Electron Scattering off Online-Produced Radioactive Isotope

- first result from RIKEN SCRIT facility -

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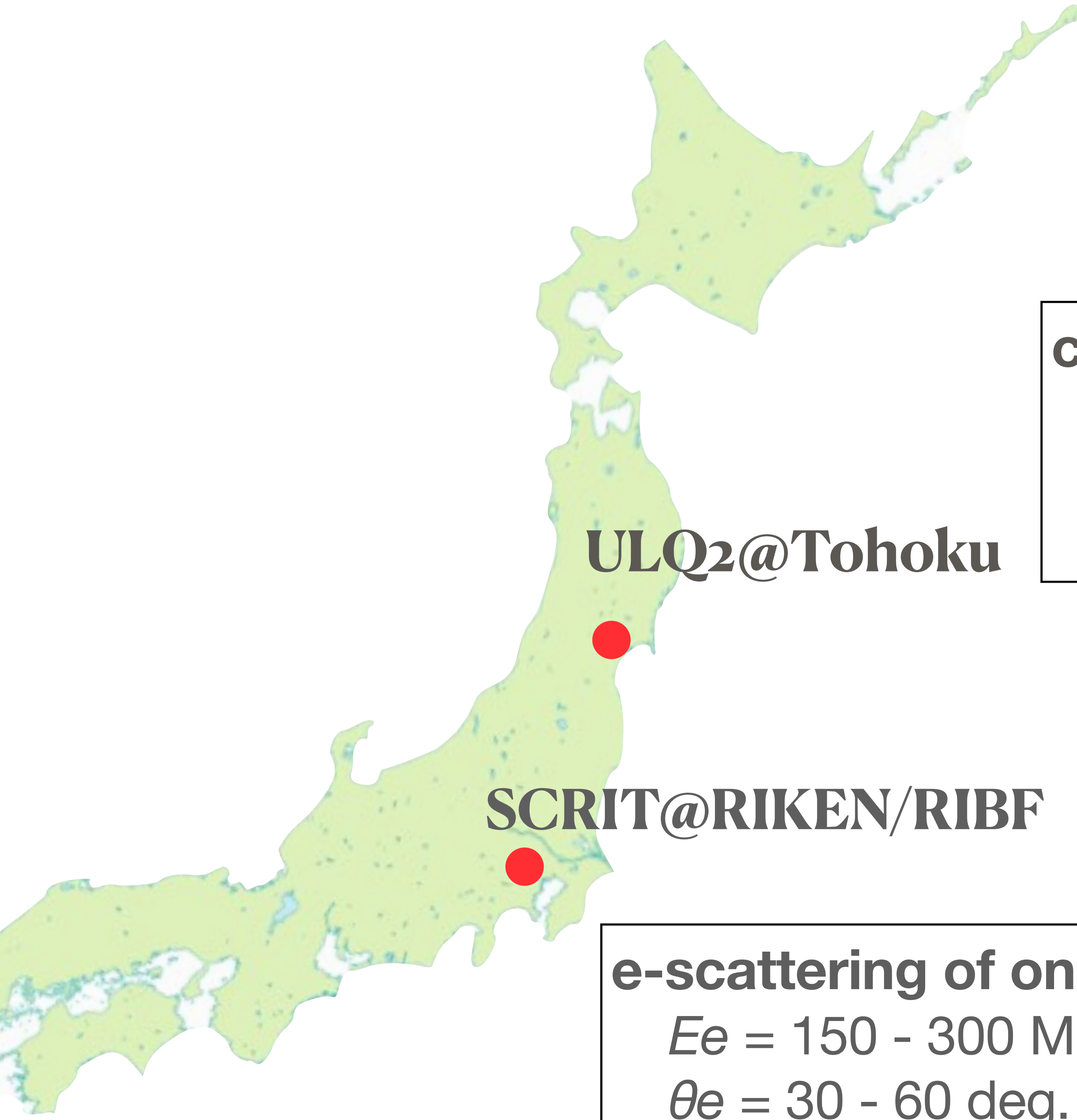
for SCRIT collaboration

Low-energy electron-scattering facilities in Japan



charge radii of proton and deuteron

Ee = 10 - 60 MeV

θe = 30 - 150 deg.

=> Q^2 = 3x10^{-5} - 0.013 (GeV/c)^2

⇨ **Yuki's talk**

e-scattering of online-produced exotic nuclei (~10^8/sec)

Ee = 150 - 300 MeV

θe = 30 - 60 deg.

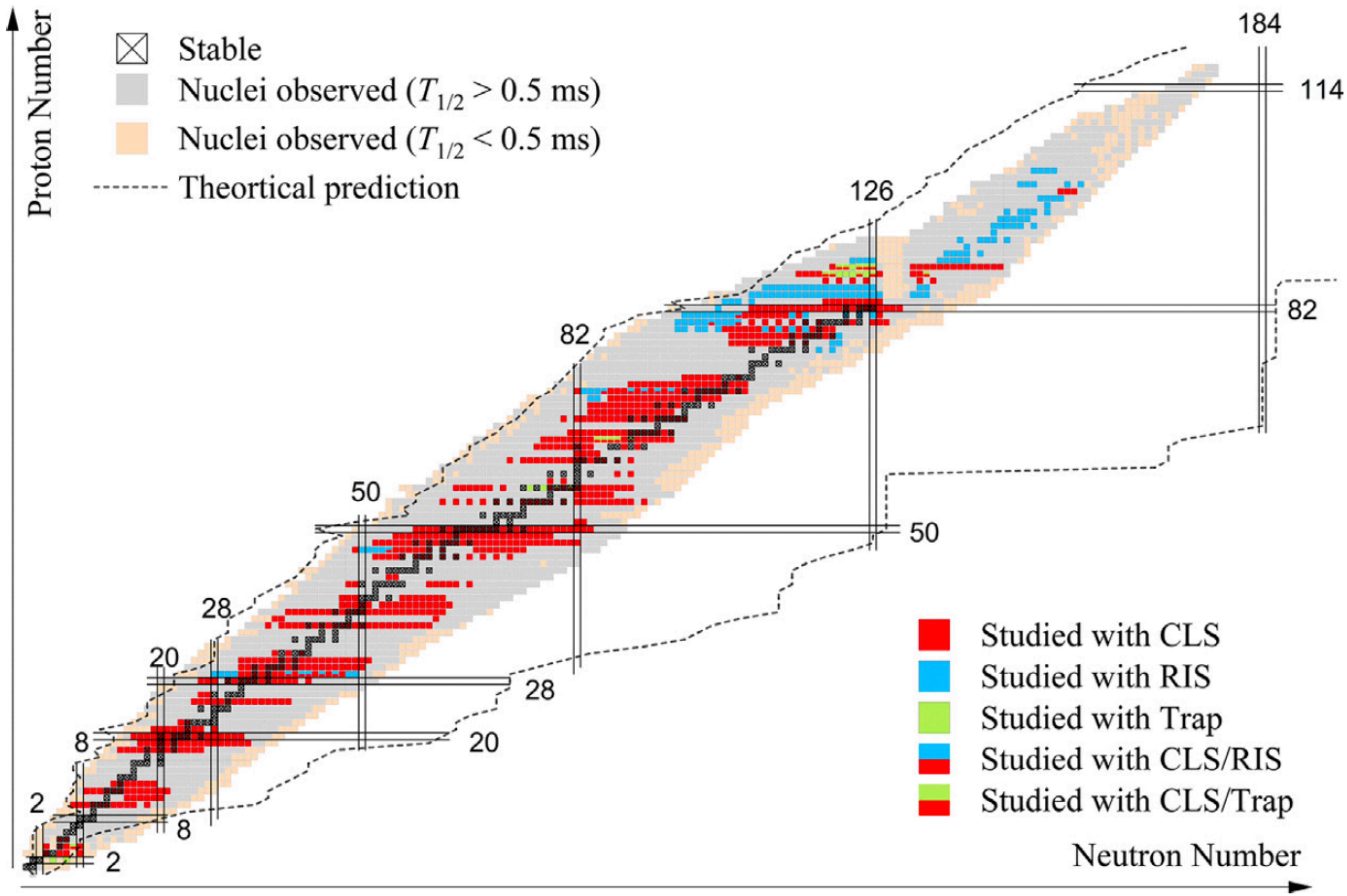
=> q = 80 - 300 MeV/c

Q^2 = 0.006 - 0.09 (GeV/c)^2

⇨ **this talk**

Isotope-shift measurements

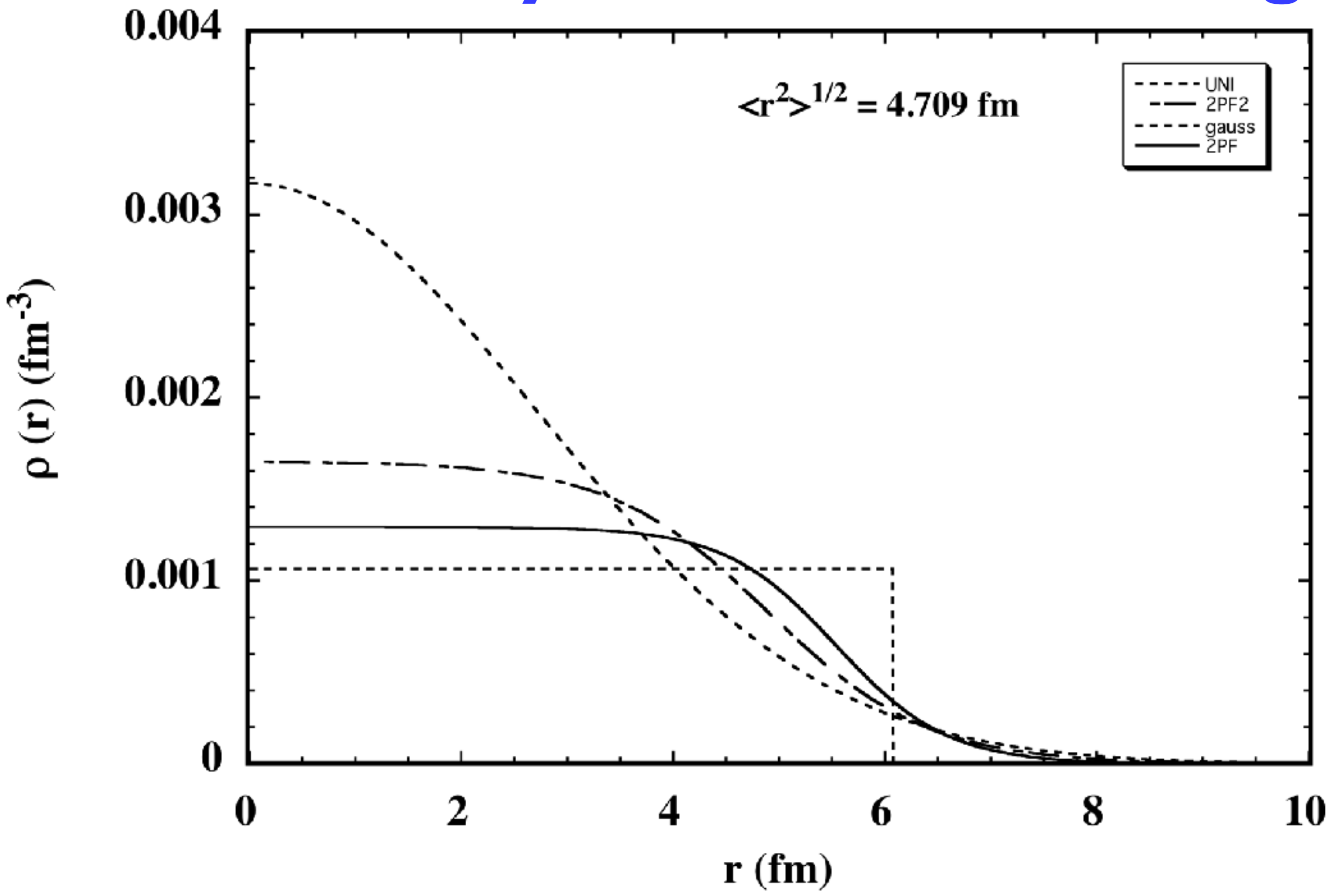
Ronald's talk

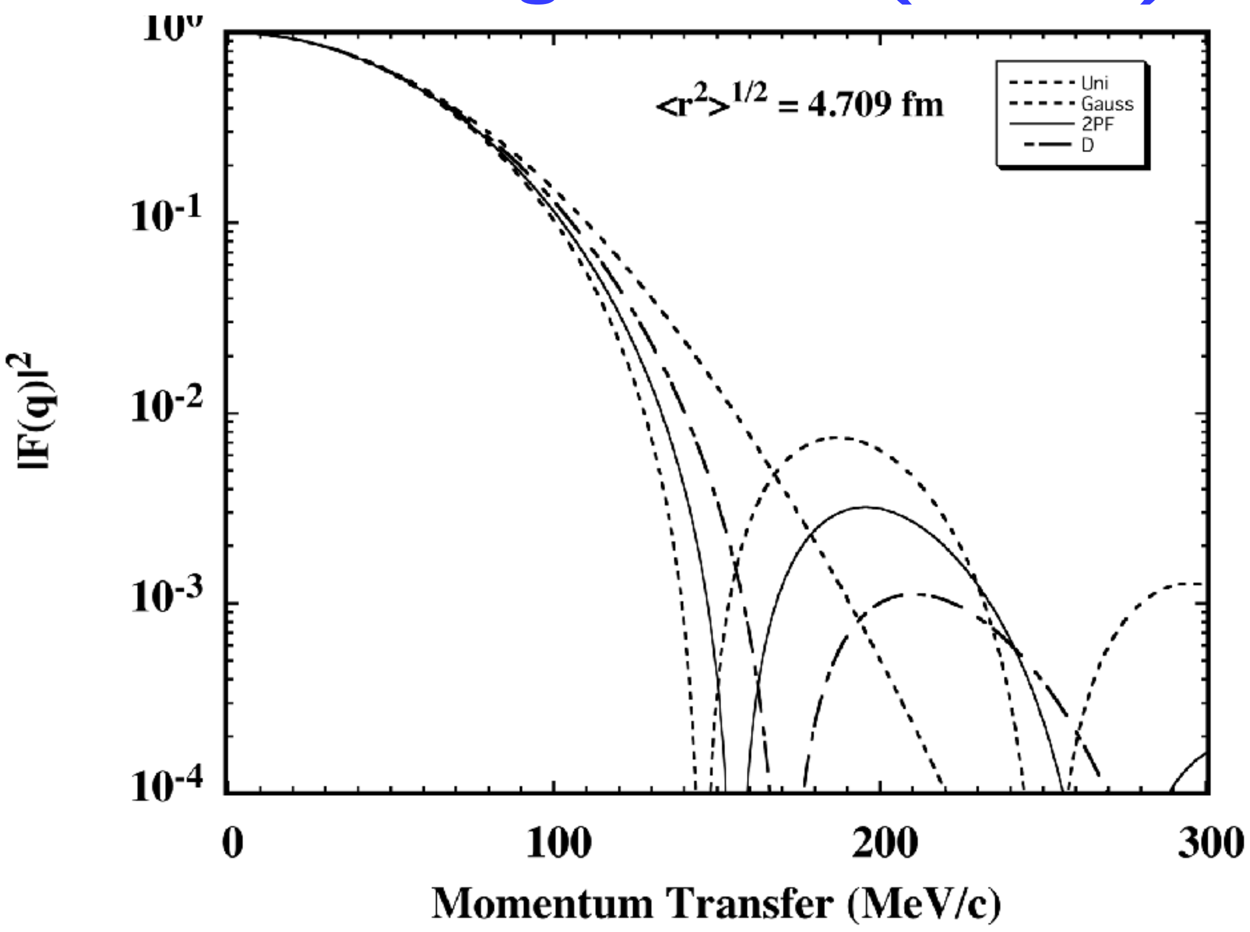


X. F. Yang *et al.*,
Prog. Part. Nucl. Phys. 129 (2023) 104005.

Beyond charge radii (isotope shifts)

Density distributions having the same charge radius (4.7 fm)



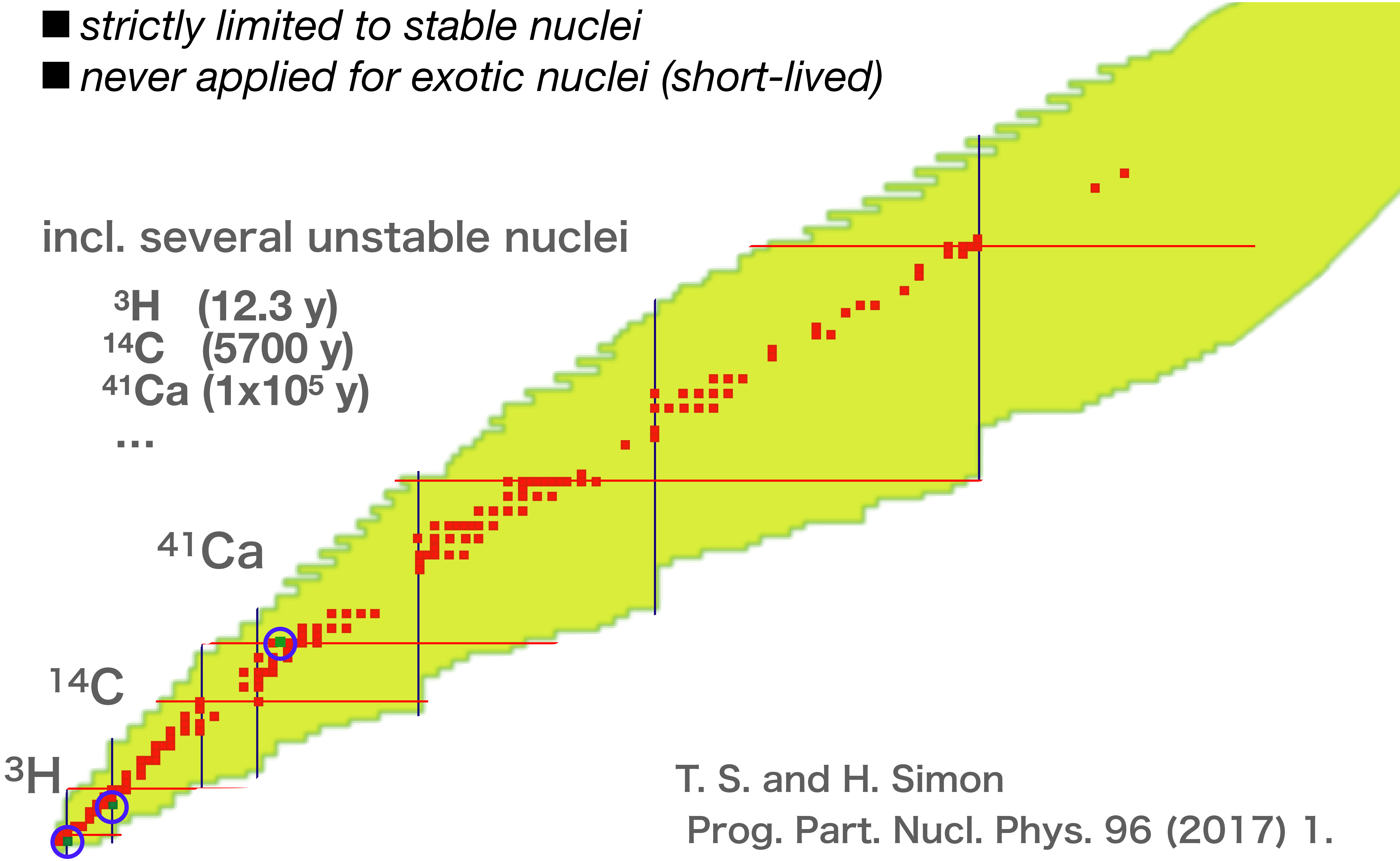


Nuclei ever studied by electron scattering

- *strictly limited to stable nuclei*
- *never applied for exotic nuclei (short-lived)*

incl. several unstable nuclei

^{3}H (12.3 y)
^{14}C (5700 y)
^{41}Ca (1x10^{5} y)
…



T. S. and H. Simon
Prog. Part. Nucl. Phys. 96 (2017) 1.

world's first e-scattering for online-produced radioactive isotope

PHYSICAL REVIEW LETTERS **131**, 092502 (2023)

Editors' Suggestion | Featured in Physics

First Observation of Electron Scattering from Online-Produced Radioactive Target

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(Received 7 March 2023; accepted 21 June 2023; published 30 August 2023)

We successfully performed electron scattering off unstable nuclei which were produced online from the photofission of uranium. The target ^{137}Cs ions were trapped with a new target-forming technique that makes a high-density stationary target from a small number of ions by confining them in an electron storage ring. After developments of target generation and transportation systems and the beam stacking method to increase the ion beam intensity up to approximately 2×10^7 ions per pulse beam, an average luminosity of $0.9 \times 10^{26}\ \mathrm{cm^{-2}\ s^{-1}}$ was achieved for ^{137}Cs. The obtained angular distribution of elastically scattered electrons is consistent with a calculation. This success marks the realization of the anticipated femtoscope which clarifies the structures of exotic and short-lived unstable nuclei.

DOI: 10.1103/PhysRevLett.131.092502

Short-lived unstable nuclei have been intensively investigated worldwide following the discovery of exotic phenomena, such as halos, neutron skins, and losses and appearances of nuclear magicities [1]. Advances in accelerator technology and the radioactive isotope (RI) production method have helped expand the accessible areas of unstable nuclei in the nuclear chart and improved the understanding of those exotic features of interest not only for the study of nuclear structures, but also for applications such as nucleosynthesis in the field of astrophysics [2]. The sizes and shapes of nuclei are particularly important for establishing nuclear structure models that can be applied to these unstable nuclei. The root-mean-squared (rms) nuclear-matter (both proton and neutron) radii of unstable nuclei have been measured using the total reaction cross section with a transmission method [3]. Elastic proton scattering in inverse kinematics with an RI beam provides nuclear-matter distribution information [4,5]. These methods use hadronic probes to investigate unstable nuclei owing to their relatively large reaction rates, but they are affected by unavoidable ambiguities in the reaction mechanism due to the strong nuclear force.

