Overview of the RI Beam Facility (RIBF)

Aiko Takamine

Riken Nishina Center

icot@riken.jp

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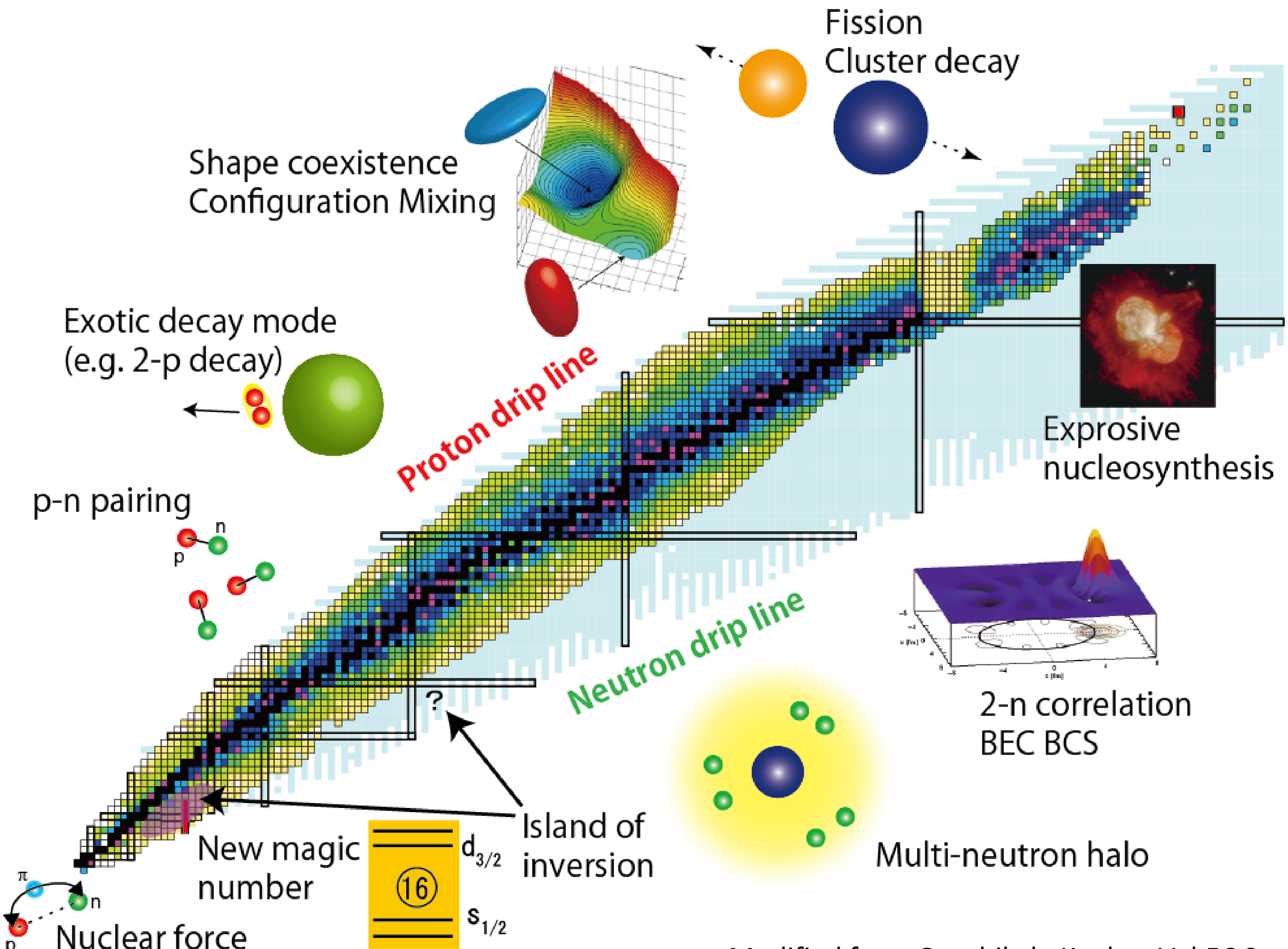
August 23 - 29, 2017 Nishina Hall, Riken, Wako

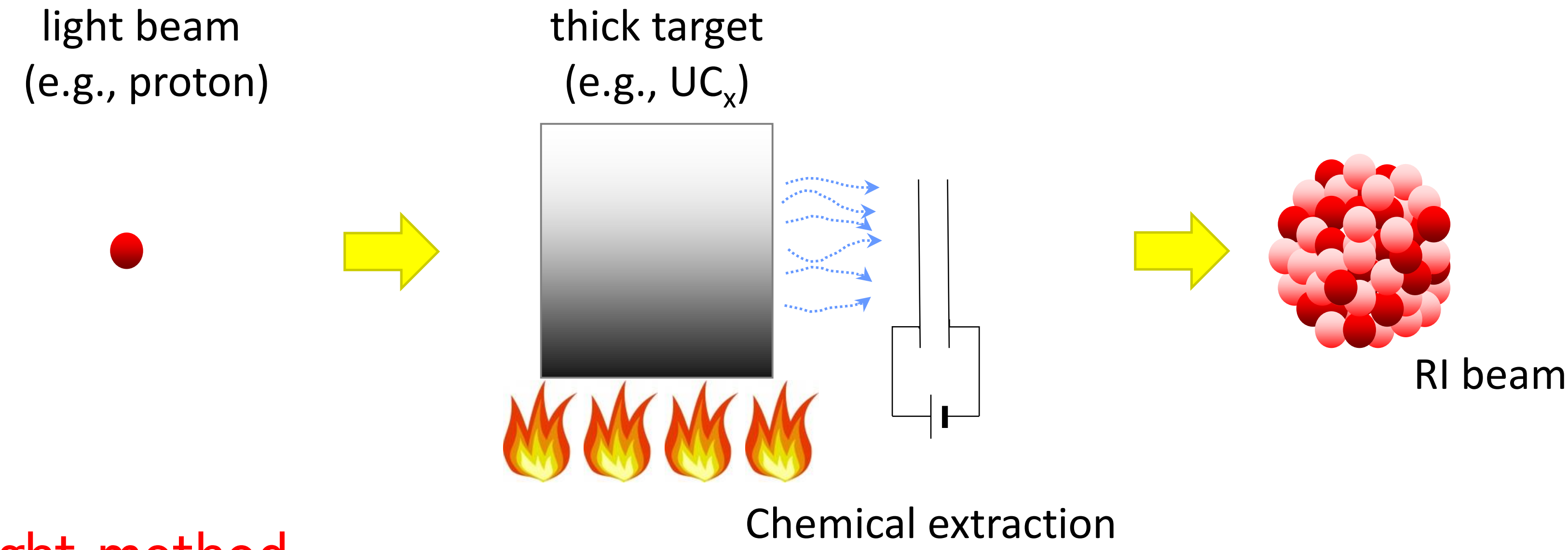
Variety physics of unstable nuclei



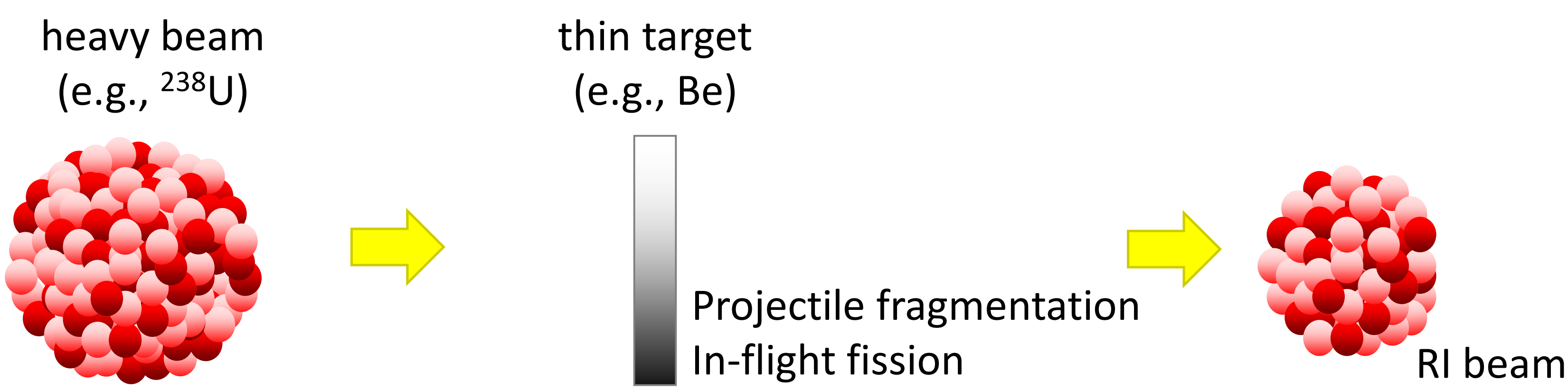
Modified from GenshikakuKenkyu Vol.56 Suppl.3

Two ways of RI beam production

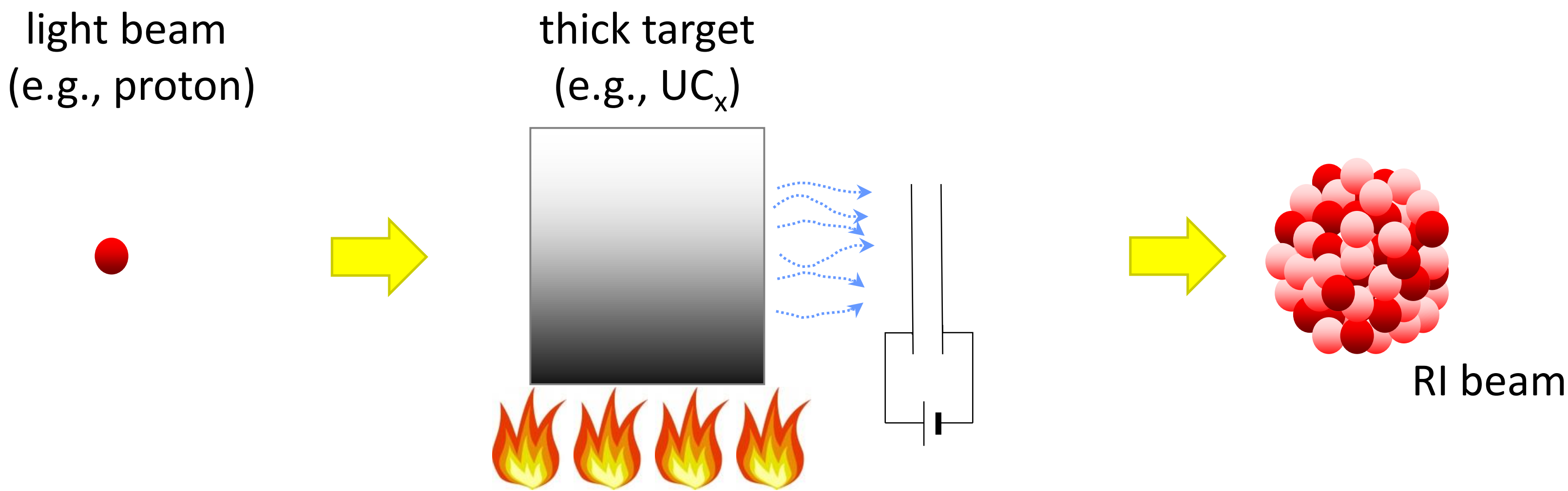
ISOL method (Isotope Separation On-Line)



In-flight method



ISOL method (Isotope Separation On-Line)

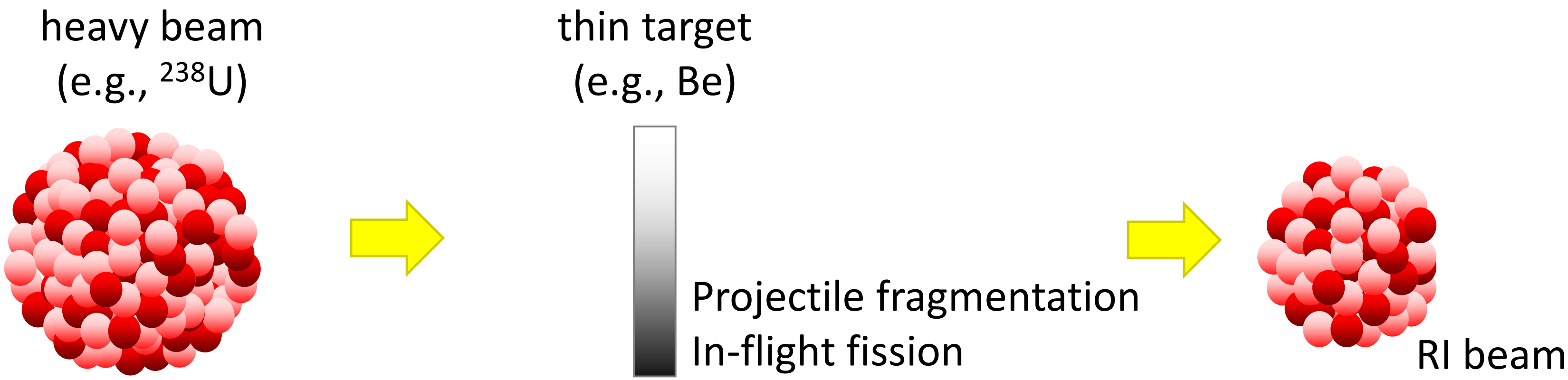


- Fission (spontaneous, induced e^-, *p*, *d*)
- Spallation (*p* ~1 GeV)
- Light beam and heavy thick target

☺ High production yields
☺ Low costs

☹ Lifetime limitation (slow extraction)
☹ Z limitation (Chemical property)

In-flight method



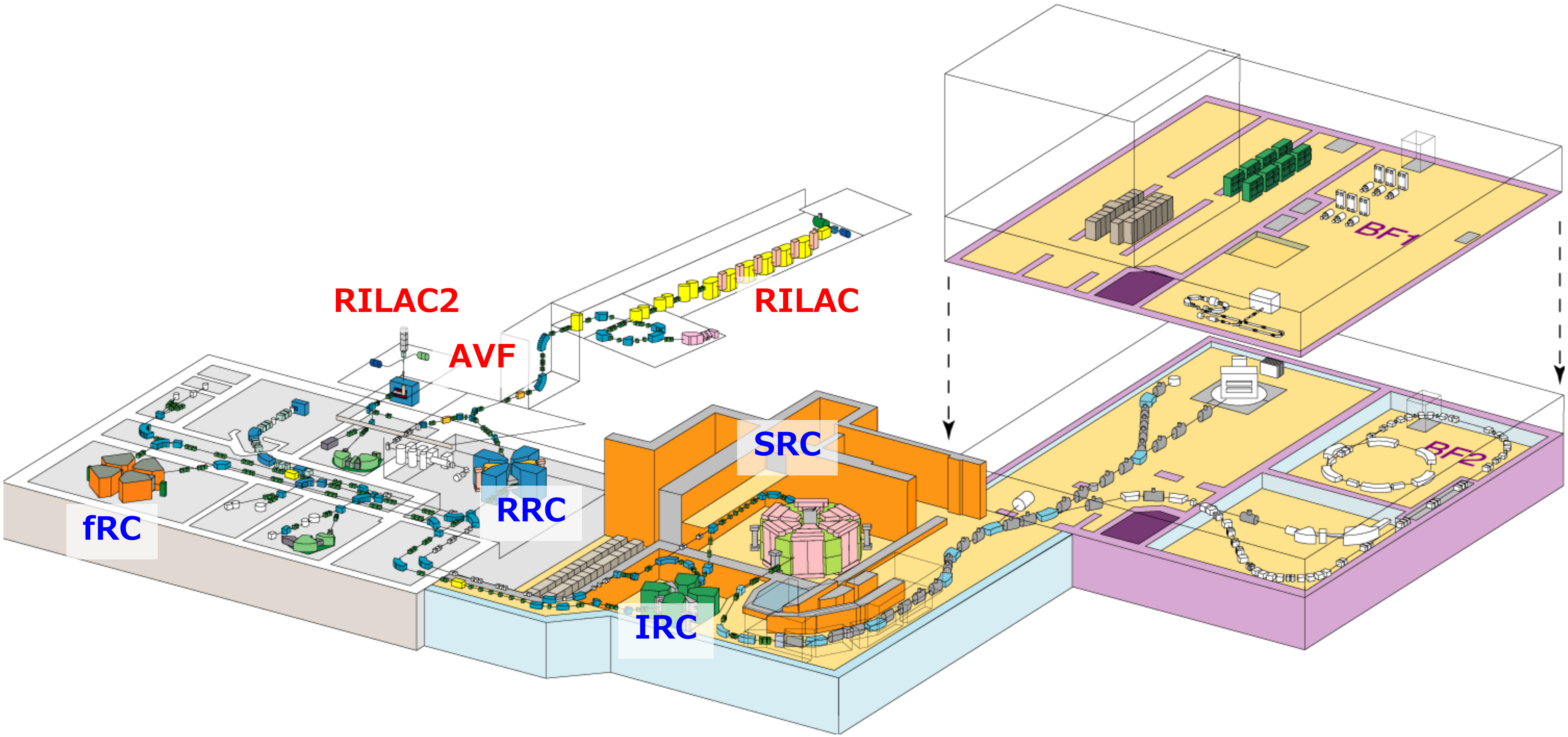
- Projectile fragmentation reaction
- Uranium fission
- Heavy beam and light thin target (Be, C)

☺ No limitation from lifetime and chemical property
☺ Access far from stability

☹High cost
☹Large spread of momentum & beam divergence

RIBF (Radioactive Isotope Beam Factory)

- 3 injectors + 4 cyclotrons
- A variety of primary beam up to U
- Energy up to 345 MeV/nucleon



How to accelerate?
SRC (Superconducting Ring Cyclotron)

Diameter : 18.4m
Weight : 8,300 tons

- K2500MeV
  - 345 MeV/nucleon for U beam
  - 400 MeV/nucleon for Light-ion beam
- Self magnetic shield
  - Up to 8 Tm

How to produce?

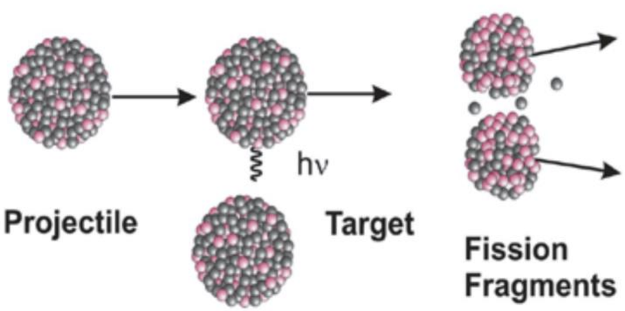
Production of exotic nuclei at relativistic energies

Projectile Fragmentation

Nucleon-nucleon collisions, abrasion, ablation

$$\vec{V}_f \approx \vec{V}_p$$

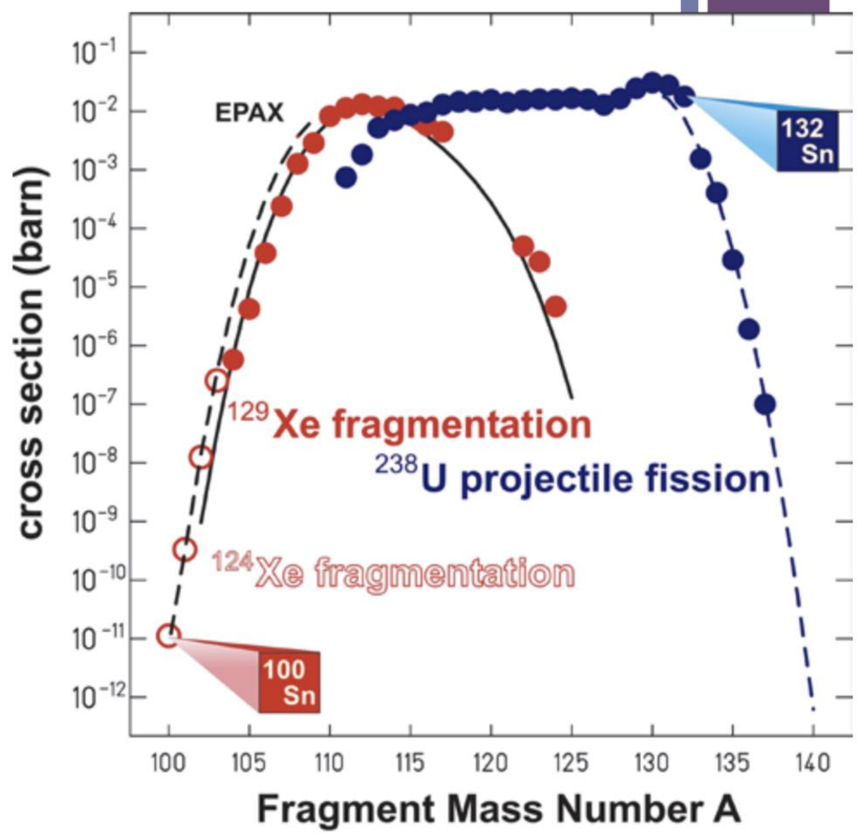
Projectile Fission



Electromagnetic excitation, fission in flight

$$\vec{V}_f \approx \vec{V}_p + \vec{V}_{fission}$$

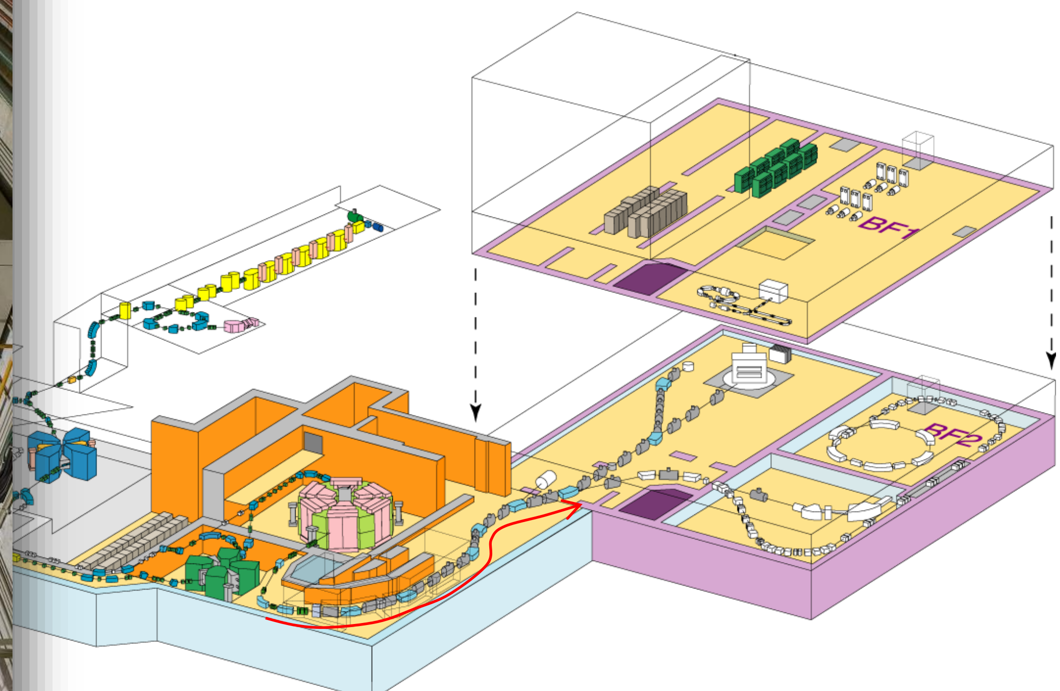
Sn isotope production



K.Sümmerer

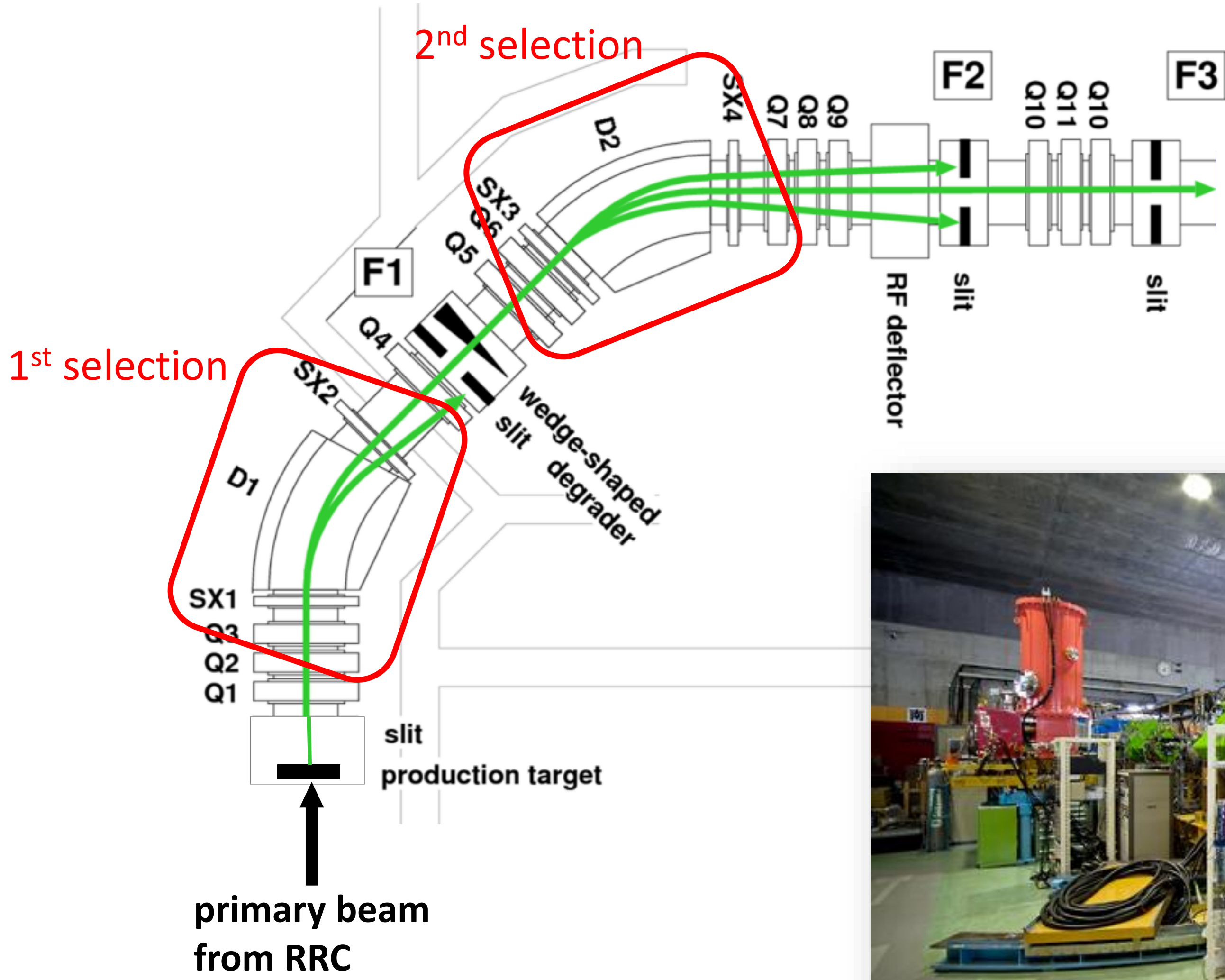
BigRIPS: How to separate and identify?

