Low-energy electron scattering

1) *beyond proton radius at ULQ2*
2) *online-produced exotic nuclei at SCRIT*

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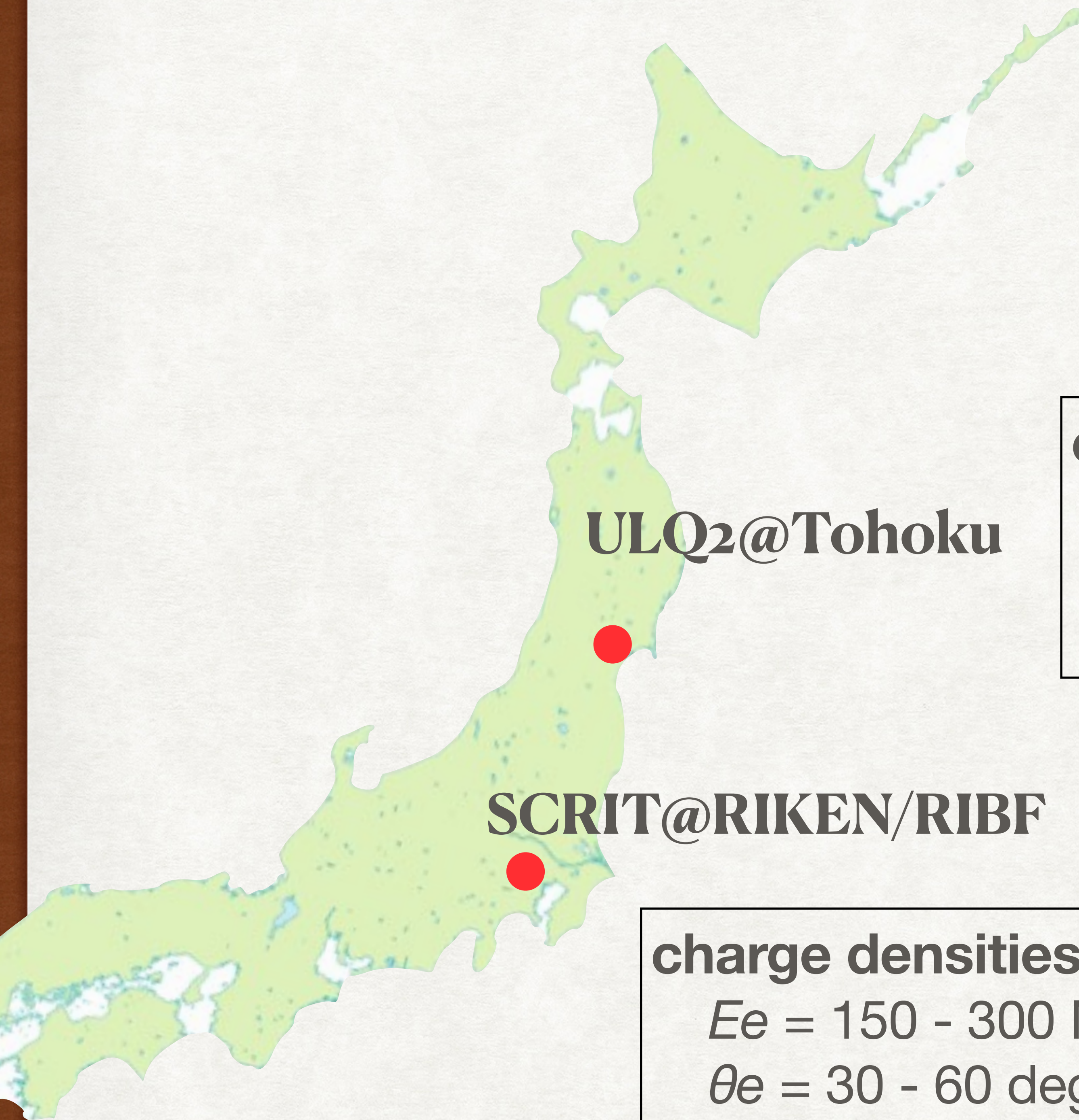
Tohoku University, Sendai, JAPAN

For the ULQ2 and SCRIT collaboration

Low-q electron-scattering activities in Japan



charge radii of proton and deuteron

E_e = 10 - 60 MeV
θ_e = 30 - 150 deg.
=> $Q^2 = 3\times10^{-5} - 0.013\ (\text{GeV/c})^2$

charge densities of short-lived exotic nuclei

E_e = 150 - 300 MeV
θ_e = 30 - 60 deg.
=> q = 80 - 300 MeV/c
$Q^2 = 0.006 - 0.09\ (\text{GeV/c})^2$

4^{th} moment of the charge distribution

Arseniy Filin et al., in preparation

E. Epelbaum's talk

The fourth-order moment $\langle r_d^4 \rangle := 60\, G_C''(0)$ is being measured in the ULQ2 exp Toshimi Suda et al.

$$\langle r_d^4 \rangle = r_{\rm str}^{(4)} + \frac{10}{3} r_{\rm str}^{(2)} \left(r_n^{(2)} + r_p^{(2)} + \frac{3}{4m^2} \right) + \left(r_n^{(4)} + \frac{5}{2m^2} r_n^{(2)} \right) + \left(r_p^{(4)} + \frac{5}{2m^2} r_p^{(2)} + \frac{45}{16m^4} \right)$$

Results for $\Lambda = 500$ MeV:
(very preliminary, likely to change)

$$r_{\rm str}^{(4)} = \underbrace{r_{\rm matter}^{(4)}}_{55.442} + \underbrace{r_{\rm boost}^{(4)}}_{0.215} + \underbrace{r_{\rm SO}^{(4)}}_{-0.007} + \underbrace{r_{\rm 2N,OPE}^{(4)}}_{0.025} + \underbrace{r_{\rm 2N,CT}^{(4)}}_{0.008} = 55.68(5)\ {\rm fm}^4$$

Error budget (preliminary):

Truncation (N^4LO): ± 0.035, πN LECs: ± 0.005, NN LECs: ± 0.04, other errors negligible

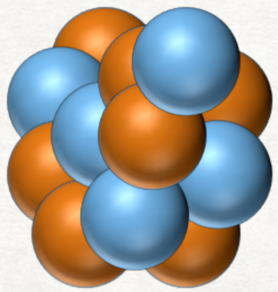
As an application, one can predict $\langle r_d^4 \rangle = 64.62 \pm 0.05_{\chi \rm EFT} \pm \underbrace{0.05_{r_N^{(2)}}}_{\text{CODATA + PDG}} \pm \underbrace{0.36_{r_N^{(4)}}}_{\substack{r_p^{(4)} = 1.3 \pm 0.3\ {\rm fm}^4 \\ r_n^{(4)} = -0.5 \pm 0.2\ {\rm fm}^4}}\ {\rm fm}^4$
(very preliminary, likely to change)

Alternative determination of the nucleon isoscalar radius?

1% accuracy $\Rightarrow$ 8% accuracy for $r_n^{(2)} + r_p^{(2)}$ ...

$$r_p^{(2)} + r_n^{(2)} = \frac{\overbrace{\left[\langle r_d^4 \rangle - r_p^{(4)} - r_n^{(4)}\right]} - r_{\rm str}^{(4)} - \frac{15}{16m^4}}{\frac{10}{3} r_{\rm str}^{(2)} + \frac{5}{2m^2}} - \frac{3}{4m^2}$$

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

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

3) 4th moment

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

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

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

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

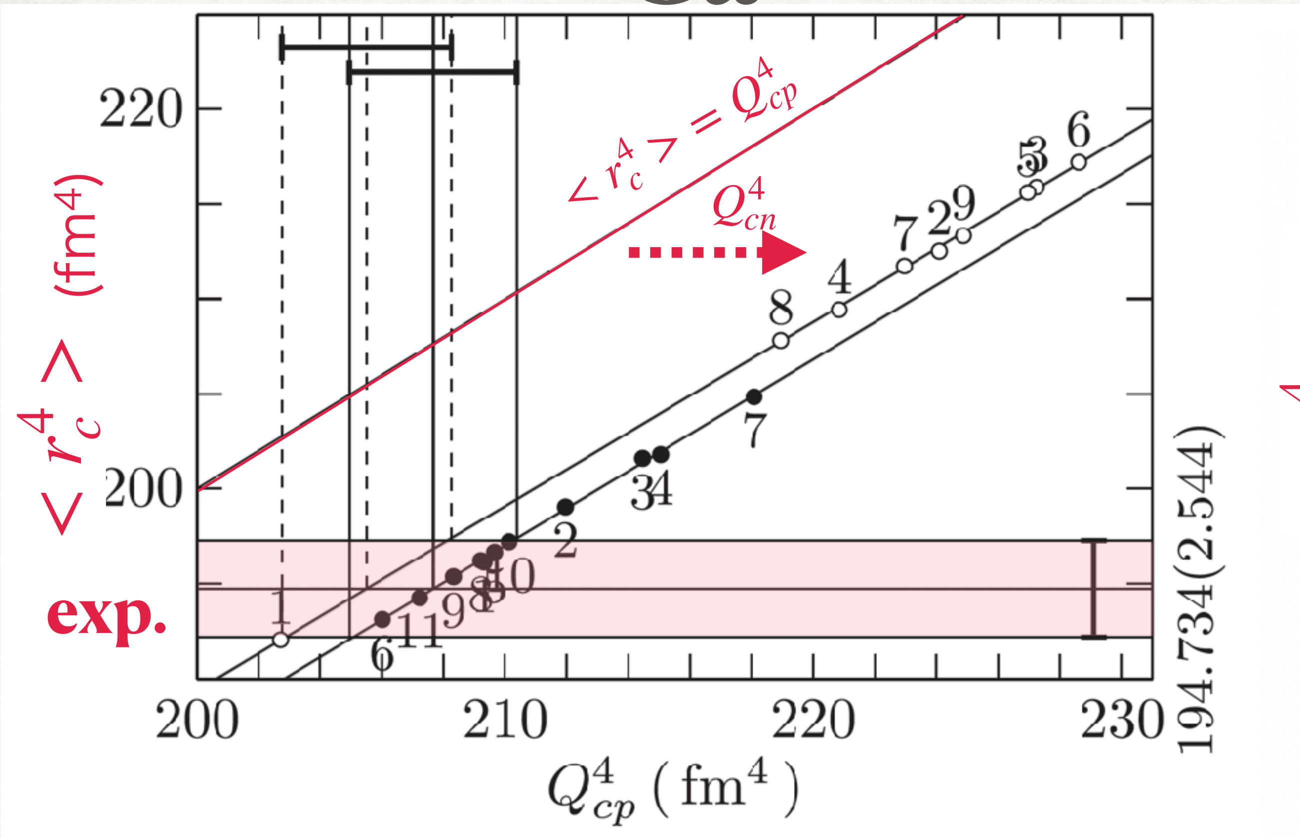
RMS n-radius

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. submitted

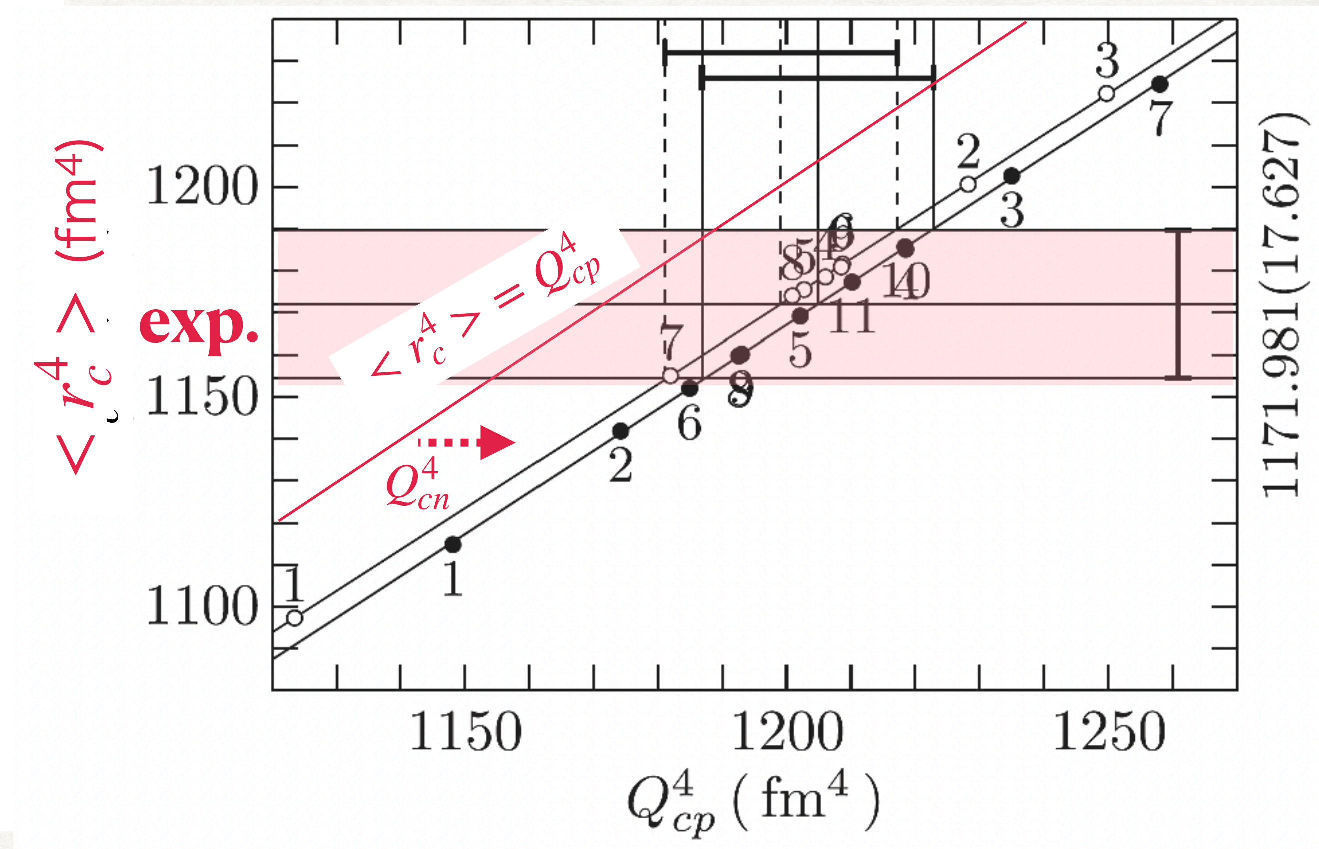
$<r_c^4>$ of ^{48}Ca and ^{208}Pb

$$< r_c^4 > = \int r^4 \rho_c(r)\, \mathrm{d}^3 r \equiv Q_{cp}^4 \; - Q_{cn}^4$$

^{48}Ca



^{208}Pb



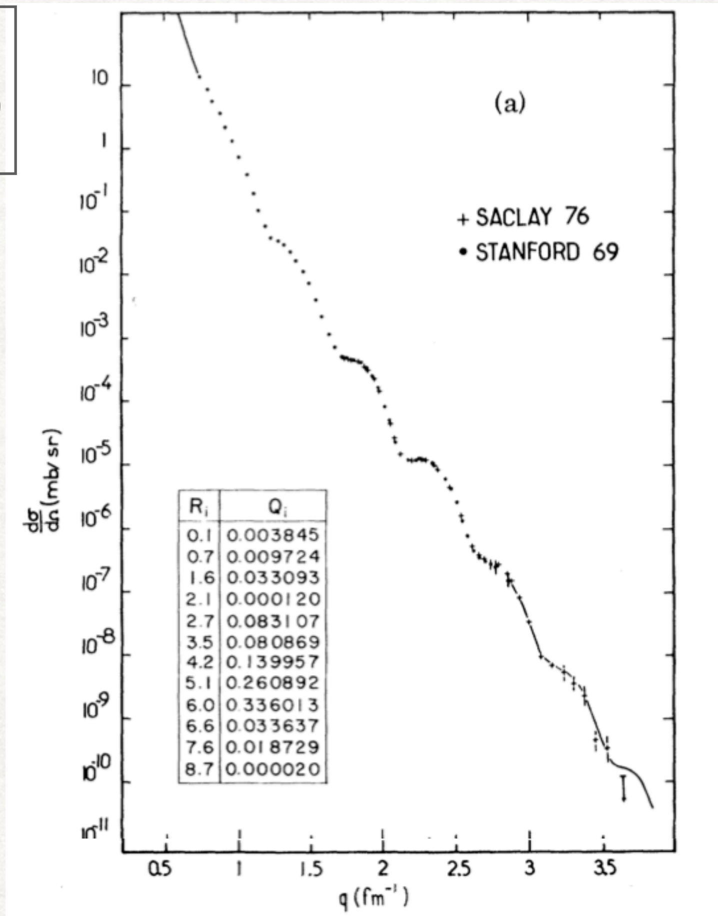
- neutron contributions are essential to account for the observed $<r_c^4>$ of ^{48}Ca and ^{208}Pb by electron scattering

