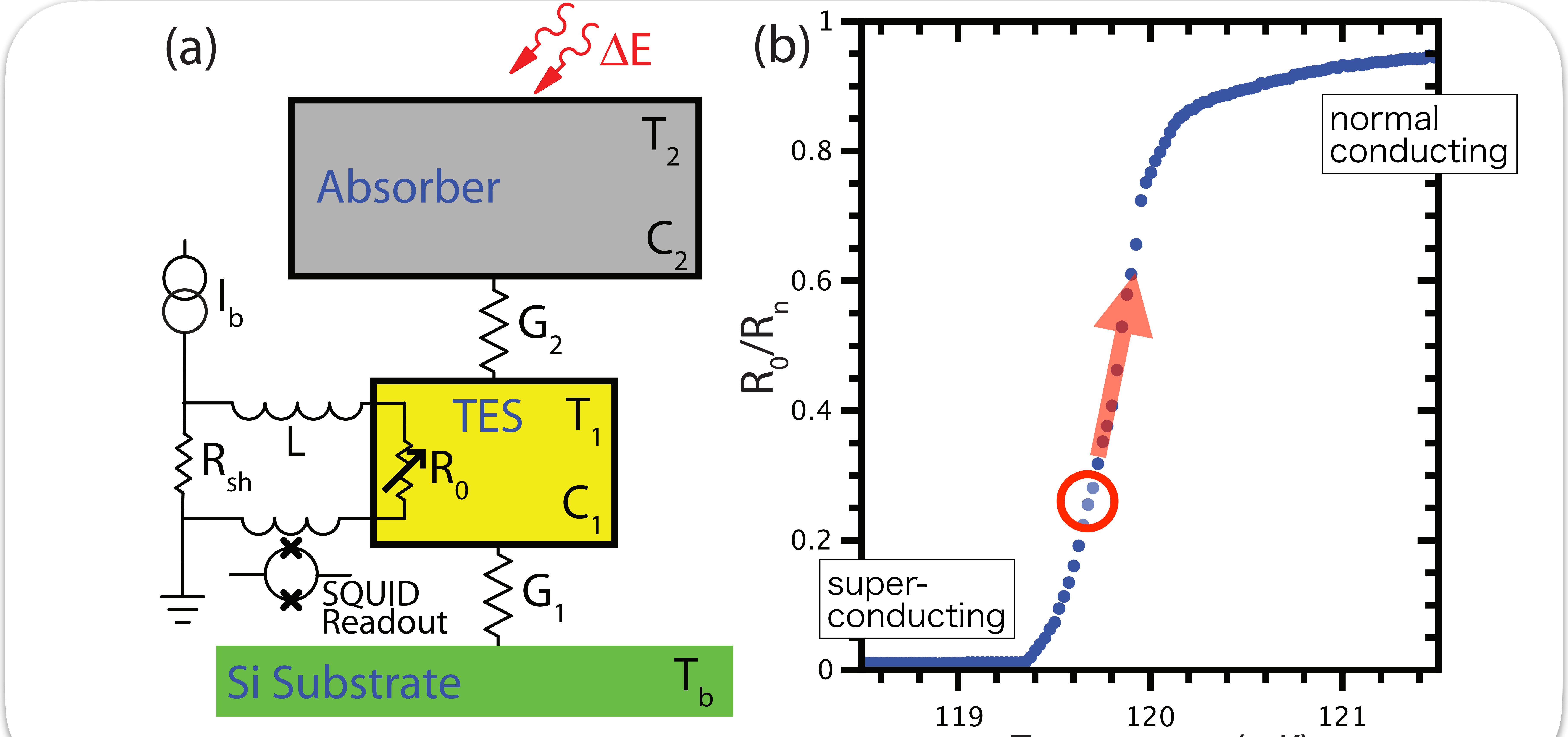
X-ray spectroscopy of exotic atoms using TES microcalorimeters

Transition Edge Sensor

Tadashi Hashimoto (RIKEN PRI/RNC)
for the HEATES collaboration

High Precision X-ray Measurements 2025, Frascati, Italy, June. 16—20, 2025

Transition-Edge-Sensor microcalorimeters



Rev. Sci. Instrum. **83**, 093113 (2012)

