

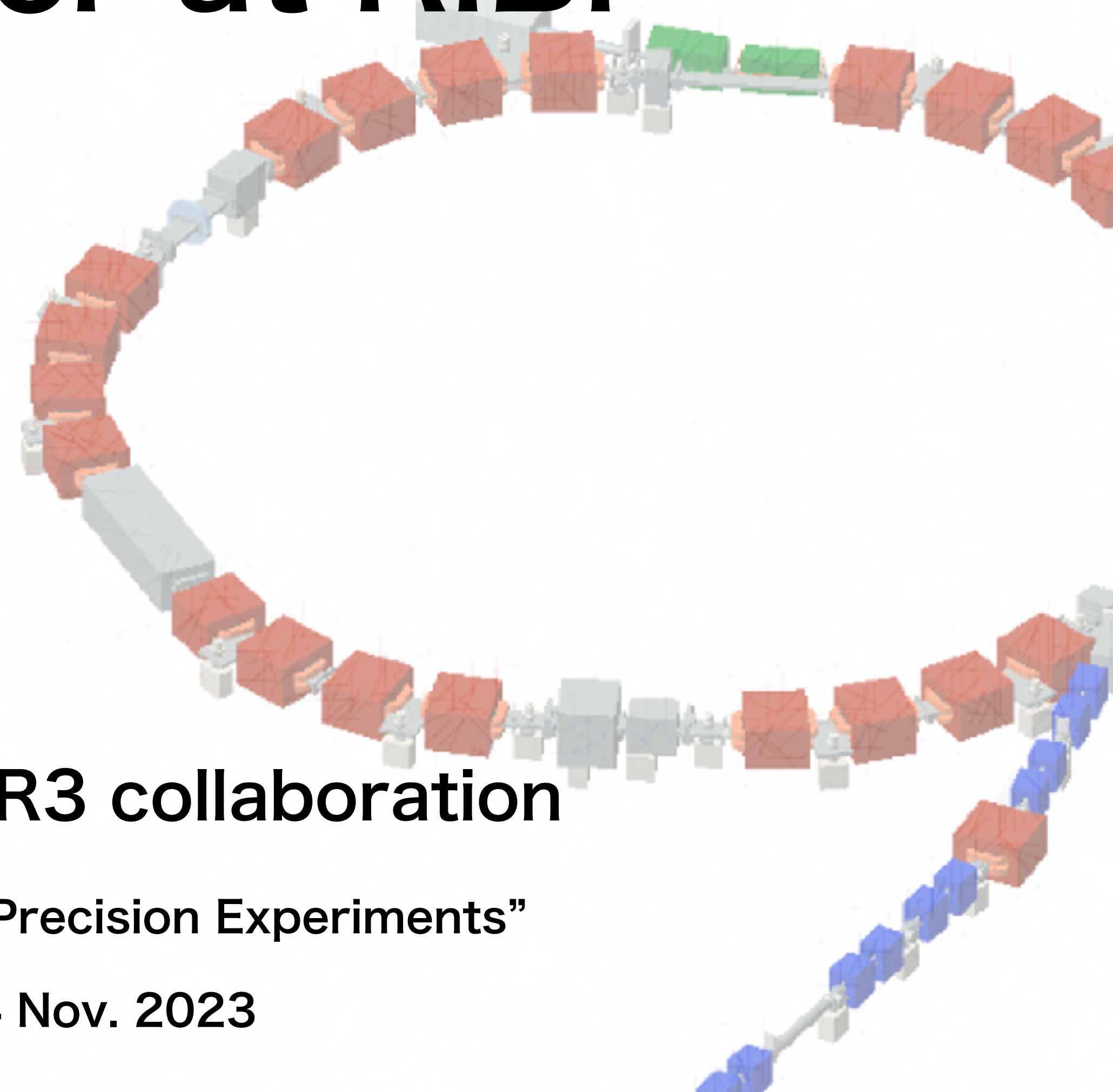
Present status of the storage-ring mass spectrometer at RIBF

1. Mass measurement principle
2. Commissioning with ^{238}U fragments
3. Latest results: masses near the r-process
4. New developments for Schottky detectors

T. Yamaguchi (Saitama) for the R3 collaboration

International Symposium on “Stored Ions for Precision Experiments”

Fudan University, Shanghai, 22-24 Nov. 2023





Where is Saitama?



Where is Saitama?

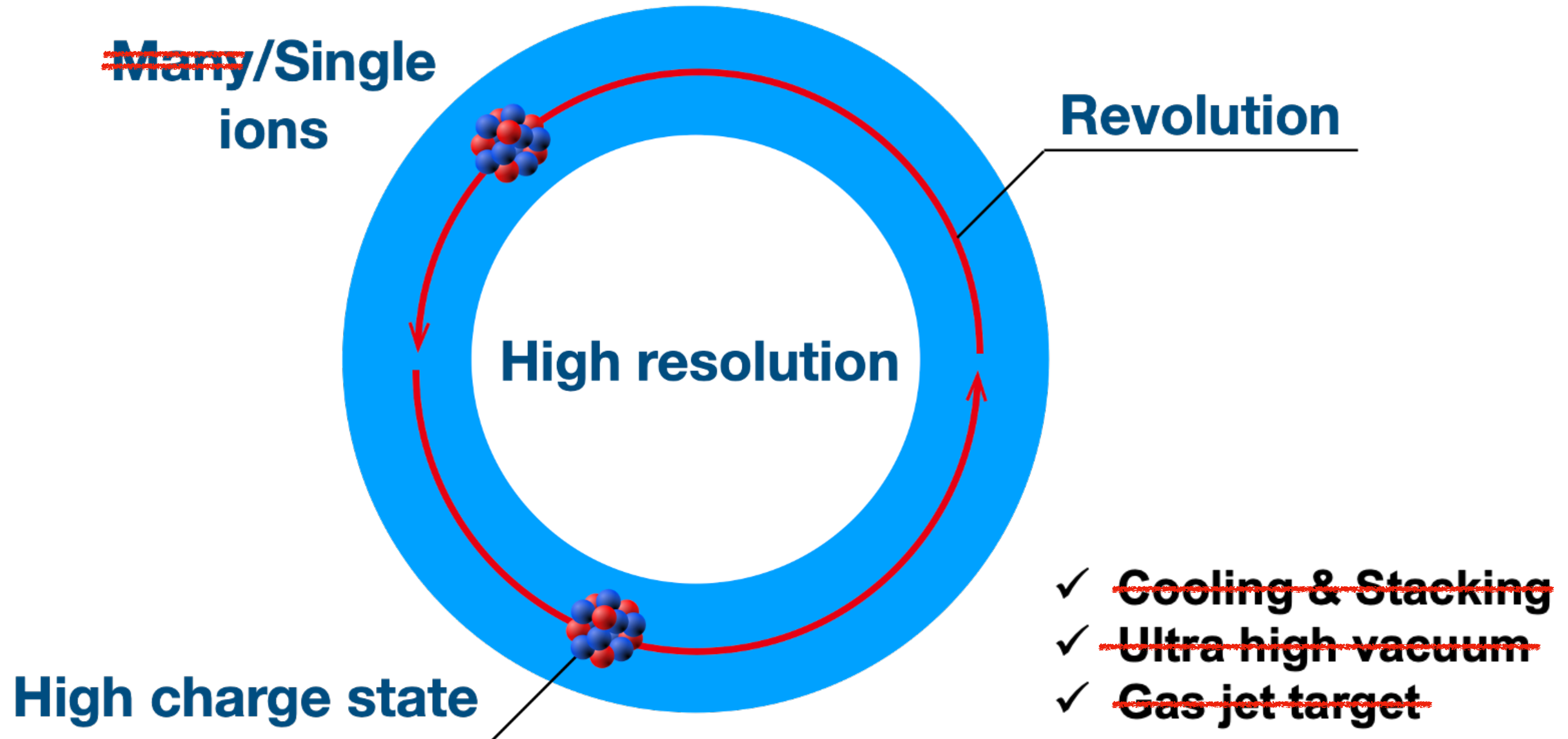


A map of Japan with the text "日本 JAPAN" in the center. A red circle highlights the Tokyo area, with the text "東京 Tokyo" inside it. To the right, a small inset map shows a yellow line representing a road or route, with the text "甲府 Kofu" next to it.



