

# **ULQ2 (Ultra-Low Q2)**

**Toshimi Suda**  
**Research Center for Electron-Photon Science**  
**Tohoku University, Sendai, JAPAN**

**on behalf of the ULQ2 collaboration**

# Low- $q$ electron-scattering activities in Japan



**charge radii of proton and deuteron**

$$E_e = 10 - 60 \text{ MeV}$$

$$\theta_e = 30 - 150 \text{ deg.}$$

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

**e-scattering of online-produced exotic nuclei ( $\sim 10^8/\text{sec}$ )**

$$E_e = 150 - 300 \text{ MeV}$$

$$\theta_e = 30 - 60 \text{ deg.}$$

$$\Rightarrow q = 80 - 300 \text{ MeV/c}$$

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

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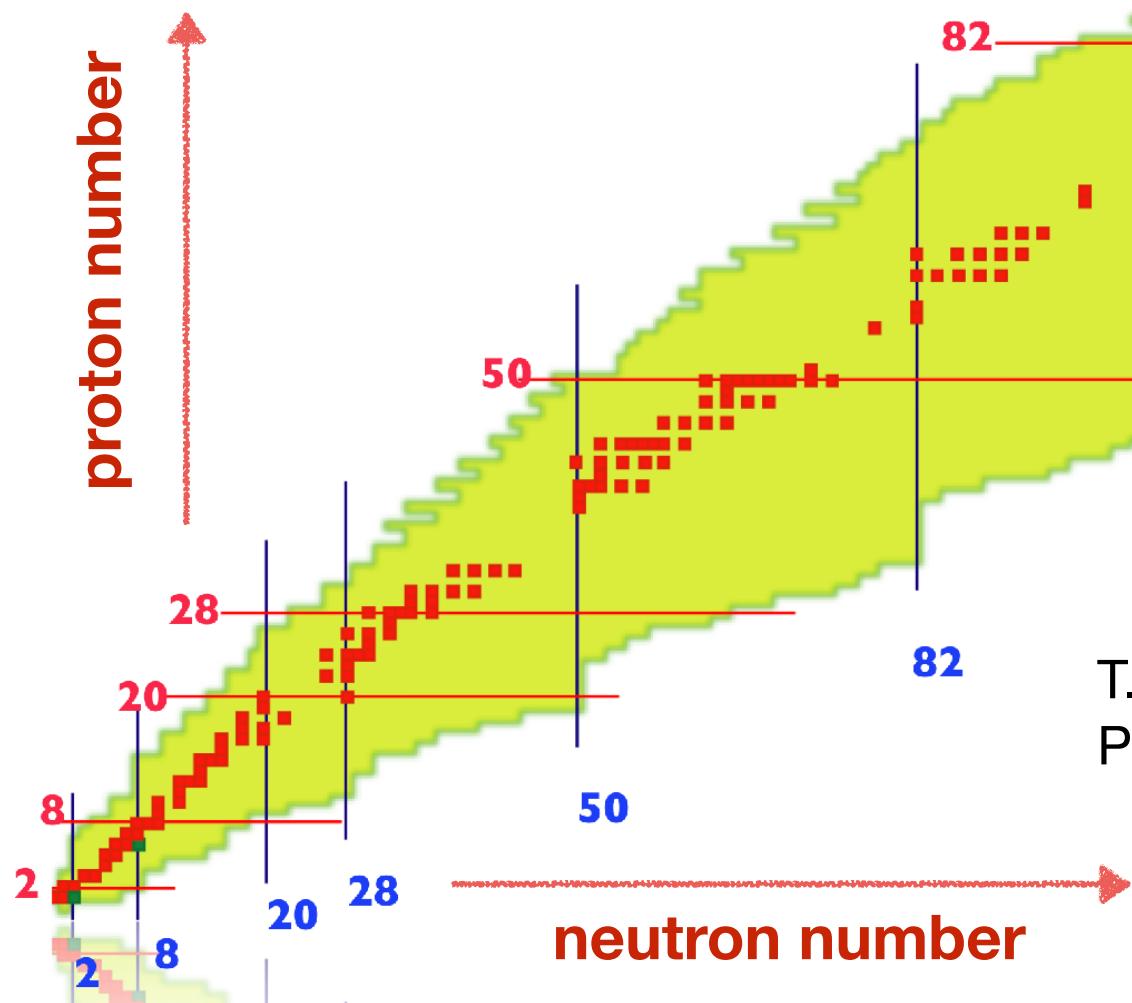
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# Nuclei ever studied with electron scattering

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



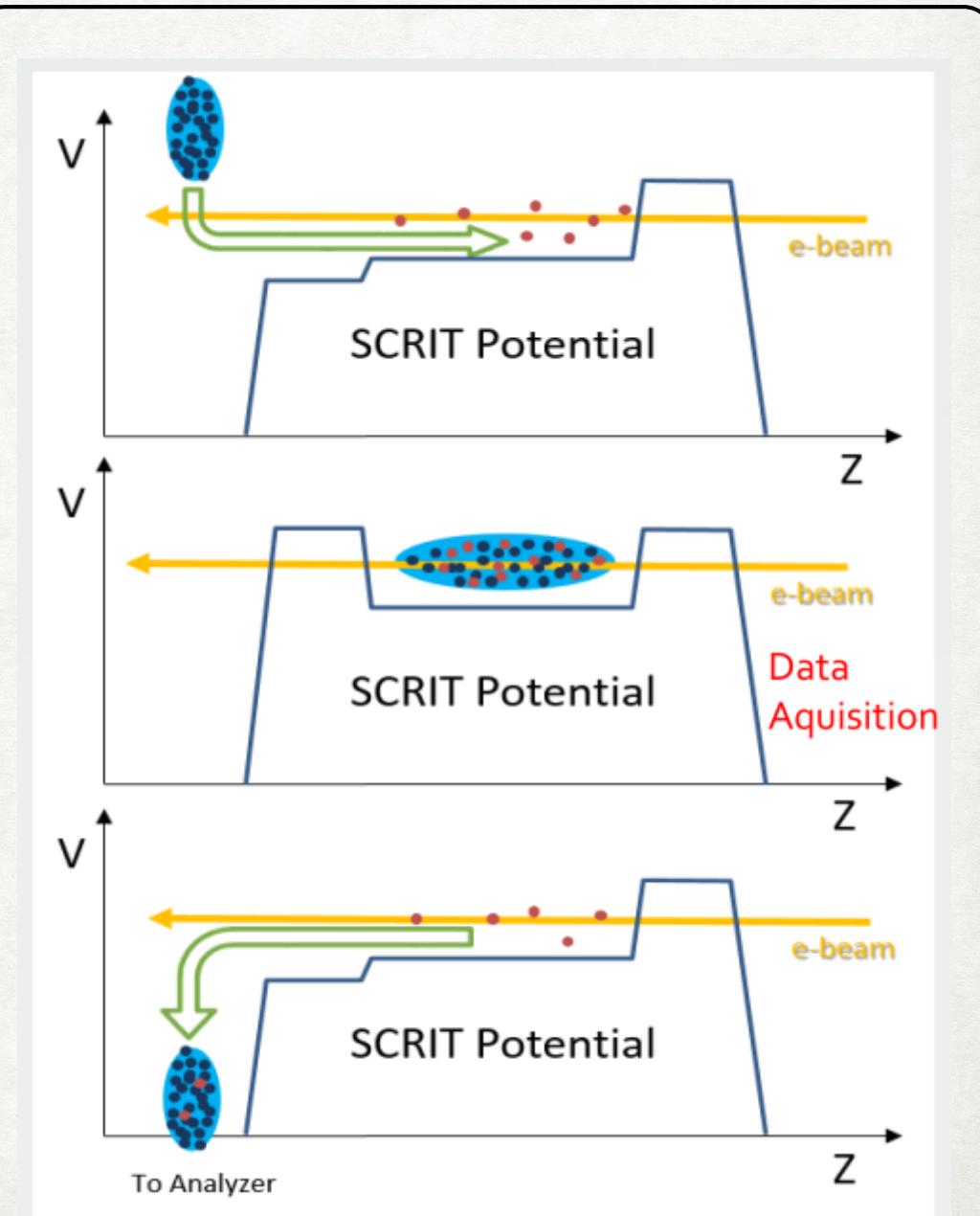
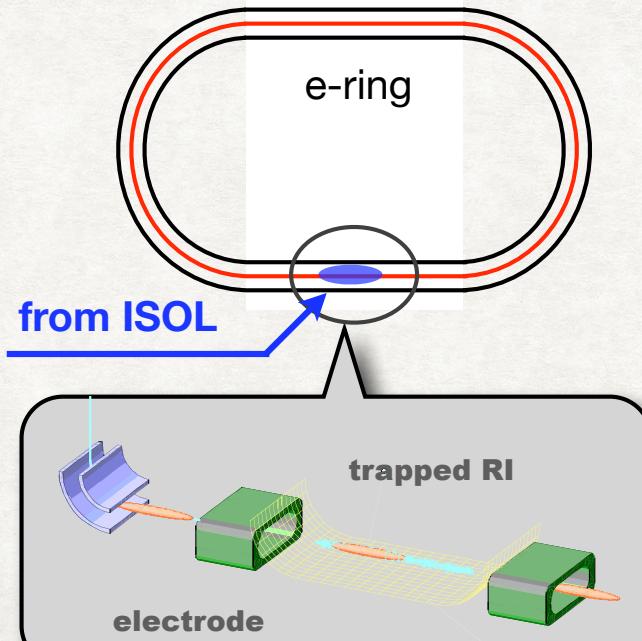
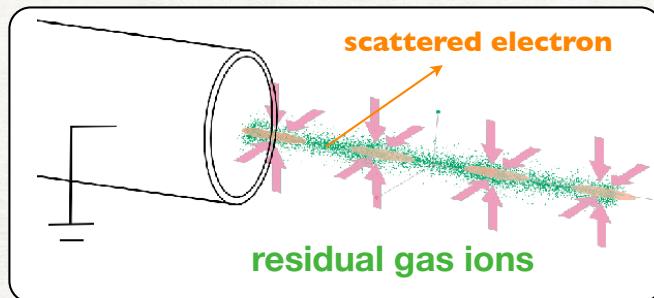
T. S. and H. Simon,  
Prog. Part. Nucl. Phys. 96 (2017) 1-31.

# SCRIT (Self-Confining RI Ion Target)

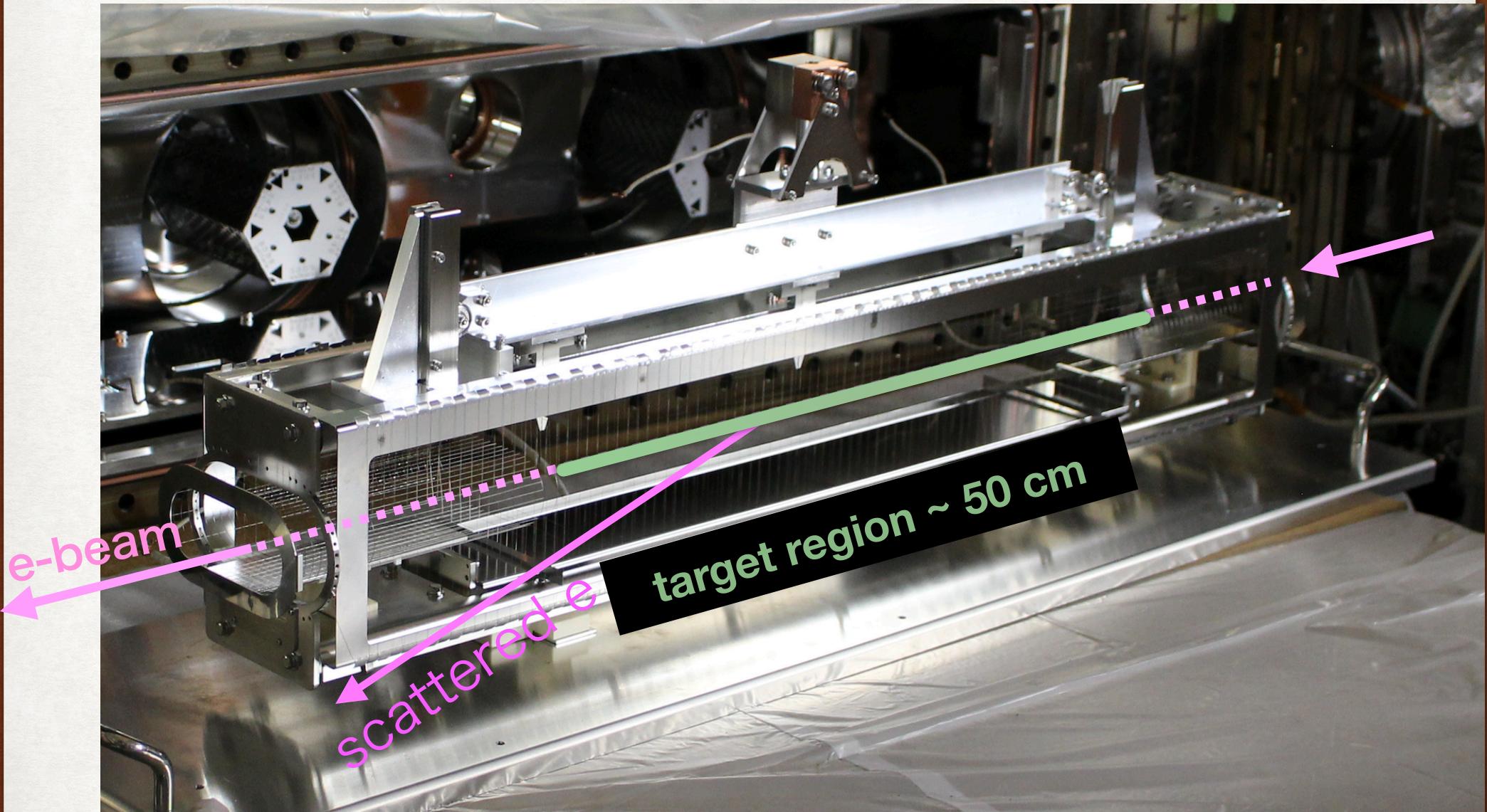
Idea : “ion trapping” at SR facilities.

