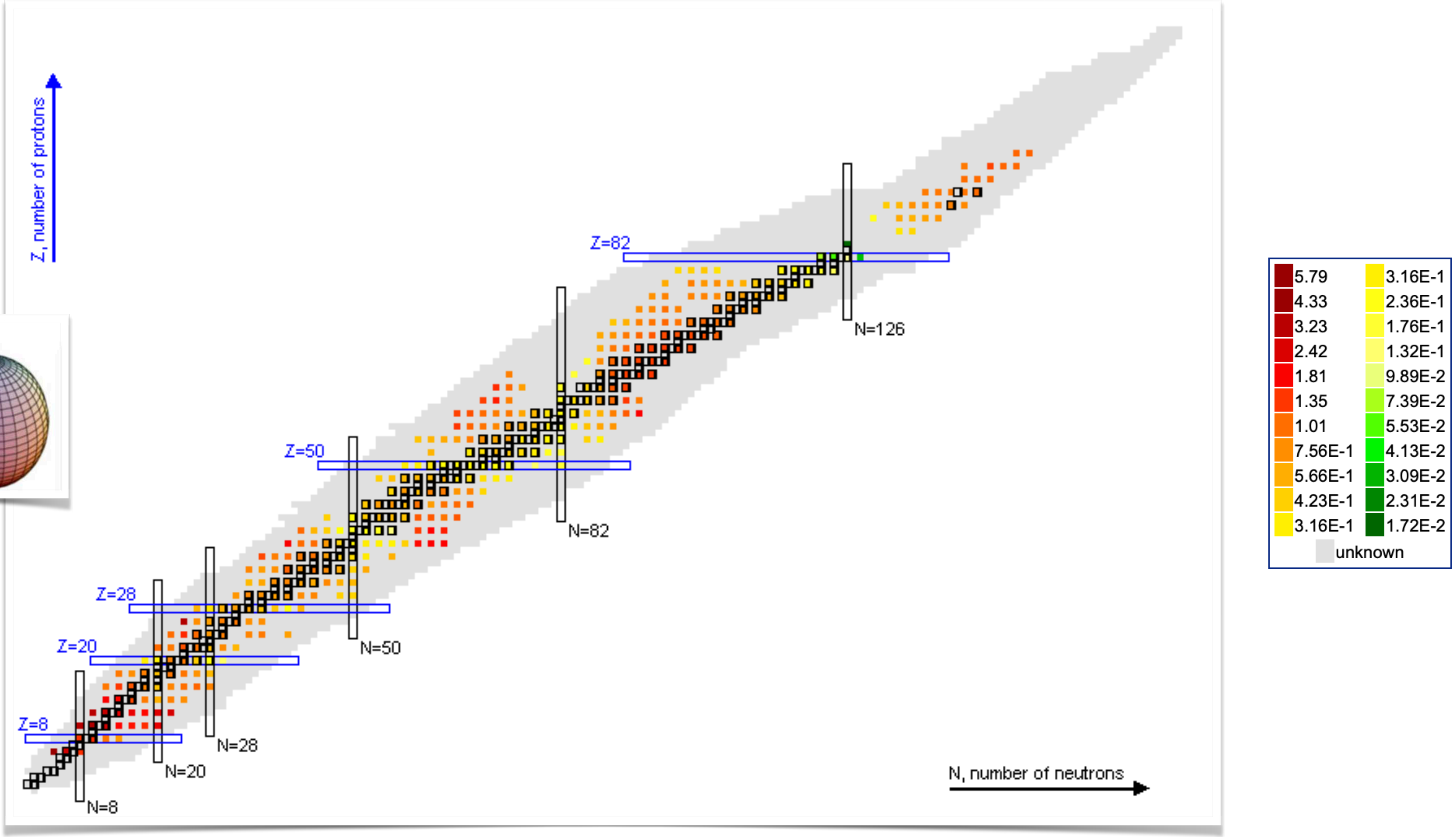
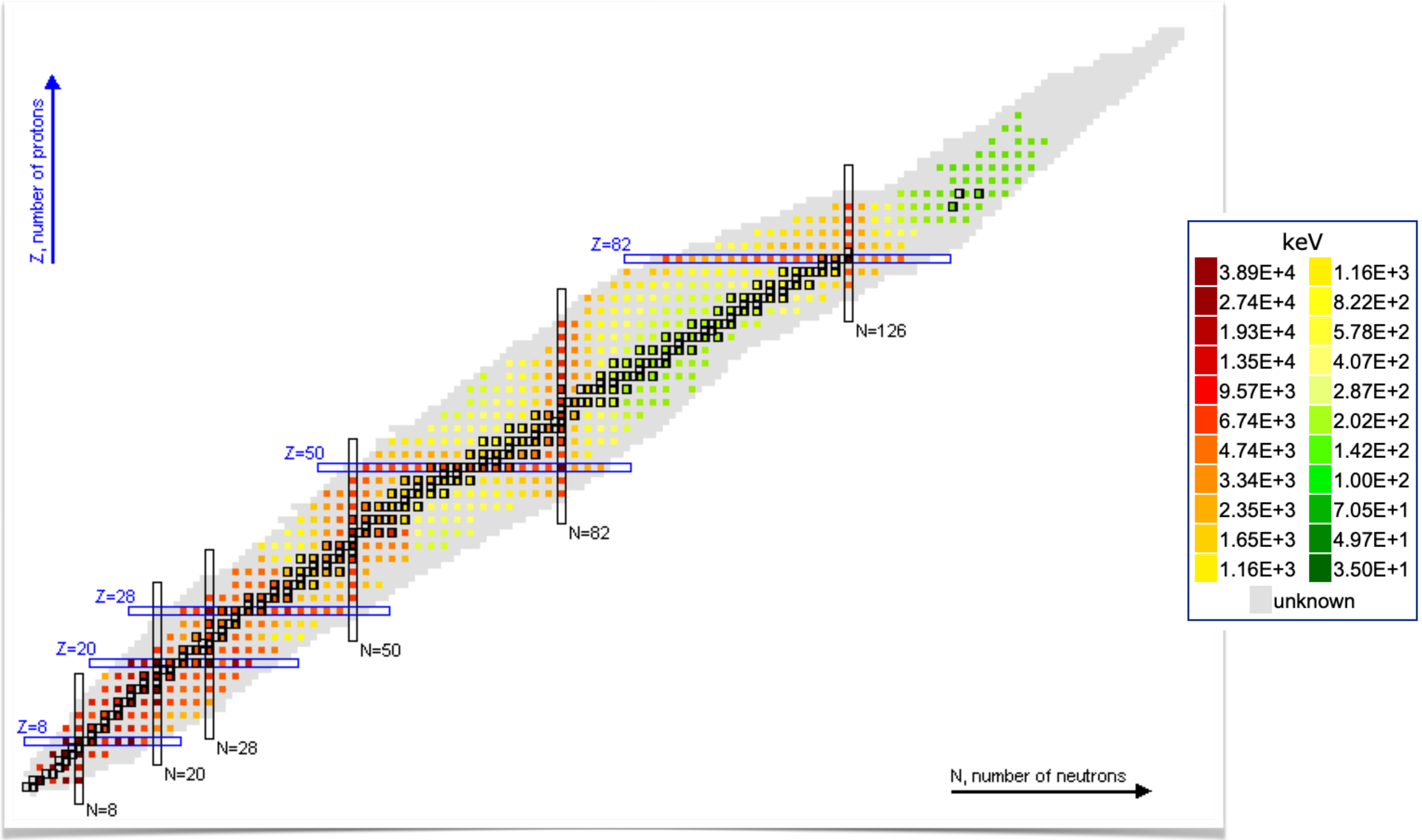
Shapes, spectroscopy





https://www.nndc.bnl.gov/nudat2/, quadrupole deformation (β_2)

