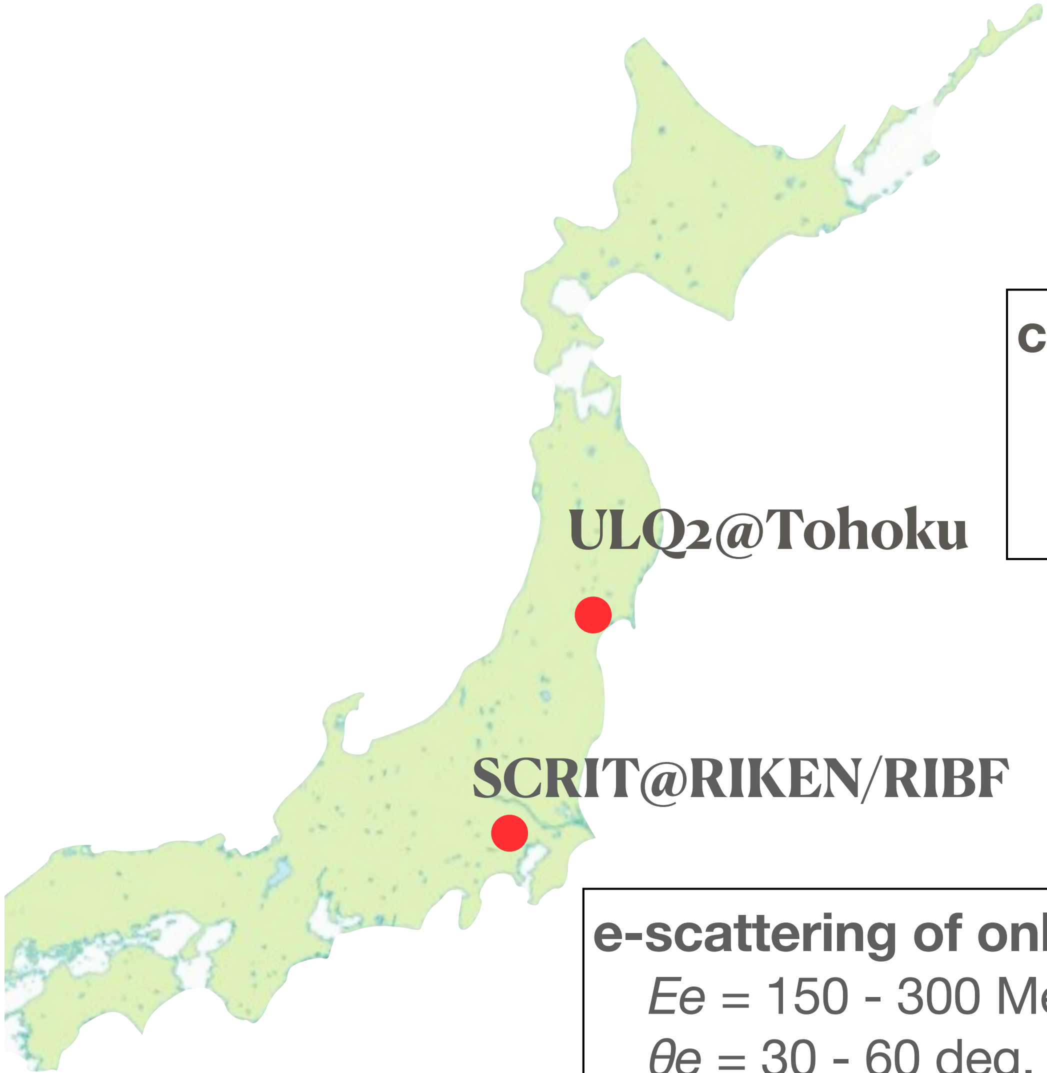
Electron Scattering off Protons and Exotic Nuclei

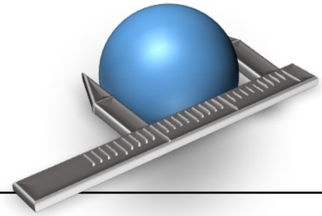
- ULQ2 and SCRIT -

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

for SCRIT collaboration
ULQ2 collaboration

Low-energy electron-scattering facilities in Japan





charge radii of proton and deuteron

Ee = 10 - 60 MeV

θe = 30 - 150 deg.

=> $Q^2 = 3\times10^{-5}$ - 0.013 $(\text{GeV}/c)^2$

lowest-ever Q^2 !!

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 $(\text{GeV}/c)^2$

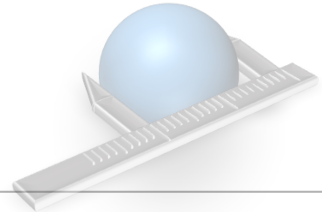
world's first !!

this talk

ULQ2 (Ultra-Low Q2) for proton-radius measurement

ULQ2 collaboration: Tohoku, Kyoto, RIKEN and IJCLab

Low-energy electron-scattering facilities in Japan



charge radii of proton and deuteron

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world's first !!

⇨ **this talk**

Edito

Electron scattering provides a long-awaited view of unstable nuclei

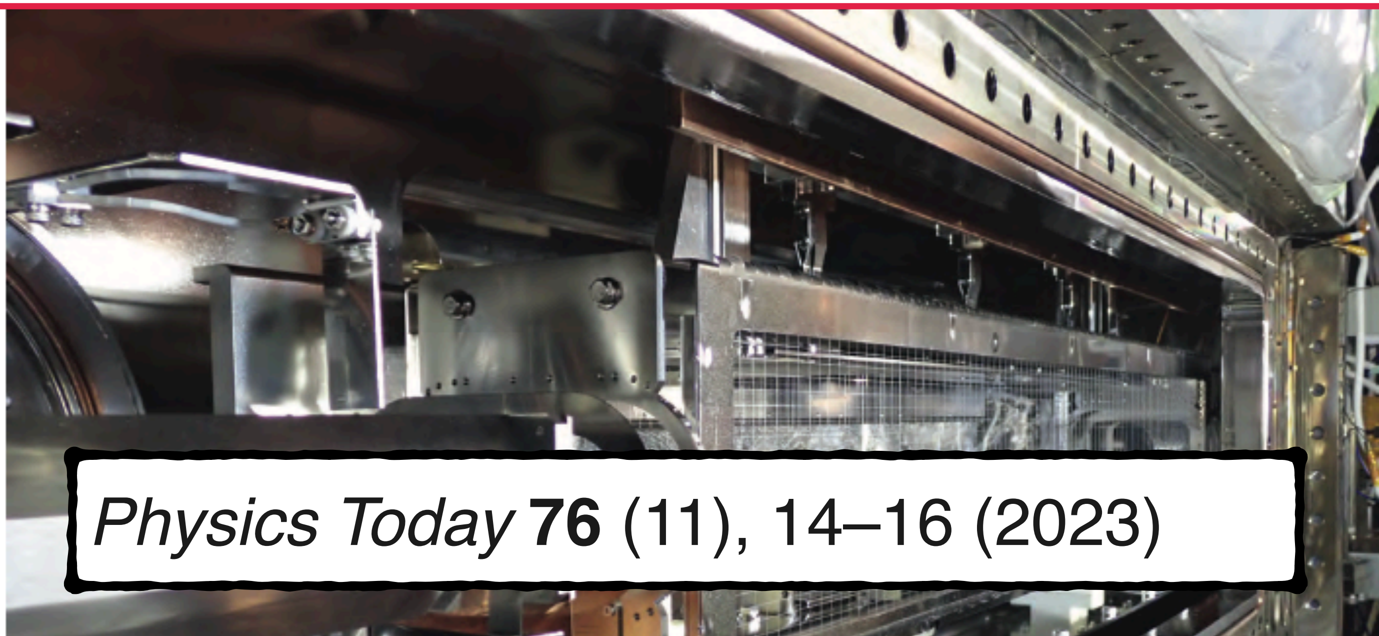
Nuclear reactions produce a plethora of short-lived artificial isotopes. Figuring out what they look like has been a challenge.

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,

stranger the structures it can adopt. Short-lived nuclei might form bubble structures with depleted central density, or they might have a valence nu-

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 research-

electron scattering - the gold standard for probing nuclear structure - has been off limits to short-lived exotic nuclei

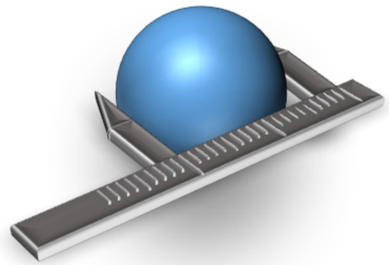


Physics Today **76** (11), 14–16 (2023)

Shor
tigated

Contents

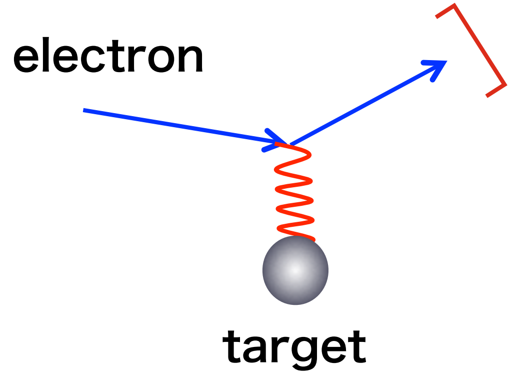
1. electron scattering
2. SCRIT facility for short-lived unstable nuclei
3. first result for online-produced unstable nuclei
4. new research possibilities
    1. neutron distribution by electron scattering
    2. photonuclear response
5. ULQ2 at Tohoku for proton radius



Contents

Electron scattering

Electron scattering has consistently played an essential role to reveal detailed structures of nucleon and nuclei



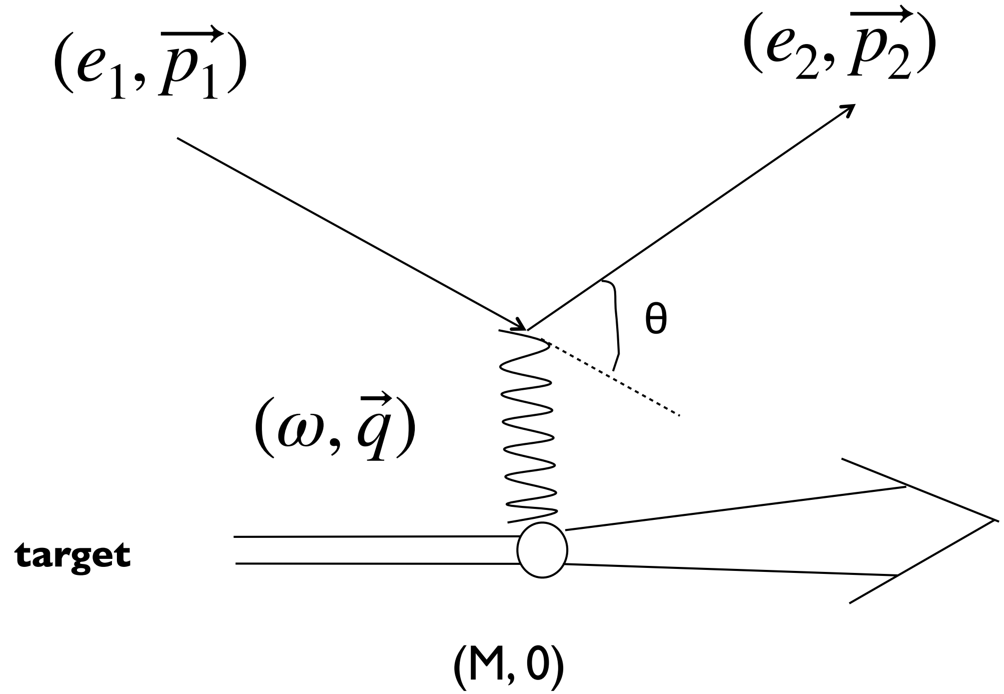
one detects only scattered electrons

→ very "simple" measurements

1. **elementary particle** **- structure-less -**
2. **electro-weak interaction** **- best understood -**
3. **"relatively" weak** **- probing deep inside of the target -**

Electrons do not experience the nuclear strong force.

Electron scattering



kinematical variables Under URL (Ultra-Rel. Limit) : me -> 0

energy transfer $$\omega = e_1 - e_2$$

momentum transfer $$\vec{q} = \vec{e_1} - \vec{e_2}$$

4-momentum transfer $$Q^2 = \omega^2 - \vec{q}^2 = 4e_1 e_2 \sin^2 \frac{\theta}{2}$$

for (spin-less) nuclei

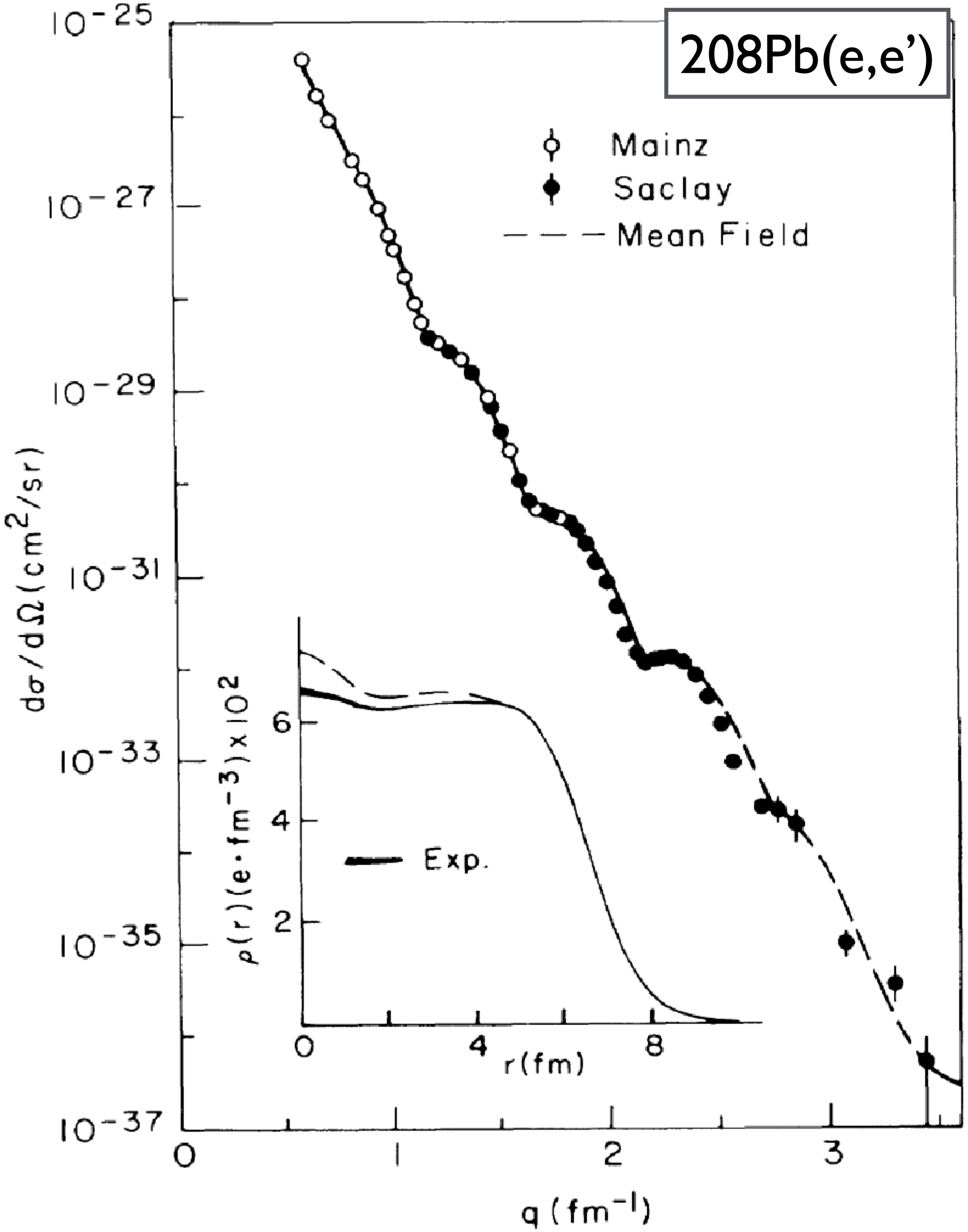
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{Mott}}{d\Omega} \, |F_c(q)|^2$$

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

charge distribution

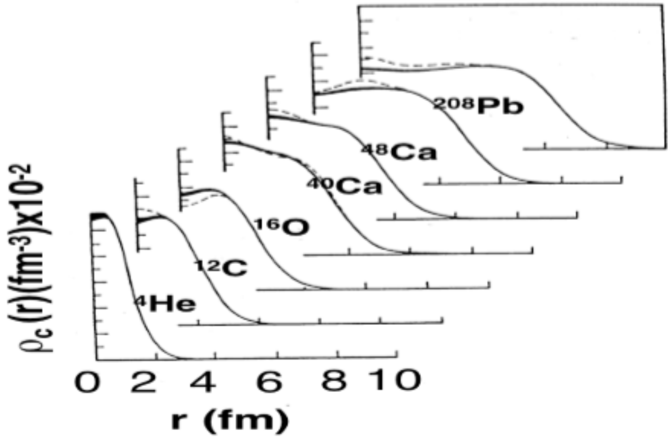
$$\frac{d\sigma_{Mott}}{d\Omega} \propto e^2/q^4$$

208Pb(e,e')

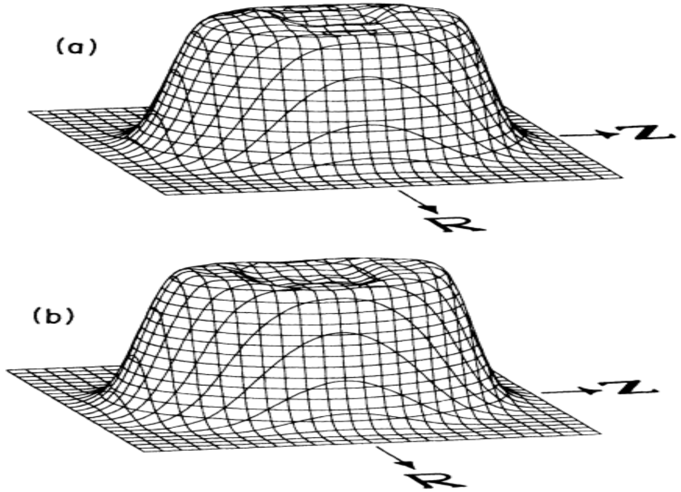


J. M. Cavedon et al. PRL 58 (1987) 195

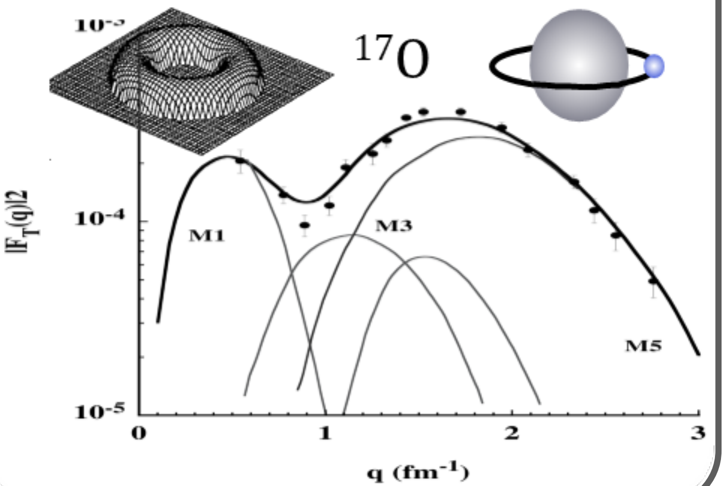
elastic scattering
→ charge distribution