$$\alpha \equiv \frac{d \ln R}{d \ln T},$$

$$\Delta E \propto \sqrt{\frac{k_B T^2 C}{\alpha}},$$

$$E_{max} \sim \frac{C T_C}{\alpha},$$

$$\tau_{eff} \sim \frac{n}{\alpha}\frac{C}{G}$$

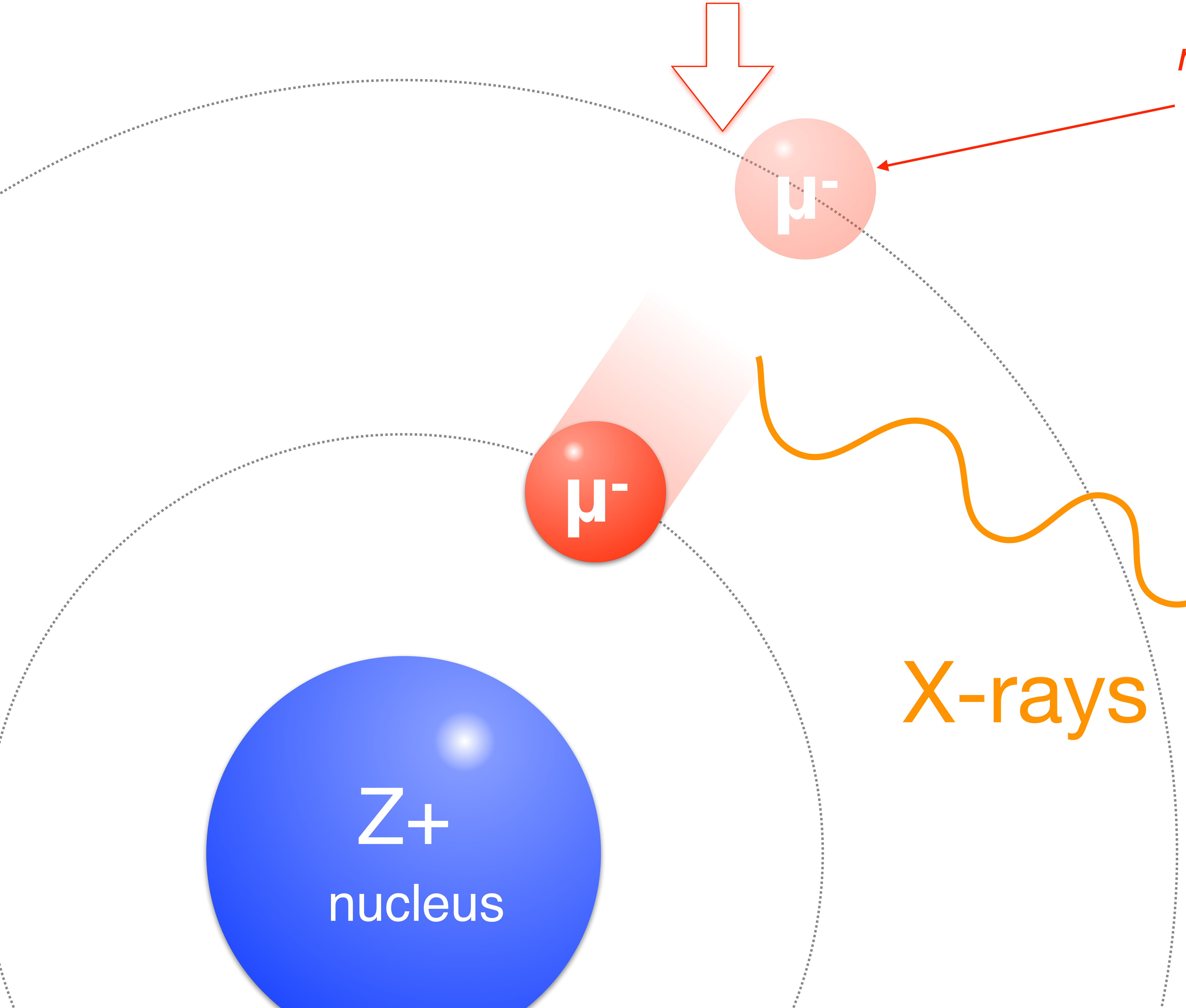
Excellent energy resolution as an energy dispersive detector

Variety of applications dependent on the detector parameters


✓ 1 pixel : 300 x 320 um² (~ 0.1 mm²)
✓ Mo-Cu bilayer TES
✓ 4-µm-thick Bi absorber (eff.~ 85% @ 6 keV)
Φ ~1 cm
✓ 240 pixels
✓ 23 mm² eff. area
NIST
photo credit:
D.R. Schmidt

