宇宙での元素合成過程とRIBFでの不安定核の質量測定

Nucleosynthesis in Cosmos & Mass measurements at RIBF/RIKEN

石山　博恒
理化学研究所仁科加速器科学研究センター

宇宙史研究センター2023年度第2回構成員会議・成果報告&交流会
筑波大学、2023年12月8日

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   - Beginning of Nuclear Astrophysics
   - Rapid neutron capture (r) process
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1. Introduction

~ The origin of Gold and Platinum~

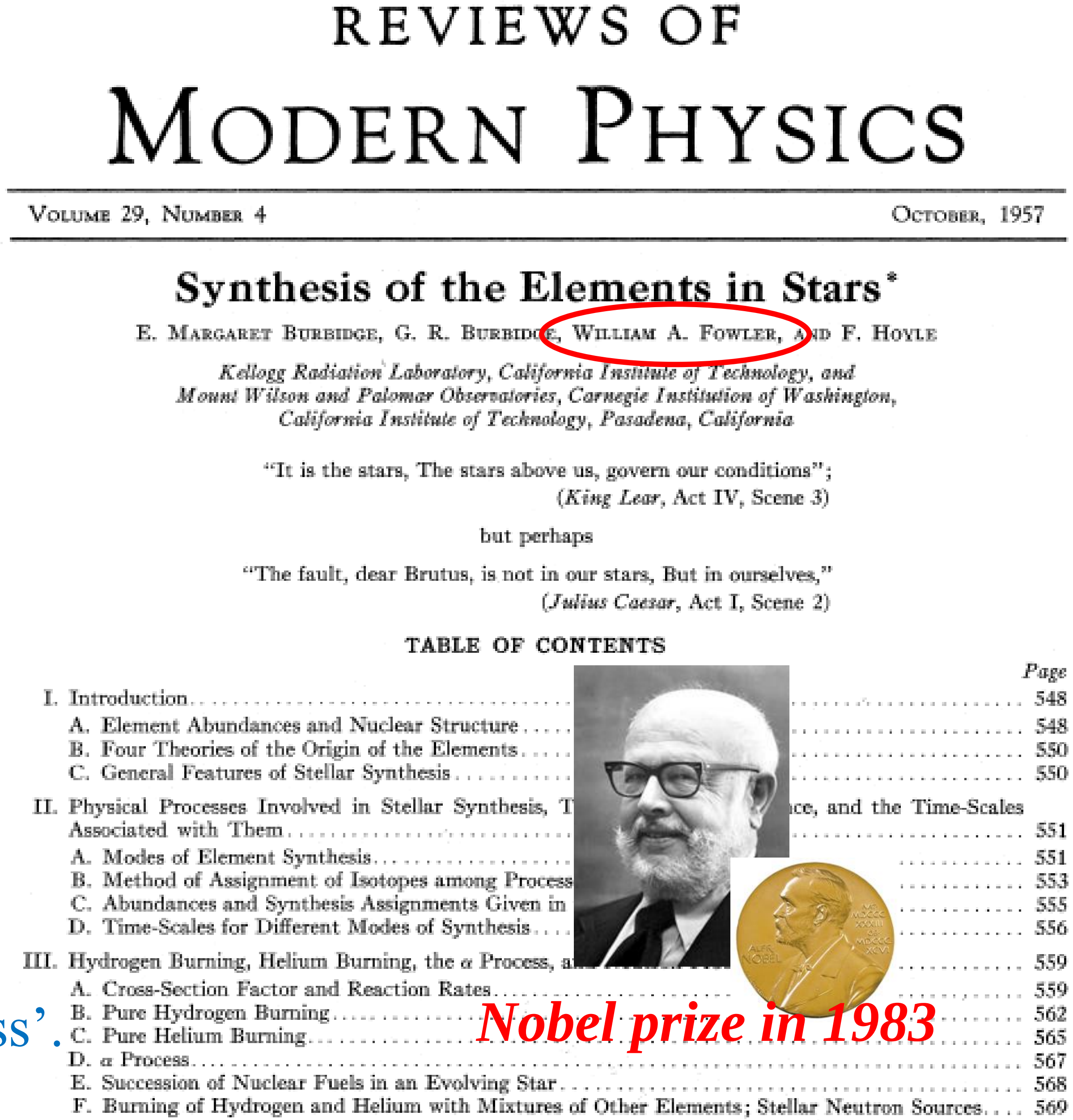
This year, 2023 marks the 76^{th} anniversary of the beginning of 'Nuclear Astrophysics'.

Nuclear Astrophysics started from B2FH paper and Cameron paper published in 1957.

The origins of elements were clarified with several process in this paper.

Especially, beyond iron, half of elements are produced in 'rapid neutron capture process'.

However, until now, the site of r-process still remains as a mystery.



REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions"; (*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves," (*Julius Caesar*, Act I, Scene 2)

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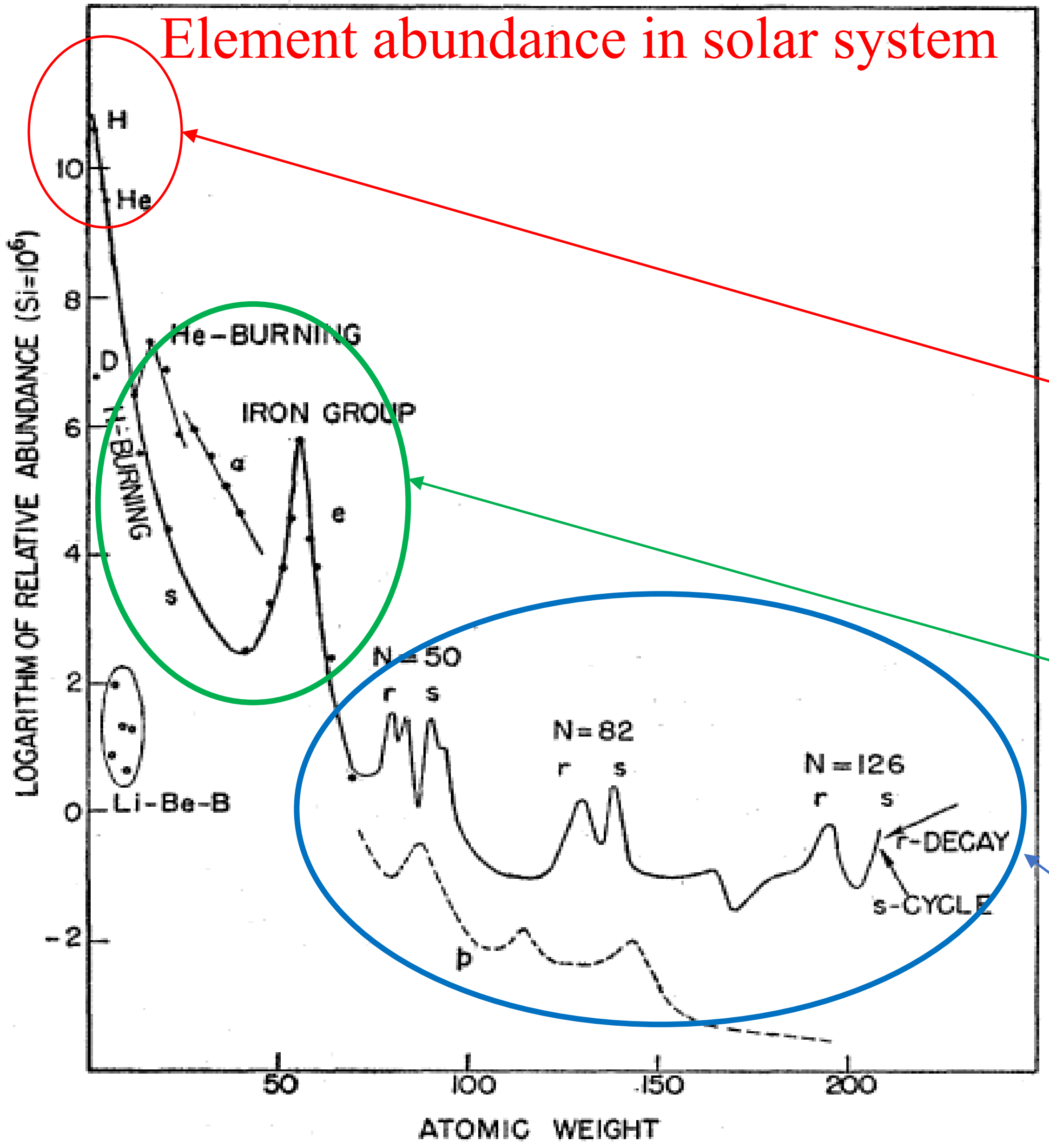


B2FH, Rev. Mod. Phys. 29 (1957) 547.

Mass ratio
H: 70.7%
He: 27.4%
Others: 1.9%
Heavy elements (> Ni): 4E-4%

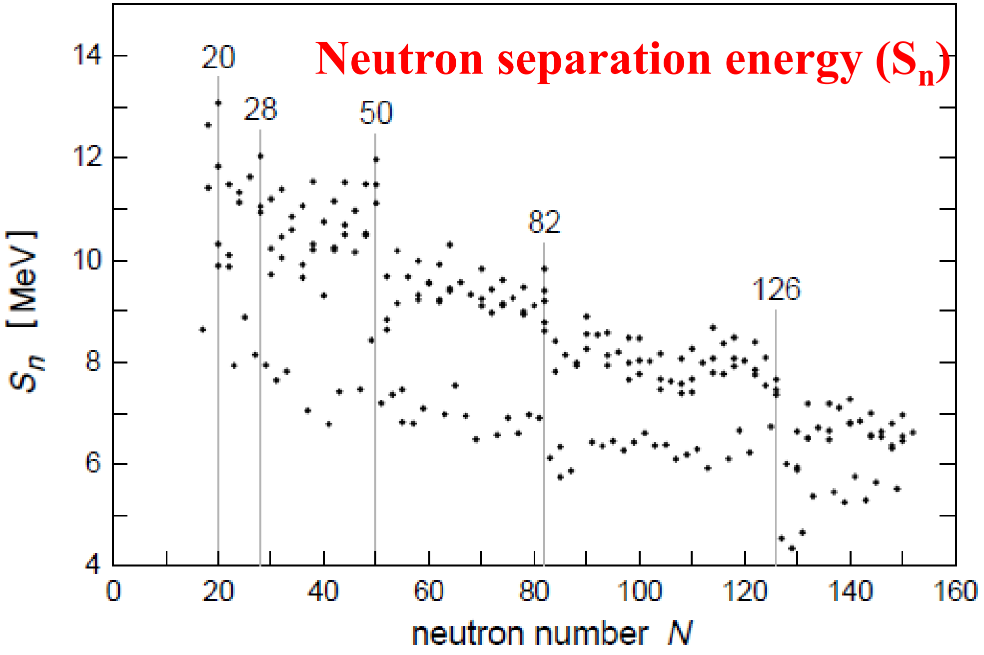
Big Bang Nucleosynthesis:
Main production of H, He (Li, Be)
No stable isotope : A = 5, 8