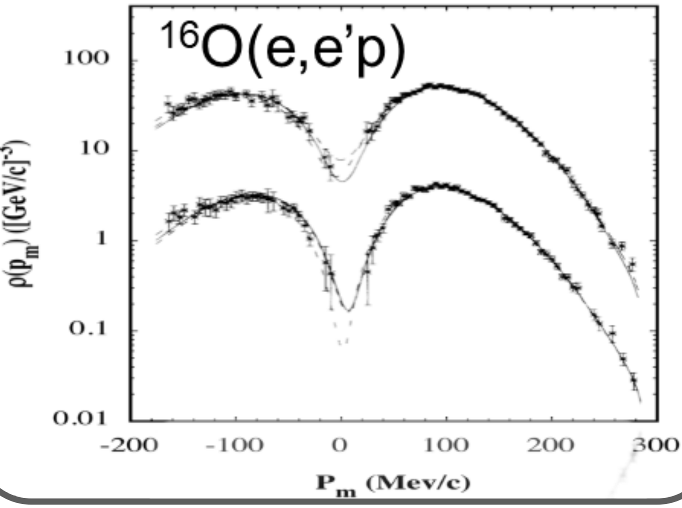
elastic + inelasticscattering
→ deformation



magnetic scattering
→valence neutron



quasi-elastic (e,e'p)
→ S-factor

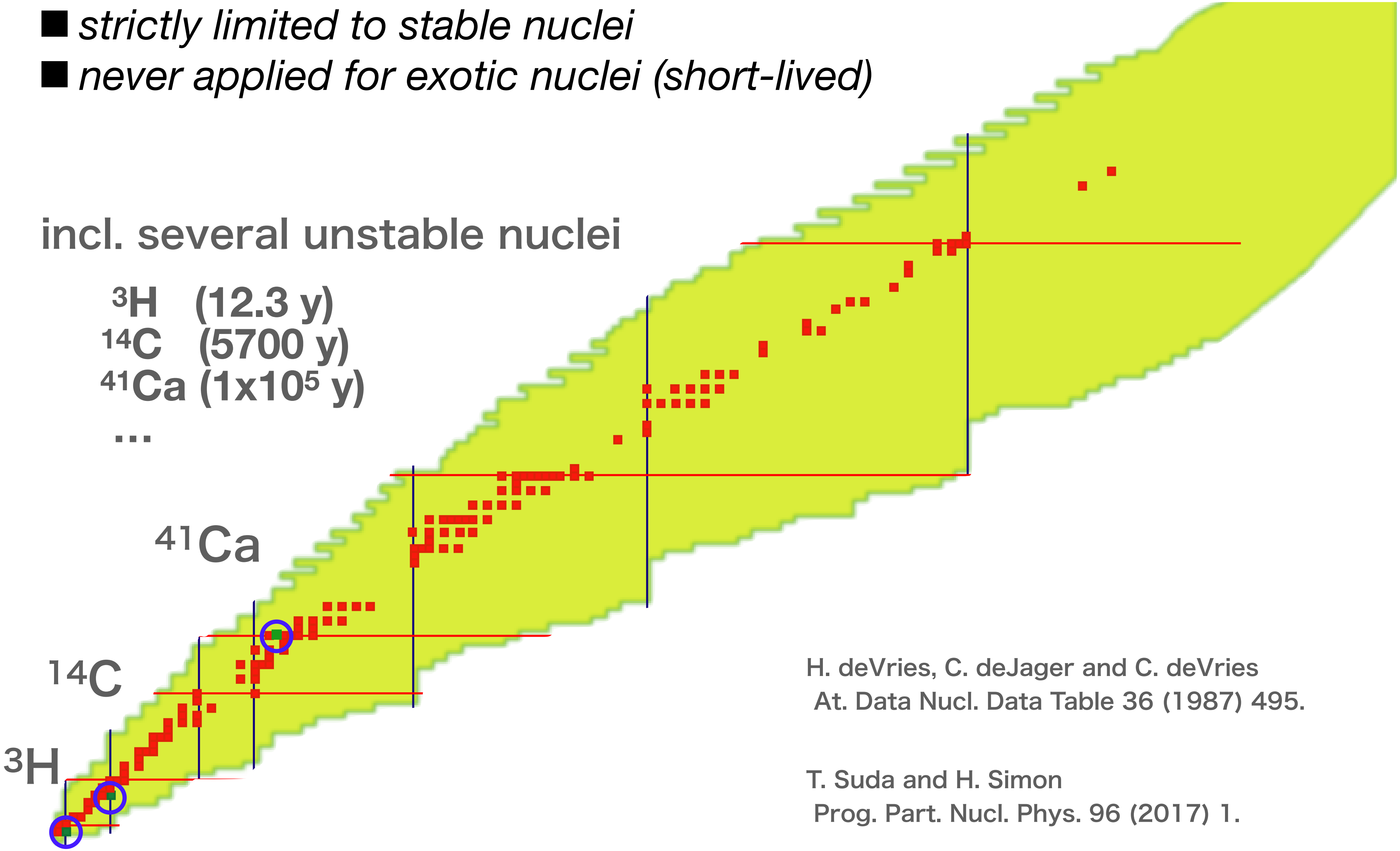


Nuclei ever studied by electron scattering

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

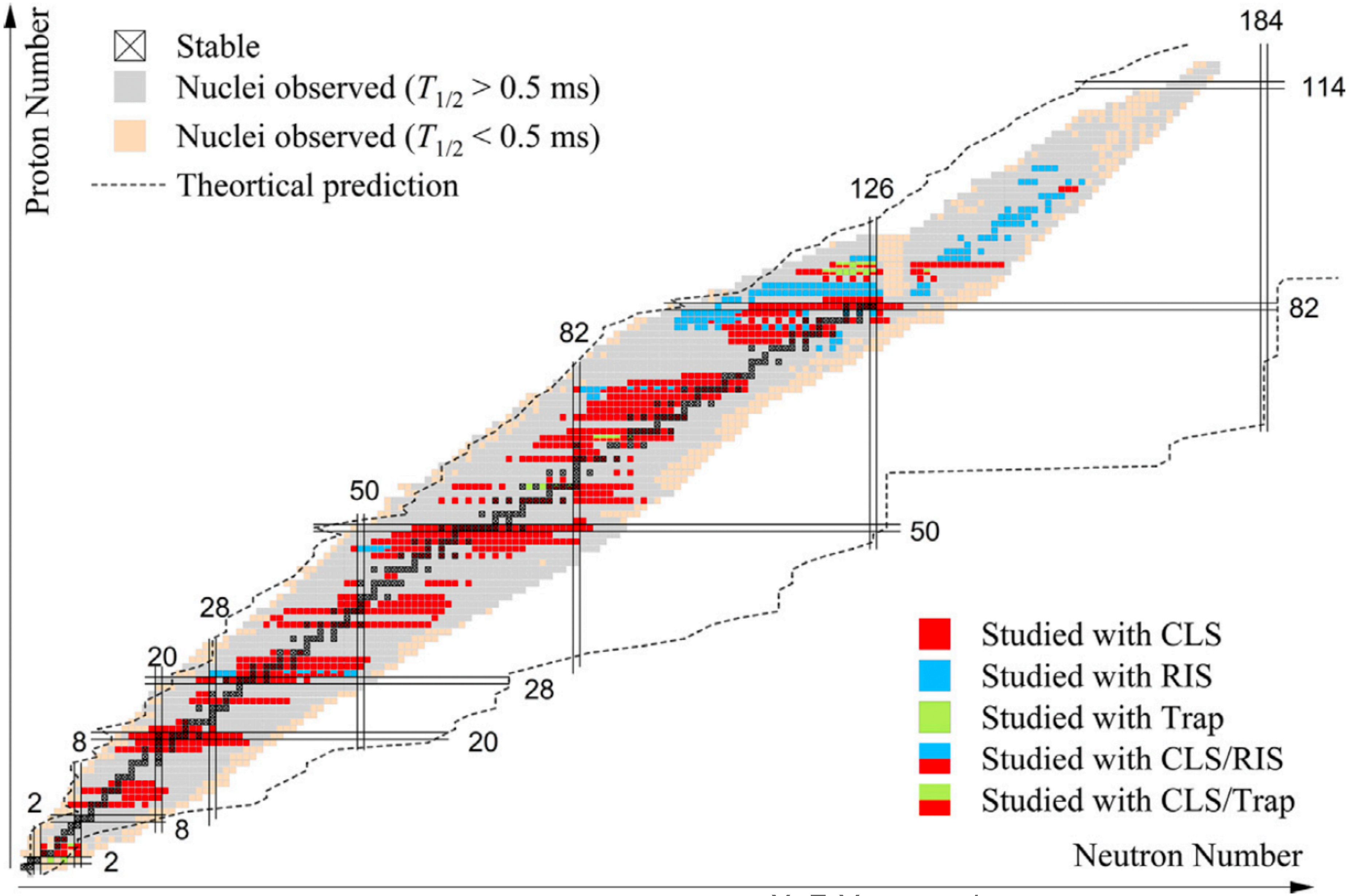
incl. several unstable nuclei

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



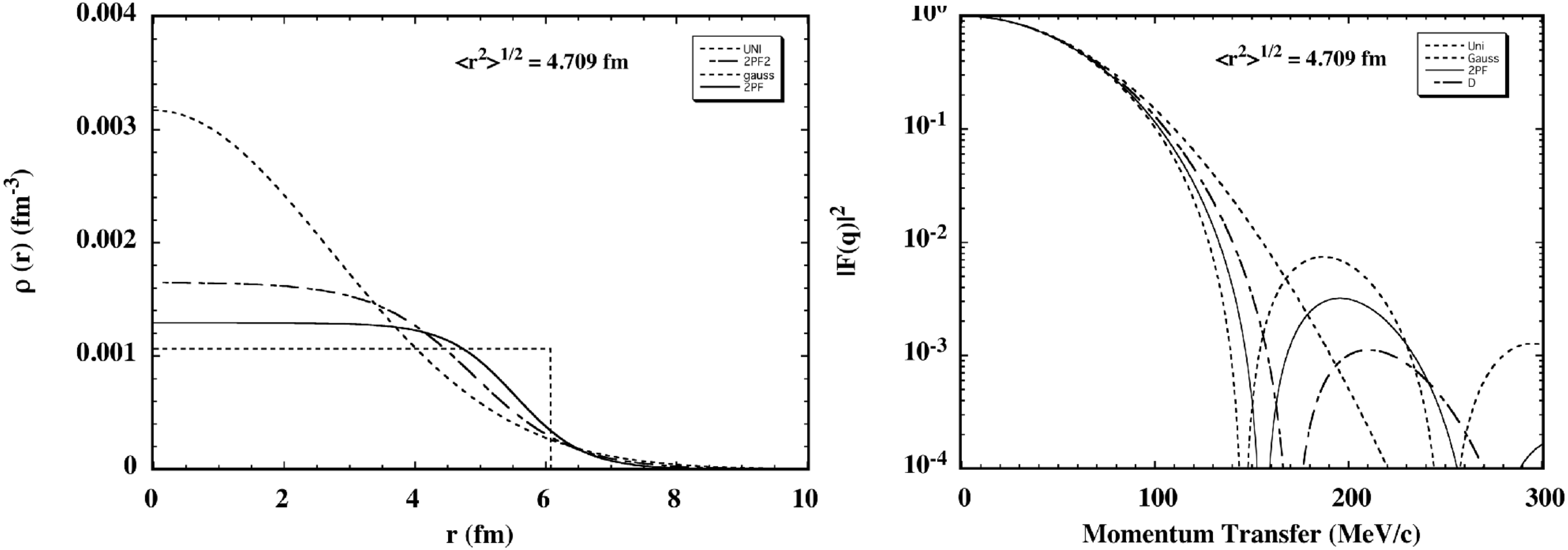
H. deVries, C. deJager and C. deVries
At. Data Nucl. Data Table 36 (1987) 495.

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



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

Density distributions having the same charge radius (4.7 fm)



further beyond "proton distribution" for exotic nuclei ??

=> *possible new opportunities*
neutron distribution
photonuclear reaction

$$\frac{dN}{dt} = L \times \frac{d\sigma}{d\Omega}$$

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)

	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

Contents

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*

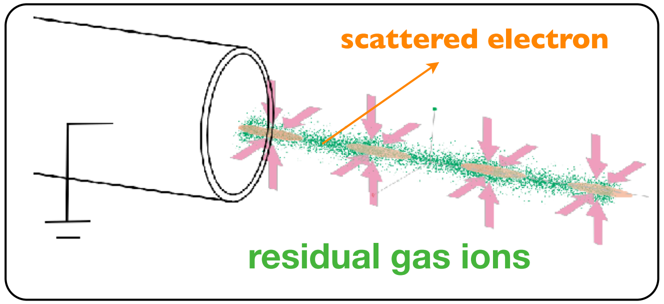
[b] *RI Beam Science Laboratory, RIKEN, Wako-shi, Saitama 351-0198, Japan*

Available online 3 August 2004

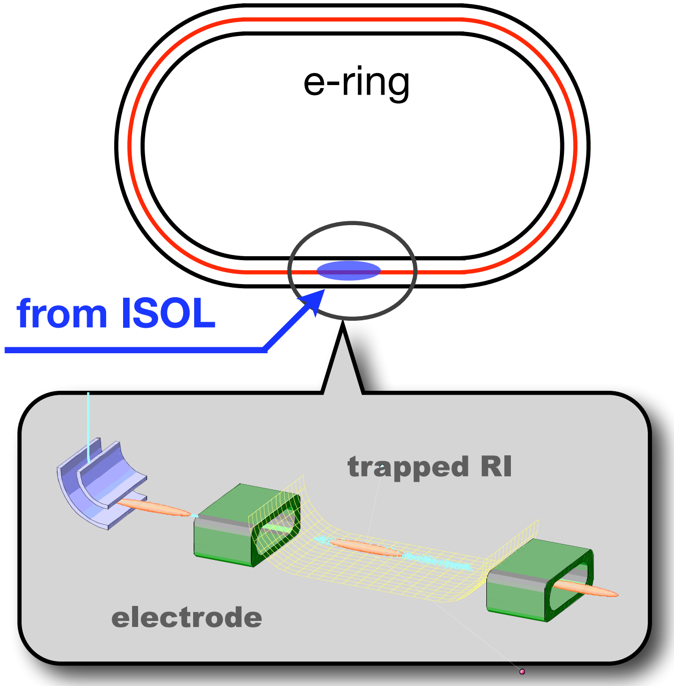
SCRIT（Self-Confining RI Ion Target)

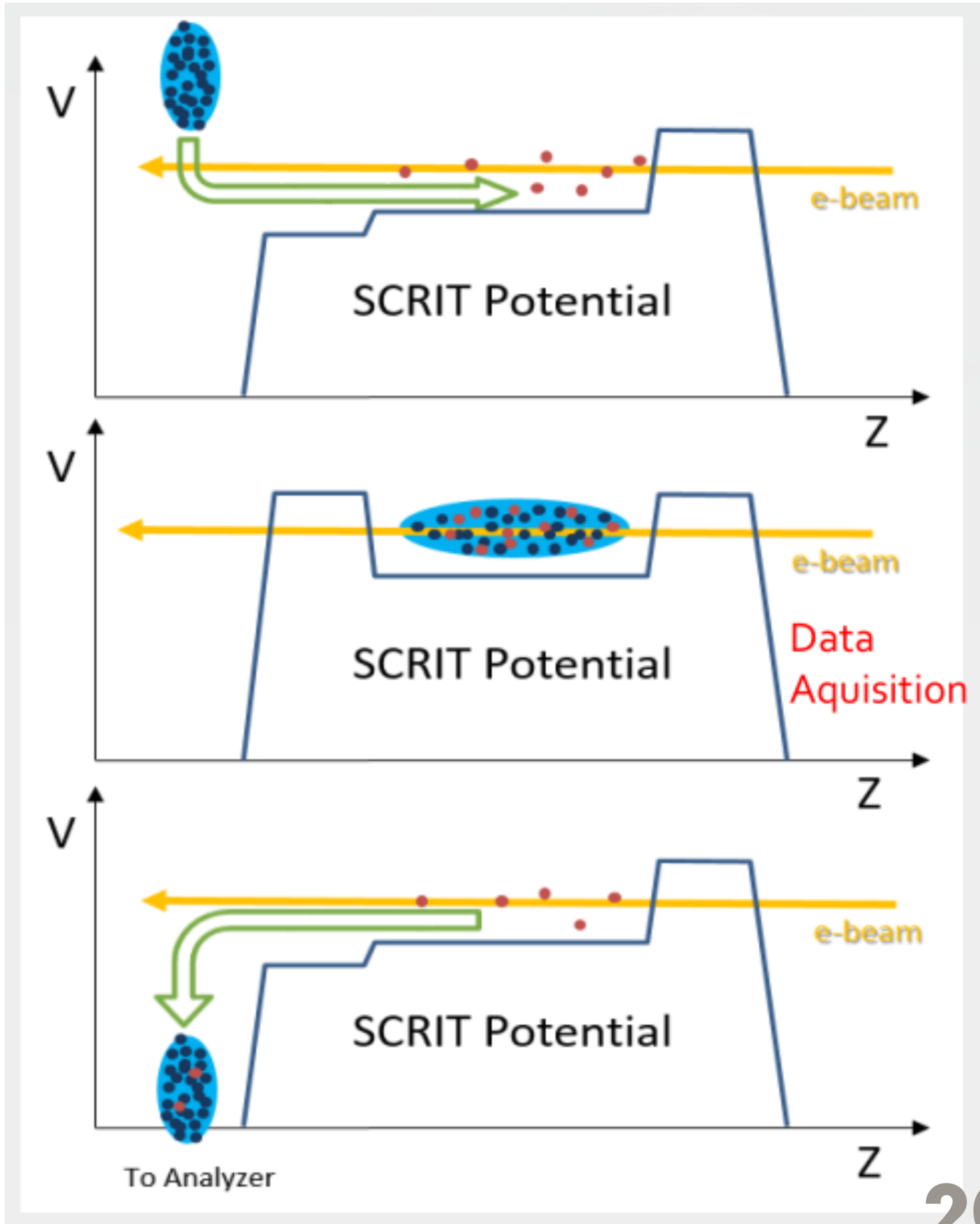
Idea : "ion trapping" at SR facilities.