HEATES project

High-resolution **E**xotic **A**tom x-ray spectroscopy with **TES**



negative charged

μ^- : Muon

π^- : Pion

K^- : Kaon

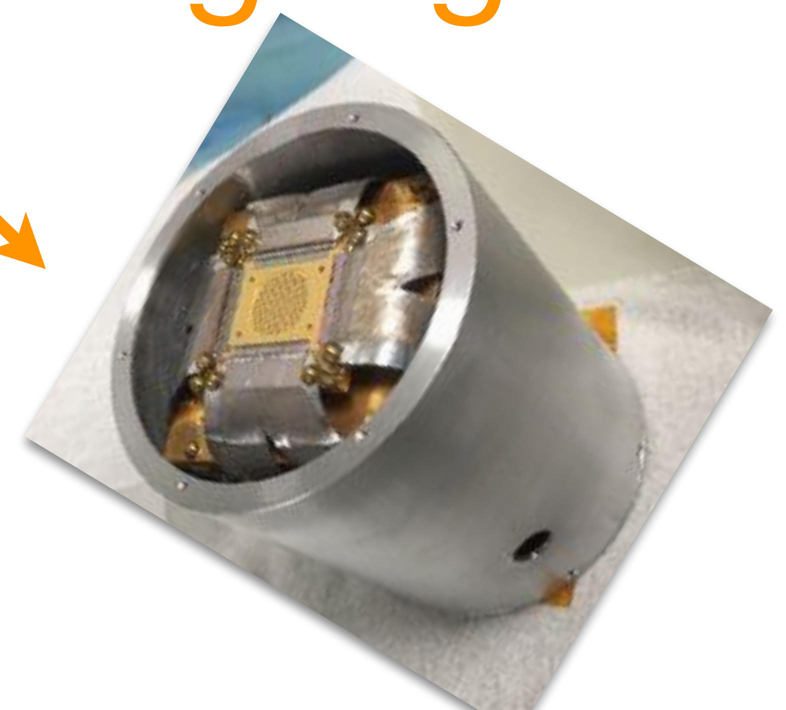
$\bar{p}$: anti-proton …

named after microcalorimeter
*being a **heat** measuring device*

TES microcalorimeter

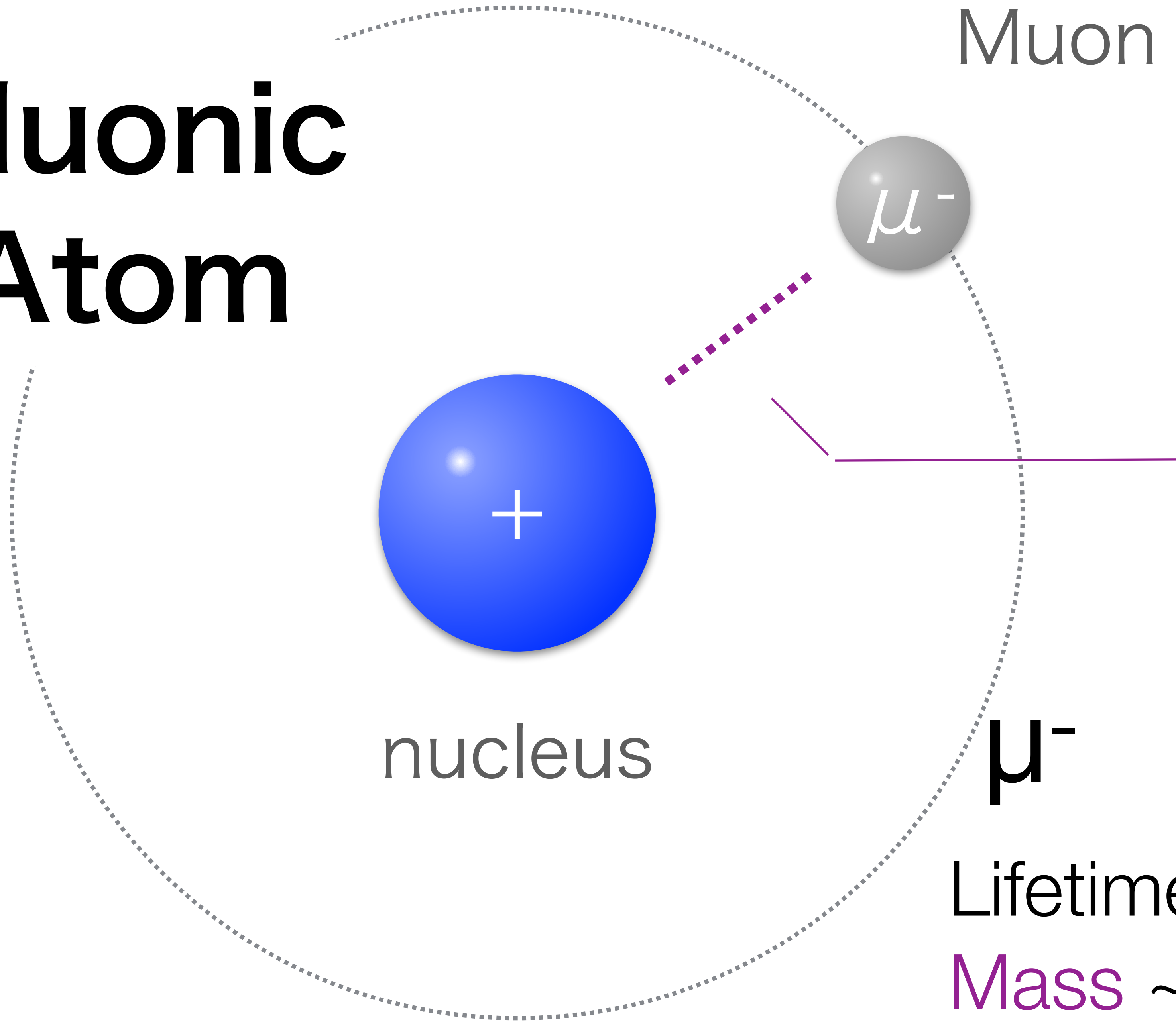
(Cryogenic detector)