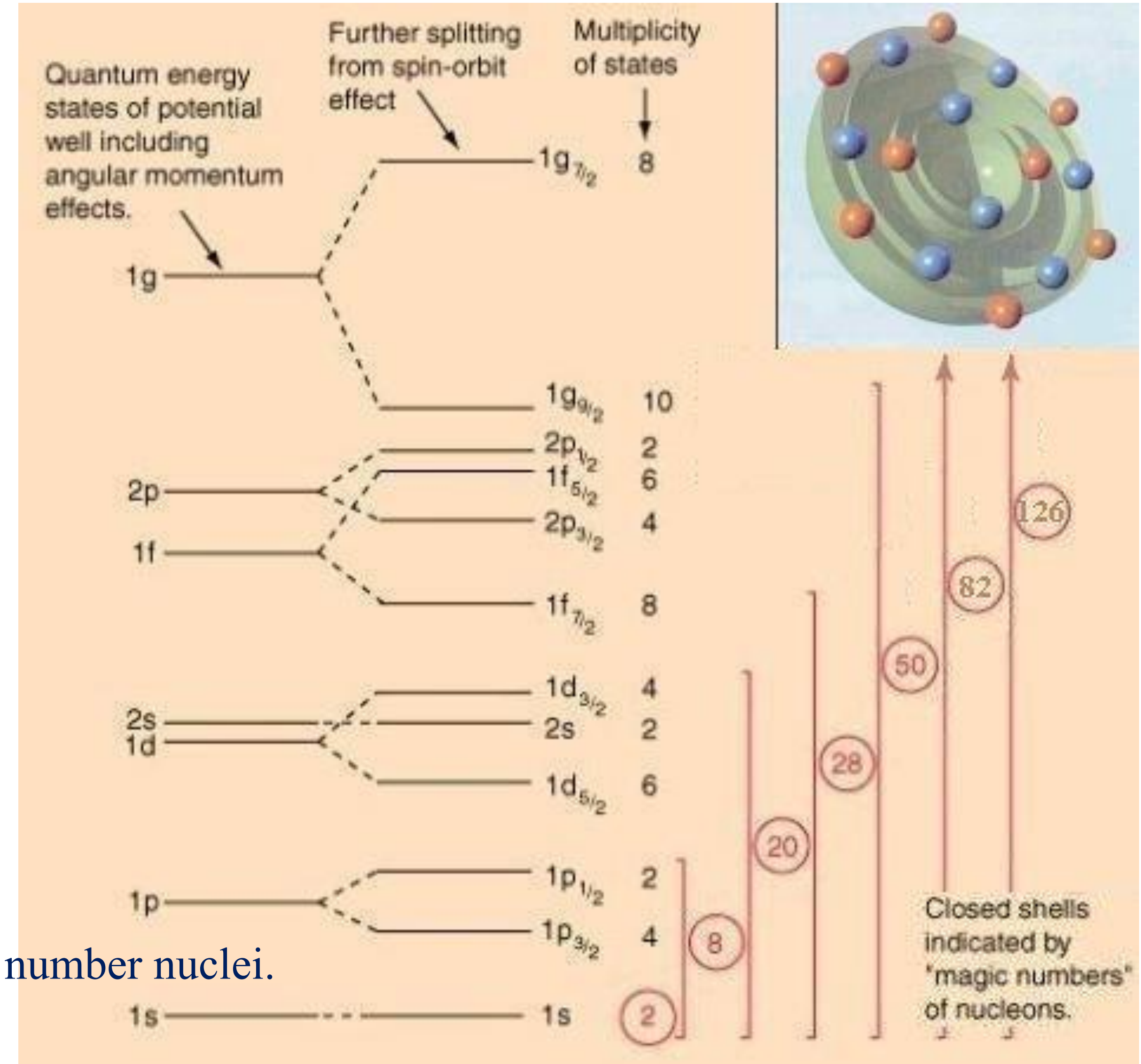
Thermo-nuclear reactions (charged particle) in Stars:
Up to Fe
Fe: Maximal binding energy / nucleon ⇒ Stable

Beyond Fe ⇒ neutron capture reactions: (n, γ)
Why do two peaks exist?
Slow (s-) process
Rapid (r-) process

Beyond Fe, why do several peaks exist? (before double peaks problem)

Shell model
⇒ Magic number = 2, 8, 20, 28, 50, 82, 126,..
We call 'Shell closure'.
Typically, ^{4}He, ^{16}O, ^{20}Ne, ^{40}Ca (double magic nuclei)

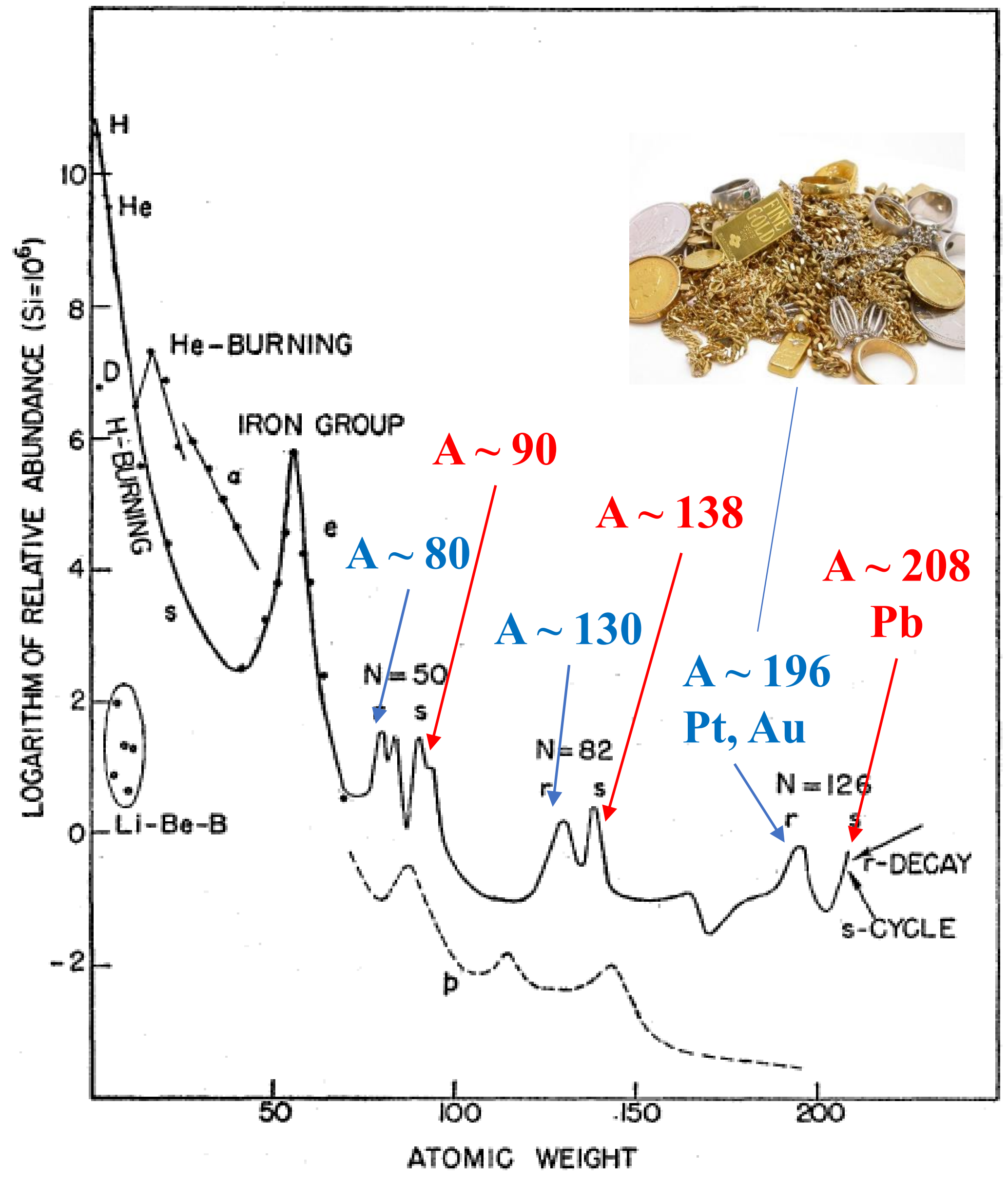


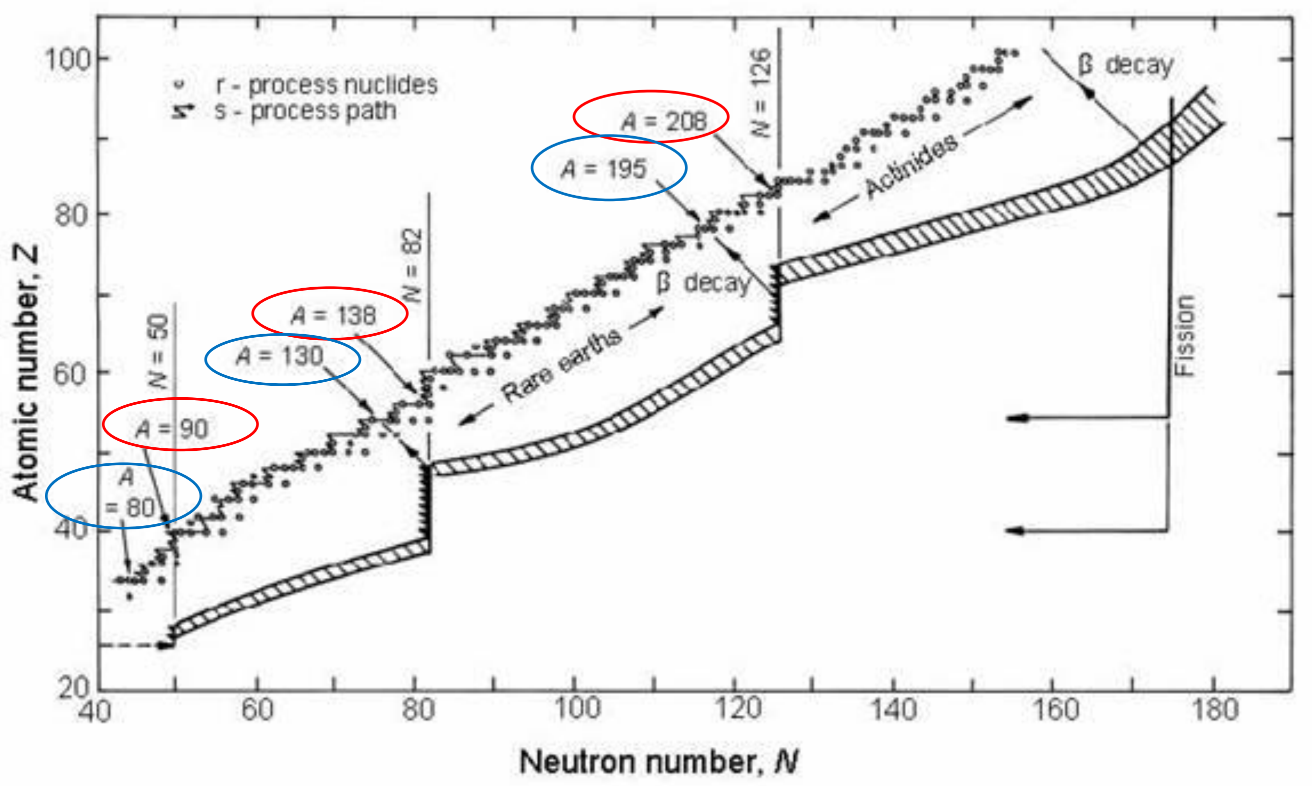


High S_n around magic numbers = stable
⇒ Reversely speaking, neutron capture is not easy after magic number nuclei.
⇒ Suppression of neutron capture reaction
⇒ Peak formation (accumulation at around magic number)

Why are double peaks generated?

Clayton, Principles of stellar Evolution
And Nucleosynthesis (1983)

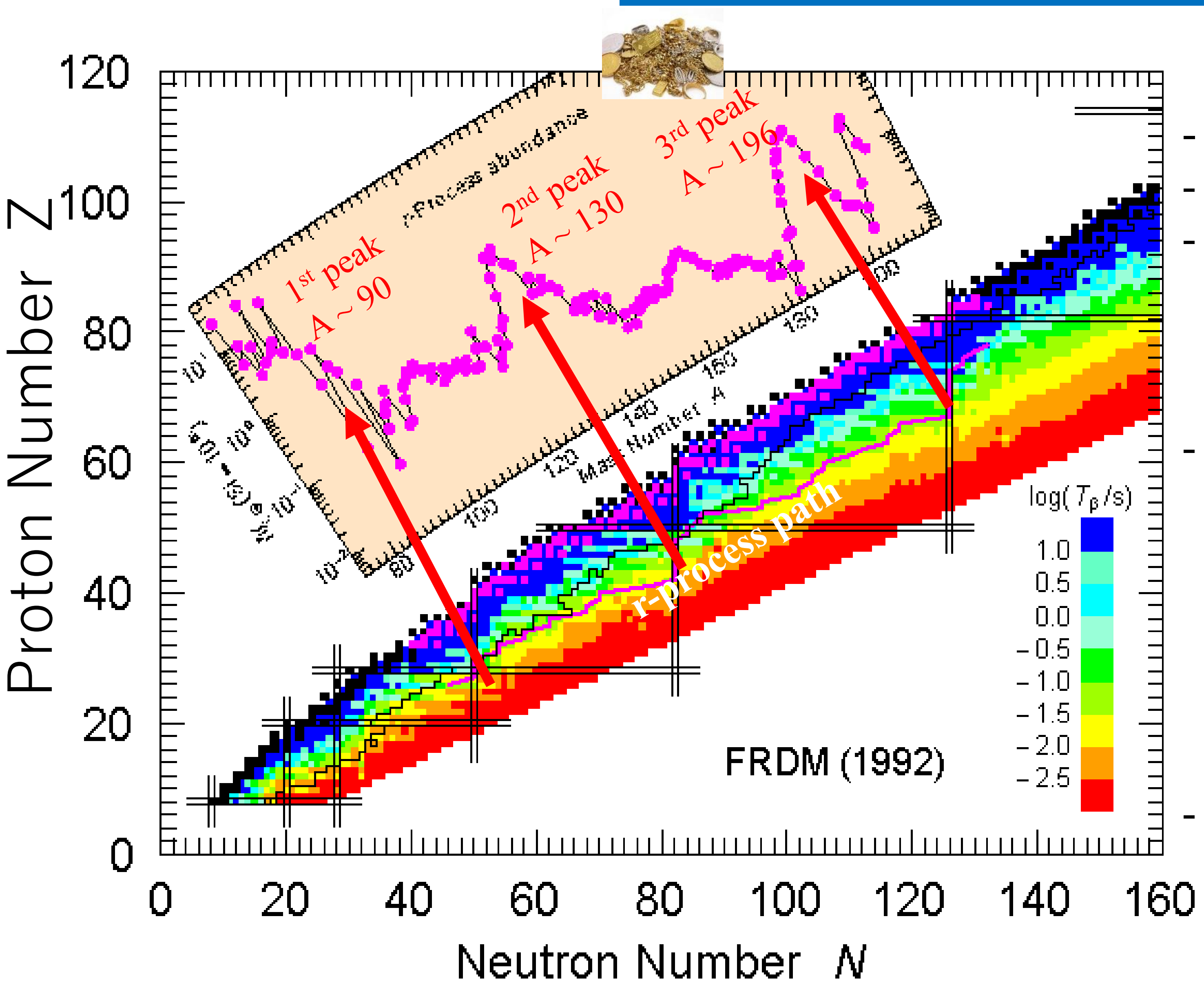




Neutron capture process along stable nuclei
⇒ - slower than β-decay, Slow(s-) process

