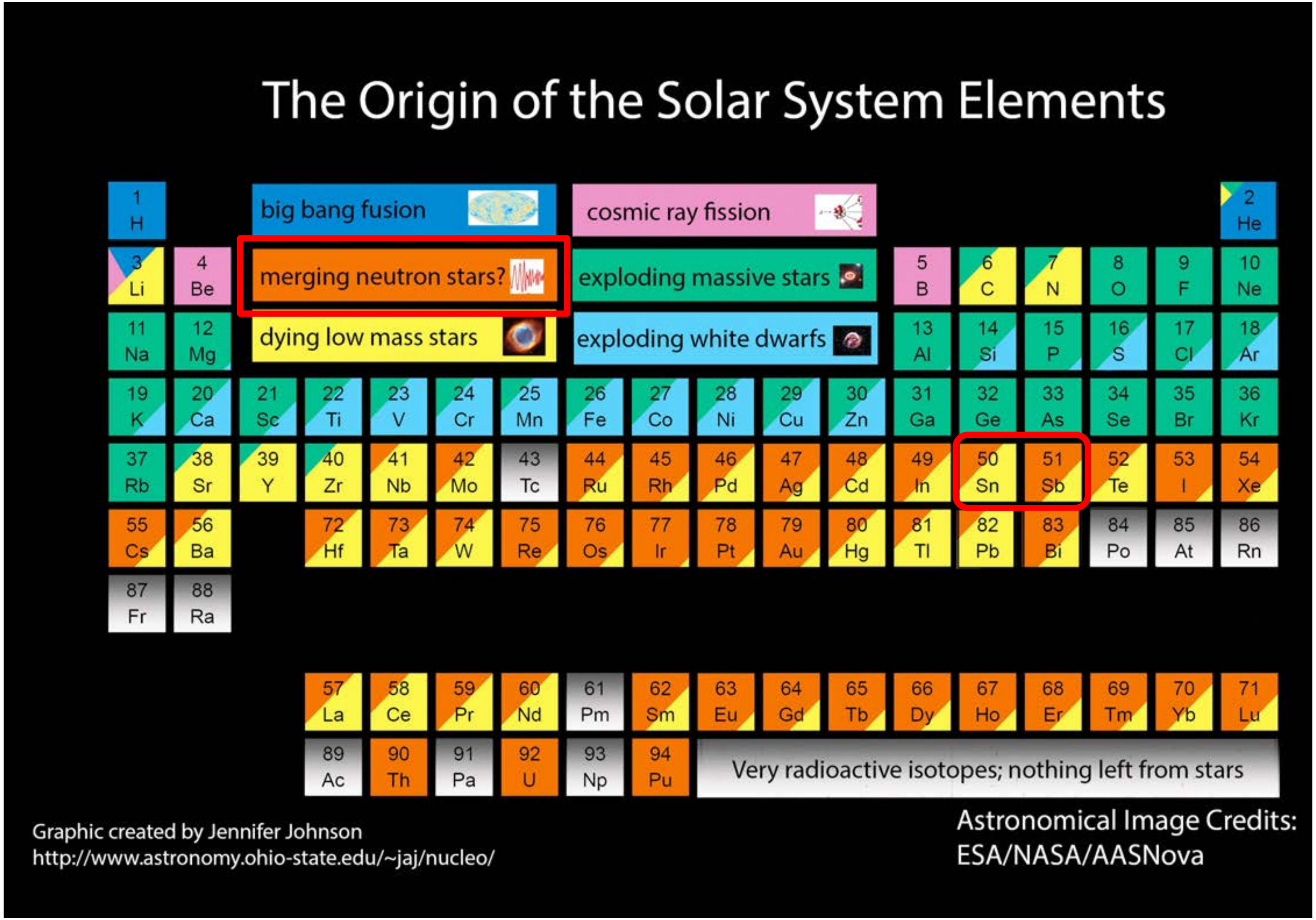
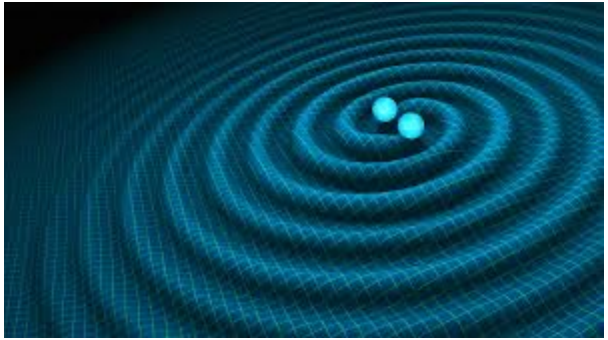
Mass measurement with the Rare-RI Ring at RIBF/Riken elucidates r-process abundances of heavy elements at A=122,123

Sarah Naimi


The Origin of the Solar System Elements
big bang fusion
cosmic ray fission
merging neutron stars?
exploding massive stars
dying low mass stars
exploding white dwarfs
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U
93 Np
94 Pu
Very radioactive isotopes; nothing left from stars
Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/
Astronomical Image Credits:
ESA/NASA/AASNova

Gravitational Waves discovery

Neutron star mergers!

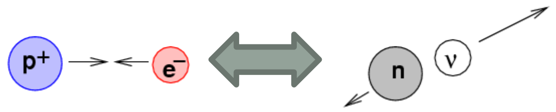


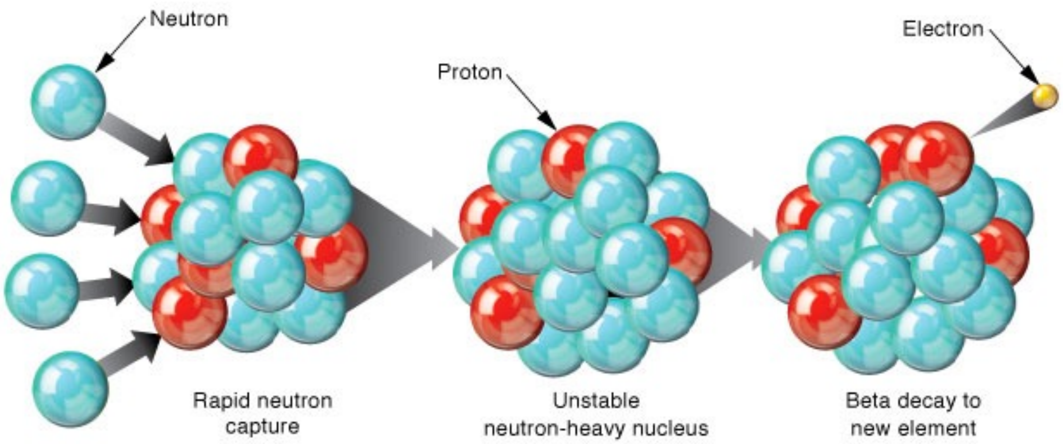
LIGO observatory in USA

The light was also observed

This is very exciting for our field!!!

The nuclear physics

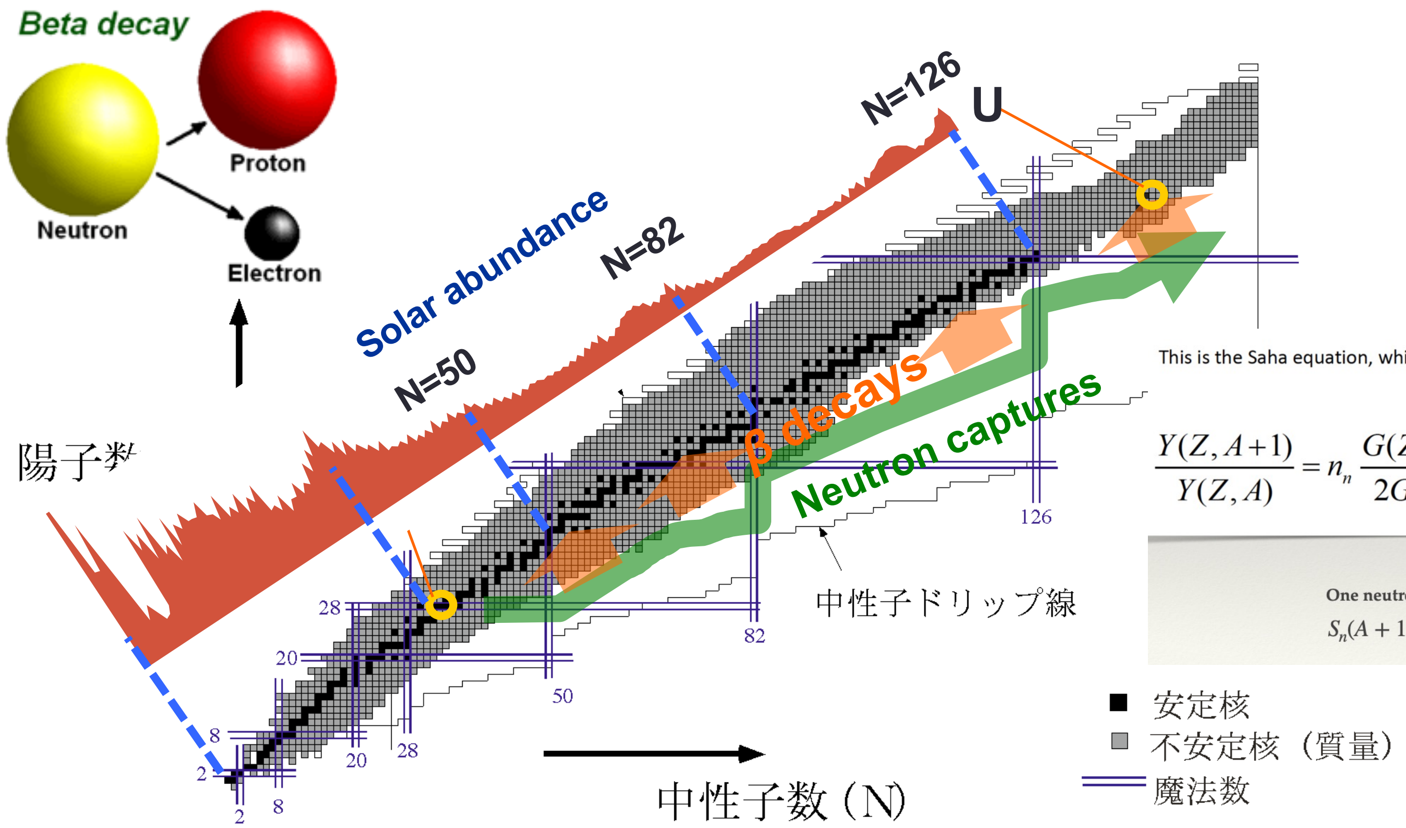




Neutron is converted to proton via beta decay. Number of protons defines the element.

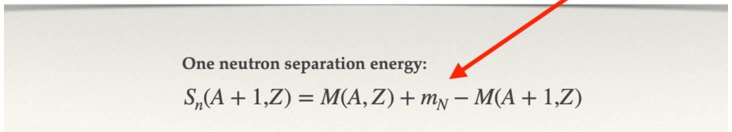
『How were heavy elements made ?』

rapid neutron capture: r-process

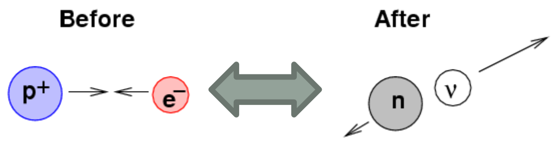


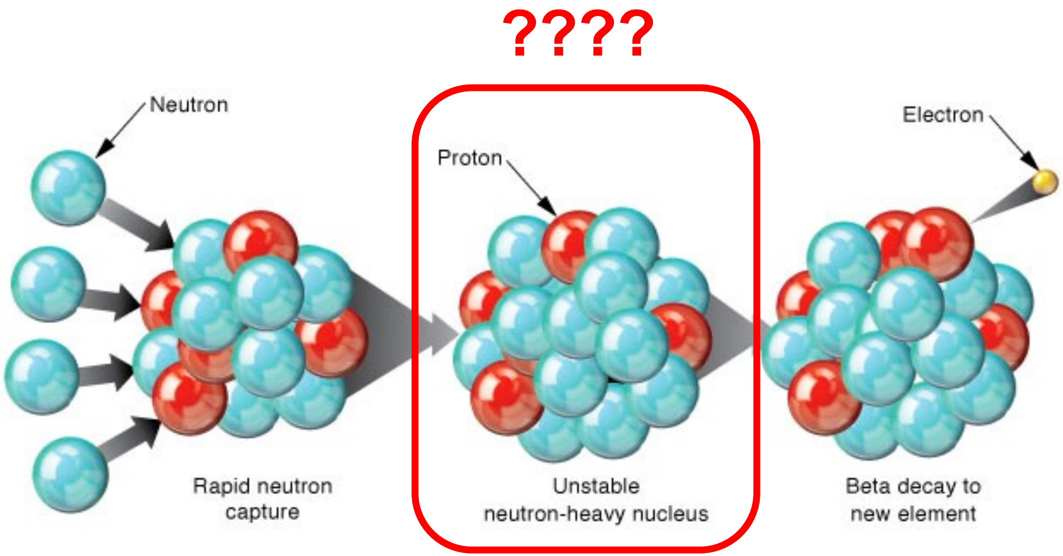
This is the Saha equation, which is true when (n,g)=(g,n) equilibrium holds:

$$\frac{Y(Z,A+1)}{Y(Z,A)} = n_n \frac{G(Z,A+1)}{2G(Z,A)} \left[\frac{A+1}{A} \frac{2\pi\hbar^2}{m_u kT} \right]^{3/2} \exp(S_n / kT)$$



The nuclear physics



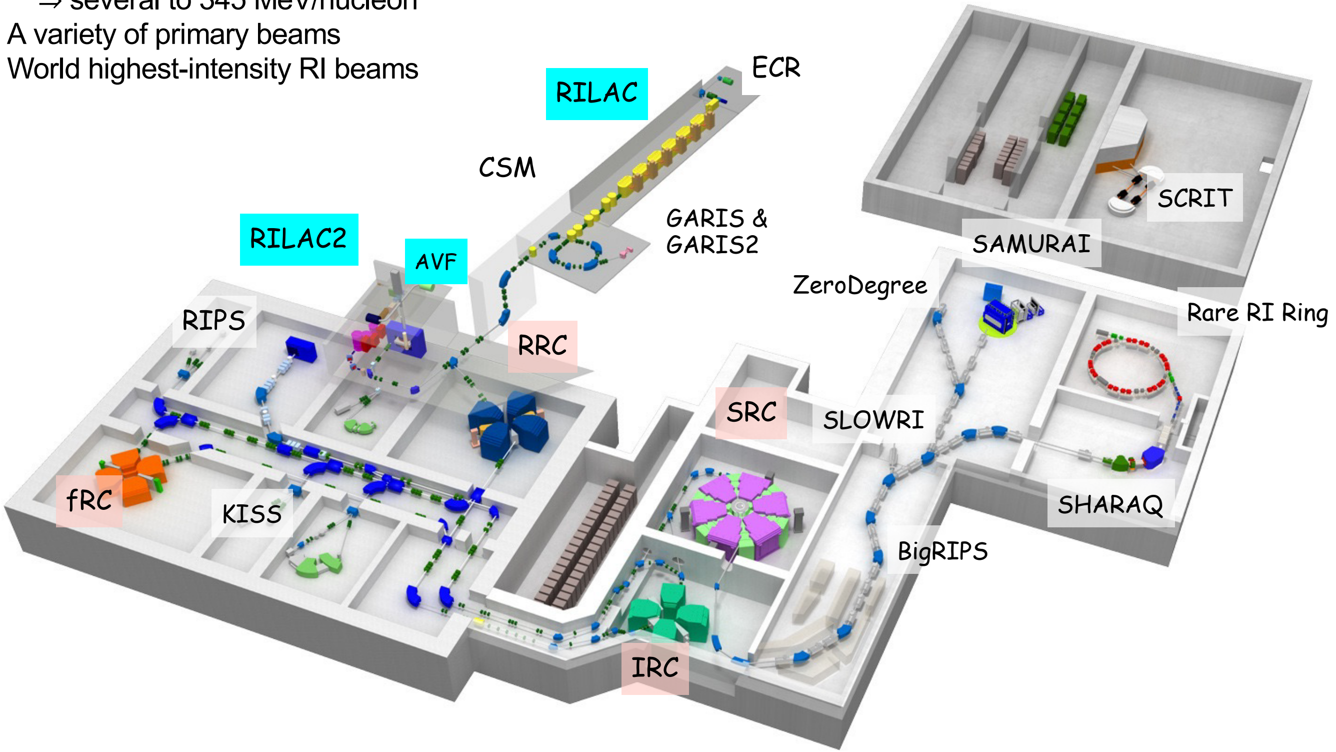


Neutron is converted to proton via beta decay. Number of protons defines the element.

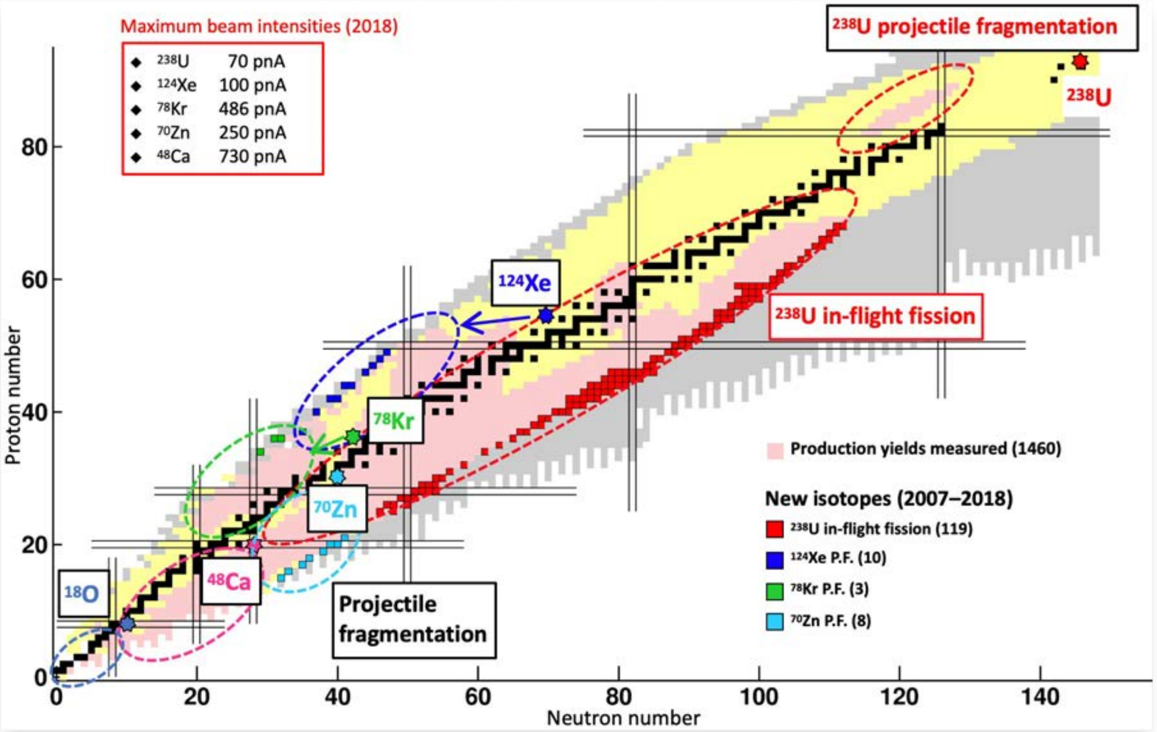
RIKEN Campus & RIBF

RI Beam Factory at RIKEN

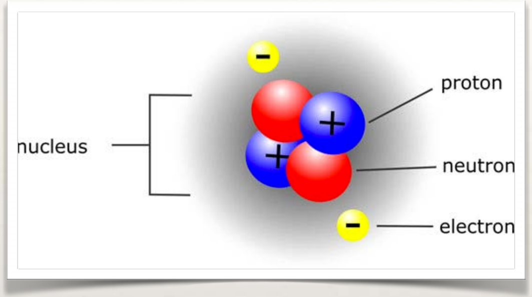
3 injectors + cascade of 4 cyclotrons
⇒ several to 345 MeV/nucleon
A variety of primary beams
World highest-intensity RI beams