ionized residual gases are trapped by the circulating electron beam

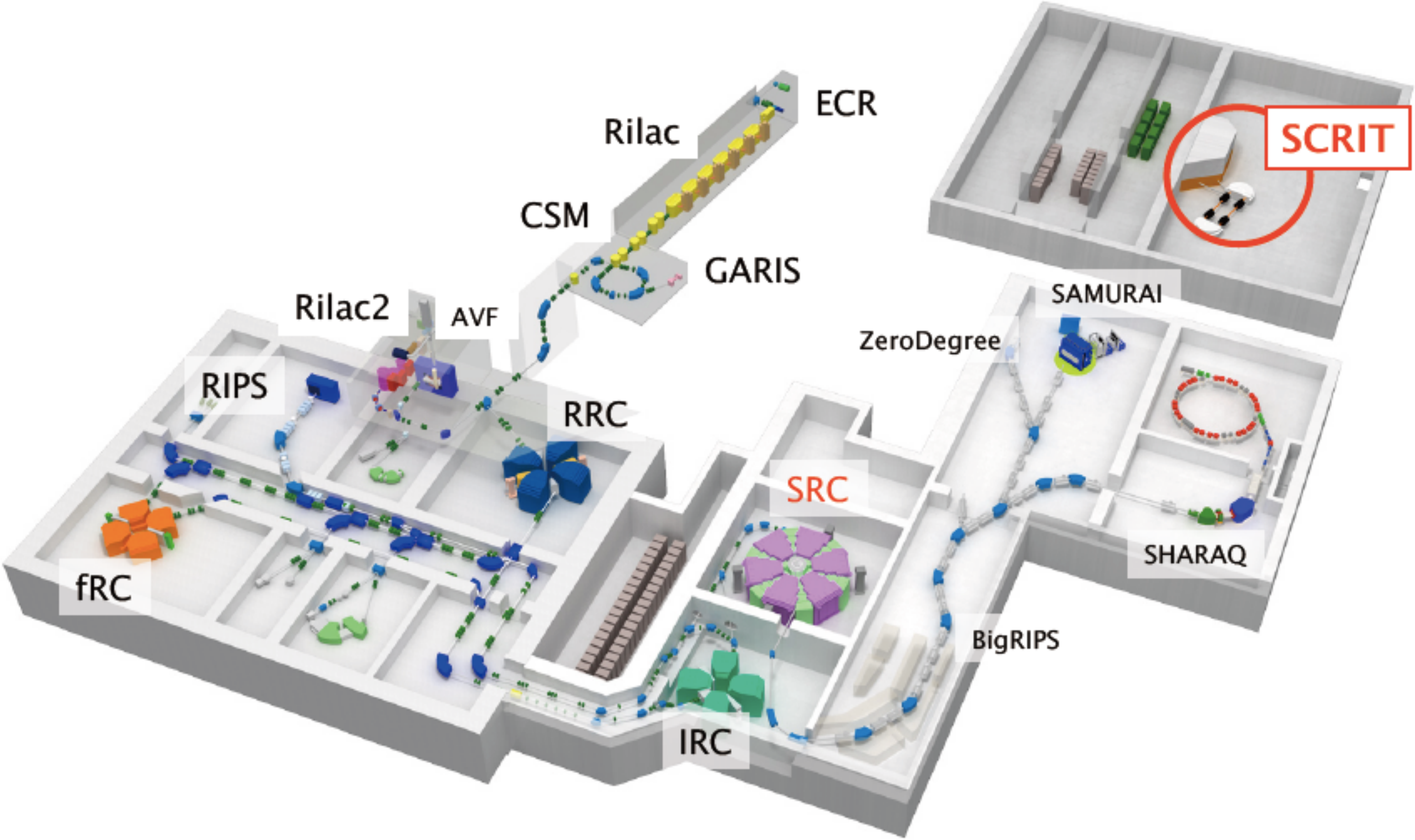


ill problem of e-storage rings



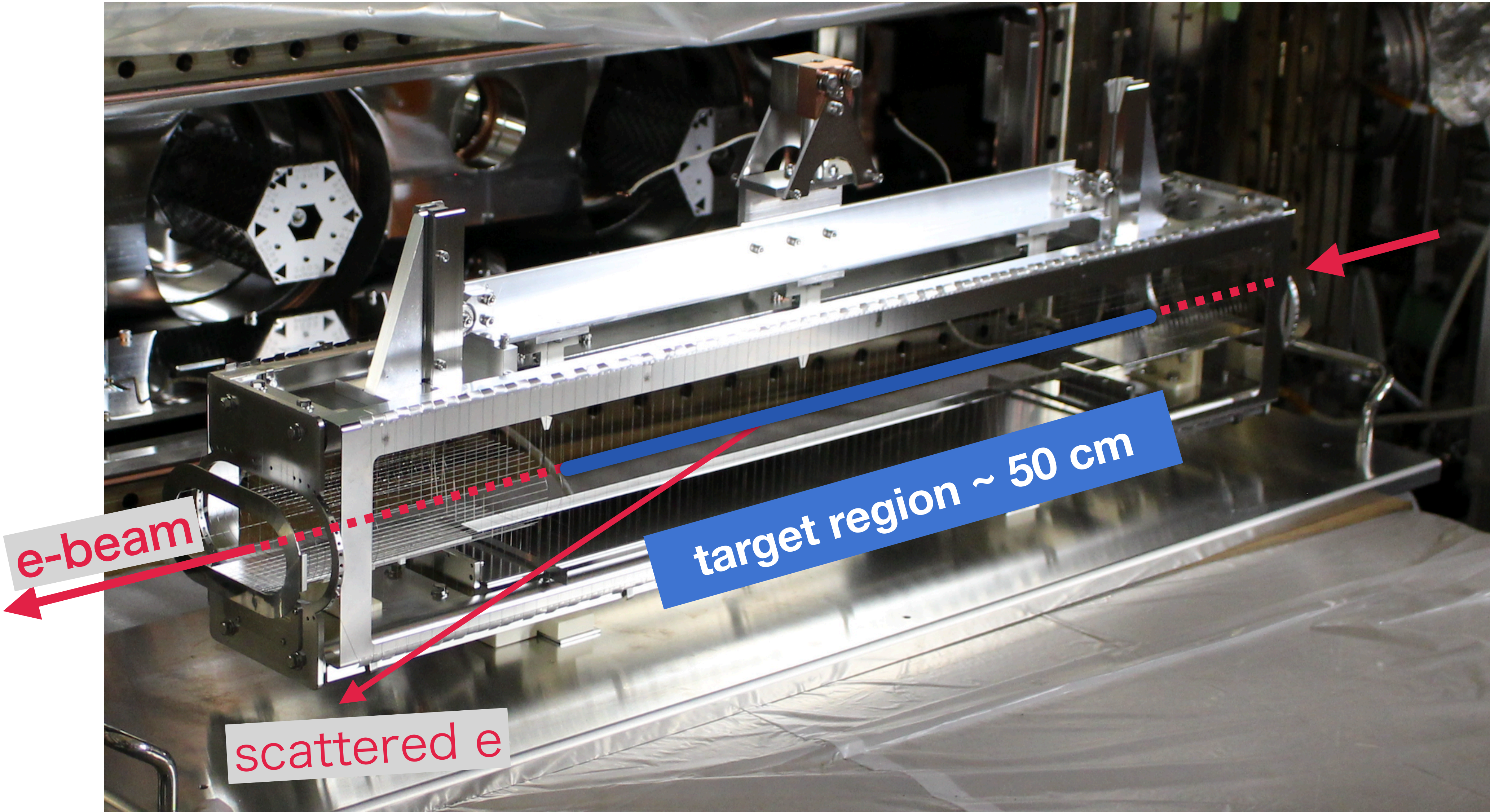


World's first electron facility dedicated for exotic nuclei



RIKEN RI Beam Factory (Japan)

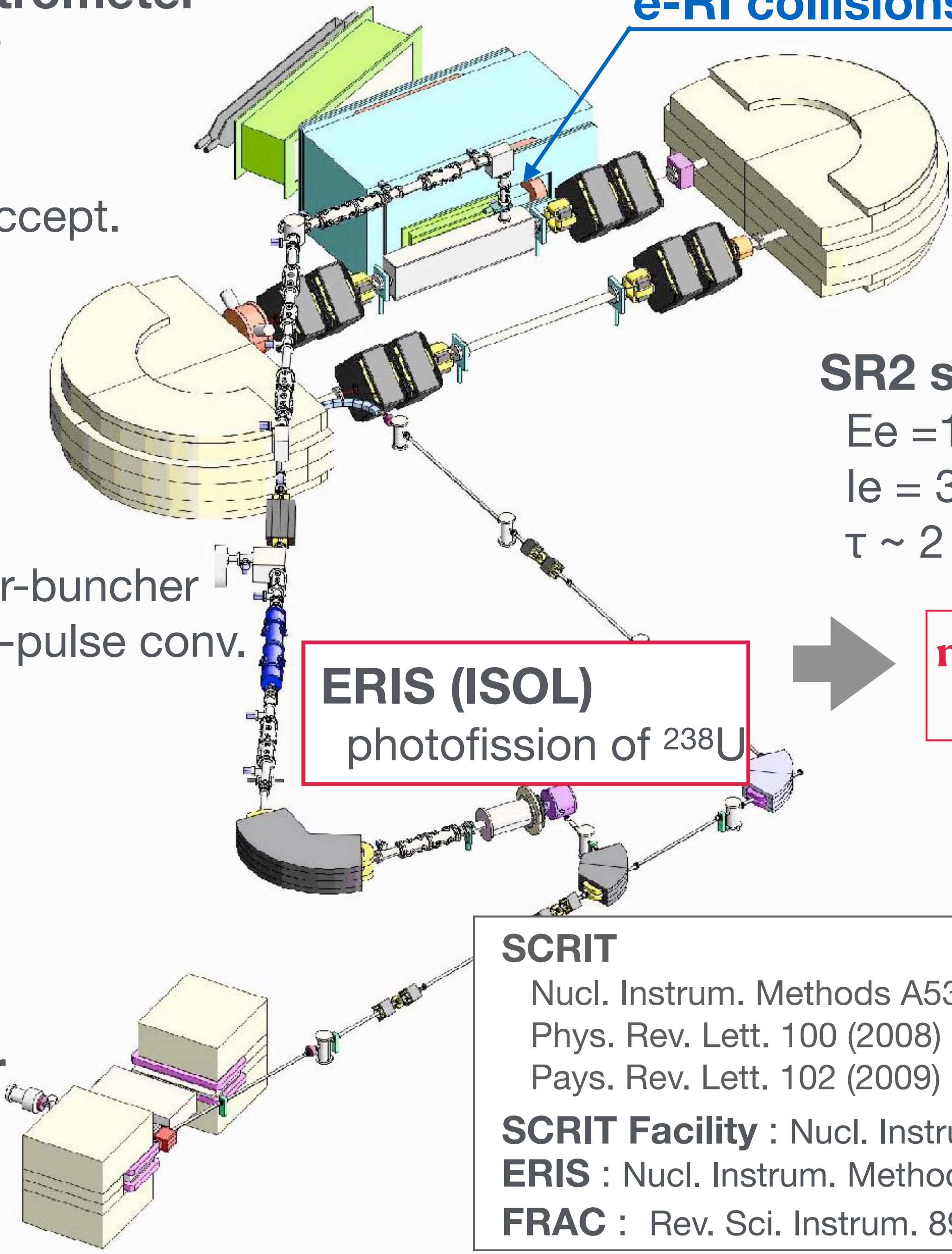
SCRIT device for preparing a target on e-beam



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.

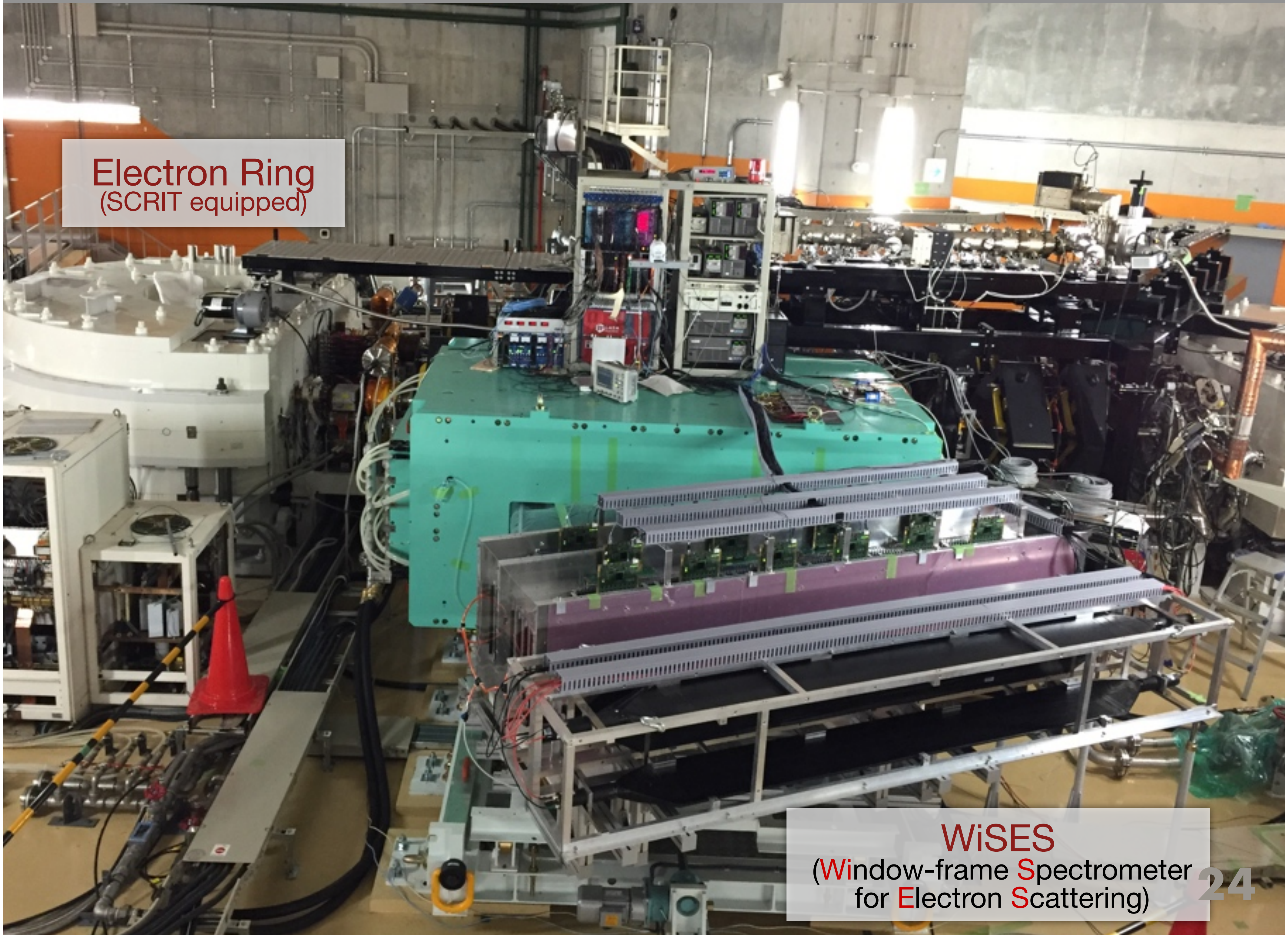
ERIS (ISOL)
photofission of ^{238}U

neutron-rich nuclei by γ+^{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.

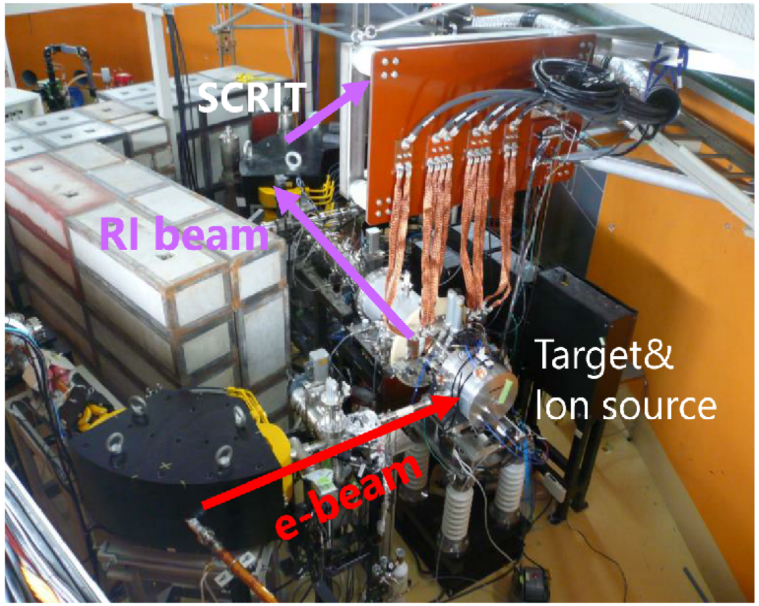

Electron Ring
(SCRIT equipped)
WiSES
(Window-frame Spectrometer
for Electron Scattering)

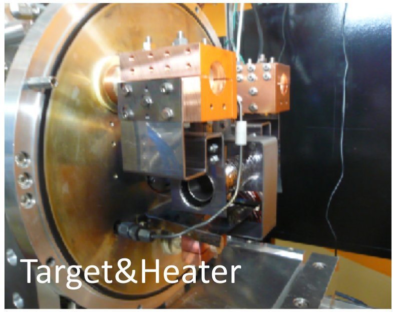
ERIS (Electron-beam-driven RI separator for SCRIT)

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

House-made Uranium carbide (UCx)

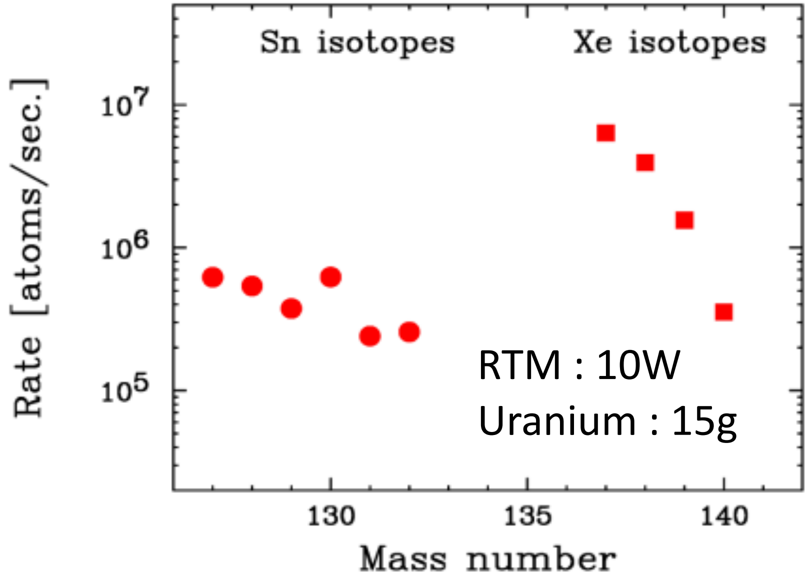
φ 18 mm, t 0.8 mm disks





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

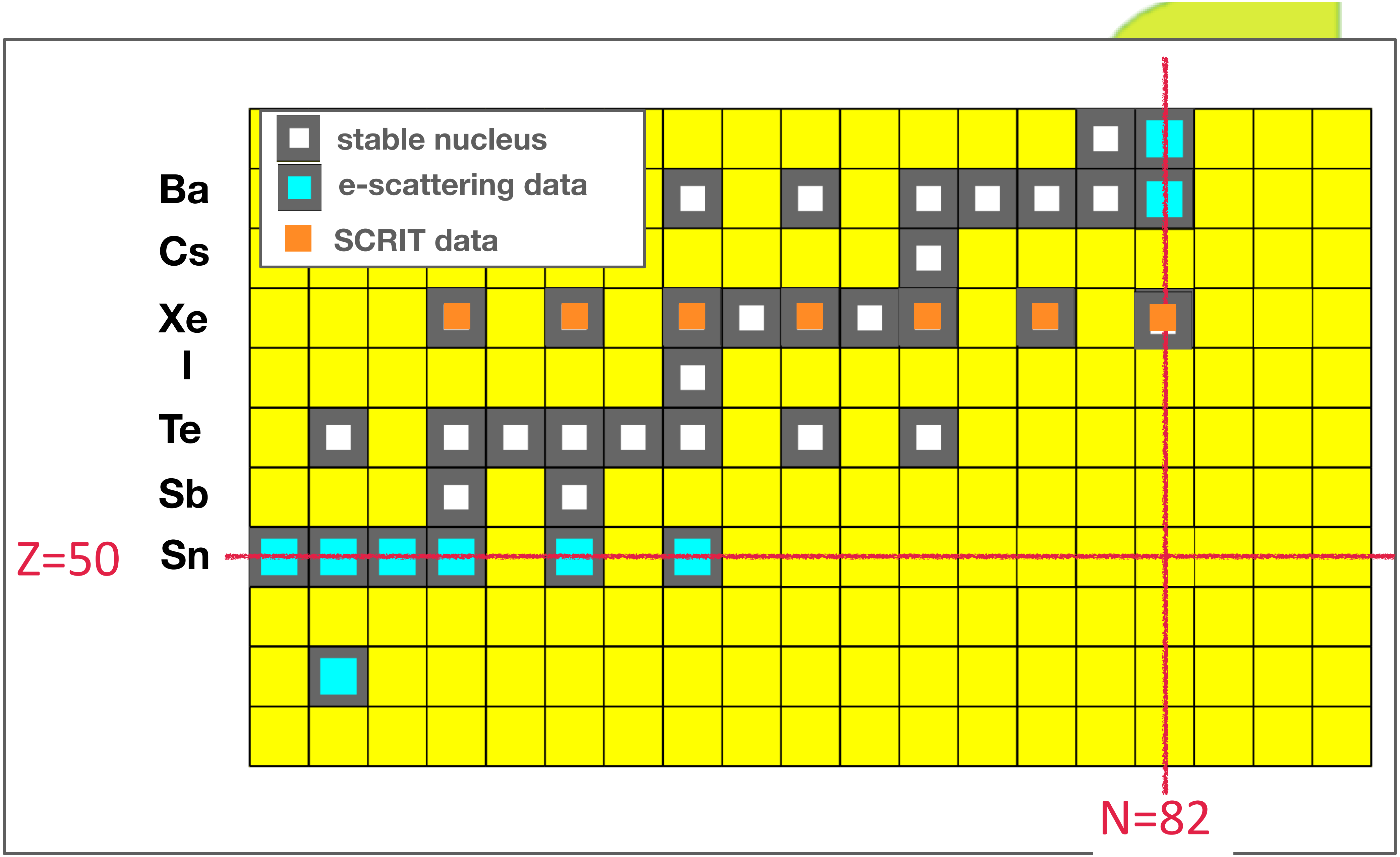
beam power : ~ 20W (today)
~ 2 kW (in a few years)



^{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.