ionized residual gases are trapped by the circulating electron beam

problem of e-storage rings



# SCRIT electrodes



# RIKEN SCRIT Electron Scattering Facility

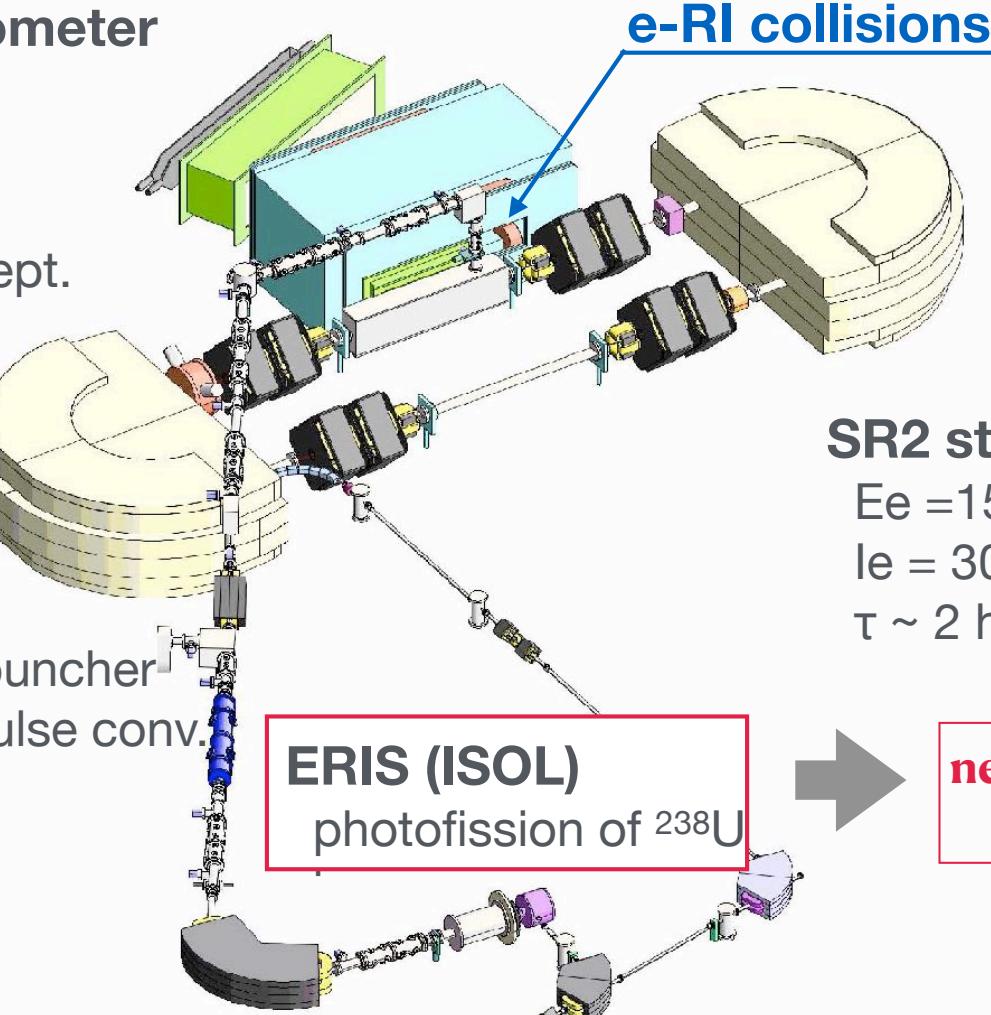
## WiSES spectrometer

$\Delta\Omega \sim 90$  mSr

$\theta = 30 - 60^\circ$

$\Delta p/p \sim 10^{-3}$

long target accept.



## SR2 storage ring

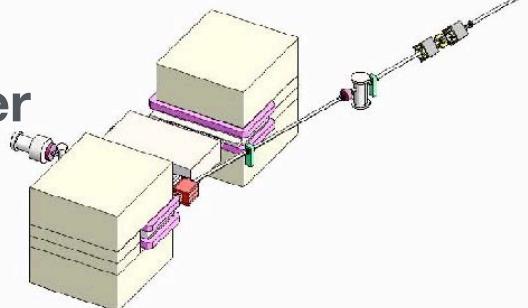
$E_e = 150 - 700$  MeV

$I_e = 300$  mA

$\tau \sim 2$  hours

## 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.

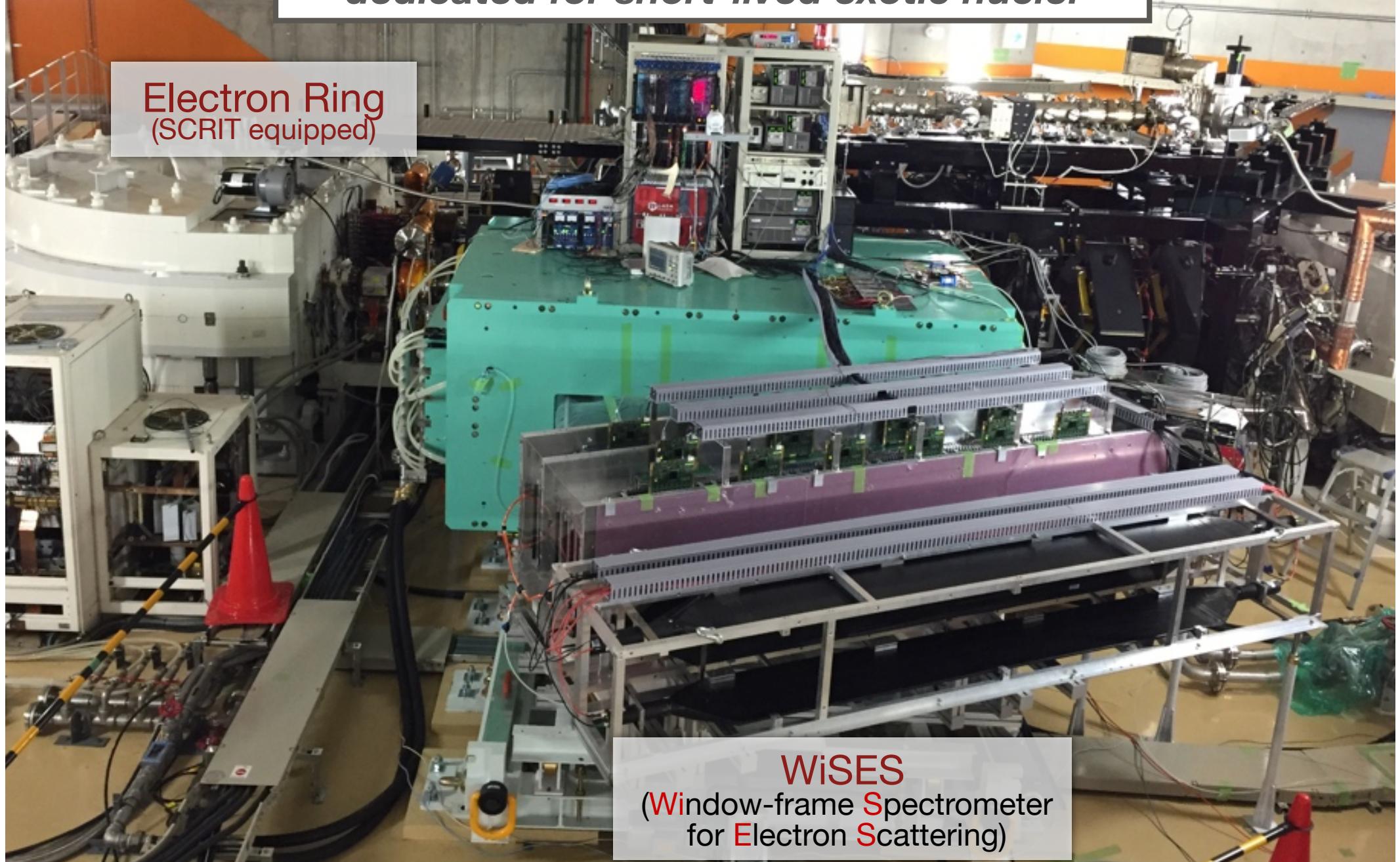
**ERIS** : Nucl. Instrum. Method B317 (2013) 357.

**FRAC** : Rev. Sci. Instrum. 89 (2018) 095107.

# RIKEN SCRIT facility

*The world's first electron-scattering facility  
dedicated for short-lived exotic nuclei*

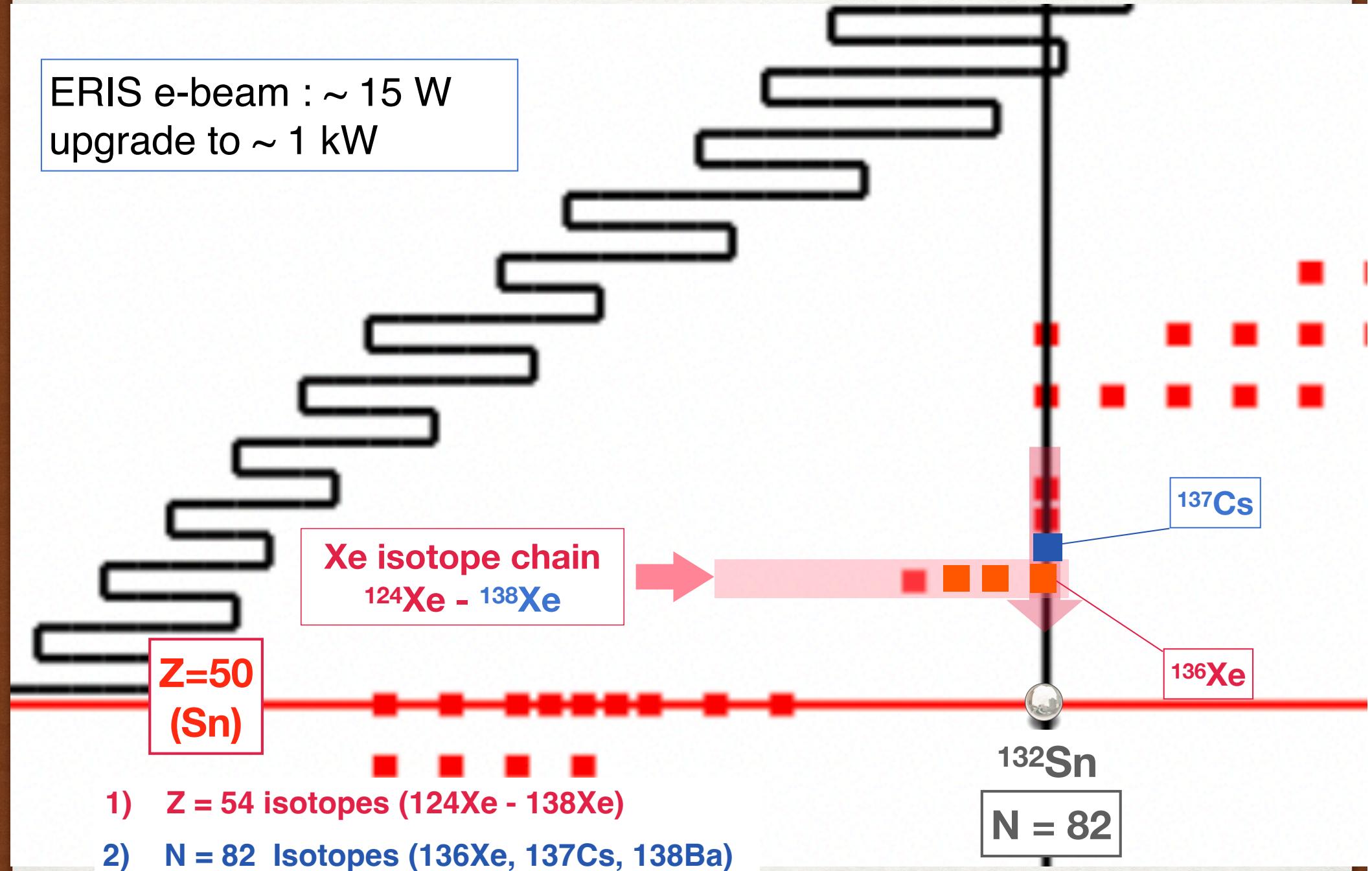
Electron Ring  
(SCRIT equipped)



WiSES  
(Window-frame Spectrometer  
for Electron Scattering)

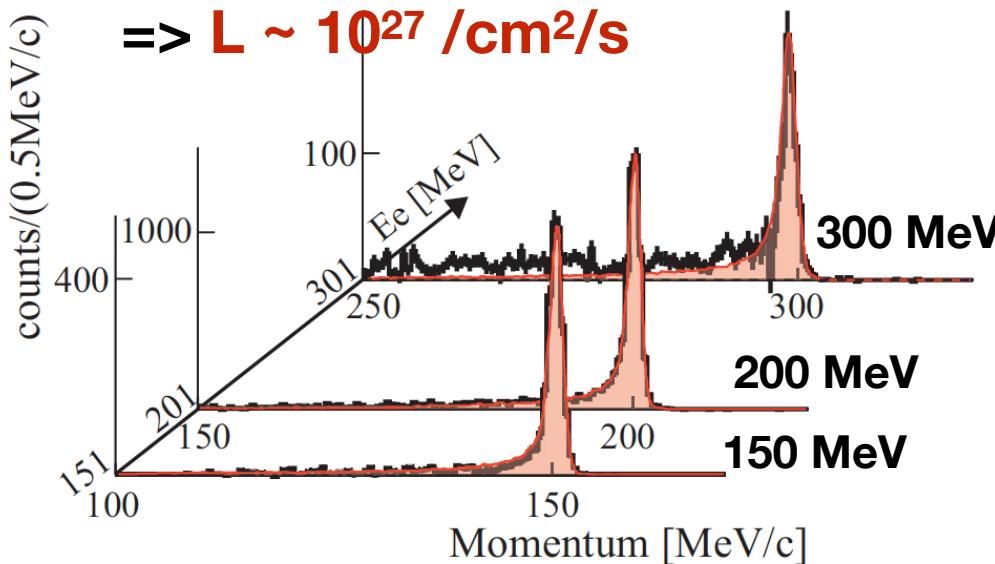
# On-going Physics Program at the SCRIT facility

ERIS e-beam :  $\sim 15$  W  
upgrade to  $\sim 1$  kW

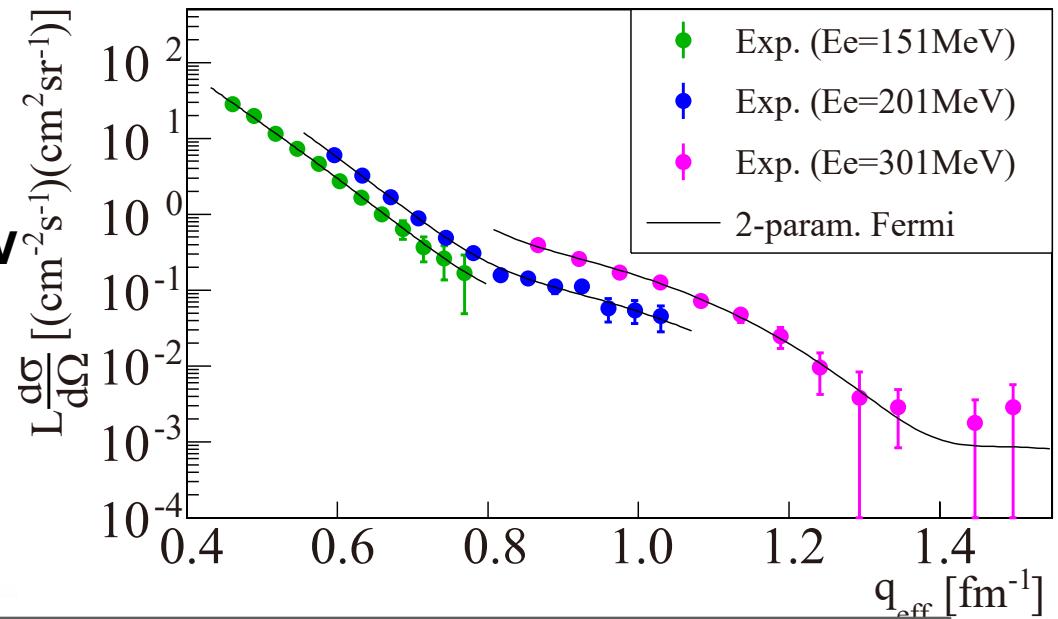


# SCRIT facility

$N_{\text{trapped}} \sim 10^8$  @  $I_e = 250$  mA



PRL 118 (2017) 262501.