- ☐ In-flight separator
- ☐ Largest acceptance up to 9 Tm



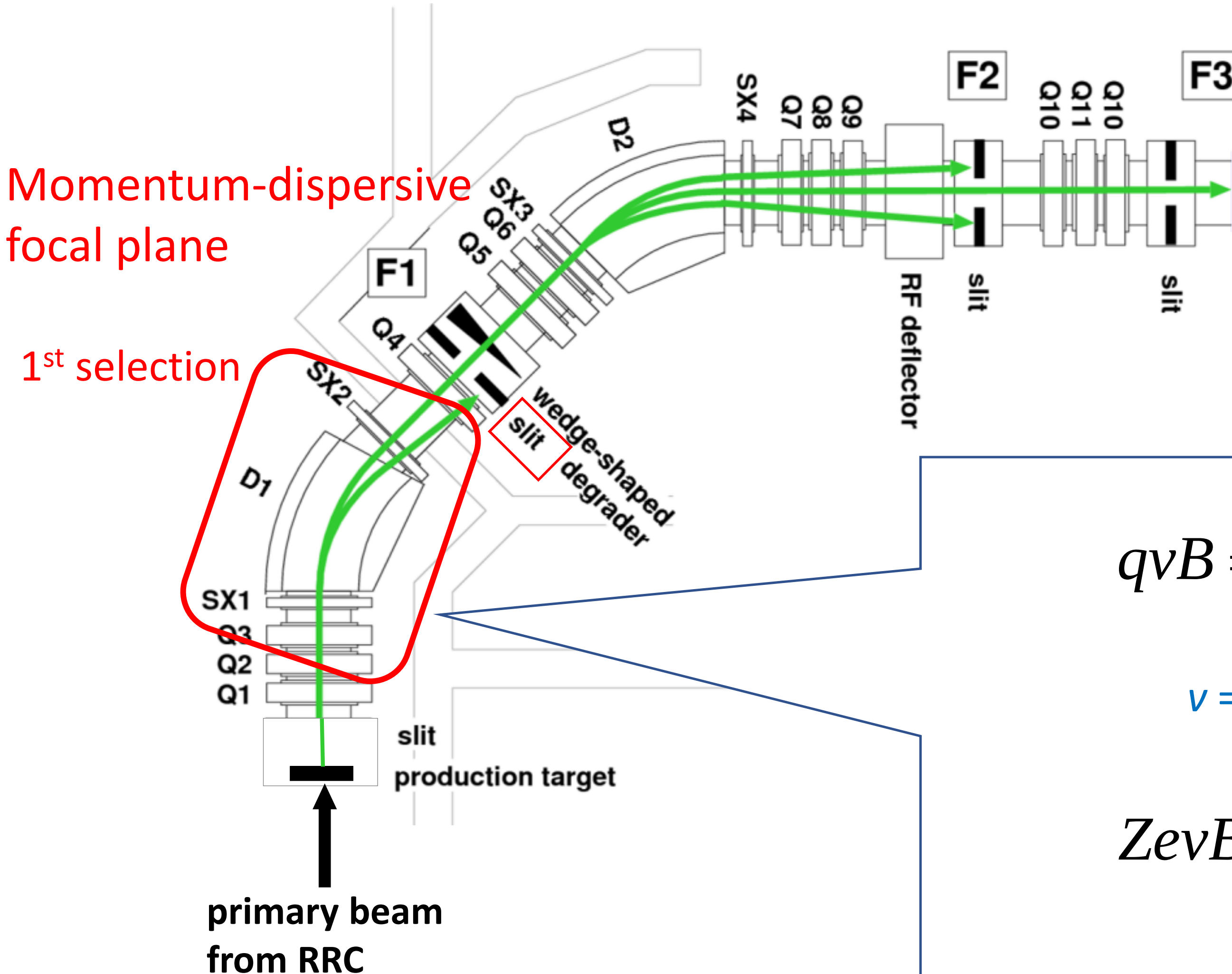
BigRips: T. Kubo, Nucl. Instr. Meth. B 204, 97 ('03)

RIPS: precursor of BigRIPS



RIPS: T. Kubo *et al.*, Nucl. Instr. Meth. B 70, 309 ('92)

1^{st} stage selection



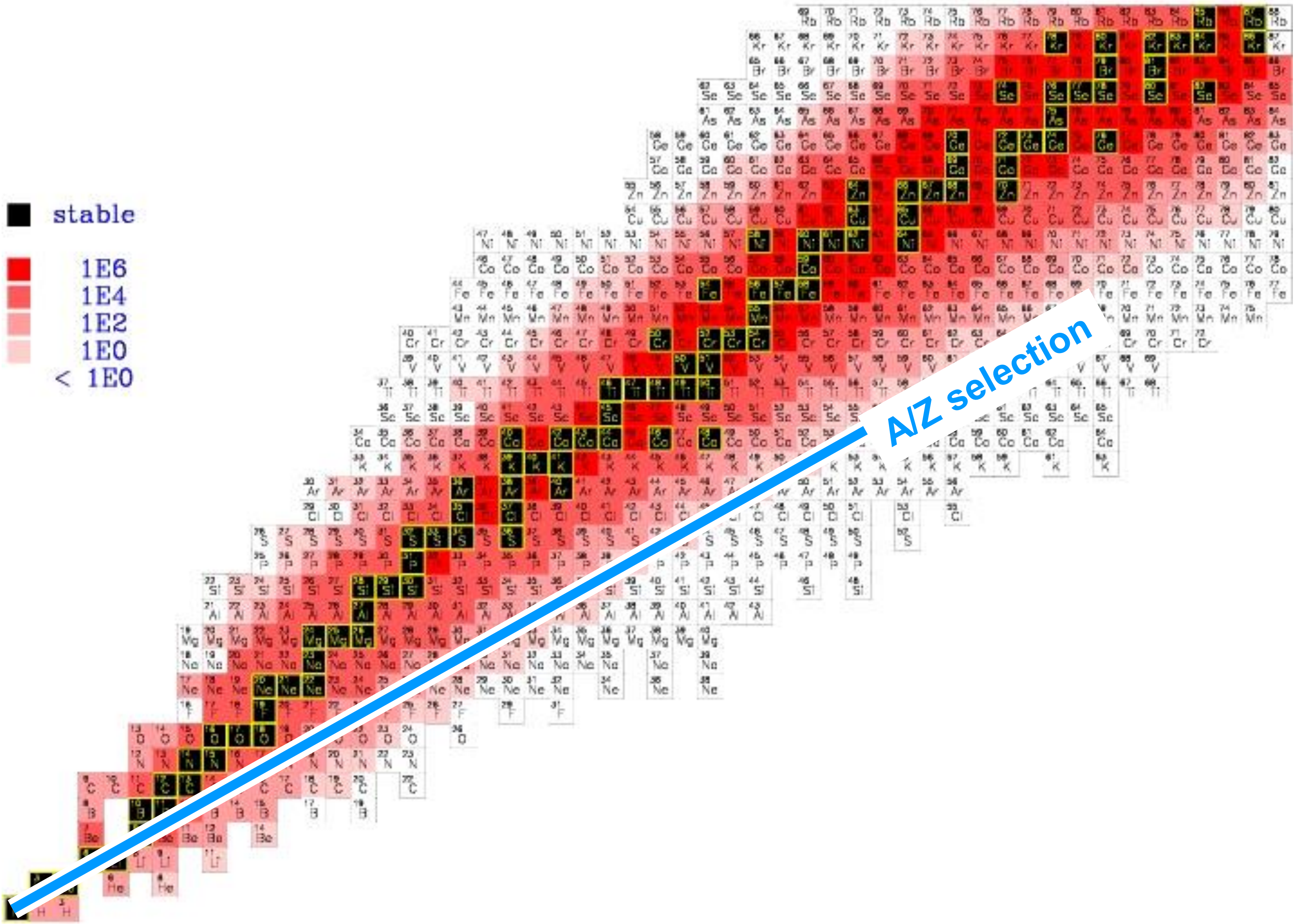
$$qvB = m\frac{v^2}{\rho}$$

$v = v_{beam}$ for all fragments

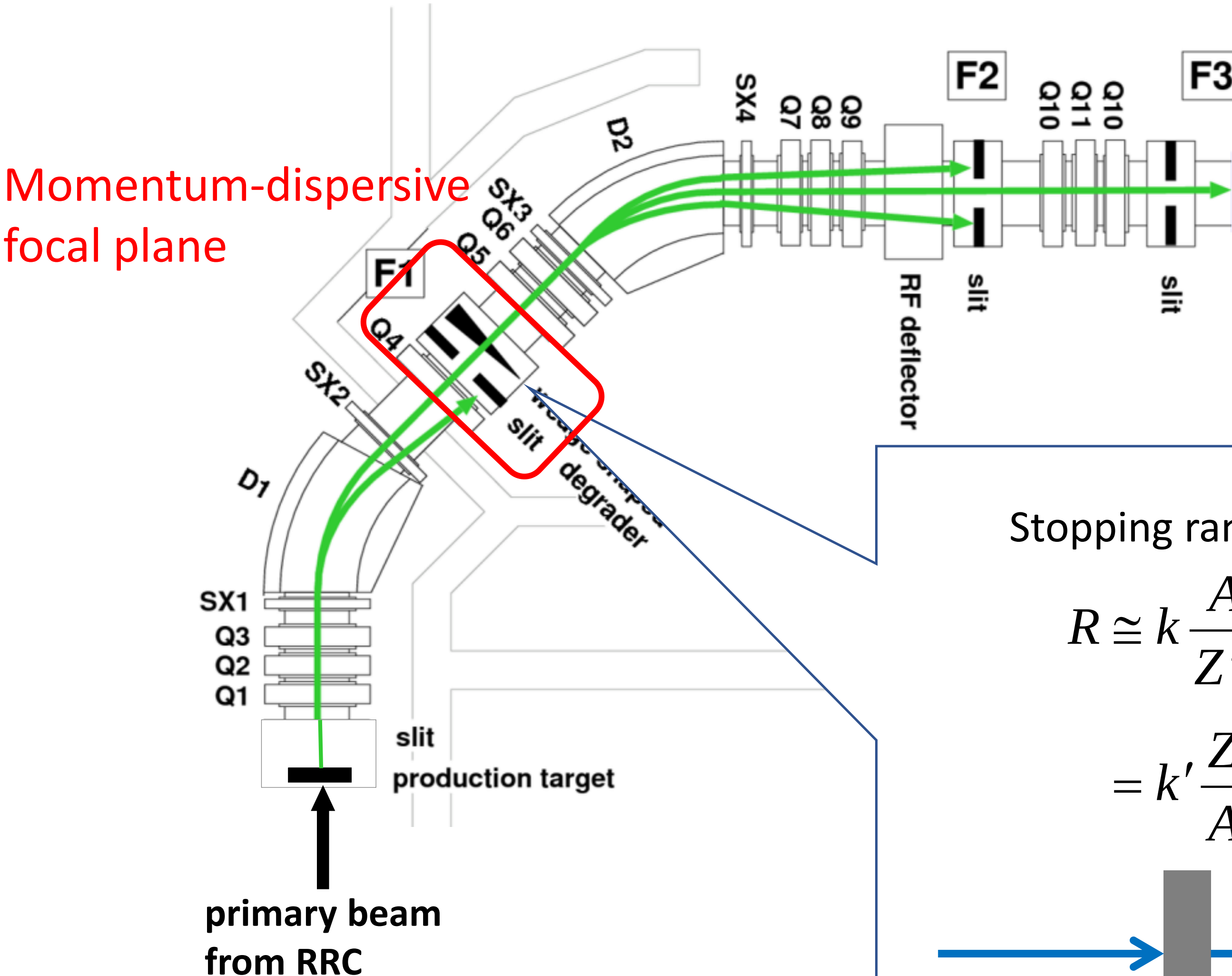
$$ZevB = Am_{\mathrm{nucl}}\frac{v^2}{\rho}$$

$$B\rho = \frac{A}{Z}\frac{p_{\mathrm{nucl}}}{e}$$

Isotope separation (stage1)



Between 1st and 2nd selections

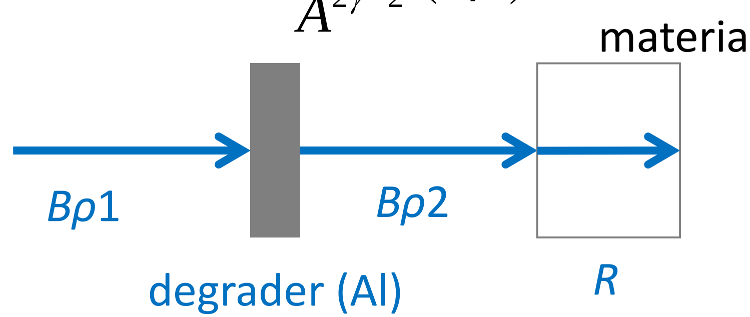


Stopping range

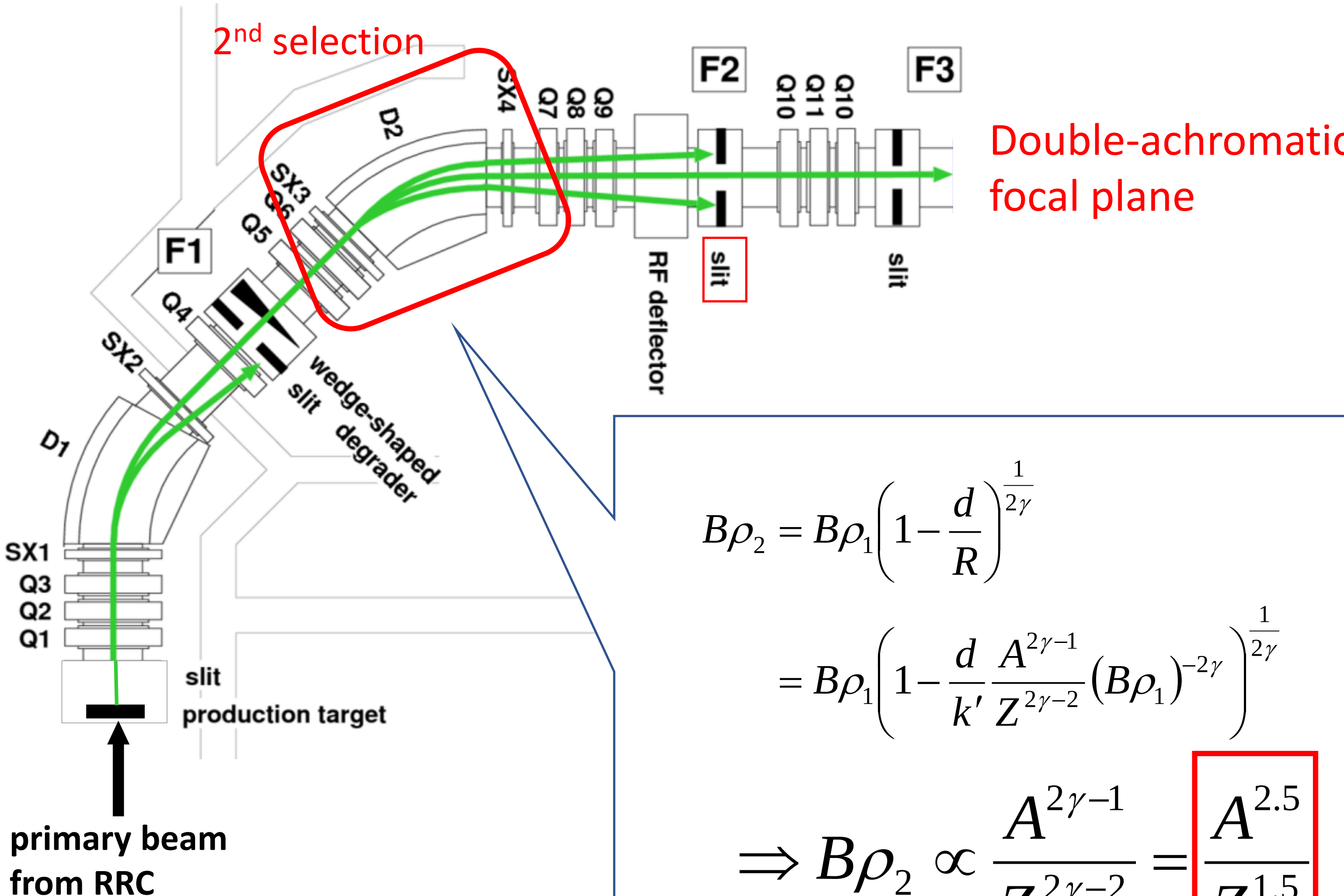
$$R \cong k \frac{A}{Z^2} \left(\frac{E}{A} \right)^{\gamma}$$

γ =1.75
(at intermediate beam energies)

$$= k' \frac{Z^{2\gamma-1}}{A^{2\gamma-2}} (B\rho)^{2\gamma}$$



2nd stage selection

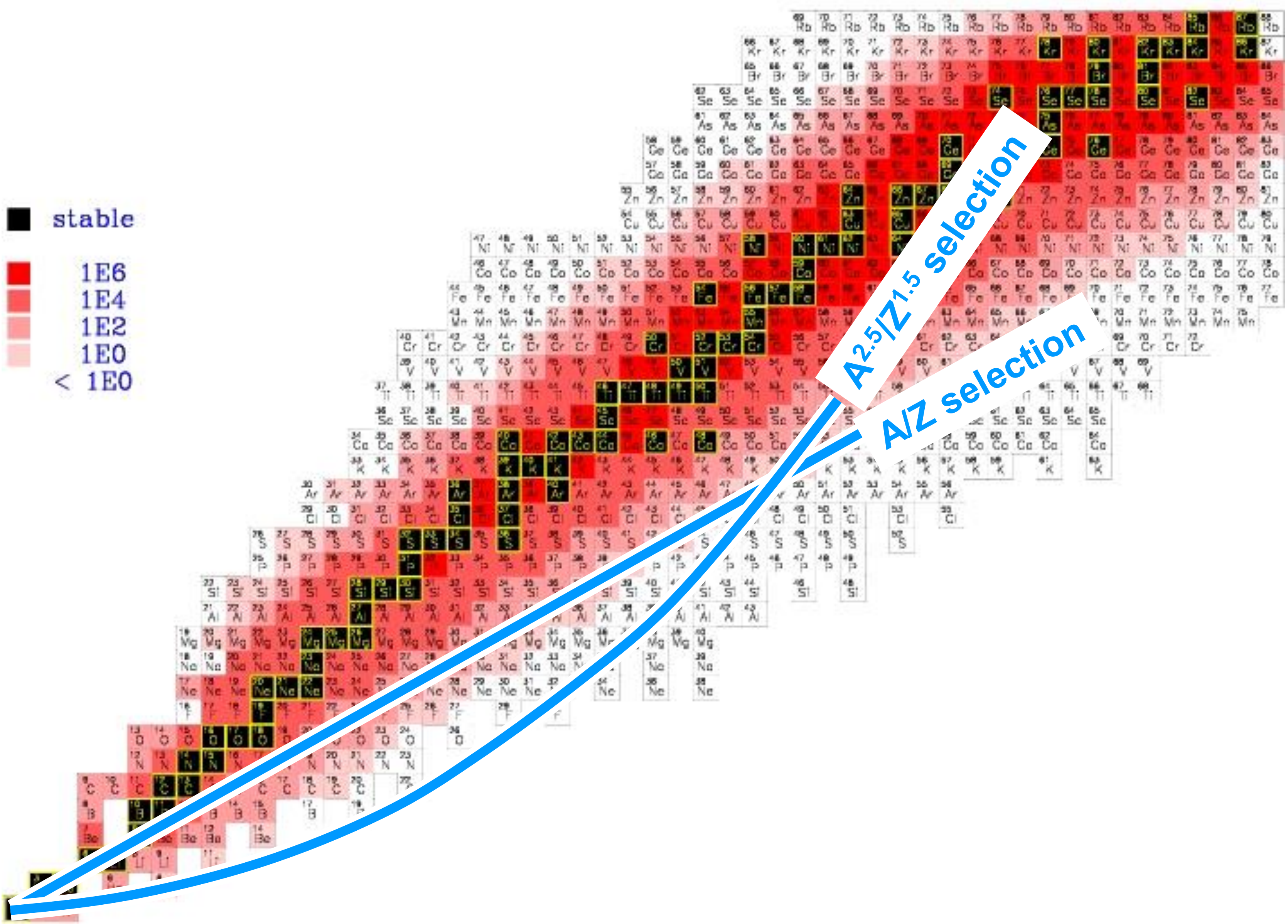


$$B\rho_2 = B\rho_1\left(1-\frac{d}{R}\right)^{\frac{1}{2\gamma}}$$

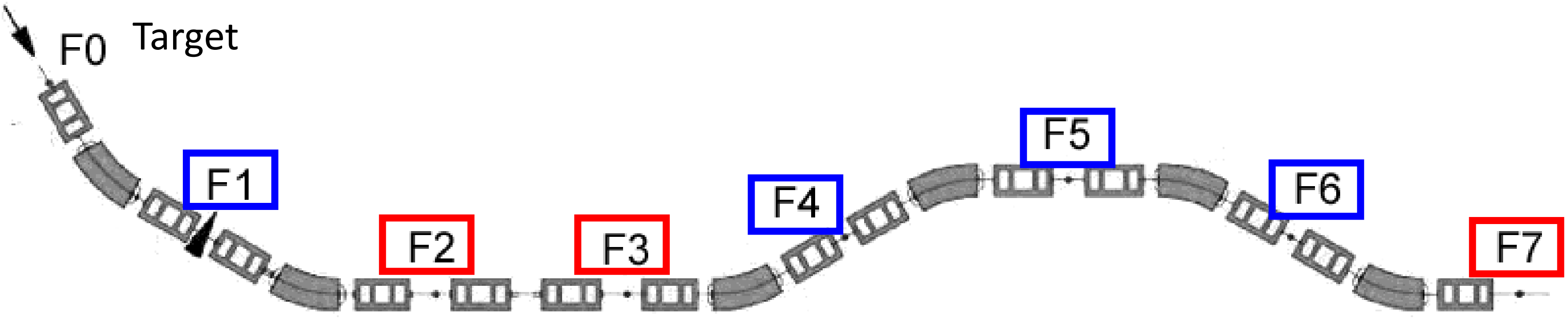
$$= B\rho_1\left(1-\frac{d}{k'}\frac{A^{2\gamma-1}}{Z^{2\gamma-2}}\left(B\rho_1\right)^{-2\gamma}\right)^{\frac{1}{2\gamma}}$$

$$\Rightarrow B\rho_2 \propto \frac{A^{2\gamma-1}}{Z^{2\gamma-2}} = \boxed{\frac{A^{2.5}}{Z^{1.5}}}$$

Isotope separation (stage2)