Production of RI beam at RIBF

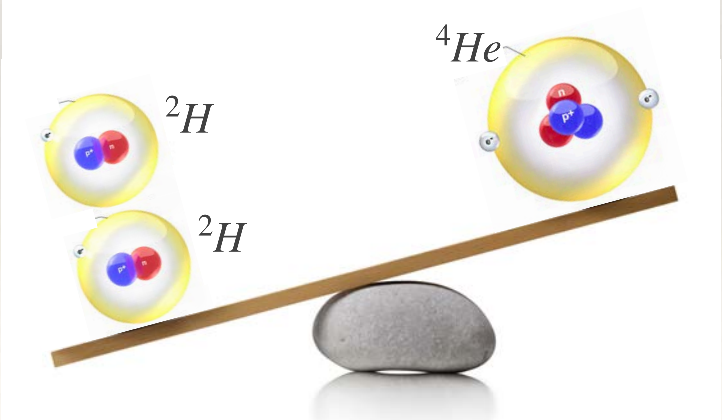


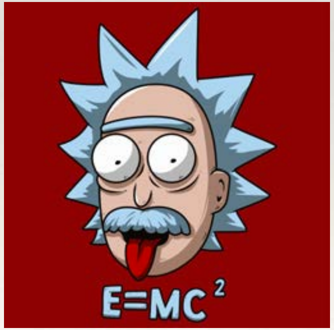
Nuclear binding energy

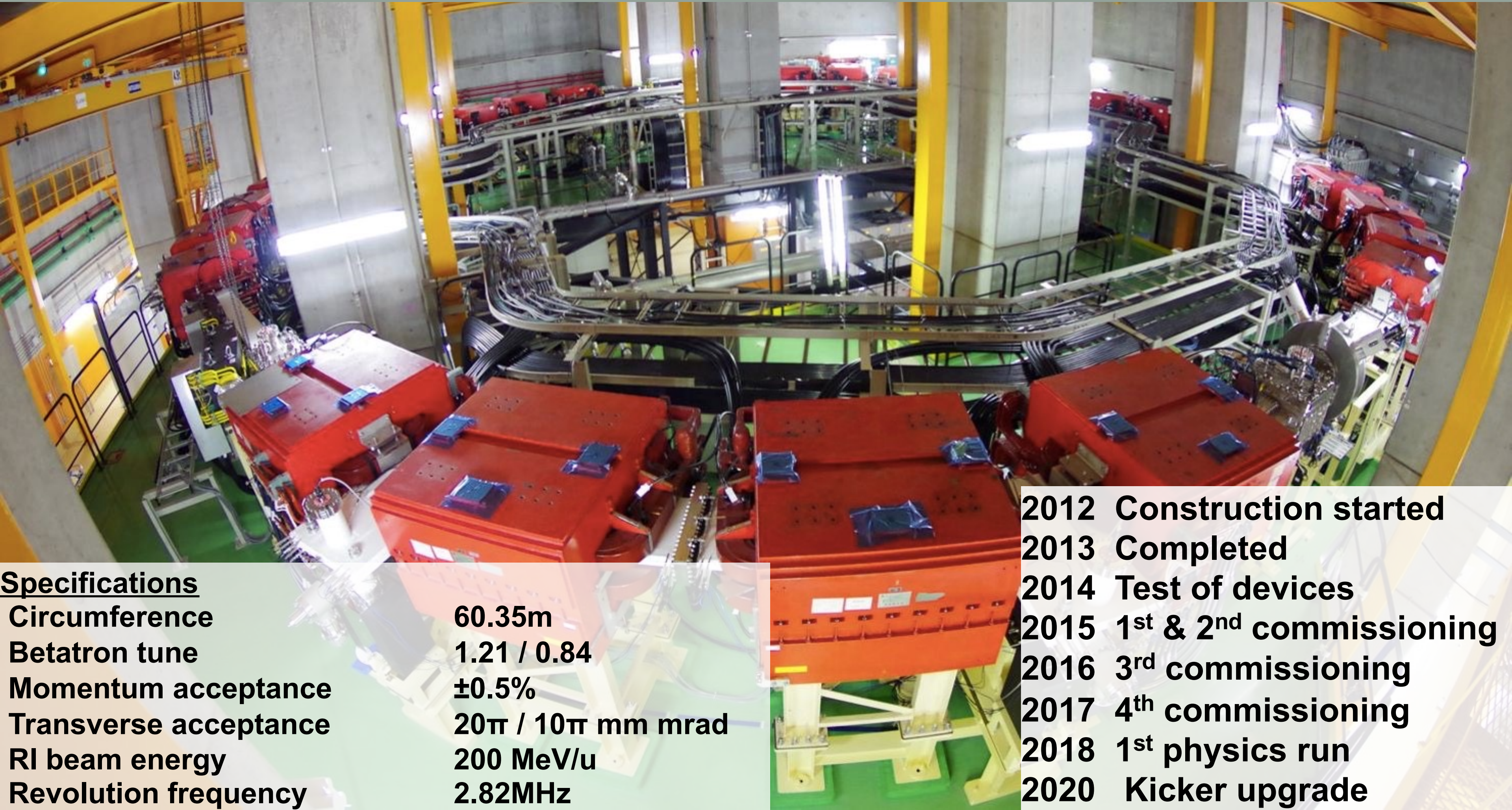


$$M(^4He) = 2 \cdot m_p + 2 \cdot m_n + 2 \cdot m_e$$

- Binding Energy







Specifications

Circumference	60.35m
Betatron tune	1.21 / 0.84
Momentum acceptance	±0.5%
Transverse acceptance	20π / 10π mm mrad
RI beam energy	200 MeV/u
Revolution frequency	2.82MHz

- **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

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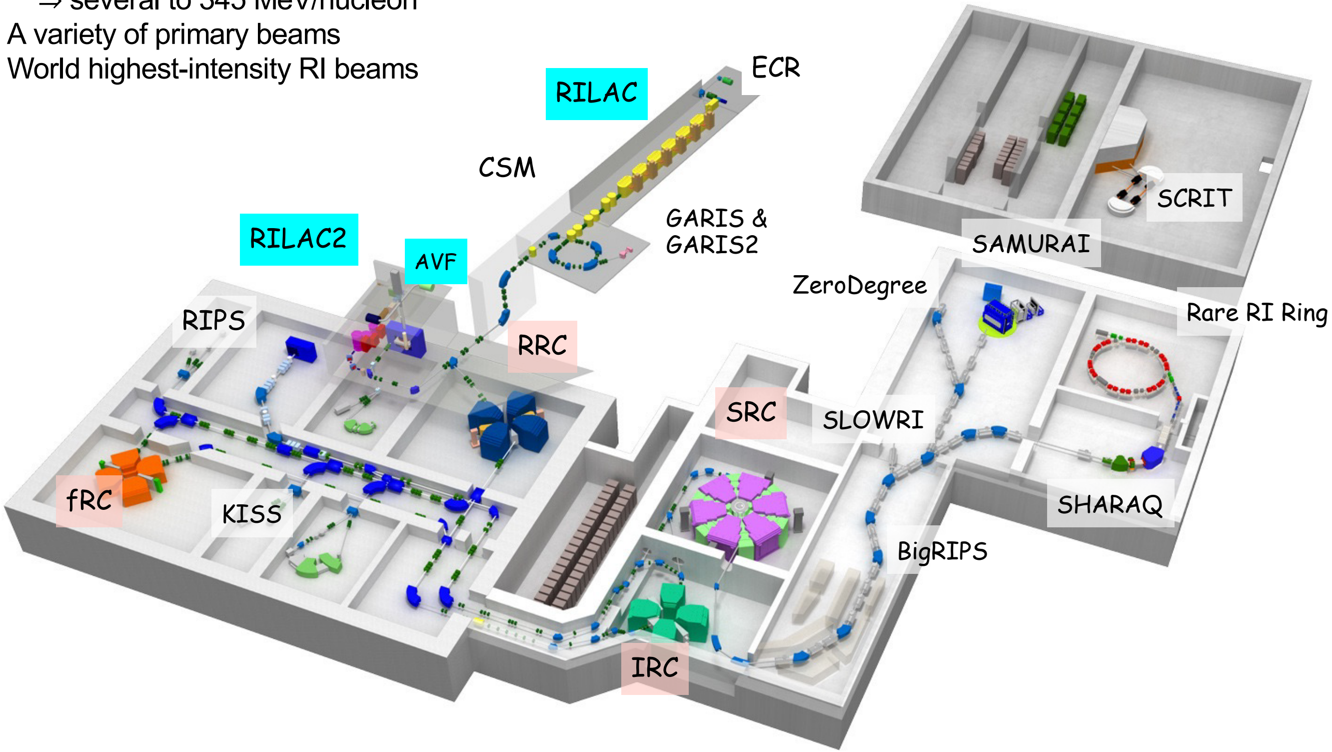
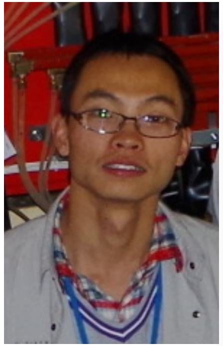
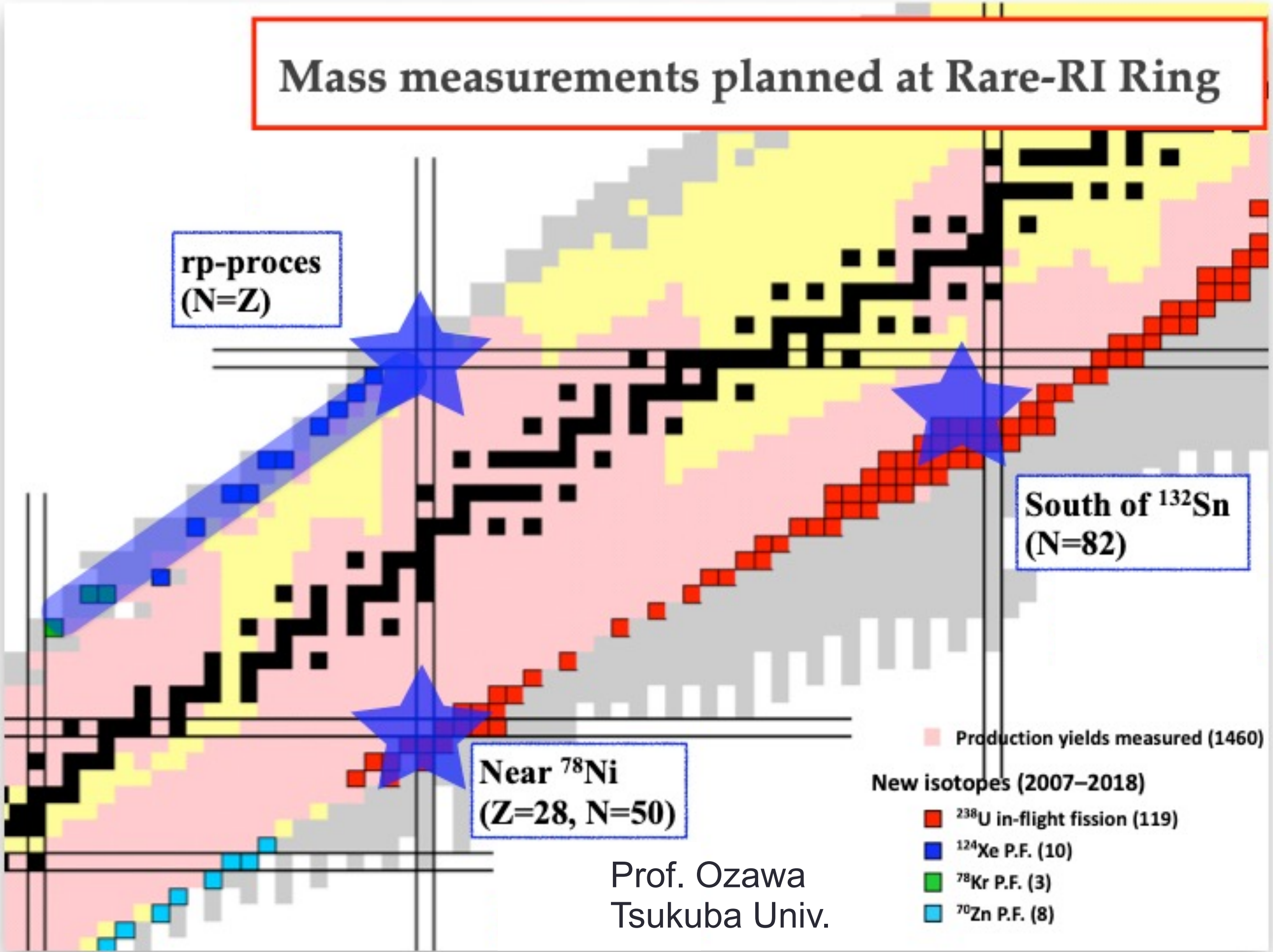


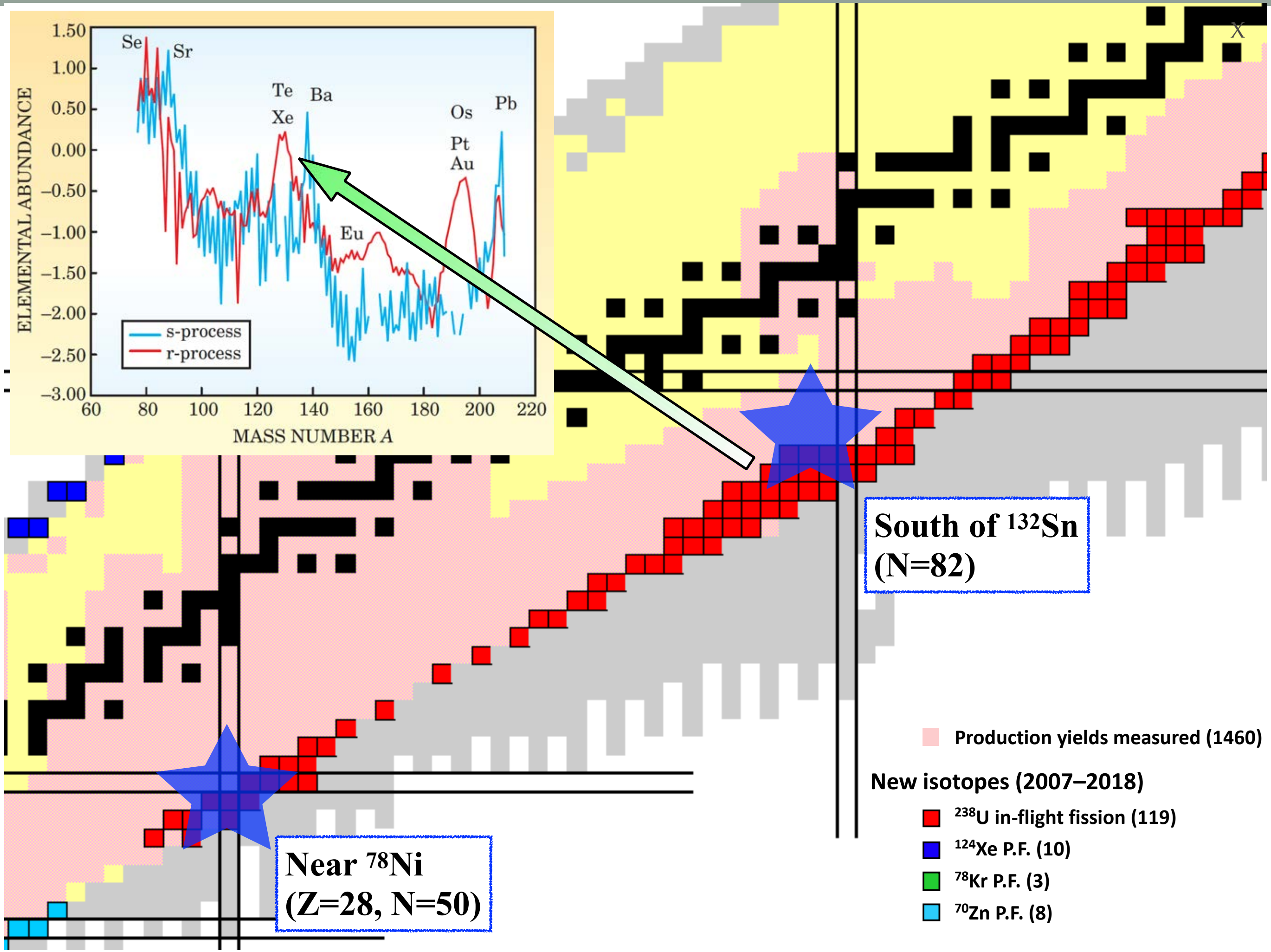


Z. Ge (IMP)



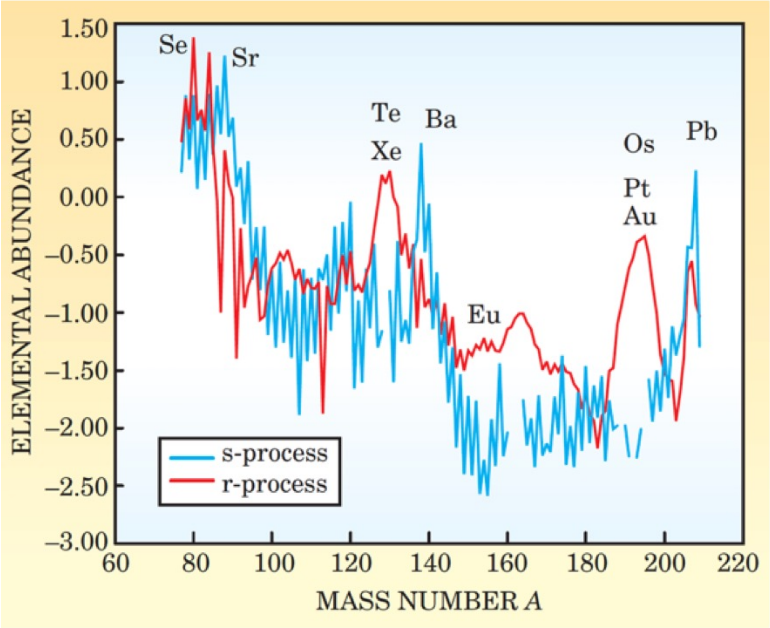
Prof. Ozawa
Tsukuba Univ.

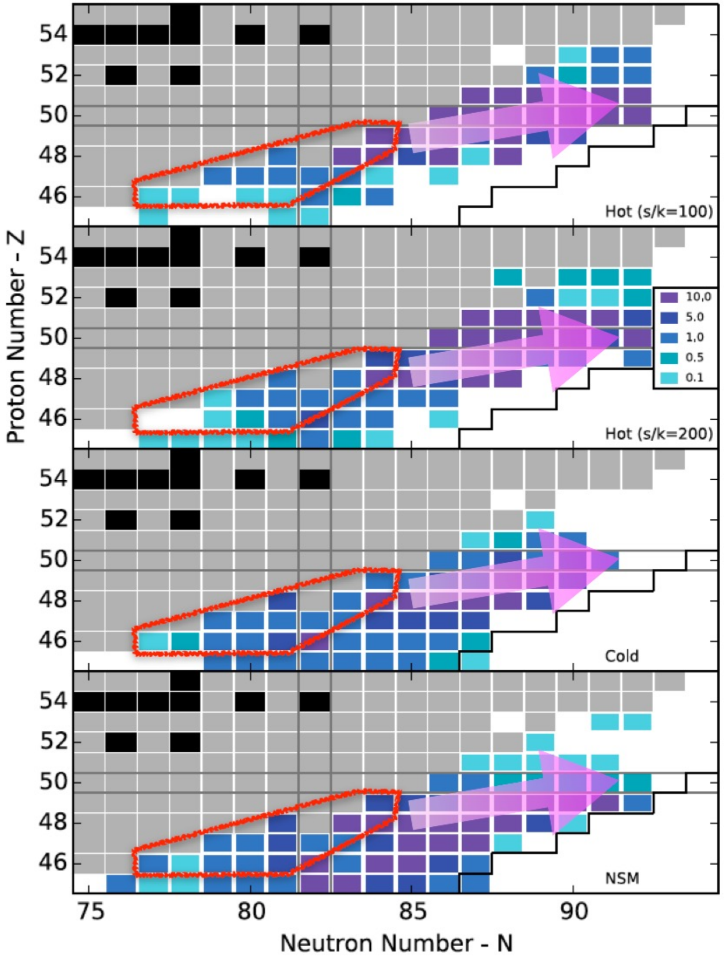
Hongfu Li
PhD Riken/IMP



ELEMENTAL ABUNDANCE
MASS NUMBER A
Se
Sr
Te
Xe
Ba
Os
Pt
Au
Pb
Eu
s-process
r-process
South of 132Sn (N=82)
Near 78Ni (Z=28, N=50)
Production yields measured (1460)
New isotopes (2007–2018)
238U in-flight fission (119)
124Xe P.F. (10)
78Kr P.F. (3)
70Zn P.F. (8)

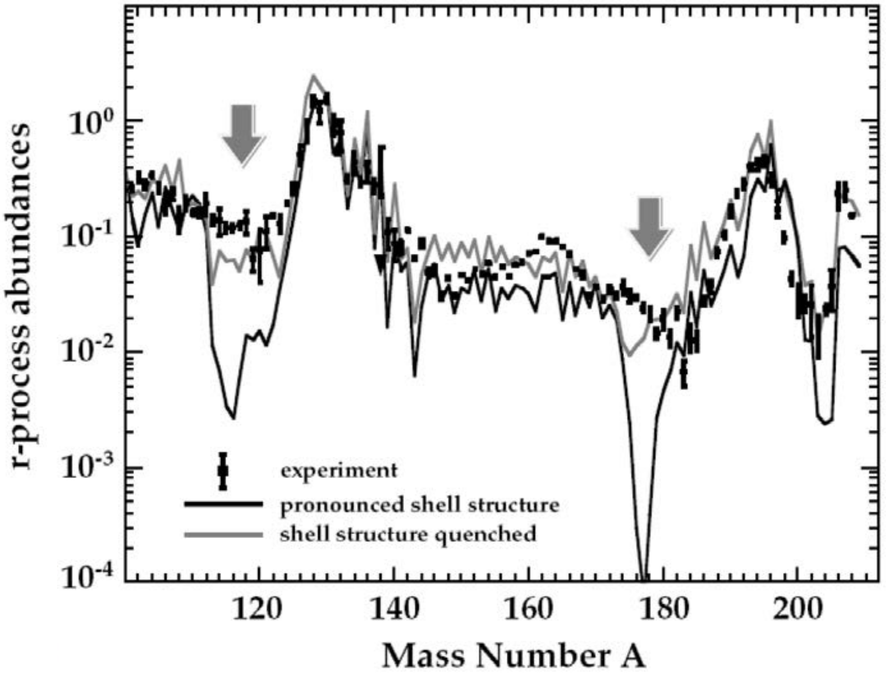
Different Astrophysical conditions



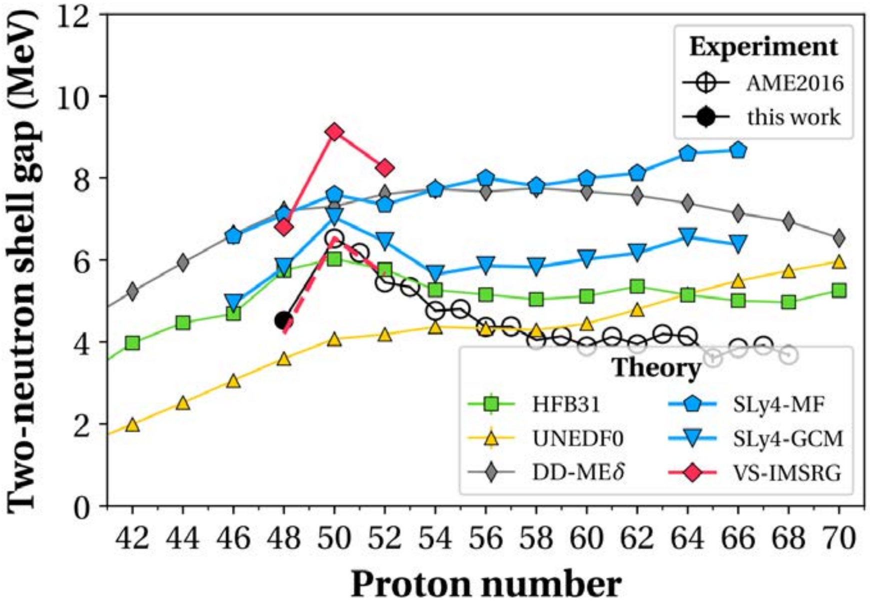


M. Mumpower et al, 2015

Shell quenching at N=82 & Z<50?