Shapes, spectroscopy



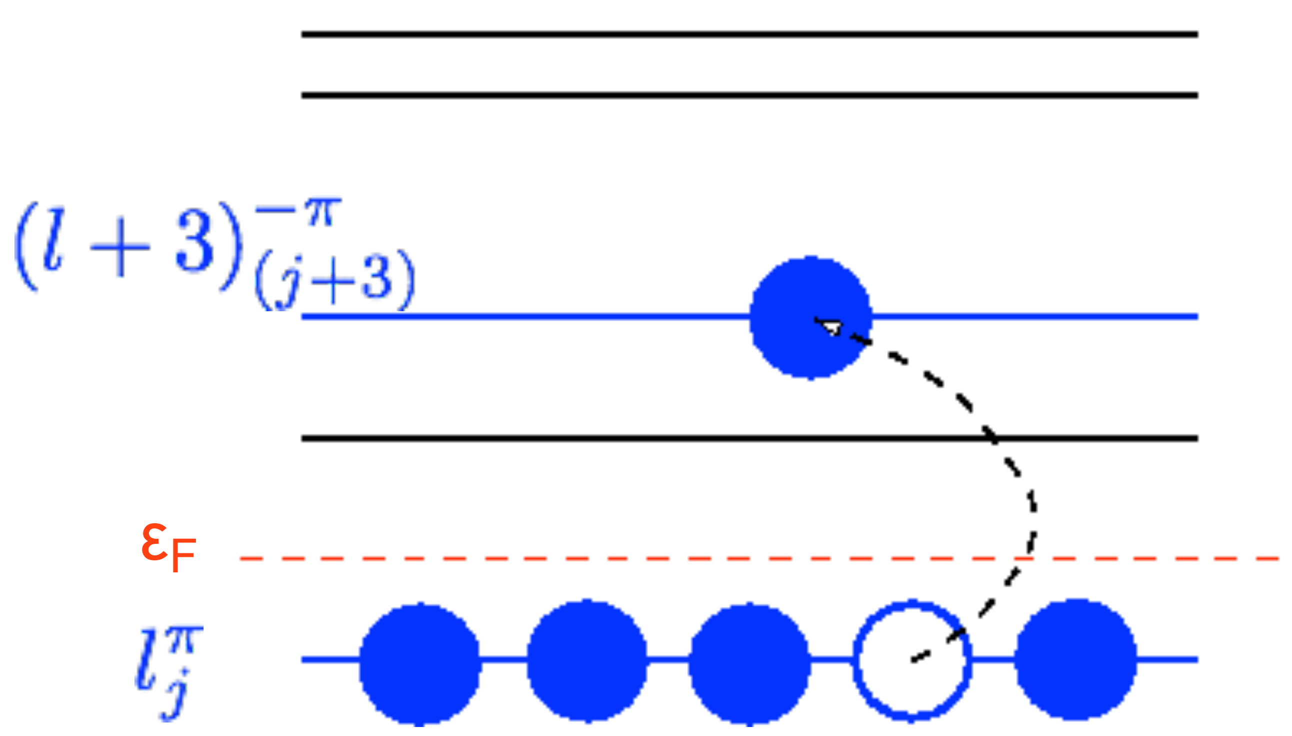
https://www.nndc.bnl.gov/nudat2/, *energy of the first excited 2+ state*

Strange shapes … "pears"

Reflection Asymmetry

Microscopically driven...

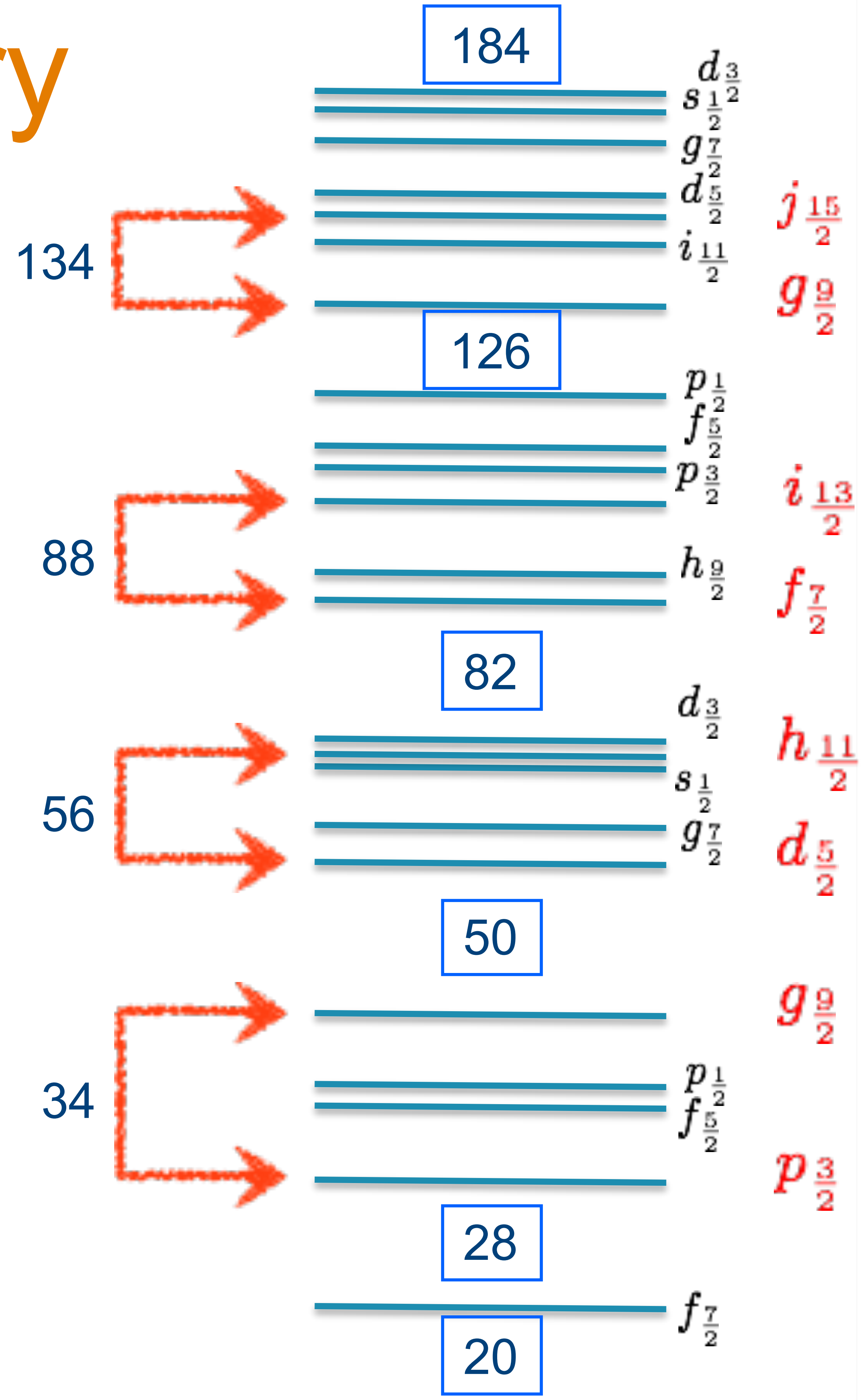
Intruder orbitals of opposite parity and
ΔJ, ΔL = 3 close to the Fermi level

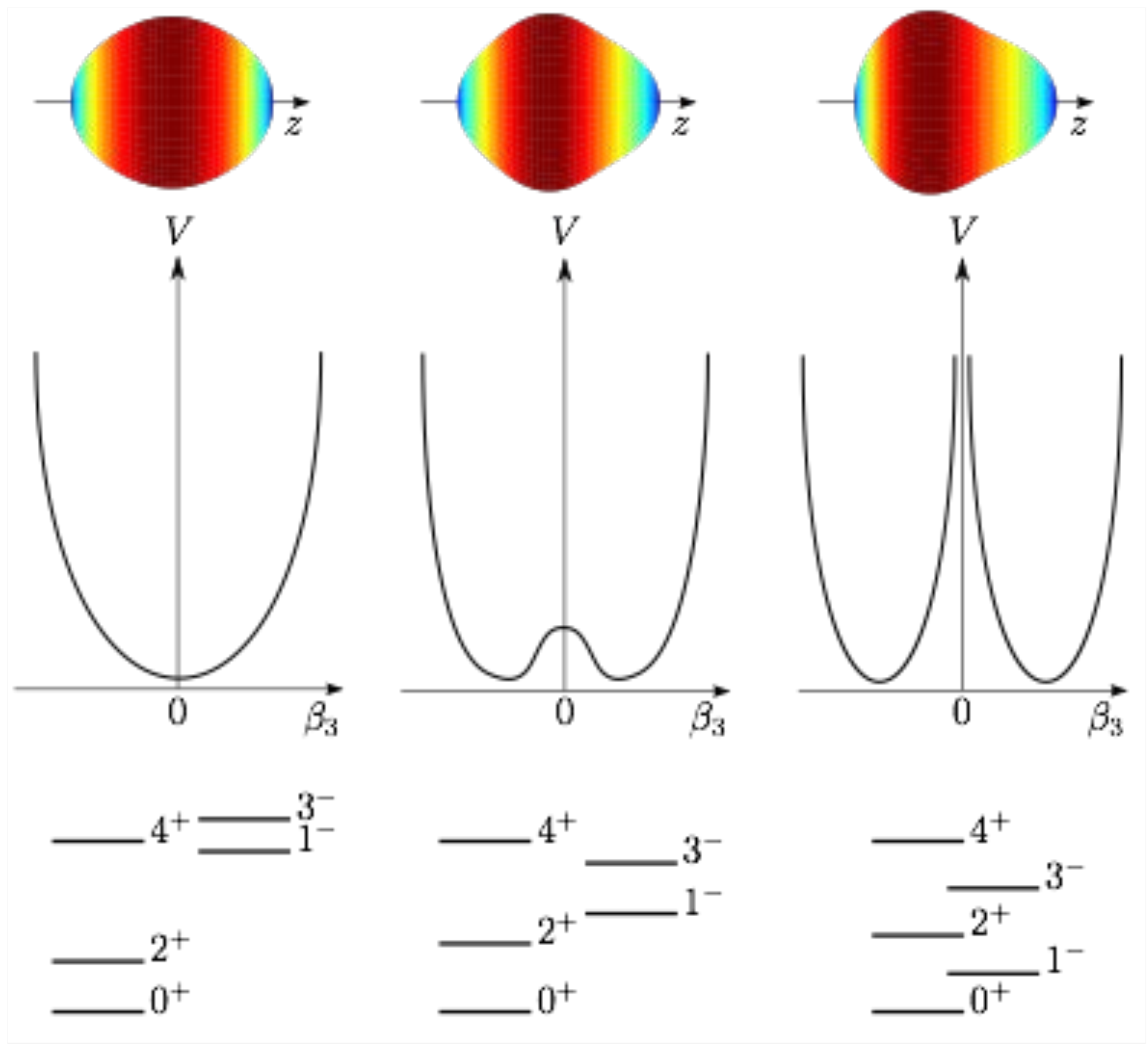


Enhancement of octupole part of
nucleon-nucleon force...