having high resolution



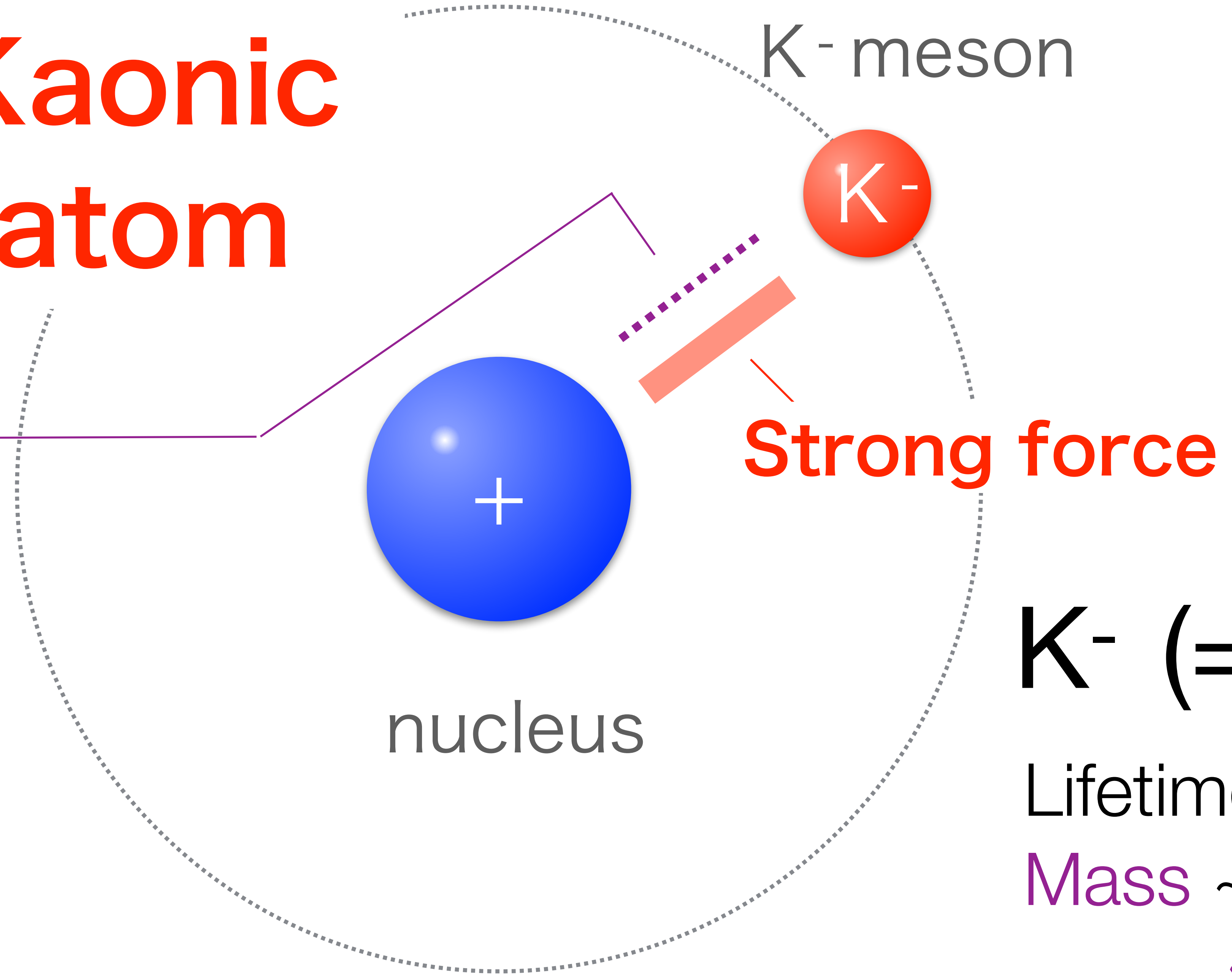
Muonic atom vs. Kaonic atom

Muonic Atom



Coulomb force

Kaonic atom



μ-

Lifetime ~ 2.2 μsec
Mass ~ 106 MeV
~ 200 m_e

K- $(= \bar{u}s)$

Lifetime ~ 12 nsec
Mass ~ 494 MeV
~ 1000 m_e

$$E_X = E_{Dirac/Klein-Gordon} + E_{QED} + E_{FNS} + (E_{strong} + \Gamma_{strong})$$

electric field
$\propto m_x^2$

close to nuclues
$R \propto 1/m_x$

Precision X-ray spectroscpy provides various physics cases

History of HEATES project

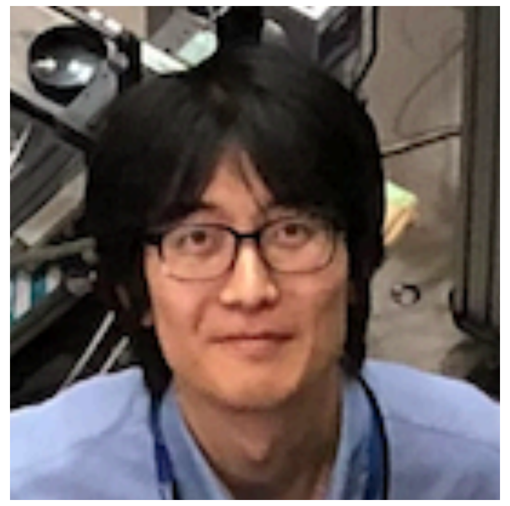
2014	**π^- atom** @ PSI (Switzerland)	*Feasibility study* *PTEP(2016)*
2016–2018	**K^- atom** @ J-PARC hadron	*Strong force study* *PRL(2022)*
2020	**μ^- atom** @ J-PARC MLF	*Study of BSQED* *PRL(2023)* *Cascade dynamics* *PRL(2021)*
2022	**μ^- molecule** @ J-PARC MLF	*Study for μCF*
2024	**μ^- atom** @ J-PARC MLF	*Study of BSQED*

1st gen. TES < 20 keV

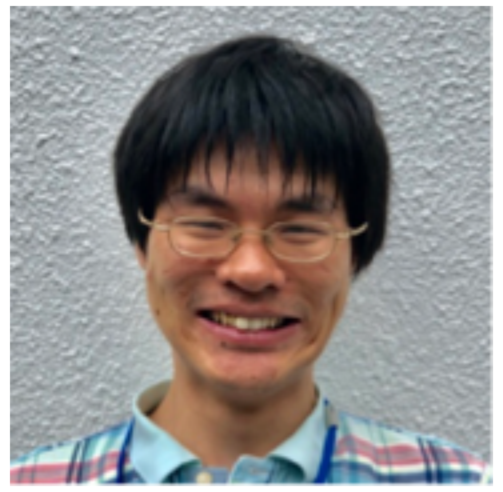
2nd gen. TES < 150 keV

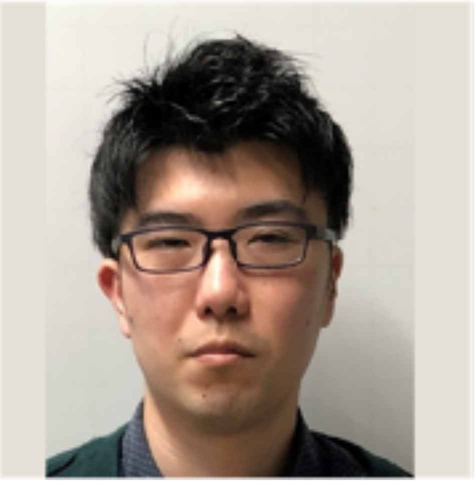

S. Okada

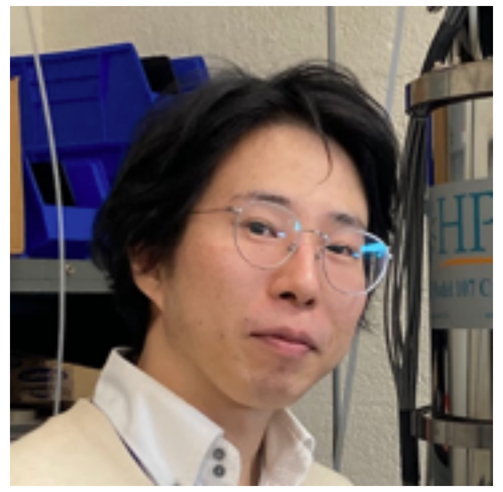

S. Yamada


H. Tatsuno


T. Hashimoto

T. Okumura


Y. Toyama


T. Saito



SPring-8
SACLA
SPring-8
x4 from 2019
x(6+2) from 2016
J-PARC
RIKEN
Narita
Sea of Japan
Hirosaki
弘前
青森
Akita
秋田
Morioka
盛岡
Sendai
仙台
Niigata
新潟
Japan
Tokyo
東京
Nagoya
名古屋
Kobe
神戸
Osaka
大阪
Hiroshima
広島
Takamatsu
高松
Shikoku
四国
Fukuoka
福岡
Nagasaki
長崎
Kyushu
九州
Miyazaki
宮崎
Kagoshima
鹿児島