RIKEN RI Beam Factory

Storage ring for Rare Isotopes

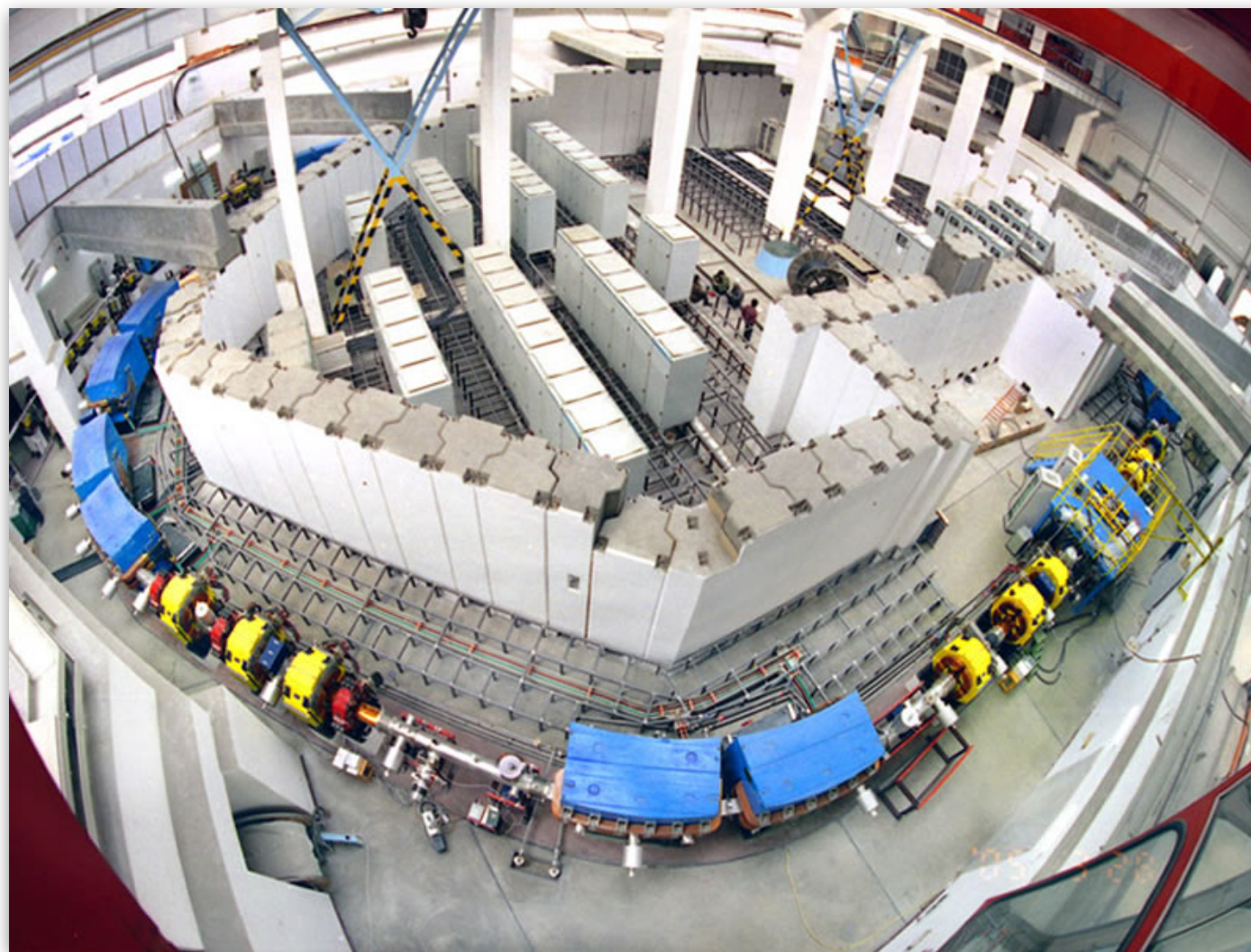


RI Beam Storage Rings in Operation



ESR@GSI, Germany

+CRYRING@ESR

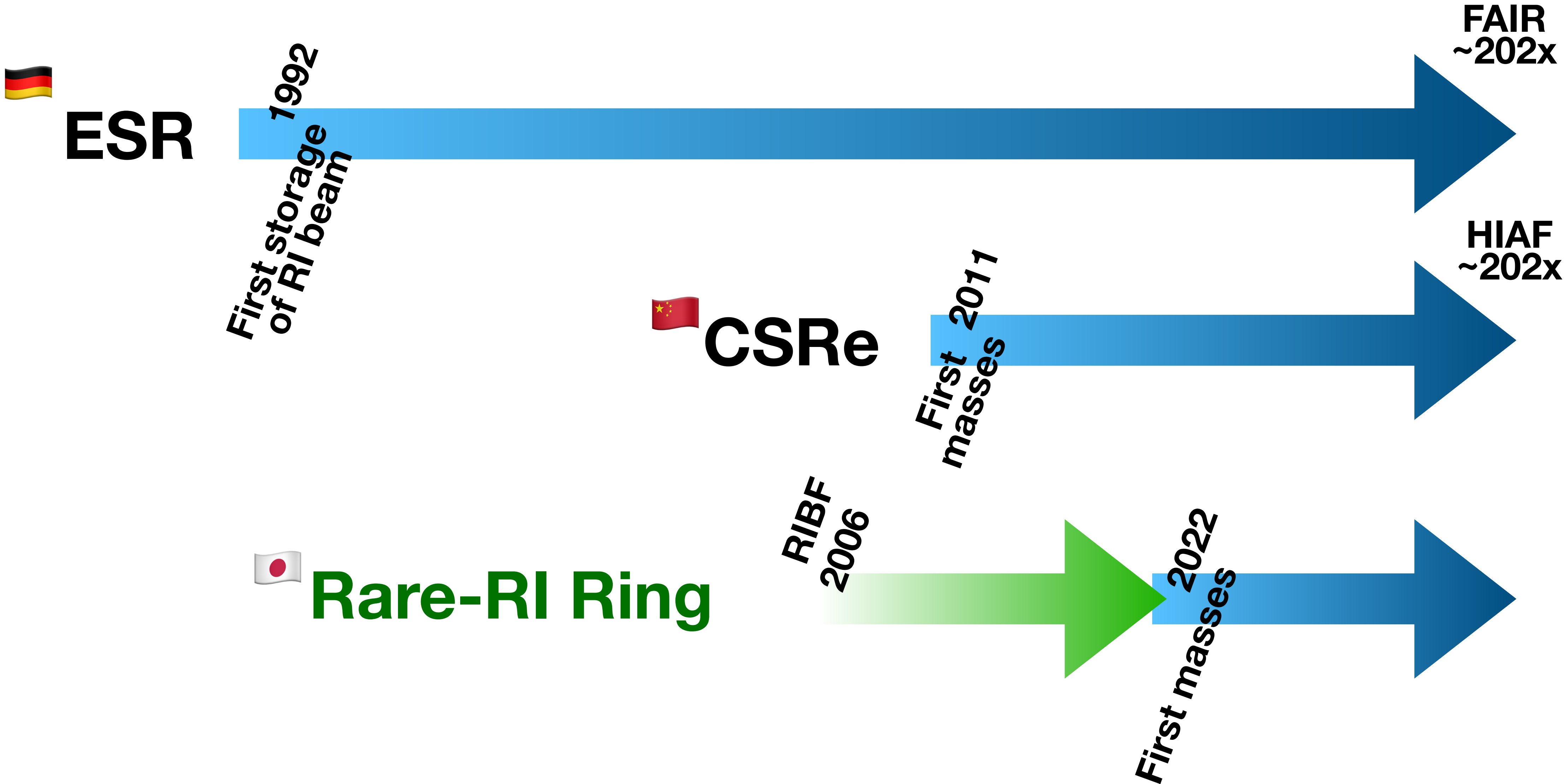


CSRe@IMP, China

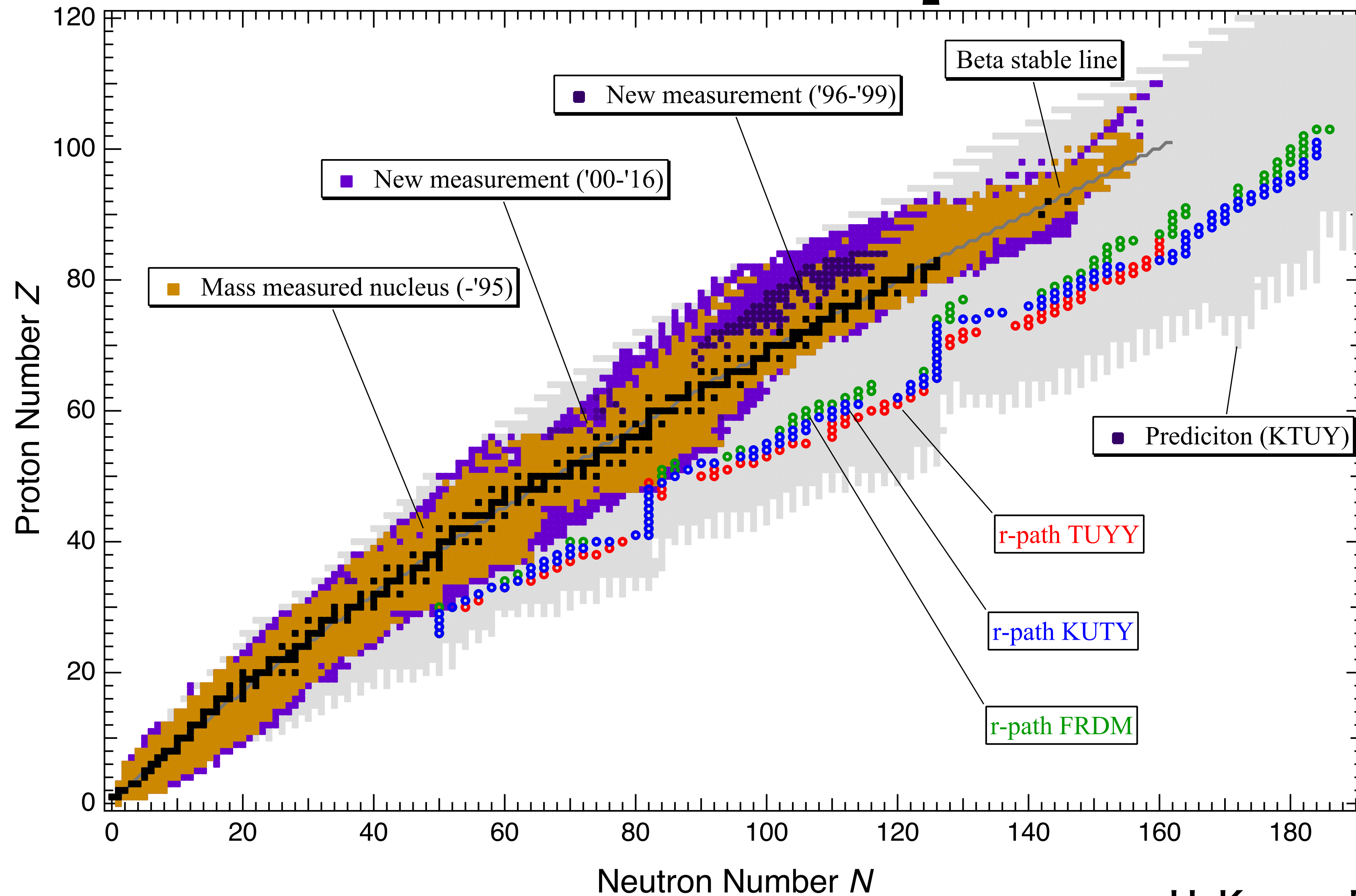


Rare-RI Ring@RIBF

Storage Rings In Comparison



Masses and R-process

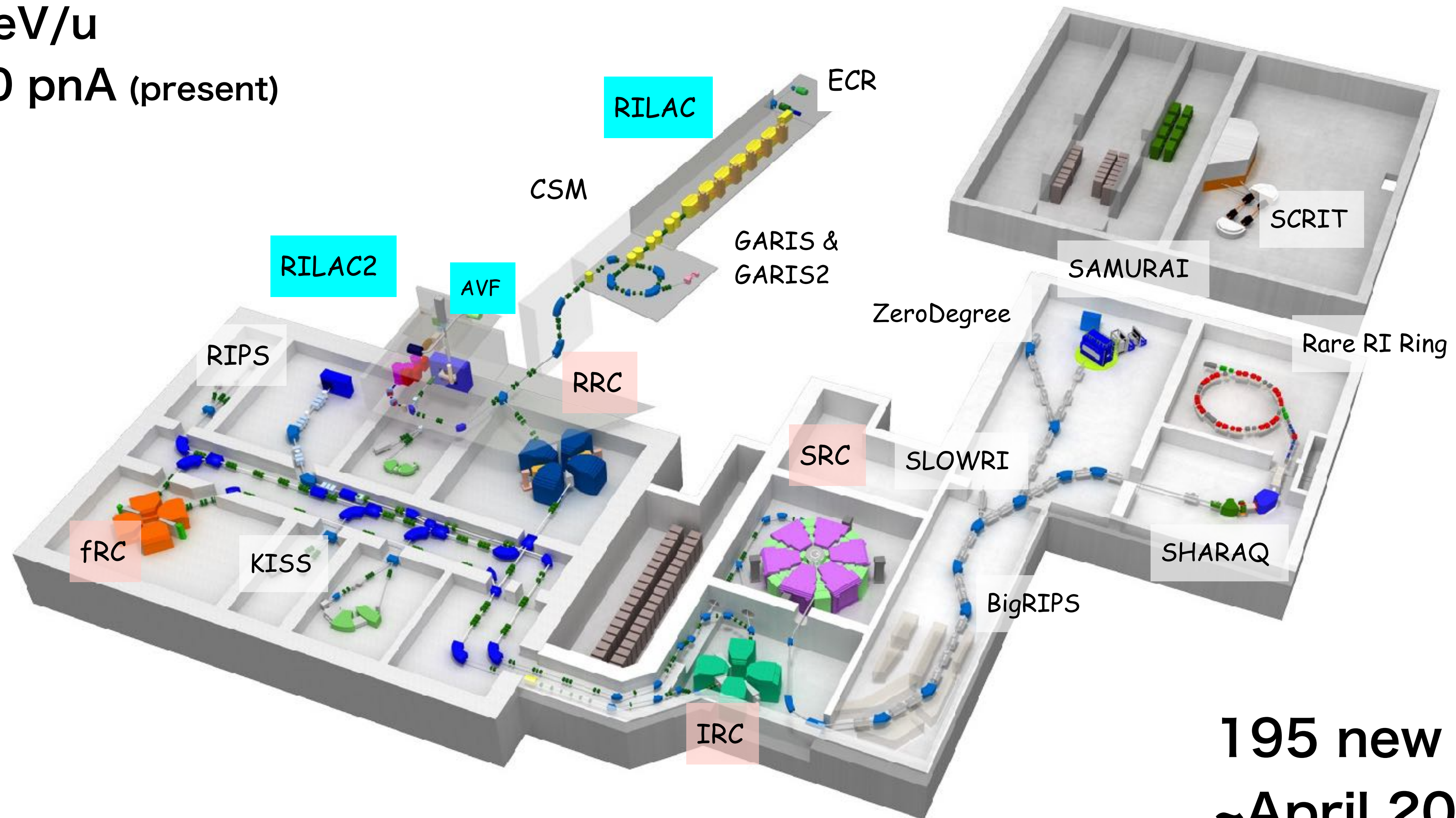


RI Beam Factory at RIKEN

4 Cyclotrons cascade operation

345 MeV/u

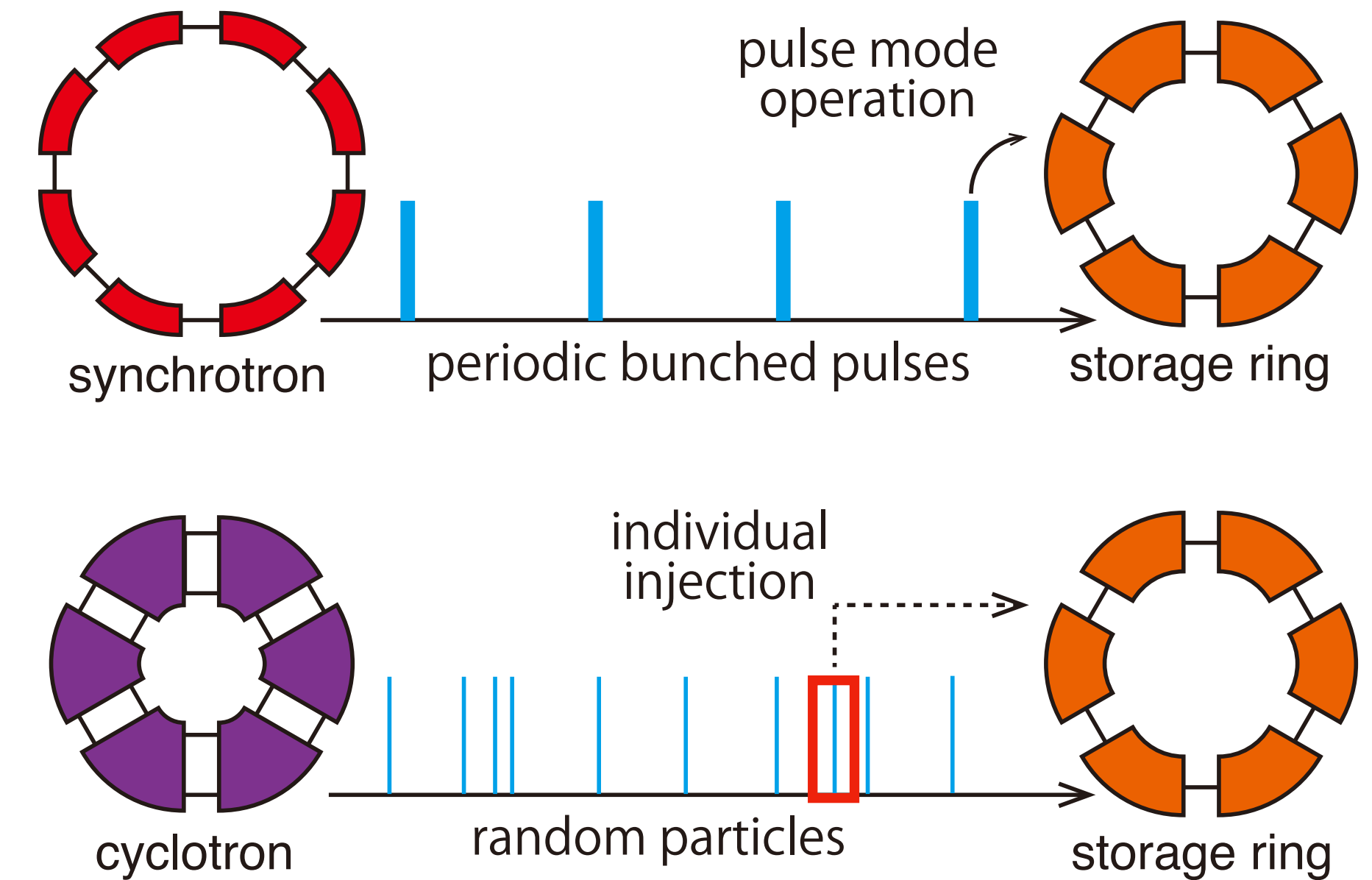
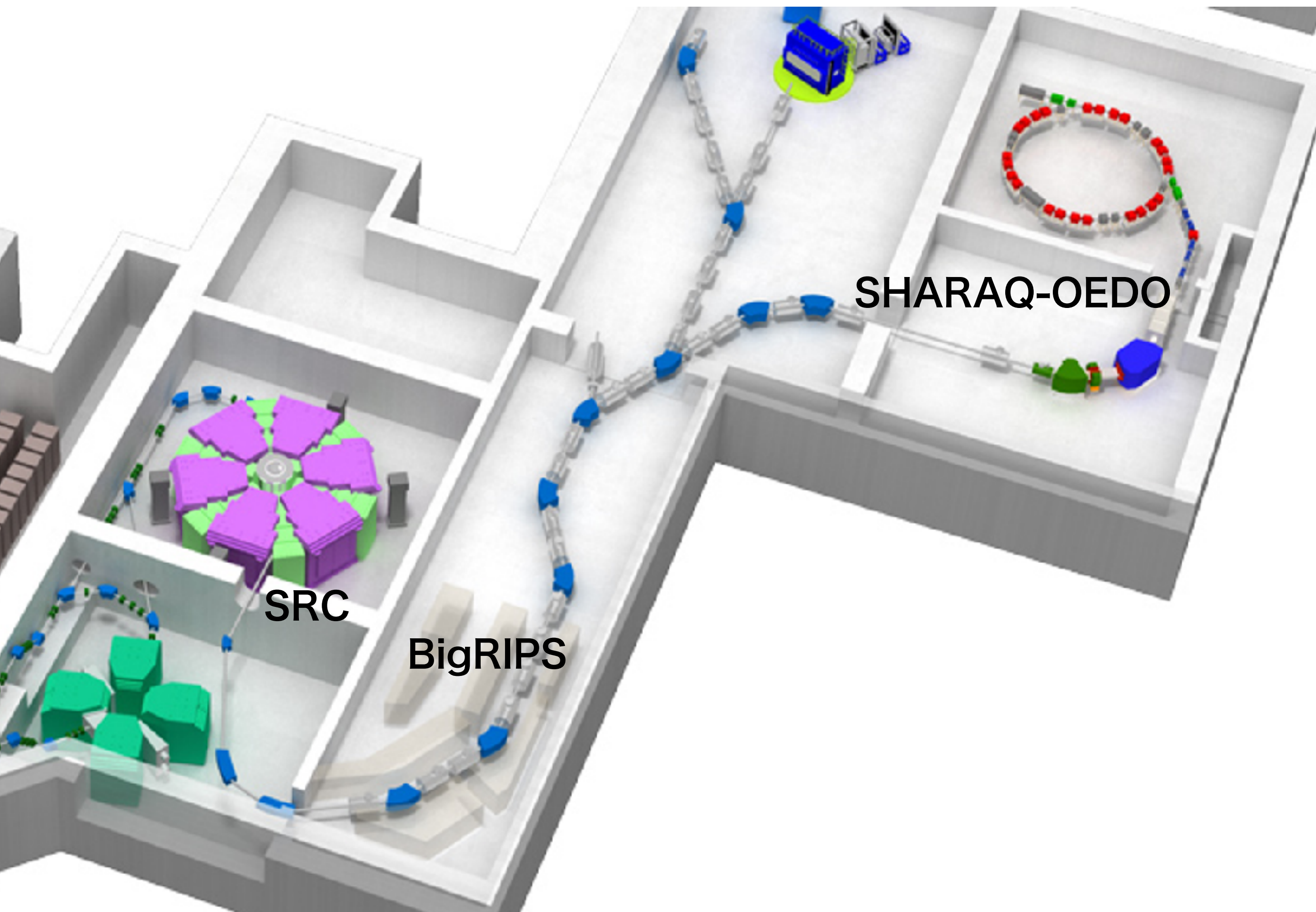
^{238}U 70 pA (present)



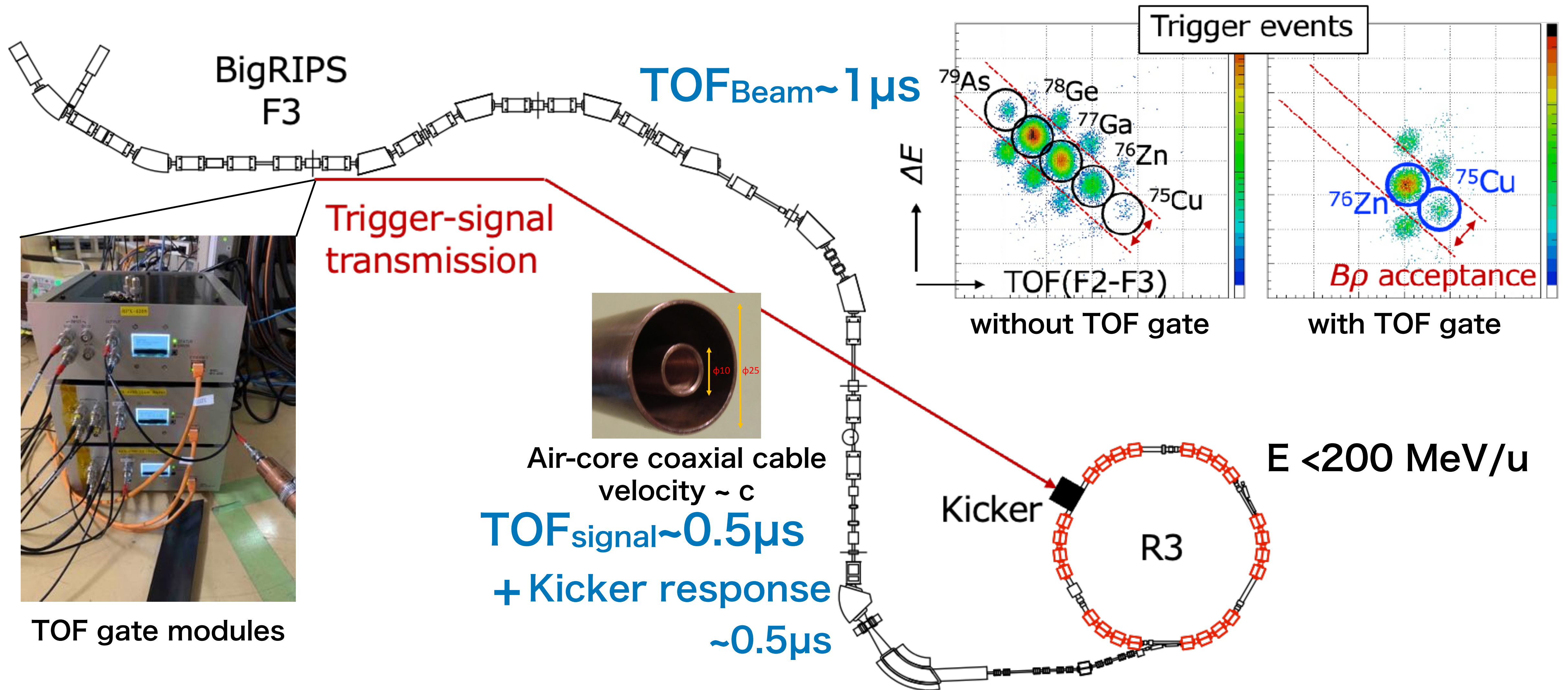
195 new isotopes
~April 2023

Rare-RI Ring facility

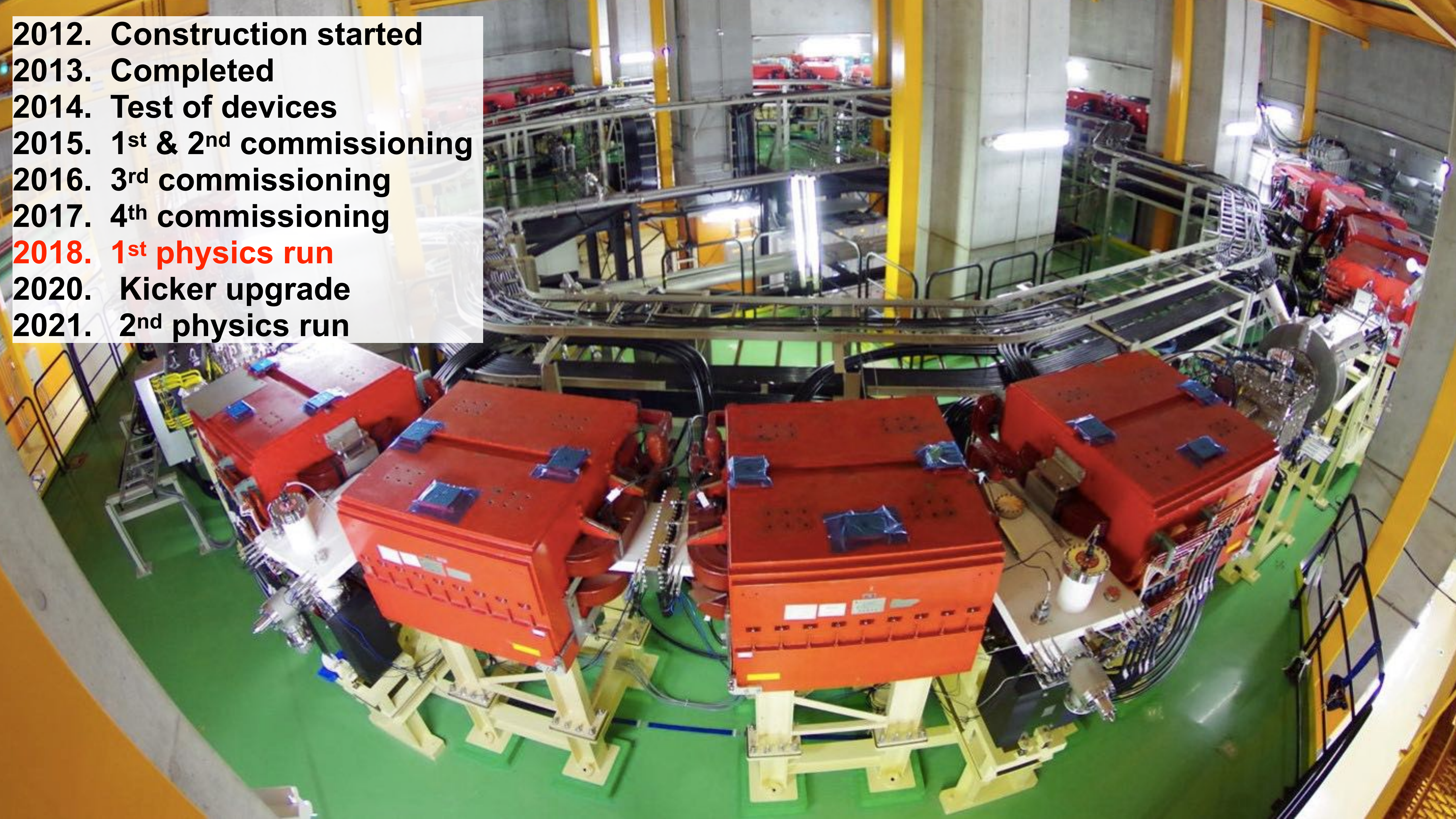
- ✓ Individual injection method
- ✓ Single-ion Isochronous Mass Spectrometry



Individual Injection



2012. Construction started
2013. Completed
2014. Test of devices
2015. 1st & 2nd commissioning
2016. 3rd commissioning
2017. 4th commissioning
2018. 1st physics run
2020. Kicker upgrade
2021. 2nd physics run



Rare-R1 Ring facility: R3

Lattice Structure & Devices



10 trim coils for precise isochronous field

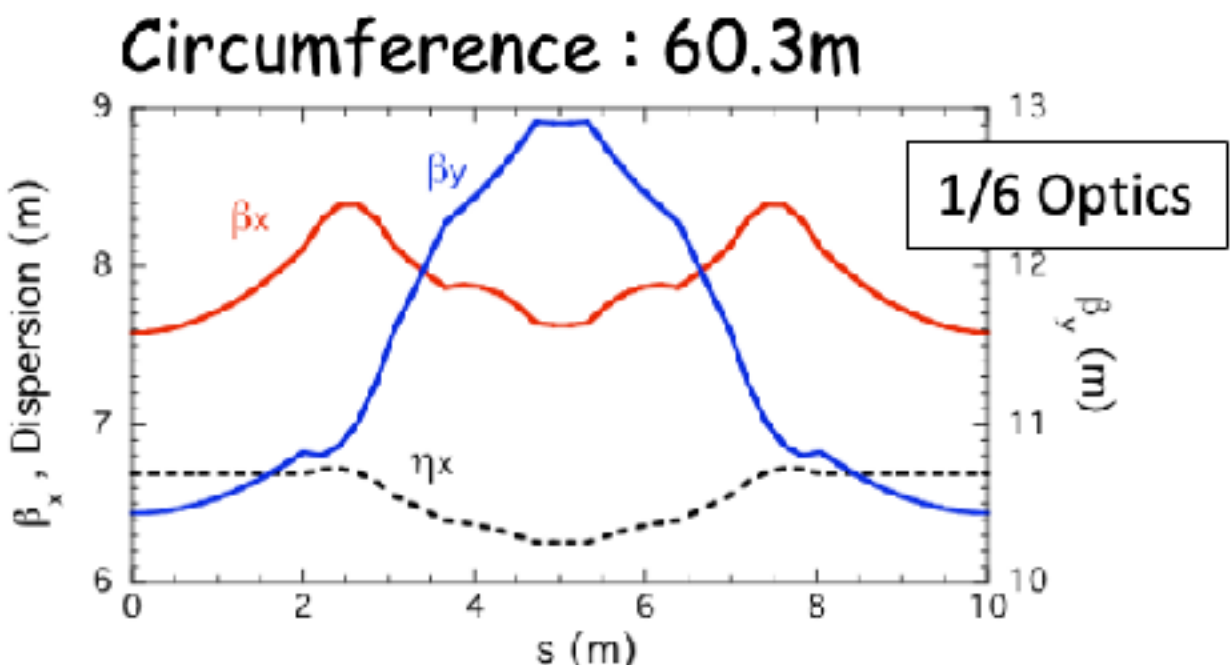
Sector magnets

Extraction septum magnets

Injection septum magnets

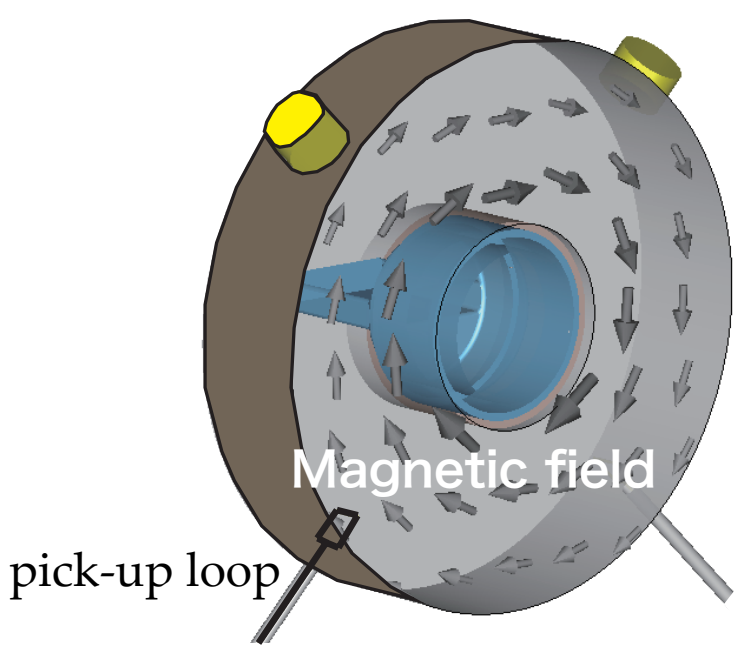
Injection beam line

Hexagonal-Symmetry
Weak-Focusing Lattice Structure



Tunes: 1.21 / 0.84
Acceptance :
Momentum $\Delta P/P = \pm 0.5\%$
Transverse $20\pi / 10\pi$ mm mrad

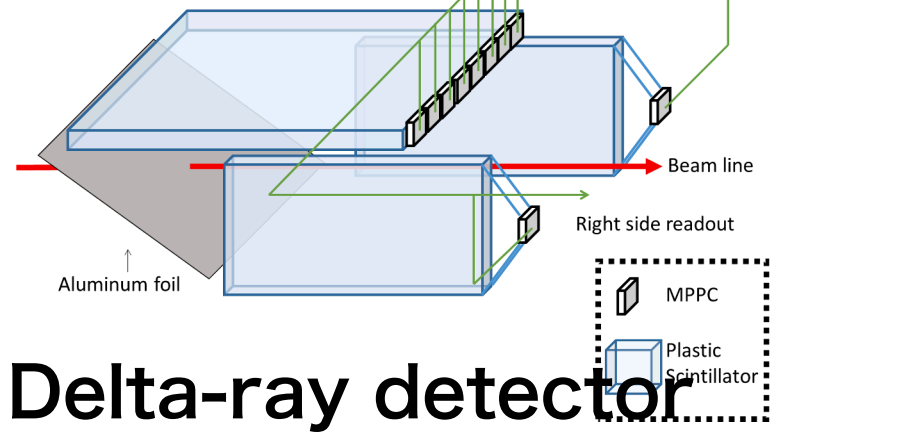
(Stop and PID)



Resonant Schottky pickup

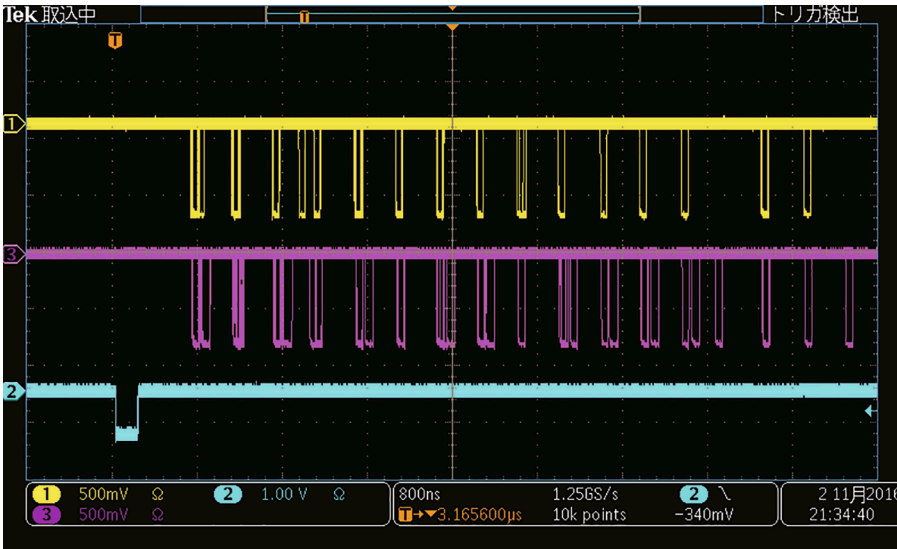
Fast kicker magnet system

Al-foil + PI. scint.