- Small energy gap
- High sub-state density

} Heaviest nuclei





Taken from L. P. Gaffney talk, EuNPC 2015

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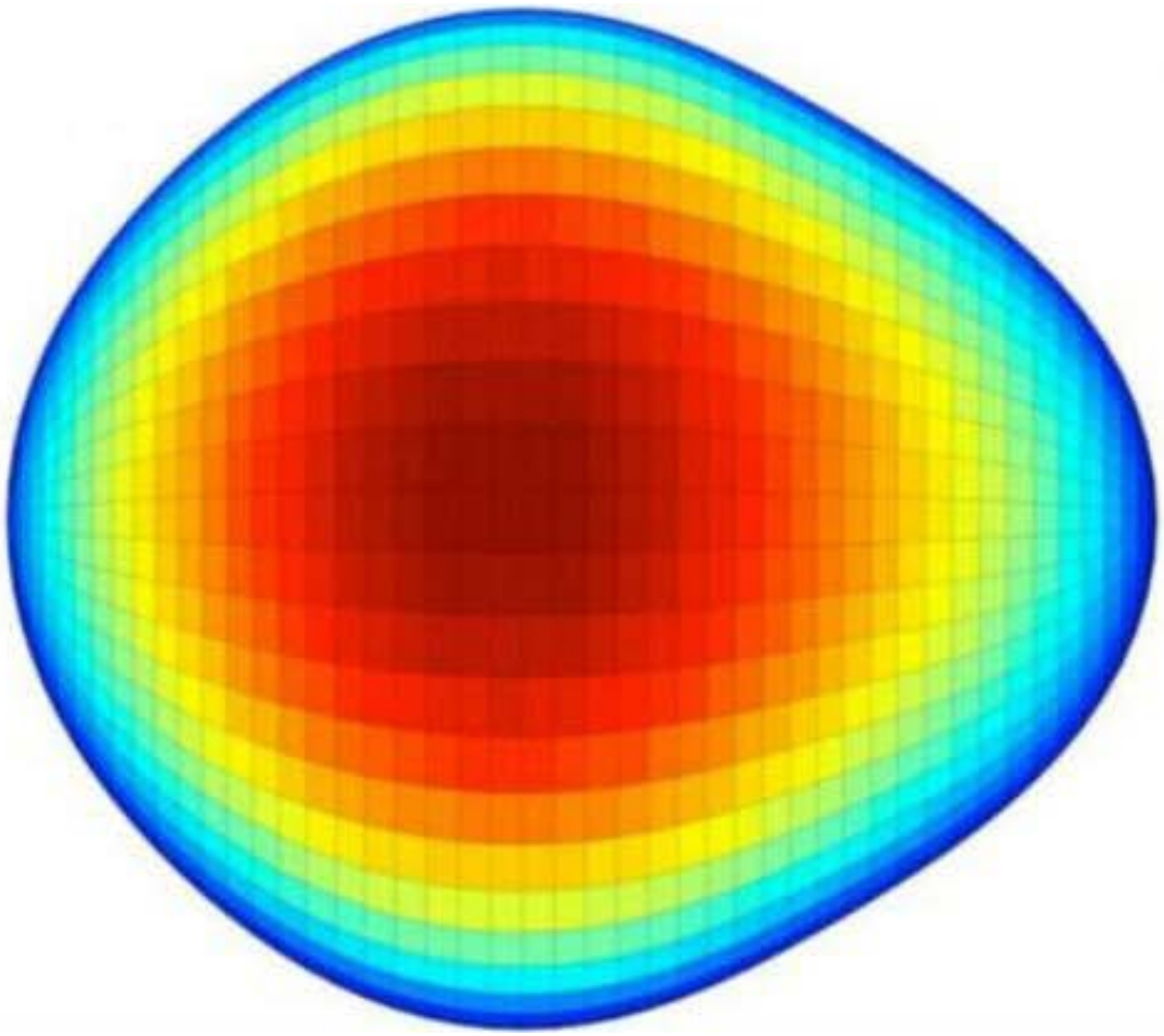
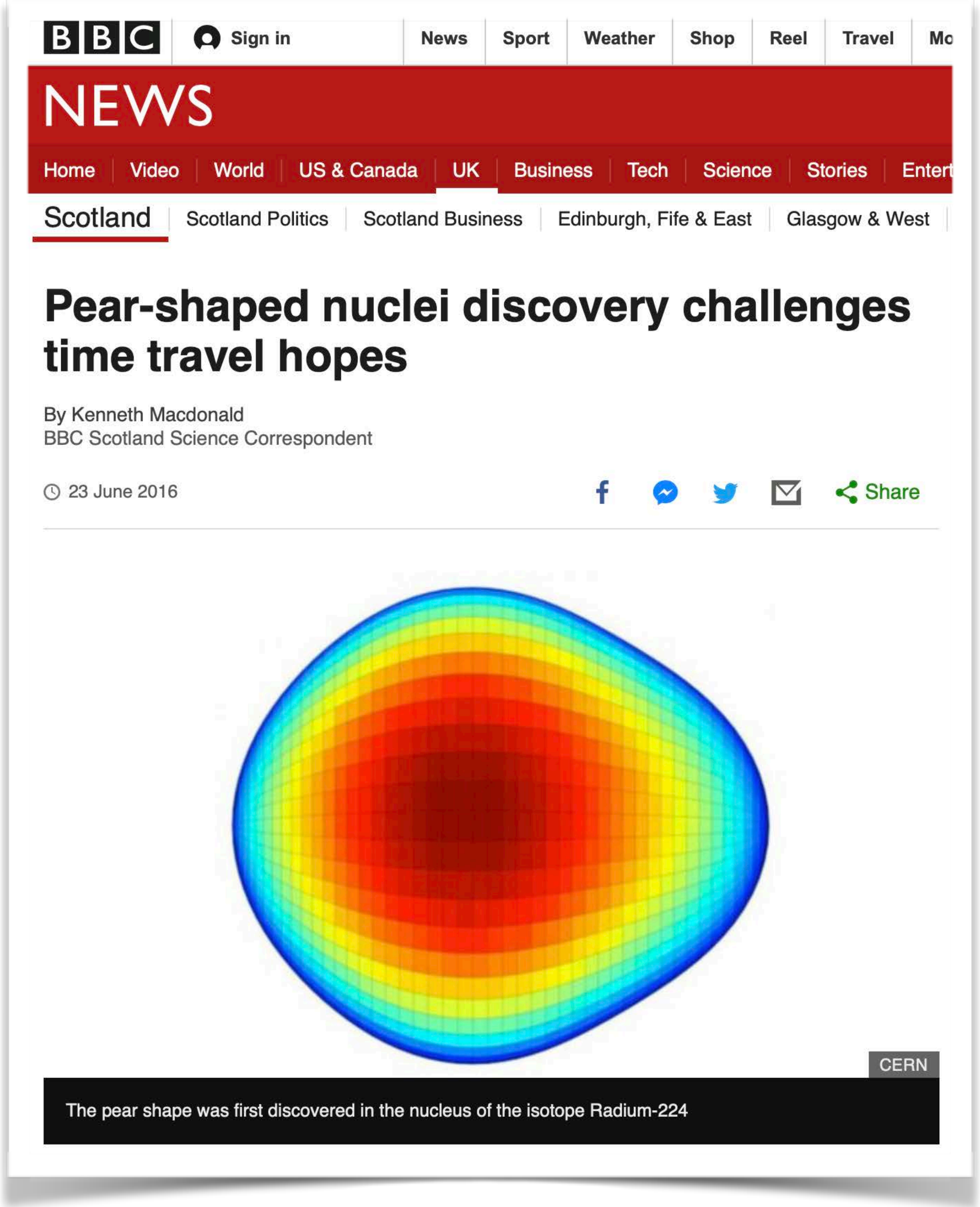
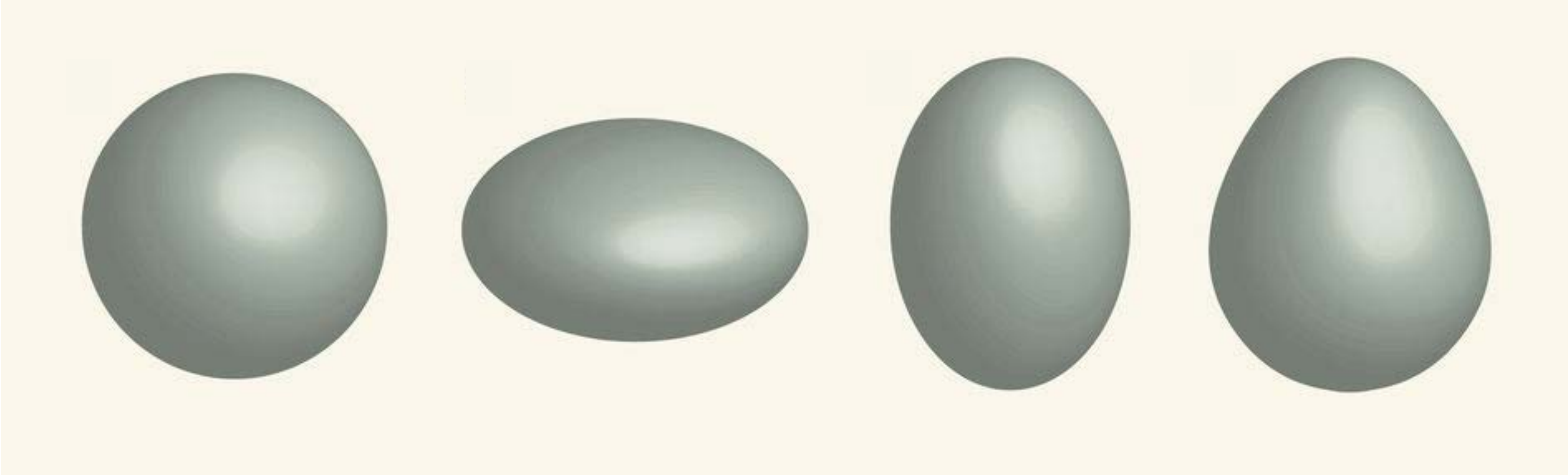
It's all gone ... pear shaped

