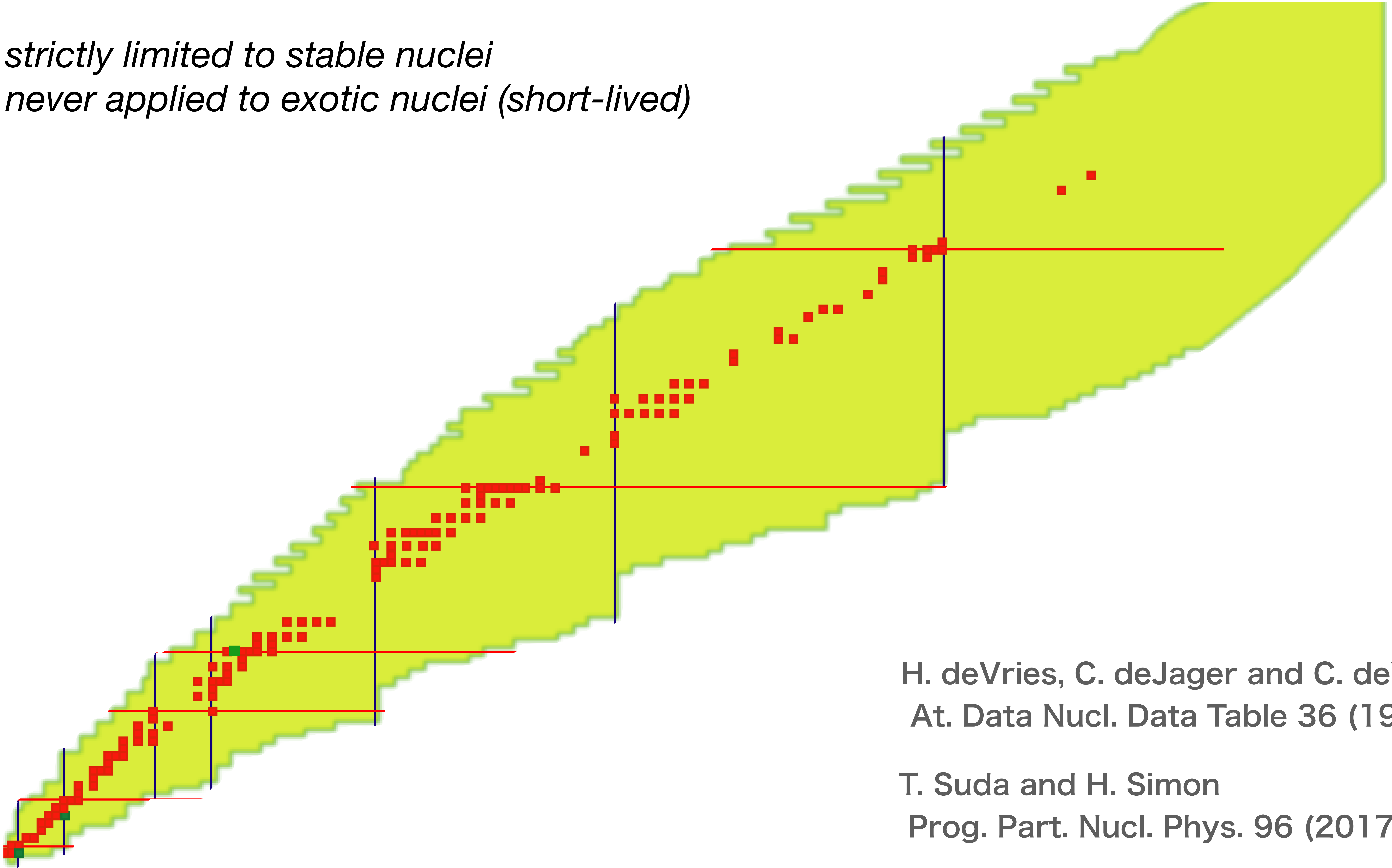
# The SCRIT Electron-Scattering Facility for Short-Lived Exotic Nuclei

Toshimi Suda (RARiS, Tohoku Univ.)
suda@lns.tohoku.ac.jp

for SCRIT collaboration

# Nuclei studied by electron scattering

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



H. deVries, C. deJager and C. deVries
At. Data Nucl. Data Table 36 (1987) 495.

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

# world’s first e-scattering from an 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**

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*

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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 $0.9 \times 10^{26}$ 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 ... harge density distribution
tigated world ... ture determined by elastic

K. Tsukada et al.,
*Phys. Rev. Lett. 131 (2023) 092502.*

# world's first e-scattering from an online-produced radioactive isotope

PHYSICAL REVIEW L

Editors' Suggestion | Featured in Physics

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Short-lived
tigated world

K. Tsukada et al.,
*Phys. Rev. Lett.* 131

# 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.

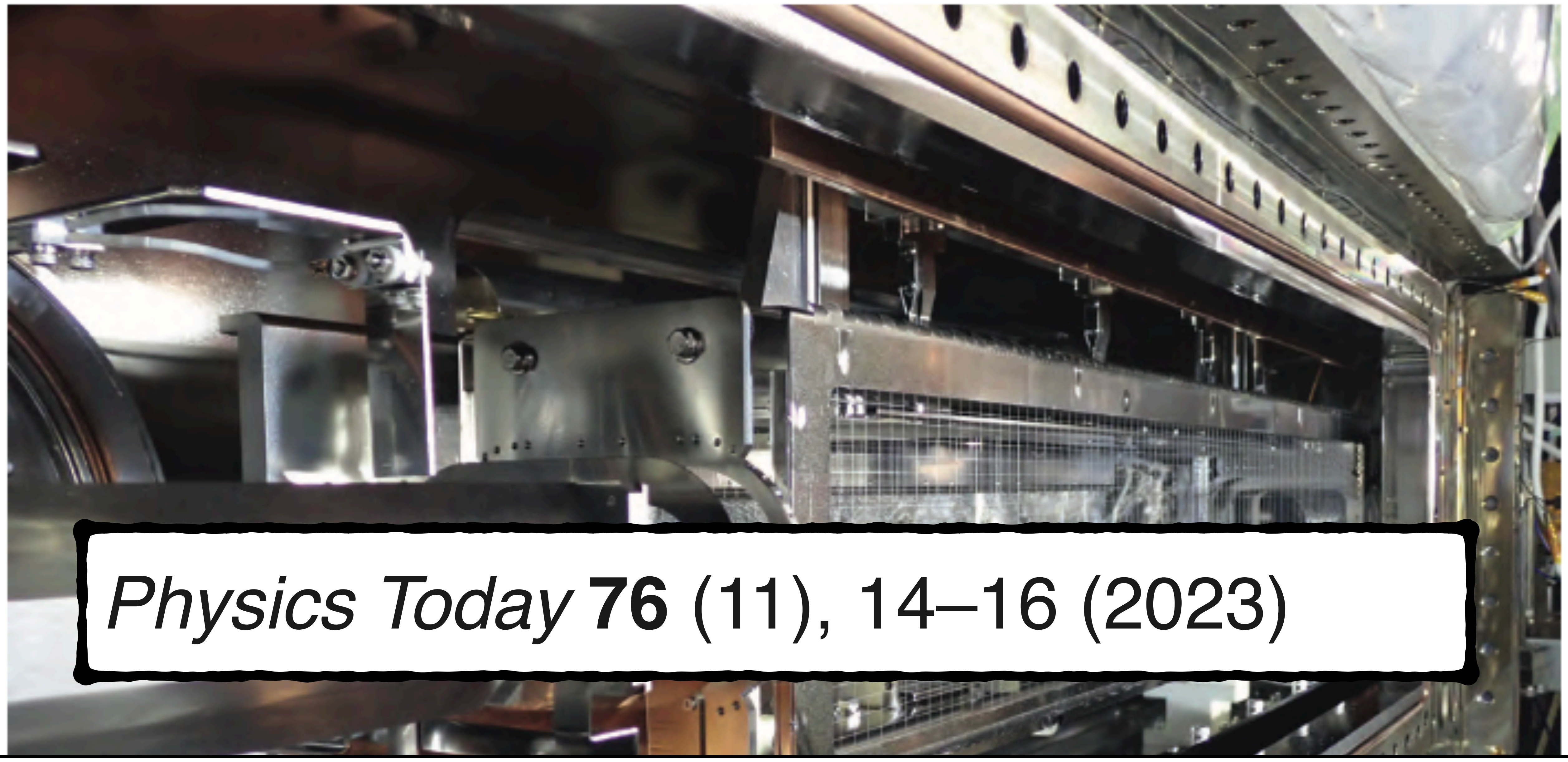
That's not generally what real nuclei look like. Neutron-rich lead-208, for example, has a thick skin of neutrons encasing its proton-endowed core (see Physics Today, July 2021, page 12). Some nuclei are flattened, and some are elongated. Some are even pear shaped.

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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PHYSICAL REVIEW L

Editors' Suggestion | Featured in Physics

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*Phys. Rev. Lett.* *131*

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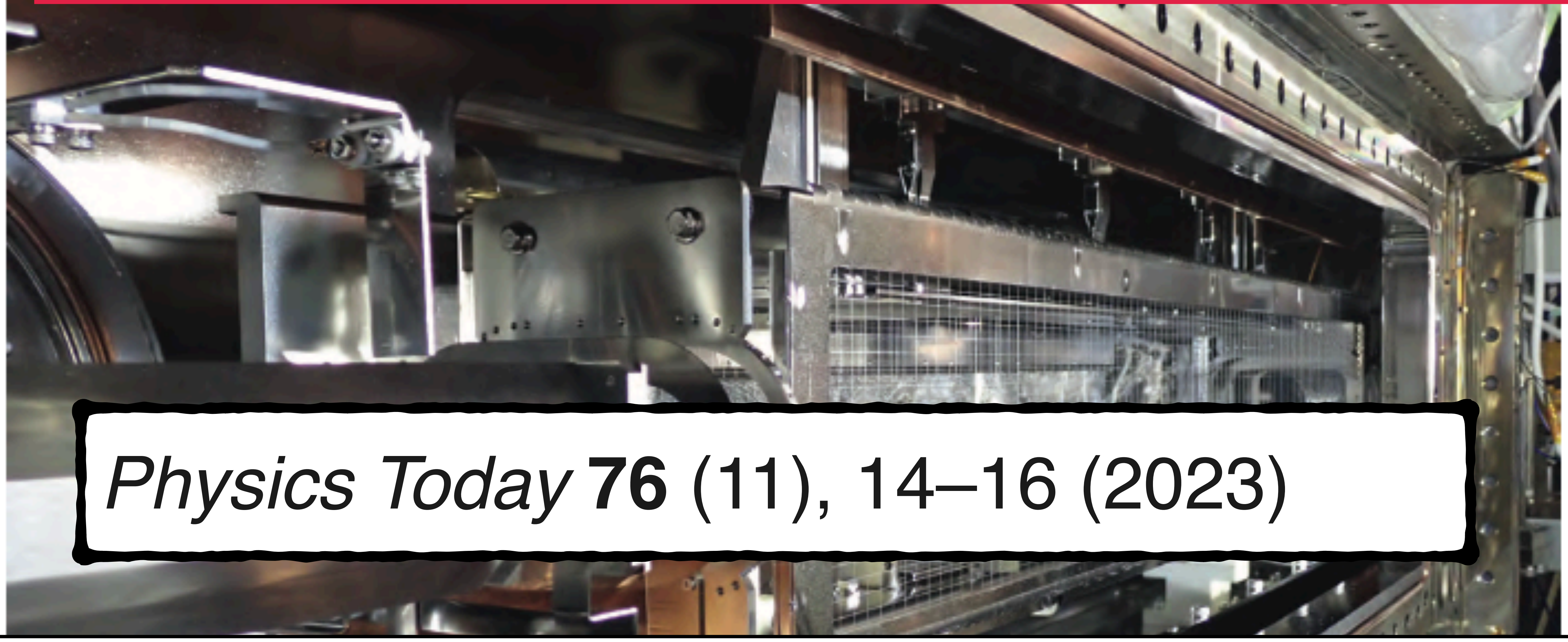


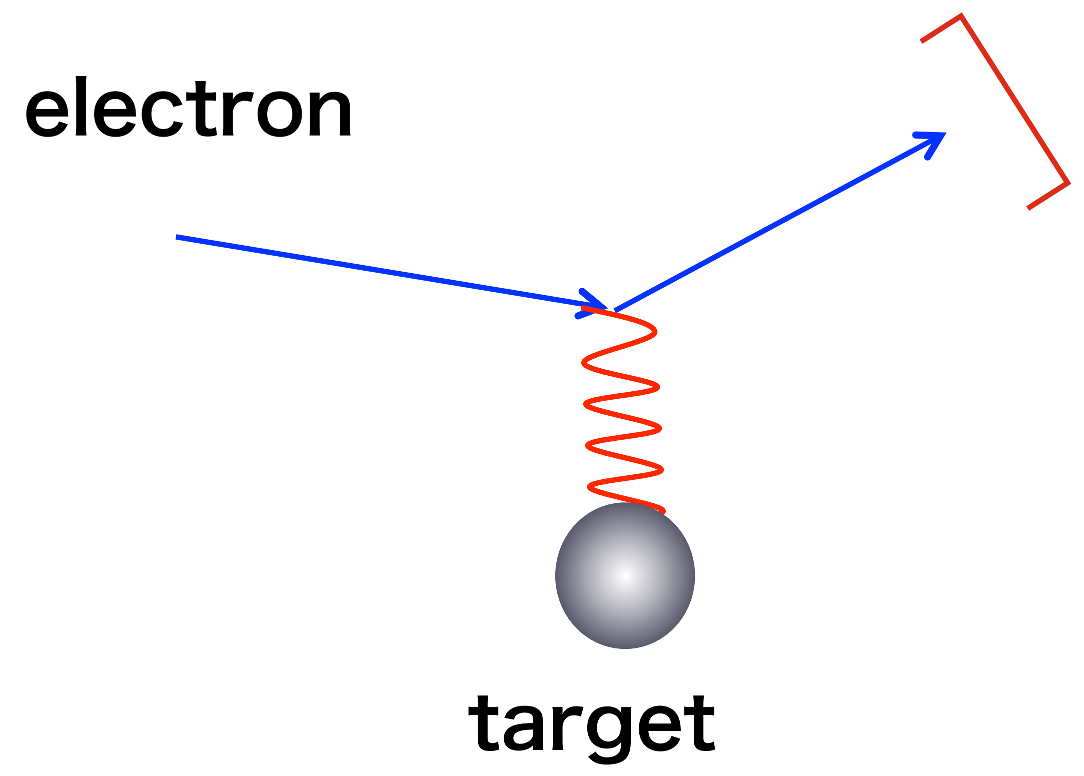
*Physics Today* **76** (11), 14–16 (2023)

# Electron Scattering

# Electron scattering for nuclear physics

## a unique and powerful probe for structure studies

1. elementary particle - structureless -
2. electro-weak interaction - best understood -
3. “relatively” weak - probing deep inside of the target -
4. variable q (mom. transfer) for fixed ω (energy transfer)



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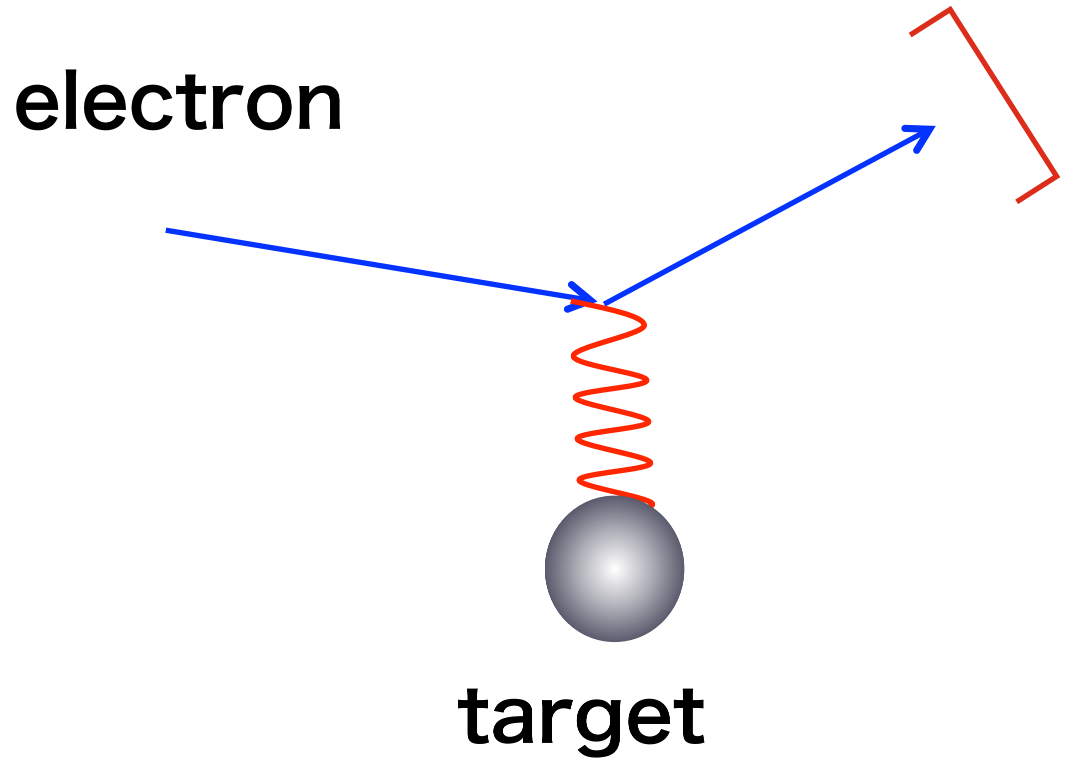
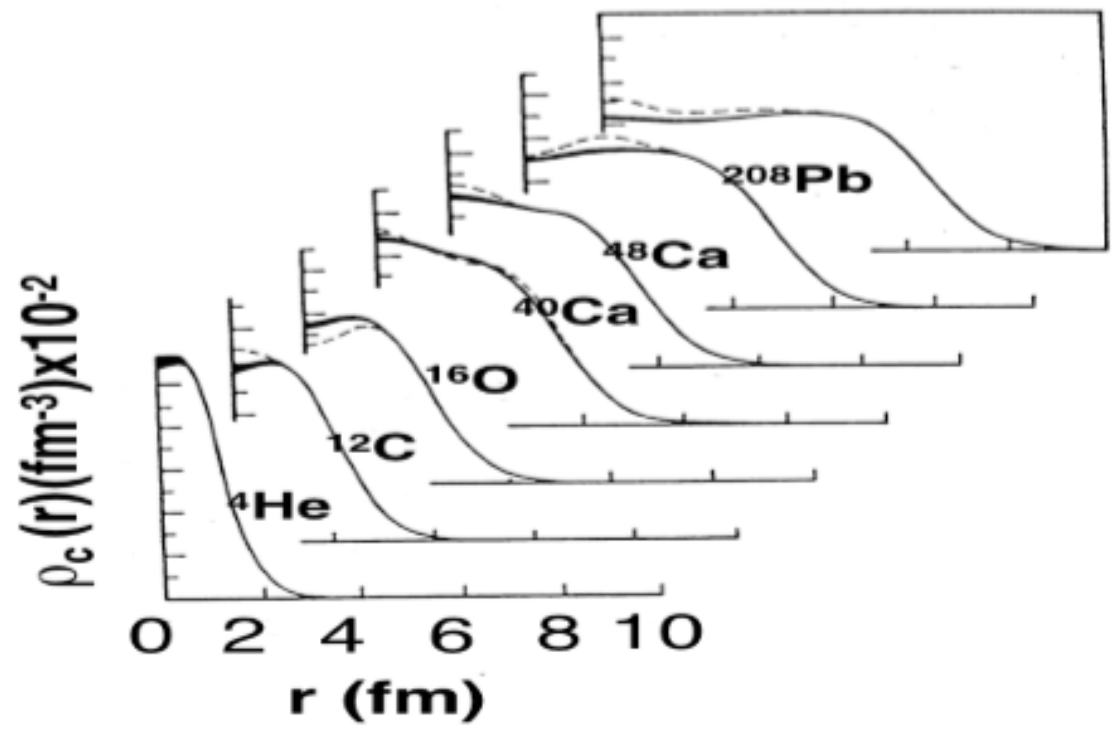
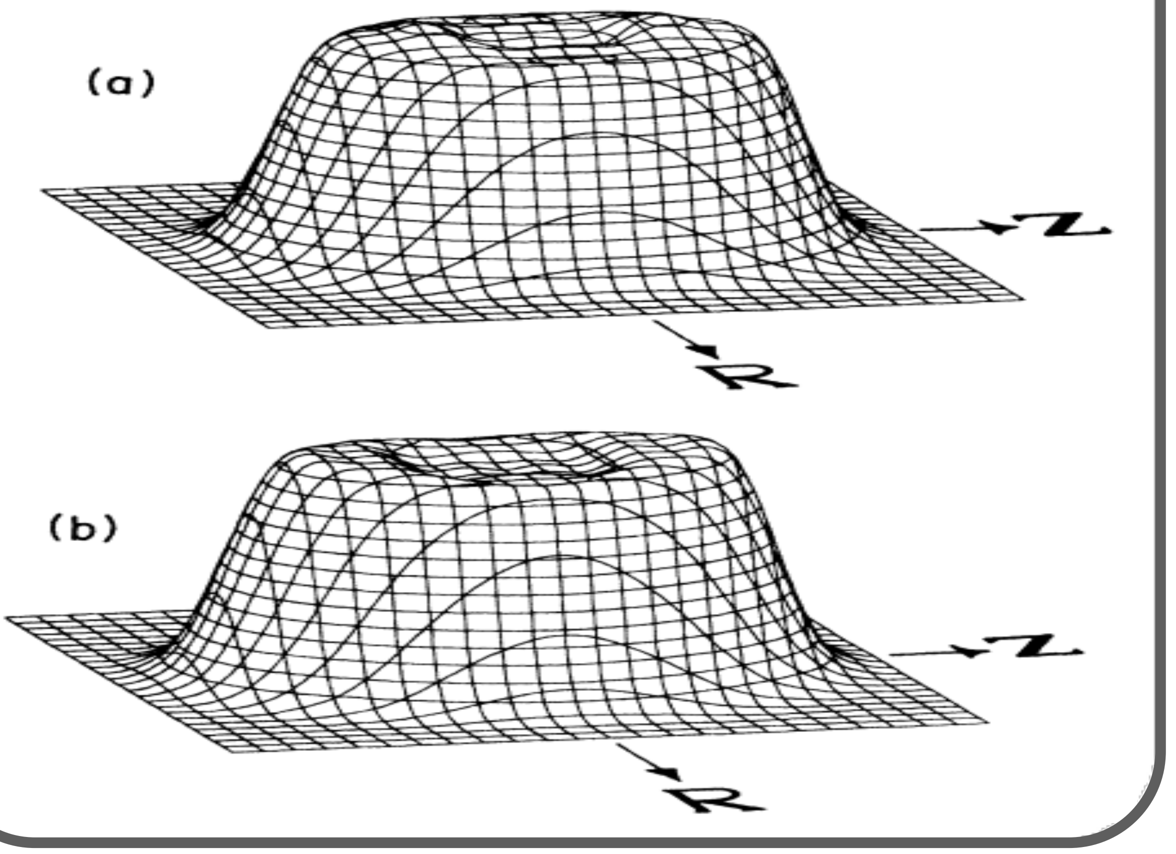


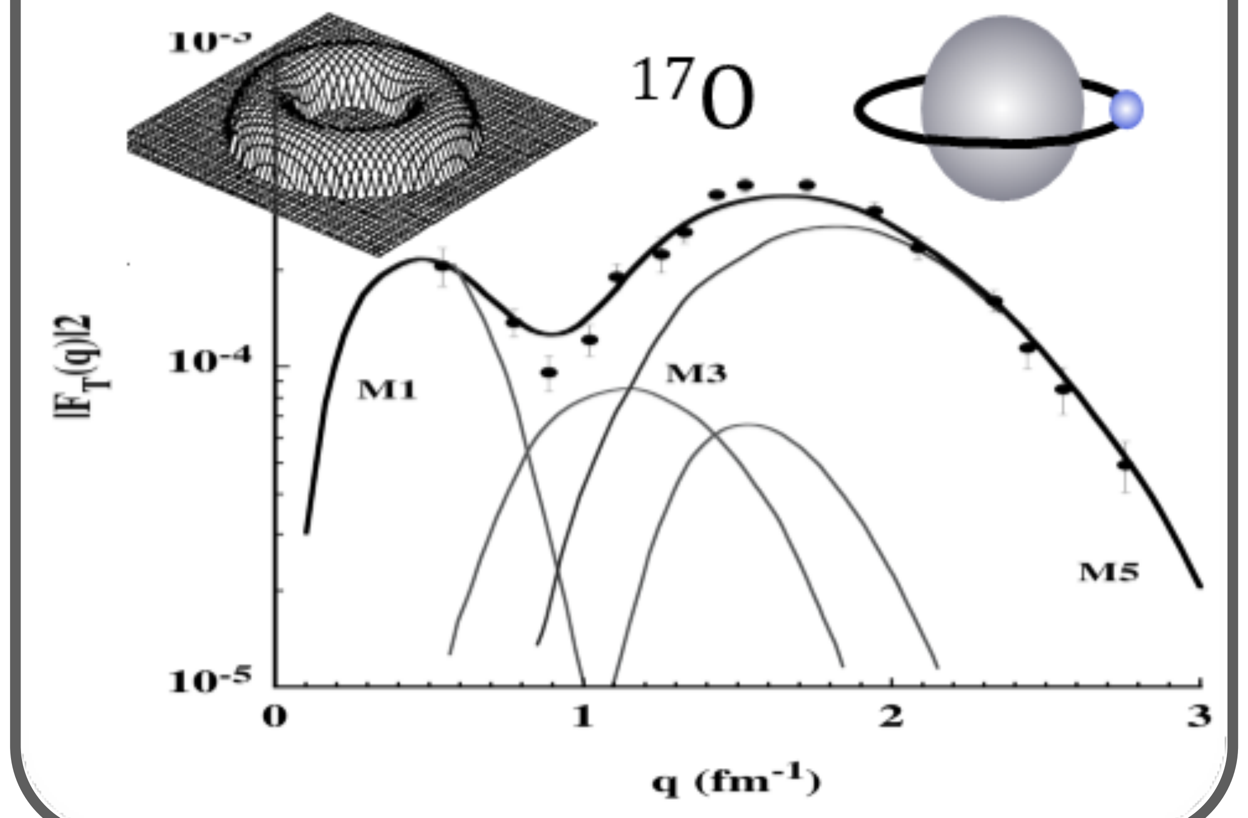

elastic scattering
→ charge distribution



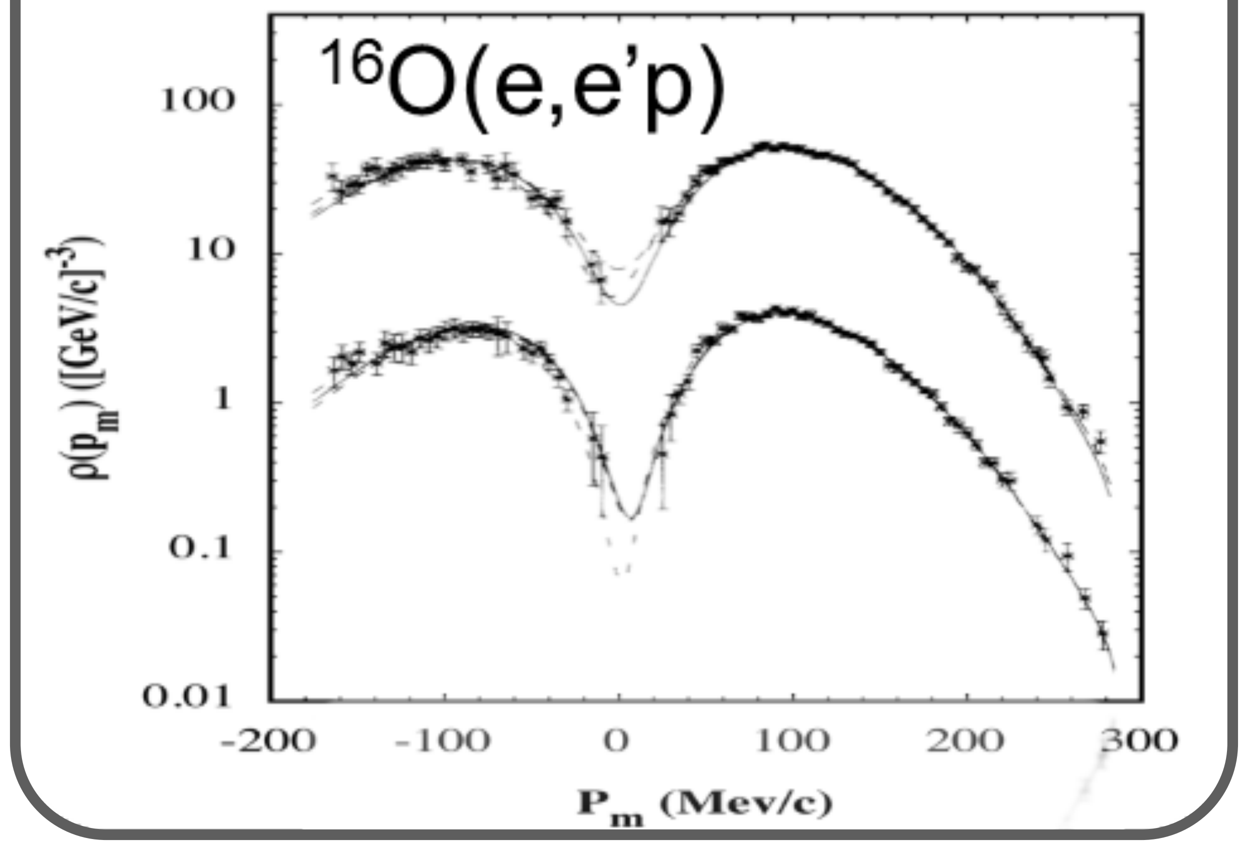

elastic + inelasticscattering
→ deformation




magnetic scattering
→valence neutron




quasi-elastic (e,e’p)
→ S-factor



# Elastic electron scattering and charge density distribution

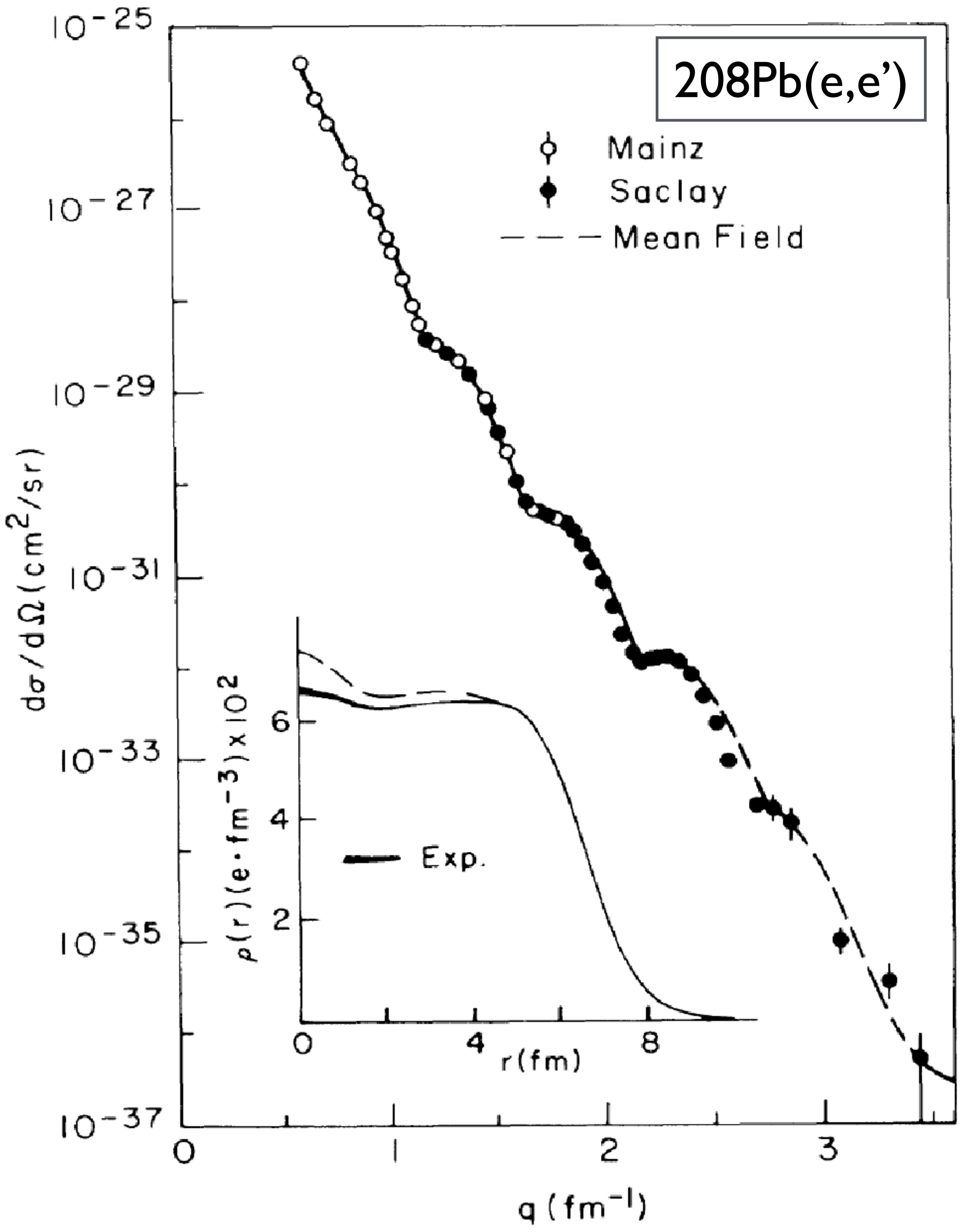
Elastic scattering
for (spin-less) nuclei

