Low-energy electron scattering

- beyond proton radius -

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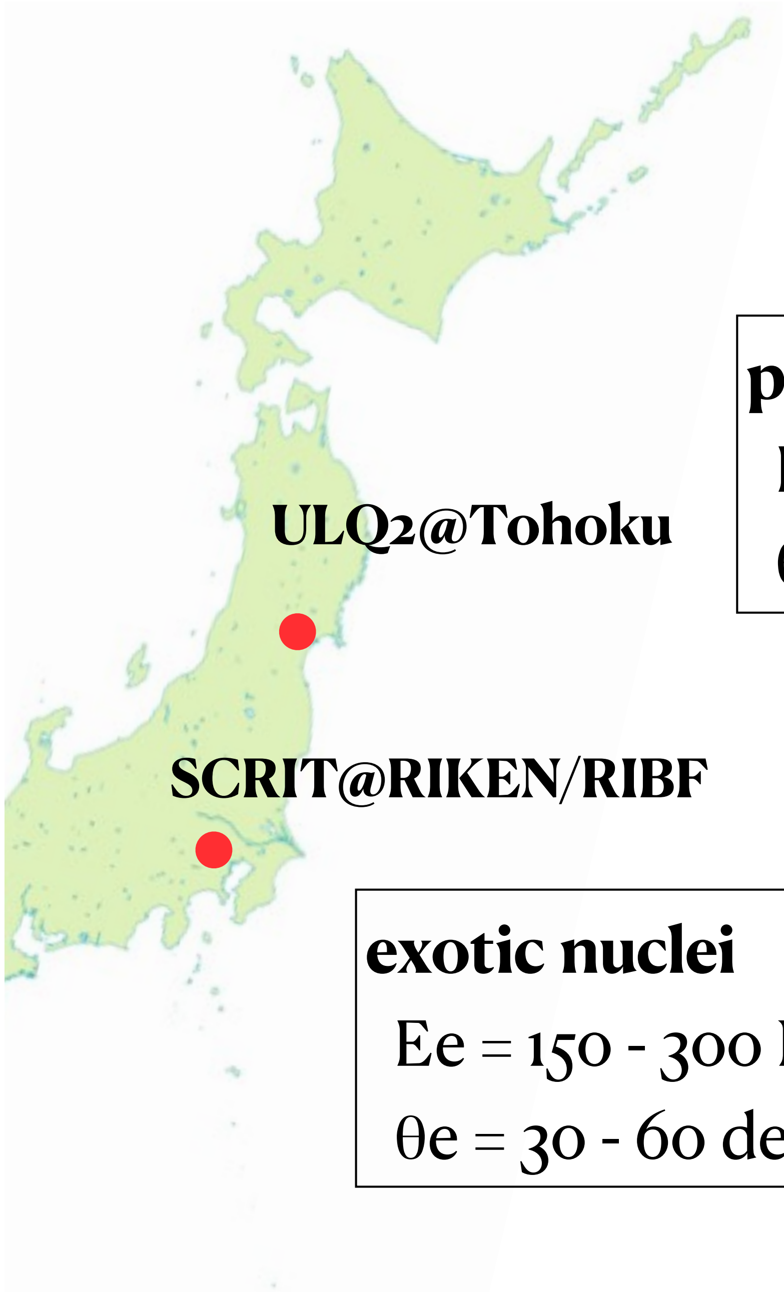
Low-energy electron-scattering facilities



proton radius

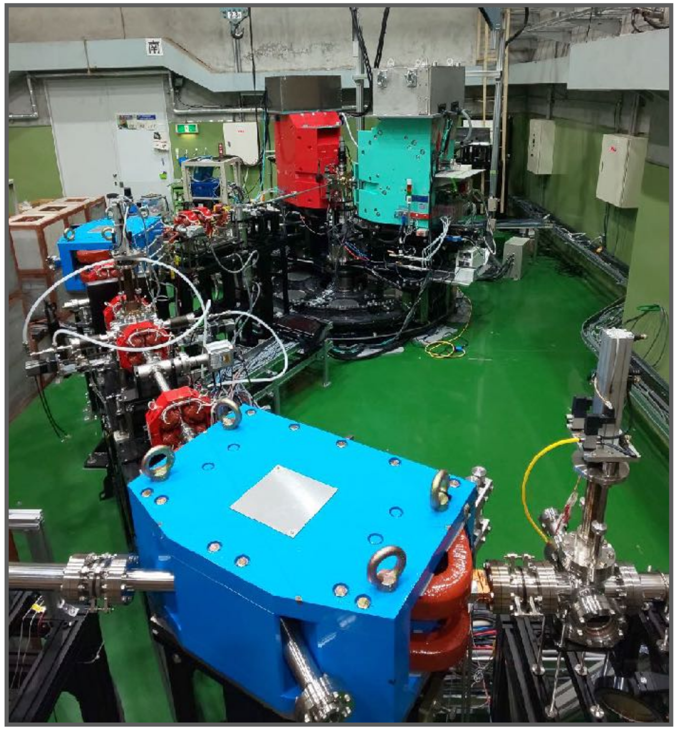
Ee = 10 - 60 MeV

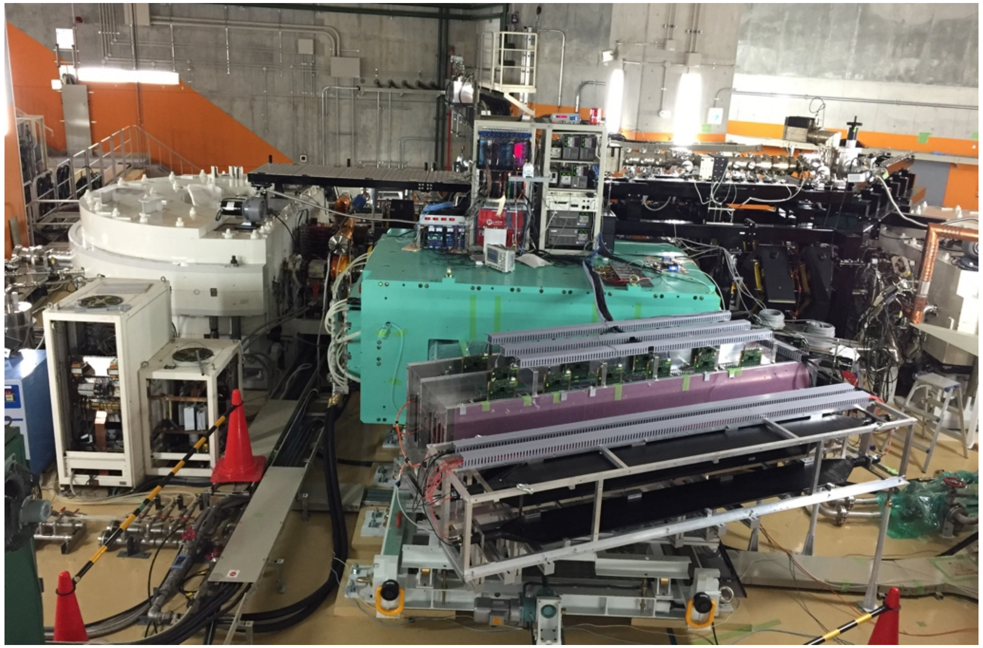
θe = 30 - 150 deg.

exotic nuclei

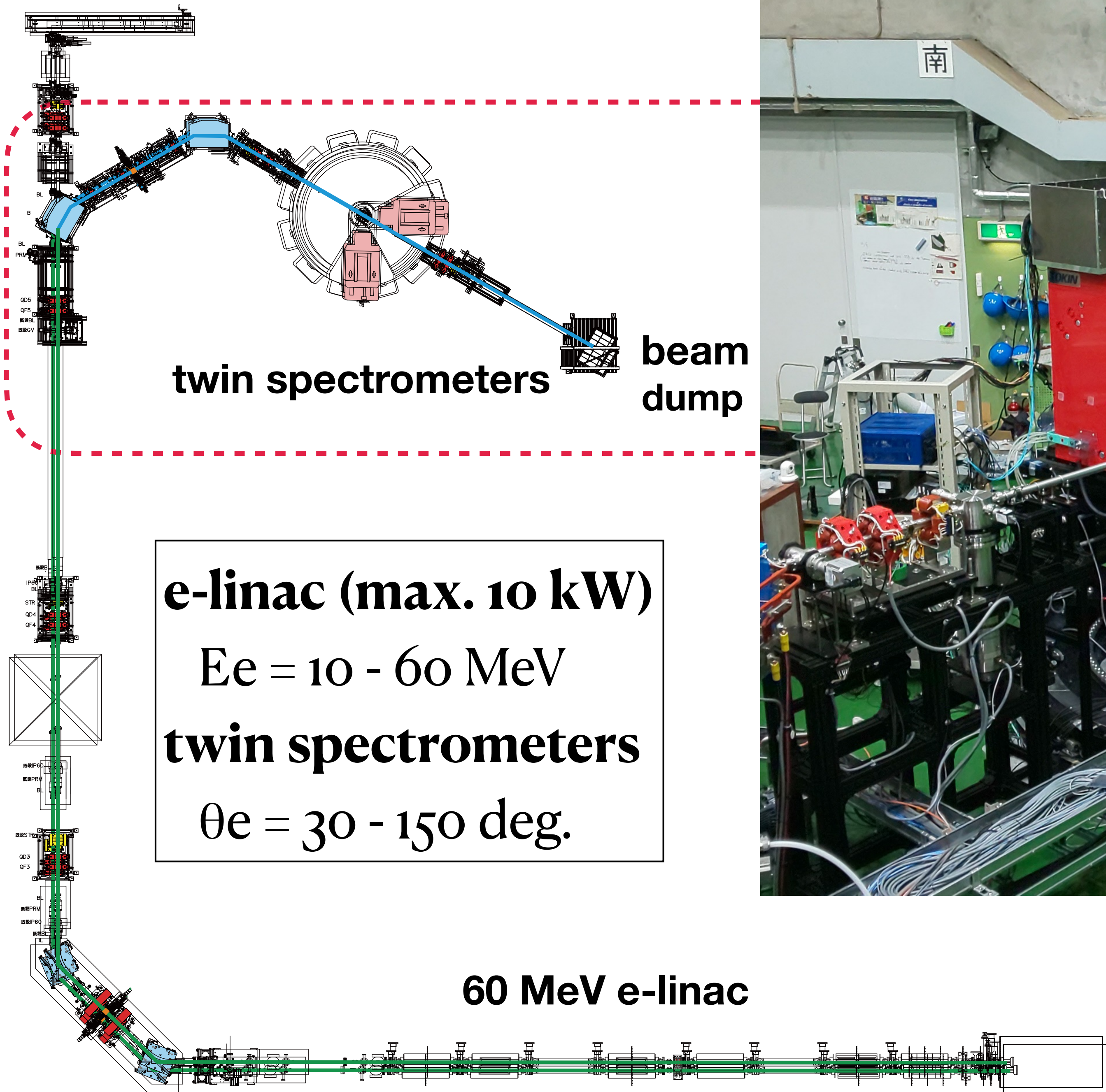
Ee = 150 - 300 MeV

θe = 30 - 60 deg.





ULQ2 setup at ELPH, Tohoku Univ.

