NUSYS 2024 ZuHai

Mass spectrometry of short-lived nuclides (for origins of heavy elements)

Michiharu Wada, KEK, Japan

1. Synthesis of heavy elements in the universe

   review of very basics

   why we measure atomic masses

2. Comprehensive mass measurement of short-lived nuclides

   mass as finger print

   nuclear structure studies

   heavy element synthesis

   toward islands of stability

very basics but I didn't know in your age

Michiharu Wada: Personnel background

- **Tohoku University** 1979~1991

  Laser spectroscopy of trapped Sr ions
  Alpine expedition to Tibet, China (1986)

- **INS, Univ. Tokyo** 1991~1999

  R&D for E-arena, JHP
  Innovation of RF-ion guide

- **RIKEN** 1999~2015

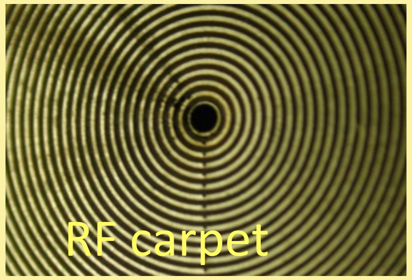
  Laser spectroscopy of trapped short-lived Be ions
  Innovation of RF carpet
  R&D of SLOWRI @ RIBF

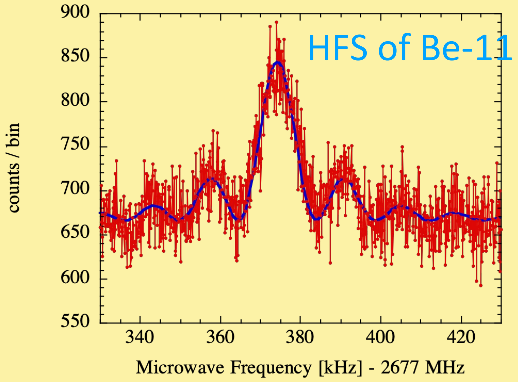
- **KEK** 2015~Mar2024 retired

  Comprehensive mass measurements with MRTOF
  MNT for n-rich nuclides at KISS

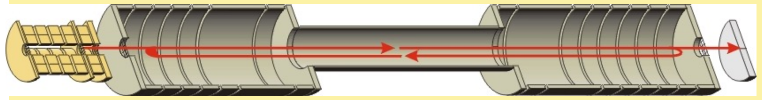
☆ ***Scientific Expedition "for the first time"***

念青唐古拉峰(7162m) First accent



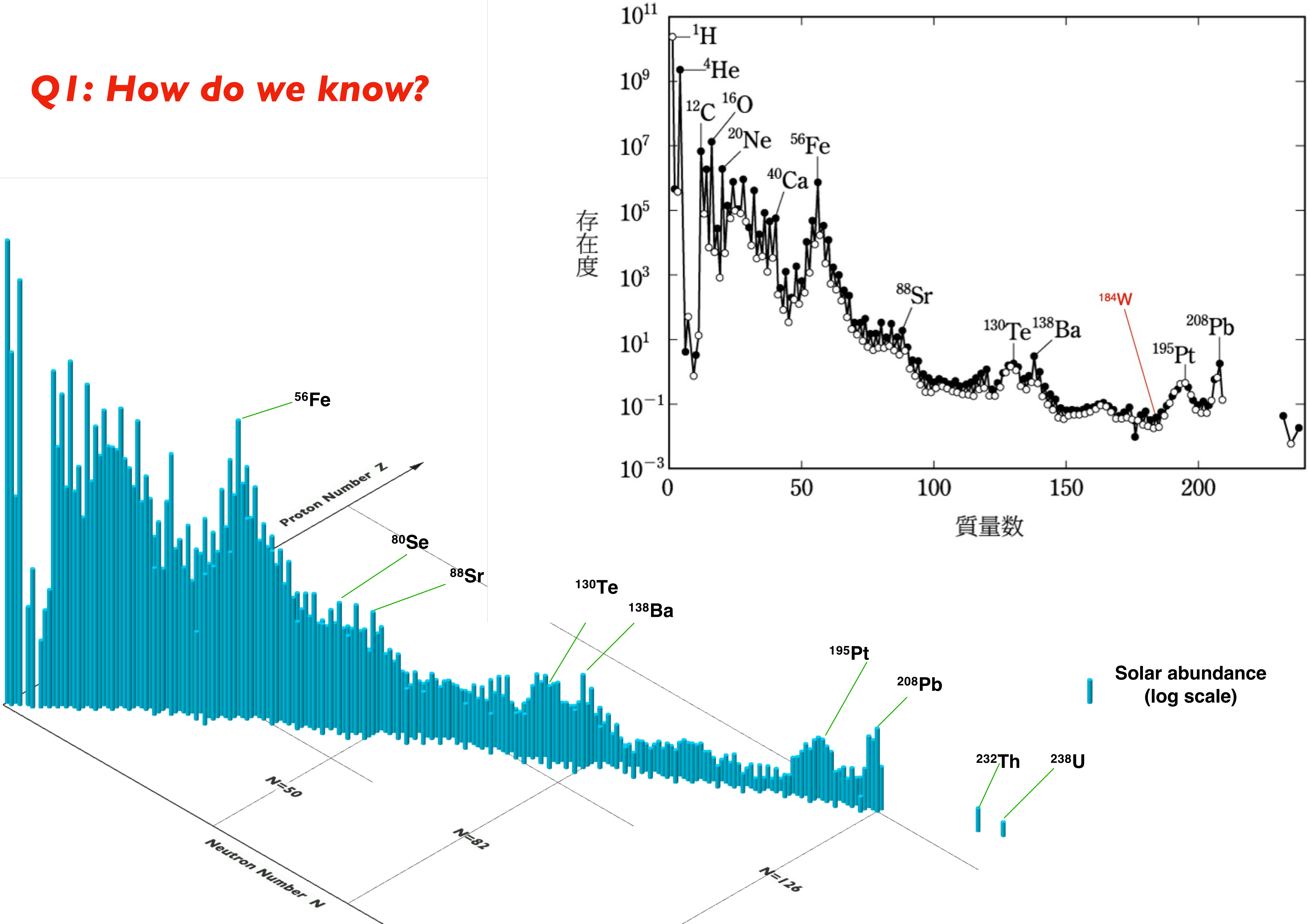


MRTOF mass spectrograph

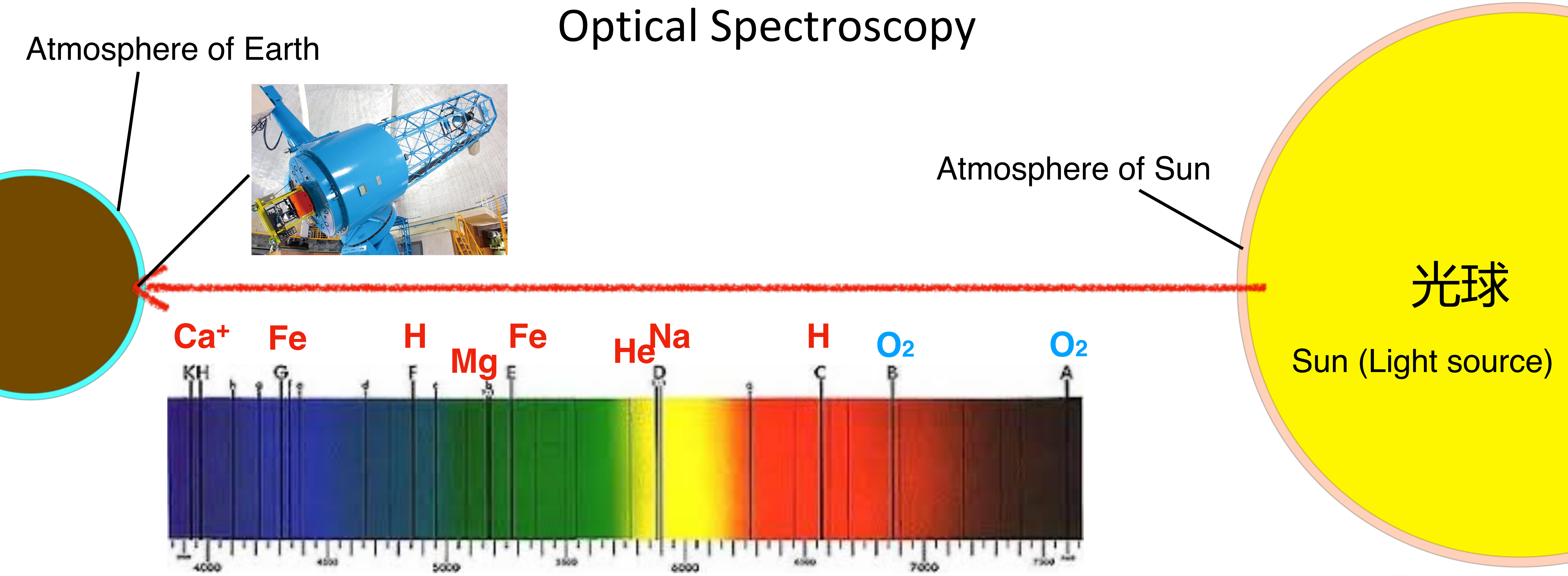


We have various elements (~83) and their isotopes (~255)

Q1: How do we know?



Optical Spectroscopy



Absorption lines (or Fraunhofer lines) in optical spectrum

- Volatile elements in “atmosphere” of Sun are observable
- Isotopes identification is difficult
- Contents in atmosphere and core are identical?
    - Solar quakes can model internal structure of the Sun

1814, J. von Fraunhofer discovered >500 “dark lines” in spectrum. However, the origin of the “lines” were determined by Bunsen & Kirchhoff 40 years later.

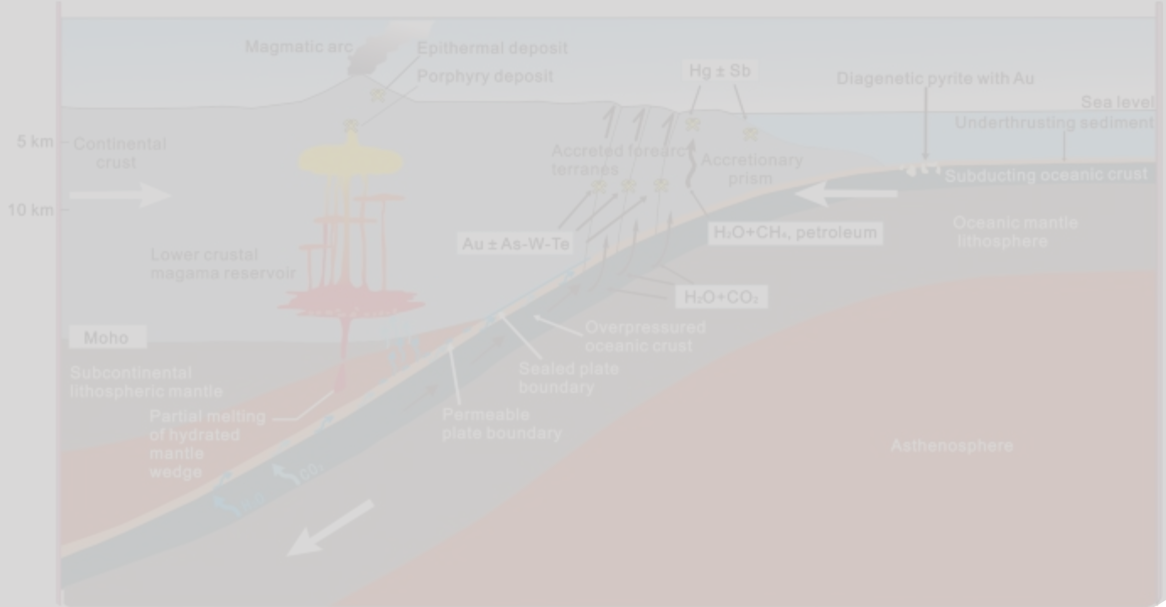
Elemental & Isotopic Analyses of Meteorite

- A specific meteorite contains materials formed 4.5 G year ago.
- Moon stones formed 3.2~4.4 G years ago.
  - ☆ non-volatile elements with isotopic ratios
  - ● How accurately confirm it represent the original abundance?

A flake of Allende meteorite fell in Mexico in 1969.

Q1: Why not stones or soil on the Earth's surface ?

Orogeny (mountain-building processes) has led to the formation of metal deposits, resulting in the uneven distribution of elements.



Moon stone from Apollo15, 1971

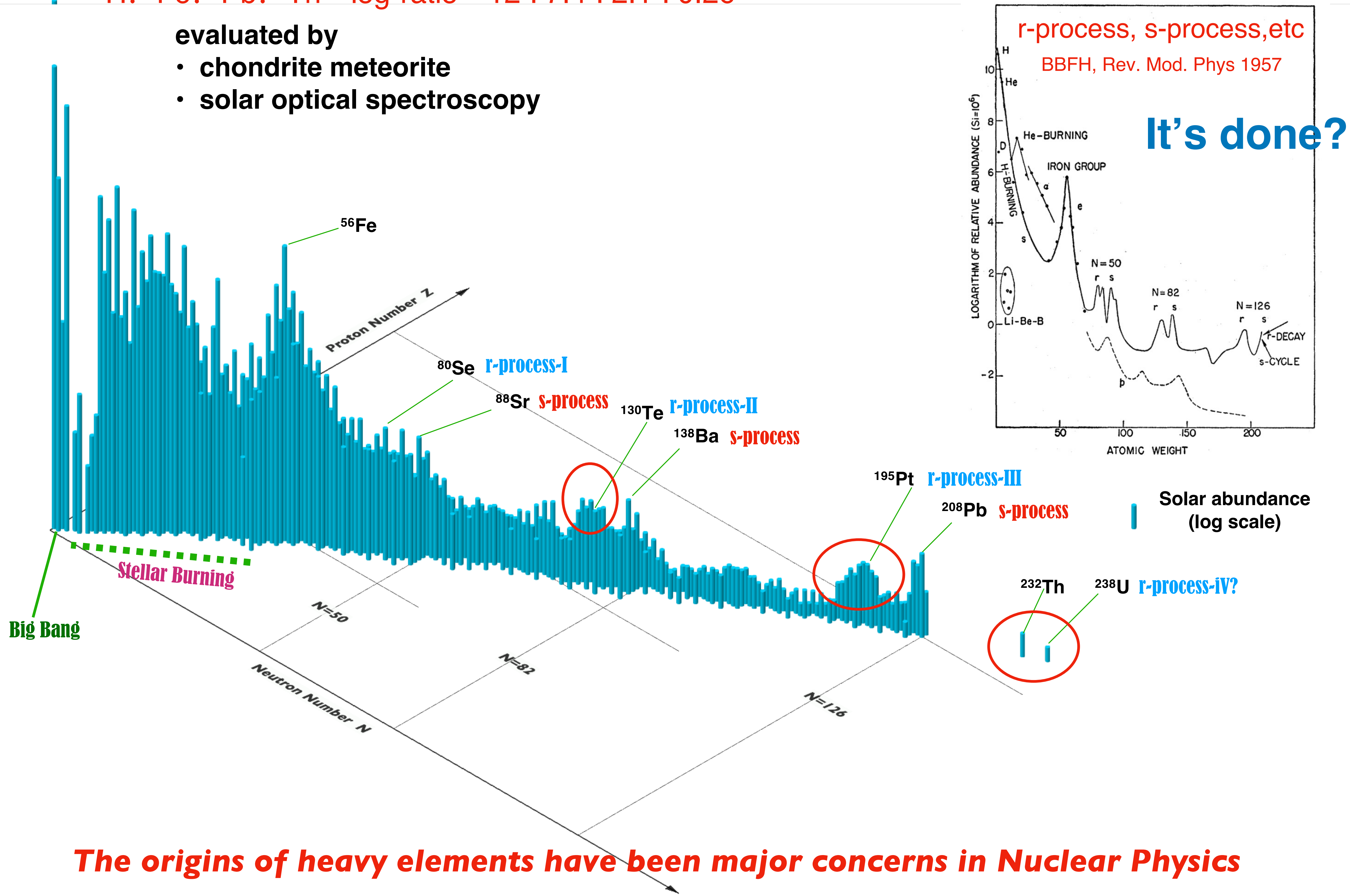
Nuclides Abundance in the Solar System

~83 elements、~255 nuclides

H：Fe：Pb：Th log-ratio 12 : 7.4 : 2.1 : 0.26

evaluated by

- **chondrite meteorite**
- **solar optical spectroscopy**



r-process, s-process,etc

BBFH, Rev. Mod. Phys 1957

It’s done?

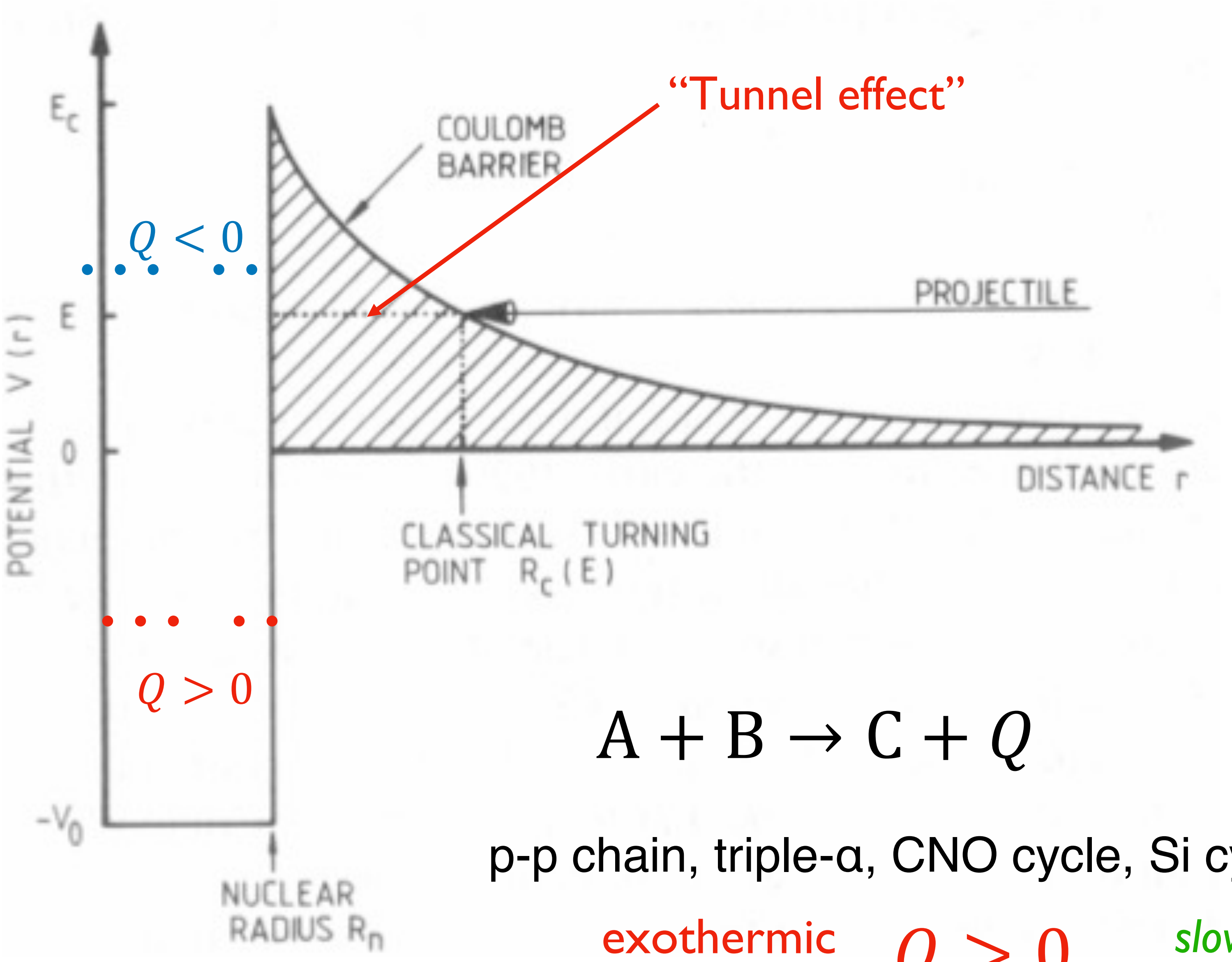
The origins of heavy elements have been major concerns in Nuclear Physics

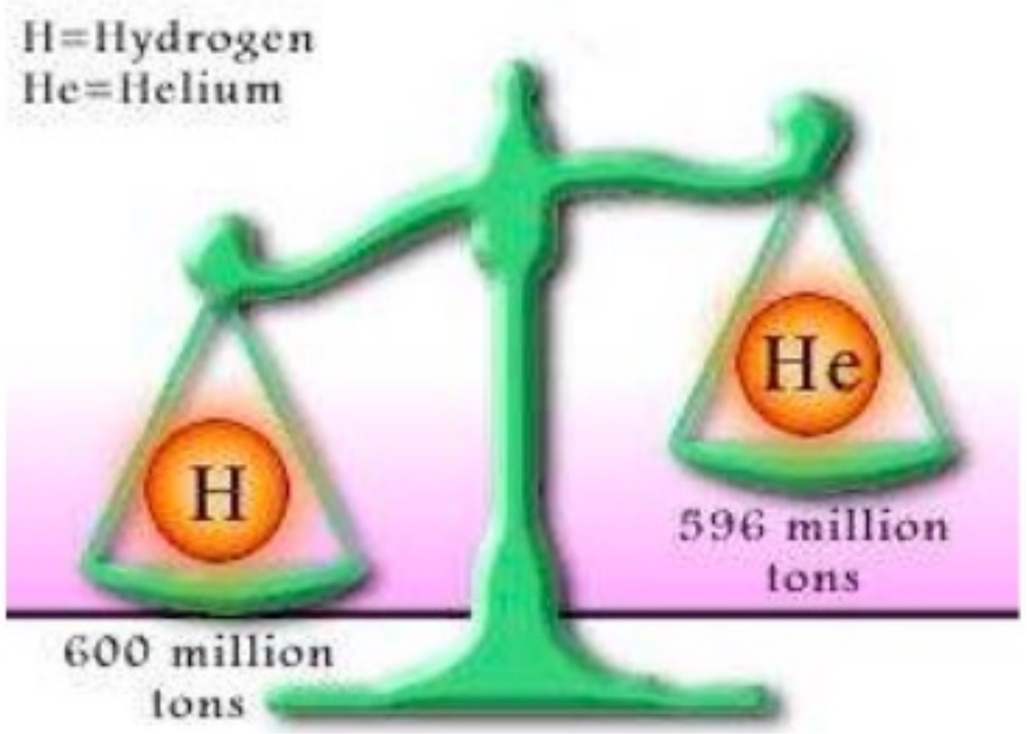
Stellar Burning

$$4\,{}^{1}\text{H} \rightarrow {}^{4}\text{He} + \text{neutrinos} + 26.7\text{MeV}$$

(Thermal) projectile energy is much less than Coulomb barrier

1.35 keV 550keV





600Mt/s of Hydrogen convert to He 596Mt at Sun

$$\text{A} + \text{B} \rightarrow \text{C} + Q$$

p-p chain, triple-α, CNO cycle, Si cycle, etc

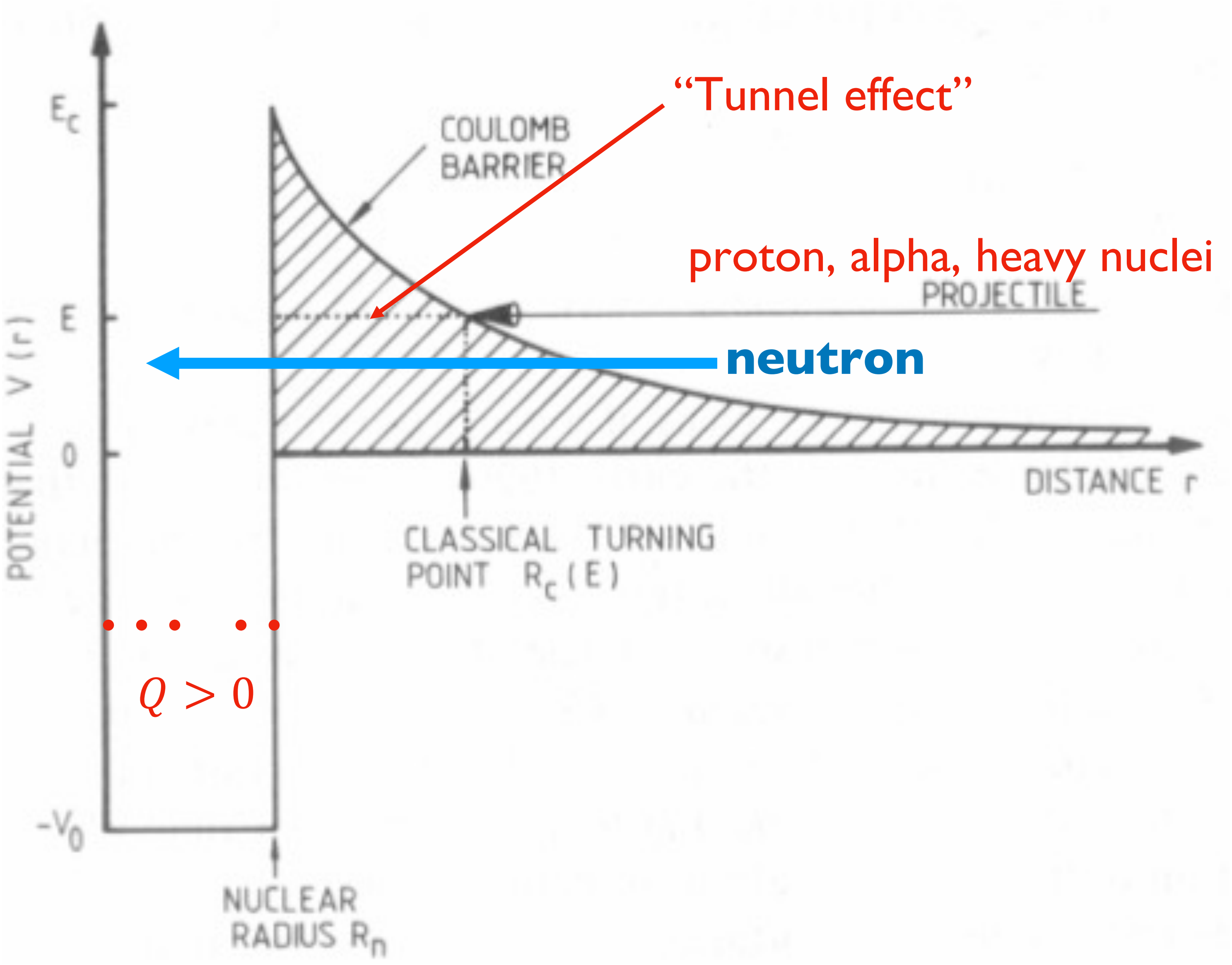
exothermic $Q > 0$ *slowly take place via tunnel effect*

Majority of possible reactions for heavier than Fe, Ni

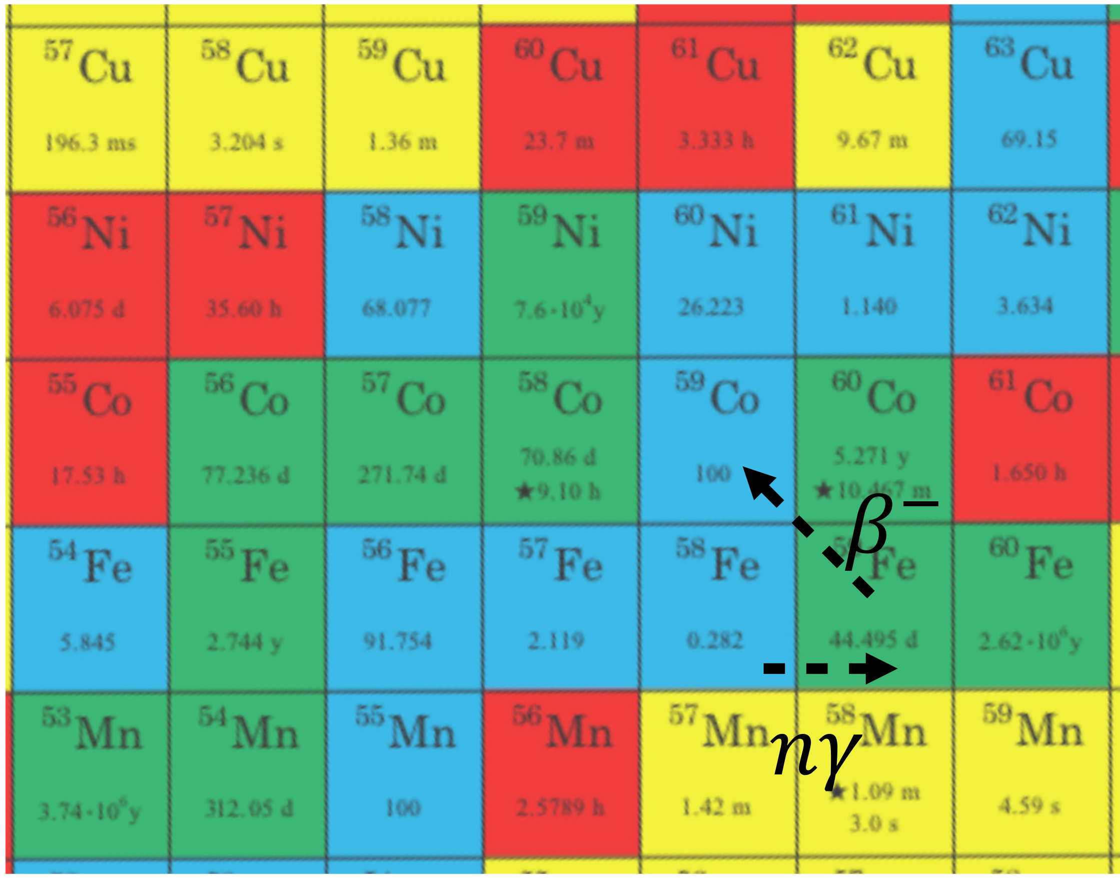
endothermic $Q < 0$ *difficult to take place with thermal kinetic energies*

What about neutron capture?

No Coulomb barrier



neutron capture and successive β^- decay produces Z+1 nuclide



^{57}Cu 196.3 ms	^{58}Cu 3.204 s	^{59}Cu 1.36 m	^{60}Cu 23.7 m	^{61}Cu 3.333 h	^{62}Cu 9.67 m	^{63}Cu 69.15
^{56}Ni 6.075 d	^{57}Ni 35.60 h	^{58}Ni 68.077	^{59}Ni $7.6 \cdot 10^4$y	^{60}Ni 26.223	^{61}Ni 1.140	^{62}Ni 3.634
^{55}Co 17.53 h	^{56}Co 77.236 d	^{57}Co 271.74 d	^{58}Co 70.86 d ★9.10 h	^{59}Co 100	^{60}Co 5.271 y ★10.467 m	^{61}Co 1.650 h
^{54}Fe 5.845	^{55}Fe 2.744 y	^{56}Fe 91.754	^{57}Fe 2.119	^{58}Fe 0.282	^{59}Fe 44.495 d	^{60}Fe $2.62 \cdot 10^6$y
^{53}Mn $3.74 \cdot 10^6$y	^{54}Mn 312.05 d	^{55}Mn 100	^{56}Mn 2.5789 h	^{57}Mn 1.42 m	^{58}Mn ★1.09 m 3.0 s	^{59}Mn 4.59 s

S-process for heavy element synthesis

source of neutrons

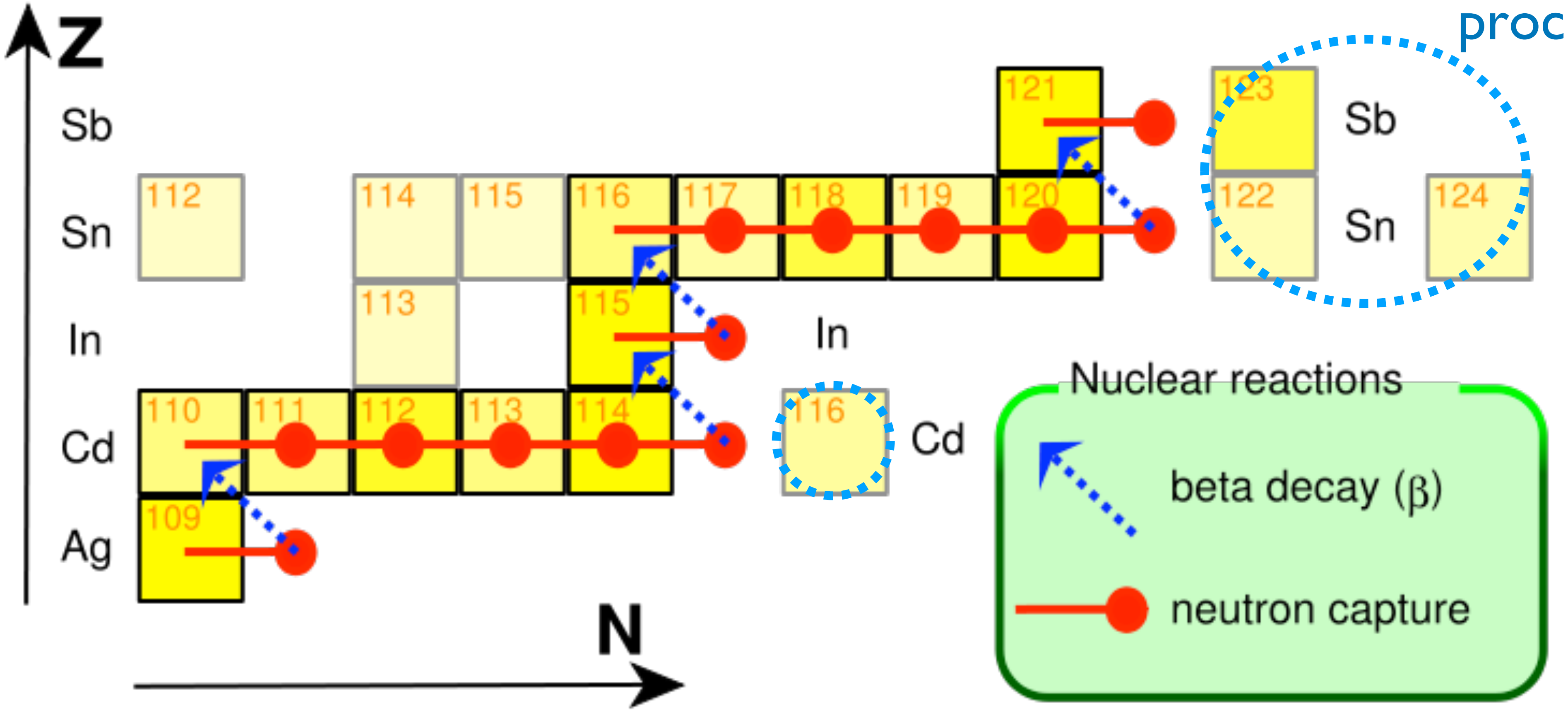
$^{13}_{6}\mathrm{C} + ^{4}_{2}\mathrm{He} \rightarrow ^{16}_{8}\mathrm{O} + n$

$^{22}_{10}\mathrm{Ne} + ^{4}_{2}\mathrm{He} \rightarrow ^{25}_{12}\mathrm{Mg} + n$

Asymptotic Giant Brach of 0.6~10 solar mass stars

at the end of life, 1,000-1,000,000 years of slow process

not accessible in s-process



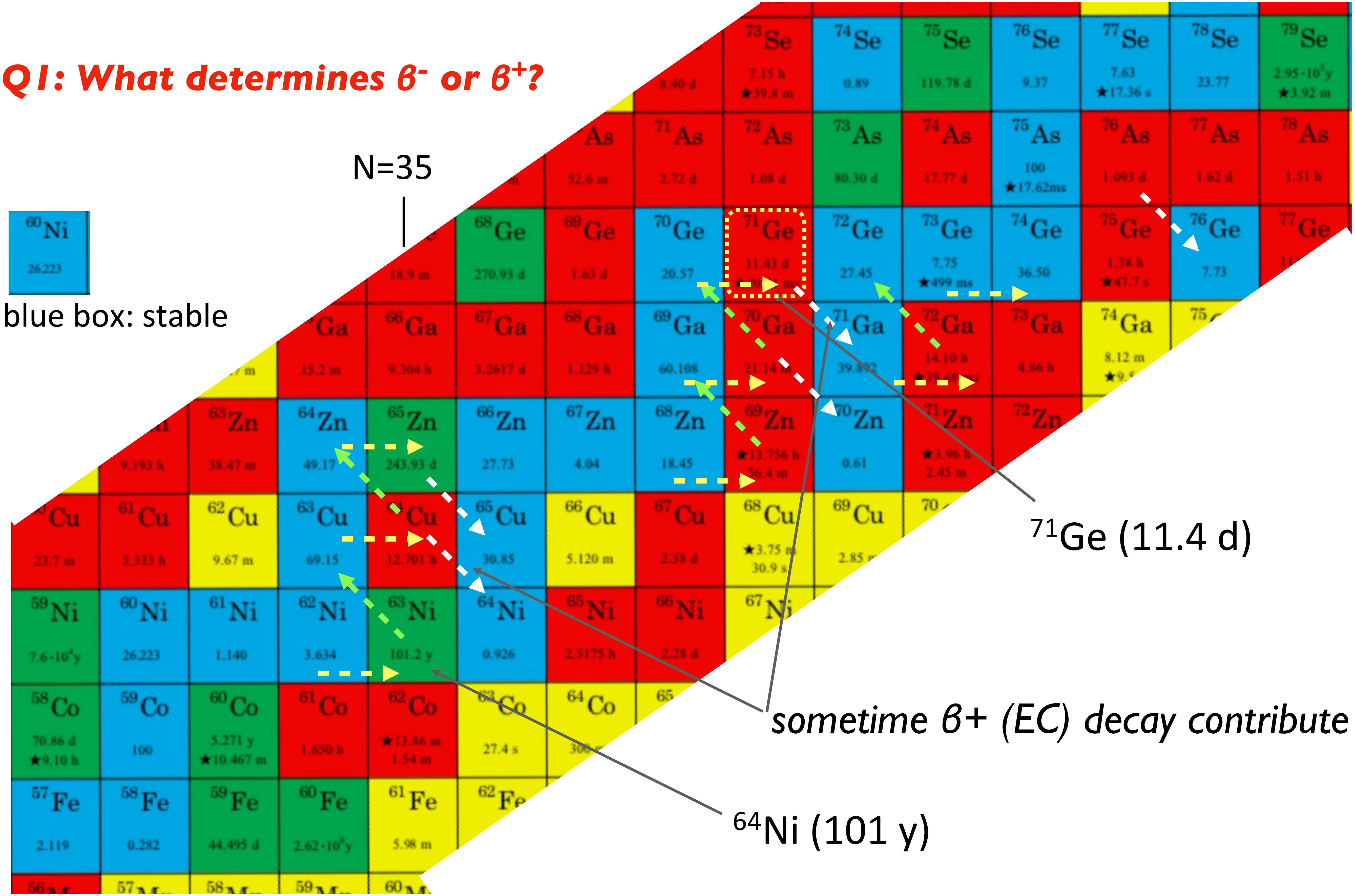
neutron capture &

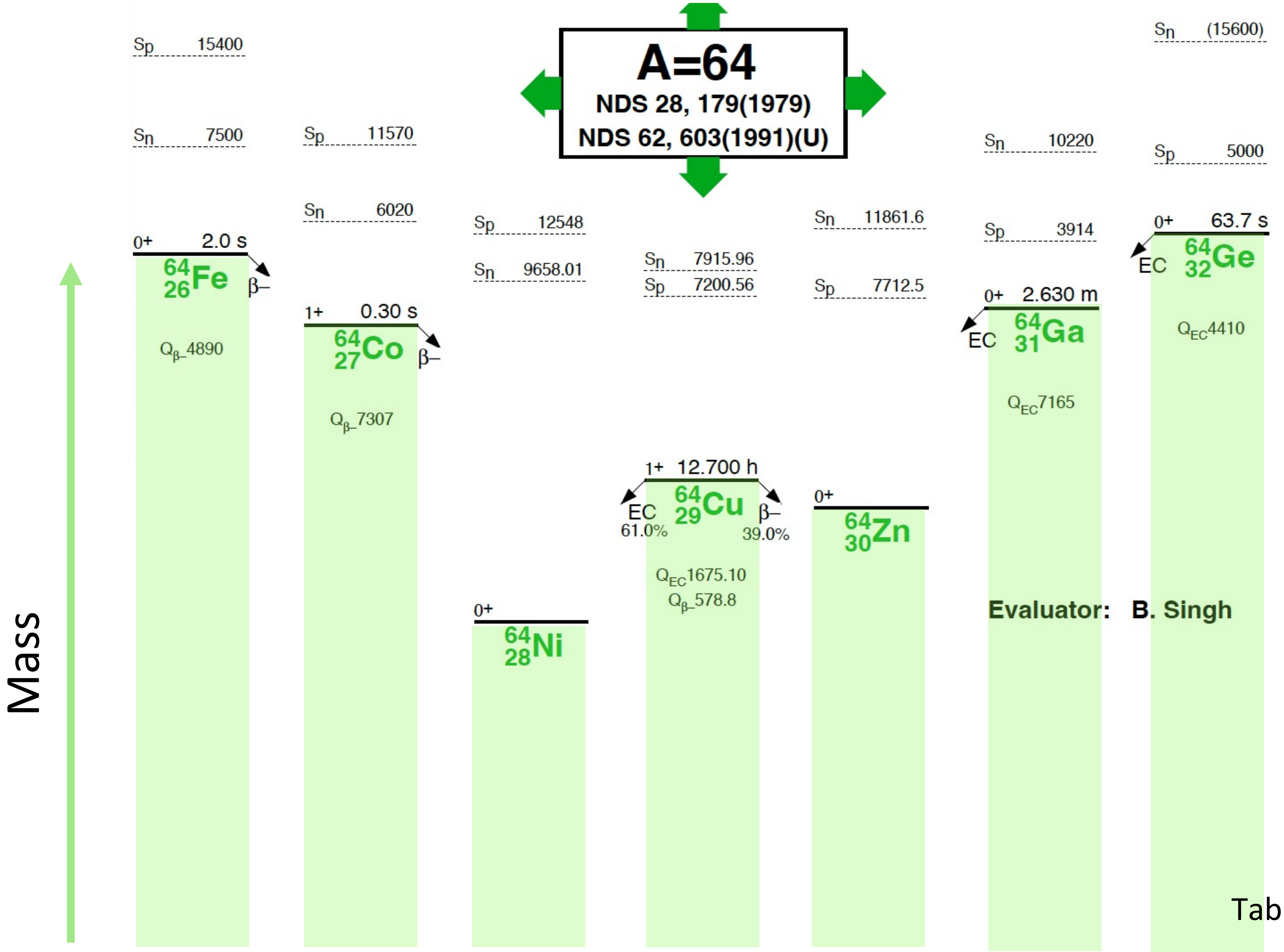
Heavy nuclides can be synthesized up to 208Pb and 209Bi

Q1: Have you tried tracing the path?

s-process follows stable nuclides via β- decay??

Q1: What determines β⁻ or β⁺?





A=64

NDS 28, 179(1979)

NDS 62, 603(1991)(U)

Mass

$^{64}_{26}$Fe: 0+ 2.0 s; β−; $Q_{\beta-}$4890; Sp 15400; Sn 7500

$^{64}_{27}$Co: 1+ 0.30 s; β−; $Q_{\beta-}$7307; Sp 11570; Sn 6020

$^{64}_{28}$Ni: 0+; Sp 12548; Sn 9658.01

$^{64}_{29}$Cu: 1+ 12.700 h; EC 61.0%; β− 39.0%; Q_{EC}1675.10; $Q_{\beta-}$578.8; Sn 7915.96; Sp 7200.56

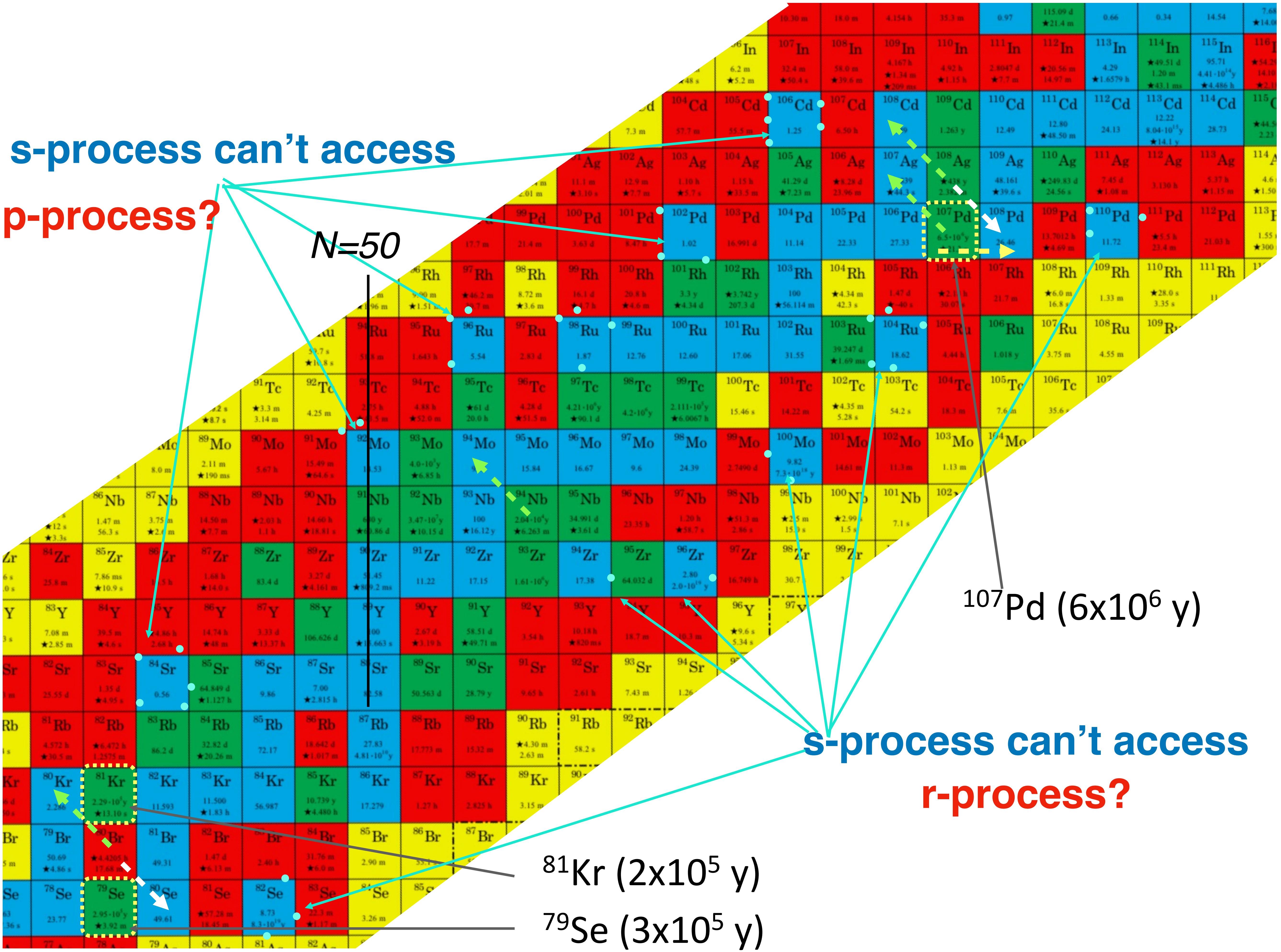
$^{64}_{30}$Zn: 0+; Sn 11861.6; Sp 7712.5

$^{64}_{31}$Ga: 0+ 2.630 m; EC; Q_{EC}7165; Sn 10220; Sp 3914

$^{64}_{32}$Ge: 0+ 63.7 s; EC; Q_{EC}4410; Sn (15600); Sp 5000

Evaluator: B. Singh

Table of Isotopes



s-process can't access

p-process?