○ open circles (non.-rel.) 1 SK1, 2 SKII, 3 SKIII, 4 SKIV, 5 kMm, 6 SLy4, 7 ST6, 8 SGII, 9 SkP

● filled circles (rel.) 1 L2, 2 NLB, 3 NL1, 4 NL2, 5 NL3, 6 NL-SH, 7 NL-Z, 8 NL-S, 9 NL3II, 10 FSUGold

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

^{208}Pb



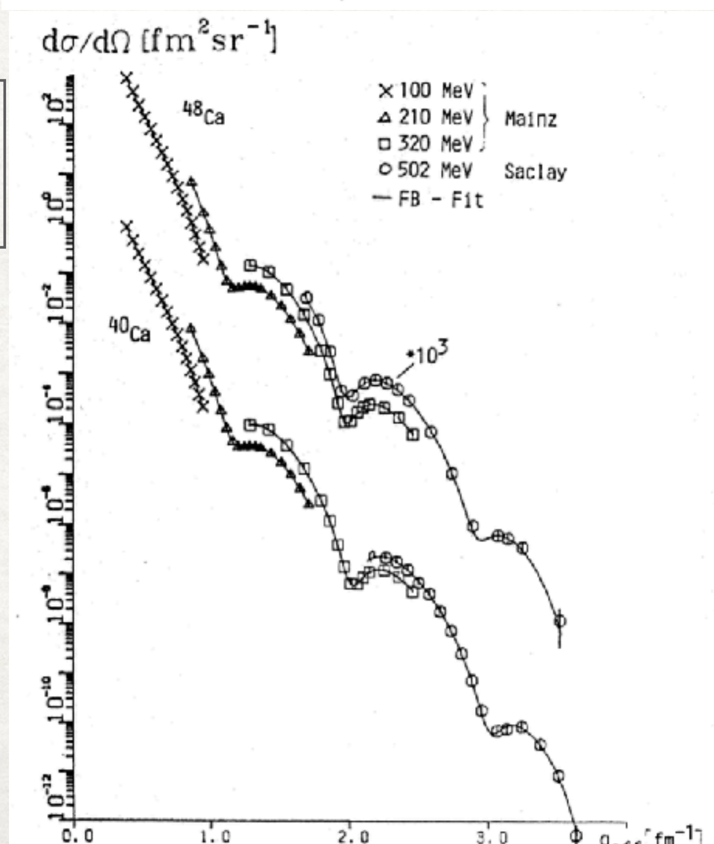
		R_p	R_n	δR
^{208}Pb	Rel.	5.454(0.013)	5.728(0.057)	0.275(0.070)
	Non.	5.447(0.014)	5.609(0.054)	0.162(0.068)
	Exp.	$R_c = 5.503(0.014)$		

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)

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

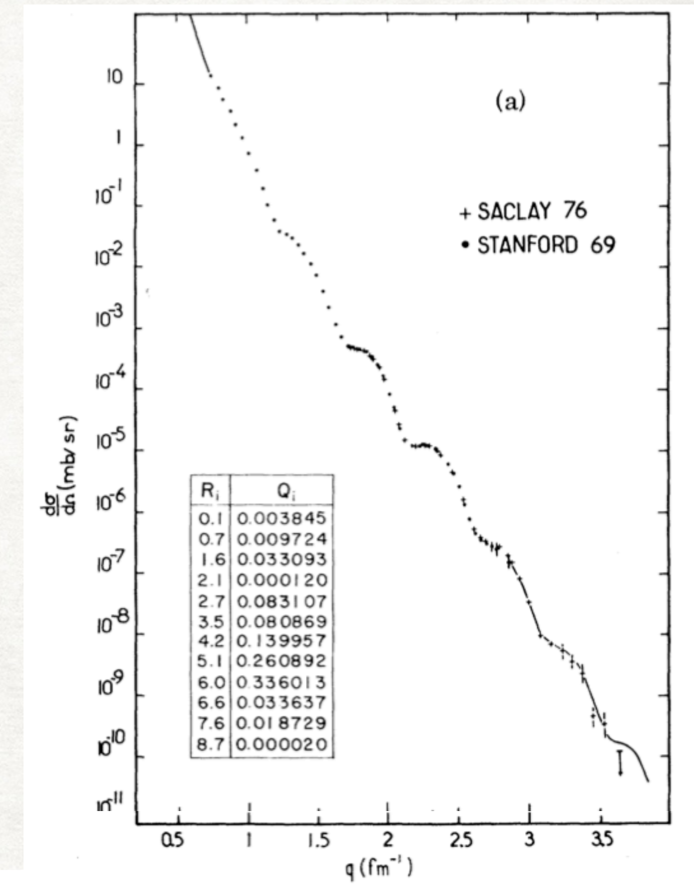
ways to access the fourth moment, $<r_c^4>$

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

1) elastic scattering at very high *q*

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma_{\mathrm{Mott}}}{\mathrm{d}\Omega} |F_c(q)|^2$$ (0^+ nuclei)

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

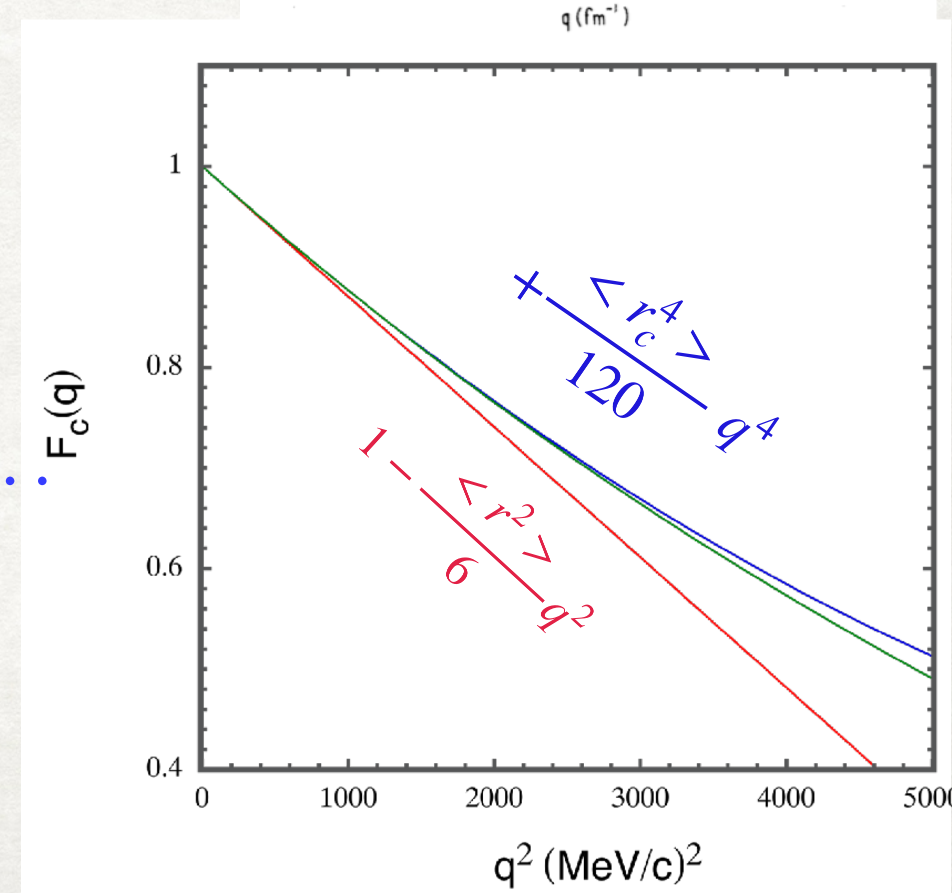


R_i	Q_i
0.1	0.003845
0.7	0.009724
1.6	0.033093
2.1	0.000120
2.7	0.083107
3.5	0.080869
4.2	0.139957
5.1	0.260892
6.0	0.336013
6.6	0.033637
7.6	0.018729
8.7	0.000020

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-q electron-scattering activities in Japan

charge radii of proton and deuteron

E_e = 10 - 60 MeV

θ_e = 30 - 150 deg.

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

E_e = 150 - 300 MeV

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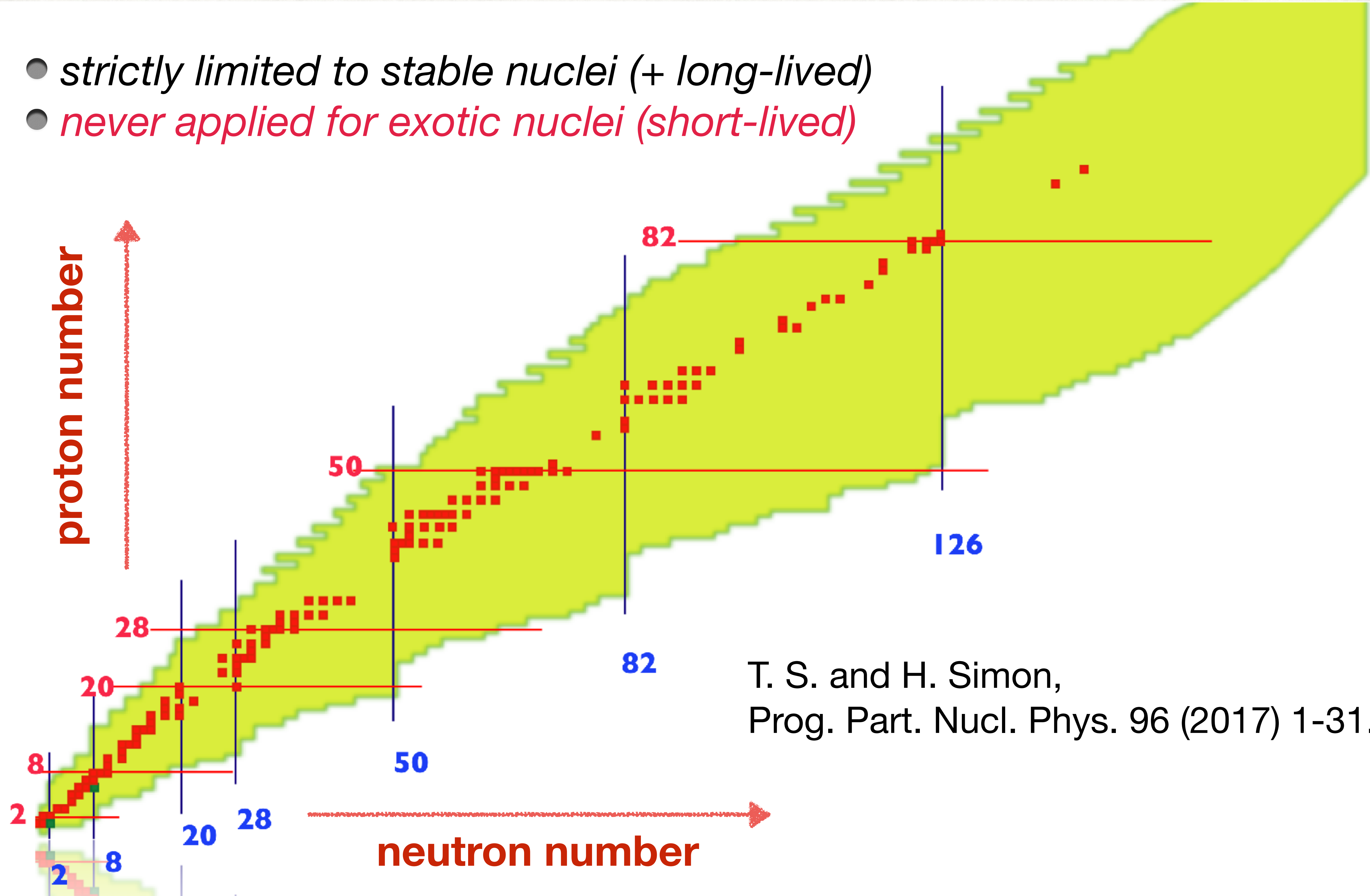
=> q = 80 - 300 MeV/c

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

Nuclei ever studied with electron scattering

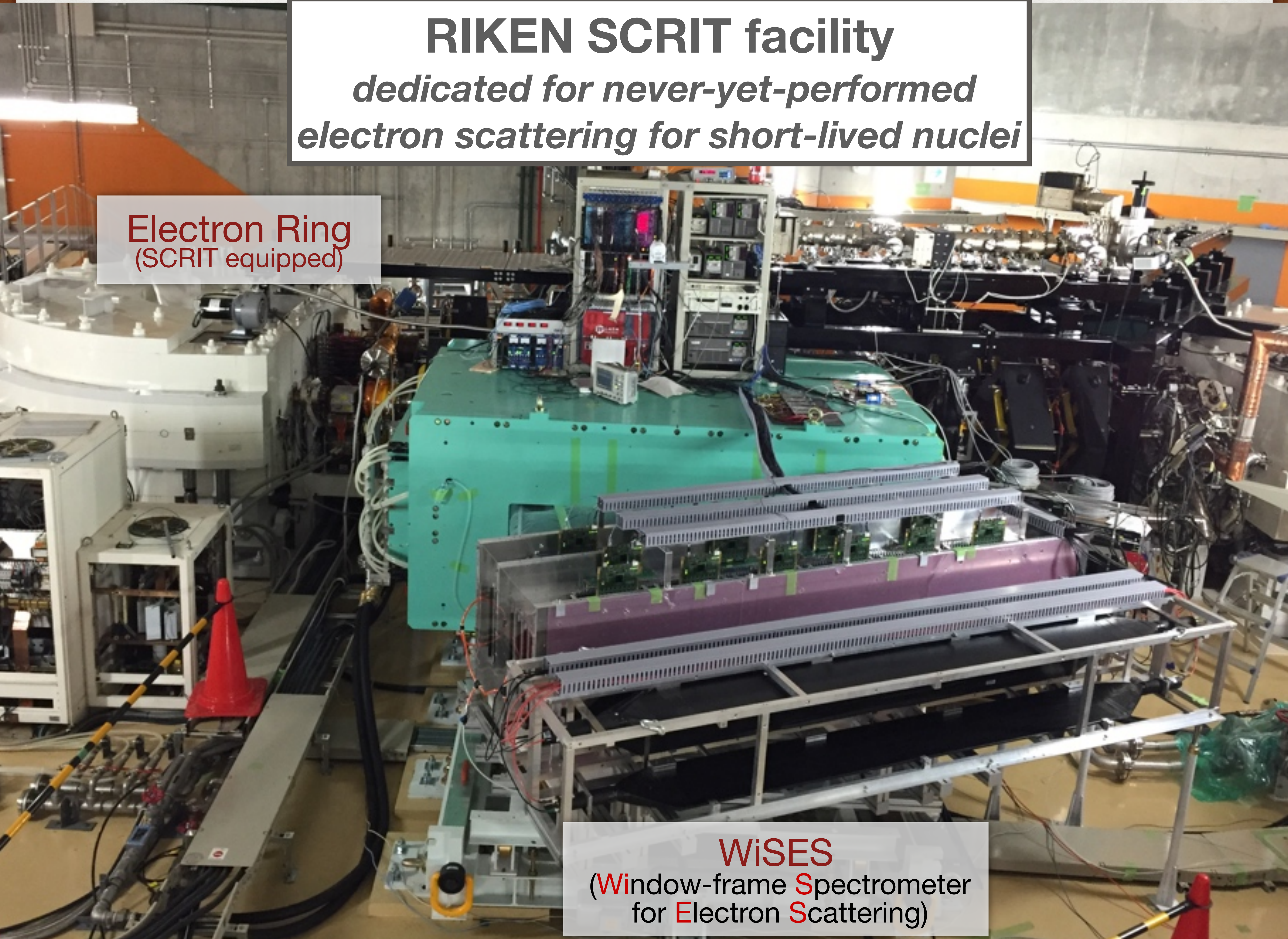
- *strictly limited to stable nuclei (+ long-lived)*
- *never applied for exotic nuclei (short-lived)*