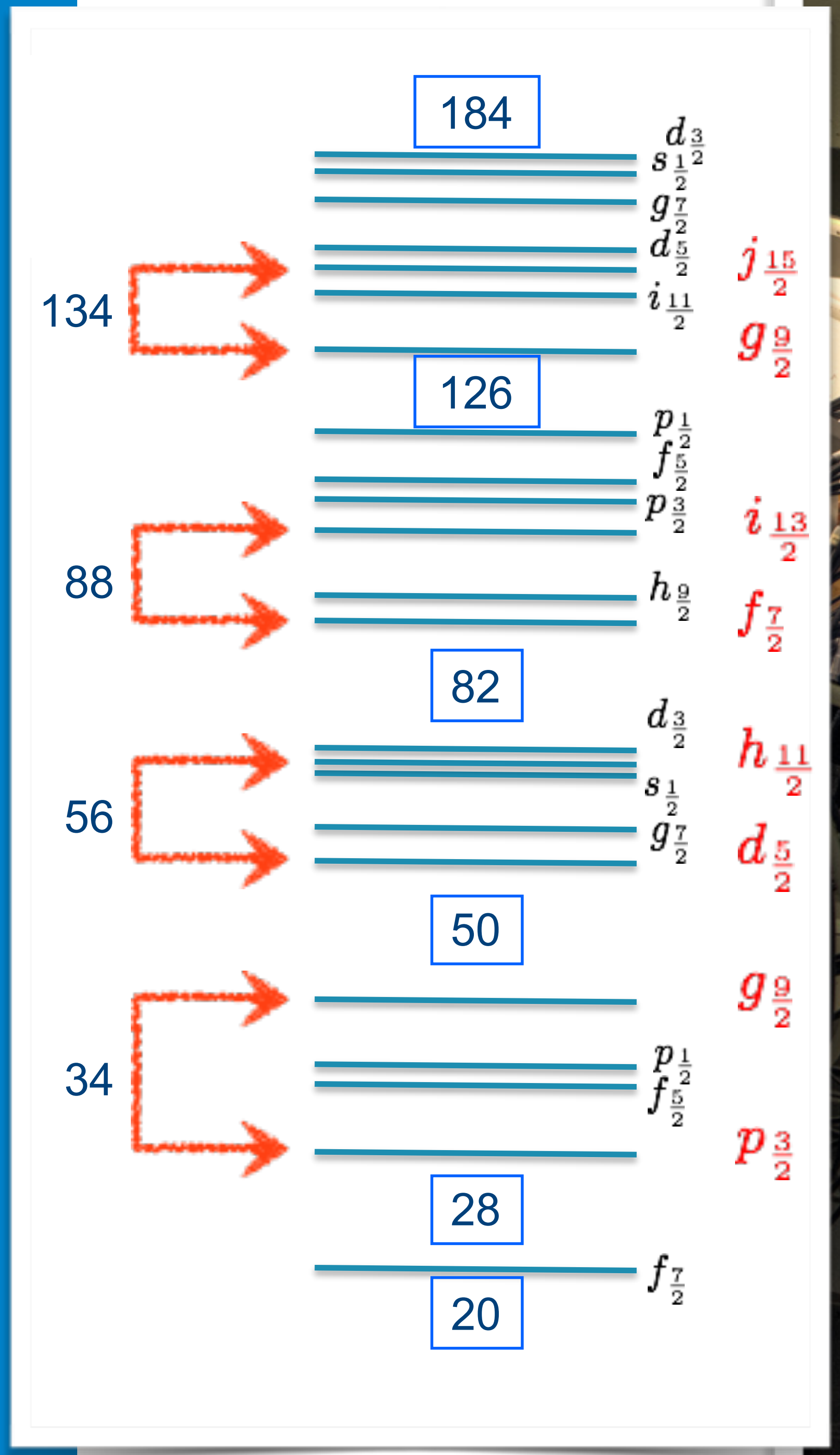


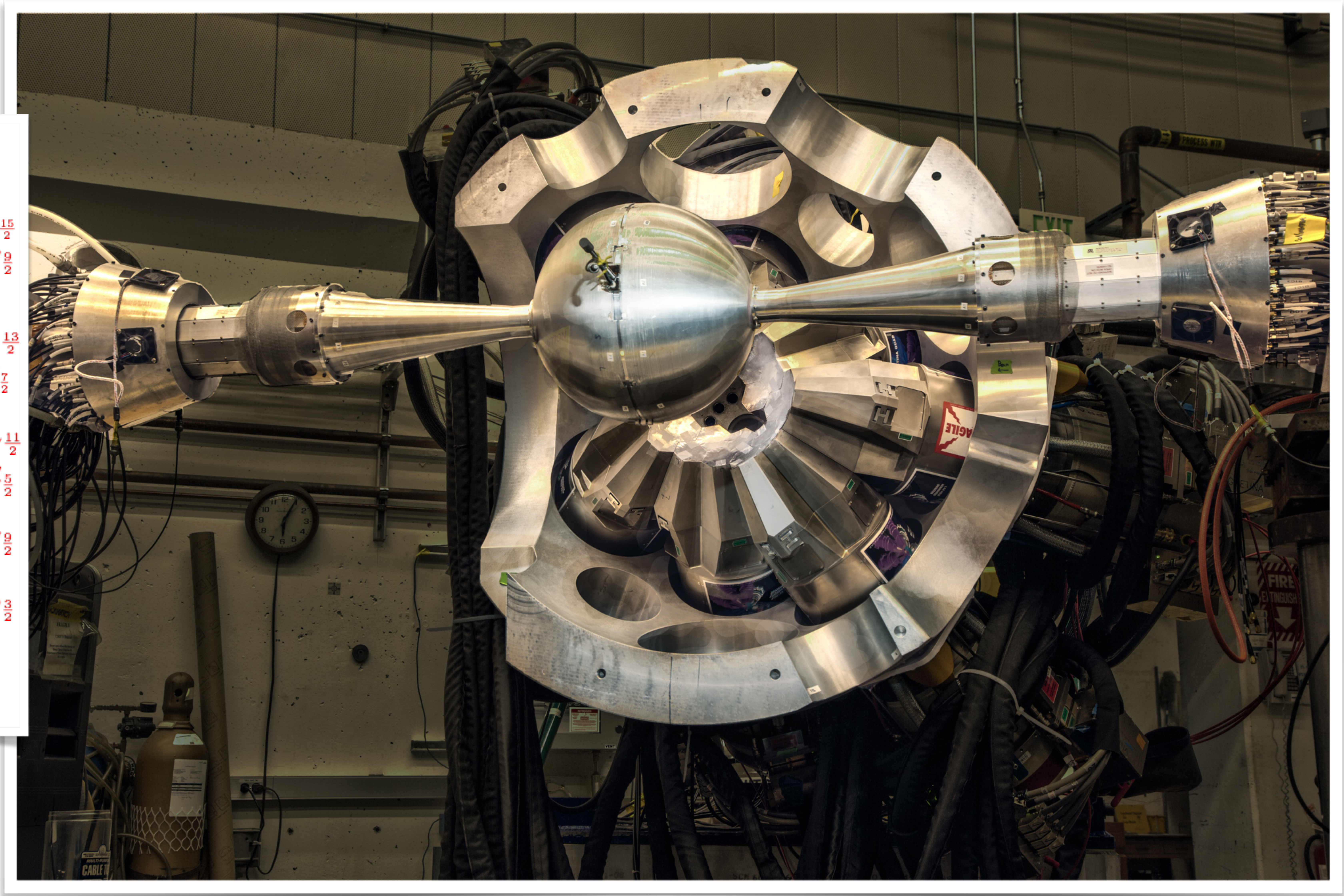




*See write up in Nature **497**, 190 (**2013**) [by C. J. (Kim) Lister ...] ... and the BBC*

