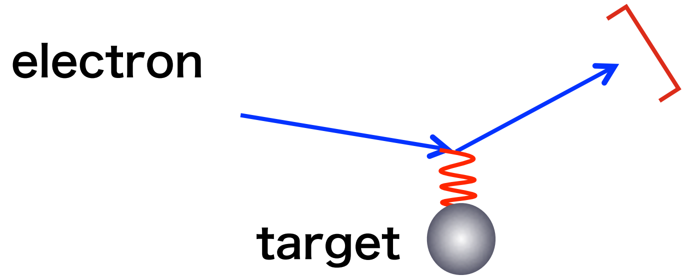
electron scattering off short-lived exotic nuclei

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

for SCRIT collaboration

Electron scattering for Nuclear Physics



one detects only scattered electrons

→ **very "simple" measurements**

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

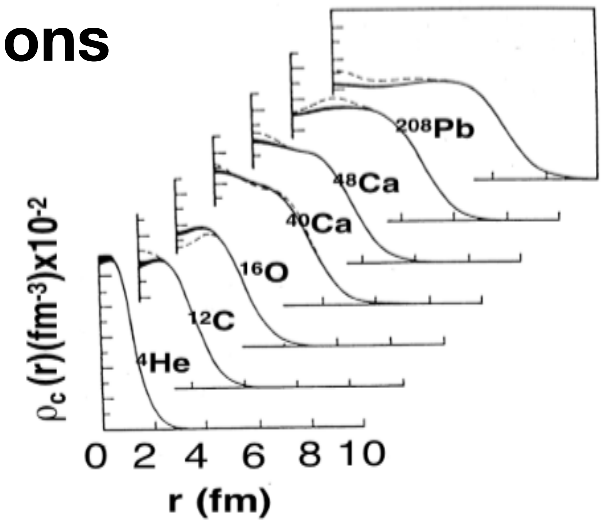
1. **elementary particle** - structure-less -
2. **electro-weak interaction** - best understood -
3. **"relatively" weak** - probing the whole volume of target nucleus -

charge density distributions

by elastic scattering

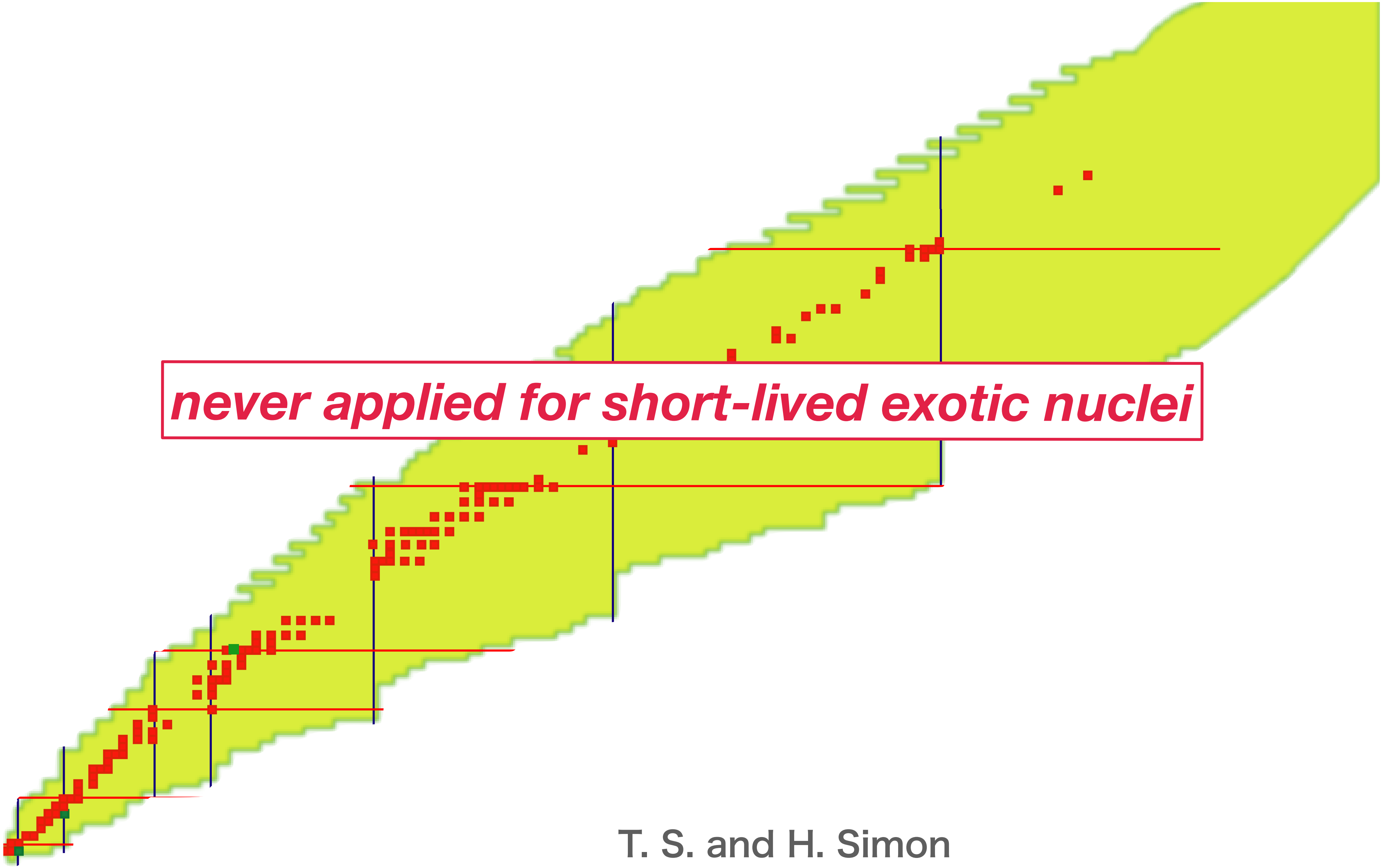
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{Mott}}{d\Omega} |F_c(q)|^2$$

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



- deformation
- transition densities
- valence n orbital
- S-factor
- …

Nuclei ever studied by electron scattering



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

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

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.

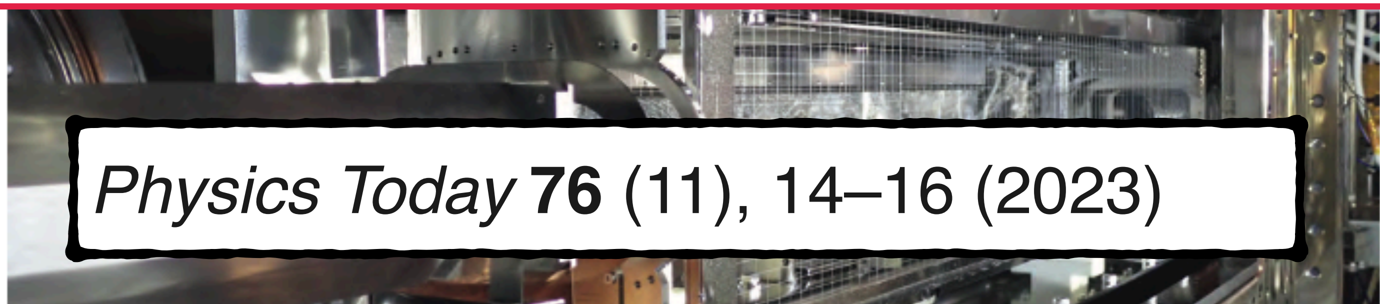
The more unstable a nucleus, the stranger the structures it can adopt. Short-lived nuclei might form bubble structures with depleted central density, or they might have a valence nucleon or two that form a halo around a compact central core. (See the article by Filomena Nunes, PHYSICS TODAY, May 2021, 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

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



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

e-scattering for short-lived exotic nuclei

- Key parameter : L

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

- typical L for e-scattering used for stable nuclei

R. Hofstadter
(Nobel prize : 1961)

	Ee	N_{beam}	target	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

- minimum required L for exotic nuclei

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

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

e-scattering for short-lived exotic nuclei

- challenges
  - $L \gtrsim 10^{27}/\mathrm{cm}^2/\mathrm{s}$ with small # of exotic nuclei
  - exotic nuclei : production-hard & short-lived

- **a novel way to form "thick-enough" target for e-scattering with only ~10^7 /s**

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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

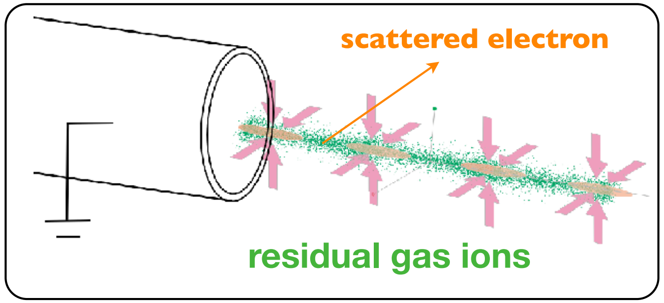
Available online 3 August 2004

SCRIT : Self-Confining Radioactive Ion Target

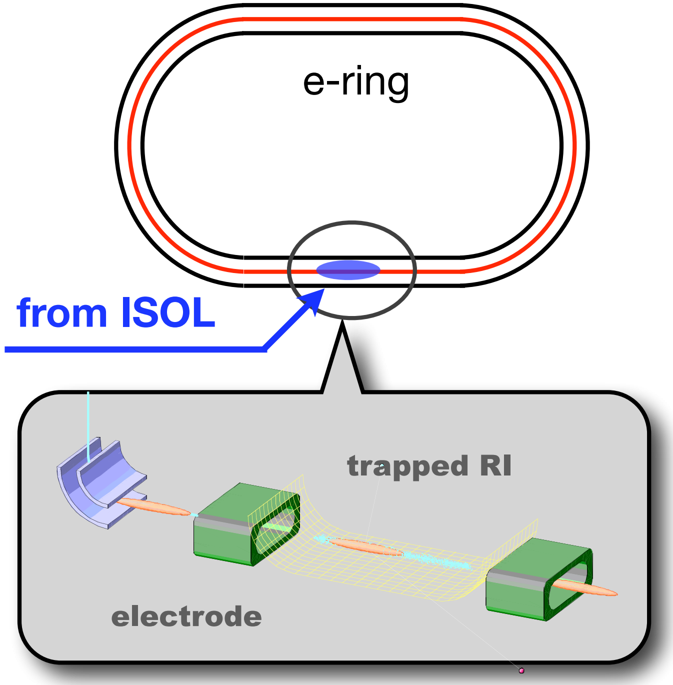
SCRIT（Self-Confining RI Ion Target)