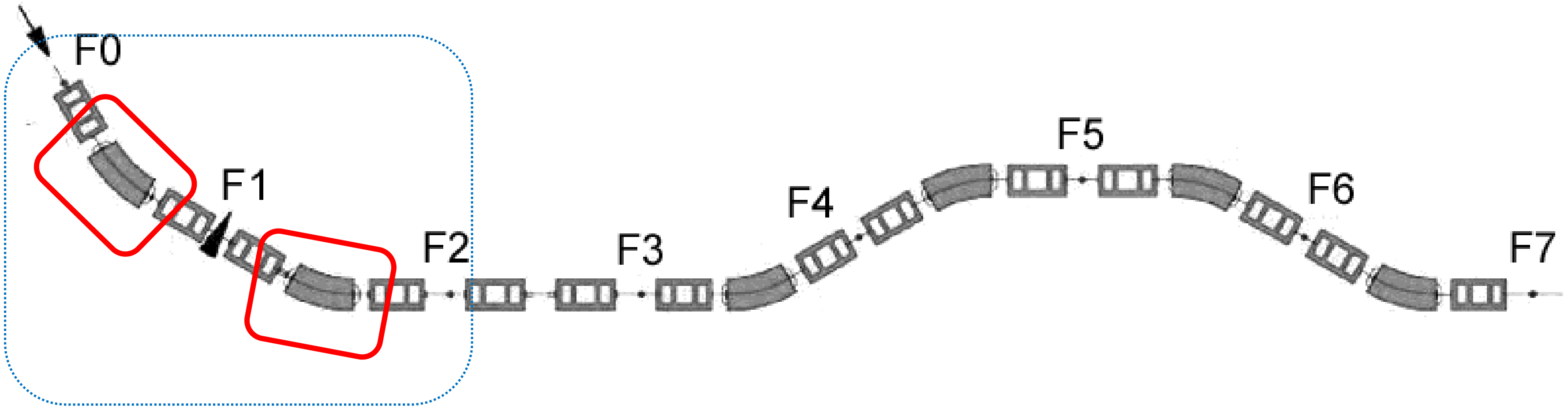
BigRIPS configuration



Momentum-dispersive focal planes

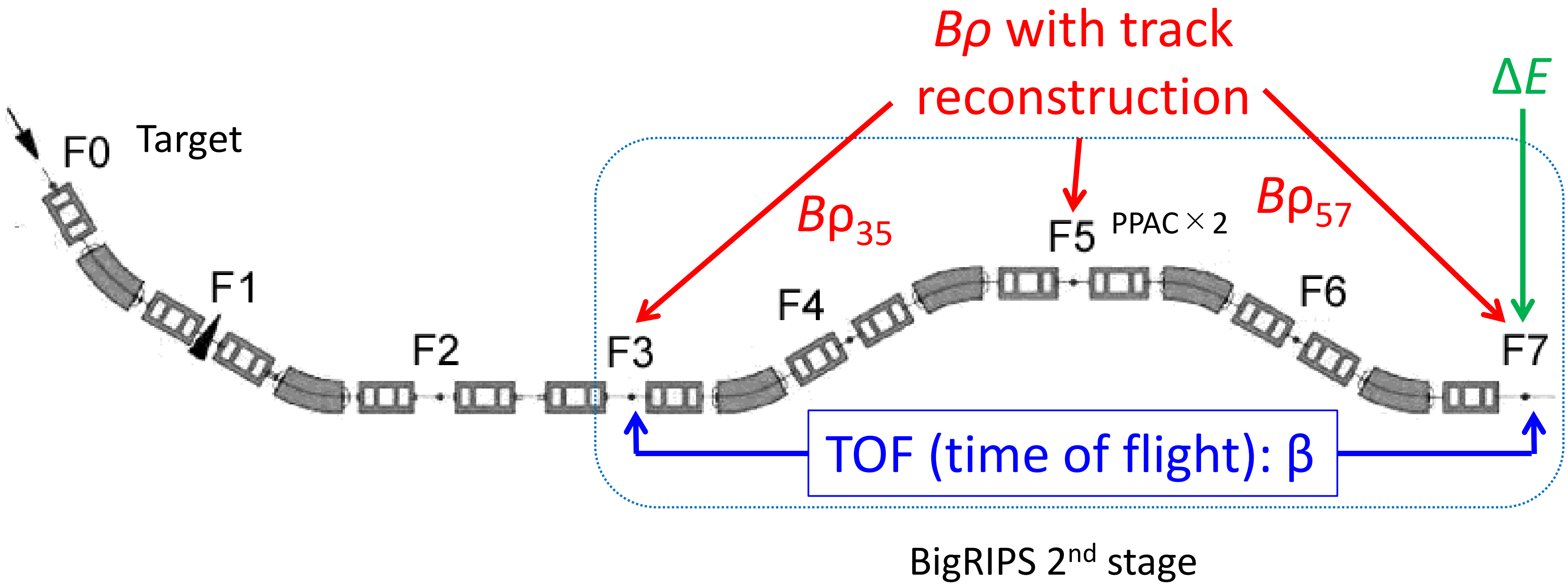
Double-achromatic focal planes

Isotope separation



BigRIPS 1st stage

Particle identification



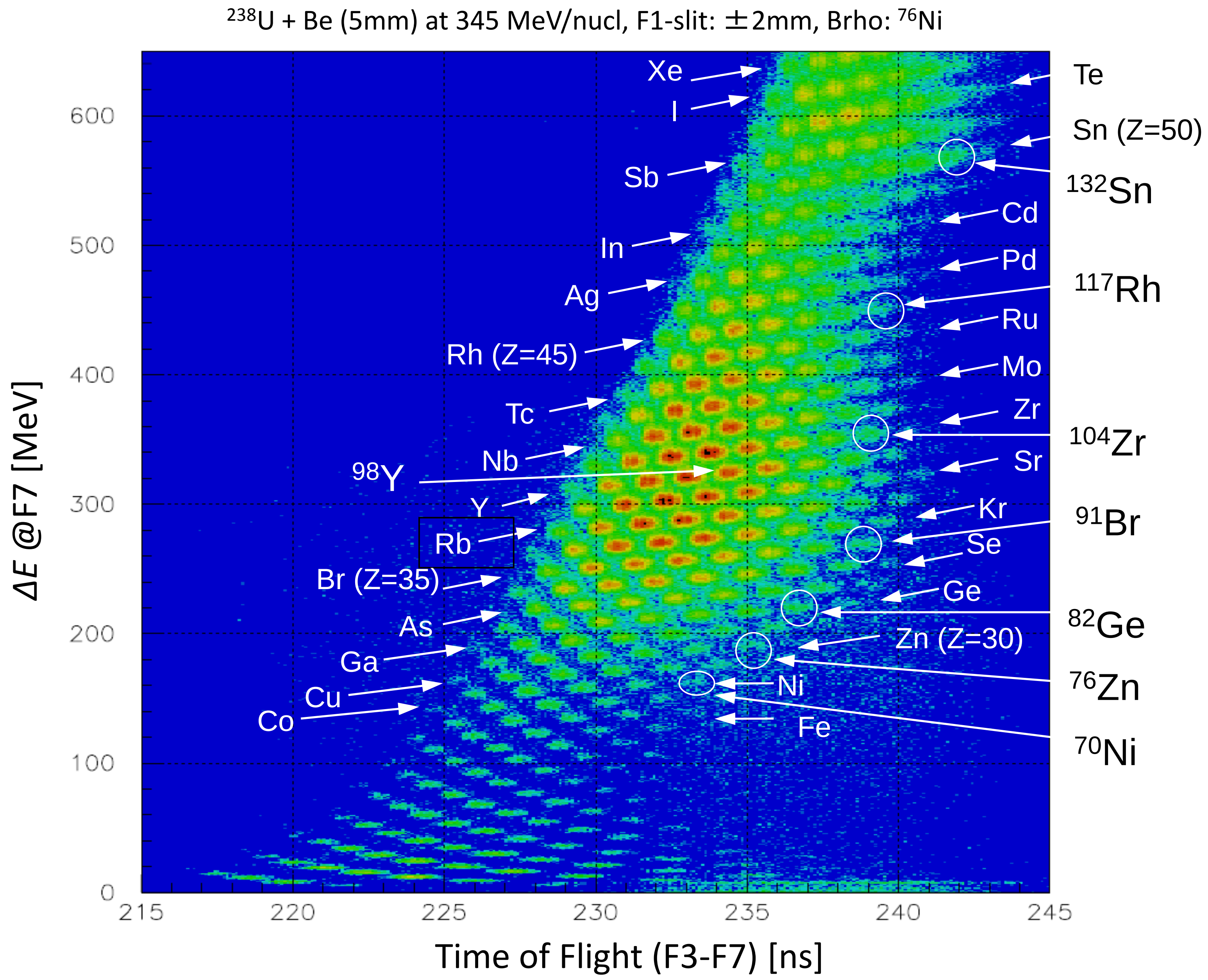
TOF-*B*ρ-Δ*E* method

$$\frac{A}{Q} = \frac{B\rho}{\gamma\beta}\frac{c}{m_{\mathrm{nucl}}}$$

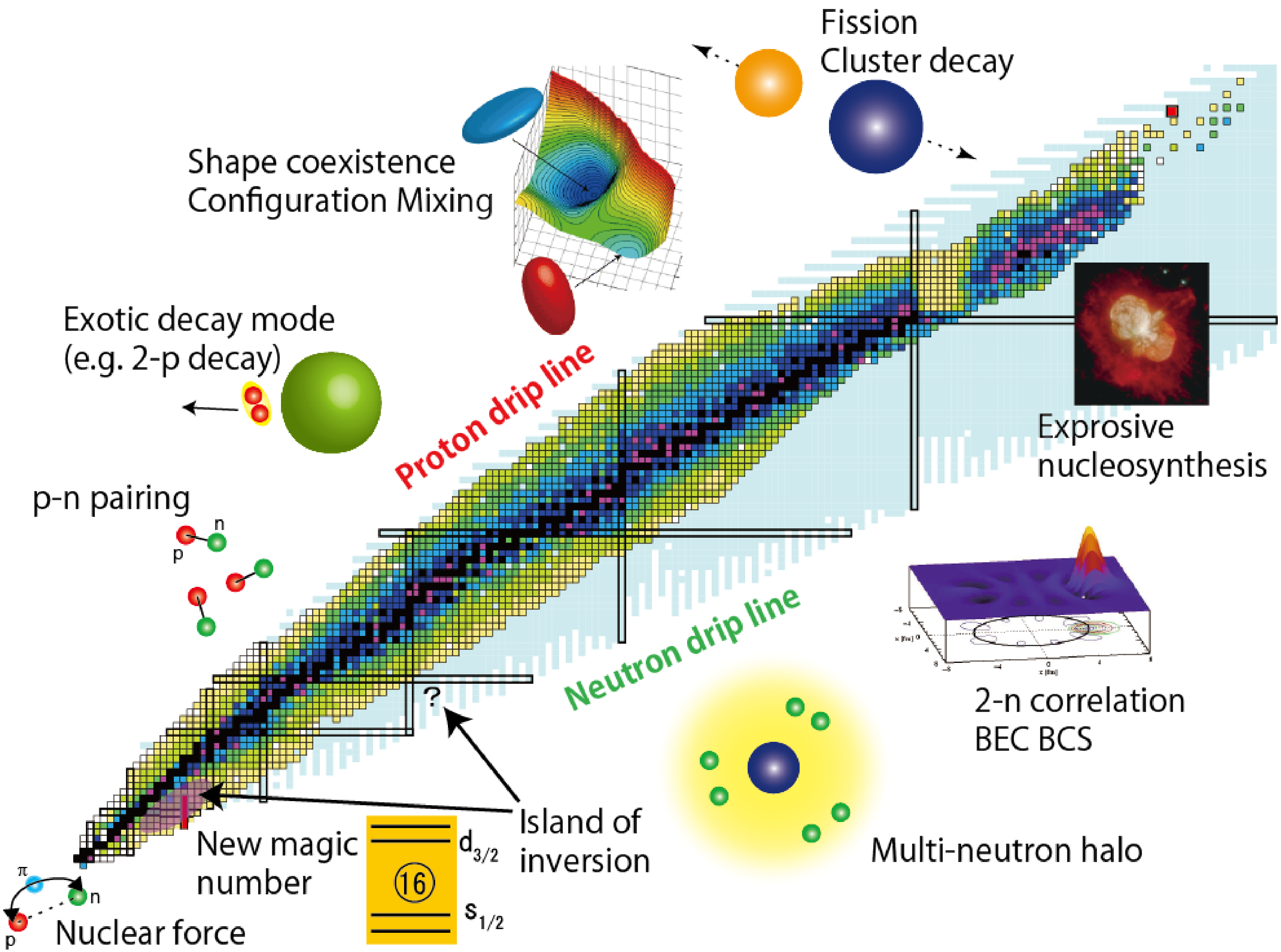
$$Z \leftarrow \Delta E = f(Z, \beta)$$

Bethe-Bloch formula

Example of PID plot



Different physics requires …



Different observables

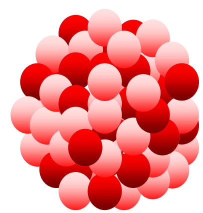
Mass

Excitation energy

Half-life

Decay scheme

Transition strength



Charge distribution

Cross sections

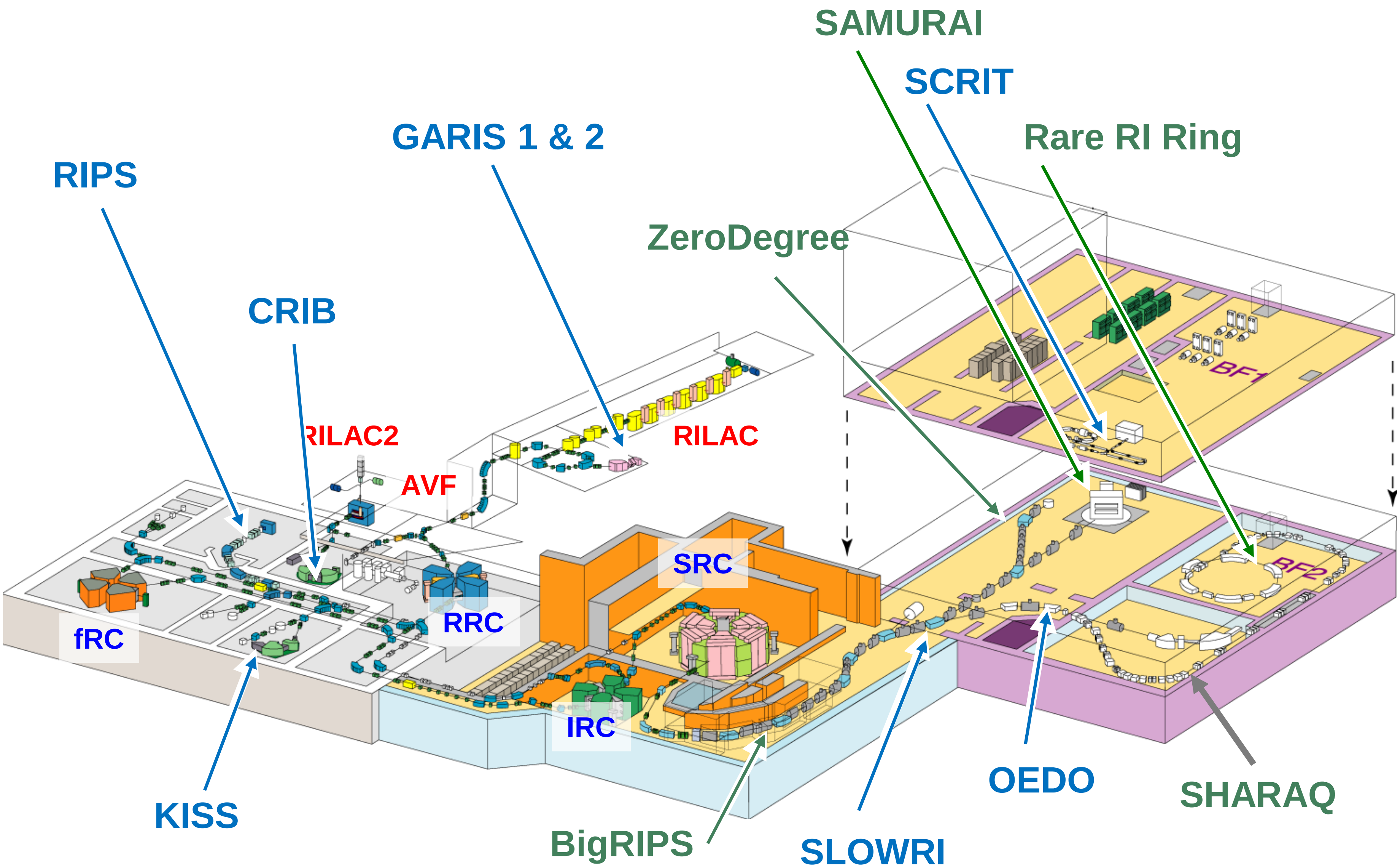
Matter distribution

Charge radius

Nuclear moment

Nuclear EOS

and Different devices



What are you interested in?

Limitation of existence

Shell evolution

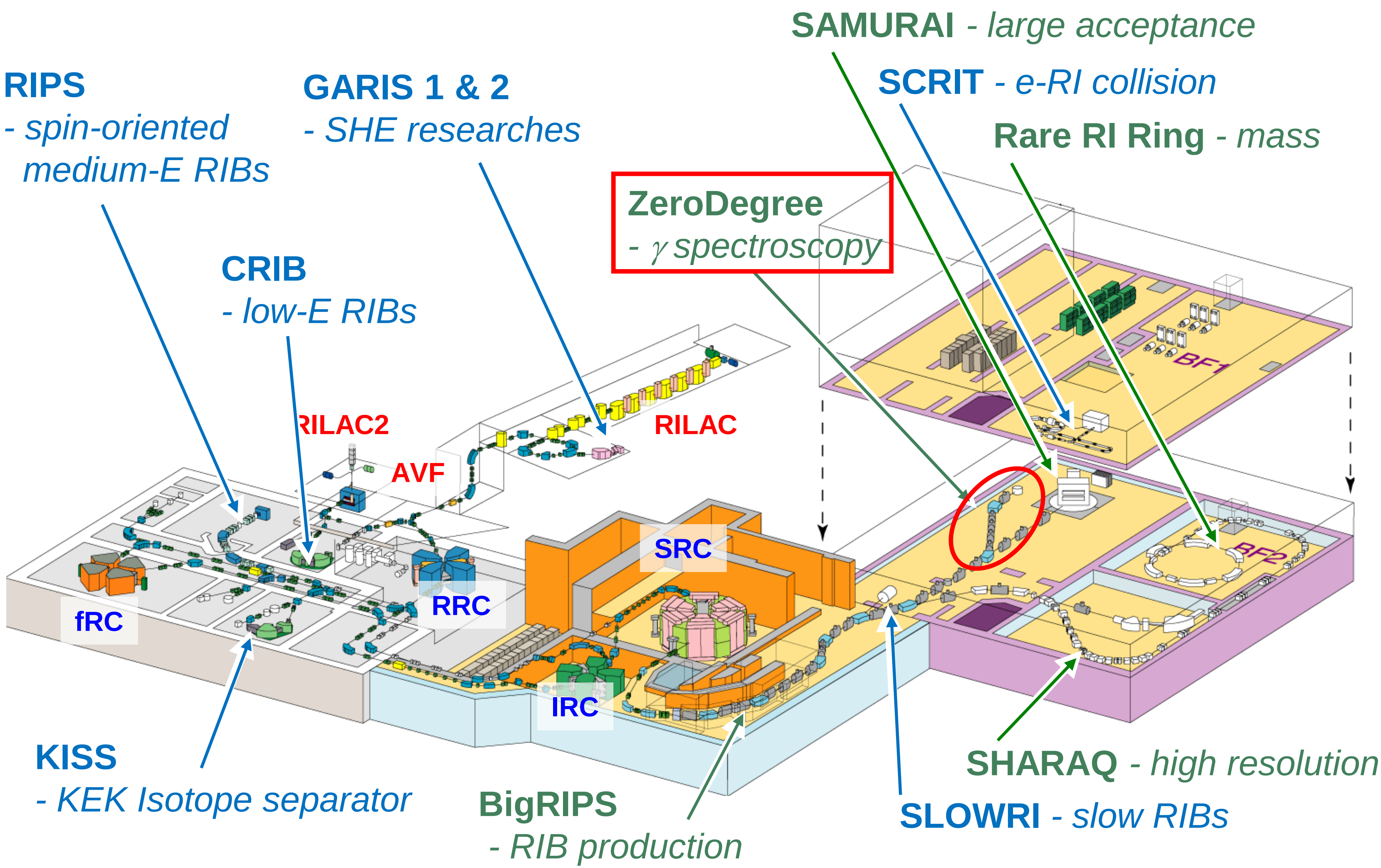
Collectivity

Nucleon correlation

Nuclear EOS

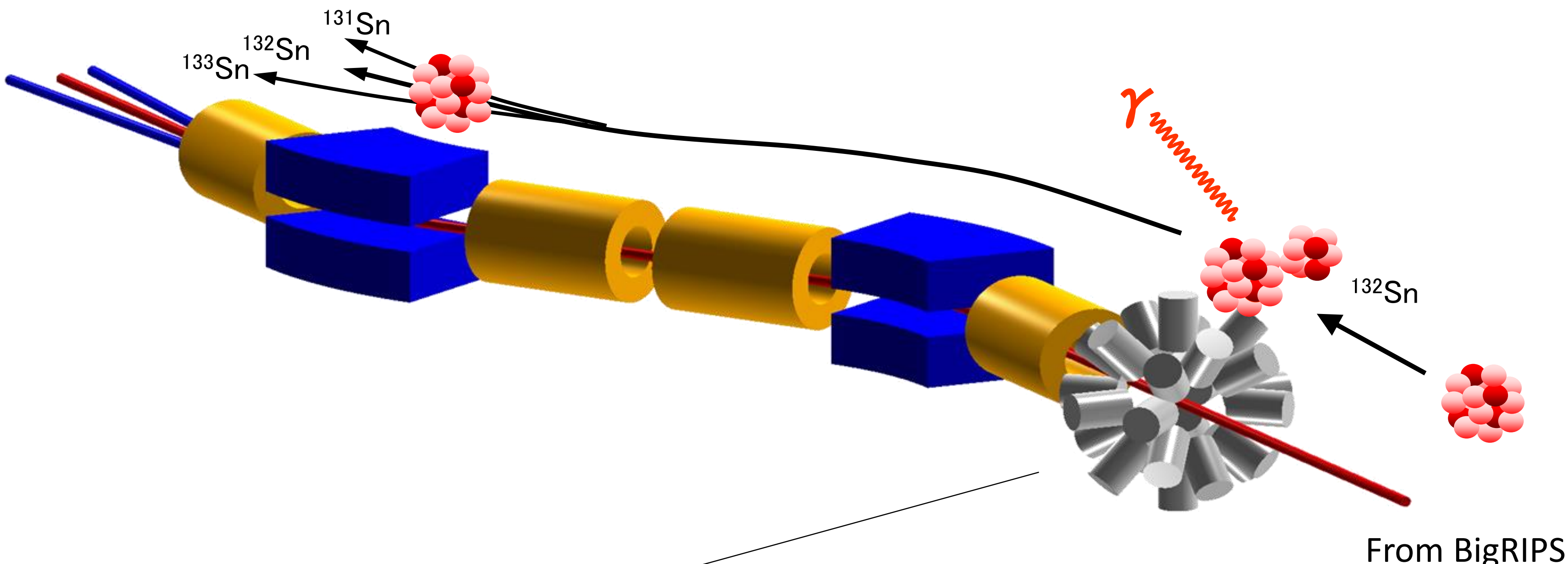
Nucleosynthesis

ZDS(Zero-degree spectrometer)



ZDS(Zero-degree spectrometer)

Spectrometer for in-beam gamma-ray measurement



Grape (Ge detectors): S. Shimoura, Nucl. Instr. Meth. B 525, 188 ('04)
DALI2 (NaI scintillators): S. Takeuchi *et al.*, Nucl. Instr. Meth. B 763, 596 ('14)

ZDS(Zero-degree spectrometer)

^{54}Ca and new magic number N = 34

LETTER

Nature 502, 207 ('13)

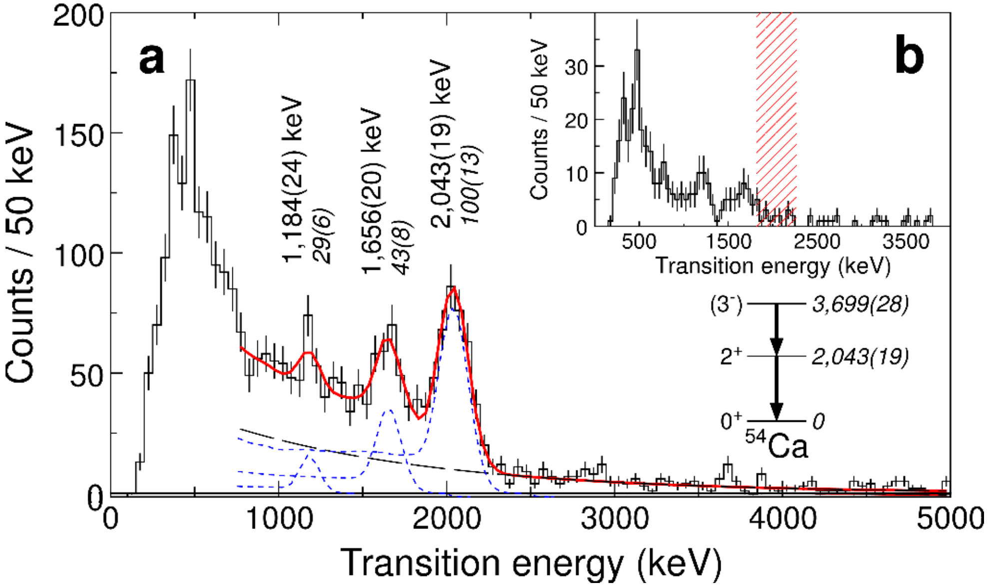
doi:10.1038/nature12522

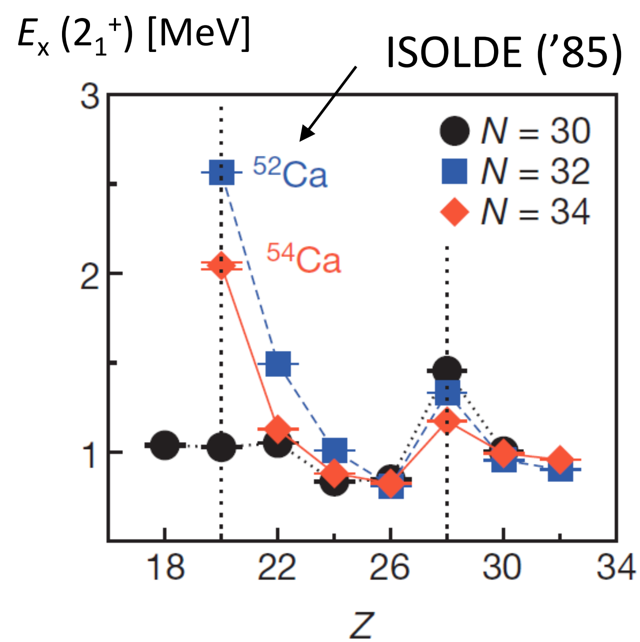
Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

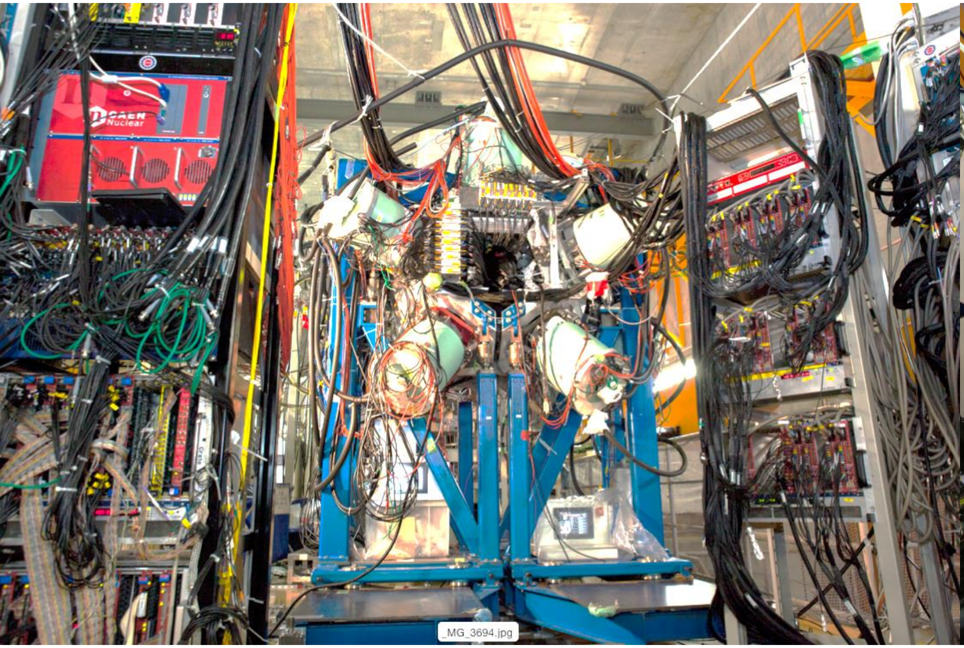
^{55}Sc/^{56}Ti on a 1.85 g/cm^2 Be target

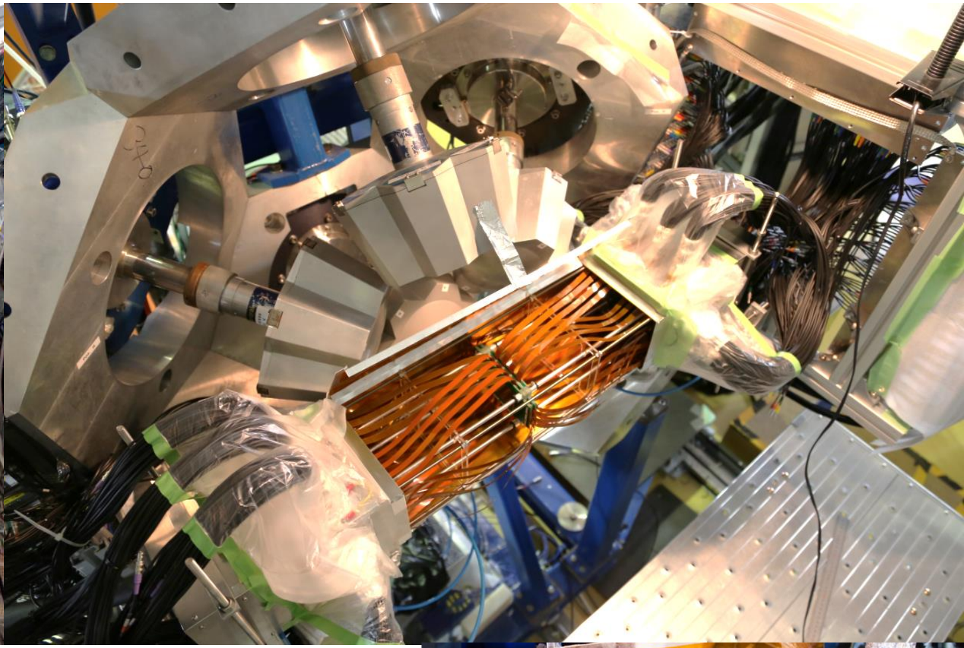
40 hours of data taking

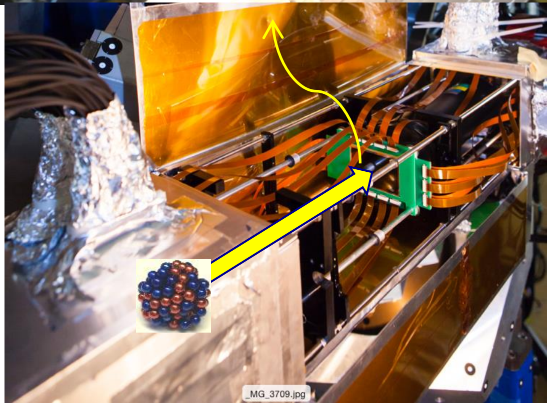




EURICA (Euroball RIKEN Cluster Array)





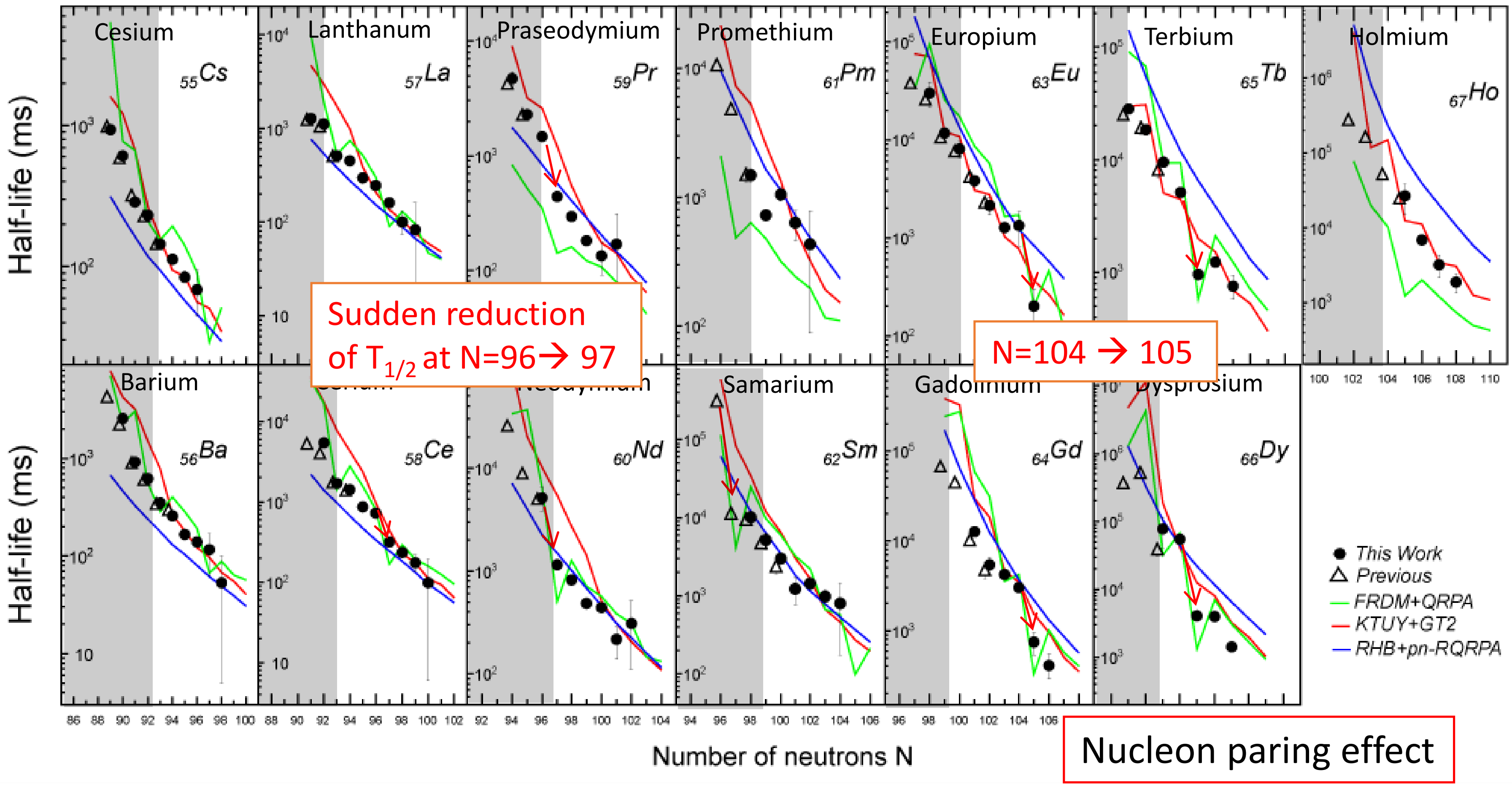


β-delayed γ-ray spectroscopy station at ZDS

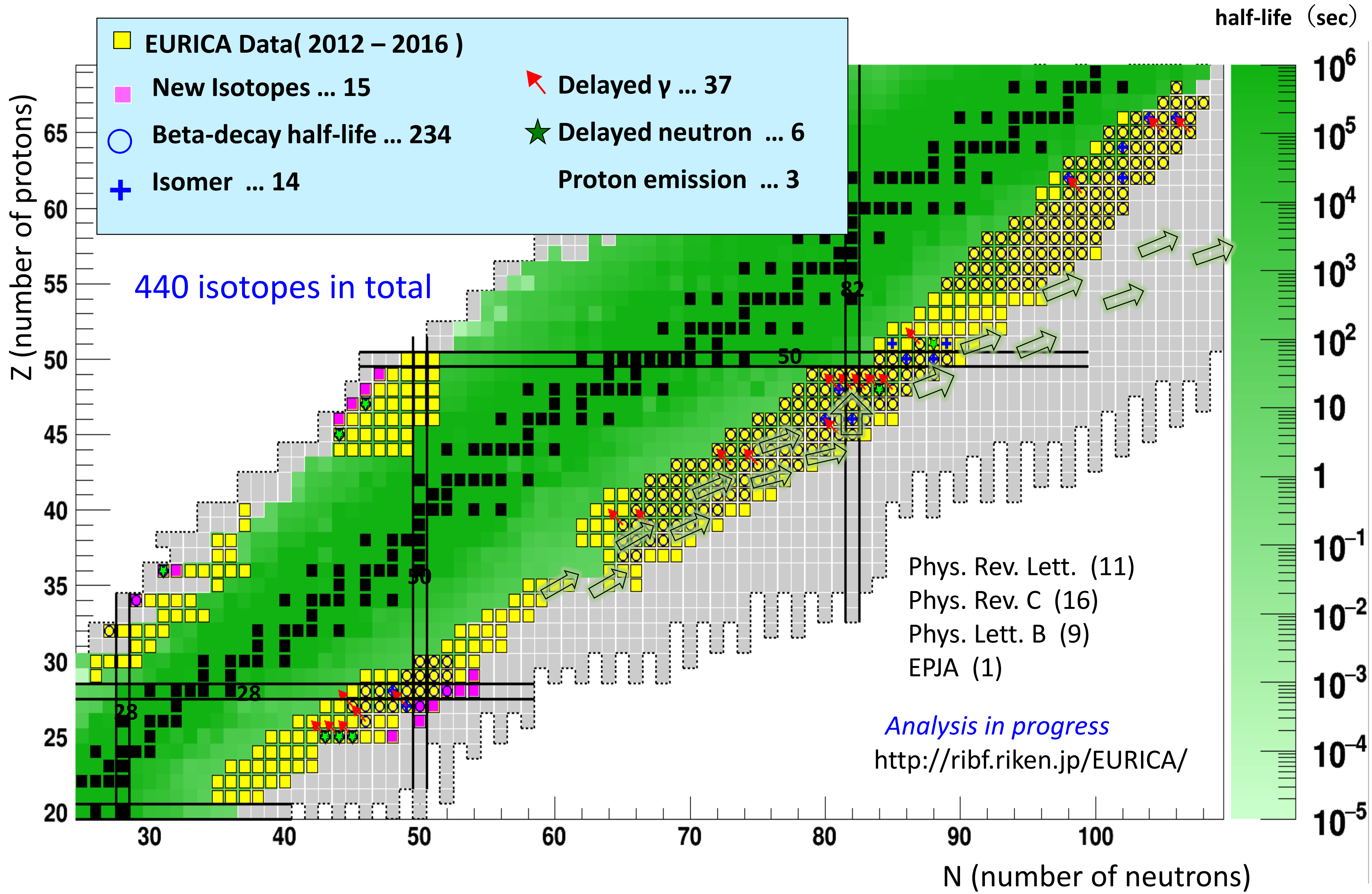
- 84 high-purity Ge crystals in 12 clusters
  - ❑ Resolution : 2.5 keV @1.3MeV
  - ❑ Efficiency : 13% @1MeV
- 8 double-sided strip silicon detector (DSSD)
  - ❑ 60 × 40 pixels
  - ❑ Detect β-ray from implanted radioactive nuclei

92 β-Decay Half-lives (Mass A = 144 – 175)