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

$$F_c(q) = \int \rho_c(r) e^{iqr} \, d^3r$$

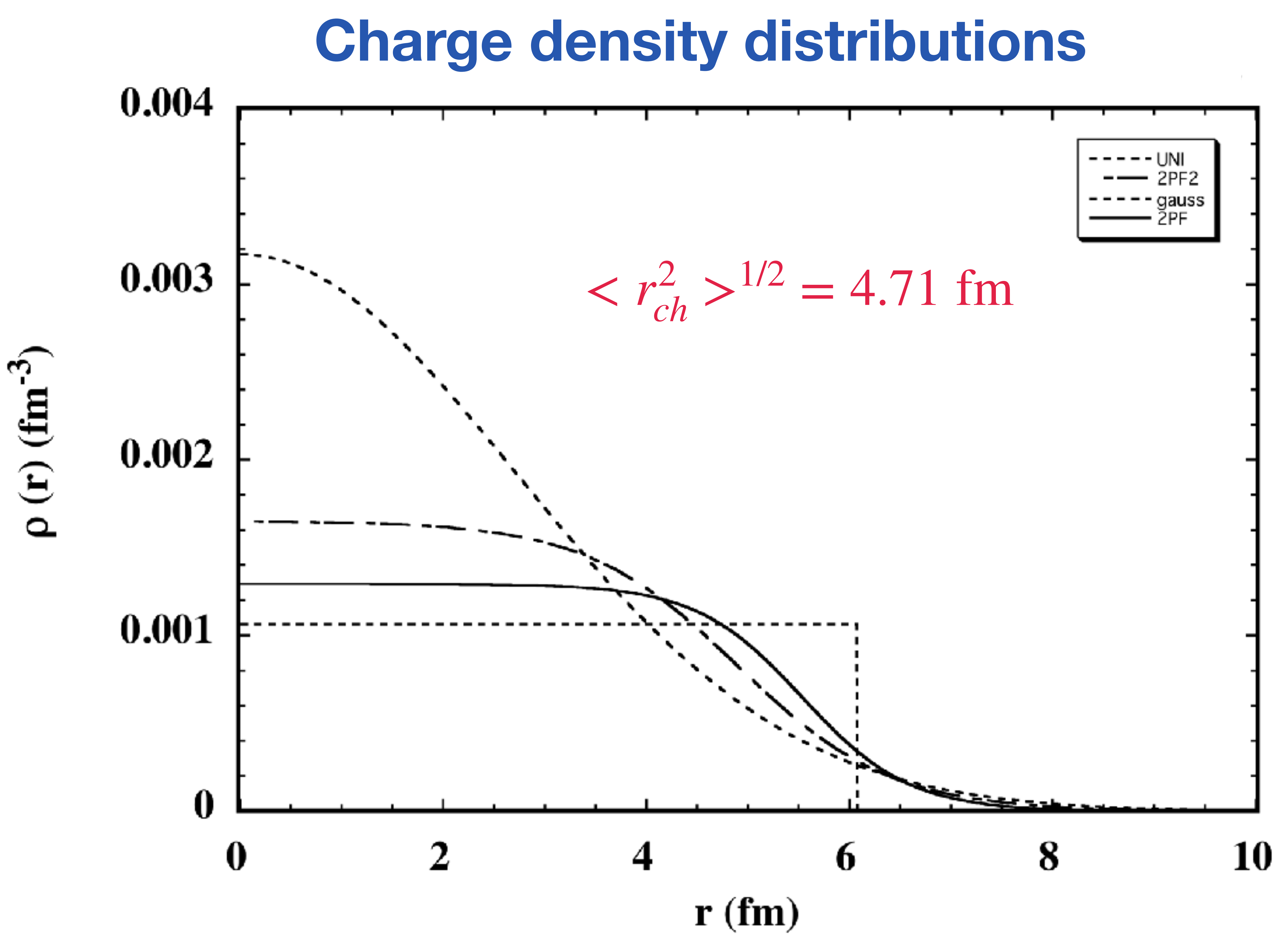
charge distribution

$$\frac{d\sigma_{Mott}}{d\Omega} \propto e^2/q^4$$



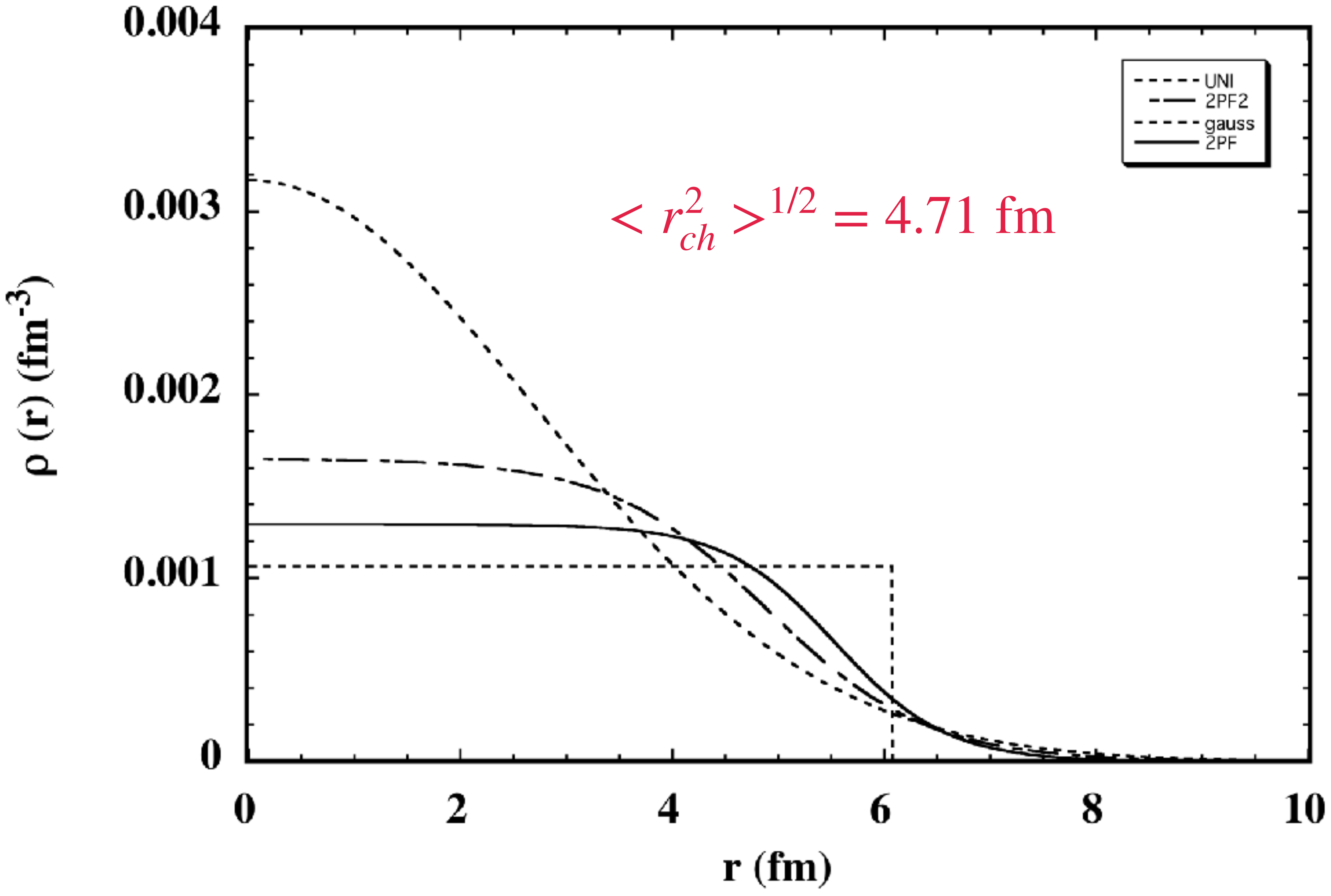

J. M. Cavedon et al. PRL 58 (1987) 195

# Beyond charge radii (isotope shifts)

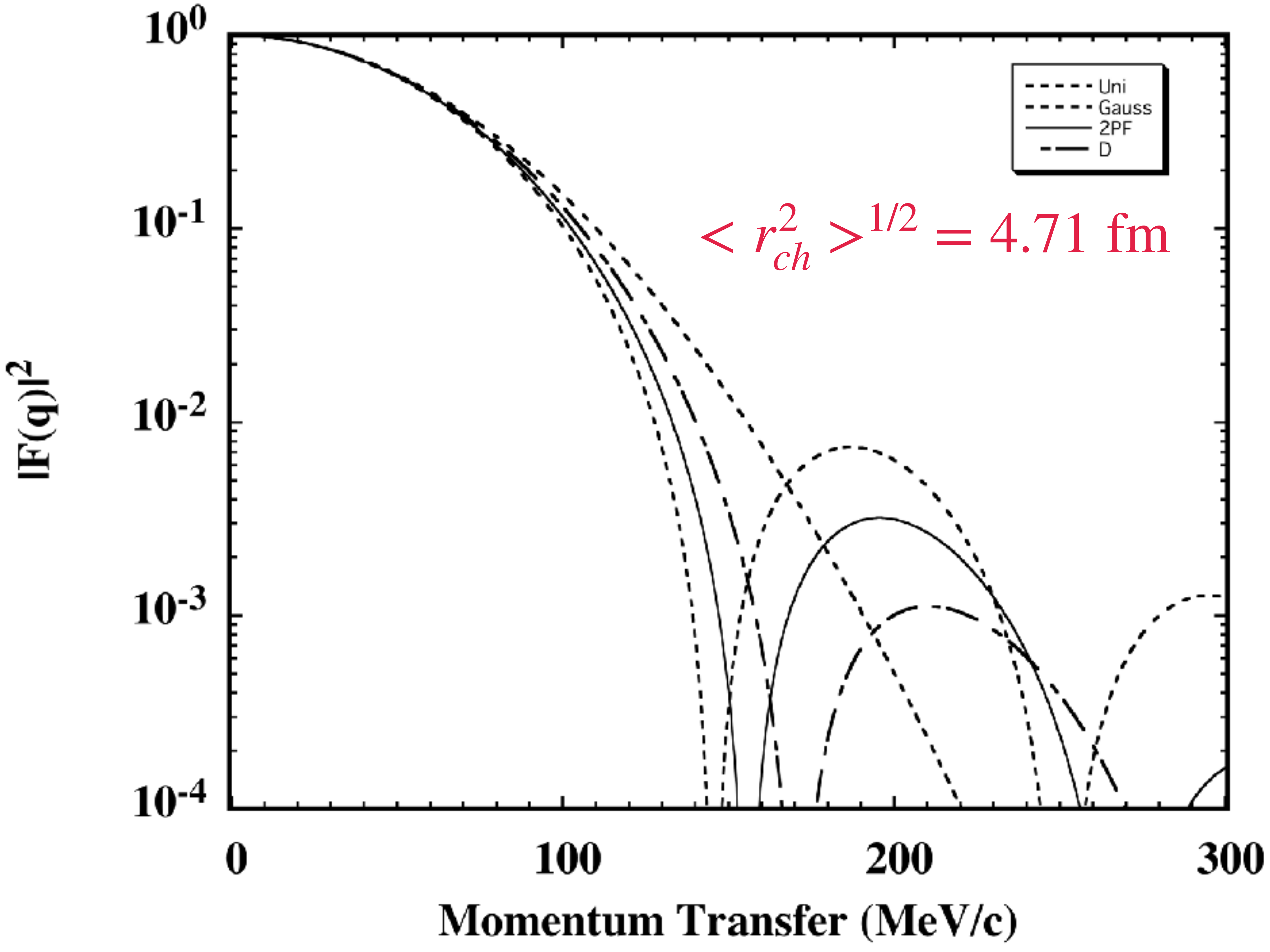


# Beyond charge radii (isotope shifts)

## Charge density distributions




## Charge form factors



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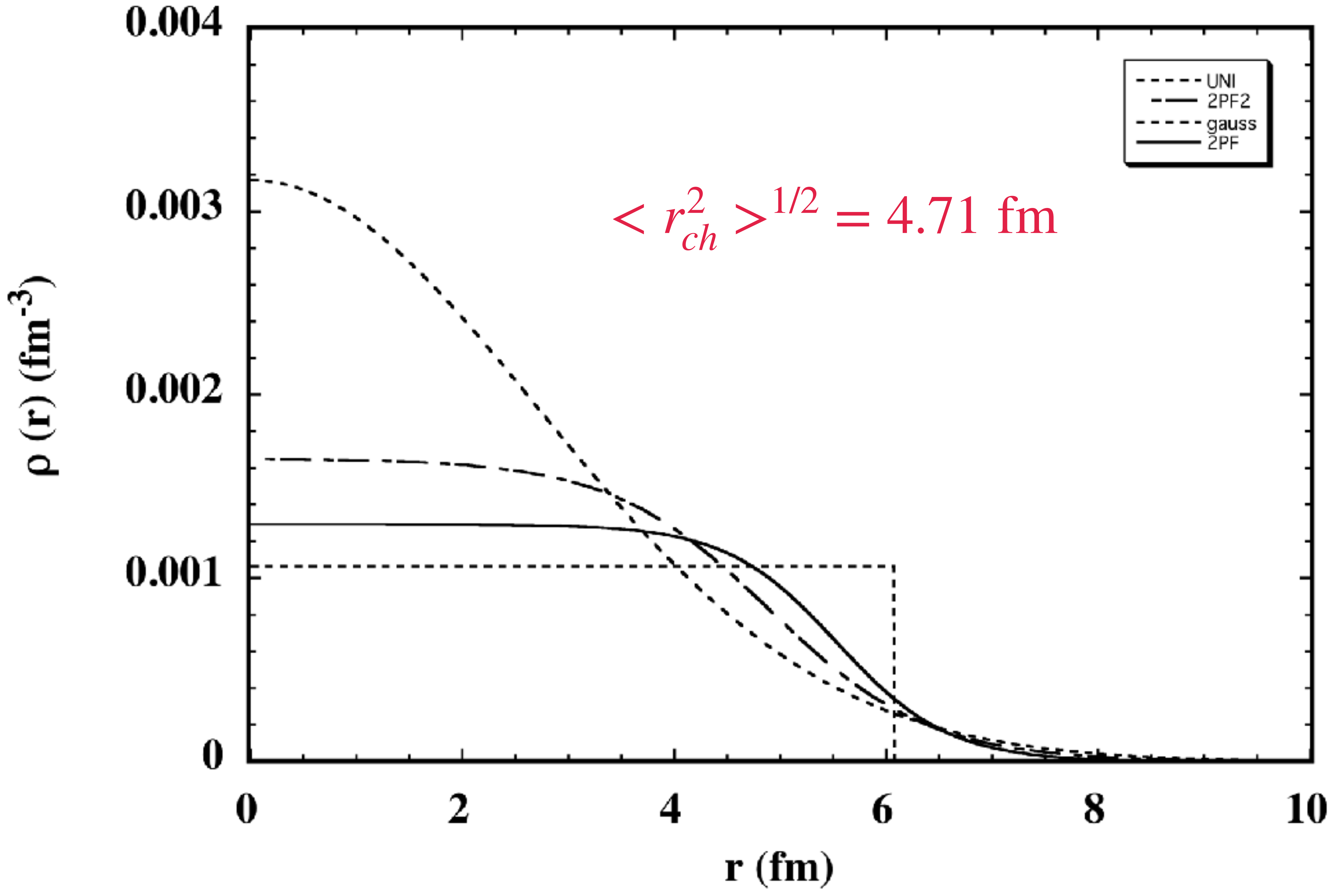


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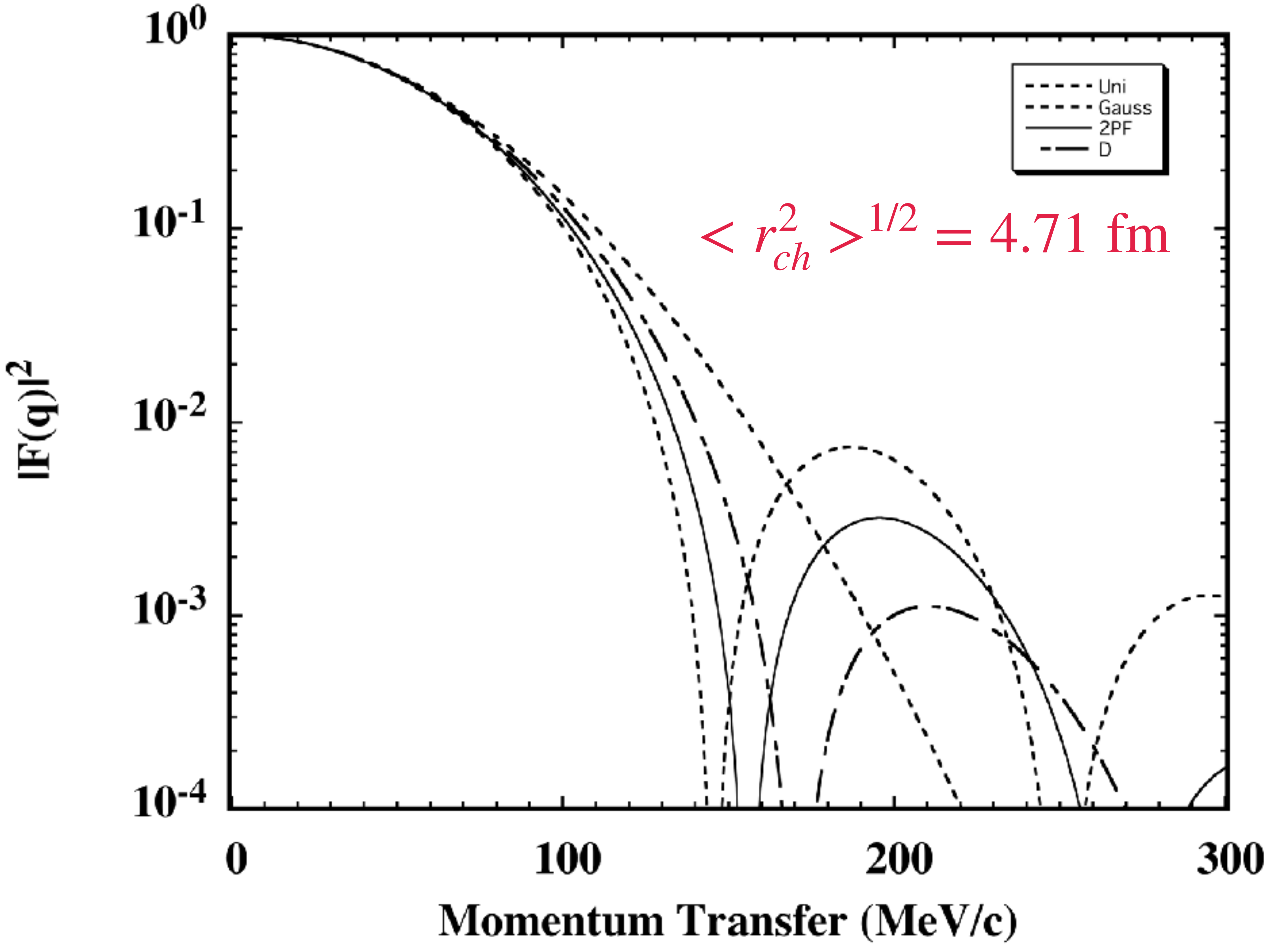


**Electron scattering reveals both size and shape**

## Key parameter for e-scattering of exotic nuclei

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

Luminosity

## Elastic Scattering for Exotic Nuclei

(for medium-heavy nuclei)

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

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

# Minimum Required Luminosity

## Elastic Scattering for Exotic Nuclei

(for medium-heavy nuclei)

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

**How to realize this *L* with small number of exotic nuclei?**

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

# The idea of “SCRIT” originated in 2004

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

Available online at www.sciencedirect.com

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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]

[a] *Cyclotron center, RIKEN, Wako-shi, Saitama 351-0198, Japan*

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

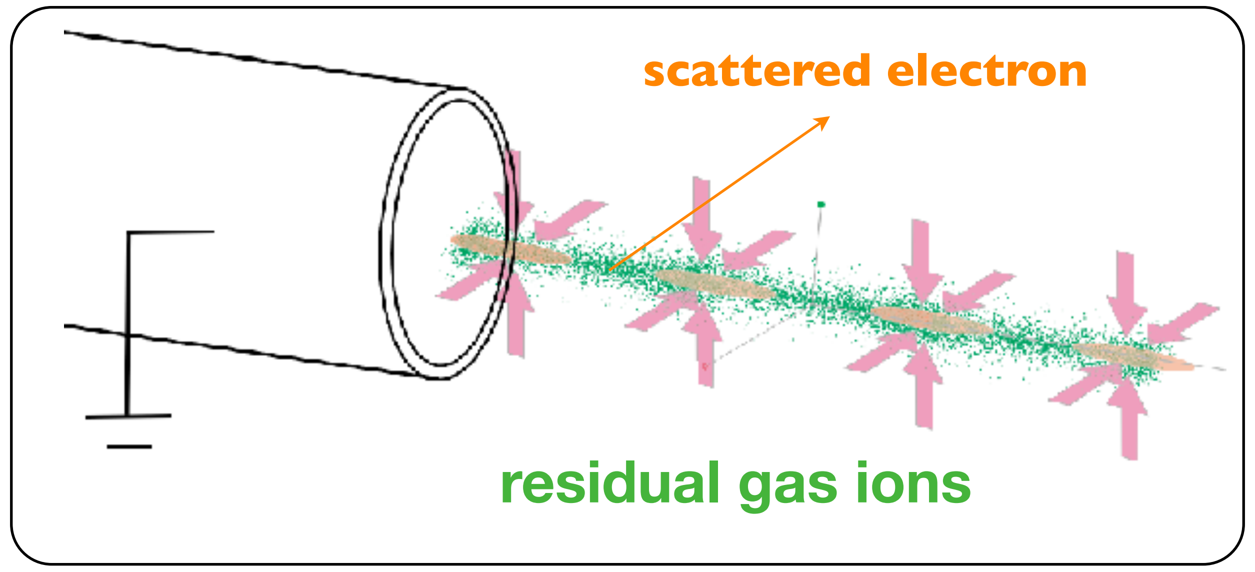
Available online 3 August 2004

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

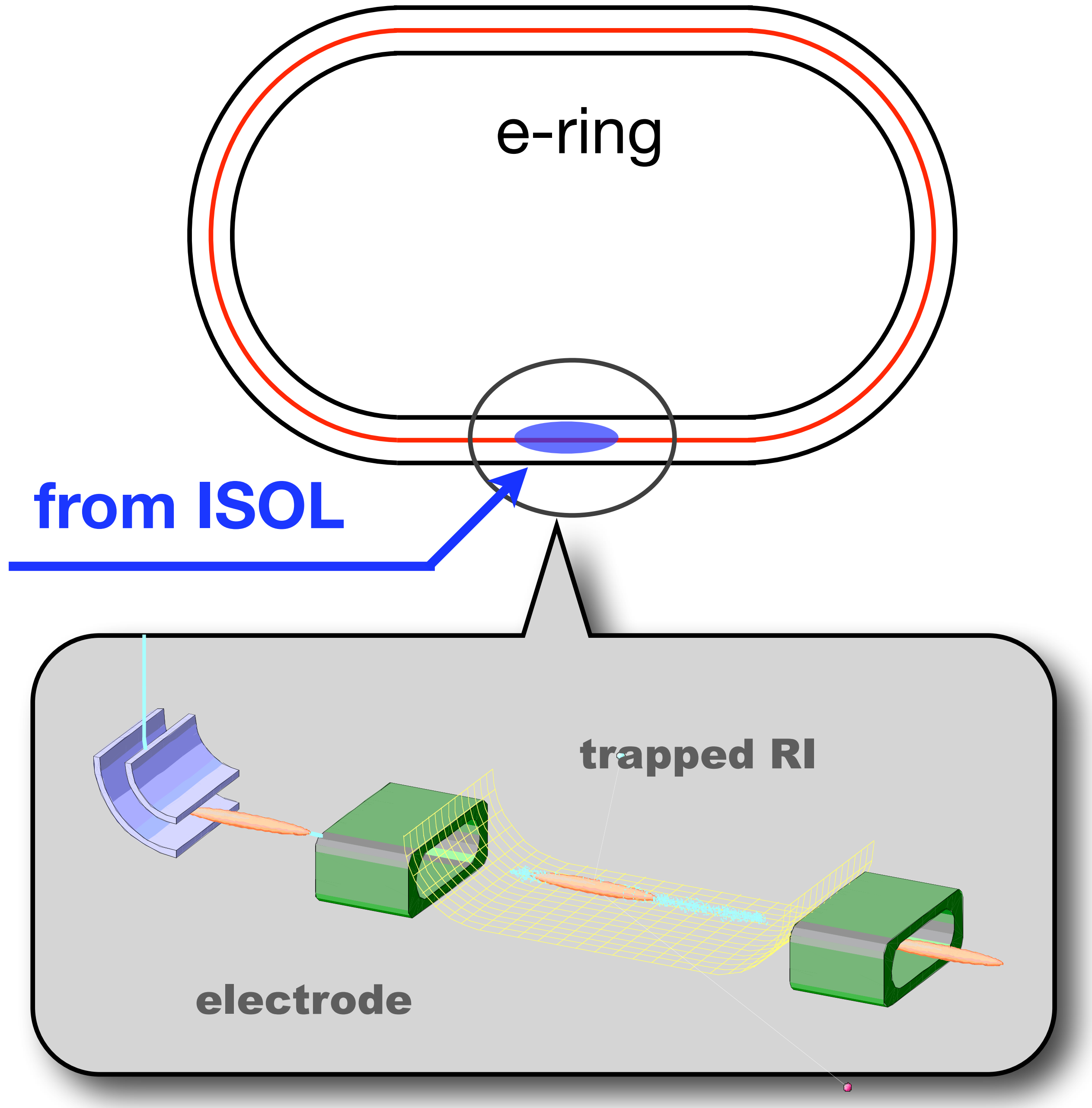
# SCRIT (Self-Confining RI Ion Target)

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

ionized residual gases are trapped
by the circulating electron beam




*ill problem of e-storage rings*



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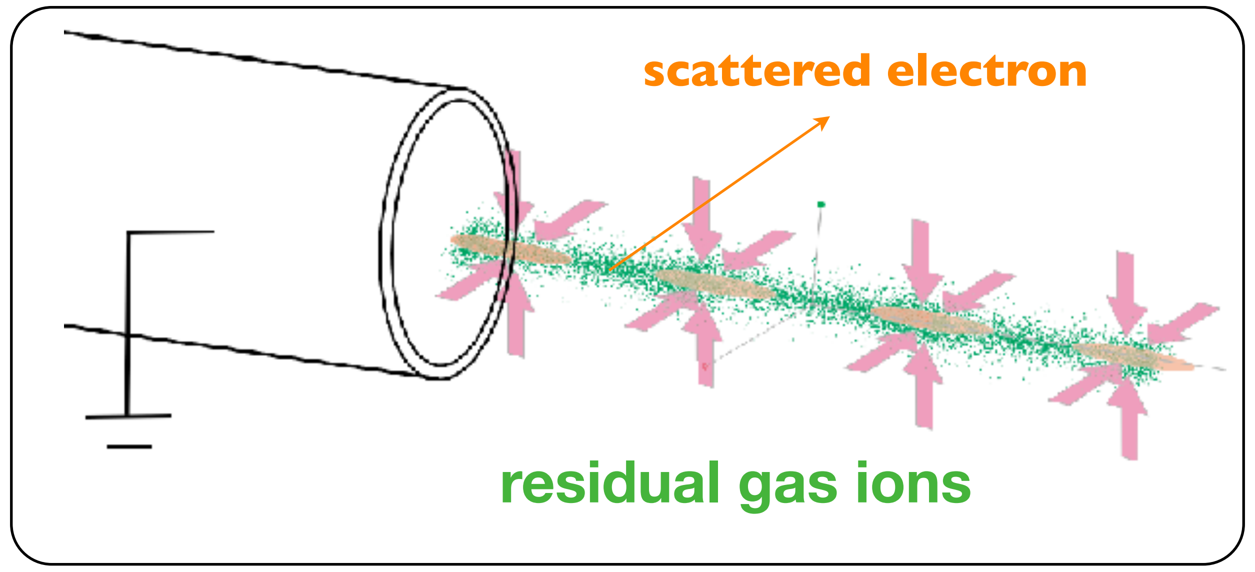


