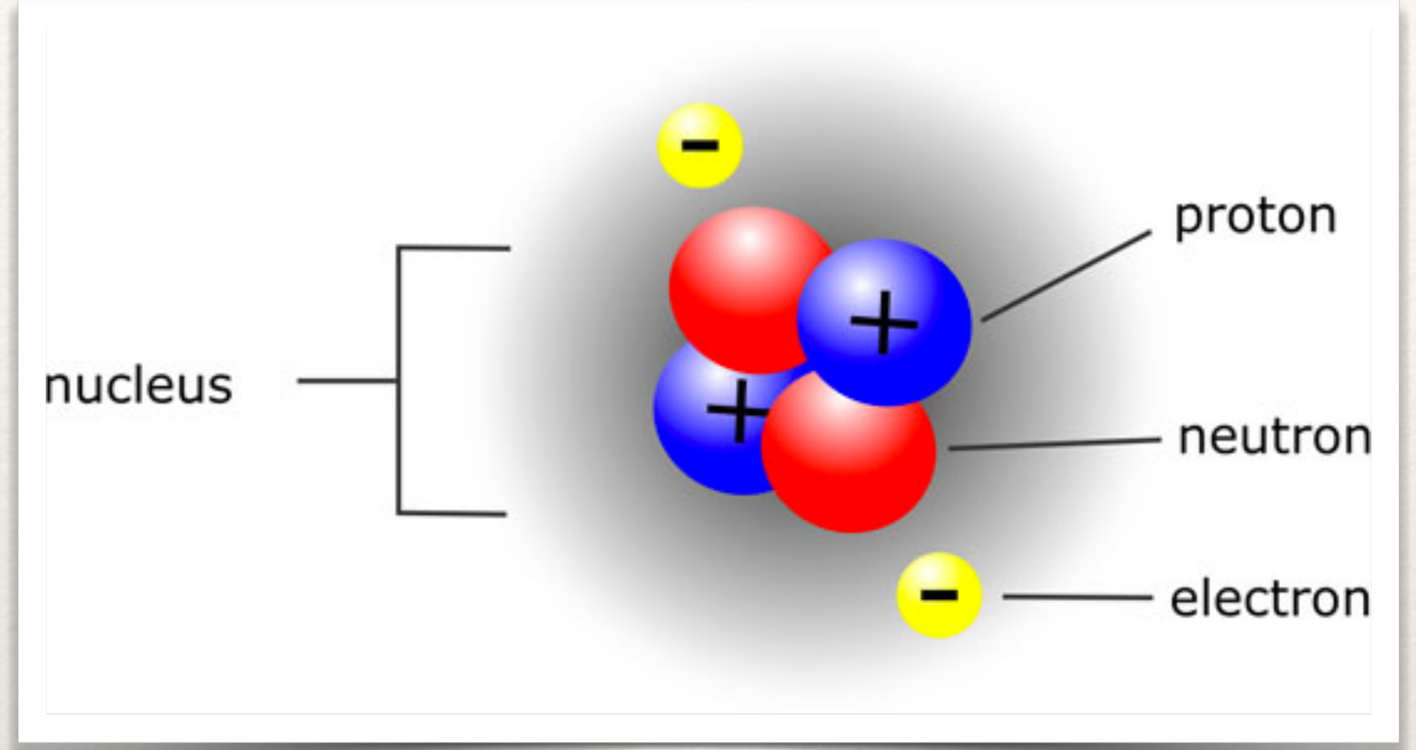
Sarah NAIMI (IJCLab/Paris-Saclay University)
3rd Rencontre PhyNuBe 6-11 Oct. 2024

Mass Measurements for Nuclear Astrophysics

Reminder: Atomic mass



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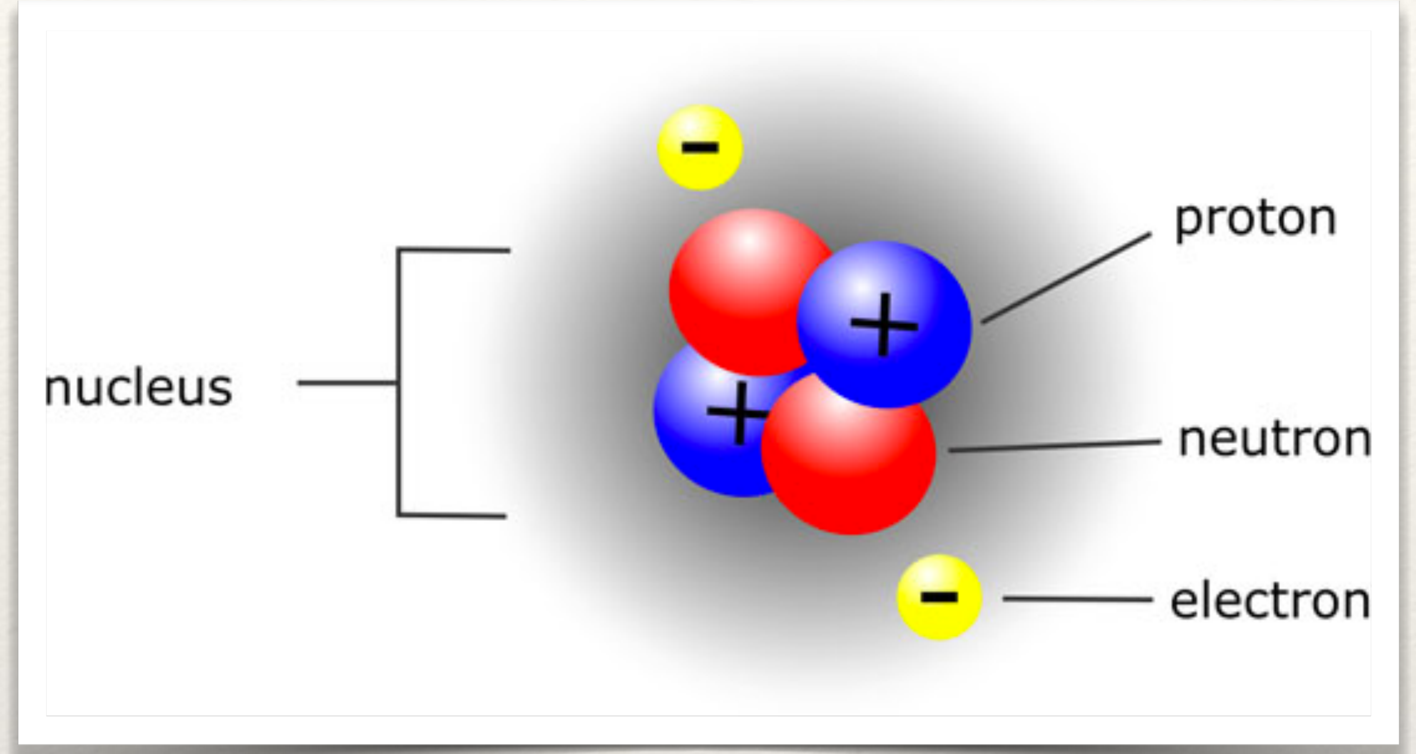

$$M(^4He) = 2 \cdot m_p + 2 \cdot m_n + 2 \cdot m_e$$

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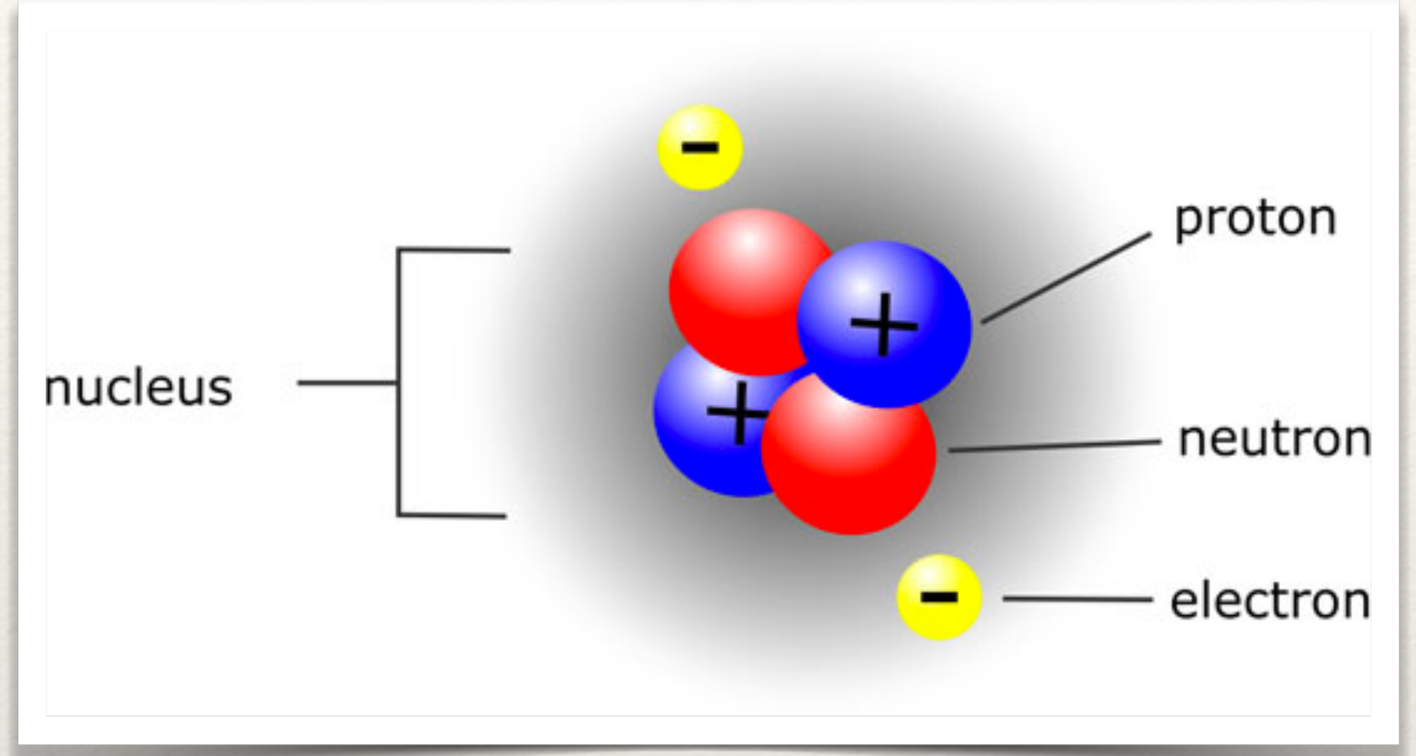

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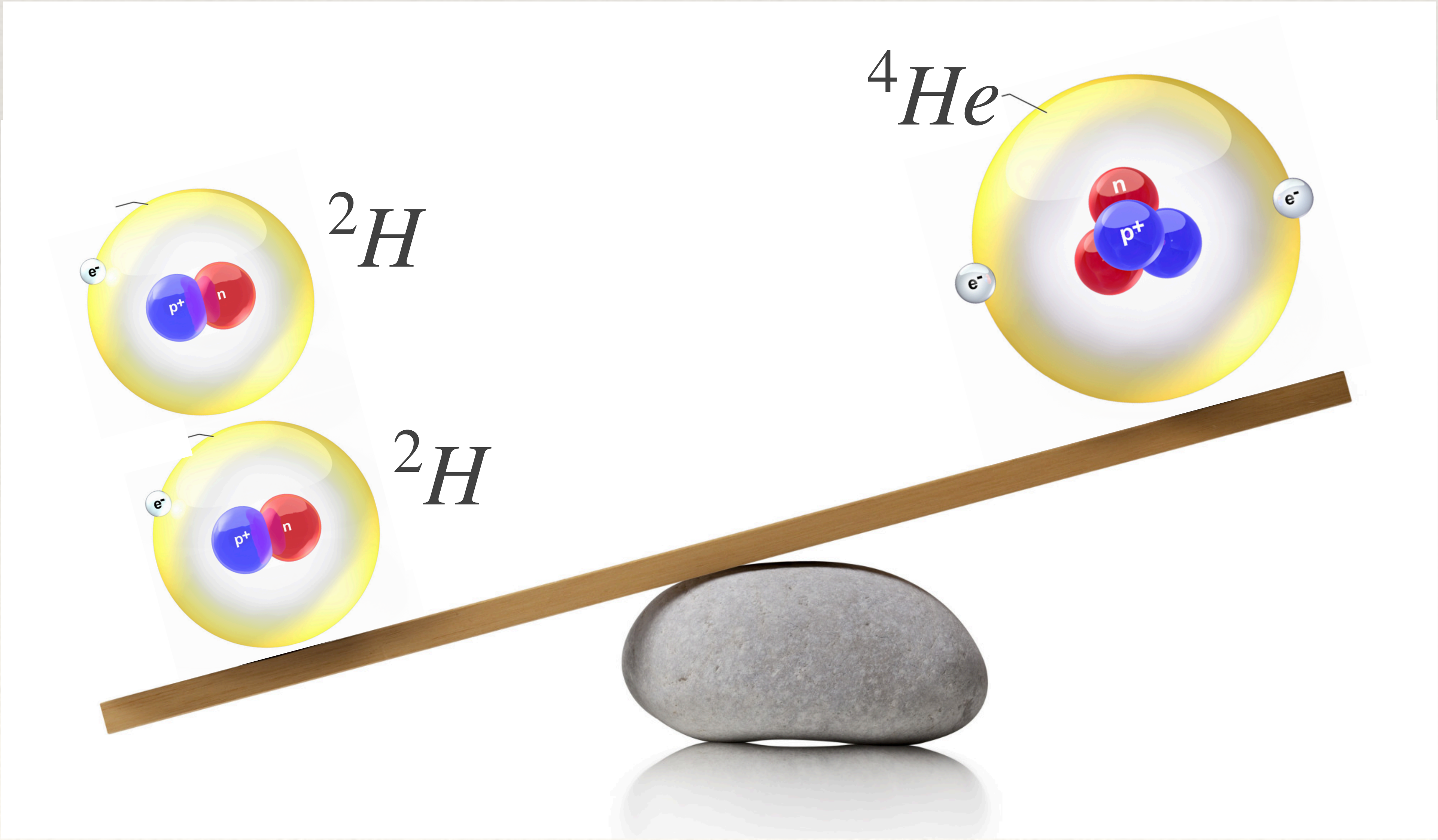

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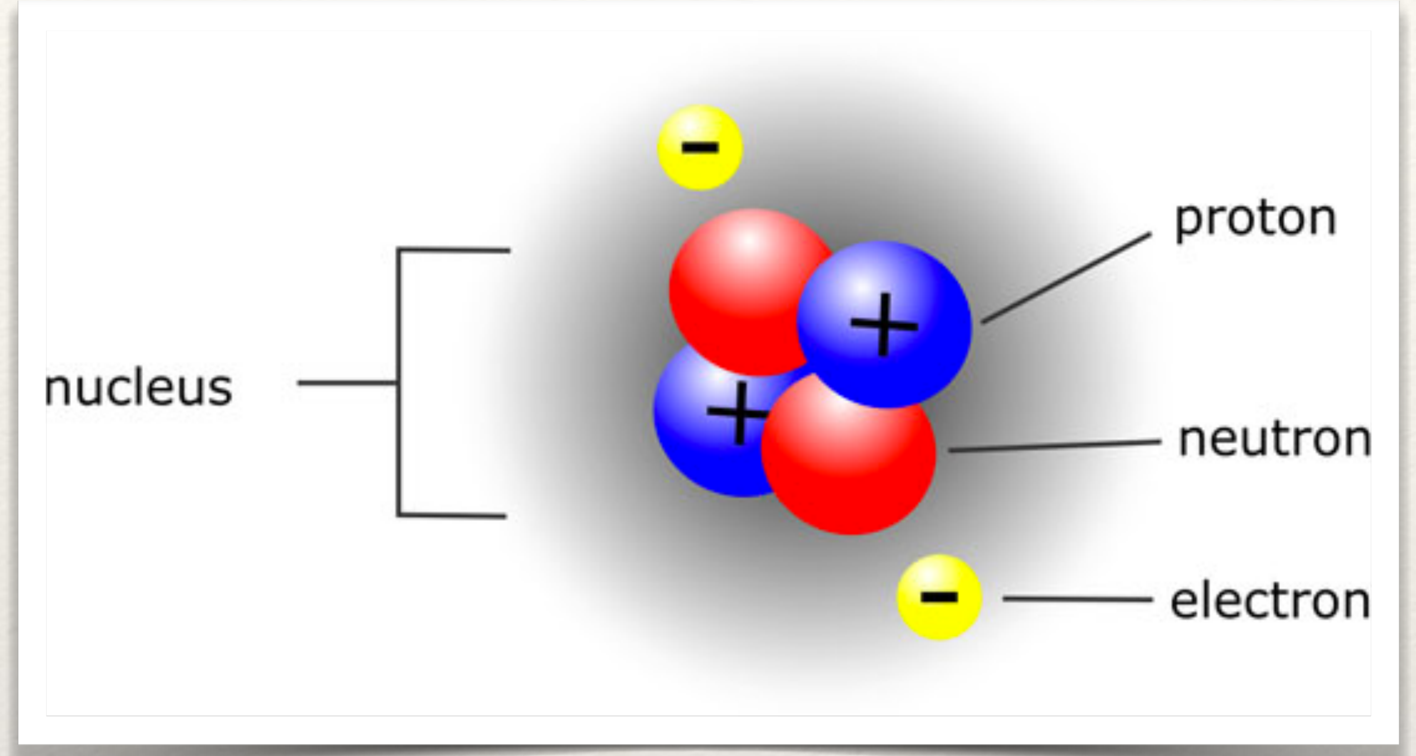

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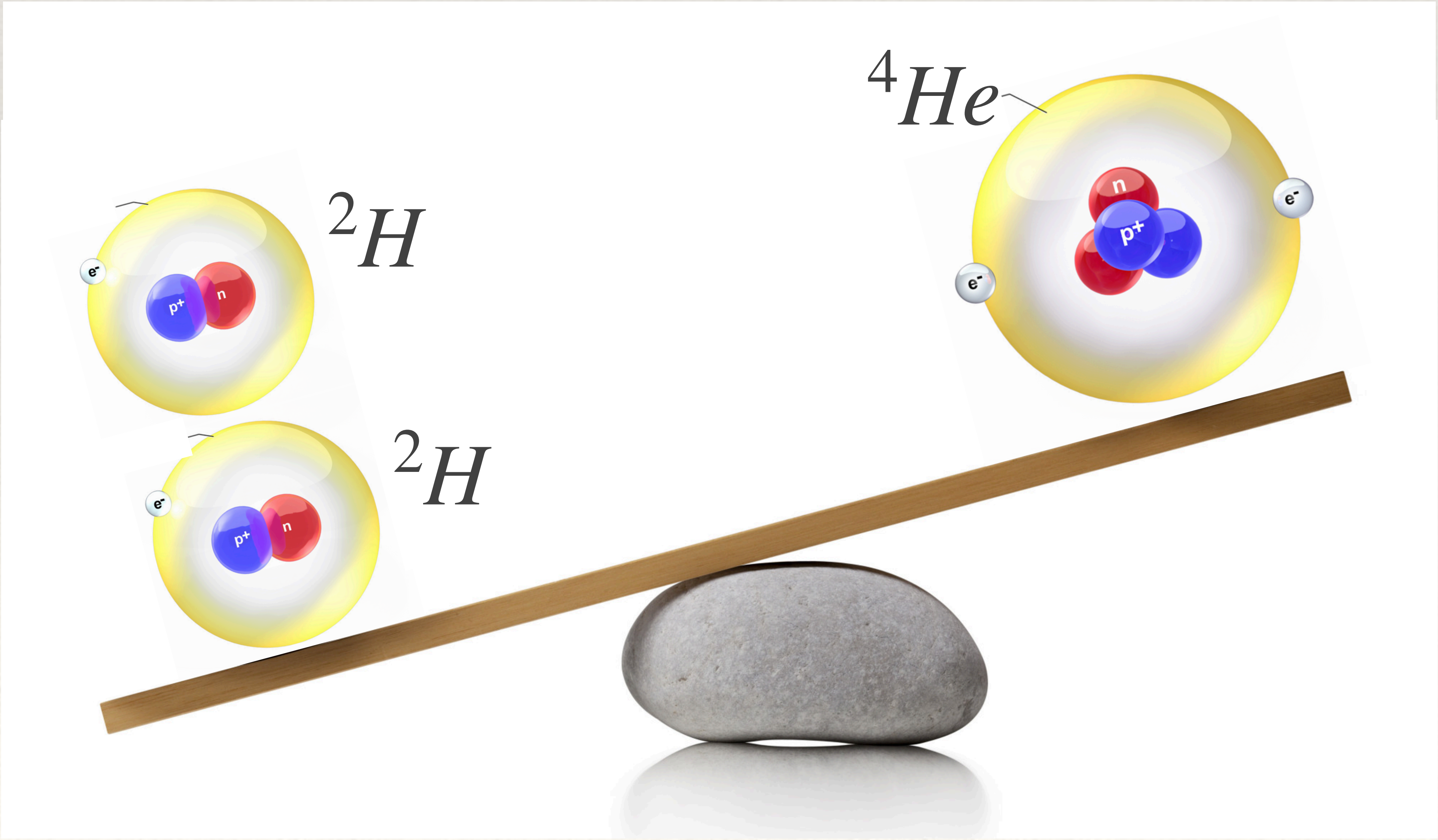

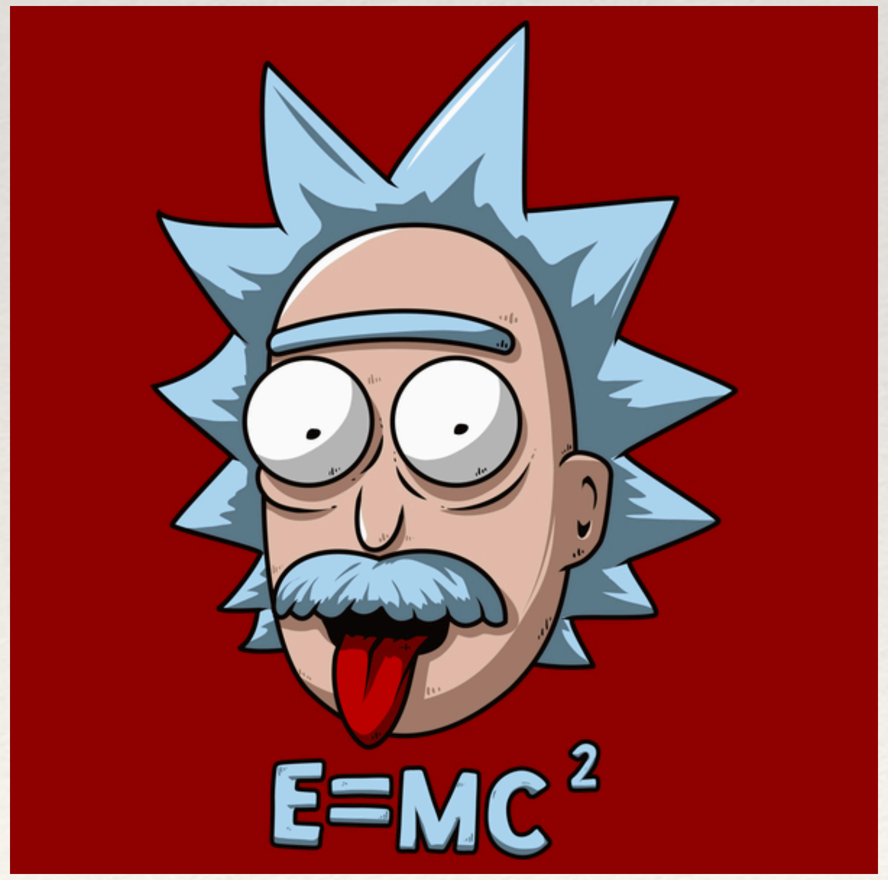

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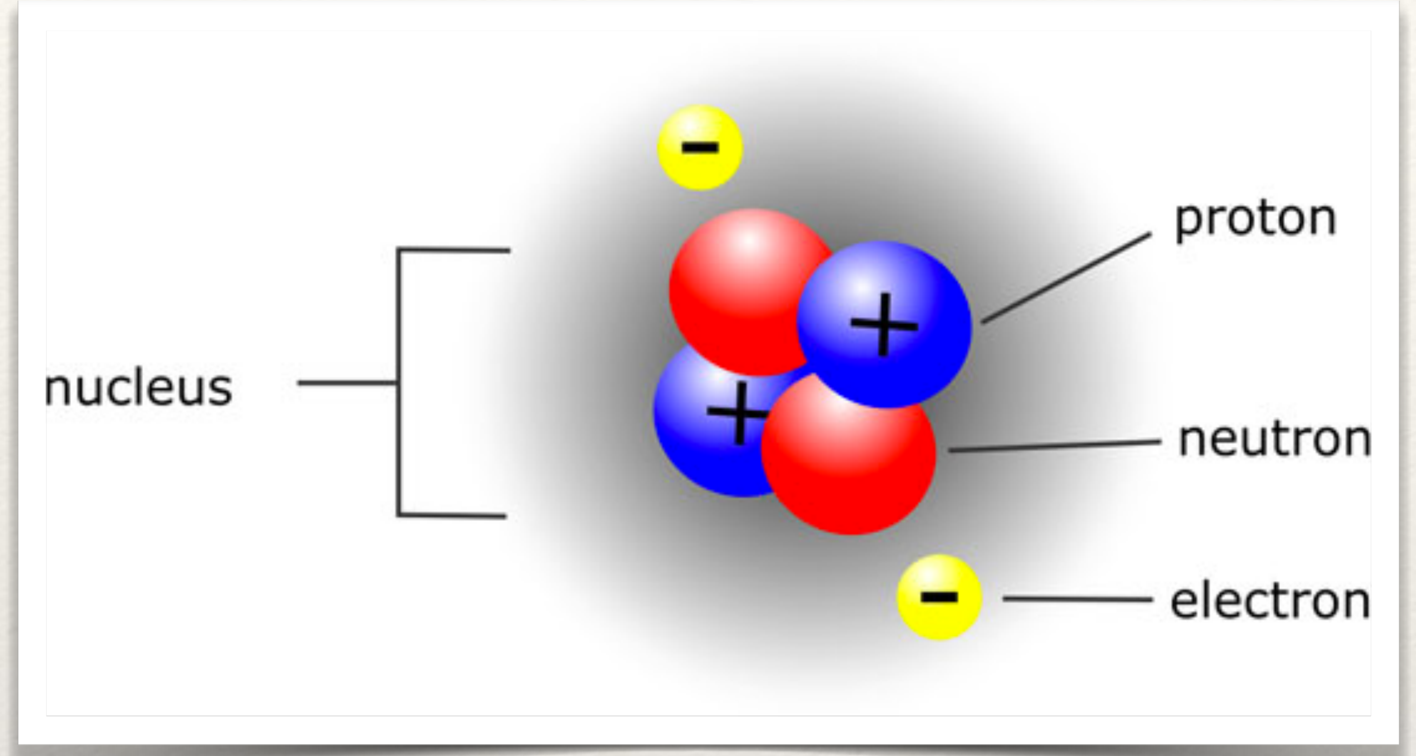

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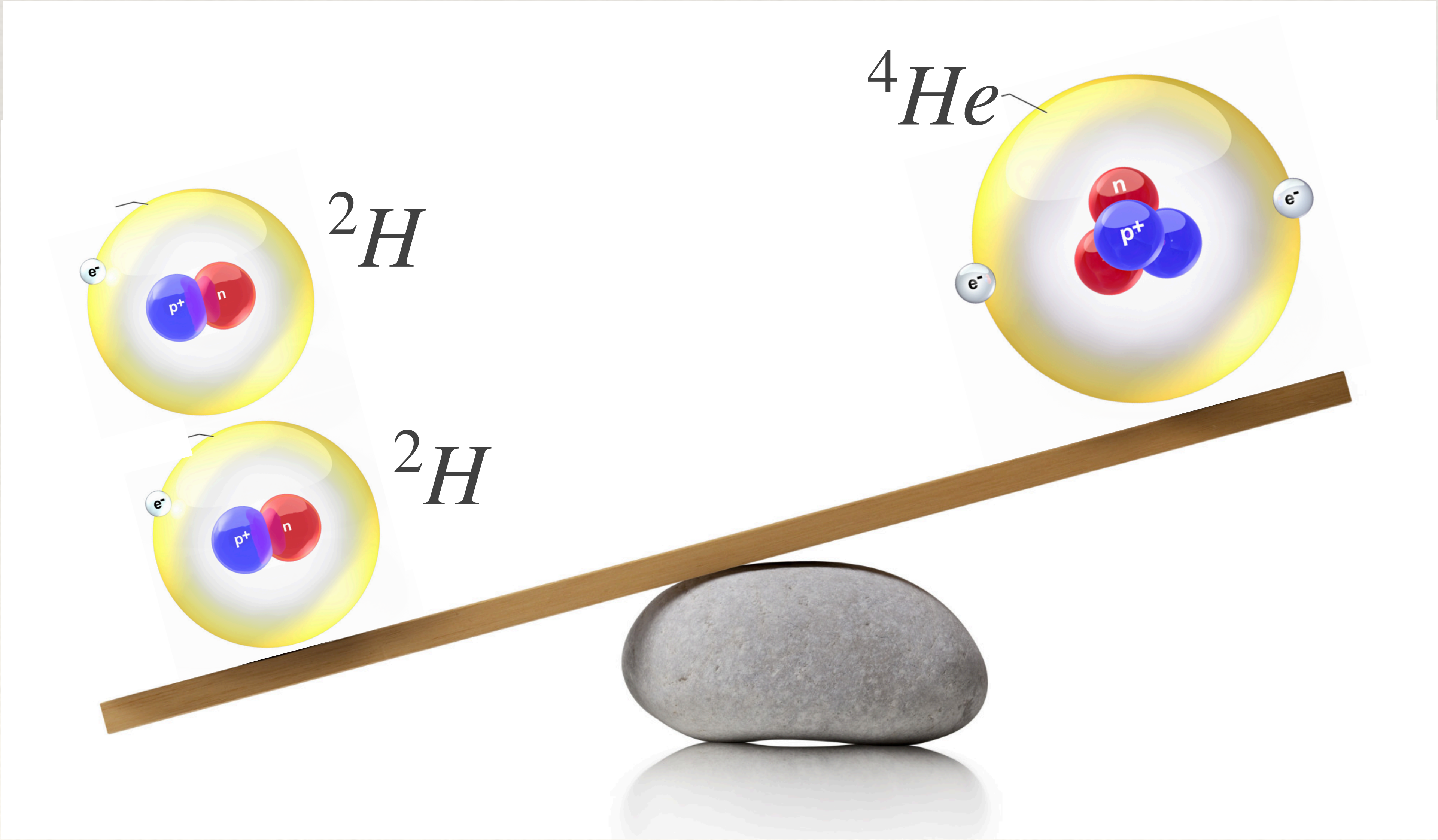
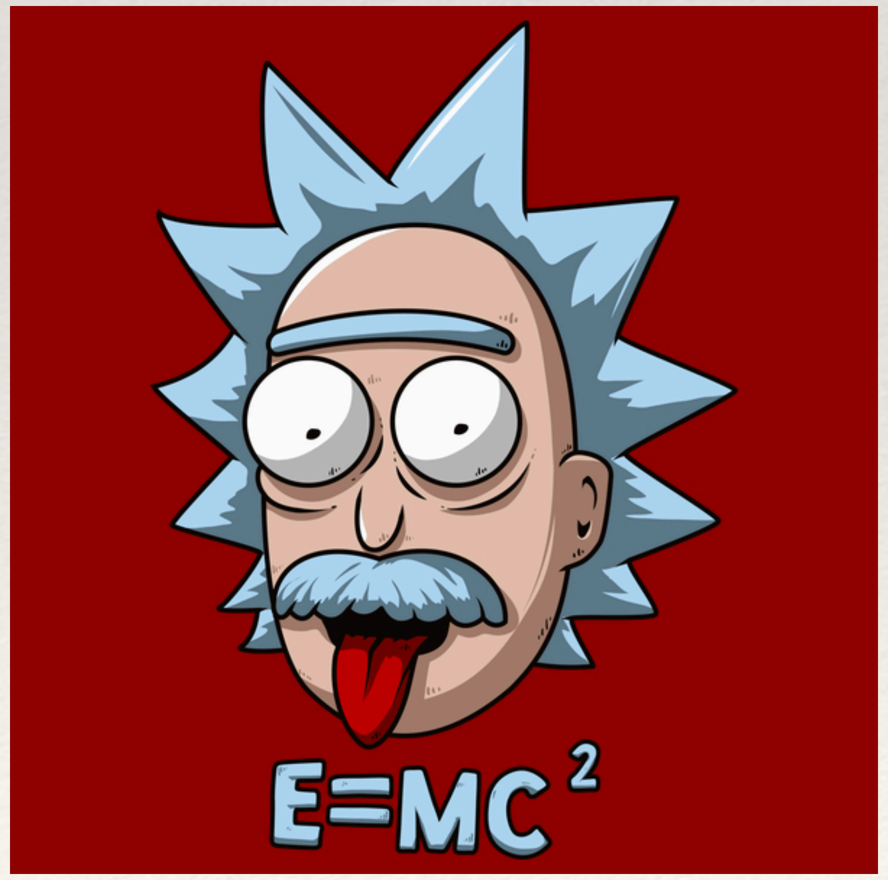
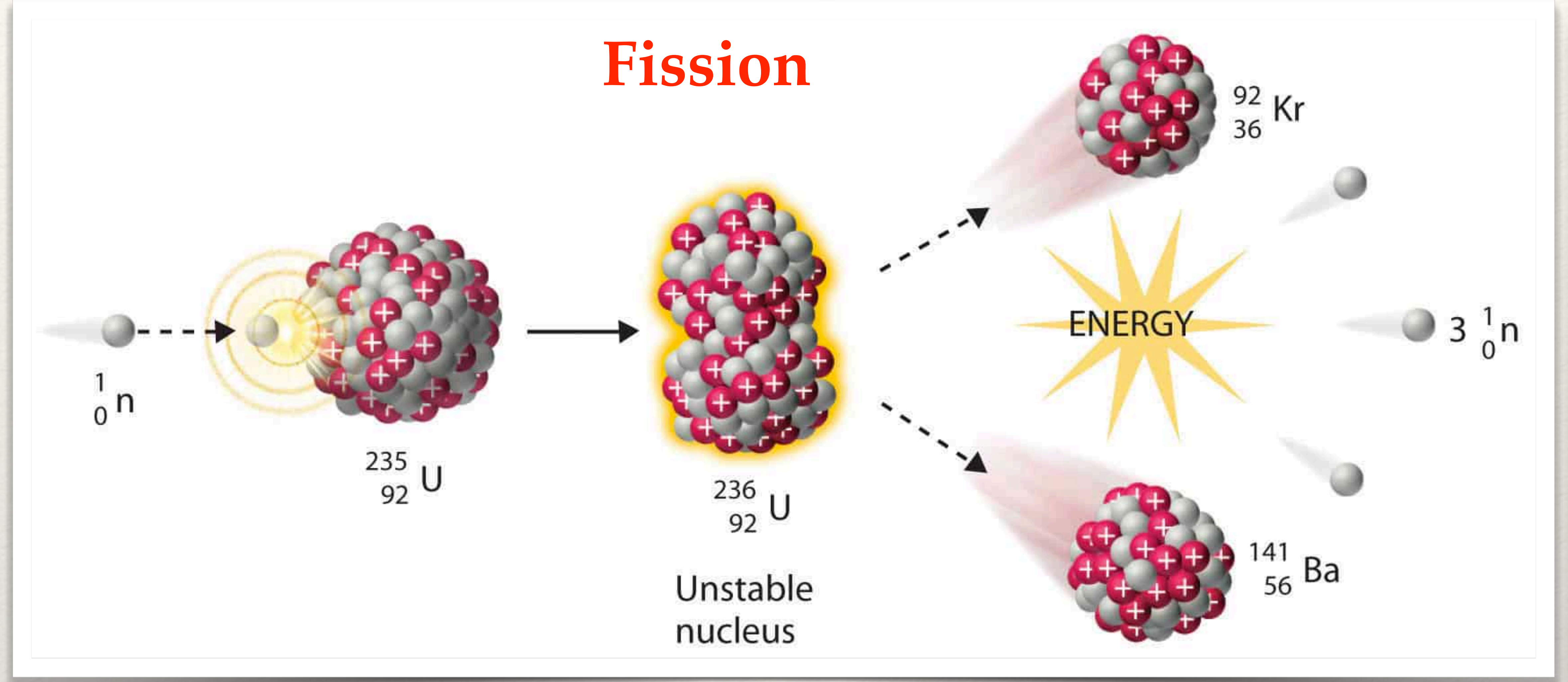
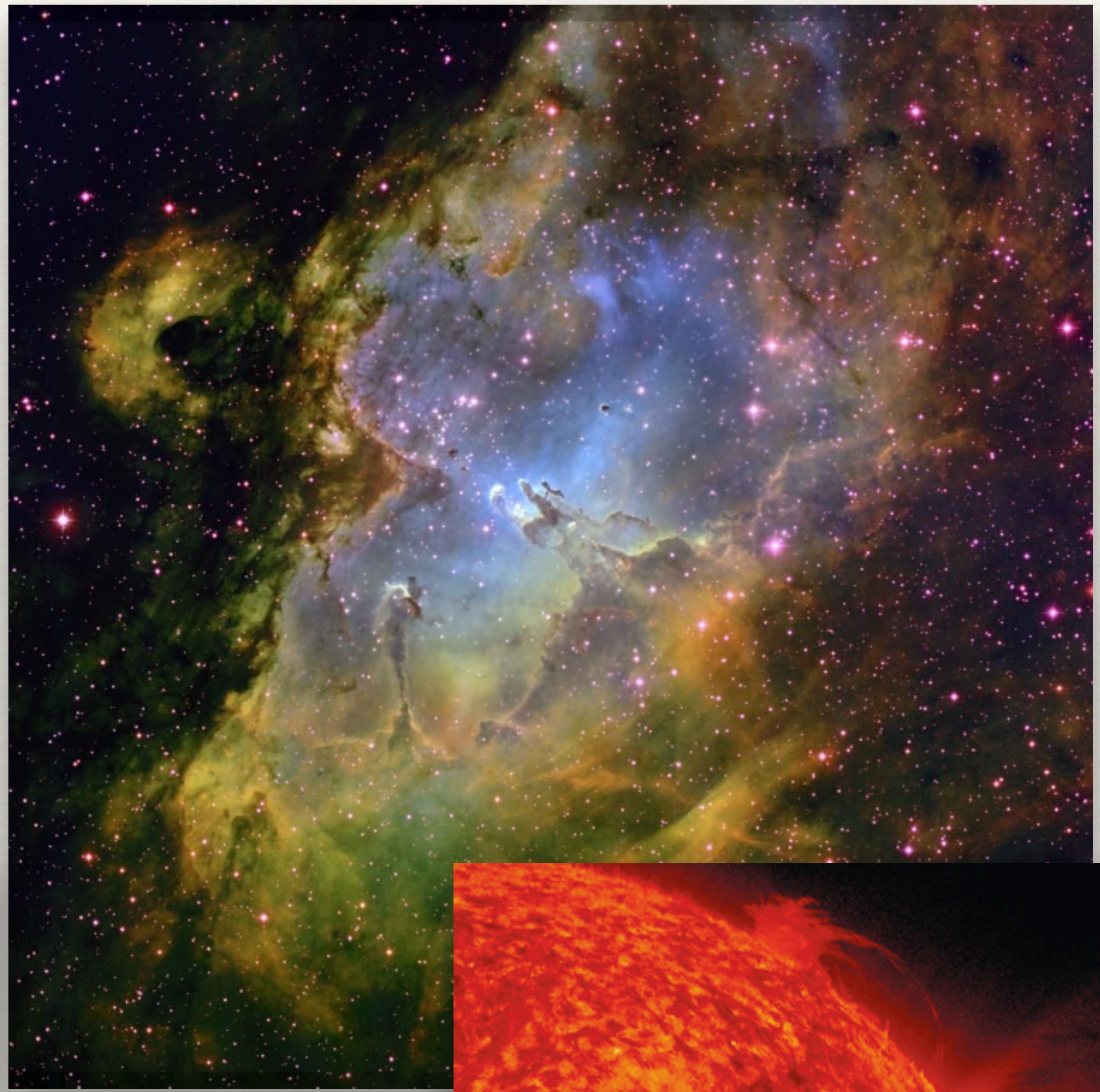
- Binding Energy

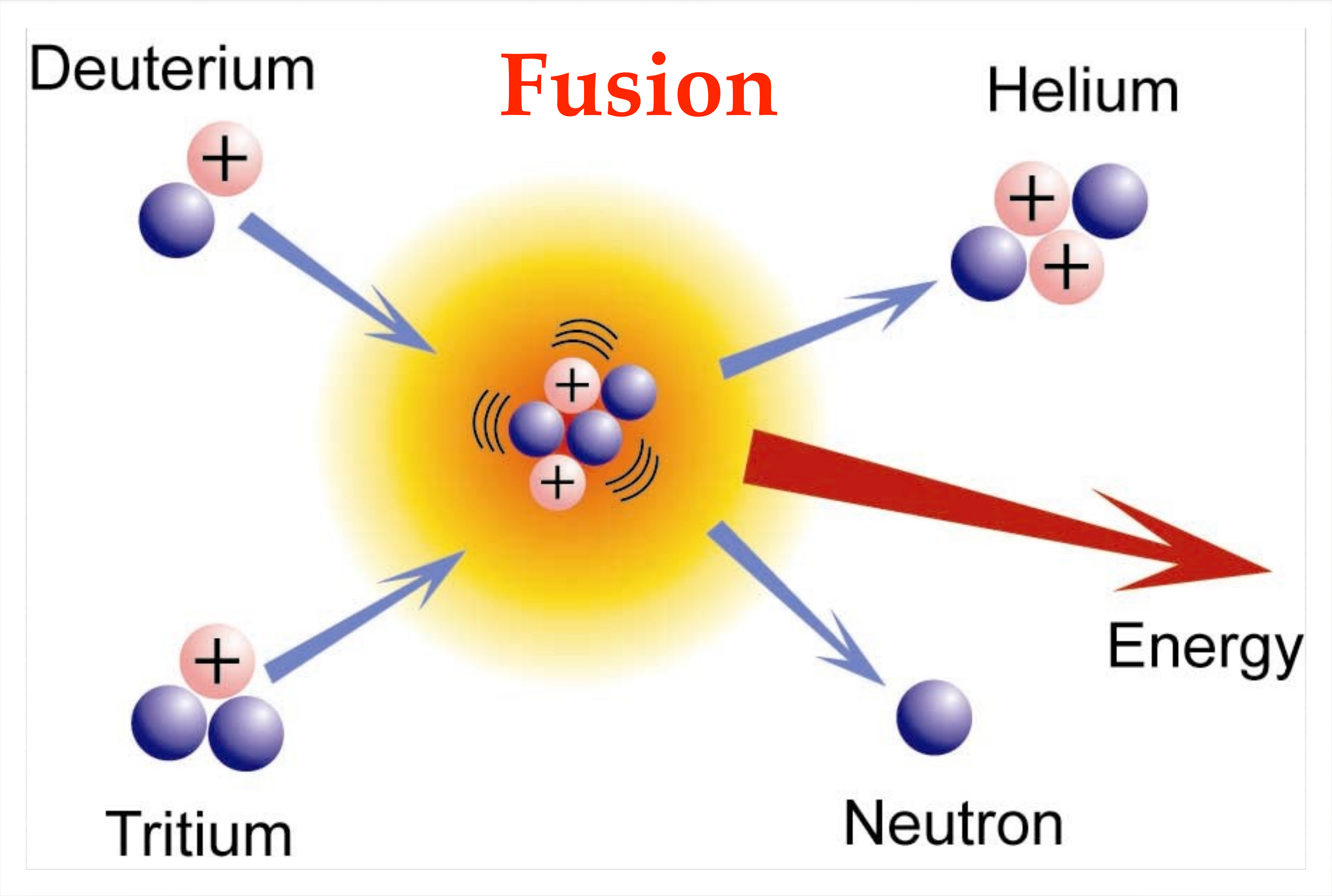


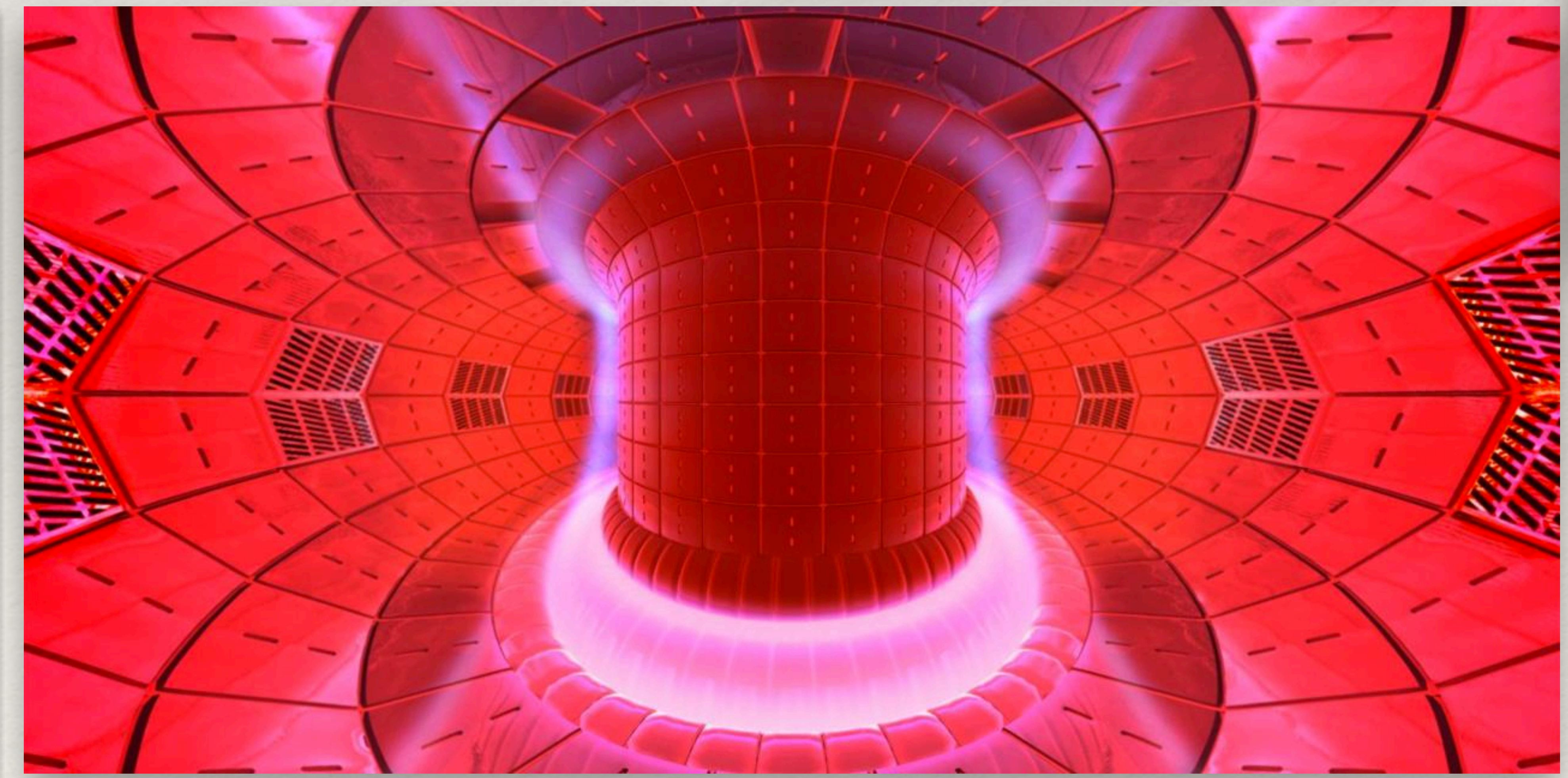


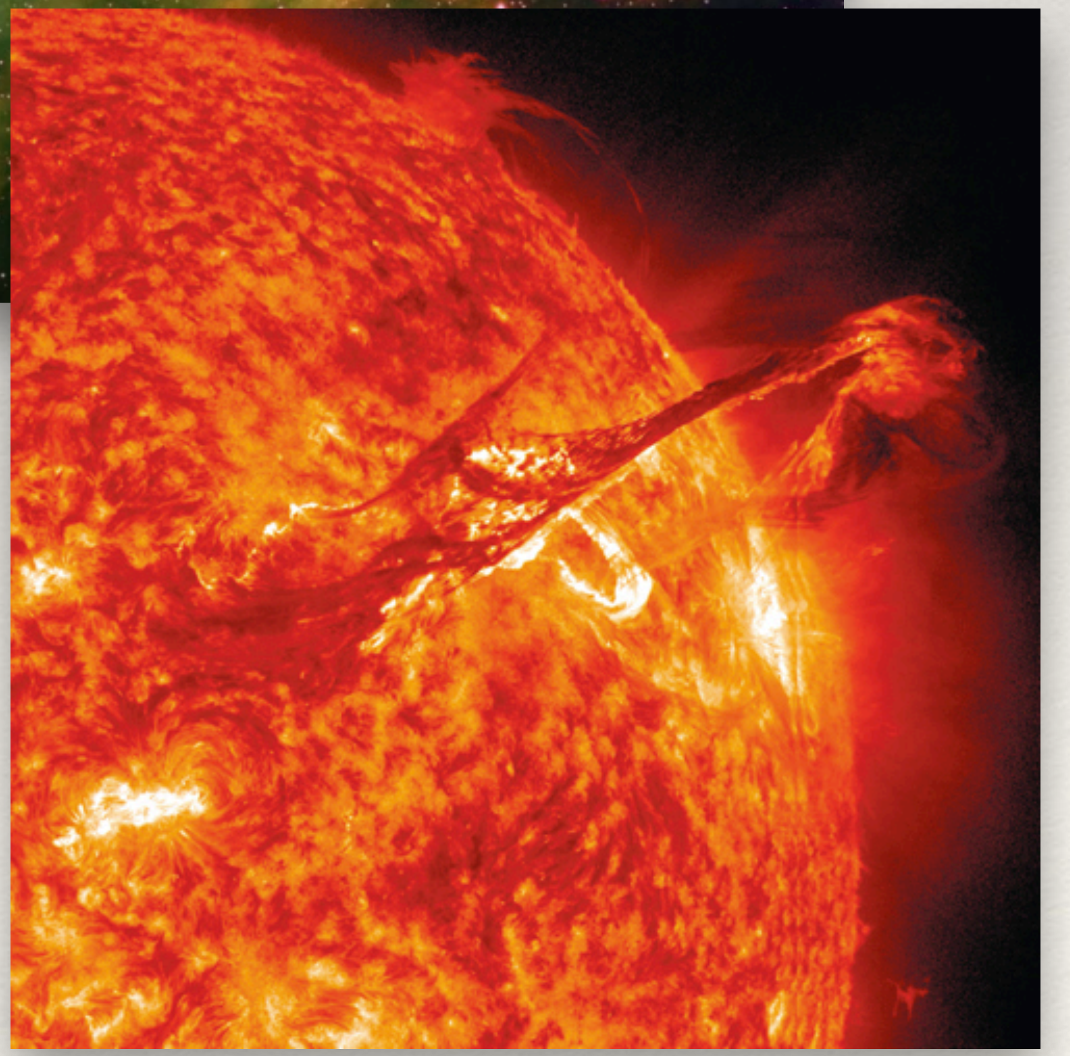
Source of Energy in the Universe



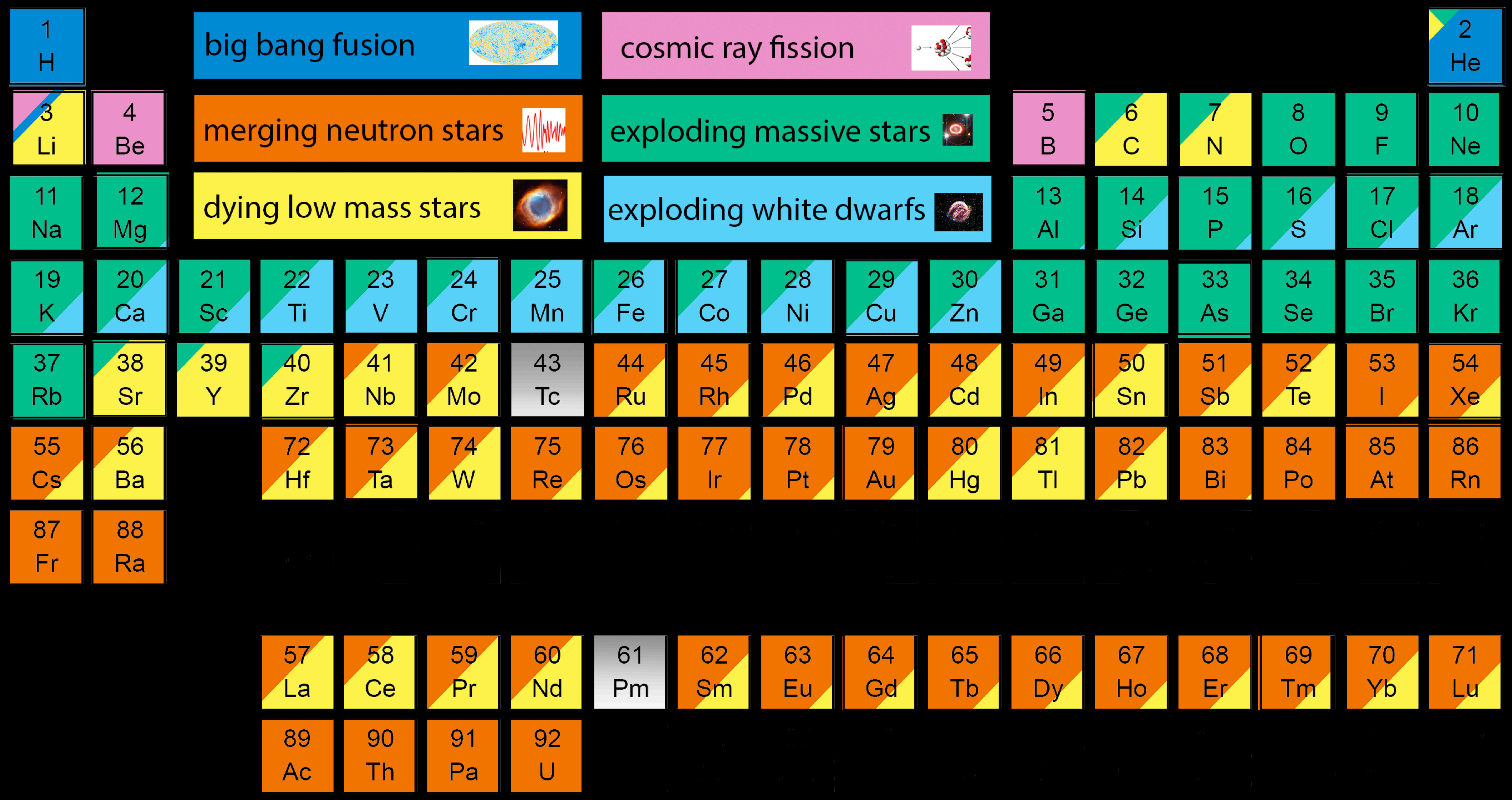








The Origin of the Solar System Elements



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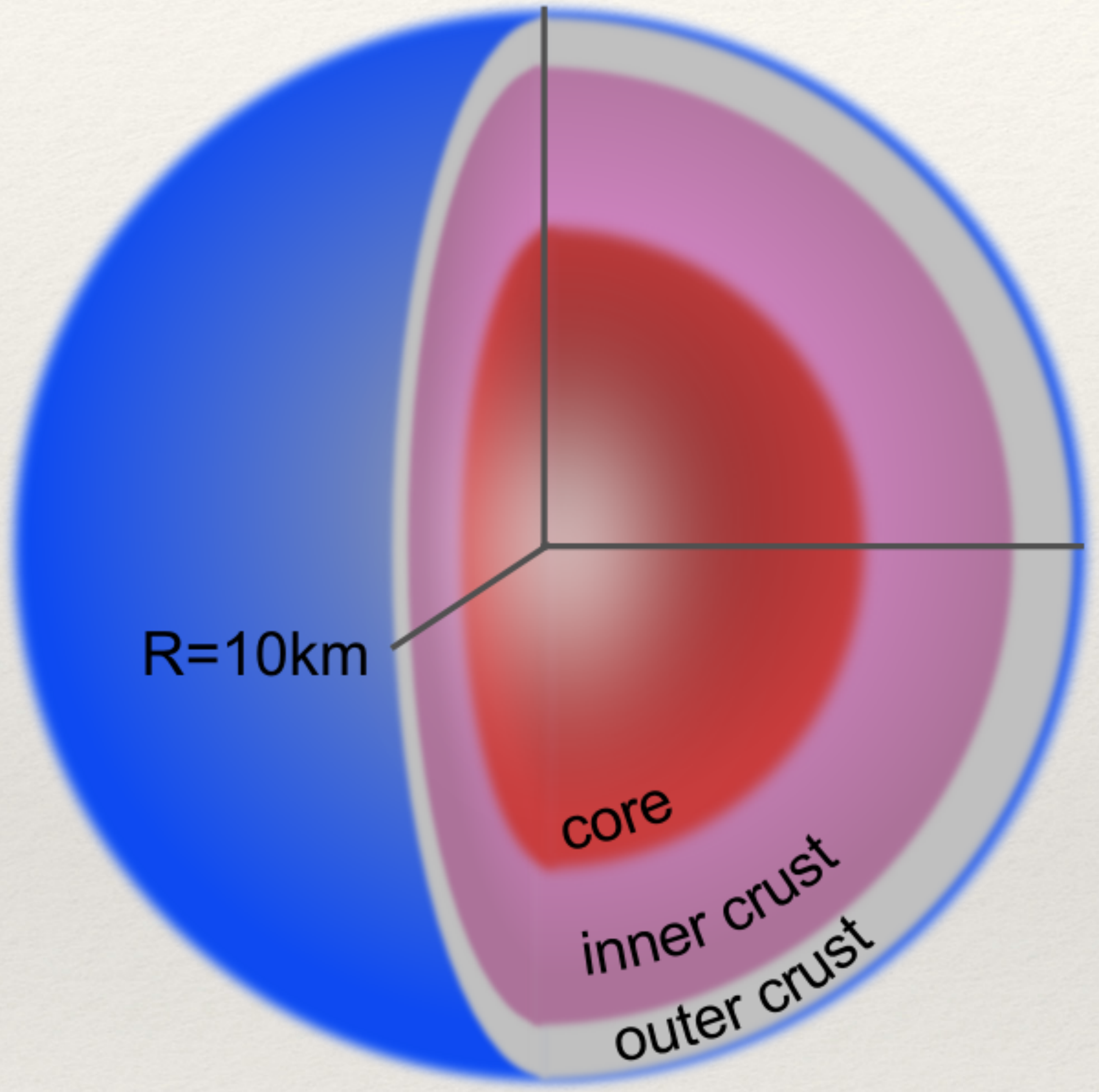
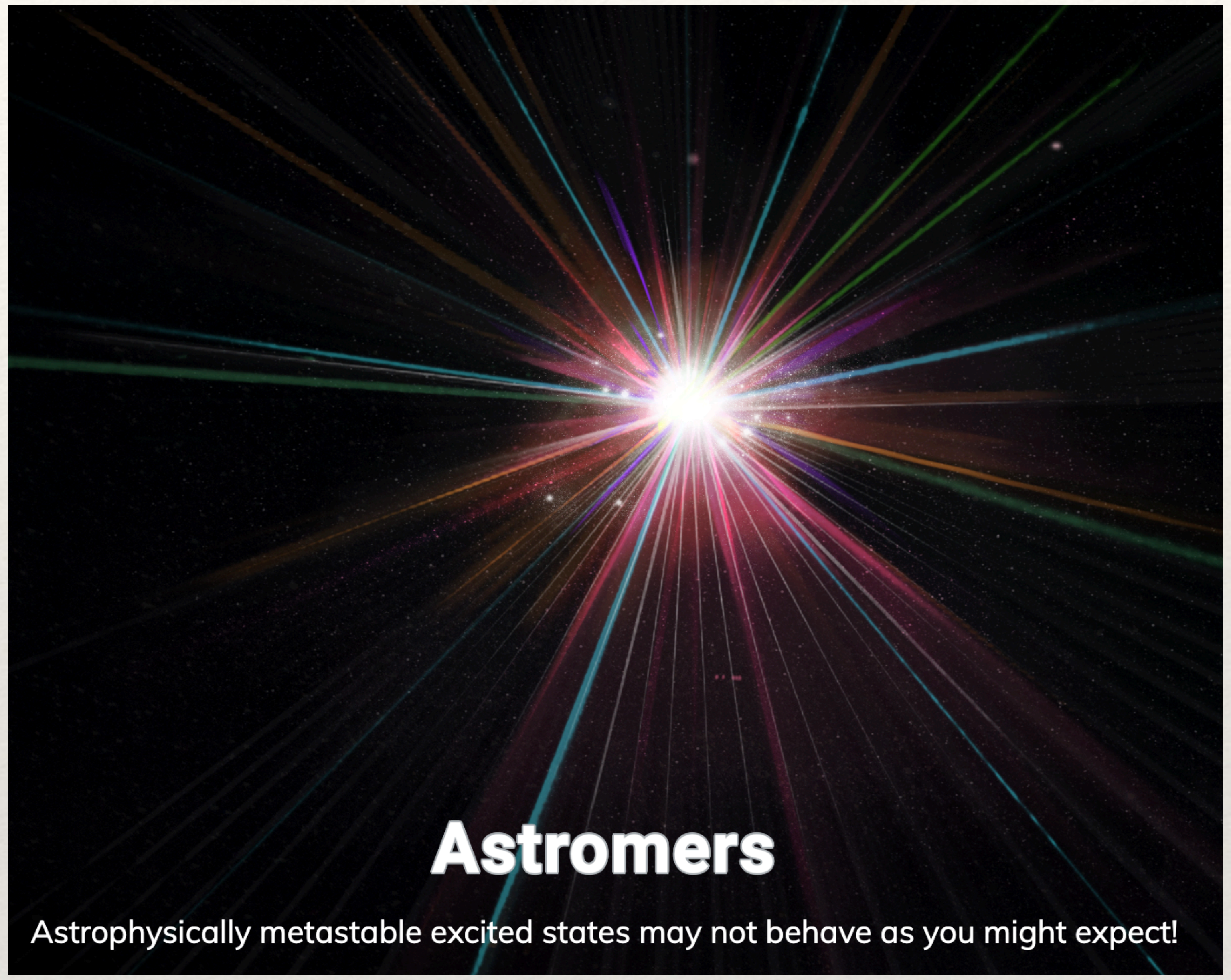
Graphic created by Jennifer Johnson

