# World's first electron scattering off online-produced radioactive isotope

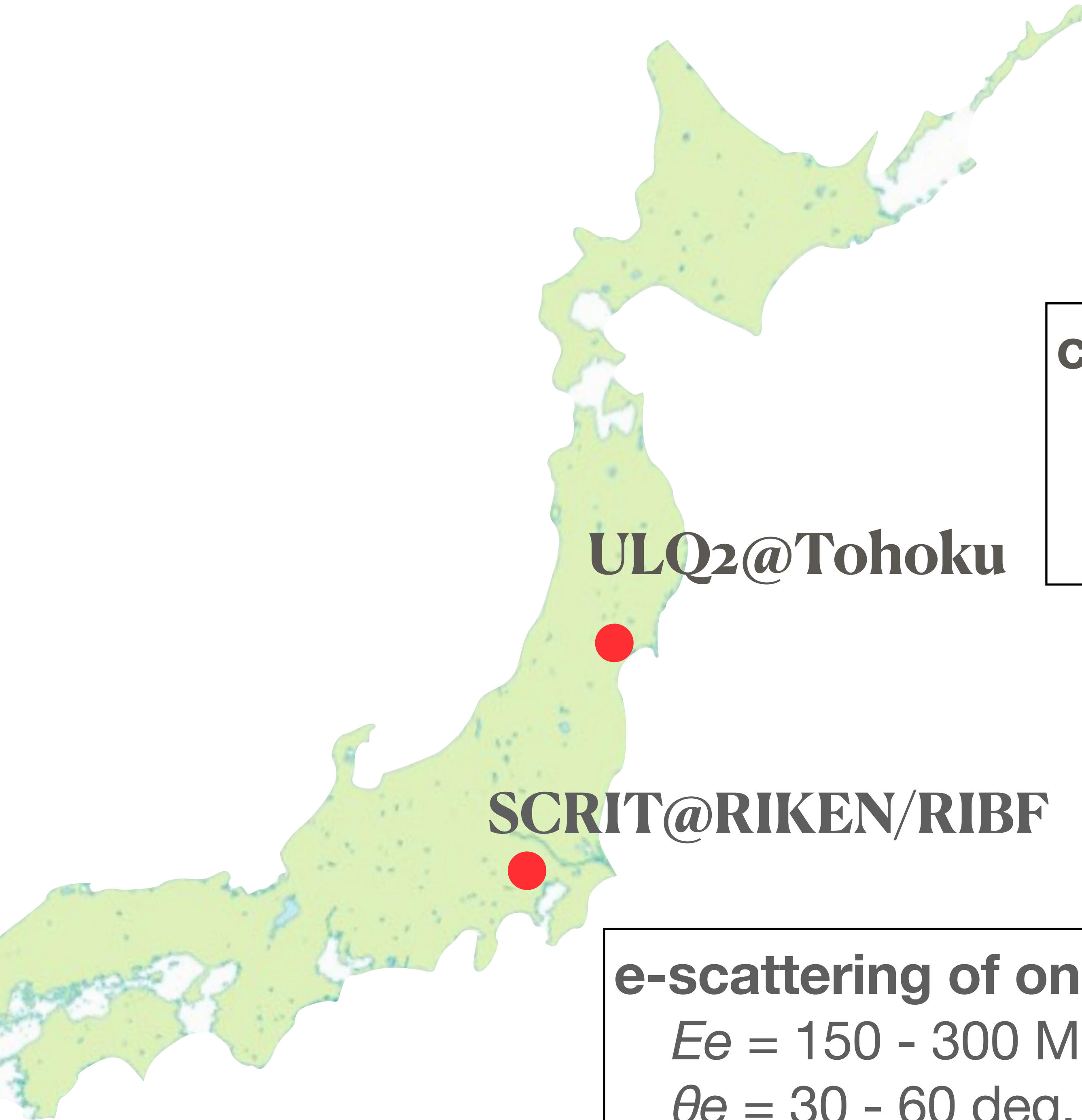
**Toshimi Suda (RARIS, Tohoku Univ.)**

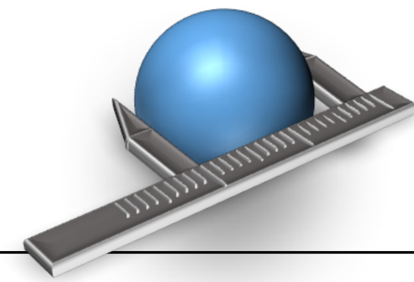
**suda@lns.tohoku.ac.jp**

**for SCRIT collaboration**

# Low-energy electron-scattering facilities in Japan





**charge radii of proton and deuteron**

$Ee$ = 10 - 60 MeV
$\theta e$ = 30 - 150 deg.
=> $Q^2$ = 3x10$^{-5}$ - 0.013 (GeV/c)$^2$

**lowest-ever $Q^2$ !!**

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

$Ee$ = 150 - 300 MeV
$\theta e$ = 30 - 60 deg.
=> $q$ = 80 - 300 MeV/c
$Q^2$ = 0.006 - 0.09 (GeV/c)$^2$

**world's first !!**

⇨ **this talk**

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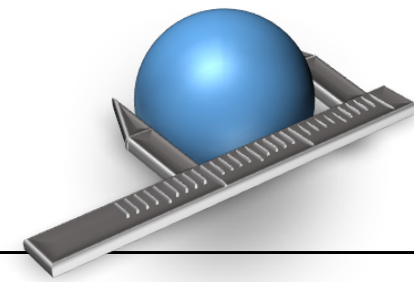

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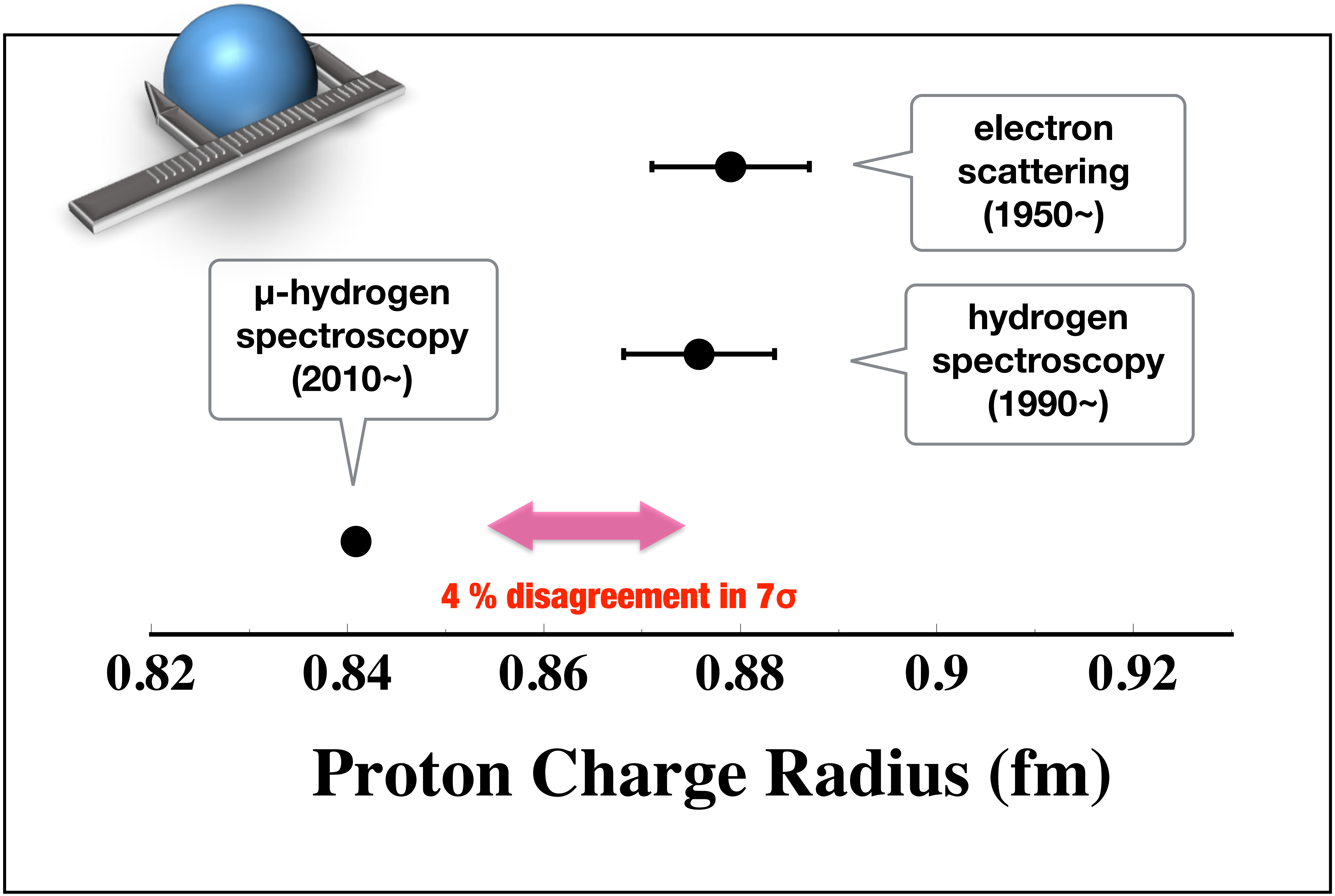
# Proton Radius Puzzle




C. Carlson, Prog. Part. Nucl. Phys. 82 (2015) 59.

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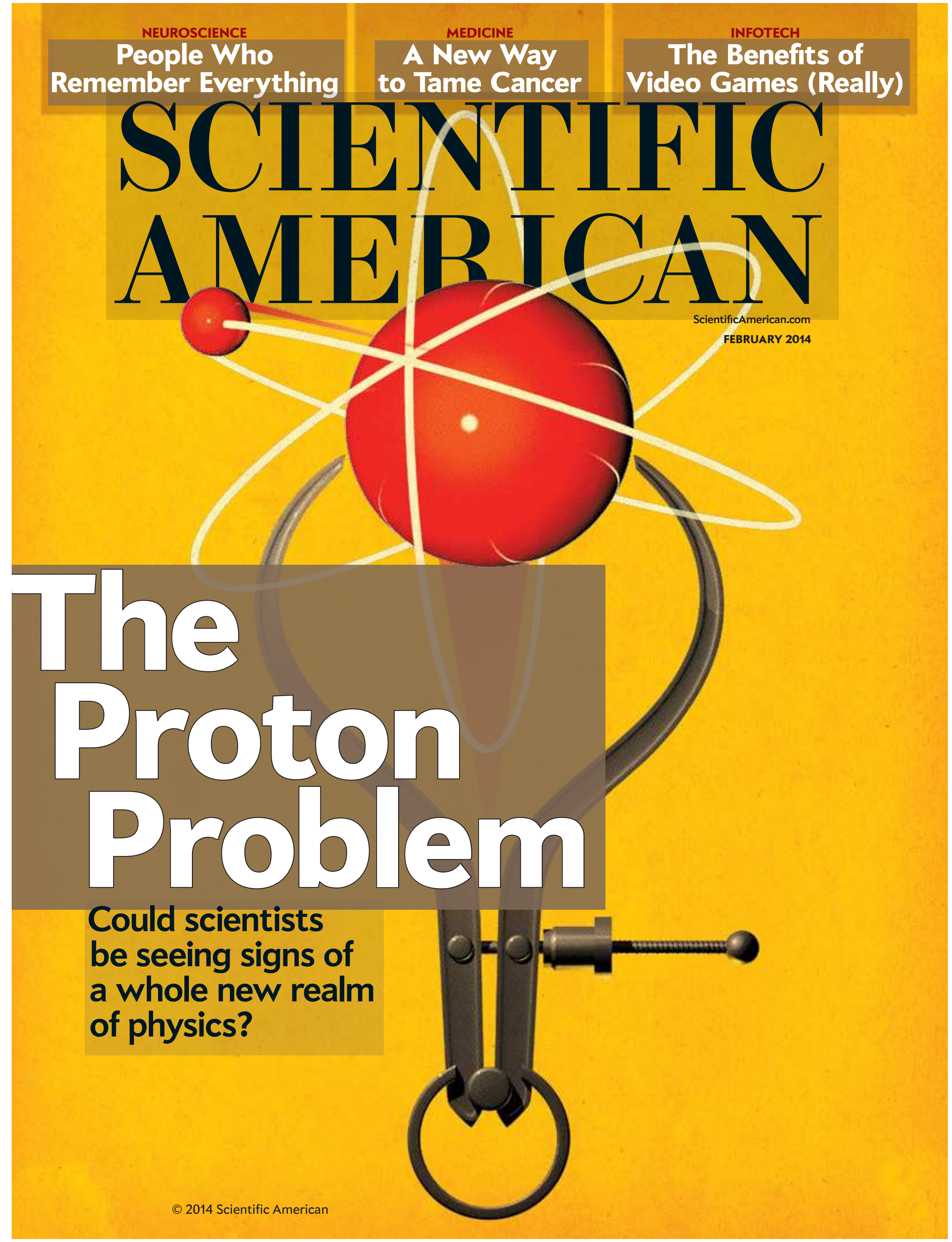


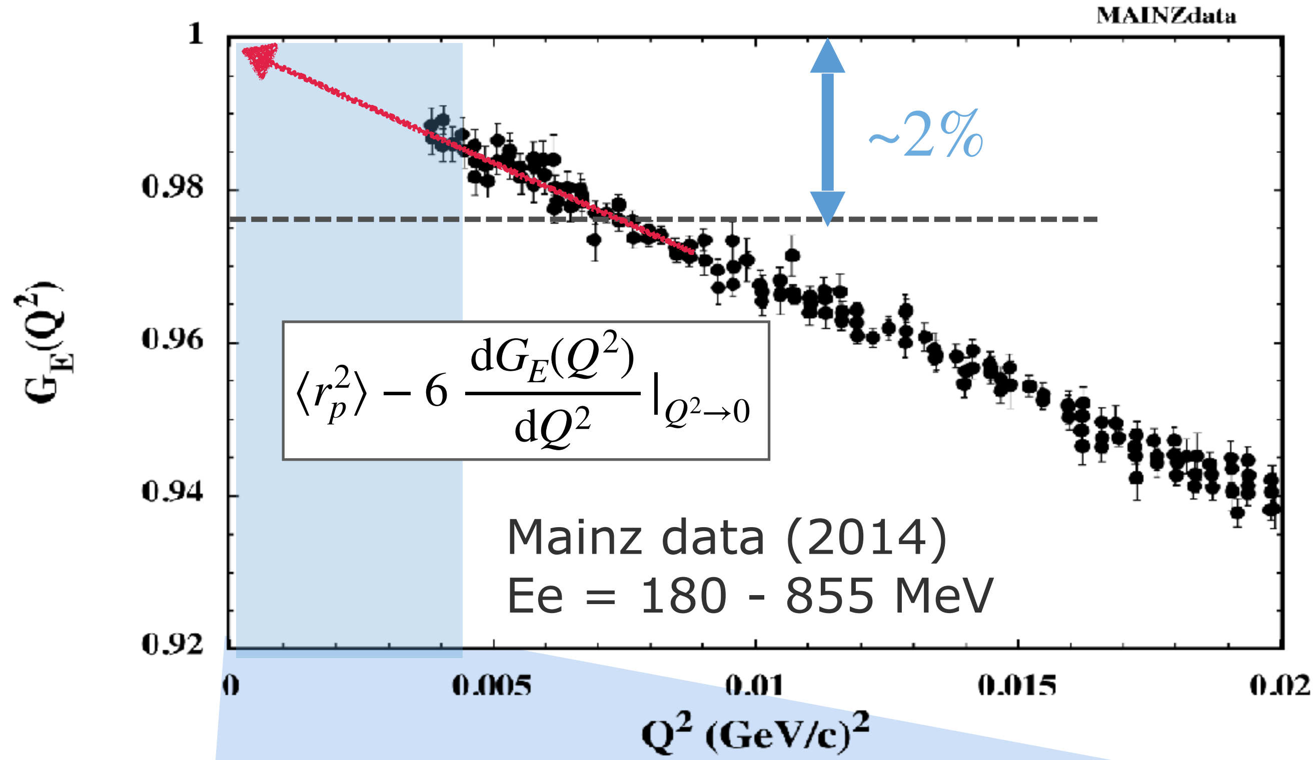

C. Carlson, Prog. Part. Nucl. Phys. 82 (2015) 59.

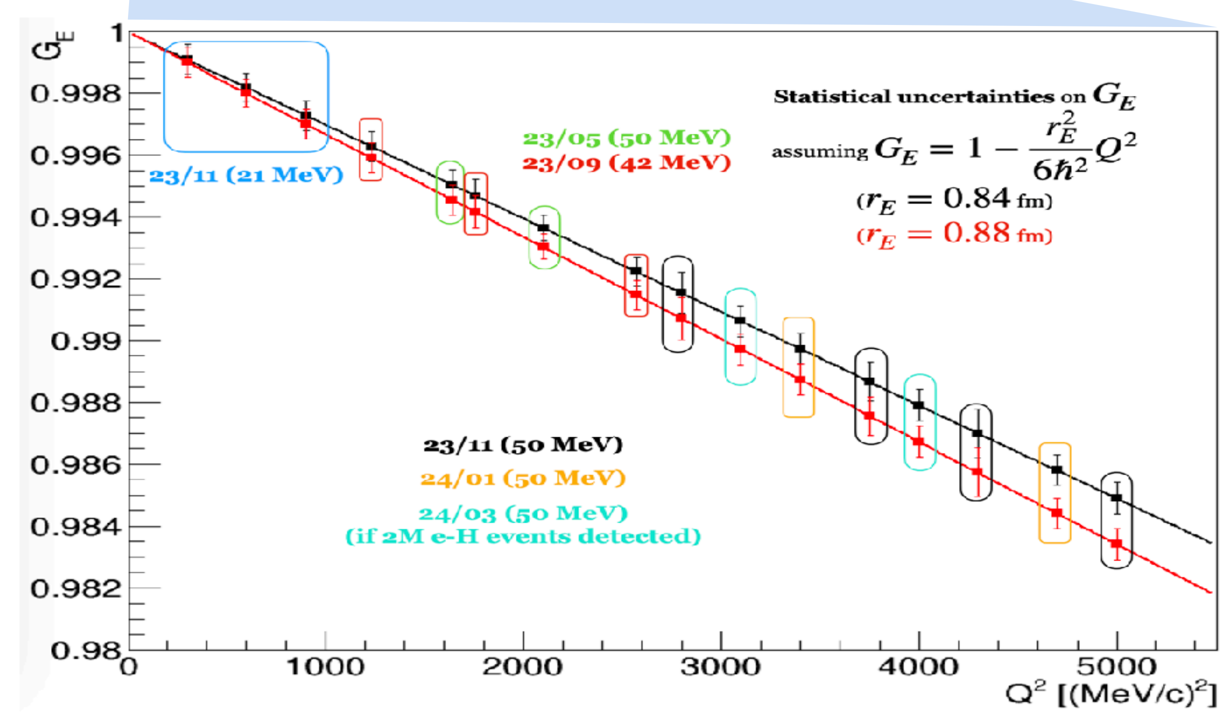
# ULQ2 (Ultra-Low Q2) at Tohoku, JAPAN



**Proton Charge Radius**

① Ee = 10 - 60 MeV, θ = 30 - 150°
② lowest-ever $Q^2$ : $0.0003 \le Q^2 \le 0.008$ $(\mathrm{GeV}/c)^2$.
③ e+p absolute cross section with $\sim 10^{-3}$ accuracy.