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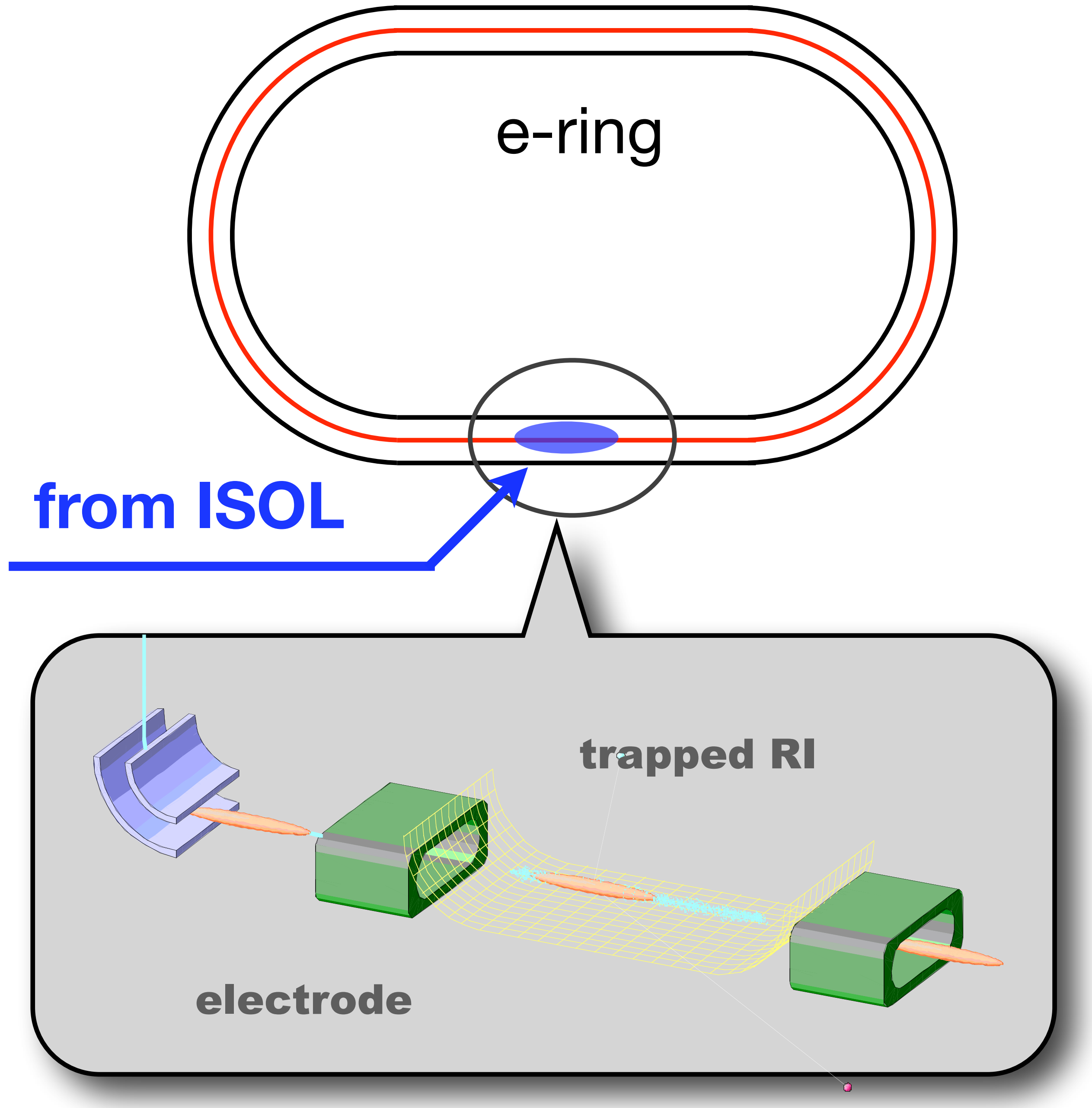
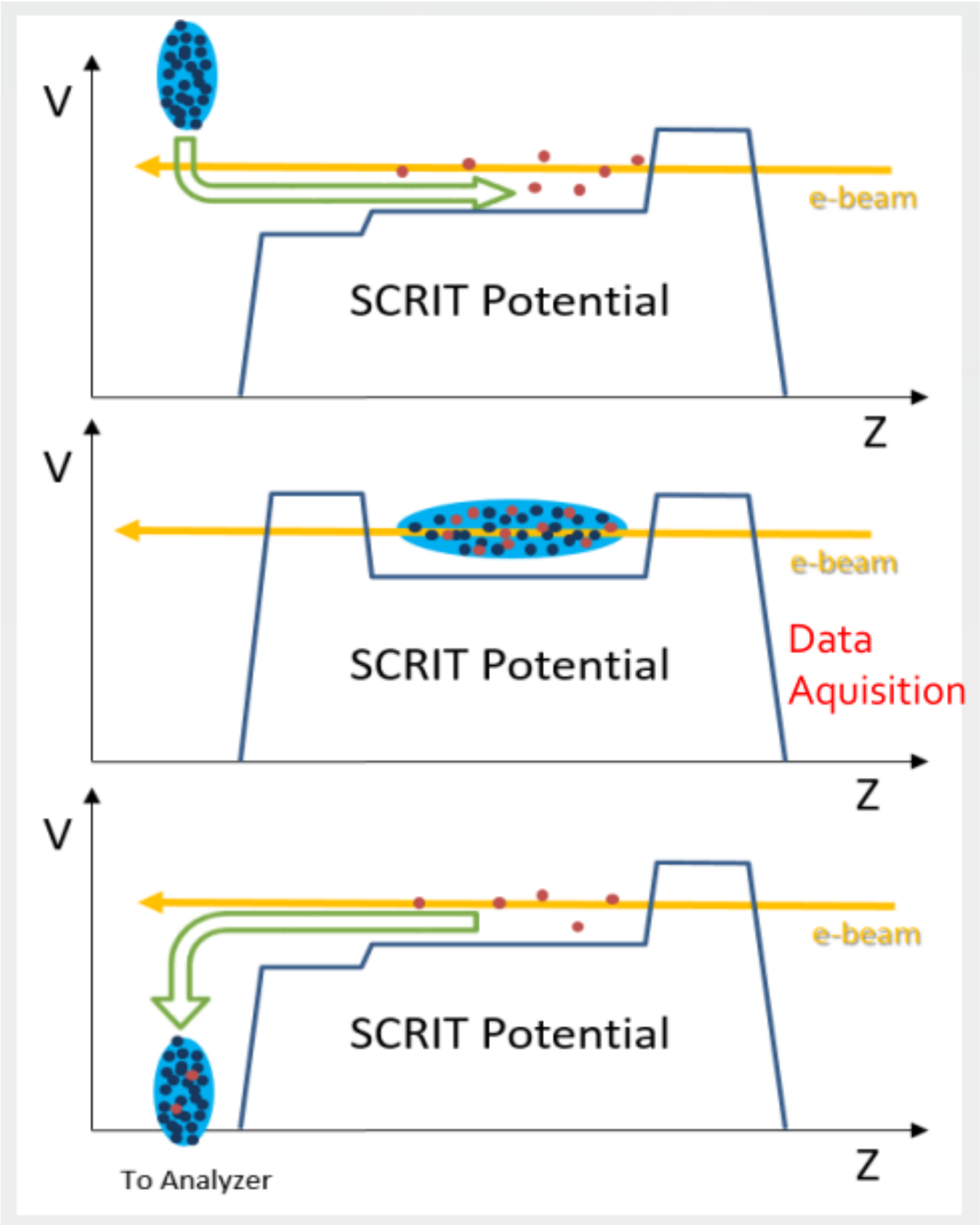
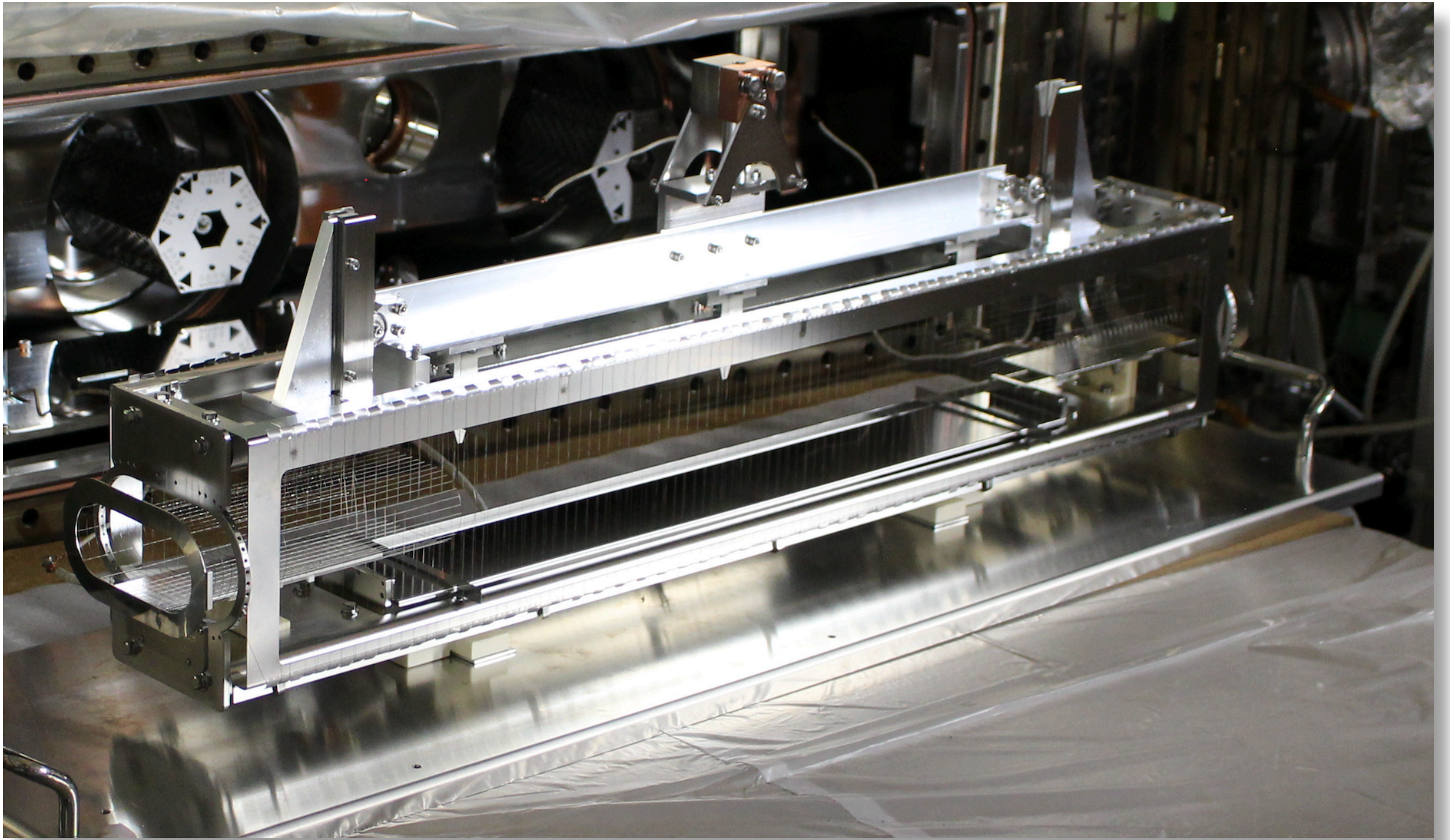


# SCRIT device for preparing a target on e-beam



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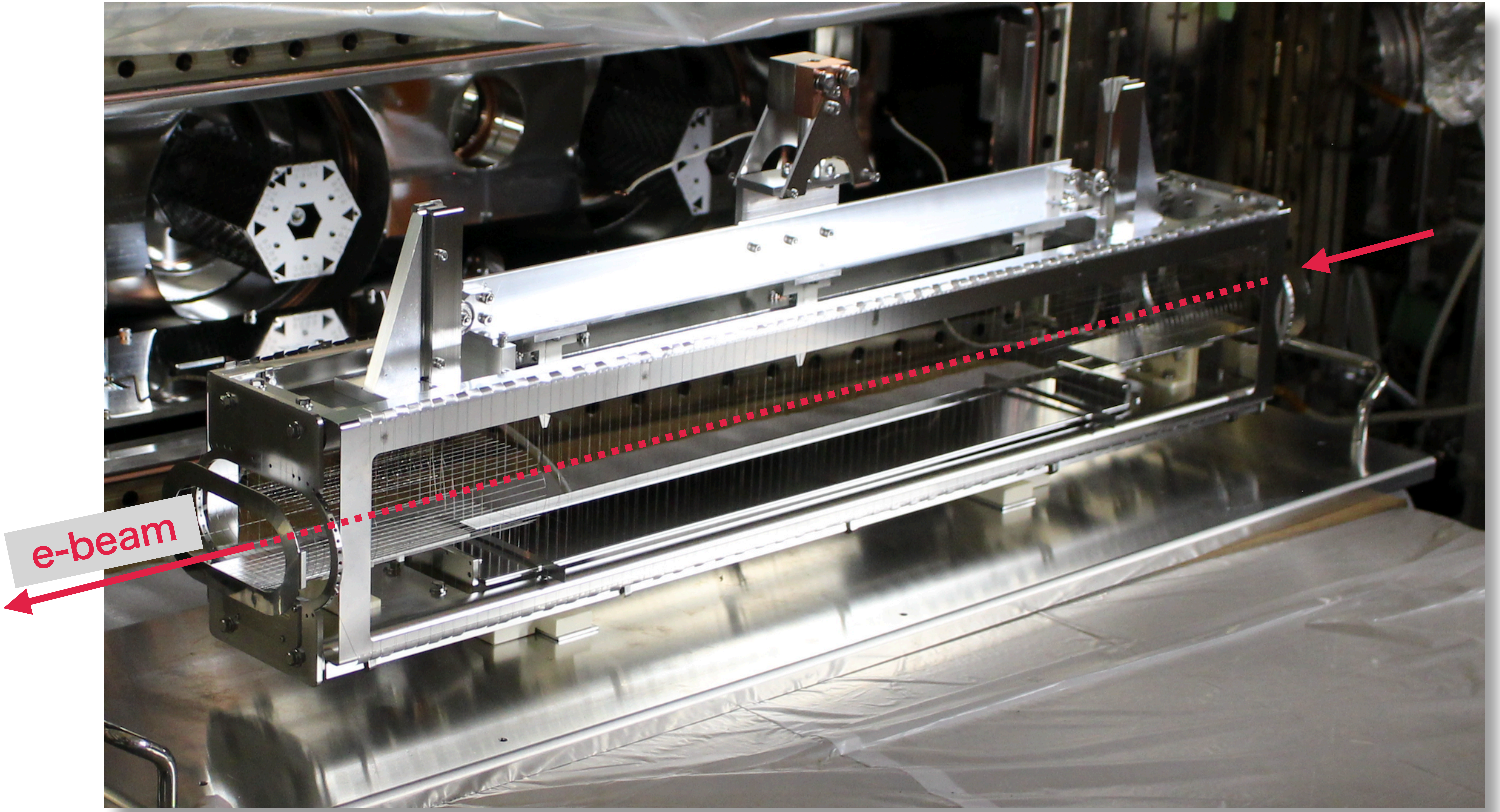

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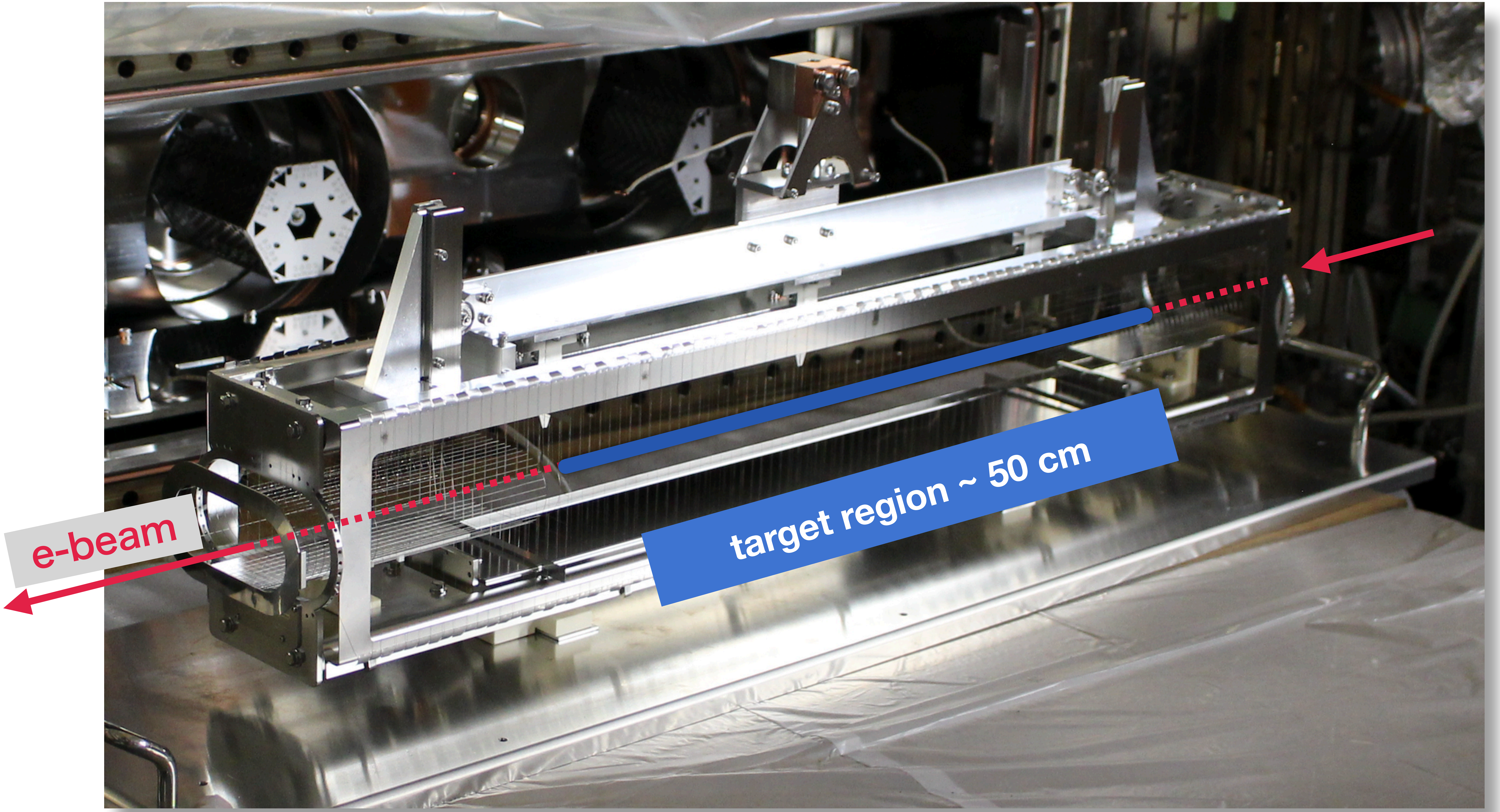

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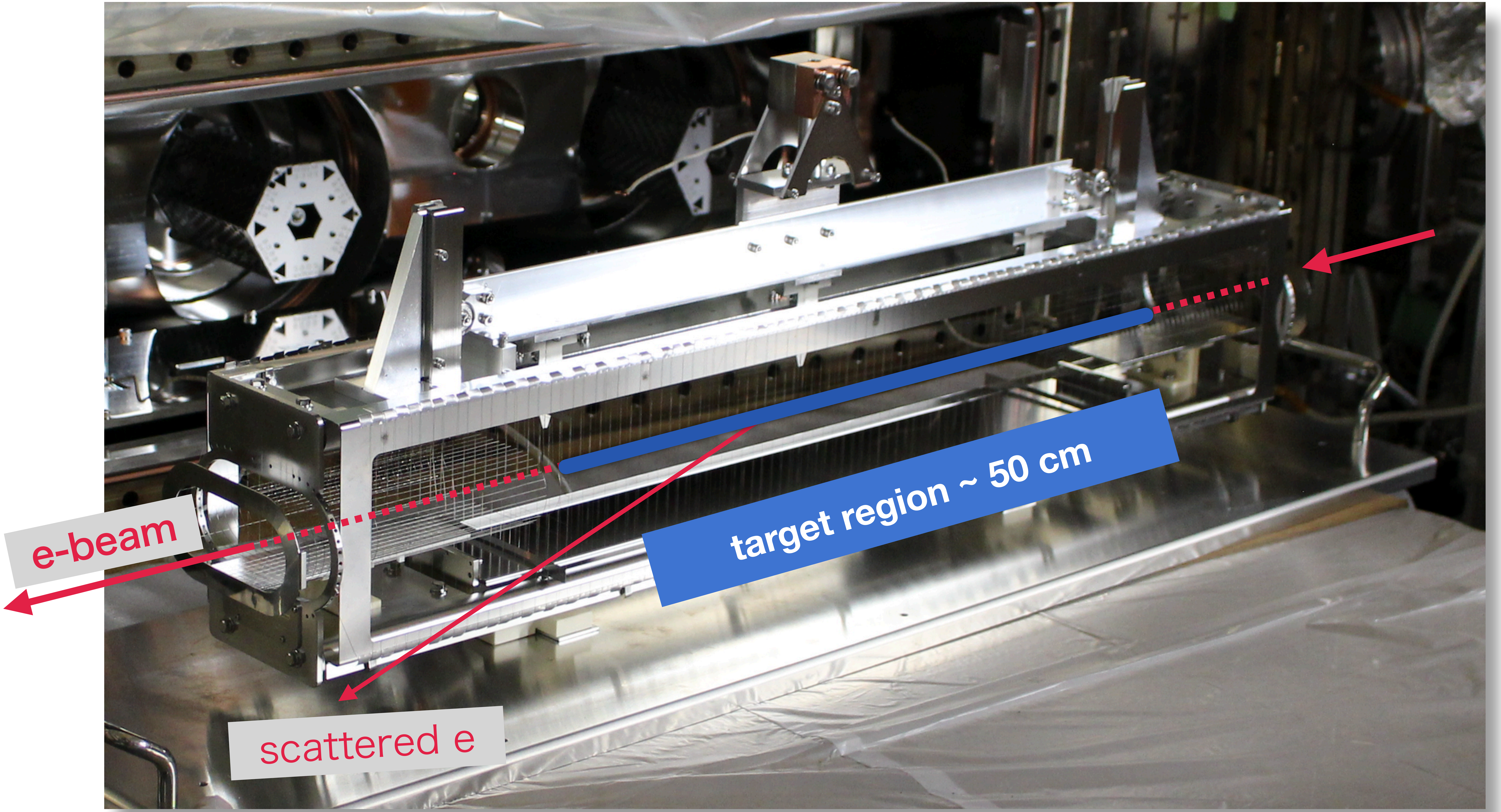
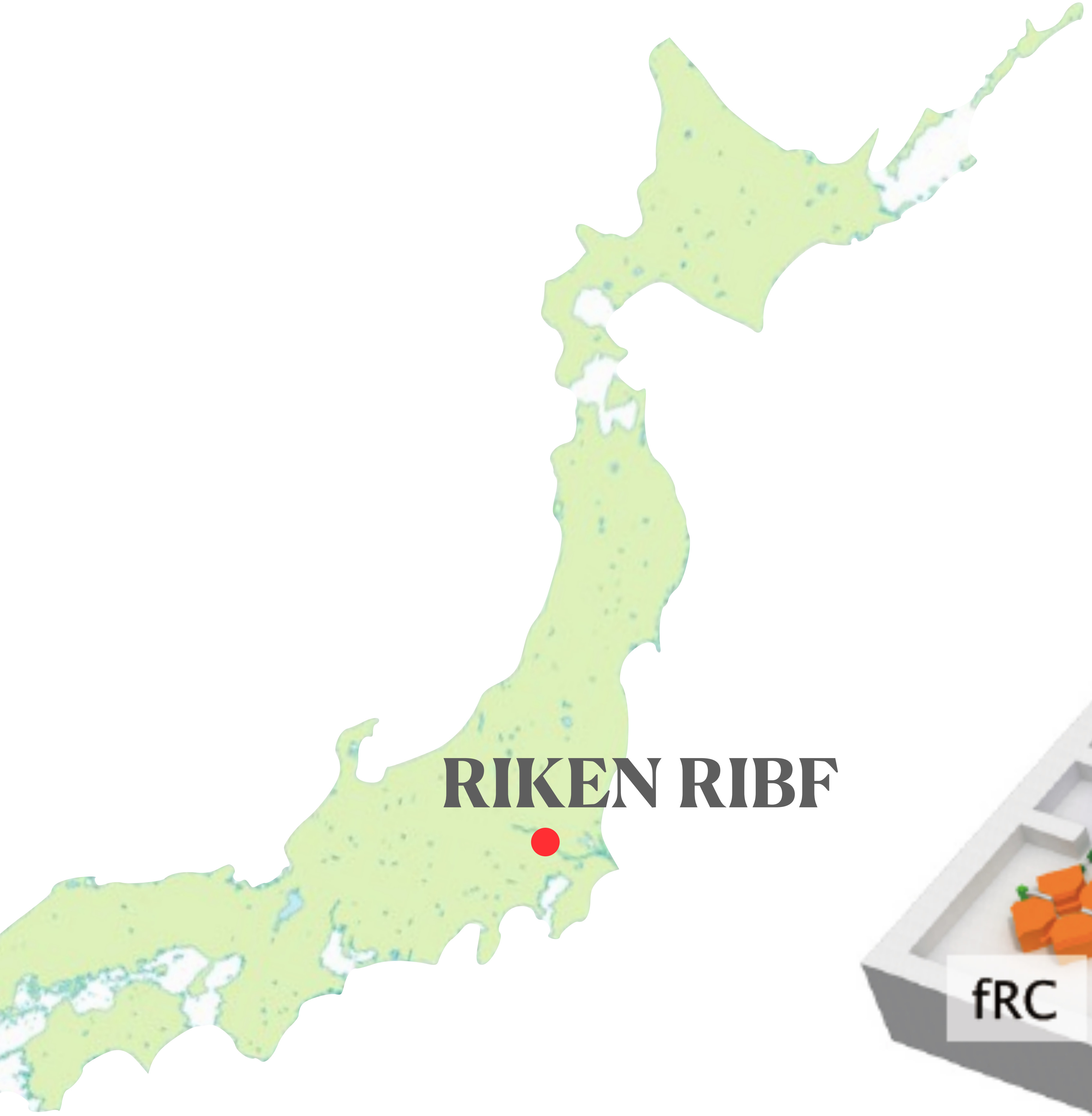
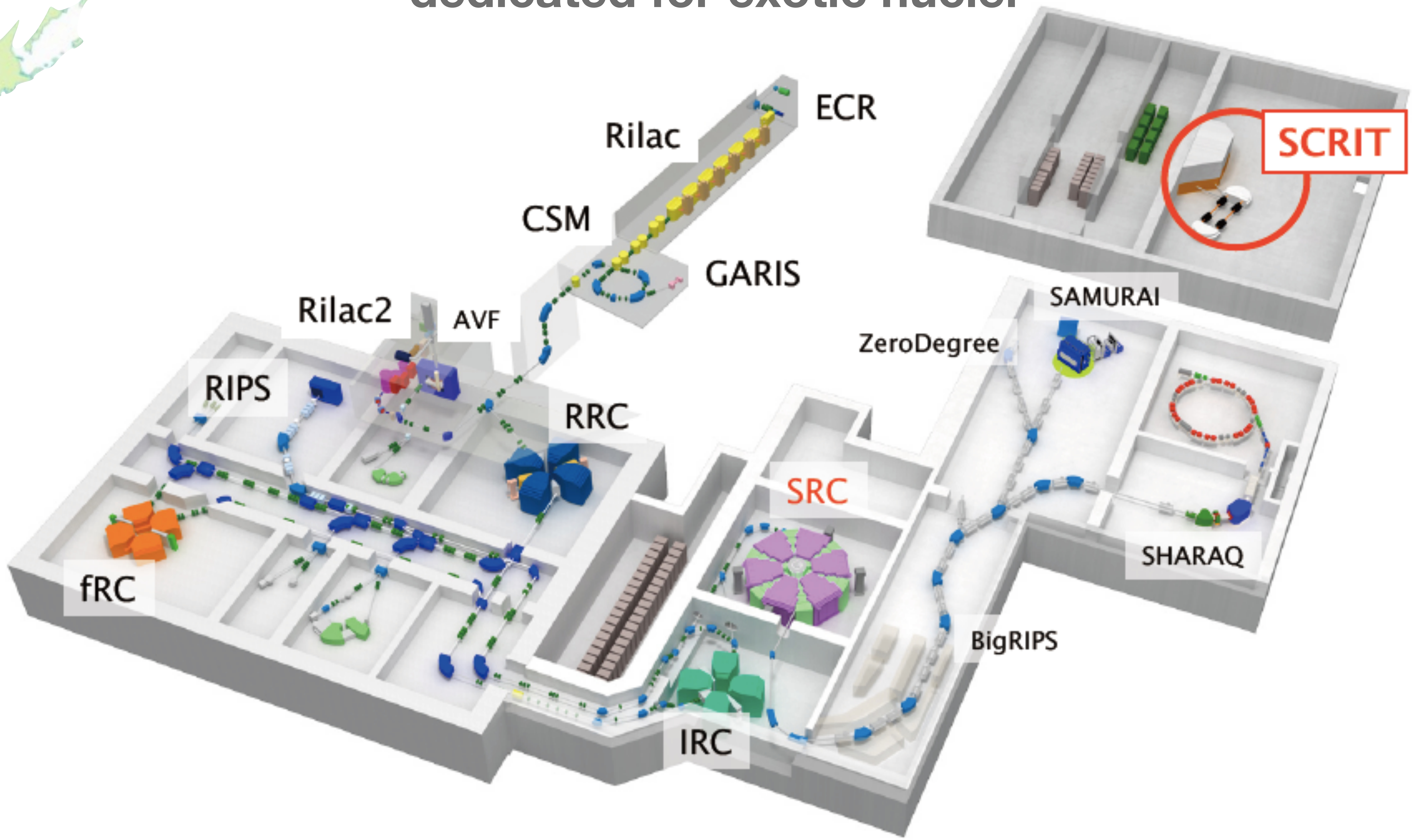


# SCRIT electron scattering facility @ RIBF



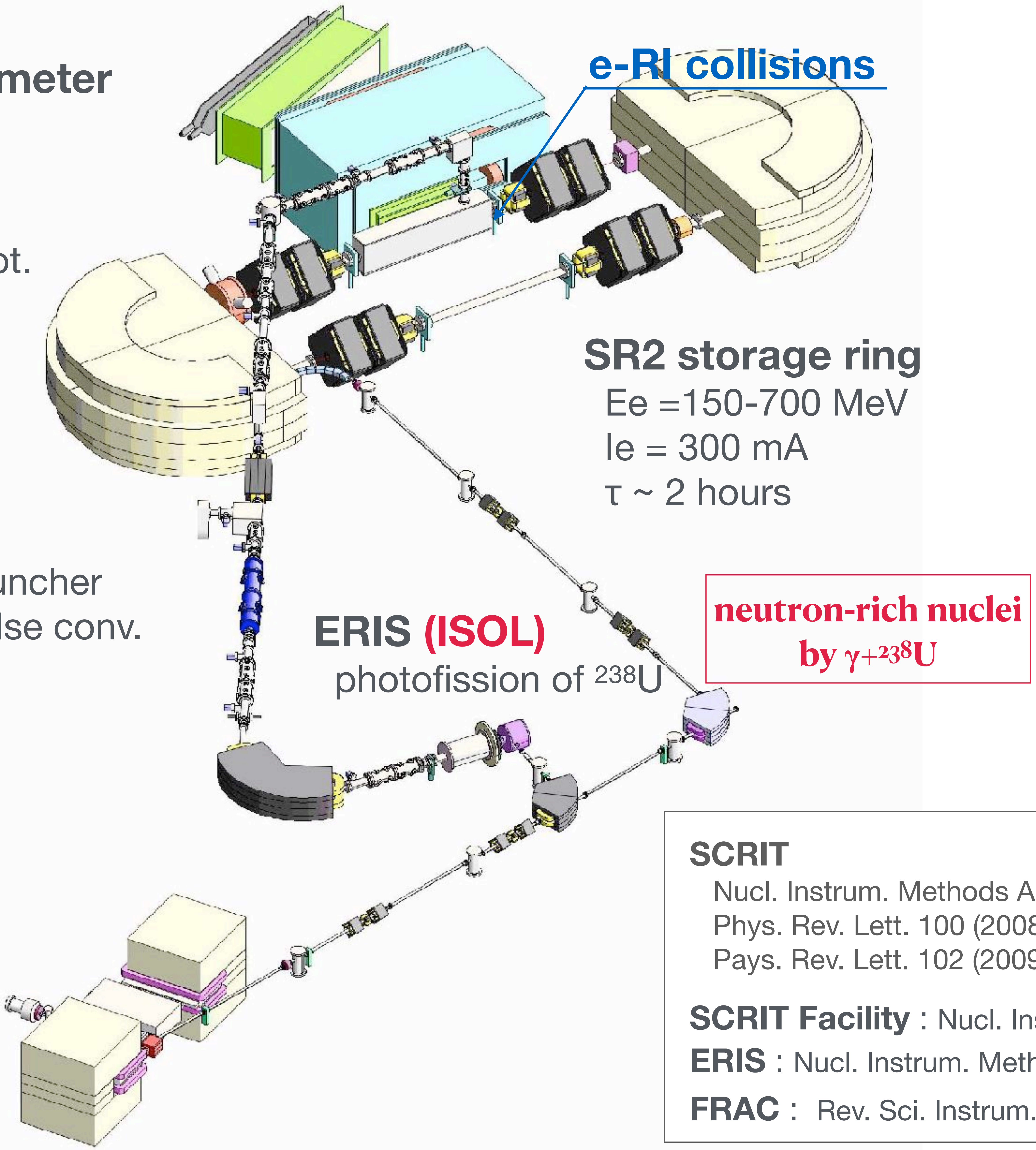

**World's first and currently only one facility**

dedicated for exotic nuclei




RIKEN RI Beam Factory (Japan)

# RIKEN SCRIT Electron Scattering Facility




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

**SR2 storage ring**
$E_e = 150\text{-}700$ MeV
$I_e = 300$ mA
$\tau \sim 2$ hours

**FRAC**
cooler-buncher
dc-to-pulse conv.

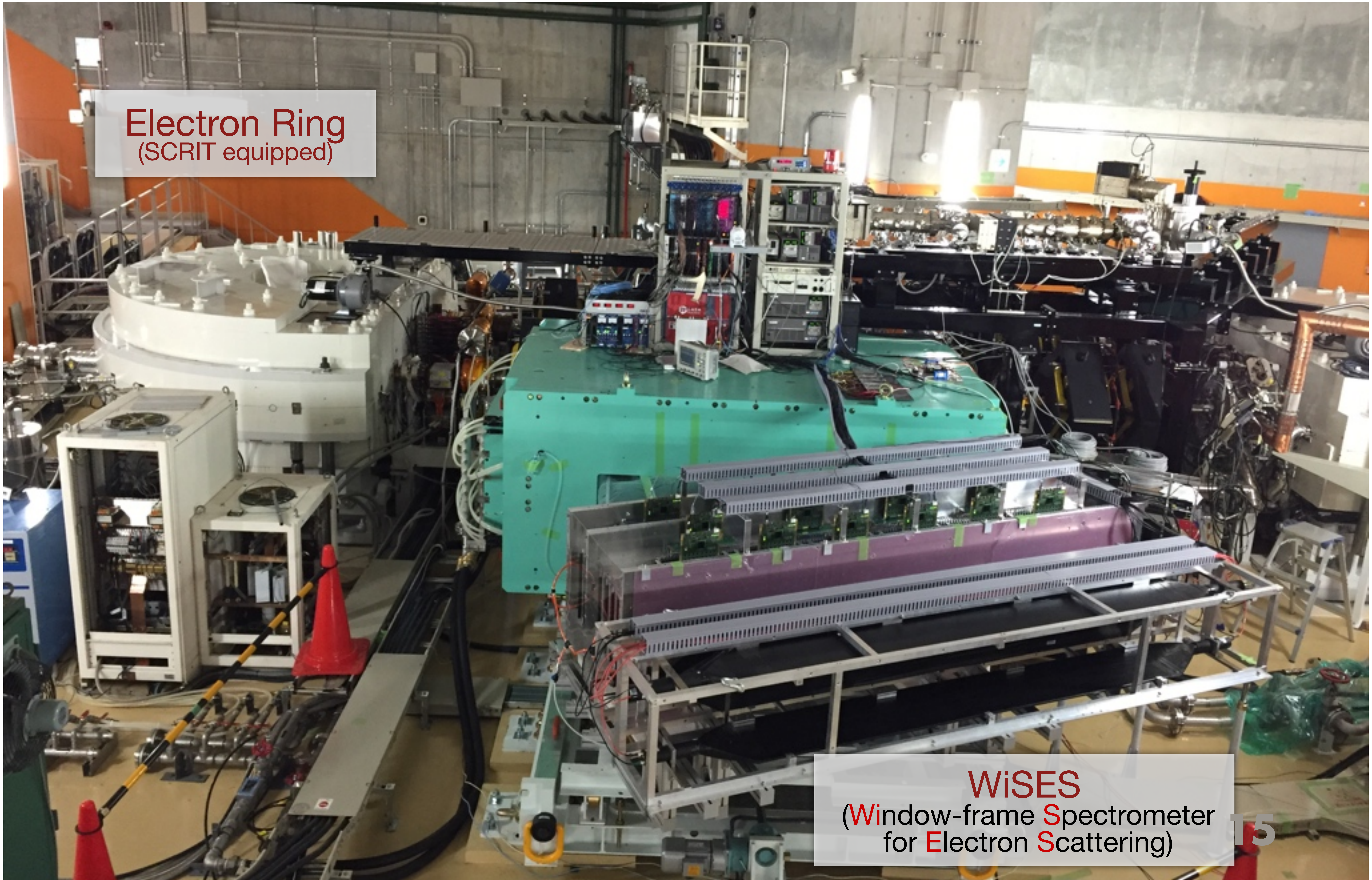
**ERIS (ISOL)**
photofission of $^{238}U$

**Injector + ISOL driver**
150 MeV Microtron

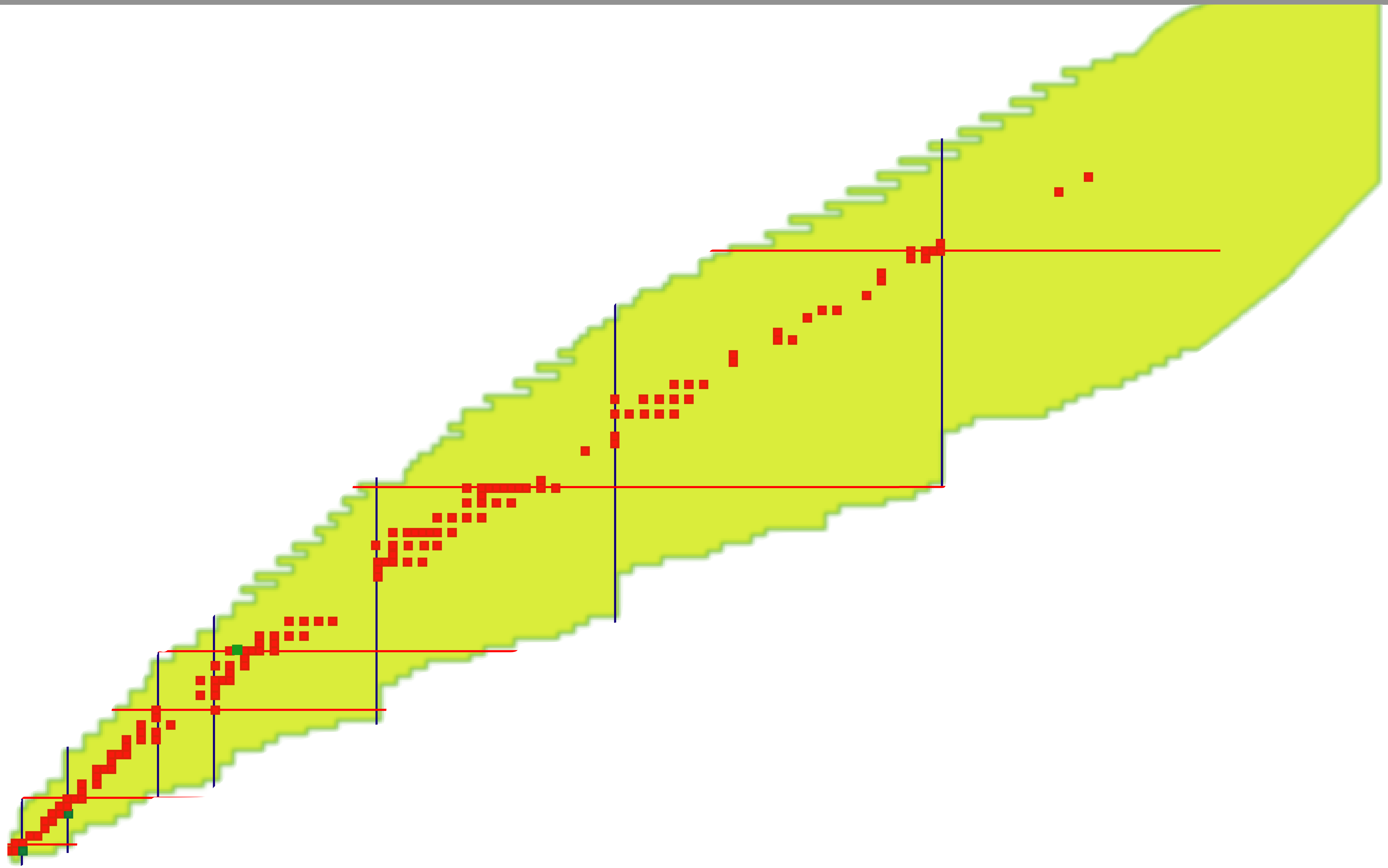
**SCRIT**
Nucl. Instrum. Methods A532 (2004) 216.
Phys. Rev. Lett. 100 (2008) 164801.
Pays. Rev. Lett. 102 (2009) 102501.