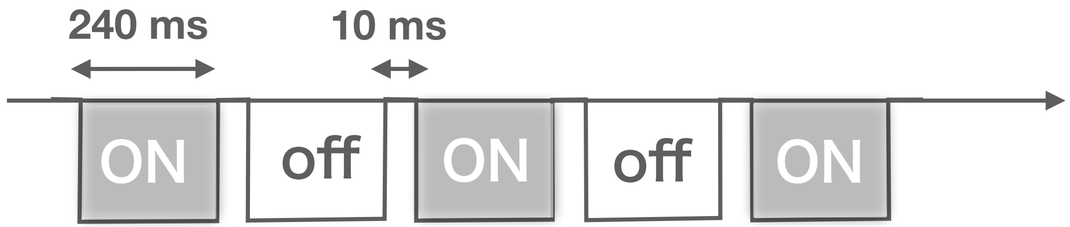
"Day-one exp." region for our facility



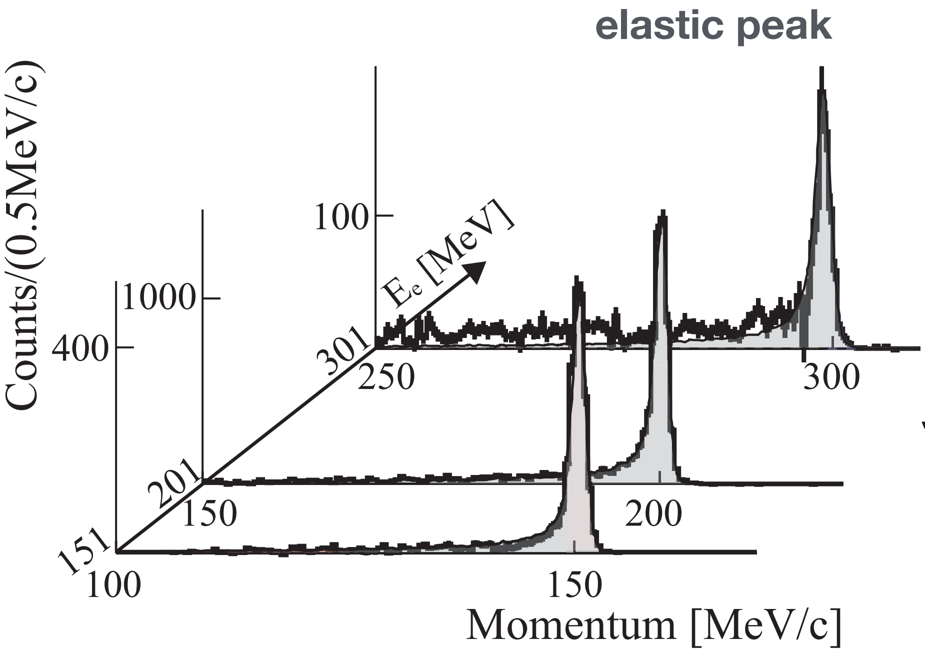
SCRIT facility commissioning : (stable) ^{132}Xe(e,e')

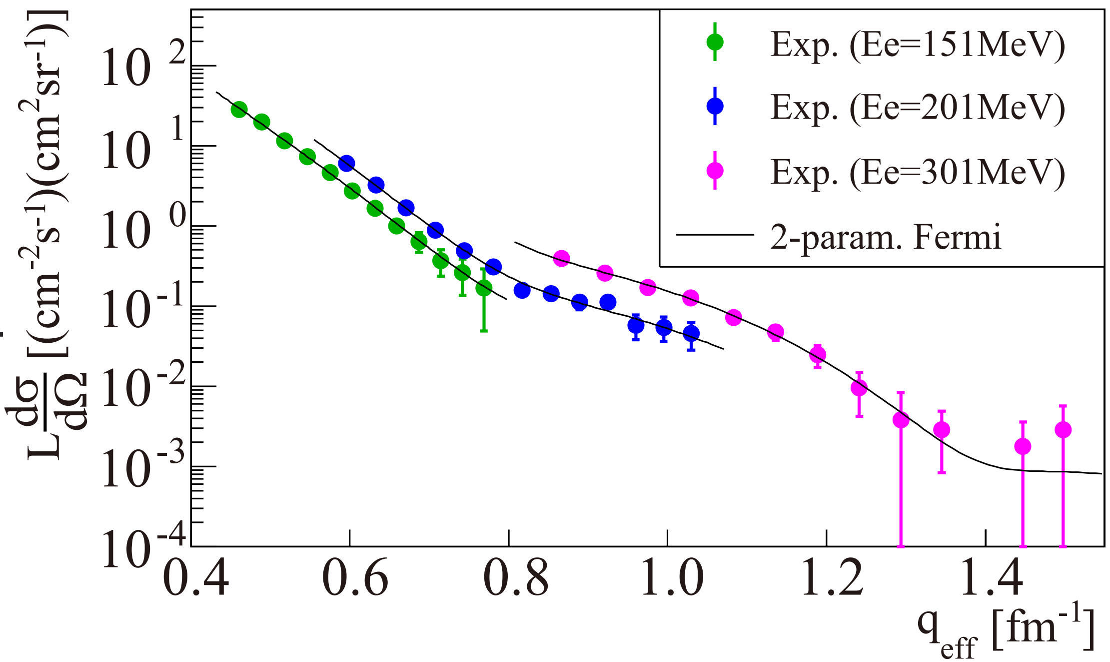
K. Tsukada et al., Phys. Rev. Lett. 118 (2017) 262501.

trapping duration
240 ms



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

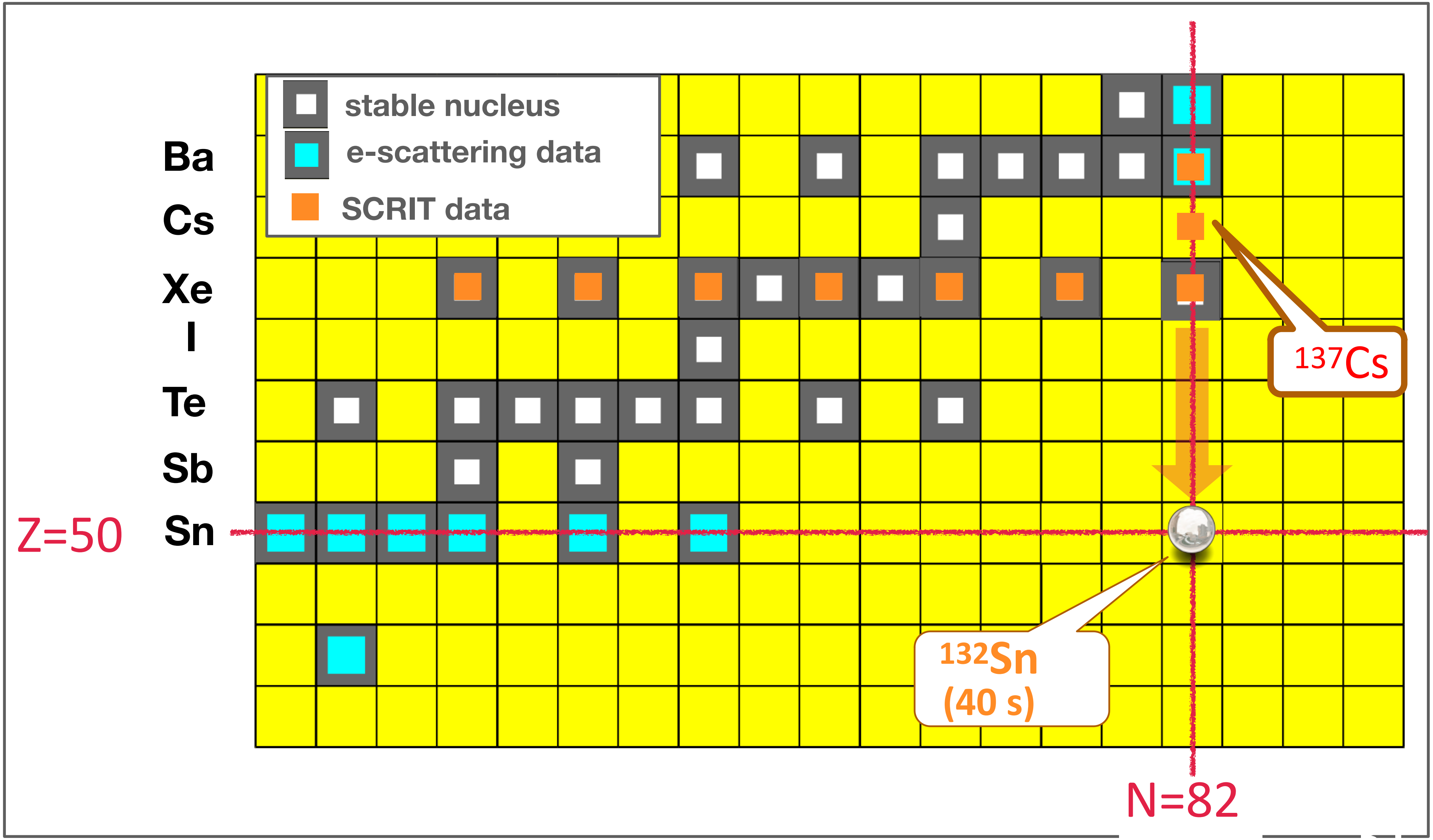




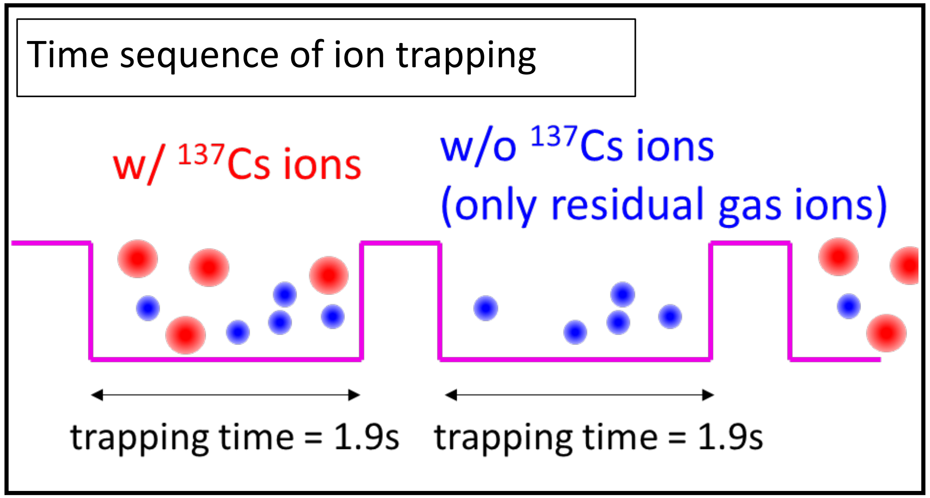
$\langle r^2 \rangle^{1/2} = 4.789 \, ^{+0.12}_{-0.10}$ fm

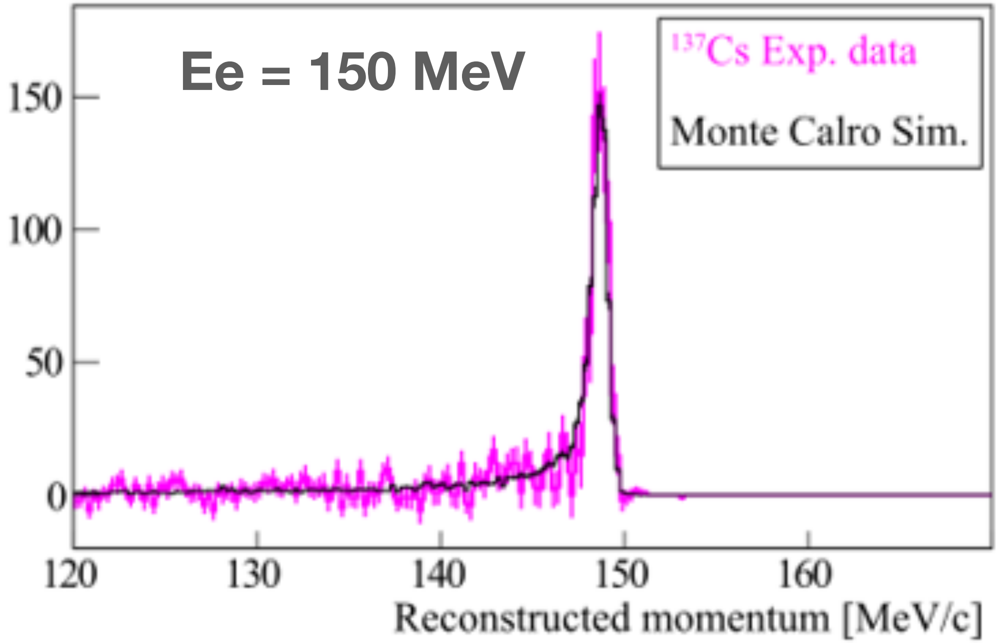
$\langle r^2 \rangle^{1/2} = 4.787$ fm(μ-atom X-rays)

"Day-one exp." region for our facility



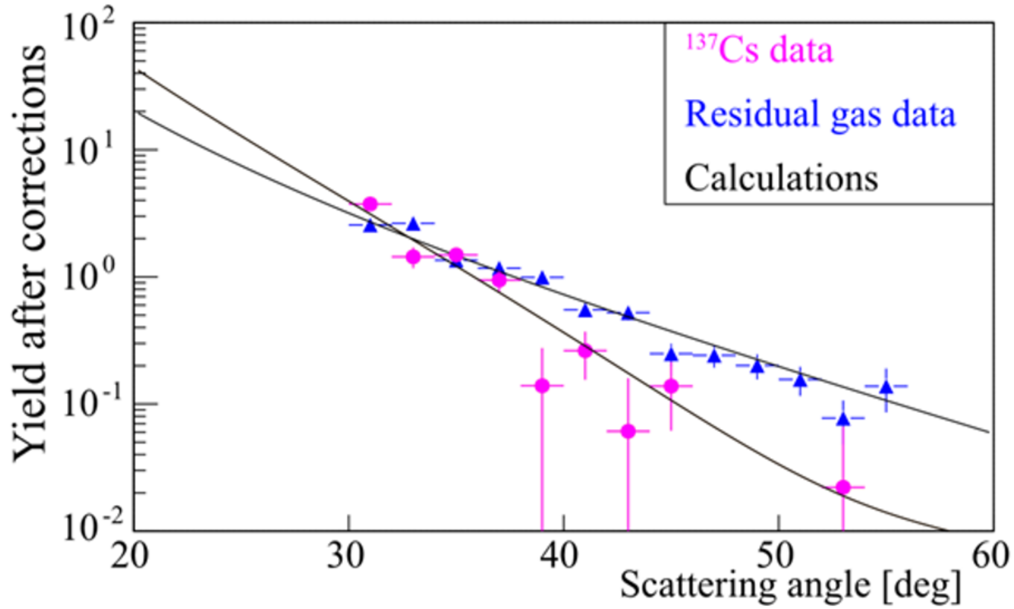
First demonstration of e-scattering off online-produced radioactive isotope : ^{137}Cs(e,e')