J. Wu, PRL 118, 072701 (2017)

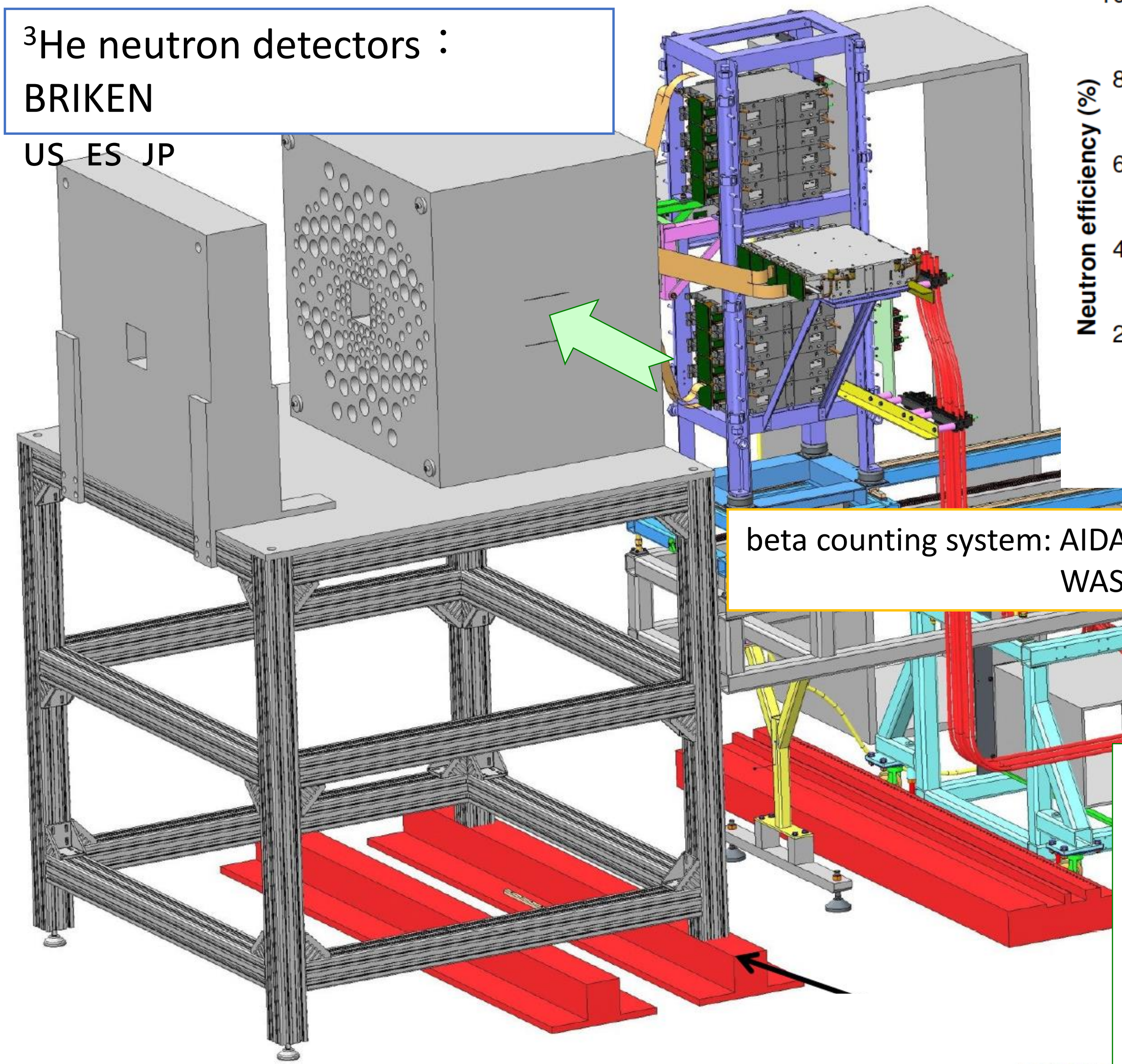


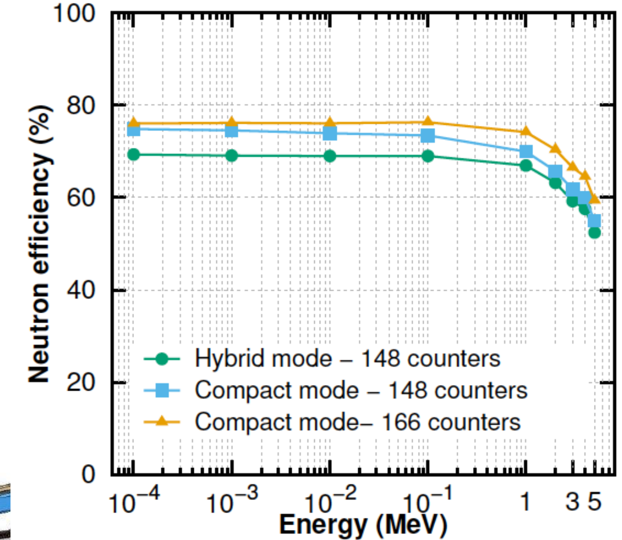
EURICA (2012 – 2016)



BRIKEN at ZDS (2016 ~)

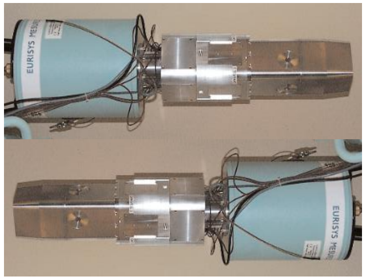
^{3}He neutron detectors：
BRIKEN
US ES JP





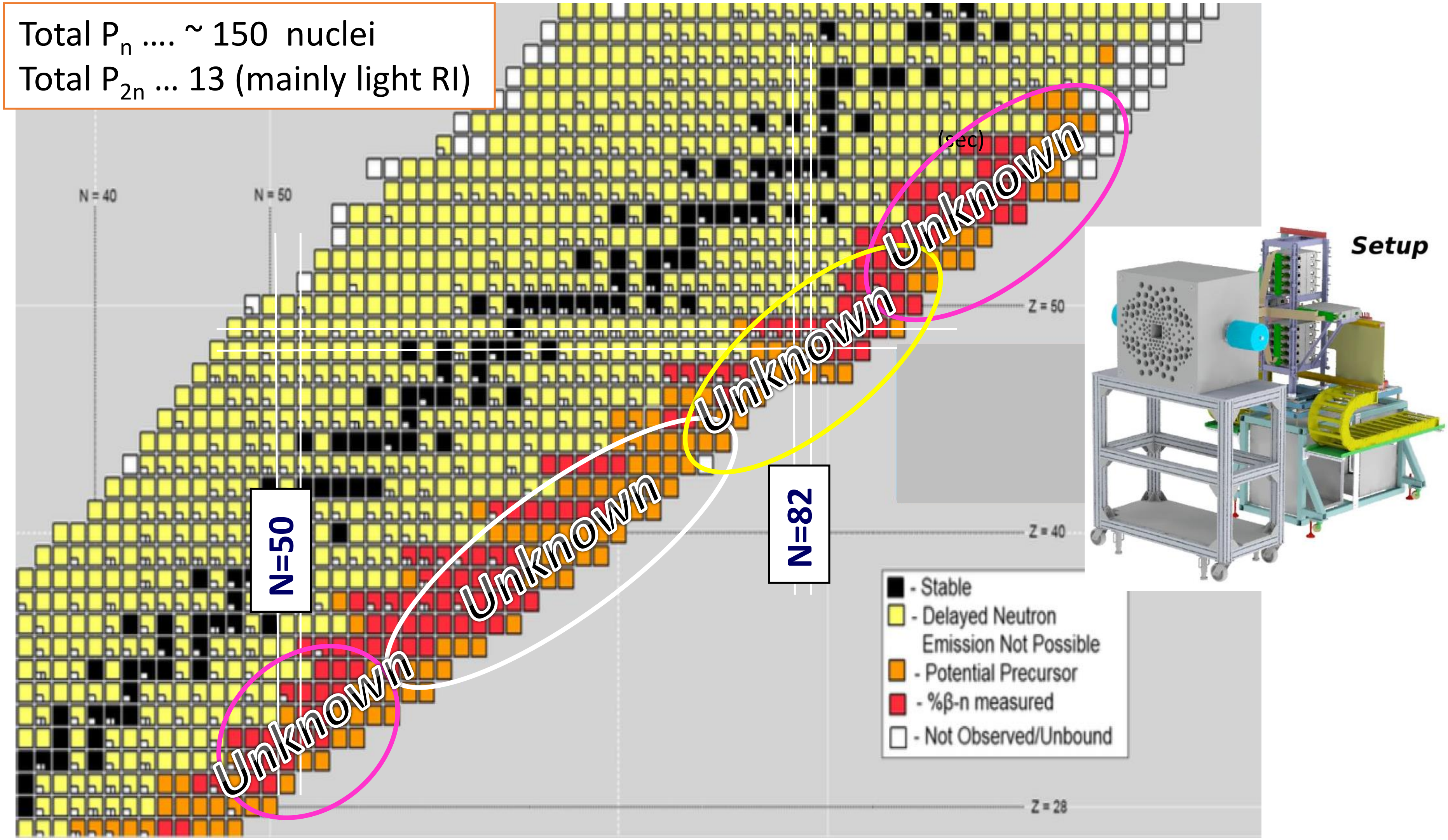
beta counting system: AIDA GB
WAS3ABi JP

γ-ray:
Two clover Ge detectors US



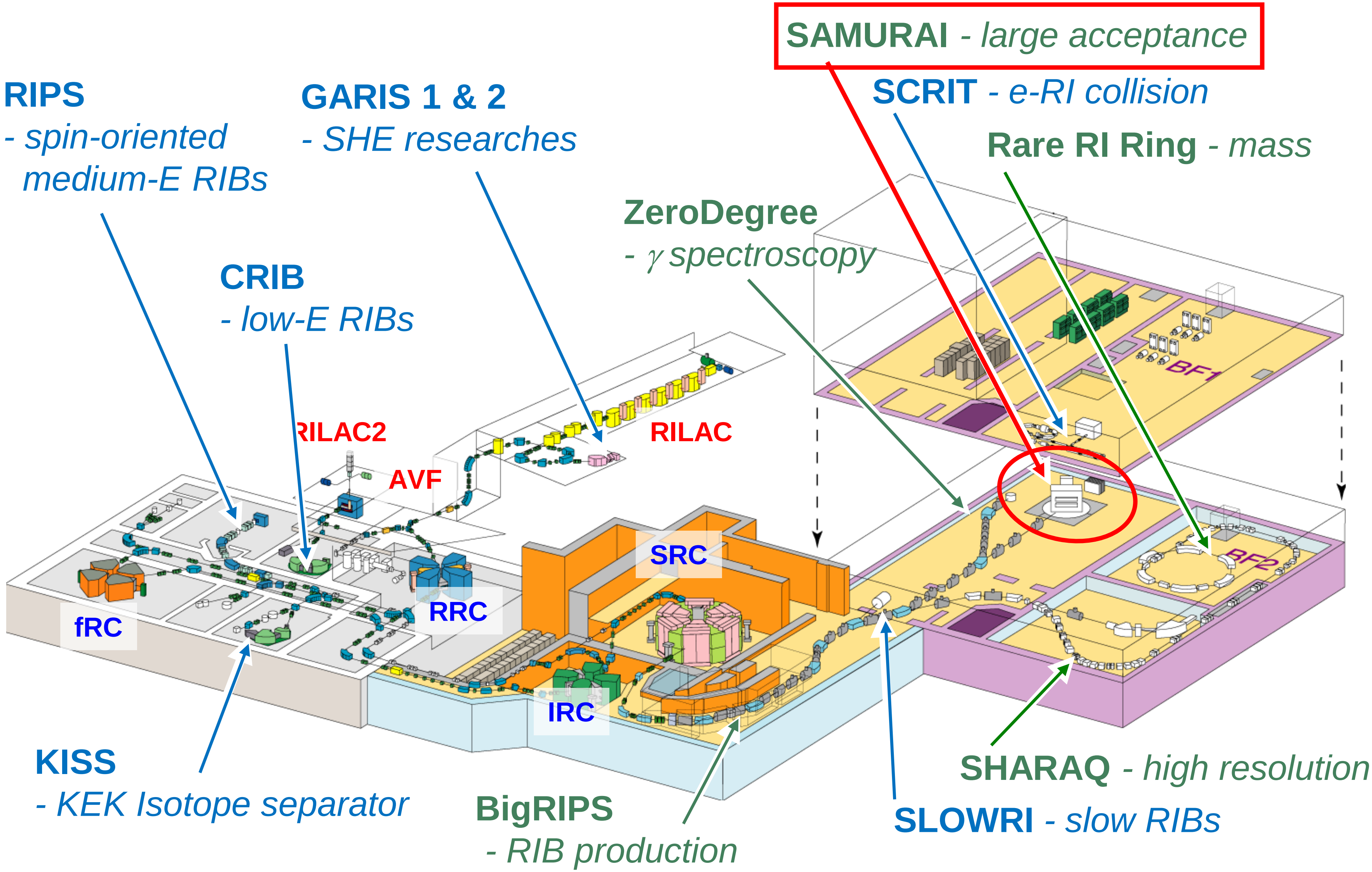
Beta-delayed neutron emission probabilities

Total P_n …. ~ 150 nuclei
Total P_{2n} … 13 (mainly light RI)



Several hundreads of beta-delayed neutron emission P_n (n) together with $T_{1/2}$ (β) & level scheme (γ)

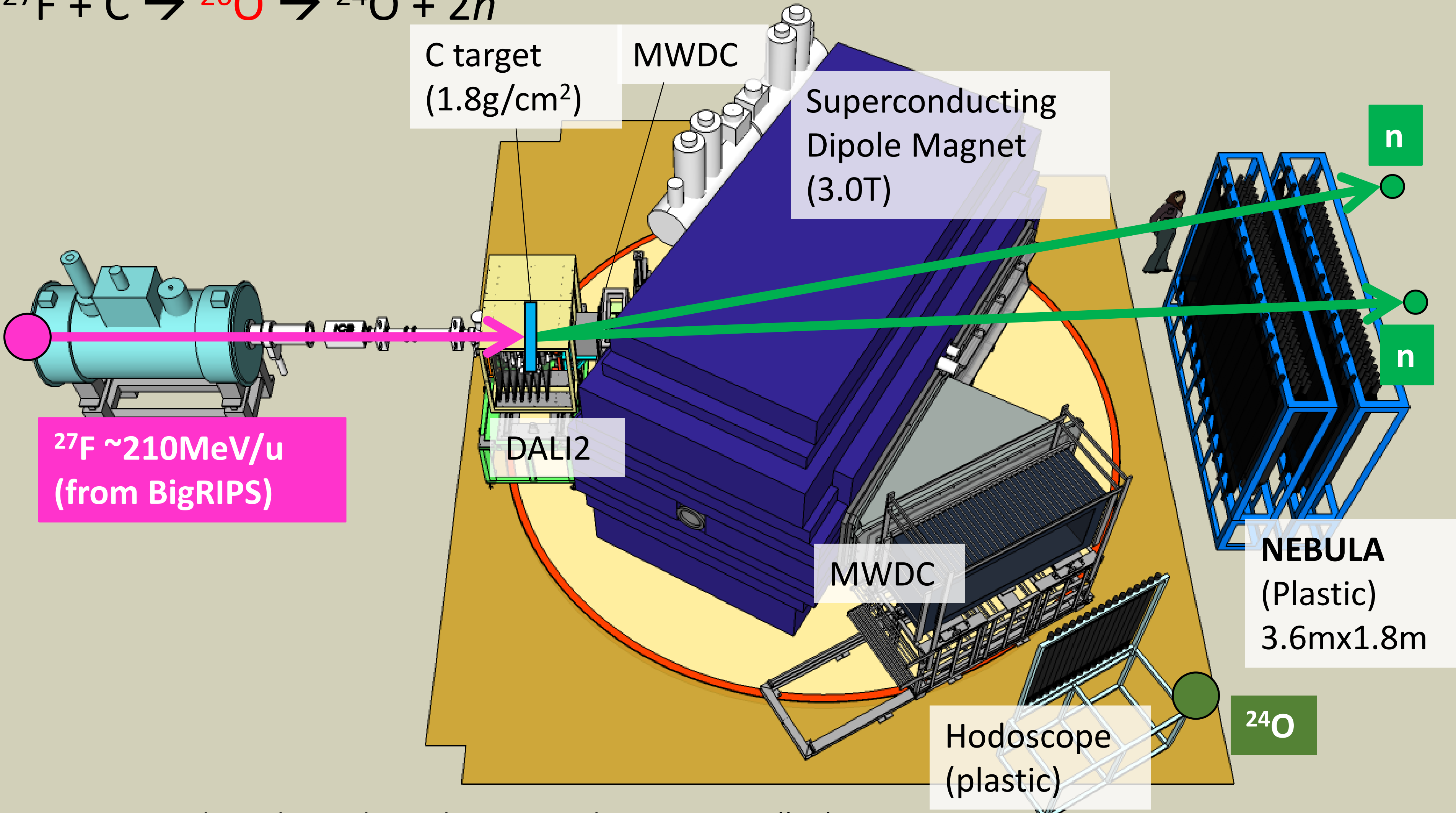
SAMURAI


SAMURAI - large acceptance
SCRIT - e-RI collision
Rare RI Ring - mass
RIPS
- spin-oriented
medium-E RIBs
GARIS 1 & 2
- SHE researches
ZeroDegree
- γ spectroscopy
CRIB
- low-E RIBs
RILAC2
RILAC
AVF
BF1
BF2
SRC
RRC
fRC
IRC
KISS
- KEK Isotope separator
BigRIPS
- RIB production
SHARAQ - high resolution
SLOWRI - slow RIBs

SAMURAI

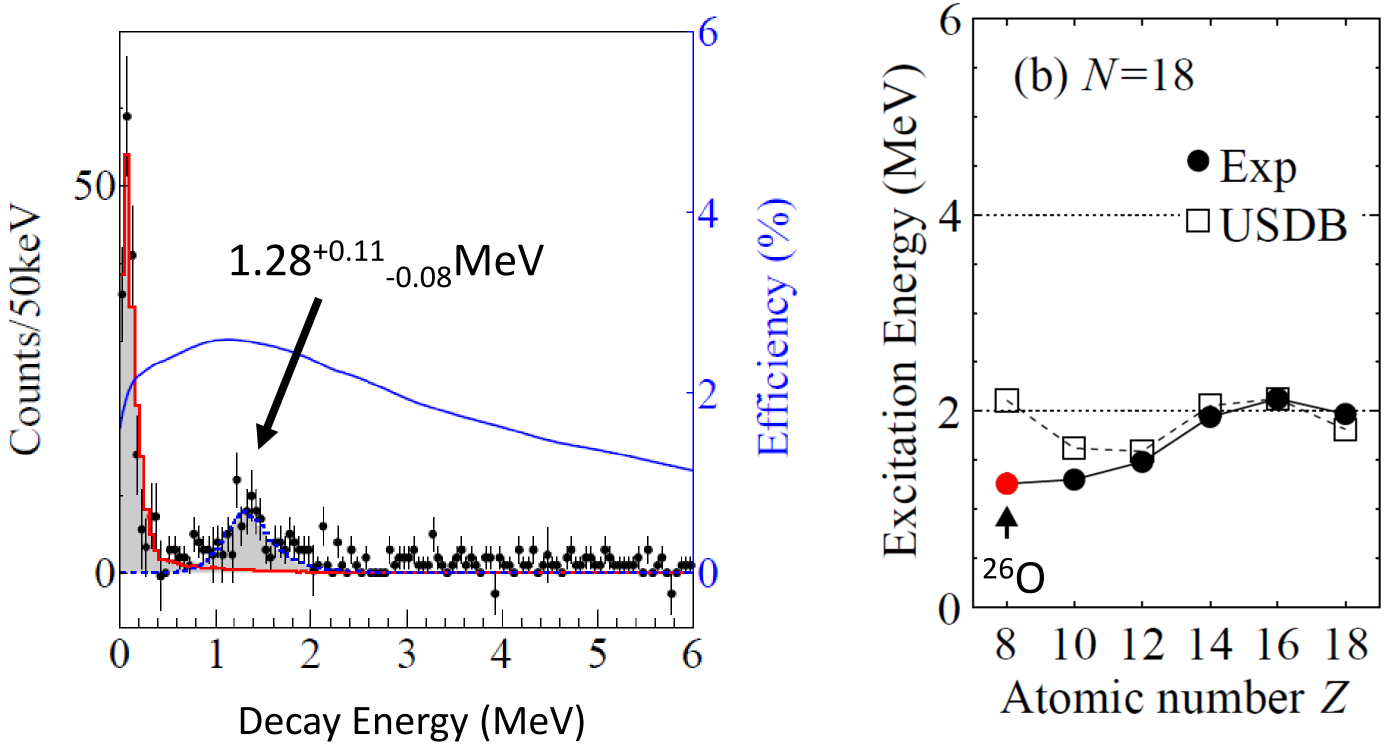
Superconducting Analyzer for MUlti-particle from RAdioIsotope beams

$^{27}F + C \rightarrow {}^{26}O \rightarrow {}^{24}O + 2n$



Samurai: T. Kobayashi *et al.*, Nucl. Instr. Meth. A 317, 294 ('13)

First 2^+ state of unbound ^{26}O



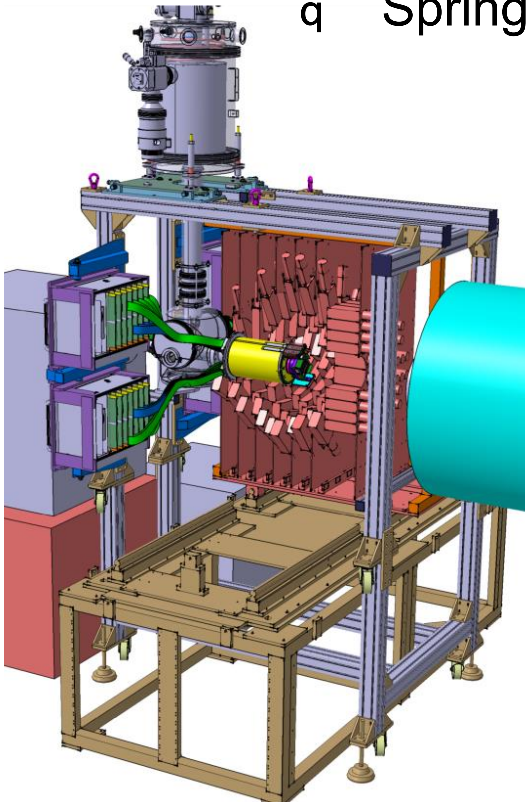
- USDB cannot reproduce the 2^+ energy of ^{26}O
- Effect of *pf* shell? and/or continuum? Or other effects (such as 3N forces, 2n correlation)
- Further studies are desired to pin down the various effects quantitatively. (Experiment was done for ^{27}O and ^{28}O.)

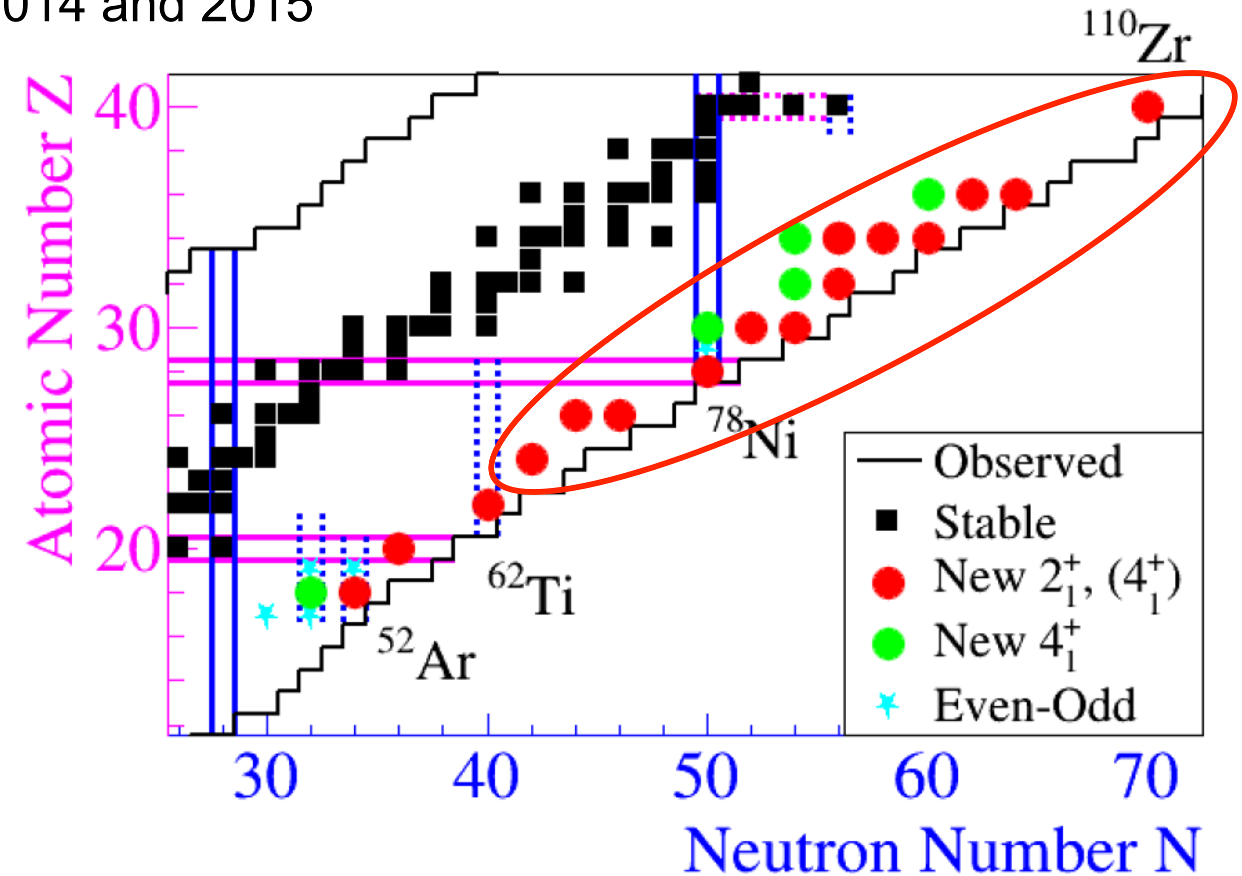
Y. Kondo *et al.*, Phys. Rev. Lett. 116, 102503 ('16)

SEASTAR at ZDS

Shell evolution and search for 2^+ energies

- First 2 campaigns at F8 (Zero Degree Spectrometer)
- Spring 2014 and 2015

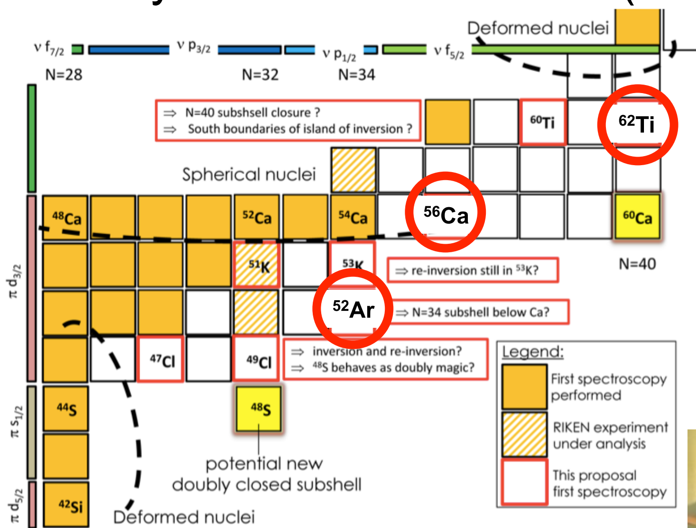




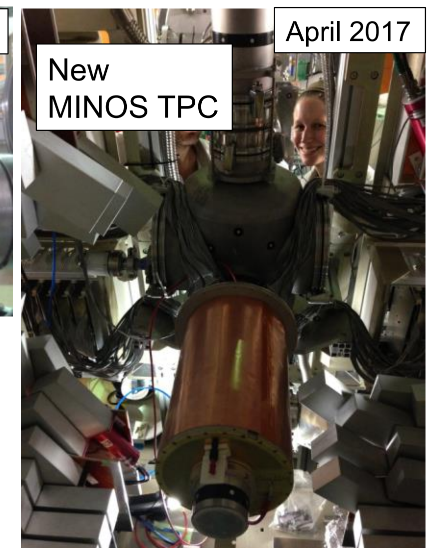
http://www.nishina.riken.jp/collaboration/SUNFLOWER/

SEASTAR3 at SAMURAI

focus on medium-mass nuclei with A<62 (good Z,A separation at reach)
low neutron separation energy (benefit from neutron detection)
many reactions of interest (benefit from large momentum acceptance)



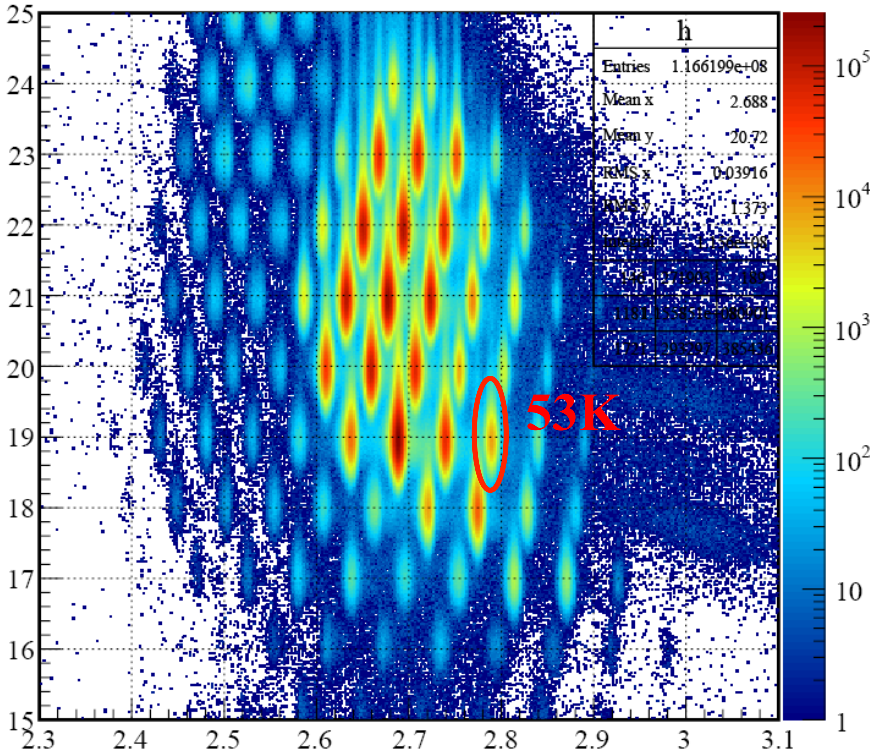
Target: 150 mm
[75 kg.m^{-3}]



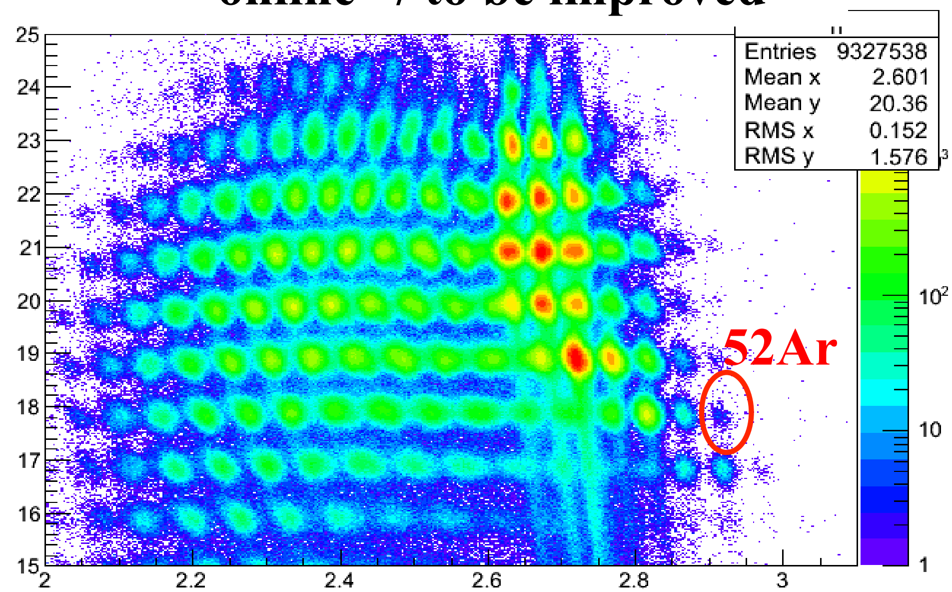
DALI2+:
226 detectors
5.5% @ 1.3 MeV
+20% in eff.