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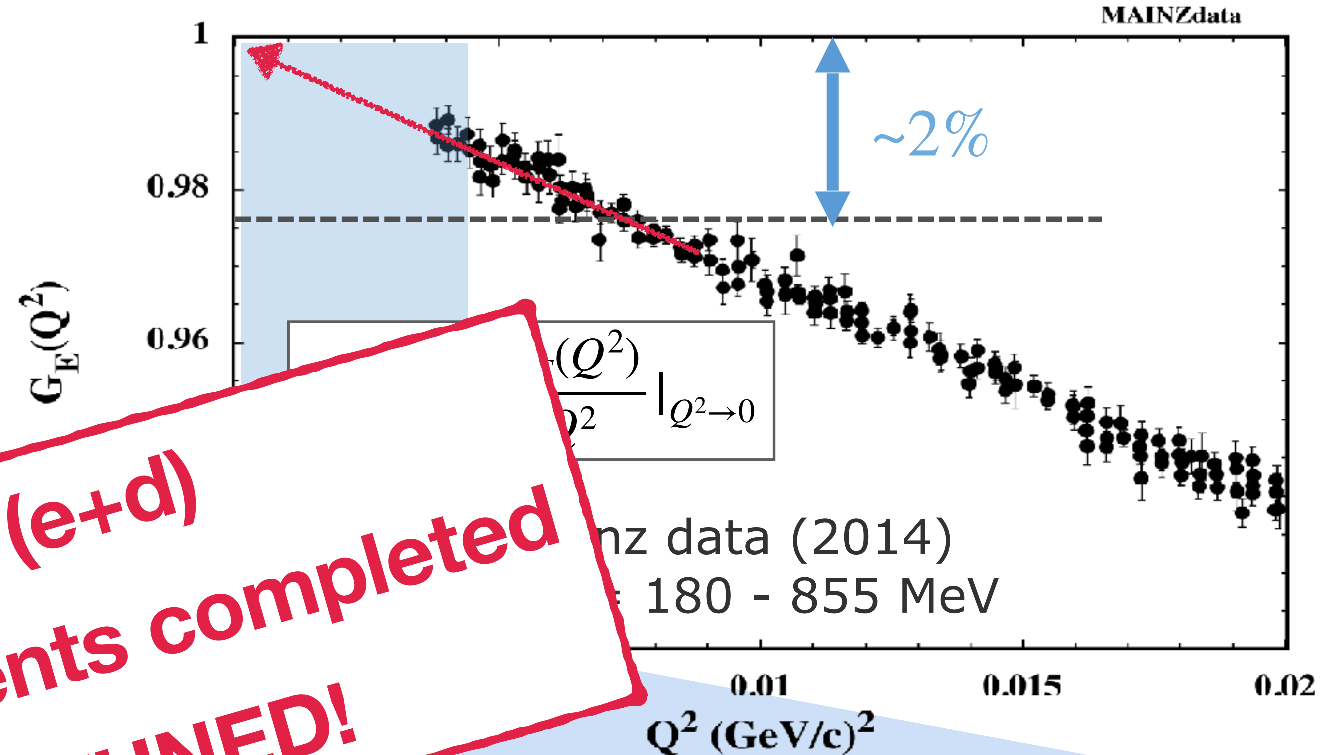
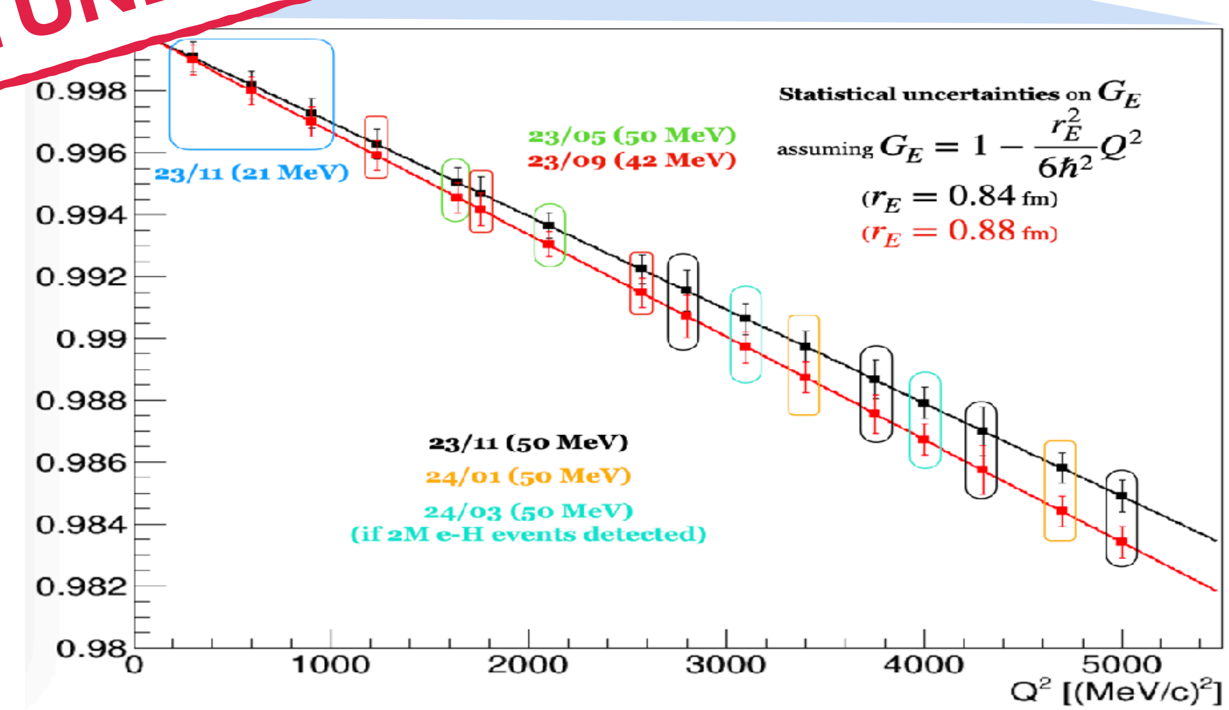
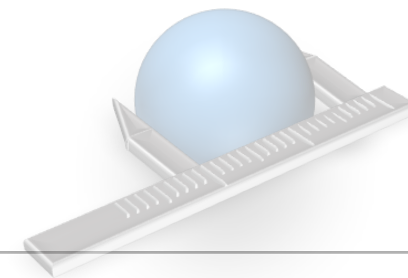



**e+p (e+d)**
**Measurements completed**
**STAY TUNED!**

# Low-energy electron-scattering facilities in Japan

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# world's first e-scattering for online-produced radioactive isotope 7

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

Editors' Suggestion | Featured in Physics

## First Observation of Electron Scattering from Online-Produced Radioactive Target

K. Tsukada,[1,2] Y. Abe,[2] A. Enokizono,[2,3] T. Goke,[4] M. Hara,[2] Y. Honda,[2,4] T. Hori,[2] S. Ichikawa,[2,*] Y. Ito,[1] K. Kurita,[3] C. Legris,[4] Y. Maehara,[1] T. Ohnishi,[2] R. Ogawara,[1,2] T. Suda,[2,4] T. Tamae,[4] M. Wakasugi,[1,2] M. Watanabe,[2] and H. Wauke[2,4]

[1]*Institute for Chemical Research, Kyoto University, Uji, Kyoto 611-0011, Japan*
[2]*Nishina Center for Accelerator-Based Science, RIKEN, Wako, Saitama 351-0198, Japan*
[3]*Department of Physics, Rikkyo University, Toshima, Tokyo 171-8501, Japan*
[4]*Research Center for Electron Photon Science, Tohoku University, Sendai, Miyagi 982-0826, Japan*

(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 $2 \times 10^{7}$ 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 un ... ge density distribution
tigated worldwic ... re determined by elastic

*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.

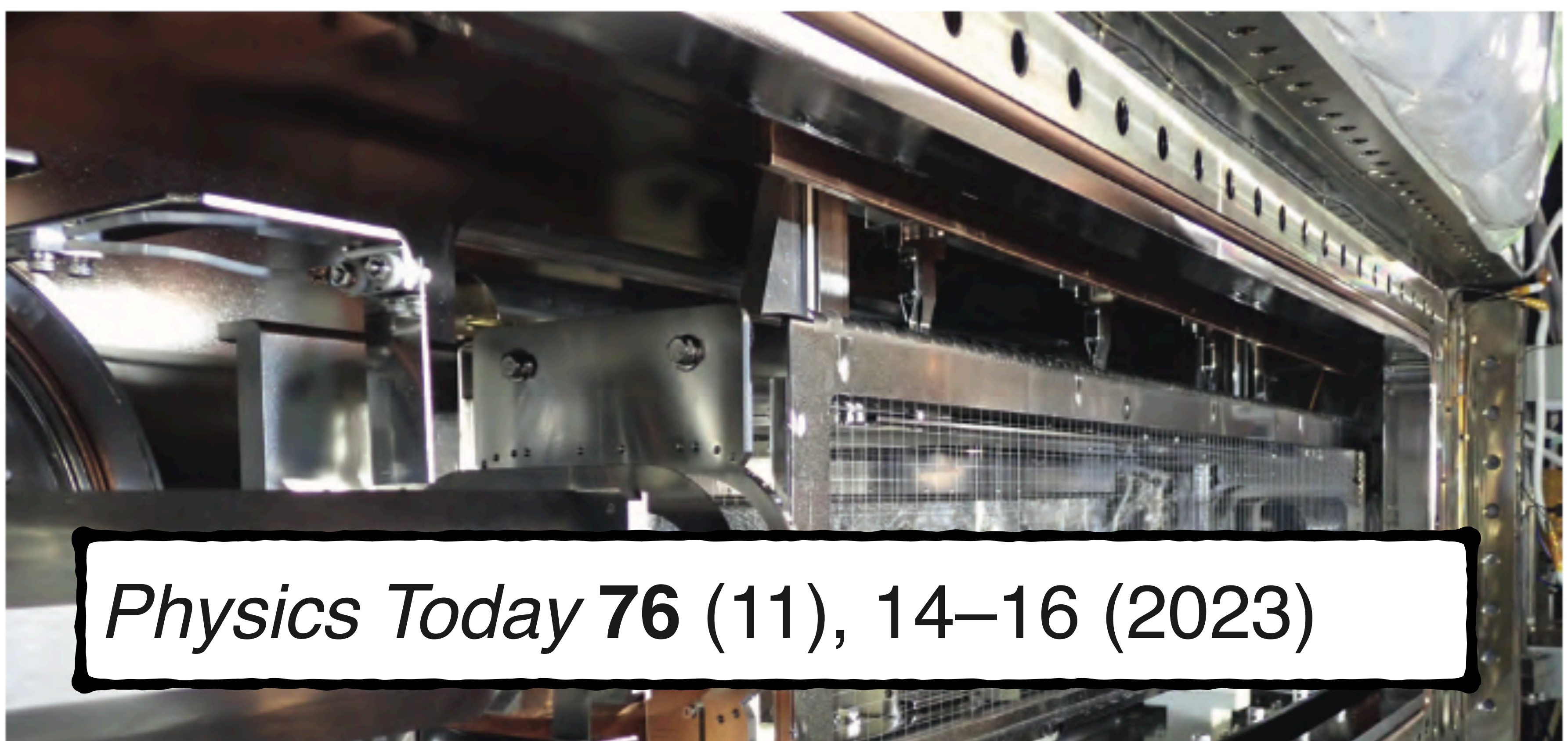
That's not generally what real nuclei look like. Neutron-rich lead-208, for example, has a thick skin of neutrons encasing its proton-endowed core (see PHYSICS TODAY, July 2021, page 12). Some nuclei are flattened, and some are elongated. Some are even pear shaped.

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



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

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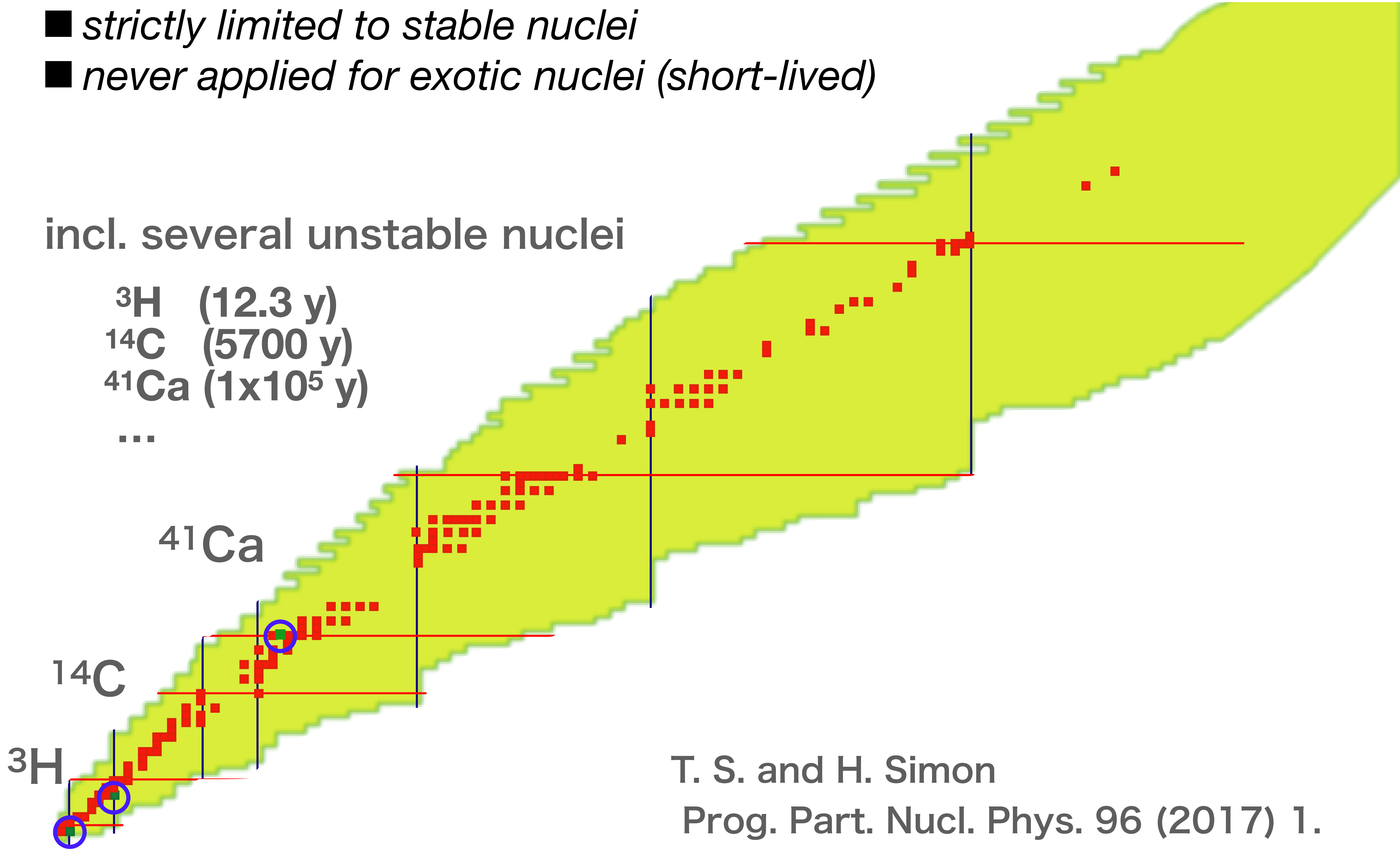
*Physics Today* **76** (11), 14–16 (2023)