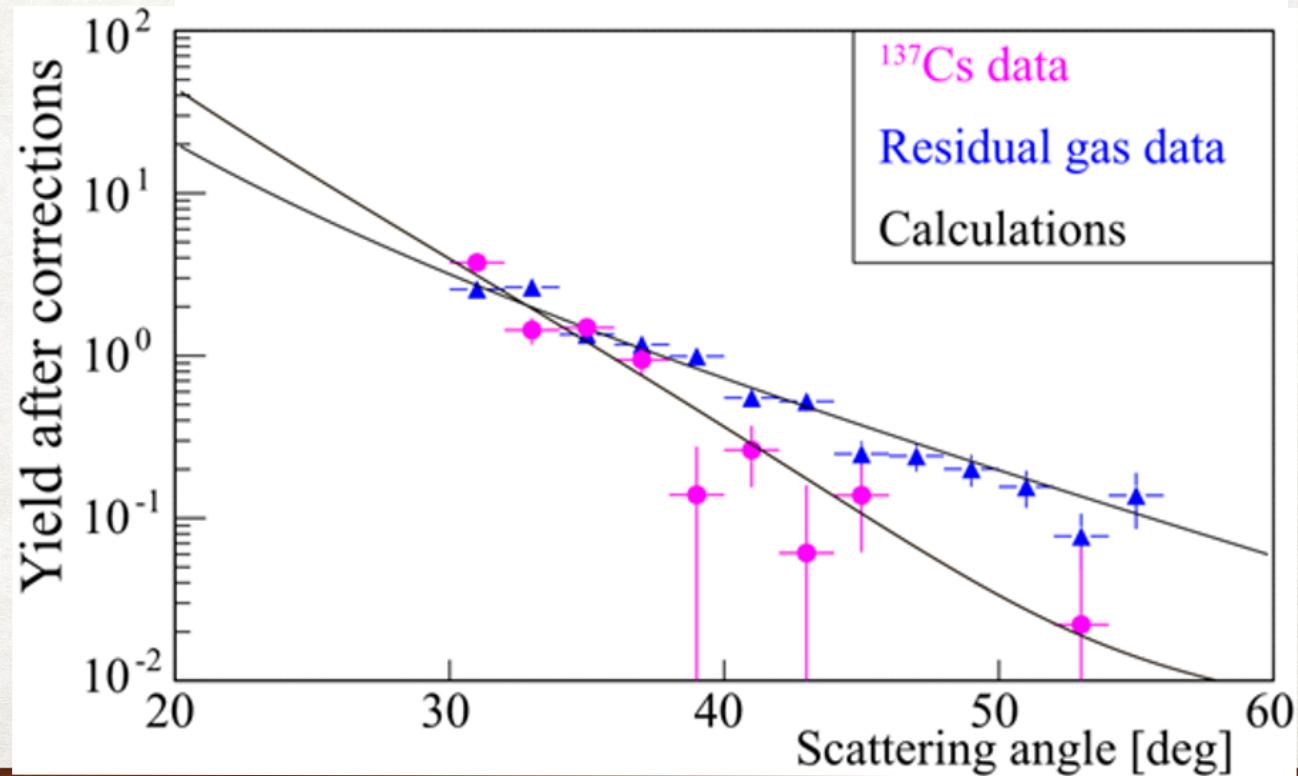
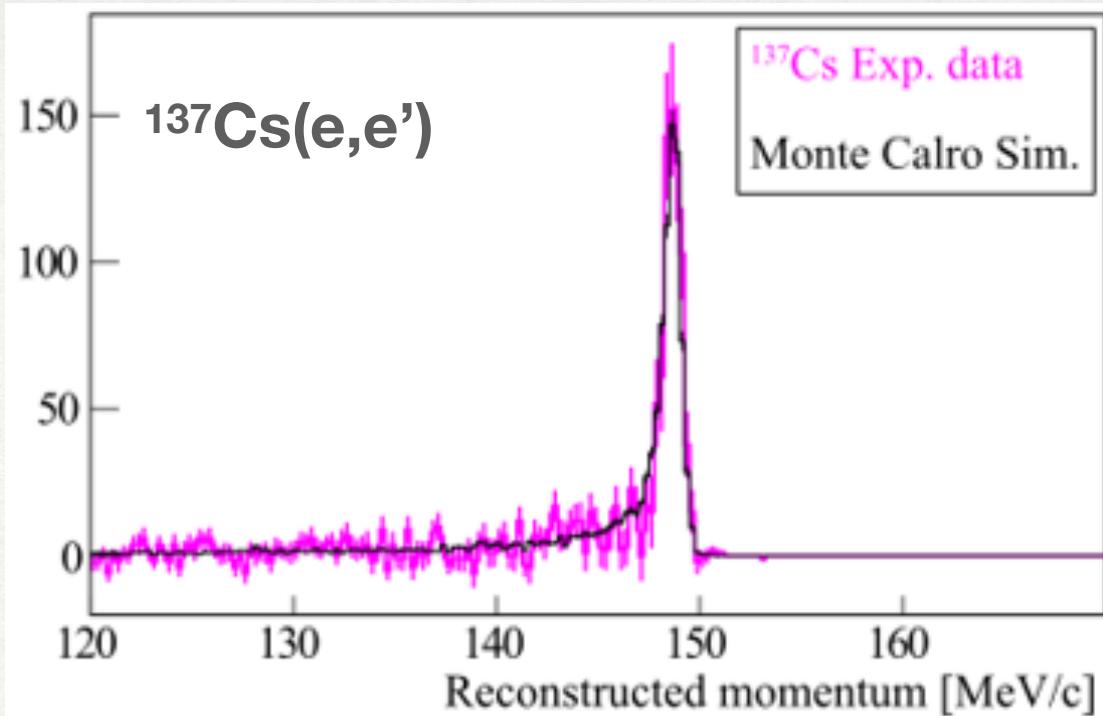
	E <sub>e</sub>	N <sub>beam</sub>	target thickness	L
Hofstadter's era (1950s)	150 MeV	$\sim 1 \text{nA}$ ( $\sim 10^9 / \text{s}$ )	$\sim 10^{19} / \text{cm}^2$	$\sim 10^{28} / \text{cm}^2/\text{s}$
JLAB	12 GeV	$\sim 100 \mu\text{A}$ ( $\sim 10^{14} / \text{s}$ )	$\sim 10^{22} / \text{cm}^2$	$\sim 10^{36} / \text{cm}^2/\text{s}$
SCRIT	150-300 MeV	$300 \text{ mA}$ ( $\sim 10^{18} / \text{s}$ )	$\sim 10^9 / \text{cm}^2$	$\sim 10^{27} / \text{cm}^2/\text{s}$

$\sim 10^7$  trapped ions in e-beam  
of  $\sim 1 \text{ mm}^2$

**$^{137}\text{Cs}(e,e')$**

e-scattering off  
*online-produced*  
*exotic nucleus*

$^{137}\text{Cs}$  : photofission of  $^{238}\text{U}$



# Low- $q$ electron-scattering activities in Japan



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

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- 1) Tohoku ULQ2 facility**
- 2) ULQ2 physics program and current status**
- 3) Summary**

# ULQ2 members



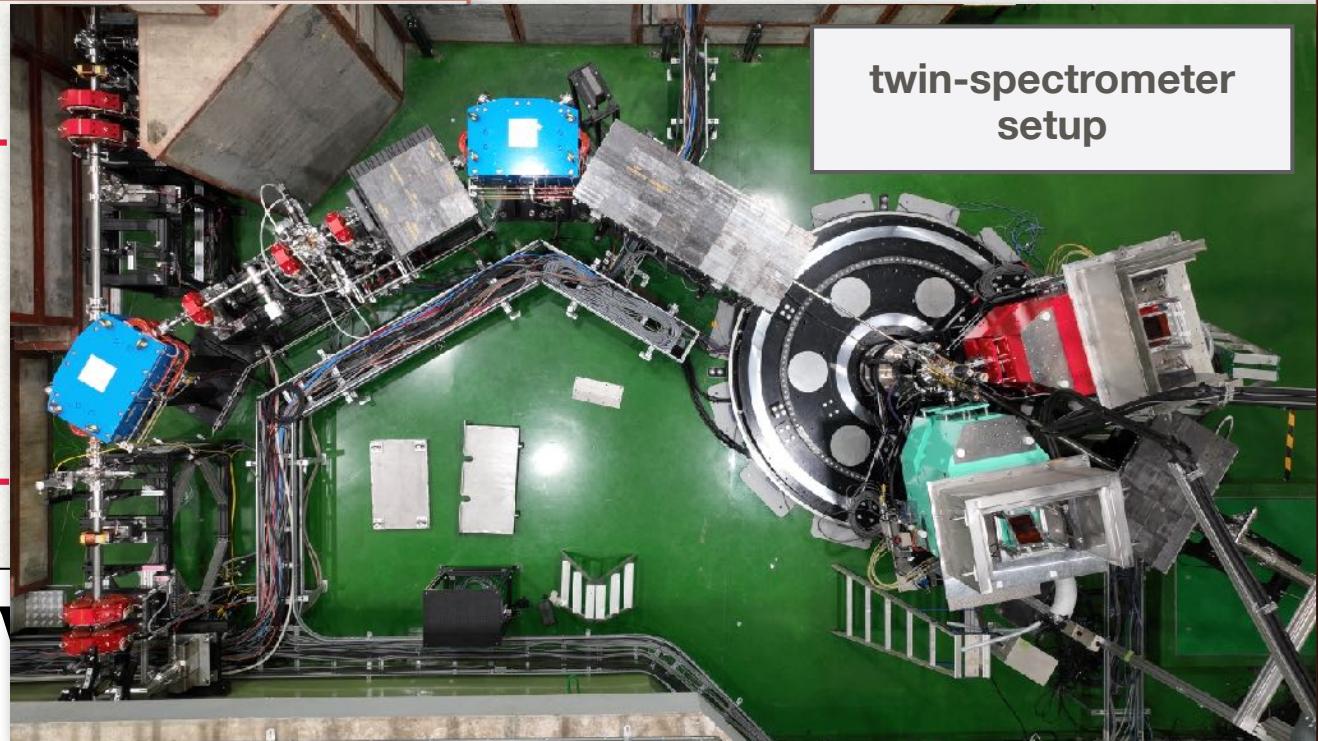
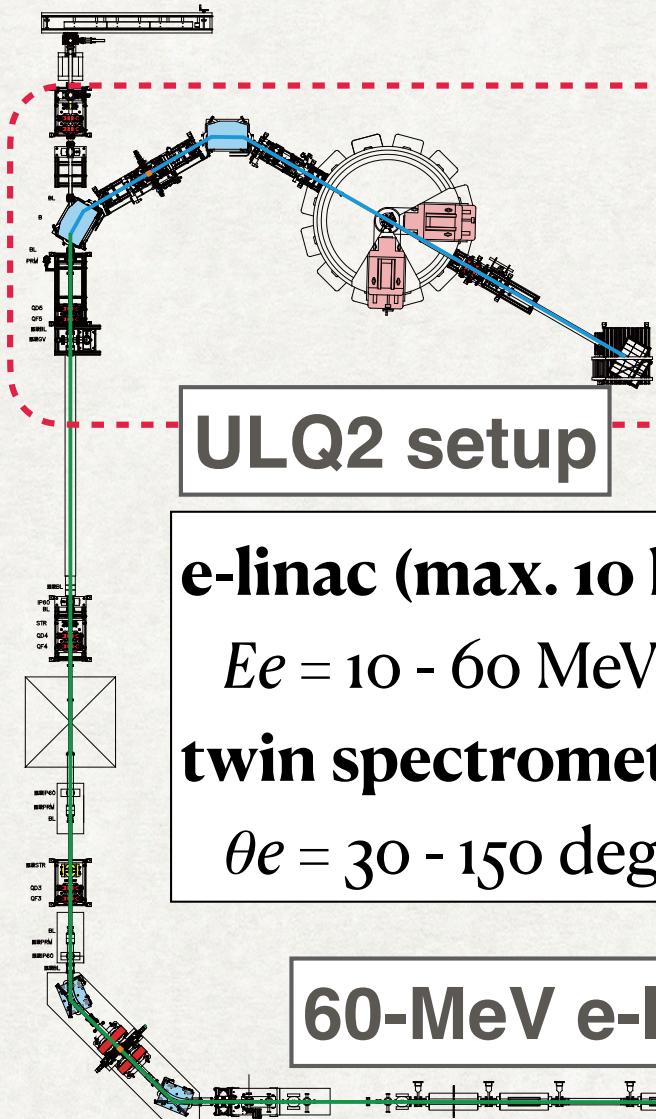


**Sendai**



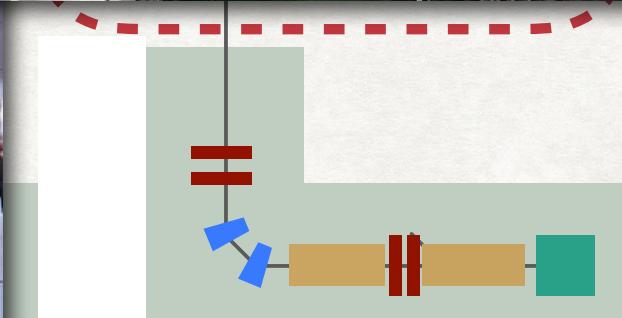
**Research Center for Electron-Photon Science  
Tohoku University**