SEASTAR3 at SAMURAI

In total ^{53}K: 6. 1E^5 counts
Beam PID (online)



Fragment PID (13 runs)
"online" / to be improved

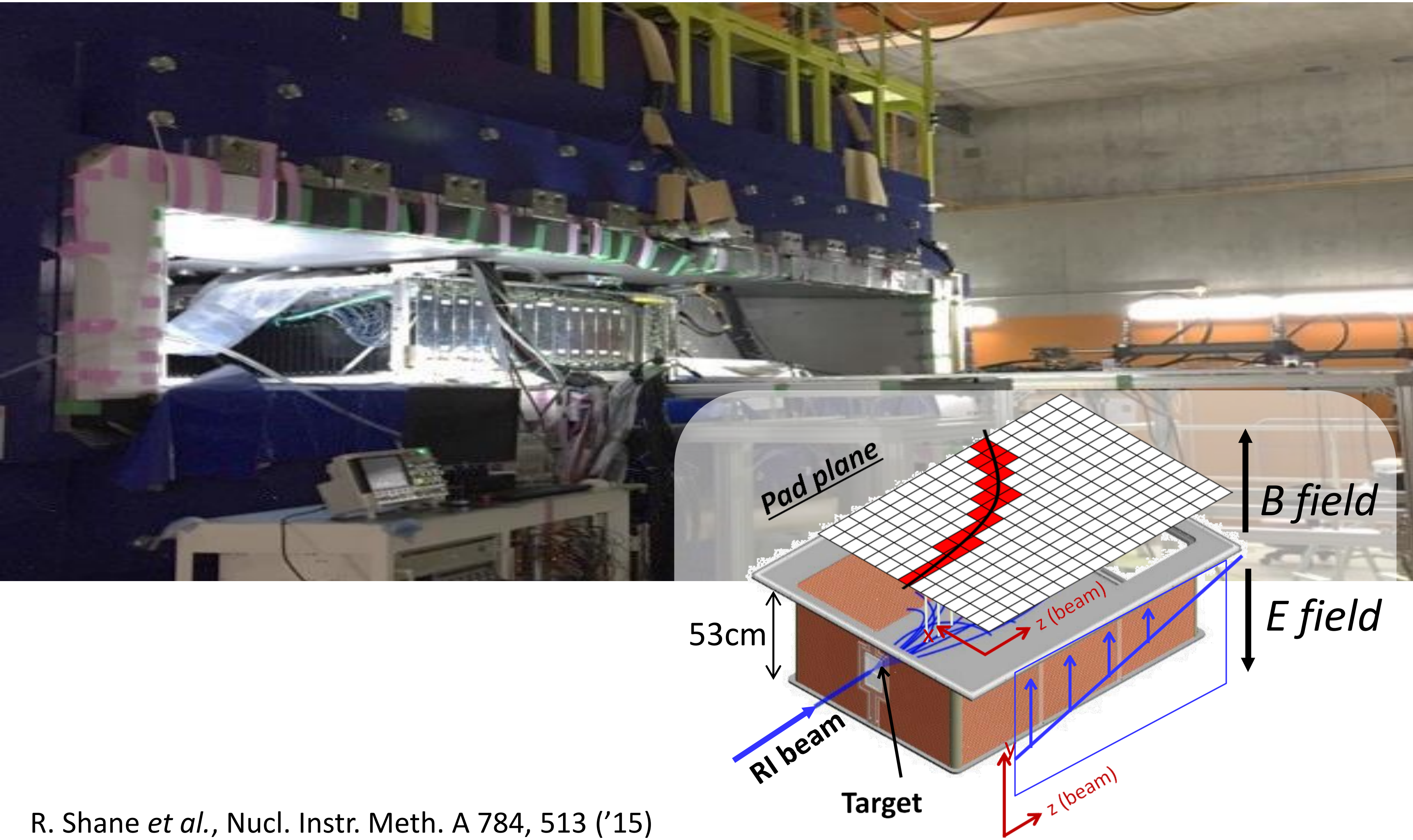


σ_A (FWHM) = 0.13
σ_Z (FWHM) = 0.51

σ_A (FWHM) = 0.34
σ_Z (FWHM) = 0.29

SPiRIT
(SAMURAI Pion Reconstruction and Ion Tracker)

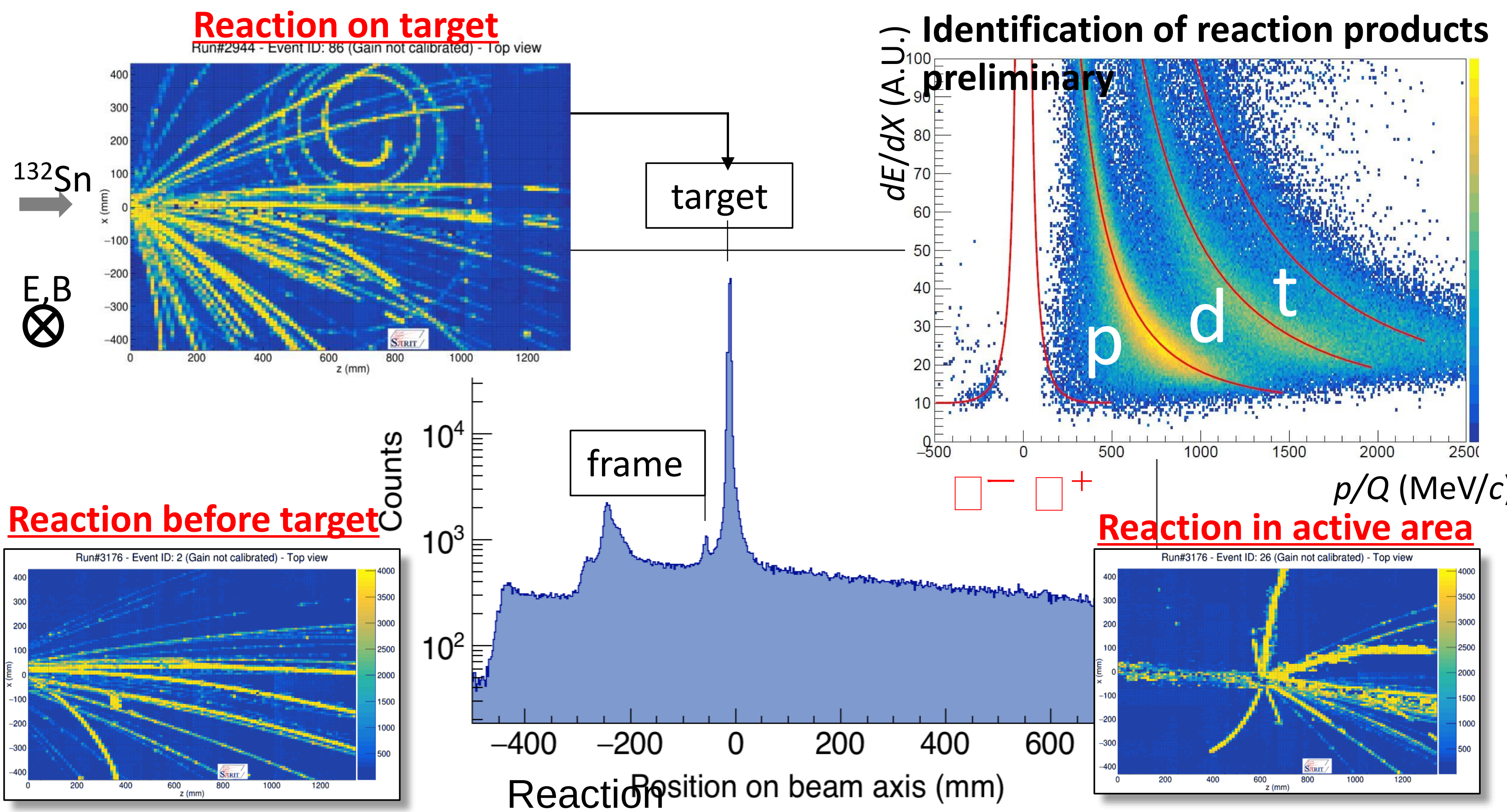
Nuclear equation of state via π^+/π^- production ratio in heavy RI collision



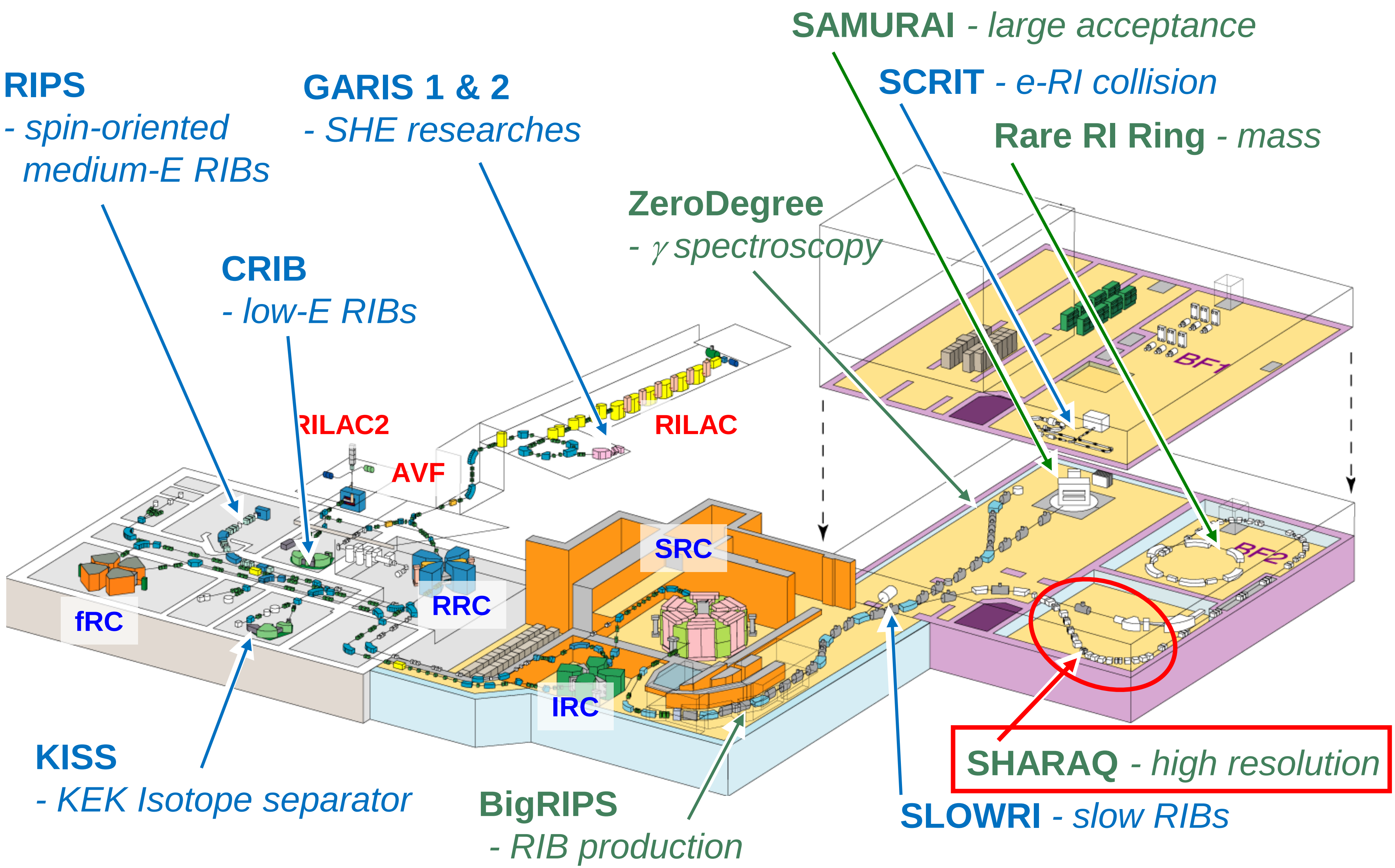
R. Shane *et al.*, Nucl. Instr. Meth. A 784, 513 ('15)

SPiRIT
(SAMURAI Pion Reconstruction and Ion Tracker)

Sn @280 MeV/u + Sn (Apr.-Mar. 2016)



SHARAQ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GARIS 1 & 2
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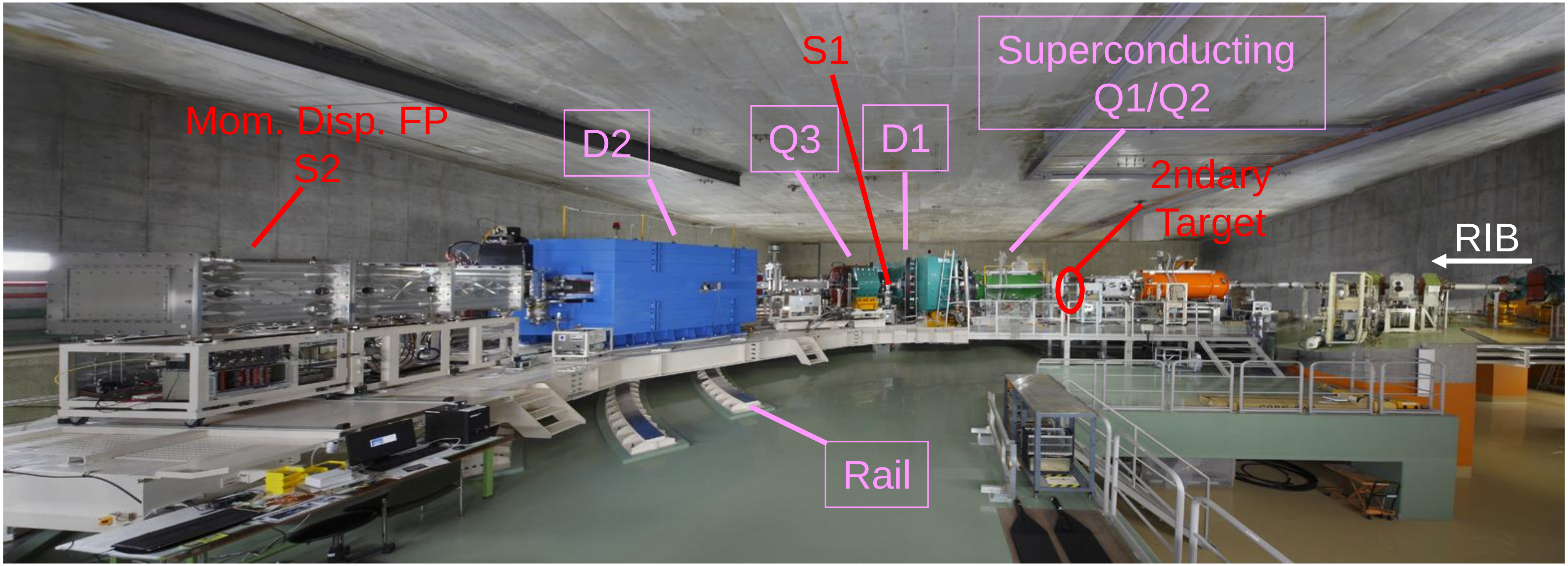
- γ spectroscopy
CRIB
- low-E RIBs
RILAC2
RILAC
AVF
BF1
BF2
SRC
RRC
fRC
IRC
KISS
- KEK Isotope separator
BigRIPS
- RIB production
SHARAQ - high resolution
SLOWRI - slow RIBs

SHARAQ

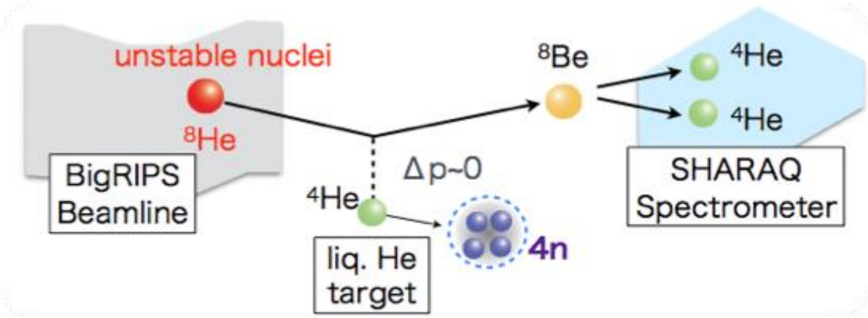
Spectroscopy using RI beam as a reaction probe



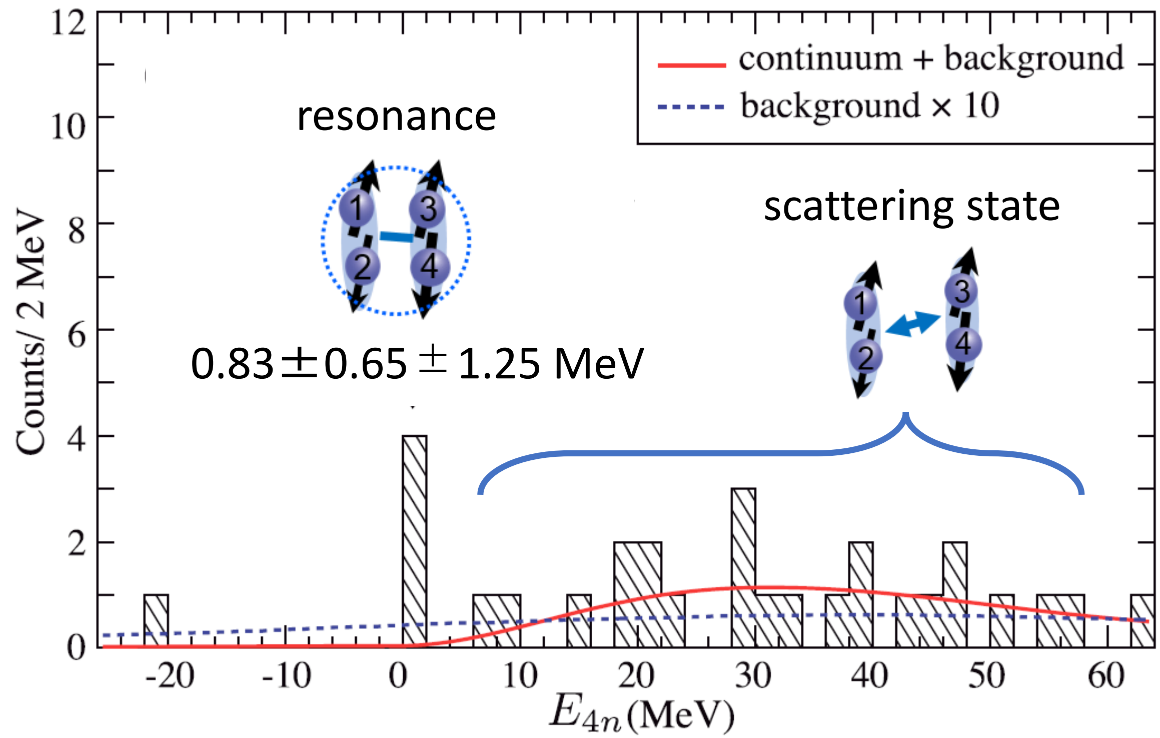
T. Uesaka *et al.*, Nucl. Instr. Meth. B 266, 4218 (’08)
T. Uesaka, S. Shimoura, and H. Sakai, Prog. Theor. Exp. Phys. 03C007 (’12)

SHARAQ

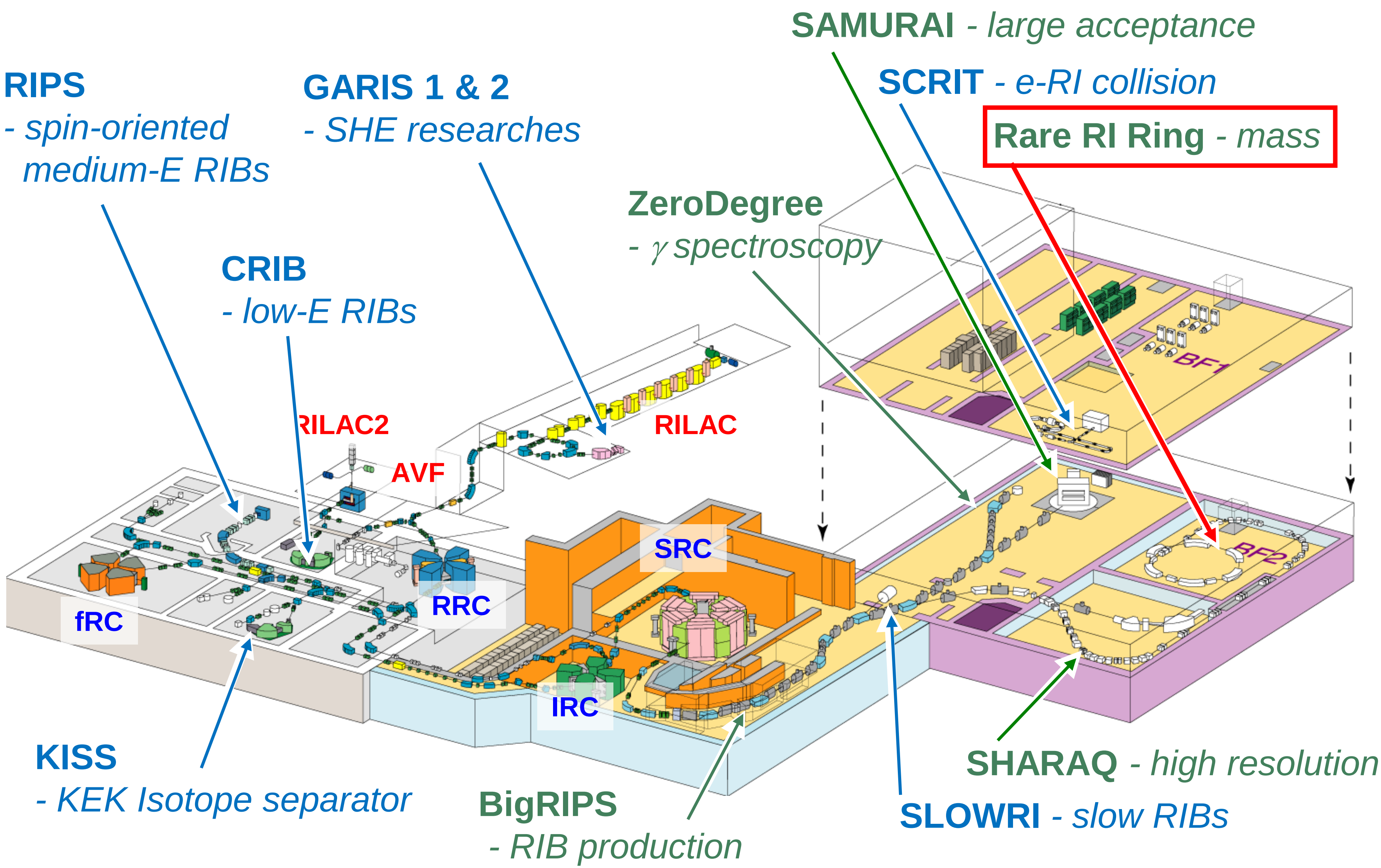
Neutral nucleus ‘tetraneutron’ candidate



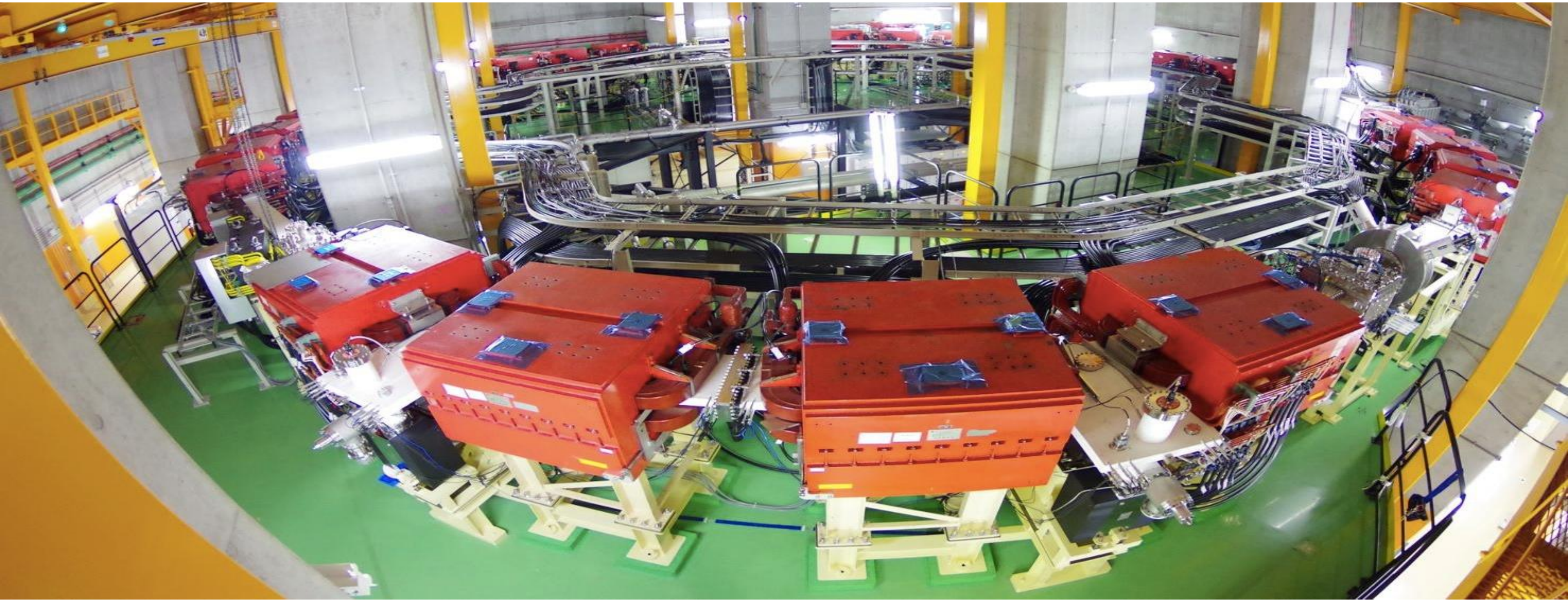
Kisamori *et al.*,
Phys. Rev. Lett. 116, 052501 (’16)



Rare RI Ring (R3)



Rare RI Ring (R3)

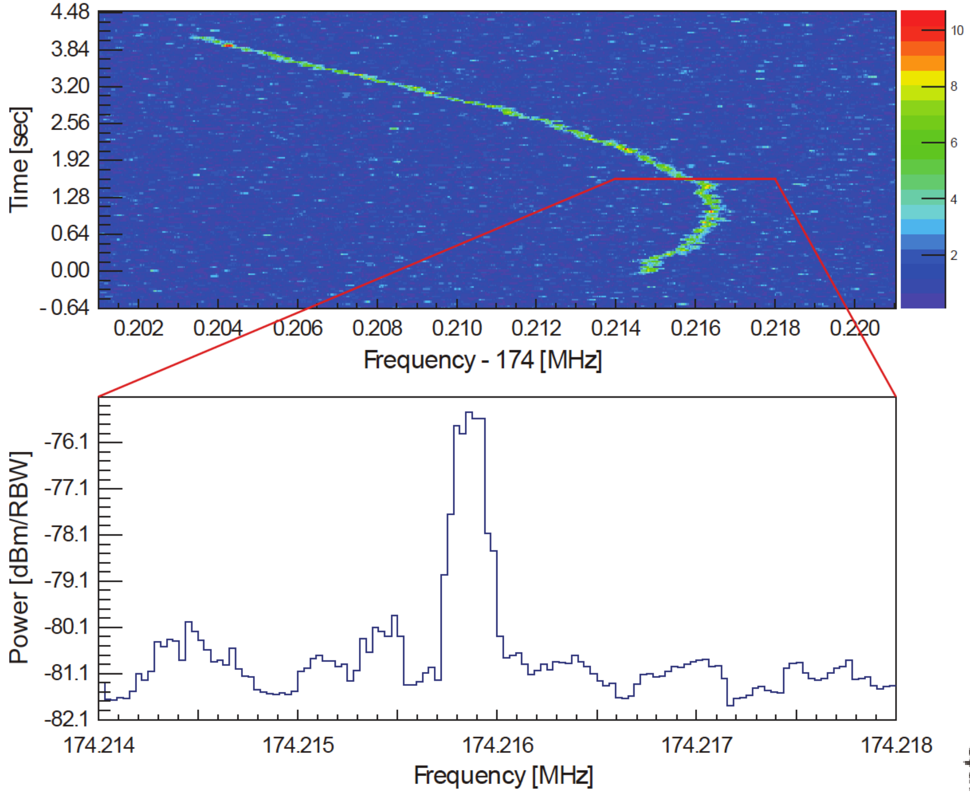


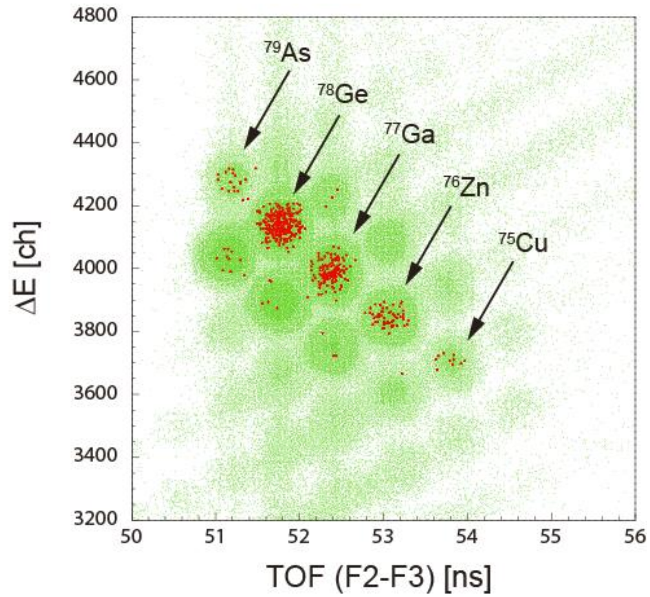
Mass measurement in an ‘isochronous’ storage ring