Electron scattering is one of the most powerful and reliable tools for investigating the internal structure of atomic nuclei owing to its weakness compared to the strong nuclear force and its well-understood interaction mechanism [6]. Many important features of atomic nuclei have been unambiguously clarified via high-energy electron scattering aimed at stable nuclei since Hofstadter and his colleagues established the effectiveness of electron scattering for nuclear structure studies approximately a half century ago [7]. The spatial charge density distribution in the nucleus is an important feature determined by elastic electron scattering, because it is directly related to the sum of squares of all proton wave functions in the independent single-particle model. The rms charge radii of nuclei including unstable ones have been determined by isotope shift measurements via laser spectroscopies [8,9], which are very precise but sensitive to only the relative radius difference between two isotopes. The investigation of unstable nuclei via elastic electron scattering provides important and direct information for understanding their internal structures, as it clearly determines not only the size, but also the shape by measuring the diffraction pattern of the charge form factors. However, electron scattering has not been applied to unstable nuclei thus far. A few exceptions are, for example, ^{3}H, ^{14}C, and ^{41}Ca, whose lifetimes of 12.3, 5700, and 10^5 yr, respectively, are long enough to prepare targets of adequate thickness [10–12]. For example, a 1-g ^{3}H target was used to achieve the luminosity required for electron scattering experiments [13]. It is, however, impossible to prepare a large amount of targets for more production-hard, short-lived unstable nuclei. To overcome this difficulty and realize electron scattering for short-lived unstable nuclei, we developed a novel internal target-forming technique, self-confining RI ion target (SCRIT) [14]. It allows us to form a stationary target along the electron beam and achieve high luminosity with a small number of online-produced radioactive nuclear ions owing to the effective large current in a storage ring. The target ions are prepared at an isotope separation online (ISOL) system and transported to the SCRIT system [15]

Phys. Rev. Lett. 131 (2023) 092502.

Electron scattering provides a long-awaited view of unstable nuclei

Nuclear reactions produce a plethora of short-lived artificial isotopes. Figuring out what they look like has been a challenge.

The cartoon picture of an atomic nucleus looks kind of like the inside of a gumball machine that dispenses only two flavors: protons and neutrons, evenly mixed in a compact, spherical cluster.

That's not generally what real nuclei look like. Neutron-rich lead-208, for example, has a thick skin of neutrons encasing its proton-endowed core (see Physics Today, July 2021, page 12). Some nuclei are flattened, and some are elongated. Some are even pear shaped.

The more unstable a nucleus, the stranger the structures it can adopt. Short-lived nuclei might form bubble structures with depleted central density, or they might have a valence nucleon or two that form a halo around a compact central core. (See the article by Filomena Nunes, Physics Today, May 2021, page 34.) Frustratingly, though, those exotic structures are hard to experimentally confirm, because the gold standard for probing nuclear structure—electron scattering—has been off limits to short-lived nuclei.

That could change soon. Kyo Tsukada and colleagues, working at RIKEN's Radioactive Isotope Beam Factory (RIBF) in Wako, Japan, have performed the first electron-scattering experiment on unstable nuclei produced on the fly in a nuclear reaction.[1] Their isotope of choice, cesium-137, has a half-life of 30 years. It's not so exotic that the researchers expected—or found—anything unusual about its structure. But the technique they used is applicable to shorter-lived nuclei, so more experiments are on the way.

Backscatter

Probing nuclei through particle scattering dates back to the discovery of the nucleus itself, in 1911, when Ernest

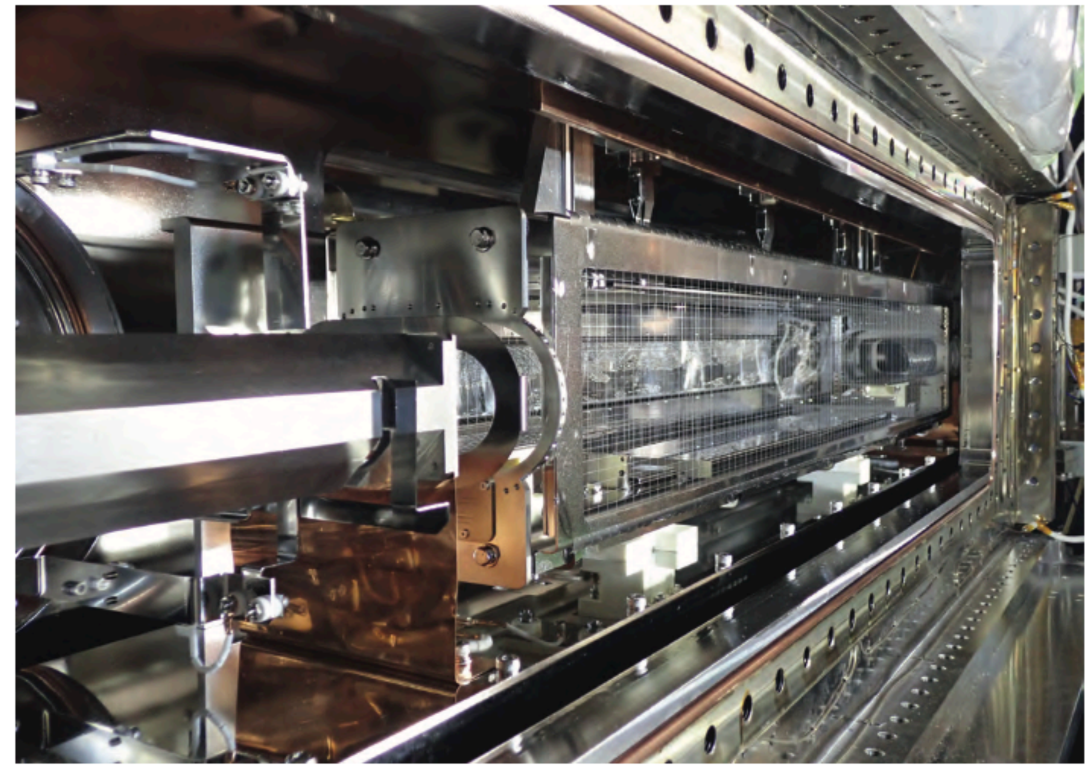

FIGURE 1. RADIOACTIVE IONS too short-lived to be made into a solid target can nevertheless be trapped in an electron beam. The beam itself traps the ions in two dimensions; the cage of thin wire electrodes creates an electric potential that traps them in the third. (Courtesy of Tetsuya Ohnishi.)

Physics Today **76** (11), 14–16 (2023)

$$\frac{\mathrm{d}N}{\mathrm{d}t} = L \times \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}$$

Luminosity

Electron scattering for exotic nuclei

Exotic nuclei (production-hard & short-lived)

Extremely “thin” targets

→ Low luminosity

Elastic scattering

largest σ up to modest q

“Hofstadter’s” exp. for exotic nuclei

R. Hofstadter
(Nobel prize : 1961)

Luminosities for e-scattering

	Ee	N_{beam}	target thickness	L
Hofstadter's era (1950s)	150 MeV	~ 1nA (~10^9 /s)	~10^{19} /cm^2	~10^{28} /cm^2/s

Elastic Scattering for Exotic Nuclei

(for medium-heavy nuclei)

$$L \gtrsim 10^{27}/\mathrm{cm}^2/\mathrm{s}$$

with a “medium-angular-accept.” spectrometer (~100 mSr)

T.S. and H. Simon, Prog. Part. Nucl. Phys. 96 (2017) 1

First idea in 2004

SCRIT : Self-Confining Radioactive Ion Target

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Nuclear Instruments and Methods in Physics Research A 532 (2004) 216–223

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

A new method for electron-scattering experiments using a self-confining radioactive ion target in an electron storage ring

M. Wakasugi[a,*], T. Suda[b], Y. Yano[a]

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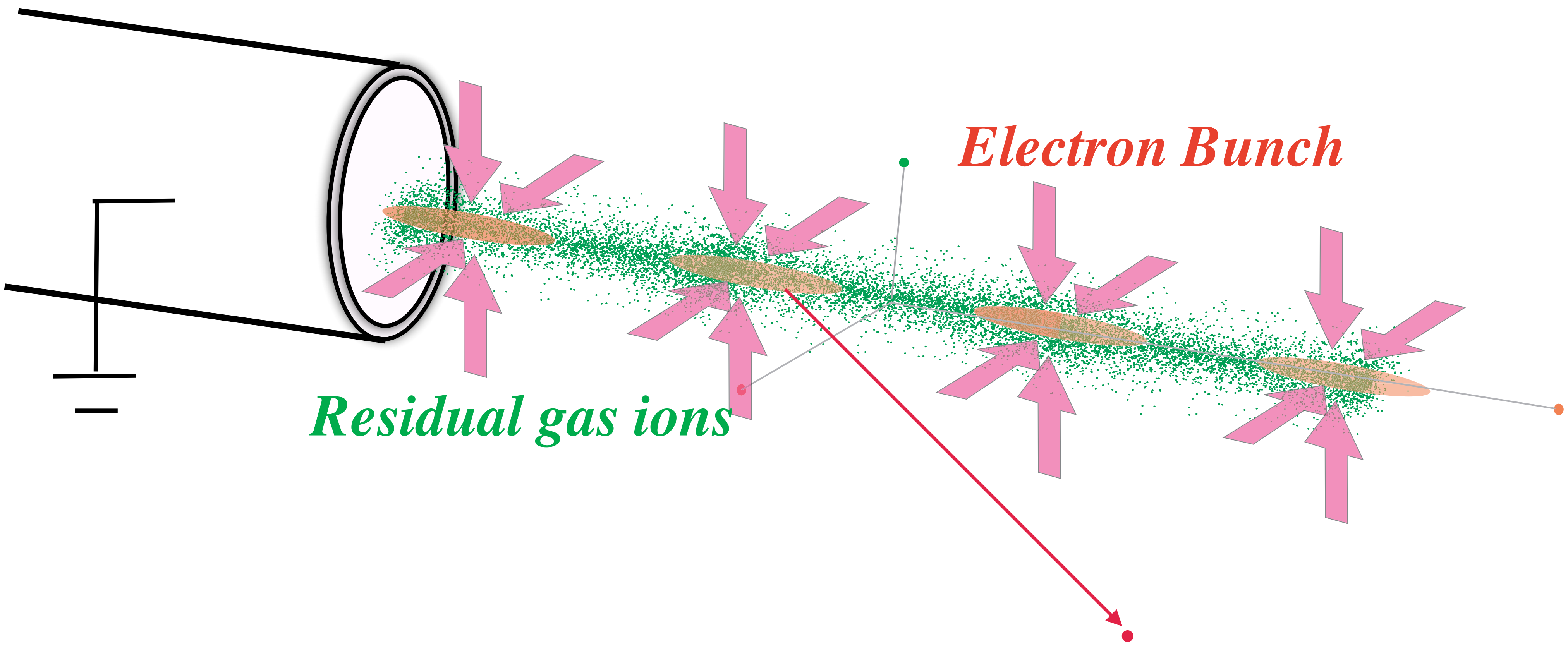
[b] *RI Beam Science Laboratory, RIKEN, Wako-shi, Saitama 351-0198, Japan*

Available online 3 August 2004

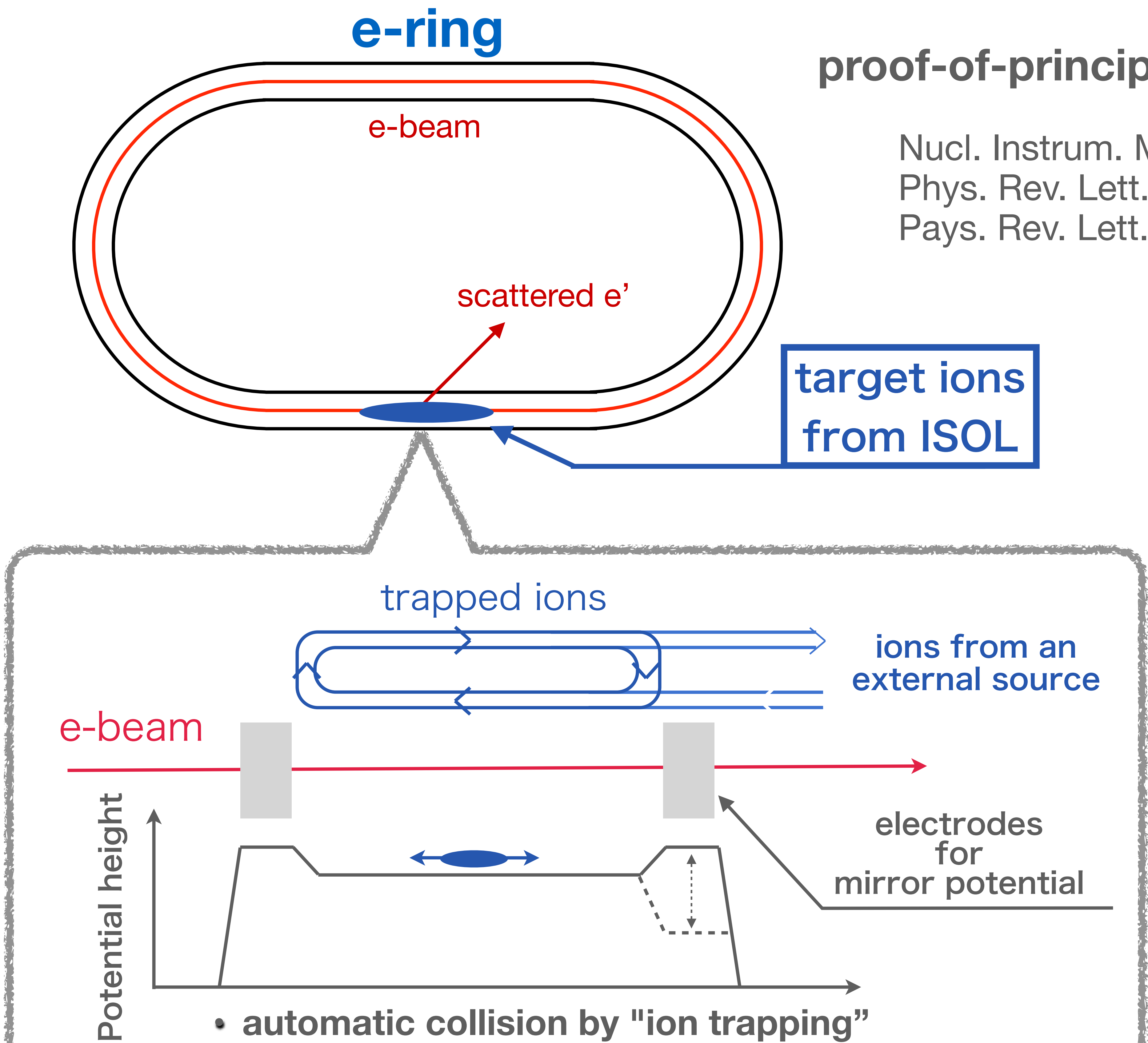
A novel "Ion Trap" using high-energy e-beam

based on (notoriously) known "ion trapping" at "light-source" facilities.

ionized residual gases are trapped by circulating electron beam



SCRIT-based electron scattering facility



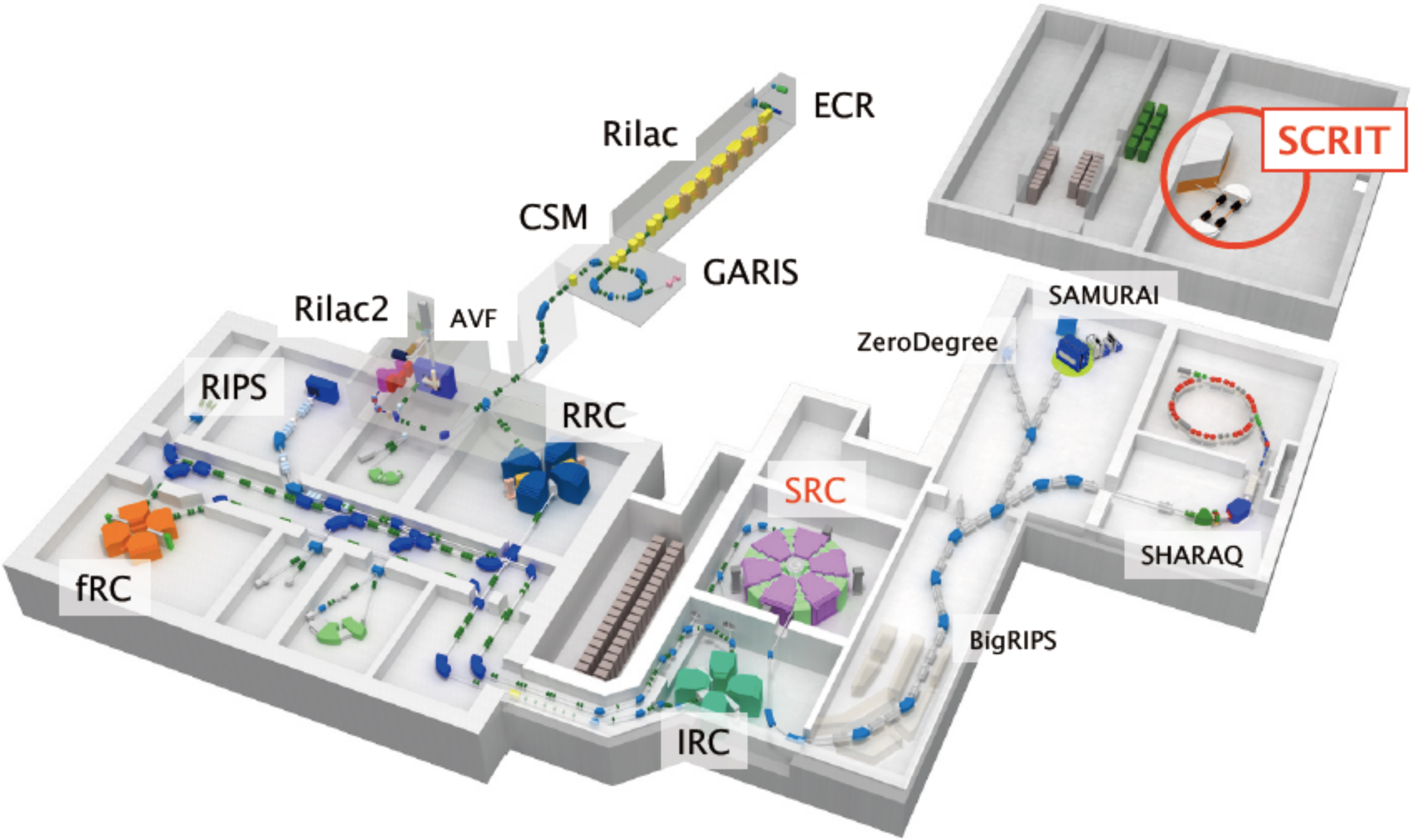
proof-of-principle studies

Nucl. Instrum. Methods A532 (2004) 216.
Phys. Rev. Lett. 100 (2008) 164801.
Pays. Rev. Lett. 102 (2009) 102501.

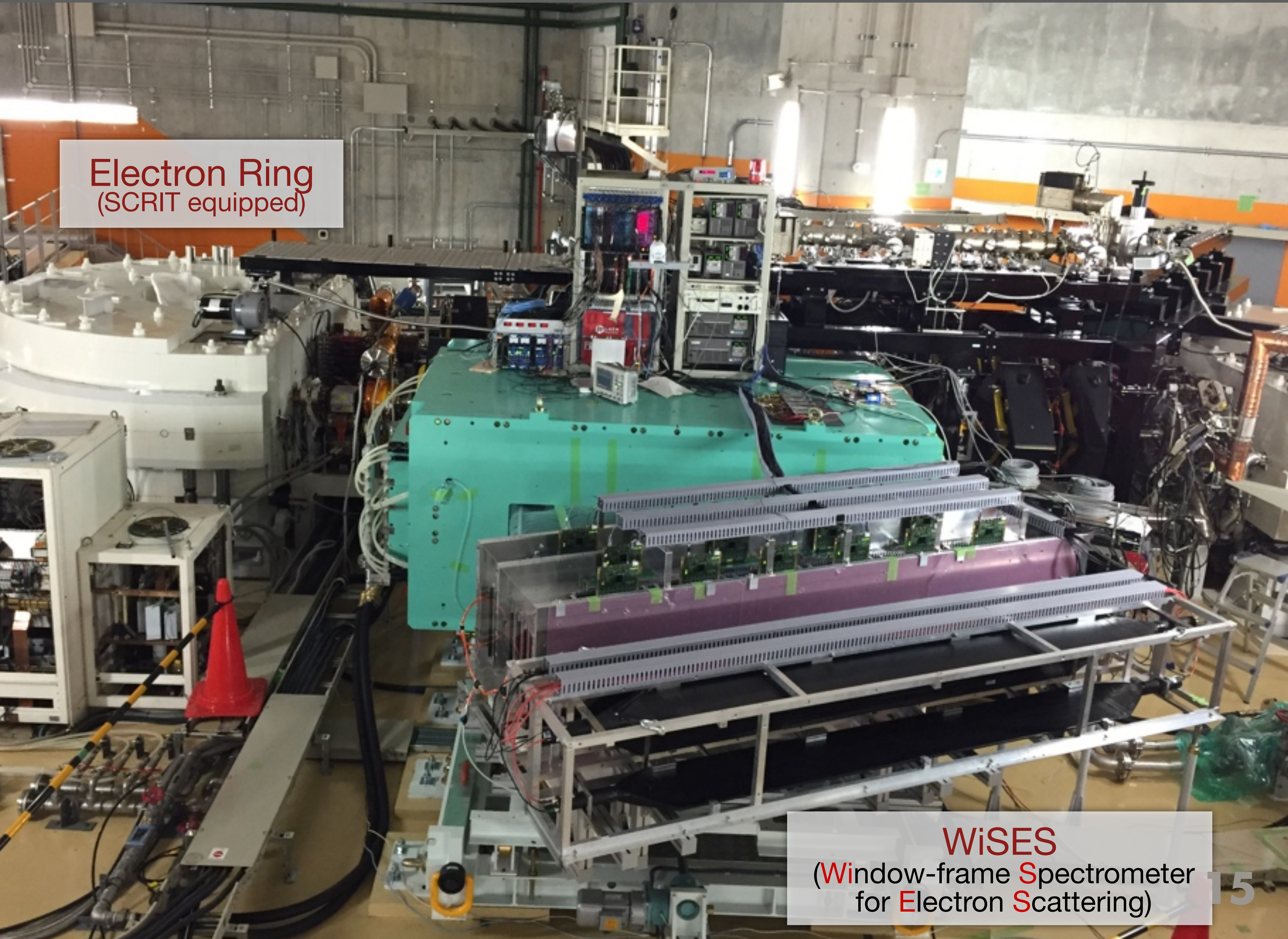
- **automatic collision by "ion trapping"**
- **fast ion manipulation for short-lived nuclei**