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

# SCRIT electron scattering facility



# Facility Commissioning with Stable Xe(e,e')



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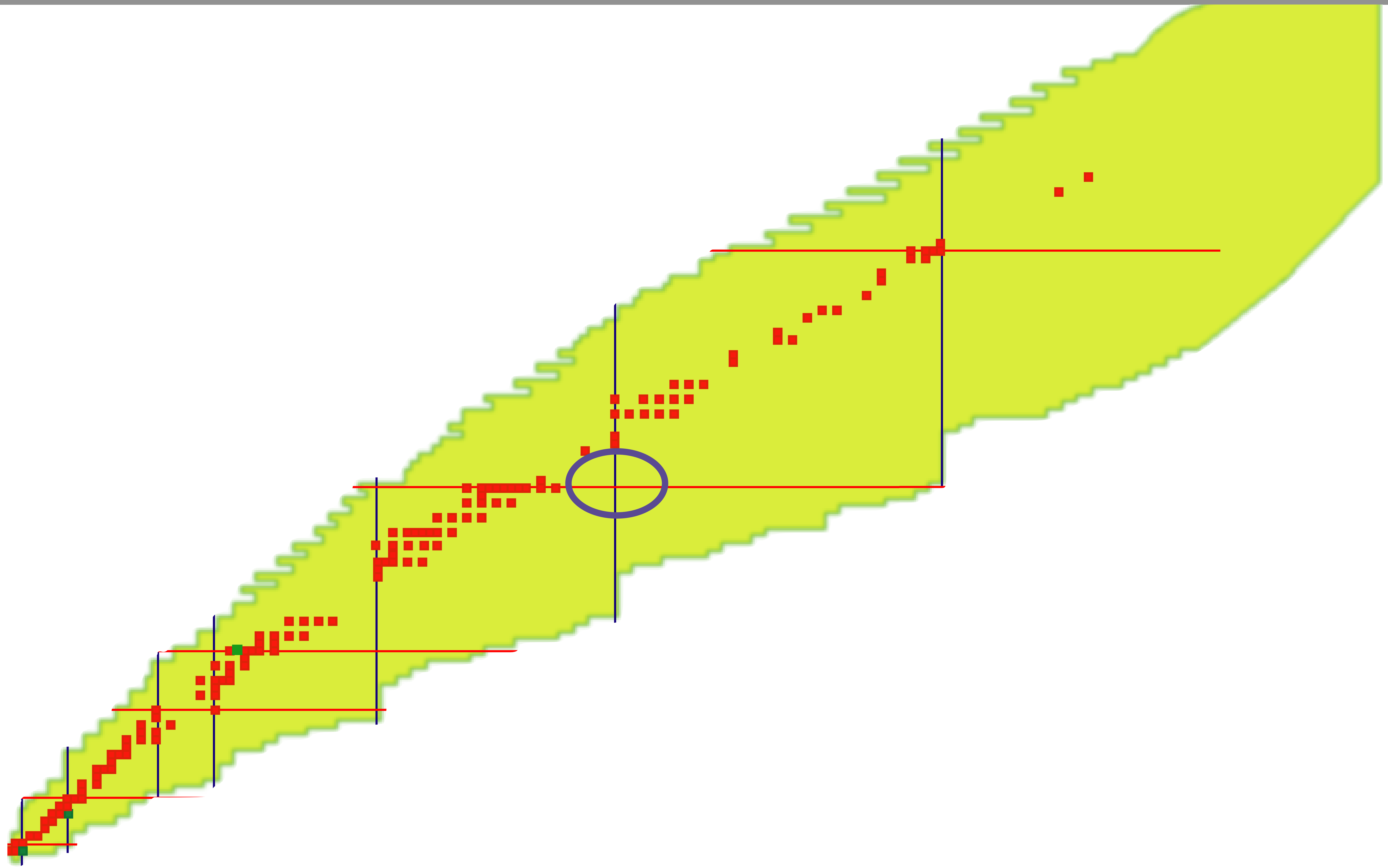

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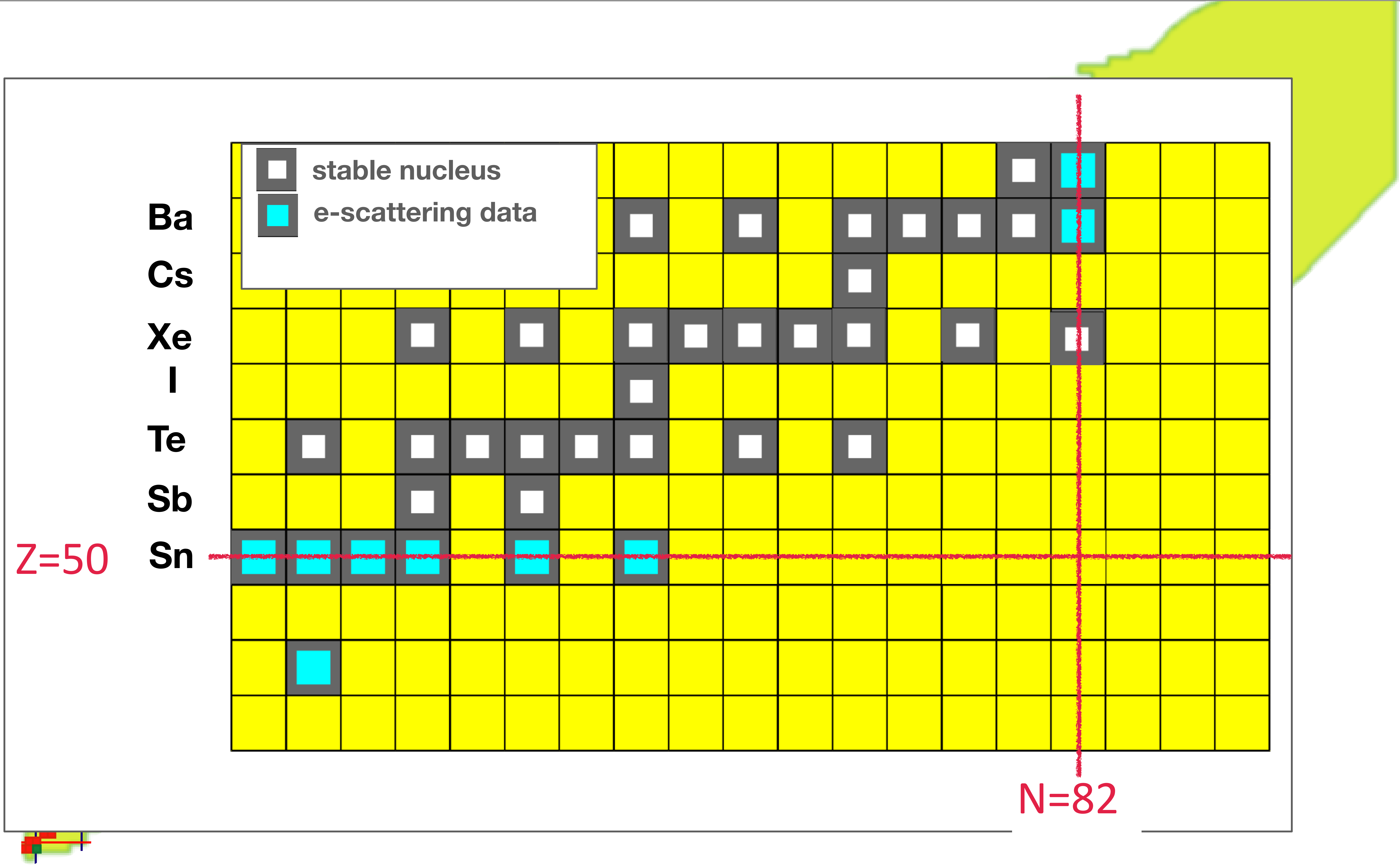

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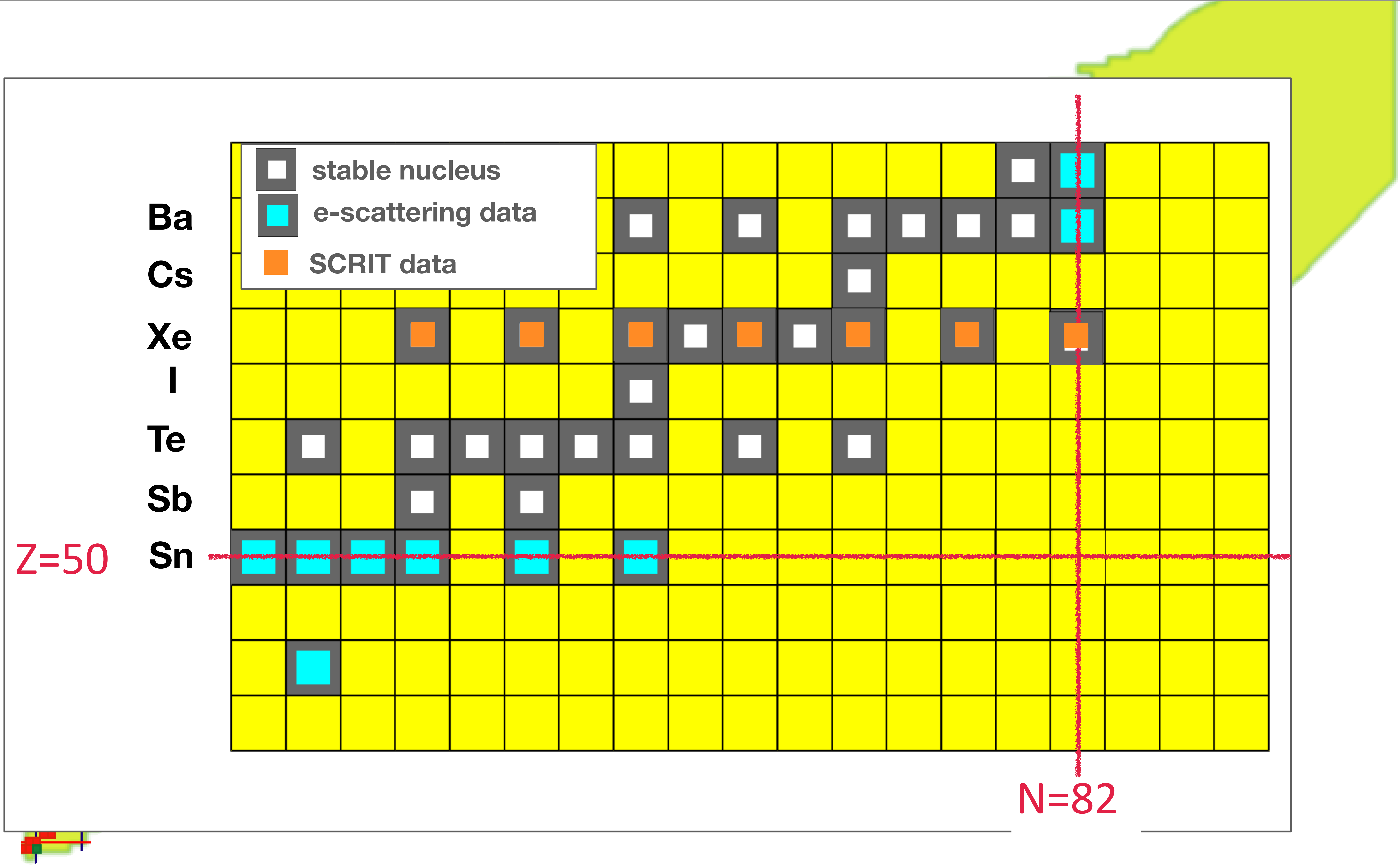
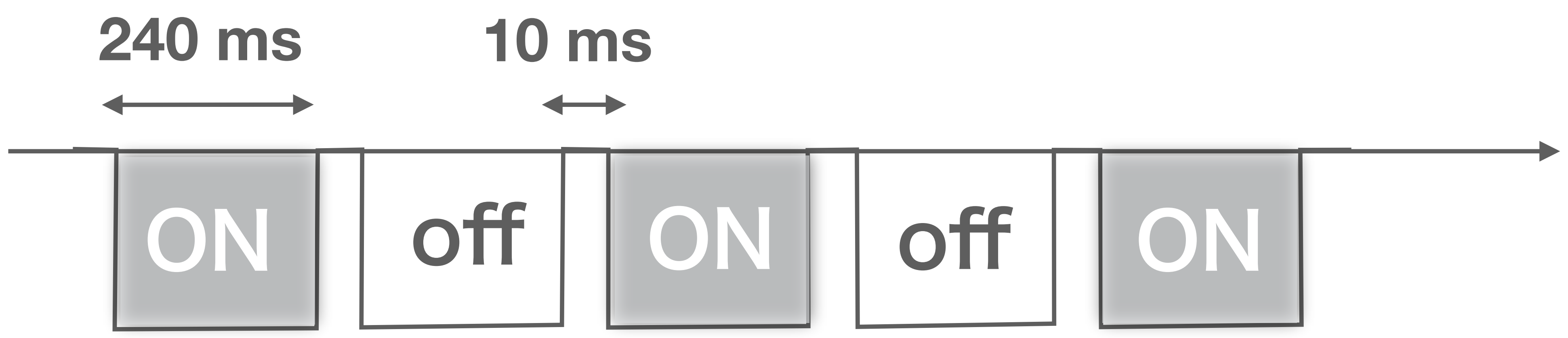


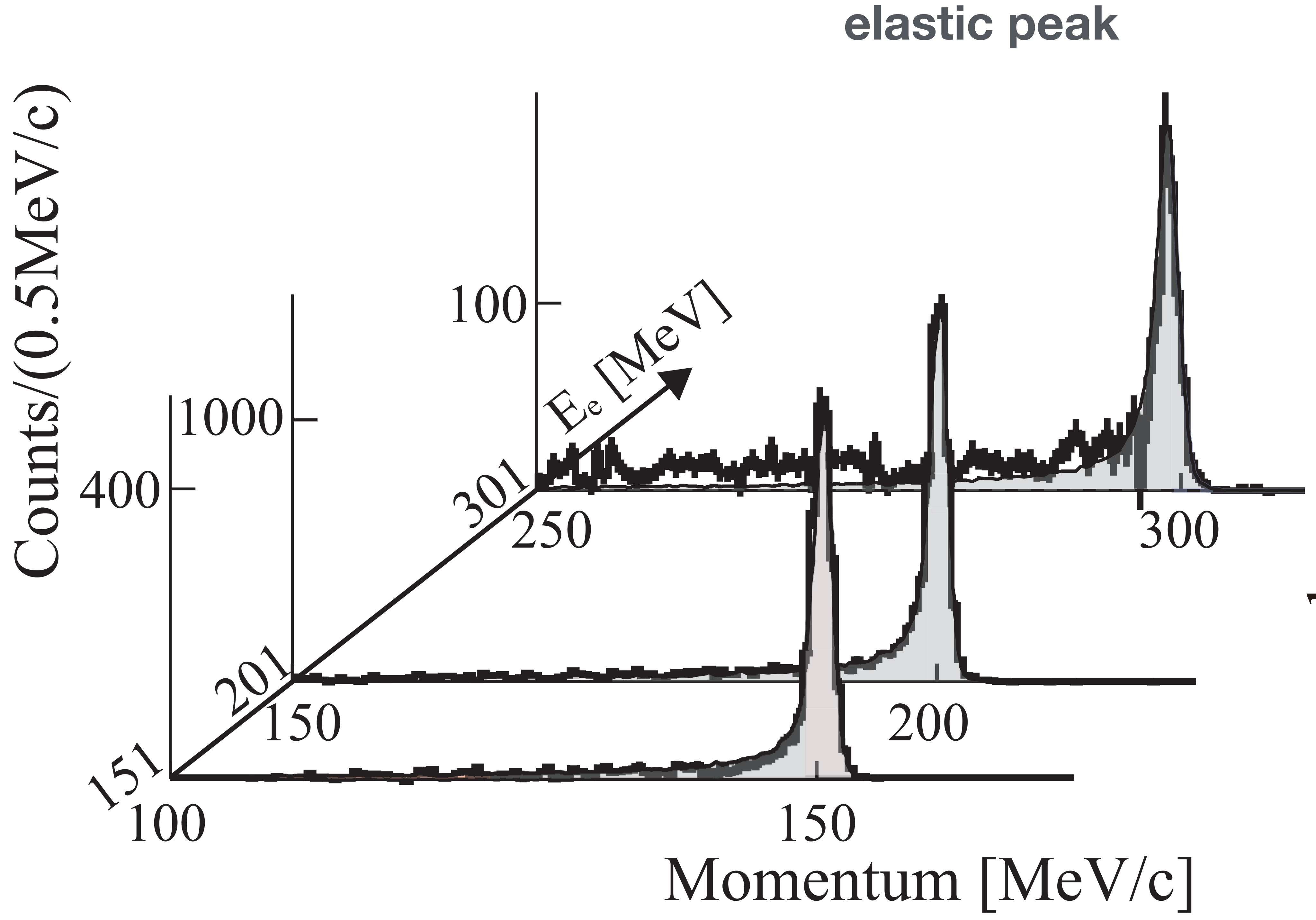
# Facility Commissioning with Stable Xe(e,e')

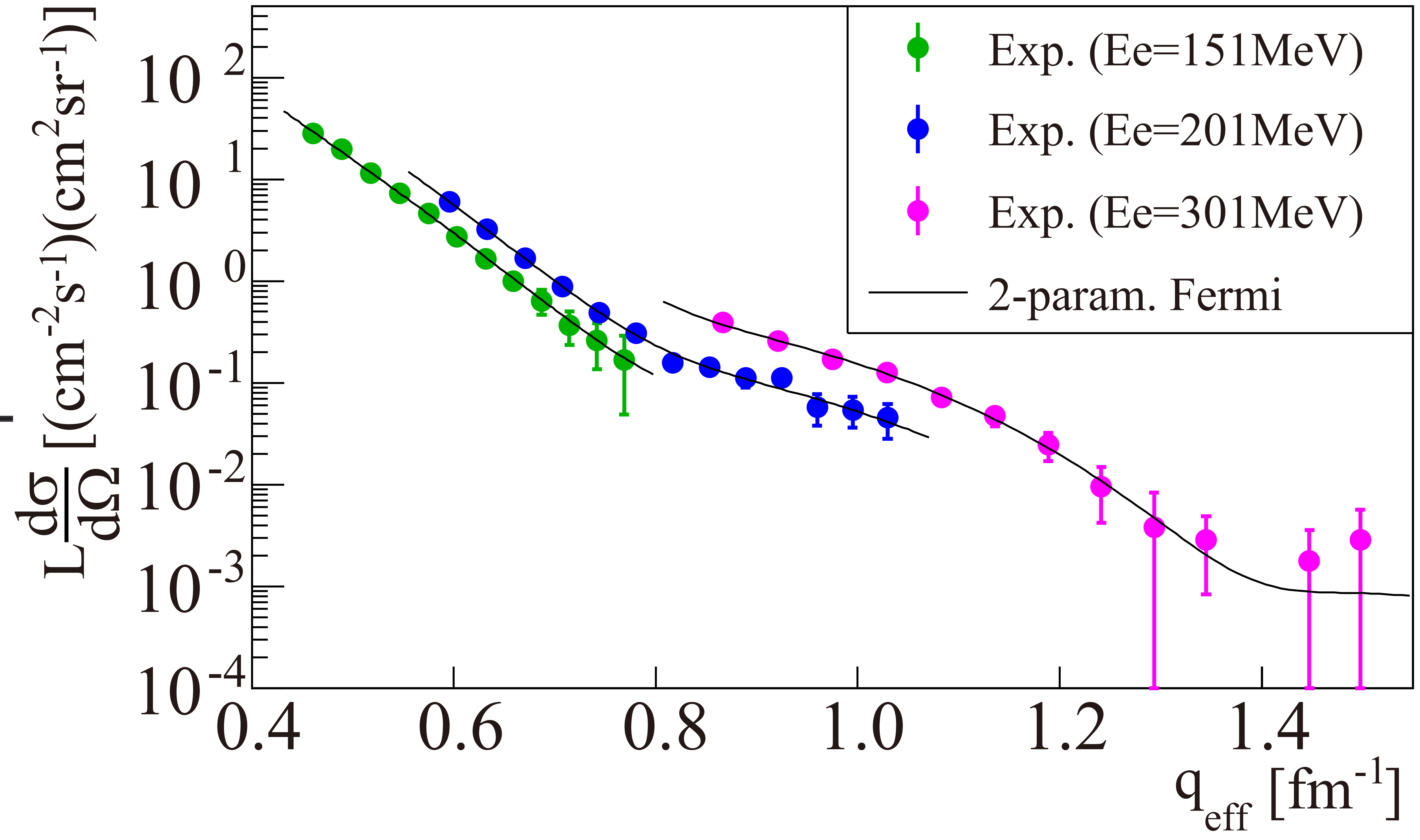
trapping sequence




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

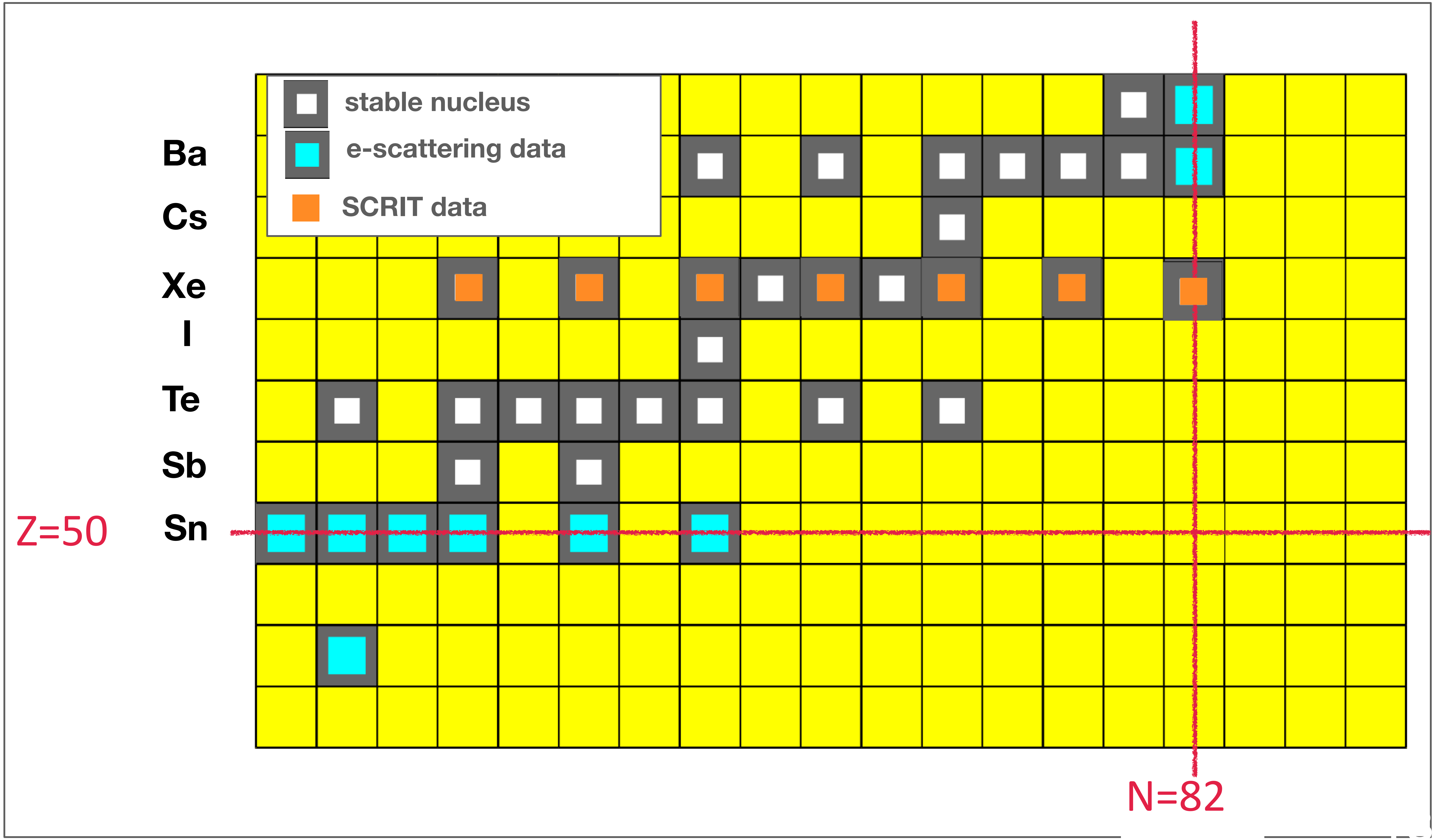
L ~ $10^{27}$ /cm$^2$/s with $N_{trapped}$ ~ $10^7$




$\langle r^2 \rangle^{1/2}$= 4.789 $^{+0.12}_{-0.10}$ fm ⟷ $\langle r^2 \rangle^{1/2}$= 4.787 fm( μ-atom X-rays )

# Towards the doubly magic nucleus $^{132}$Sn



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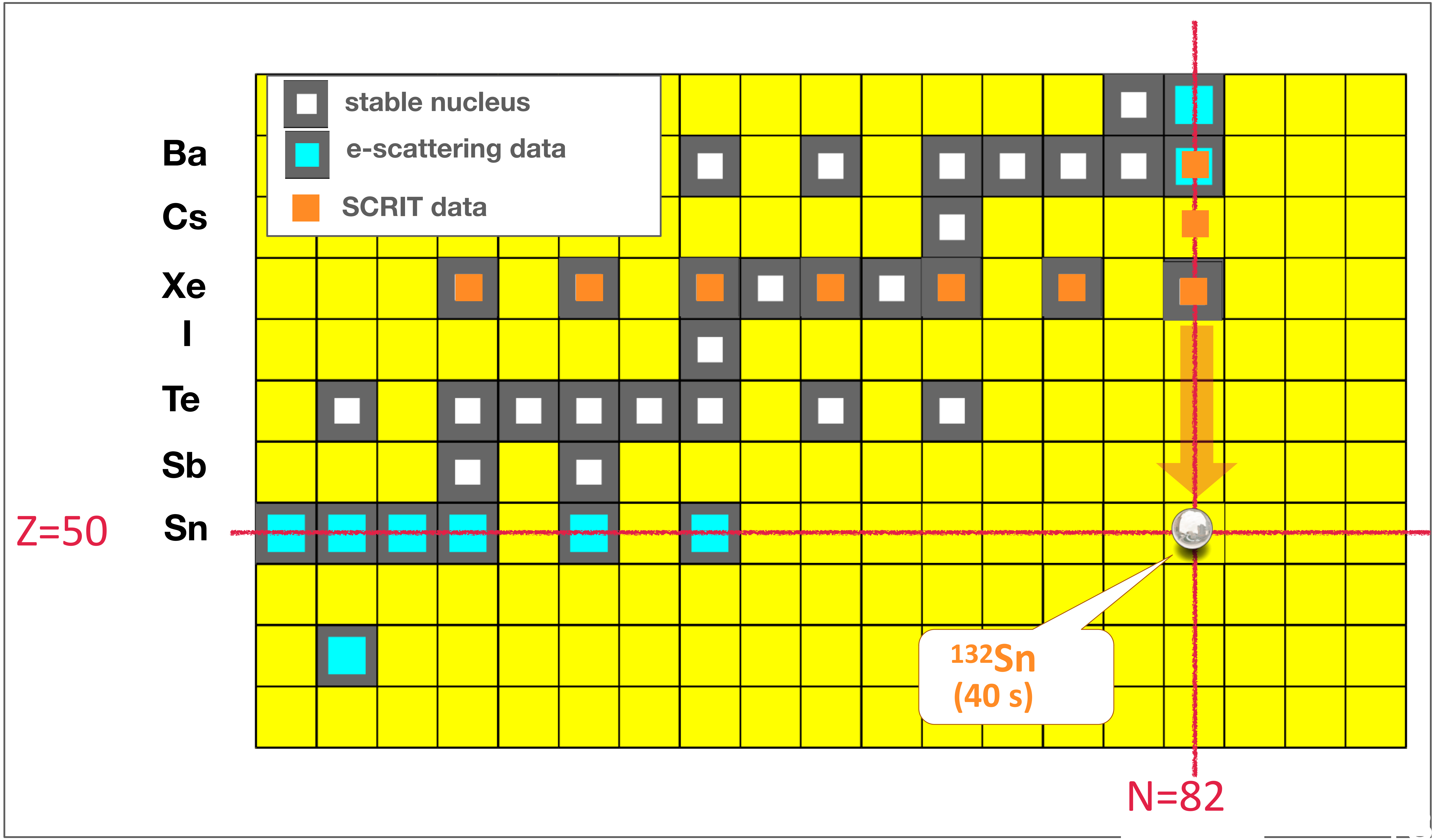