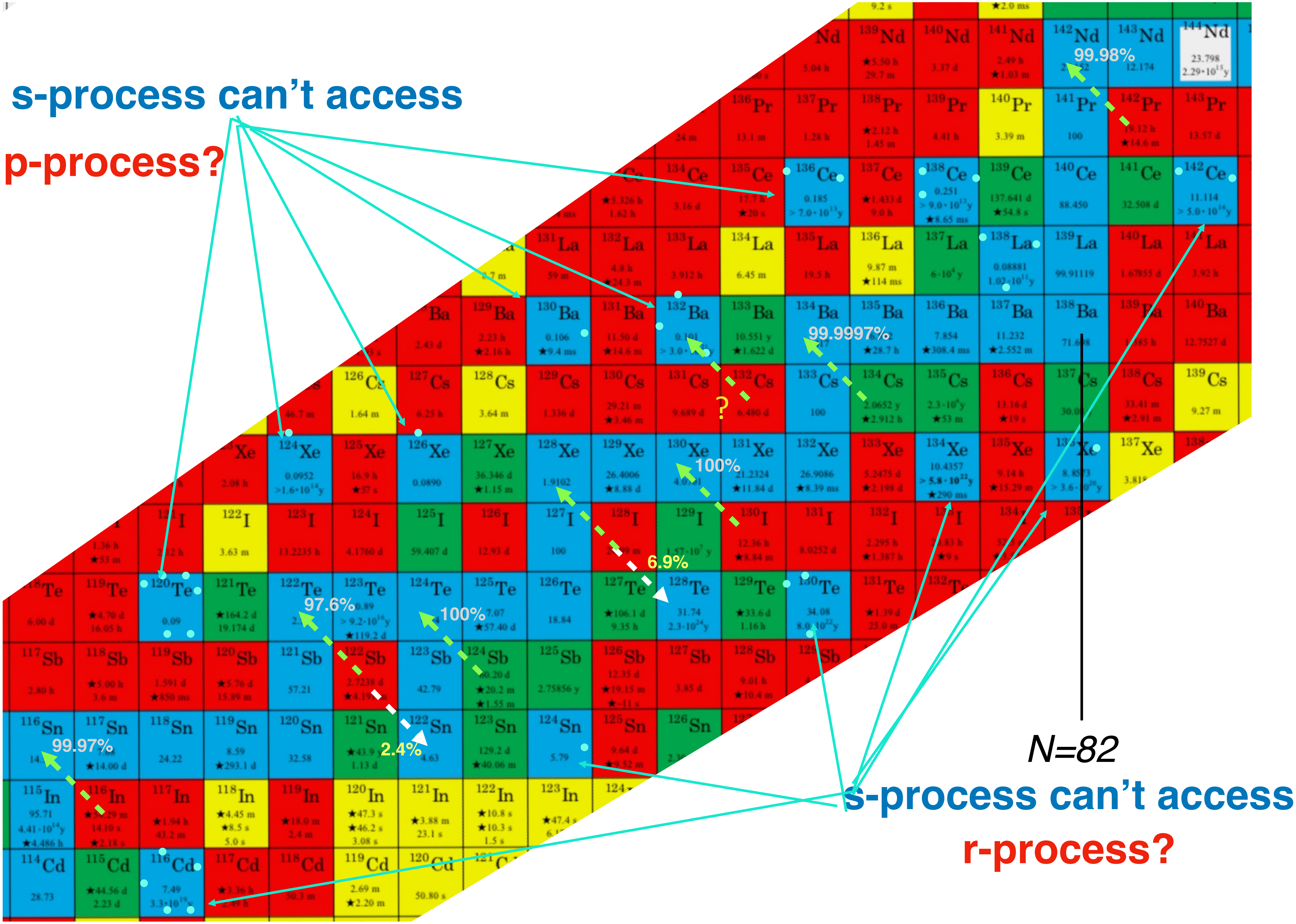
^{107}Pd (6x10^{6} y)

s-process can't access

r-process?

^{81}Kr (2x10^{5} y)

^{79}Se (3x10^{5} y)



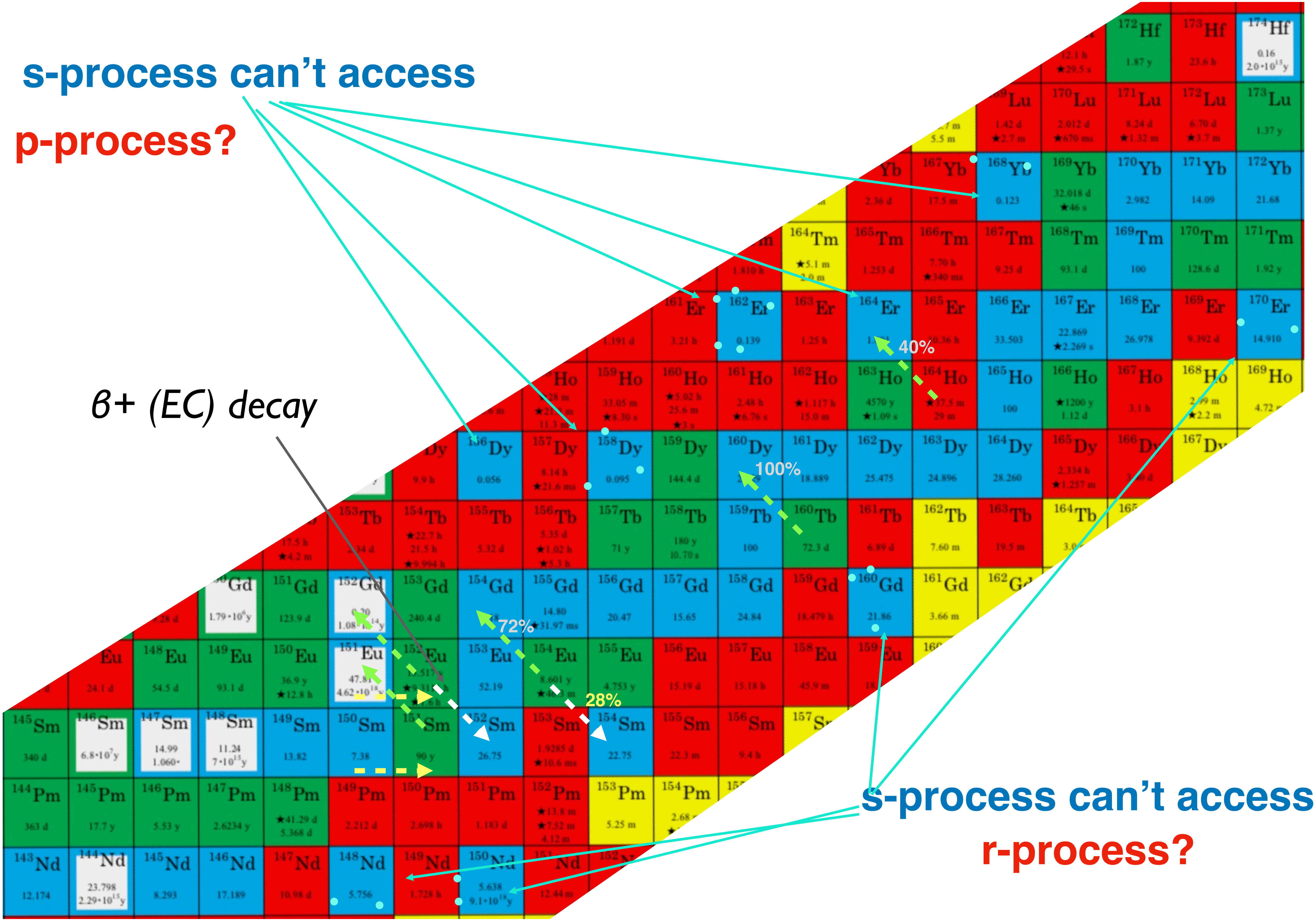
s-process can’t access

p-process?

N=82

s-process can’t access

r-process?



s-process can’t access

p-process?

β+ (EC) decay

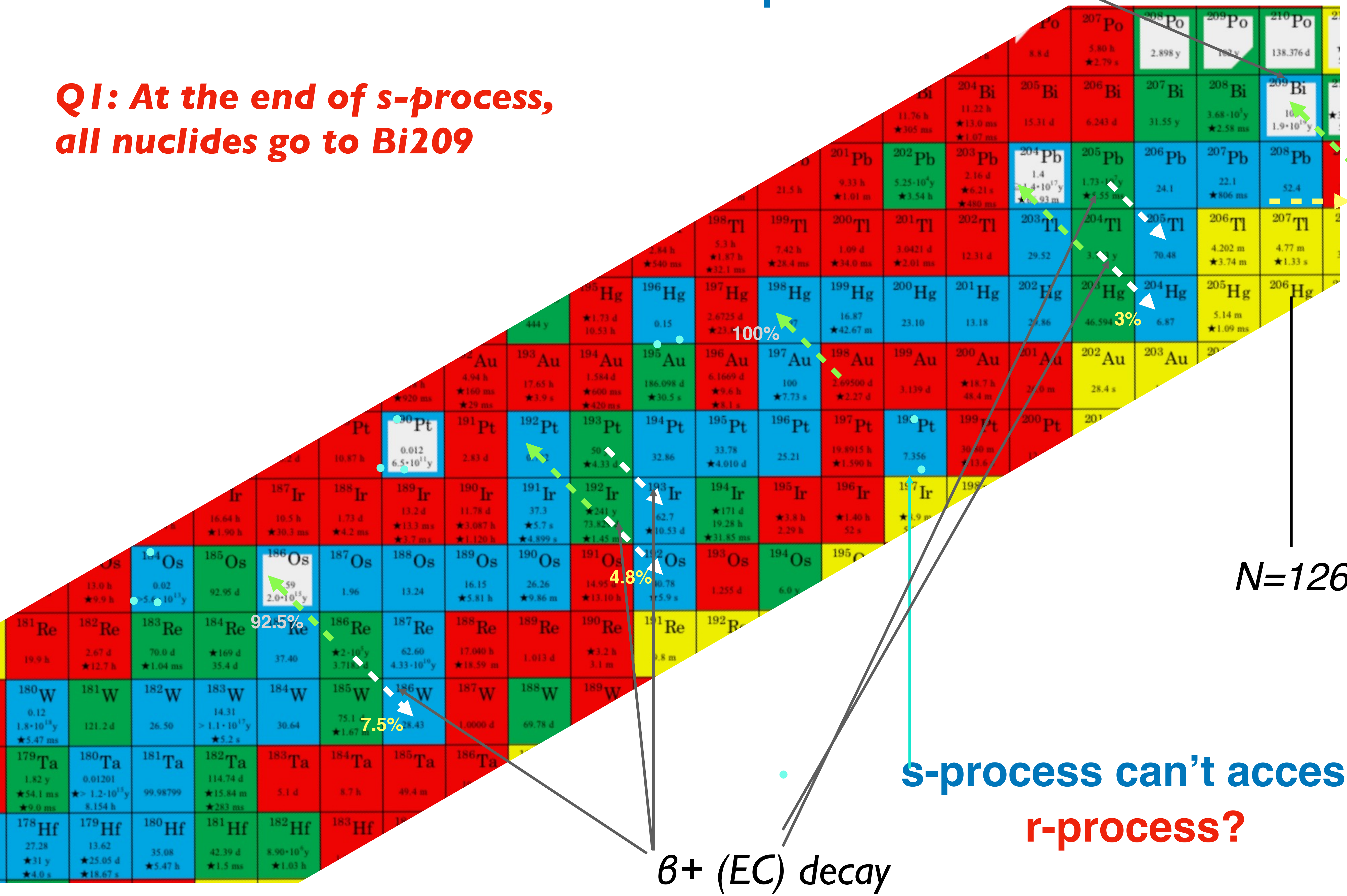
s-process can’t access

r-process?

End point of s-process

^{209}Bi

Q1: At the end of s-process, all nuclides go to Bi209

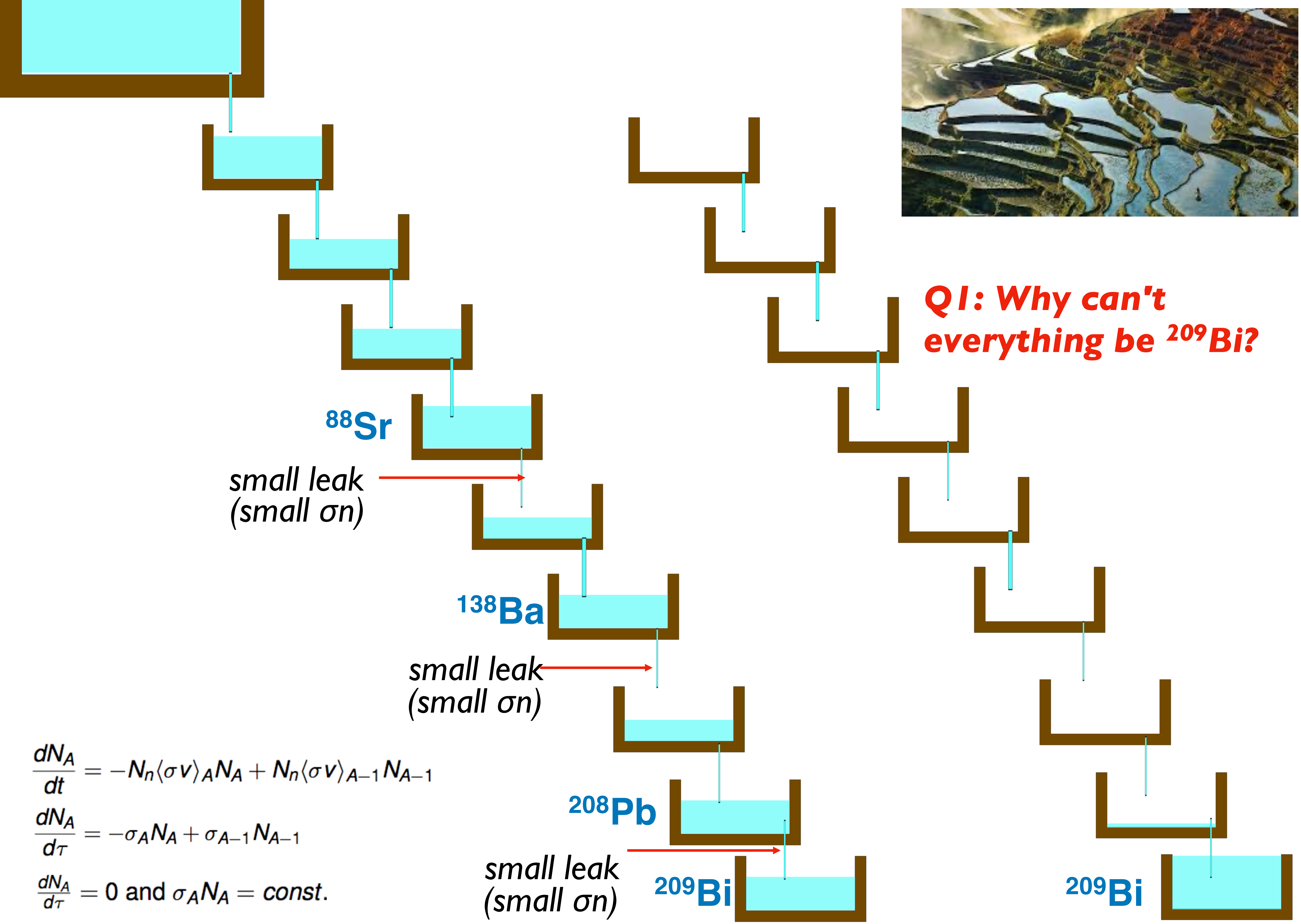


N=126

β+ (EC) decay

s-process can't access r-process?

Q1: Why can't everything be ^{209}Bi?



^{88}Sr

small leak (small σn)

^{138}Ba

small leak (small σn)

^{208}Pb

small leak (small σn)

^{209}Bi

no leak

^{209}Bi

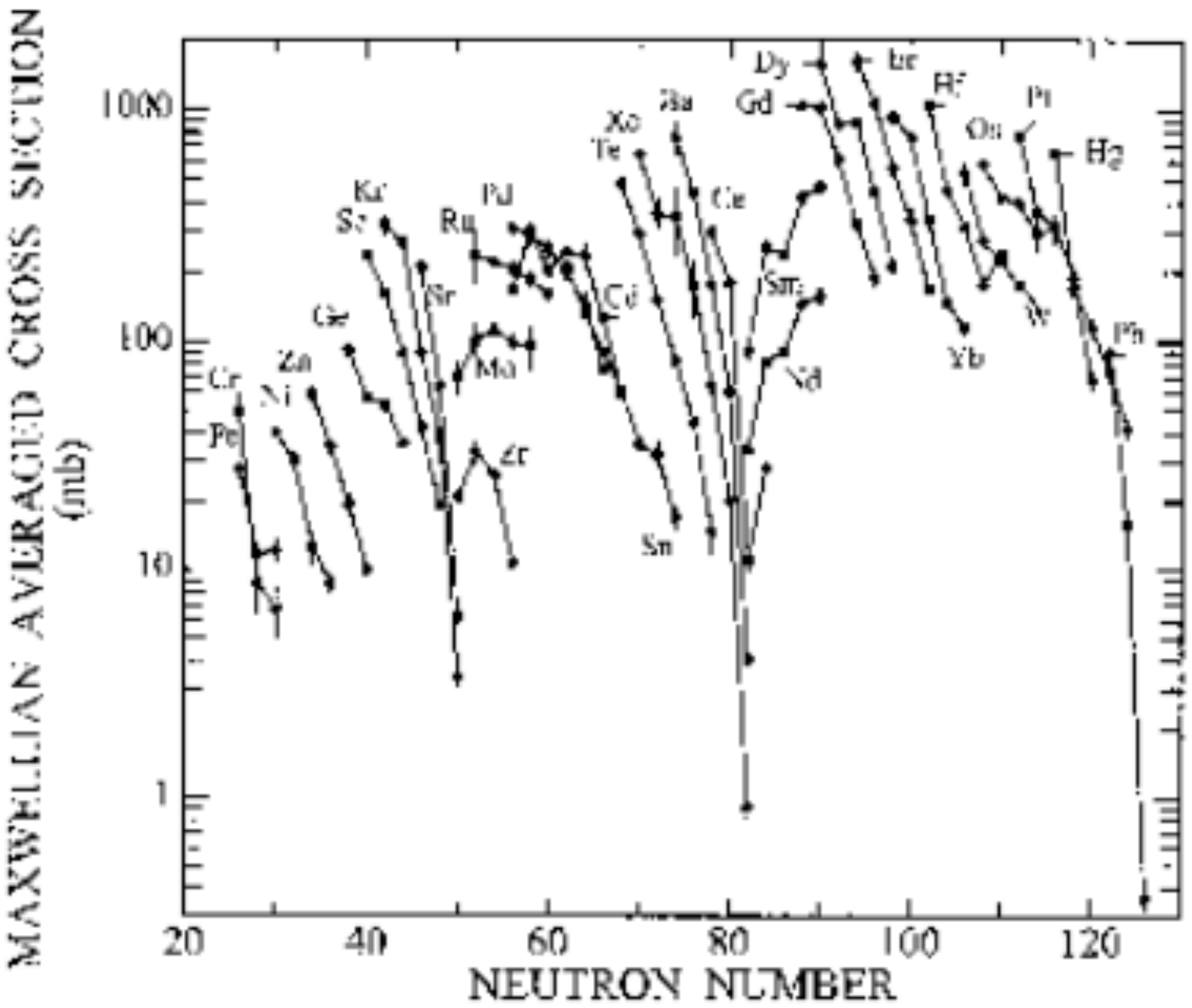
no leak

$$\frac{dN_A}{dt} = -N_n \langle \sigma v \rangle_A N_A + N_n \langle \sigma v \rangle_{A-1} N_{A-1}$$

$$\frac{dN_A}{d\tau} = -\sigma_A N_A + \sigma_{A-1} N_{A-1}$$

$$\frac{dN_A}{d\tau} = 0 \text{ and } \sigma_A N_A = const.$$

n-capture cross section becomes minimum at n-magic number



$\sigma_A N_A = const.$ At minimum σn, Abundance max

Nuclides Abundance in the Solar System

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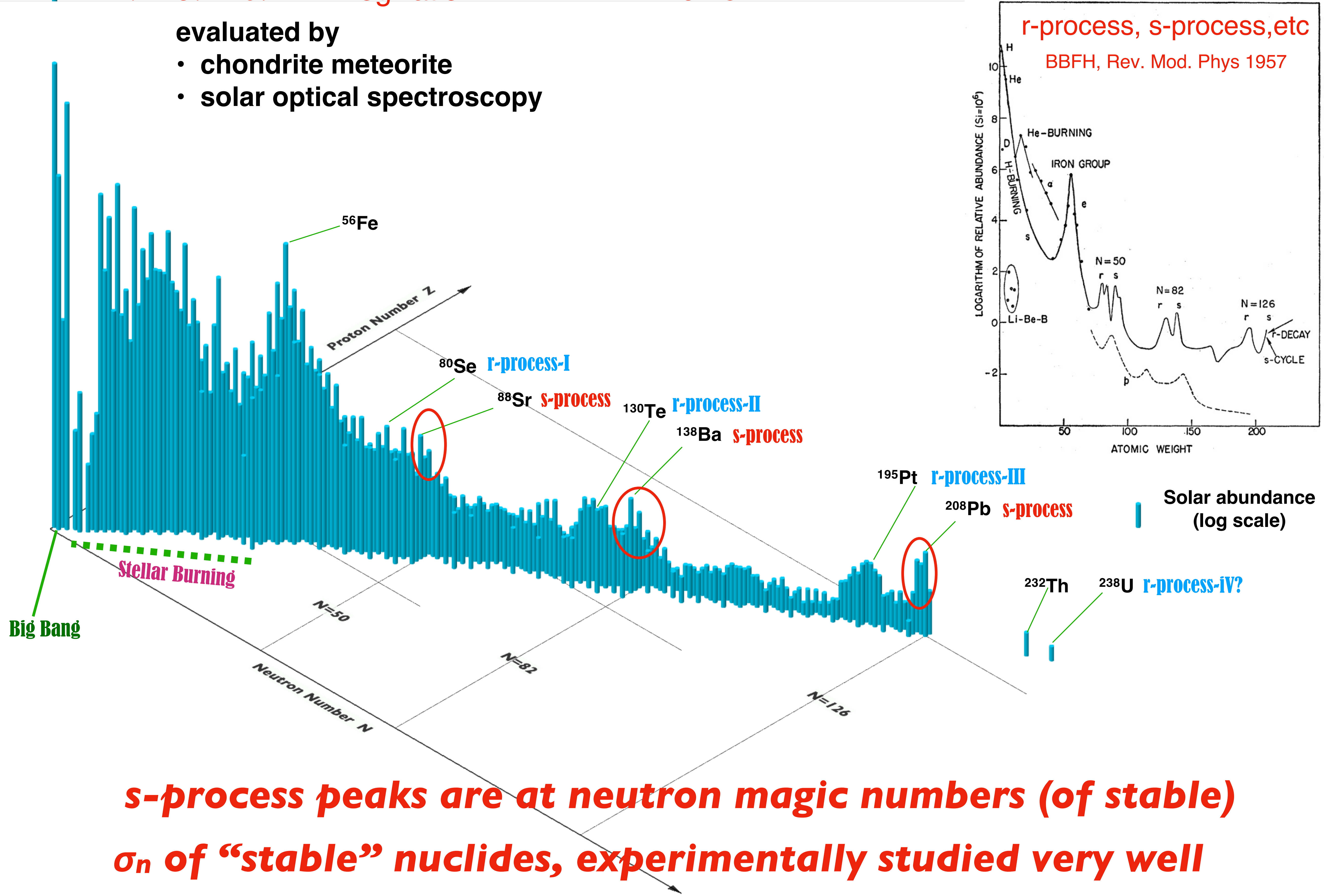
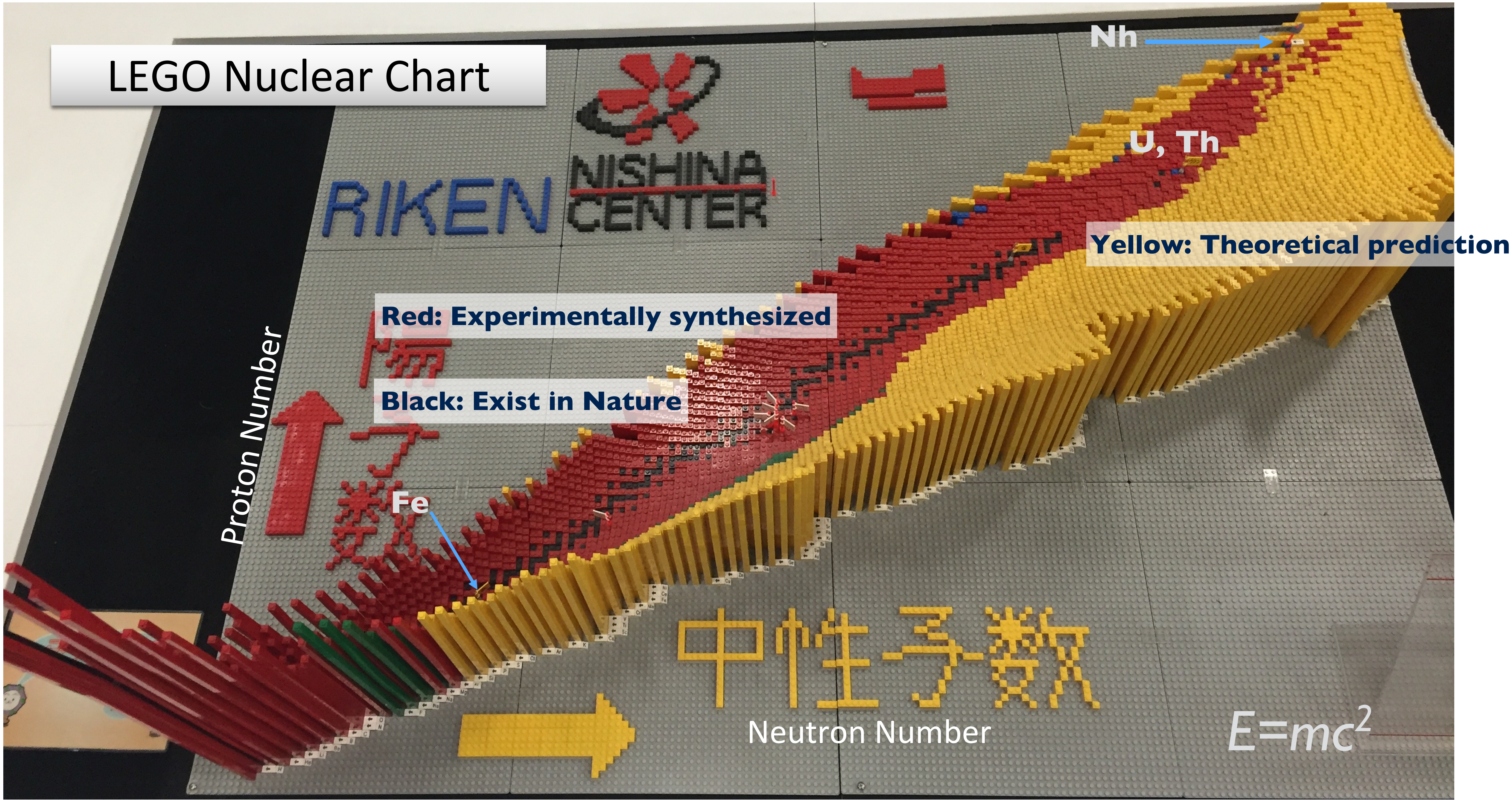
evaluated by
- chondrite meteorite
- solar optical spectroscopy


r-process, s-process,etc

BBFH, Rev. Mod. Phys 1957

s-process peaks are at neutron magic numbers (of stable)

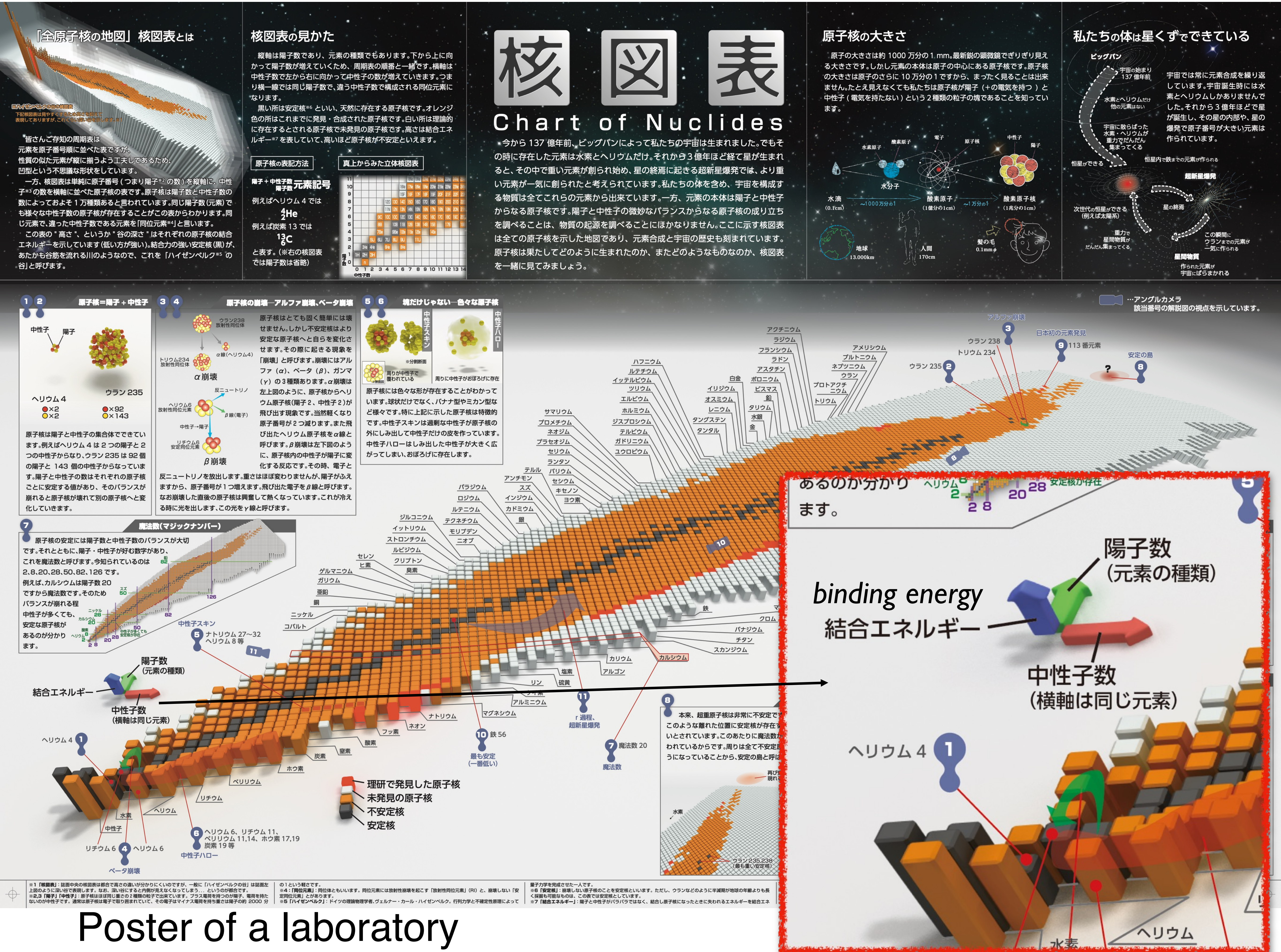
σ_n of “stable” nuclides, experimentally studied very well



Q1: What is the height of pillar?

The heights indicates the mass

But divided by A and magnify around mass/A =1



核図表
Chart of Nuclides

今から 137 億年前、ビッグバンによって私たちの宇宙は生まれました。でもその時に存在した元素は水素とヘリウムだけ。それから 3 億年ほど経て星が生まれると、その中で重い元素が創られ始め、星の終焉に起きる超新星爆発では、より重い元素が一気に創られたと考えられています。私たちの体を含め、宇宙を構成する物質は全てこれらの元素から出来ています。一方、元素の本体は陽子と中性子からなる原子核です。陽子と中性子の微妙なバランスからなる原子核の成り立ちを調べることは、物質の起源を調べることにほかなりません。ここに示す核図表は全ての原子核を示した地図であり、元素合成と宇宙の歴史も刻まれています。原子核は果たしてどのように生まれたのか、またどのようなものなのか、核図表を一緒に見てみましょう。

「全原子核の地図」核図表とは

※ハイゼンベルクの谷の核図表

下記核図表は見やすくするため高さを抑えて表現してありますが、これくらい深い谷を示します。※1

皆さんご存知の周期表は元素を原子番号順に並べた表ですが、性質の似た元素が縦に揃うよう工夫してあるため、凹型という不思議な形状をしています。

一方、核図表は単純に原子番号（つまり陽子※2 の数）を縦軸に、中性子※3 の数を横軸に並べた原子核の表です。原子核は陽子数と中性子数の数によっておよそ 1 万種類あると言われています。同じ陽子数（元素）でも様々な中性子数の原子核が存在することがこの表からわかります。同じ元素で、違った中性子数である元素を「同位元素※4」と言います。

この表の " 高さ "、というか " 谷の深さ " はそれぞれの原子核の結合エネルギーを示しています（低い方が強い）。結合力の強い安定核（黒）が、あたかも谷筋を流れる川のようなので、これを「ハイゼンベルク※5 の谷」と呼びます。

核図表の見かた

縦軸は陽子数であり、元素の種類でもあります。下から上に向かって陽子数が増えていくため、周期表の順番と一緒です。横軸は中性子数で左から右に向かって中性子の数が増えていきます。つまり横一線では同じ陽子数で、違う中性子数で構成される同位元素になります。

黒い所は安定核※6 といい、天然に存在する原子核です。オレンジ色の所はこれまでに発見・合成された原子核です。白い所は理論的に存在するとされる原子核で未発見の原子核です。高さは結合エネルギー※7 を表していて、高いほど原子核が不安定といえます。

原子核の表記方法

$^{\text{陽子＋中性子数}}_{\text{陽子数}}\text{元素記号}$

例えばヘリウム 4 では

$^{4}_{2}\mathrm{He}$

例えば炭素 13 では

$^{13}_{6}\mathrm{C}$

と表す。（※右の核図表では陽子数は省略）

真上からみた立体核図表

陽子数 \ 中性子数	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
11								18Na	19Na	20Na	21Na	22Na	23Na	24Na	25Na
10							16Ne	17Ne	18Ne	19Ne	20Ne	21Ne	22Ne	23Ne	24Ne
9							15F	16F	17F	18F	19F	20F	21F	22F	23F
8					12O	13O	14O	15O	16O	17O	18O	19O	20O	21O	22O
7					11N	12N	13N	14N	15N	16N	17N	18N	19N	20N	21N
6				9C	10C	10C	12C	13C	14C	15C	16C	17C	18C	19C	20C
5				8B		10B	11B	12B	13B	14B	15B		17B		19B
4				7Be		9Be	10Be	11Be	12Be		14Be				
3			5Li	6Li	7Li	8Li	9Li		11Li						
2		3He	4He		6He		8He								
1	1H	2H	3H												
0		n													

原子核の大きさ

原子の大きさは約 1000 万分の 1 mm。最新鋭の顕微鏡でぎりぎり見える大きさです。しかし元素の本体は原子の中心にある原子核です。原子核の大きさは原子のさらに 10 万分の 1 ですから、まったく見ることは出来ません。たとえ見えなくても私たちは原子核が陽子（＋の電気を持つ）と中性子（電気を持たない）という 2 種類の粒子の塊であることを知っています。

私たちの体は星くずでできている

宇宙では常に元素合成を繰り返しています。宇宙誕生時には水素とヘリウムしかありませんでした。それから 3 億年ほどで星が誕生し、その星の内部や、星の爆発で原子番号が大きい元素は作られています。

…アングルカメラ
該当番号の解説図の視点を示しています。

1 2 原子核＝陽子＋中性子

原子核は陽子と中性子の集合体でできています。例えばヘリウム 4 は 2 つの陽子と 2 つの中性子からなり、ウラン 235 は 92 個の陽子と 143 個の中性子からなっています。陽子と中性子の数はそれぞれの原子核ごとに安定する値があり、そのバランスが崩れると原子核が壊れて別の原子核へと変化していきます。

3 4 原子核の崩壊―アルファ崩壊、ベータ崩壊

原子核はとても固く簡単には壊せません。しかし不安定核はより安定な原子核へと自らを変化させます。その際に起きる現象を「崩壊」と呼びます。崩壊にはアルファ（α）、ベータ（β）、ガンマ（γ）の 3 種類あります。α崩壊は左上図のように、原子核からヘリウム原子核（陽子 2、中性子 2）が飛び出す現象です。当然軽くなり原子番号が 2 つ減ります。また飛び出たヘリウム原子核をα線と呼びます。β崩壊は左下図のように、原子核内の中性子が陽子に変化する反応です。その時、電子と反ニュートリノを放出します。重さはほぼ変わりませんが、陽子がふえますから、原子番号が 1 つ増えます。飛び出た電子をβ線と呼びます。なお崩壊した直後の原子核は興奮して熱くなっています。これが冷える時に光を出します、この光をγ線と呼びます。

5 6 塊だけじゃない―色々な原子核

原子核には色々な形が存在することがわかっています。球状だけでなく、バナナ型やミカン型など様々です。特に上記に示した原子核は特徴的です。中性子スキンは過剰な中性子が原子核の外にしみ出して中性子だけの皮を作っています。中性子ハローはしみ出した中性子が大きく広がってしまい、おぼろげに存在します。

7 魔法数（マジックナンバー）

原子核の安定には陽子数と中性子数のバランスが大切です。それとともに、陽子・中性子が好む数字があり、これを魔法数と呼びます。今知られているのは 2、8、20、28、50、82、126 です。例えば、カルシウムは陽子数 20 ですから魔法数です。そのためバランスが崩れる程中性子が多くても、安定な原子核があるのが分かります。

8

本来、超重原子核は非常に不安定ですこのような離れた位置に安定核が存在すいとされています。このあたりに魔法数かわれているからです。周りは全て不安定原うになっていることから、安定の島と呼は

※1「核図表」: 誌面中央の核図表は都合で高さの違いが分かりにくいのですが、一般に「ハイゼンベルクの谷」は誌面左上図のように深い谷で表現します。なお、深い谷にすると内側が見えなくなってしまう... というのが都合です。

※2,3「陽子」「中性子」: 原子核はほぼ同じ重さの 2 種類の粒子で出来ています。プラス電荷を持つのが陽子、電荷を持たないのが中性子です。通常は原子核は電子で取り囲まれていて、その電子はマイナス電荷を持ち重さは陽子の約 2000 分の 1 という軽さです。

※4:「同位元素」: 同位体ともいいます。同位元素には放射性崩壊を起こす「放射性同位元素」(RI) と、崩壊しない「安定同位元素」とがあります。

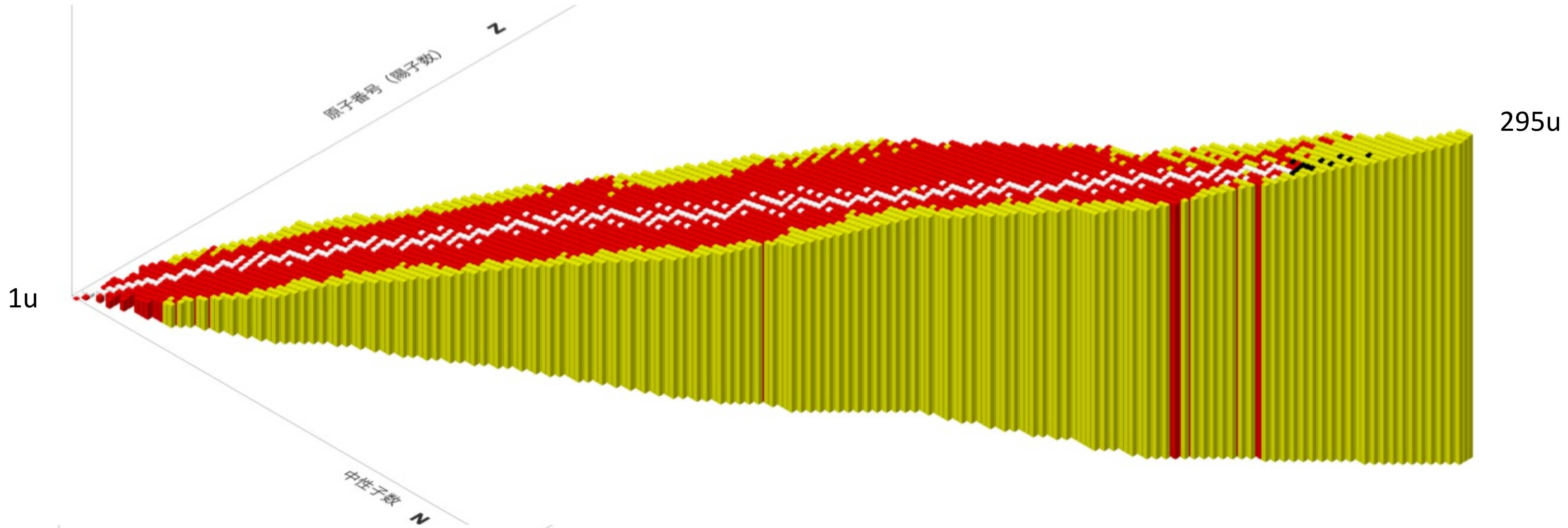
※5「ハイゼンベルク」: ドイツの理論物理学者、ヴェルナー・カール・ハイゼンベルク。行列力学と不確定性原理によって量子力学を完成させた一人です。

※6「安定核」: 崩壊しない原子核のことを安定核といいます。ただし、ウランなどのように半減期が地球の年齢よりも長く採掘も可能なものは、この表では安定核としています。

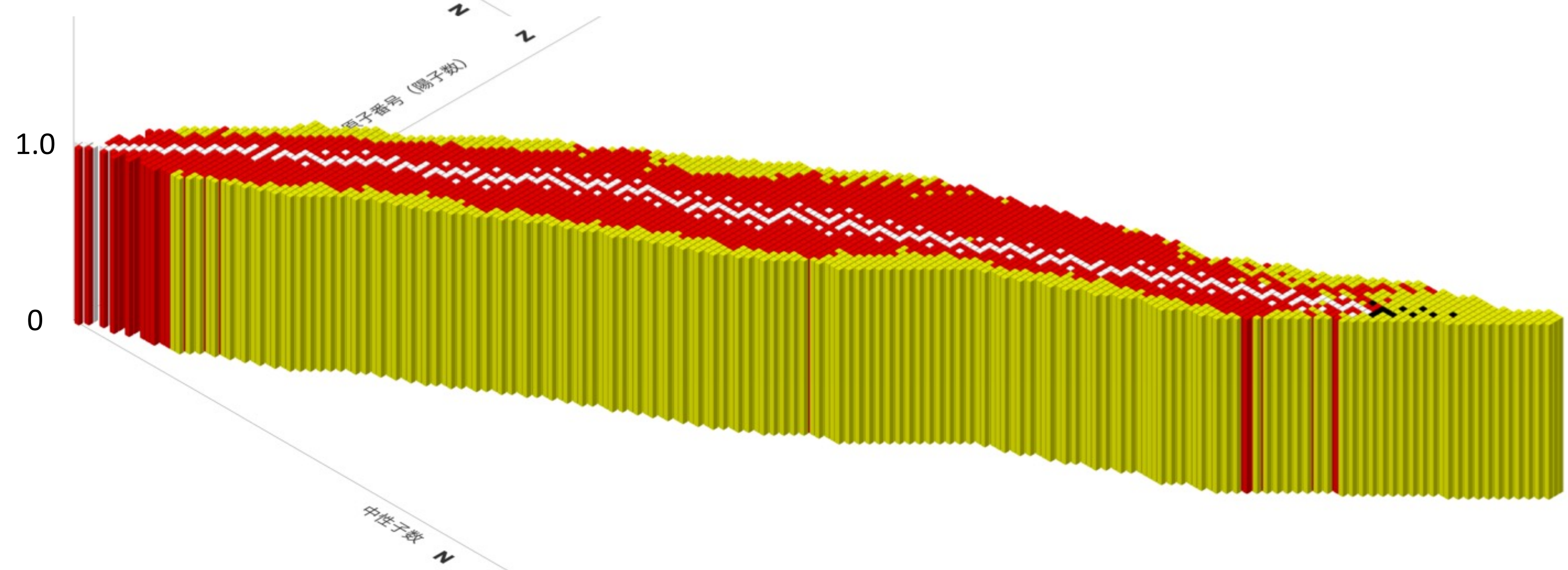
※7「結合エネルギー」: 陽子と中性子がバラバラではなく、結合し原子核になったときに失われるエネルギーを結合エネ