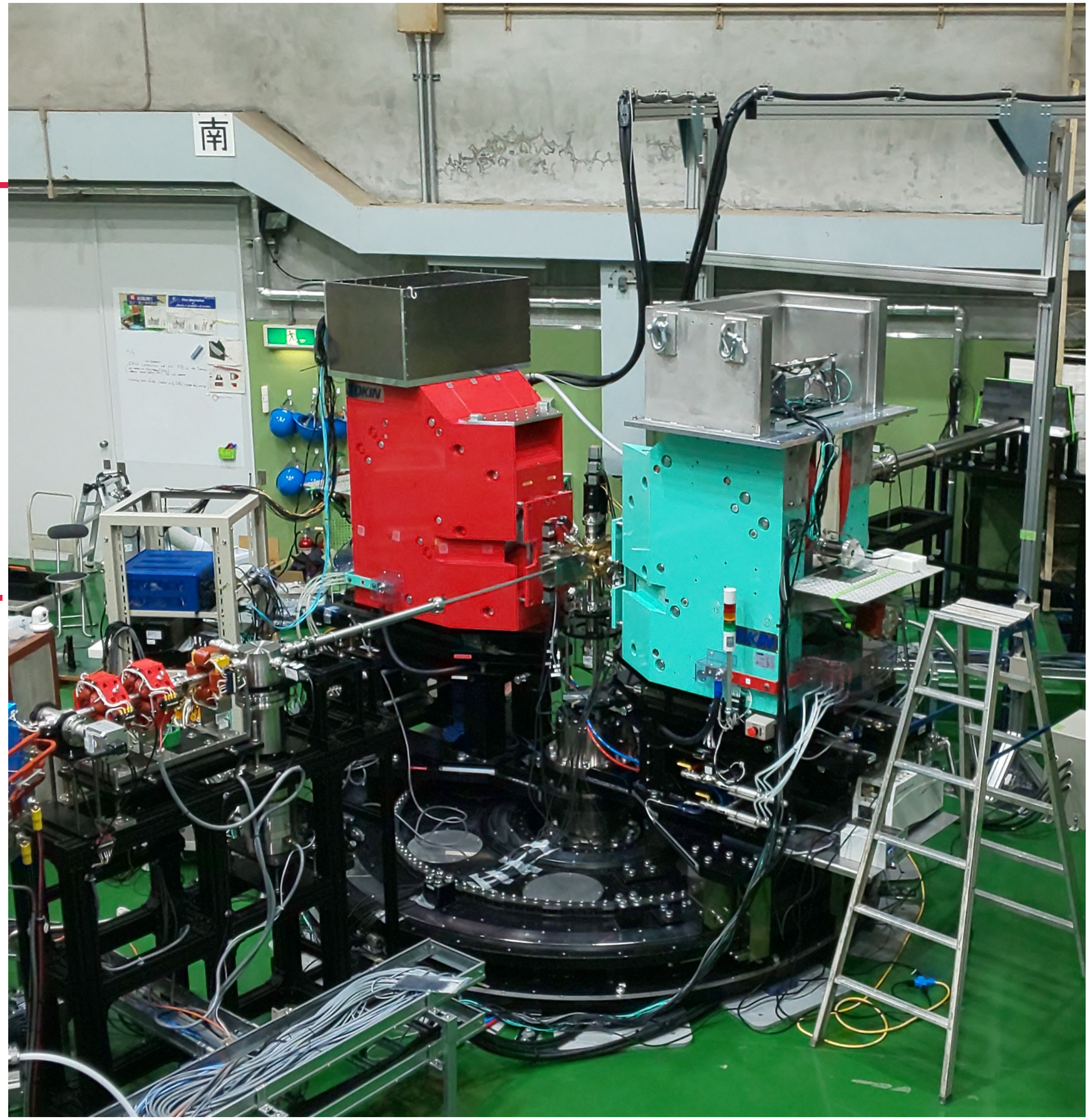


e-linac (max. 10 kW)

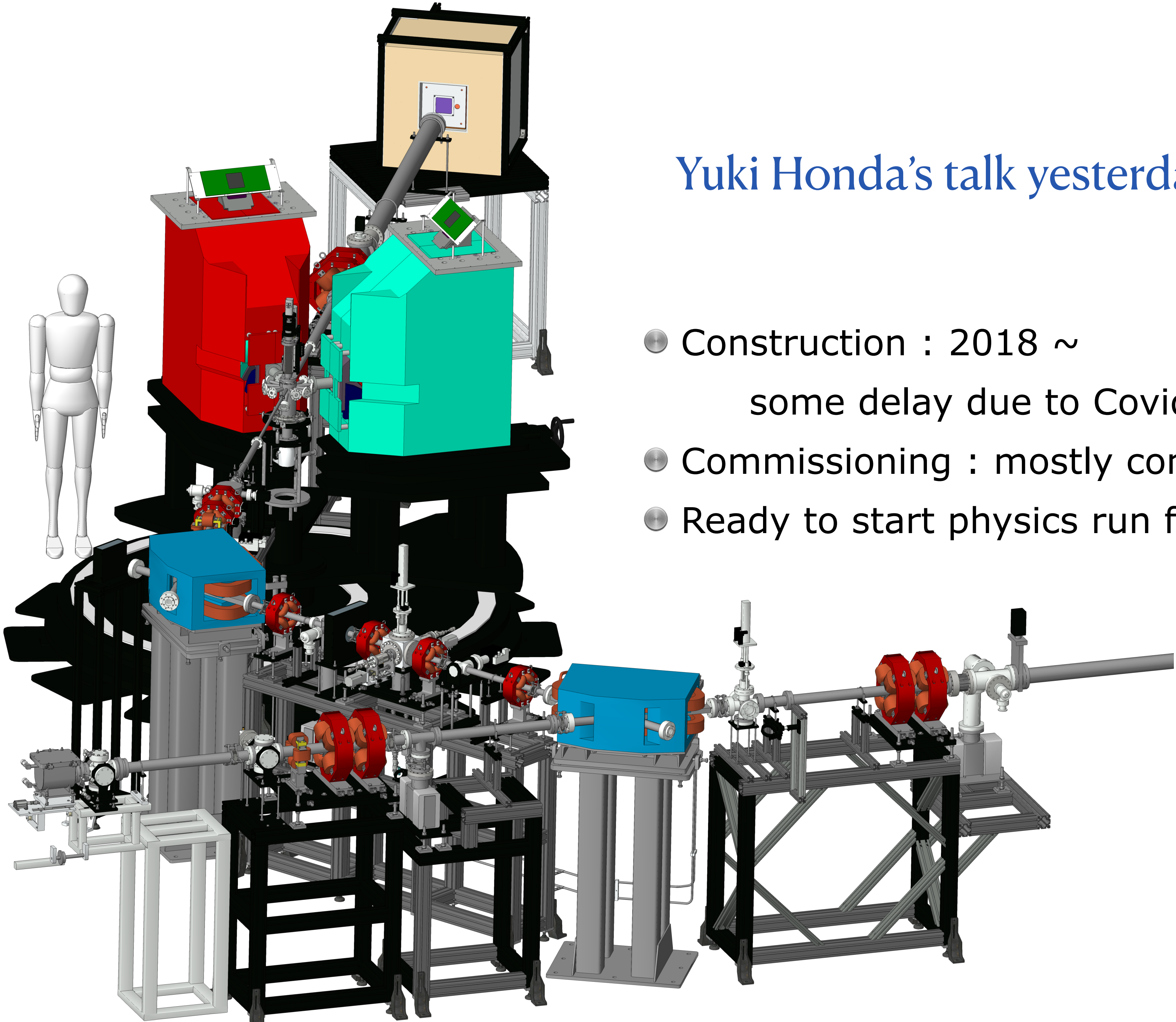
Ee = 10 - 60 MeV

twin spectrometers

θe = 30 - 150 deg.



ULQ2 setup at ELPH, Tohoku Univ.



Yuki Honda's talk yesterday

- Construction : 2018 ~
  some delay due to Covid19
- Commissioning : mostly completed.
- Ready to start physics run from this year

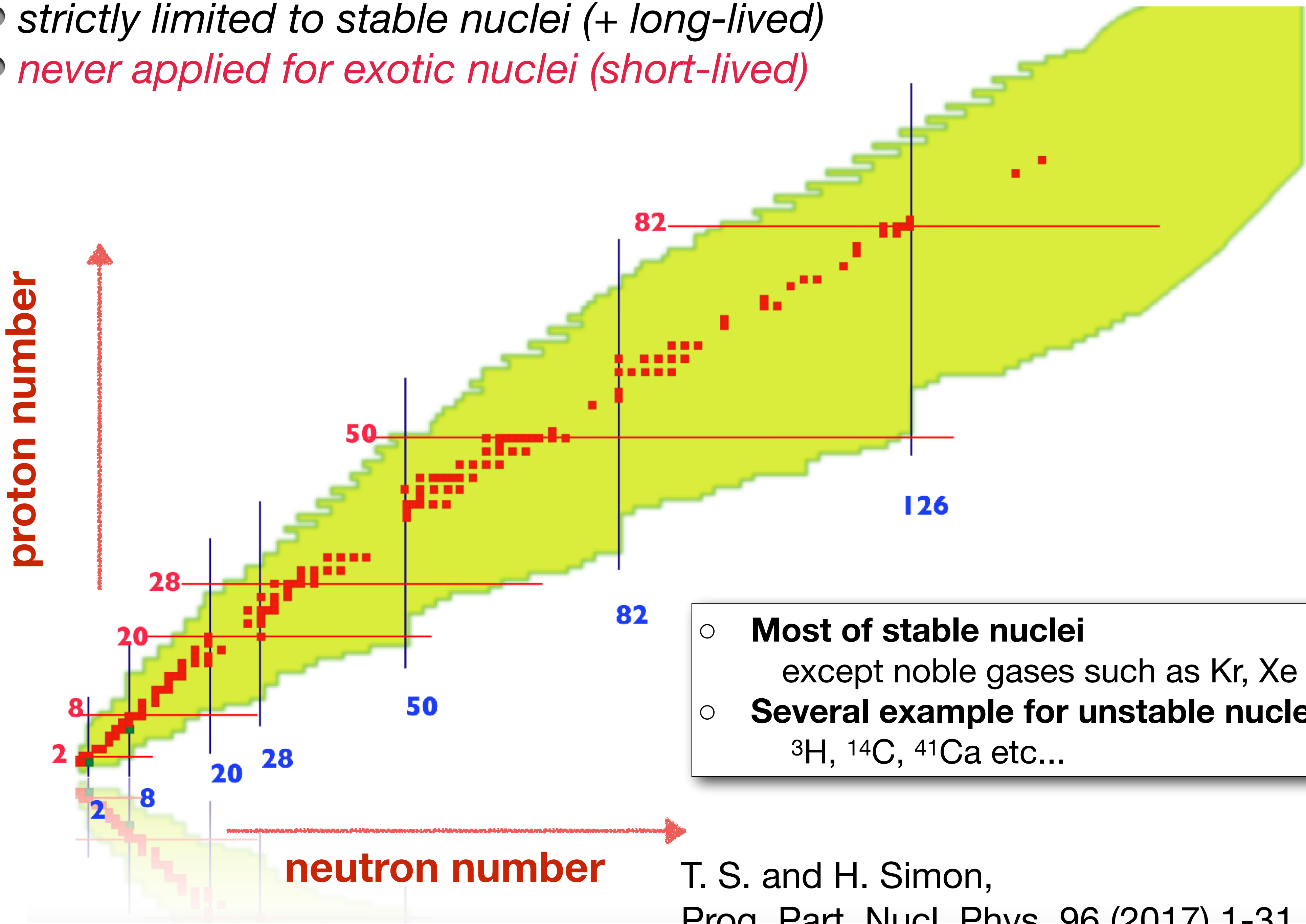
SCRIT @ RIKEN/RIBF

(Self-Confining RI Ion Target)

the world's first electron scattering facility for short-lived radioactive nuclei

Nuclei ever studied by electron scattering

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



- **Most of stable nuclei**
  except noble gases such as Kr, Xe
- **Several example for unstable nuclei**
  ^{3}H, ^{14}C, ^{41}Ca etc...

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

Key parameter for e-scattering of exotic nuclei

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

Luminosity

Luminosity

	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
JLAB	12 GeV	~100μA (~10^{14} /s)	~10^{22} /cm2	~10^{36} /cm^2/s

- **Exotic nuclei** : production-hard & short-lived

  Extremely "thin" targets

  ➡ expected low luminosities

- **First generation exp.**

  ➡ Elastic scattering : largest σ up to modest q

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

R. Hofstadter

"Hofstadter's" exp. for exotic nuclei

main subject of e-scattering for exotic nuclei

- no limitation for target nuclei

  isotopes, isotopes etc.