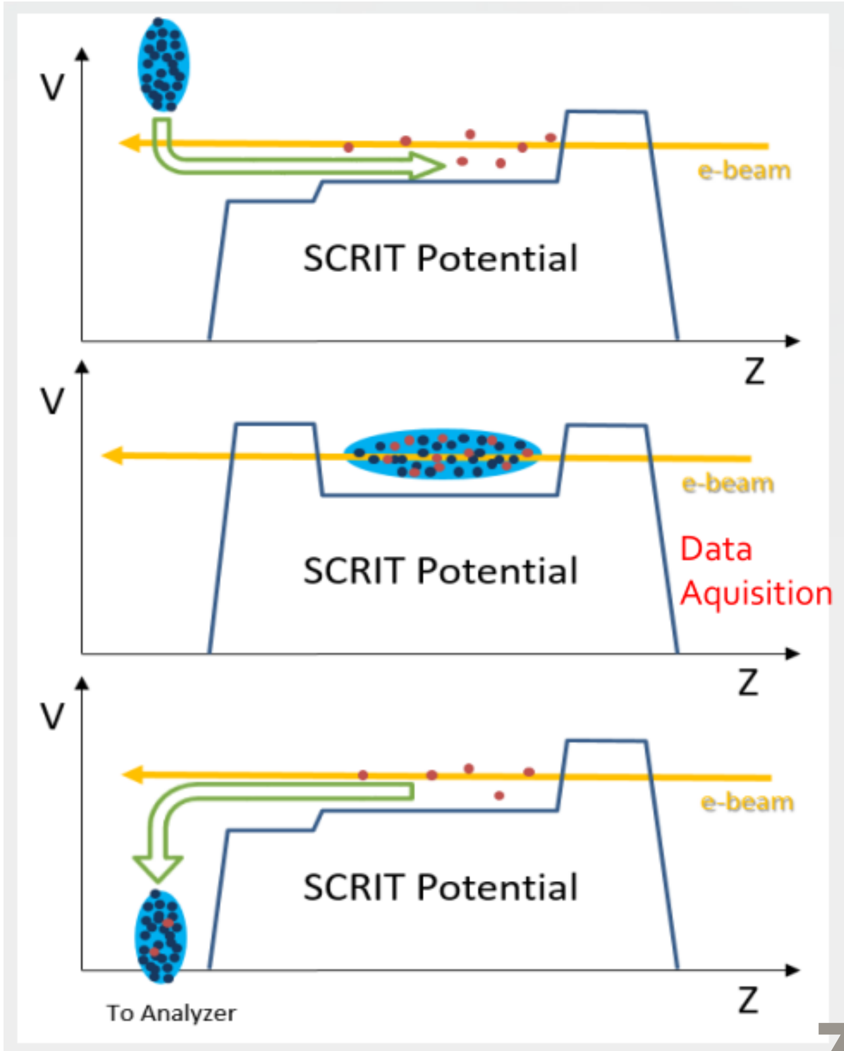
Idea : "ion trapping" at SR facilities.

ionized residual gases are trapped by the circulating electron beam



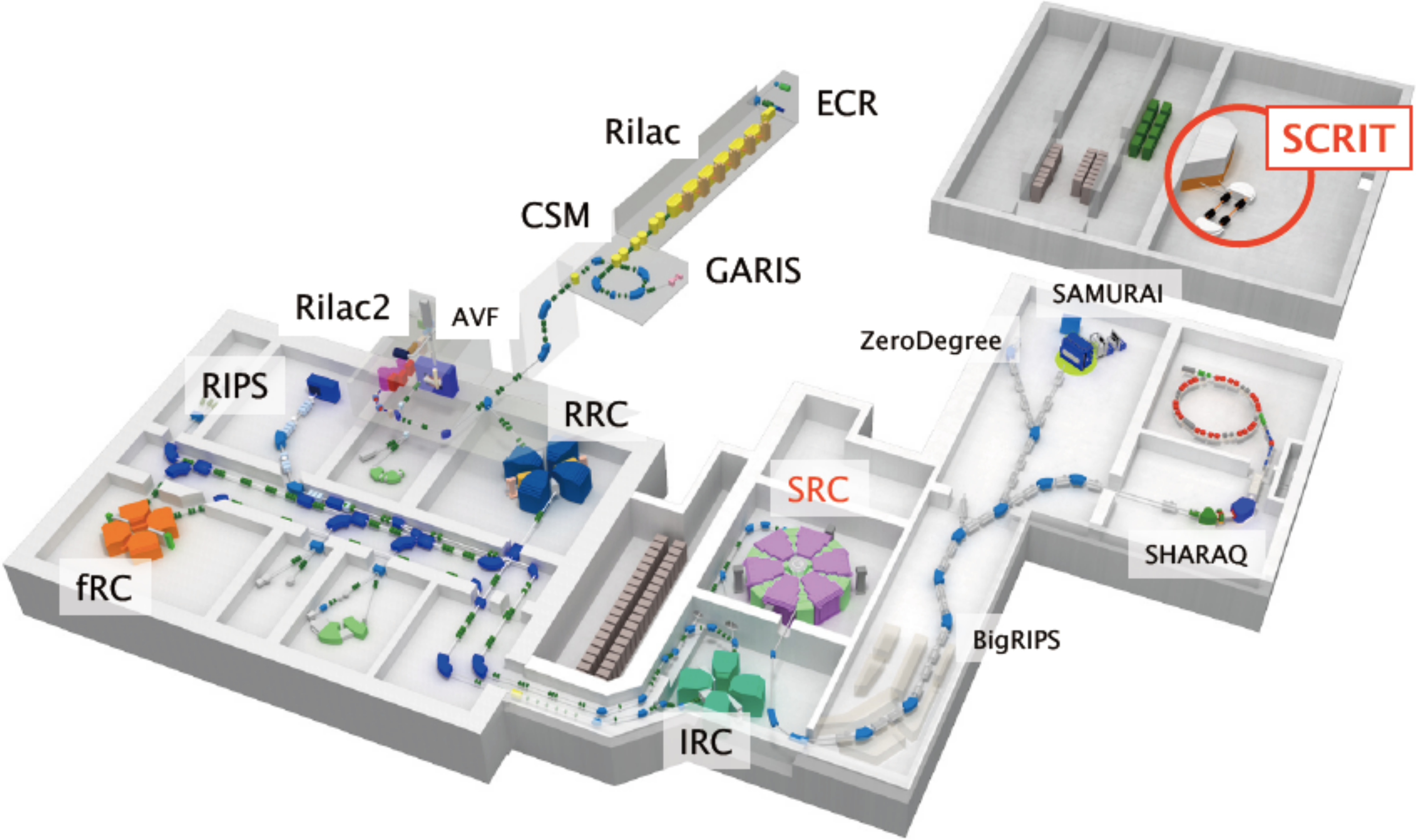
ill problem of e-storage rings





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

<u>World's first electron facility</u> dedicated for exotic nuclei

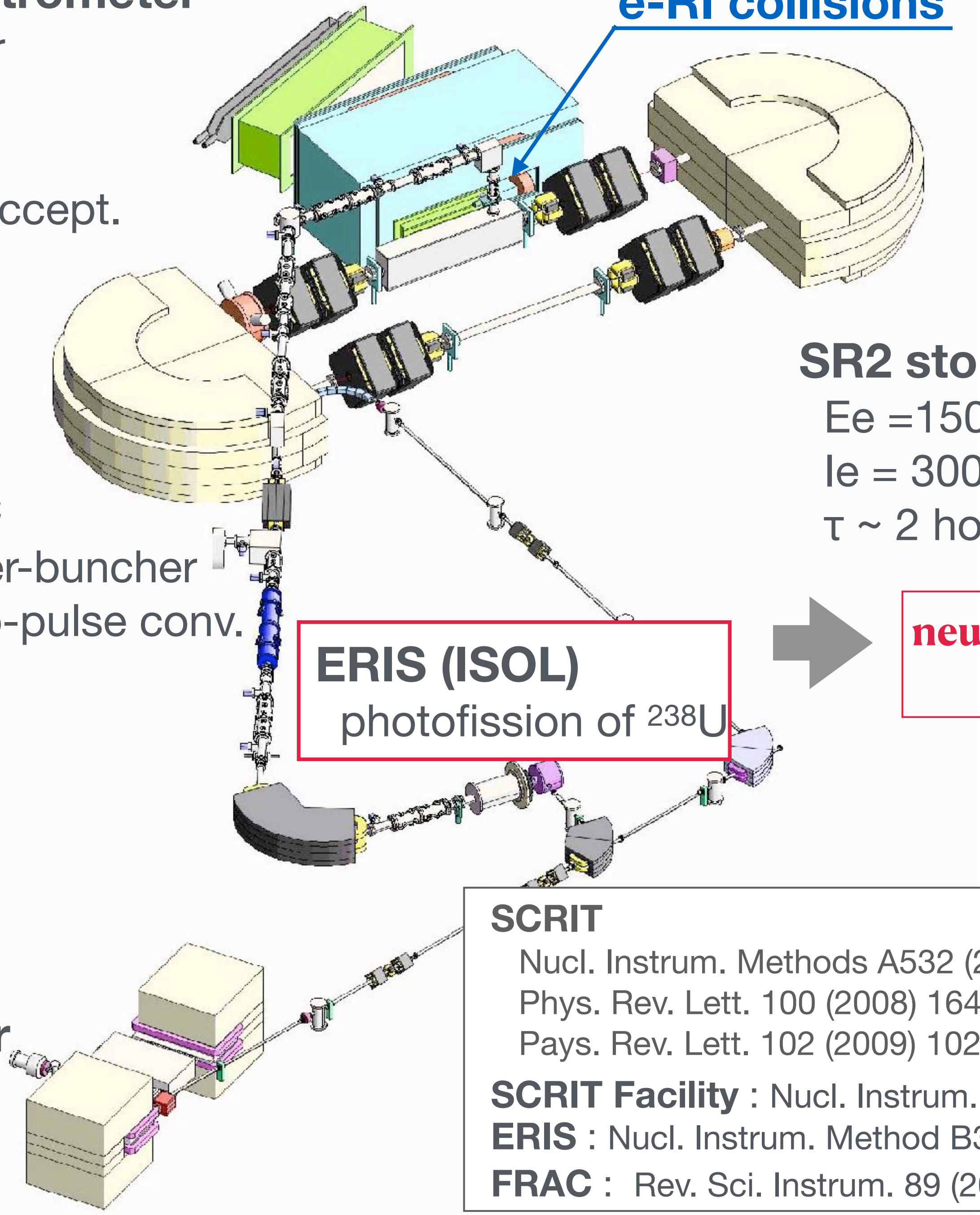


RIKEN RI Beam Factory

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.