# Tohoku University Research Center for EElectron-PHoton Science (ELPH)



**e-linac (max. 10 kV)**  
 $E_e = 10 - 60 \text{ MeV}$   
**twin spectrometers**  
 $\theta_e = 30 - 150 \text{ deg.}$

**60-MeV e-linac**



## 60 MeV electron linac

$E_e = 10 - 60 \text{ MeV}$

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

beam size  $\sim 0.6 \text{ mm}$  on target

duty factor  $= 10^{-3}$

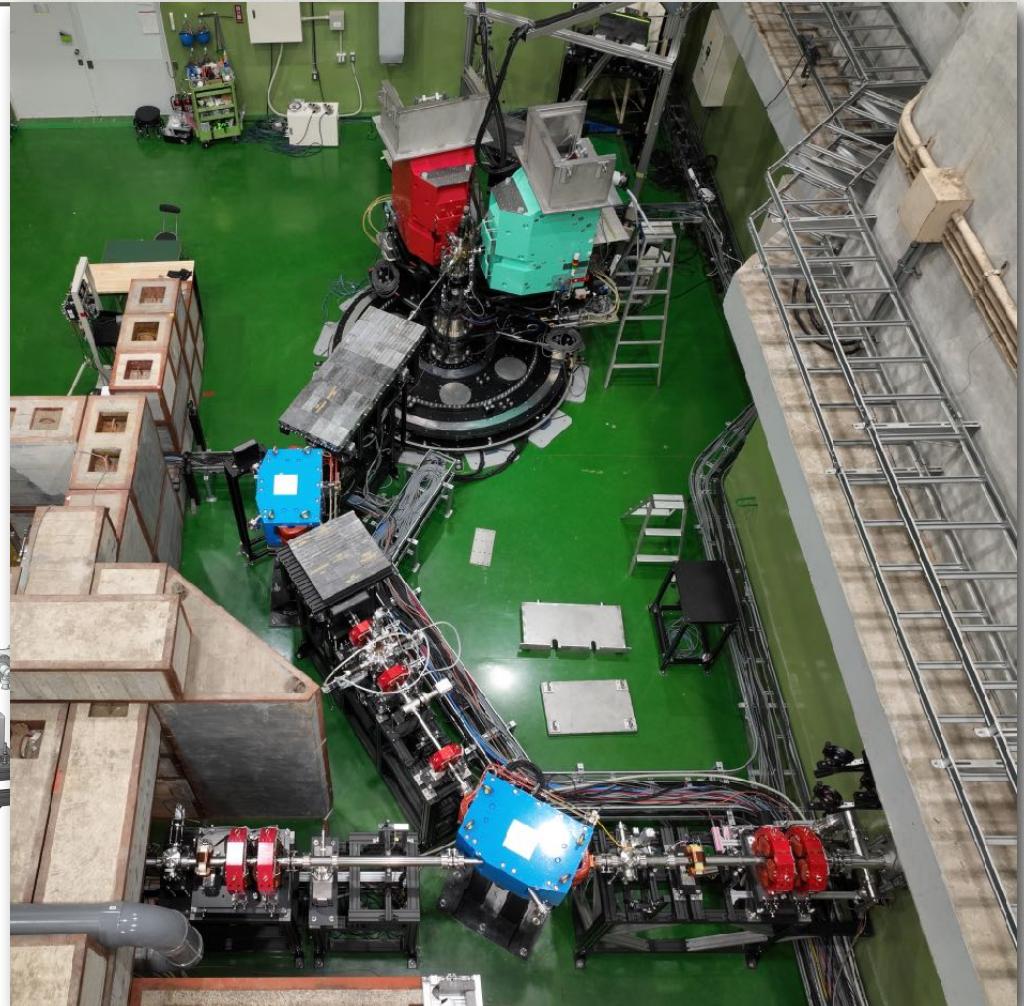
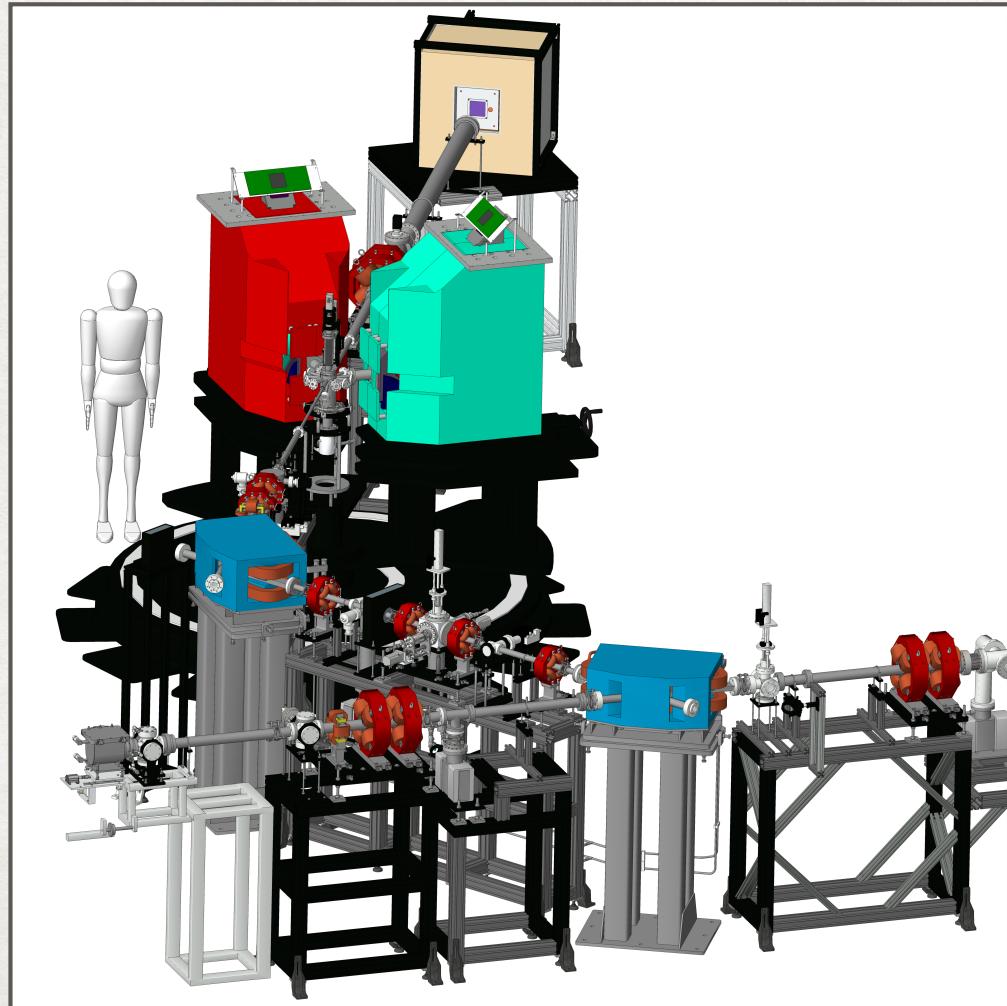
## ULQ2 twin-spectrometer setup

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

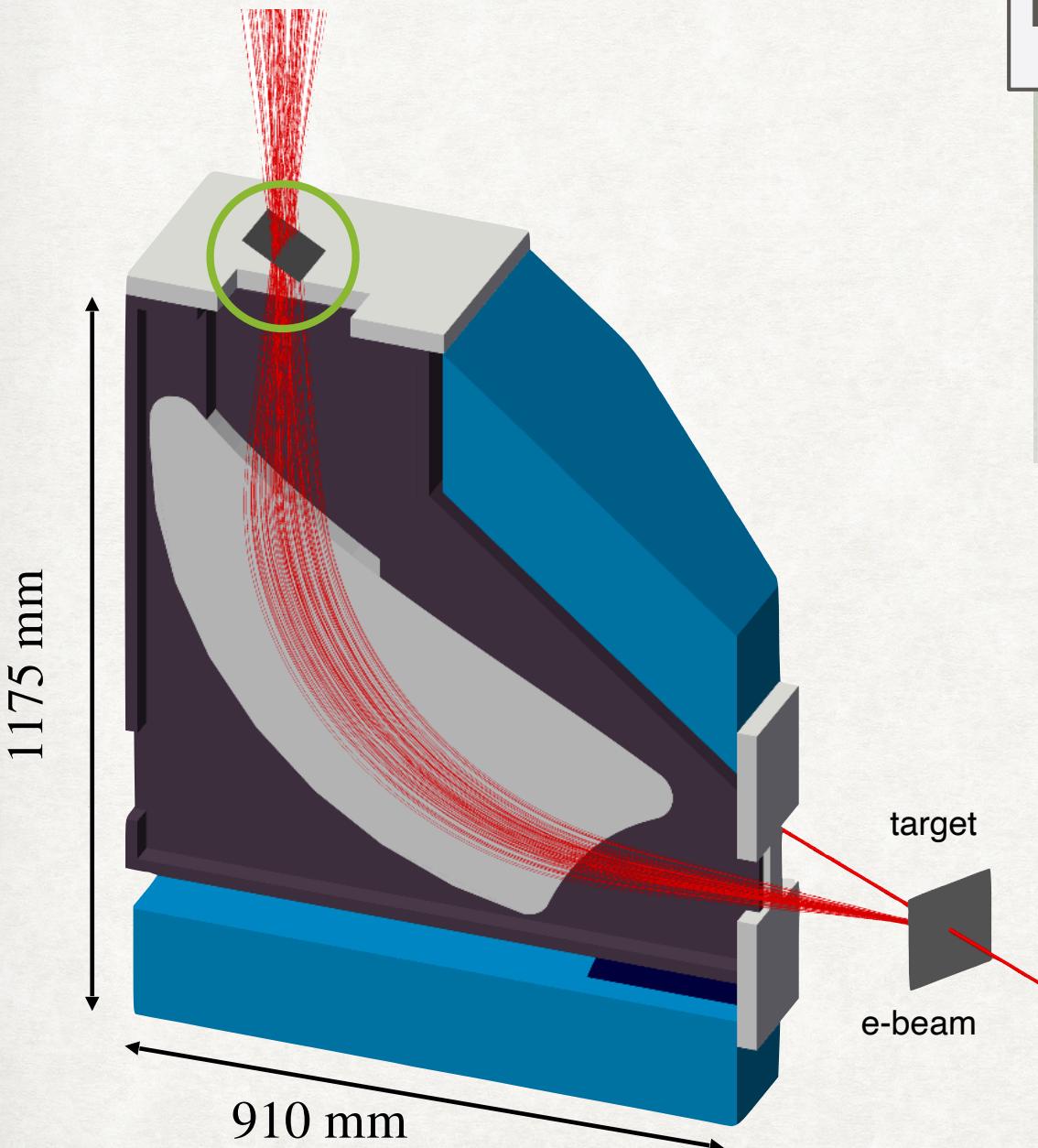
$\Delta\Omega = 6 \text{ mSr}$

$\theta = 30 - 150 \text{ deg.}$

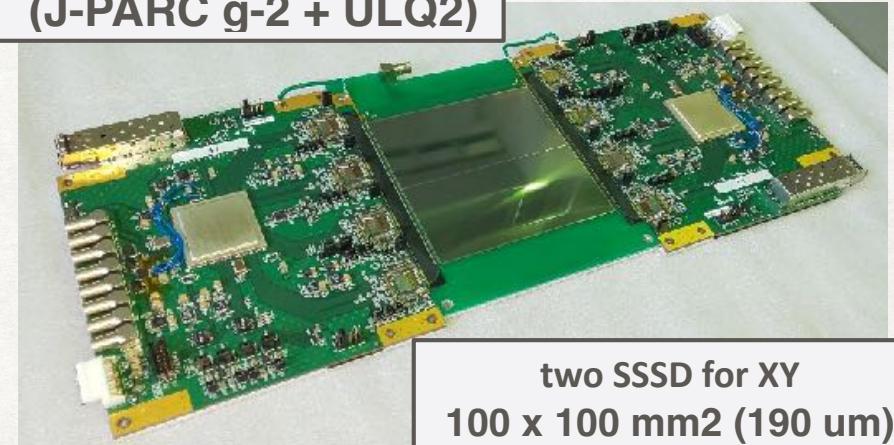
$Q^2 = 3 \times 10^{-5} - 0.013 \text{ (GeV/c)}^2$



# ULQ2 twin spectrometers



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



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

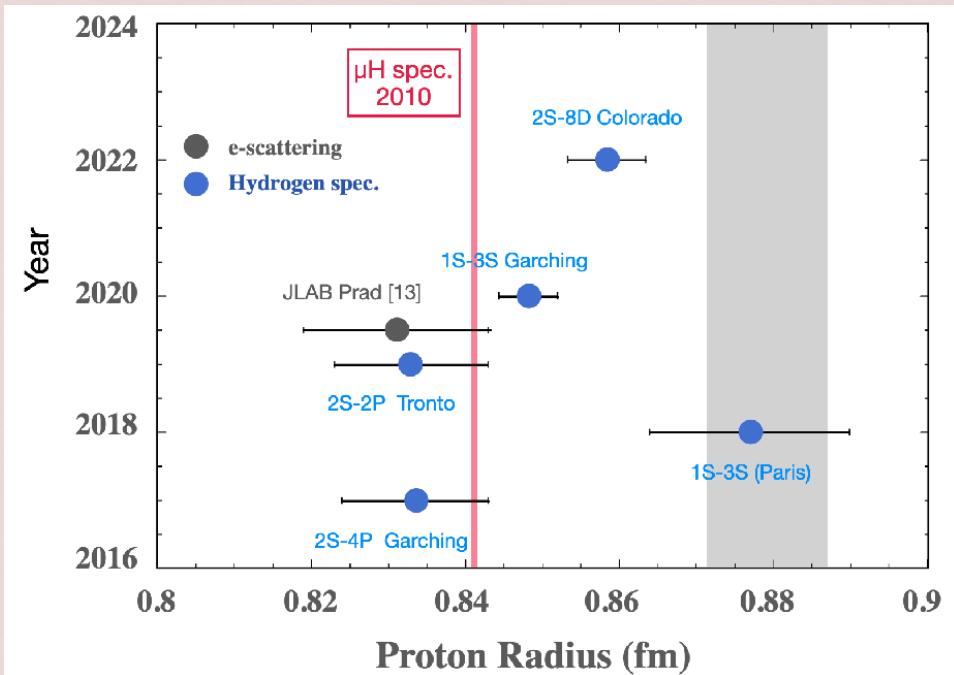
# ULQ2 spectrometer optics up to 2nd order

Parameters	Spectrometer 1	Spectrometer 2
$x_0$ [mm]	4.9	-1.8
$(x_d \delta)$ [mm]	866.1(7)	862.4(7)
$(x_d^2 \delta)$ [mm]	-174(26)	-164(26)
$(x_d \Delta\theta^2)$ [ $10^{-4}$ mm/mrad <sup>2</sup> ]	-4.1(2)	-3.6(2)
$\theta_0$ [mrad]	-2.9(5)	6.8(6)
$(y_d \Delta\theta)$ [mm/mrad]	0.999(4)	0.997(3)
$(y_d \delta\Delta\theta)$ [mm/mrad]	2.01(14)	1.92(11)
$(x_d x_b), (y_d y_b)$ [mm/mm]	$\sim 0.5, 1.8$	