Poster of a laboratory

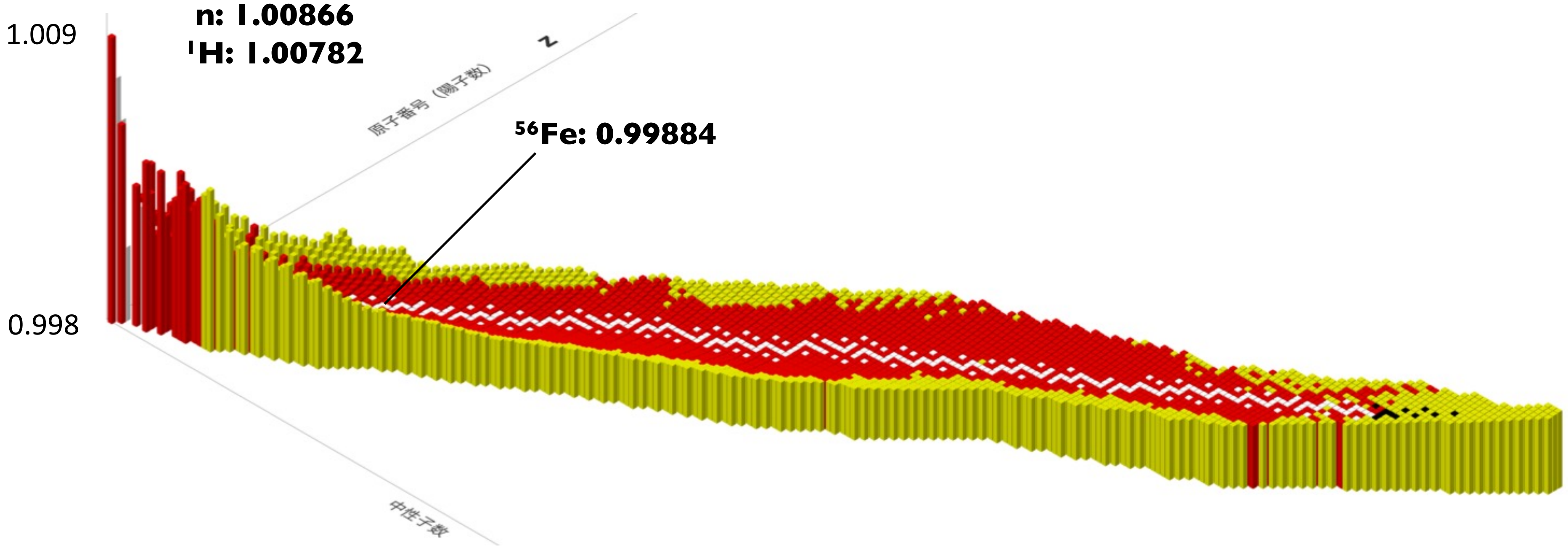
mass



mass/A



Expand m/A=1.0

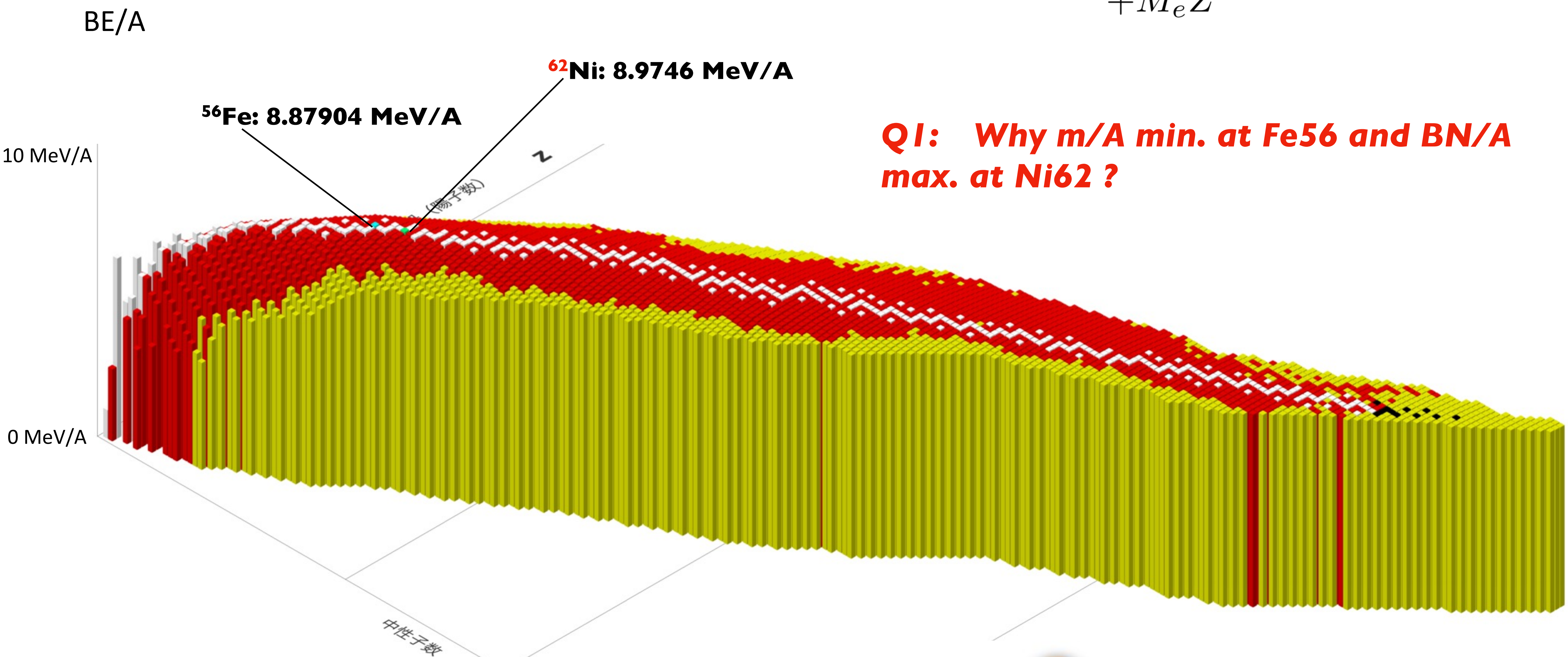


n: 1.00866
^{1}H: 1.00782

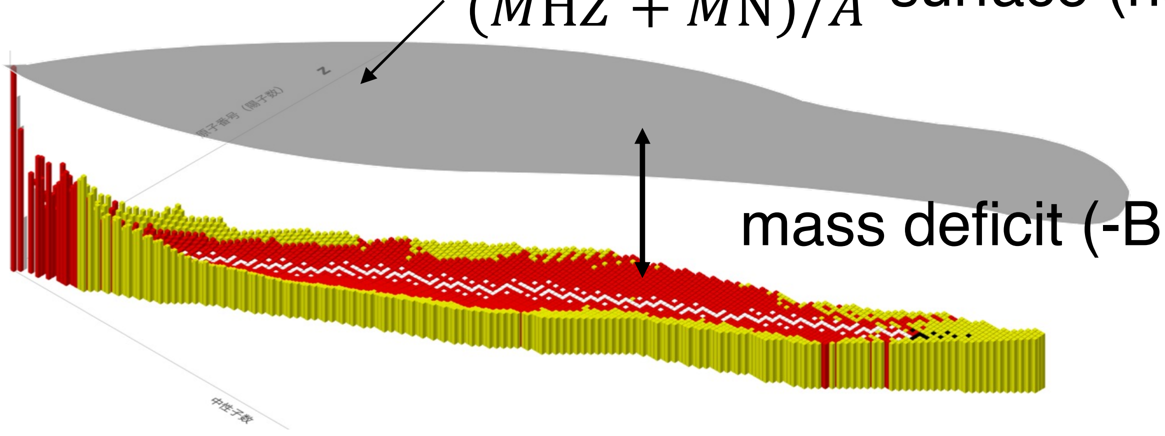
^{56}Fe: 0.99884

What is the Binding Energy(BE)?

$$B_{Z,N} = M_p Z + M_n N - M_{Z,N} + M_e Z$$

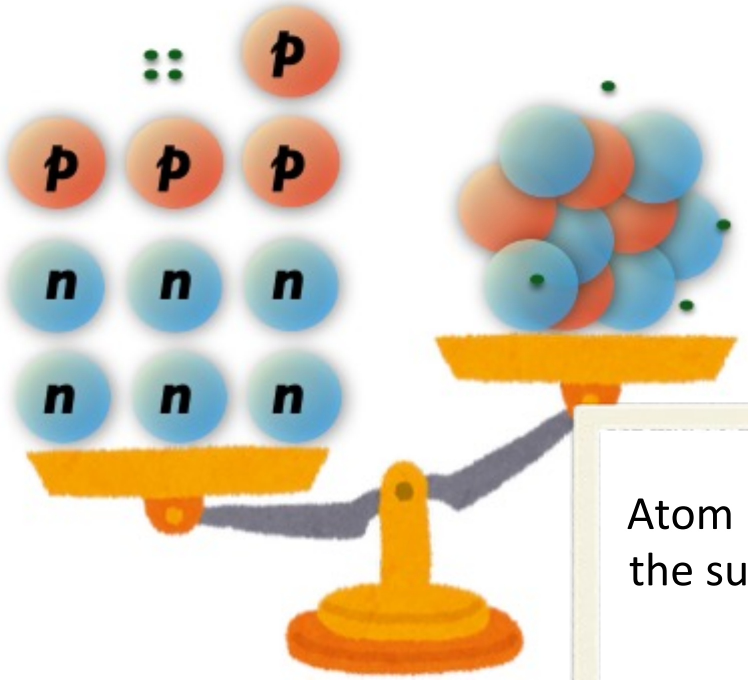


Q1: Why m/A min. at Fe56 and BN/A max. at Ni62 ?



$(MHZ + MN)/A$ surface (not flat)

mass deficit (-BN)



Atom is ~1% lighter than the sum of constituents: Mass deficit

What is the difference of mass deficit & mass excess?

Chat GPT 2023

Mass Deficiency and Mass Excess are terms used in the context of nuclear physics.

Mass deficiency refers to the phenomenon where an atomic nucleus is lighter than the sum of the masses of its constituent particles (protons and neutrons). This is because the nucleus possesses binding energy, and energy and mass are mutually convertible. Mass deficiency is explained based on

E=mc2 (Einstein's mass-energy equivalence).

~~**Mass excess** refers to the situation where **the actual mass of an atomic nucleus is greater than the sum of the masses** of the protons and neutrons that make it up. This excess mass indicates that the nucleus possesses binding energy.~~

Chat GPT 2024/7/30

Mass Deficit

Definition: The mass deficit of a nucleus is the difference between the total mass of its individual protons and neutrons (when they are free and not bound in the nucleus) and the actual mass of the nucleus.

Mass Excess

Definition: The mass excess of a nucleus is the difference between the actual mass of the nucleus and its mass number (A) expressed in atomic mass units (u).

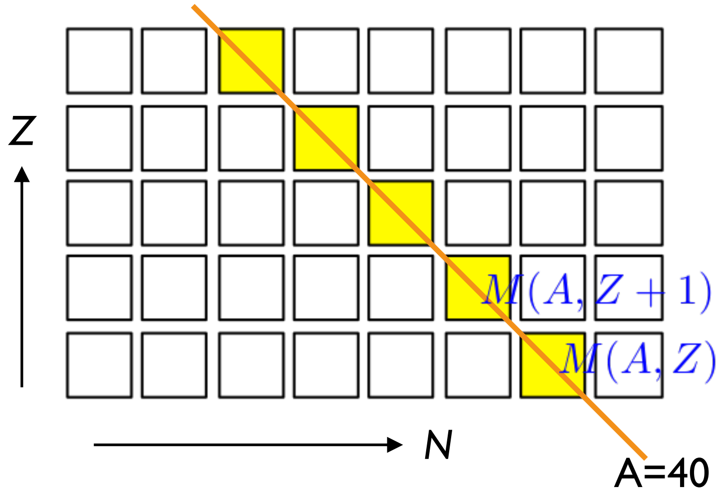
Mass excess is just for convenience.

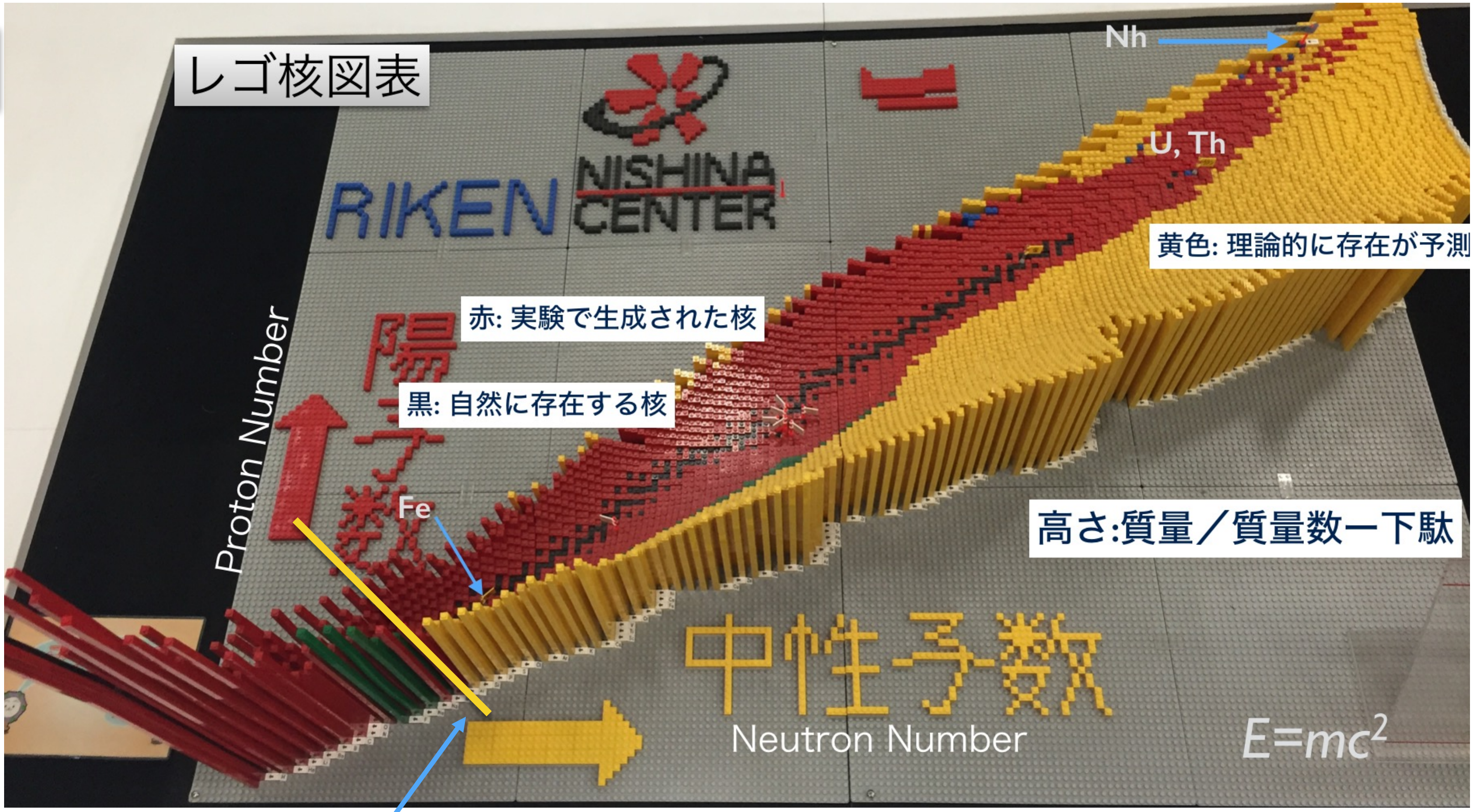
m(^{238}U)= 238. 0507869(16) u   ME(^{238}U)=0.0507869(16) u   or ME(^{238}U)=47307.7(1.5) keV

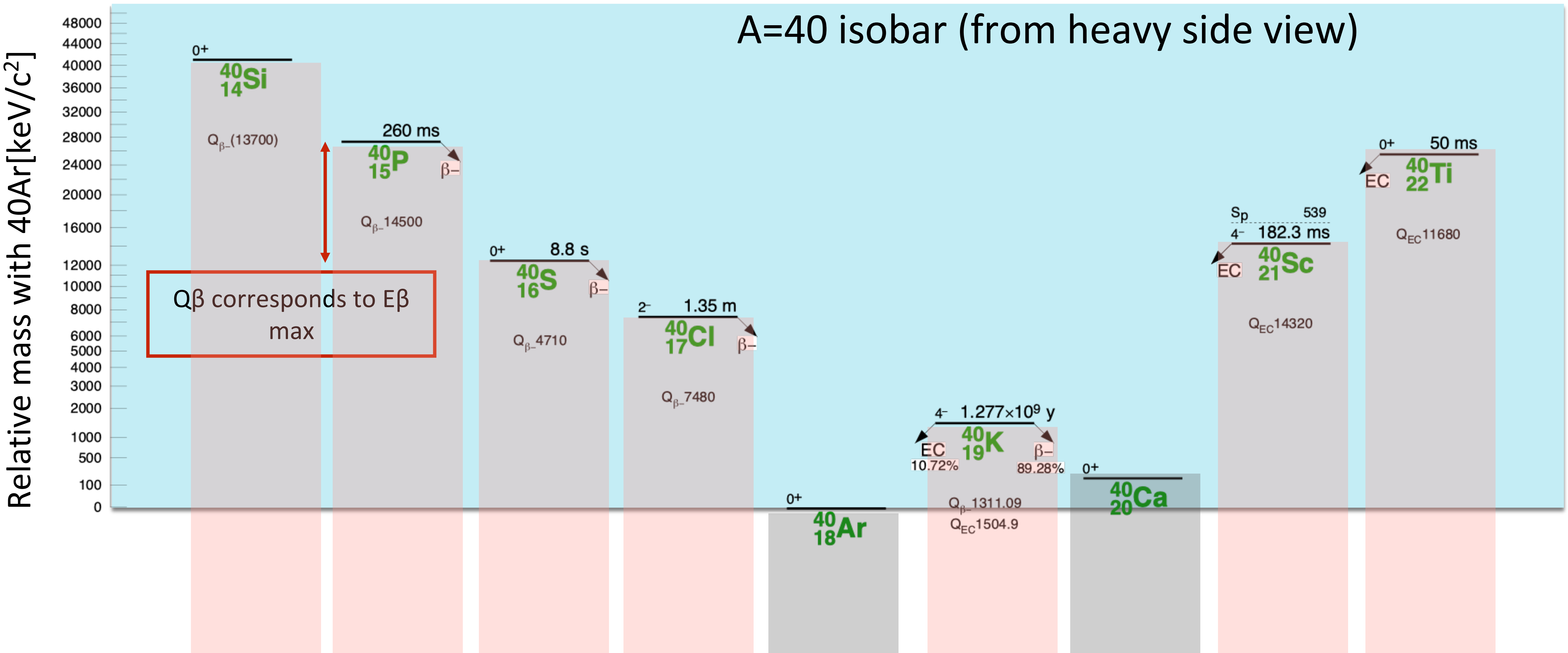
Comparison with neighborhood

in isobar : beta stability

$$Q_{\beta^-} = M(A,Z) - M(A,Z+1)$$






A=40 isobar (from heavy side view)

Qβ corresponds to Eβ max

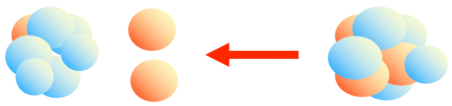
Comparison with neighborhood 2

separation energies

$$S_p = M(N, Z-1) + M_p - M(N, Z)$$

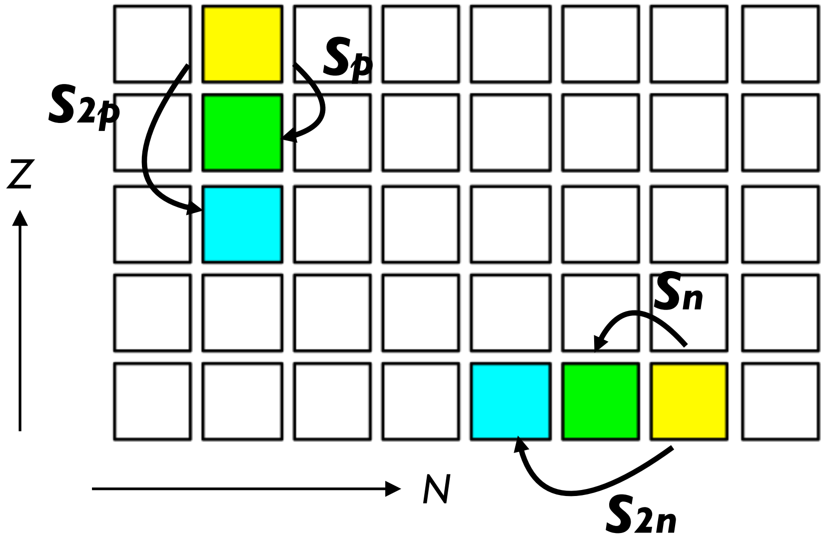
proton separation energy

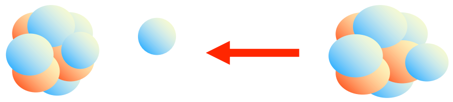
Separation energy = 0: Drip line



$$S_{2p} = M(N, Z-2) + 2M_p - M(N, Z)$$

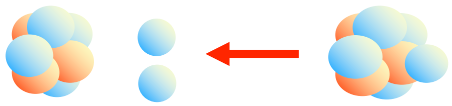
two proton separation energy





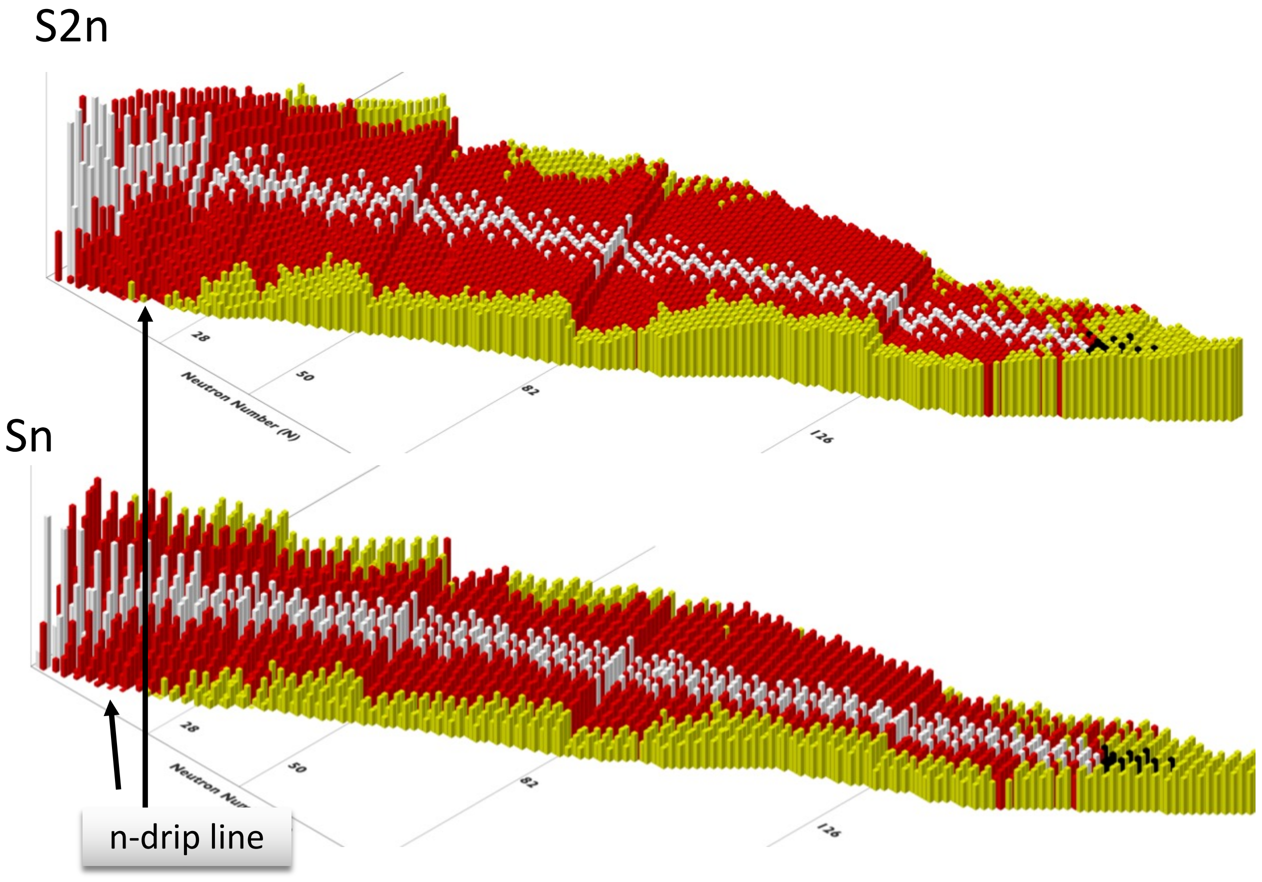
$$S_n = M(N-1.Z) + M_n - M(N, Z)$$

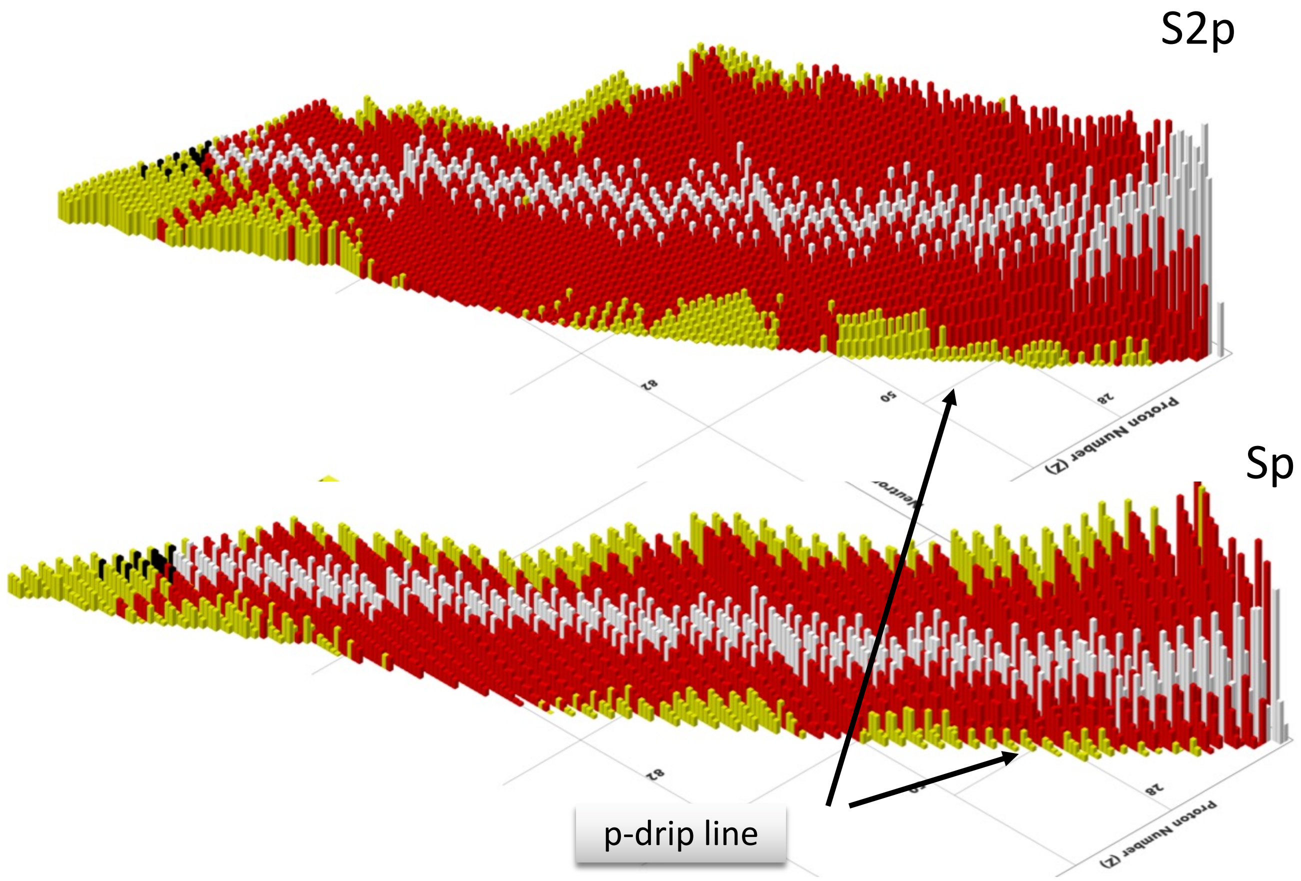
neutron separation e.



$$S_{2n} = M(N-2, Z) + 2M_n - M(N, Z)$$

two neutron sep. e.





r-process

Nuclides in Solar System

~83 elements、~255 nuclides

W. Fowler et al,1957
(Nobel prize in 1983)

s-process

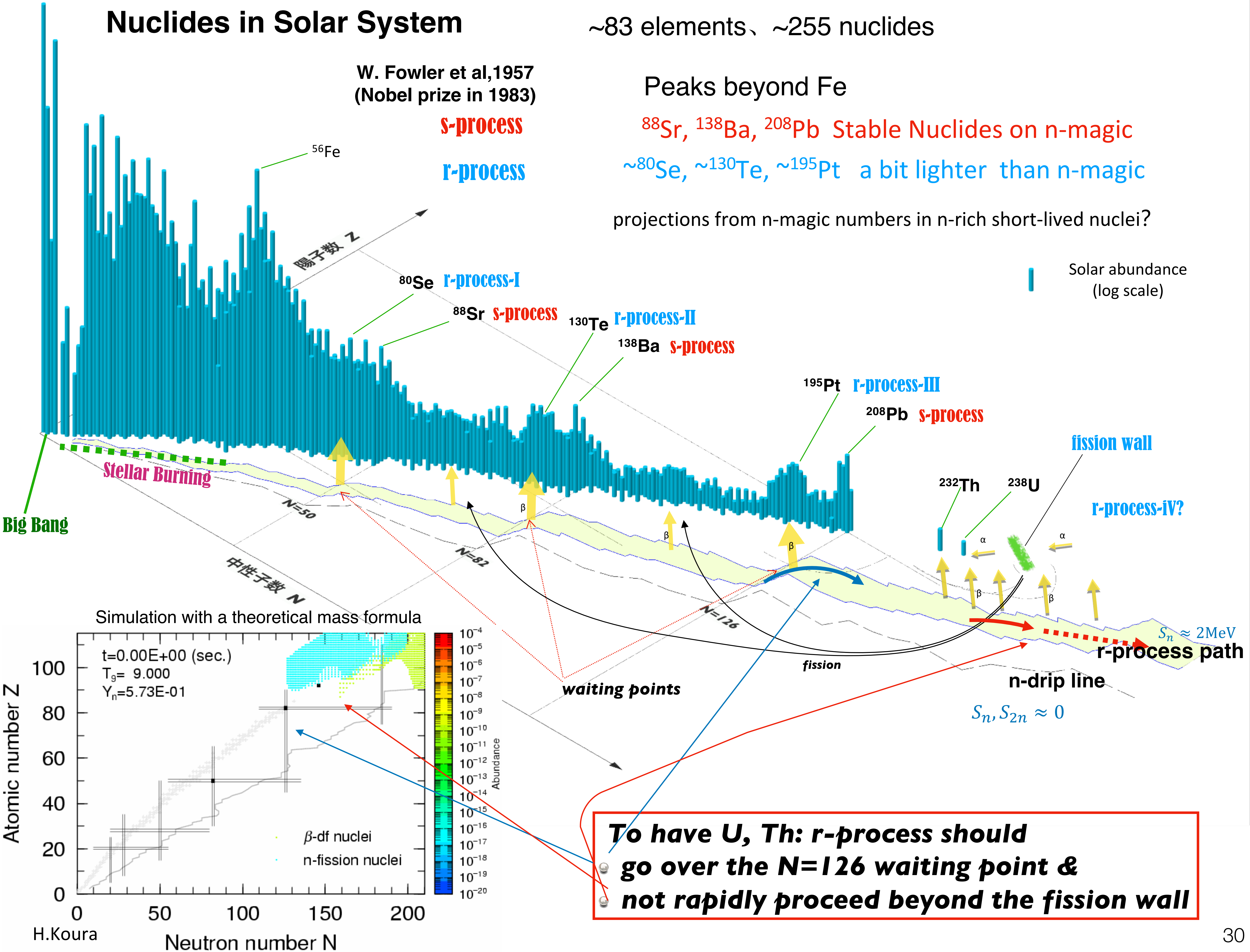
r-process

Peaks beyond Fe

^{88}Sr, ^{138}Ba, ^{208}Pb Stable Nuclides on n-magic

~^{80}Se, ~^{130}Te, ~^{195}Pt a bit lighter than n-magic

projections from n-magic numbers in n-rich short-lived nuclei?



To have U, Th: r-process should
- ***go over the N=126 waiting point &***
- ***not rapidly proceed beyond the fission wall***

r-process (equilibrium model)

High Temp.

1) $(\mathrm{n},\gamma) \leftrightarrow (\gamma,\mathrm{n})$ equilibrium

$$\frac{Y(Z,A+1)}{Y(Z,A)} \propto \rho_{\mathrm{n}} \exp\frac{S_{\mathrm{n}}(Z,A+1)}{kT}$$

Sn (Mass) is essential

2) β^{-}decay (Z=Z+1)

$T_{1/2}$ is essential

Clearing up

non-equilibrium, intermediate

(A=A+1, A-1)

S_n, σ_n

cross sections appear

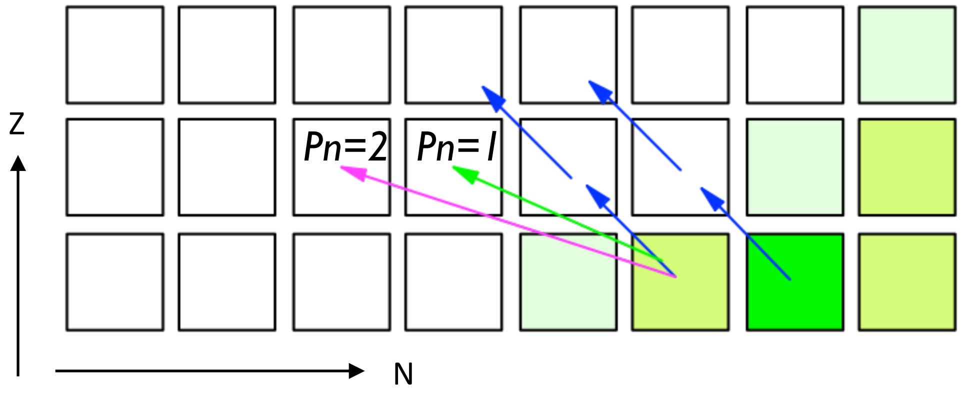
Cool down

β-Decay (Z=Z+1)

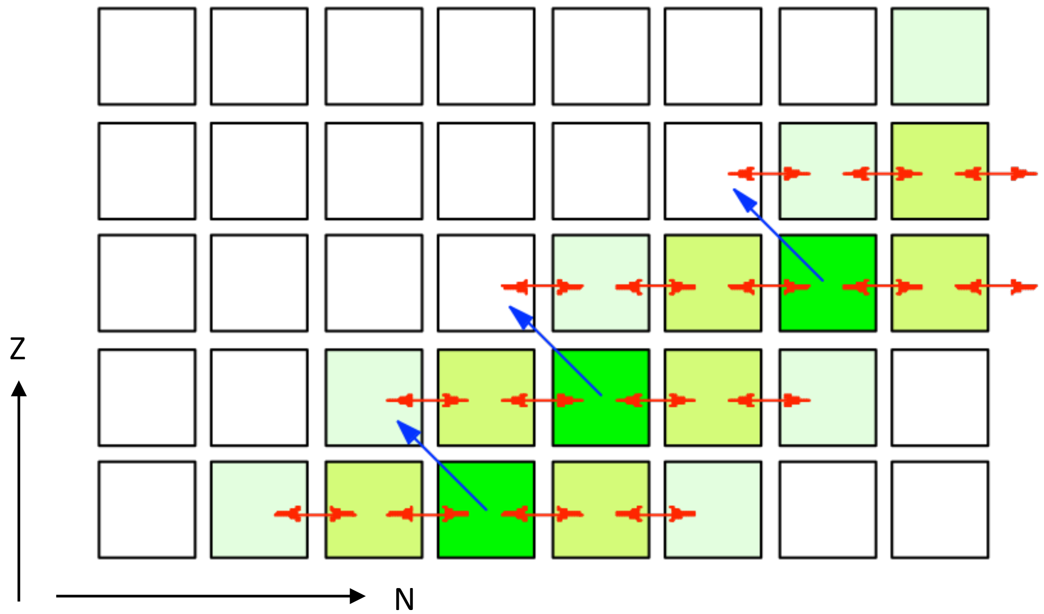
(A=A, A-1, A-2)

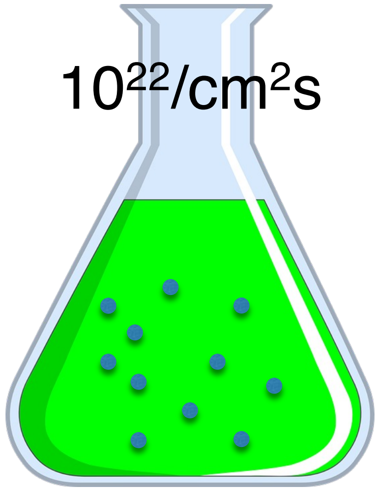
β-delayed neutron

P_{n}



β-decay toward stable preserving A,
(If n-emissions occur, shift to A-1, A-2…)





⟷ $(\mathrm{n},\gamma) \leftrightarrow (\gamma,\mathrm{n})$

↖ β^{-}decay (Z=Z+1)

In equilibrium, abundance is given by Sn and Temp.
(Chemical process with neutron water)

$$\exp\frac{\mu}{kT}$$

chemical potential μ

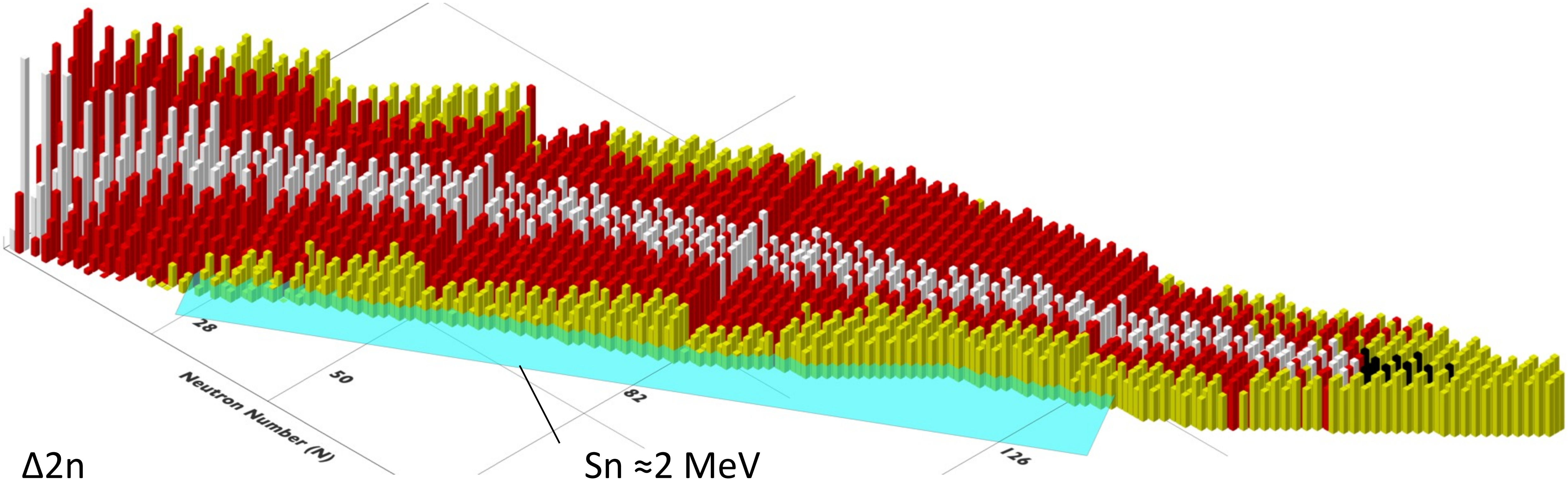
↓

neutron separation energy Sn

Sn ~ 2 MeV is the r-process path

r-process path and waiting point (neutron-magic)

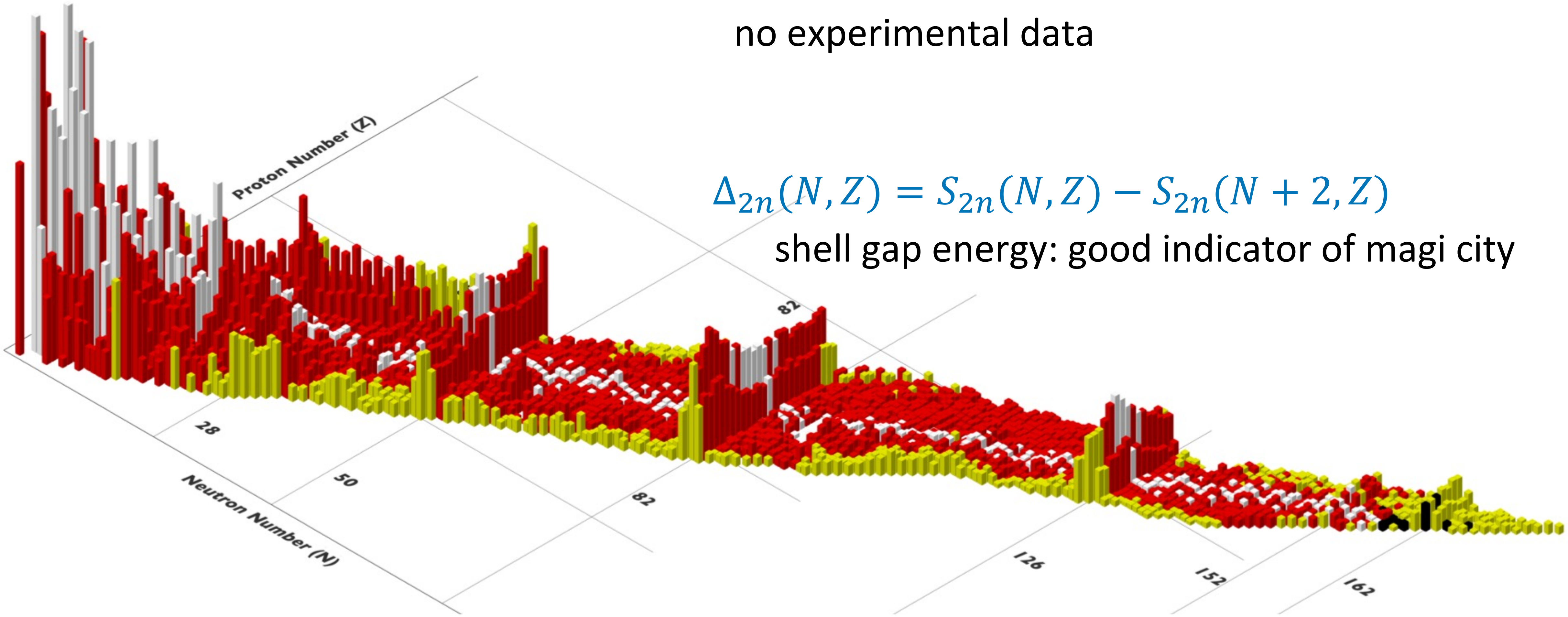
Sn



Sn ≈2 MeV

no experimental data

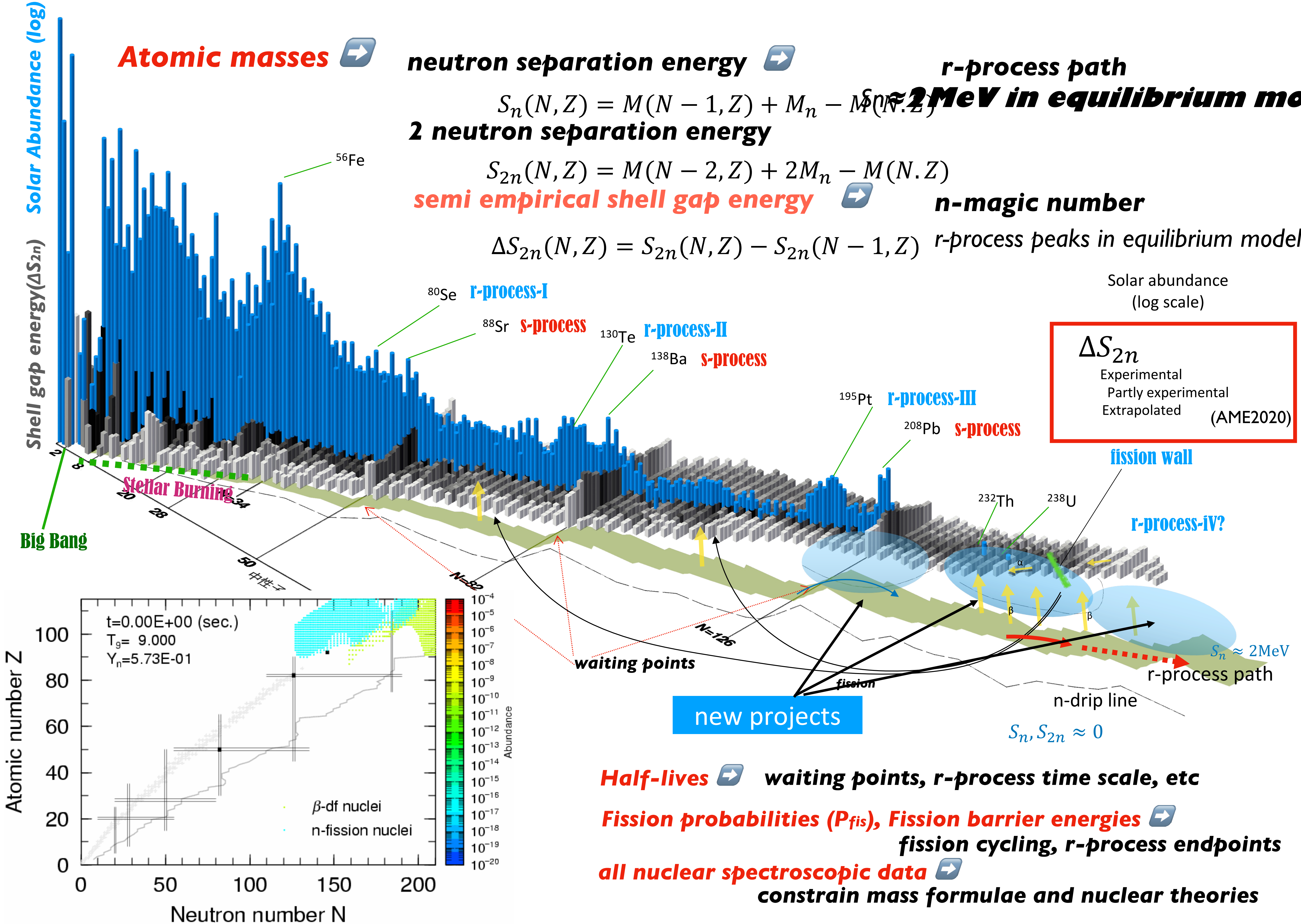
Δ2n



$$\Delta_{2n}(N,Z) = S_{2n}(N,Z) - S_{2n}(N+2,Z)$$

shell gap energy: good indicator of magi city

Solar abundances and atomic masses (ΔS_{2n})



Atomic masses

neutron separation energy

$$S_n(N,Z) = M(N-1,Z) + M_n - M(N.Z)$$

r-process path

S_n≈2MeV in equilibrium mo

2 neutron separation energy

$$S_{2n}(N,Z) = M(N-2,Z) + 2M_n - M(N.Z)$$

semi empirical shell gap energy

n-magic number

$$\Delta S_{2n}(N,Z) = S_{2n}(N,Z) - S_{2n}(N-1,Z)$$

r-process peaks in equilibrium model

new projects

Half-lives ***waiting points, r-process time scale, etc***

Fission probabilities (P_{fis}), Fission barrier energies

fission cycling, r-process endpoints

all nuclear spectroscopic data

constrain mass formulae and nuclear theories

r-process　dynamic calculation

Thomas Rauscher, Essentials for Nucleosynthesis and Thoretical Nuclear Astrophysics, Iop Publishing Ltd, (2020)

n-capture　　　　photo dissociation

$$\frac{dY_{Z,N}}{dt} = \rho N_{\mathrm{A}} Y_{\mathrm{n}} \langle\sigma v\rangle^{(\mathrm{n},\gamma)}_{Z,N-1} Y_{Z,N-1} - \rho N_{\mathrm{A}} Y_{\mathrm{n}} \langle\sigma v\rangle^{(\mathrm{n},\gamma)}_{Z,N} Y_{Z,N} + \lambda^{(\gamma,\mathrm{n})}_{Z,N+1} Y_{Z,N+1} - \lambda^{(\gamma,\mathrm{n})}_{Z,N} Y_{Z,N}$$

$$+ \sum_{k_{\mathrm{n}}\geq 0} \lambda^{\beta,k_{\mathrm{n}}}_{Z-1,N+1+k_{\mathrm{n}}} Y_{Z-1,N+1+k_{\mathrm{n}}} - \sum_{k_{\mathrm{n}}\geq 0} \lambda^{\beta,k_{\mathrm{n}}}_{Z,N} Y_{Z,N}$$

