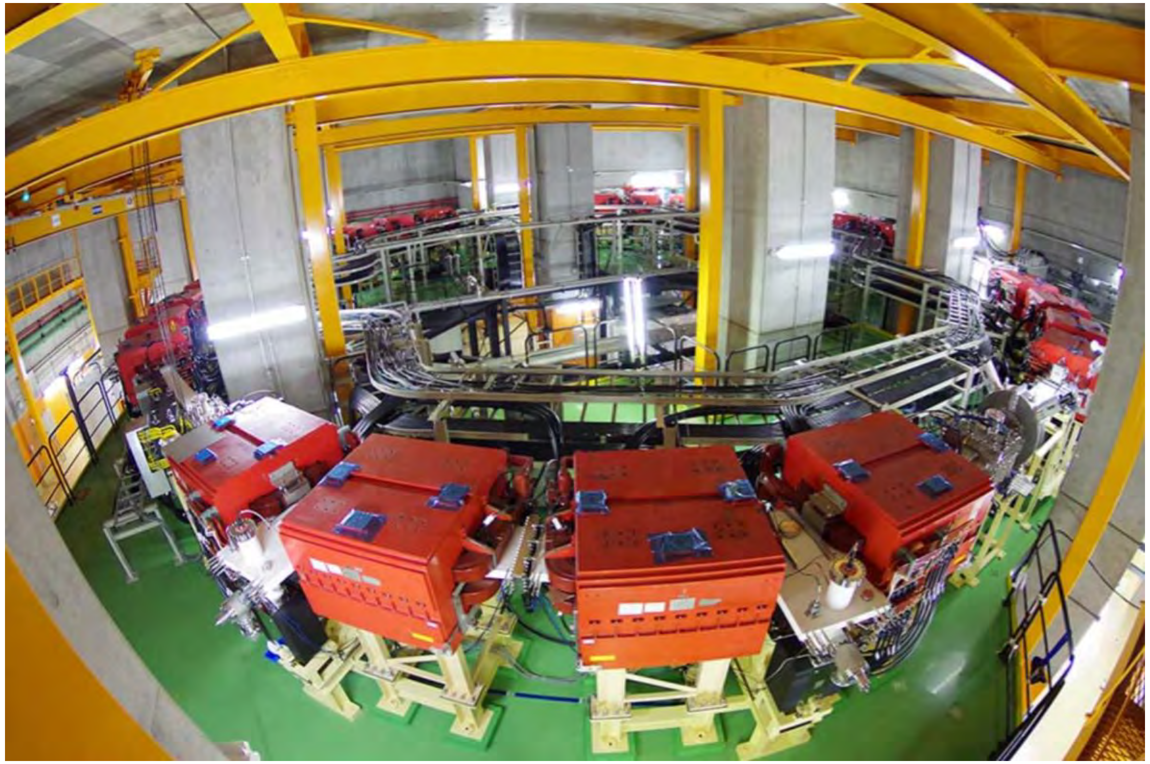
Present and future mass measurement methods of the Rare-RI Ring



A. Yano (Univ. of Tsukuba / RIKEN)

for the Rare-RI Ring collaboration

宇宙史センター構成員会議、筑波大、2025年12月16日

RIKEN

Programs for Junior Scientists

Outline

Physical motivation

- Nucleosynthesis in the universe
- Why nuclear masses?

Experimental method

- Principle of isochronous mass spectrometry
- The Rare-RI Ring facility@RIBF
- Achieved isochronism & mass precision

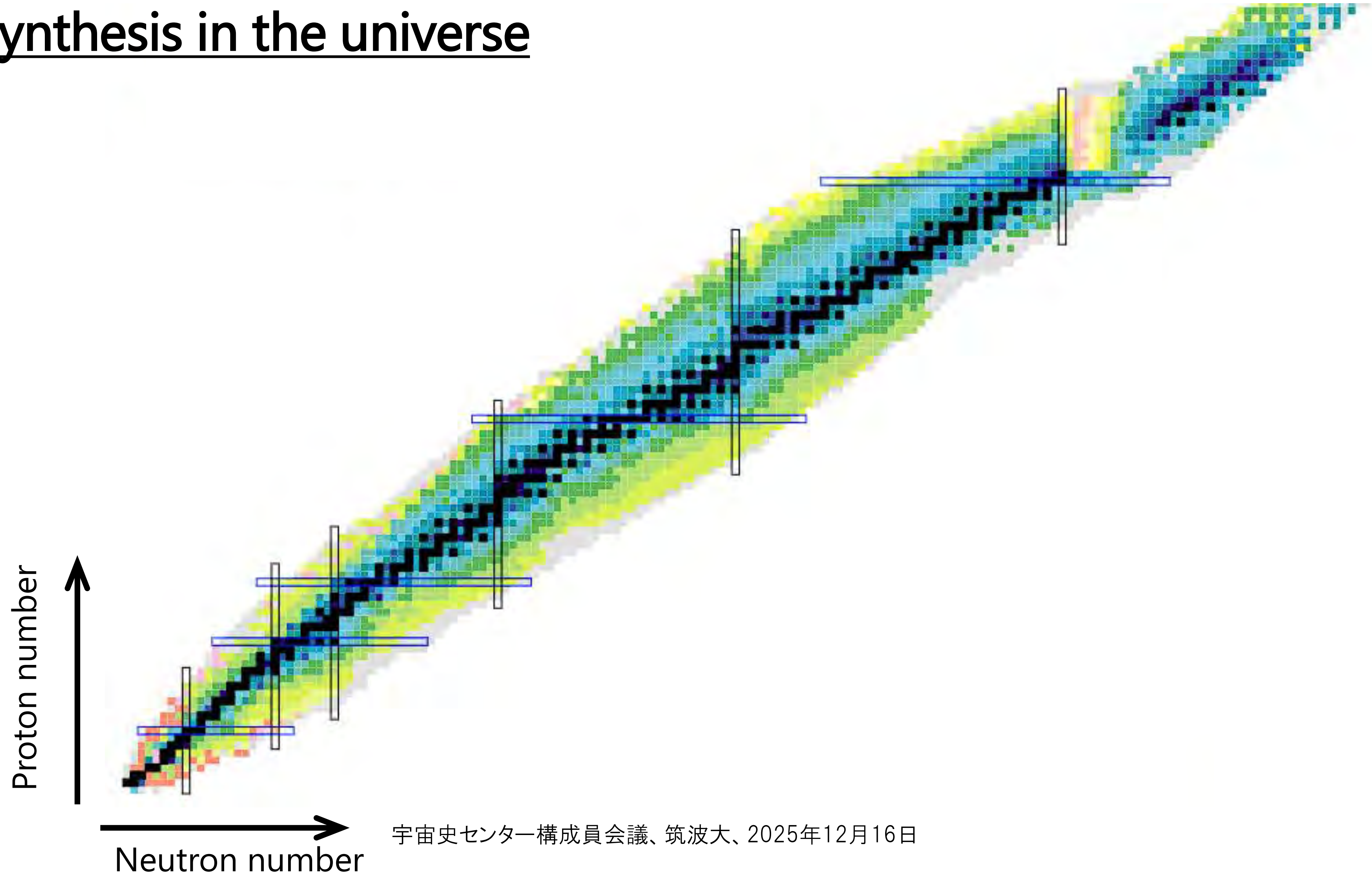
Recent upgrades

- Injection to the Rare-RI Ring
- Extraction from the Rare-RI Ring
- Future mass measurements in the Rare-RI Ring