1.9 s trapping

=> mimicking "short-lived" nuclei



$N_{trapped}$ ~ 2 x10^7

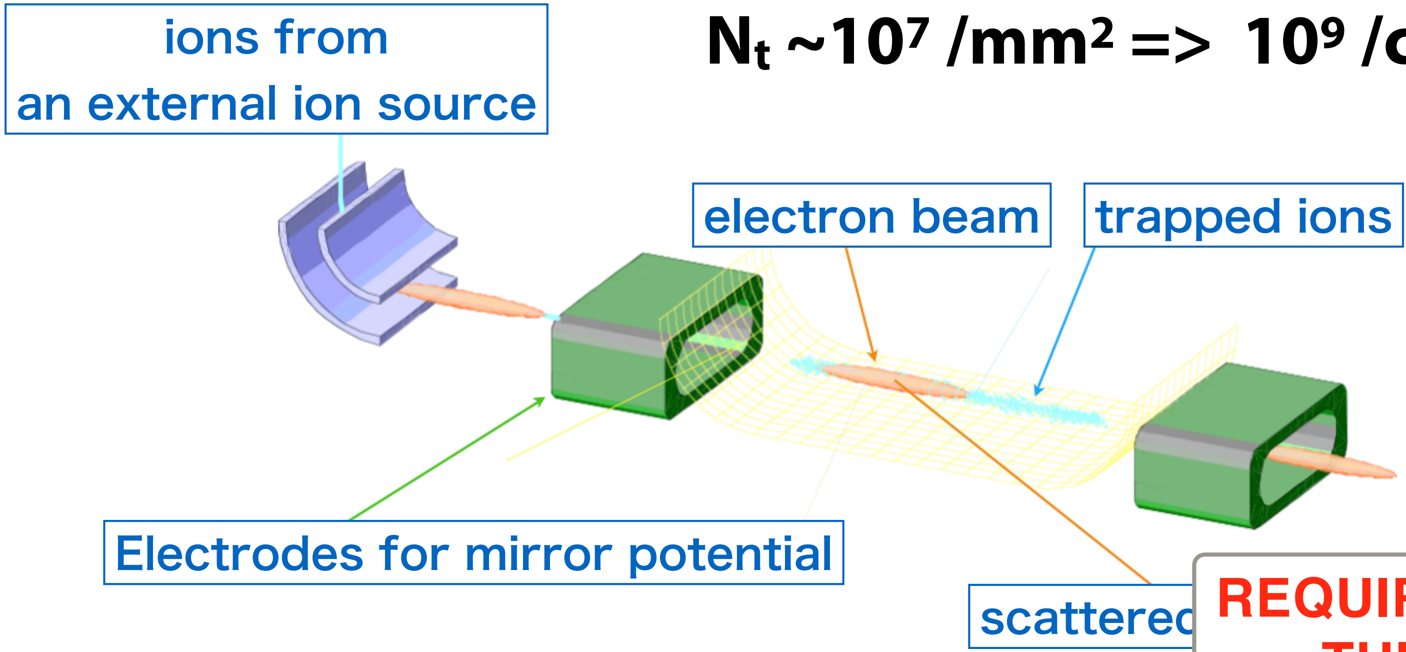
=> L ~ 0.9 x 10^{26} /cm^2/s

successful demonstration for online-produced unstable nuclei

Luminosities

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

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

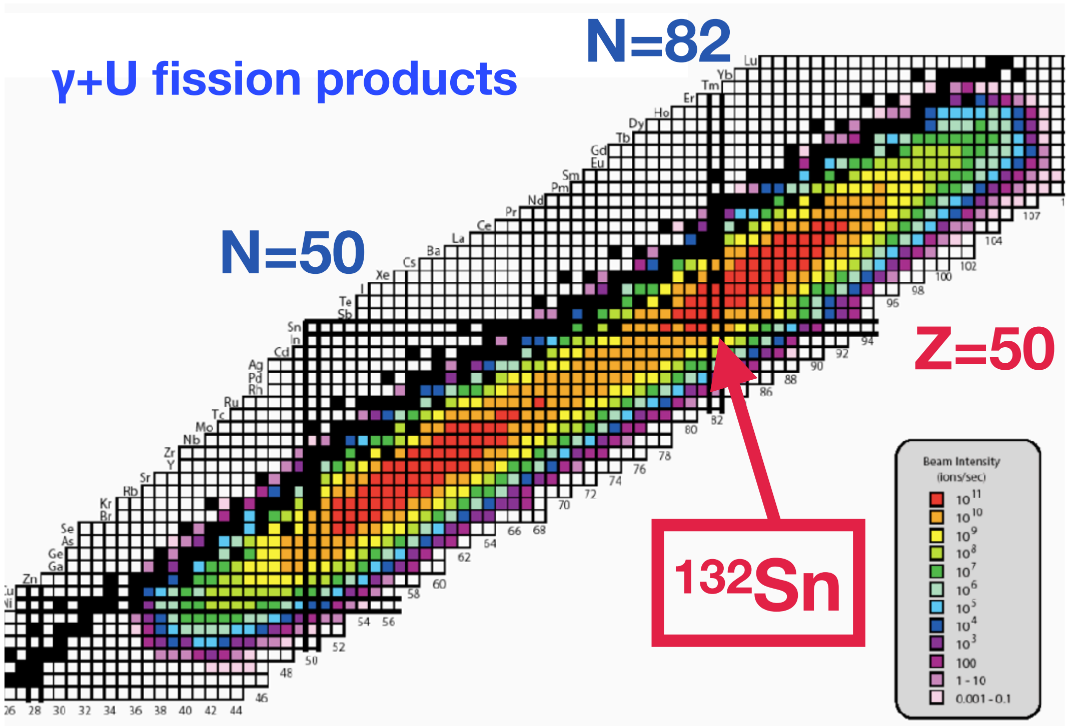


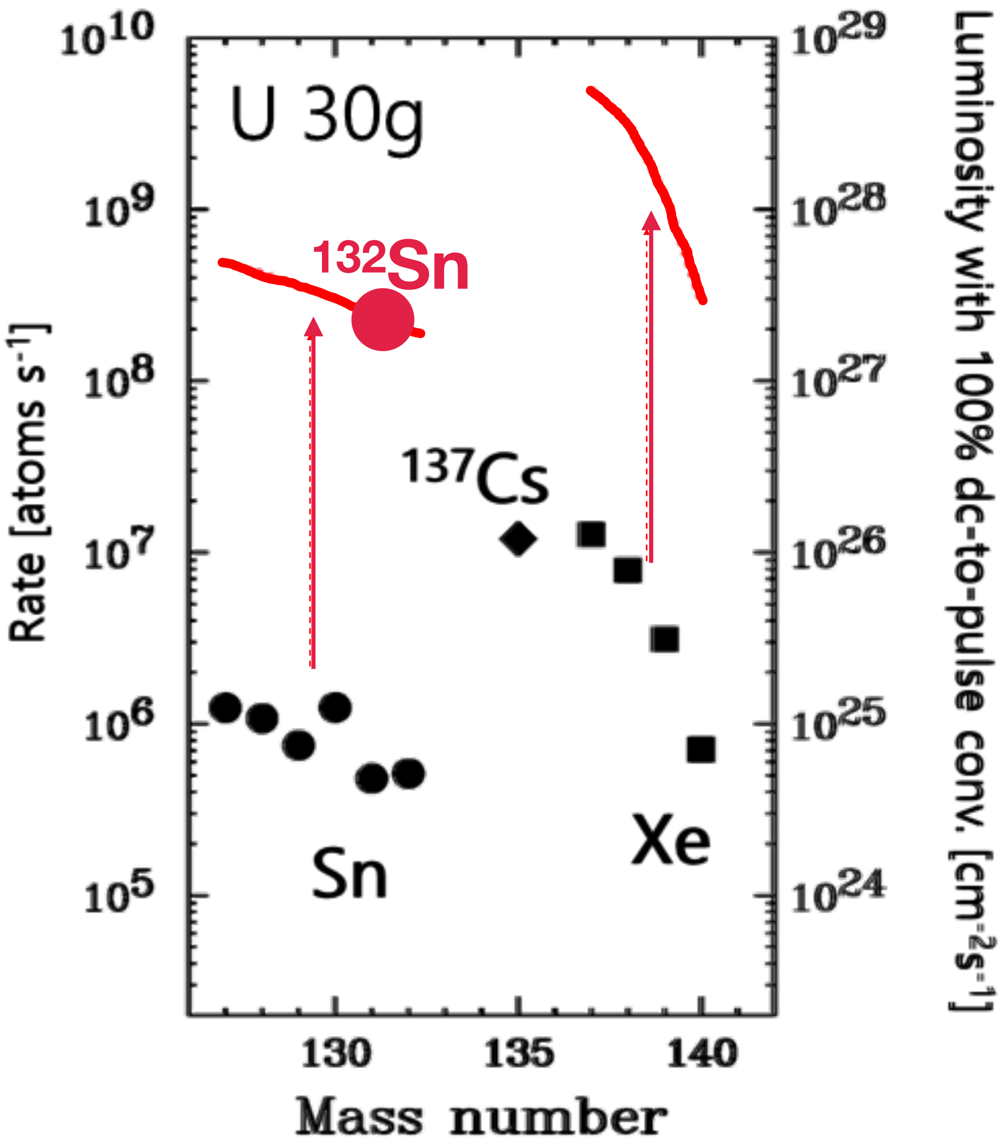
REQUIRED TARGET THICKNESS 10^{-10}!!!

	Ee	N_{beam}	ρ ·	
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**

Upgrade of ISOL driver : underway

towards 2 kW e-beam
- higher repetition
- higher peak intensity





Contents

4th moment of the charge distribution of a nucleus

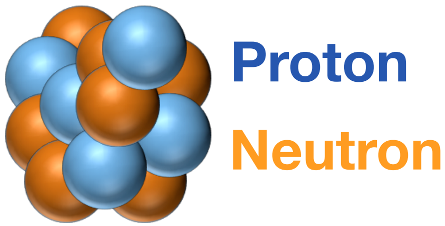
and

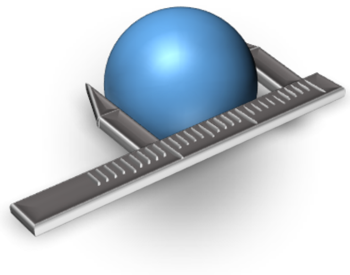
RMS radius of neutron distribution

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

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

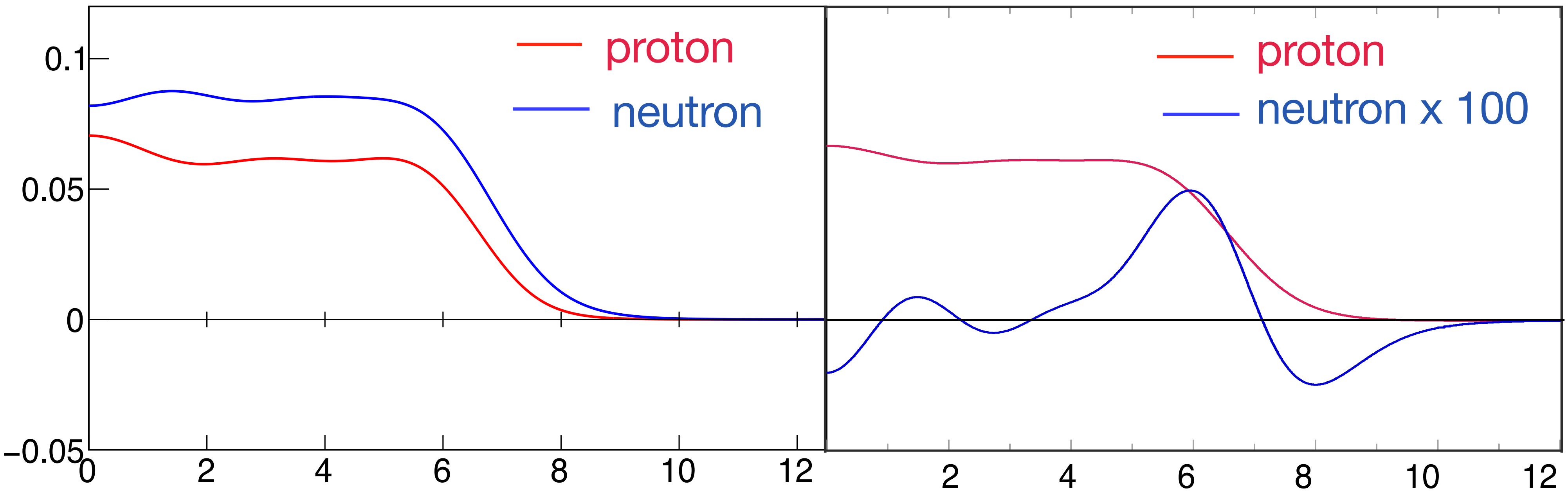
neutron distribution by electron scattering??





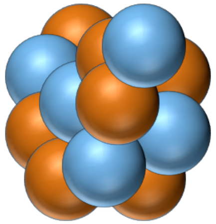
(point) nucleon density

charge density distributions



RMF NL3 (H. Kurasawa)

nuclear charge density, moments



1) charge density

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

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

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

2) 2nd moment

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

Proton　　　　Neutron

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

3) 4th moment

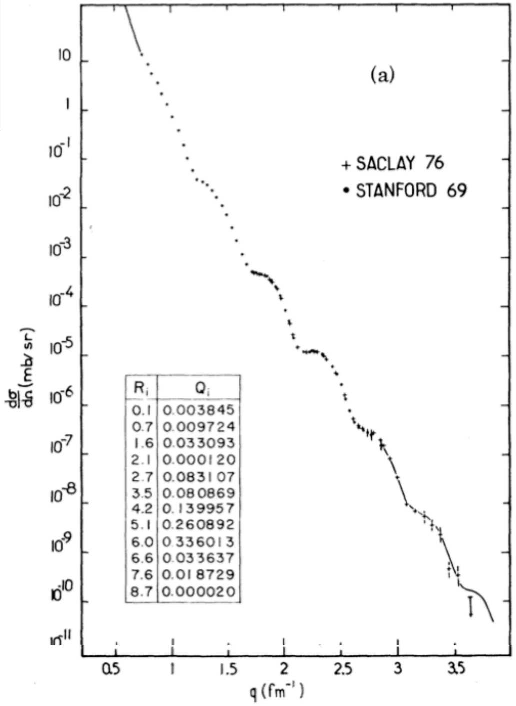
RMS n-radius

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

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

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

^{208}Pb



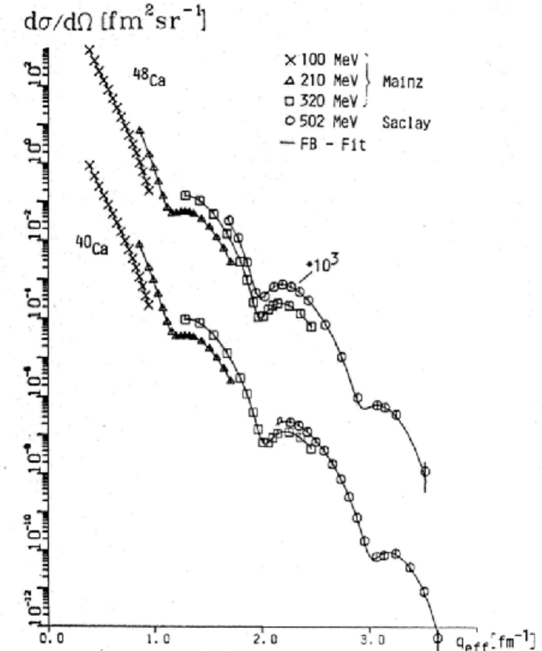
		R_p	R_n	δR
^{208}Pb	Rel.	5.454(0.013)	5.728(0.057)	0.275(0.070)
	Non.	5.447(0.014)	5.609(0.054)	0.162(0.068)
	Exp.	$R_c = 5.503(0.014)$		

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)

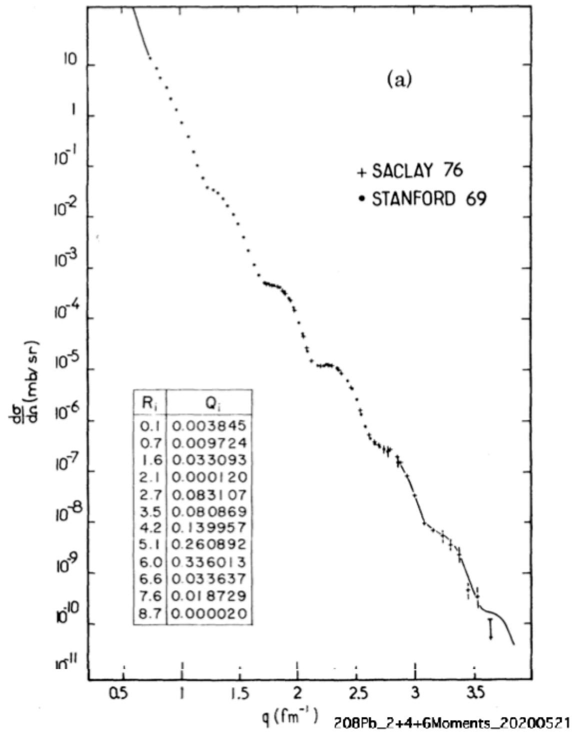
$$\Delta r_{np} \equiv R_n - R_p = 0.121 \pm 0.026 \text{ fm}$$

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

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

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

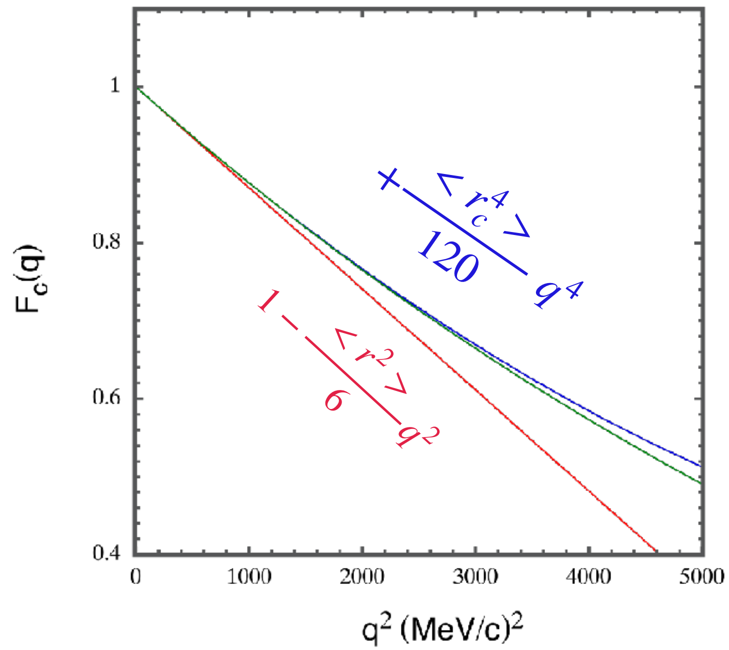
$$F_c(q) = \int \rho_c(\vec{r}) e^{i\vec{q}\vec{r}} d\vec{r}$$



