Electron scattering from nucleon and nuclei

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Sendai

Lecture 1 : electron scattering in general

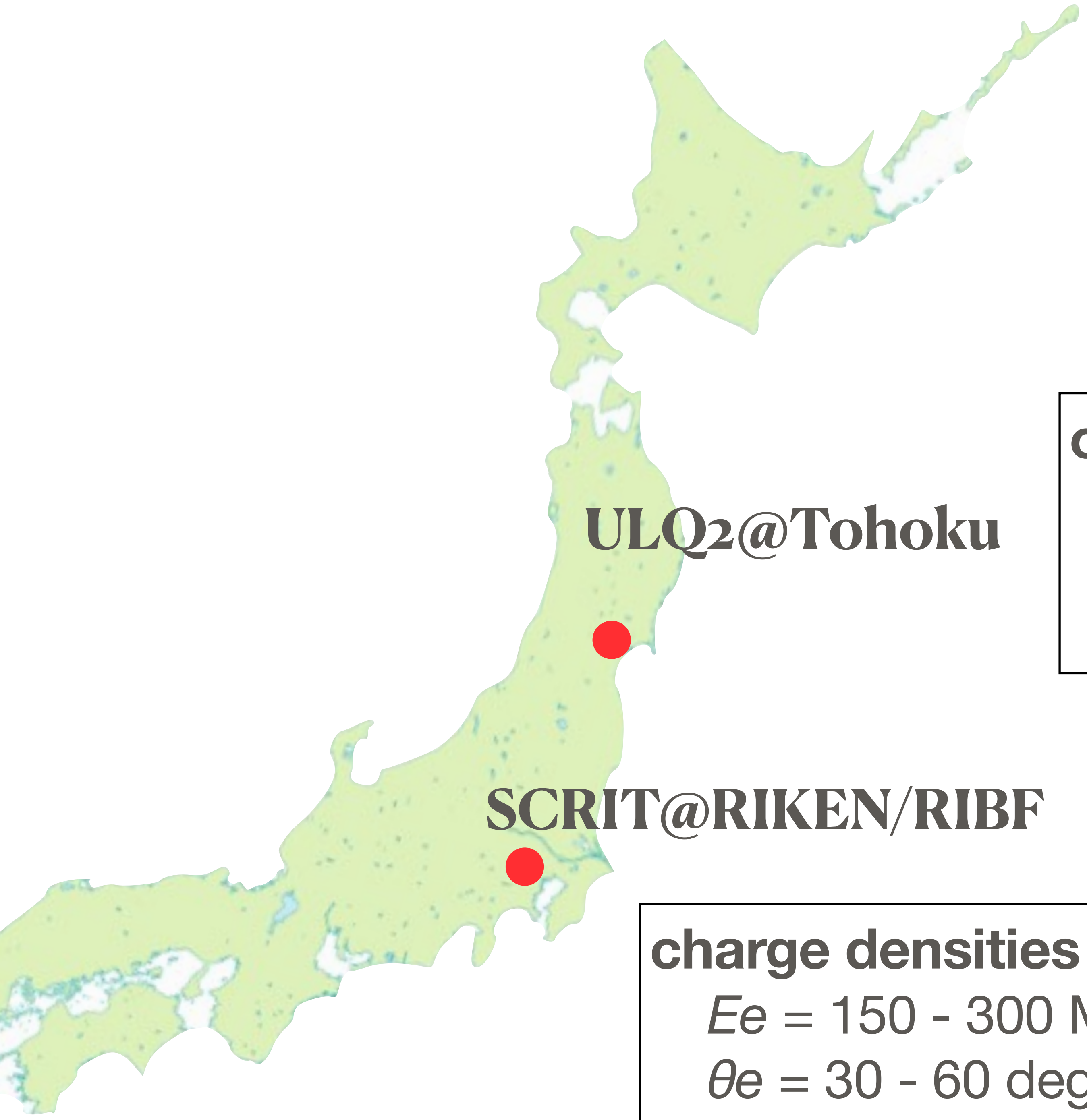
What is electron scattering?
what can we learn by electron scattering?
what have been revealed so far for stable nuclei?

Lecture 2 : selected topics

electron scattering for

- proton charge radius
- exotic nuclei
- neutron distribution in nuclei

Low-q electron-scattering activities in Japan



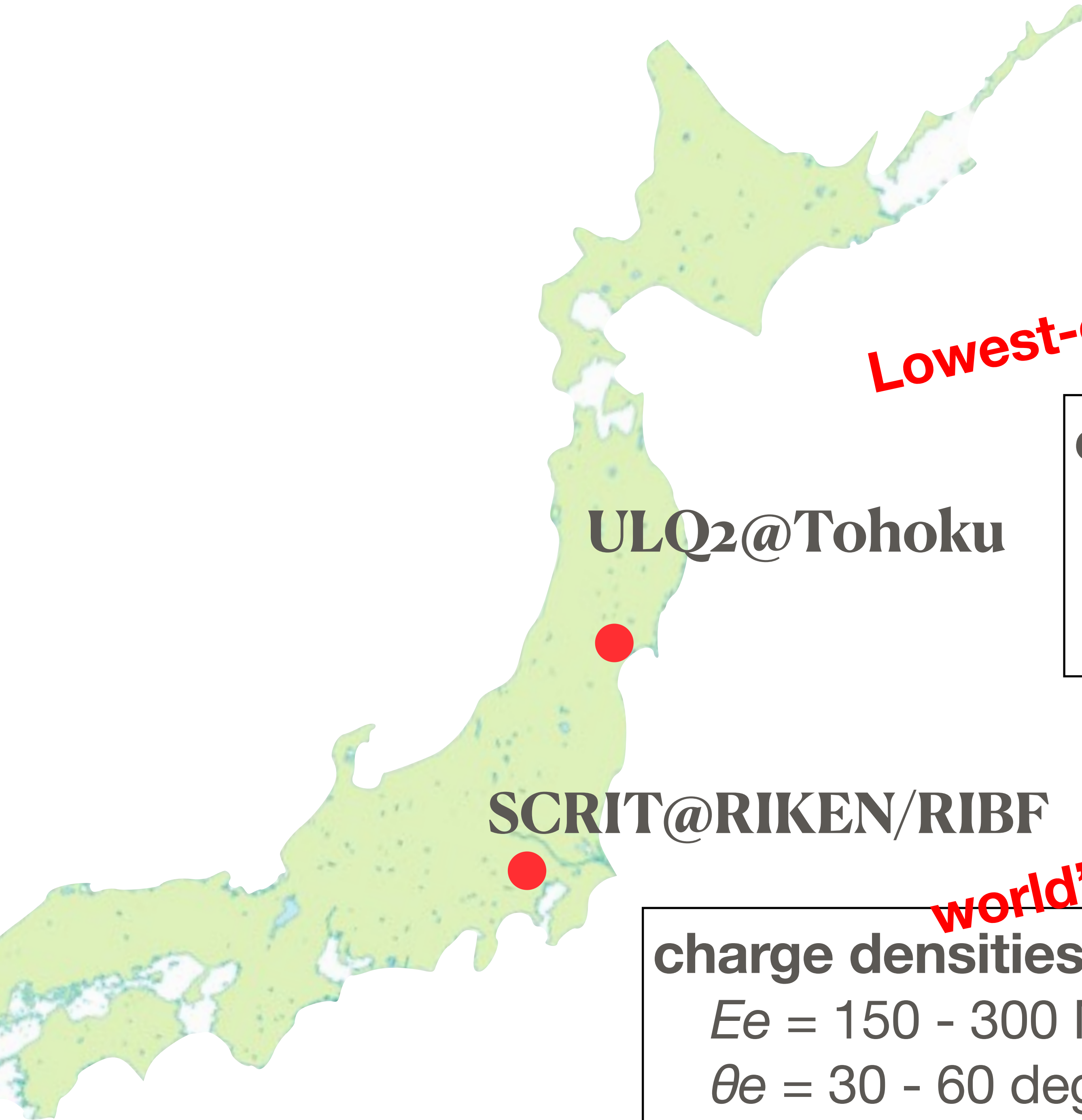
charge radii of proton and deuteron

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

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

Low-q electron-scattering activities in Japan



Lowest-ever energy electron scattering

charge radii of proton and deuteron

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

world's first e-scattering facility for exotic nuclei

charge densities of short-lived exotic nuclei

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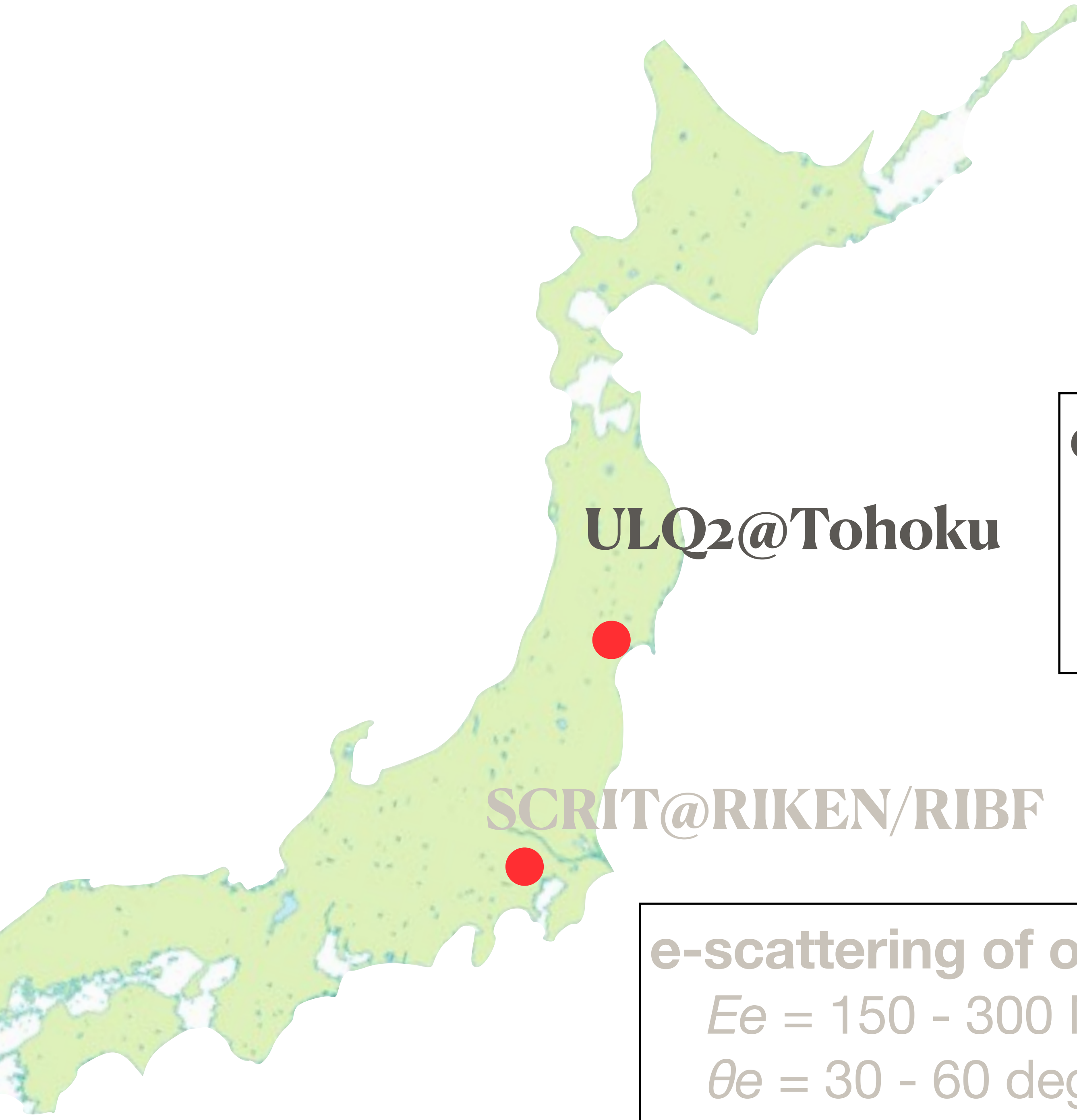


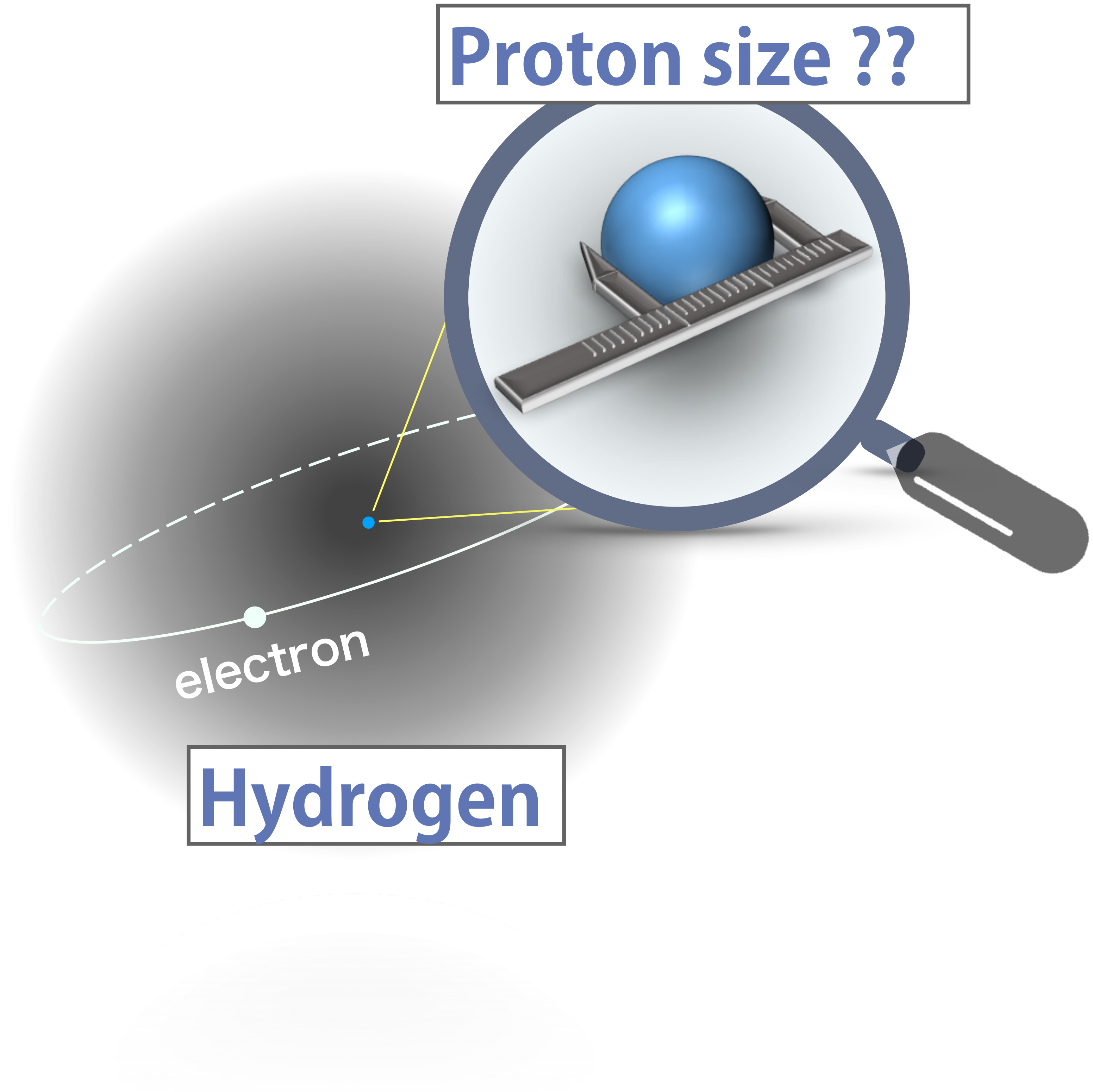
charge radii of proton and deuteron

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

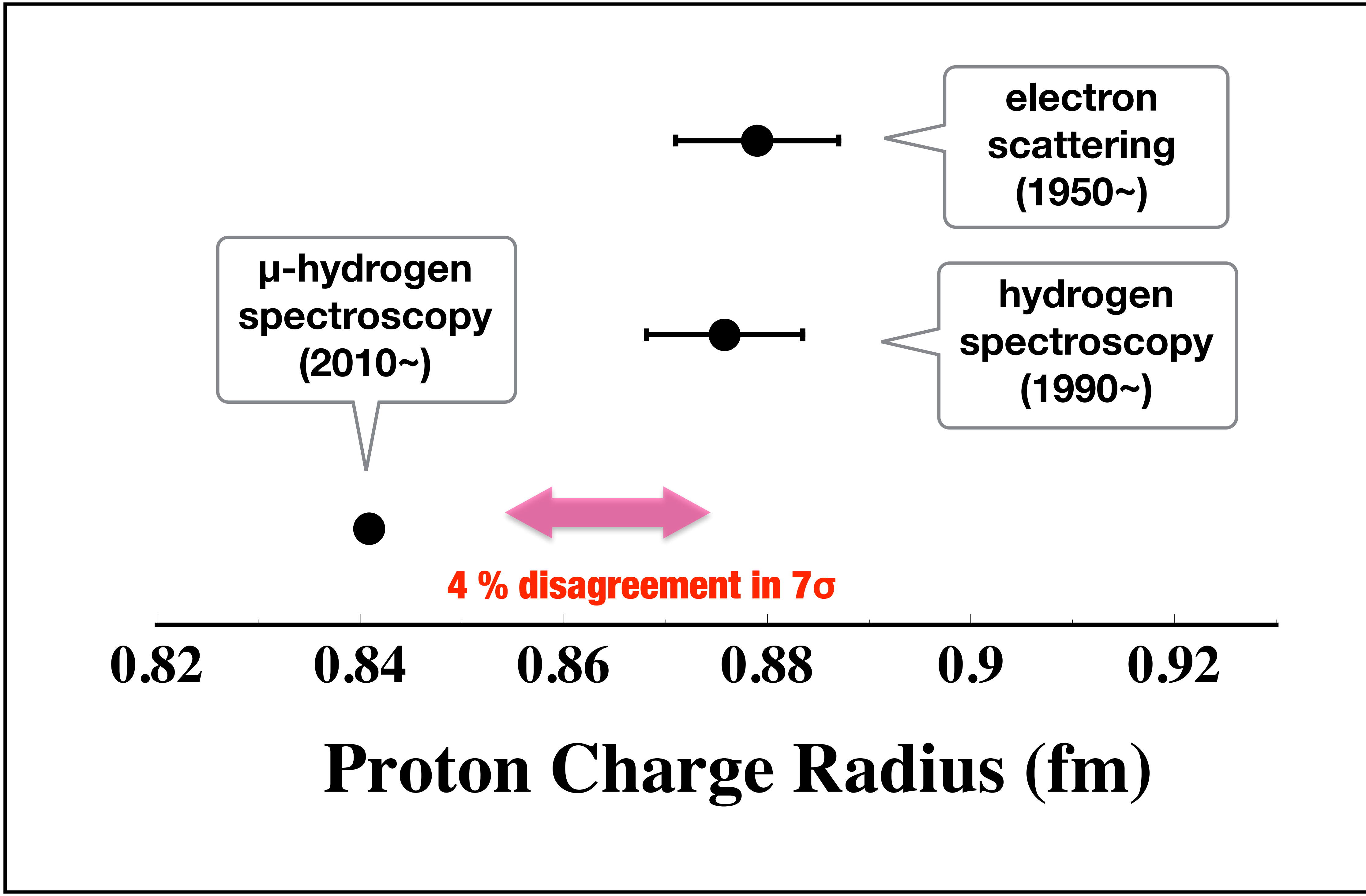
e-scattering of online-produced exotic nuclei (~10^8/sec)

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

Proton Radius Puzzle since 2010

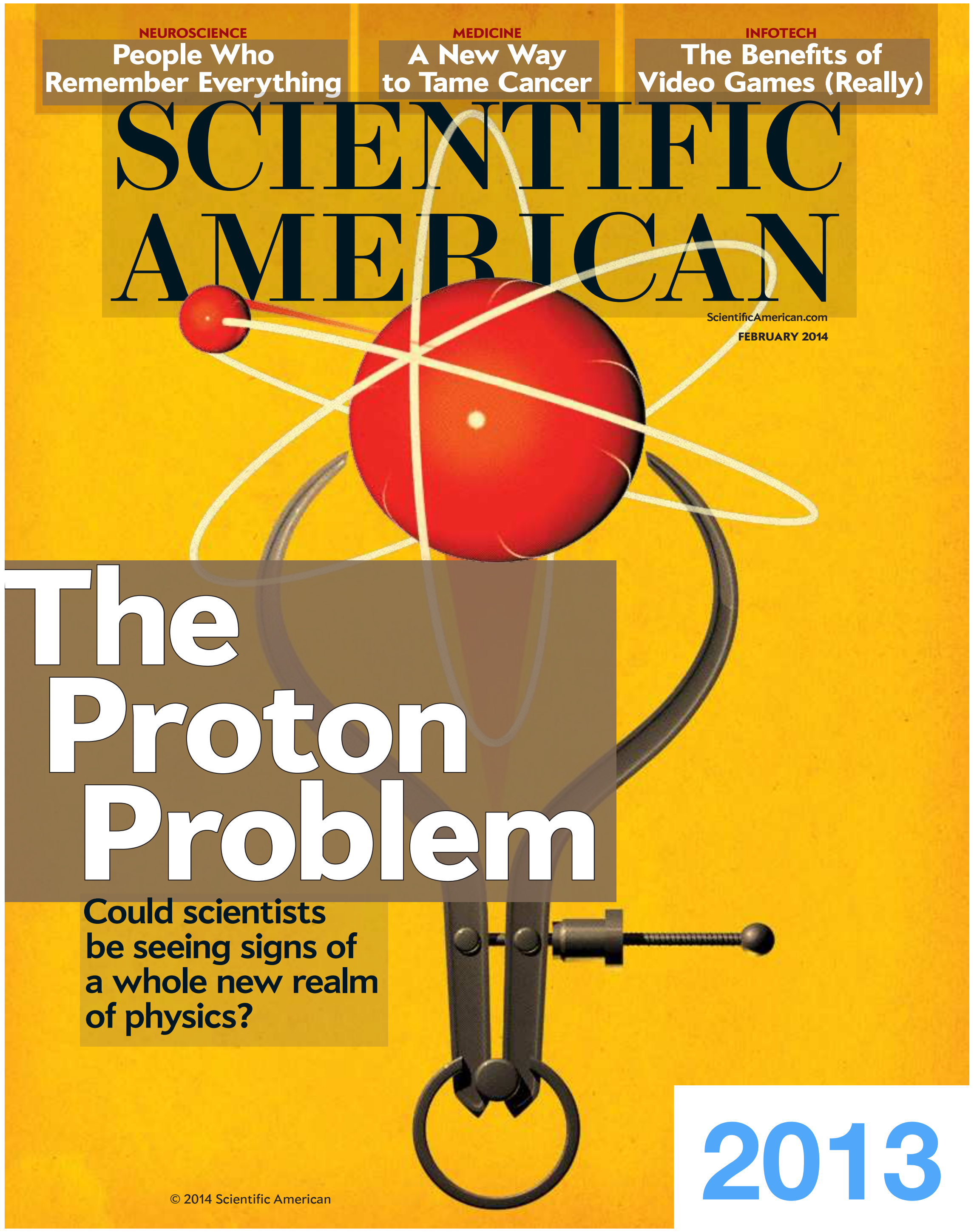


Proton Radius Puzzle



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

Proton Charge Radius Puzzle



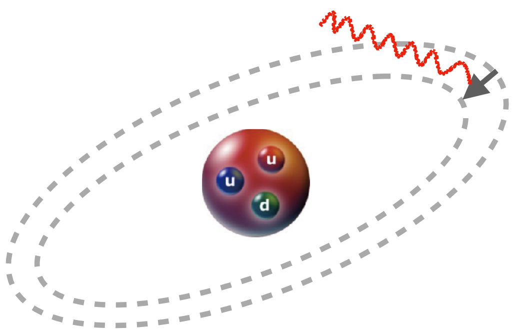
R. Pohl *et al.*,
Nature 466 (2010) 213.

A. Antognini *et al.*,
Science 339 (2013) 417.

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 $g = 2(1 + a_\mu)$

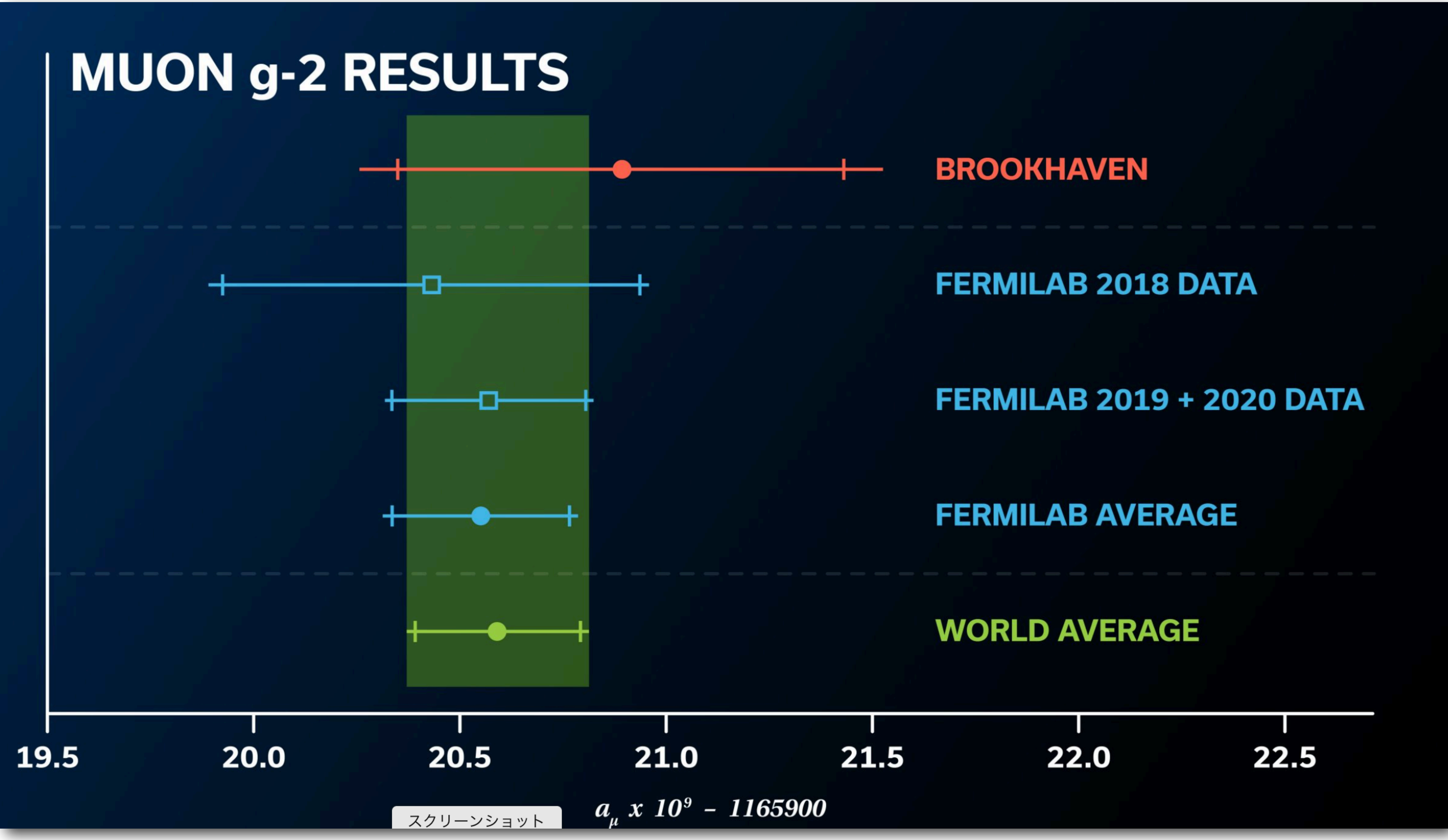
$$a_\mu^{exp} = 1\ 165\ 920.89\ (0.63) \times 10^{-9}$$

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

3.5 σ discrepancy

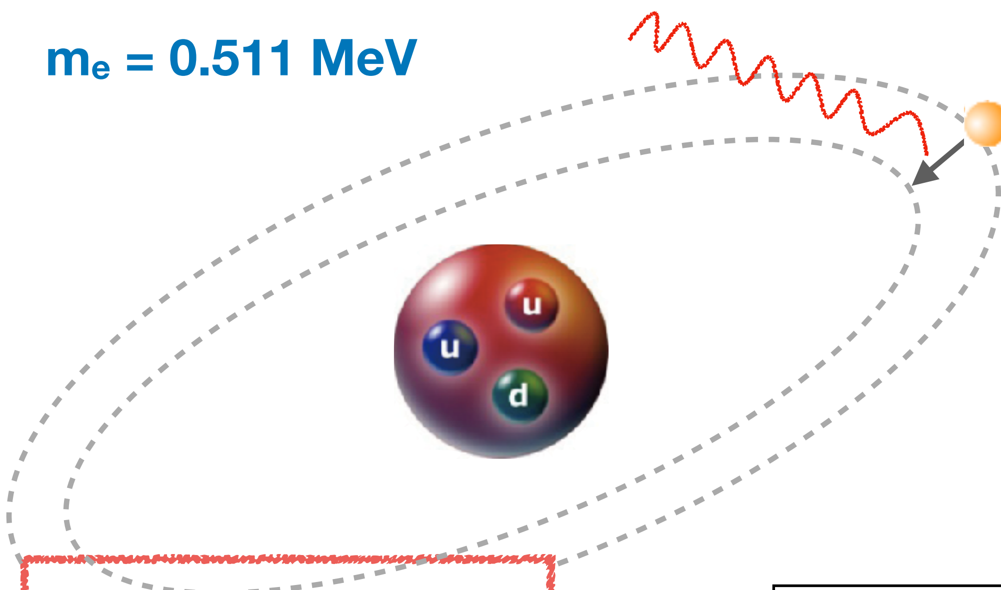
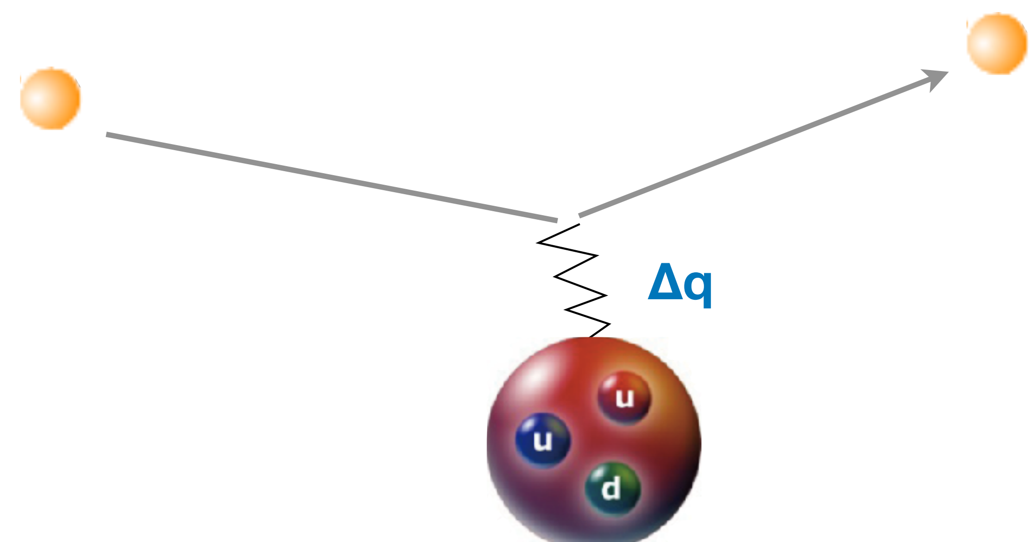
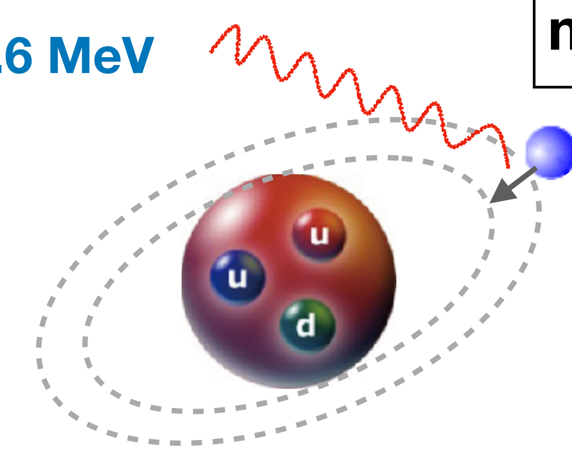
possible MeV-order force carrier (dark photon ...?)

press release from Fermi Lab. on Aug. 11



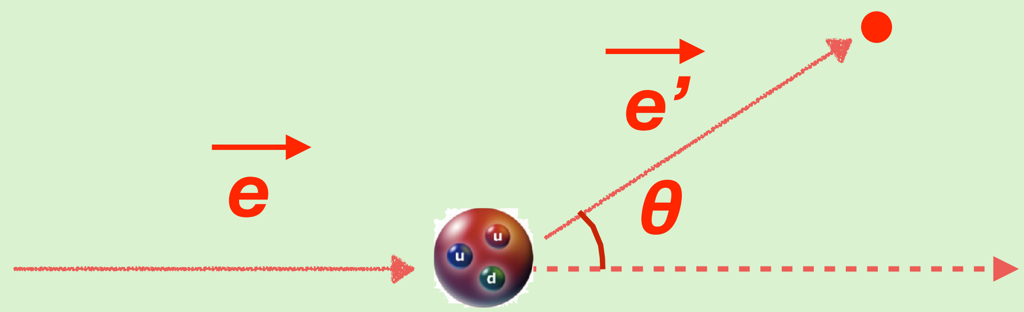
g-2 = 0.00233184110 +/- 0.00000000043 (stat.) +/- 0.00000000019 (syst.)

ways to determine the proton charge radius

	Spectroscopy	Scattering
e^-	m_e = 0.511 MeV  0.8758(77)	 0.8770(60)
μ^-	m_μ = 105.6 MeV  0.8409(4)	underway at PSI, Switzerland

proton size ~ 10^{-15} m
electron orbit ~ 10^{-10} m
muon orbit ~ 10^{-12} m

electron scattering and proton charge radius



Charge FF Magnetic FF

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

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

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

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

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

energy transfer $\omega = e - e'$

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

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

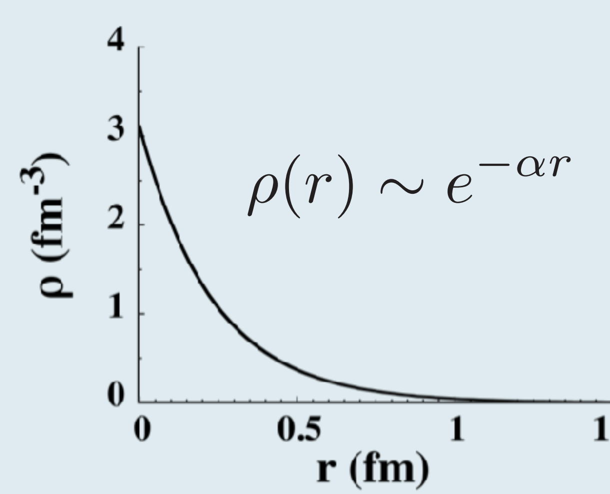
G. A. Miller, PRC 99 (2019) 035202

2nd moment of charge density ρ(r) ??