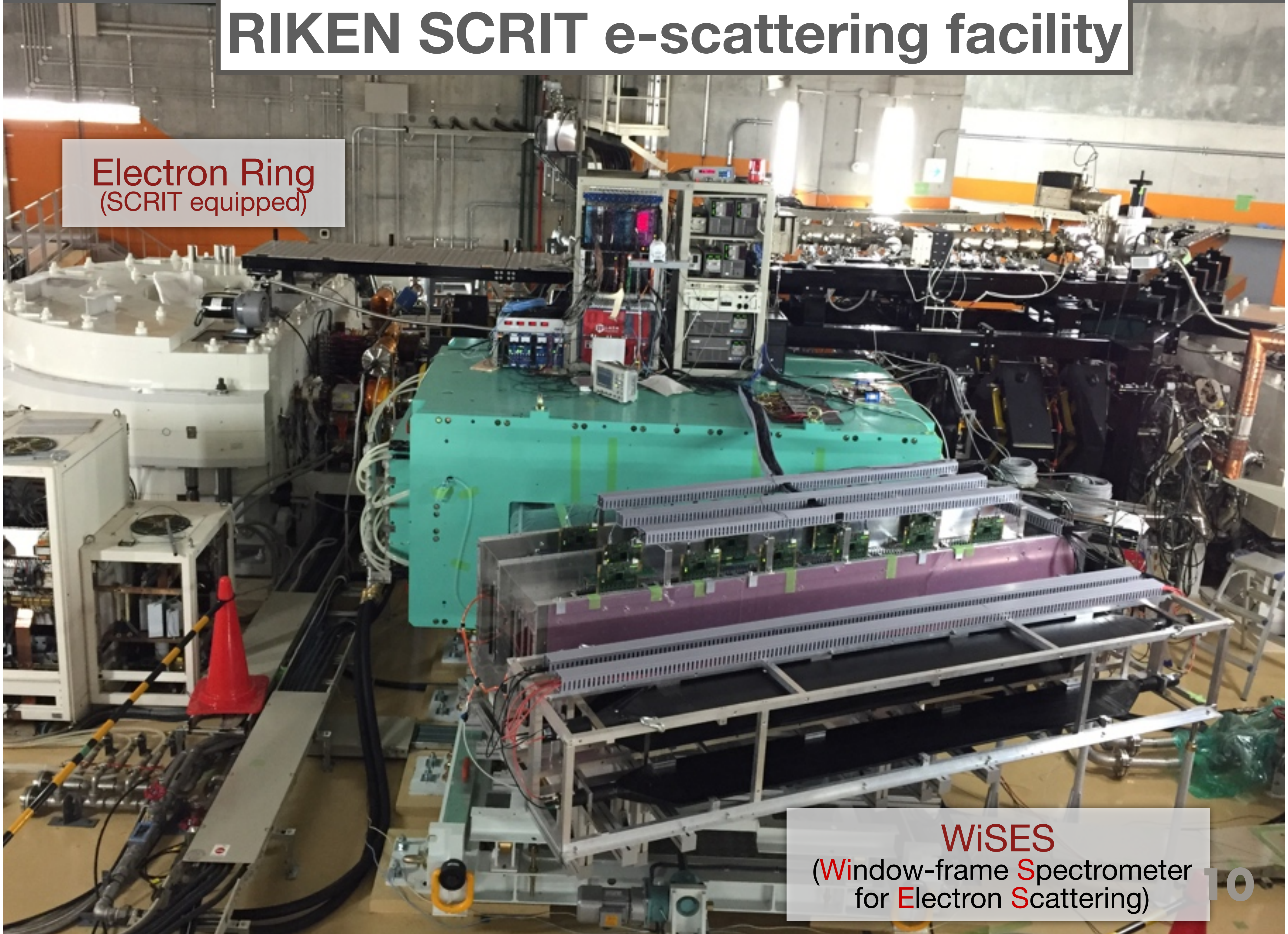
ERIS (ISOL)
photofission of ^{238}U

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

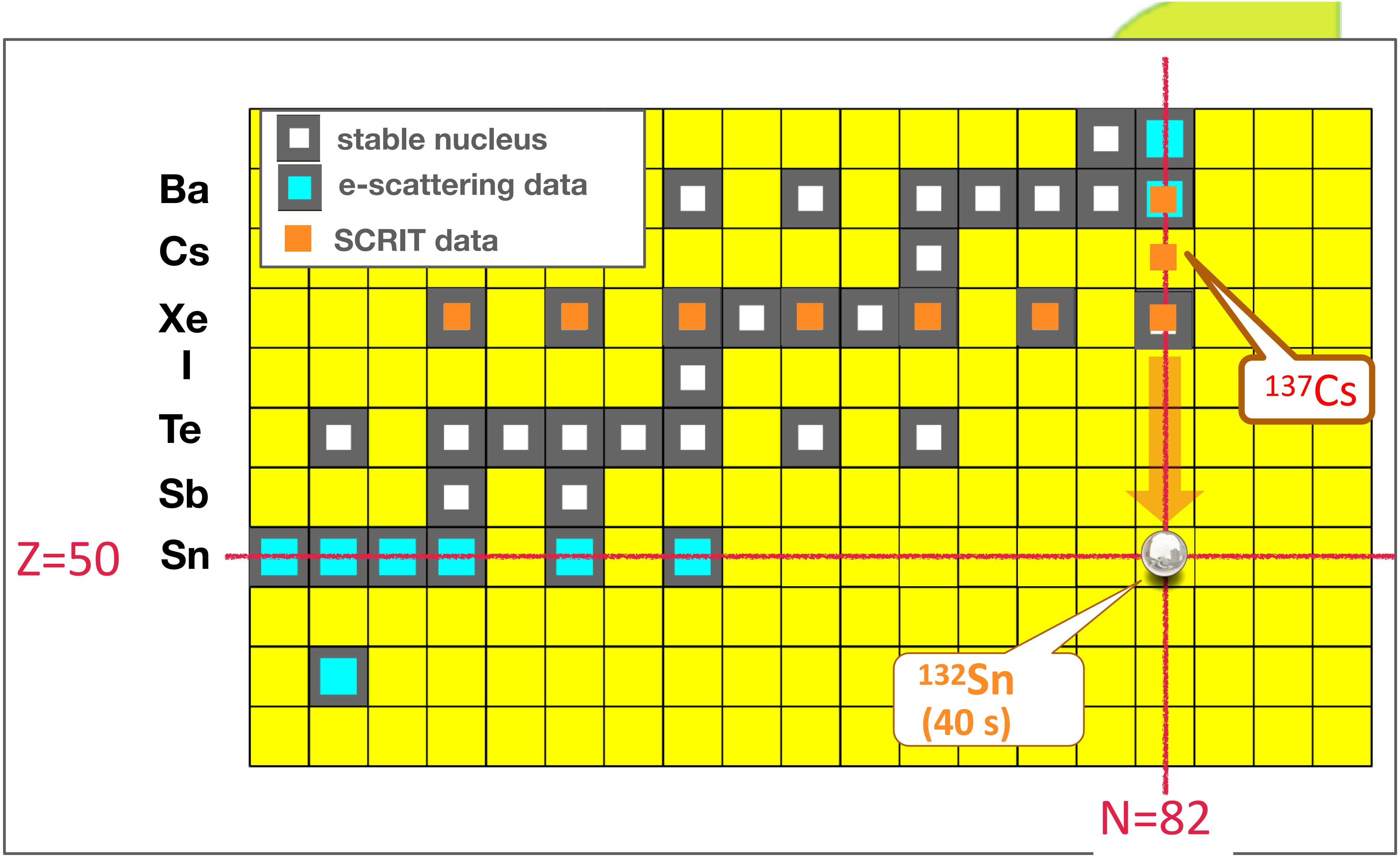
Injector + ISOL driver
150 MeV Microtron

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.