T. S. and H. Simon,
Prog. Part. Nucl. Phys. 96 (2017) 1-31.

RIKEN SCRIT facility

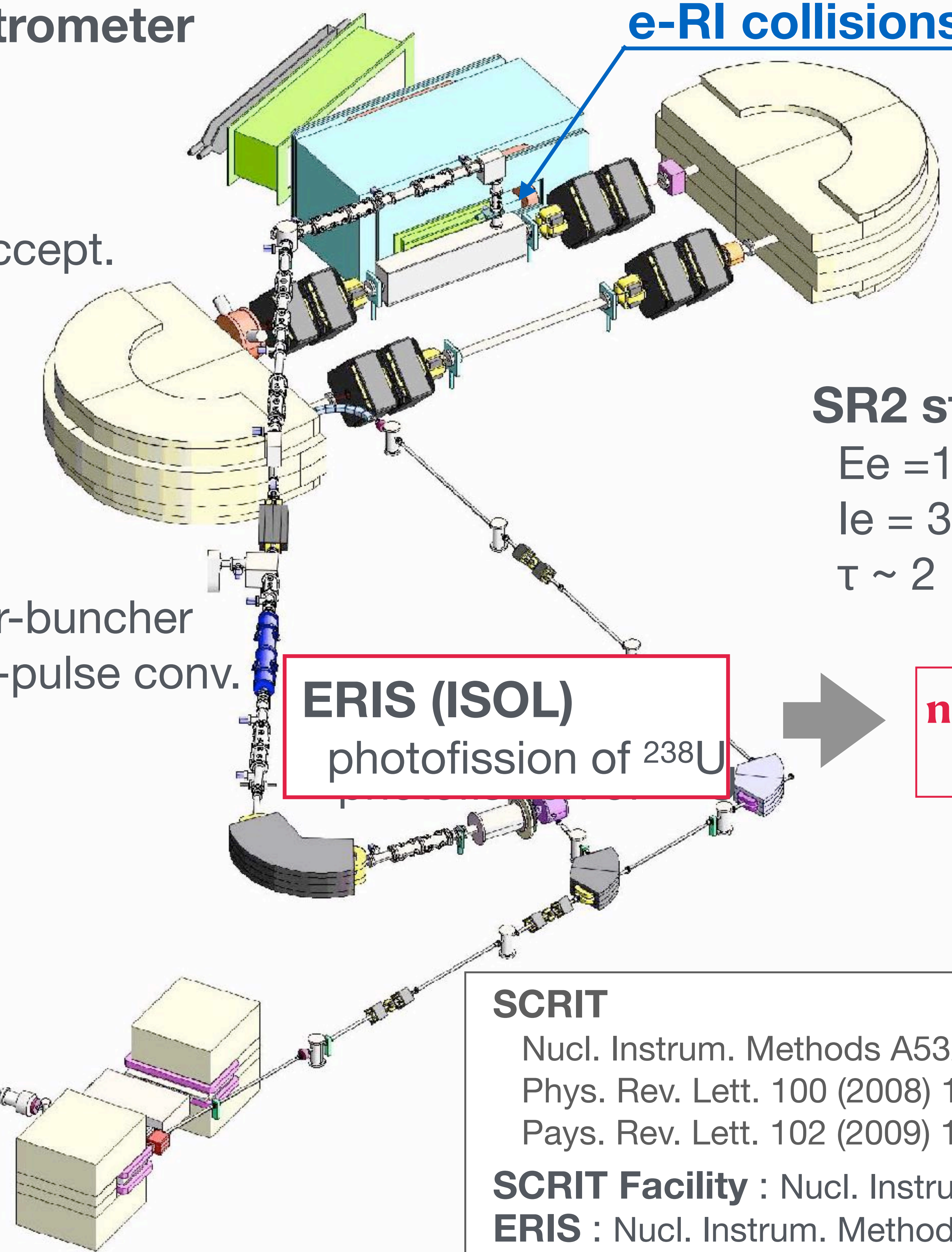
dedicated for never-yet-performed electron scattering for short-lived nuclei



RIKEN SCRIT Electron Scattering Facility

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

e-RI collisions



SR2 storage ring
Ee =150-700 MeV
Ie = 300 mA
$\tau \sim 2$ 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

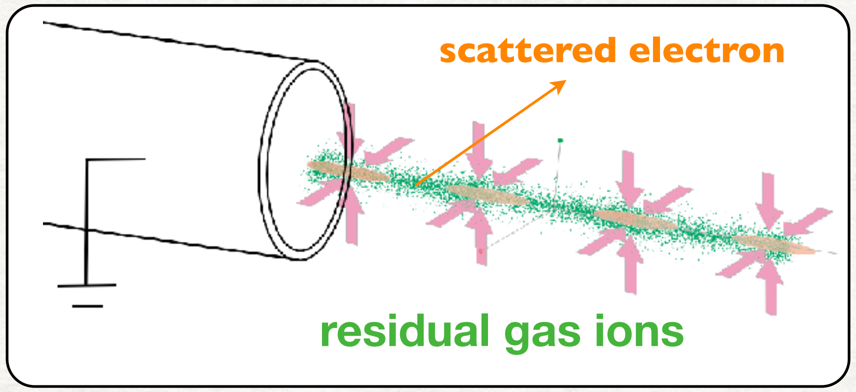
SCRIT
Nucl. Instrum. Methods A532 (2004) 216.
Phys. Rev. Lett. 100 (2008) 164801.
Pays. Rev. Lett. 102 (2009) 102501.

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

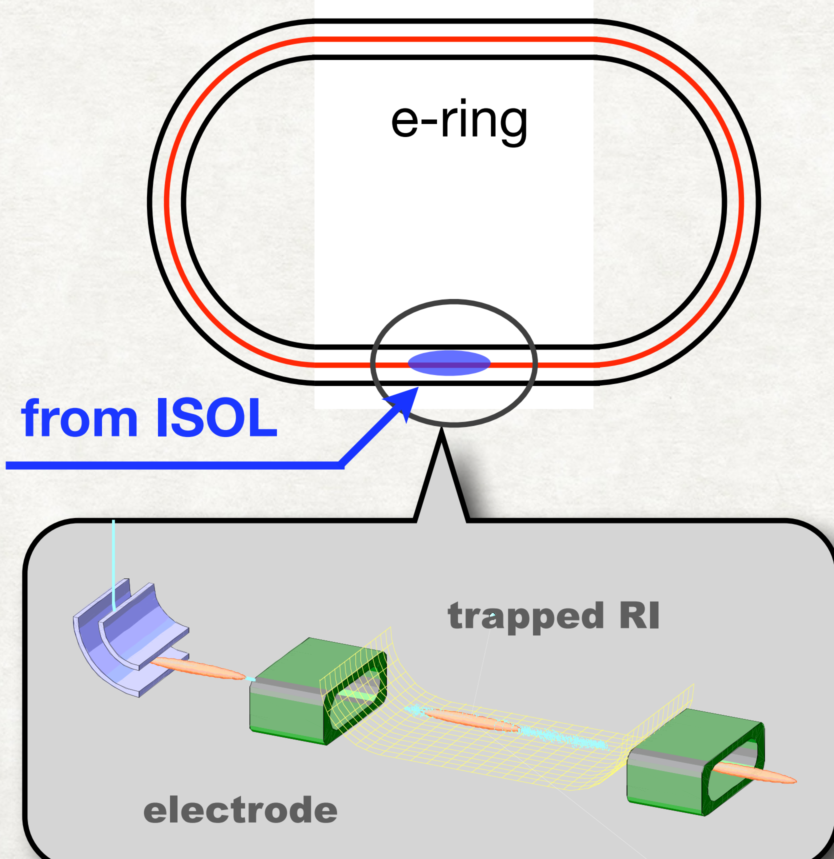
SCRIT（Self-Confining RI Ion Target)

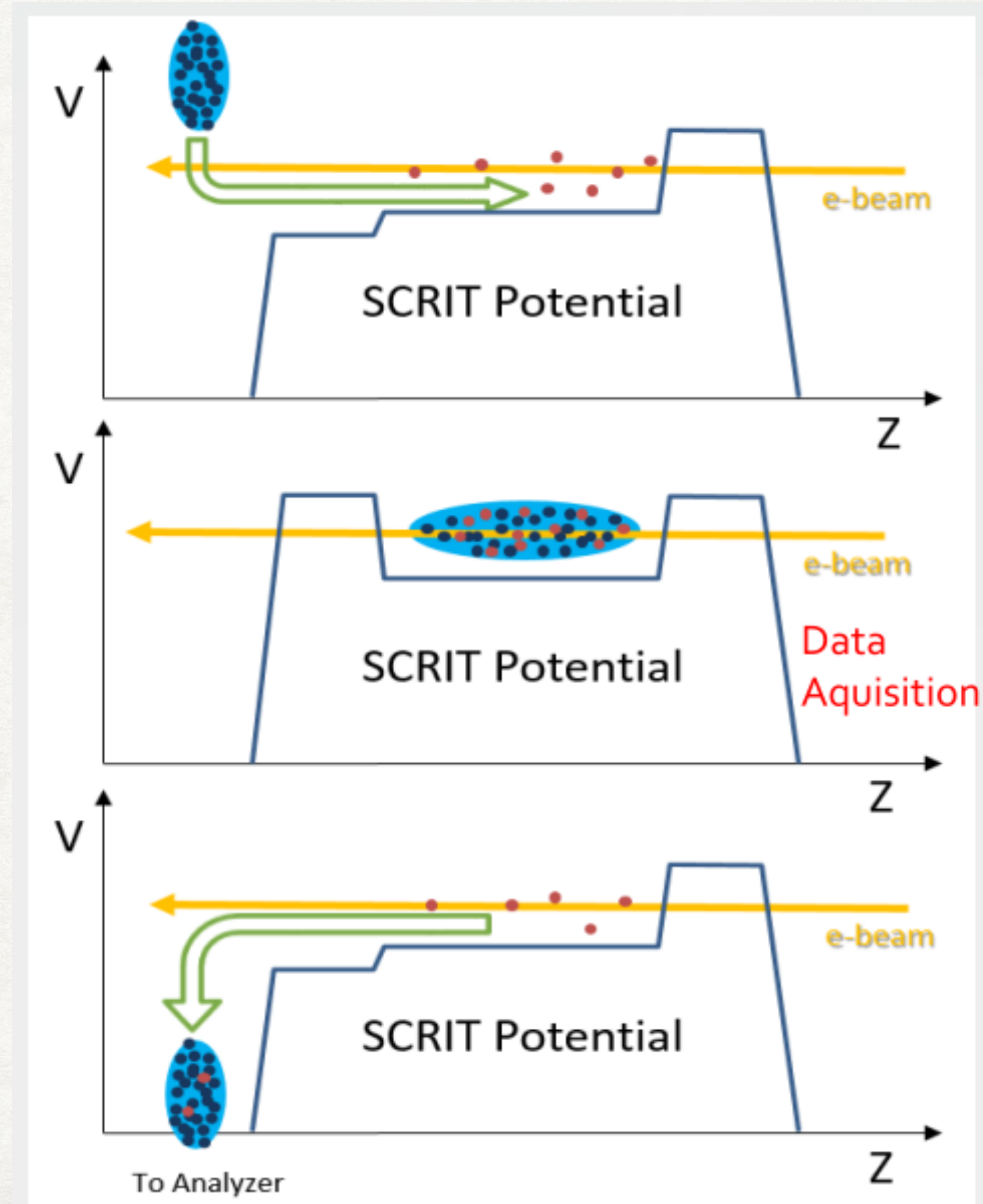
Idea : “ion trapping” at SR facilities.