Summay & Outlook

Physical motivation

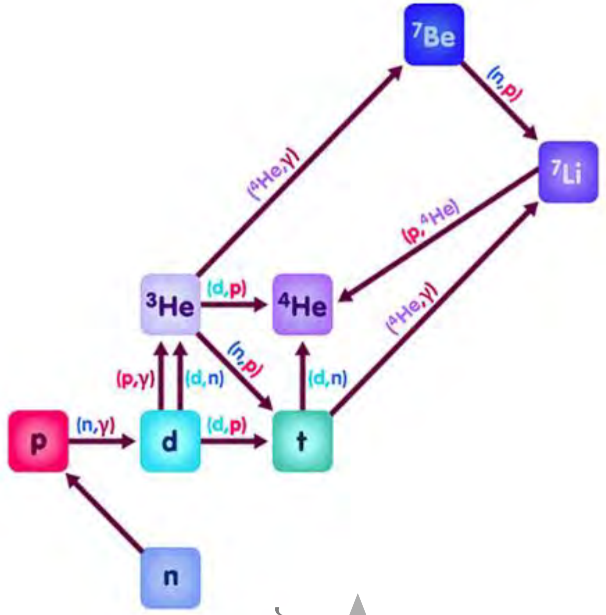
Nucleosynthesis in the universe

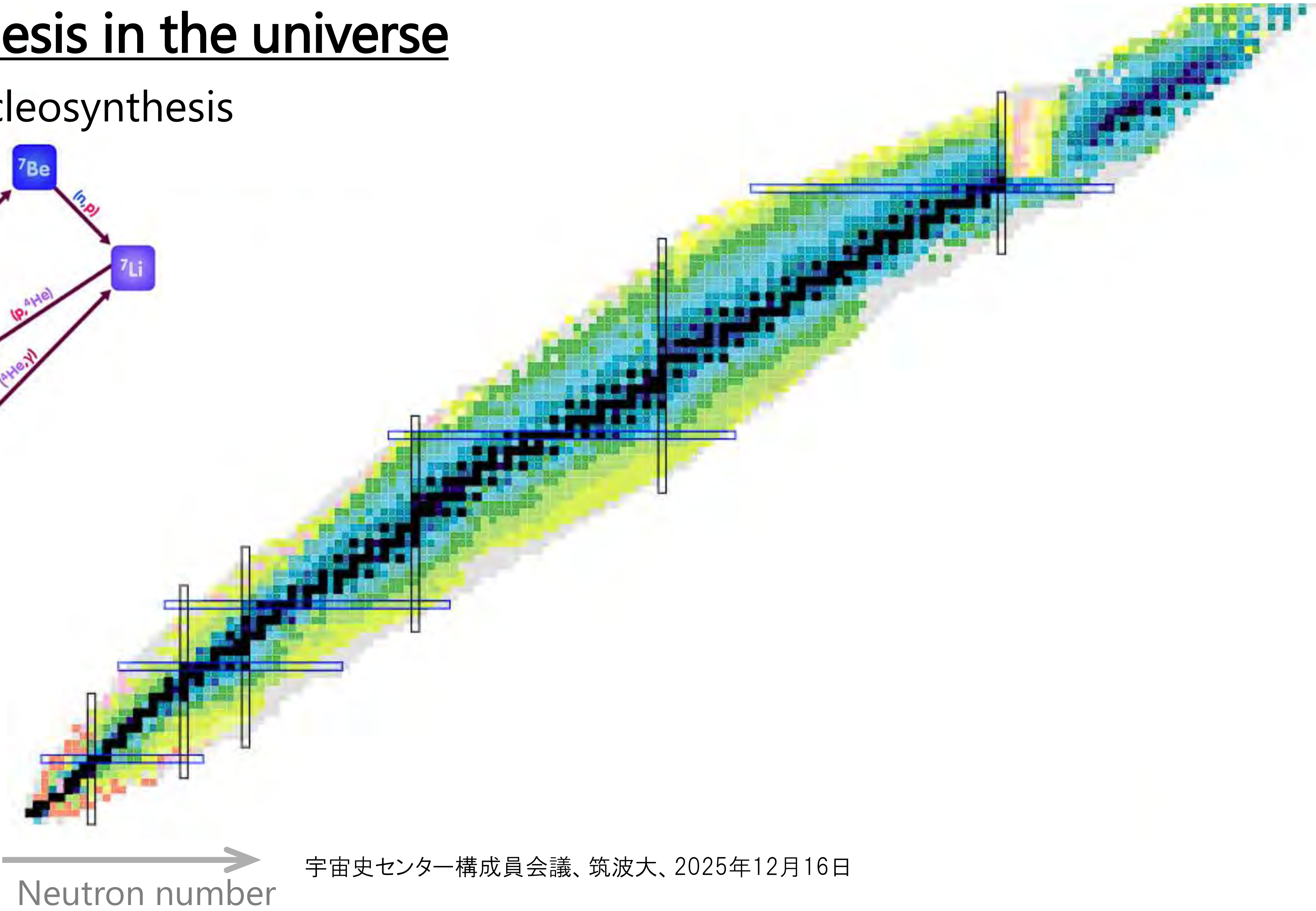


Physical motivation

Nucleosynthesis in the universe

1. Big-bang nucleosynthesis





Physical motivation

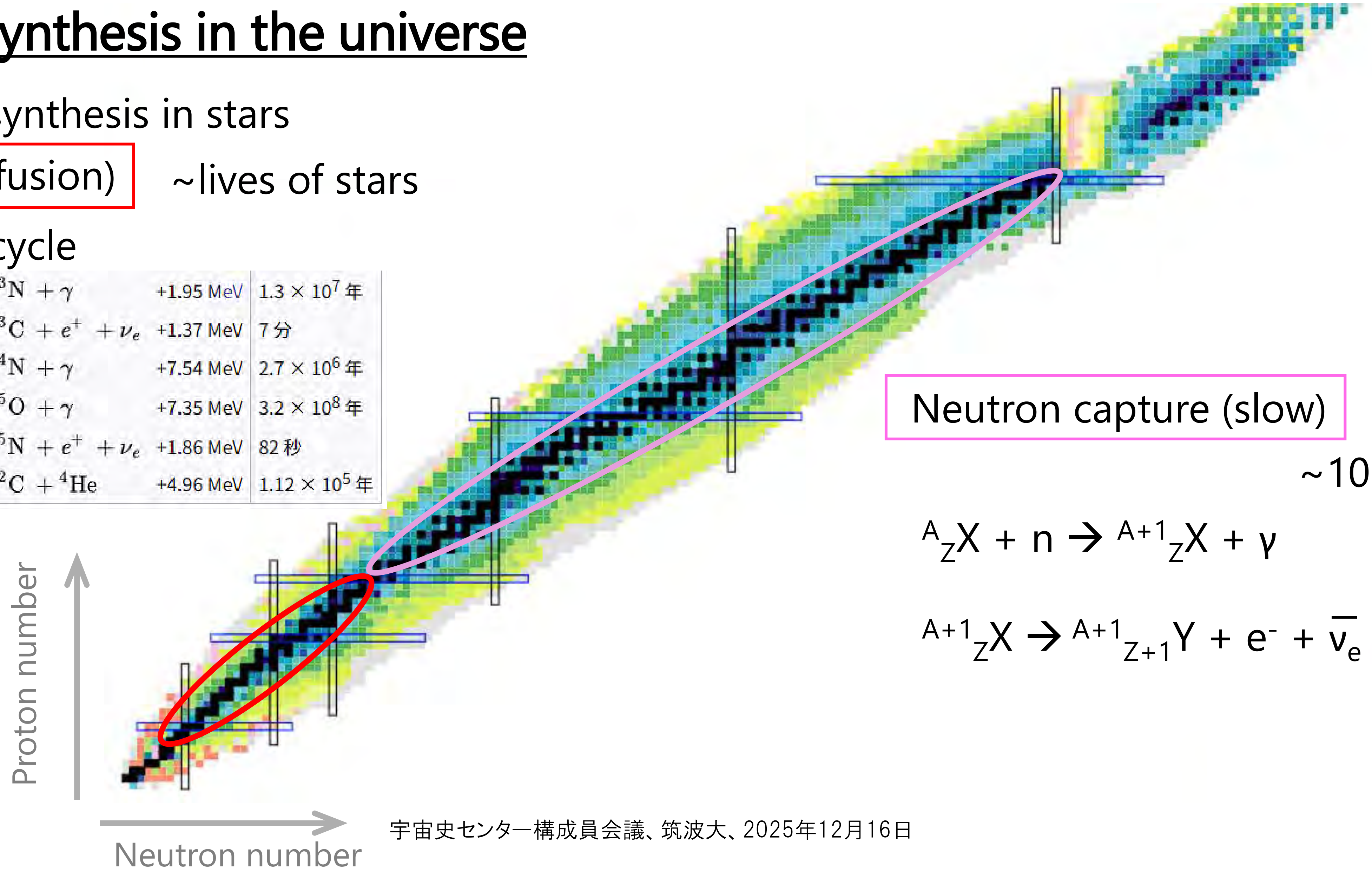
Nucleosynthesis in the universe

2. Nucleosynthesis in stars

Burning (fusion)　~lives of stars

ex) CNO cycle

$^{12}C + {}^{1}H \longrightarrow {}^{13}N + \gamma$		+1.95 MeV	1.3×10^{7} 年
$^{13}N \longrightarrow {}^{13}C + e^{+} + \nu_e$		+1.37 MeV	7 分
$^{13}C + {}^{1}H \longrightarrow {}^{14}N + \gamma$		+7.54 MeV	2.7×10^{6} 年
$^{14}N + {}^{1}H \longrightarrow {}^{15}O + \gamma$		+7.35 MeV	3.2×10^{8} 年
$^{15}O \longrightarrow {}^{15}N + e^{+} + \nu_e$		+1.86 MeV	82 秒
$^{15}N + {}^{1}H \longrightarrow {}^{12}C + {}^{4}He$		+4.96 MeV	1.12×10^{5} 年



Neutron capture (slow)

~1000 years

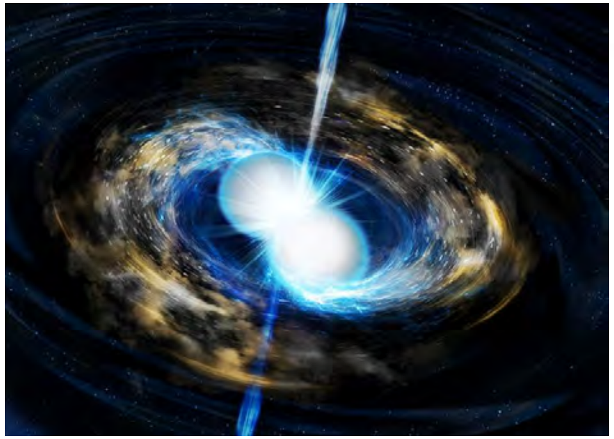
$^{A}_{Z}X + n \rightarrow {}^{A+1}_{Z}X + \gamma$