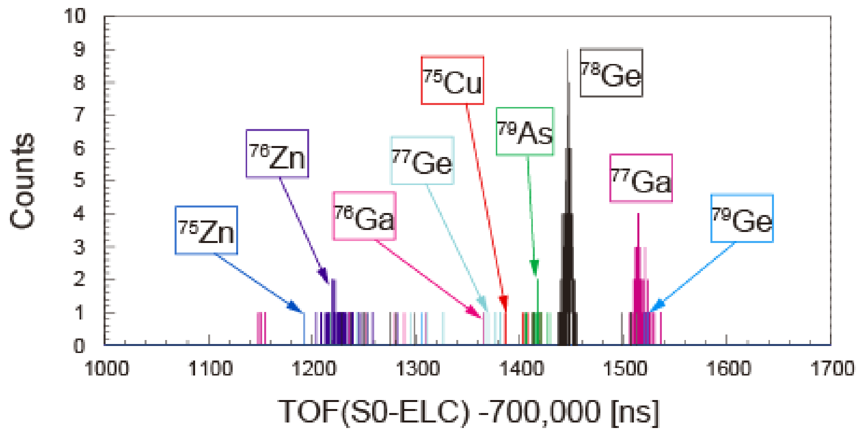
$$f_c = \frac{1}{2\pi}\frac{qB}{m}$$

Rare RI Ring (R3)

Stable $^{78}Kr^{36+}$ beam (June '15)





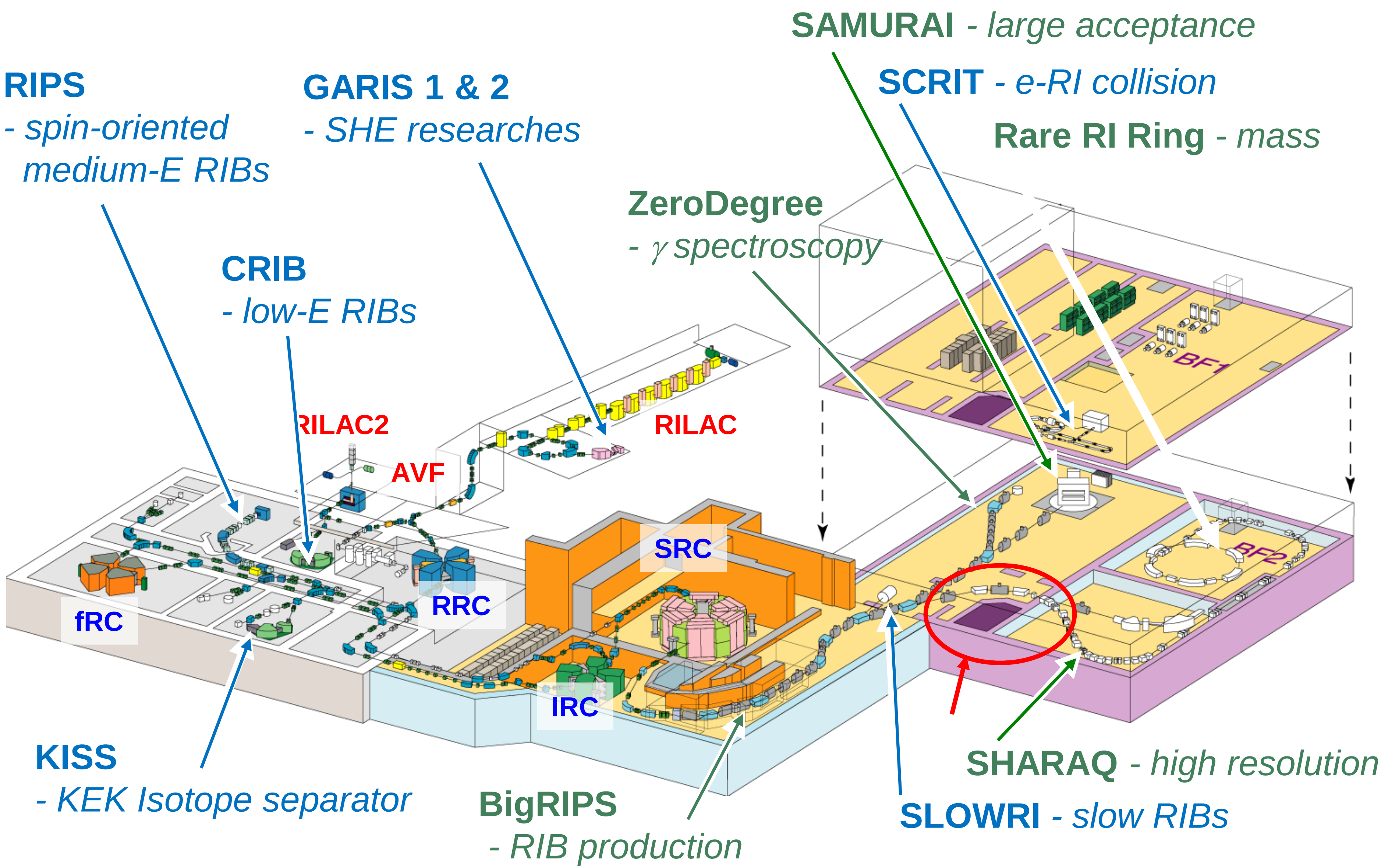


1 particle/day

$\tau_{measure} < 1$ ms

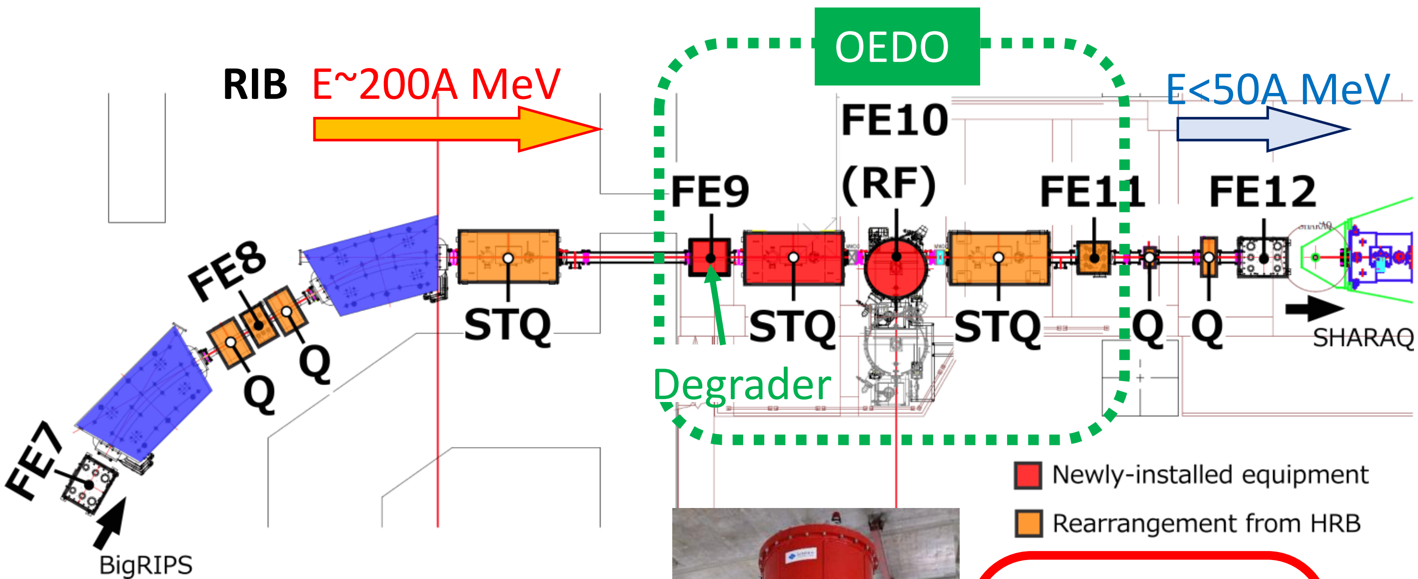
$\Delta M/M = 10^{-6}$

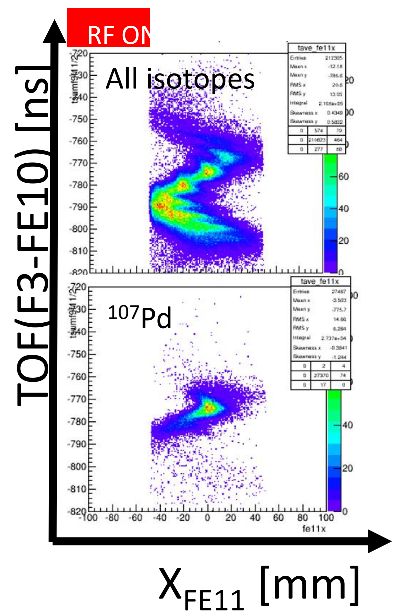
OEDO


RIPS
- spin-oriented medium-E RIBs
GARIS 1 & 2
- SHE researches
SAMURAI - large acceptance
SCRIT - e-RI collision
Rare RI Ring - mass
ZeroDegree
- γ spectroscopy
CRIB
- low-E RIBs
RILAC2
RILAC
AVF
BF1
BF2
SRC
RRC
fRC
IRC
KISS
- KEK Isotope separator
BigRIPS
- RIB production
SHARAQ - high resolution
SLOWRI - slow RIBs

OEDO

Rep. on Commissioning
2017/6/15-21





OEDO RFD

f_{RF} = 18.25 MHz

V_{max} = 350 kV

Gap(H) = 200 mm

L (Z) = 1200 mm

W(V) = 400 mm

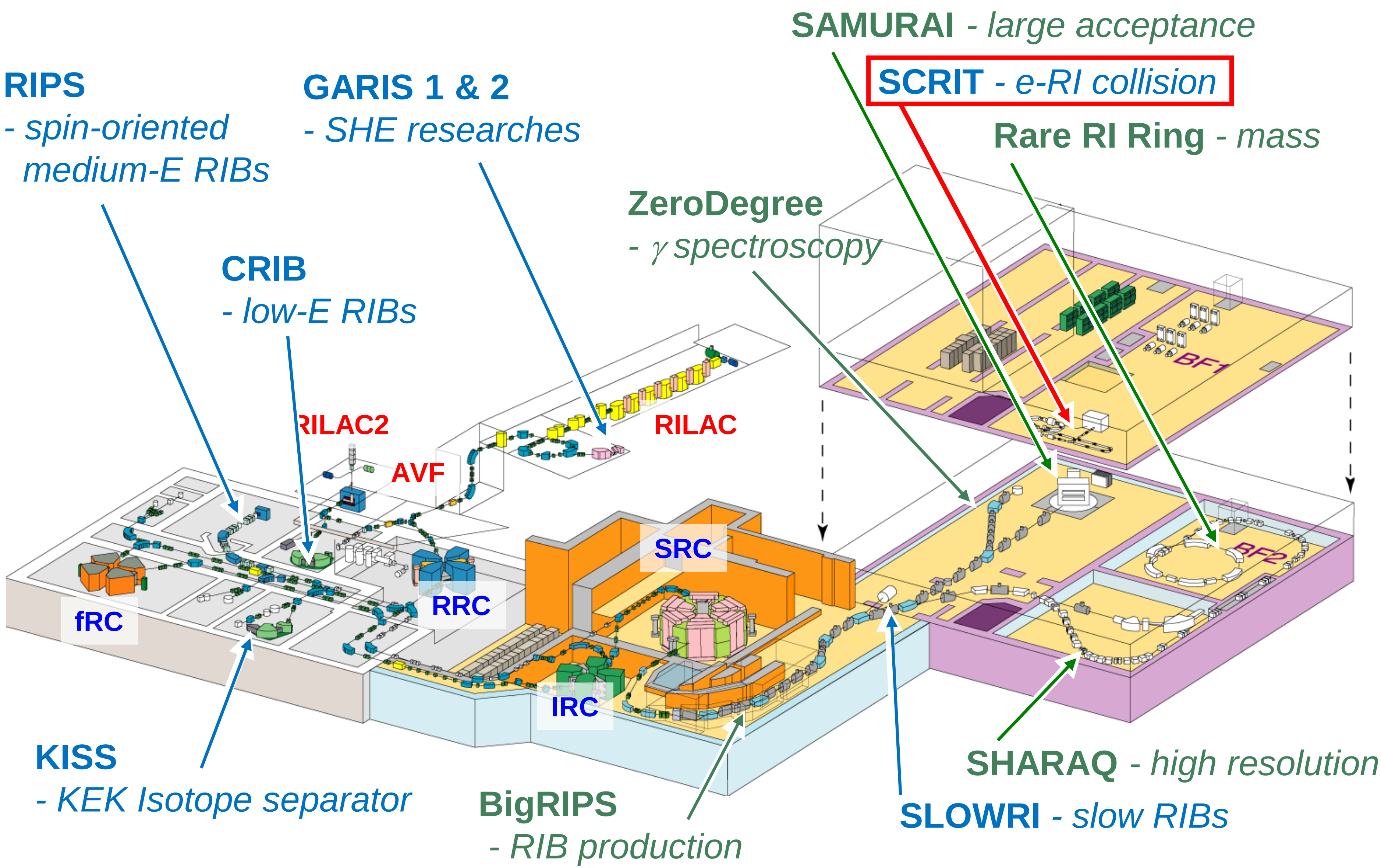
^{107}Pd:

170A MeV → 33A MeV

20mm(FWHM) @ 2nd target

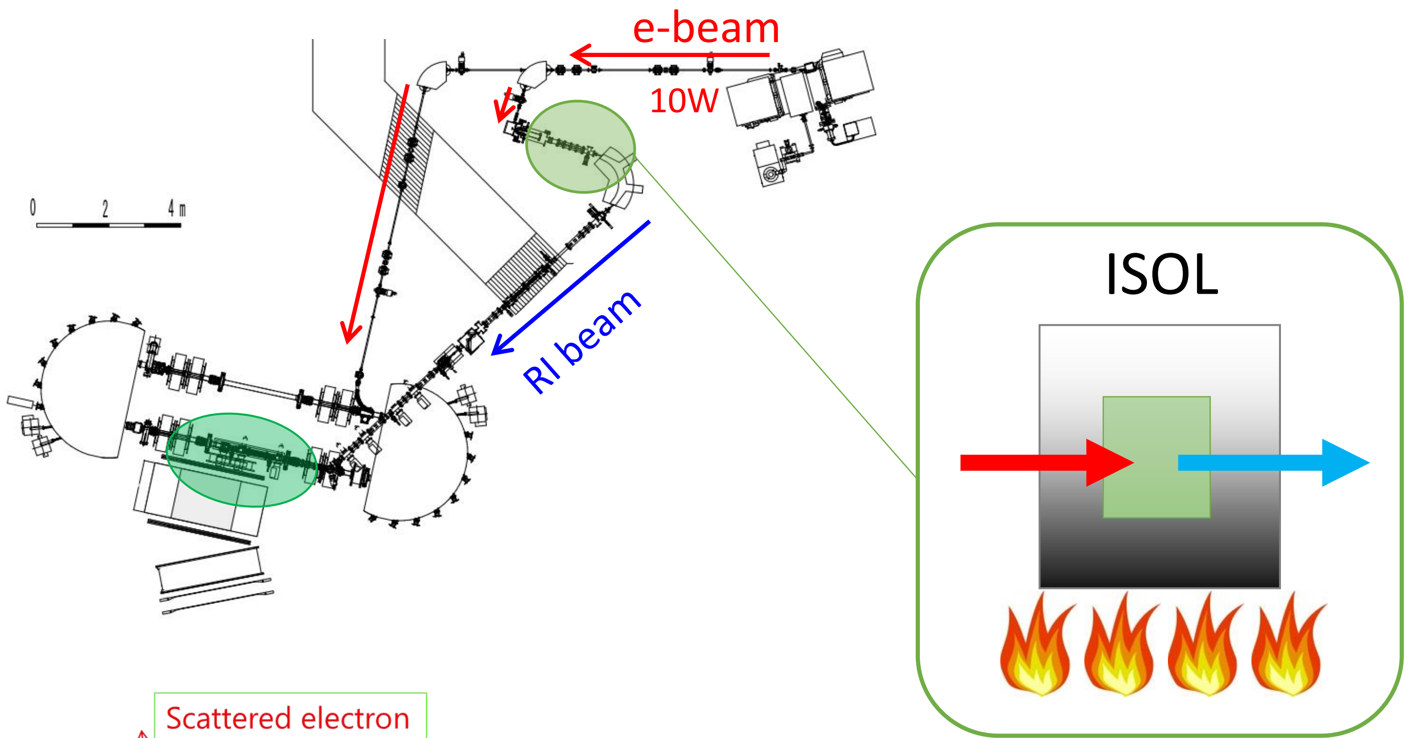
➡ **OEDO works well as designed!!**

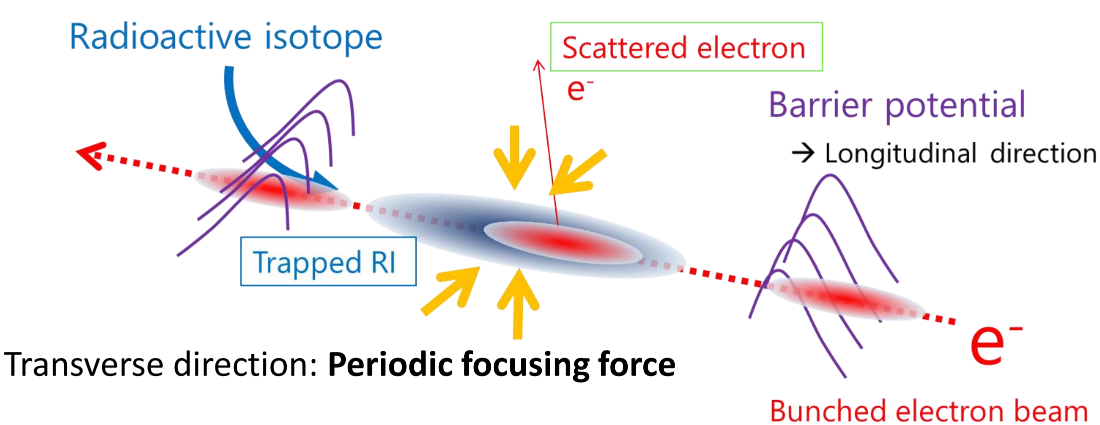
SCRIT (Self Confining RI Ion Target)



SCRIT (Self Confining RI Ion Target)

Electron scattering off RI beam

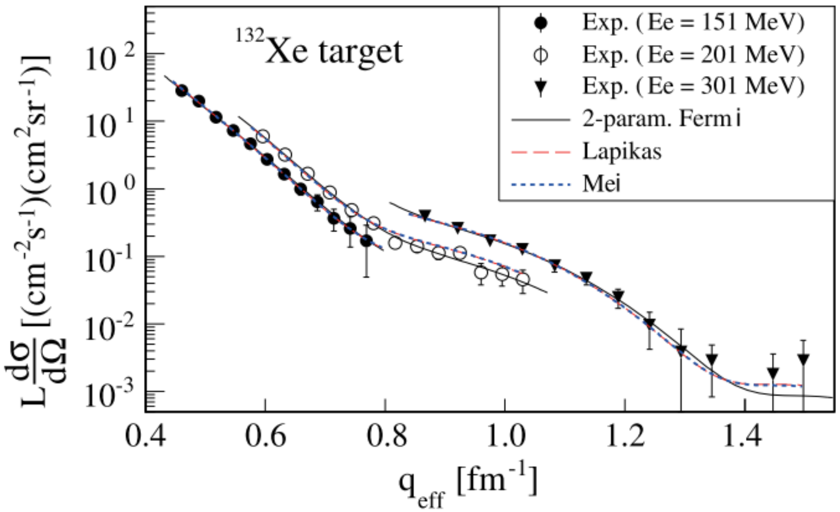




M. Wakasugi *et al.*, Nucl. Inst. Meth. A 532, 216 ('04)
M. Wakasugi *et al.*, Phys. Rev. Lett. 100, 164801 ('08)
T. Ohnishi *et al.*, Phys. Scr. T166, 014071 ('15)
T. Ohnishi *et al.*, PoS (INPC2016) 088.

SCRIT (Self Confining RI Ion Target)

First electron scattering of ^{132}Xe

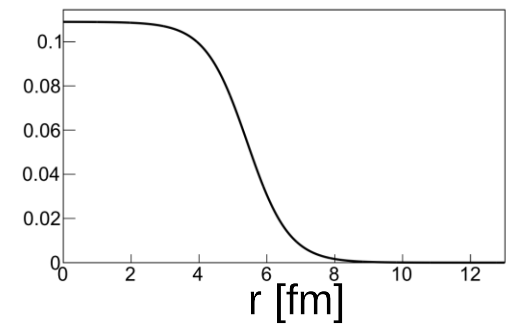


$$\rho_C = \rho/(1 + e^{4.4(r-C)/t})$$

$$C = 5.42^{+0.11}_{-0.08}$$

$$t = 2.71^{+0.29}_{-0.38}$$

$$\langle r \rangle^{1/2} = 4.79^{+0.12}_{-0.10}$$



Achieved luminosity: 1.8×10^{27} cm^{-2}s^{-1} at 250 mA

with 2×10^{8} ions /(1pulse injection)

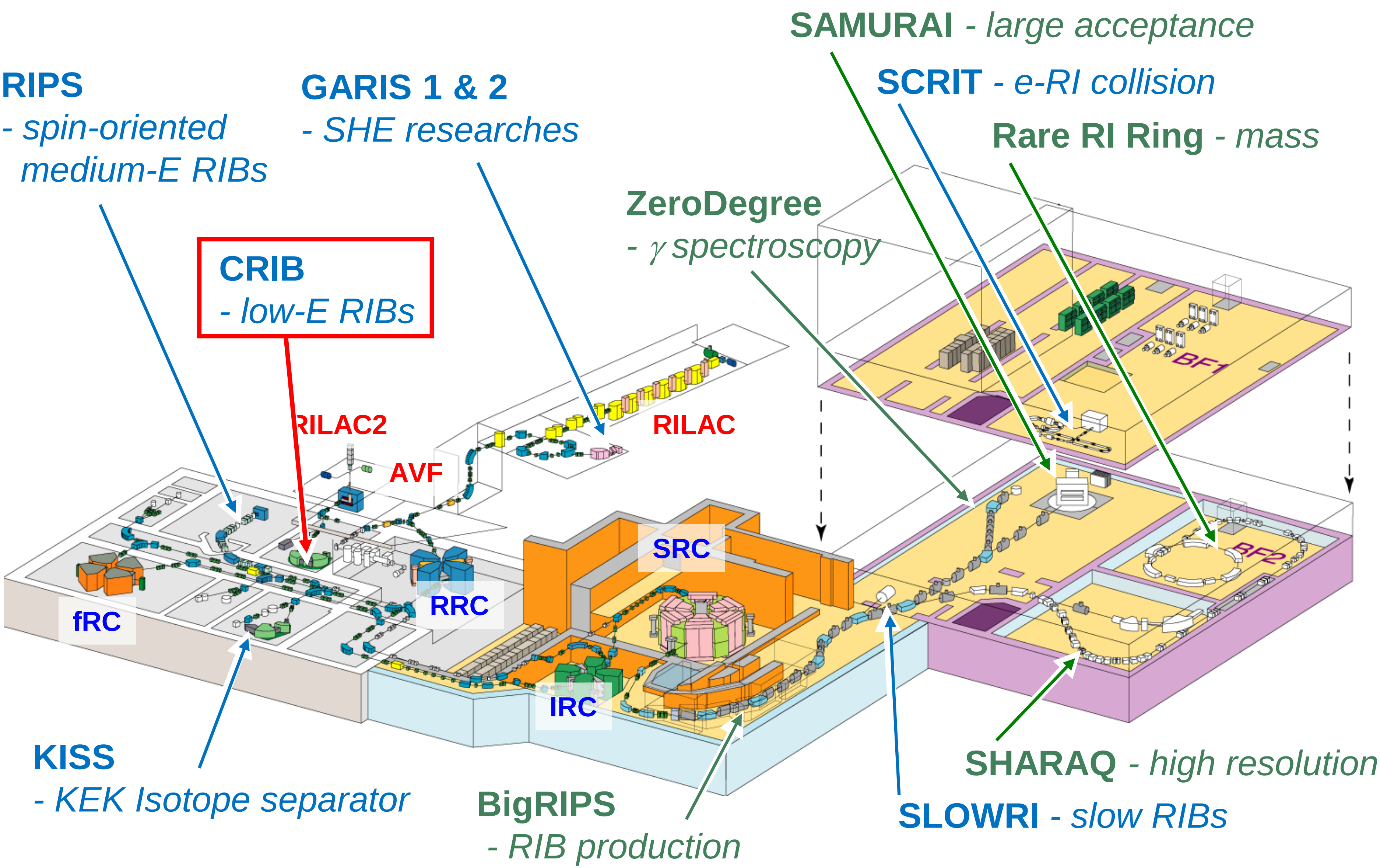
K. Tsukada et al., Phys.Rev.Lett. **118** (2017) 262502.

Ready for unstable nuclei !

e-beam power upgrade : ~ 50W (Now going)

1kW (Future plan)

CRIB



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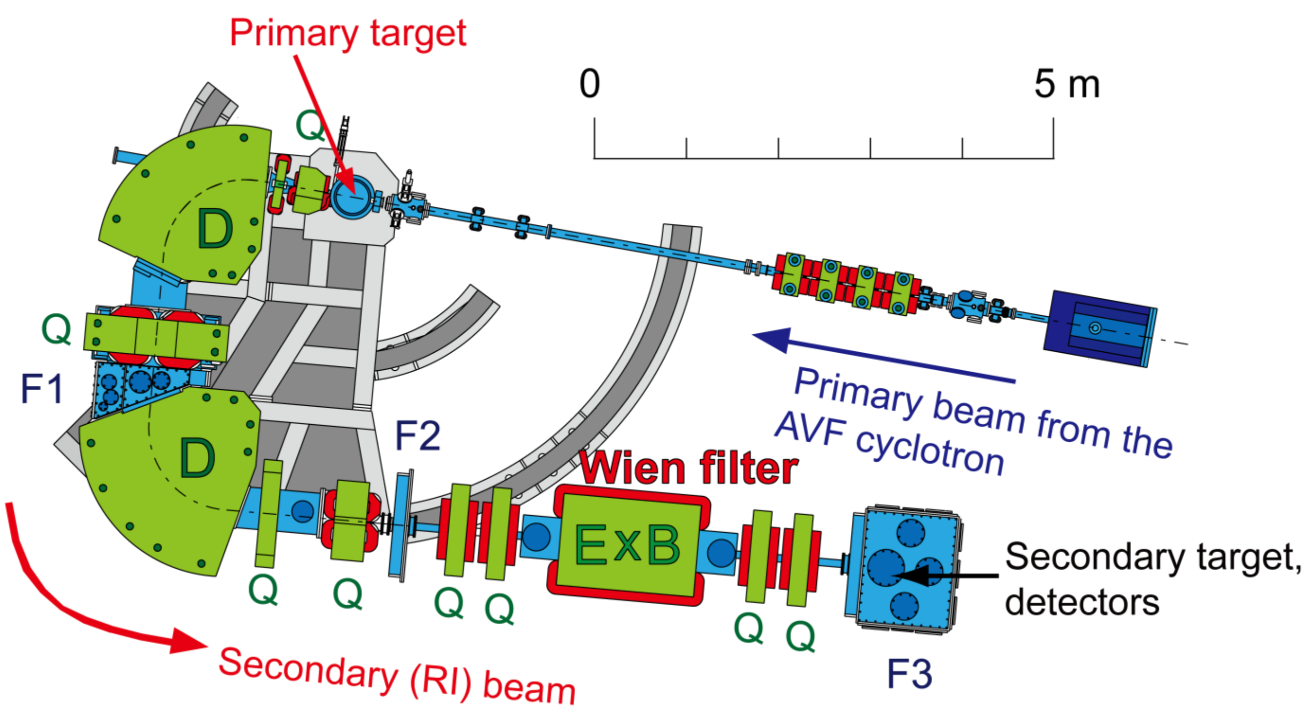
BF2
KISS
- KEK Isotope separator
BigRIPS
- RIB production
SHARAQ - high resolution
SLOWRI - slow RIBs

CRIB (CNS Radio-Isotope Beam Separator)

Low-energy RI beams (<10 MeV/u) for astrophysical reactions

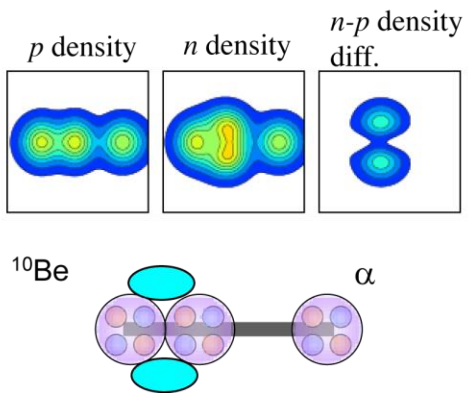
- **Low-energy(<10MeV/u) RI beam** production with in-flight method.
- Two stages of electromagnetic beam purification.
- Typical intensity 10^4-10^6 pps (10^8 pps for 7Be).
- Suitable for **nuclear astrophysics** and **nuclear structure** study.