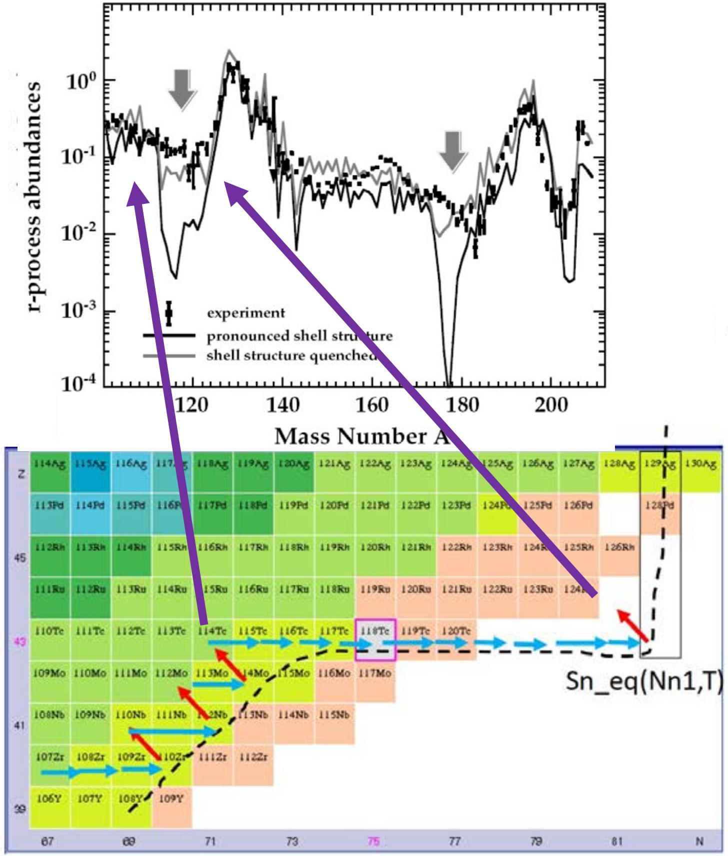
Pearson et al. Phys. Lett. B 387, 455 (1996).

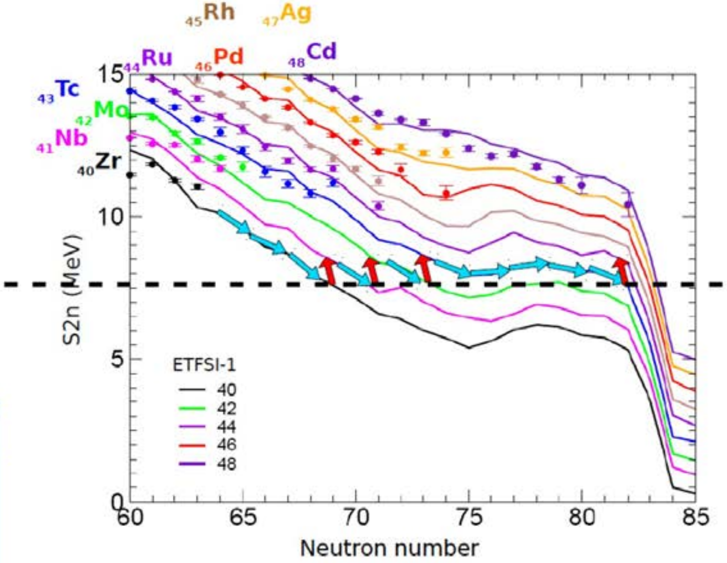


Mass measurement across N=82 132Cd @ISOLDE/CERN

Manea et al., Phys. Rev. Lett. 124, 092502 (2020).

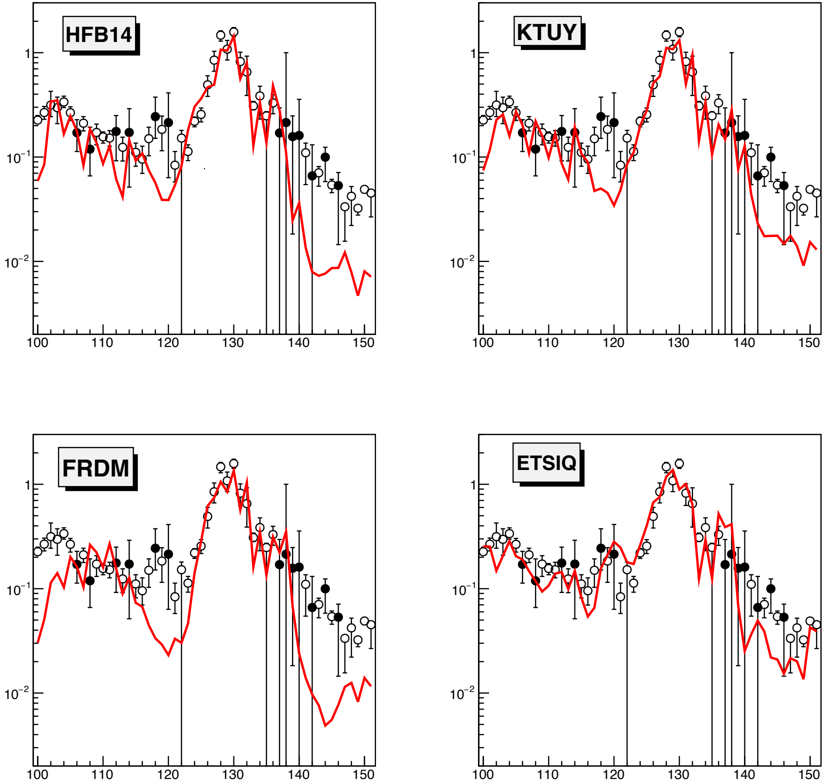
Deformation below Z=50?

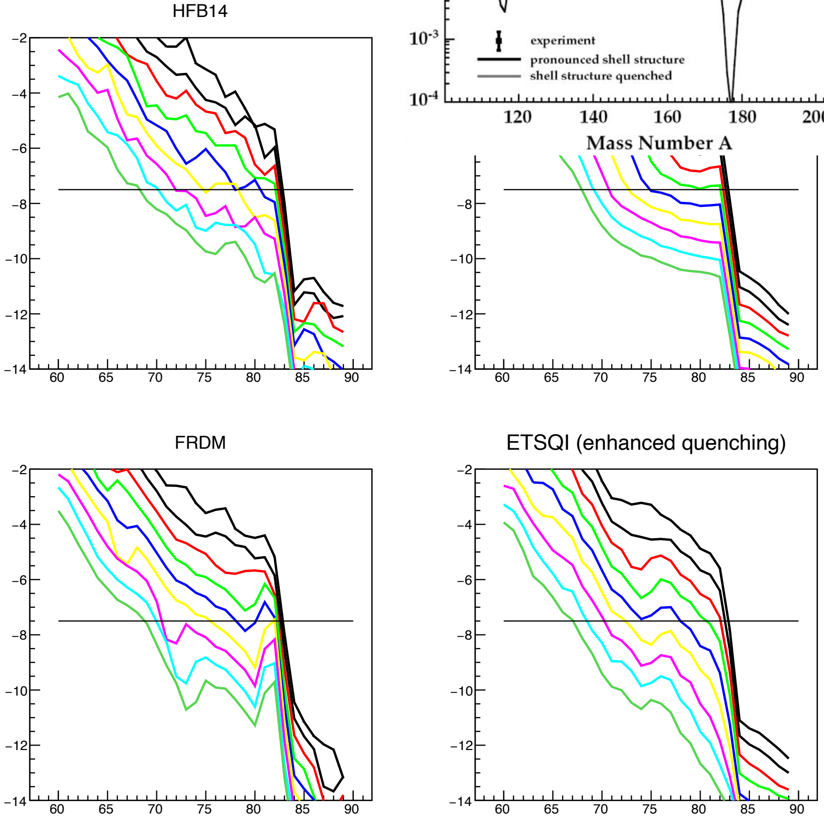


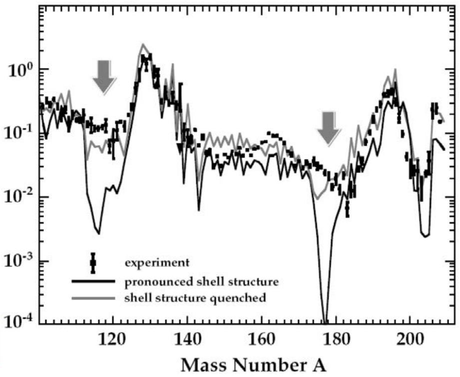


Deformation below Z=50?

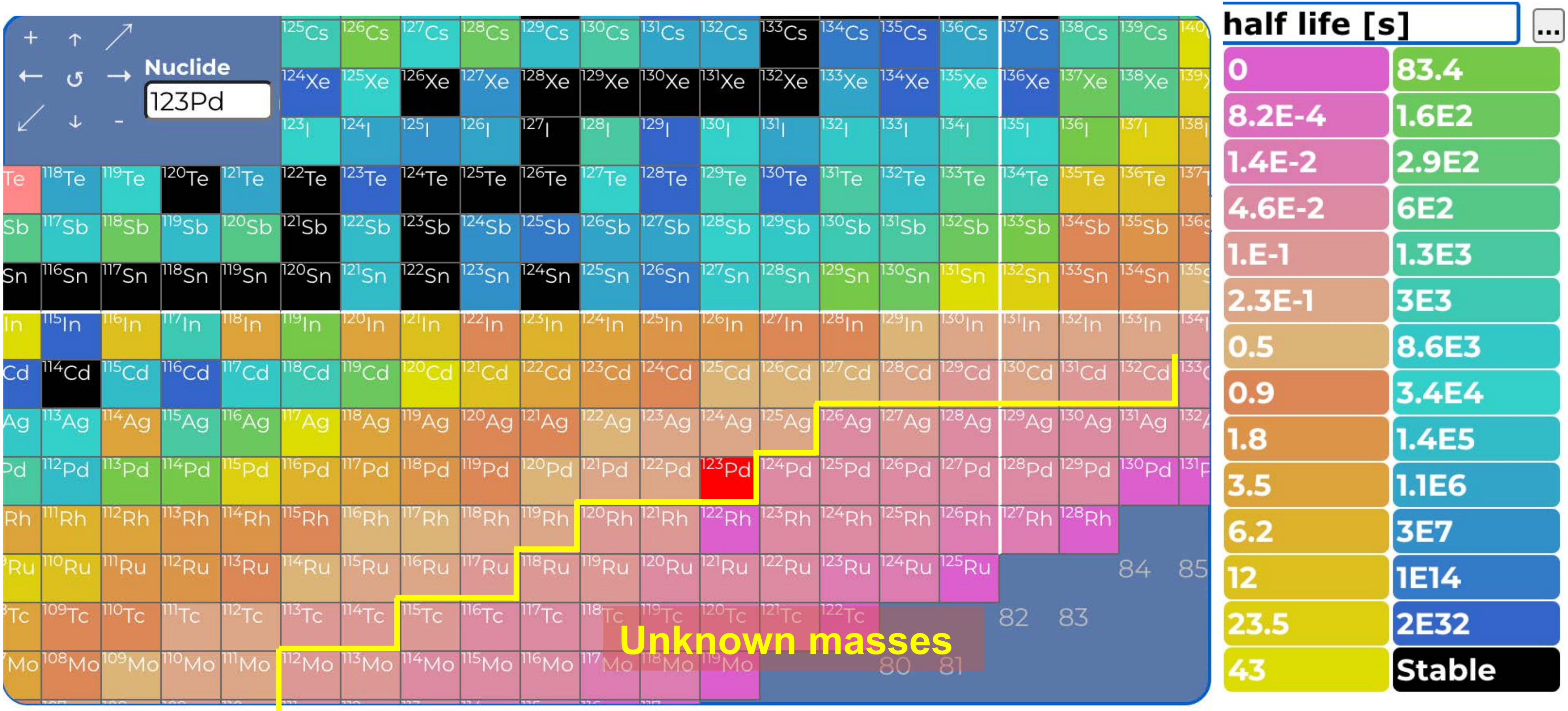
<

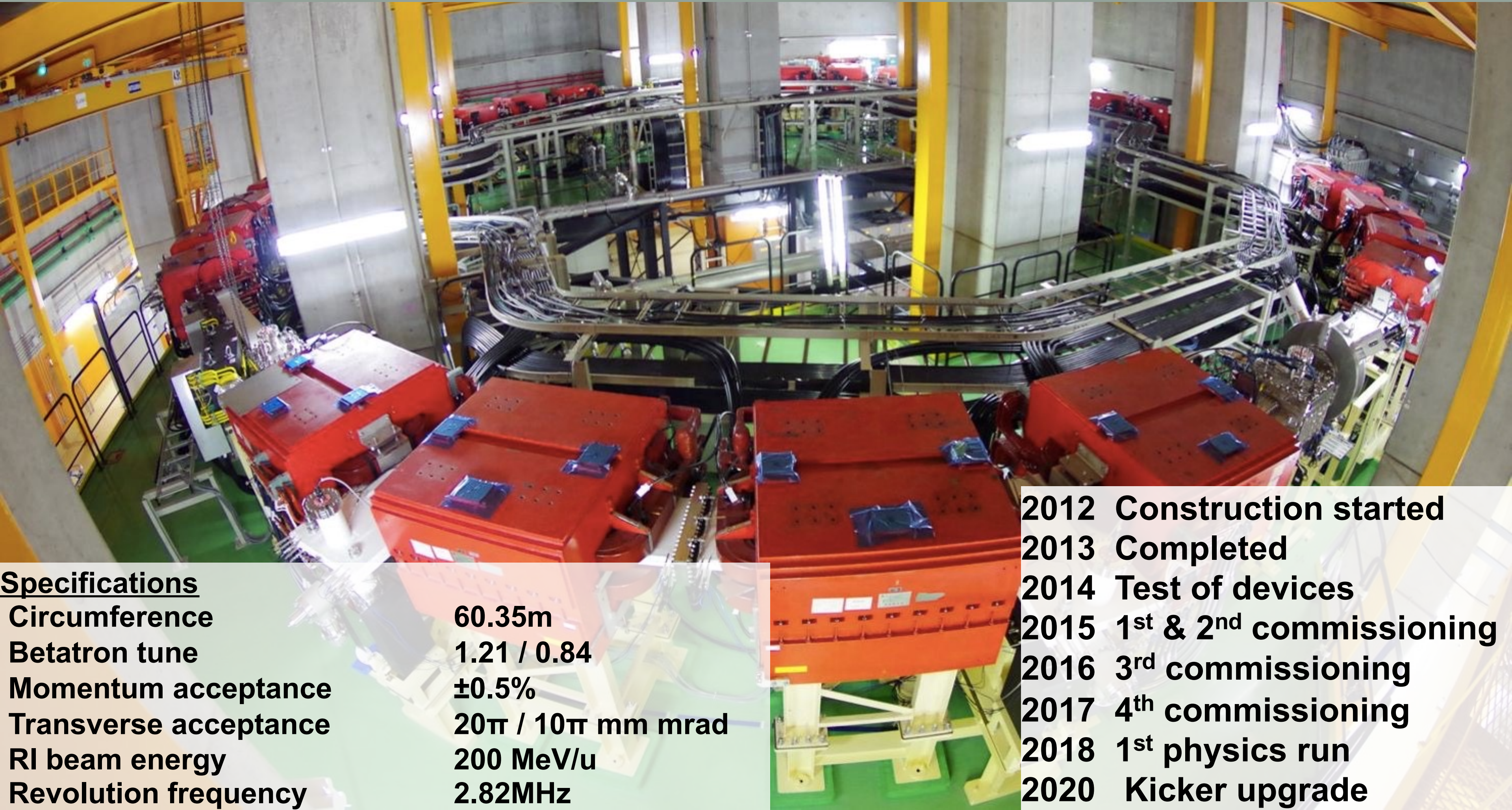






RI with short half-lives and low production yield





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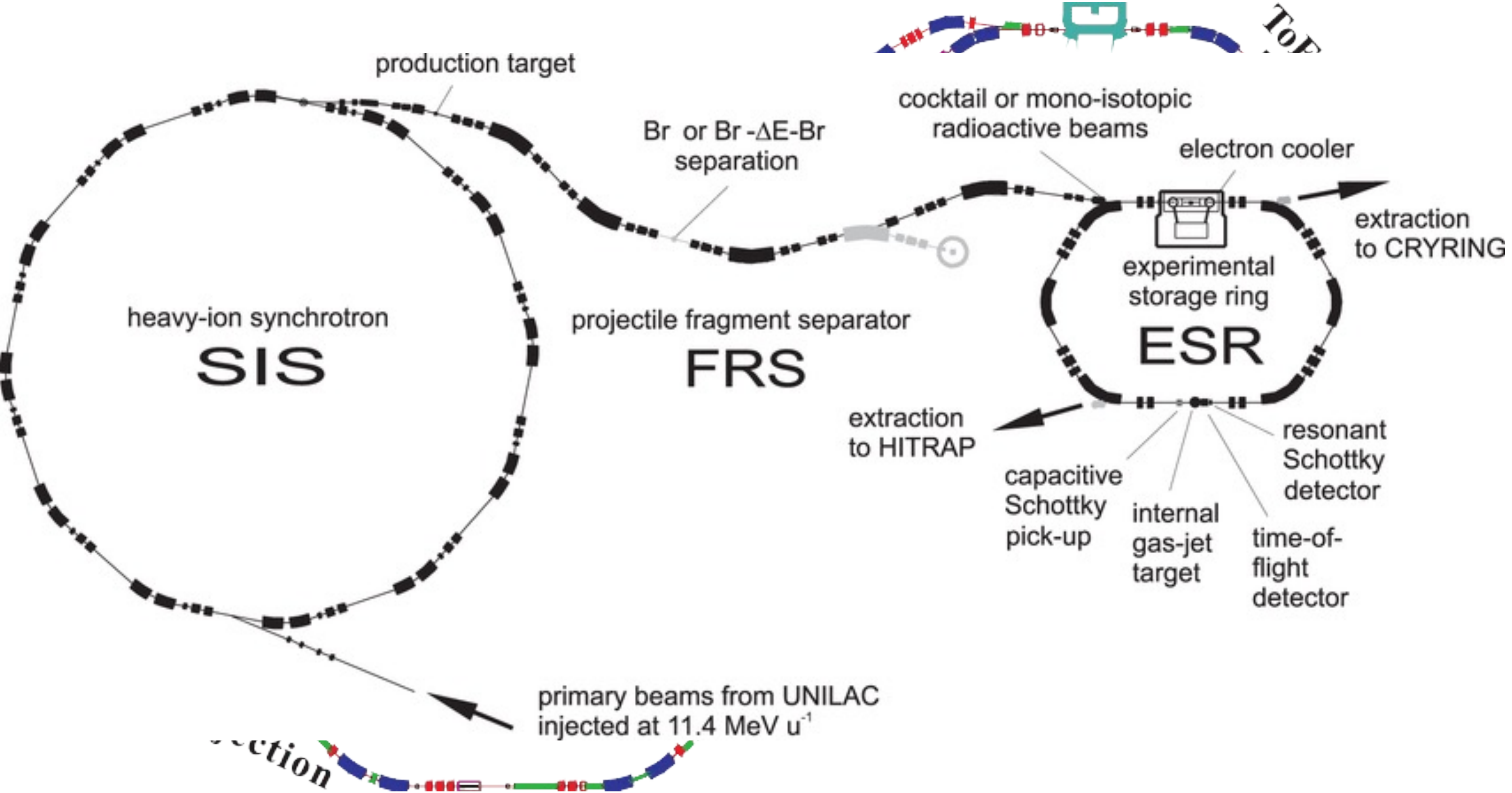
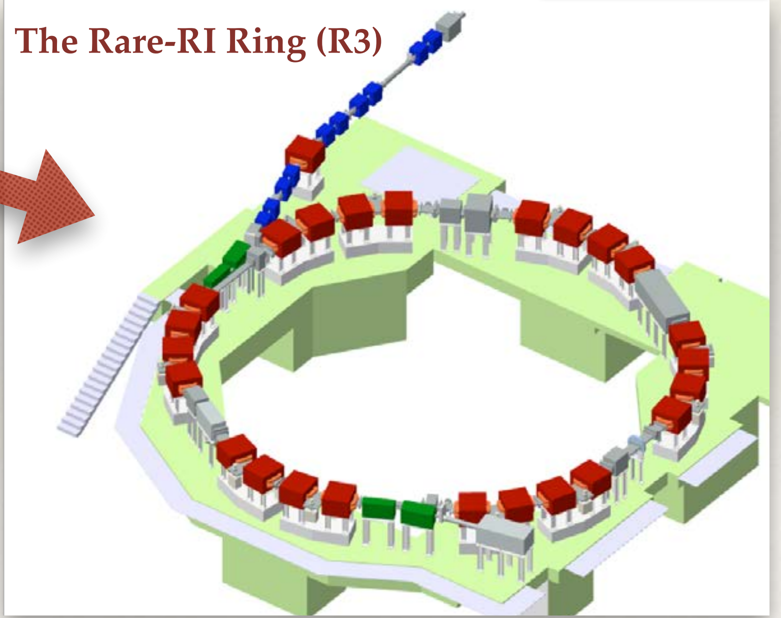


production target
Br or Br -ΔE-Br
separation
cocktail or mono-isotopic
radioactive beams
electron cooler
extraction
to CRYRING
experimental
storage ring
ESR
heavy-ion synchrotron
SIS
projectile fragment separator
FRS
extraction
to HITRAP
resonant
Schottky
detector
capacitive
Schottky
pick-up
internal
gas-jet
target
time-of-
flight
detector
primary beams from UNILAC
injected at 11.4 MeV u^{-1}

Critical Mismatch!!