$^{A+1}_{Z}X \rightarrow {}^{A+1}_{Z+1}Y + e^{-} + \overline{\nu}_e$

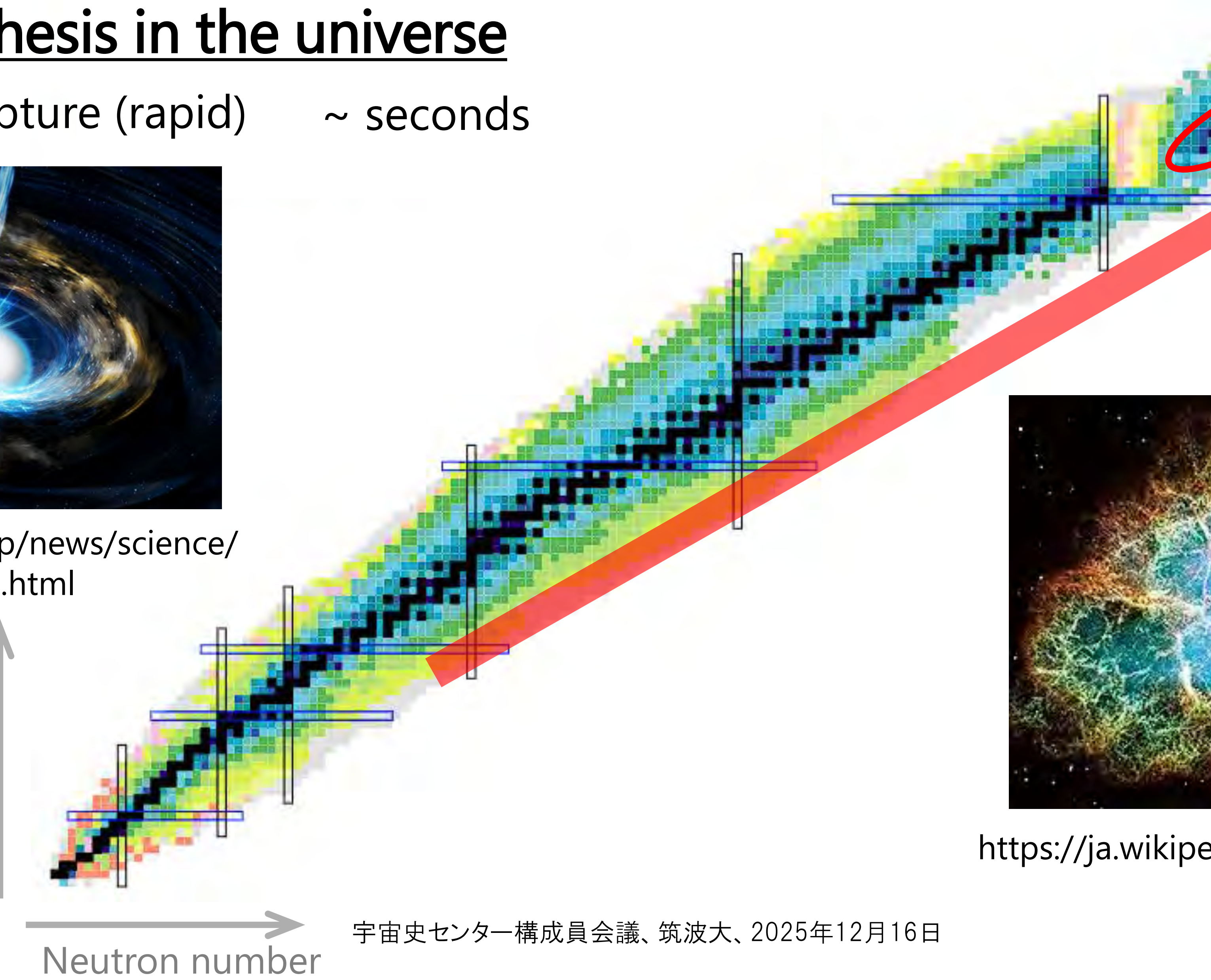
Physical motivation

Nucleosynthesis in the universe

3. Neutron capture (rapid) ~ seconds



https://www.nao.ac.jp/news/science/2022/20221027-cfca.html



https://ja.wikipedia.org/wiki/SN_1054

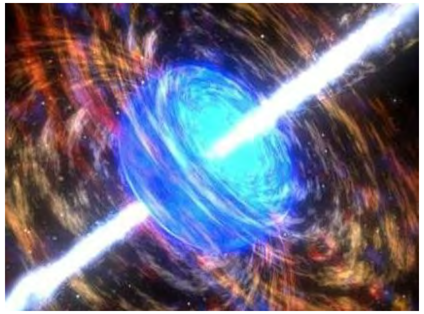
Physical motivation

Nucleosynthesis in the universe

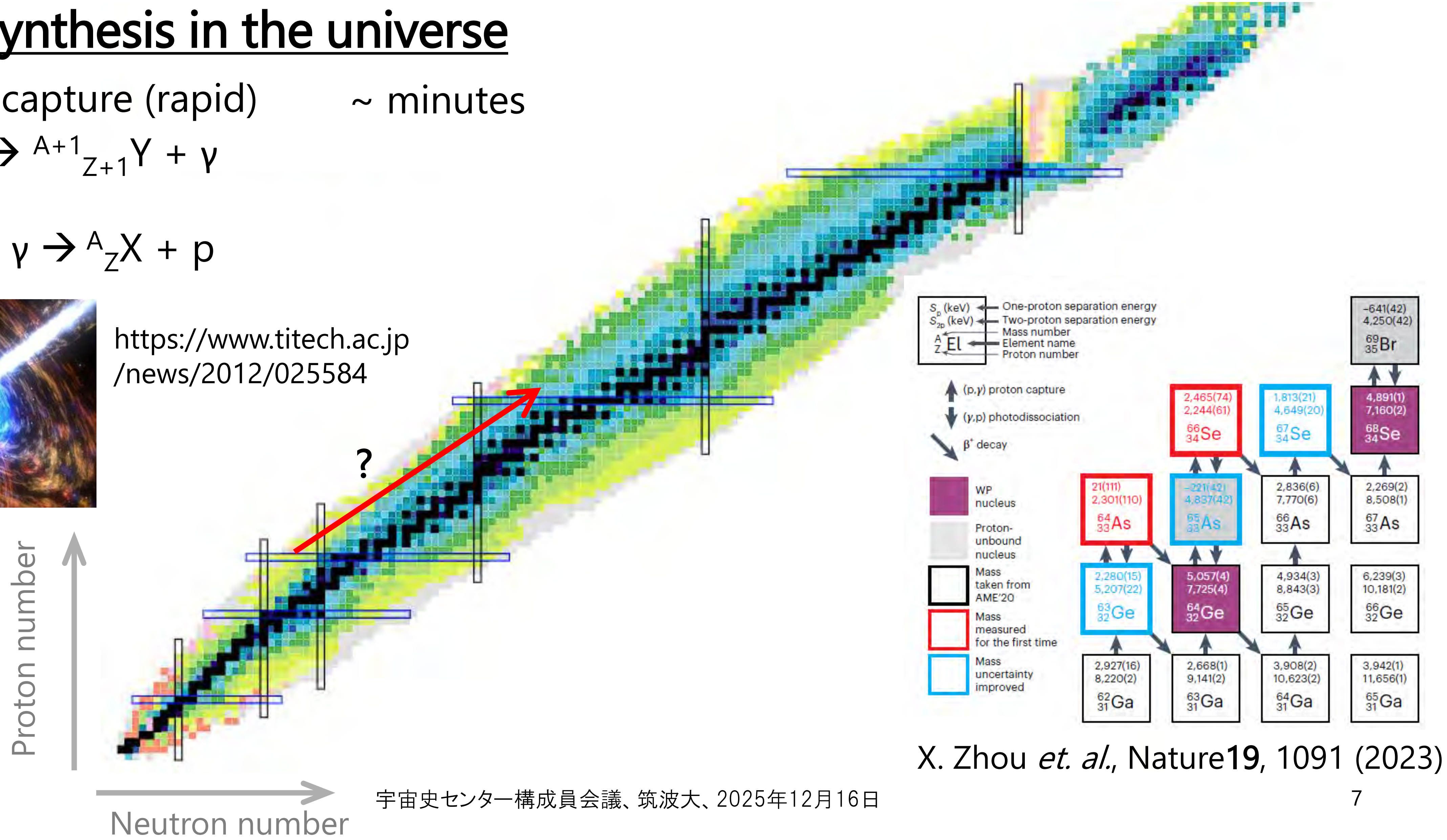
4. Proton capture (rapid) ~ minutes

$^{A}_{Z}X + p \rightarrow {}^{A+1}_{Z+1}Y + \gamma$

$^{A+1}_{Z+1}Y + \gamma \rightarrow {}^{A}_{Z}X + p$



https://www.titech.ac.jp
/news/2012/025584



X. Zhou *et. al.*, Nature**19**, 1091 (2023)

Why nuclear masses?

How to measure reaction rates, e.g., (n, γ) or (p, γ) ?

☹ Produce and use rare isotope beams

Short half lives (~ms), Low yield (few events/day)

☹ Neutron target for the measurements of neutron capture rate

Neutron target is not available

→Calculation based on nuclear masses

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$\boxed{\rightarrow \text{Calculation based on nuclear masses}}$

Ex) Reaction rate formalism of A(p, γ)B ⇔ B(γ, p)C

$$\lambda_{A\to B\to C} = N_p \left(\frac{h^2}{2\pi}\right)^{3/2} \frac{1}{(m_{Ap}kT)^{3/2}} \frac{(2j_B+1)}{(2j_A+1)(2j_p+1)} \frac{G_B^{\mathrm{norm}}}{G_A^{\mathrm{norm}} G_p^{\mathrm{norm}}} e^{Q_{A\to B}/kT} \lambda_{B\to C}$$

A. Parikh *et. al.*, PPNP**69**, 225 (2013)

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A. Parikh *et. al.*, PPNP**69**, 225 (2013)

Reduced mass of A+p

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Neutron target is not available

→Calculation based on nuclear masses

Ex) Reaction rate formalism of A(p, γ)B ⇔ B(γ, p)C

Q-value of the reaction

$m_A + m_p - m_B$

$$\lambda_{A\to B\to C} = N_p \left(\frac{h^2}{2\pi}\right)^{3/2} \frac{1}{(m_{Ap}kT)^{3/2}} \frac{(2j_B+1)}{(2j_A+1)(2j_p+1)} \frac{G_B^{\mathrm{norm}}}{G_A^{\mathrm{norm}} G_p^{\mathrm{norm}}} e^{Q_{A\to B}/kT} \lambda_{B\to C}$$

A. Parikh *et. al.*, PPNP**69**, 225 (2013)

Reduced mass of A+p

Experimental method

Principle of mass measurements

The Rare-RI Ring facility

Achieved isochronism & mass precision

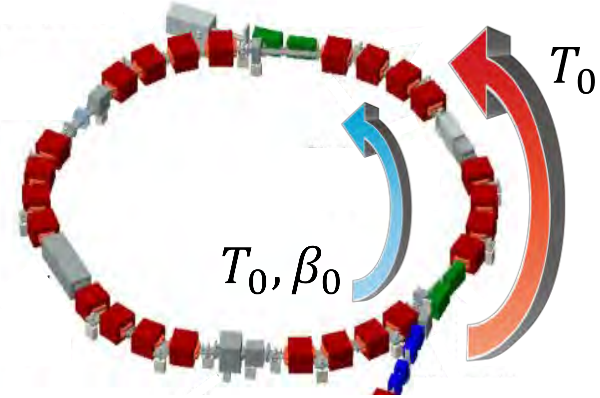
Principle of mass measurements

Isochronous mass spectrometry (IMS)

- Isochronism: constant revolution time (T)

$\boxed{\boldsymbol{T_0 = T_0{}'} \text{ for the reference particles}}$

$\beta_0 < \beta_0{}'$



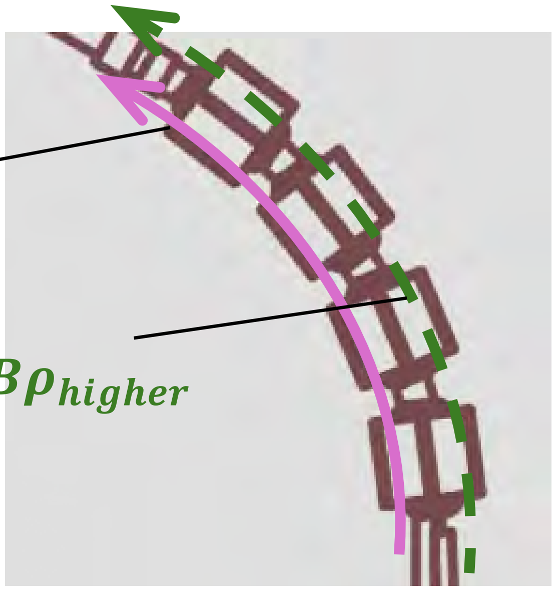
- Orbit length (L) ⇔ Magnetic rigidity $(B\rho)$