β-decay, β-delayed neutron

$$+ \rho N_{\mathrm{A}} Y_{\mathrm{n}} \sum_{Z',N'} \sum_{k_{\mathrm{n}}\geq 0} \langle\sigma v\rangle^{\mathrm{nf},Z,N,k_{\mathrm{n}}}_{Z',N'} Y_{Z',N'} - \rho N_{\mathrm{A}} Y_{\mathrm{n}} \sum_{k_{\mathrm{n}}\geq 0} \langle\sigma v\rangle^{\mathrm{nf},k_{\mathrm{n}}}_{Z,N} Y_{Z,N}$$

n-induced fission

$$+ \sum_{Z',N'} \sum_{k_{\mathrm{n}}\geq 0} \lambda^{\beta\mathrm{df},Z,N,k_{\mathrm{n}}}_{Z',N'} Y_{Z',N'} - \sum_{k_{\mathrm{n}}\geq 0} \lambda^{\beta\mathrm{df},k_{\mathrm{n}}}_{Z,N} Y_{Z,N}\,,$$

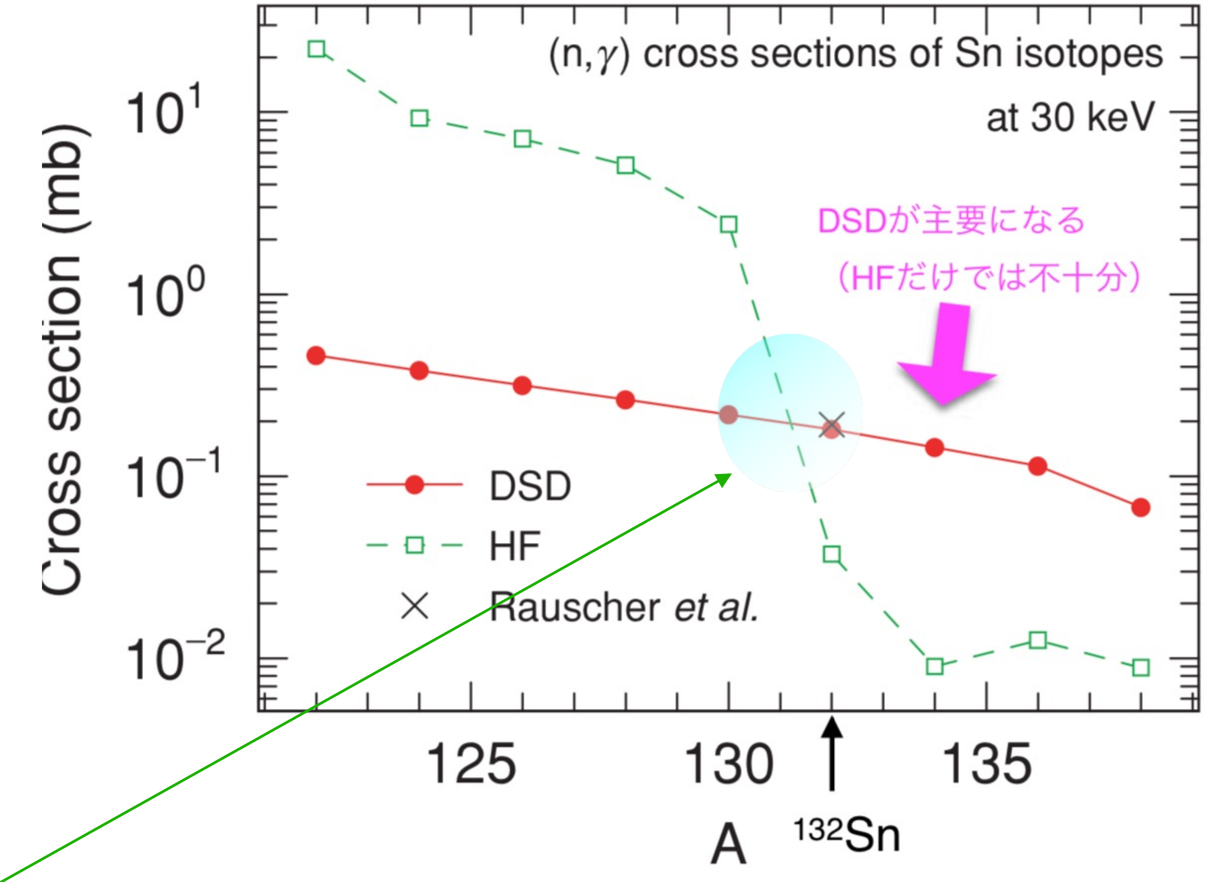
β-delayed fission

$< \sigma v >$ calculation required

σ：Hauser-Feshbach statistical model
Direct-semi-direct reaction (DSD) etc

v：　sensitive to resonant state

Mass is essential, but not only mass



DSDが主要になる
（HFだけでは不十分）

Sn: rapid decrease observed

S.Chiba, H. Koura, T. Hayakawa, T, Kawano *et al.*, PRC**77** 015809 (2008)

●単一粒子準位計算はmodified WS pot (Koura, Yamada, 2000))より

https://www2.yukawa.kyoto-u.ac.jp/~rp2019/slides/190523_09_koura.pdf

A big news in 2017

gravitation wave from n-star merger

金やプラチナ大量生成　中性子星合体の重力波観測で (2017/10/17 11:55)

「中性子星」と呼ばれる重力の強い星と星が衝突して合体したことを重力波と光で観測することに成功したとアメリカなどの研究チームが発表しました。世界初の快挙です。

アメリカなどの研究チームは今年8月、地球から1億3000万光年離れた宇宙で、2つの中性子星が衝突して合体した際に生じた重力波を観測しました。この観測を受け、国立天文台など日本の研究チームは衝撃で生じた光を半月にわたって観測しました。この光を分析した結果、中性子星の合体により、金やプラチナなどの重元素が大量に作られたことが分かったということです。

They observe the moment of Au, Pt are born

IEW LETTERS

week ending
20 OCTOBER 2017

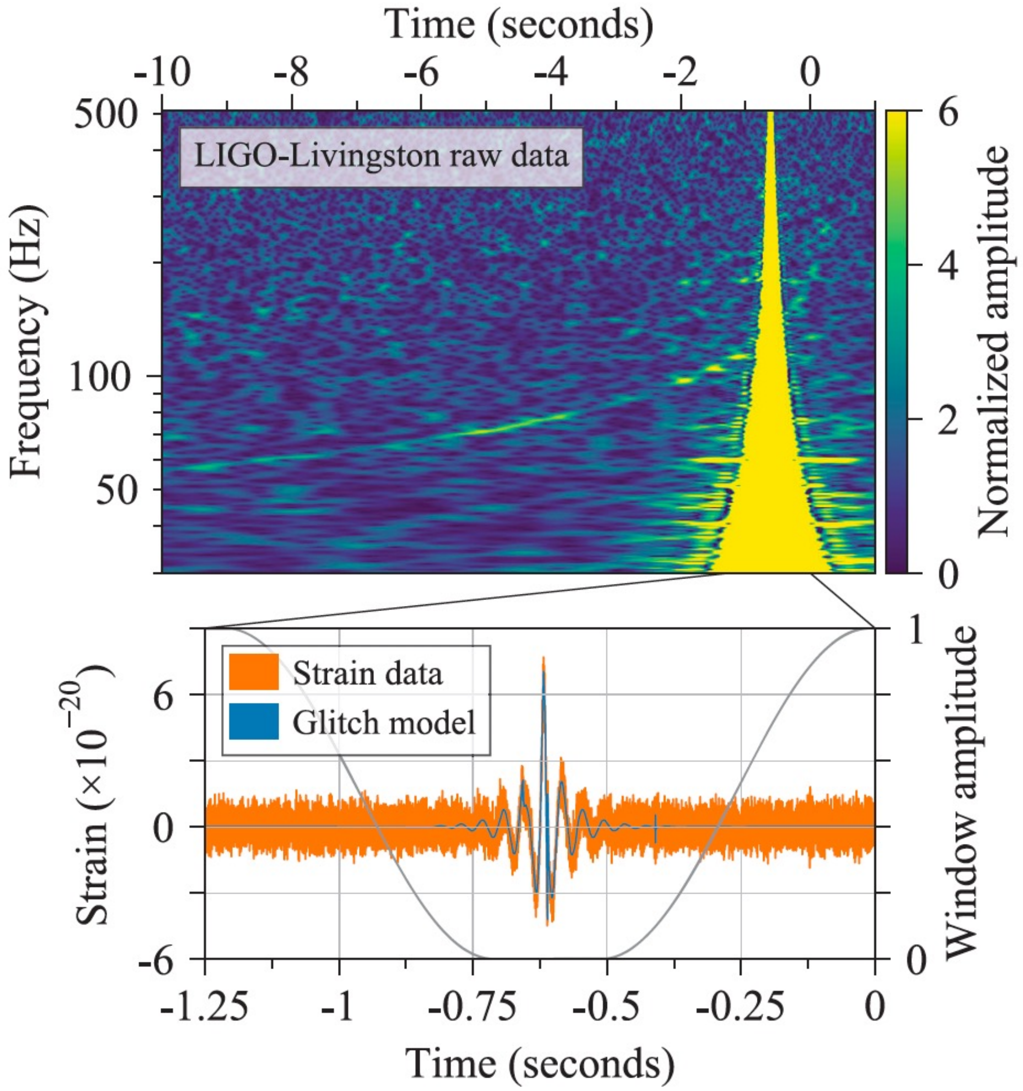
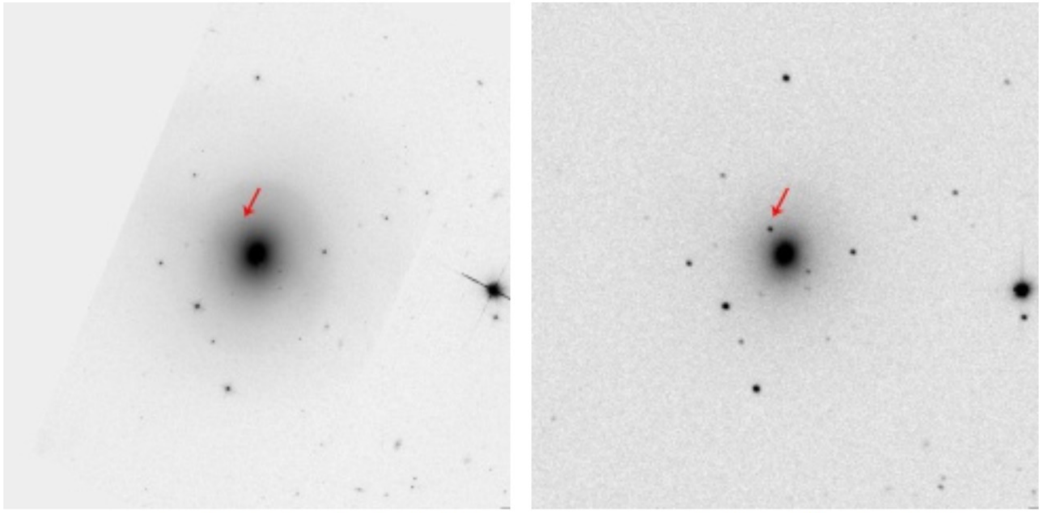


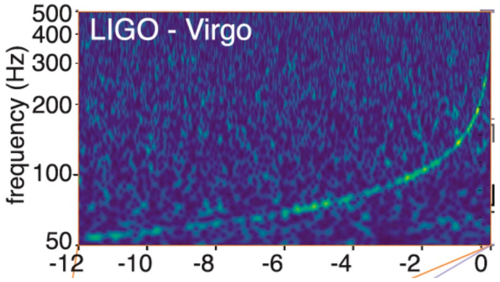
FIG. 2. Mitigation of the glitch in LIGO-Livingston data. Times

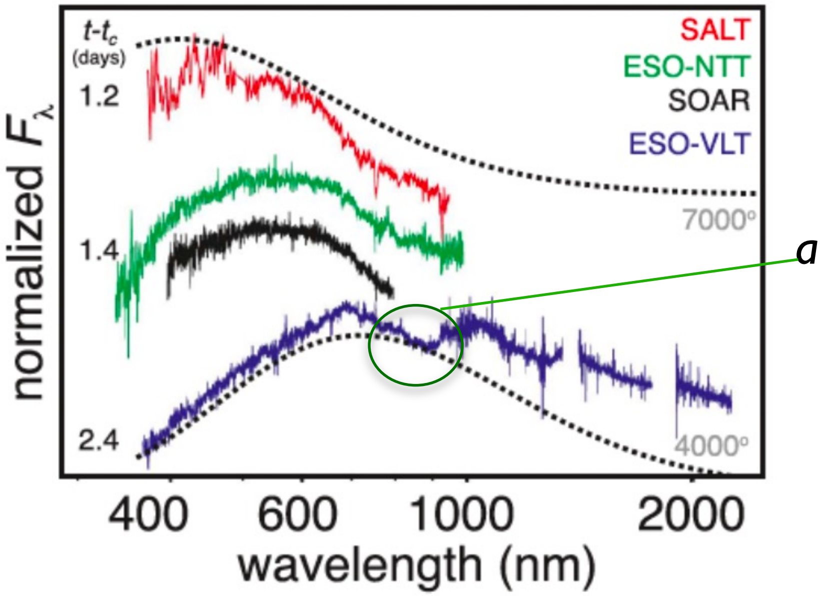


[画像のクリックで拡大表示]　[画像のクリックで拡大表示]

新たな重力波が検出される4カ月前にハッブル宇宙望遠鏡がとらえた楕円形の銀河「NGC4993」（左）。一方、チリのスウォープ望遠鏡の画像（右）には、2017年8月に現れた明るい点が見える。（PHOTOGRAPH BY HUBBLE/STSCI (LEFT) AND

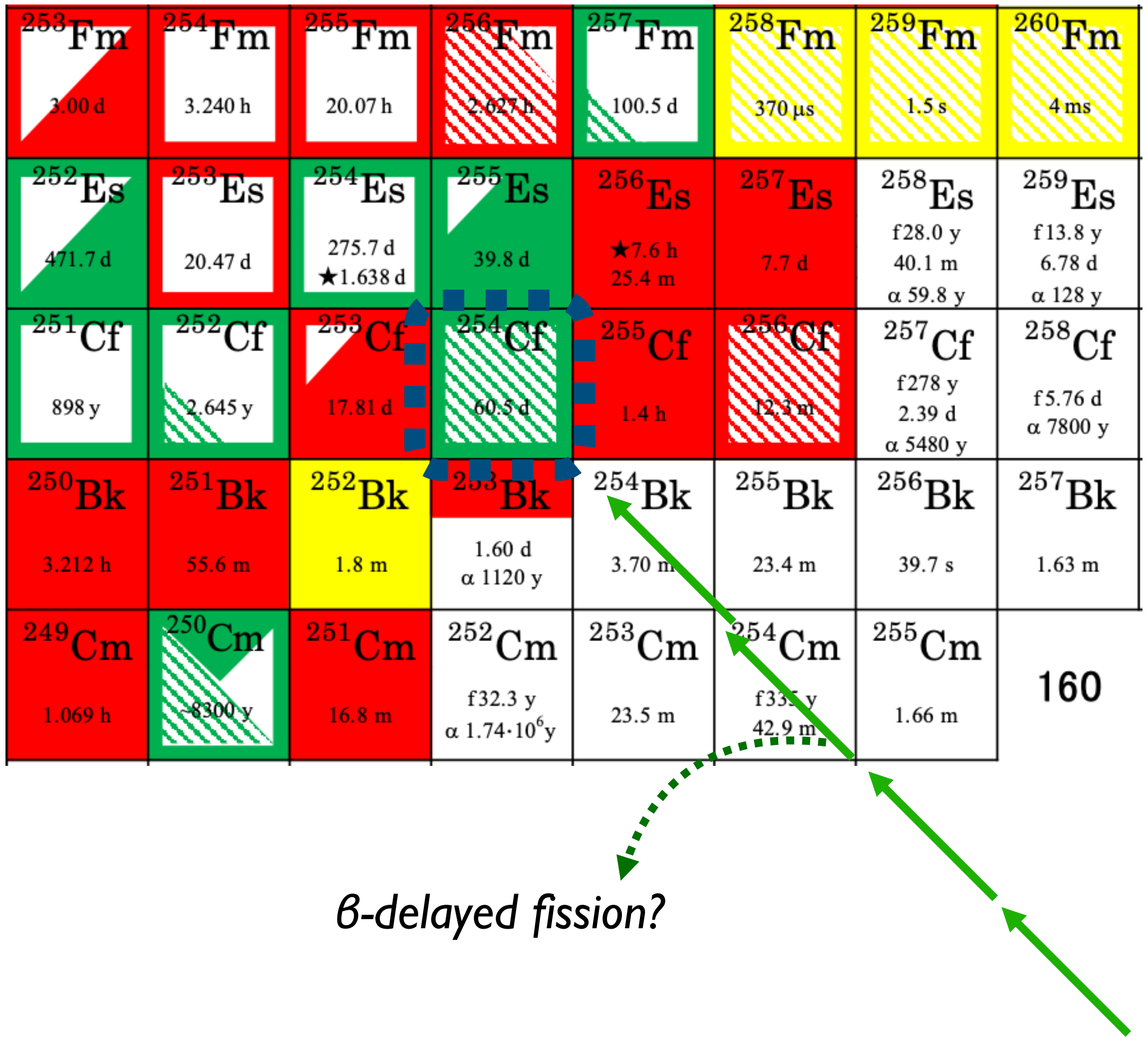
Multi-messenger astronomy after n-star merger





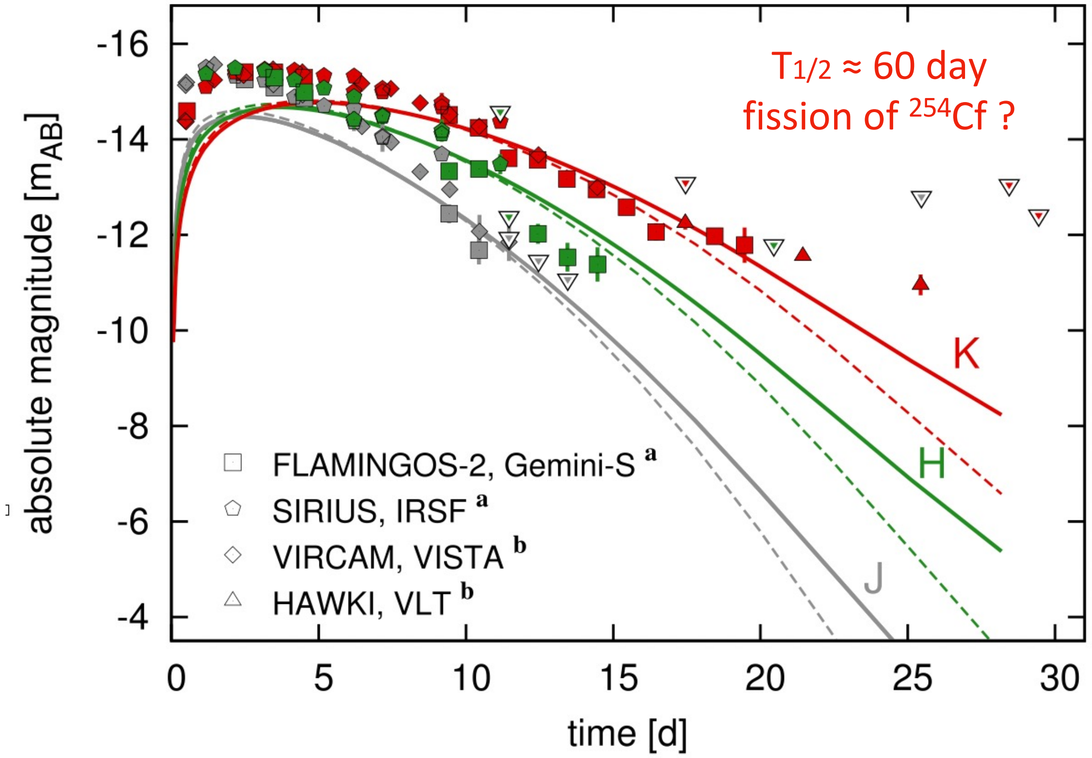
absorption of Sr II ?

Optical spectroscopy of remnant of NSM, kilo nova (r-process nova), wavelength, time profiles agree with predicted r-process !



^{253}Fm 3.00 d	^{254}Fm 3.240 h	^{255}Fm 20.07 h	^{256}Fm 2.627 h	^{257}Fm 100.5 d	^{258}Fm 370 µs	^{259}Fm 1.5 s	^{260}Fm 4 ms
^{252}Es 471.7 d	^{253}Es 20.47 d	^{254}Es 275.7 d ★1.638 d	^{255}Es 39.8 d	^{256}Es ★7.6 h 25.4 m	^{257}Es 7.7 d	^{258}Es f28.0 y 40.1 m α 59.8 y	^{259}Es f13.8 y 6.78 d α 128 y
^{251}Cf 898 y	^{252}Cf 2.645 y	^{253}Cf 17.81 d	^{254}Cf 60.5 d	^{255}Cf 1.4 h	^{256}Cf 12.3 m	^{257}Cf f278 y 2.39 d α 5480 y	^{258}Cf f5.76 d α 7800 y
^{250}Bk 3.212 h	^{251}Bk 55.6 m	^{252}Bk 1.8 m	^{253}Bk 1.60 d α 1120 y	^{254}Bk 3.70 m	^{255}Bk 23.4 m	^{256}Bk 39.7 s	^{257}Bk 1.63 m
^{249}Cm 1.069 h	^{250}Cm ~8300 y	^{251}Cm 16.8 m	^{252}Cm f32.3 y α $1.74 \cdot 10^6$y	^{253}Cm 23.5 m	^{254}Cm f335 y 42.9 m	^{255}Cm 1.66 m	160

β-delayed fission?



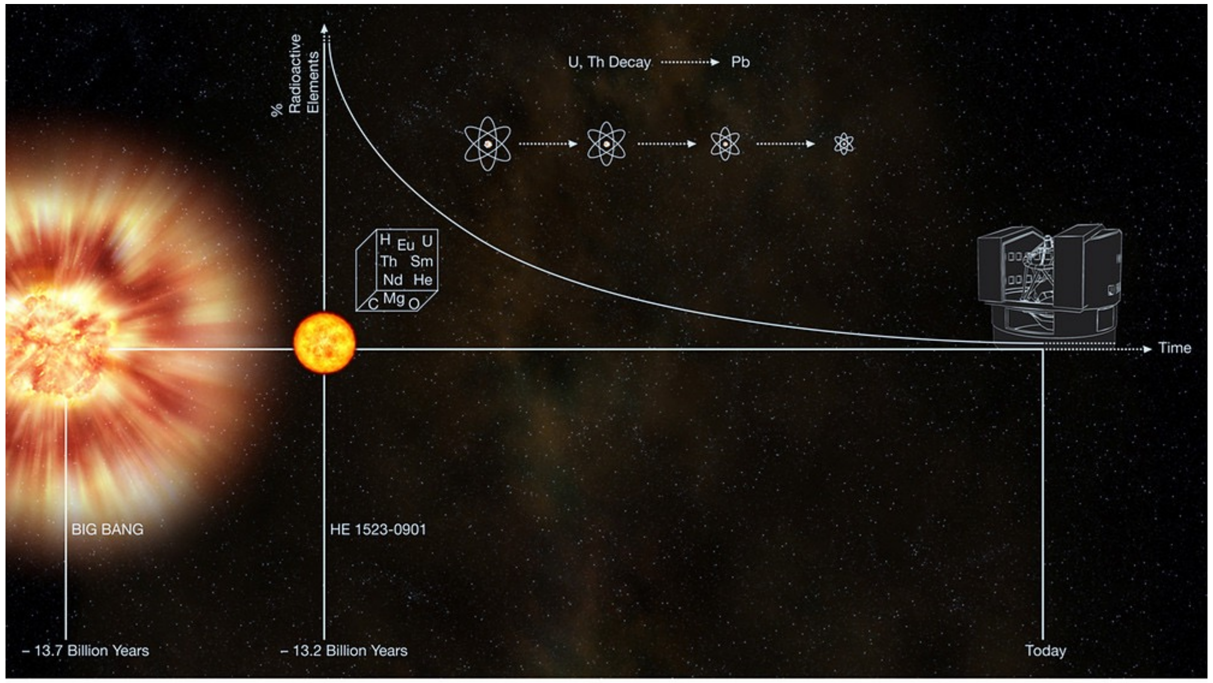
$T_{1/2} \approx 60$ day fission of ^{254}Cf ?

We will provide mass and decay properties of the progenitors of ^{254}Cf

Zhu et al. The Astrophysical Journal Letters, 863:L23 (6pp), 2018 August 20

Wanajo et al. The Astrophysical Journal Letters, 789:L39 (6pp), 2014 July 10 *predicted before NSM in 2017*

Cosmochronometry



The Cosmic Clock
(Artist's Impression)

ESO Press Photo 23a/07 (10 May 2007)

Using ^{232}Th ($T_{1/2}$=14.0 Gyr) and ^{238}U ($T_{1/2}$=4.47 Gyr)

age of a star can be:

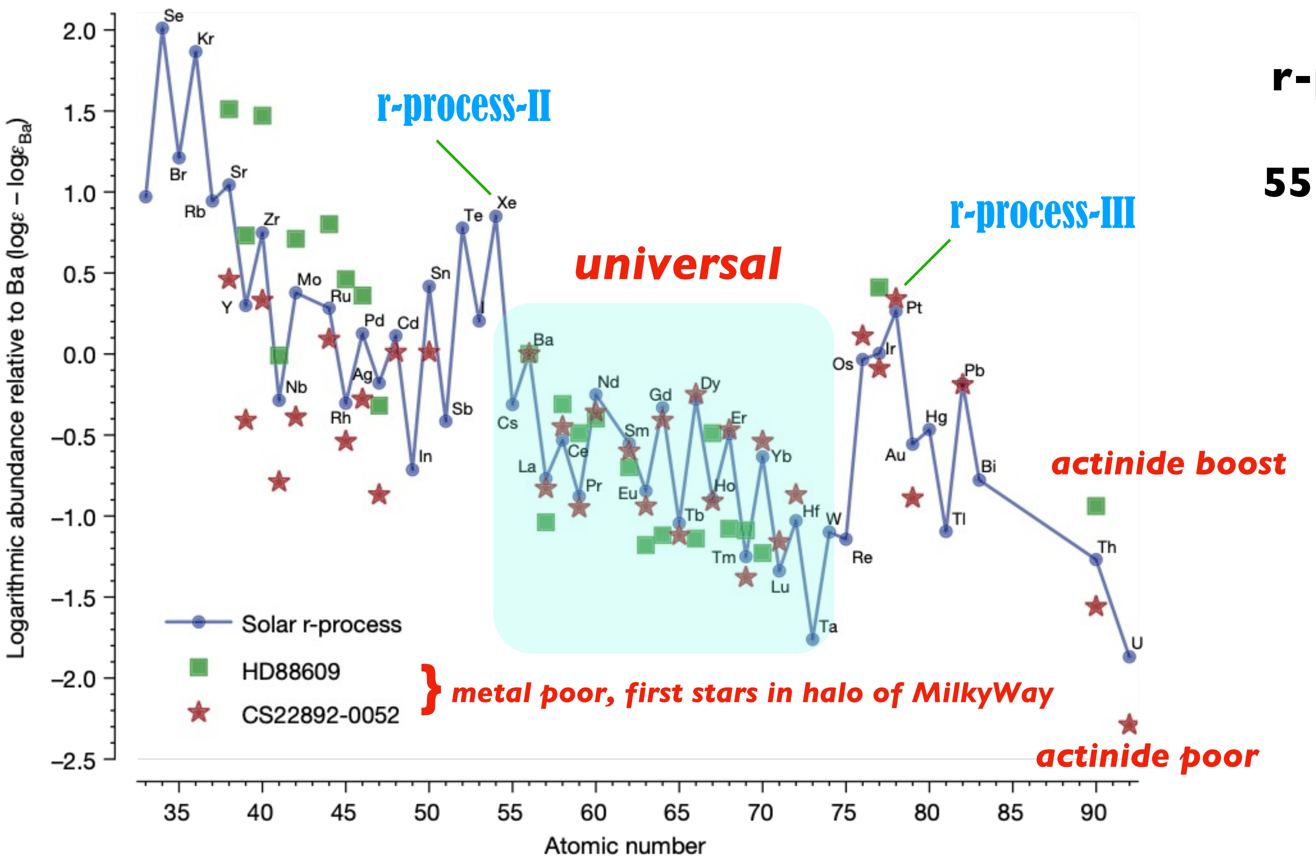
$$t = 46.67\mathrm{Gyr}[\boxed{\log(\mathrm{Th/Eu})_{\mathrm{init}}} - \log(\mathrm{Th/Eu}_{\mathrm{obs}}]$$
$$t = 14.83\mathrm{Gyr}[\boxed{\log(\mathrm{U/Eu})_{\mathrm{init}}} - \log(\mathrm{U/Eu}_{\mathrm{obs}}]$$
$$t = 21.80\mathrm{Gyr}[\boxed{\log(\mathrm{U/Th})_{\mathrm{init}}} - \log(\mathrm{U/Th}_{\mathrm{obs}}]$$

initial ratios are determined from r-process model

If we use bare theoretical mass formulae, the age can be varied
t > 14 Gyr (greater than the age of universe),
t < 0 Gyr (negative age !)

We will provide constraints for more accurate mass formulae

Universality? of r-process



Nature **574**, 497–500 (2019)

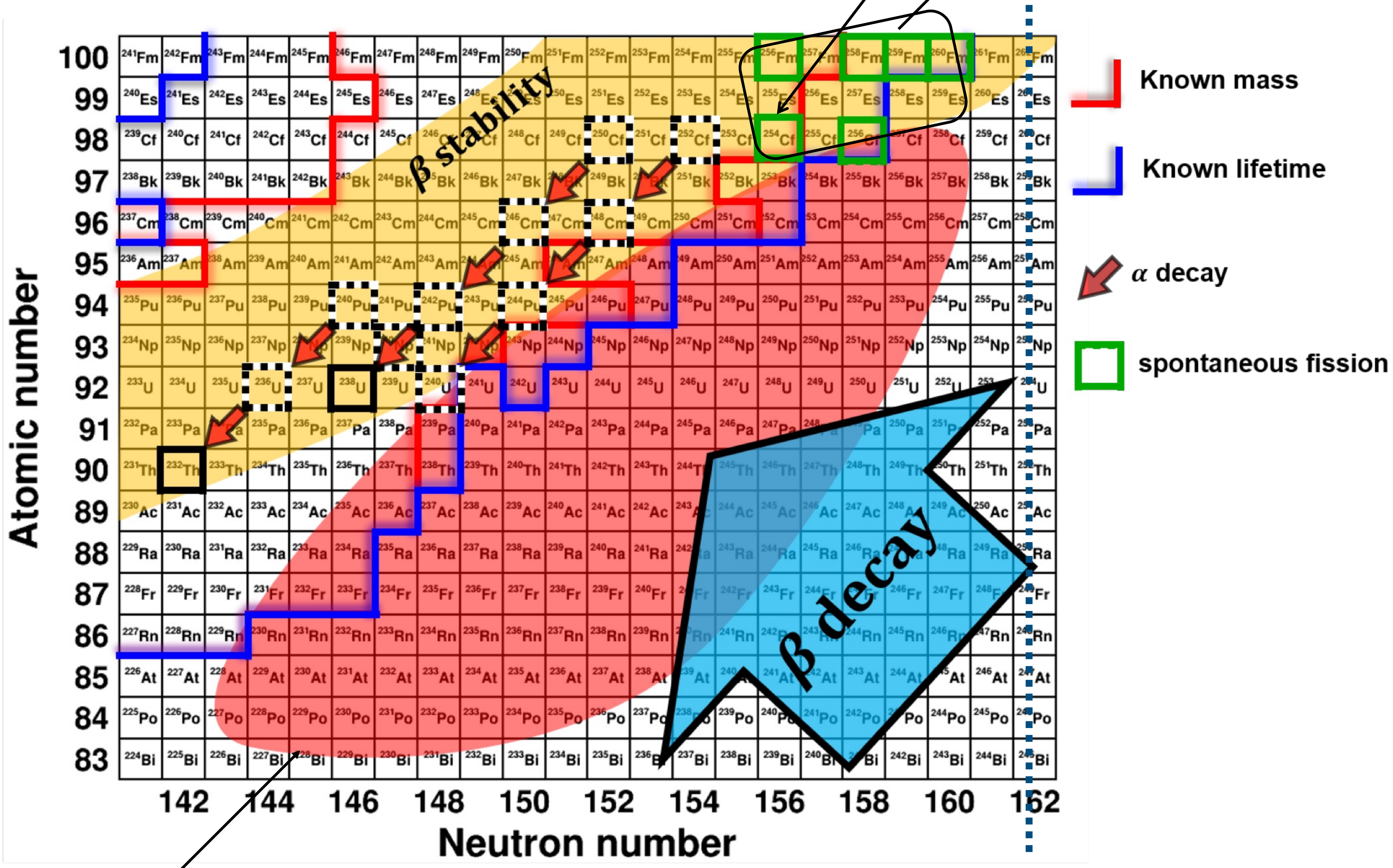
r-process has been considered to be "universal",

55 < A <75 is universal, but "actinide boost" and "actinide poor" stars are found in metal poor stars (first stars in halo of our galaxy)

- ***not all r-process go over N=126 waiting point?***
- ***some r-process rapidly proceed beyond fission wall?***
- ***part of 55<A<75 nuclides are considered to be from fission fragments, why they are universal?***

We will provide key experimental data

Pathways to Th, U



^{254}Cf

spontaneous fission wall

N=162 semi-magic number?

We will access these nuclides

KISS-II Design Report, 2021 Nov. 30

end of part I

part -II

Solar abundances and atomic masses (ΔS_{2n})

Atomic masses

neutron separation energy

$$S_n(N,Z) = M(N-1,Z) + M_n - M(N.Z)$$

2 neutron separation energy

$$S_{2n}(N,Z) = M(N-2,Z) + 2M_n - M(N.Z)$$

semi empirical shell gap energy

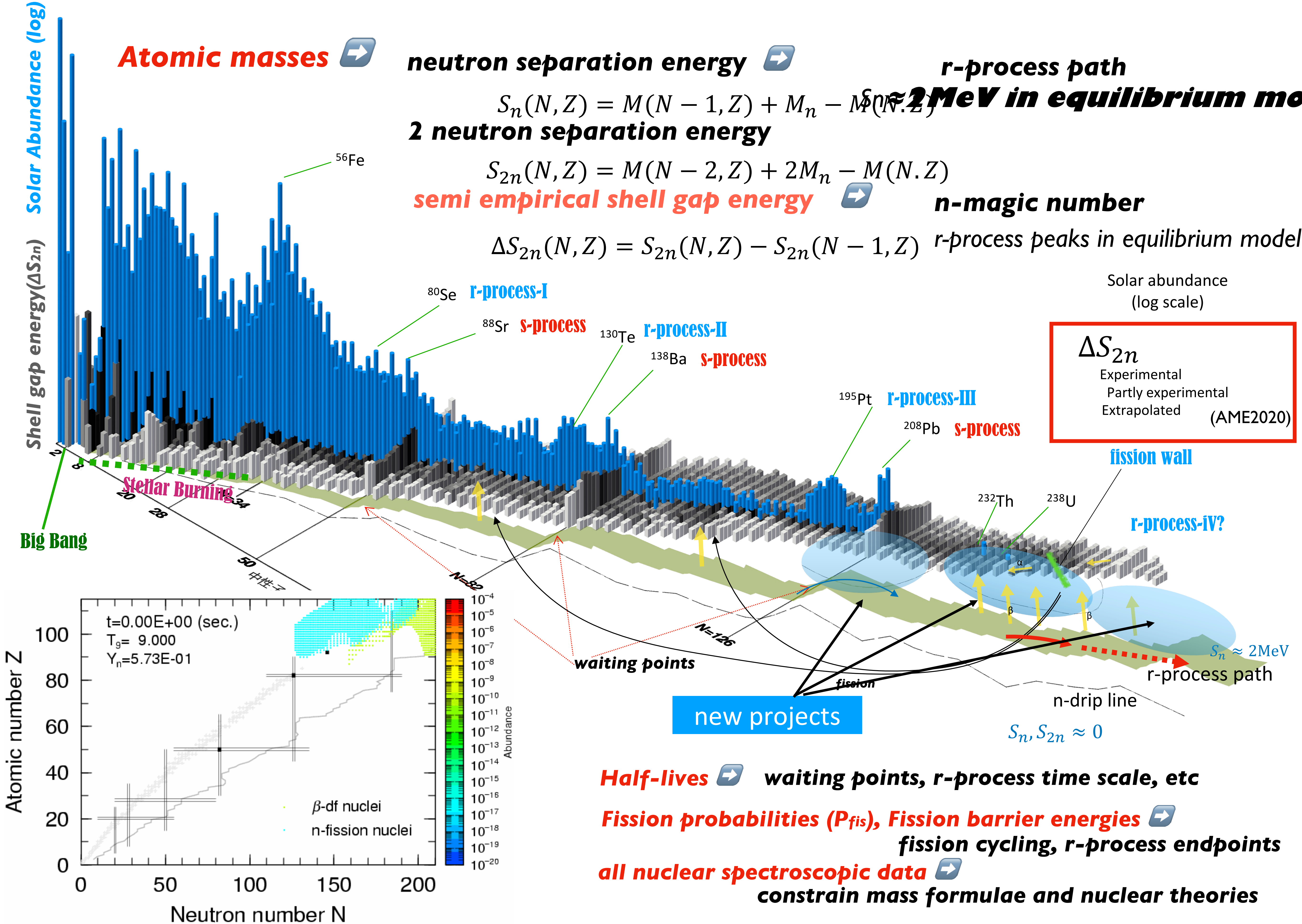
$$\Delta S_{2n}(N,Z) = S_{2n}(N,Z) - S_{2n}(N-1,Z)$$

r-process path

$S_n \approx$2MeV in equilibrium mo

n-magic number

r-process peaks in equilibrium model



Half-lives ***waiting points, r-process time scale, etc***

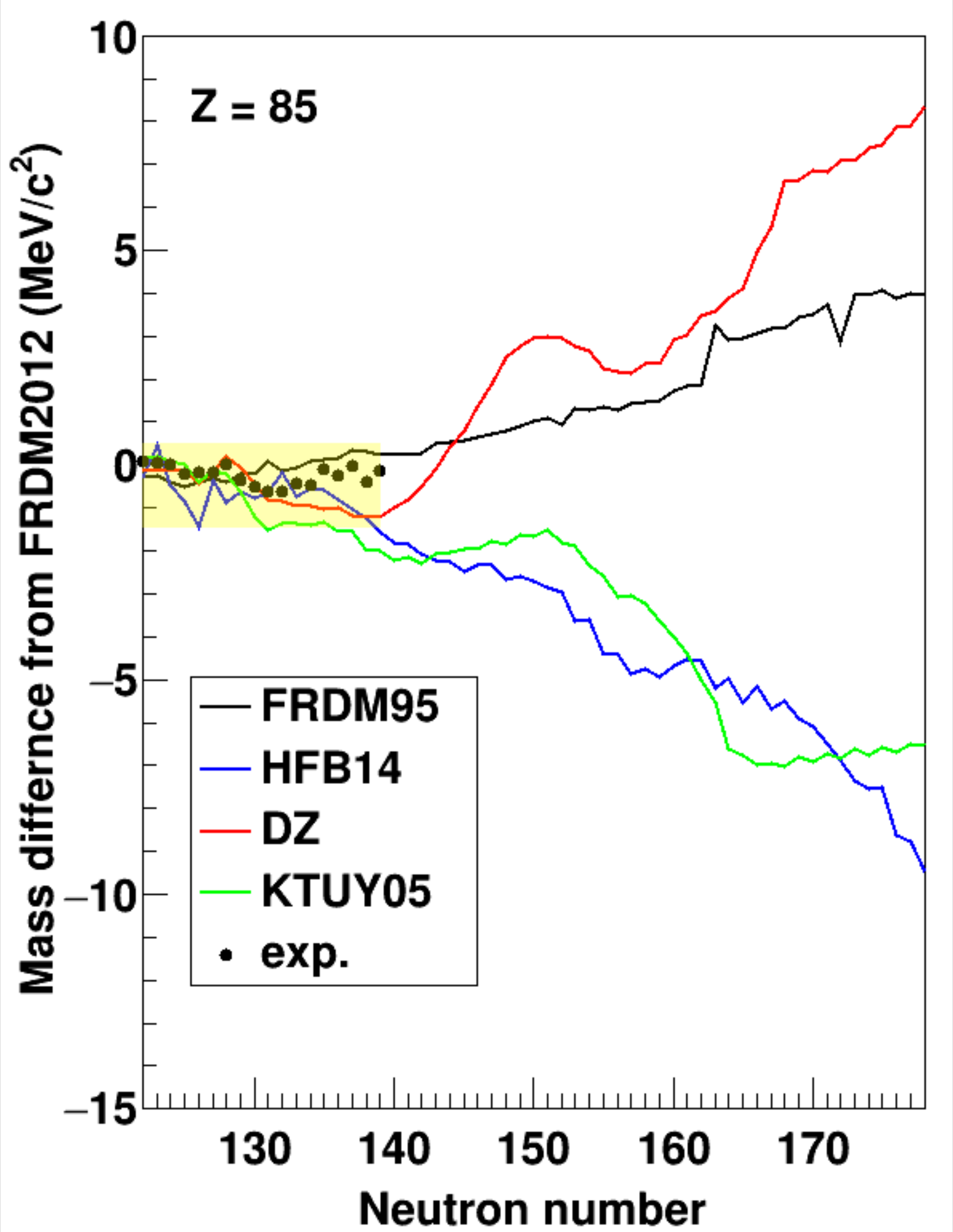
Fission probabilities (P_{fis}), Fission barrier energies

fission cycling, r-process endpoints

all nuclear spectroscopic data

constrain mass formulae and nuclear theories

Theoretical mass predictions are scattered very much



Experimentally observable data for r-process study

Mass:

- *r-process path*
- *waiting points*

$T_{1/2}$:

- *r-process time scale*
- *waiting points*

P_{fission}:

- *fission cycling*
- *r-process termination*
- *final abundance*

$P_{\mathrm{delayed\text{-}neutron}}$:

- *final abundance*

Isomeric state:

- *r-process path*
- *final abundance*

Any nuclear data constrain mass formulae and nuclear theories

cf. AME2016

Masses to be measured

note: many known masses were measured indirectly

Experimentally Synthesized: ≈3300

Mass Known(δm/m<10^{-6})**: 2300** →

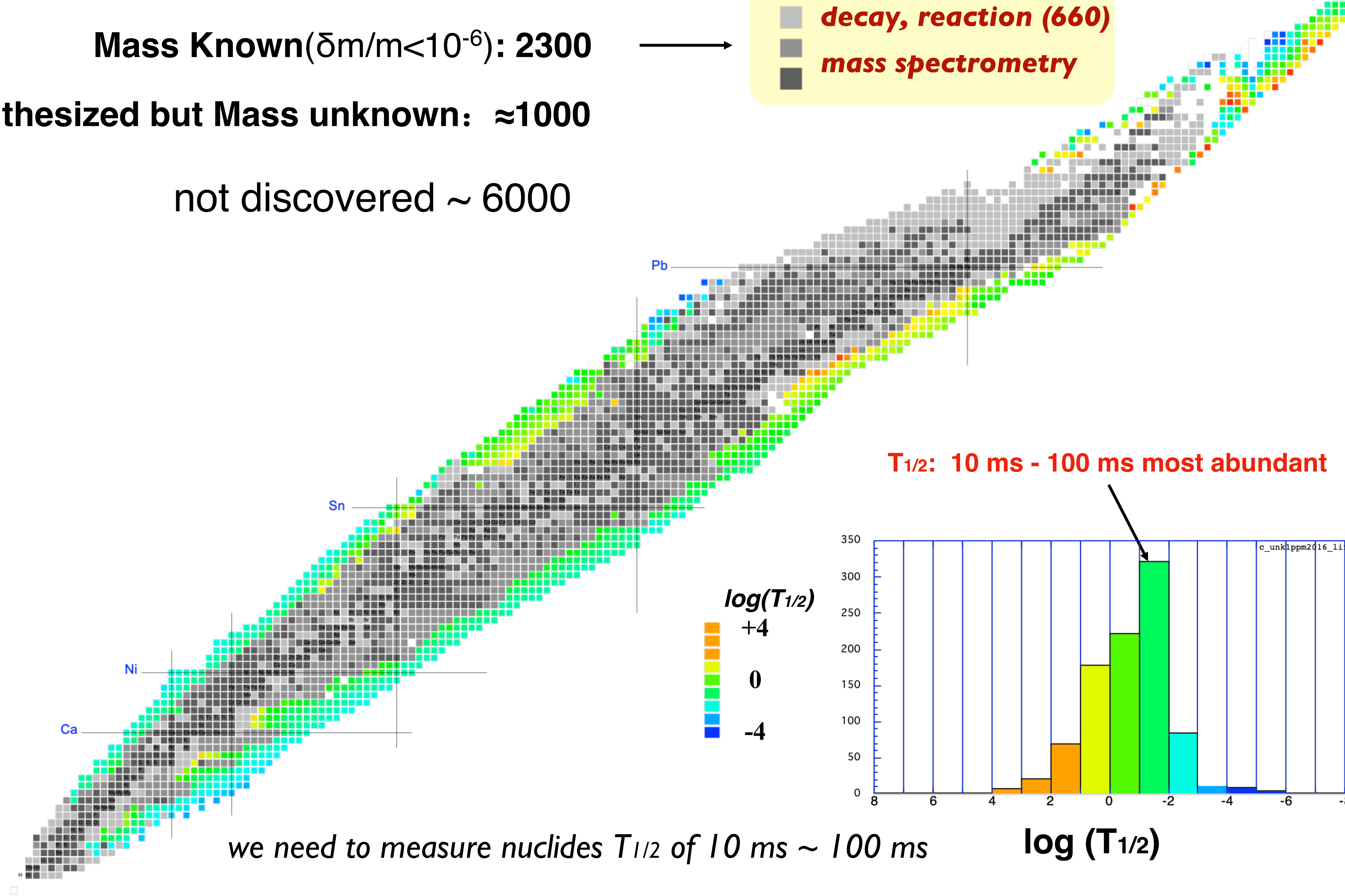
▨ ***decay, reaction (660)***

▨ ***mass spectrometry***

▨

Synthesized but Mass unknown: ≈1000

not discovered ~ 6000

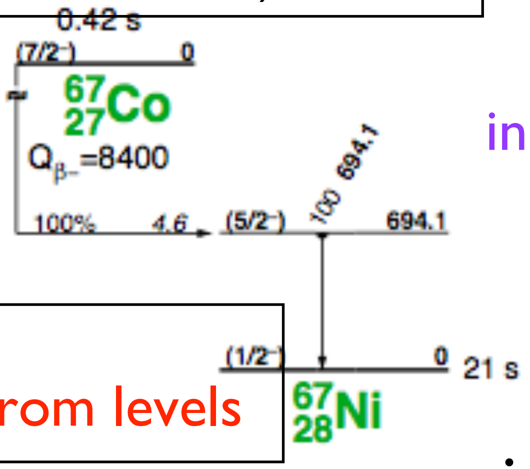


T1/2: 10 ms - 100 ms most abundant

we need to measure nuclides T1/2 of 10 ms ~ 100 ms

Mass Measurements of Short-lived Nuclei

Q-value (decay or reaction)

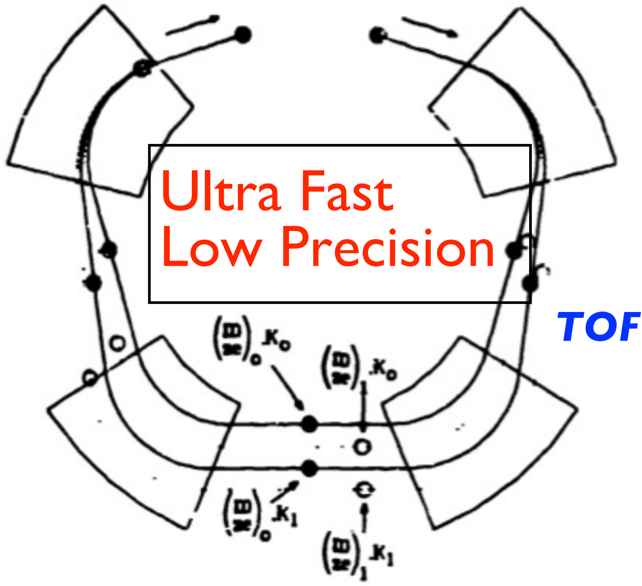


Universal
Ambiguity from levels

indirect

direct

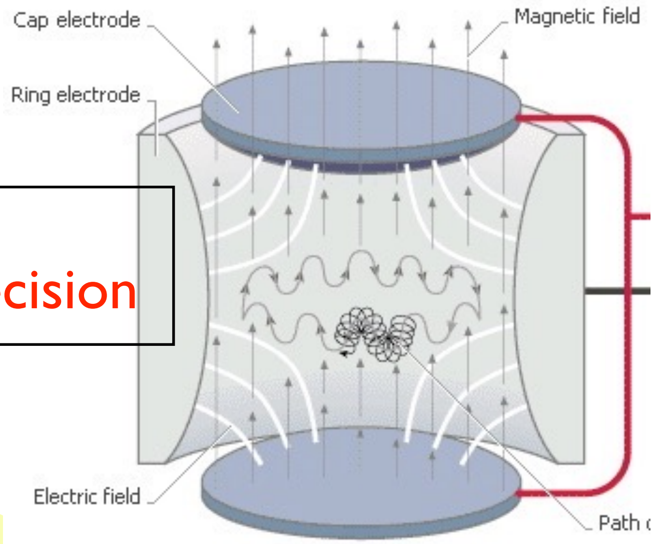
In-flight spectrometer



Ultra Fast
Low Precision

TOFI, SPEG ..