2) elastic scattering at very low *q*

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

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

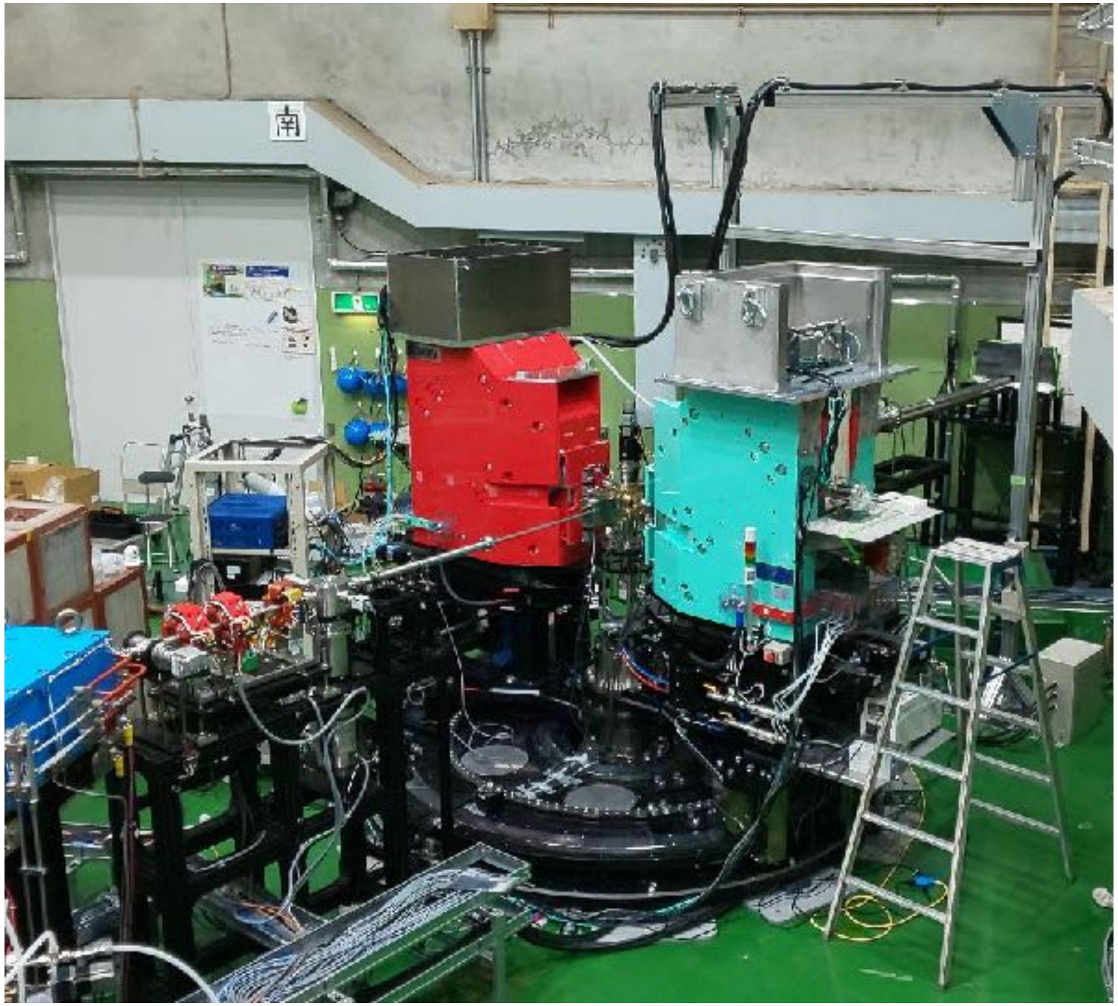


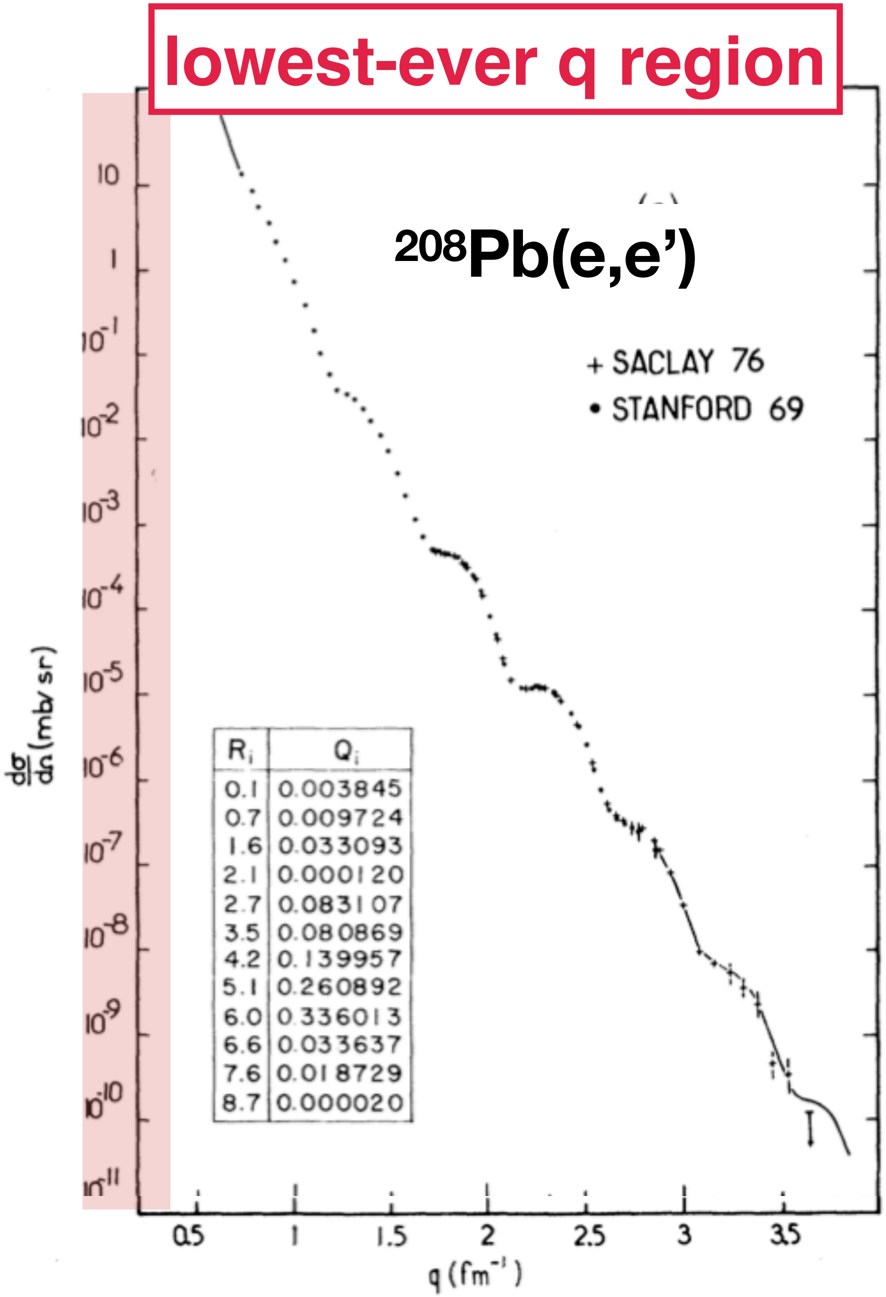
=> low-L SCRIT exp. ??

feasibility study Rn determination by ^{208}Pb(e,e')

- ^{208}Pb(e,e') at the lowest-ever q region

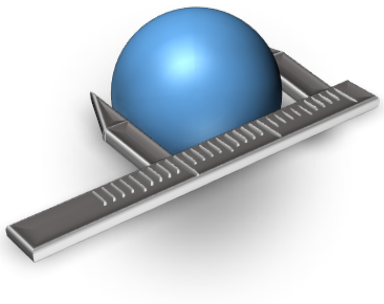
Ee ~ 10 - 50 MeV
θ = 30 - 150°
q = 5 - 50 MeV/c



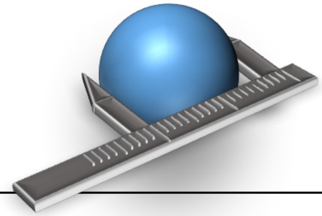


R_i	Q_i
0.1	0.003845
0.7	0.009724
1.6	0.033093
2.1	0.000120
2.7	0.083107
3.5	0.080869
4.2	0.139957
5.1	0.260892
6.0	0.336013
6.6	0.033637
7.6	0.018729
8.7	0.000020

Contents



Low-energy electron-scattering facilities in Japan



old accelerator

charge radii of proton and deuteron

Ee = 10 - 60 MeV

θe = 30 - 150 deg.

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

lowest-ever Q^2 !!

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

Ee = 150 - 300 MeV

θe = 30 - 60 deg.

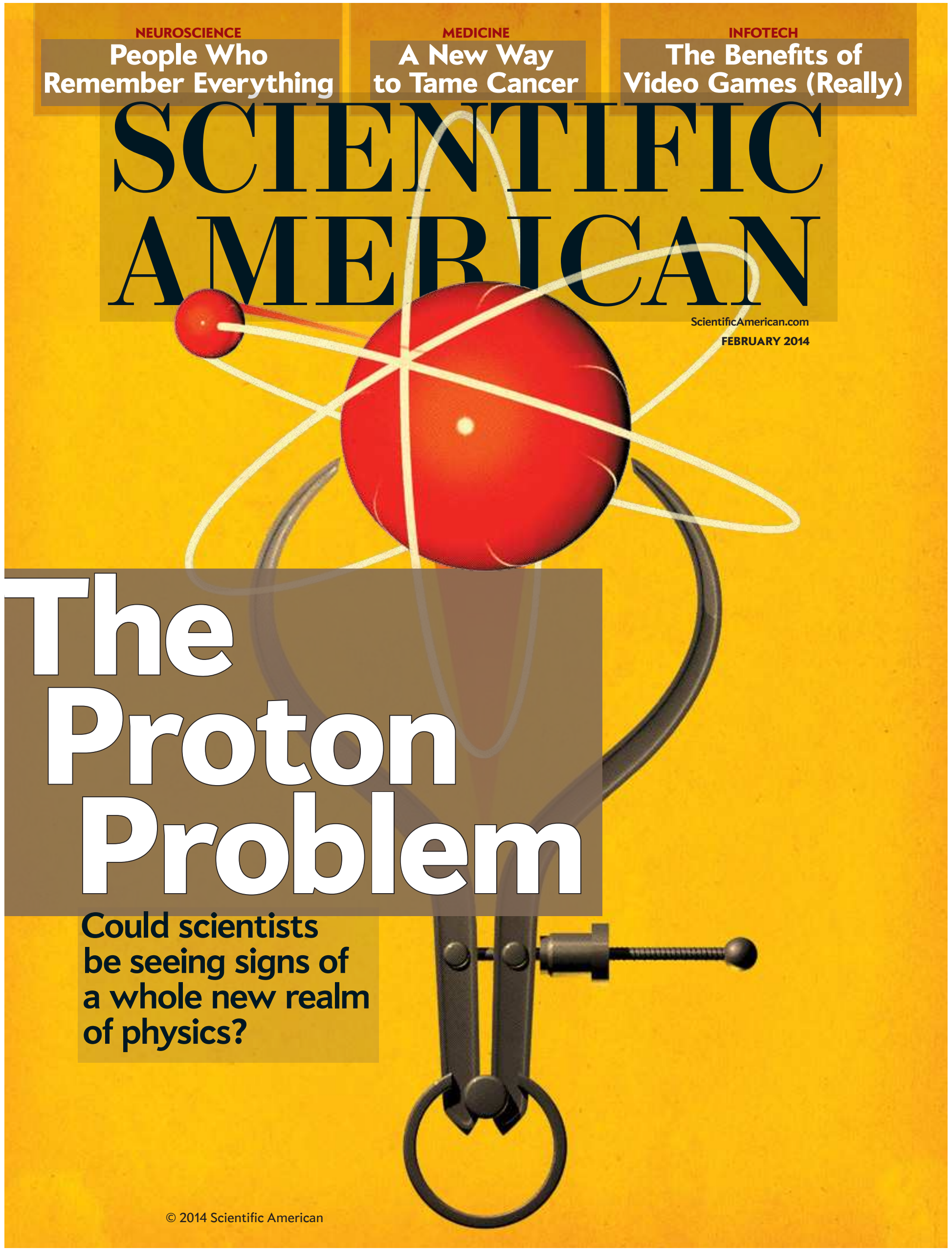
=> q = 80 - 300 MeV/c

$Q^2 = 0.006 - 0.09\ (\mathrm{GeV}/c)^2$

world's first !!

⇨ this talk

Proton Radius Puzzle

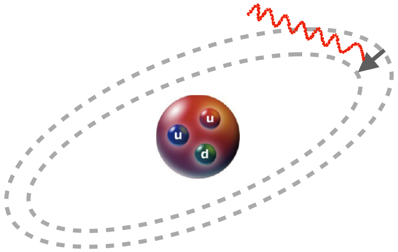


C. Carlson, Prog. Part. Nucl. Phys. 82 (2015) 59.

Why is the proton (charge) radius a hot topics ?

1) the radius is one of the basic properties of the nucleon

2) the radius is strongly correlated to the Rydberg constant



$$\Delta E = R_{Rydberg}\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

$$\Delta E = \alpha \cdot R_{Rydberg} + \beta \cdot < r^2 >$$

3) possible new physics beyond Standard Model (??)

Lepton Universality (e <-> μ) ??

muon magnetic moment $g = 2(1 + a_\mu)$

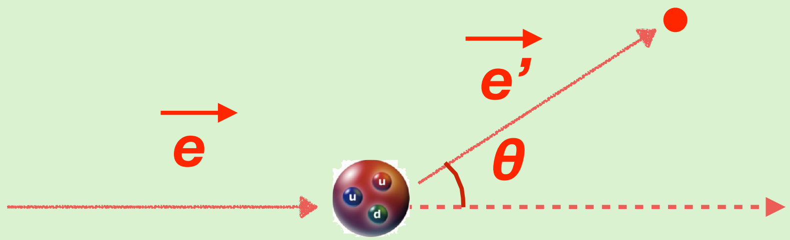
$$a_\mu^{exp} = 1\ 165\ 920.89\ (0.63) \times 10^{-9}$$

$$a_\mu^{SM} = 1\ 165\ 918.28\ (0.49) \times 10^{-9}$$

3.5σ discrepancy

possible MeV-order force carrier (dark photon ...?)

electron scattering and proton charge radius



Charge FF Magnetic FF

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{\boxed{G_E^2(Q^2)} + \frac{\tau}{\epsilon}\boxed{G_M^2(Q^2)}}{1+\tau}$$

momentum transfer $\vec{q} = \vec{e} - \vec{e'}$

energy transfer $\omega = e - e'$

4 momentum transfer $Q^2 = q^2 - \omega^2$
$= 4\, e\, e' \sin^2(\theta/2)$

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{Mott} = \frac{z^2\alpha^2}{4e^2}\frac{\cos^2(\theta/2)}{\sin^4(\theta/2)} \propto \frac{e^2}{q^4}$$

$$\epsilon = \frac{1}{1+2(1+\tau)\tan^2\frac{\theta}{2}}$$

$$\tau = \frac{Q^2}{4m_p^2}$$

Proton charge radius

$$\boxed{< r^2 > \equiv -6 \frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2}\Big|_{Q^2\to 0}}$$

no measurement is possible at $Q^2 = 0$

$G_E(Q^2)$ at low Q^2 as possible

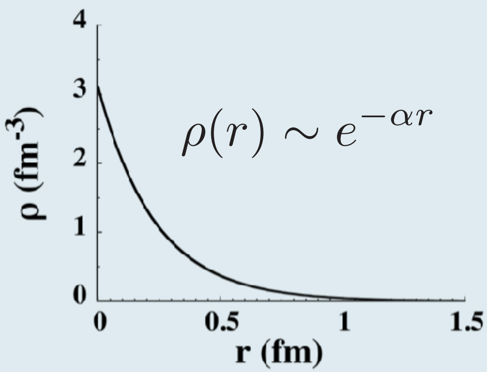
G. A. Miller, PRC 99 (2019) 035202

2nd moment of charge density ρ(r) ??

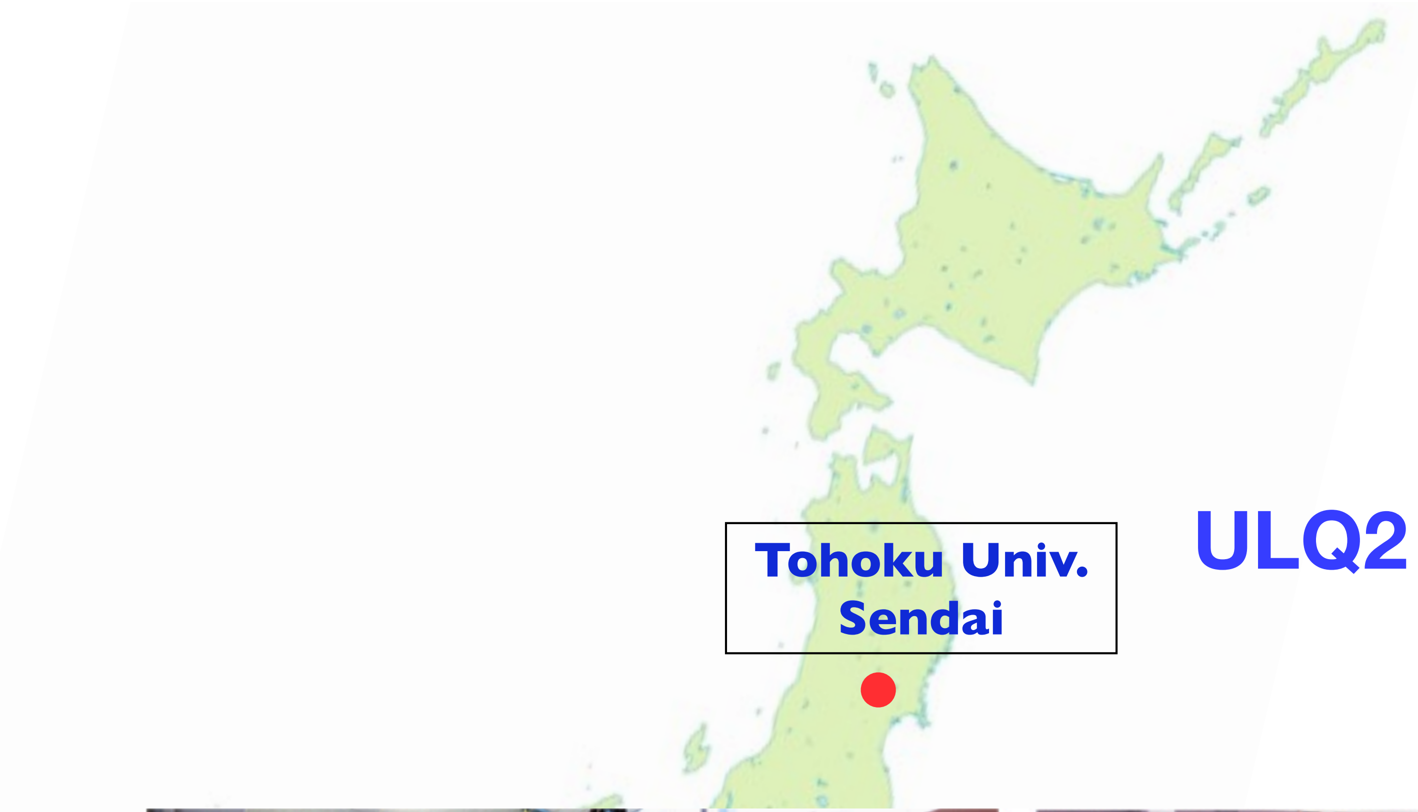
Electric Form FactorGE

non-rel. limit

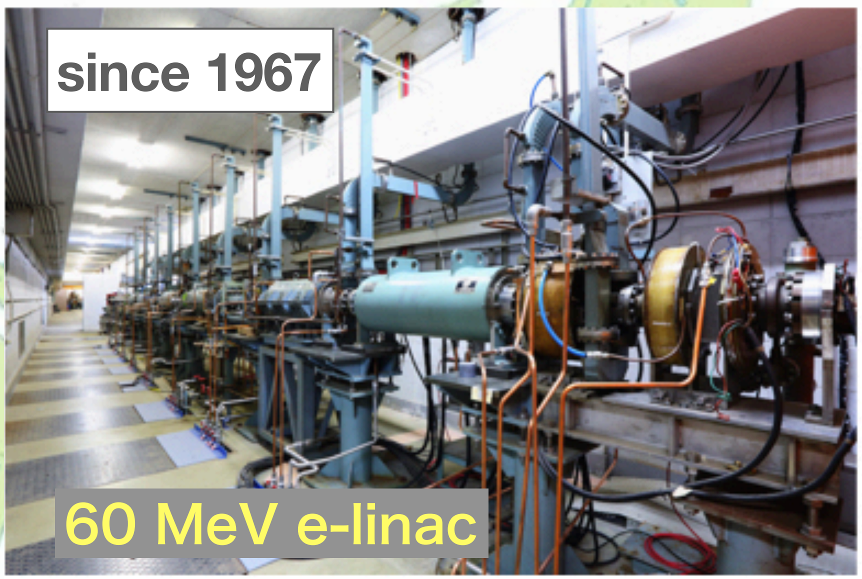
ρ(r)