$\boxed{\boldsymbol{L = \beta_0 T_0 = \beta_1 T_1}}$

$m_0/q_0, \beta_0$, $m_1/q_1, \beta_1$, $\boldsymbol{B\rho_{lower}}$

Reference particles　Target particles

$m_0/q_0, \beta_0{}', m_1/q_1, \beta_1{}', \boldsymbol{B\rho_{higher}}$



$$\frac{m_1}{q_1} = \frac{m_0}{q_0}\frac{T_1}{T_0}\sqrt{\frac{1-\beta_1{}^2}{1-\left(\left(\frac{T_0}{T_1}\right)\beta_1\right)^2}} = \frac{m_0}{q_0}\frac{T_1}{T_0}\sqrt{1+\frac{1-\left({}^{T_0}/{}_{T_1}\right)^2}{\left(\left(\frac{m_0/q_0}{B\rho}\right)c\right)^2}}$$

where $T = 2\pi\frac{m}{qB}$

β correction method　　$B\rho$ correction method

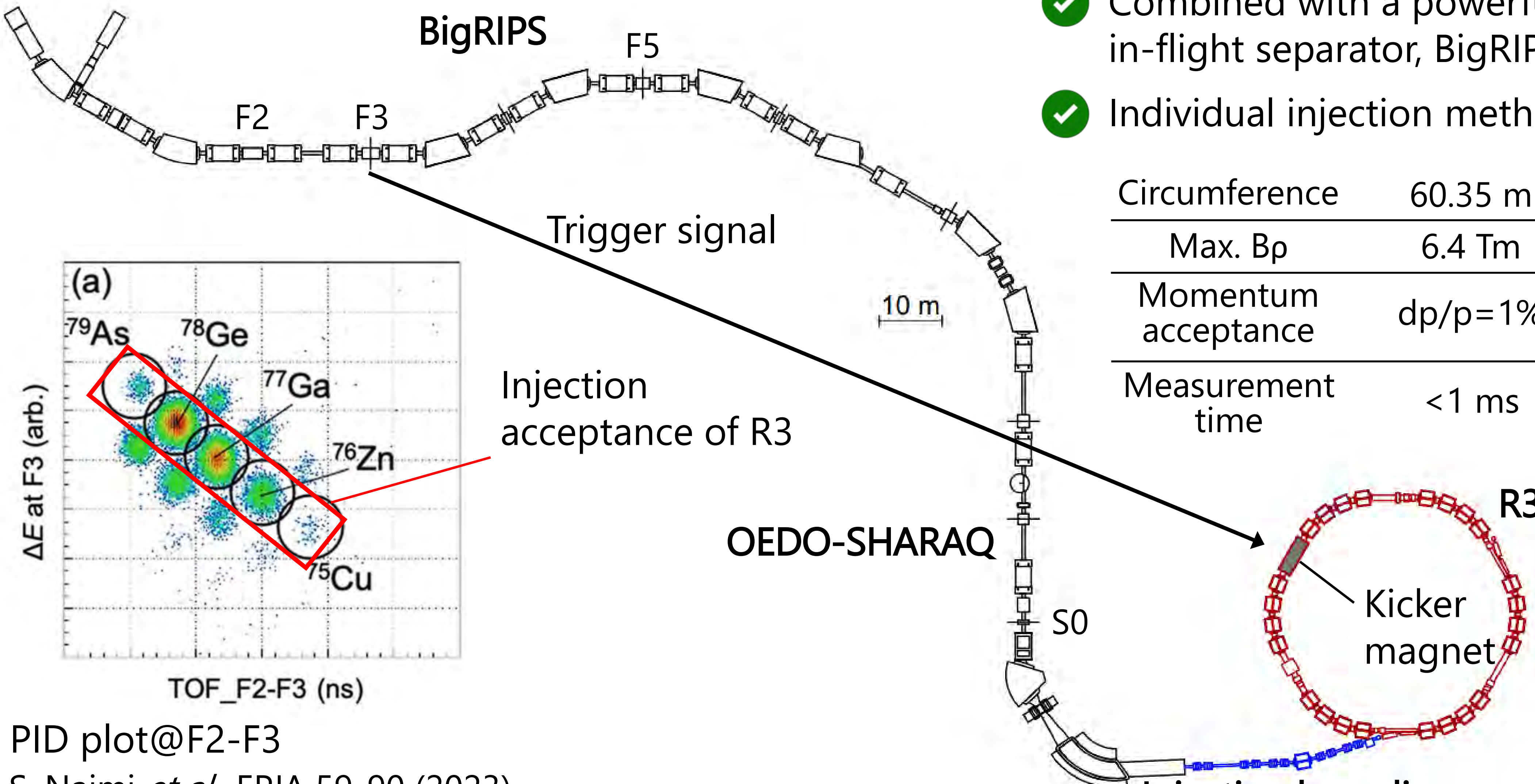
Revolution times, Velocity, or **Magnetic rigidity**

The Rare-RI Ring (R3) facility

A. Ozawa *et al.*, PTEP**2012** 03C009 (2012)

- ✅ Combined with a powerful in-flight separator, BigRIPS
- ✅ Individual injection method

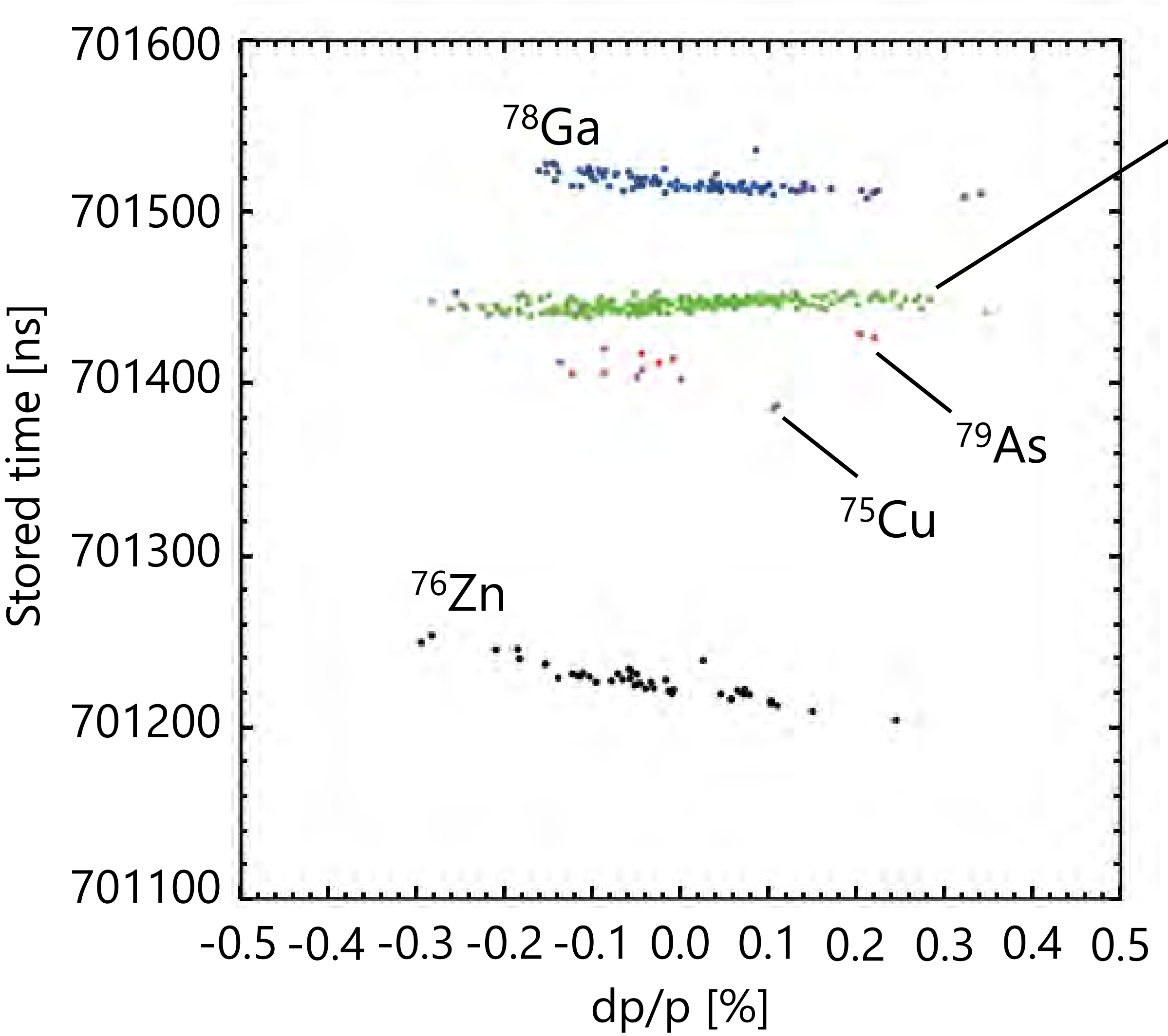
Circumference	60.35 m
Max. Bρ	6.4 Tm
Momentum acceptance	dp/p=1%
Measurement time	<1 ms



PID plot@F2-F3

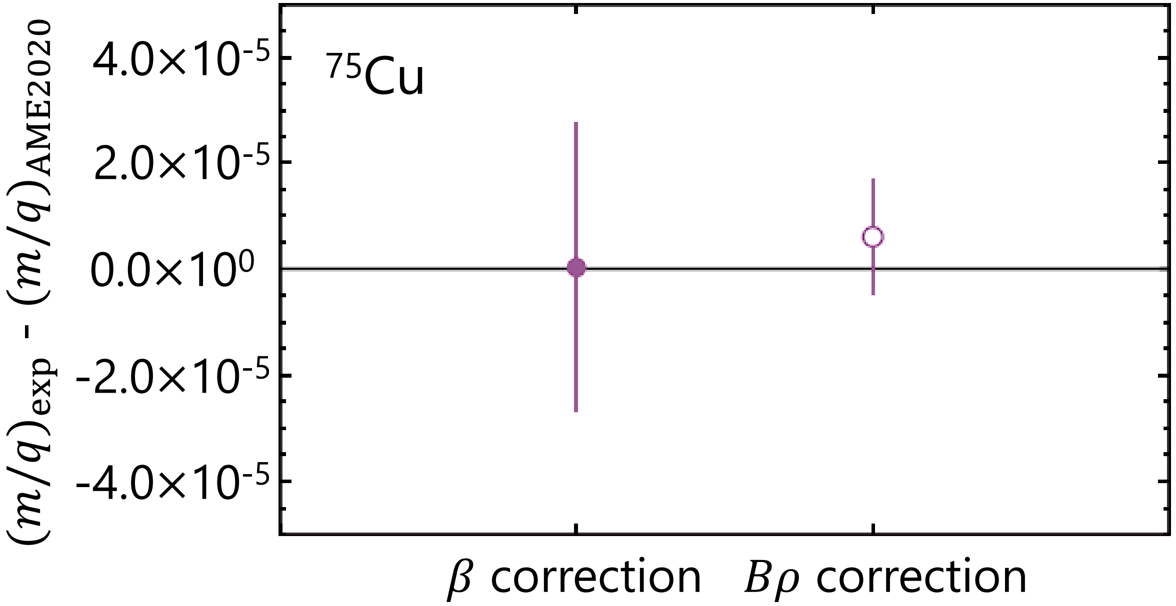
S. Naimi *et al.*, EPJA 59-90 (2023)

Achieved isochronism & mass precision



^{78}Ge (isochronous reference)