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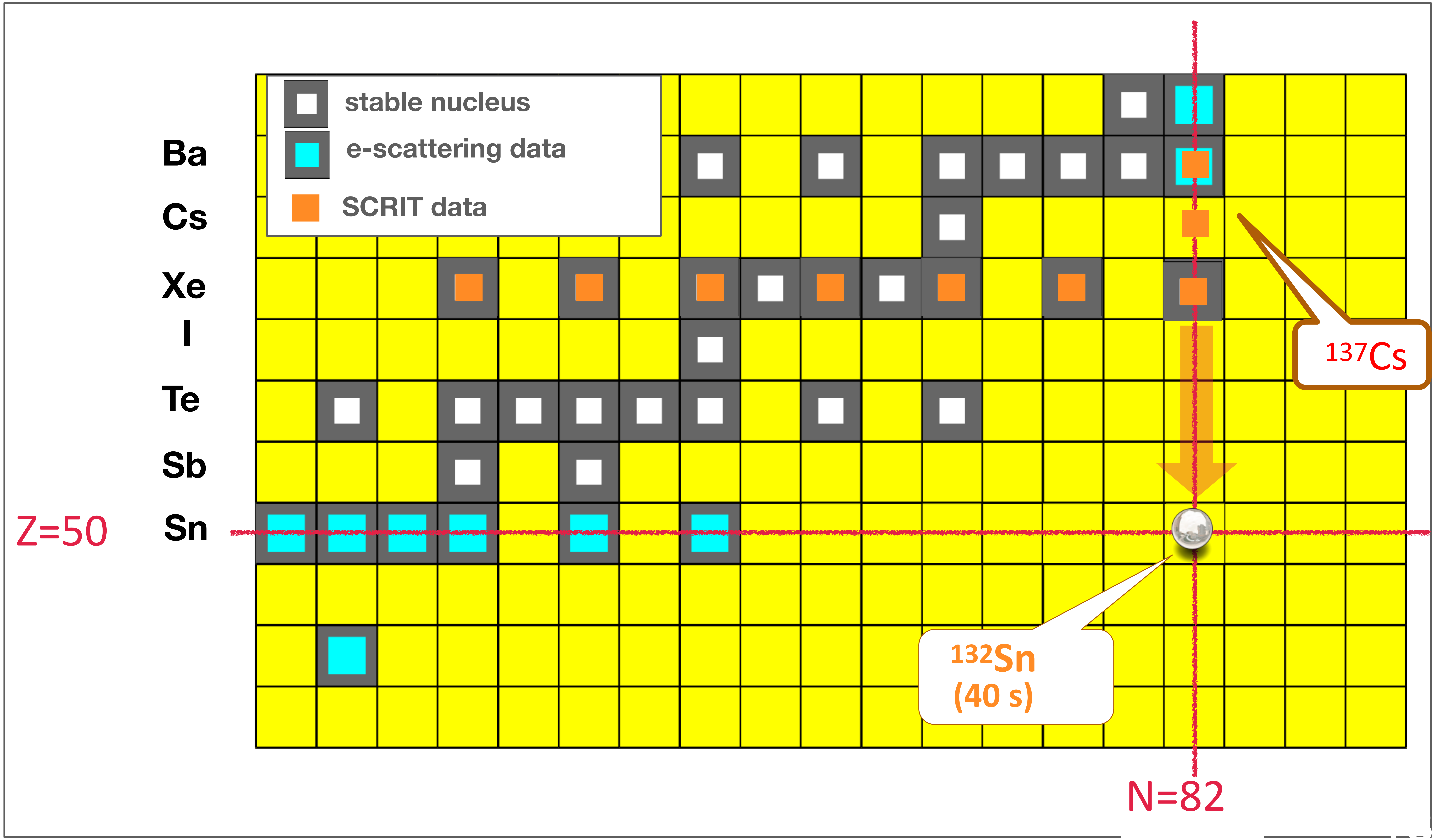
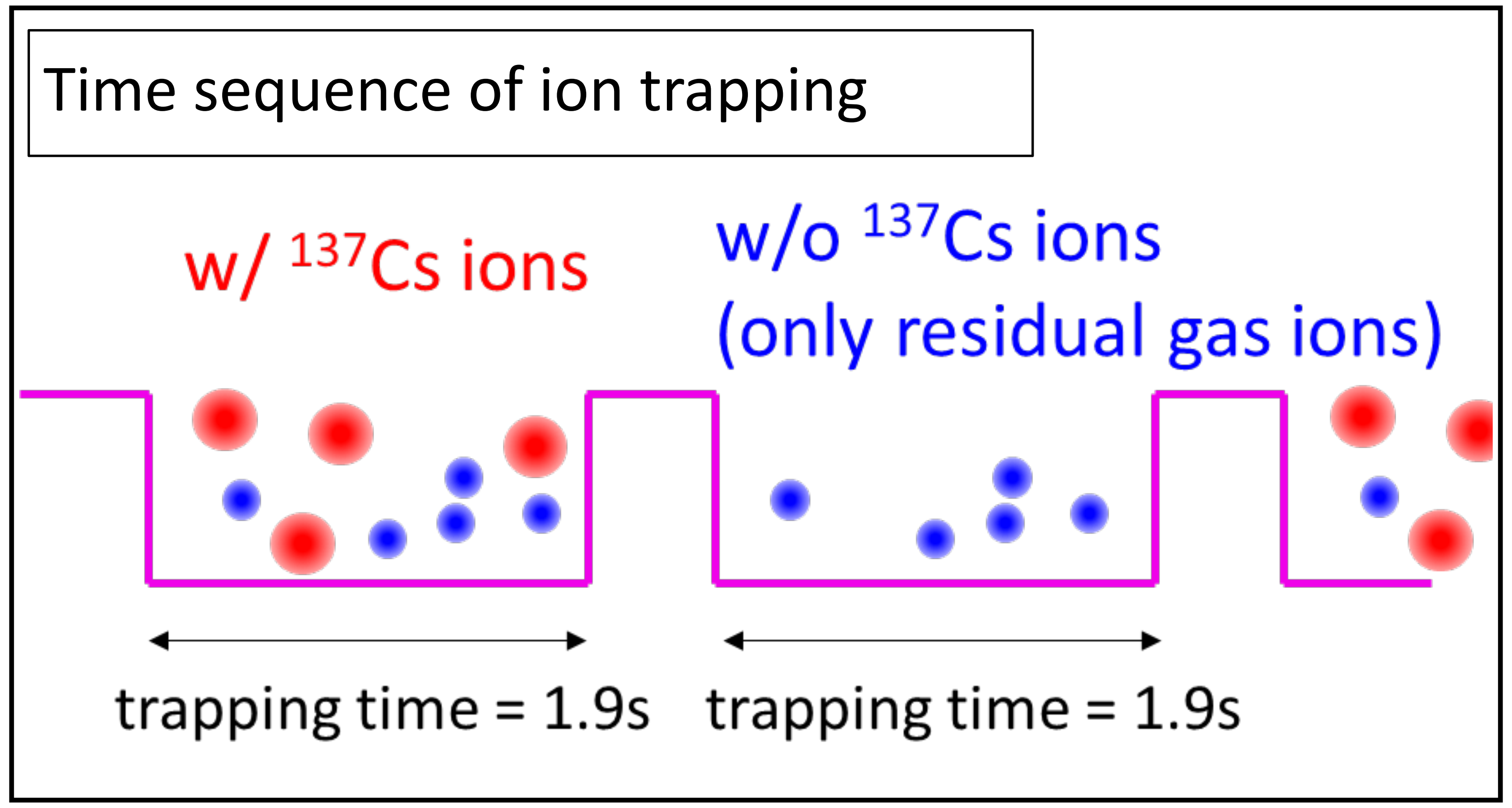


# World's first (e,e') for Online-Produced Unstable Nuclide ($^{137}Cs$)

**1.9 s trapping**

**=> mimicking "short-lived" nuclei**

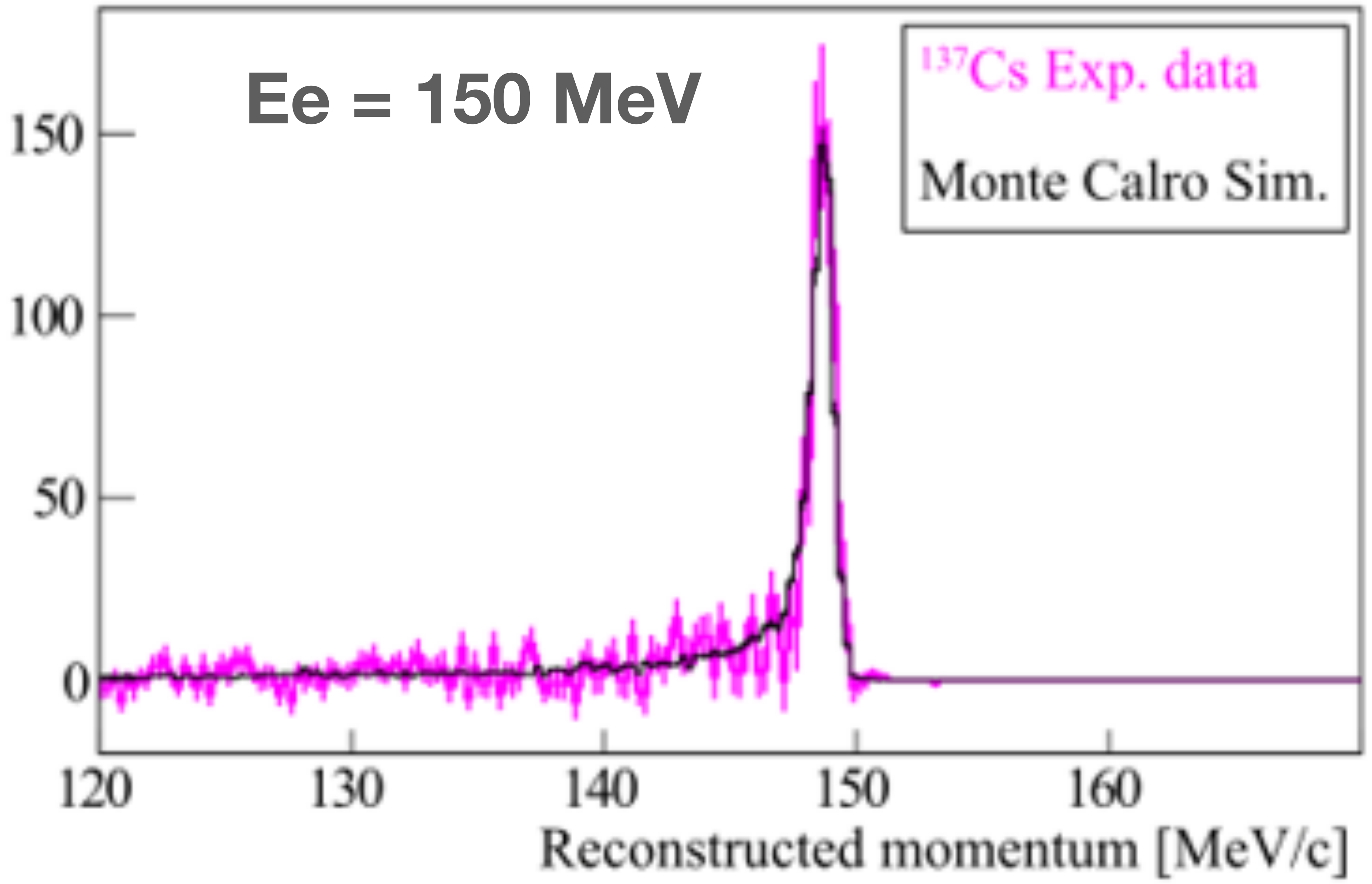


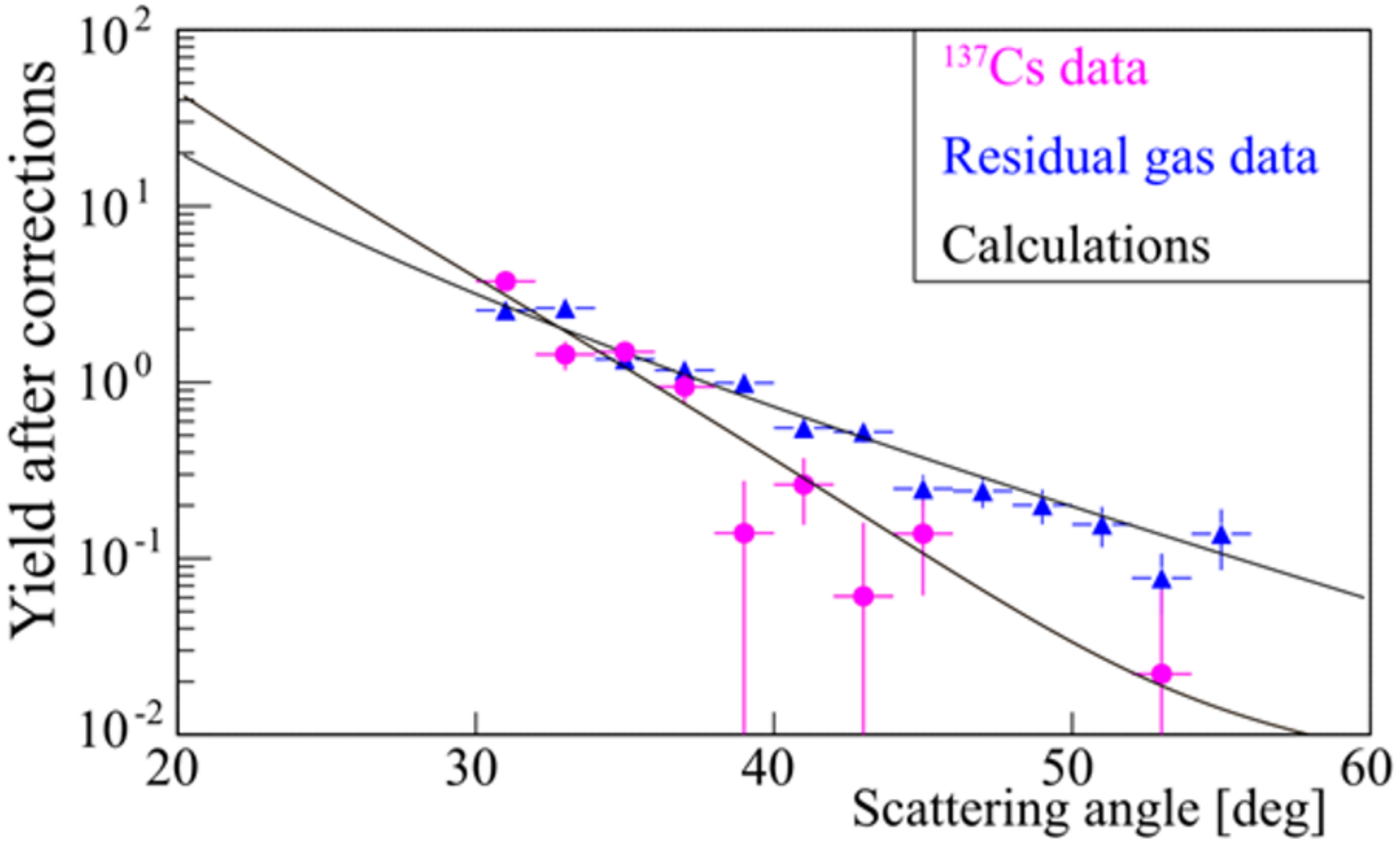

**Ntrapped ~ 2 x$10^{7}$**

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

**Successful demonstration with online-produced unstable nuclei**

K. Tsukada et al.,
Phys. Rev. Lett. 131 (2023) 092502.



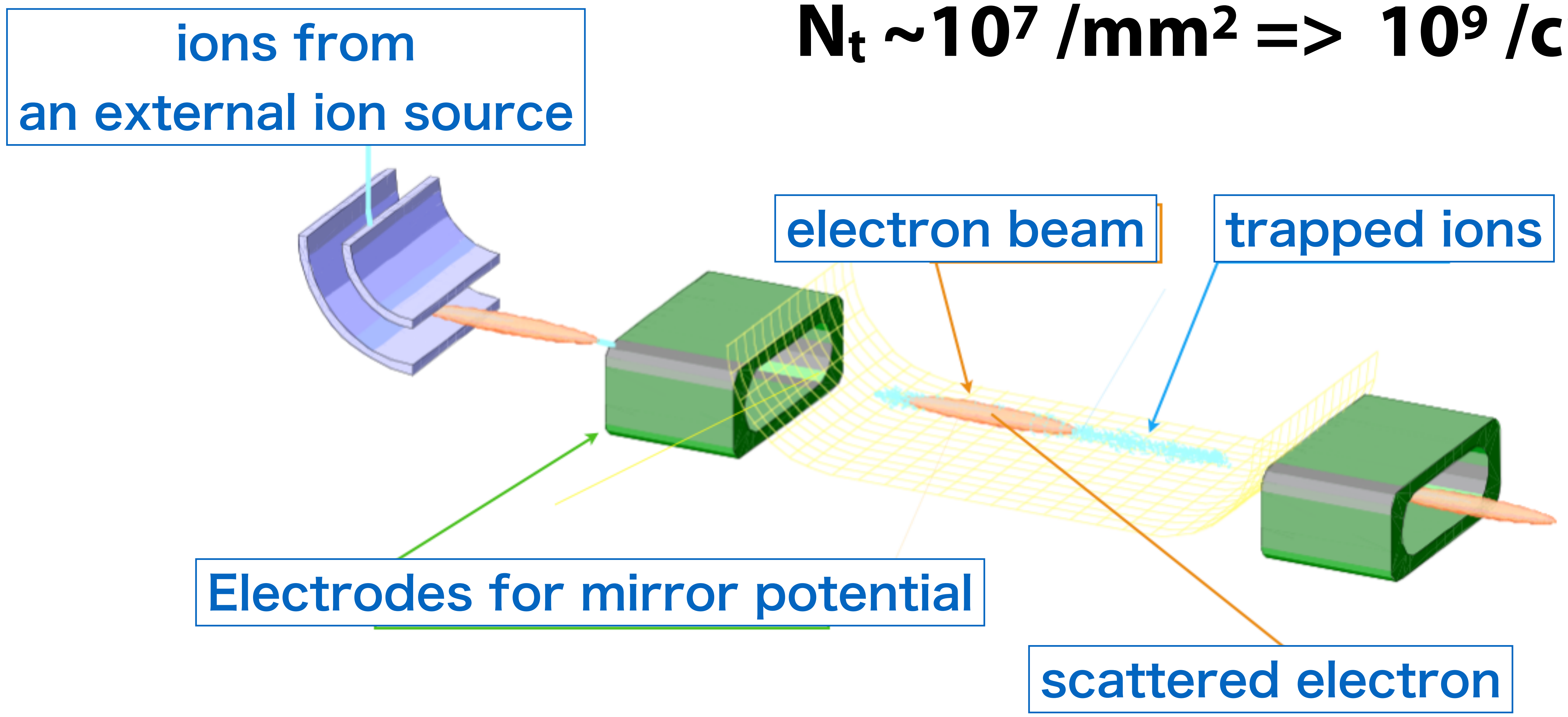

**=> further details**

**Kyo Tsukada's talk (Thursday, May 29, Room9, 16:55 -)**

# The SCRIT concept and Luminosity

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

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




| | 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 | 12 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 |

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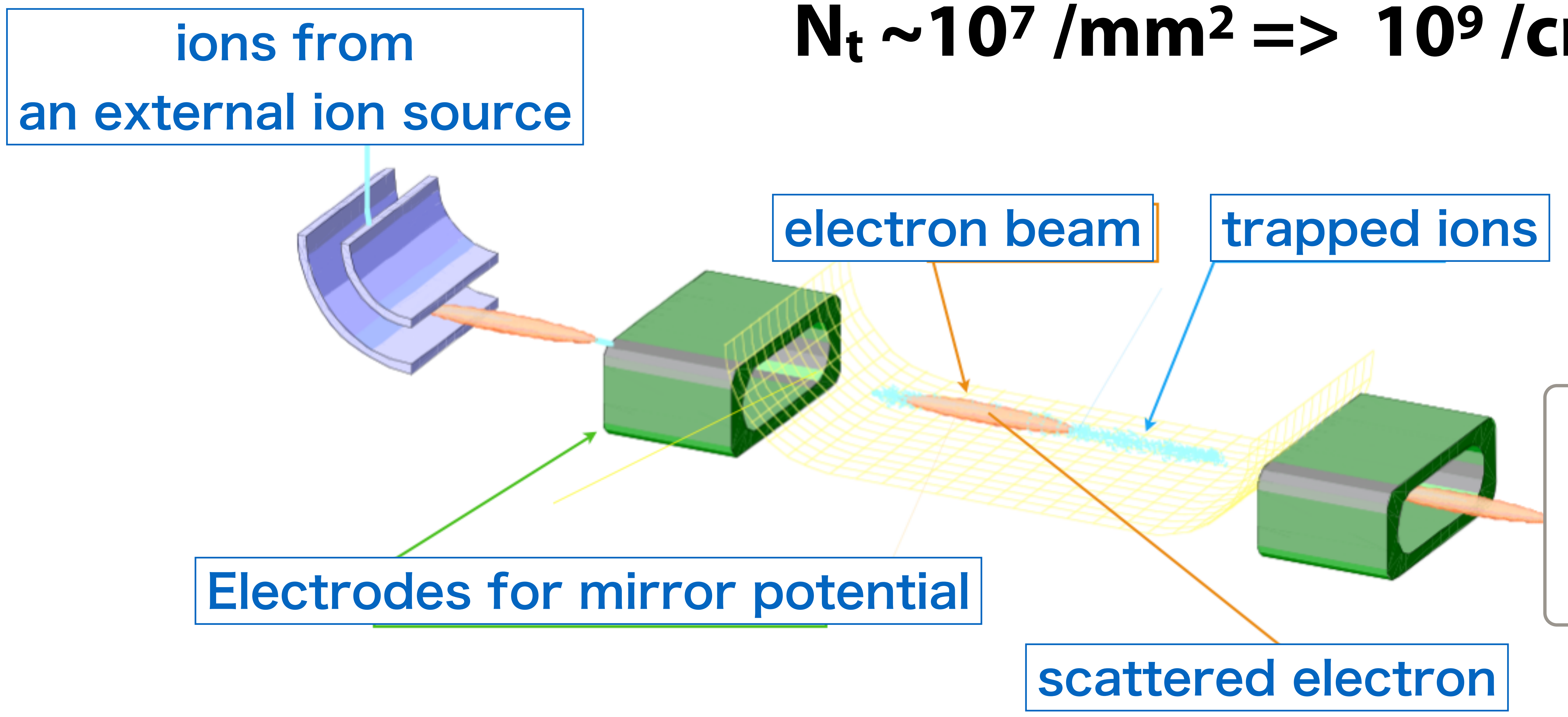


REQUIRED TARGET THICKNESS
$10^{-10}$!!!

| | Ee | $N_{beam}$ | ρ • t | L |
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# ISOL upgrade: towards $^{132}$Sn

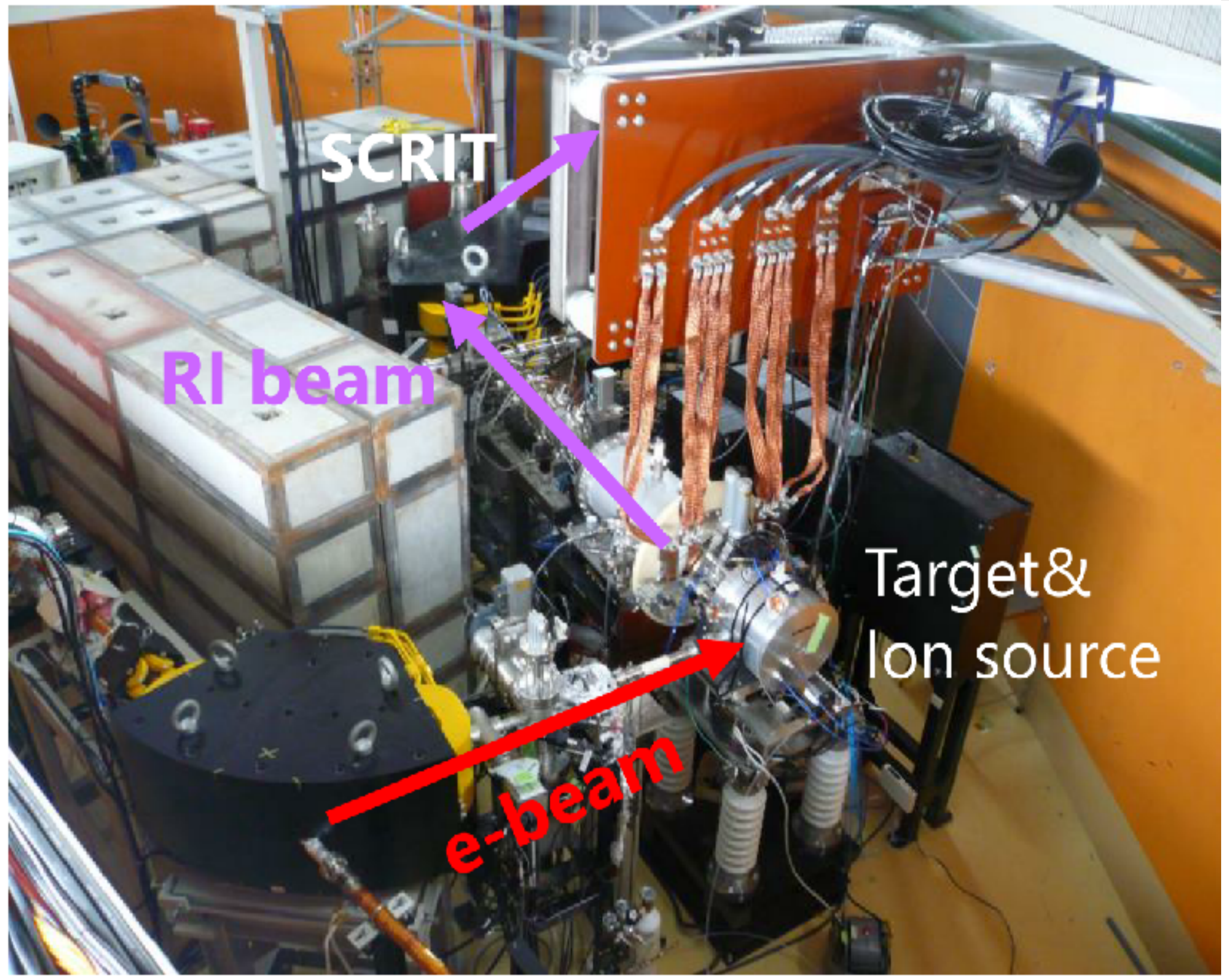
**Production Rate**

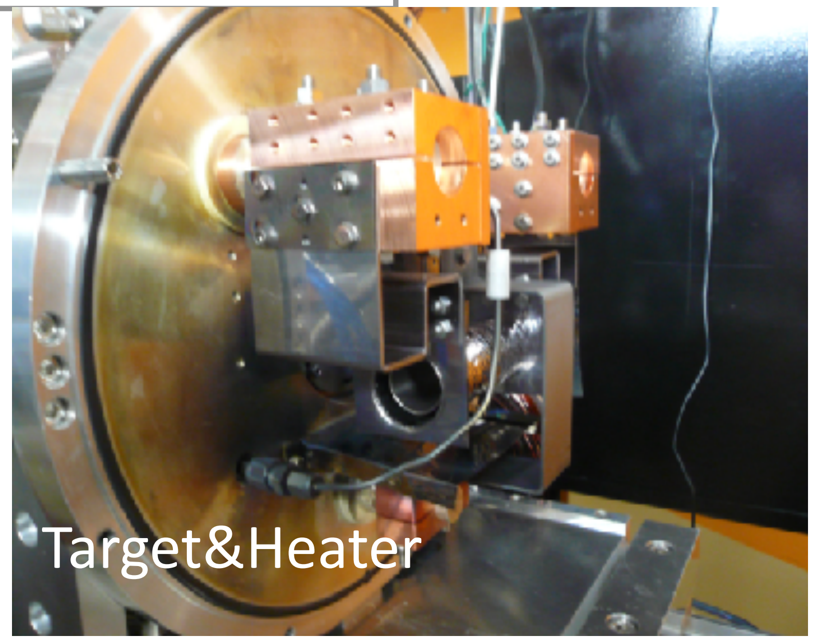
$N_{fission}$ ~ $10^8$ /watt

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

beam power : ~ 20W (today)

~ 2 kW (underway)



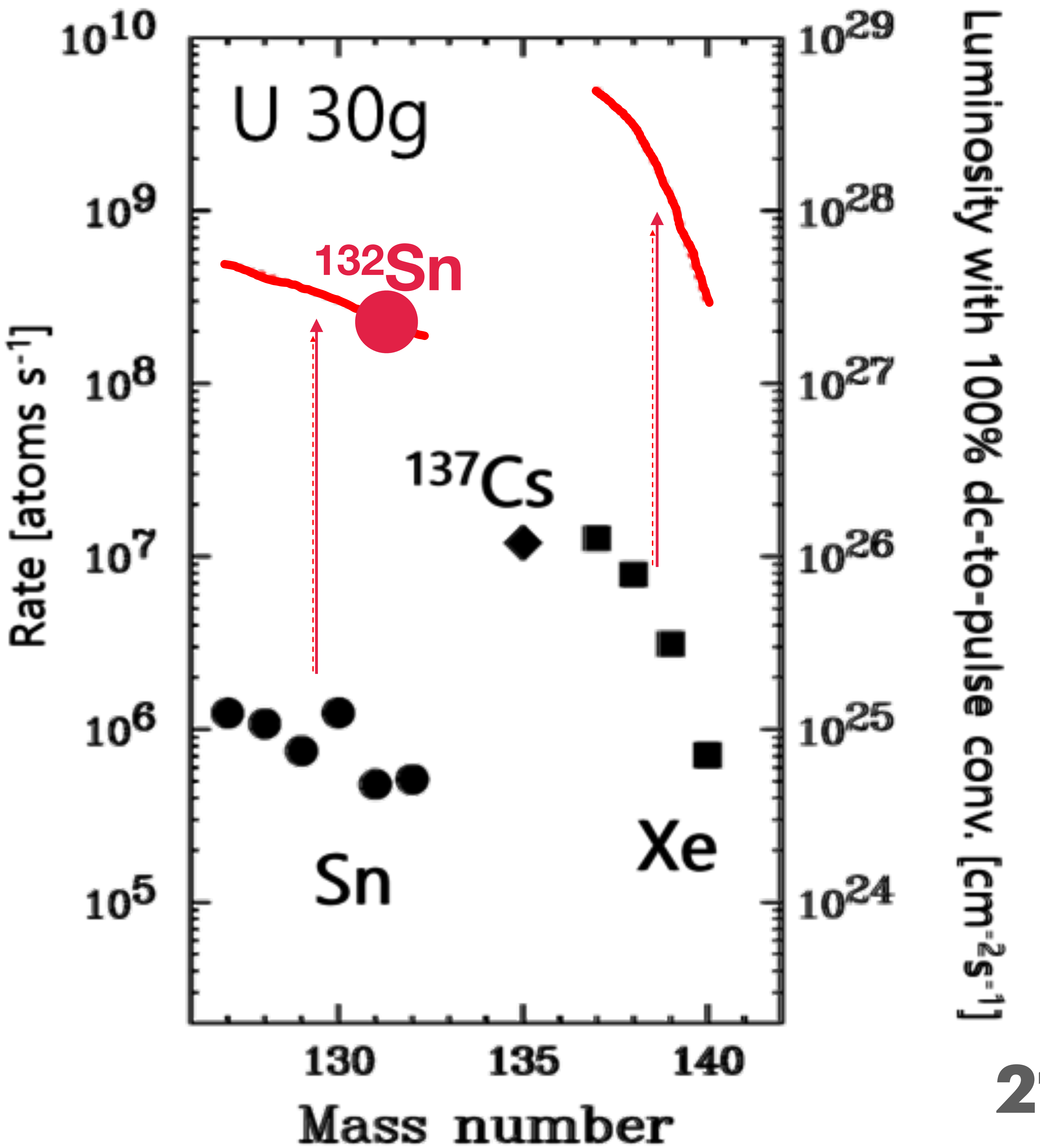





House-made
Uranium carbide (UCx)

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

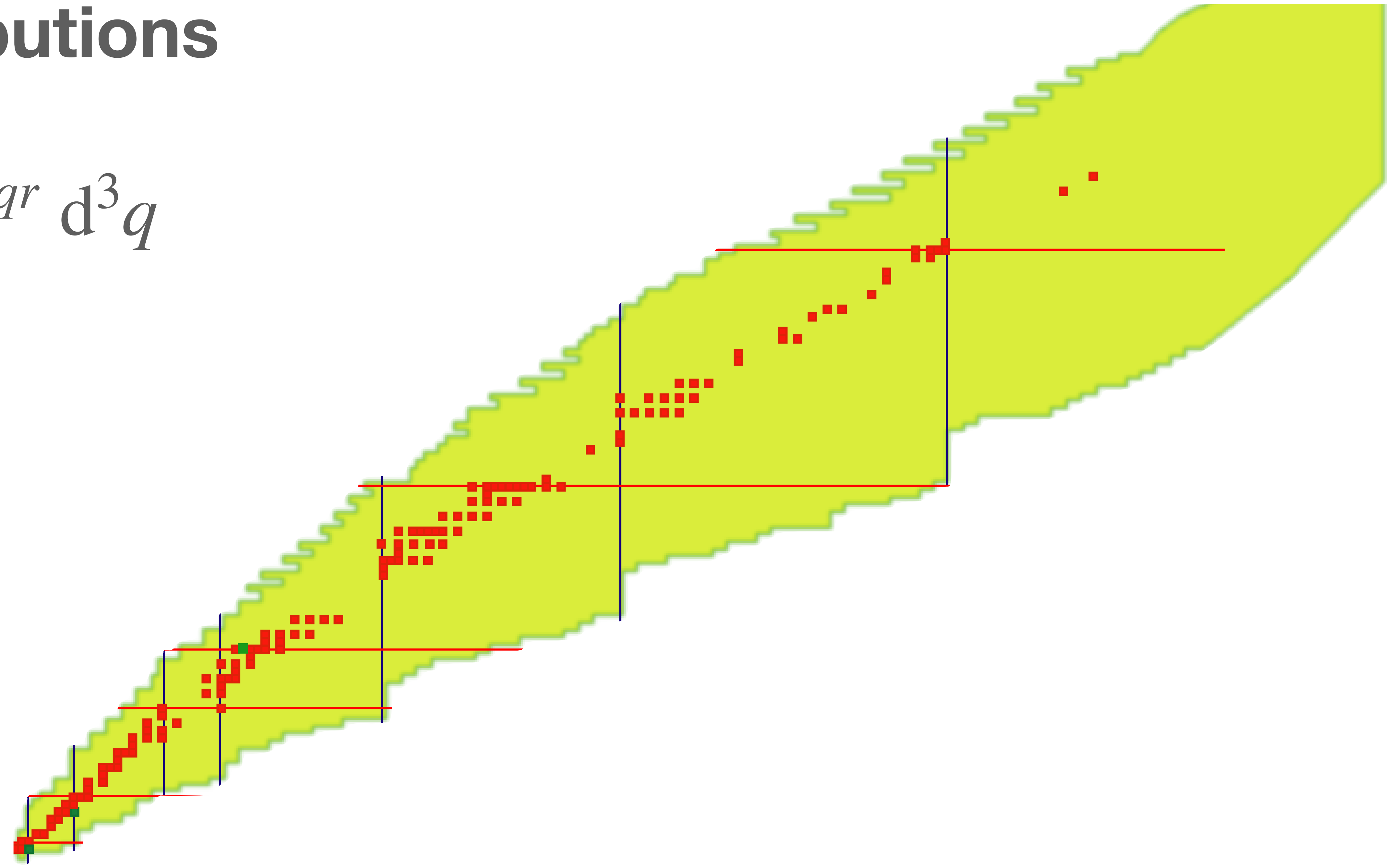
towards 2 kW e-beam
higher repetition
higher peak intensity



# Research possibilities at the SCRIT facility

- **elastic scattering** ➡ **charge density distributions**

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{Mott}}{d\Omega} \,|F_c(q)|^2 \qquad \rho_c(r) = \int F_c(q)\, e^{-iqr}\, d^3q$$