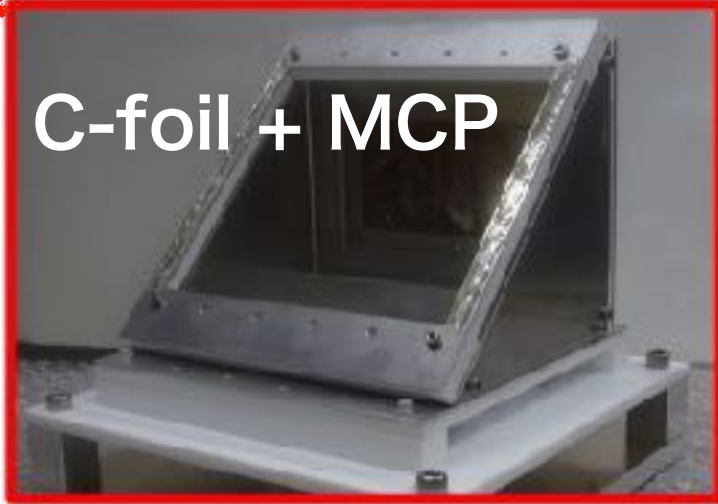


Delta-ray detector

Periodic pulses successfully observed



C-foil + MCP



Secondary electrons TOF detector



Mass Measurement Principle

$$\frac{T_0}{2\pi} = \frac{m_0 \cancel{\gamma_0} / q}{B \cancel{\gamma_0}}$$

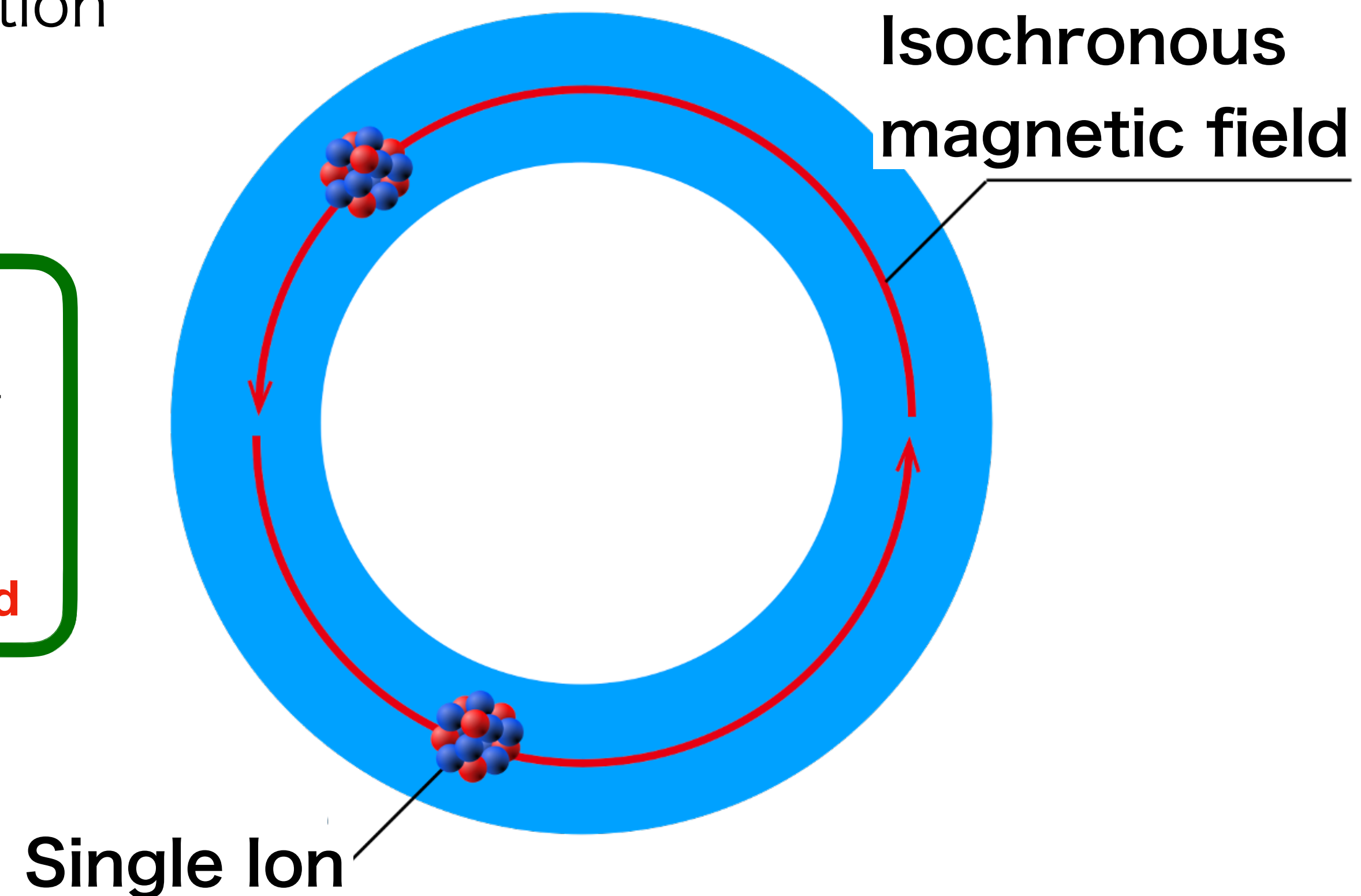
Isochronous condition
for reference particle

$$\frac{T_1}{2\pi} = \frac{m_1 \gamma_1 / q}{B \gamma_0}$$

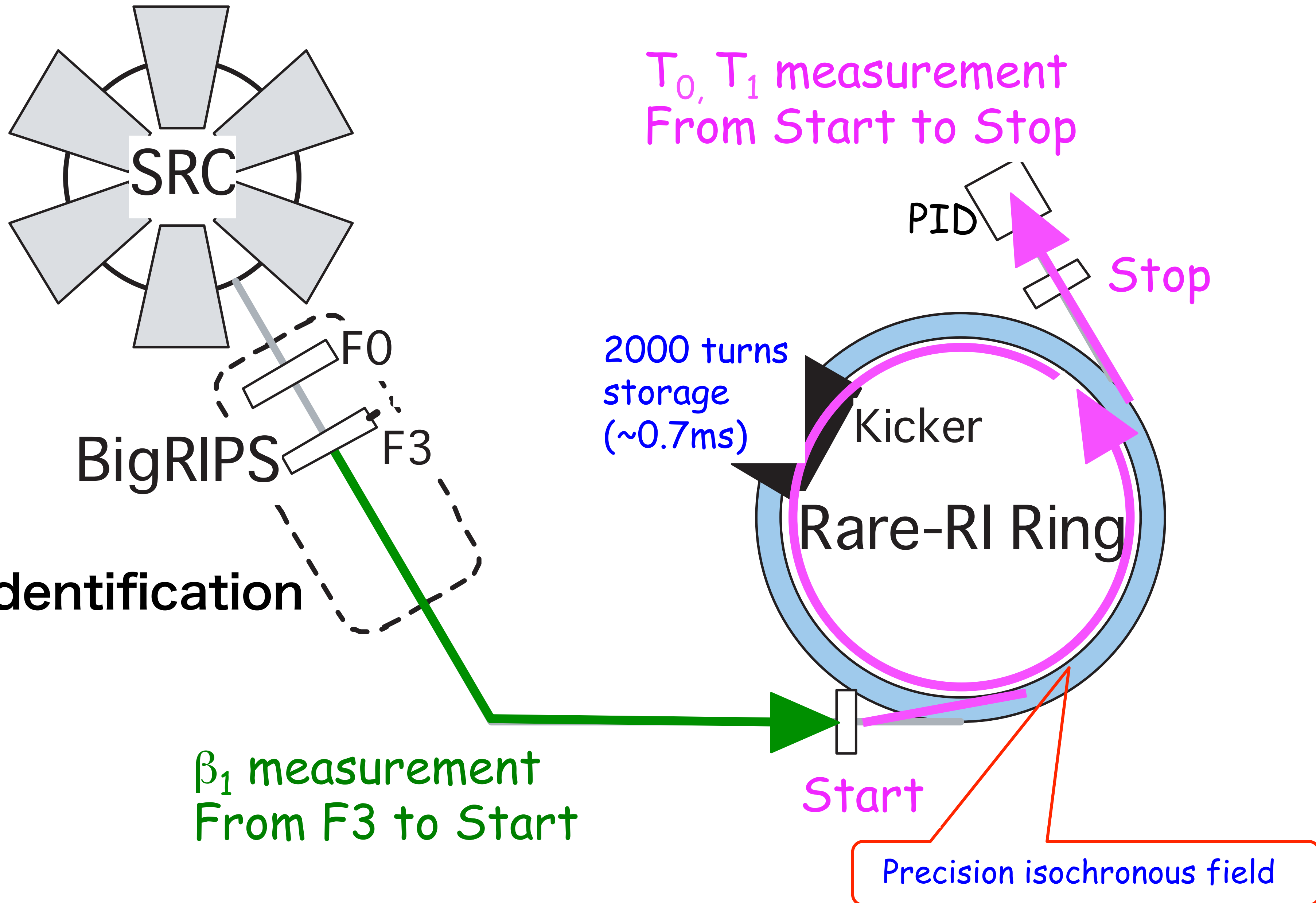
Non-isochronous condition
for particle of interest

$$\frac{m_1}{q_1} = \underbrace{\left(\frac{m_0}{q_0} \right)}_{\text{Isochronous reference}} \underbrace{\frac{1}{T_0}}_{\text{to be measured}} \underbrace{T_1}_{\text{to be measured}} \sqrt{\frac{1 + \beta_1^2}{1 - \left\{ (T_1/T_0) \beta_1 \right\}^2}} = \left(\frac{m_0}{q_0} \right) \frac{T_{1corr}}{T_0}$$

Use particles
with same Bp

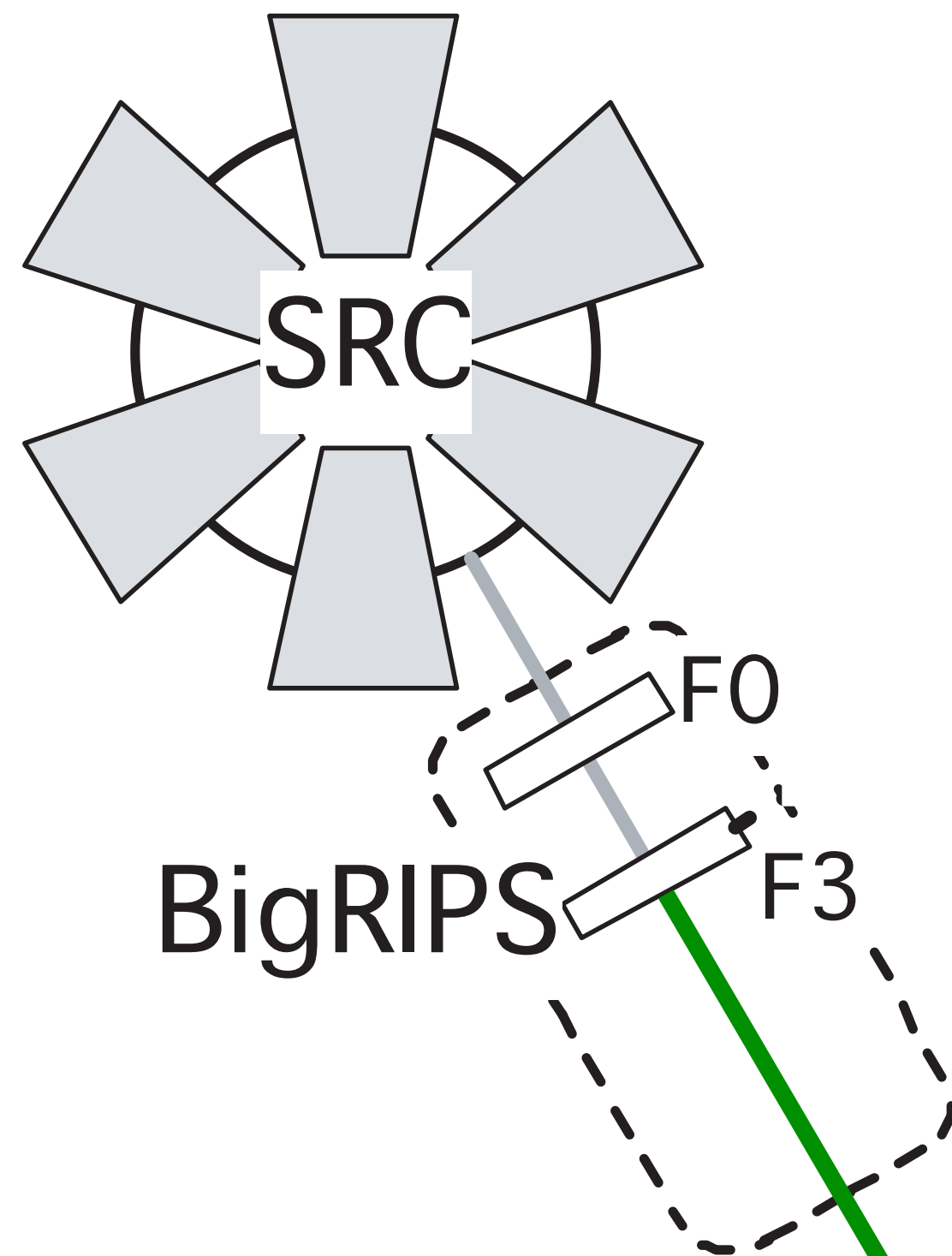


Mass Measurement Principle



Commissioning

^{238}U 345 MeV/u $\rightarrow$ ^{78}Ge 168 MeV/u fission fragments

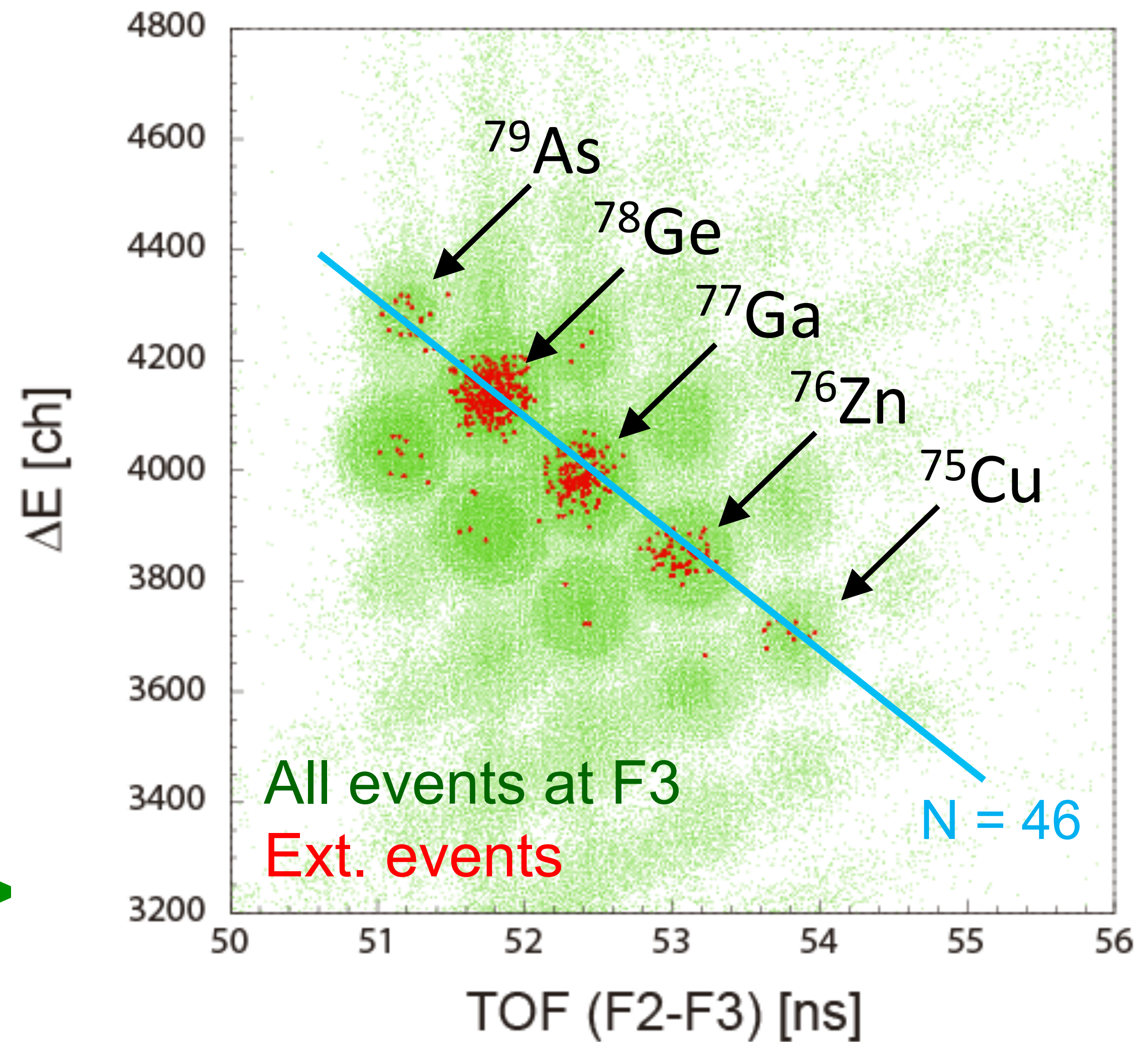
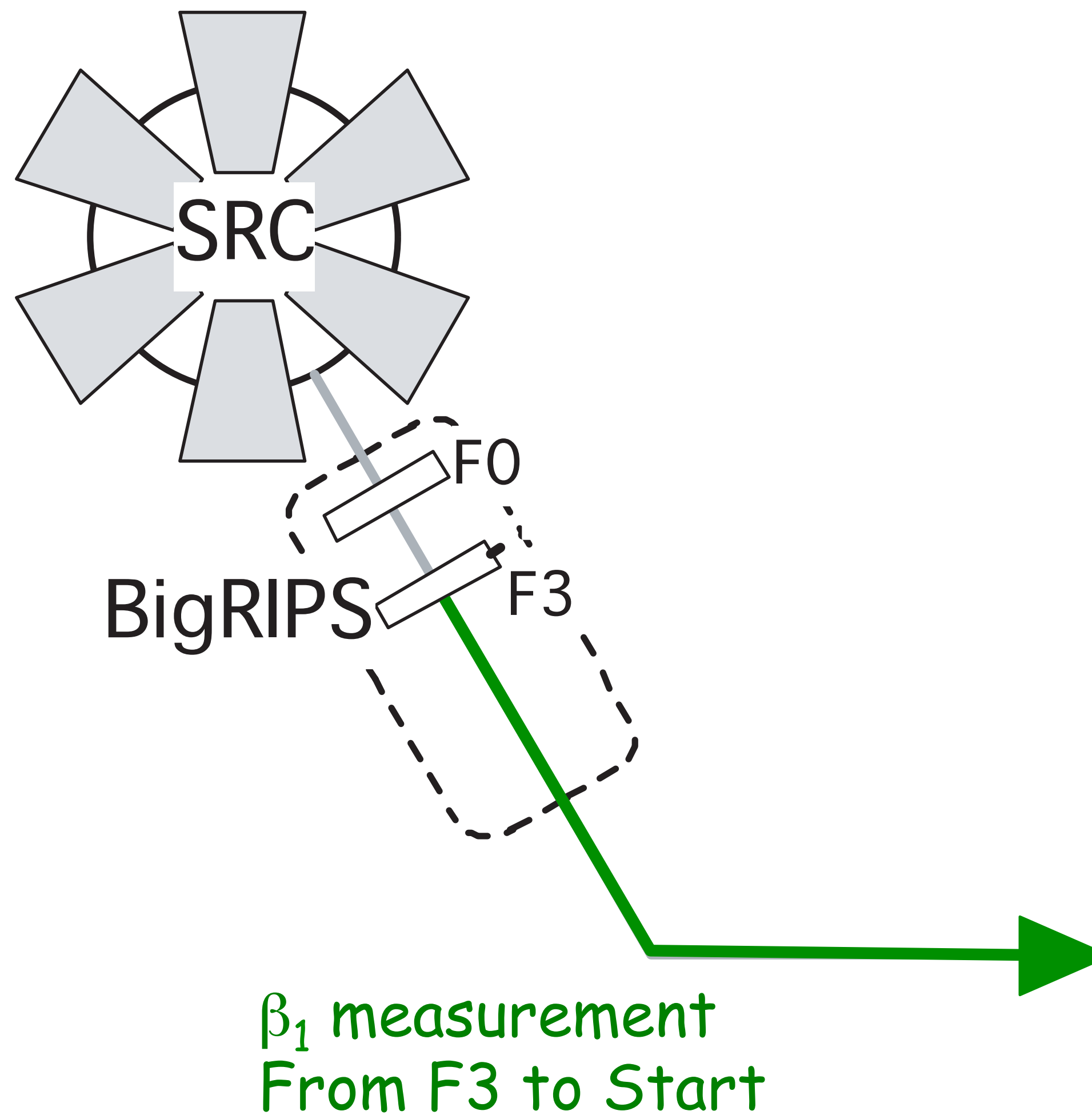