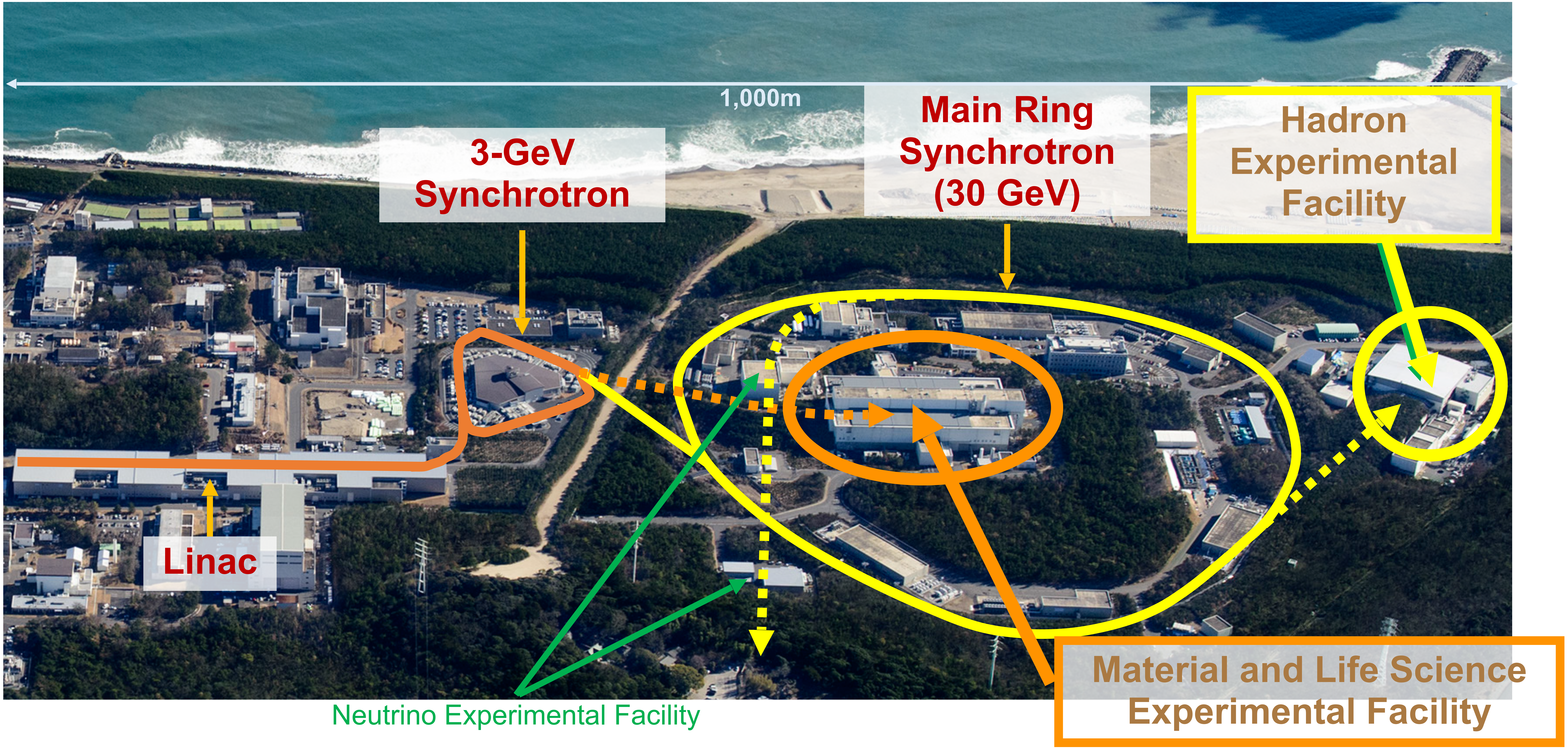
NIST-TES system

HPD102 + TDM system

HPD107K2 system on a 4t track

“Portability” is essential for our use case. ~1 week setup time.

J-PARC Japan Proton Accelerator Research Complex



World's highest intensity proton driver→ high-intensity secondary K/μ beam

Highlighted results

1. Kaonic Helium 3d→2p: Strong ineraction
2. Muonic Neon 5g→4f: QED at Strong E-field
3. Muonic Fe/Ar: Cascade
4. Preliminary results with high-E TES system