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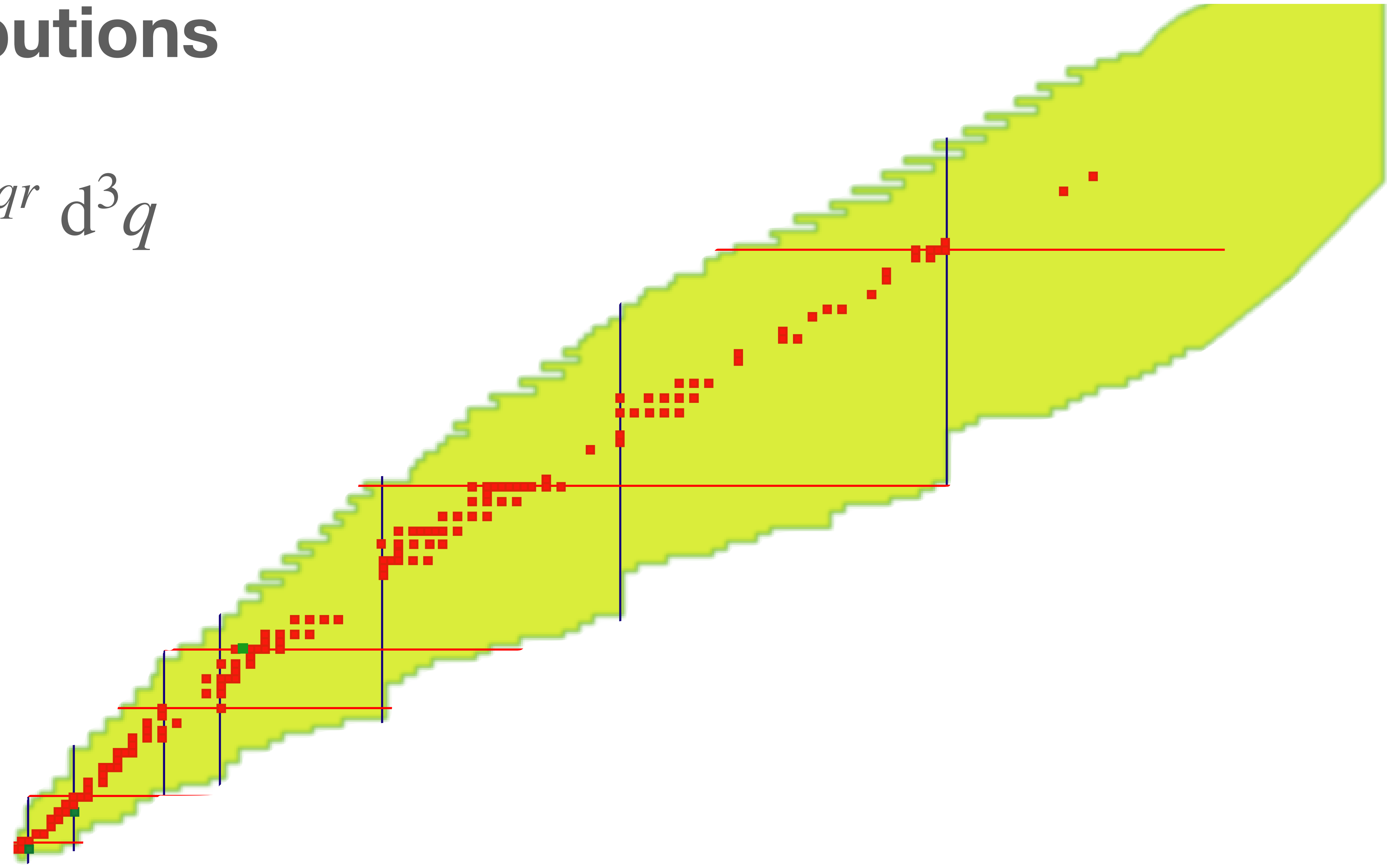


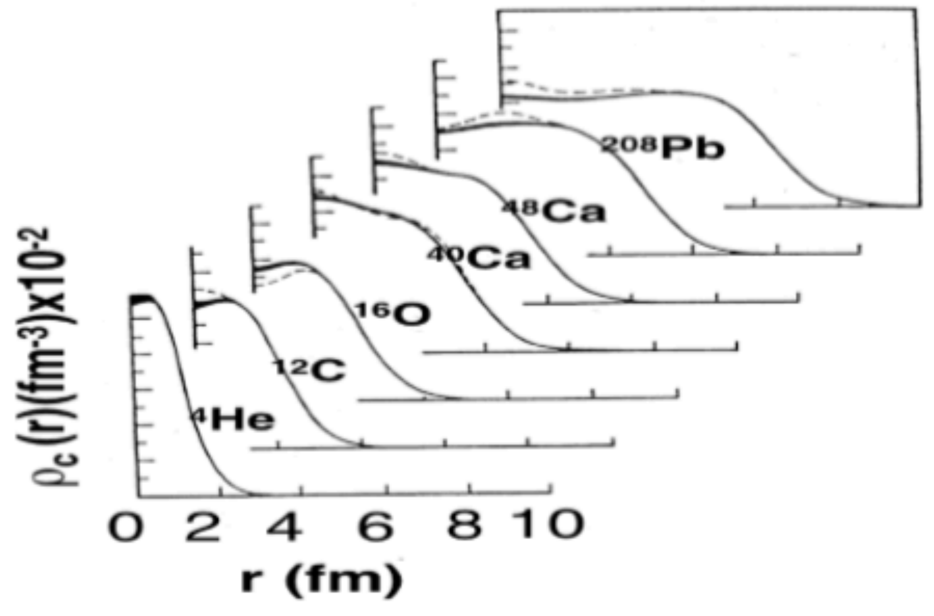
- **beyond elastic scattering**

| 10^26 | 10^27 | 10^28 | 10^29 | 10^30 | 10^31 | 10^32 |
|---|---|---|---|---|---|---|

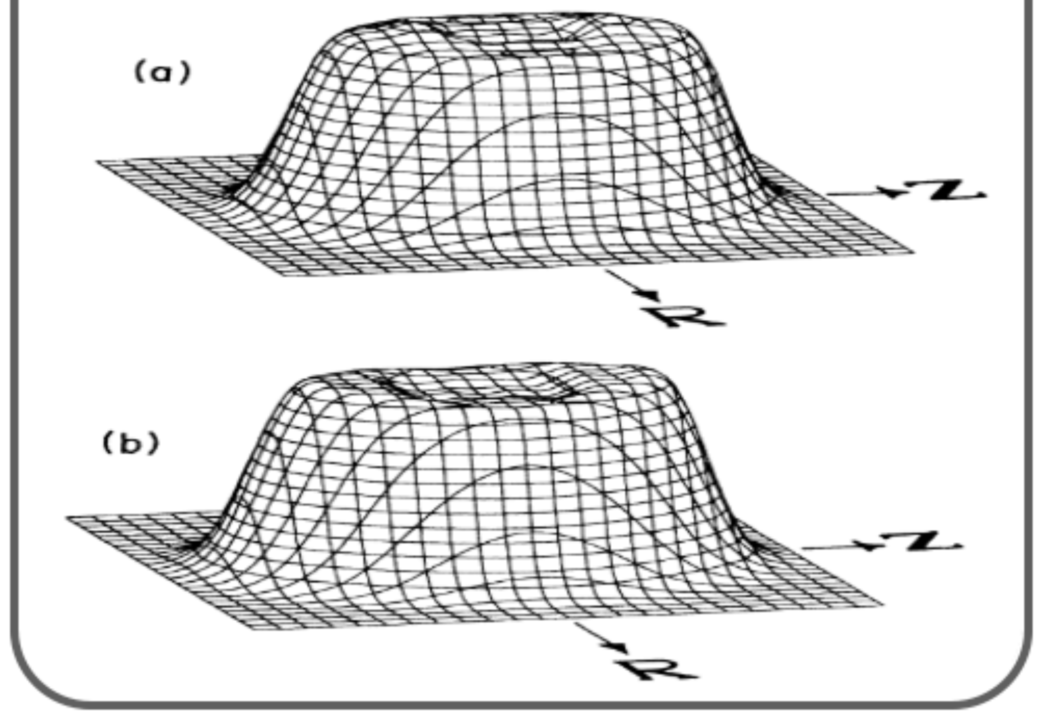
(/cm²/s)

elastic scattering
inelastic scattering
Giant Resonance
quasi-elastic (e,e'p)
magnetic scattering

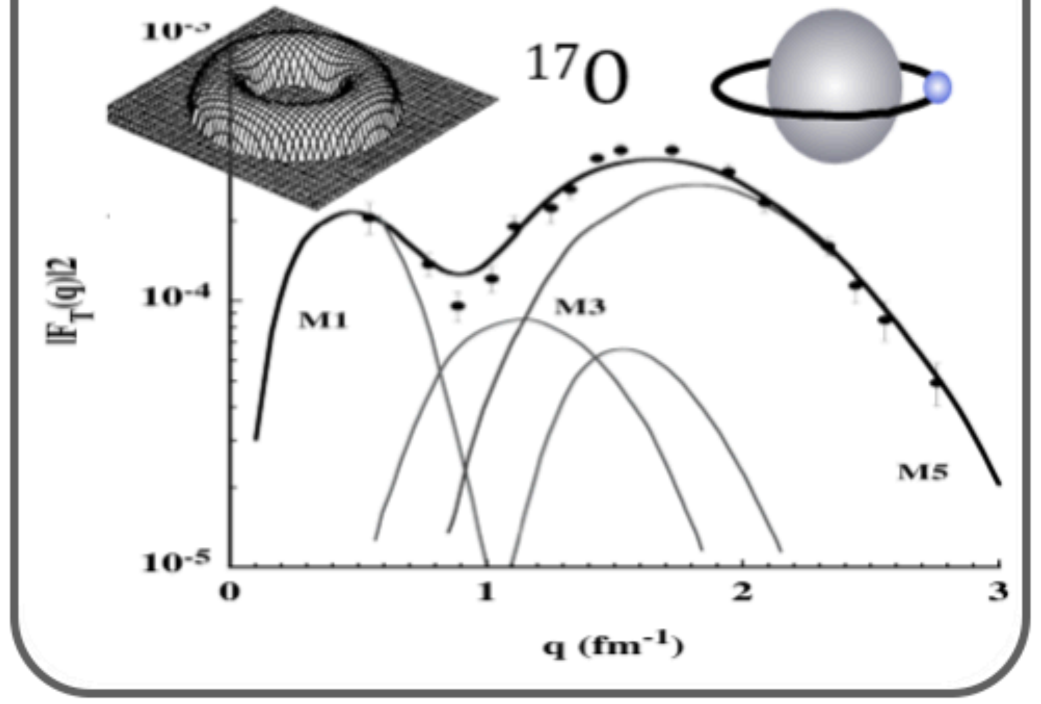
elastic scattering
→ charge distribution



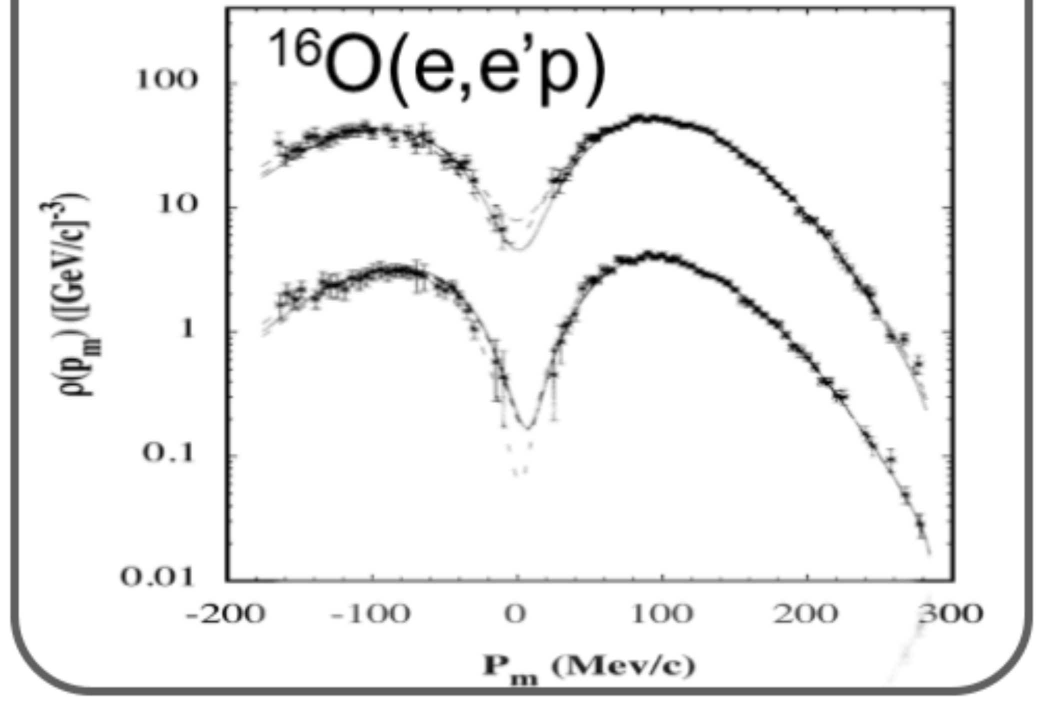

elastic + inelasticscattering
→ deformation




magnetic scattering
→valence neutron




quasi-elastic (e,e'p)
→ S-factor



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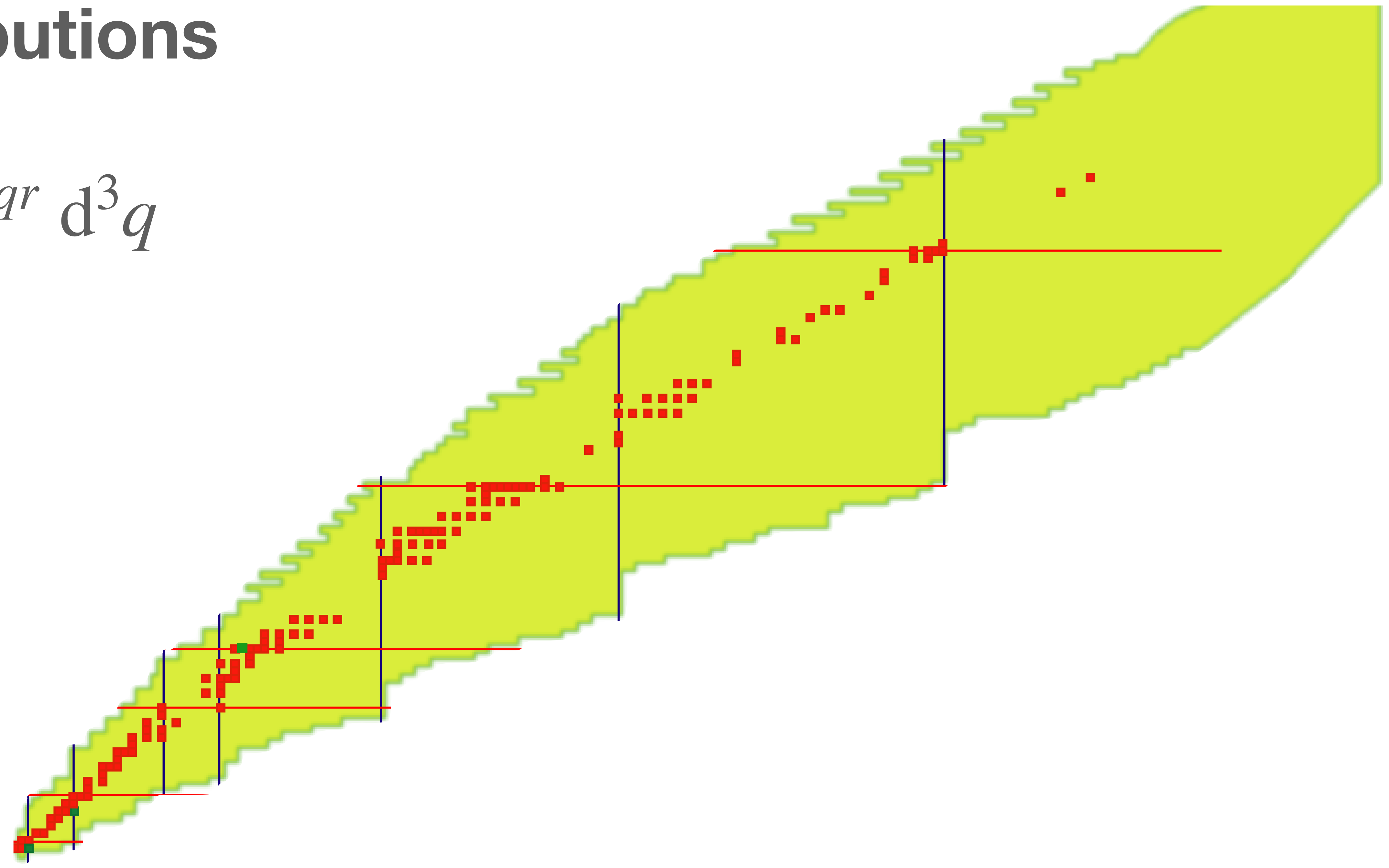

- **beyond elastic scattering**

| | | | | | | |
|---|---|---|---|---|---|---|
| $10^{26}$ | $10^{27}$ | $10^{28}$ | $10^{29}$ | $10^{30}$ | $10^{31}$ | $10^{32}$ |

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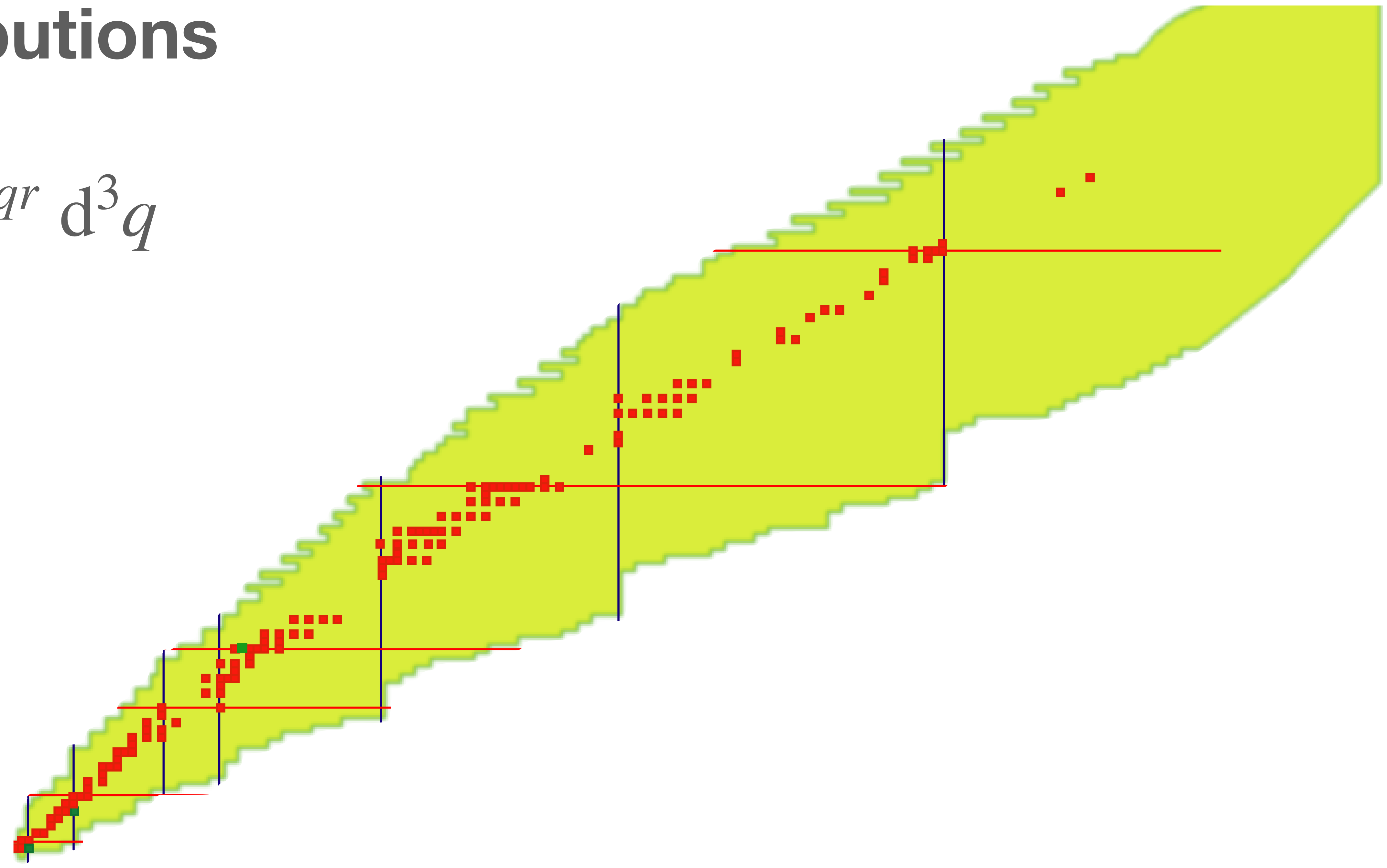

- **beyond elastic scattering**

| | | | | | | |
|---|---|---|---|---|---|---|
| $10^{26}$ | $10^{27}$ | $10^{28}$ | $10^{29}$ | $10^{30}$ | $10^{31}$ | $10^{32}$ |

(/cm$^2$/s)

elastic scattering
inelastic scattering
Giant Resonance
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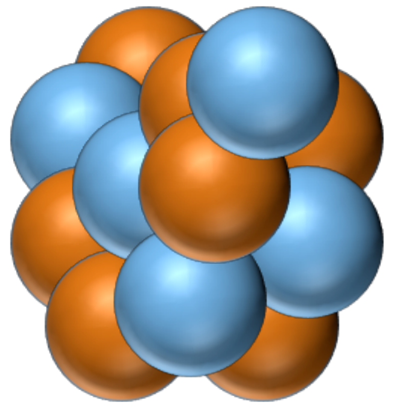
- **additional research opportunity recently pointed out**

4th moment of $\rho_c(r)$ → RMS of neutron distribution

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


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
4) T. Suzuki, Prog. Theor. Exp. Phys. 2023, 013D02




## 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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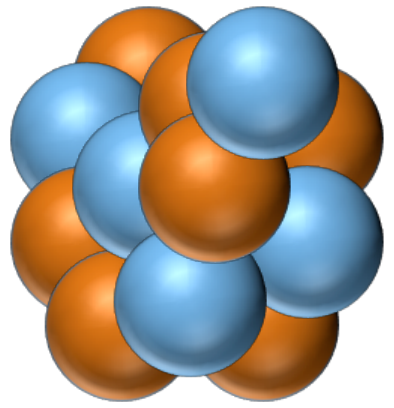

Proton

Neutron

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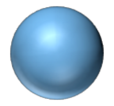
## 2) 2nd moment

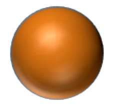
Proton

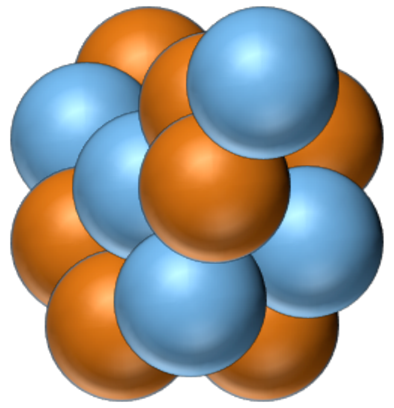


$$< r_c^2 > = \int r^2\, \rho_c(r)\, \mathrm{d}^3 r \quad = < r^2_{p(point)} > + < r_p^2 >$$

$$+ \frac{N}{Z} < r_n^2 > + \mathrm{rel\,.\,corr\,.}$$

Neutron





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Proton

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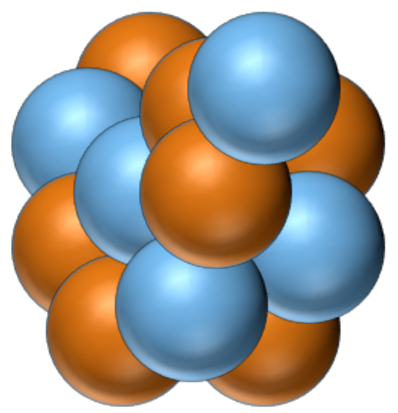
Neutron

## 3) 4th moment

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

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

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

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Proton

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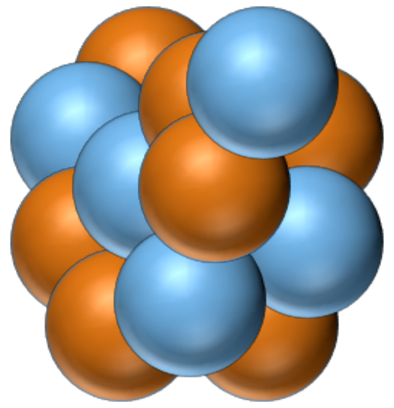
RMS n-radius

# neutron distribution by electron scattering??

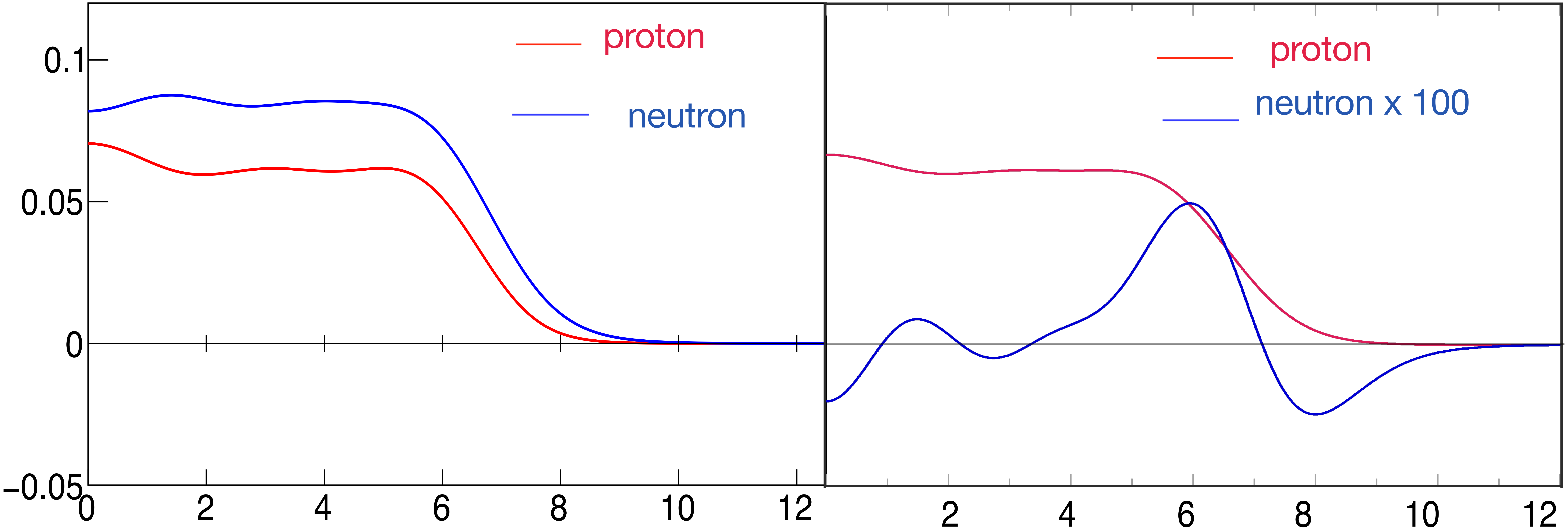


**Proton**

**Neutron**

RMF NL3 (H. Kurasawa)

**(point) nucleon density** | **charge density distributions**



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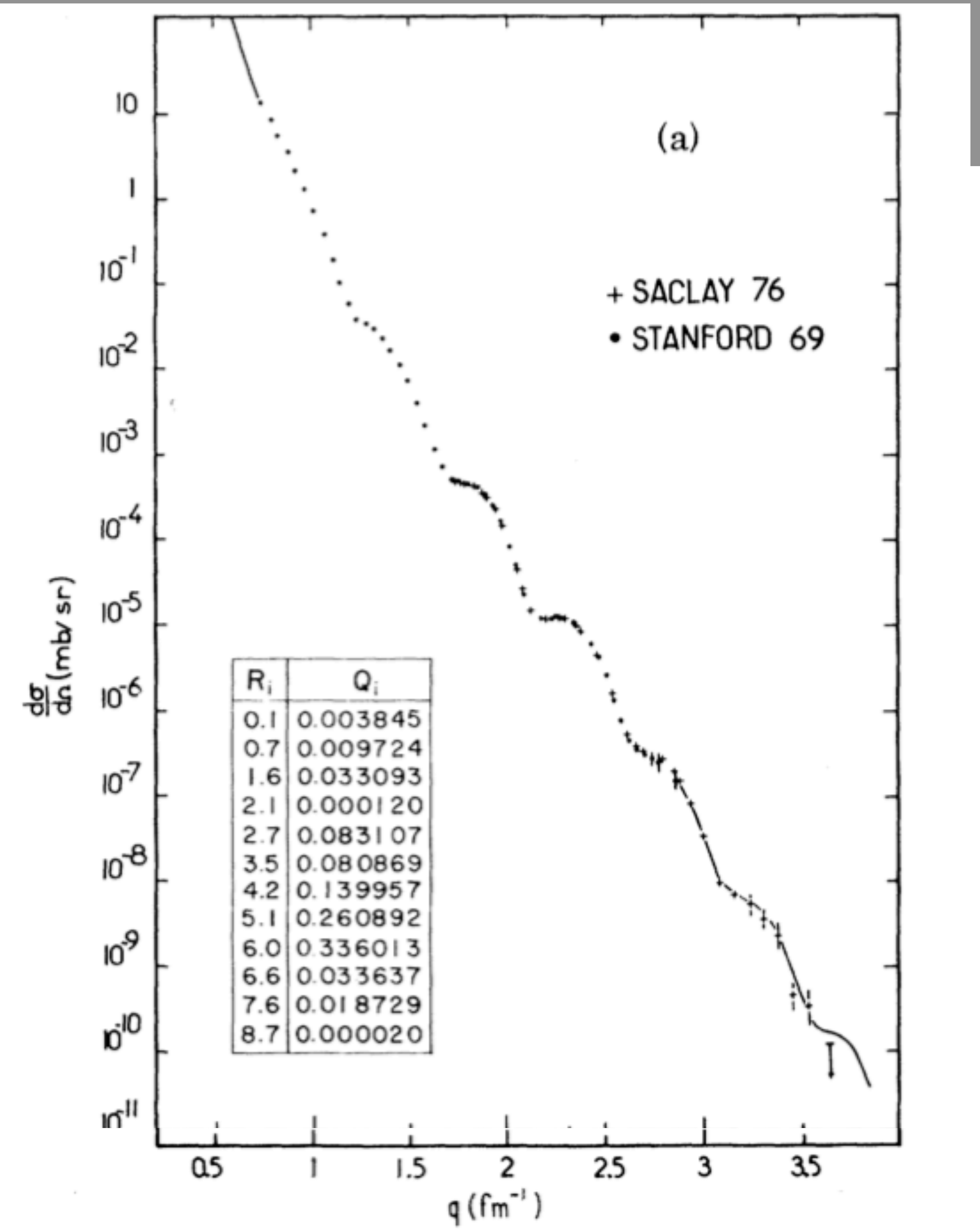


## 1) elastic scattering covering upto very high *q*

$^{208}$Pb $\quad R_n = 5.728 \pm 0.057$ fm $\quad \Delta r_{np} = 0.275 \pm 0.070$ fm

$^{48}$Ca $\quad R_n = 3.597 \pm 0.021$ fm $\quad \Delta r_{np} = 0.220 \pm 0.026$ fm

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

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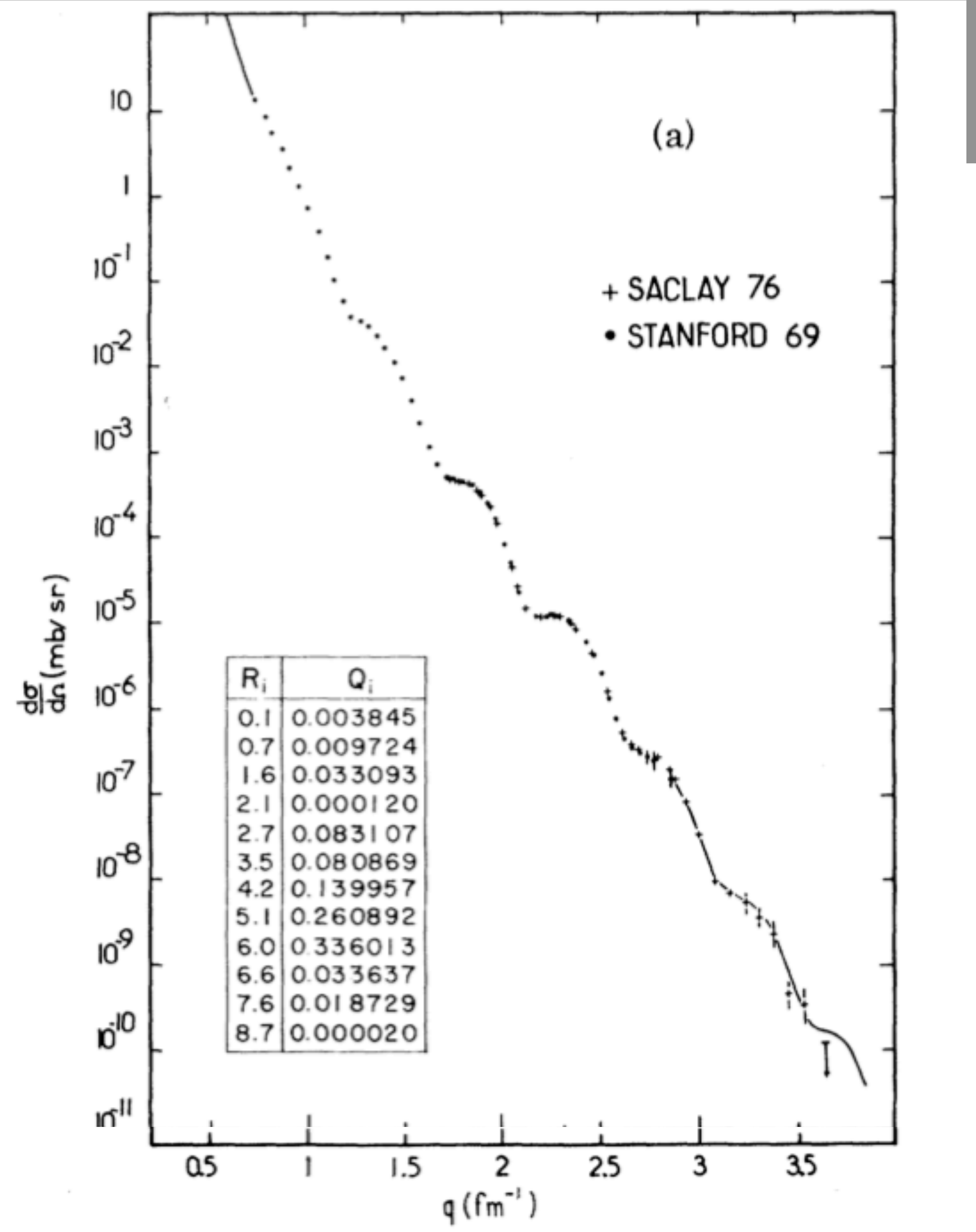