β_1 measurement
From F3 to Start

Se- 78 23.77	Se- 79 2.95E5y *3.92m	Se- 80 49.61	Se- 81 *57.28m 18.45m	Se- 82 8.73 8.3E19y
As- 77 1.62d	As- 78 1.51h	As- 79 9.01m	As- 80 15.2s	As- 81 33.3s
Ge- 76 7.73	Ge- 77 11.211h *53.7s	Ge- 78 1.47h	Ge- 79 *39.0s 18.98s	Ge- 80 29.5s
Ga- 75 2.10m	Ga- 76 32.6s	Ga- 77 13.2s	Ga- 78 5.09s	Ga- 79 2.847s
Zn- 74 1.59m	Zn- 75 10.2s	Zn- 76 5.7s	Zn- 77 2.08s *1.05s	Zn- 78 1.47s
Cu- 73 4.2s	Cu- 74 1.63s	Cu- 75 1.224s	Cu- 76 641ms	Cu- 77 467.9ms
Ni- 72 1.57s	Ni- 73 840ms	Ni- 74 680ms	Ni- 75 344ms	Ni- 76 238ms

Commissioning

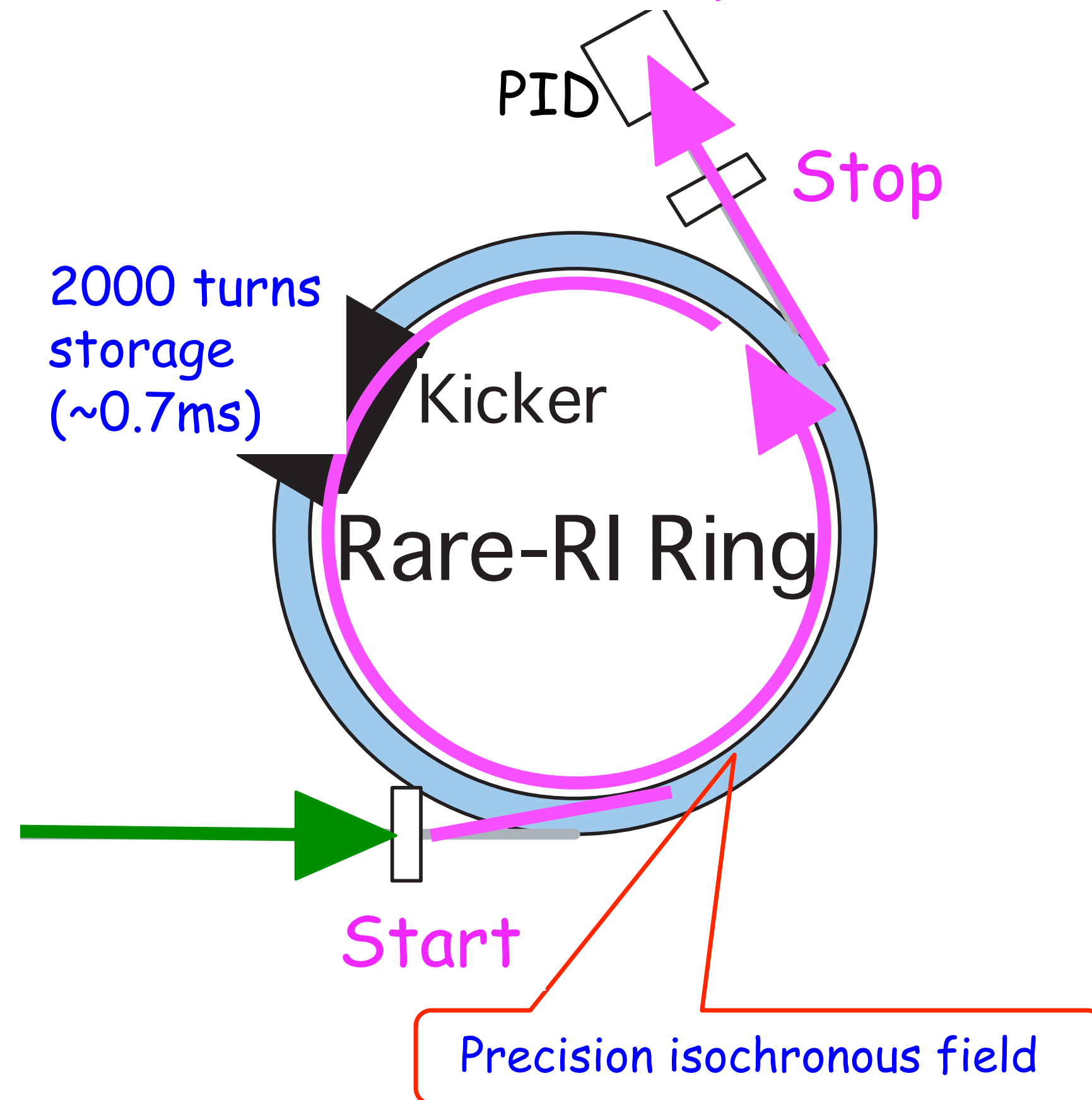
^{238}U 345 MeV/u $\rightarrow$ ^{78}Ge 168 MeV/u fission fragments



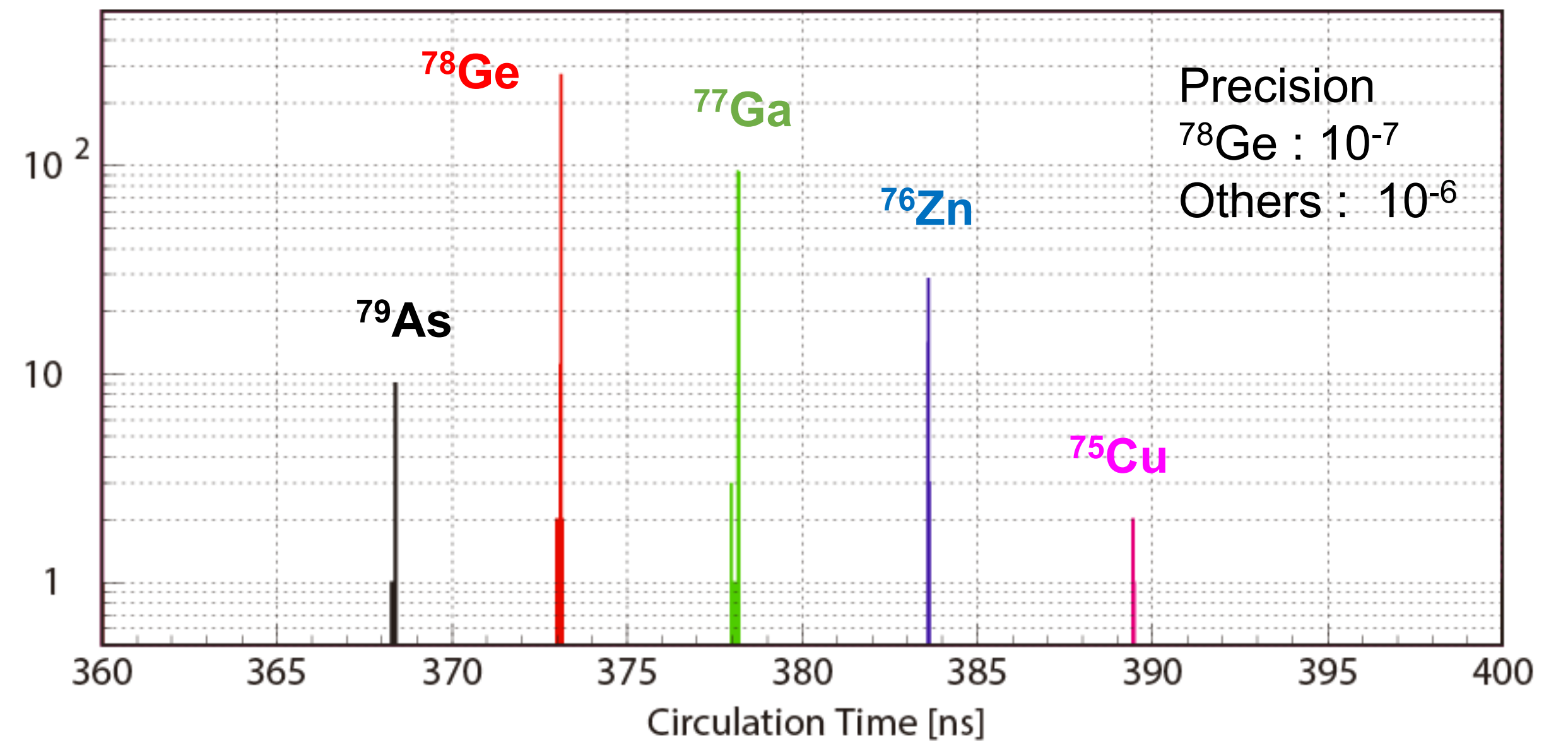
Commissioning

^{238}U 345 MeV/u $\rightarrow$ ^{78}Ge 168 MeV/u fission fragments

T_0, T_1 measurement
From Start to Stop



Revolution Time Spectrum

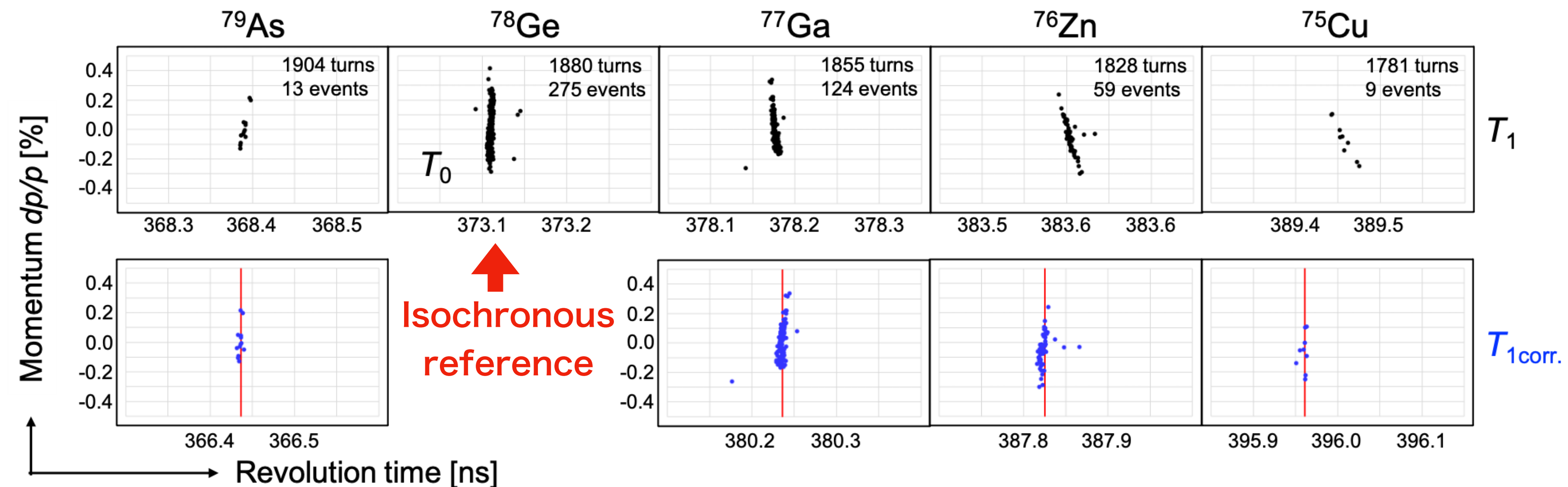


Mass Commissioning

With known masses

^{238}U 345 MeV/u $\rightarrow$ ^{78}Ge 168 MeV/u fission fragments

Se- 78 23.77	Se- 79 2.95E5y *3.92m	Se- 80 49.61	Se- 81 *57.28m 18.45m	Se- 82 8.73 8.3E19y
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Zn- 74 1.59m	Zn- 75 10.2s	Zn- 76 5.7s	Zn- 77 2.08s *1.05s	Zn- 78 1.47s
Cu- 73 4.2s	Cu- 74 1.63s	Cu- 75 1.224s	Cu- 76 641ms	Cu- 77 467.9ms
Ni- 72 1.57s	Ni- 73 840ms	Ni- 74 680ms	Ni- 75 344ms	Ni- 76 238ms



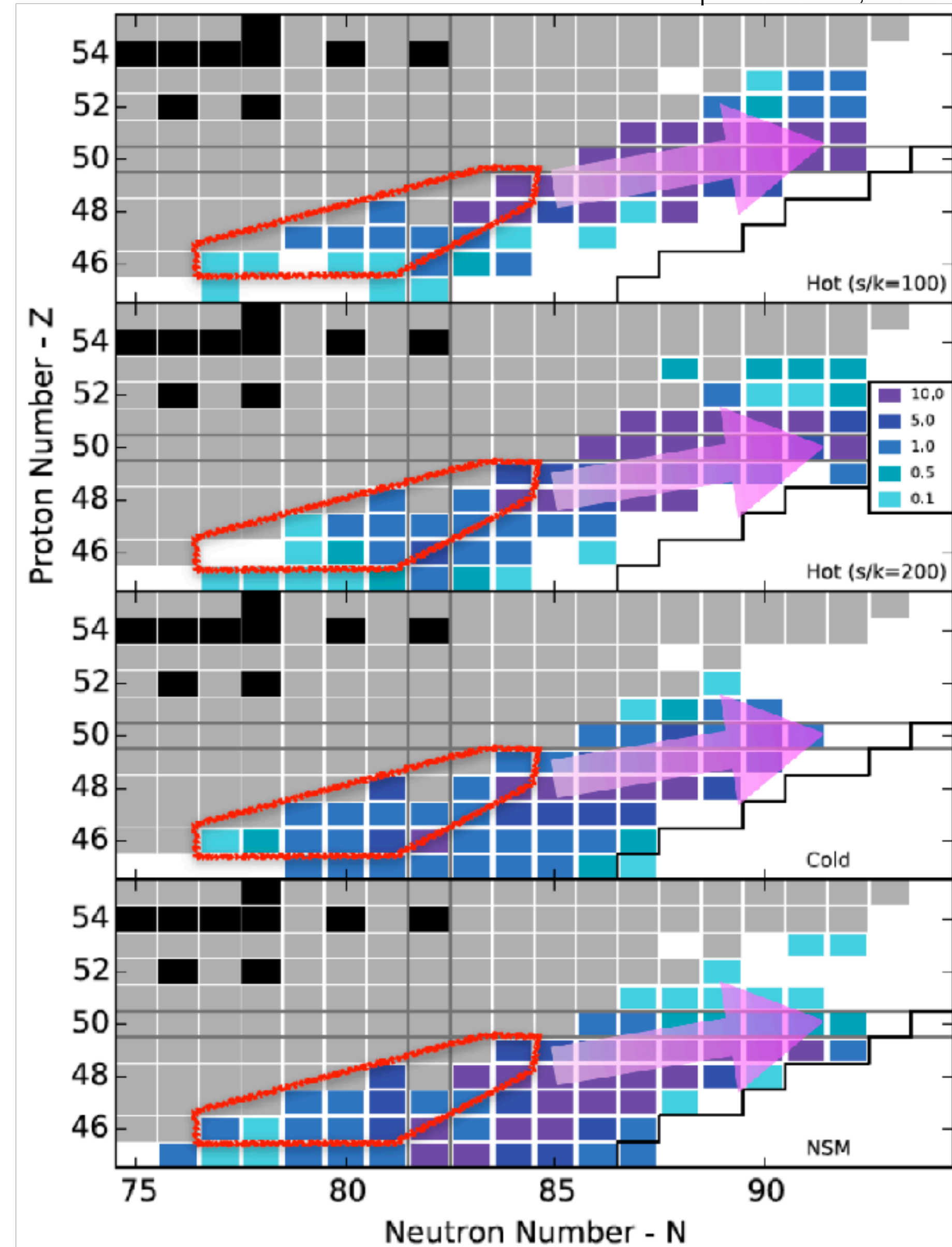
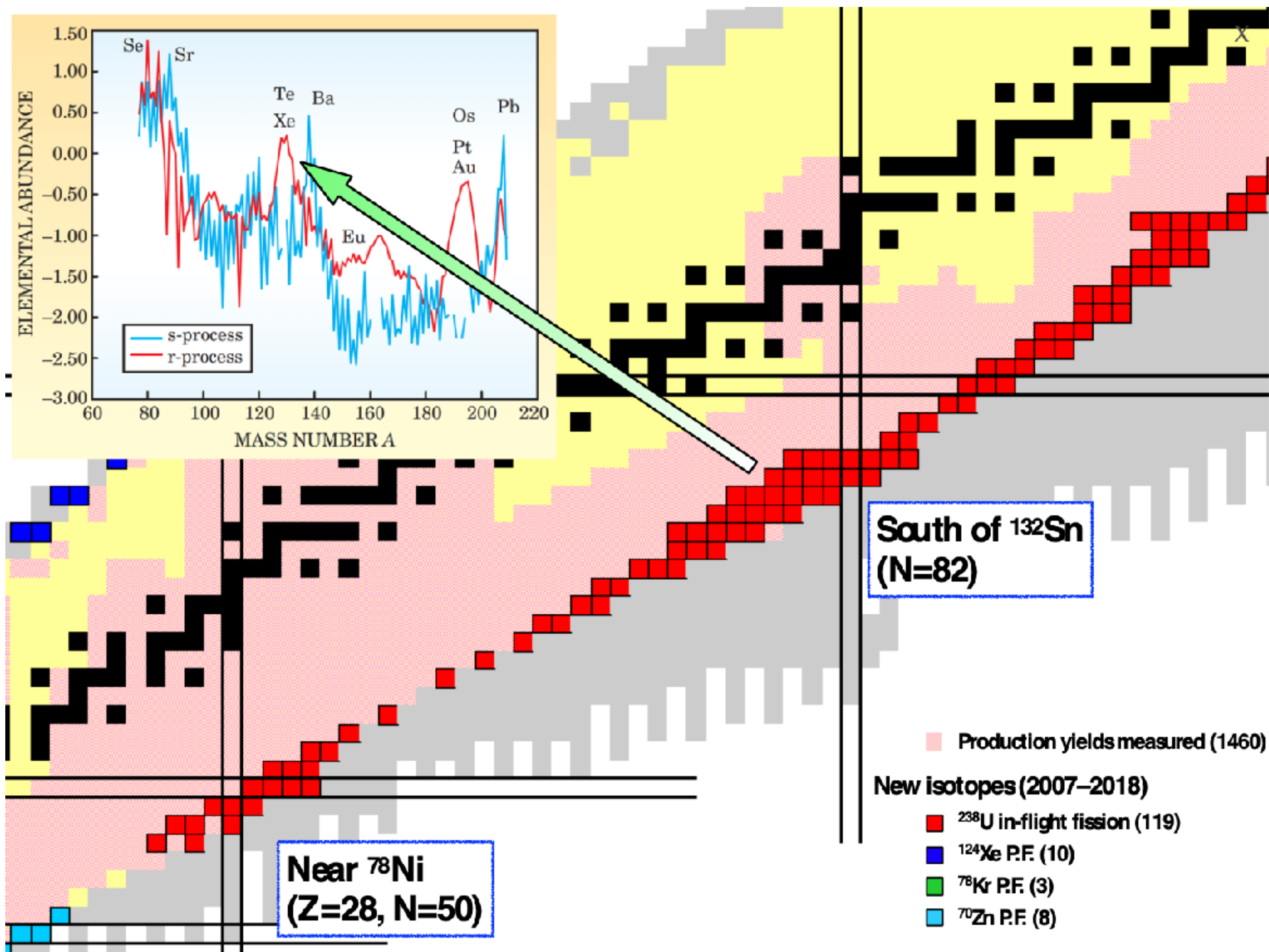
Results consistent with AME2020
Accuracy $< \sim 10^{-5}$