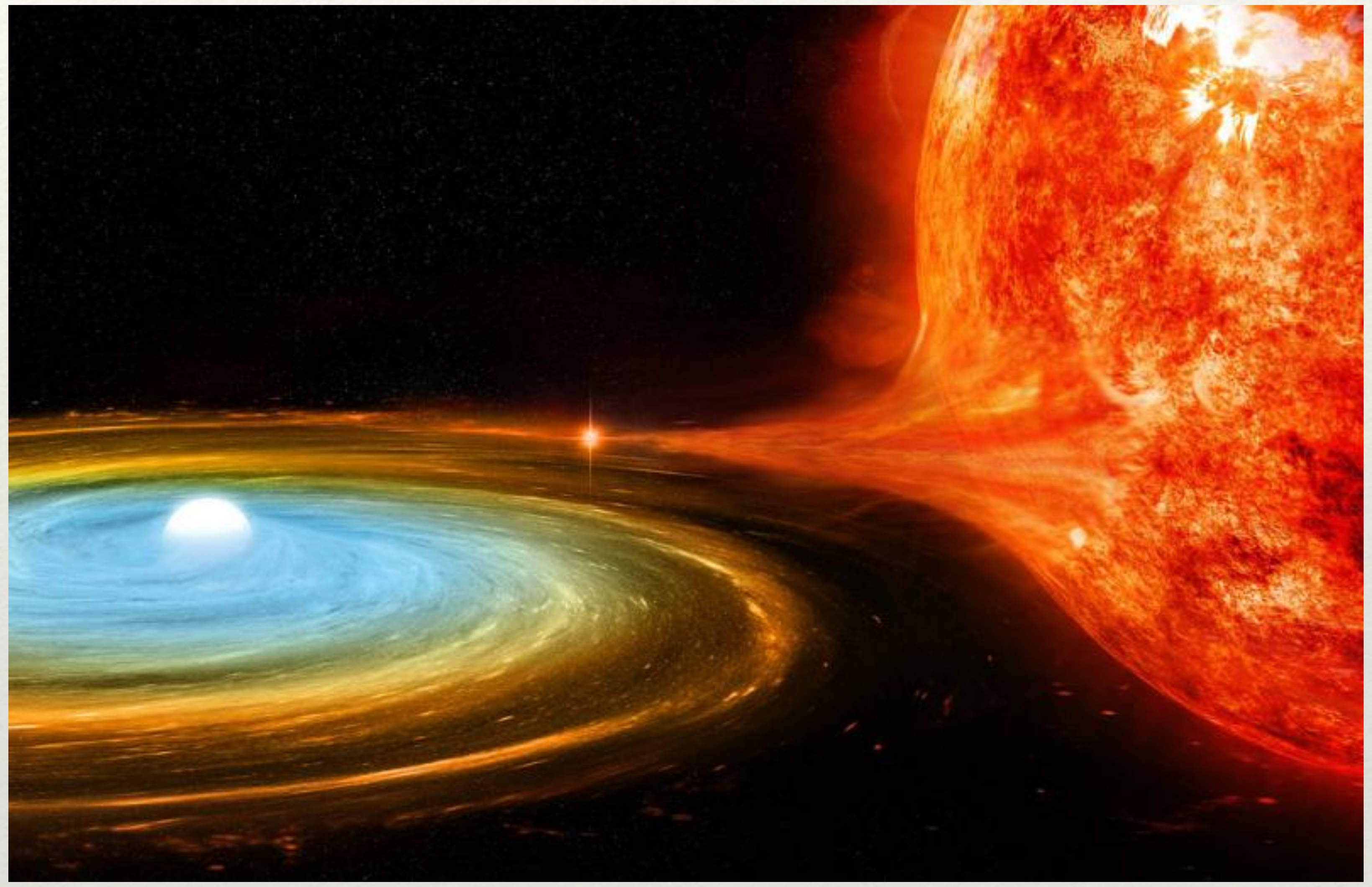
Other topics

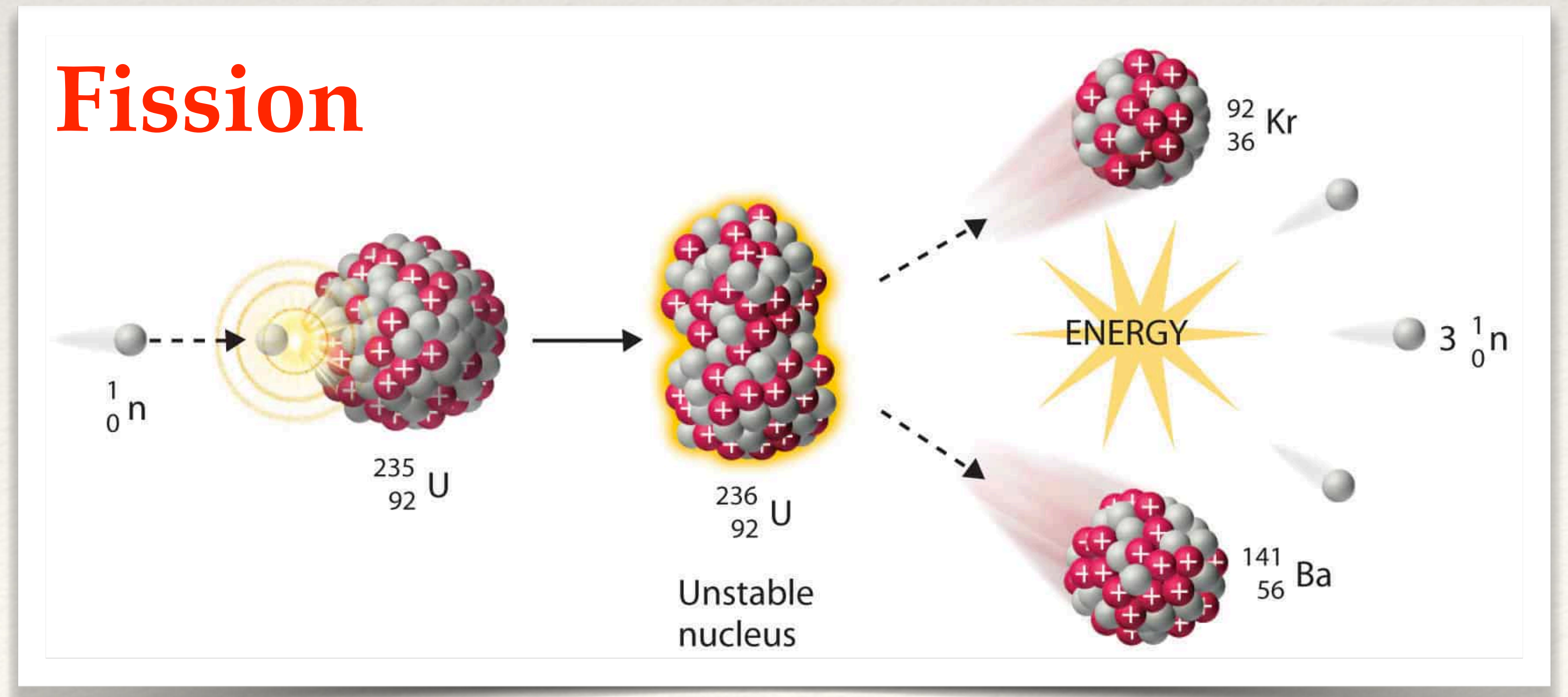
Neutron stars structure





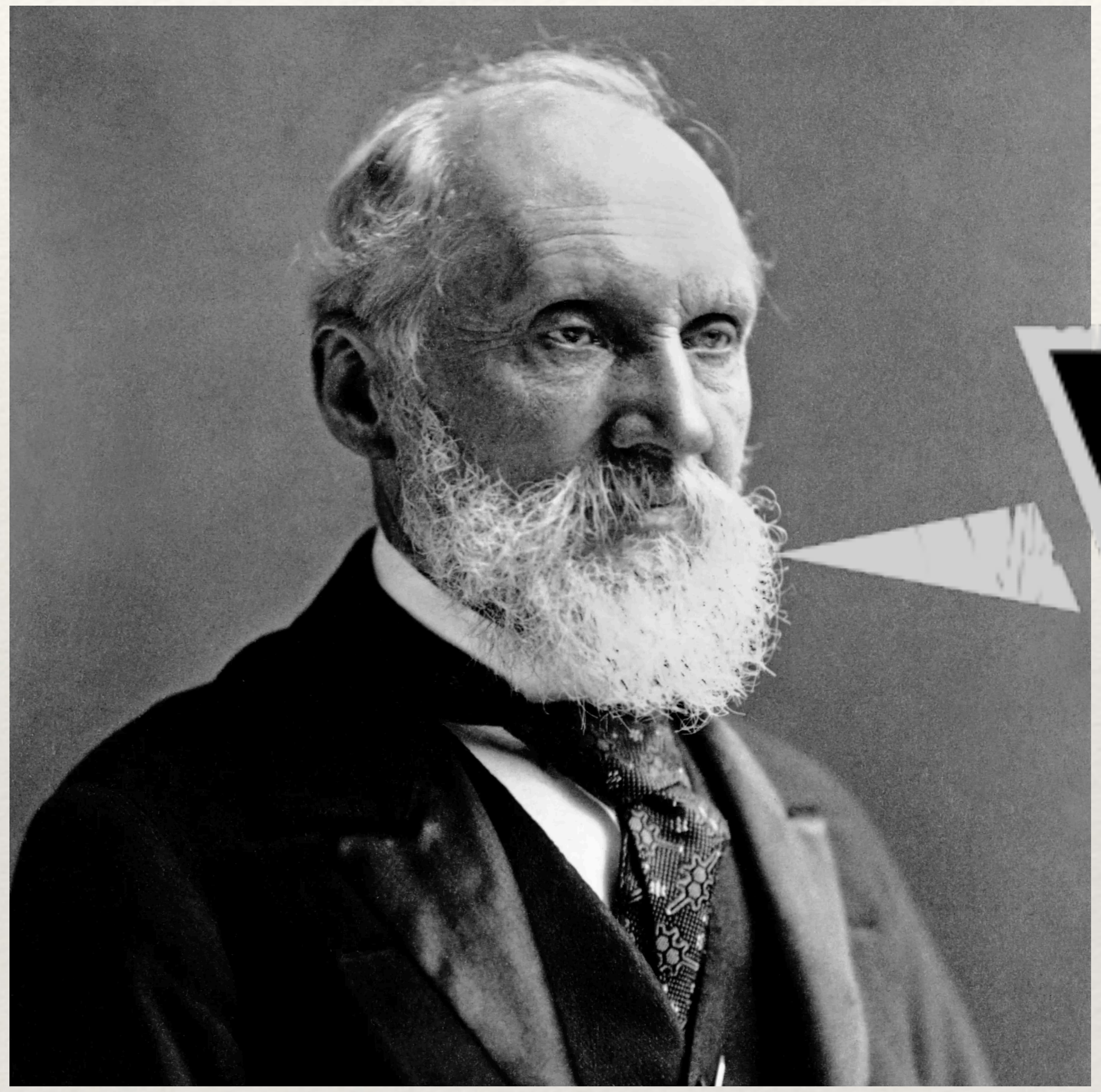
rp-process (Type I X-ray Bursts)



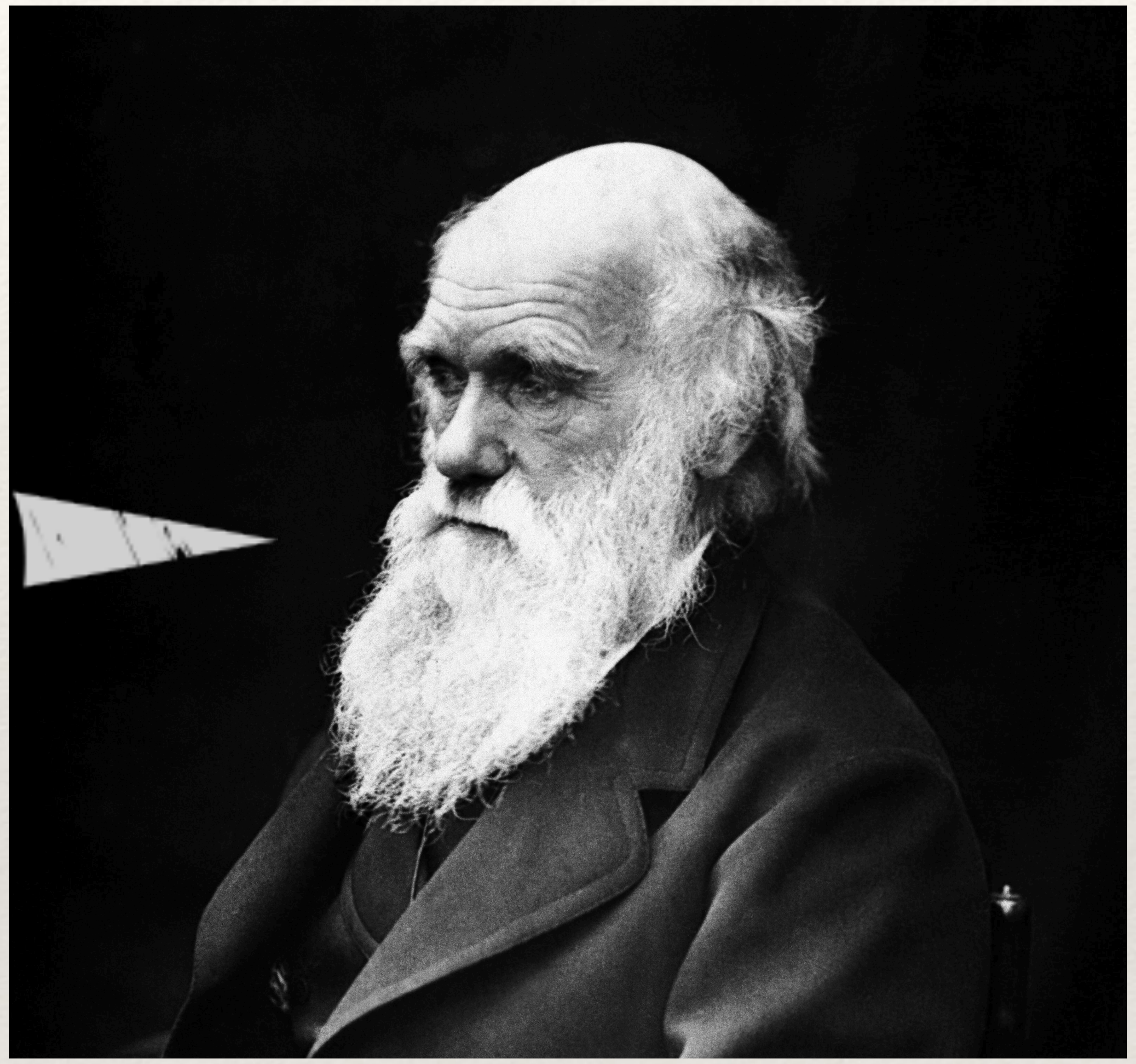


Age of the Earth crisis 1800s

Kelvin



Darwin

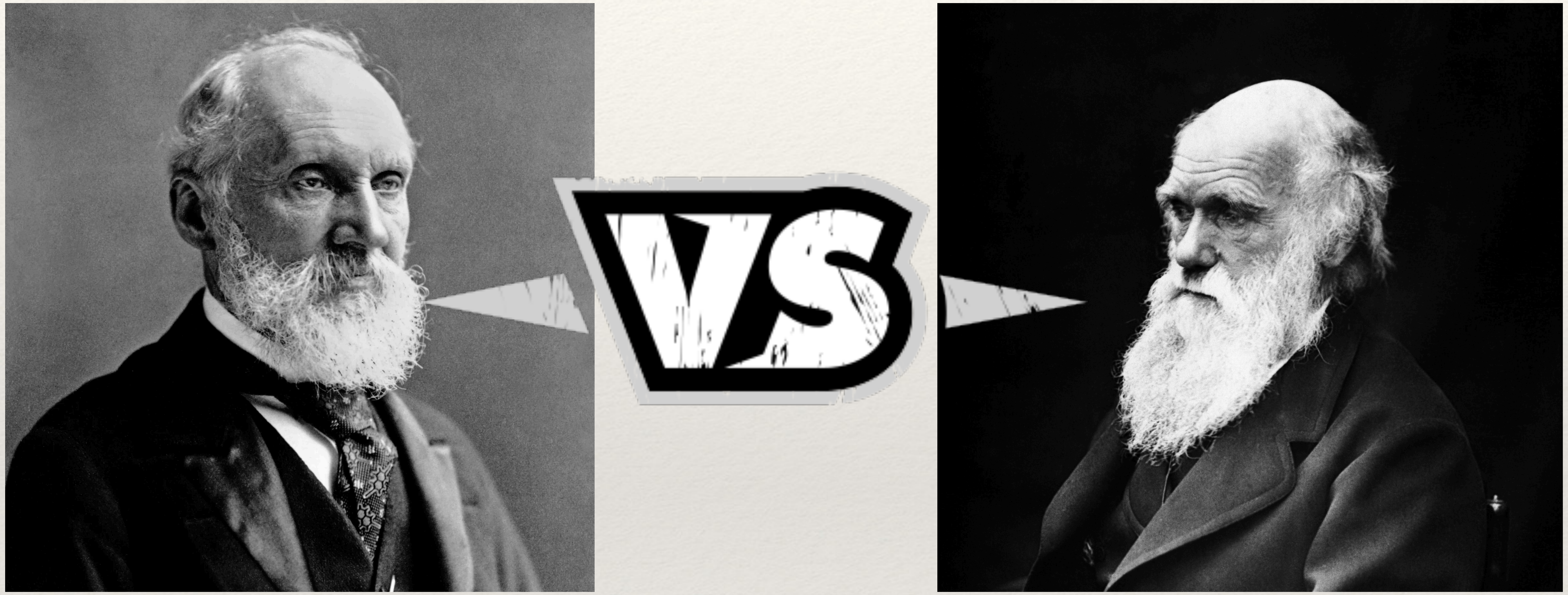


Age of Sun: 20 million years

Age of Earth: few 100s million years
Following geologist's estimation

Age of the Earth crisis 1800s

Kelvin | **Darwin**



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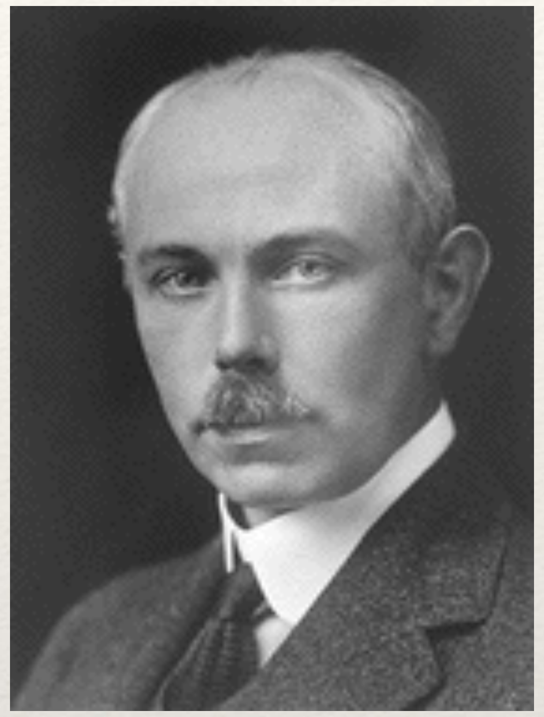
Radio France Inter
Darwin et le problème de l'age de la Terre

Discovery Atomic Mass defect

First Mass Spectrograph

$M_H = 1.008\ \mathrm{u}$

F.W. Aston



Discovering about 200 isotopes

Discovery Atomic Mass defect

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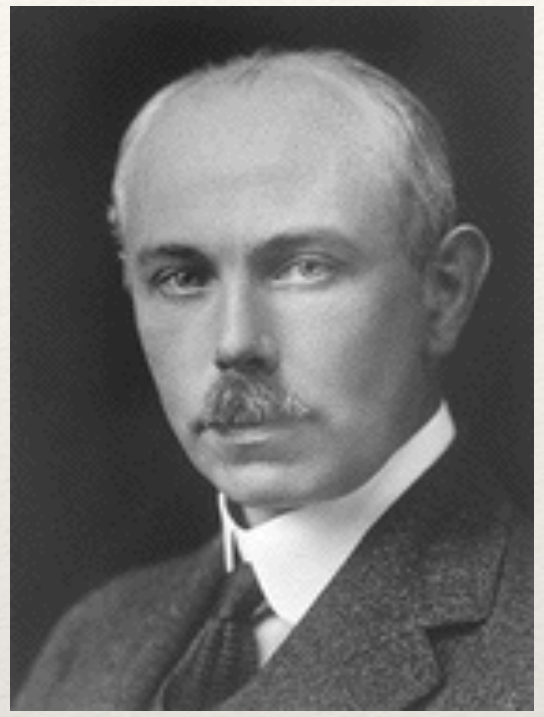

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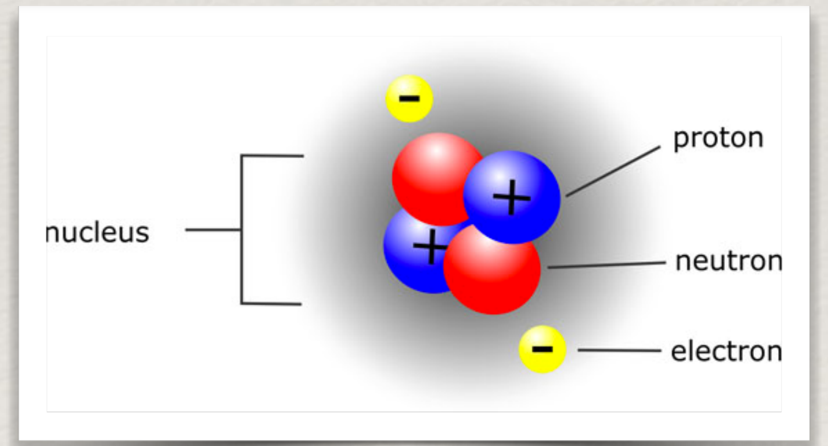

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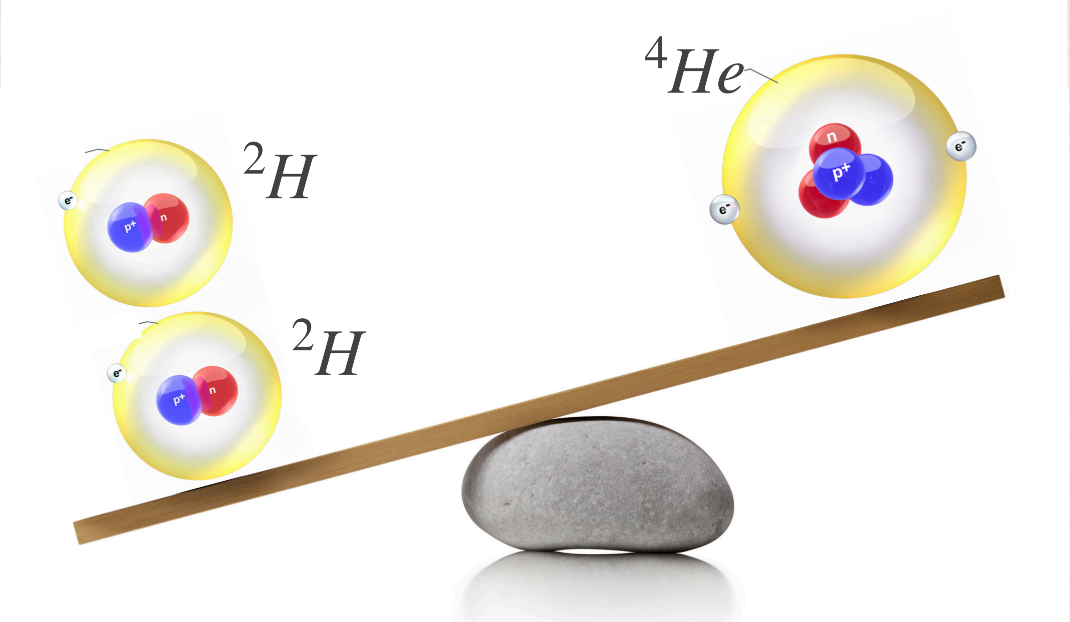

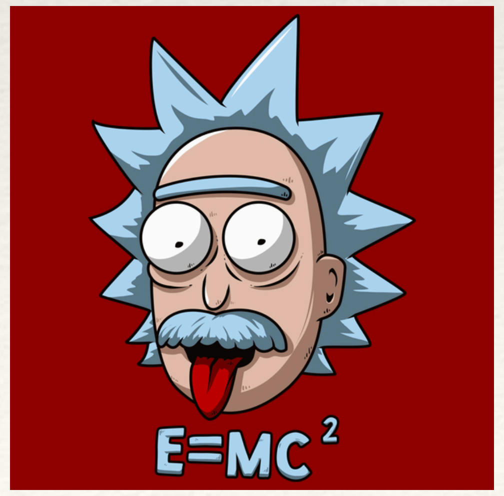

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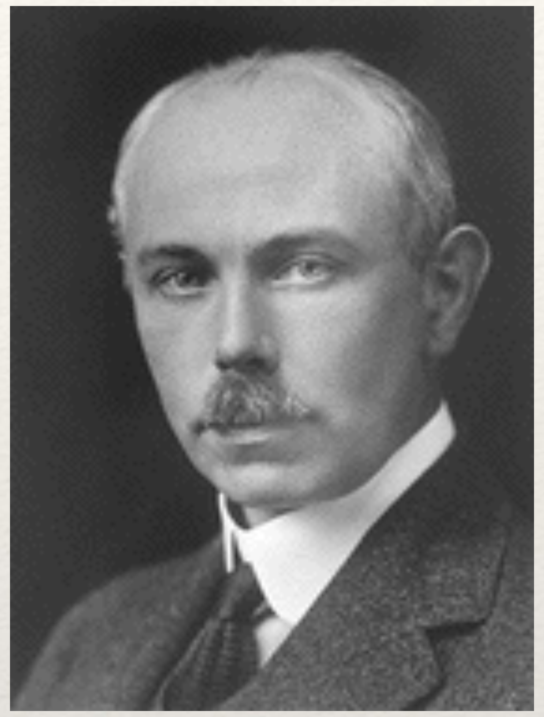

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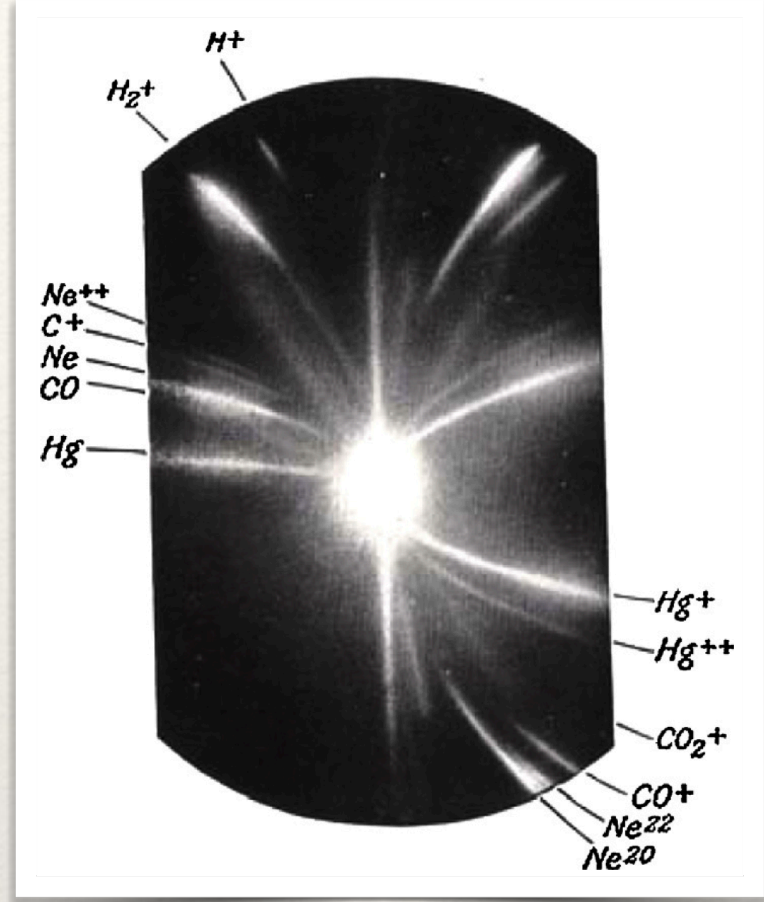
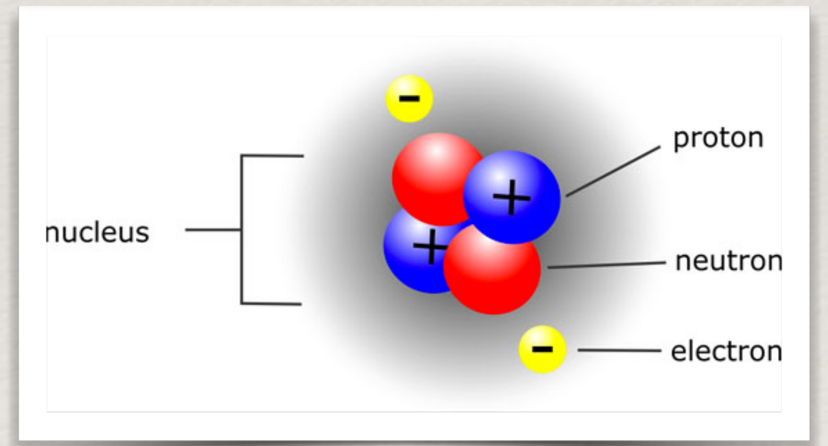


1913 discovery of isotopes (Ne)



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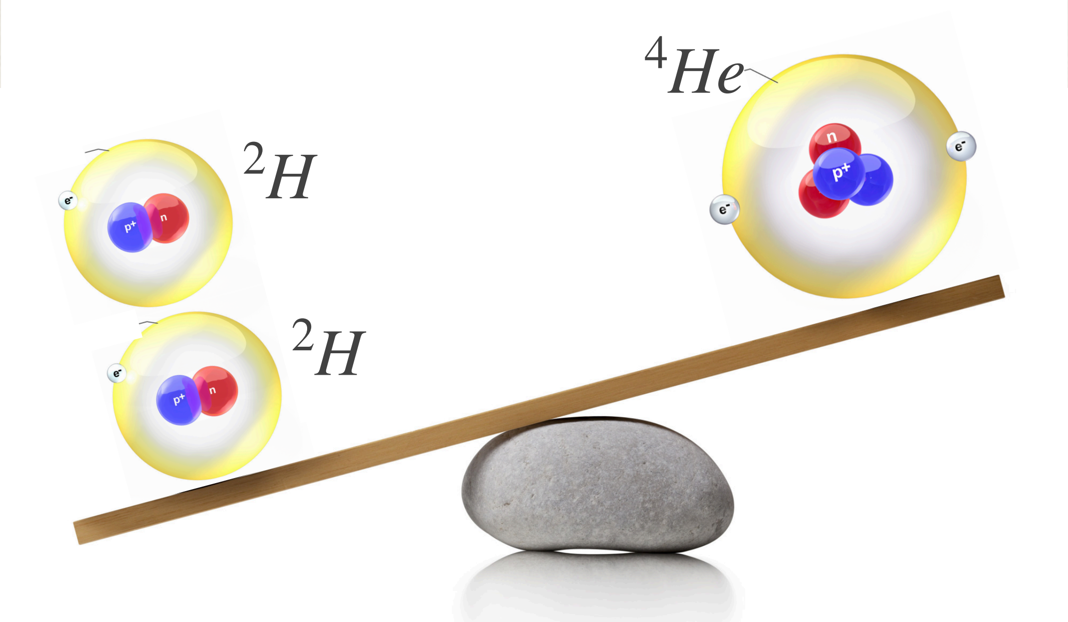
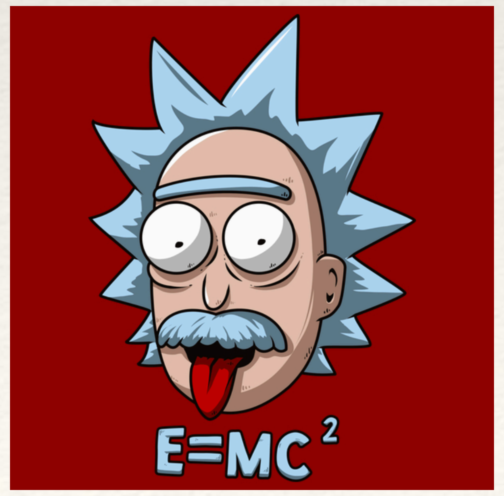
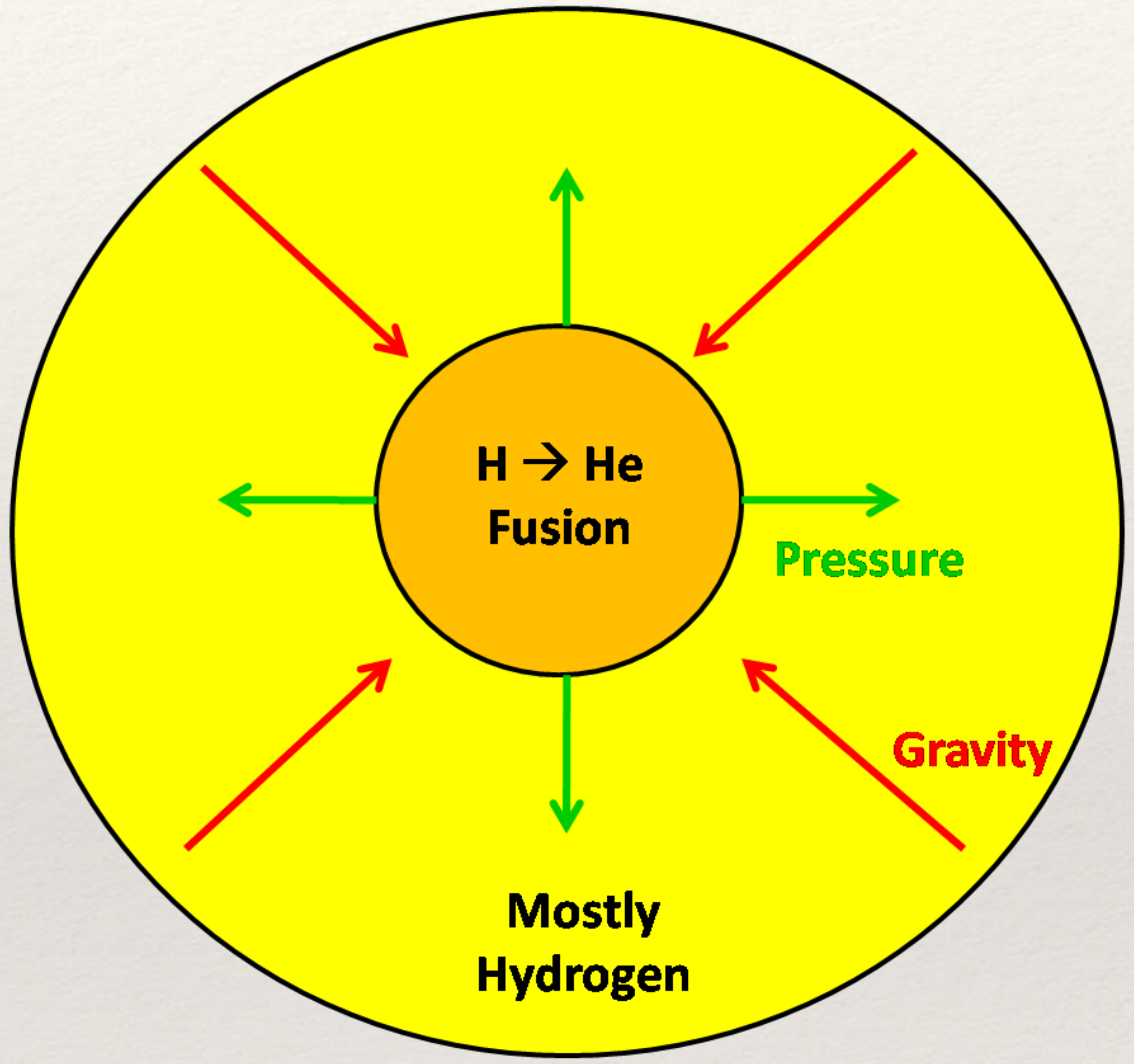




Solving the age of the Earth crisis

Eddington

The Sun



$$Lifetime = \frac{Energy}{Luminosity} = \frac{Mc^2}{L_{sun}} = \frac{0.007 \cdot 0.1 \cdot M_{sun} \cdot c^2}{L_{sun}} \approx \text{10 Billion years}$$

$[L_{sun}] = E/t$

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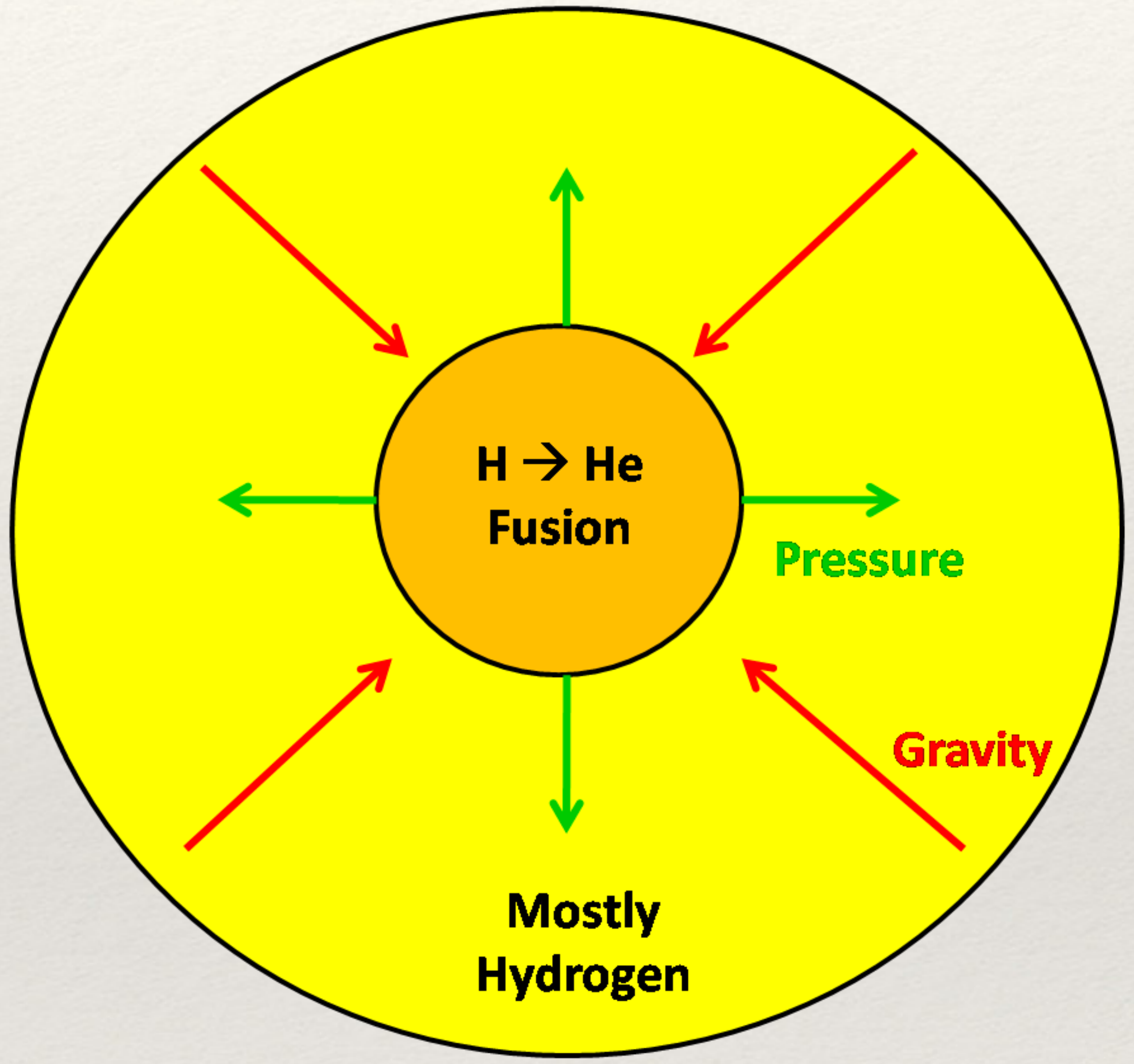

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10% of the Sun undergo fusion

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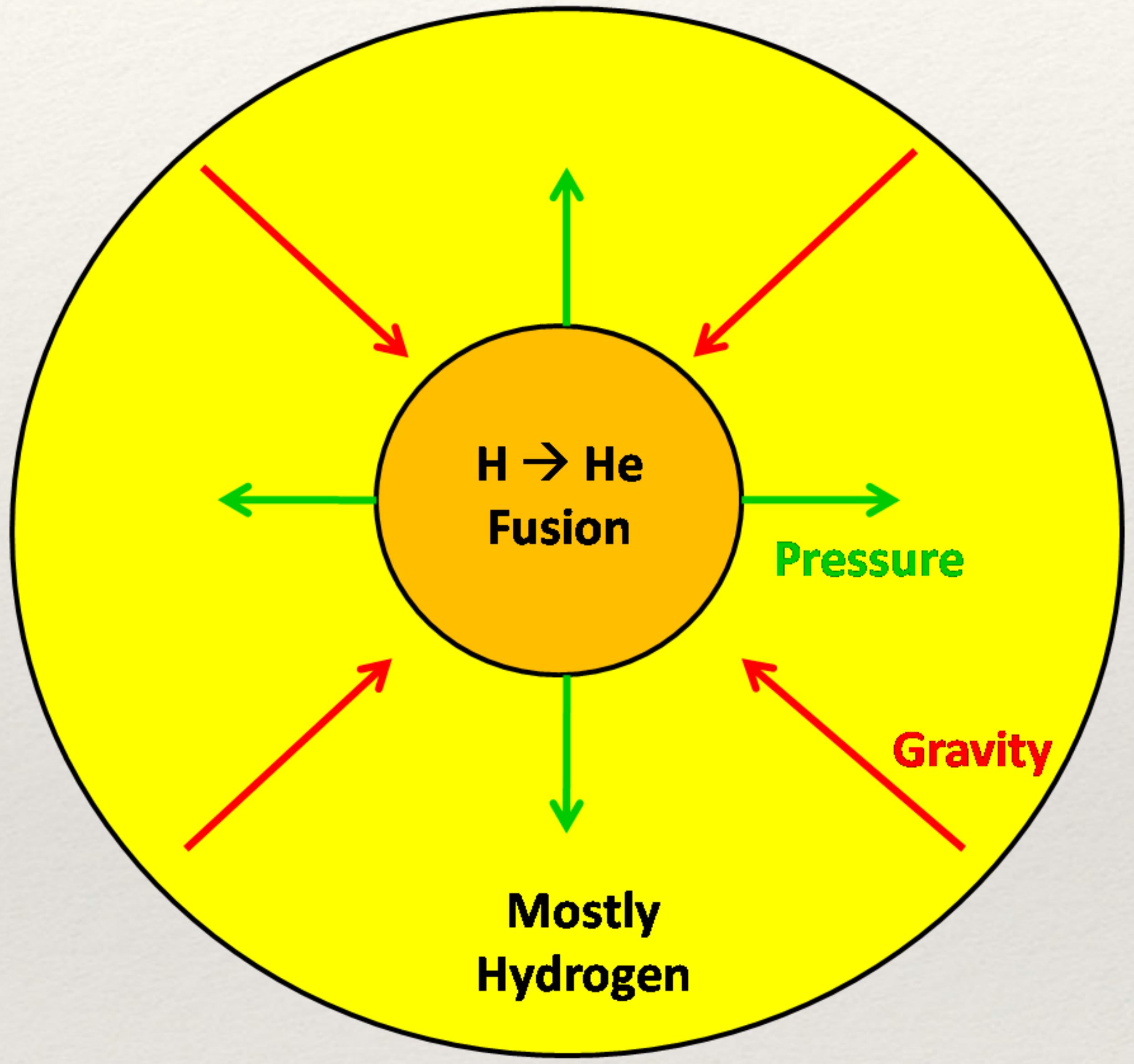

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10% of the Sun undergo fusion

0.7% atomic mass difference between 4xH and ^{4}He

Nier's mass spectrometer

Transition from Spectrograph to Spectrometer

A. O. Nier 1951, Phys. Rev 81, 507

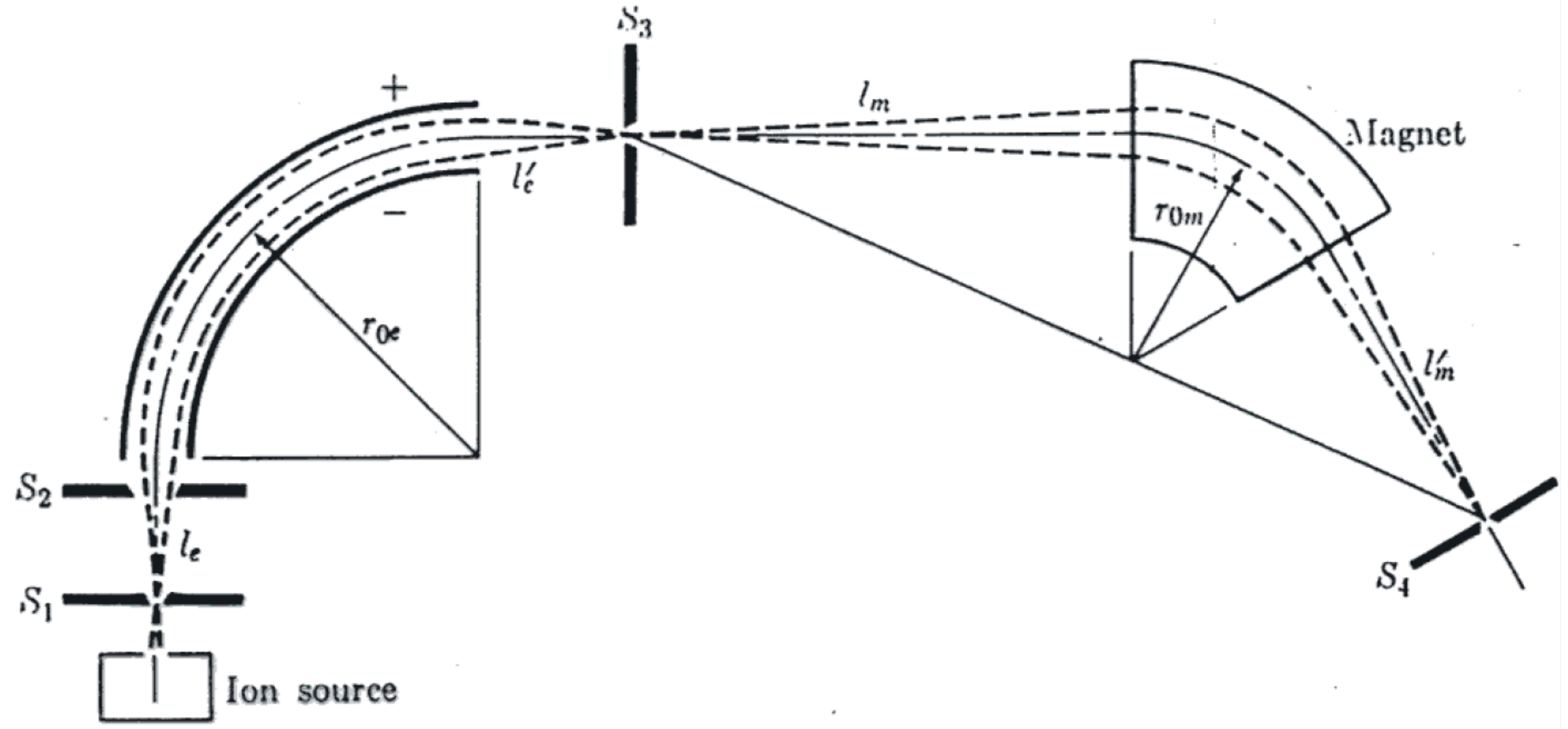


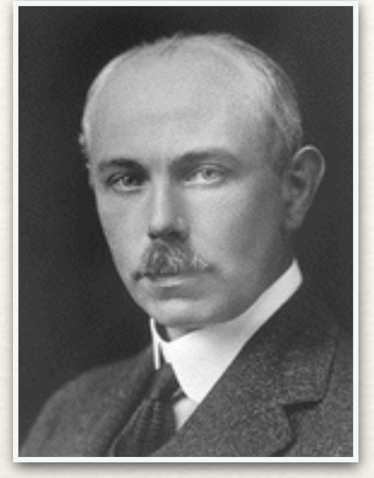
Fig. 4-3. Principle of operation of Nier's spectrograph.

For NASA

Large impact in many areas:

- Geochronology
  - ^{40}K discovery—> K-Ar Geochronology
  - Age of the earth from U,Th-Pb technique
- Stable isotope geochemistry
- Nuclear physics (U isotopic separation—> fission 1st controlled nuclear chain reaction)
- Extra-terrestrial materials (Mars & Venus Atmosphere)

Atomic Masses & Nuclear Physics Discoveries



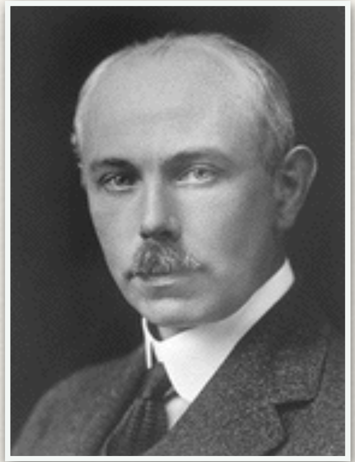
F.W. Aston

Mass defect

$M_H = 1.008$ u

1919 1933-1934 1948 1951 1954 1974

Atomic Masses & Nuclear Physics Discoveries



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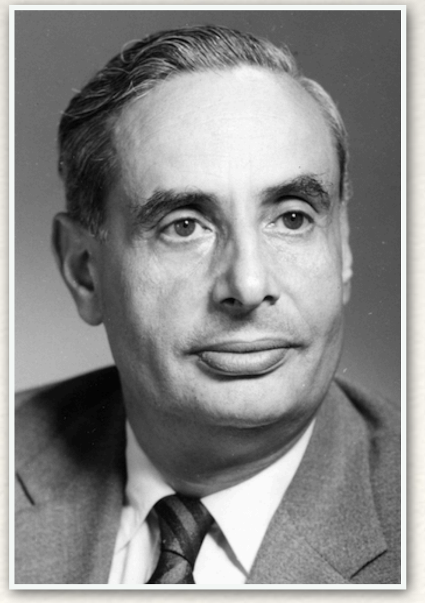
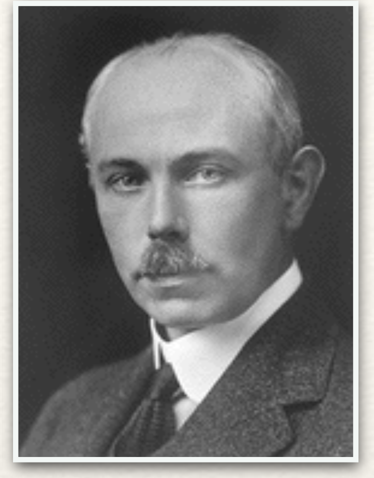


Discovery of
magic numbers
Z=2,8,20,28,50
N=126,82

Atomic Masses & Nuclear Physics Discoveries



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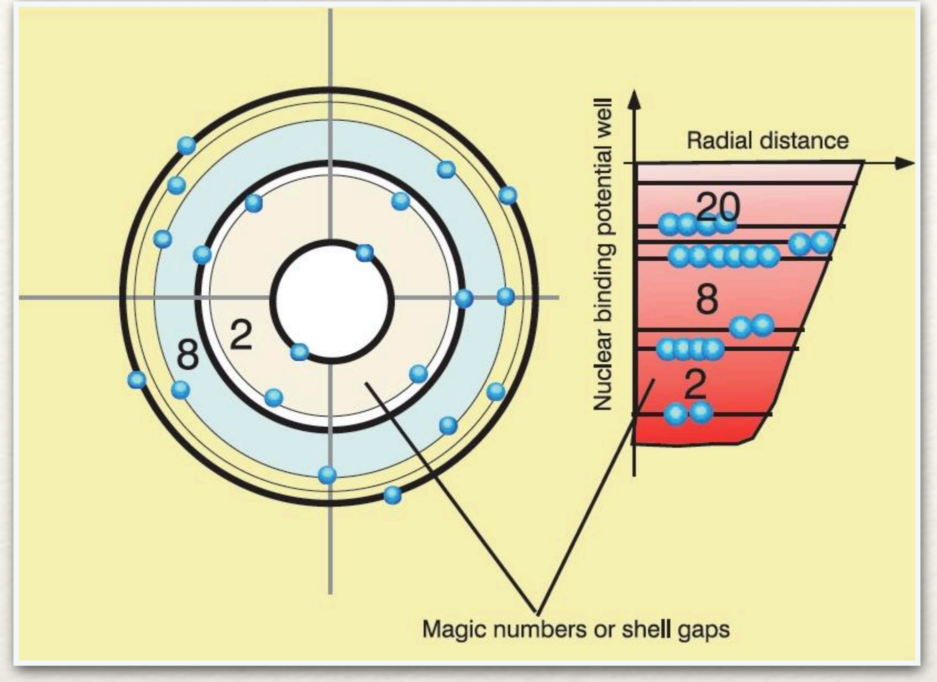

Nuclear Shell Model

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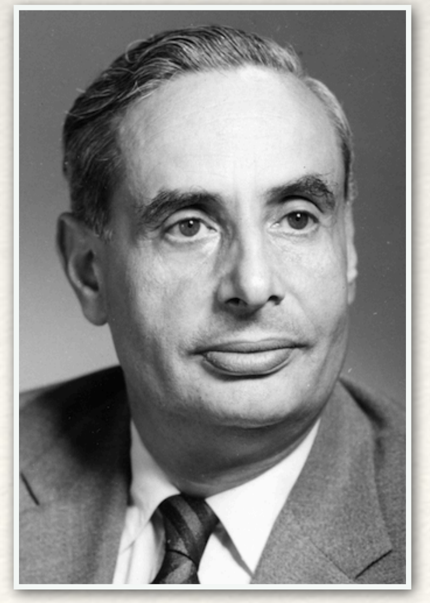
W. Elsasser



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Goeppert-Mayer

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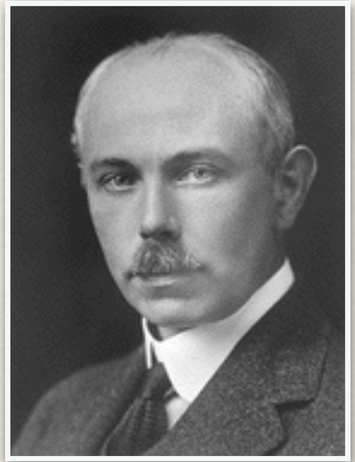

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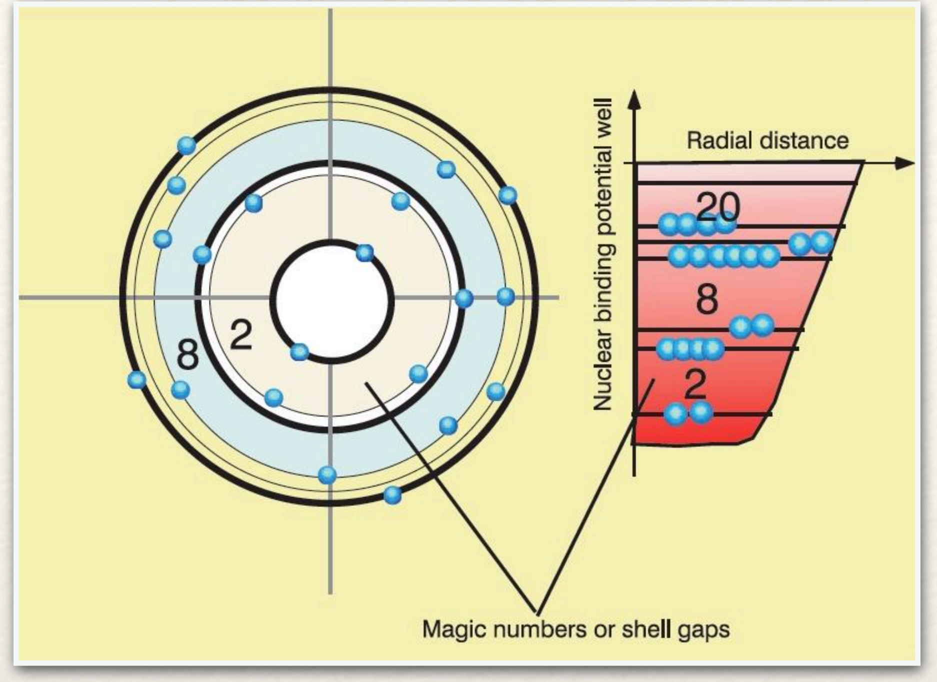

Nuclear Shell Model

Nier's spectrometry

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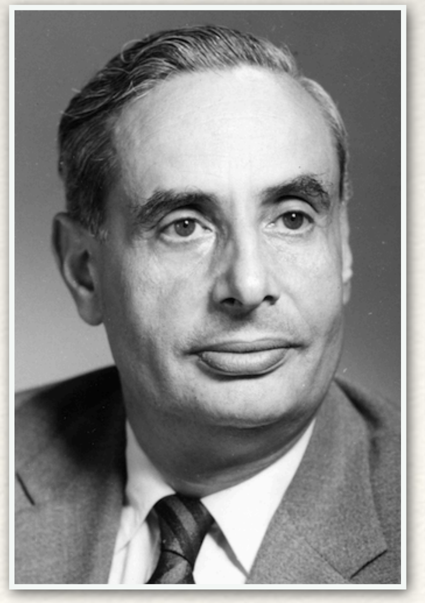

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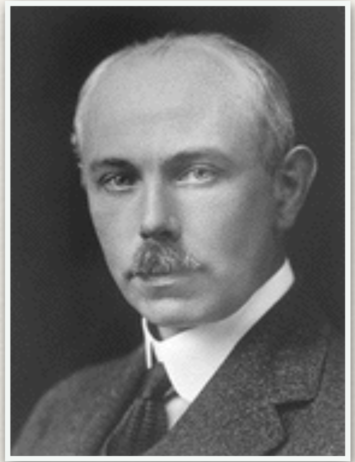

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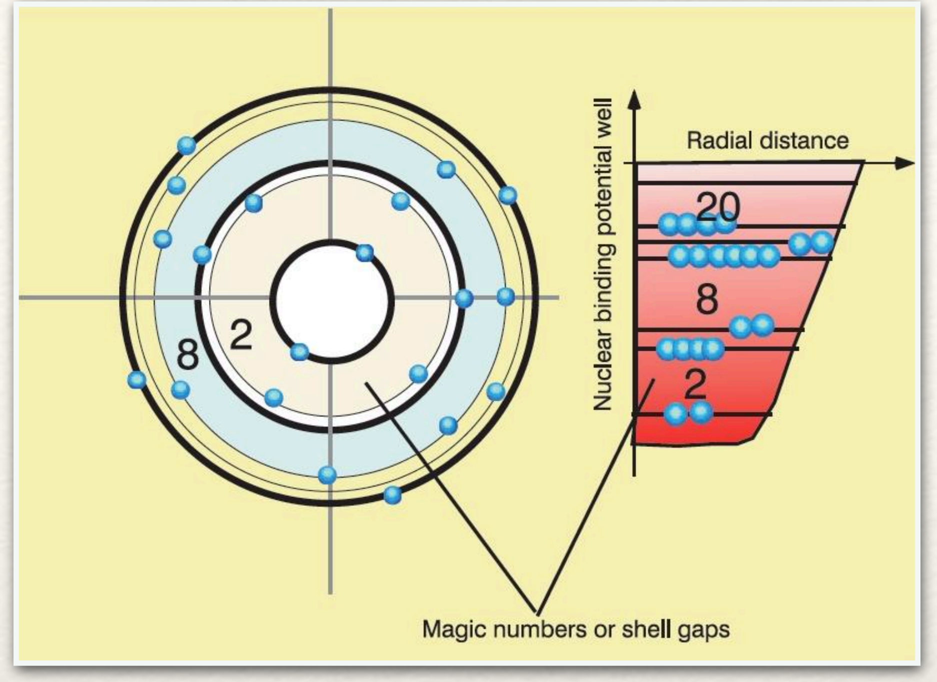