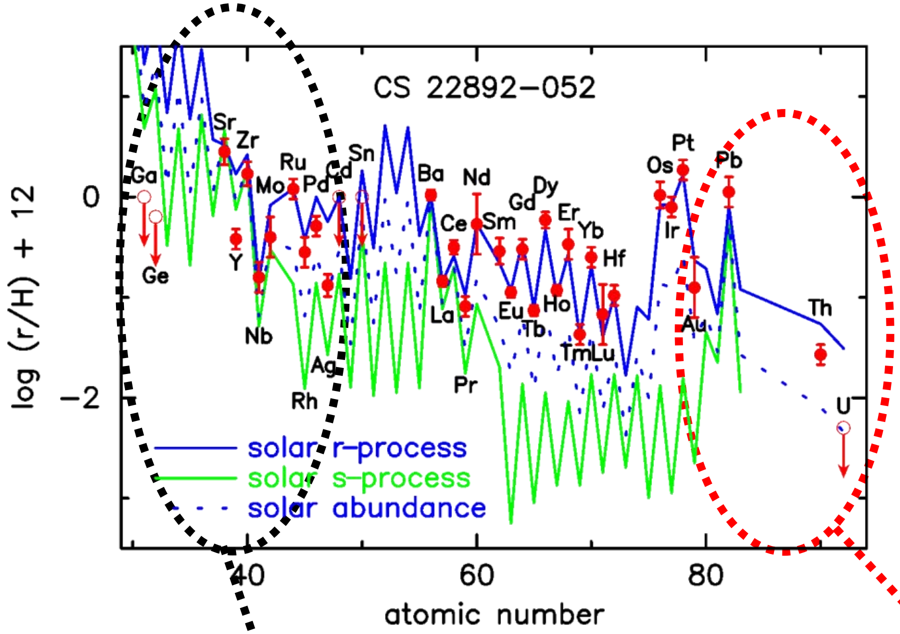
Neutron capture process on radioactive nuclei
⇒ faster than β-decay, Rapid (r-) process

Features of r-process



- Neuron capture is faster than beta decay
- Uranium, Th, etc. productions beyond Bi
- (n, γ) – (γ, n) equilibrium @ high temperature
  T ~ 10^9 K
  neutron capture reactions & photo-distinguish reactions equilibrium
- Waiting point nuclei
  N = 50, 82, 126 : Sn ⇒ high,
  Magic number + 1: Sn ⇒ low
  ⇒ Neutron capture reaction ceases on those nuclei have to wait for β-decay
  'Waiting point nuclei'
  ⇒ Peak formation
- High neutron density > 10^{20} cm^{-3}

Recent Astronomical observations of r-process abundance in galactic halo stars



C. Sneden, et al., 2003

R-process has already occurred in the early stage in galaxy.

$56 < Z < 78$ (*Universality*)

Main r-process ?

Single episode / Single event ?

2nd-3rd peak

2nd peak : Ba

3rd peak : Os, Ir, Pt, Au

Z < 56 (*Dispersive*)

α-process

and/or weak r-process ?

1st peak

Z > 78 (*Dispersive*) ?

Cosmo-chronometer:

^{238}U (4.5Gy) / ^{232}Th (14Gy)

Stellar chronometer ?

Pb, Actinoides

Candidates for r-process site

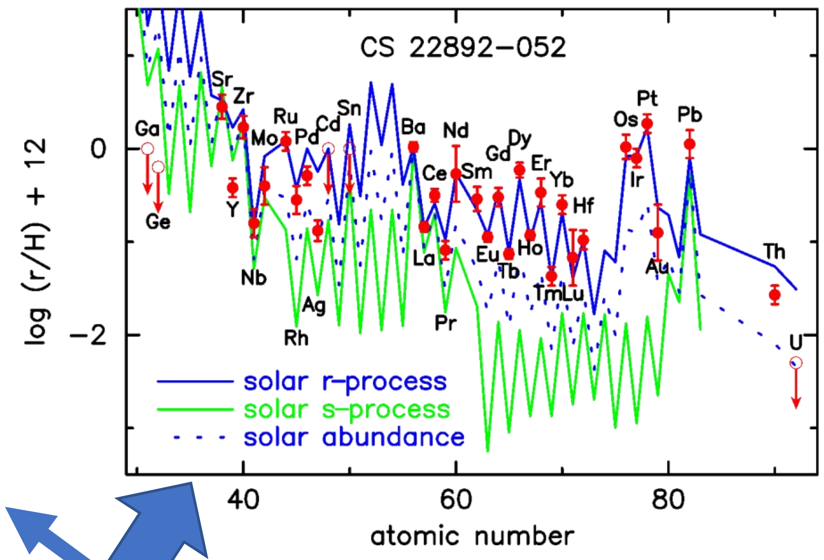
Rapid neutron capture

- high temperature ($T_9 \sim 1$)
- High neutron number density ($10^{20} \sim 10^{30}/cm^3$)
- Short time scale (several seconds)

➔Stellar explosion ?

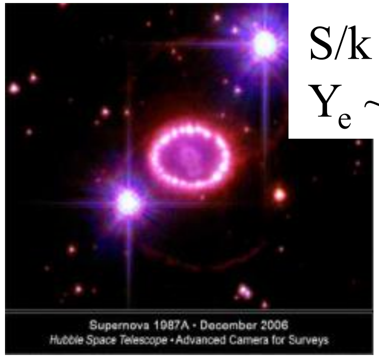
Site parameters

- Ye (electron fraction): Yp = Ye, Yn = 1-Ye
- S/k (entropy) $\propto T^3/\rho$ (density @ same T)
- τ_{dyn} (dynamic time scale) ～ duration time for α-process & r-process



High S/k site

Neutrino driven wind in type II Sne (NDW)



S/k ~ several 100

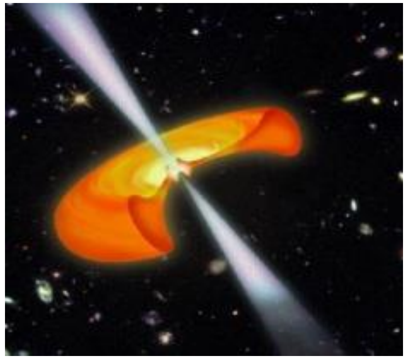
$Y_e \sim 0.45$

High Ye value?

High S/k ?

Low Ye site

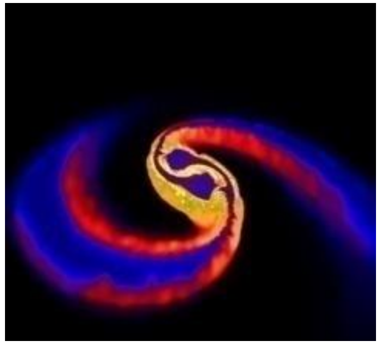
MHD jet /Collapsar



S/k < several 10

$Y_e < 0.2$

Neutron star merger



Event rate, early universe ?