First application

Spokesperson: S. Naimi

Masses around N=82

M. Mumpower et al., 2015



New mass measurement with R3

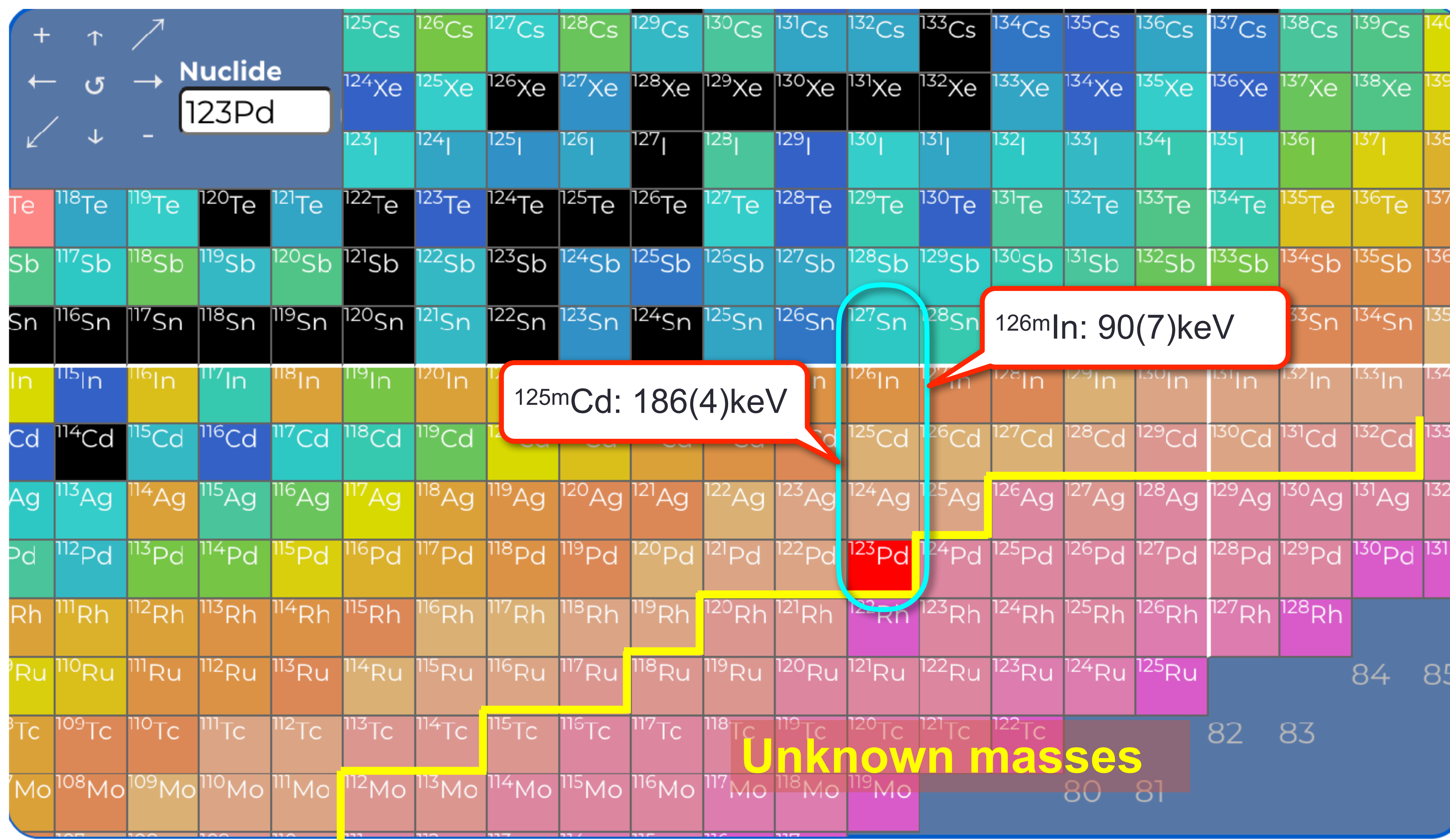
Nuclide 123Pd																125Cs	126Cs	127Cs	128Cs	129Cs	130Cs	131Cs	132Cs	133Cs	134Cs	135Cs	136Cs	137Cs	138Cs	139Cs	140Cs
																124Xe	125Xe	126Xe	127Xe	128Xe	129Xe	130Xe	131Xe	132Xe	133Xe	134Xe	135Xe	136Xe	137Xe	138Xe	139Xe
																123I	124I	125I	126I	127I	128I	129I	130I	131I	132I	133I	134I	135I	136I	137I	138I
Te	118Te	119Te	120Te	121Te	122Te	123Te	124Te	125Te	126Te	127Te	128Te	129Te	130Te	131Te	132Te	133Te	134Te	135Te	136Te	137Te											
Sb	117Sb	118Sb	119Sb	120Sb	121Sb	122Sb	123Sb	124Sb	125Sb	126Sb	127Sb	128Sb	129Sb	130Sb	131Sb	132Sb	133Sb	134Sb	135Sb	136Sb											
Sn	116Sn	117Sn	118Sn	119Sn	120Sn	121Sn	122Sn	123Sn	124Sn	125Sn	126Sn	127Sn	128Sn	129Sn	130Sn	131Sn	132Sn	133Sn	134Sn	135Sn											
In	115In	116In	117In	118In	119In	120In	121In	122In	123In	124In	125In	126In	127In	128In	129In	130In	131In	132In	133In	134In											
Cd	114Cd	115Cd	116Cd	117Cd	118Cd	119Cd	120Cd	121Cd	122Cd	123Cd	124Cd	125Cd	126Cd	127Cd	128Cd	129Cd	130Cd	131Cd	132Cd	133Cd											
Ag	113Ag	114Ag	115Ag	116Ag	117Ag	118Ag	119Ag	120Ag	121Ag	122Ag	123Ag	124Ag	125Ag	126Ag	127Ag	128Ag	129Ag	130Ag	131Ag	132Ag											
Pd	112Pd	113Pd	114Pd	115Pd	116Pd	117Pd	118Pd	119Pd	120Pd	121Pd	122Pd	123Pd	124Pd	125Pd	126Pd	127Pd	128Pd	129Pd	130Pd	131Pd											
Rh	111Rh	112Rh	113Rh	114Rh	115Rh	116Rh	117Rh	118Rh	119Rh	120Rh	121Rh	122Rh	123Rh	124Rh	125Rh	126Rh	127Rh	128Rh													
Ru	110Ru	111Ru	112Ru	113Ru	114Ru	115Ru	116Ru	117Ru	118Ru	119Ru	120Ru	121Ru	122Ru	123Ru	124Ru	125Ru															
Tc	109Tc	110Tc	111Tc	112Tc	113Tc	114Tc	115Tc	116Tc	117Tc	118Tc	119Tc	120Tc	121Tc	122Tc																	
Mo	108Mo	109Mo	110Mo	111Mo	112Mo	113Mo	114Mo	115Mo	116Mo	117Mo	118Mo	119Mo																			

Unknown masses

Unknown masses

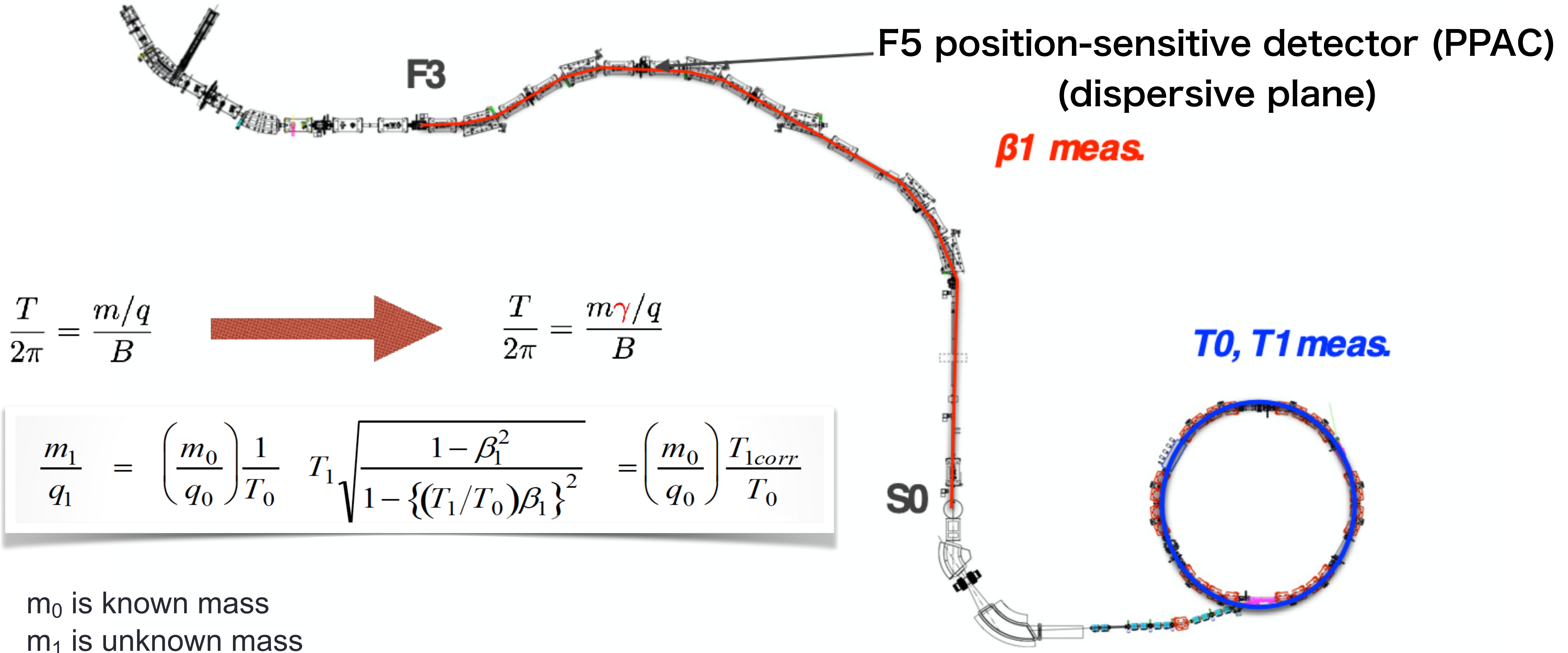
half life [s]		
0	83.4	
8.2E-4	1.6E2	
1.4E-2	2.9E2	
4.6E-2	6E2	
1.E-1	1.3E3	
2.3E-1	3E3	
0.5	8.6E3	
0.9	3.4E4	
1.8	1.4E5	
3.5	1.1E6	
6.2	3E7	
12	1E14	
23.5	2E32	
43	Stable	

New mass measurement with R3

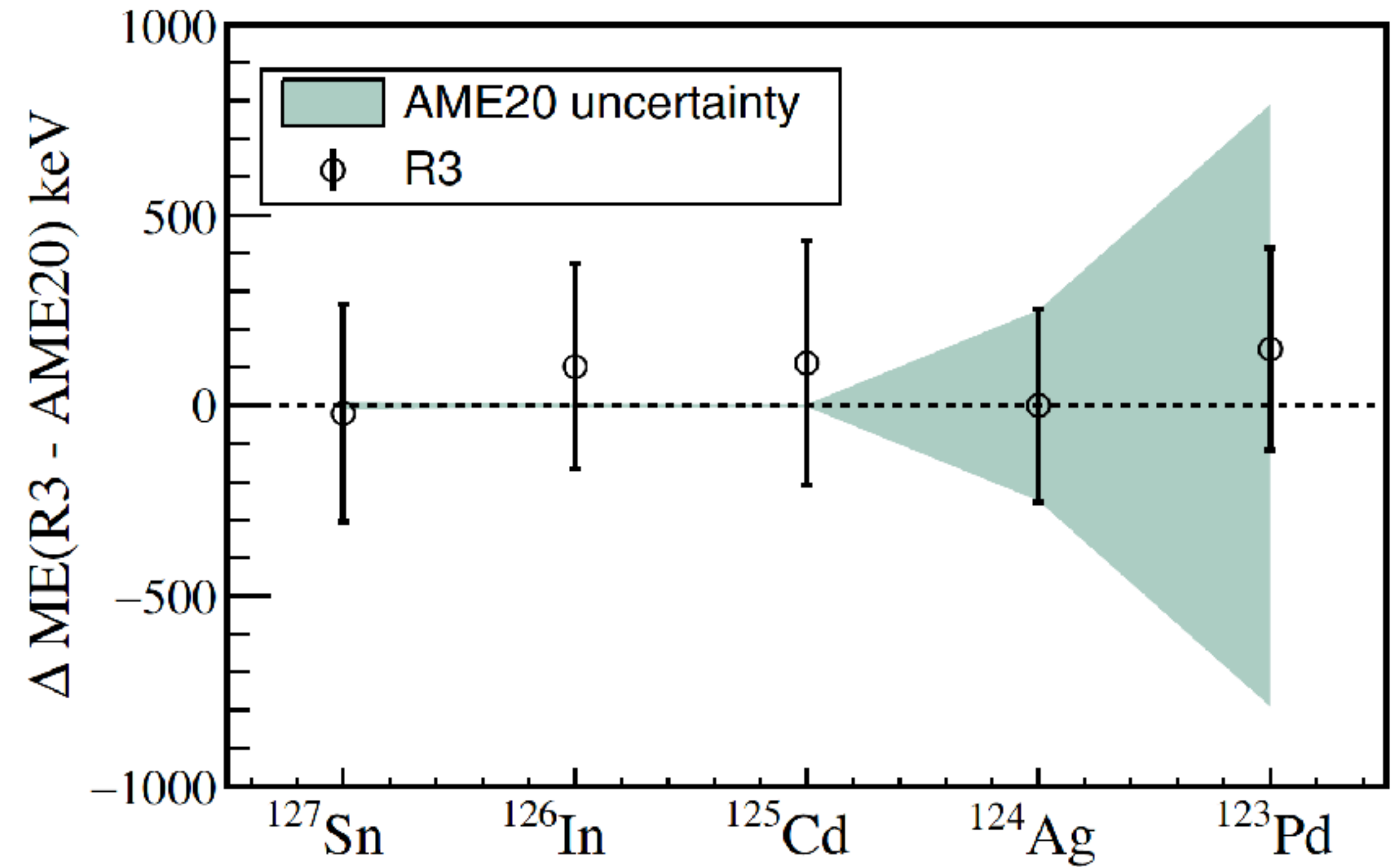
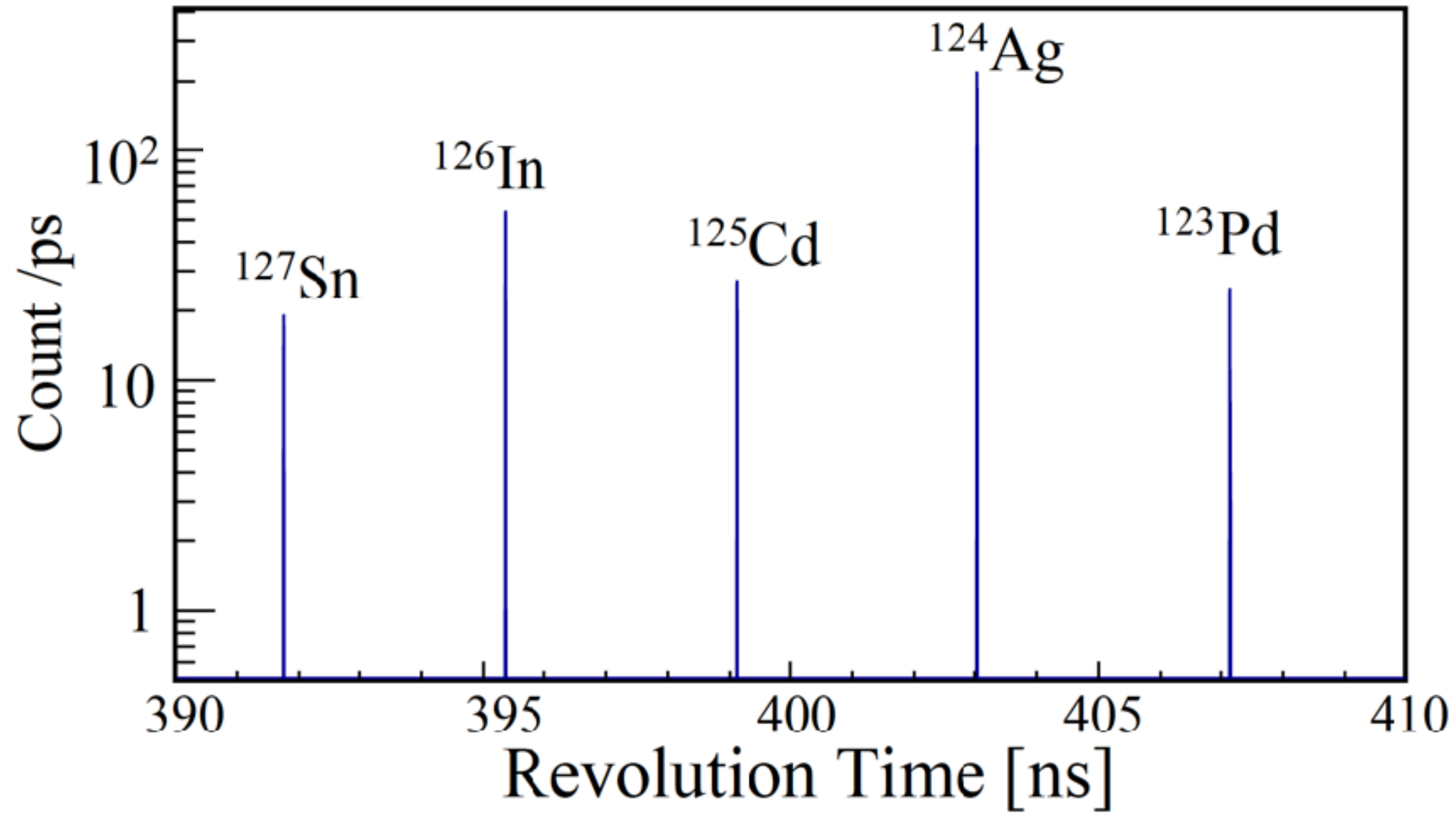


half life [s]		
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0.5	8.6E3	
0.9	3.4E4	
1.8	1.4E5	
3.5	1.1E6	
6.2	3E7	
12	1E14	
23.5	2E32	
43	Stable	