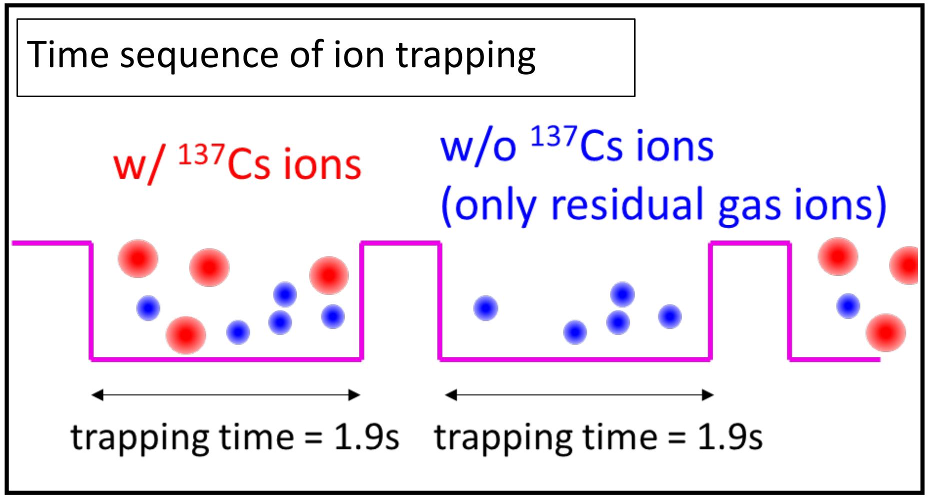
RIKEN SCRIT e-scattering facility

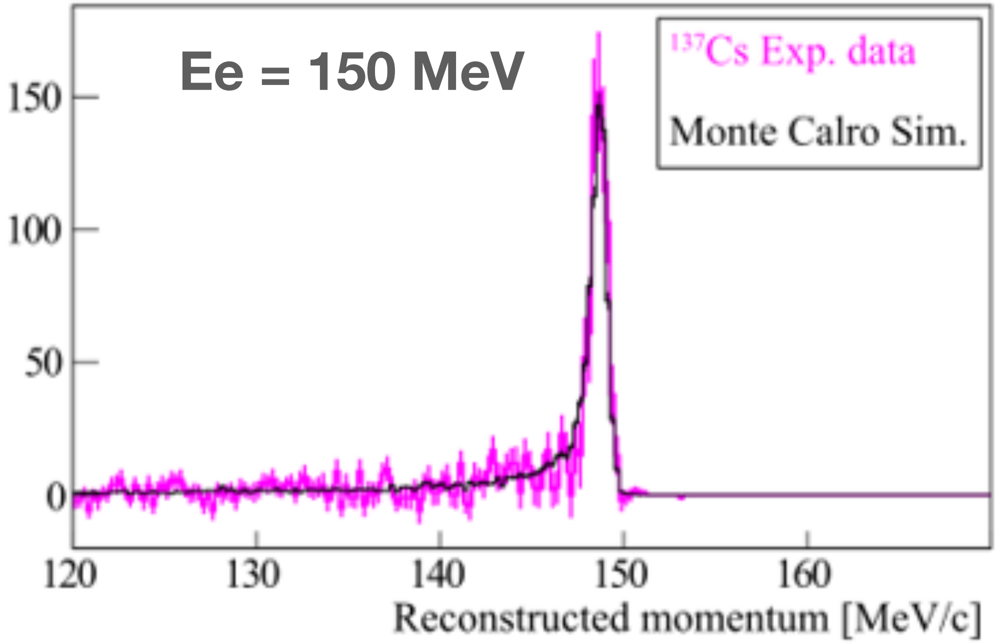


e-scattering at the RIKEN SCRIT facility



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



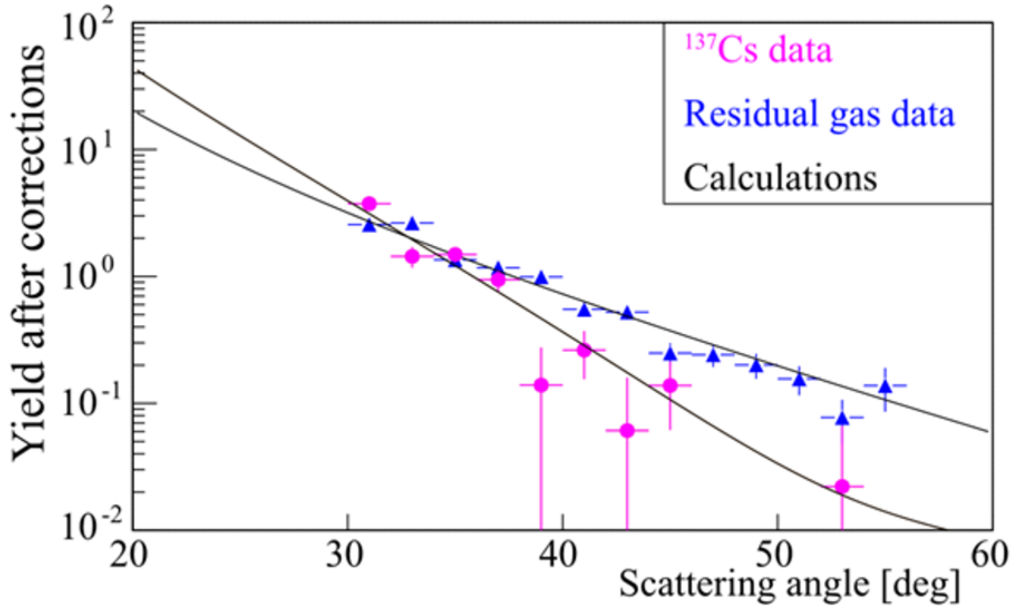


1.9 s trapping

=> mimicking "short-lived" nuclei

$N_{trapped}$ ~ 2 x10^7

=> L ~ 0.9 x 10^{26} /cm²/s

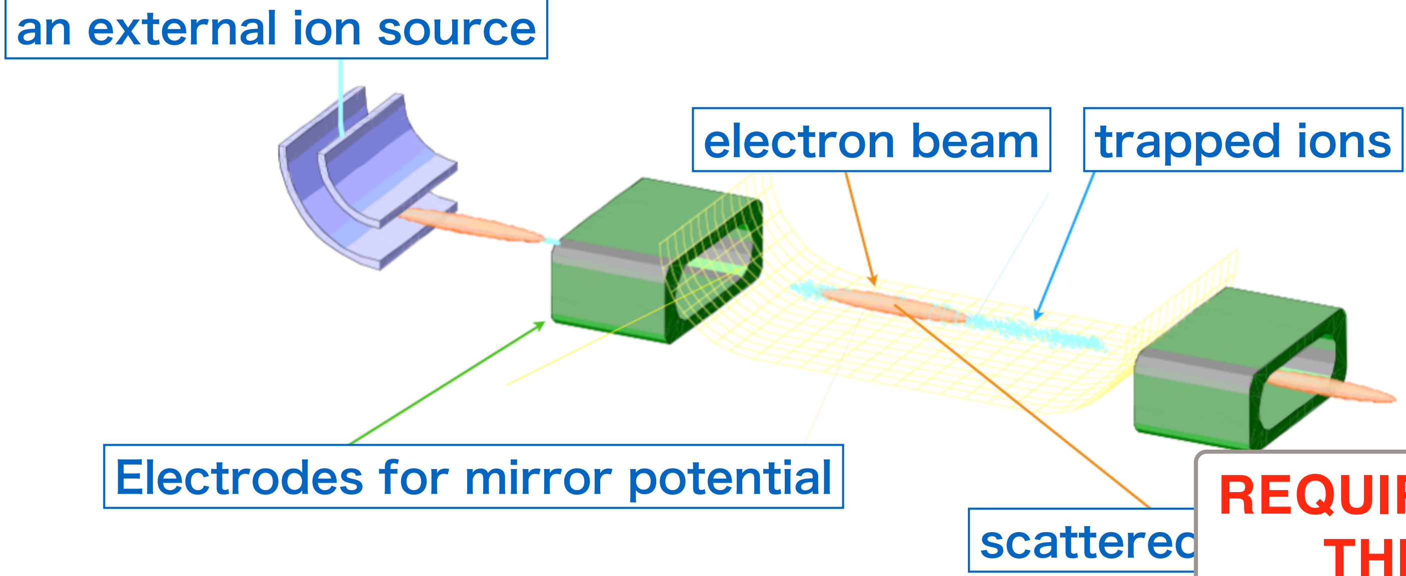


successful demonstration for online-produced unstable nuclei

Luminosities

~10^7 ions are trapped on e-beam (~ 1 mm²)

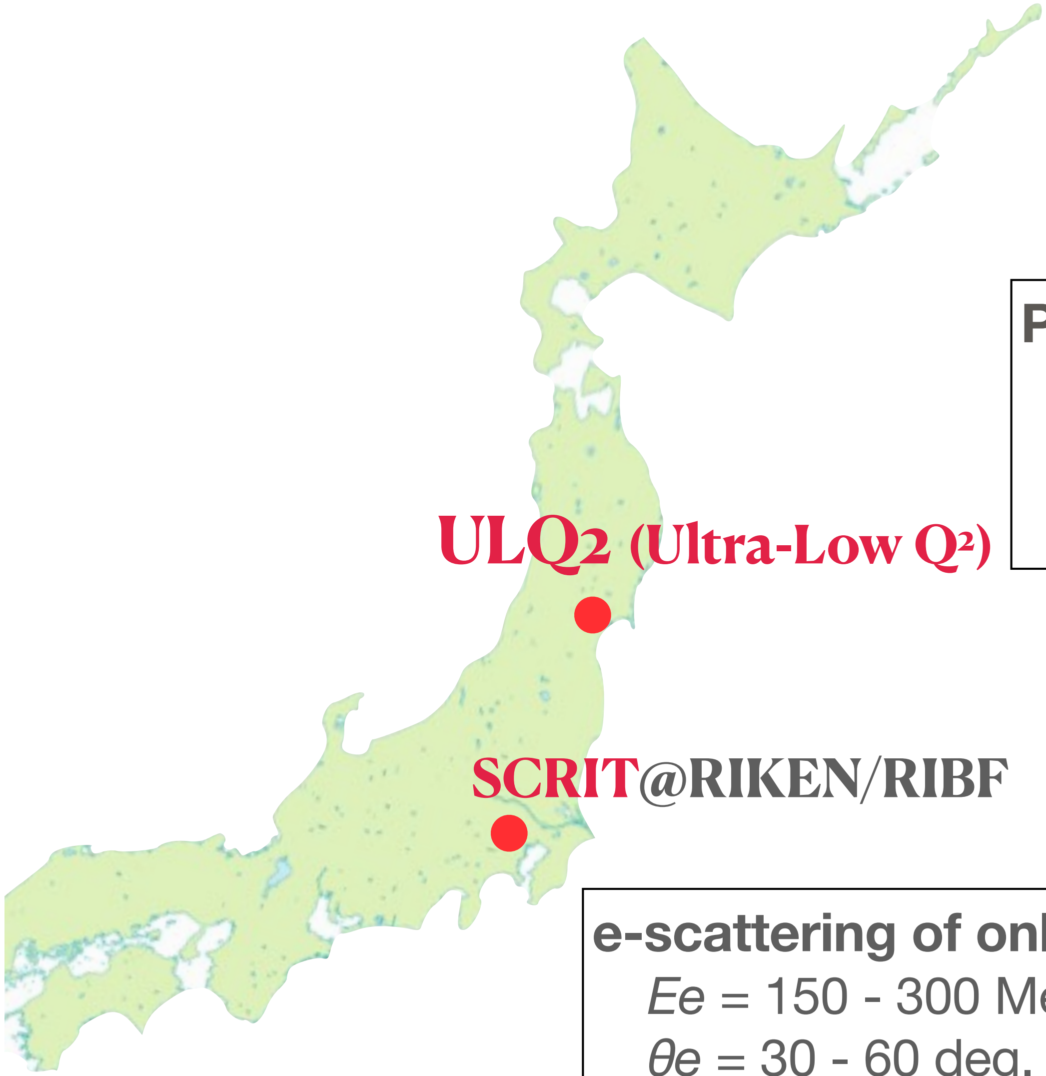
$N_t \sim 10^7\ /\mathrm{mm}^2 \Rightarrow\ 10^9\ /\mathrm{cm}^2$