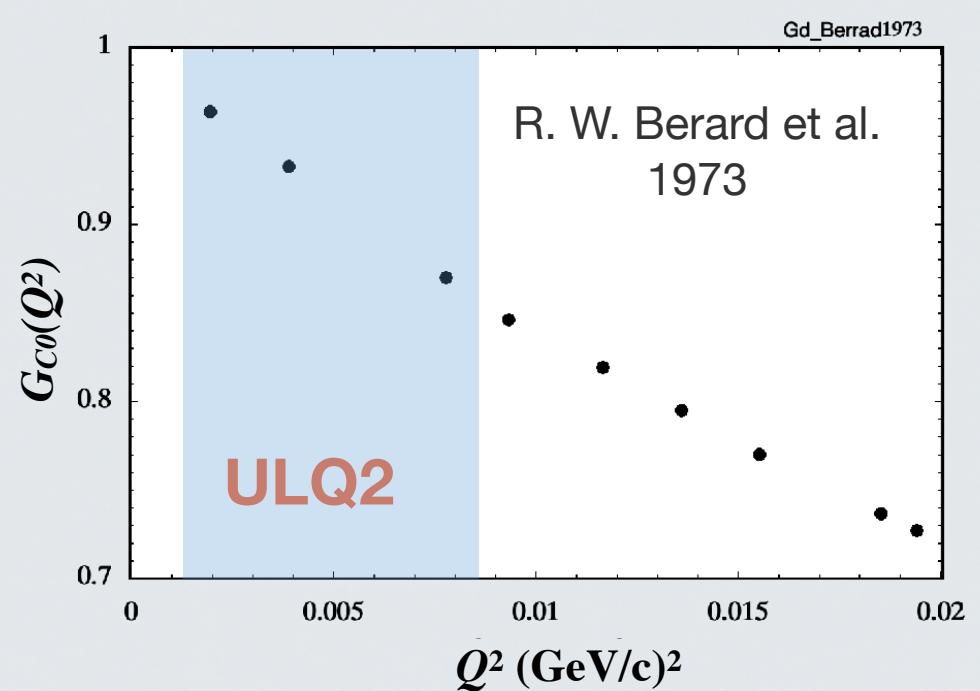
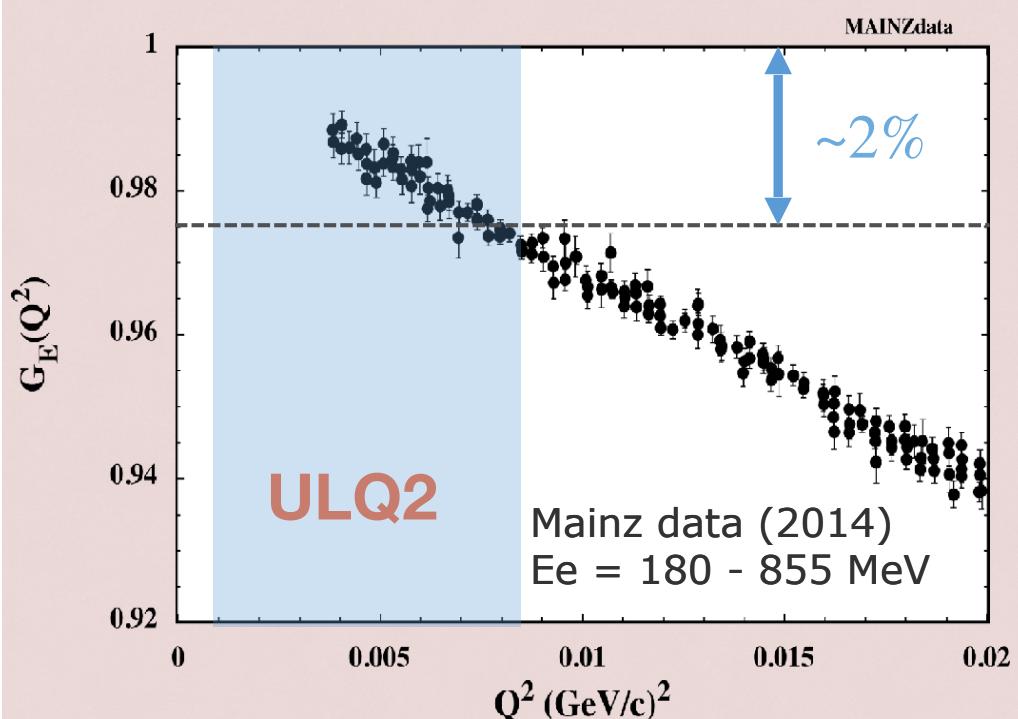
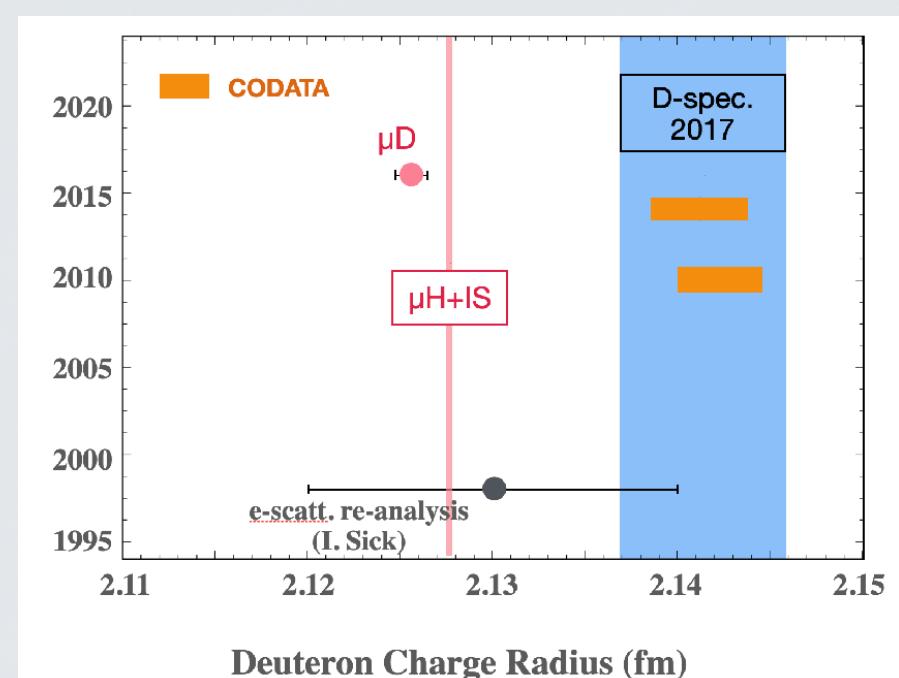
# ULQ2 Physics Program

- 1) Proton : charge radius**       $\text{CH}_2(\text{e},\text{e}')$ 
    - 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  $G_M(Q^2)$
  - 2) Deuteron : charge radius**       $\text{CD}_2(\text{e},\text{e}')$
  - 3)  $^{208}\text{Pb}$  elastic scattering**       $^{208}\text{Pb}(\text{e},\text{e}')$ 
    - cross section under never-yet-measured low- $q$  region
    - $q = 5 - 100 \text{ MeV}$

# proton



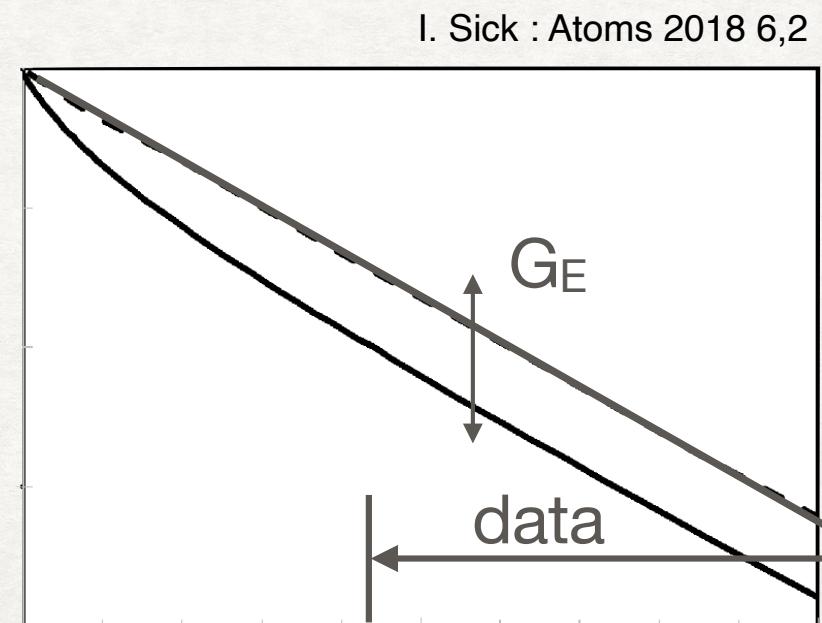
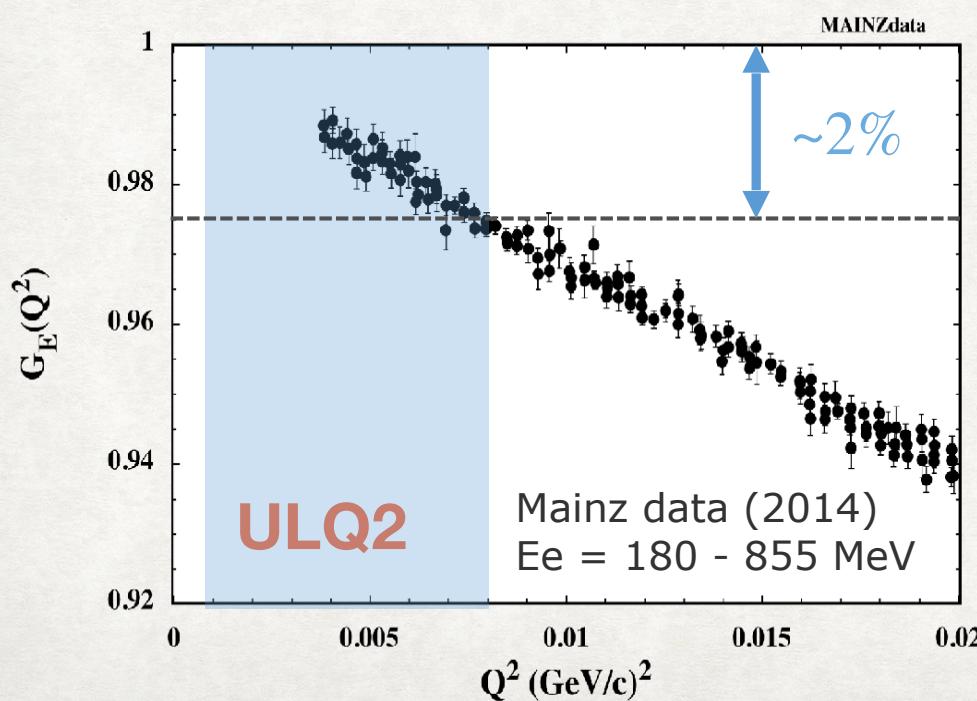
# deuteron



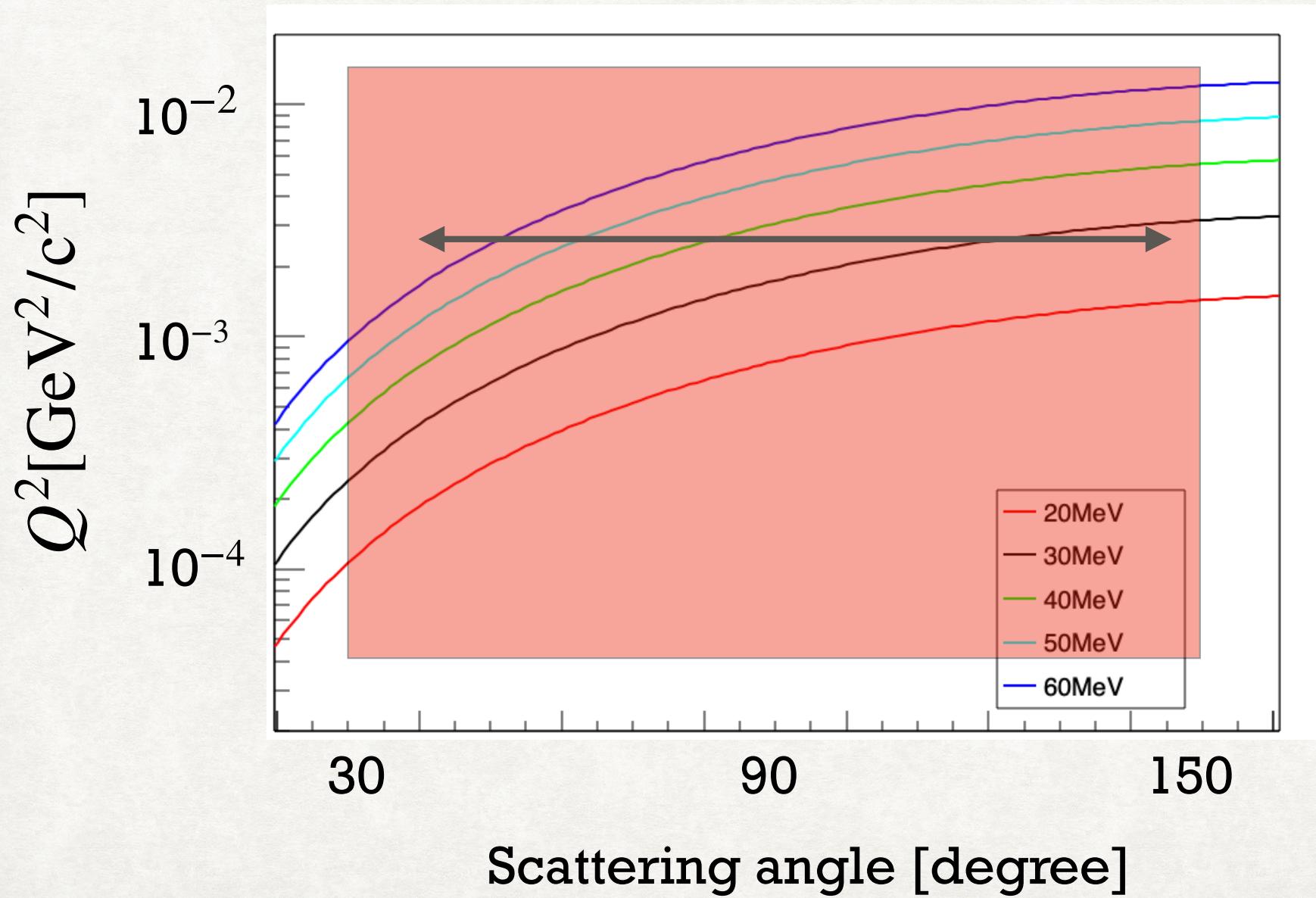
# e+p and e+D at ULQ2

- ① lowest-ever low  $Q^2$  :  $3 \times 10^{-5} - 0.013 \text{ (GeV/c)}^2$
- ② Rosenbluth separation for L/T
  - Ee : 10 - 60 MeV
  - scattering angle : 30 - 150°
- ③ e+p, e+D **absolute cross section relative to e+ $^{12}\text{C}$**