- beyond charge radii

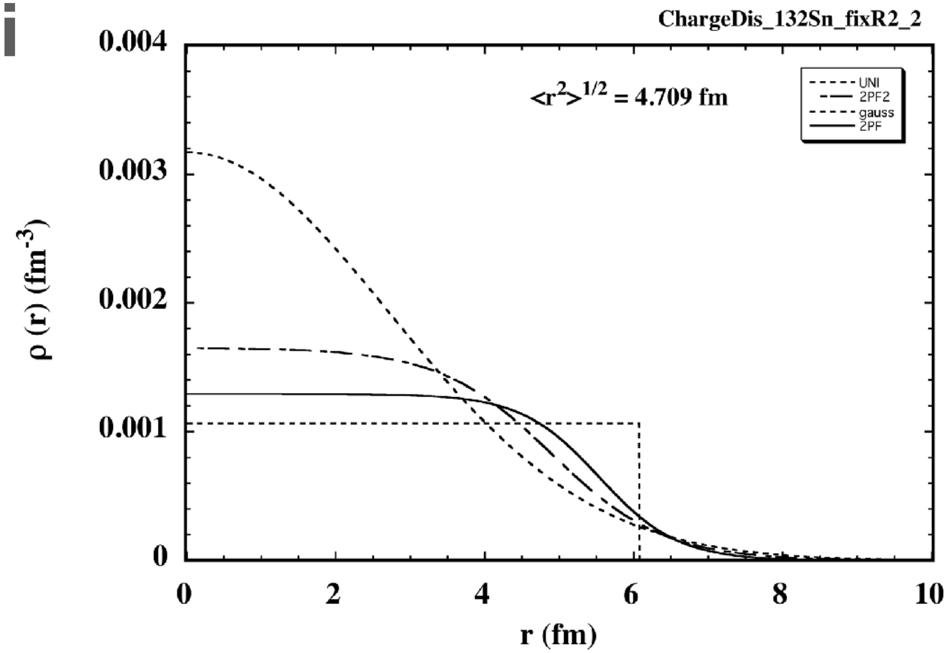
  ⇦ isotope shift

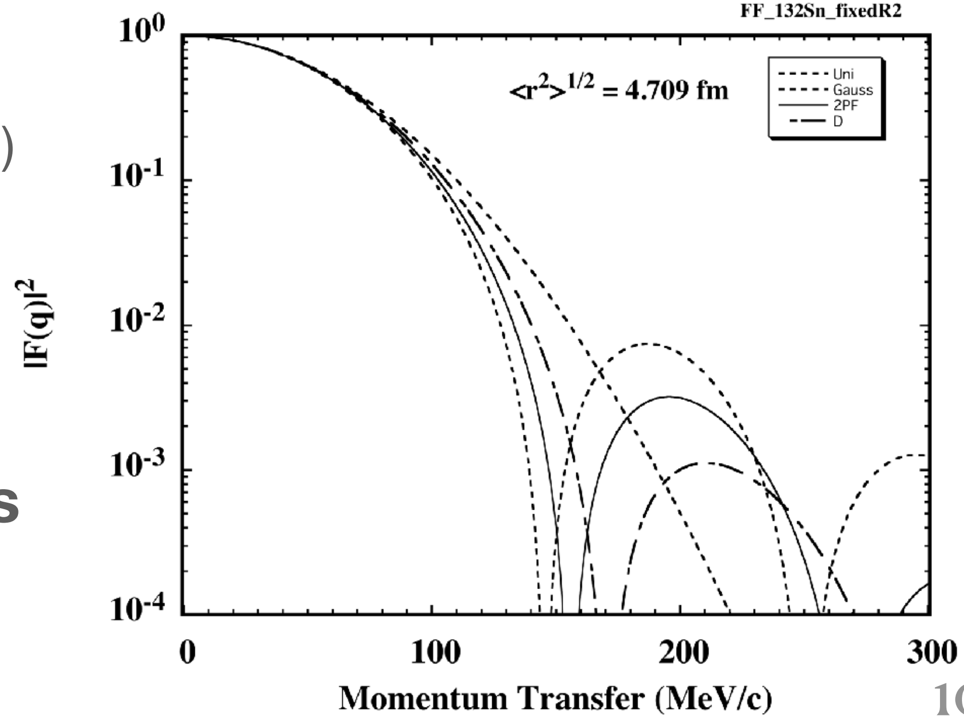
- charge density distribution

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

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

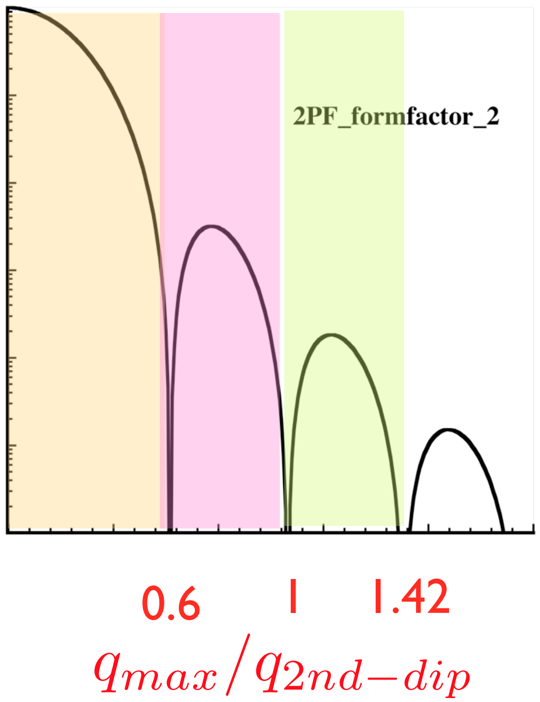
limited L => model dep. analysis

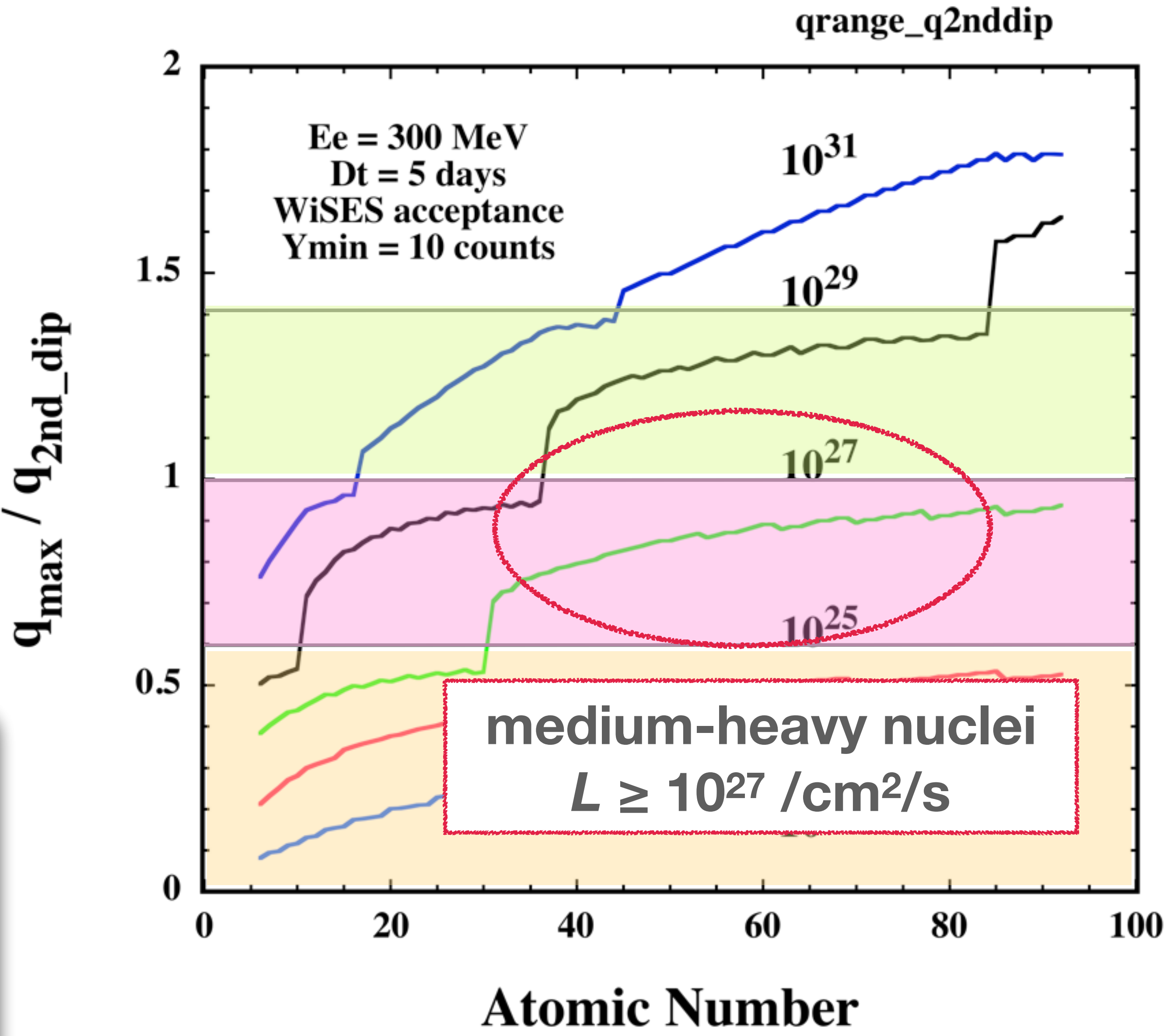




required luminosities

charge form factor





First generation exp.