SCRIT electron scattering facility @ RIBF

World's first electron facility dedicated for exotic nuclei



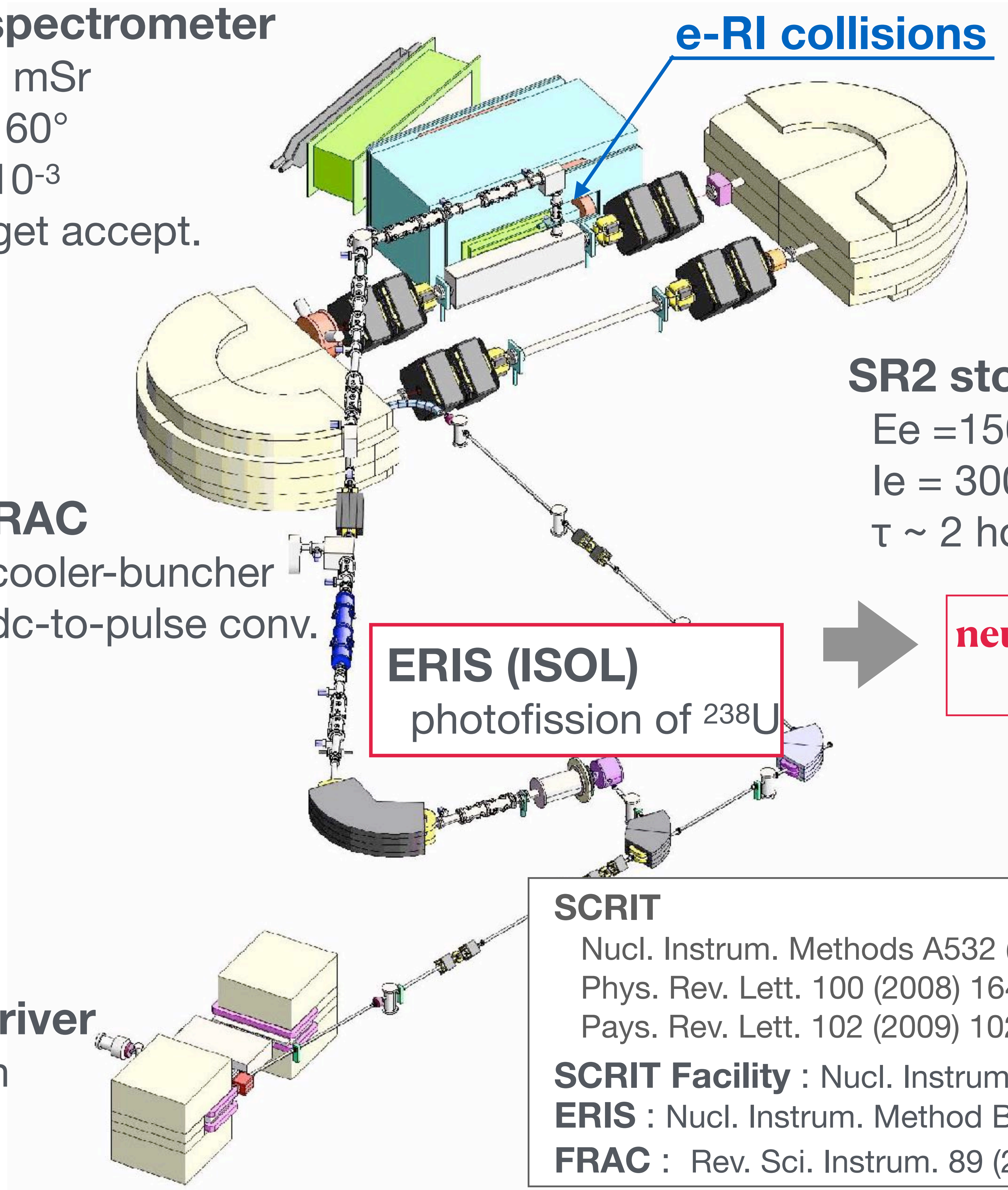
RIKEN RI Beam Factory (Japan)


Electron Ring
(SCRIT equipped)
WiSES
(Window-frame Spectrometer
for Electron Scattering)

RIKEN SCRIT Electron Scattering Facility

WiSES spectrometer
$\Delta\Omega$ ~ 90 mSr
θ = 30 - 60°
$\Delta p/p$ ~ 10^{-3}
long target accept.

e-RI collisions



SR2 storage ring
Ee =150-700 MeV
Ie = 300 mA
τ ~ 2 hours

FRAC
cooler-buncher
dc-to-pulse conv.

ERIS (ISOL)
photofission of ^{238}U

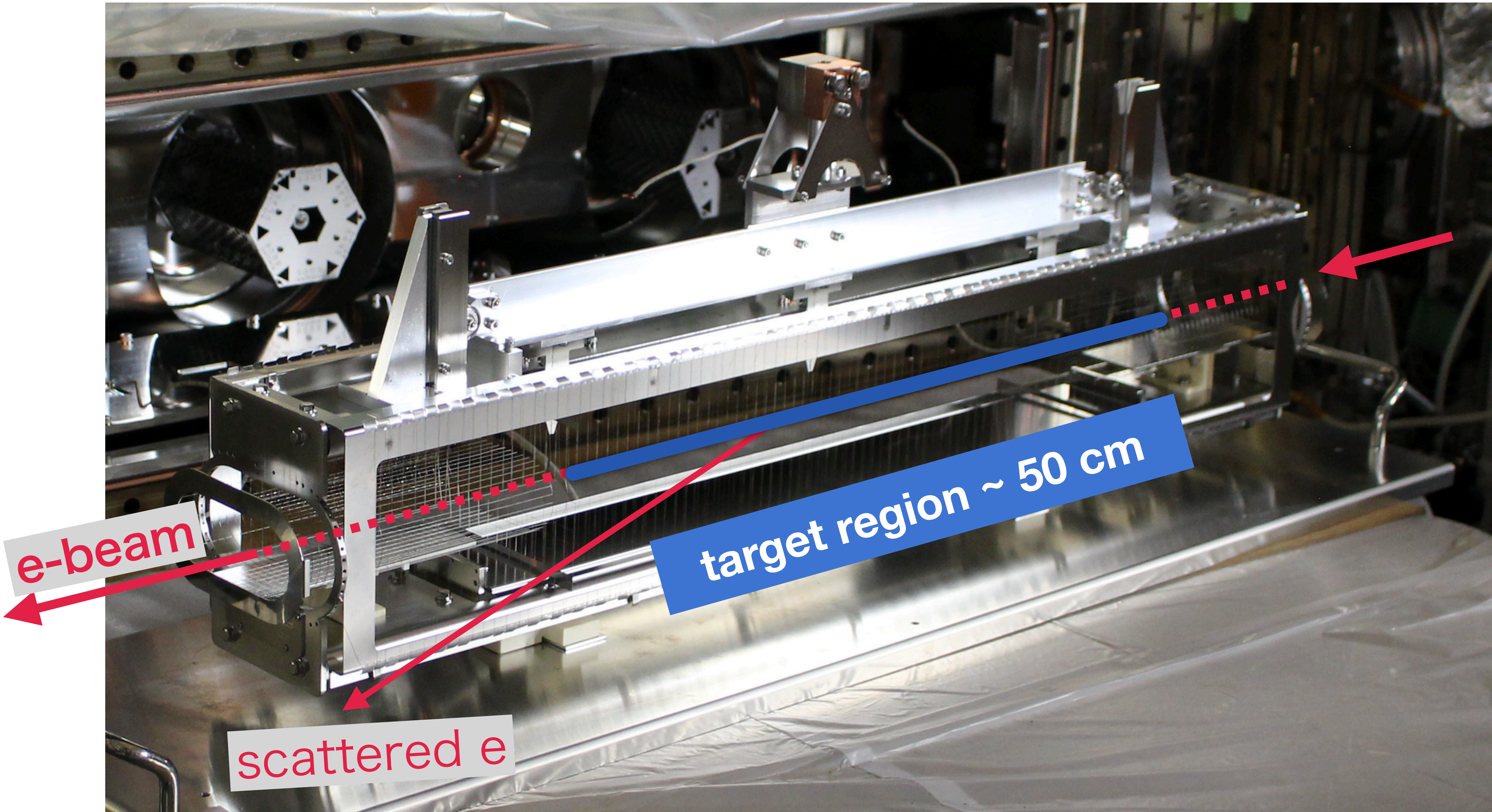
neutron-rich nuclei by $\gamma + ^{238}U$

Injector + ISOL driver
150 MeV Microtron

SCRIT
Nucl. Instrum. Methods A532 (2004) 216.
Phys. Rev. Lett. 100 (2008) 164801.
Pays. Rev. Lett. 102 (2009) 102501.

SCRIT Facility : Nucl. Instrum. Method B317 (2013) 668.
ERIS : Nucl. Instrum. Method B317 (2013) 357.
FRAC : Rev. Sci. Instrum. 89 (2018) 095107.

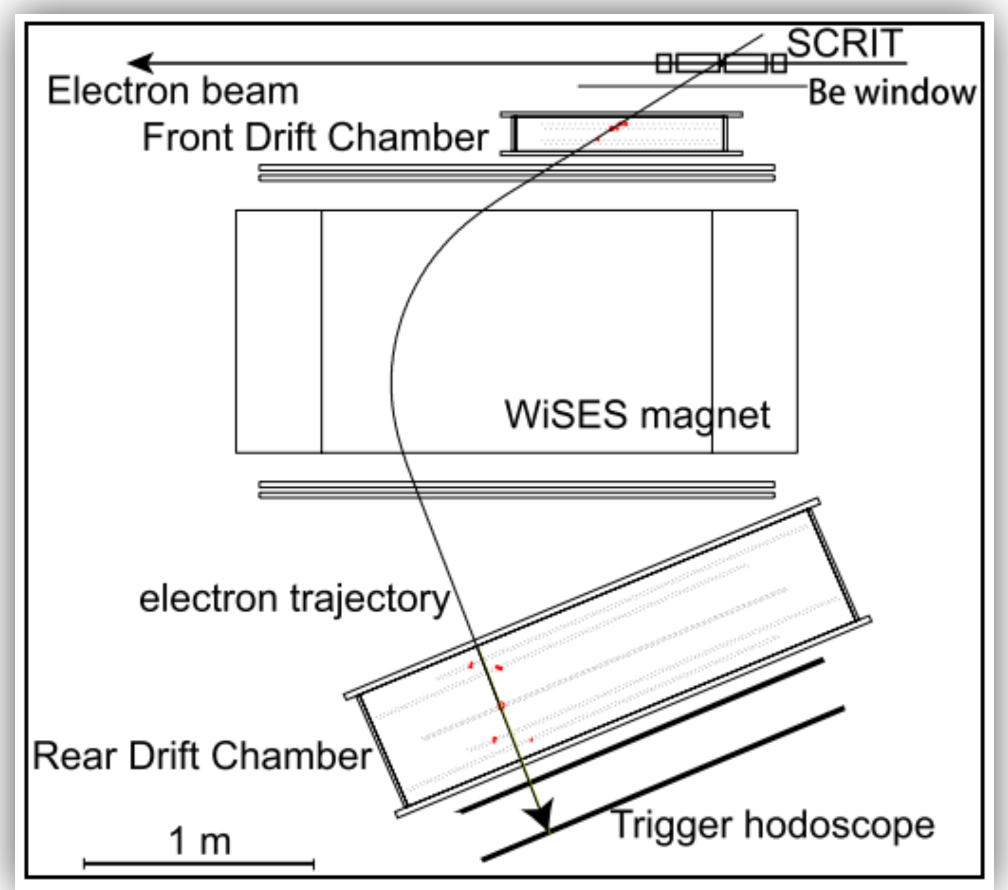
SCRIT device for preparing a target on e-beam

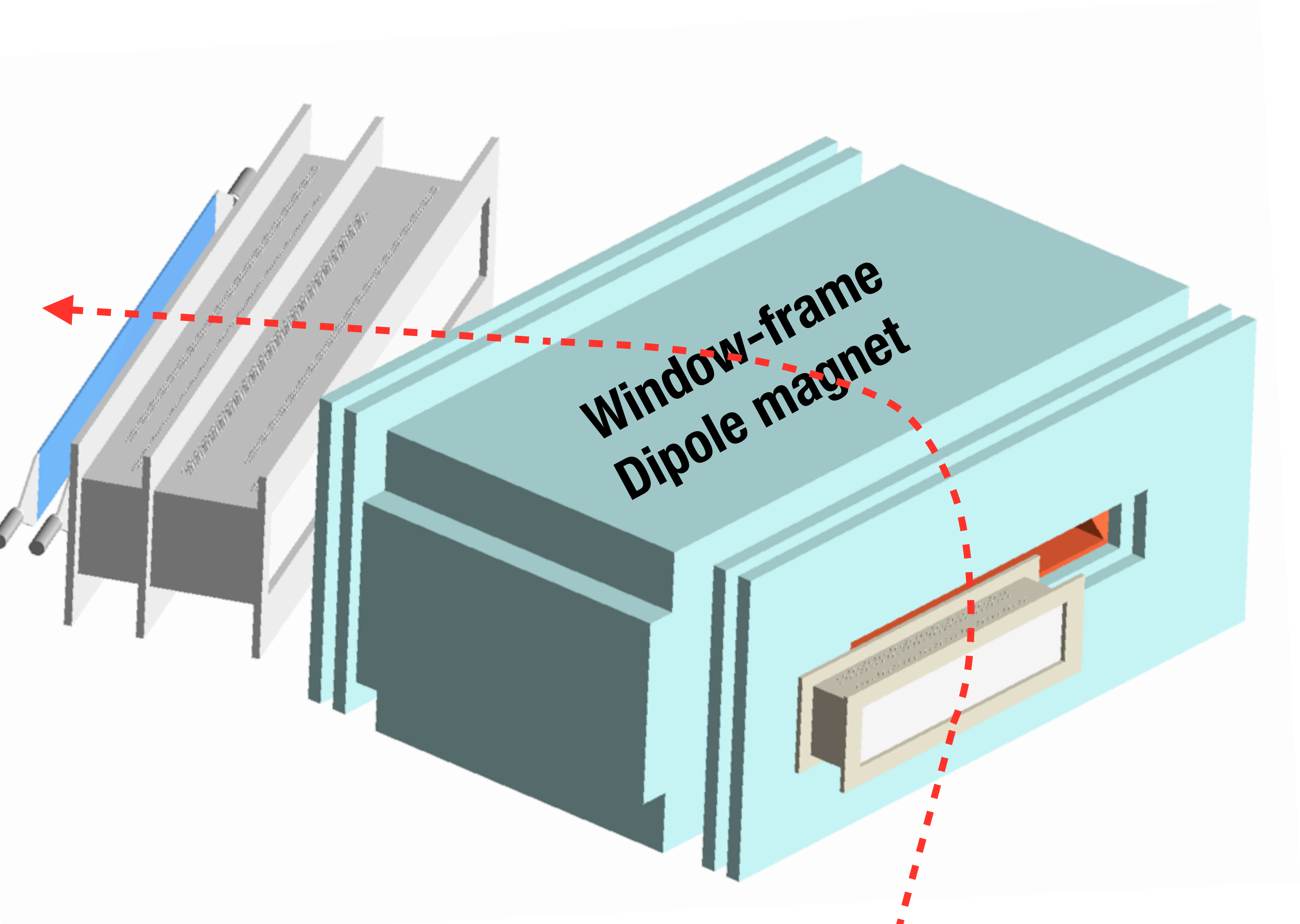


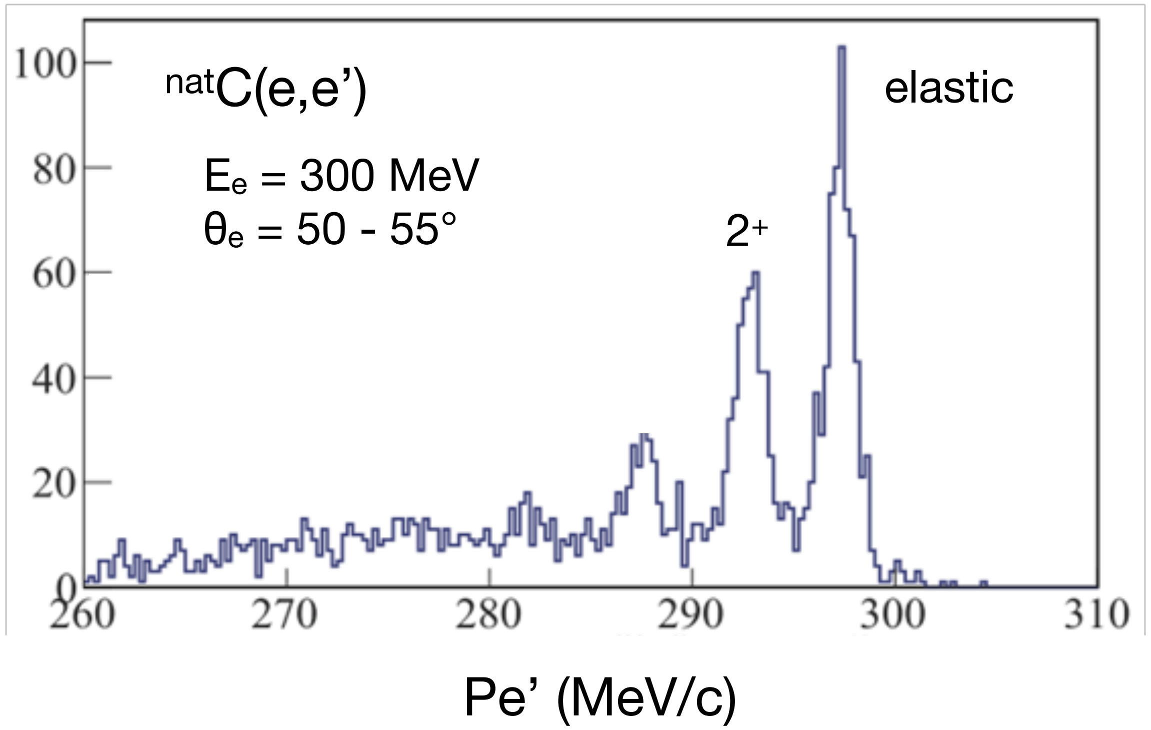
WiSES (Window-frame Spectrometer for Electron Scattering)

- long target acceptance (50cm)
- wide scattering angle coverage

- $\Delta p/p \leq 10^{-3}$ (ΔE<300keV@300MeV)
- Bmax = 0.8 T
- $\Delta\theta = 30°$ (45±15°)
- $\Delta\Omega$~ 100 msr







ERIS (Electron-beam-driven RI separator for SCRIT)

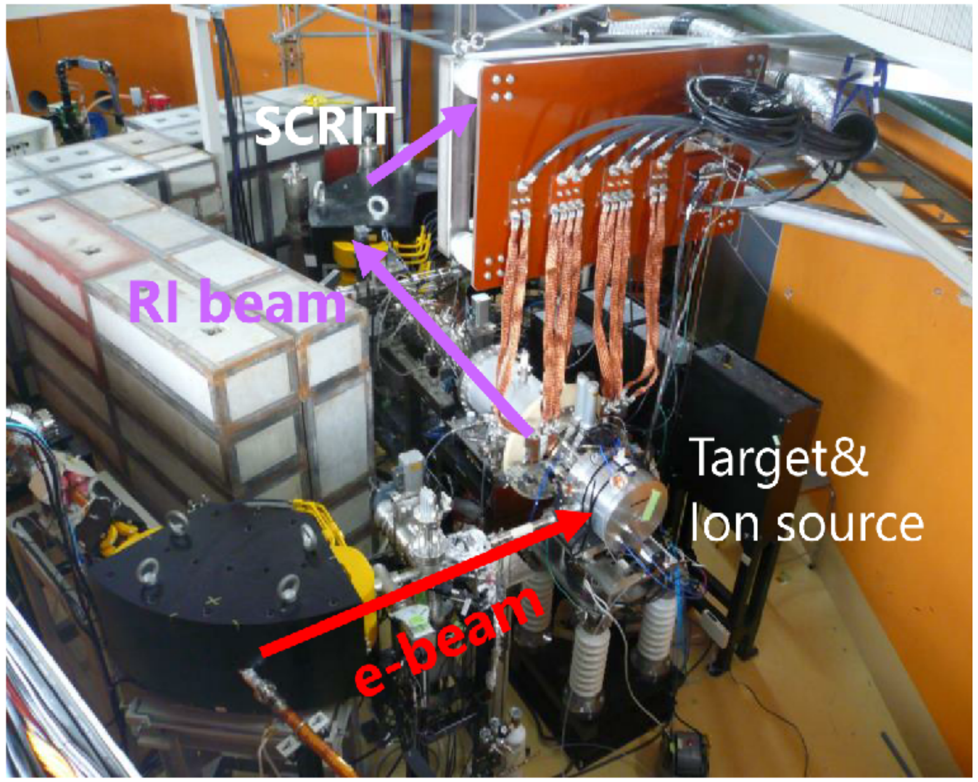
Reaction : photo- (electro-) fission of ^{238}U.
Ion Source : FEBIAD type (Sn, Xe…)
Surface Ionization (Cs, Ba,…)

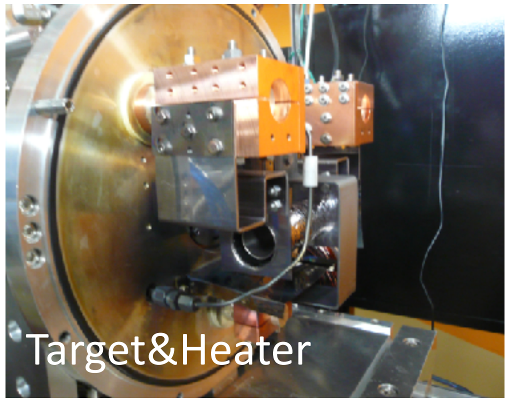
Production Rate
$N_{fission}$ ~ 10^8 /watt
$N_{^{132}Sn}$ ~ 10^6 /watt * 1% ($\varepsilon_{trans.}$)