*aiming at “least model-dependent”  $G_E(Q^2)$  determination*



# ULQ2 kinematics

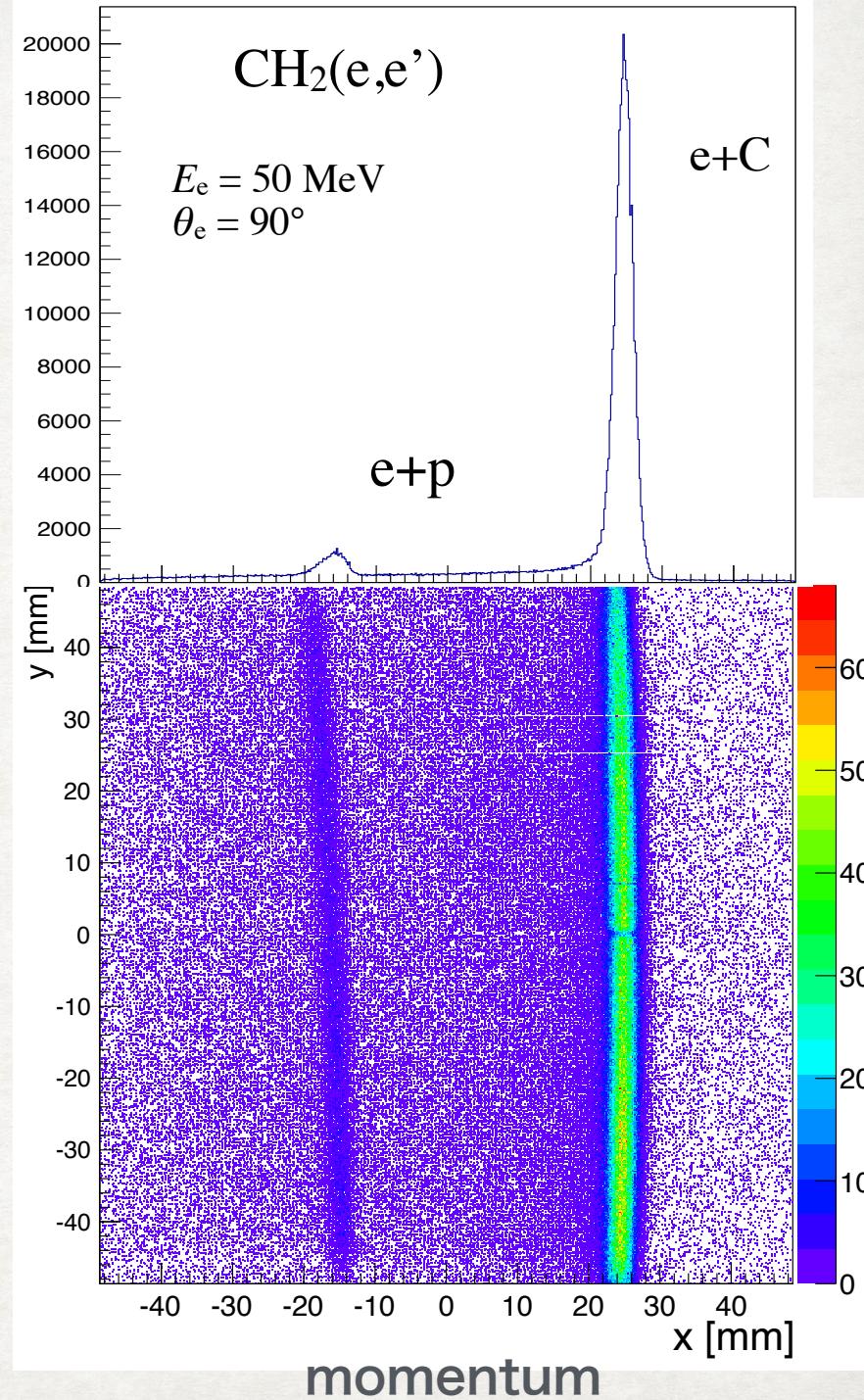


## Absolute cross section

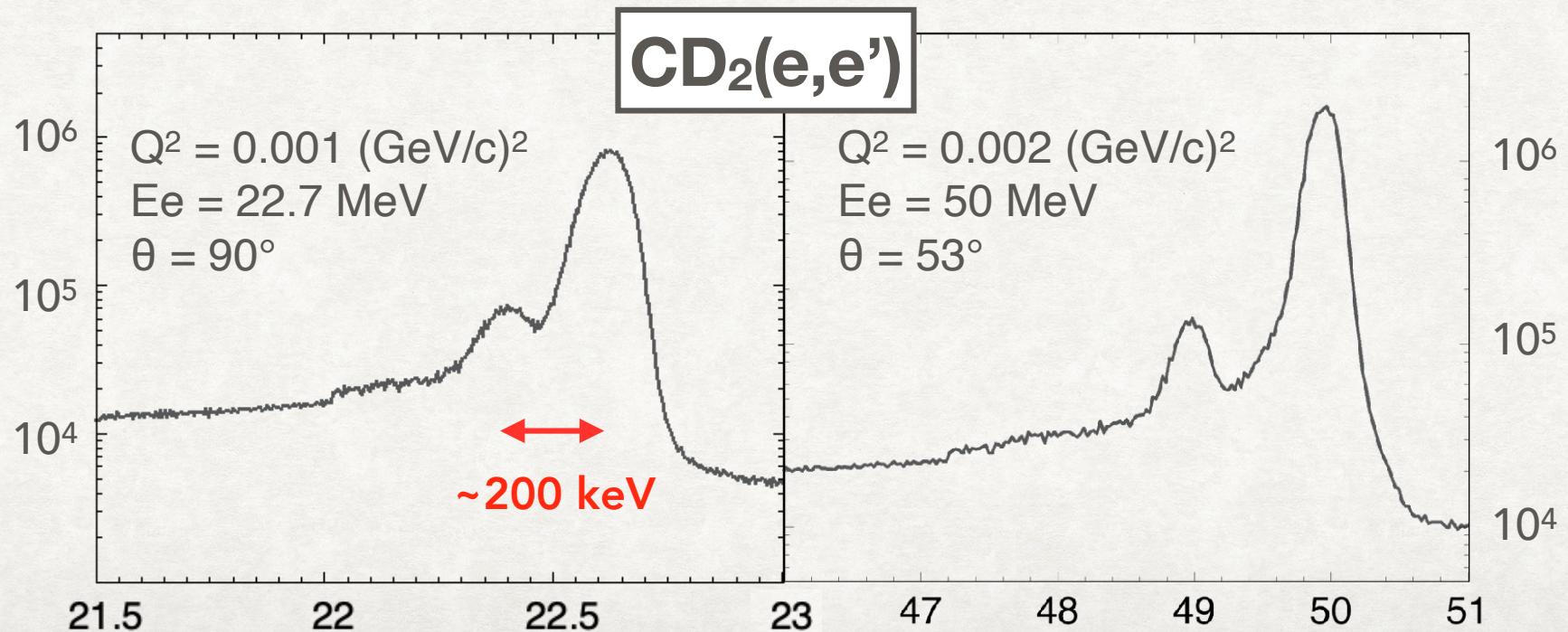
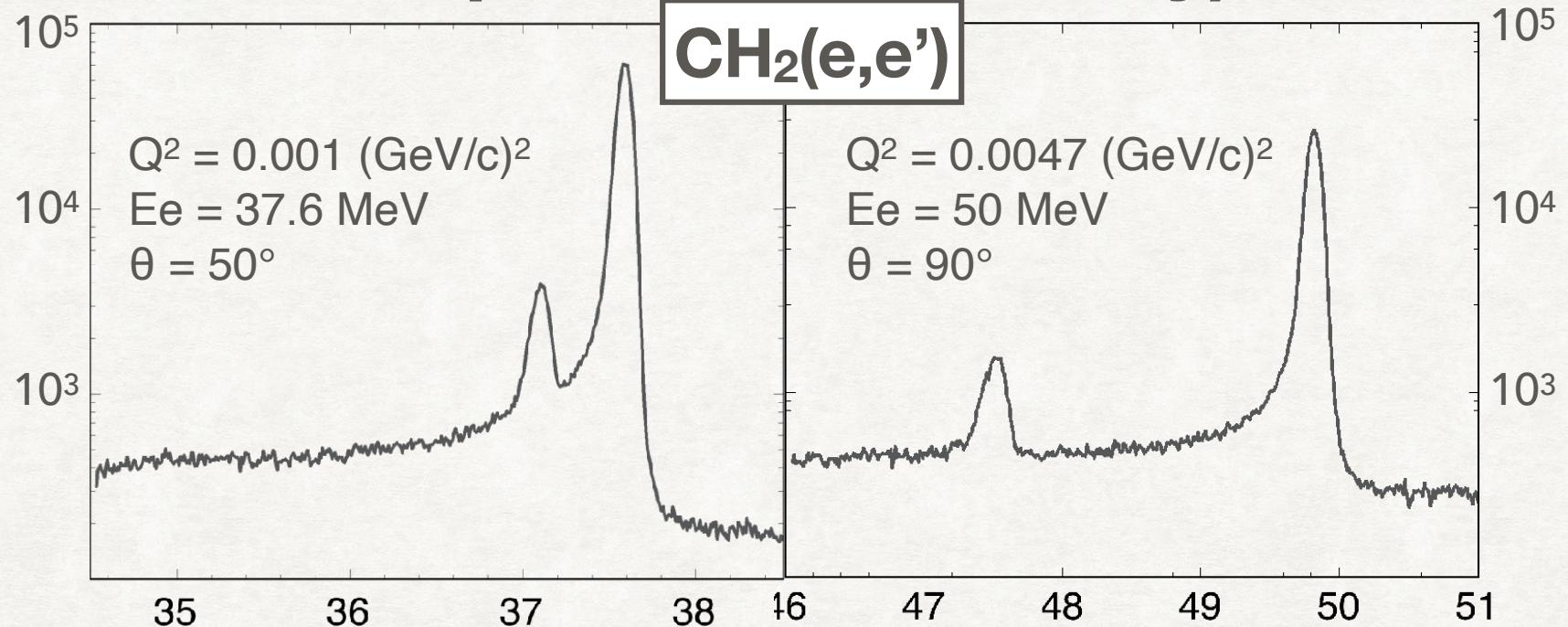
### $\text{CH}_2$ ( $\text{CD}_2$ ) as targets

- 1) thin solid target ( $\sim 100 \text{ }\mu\text{m}$ )
- 2) simultaneous detection  
of  $e+C$  and  $e+p$  (d) scattering
- 3)  $\langle r_c^2 \rangle$  of  $^{12}\text{C}$  : accuracy  $\sim 10^{-3}$

scattering angle

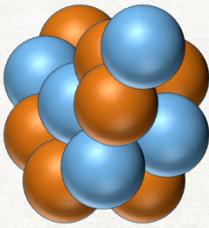


# Online spectra (preliminary)



**additional physics opportunity  
at ULQ2**

# nuclear charge density, moments



Proton

Neutron

## 1) charge density

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

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

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

## 2) 2nd moment

exp.

$$\langle r_c^2 \rangle = \int r^2 \rho_c(r) d^3r \quad \text{Proton}$$

$$= \cancel{\langle r_{p(point)}^2 \rangle} + \langle r_p^2 \rangle +$$



Neutron



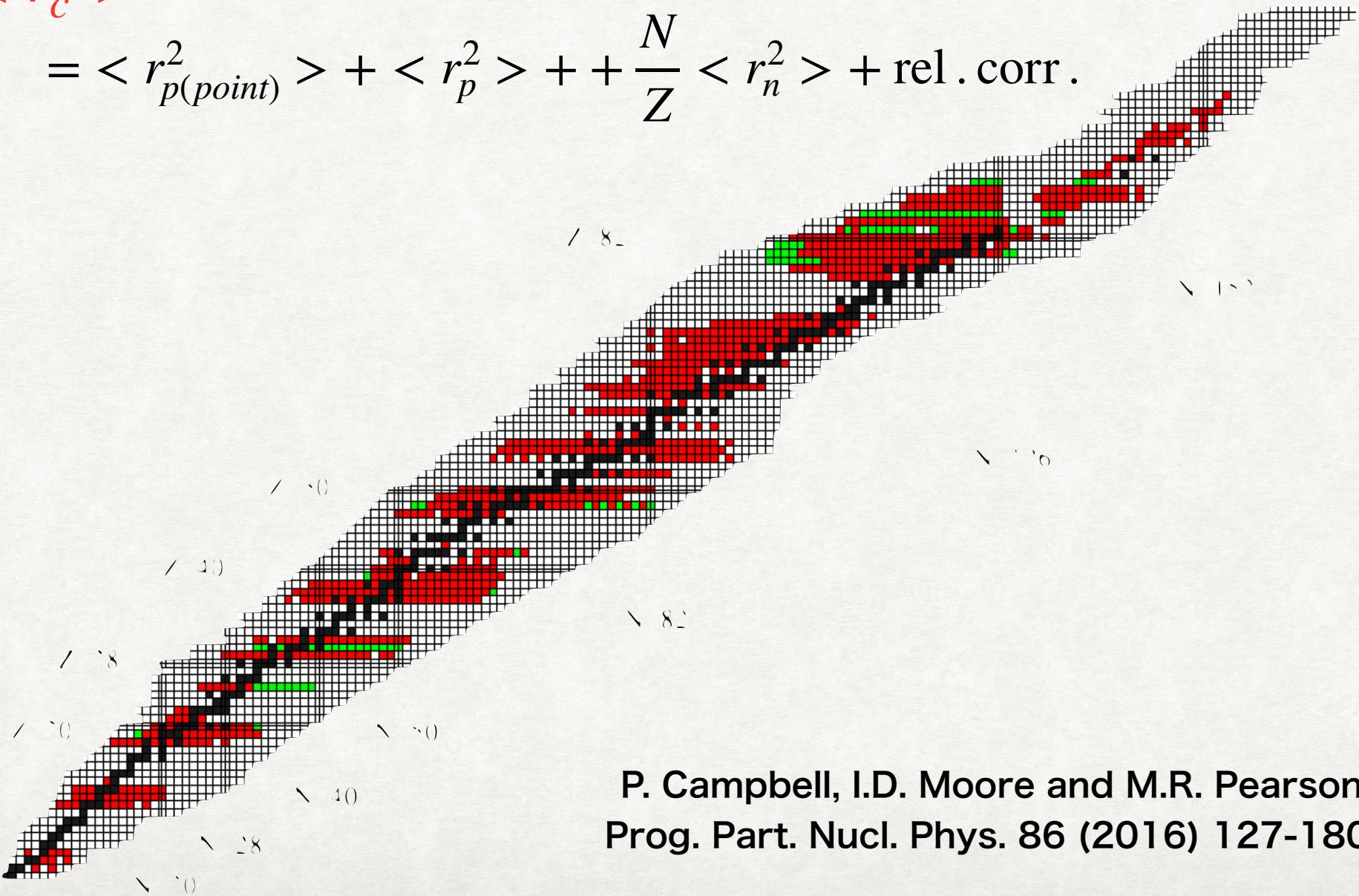
$$\cancel{\langle r_{n(point)}^2 \rangle} + \frac{N}{Z} \langle r_n^2 \rangle + \text{rel. corr.}$$

theories

# Nuclear Chart

$$\langle r_c^2 \rangle$$

$$= \langle r_{p(point)}^2 \rangle + \langle r_p^2 \rangle + + \frac{N}{Z} \langle r_n^2 \rangle + \text{rel. corr.}$$



P. Campbell, I.D. Moore and M.R. Pearson  
Prog. Part. Nucl. Phys. 86 (2016) 127-180.

### 3) 4th moment

$$\langle r_c^4 \rangle = \int r^4 \rho_c(r) d^3r$$

exp.

theories

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

$$+ \cancel{\langle r_{n(point)}^4 \rangle} + \frac{10}{3} \cancel{\langle r_{n(point)}^2 \rangle} \langle r_n^2 \rangle \frac{N}{Z}$$



+ rel. corr.