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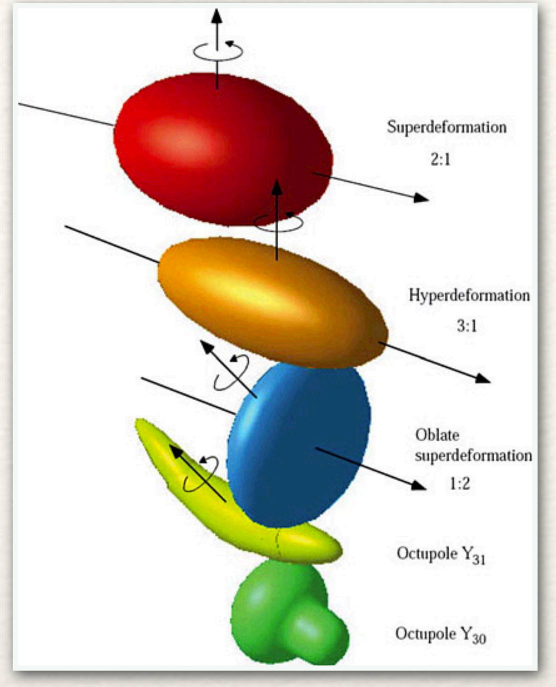
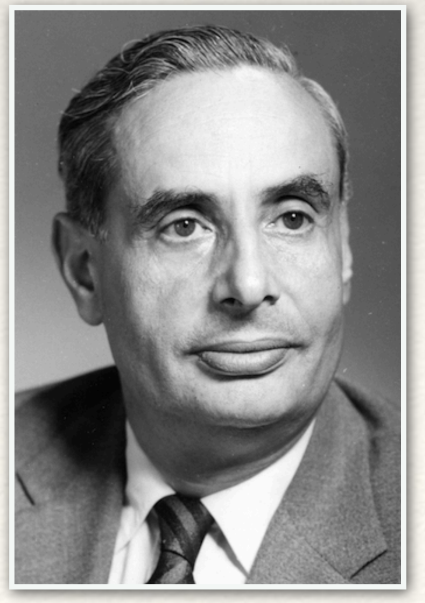


Nuclear deformation at N=90

1919 | 1933-1934 | 1948 | 1951 | 1954 | 1974

W. Elsasser



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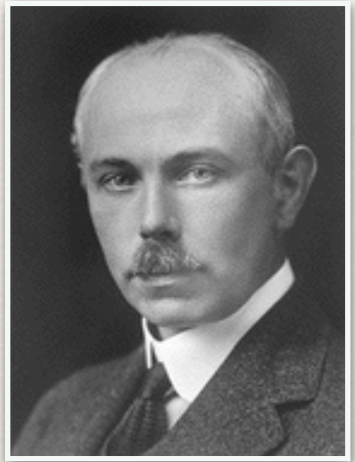

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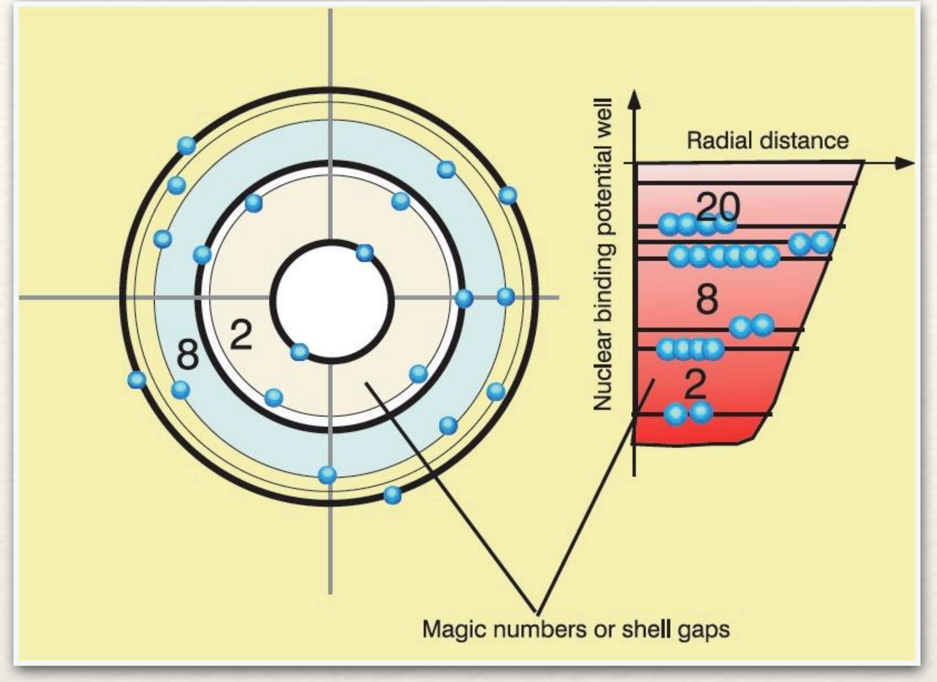
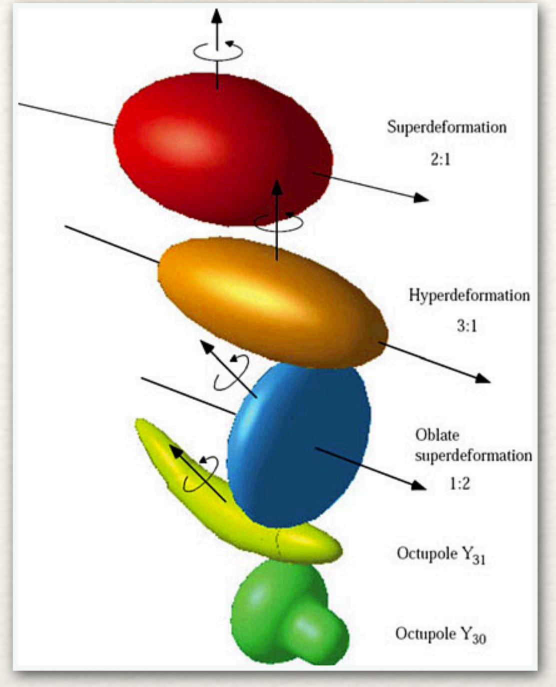


Nuclear Shell Model

Nier's spectrometry



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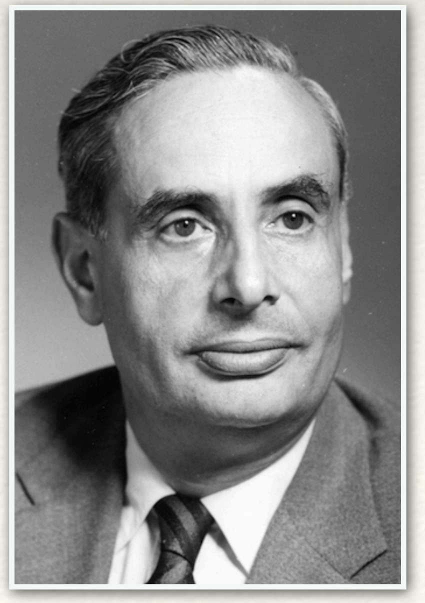


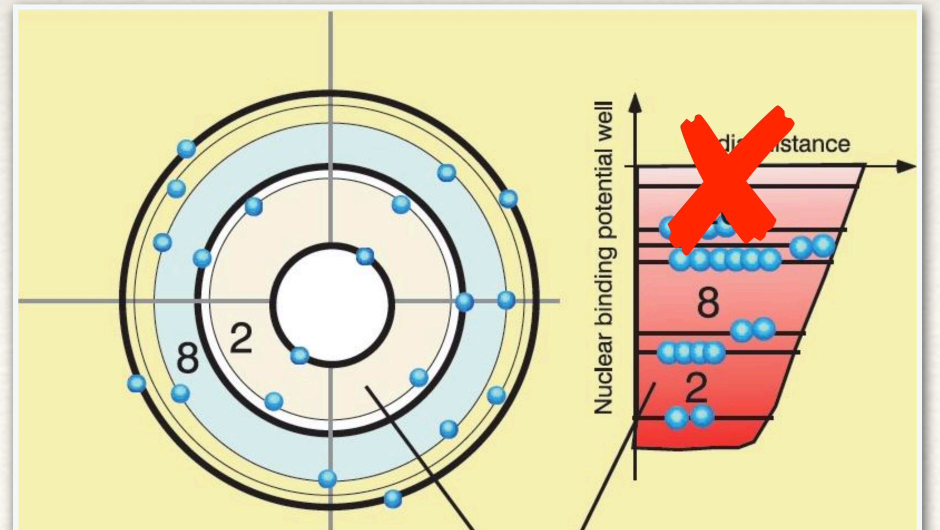
Discovery of **magic numbers**

Z=2,8,20,28,50

N=126,82

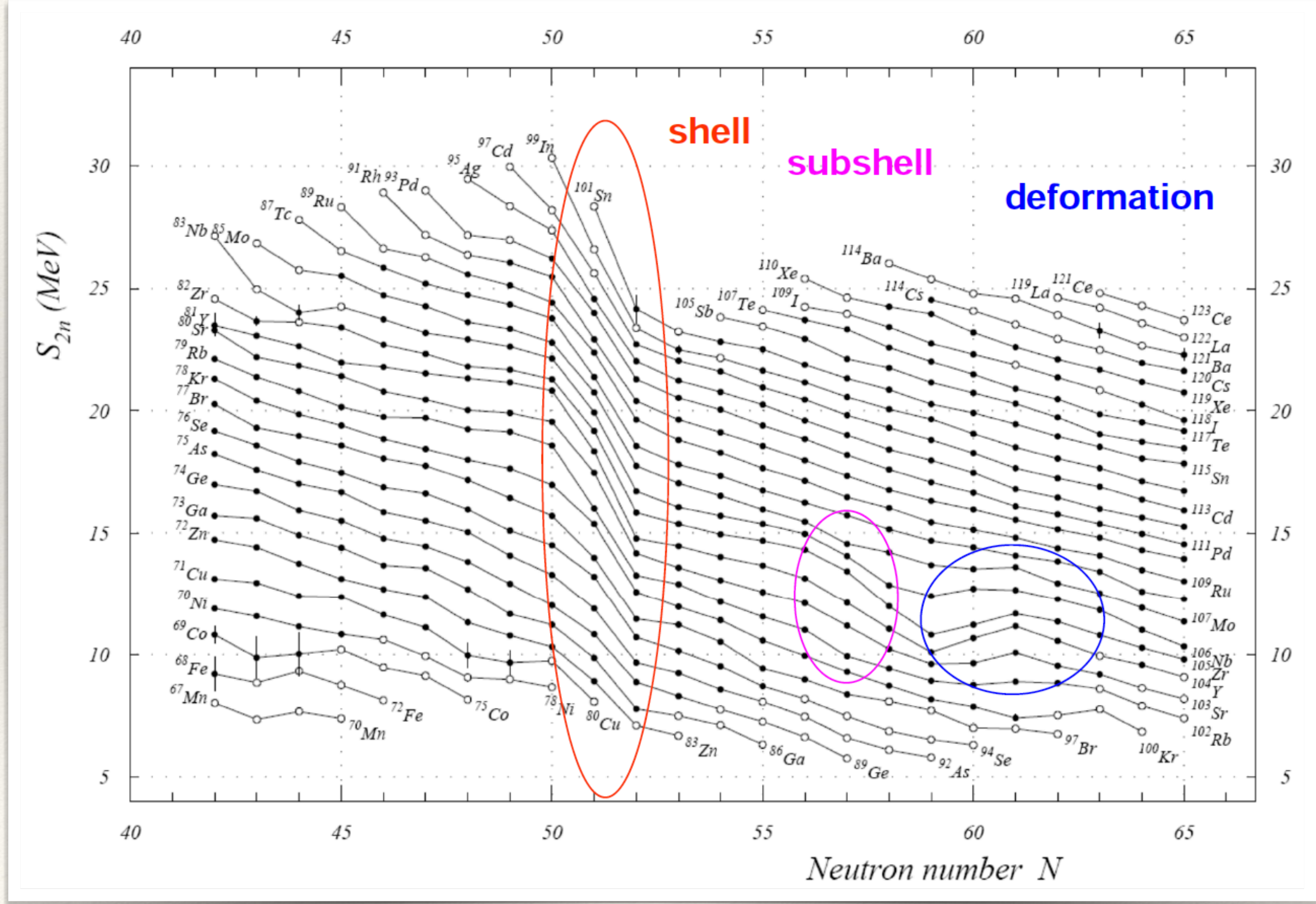
Goeppert-Mayer

Disappearance of magic number N=20



Nuclear Structure from Atomic Masses

Two neutron separation energy $S_{2n}(Z, N) = B(Z, N) - B(Z, N - 2)$



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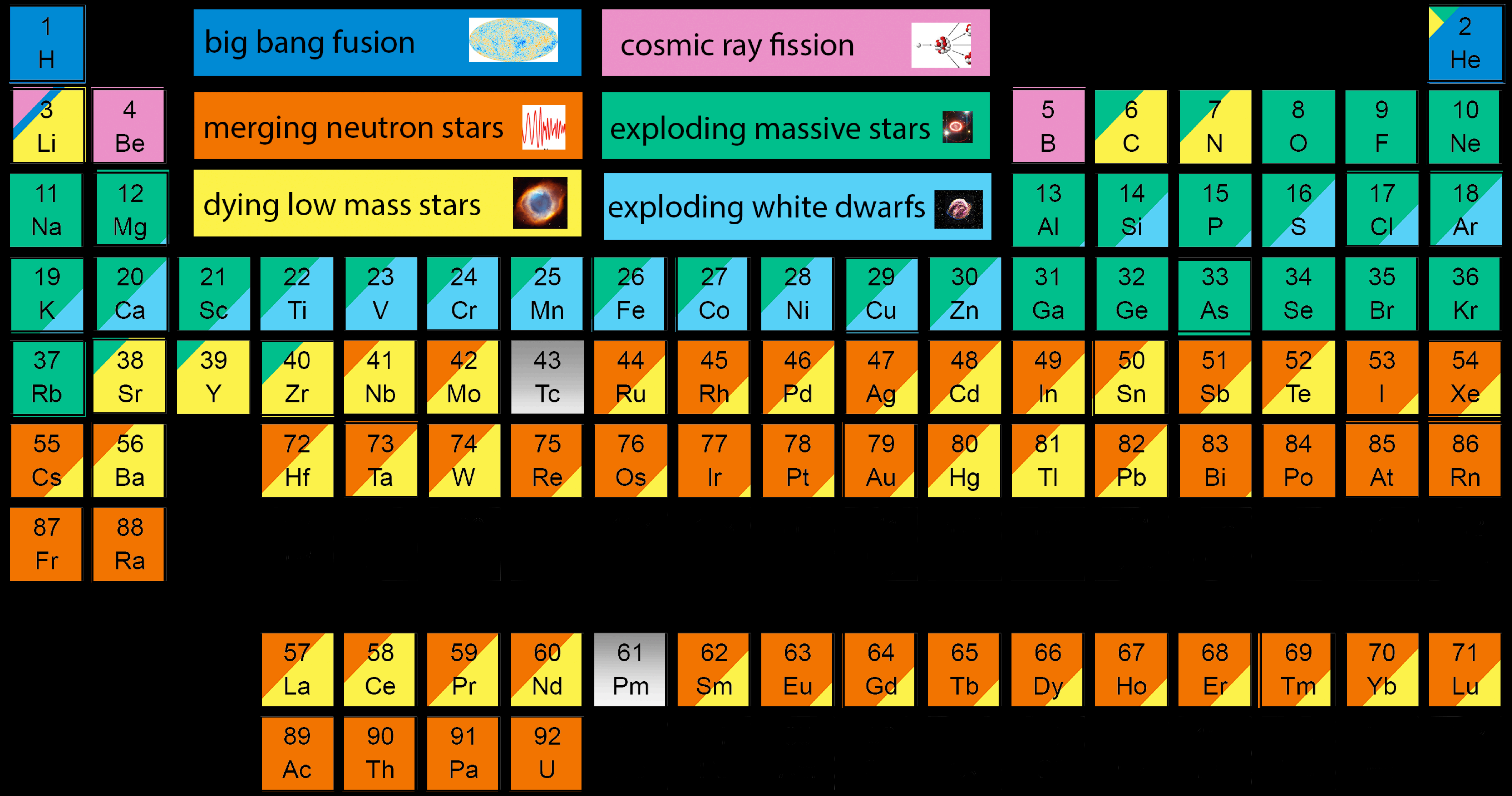

Astronomical Image Credits:
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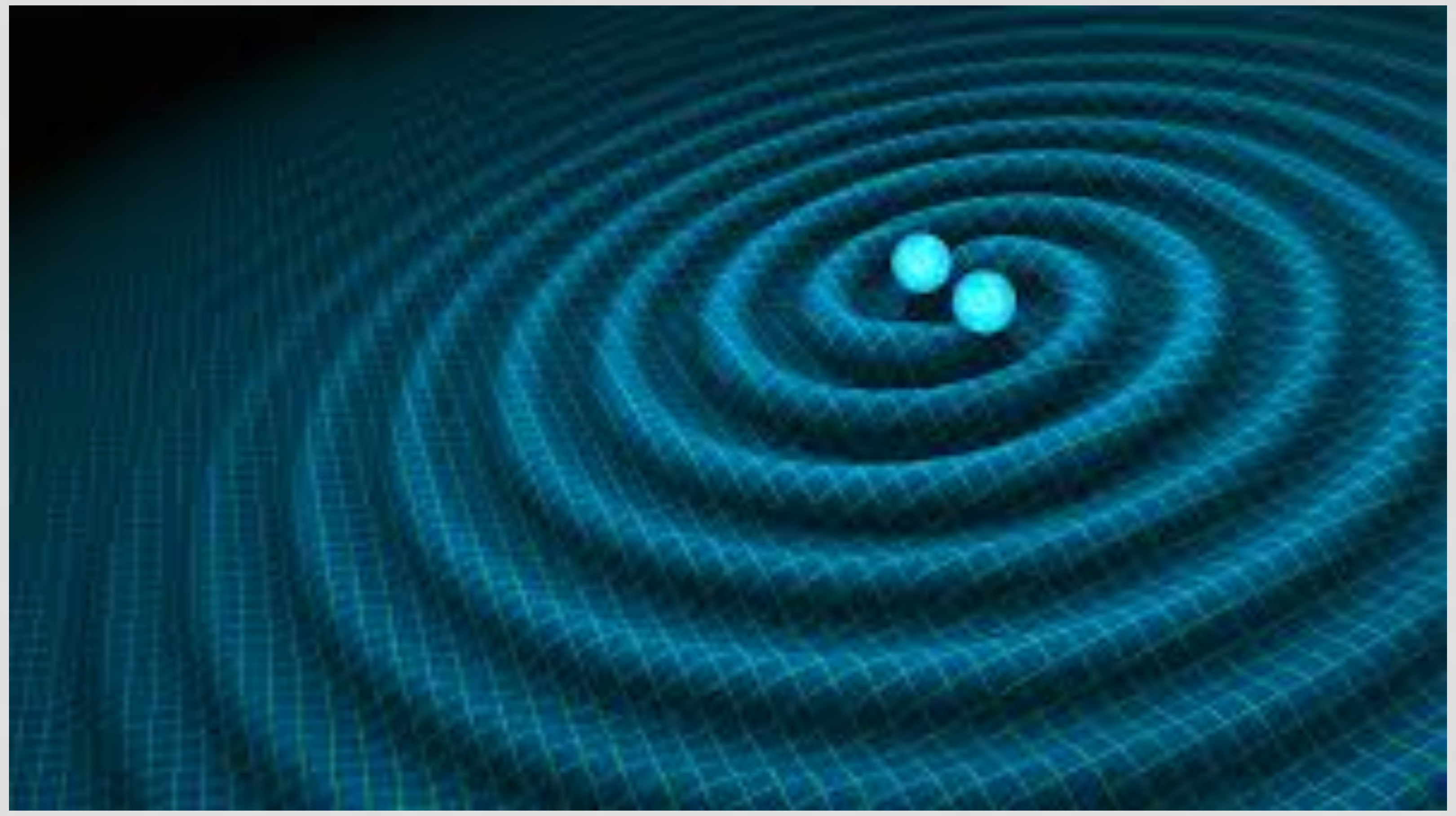
Graphic created by Jennifer Johnson

GRAVITATIONAL WAVES DISCOVERY

Neutron star mergers!

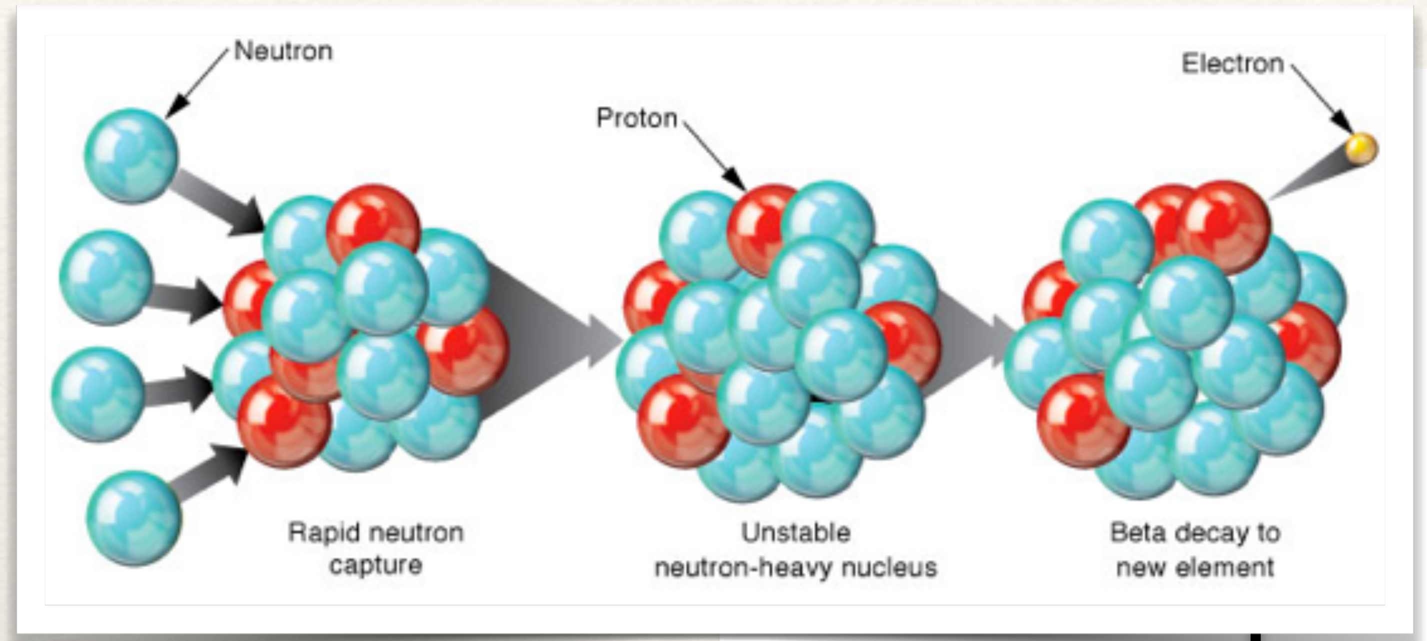
LIGO observatory is USA

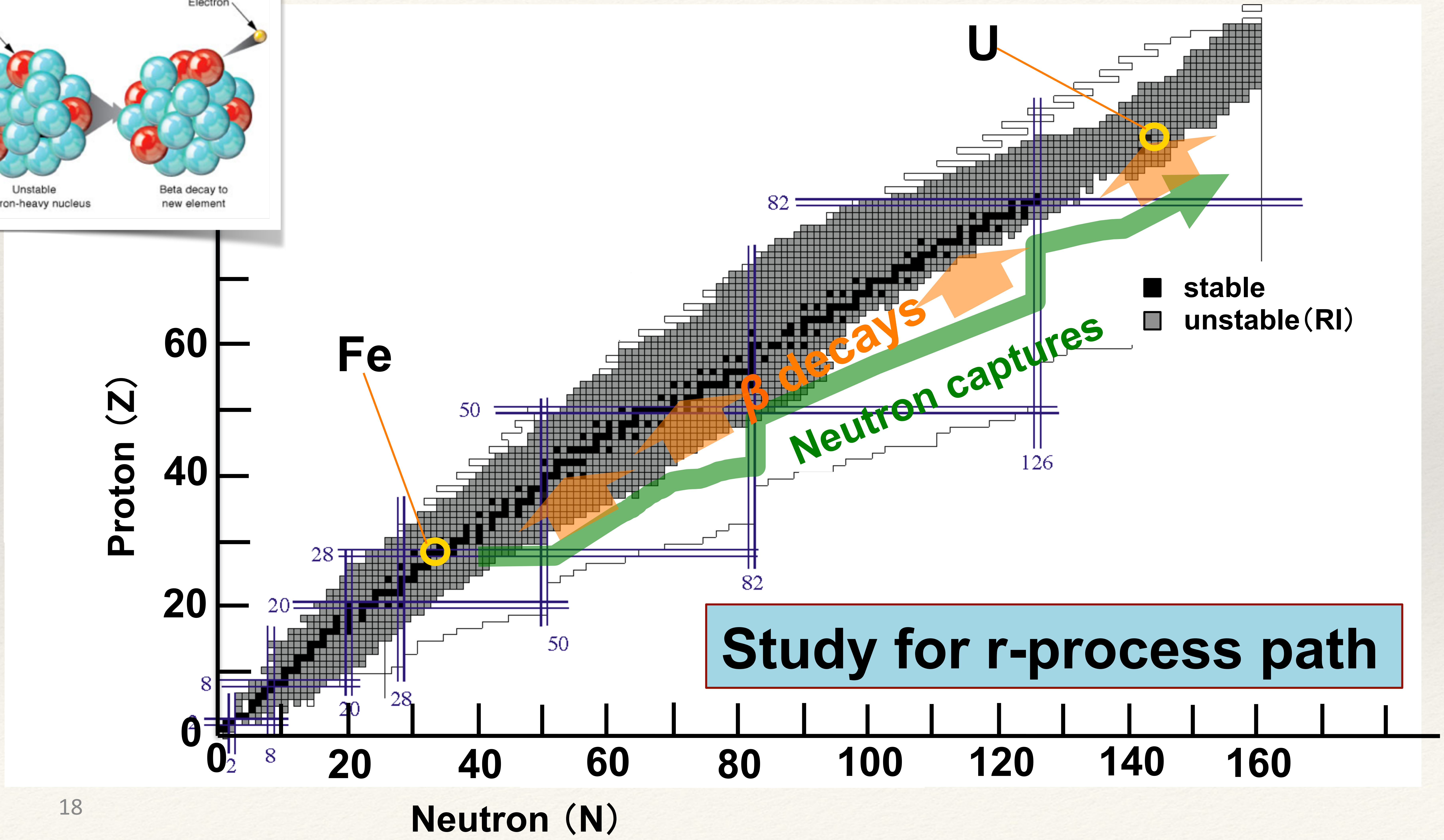


The light was also observed

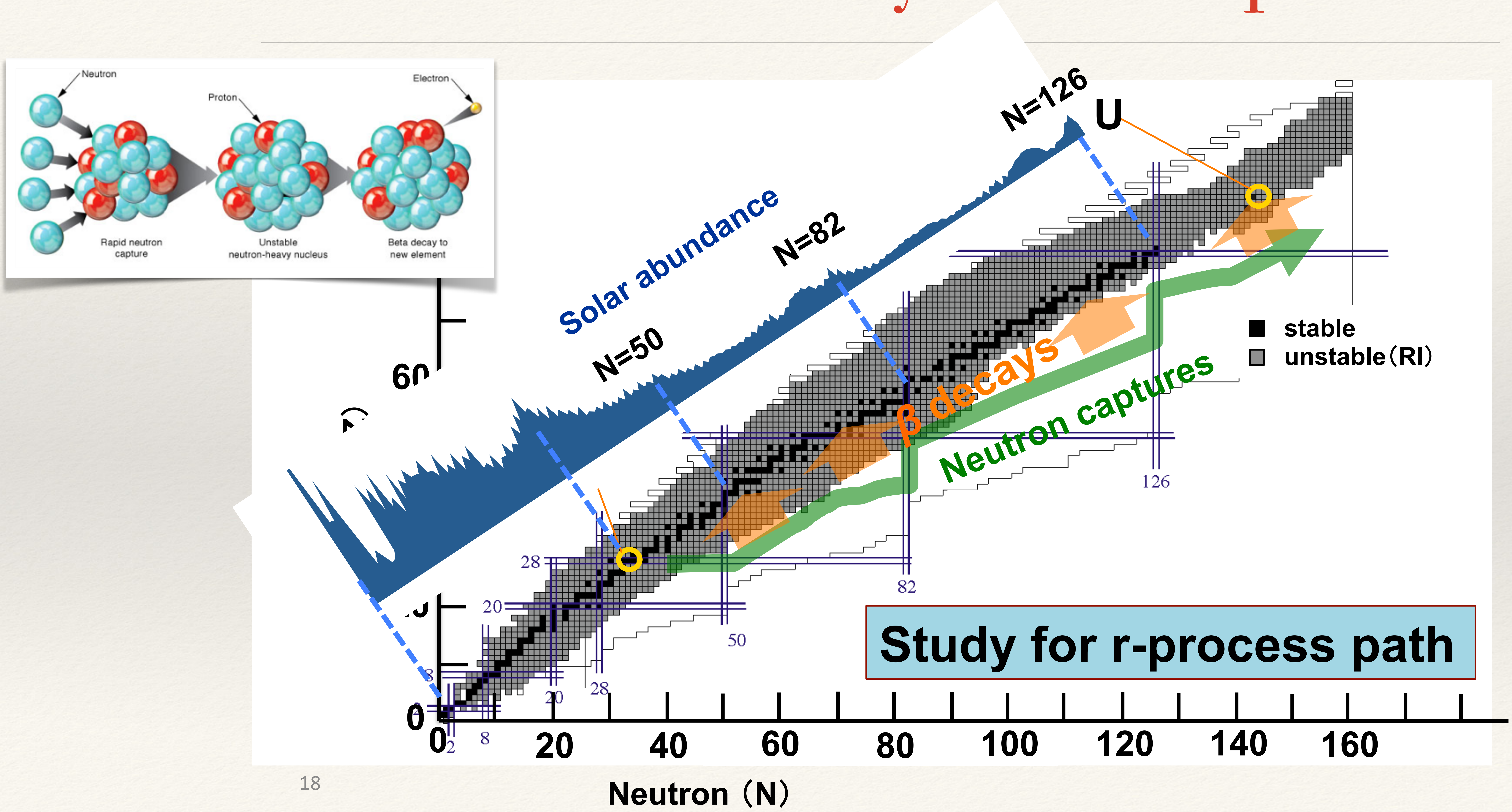
This is very exciting for our field!!!

Chemical element synthesis: r-process



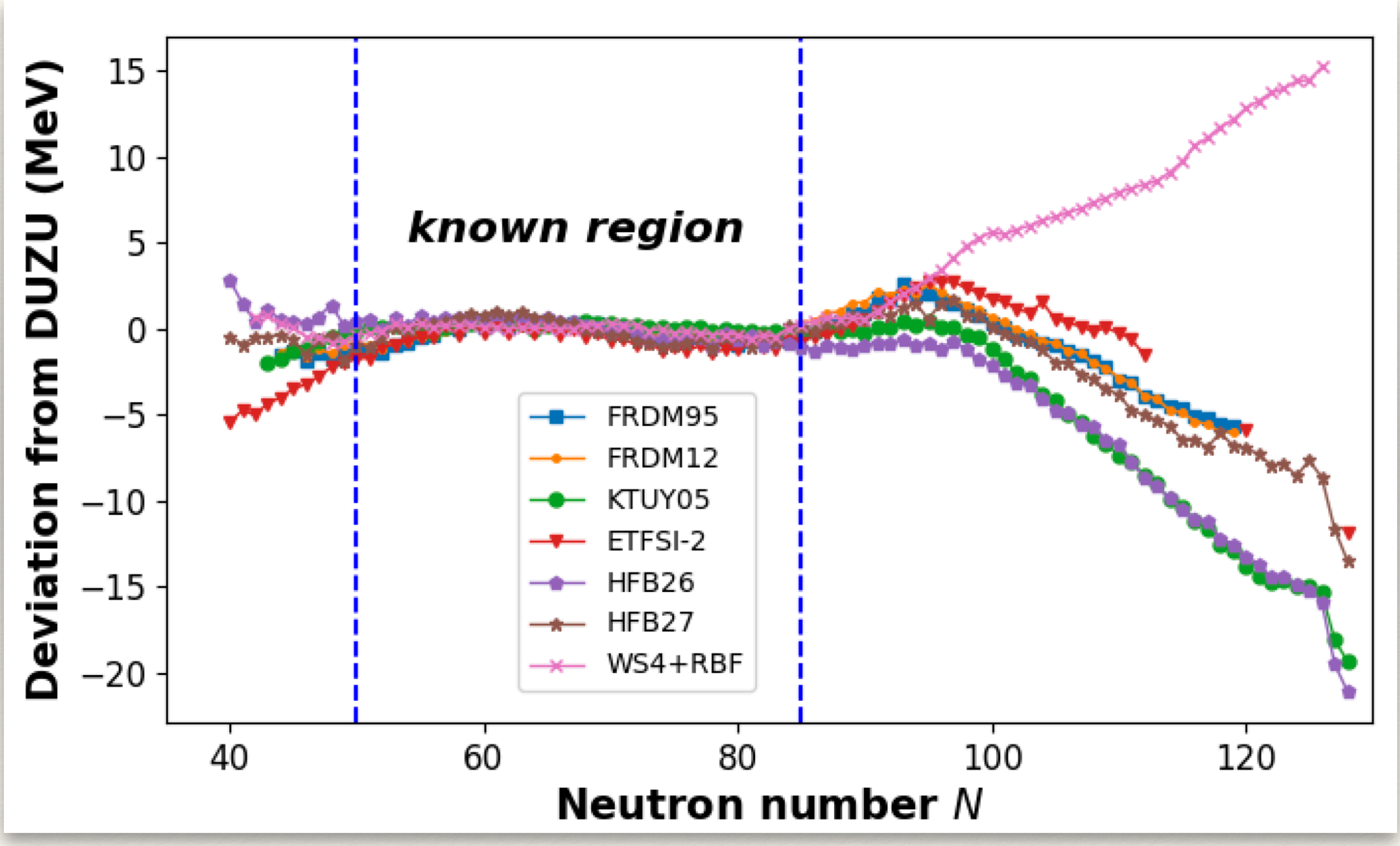


Chemical element synthesis: r-process

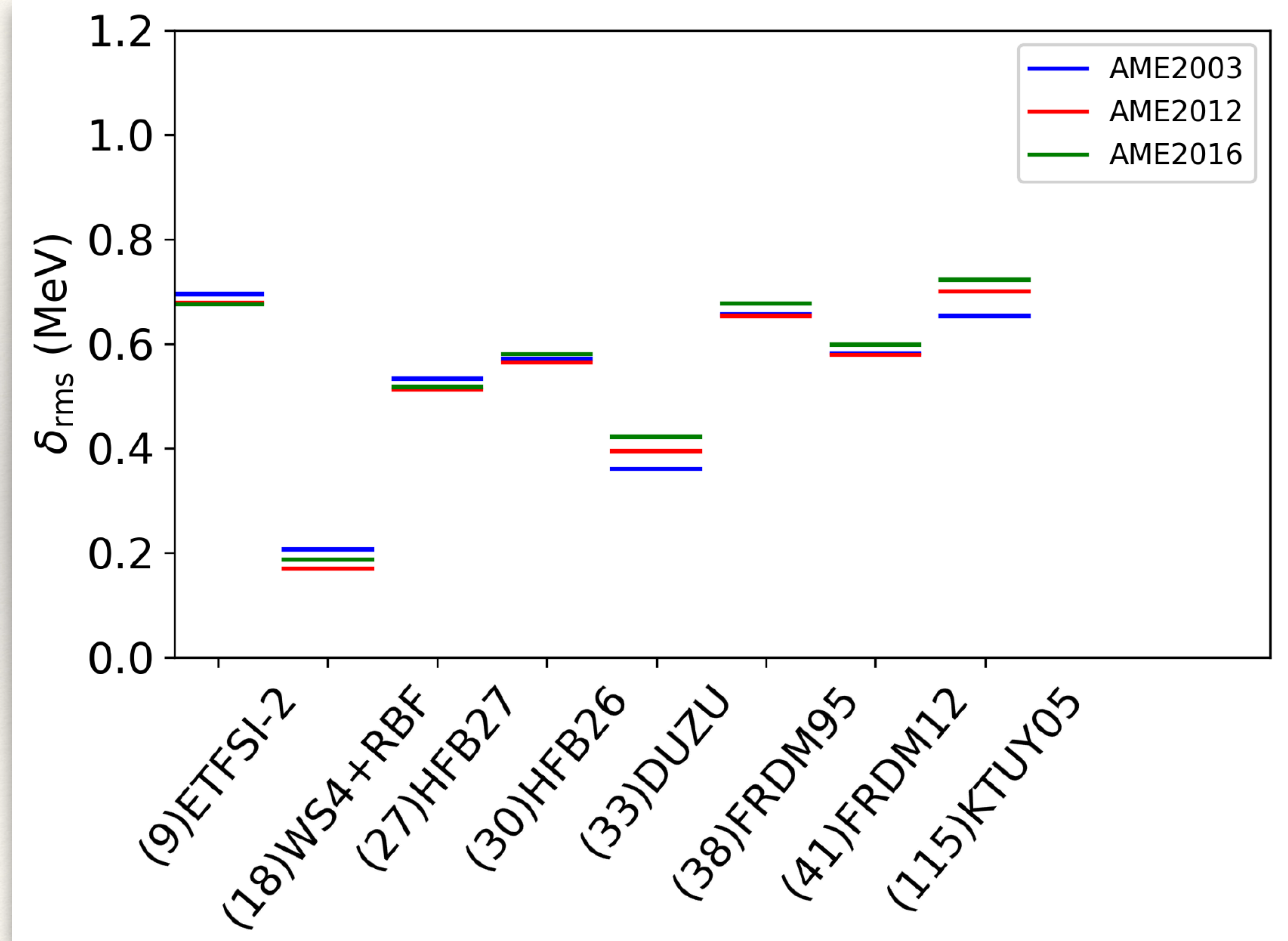


Chemical element synthesis: r-process

Why measure masses?



Why measure masses?



Mass Measurement Market

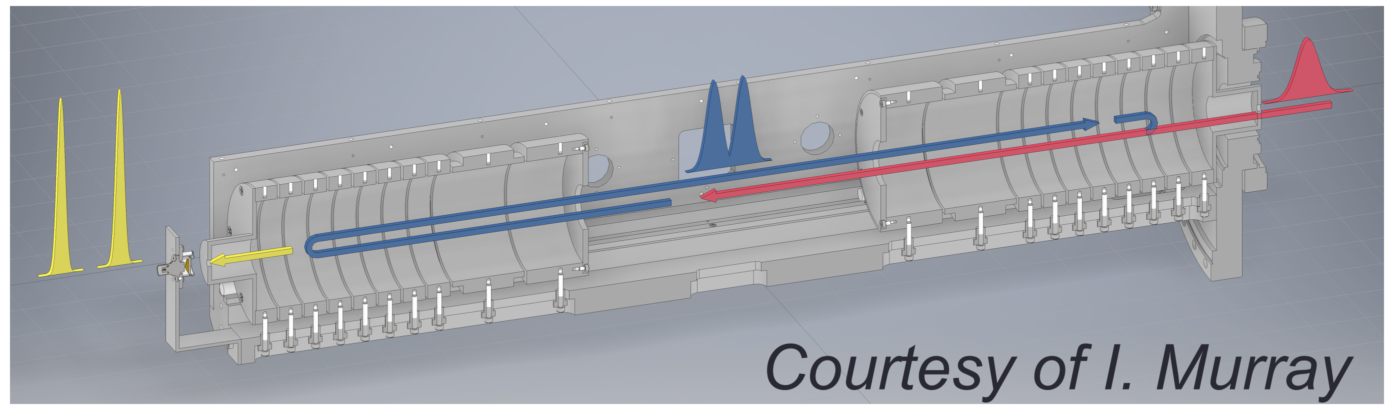
Low Energy | **High Energy**

Penning, MR-TOF-MS

100ms~1s

Precision <10^{-8}

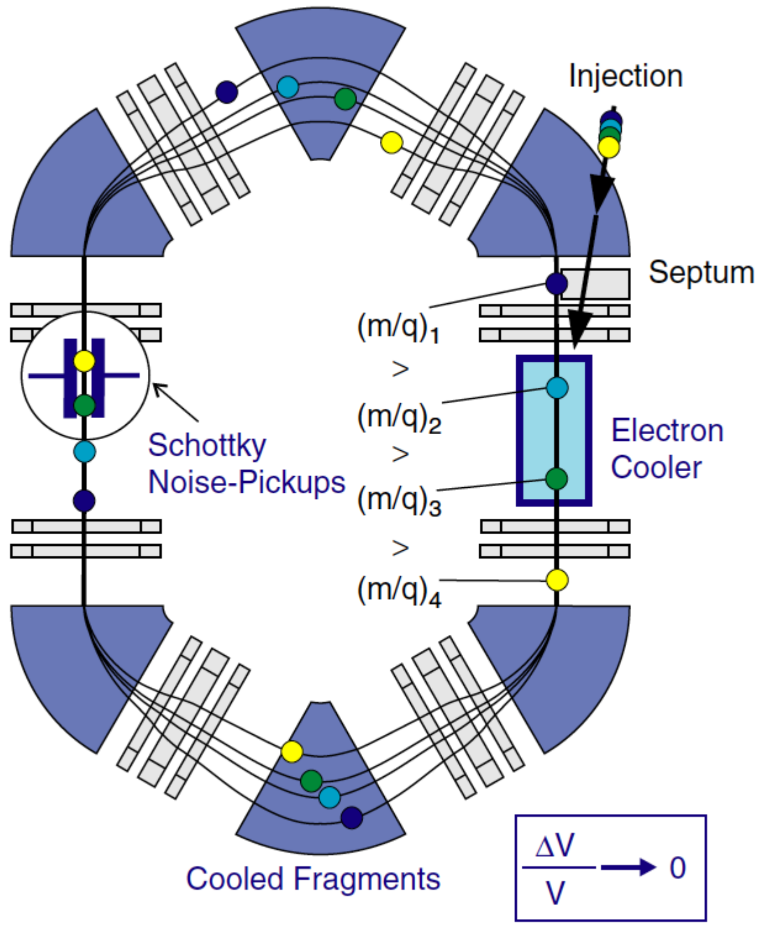
1~10 ms



Precision 10^{-7}

Storage Rings

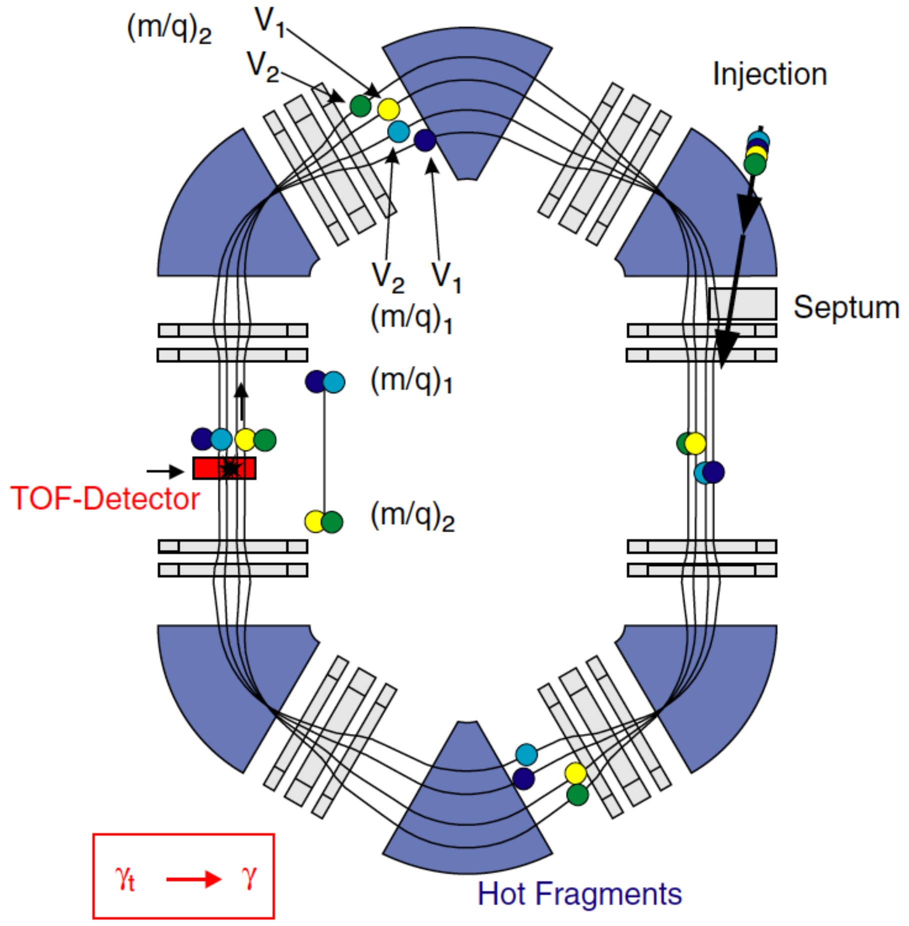
1~10 s



Precision 10^{-7}

Isochronous

< 1ms



Precision 10^{-6}

Low energy vs. High energy

Low precision

Fast measurement time

High precision

Long measurement time

The Atomic Mass Evaluation (AME)

Mass measurement: ✘ absolute mass ✔ connection between masses

Basic properties of the atomic mass: constant & additive

Experimental data

—> linear equations

$$\sum_{\mu=1}^{M} k_i^{\mu} m_{\mu} = q_i \pm dq_i$$

$$m_{\mathrm{A}} + m_{\mathrm{a}} - m_{\mathrm{b}} - m_{\mathrm{B}} = q_i \pm dq_i$$

All data available for 135Ba

68De17	162731	48	C8 N O H9-135Ba
68De17	117822	77	C11 H3-135Ba
68De17	154160	46	C12 H7-135Ba O
20De20	288.43	0.32	135Cs-135Ba
66Be10	-203860	20	135Ba-C10 H14
66Be10	1177	2	135Ba-134Ba
68De17	1161	70	135Ba-134Ba
68De17	1168	78	135Ba-134Ba
77Ko.A	6973.2	0.4	134Ba(n,g)135Ba
90Is07,Z	6972.17	0.18	134Ba(n,g)135Ba
93Bo01,Z	6971.84	0.17	134Ba(n,g)135Ba
93Ch21	6973.24	0.22	134Ba(n,g)135Ba
06Fi.A	6971.87	0.18	134Ba(n,g)135Ba
70Vo04	4746	15	134Ba(d,p)135Ba
53Li01	205	5	135Cs(B-)135Ba
71Ba18,*	1200	10	135La(B+)135Ba
66Be10	-1115	3	136Ba-135Ba
68De17	-1119	50	136Ba-135Ba
68De17	-1074	50	136Ba-135Ba
69Ge07	9106.4	0.8	135Ba(n,g)136Ba
90Is07,Z	9107.74	0.04	135Ba(n,g)136Ba
06Fi.A	9107.73	0.19	135Ba(n,g)136Ba
70Vo04	6886	15	135Ba(d,p)136Ba
10Mc04	3089.1	0.6	137Ba 35Cl-135Ba 37Cl
66Be10	143	3	137Ba-135Ba
68De17	69	63	137Ba-135Ba
68De17	106	46	137Ba-135Ba

All data available for 134Ba

66Be10	205025	20	C10 H14-134Ba
68De17	205010	46	C10 H14-134Ba
68De17	111125	48	C11 H2-134Ba
68De17	156063	78	C8 N O H8-134Ba
68De17	147531	64	C12 H6-134Ba O
134Ba+0	-91442	54	134La-u
134Ba+0	-91528	32	134La-u
66Be10	-197229	20	134Ba-C10 H13
66Be10	-553	4	134Ba-132Ba
68De17	-550	121	134Ba-132Ba
68Hs01,*	2058.6	0.4	134Cs(B-)134Ba
65Bi12	3772	50	134La(B+)134Ba
73Al20	3692	30	134La(B+)134Ba
66Be10	1177	2	135Ba-134Ba
68De17	1161	70	135Ba-134Ba
68De17	1168	78	135Ba-134Ba
77Ko.A	6973.2	0.4	134Ba(n,g)135Ba
90Is07,Z	6972.17	0.18	134Ba(n,g)135Ba
93Bo01,Z	6971.84	0.17	134Ba(n,g)135Ba
93Ch21	6973.24	0.22	134Ba(n,g)135Ba
06Fi.A	6971.87	0.18	134Ba(n,g)135Ba
70Vo04	4746	15	134Ba(d,p)135Ba
66Be10	67	5	136Ba-134Ba
68De17	69	128	136Ba-134Ba
68De17	72	78	136Ba-134Ba

All data available for 136Ba

68De17	126737	56	C11 H4-136Ba
68De17	171635	56	C8 N O H10-136Ba
68De17	163094	40	C12 H8-136Ba O
136Ba+0	-92344	75	136La-u
10Mc04	2639.6	0.6	136Xe-136Ba
11Ko03	2638.62	0.52	136Xe-136Ba
11Ko03	2553.46	0.29	136Ce-136Ba
12Ne10	2553.42	0.37	136Ce-136Ba
66Be10	-1115	3	136Ba-135Ba
68De17	-1119	50	136Ba-135Ba
68De17	-1074	50	136Ba-135Ba
66Be10	67	5	136Ba-134Ba
68De17	69	128	136Ba-134Ba
68De17	72	78	136Ba-134Ba
69Ge07	9106.4	0.8	135Ba(n,g)136Ba
90Is07,Z	9107.74	0.04	135Ba(n,g)136Ba
06Fi.A	9107.73	0.19	135Ba(n,g)136Ba
70Vo04	6886	15	135Ba(d,p)136Ba
54Ol05,*	2548.1	2.0	136Cs(B-)136Ba
65Re07,*	2549	5	136Cs(B-)136Ba
59Gi50	2870	70	136La(B+)136Ba
66Be10	1249	3	137Ba-136Ba
68De17	1222	50	137Ba-136Ba
68De17	1227	44	137Ba-136Ba
69Gr31	6891	5	136Ba(n,g)137Ba
90Is07,Z	6905.54	0.10	136Ba(n,g)137Ba
95Bo03,Z	6905.70	0.12	136Ba(n,g)137Ba
06Fi.A	6905.74	0.16	136Ba(n,g)137Ba
60Ge01	-6949	38	137Ba(g,n)136Ba
70Vo04	4680	15	136Ba(d,p)137Ba
10Mc04	3621.1	0.6	138Ba 35Cl-136Ba 37Cl
66Be10	676	3	138Ba-136Ba
68De17	658	98	138Ba-136Ba
68De17	628	43	138Ba-136Ba

Example 1, linear system of equations:

$x_1 = 10 \pm 0.5,$

$x_1 - x_2 = 5 \pm 1,$

$x_1 + x_2 = 13 \pm 0.5,$

$x_3 - x_1 = 4 \pm 1;$

Overdetermined systems

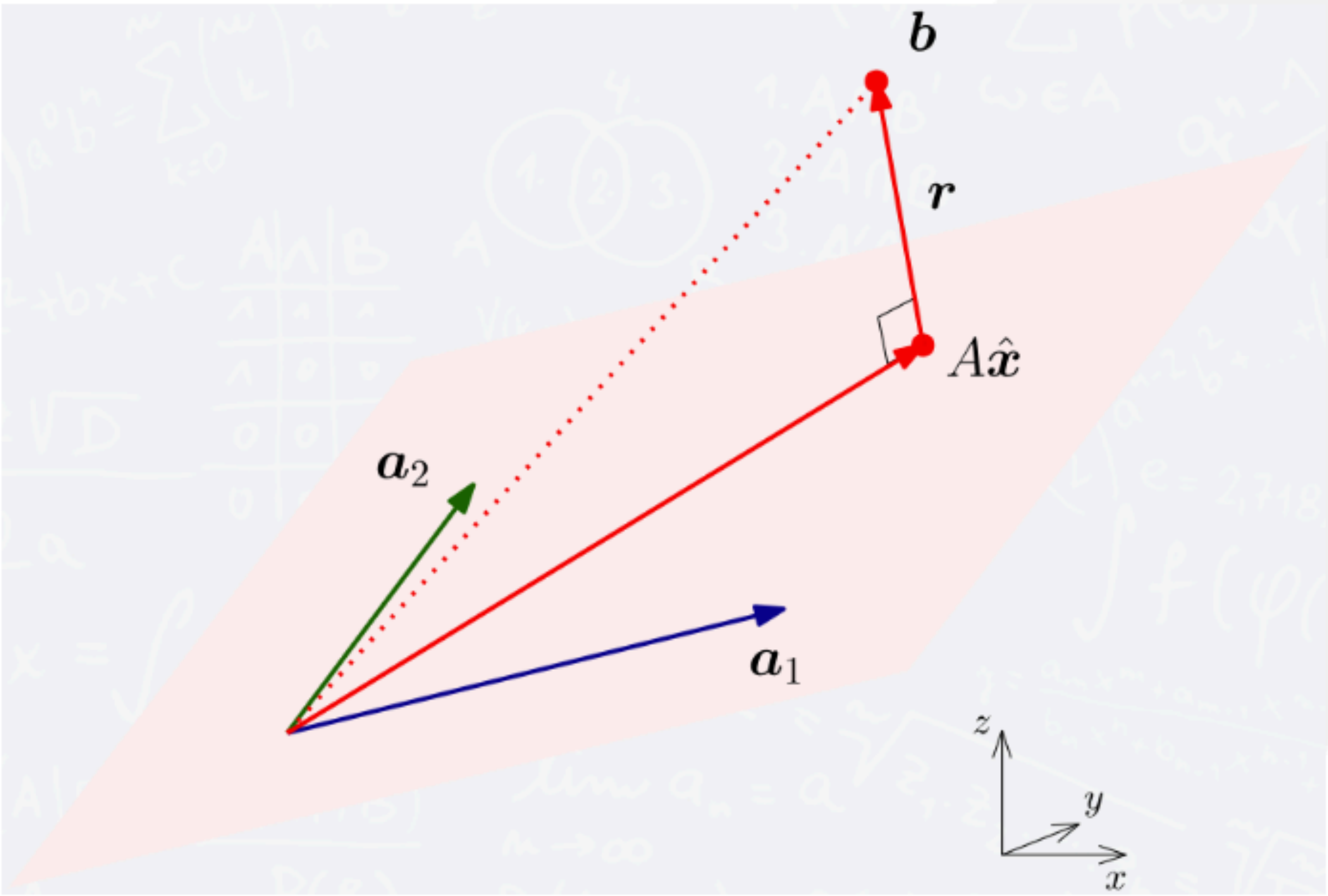
The AME least-square method

$$\begin{aligned} 2x &+ y &= 7, \\ x &+ 3y &= 6, \\ 3x &- y &= 3. \end{aligned}$$

No solution

$$\begin{bmatrix} 2 & 1 \\ 1 & 3 \\ 3 & -1 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = x \begin{bmatrix} 2 \\ 1 \\ 3 \end{bmatrix} + y \begin{bmatrix} 1 \\ 3 \\ -1 \end{bmatrix} = \begin{bmatrix} 7 \\ 6 \\ 3 \end{bmatrix}$$

$$A\boldsymbol{x} = x\boldsymbol{a}_1 + y\boldsymbol{a}_2 = \boldsymbol{b}.$$



No combination of a_1 & a_2 can give b

But the best solution could be found by minimizing $\|A\hat{\boldsymbol{x}} - \boldsymbol{b}\|^2$

Which is the sum of squares of deviations

How do experimental uncertainties affect the mass determination?

Example 1, linear system of equations:

$x_1 = 10 \pm 0.5,$

$x_1 - x_2 = 5 \pm 1,$

$x_1 + x_2 = 13 \pm 0.5,$

$x_3 - x_1 = 4 \pm 1;$

Nuclear Instruments and Methods in Physics Research A249 (1986) 443–450 443
North-Holland, Amsterdam

A METHOD OF DETERMINING THE RELATIVE IMPORTANCE OF PARTICULAR DATA ON SELECTED PARAMETERS IN THE LEAST-SQUARES ANALYSIS OF EXPERIMENTAL DATA

Georges AUDI *
Laboratoire René Bernas du CSNSM, Bat, 108, 91406 Orsay, France

Walter G. DAVIES and Graham E. LEE-WHITING
Atomic Energy of Canada Limited Research Company, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada KOJ IJO

Received 17 March 1986

In the framework of least-squares analysis of experimental data, a “flow-of-information” matrix is defined. This matrix displays the flow of information within the least-squares adjustment. Its elements, called “influences”, show the relative importance of each datum in the determination of each of the adjusted parameters. The “significance”, or quantity of information brought by each datum is defined. Illustrative examples are given.

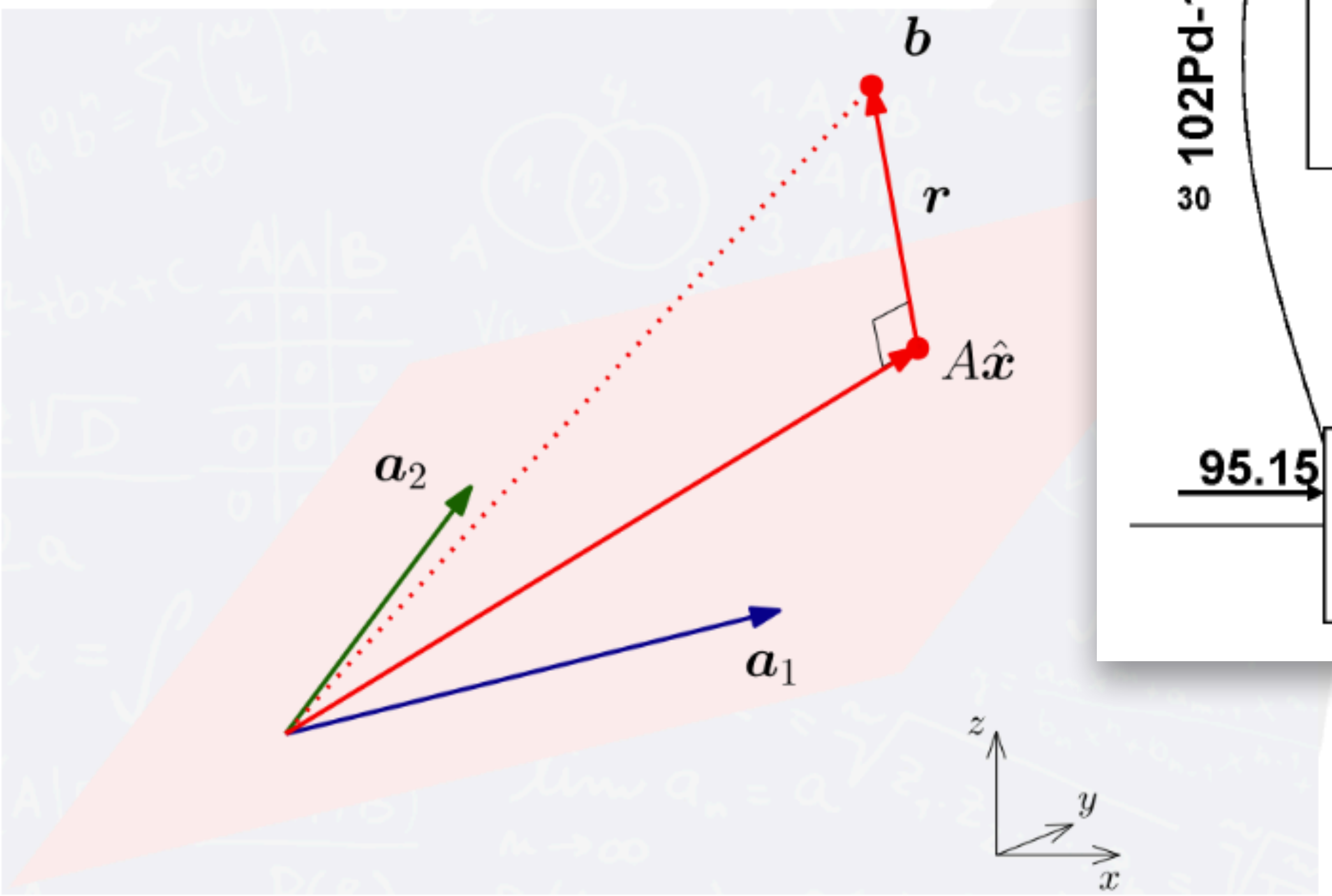
The AME least-square method

$$\begin{aligned} 2x + y &= 7, \\ x + 3y &= 6, \\ 3x - y &= 3. \end{aligned}$$

No solution

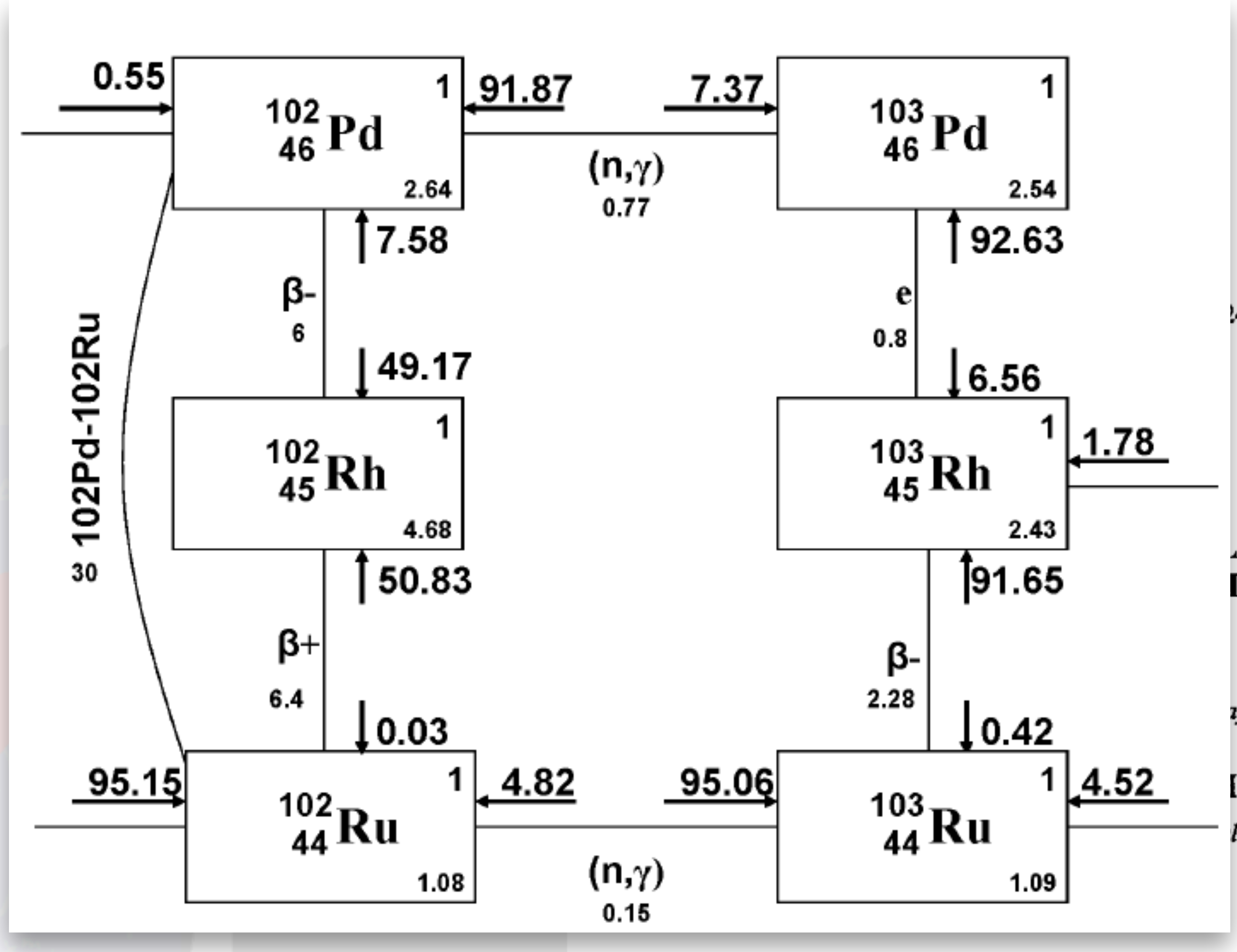
$$\begin{bmatrix} 2 & 1 \\ 1 & 3 \\ 3 & -1 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = x \begin{bmatrix} 2 \\ 1 \\ 3 \end{bmatrix} + y \begin{bmatrix} 1 \\ 3 \\ -1 \end{bmatrix} = \begin{bmatrix} 7 \\ 6 \\ 3 \end{bmatrix}$$

$$A\boldsymbol{x} = x\boldsymbol{a}_1 + y\boldsymbol{a}_2 = \boldsymbol{b}.$$



No combination of a_1 & a_2 can give b

But the best solution could be found by



How do experimental uncertainties affect the mass determination?