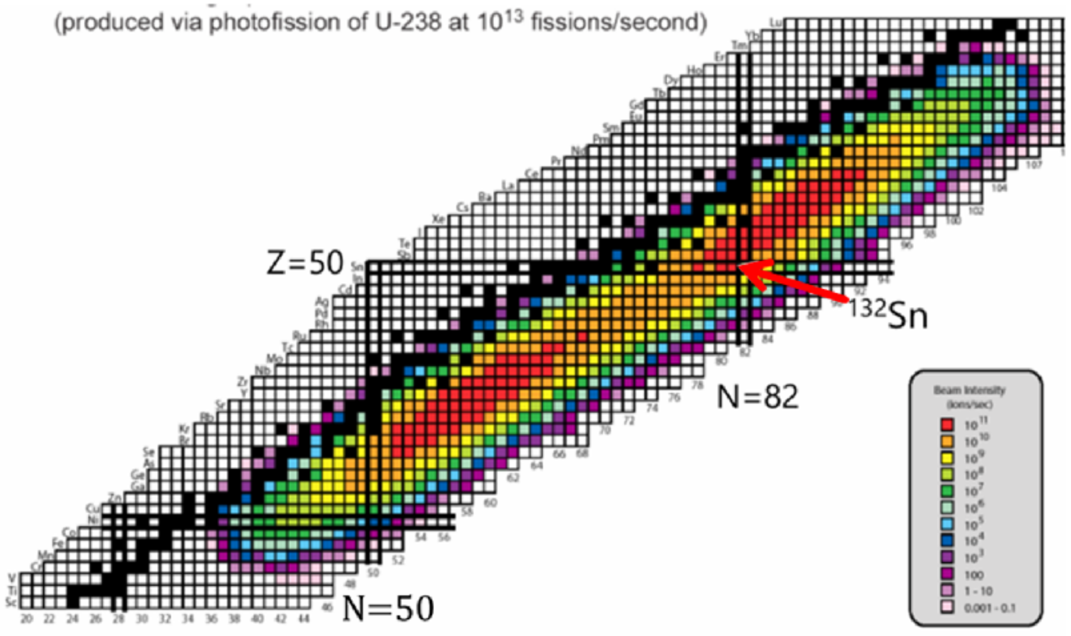
beam power : ~ 20W (today)
~ 2 kW (in a few years)

House-made Uranium carbide (UCx)

φ 18 mm, t 0.8 mm disks



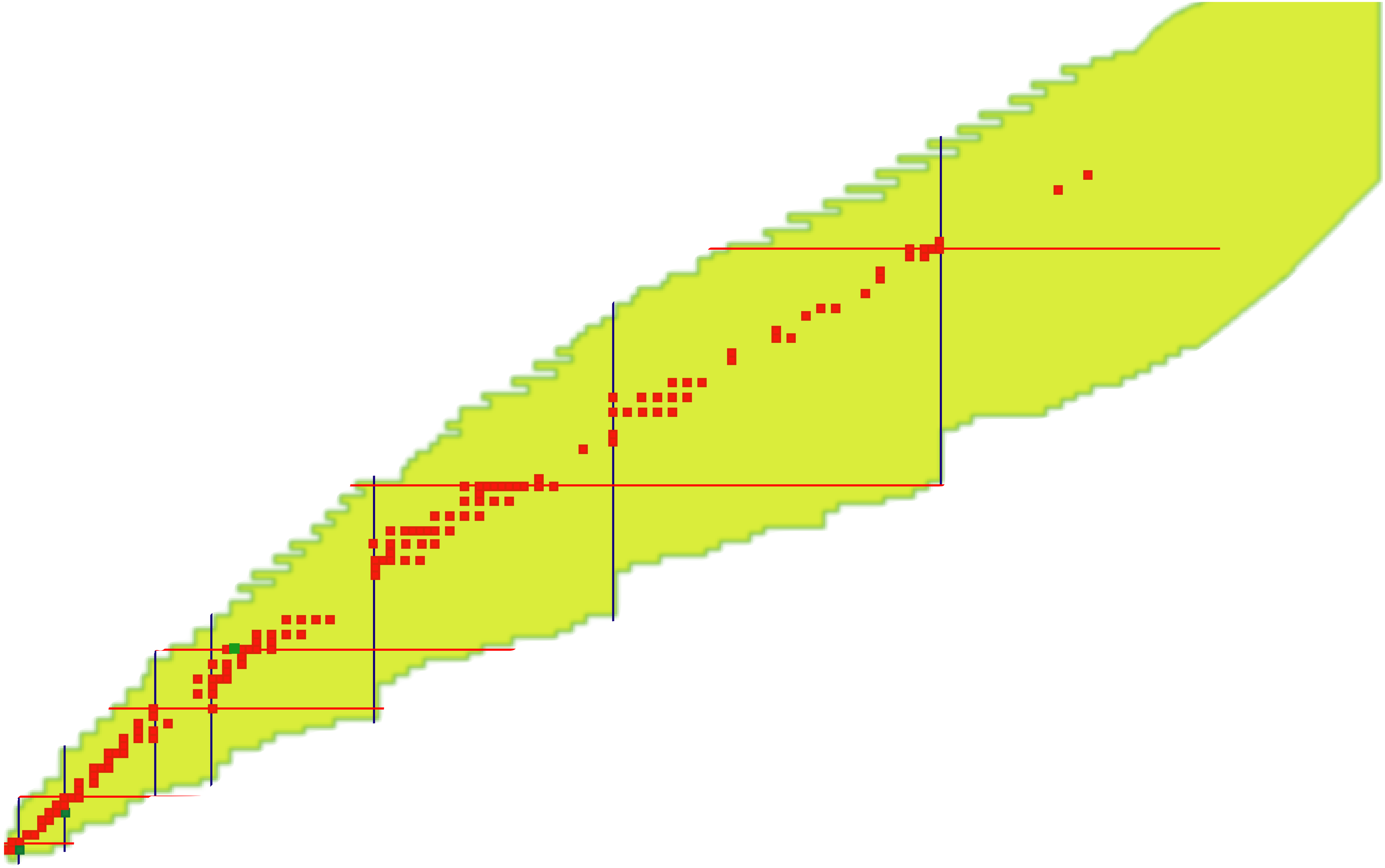




^{138}Xe : 3.9 x 10^6 cps
^{132}Sn : 2.6 x 10^5 cps
^{137}Cs : 8.0 x 10^6 cps (28-g U)

T. Ohnishi *et al.* NIM B317 (2013) 357.

“Day-one exp.” region for our facility



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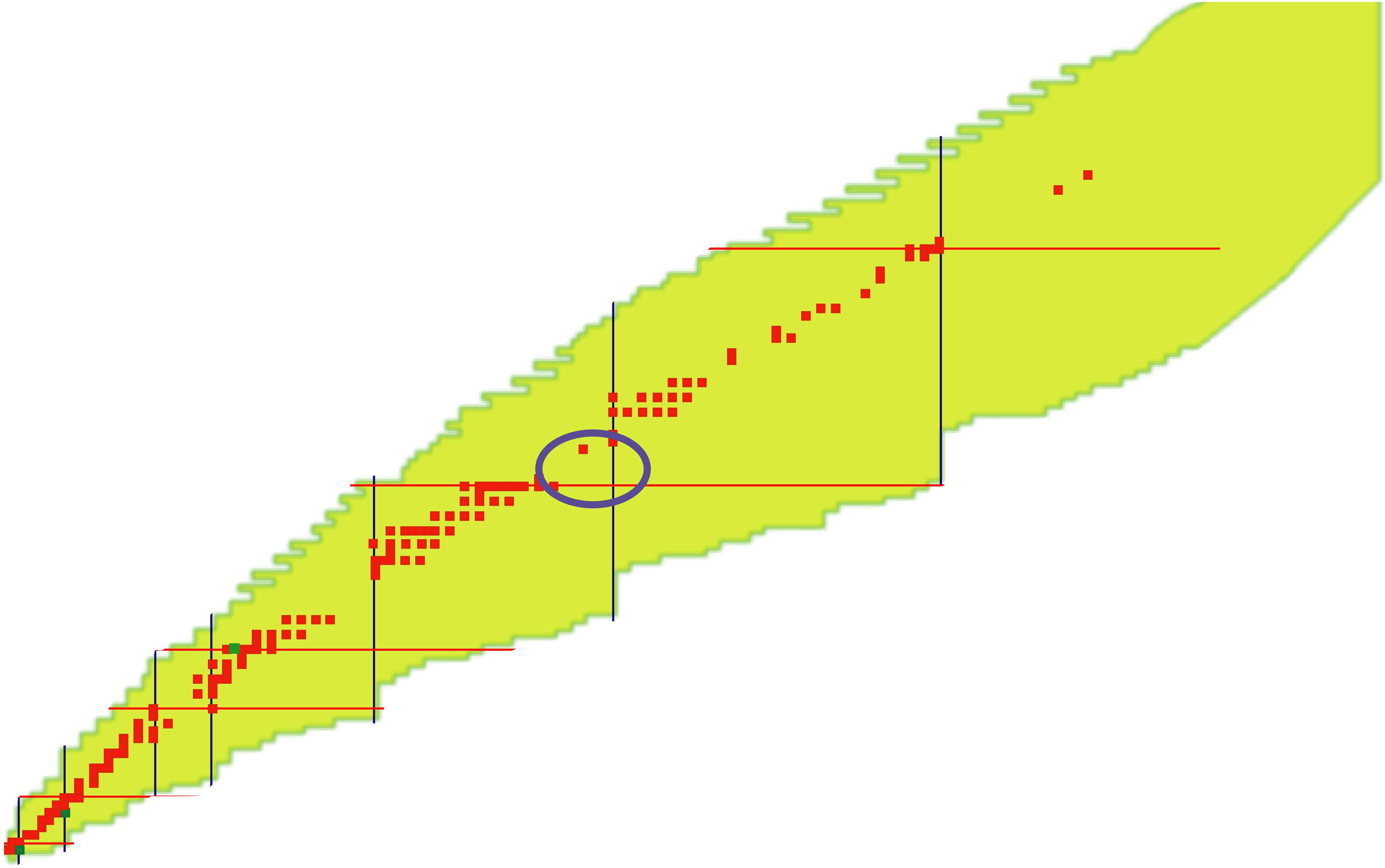

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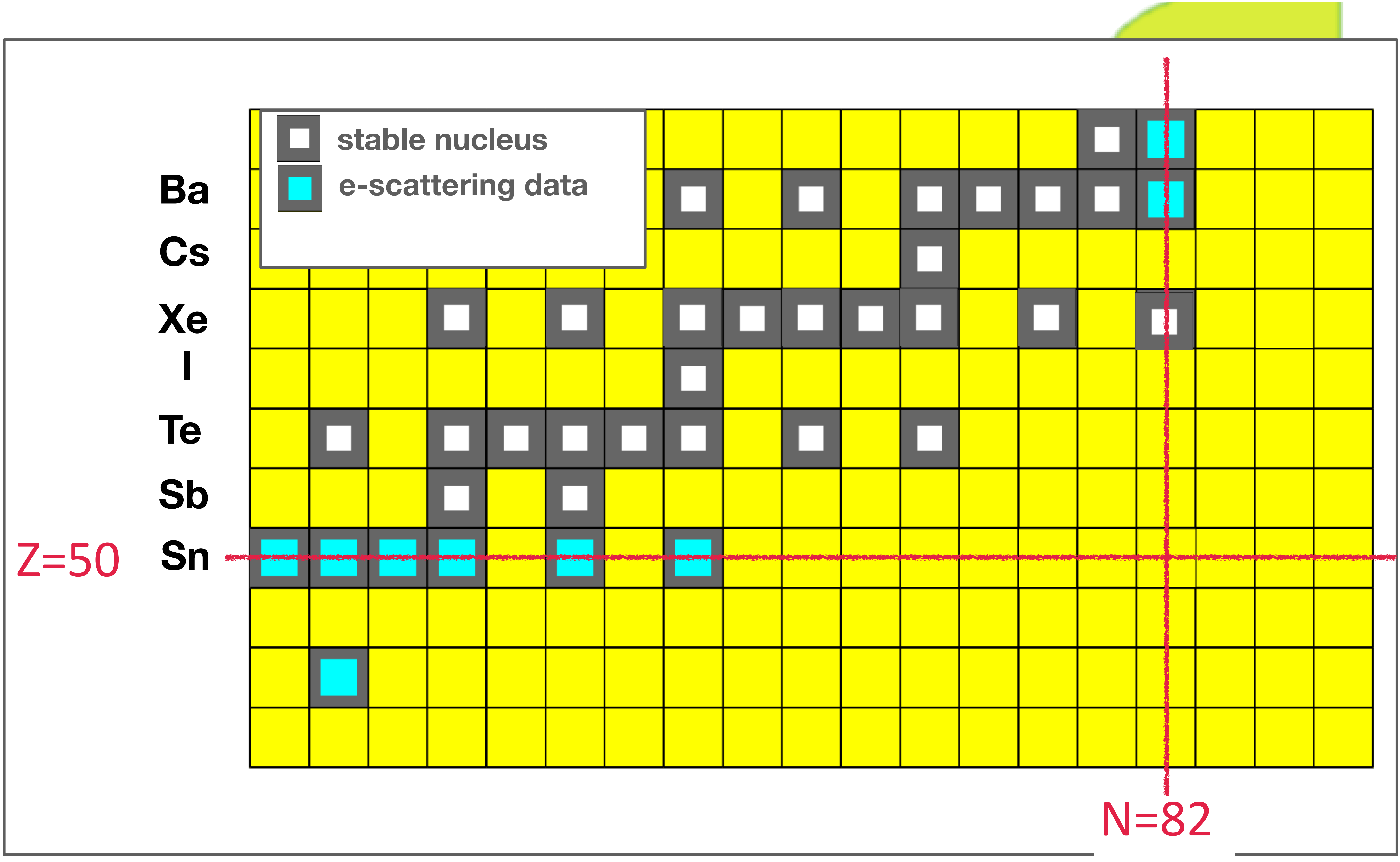

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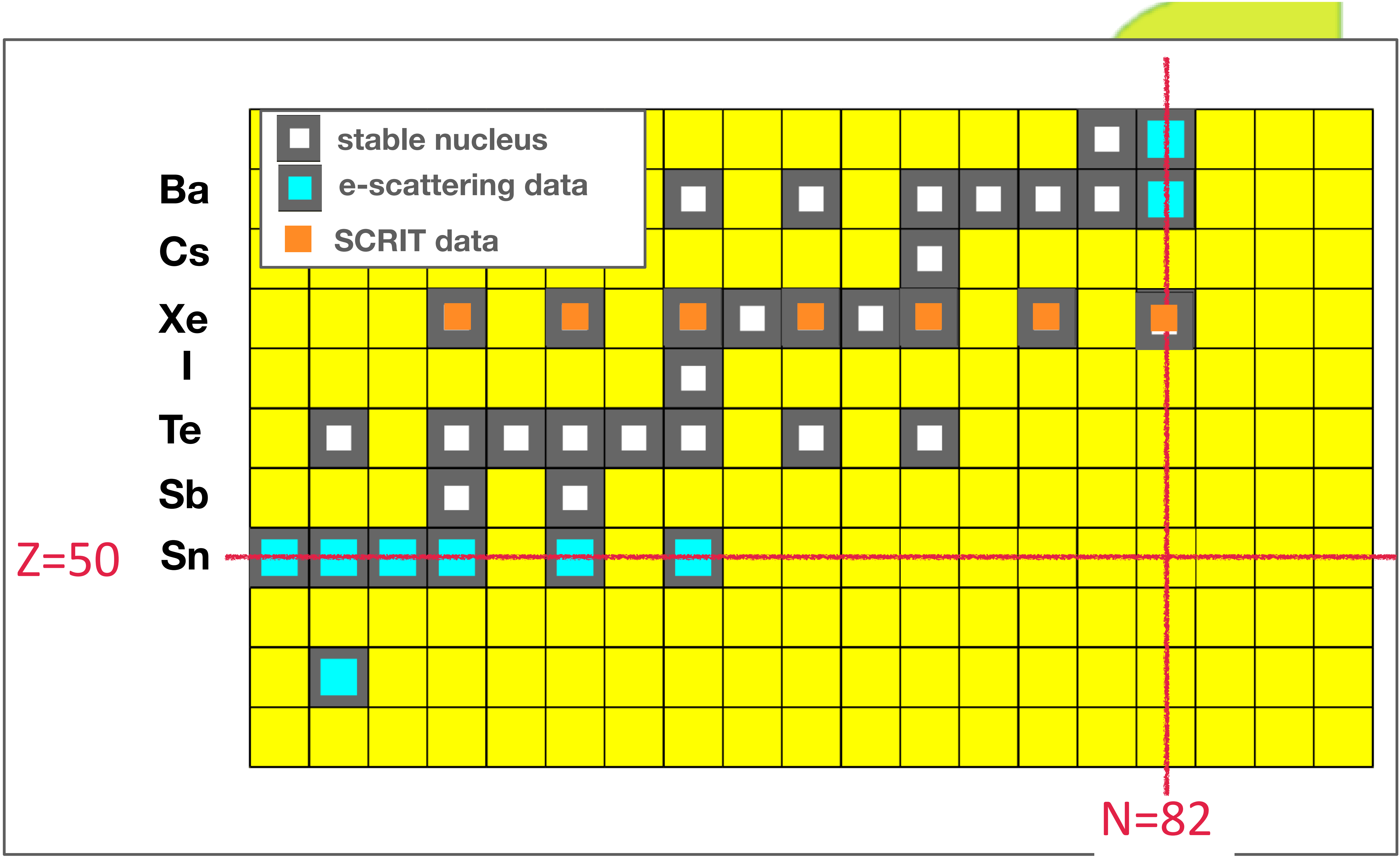

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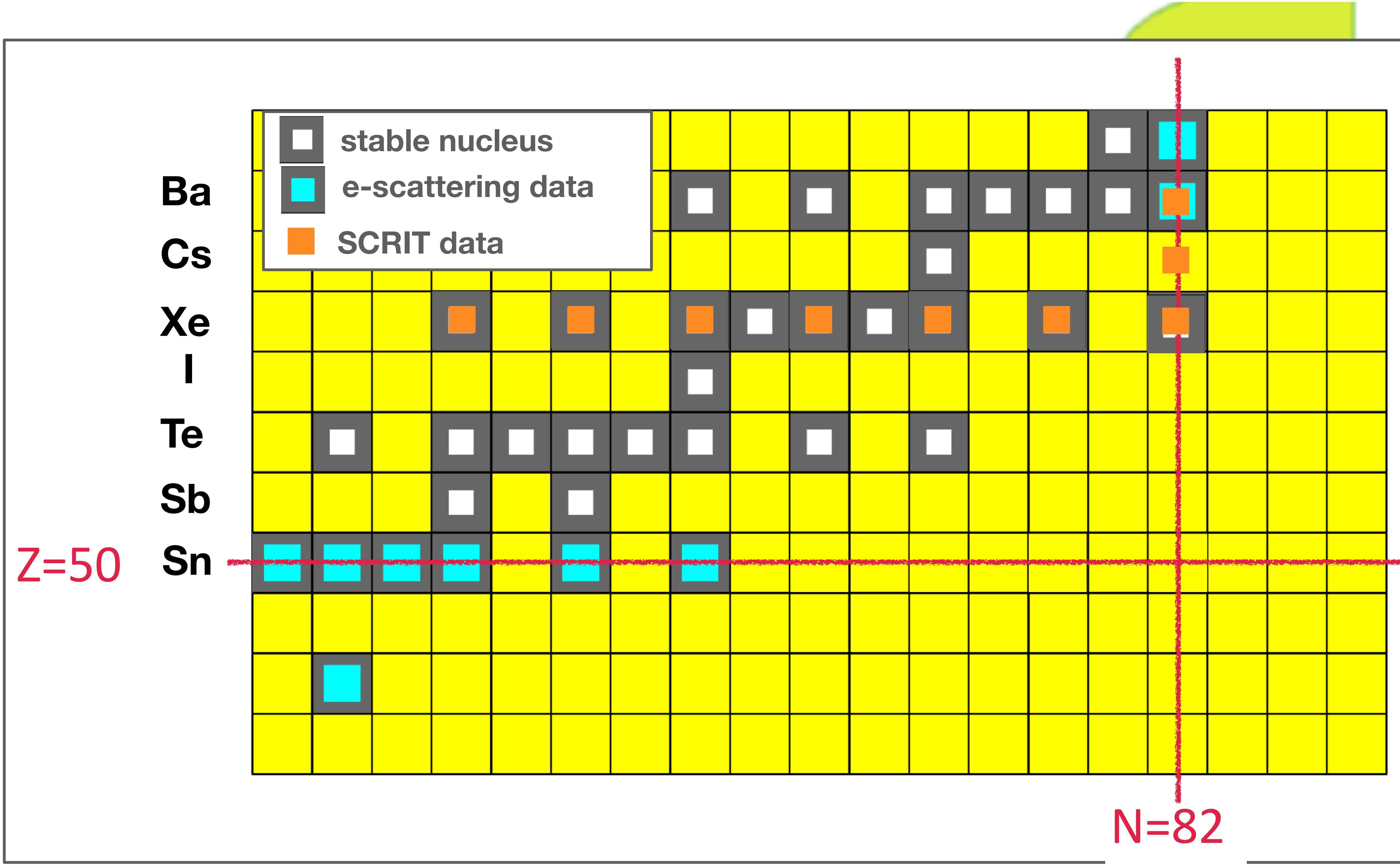