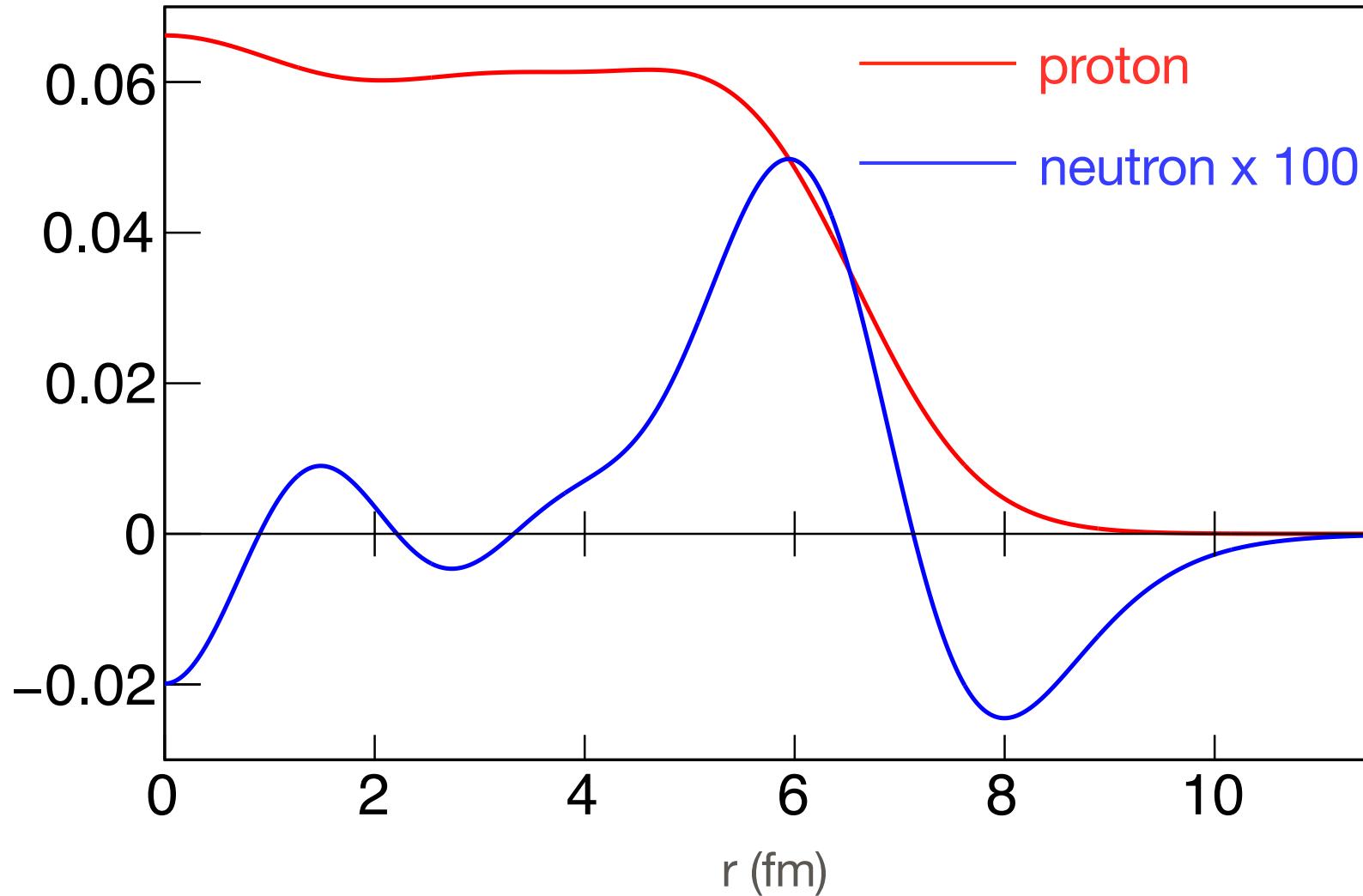
RMS n-radius

- 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

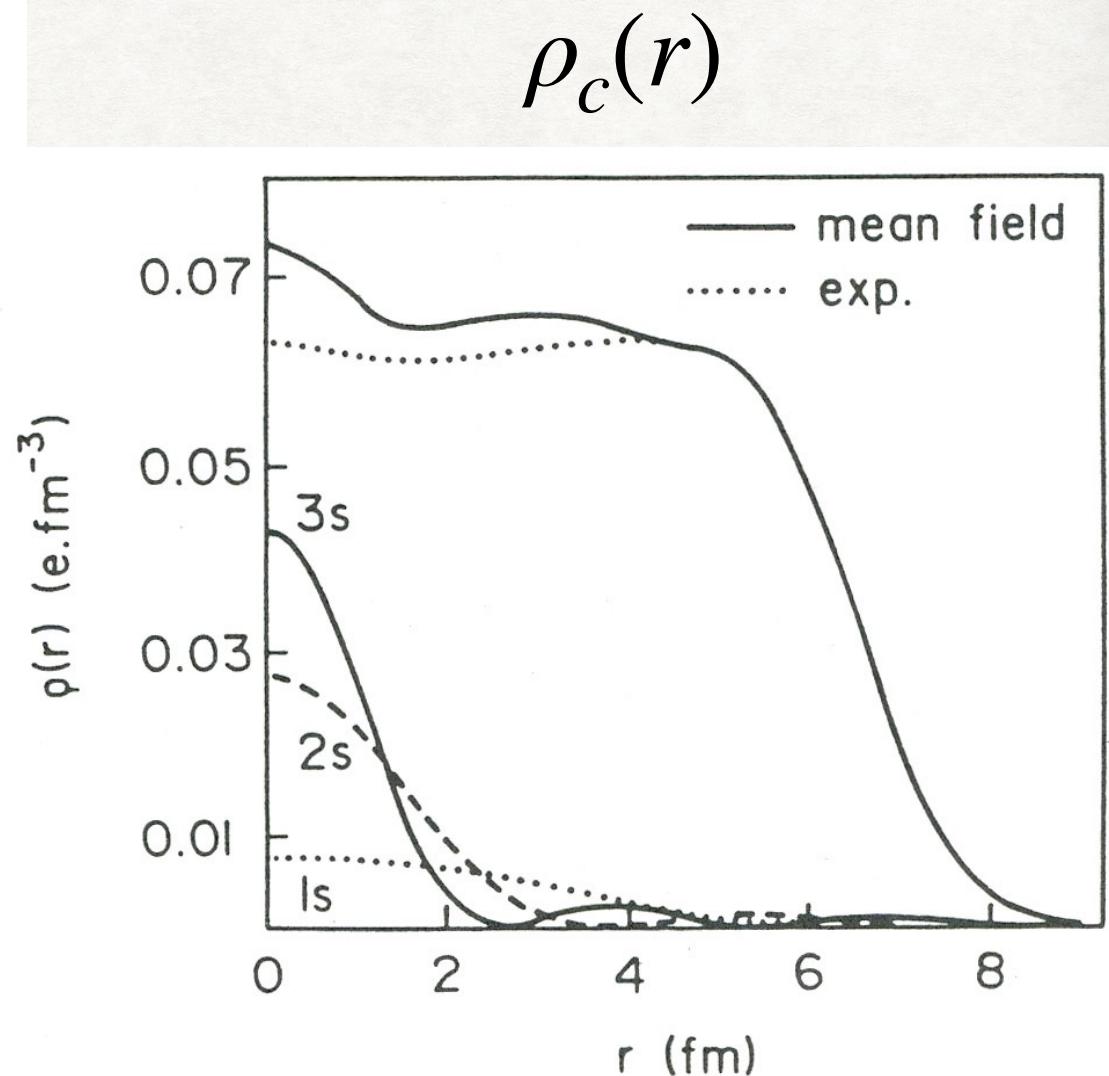
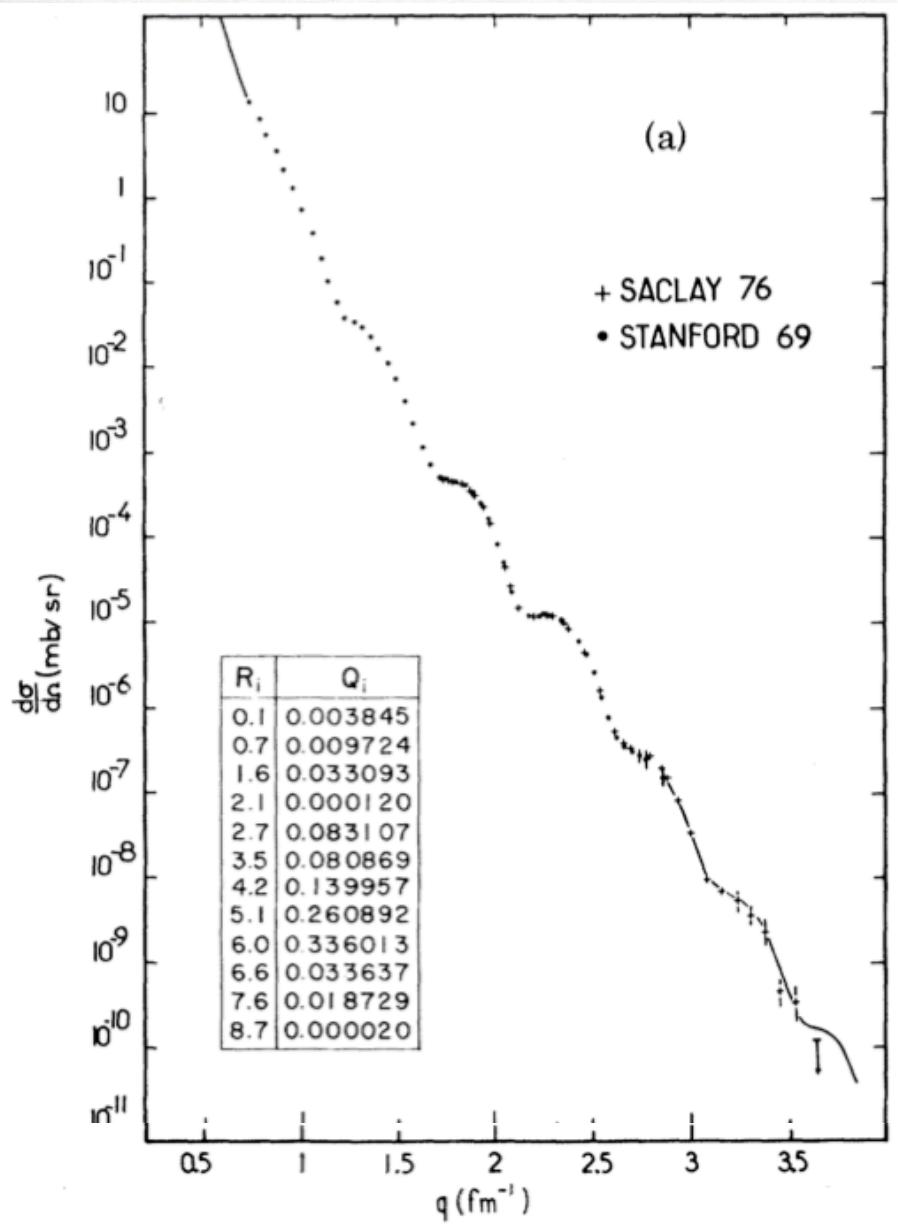
**208Pb**

**RMF NL3**

charge density distributions

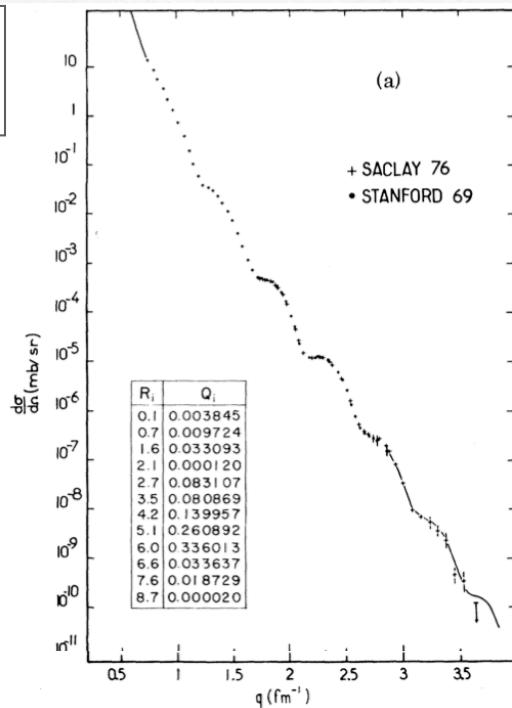


# $^{208}\text{Pb}$



# RMS radii of (point) proton and neutron of $^{208}\text{Pb}$

$^{208}\text{Pb}$



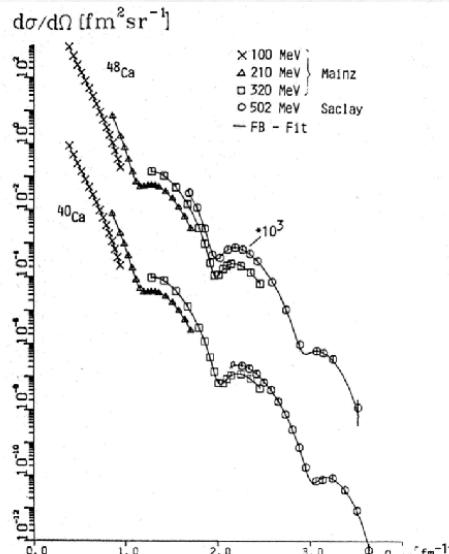
	$R_p$	$R_n$	$\delta R$
$^{208}\text{Pb}$	Rel.	5.454(0.013)	5.728(0.057)
	Non.	5.447(0.014)	5.609(0.054)
	Exp.	$R_c = 5.503(0.014)$	

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)

$^{48}\text{Ca}$



Figur 2.12 : Wirkungsquerschnitte für  $^{40}\text{Ca}$  und  $^{48}\text{Ca}$ , aufgetragen über  $q_{\text{eff}}$ . Die durchgezogene Linie ist durch Anpassen einer Fourier-Bessel-Ladungsverteilung (s. Abschnitt 3) an diese Daten festgelegt. Die eingezeichneten statistischen Fehler sind überwiegend kleiner als die zur Darstellung benutzten Symbole.