Electric Form FactorGE

non-rel. limit

ρ(r)



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

Proton radius by electron scattering

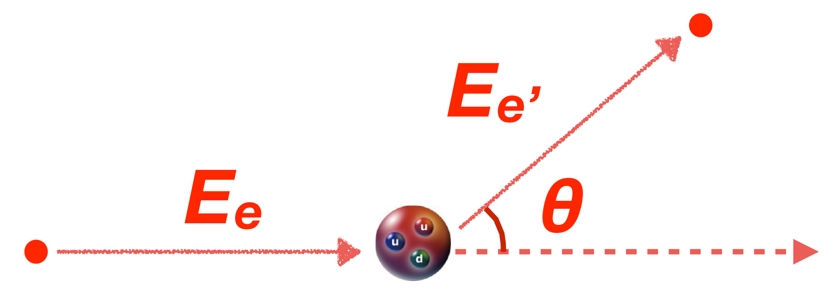
elastic cross section

$$\frac{d\sigma}{d\Omega} \propto \boxed{G_E^2(Q^2)} + \alpha(\theta) \boxed{G_M^2(Q^2)}$$

Charge FF

Function on only θ

Magnetic FF



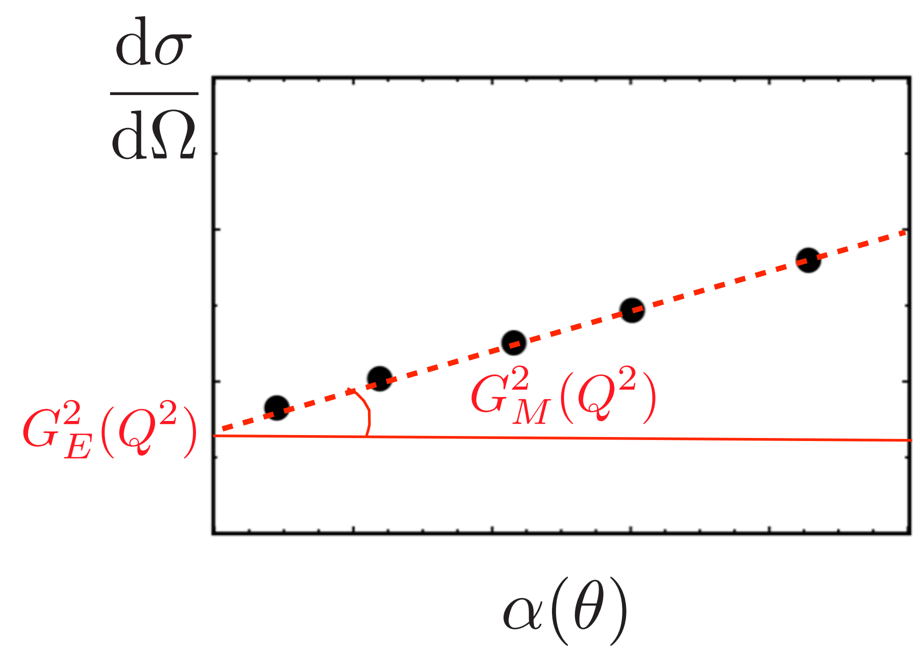
4-momentum transfer

$$Q^2 = 4\ E_e E'_e \sin^2(\theta/2)$$

1 $G_E(Q^2)$ by Rosenbluth separation

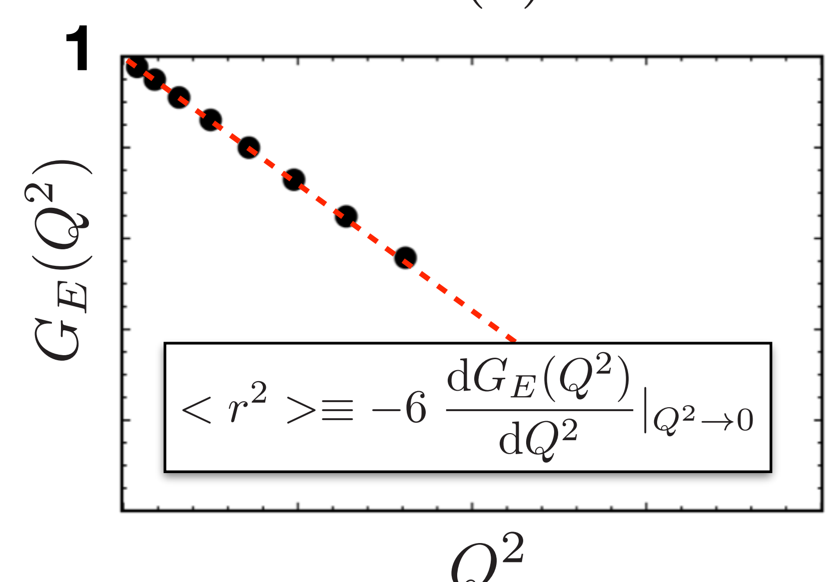
measurements for various θ under fixed Q^2

→ **changing Ee for each measurement**



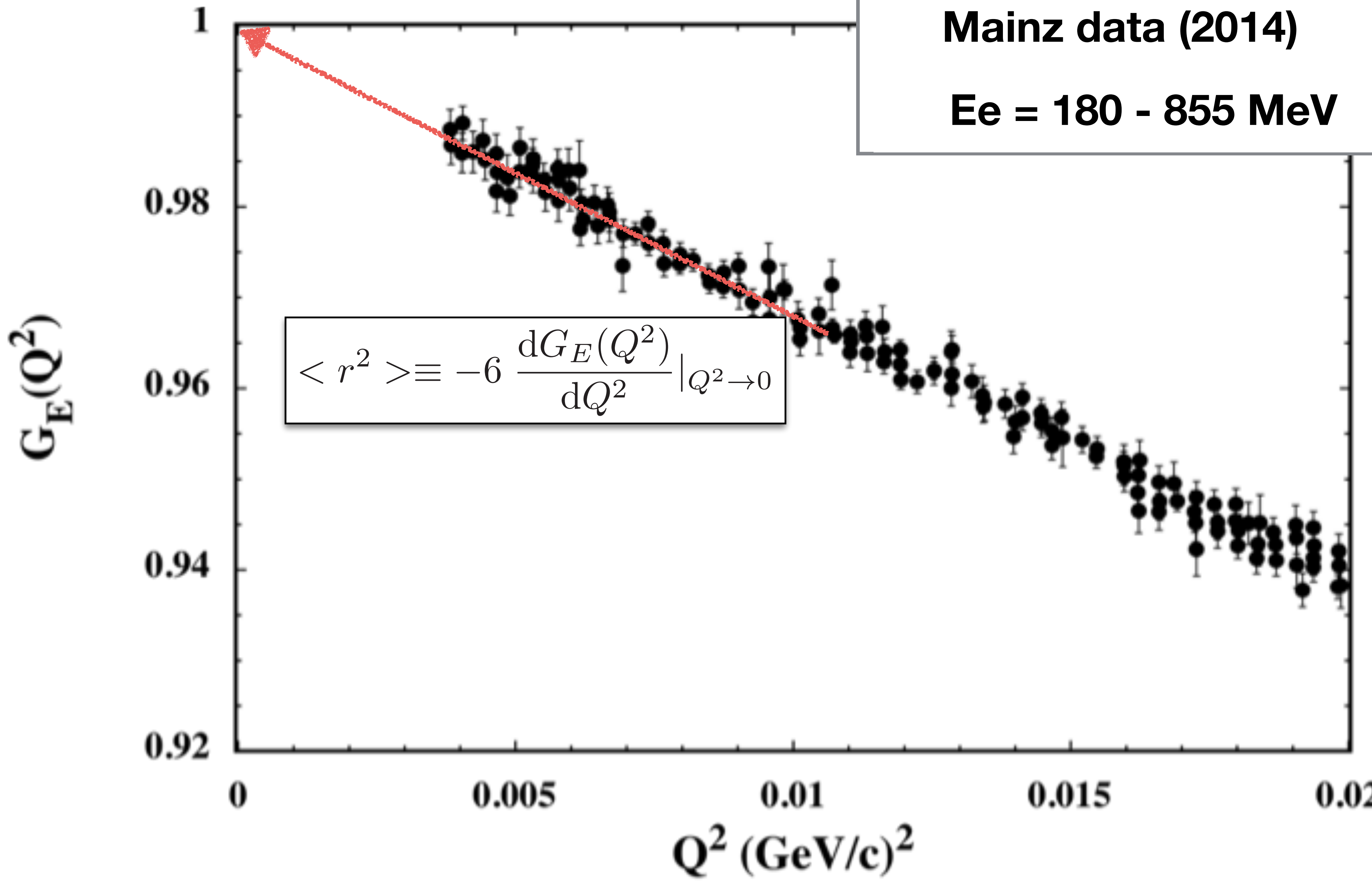
2 Charge radius and $G_E(Q^2)$ (Q^2-> 0)

$$G_E(Q^2) \sim 1 - \frac{< r^2 >}{6} Q^2 + \frac{< r^4 >}{120} Q^4 - \frac{< r^6 >}{5040} Q^6 + \ldots$$



Mainz electron scattering facility

Recent Mainz data (2014)

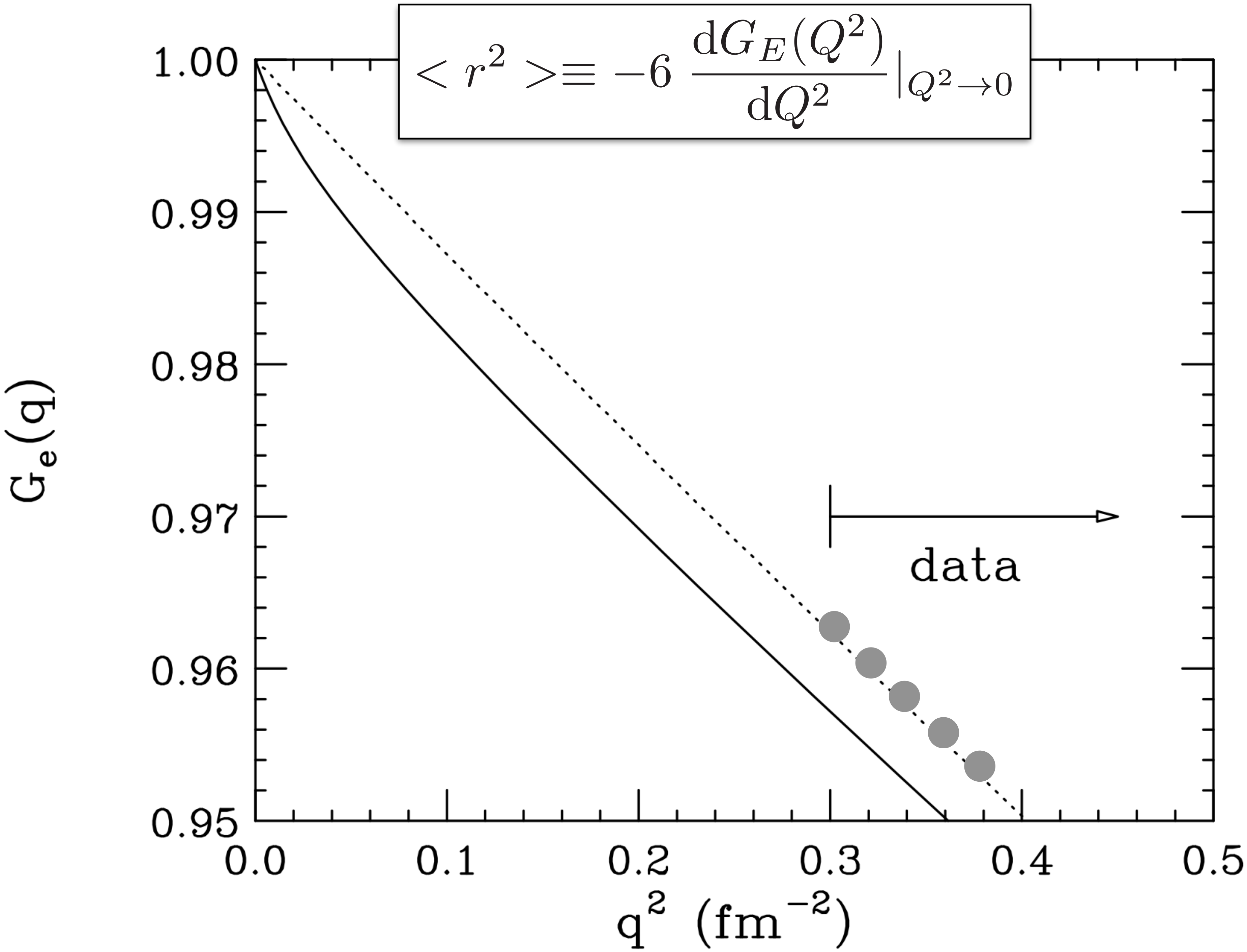


Mainz data (2014)

Ee = 180 - 855 MeV

problems	suggested
no “ultra-“ low Q^2 data	min. Ee = 180 MeV
no Rosenbluth separation	no frequent change of Ee
no absolute cross section	liq. H_2 target + spectrometer

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



I. Sick, Atoms 2018, 6, 2

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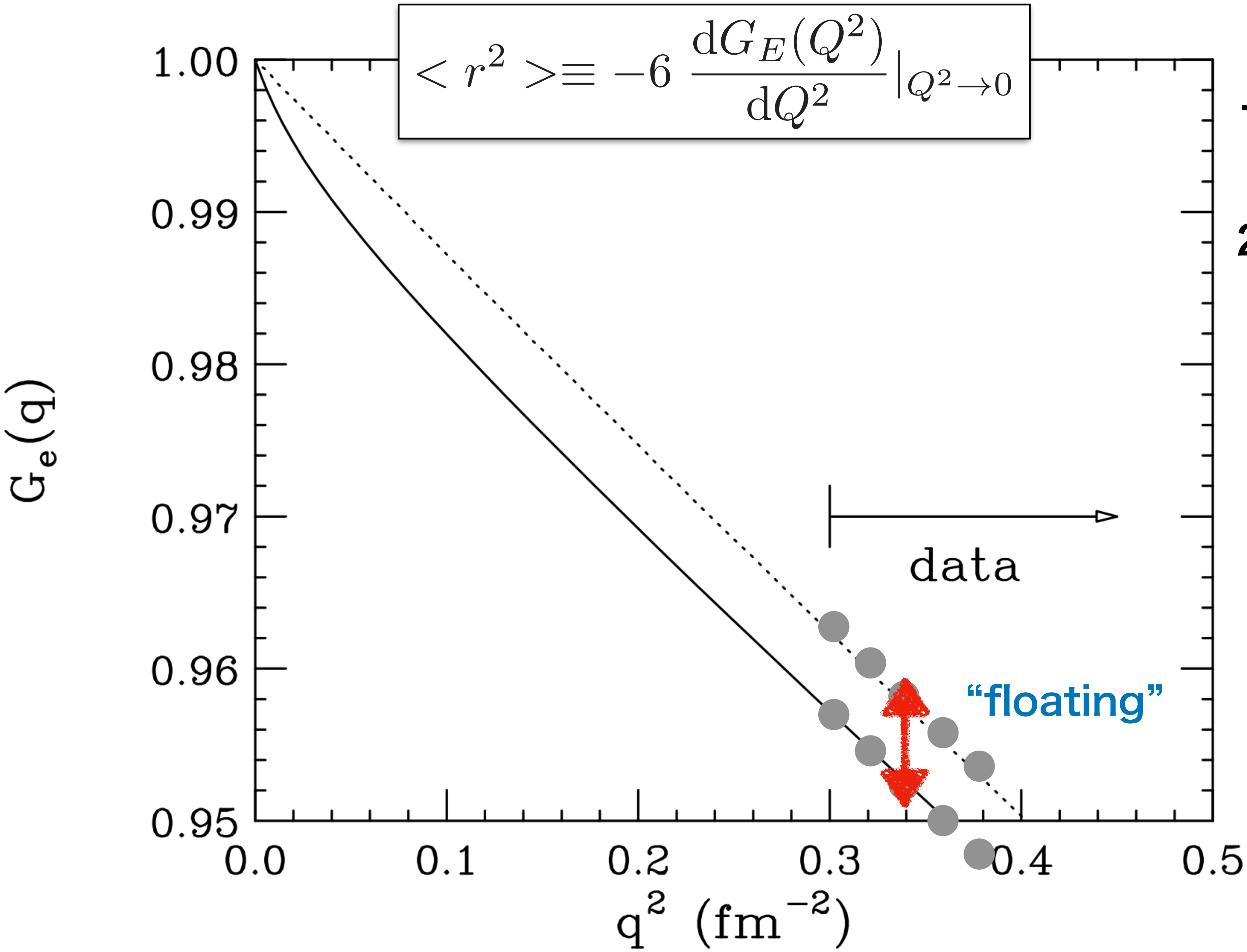


1) no absolute GE(Q2) ("floating")
2) χ^2 is similar for both

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

I. Sick, Atoms 2018, 6, 2

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) Rosenbluth-separated $G_E(Q^2)$

small-scale low-energy accelerator

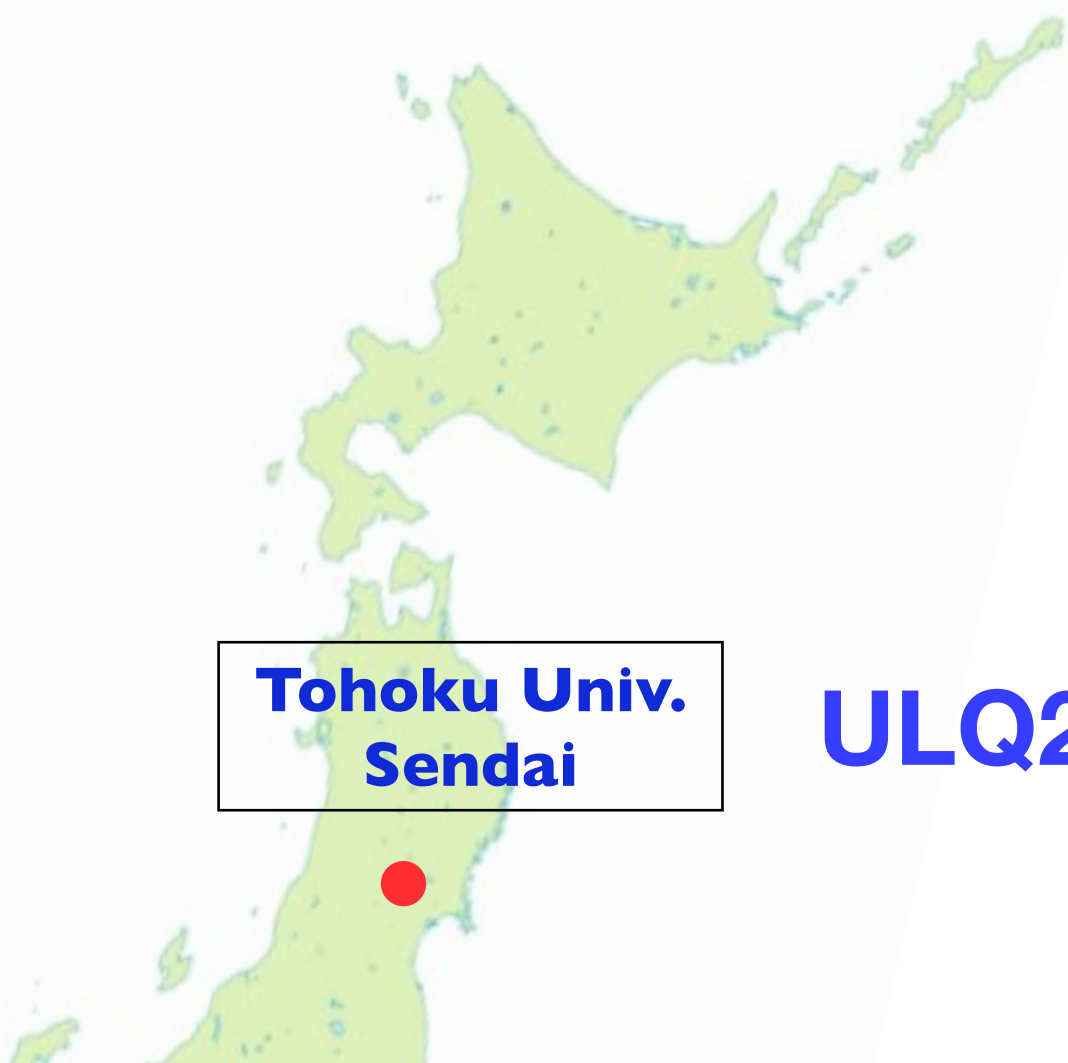
3) absolute cross section measurement with 10^{-3}

CH2 target

$\langle r_C^2 \rangle$ (ρ(r)) of 12C is best known with 10^{-3} accuracy

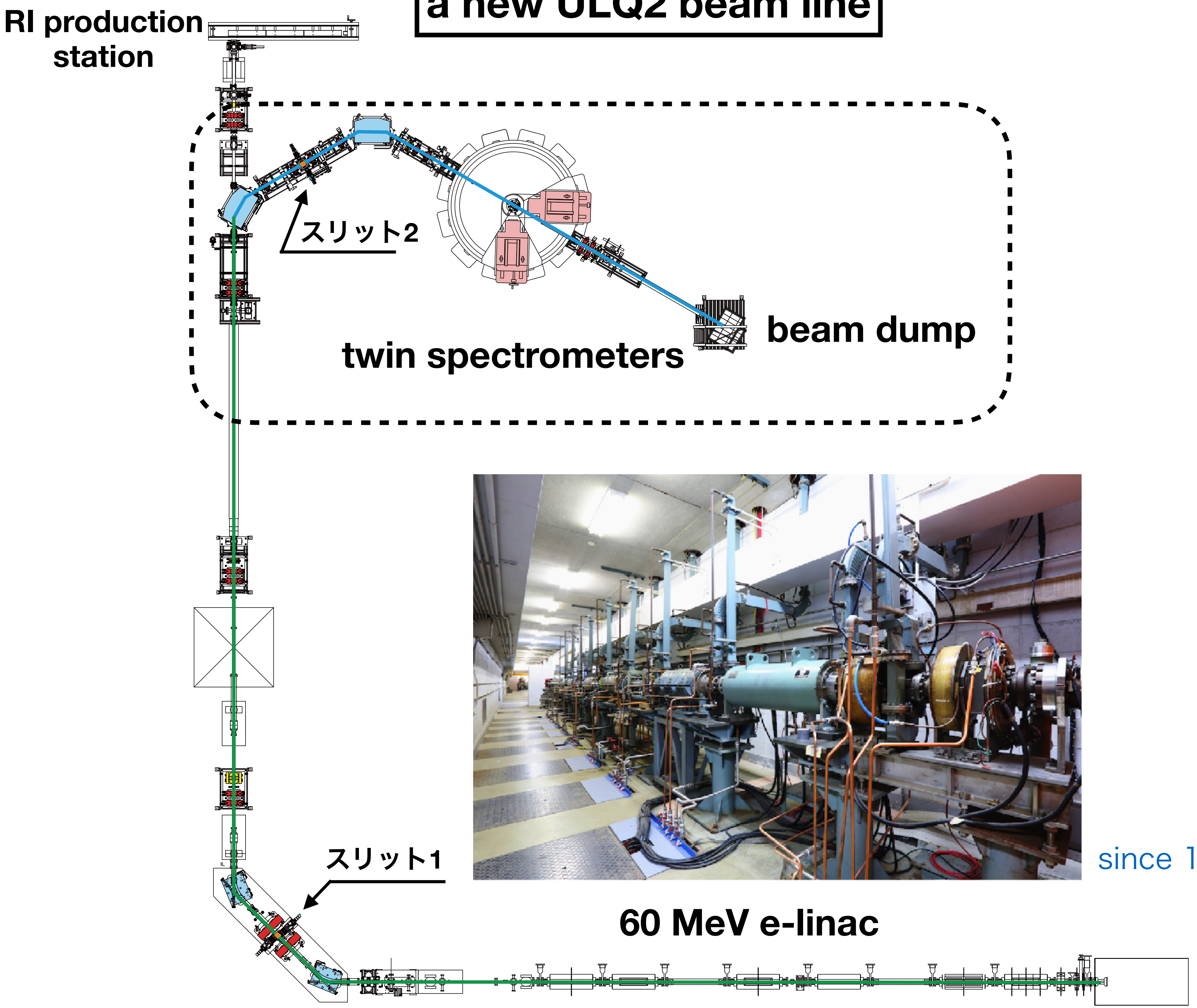
Tohoku ELPH is only facility for such measures