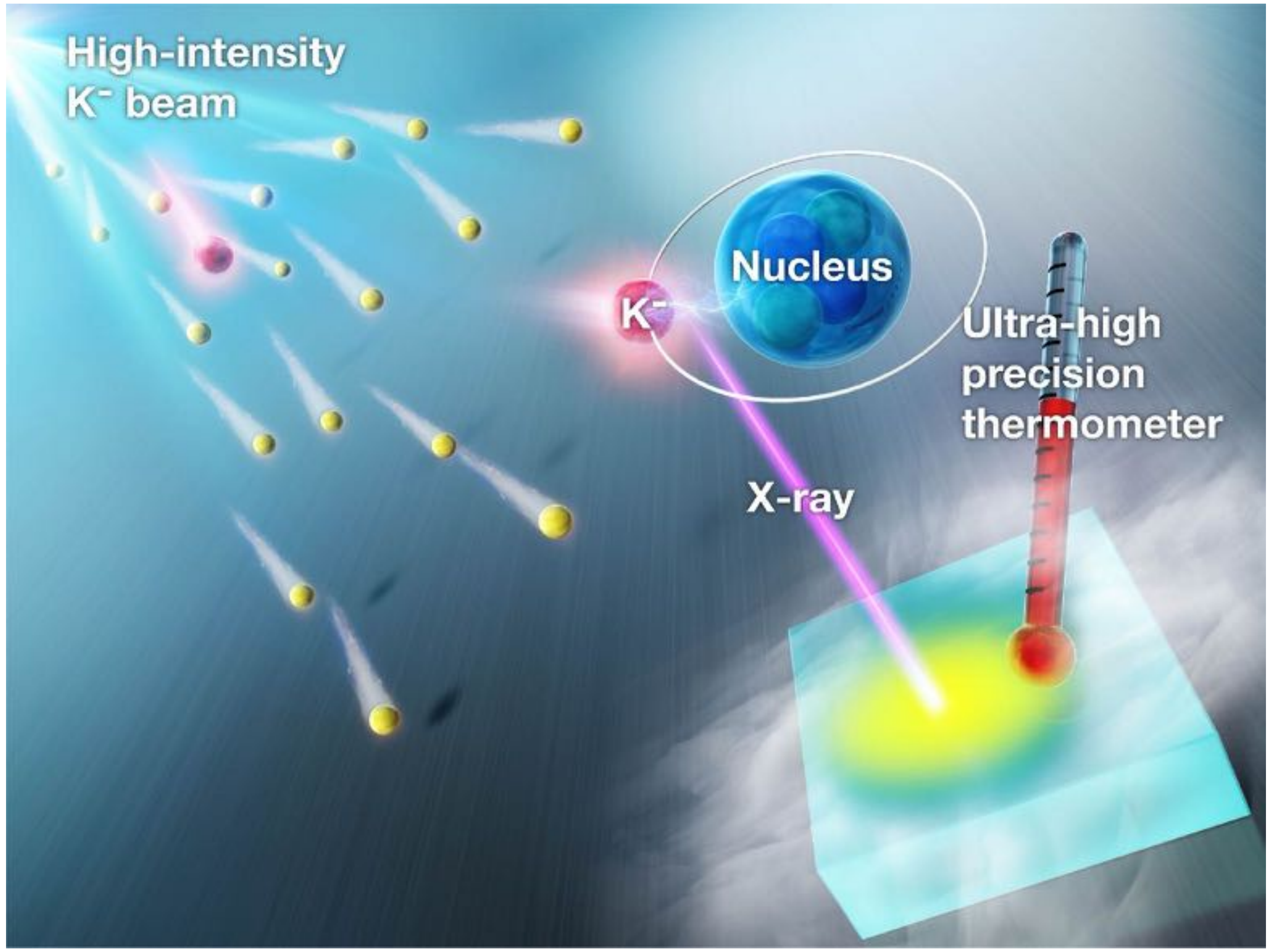
1. K^{-} $^{3/4}$He atom X-rays

PHYSICAL REVIEW LETTERS **128,** 112503 (2022)

Measurements of Strong-Interaction Effects in Kaonic-Helium Isotopes at Sub-eV Precision with X-Ray Microcalorimeters