Example 1, linear system of equations:

$x_1 = 10 \pm 0.5,$

$x_1 - x_2 = 5 \pm 1,$

$x_1 + x_2 = 13 \pm 0.5,$

$x_3 - x_1 = 4 \pm 1;$

249 (1986) 443–450 443

ATIVE IMPORTANCE OF PARTICULAR DATA ON
T-SQUARES ANALYSIS OF EXPERIMENTAL DATA

y, France
ITING
lk River Nuclear Laboratories, Chalk River, Ontario, Canada KOJ IJO

In the framework of least-squares analysis of experimental data, a "flow-of-information" matrix is defined. This matrix displays the flow of information within the least-squares adjustment. Its elements, called "influences", show the relative importance of each datum in the determination of each of the adjusted parameters. The "significance", or quantity of information brought by each datum is defined. Illustrative examples are given.

Brief history of AME (11 tables since 1955)

1955: A.H. Wapstra established least-squares method to solve the overdetermination problem

1986: G. Audi discovered the flow of information matrix

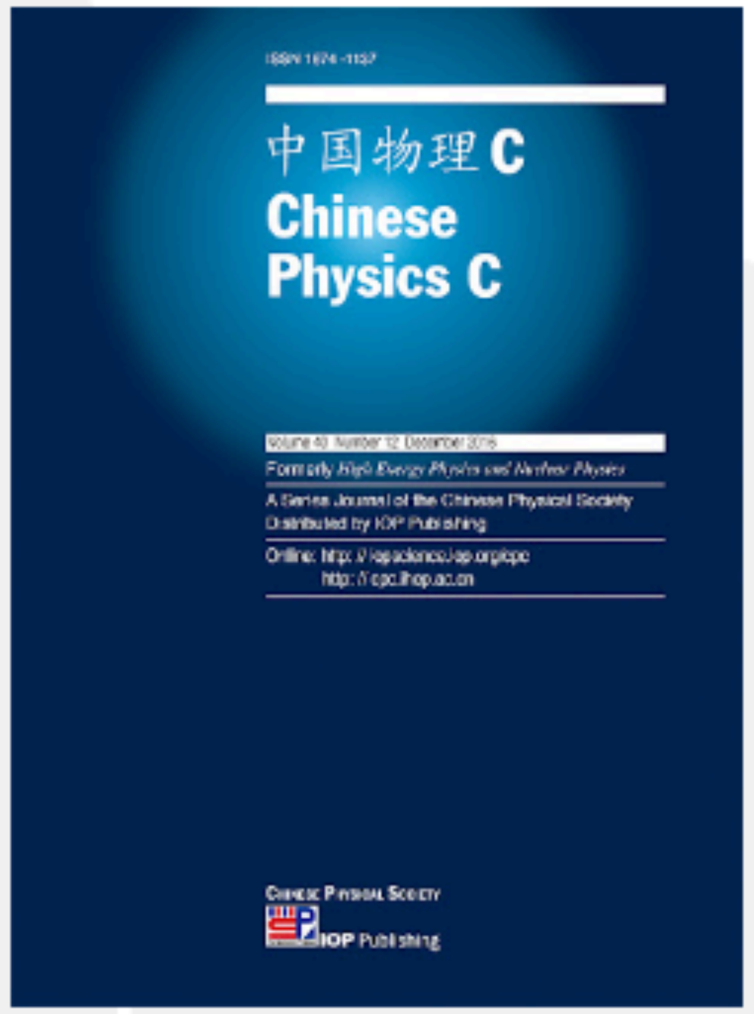
2006: A.H. Wapstra passed away

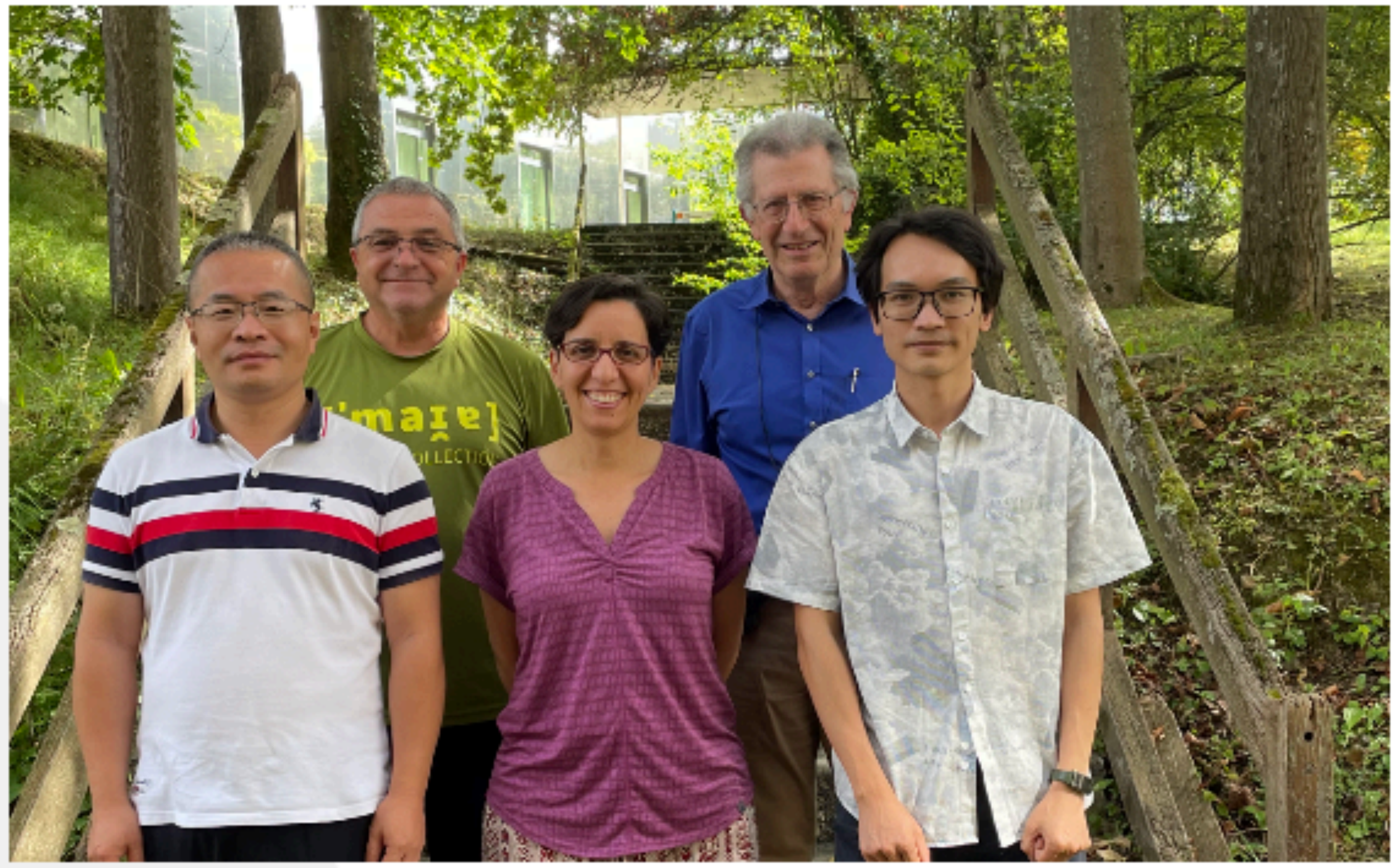
2008: G. Audi established the AME collaboration with China

Tables: **AME1955, AME1961, AME1964, AME1971, AME1977, AME1983, AME1993, AME2003, AME2012, AME2016, AME2020**

A.H. Wapstra

Memorandum signing in China

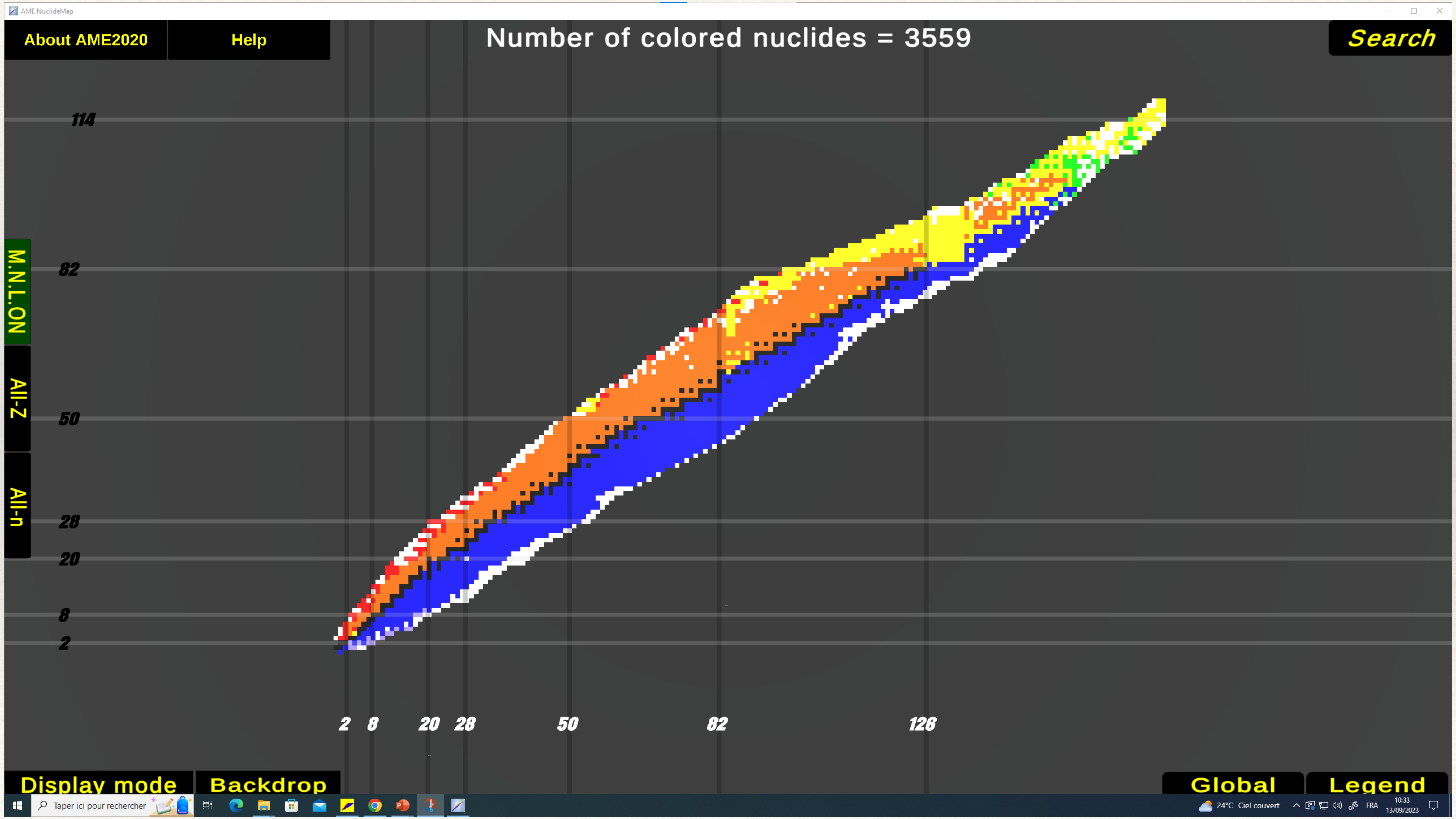




Collaboration meeting in Orsay Sep. 2023

New tool: Nucleus++

Download here: http://amdc.impcas.ac.cn/
available on Windows, Mac, Android, (iOS)
JY. Shi et al, NST 35 (2024)



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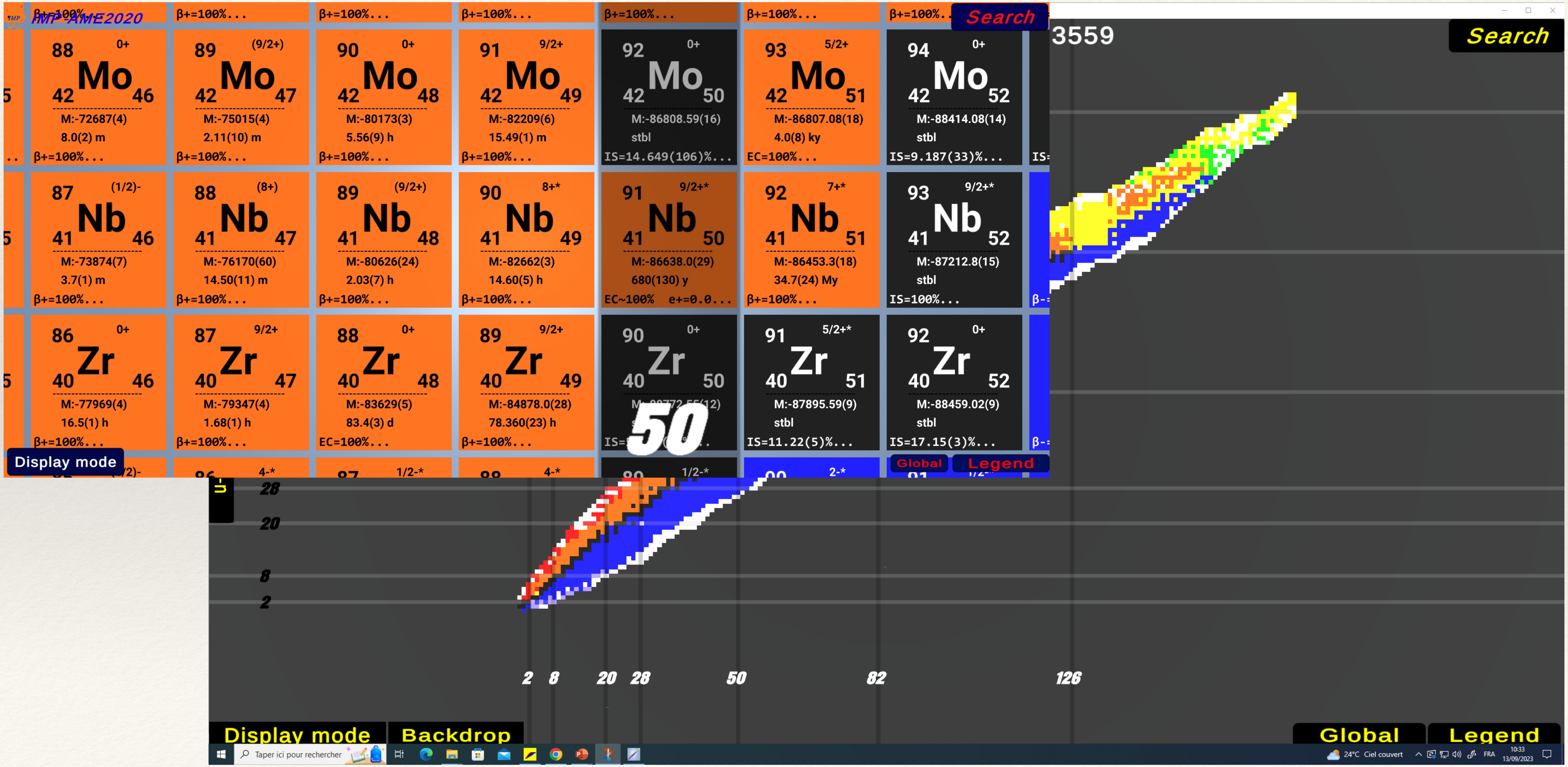

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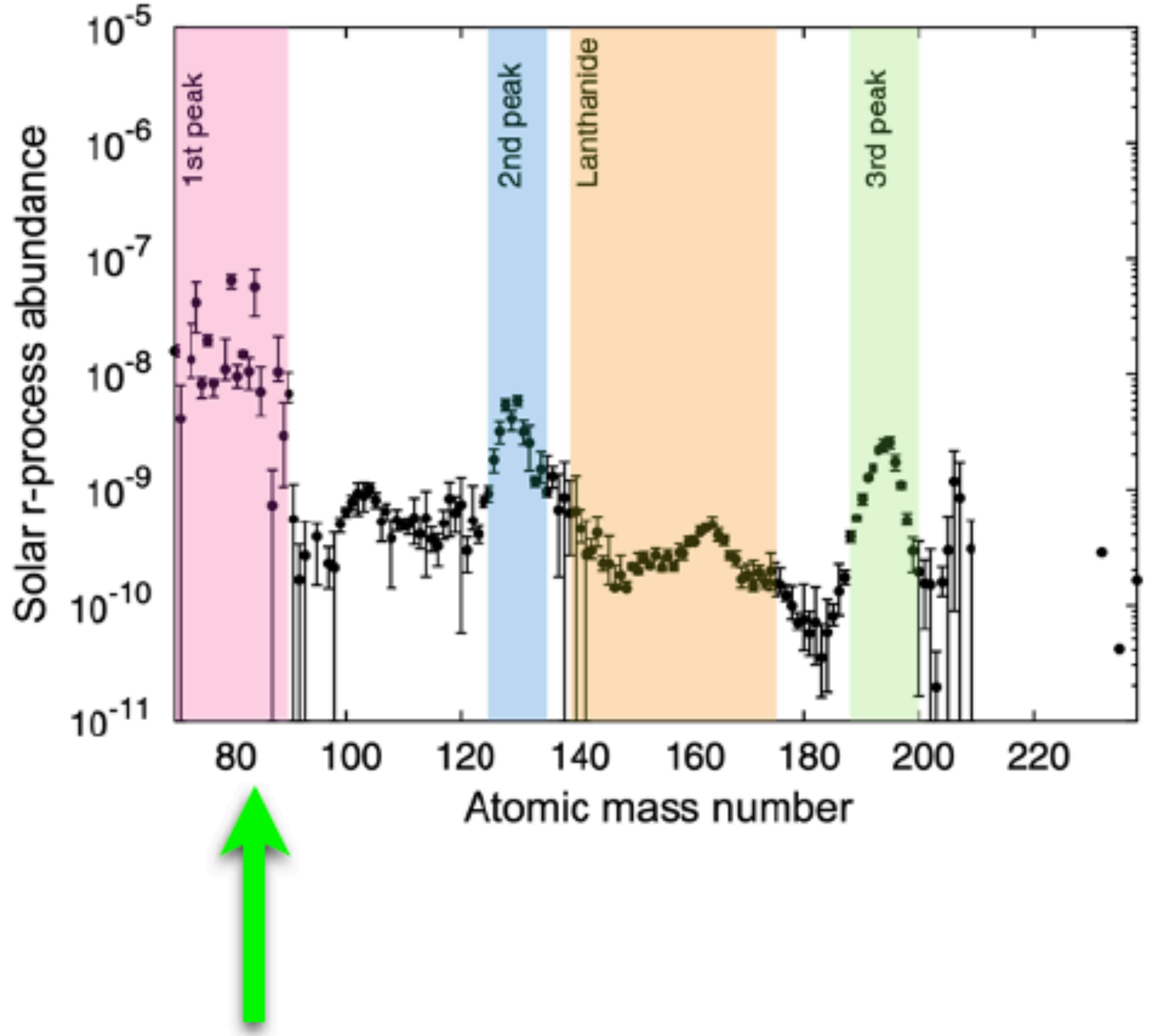
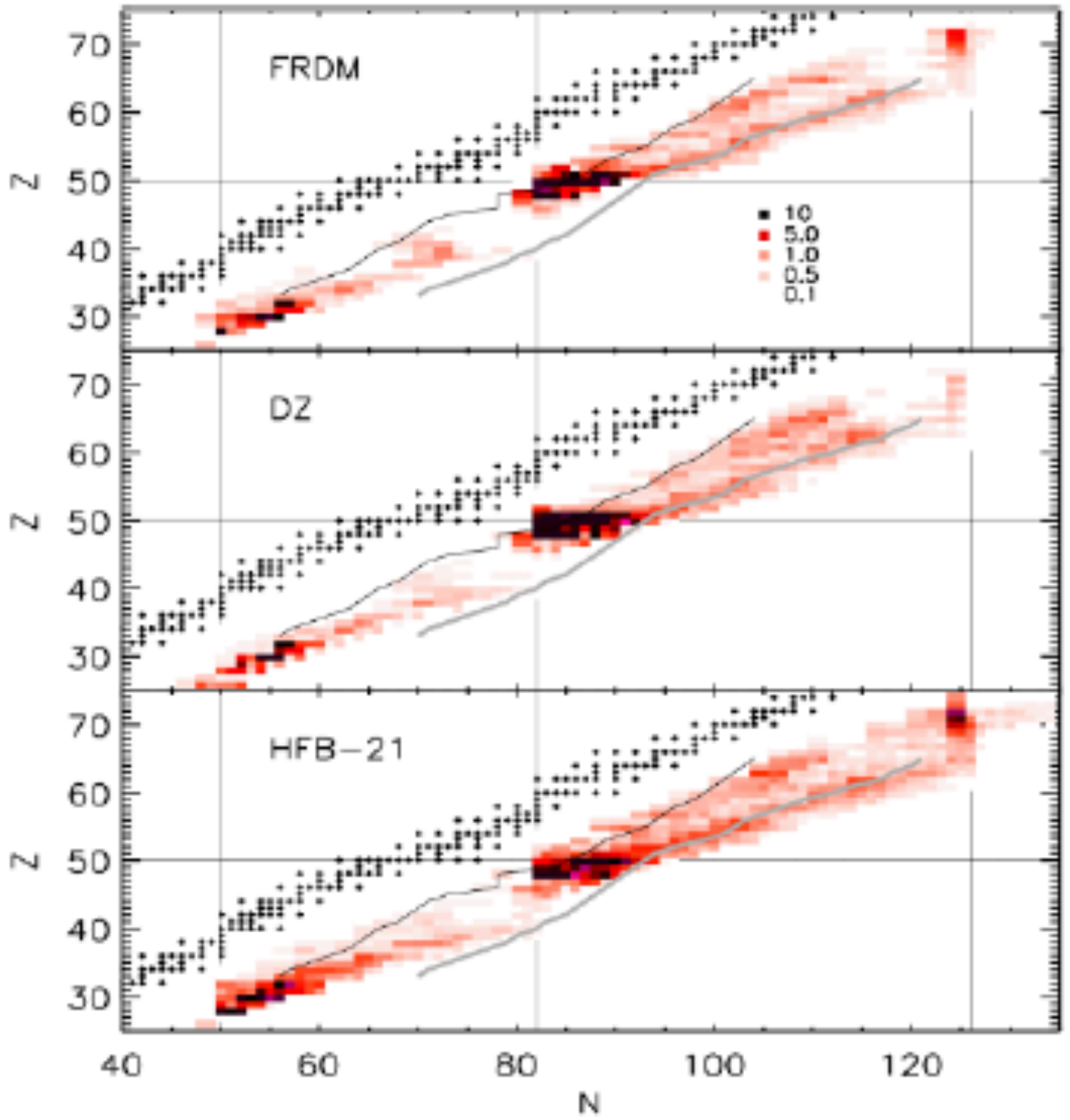
JY. Shi et al, NST 35 (2024)

r-process: which masses to measure?



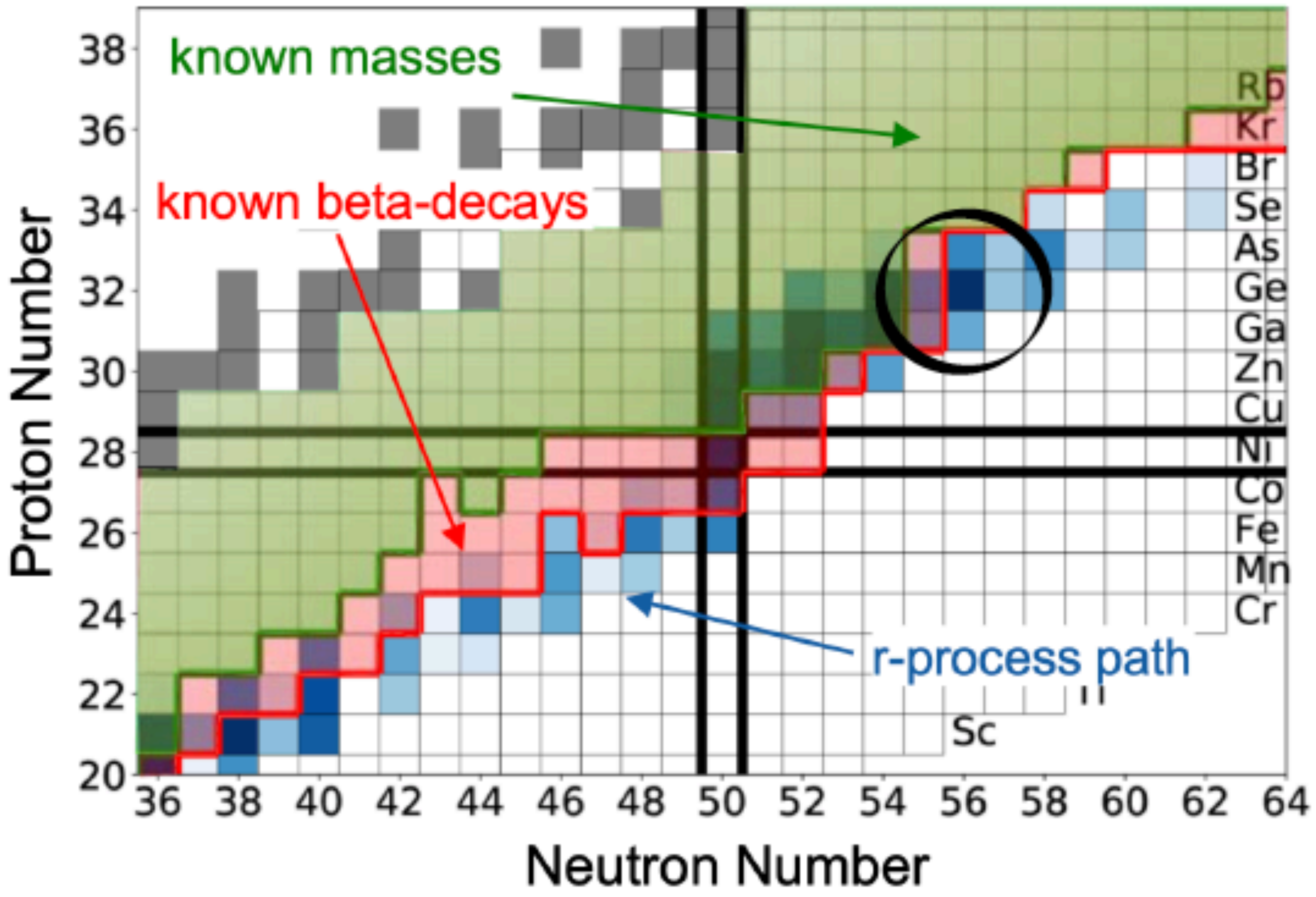
M. P. Reiter et al., PRC 101, 025803 (2020); Brett et al., EPJA (2012) 48



These masses have the largest impact on abundance peak as concluded in sensitivity studies.

The masses of neutron-rich nuclei with the largest impact

S. Nikas *et al.*, NPA-IX **1668**, 012029 (2020).



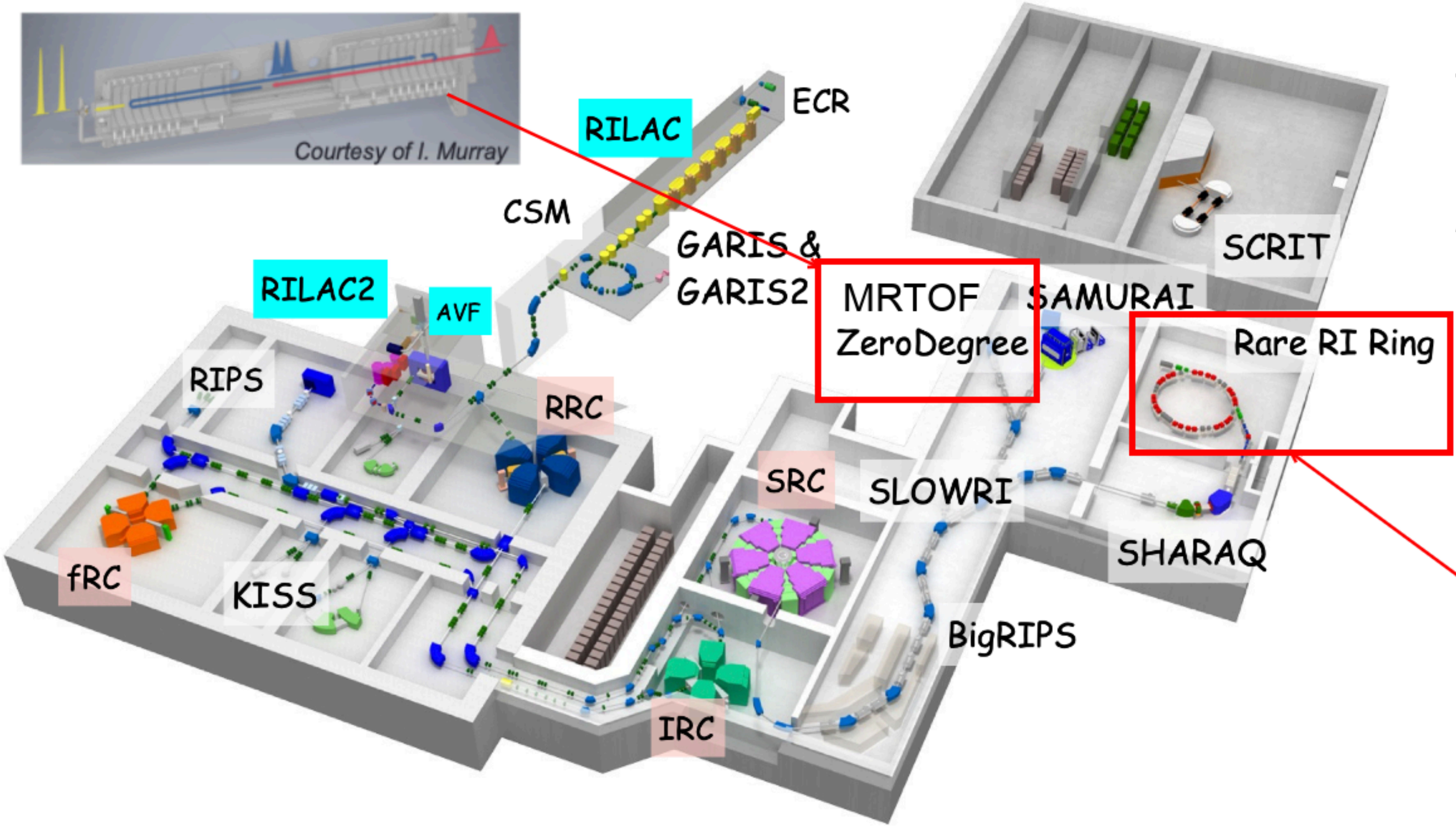
The path of r-process in the region of N=50 including the isotopes of interest at N=55, N=56 (sub-shell closure) and N=57.

Isotopes of interest: Ga, Ge, As

- These isotopes have a direct influence on the production of Sr, Y, Zr.

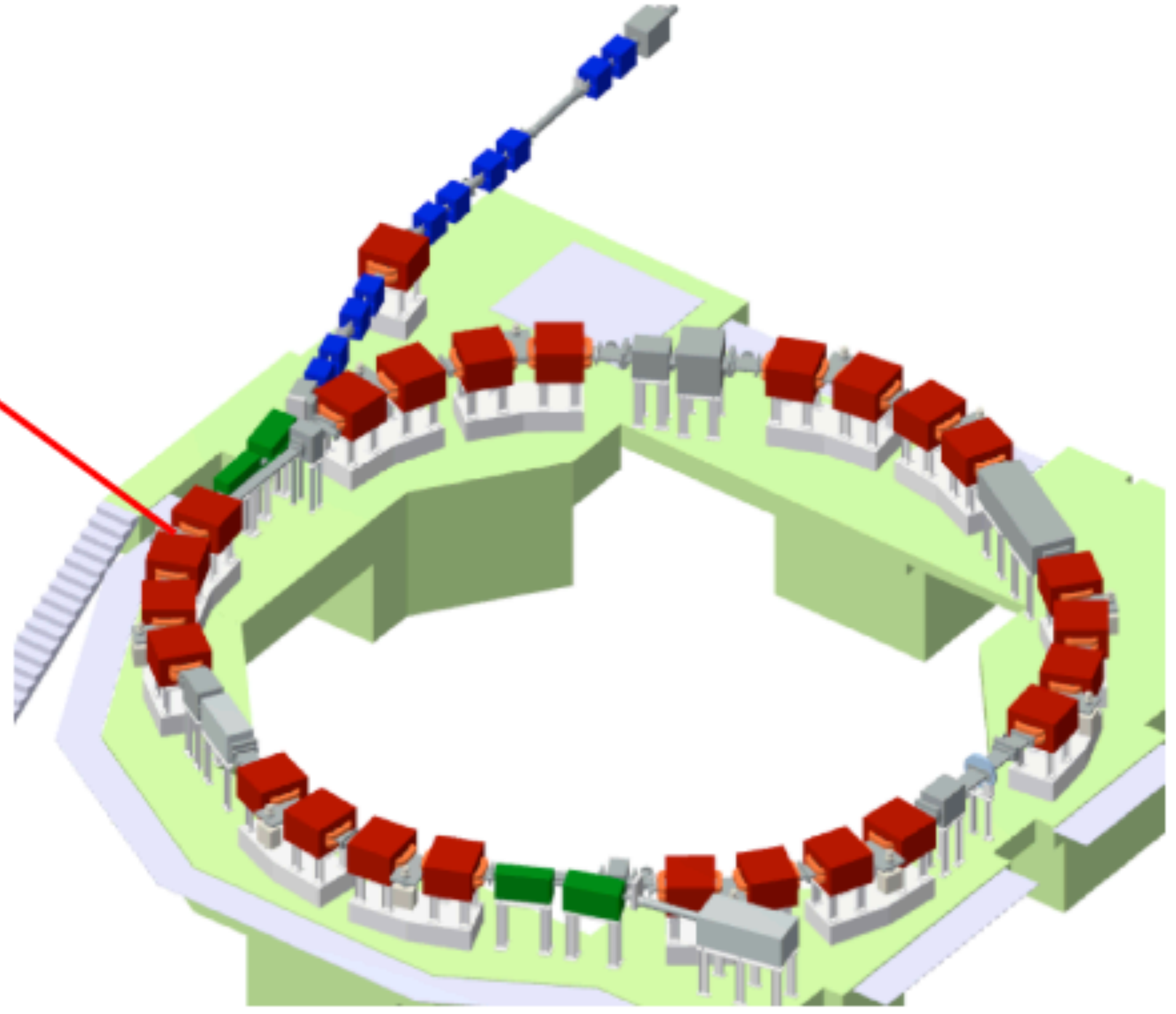
- Masses of very neutron-rich Ge will help to understand additional fine features of the abundance pattern, for instance, the production of Sr in neutron star mergers.

Mass measurements at RIBF/Riken

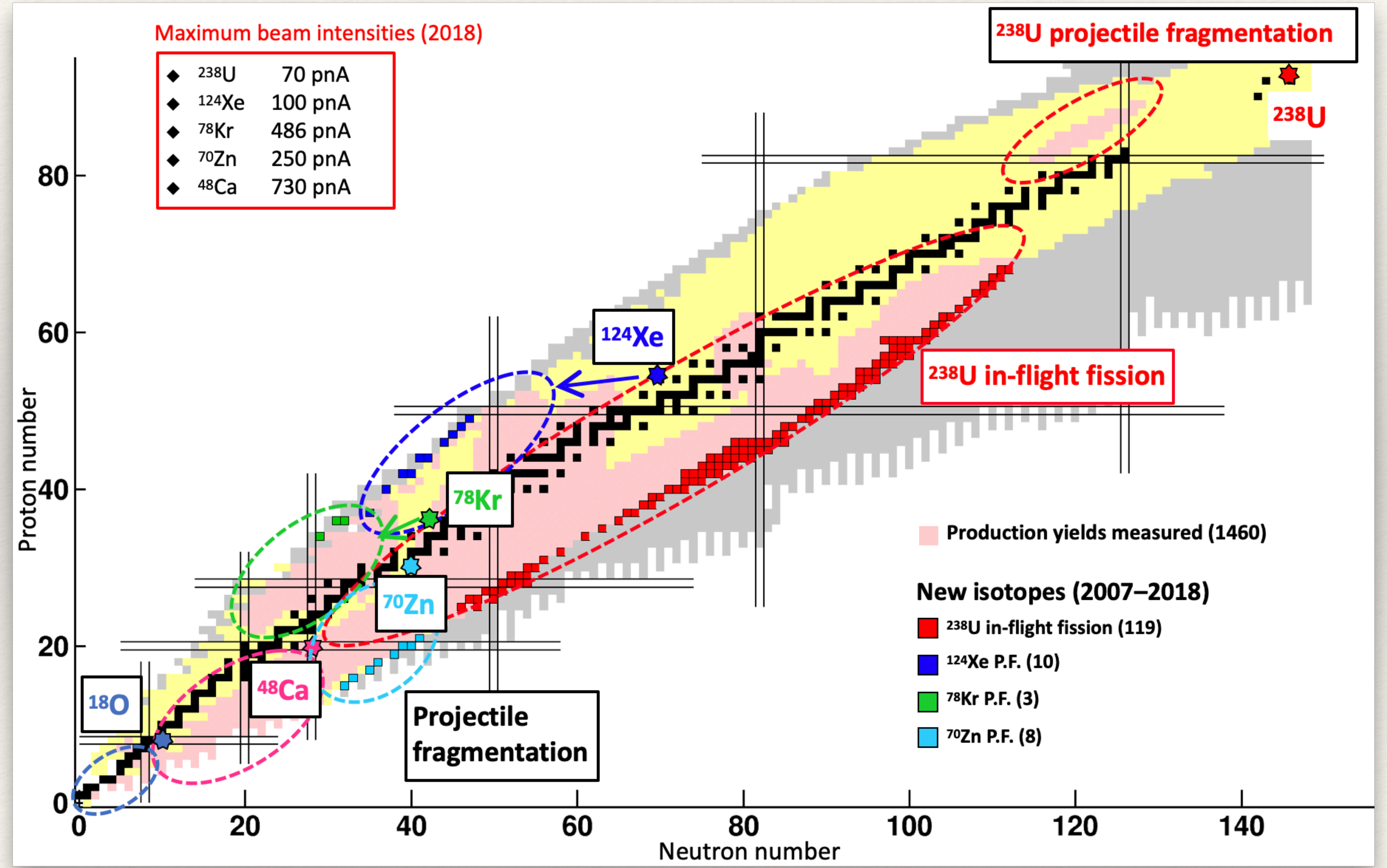


Measurement based on time-of-flight at low energy (MRTOF) and high energy (Ring)

Advantages:
MRTOF: higher precision <10^{-7}
Ring: faster measurement <1ms

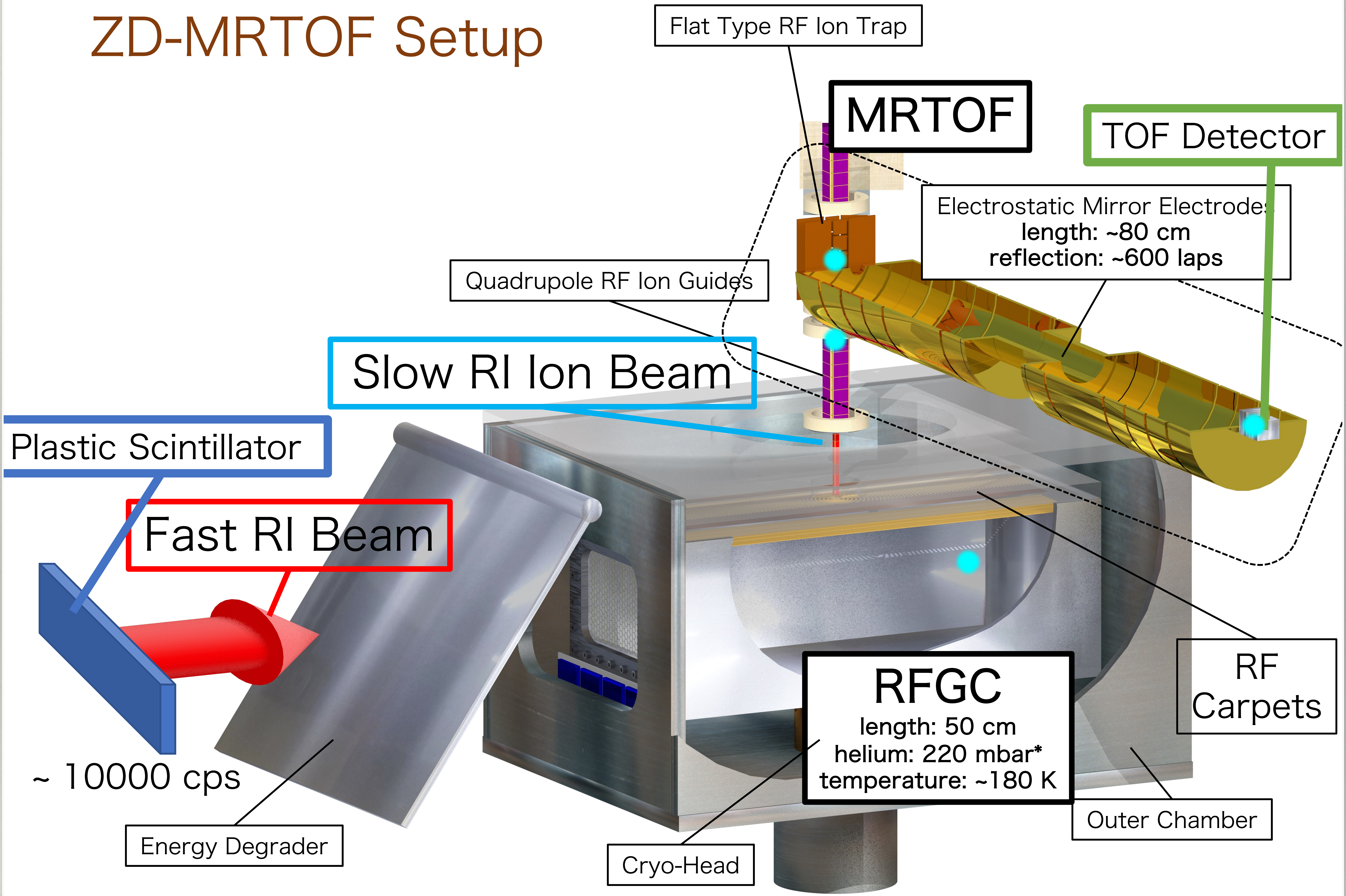


Production of n-rich nuclei at Riken/Japan



Courtesy of M. Rosenbusch

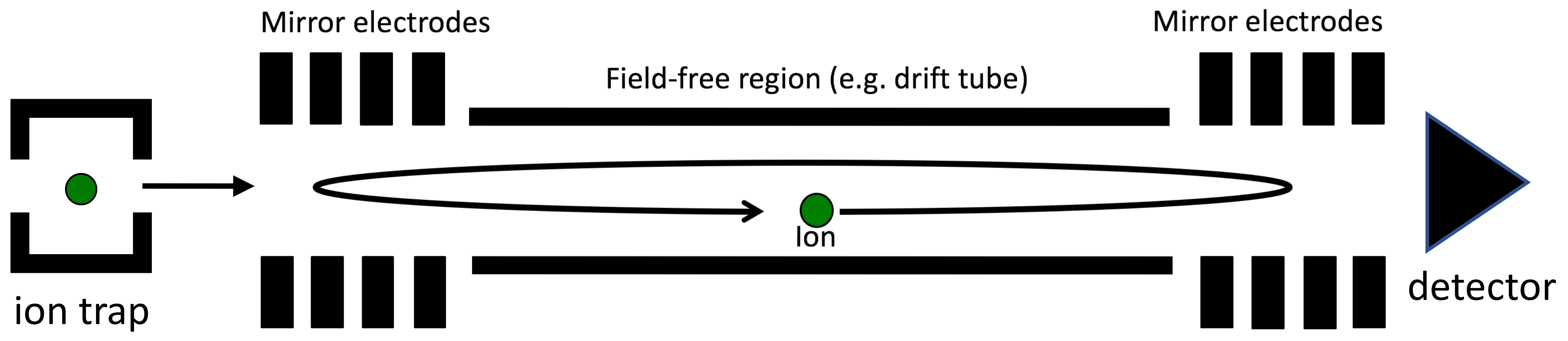
ZD-MRTOF Setup



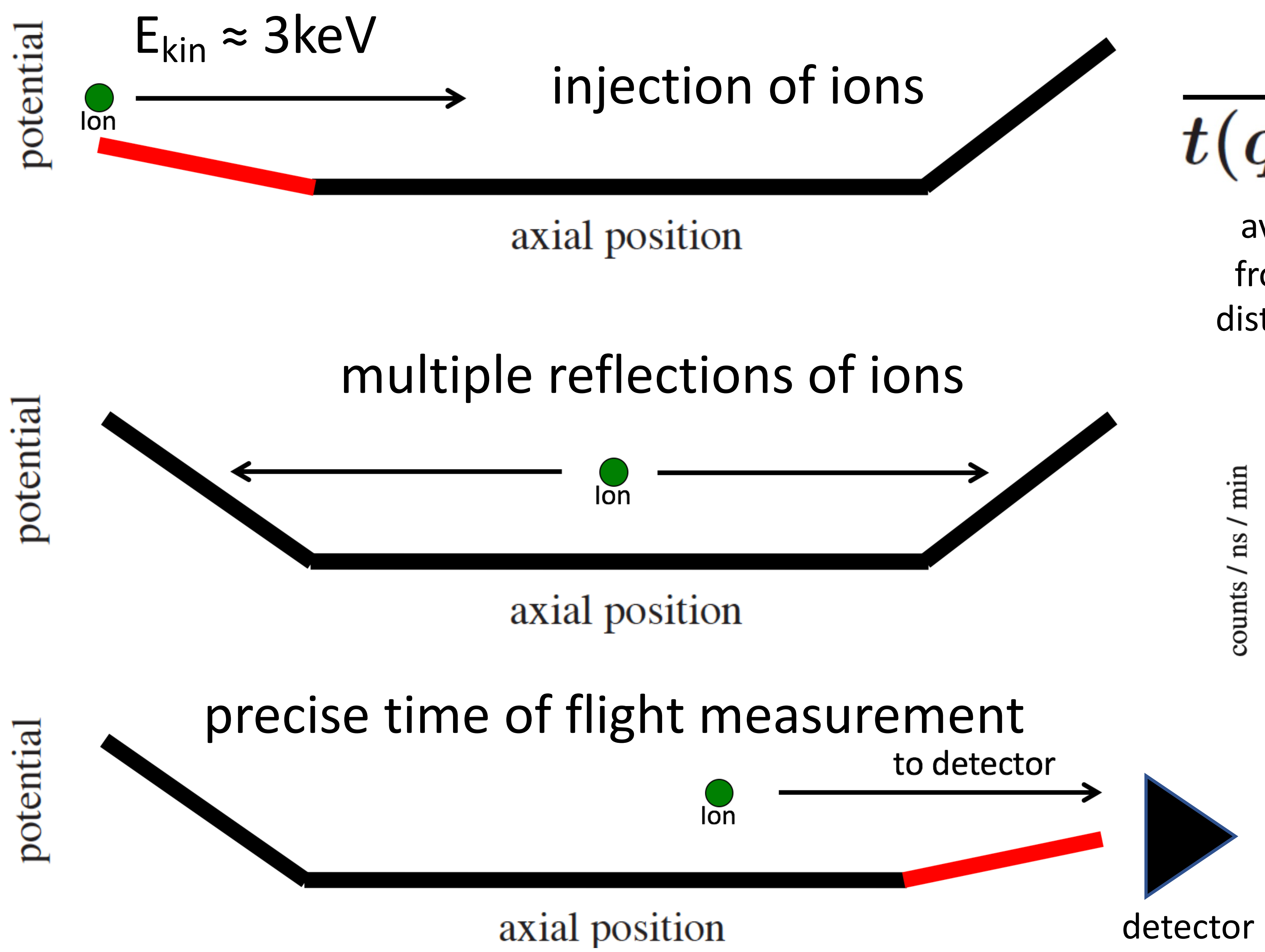
* room temperature equivalent pressure

The MR-TOF-MS principle

H.Wollnik and M. Przewloka, Int. J. Mass Spectrom. Ion Proc. 96, 267 (1990)



Total time of flight predominantly determined by the electrostatic term of the system

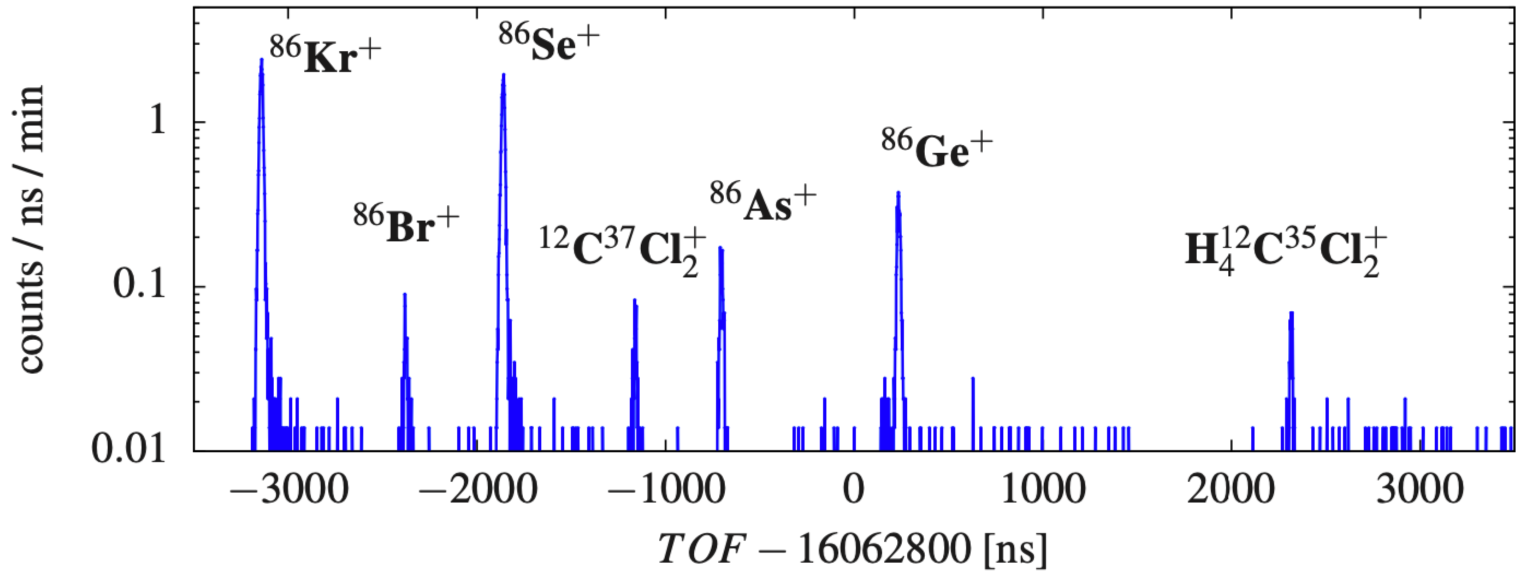


$$\overline{t(q,m)} = A \cdot \sqrt{\frac{m}{q}}$$

average from ion distribution

device constant

electrostatic contribution



Flight path of a few kilometers possible

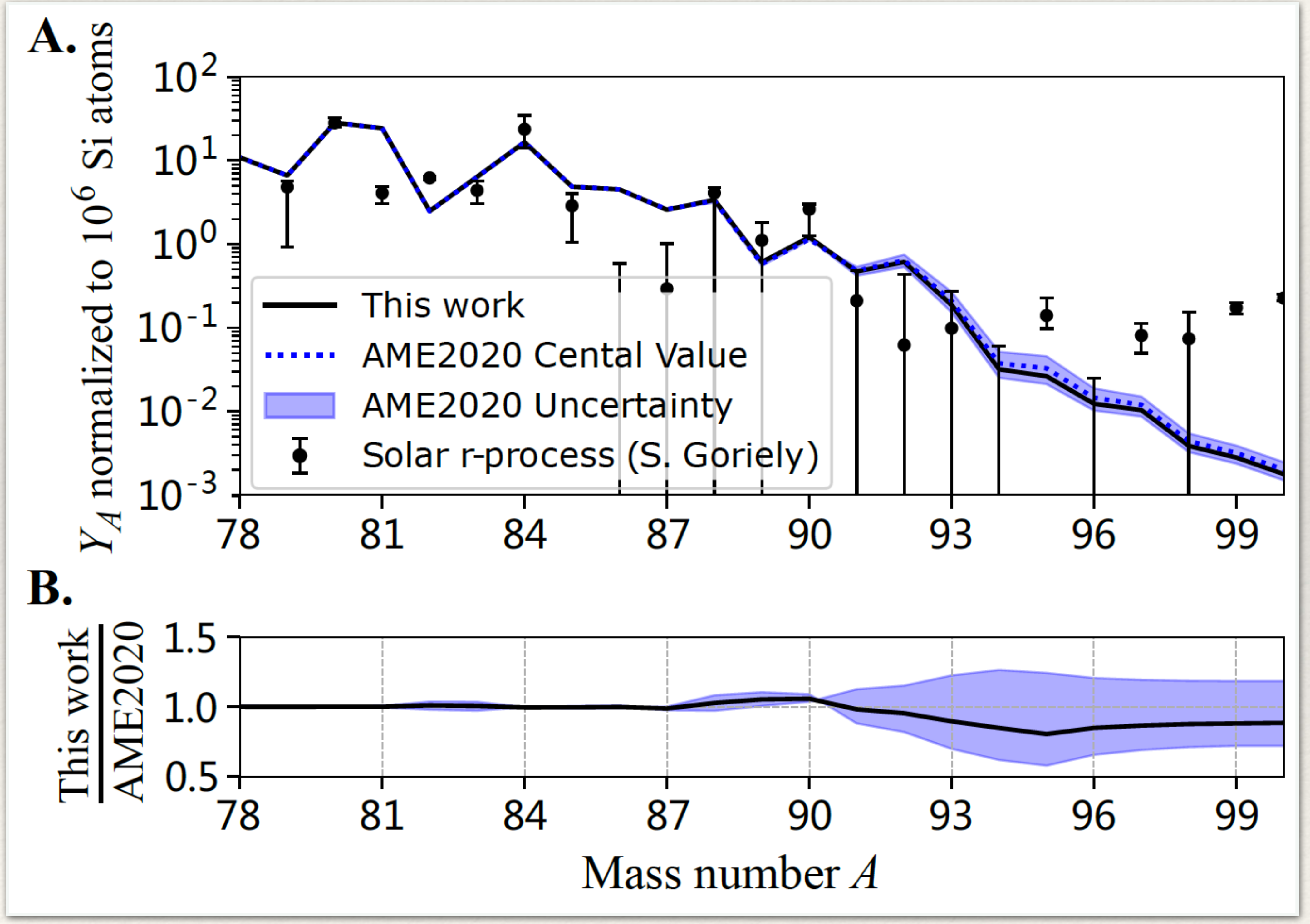
Courtesy of M. Rosenbusch

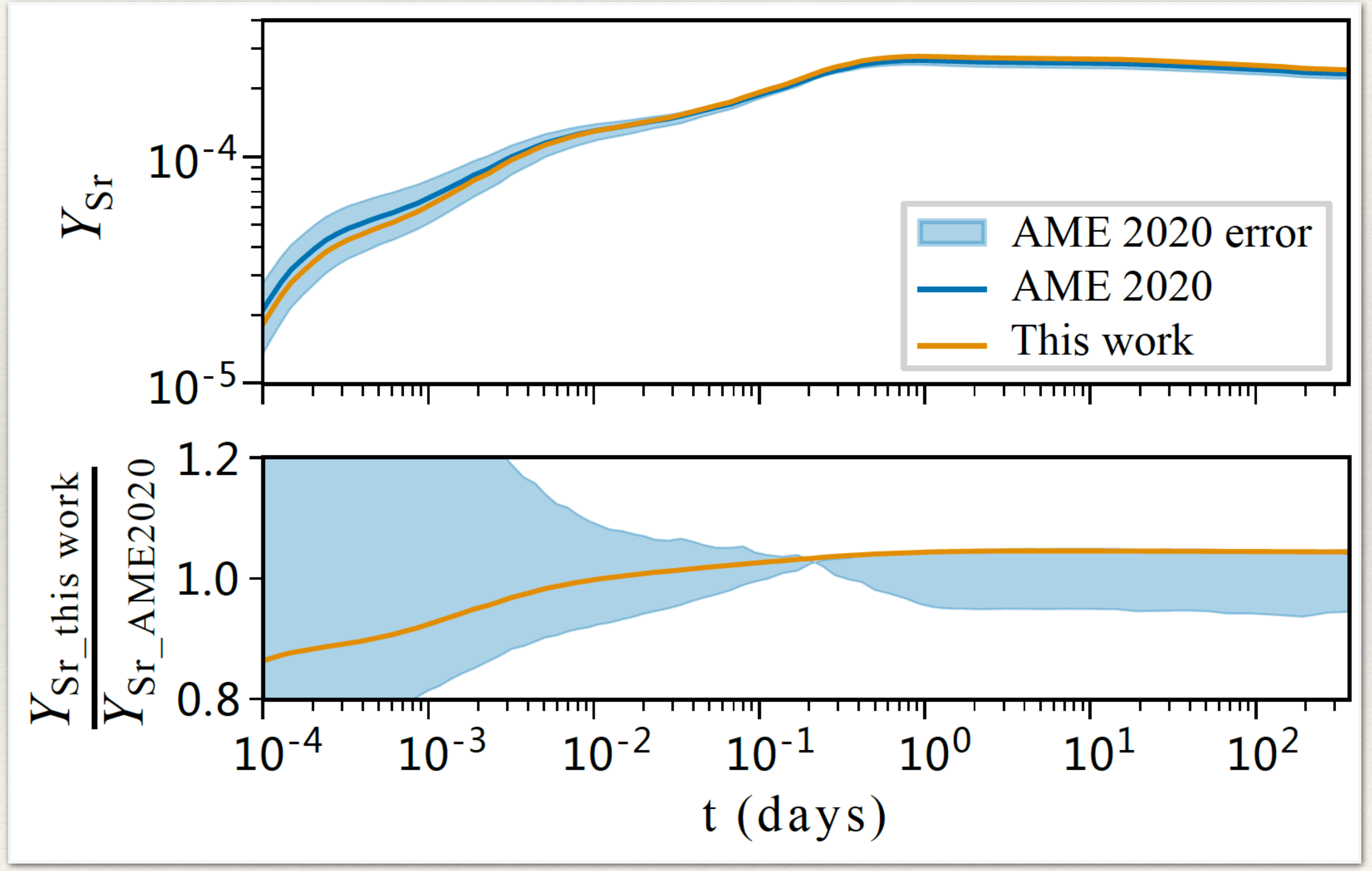
Mass measurements around A=90

^{83,84}Ga, $^{82-86}$Ge, $^{82-89}$As, $^{82,84-91}$Se, $^{85,86,89-92}$Br, ^{89,91,92}Kr, and ^{91}Rb *Xian et al, PRC109 (2024)*