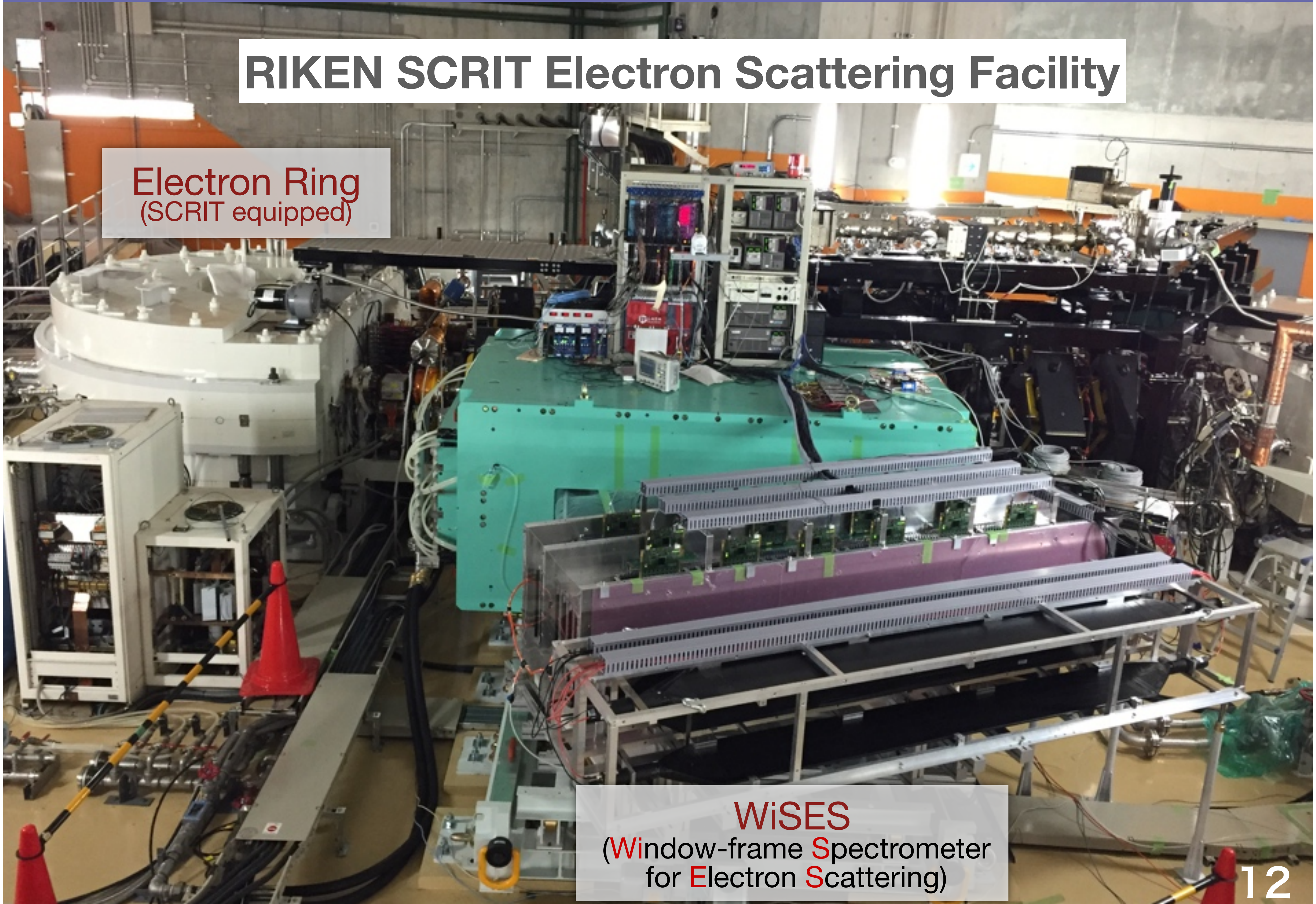
$$\sigma \propto Z^2$$

$$\sigma \propto 1/q^4$$

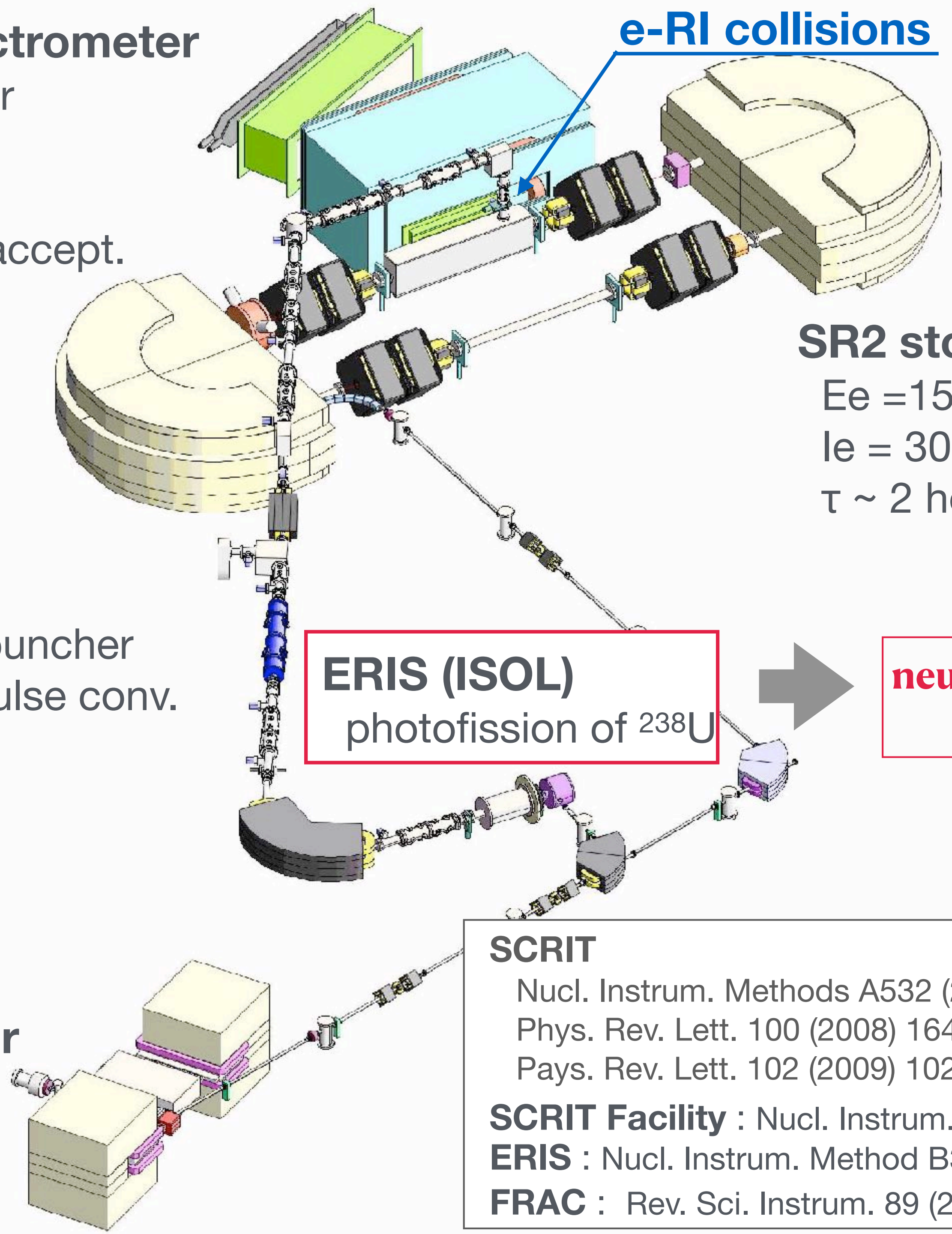
L ~ 10^{27} /cm²/s

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

World's first e-facility for exotic 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.

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.

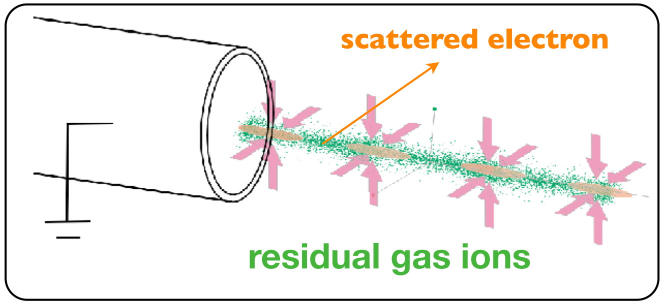
SCRIT Facility : Nucl. Instrum. Method B317 (2013) 668.
ERIS : Nucl. Instrum. Method B317 (2013) 357.
FRAC : Rev. Sci. Instrum. 89 (2018) 095107.

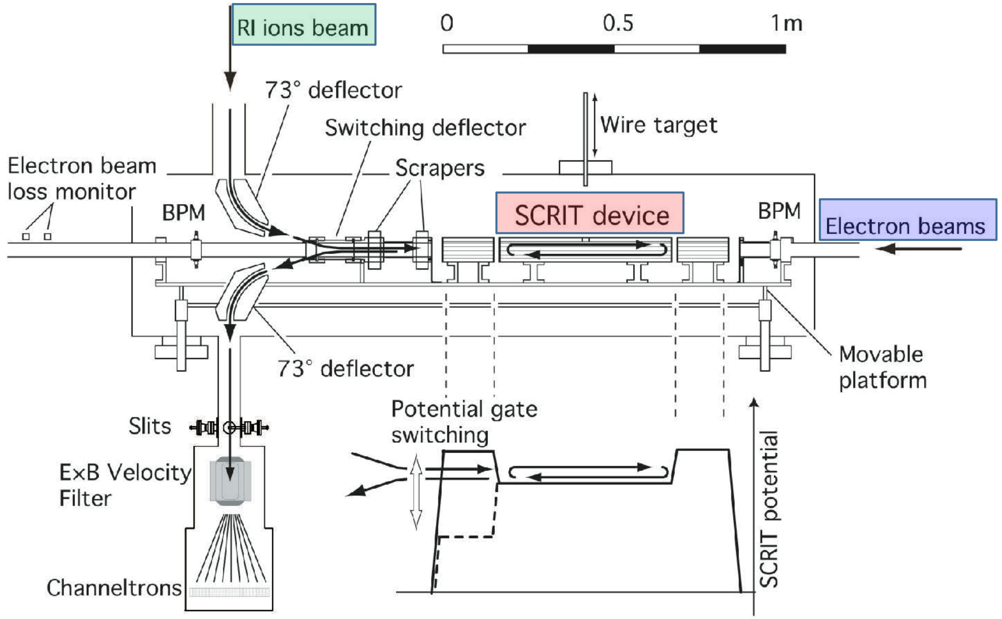
SCRIT (Self-Confining RI Ion Target)

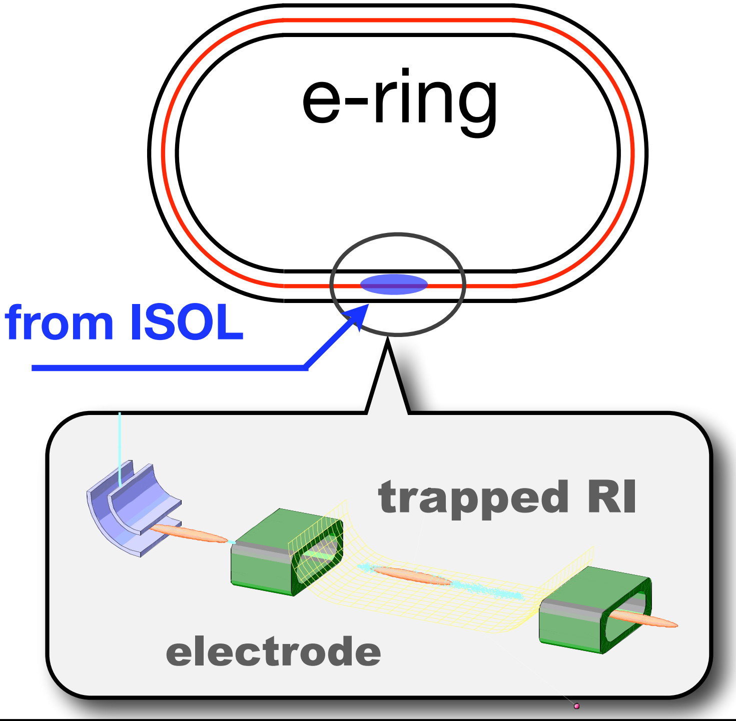
Idea : "ion trapping" at SR facilities.

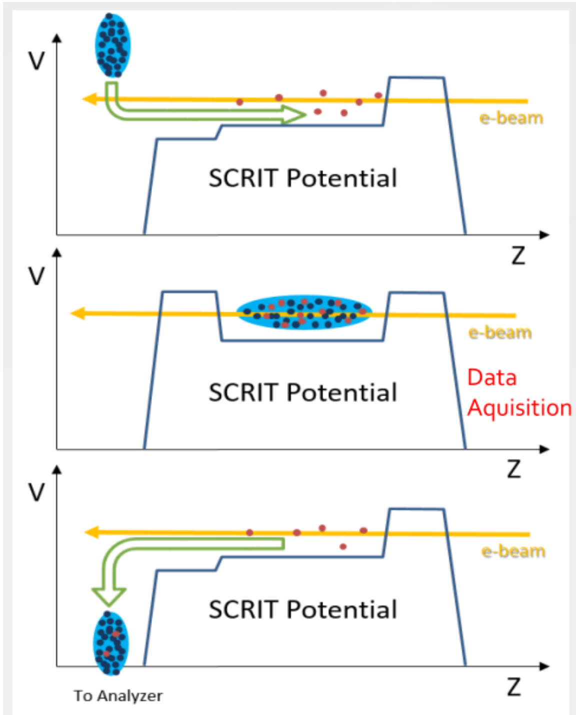
ionized residual gases are trapped by the circulating electron beam