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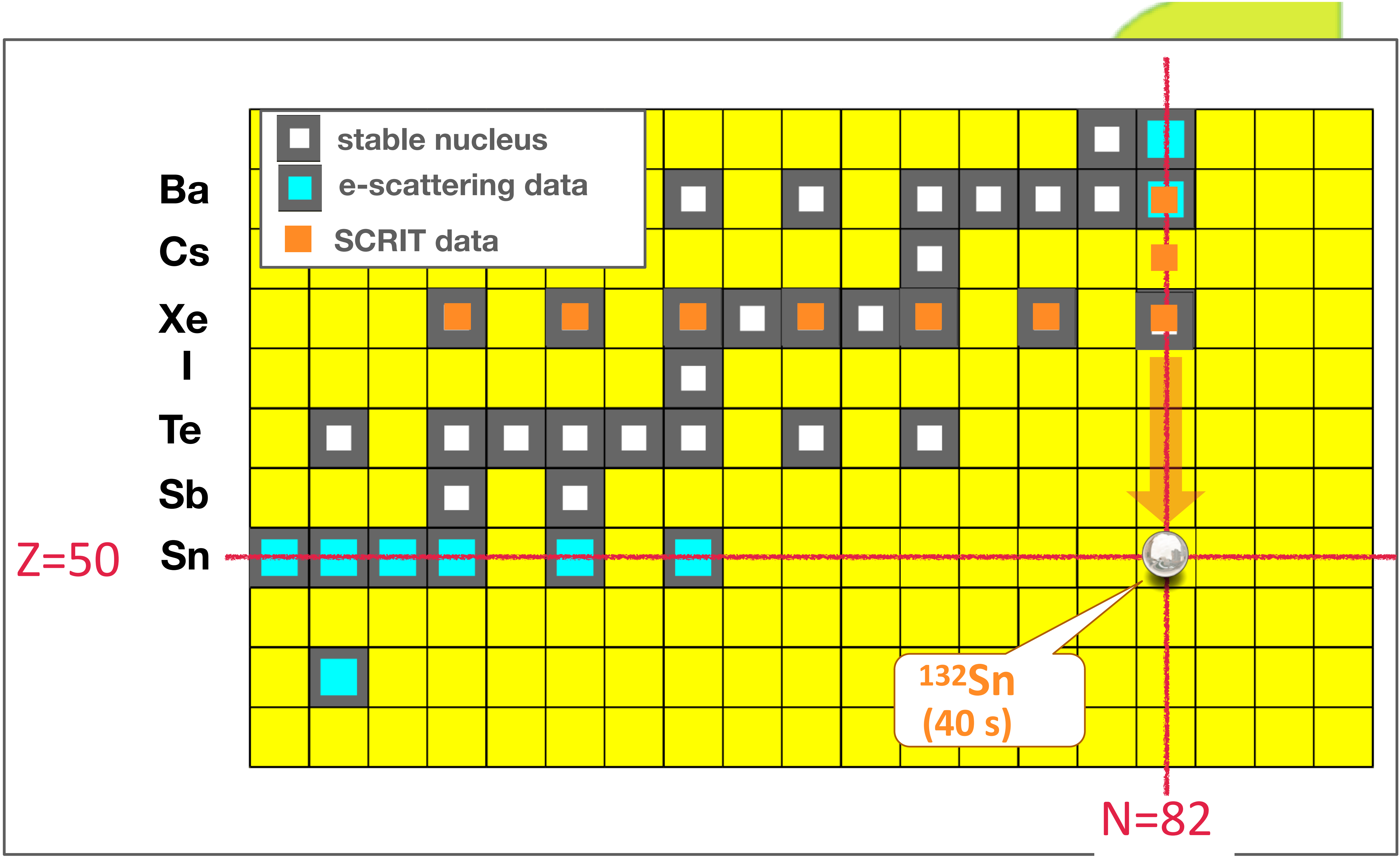

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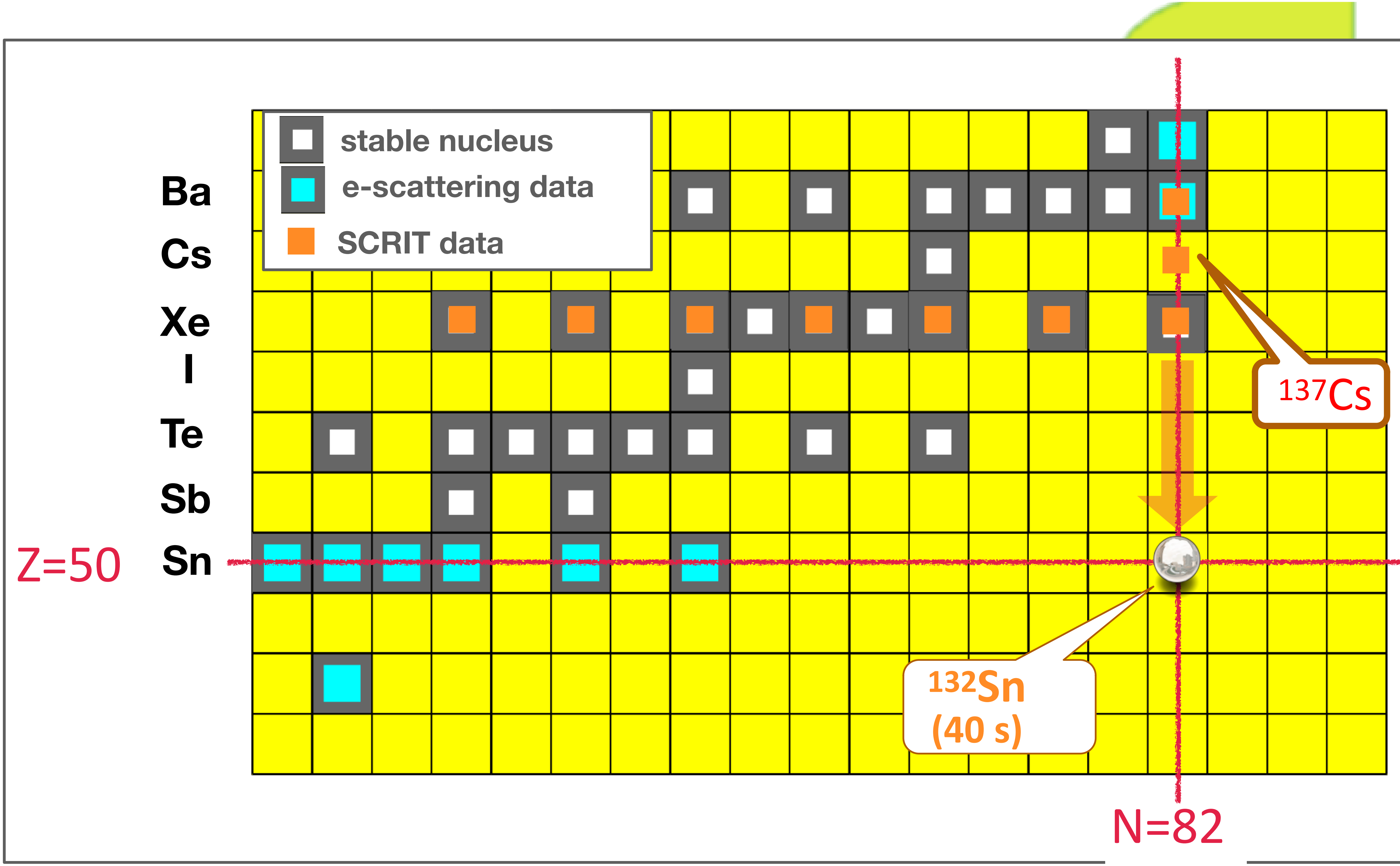
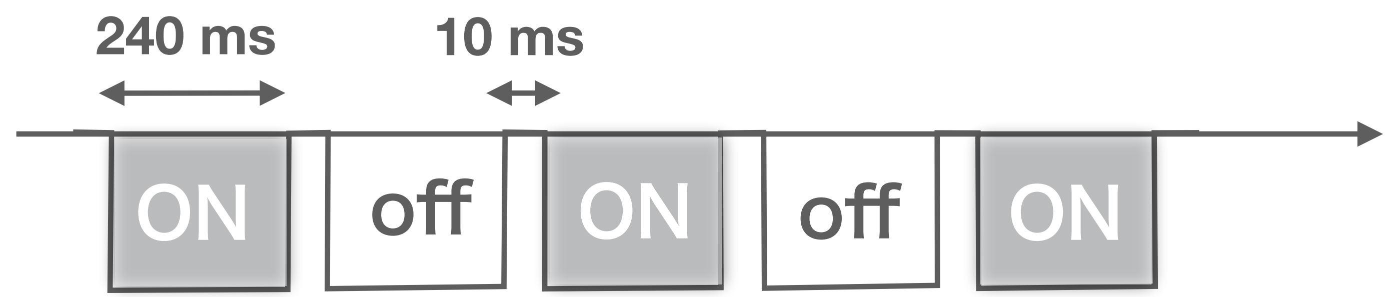


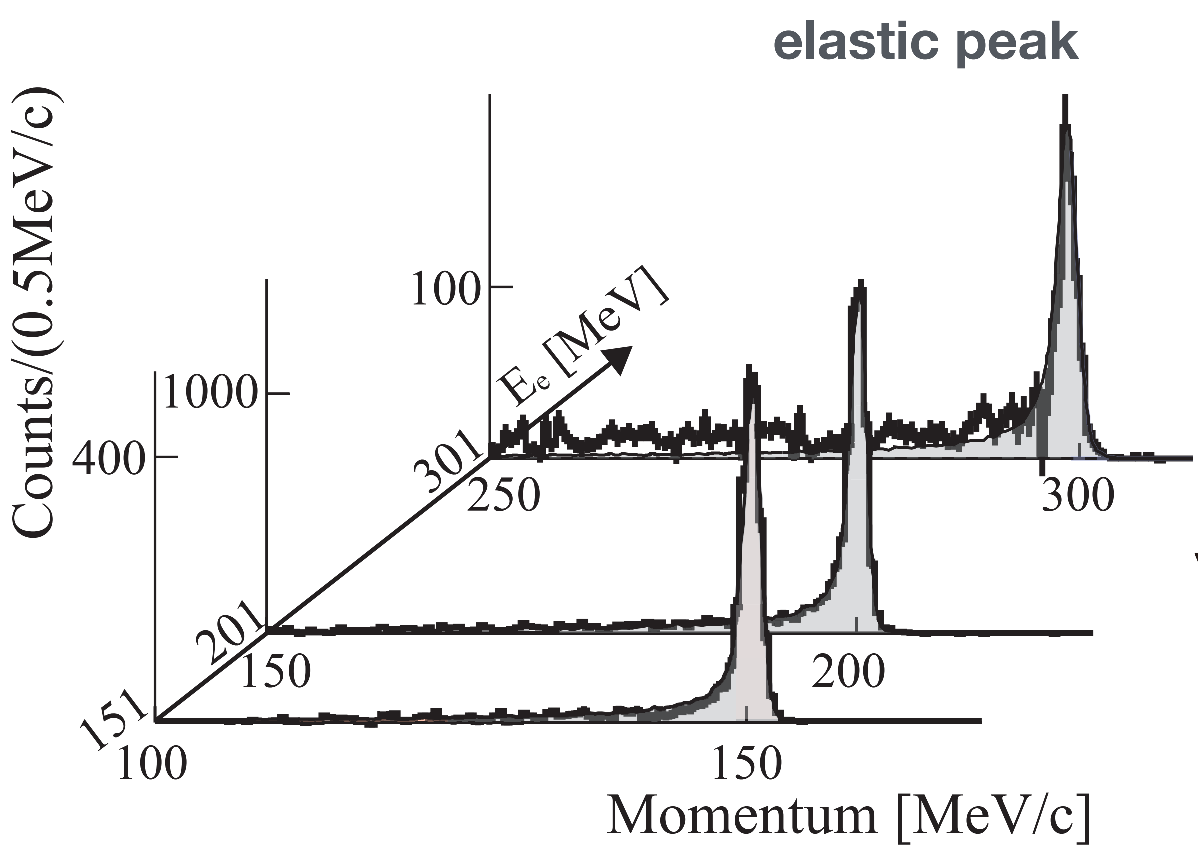
SCRIT facility commissioning : (stable) $^{132}Xe(e,e')$

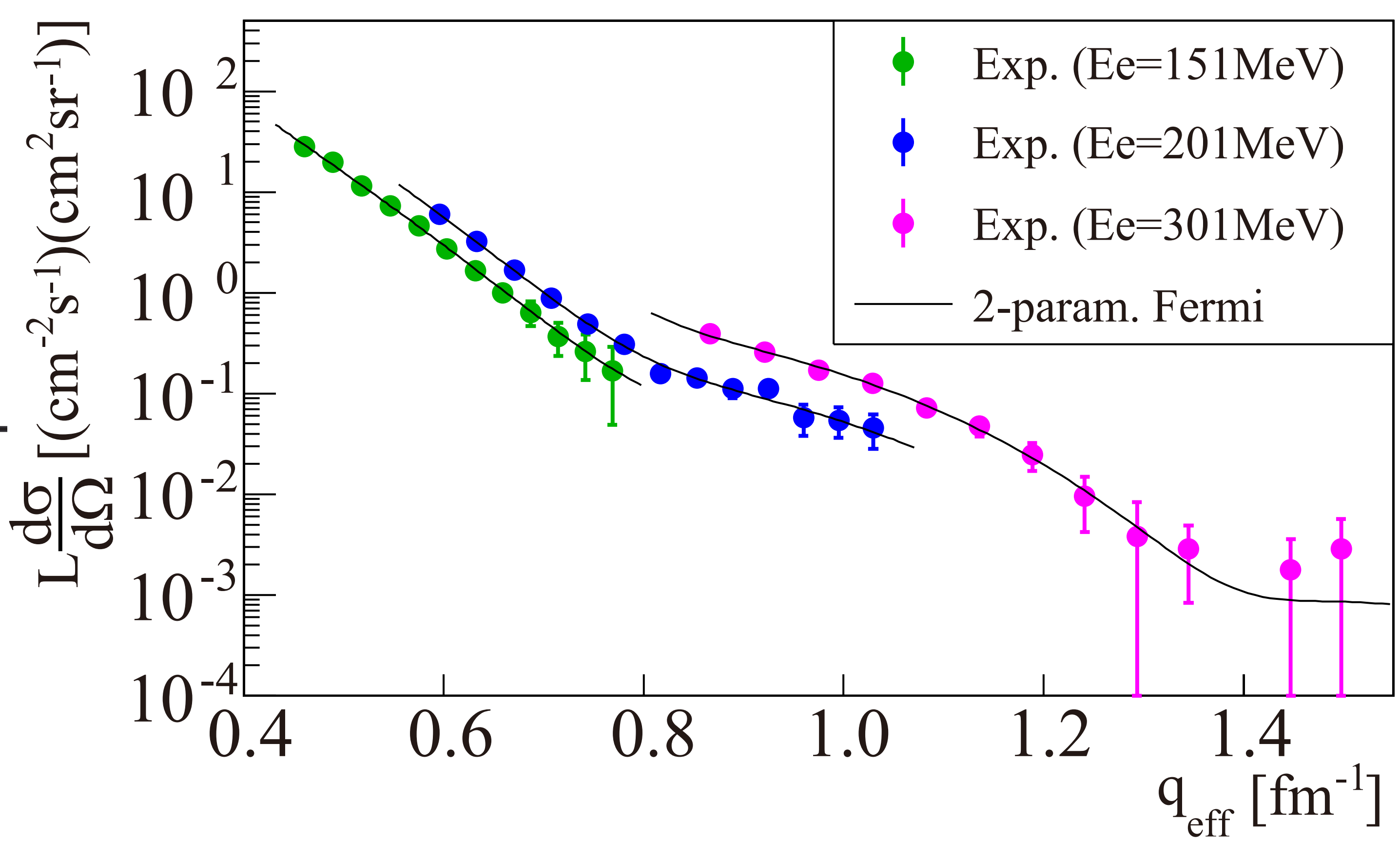
K. Tsukada et al., Phys. Rev. Lett. 118 (2017) 262501.

trapping duration
240 ms



L ~ 10^{27} /cm^2/s with $N_{trapped}$ ~ 10^7

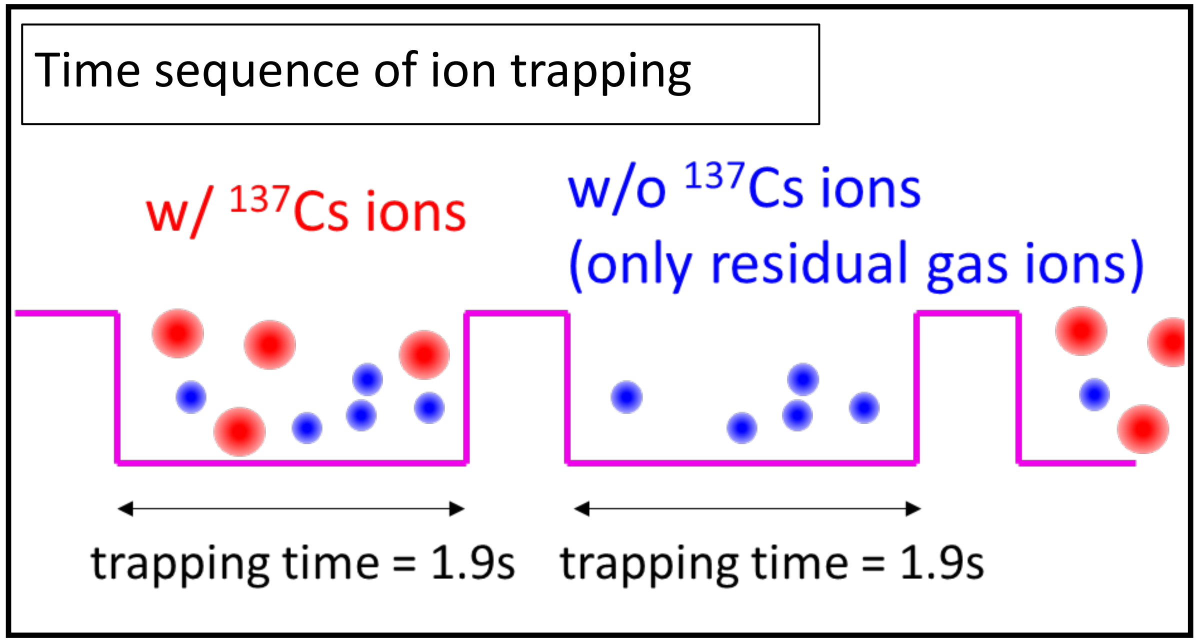


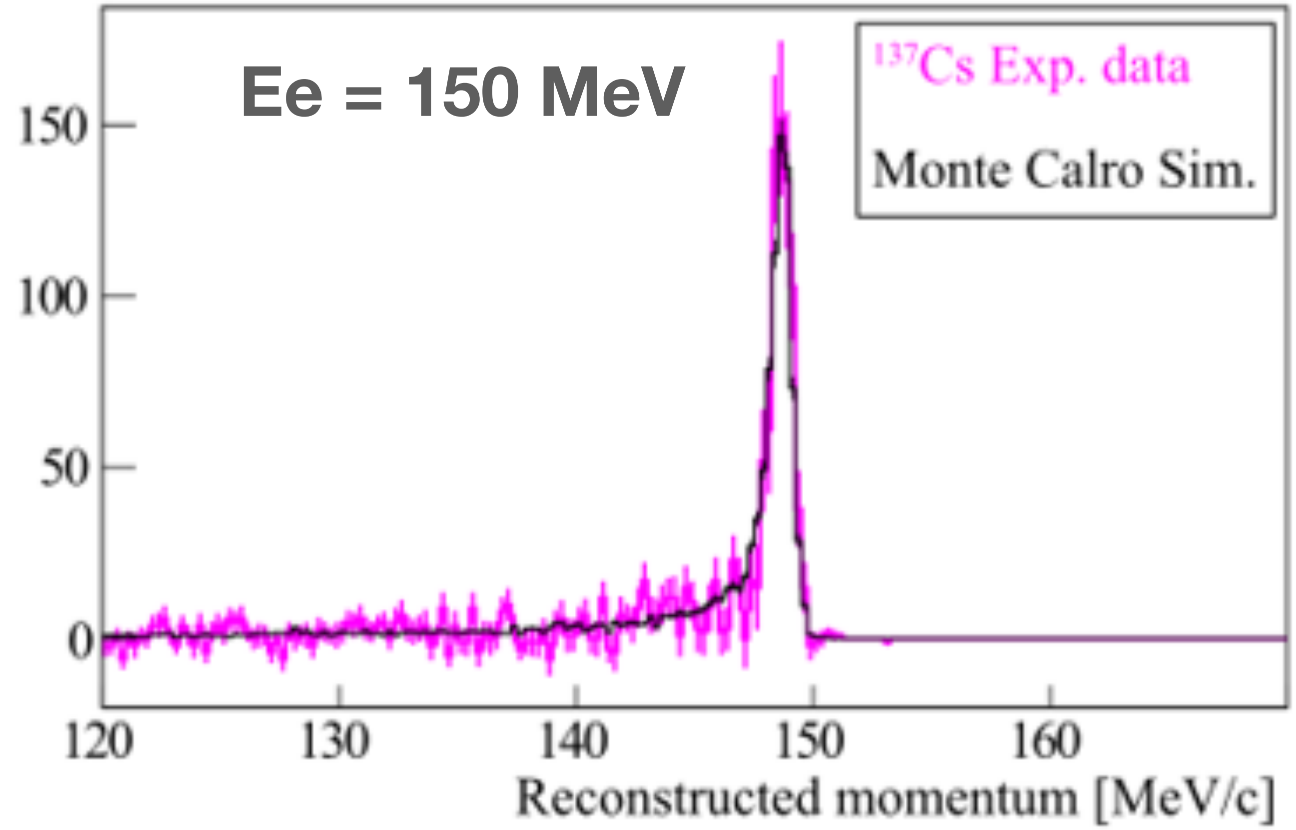


$\langle r^2\rangle^{1/2} = 4.789 \, ^{+0.12}_{-0.10}$ fm

$\langle r^2\rangle^{1/2} = 4.787$ fm(μ-atom X-rays)