DC beam vs. pulsed beam

How to solve?



DC

AC

Phys. Scr. **T166** (2015) 014039

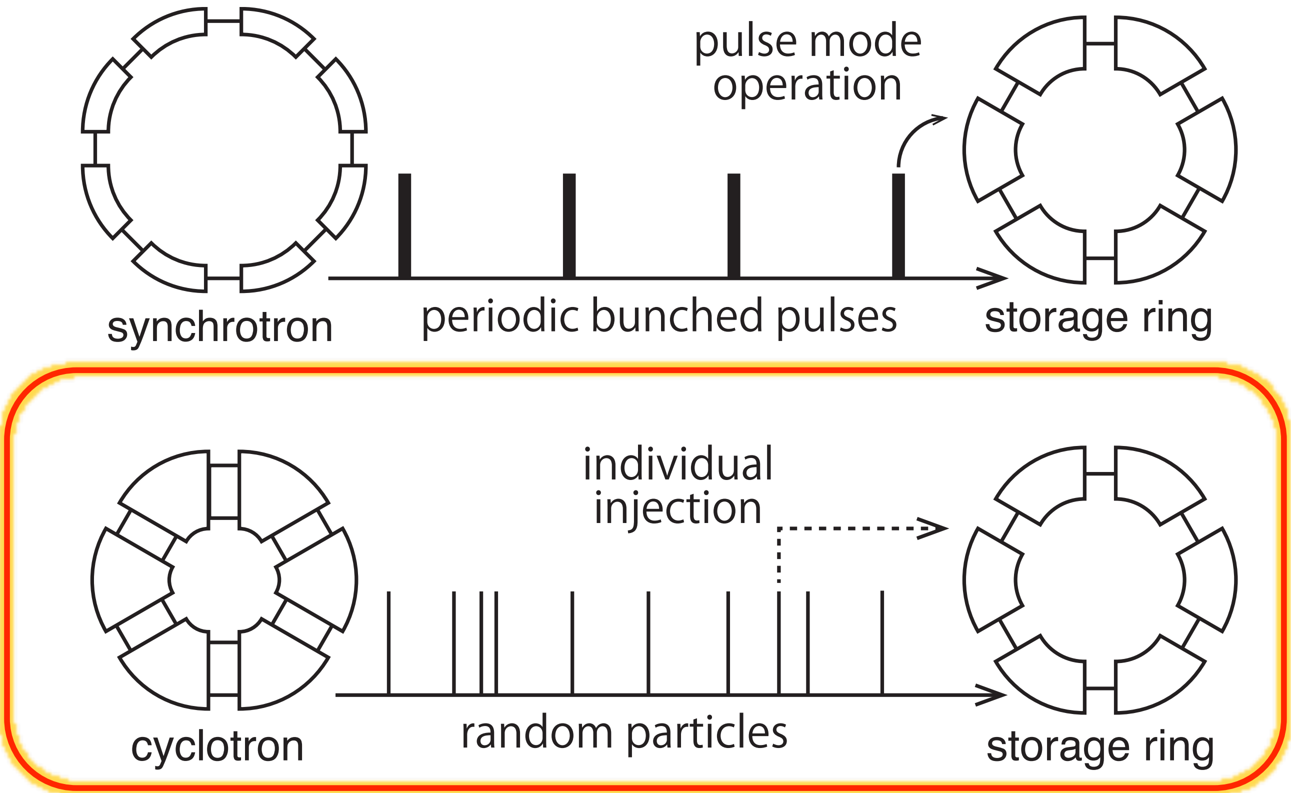
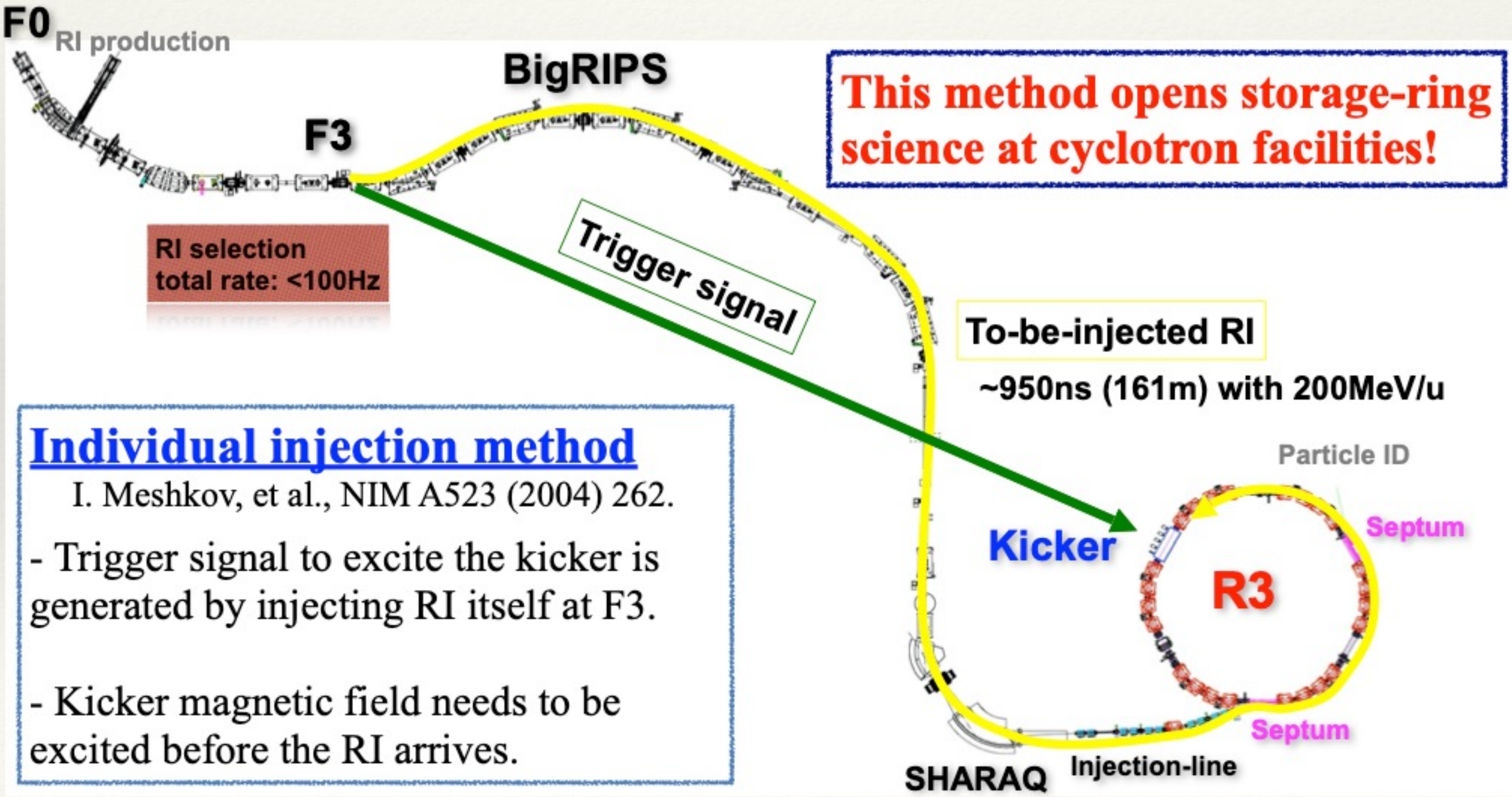


Figure 1. Schematic drawing of the beam structures of the synchrotron- and cyclotron-based storage ring.

Nucleus of interest itself triggers its injection to the ring!



This method opens storage-ring science at cyclotron facilities!

Individual injection method

I. Meshkov, et al., NIM A523 (2004) 262.

- Trigger signal to excite the kicker is generated by injecting RI itself at F3.

- Kicker magnetic field needs to be excited before the RI arrives.

Enhancement of particle selection for R3

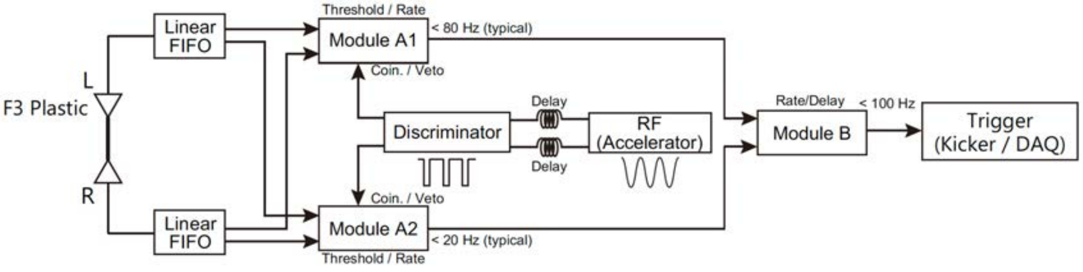
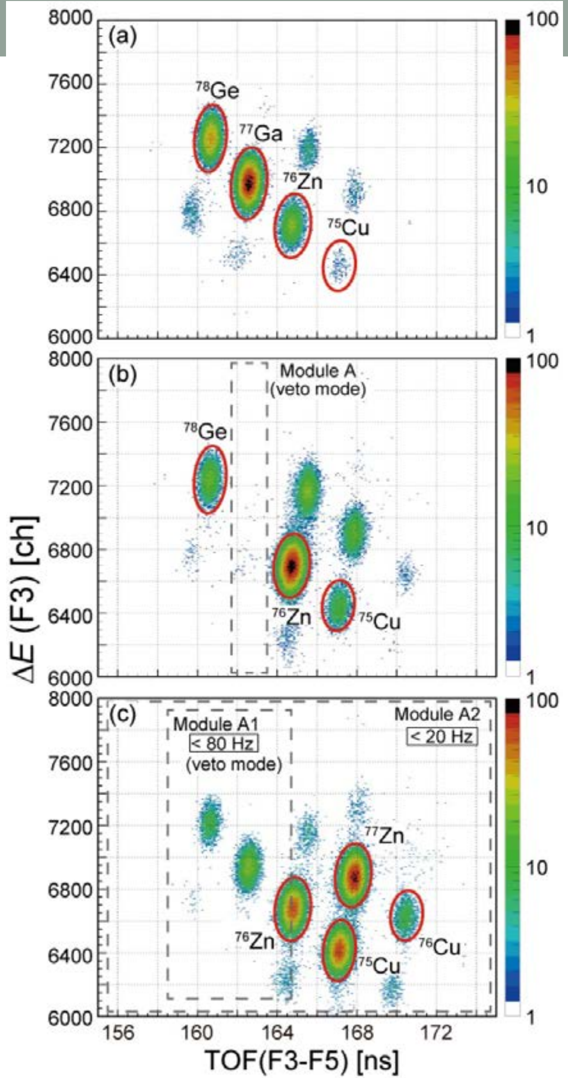
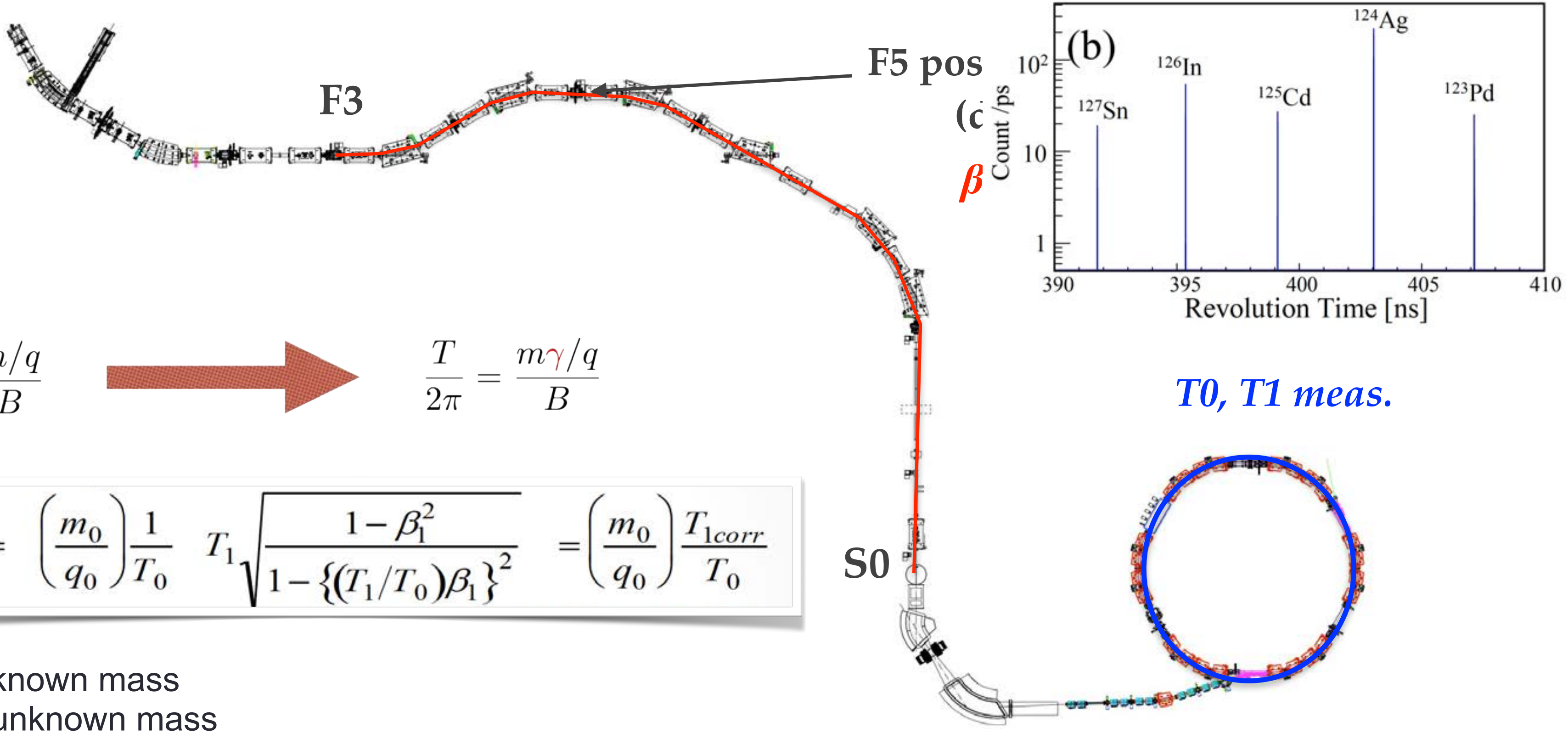


Fig. 1. Conceptual circuit diagram for particle selection and abundance tuning. Frequency of the output signal is adjustable.



Y. Abe et al., RIKEN Acc. Prog. Rep. 52 (2019)

Mass measurement principle



$$\frac{T}{2\pi} = \frac{m/q}{B} \quad \Rightarrow \quad \frac{T}{2\pi} = \frac{m\gamma/q}{B}$$

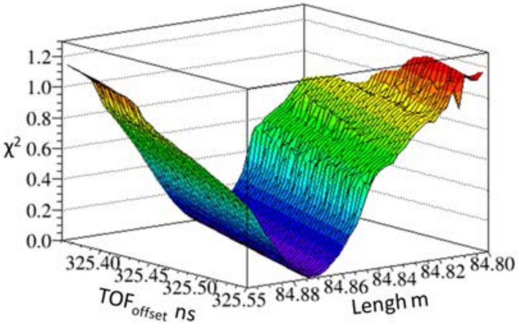
$$\frac{m_1}{q_1} = \left(\frac{m_0}{q_0}\right)\frac{1}{T_0}\, T_1\sqrt{\frac{1-\beta_1^2}{1-\{(T_1/T_0)\beta_1\}^2}} = \left(\frac{m_0}{q_0}\right)\frac{T_{1corr}}{T_0}$$

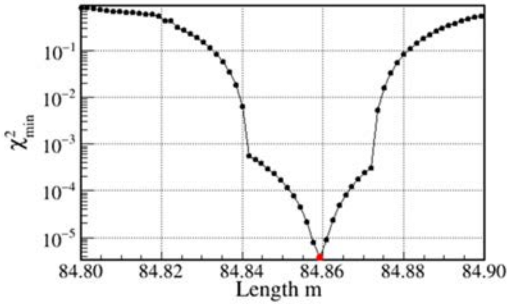
m_0 is known mass
m_1 is unknown mass

Beta determination

$$\frac{m_1}{q_1} = \left(\frac{m_0}{q_0}\right)\frac{1}{T_0}\; T_1\sqrt{\frac{1-\beta_1^2}{1-\{(T_1/T_0)\beta_1\}^2}}$$

$$\beta = \frac{Length_{3S0}}{(TOF_{3S0} + TOF_{offset})\, c}$$





^{127}Sn and ^{124}Ag were used to determine the two parameters
Search ranges: Length = [84.8m, 84.9m], TOFoffset = [325.35ns, 325.55ns]

$$C = \beta T_{rev} c$$

$$B\rho = \frac{m}{q}\gamma\beta c = B\rho_0\left(\frac{C}{C_0}\right)^{\gamma_t^2}$$