ill problem of e-storage rings





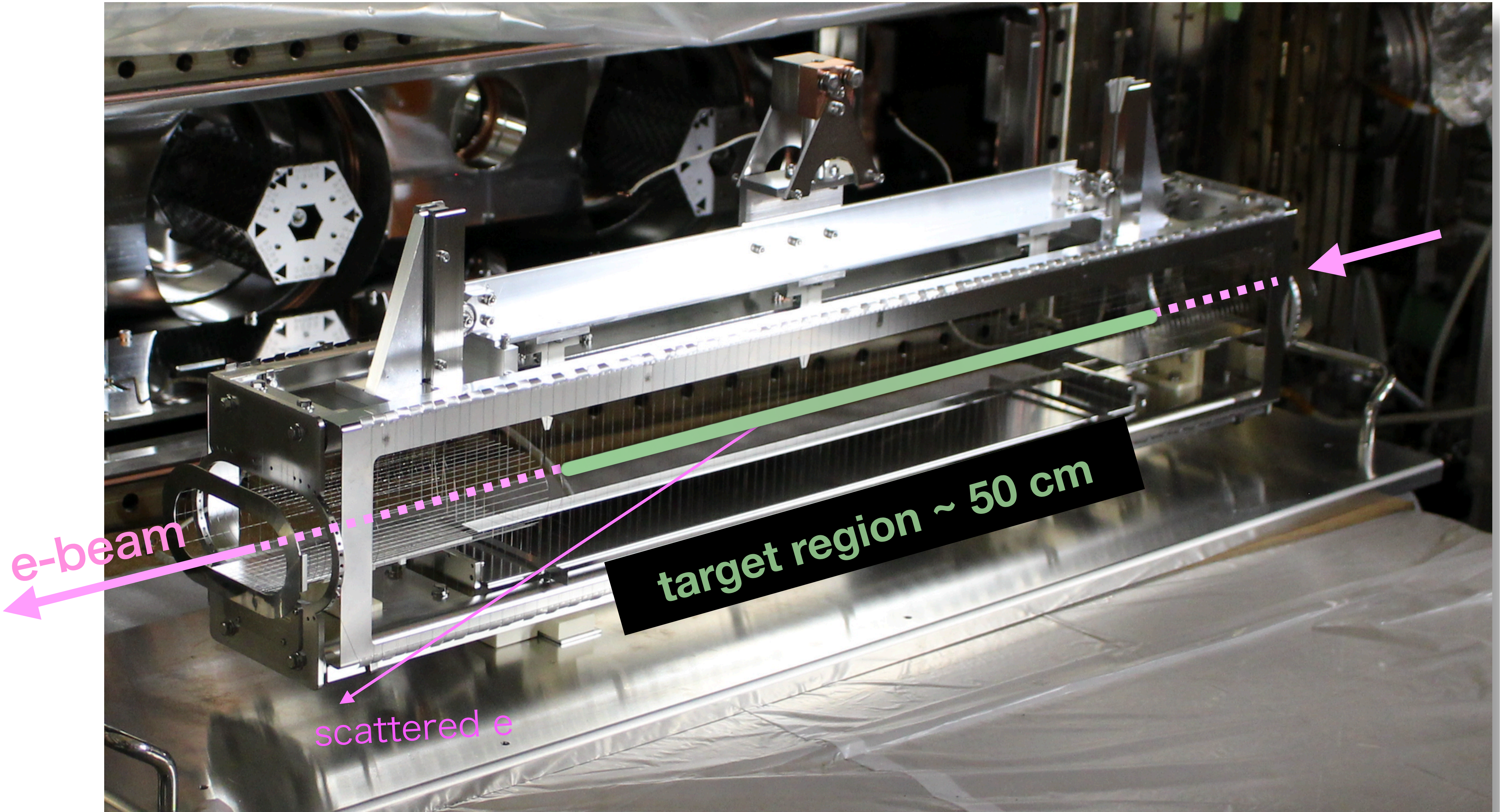




trapping time

life time
(a few sec.)

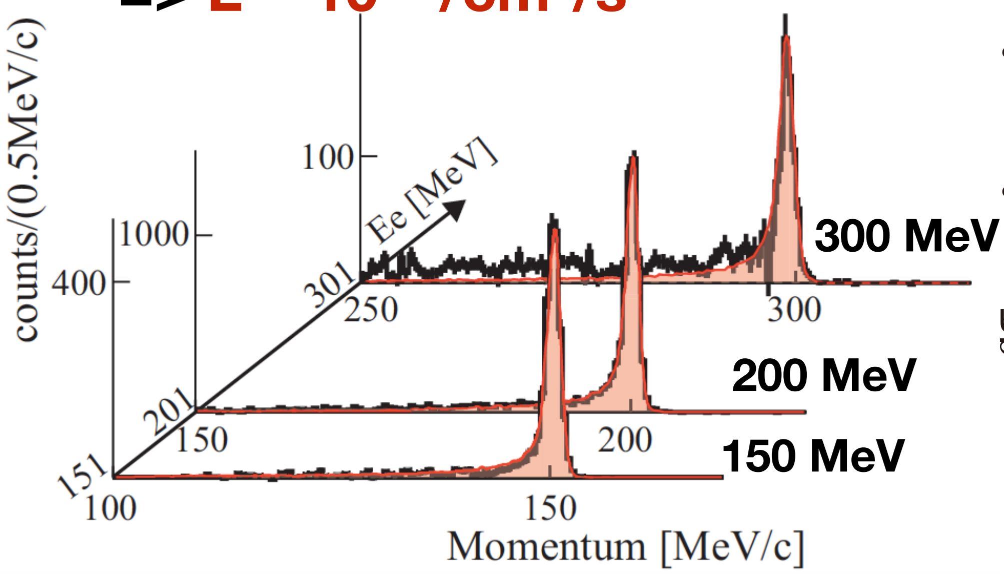
SCRIT electrodes



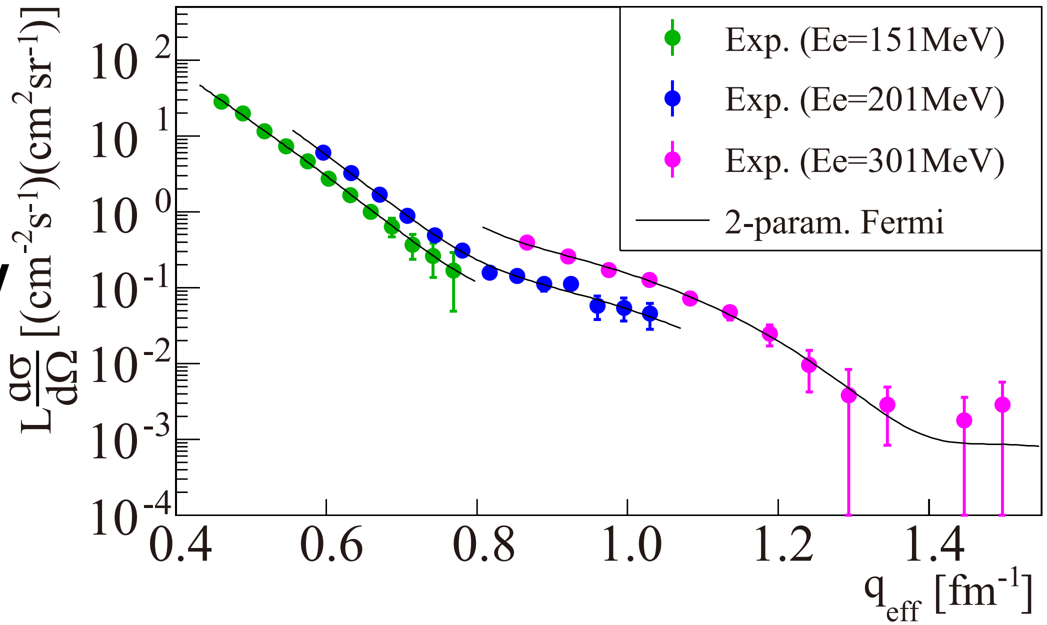
Commissioning : $^{132}Xe(e,e')$

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

=> L ~ 10^{27} /cm²/s



K. Tsukada et al., PRL 118 (2017) 262501.



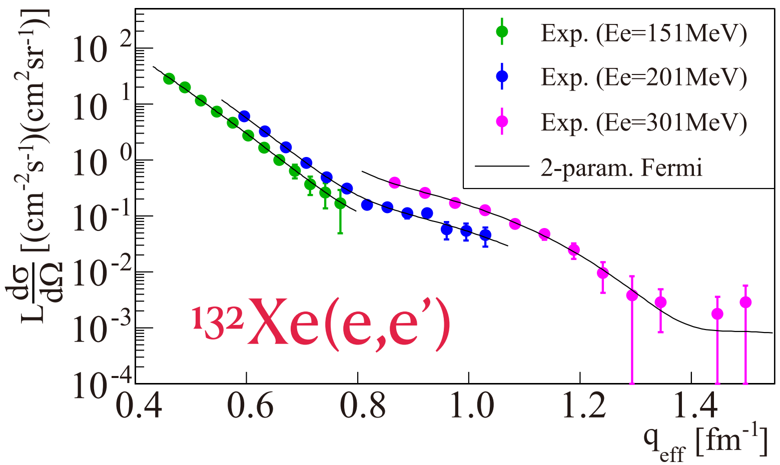
	Ee	N_{beam}	target thickness	L
Hofstadter's era (1950s)	150 MeV	~ 1nA (~10^9 /s)	~10^{19} /cm²	~10^{28} /cm²/s
JLAB	12 GeV	~100μA (~10^{14} /s)	~10^{22} /cm2	~10^{36} /cm²/s
SCRIT	150-300 MeV	300 mA (~10^{18} /s)	~10^9 /cm²	~10^{27} /cm²/s

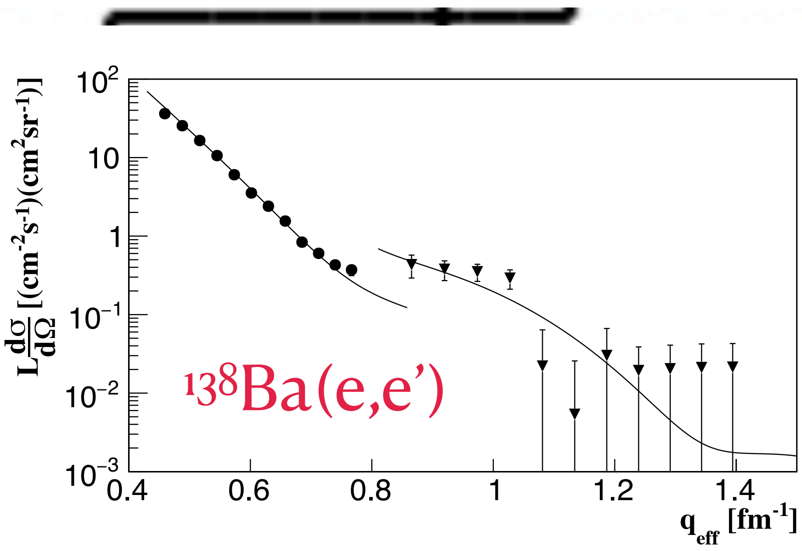
~10^7 trapped ions in e-beam of ~1 mm²

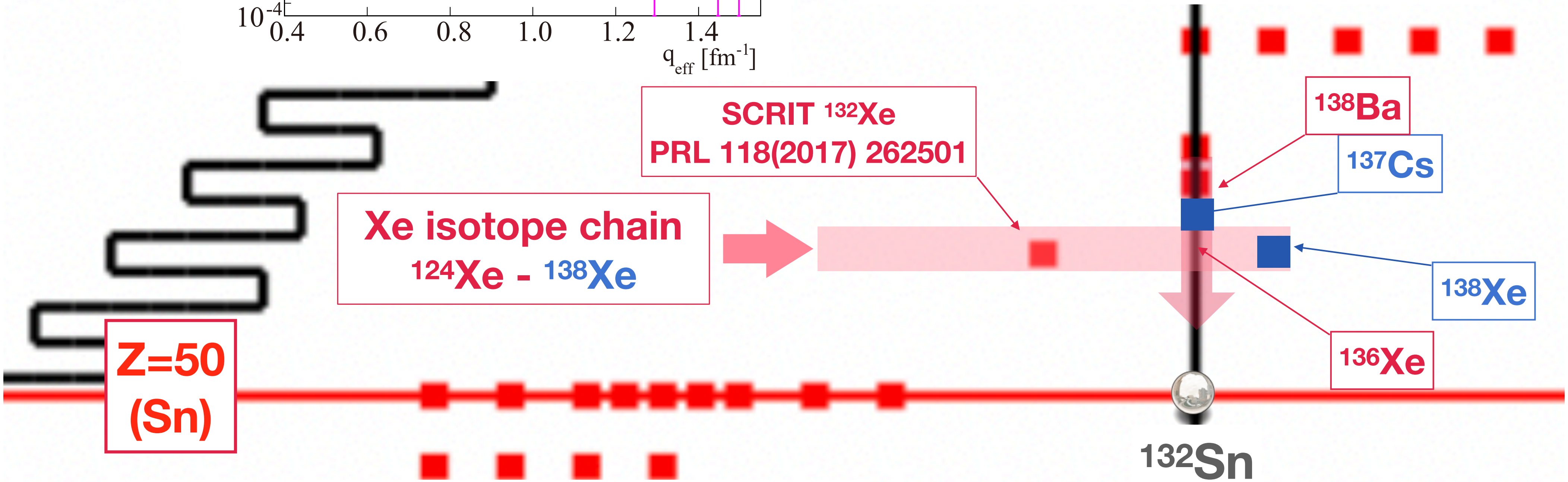
required target thickness ~ 10^{-10} !!