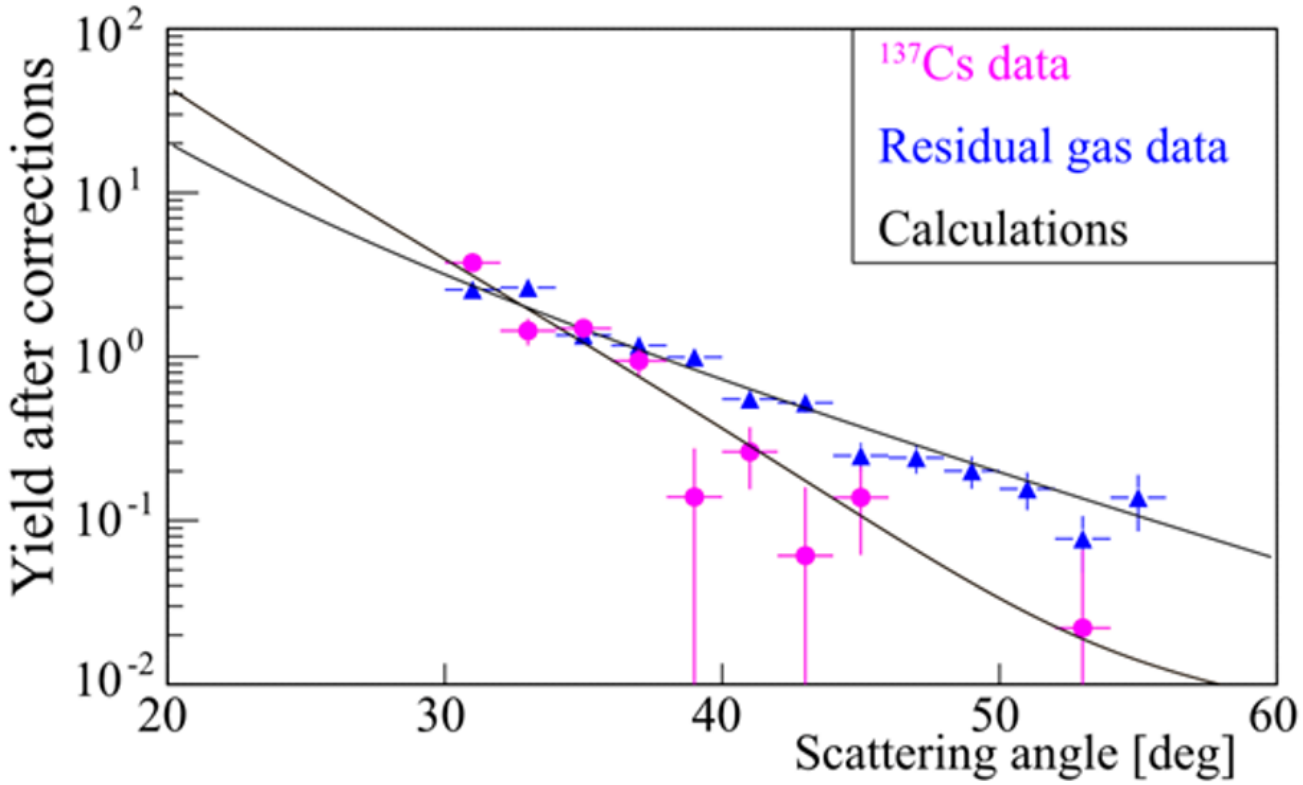
^{137}Cs(e,e') with online-produced Cs ions





1.9 s trapping

=> mimicking "short-lived" nuclei



$N_{trapped}$ ~ 2 x10^7

=> L ~ 0.9 x 10^{26} /cm^2/s

successful demonstration for online-produced unstable nuclei

Luminosities for e-scattering

	Ee	N_{beam}	target thickness	L
Hofstadter's era (1950s)	150 MeV	~ 1nA (~10^9 /s)	~10^{19} /cm^2	~10^{28} /cm^2/s

Luminosities for e-scattering

	Ee	N_{beam}	target thickness	L
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SCRIT	150-300 MeV	300 mA (~10^{18} /s)	~10^9 /cm^2	~10^{27} /cm^2/s

Luminosities for e-scattering

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~10^7 trapped ions in e-beam of ~1 mm^2

Luminosities for e-scattering

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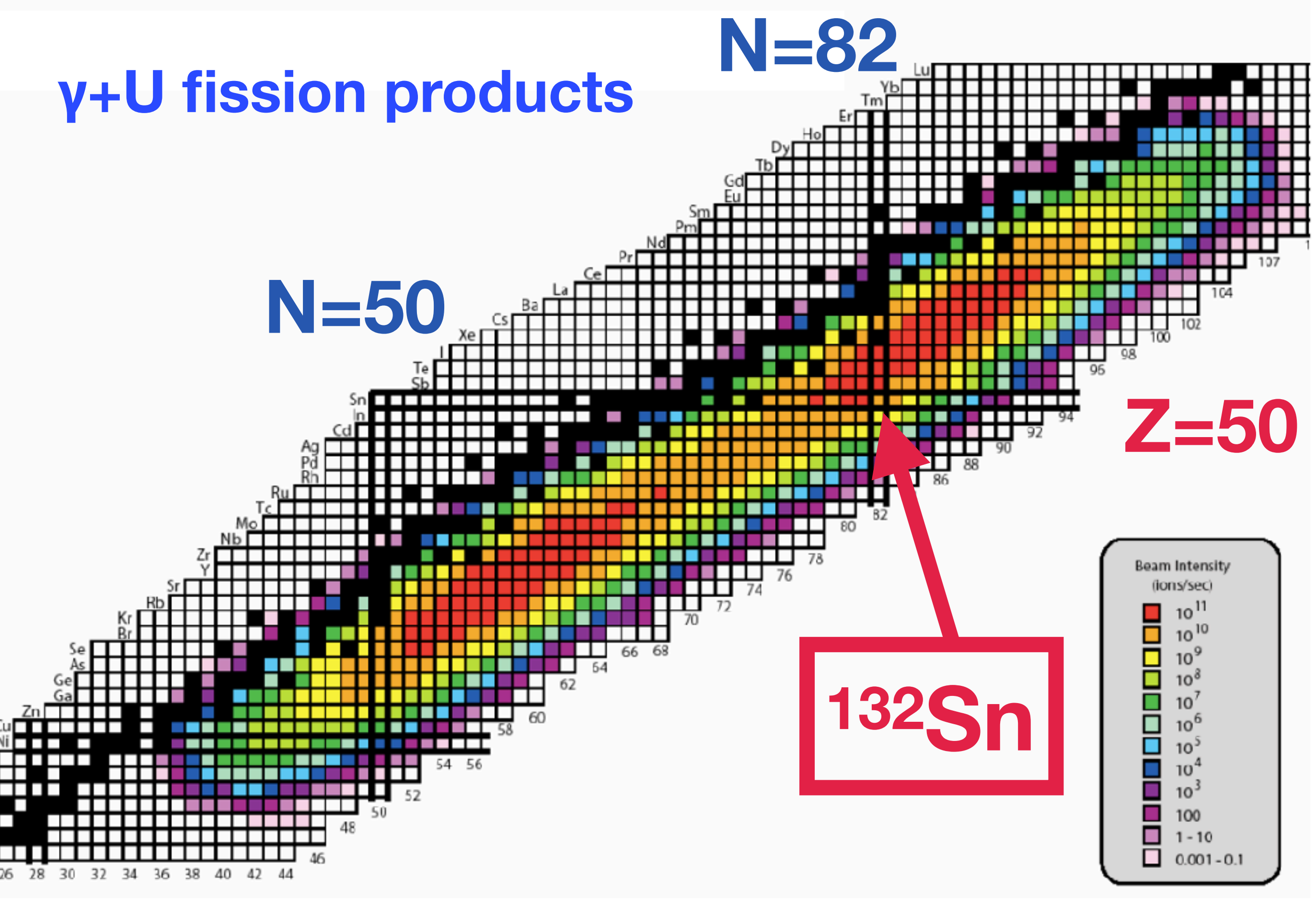
~10^7 trapped ions in e-beam of ~1 mm^2

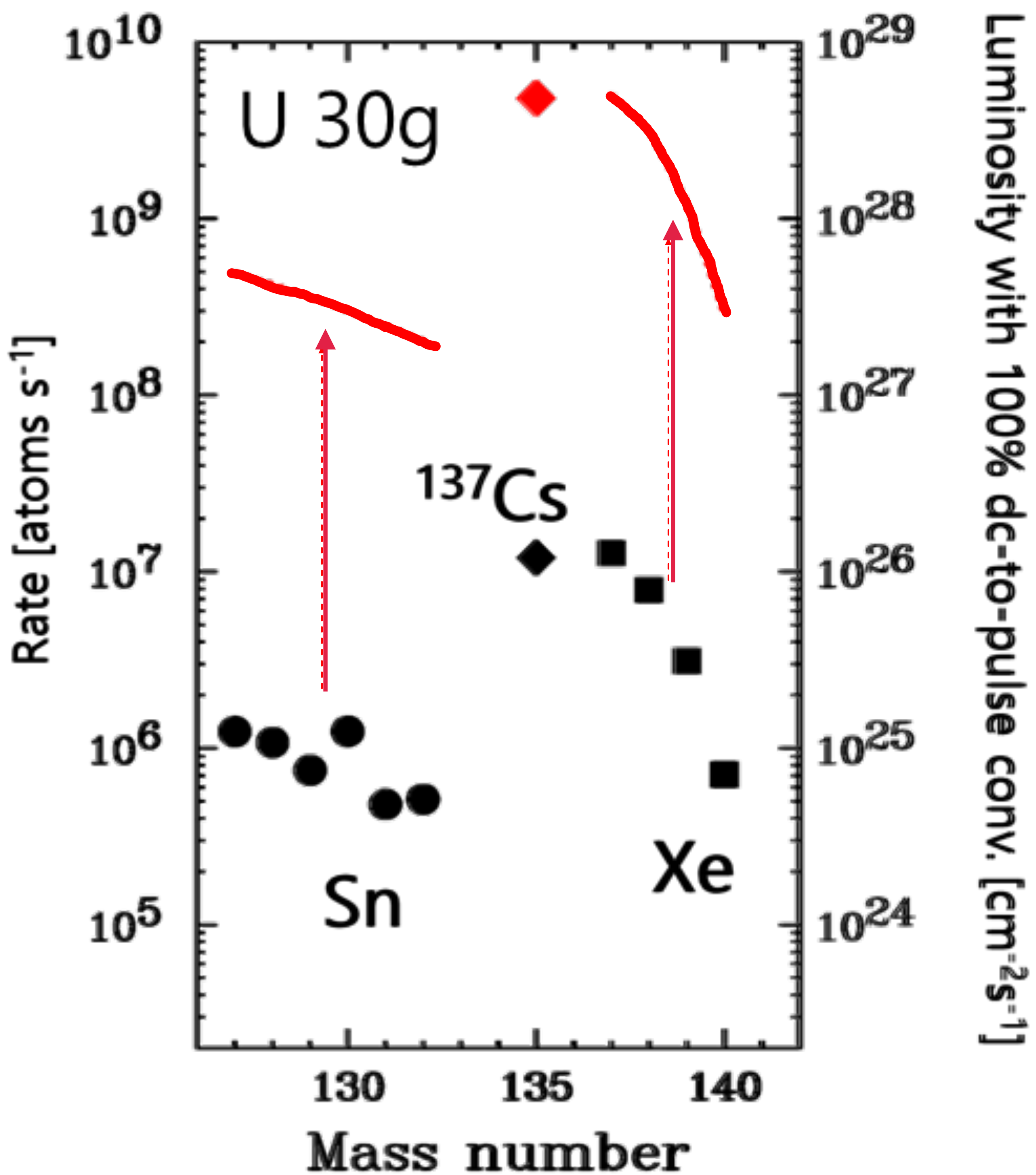
required target thickness ~ 10^{-10} !!

towards ^{132}Sn (40s)

Upgrade of ISOL driver

- towards 2 kW e-beam
  - higher repetition
  - higher peak intensity
- remote handling system
- Isobar separation system





1) neutron distribution through <r_c^4>

1) H. Kurasawa and T. Suzuki, Prog. Theor. Exp. Phys. 2019, 113D01
2) H. Kurasawa, T. S. and T. Suzuki, Prog. Theor. Exp. Phys. 2021, 013D02
3) H. Kurasawa and T. Suzuki, Prog. Theor. Exp. Phys. 2022, 023D03

2) shapes though photonuclear response at GDR

1) T. Suda and H. Simon, Prog. Part. Nucl. Phys. 96 (2017) 1.
2) T. Suda , Handbook of Nuclear Physics, Springer, 2023, 1591–1614.

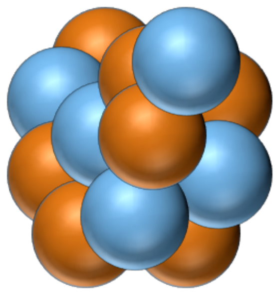
1) neutron distribution through $\langle r_c^4 \rangle$

1) H. Kurasawa and T. Suzuki, Prog. Theor. Exp. Phys. 2019, 113D01
2) H. Kurasawa, T. S. and T. Suzuki, Prog. Theor. Exp. Phys. 2021, 013D02
3) H. Kurasawa and T. Suzuki, Prog. Theor. Exp. Phys. 2022, 023D03

2) shapes though photonuclear response at GDR

1) T. Suda and H. Simon, Prog. Part. Nucl. Phys. 96 (2017) 1.
2) T. Suda , Handbook of Nuclear Physics, Springer, 2023, 1591–1614.

nuclear charge density, moments



Proton

Neutron

1) charge density

$$\rho_c(r) = \rho_c^p(r) + \rho_c^n(r)$$

$$\rho_c^p(r) = \int \rho_p(r)\, \rho_{p(point)}(r - r')\ \mathrm{d}^3 r'$$

$$\rho_c^n(r) = \int \rho_n(r)\, \rho_{n(point)}(r - r')\ \mathrm{d}^3 r'$$

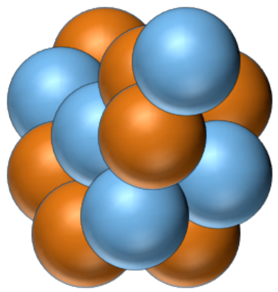
2) 2nd moment

$$< r_c^2 > = \int r^2\, \rho_c(r)\ \mathrm{d}^3 r$$

Proton | Neutron

$$= < r^2_{p(point)} > + < r_p^2 > + \quad < r^2_{n(point)} > + \frac{N}{Z} < r_n^2 > + \mathrm{rel\,.\,corr\,.}$$

nuclear charge density, moments



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2) 2nd moment

$$< r_c^2 > = \int r^2\, \rho_c(r)\, \mathrm{d}^3 r$$

Proton

Neutron

$$= < r_{p(point)}^2 > + < r_p^2 > + < r_{n(point)}^2 > + \frac{N}{Z} < r_n^2 > + \mathrm{rel\,.\,corr\,.}$$

4th moment of the charge density distribution

$$< r_c^4 > = \int r^4 \rho_c(r)\, \mathrm{d}^3 r$$

$$= < r_{p(point)}^4 > + \frac{10}{3} < r_{p(point)}^2 > < r_p^2 >$$

$$+ < r_{n(point)}^4 > + \frac{10}{3} < r_{n(point)}^2 > < r_n^2 > \frac{N}{Z}$$

$$+ \mathrm{rel.\ corr.}$$

4th moment of the charge density distribution

$$< r_c^4 > = \int r^4 \rho_c(r)\, \mathrm{d}^3 r$$

$$= < r^4_{p(point)} > + \frac{10}{3} < r^2_{p(point)} > < r_p^2 >$$

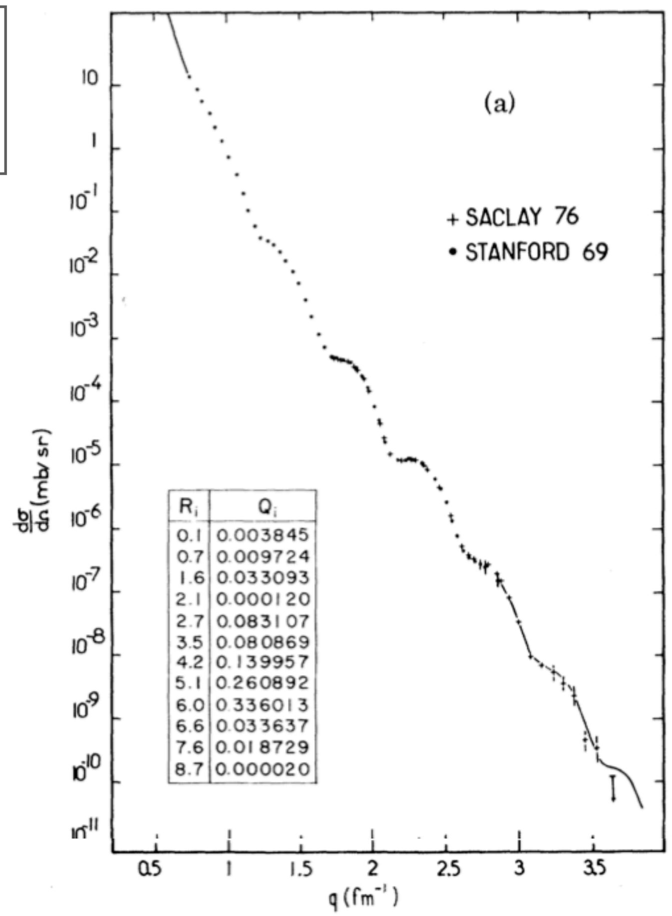
$$+ < r^4_{n(point)} > + \frac{10}{3} < r^2_{n(point)} > < r_n^2 > \frac{N}{Z}$$

$$+ \mathrm{rel.\,corr.}$$

(The $< r^4_{n(point)} >$ term is crossed out; $< r^2_{n(point)} >$ is marked:) RMS n-radius

RMS radii of (point) proton and neutron of ^{208}Pb

^{208}Pb



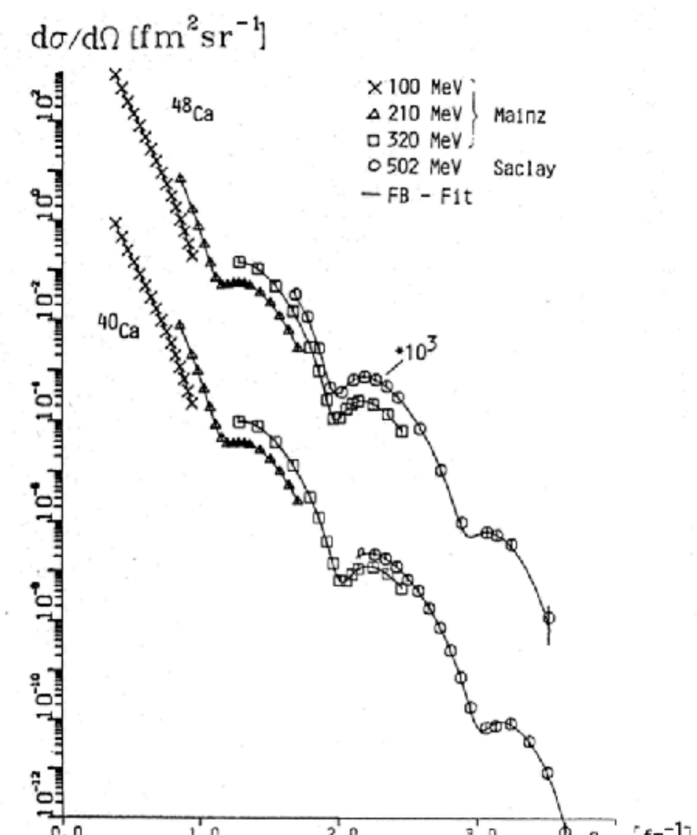
		R_p	R_n	δR
^{208}Pb	Rel.	5.454(0.013)	5.728(0.057)	0.275(0.070)
	Non.	5.447(0.014)	5.609(0.054)	0.162(0.068)
	Exp.	$R_c = 5.503(0.014)$		

JLab : PREX I,II (parity-violating e-scattering)

$$\Delta r_{np} \equiv R_n - R_p = 0.283 \pm 0.071 \text{ fm}$$

PRL 126, 172502 (2021)

^{48}Ca



Figur 2.12 : Wirkungsquerschnitte für ^{40}Ca und ^{48}Ca, aufgetragen über q_{eff}. Die durchgezogene Linie ist durch Anpassen einer Fourier-

		R_p	R_n	δR
^{48}Ca	Rel.	3.378(0.005)	3.597(0.021)	0.220(0.026)
	Non.	3.372(0.009)	3.492(0.028)	0.121(0.036)
	Exp.	$R_c = 3.451(0.009)$		