Mass measurement principle

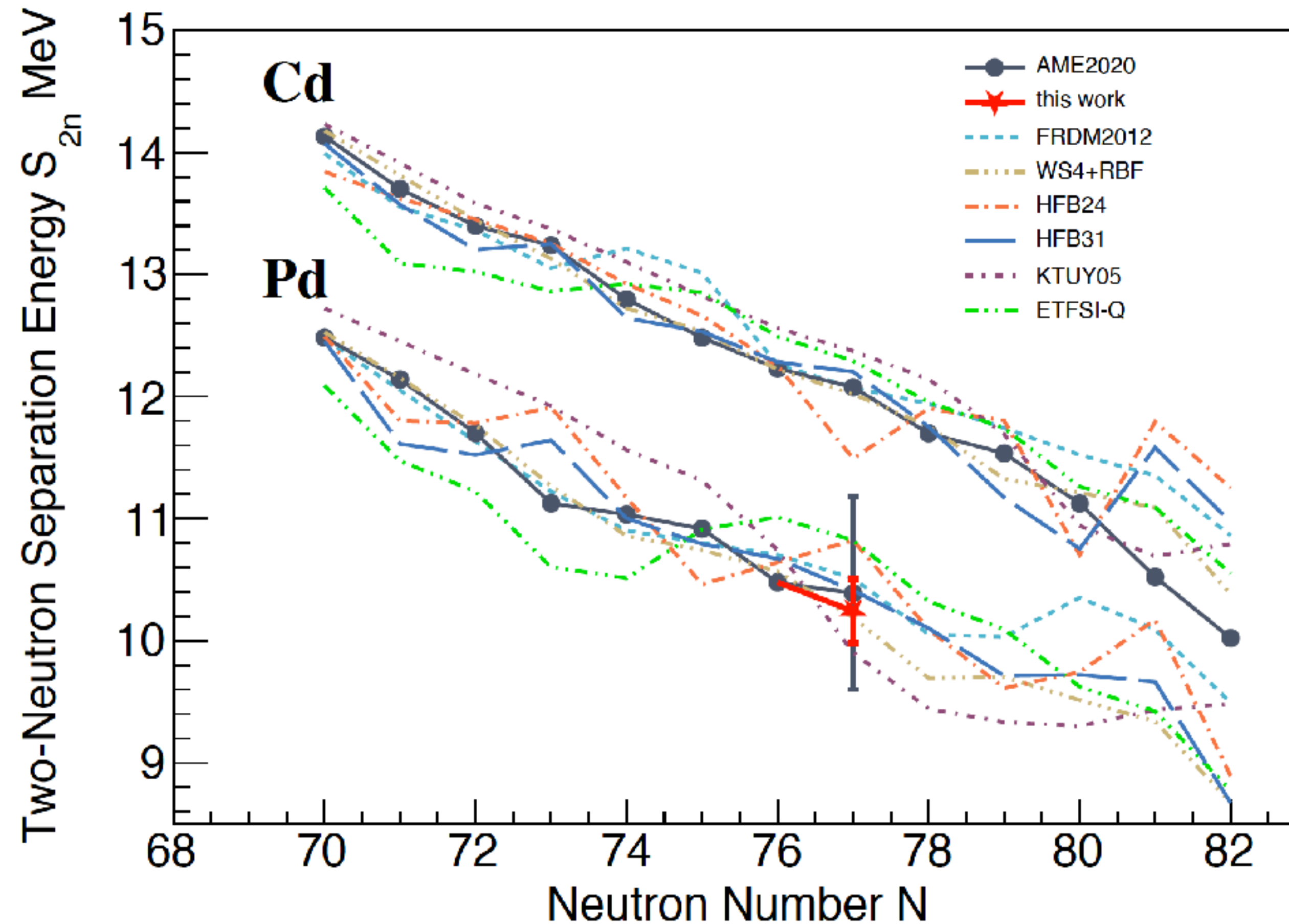


New R3 mass measurement result



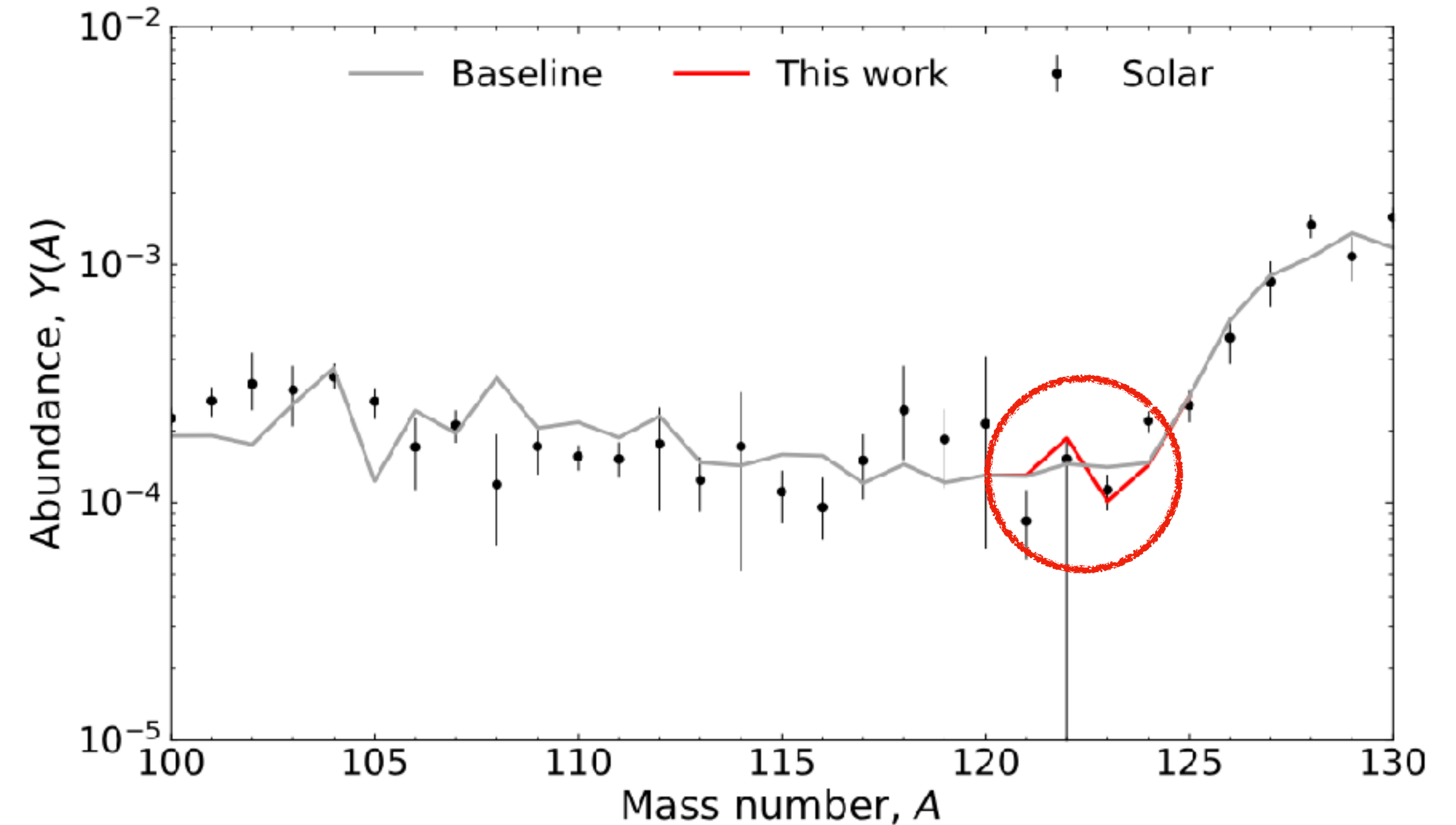
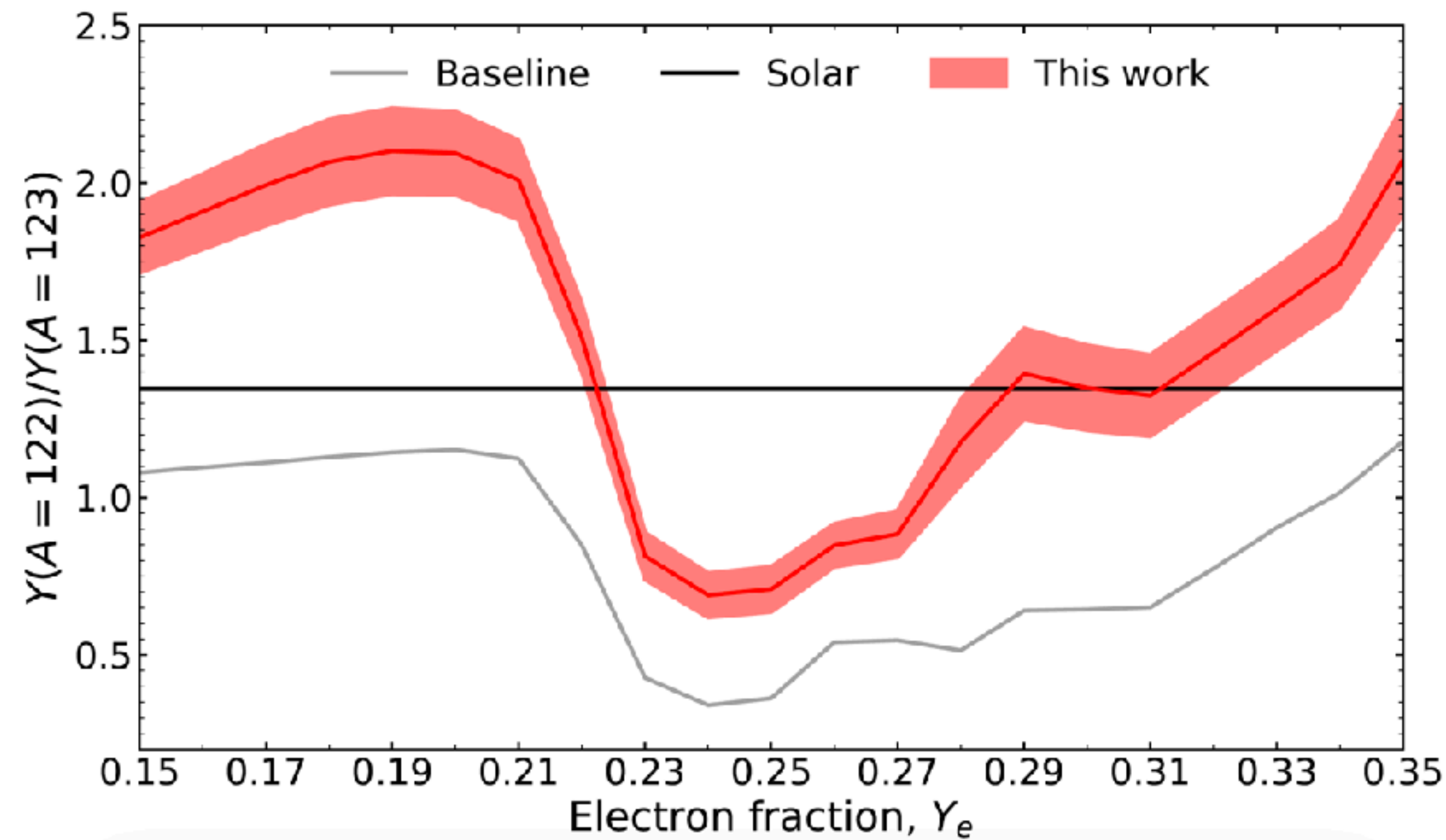
Nucleus	ME_{AME20} [keV]	ME_{R3} [keV]	σ_{total} [keV]	σ_{m_0} [keV]	σ_{stat} [keV]	σ_{sys} [keV]
^{126}In	-77809(4)	-77707	269	254	65	62
^{125}Cd	-73348.1(29)	-73237	320	252	192	40
^{123}Pd	-60430(790)	-60282	265	248	86	40

New R3 mass measurement result



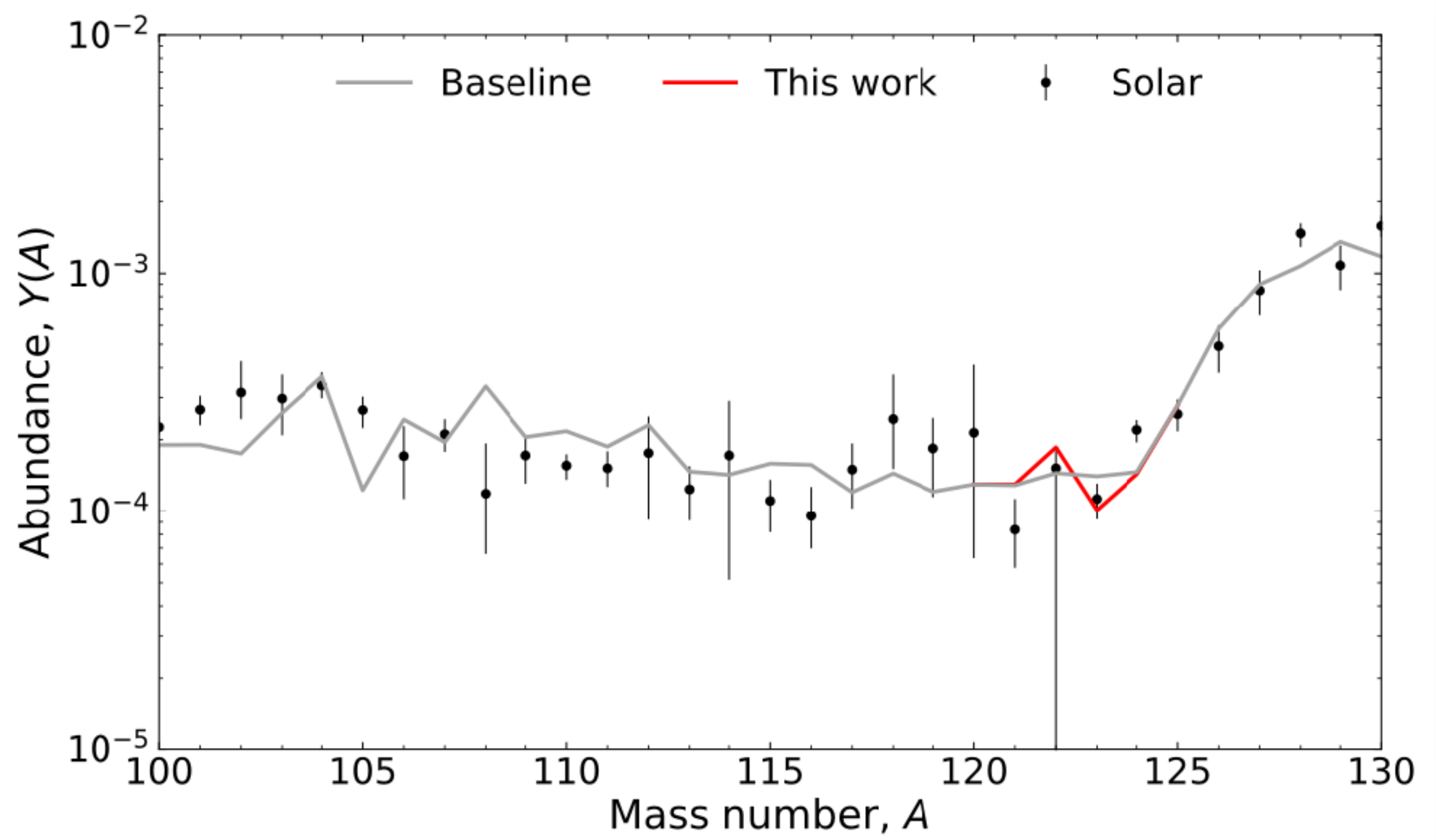
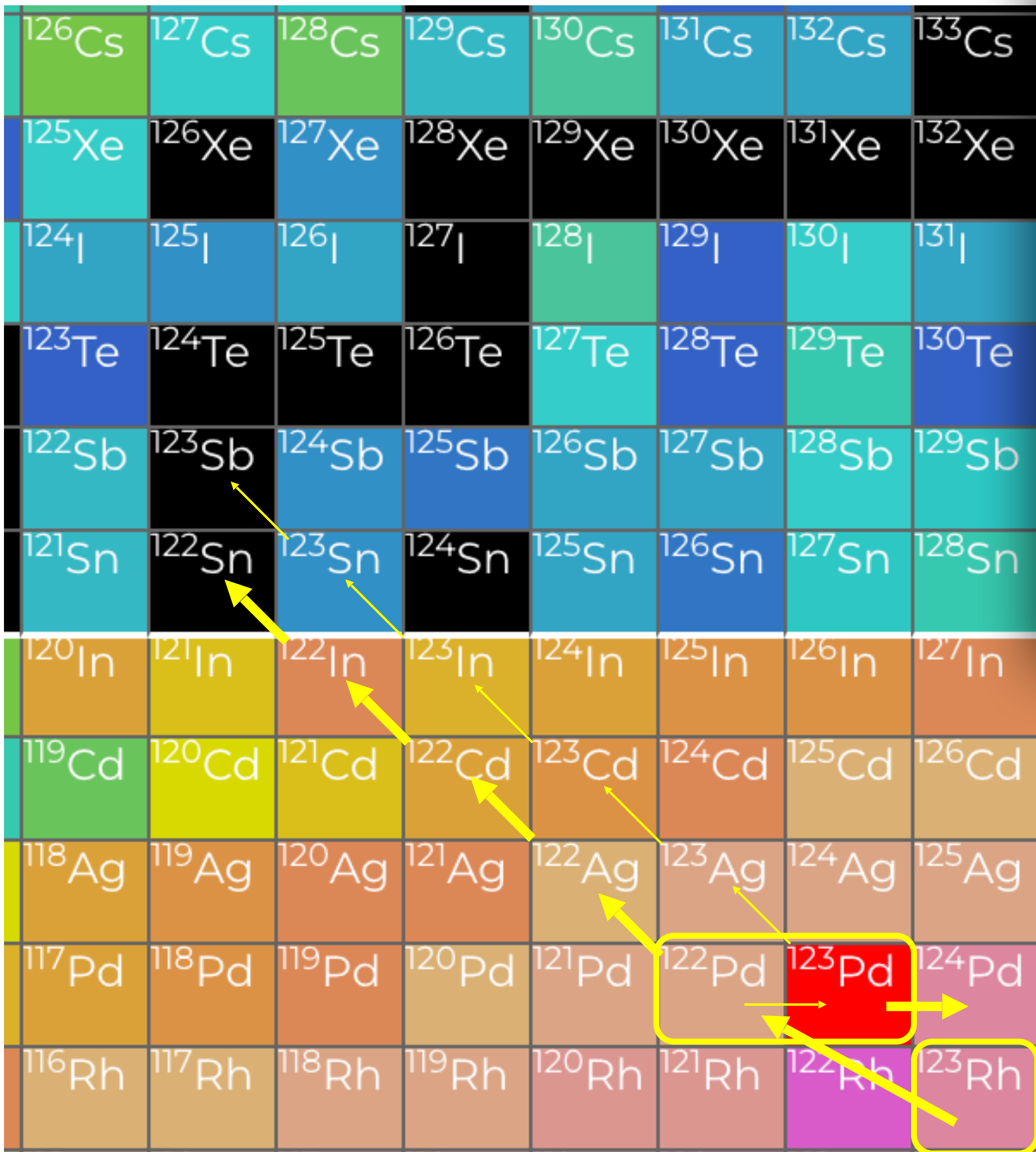
No evidence of large deformation below $Z=50$!!

Impact in r-process abundances



Portable Routines for Integrated nucleoSynthesis Modeling (PRISM)
reaction network, neutron star merger condition; entropy 40kB/baryon,
timescale 20ms, electron fraction $Y_e=0.15\sim0.35$.
Mumpower et al. PRC92(2015), Zhu et al., Astro. J. 863 (2018)

Mass model FRDM (baseline),
Our new mass measurement of ^{123}Pd (redline) with its uncertainty



Impact of ^{123}Pd mass

Neutron capture cross section:

$^{122}\text{Pd} \downarrow 2.6$

$^{123}\text{Pd} \uparrow 2.2$

Probability β -delayed neutron emission

$^{123}\text{Rh} \uparrow$

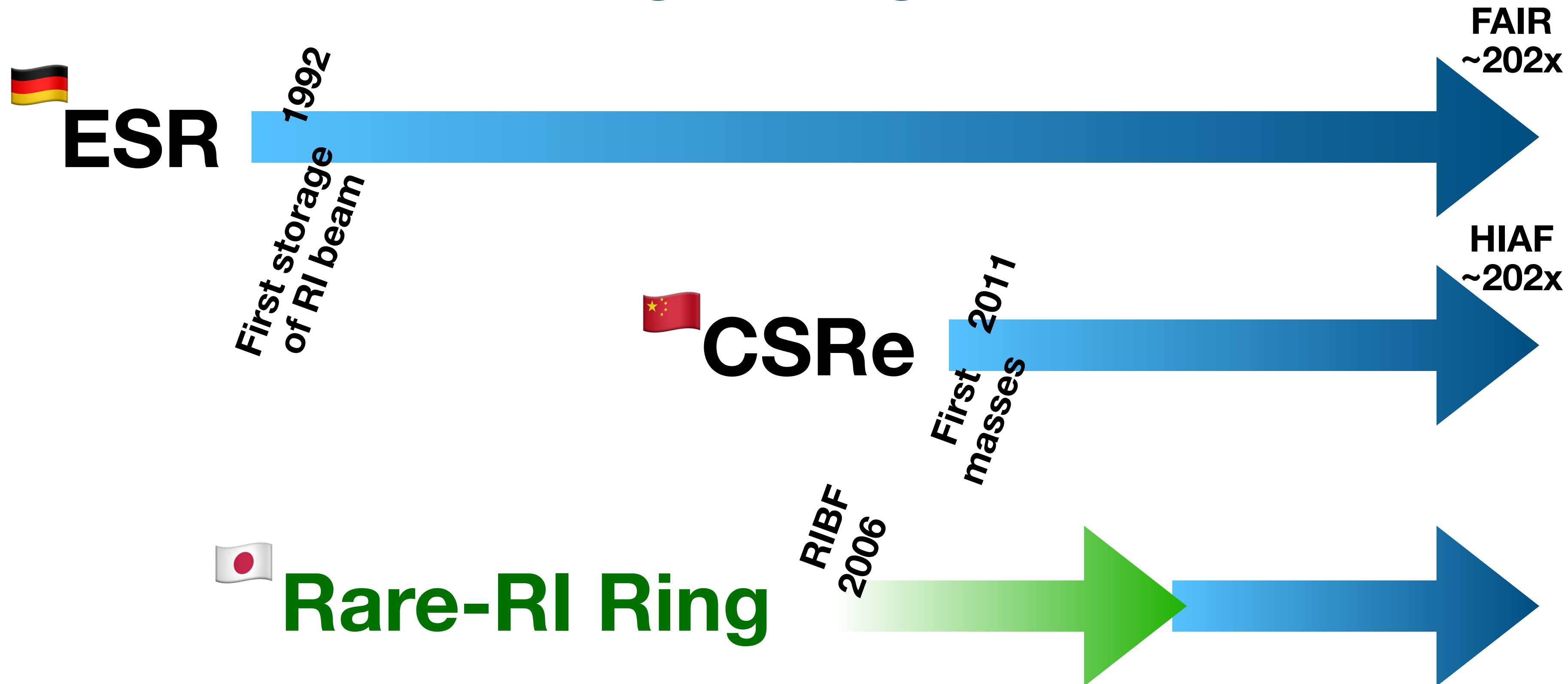
Mass difference FRDM $\sim 500\text{keV}$

First Application of Mass Measurements with the Rare-RI Ring Reveals the Solar *r*-Process Abundance Trend at $A = 122$ and $A = 123$

H. F. Li,^{1,2,3,4} S. Naimi^{3,*} T. M. Sprouse,⁵ M. R. Mumpower,⁵ Y. Abe,³ Y. Yamaguchi,³ D. Nagae,^{3,†} F. Suzuki,^{3,‡} M. Wakasugi,³ H. Arakawa,⁶ W. B. Dou,⁶ D. Hamakawa,⁶ S. Hosoi,⁶ Y. Inada,⁶ D. Kajiki,⁶ T. Kobayashi,⁶ M. Sakaue,⁶ Y. Yokoda,⁶ T. Yamaguchi,⁶ R. Kagesawa,⁷ D. Kamioka,⁷ T. Moriguchi,⁷ M. Mukai,^{7,§} A. Ozawa,⁷ S. Ota,^{8,||} N. Kitamura,⁸ S. Masuoka,⁸ S. Michimasa,⁸ H. Baba,³ N. Fukuda,³ Y. Shimizu,³ H. Suzuki,³ H. Takeda,³ D. S. Ahn,^{3,9} M. Wang,¹ C. Y. Fu,¹ Q. Wang,¹ S. Suzuki,¹ Z. Ge,^{1,¶} Yu. A. Litvinov,¹⁰ G. Lorusso,^{11,12} P. M. Walker,¹² Zs. Podolyak,¹² and T. Uesaka³



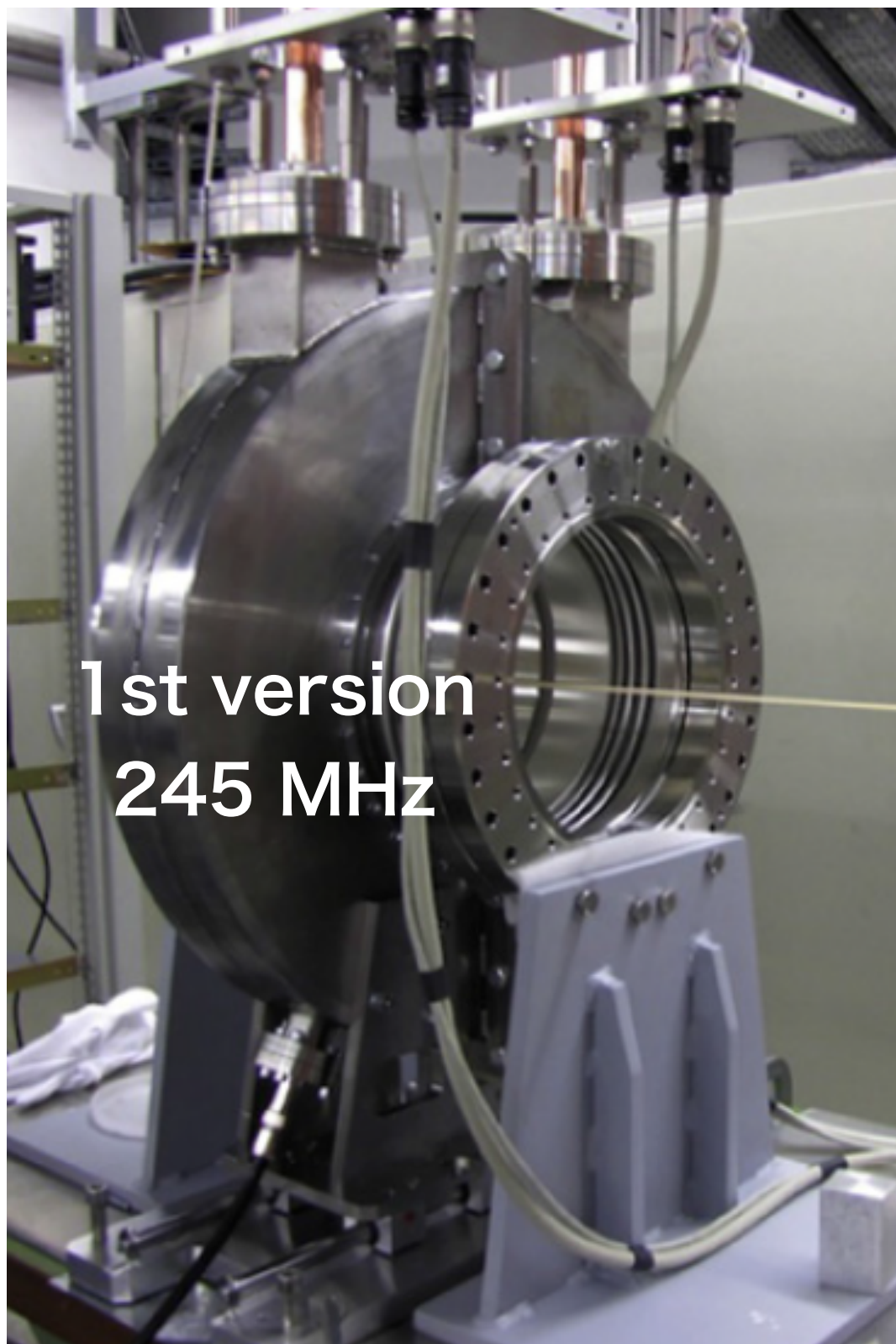
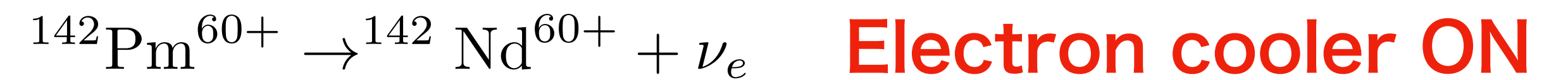
Storage Rings In Comparison