ionized residual gases are trapped by the circulating electron beam

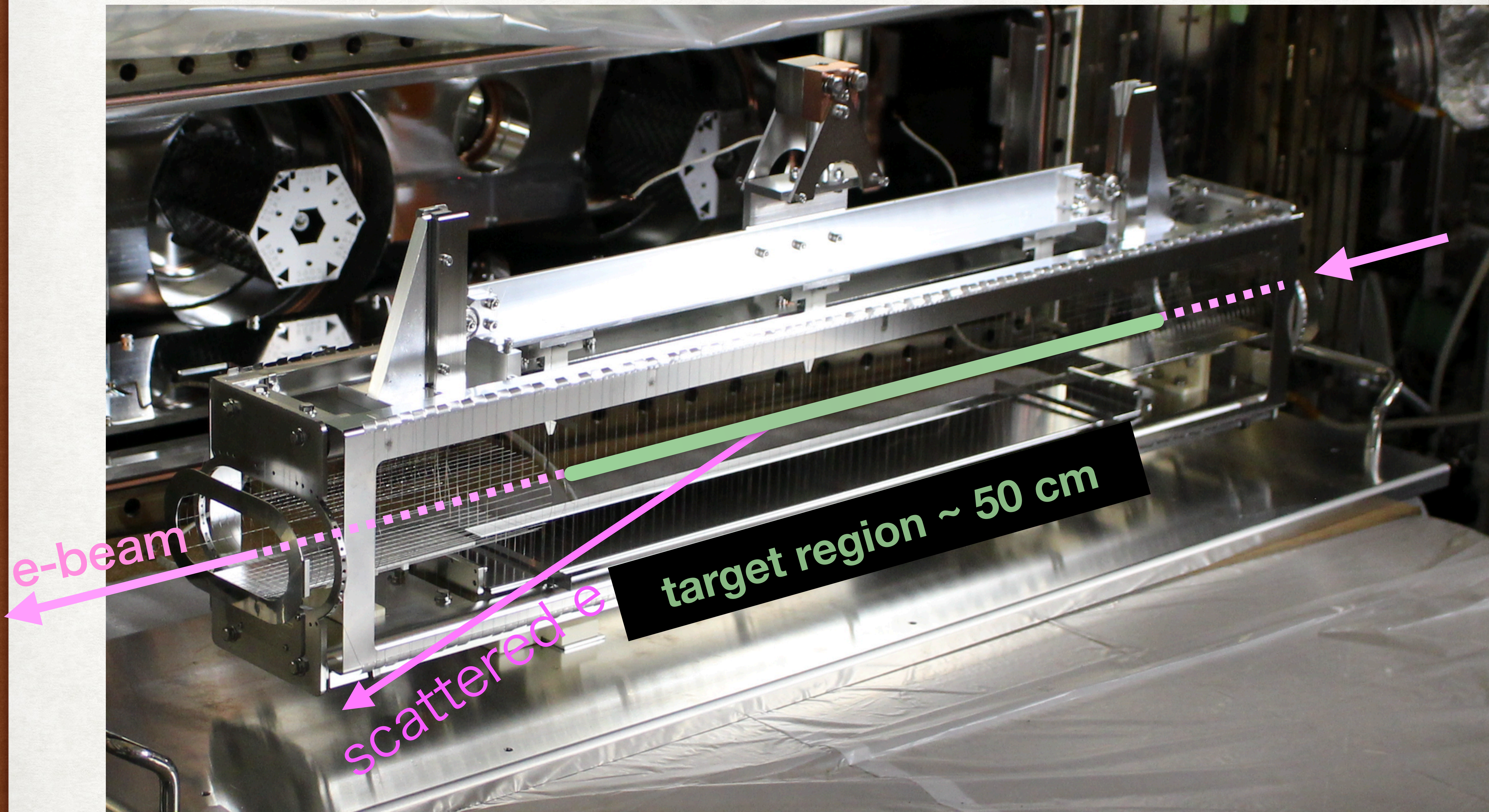


ill problem of e-storage rings





SCRIT electrodes



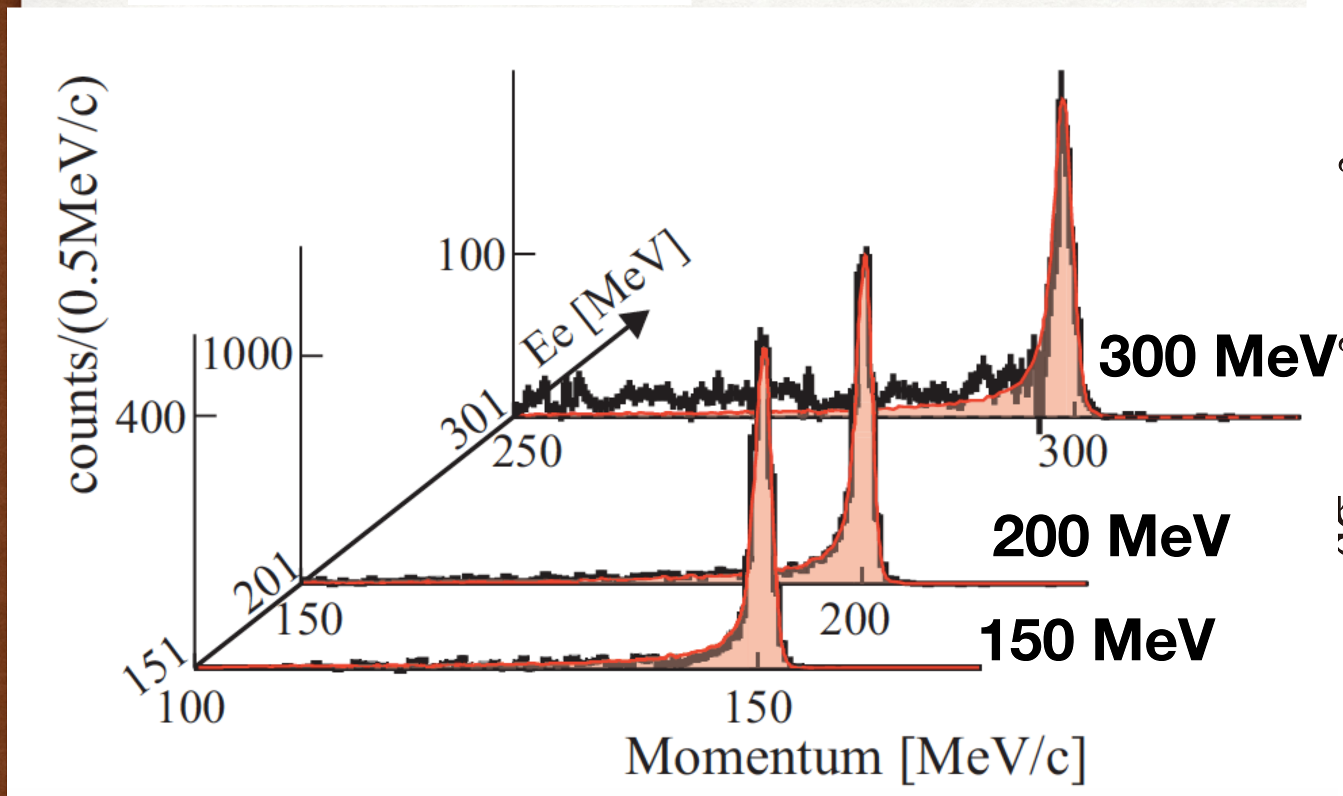
first demonstration of RIKEN SCRIT facility

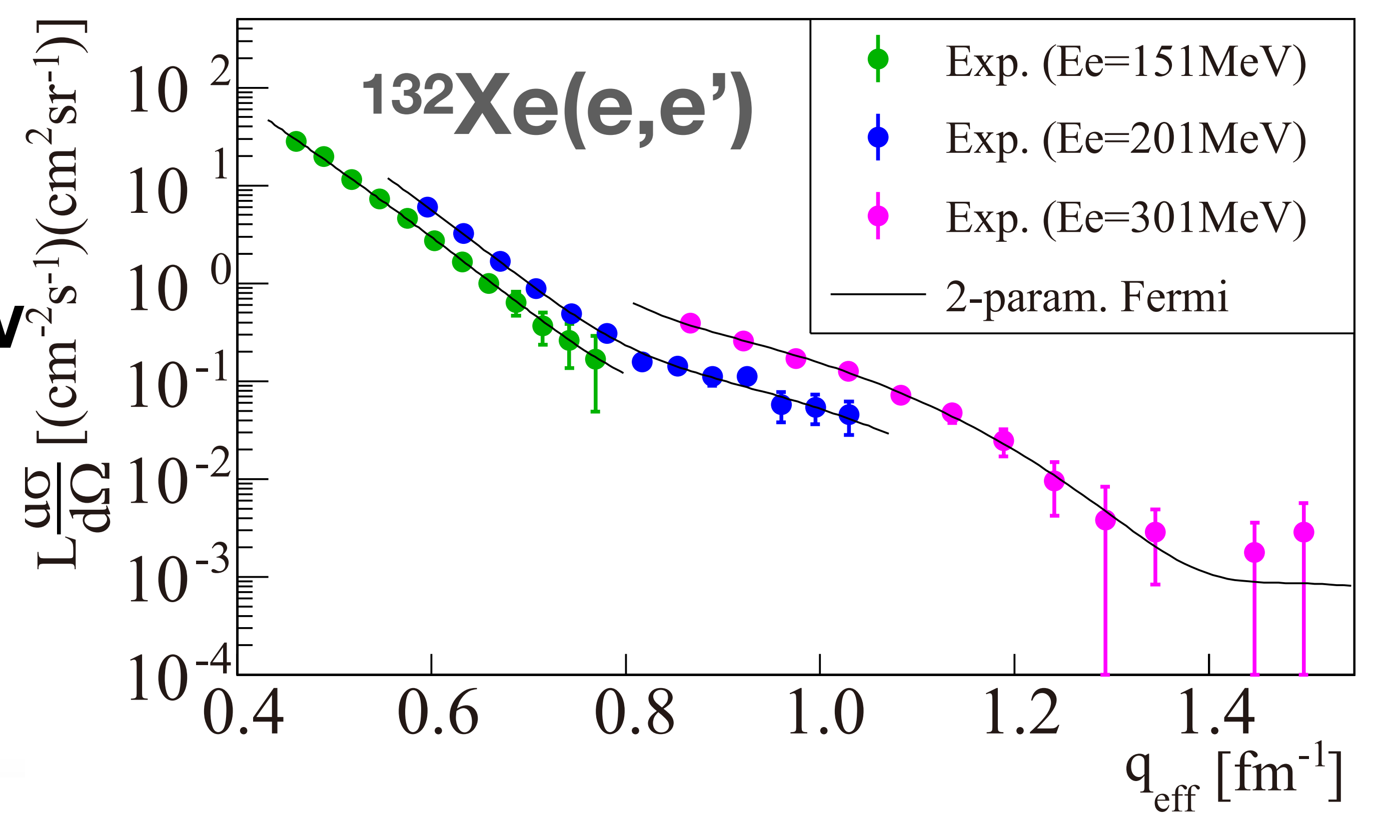
$N_{trapped}$ ~ 10^8 @ Ie = 250 mA

=> L ~ 10^{27} /cm²/s

PRL 118 (2017) 262501.

^{132}Xe (stable)



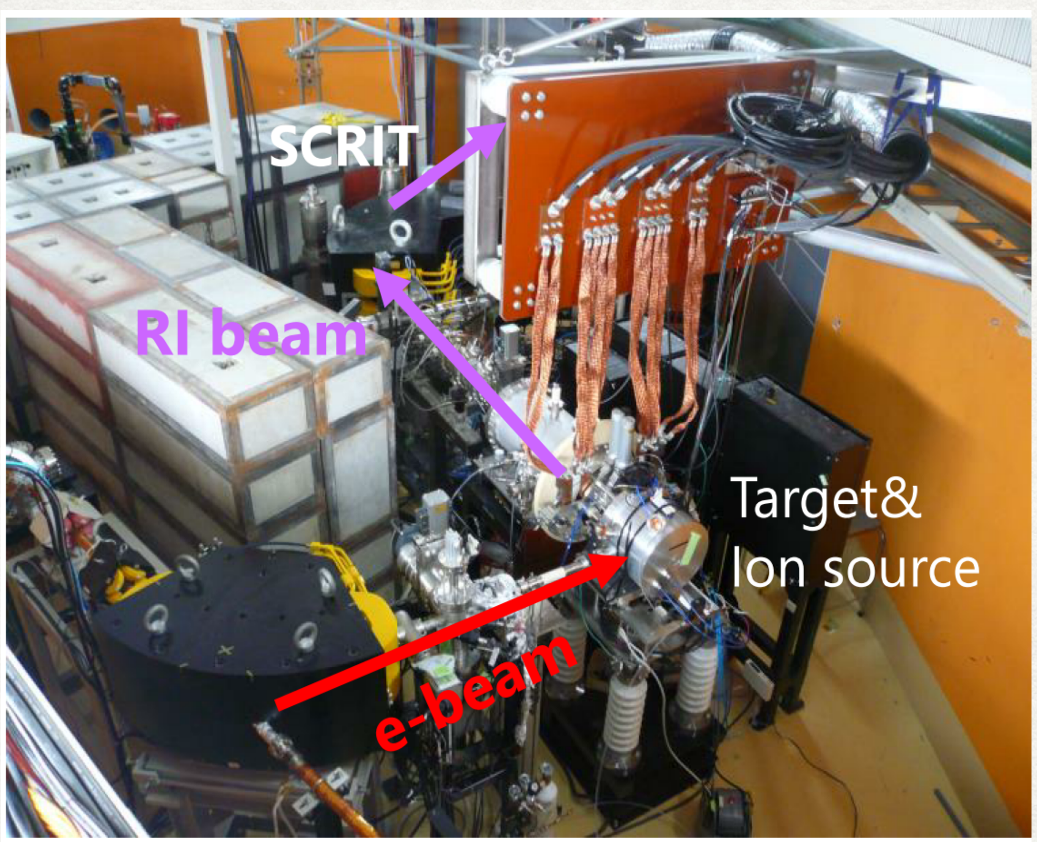


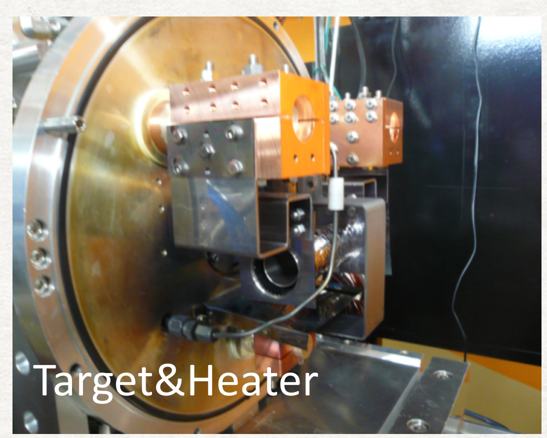
	Ee	N_{beam}	target thickness	L
Hofstadter's era (1950s)	150 MeV	~ 1nA (~10^9 /s)	~10^{19} /cm²	~10^{28} /cm²/s
JLab	12 GeV	~100μA (~10^{14} /s)	~10^{22} /cm2	~10^{36} /cm²/s
SCRIT	150-300 MeV	300 mA (~10^{18} /s)	~10^9 /cm²	~10^{27} /cm²/s

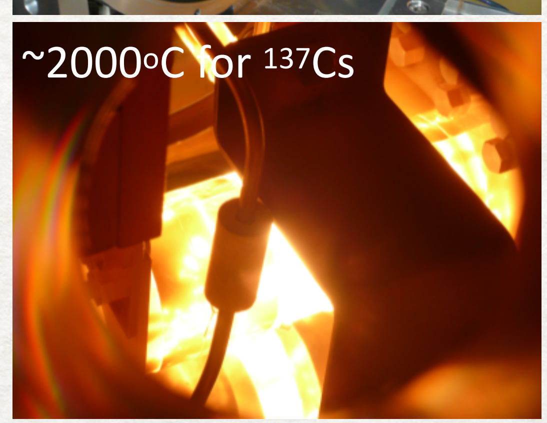
ERIS (Electron-beam-driven RI separator for SCRIT)

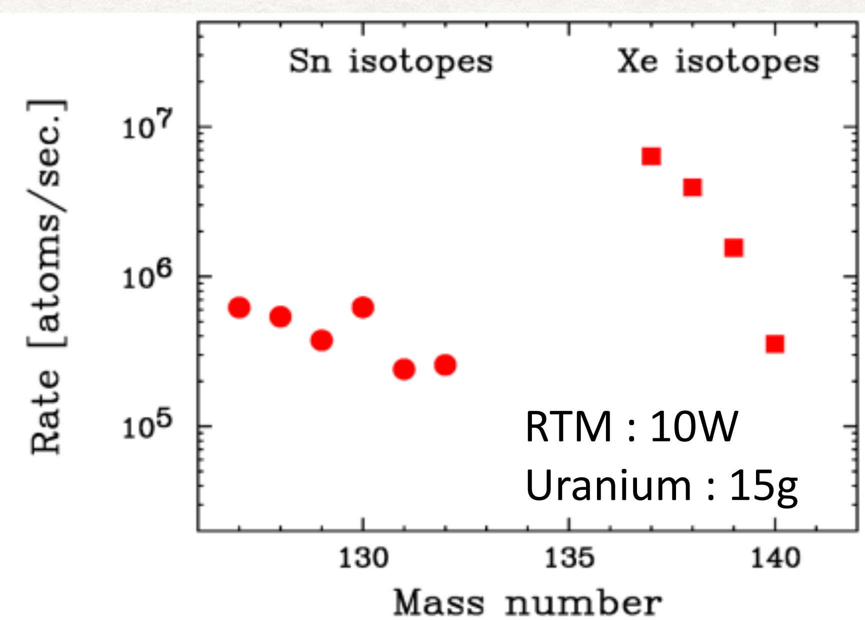
- RI Production : photo-fission of uranium
- Two ionization methods are available:
  - FEBIAD (Sn, Xe, etc.)
  - Surface Ionization (Cs, Ba, etc.)
- Extraction : DC or bunched beam