# Nuclei ever studied by electron scattering

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

incl. several unstable nuclei

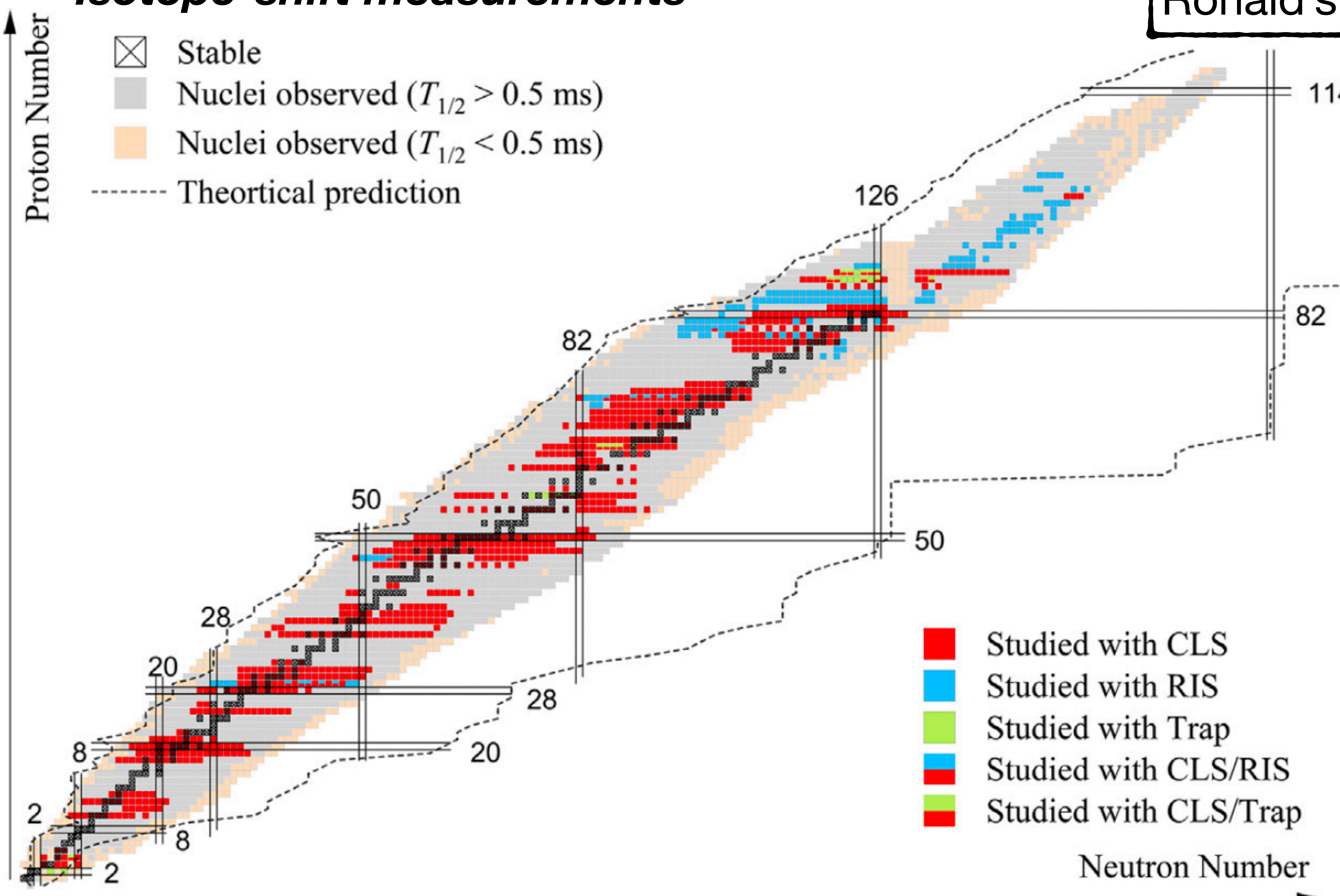
**$^{3}H$ (12.3 y)**
**$^{14}C$ (5700 y)**
**$^{41}Ca$ ($1 \times 10^{5}$ y)**
**...**




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

***Isotope-shift measurements***

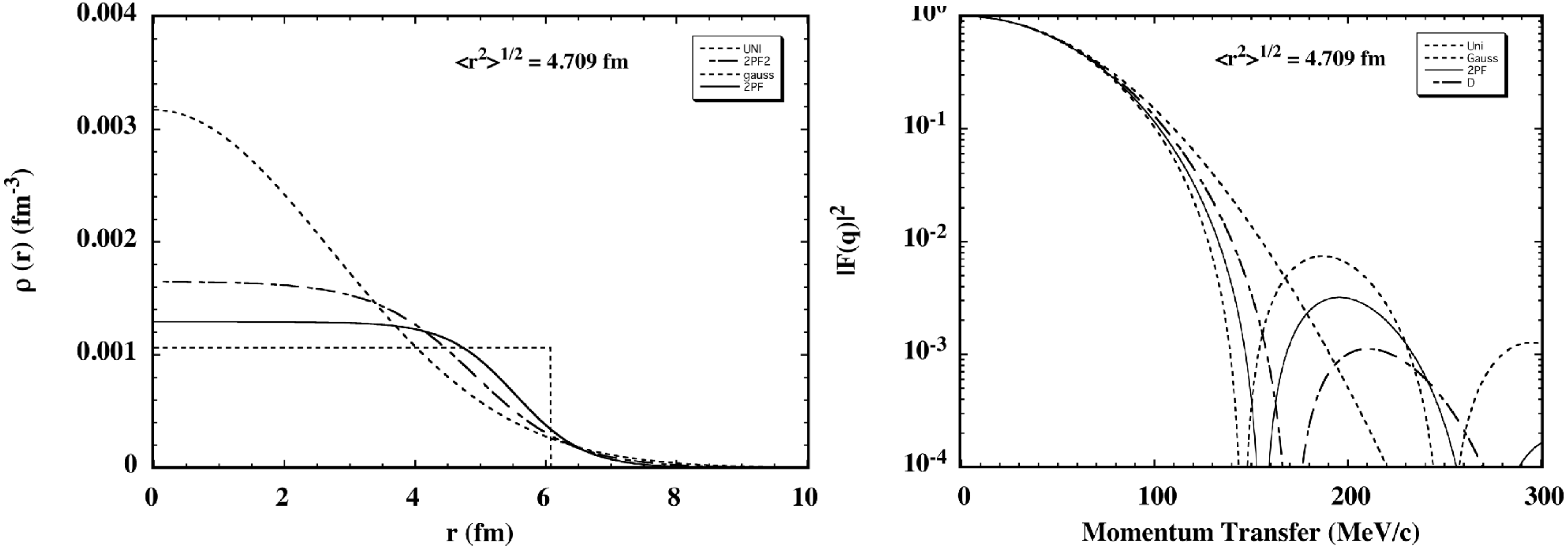
Ronald's talk




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)



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

Luminosity

# Electron scattering for exotic nuclei

**Exotic nuclei** ( production-hard & short-lived)

Extremely “thin” targets

→ Low luminosity

**Elastic scattering**

largest $\sigma$ up to modest q

***“Hofstadter’s” exp. for exotic nuclei***

**R. Hofstadter**
**(Nobel prize : 1961)**

# Luminosities for e-scattering

| | $E_e$ | $N_{beam}$ | 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

# Idea of “SCRIT” stated in 2004



**SCRIT :** Self-Confining Radioactive Ion Target

Available online at www.sciencedirect.com
SCIENCE DIRECT®

ELSEVIER

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]

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

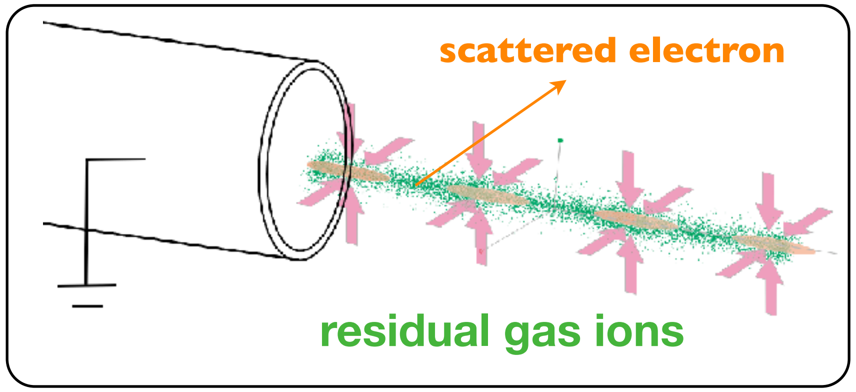
Available online 3 August 2004

# SCRIT（Self-Confining RI Ion Target)

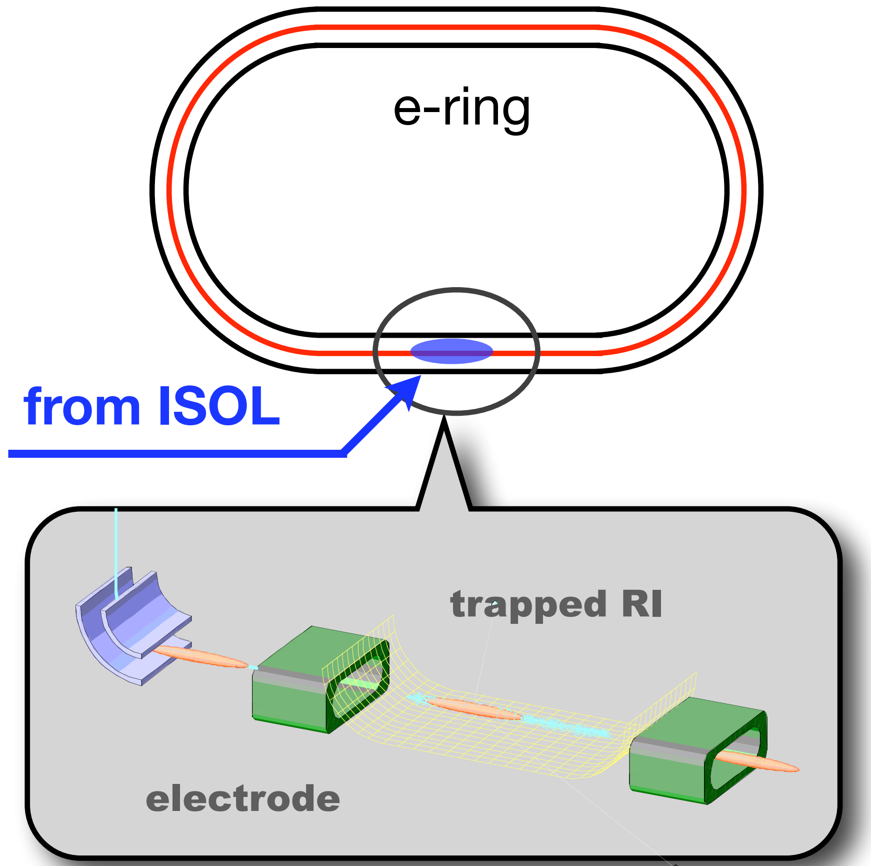


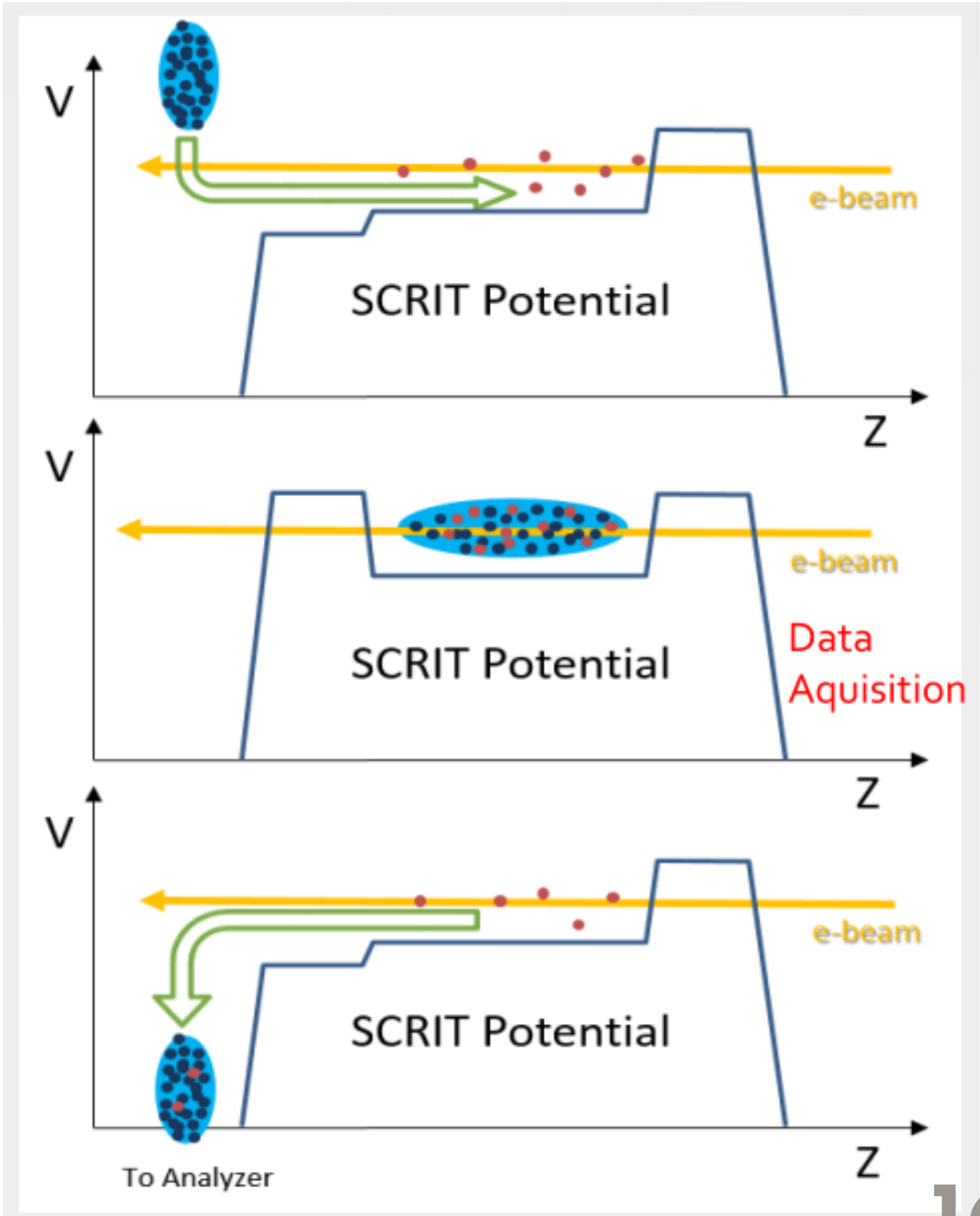
**Idea : "ion trapping" at SR facilities.**