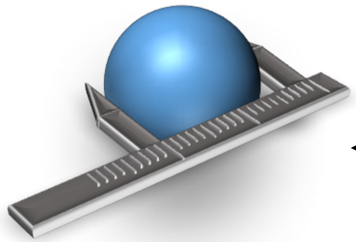


REQUIRED TARGET THICKNESS 10^{-10}!!!

	Ee	N_{beam}	ρ · t	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**	**~200 mA (~10^{18} /s)**	**~ 10^9 /cm²**	**~10^{27} /cm²/s**

our e-scattering activities





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

Proton (charge) size

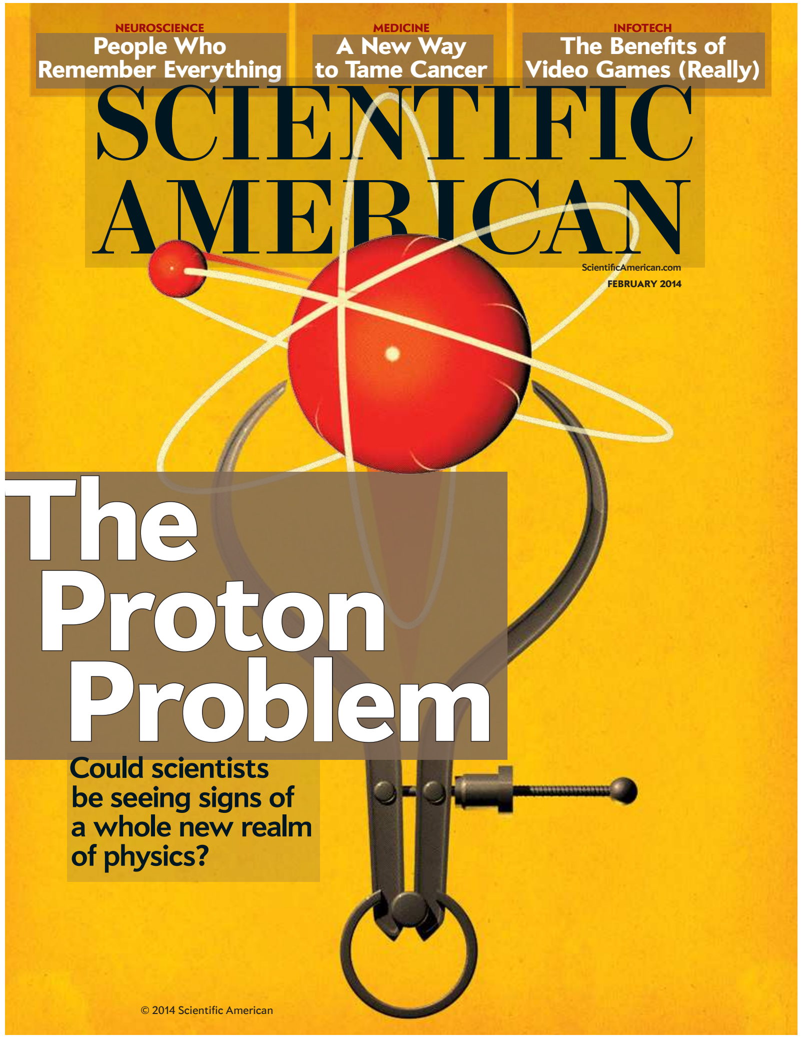
Ee = 10 - 60 MeV
θe = 30 - 150 deg.
=> Q^2 = 3x10^{-5} - 0.013 (GeV/c)^2

world's 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 (GeV/c)^2

world's first !!