Some mass uncertainties improved from hundreds keV to <10keV

Reaction rates for all these nuclei were calculate then used to estimate the final r-process abundances

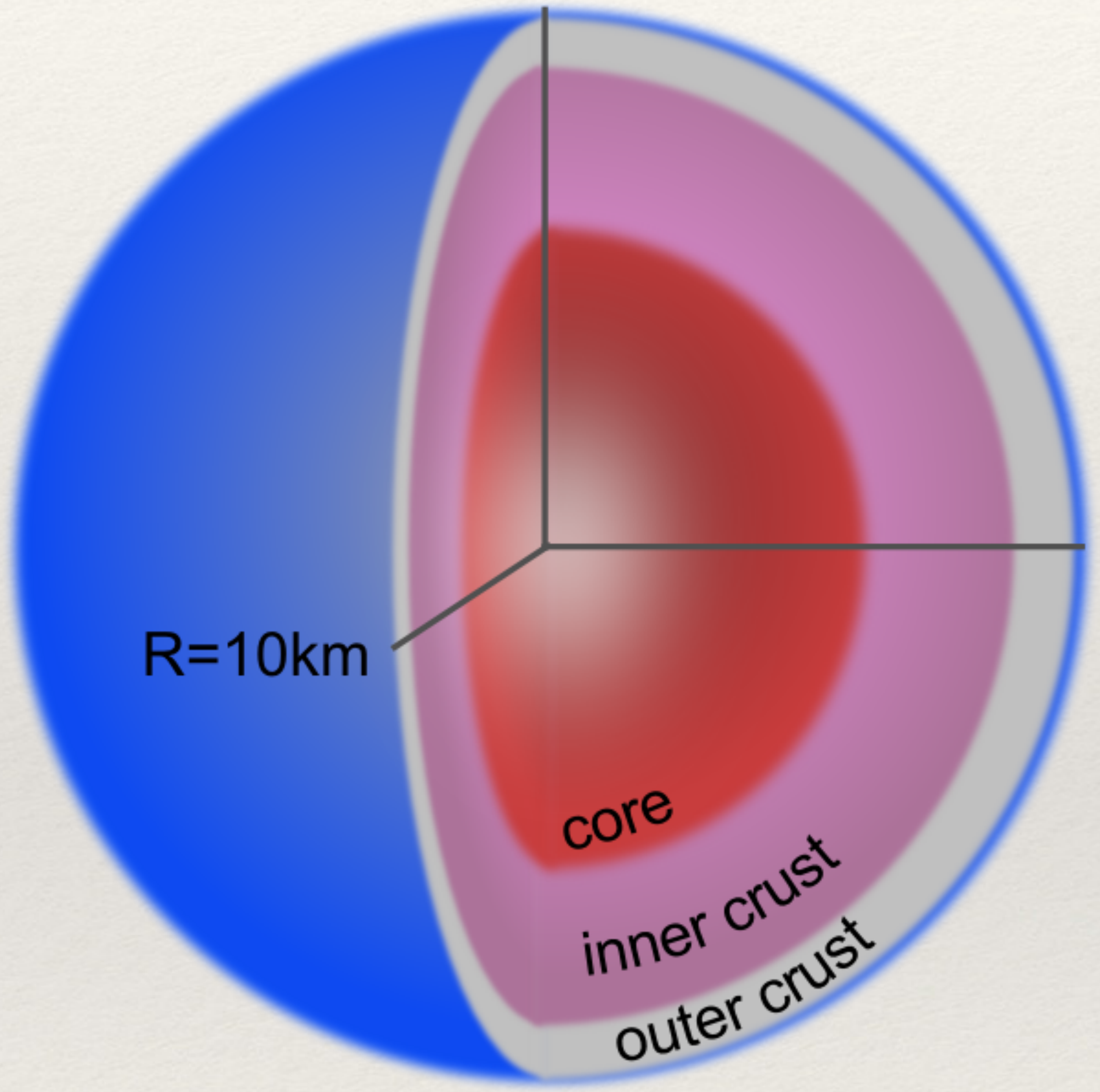




Astrophysical conditions 0.3<Ye<0.42 and entropy S = 10 kb/baryon
up to 20% difference in abundances compared to AME2020
Moderately n-rich

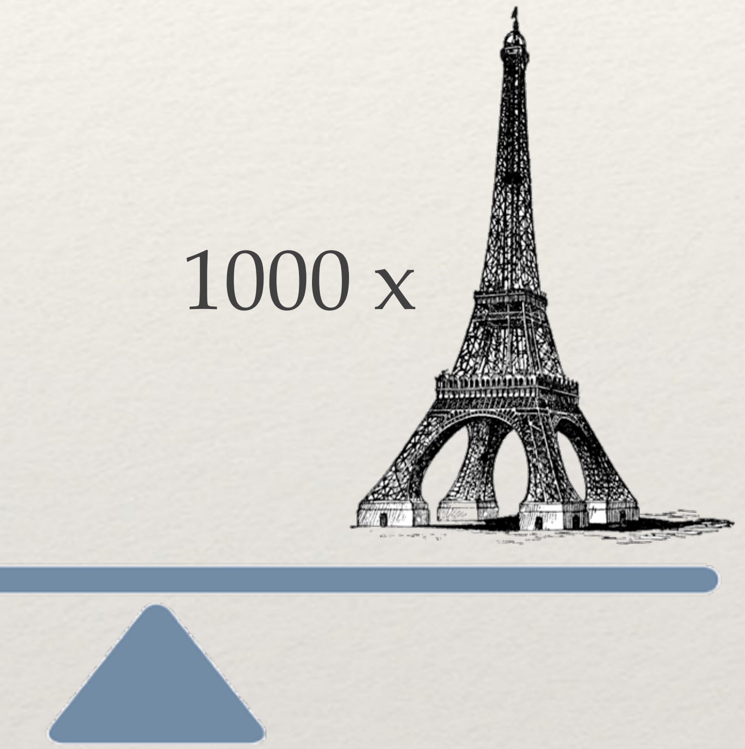
Later time -> smaller difference in Sr abundance

The Structure of Neutron Stars

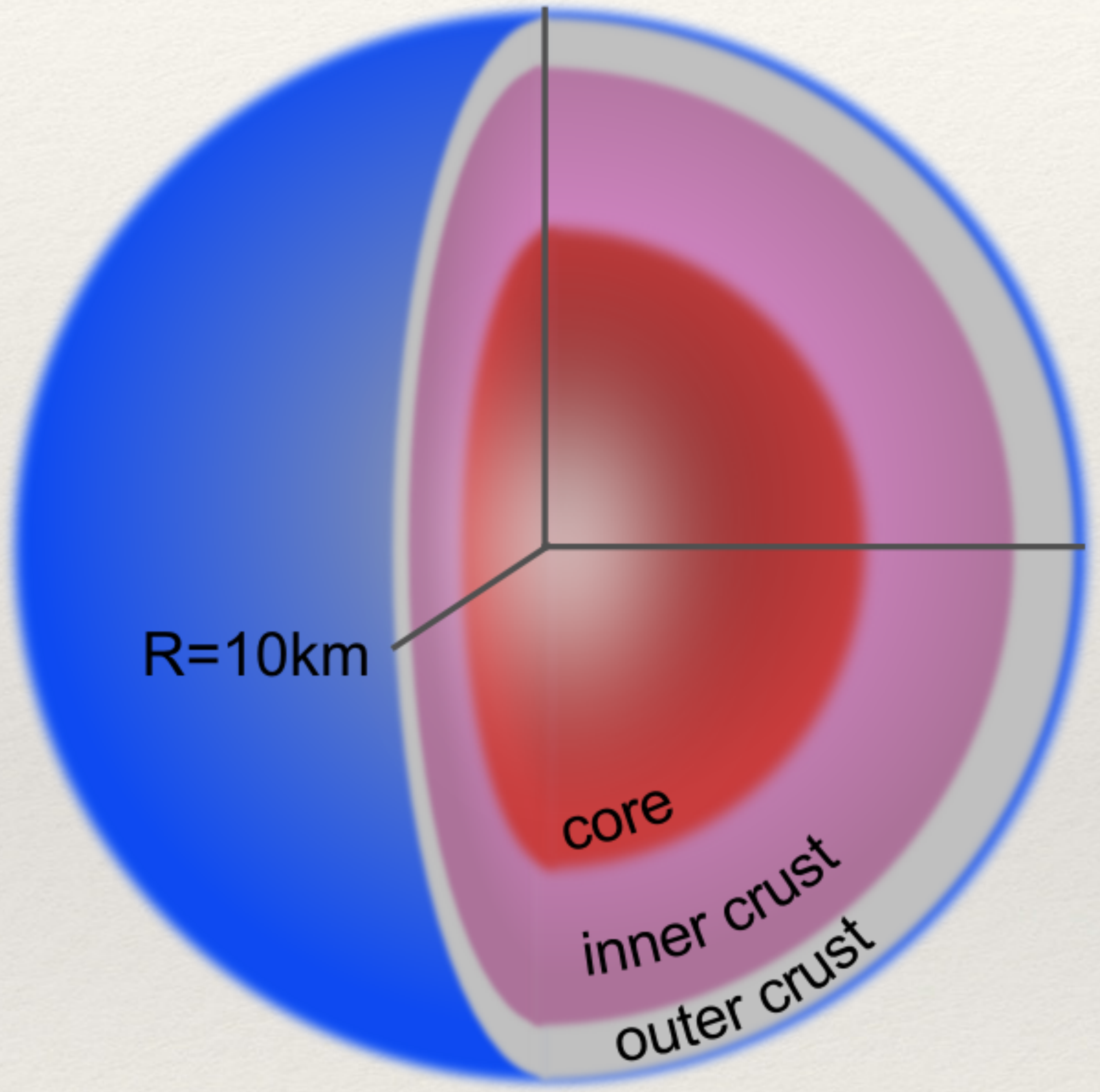


Neutron star: very compact object
1 $M_\odot$ in about 10km

1000 x



The Structure of Neutron Stars

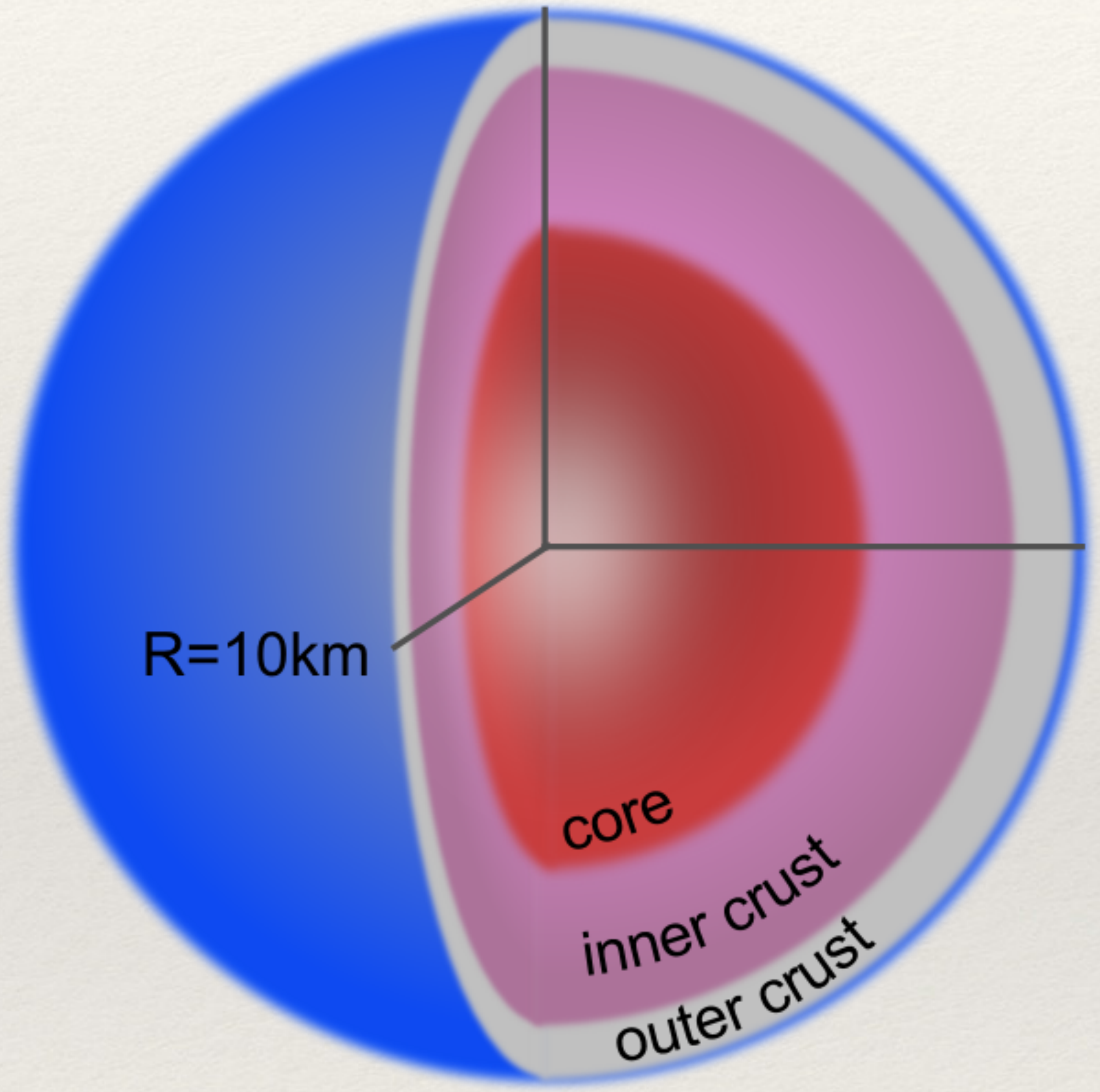


Neutron star: very compact object
1 $M_\odot$ in about 10km

1000 x

The outer crust contains neutron-rich isotopes

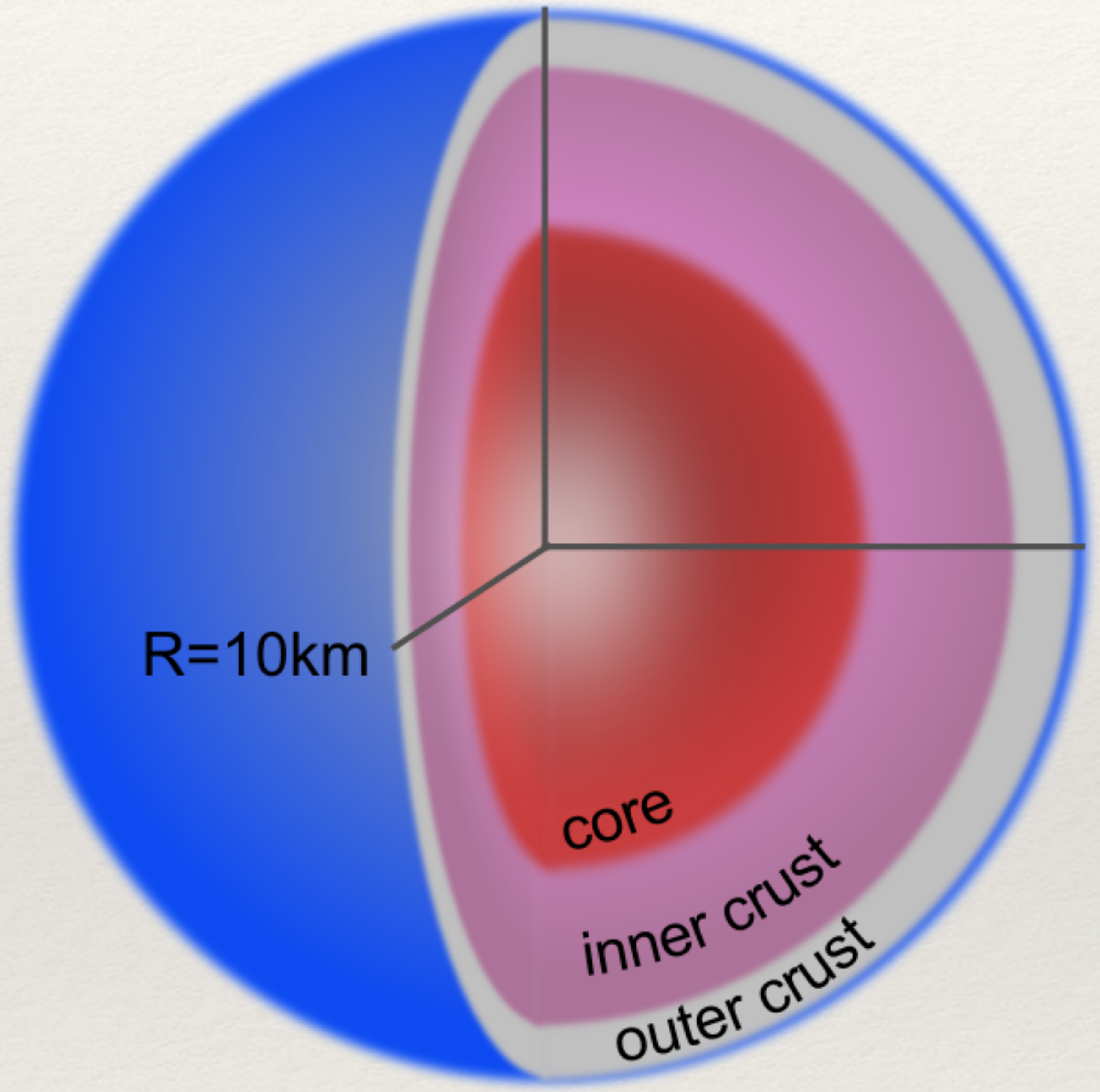
The Structure of Neutron Stars



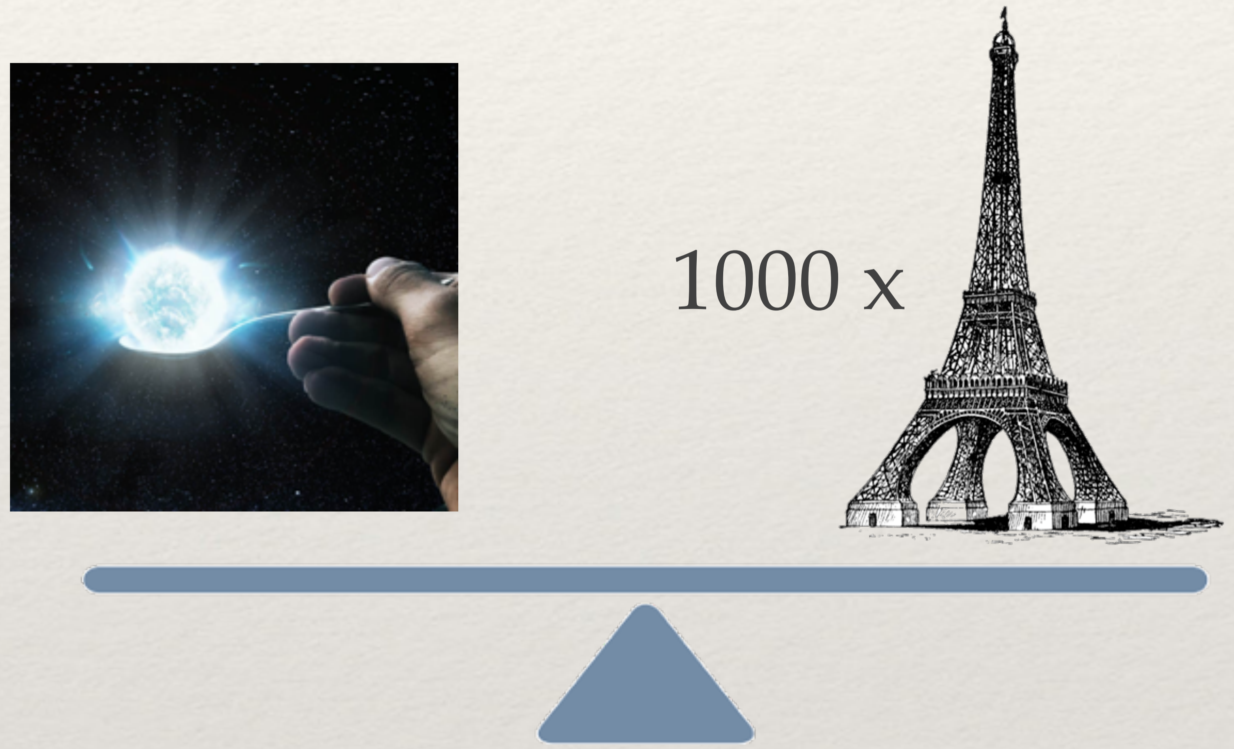
Neutron star: very compact object
1 M⊙ in about 10km

The outer crust contains neutron-rich isotopes

The Structure of Neutron Stars



Neutron star: very compact object
$1\ M_\odot$ in about 10km

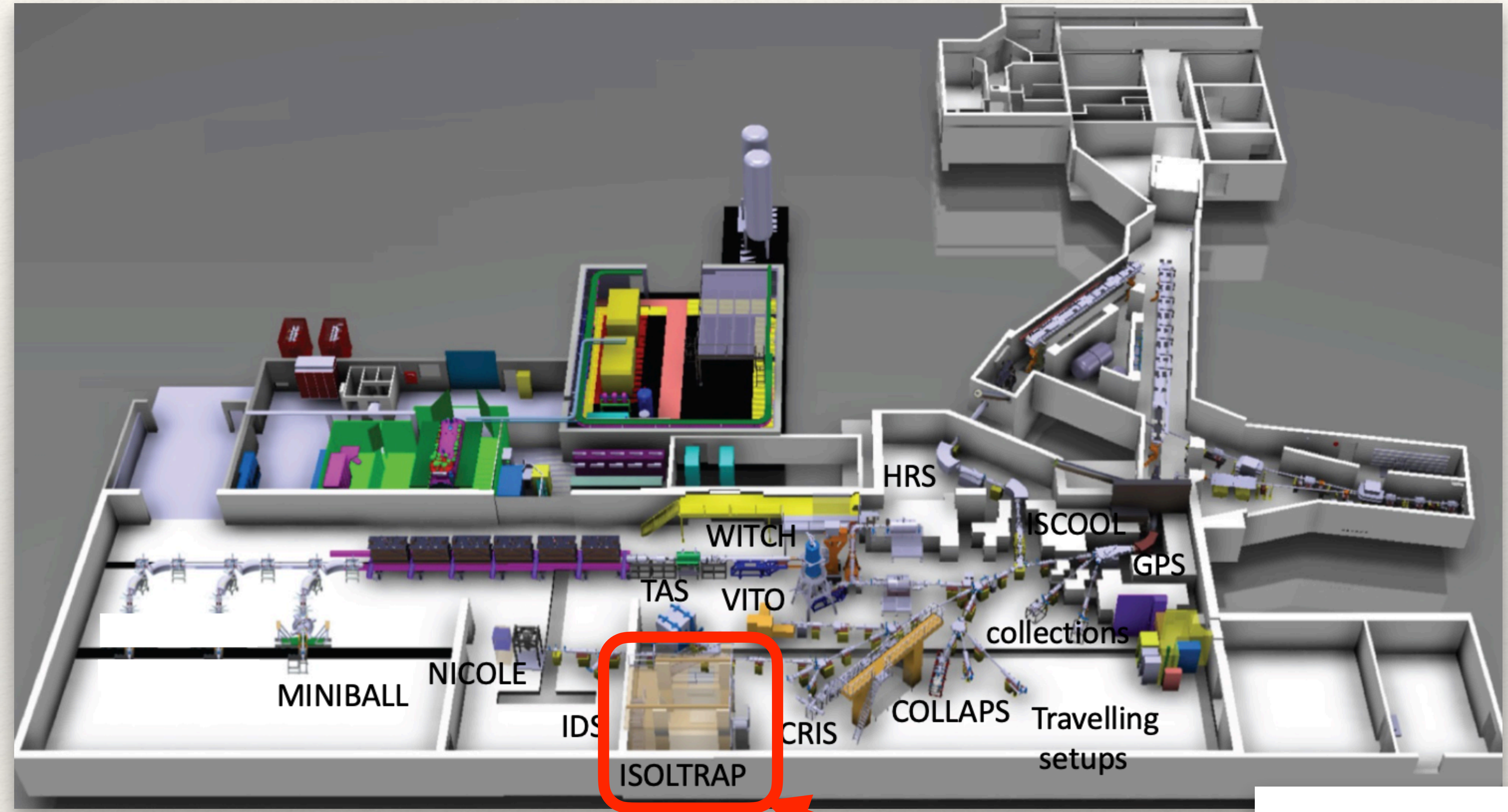


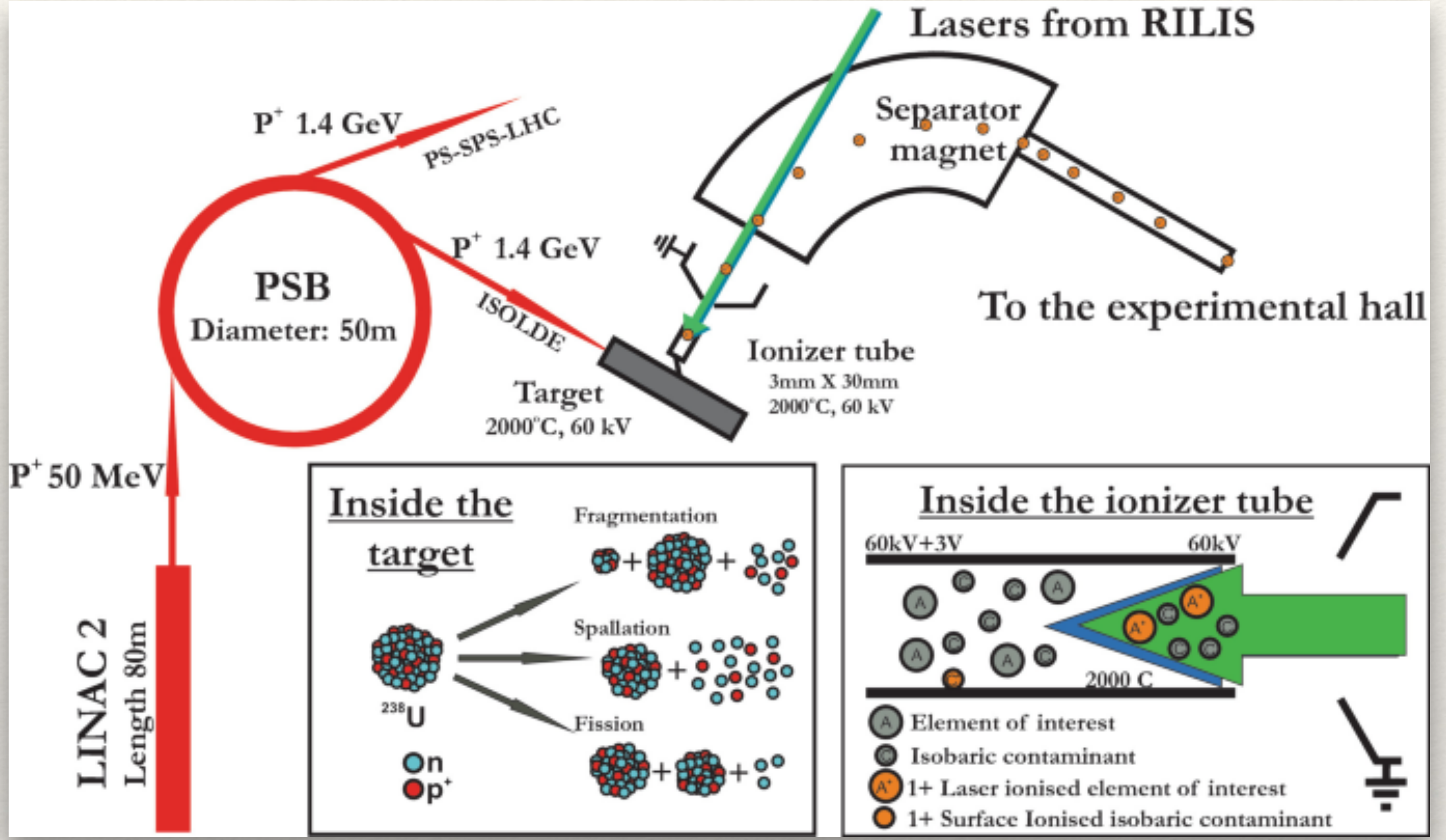
The outer crust contains neutron-rich isotopes

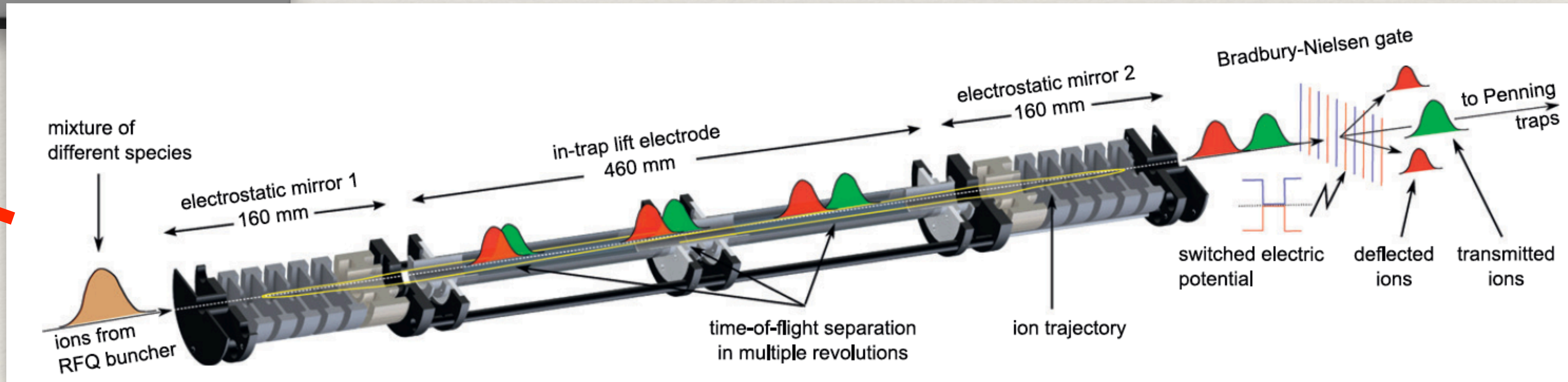
↓

Neutron-rich isotopes properties?

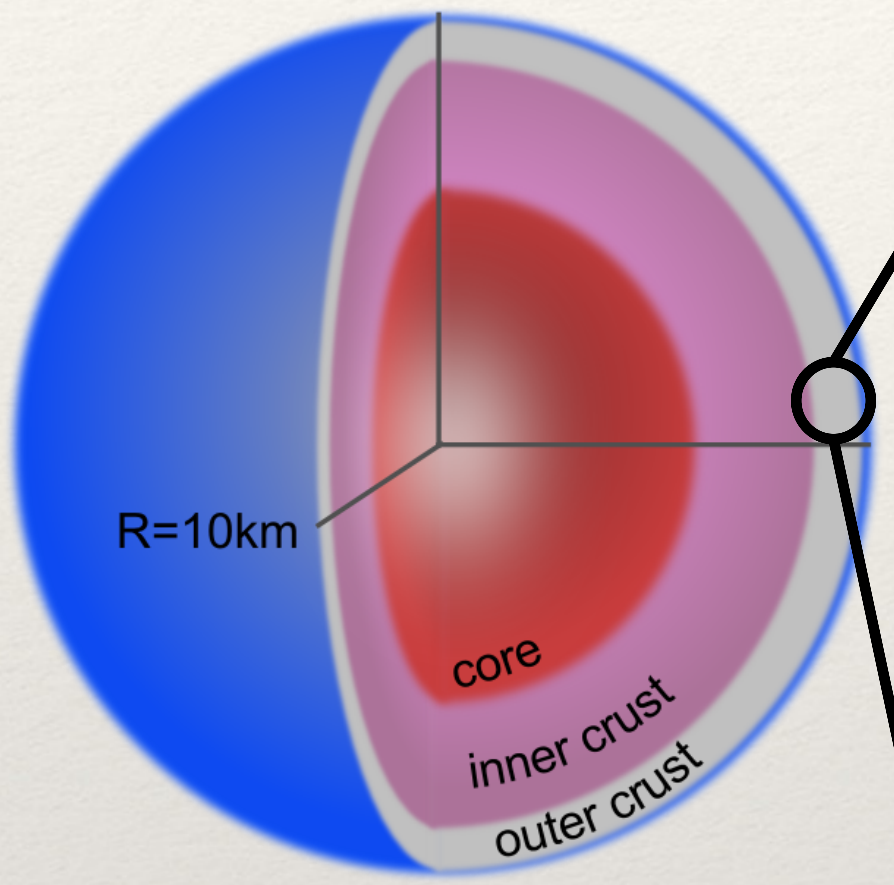
Mass measurement at ISOLDE/CERN





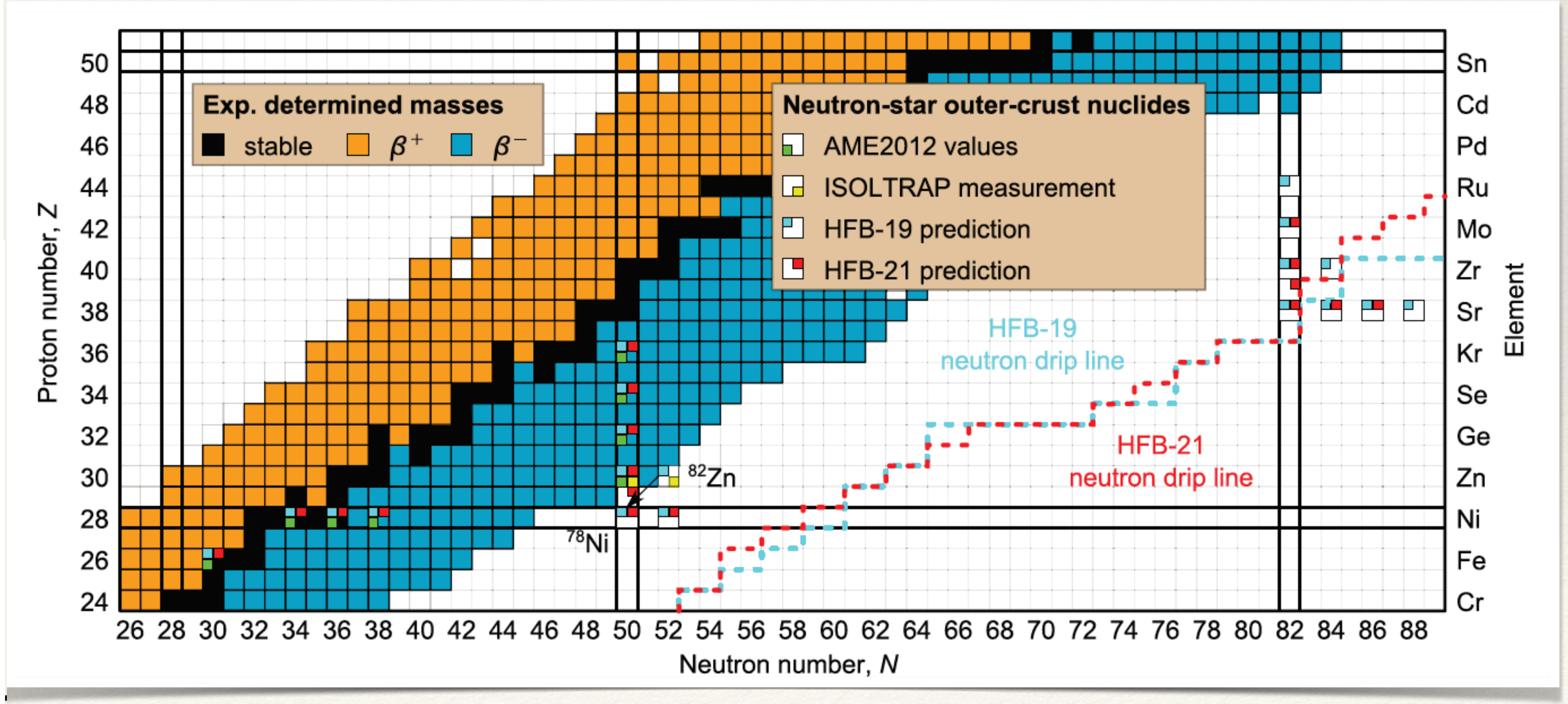


Impact on neutron star crust

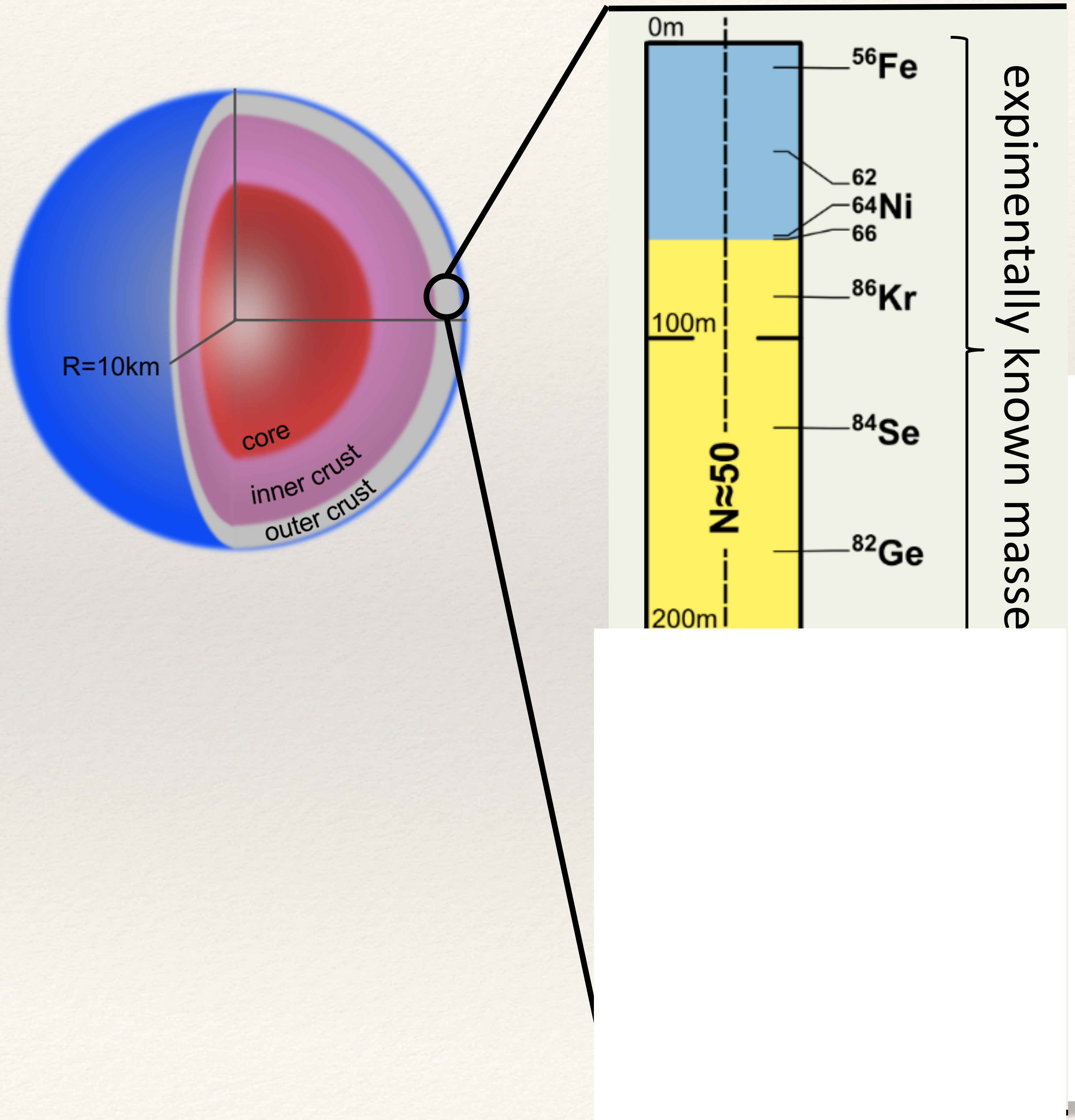


R.N. Wolf et al., PRL110, 041101 (2013)

Neutron star crust composition:
General relativity equations for hydrostatic equilibrium (TOV equations)
Relate pressure, mass-energy density with the neutron star mass and radius



Impact on neutron star crust



R.N. Wolf et al., PRL110, 041101 (2013)

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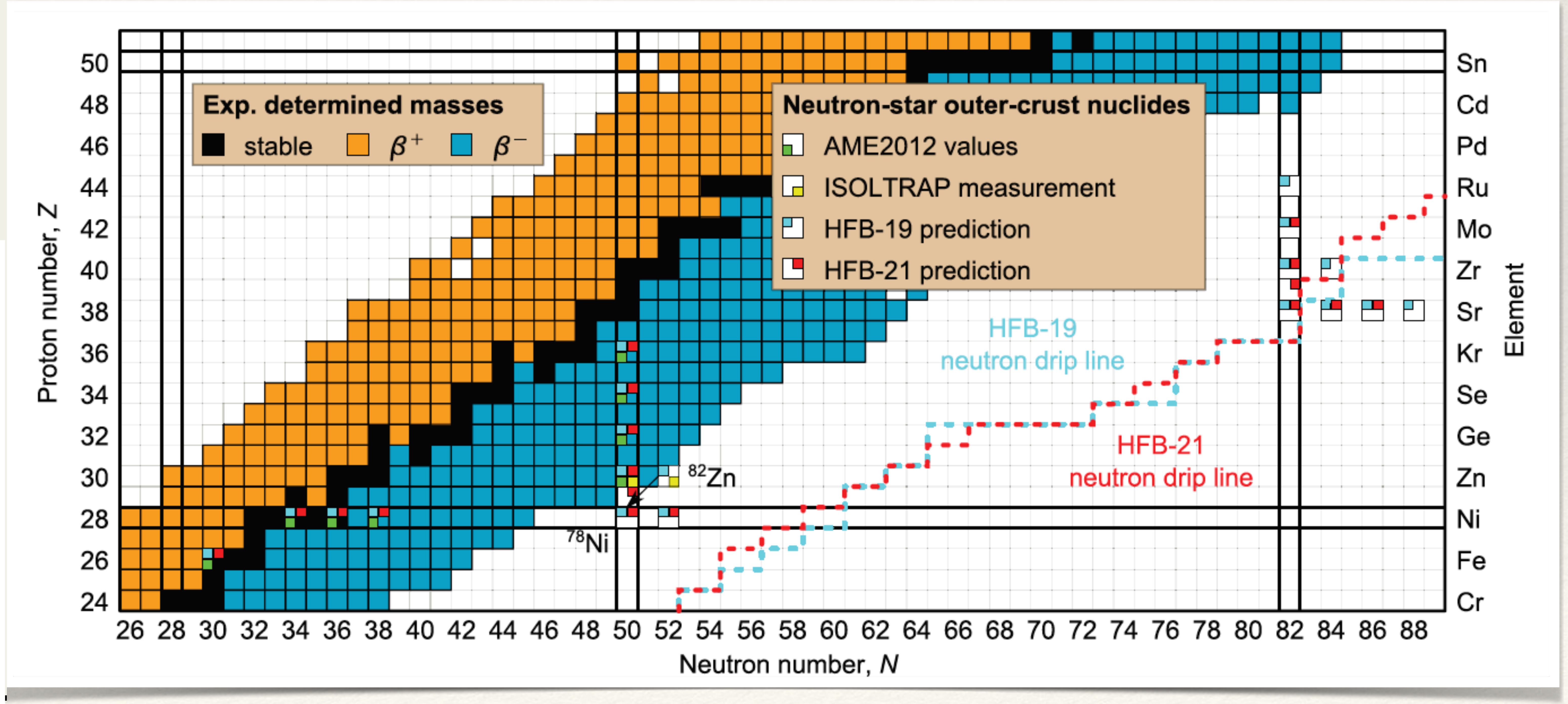
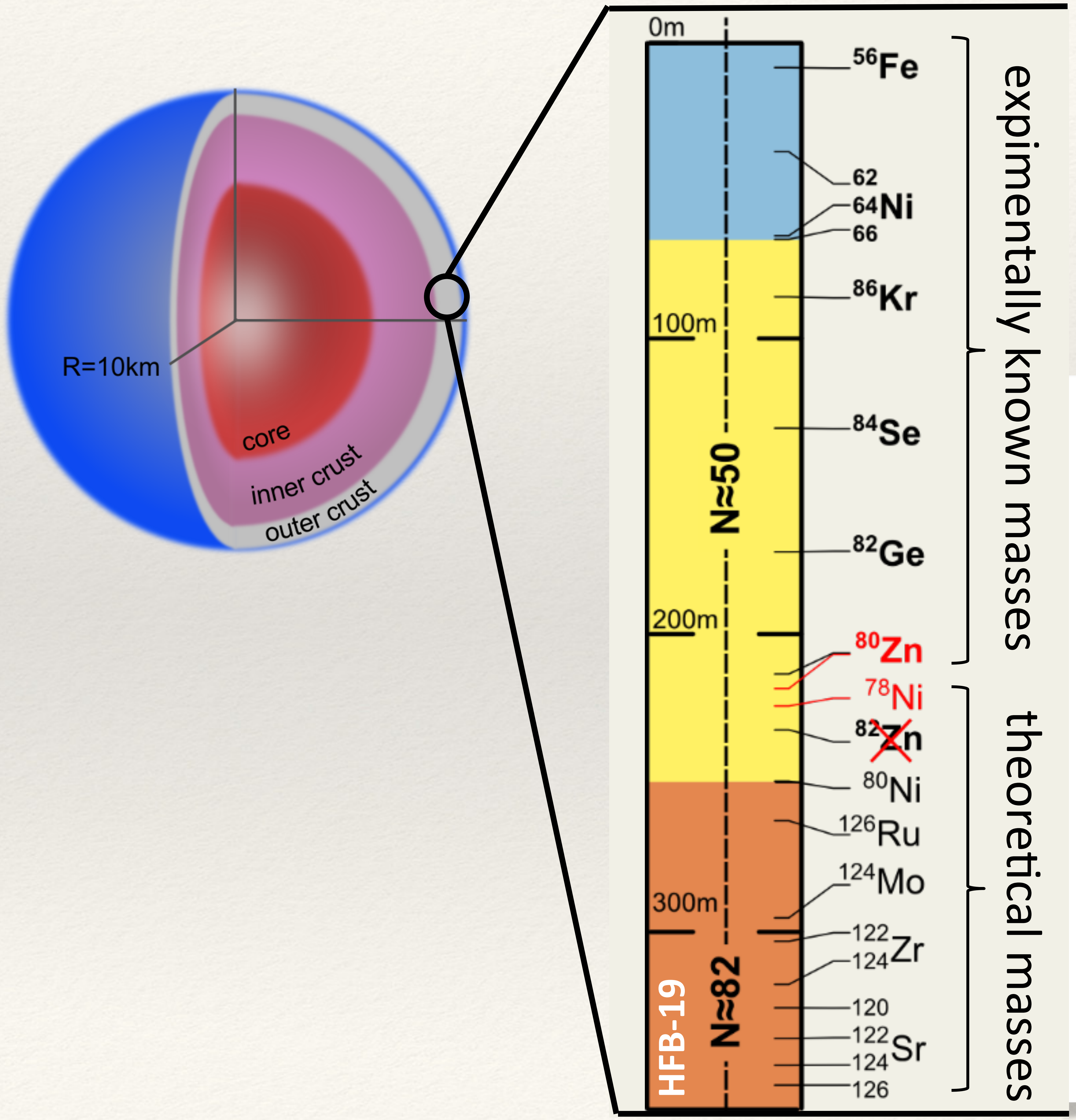
General relativity equations for hydrostatic equilibrium (TOV equations)
Relate pressure, mass-energy density with the neutron star mass and radius



Impact on neutron star crust

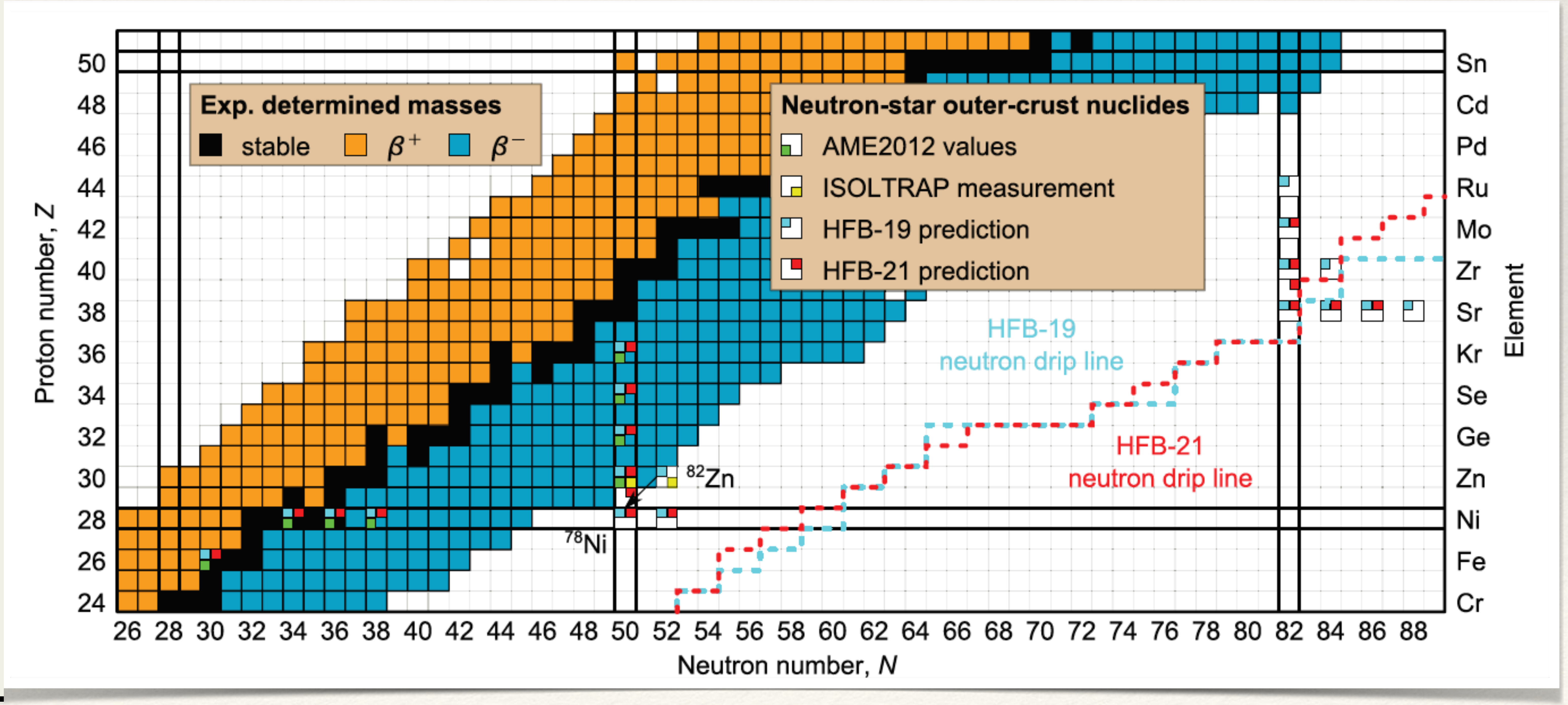


R.N. Wolf et al., PRL110, 041101 (2013)

Neutron star crust composition:

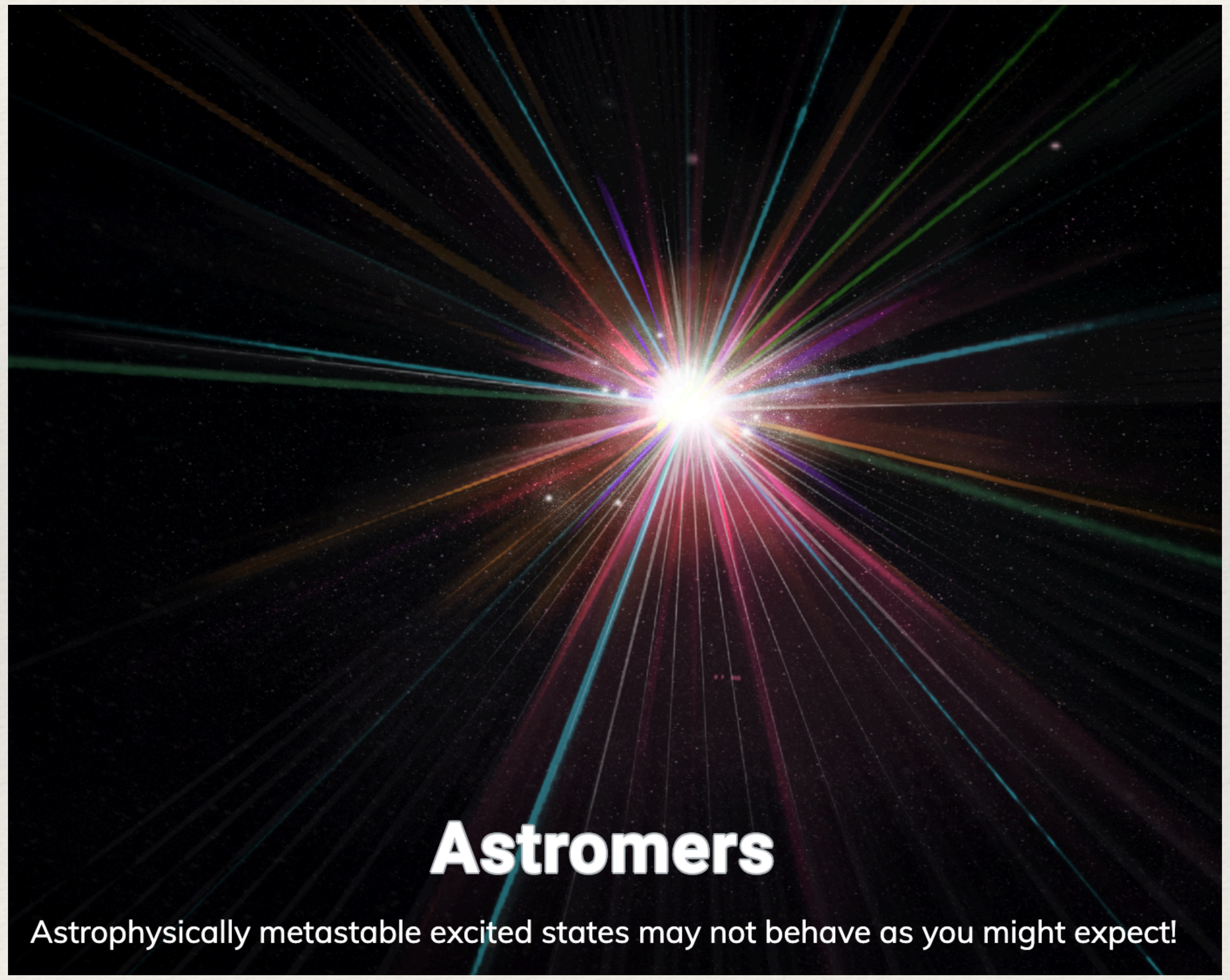
General relativity equations for hydrostatic equilibrium (TOV equations)

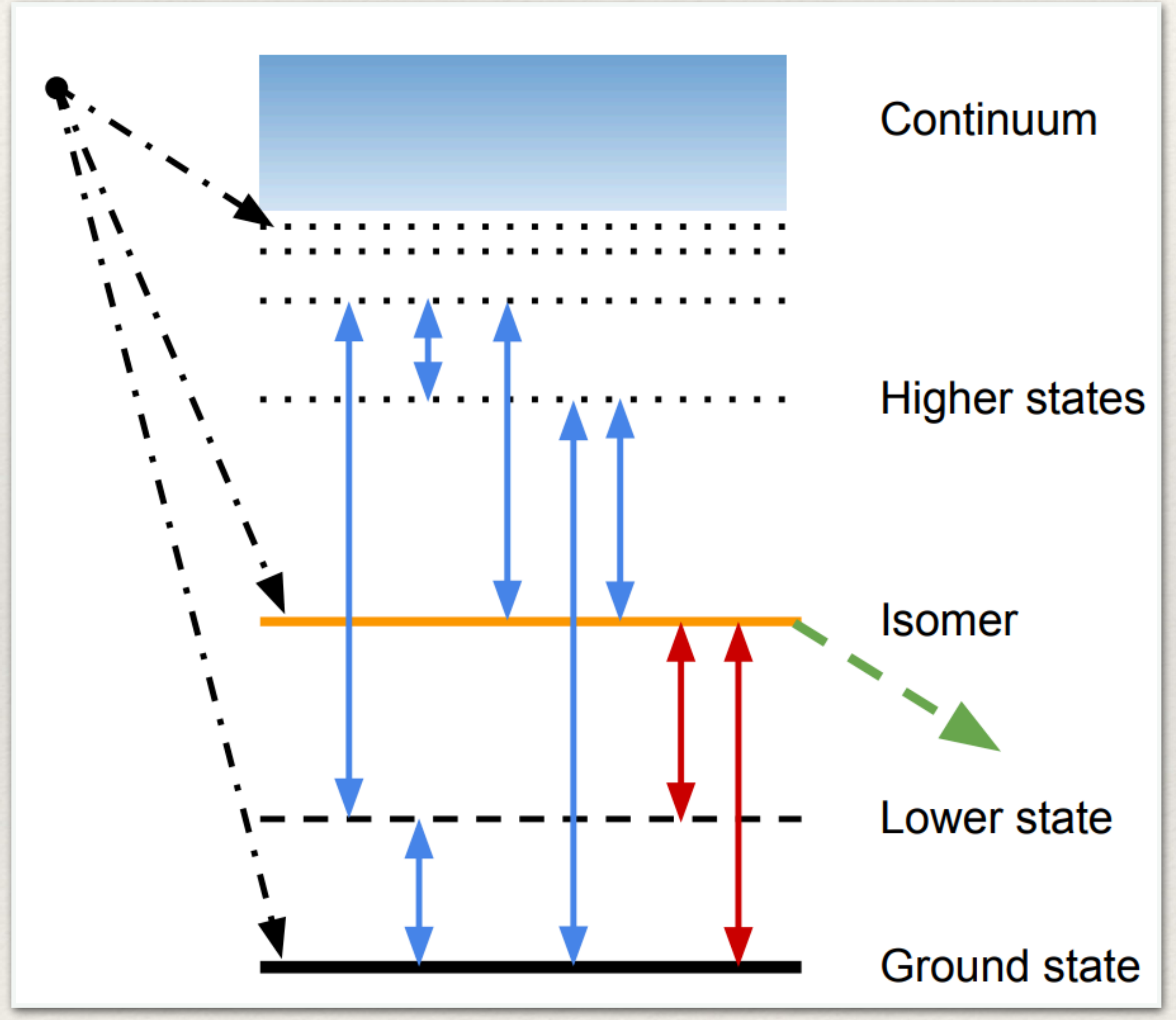
Relate pressure, mass-energy density with the neutron star mass and radius



Mass spectrometry and Astromers

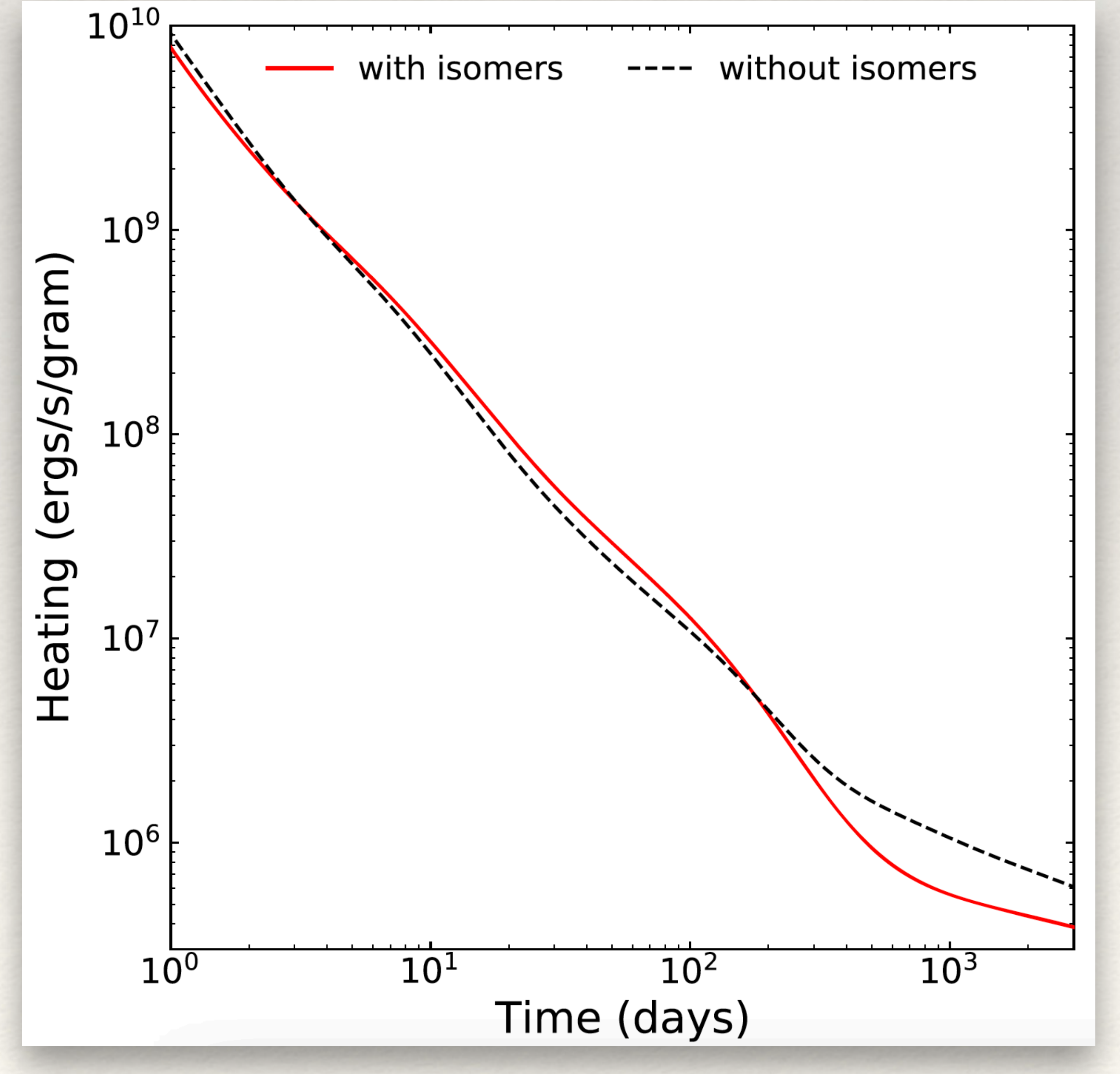
Astromer: a nuclear isomer that retains its metastable character in an astrophysical environment
Misch et al., ApJS 252 2 (2021)





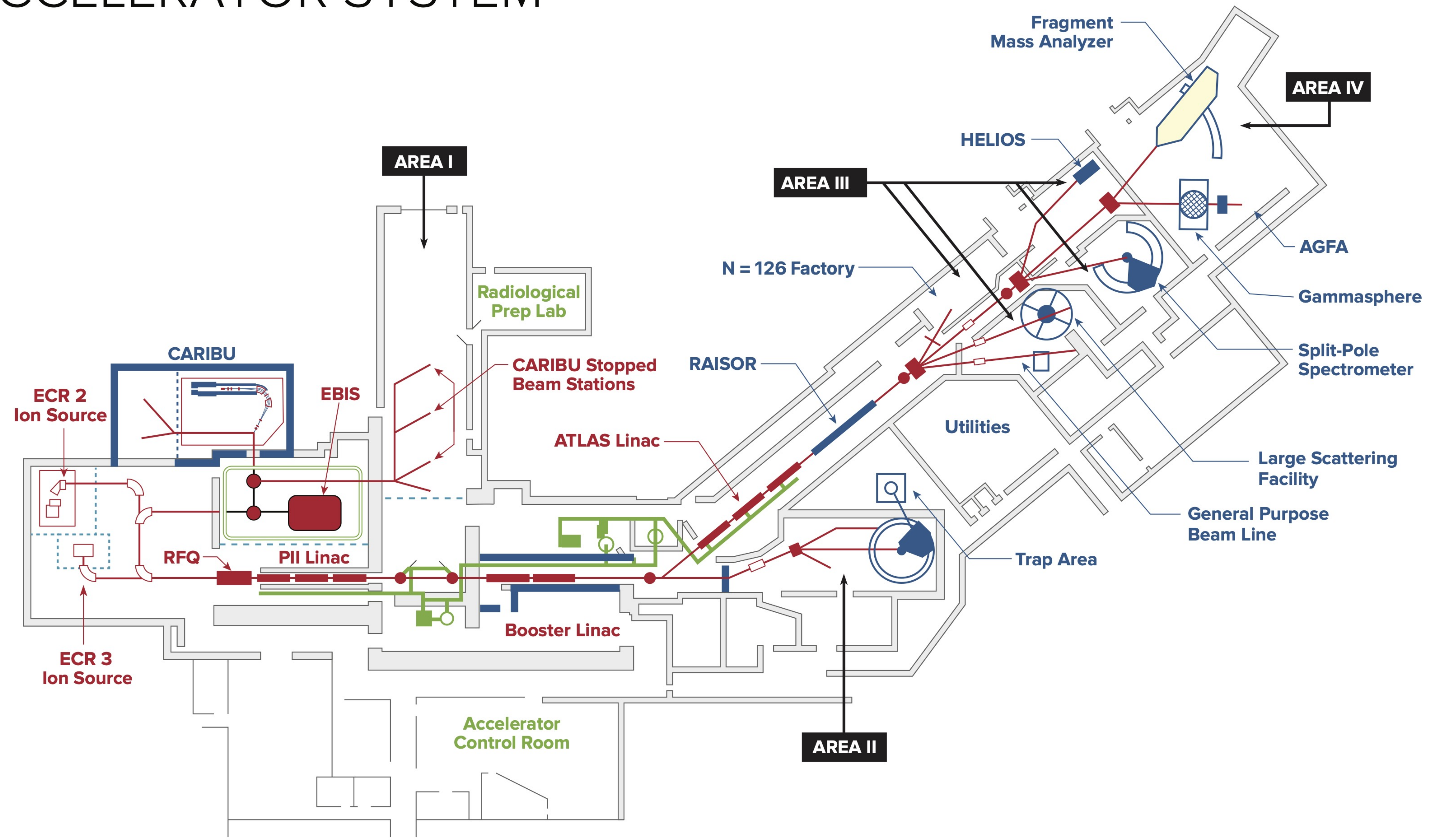
In the hot thermal bath of the stellar environment, the isomeric state is excited to higher intermediate states which in turn populate the ground state after de-excitation.