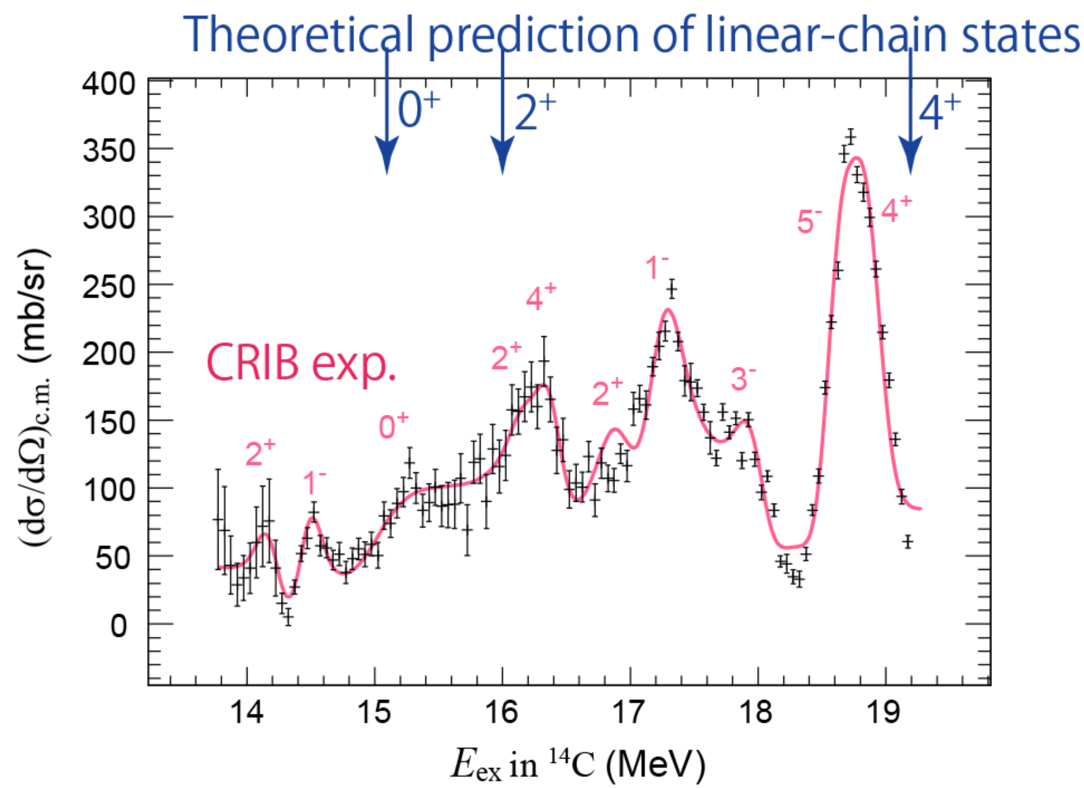


CRIB (CNS Radio-Isotope Beam Separator)

Strong indication of linear-chain structured nucleus found in ^{14}C
- H. Yamaguchi et al., Phys. Lett. B (2017)

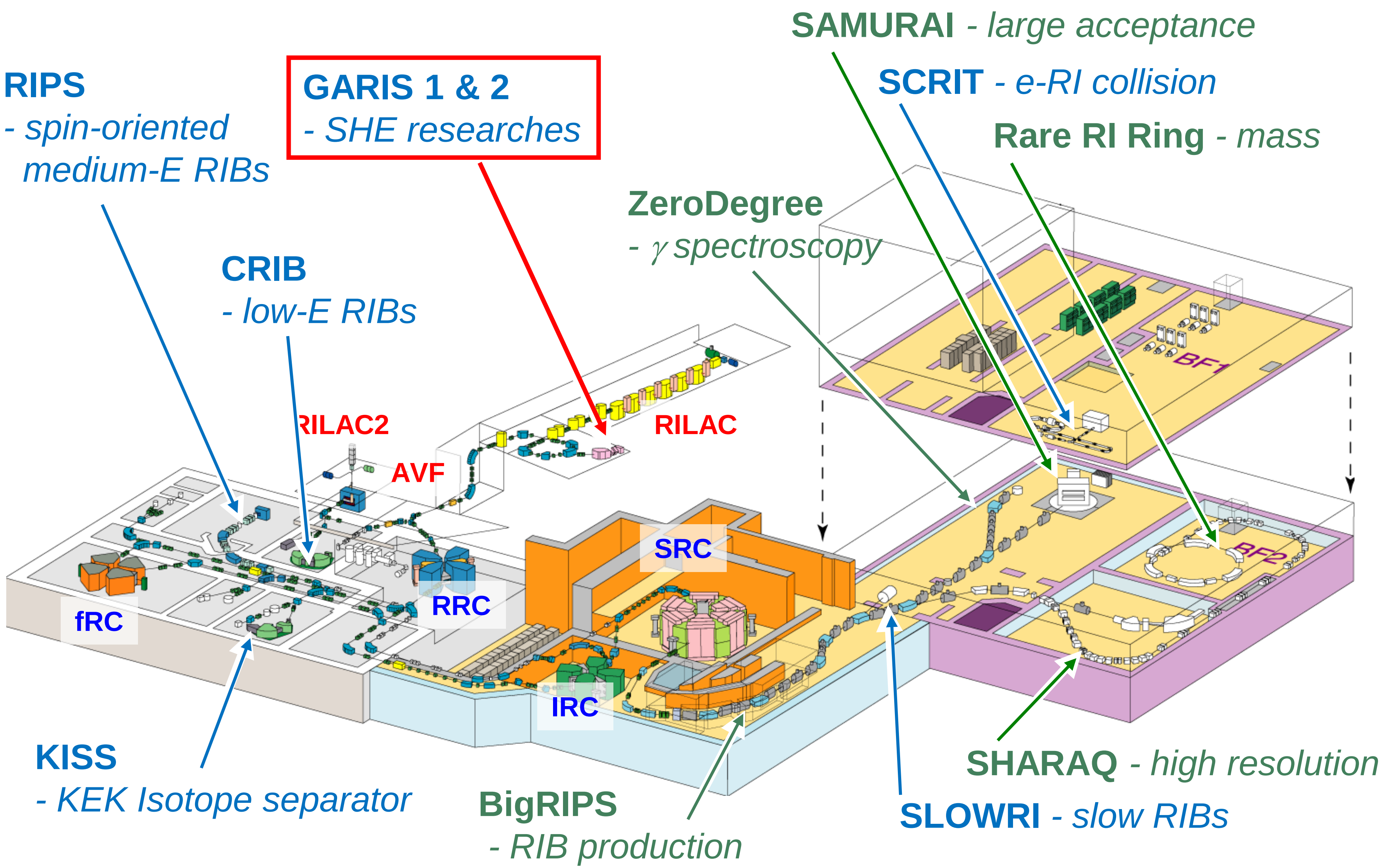
Suhara & En'yo, PRC 2010 and 2011:





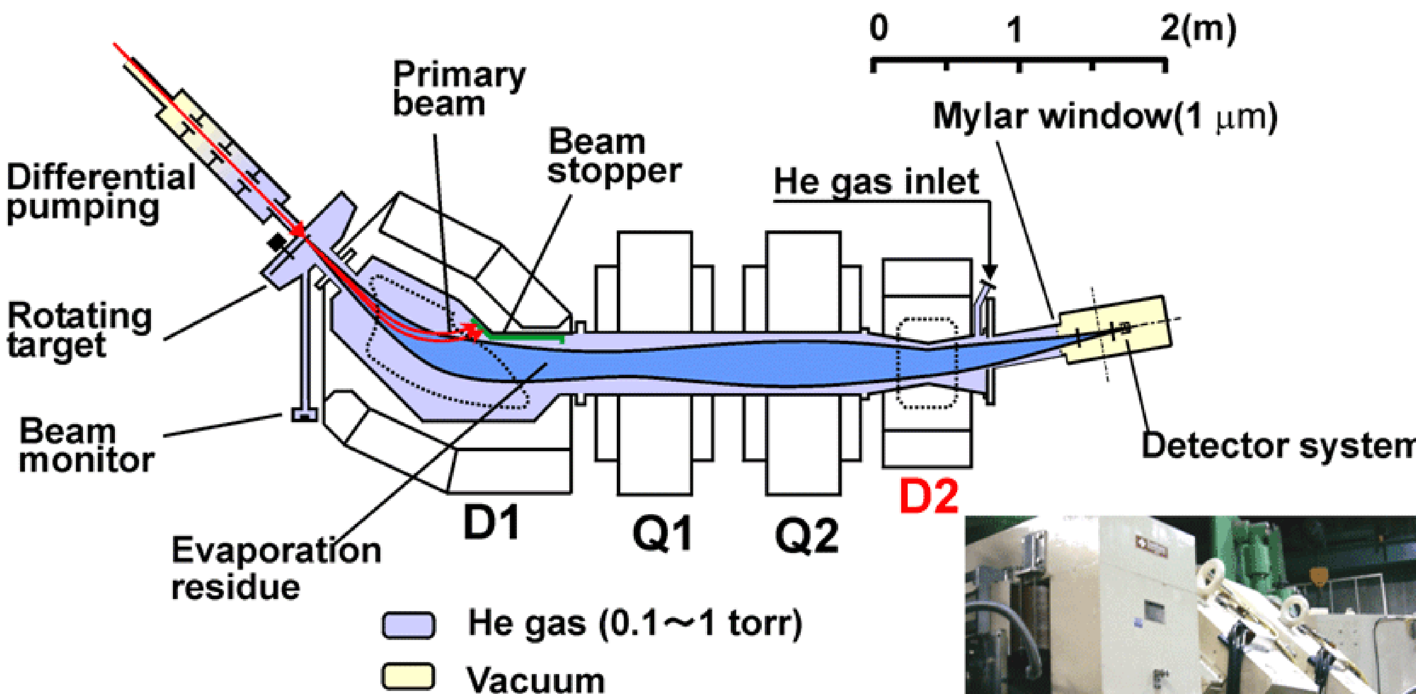
Excellent agreement between experiment and theoretical prediction of the linear-chain (0^+, 2^+, 4^+) states.

GARIS (Gas-filled Recoil Ion Separator)



GARIS (Gas-filled Recoil Ion Separator)

Search for super heavy elements



Magnification	X	-0.76
	Y	-1.99
Dispersion		0.97 cm/%
Total length		5760 mm
Acceptance	Δθ	±68 mrad
	Δφ	±57 mrad
	ΔΩ	12.2 msr

GARIS (Gas-filled Recoil Ion Separator)

The name of nihonium (Nh) is approved for element 113

$$^{209}\text{Bi} + {}^{70}\text{Zn} \rightarrow {}^{278}\text{Nh} + n$$

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For Immediate Release 30 November 2016

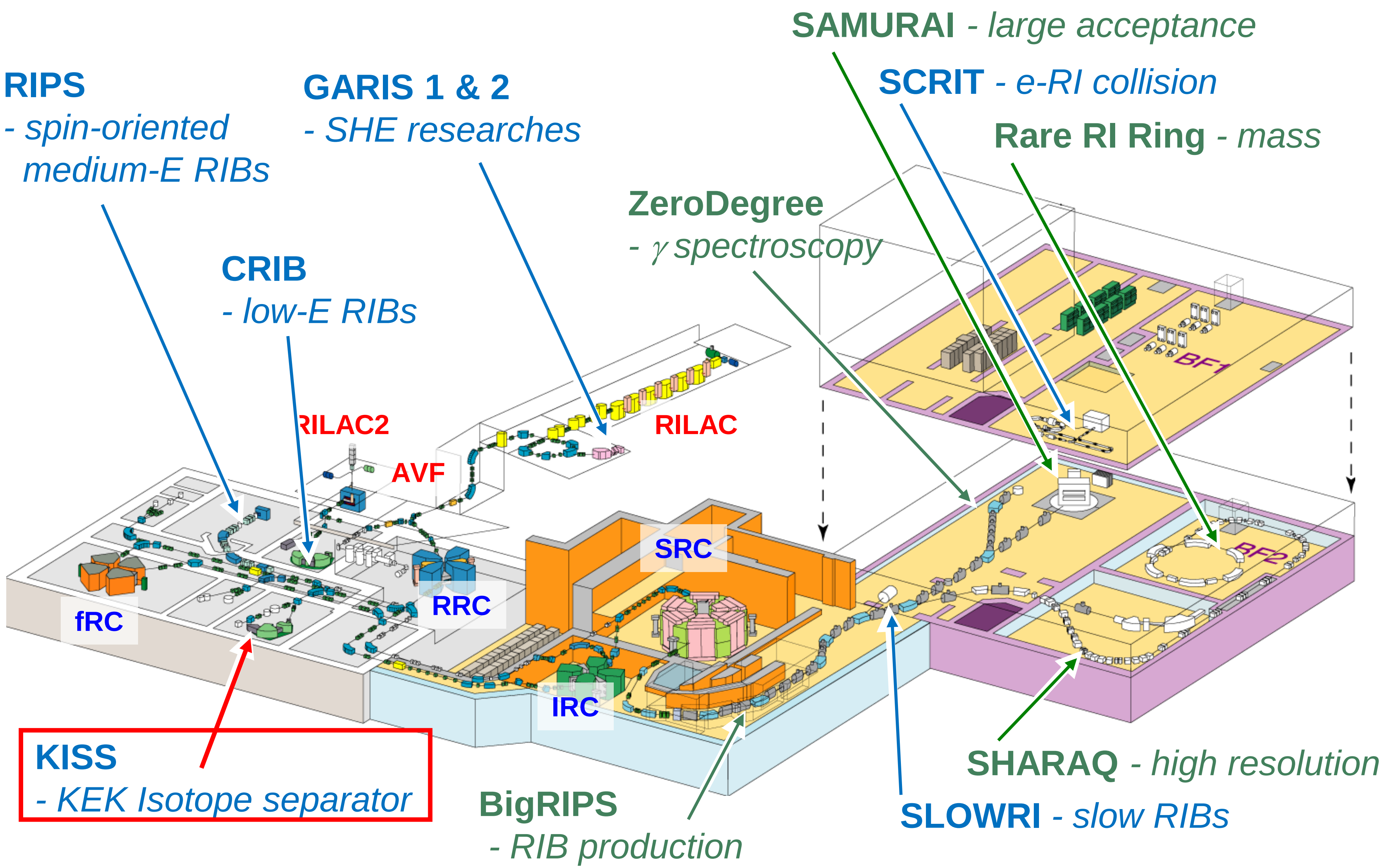
IUPAC Announces the Names of the Elements 113, 115, 117, and 118

Elements 113, 115, 117, and 118 are now formally named nihonium (Nh), moscovium (Mc), tennessine (Ts), and oganesson (Og)

Research Triangle Park, NC (USA): On 28 November 2016, the International Union of Pure and Applied Chemistry (IUPAC) approved the names and symbols for four elements: nihonium (Nh), moscovium (Mc), tennessine (Ts), and oganesson (Og), respectively for element 113, 115, 117, and 118.

Atomic number	Element name	Atomic symbol
113	nihonium	Nh
115	moscovium	Mc
117	tennessine	Ts
118	oganesson	Og

KISS (KEK Isotope Separator)

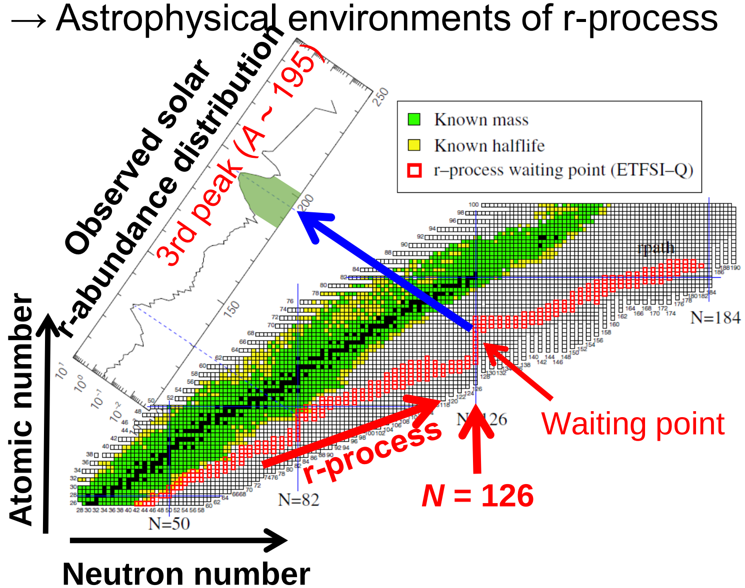


KISS (KEK Isotope Separator)

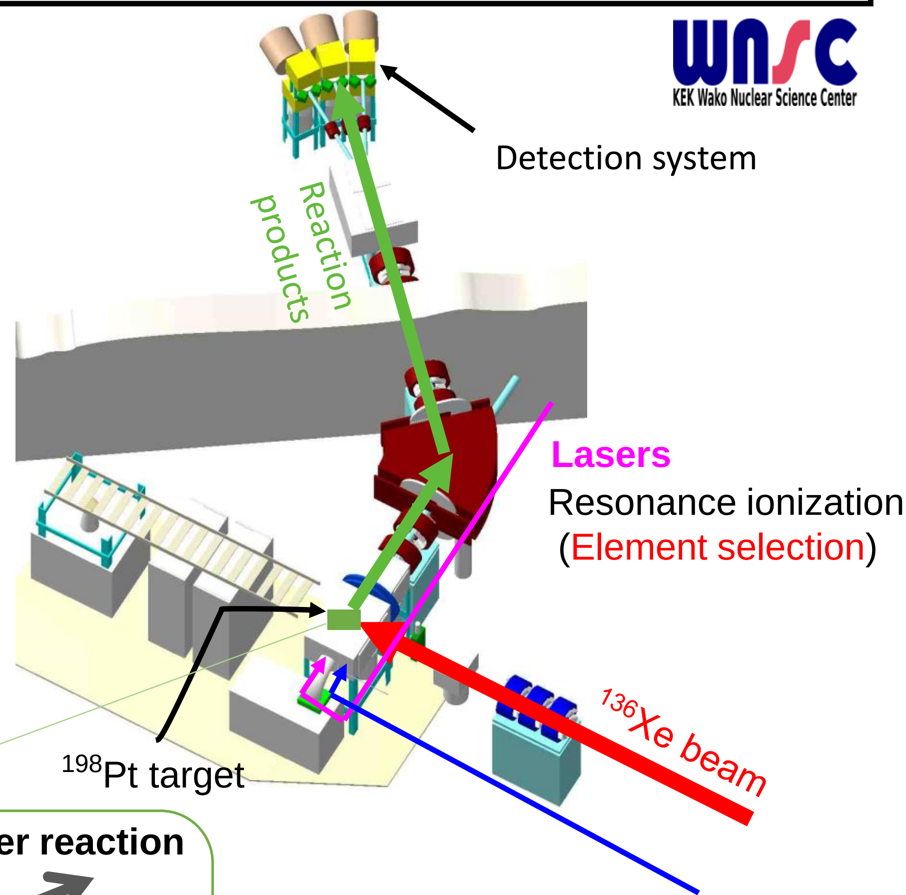
KISS has been constructed at RIKEN to measure lifetimes and masses of radioactive nuclei relevant to the r-process nucleosynthesis.

Nuclear properties of neutron-rich nuclei around the closed shell N = 126

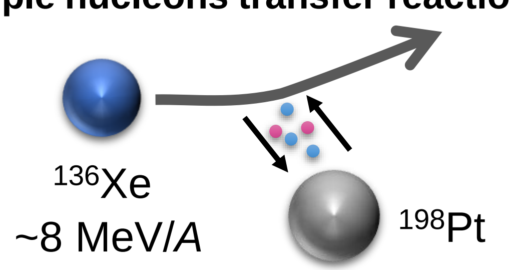
→ Astrophysical environments of r-process



H. Grawe et al., Rept. Prog. Phys. 70, 1525 – 1582 (2007).



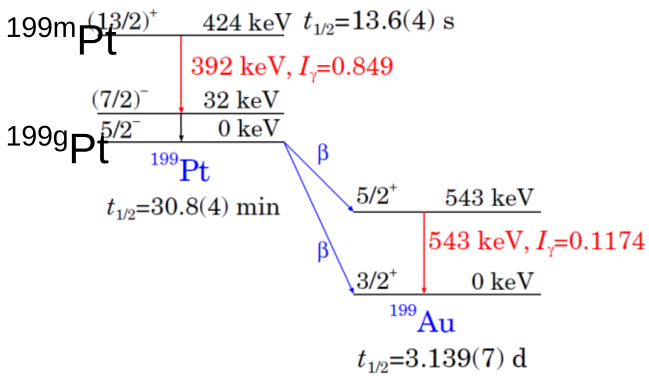
Multiple nucleons transfer reaction



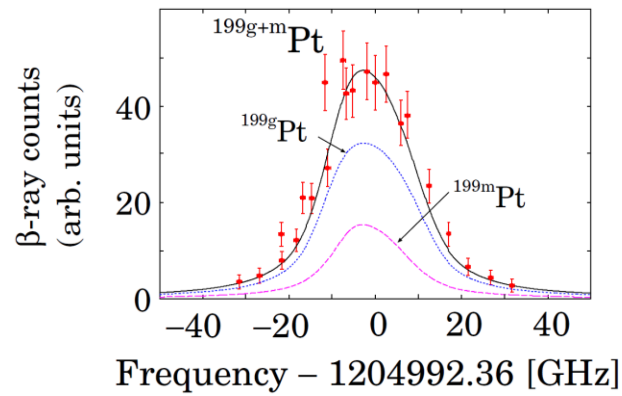
Y. Hirayama et al., Nucl. Instrum. and Meth. B 353, 4 – 15 (2015).

Laser spectroscopy of $^{199g,m}Pt$

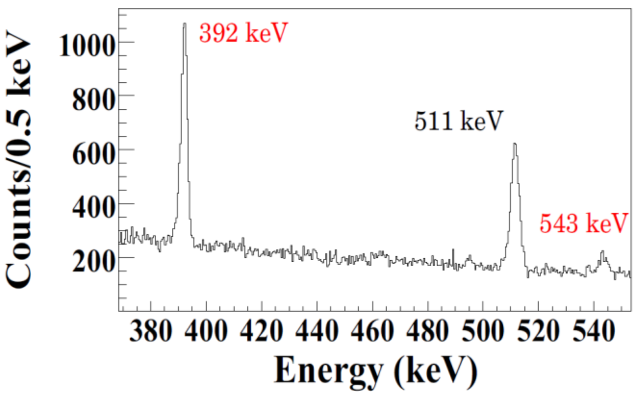
Decay scheme of $^{199g,m}Pt$



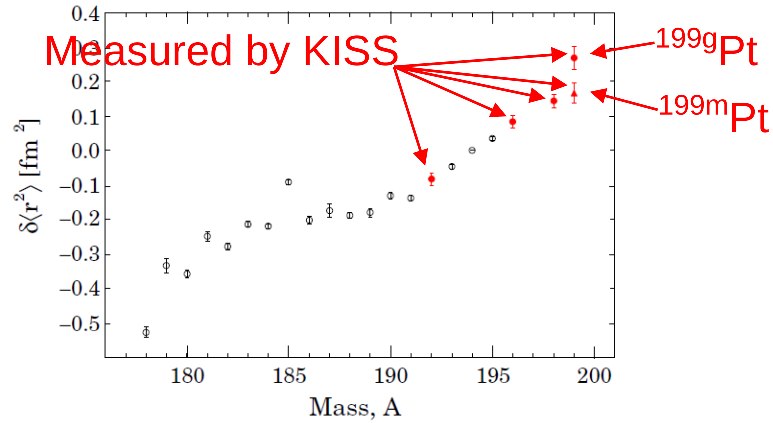
Laser resonance spectrum



Measured γ-ray spectrum

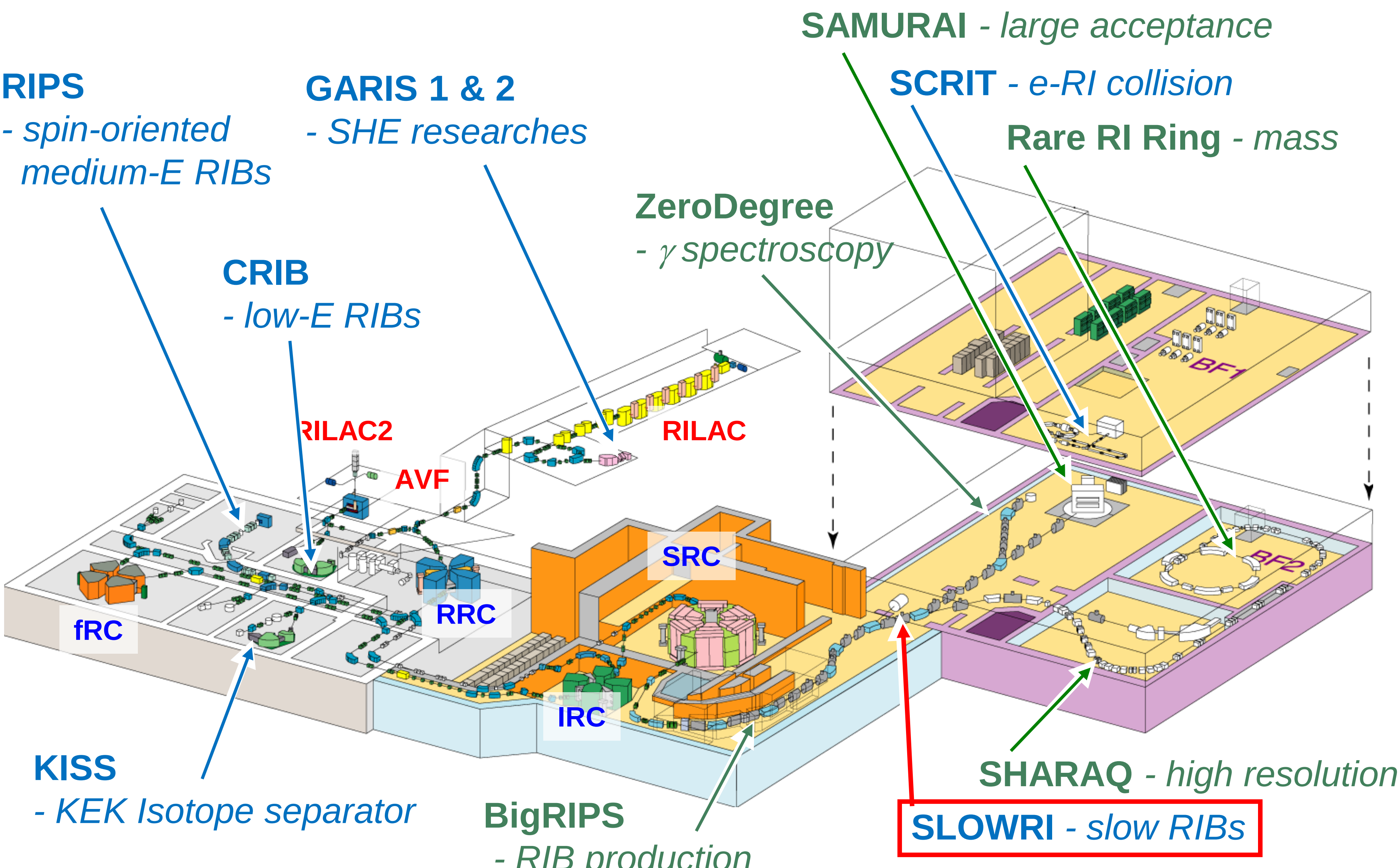


Mean square charge radii of Pt isotopes



Y. Hirayama et al., Phys. Rev. C 96, 014307 (2017).

SLOWRI



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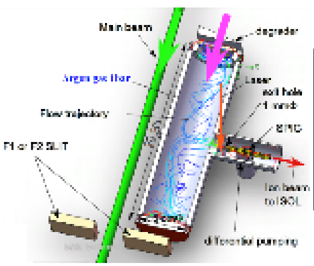
KISS
- KEK Isotope separator
BigRIPS
- RIB production
SHARAQ - high resolution
SLOWRI - slow RIBs

SLOWRI

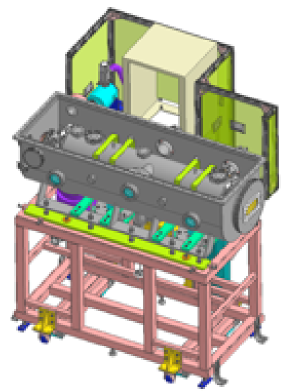
Universal ultra-slow beam production

BigRIPS

Relativistic RI Beam

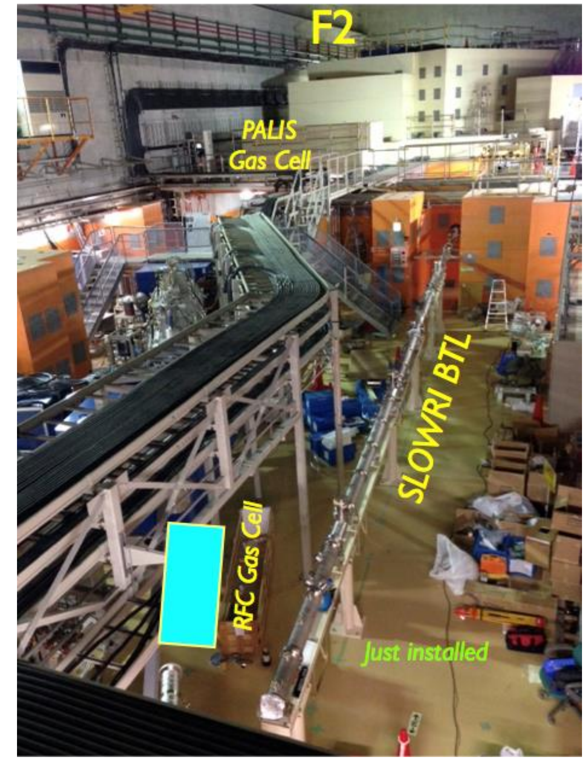


PALIS Gas Cell	***RF Carpet Gas Cell***
Parasitic RI	*Universal RI*



Low-energy or Trapped RI Beam

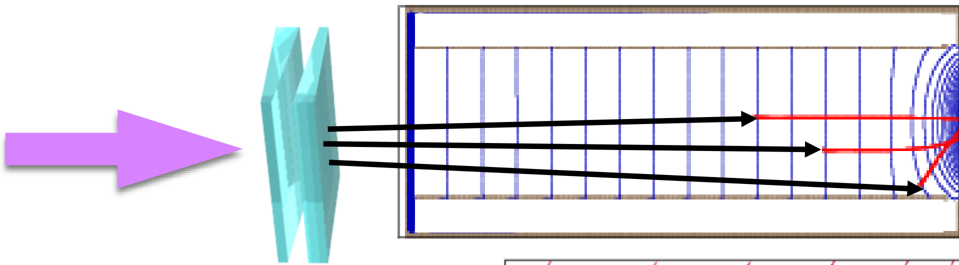
Mass Spectrograph
Laser Spectroscopy
Trap Apparatuses
αβγn spectrometers



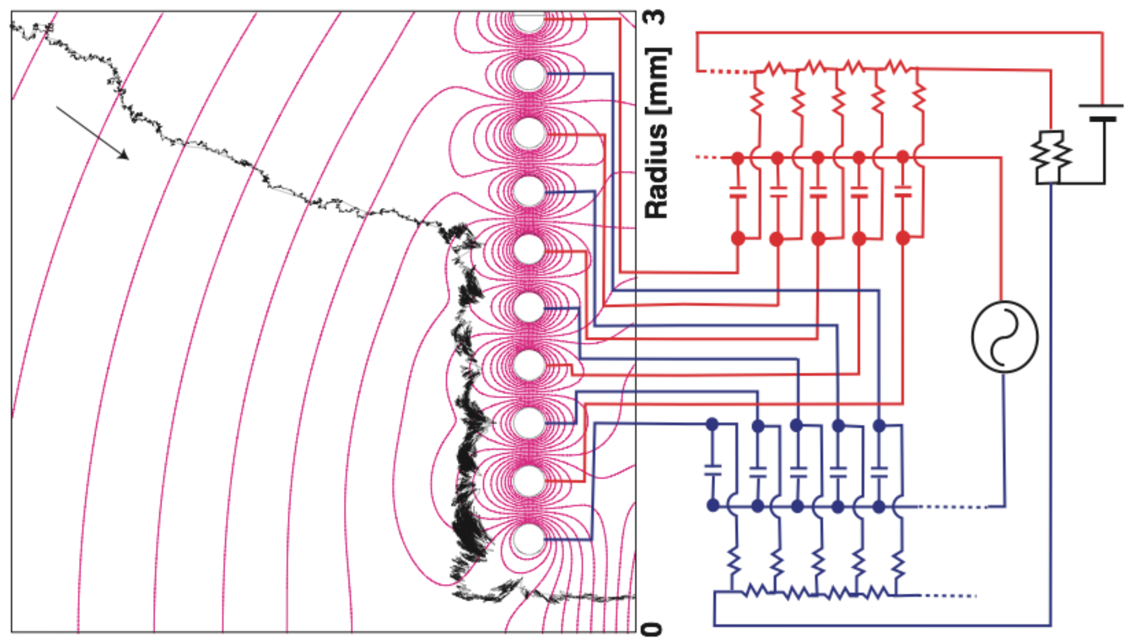
1. Wide Range of Nuclides
2. High Purity
   No Isobar No Isotone Contamination
3. Small Emittance
   ～πmm･rad
4. Variable Beam Energy
   1-50 keV Slow Beam, <1eV Trapped RI, 1MeV/u (future)
5. Human Accessibility during On-line Exp.