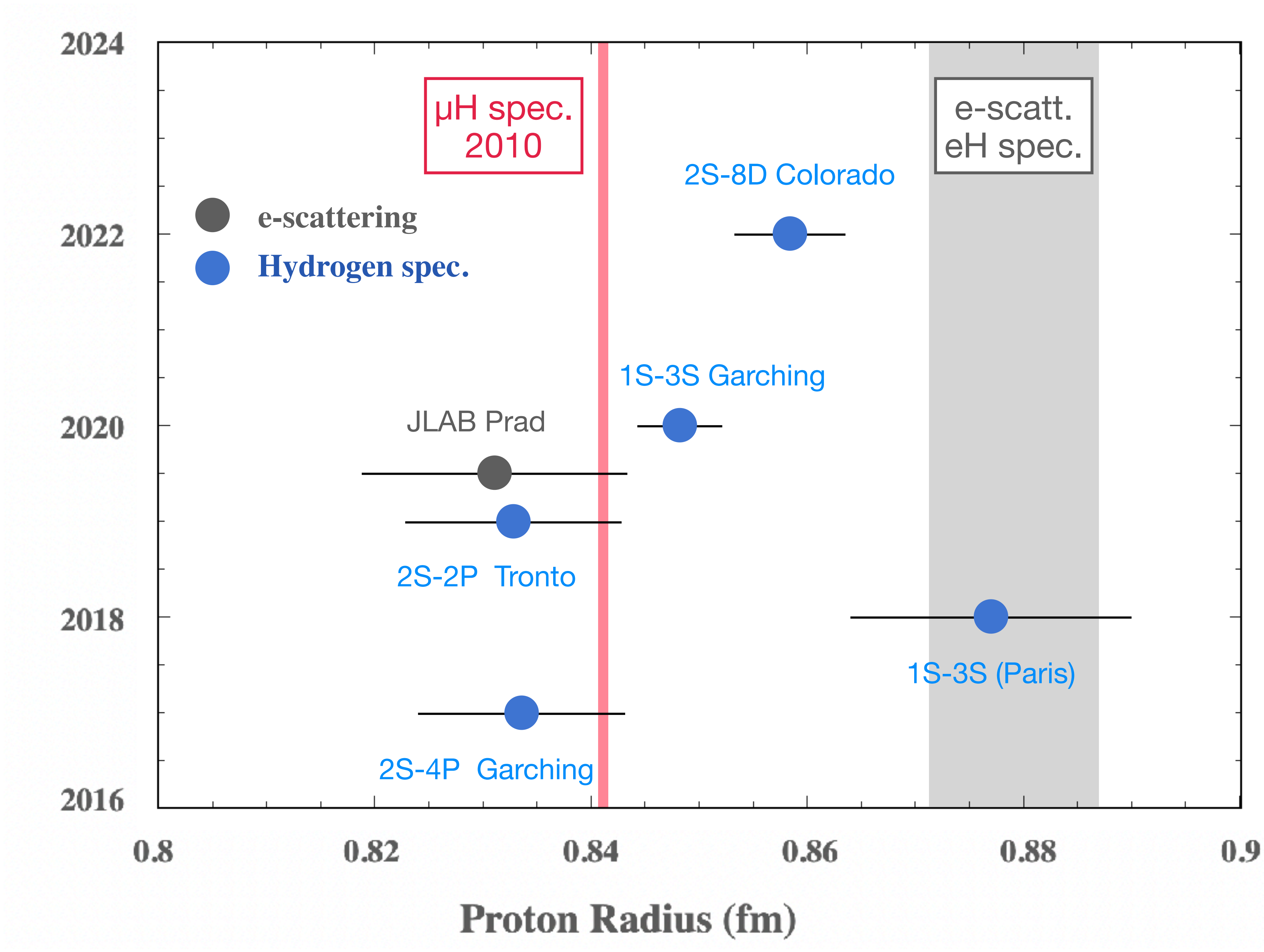


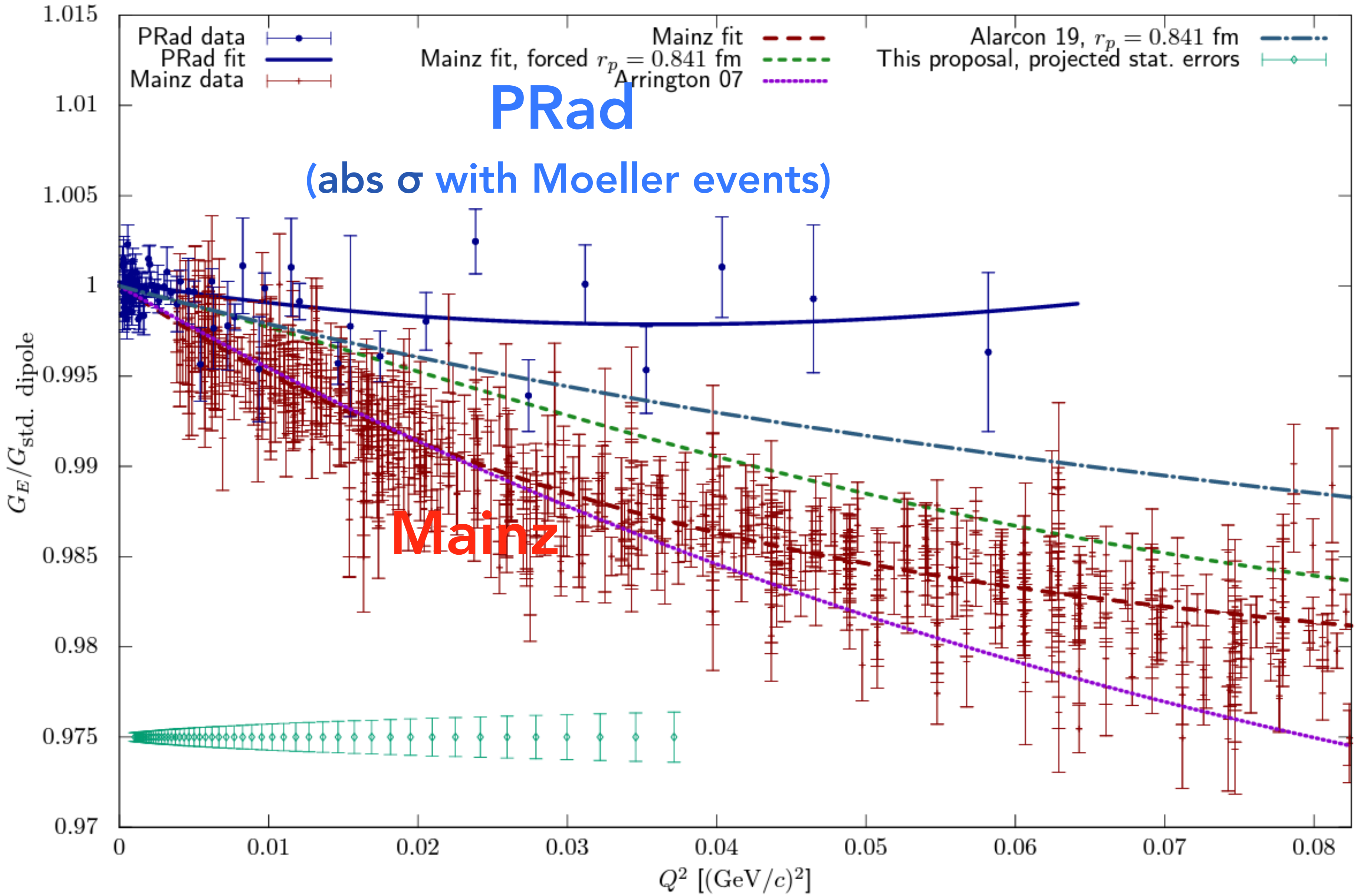
1) one of the most important basic properties of nucleon

2) Rydberg constant : $\Delta E = R_{Rydberg}(\frac{1}{n^2} - \frac{1}{m^2}) + \alpha\, \delta_{l0} < r_p^2 >$

proton charge radius as of today

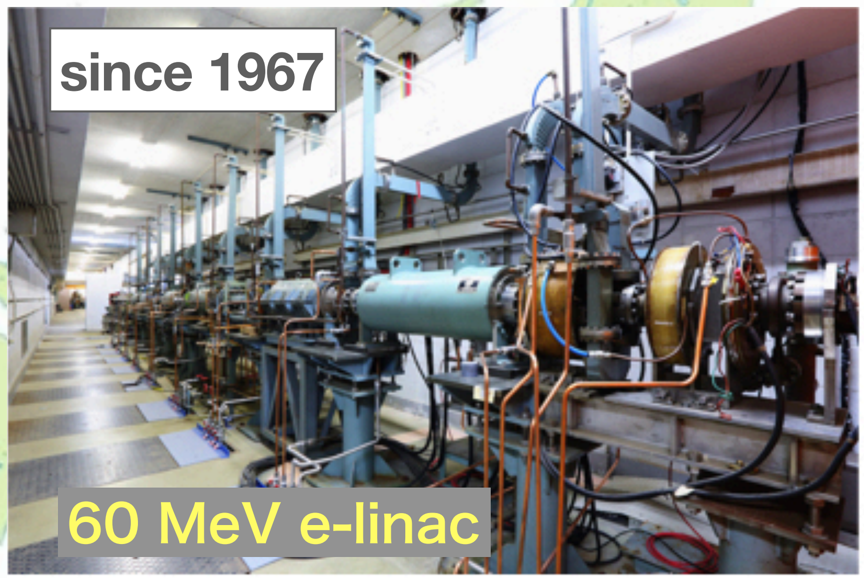
陽子半径グラフ2022_KGraph



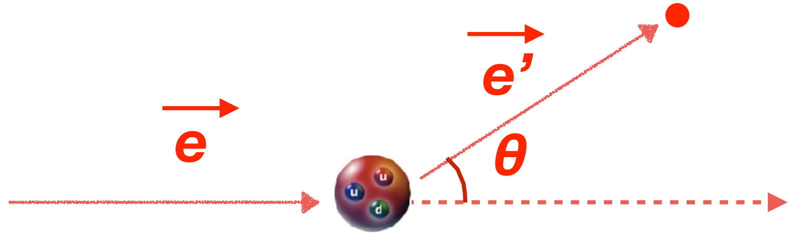


PRad data
PRad fit
Mainz data
Mainz fit
Mainz fit, forced $r_p = 0.841$ fm
Arrington 07
Alarcon 19, $r_p = 0.841$ fm
This proposal, projected stat. errors
PRad
(abs σ with Moeller events)
Mainz
$G_E/G_{\mathrm{std.\ dipole}}$
Q^2 [(GeV/c)^2]
1.015
1.01
1.005
1
0.995
0.99
0.985
0.98
0.975
0.97
0
0.01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

ULQ2 : Ultra-Low Q2



electron scattering off proton



electric magnetic

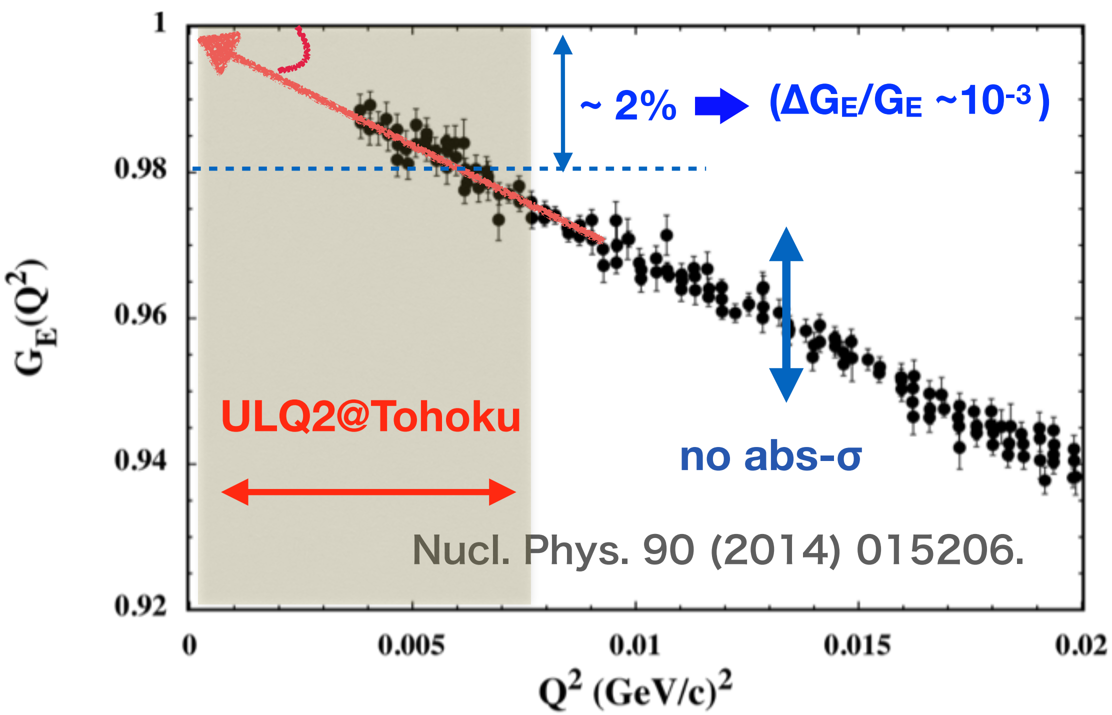
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{G_E^2(Q^2) + \frac{\tau}{\epsilon} G_M^2(Q^2)}{1+\tau}$$