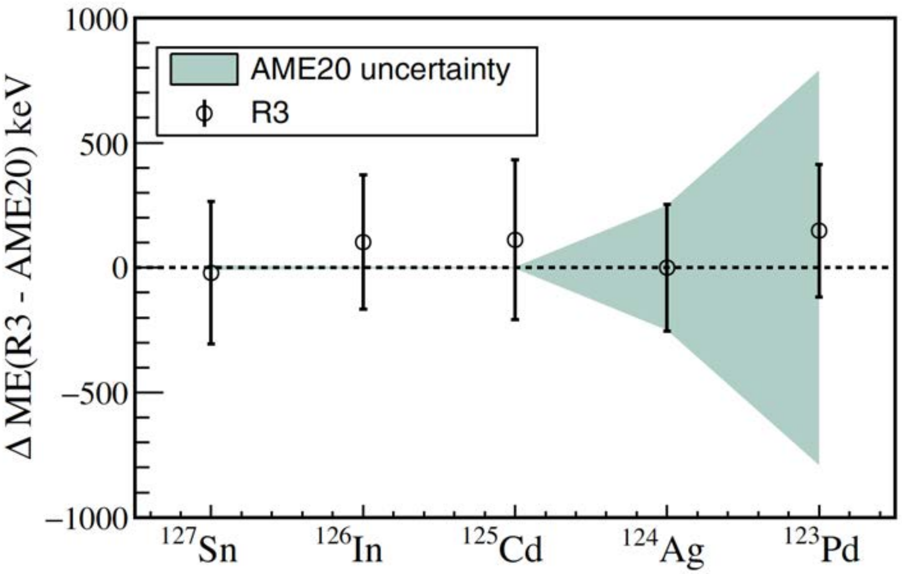
Get $B\rho_0$ & γ_t
C_0 = 60.3507 m

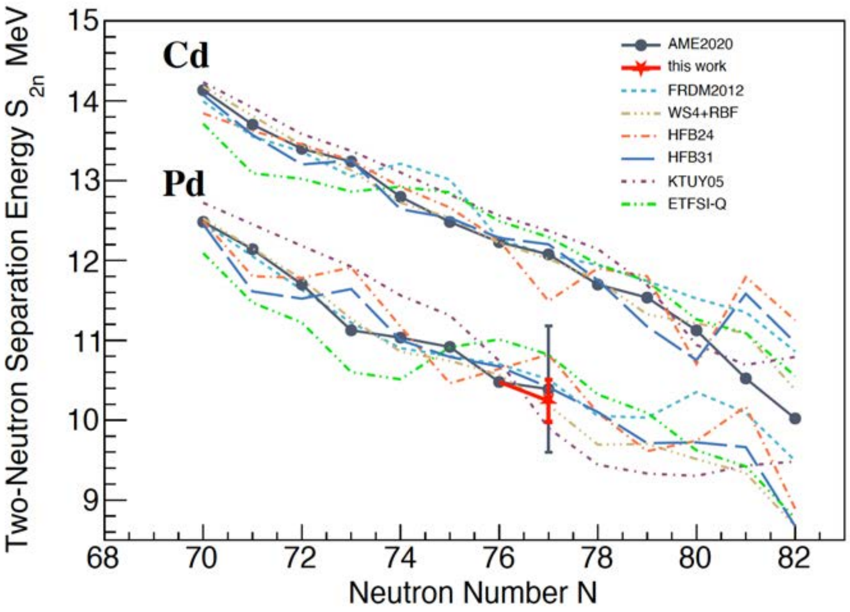
$$\frac{m}{q} = \frac{B\rho}{\gamma\beta c}$$

$$\chi^2 = \frac{(m/q - m/q_{AME})^2}{\sigma^2 + \sigma_{AME}^2}$$

Length = 84.8592 m
TOFoffset = 325.47 ns

New R3 mass measurement result

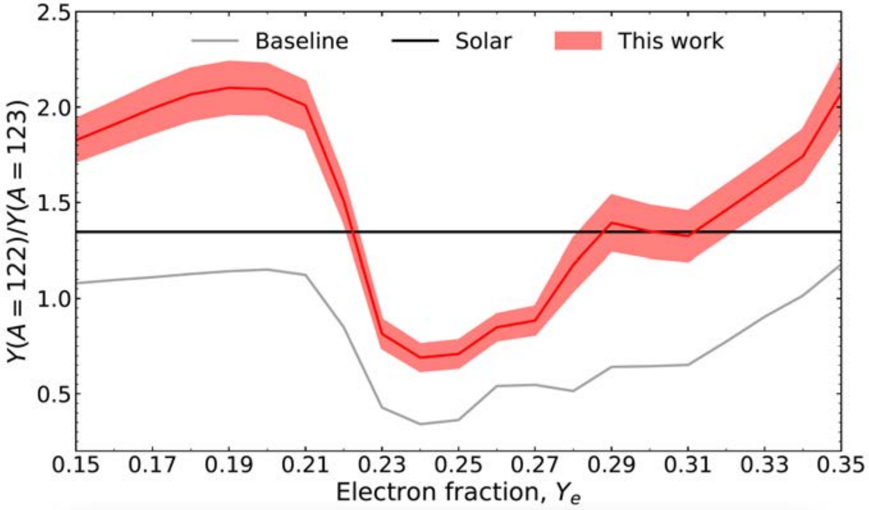


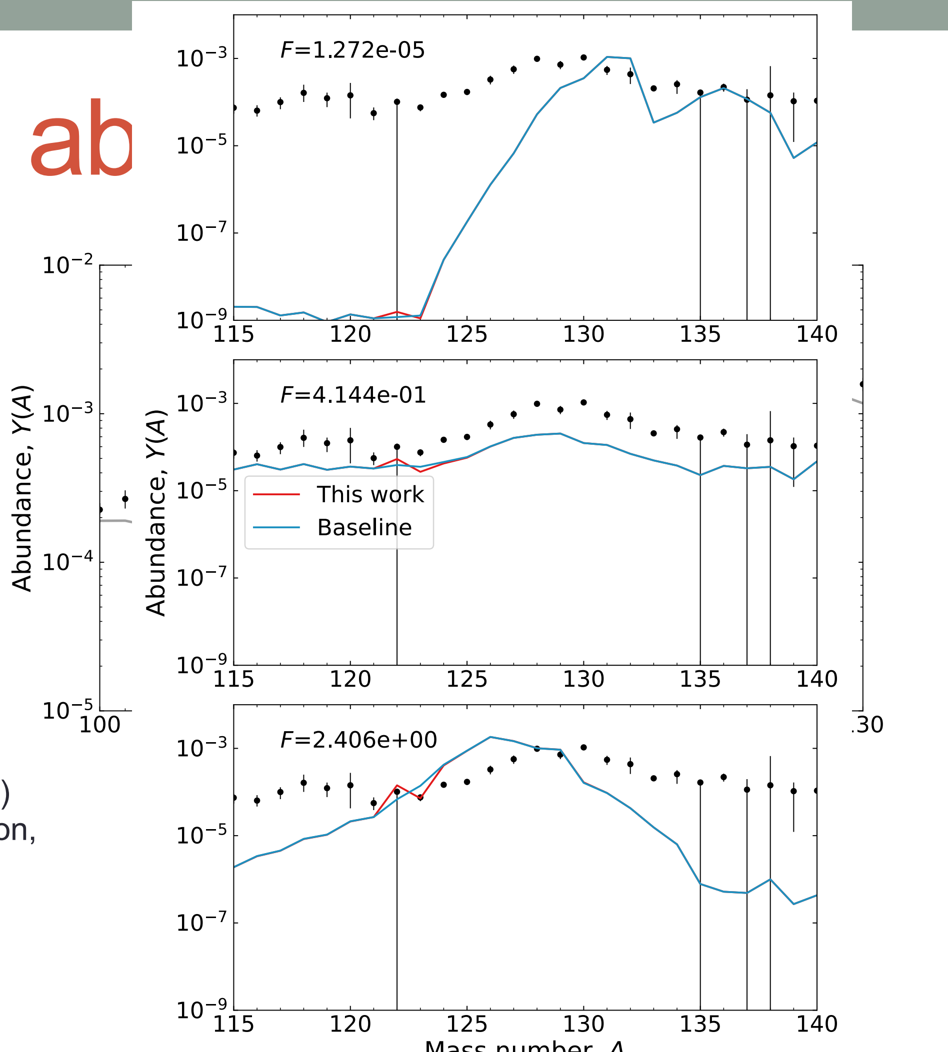


H.F. Li et al. PRL 2022 accepted

No evidence of large deformation below Z=50!!

Impact in r-process ab



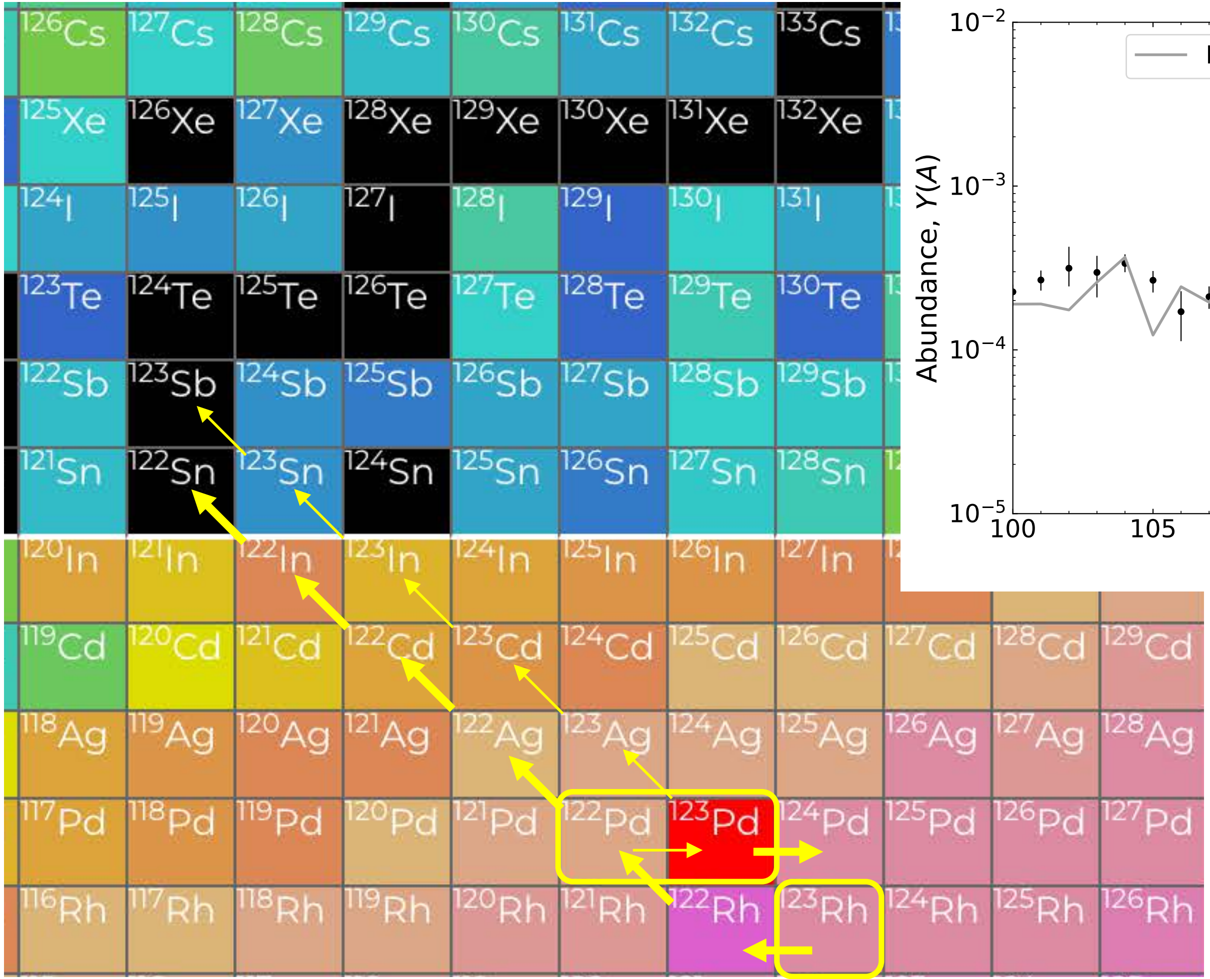


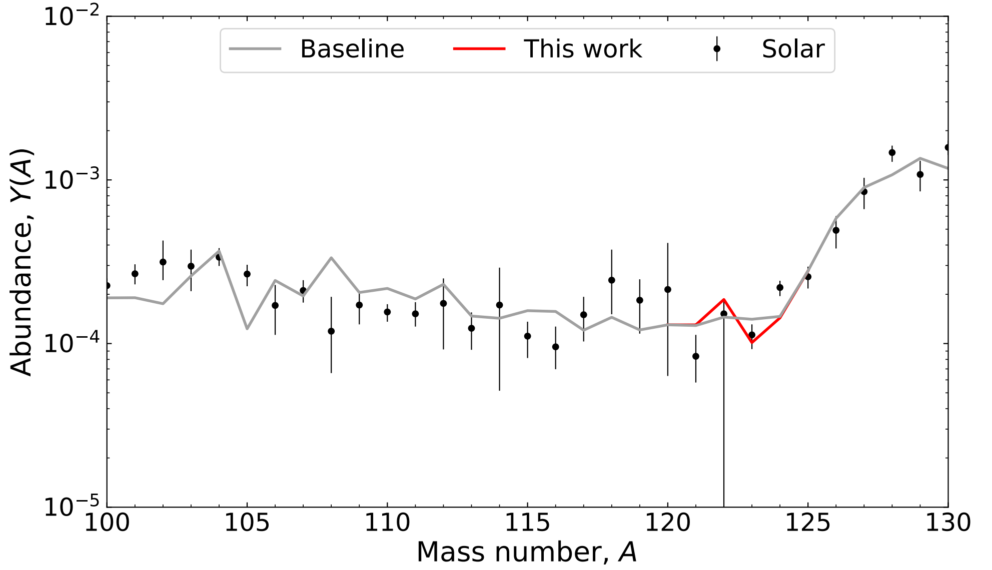
Portable Routines for Integrated nucleoSynthesis Modeling (PRISM) reaction network, neutron star merger condition; entropy 40kB/baryon, timescale 20ms, electron fraction Ye=0.15~0.35.

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:

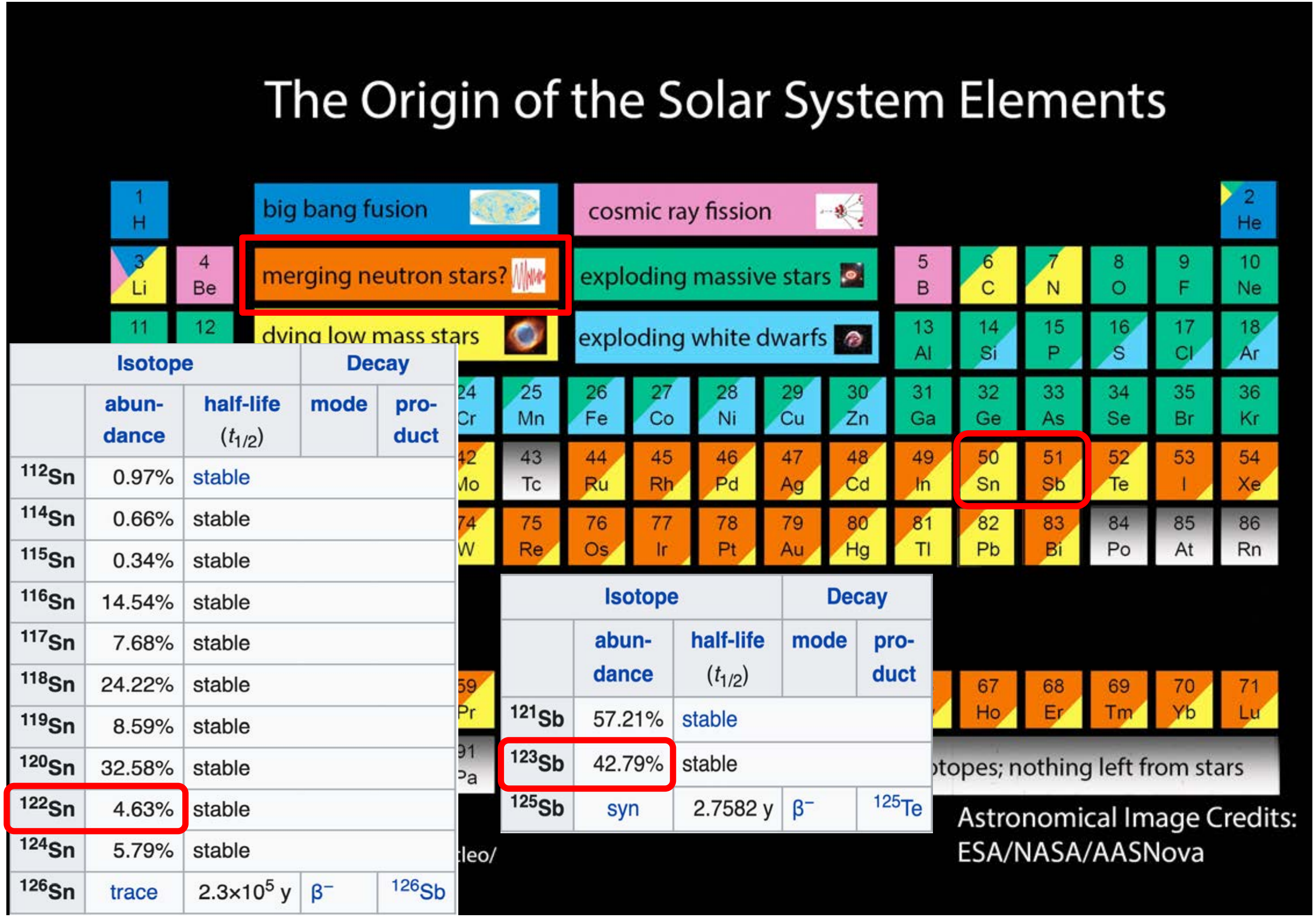
122Pd ↓ 2.6

123Pd ↑ 2.2

Probability β-delayed neutron emission

123Rh ↑

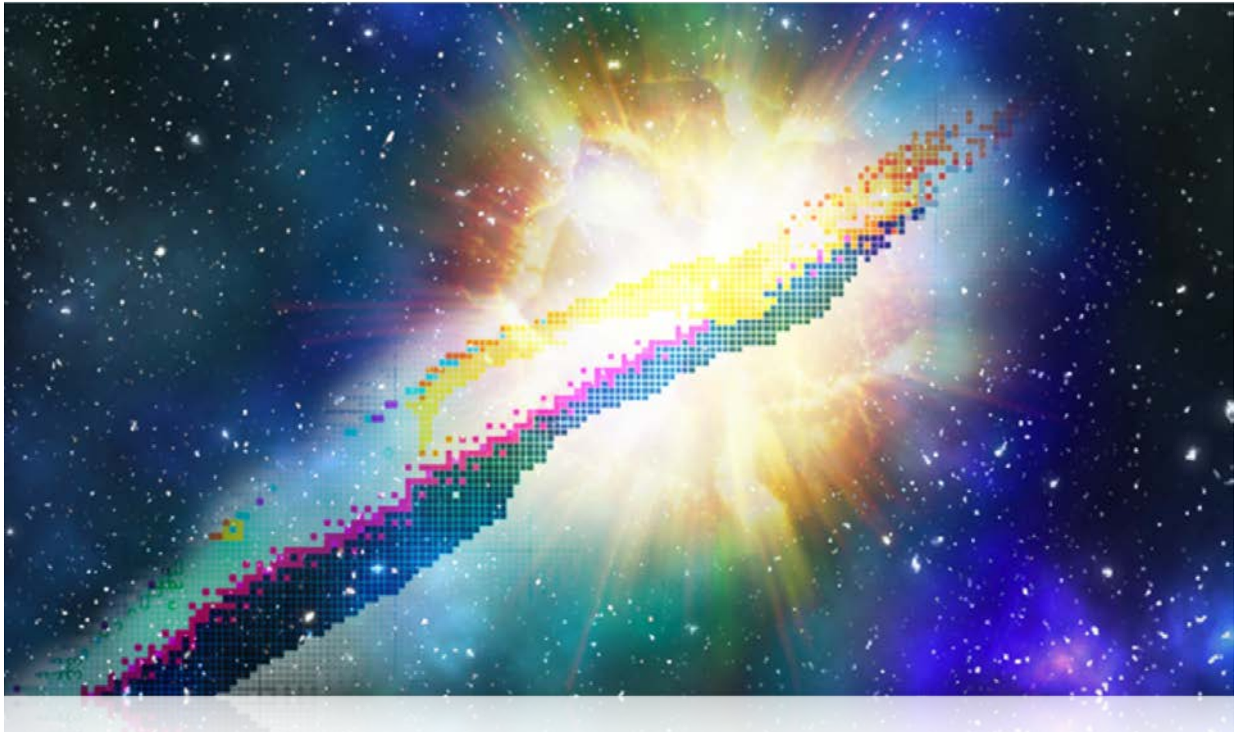
Mass difference FRDM ~500keV



Isotope		Decay		
	abun-dance	half-life ($t_{1/2}$)	mode	pro-duct
^{112}Sn	0.97%	stable		
^{114}Sn	0.66%	stable		
^{115}Sn	0.34%	stable		
^{116}Sn	14.54%	stable		
^{117}Sn	7.68%	stable		
^{118}Sn	24.22%	stable		
^{119}Sn	8.59%	stable		
^{120}Sn	32.58%	stable		
^{122}Sn	4.63%	stable		
^{124}Sn	5.79%	stable		
^{126}Sn	trace	2.3×10^5 y	β^-	^{126}Sb

Isotope		Decay		
	abun-dance	half-life ($t_{1/2}$)	mode	pro-duct
^{121}Sb	57.21%	stable		
^{123}Sb	42.79%	stable		
^{125}Sb	syn	2.7582 y	β^-	^{125}Te