Not Astromer: Ground state = isomeric state
Astromer: Ground state ≠ isomeric state



ATLAS
ARGONNE TANDEM LINAC ACCELERATOR SYSTEM

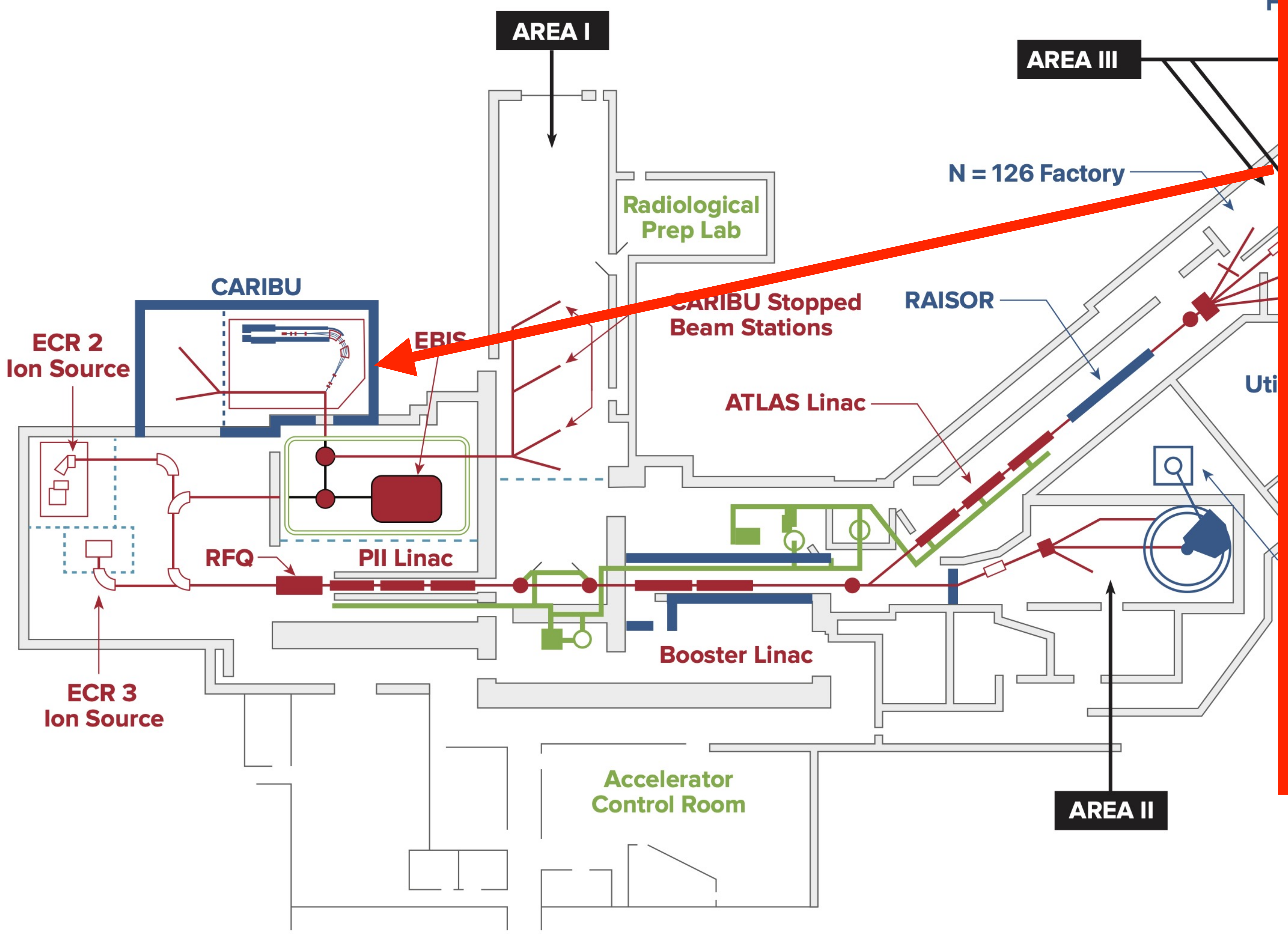
Argonne NATIONAL LABORATORY

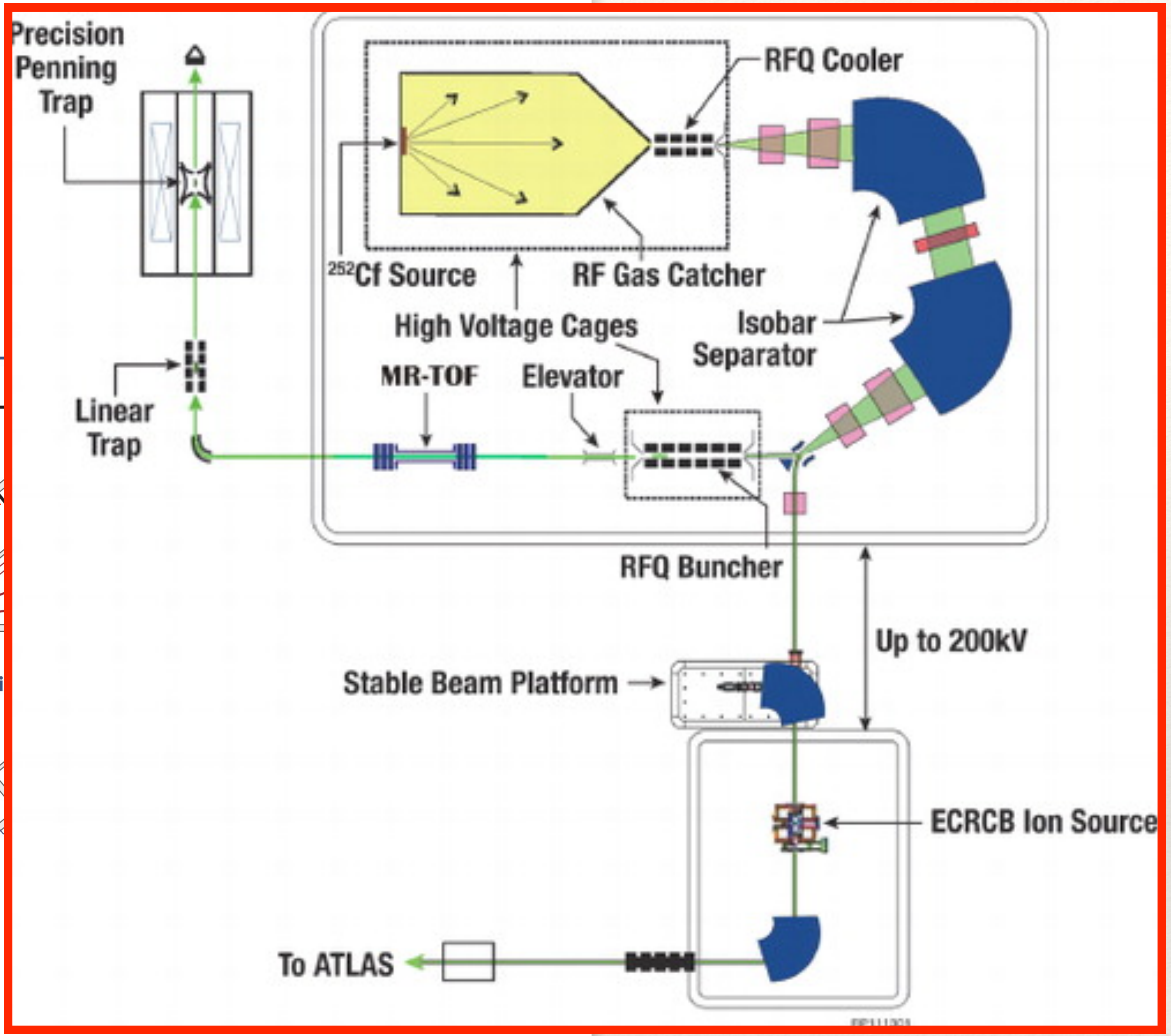


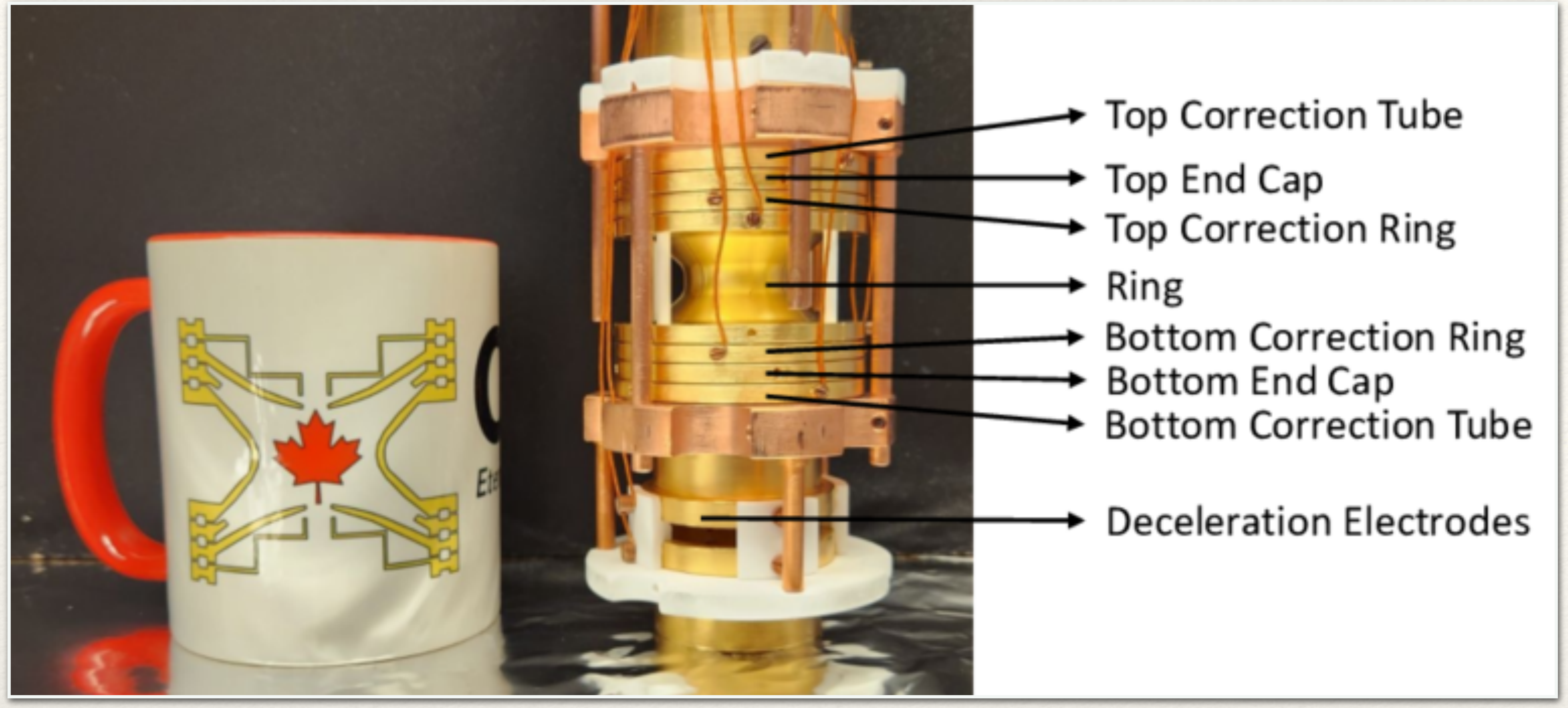
U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

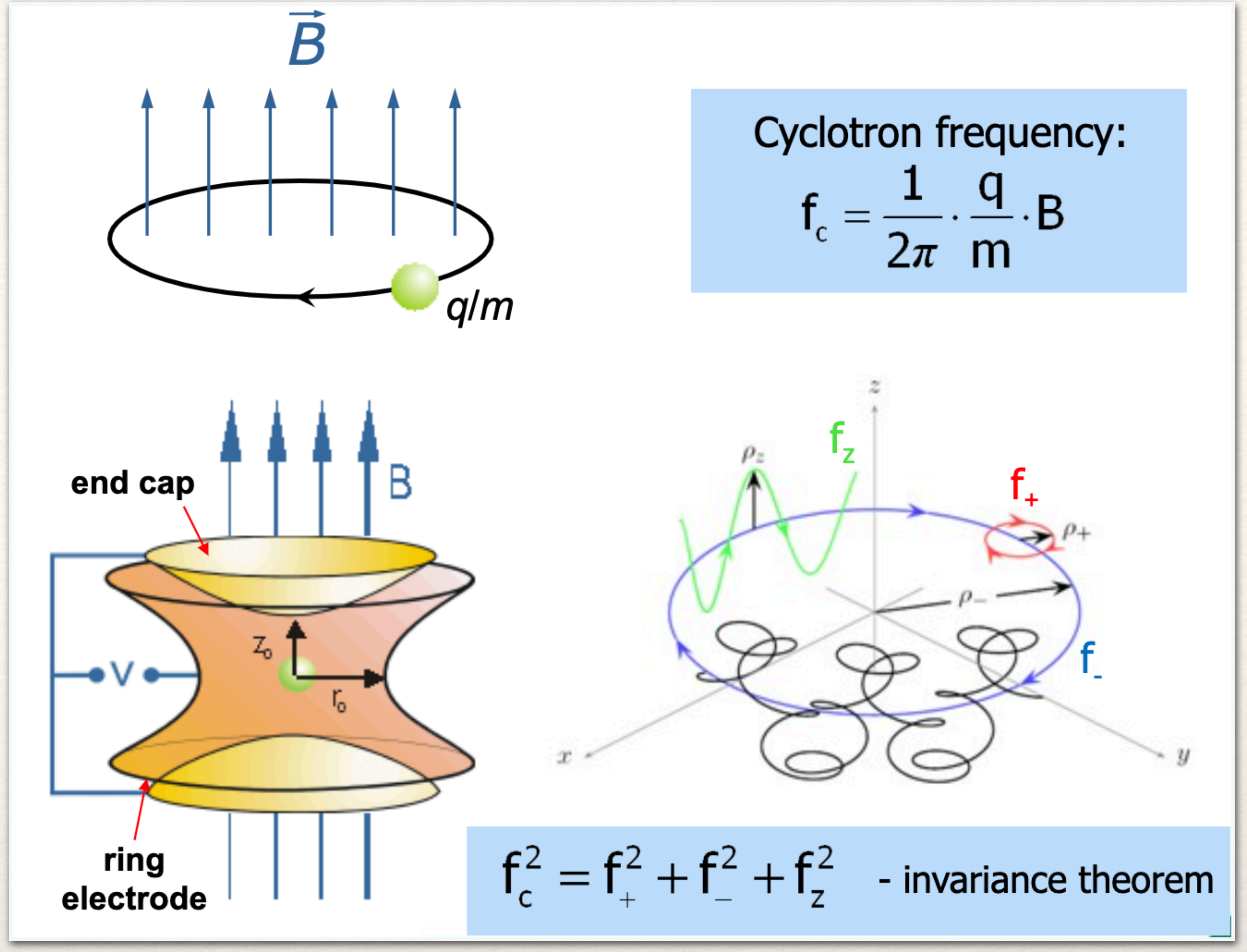
April 5, 2021

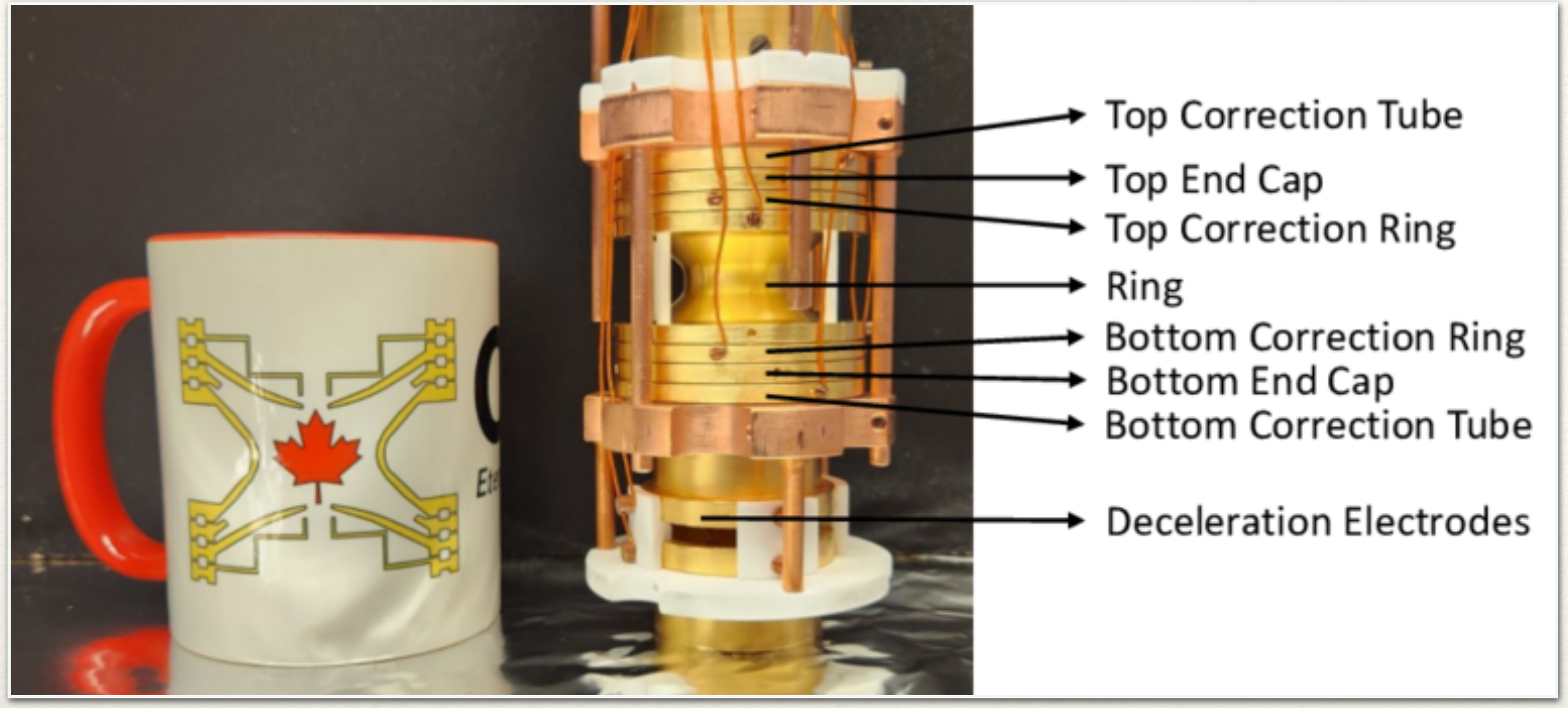
ATLAS
ARGONNE TANDEM LINAC
ACCELERATOR SYSTEM

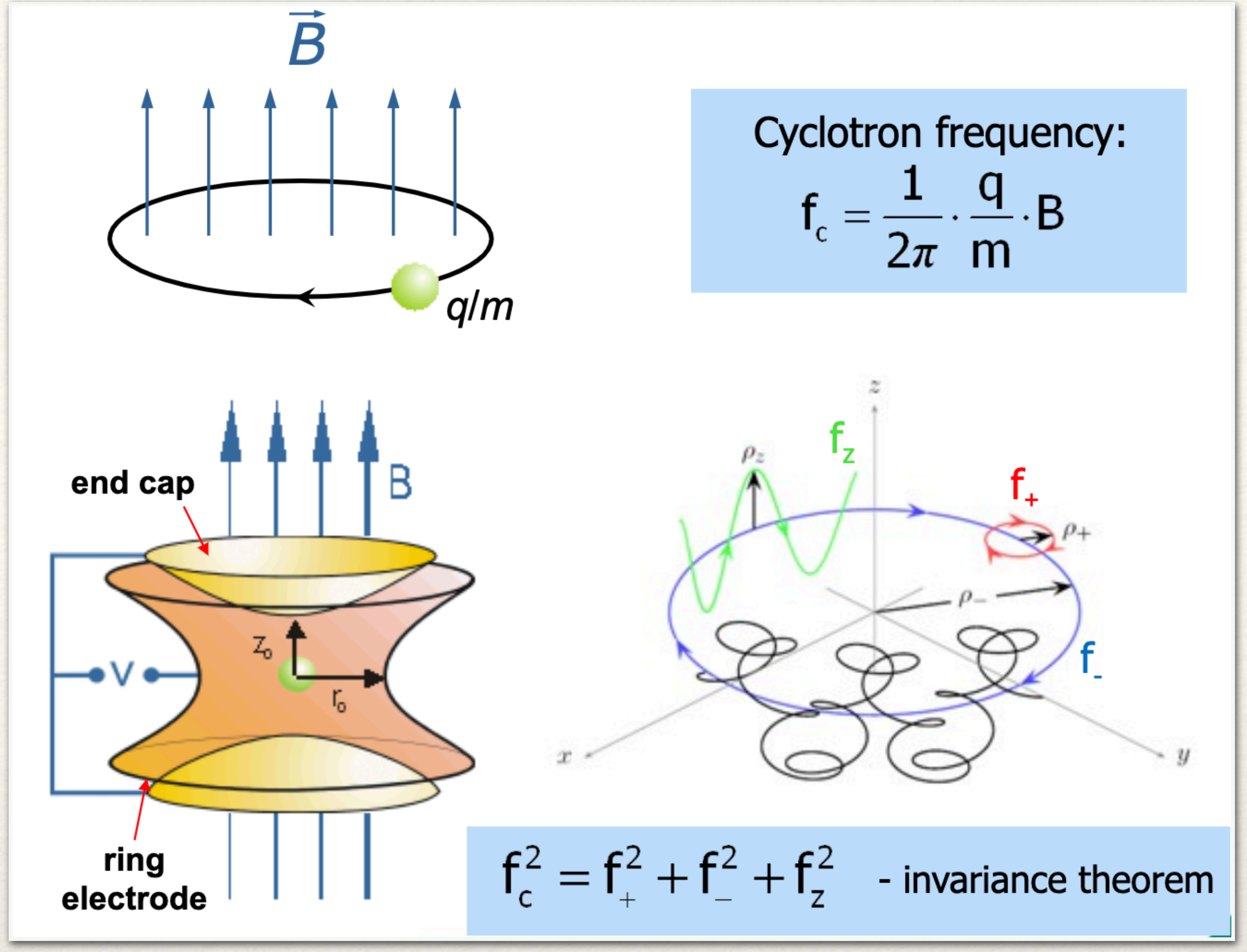


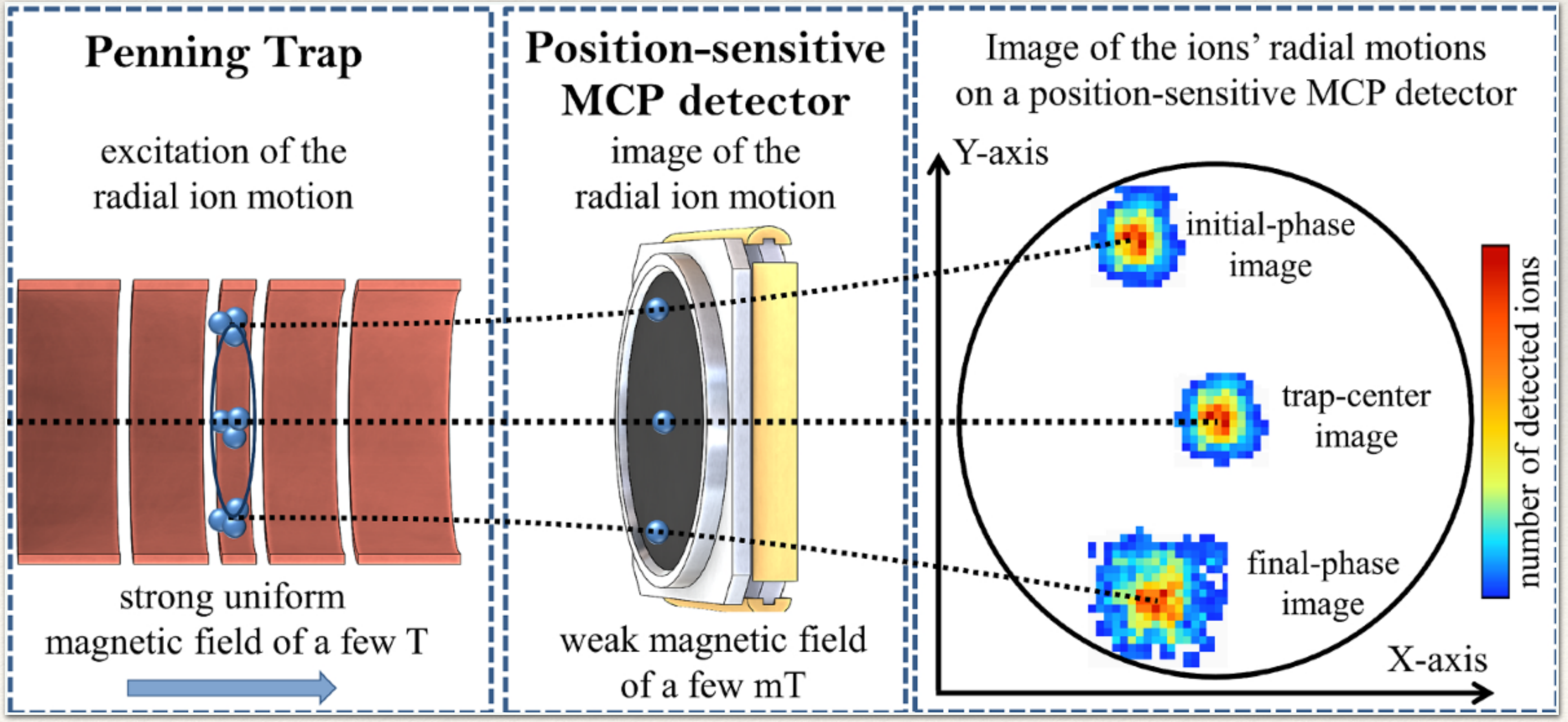



Top Correction Tube
Top End Cap
Top Correction Ring
Ring
Bottom Correction Ring
Bottom End Cap
Bottom Correction Tube
Deceleration Electrodes


$\vec{B}$
q/m
Cyclotron frequency:
$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$
end cap
B
V
z_0
r_0
ring electrode
f_z
f_+
f_-
$f_c^2 = f_+^2 + f_-^2 + f_z^2$ - invariance theorem

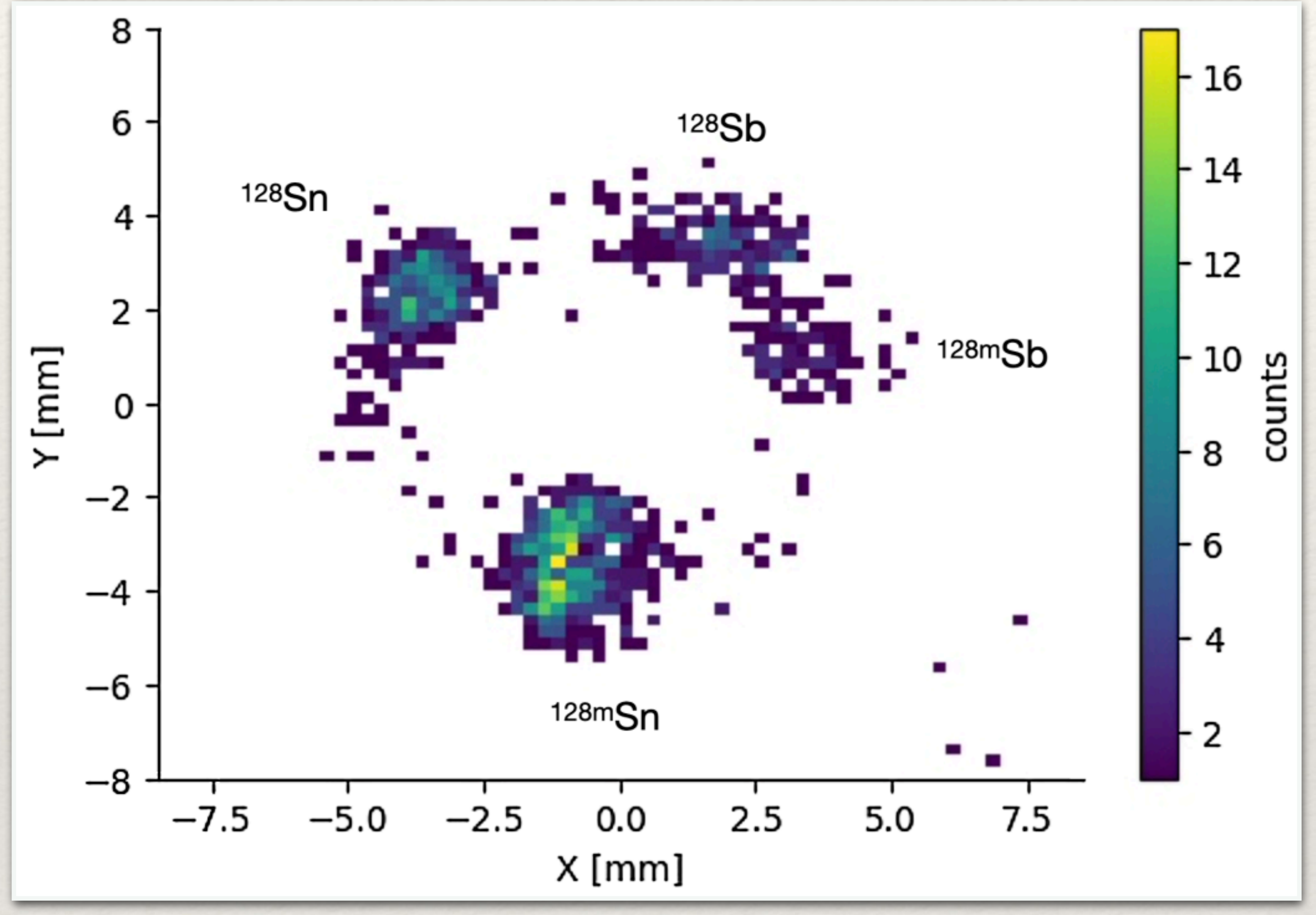

Top Correction Tube
Top End Cap
Top Correction Ring
Ring
Bottom Correction Ring
Bottom End Cap
Bottom Correction Tube
Deceleration Electrodes


B
q/m
Cyclotron frequency:
$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$
end cap
B
V
z_0
r_0
ring electrode
f_z
f_+
f_-
$f_c^2 = f_+^2 + f_-^2 + f_z^2$ - invariance theorem

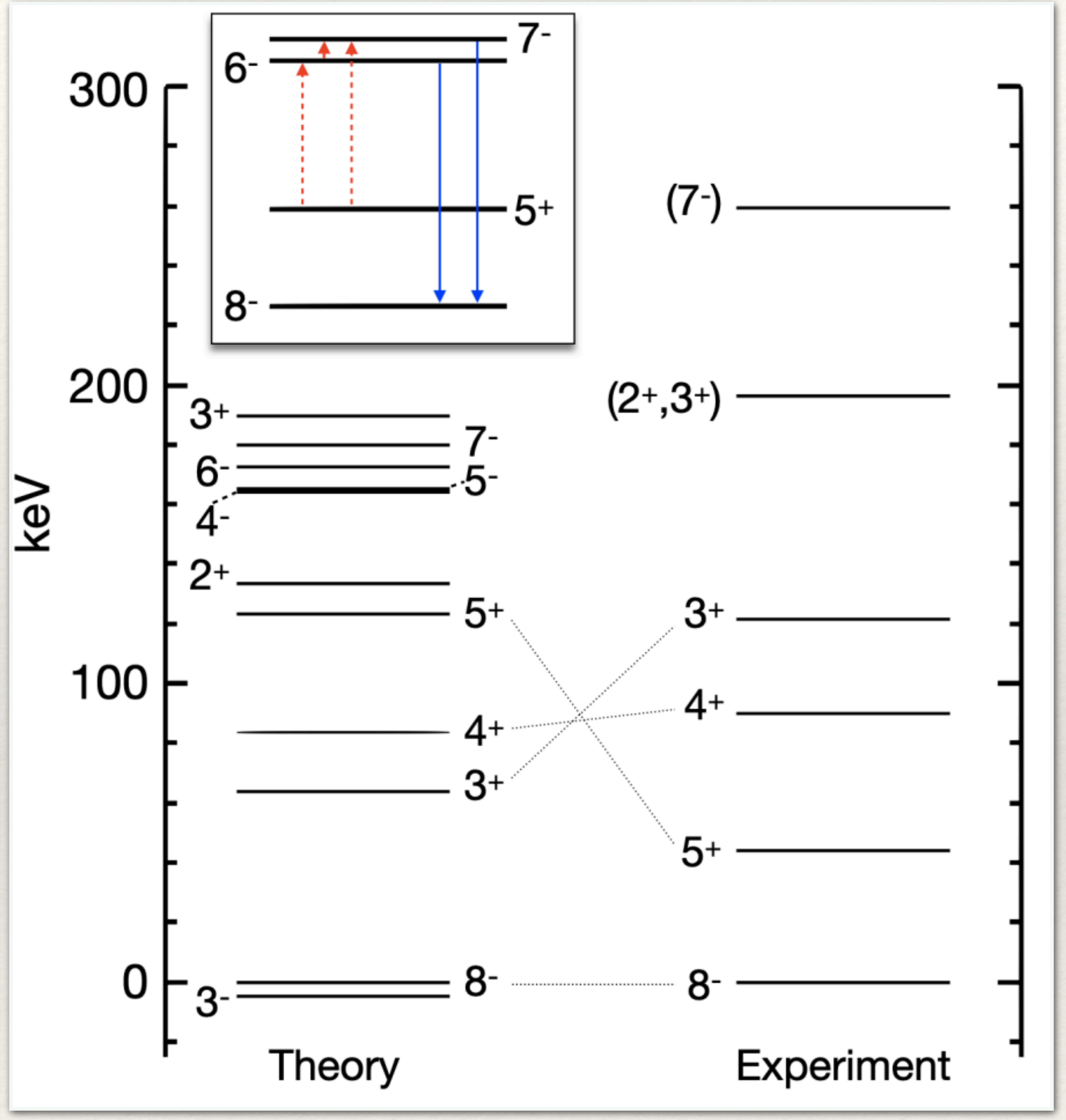

Penning Trap
excitation of the radial ion motion
strong uniform magnetic field of a few T
Position-sensitive MCP detector
image of the radial ion motion
weak magnetic field of a few mT
Image of the ions' radial motions on a position-sensitive MCP detector
Y-axis
initial-phase image
trap-center image
final-phase image
X-axis
number of detected ions

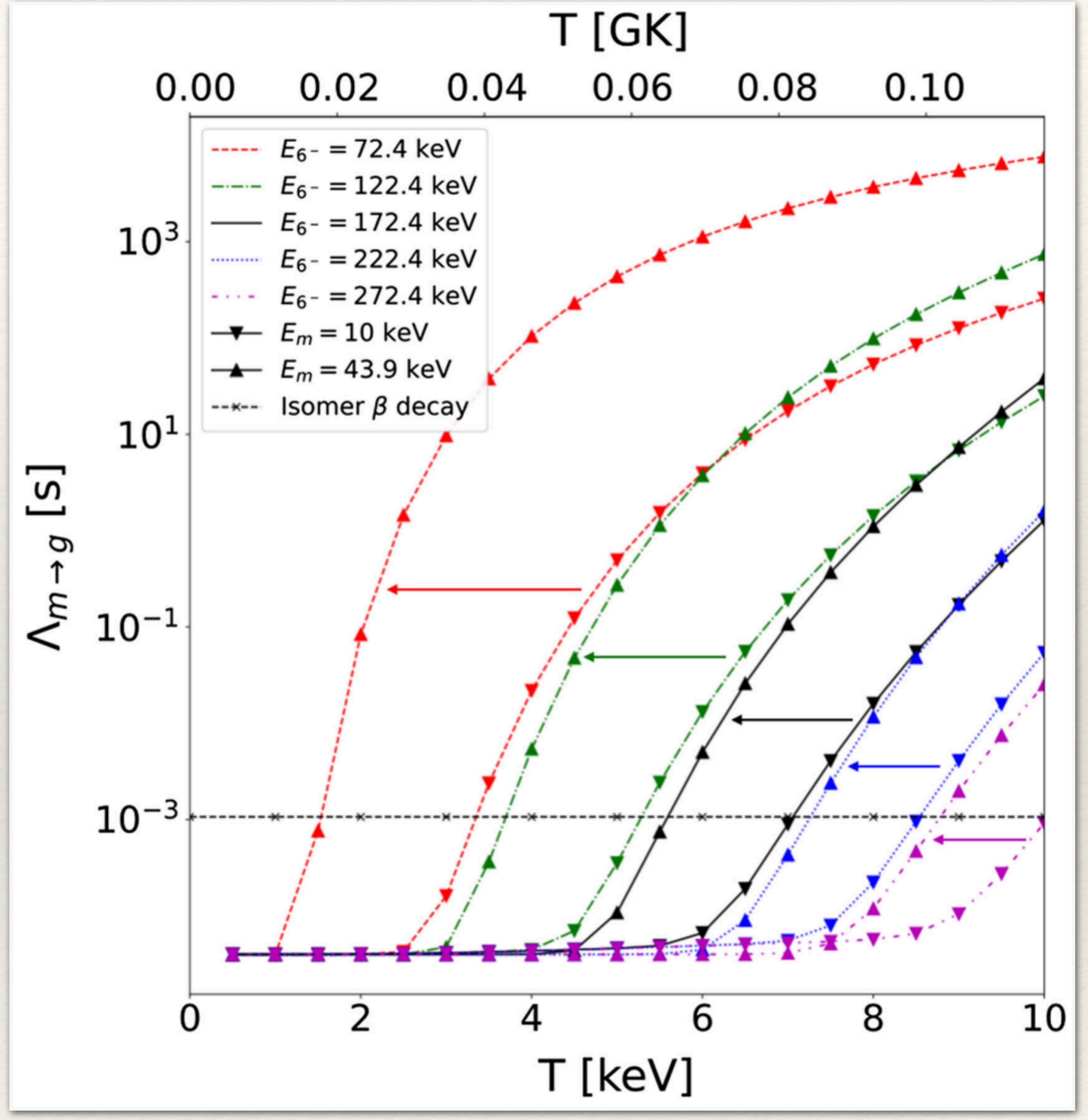
Excitation energy measurement of ^{128}Sb

Hoff et al, PRL131 (2023)



Species	$r = (\nu_c^{cal}/\nu_c)$	Mass excess (keV) this Letter	Mass excess (keV) evaluated
$^{128}Sb^+$	0.962407089(17)	−84608.8 ± 2.1	−84630 ± 19[a]
$^{128m}Sb^+$	0.962407444(20)	−84564.8 ± 2.5	−84620 ± 18[b]
	Excitation energy	43.9 ± 3.3	10 ± 6[b]



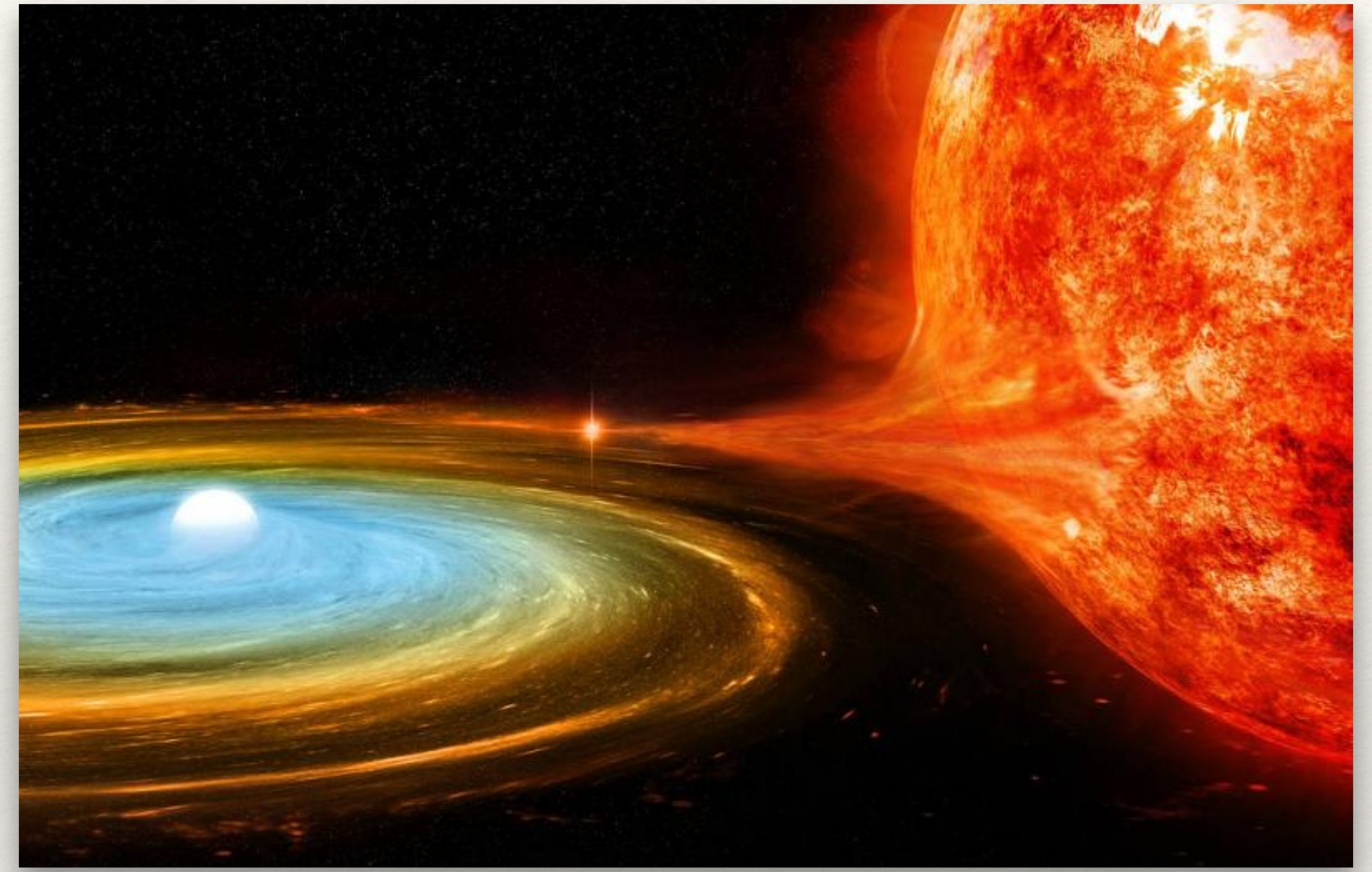


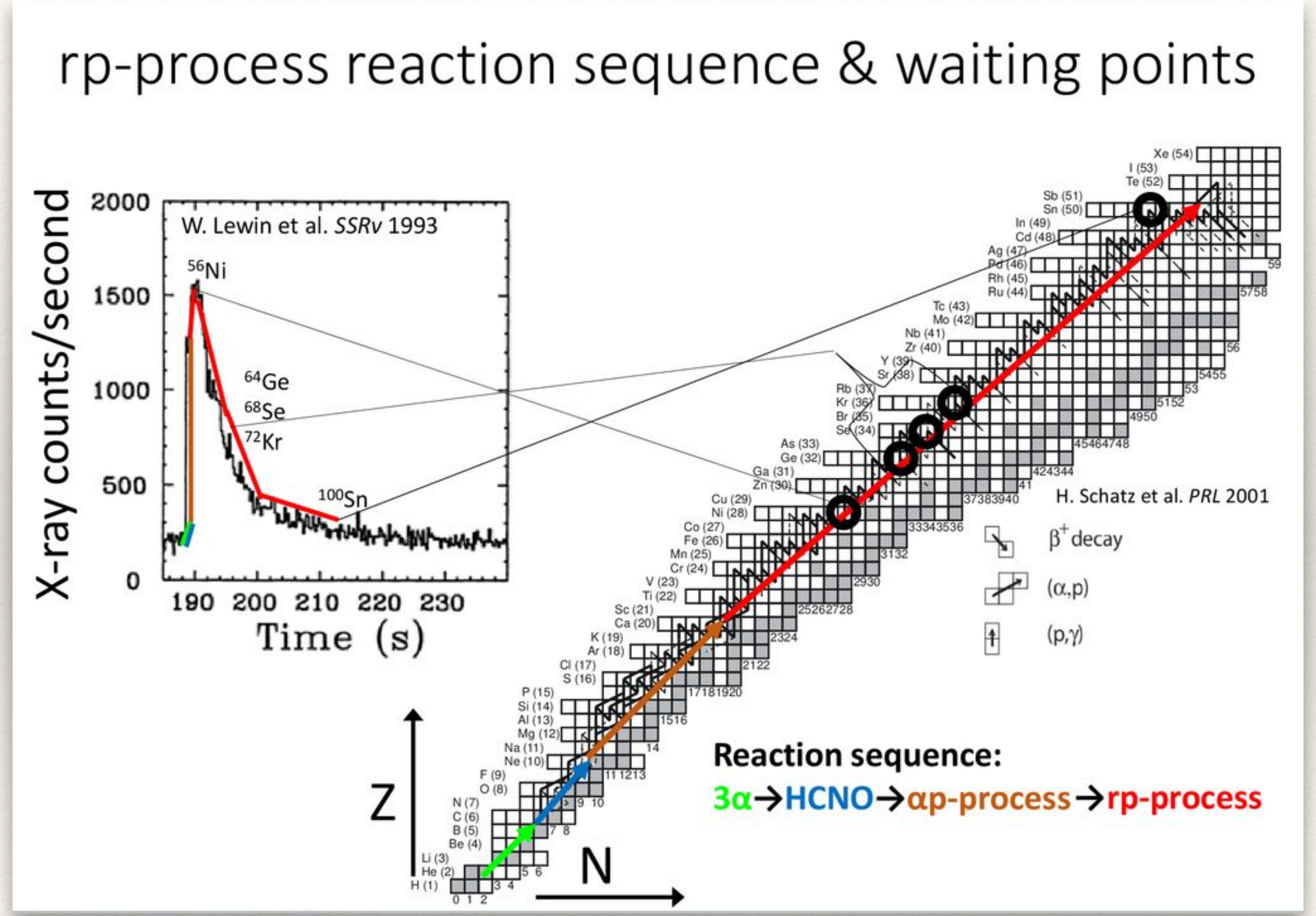
Calculated transition rates m->gs through 6^- state vs thermalization temperature

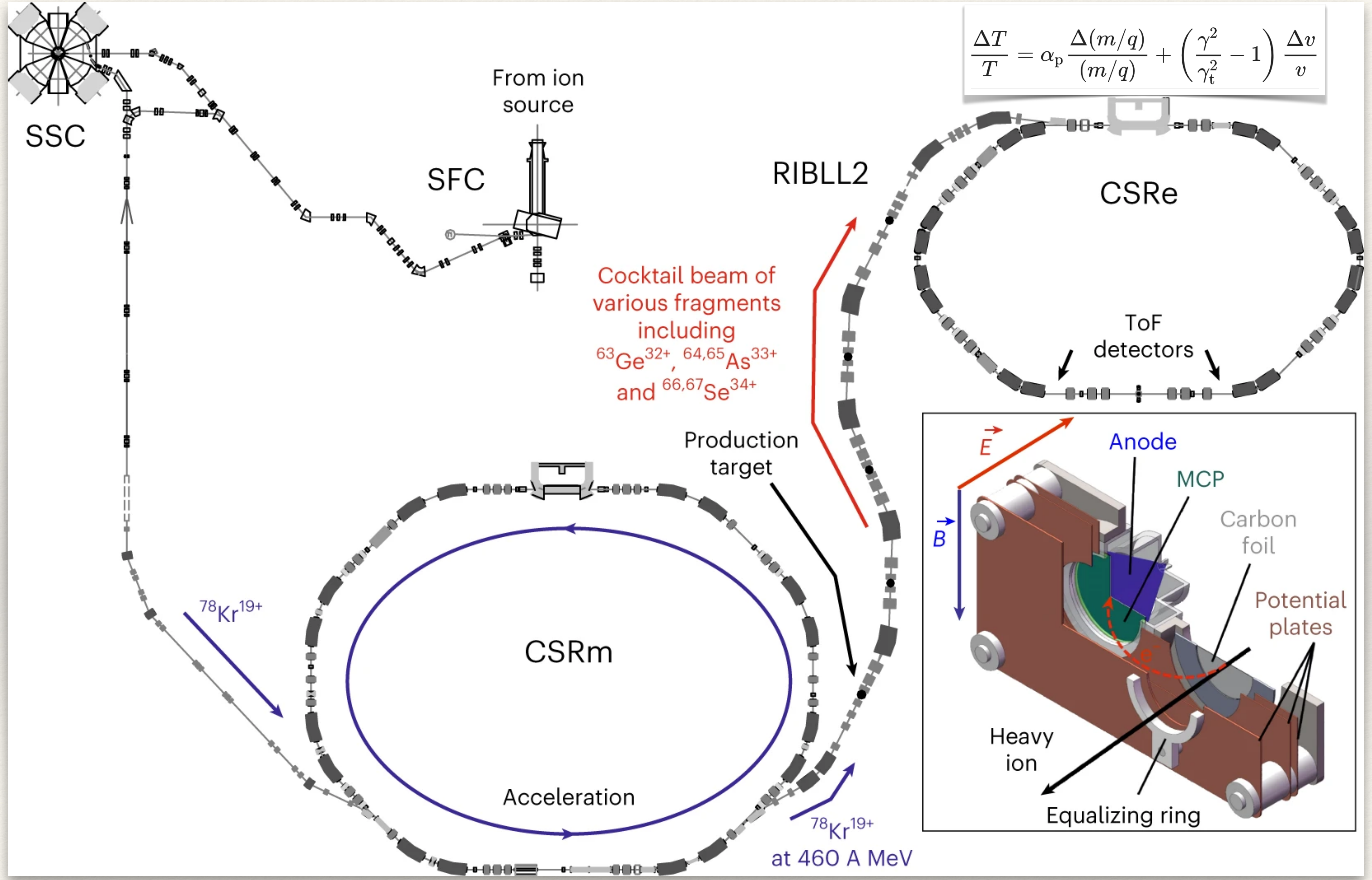
during r-process ^{128}Sb is populated in 10min (1keV)

Conclusion: ^{128m}Sb is an astromer and accelerant ($t_{1/2}$ 10min vs. gs 9h)

rp-process in Type I X-ray Bursts

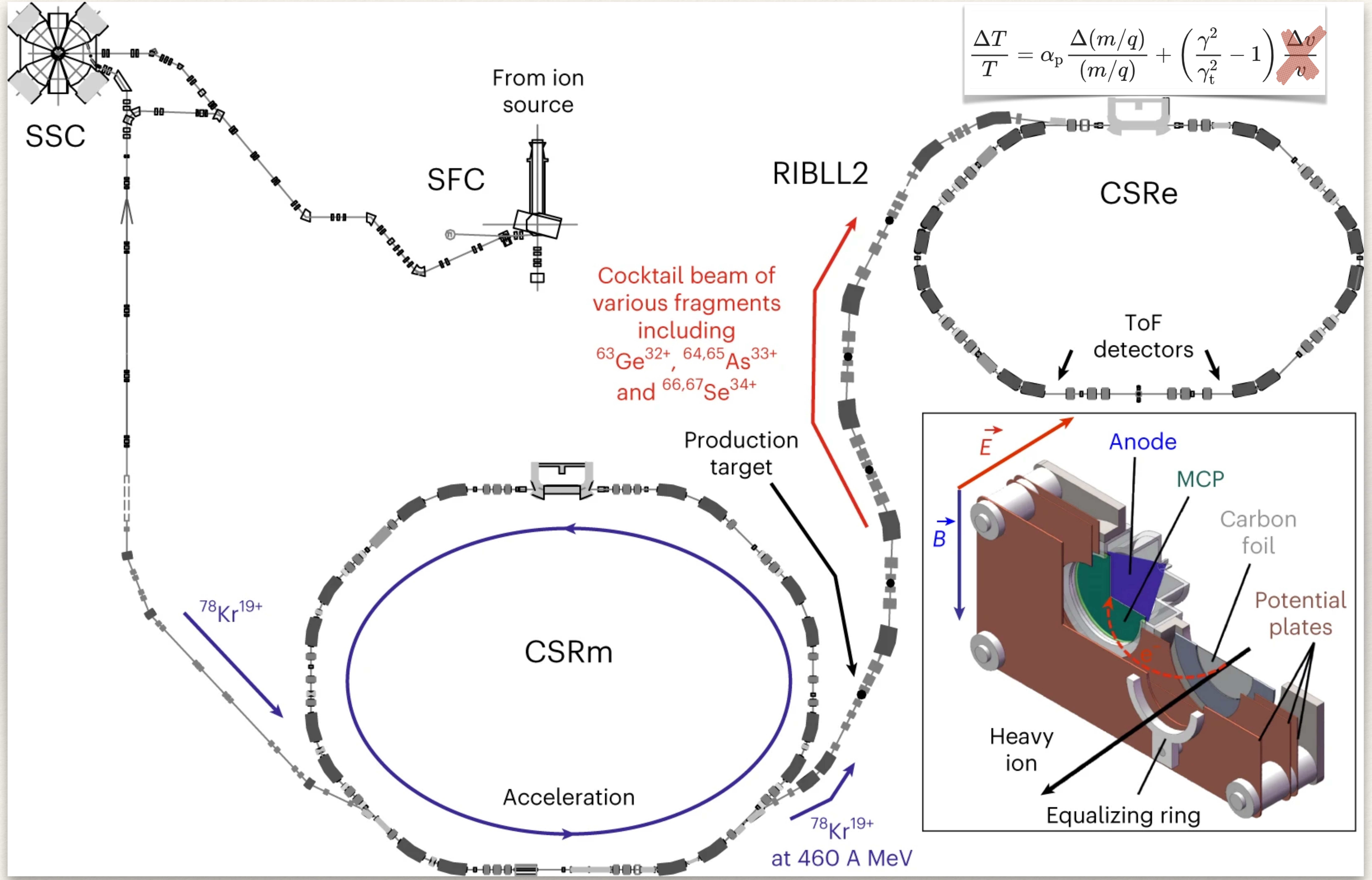






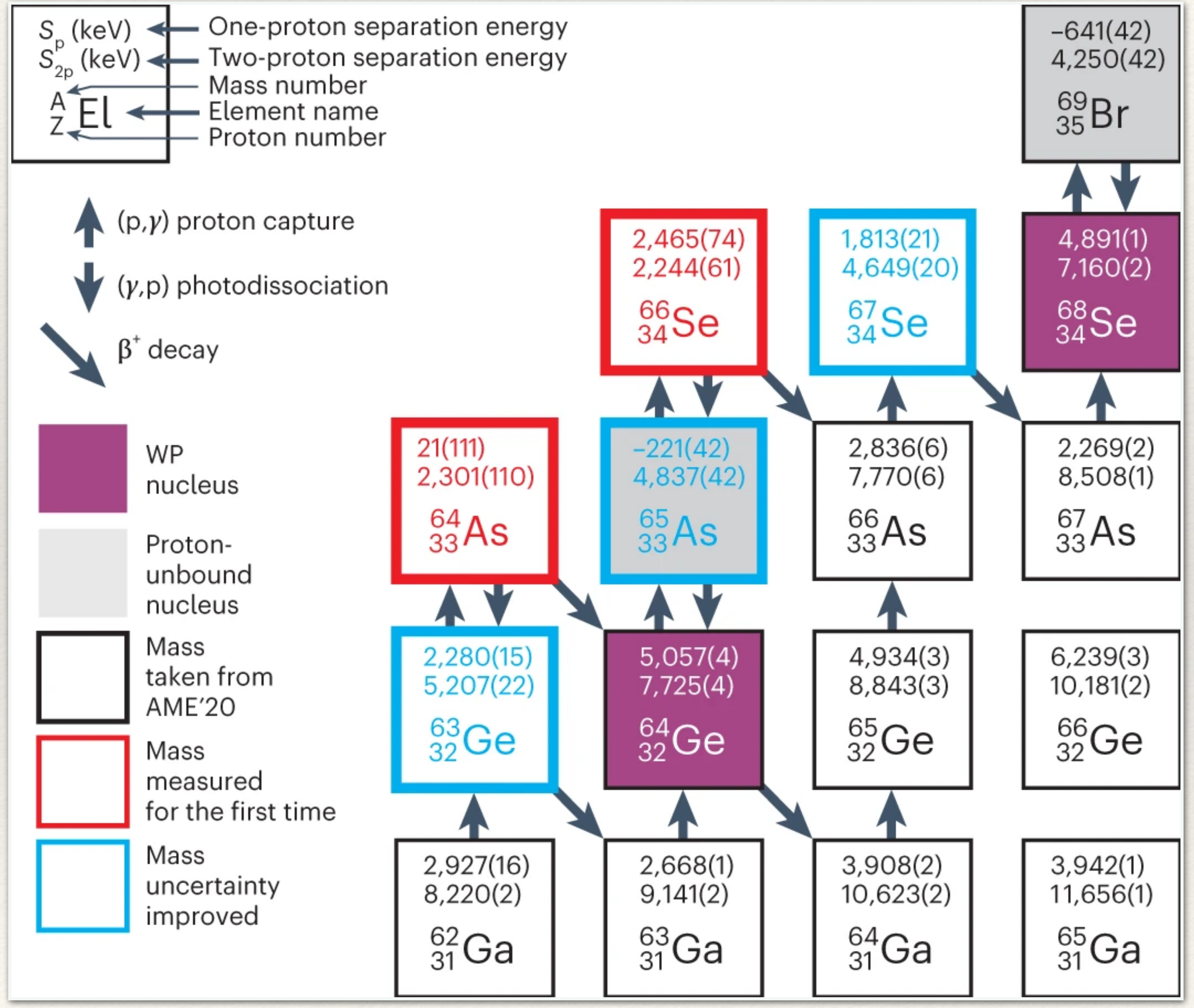
$$\frac{\Delta T}{T} = \alpha_p \frac{\Delta(m/q)}{(m/q)} + \left(\frac{\gamma^2}{\gamma_t^2} - 1\right)\frac{\Delta v}{v}$$
SSC
From ion source
SFC
RIBLL2
CSRe
Cocktail beam of various fragments including $^{63}Ge^{32+}$, $^{64,65}As^{33+}$ and $^{66,67}Se^{34+}$
ToF detectors
Production target
$\vec{E}$
Anode
MCP
Carbon foil
$\vec{B}$
Potential plates
e^-
Heavy ion
Equalizing ring
$^{78}Kr^{19+}$
CSRm
Acceleration
$^{78}Kr^{19+}$ at 460 A MeV