φ 18 mm, t 0.8 mm disks



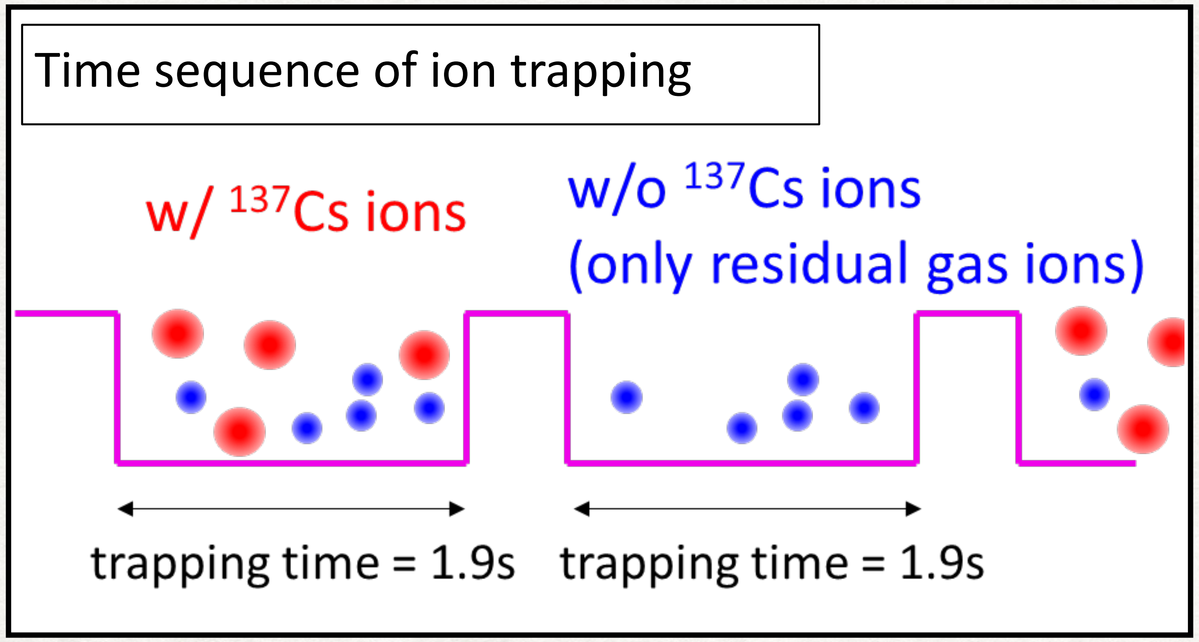


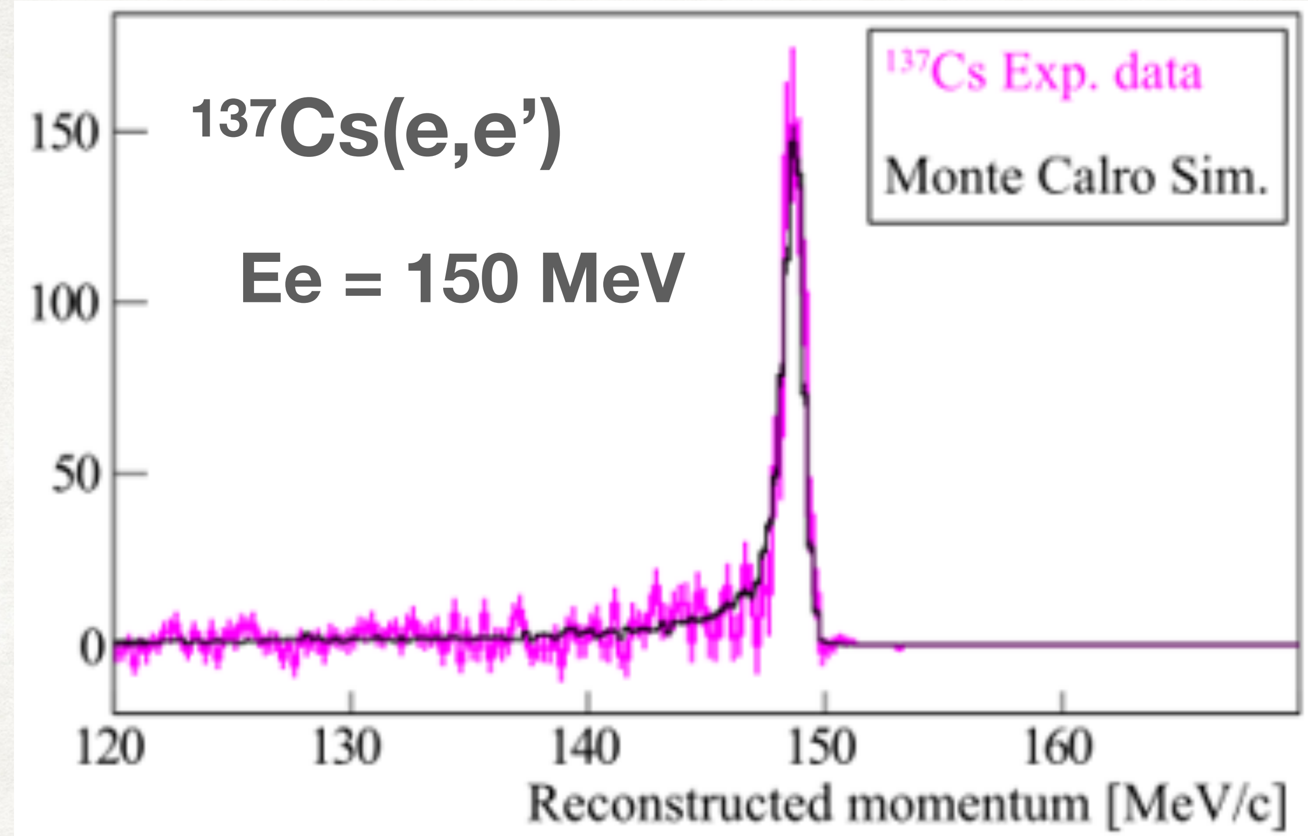




^{138}Xe : 3.9 x 10^6 cps
^{132}Sn : 2.6 x 10^5 cps
^{137}Cs : 8.0 x 10^6 cps (28-g U)

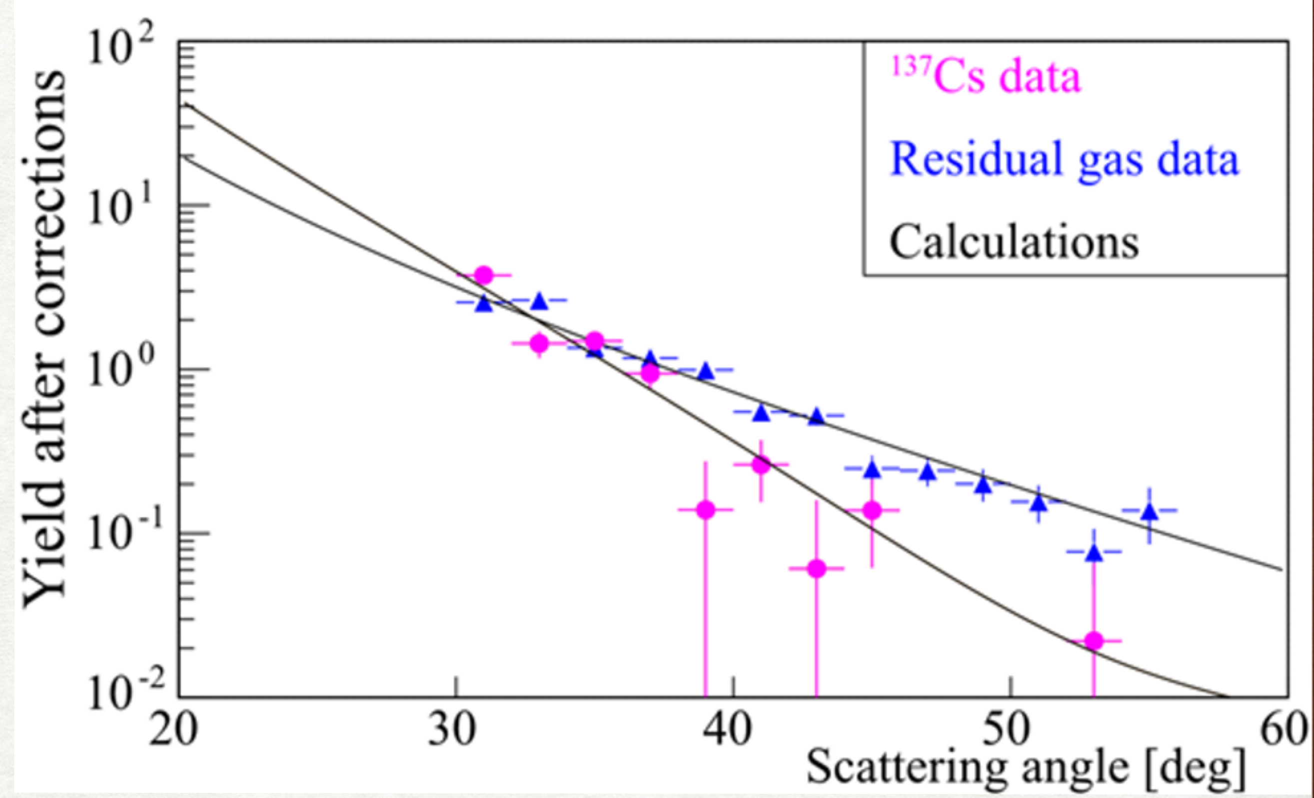
^{137}Cs(e,e') photofission of ^{238}U





$N_{trapped}$ ~ 2 x10^7

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



successful demonstration for online-produced unstable nuclei

K. Tsukada et al.

PRL in press

Low-q electron-scattering activities in Japan

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60 MeV electron linac

E_e = 10 - 60 MeV

$\Delta E/E$ = 0.6 x 10^{-4}

beam size ~ 0.6 mm on target

duty factor = 10^{-3}

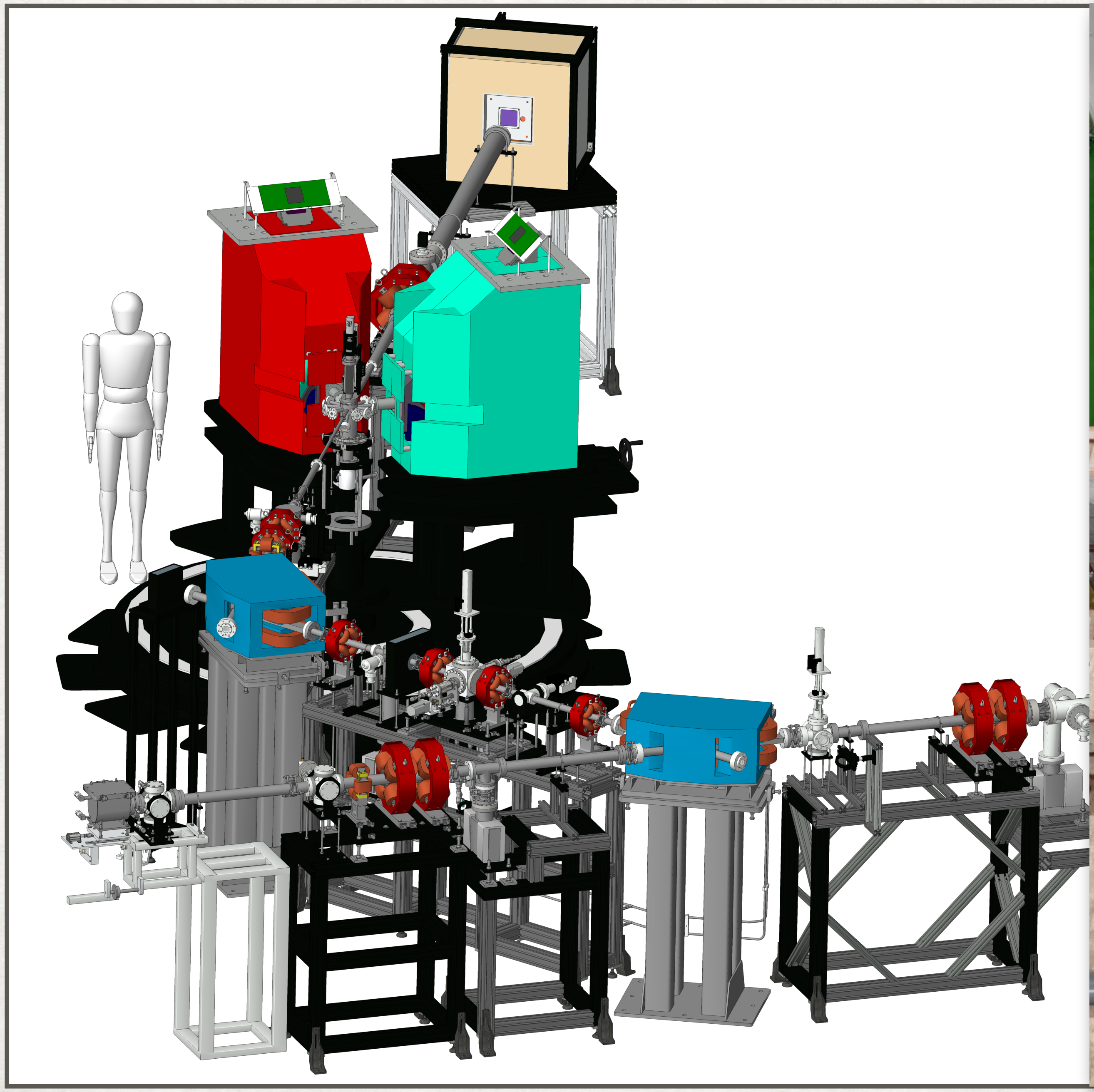
ULQ2 twin-spectrometer setup

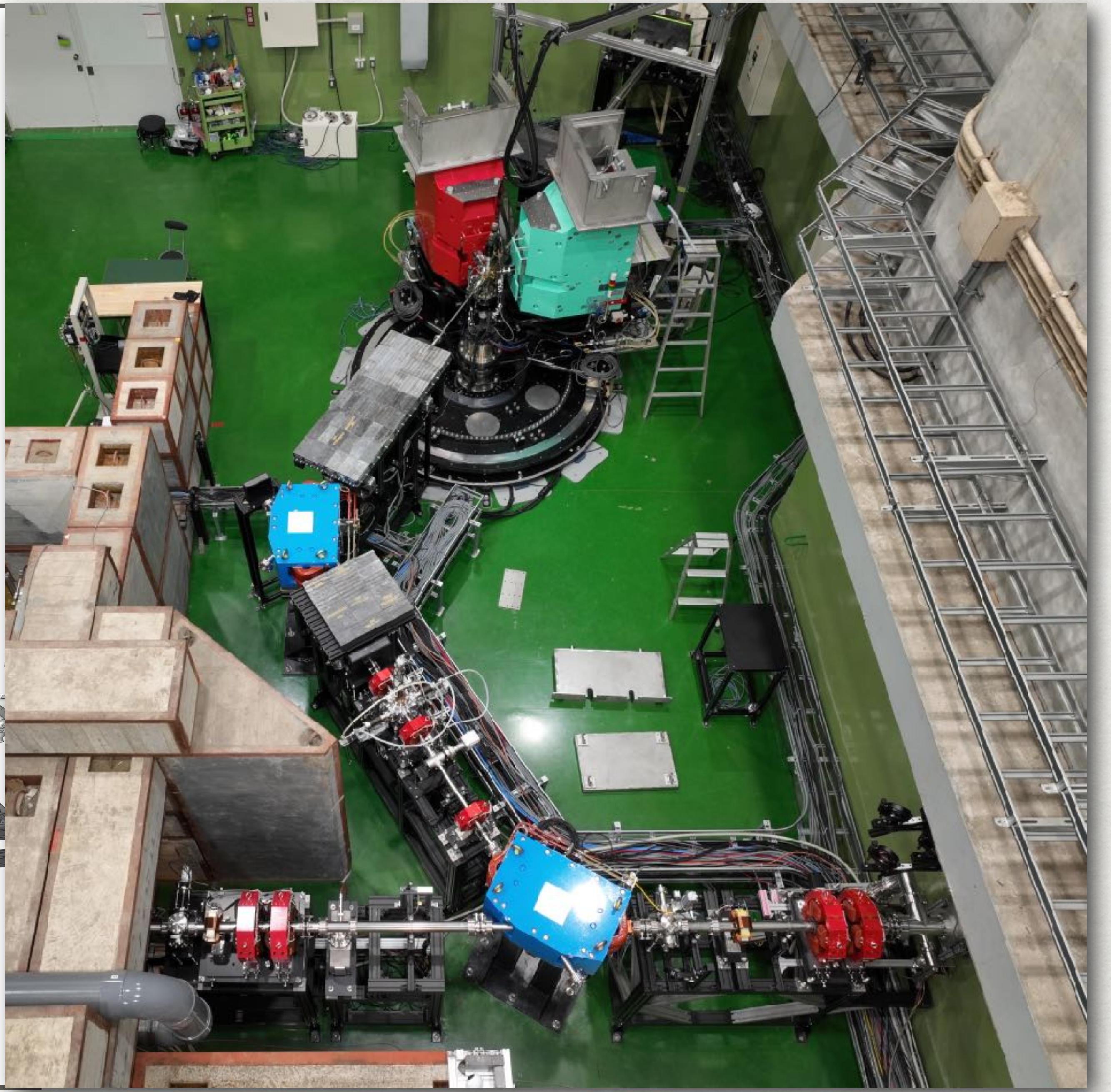
$\Delta p/p$ = 5.6 x 10^{-3}

$\Delta\Omega$ = 6 mSr

θ = 30 - 150 deg.