Isochronous cond.: $\sim 10^{-6}$
Total transmission: $\sim 10^{-2}$ *
Mass accuracy: 10^{-6} - 10^{-5} *

- Ongoing developments
 - **Kicker upgrade**
 - Long flat-top
 - New capacitances
 - **Steering magnets**
 - Vertical beam control

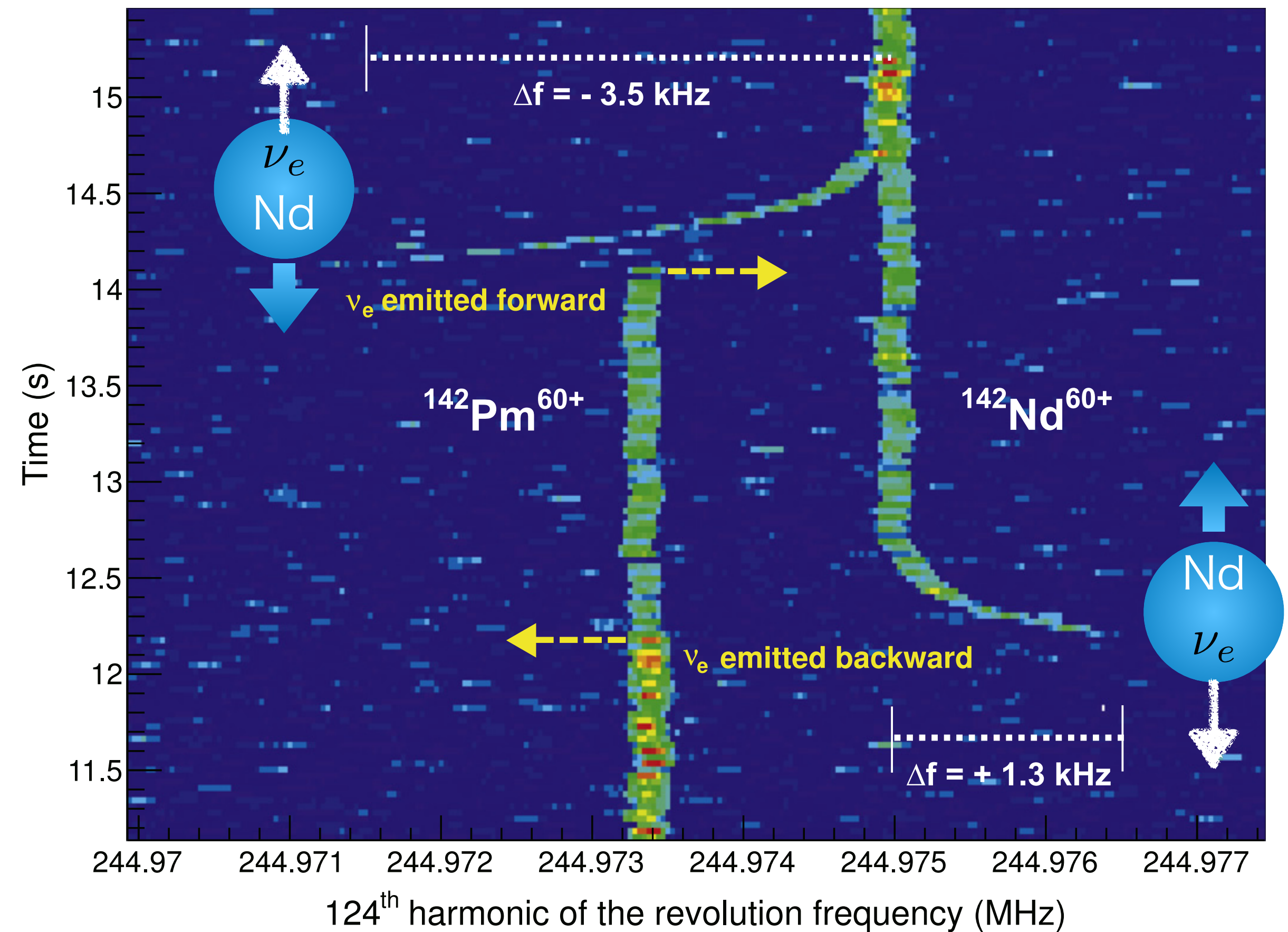
Schottky at GSI



1st version
245 MHz

F. Nolden et al.,
Nucl. Instrum. Methods A 659 (2011) 69.

Latest cavity: 410 MHz

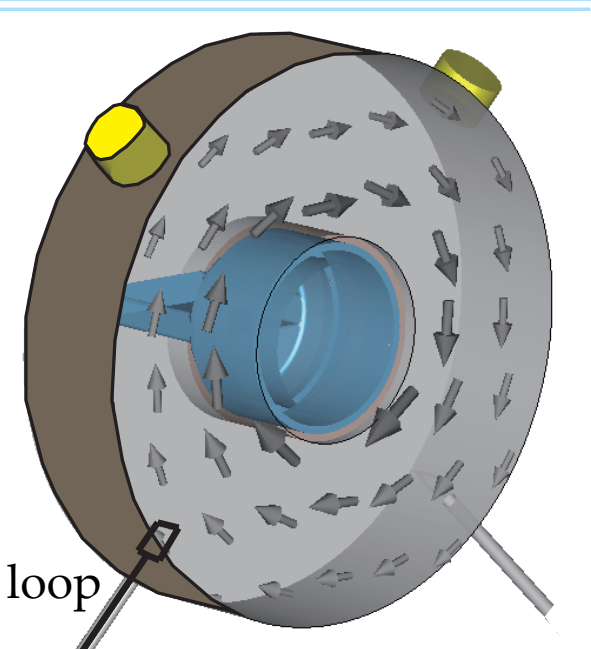


P. Kienle, Two-Body-Weak-Decays Collaboration,
Phys. Lett. B 726 (2013) 638.

Resonant Schottky

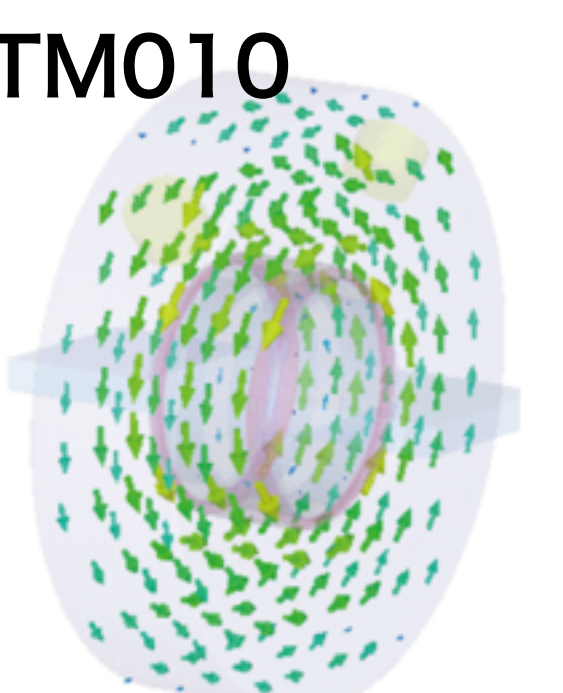
Non-destructive single-ion detection

Pillbox cavity



pick-up loop

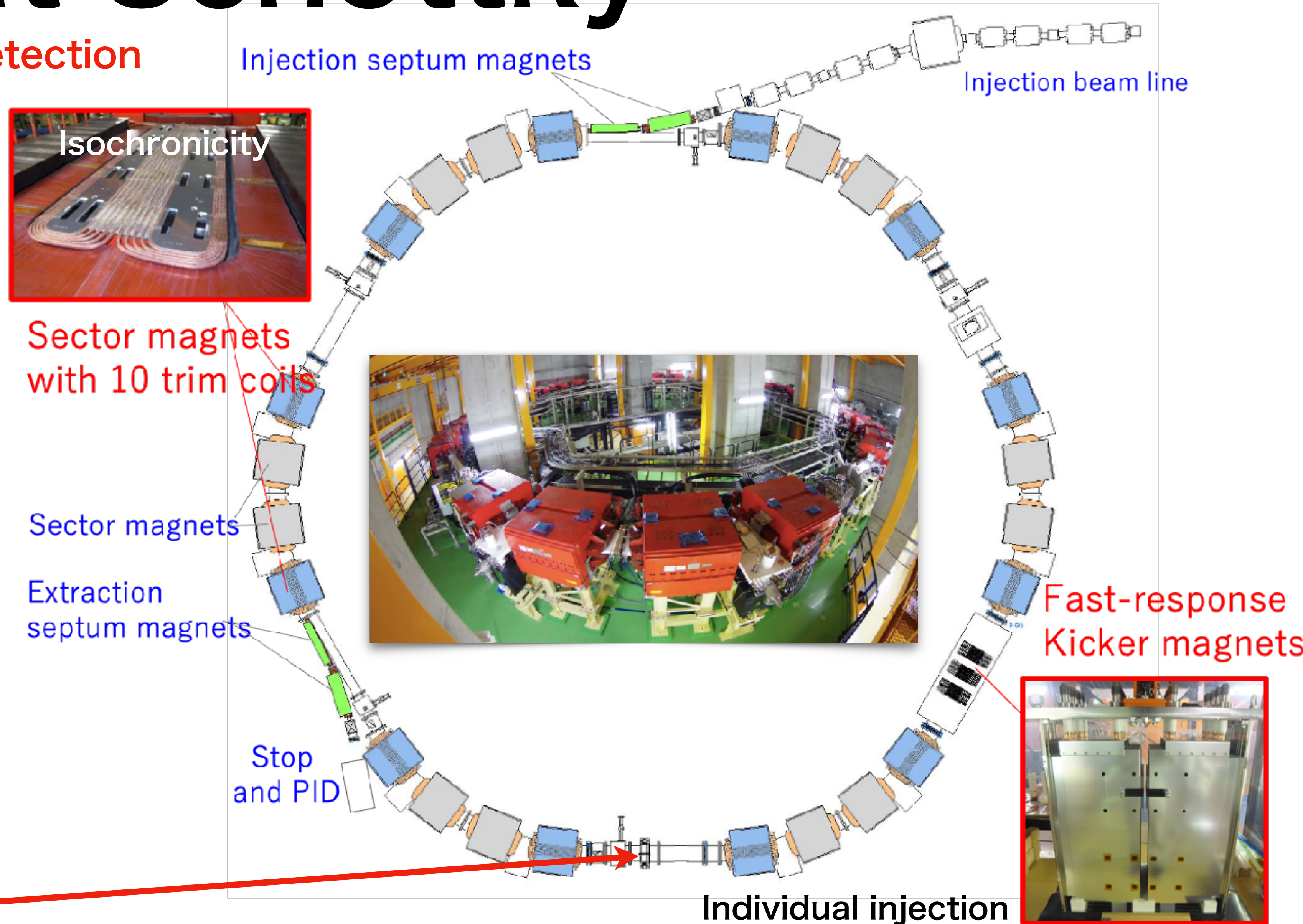
TM010



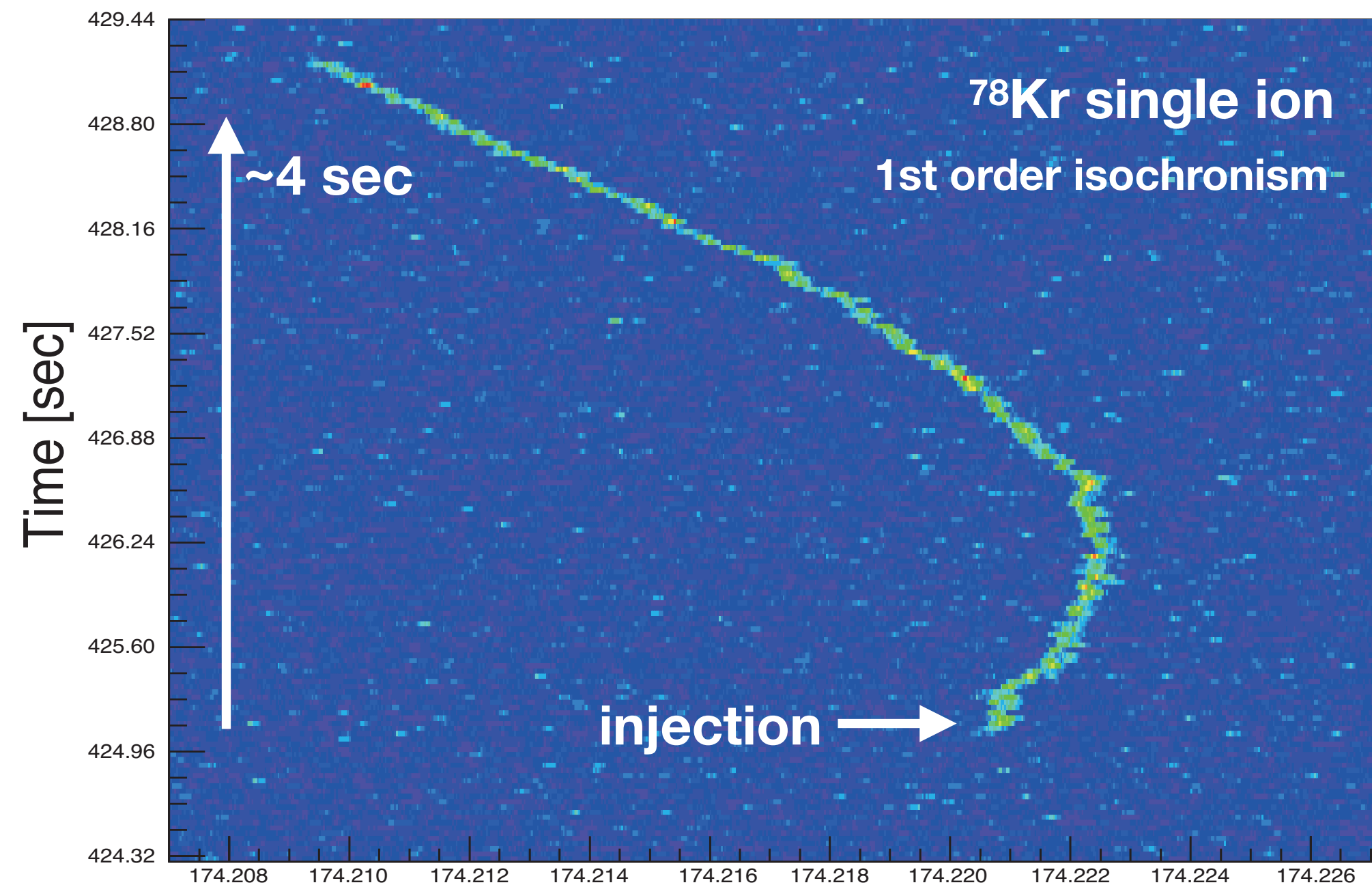
Magnetic field

QL-factor
~1880

Shunt Impedance
~160 k Ω



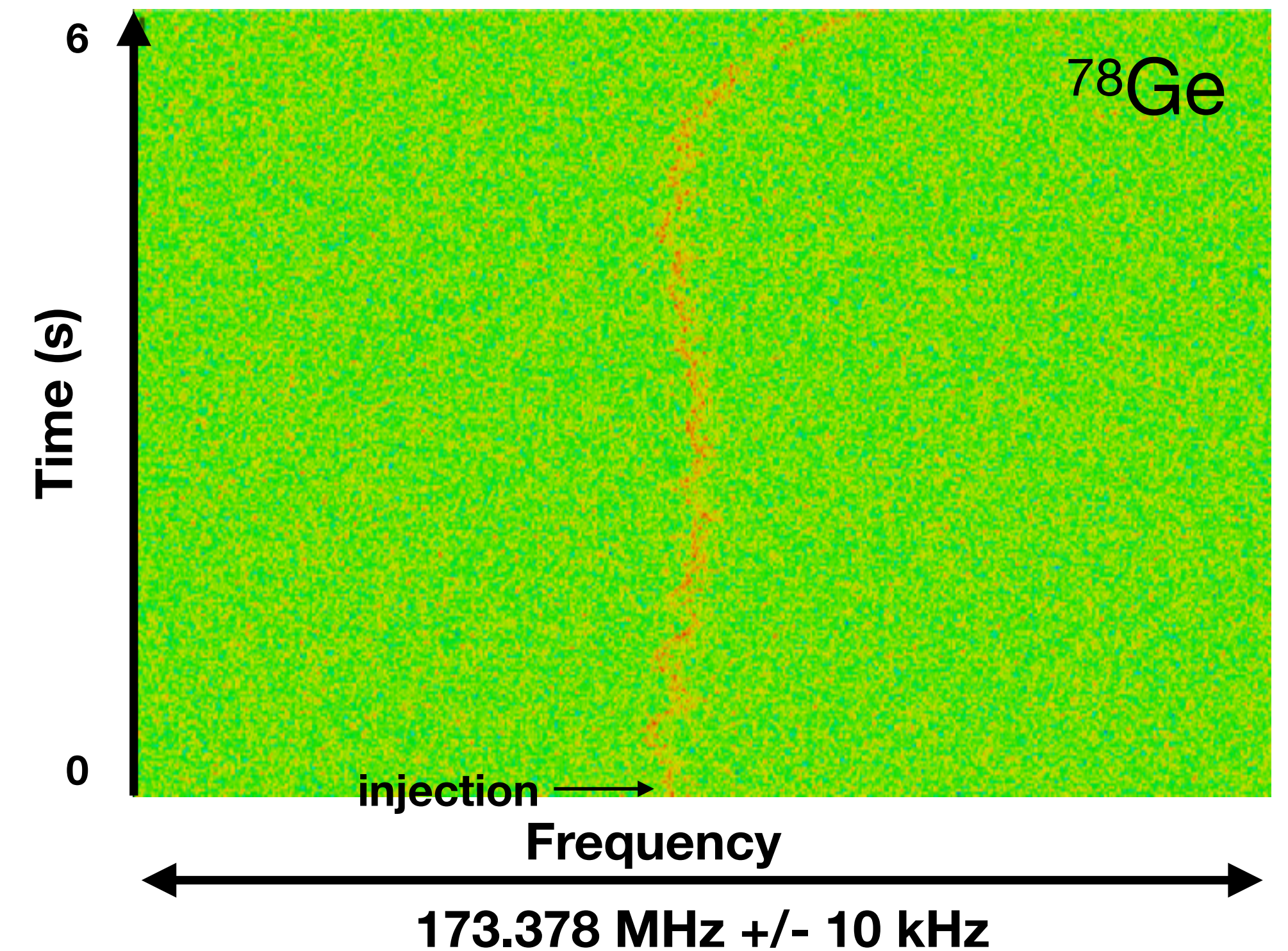
Schottky at R3



Frequency [MHz]