Research Center for Electron-Photon Science



ULQ2 : Ultra-Low Q2

a new ULQ2 beam line



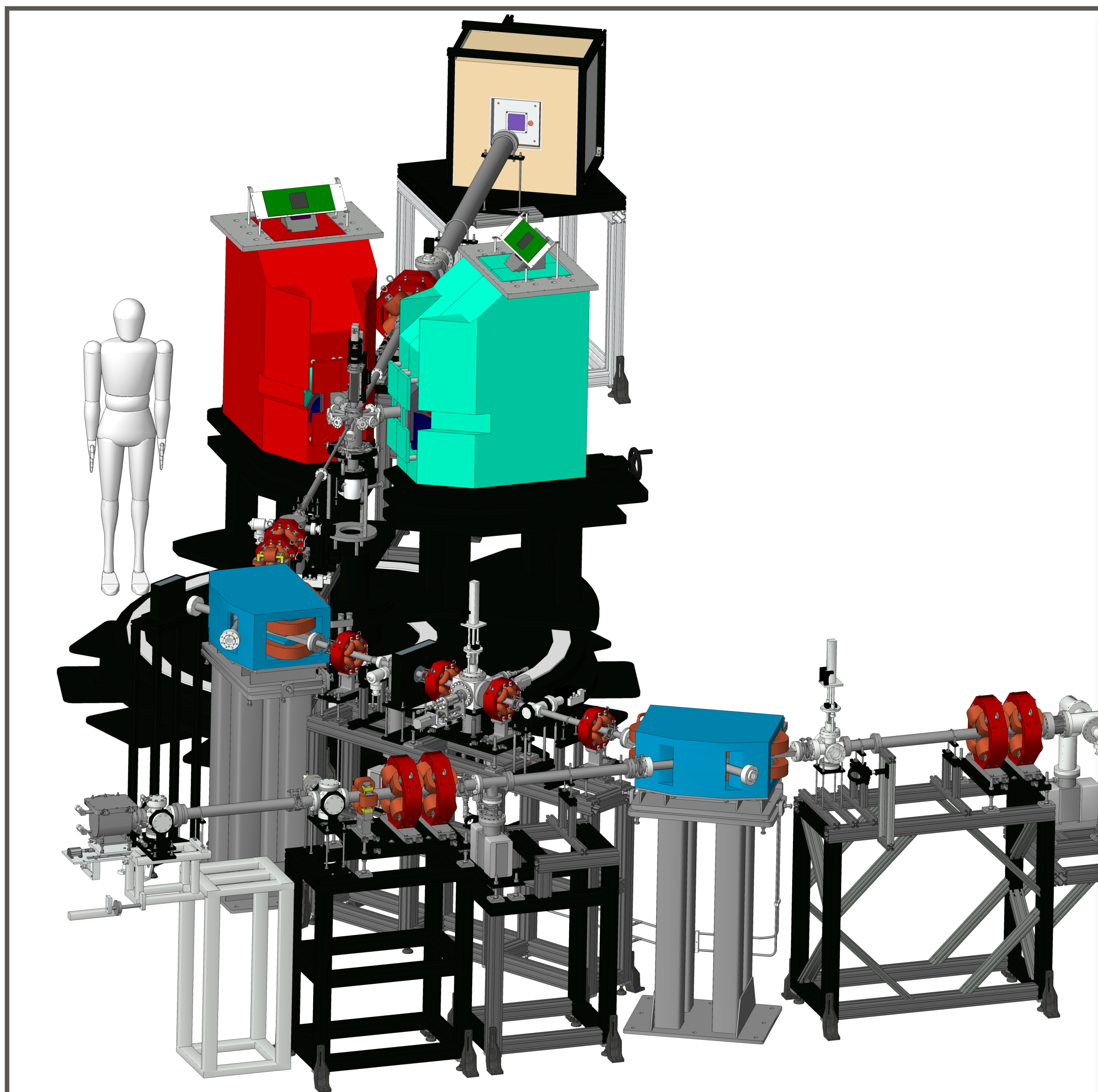
since 1967 -

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}

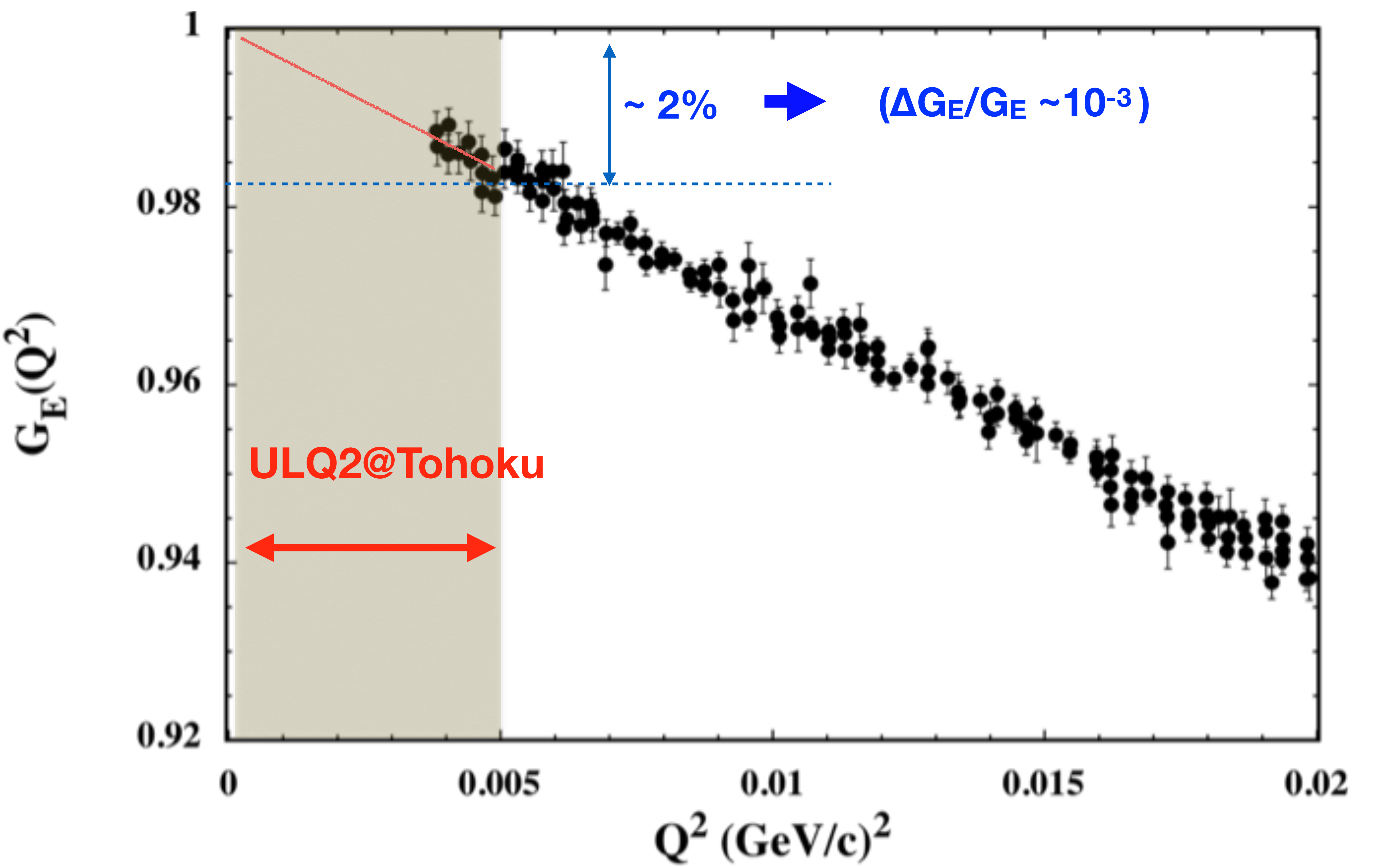
ULQ2 twin-spectrometer setup

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



A key of the e+p experiments at ULQ^2

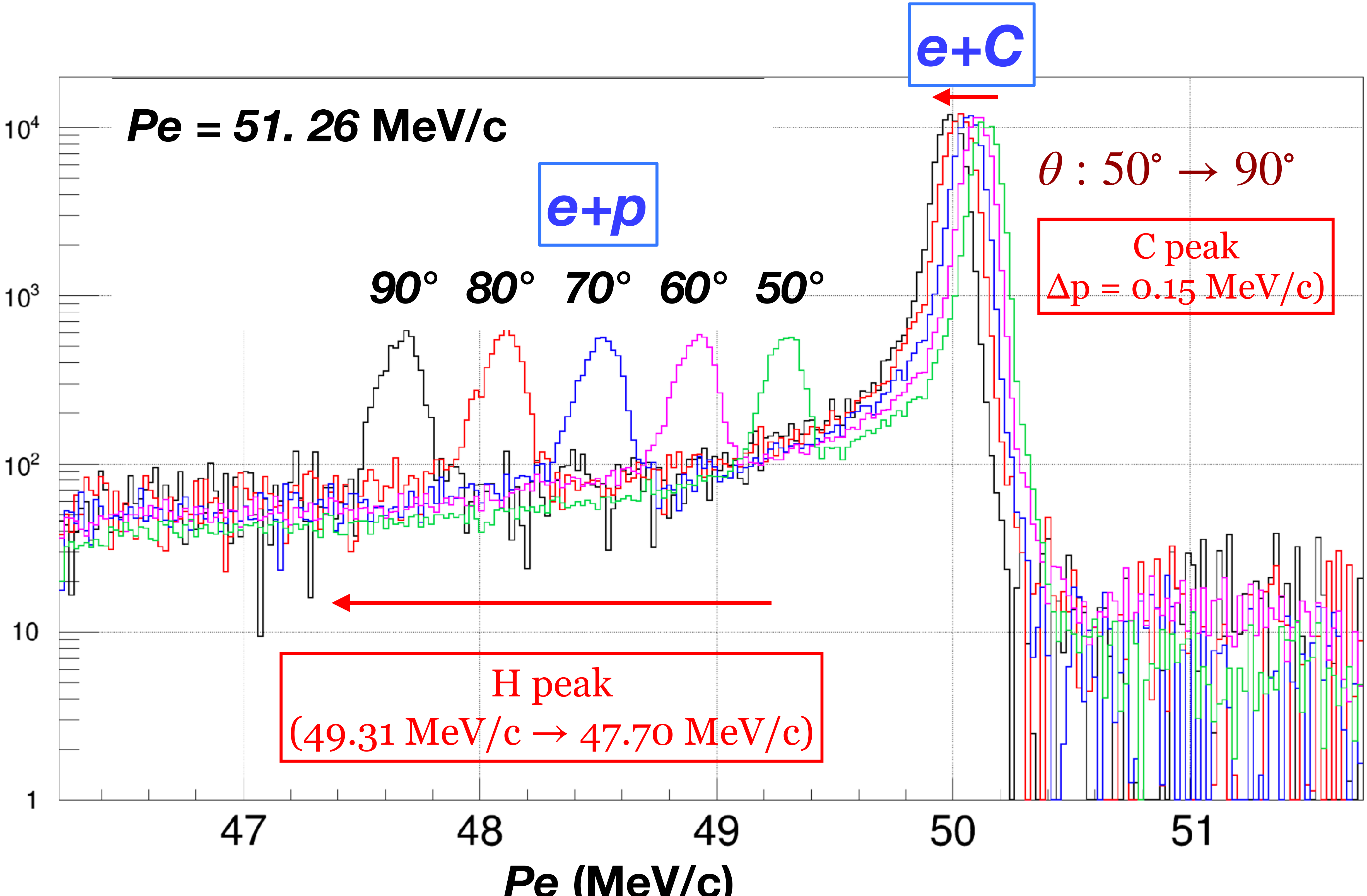
ULQ2 (Ultra-Low Q2)



Physics data production run just started

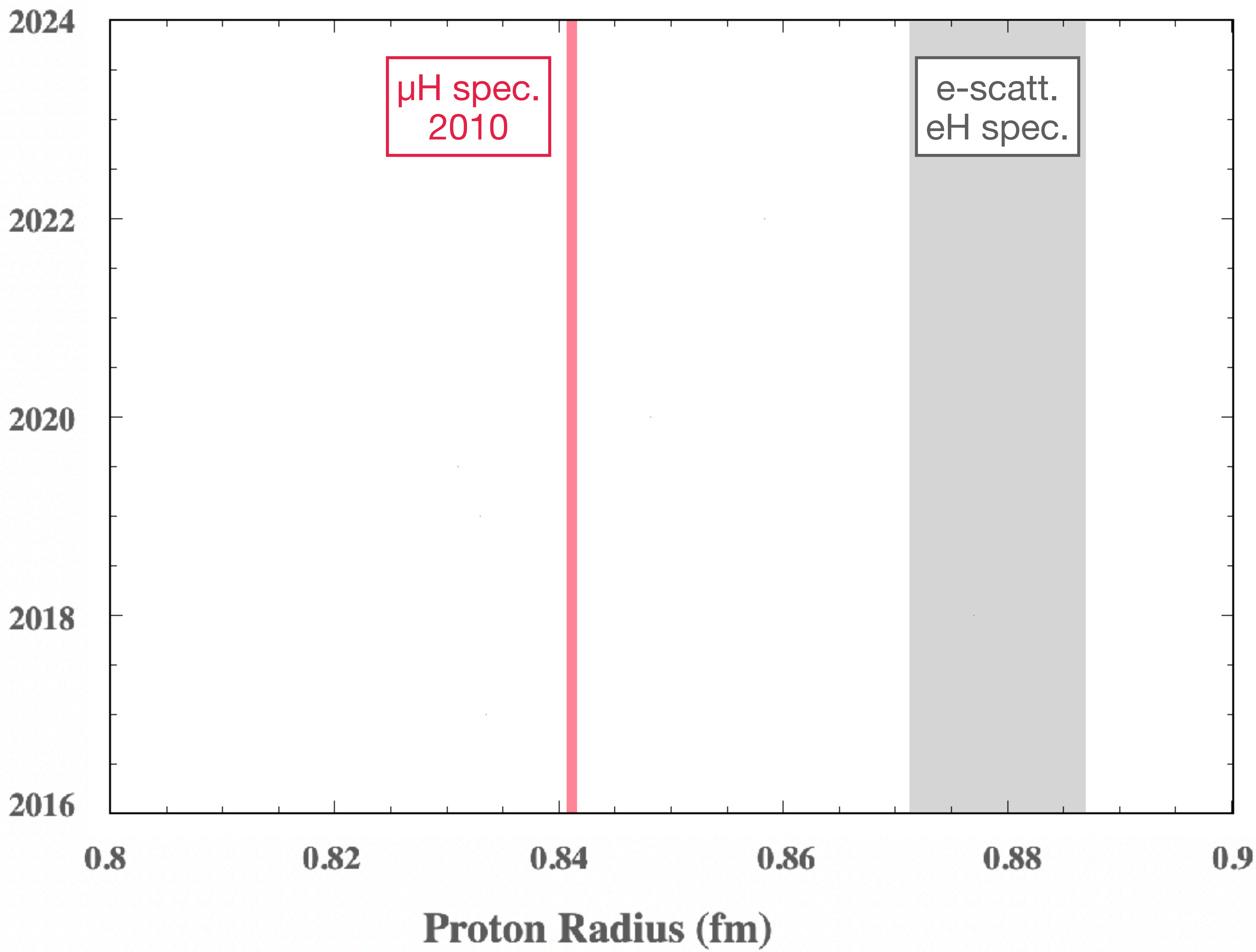
CH_2 target

relative measurement to well-known e+^{12}C scattering



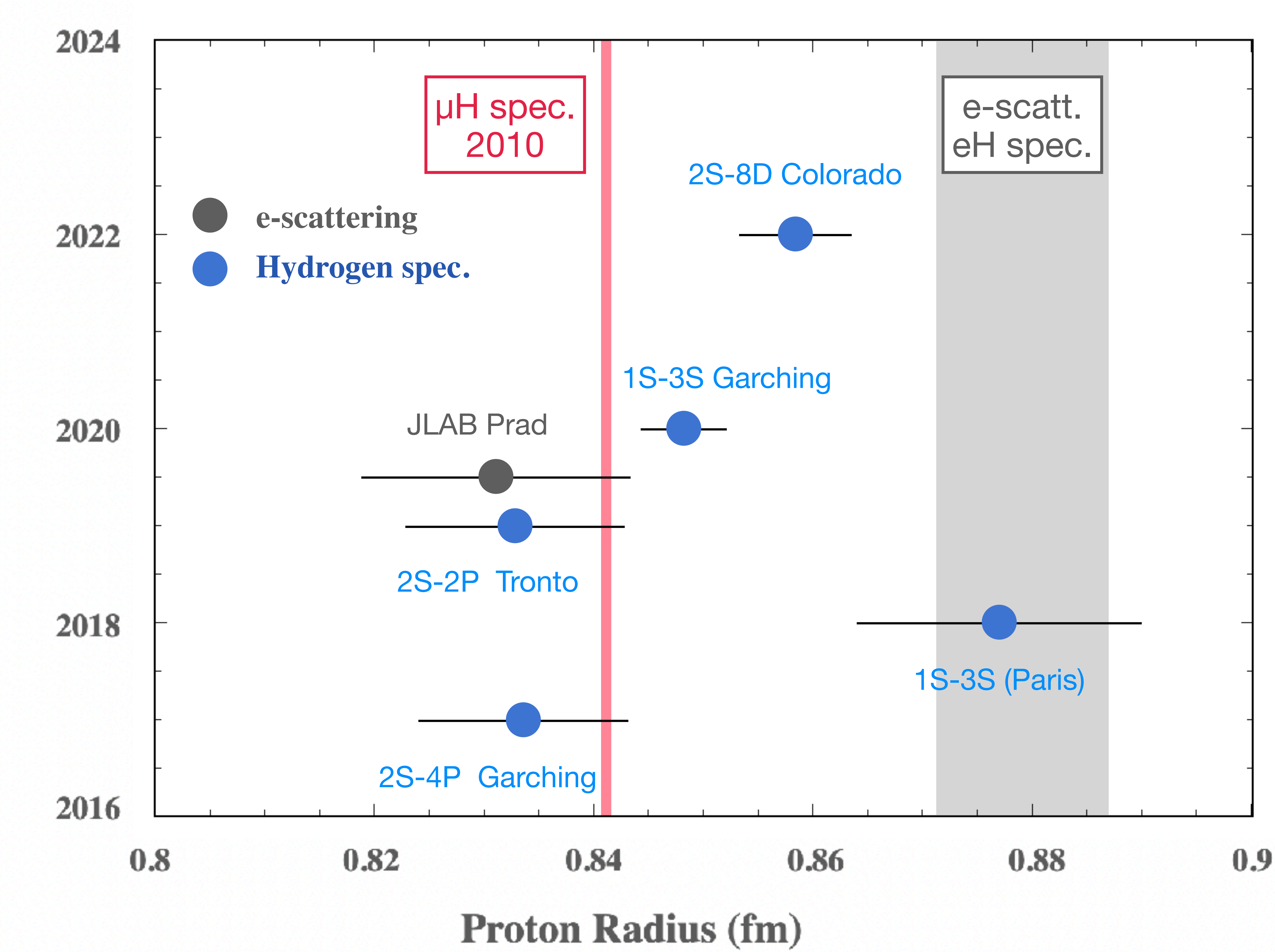
proton charge radius as of today

陽子半径グラフ2022_KGraph

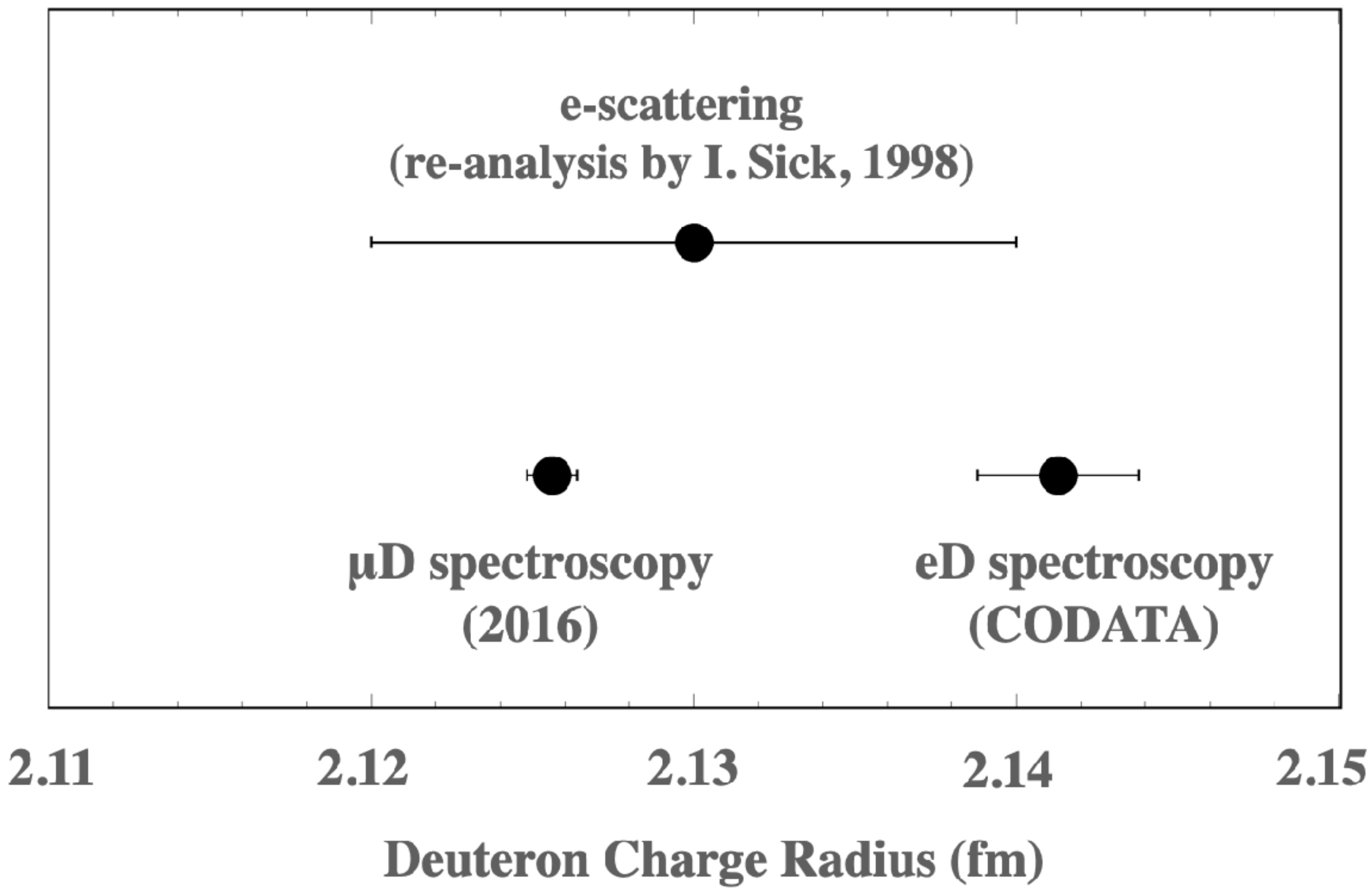


proton charge radius as of today

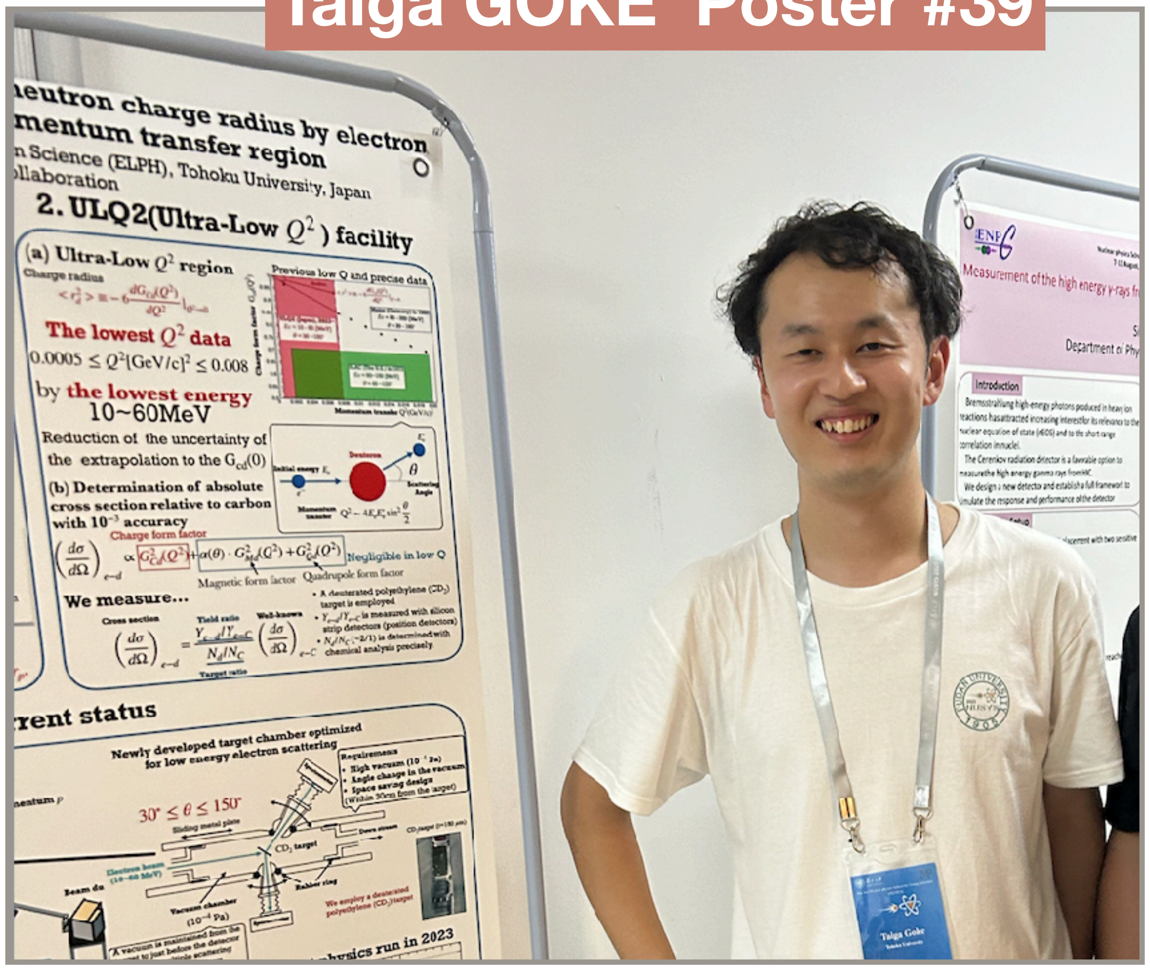
陽子半径グラフ2022_KGraph



Deuteron charge radius



Taiga GOKE Poster #39



1) *it provides important input for NN interaction*
2) *possible access to the neutron charge radius*

$$< r_d^2 > = r_{str}^2 + r_p^2 + r_n^2 + 3/4m_p^2$$

charge radius | str. radius | Proton | Neutron | Foldy-Darwin + spin-orbit

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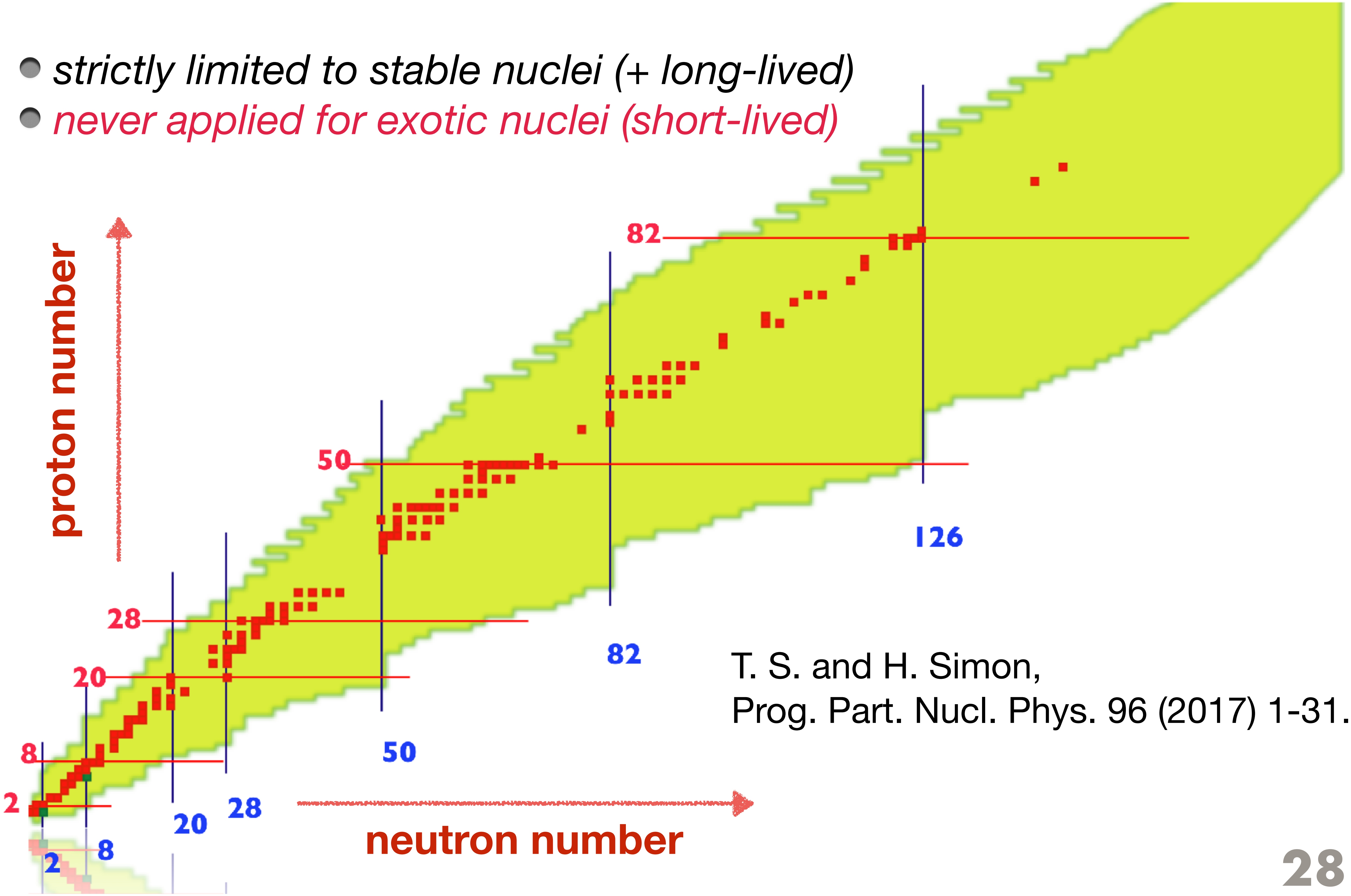
Q^2 = 0.006 - 0.09 $(\mathrm{GeV}/c)^2$

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.

papers on e-scattering of exotic nuclei

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

Handbook of Nuclear Physics (2023)
T. Suda

Progress in Particle and Nuclear Physics 96 (2017) 1–31

Contents lists available at ScienceDirect

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Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Prospects for electron scattering on unstable, exotic nuclei

CrossMark

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ABSTRACT

Electron scattering off radioactive ions becomes feasible for the first time due to advances in storage ring and trapping techniques in conjunction with intense secondary beams from novel beam facilities. Using a point-like purely leptonic probe enables the investigation of charge distributions and electromagnetic excitations in β-unstable exotic nuclei with an enhanced overshoot in proton and neutron numbers and the use of QED, one of the most precisely studied theories, for describing the scattering process.

LIVE
Handbook of Nuclear Physics

Handbook of Nuclear Physics pp 1–24 | Cite as

Home › Handbook of Nuclear Physics › Living reference work entry

Electron Scattering Off Stable and Unstable Nuclei

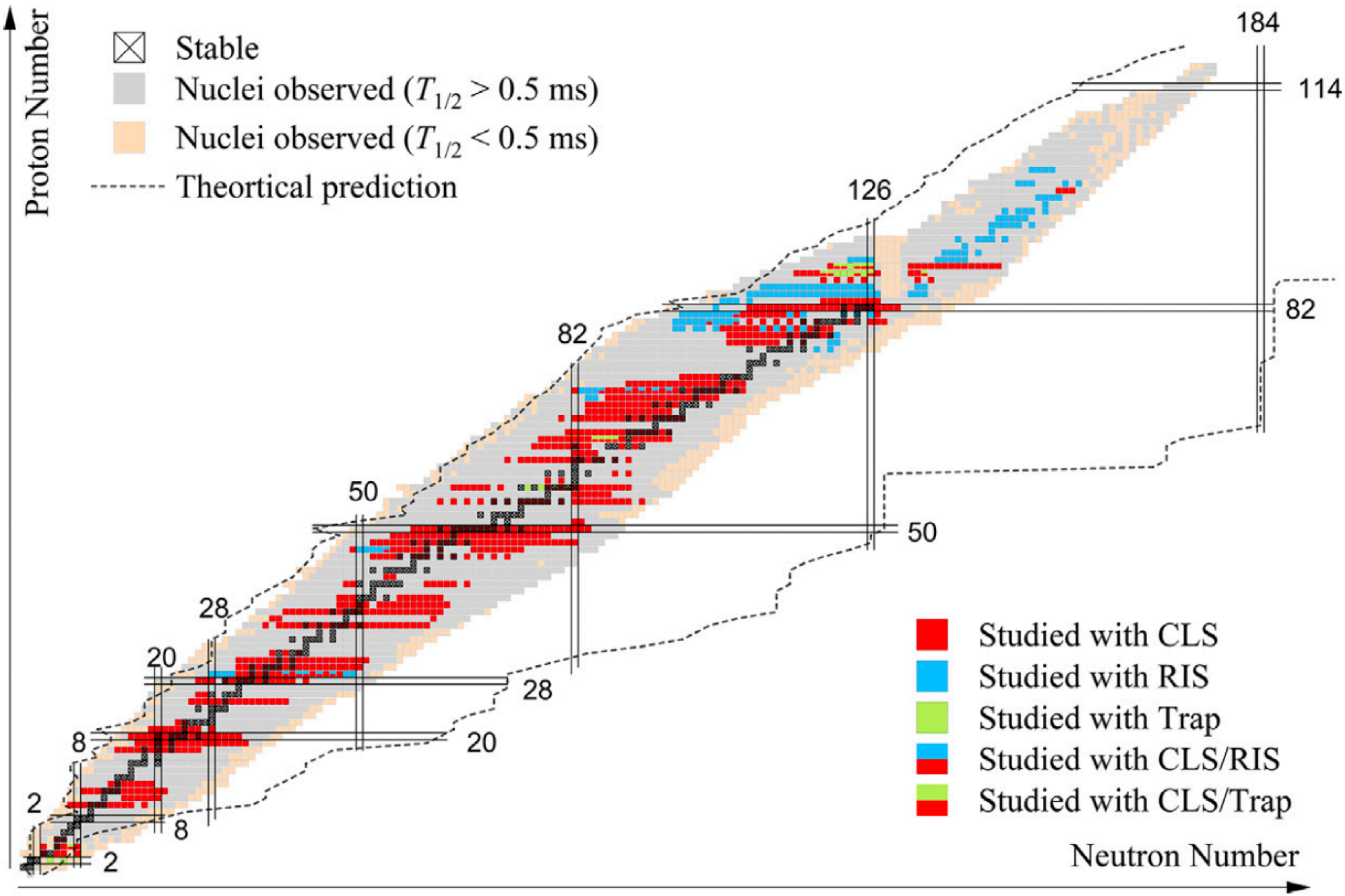
Toshimi Suda

Living reference work entry First Online: 10 September 2022

Abstract

Electron scattering is one of the experimental tools used to study the internal structures of atomic nuclei, playing an essential role in revealing their detailed structure and establishing modern pictures of nuclear structures. This chapter first reviews the research on the nuclear structure using electron scattering carried out to date, wherein the targeted nuclei were strictly limited to stable nuclei, while no electron scattering has yet been conducted for short-lived nuclei. However, following long-term efforts, electron scattering for such unstable nuclei is about to becom スクリーンショット the world's first electron

charge radii of nuclei including exotic



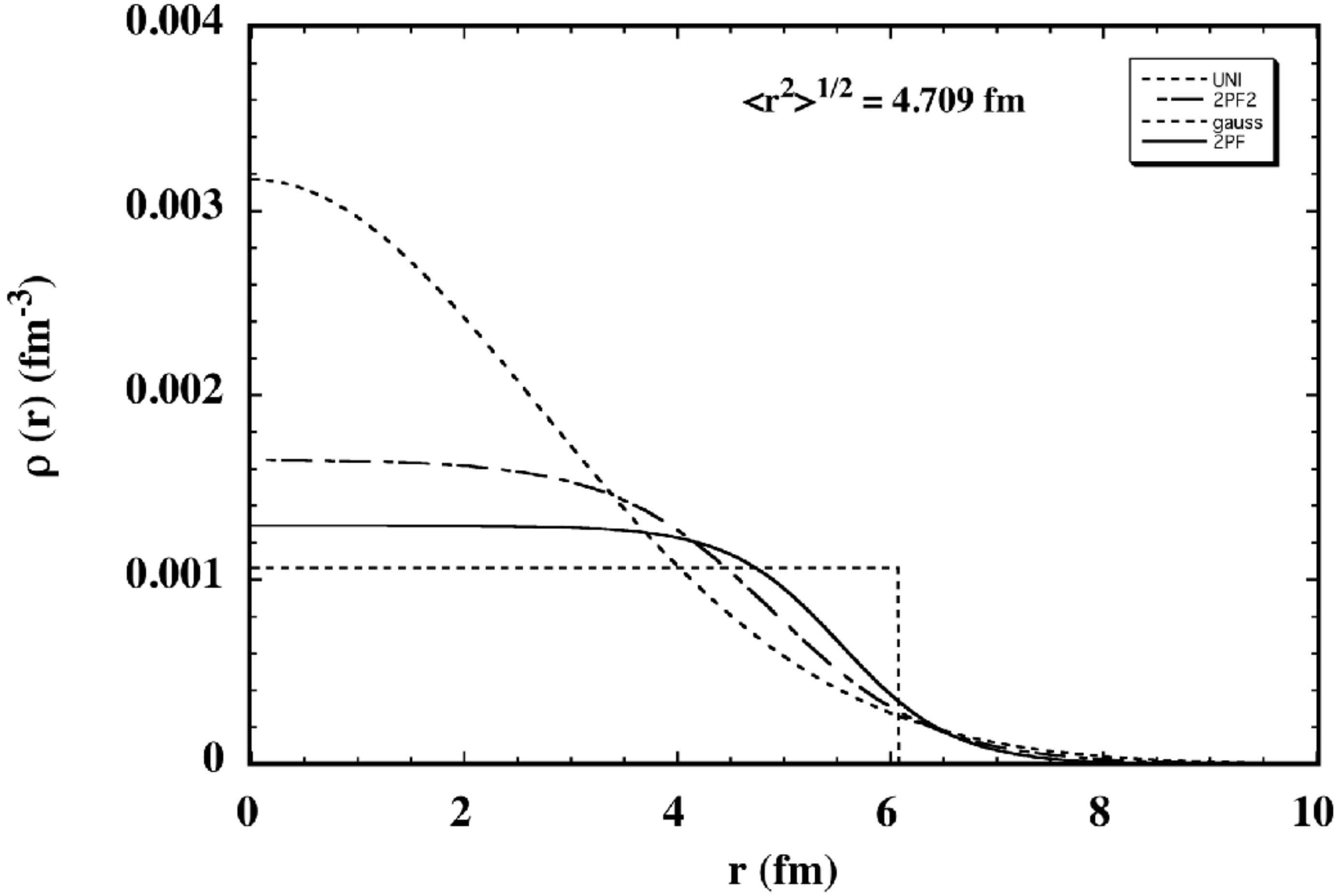
X. F. Yang et al, PPNP 129 (2023) 104005.