Thank you!
ありがとうございます！



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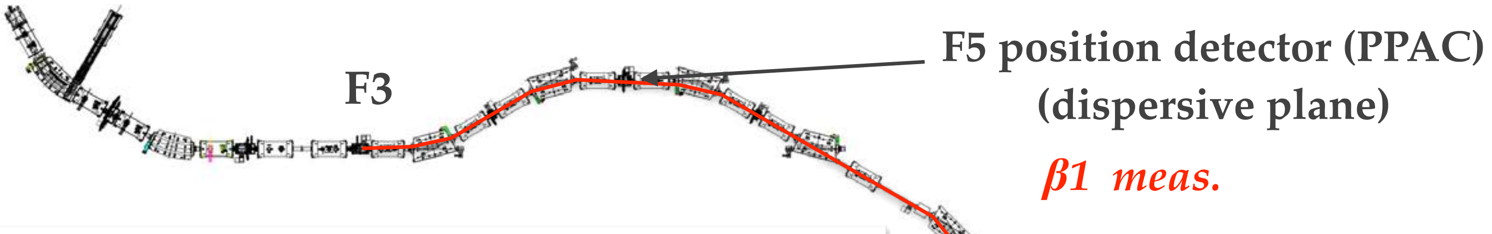
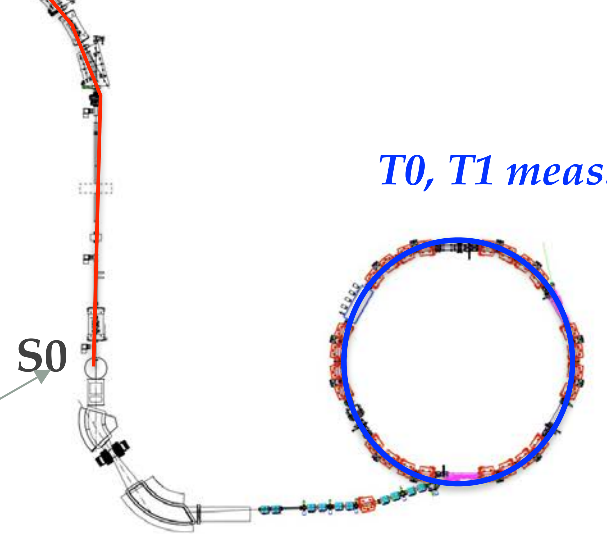
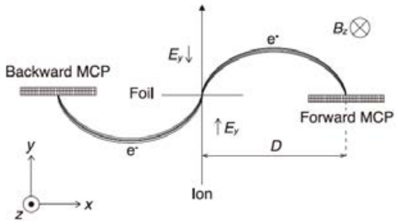
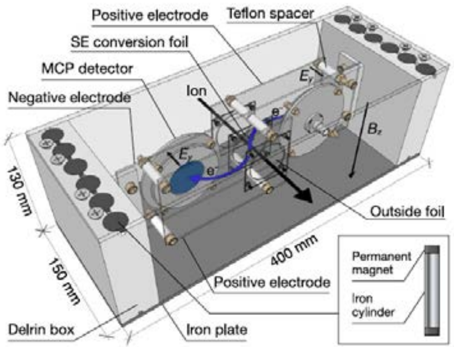
Challenge #2
Minimizing energy loss on beamline

$$\frac{m_1}{q_1} = \left(\frac{m_0}{q_0}\right)\frac{1}{T_0}\; T_1\sqrt{\frac{1-\beta_1^2}{1-\{(T_1/T_0)\beta_1\}^2}} = \left(\frac{m_0}{q_0}\right)\frac{T_{1corr}}{T_0}$$



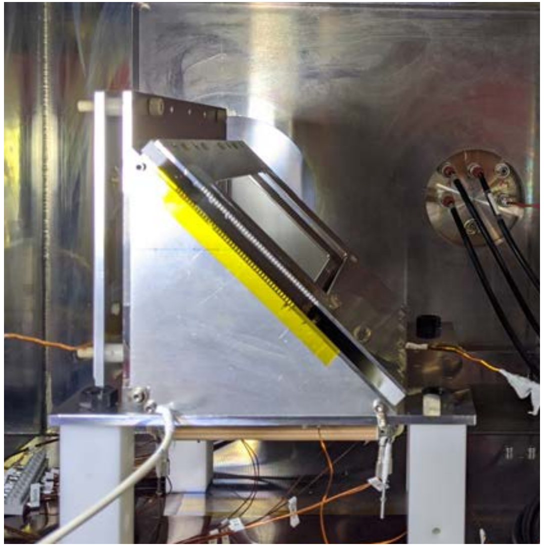


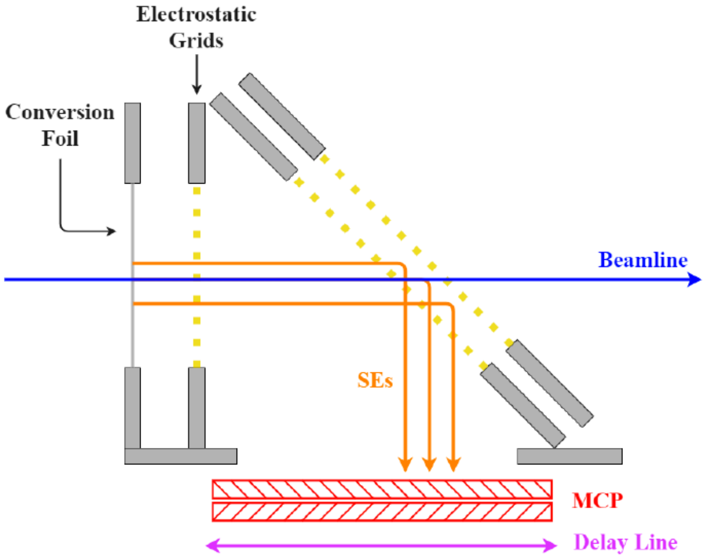
S. Suzuki, NIMA 965 (2020)

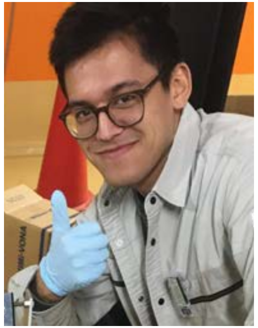
σ = 38ps, eff = 95%, $dE/E<10^{-5}$

Large area position-sensitive DL-E-MCP

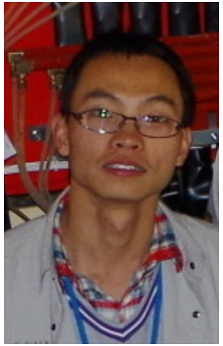
Thin foil → low energy loss







G. Hudson-Chang
Master (Surrey Uni.)

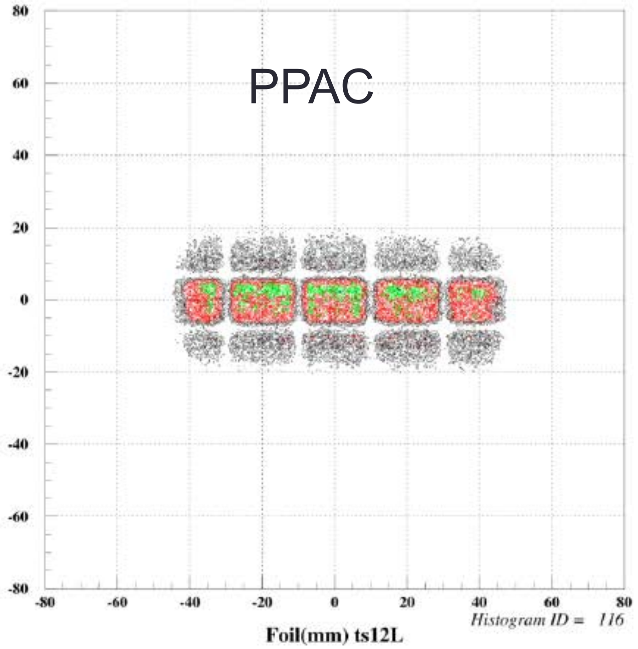


Z. Ge, PhD
(IMP/Riken)

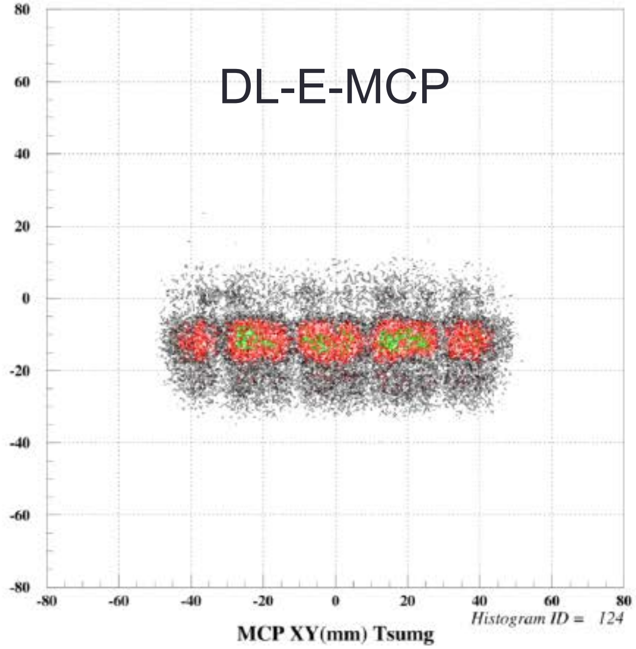
R. Crane
Master (Surrey Uni)

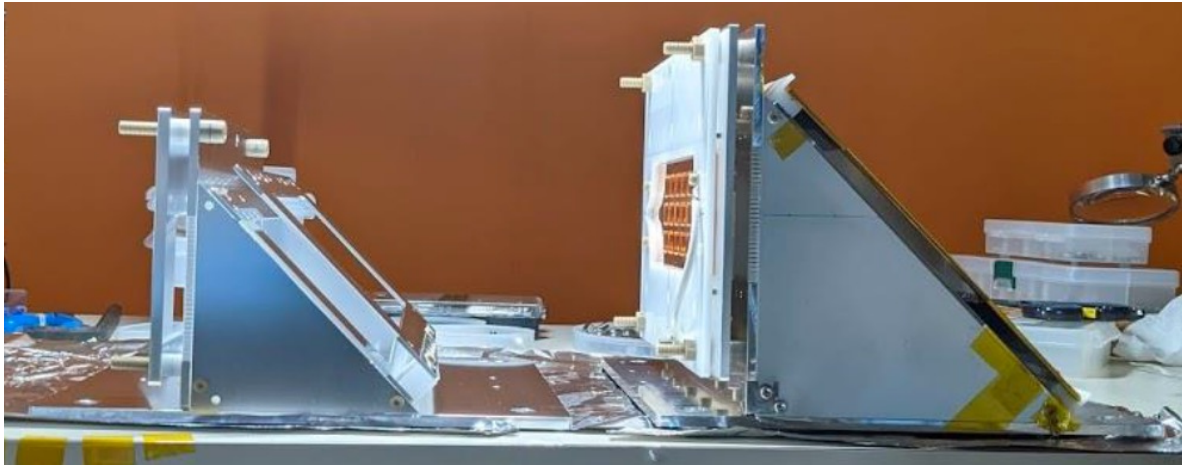
Comparison with PPAC resolution

Foil Image



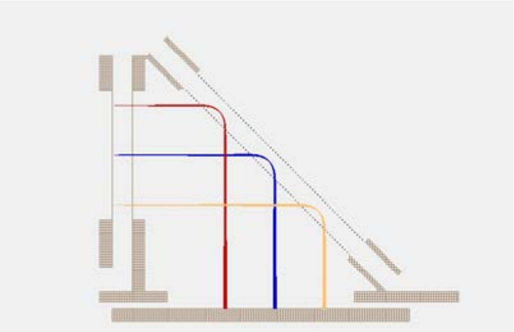
MCP Image

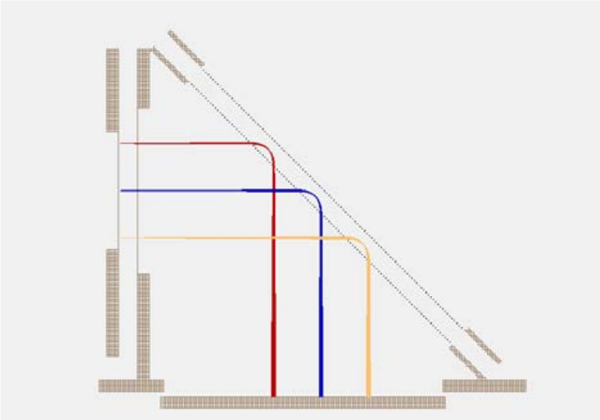


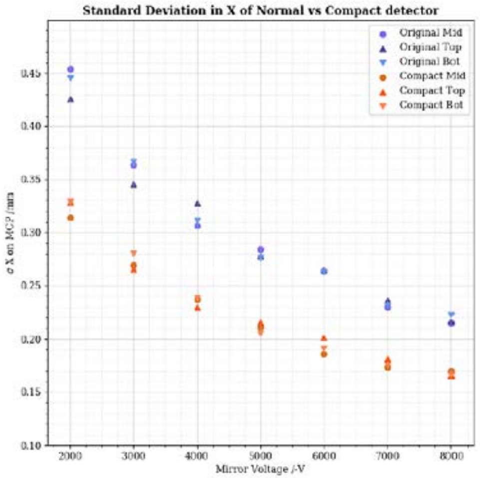


G. Hudson-Chang
Master (Riken/Surrey)

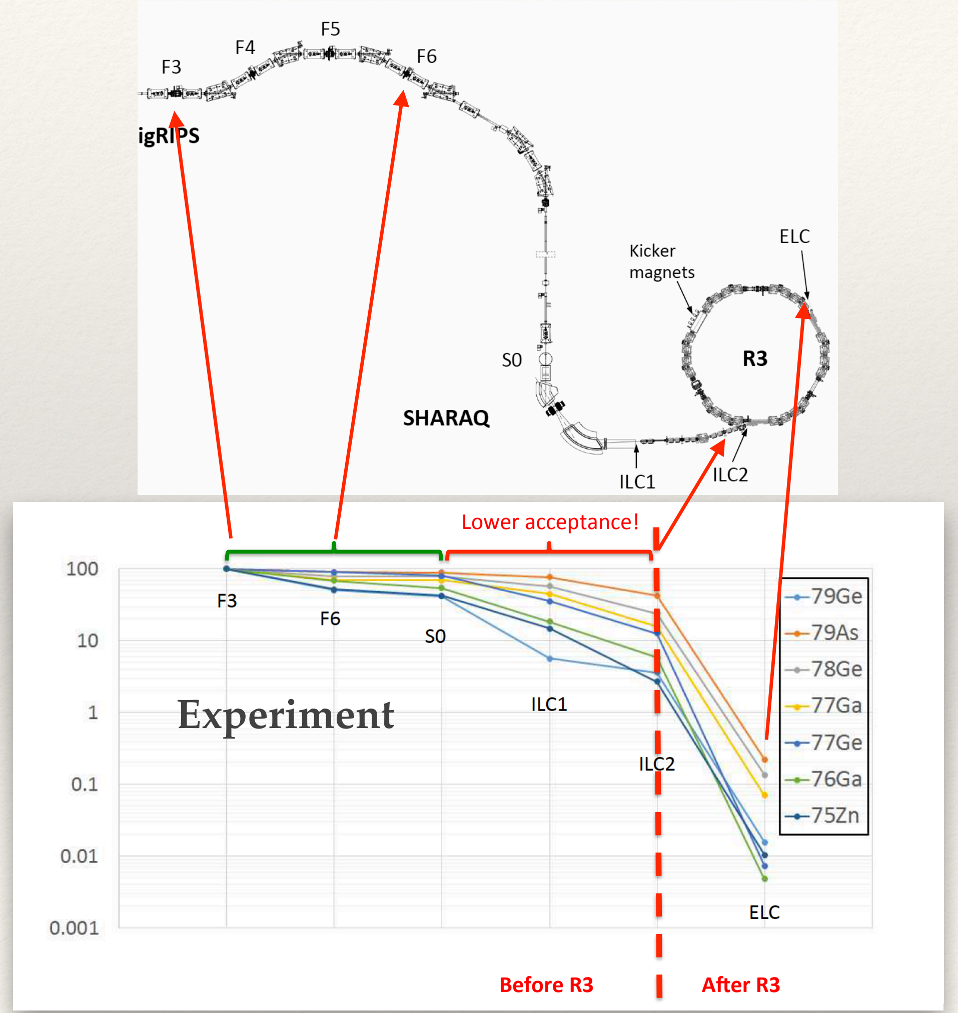
Compact

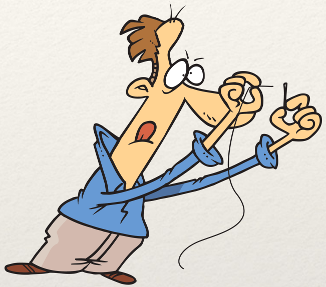


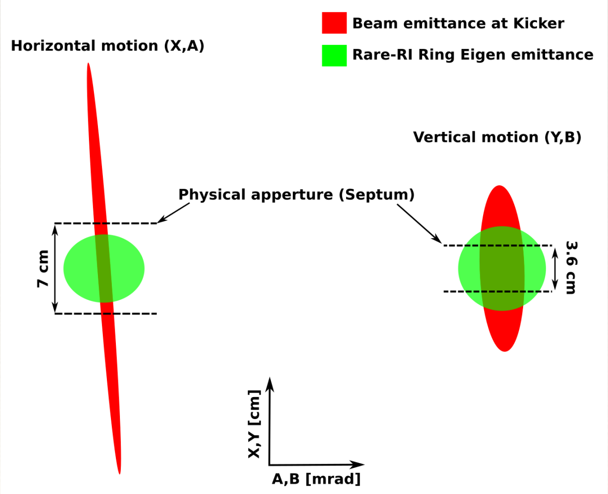




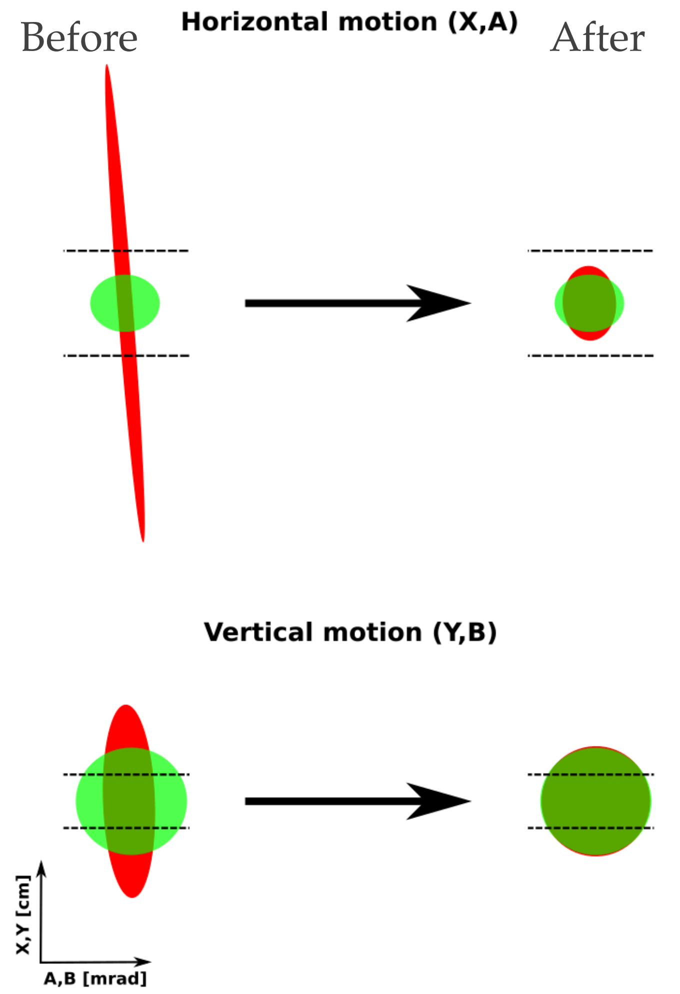
Challenge #3
Matching emittance at ring injection


F3
F4
F5
F6
igRIPS
Kicker magnets
ELC
SO
R3
SHARAQ
ILC1
ILC2
Lower acceptance!
100
10
1
0.1
0.01
0.001
F3
F6
SO
ILC1
ILC2
ELC
Experiment
79Ge
79As
78Ge
77Ga
77Ge
76Ga
75Zn
Before R3
After R3

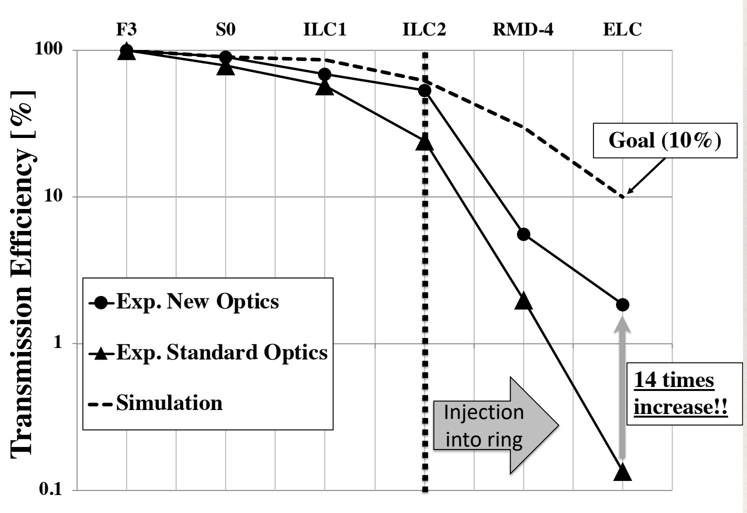



Beam emittance at Kicker
Rare-RI Ring Eigen emittance
Horizontal motion (X,A)
Vertical motion (Y,B)
Physical apperture (Septum)
7 cm
3.6 cm
X,Y [cm]
A,B [mrad]