Take a look at the Ba isotopes





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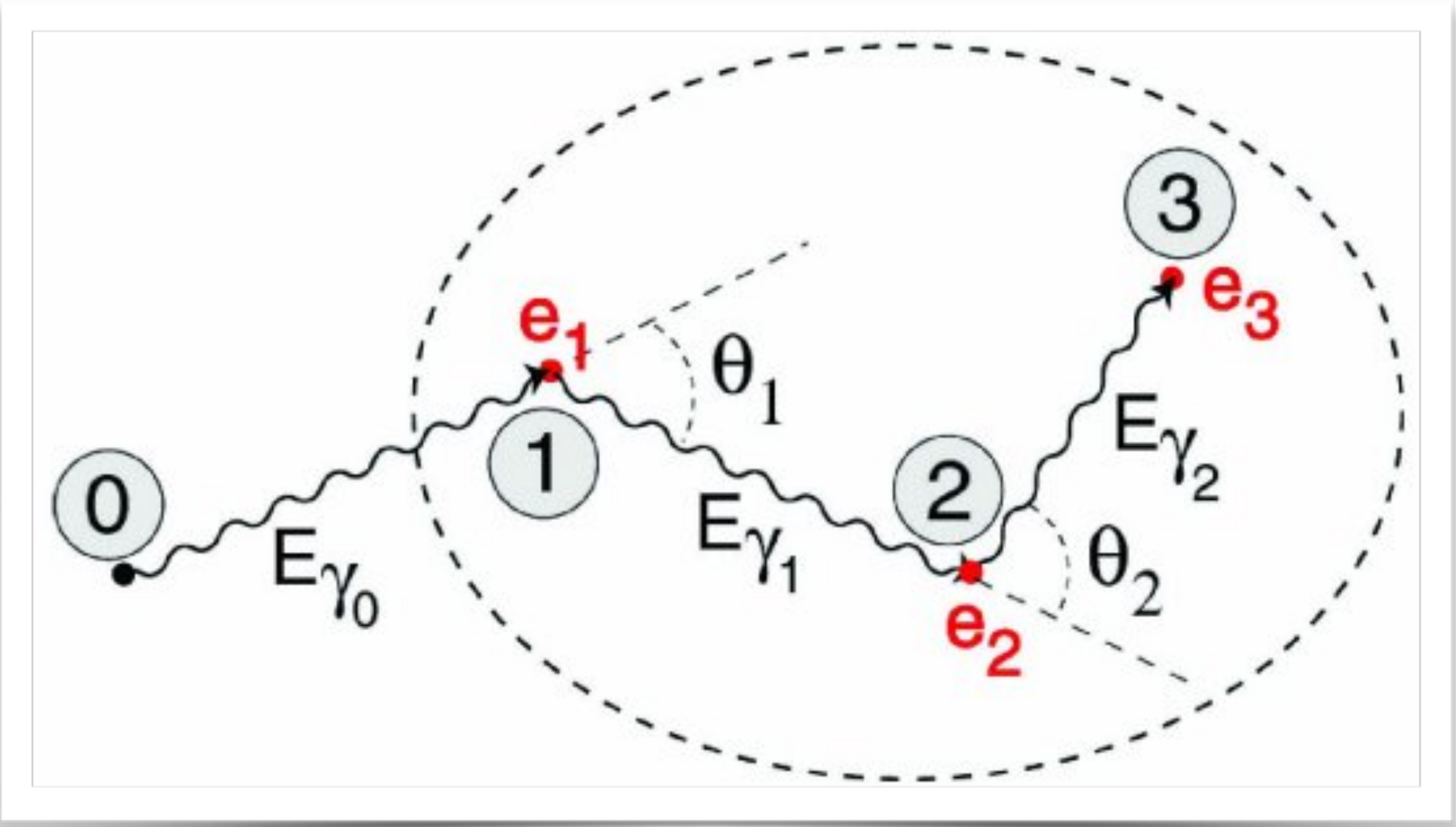
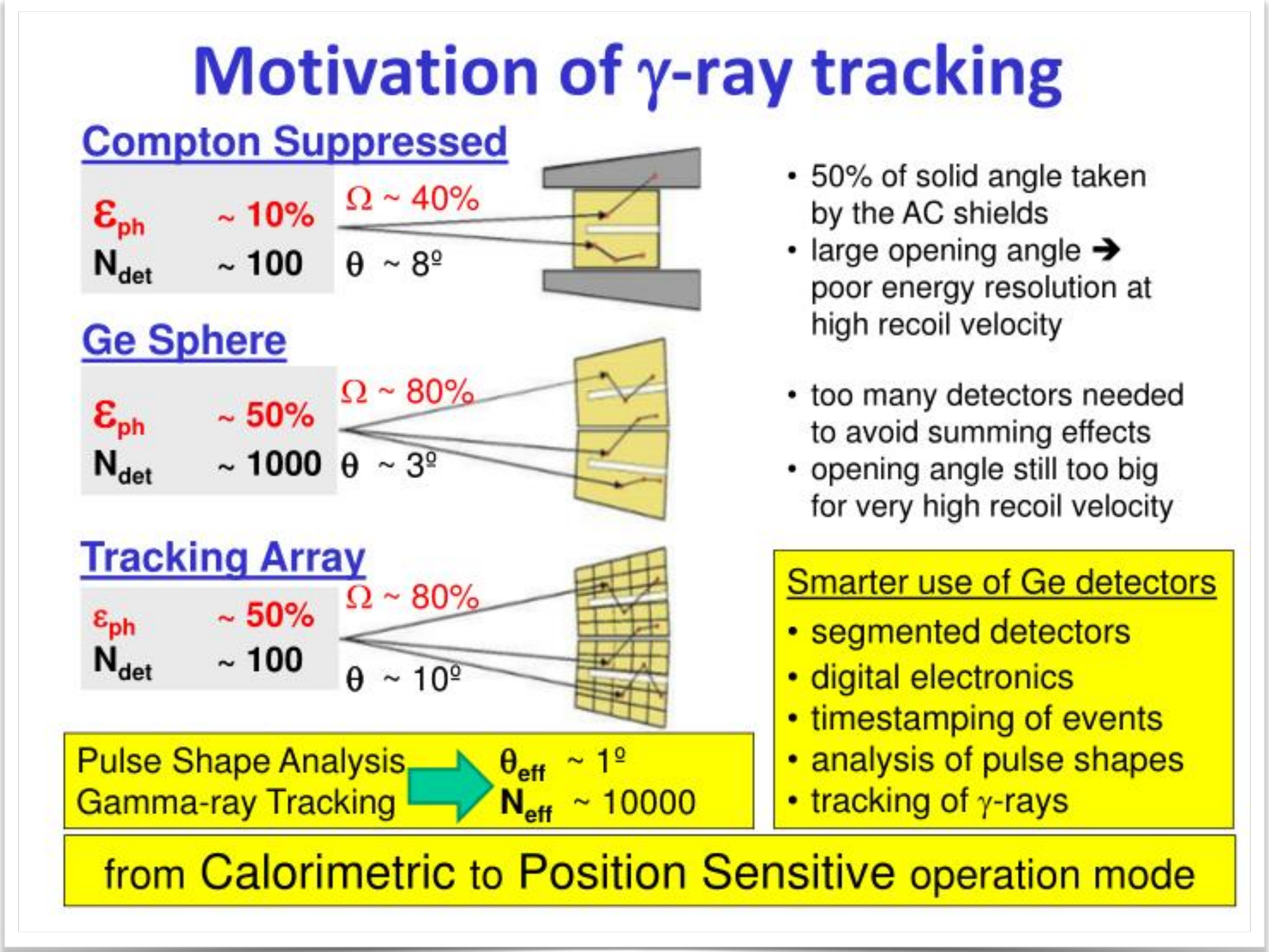
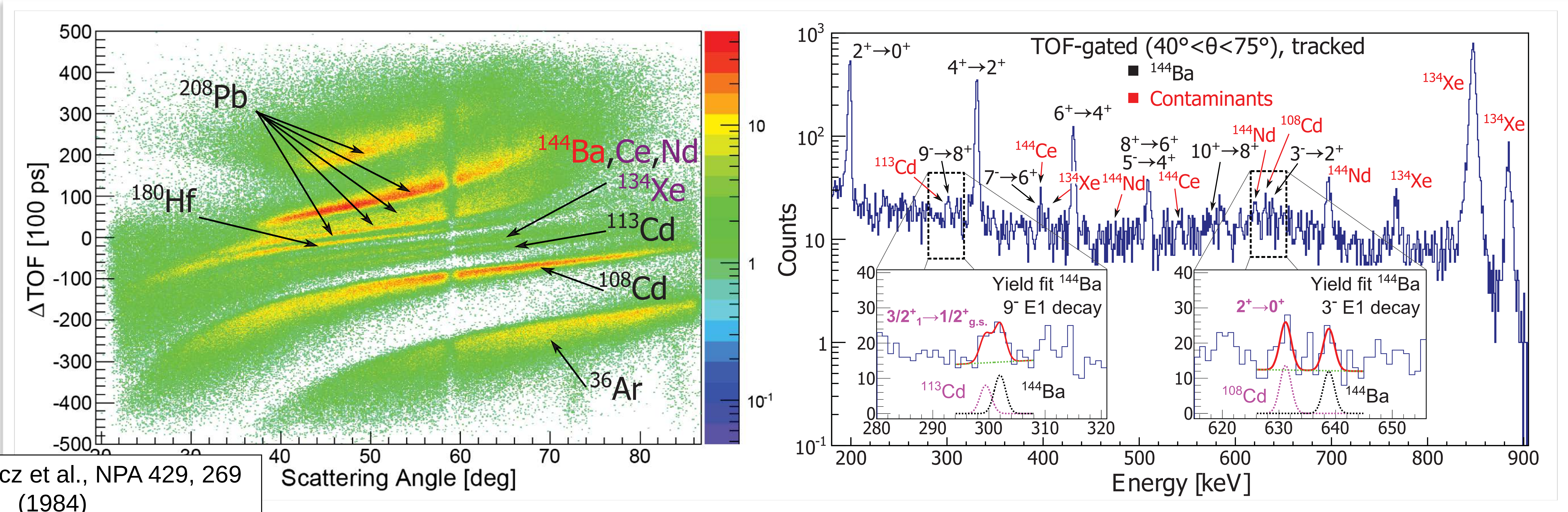
Gamma ray tracking