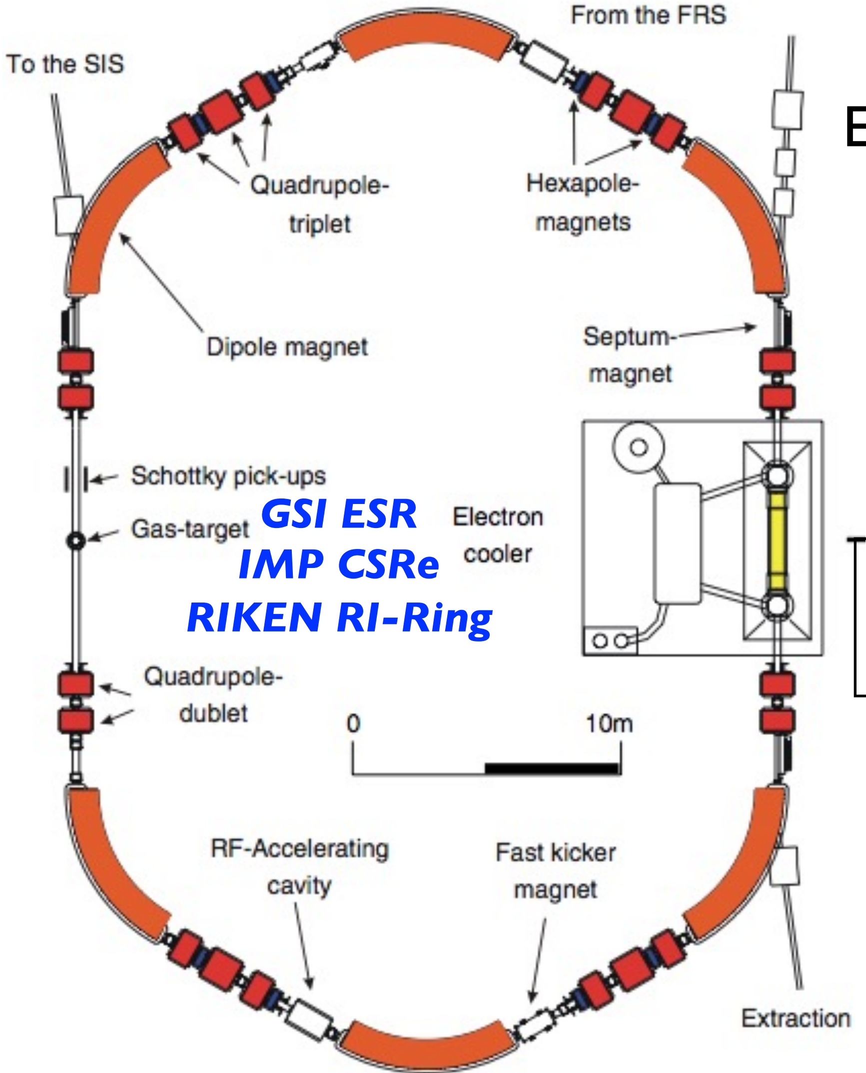
Penning Trap



Slow
Ultra precision

ISOLDE, JYFL...

Storage Ring



GSI ESR
IMP CSRe
RIKEN RI-Ring

Electron Cooling

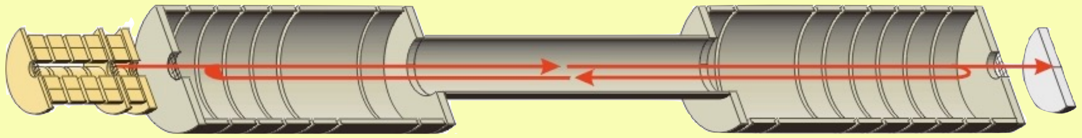
Very Slow
High Precision

Isochronous

Fast
Low Precision

New method

MRTOF (multi-reflection TOF)

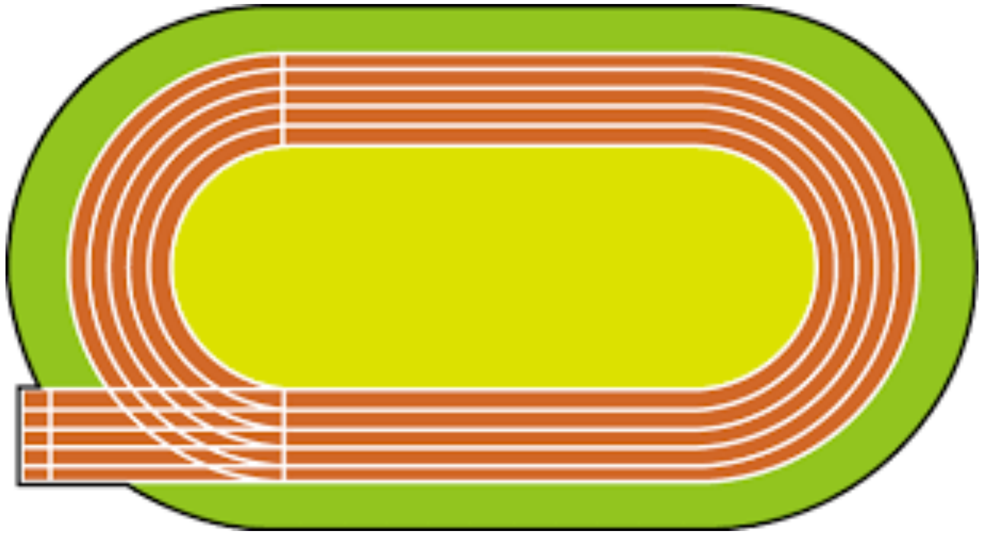


RIKEN-KEK, Giessen, ISOLDE ..

Fast
High Precision

Time of Flight Mass Measurement

徒競走（Time∝√**Mass**）
if kinetic energy is constant



Use of a Track extends the distance

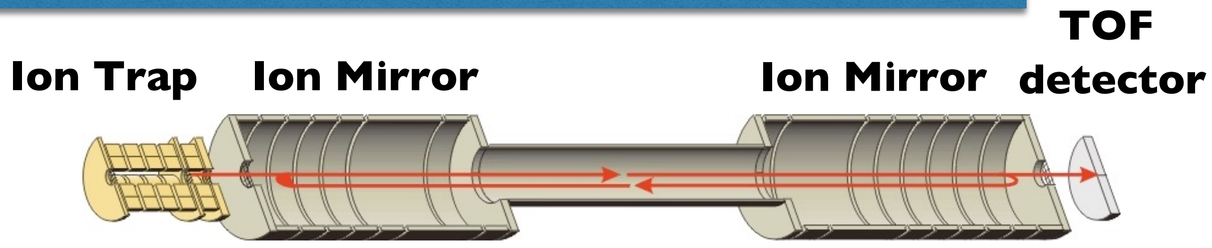
Not much difference in 100m race

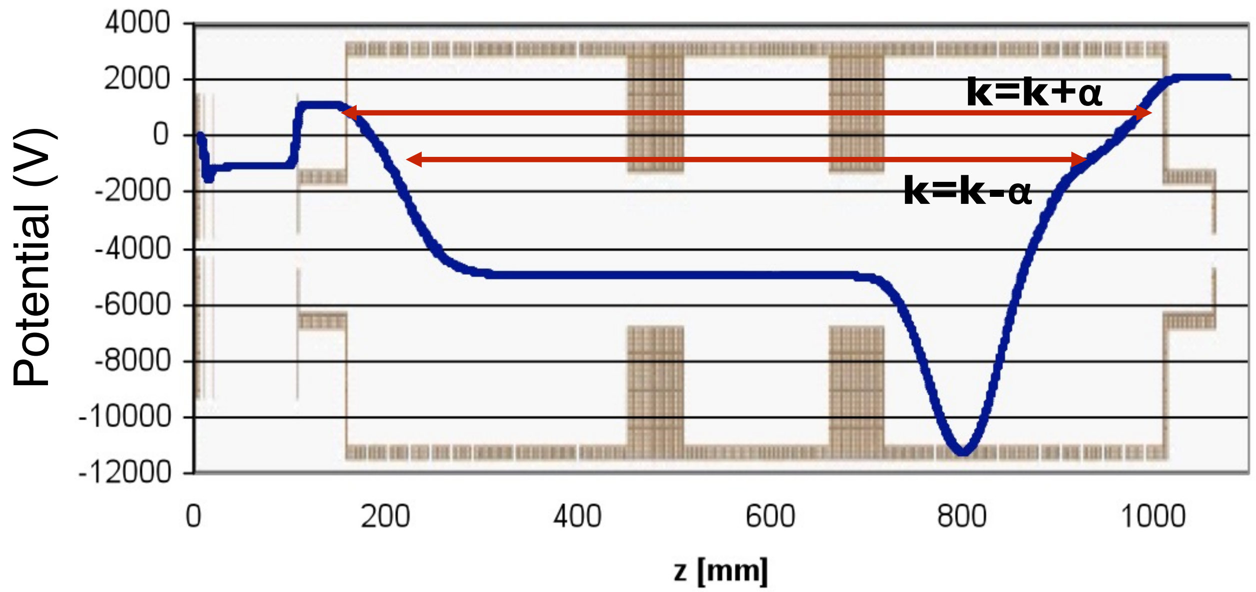
go back and forth in a swimming pool

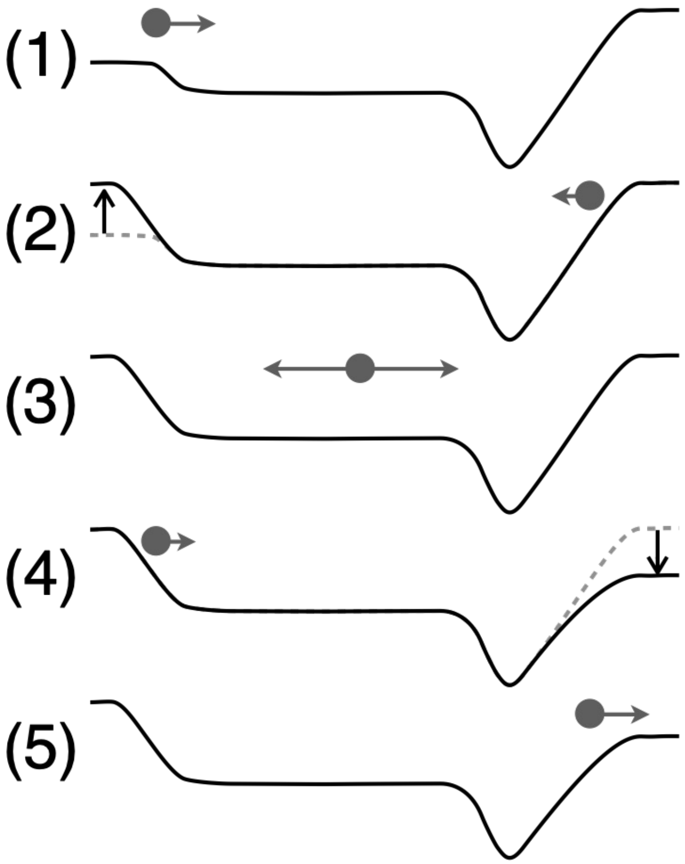
For atoms (ions), go back and forth between a pair of (electric) mirrors.

MRTOF Mass Spectrograph

(Multi Reflection Time of Flight…)







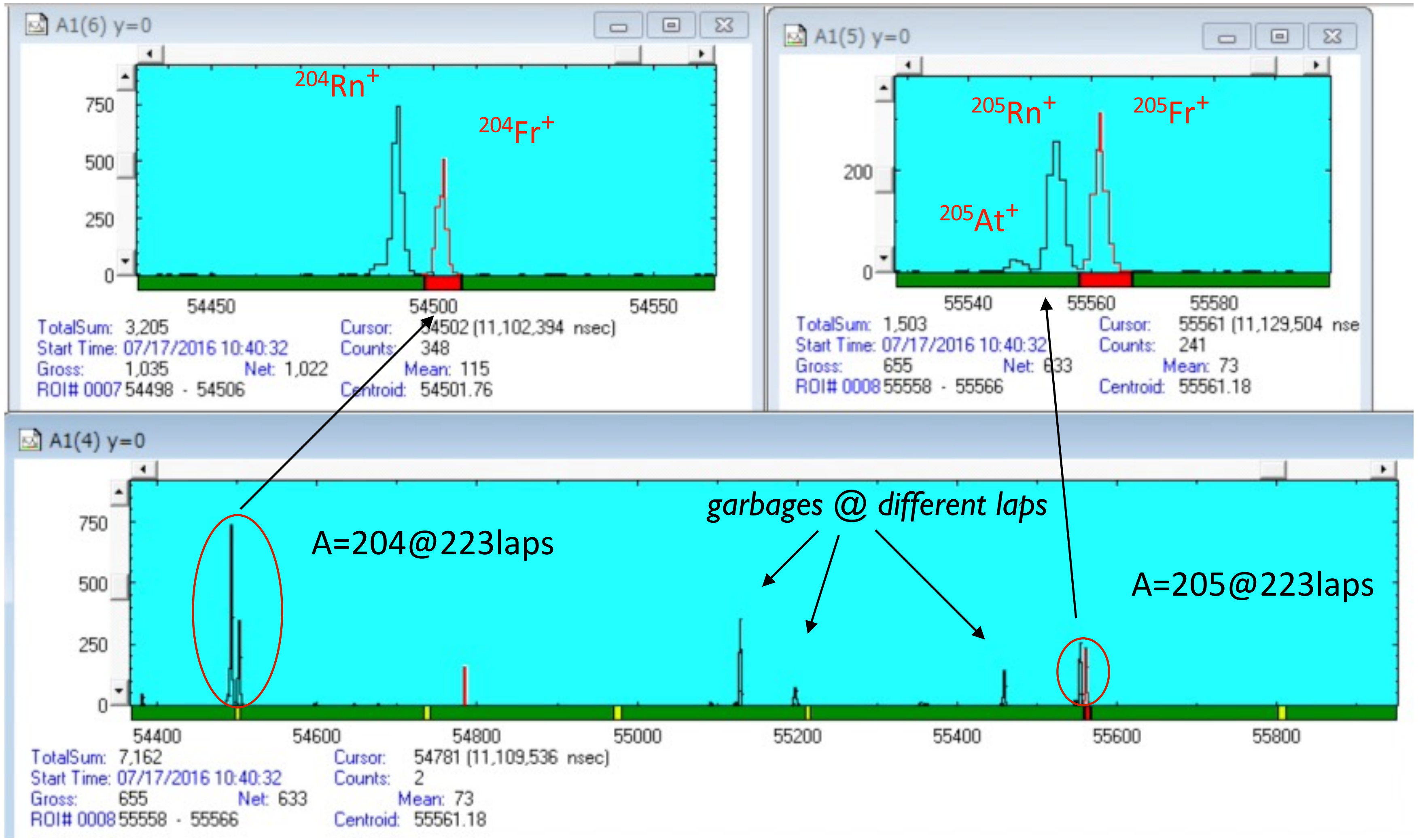
Open entrance to inject

Close entrance before coming back

go back and forth for ***≈200 times***

Open exit at pre-defined timing

Detect ions' ToF



TotalSum: 3,205
Start Time: 07/17/2016 10:40:32
Gross: 1,035 Net: 1,022
ROI# 0007 54498 - 54506
Cursor: 54502 (11,102,394 nsec)
Counts: 348
Mean: 115
Centroid: 54501.76

TotalSum: 1,503
Start Time: 07/17/2016 10:40:32
Gross: 655 Net: 633
ROI# 0008 55558 - 55566
Cursor: 55561 (11,129,504 nse
Counts: 241
Mean: 73
Centroid: 55561.18

TotalSum: 7,162
Start Time: 07/17/2016 10:40:32
Gross: 655 Net: 633
ROI# 0008 55558 - 55566
Cursor: 54781 (11,109,536 nsec)
Counts: 2
Mean: 73
Centroid: 55561.18

A=204@223laps

garbages @ different laps

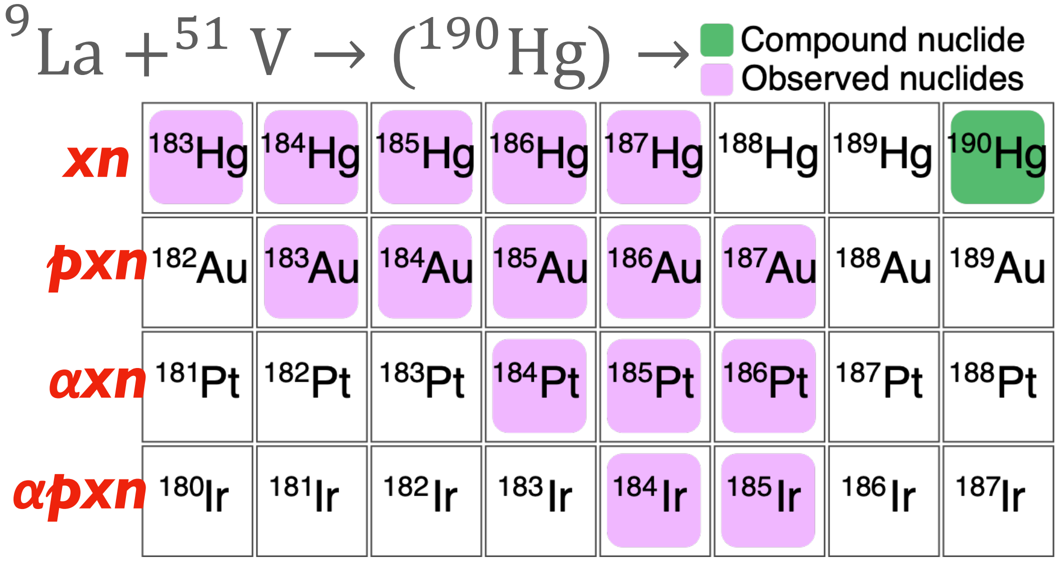
A=205@223laps

$$m_x = \left(\frac{ToF_x}{ToF_r}\right)^2 m_r$$

- **fast (~10 ms)**
- **high precision (MRP~1M)**
- **high accuracy**
- **high efficacy**

Example of high efficient measurement

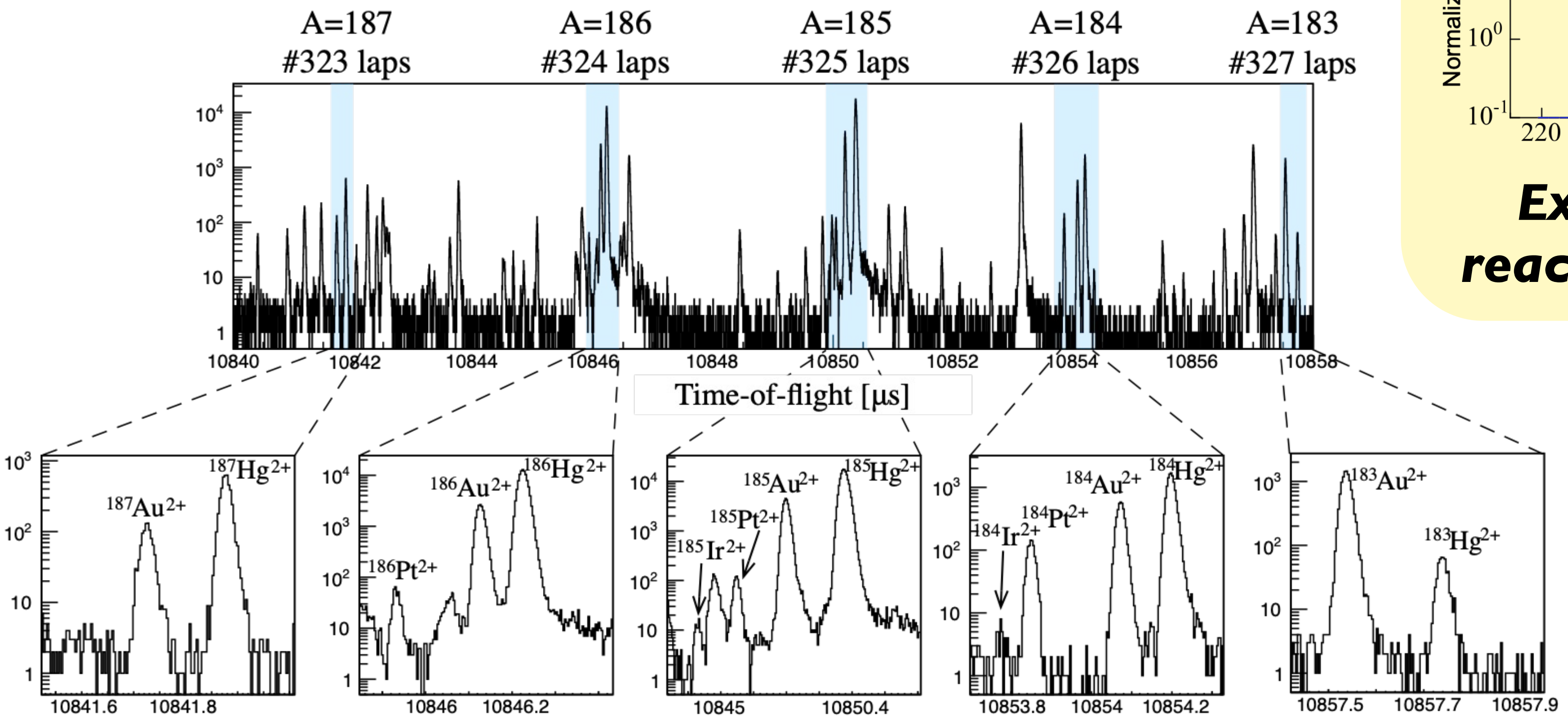
$^{139}\mathrm{La} + ^{51}\mathrm{V} \rightarrow (^{190}\mathrm{Hg}) \rightarrow$

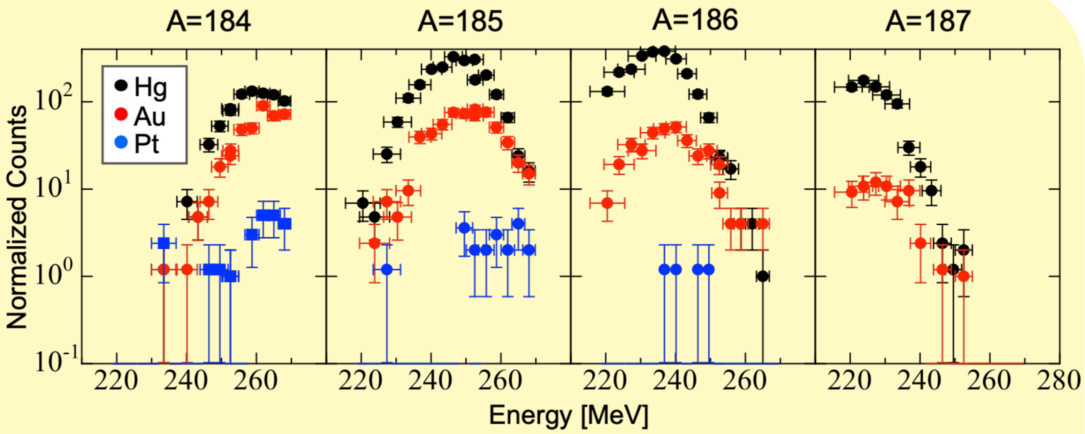


🟩 Compound nuclide
🟪 Observed nuclides

xn	🟪 ^{183}Hg	🟪 ^{184}Hg	🟪 ^{185}Hg	🟪 ^{186}Hg	🟪 ^{187}Hg	^{188}Hg	^{189}Hg	🟩 ^{190}Hg
pxn	^{182}Au	🟪 ^{183}Au	🟪 ^{184}Au	🟪 ^{185}Au	🟪 ^{186}Au	🟪 ^{187}Au	^{188}Au	^{189}Au
αxn	^{181}Pt	^{182}Pt	^{183}Pt	🟪 ^{184}Pt	🟪 ^{185}Pt	🟪 ^{186}Pt	^{187}Pt	^{188}Pt
αpxn	^{180}Ir	^{181}Ir	^{182}Ir	^{183}Ir	🟪 ^{184}Ir	🟪 ^{185}Ir	^{186}Ir	^{187}Ir

Products of multiple reaction channels were measured in a single ToF spectrum





Excitation functions of multiple reaction channels were measured by a single energy scan

Why we use MRTOF?

- High efficacy

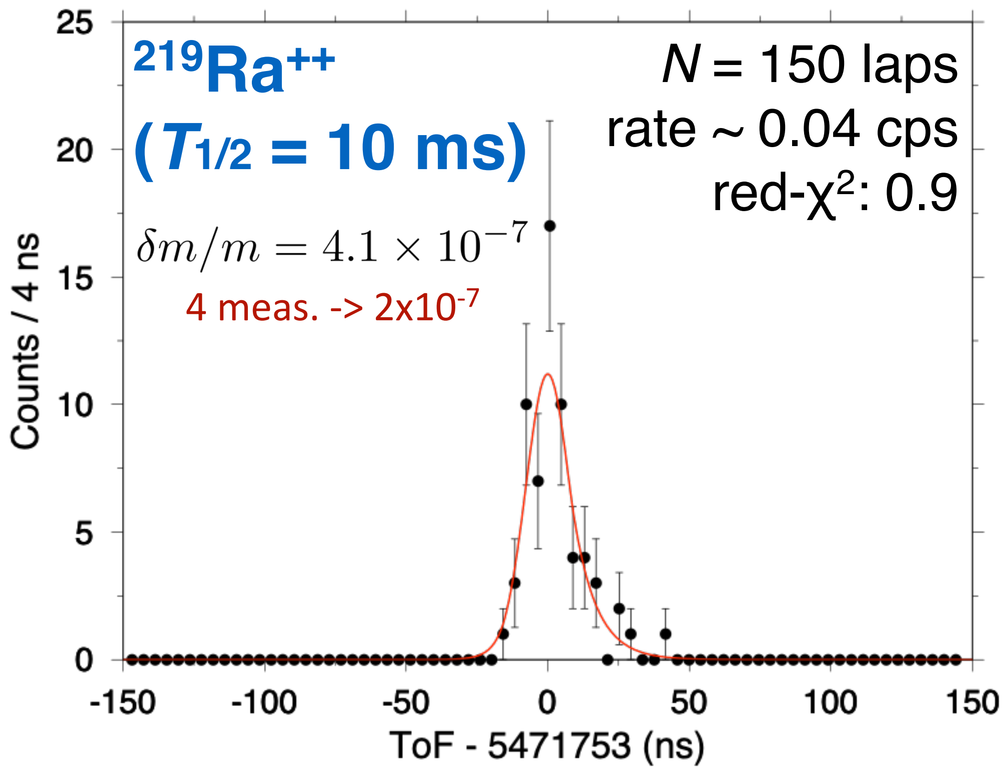
  Multiple spices at once
  (no scan, no pre-purification)

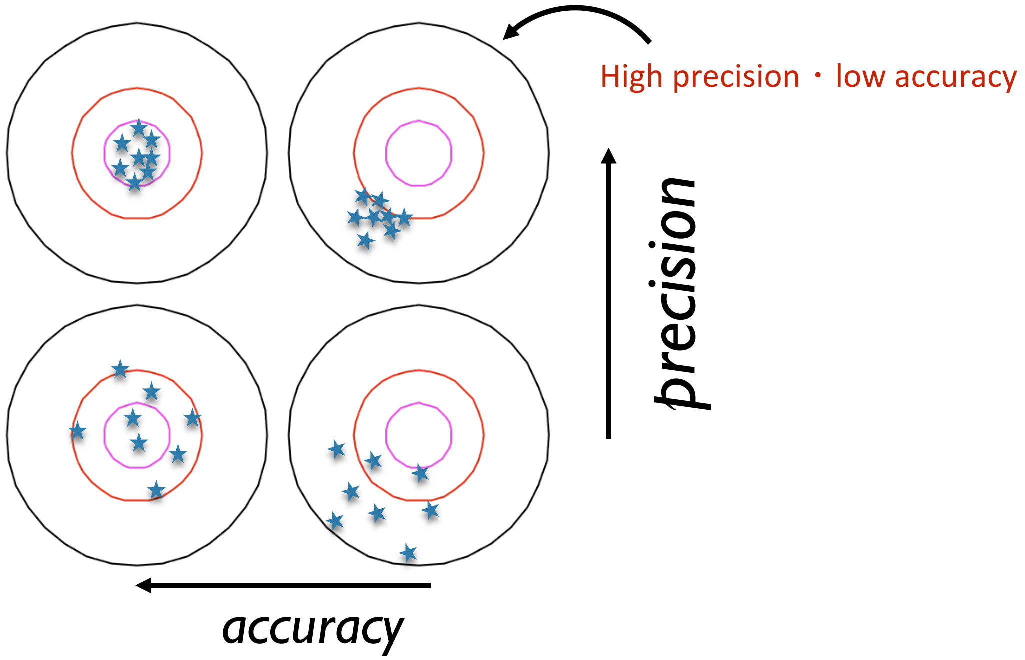
- *Short-lived, Heavy nuclides*

  $T_{1/2}$ = 10 ms, A>200 no loss in precision

- High precision, High accuracy

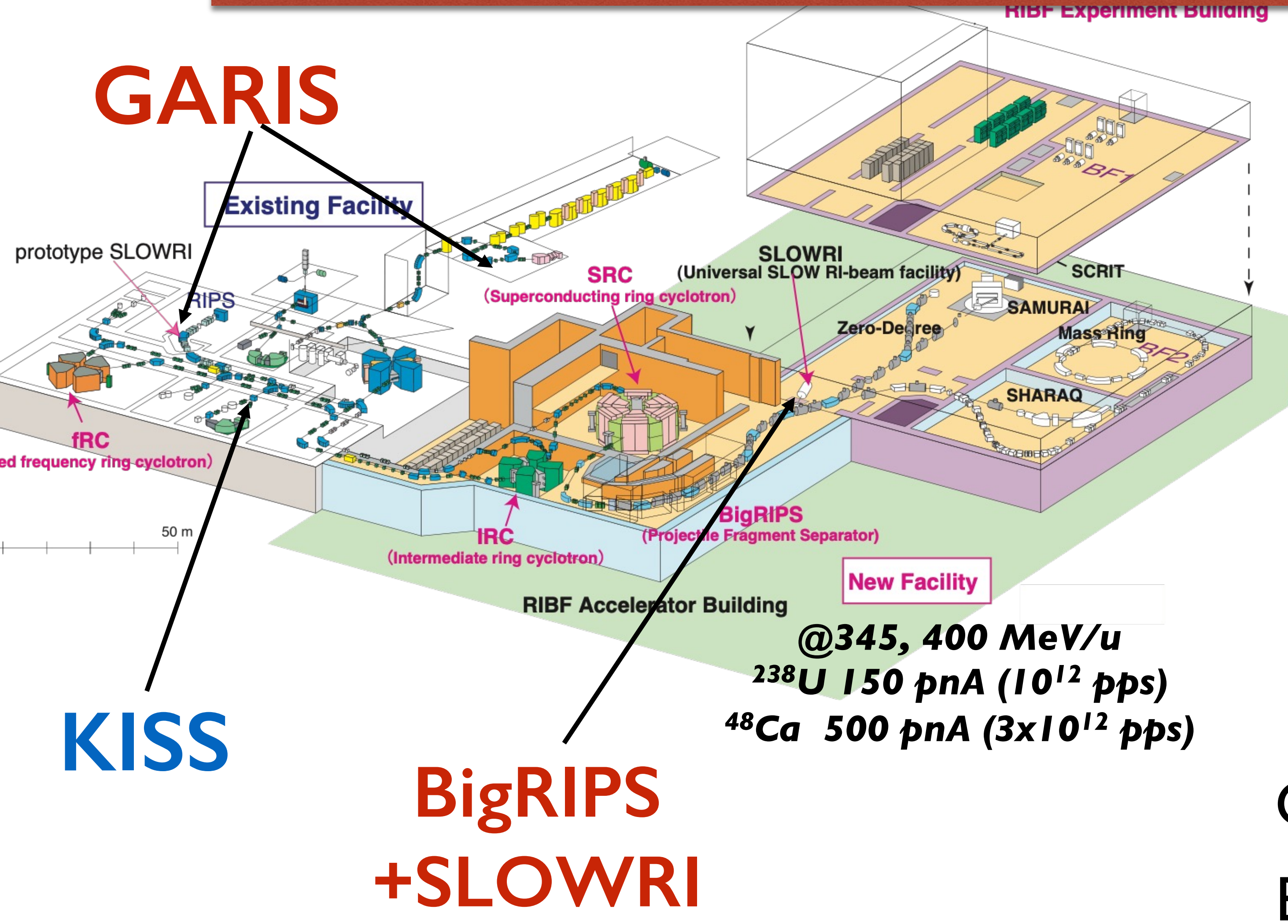
  Mass resolving power (R$_m$= 1,000,000)
  Excellent referencing methods





Q1: What is the best?

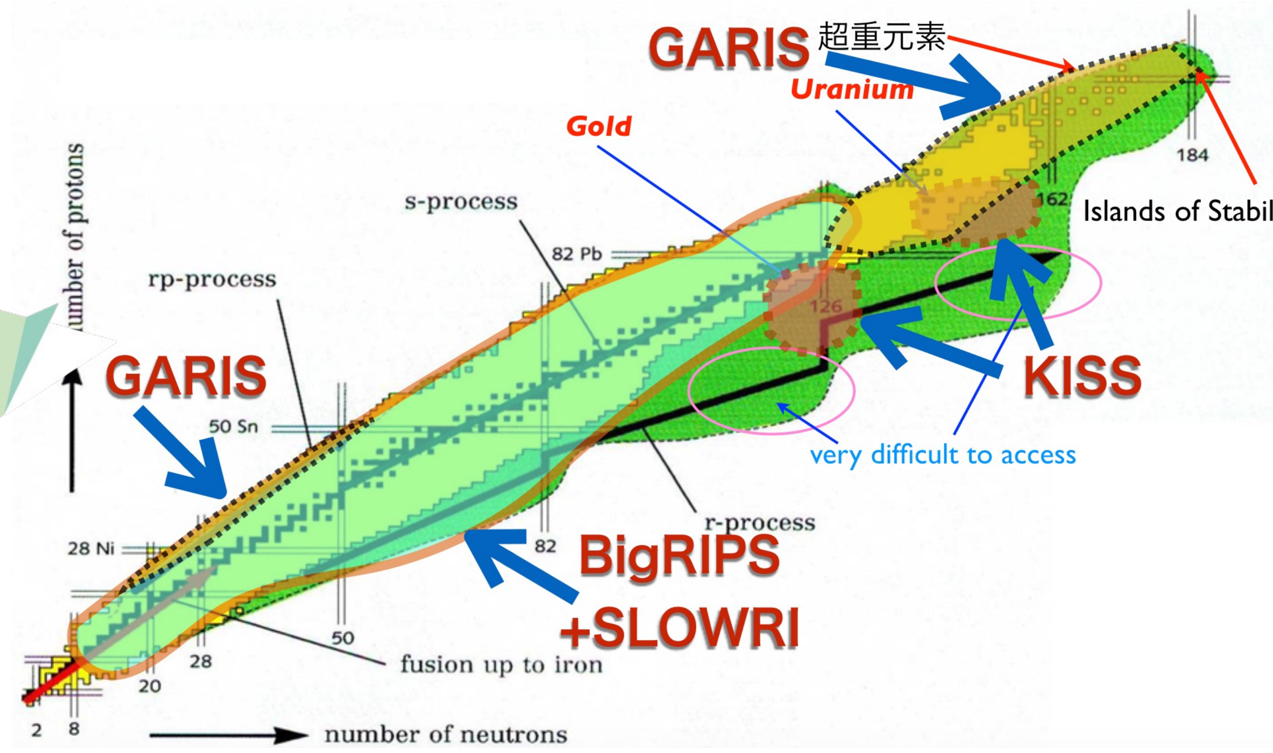
Comprehensive Mass measurements at RIBF with MRTOF



@345, 400 MeV/u

^{238}U 150 pnA (10^{12} pps)

^{48}Ca 500 pnA (3×10^{12} pps)



GARIS: SHE, fusion products

BigRIPS: fragmentation/fission lower than U

KISS: n-rich nuclides via MNT

RIBF provides world highest number of nuclides
from Hydrogen to Nihonium

slogan:

Measure masses of all ~~available~~ possible nuclides

Other Mass spectrometers at RIKEN RIBF (BigRIPS)

Cover article of RIKEN Accel. Prog. Rep. 56 (2023)

Bρ-ToF at SHARAQ

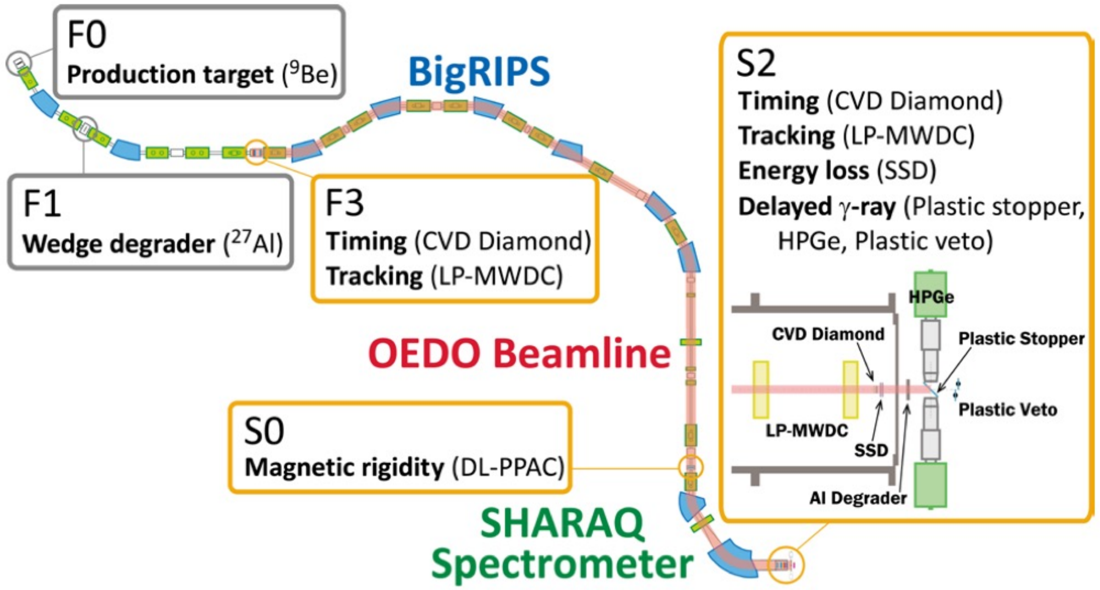


Fig. 2. Experimental detector setup in the OEDO-SHARAQ system for the direct mass measurements.

Isochronous storage ring: R3

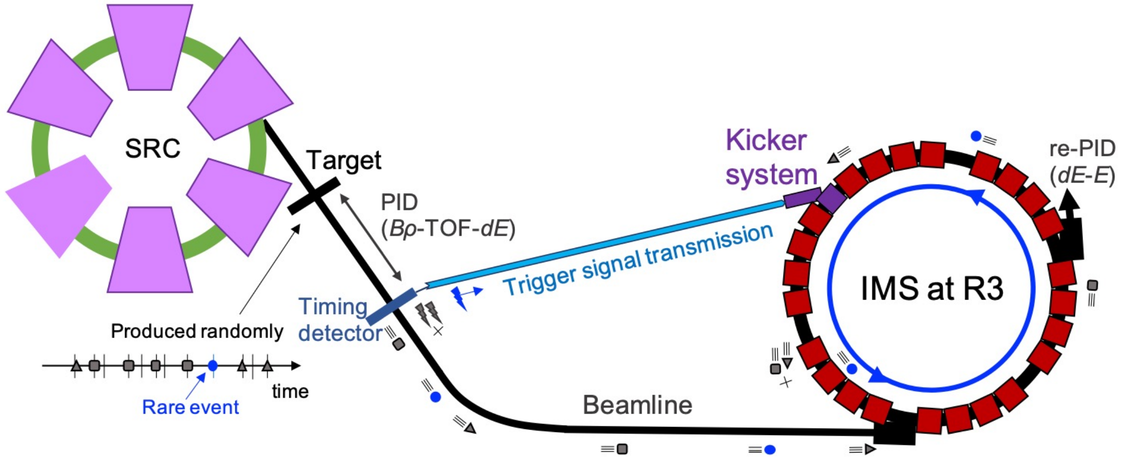


Fig. 3. Conceptual design and method for measuring the mass of short-lived rare nuclei using R3.