Redesign the injection optics for Rare-RI Ring

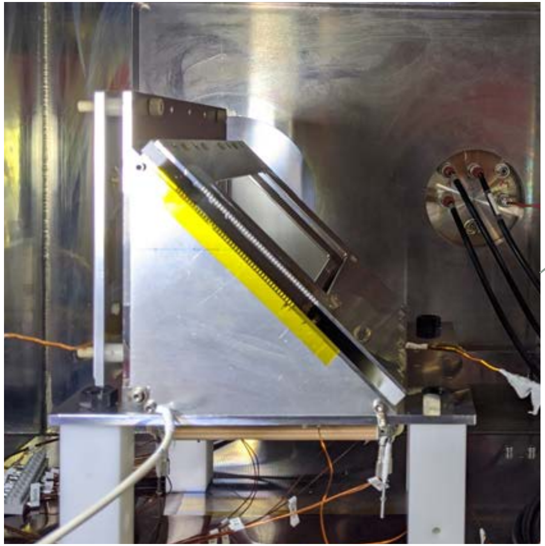


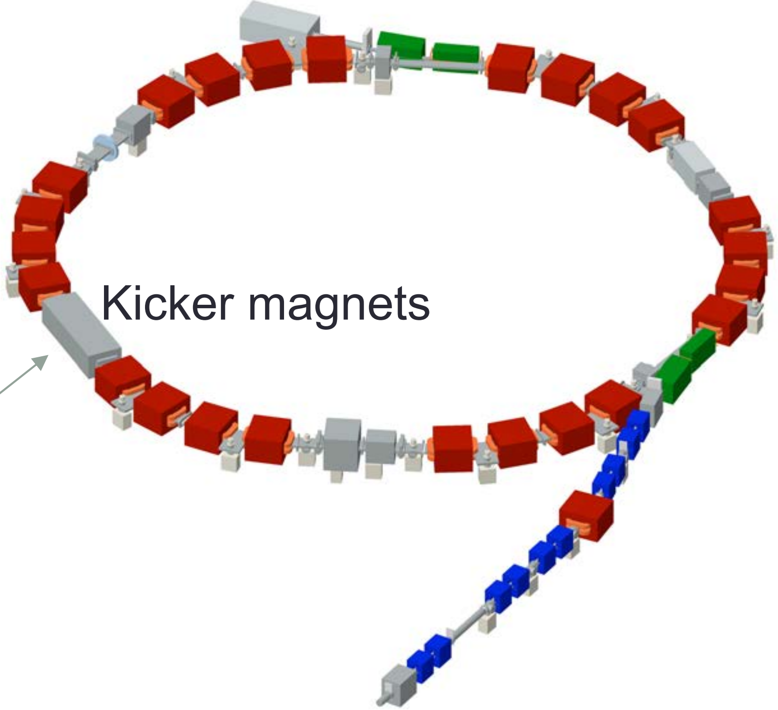
Efficiency: x14 times
Total R3 eff. 2%



Large area position-sensitive DL-E-MCP

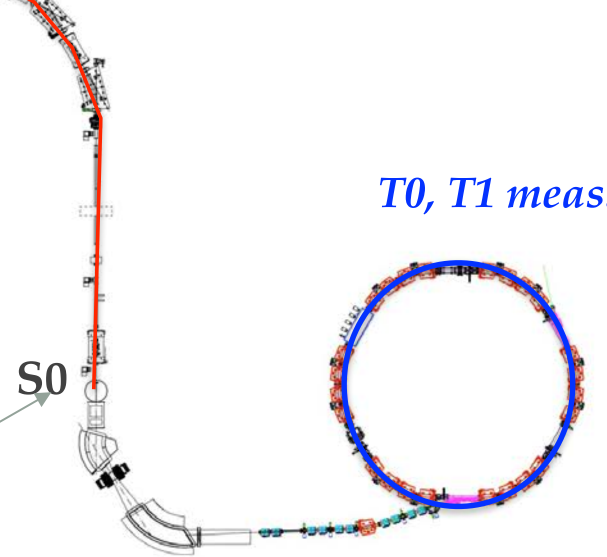
New kicker magnets configuration



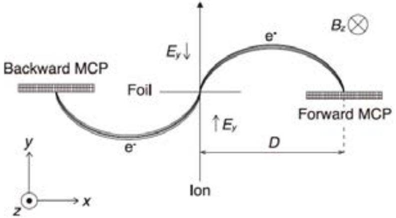


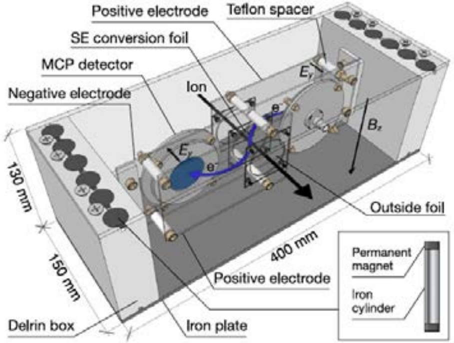
DL-E-MCP could be placed inside the kicker magnet to monitor emittance

Challenge #4
Determination of revolution time



$$\frac{m_1}{q_1} = \left(\frac{m_0}{q_0}\right)\frac{1}{T_0}\; T_1\sqrt{\frac{1-\beta_1^2}{1-\{(T_1/T_0)\beta_1\}^2}} = \left(\frac{m_0}{q_0}\right)\frac{T_{1corr}}{T_0}$$

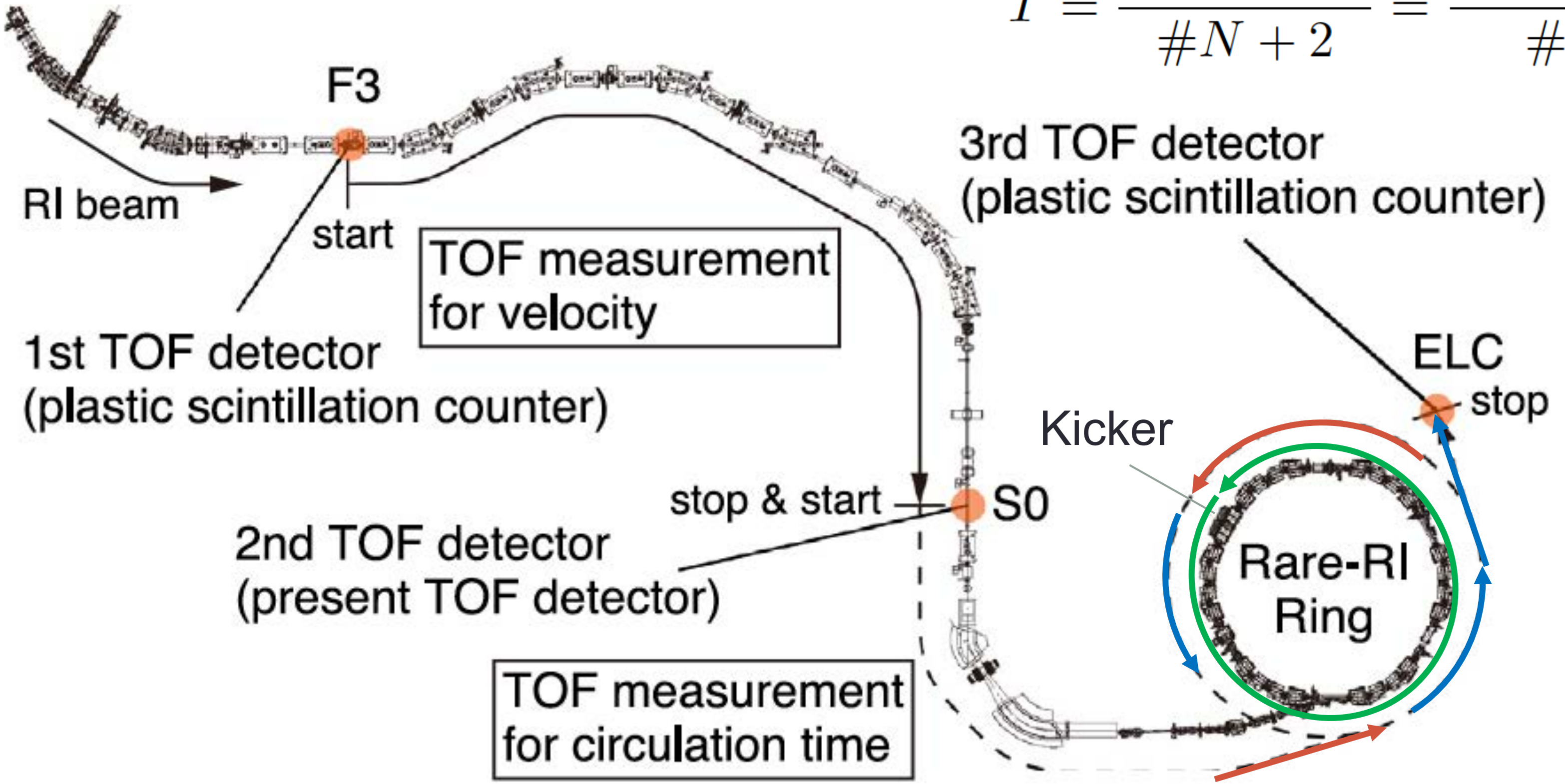




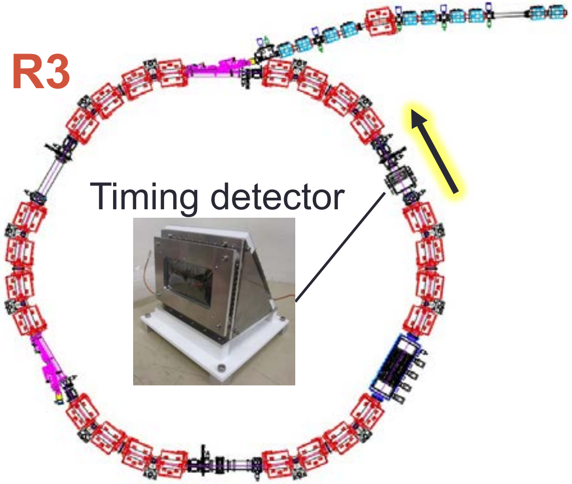
S. Suzuki, NIMA 965 (2020)

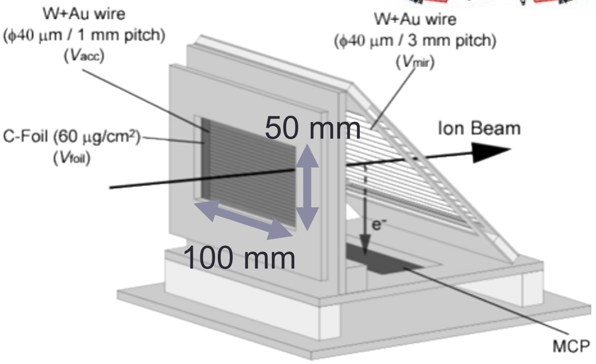
σ = 38ps, eff = 95%, dE/E<10^{-5}

$$T = \frac{ToF_{\mathrm{S0-ELC}}}{\#N+2} = \frac{ToF_{\mathrm{S0-ELC}}}{\#N'}$$

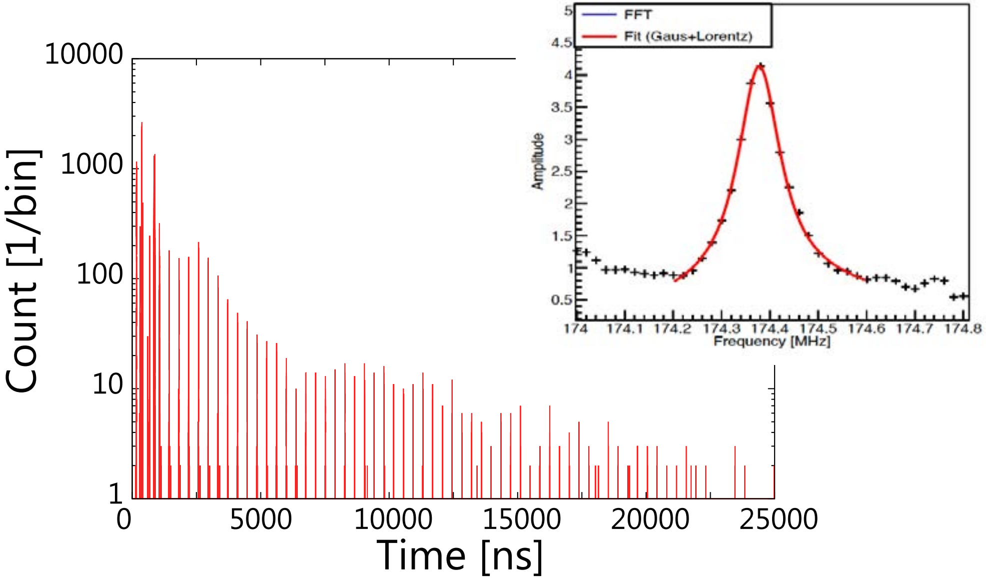


Rough determination of revolution time → deduce turn number





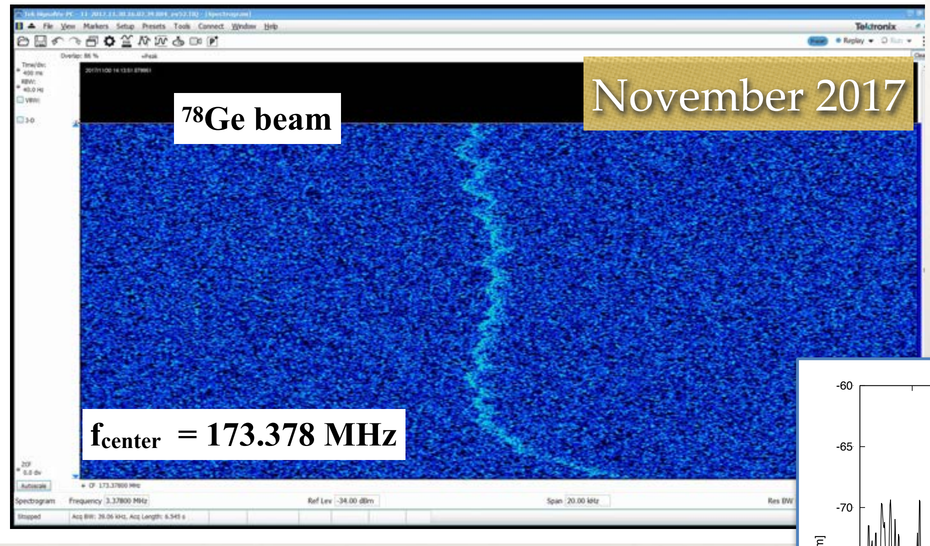
- Efficiency: 90 %
- Time resolution: 70ps

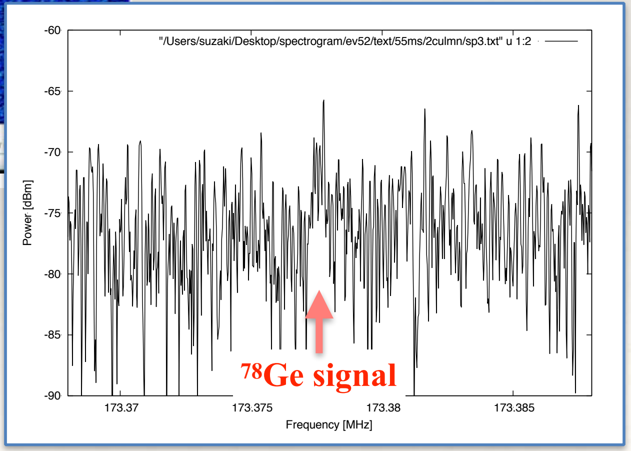


Nucleus	DFT Rev. T[ns]	ToF_{S0-ELC}[ns]	$\#N'$
^{128}Sn	393.9660±0.0268	725781.69±0.98	1842
^{127}In	397.6030±0.0387	725726.56±1.07	1825
^{126}Cd	401.4275±0.0108	725835.75±0.13	1808
^{125}Ag	405.4414±0.0353*	725747.62±0.40	1790
^{124}Pd	409.6077±0.0356*	725830.25±1.61	1772

D. Nagae et al., NIMA 2020

(almost) Perfect Isochronicity!

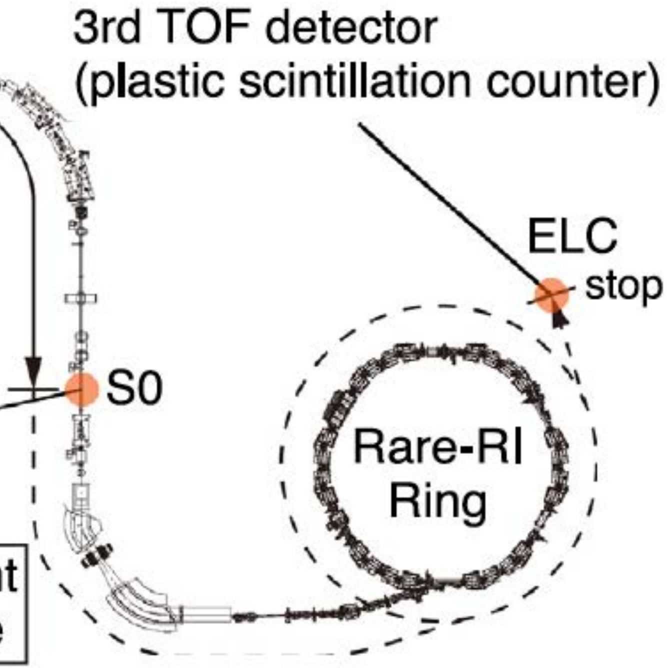


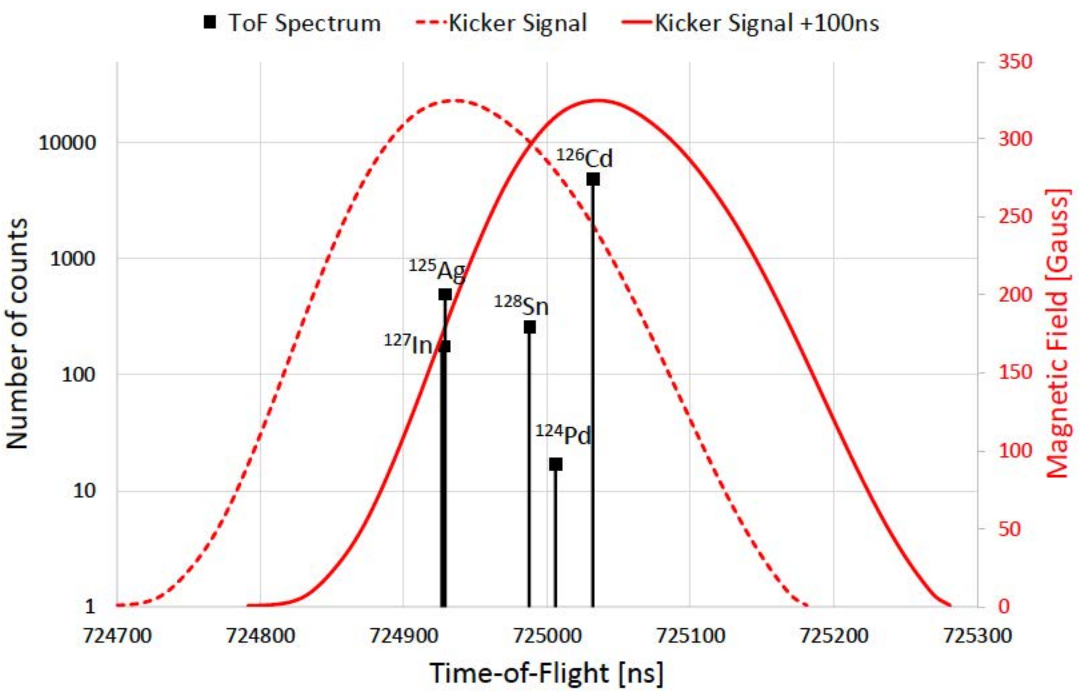


Highest sensitivity Schottky pickup detector
→ detection of Z=32 (lightest isotope ever)

Challenge #5
Ejection from the ring

Kicker limitation at ejection





Upgrade of the kicker magnets

Previous config.