$$\vec{q} = \vec{e} - \vec{e}' \qquad Q^2 = \vec{q}^2 - \omega^2$$

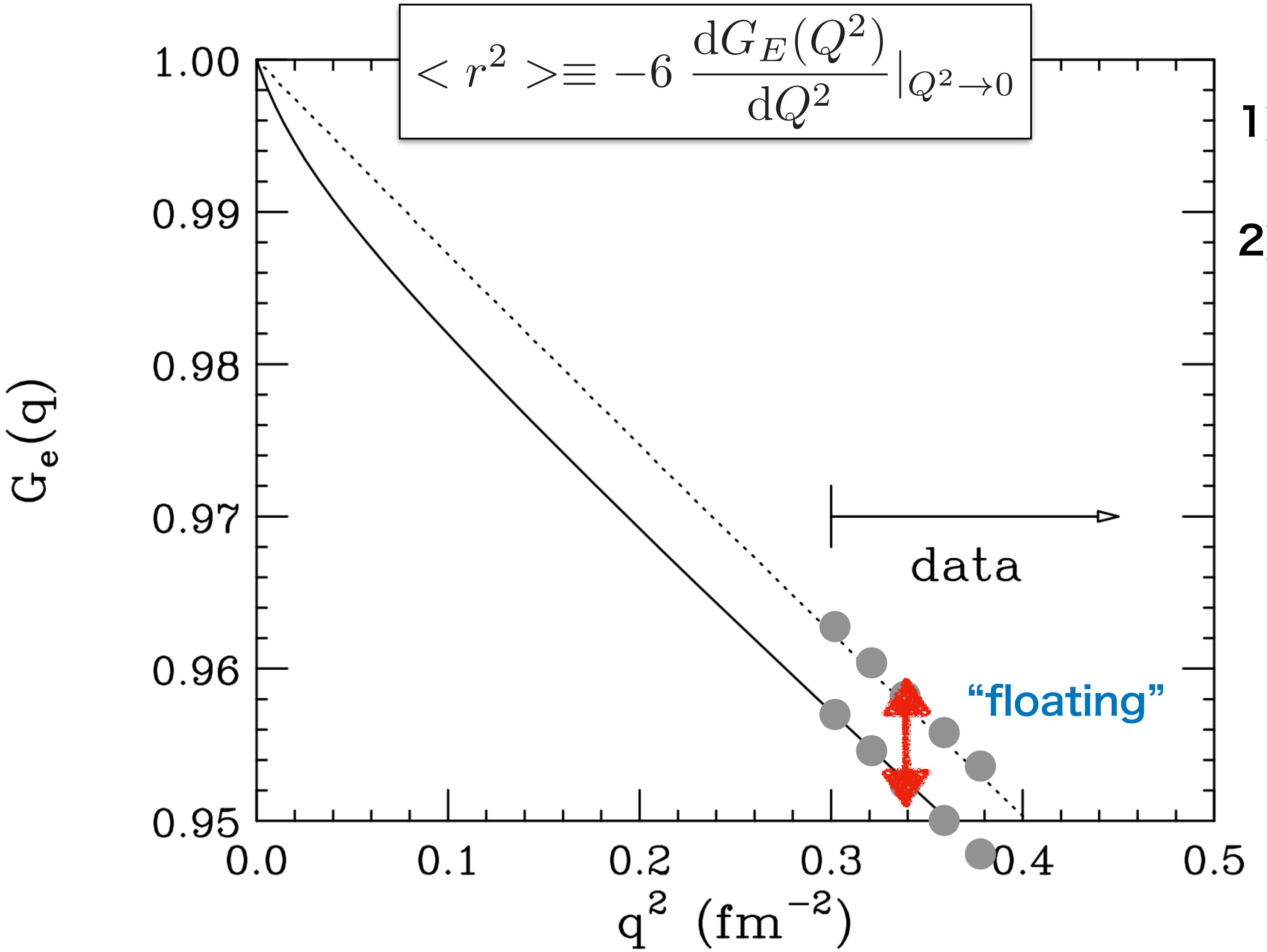
$$\omega = e - e' \qquad = 4\, e\, e' \sin^2(\theta/2)$$

proton charge radius

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



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 Q^2) at Tohoku, JAPAN since 2016~

"*least model-dependent*" proton charge radius

1) lowest-ever Q^2 by lowest-ever energy e-scattering (10-60 MeV)
2) absolute σ measurements with 10^{-3} accuracy
3) Rosenbluth-separated $G_E(Q^2)$ and $G_M(Q^2)$

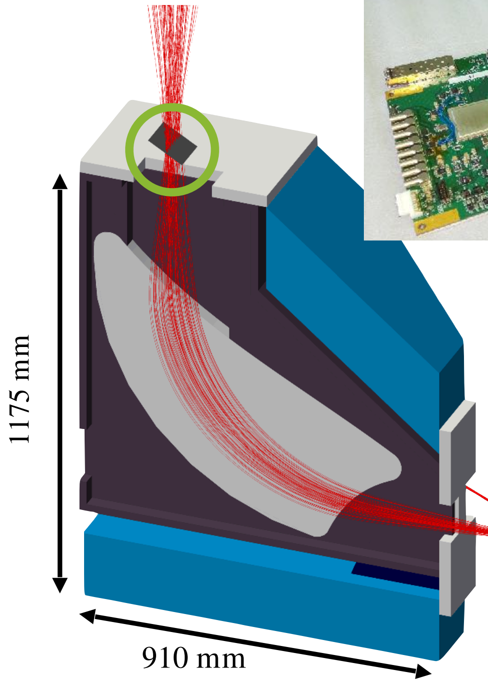
possible only at Tohoku accel.