On-going Physics Program at the SCRIT facility

ERIS e-beam : ~ 15 W only as of today
upgrade to ~ 1 kW







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

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

New physics in "traditional" low-energy electron scattering

4-th moments of charge distribution
and
neutron distribution

H. Kurasawa and T. Suzuki, Prog. Theor. Exp. Phys., 2019, 113D01
H. Kurasawa, T. Suda and T, Suzuki, Prog. Theor. Exp. Phys., 2021, 013D02
H. Kurasawa and T. Suzuki, Prog. Theor. Exp. Phys. 2022 023D03

Charge density and its moments

H. Kurasawa and T. Suzuki, PTEP 2019, 113D01

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. ↕ structure theories ↕ Proton Neutron

$$< r_c^2 > = \int r^2 \rho_c(r)\, d^3r \;= < r^2_{p(point)} > + < r_p^2 > + \frac{N}{Z} < r_n^2 > + \text{rel. corr.}$$

3) 4th moment

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

exp. known

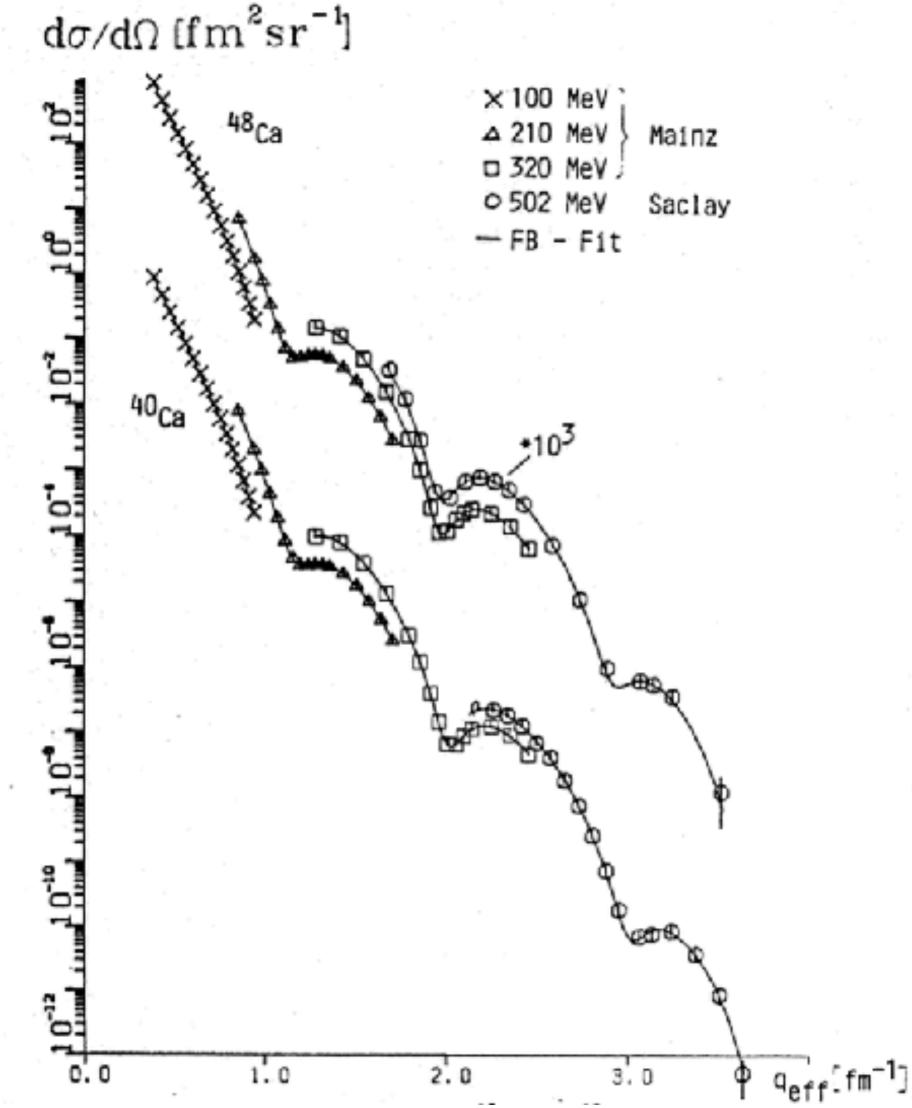
$$= < r^4_{p(point)} > + \frac{10}{3} < r^2_{p(point)} > < r_p^2 > + \text{rel. corr.}$$ ← proton

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

RMS n-radius

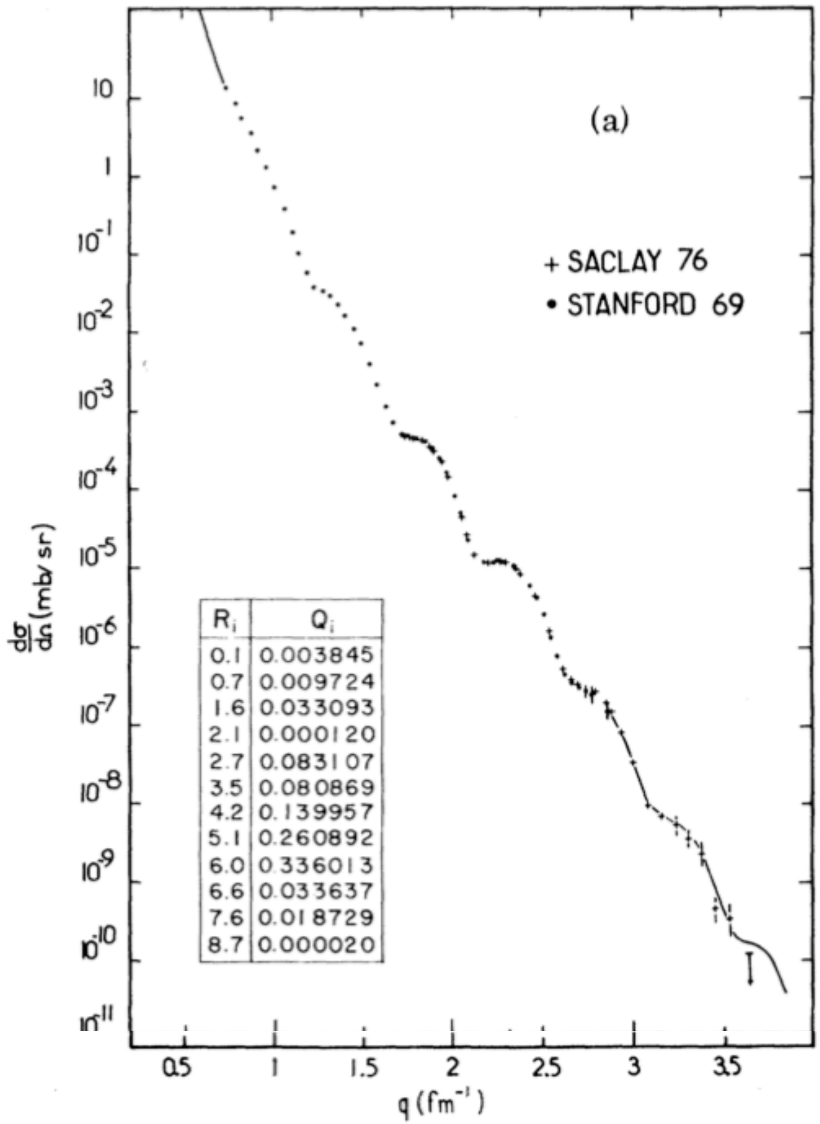
Elastic cross section and charge density

^{48}Ca



Emrich Ph.D thesis, 1983, Mainz

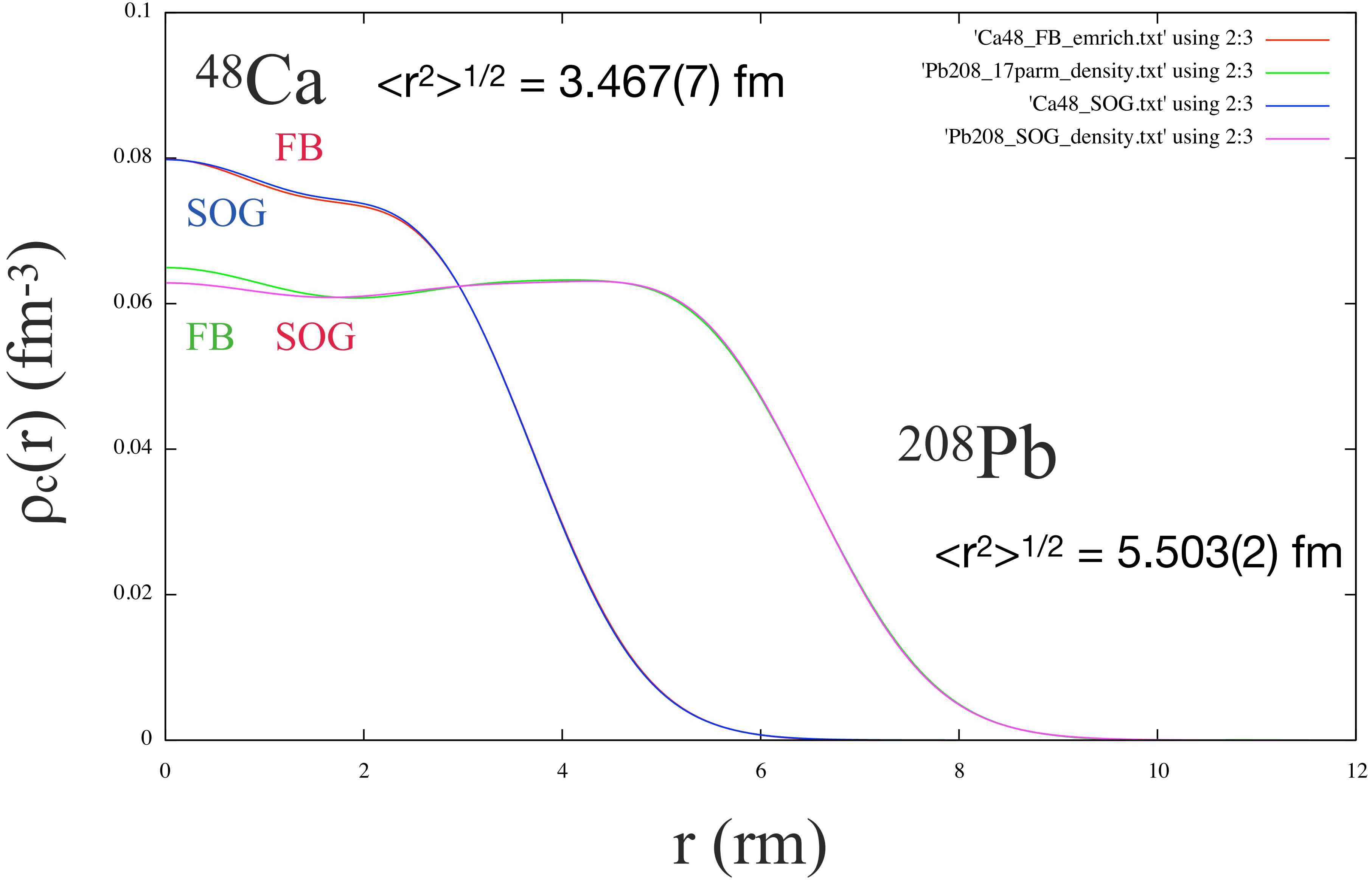
^{208}Pb



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

Charge density distributions of ^{208}Pb and ^{48}Ca

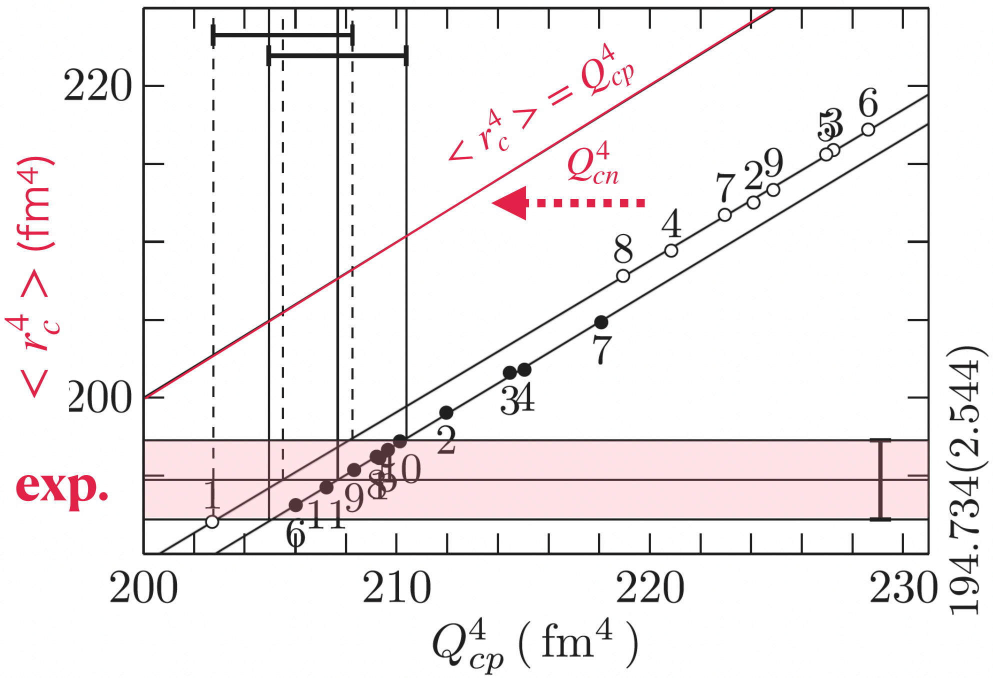
"model independent" analysis :
Fourier-Bessel and Sum-of-Gaussian