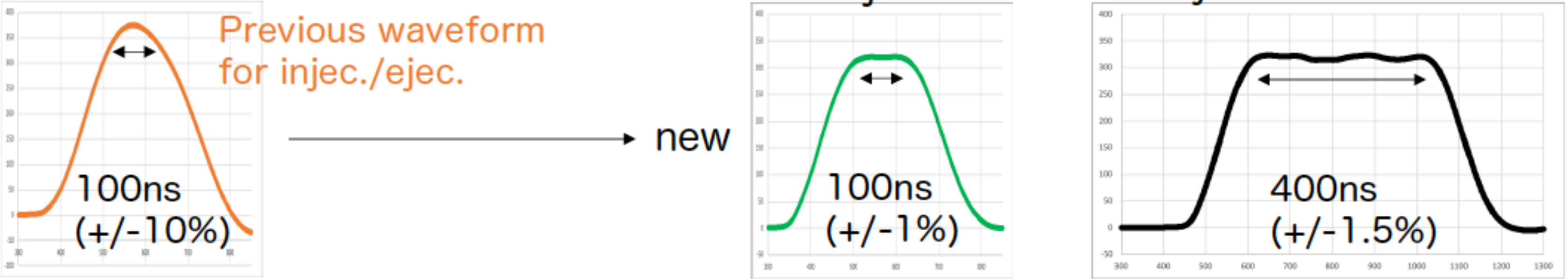
b, c for injection

a, d for ejection

Successfully tested
Nov. 2020

Substantial kicker field for particles

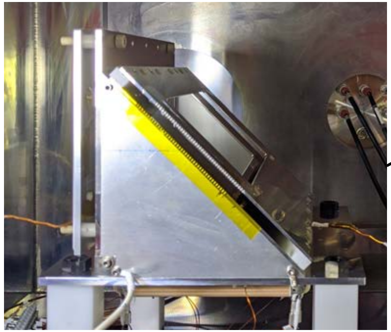
For injection For ejection

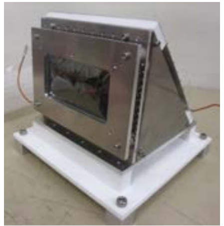


R3 in-ring detectors

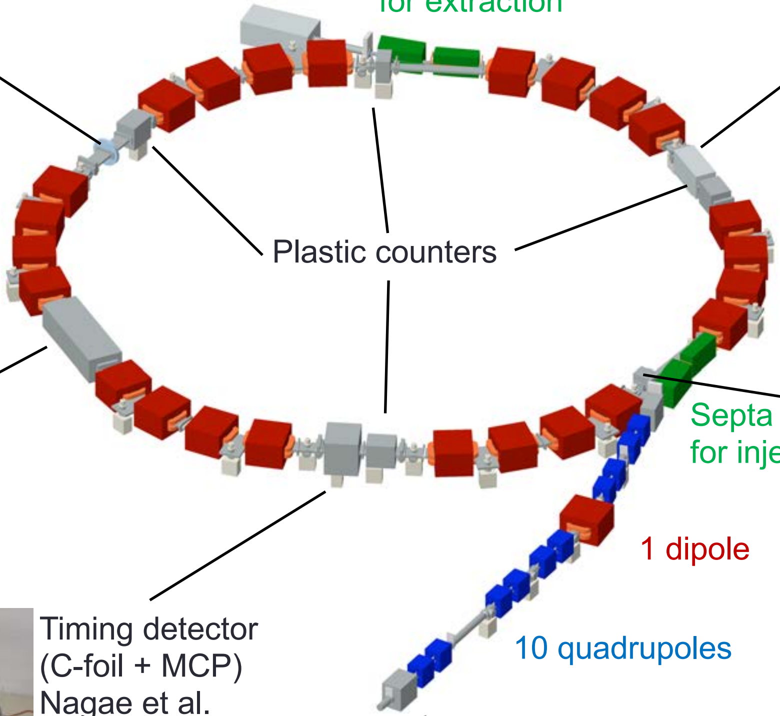
Resonant
Schottky pick-up

DL-E-MCP
Position-sensitive

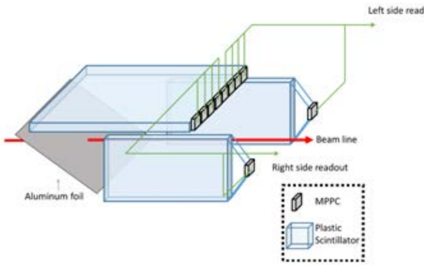




Timing detector
(C-foil + MCP)
Nagae et al.
NIMA 2020

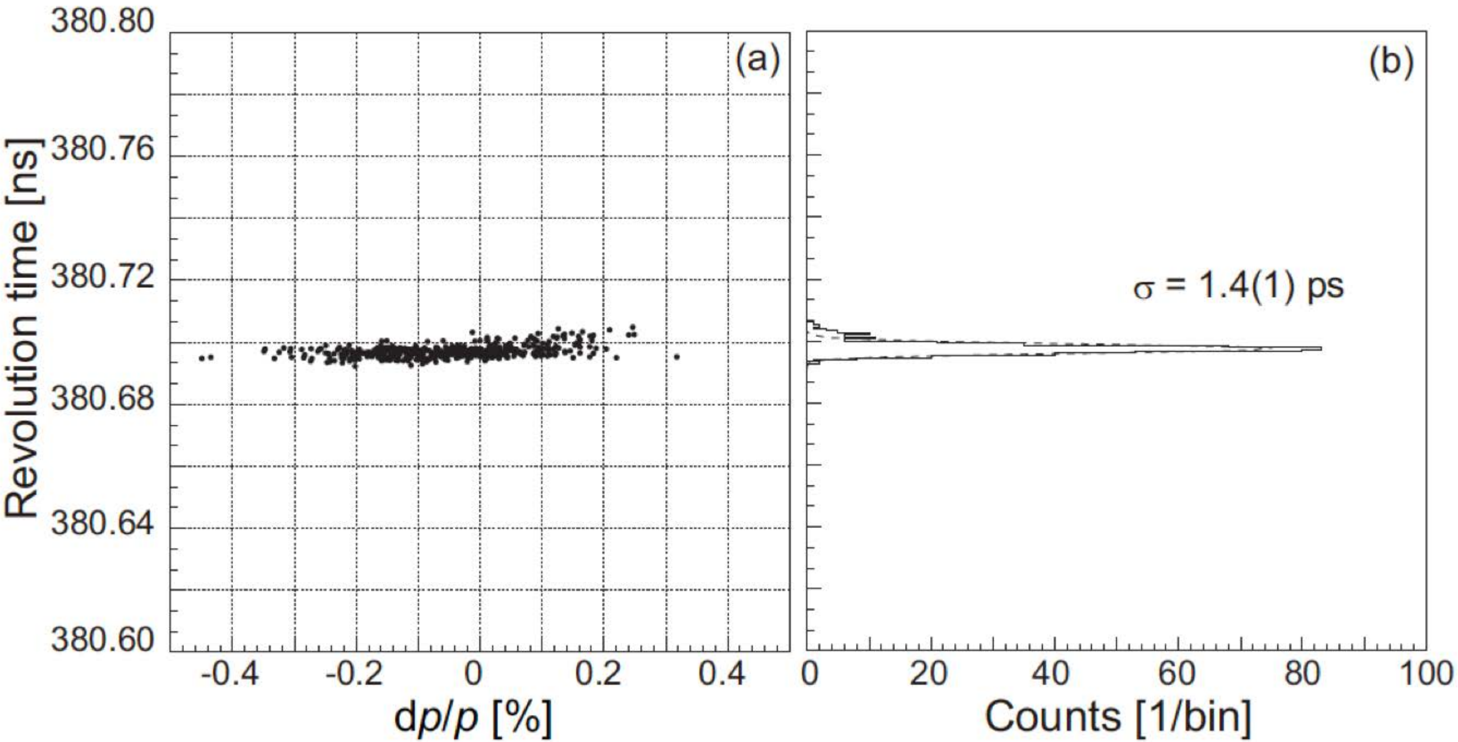


Position-sensitive
Schottky pick-up ?



Delta-ray monitor
Timing detector
Omika et al., NIMB 2020

Monitoring F5 position is necessary for verifying the isochonicity*

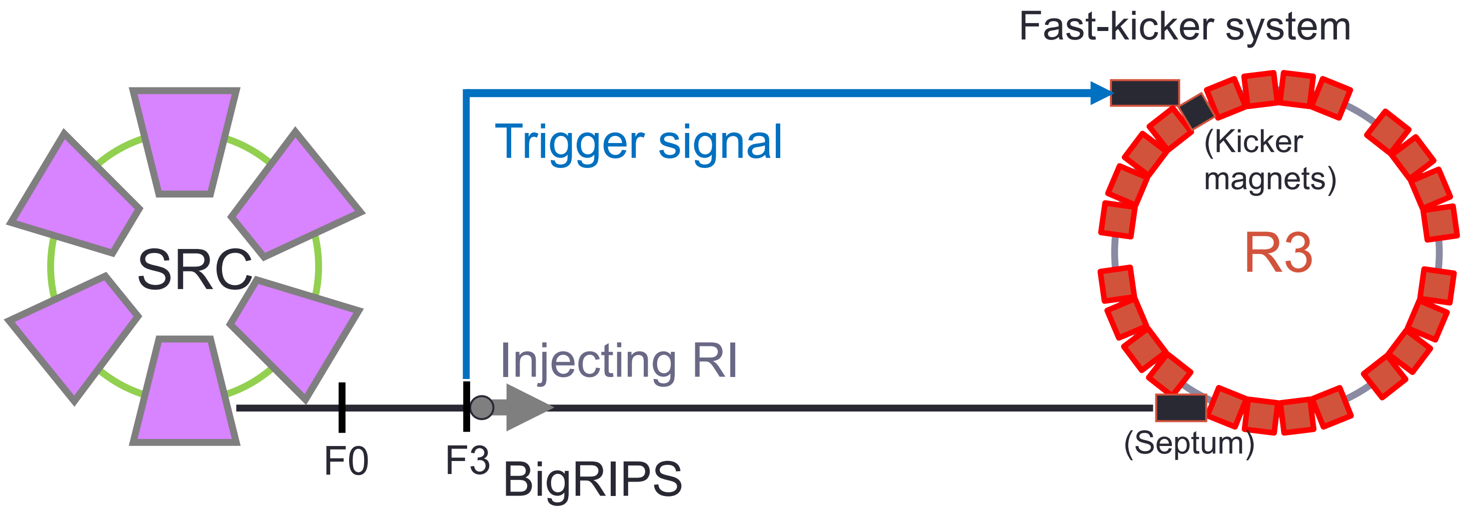


* Revolution time is independent of momentum

Self-trigger injection method

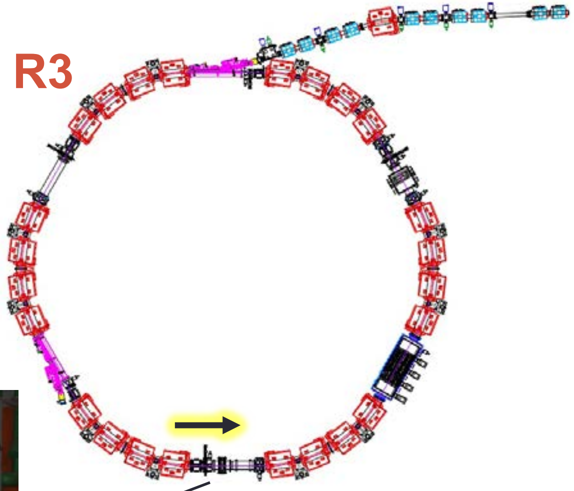
Cyclotron — In-flight separator — Storage ring

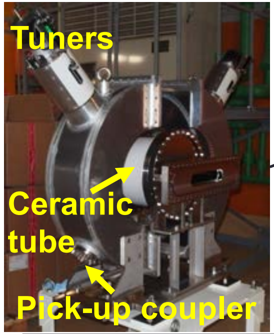
NEW!!



Proposed by I. Meshkov et al., NIMA523 (2004)

Storage of single-ion (@MS01)

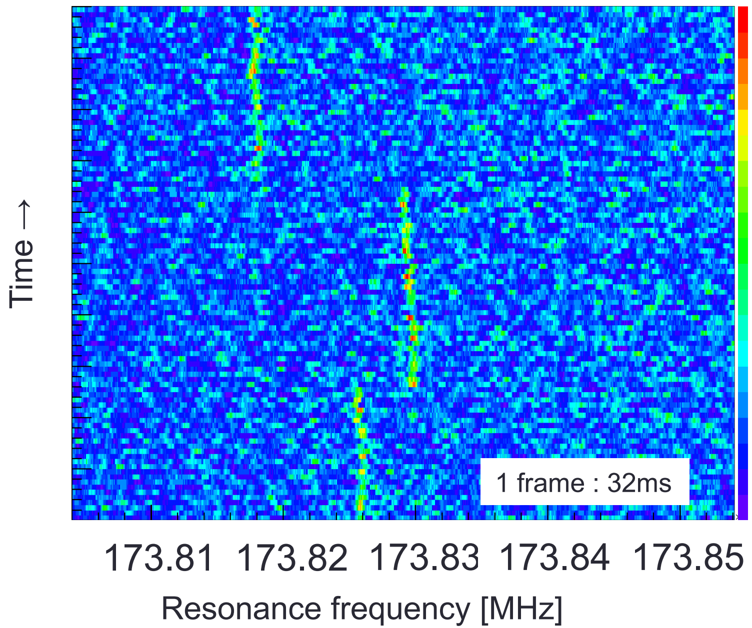




Resonant Schottky pick-up

Resonance frequency :	173MHz (TM_{010})
Tuning range : ±1.5MHz	
Shunt Impedance R_{sh} :	161kΩ
Quality factor Q_0 :	1880
Ceramic tube size : thickness	290mmΦ, 15mm

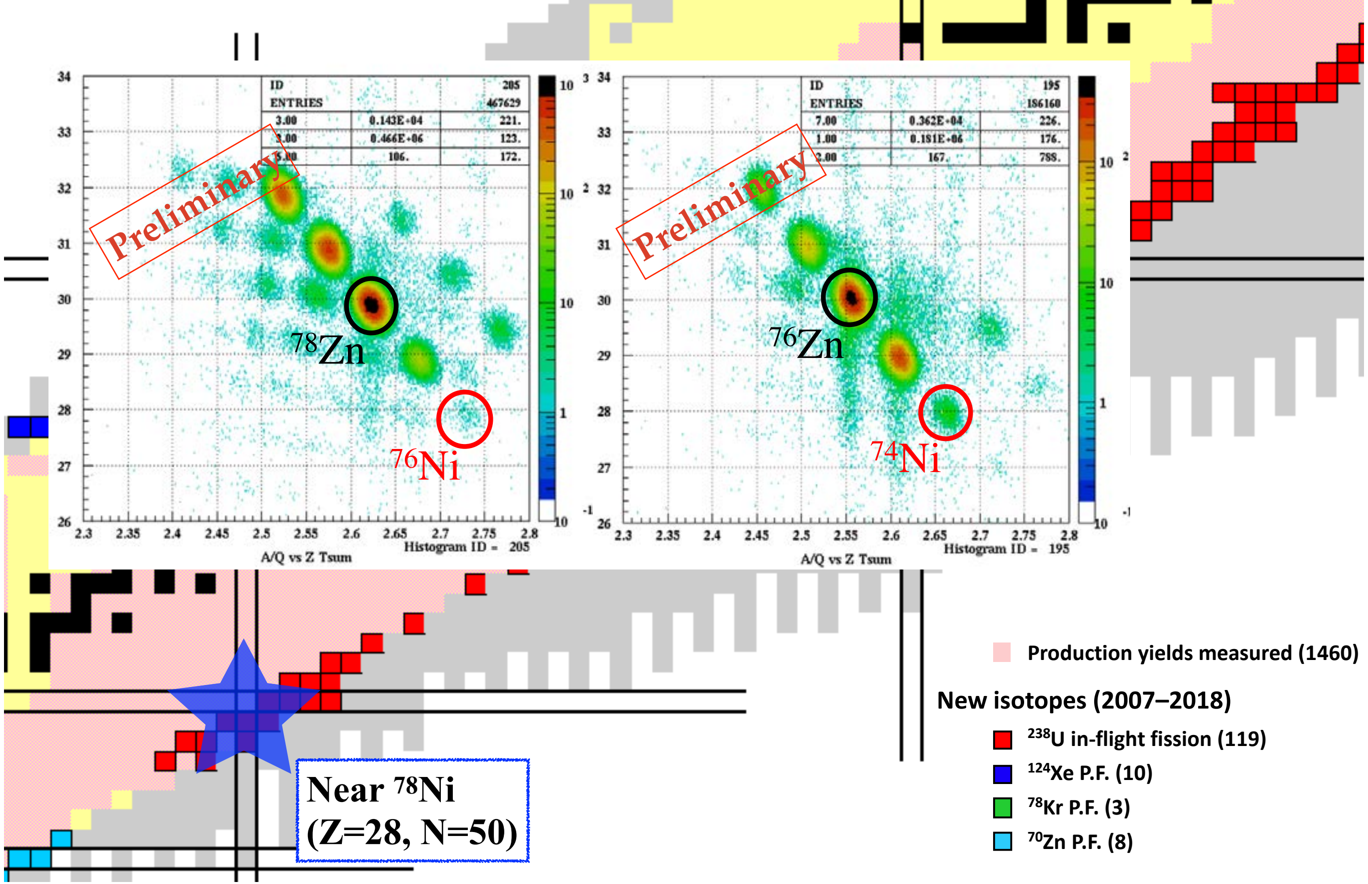
Repetition time of injection : 0.5s

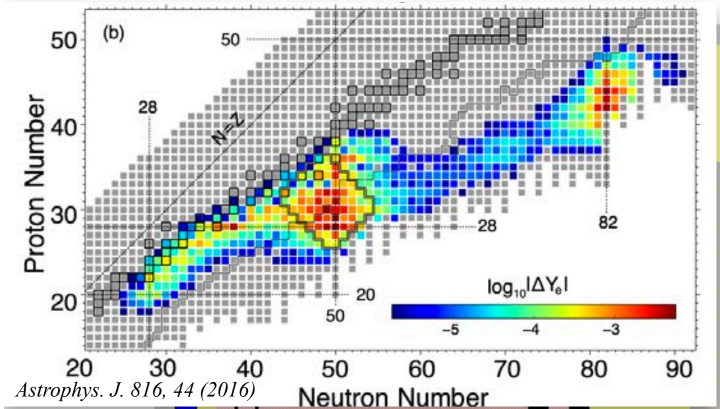


- Succeeded in detecting the single $^{78}Kr^{36+}$ ion
- Frequency resolution: ~1.3×10^{-6} (FWHM)

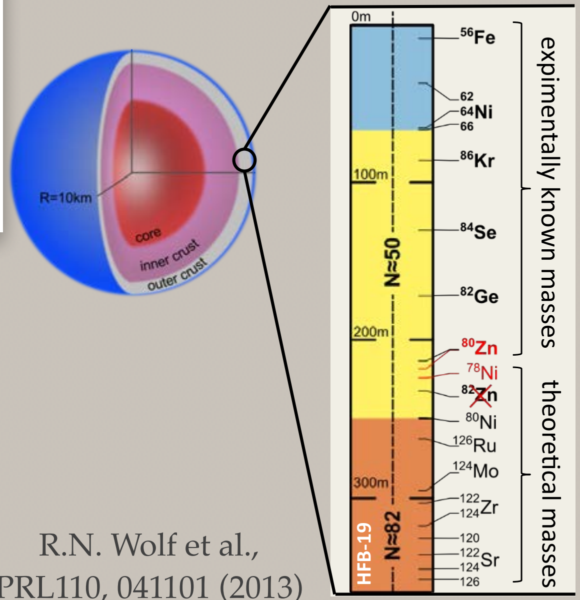
In November 2018: ^{74,76}Ni isotopes were measured

^{77}Ni is planned to be measured in 2021

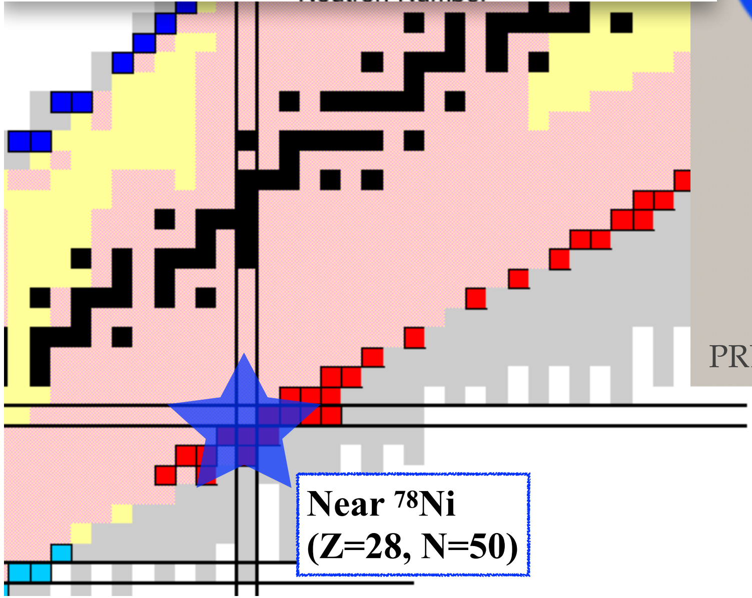




Astrophys. J. 816, 44 (2016)



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



New isotopes (2007–2018)

- ^{238}U in-flight fission (119)
- ^{124}Xe P.F. (10)
- ^{78}Kr P.F. (3)
- ^{70}Zn P.F. (8)