174.217 MHz +/- 10 kHz

Resolution: 1.3×10^{-6} /frame

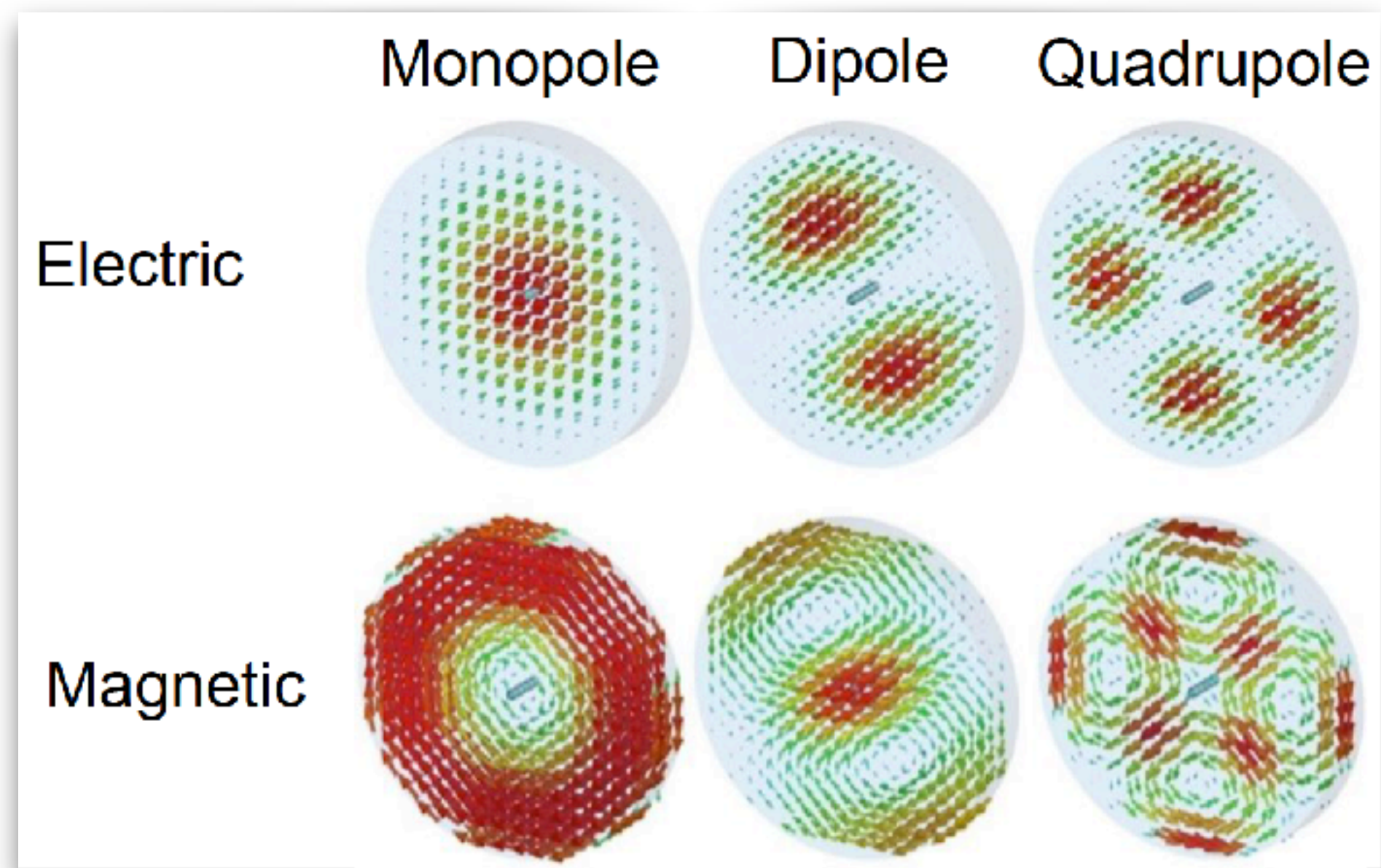


First long time storage of RI beam: 6 sec

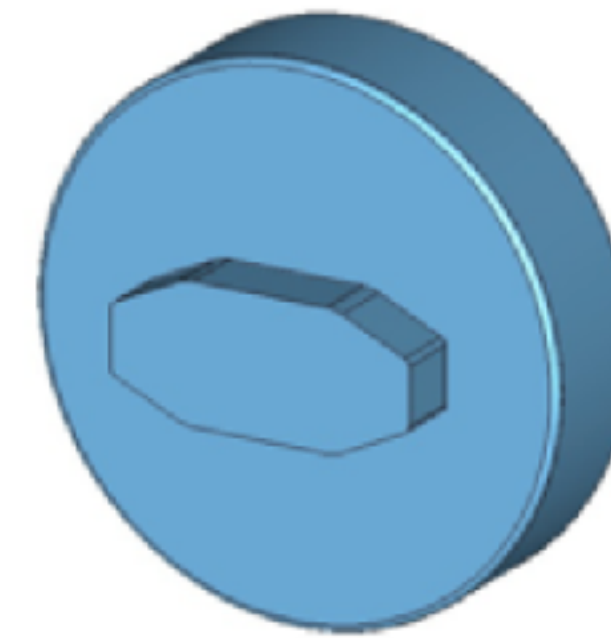
Position-sensitive Schottky

GSI-R3 collaboration

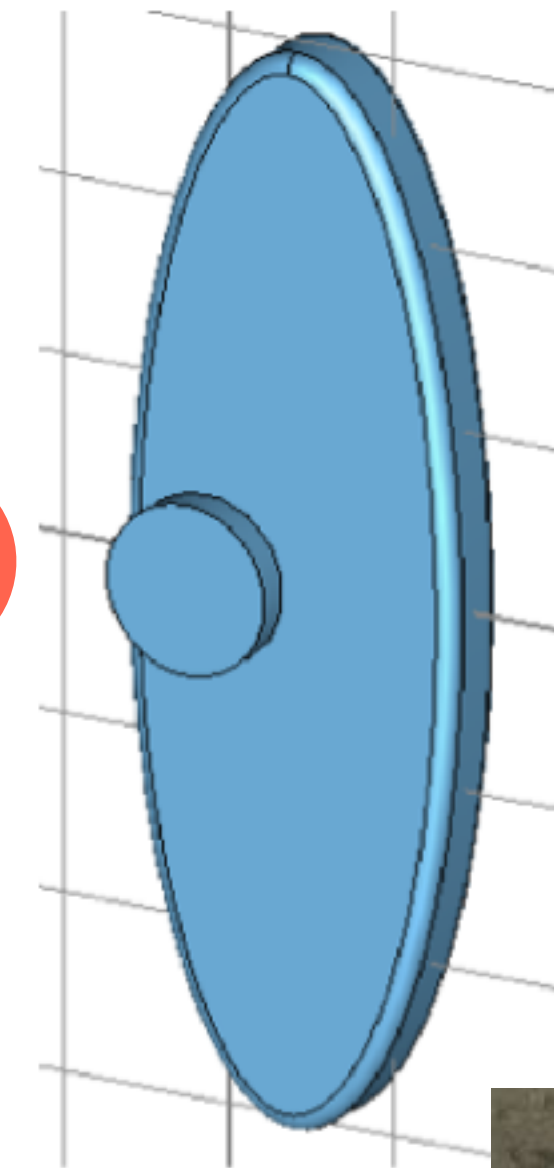
Eigenmodes in a resonant cavity



Circular cavity
(reference)



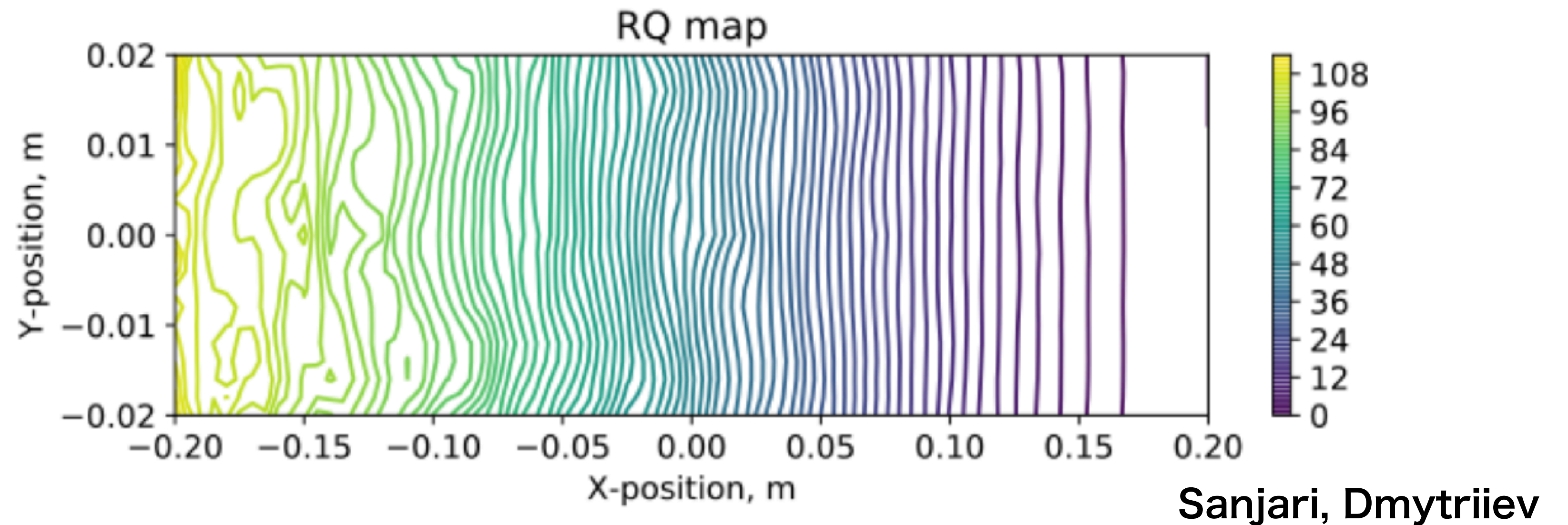
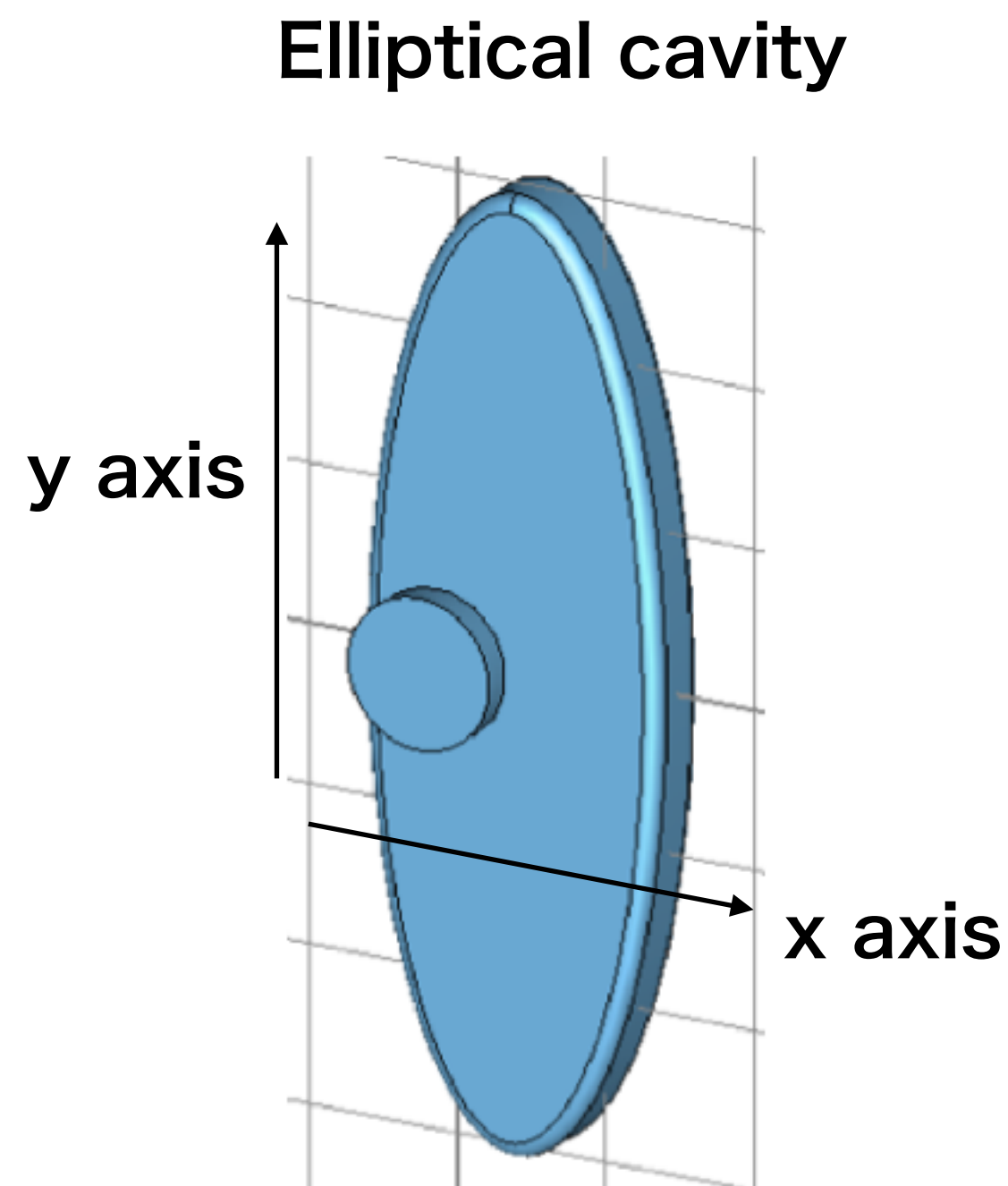
Elliptical cavity



Under construction just now

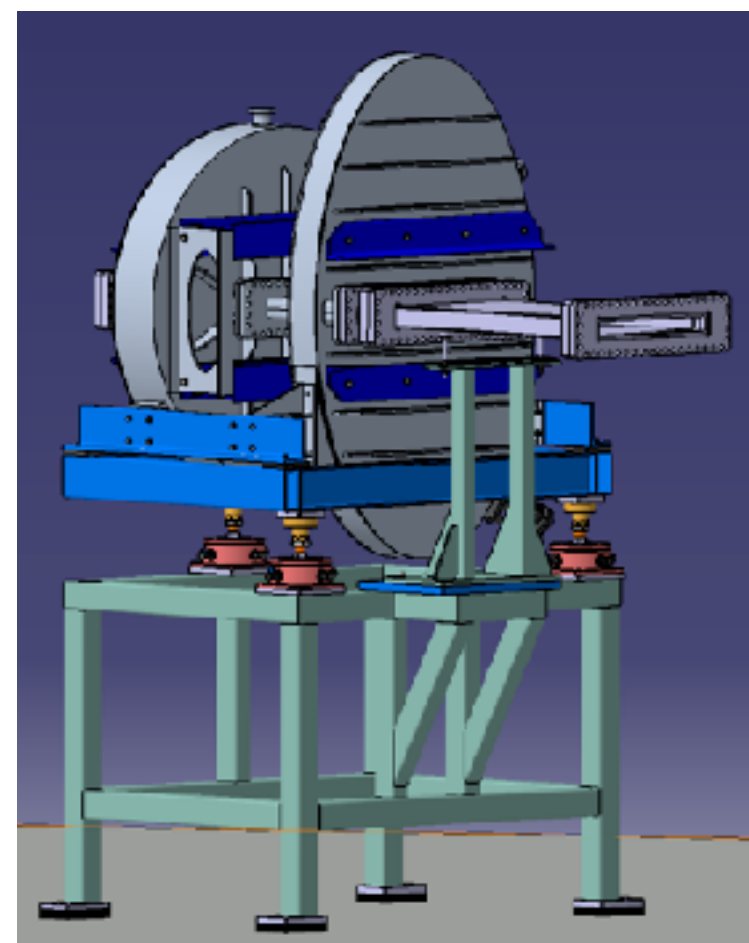
Position-sensitive Schottky

GSI-R3 collaboration

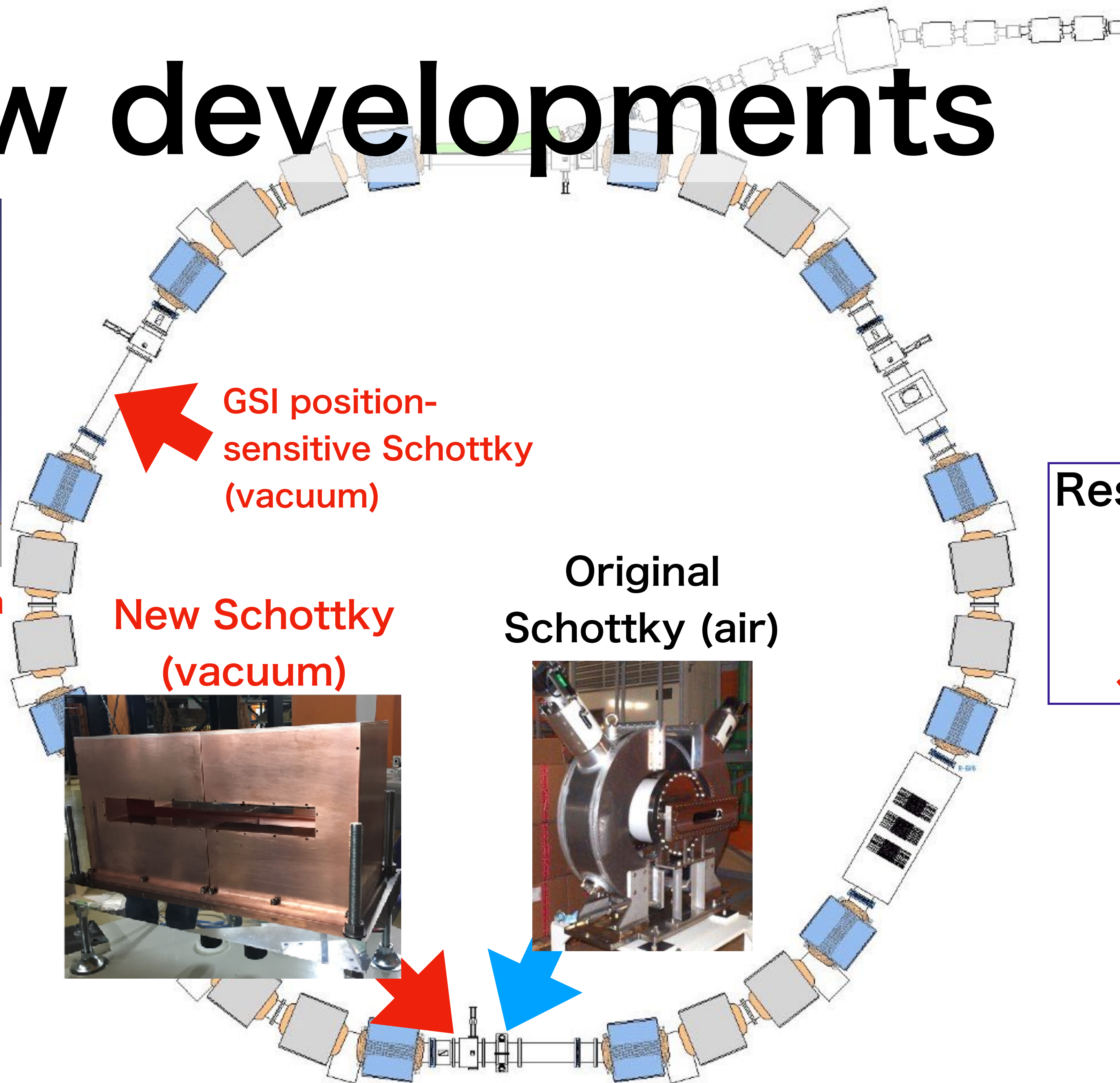


- ✓ Sensitivity changes linearly.
- ✓ Signal amplitude proportional to x-position.

New developments



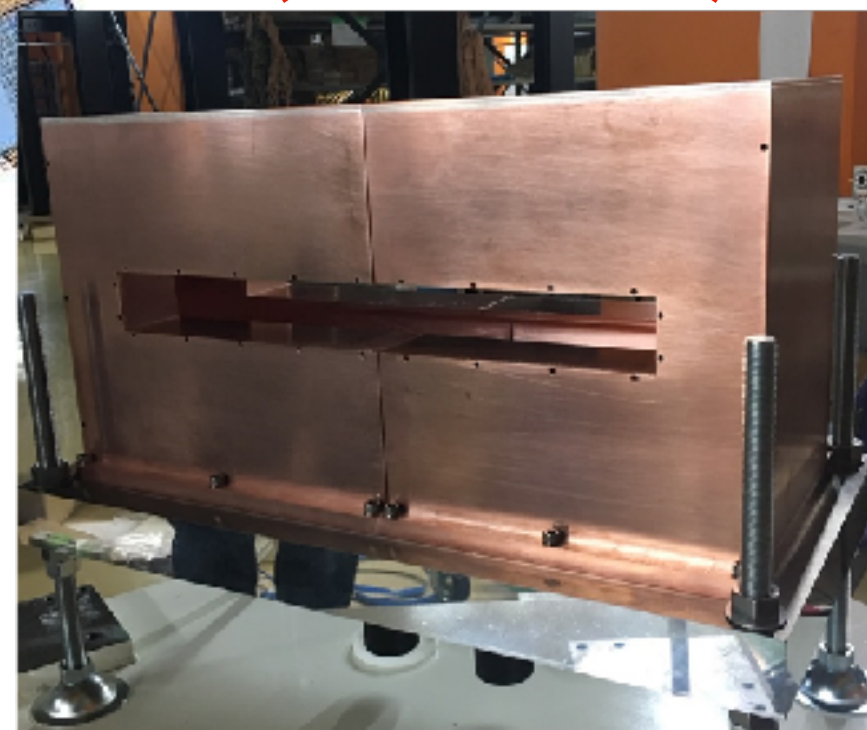
Under construction
Delivery in 2023



GSI position-
sensitive Schottky
(vacuum)

New Schottky
(vacuum)

Original
Schottky (air)



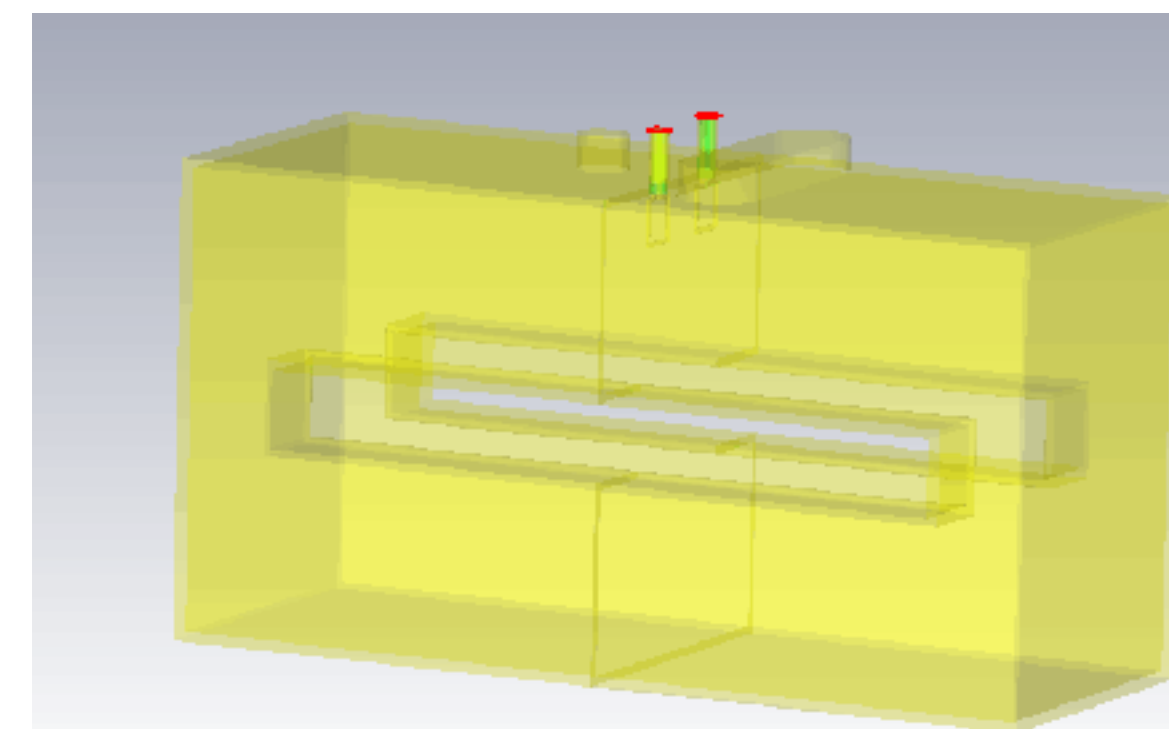
Saitama Schottky

Resonant freq. ~ 503 MHz

$Q_L \sim 3200$

$R_{sh} \sim 1020$ k Ω

$\sim 10x$ more sensitive



In summary

- New storage ring “Rare-RI Ring (R3)” has been built at RIBF.
 - Single-ion isochronous mass spectrometry with individual injection technique
- Commissioning of the uranium fission fragments was successful.
 - Mass precision $<10^{-5}$
- First application for neutron-rich Pd isotopes: update of ^{123}Pd
- Upgrades of the facility
 - New Schottky detectors will be ready soon.

Thank you