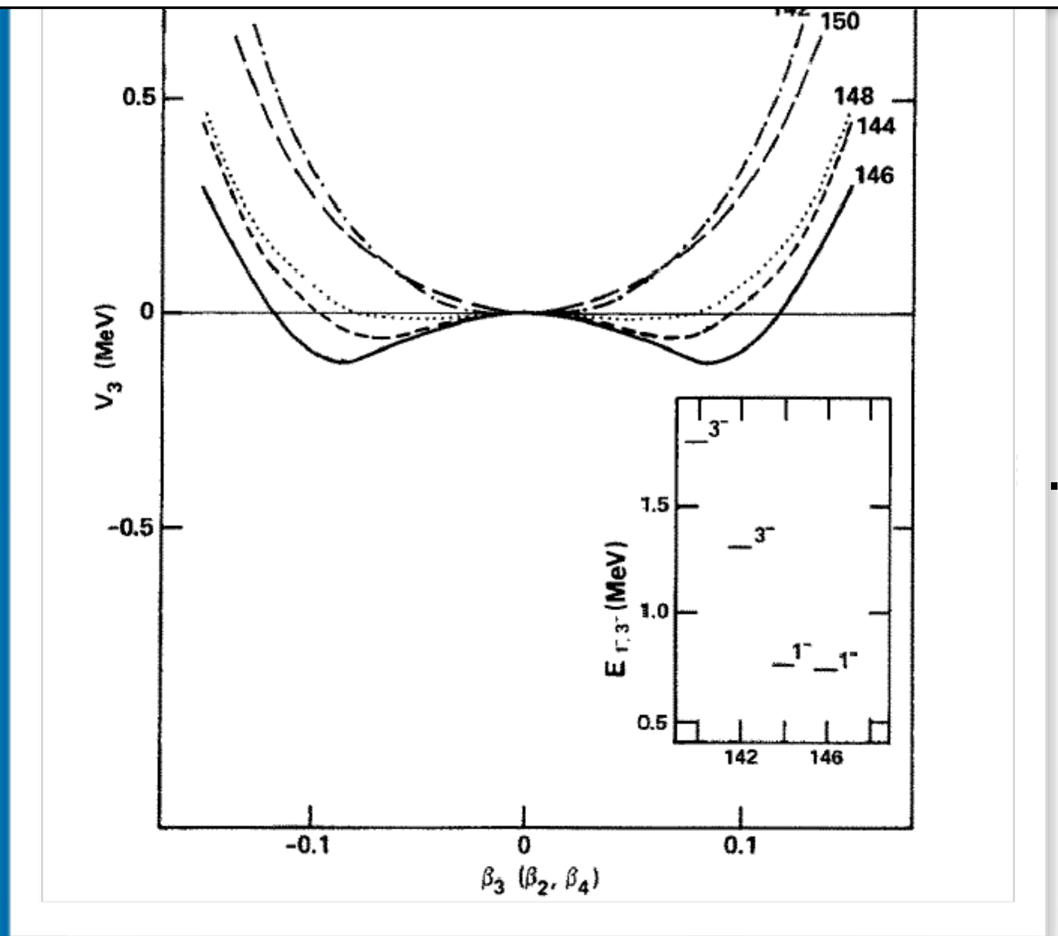




Coulomb excitation of ^{144}Ba



W. Nazarewicz et al., NPA 429, 269 (1984)



., Phys. Rev. Lett. 116, 112503 (2016)

- ^{144}Ba lies in a region where suspected enhanced octupole correlations occur
  - where long-range interactions between $\Delta j = \Delta l = 3$ configurations, namely the $\pi h_{11/2} \otimes \pi d_{5/2}$ and $\nu i_{13/2} \otimes \nu f_{7/2}$, occur
- Coulomb excitation is a reliable probe to extract B(E3) values
  - B(E3) = $48(^{+25}_{-34})$ W.u., consistent with octupole collectivity