Nuclear physics inputs

- **Nuclear mass**

-> Sn, r-process path

- **Half life**

-> r-process speed, waiting point

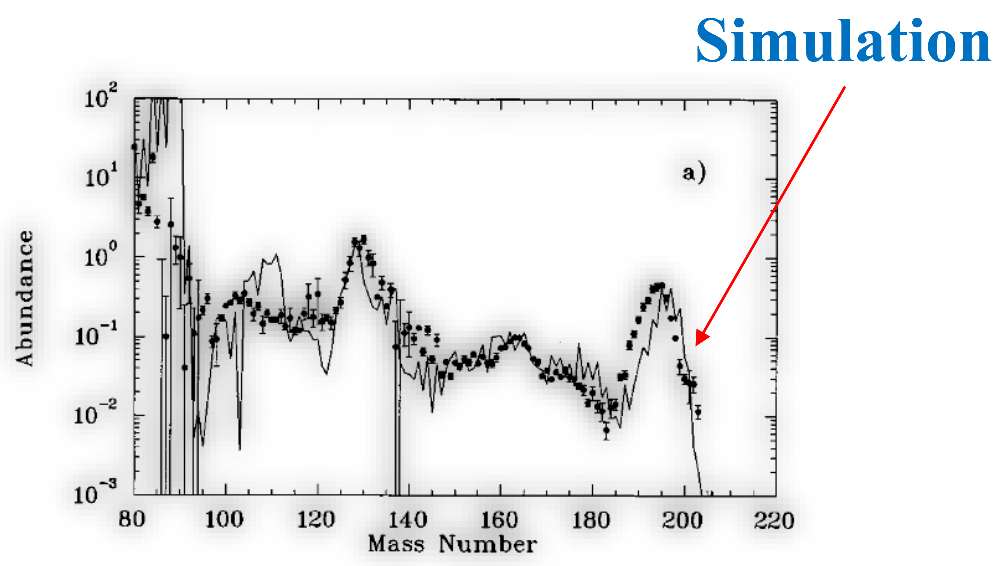
- **neutron branching ratio**

-> r-process abundance pattern

- **neutron capture rate & other reaction**

-> r-process path when the equilibrium is broken

Network calculation for r-process nucleosynthesis

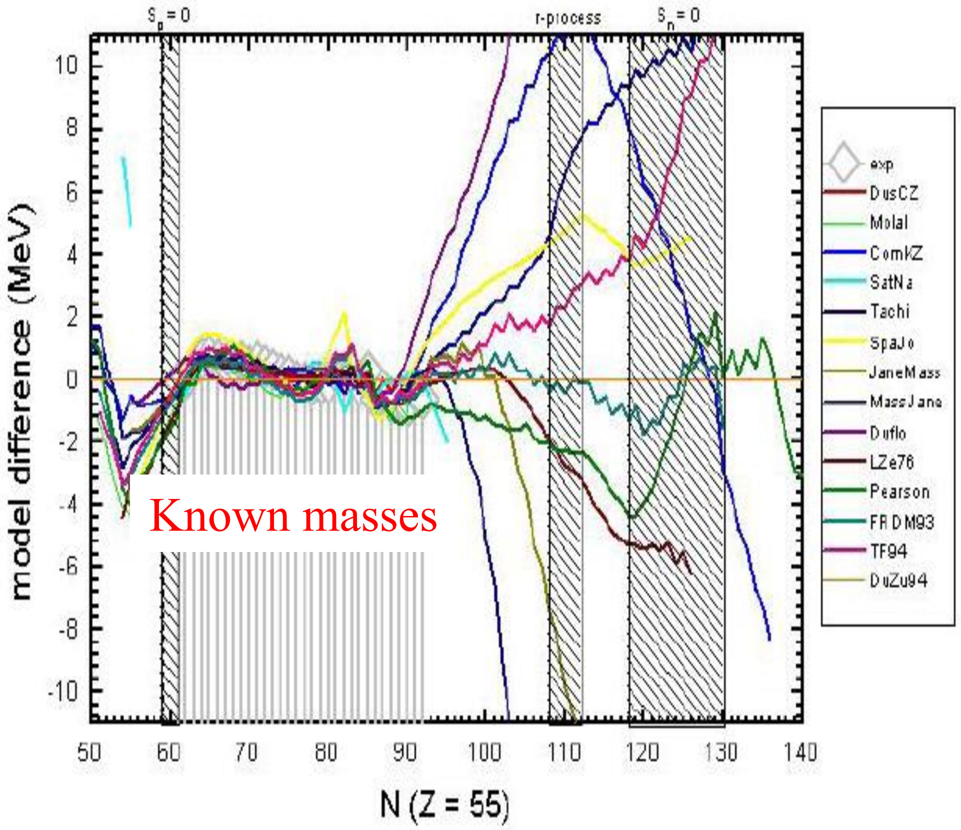


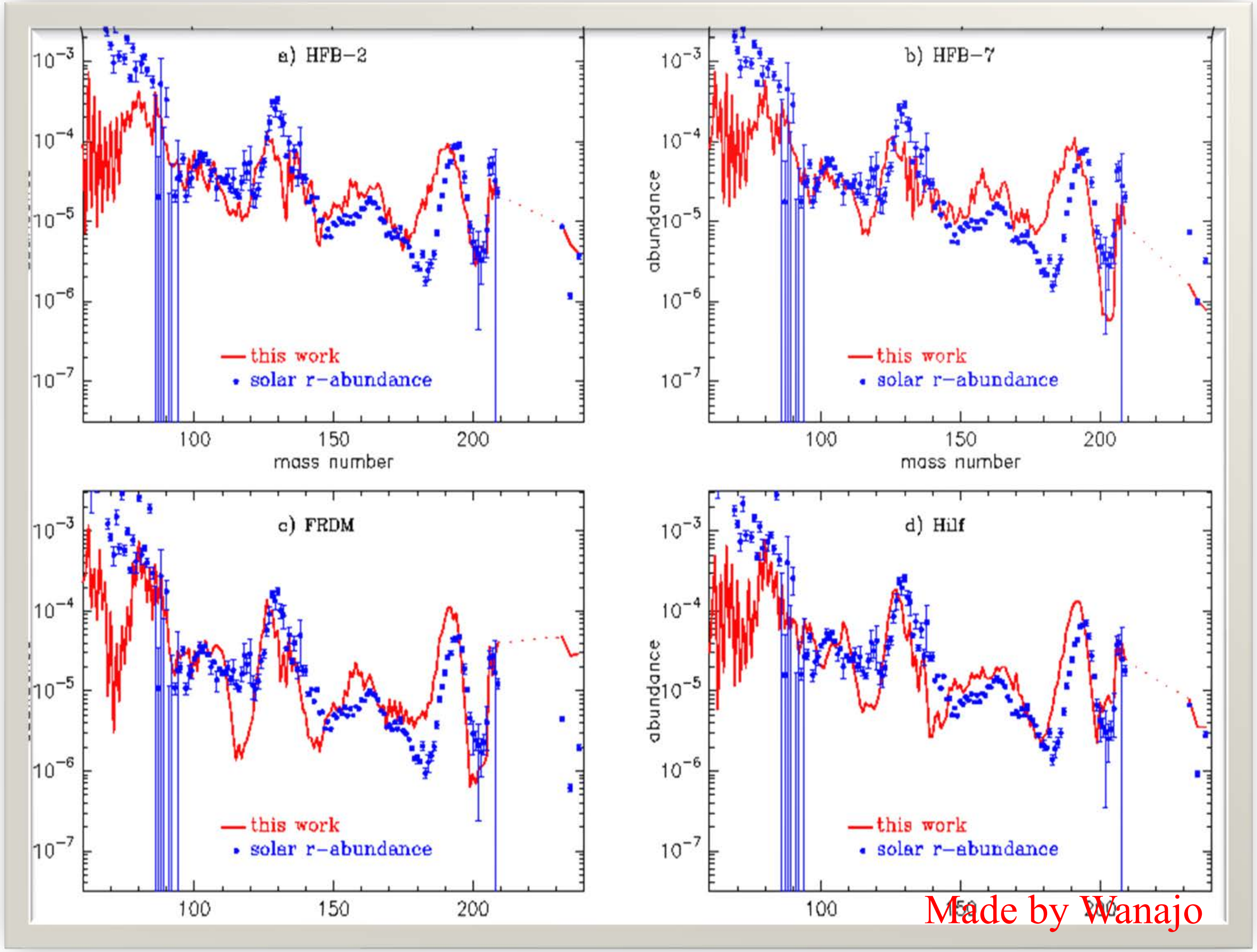
(Woosley et al. 1994; Meyer 1995)

Effect of (unknown) nuclear physics inputs

For example, MASS

microscopic: **(a) HFB-2**, (b) HFB-7 (Goriely et al. 2002, 2003)
macroscopic: (c) FRDM (Möller et al. 1995), (d) Hilf et al. 1976

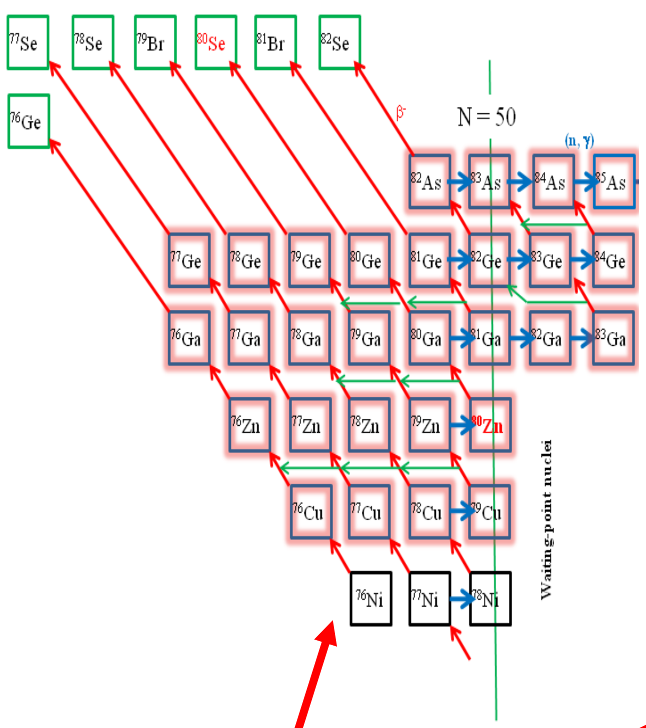


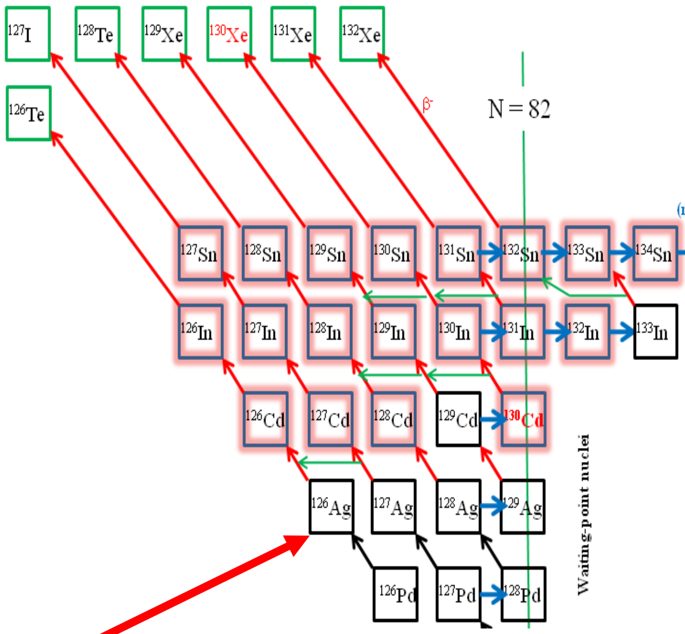


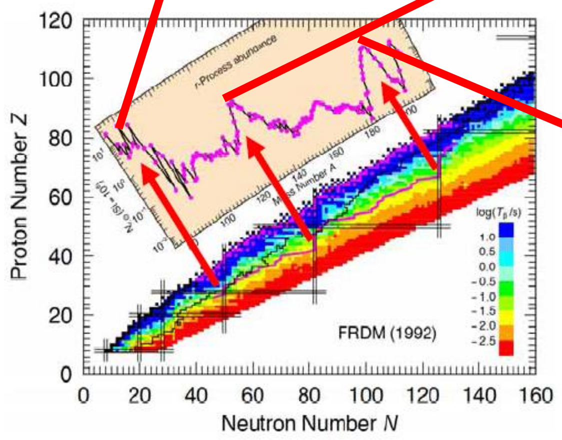
Made by Wanajo

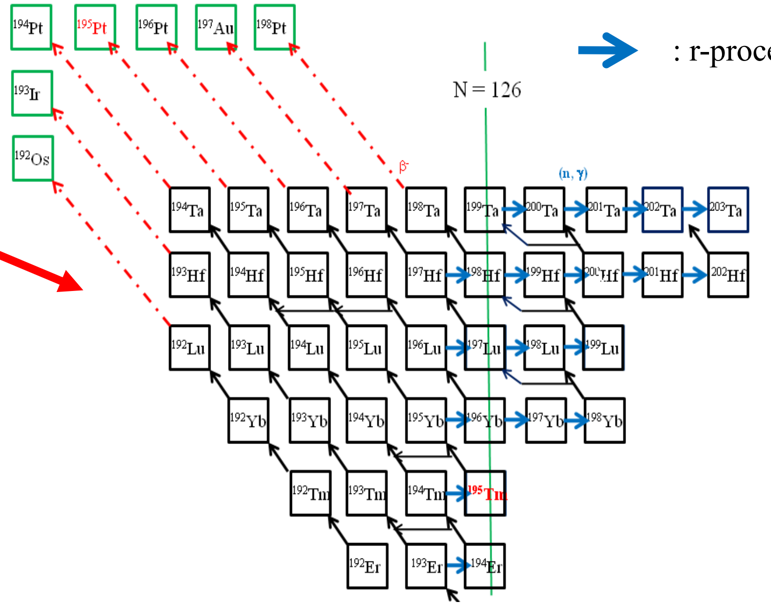
Status of measurements for mass, half life and n-branching ratio

Made by HI in 2009









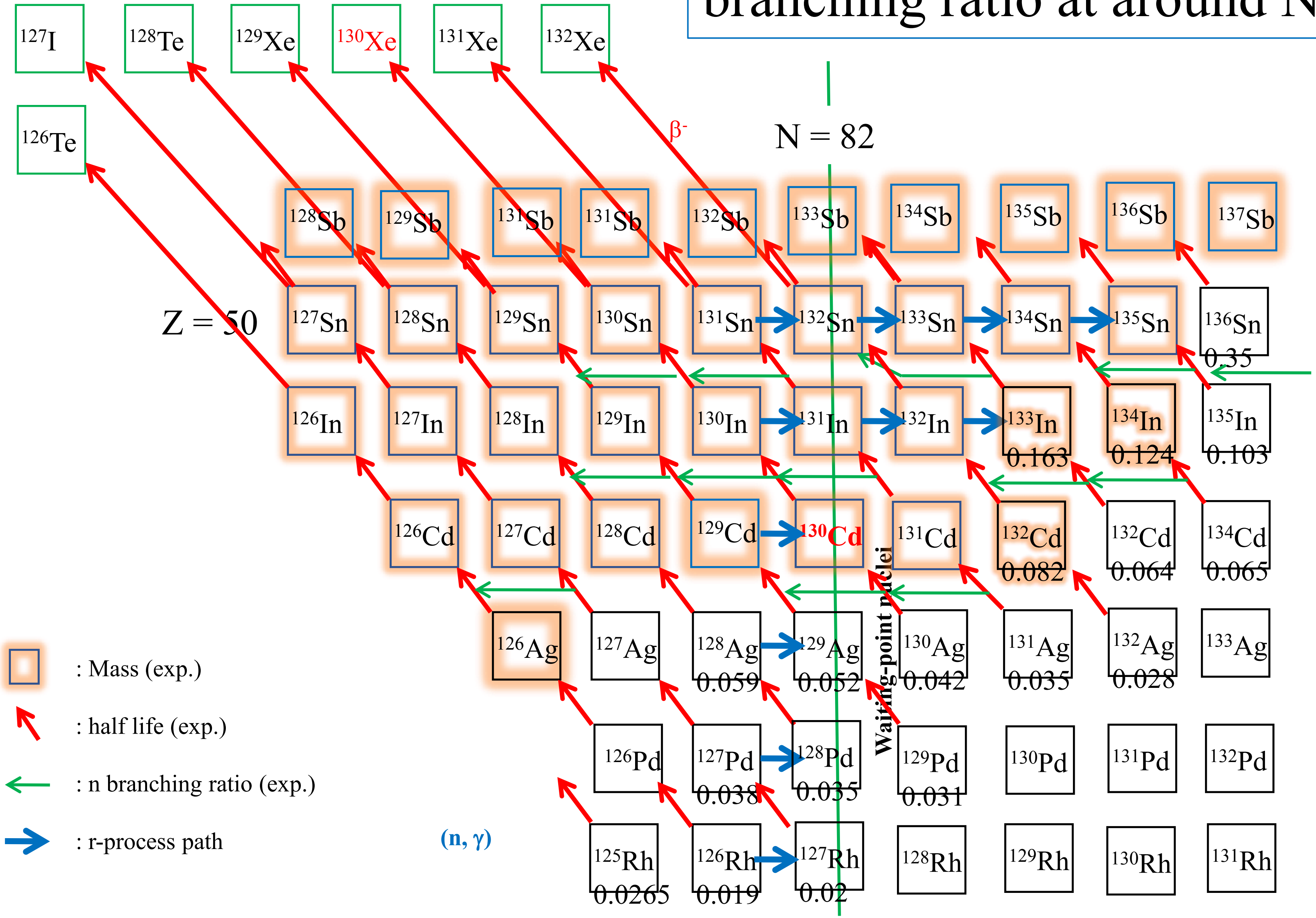
: Mass (exp.)