ionized residual gases are trapped by the circulating electron beam



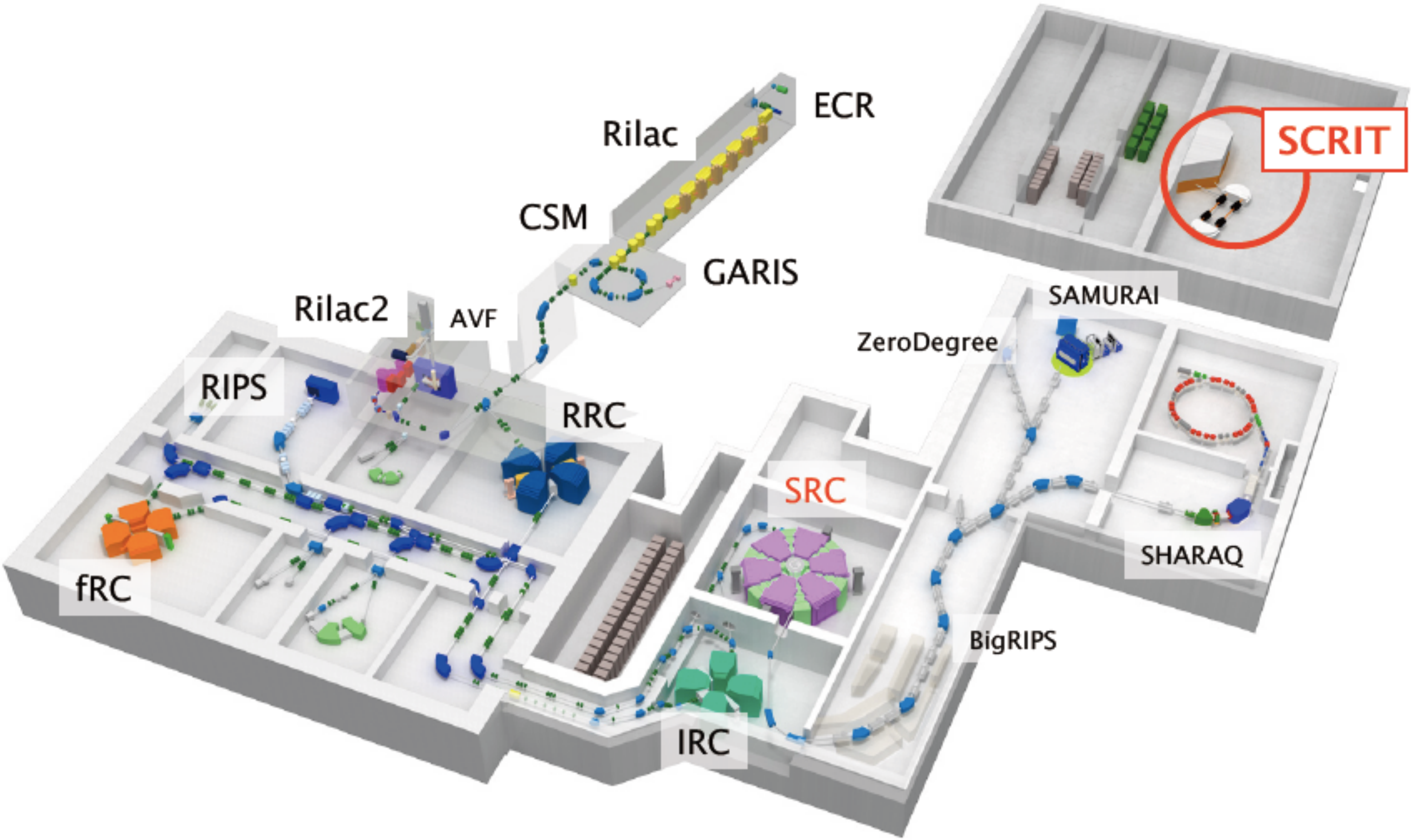

*ill problem of e-storage rings*



# SCRIT electron scattering facility @ RIBF

## World's first electron facility dedicated for exotic nuclei



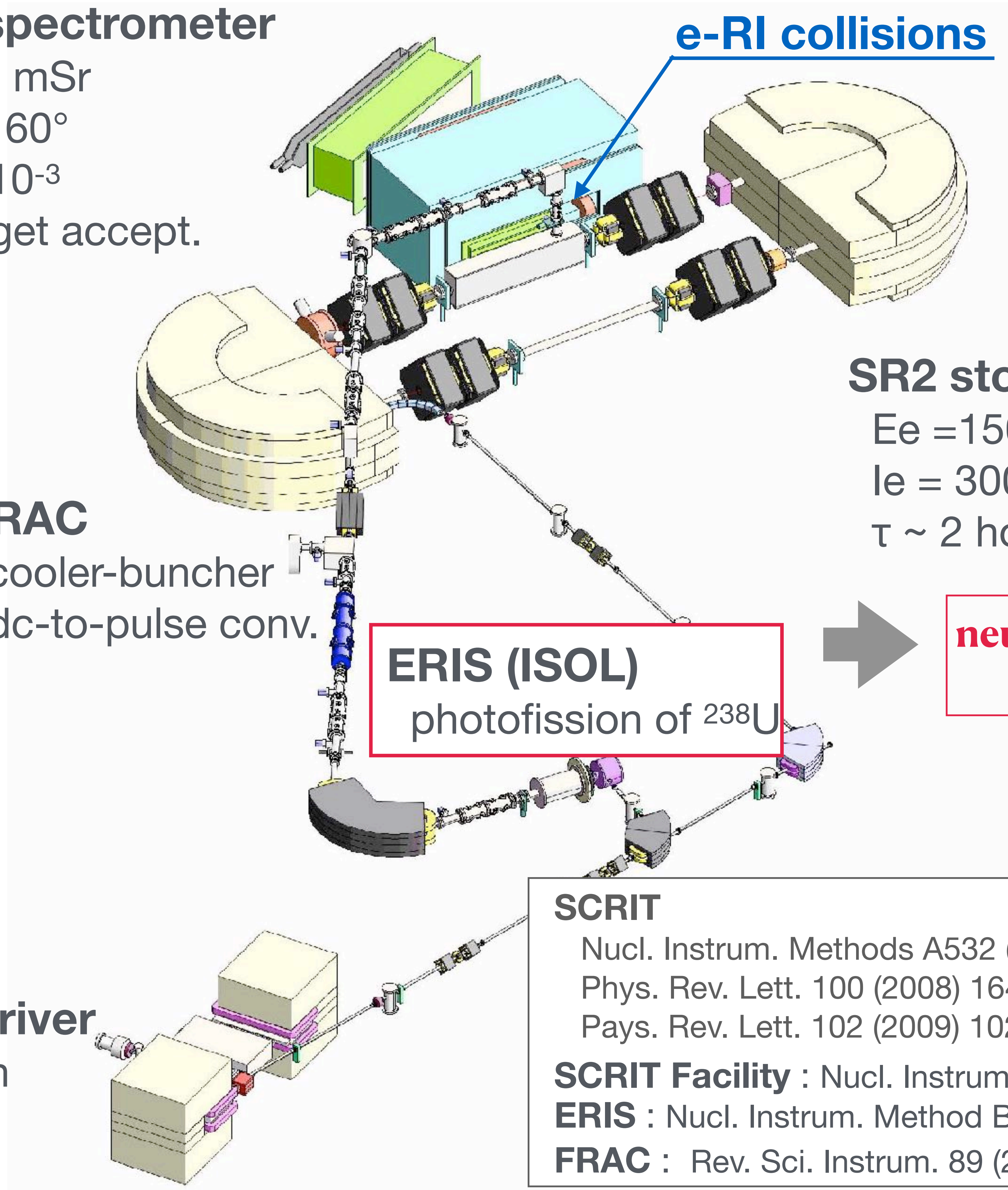

RIKEN RI Beam Factory (Japan)

# RIKEN SCRIT Electron Scattering Facility



**WiSES spectrometer**
ΔΩ ~ 90 mSr
θ = 30 - 60°
Δp/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.

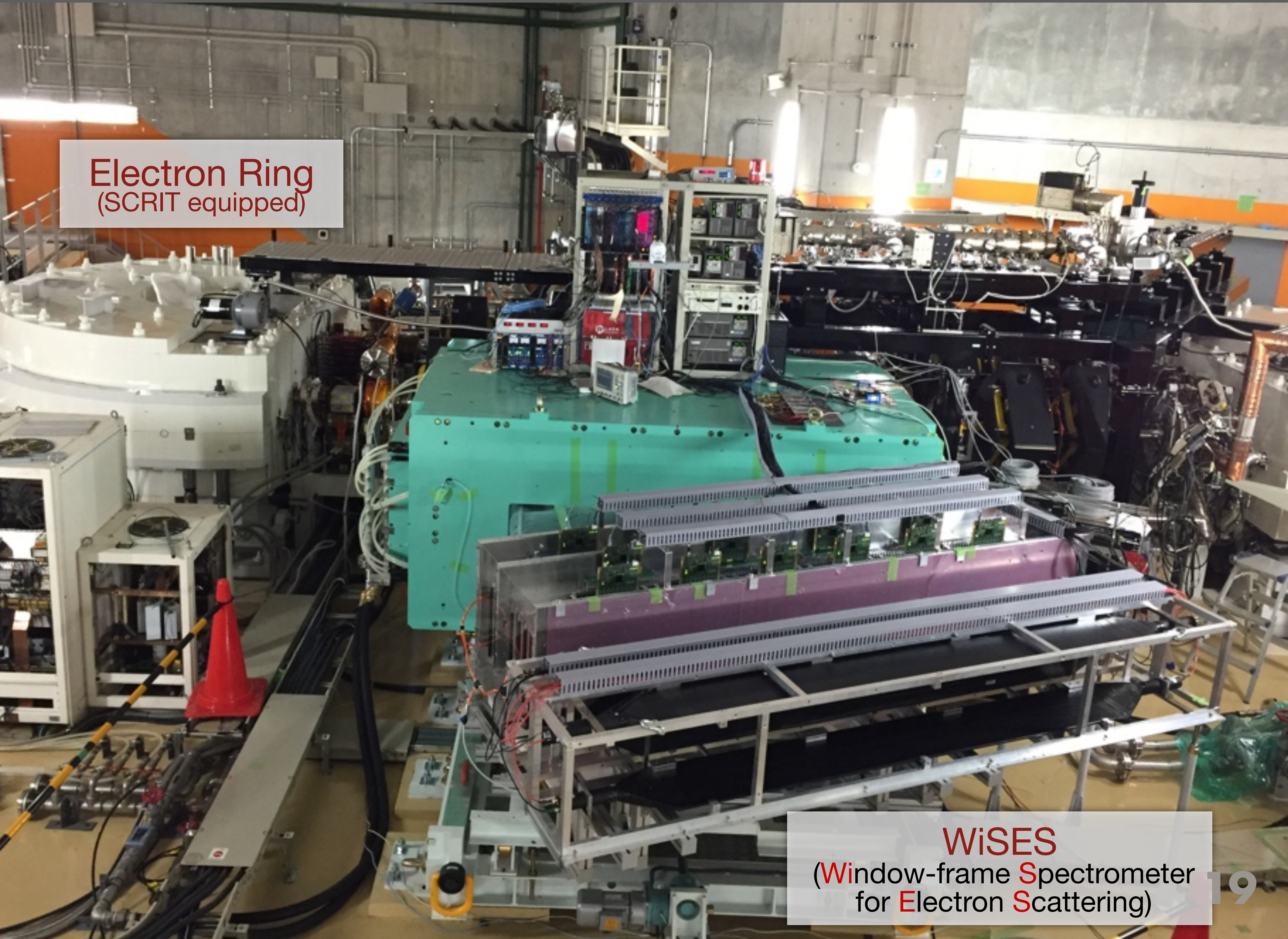
**ERIS (ISOL)**
photofission of $^{238}$U

**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.


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

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



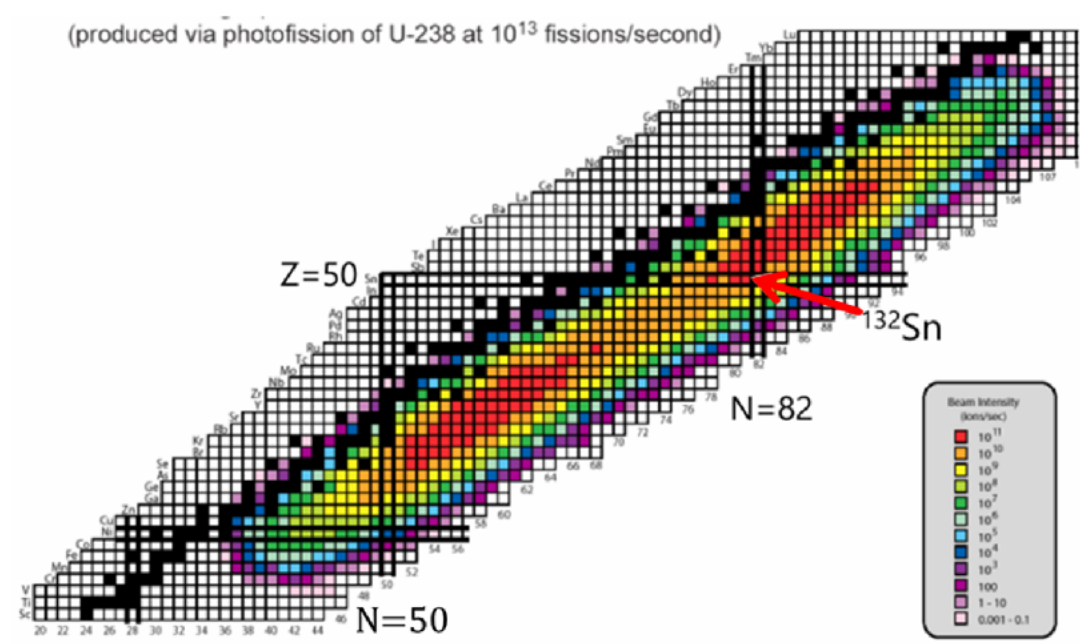
**Reaction** : photo- (electro-) fission of $^{238}$U.
**Ion Source** : FEBIAD type (Sn, Xe…)
Surface Ionization (Cs, Ba,…)

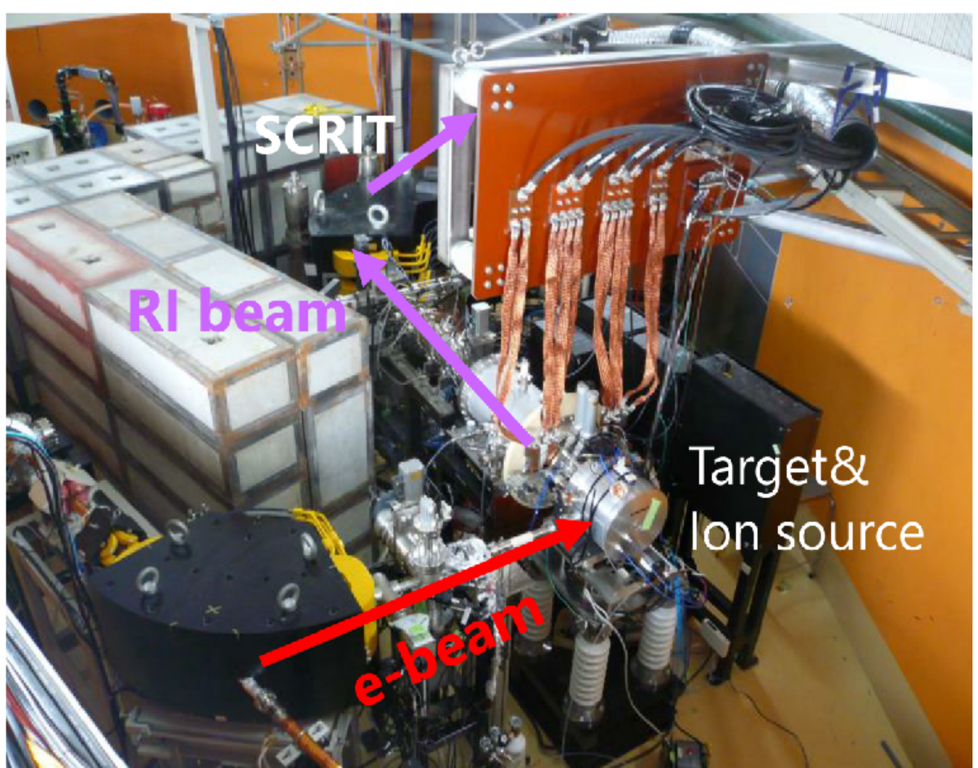
Production Rate
$N_{fission}$ ~ $10^8$ /watt
$N_{^{132}Sn}$ ~ $10^6$ /watt * 1% ($\varepsilon_{trans.}$)

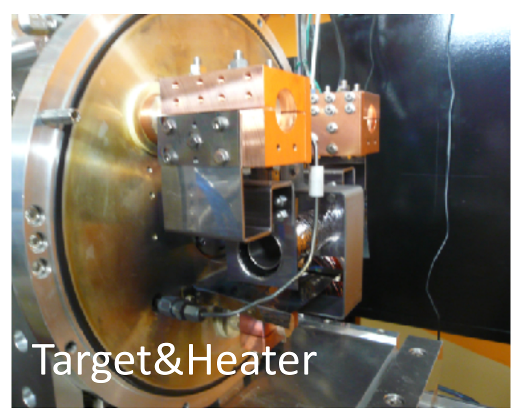
beam power : ~ 20W (today)
~ 2 kW (in a few years)