B. Bucher, S. Zhu et al., Phys. Rev. Lett. ***116****, 112503 (****2016****)*

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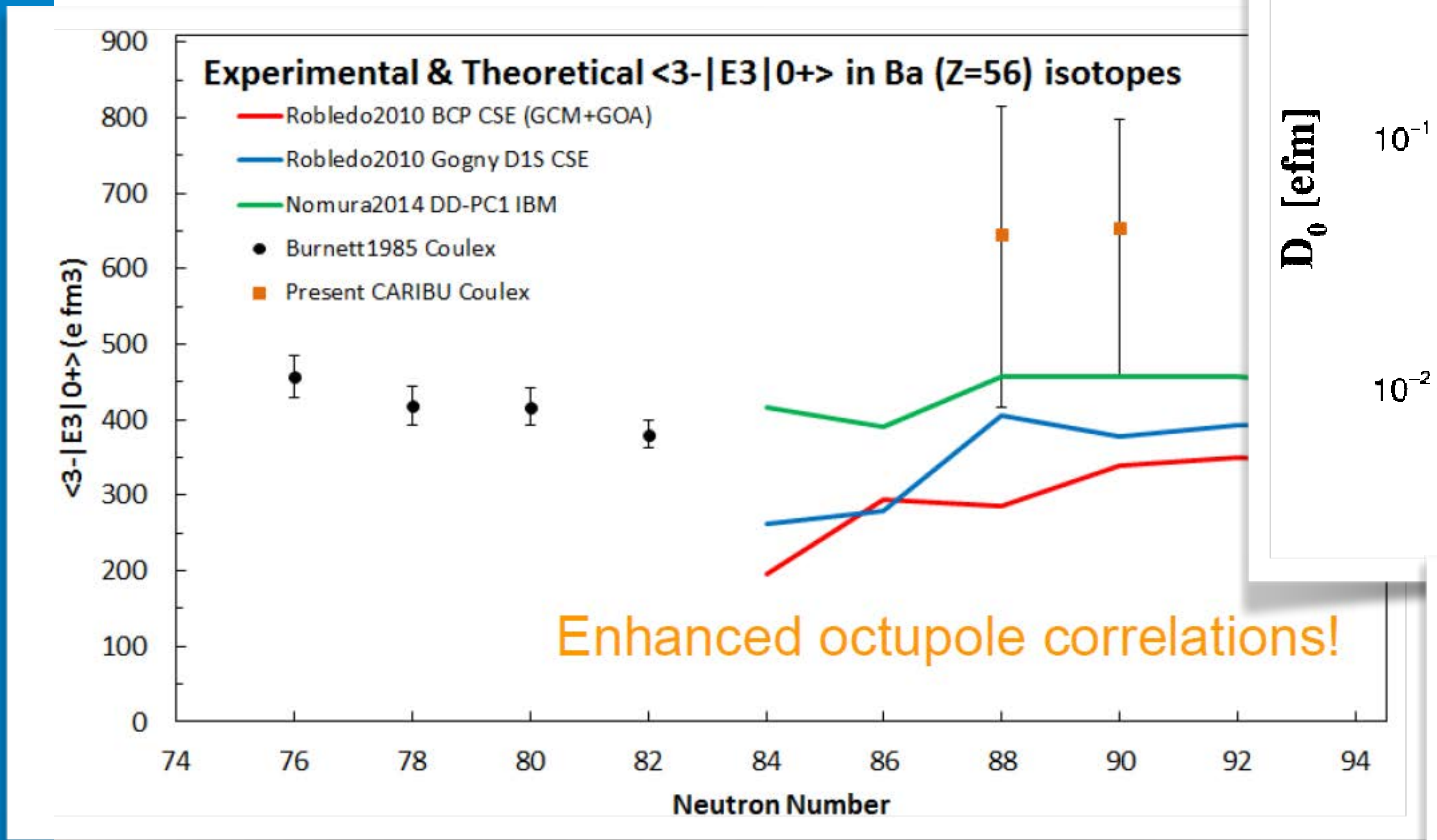
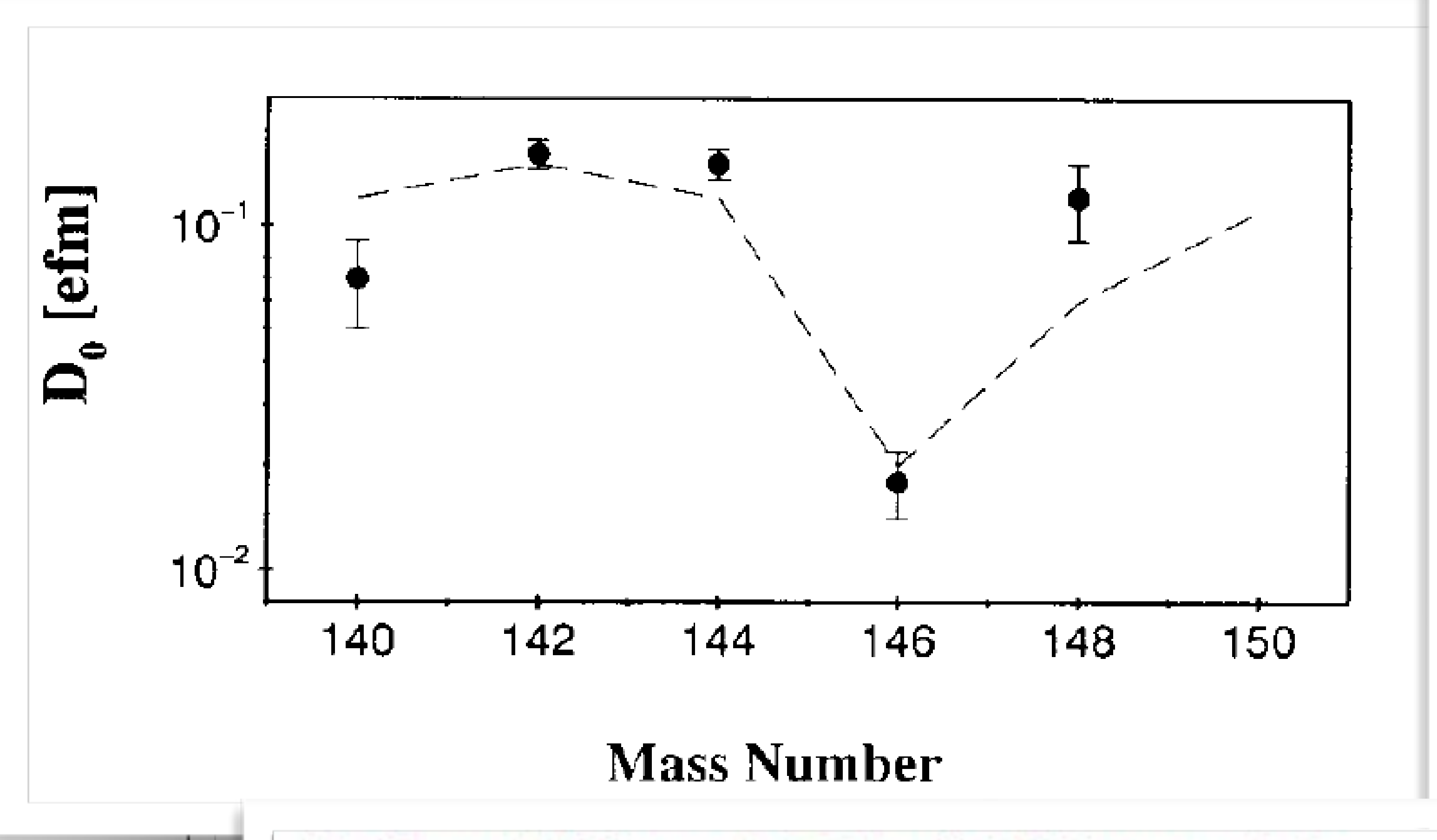
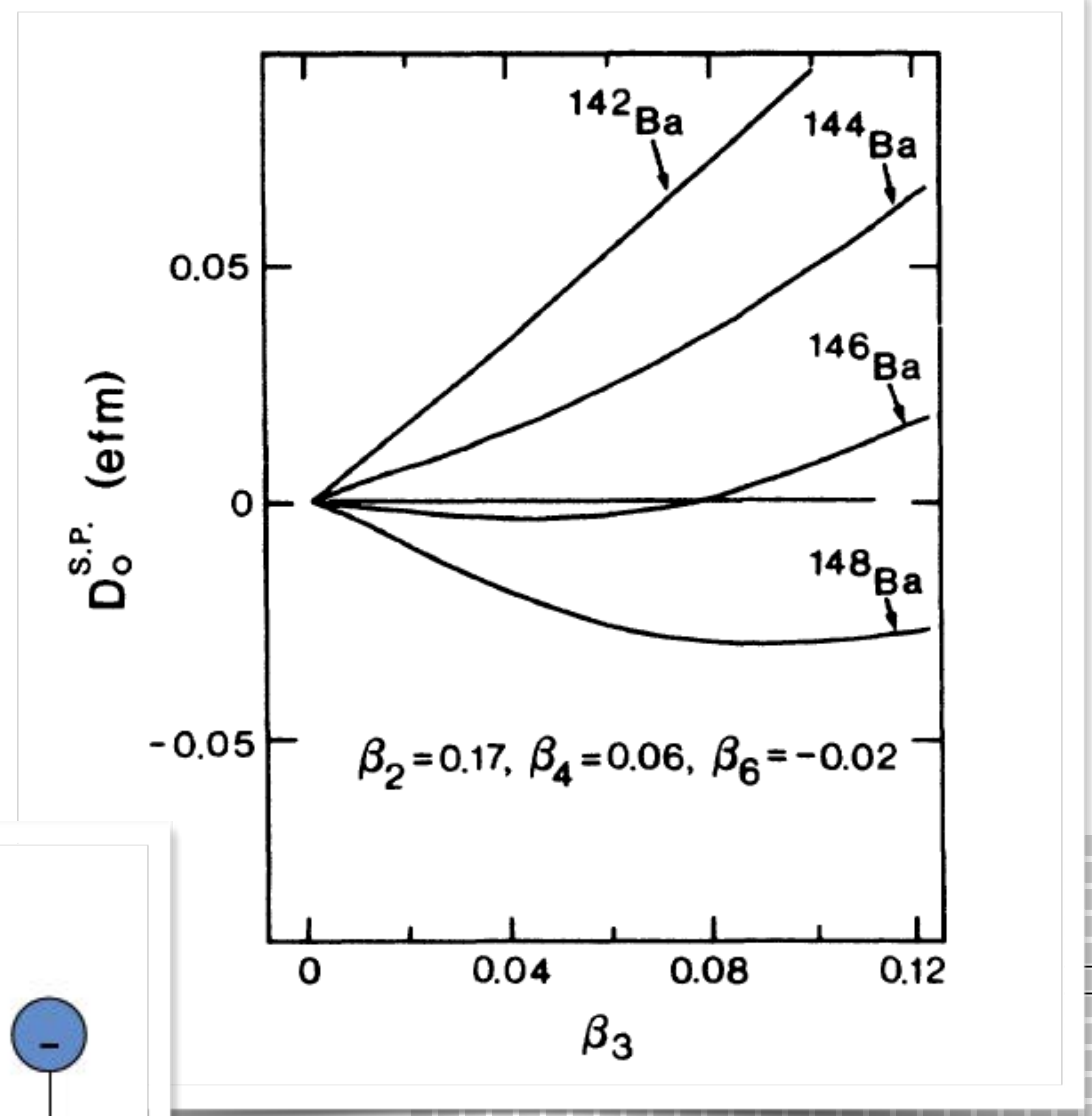
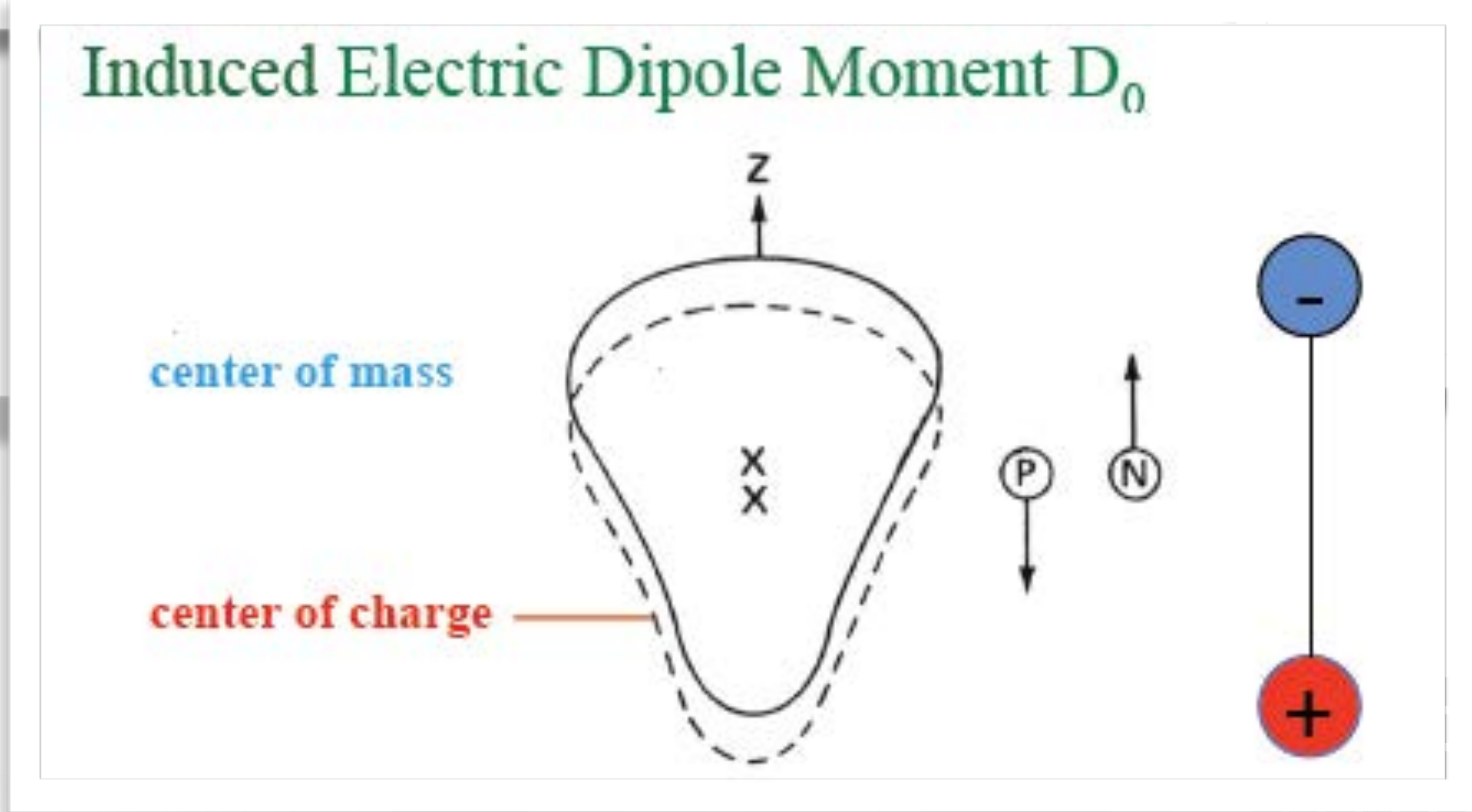
Coulomb excitation of ^{144}Ba