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H. Kurasawa, T. S. and T. Suzuki, Prog. Theor. Exp. Phys. 2021, 013D02

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

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

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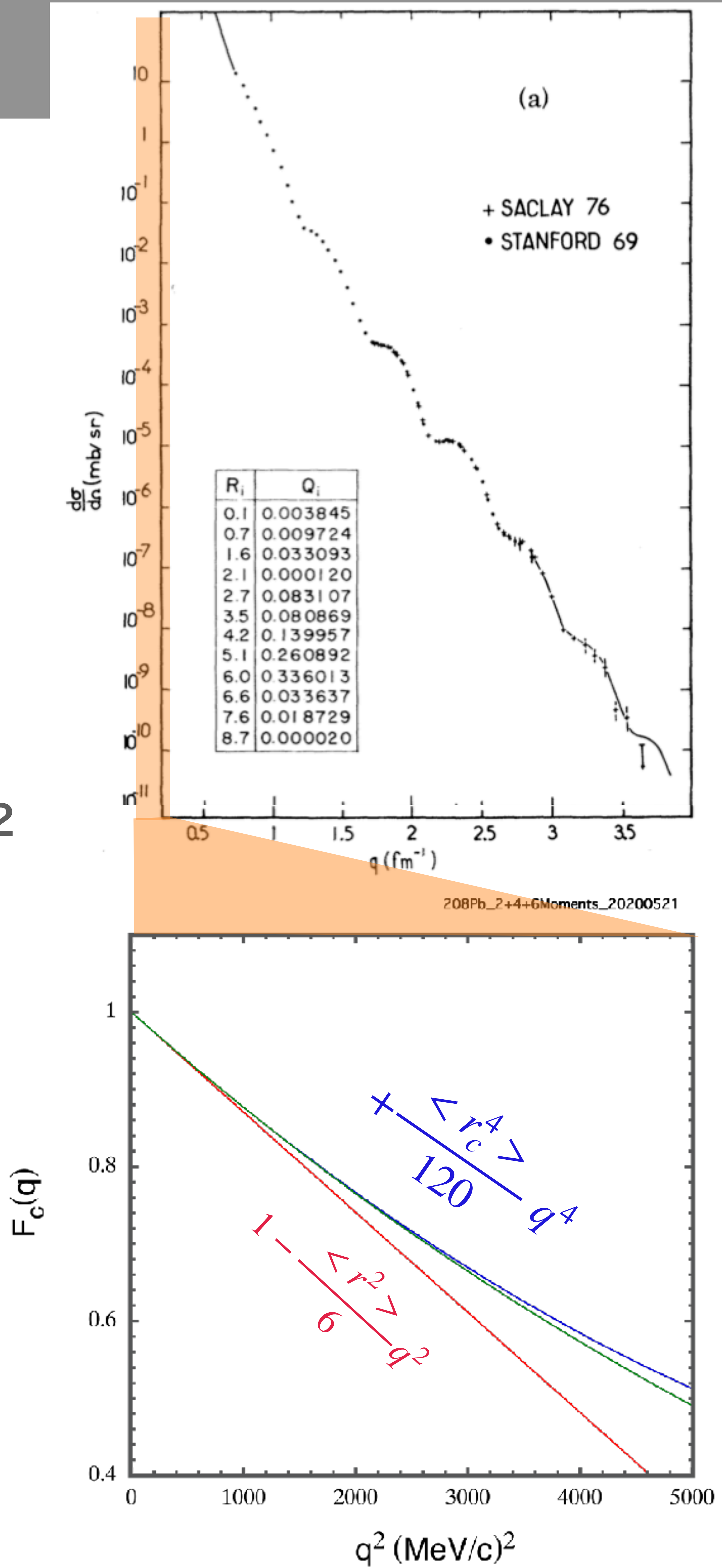

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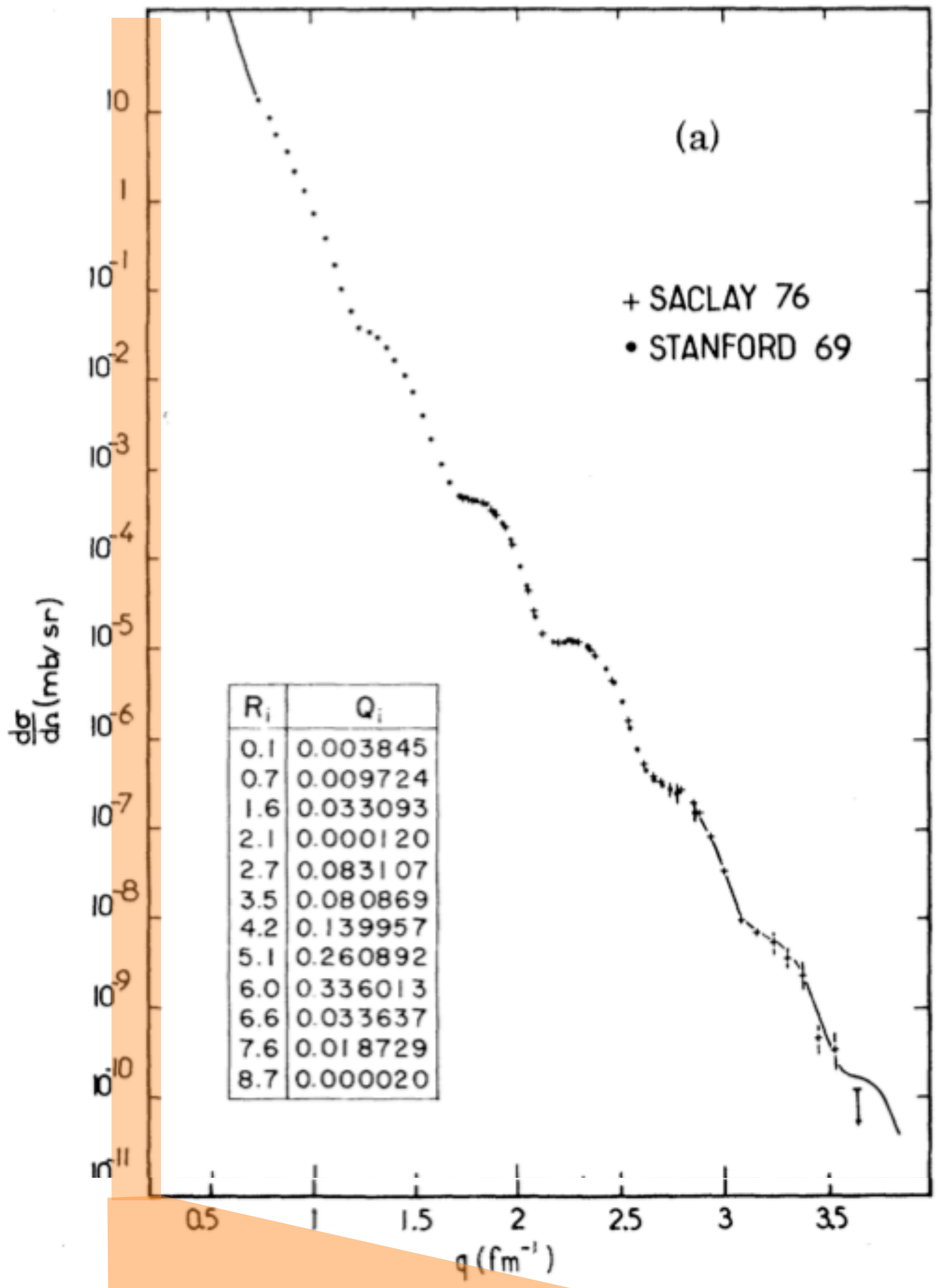
H. Kurasawa, T. S. and T. Suzuki, Prog. Theor. Exp. Phys. 2021, 013D02




| $R_i$ | $Q_i$ |
|---|---|
| 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 |

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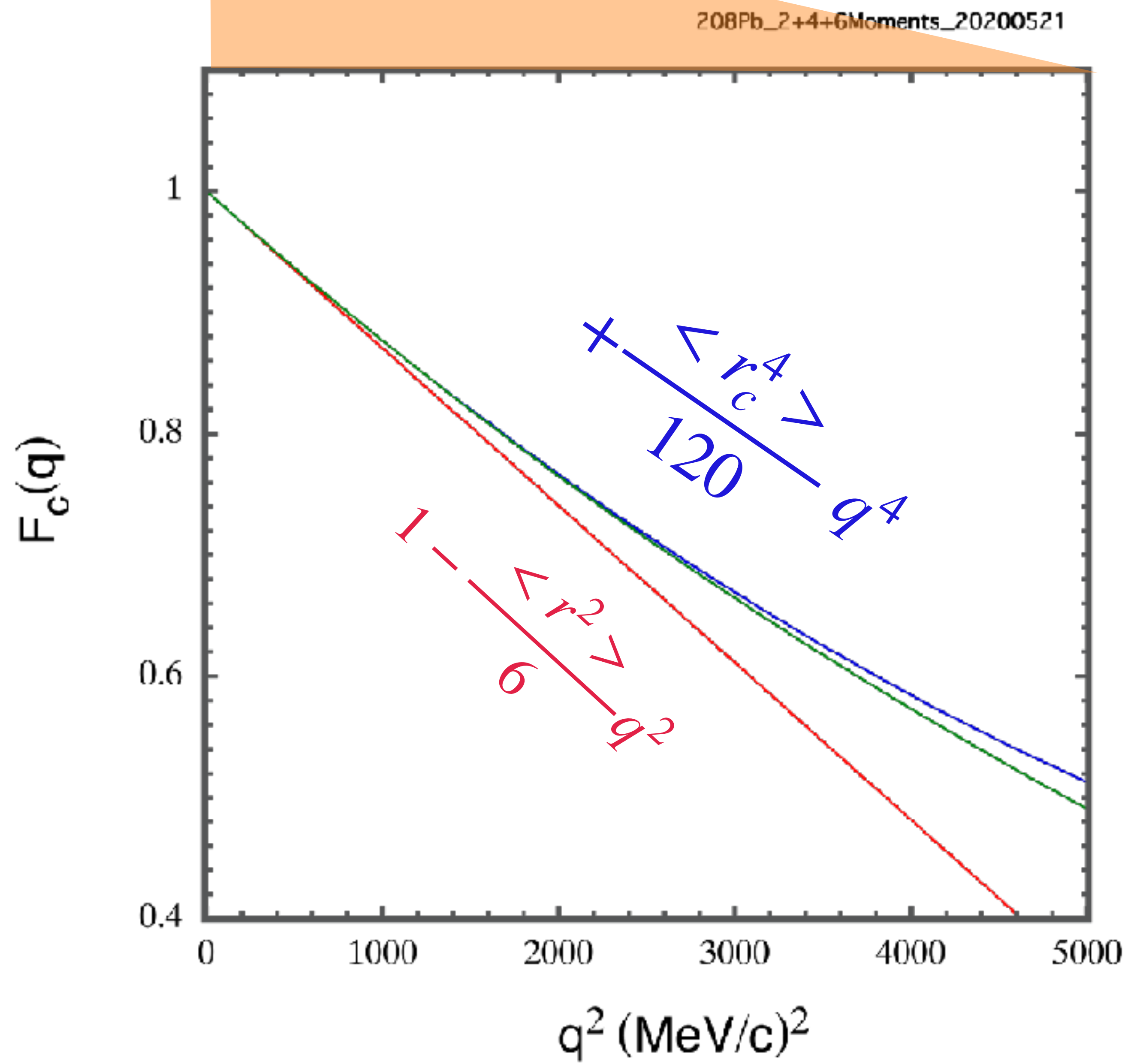
$$\frac{d\sigma_{\rm Mott}}{d\Omega} \propto 1/q^4$$

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



# conclusions

- **The SCRIT facility started its operation**
  - the world's first and currently only-one facility
  - successful demonstration with online-produced radioactive isotope
  - ISOL upgrade to 2kW is underway for $^{132}Sn(e,e')$

# conclusions

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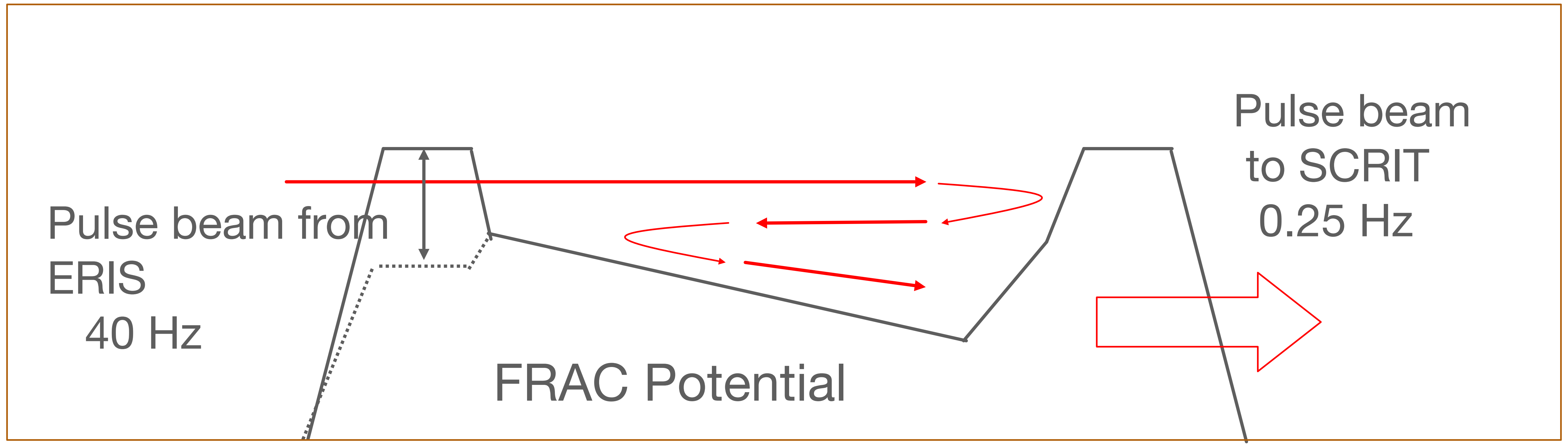
  - successful demonstration with online-produced radioactive isotope
  - ISOL upgrade to 2kW is underway for $^{132}$Sn(e,e')

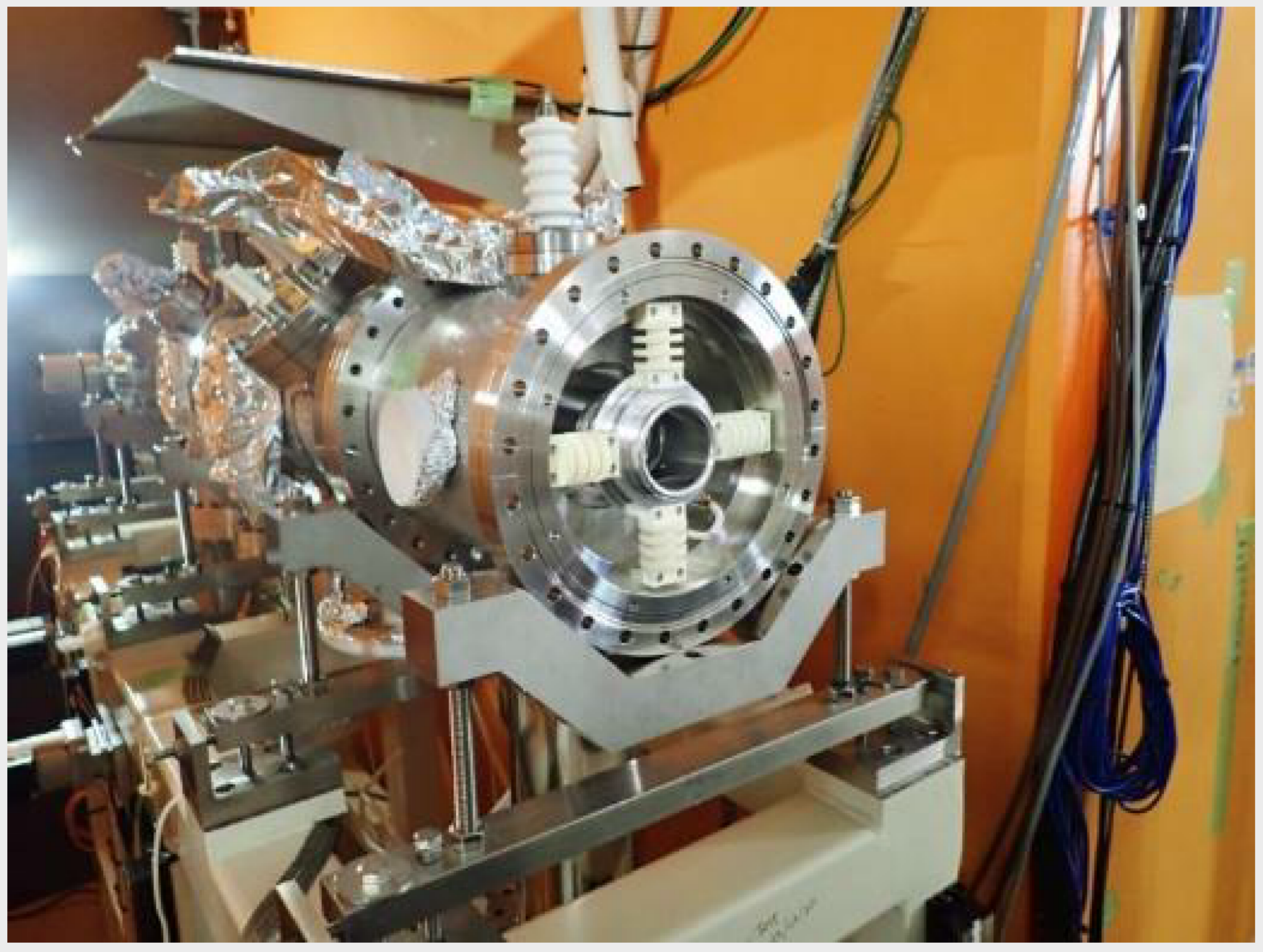
- **electron scattering for exotic nuclei is no long just a dream**
  - charge density distributions by elastic scattering
  - inelastic scattering with higher *L*
  - higher moments of charge density => neutron distributions

# FRAC : Cooler and Buncher

**Ion beams are stacked in the FRAC for:**

- ✓ **Cooling by collision with Ne buffer gas**
- ✓ **Increasing #RI-ions in single pulses**



**M. Wakasugi, Rev. Sci. Instrum. 89 (2018) 095107**
**H. Ohnishi, Nucl.Instr.Meth.B541(2023)380-384**

**Total dc-to-pulse conversion eff. ~ 80 %**

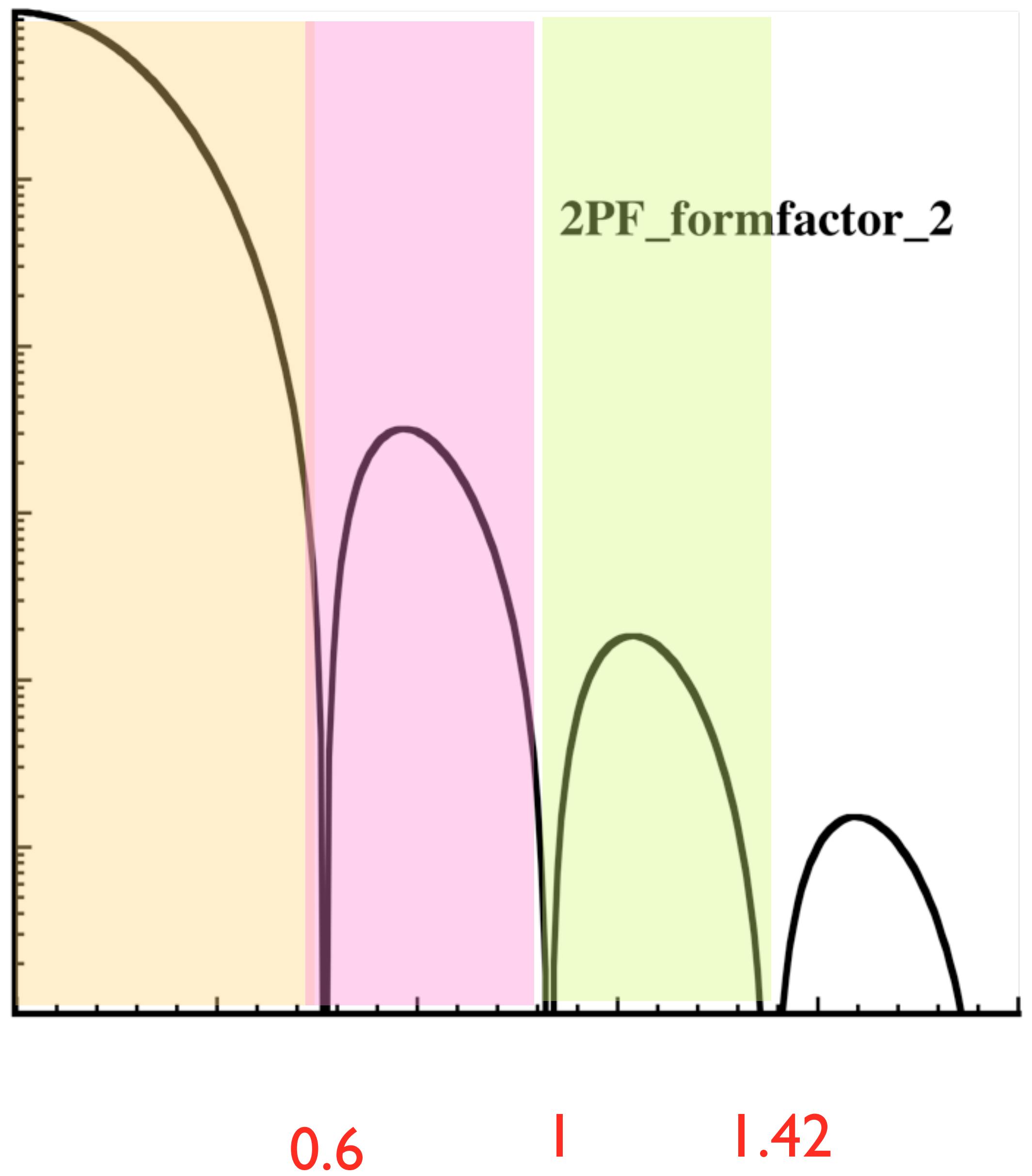
→ **#$^{137}$Cs ions injected into SCRIT : 2×10$^{7}$ ions/pulse**

*FRAC: Fringing-RF-field-activated dc-to-pulse converter for low-energy ion beams*

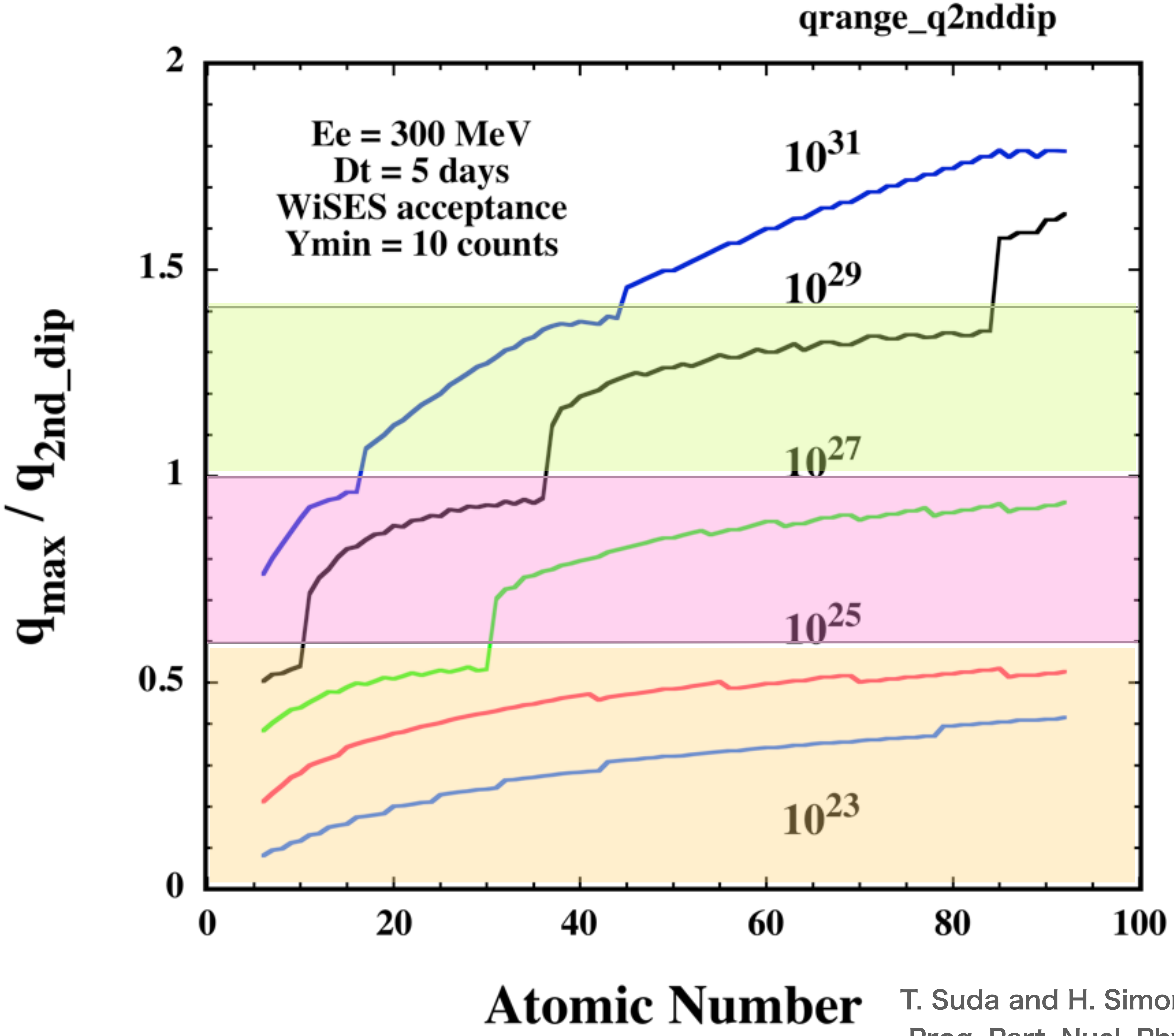
# Accessible q-range for *L* and *Z*

$$\sigma \propto Z^2$$

$$\sigma \propto 1/q^4$$



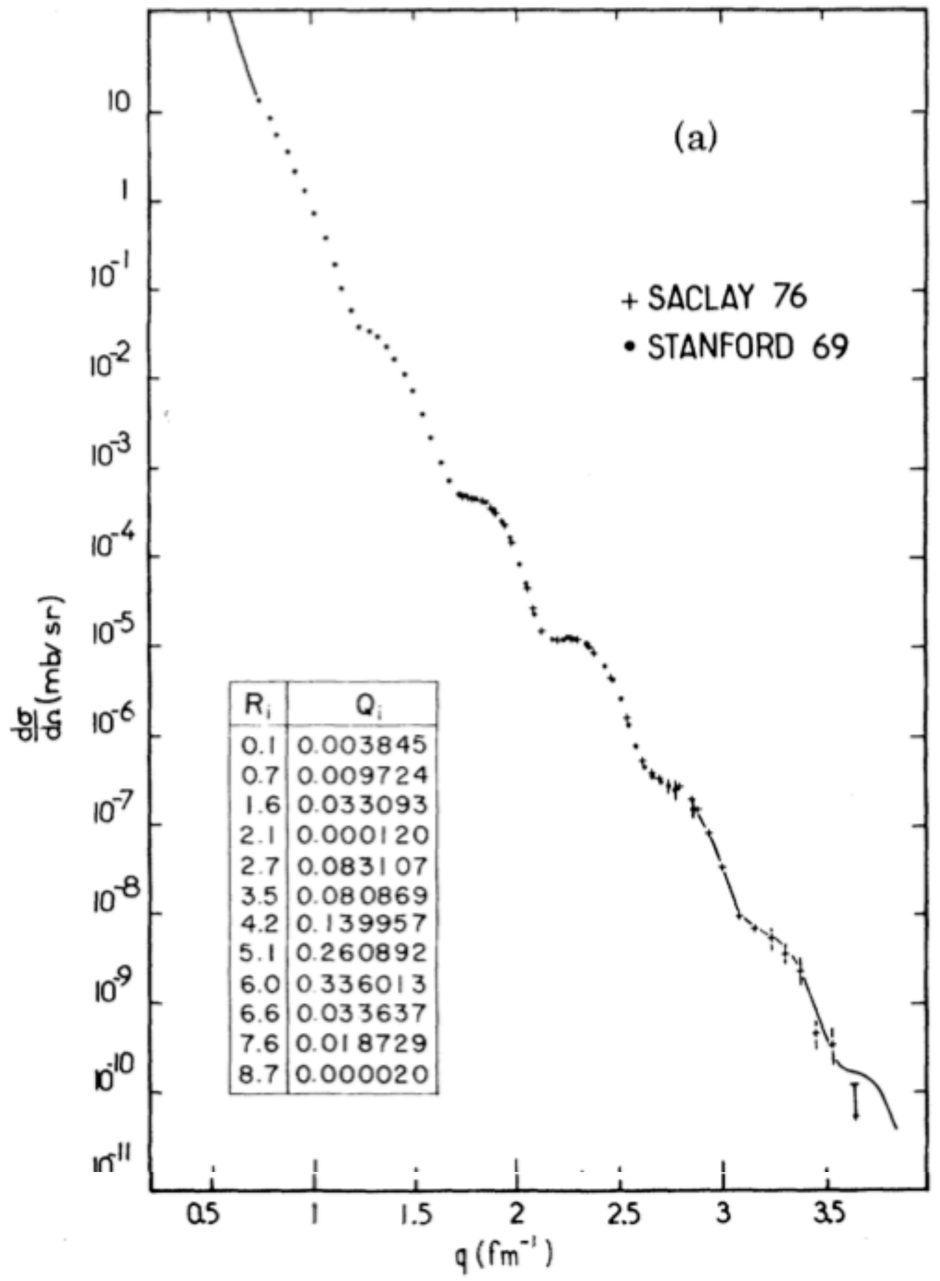

$q_{max}/q_{2nd-dip}$




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

# 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)

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

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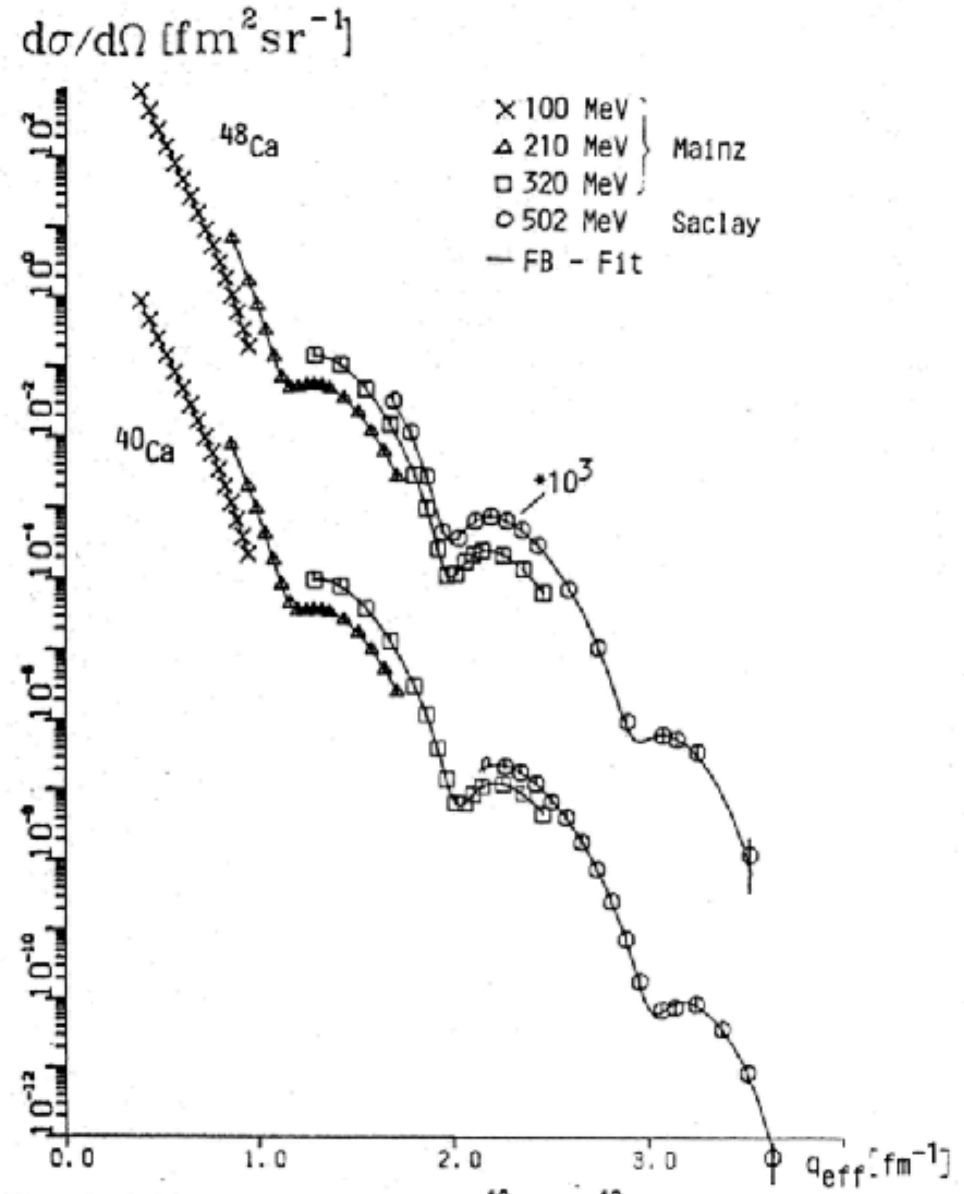
**$^{48}$Ca**