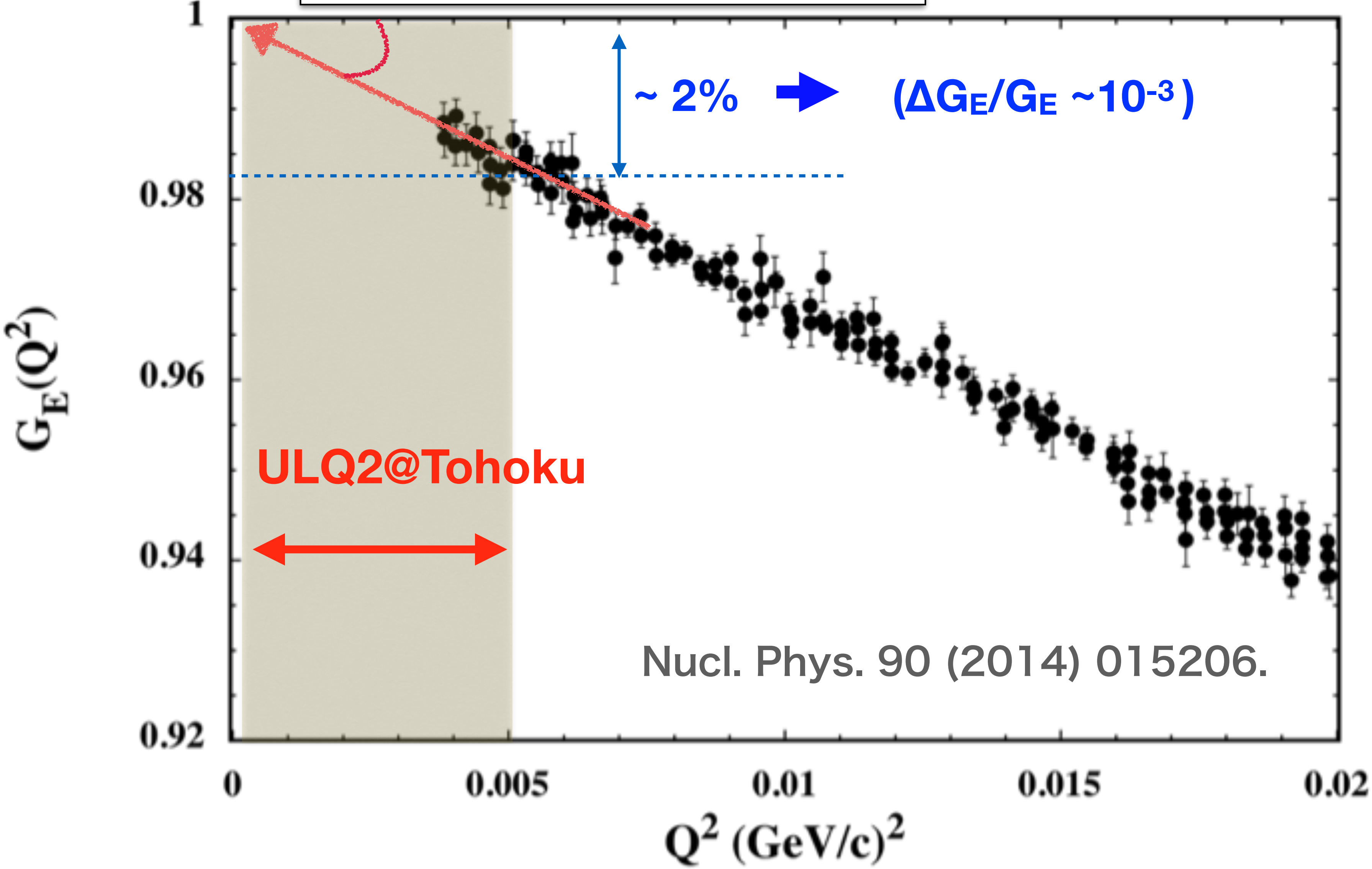
$$< r^2 > = \int r^2 \rho(\vec{r}) d\vec{r}$$



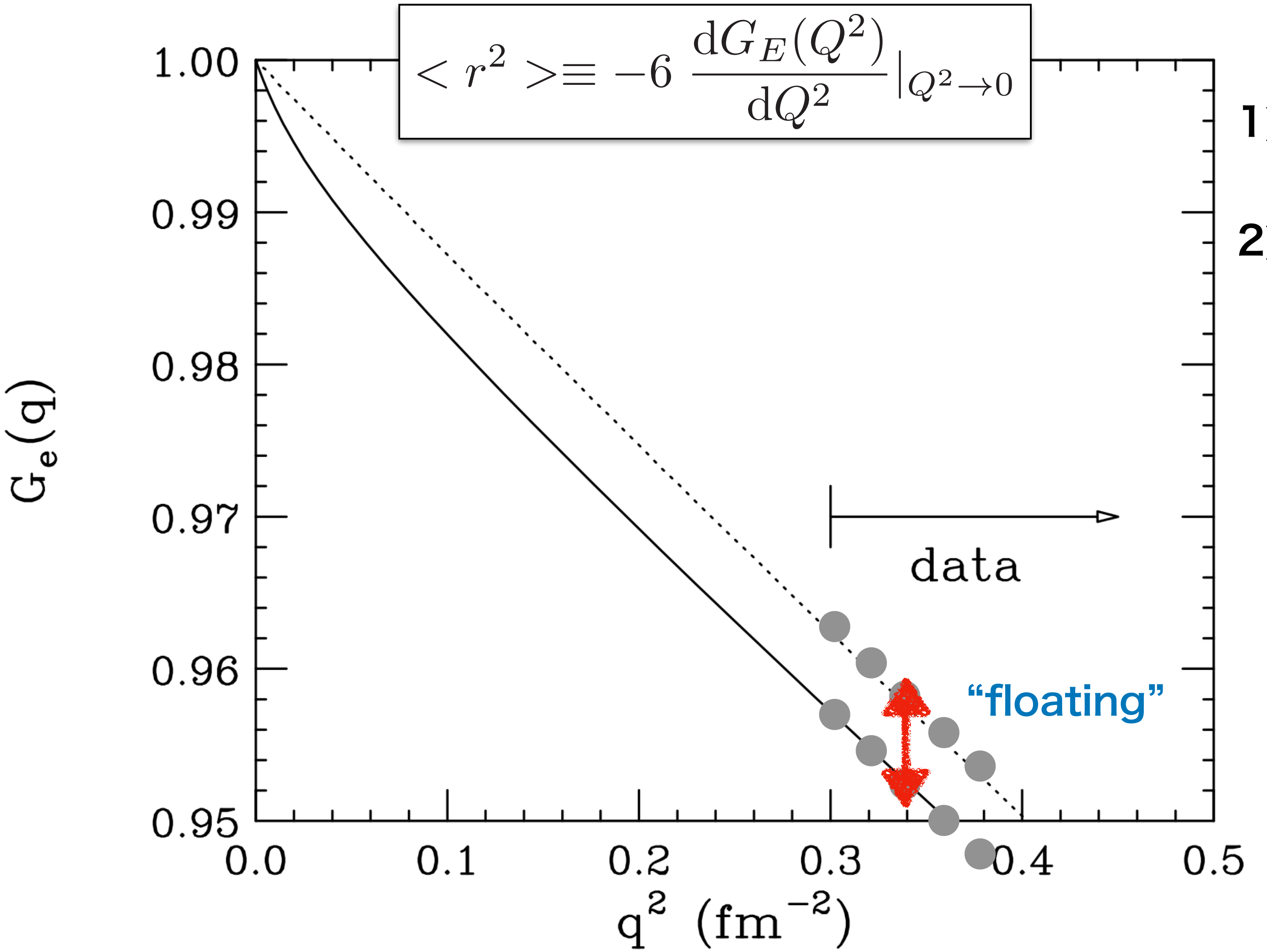
ULQ2 : Ultra-Low Q2



$$< r^2 > \equiv -6 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2 \to 0}$$



Absolute $G_E(Q^2)$ at lower Q^2 region



1) no absolute GE(Q2) ("floating")
2) χ^2 is similar for both

ABSOLUTE $G_E(Q^2)$ at lower Q^2 region

I. Sick, Atoms 2018, 6, 2

ULQ2 (Ultra-Low Q2) project

aiming at the *least model-dependent* proton charge radius

1) covering the lowest-ever Q^2 for $G_E(Q^2)$

lowest-energy electron scattering ever

(Ee = 10 - 60 MeV)

2) absolute cross section measurement with 10^{-3}

CH_2 target

$\langle r_c^2 \rangle$ of ^{12}C is best known with 10^{-3} accuracy

Our (old) accelerator is only facility for such measures

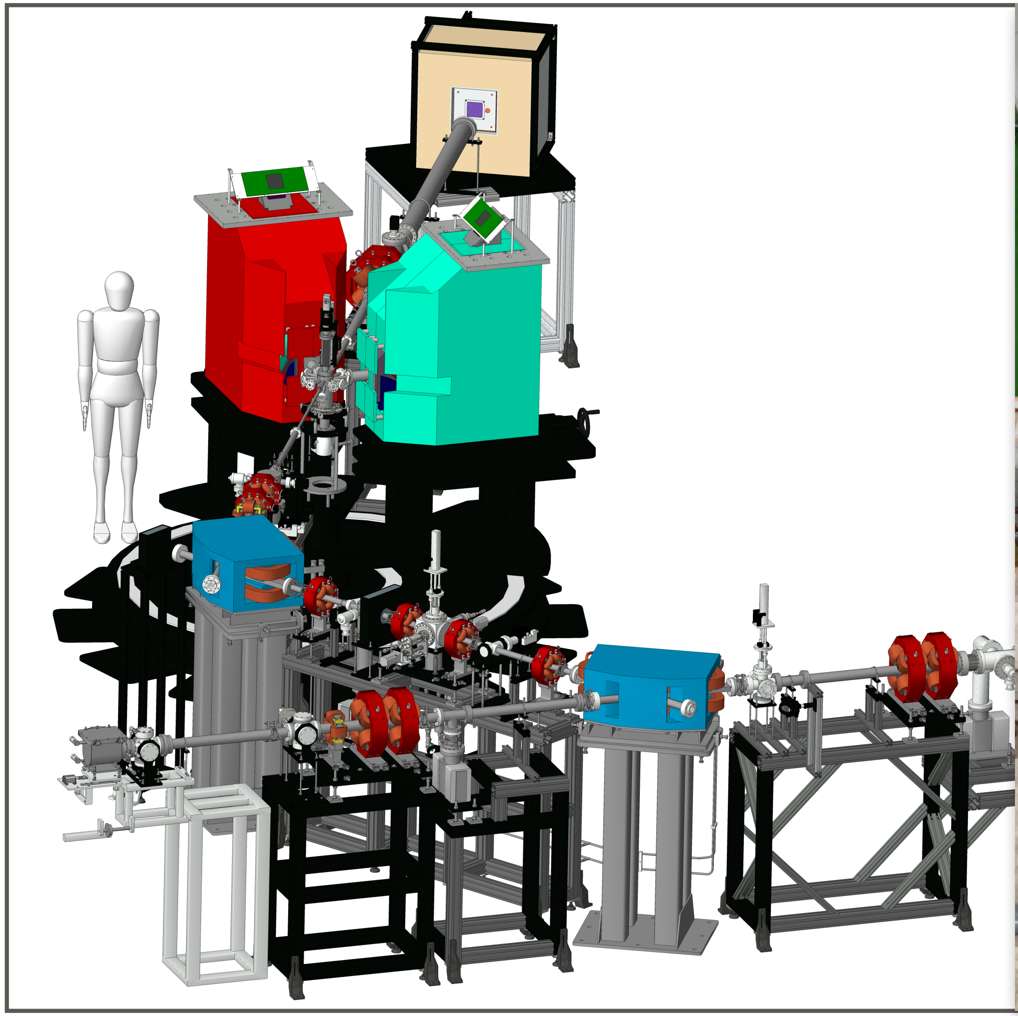
ULQ2 (Ultra-Low Q2) beam line

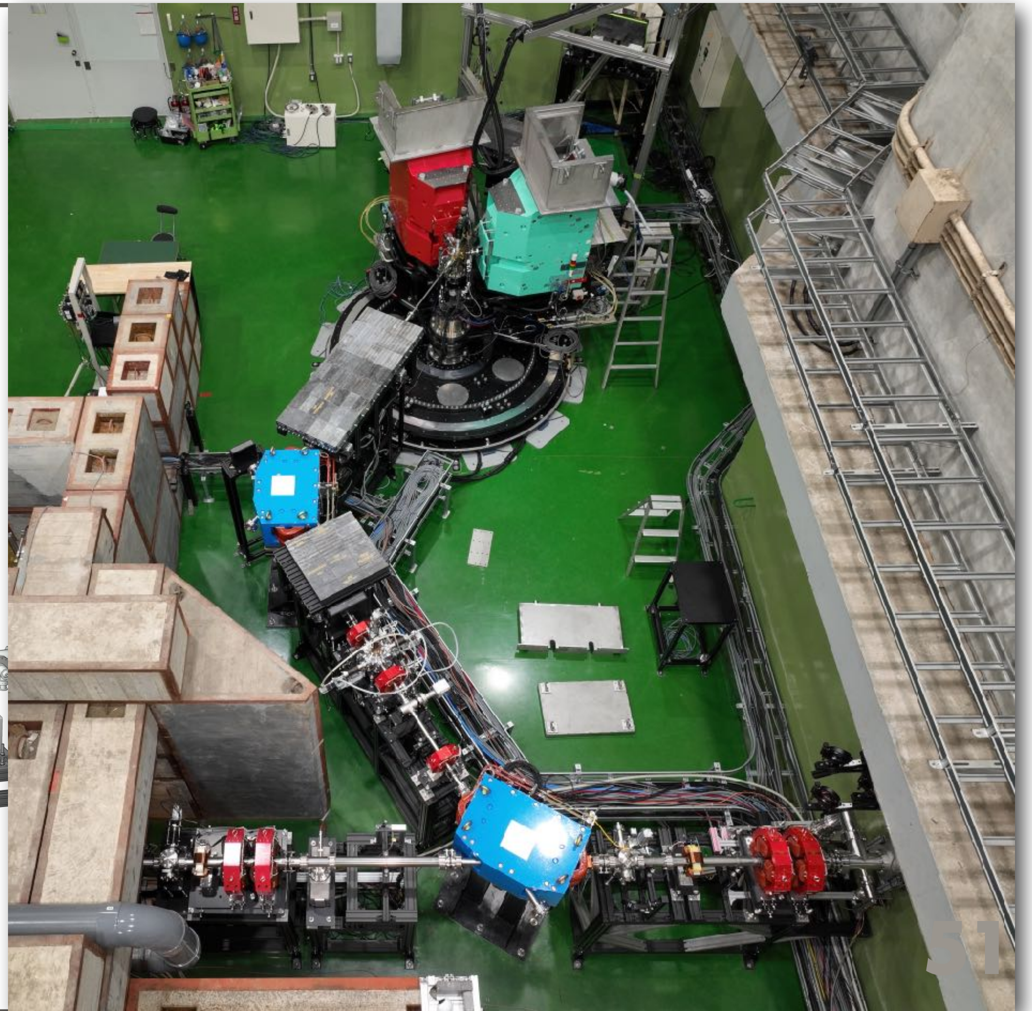
60 MeV electron linac

- E_e = 10 - 60 MeV
- $\Delta E/E = 0.6 \times 10^{-4}$
- beam size ~ 0.6 mm on target
- duty factor = 10^{-3}

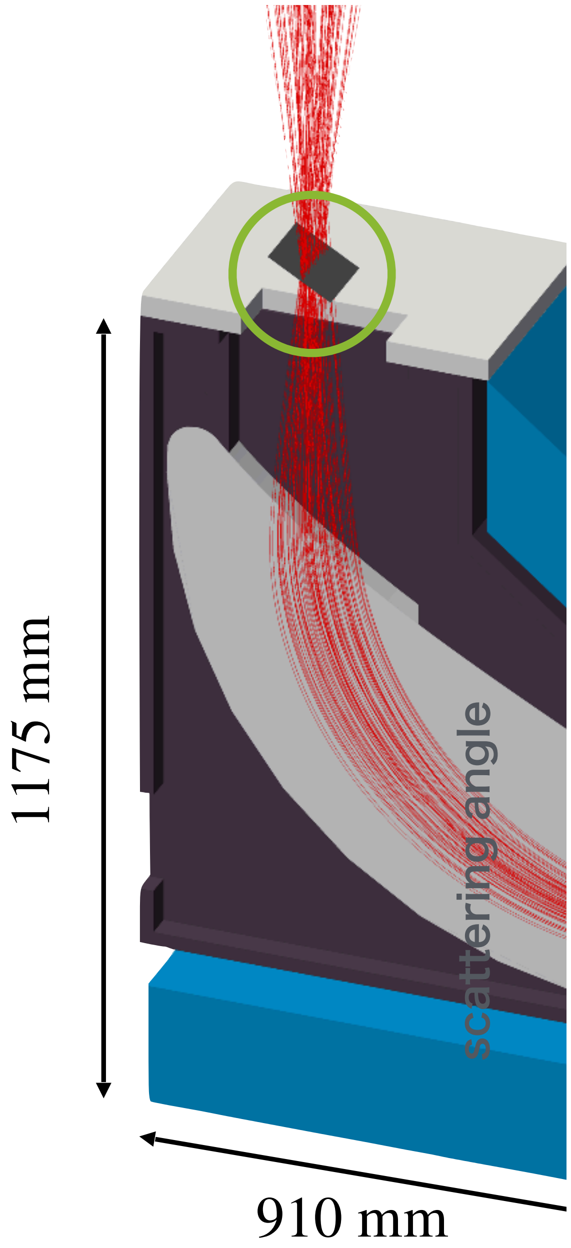
ULQ2 twin-spectrometer setup

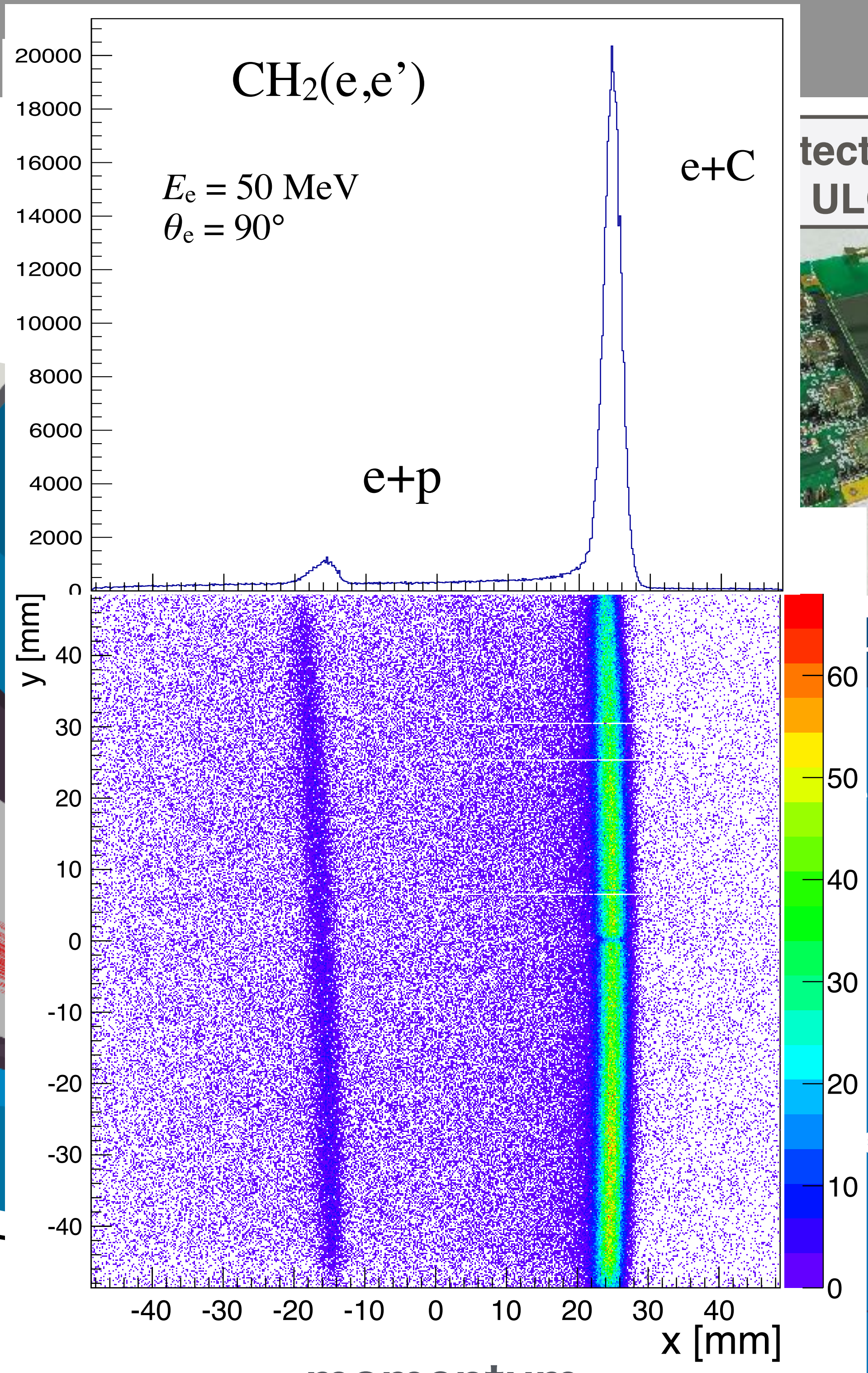
- $\Delta p/p = 5.6 \times 10^{-3}$
- $\Delta\Omega$ = 6 mSr
- θ = 30 - 150 deg.
- $Q^2 = 3 \times 10^{-5}$ - 0.013 $(\mathrm{GeV}/c)^2$