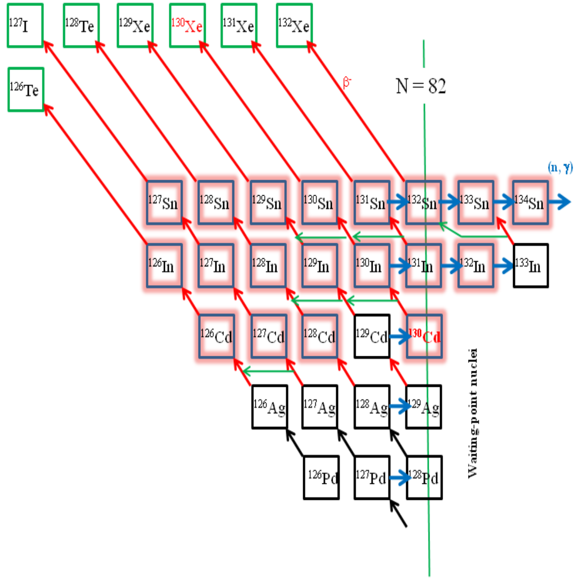
: half life (exp.)

: n branching ratio (exp.)

: r-process path

Present status (2023) for mass, half life, neutron branching ratio at around N = 82





2. Mass measurements at RIBF/RIKEN

1. Bρ-TOF
at OEDO-SHARAQ

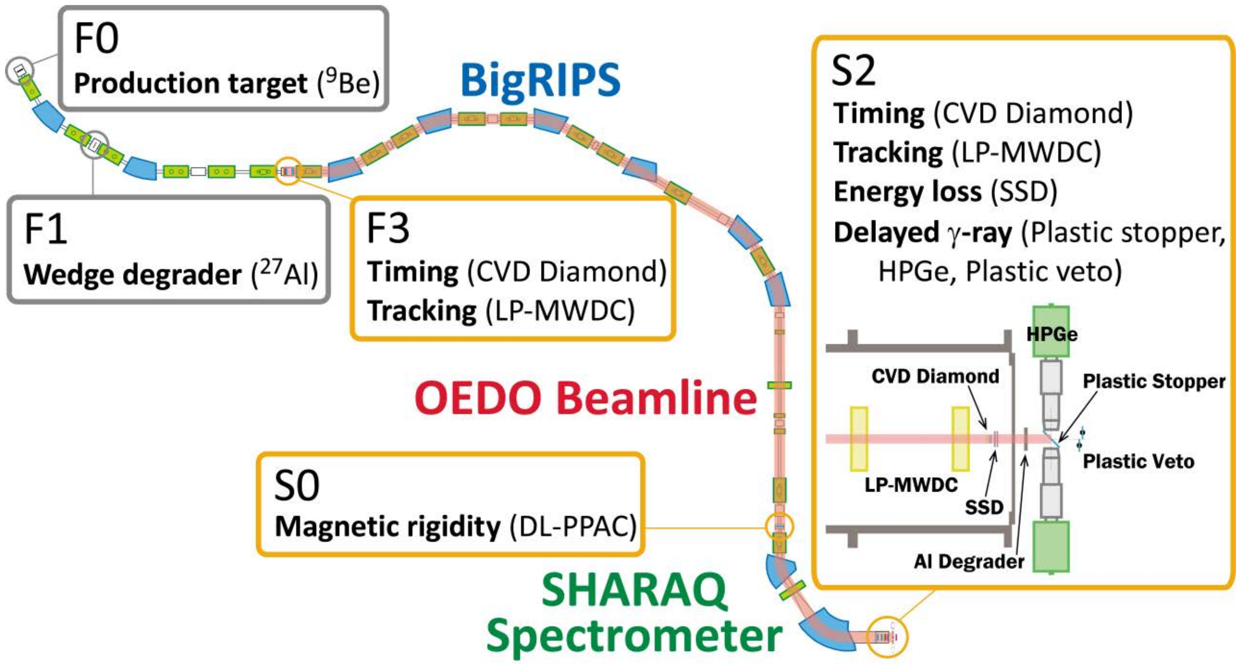
$$\mathbf{TOF \propto L \sqrt{E/M}}$$

3. MRTOF-MS

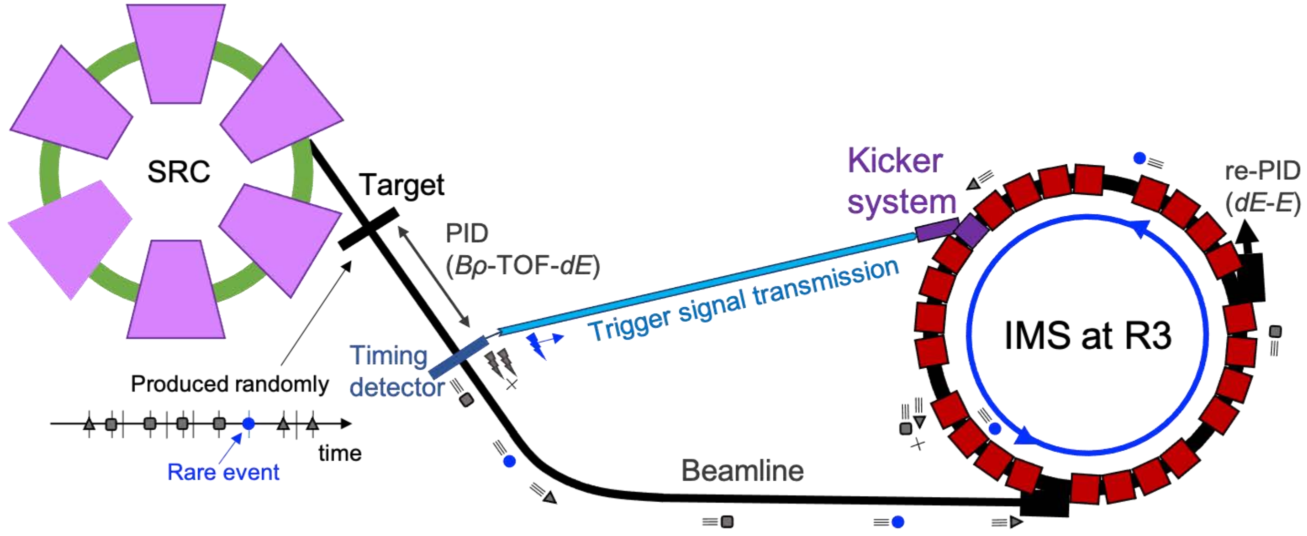
2. Rare RI Ring (R3)

To be published in RIKEN Accelerator Progress Report 56 (2023)