JLab : CREX (parity-violating e-scattering)

$$\Delta r_{np} \equiv R_n - R_p = 0.121 \pm 0.026 \text{ fm}$$

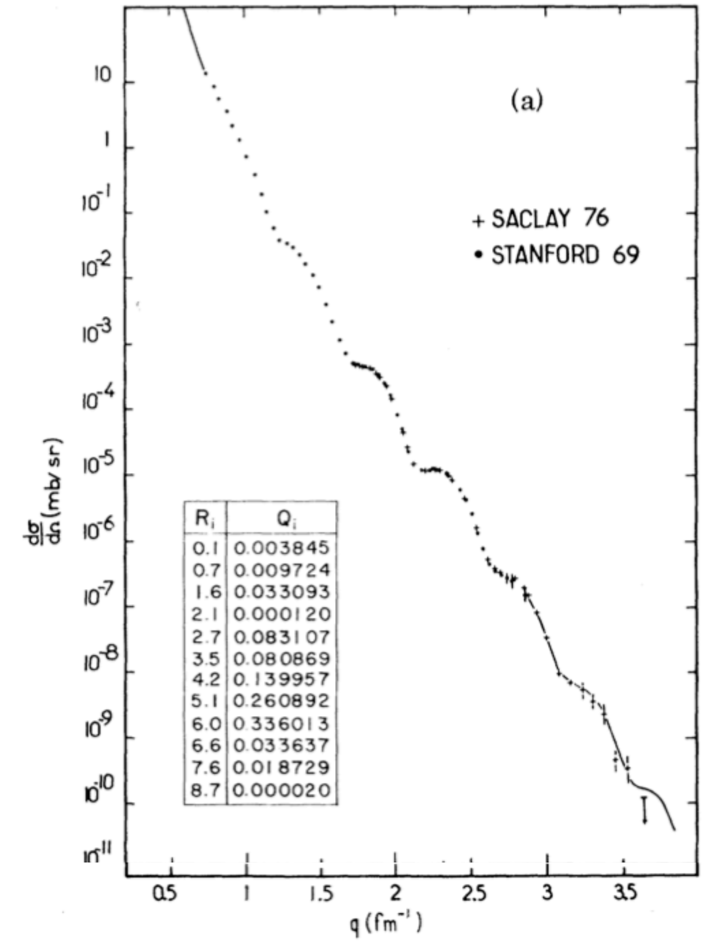
ways to access the fourth moment, $<r_c^4>$

$$< r_c^4 > = \int r^4 \rho_c(r)\, \mathrm{d}^3 r$$

1) elastic scattering at very high *q* (0^+ nuclei)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma_{\mathrm{Mott}}}{\mathrm{d}\Omega} |F_c(q)|^2$$

$$F_c(q) = \int \rho_c(\vec{r}) e^{i\vec{q}\vec{r}} d\vec{r}$$

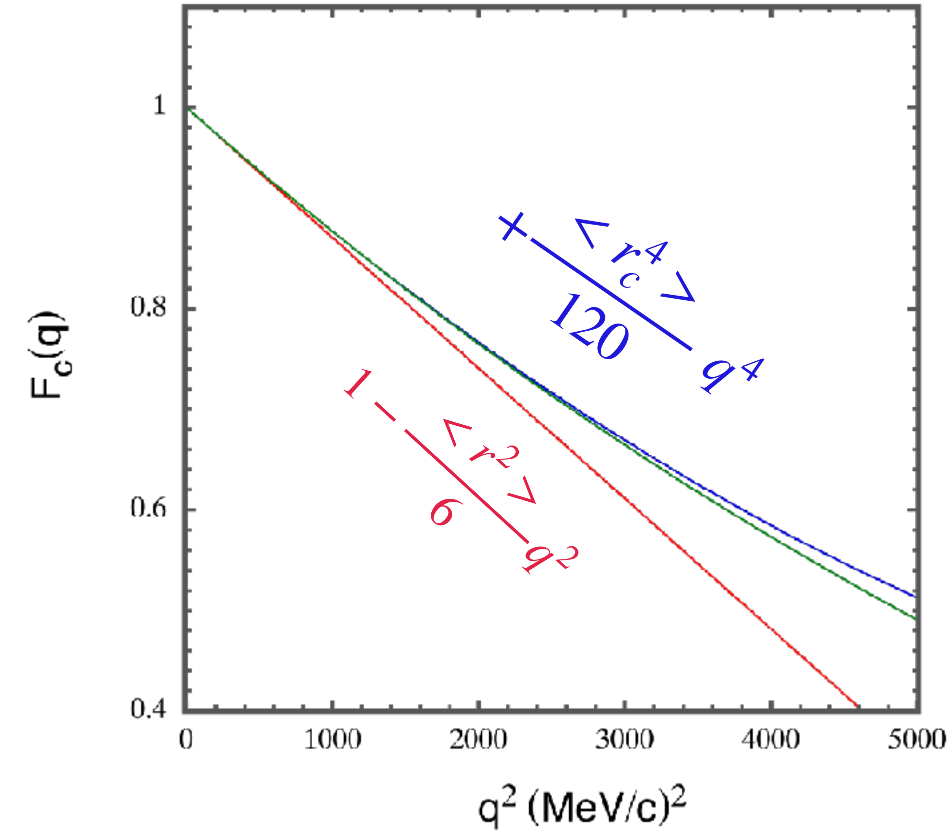


208Pb_2+4+6Moments_20200521

2) elastic scattering at very low *q*

$$F_c(q) \sim 1 - \frac{< r_c^2 >}{6} q^2 + \frac{< r_c^4 >}{120} q^4 + \dots$$

$$\frac{\mathrm{d}\sigma_{\mathrm{Mott}}}{\mathrm{d}\Omega} \propto 1/q^4$$

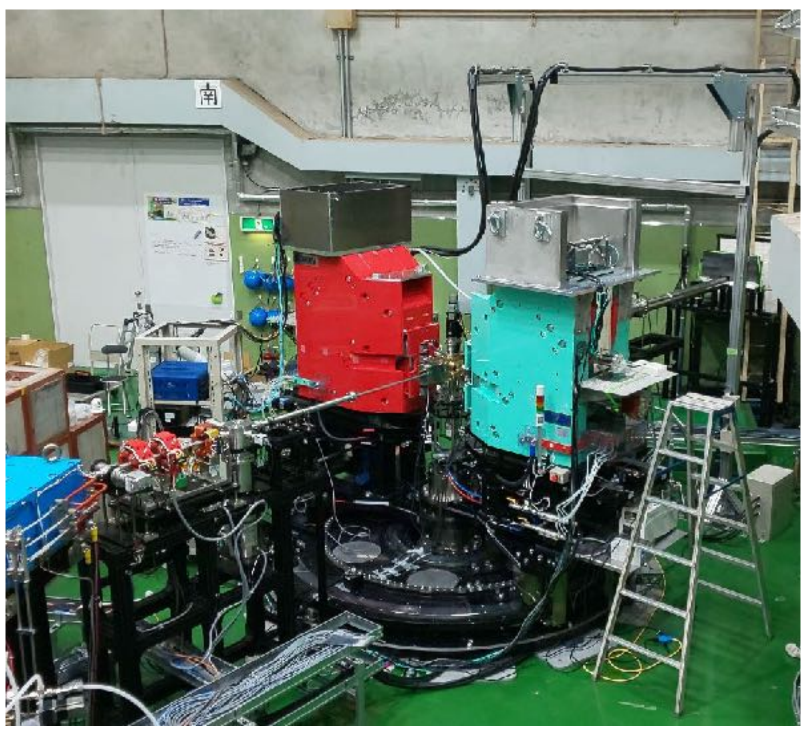


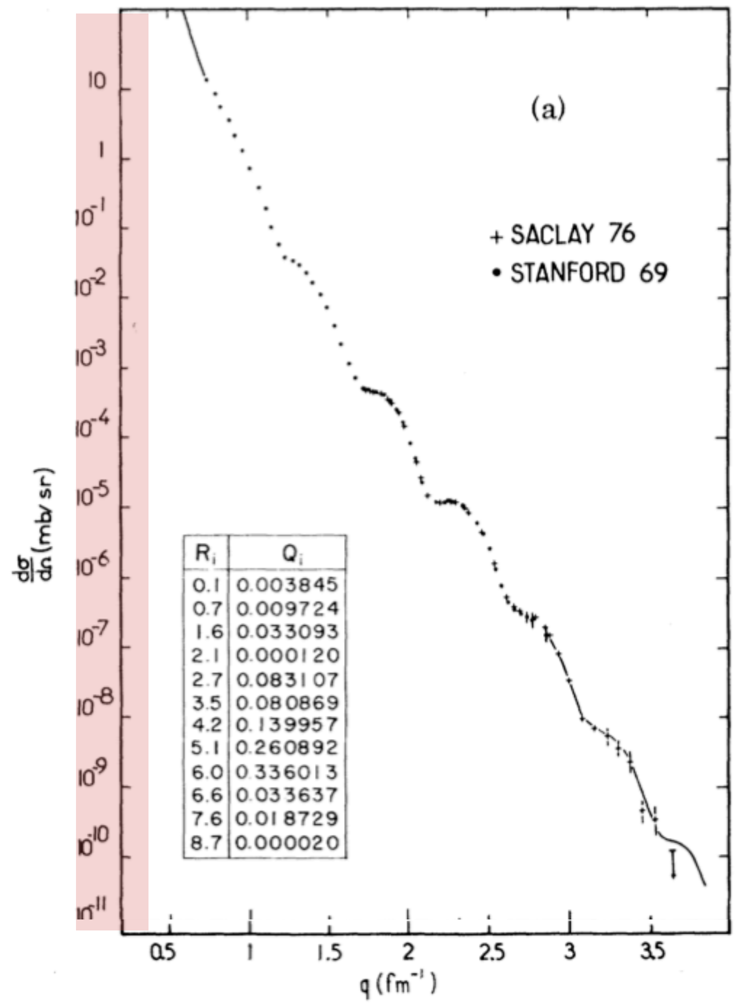
=> low-L SCRIT exp. !!

Rn determination at extremely low-q (e,e’) ?

- ^{208}Pb(e,e’) at the ULQ2 beam line at Tohoku

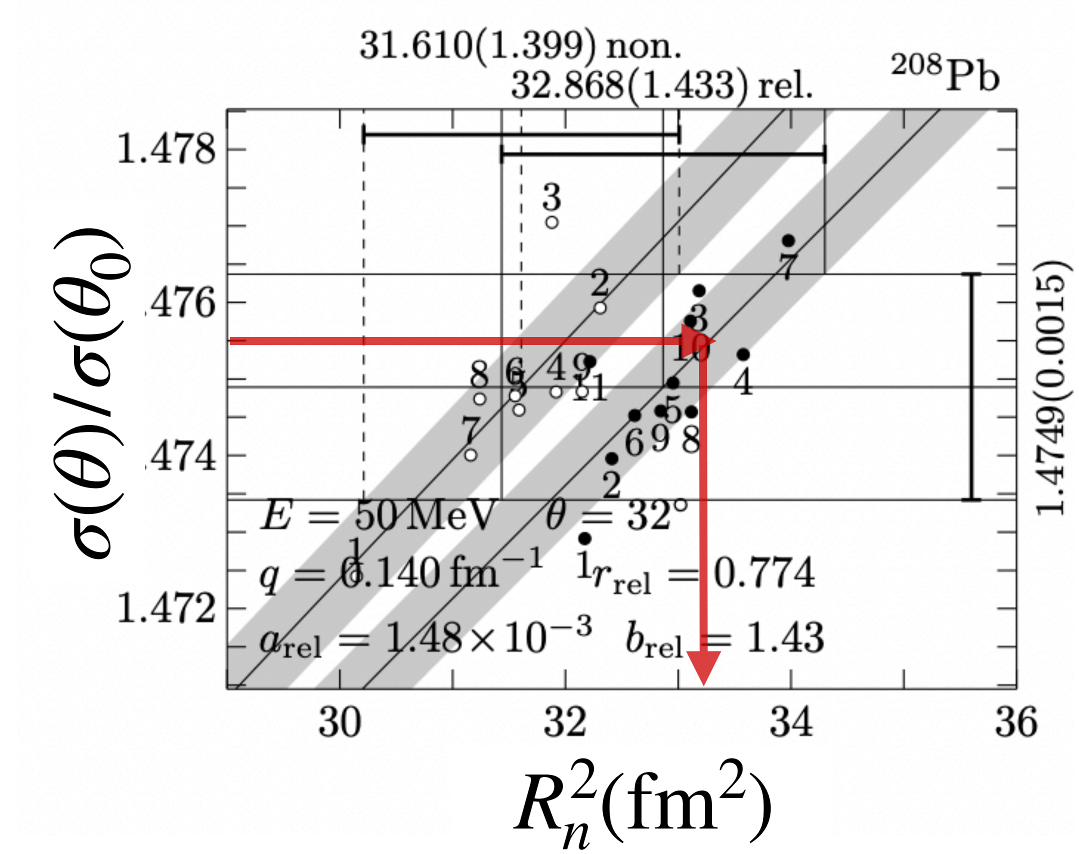
Ee ~ 10 - 50 MeV
θ = 30 - 150°
q = 5 - 50 MeV/c





R_i	Q_i
0.1	0.003845
0.7	0.009724
1.6	0.033093
2.1	0.000120
2.7	0.083107
3.5	0.080869
4.2	0.139957
5.1	0.260892
6.0	0.336013
6.6	0.033637
7.6	0.018729
8.7	0.000020

$\sigma(\theta)/\sigma(\theta_0)$ vs R_n^2



by H. Kurasawa

- precise $\sigma(\theta)/\sigma(\theta_0)$ with the twin spectrometers : 10^{-3}
- phase-shift calculations for R_n^2
- feasibility studies

1) neutron distribution through <r_c^4>

1) H. Kurasawa and T. Suzuki, Prog. Theor. Exp. Phys. 2019, 113D01
2) H. Kurasawa, T. S. and T. Suzuki, Prog. Theor. Exp. Phys. 2021, 013D02
3) H. Kurasawa and T. Suzuki, Prog. Theor. Exp. Phys. 2022, 023D03

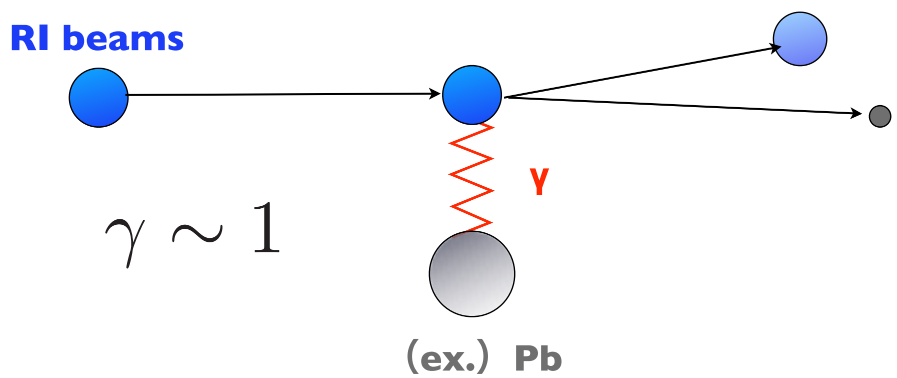
2) shapes though photonuclear response at GDR

1) T. Suda and H. Simon, Prog. Part. Nucl. Phys. 96 (2017) 1.
2) T. Suda , Handbook of Nuclear Physics, Springer, 2023, 1591–1614.

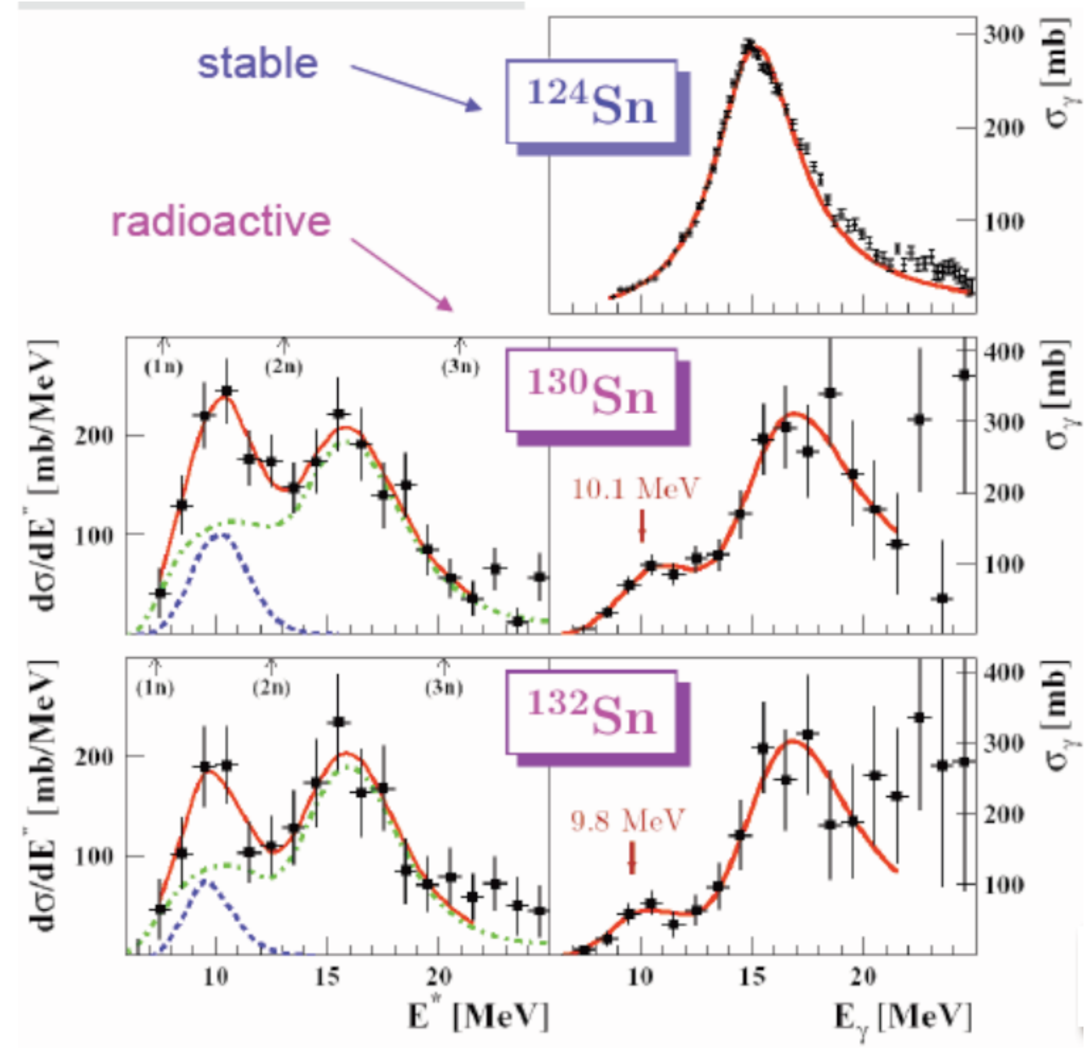
photonuclear reaction for exotic nuclei

so far

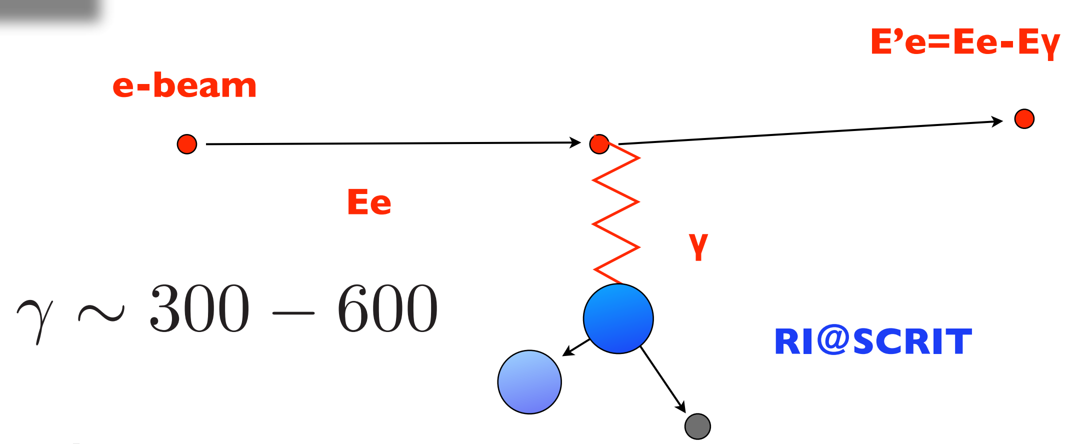
Coulomb excitation in heavy ion reaction
reaction mechanism?



^{132}Sn+Pb -> ^{131}Sn + n + X @ GSI



SCRIT facility



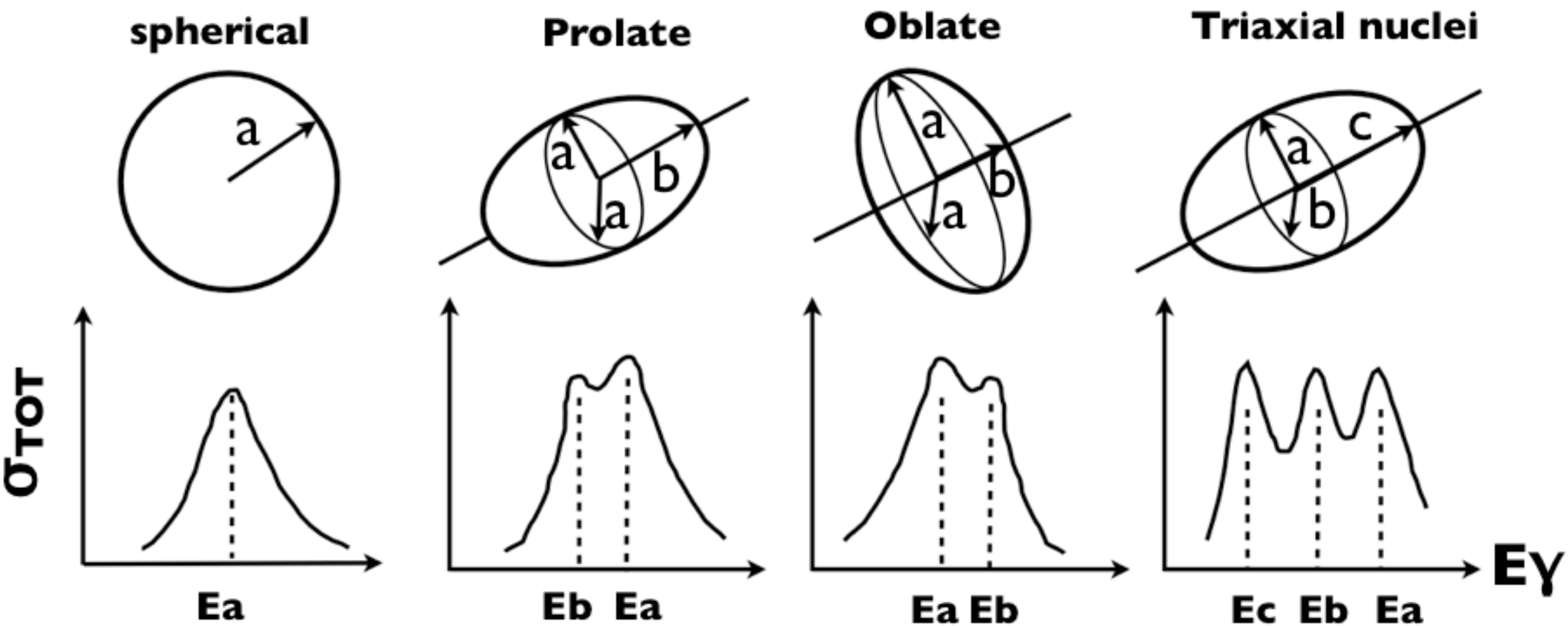
purely EM probe

ultra-forward
electron scattering
=> bg: bremsstrahlung

Virtual Photon flux

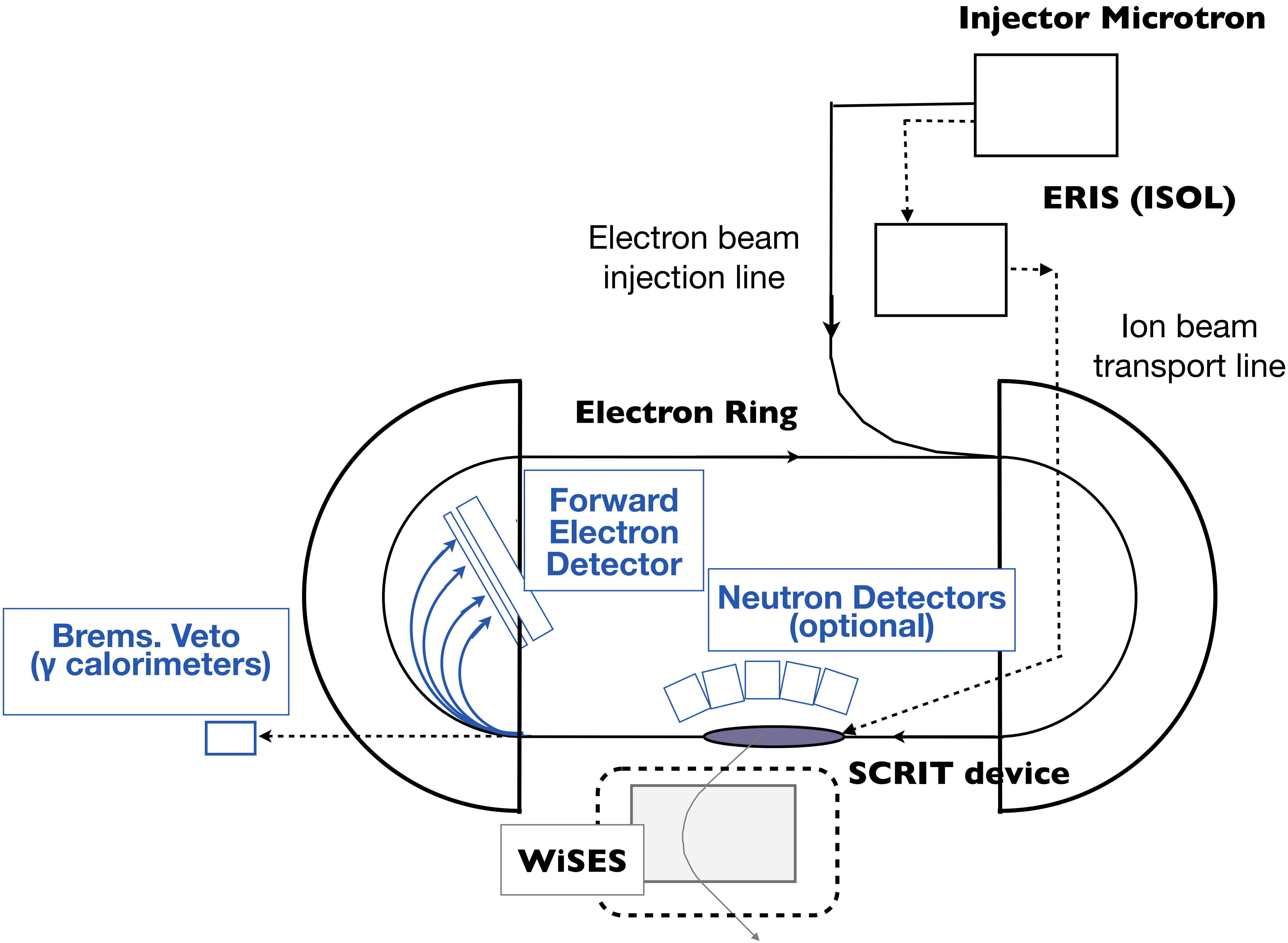
$$\frac{d^2\sigma}{dE_e d\Omega} = \sum \frac{d^2 N_e^{EL}(E, E_\gamma, \theta)}{dE_\gamma d\Omega} \cdot \sigma_\gamma^{EL}(E_\gamma)$$