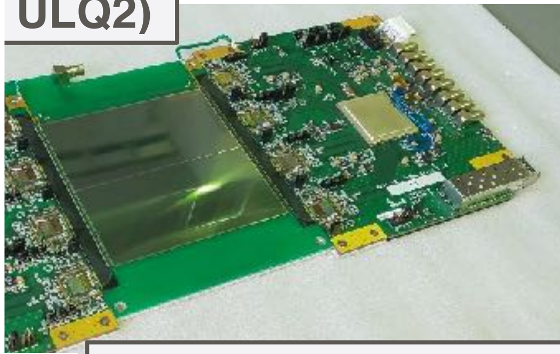


ULQ2 twin s





tectors
ULQ2)



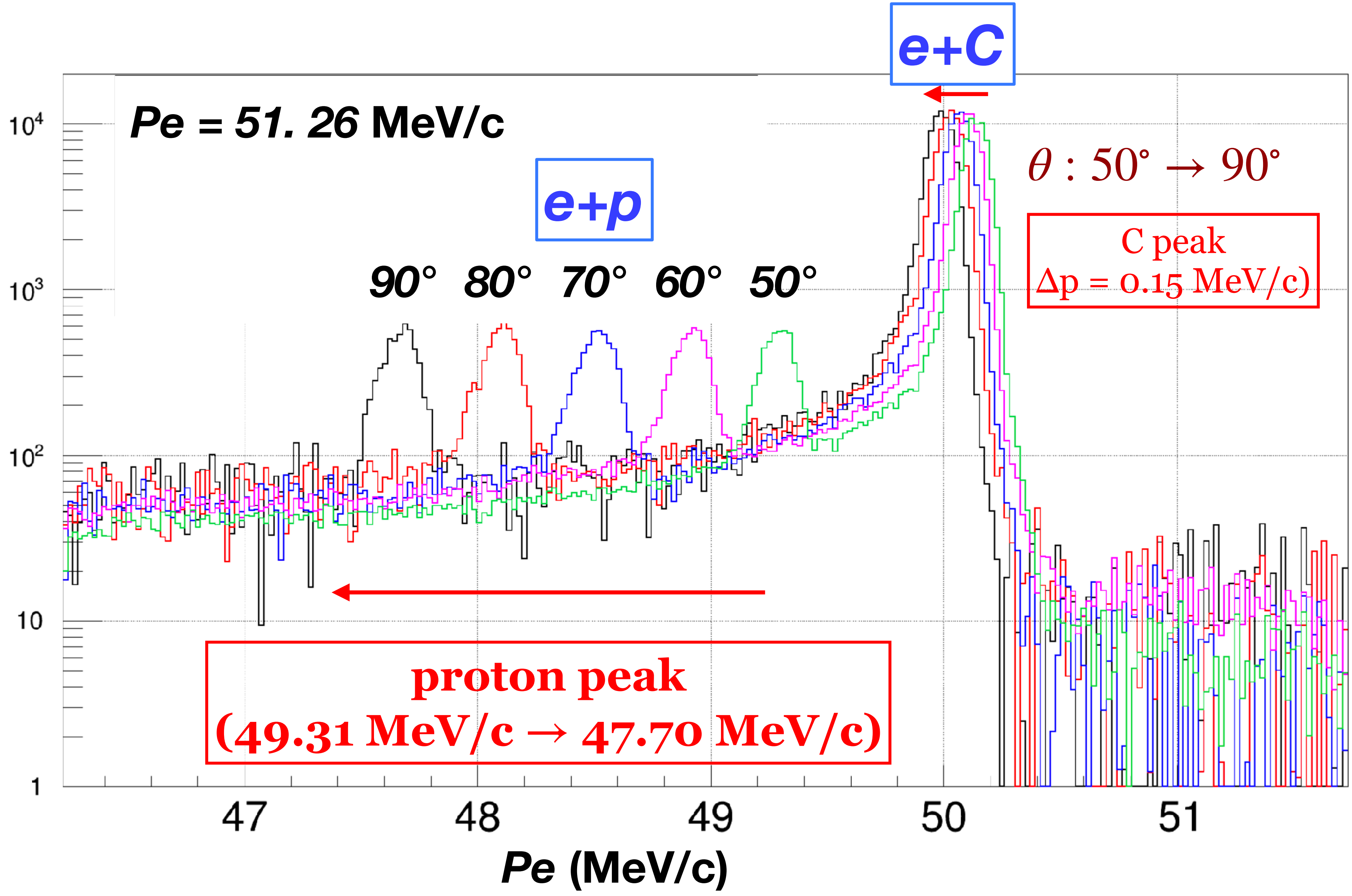
two SSSD for XY
100 x 100 mm2 (190 um)

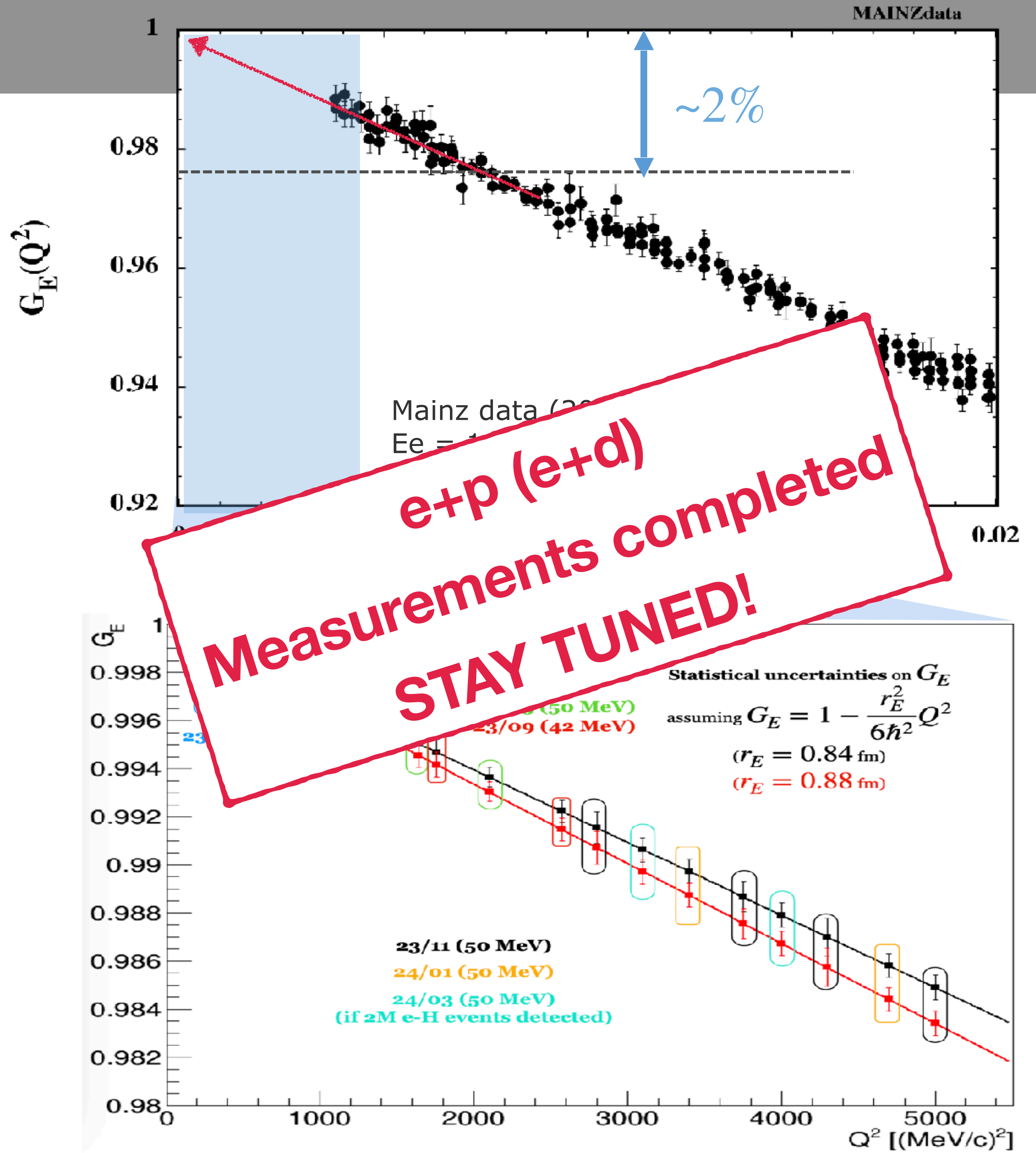
n spectrometer
500 mm
90°
0.4T @ 60MeV
70 mm
866 mm
5.6×10^{-4}
10%
5 mrad
6 mSr
5 ton

momentum

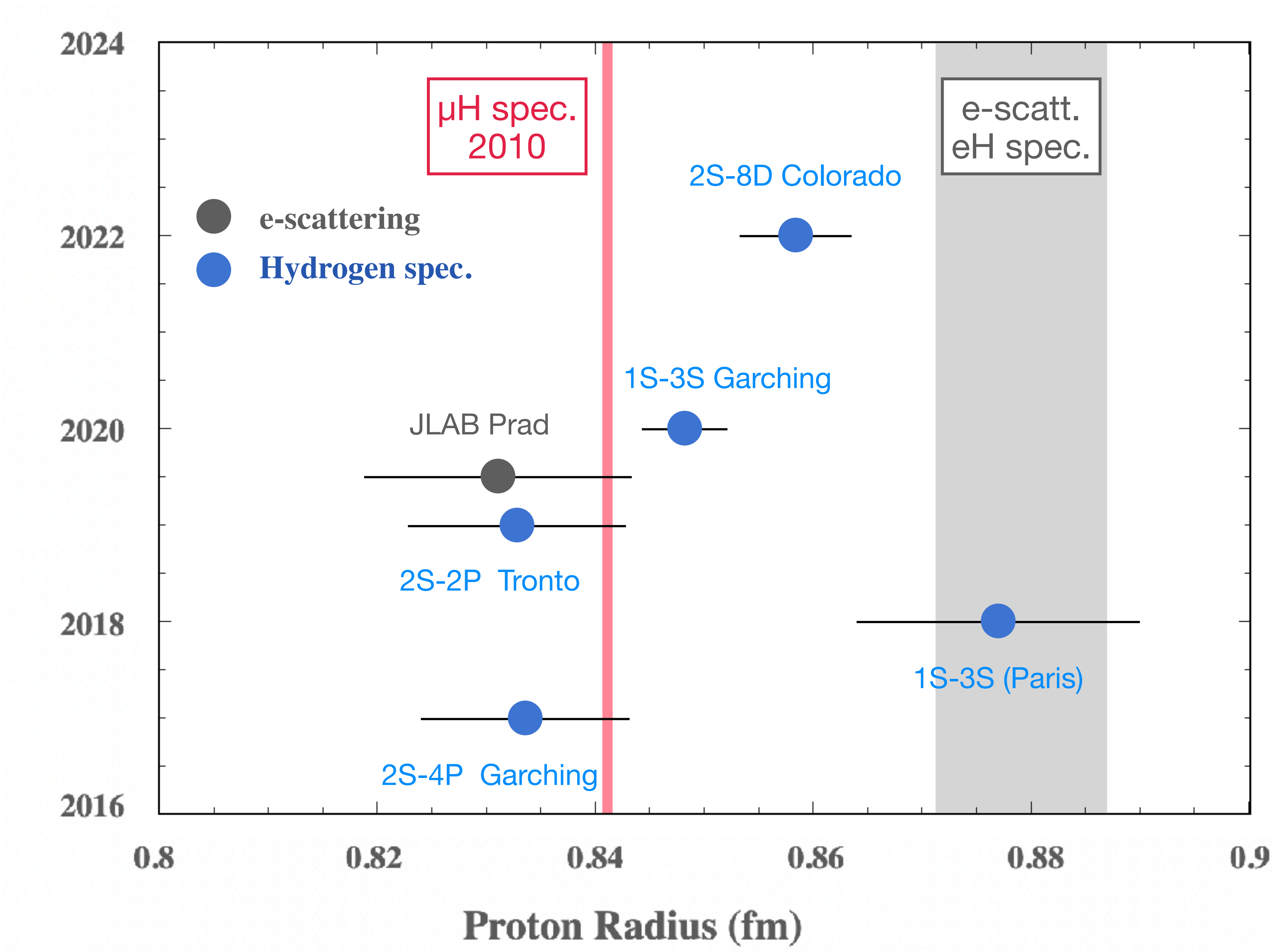
Y. Honda

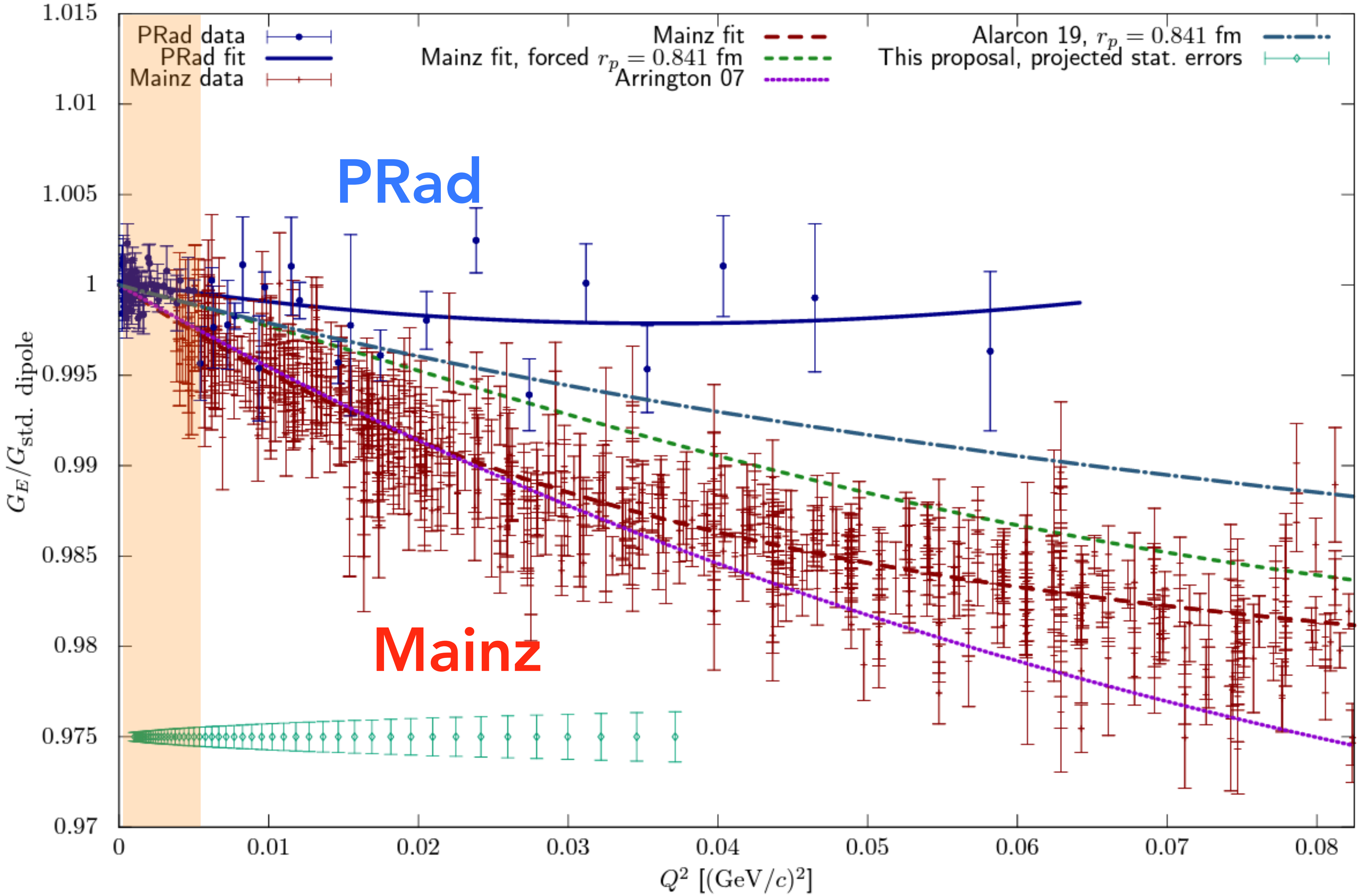
Physics data production run just started with CH2 target




MAINZdata
~2%
$G_E(Q^2)$
1
0.98
0.96
0.94
0.92
0.02
Mainz data (20
Ee = 1
e+p (e+d)
Measurements completed
STAY TUNED!
Statistical uncertainties on G_E
assuming $G_E = 1 - \frac{r_E^2}{6\hbar^2}Q^2$
($r_E = 0.84$ fm)
($r_E = 0.88$ fm)
(50 MeV)
23/09 (42 MeV)
23/11 (50 MeV)
24/01 (50 MeV)
24/03 (50 MeV)
(if 2M e-H events detected)
G_E
1
0.998
0.996
0.994
0.992
0.99
0.988
0.986
0.984
0.982
0.98
0
1000
2000
3000
4000
5000
Q^2 [(MeV/c)^2]

proton charge radius as of today





PRad data
PRad fit
Mainz data
Mainz fit
Mainz fit, forced $r_p = 0.841$ fm
Arrington 07
Alarcon 19, $r_p = 0.841$ fm
This proposal, projected stat. errors
PRad
Mainz
$G_E/G_{\mathrm{std.\ dipole}}$
Q^2 [(GeV/c)^2]
1.015
1.01
1.005
1
0.995
0.99
0.985
0.98
0.975
0.97
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08

conclusions

- The SCRIT facility started its operation
  - the world's first and currently only-one facility
  - e-scattering for short-lived nuclei
  - ISOL upgrade to 2kW is underway for ^{132}Sn(e,e')

- Low-energy e-scattering activities in Japan
  - ULQ2 : 1) e+p, e+D scattering (data collection completed)
    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 Tohoku visit!!