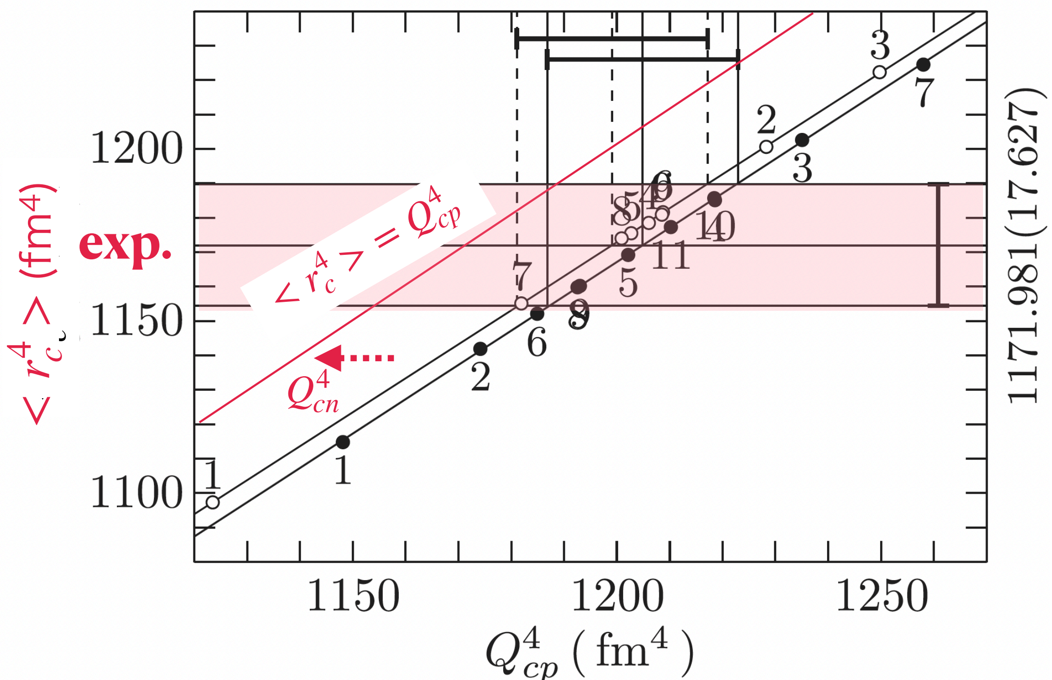


$\langle r_c^4 \rangle$ of ^{48}Ca and ^{208}Pb

exp.

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





- neutron contributions are essential to account for experimental values of $\langle r_c^4 \rangle$ of ^{48}Ca and ^{208}Pb
- depending on the theoretical framework (rel. vs. non-rel.)

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

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

Neutron radius and neutron-skin thickness

neutron skin thickness, Δr_{np}, derived from

- $\langle r_c^4 \rangle$ of the charge density distribution (Kurasawa-Suda-Suzuki)
- parity-violating electron scattering (PREX+CREX@JLab)

$\langle r_c^4 \rangle$

^{208}Pb

	R_p	R_n	δR
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.	$R_c = 5.503(0.014)$		

^{48}Ca

	R_p	R_n	δR
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.	$R_c = 3.451(0.009)$		

H. Kurasawa, T. S. and T, Suzuki, PTEP, 2021, 013D02

parity-violating e-scattering

JLab : PREX ^{208}Pb

$$\Delta r_{np} \equiv R_n - R_p = 0.283 \pm 0.071 \text{ fm}$$

PRL 126, 172502 (2021)

JLab : CREX for ^{48}Ca

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

arXiv:2205.11593

neutron distribution vs <r_c^4> of charge densities

- ***Rn*** by parity-violating e-scattering

  el.mag. - weak interference : extremely difficult
  no chance for radioactive nuclei

- ***Rn*** from <r_c^4>

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

1) obtain $\rho_C(r)$ by electron scattering covering upto high *q*

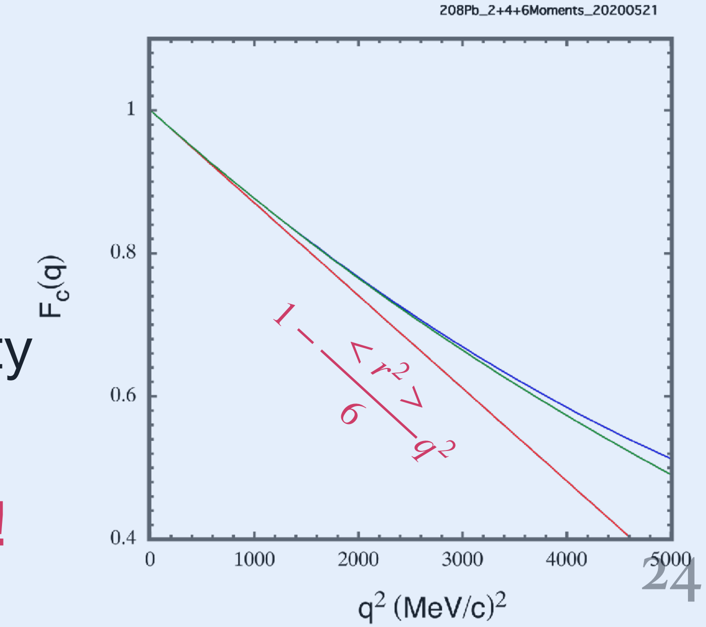
$$\frac{d\sigma_{\mathrm{Mott}}}{d\Omega} \propto e^2/q^4$$ ⬌ no chance for exotic nuclei

2) low-q electron scattering

known

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

huge $d\sigma_{\mathrm{Mott}}/d\Omega$ ⬌ low luminosity

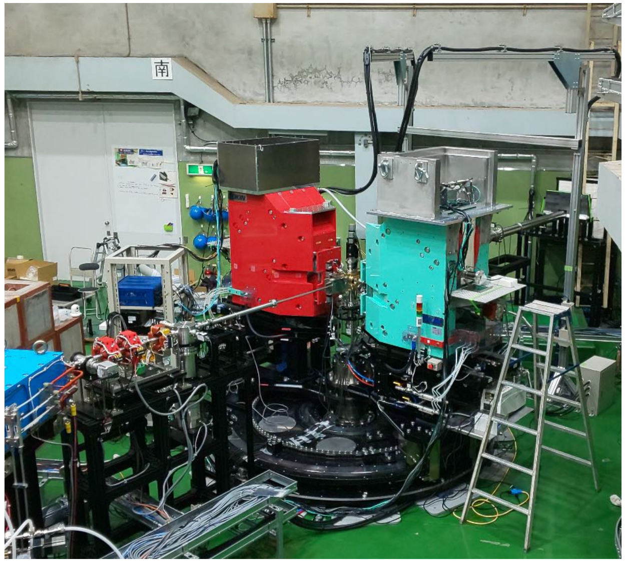


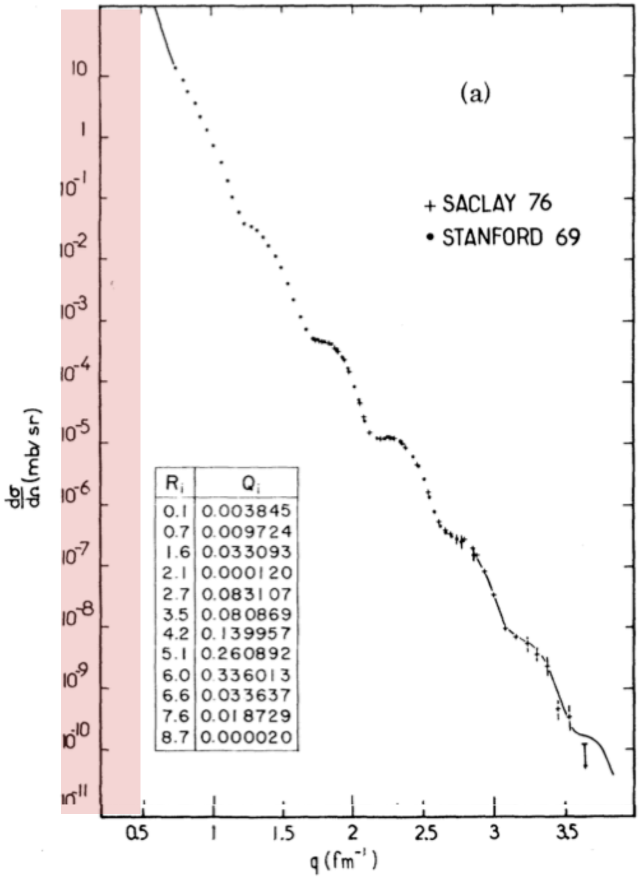
probably applicable for unstable nuclei!!!