60 MeV electron linac (since 1967)

Ee = 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

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

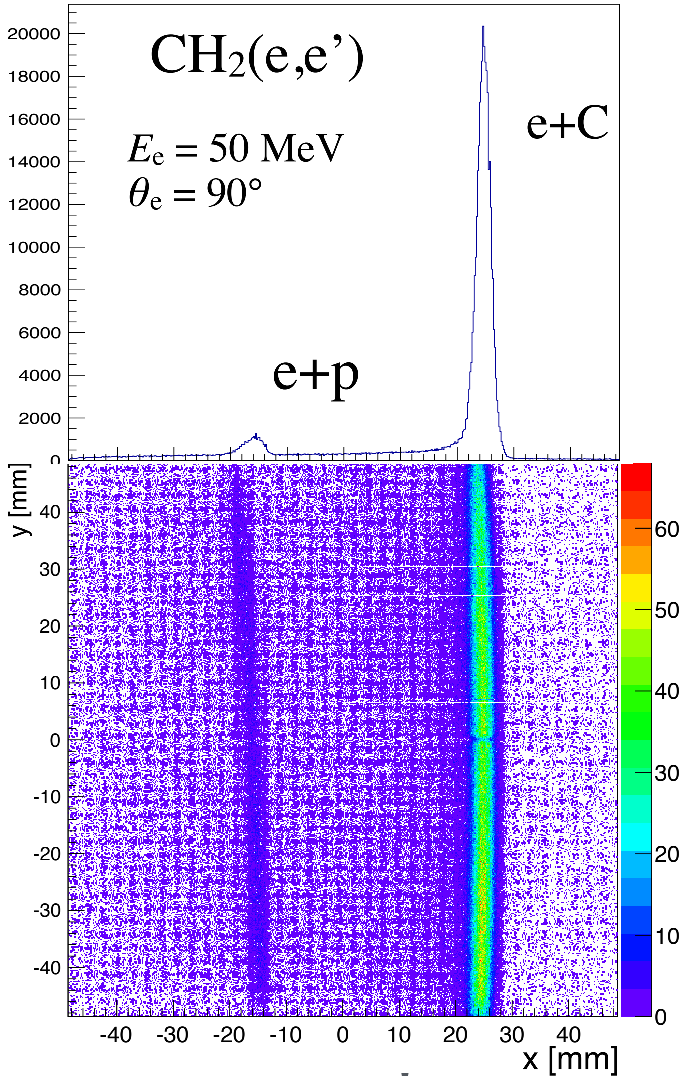


Focal plane detectors
(J-PARC g-2 + ULQ2)
190 um x 4k ch

Y. Honda

$^{12}CH_2$(e,e') data

2D hit pattern @ focal plane



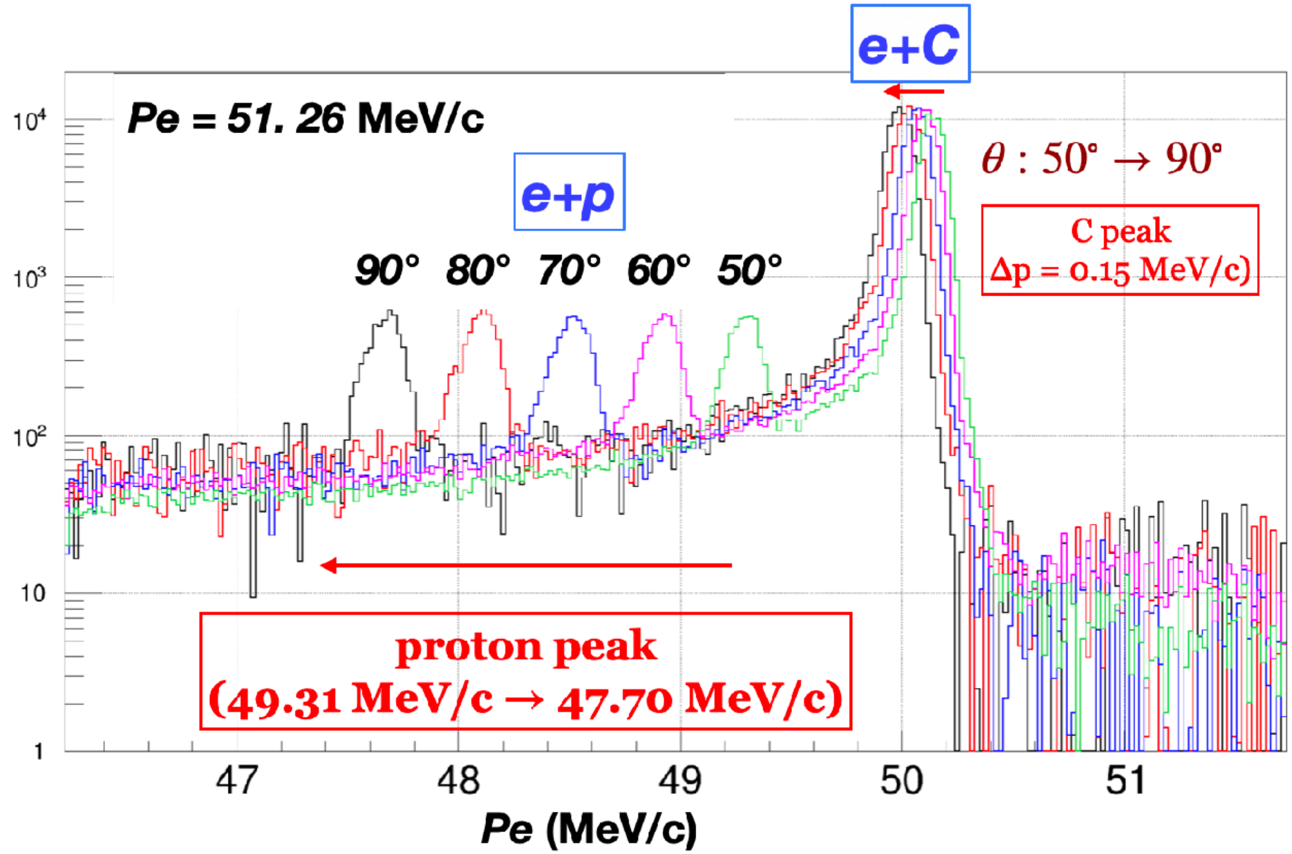
scattering angle

momentum

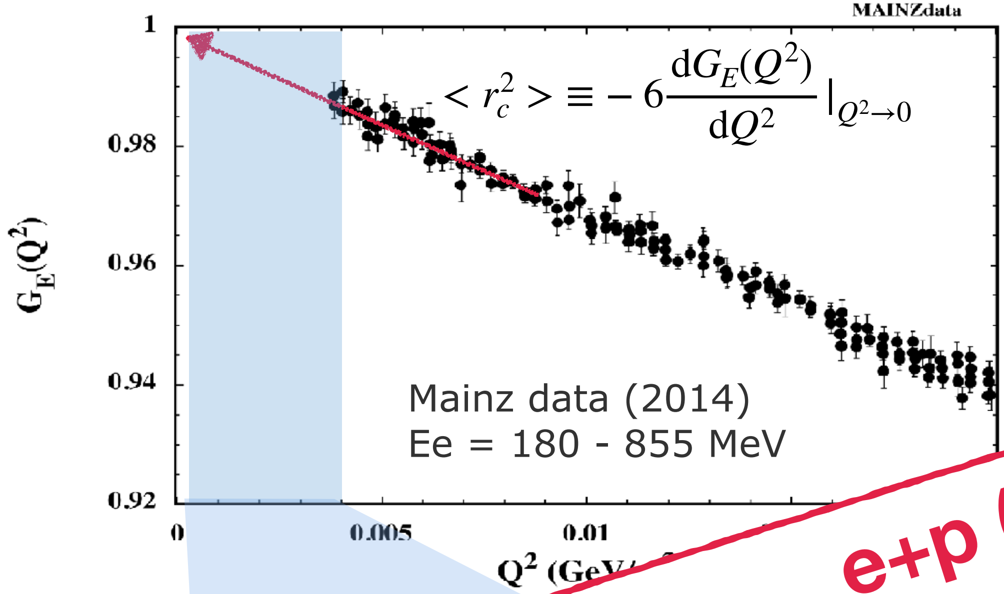
Momentum spectra of scattered electrons

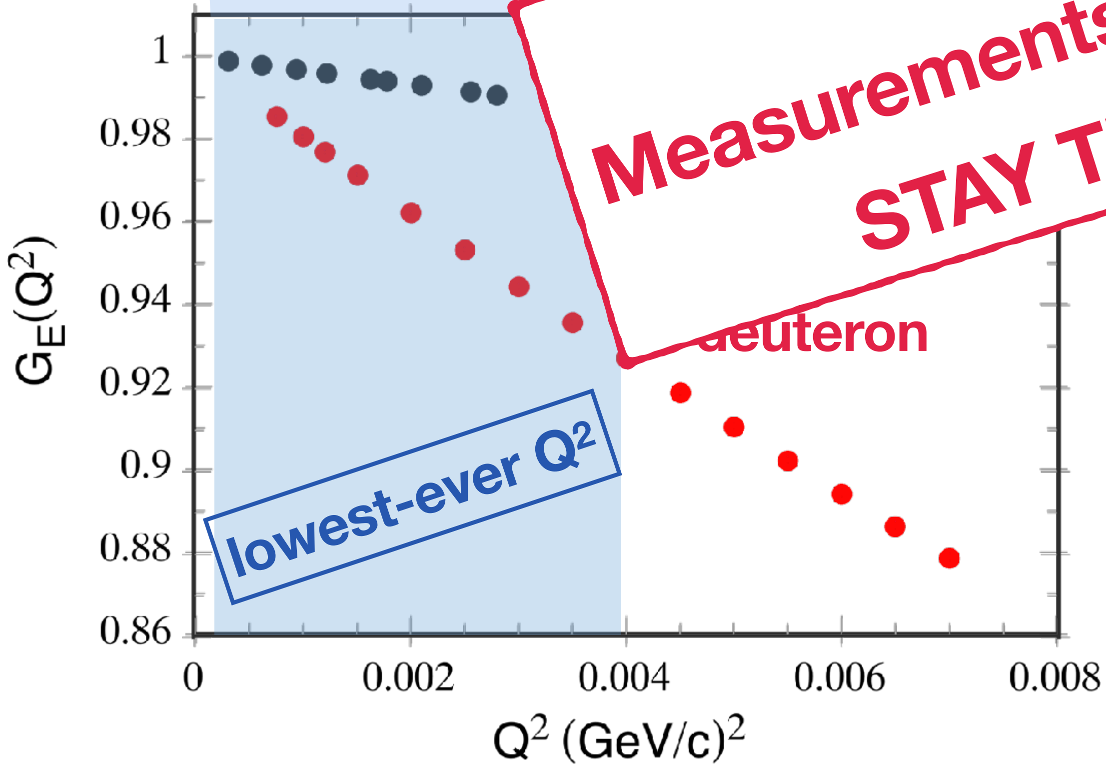
$$\left(\frac{d\sigma}{d\Omega}\right)_{ep} = \frac{Y(ep)/Y(e^{12}C)}{N_p/N_{^{12}C}}\left(\frac{d\sigma}{d\Omega}\right)_{e^{12}C}$$

well-known better th



ULQ2 measurements for e+p and e+d





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

three-year data-collection completed (2024, May)

Yuki Honda
Ph.D. student (C. Legris, T. Goke)

1)

dius

adius (next step)

deuteron charge radius
=> neutron charge radius

$$< r_d^2 > = < r_{str}^2 > + < r_p^2 > + < r_n^2 > + \mathrm{RC}$$

ULQ2 **theory**

$$< r_d^4 > = < r_{str)}^4 > + \frac{10}{3} < r_{pstr}^2 > (< r_p^2 > + < r_n^2 >) + O(4) + \mathrm{RC}$$

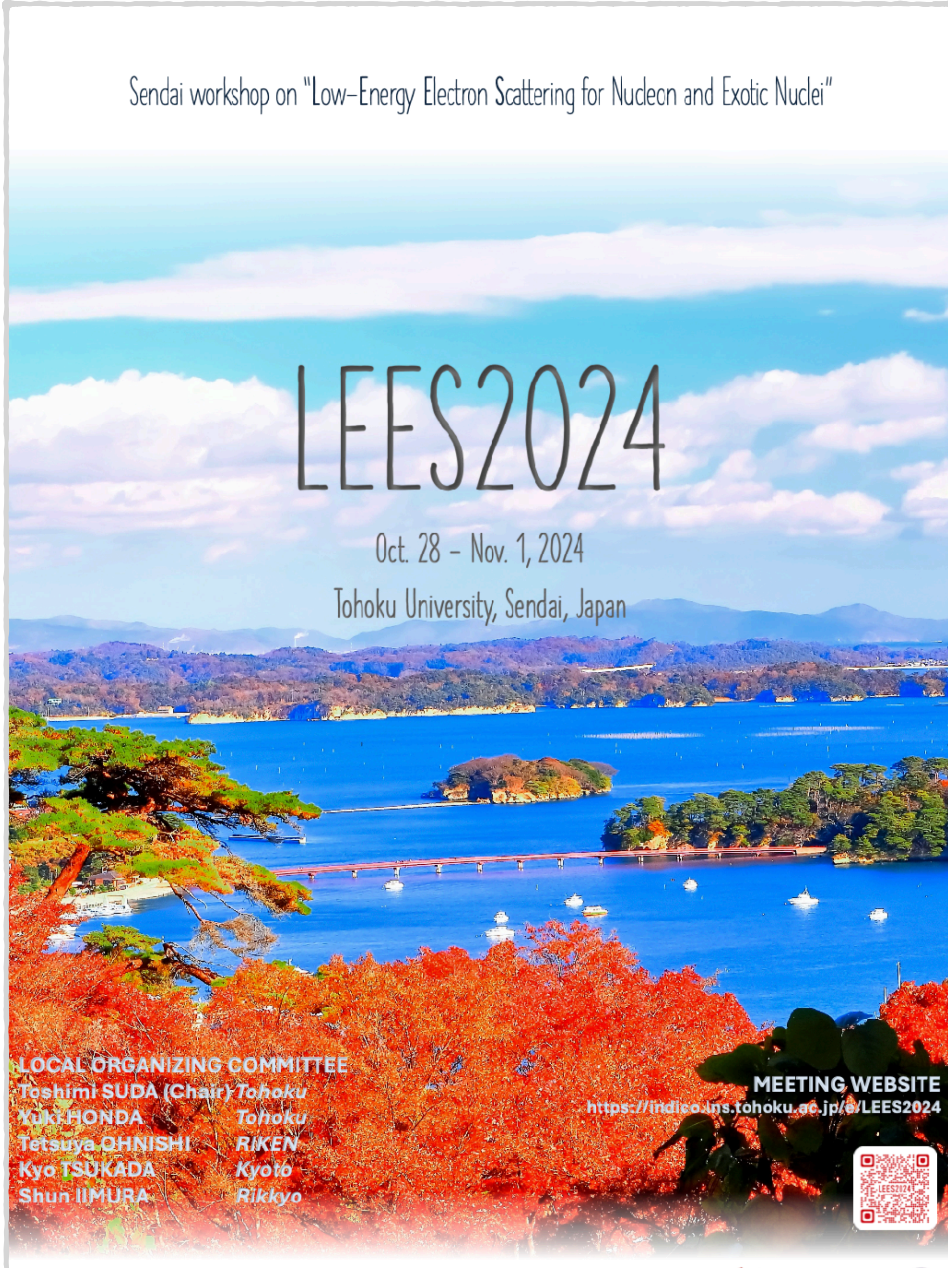
ULQ2 **theory** **theory**

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



conclusions

- **SCRIT facility :**
  started operation for online-produced radioactive isotopes

  the world's first and currently only-one facility
  ISOL upgrade to 2kW is underway for ^{132}Sn(e,e')

- **e-scattering for exotic nuclei is feasible with N ~ 10^7 /s**

- **many new research possibilities**
  - **charge density distributions**
  - **neutron-skin of neutron-rich nuclei**
  - **GDR and deformation**
  - **……**