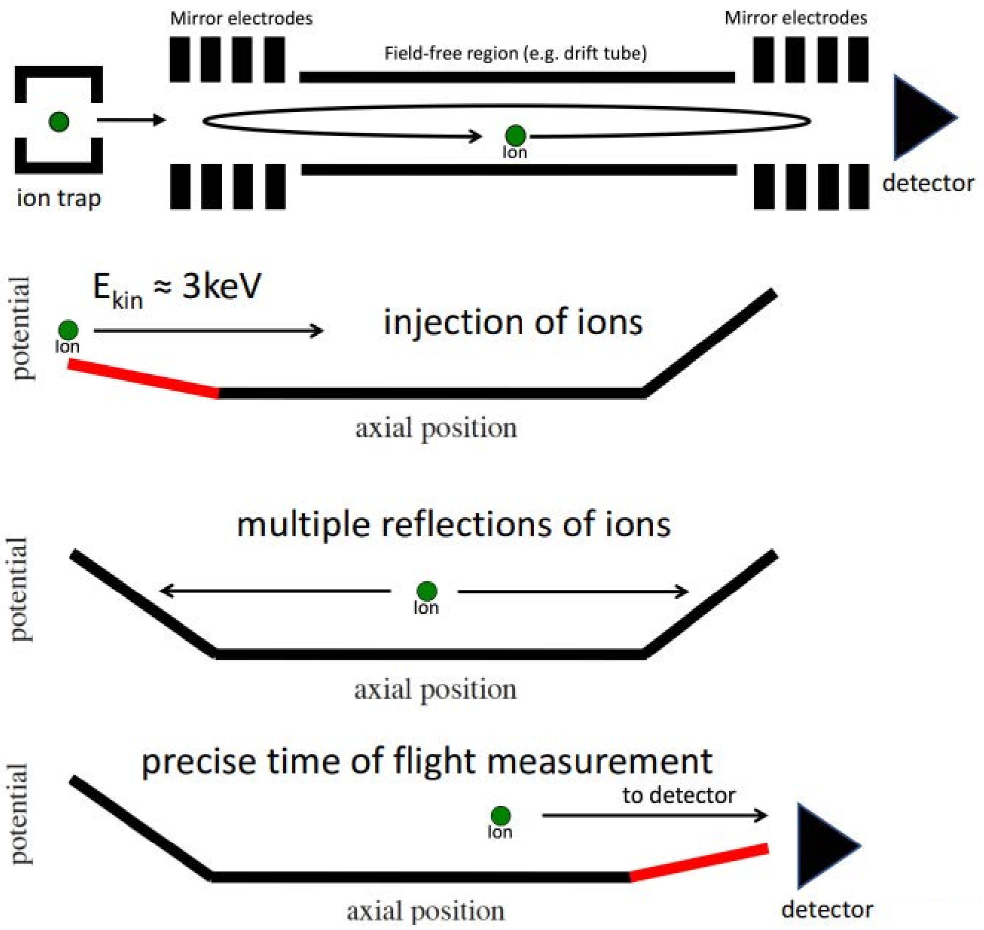
1. Bρ-TOF at OEDO-SHARAQ



2. Rare RI Ring (R3)



3. MRTOF(multi-reflection time-of-flight)-MS



2022年4月28日

← 前の記事　↑ 一覧へ戻る　→ 次の記事

理化学研究所

筑波大学

埼玉大学

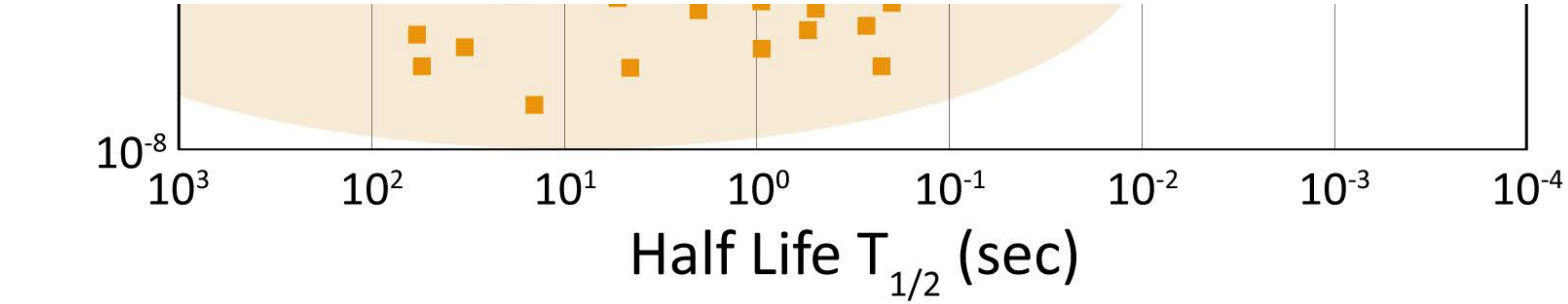
東京大学大学院理学系研究科

元素起源の謎の解明に向けた世界最速質量測定が始動

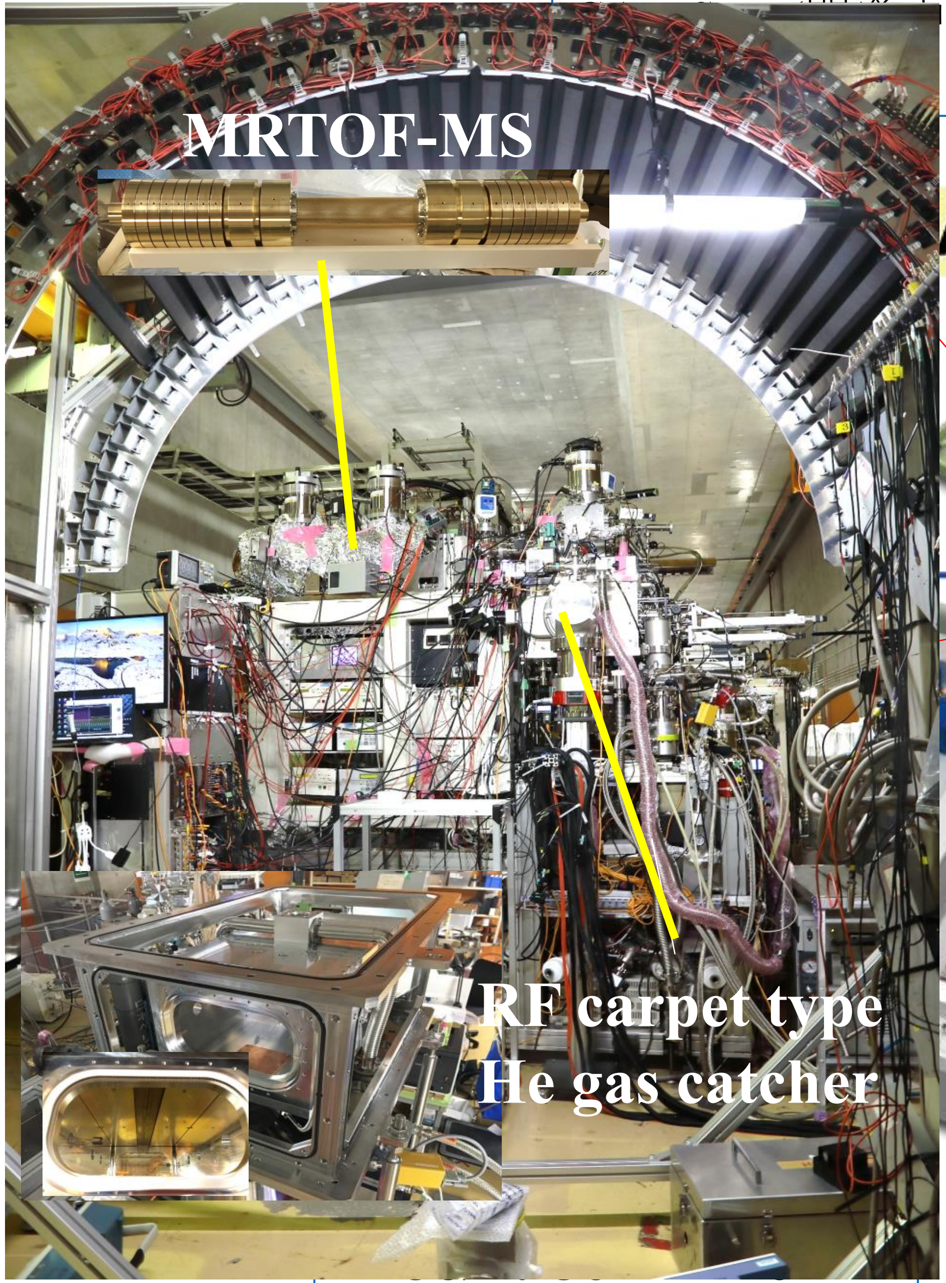
－稀少RIリングを用いた短寿命放射性同位体の質量決定に成功－

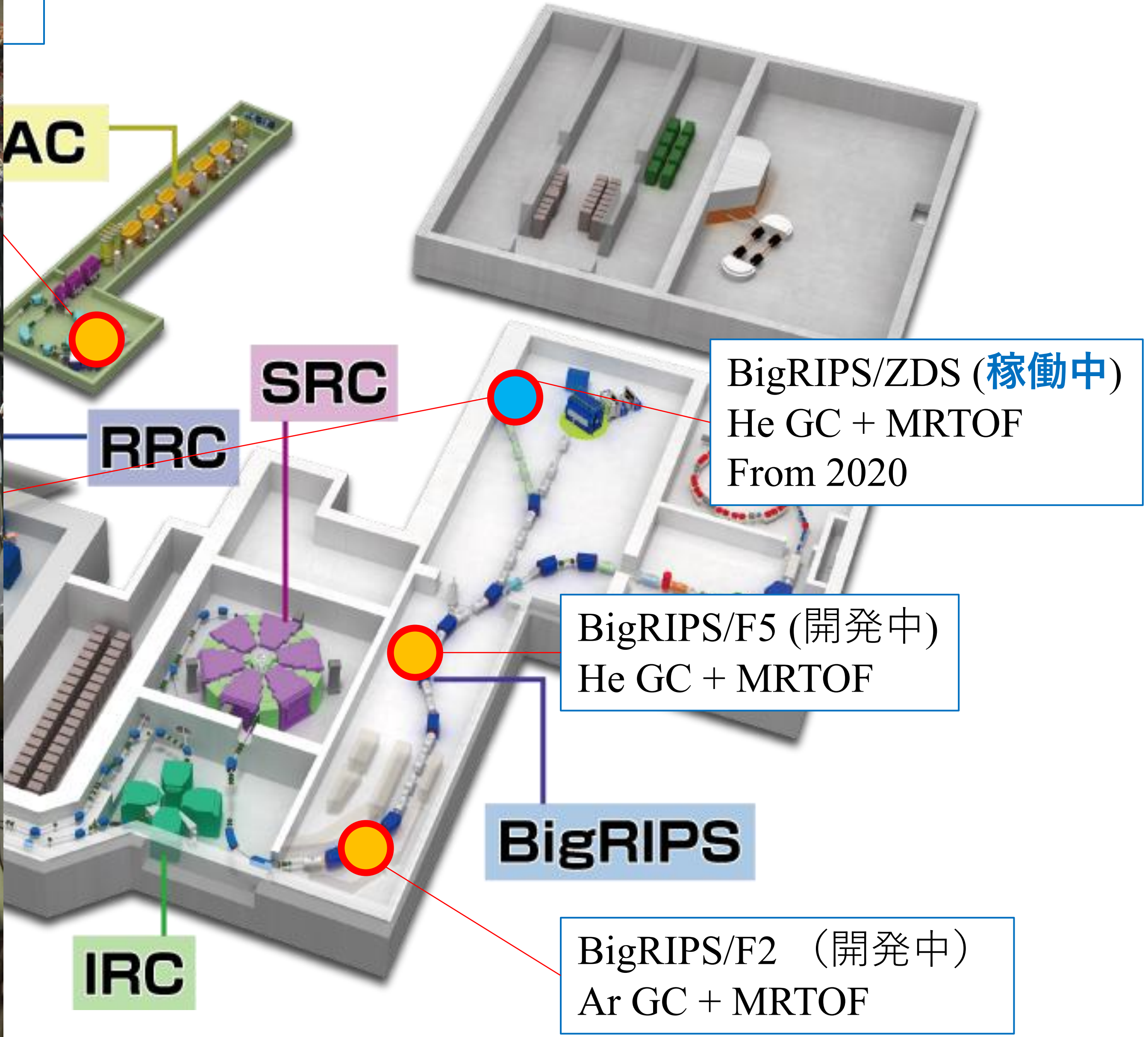
理化学研究所（理研）仁科加速器科学研究センタースピン・アイソスピン研究室サラ・ナイミ研究員（研究当時）、ホンフー・リー国際プログラム・アソシエイト（研究当時）、上坂友洋室長、短寿命核質量測定装置開発チームの山口由高技師、筑波大学数理物質系の小沢顕教授、埼玉大学大学院理工学研究科の山口貴之准教授、東京大学大学院理学系研究科の道正新一郎助教らの国際共同研究グループは、RIビームファクトリー[1]の「稀少RIリング[2]」を用いて、新たに確立した超高速質量測定法により、極短寿命同位体（RI）の一つである中性子過剰なパラジウム-123（^{123}Pd：原子番号46、中性子数77）核の質量を精密に決めることに初めて成功しました。

本研究成果は、鉄よりも重い元素の起源の解明に向け、速い中性子捕獲過程（r過程）[3]に関わる多くの稀少RIの質量精密決定への道を開くものです。

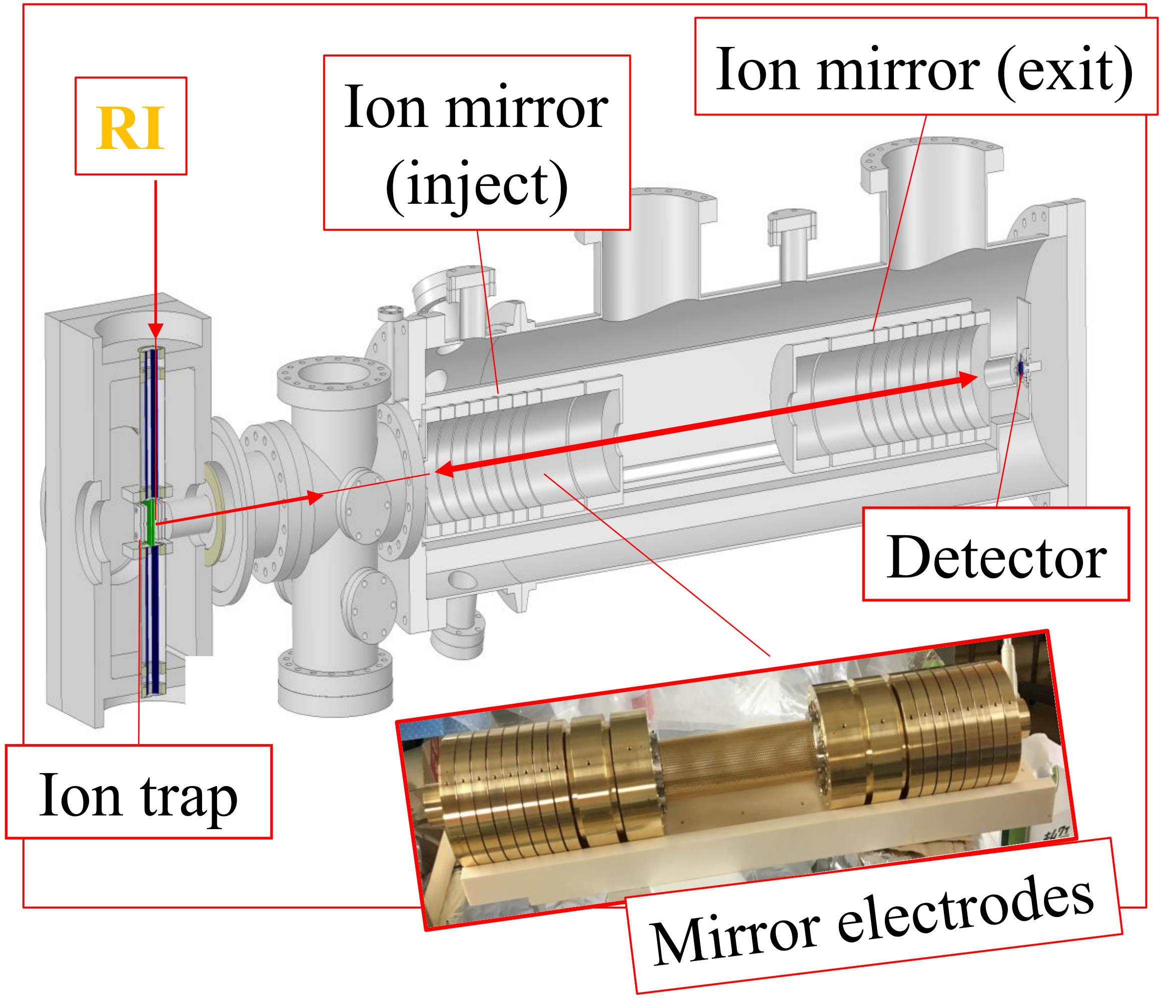


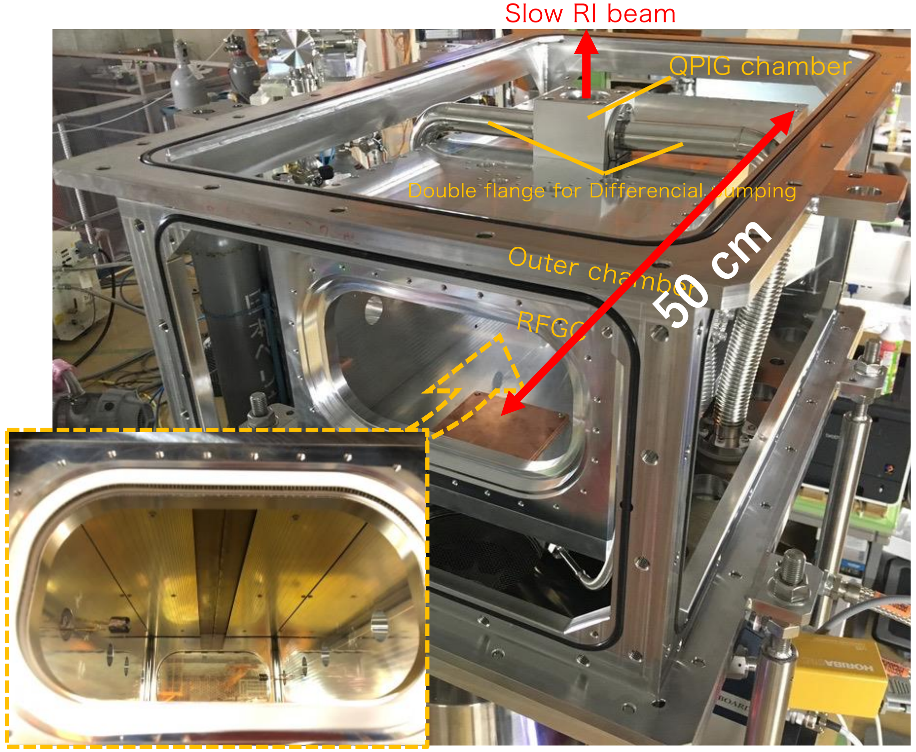
3. Mass measurements with SLOWRI/ZD-MRTOF