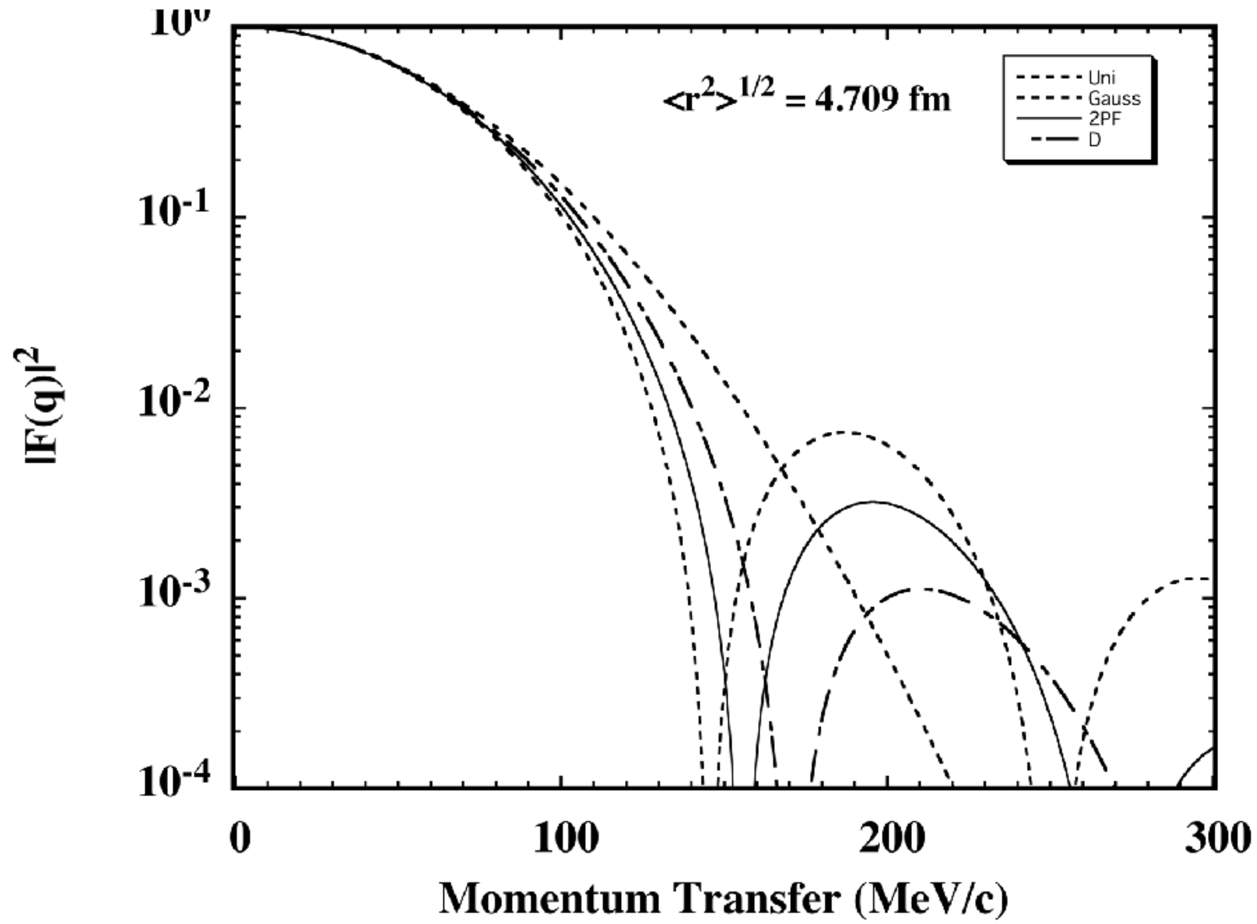
charge density $$\rho_c(\vec{r}) = \sum_p \psi^*(\vec{r})\psi(\vec{r})$$

charge radius $$< r_c^2 >= \int r^2 \rho_c(r)\ d\vec{r}$$

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

Density distributions having the same charge radius (4.7 fm)





e-scattering off short-lived exotic nuclei

R. Hofstadter
1961 Nobel Prize

"Hofstadter's experiments for exotic nuclei"

low production rate short half lives	⇨	no "thick" target
expected low luminosity	⇨	elastic scattering (largest σ)

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

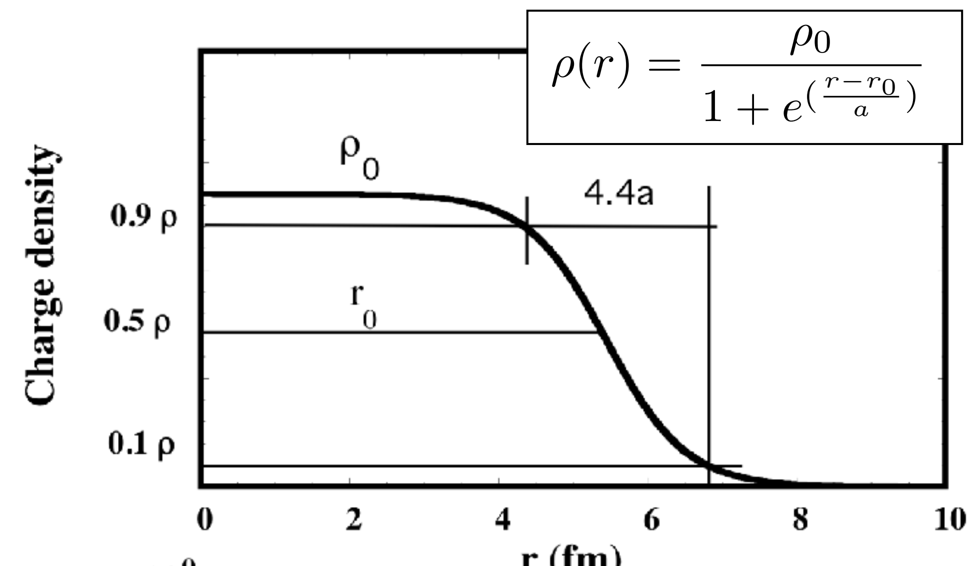
Elastic Scattering for spinless nuclei

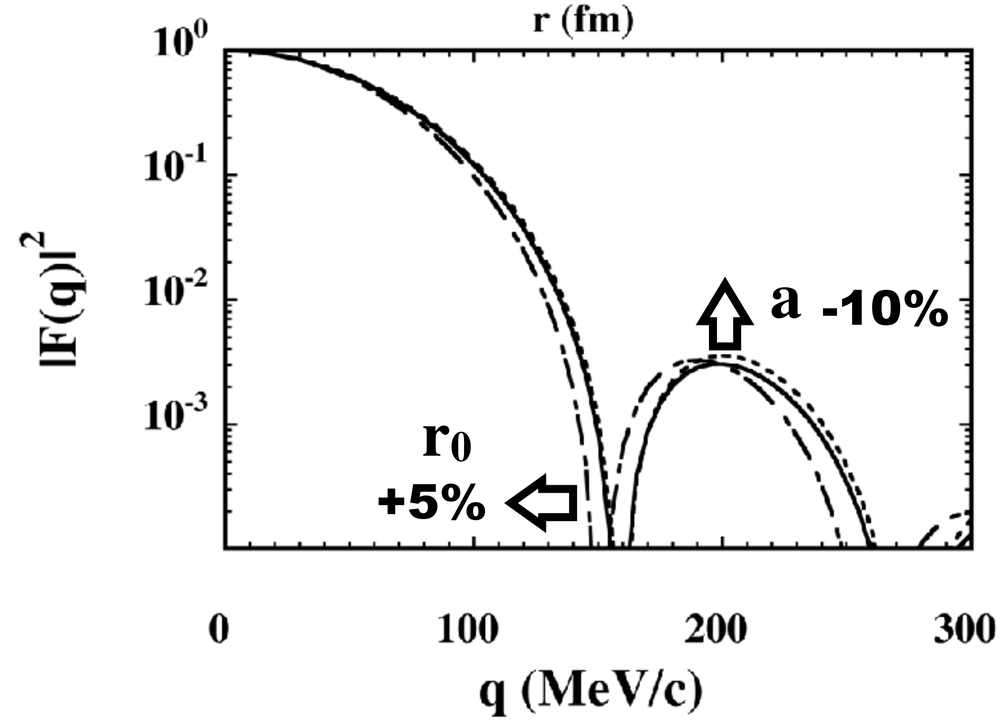
PWIA

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

$$\frac{\mathrm{d}\sigma_{\mathrm{Mott}}}{\mathrm{d}\Omega} = \frac{z^2\alpha^2}{4e^2}\ \frac{\cos^2\theta}{\sin^4\theta}.$$

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

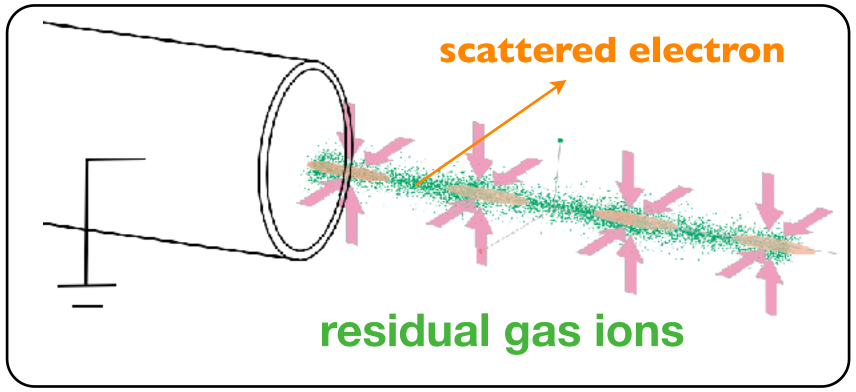




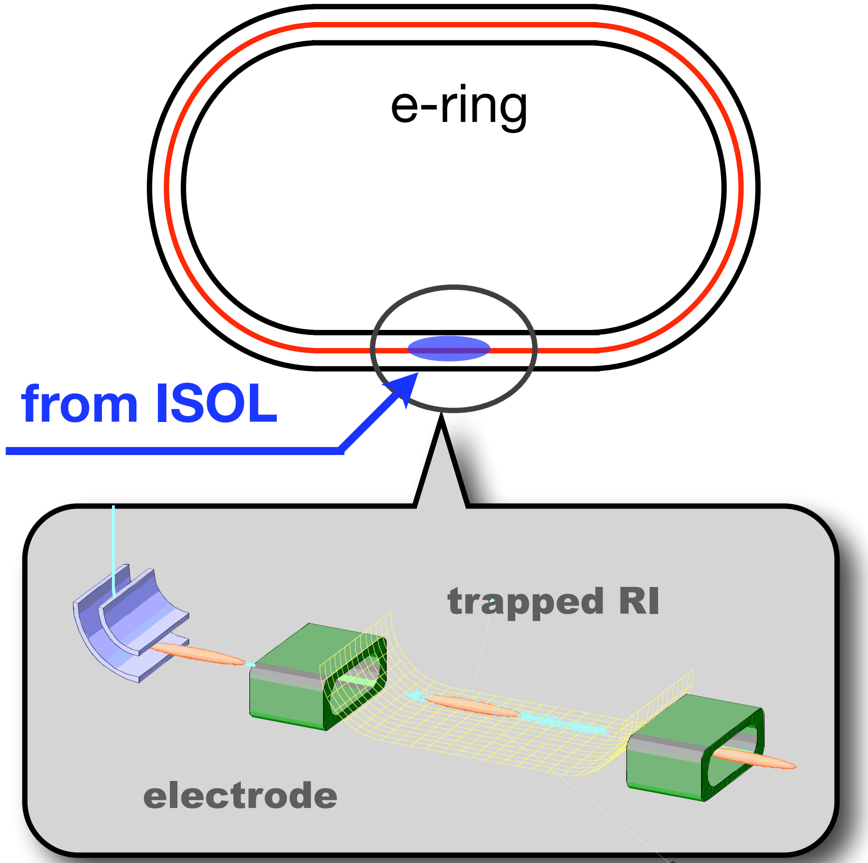
SCRIT (Self-Confining RI Ion Target)

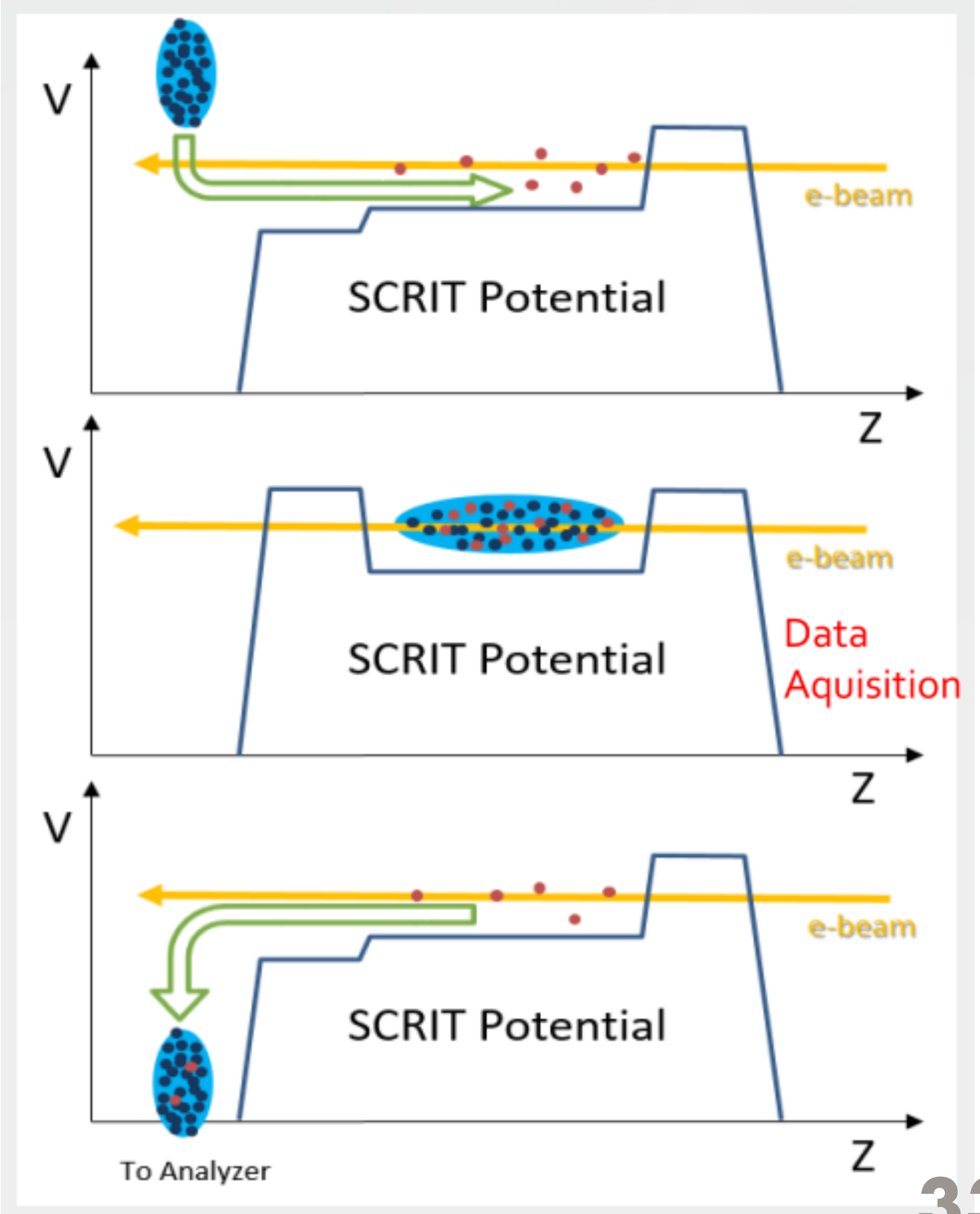
Idea : "ion trapping" at SR facilities.

ionized residual gases are trapped by the circulating electron beam



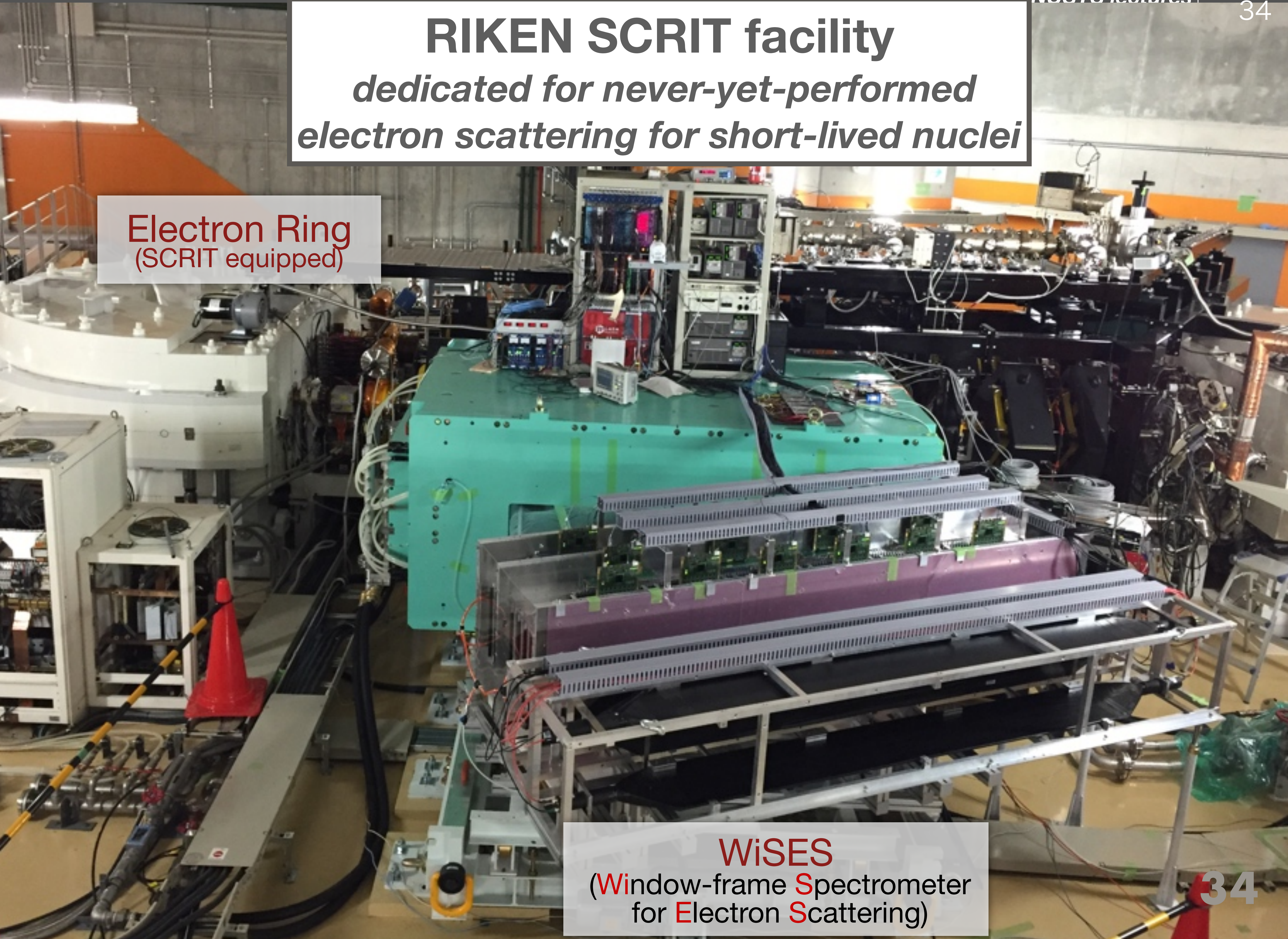
ill problem of e-storage rings



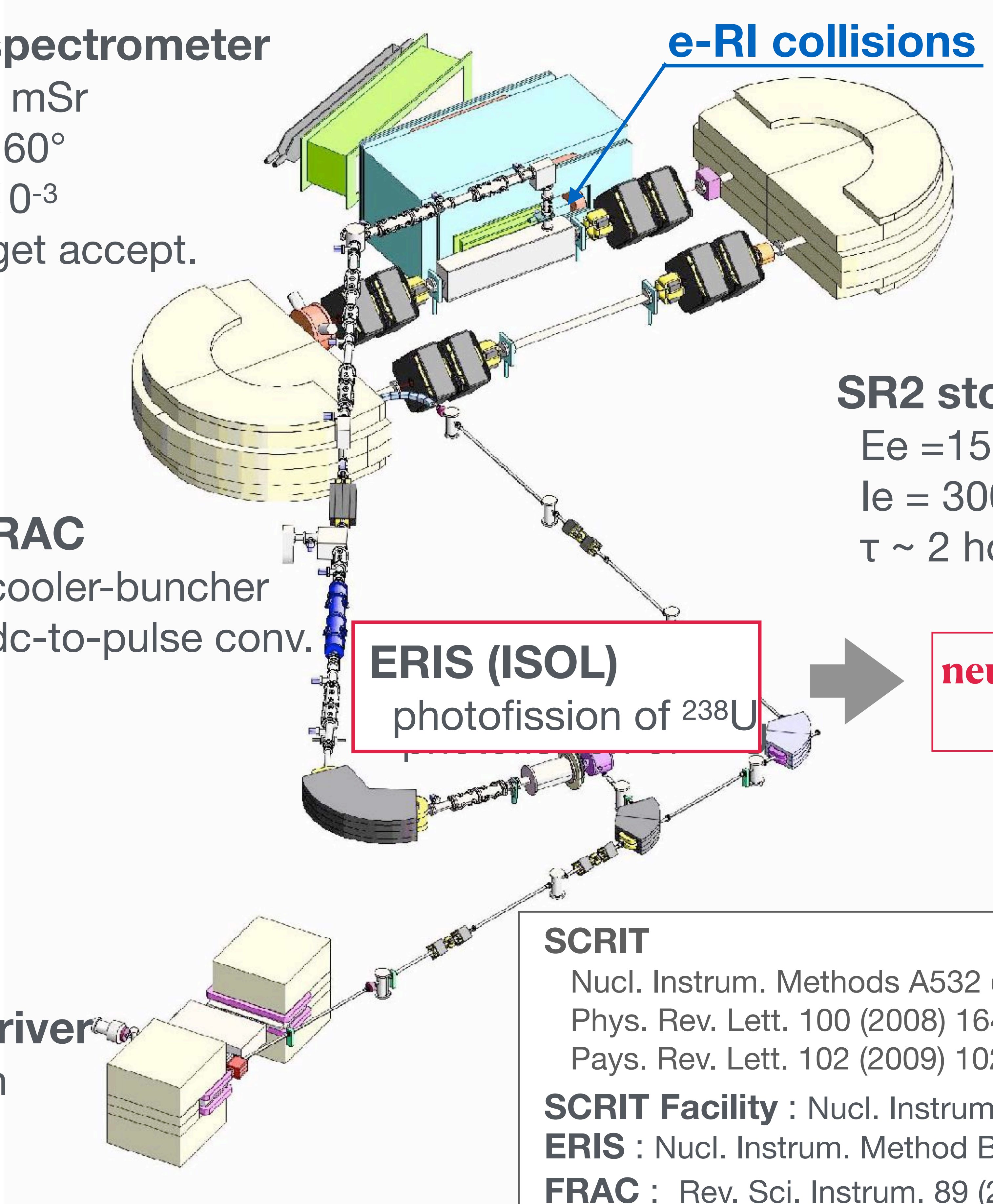


RIKEN SCRIT facility

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



RIKEN SCRIT Electron Scattering Facility



WiSES spectrometer
$\Delta\Omega$ ~ 90 mSr
θ = 30 - 60°
$\Delta p/p$ ~ 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 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.

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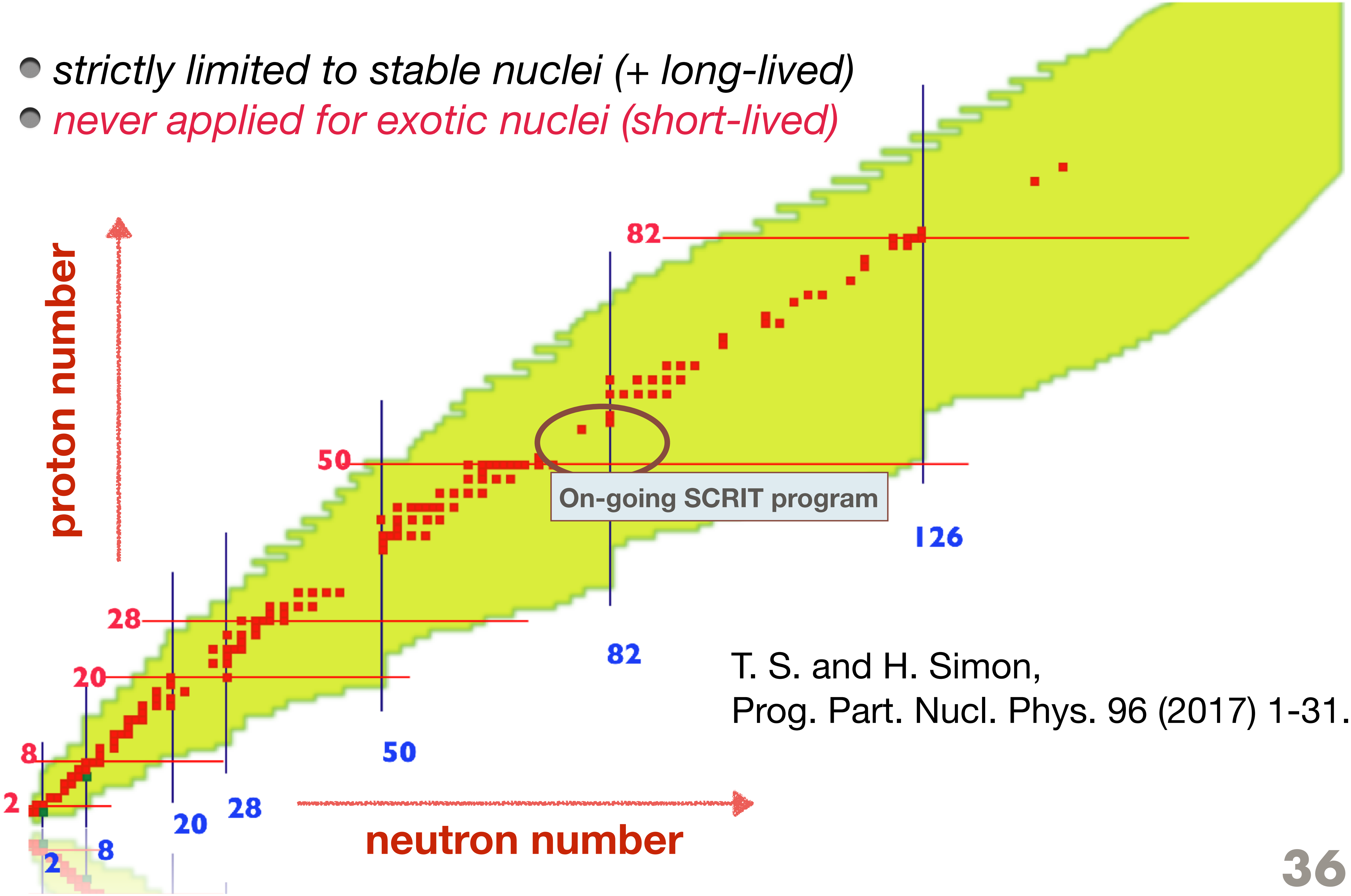
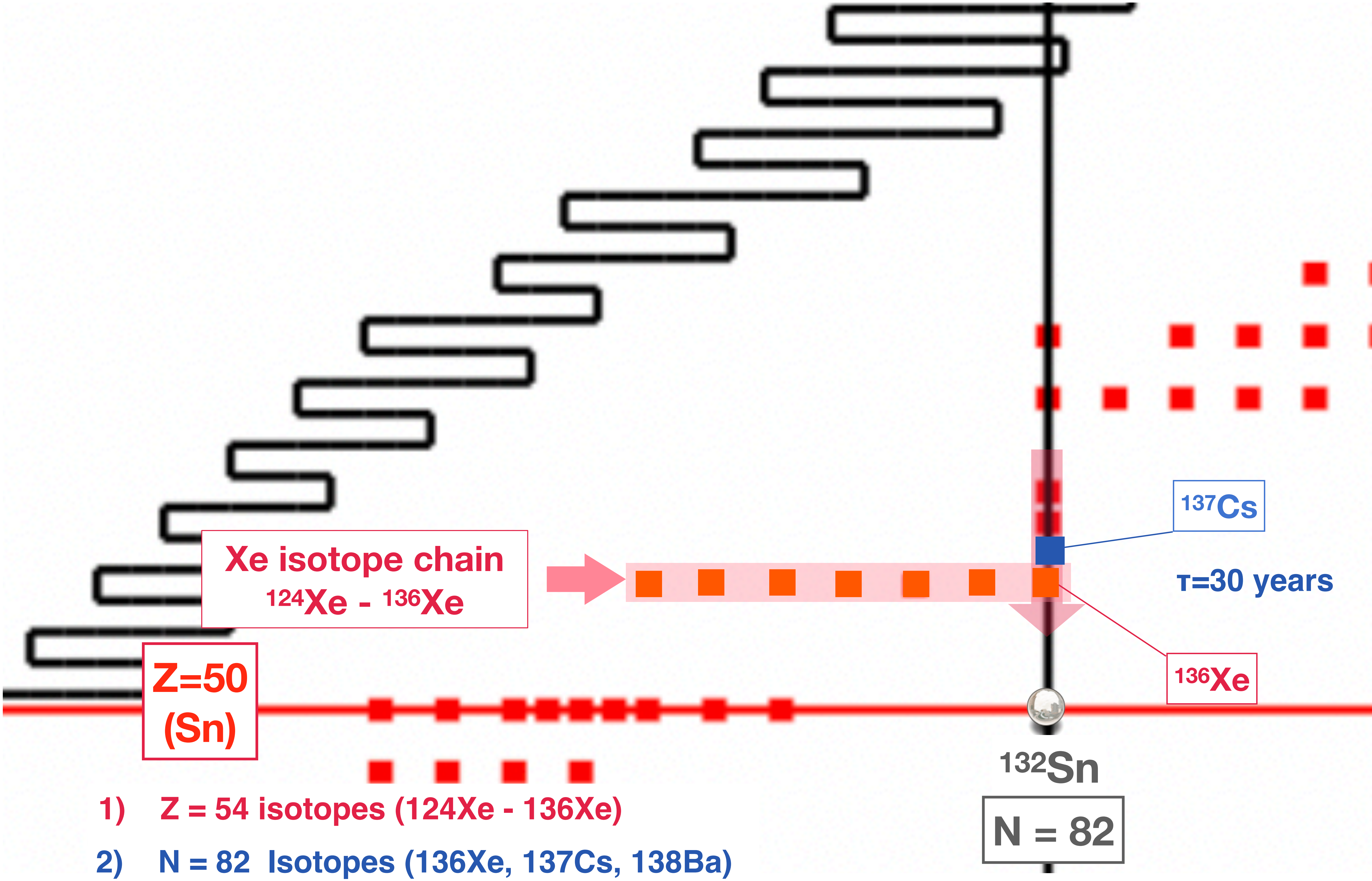
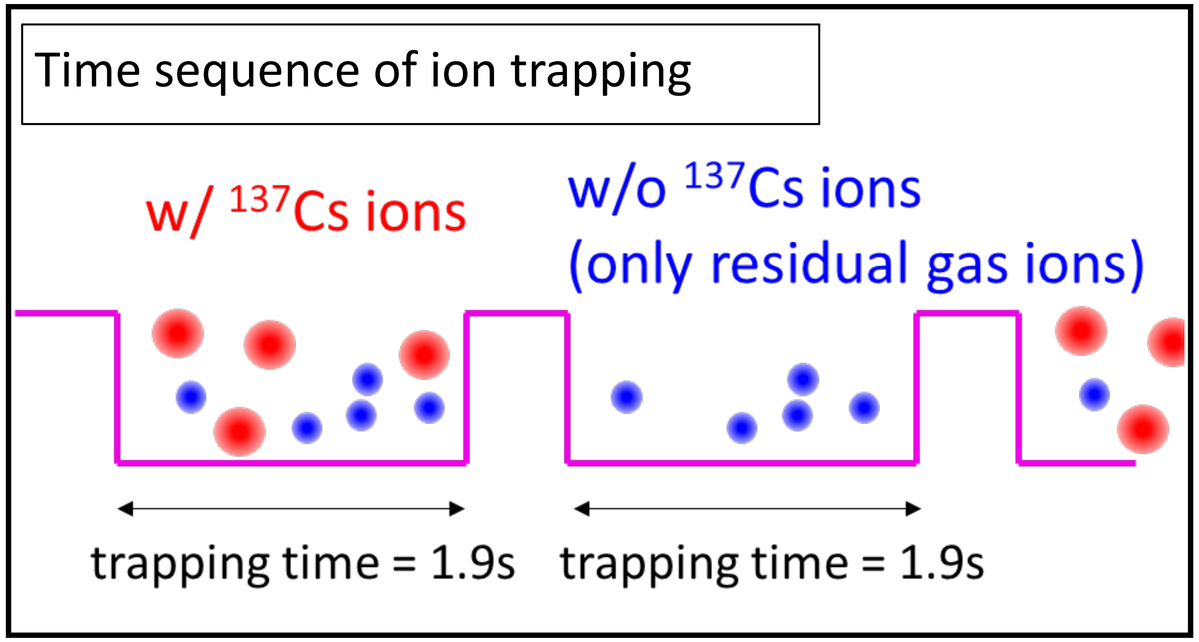
- *strictly limited to stable nuclei (+ long-lived)*
- *never applied for exotic nuclei (short-lived)*