Q^2 = 3 x 10^{-5} - 0.013 $(\mathrm{GeV}/c)^2$





ULQ2 Physics Program

1) Proton : charge radius $CH_2(e,e')$

aiming at the "least model-dependent" $G_E(Q^2)$ determination

under lowest-ever Q^2
absolute cross section measurement
Rosenbluth separated $G_E(Q^2)$ and $G_M(Q^2)$

Clement's talk

2) Deuteron : charge radius $CD_2(e,e')$

charge radii of deuteron

3) ^{208}Pb elastic scattering $^{208}Pb(e,e')$

cross section under never-yet-measured low-*q* region
q = 5 - 50 MeV/c

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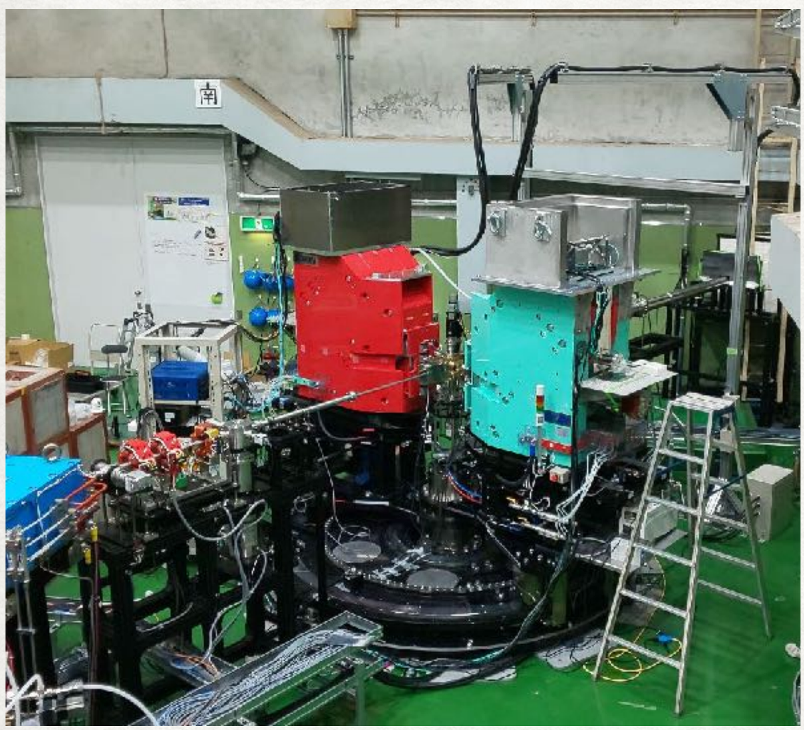
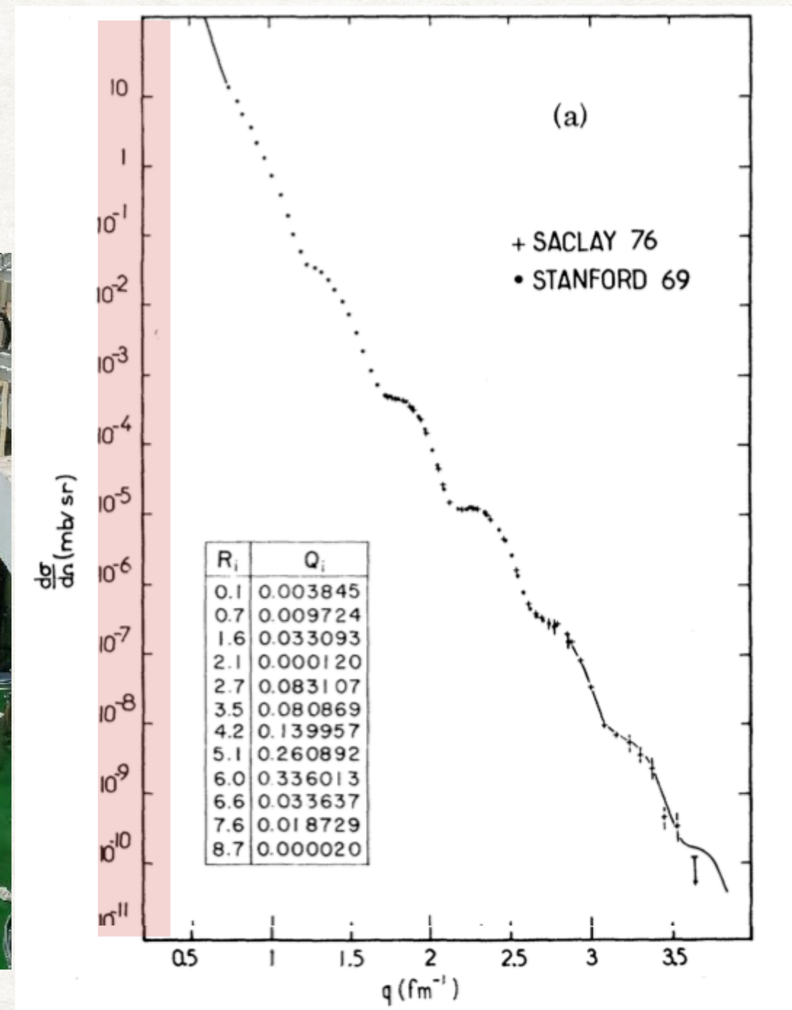
Rn determination at extremely low-q (e,e’) ?

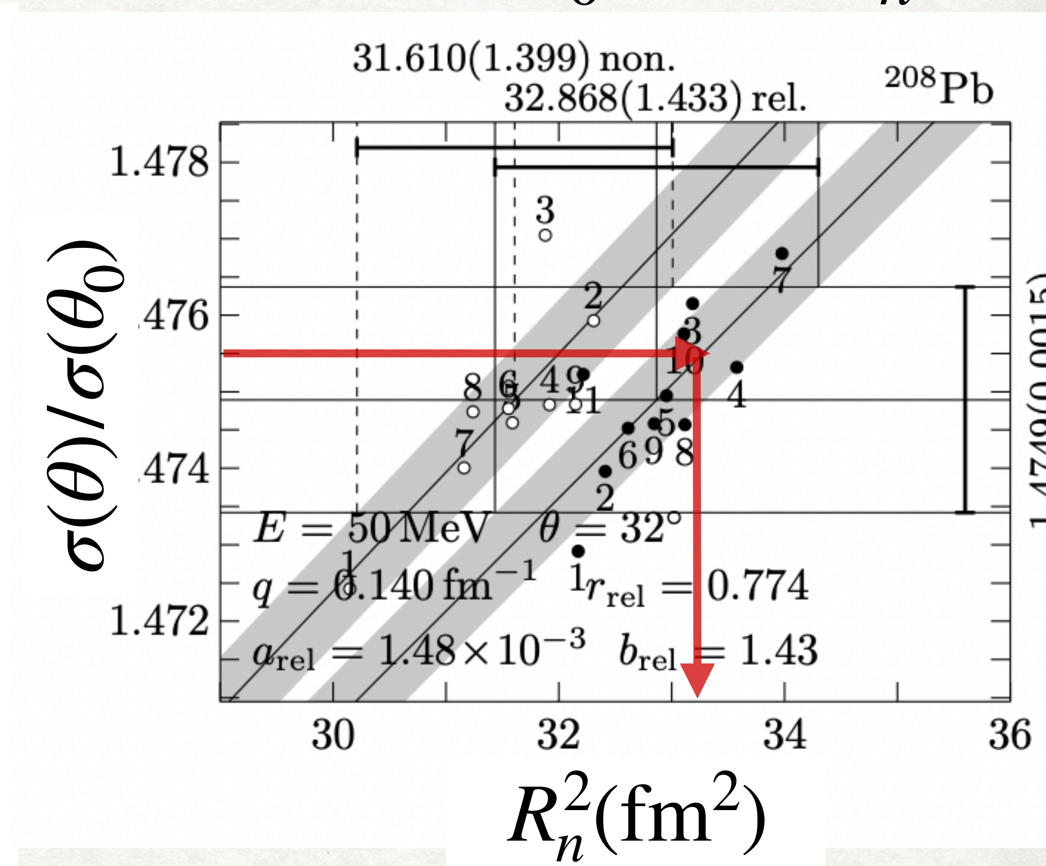
- **^{208}Pb(e,e’) at the ULQ2 beam line**

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





$\sigma(\theta)/\sigma(\theta_0)$ 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

ULQ2 Physics Program

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$CH_2(e,e')$

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Clement's talk

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$CD_2(e,e')$

charge radii of deuteron

3) ^{208}Pb elastic scattering

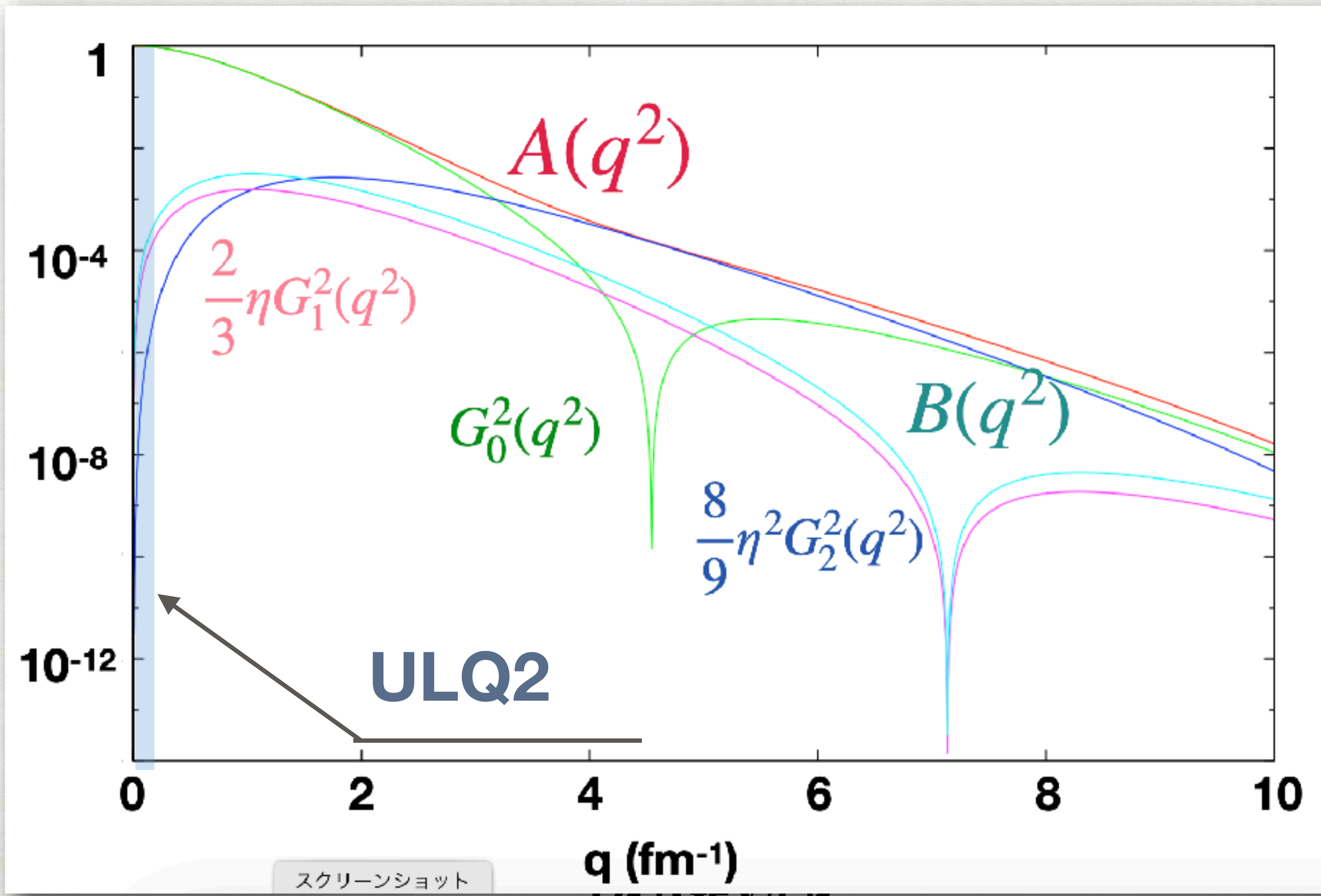
$^{208}Pb(e,e')$

cross section under never-yet-measured low-*q* region
$q = 5 - 50$ MeV/c

e+D at ULQ2

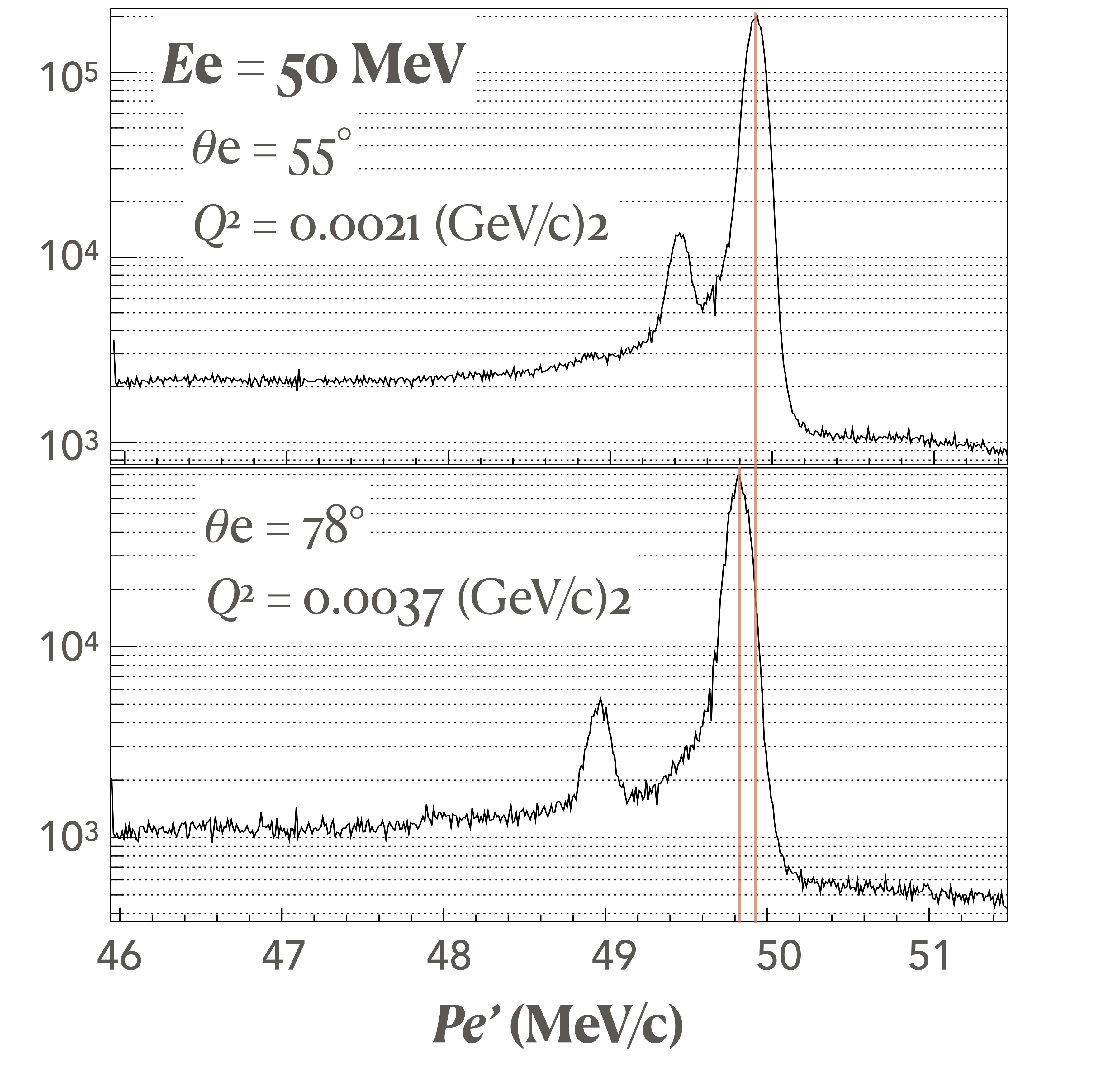
① lowest-ever low Q^2 : 2x10^{-3} - 0.013 (GeV/c)^2
② Rosenbluth separation for L/T if necessary
Ee : 10 - 60 MeV
scattering angle : 30 - 150°
③ e+D **absolute cross section** relative to e+^{12}C

aiming at "least model-dependent" charge radius



CD_2(e,e') online spectra

~30 min. data



PHYSICAL REVIEW LETTERS **124**, 082501 (2020)