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

JLab : CREX for  $^{48}\text{Ca}$  (parity-violating e-scattering)

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

# possible application for n-rich exotic nuclei at SCRIT

$$\langle r_c^4 \rangle = \int r^4 \rho_c(r) d^3r$$

- no hope to determine  $\rho_c(r)$  precisely at low- $L$  SCRIT facility

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

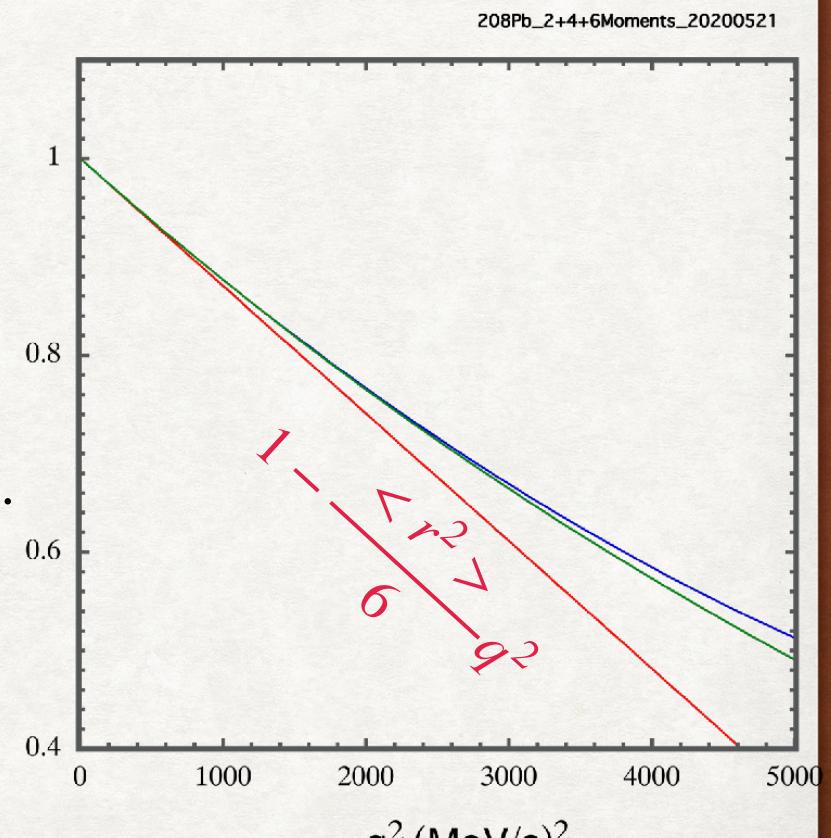
- charge form factor at low  $q$

$$F_c(q) \sim 1 - \frac{\langle r^2 \rangle_c}{6} q^2 + \frac{\langle r^4 \rangle_c}{120} q^4 + \dots$$

large cross section at low  $q$



Low-luminosity e-RI scattering



# deuteron

# 2nd moment

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

## isotope shift measurement

$$\langle r_c^2 \rangle - \langle r_p^2 \rangle = 3.82070(31) \text{ fm}^2$$

# 4th moment

$$\langle r_c^4 \rangle = \langle r_{p(point)}^4 \rangle + \frac{10}{3} \langle r_{p(point)}^2 \rangle \langle r_p^2 \rangle$$

$$+\frac{10}{3} \langle r_{n(point)}^2 \rangle - \langle r_n^2 \rangle + \text{rel. corr.}$$

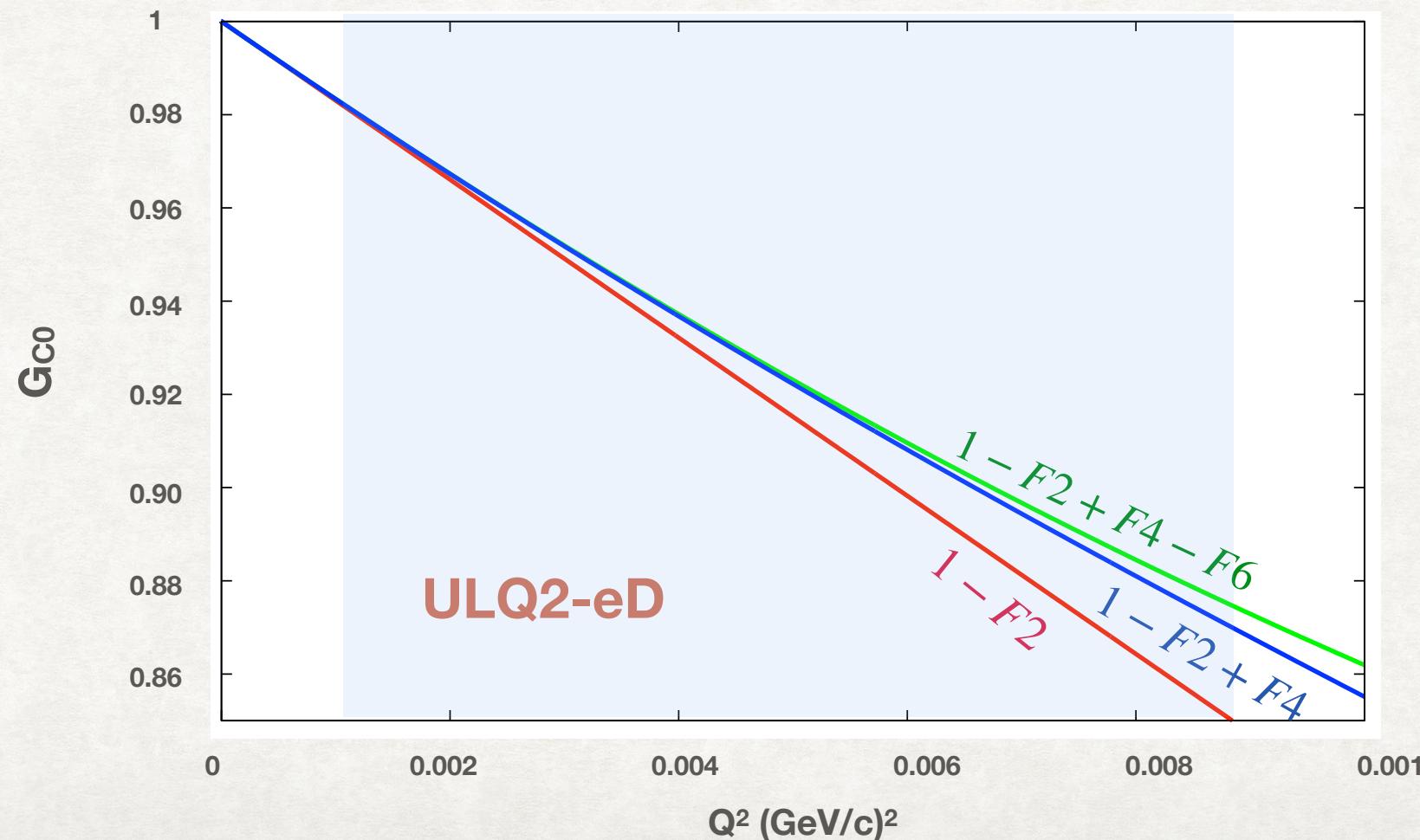


$$= \boxed{\langle r_{p(point)}^4 \rangle} + \frac{10}{3} \boxed{\langle r_{p(point)}^2 \rangle} (\langle r_p^2 \rangle + \langle r_n^2 \rangle) + \text{rel. corr.}$$

# Low-energy electron scattering provides $\langle r^4 \rangle$

charge form factor at low  $q$

$$G_{C0} \sim 1 - \frac{\langle r_c^2 \rangle}{3!} Q^2 + \frac{\langle r_c^4 \rangle}{5!} Q^4 - \dots$$



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

A. A. Filin<sup>1</sup>, V. Baru<sup>2,3,4</sup>, E. Epelbaum<sup>1</sup>, H. Krebs<sup>1</sup>, D. Möller<sup>1</sup> and P. Reinert<sup>1</sup>

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<sup>2</sup>Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn,  
D-53115 Bonn, Germany

<sup>3</sup>Institute for Theoretical and Experimental Physics NRC “Kurchatov Institute”, Moscow 117218, Russia

<sup>4</sup>P.N. Lebedev Physical Institute of the Russian Academy of Sciences, 119991, Leninskiy Prospect 53, Moscow, Russia

$$\langle r_c^2 \rangle = \langle r_{str}^2 \rangle + \langle r_p^2 \rangle + \langle r_n^2 \rangle + \text{rel. corr.}$$

μD spec.

χEFT

$$\langle r_{str}^2 \rangle = (1.9731^{+0.0013}_{-0.0018})^2 \text{ fm}^2$$

$$\langle r_c^2 \rangle = (2.12560(78))^2 \text{ fm}^2$$

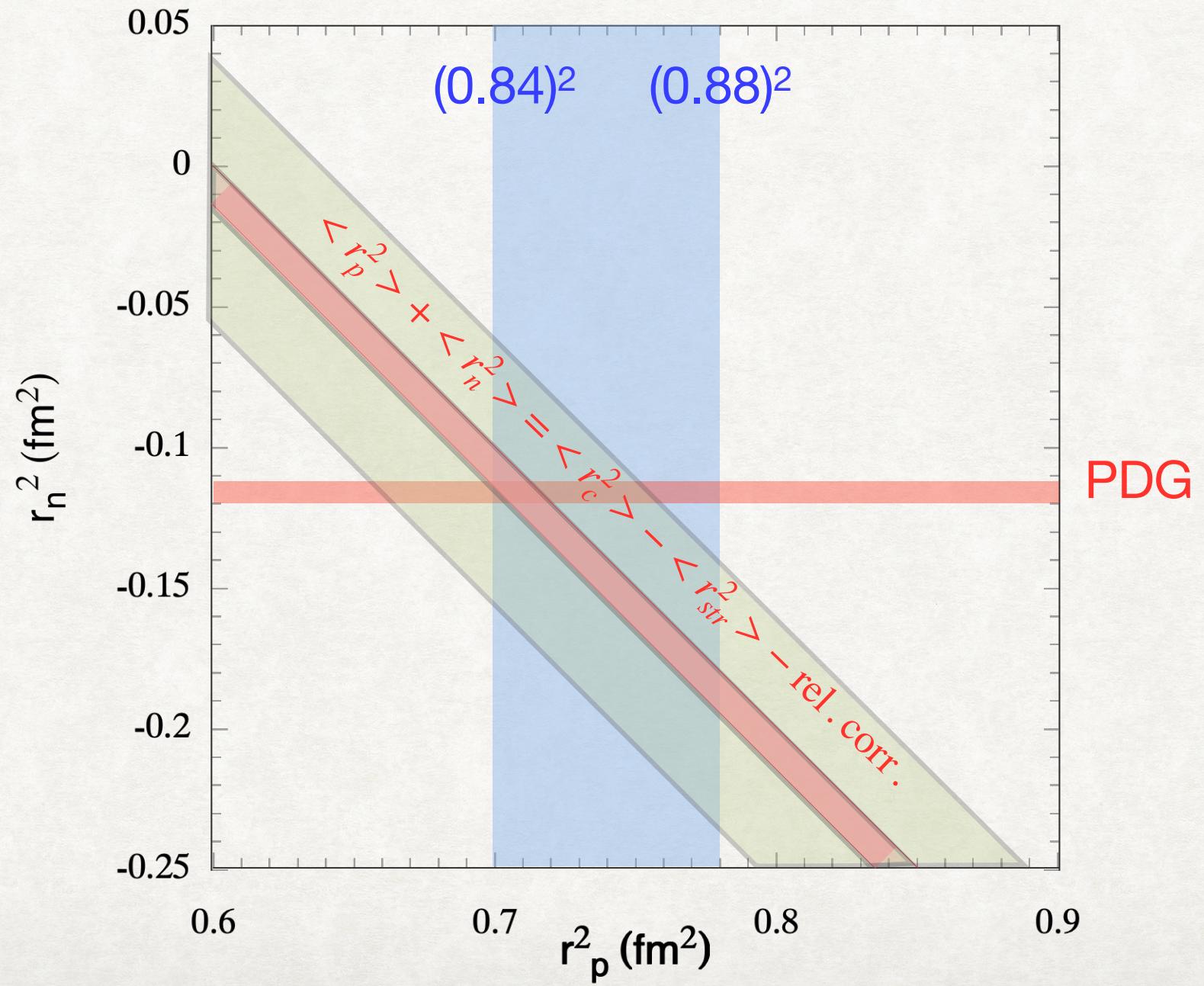
$$\langle r_p^2 \rangle = (0.8414(9))^2 \text{ fm}^2$$

$$\text{rel. corr. : } -\frac{3}{4m^2} \quad (\text{Darwin-Foldy})$$



$$\langle r_n^2 \rangle = -0.106^{+0.007}_{-0.005} \text{ fm}^2$$

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



# conclusions

- low-q e-scattering activities in Japan  
Tohoku ULQ2 for proton radius etc.  
RIKEN SCRIT for structure studies of exotic nuclei
- Tohoku ULQ2 (Ultra-Low Q2)  
 $E_e = 10 - 60 \text{ MeV}$   
 $\theta_e = 30 - 150 \text{ deg.}$   
high-resolution twin spectrometers  
 $Q^2 = 3 \times 10^{-5} - 0.013 (\text{GeV}/c)^2$  : lowest-ever
- Physics run just started!!

stay tuned.

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), TS (Tohoku)