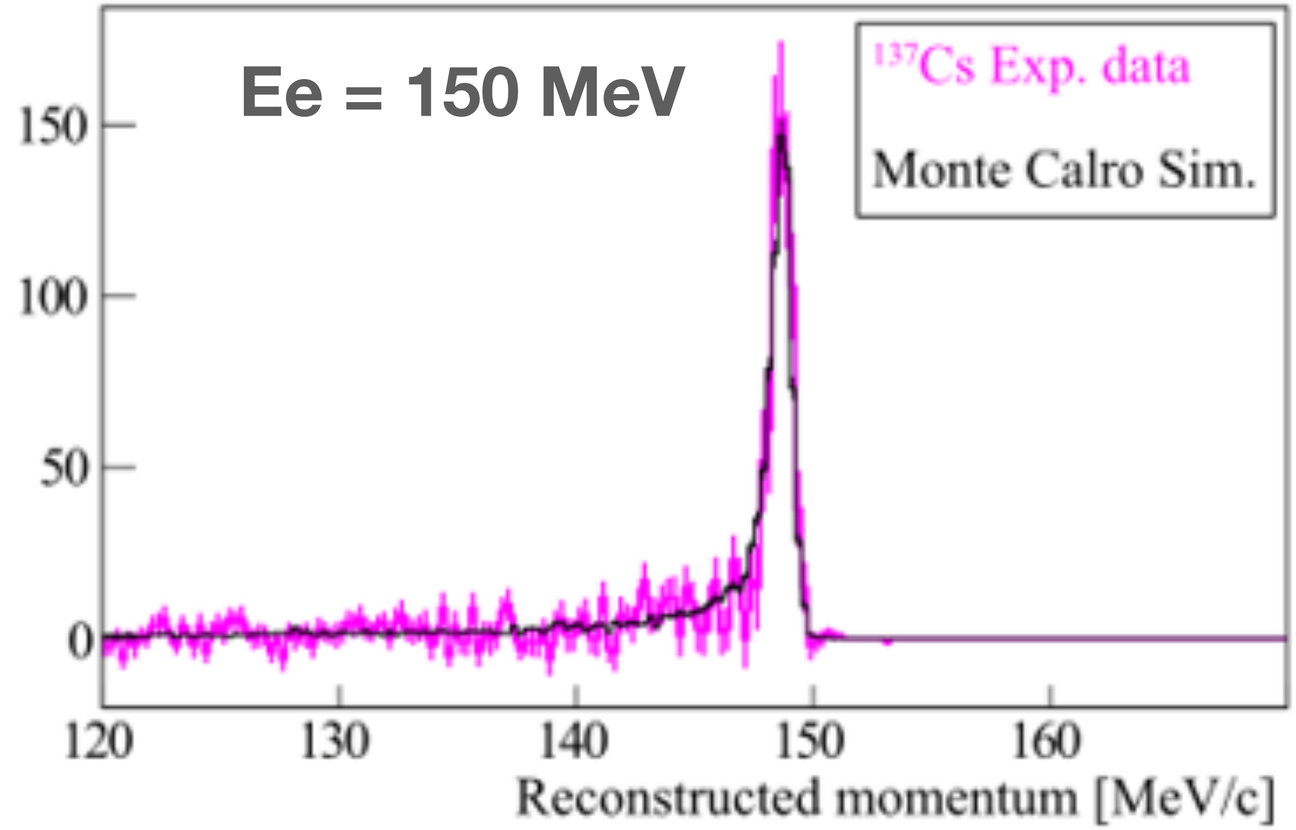
T. S. and H. Simon,
Prog. Part. Nucl. Phys. 96 (2017) 1-31.



1) Z = 54 isotopes (124Xe - 136Xe)
2) N = 82 Isotopes (136Xe, 137Cs, 138Ba)

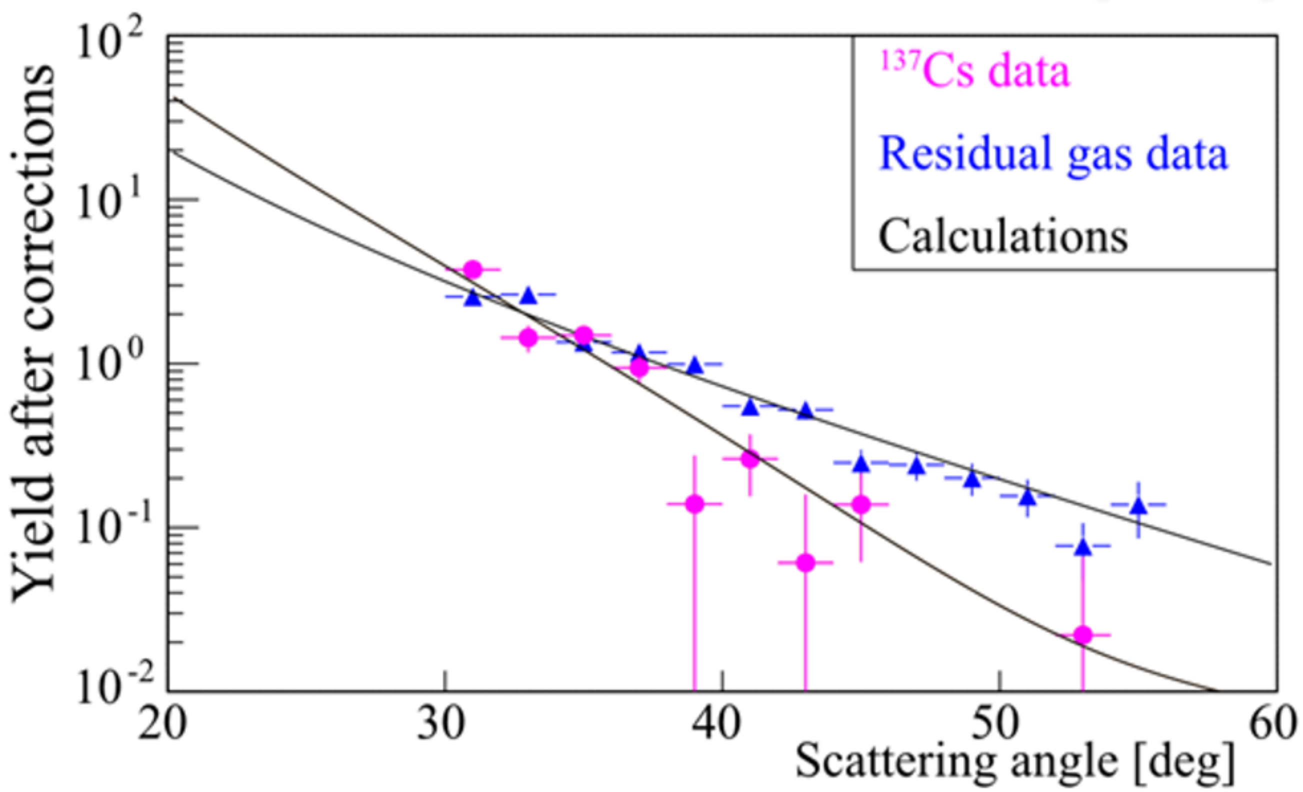


^{137}Cs(e,e')



$N_{trapped}$ ~ 2 x10^7

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



successful demonstration for online-produced unstable nuclei

1.9 s trapping

mimicking production-hard & short-lived nuclei

world's first e-scattering off online-produced exotic nucleus at the SCRIT facility

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, Japan*
[4]*Research Center for Electron Photon Science, Tohoku University, Sendai, Miyagi 982-0826, Japan*

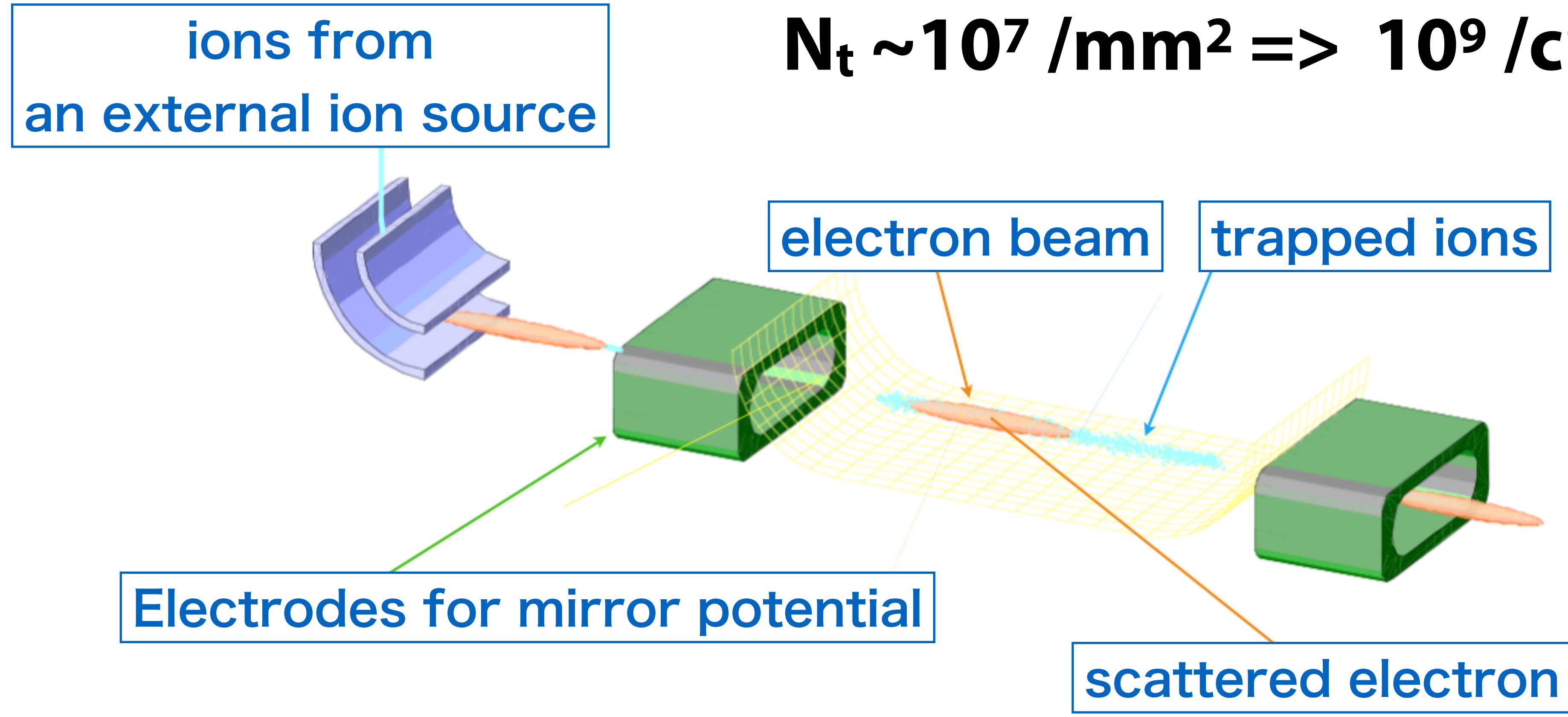
(Dated: June 16, 2023)

We successfully performed electron scattering off unstable nuclei which were produced online from the photofission of uranium. The target ^{137}Cs ions were trapped with a new target-forming technique that makes a high-density stationary target from a small number of ions by confining them in an electron storage ring. After developments of target generation and transportation systems, and the beam stacking method to increase the ion beam intensity up to approximately 2×10^7 ions/pulse beam, an average luminosity of 0.9×10^{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.

to be appeared in PRL during August

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

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

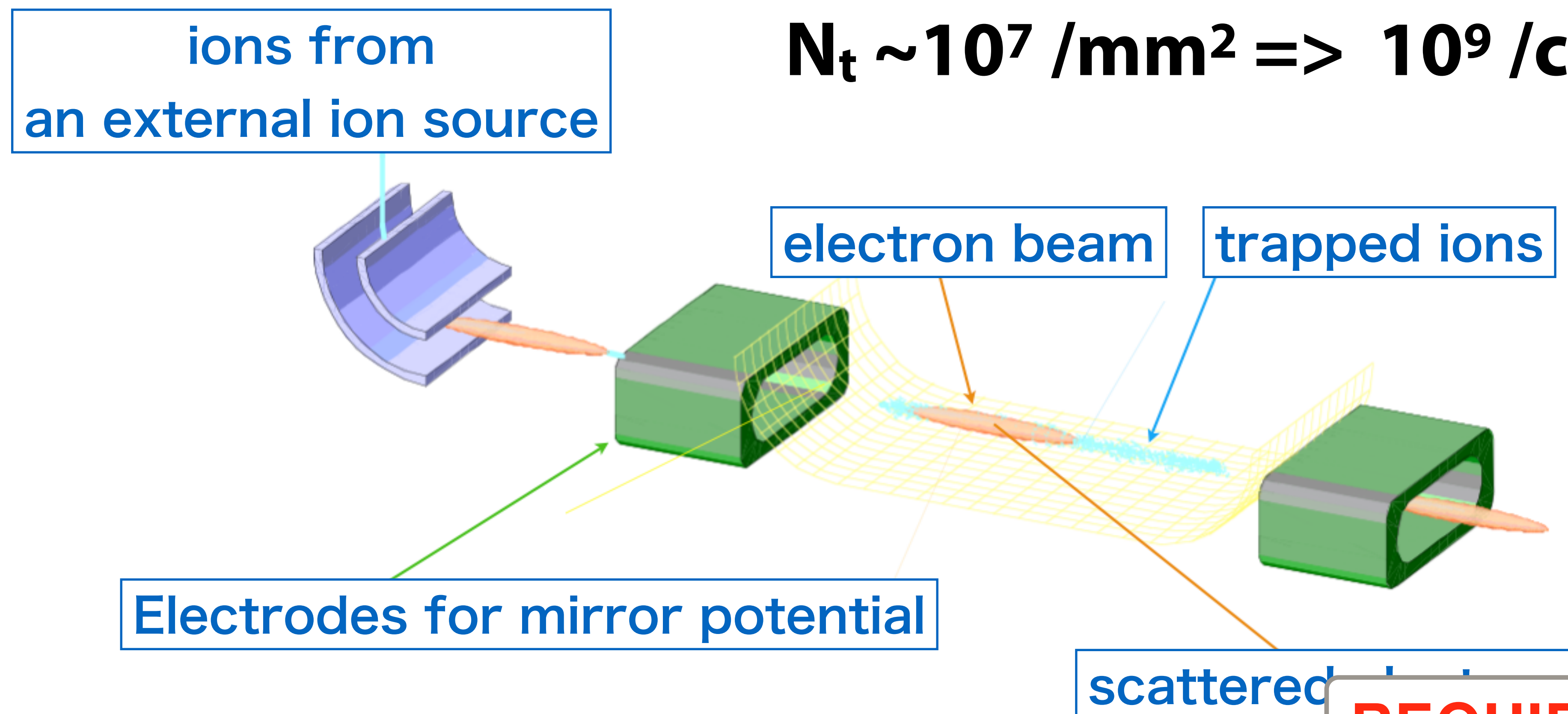


	Ee	N_{beam}	ρ・t	L
Hofstadter's era (1950s)	150 MeV	~ 1nA (~10^9 /s)	~10^{19} /cm^2	~10^{28} /cm^2/s
JLAB	6 GeV	~100μA (~10^{14} /s)	~10^{22} /cm2	~10^{36} /cm^2/s
SCRIT	**150 - 300 MeV**	**~200 mA (~10^{18} /s)**	**~ 10^9 /cm^2**	**~10^{27} /cm^2/s**

Luminosities

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

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



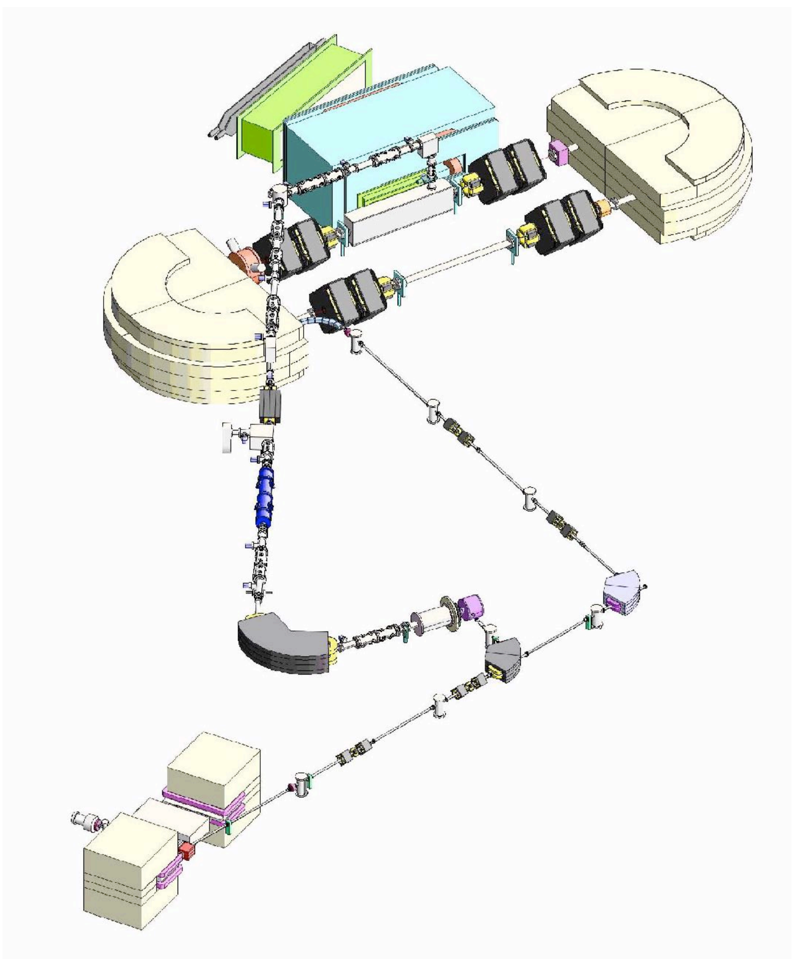
REQUIRED TARGET THICKNESS 10^{-10}!!!

	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**

in operation

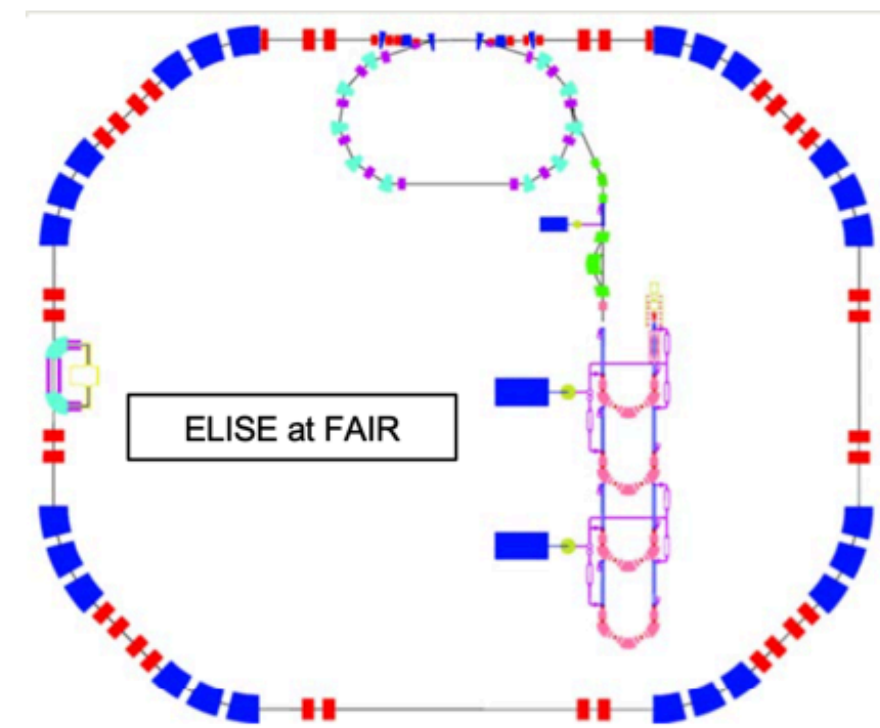
RIKEN SCRIT

Ee = 150 - 300 MeV

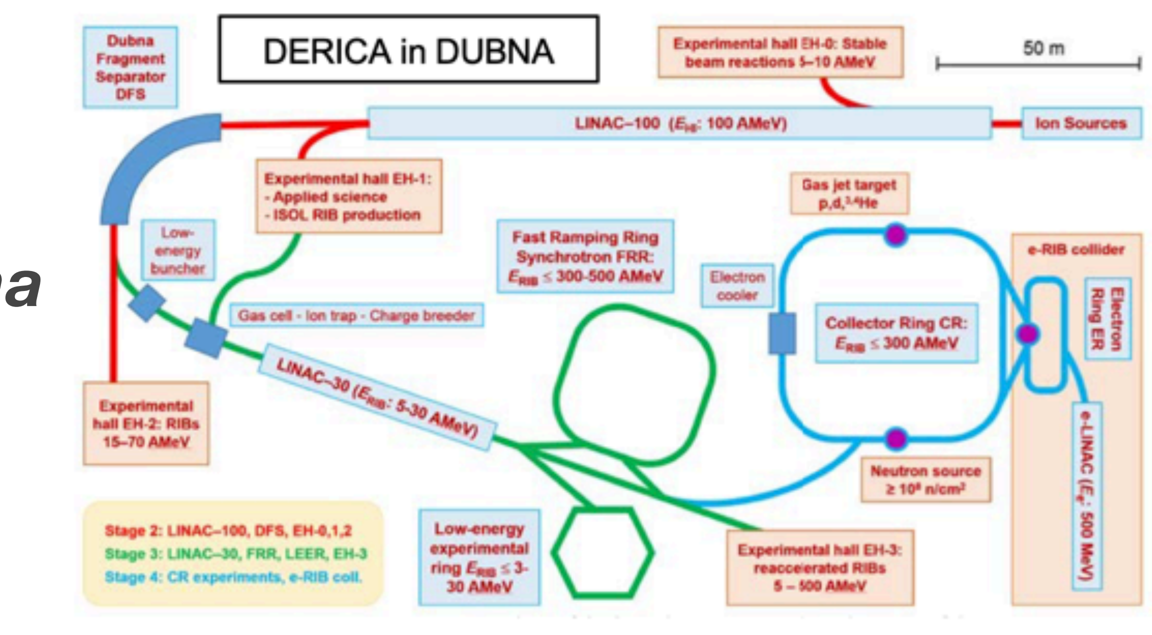


under discussion

ELISe @ FAIR Germany



DERICA @ Dubna Russia



Lecture 1 : electron scattering in general

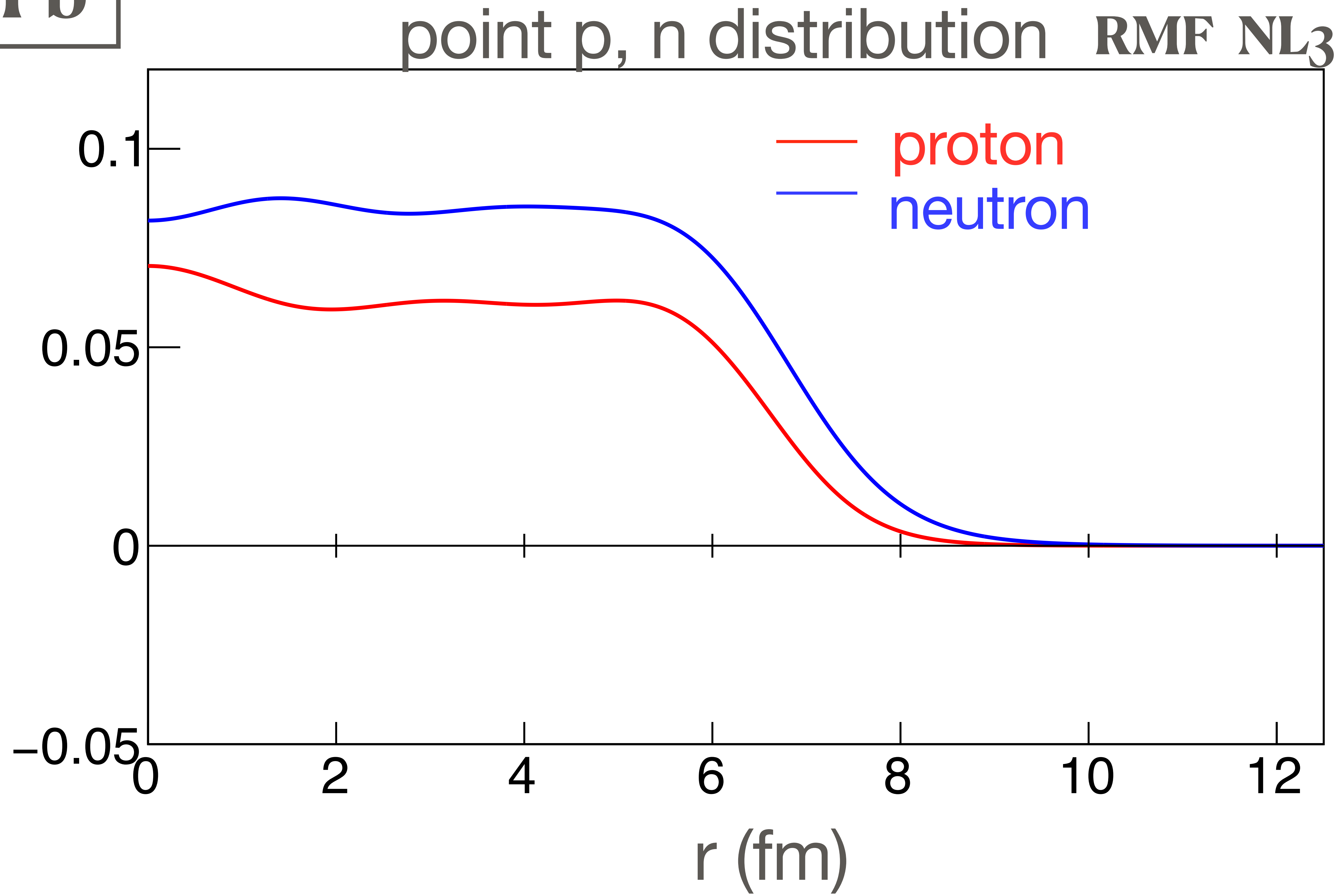
What is electron scattering?
what can we learn by electron scattering?
what have been revealed so far for stable nuclei?