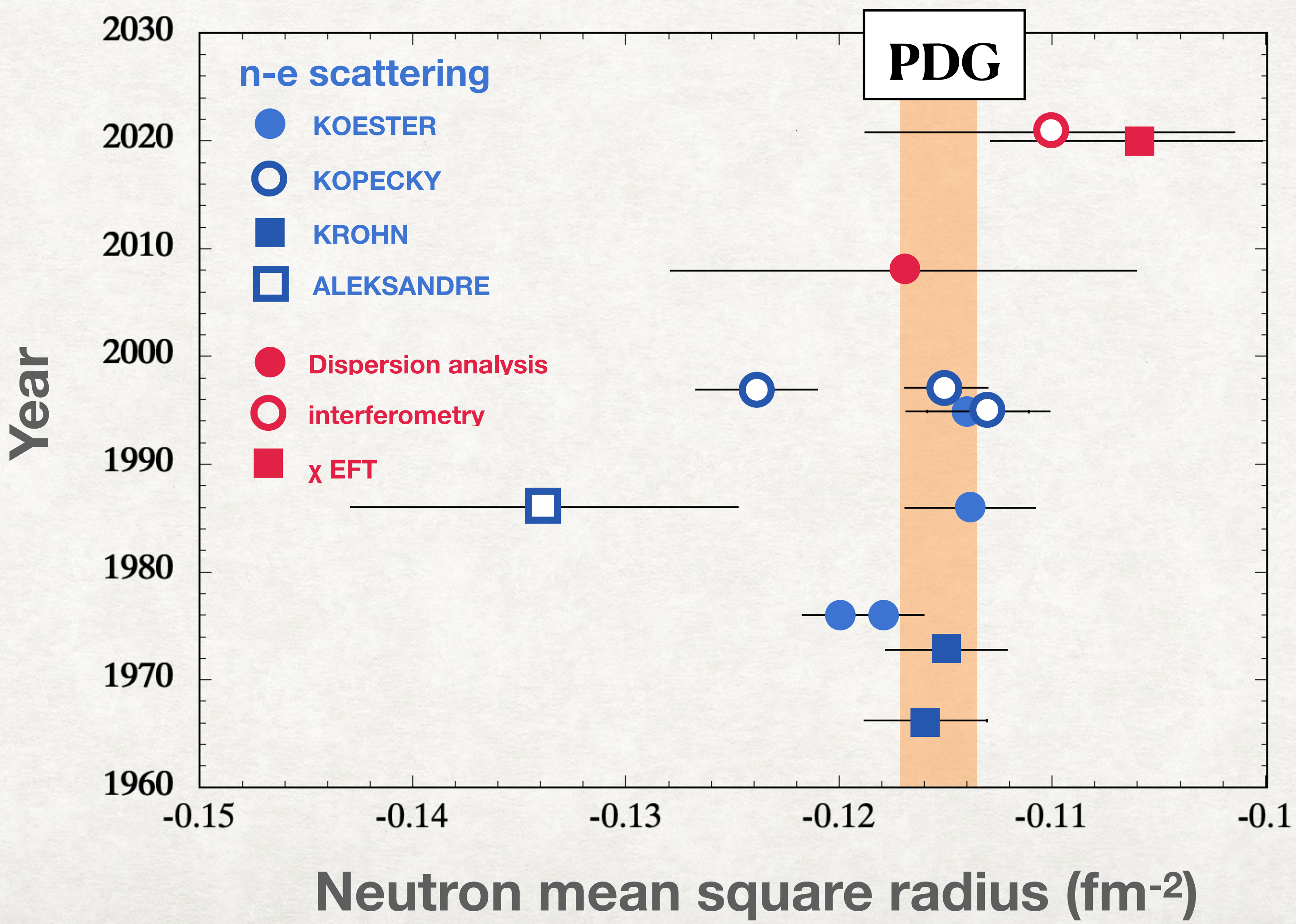
Extraction of the Neutron Charge Radius from a Precision Calculation of the Deuteron Structure Radius

A. A. Filin,[1] V. Baru,[2,3,4] E. Epelbaum,[1] H. Krebs,[1] D. Möller,[1] and P. Reinert[1]

$$< r_c^2 > = < r_{str}^2 > + < r_p^2 > + < r_n^2 > + \frac{3}{4m^2}$$

μD spec. χEFT PDG (2022)

$$\Rightarrow \quad < r_n^2 > = -0.106 \,^{+0.007}_{-0.005} \ \mathrm{fm}^2$$

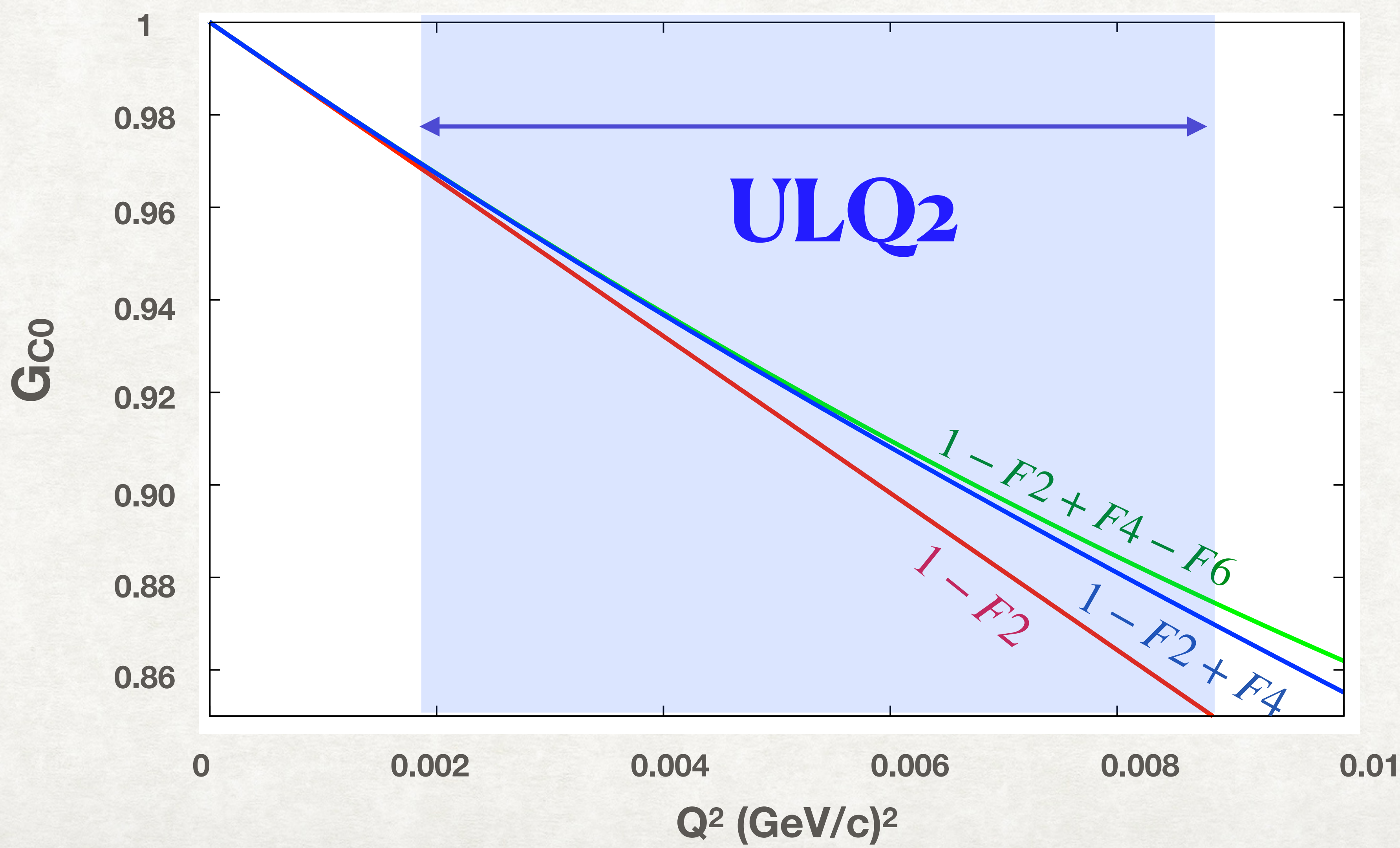


D(e,e') at ULQ2

$$< r_c^2 > = < r_{p(point)}^2 > + < r_p^2 > + < r_n^2 > + \text{rel. corr.}$$

0.5916 ± 0.0078 fm^2 Bochum group

$$< r_c^4 > = < r_{p(point)}^4 > + \frac{10}{3} < r_{p(point)}^2 > (< r_p^2 > + < r_n^2 >) + \text{rel. corr.}$$



conclusions

- low-energy electron scattering activities in JAPAN
  - Tohoku ULQ2 for proton radius etc.
  - RIKEN SCRIT for structure studies of exotic nuclei
- beyond “proton radius”
  - ULQ2 : eD scattering (+^{208}Pb(e,e’))
  - SCRIT : charge densities of short-lived exotic nuclei

workshop at the DNP-JPS joint meeting at Hawaii (Oct. 7 - 12, 2023)

“Scientific Opportunities in Nuclear Physics with High-Intensity, Low-Energy Electron Accelerators.”

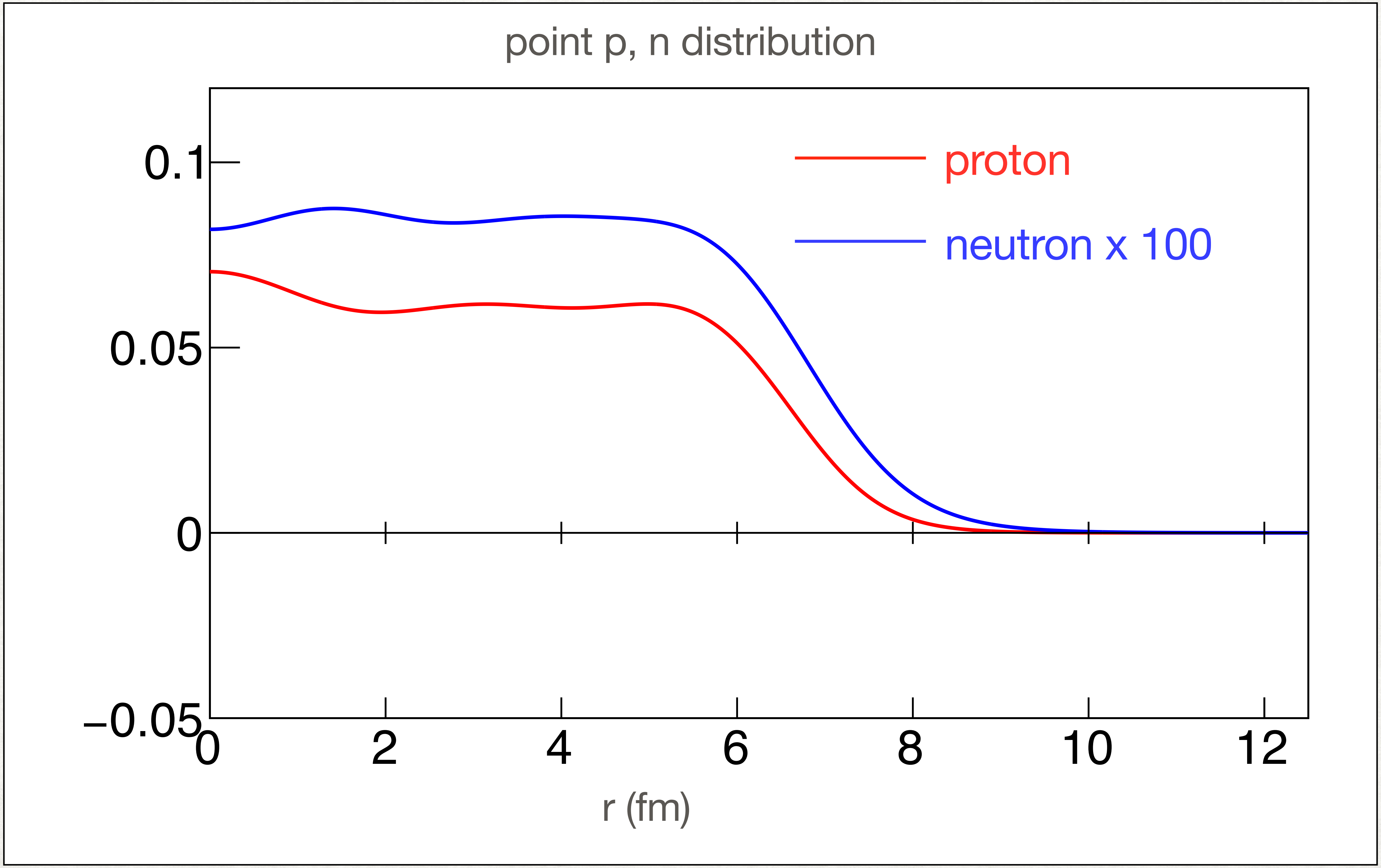
Date : Oct. 7

Organizer : R. Milner (MIT), T. Suda (Tohoku)