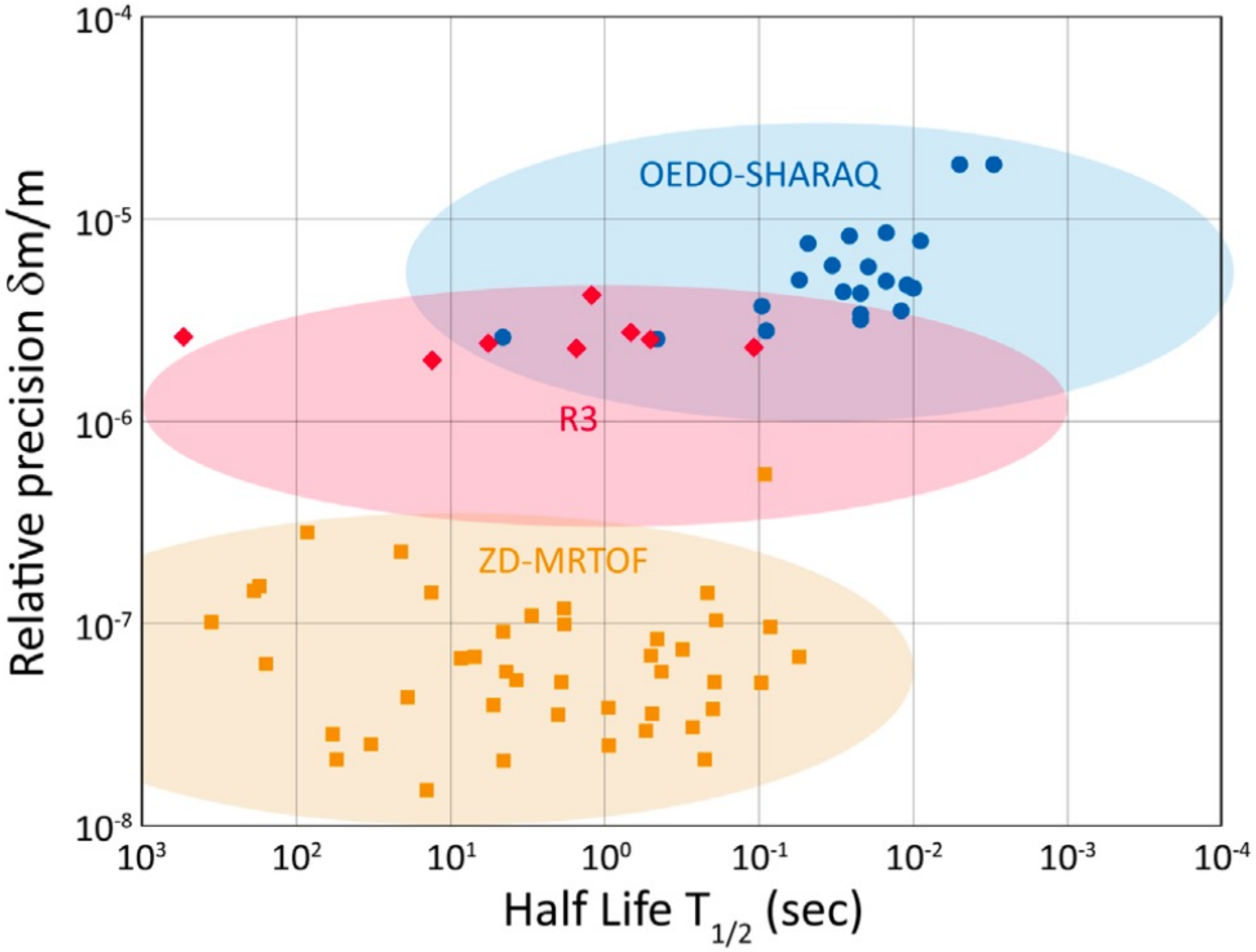
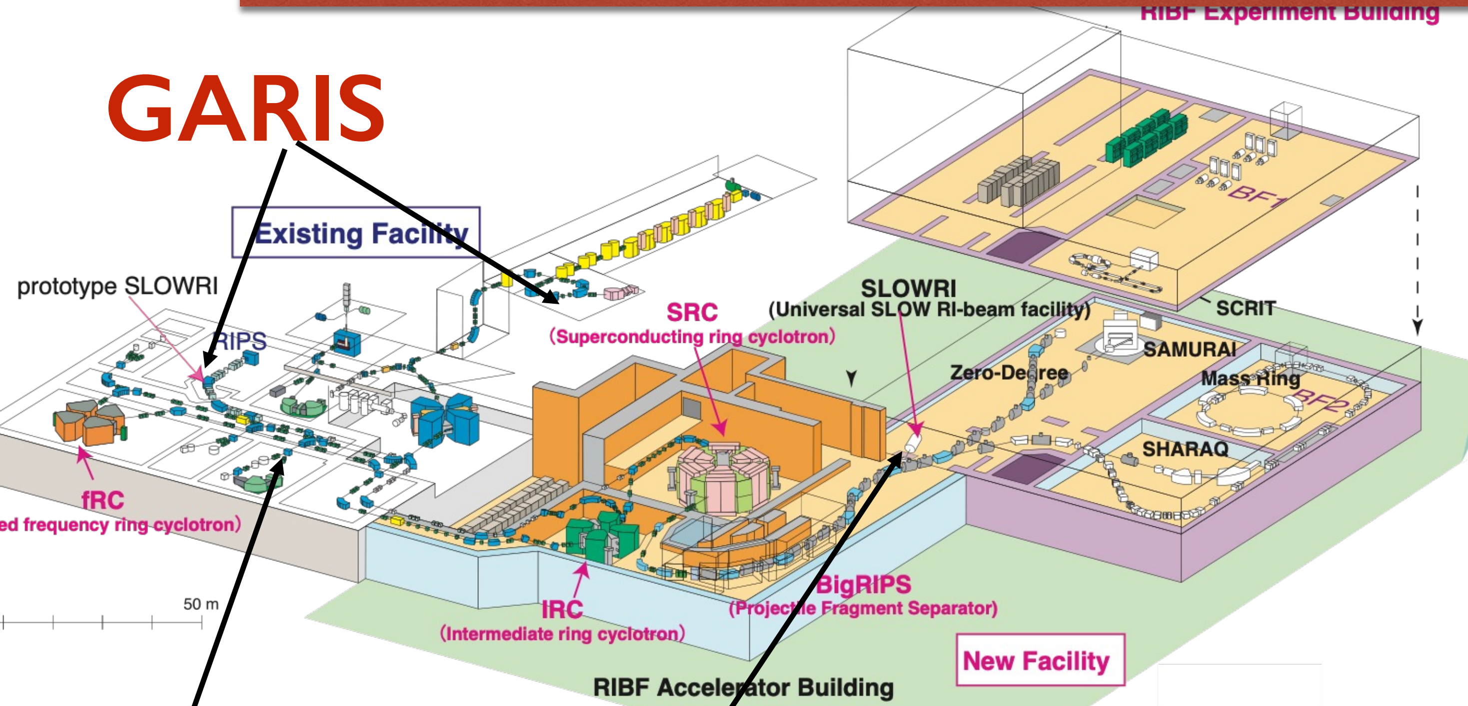
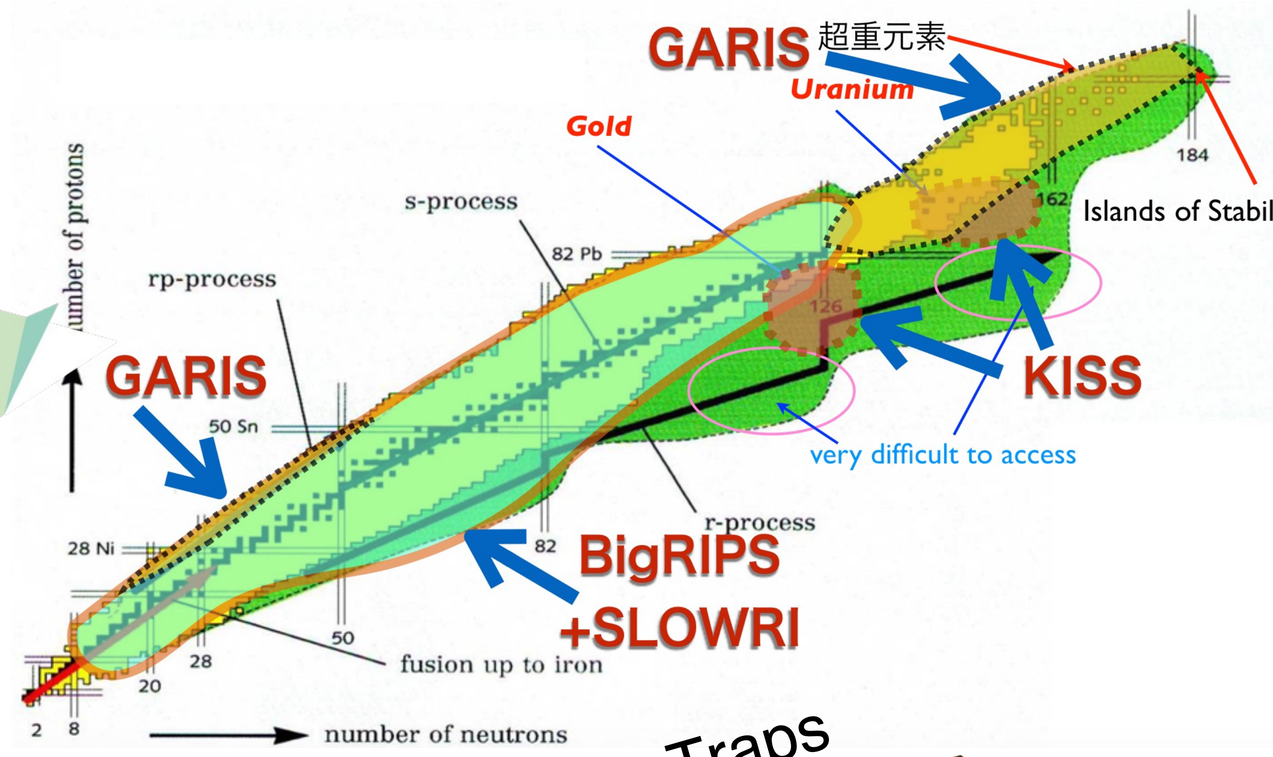


Fig. 1. Mass precision and nuclear half-life regions covered by the three mass measurement methods.

Comprehensive Mass measurements at RIBF with MRTOF

GARIS





KISS

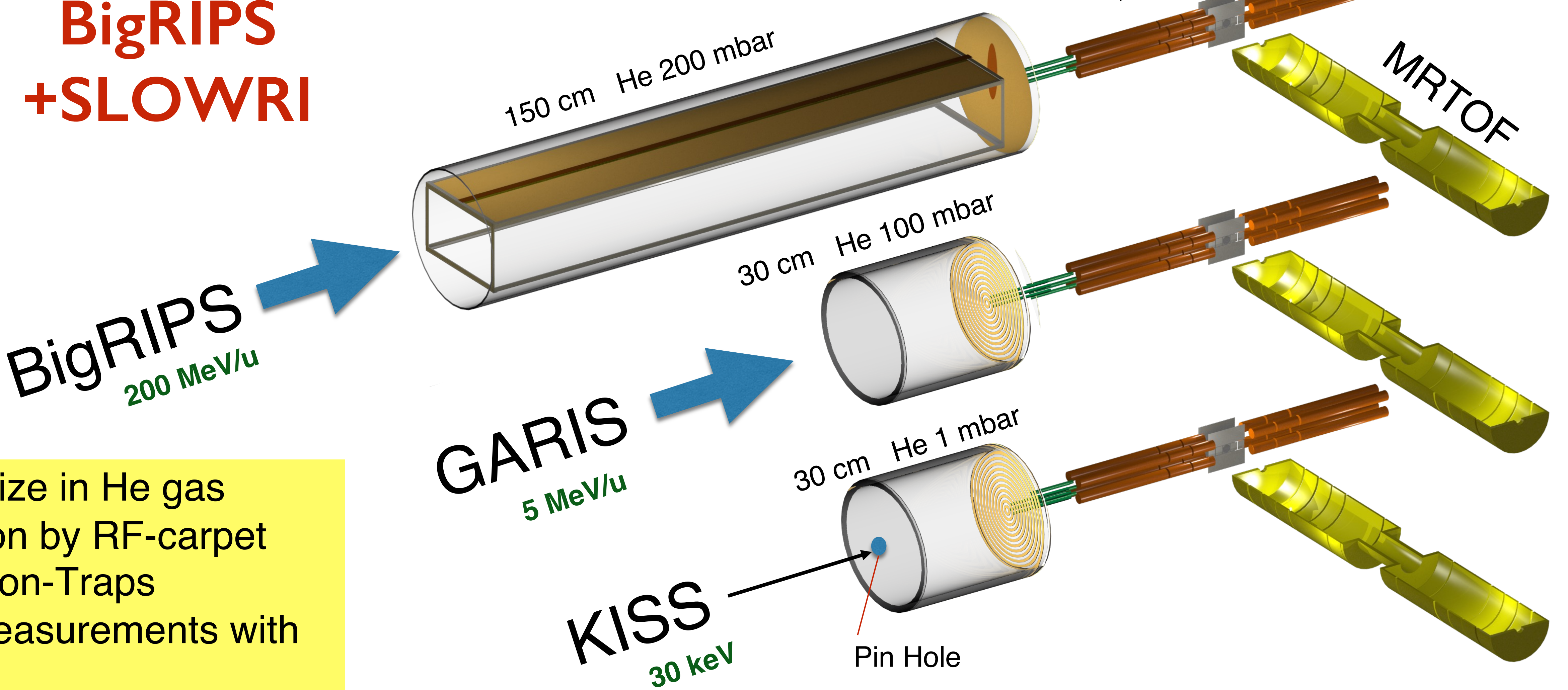
BigRIPS +SLOWRI

@345, 400 MeV/u

^{238}U 150 pnA (10^{12} pps)

^{48}Ca 500 pnA (3×10^{12} pps)

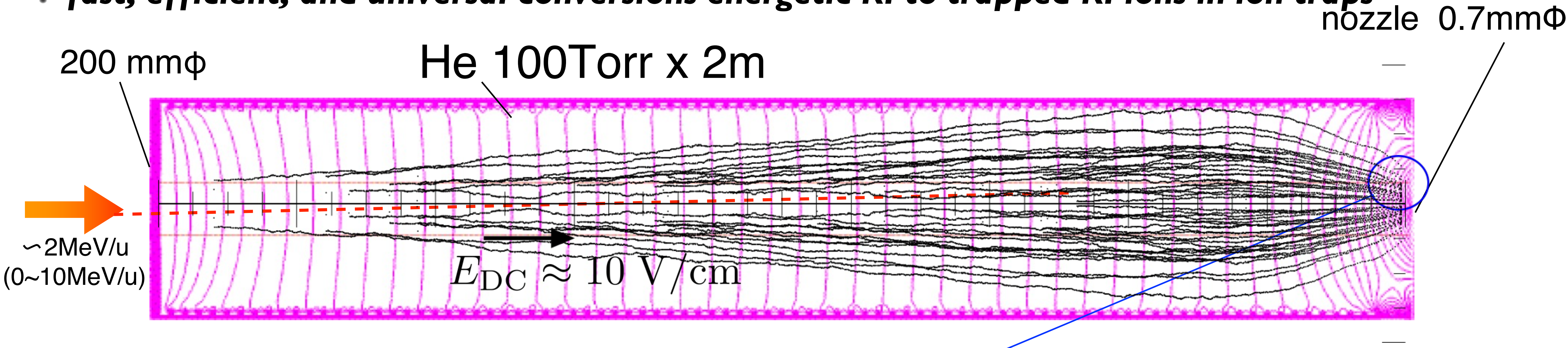
Ion Traps



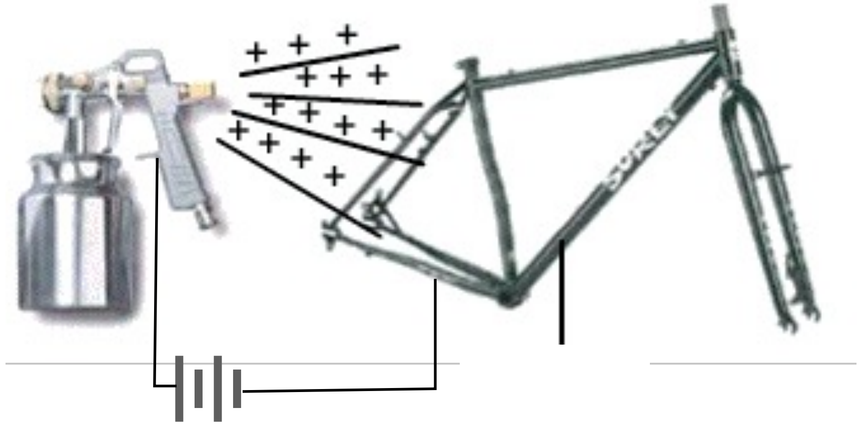
1. Thermalize in He gas
2. Extraction by RF-carpet
3. Trap in Ion-Traps
4. Mass measurements with MRTOF

Big Gas Cell —- traditional type

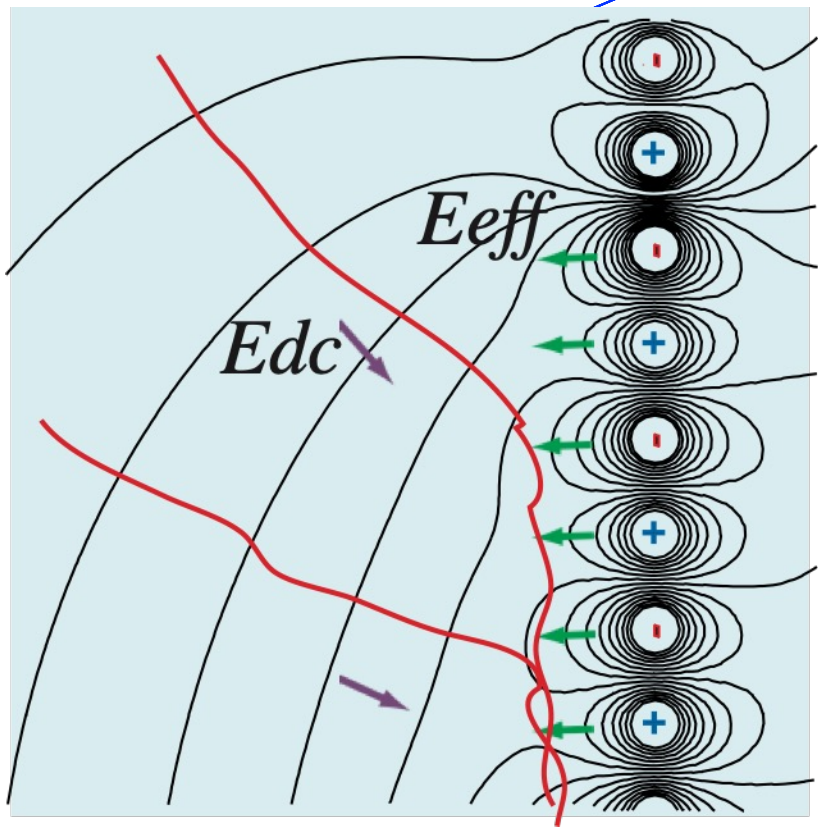
- ***Energetic ions can be stopped in He gas as ions, extracted by DC+ inhomogeneous RF fields***
- ***fast, efficient, and universal conversions energetic RI to trapped RI ions in ion traps***



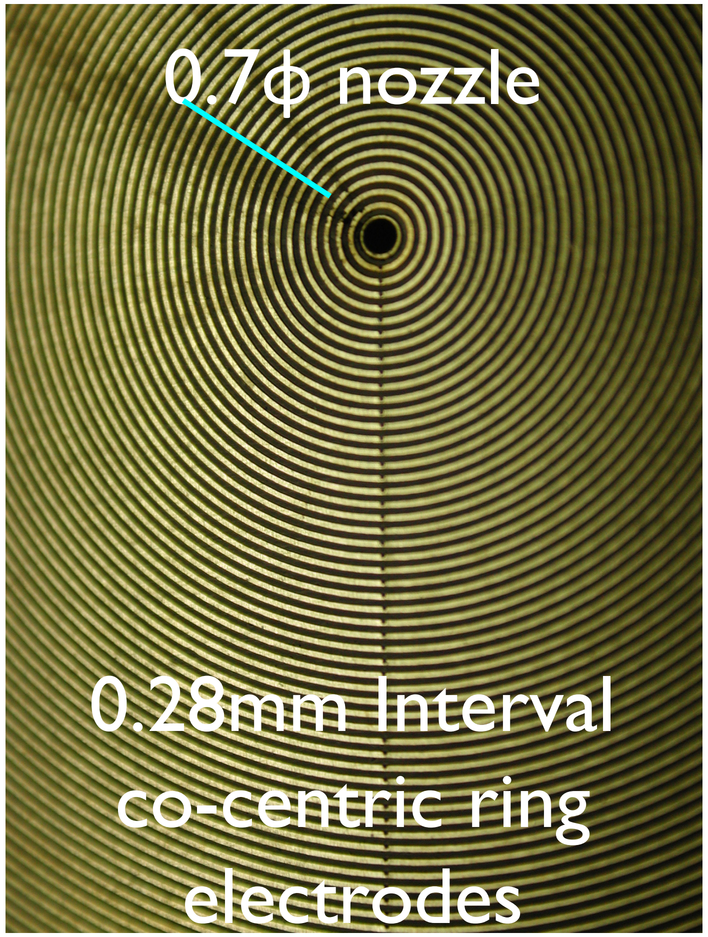
How to paint skeleton?



Electric force lines always terminated at cathode, even if it is a mesh !



Ion Barrier by RF gradient fields

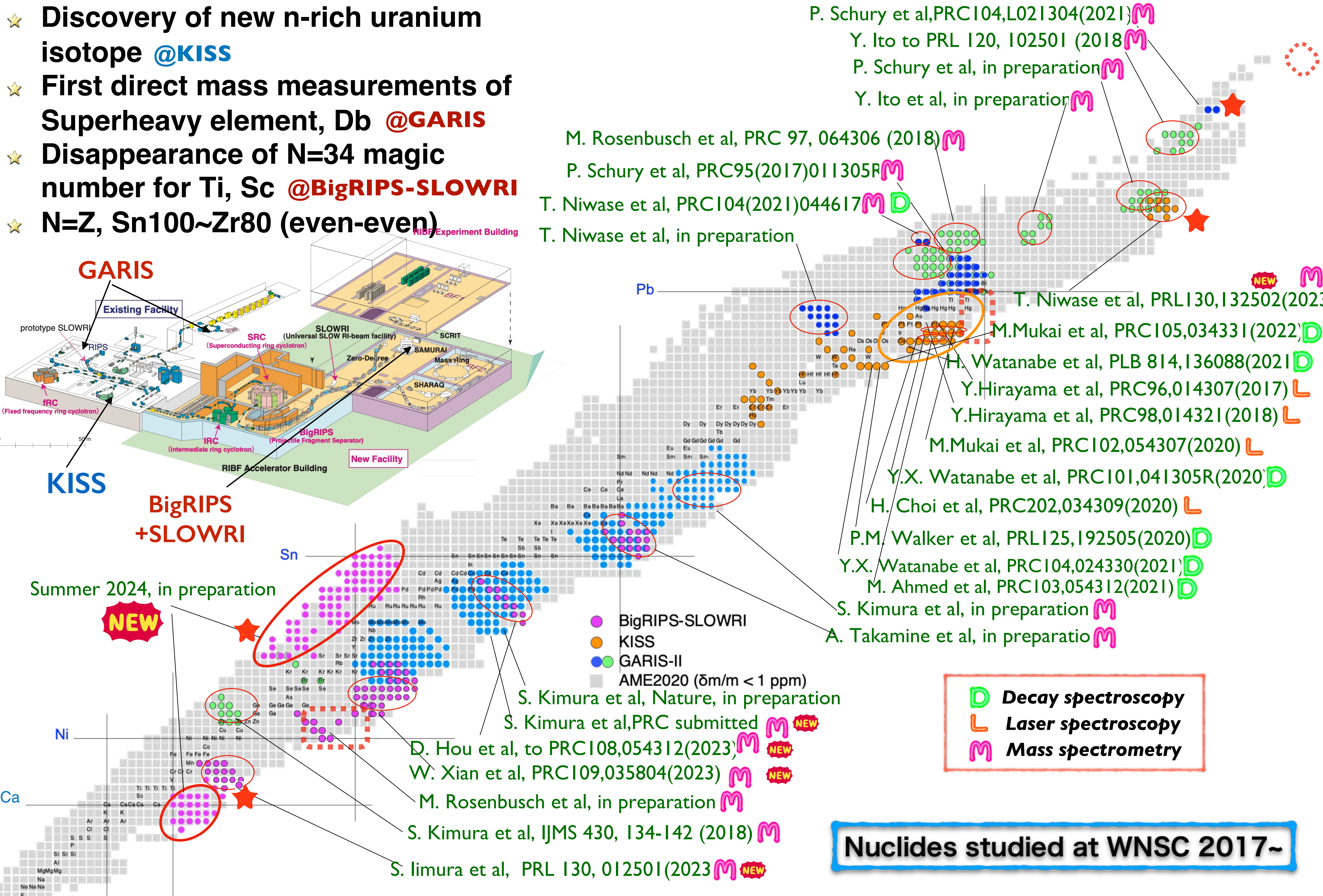


M.Wada et al, NIM B204 (2003) 570.

KEK Wako Nuclear Science Center

~recent highlights~

- ☆ **Discovery of new n-rich uranium isotope @KISS**
- ☆ **First direct mass measurements of Superheavy element, Db @GARIS**
- ☆ **Disappearance of N=34 magic number for Ti, Sc @BigRIPS-SLOWRI**
- ☆ **N=Z, Sn100~Zr80 (even-even)**



P. Schury et al,PRC104,L021304(2021) M

Y. Ito to PRL 120, 102501 (2018 M

P. Schury et al, in preparation M

Y. Ito et al, in preparation M

M. Rosenbusch et al, PRC 97, 064306 (2018) M

P. Schury et al, PRC95(2017)011305R M

T. Niwase et al, PRC104(2021)044617 M D

T. Niwase et al, in preparation

NEW M T. Niwase et al, PRL130,132502(2023

M.Mukai et al, PRC105,034331(2022) D

H. Watanabe et al, PLB 814,136088(2021 D

Y.Hirayama et al, PRC96,014307(2017) L

Y.Hirayama et al, PRC98,014321(2018) L

M.Mukai et al, PRC102,054307(2020) L

Y.X. Watanabe et al, PRC101,041305R(2020) D

H. Choi et al, PRC202,034309(2020) L

P.M. Walker et al, PRL125,192505(2020) D

Y.X. Watanabe et al, PRC104,024330(2021) D

M. Ahmed et al, PRC103,054312(2021) D

S. Kimura et al, in preparation M

A. Takamine et al, in preparatio M

Summer 2024, in preparation

NEW

S. Kimura et al, Nature, in preparation

S. Kimura et al,PRC submitted M NEW

D. Hou et al, to PRC108,054312(2023) M NEW

W. Xian et al, PRC109,035804(2023) M NEW

M. Rosenbusch et al, in preparation M

S. Kimura et al, IJMS 430, 134-142 (2018) M

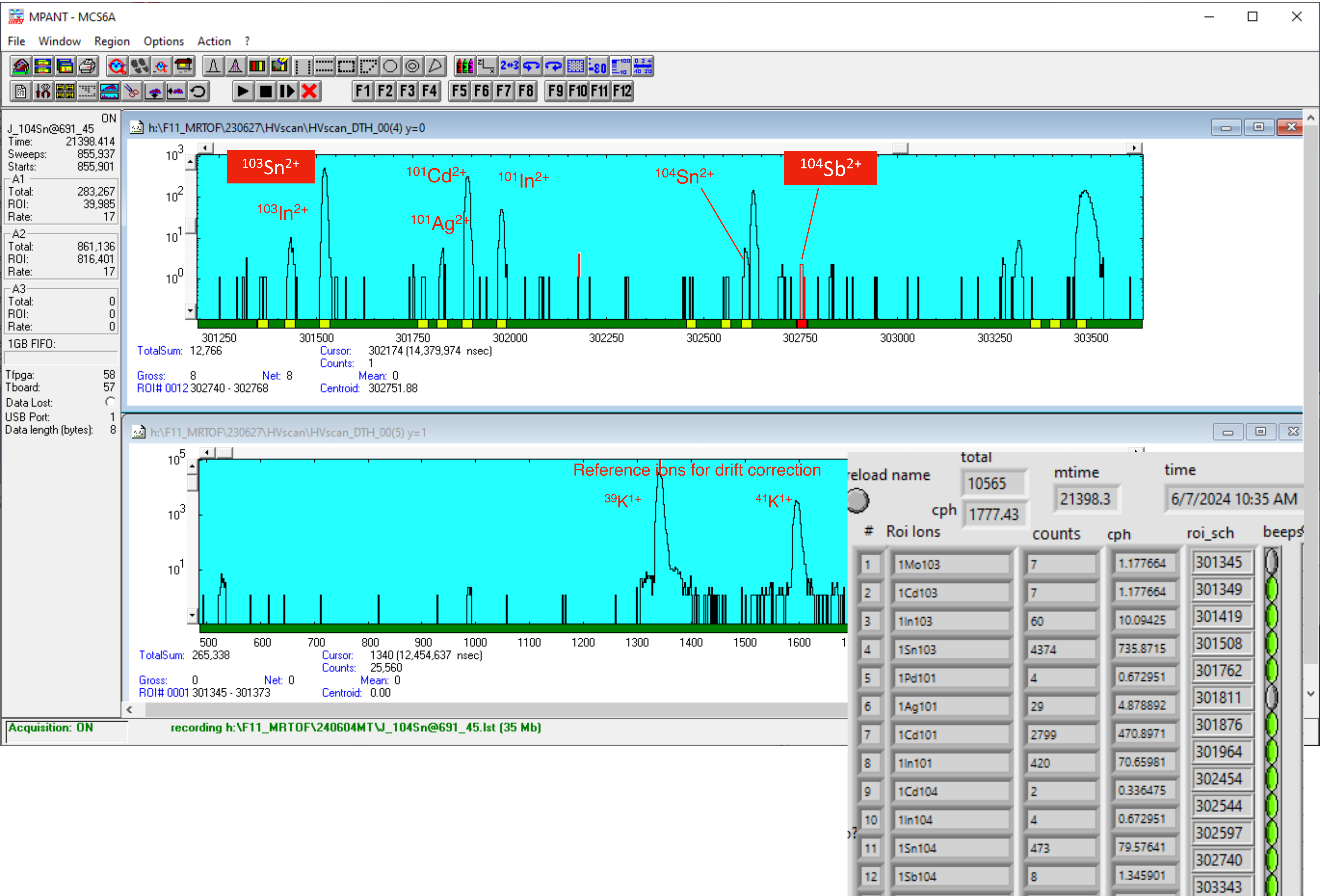
S. Iimura et al, PRL 130, 012501(2023 M NEW

- ● BigRIPS-SLOWRI
- ● KISS
- ●● GARIS-II
- ■ AME2020 (δm/m < 1 ppm)

- D ***Decay spectroscopy***
- L ***Laser spectroscopy***
- M ***Mass spectrometry***

Nuclides studied at WNSC 2017~

RIBF211, MRTOF part (7 June, day 4) Sb104, Sn103,104



MPANT - MCS6A

File Window Region Options Action ?

ON
J_104Sn@691_45
Time: 21398.414
Sweeps: 855,937
Starts: 855,901

A1
Total: 283,267
ROI: 39,985
Rate: 17

A2
Total: 861,136
ROI: 816,401
Rate: 17

A3
Total: 0
ROI: 0
Rate: 0

1GB FIFO:

Tfpga: 58
Tboard: 57
Data Lost: ○
USB Port: 1
Data length (bytes): 8

h:\F11_MRTOF\230627\HVscan\HVscan_DTH_00(4) y=0

TotalSum: 12,766
Cursor: 302174 (14,379,974 nsec)
Counts: 1
Gross: 8 Net: 8
Mean: 0
ROI# 0012 302740 - 302768
Centroid: 302751.88

h:\F11_MRTOF\230627\HVscan\HVscan_DTH_00(5) y=1

TotalSum: 265,338
Cursor: 1340 (12,454,637 nsec)
Counts: 25,560
Gross: 0 Net: 0
Mean: 0
ROI# 0001 301345 - 301373
Centroid: 0.00

Acquisition: ON

recording h:\F11_MRTOF\240604MT\J_104Sn@691_45.lst (35 Mb)

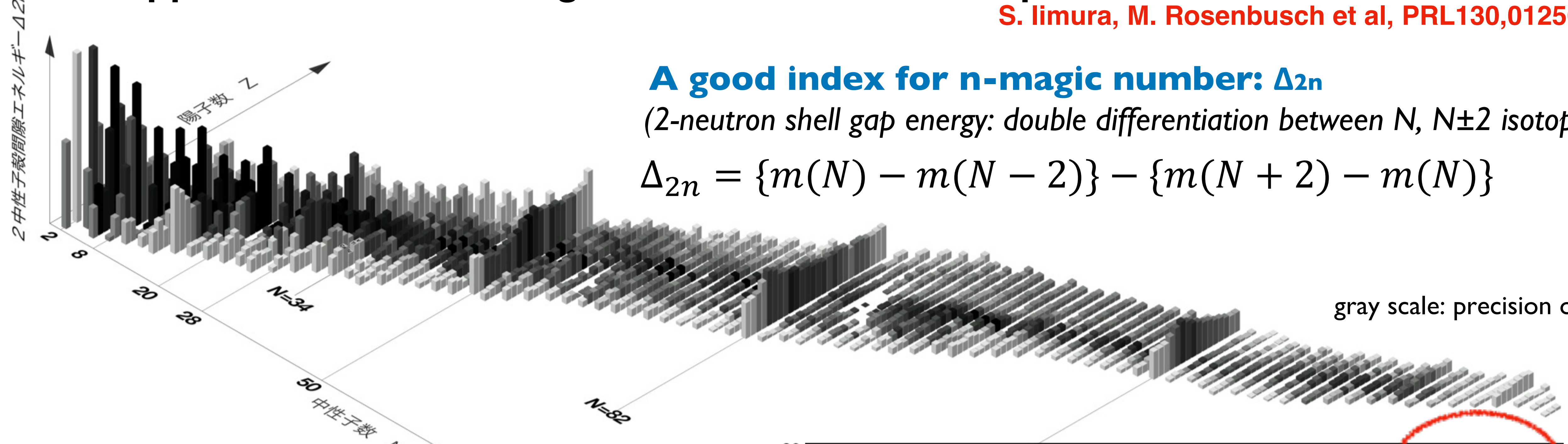
reload name ○

total 10565
cph 1777.43
mtime 21398.3
time 6/7/2024 10:35 AM

#	Roi Ions	counts	cph	roi_sch	beeps
1	1Mo103	7	1.177664	301345	○
2	1Cd103	7	1.177664	301349	●
3	1In103	60	10.09425	301419	●
4	1Sn103	4374	735.8715	301508	●
5	1Pd101	4	0.672951	301762	●
6	1Ag101	29	4.878892	301811	○
7	1Cd101	2799	470.8971	301876	●
8	1In101	420	70.65981	301964	●
9	1Cd104	2	0.336475	302454	●
10	1In104	4	0.672951	302544	●
11	1Sn104	473	79.57641	302597	●
12	1Sb104	8	1.345901	302740	●
				303343	●

Disappearance of N=34 magic number for Ti. V isotopes

S. Iimura, M. Rosenbusch et al, PRL130,012501(2023)

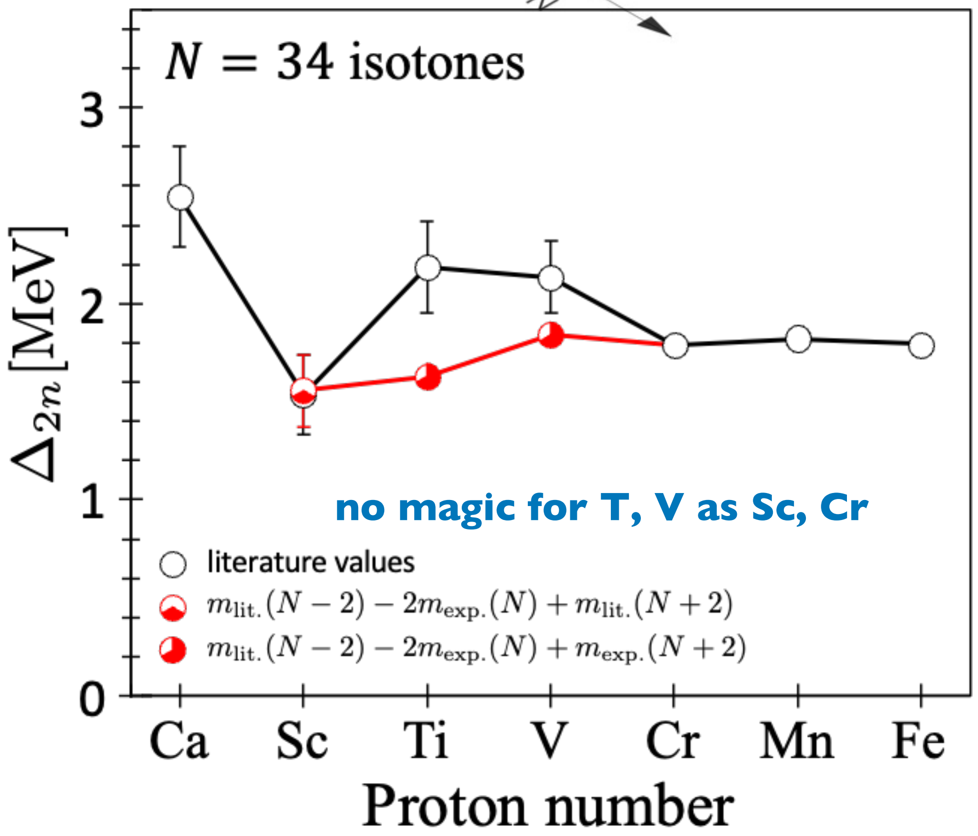


A good index for n-magic number: Δ_{2n}

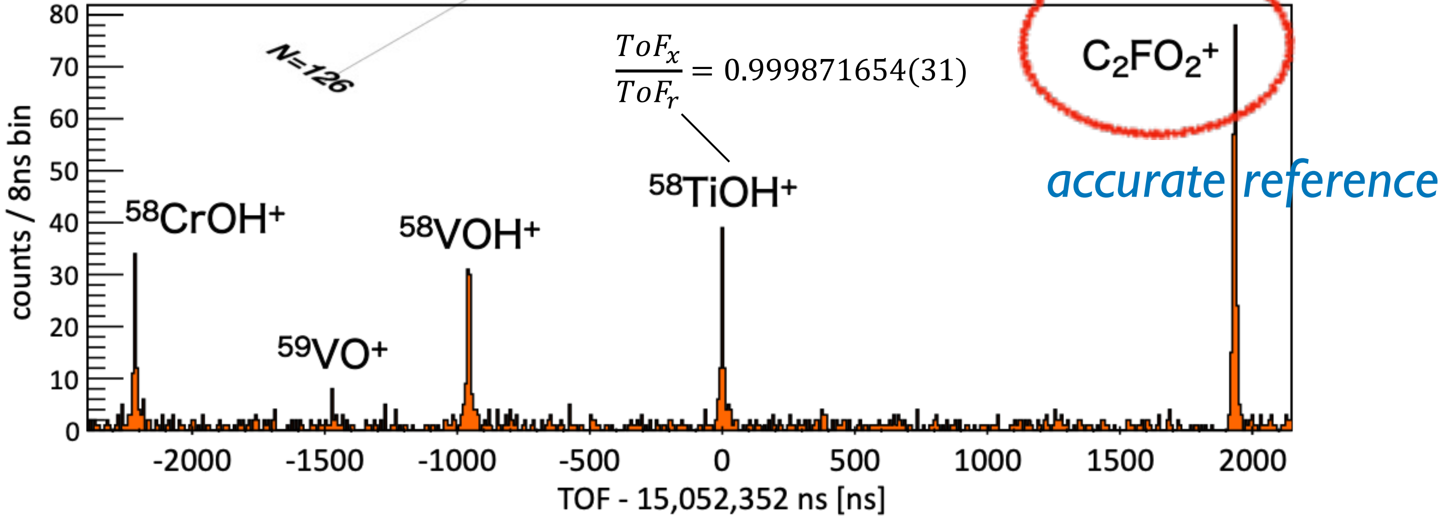
(2-neutron shell gap energy: double differentiation between N, N±2 isotopes)

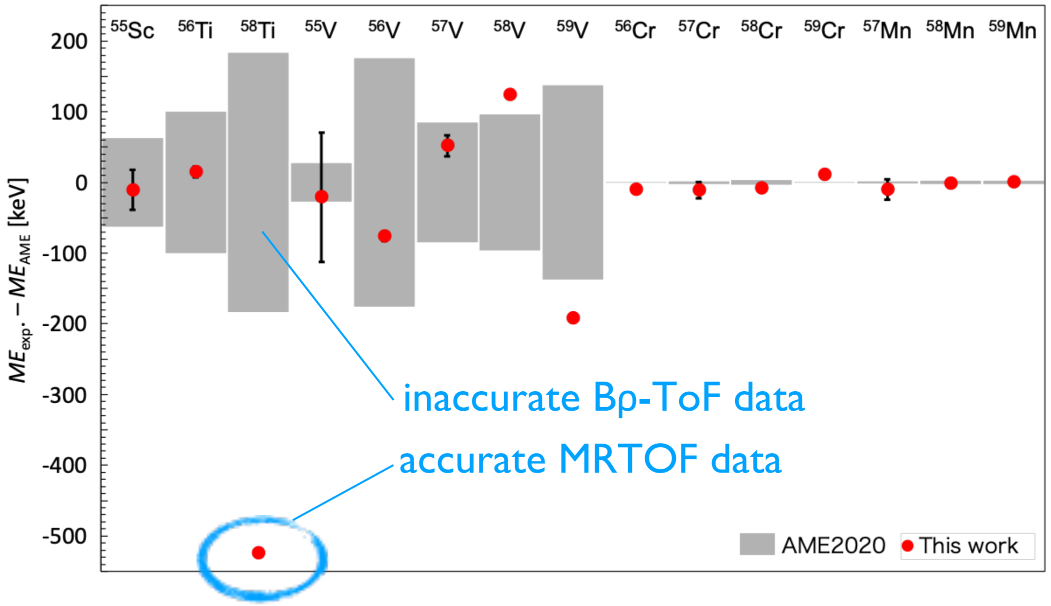
$$\Delta_{2n} = \{m(N) - m(N-2)\} - \{m(N+2) - m(N)\}$$

gray scale: precision of Δ_{2n}



no magic for T, V as Sc, Cr

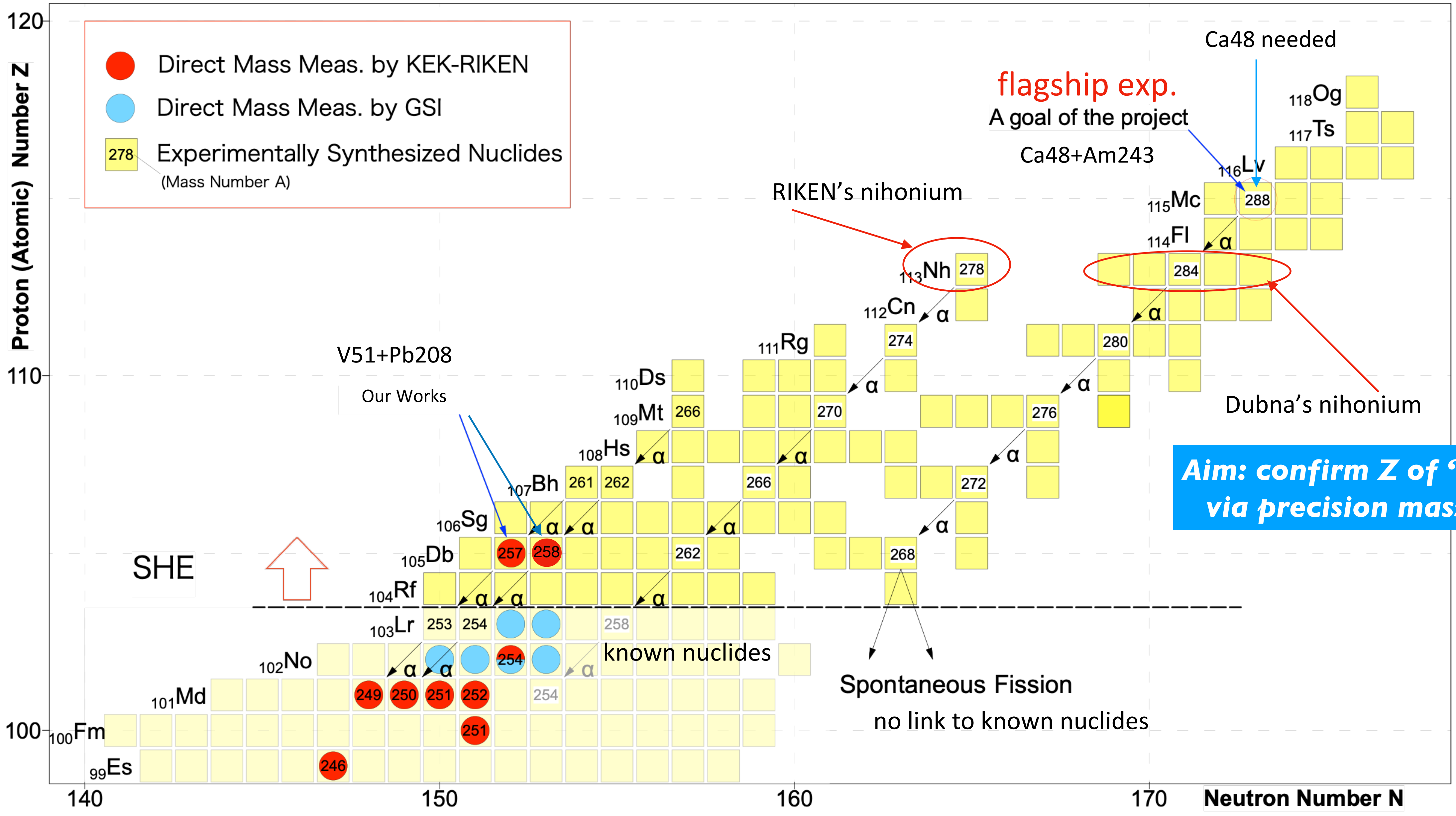




Comparison of this work with AME2020

A previous study showed that a new magic number of N=34, found in Ca isotopes, was present in Ti and V isotopes, even though it was absent in Sc. The high precision and accuracy of the mass measurement in this study proved that there is no magic number nature in Ti and V isotopes.

Mass Measurement of Superheavy elements @ GARIS-II MRTOF

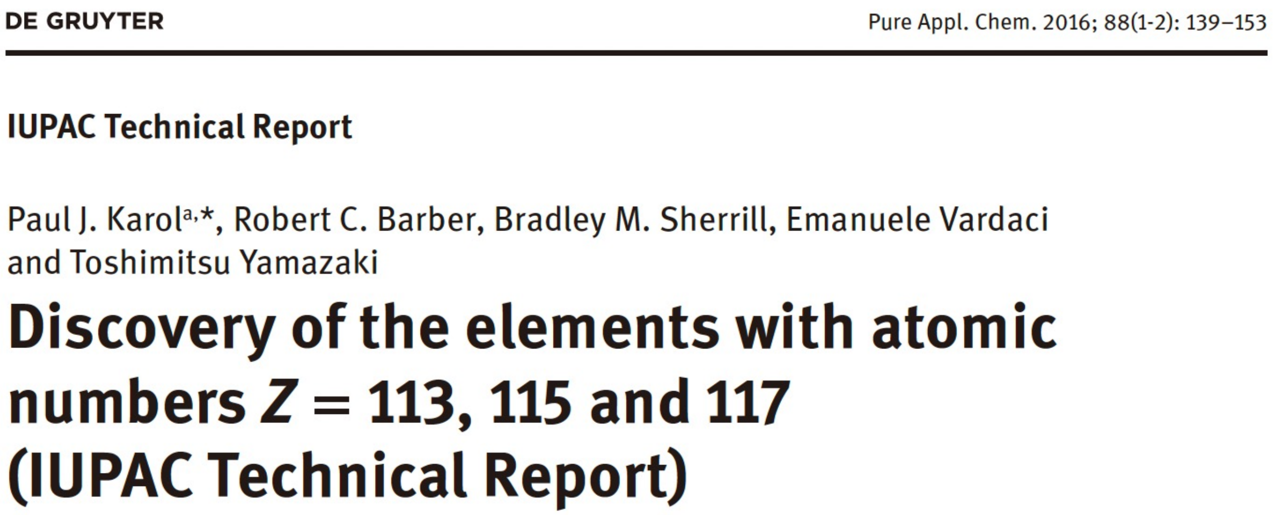


Aim: confirm Z of "hot fusion" SHNs via precision mass measurements.