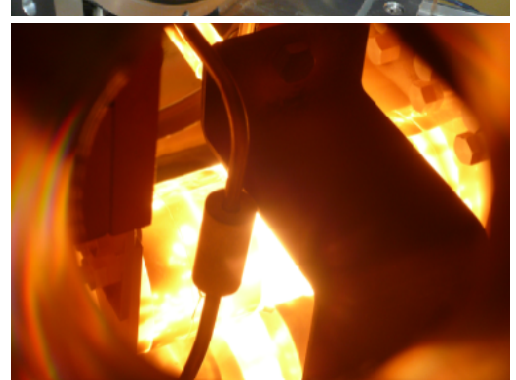
**House-made Uranium carbide (UCx)**


φ 18 mm, t 0.8 mm disks



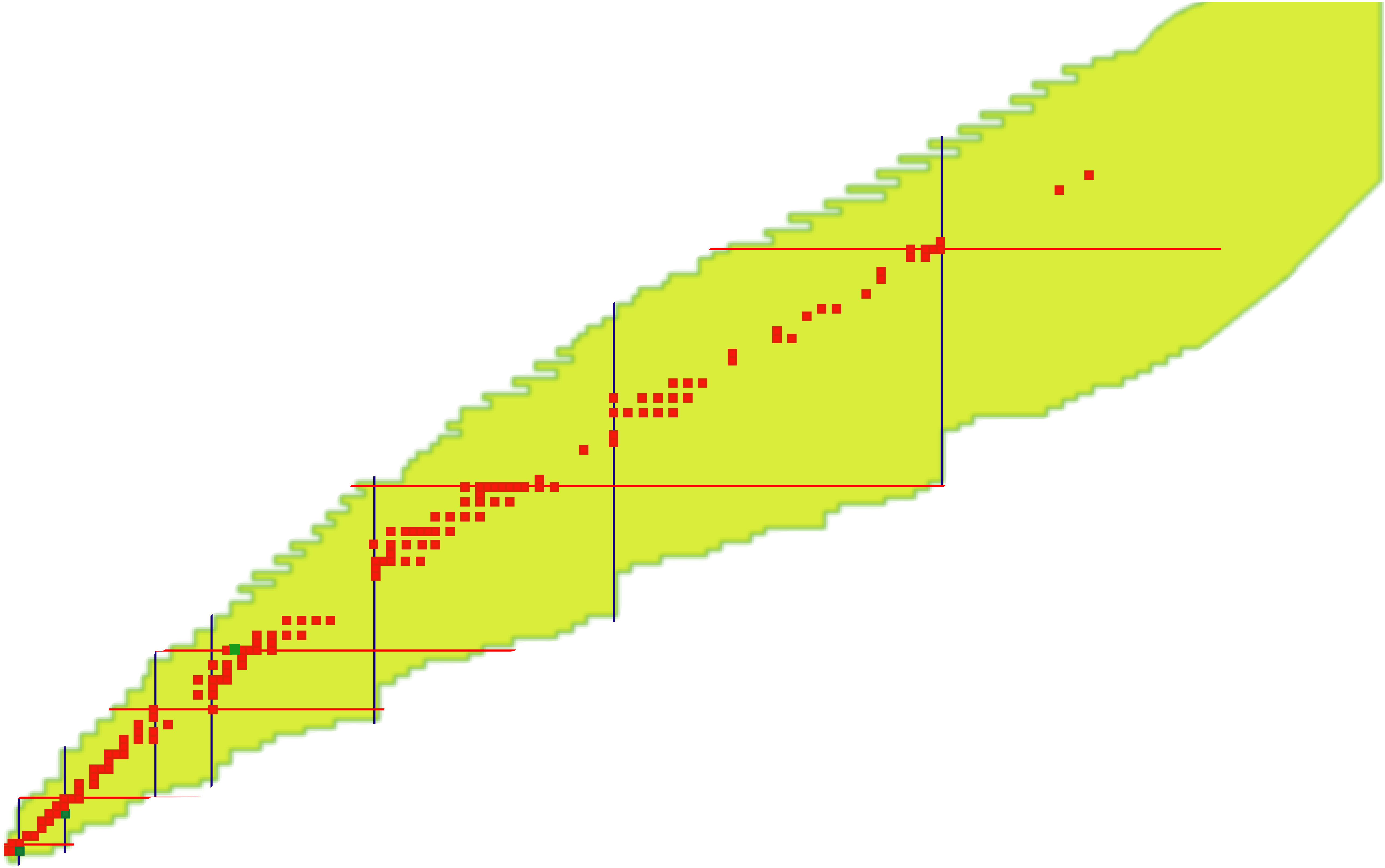



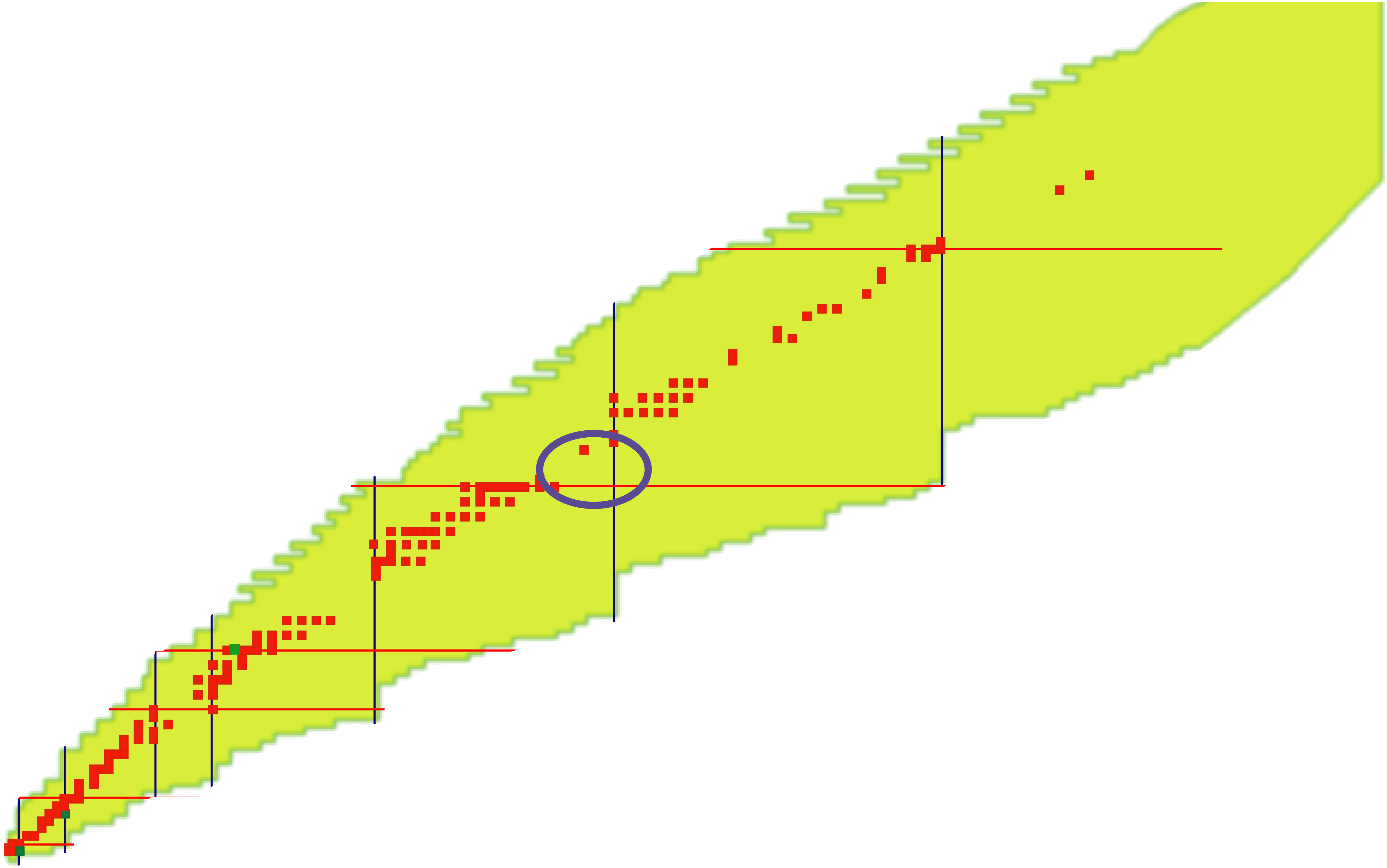
$^{138}$Xe : 3.9 x $10^6$ cps
$^{132}$Sn : 2.6 x $10^5$ cps
$^{137}$Cs : 8.0 x $10^6$ cps (28-g U)

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

# “Day-one exp.” region for our facility







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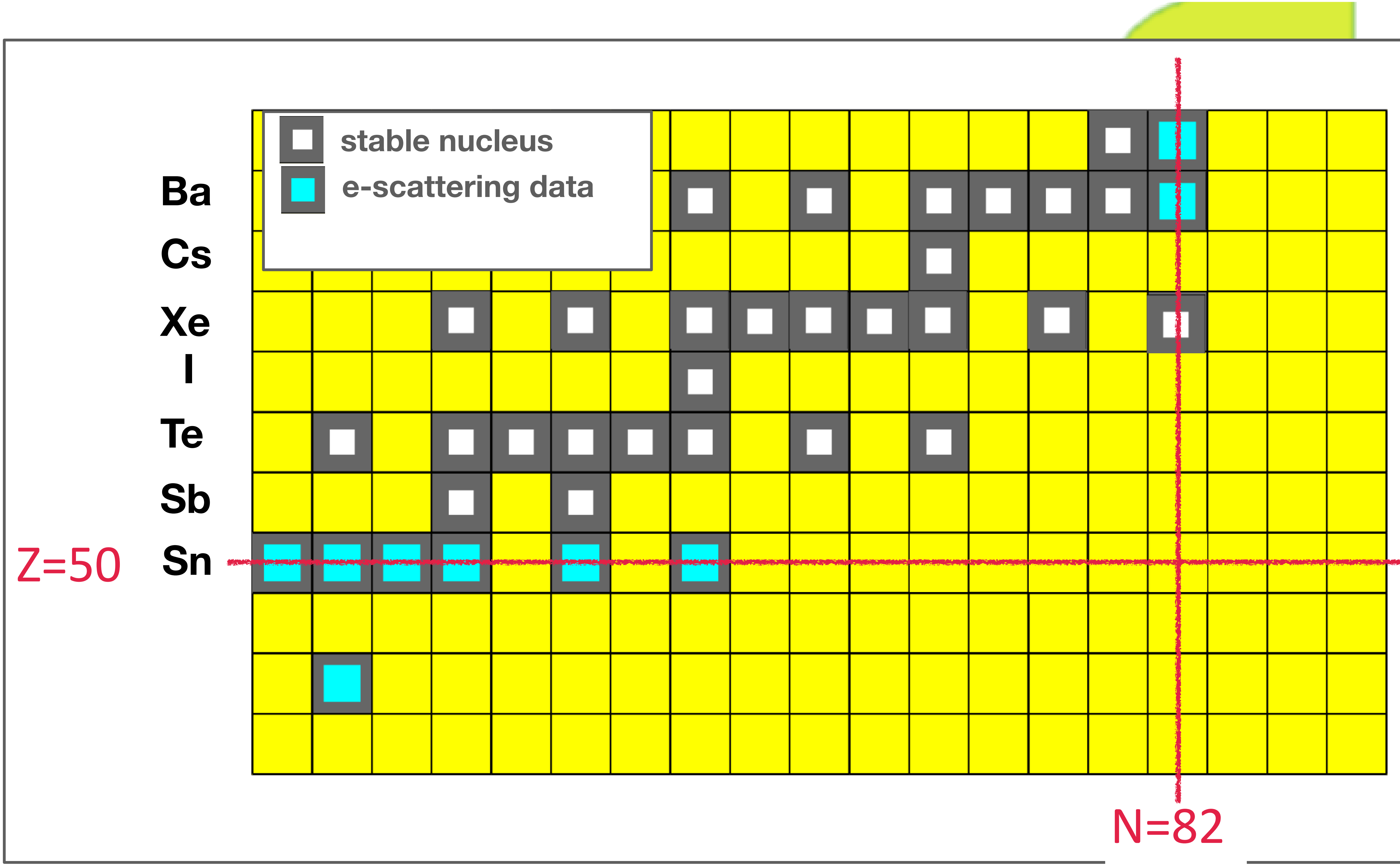

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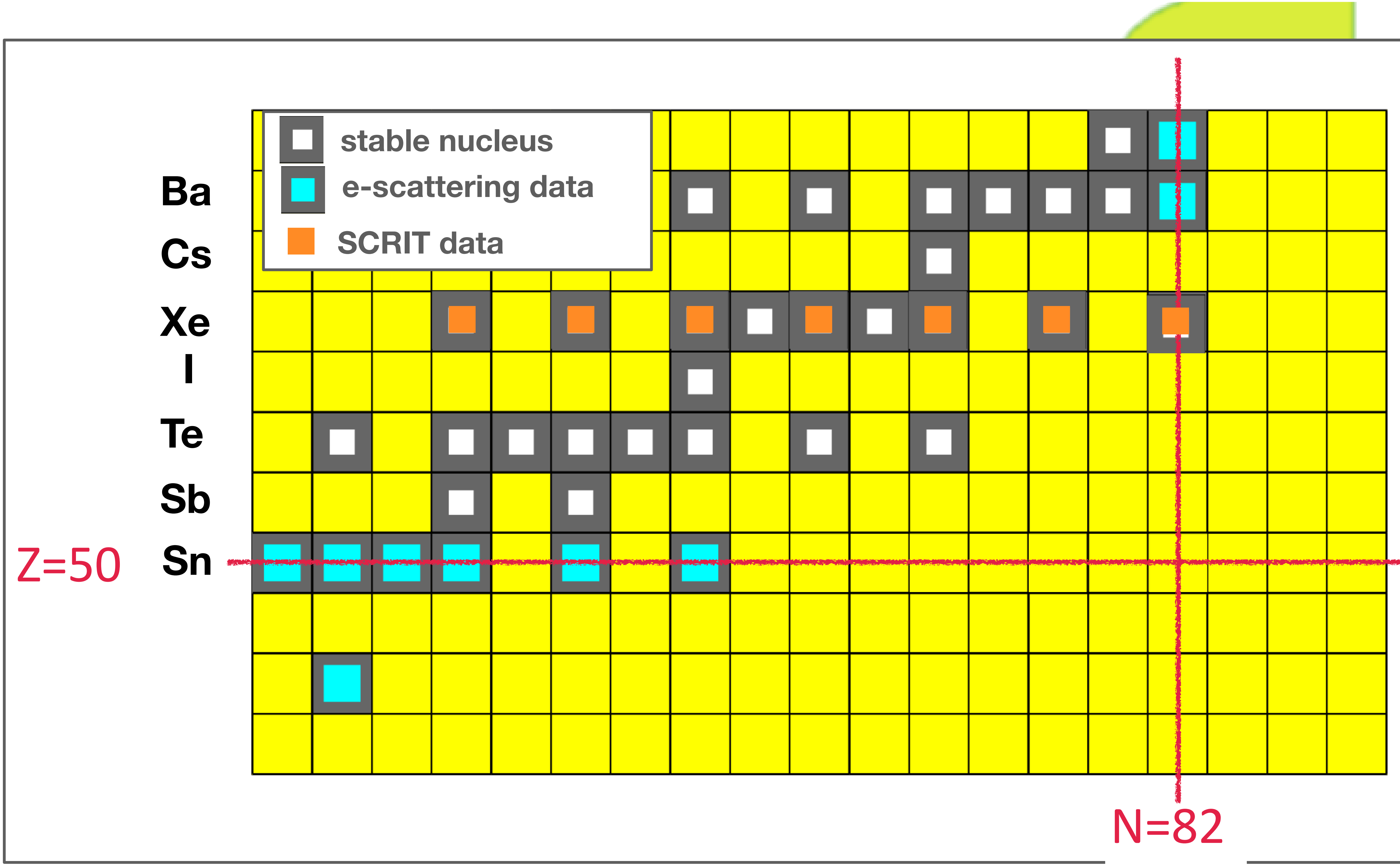

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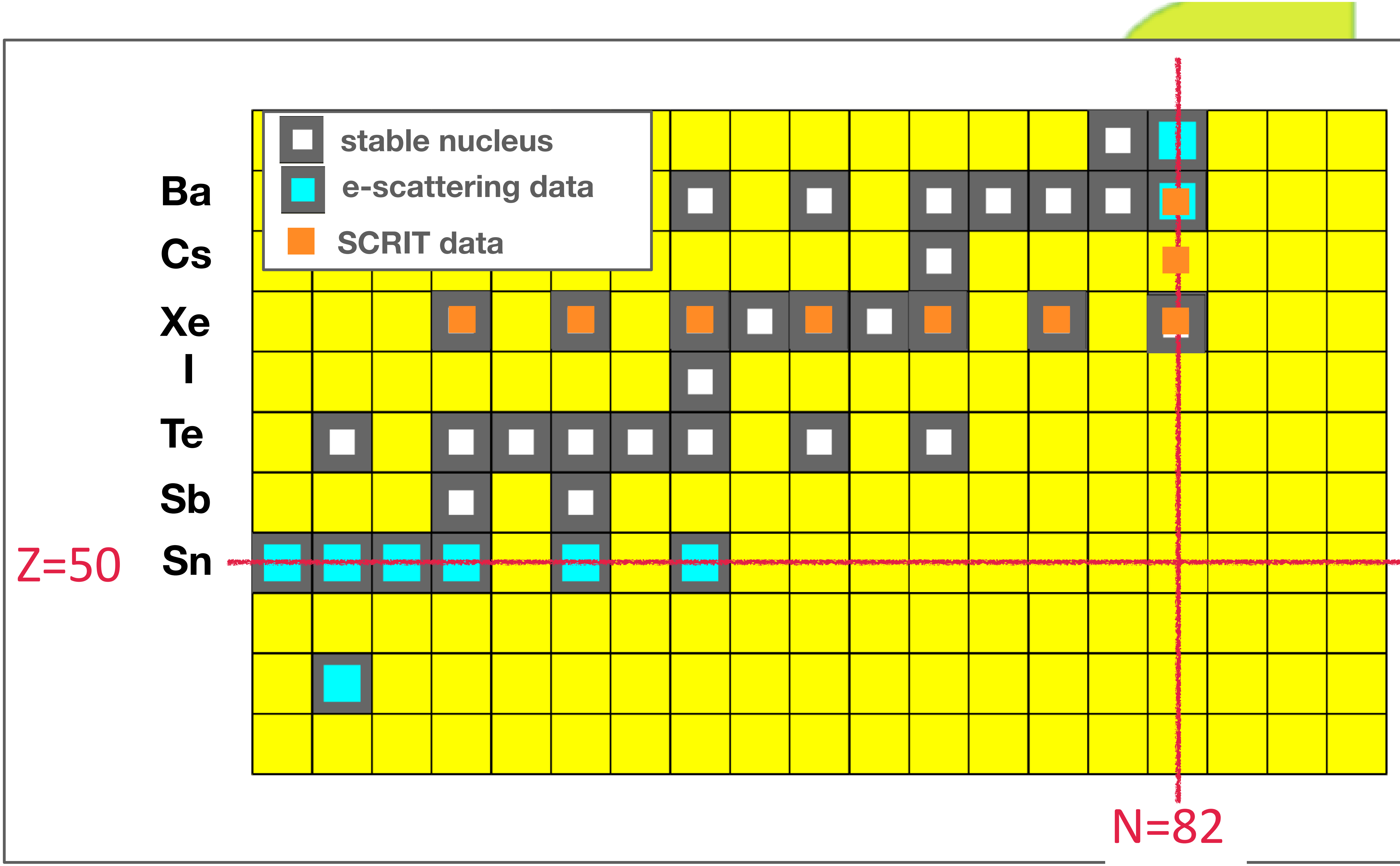

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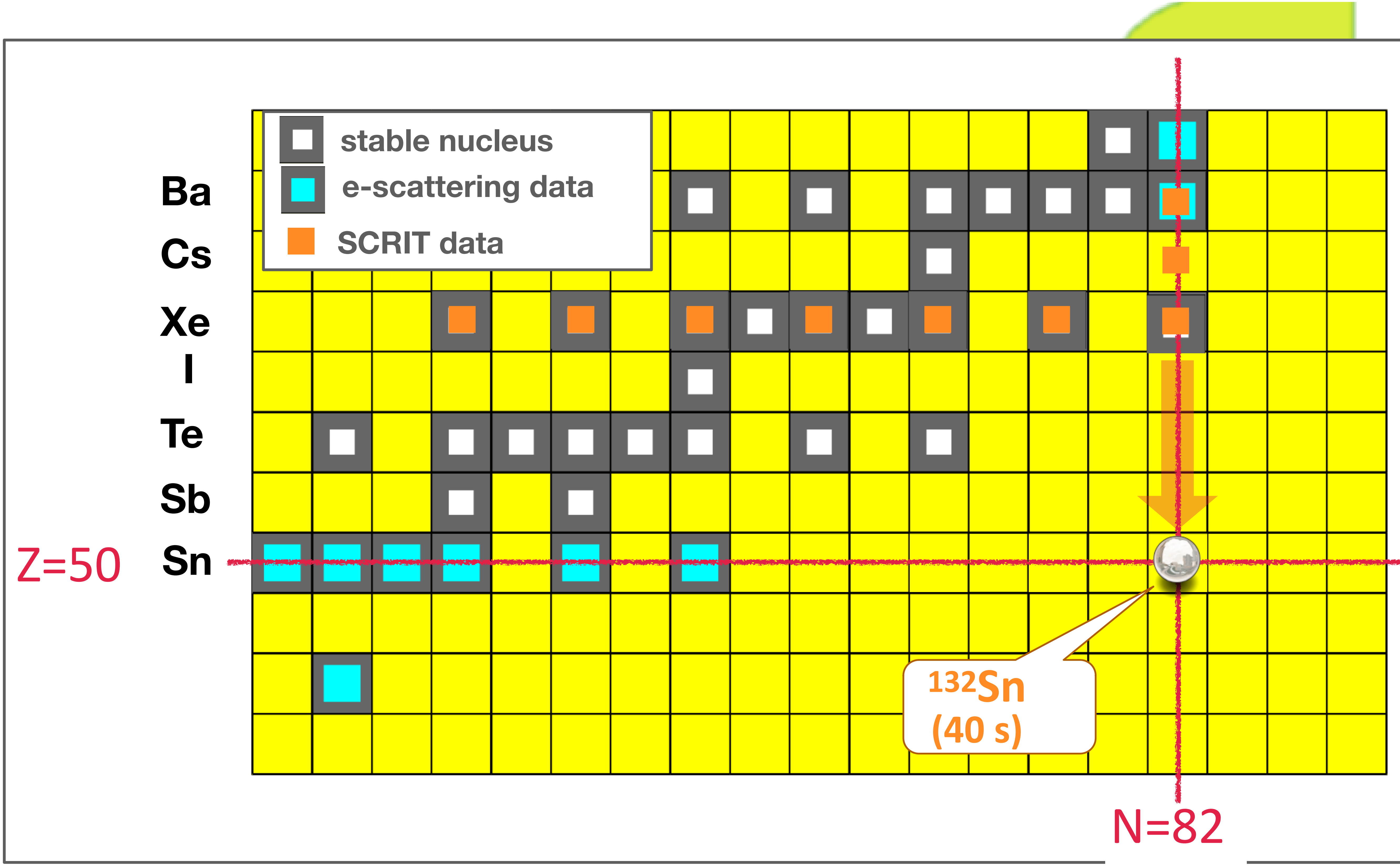