Isochronism: ~5.4x10^{-6}



	β correction	$B\rho$ correction
δ(m/q)	2.7x10^{-5}	1.1x10^{-5}
δm	**~740 keV**	**~290 keV**

D. Nagae *et al.*, PRC**110**, 014310 (2024)

Recent upgrades

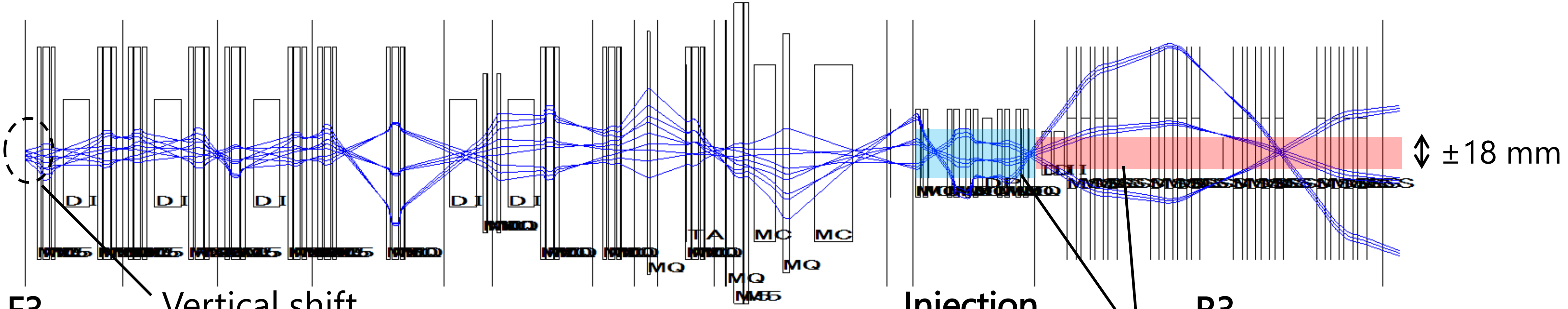
(i) Injection to R3

(ii) Extraction from R3

(iii) Future mass measurements

(i) Injection to R3

Low injection efficiency to R3



F3

Vertical shift
Y : -2.0 mm
Y′: -2.7 mrad

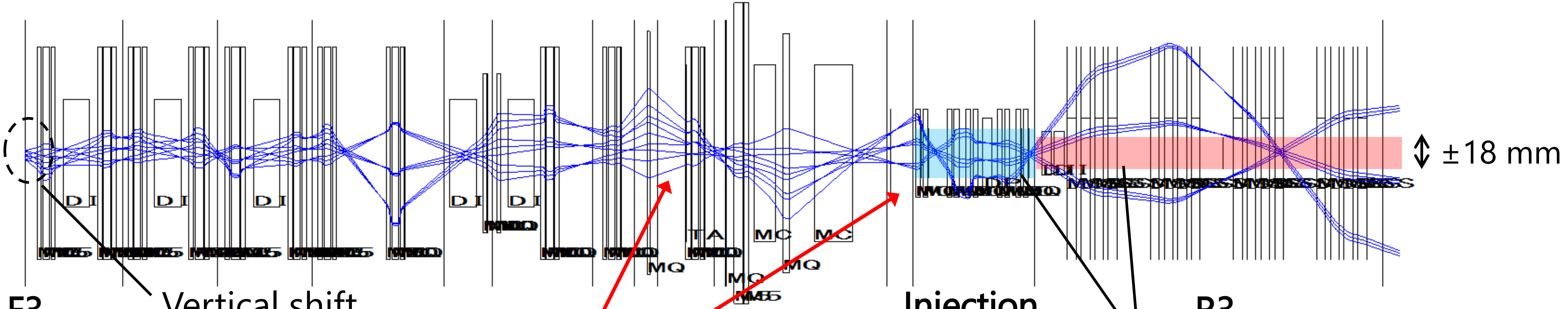
Injection line

R3

Geometrical acceptance

(i) Injection to R3

Low injection efficiency to R3



F3

Vertical shift
Y : -2.0 mm
Y′: -2.7 mrad

Injection line

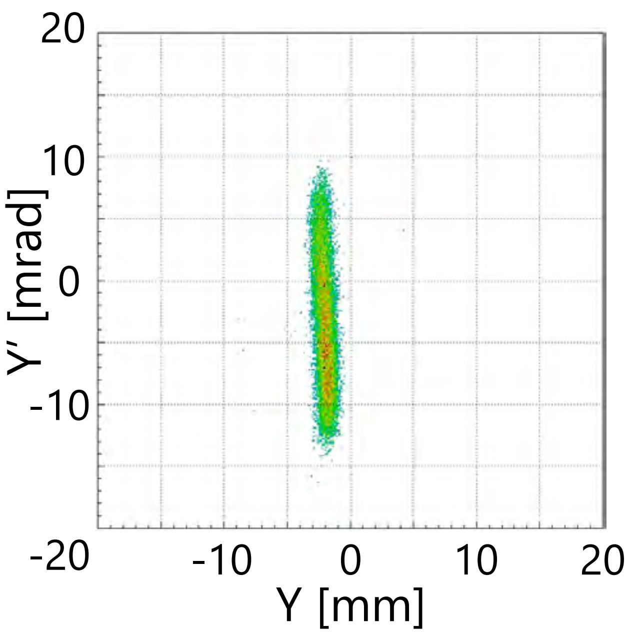
R3

Geometrical acceptance

	ST1	ST2
Magnetic flux density	0.056 T	0.067 T
Current	19 A	17 A
Size	370×430×300 mm	310×360×250 mm
Pole gap	170 mm	125 mm
Weight	180 kg	110 kg