photo-nuclear responses of exotic nuclei



R. Bergere :Lecture Note in Physics, 61 (1971) 84

possible setup for photonuclear reaction at SCRIT

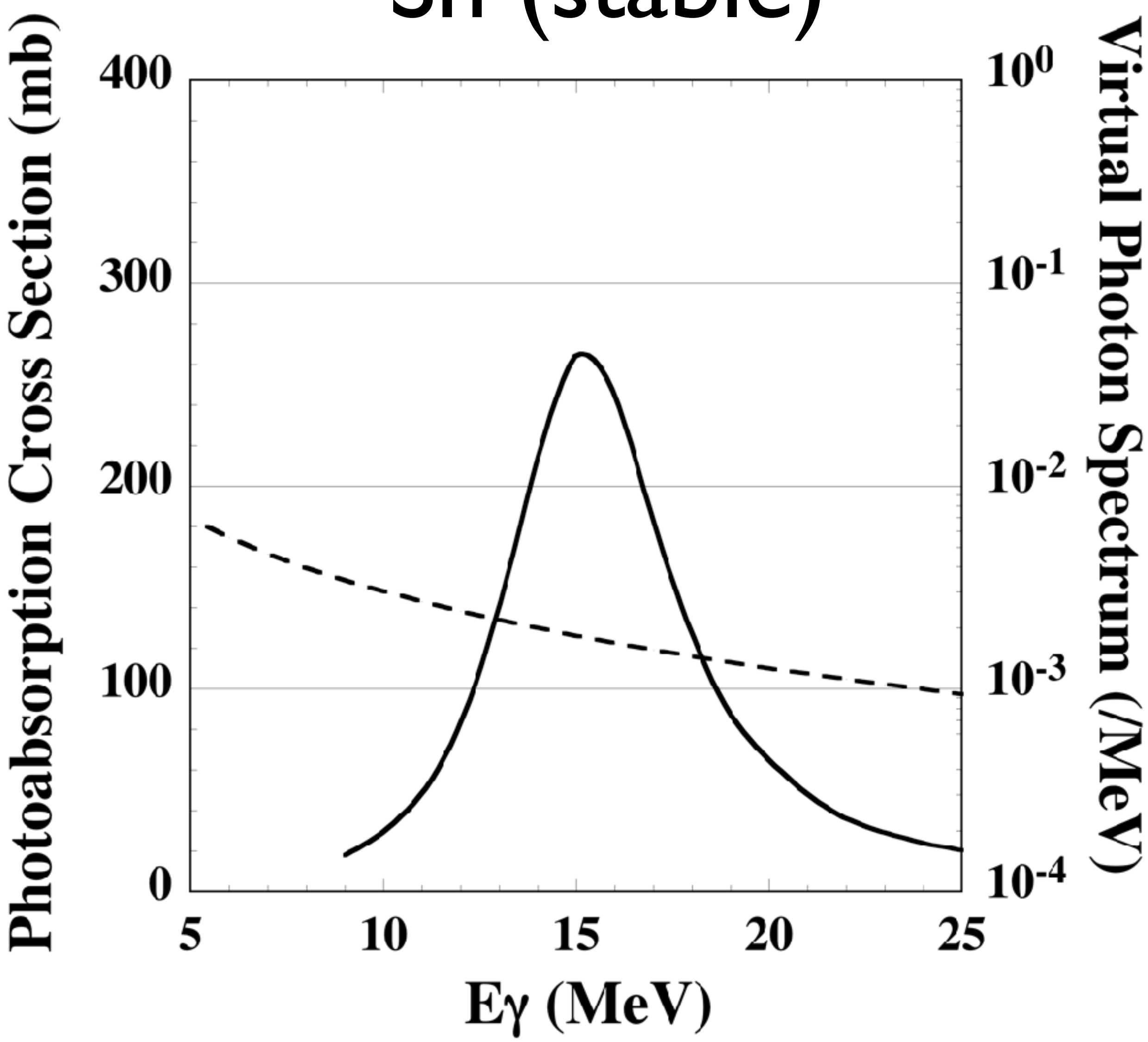


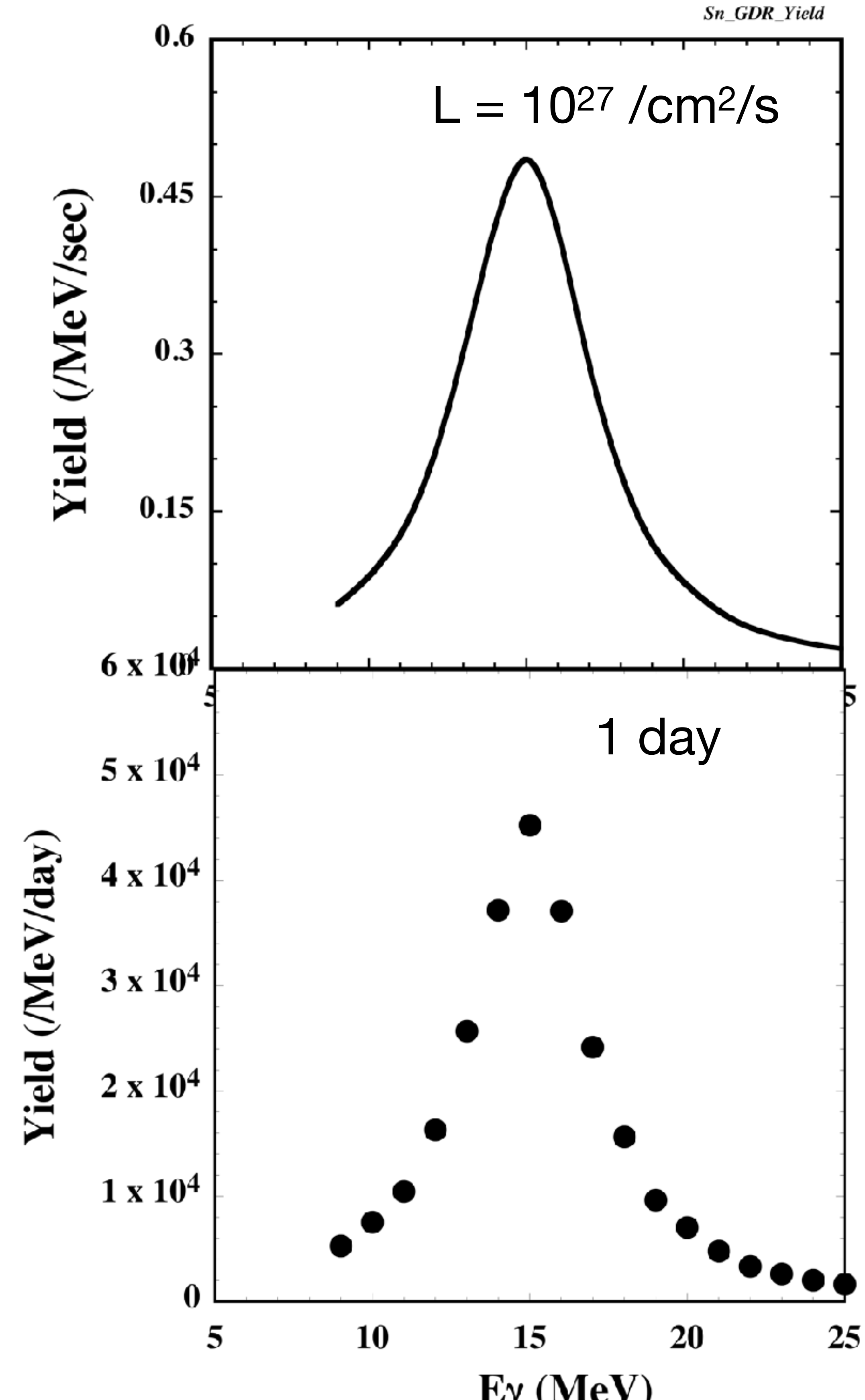
Expected reaction rate for $L = 10^{27}$ /cm²/s

virtual photon theory

$$\frac{dN}{dE_\gamma} = L \cdot \int d\Omega \frac{d^2 N_e^{E1}(E, E_\gamma, \theta)}{dE_\gamma d\Omega} \cdot \sigma_\gamma^{E1}(E_\gamma)$$

^{120}Sn (stable)





P. Durgapal and D.S. Onley
Comp. Phys. Comm. 32 (1984) 291

conclusions

- The SCRIT facility started its operation
  - the world's first and currently only-one facility
  - e-scattering for short-lived nuclei is now possible
  - we have many additional research possibilities

- Low-energy e-scattering activities in Japan
  - SCRIT : charge densities of short-lived exotic nuclei
  - ULQ2 : e+p, e+D scattering
    ^{40}Ca(e,e') and ^{208}Pb(e,e') under lowest-ever q region

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  - SCRIT : charge densities of short-lived exotic nuclei
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    ^{40}Ca(e,e') and ^{208}Pb(e,e') under lowest-ever q region

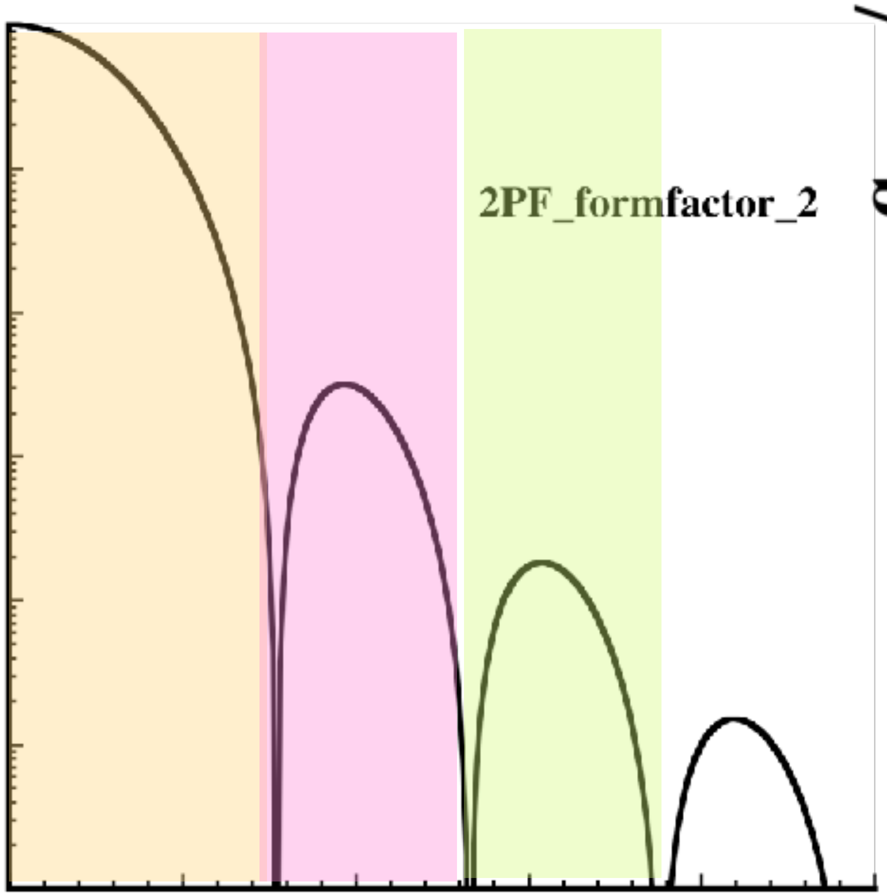
We plan to have a workshop in Sendai, Japan, on

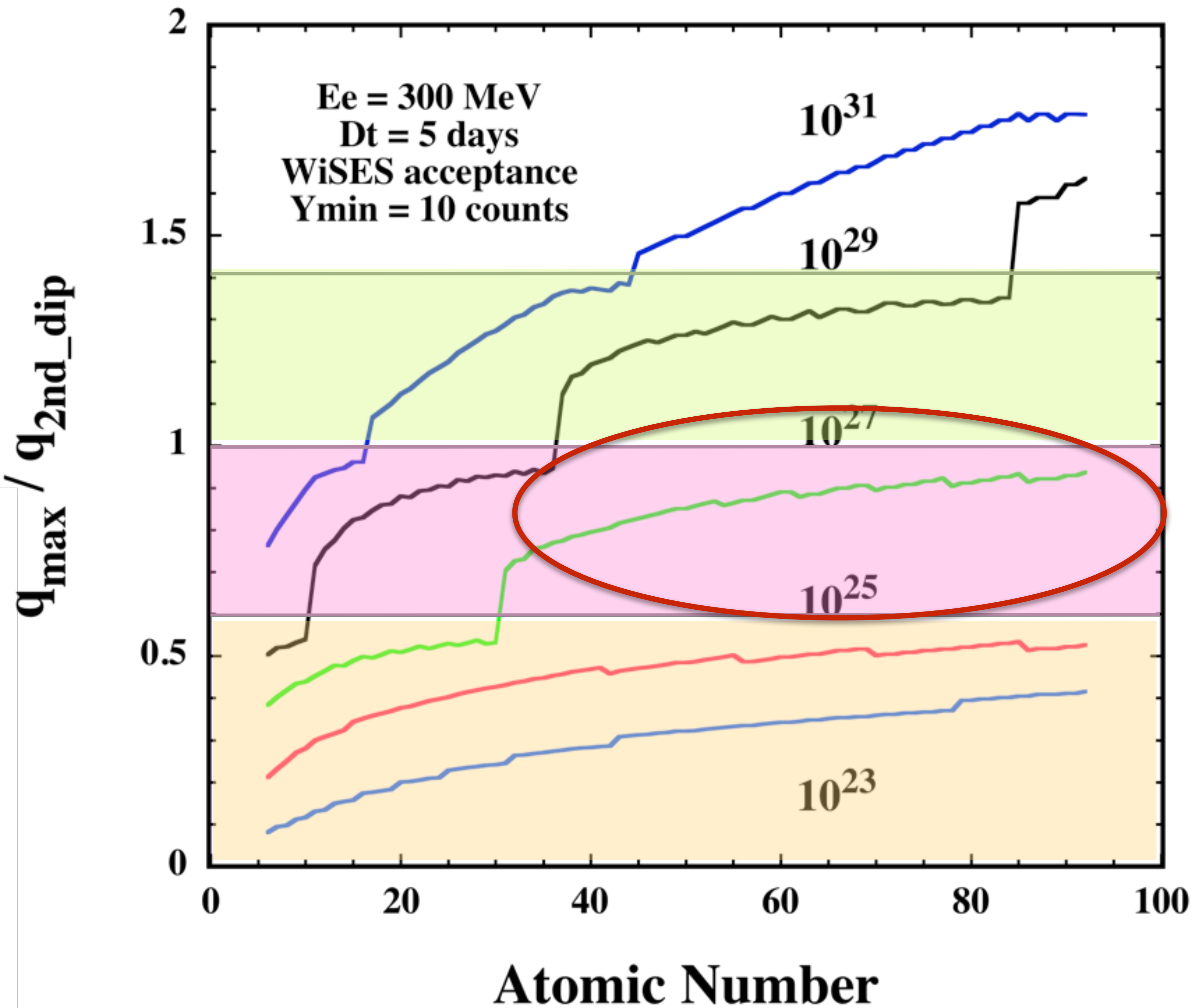
"Low-Energy Electron Scattering for Nucleon and Exotic Nuclei"

Date : Oct. 28 - Nov. 1, 2024
Place : Sendai, JAPAN

Accessible q-range for *L* and *Z*

$$\sigma \propto Z^2$$
$$\sigma \propto 1/q^4$$
$$q_{\text{diff}}^{\text{dip}} \propto 1/R$$



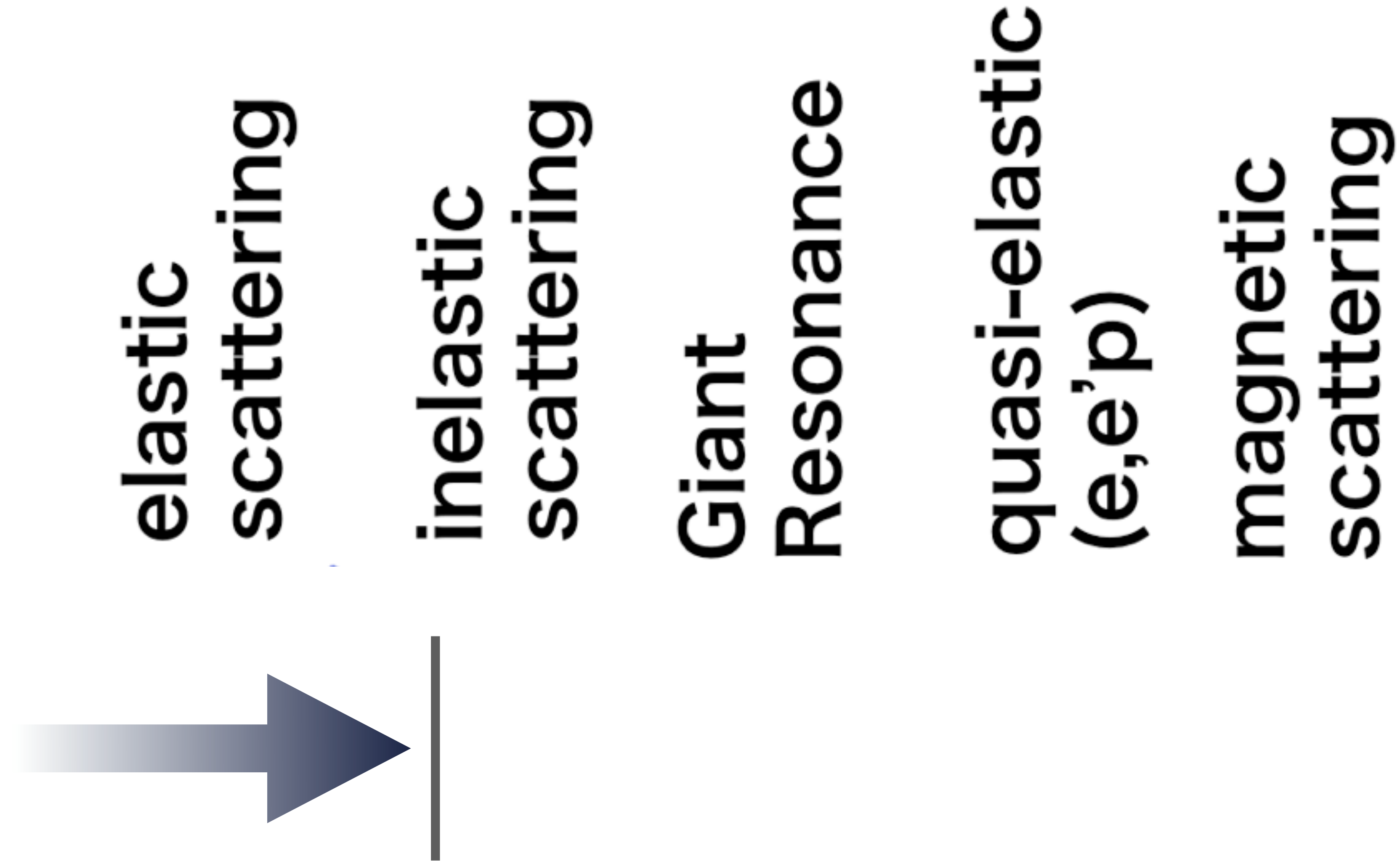


T. Suda and H. Simon
Prog. Part. Nucl. Phys. 96 (2017) 1.

minimum required luminosities

10^{26}	10^{27}	10^{28}	10^{29}	10^{30}	10^{31}	10^{32}

(/cm²/s)



as of today…