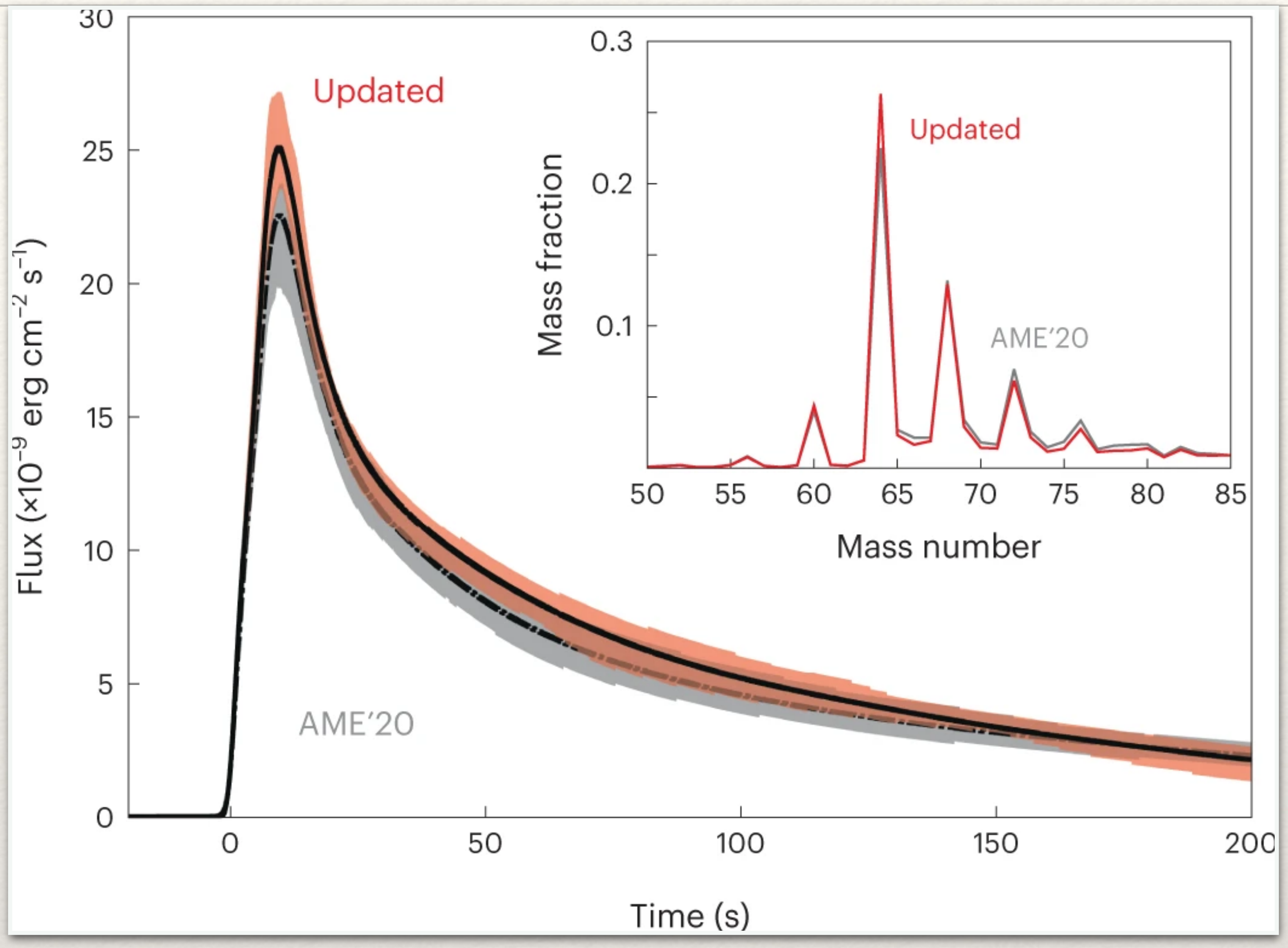
$$\frac{\Delta T}{T} = \alpha_p \frac{\Delta(m/q)}{(m/q)} + \left(\frac{\gamma^2}{\gamma_t^2} - 1\right)\frac{\Delta v}{v}$$



Mass measurements with storage ring

Zhou et al., Nature Physics 19 (2023)

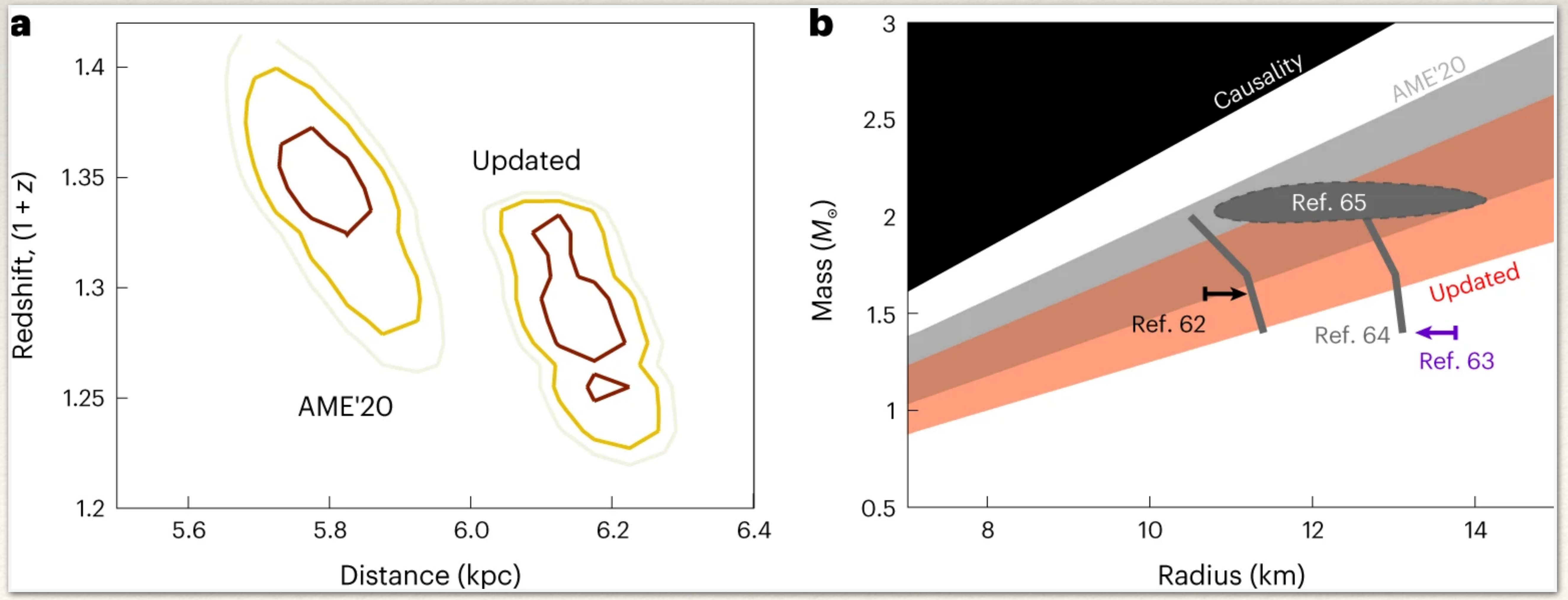




Modified light curve
Modified ash composition

Possibly warmer accreted neutron-star crust

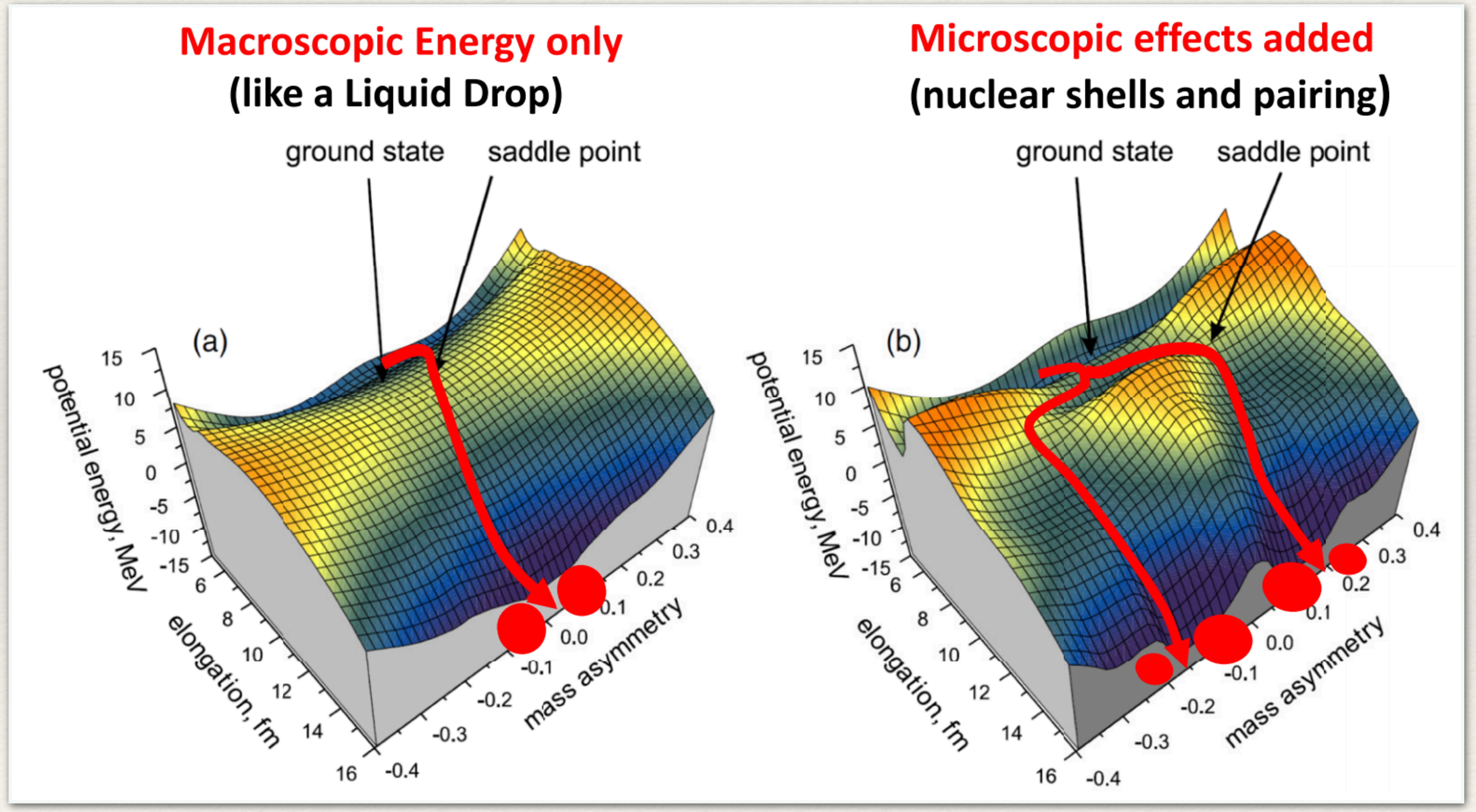
GS 1826–24 event would be further and less compact neutron star

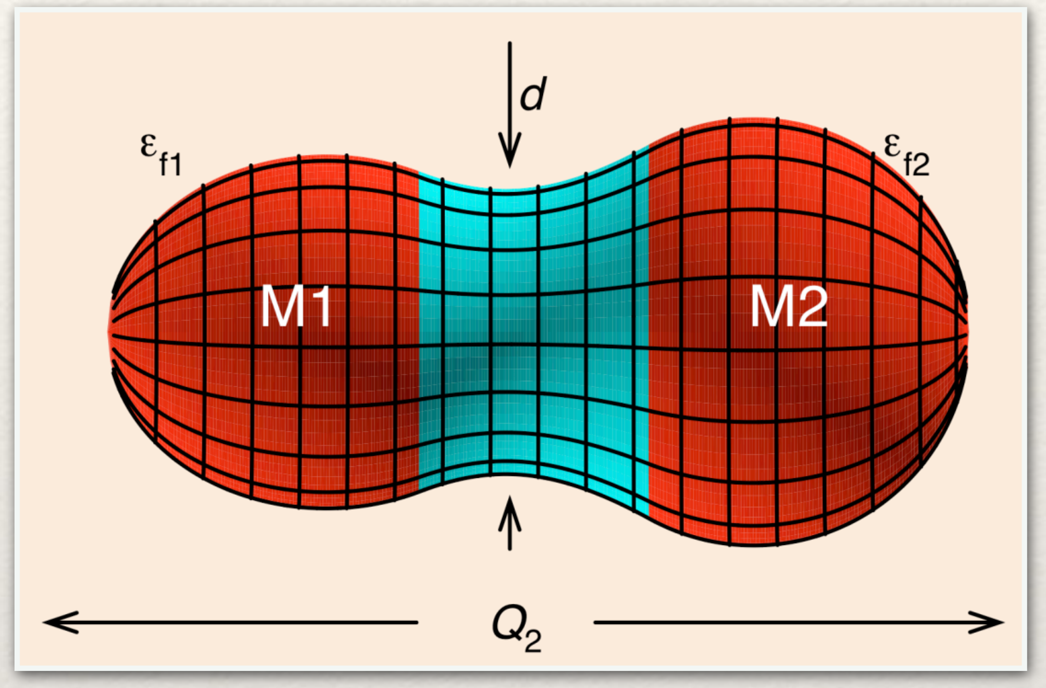


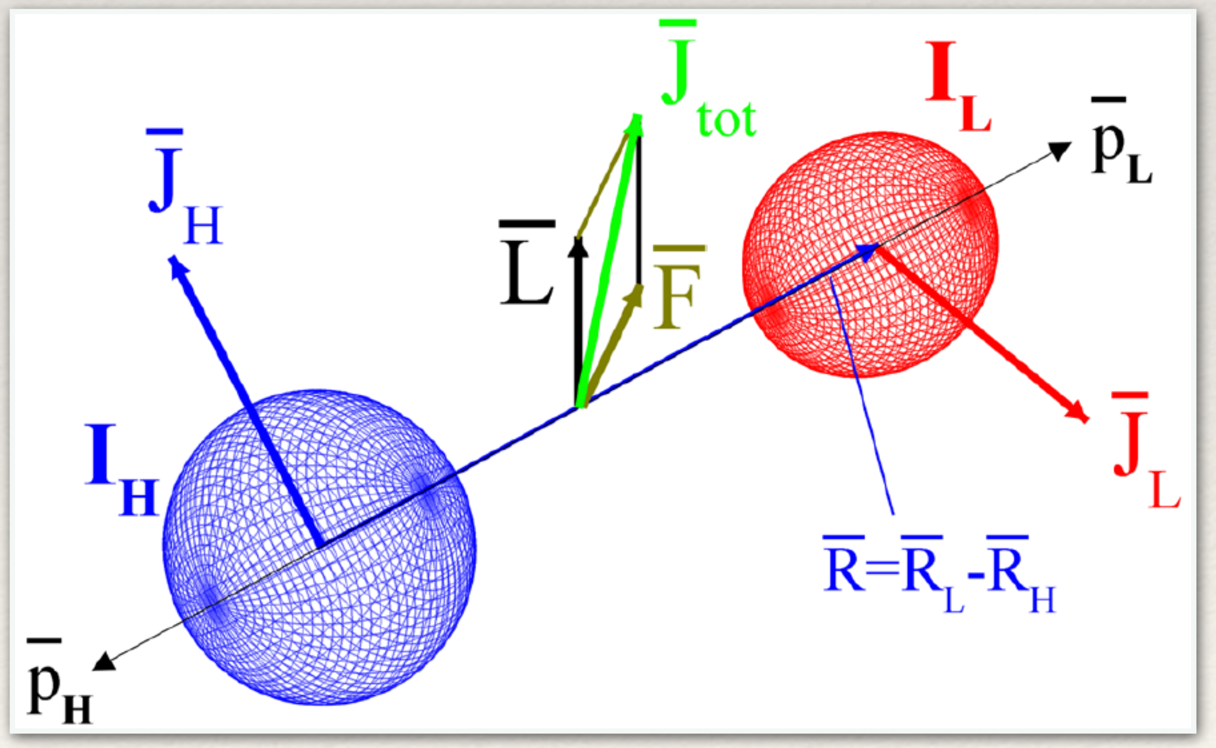
Fission study from isomeric ratios

Andreyev et al., Rep. Prog. Phys. 81 (2018)

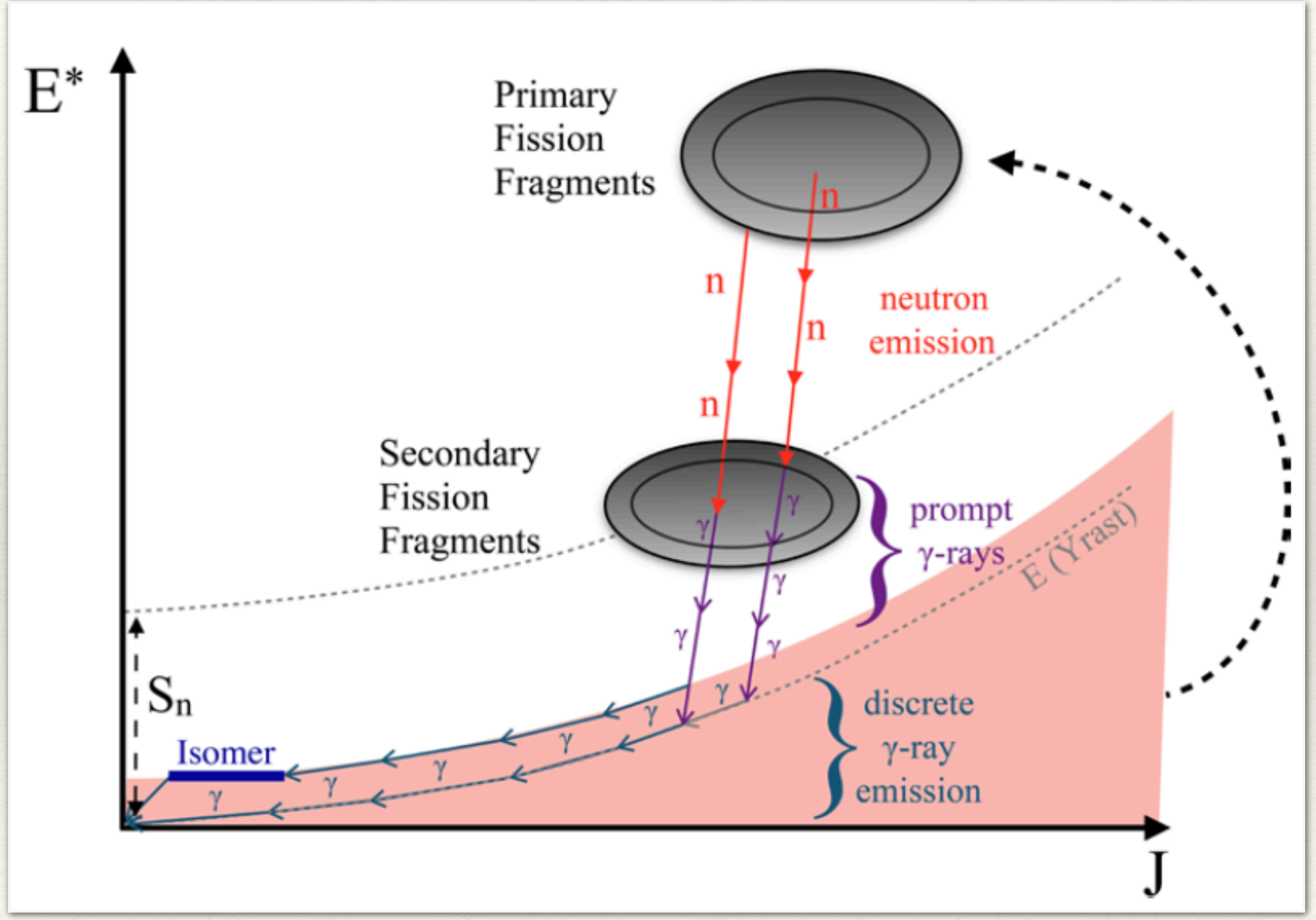
Open question in fission: **What is the origin of angular momentum?**





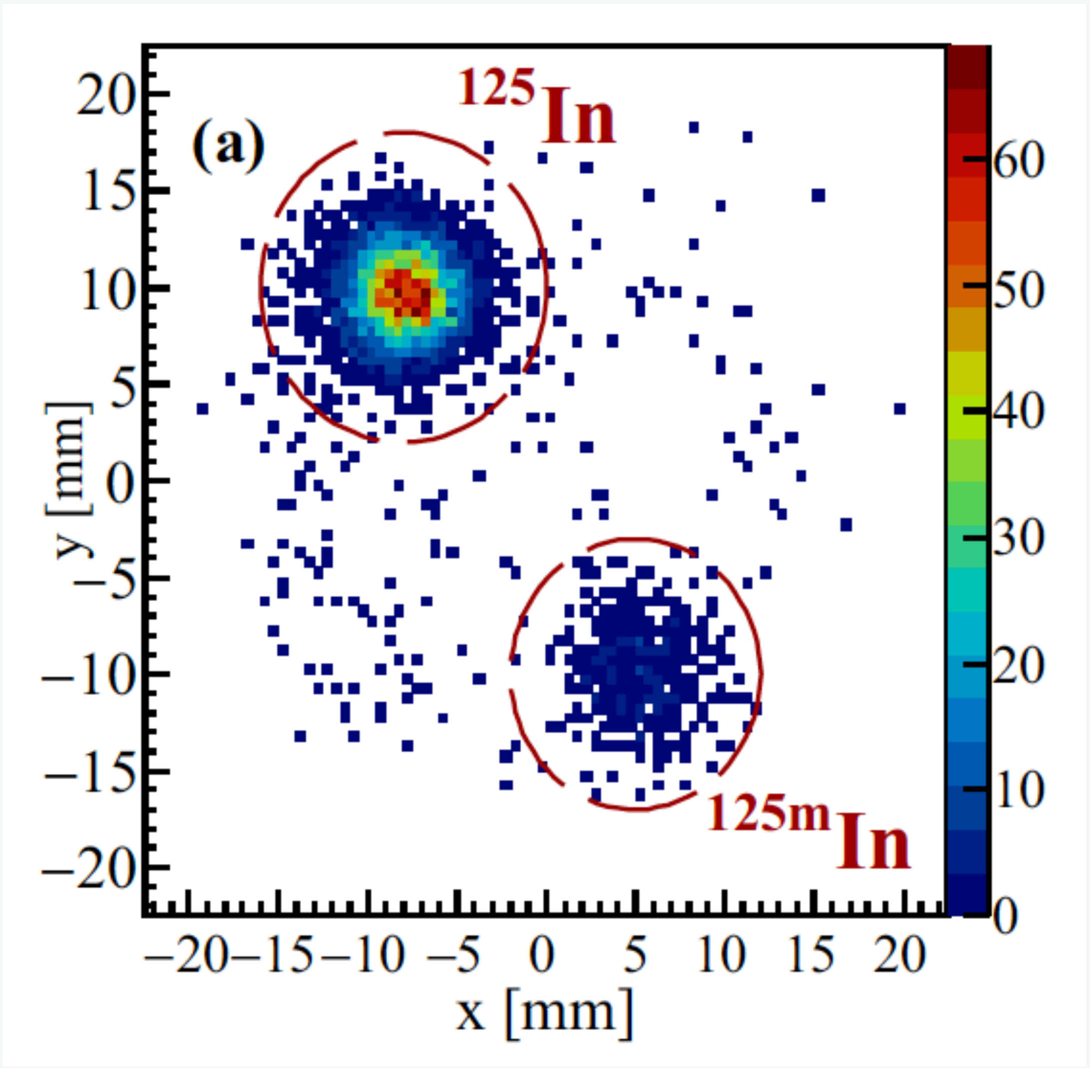


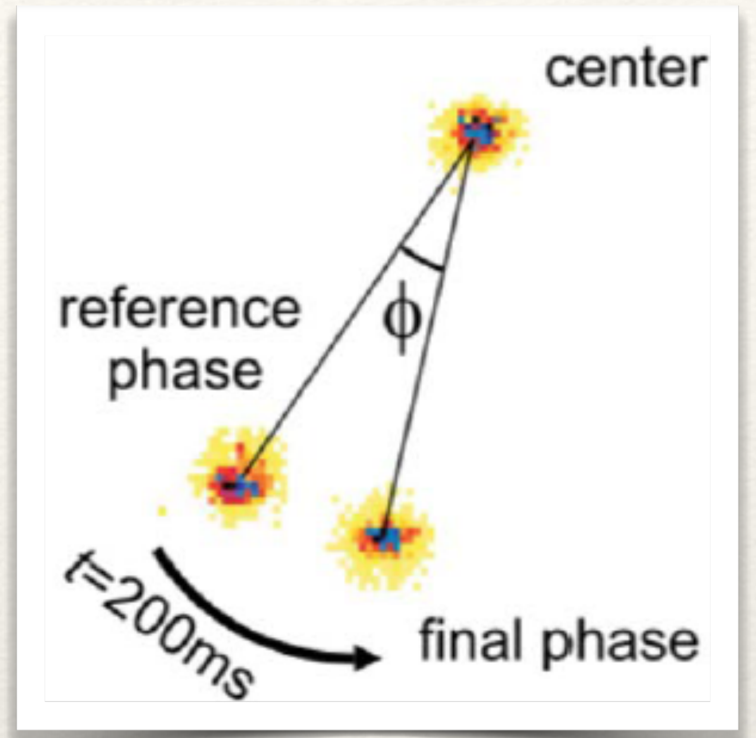
Fission study from isomeric ratios



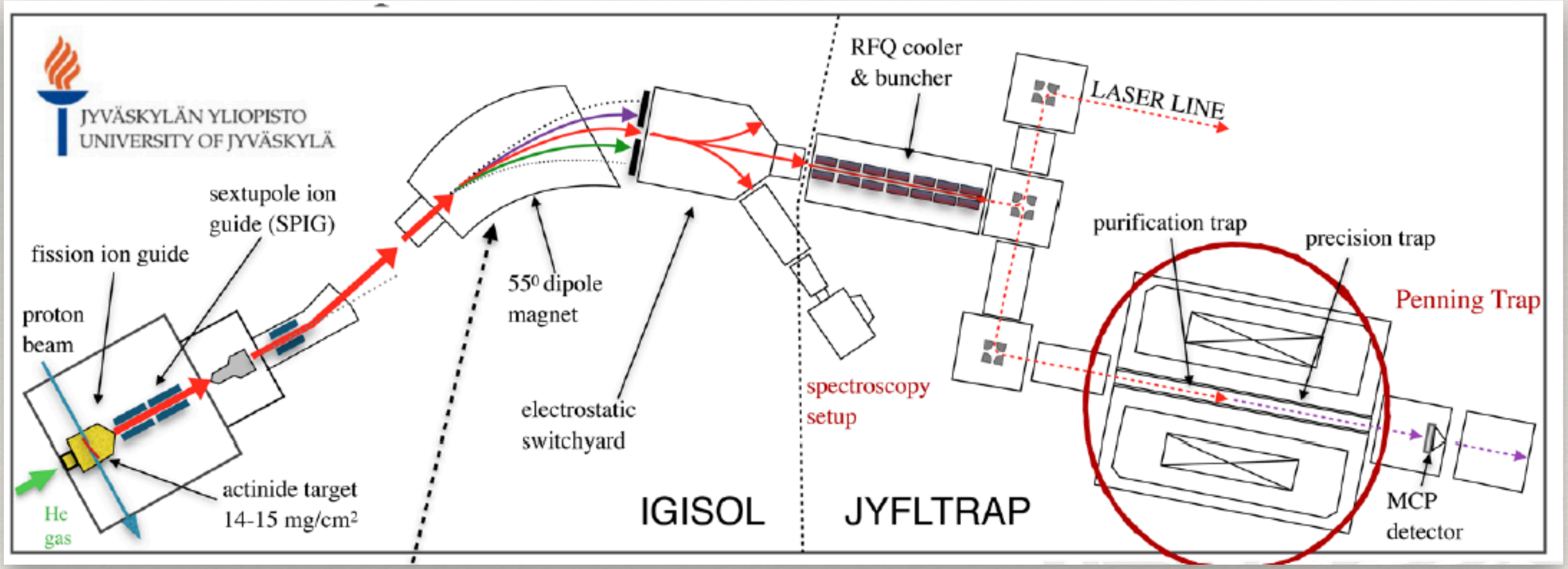
Fission study from isomeric ratios

Rakopoulos et al., PRC98(2018)
Isomeric ratios of fission fragments of proton induced fission on U and ^{232}Th @IGISOL
—> dependence on fission system
—> sensitive to nuclear structure effects





Phase-Imaging Ion Cyclotron Resonance (PI-ICR) $R>10^6$



Fission study from isomeric ratios

Rakopoulos et al., PRC98(2018)
Isomeric ratios of fission fragments of proton induced fission on U and ^{232}Th @IGISOL
—> dependence on fission system
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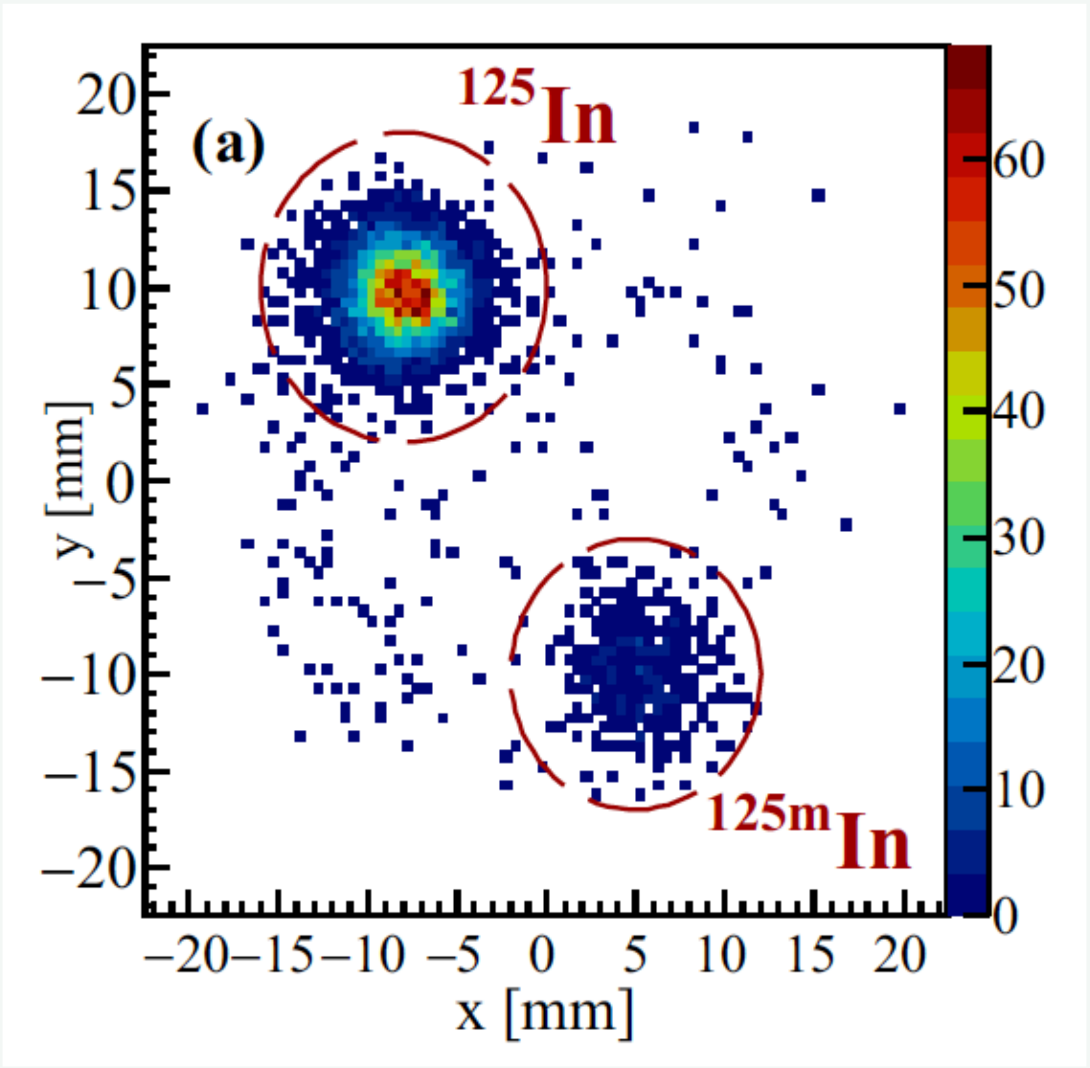
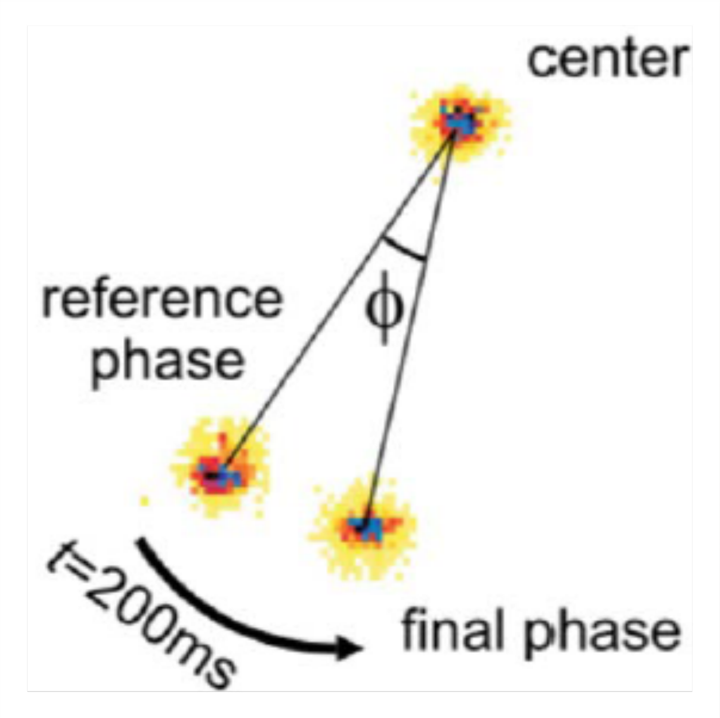
Other possible fission systems:
In-flight fission —> MRTOF & R3 @RIBF
Photofission —> MLLTrap/? @ALTO
n-induced fission —> ? @NFS/GANIL





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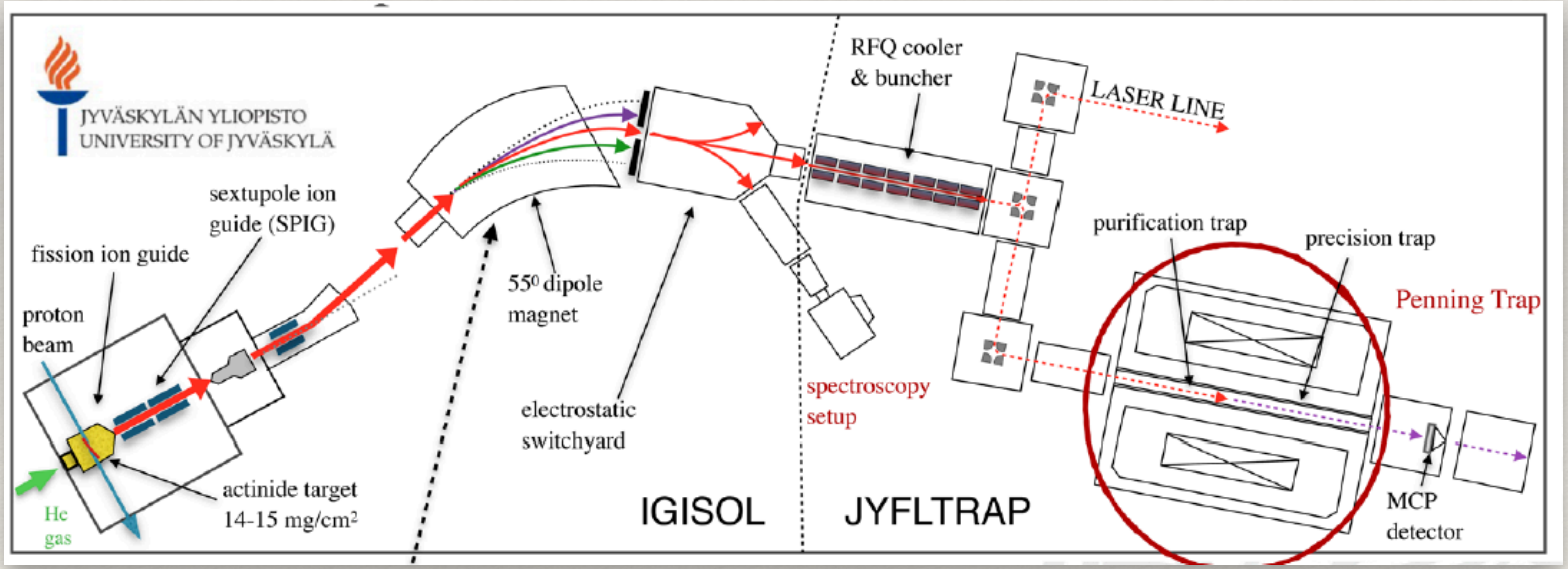
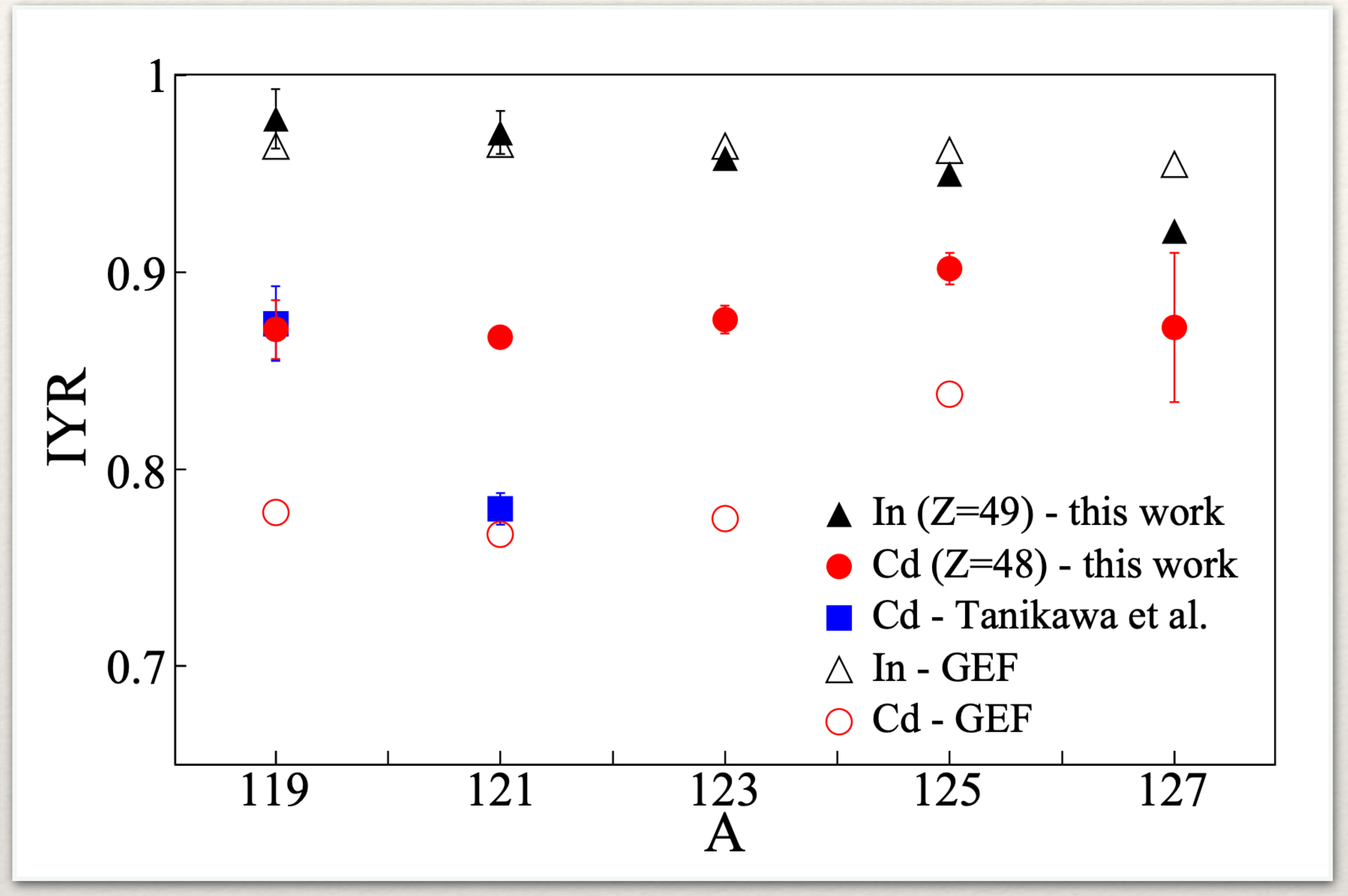


First study at IGISOL/JYFLTRAP

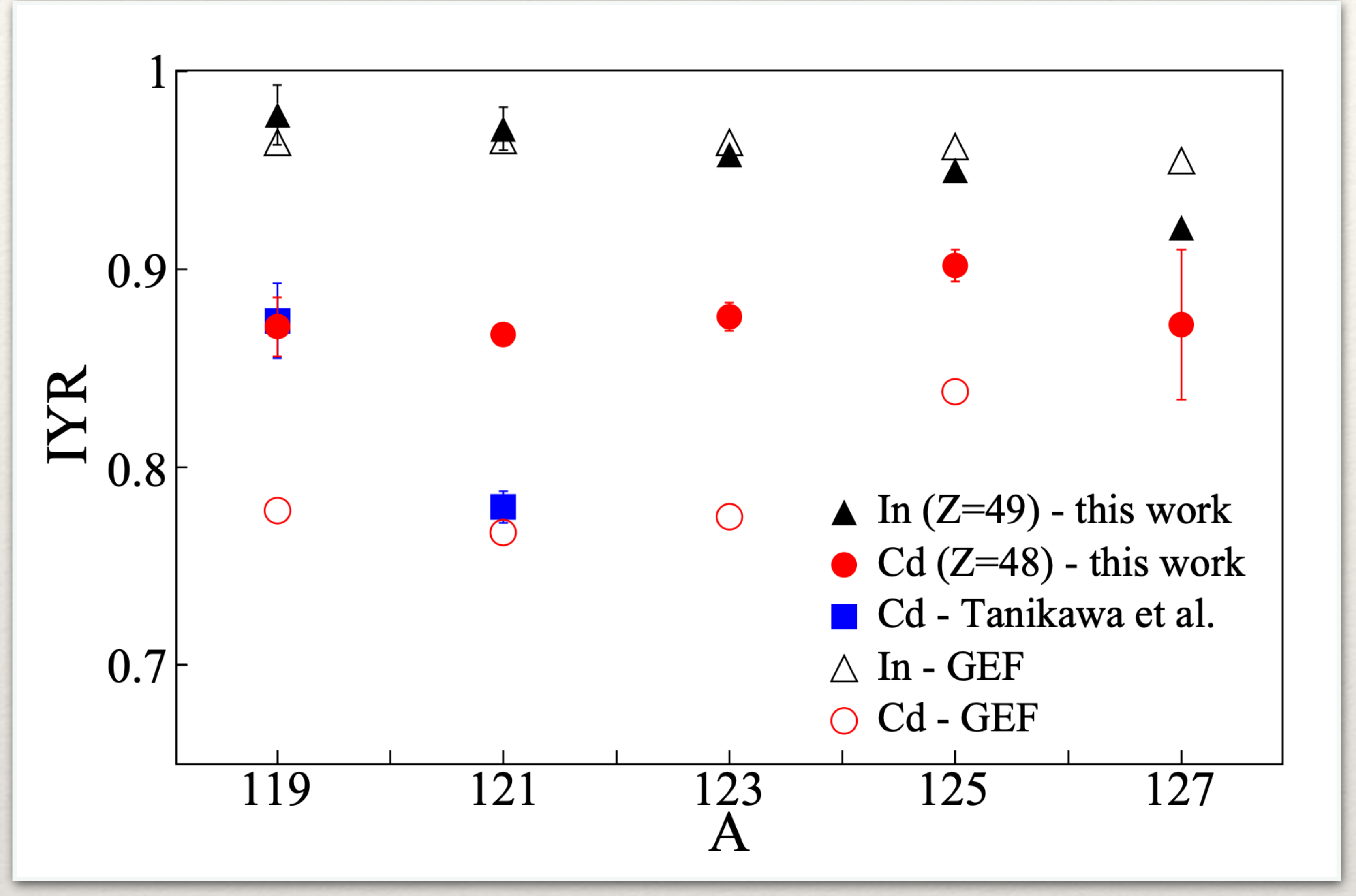
Rakopoulos et al., PRC66(2019)

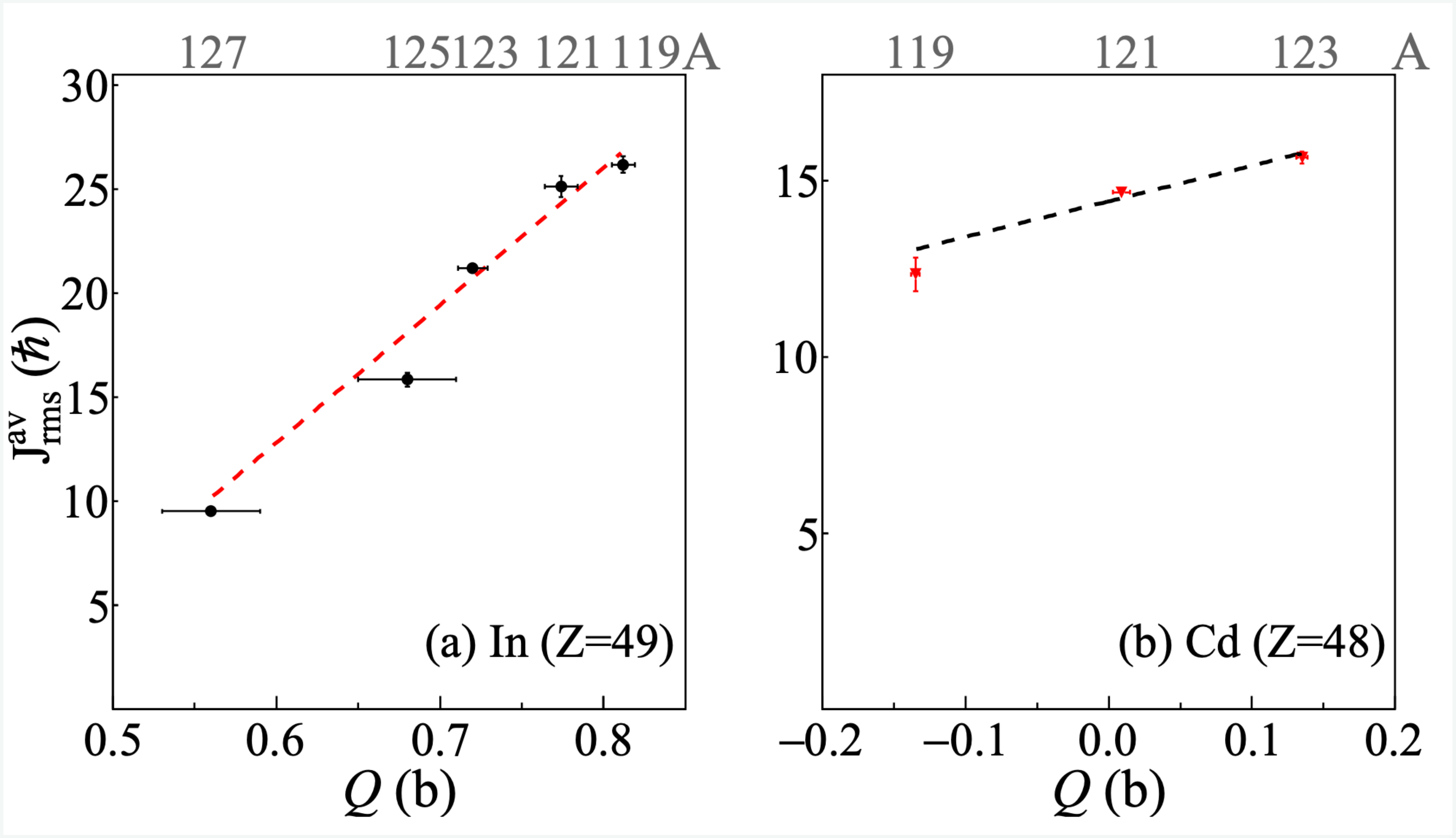


Most yields are not reproduced by theoretical models
—> Need more data, which will lead to better theoretical description

First study at IGISOL/JYFLTRAP

Rakopoulos et al., PRC66(2019)





Most yields are not reproduced by theoretical models
—> Need more data, which will lead to better theoretical description

Strong correlation of In isotopes' angular momentum with electric quadrupole moment
—> fission fragments of In retain part of their deformation during their relaxation after scission. Coulomb force might contribute to the primary fission fragments momentum in In isotopes.

Takeaway

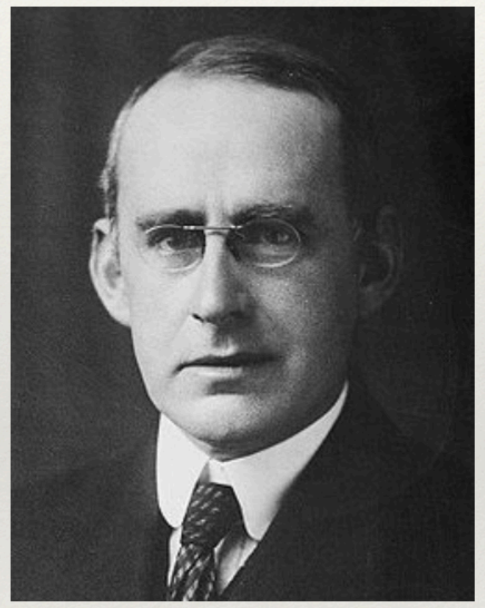
Mass spectrometry applications

Takeaway

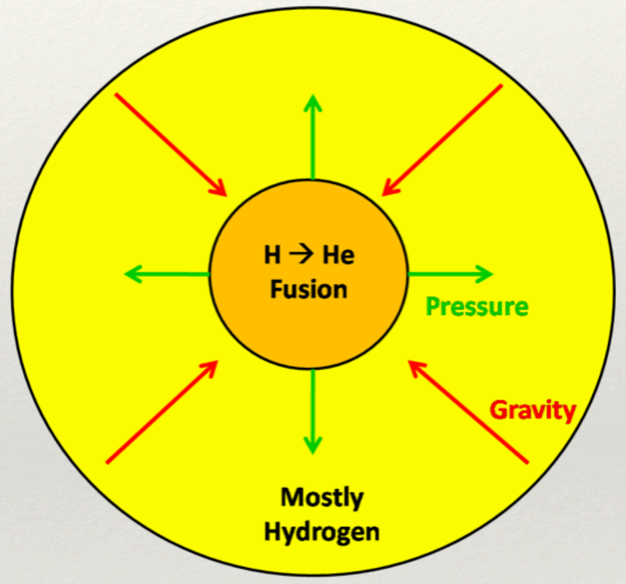
Mass spectrometry applications

Solving the age of the Sun crisis

Eddington



The Sun



$$Lifetime = \frac{Energy}{Luminosity} = \frac{Mc^2}{L_{sun}} = \frac{0.007 \cdot 0.1 \cdot M_{sun} \cdot c^2}{L_{sun}} \approx 10 \text{ Billion years}$$

$[L_{sun}] = E/t$

10% of the Sun undergo fusion

0.7% atomic mass difference between 4xH and ^4He

Takeaway

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Solving the age of the Sun crisis

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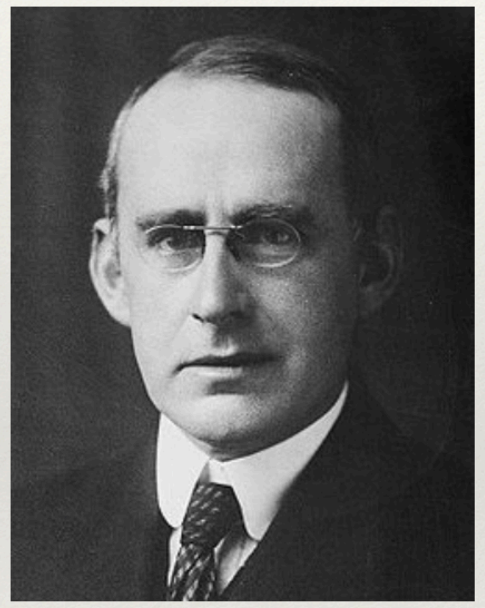

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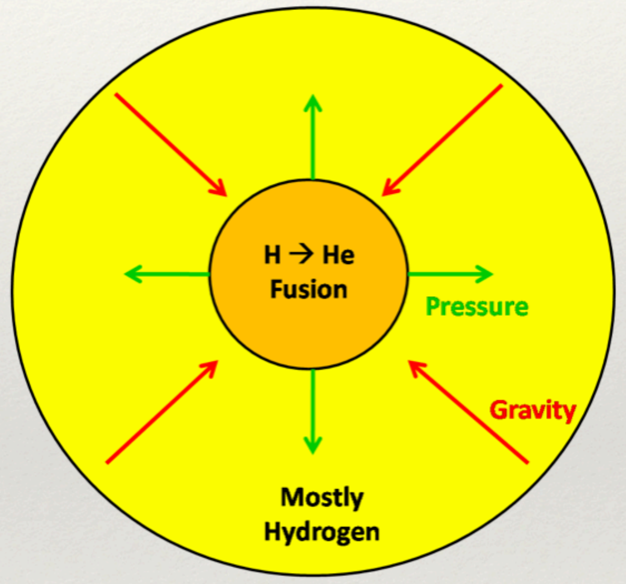

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Nier's mass spectrometer

Transition from Spectrograph to Spectrometer

A. O. Nier 1951, Phys. Rev 81, 507

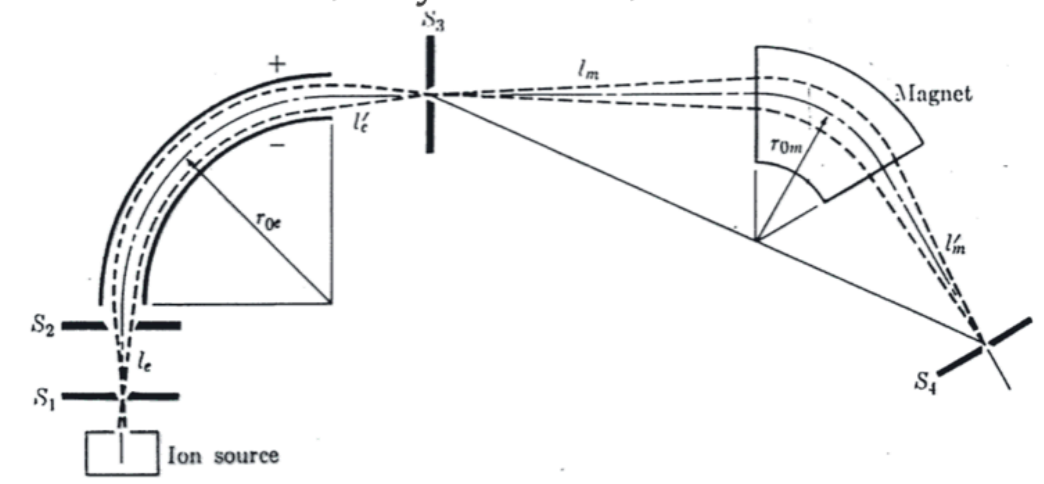
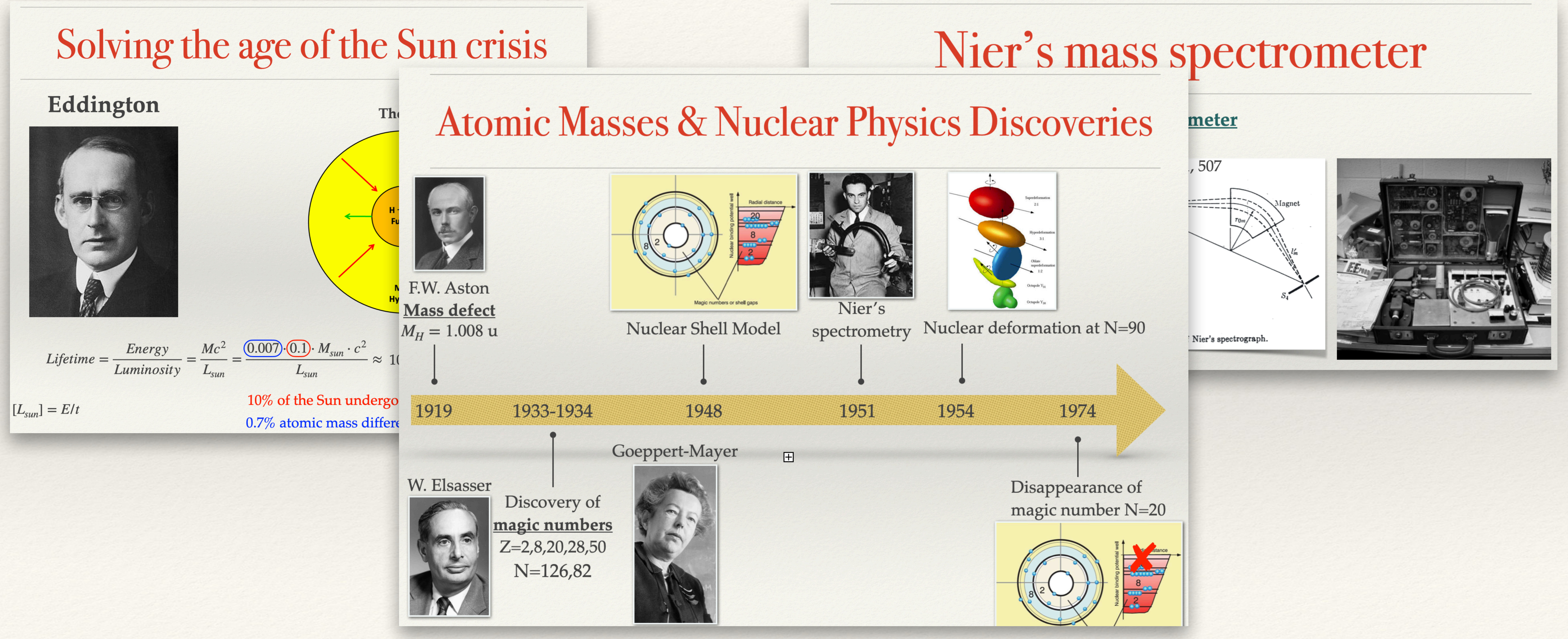


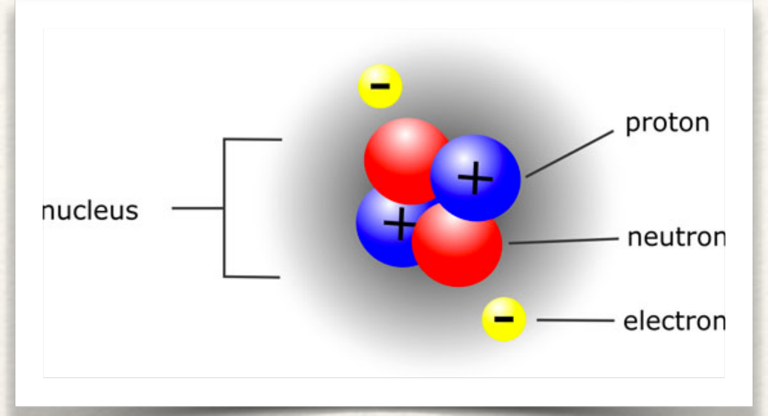
Fig. 4-3. Principle of operation of Nier's spectrograph.