Lecture 2 : selected topics

electron scattering for

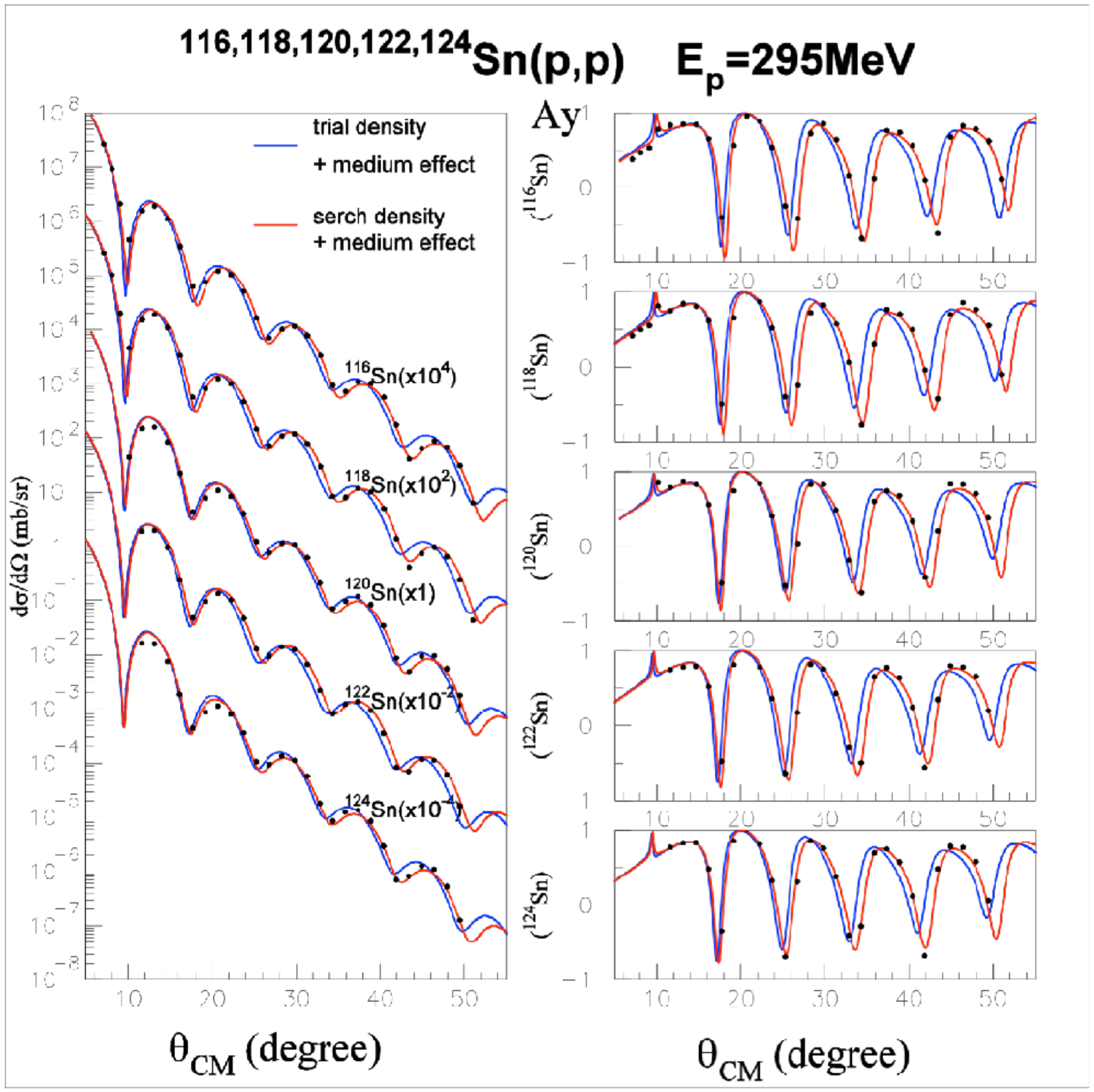
proton charge radius
exotic nuclei
neutron distribution in nuclei

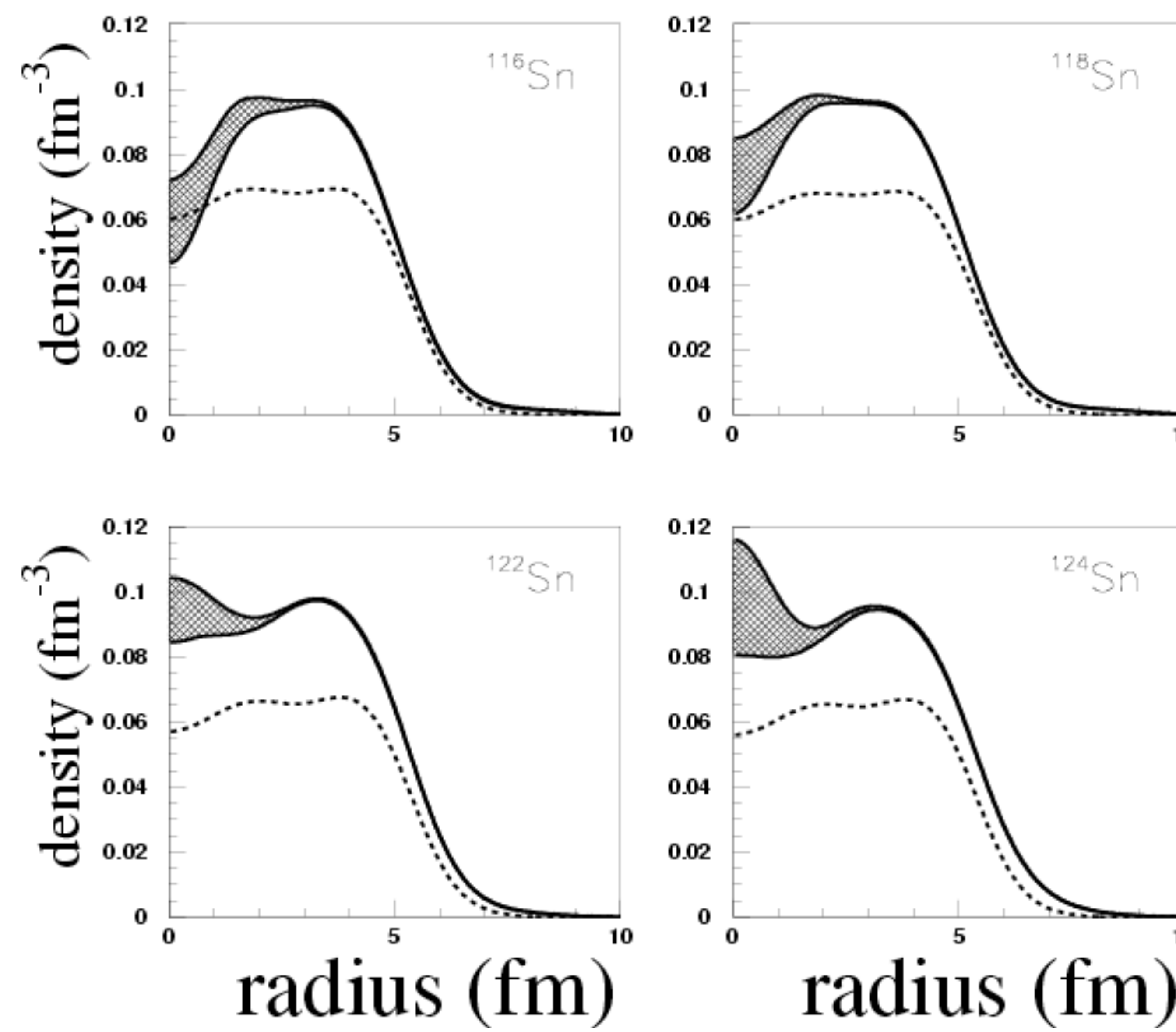
^{208}Pb


point p, n distribution
RMF NL3
proton
neutron
0.1
0.05
0
−0.05
0
2
4
6
8
10
12
r (fm)

neutron distribution in nuclei

- **scattering of strongly-interacting particles**

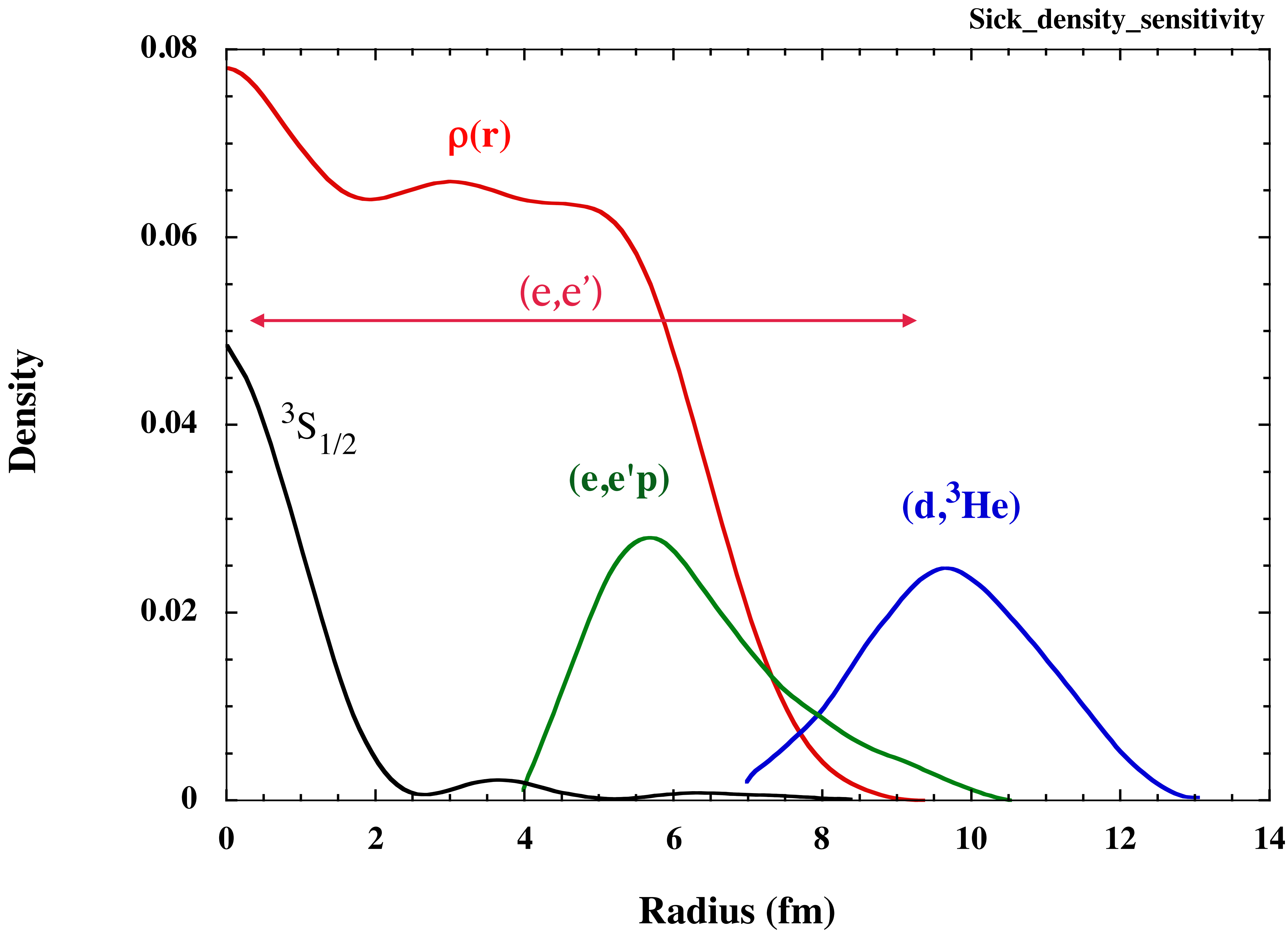




interaction itself is not clear
sensitivity is only nuclear surface

S.Terashima et al., Phys. Rev. C77 (2008) 024317.

=> unavoidable model dependence



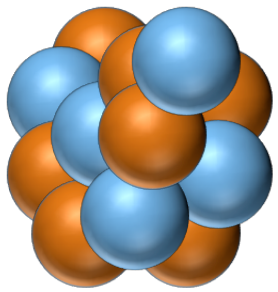
Nucl. Phys. A679(2001)267.

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. submitted

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

Proton

Neutron

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

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

4th moment of the charge density distribution

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

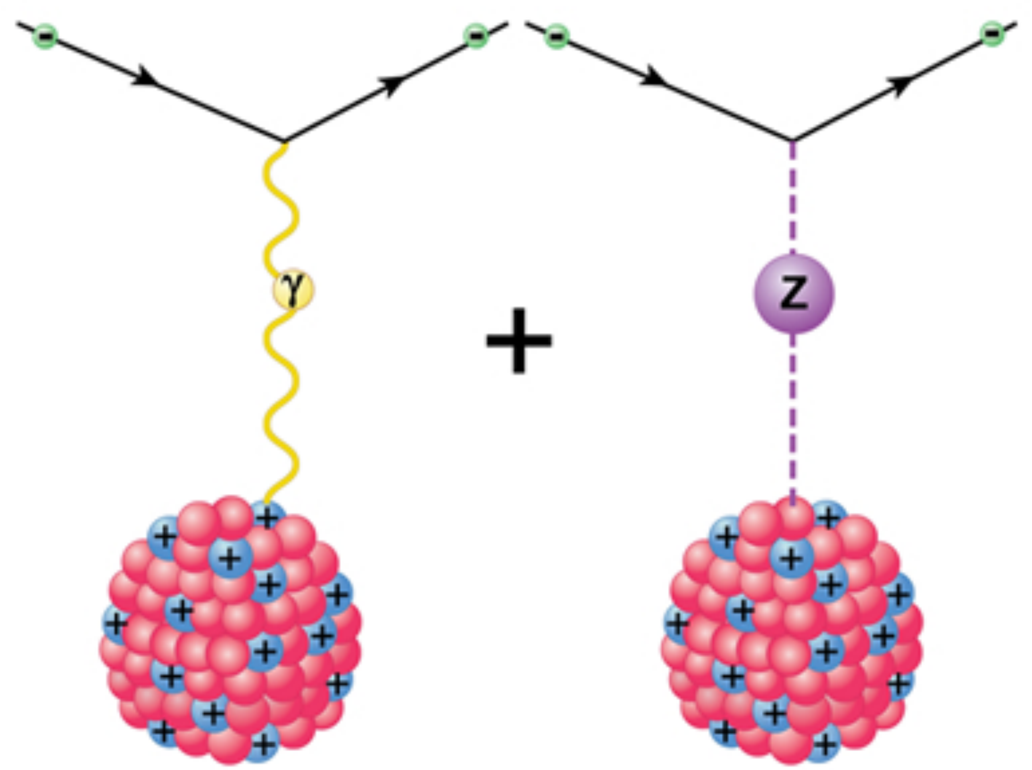
$$= < r^4_{p(point)} > + \frac{10}{3} < r^2_{p(point)} > < r_p^2 >$$

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

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

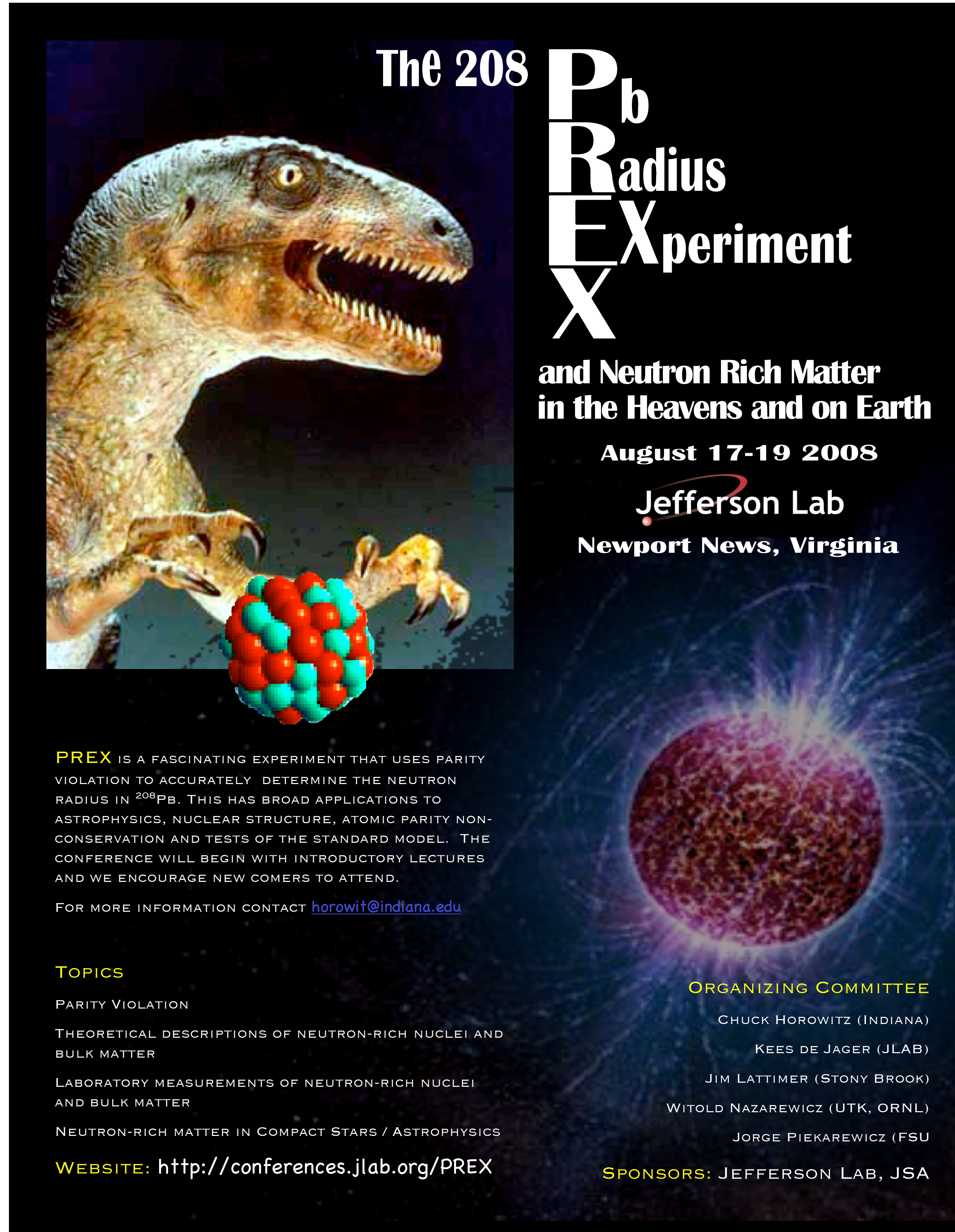
RMS n-radius

Rn of ^{208}Pb by EM(W) probe



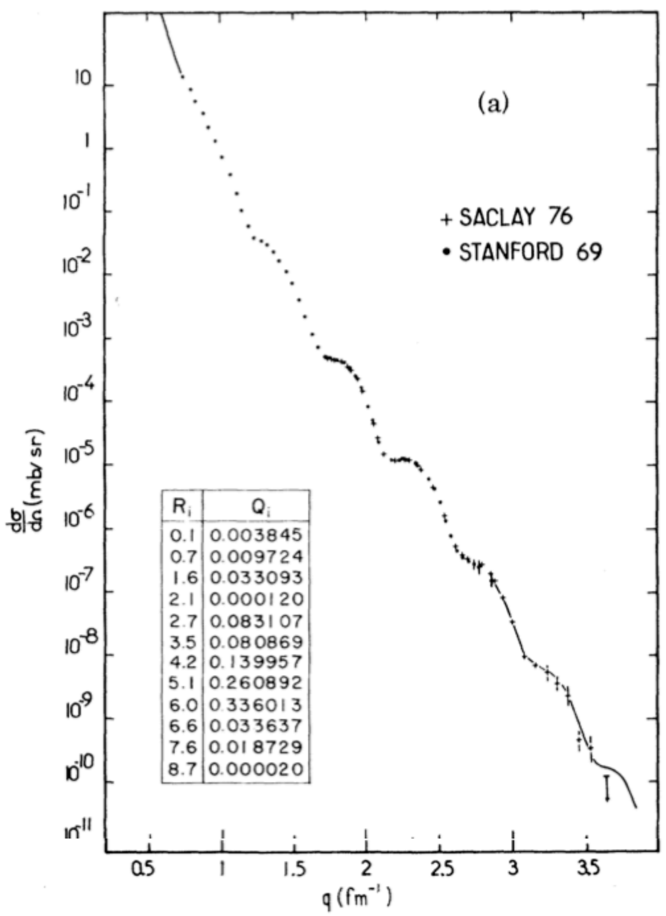
$$A_{\mathrm{PV}} \simeq \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_{\mathrm{wk}} F_{\mathrm{wk}}(Q^2)}{Z F_{\mathrm{ch}}(Q^2)}$$

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim 10^{-6}$$



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

^{208}Pb



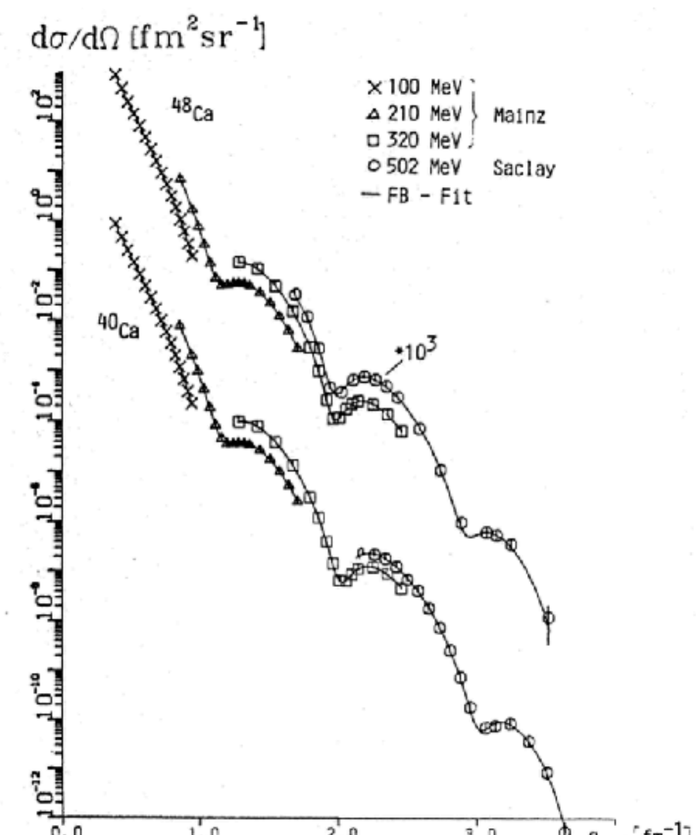
		R_p	R_n	δR
^{208}Pb	Rel.	5.454(0.013)	5.728(0.057)	0.275(0.070)
	Non.	5.447(0.014)	5.609(0.054)	0.162(0.068)
	Exp.	$R_c = 5.503(0.014)$		

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



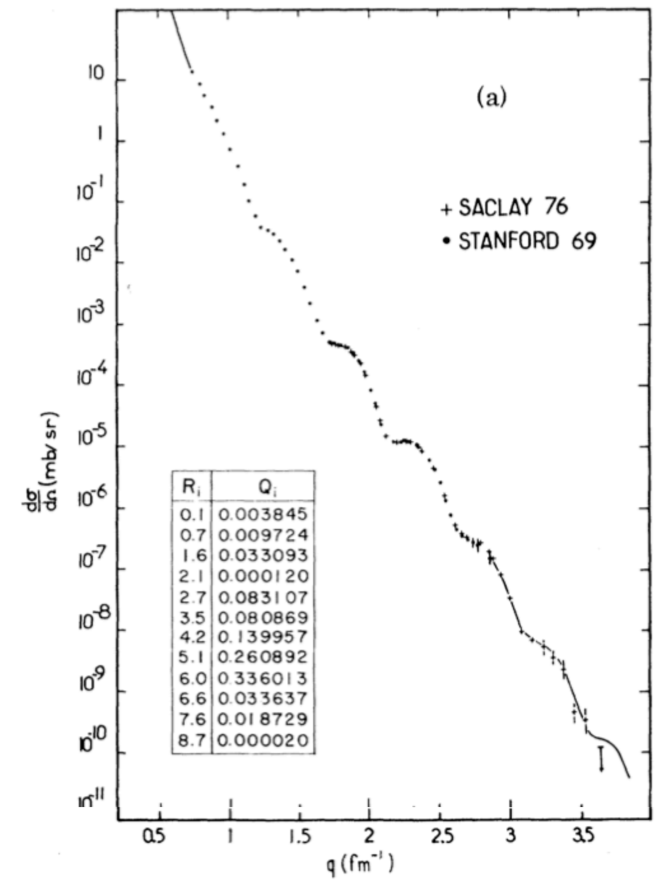
Figur 2.12 : Wirkungsquerschnitte für ^{40}Ca und ^{48}Ca, aufgetragen über q_{eff}. Die durchgezogene Linie ist durch Anpassen einer Fourier-

		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)

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

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



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

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

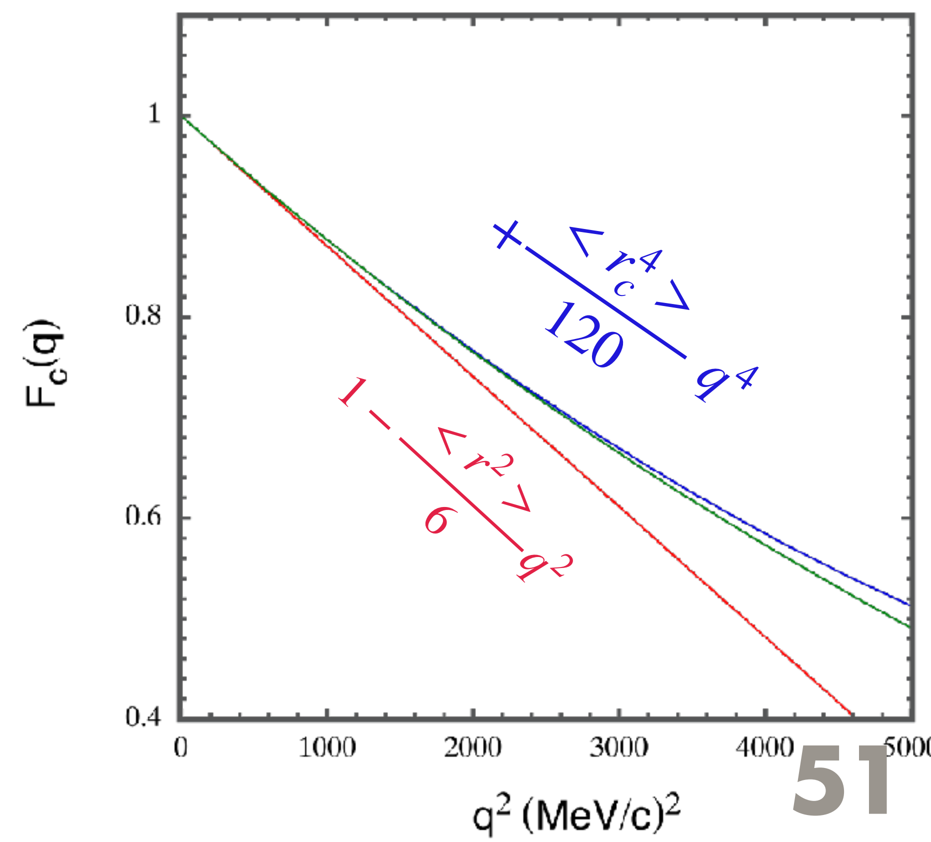
$$F_c(q) = \int \rho_c(\vec{r}) e^{i\vec{q}\vec{r}} d\vec{r}$$

2) elastic scattering at very low *q*

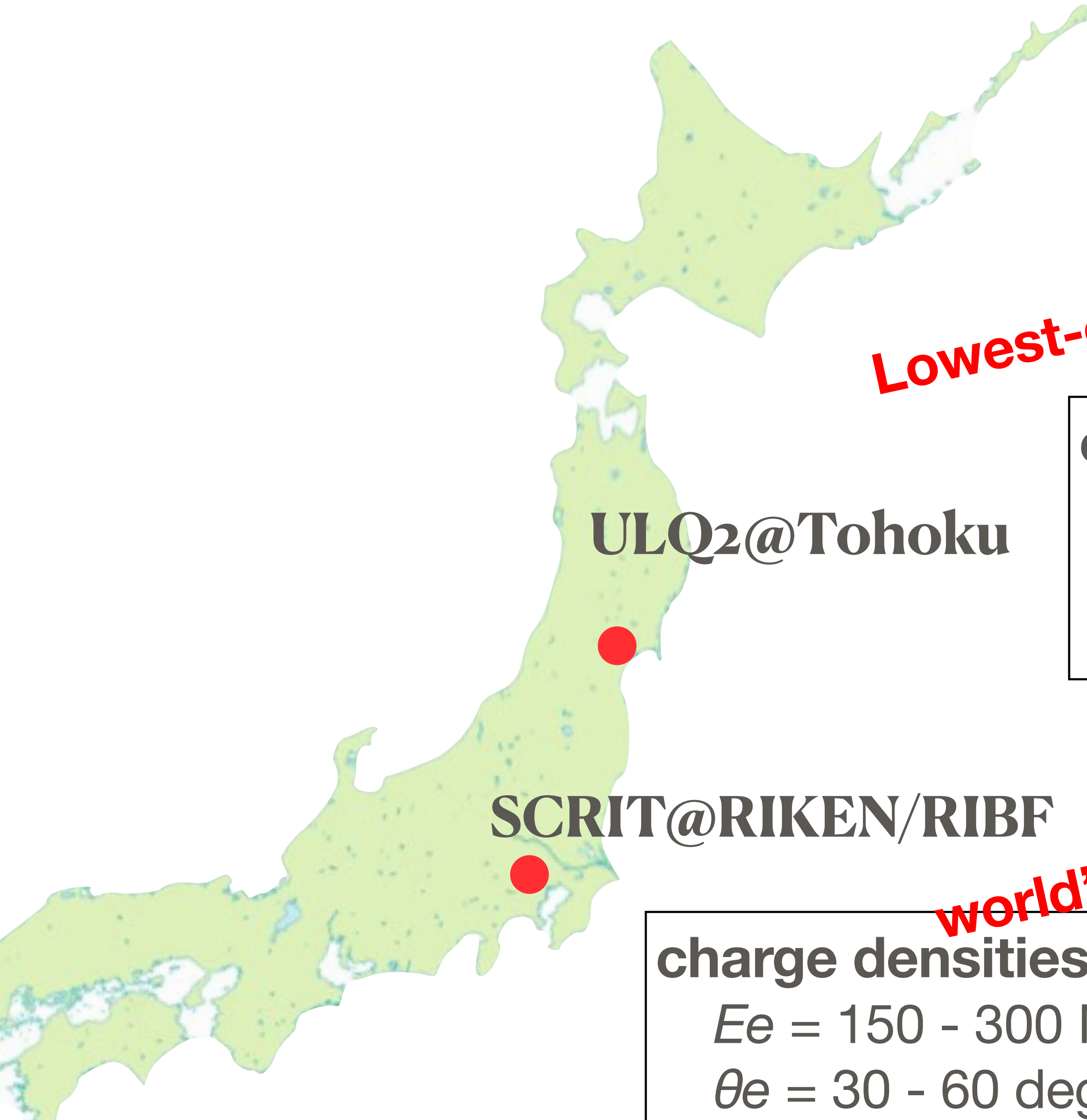
$$F_c(q) \sim 1 - \frac{< r_c^2 >}{6} q^2 + \frac{< r_c^4 >}{120} q^4 + \ldots$$

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

=> low-L SCRIT exp.



Low-q electron-scattering activities in Japan



Lowest-ever energy electron scattering

charge radii of proton and deuteron

E_e = 10 - 60 MeV

θ_e = 30 - 150 deg.

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

world's first e-scattering facility for exotic nuclei

charge densities of short-lived exotic nuclei

E_e = 150 - 300 MeV

θ_e = 30 - 60 deg.