backup

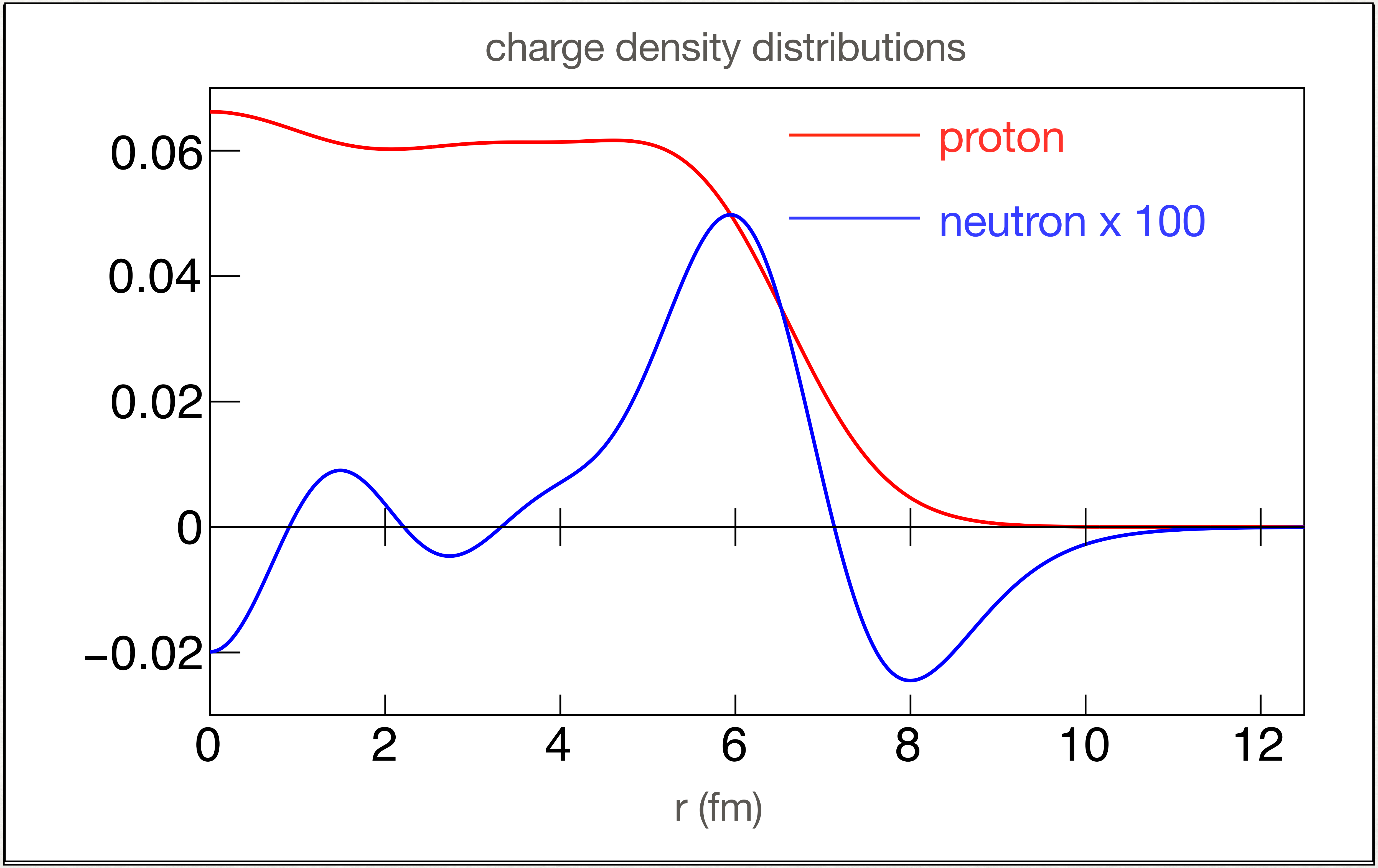
^{208}Pb

RMF NL3



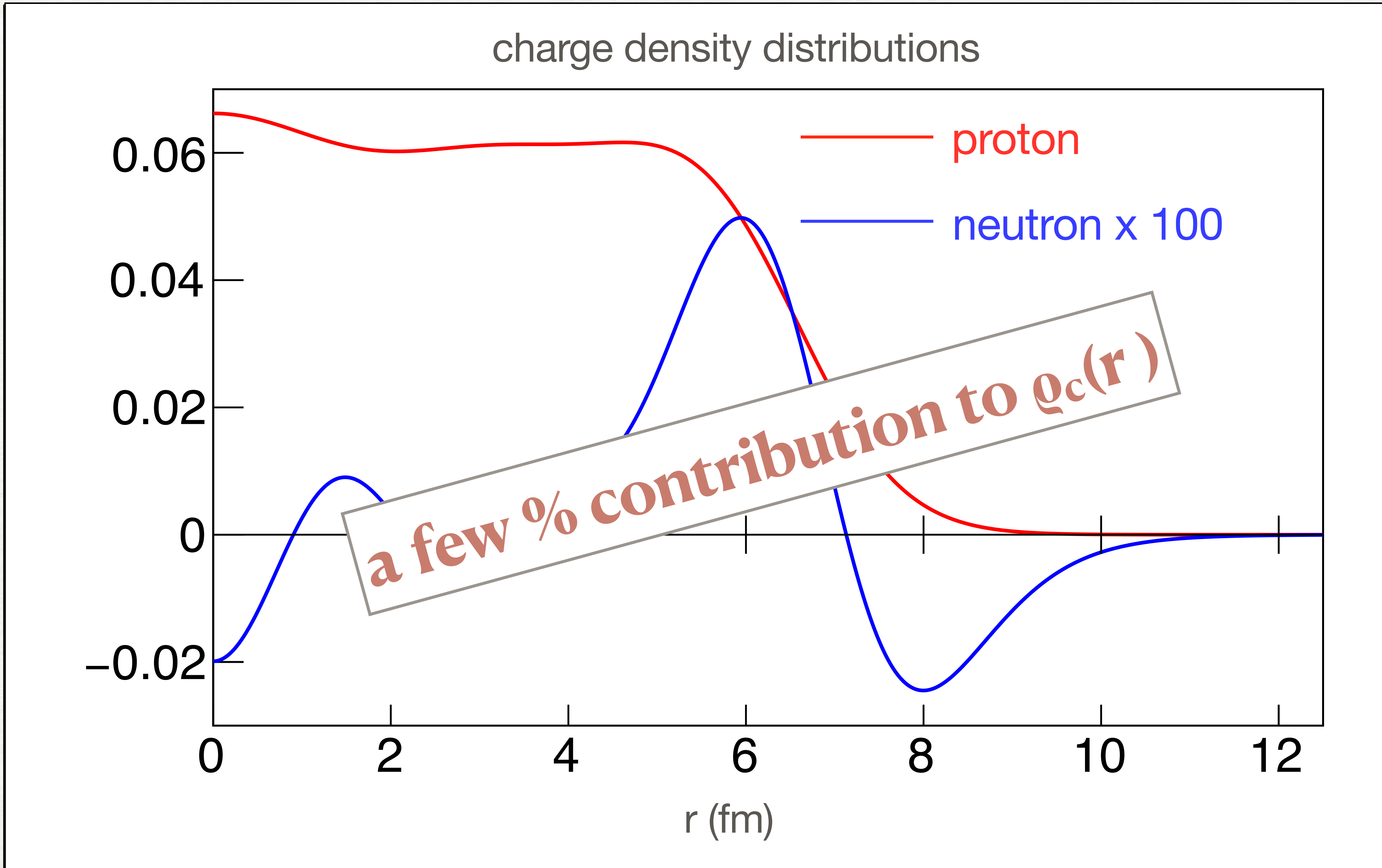
^{208}Pb

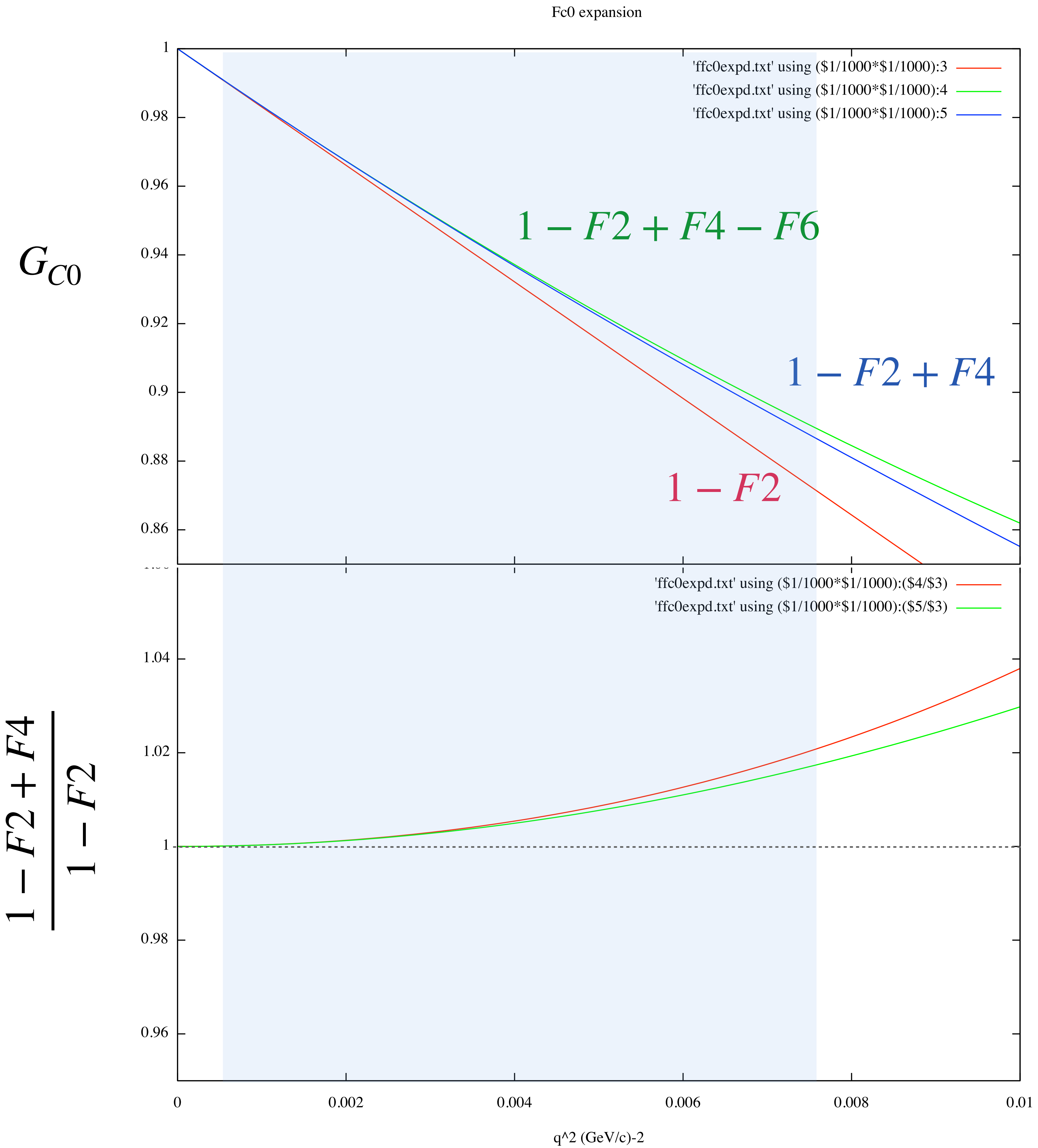
RMF NL3



^{208}Pb

RMF NL3



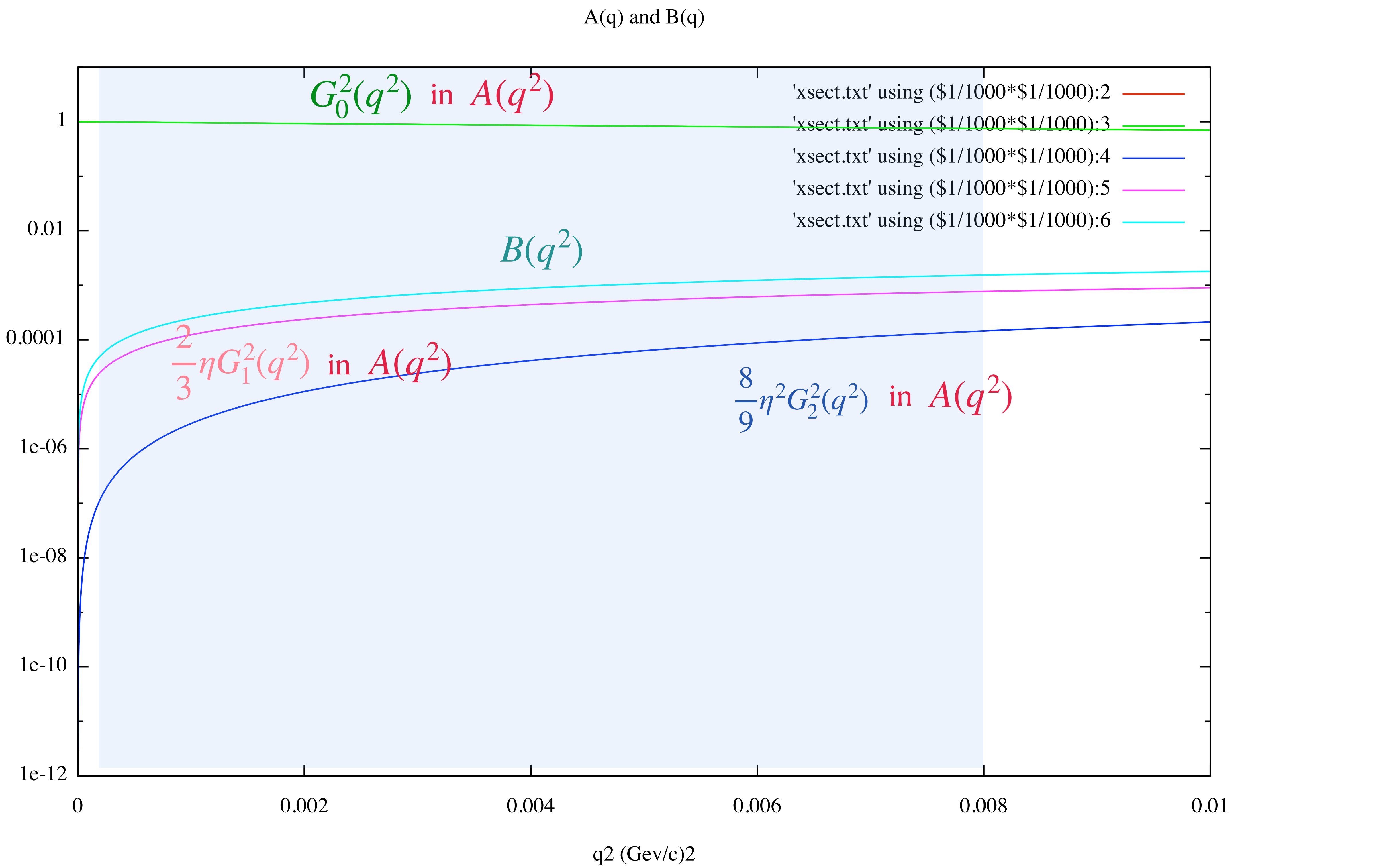


low q から４次が効いている
1-R2 に対する影響は ~１% 程度

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{Mott} [A(q^2) + B(q^2)\tan\frac{\theta}{2}]$$

$$A(q^2) = G_0^2(q^2) + \frac{8}{9}\eta^2 G_2^2(q^2) + \frac{2}{3}\eta G_1^2(q^2)$$

$$B(q^2) = \frac{4}{3}\eta(1+\eta)G_1^2(q^2)$$



eD elastic cross section

$$\frac{d\sigma}{d\Omega} / \frac{d\sigma}{d\Omega}_{Mott} = [A(q^2) + B(q^2)\tan^2\frac{\theta}{2}]$$

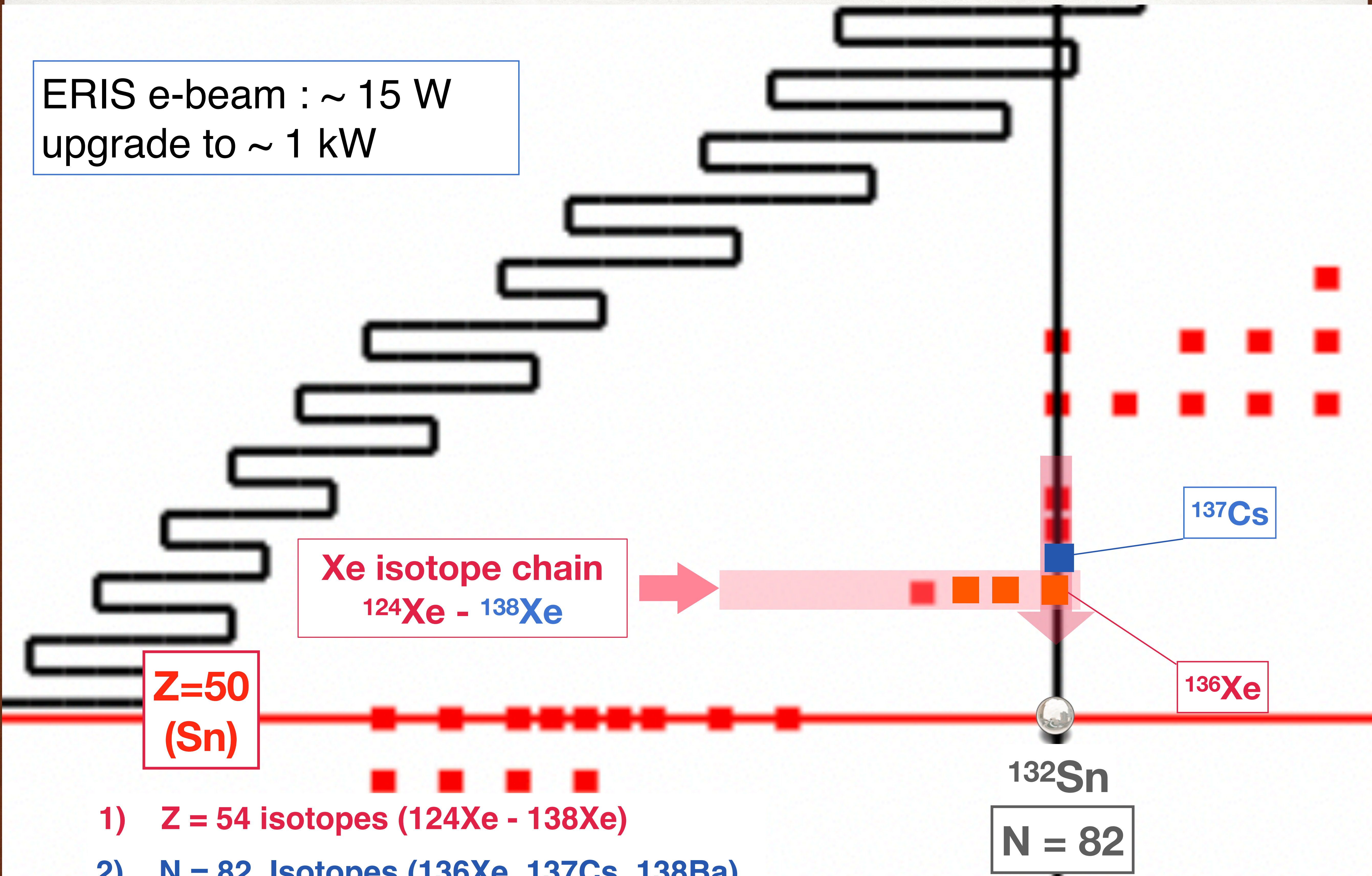
$$= G_0^2(q^2) + \frac{8}{9}\eta^2 G_2^2(q^2) + \frac{2}{3}\eta(1 + 2(1+\eta)\tan^2\frac{\theta}{2})\, G_1^2(q^2)$$

$$= L(q^2) + T(q^2)$$

$$= (C0(q^2) + C2(q^2)) + M1(q^2)$$

- L(q2) と T(q2) は Rosenbluth 分離
- L(q2) の中の C0 と C2 は分離できない。
- C2/C0 が十分小さいことを確かめる

On-going Physics Program at the SCRIT facility



1) Z = 54 isotopes (124Xe - 138Xe)

2) N = 82 Isotopes (136Xe, 137Cs, 138Ba)

Deuteron charge radius

1) electron scattering (in 1970s)
2) eH spectroscopy
3) μH spectroscopy

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