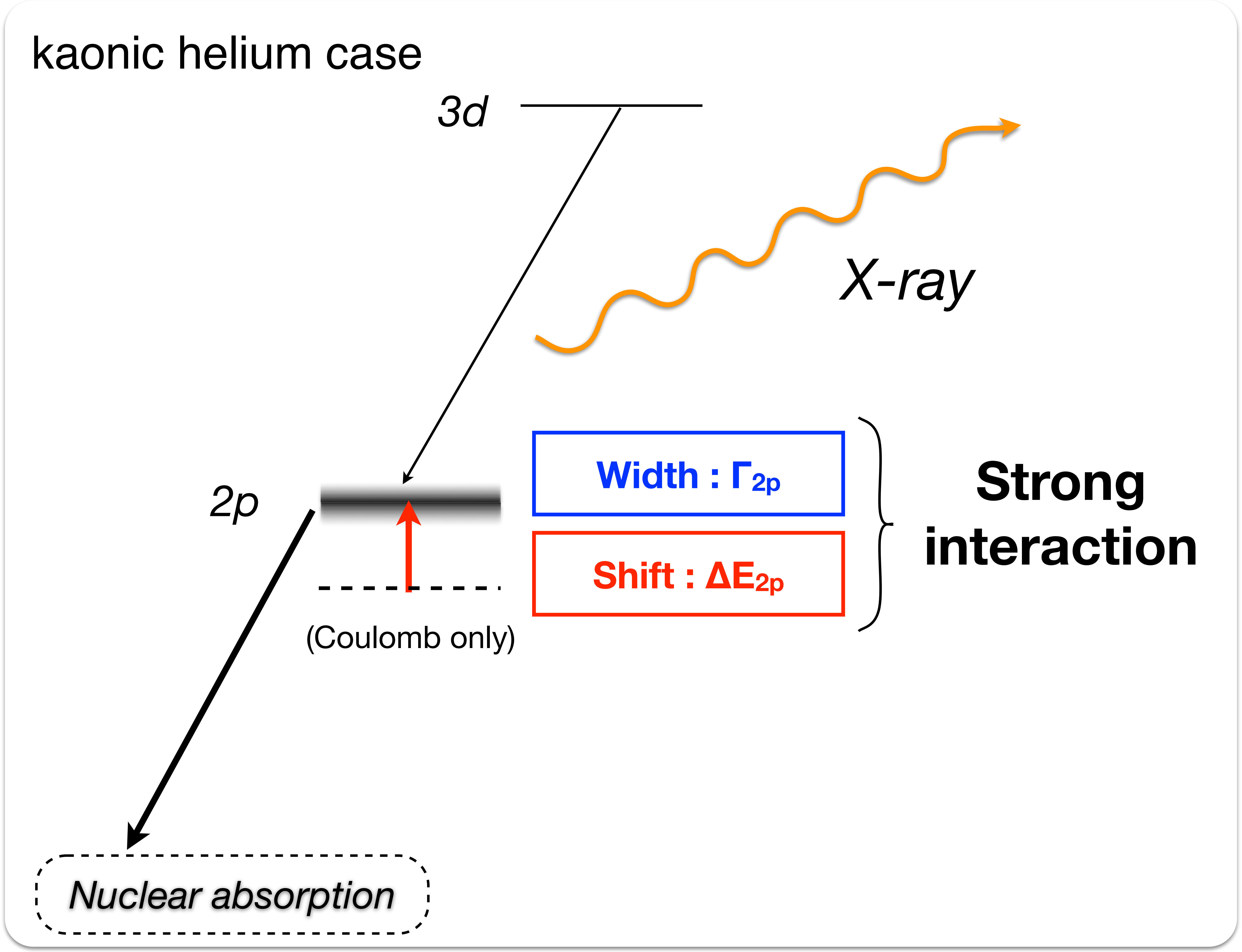
T. Hashimoto,[1,2,*] S. Aikawa,[3] T. Akaishi,[4] H. Asano,[2] M. Bazzi,[5] D. A. Bennett,[6] M. Berger,[7] D. Bosnar,[8] A. D. Butt,[9] C. Curceanu,[5] W. B. Doriese,[6] M. S. Durkin,[6] Y. Ezoe,[10] J. W. Fowler,[6] H. Fujioka,[3] J. D. Gard,[6] C. Guaraldo,[5] F. P. Gustafsson,[7] C. Han,[2] R. Hayakawa,[10] R. S. Hayano,[11] T. Hayashi,[12] J. P. Hays-Wehle,[6] G. C. Hilton,[6] T. Hiraiwa,[13] M. Hiromoto,[4] Y. Ichinohe,[14] M. Iio,[15] Y. Iizawa,[3] M. Iliescu,[5] S. Ishimoto,[15] Y. Ishisaki,[10] K. Itahashi,[2] M. Iwasaki,[2] Y. Ma,[2] T. Murakami,[11] R. Nagatomi,[4] T. Nishi,[16] H. Noda,[17] H. Noumi,[13] K. Nunomura,[10] G. C. O'Neil,[6] T. Ohashi,[10] H. Ohnishi,[18] S. Okada,[19,2,†] H. Outa,[2] K. Piscicchia,[5] C. D. Reintsema,[6] Y. Sada,[18] F. Sakuma,[2] M. Sato,[15] D. R. Schmidt,[6] A. Scordo,[5] M. Sekimoto,[15] H. Shi,[7] K. Shirotori,[13] D. Sirghi,[5] F. Sirghi,[5] K. Suzuki,[7] D. S. Swetz,[6] A. Takamine,[2] K. Tanida,[1] H. Tatsuno,[10] C. Trippl,[7] J. Uhlig,[20] J. N. Ullom,[6] S. Yamada,[14] T. Yamaga,[2] T. Yamazaki,[11] and J. Zmeskal[7]

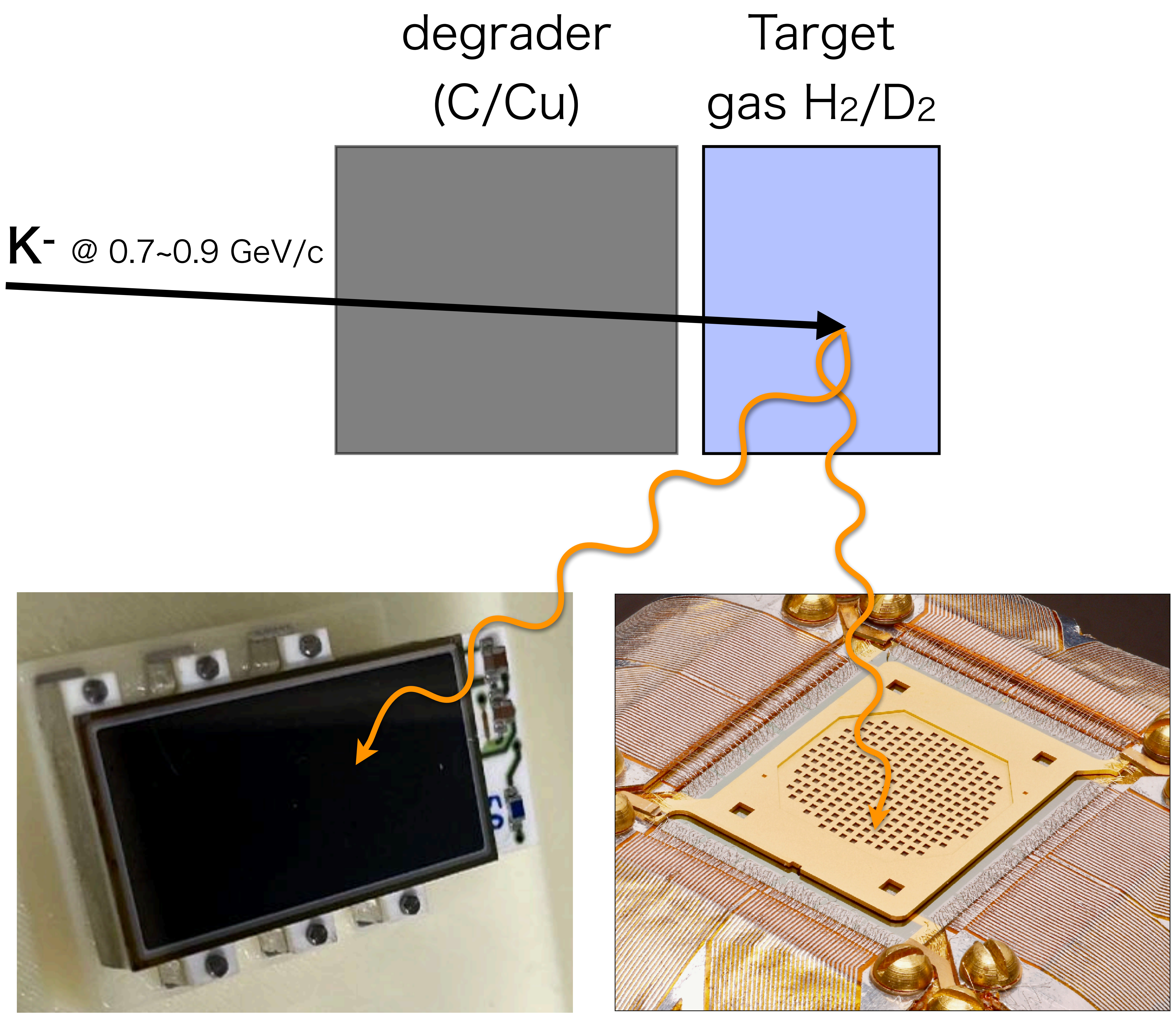
(J-PARC E62 Collaboration)