Two type gas catchers for SLOWRI

1. RF carpet gas cell



M. Wada *et al.*, NIMB **204**, 570 (2003)



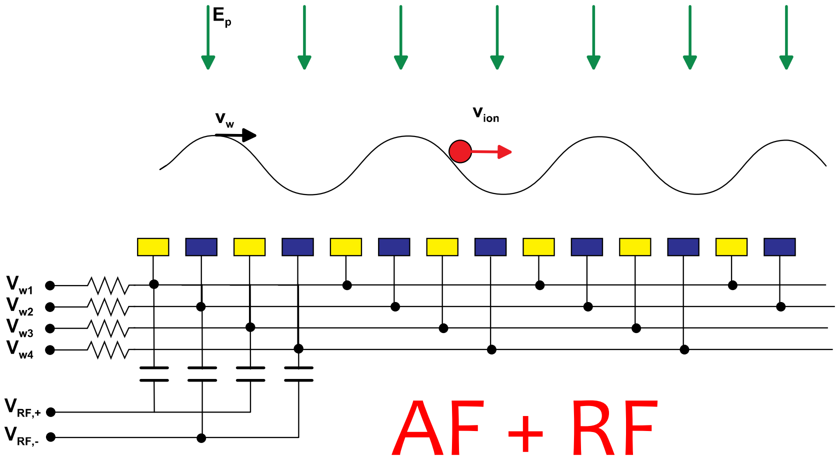
RF barrier force

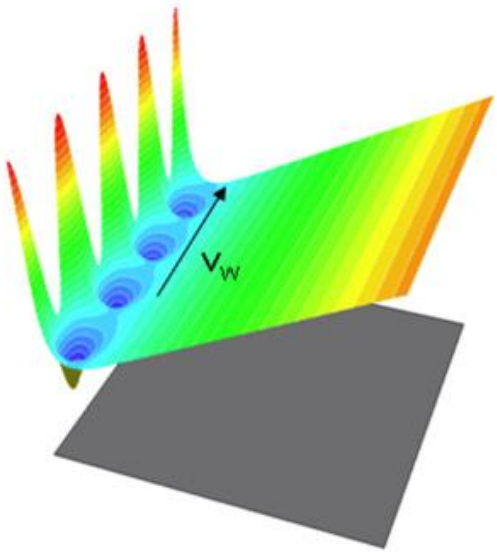
$$F = -2m\mu^2 \frac{V_{rf}^2}{r_0^3} \frac{r}{r_0}$$

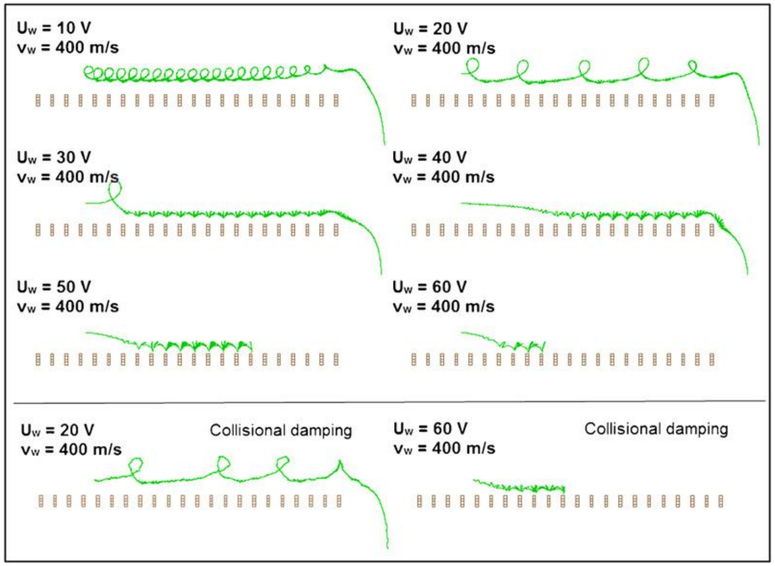
1. Stop in He (0.1 bar)
2. End up to singly charged ions
3. Extracted by DC & RF fields

Two type gas catchers for SLOWRI

Alternative RF gas catcher technique: Ion surfing



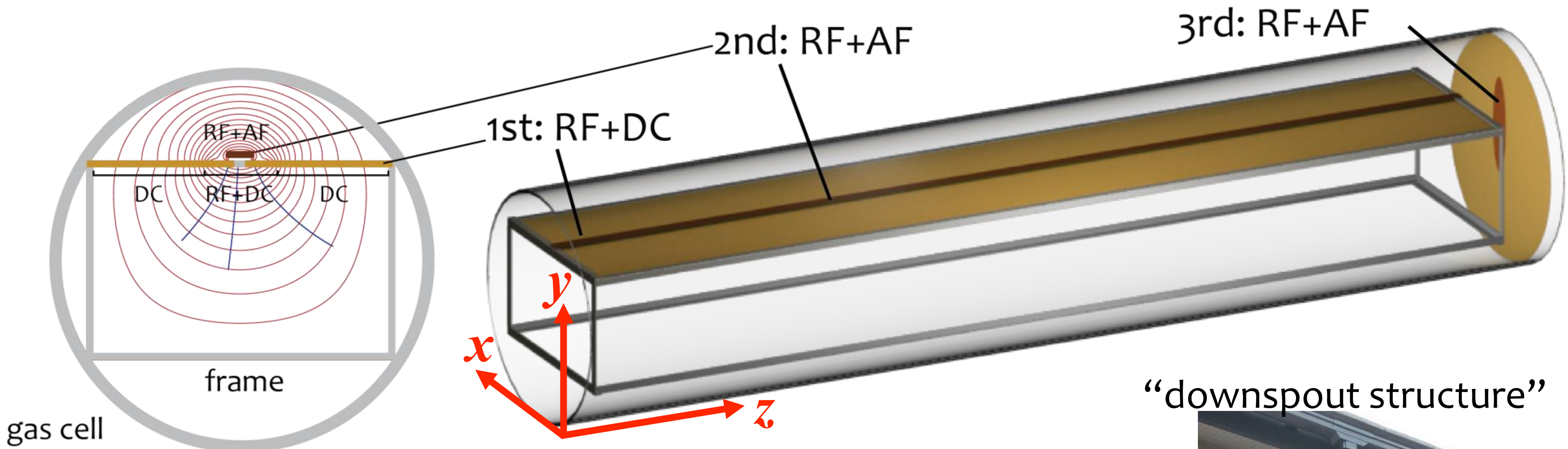




If you lock ions to the traveling wave,
you can quickly transport and extract ions.

G. Bollen, IJMS **299**, 131 (2011)

New RF carpet gas cell for BigRIPS



"downspout structure"

1st: RF+DC fields guide ions to the x-centre

He⁺ are dead on the 1st electrode.
→ no space charge for 2nd & 3rd

2nd: RF+AF traveling wave quickly guides ions downstream

"Ion surfing"

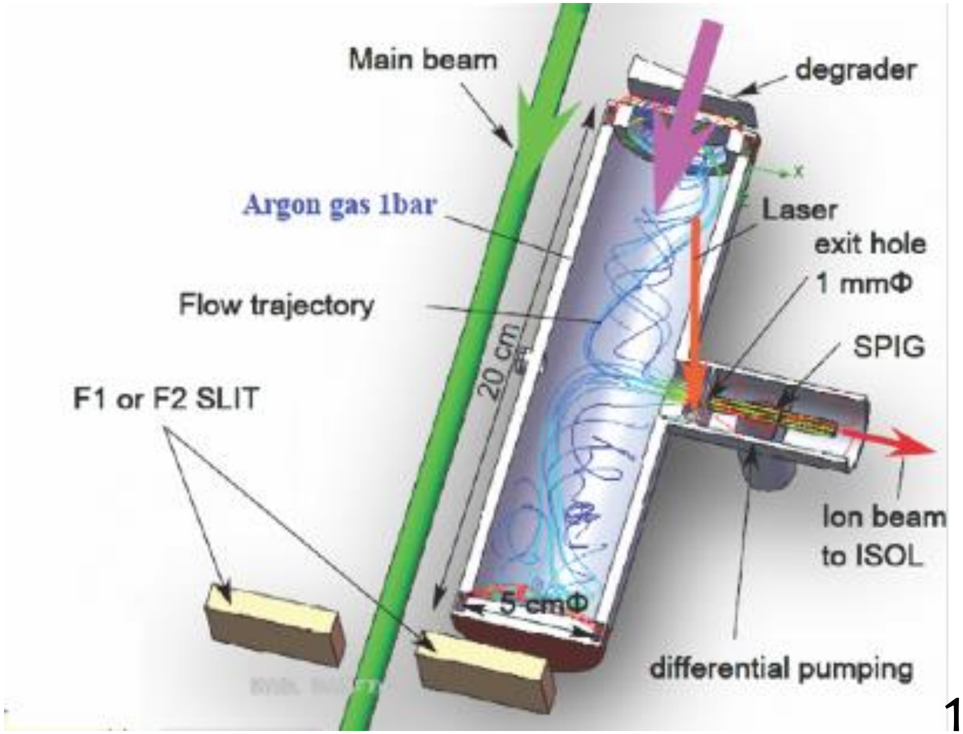
S. Masuda *et al.*, Elect. Eng. Jpn. **92,** 43 (1972).
G. Bollen, IJMS **299**, 131 (2011)

3rd: Receive ions and RF+AF guides ions to an exit hole

Two type gas catchers for SLOWRI

2. PALIS

Parasitic RI-beam production by Laser-Ion-Source

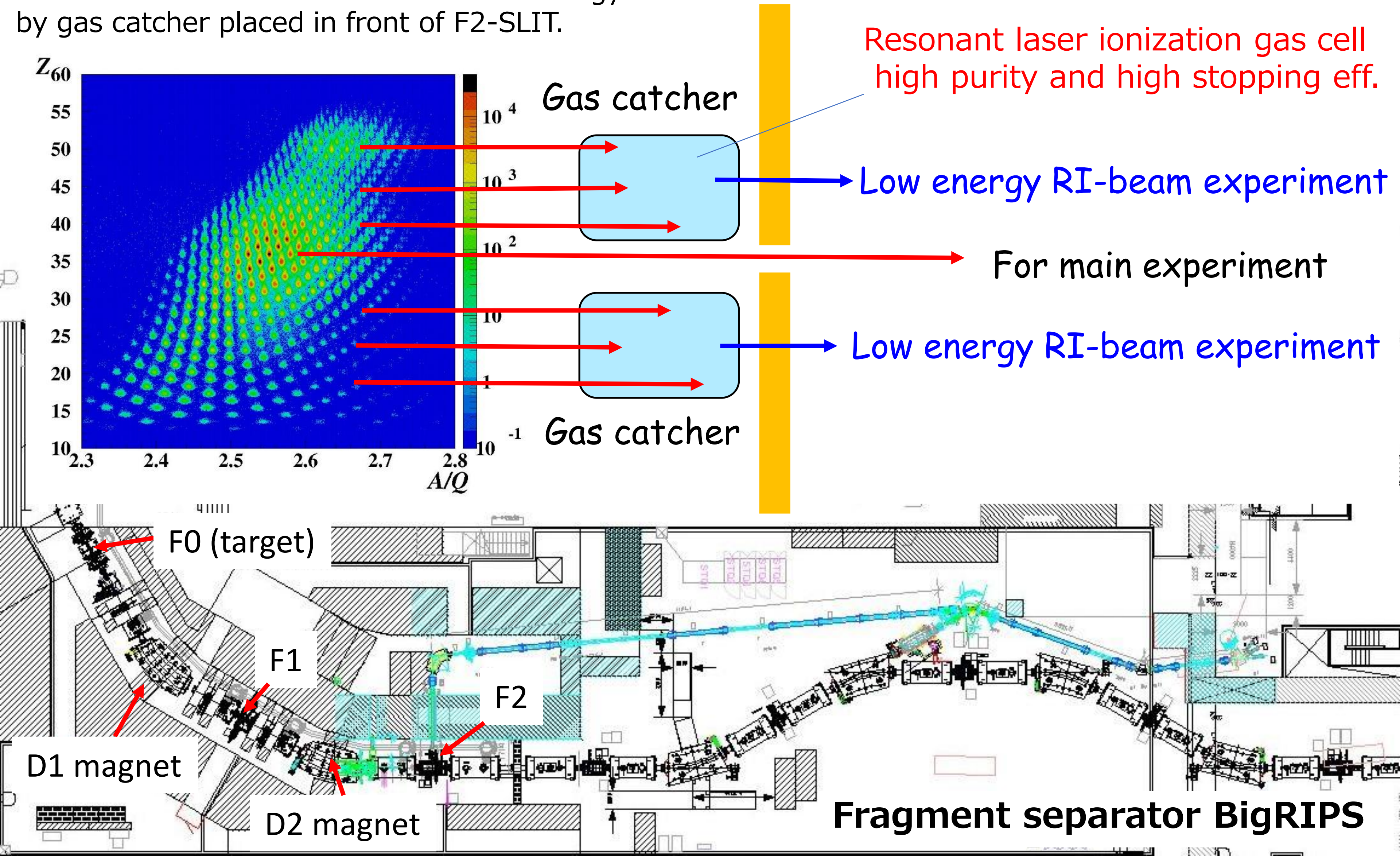


1. Stop & neutralize in Ar (1 bar)
2. Extracted by gas flow
3. Re-ionize by laser ionization at the exit and SPIG

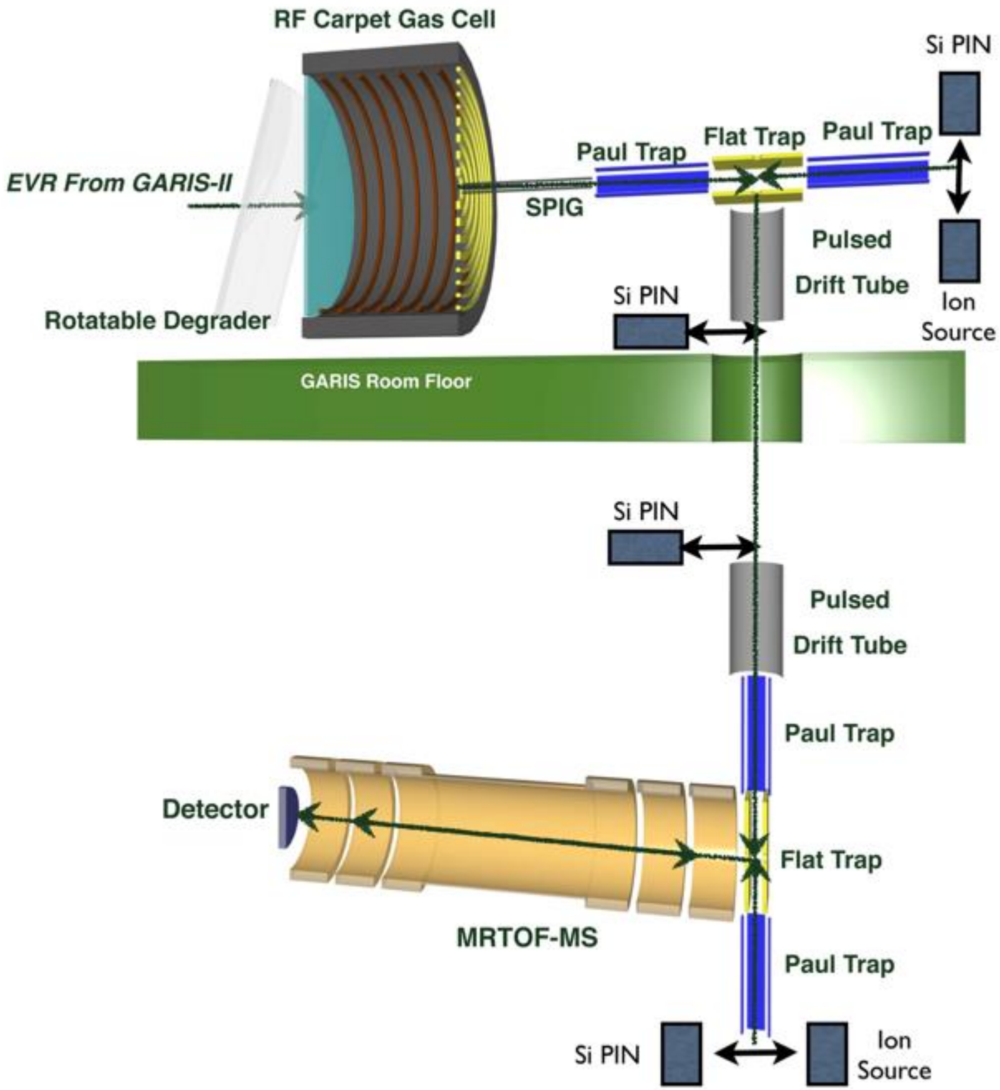
T. Sonoda *et al.*, NIMB **295**, 1 (2013)

Big advantage of PALIS: Beam availability

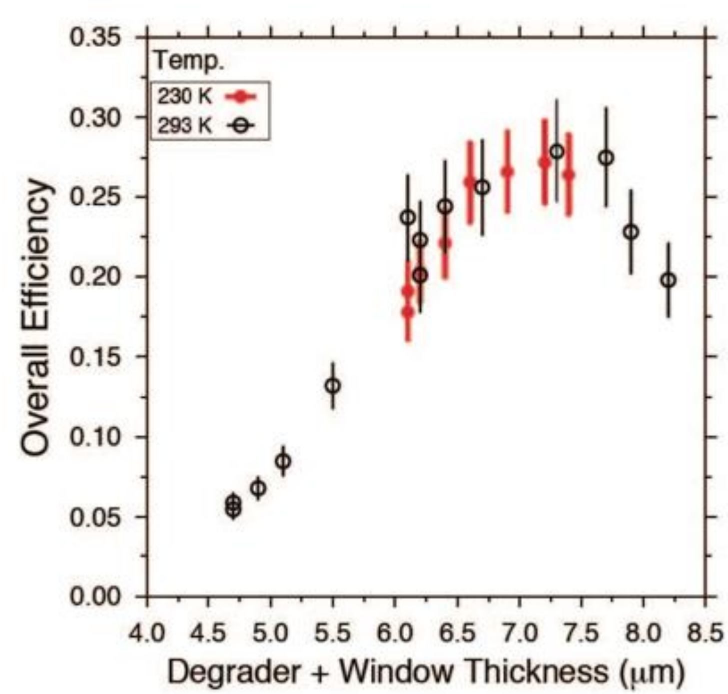
Unused RI-beams are restored as low-energy RI-beams by gas catcher placed in front of F2-SLIT.



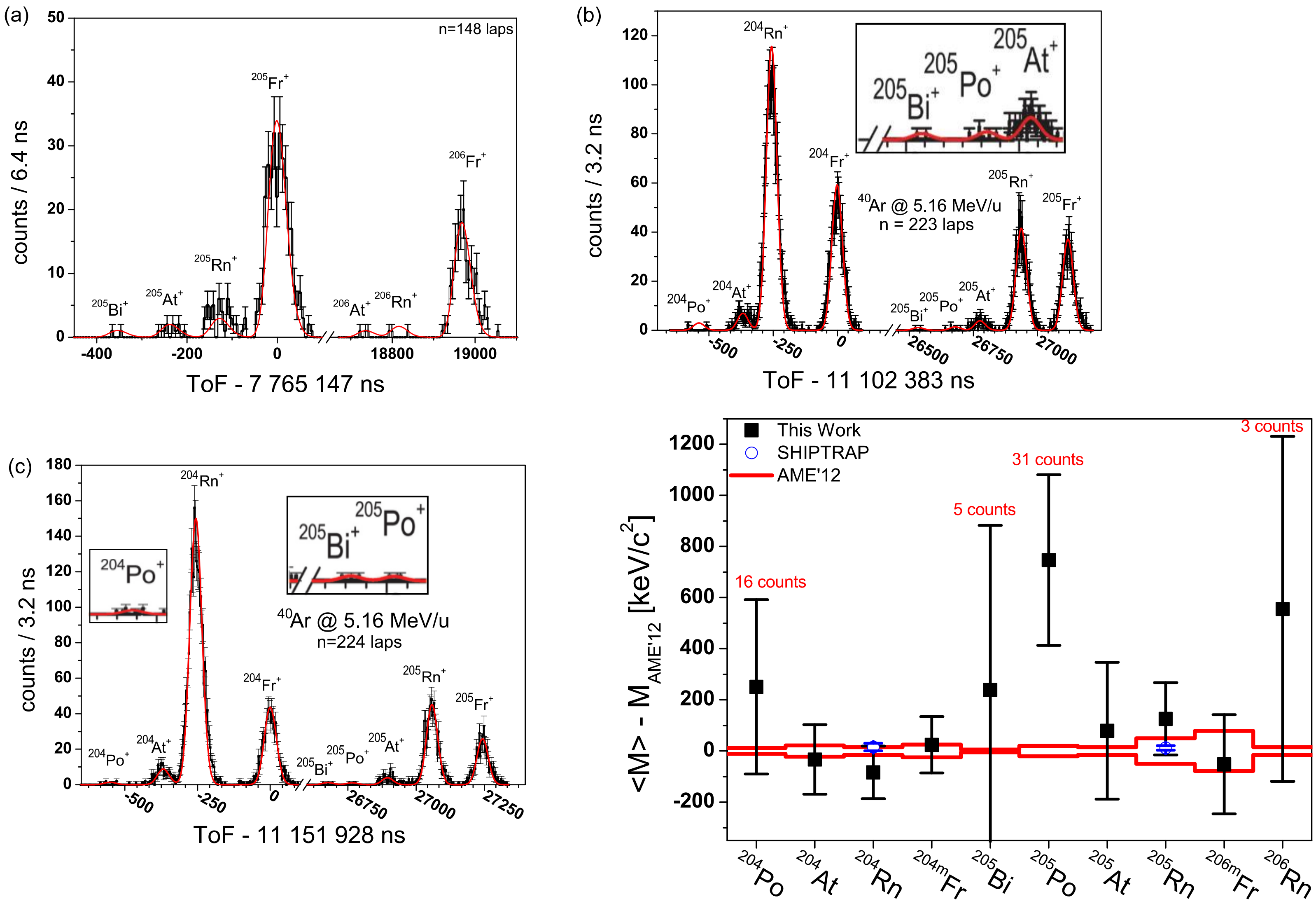
Gas catcher for GARIS: “SLOWSHE”



Extraction efficiency from the gas catcher

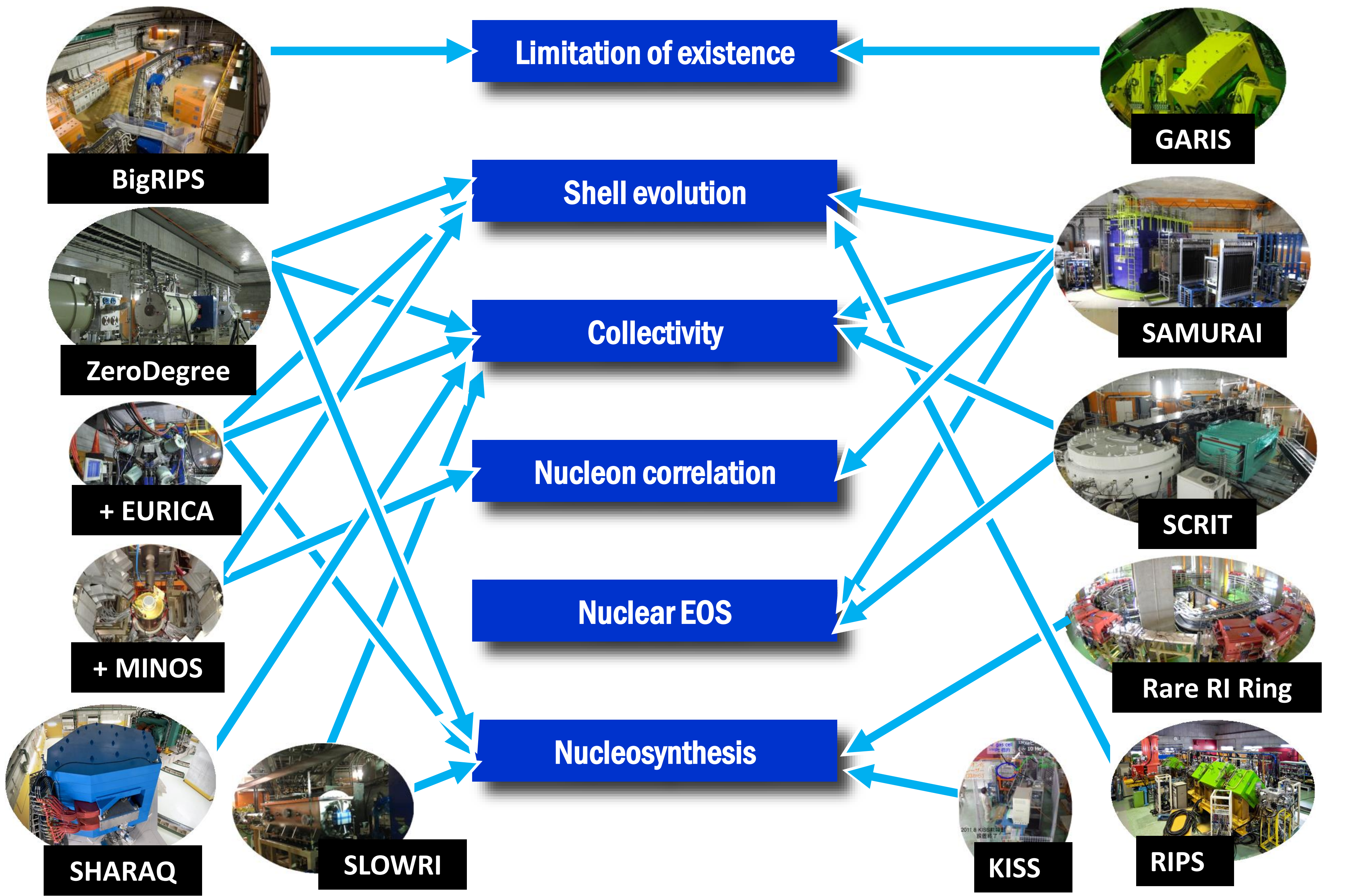


SLOWSHE MRTOF



P. Schury et al., PRC 95, 011305(R) (2017)

RIBF provides opportunities



Seeing is believing

Let's go for tour!