(i) Injection to R3

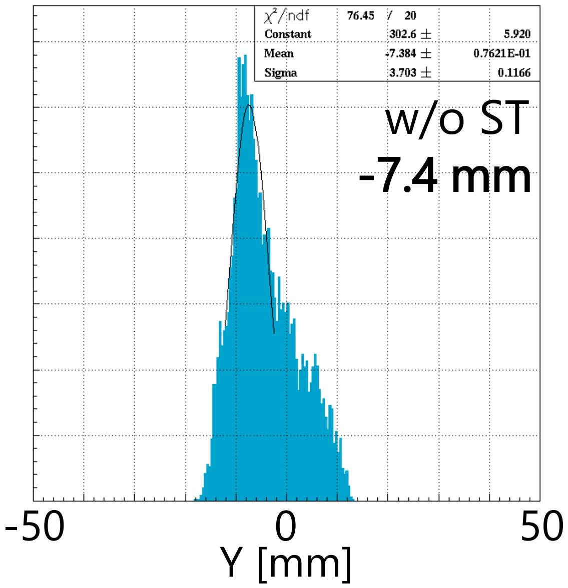
^{124}Xe ~155 MeV/u@R3

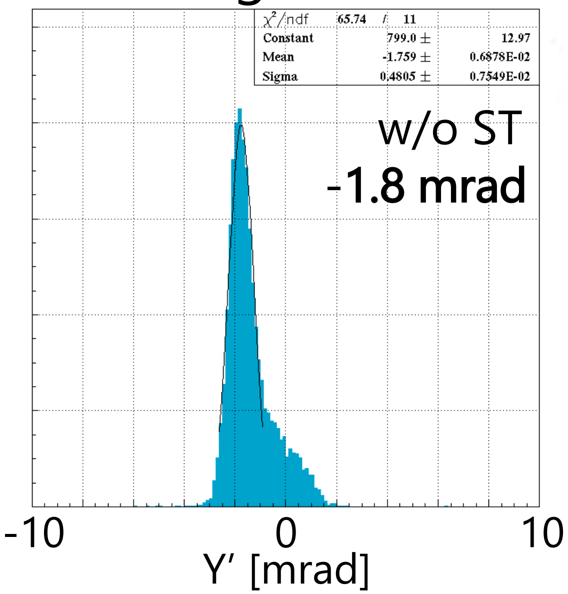


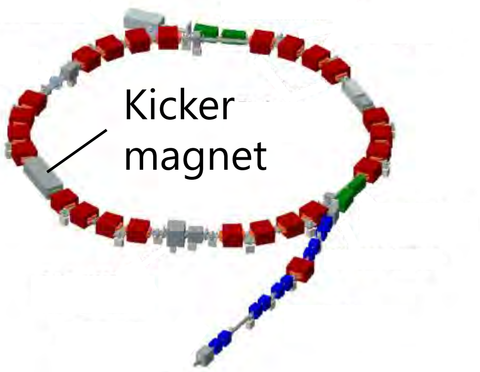
Vertical beam profile@F3

Y: -2.0 mm
Y′: -2.8 mrad

Y and Y′ at the kicker magnet



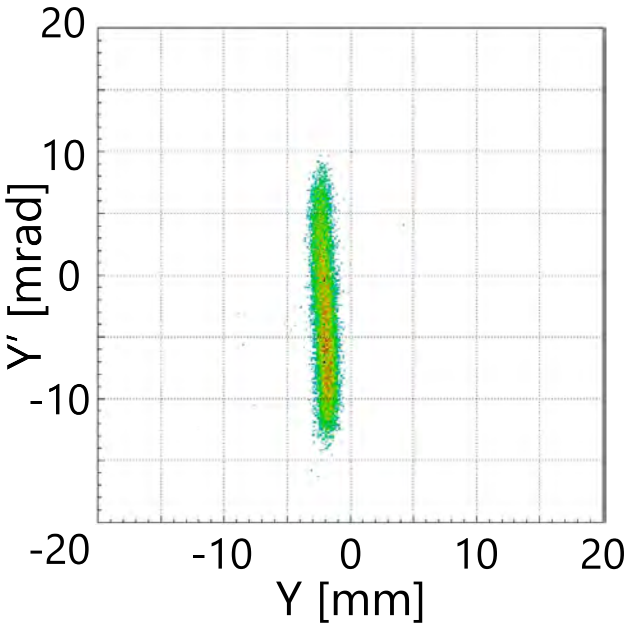




<u>Deflection angle</u>
ST1: -1.5 mrad
ST2: +1.7 mrad

(i) Injection to R3

^{124}Xe ~155 MeV/u@R3



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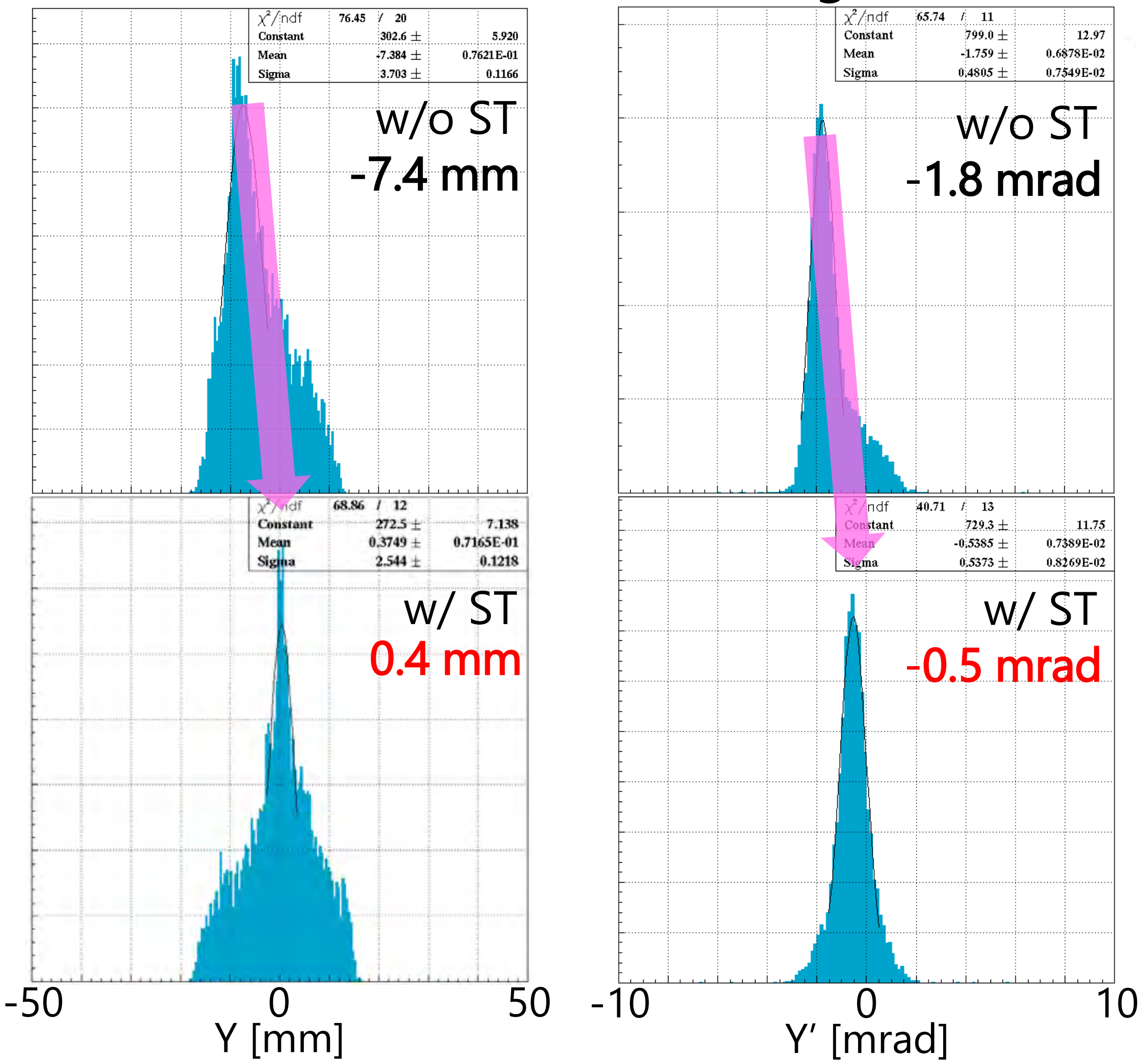
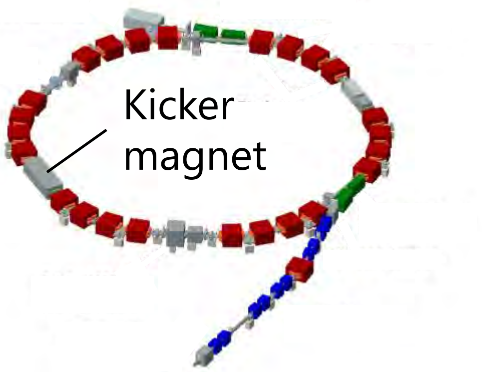
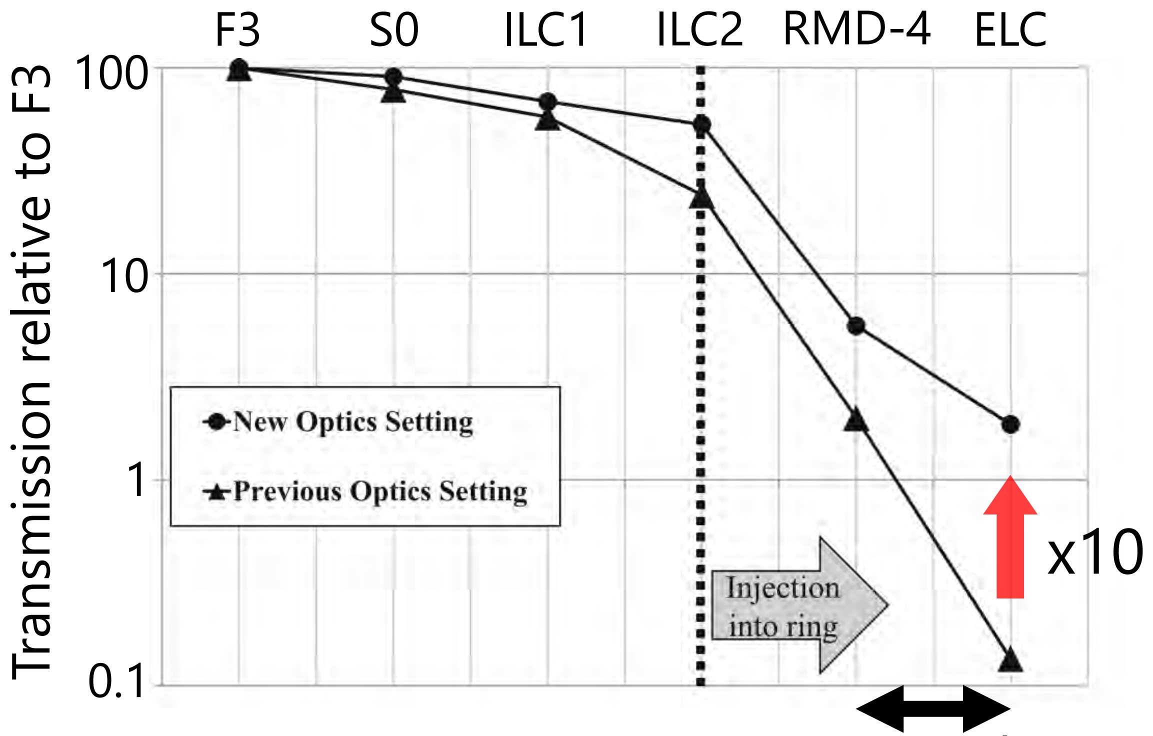