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

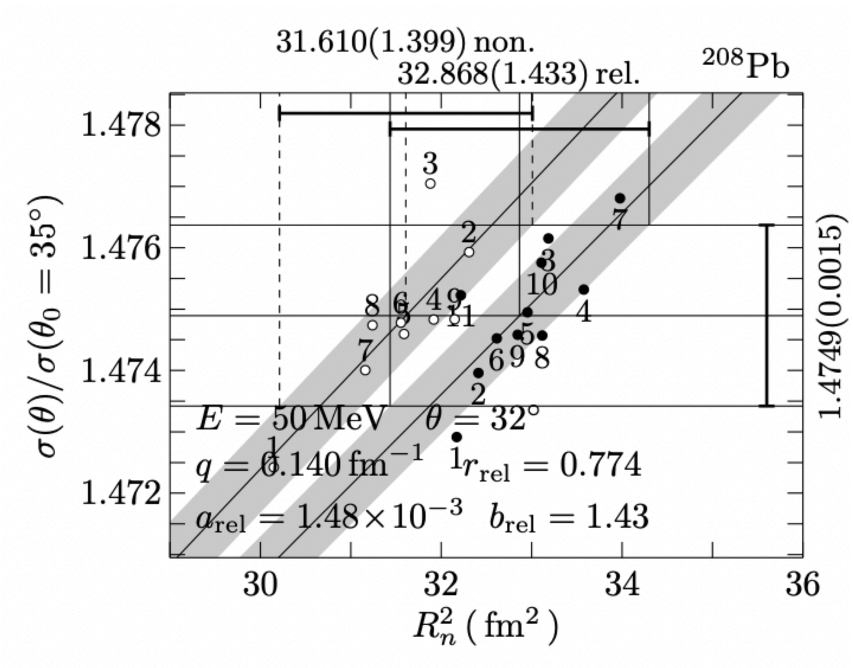
- ^{208}Pb(e,e') at the ULQ2 beam line

Ee ~ 10 - 50 MeV
θ = 30 - 150°
q = 2.5 - 100 MeV/c





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

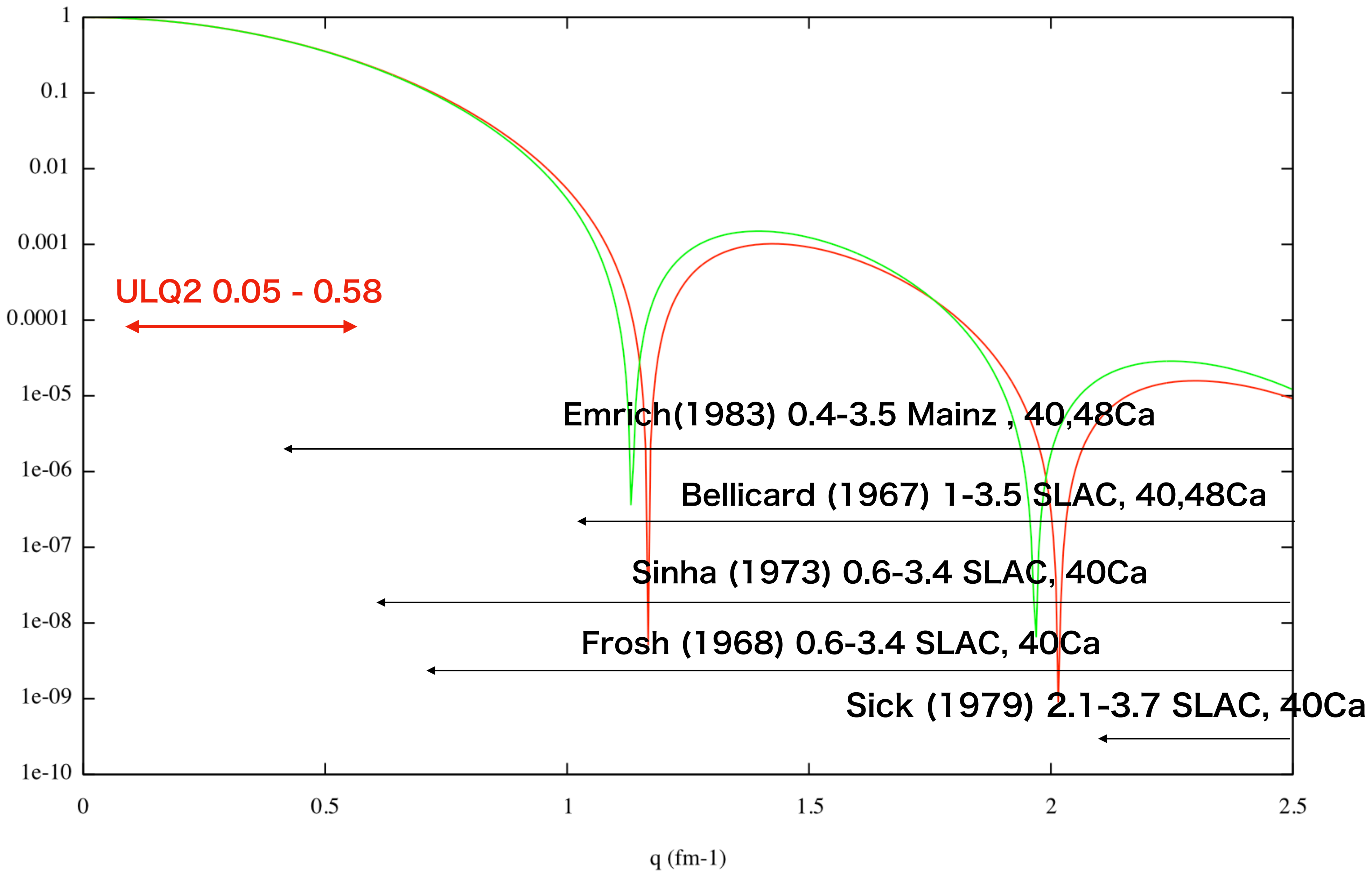


by H. Kurasawa

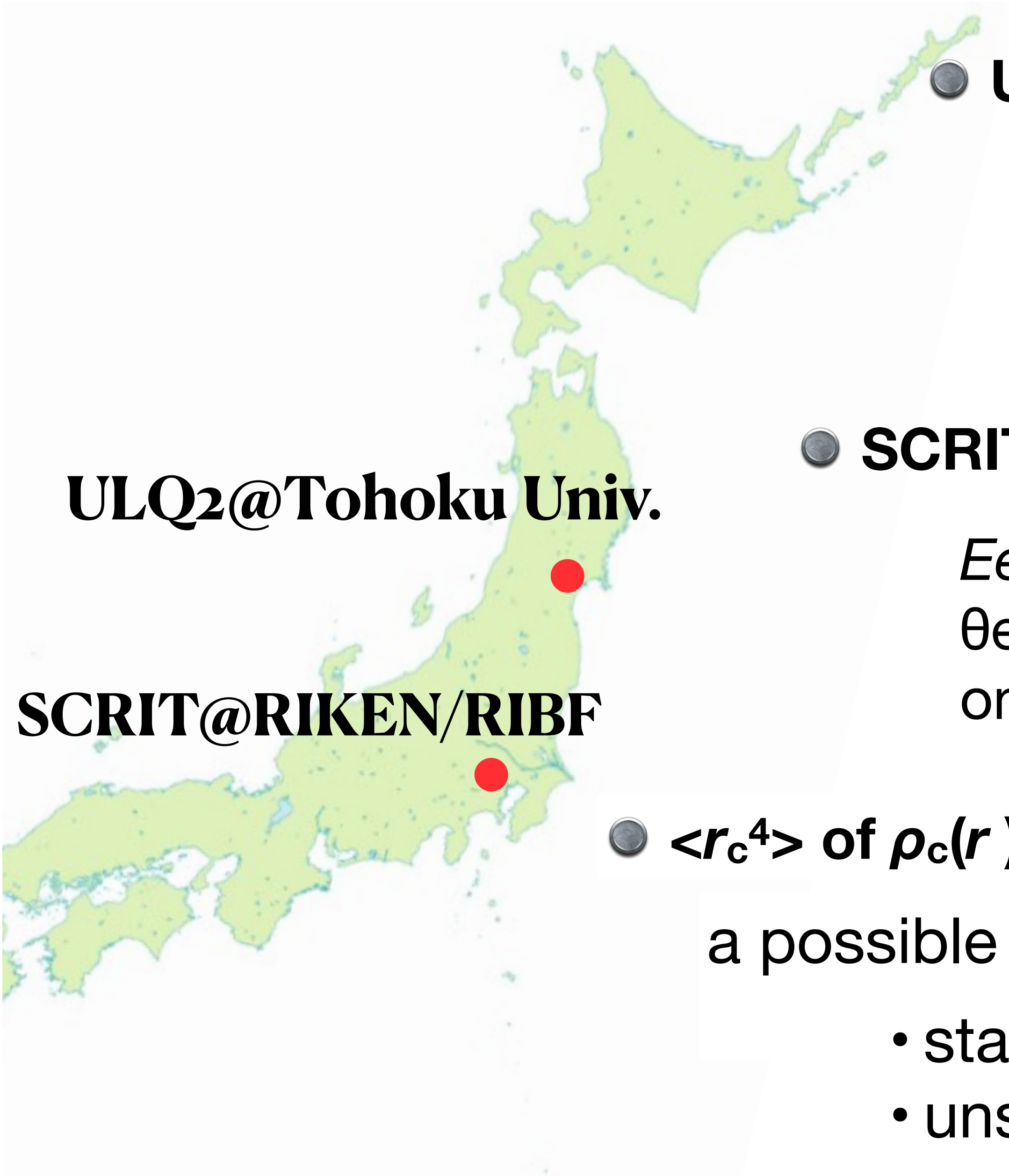
- precise σ(θ)/σ(θ$_0$) with the twin spectrometers
- phase-shift calculations are underway
- short beam time for feasibility test this fall

- if we find it works, apply to exotic nuclei at SCRIT !!

^{40,48}Ca Form Factor



Low-energy e-scattering facilities in Japan



- **ULQ2 for proton radius**

  Ee = 10 - 60 MeV
  θe = 30 - 150 deg.
  ready to run

- **SCRIT for exotic nuclei**

  Ee = 150 MeV
  θe = 30 - 60 deg.
  on-going

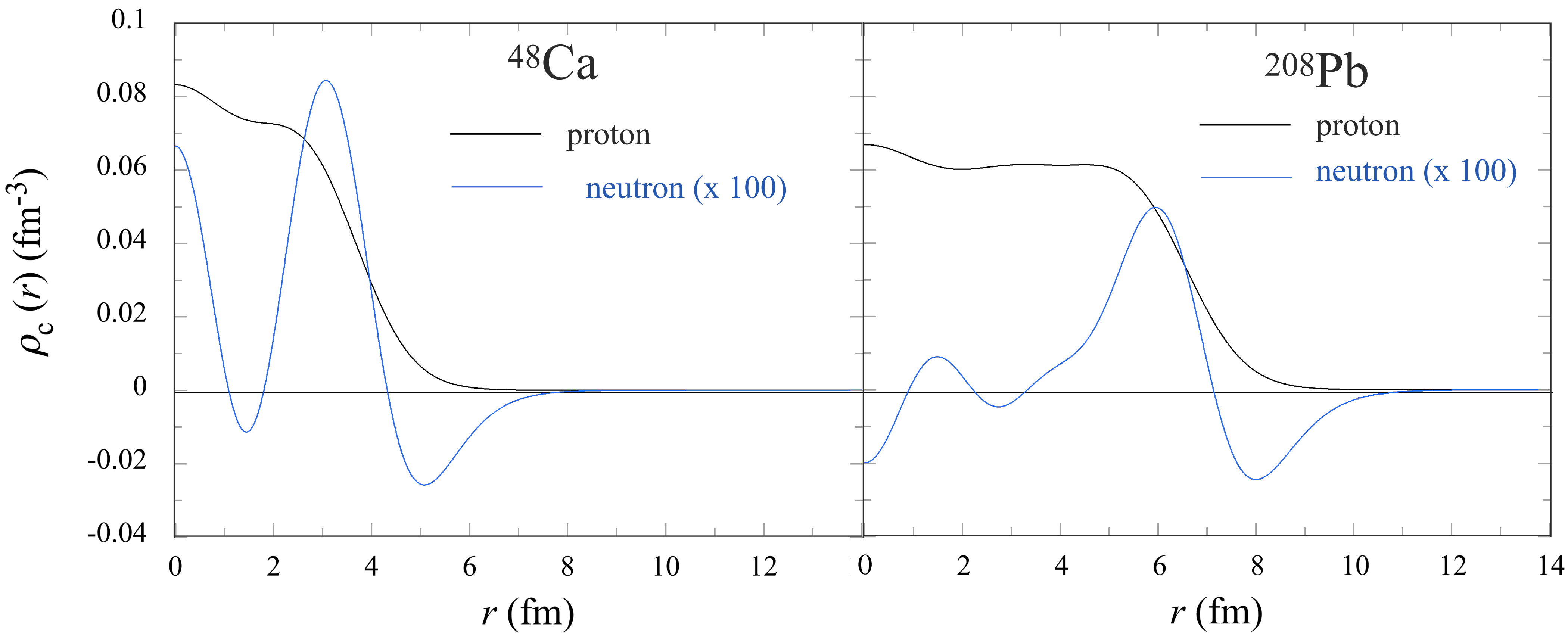
- **$\langle r_c^4 \rangle$ of $\rho_c(r)$ from low-q elastic scattering**

  a possible new way to access R_n of nuclei

  - stable nuclei at ULQ2
  - unstable nuclei at SCRIT

Backup

Charge density distributions (rel. frame work)



RMF calculation by Haruki Kurasawa

$$\rho_c(r) = \int \frac{d^3q}{(2\pi)^3} \exp(-i\boldsymbol{q}\cdot\boldsymbol{r})\tilde{\rho}(q).$$

$$\tilde{\rho}(q) = \int d^3x \exp(i\boldsymbol{q}\cdot\boldsymbol{x}) \sum_{\tau}^{\text{p,n}} \Big(G_{E\tau}(q^2)\rho_\tau(x) + F_{2\tau}(q^2)W_\tau(x)\Big)$$

$$\rho_c(r) = \sum_{\tau}^{\text{p,n}} \Big(\rho_{c\tau}(r) + W_{c\tau}(r)\Big)$$

point density spin-orbit density

$$\rho_\tau(r) = \sum_{\alpha\in\tau} \frac{2j_\alpha + 1}{4\pi r^2} (G_\alpha^2 + F_\alpha^2),$$

$$W_\tau(r) = \frac{\mu_\tau}{M} \sum_{\alpha\in\tau} \frac{2j_\alpha + 1}{4\pi r^2} \frac{d}{dr} \left(\frac{M - M^*(r)}{M} G_\alpha F_\alpha + \frac{\kappa_\alpha + 1}{2Mr} G_\alpha^2 - \frac{\kappa_\alpha - 1}{2Mr} F_\alpha^2 \right).$$