Takeaway

Mass spectrometry applications



Takeaway

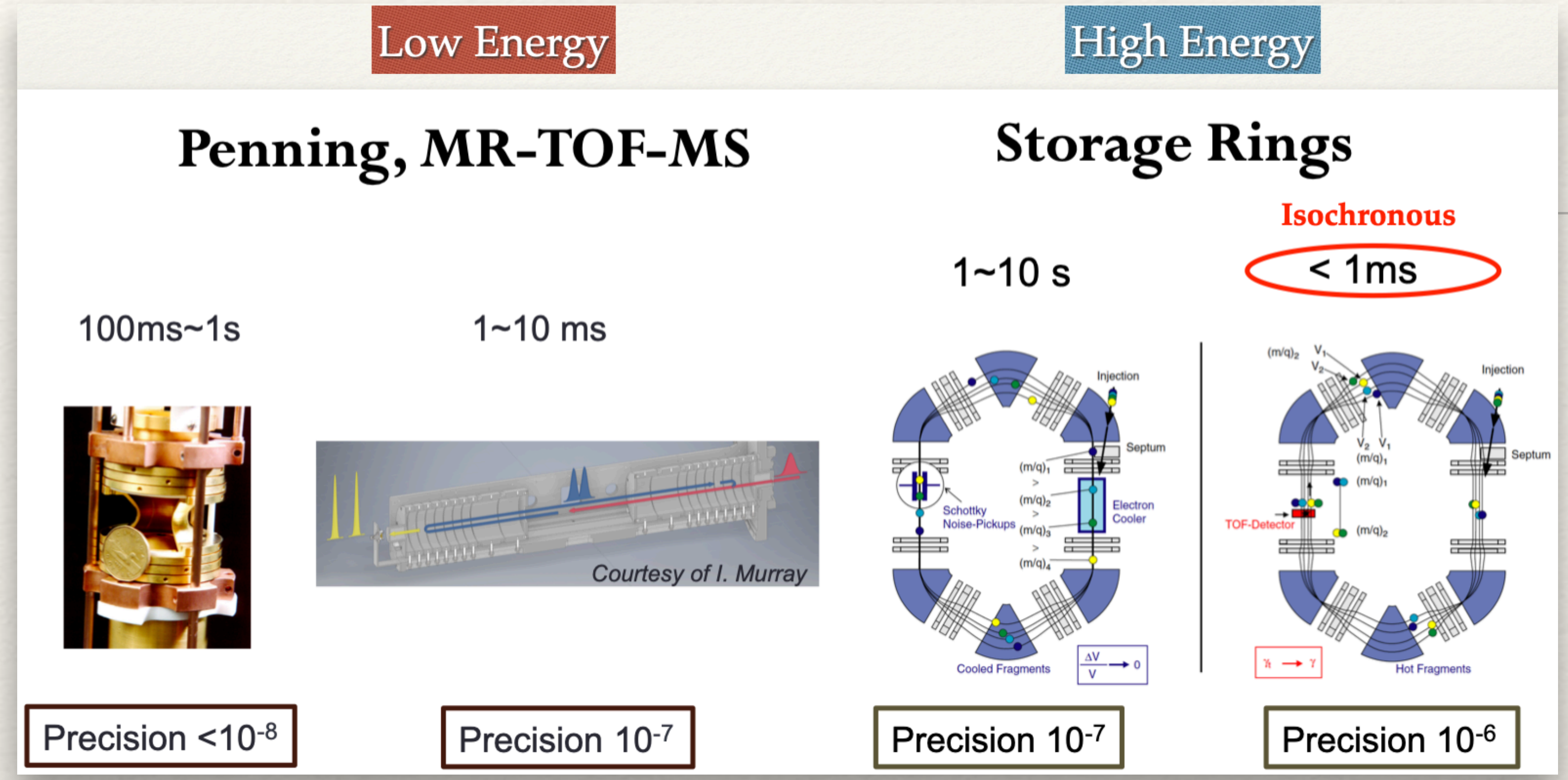


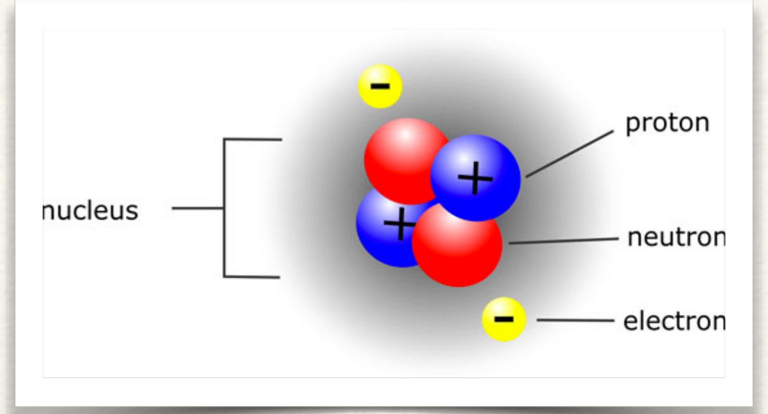
Atomic Mass

$$M(^4He) = 2 \cdot m_p + 2 \cdot m_n + 2 \cdot m_e$$

- Binding Energy

Takeaway





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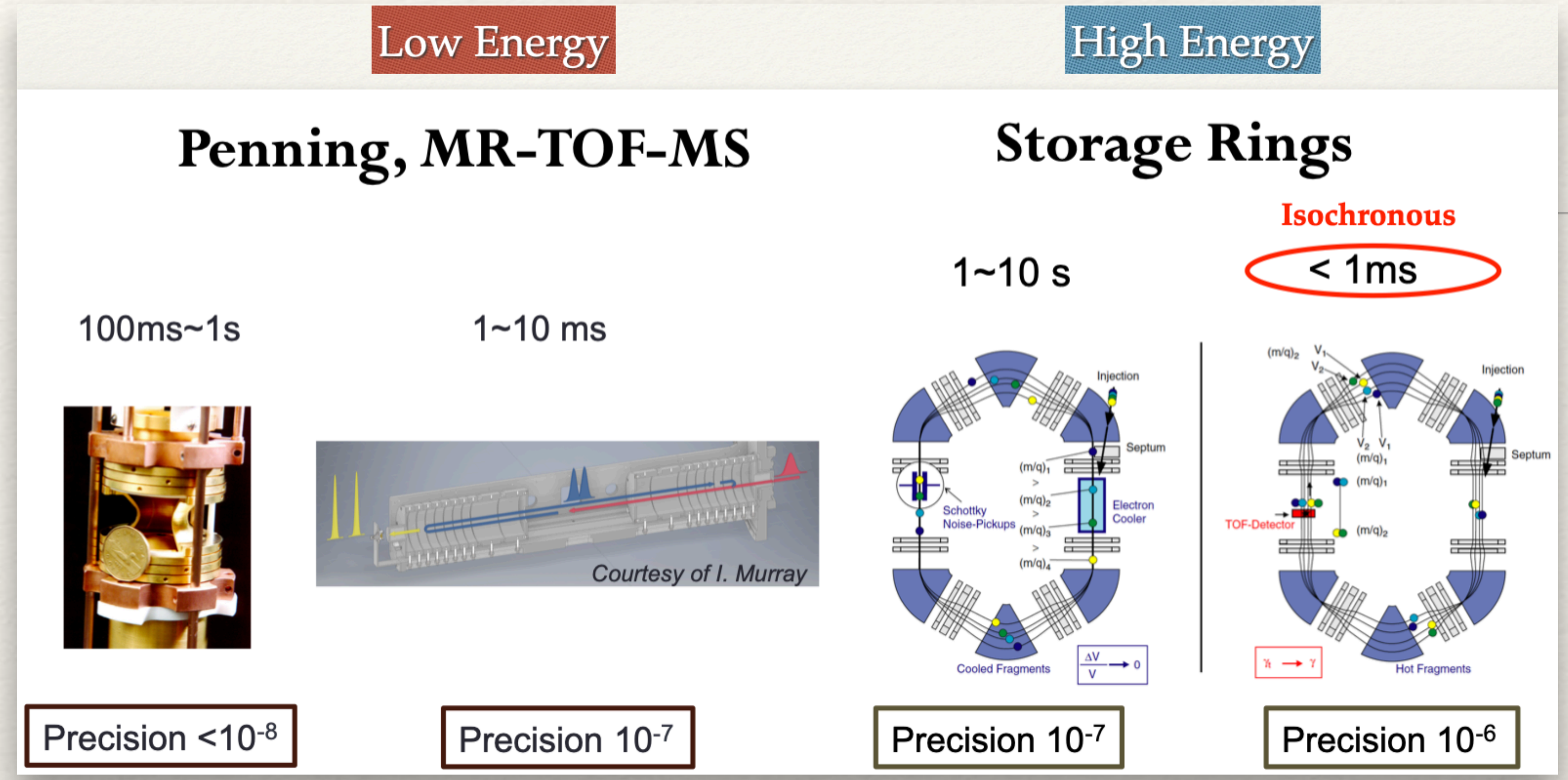

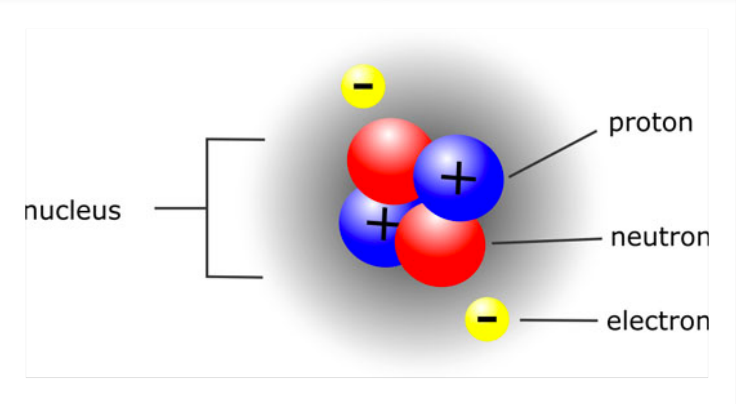

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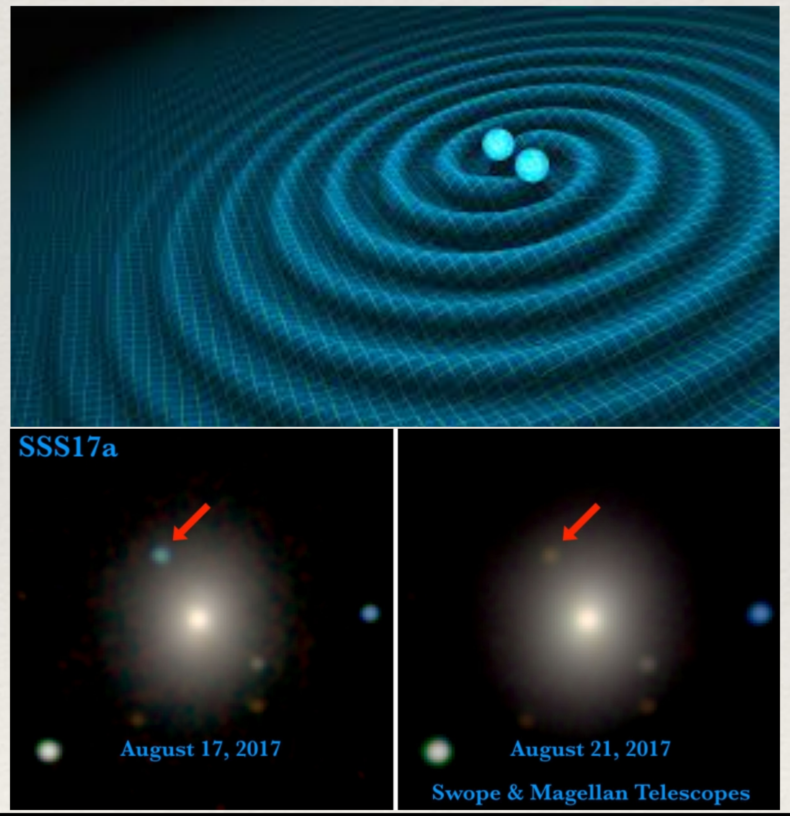
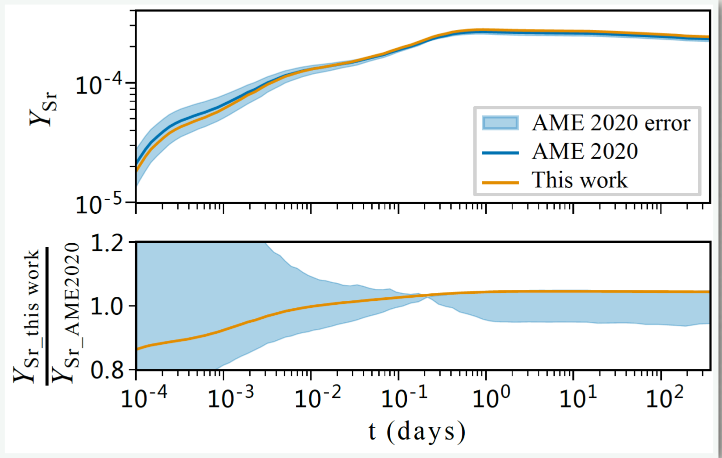
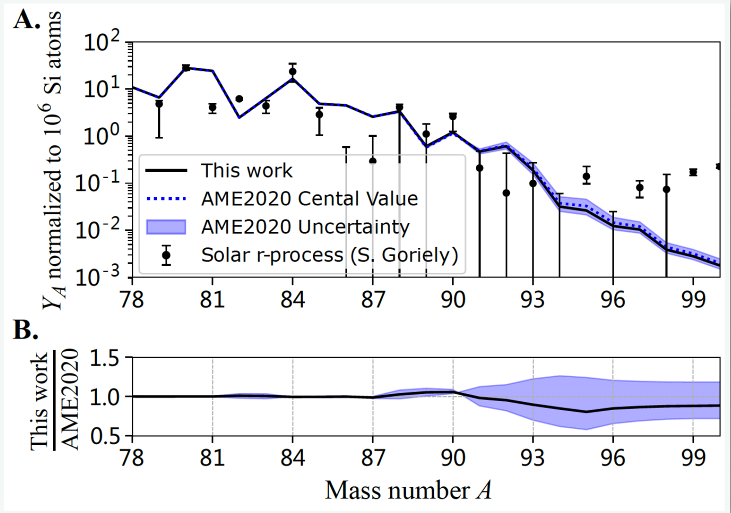
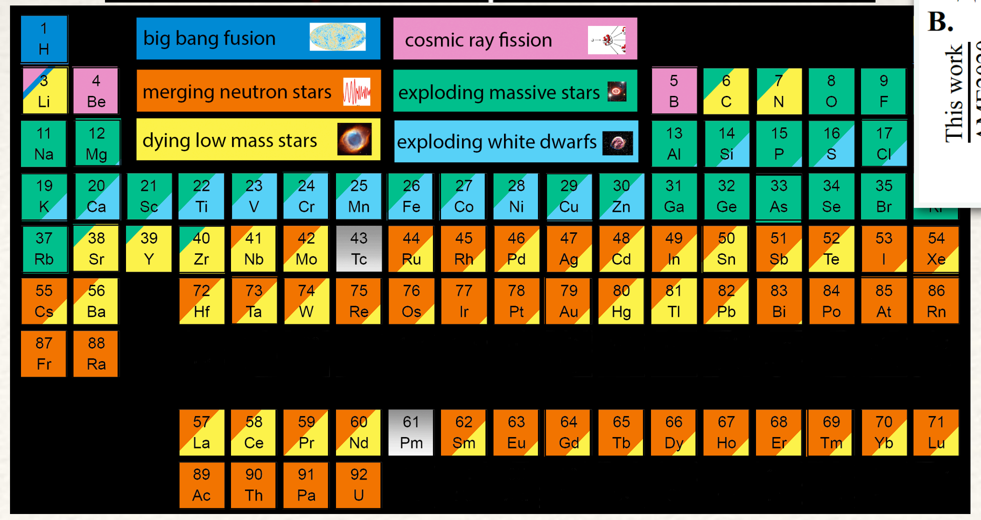
Mass measurement for the r-process

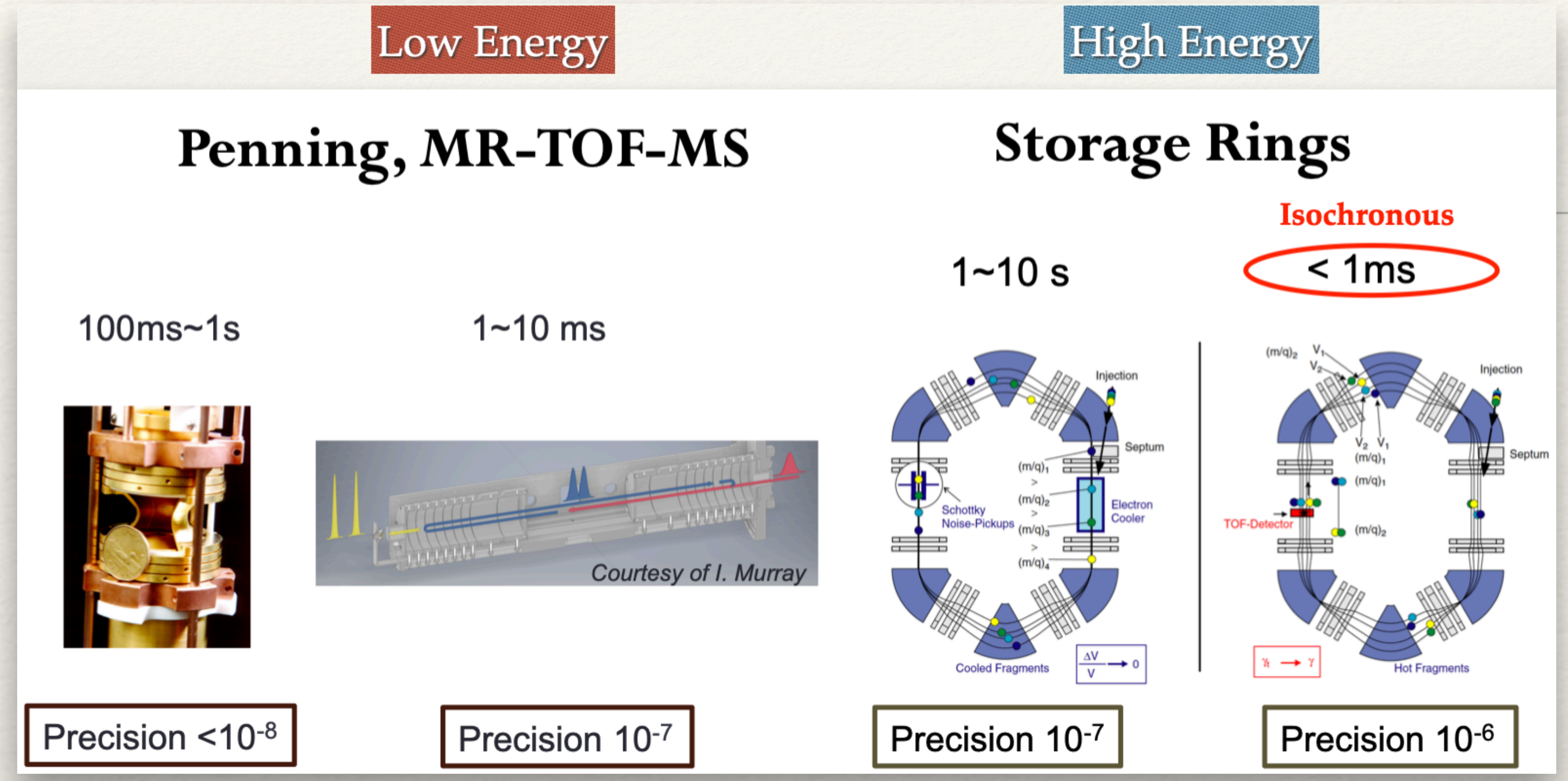


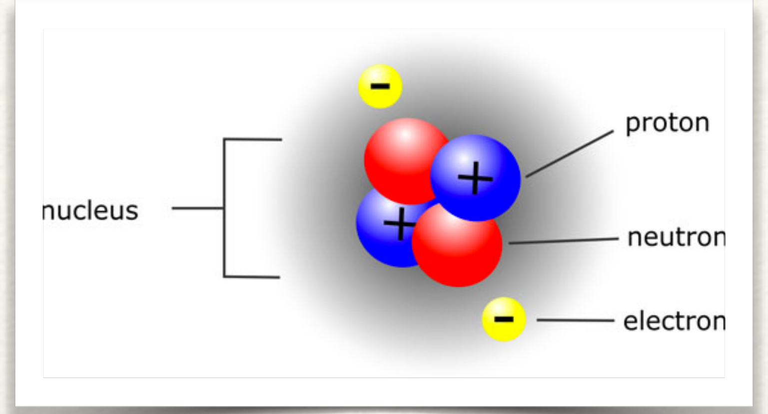






Takeaway





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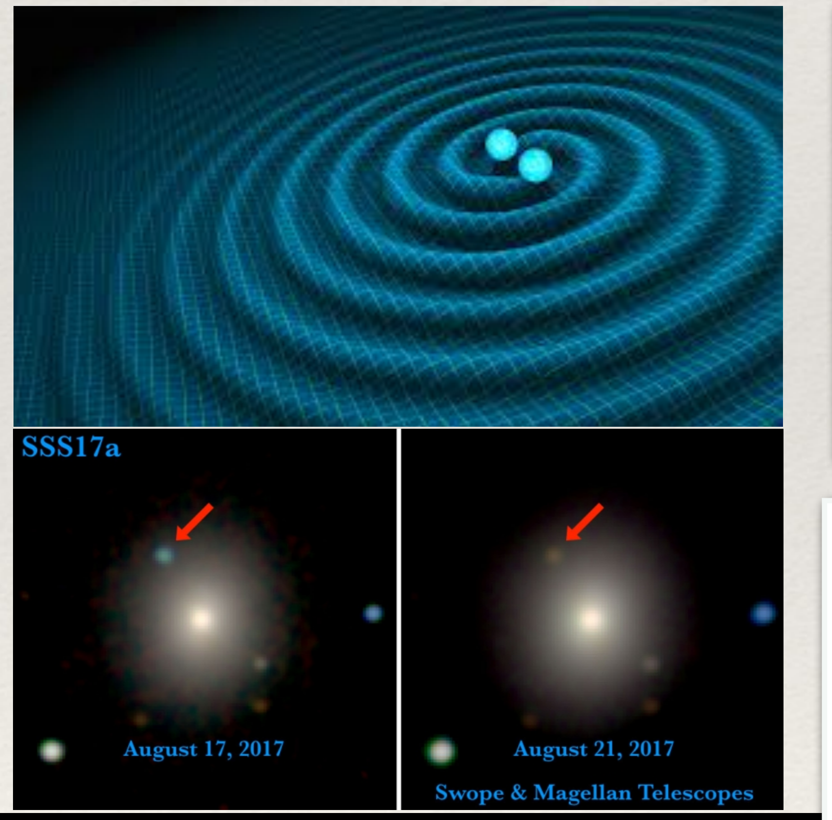
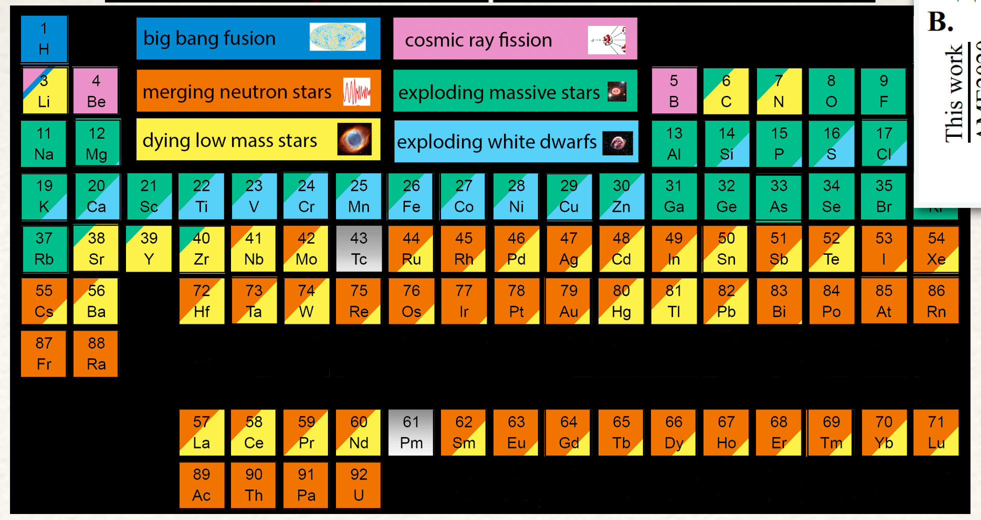
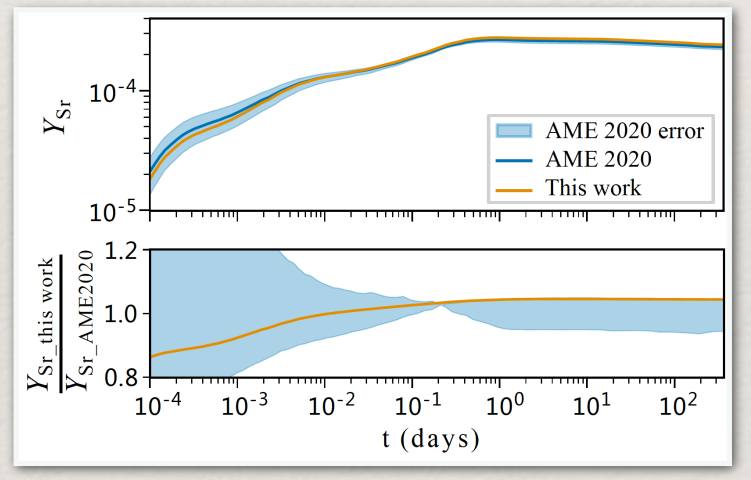
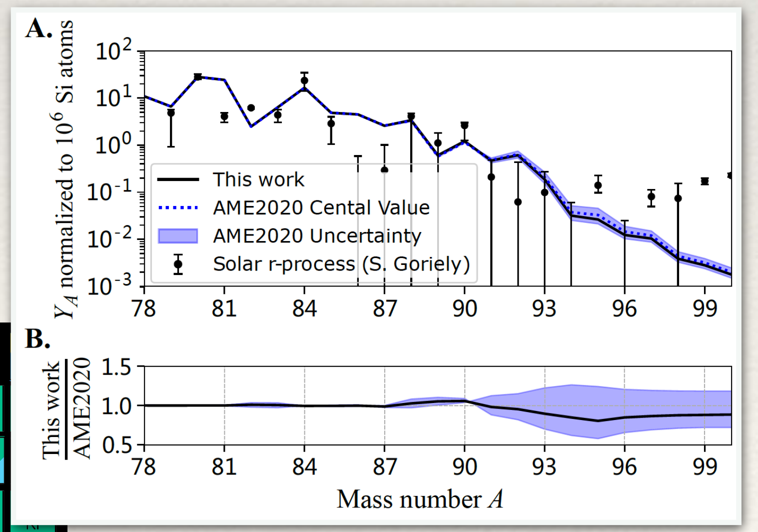
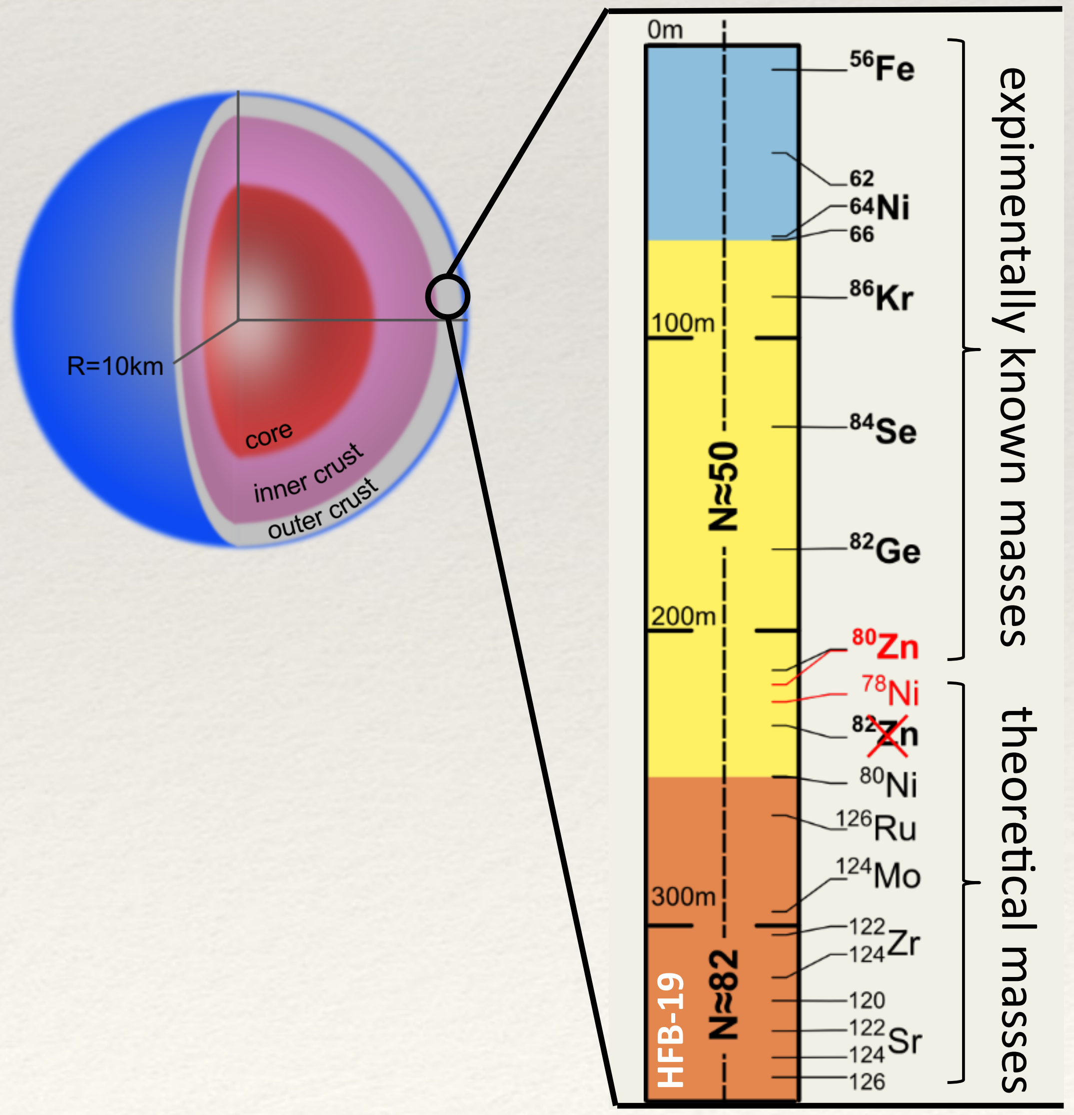




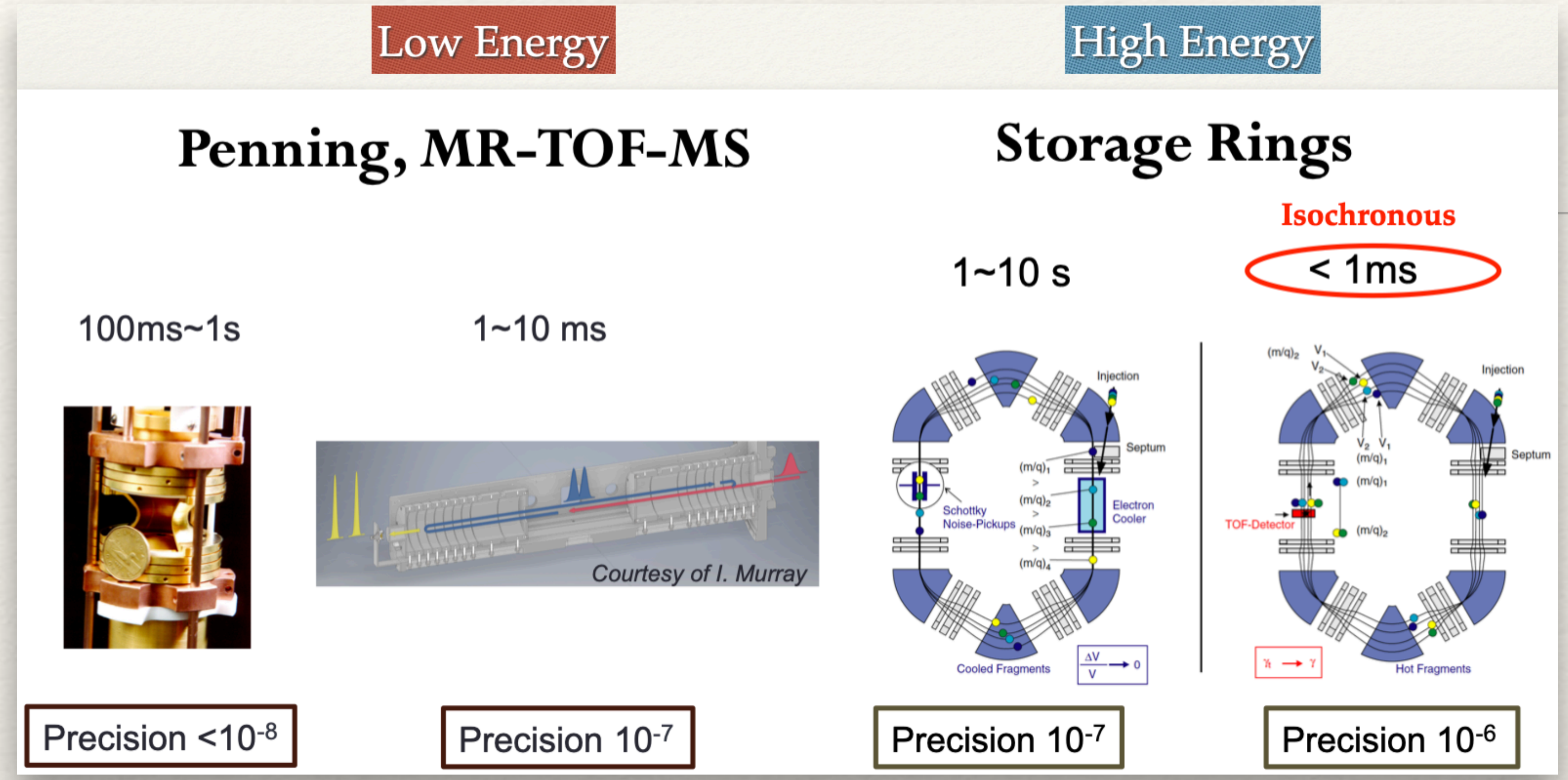


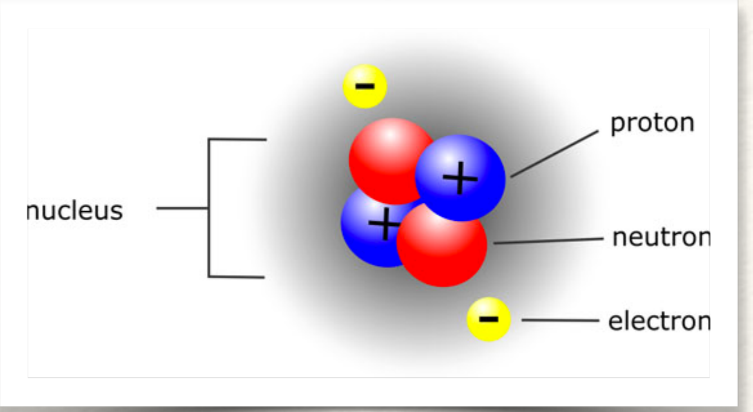


We can **"drill" into the neutron star**
to reveal its composition



Takeaway



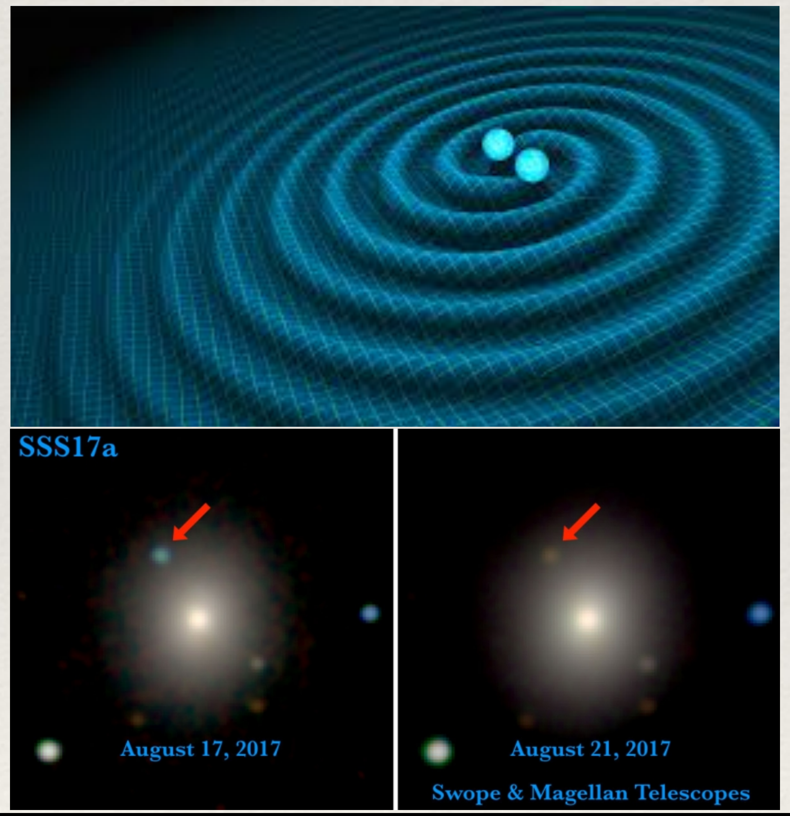


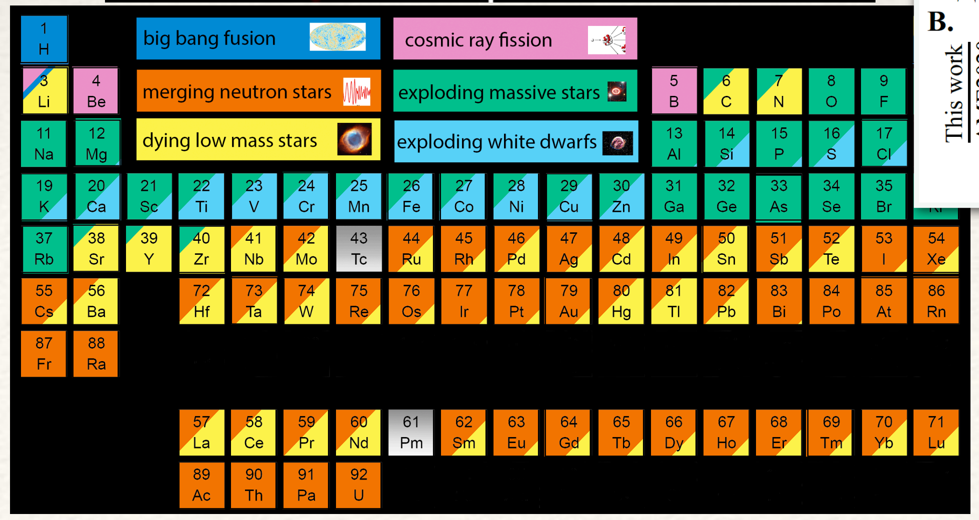
Atomic Mass

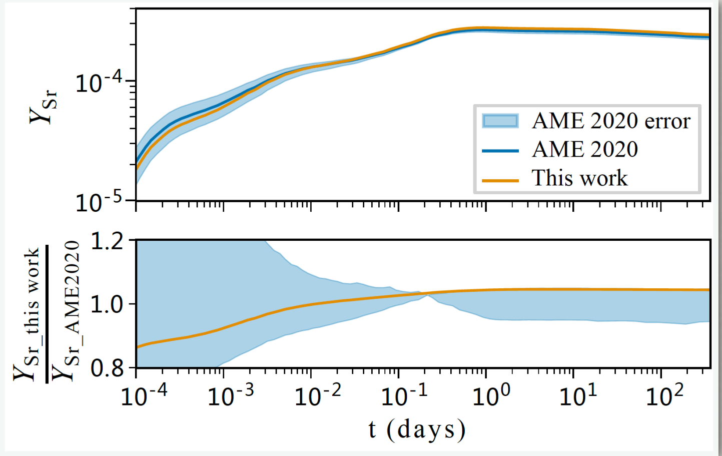
$$M(^4He) = 2 \cdot m_p + 2 \cdot m_n + 2 \cdot m_e$$

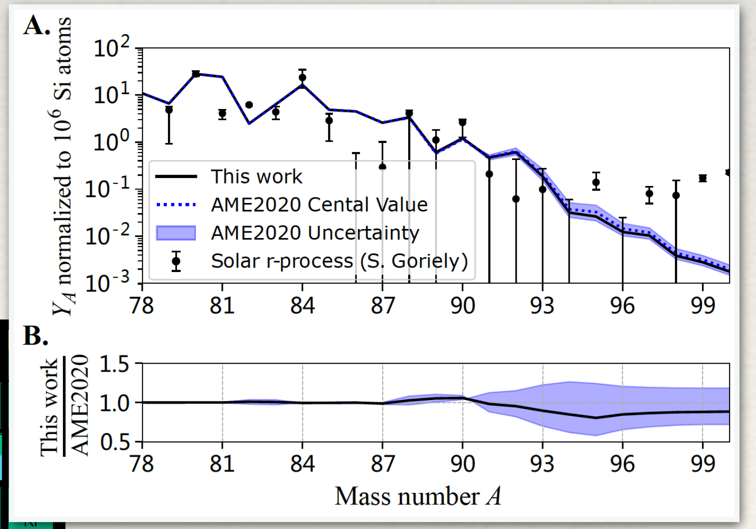
- Binding Energy

Mass measurement for the r-process









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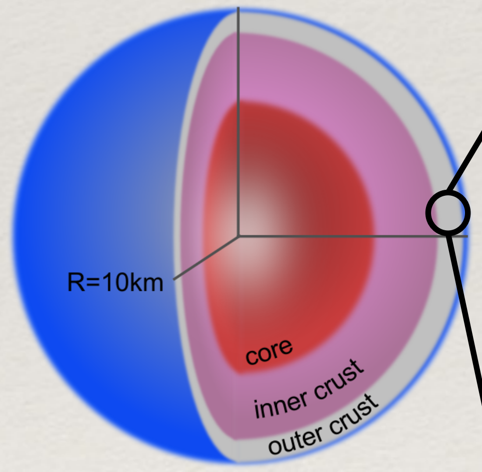
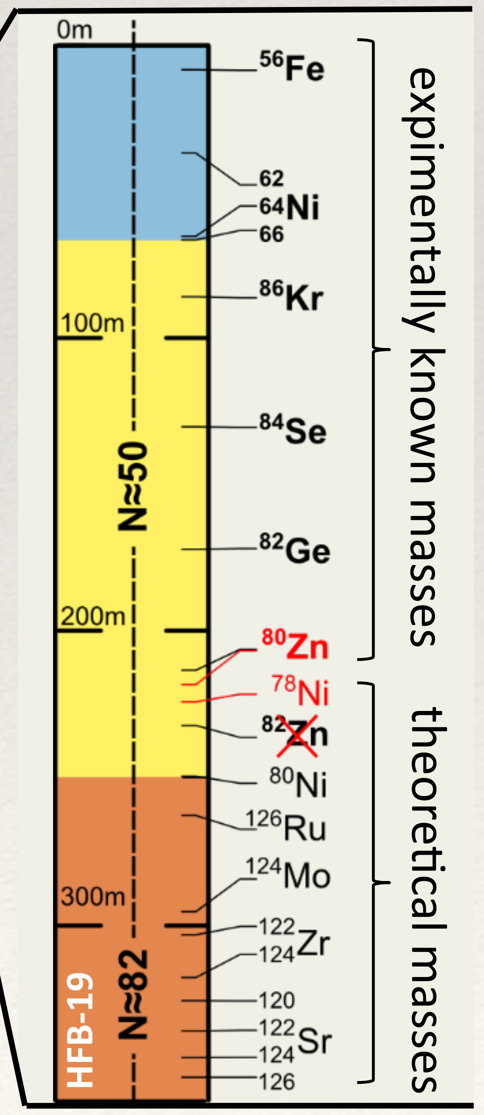
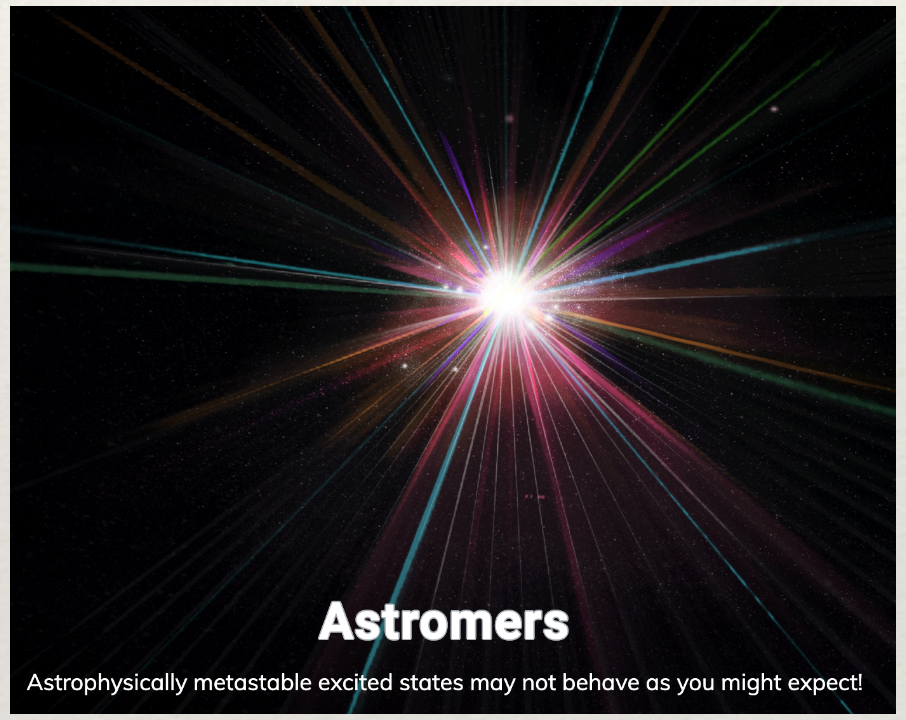
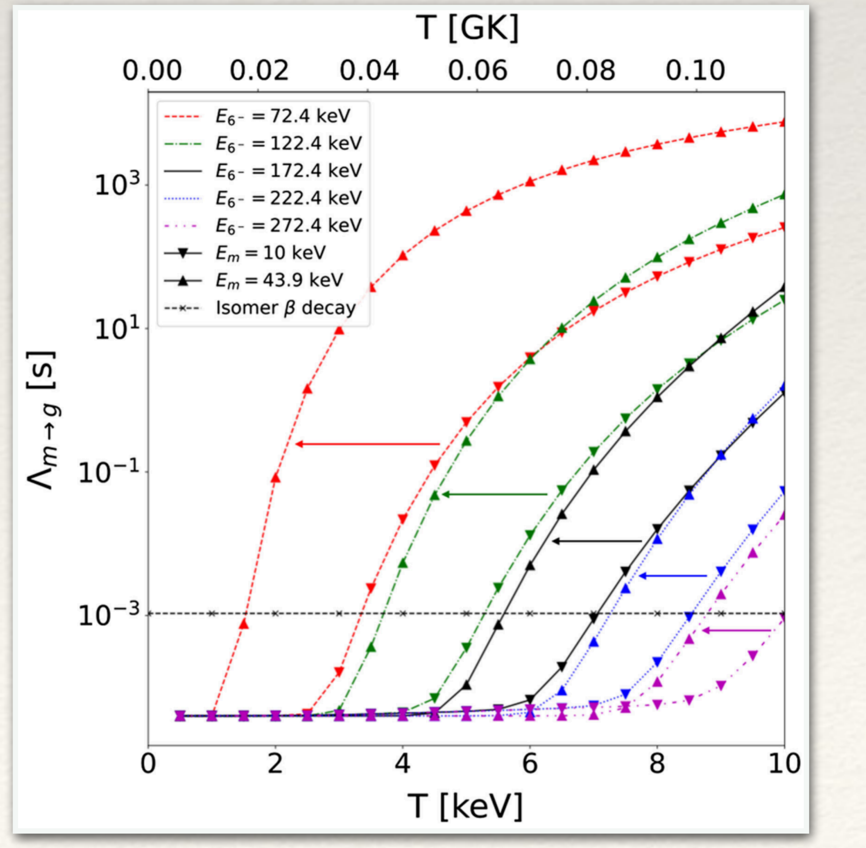
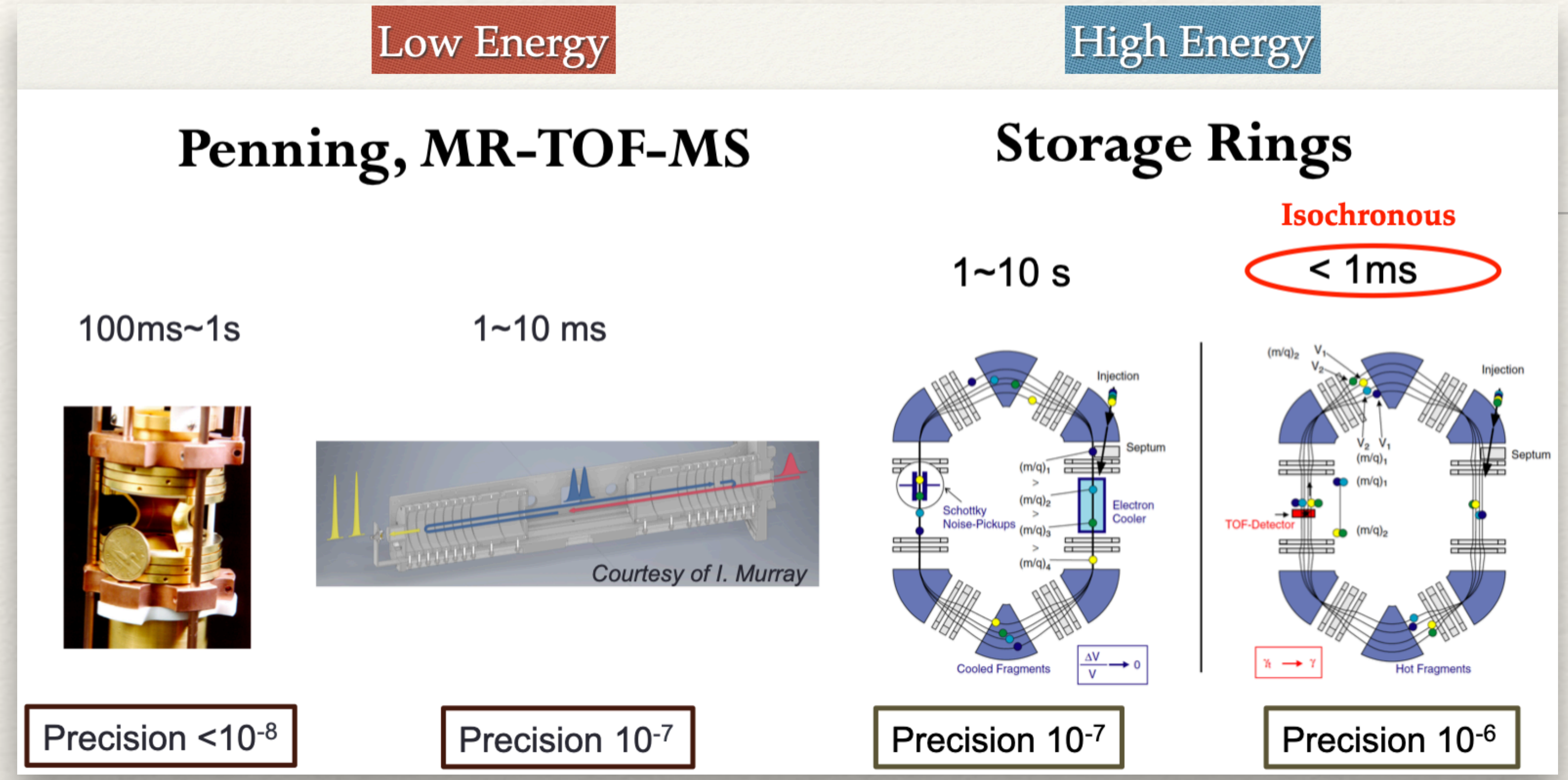


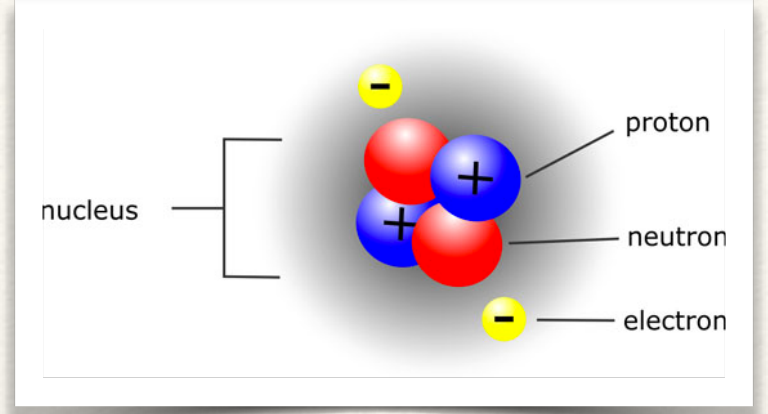






Takeaway





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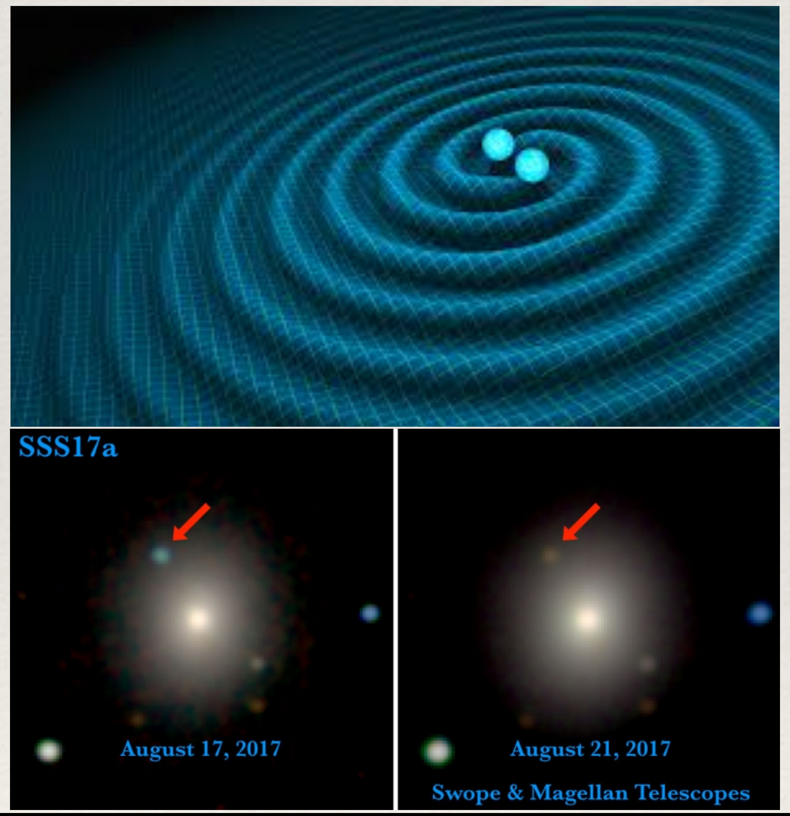

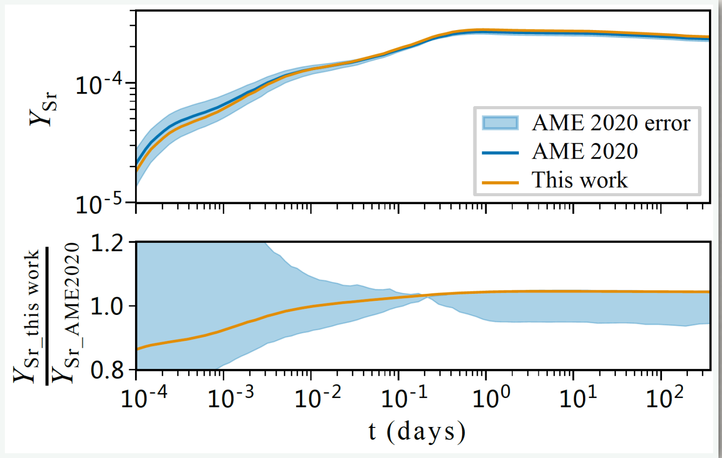

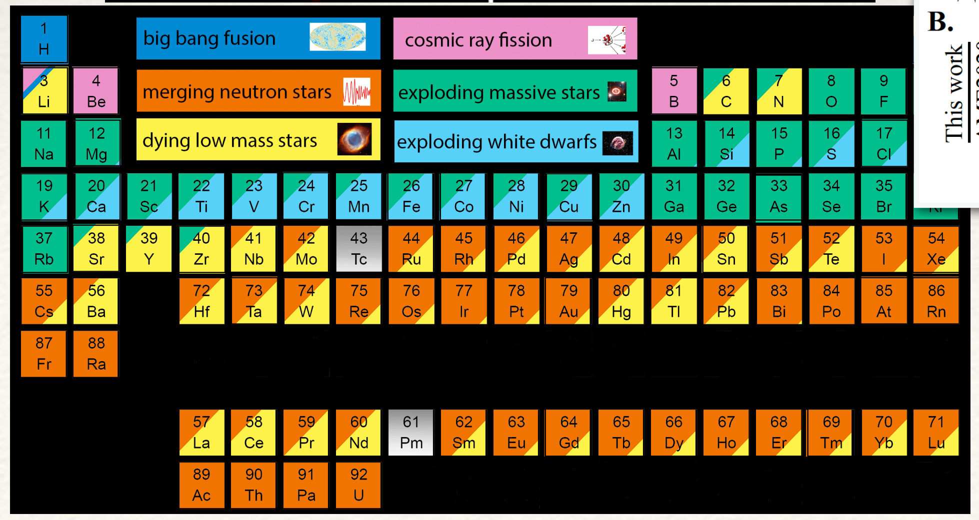

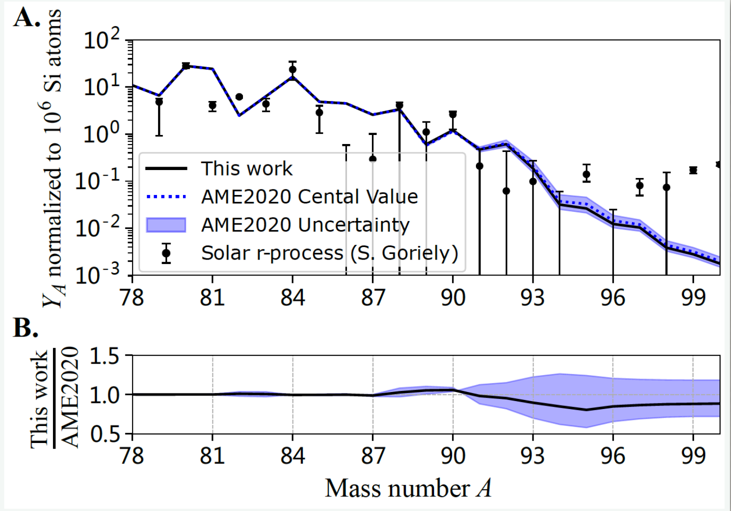

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