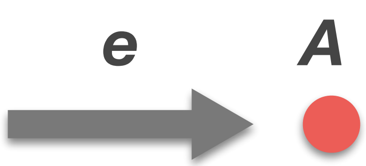
=> q = 80 - 300 MeV/c

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

Backup

Ways to realize electron scattering off exotic nuclei

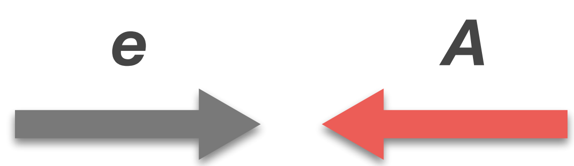
1) fixed target



$E_e \sim 300$ MeV

My talk

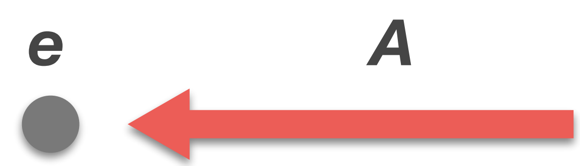
2) eA collider



$E_e \sim 300$ MeV

ELISe@FAIR

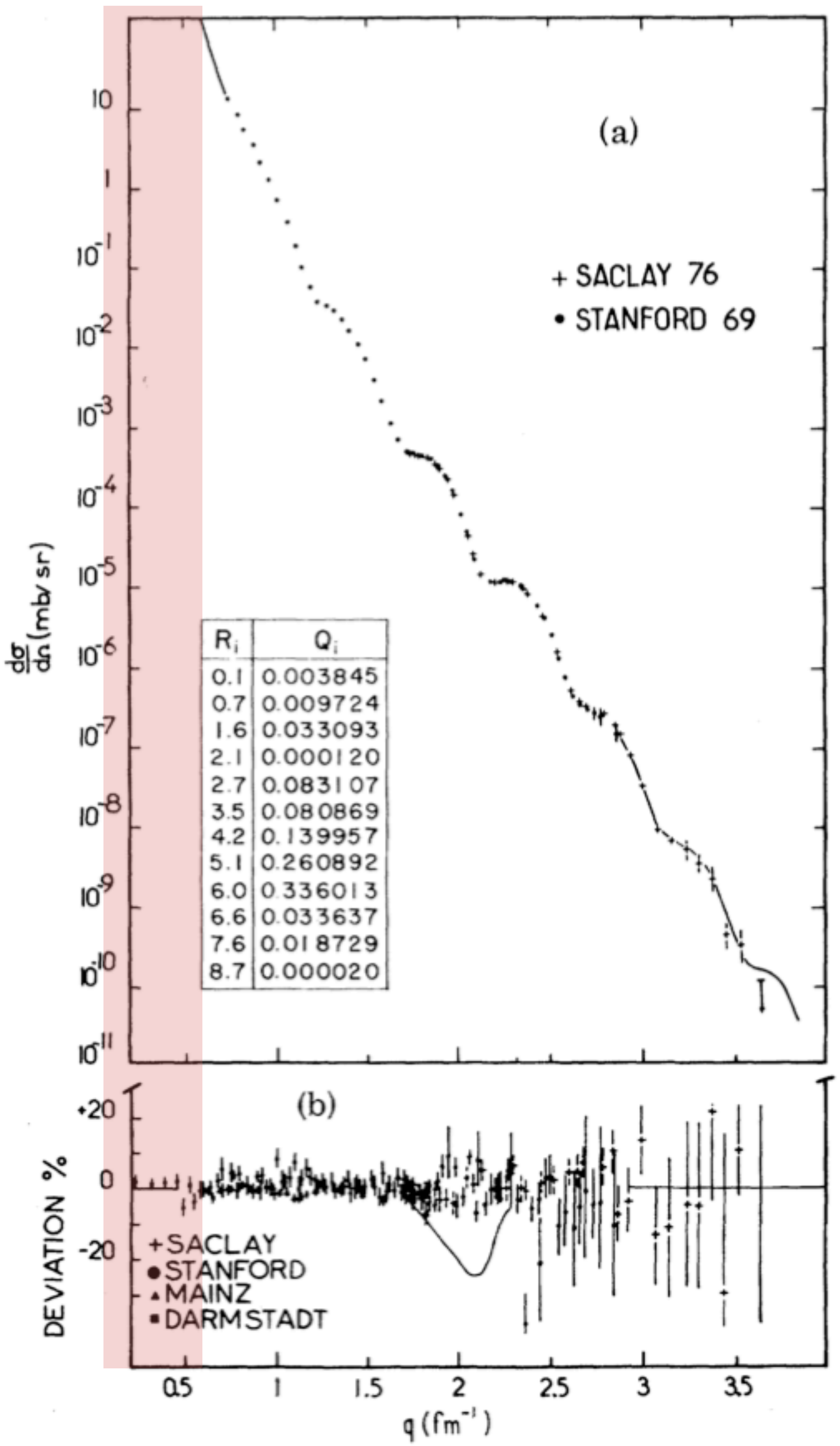
3) electron at rest



$E_A \sim 600$ GeV/A
($\gamma_A \sim 600$)

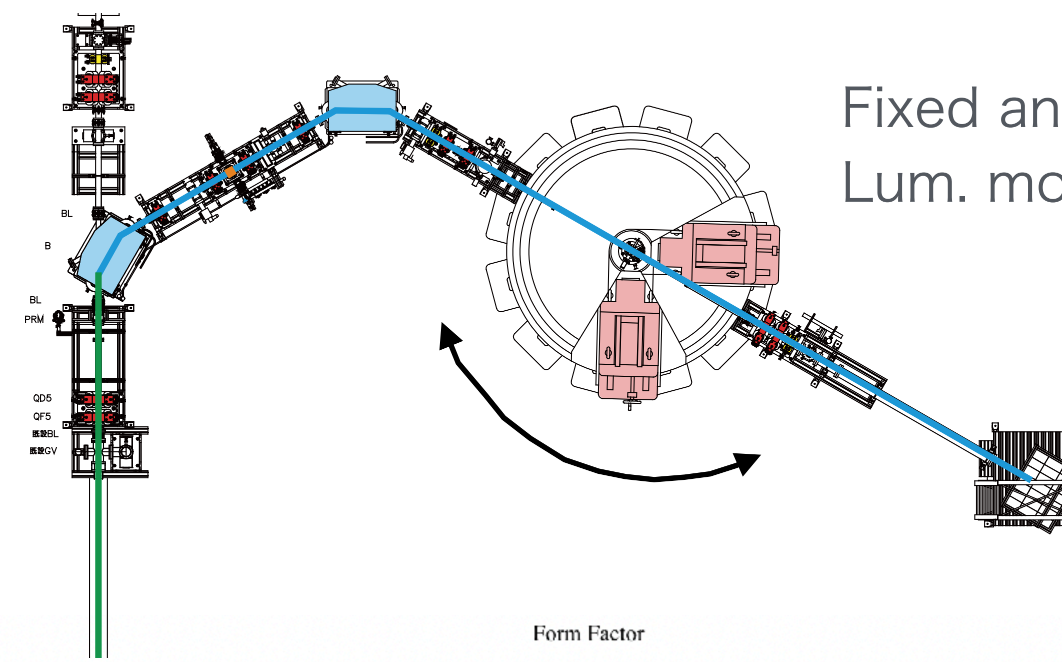
^{208}Pb(e,e') @ ULQ2 beam line

ULQ2

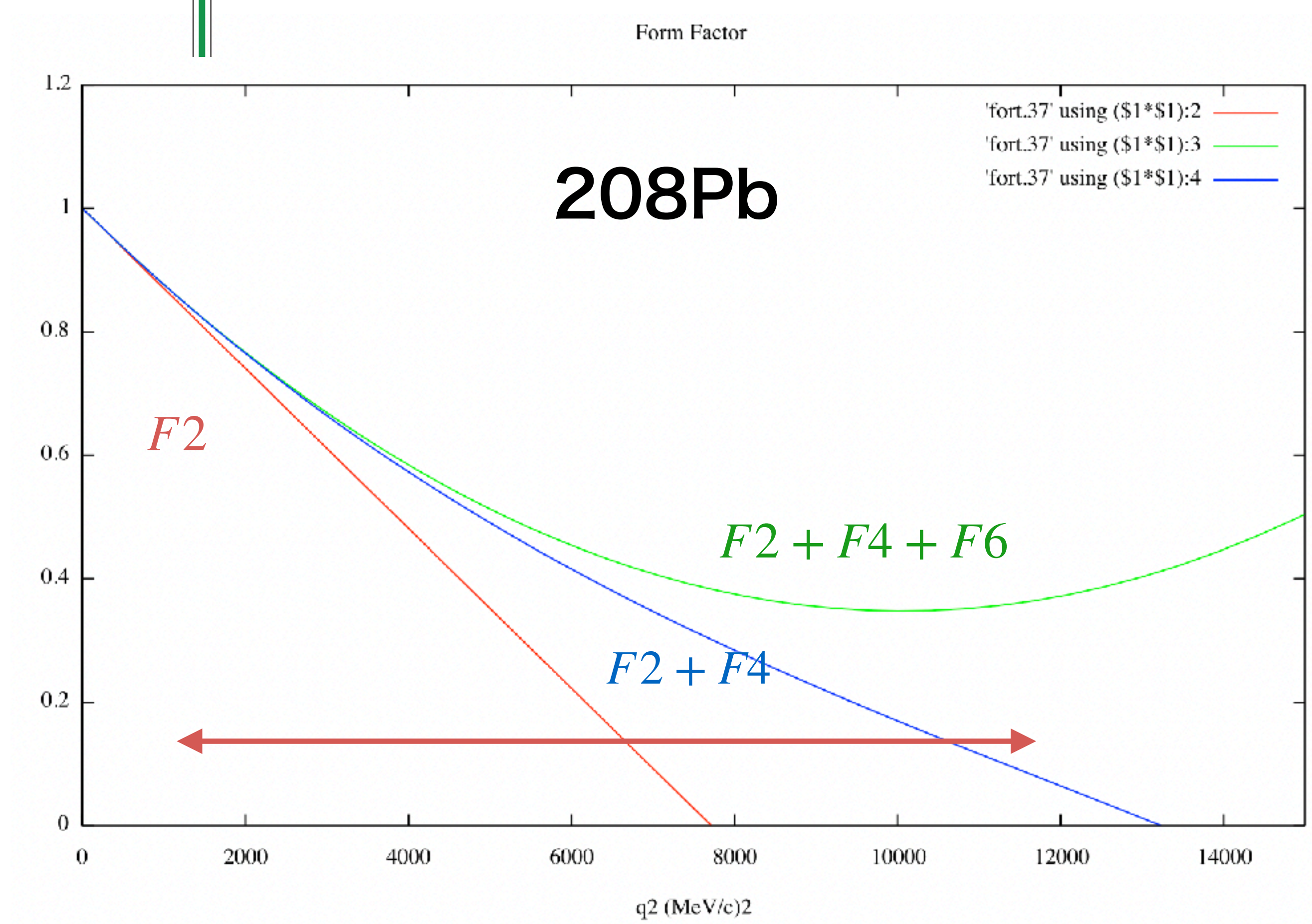


R_i	Q_i
0.1	0.003845
0.7	0.009724
1.6	0.033093
2.1	0.000120
2.7	0.083107
3.5	0.080869
4.2	0.139957
5.1	0.260892
6.0	0.336013
6.6	0.033637
7.6	0.018729
8.7	0.000020

high-precision cross section measurements
1) Ee = 20 - 60 MeV, θe = 30 - 150 °
2) q = 10 - 110 MeV/c

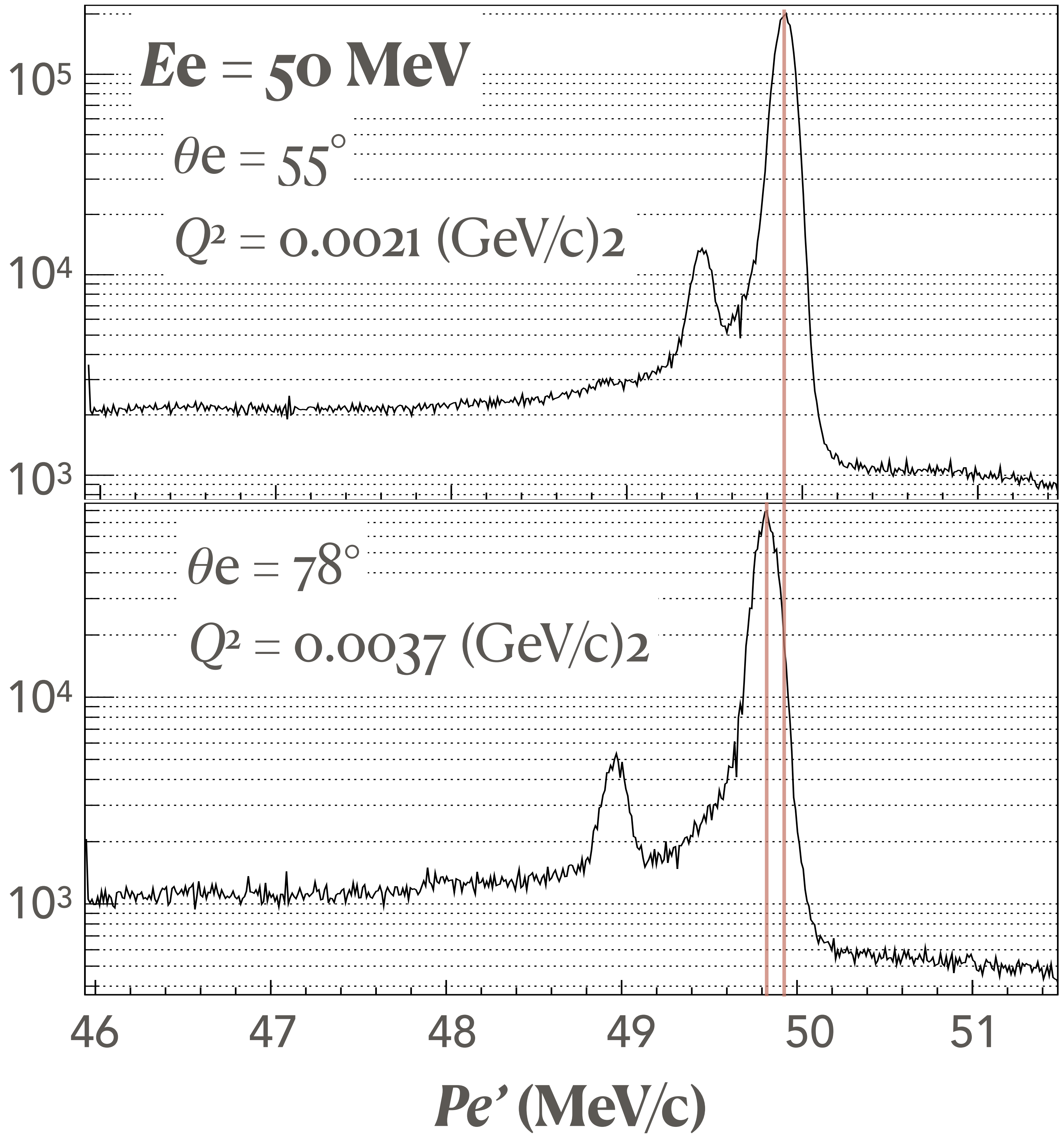


Fixed angle for Lum. monitoring



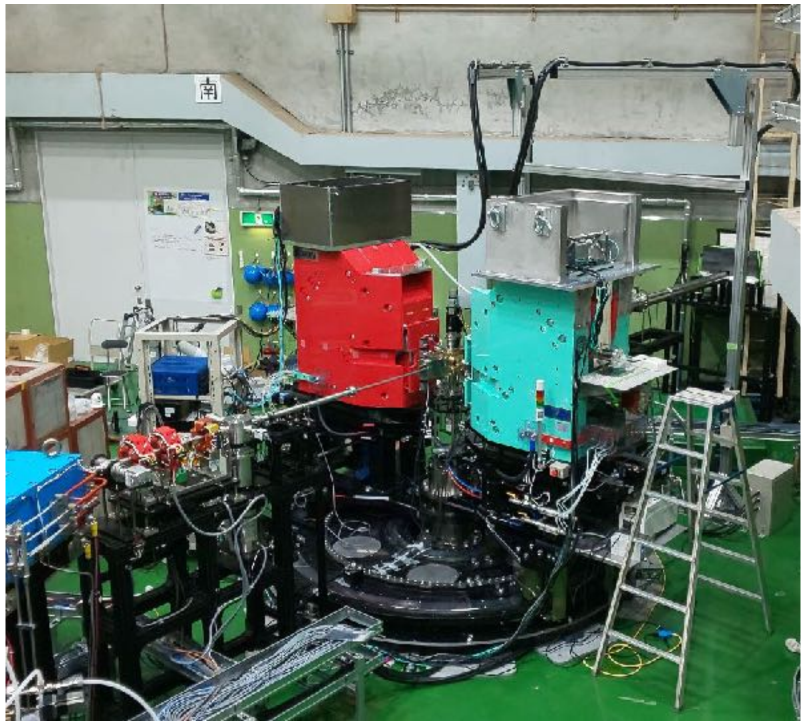
CD_2(e,e') online spectra

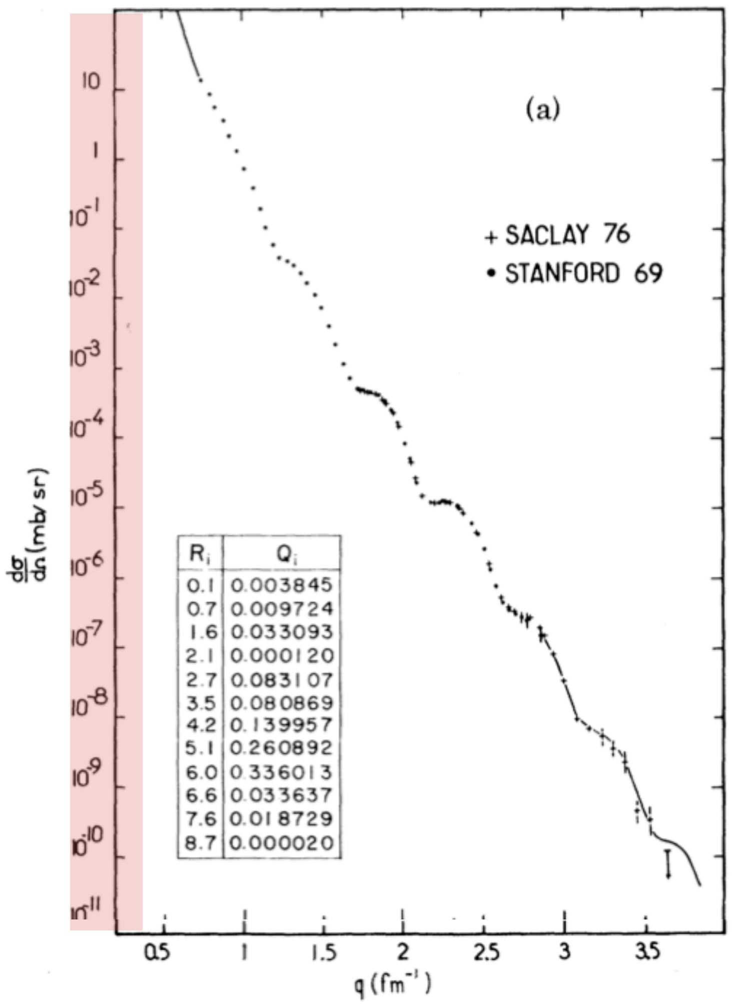
30 min. data



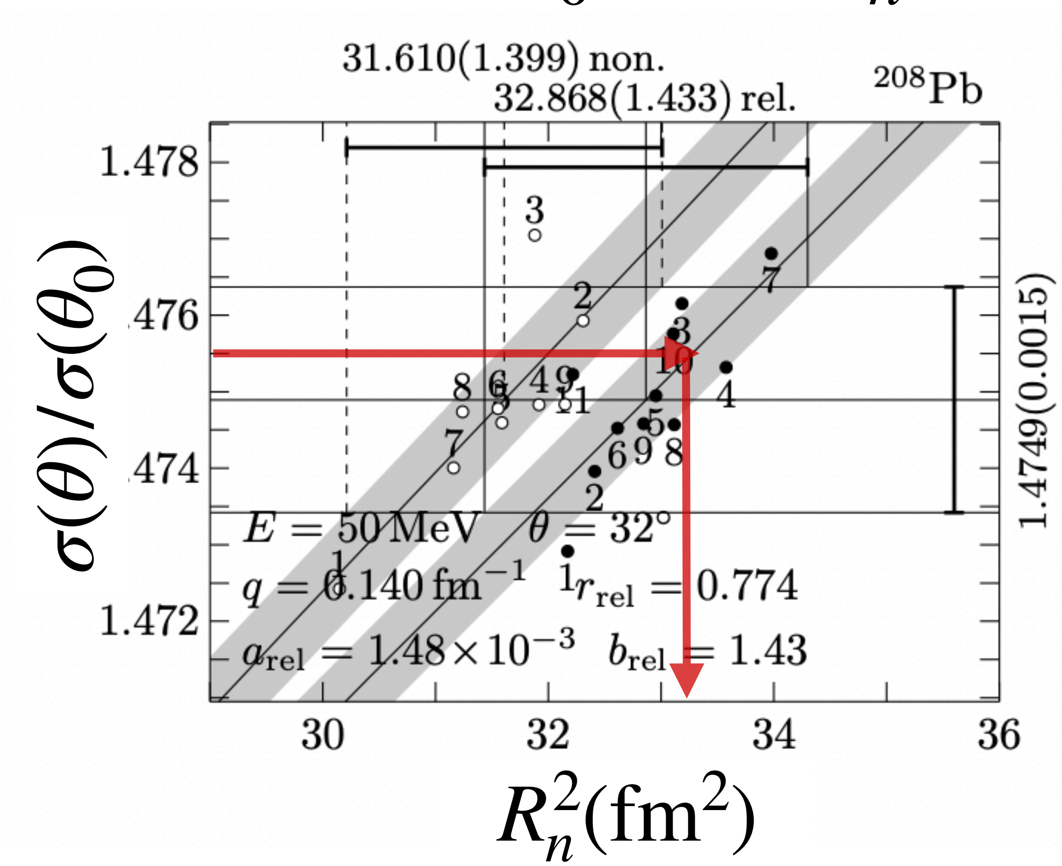
- ^{208}Pb(e,e') at the ULQ2 beam line

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





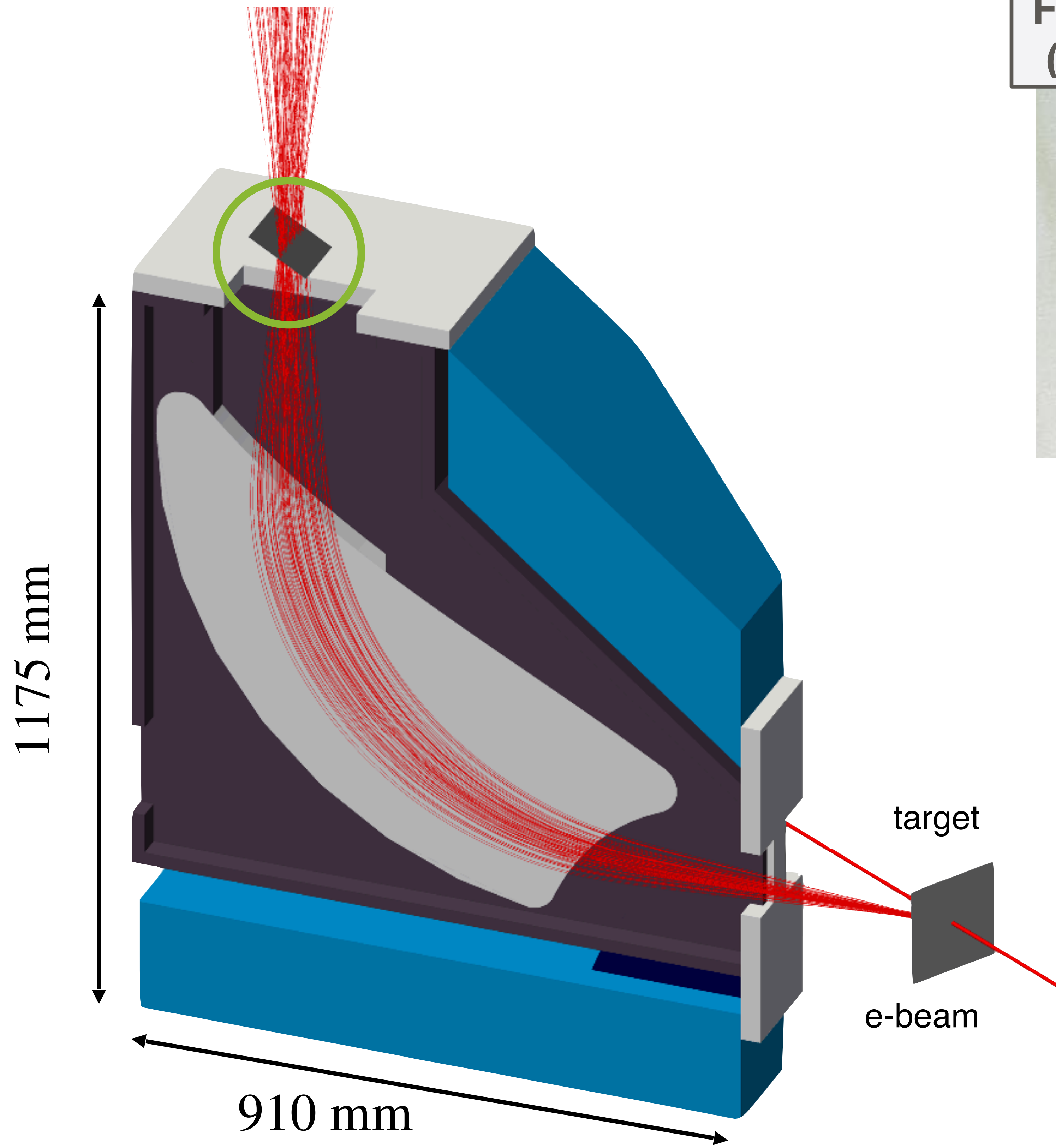
$\sigma(\theta)/\sigma(\theta_0)$ vs R_n^2



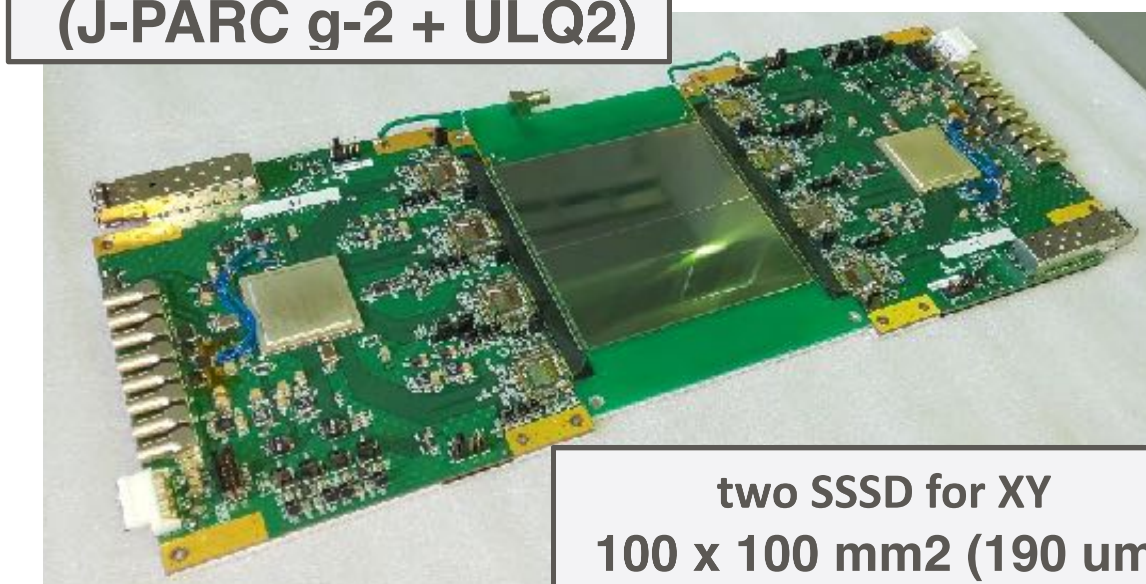
by H. Kurasawa

- precise $\sigma(\theta)/\sigma(\theta_0)$ with the twin spectrometers : 10^{-3}
- phase-shift calculations for R_n^2
- feasibility studies

ULQ2 twin spectrometers



Focal plane detectors (J-PARC g-2 + ULQ2)



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

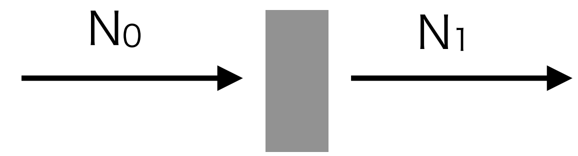
Electron spectrometer	
radius	500 mm
bending angle	90°
max. B	0.4T @ 60MeV
gap	70 mm
dispersion	866 mm
Δp/p	5.6×10^{-4}
momentum bite	10%
Δθ	5 mrad
solid angle	6 mSr
weight	5 ton

Y. Honda

neutron charge radius

1. thermal neutron-beam scattering off electrons

$$N_1 = N_0\, e^{-N\,\sigma_{tot}}$$



neutron-beam transmission in thick Pb, Bi target

$$\langle r_n^2 \rangle = \frac{3 m_e a_0}{m_n} b_{ne}\,, \qquad T(E) = \exp[-N\sigma_{\mathrm{tot}}(E)],$$

$$\sigma_{\mathrm{tot}}(E) = \sigma_{\mathrm{coh}}(E) S_{\mathrm{coh}}(E) + \sigma_{\mathrm{inc}}(E) S_{\mathrm{inc}}(E) + \sigma_{\mathrm{abs}}(E),$$

$$\sigma_{\mathrm{coh}} = 4\pi\{b_c(E) + b_R(E) - b_{ne}[Z - f(Z,E)] + b_p(E)\}^2 + \sigma_{\mathrm{LS}}(E),$$

2. electron scattering

$$Q^2 \geq 0.13 \quad (\mathrm{GeV/c})^2$$

d(e,e') A(Q^2) から $G_N^E(Q^2)$ の情報を抜き出す（Saclay)

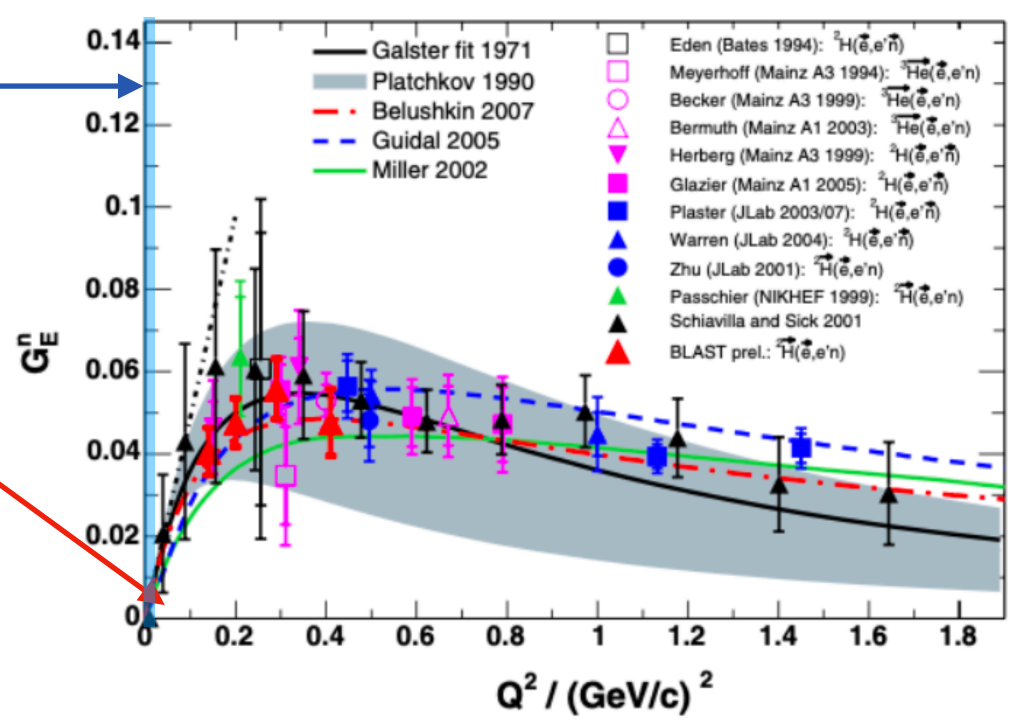
$d(\vec{e},e'\vec{n})$ quasi-free neutron knockout (MIT/Bates)

$^3\vec{He}(\vec{e},e'n)$ quasi-free neutron knockout (Mainz, JLab)

$$A = -P_e\Big[2\sqrt{\tau(1+\tau)}\tan(\frac{\vartheta}{2})G_E^n G_M^n p_x + 2\tau\sqrt{1+\tau+(1+\tau)^2\tan^2(\frac{\vartheta}{2})}\tan(\frac{\vartheta}{2})(G_M^n)^2 p_z\Big] \times \Big[(G_E^n)^2 + (G_M^n)^2\cdot(\tau + 2\tau(1+\tau)\cdot\tan^2(\frac{\vartheta}{2}))\Big]^{-1} = A_\perp \sin\theta^*\cos\phi^* + A_\parallel\cos\theta^* \quad (1)$$

$$\langle r_n^2 \rangle = -6\frac{dG_E^n(Q^2)}{dQ^2}\Big|_{Q^2\to 0}$$

ULQ2



$$G_E^n(Q^2) = \frac{A\tau}{(1+B\tau)}G_D(Q^2),$$

$$G_E^n(Q^2) = \frac{1}{(1+Q^2 r_1^2/12)^2} - \frac{1}{(1+Q^2 r_2^2/12)^2},$$

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

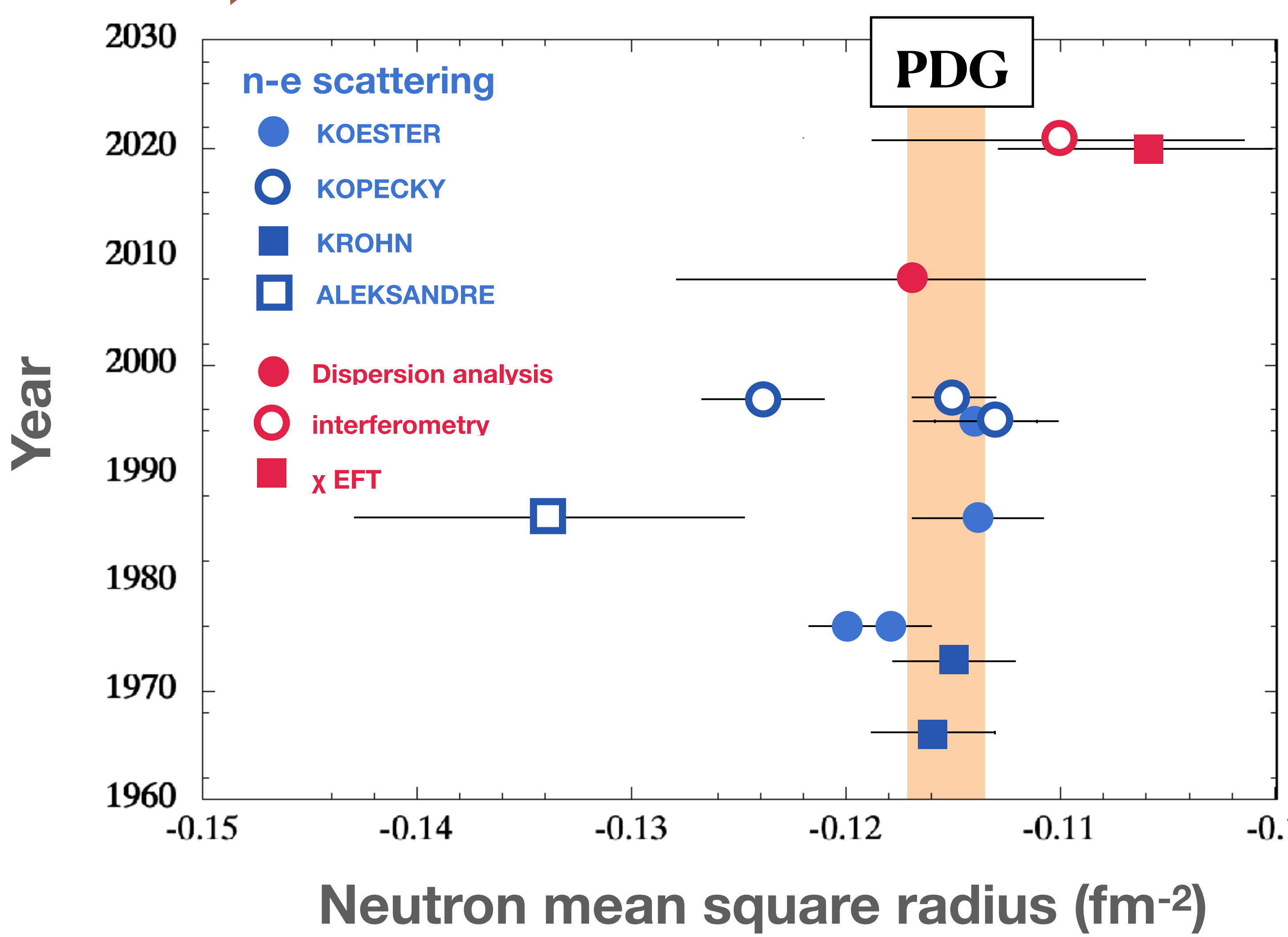
Extraction of the Neutron Charge Radius from a Precision Calculation of the Deuteron Structure Radius