Deflection angle
ST1: -1.5 mrad
ST2: +1.7 mrad

- Vertical mismatch was corrected
- Injection x2
  Extraction x3.5

(ii) Extraction from R3

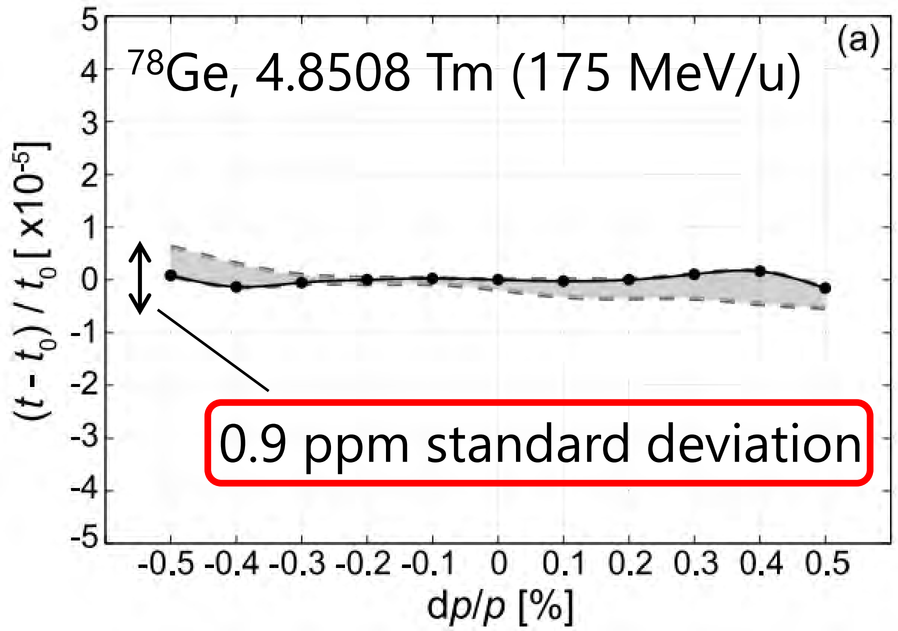


S. Naimi *et al.*, EPJA 59-90 (2023)

Still large gap between RMD-4 and ELC
→ Beam motion inside R3

Beam tracking simulation with B_y

- Runge-Kutta method
- Isochronism evaluation



Y. Abe *et al.*, NIM-A**1072**,170083 (2023)

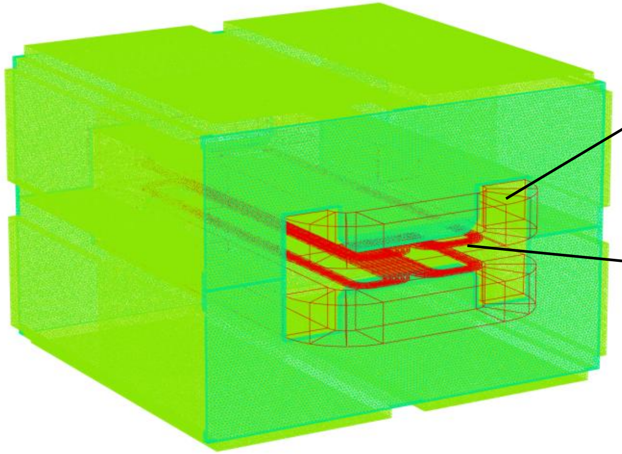
3D magnetic field

(ii) Extraction from R3

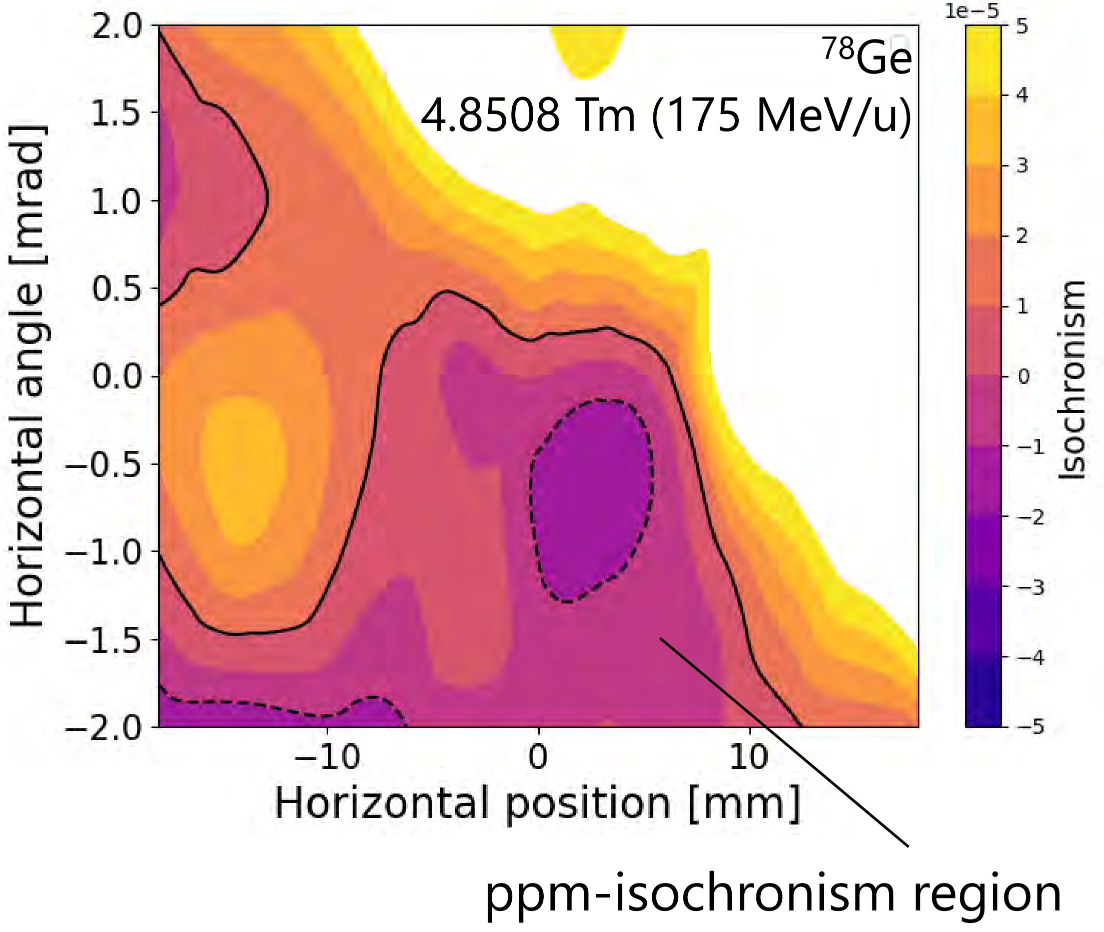
Calculate 3D magnetic field using Opera 2023

↓

Parameterize the magnetic field as a function of the beam position



Simulated isochronous acceptance in the X-X′ plane after 6 revolutions



(iii) Future mass measurements

Schottky-based IMS

<u>Present (detectors upstream R3)</u>

Velocity : TOF (F3-S0)

$B\rho$: Position@F5

<u>Future (detectors installed in R3)</u>

Velocity : Revolution time

$B\rho$: Position@R3

Whole measurements will be completed inside R3

(iii) Future mass measurements

Schottky-based IMS

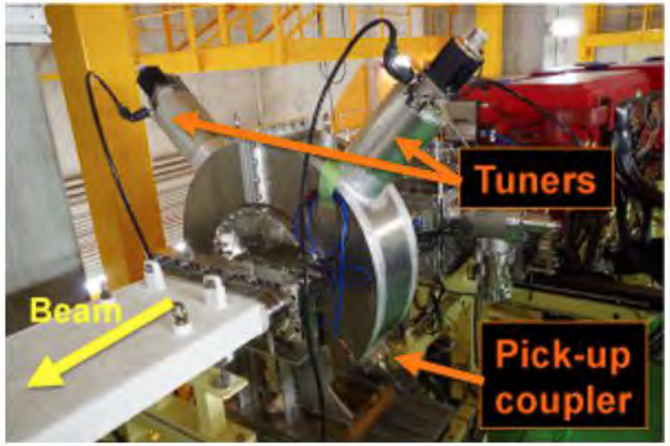
Present (detectors upstream R3)		Future (detectors installed in R3)
Velocity : TOF (F3-S0)	→	Velocity : Revolution time
$B\rho$: Position@F5		$B\rho$: Position@R3

Whole measurements will be completed inside R3

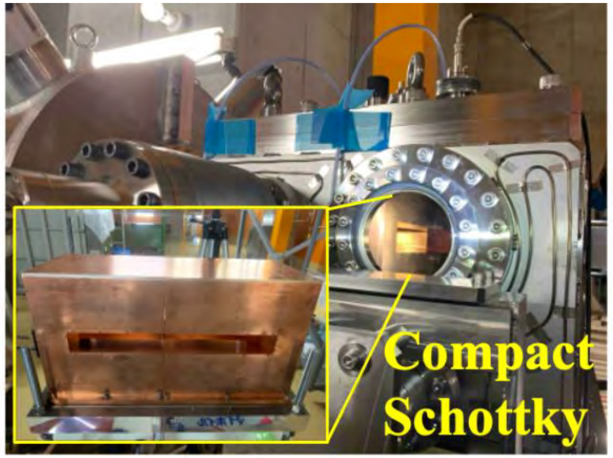
Schottky detectors

- Electric of magnetic field is induced
- Non-destructive

F. Suzaki *et al.*,
RIKEN APR**49**,179 (2016)



Compact Schottky
for velocity measurements



- Fast detection

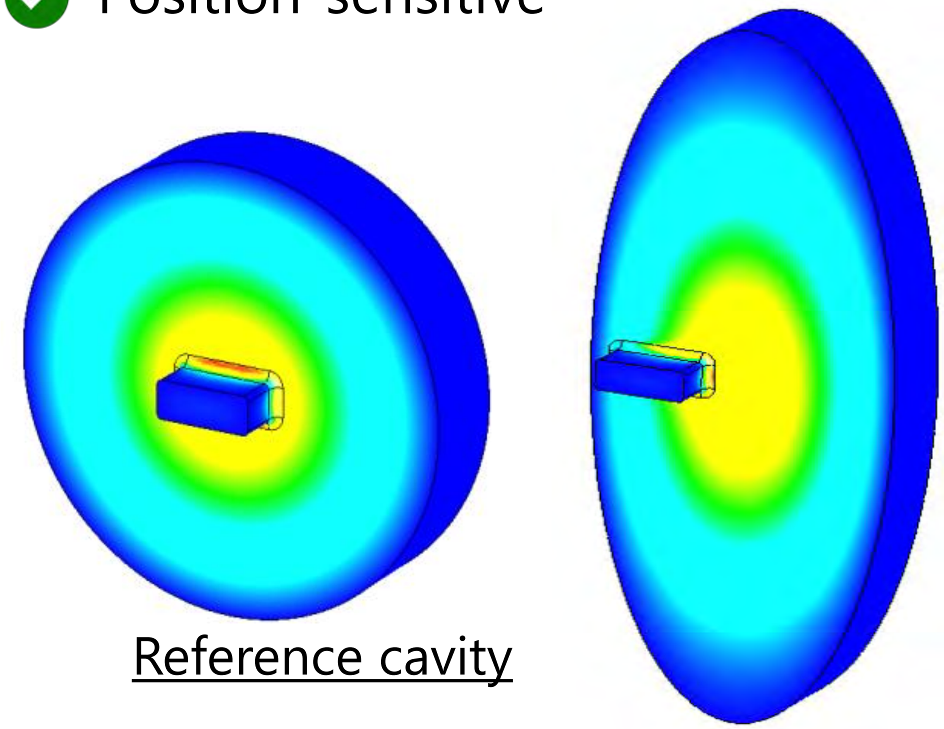
$^{124}Xe^{54+}$ (155 MeV/u)
was detected <10 ms!

T. Yamaguchi *et al.*,
RIKEN APR**58**

(iii) Future mass measurements   Schottky Cavity Doublet (SCD)

Schottky Cavity Doublet (SCD)
for $B\rho$ measurements

- ✔ Position-sensitive

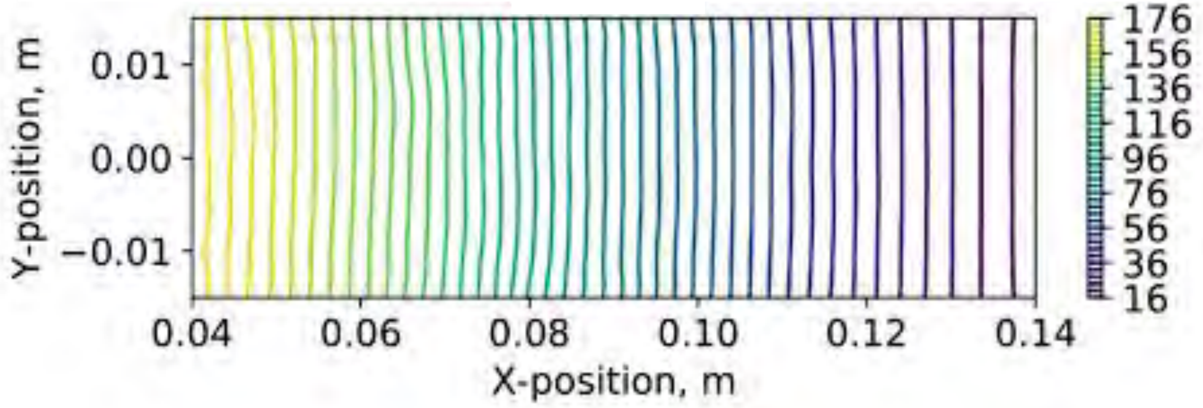


Reference cavity

Elliptical cavity

Courtesy by G. Hudson-Chang

Signal sensitivity of the elliptical cavity

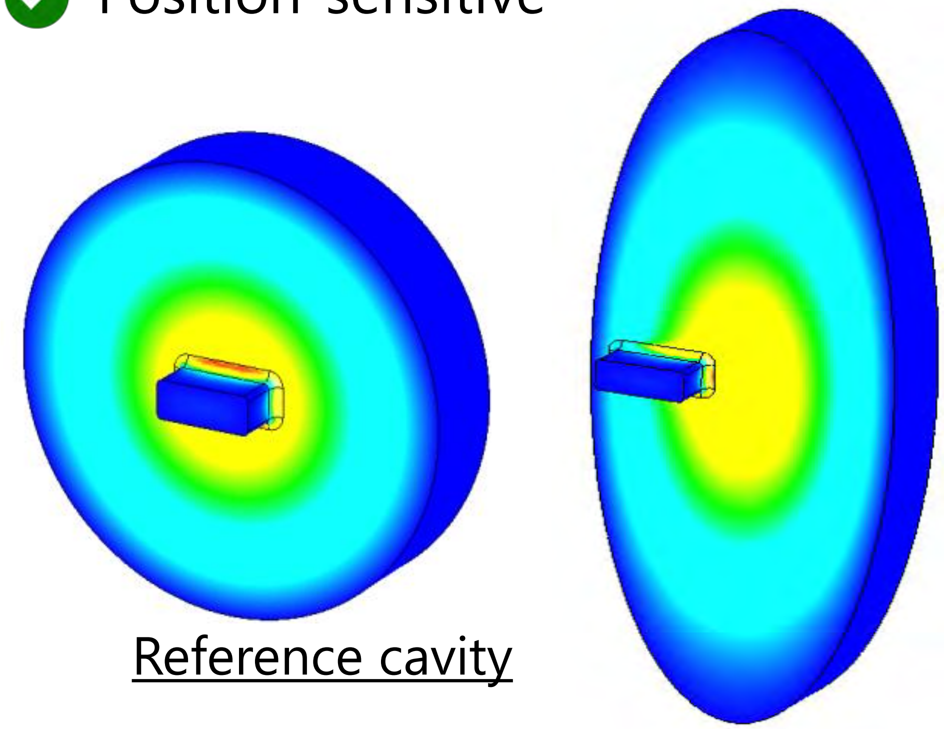


D. Dmytriiev *et al.*, NIM-B**463**, 320-323 (2020)

(iii) Future mass measurements　Schottky Cavity Doublet (SCD)