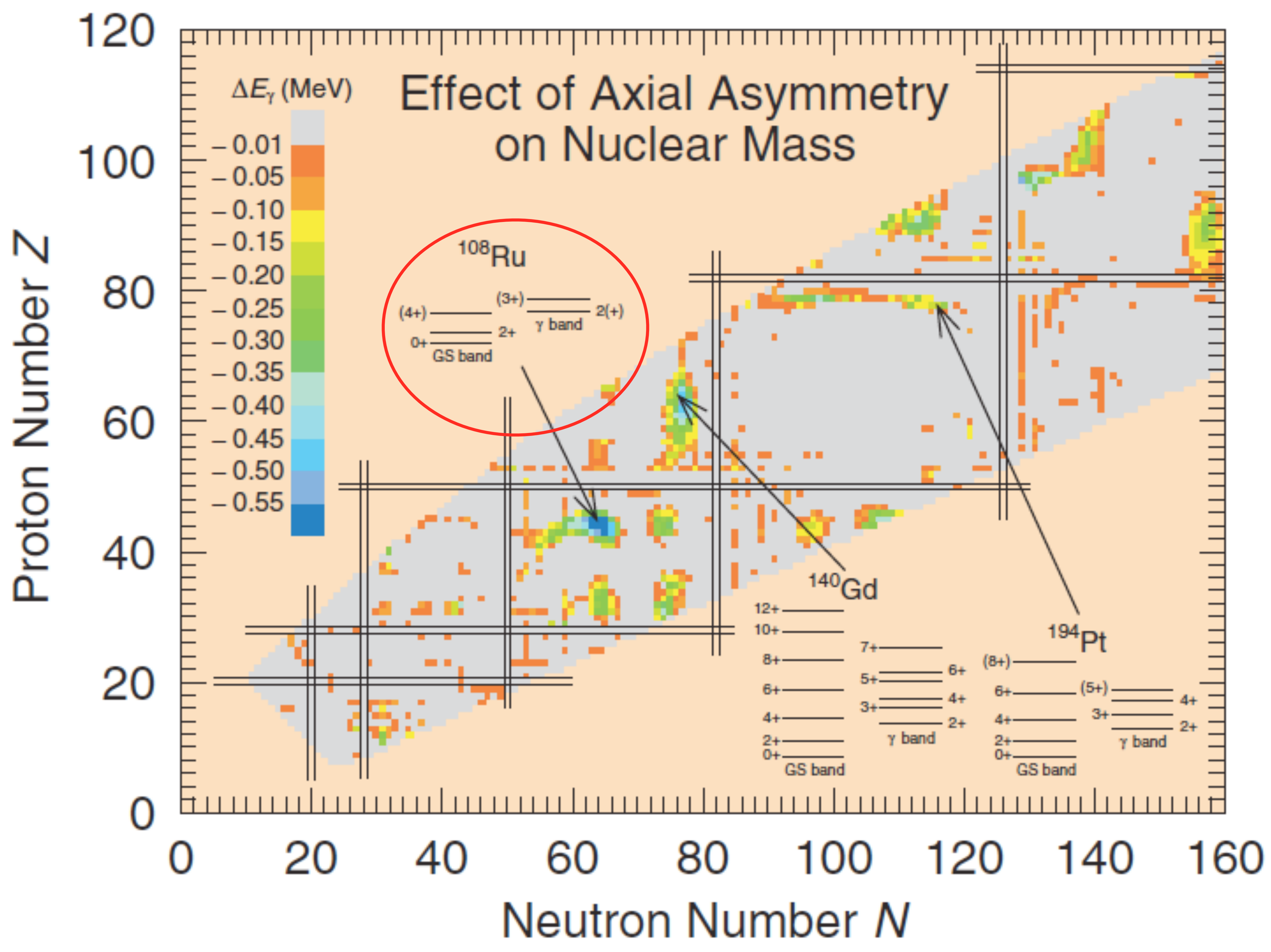

Figur 2.12 : Wirkungsquerschnitte für $^{40}$Ca und $^{48}$Ca, aufgetragen über $q_{eff}$. Die durchgezogene Linie ist durch Anpassen einer Fourier-

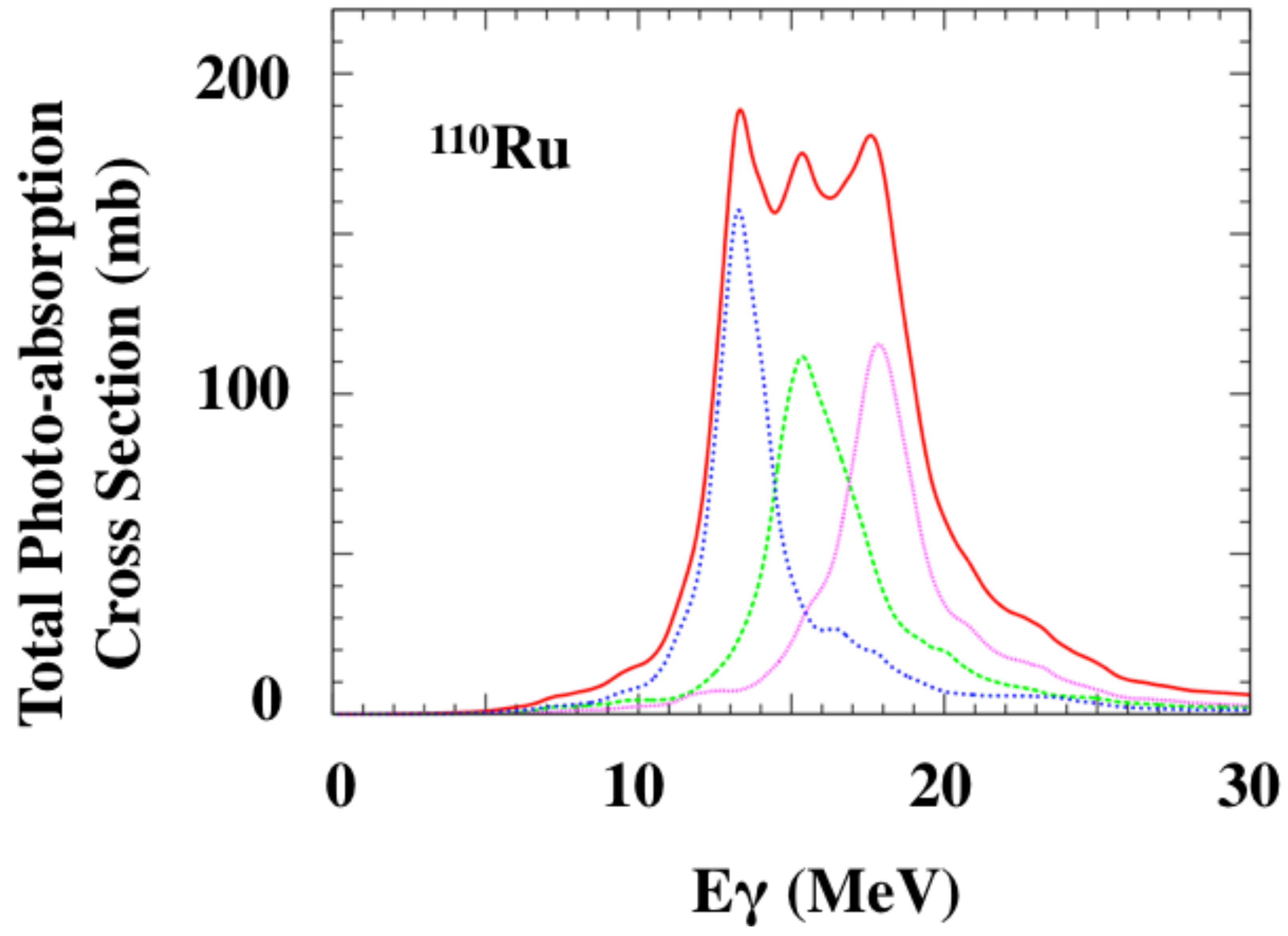
| | | $R_p$ | $R_n$ | $\delta R$ |
|---|---|---|---|---|
| $^{48}$Ca | Rel. | 3.378(0.005) | 3.597(0.021) | 0.220(0.026) |
| | Non. | 3.372(0.009) | 3.492(0.028) | 0.121(0.036) |
| | Exp. | $R_c = 3.451(0.009)$ | | |

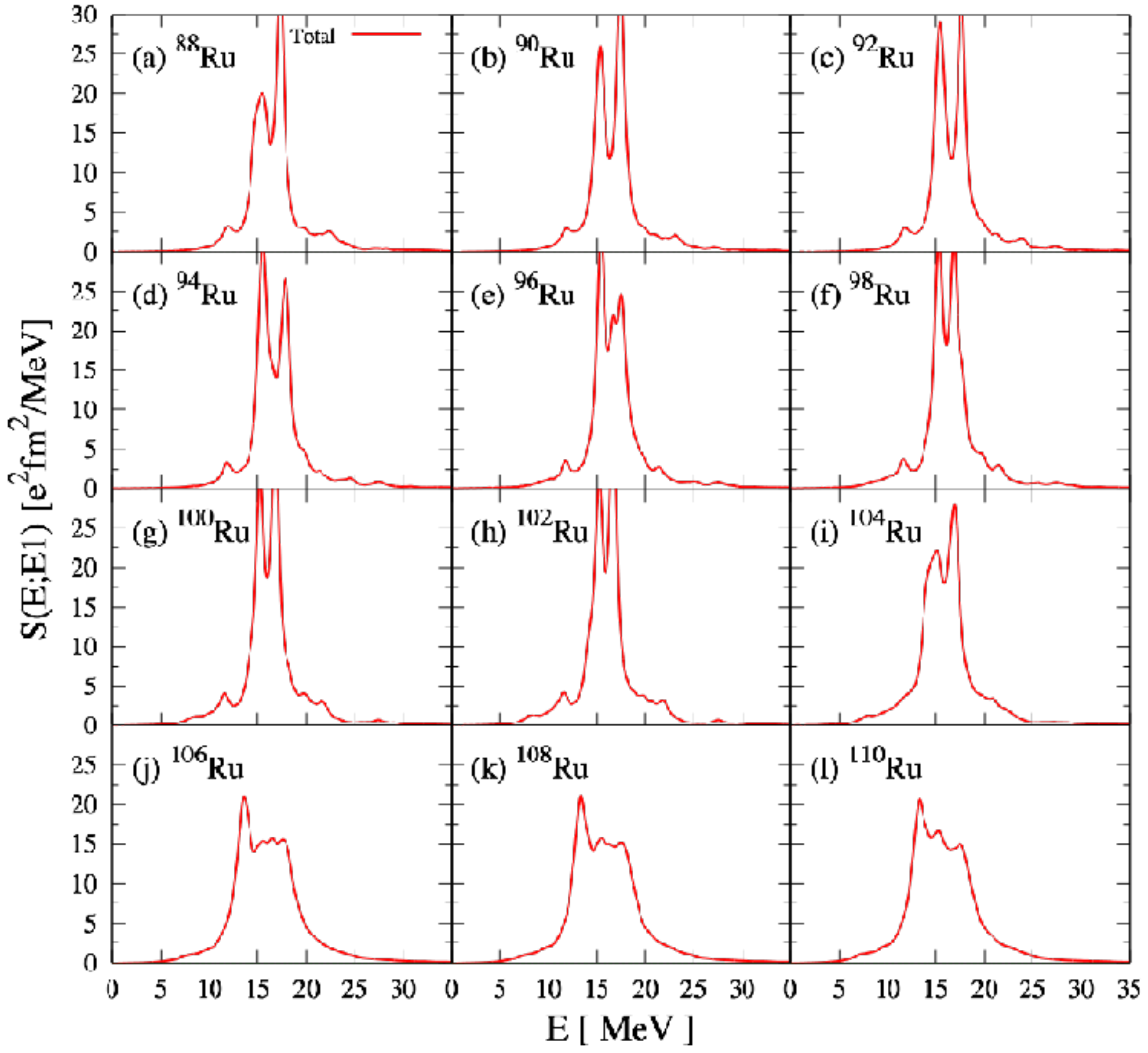
JLab : CREX (parity-violating e-scattering)

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

# triaxial nucleus expected in exotic nuclei



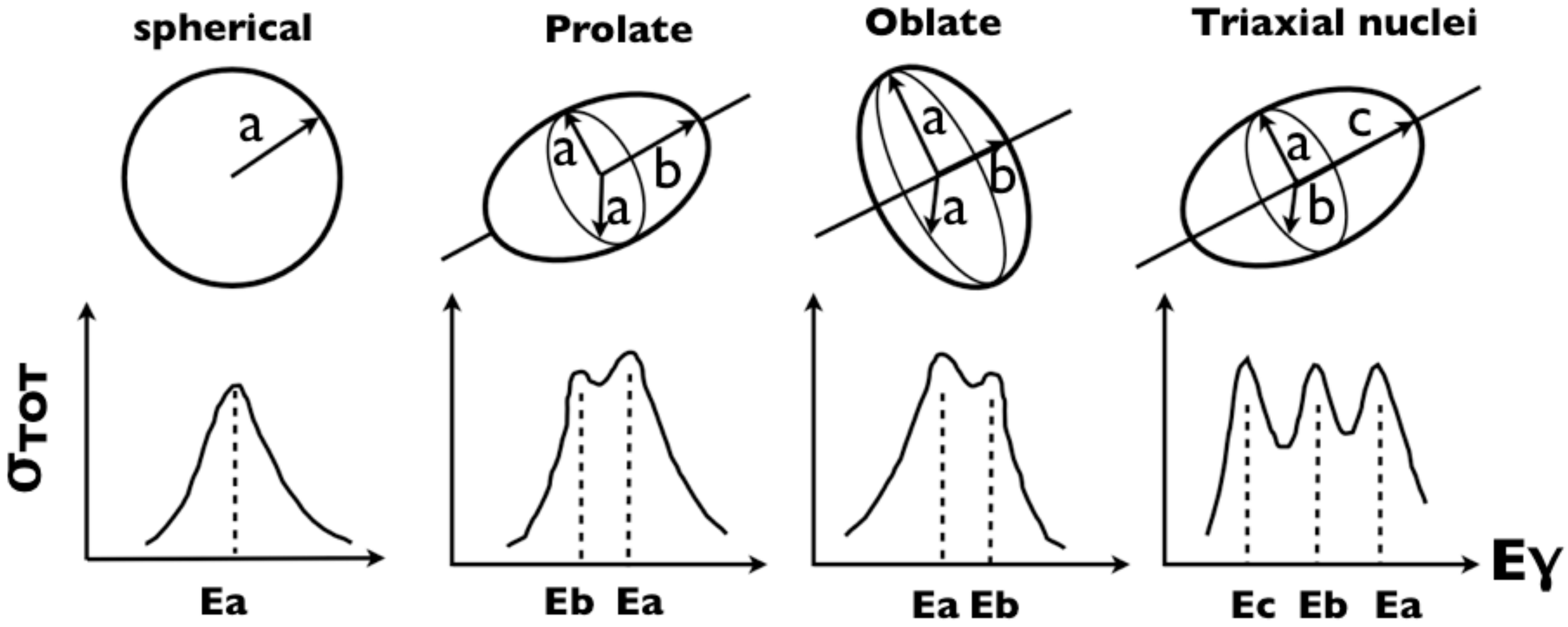

**$^{108}$Ru 273 sec**

**$^{110}$Ru 15 sec**

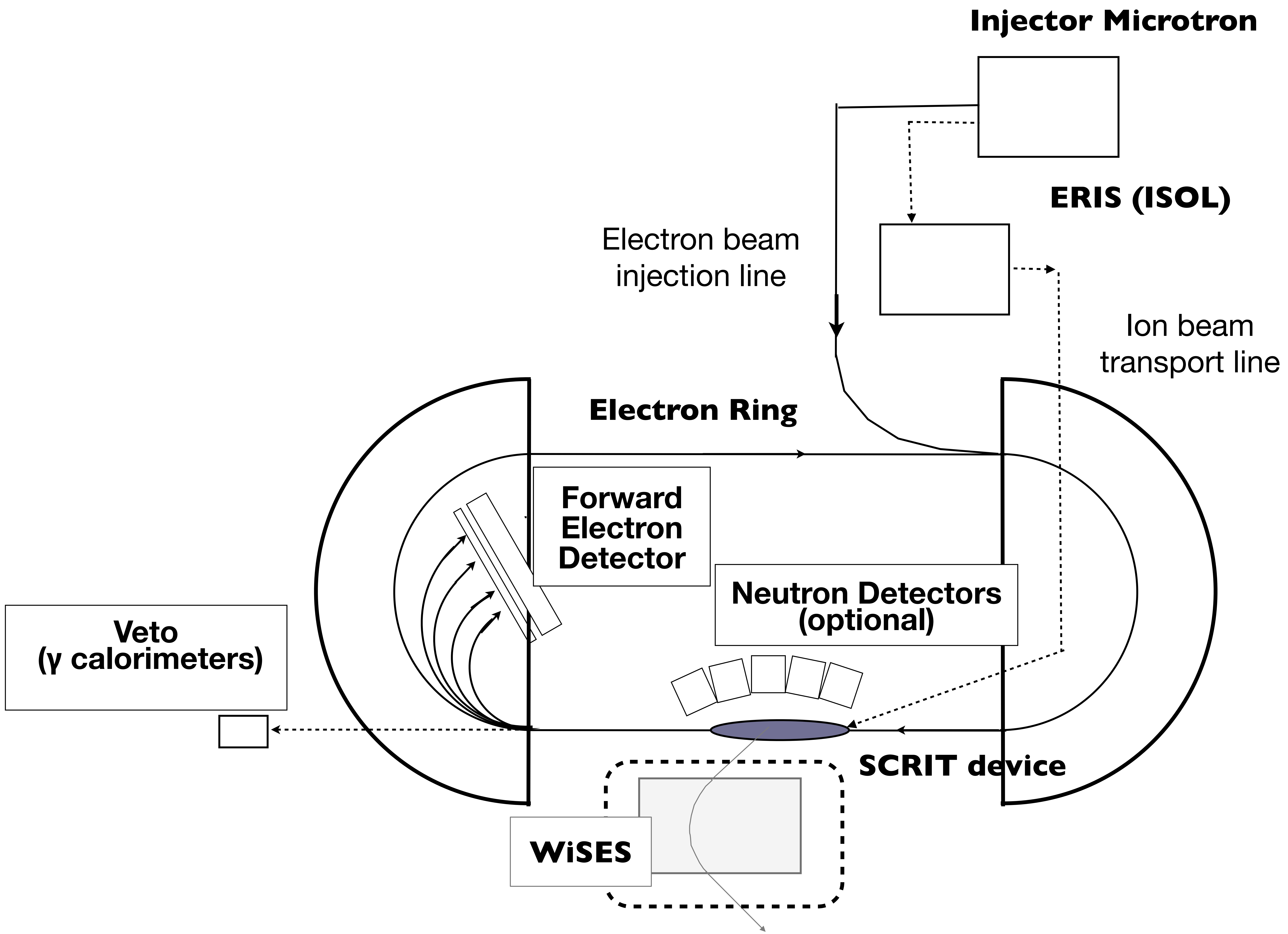
*P. Moller et al.,PRL97,162502 (2006)*

*S. Ebata : private communication*

# photo-nuclear responses of exotic nuclei

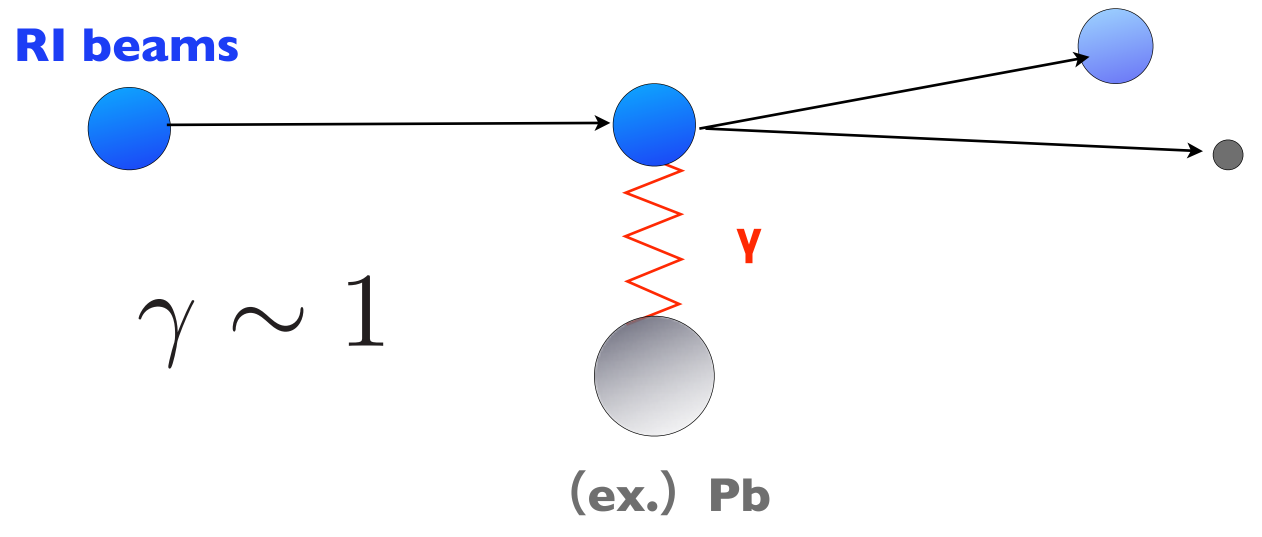



R. Bergere :Lecture Note in Physics, 61 (1971) 84

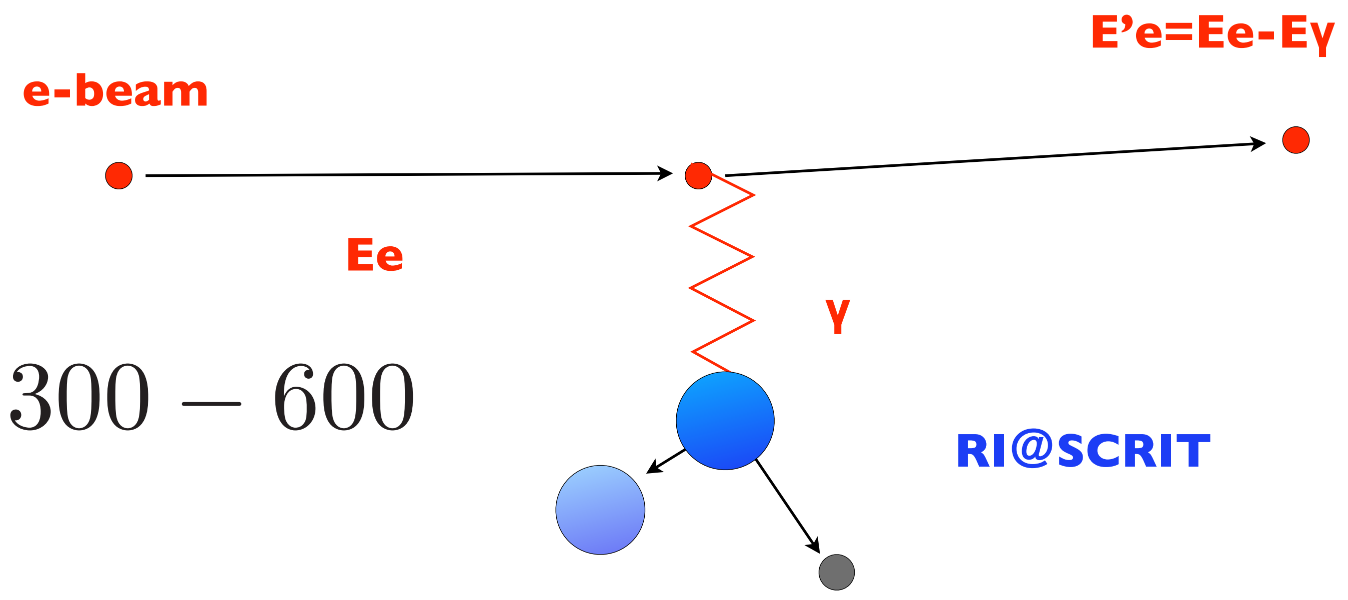

Injector Microtron
ERIS (ISOL)
Electron beam
injection line
Ion beam
transport line
Electron Ring
Forward
Electron
Detector
Neutron Detectors
(optional)
Veto
(γ calorimeters)
SCRIT device
WiSES

so far

only way : Coulomb excitation in heavy ion reaction



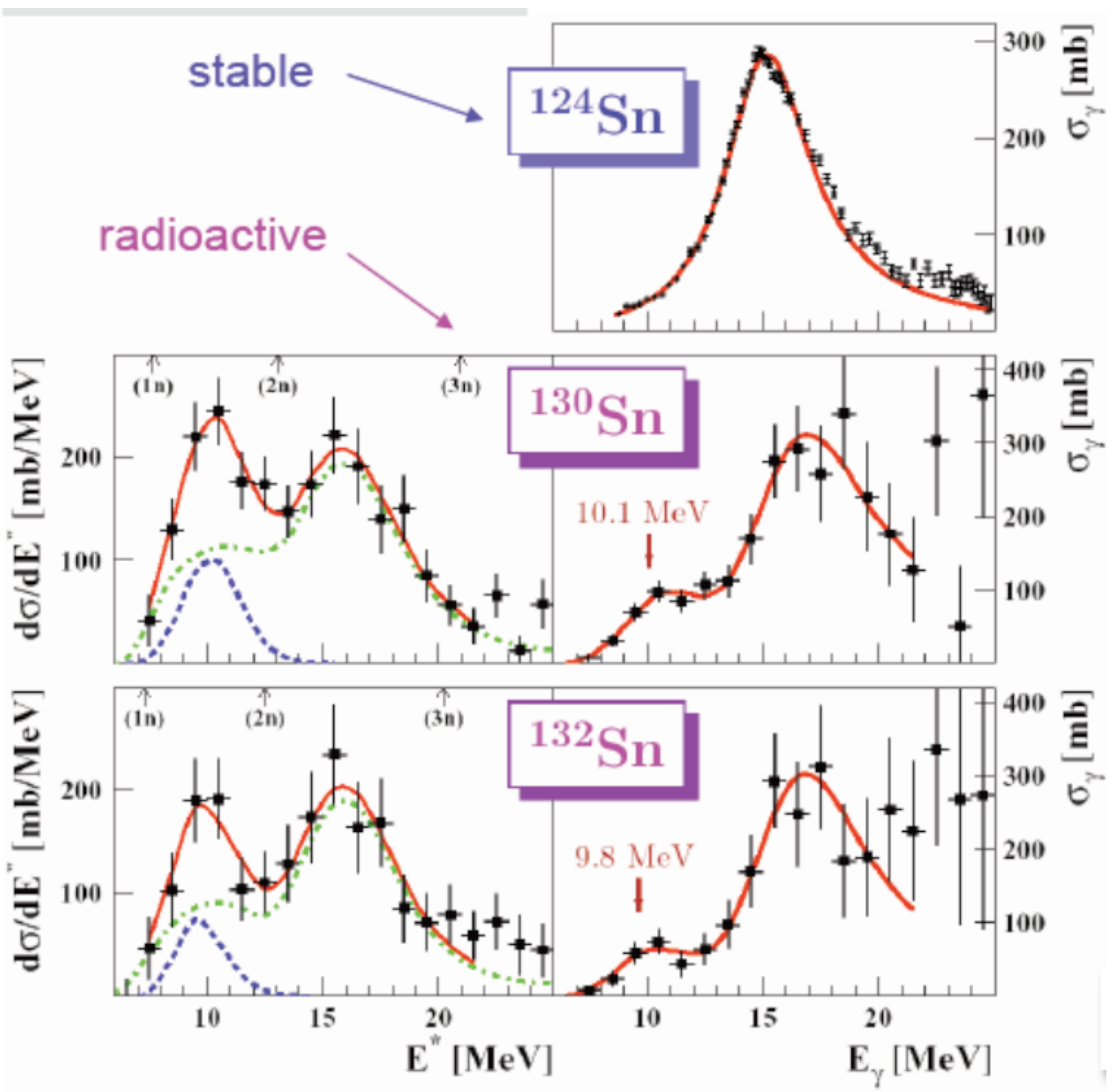

SCRIT facility




purely EM probe
  well under control
  negligible multi-stop

ultra-forward
    electron scattering

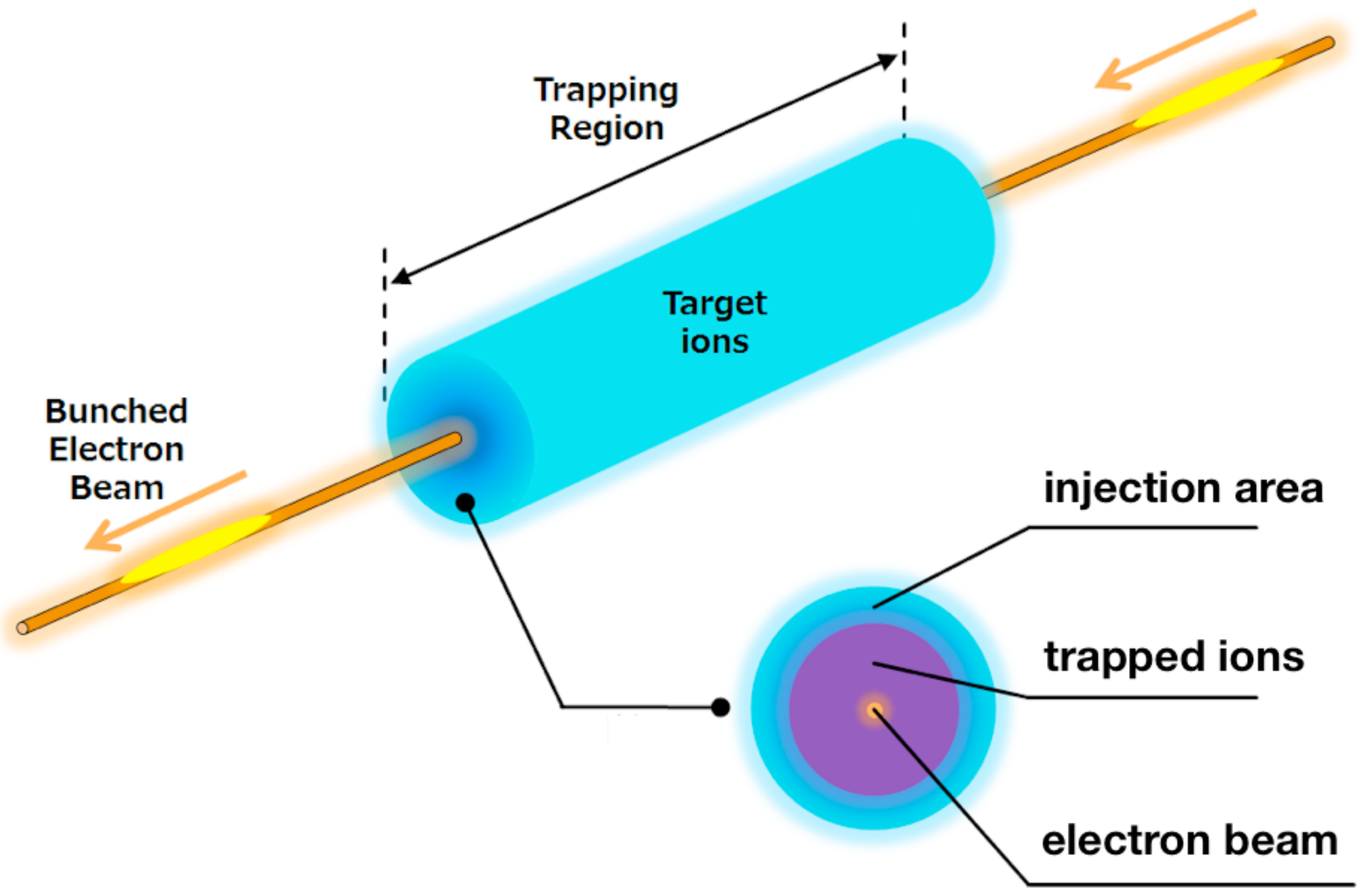
$^{132}Sn$+Pb -> $^{131}Sn$ + n + X @ GSI




Virtual Photon flux

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

# Ion trapping and luminosities




trapping efficiency ~ 100 %
overlapping efficiency ~ 17 %