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)

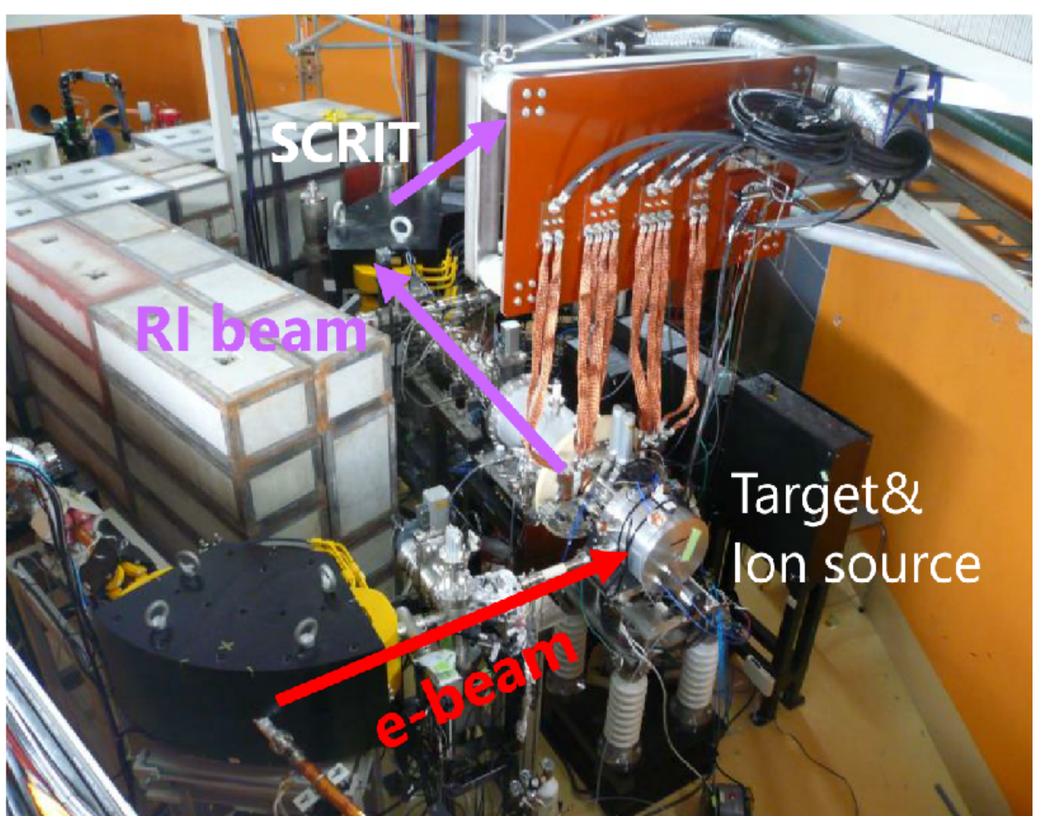
$$\Rightarrow <r_n^2> = -0.106\ ^{+0.007}_{-0.005}\ \mathrm{fm}^2$$

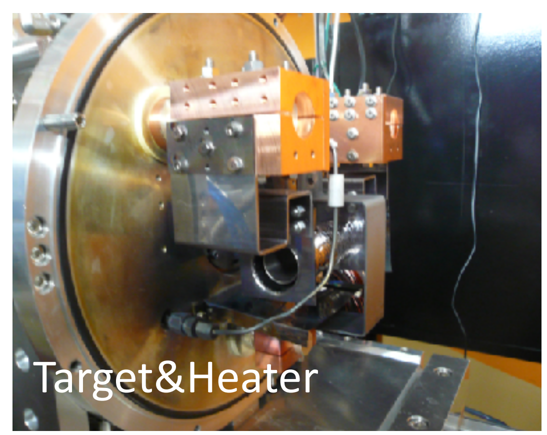


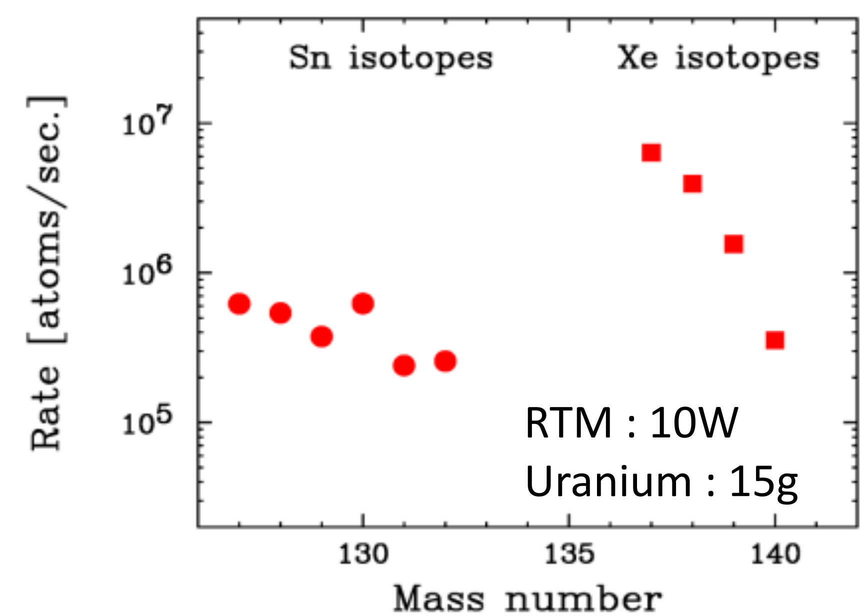
ERIS (Electron-beam-driven RI separator for SCRIT)

- 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



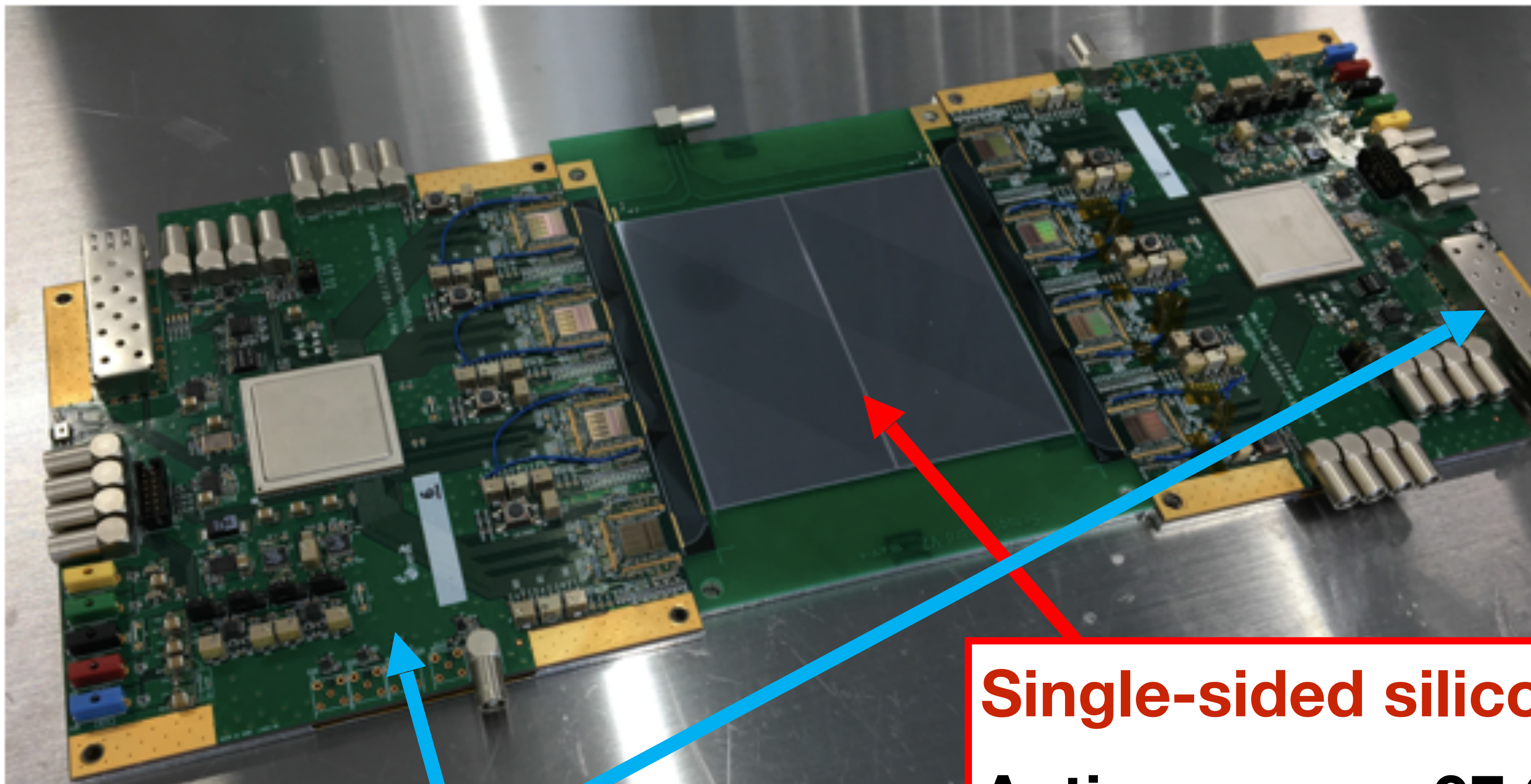




^{138}Xe : 3.9 x 10^6 cps
^{132}Sn : 2.6 x 10^5 cps
^{137}Cs : 8.0 x 10^6 cps (28-g U)

Focal plane detector(s)

Single-Sided Silicon Detector (SSSD)
developed for g-2/EDM experiments at JPARC

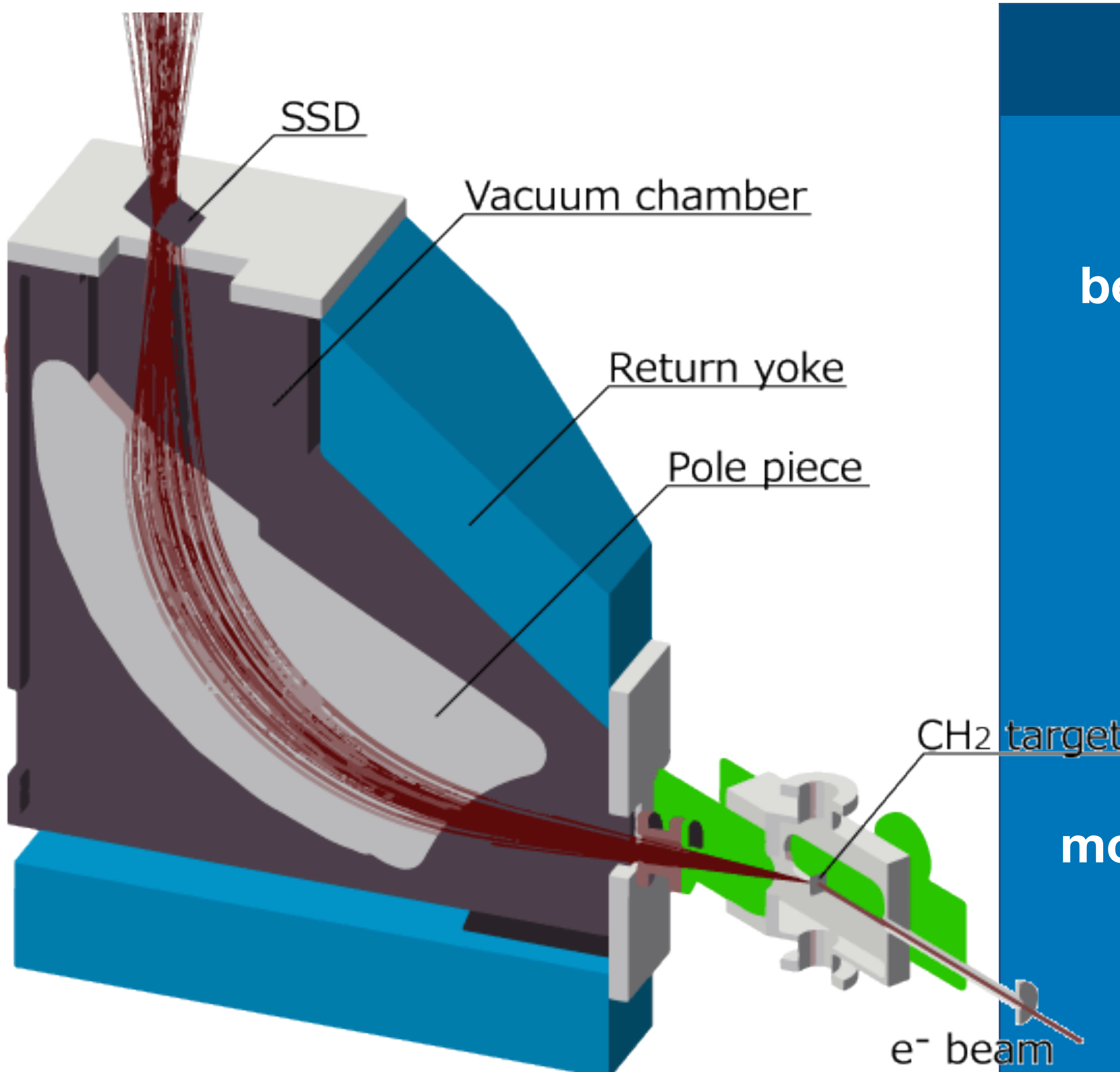


Readout boards
"Multi-Slit128A board"
Four ASICs "Slit128A"
(128 ch/chip)

Single-sided silicon detector (SSSD)

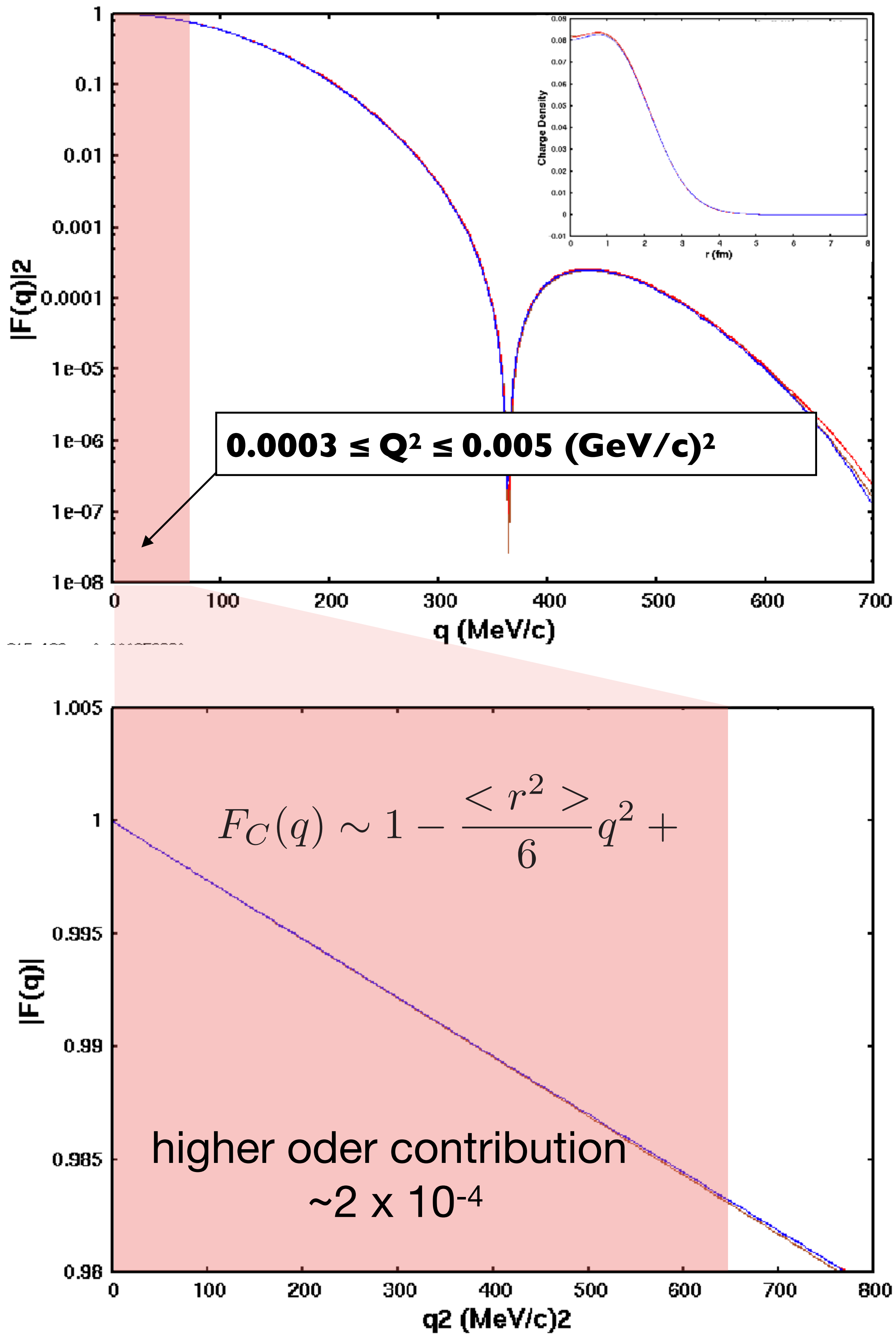
Active area	97.28 mm × 97.28 mm
Thickness	0.32 mm
Strip length	48.575 mm
Strip pitch	0.19 mm
No. of strips	512 ch × 2

Electron spectrometer (P = 20 - 60 MeV/c)



Electron spectrometer	
radius	500 mm
bending angle	90°
max. B	0.4T@60MeV
gap	70 mm
dispersion	850 mm
$\Delta p/p$	8×10^{-4}
momentum bite	10%
$\Delta\theta$	5 mrad
solid angle	10 mSr

How well-known the ^{12}C charge distribution ?



electron scattering

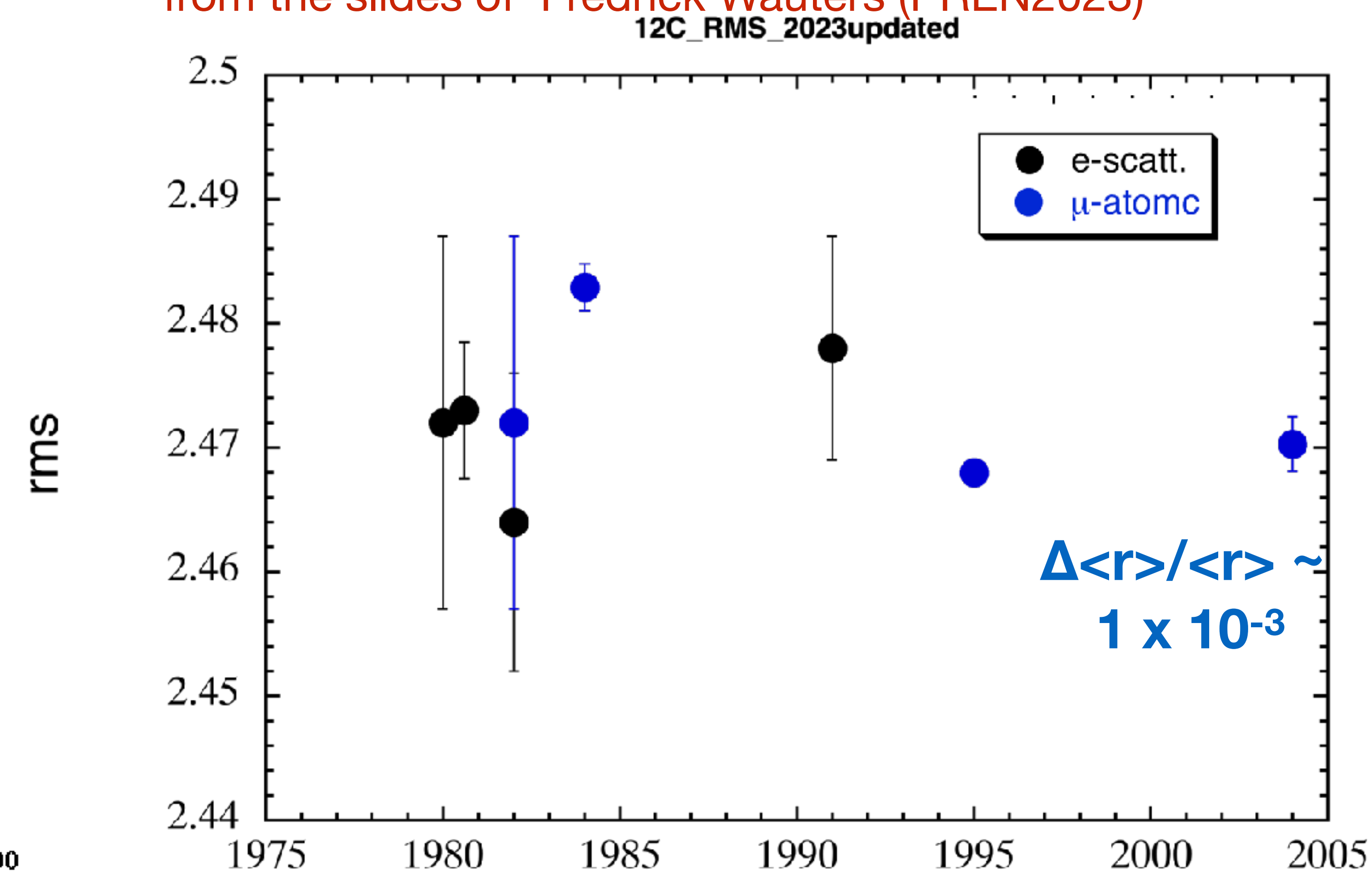
- E. Offerman et al., Phys. Rev. C44(1991)1096.
- W. Reuter et al., Phys. Rev. C26 (1982) 806.
- L. Cardman et al., Phy. Lett. 91B (1980) 203.
- ……

μ X-ray

- I. Angeli, ADNDT 87 (2004) 185.
- E. Tuckstuhl et al., Nucl. Phys. A430 (1984) 685.
- L. Schaller et al., Nucl. Phys. A379 (1982) 523.
- G. Fricke et al., ADNDT 60 (1995) 177.

I. Angeli ,ADNDT 87 (2004) 185, 2.4703(22) fm

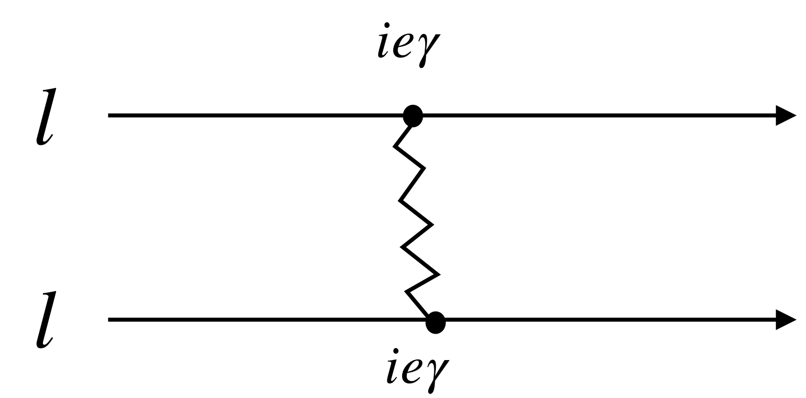
from the slides of Fredrick Wauters (PREN2023)



1) lepton-lepton scattering

(Dirac particle (point particle))

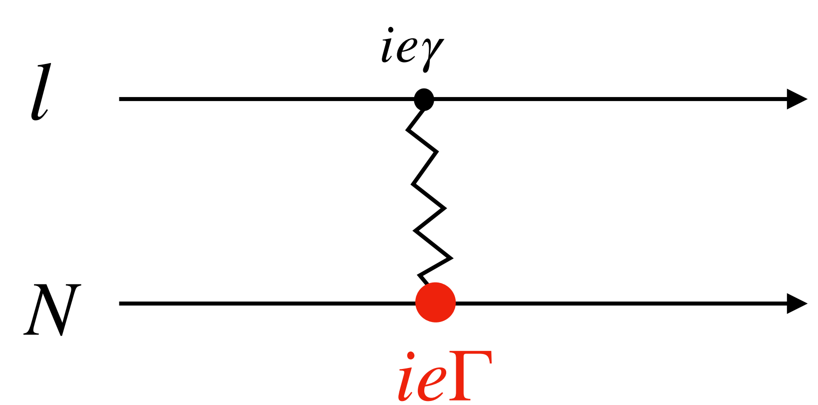
$$-iM = (ie\bar{u}\gamma^{\mu}u)(-\frac{ig_{\mu\nu}}{q^2})(ie\bar{u}\gamma^{\nu}u)$$



2) lepton-nucleon scattering

(particle having internal structure)

$$-iM = (ie\bar{u}\gamma^{\mu}u)(-\frac{ig_{\mu\nu}}{q^2})(ie\bar{u}\Gamma^{\nu}u)$$



$$\Gamma^{\nu} = \gamma^{\nu}F_1(q^2) + i\sigma^{\nu\alpha}\frac{q_{\alpha}}{2M}F_2(q^2)$$

F_1 Dirac form factor

F_2 Pauli form factor

$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$$

$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

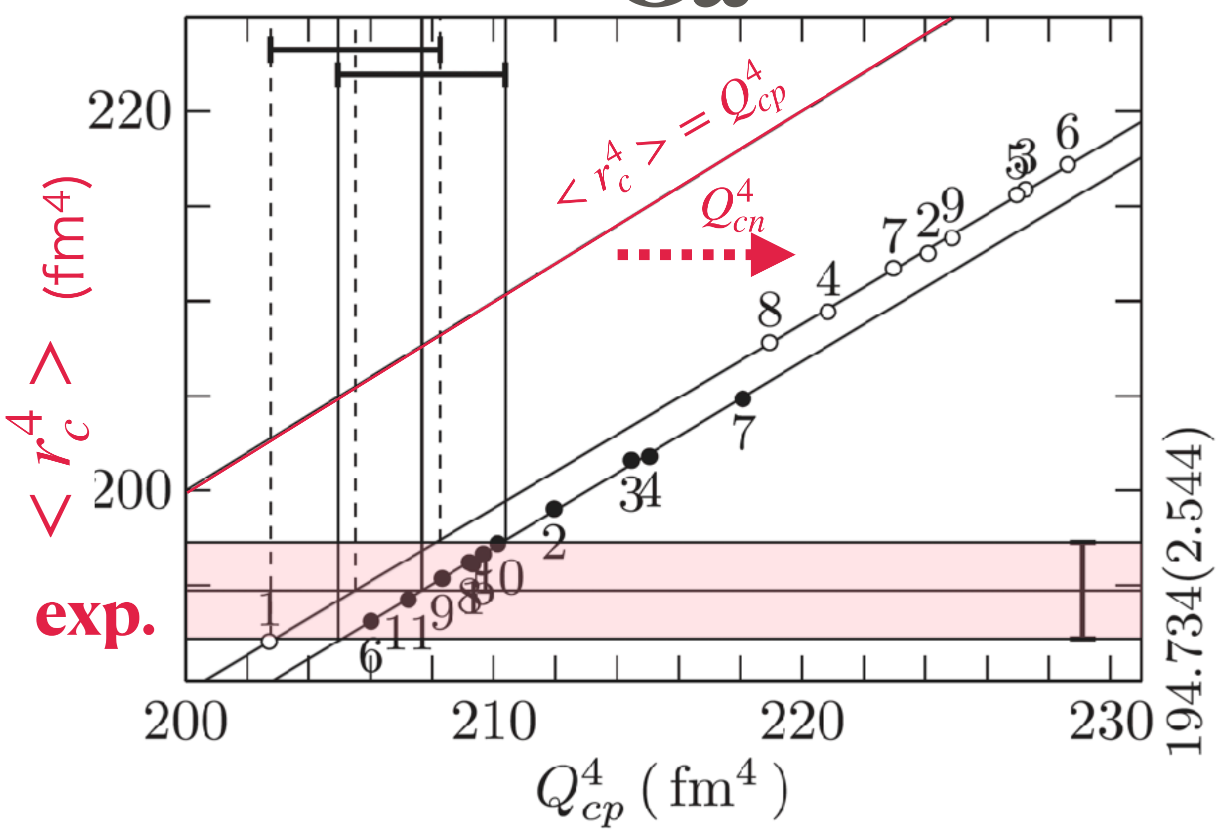
Electric, Magnetic "Sachs" form factors

$$Q^2 = -q^2 \qquad \tau = \frac{Q^2}{4M^2}$$

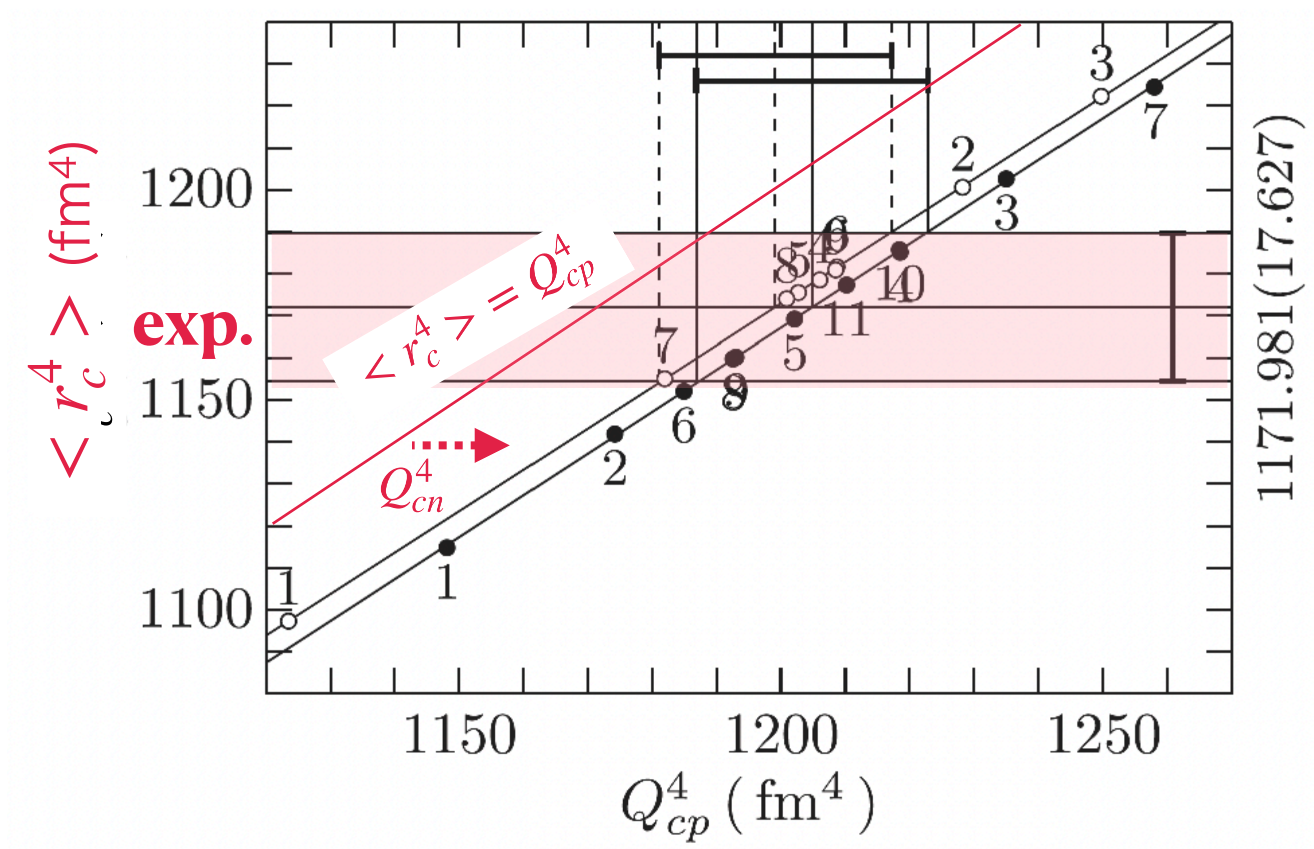
$<r_c^4>$ of ^{48}Ca and ^{208}Pb

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

^{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 SKI, 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