MRTOF-MS
RF carpet type
He gas catcher

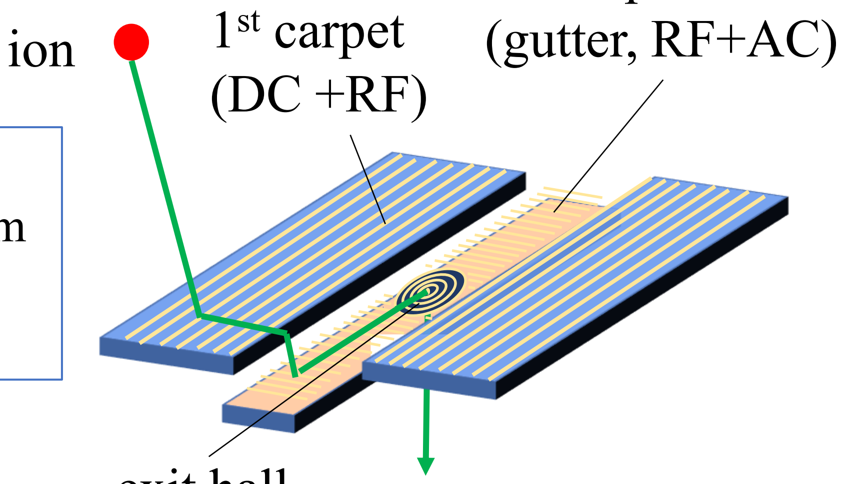

AC
SRC
RRC
IRC
BigRIPS
BigRIPS/ZDS (稼働中)
He GC + MRTOF
From 2020
BigRIPS/F5 (開発中)
He GC + MRTOF
BigRIPS/F2 （開発中）
Ar GC + MRTOF

RFGC-I: RF carpet type He gas cell + ZD-MRTOF @F11

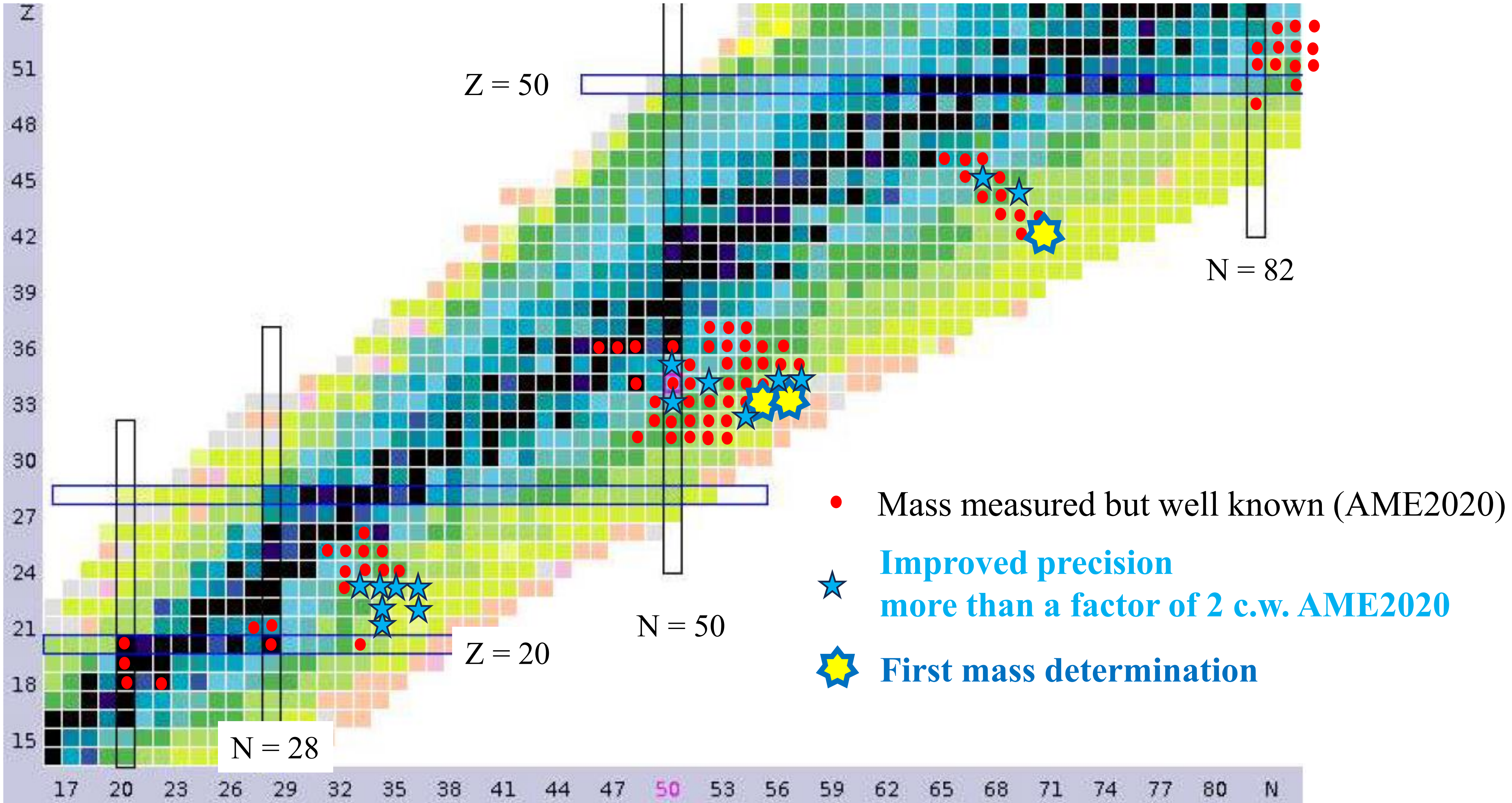




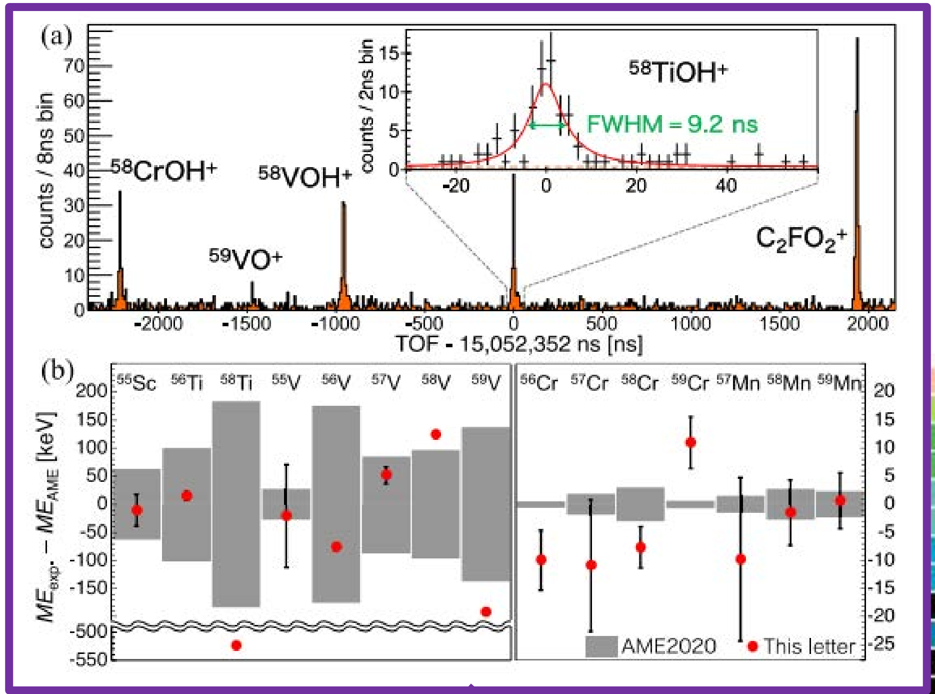
He gas cell
p ~ 150 Torr, L = 50 cm
Cryogenic operation
(T = 80 K)

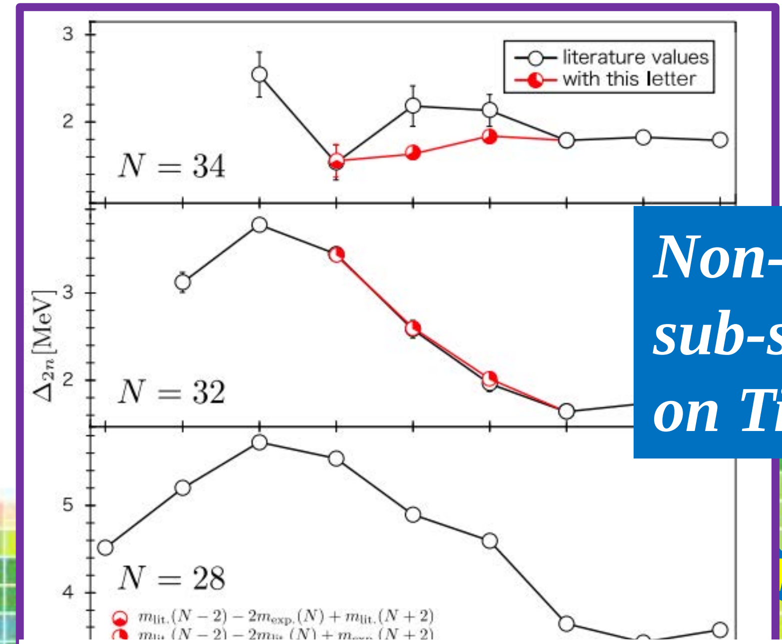


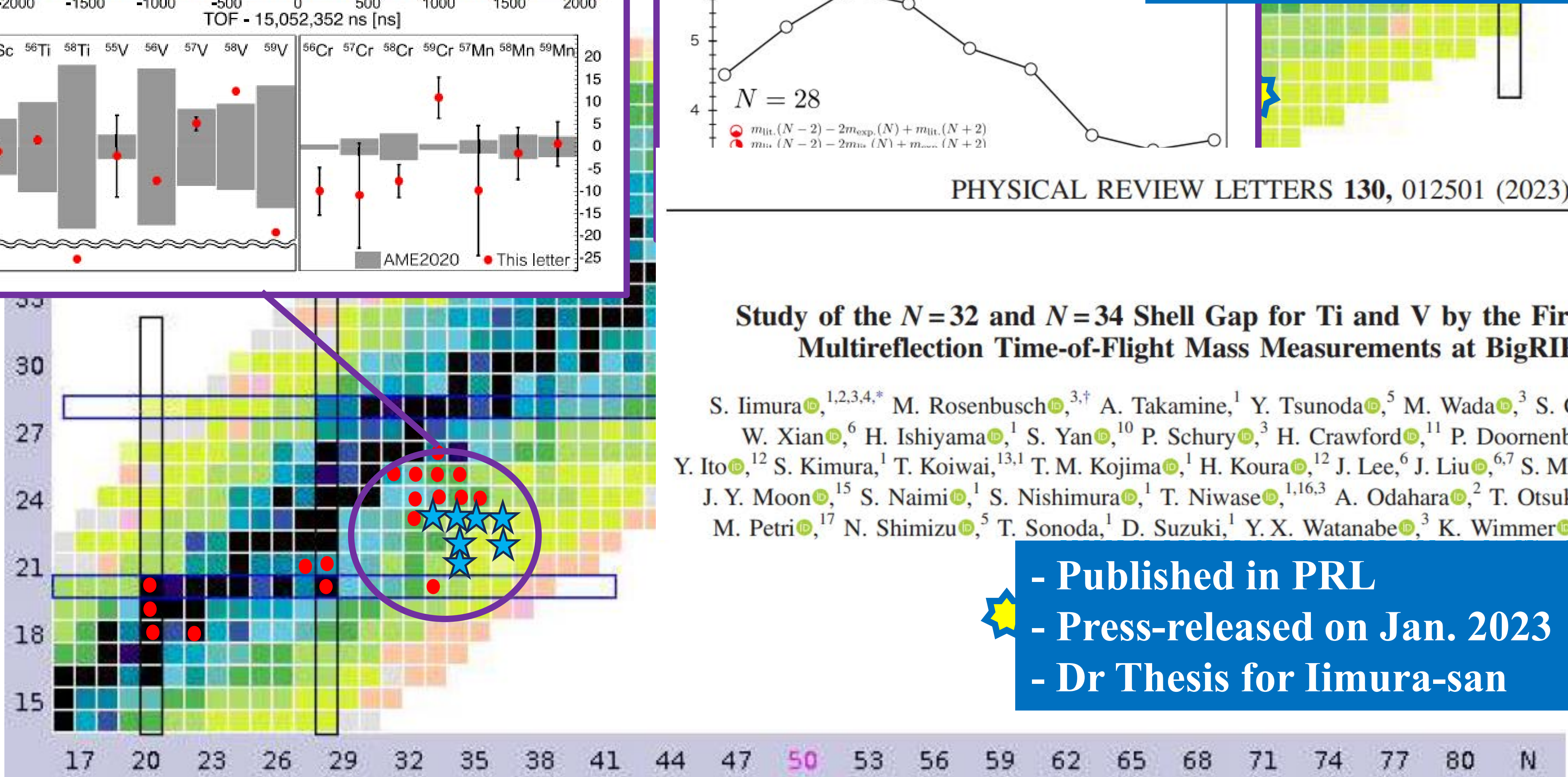
Symbiotic mass measurements with RFGC/ZD-MRTOF