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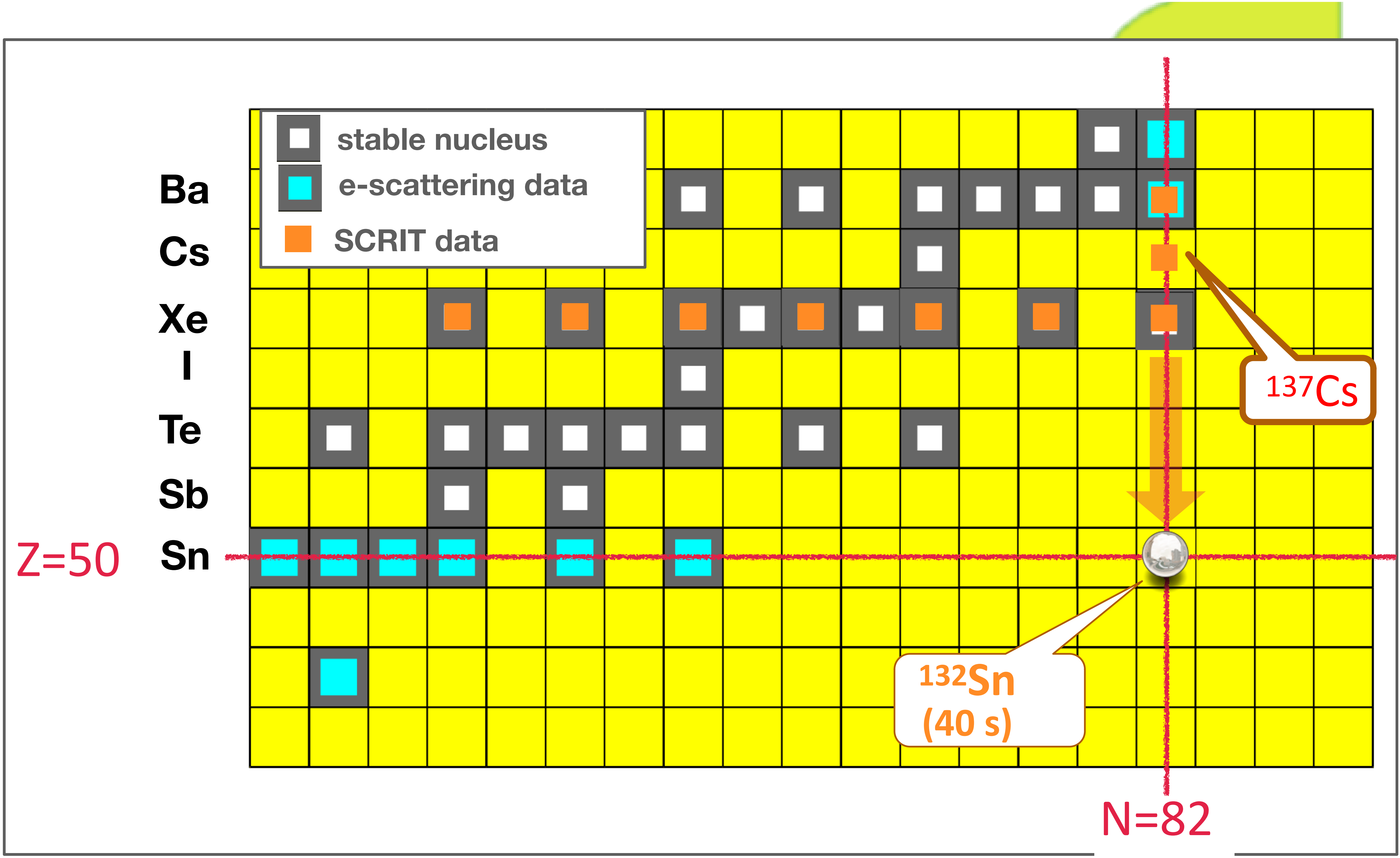
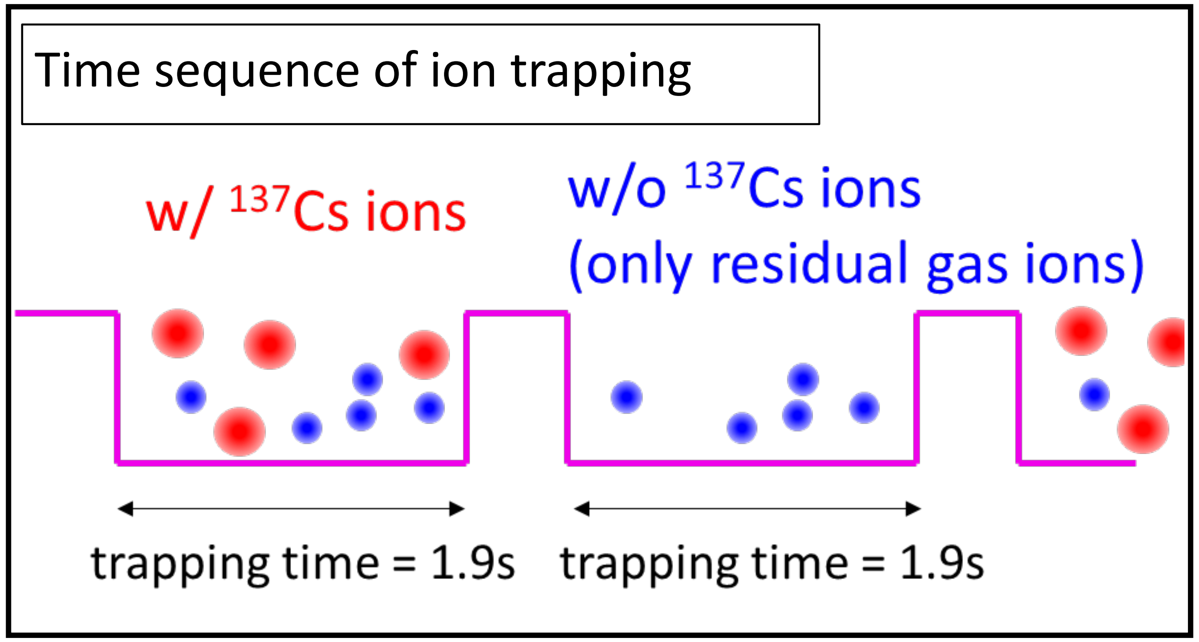
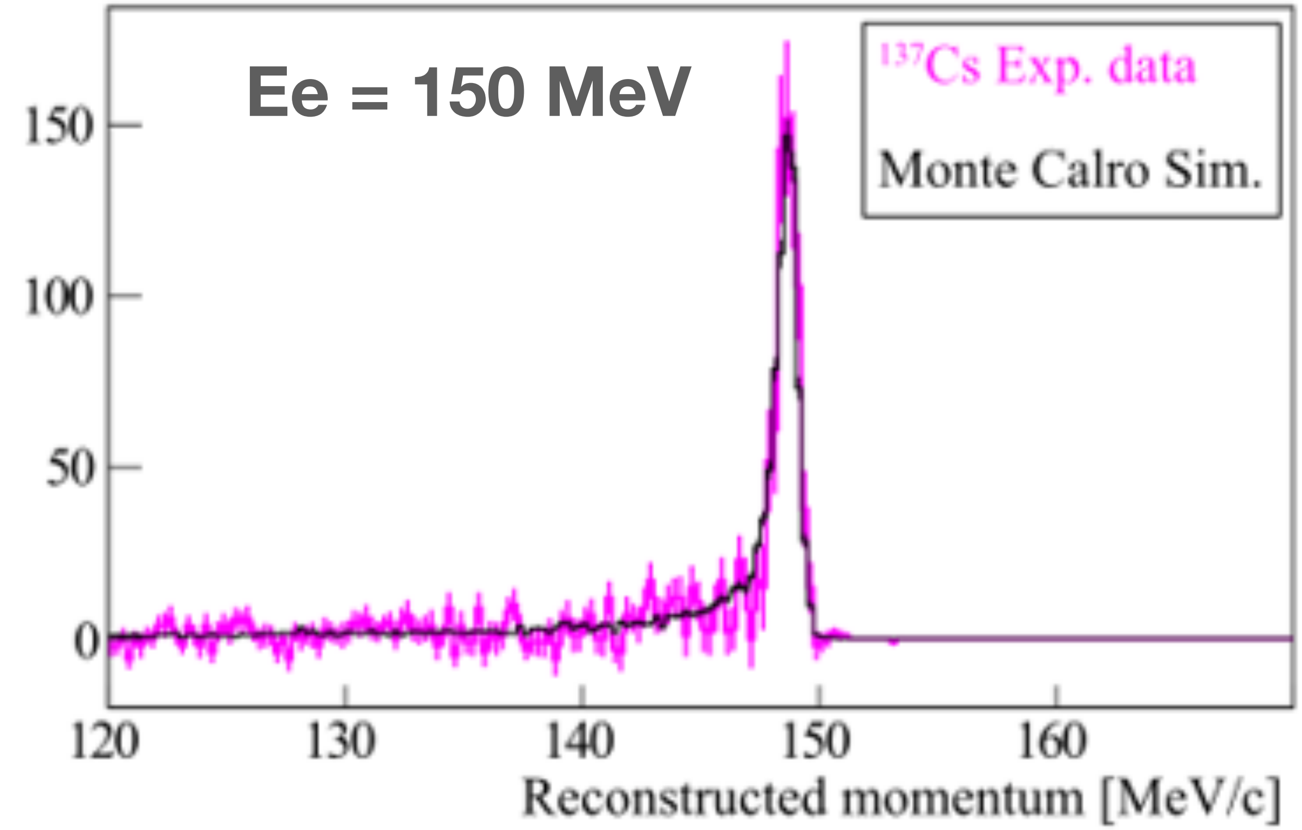


# $^{137}$Cs(e,e’) with online-produced Cs ions



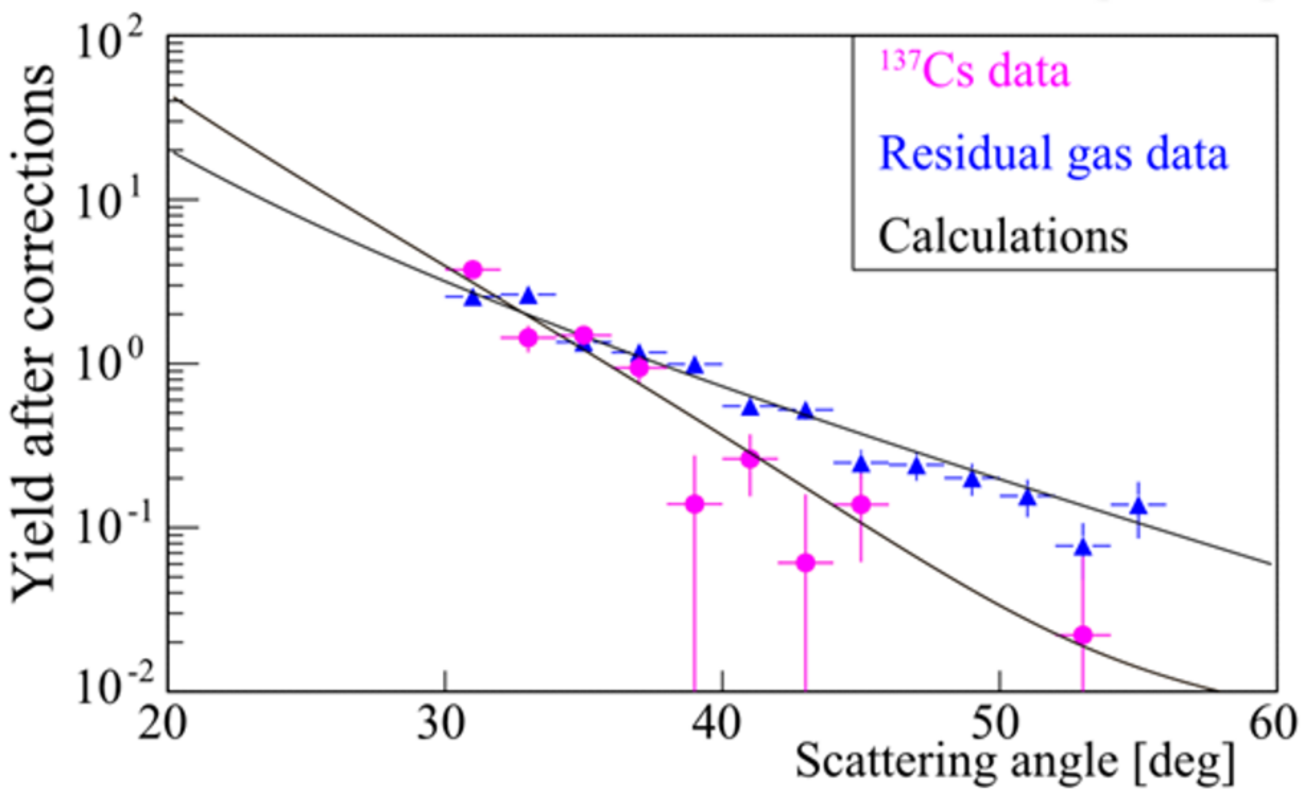




**1.9 s trapping**

**=> mimicking “short-lived” nuclei**

**$N_{trapped}$ ~ 2 x$10^7$**

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

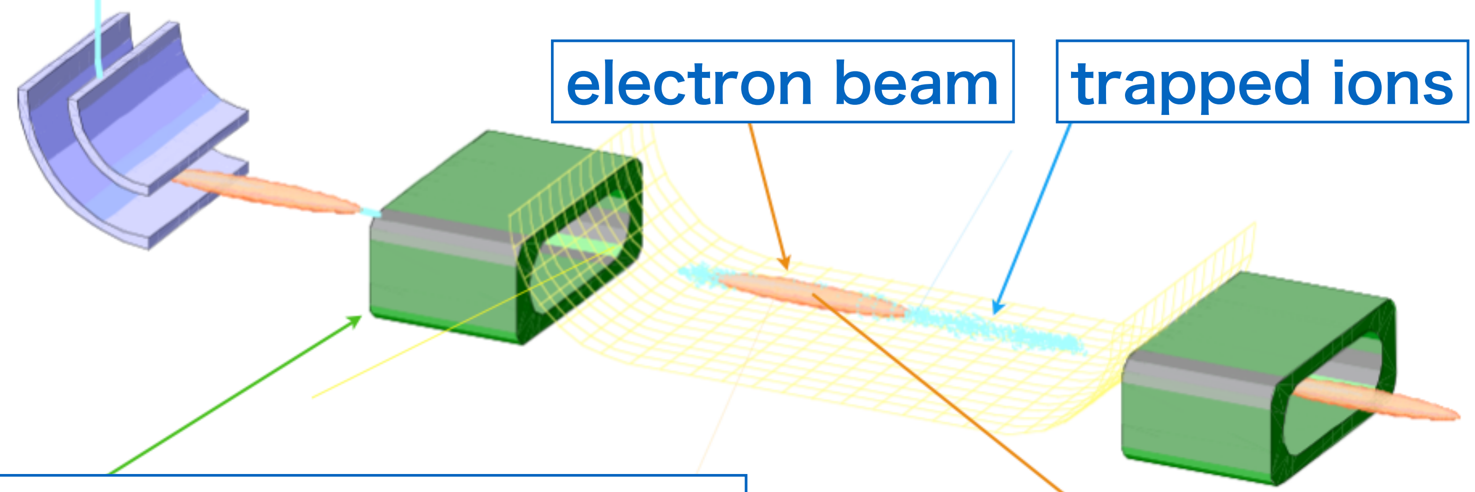



**successful demonstration for online-produced unstable nuclei**

# Luminosities

## ~$10^7$ ions are trapped on e-beam (~ 1 $mm^2$)

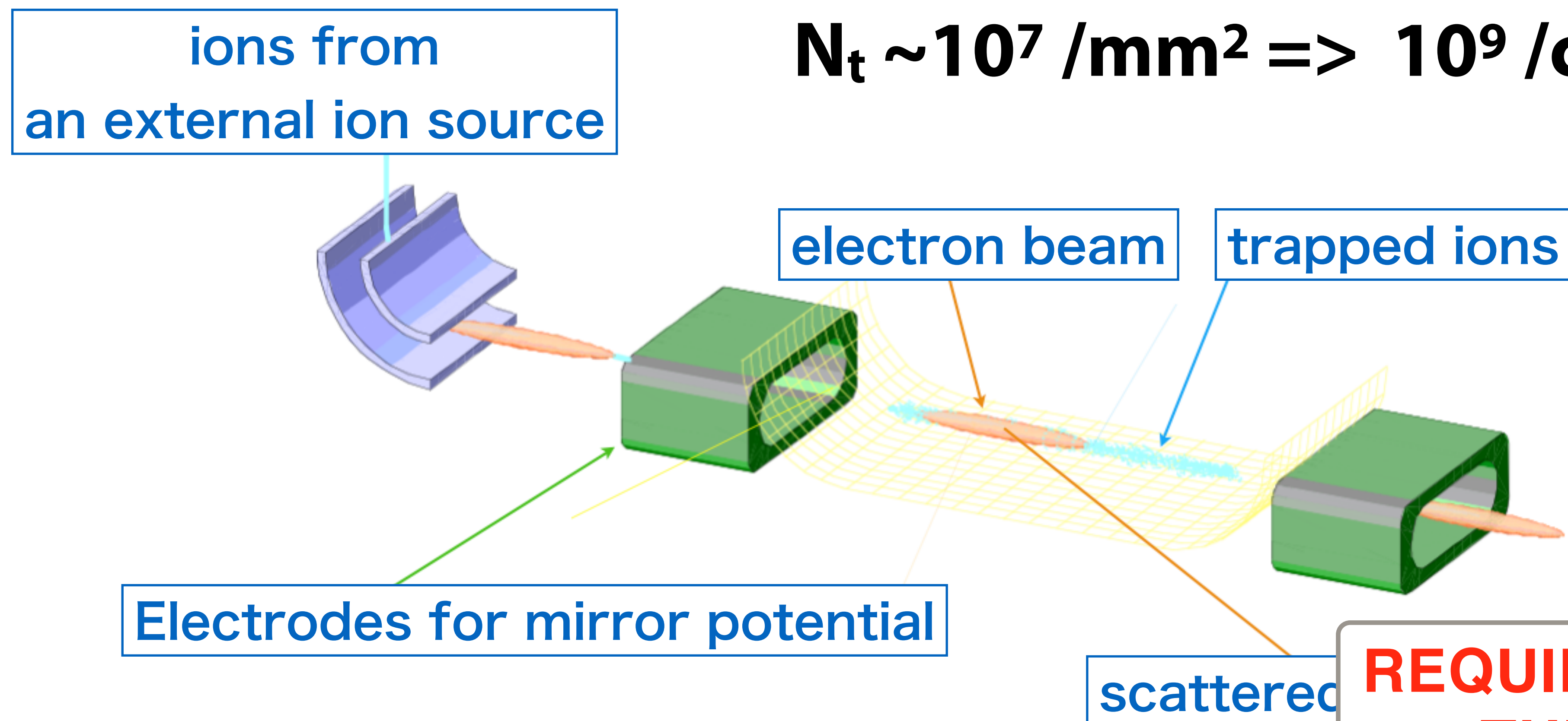
$N_t \sim 10^7\ /mm^2 \Rightarrow\ 10^9\ /cm^2$