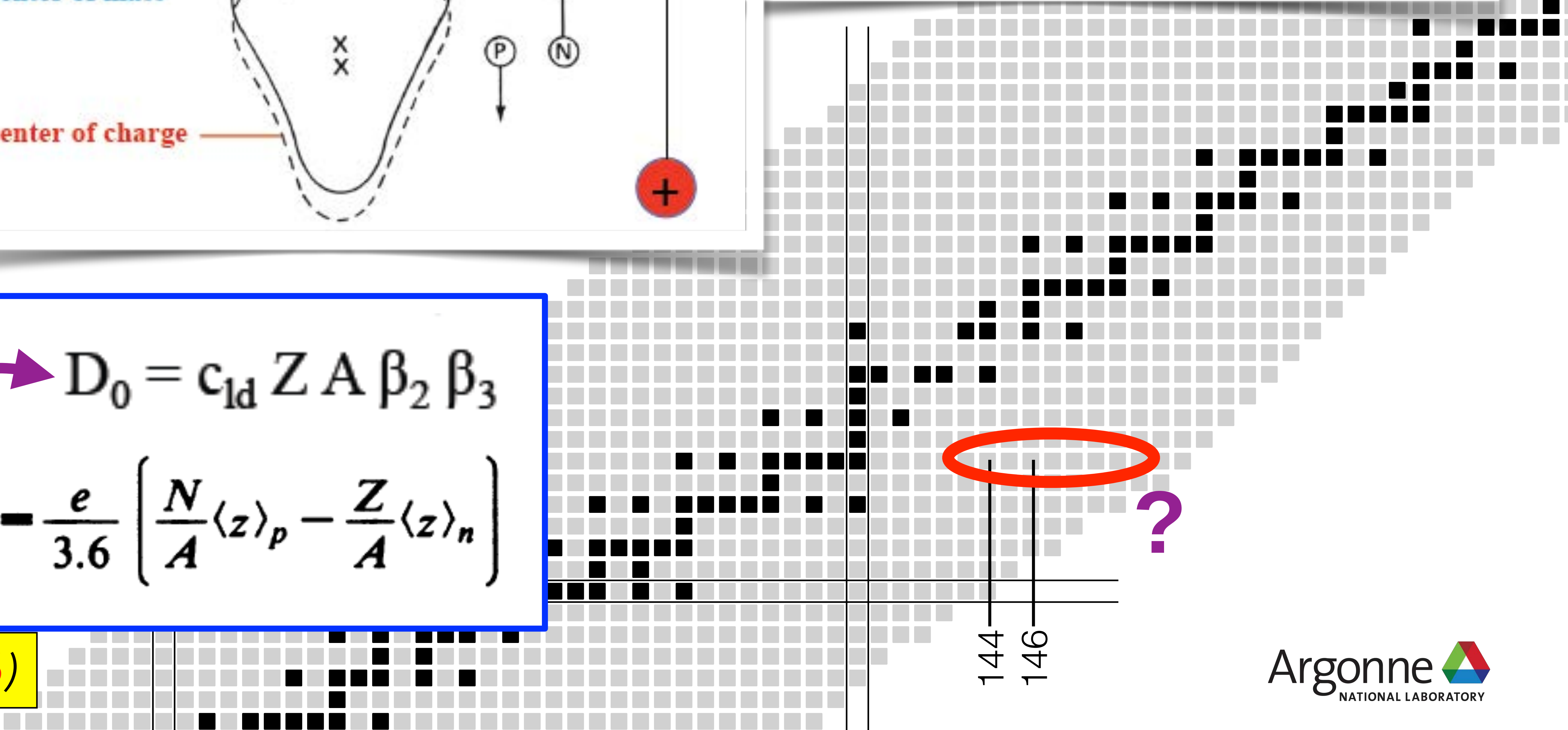




- Enhanced octupole correlations firmly established in both ^{144}Ba and ^{146}Ba
- Suggests a 'region' not just isolated cases (how far does it extend?)
- Behavior of the dipole strength shows interesting behavior

$$D_0 = c_{1d}\, Z\, A\, \beta_2\, \beta_3$$

$$D_0^{sp} = \frac{e}{3.6}\left[\frac{N}{A}\langle z\rangle_p - \frac{Z}{A}\langle z\rangle_n\right]$$



B. Bucher, S. Zhu et al., Phys. Rev. Lett. ***116****, 112503 (****2016****)*

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Summary

- *The many varied techniques associated with determining even simple properties of nuclei can give tremendous insights … and we have not even delved (much) into the microscopic structure of these systems yet ….*
- *… next two lectures focus on single-particle structure as probed through direct reactions*