Sc, Ti, V region







Non-existence of N = 34 sub-shell closure on Ti isotope

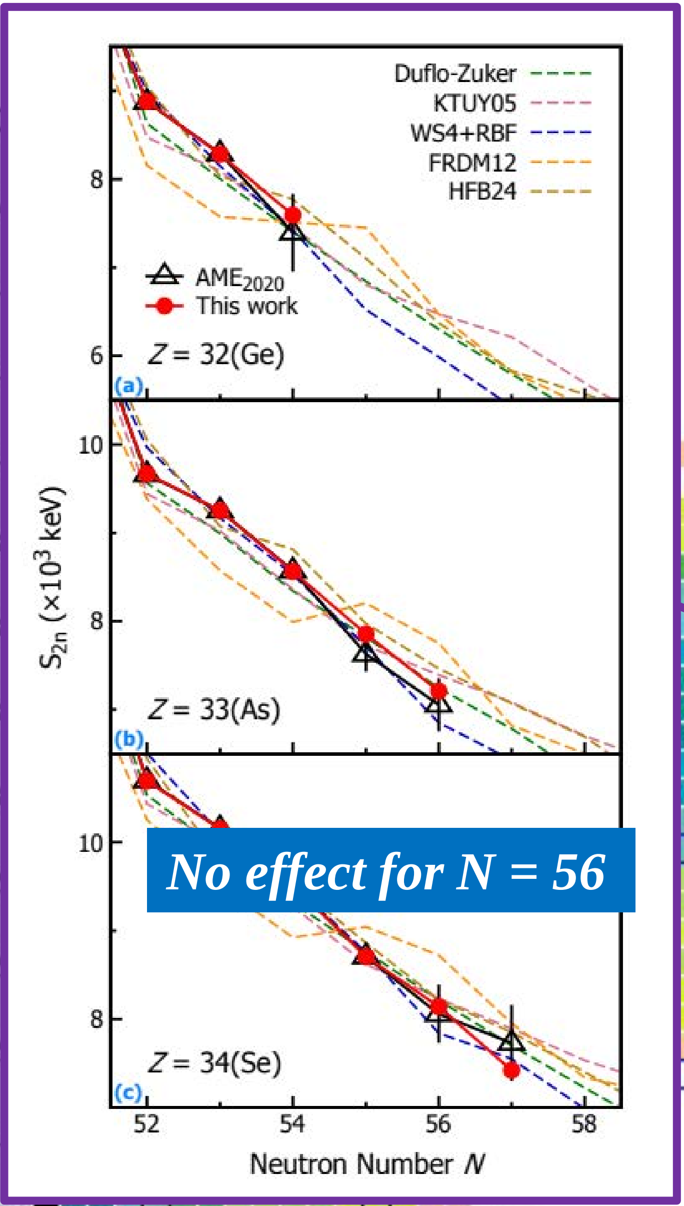
PHYSICAL REVIEW LETTERS **130,** 012501 (2023)

Study of the $N = 32$ and $N = 34$ Shell Gap for Ti and V by the First High-Precision Multireflection Time-of-Flight Mass Measurements at BigRIPS-SLOWRI

S. Iimura,[1,2,3,4,*] M. Rosenbusch,[3,†] A. Takamine,[1] Y. Tsunoda,[5] M. Wada,[3] S. Chen,[6] D. S. Hou,[7,8,9] W. Xian,[6] H. Ishiyama,[1] S. Yan,[10] P. Schury,[3] H. Crawford,[11] P. Doornenbal,[1] Y. Hirayama,[3] Y. Ito,[12] S. Kimura,[1] T. Koiwai,[13,1] T. M. Kojima,[1] H. Koura,[12] J. Lee,[6] J. Liu,[6,7] S. Michimasa,[14] H. Miyatake,[3] J. Y. Moon,[15] S. Naimi,[1] S. Nishimura,[1] T. Niwase,[1,16,3] A. Odahara,[2] T. Otsuka,[13,1,12] S. Paschalis,[17] M. Petri,[17] N. Shimizu,[5] T. Sonoda,[1] D. Suzuki,[1] Y. X. Watanabe,[3] K. Wimmer,[13,18,1] and H. Wollnik[19]

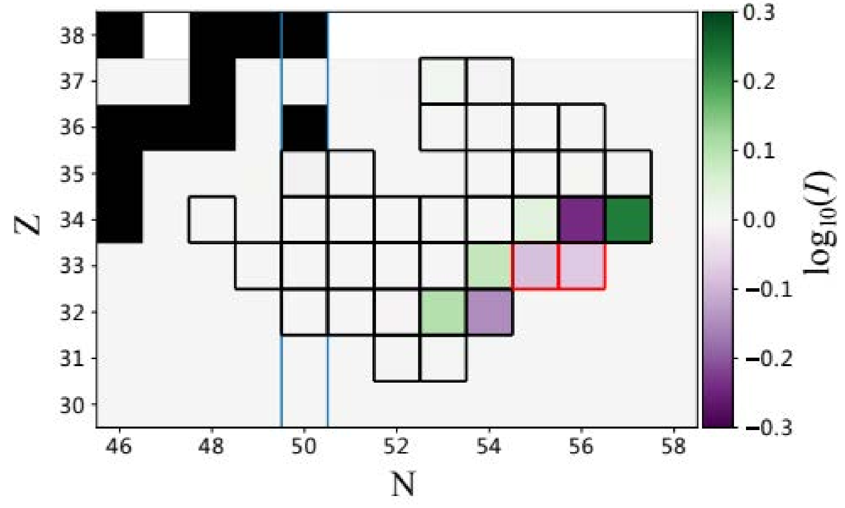
- **Published in PRL**
- **Press-released on Jan. 2023**
- **Dr Thesis for Iimura-san**

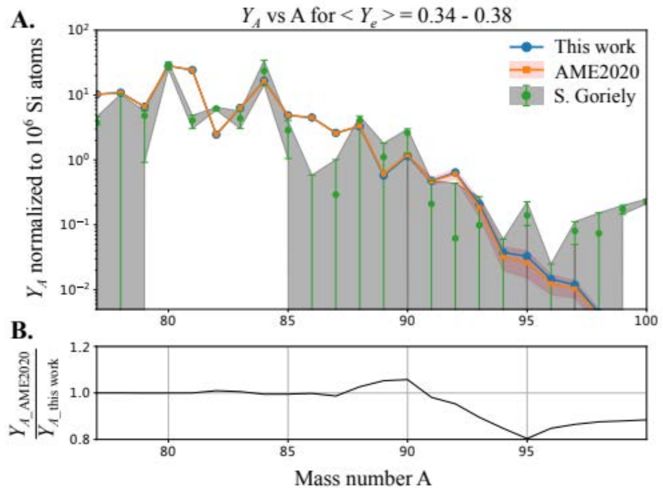
A ~ 90 region



No effect for N = 56

Ratio of reaction rates
$I = \langle\sigma v\rangle_{exp.} / \langle\sigma v\rangle_{AME2020}$





Mass measurements of neutron-rich A~90 nuclei constrain element abundances

W. Xian,[1,2,*] S. Chen,[1,2,†] S. Nikas,[3] M. Rosenbusch,[2] M. Wada,[2] H. Ishiyama,[4] D. Hou,[5] S. Iimura,[4] S. Nishimura,[4] P. Schury,[2] A. Takamine,[4] S. Yan,[6] F. Browne,[4] P. Doornenbal,[4] F. Flavigny,[7] Y. Hirayama,[2] Y. Ito,[8] S. Kimura,[4] T. M. Kojima,[4] J. Lee,[1] J. Liu,[1] H. Miyatake,[2] S. Michimasa,[9] J. Y. Moon,[10] S. Naimi,[4] T. Niwase,[2,11,4] T. Sonoda,[4] D. Suzuki,[4] Y. X. Watanabe,[2] V. Werner,[12,13] K. Wimmer,[14,15,4] and H. Wollnik[16]

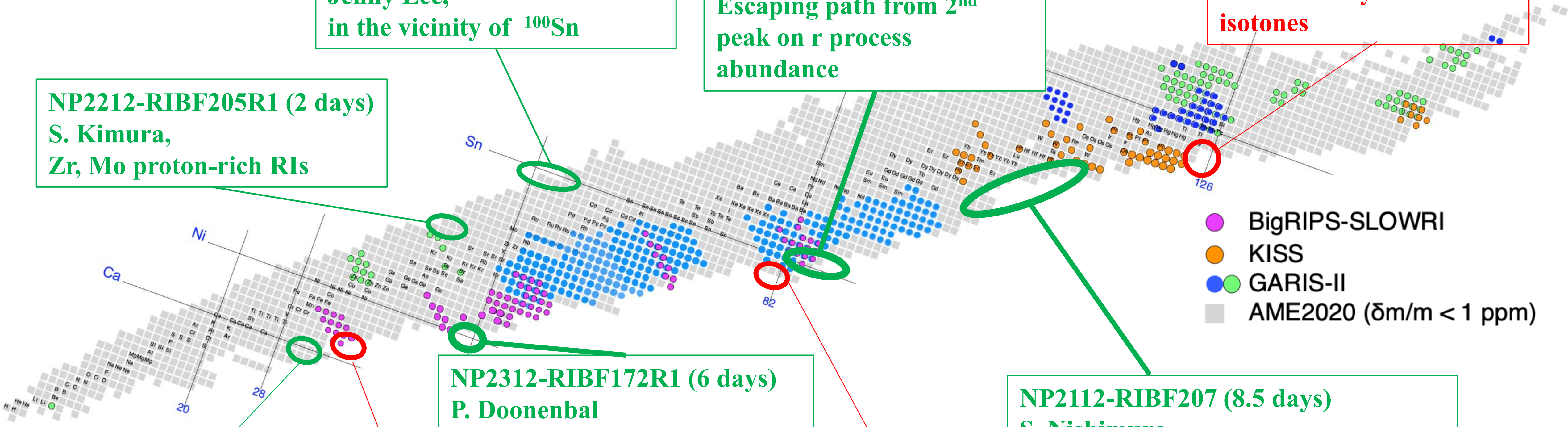
- Accepted for publication in PRC

★ more than a factor of 2 c.w. AME2020

★ First mass determination c.w. AME2020

4. Future programs

Future programs for mass measurements with SLOWRI/ZD-MRTOF



NP2112-RIBF211 (11 days)
Jenny Lee,
in the vicinity of ^{100}Sn

NP2212-RIBF216 (4 days)
Phong Vi,
Escaping path from 2nd peak on r process abundance

In planning,
S. Iimura,
in the vicinity of N = 126 isotones

NP2212-RIBF205R1 (2 days)
S. Kimura,
Zr, Mo proton-rich RIs

NP2312-RIBF172R1 (6 days)
P. Doonenbal
NP2312-RIBF202 (5 days)
M. Rosenbush
in the vicinity of ^{78}Ni

NP2112-RIBF207 (8.5 days)
S. Nishimura,
r process path on rare earth elements

PE22-01 (5 days)
Symbiotic experiment
Kanugo
Ca isotopes

In planning,
C. Fu
Around Ti isotopes

In planning,
A. Takamine,
in the vicinity of ^{129}Ag

Total Beam Time = 41.5 days


Thank you for your attention!