| | Ee | $N_{beam}$ | ρ · t | L |
|---|---|---|---|---|
| Hofstadter's era (1950s) | 150 MeV | ~ 1nA (~$10^9$ /s) | ~$10^{19}$ /$cm^2$ | ~$10^{28}$ /$cm^2$/s |
| JLAB | 6 GeV | ~100μA (~$10^{14}$ /s) | ~$10^{22}$ /cm2 | ~$10^{36}$ /$cm^2$/s |
| **SCRIT** | **150 - 300 MeV** | **~200 mA (~$10^{18}$ /s)** | **~ $10^9$ /$cm^2$** | **~$10^{27}$ /$cm^2$/s** |

# ~$10^7$ ions are trapped on e-beam (~ 1 mm$^2$)

$N_t$ ~$10^7$ /mm$^2$ => $10^9$ /cm$^2$




**REQUIRED TARGET THICKNESS $10^{-10}$!!!**

| | Ee | $N_{beam}$ | ρ · | |
|---|---|---|---|---|
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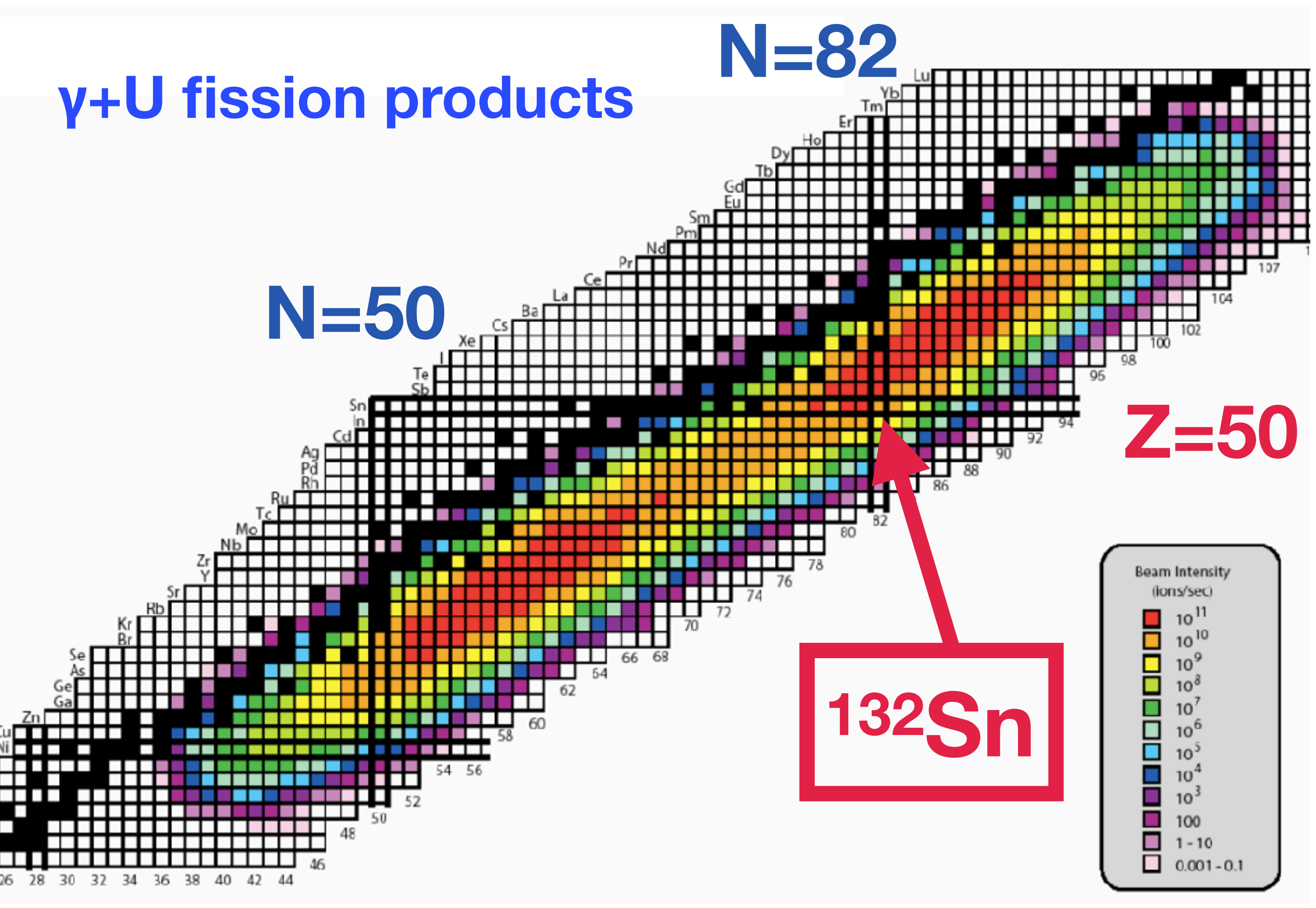
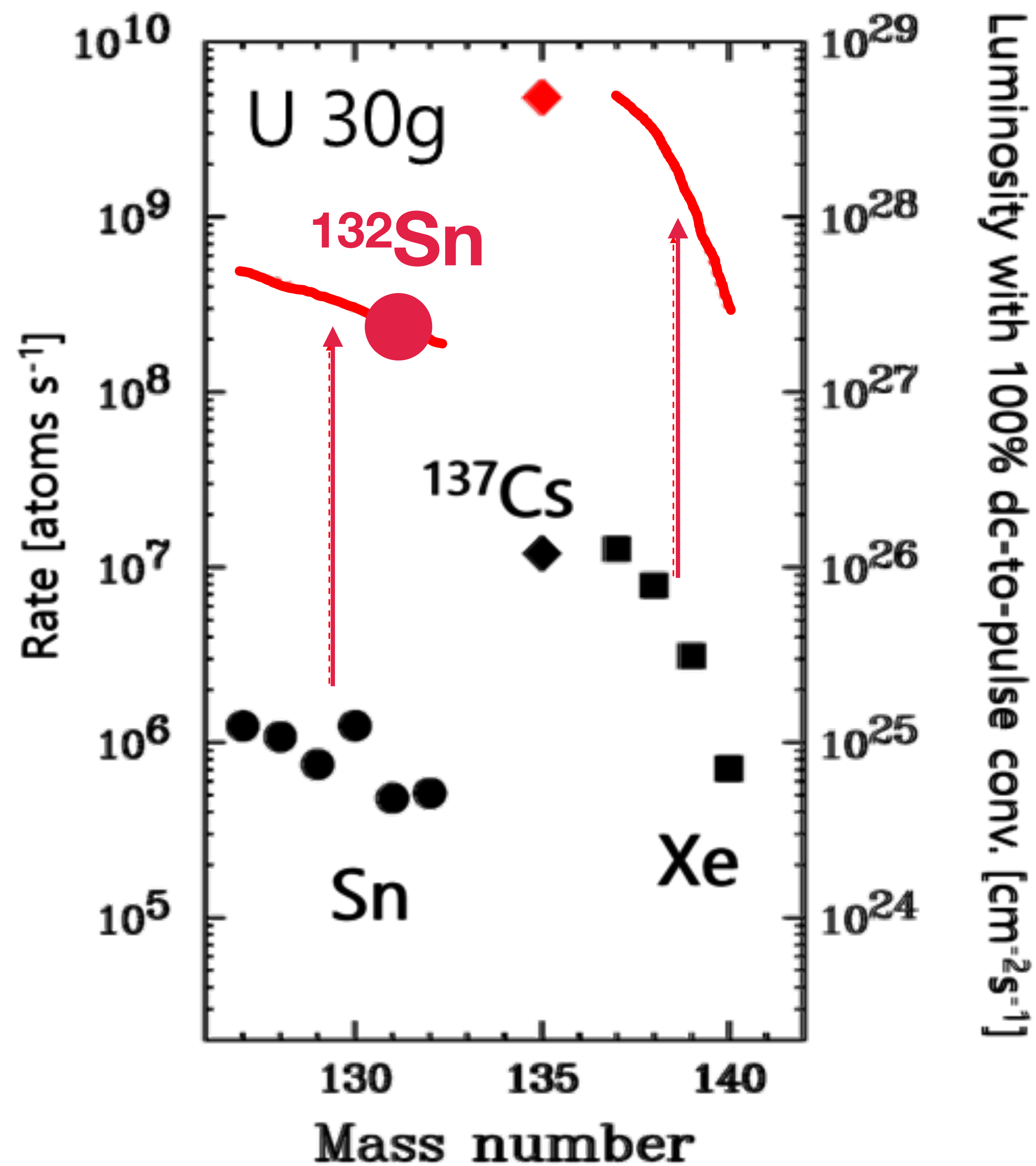
# towards $^{132}$Sn (40s)

## Upgrade of ISOL driver : underway

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



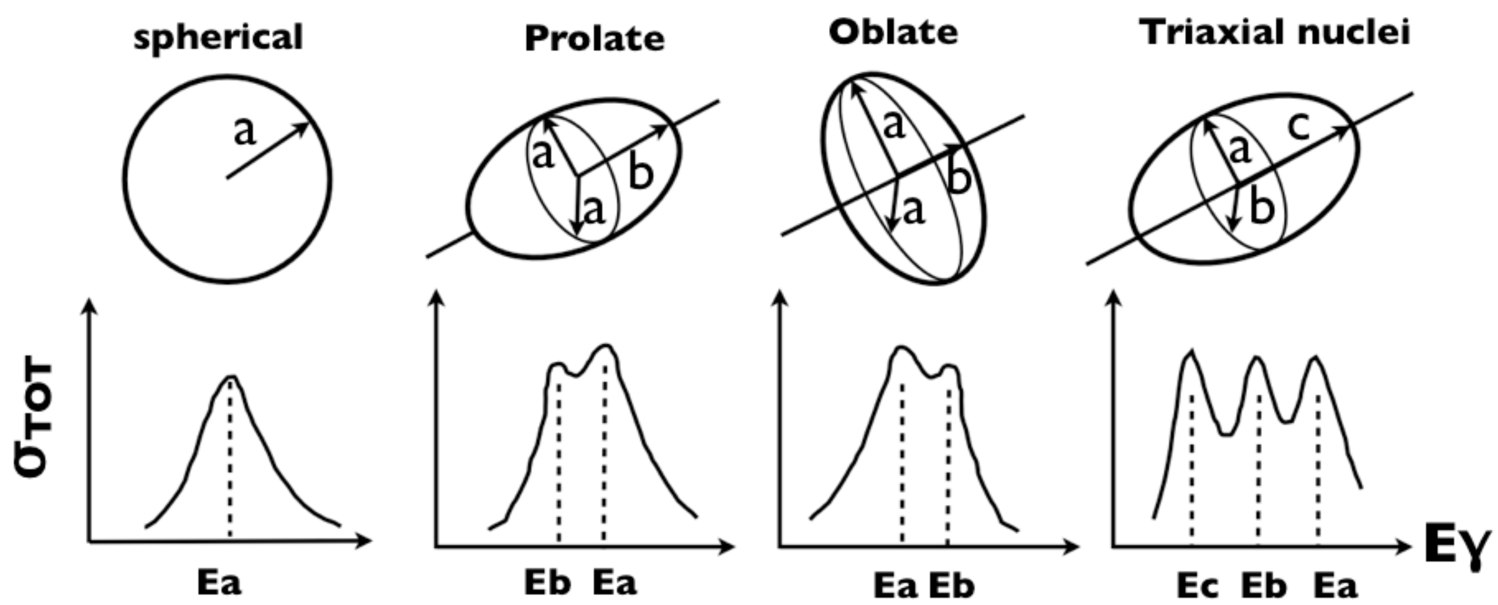
# further research possibilities at SCRIT 

## 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) 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.




## 3) inelastic scattering, such as (e,e'p) depending on L

# nuclear charge density, moments

## 1) charge density

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

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

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

# nuclear charge density, moments

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

## 2) 2nd moment

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

Proton

Neutron

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

## 1) charge density

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

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

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

Proton

Neutron

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

## 3) 4th moment

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

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

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

## 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

Proton Neutron

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

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

## 3) 4th moment

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

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

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

## 1) charge density

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

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

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## 2) 2nd moment

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

Proton

Neutron

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

## 3) 4th moment

RMS n-radius

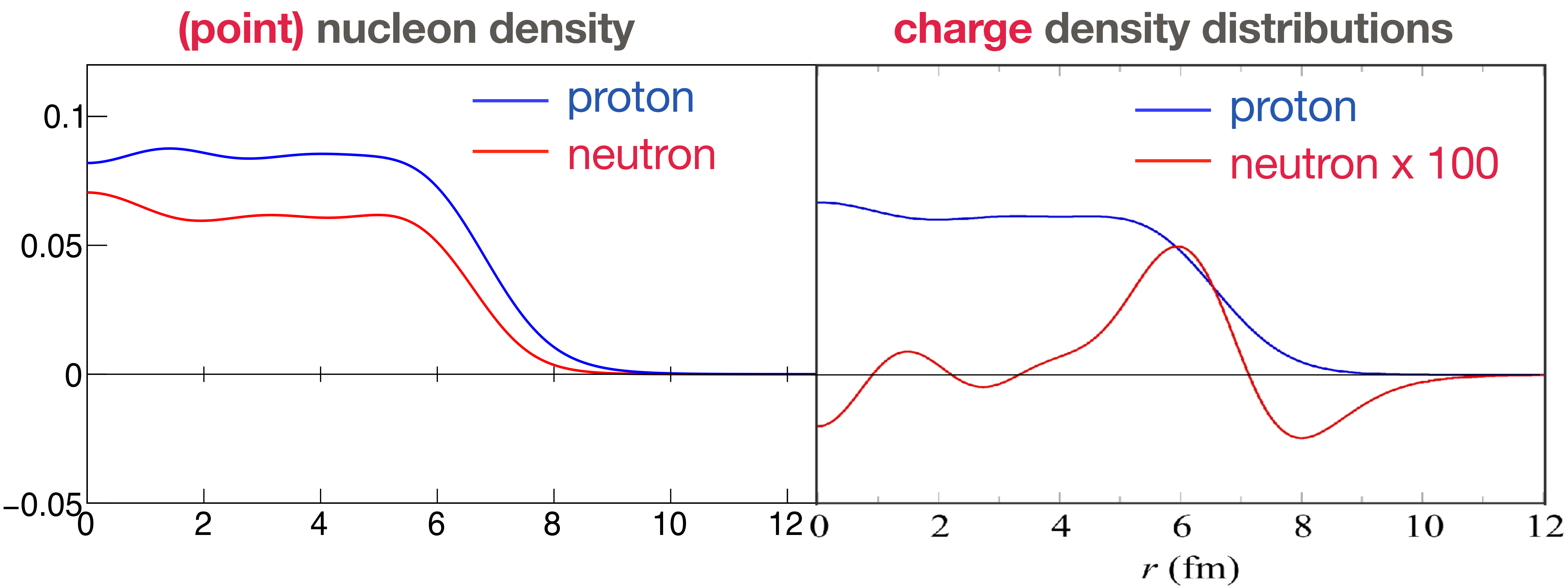
$$< r_c^4 > = \int r^4 \rho_c(r)\,\mathrm{d}^3 r$$