<u>**Schottky Cavity Doublet (SCD)**</u>
<u>for $B\rho$ measurements</u>

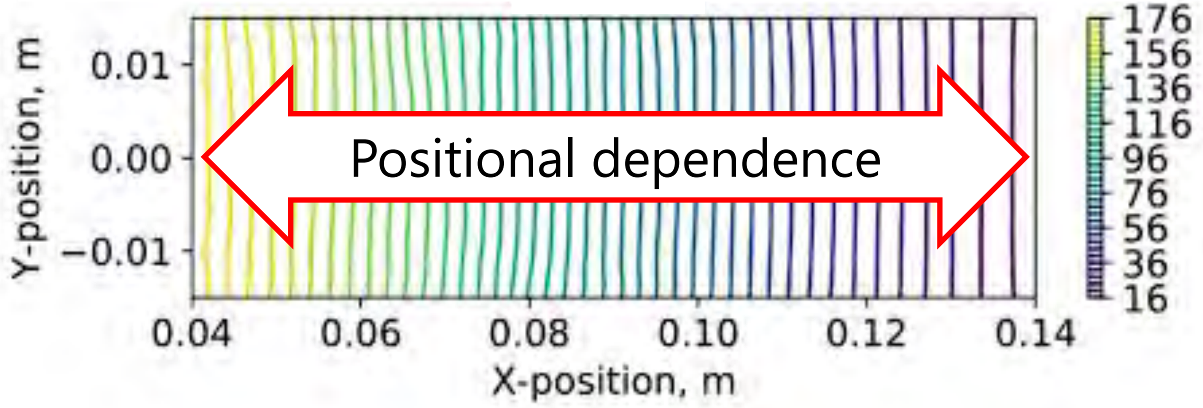
✔ Position-sensitive



<u>Reference cavity</u>

<u>Elliptical cavity</u>

Signal sensitivity of the elliptical cavity



D. Dmytriiev *et al.*, NIM-B**463**, 320-323 (2020)

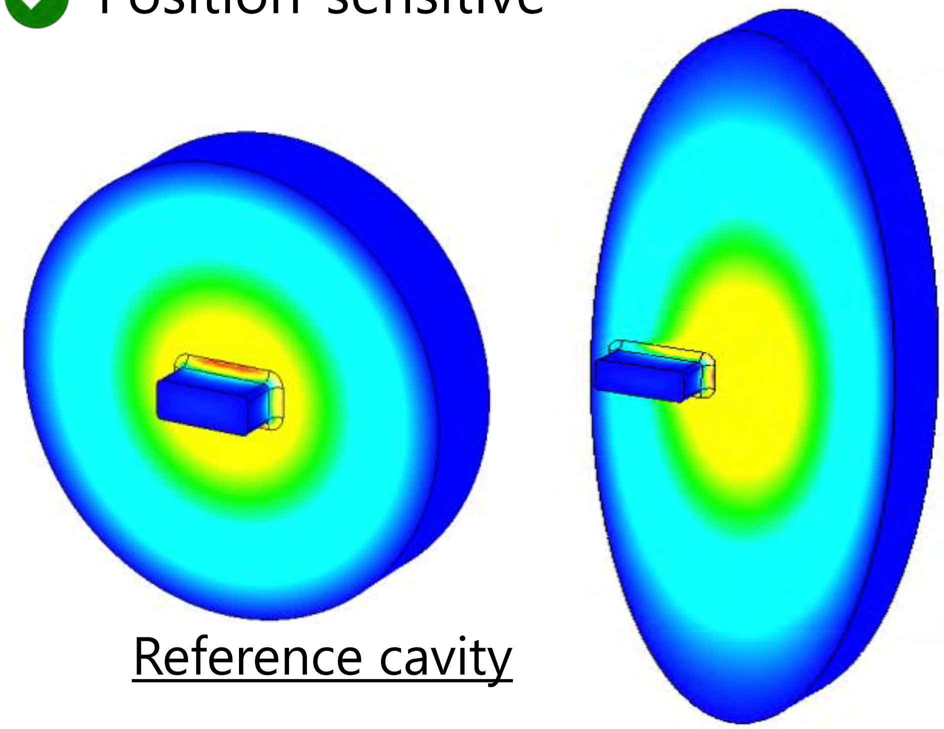
Signal height (elliptical cavity / reference cavity)
→<u>The beam position inside R3</u>

Courtesy by G. Hudson-Chang

(iii) Future mass measurements

Schottky Cavity Doublet (SCD) for $B\rho$ measurements

- ✅ Position-sensitive



Courtesy by G. Hudson-Chang

Sep. 2024
Shipped from Germany

MAX-PLANCK-INSTITUT FÜR KOLLOID- UND GRENZFLÄCHENFORSCHUNG

Summary & Outlook

To understand nucleosynthesis in the universe:

Nuclear masses play a crucial role

Unique storage ring, R3, is in operation

Some recent upgrades:

Injection to the Rare-RI Ring

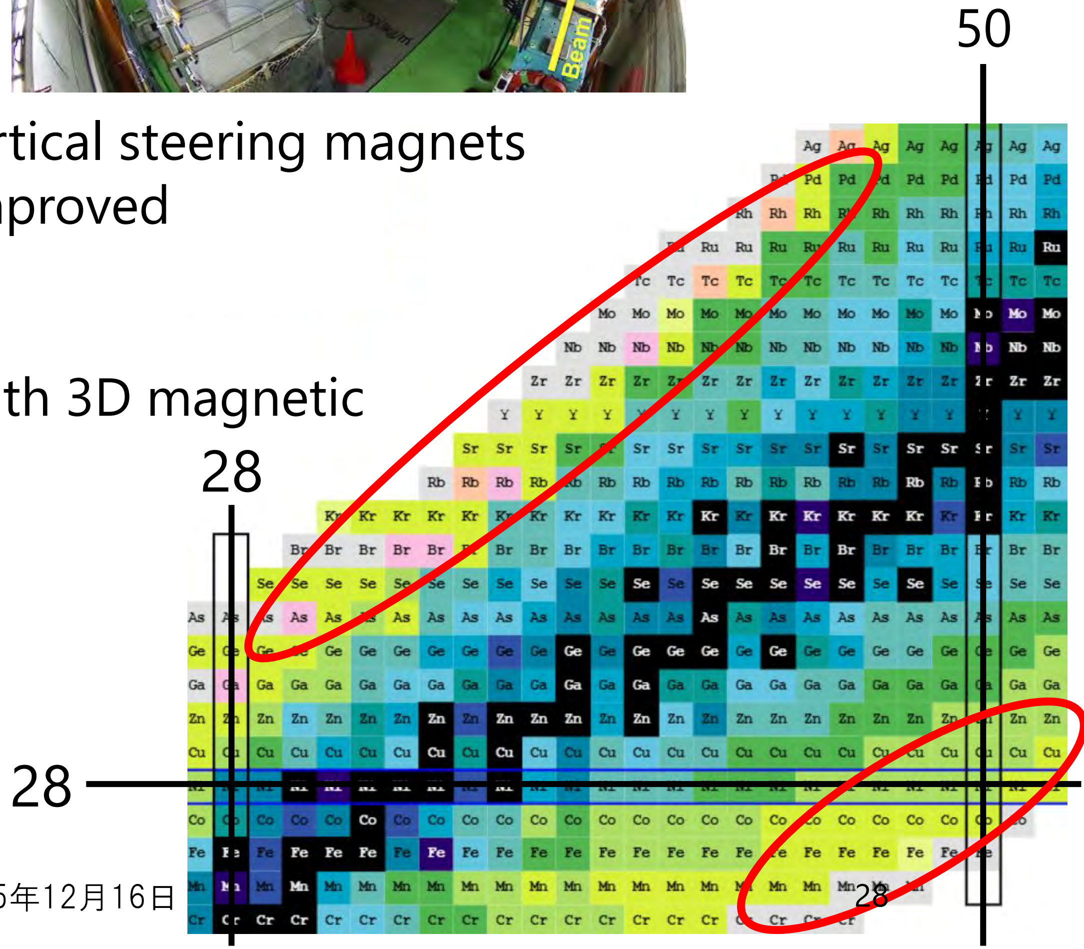
- The vertical beam trajectory correction → The vertical steering magnets
- The Injection (x2) and the extraction (x3.5) was improved

Extraction from the Rare-RI Ring

- Injected beam is not fully extracted
- Beam motion → The beam tracking simulation with 3D magnetic

Future mass measurements

- Schottky-based IMS
- Compact Schottky & Schottky Cavity Doublet



Outlook:

Test of Schottky Cavity Doublet

Mass measurements

Thank you for your listening!

M. S. Sanjari[1], A. Ozawa[2], Y. Yamaguchi[3], T. Ohnishi[3], Y. Abe[3], G. Hudson-Chang[3,4], D. Nagae[5], T. Yamaguchi[5], N. Chandratakumar[3,4], N. Imai[6], Y. Kikuchi[5], N. Kitamura[6], R. Kojima[6], J. Li[6], T. Moriguchi[2], S. Nishizawa[5], F. Suzaki[7], K. Takiura[5], N. Tomioka[5], R. Tuchiya[6], M. Wakasugi[8], K. Watanabe[5], R. Yokoyama[6], and H. Zhang[2]

1 - GSI, 2 – University of Tsukuba, 3 – RIKEN, 4 – University of Surrey, 5 – Saitama University, 6 – The university of Tokyo, 7 – JAEA, 8 – Kyoto University