- ***Proposed even before Nh granted.***
- ***PAC provided "S"-grade with 40 days MT***
- ***Setup has been ready for exp., however, difficult to obtain Ca48.***

Dev. of a self-purification system with CANDLE project (ββ)

official report from
IUPAC+IUPAP JWG

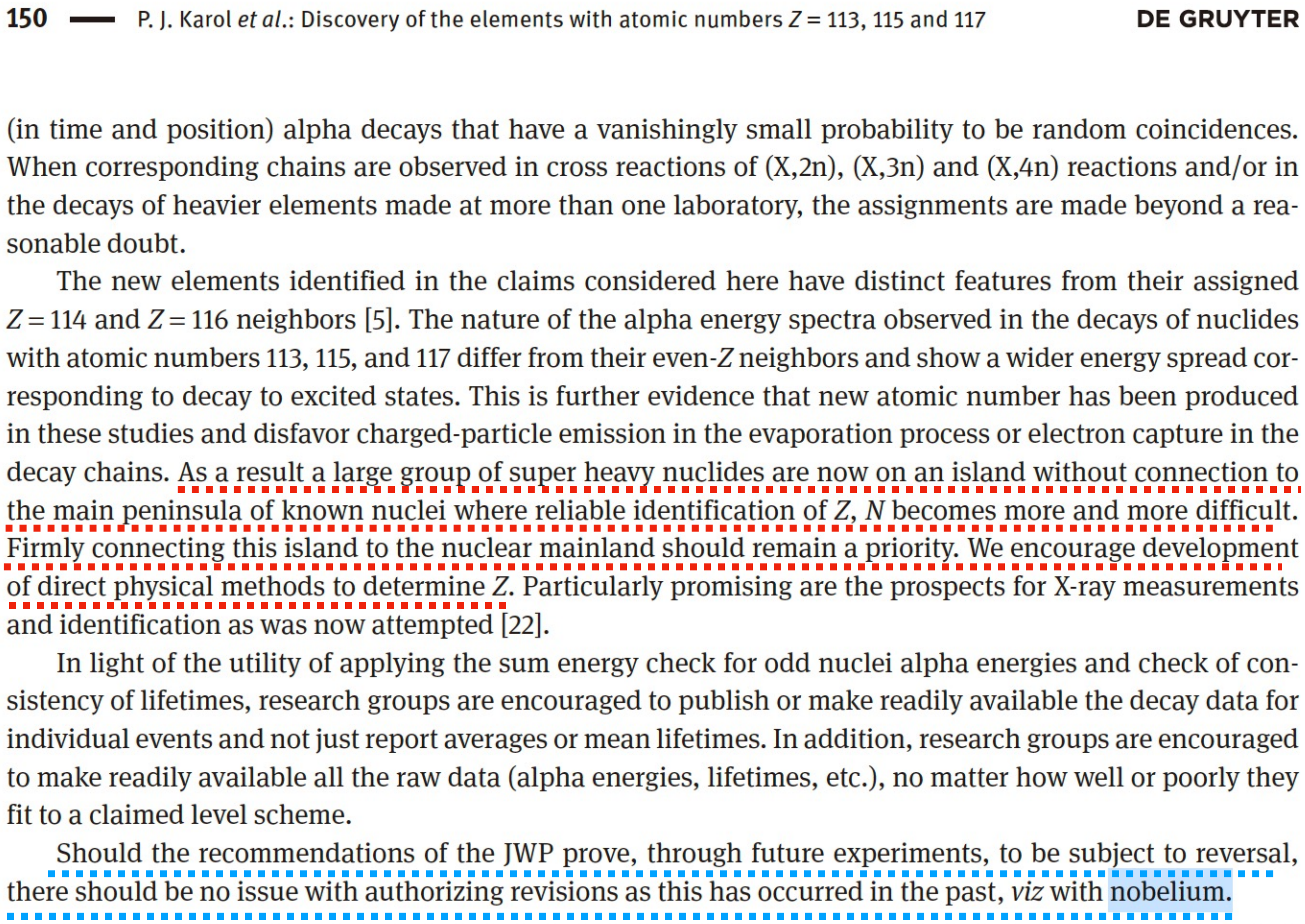


DE GRUYTER Pure Appl. Chem. 2016; 88(1-2): 139–153

IUPAC Technical Report

Paul J. Karol[a],*, Robert C. Barber, Bradley M. Sherrill, Emanuele Vardaci
and Toshimitsu Yamazaki

Discovery of the elements with atomic numbers $Z = 113$, 115 and 117 (IUPAC Technical Report)



150 — P. J. Karol *et al.*: Discovery of the elements with atomic numbers $Z = 113$, 115 and 117 **DE GRUYTER**

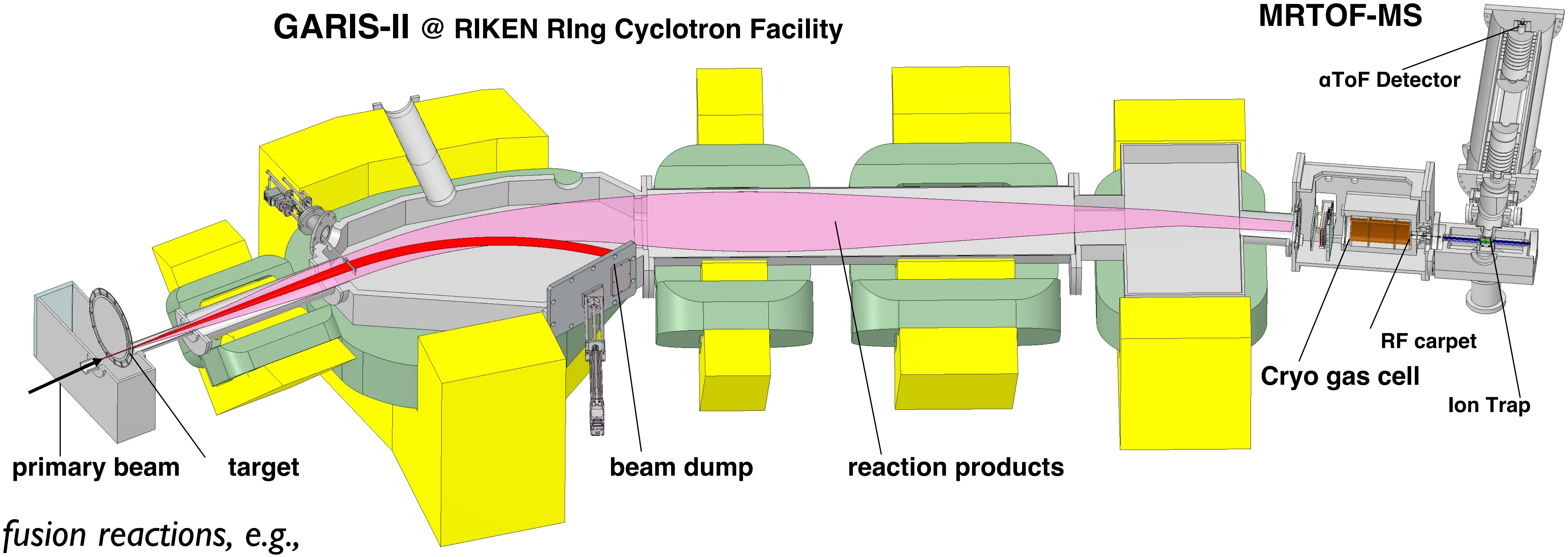
(in time and position) alpha decays that have a vanishingly small probability to be random coincidences. When corresponding chains are observed in cross reactions of (X,2n), (X,3n) and (X,4n) reactions and/or in the decays of heavier elements made at more than one laboratory, the assignments are made beyond a reasonable doubt.

The new elements identified in the claims considered here have distinct features from their assigned $Z = 114$ and $Z = 116$ neighbors [5]. The nature of the alpha energy spectra observed in the decays of nuclides with atomic numbers 113, 115, and 117 differ from their even-Z neighbors and show a wider energy spread corresponding to decay to excited states. This is further evidence that new atomic number has been produced in these studies and disfavor charged-particle emission in the evaporation process or electron capture in the decay chains. As a result a large group of super heavy nuclides are now on an island without connection to the main peninsula of known nuclei where reliable identification of Z, N becomes more and more difficult. Firmly connecting this island to the nuclear mainland should remain a priority. We encourage development of direct physical methods to determine Z. Particularly promising are the prospects for X-ray measurements and identification as was now attempted [22].

In light of the utility of applying the sum energy check for odd nuclei alpha energies and check of consistency of lifetimes, research groups are encouraged to publish or make readily available the decay data for individual events and not just report averages or mean lifetimes. In addition, research groups are encouraged to make readily available all the raw data (alpha energies, lifetimes, etc.), no matter how well or poorly they fit to a claimed level scheme.

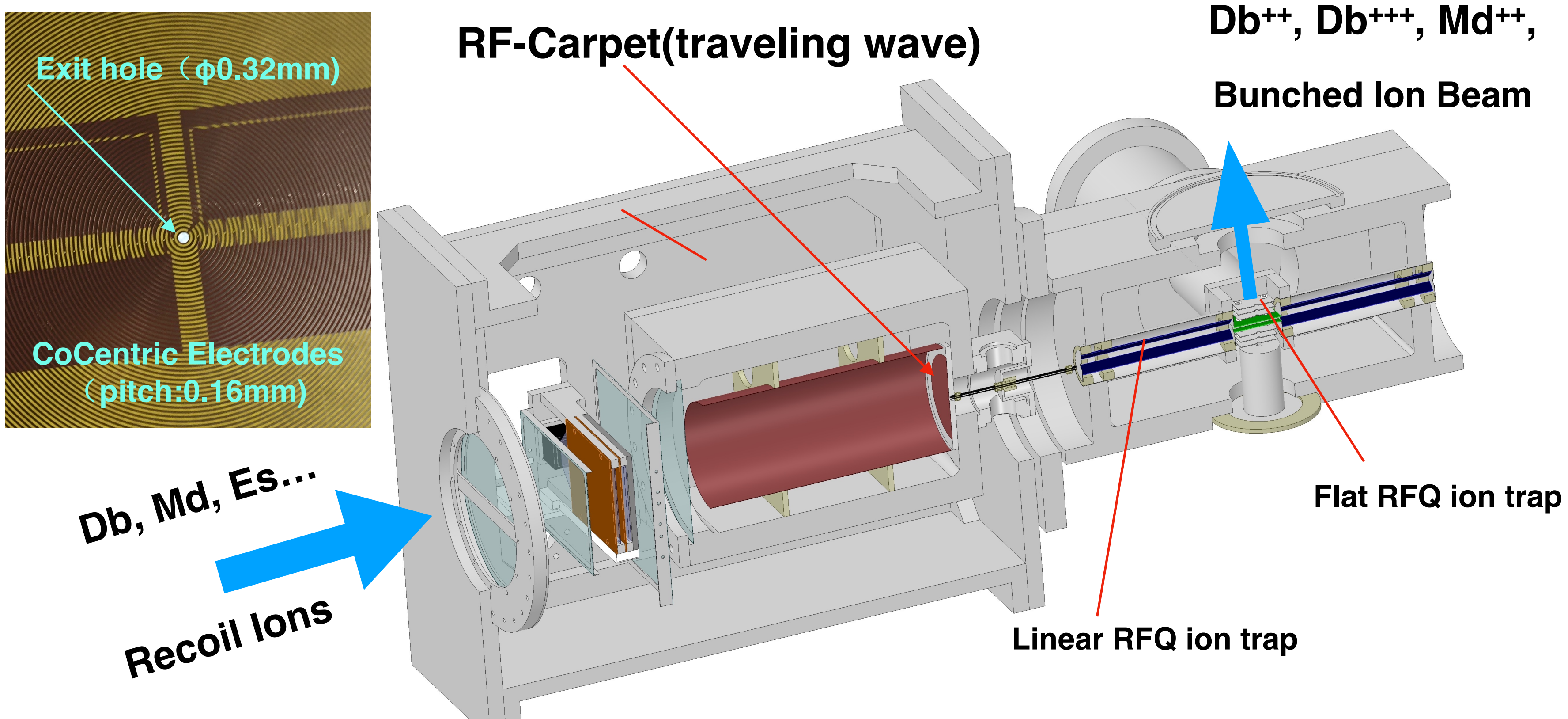
Should the recommendations of the JWP prove, through future experiments, to be subject to reversal, there should be no issue with authorizing revisions as this has occurred in the past, *viz* with nobelium.

Experimental Setup at GARIS-II *(the structure and the location have been changed for several times)*

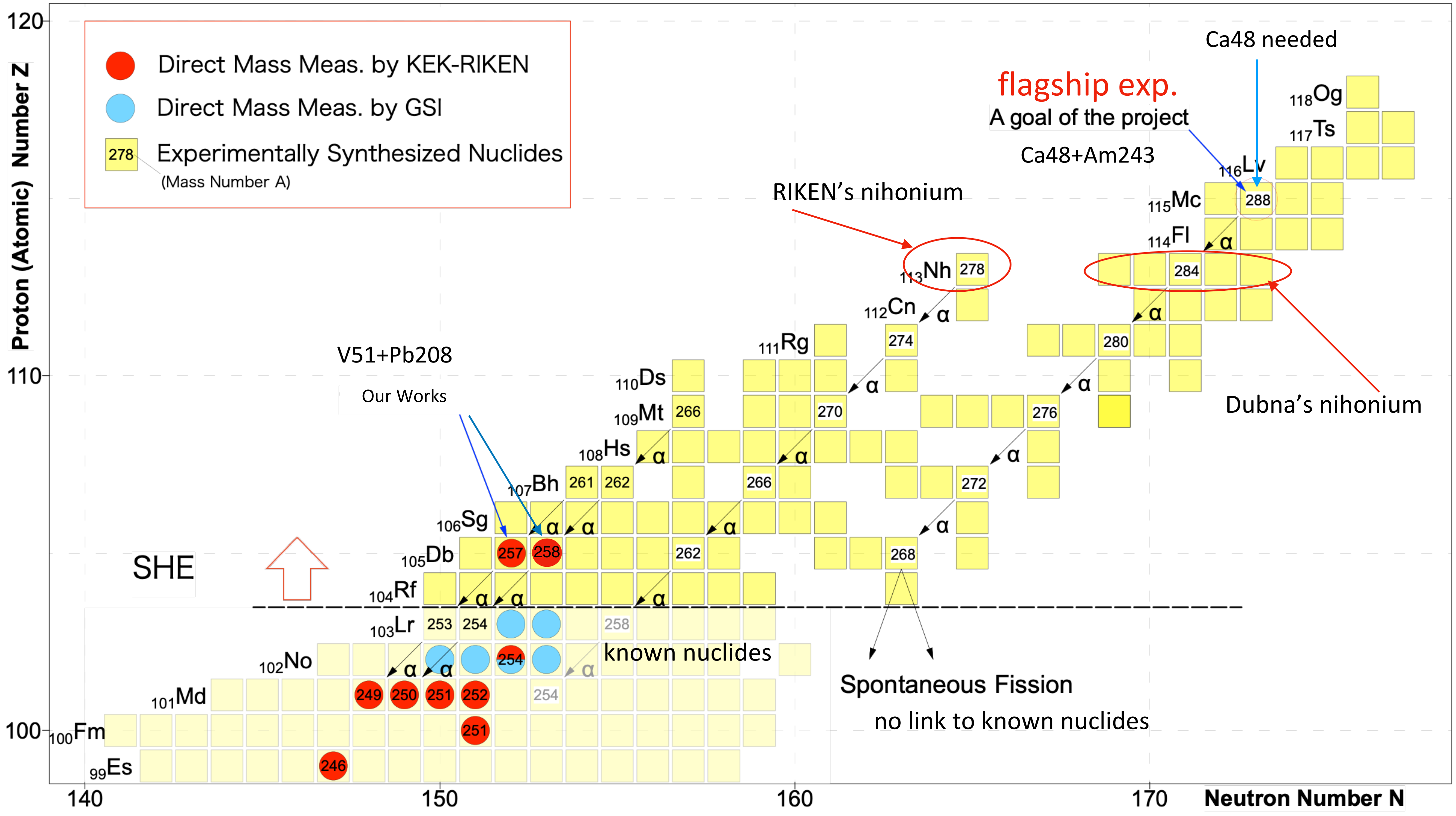


fusion reactions, e.g.,

$$^{243}\mathrm{Am} + {}^{48}\mathrm{Ca} \rightarrow {}^{288}113 + 3n$$



Mass Measurement of Superheavy elements @ GARIS-II MRTOF



V51+Pb208

Our Works

known nuclides

Spontaneous Fission

no link to known nuclides

RIKEN's nihonium

Dubna's nihonium

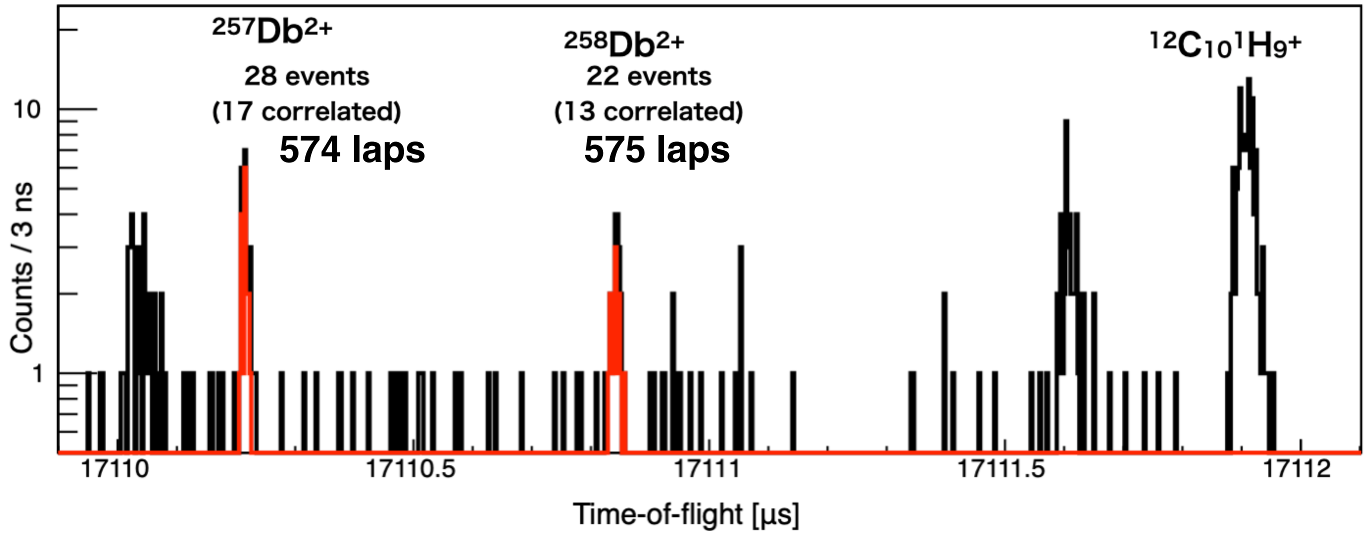
flagship exp.

A goal of the project

Ca48+Am243

Ca48 needed

ToF Singles Spectrum for Db isotopes



- ***Setup has been ready for exp., however, difficult to obtain Ca48.***

  Dev. of a self-purification system with CANDLE project

- ***First SHE mass Db in NP2020-LINAC07***

  P. Schury et al,PRC104,L021304(2021) & one in preparation

- ***a-ToF detector R&D exp. for Ra isotopes***

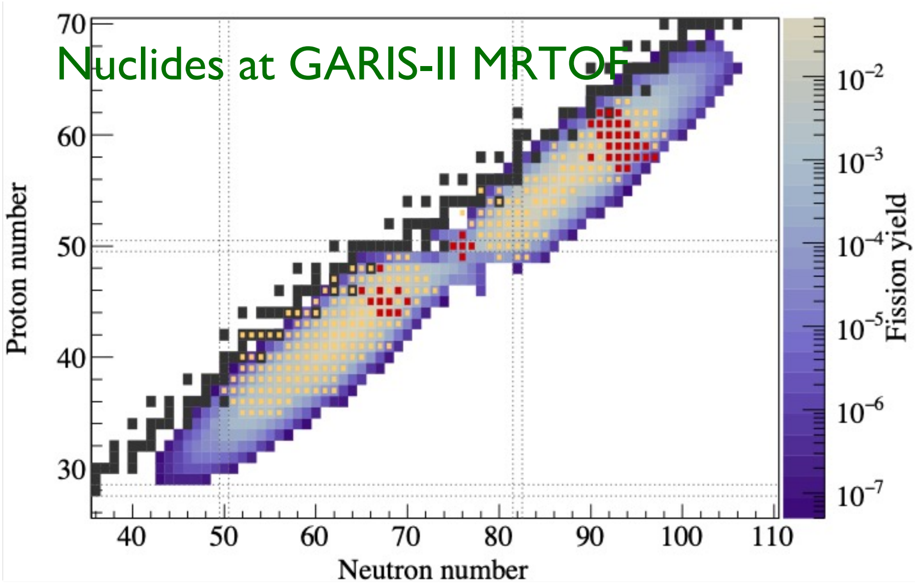
  T. Niwase et al,NIMA 953(2020)163198

  T. Niwase et al, PRC104(2021)044617

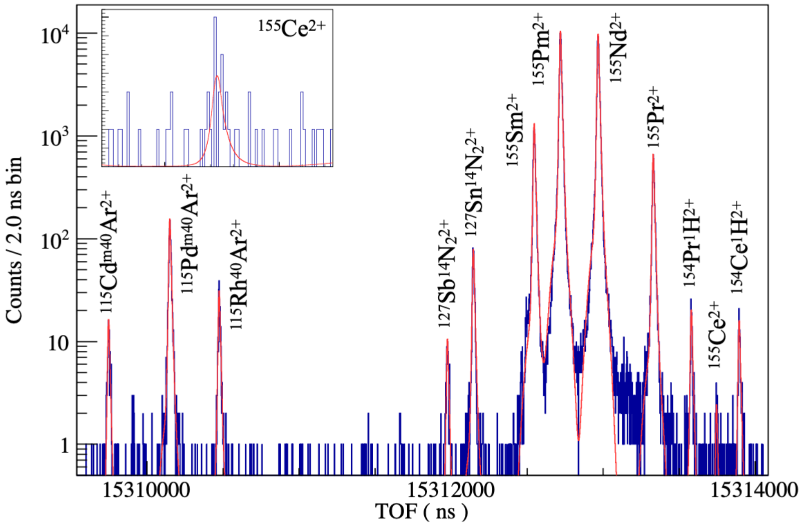
  independent $T_{1/2}$ determination of ^{206,207g,m}Ra and branching ratios

Off-line studies with Fission Source (252Cf, 248Cm)

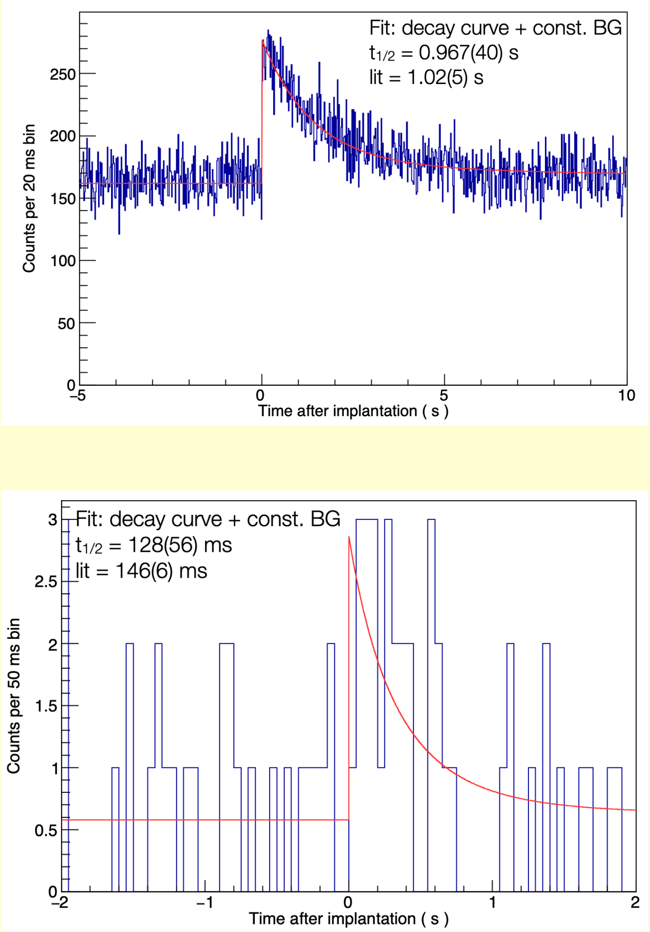
S. Kimura et al, submitting to PRC



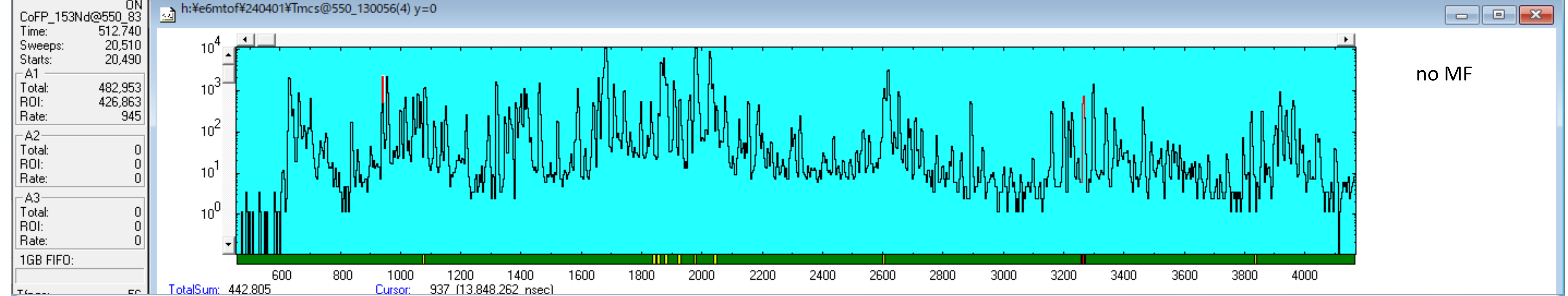
ToF of new mass for Ce155



Decay spectra with beta-ToF detector



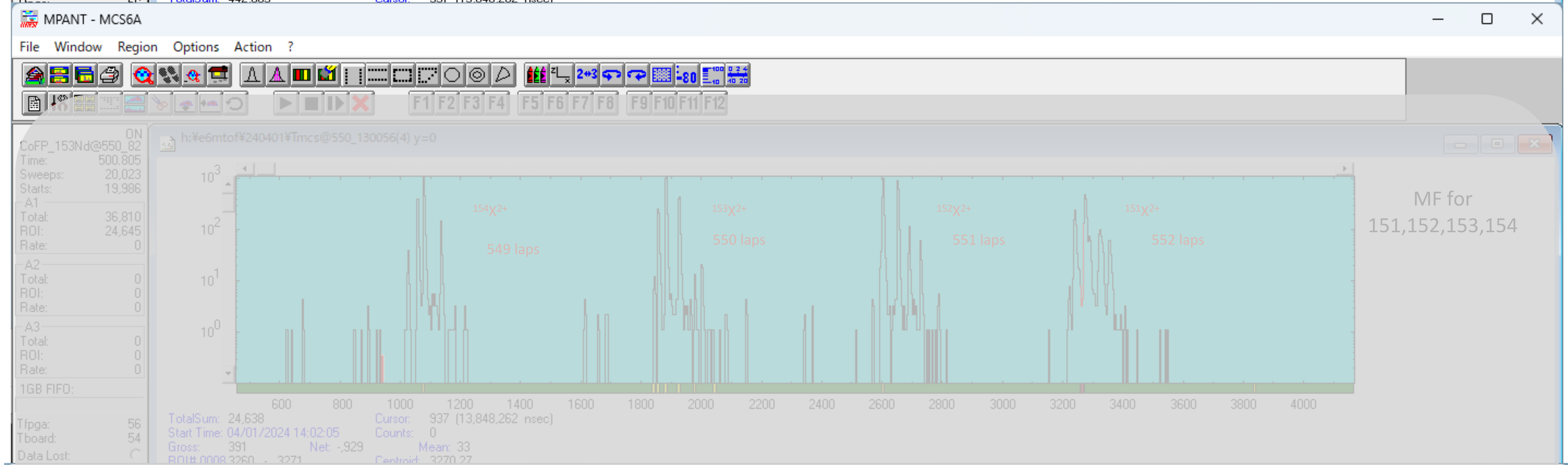
- *>300 Nuclide's Mass were measured (a few 1st masses, several improved masses).*
- *High accuracy with isobars and molecular ions in the same A/q.*
- *beta-ToF detector allows T1/2 determination and confirms short-lived nuclides (not molecular bg).*
- *New atomic physics studies with variety of elements, nuclear spins at very constant yields.*
- *Health check of the gas cell and total system*



no MF

ON
CoFP_153Nd@550_83
Time: 512.740
Sweeps: 20,510
Starts: 20,490
A1
Total: 482,953
ROI: 426,863
Rate: 945
A2
Total: 0
ROI: 0
Rate: 0
A3
Total: 0
ROI: 0
Rate: 0
1GB FIFO:

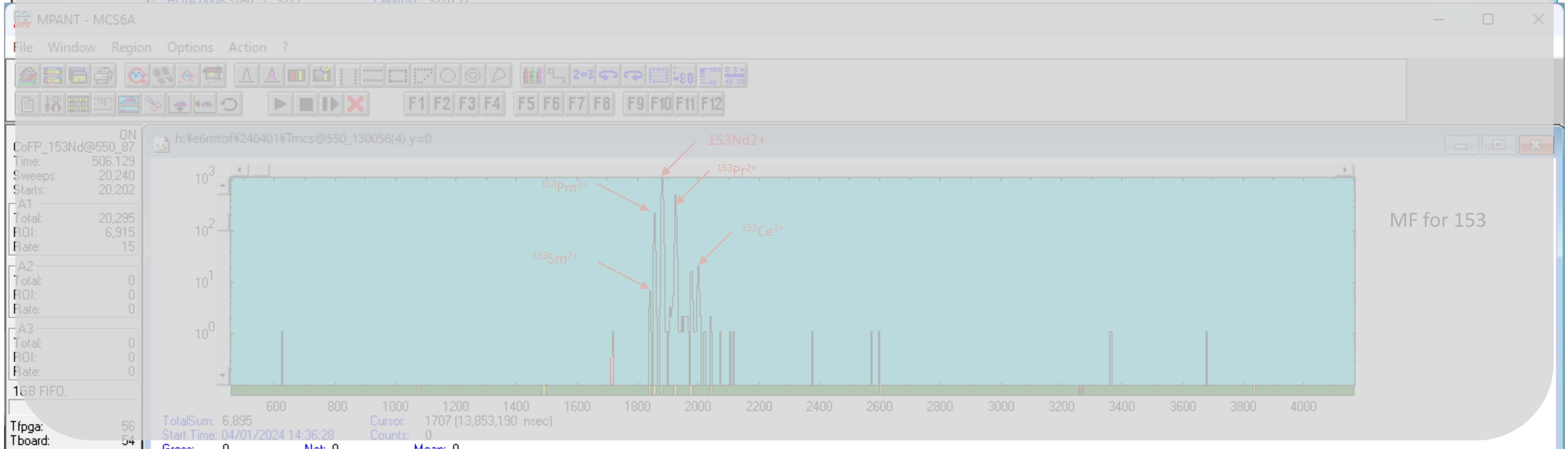
TotalSum: 442,805
Cursor: 937 (13,848,262 nsec)



MF for 151,152,153,154

ON
CoFP_153Nd@550_82
Time: 500.805
Sweeps: 20,023
Starts: 19,986
A1
Total: 36,810
ROI: 24,645
Rate: 0
A2
Total: 0
ROI: 0
Rate: 0
A3
Total: 0
ROI: 0
Rate: 0
1GB FIFO:
Tfpga: 56
Tboard: 54
Data Lost:

TotalSum: 24,638
Start Time: 04/01/2024 14:02:05
Gross: 391
Net: -,929
ROI# 0008 3260 - 3271
Cursor: 937 (13,848,262 nsec)
Counts: 0
Mean: 33
Centroid: 3270.27



MF for 153

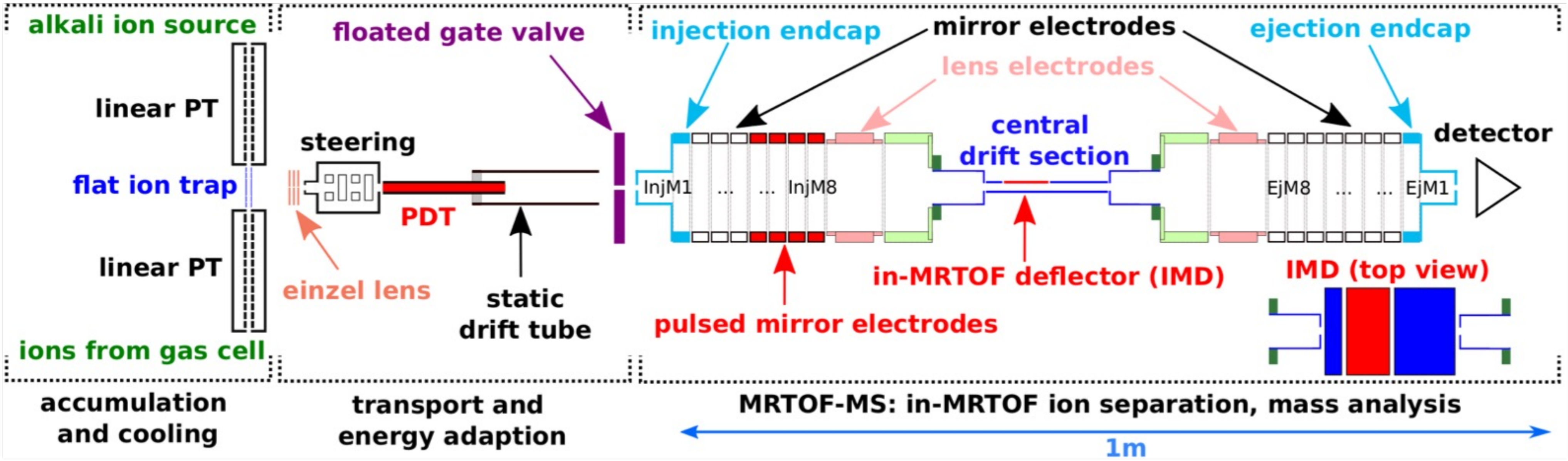
ON
CoFP_153Nd@550_87
Time: 506.129
Sweeps: 20,240
Starts: 20,202
A1
Total: 20,295
ROI: 6,915
Rate: 15
A2
Total: 0
ROI: 0
Rate: 0
A3
Total: 0
ROI: 0
Rate: 0
1GB FIFO:
Tfpga: 56
Tboard: 54

TotalSum: 6,895
Start Time: 04/01/2024 14:36:28
Gross: 0
Net: 0
Cursor: 1707 (13,853,190 nsec)
Counts: 0
Mean: 0

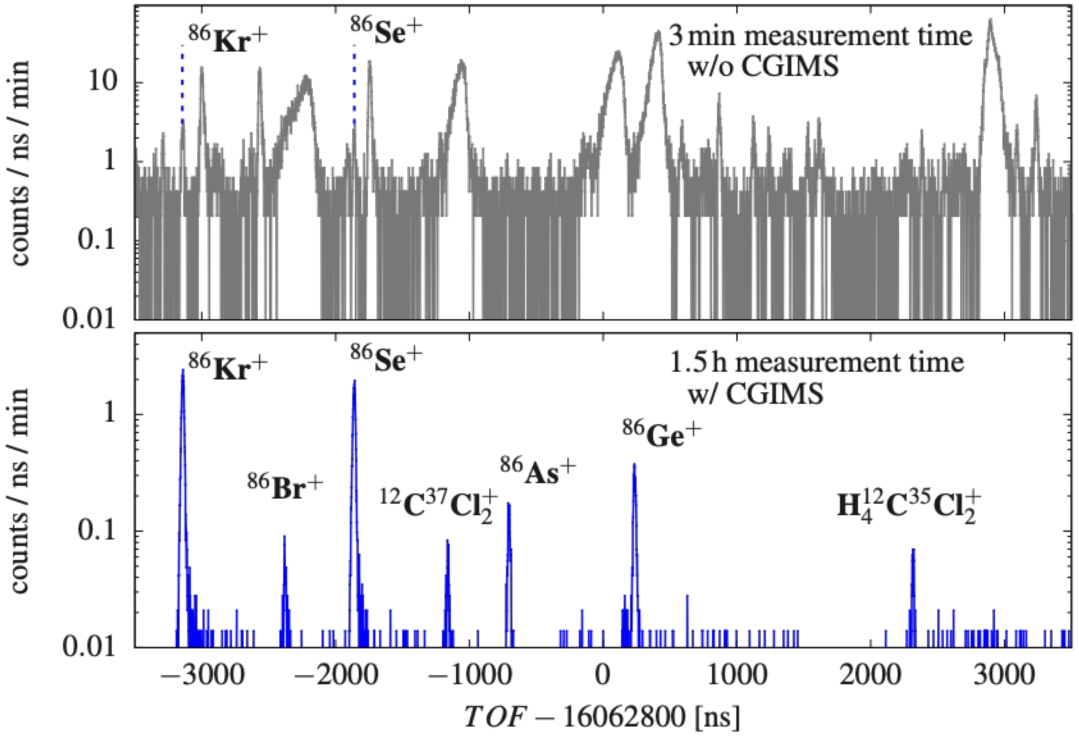
How to eliminate garbage ions?

M. Rosenbusch et al, NIMA1047, 167824 (2023)

In-MRTOF deflector



- A deflector in the flight tube of MRTOF with sophisticate pulse train kicks out unwanted mass/q ions
- Multiple (~5) sets of A/q numbers can be selected

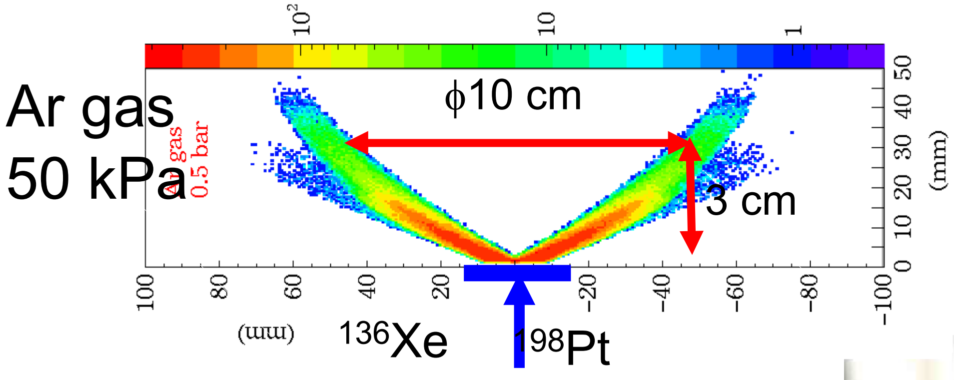


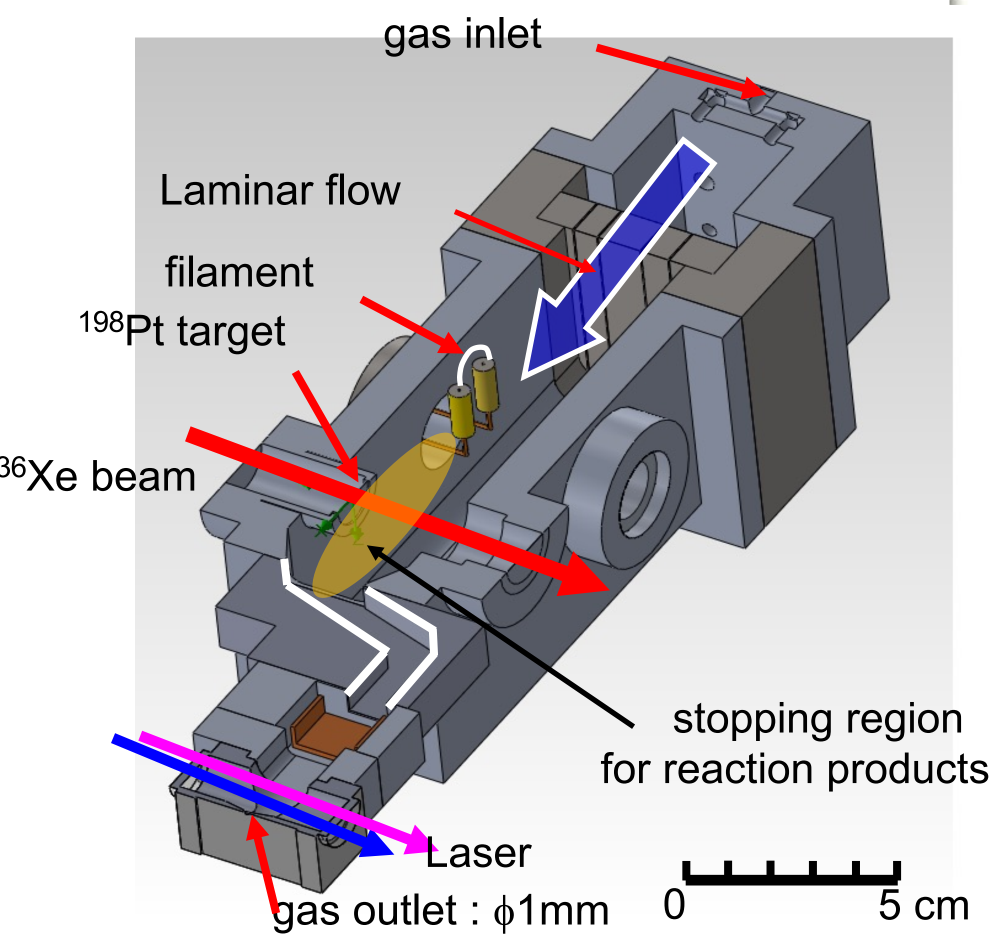
KISS: **First** and **unique** ISOL facility for online precision spectroscopy with MNT

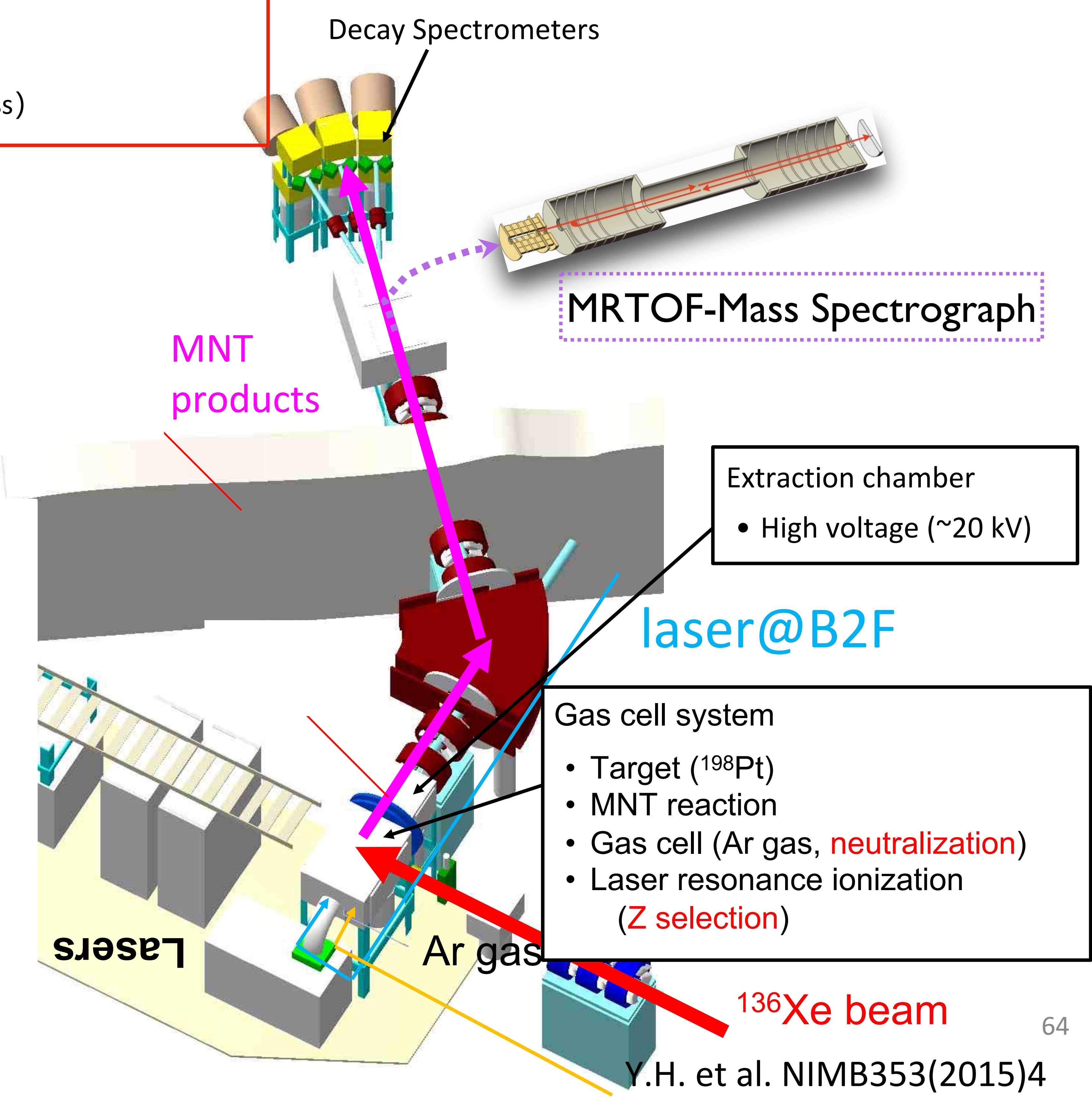
Miyatake, Jeong et al

1. MNT fragments thermalize and neutralize in Ar
2. Element selection via resonant laser ionization
3. Mass separation via magnetic separator
4. precision spectroscopy with pure nuclide (β, γ, mass)

MNT reaction: ^{136}Xe beam + ^{198}Pt target







Extraction chamber

- High voltage (~20 kV)

Gas cell system

- Target (^{198}Pt)
- MNT reaction
- Gas cell (Ar gas, neutralization)
- Laser resonance ionization (Z selection)

Y.H. et al. NIMB353(2015)4
NIMB376(2016)52

Nuclear spectroscopy at KISS

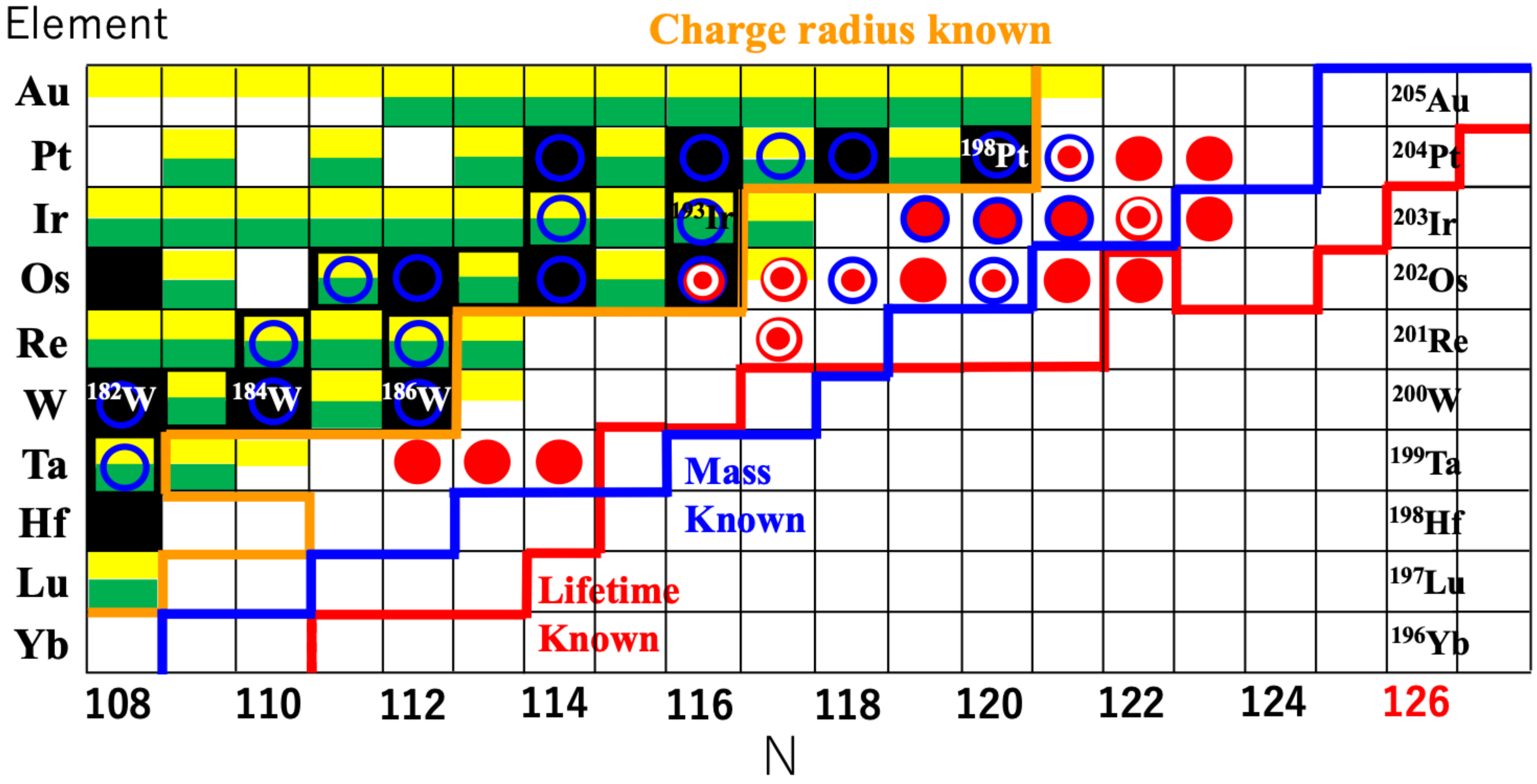
^{198}Pt, $^{nat.}$Pt, $^{nat.}$W targets