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

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

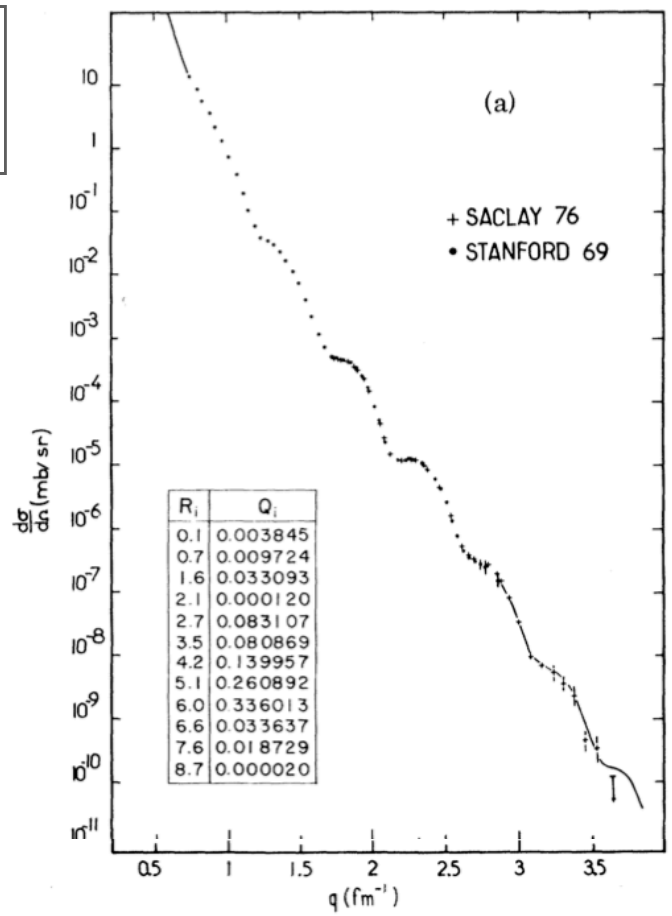
# a new research opportunity at the SCRIT facility

## neutron distribution by electron scattering



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

## $^{208}$Pb



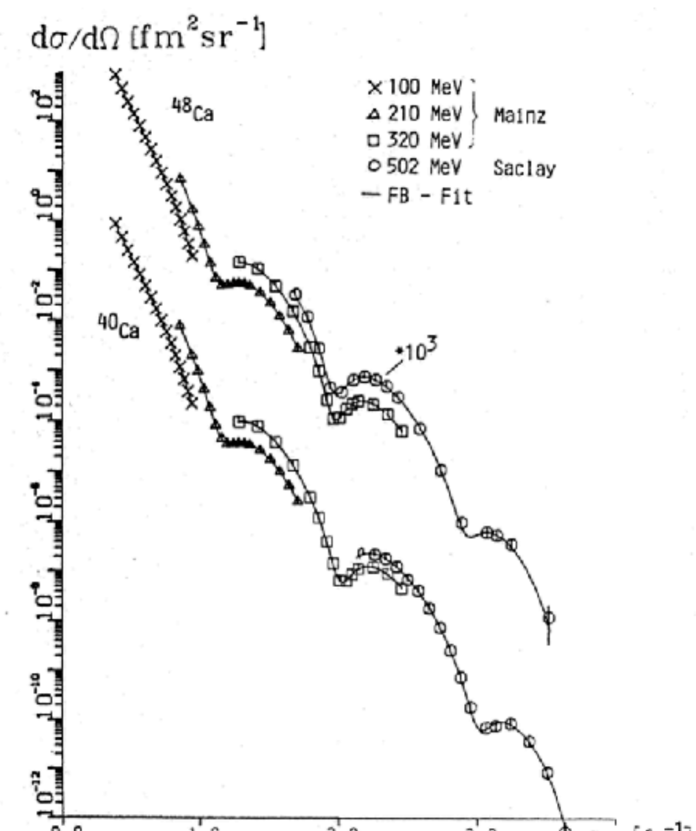

| | | $R_p$ | $R_n$ | $\delta R$ |
|---|---|---|---|---|
| $^{208}$Pb | Rel. | 5.454(0.013) | 5.728(0.057) | 0.275(0.070) |
| | Non. | 5.447(0.014) | 5.609(0.054) | 0.162(0.068) |
| | Exp. | $R_c = 5.503(0.014)$ | | |

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-

| | | $R_p$ | $R_n$ | $\delta R$ |
|---|---|---|---|---|
| $^{48}$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)

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

H. Kurasawa, T. S. and T. Suzuki,
Prog. Theor. Exp. Phys. 2021, 013D02

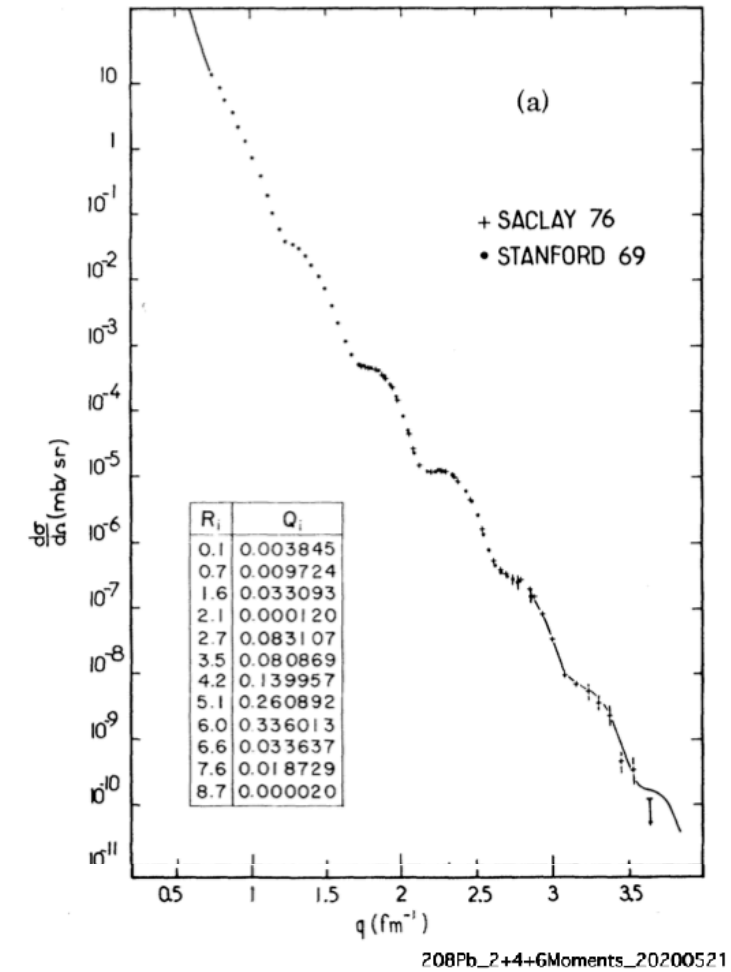
# ways to access the fourth moment, $<r_c^4>$

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

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

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

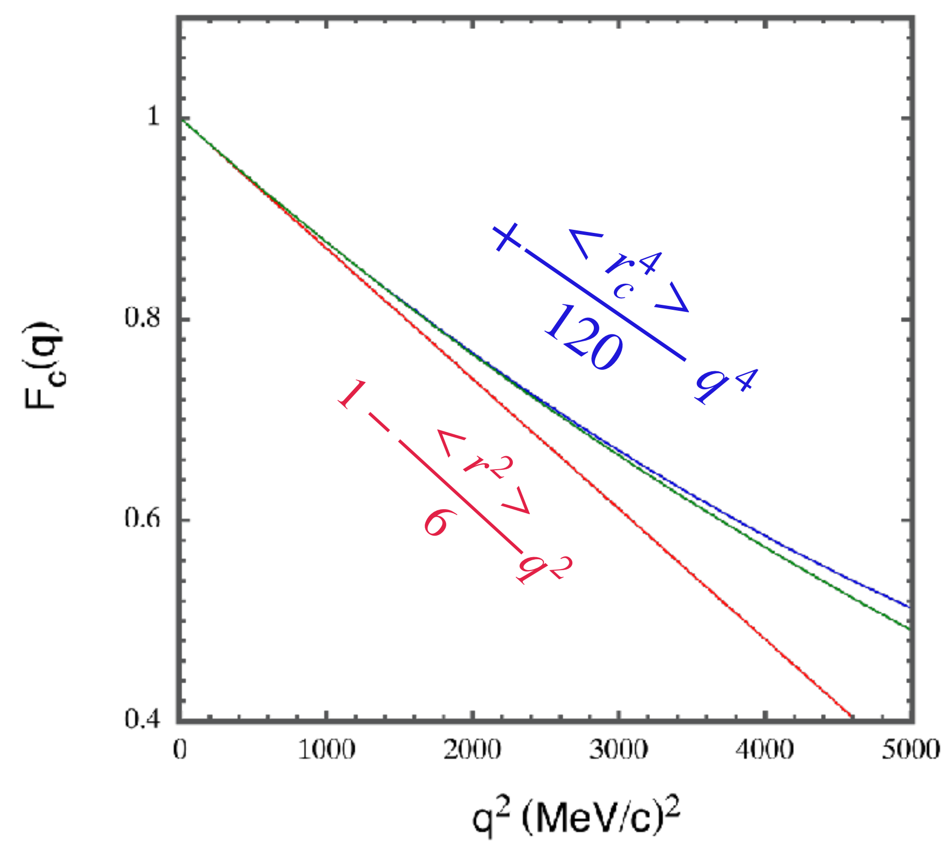
$$F_c(q) = \int \rho_c(\vec{r}) e^{i\vec{q}\vec{r}} d\vec{r}$$




## 2) elastic scattering at very low *q*

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

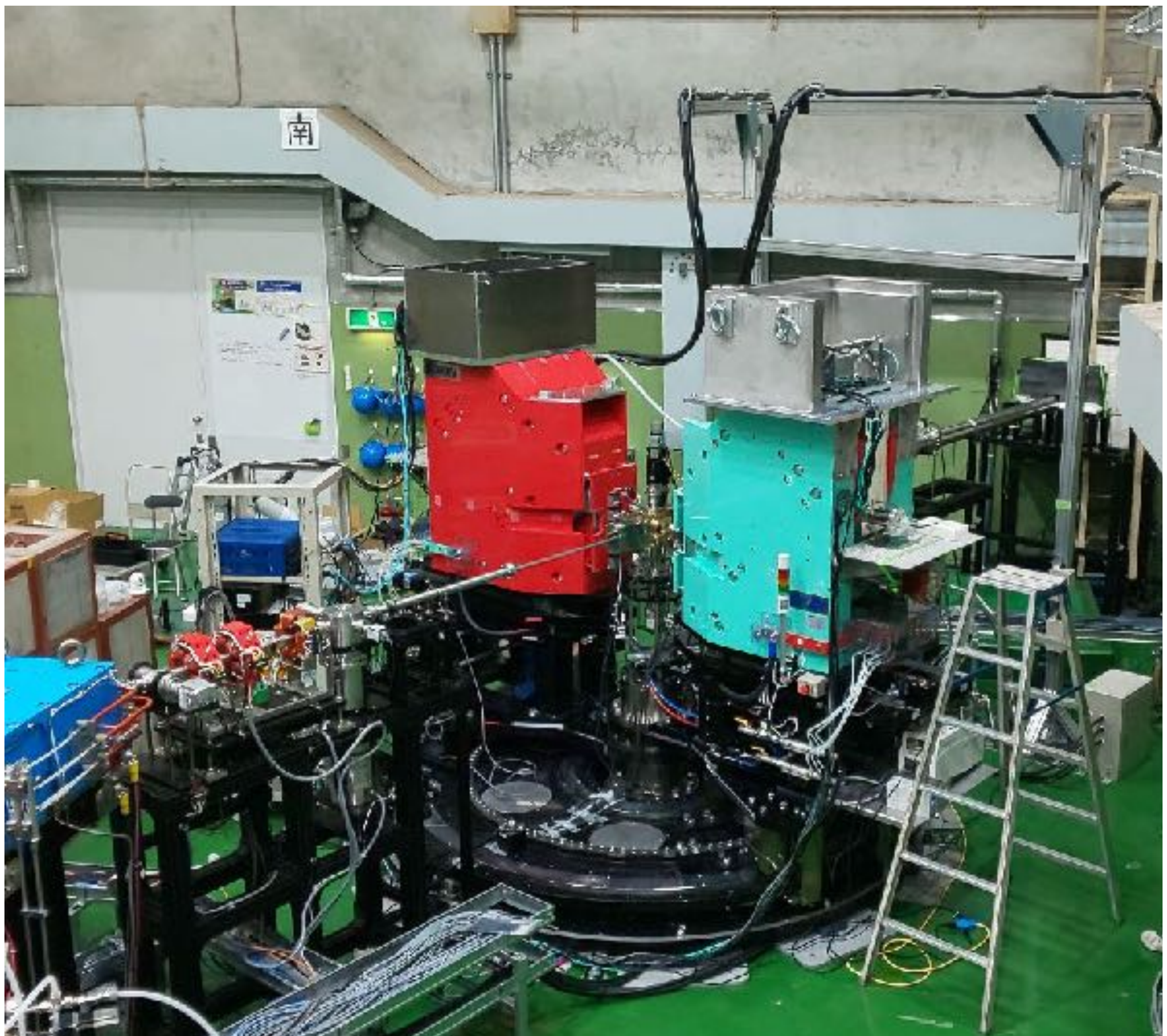
$$\frac{\mathrm{d}\sigma_{\mathrm{Mott}}}{\mathrm{d}\Omega} \propto 1/q^4$$

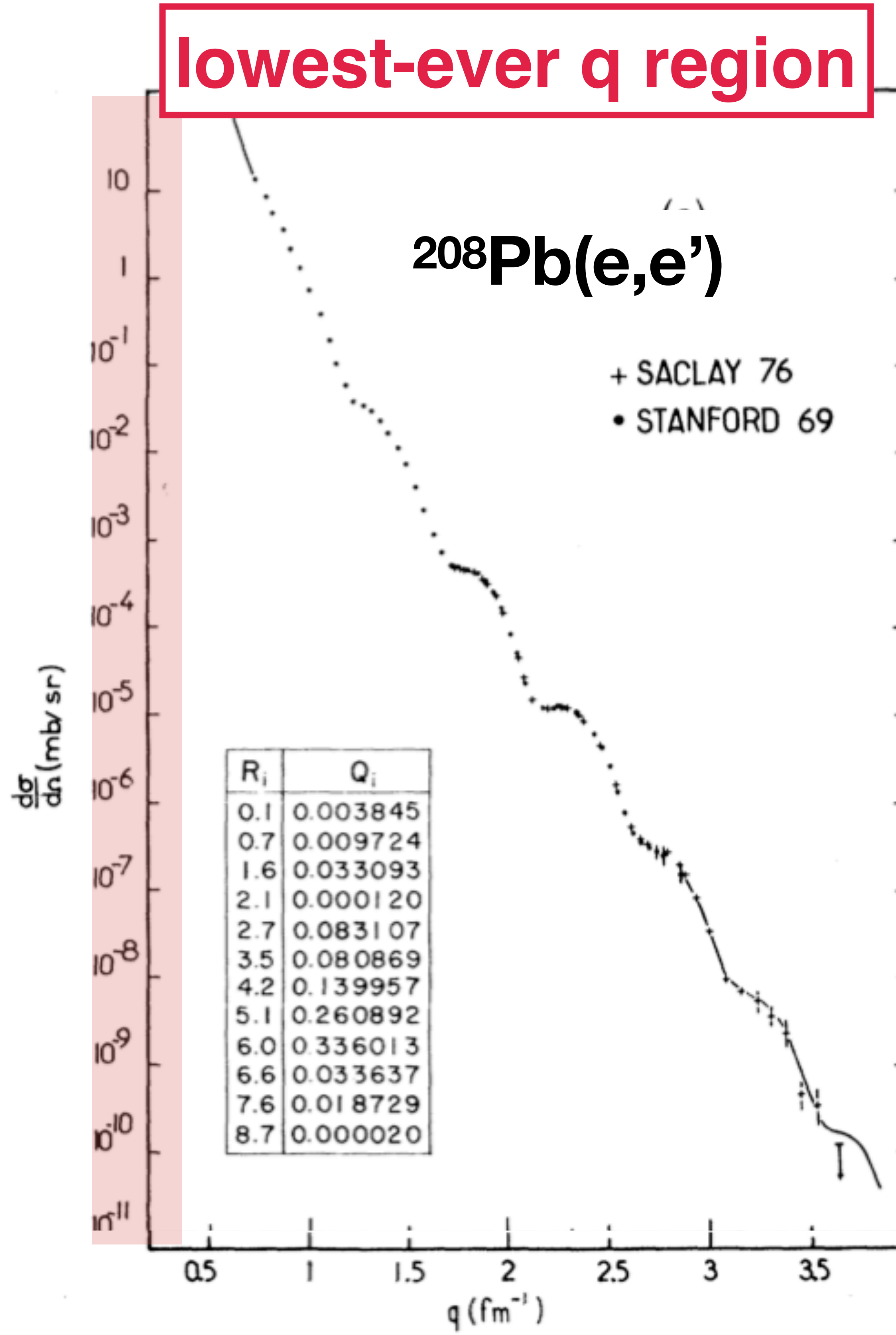



**=> low-L SCRIT exp. !!**

- $^{208}$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 |

# conclusions



- The SCRIT facility started its operation
  - the world's first and currently only-one facility
  - e-scattering for short-lived nuclei becomes now possible
  - ISOL upgrade to 2kW is underway

- Low-energy e-scattering activities in Japan
  - ULQ2 : 1) e+p, e+D scattering
    2) $^{208}$Pb(e,e')  under lowest-ever *q* region
  - SCRIT : charge densities of short-lived exotic nuclei
    neutron-distribution radius through $\langle r_c^4 \rangle$ ??

# LEES2024 at Sendai in October



**Low-Energy Electron Scattering for Nucleon and Exotic Nuclei (LEES2024)**

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

https://indico.lns.tohoku.ac.jp/e/LEES2024

late October is
the best season for tourism!!