■ Stable μ Q Known

● β-γ spectroscopy at KISS

◉ Mass at KISS

○ Laser spectroscopy at KISS

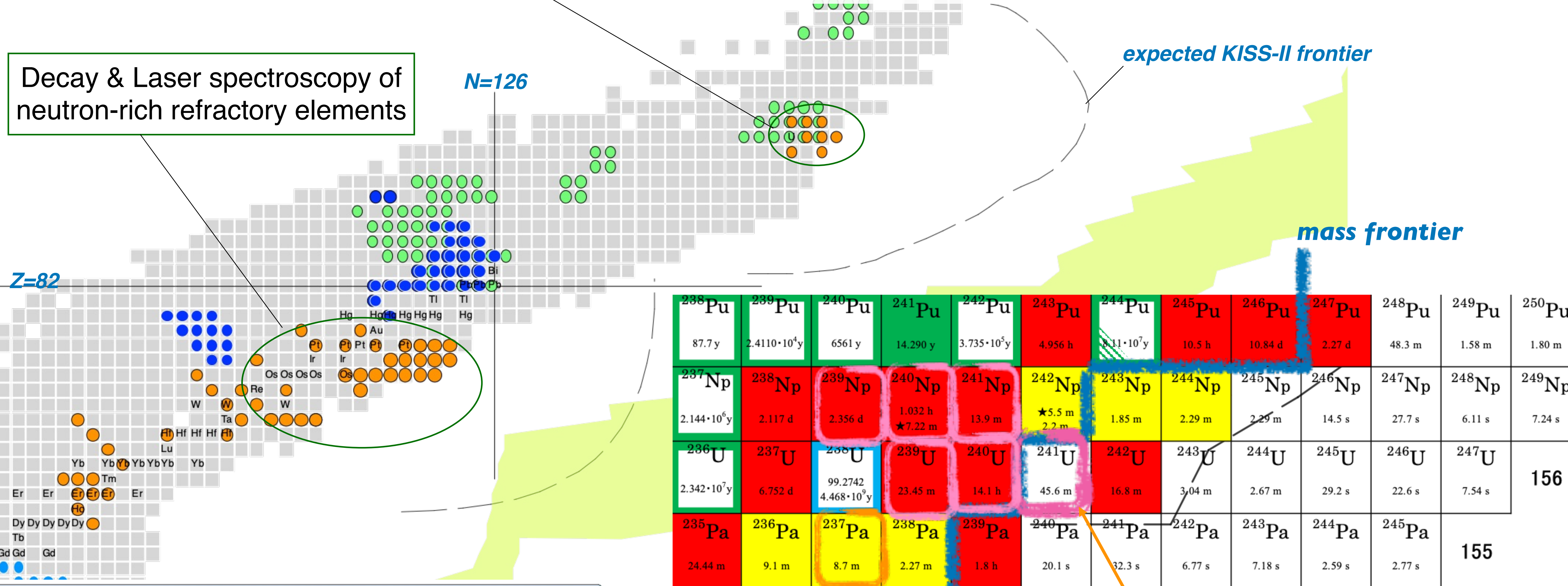


Not yet reached N=126, though ← Low primary beam intensity (10 pnA)
Low gas cell efficiency (0.1%)

- Laser Spectroscopy （Charge radii, moments）
  - βγ spectroscopy for “difficult” refractory elements (T1/2, Decay mode)
- Mass Spectroscopy with MRTOF

Steady Scientific Results have been obtained

Discovery of a new U isotope at KISS MRTOF via mass spectrometry



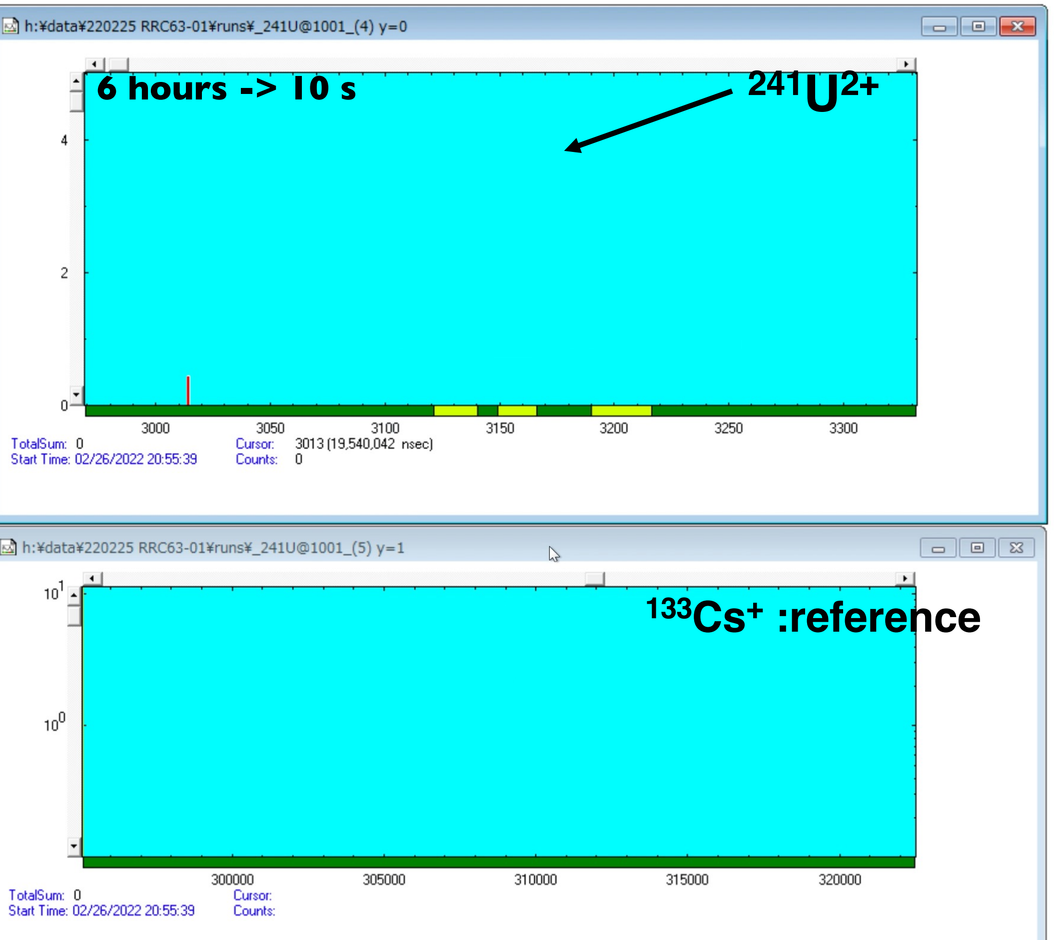
Decay & Laser spectroscopy of neutron-rich refractory elements

expected KISS-II frontier

mass frontier

^{238}Pu 87.7 y	^{239}Pu 2.4110·10^{4}y	^{240}Pu 6561 y	^{241}Pu 14.290 y	^{242}Pu 3.735·10^{5}y	^{243}Pu 4.956 h	^{244}Pu 8.11·10^{7}y	^{245}Pu 10.5 h	^{246}Pu 10.84 d	^{247}Pu 2.27 d	^{248}Pu 48.3 m	^{249}Pu 1.58 m	^{250}Pu 1.80 m
^{237}Np 2.144·10^{6}y	^{238}Np 2.117 d	^{239}Np 2.356 d	^{240}Np 1.032 h ★7.22 m	^{241}Np 13.9 m	^{242}Np ★5.5 m 2.2 m	^{243}Np 1.85 m	^{244}Np 2.29 m	^{245}Np 2.29 m	^{246}Np 14.5 s	^{247}Np 27.7 s	^{248}Np 6.11 s	^{249}Np 7.24 s
^{236}U 2.342·10^{7}y	^{237}U 6.752 d	^{238}U 99.2742 4.468·10^{9}y	^{239}U 23.45 m	^{240}U 14.1 h	^{241}U 45.6 m	^{242}U 16.8 m	^{243}U 3.04 m	^{244}U 2.67 m	^{245}U 29.2 s	^{246}U 22.6 s	^{247}U 7.54 s	156
^{235}Pa 24.44 m	^{236}Pa 9.1 m	^{237}Pa 8.7 m	^{238}Pa 2.27 m	^{239}Pa 1.8 h	^{240}Pa 20.1 s	^{241}Pa 32.3 s	^{242}Pa 6.77 s	^{243}Pa 7.18 s	^{244}Pa 2.59 s	^{245}Pa 2.77 s	155	
^{234}Th 24.10 d	^{235}Th 7.2 m	^{236}Th 37.3 m	^{237}Th 4.8 m	^{238}Th 9.4 m	^{239}Th 35.4 s	^{240}Th 33.0 s	^{241}Th 7.08 s	^{242}Th 5.76 s	153	154		

new nuclide discovered by mass measurement



h:¥data¥220225 RRC63-01¥runs¥_241U@1001_(4) y=0

6 hours -> 10 s

^{241}U^{2+}

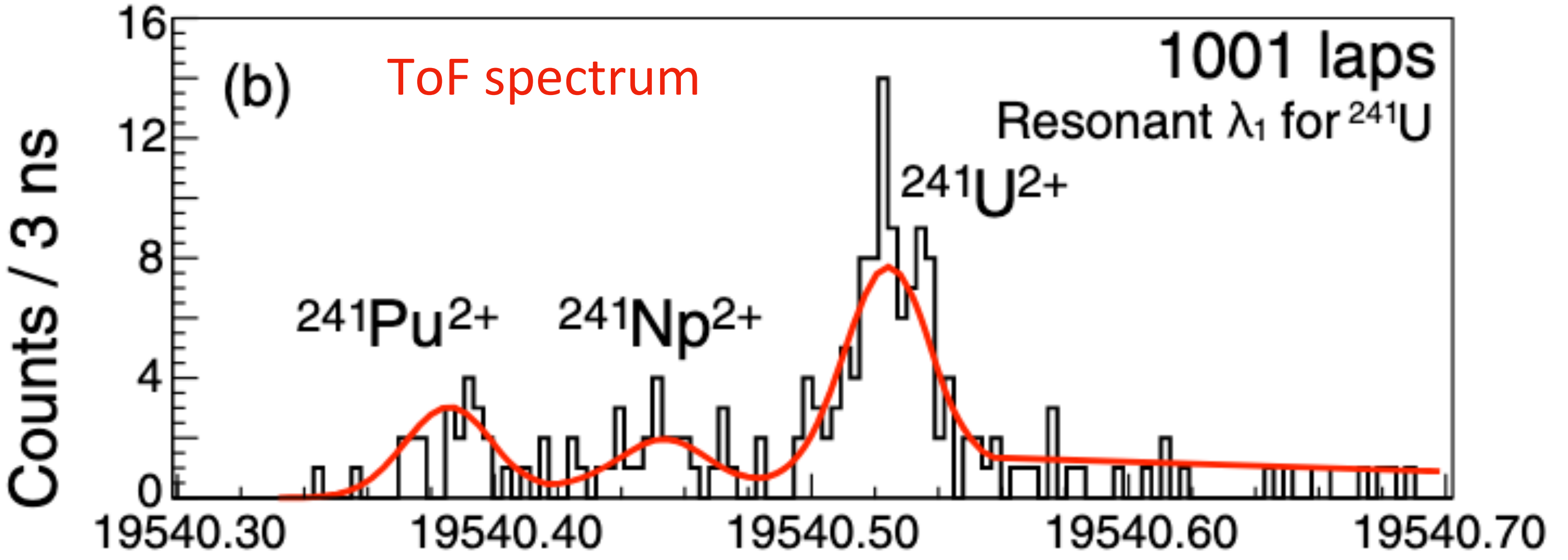
TotalSum: 0
Start Time: 02/26/2022 20:55:39
Cursor: 3013 (19,540,042 nsec)
Counts: 0

h:¥data¥220225 RRC63-01¥runs¥_241U@1001_(5) y=1

^{133}Cs^{+} :reference

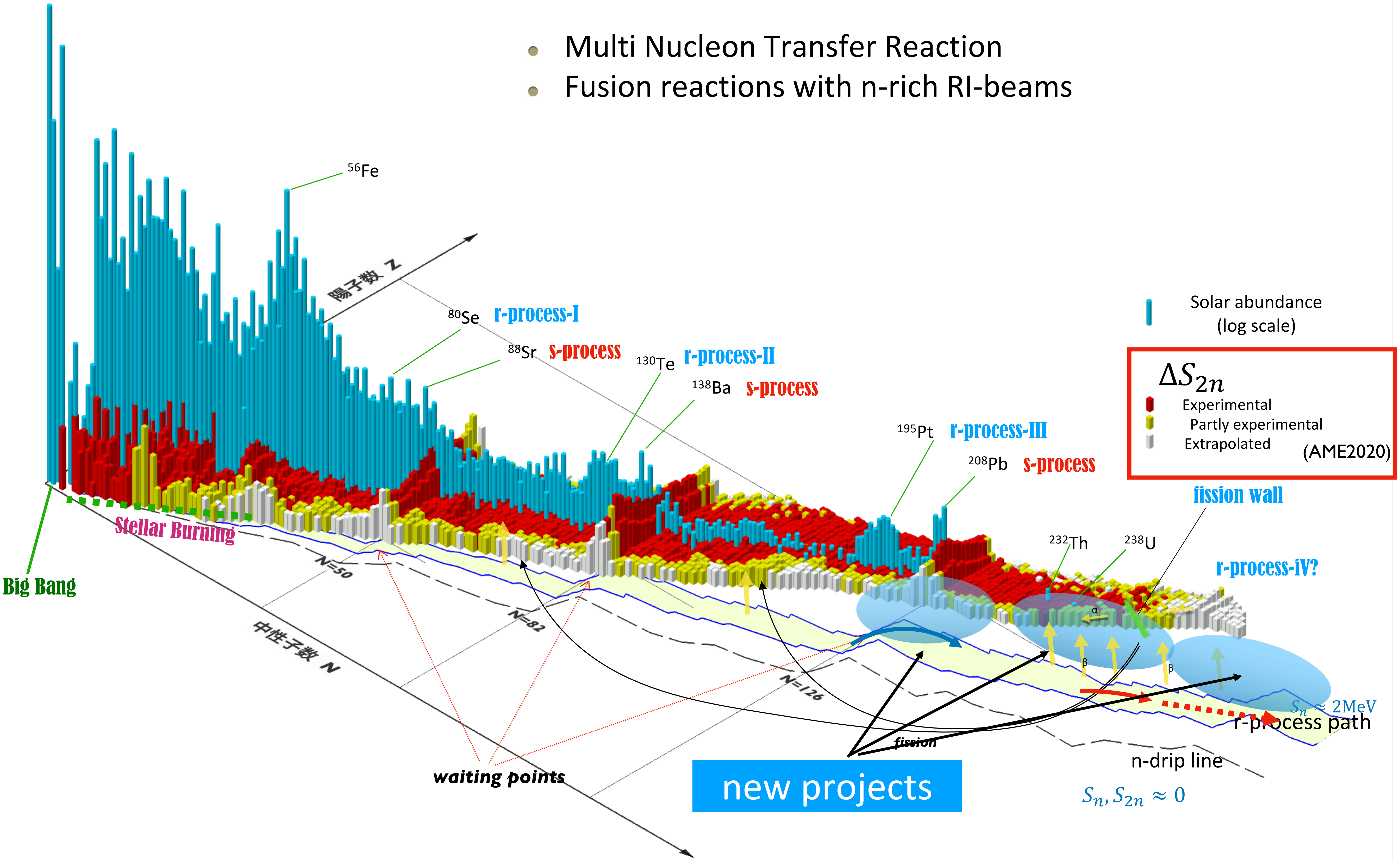
TotalSum: 0
Start Time: 02/26/2022 20:55:39
Cursor:
Counts:

T. Niwase, Y. Watanabe et al, PRL130,132502(2023)



How to access N=126, origin of Th U, end of r-process?

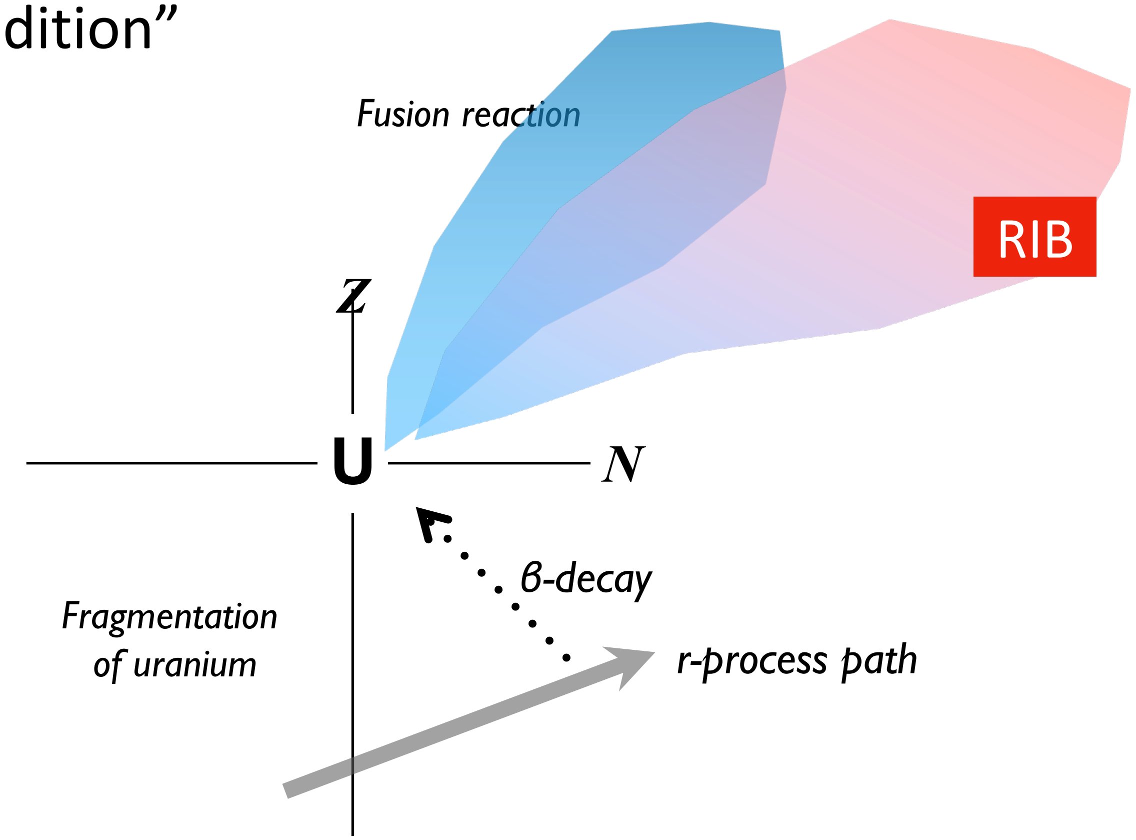
- Multi Nucleon Transfer Reaction
- Fusion reactions with n-rich RI-beams



How to access progenitors of uranium and end of r-process ?

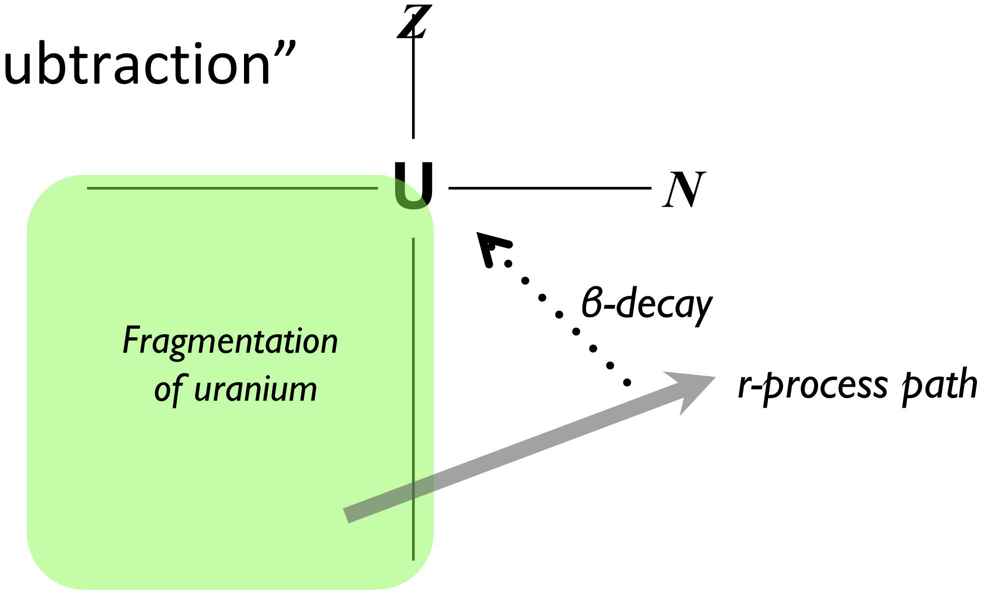
Fusion(~5 MeV/u)

“Addition”



Fragmentation/Spallation(~100 MeV/u)

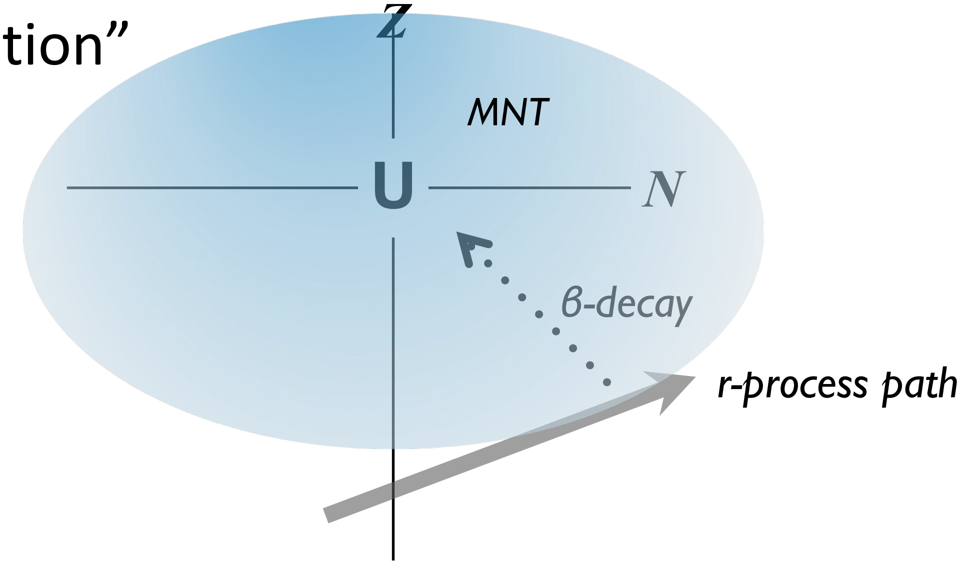
“Subtraction”



RIBF(RIKEN)
FRIB(USA), FAIR(Germany) etc

Multi-Nucleon Transfer (5~10 MeV/u)

“Addition” + ”Subtraction”



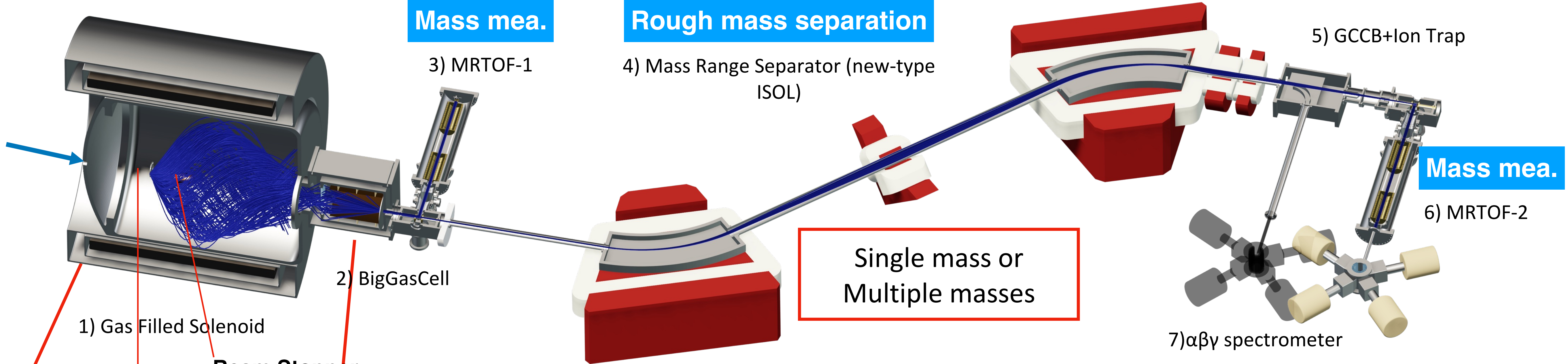
”Add” neutrons
”Subtract” protons
south-east of uranium

KISS, KISS-II
NEXT, N=126 factory,
STAR, HIAF-MNT?

KISS-II *“MNT reaction products, measure multiple species at once”*

- Primary beam separator： High intensity beam
- RF ion guide He gas cell： Efficient collection of all elements
- MRTOF： Multiple species, Tag for spectroscopy

	primary beam	total efficiency	#nuclides / unit time	total gain
KISS	10 pnA	0.1%	1	1
KISS-2	1000 pnA	>1%	>10	>10000
	primary separator	RF gas catcher	MRTOF	



Primary beam separation

Mass mea.

Rough mass separation

Single mass or Multiple masses

Mass mea.

Decay spectroscopy

Separate TLF of MNT and Primary beam

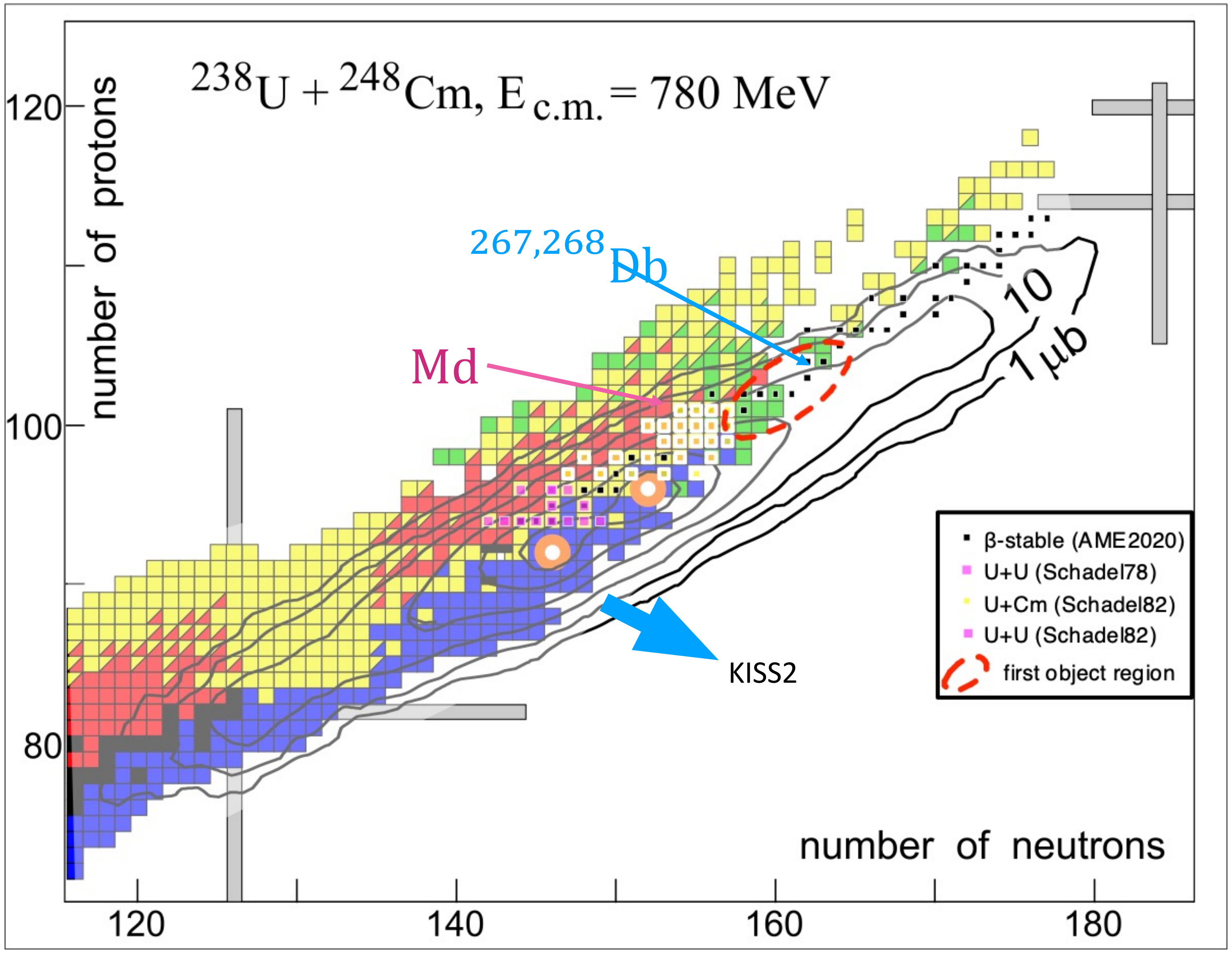
RF He gas cell for all elements

Spectroscopy with high pure nuclide or multiple nuclides with TAG by MRTOF

total budget: $15M in 5 (setup) + 5 (exp.) years , failed

KISS-1.5: $5M in 5 years, starting 2024 by Watanabe JSPS

Multi-Nucleon Transfer reaction towards SHN

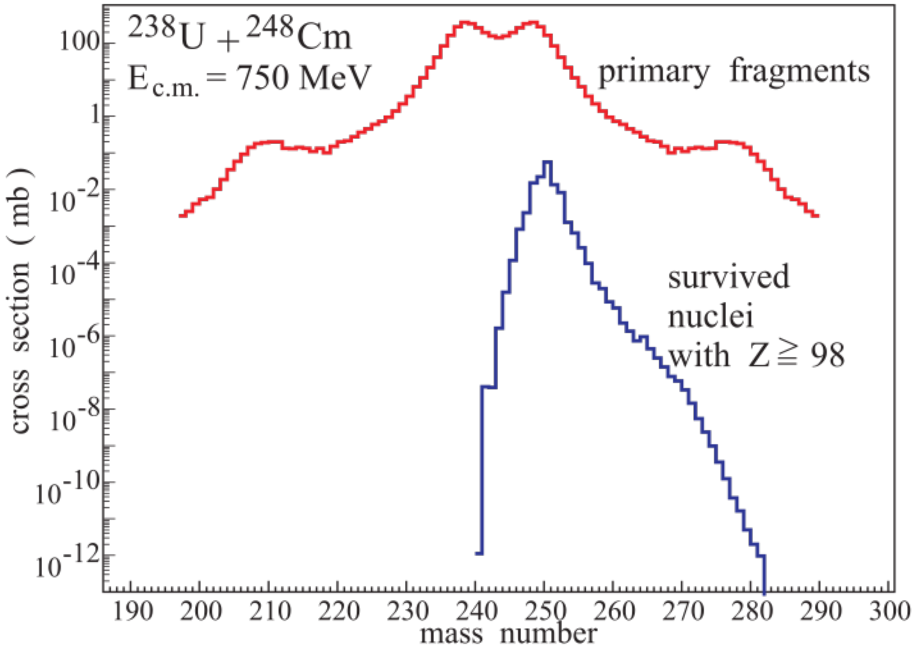


W. Greiner and V. Zagrevaev, Nucl. Phys. A 834, 323c (2010) , retouch by M.W.

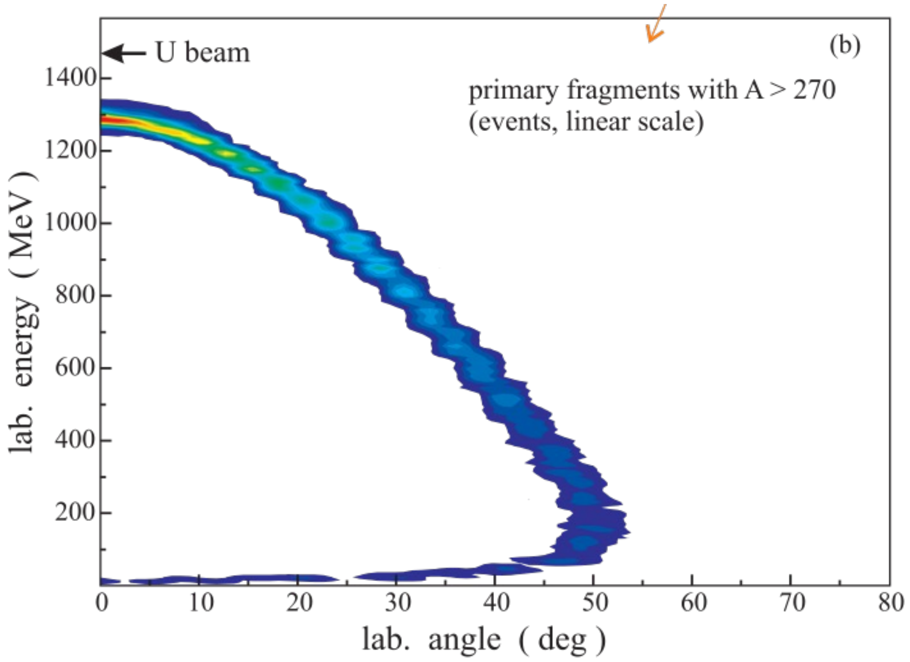
Radiochemical or Successive α-decay

are not applicable to β-decaying, long-lived nuclides

V.I. Zagrevaev and W. Greiner, Phys. Rev. C83, 044618 (2011).

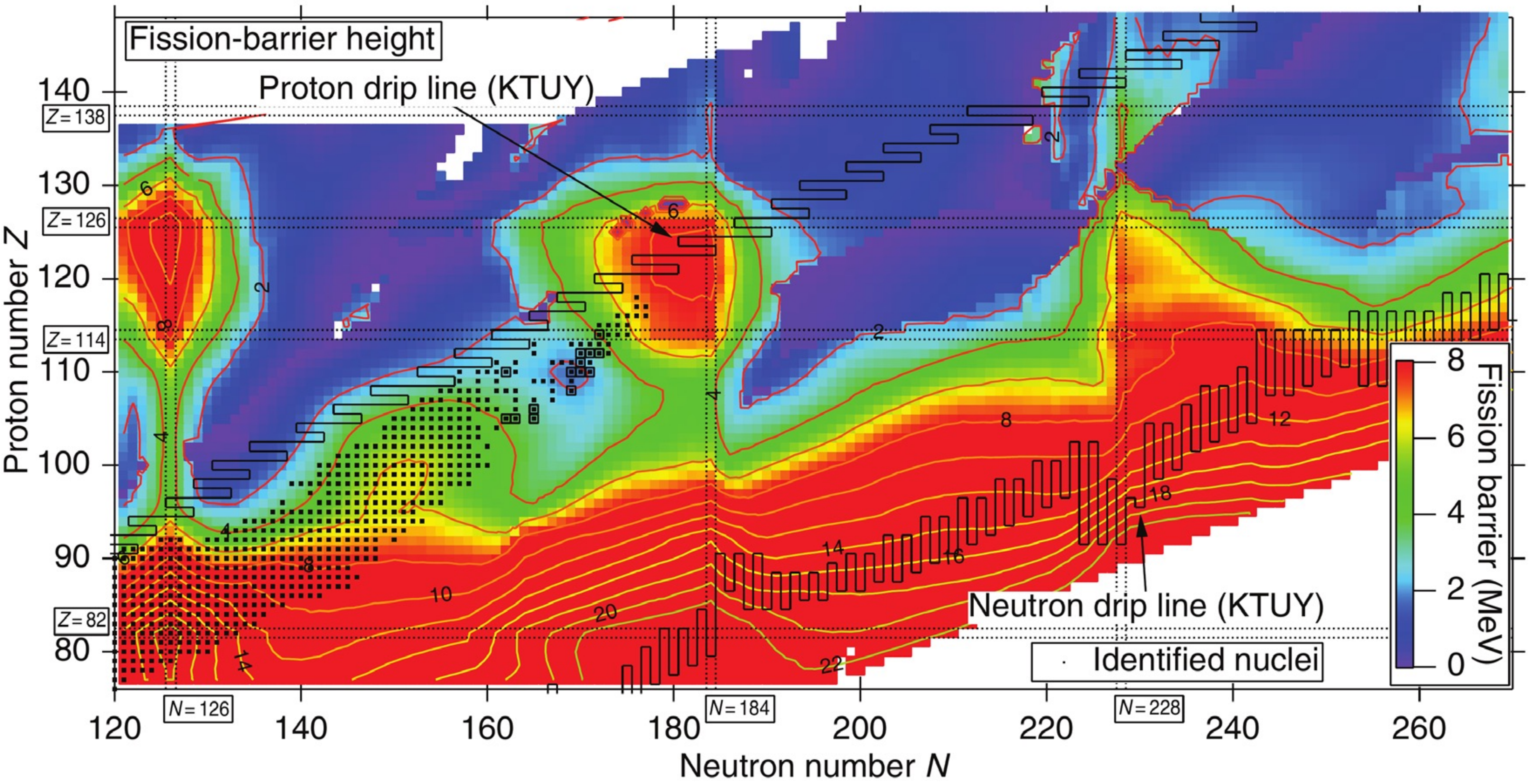


Survival probabilities are orders of mag. low



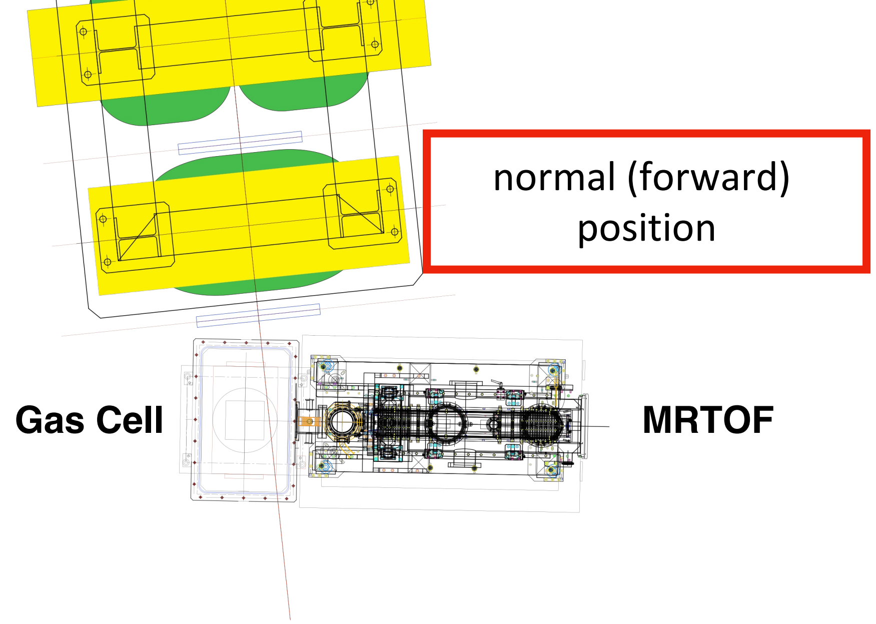
Heavy fragments go forward

Fission barrier increases approaching to IoS

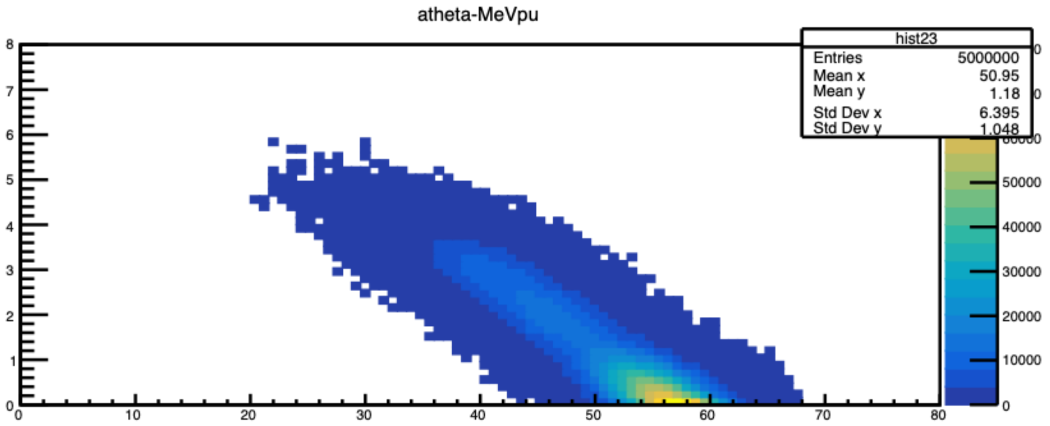


Two Configurations of BigGARIS with MRTOF Mass Spectrograph

inclined (54°)
position



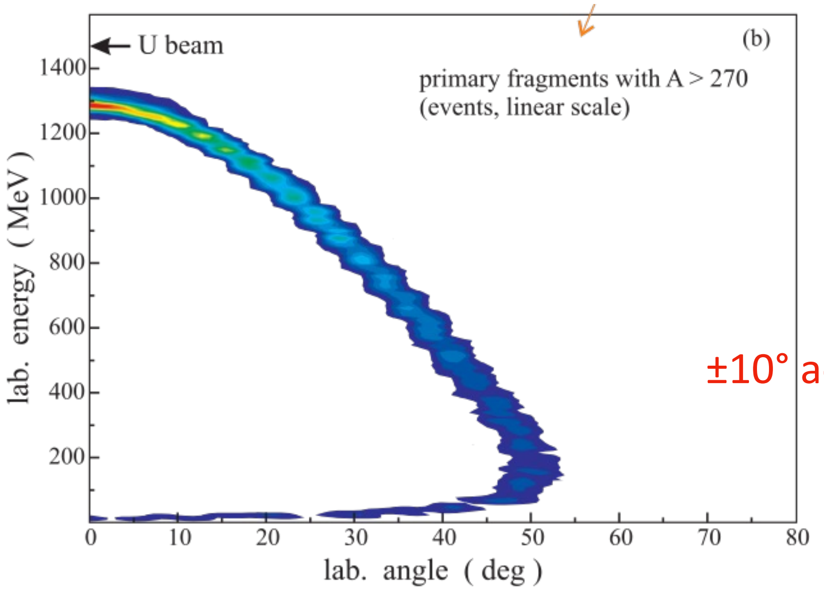
normal (forward)
position



n-rich direction (E, SE)
“Large angle horn”

Part of the “Horn”, $\varepsilon_{\text{collection}}$ ~5% feasible

KISS 1.7 ?



SHE direction (NE)
“Forward”

±10° accepts, $\varepsilon_{\text{collection}}$ ~50% feasible

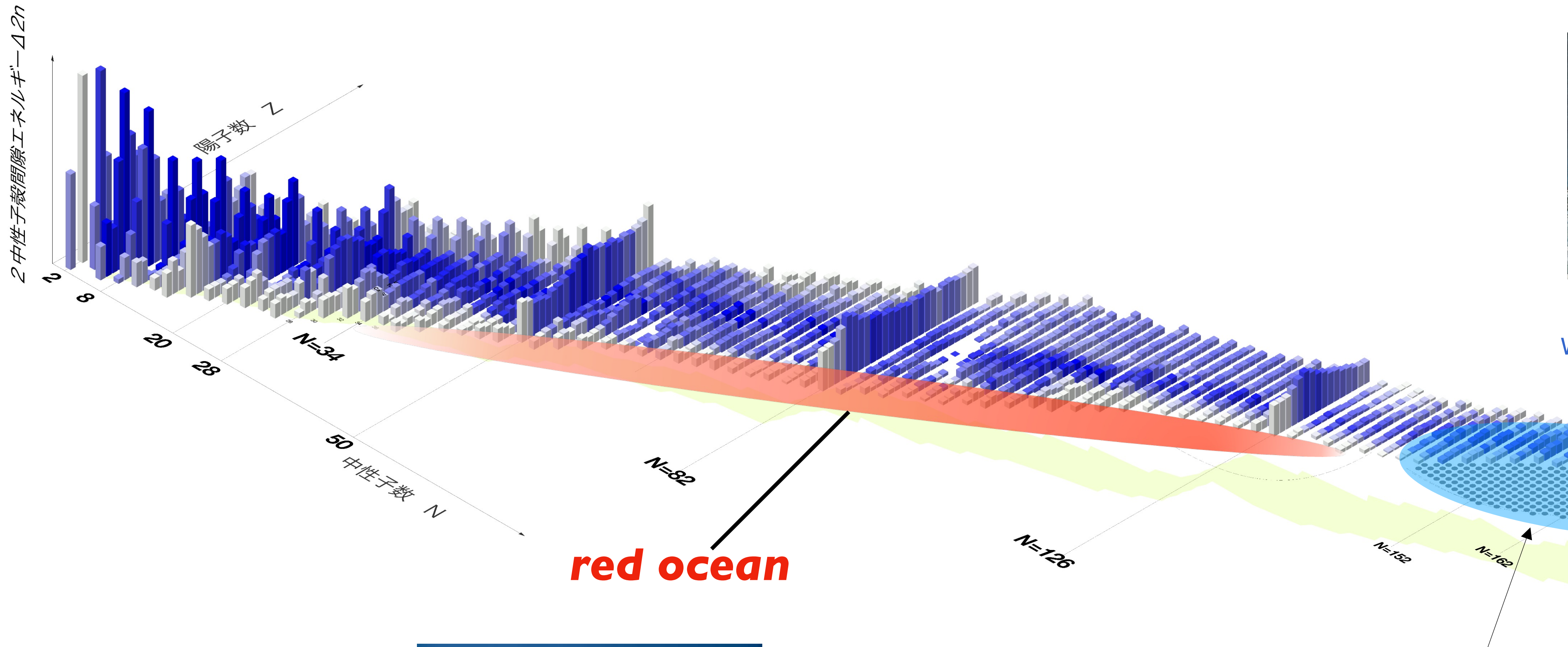
V.I. Zagrebaev, W. Greiner, PRC83, 044618(2011)

Cm target 1 mg/cm^2, U beam 3 puA, $\varepsilon_{\text{collection}} \times \varepsilon_{\text{measure}}$ ~6% :

10 pb (267,268Db) produces 1 event/2 days

W. Greiner and V. Zagrevaev, Nucl. Phys. A 834, 323c (2010)

“Boldly go where no man has gone before” ©Star Trek



red ocean

IoS

n-rich actinide is “blue ocean,”
>200 nuclides are waiting to discover

念青唐古拉峰(7162m)

Wada, Maruyama, Naganuma 1986

珠穆朗玛峰(8192m)

Tenzing Norgay and Edmund Hillary, 1953