Hadoron physicists + TES experts + Astro physicists

Kaonic atom X-rays



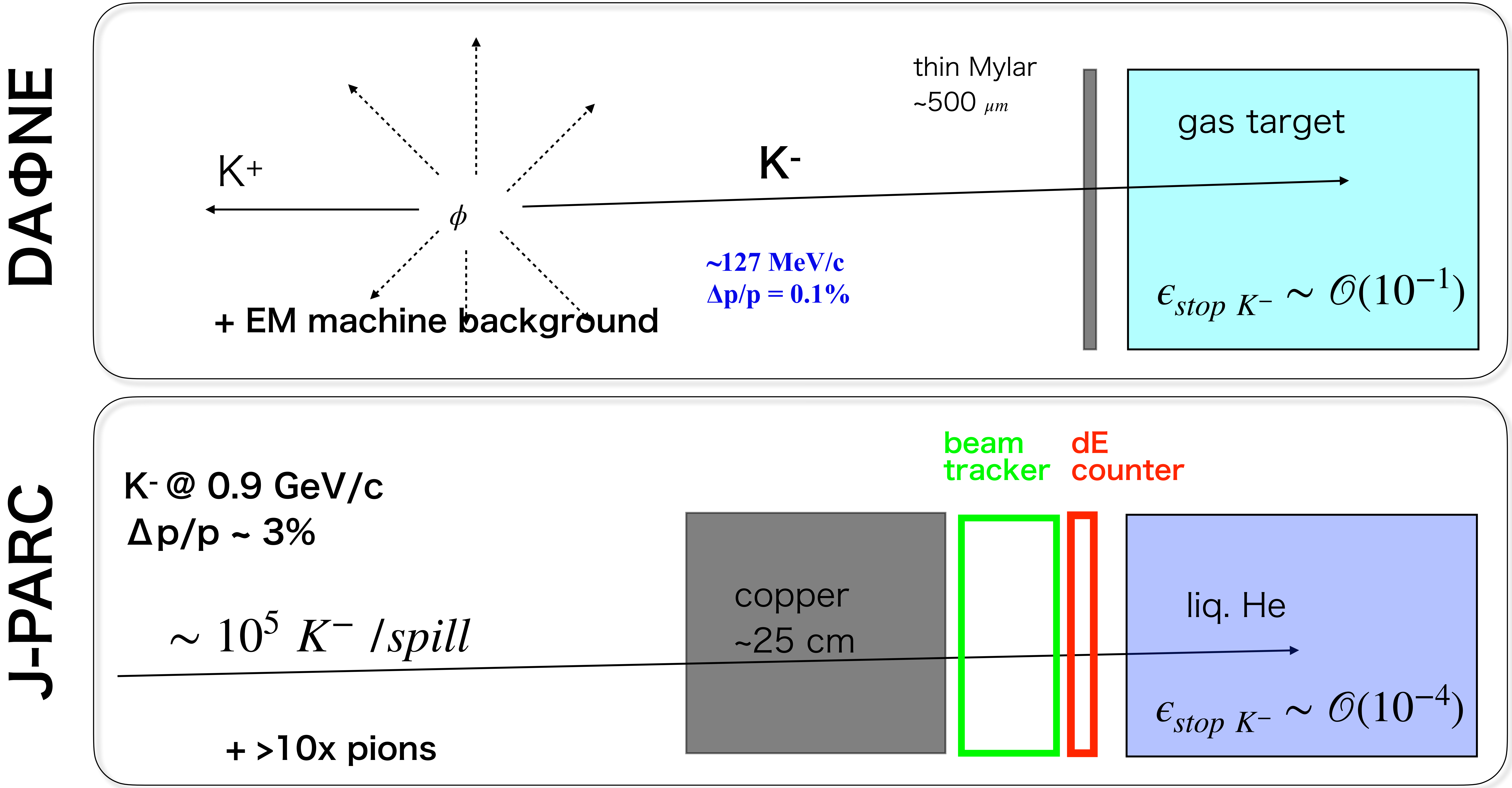


SDDs
Moderate resolution
Large solid angle
K^-p,/K^-d 1s
(**SIDDHARTA**/E57)
High sensitivity

Microcalorimeter
Excellent resolution
Limited effective area
K^-He 2p (E62)
Ultra high resolution

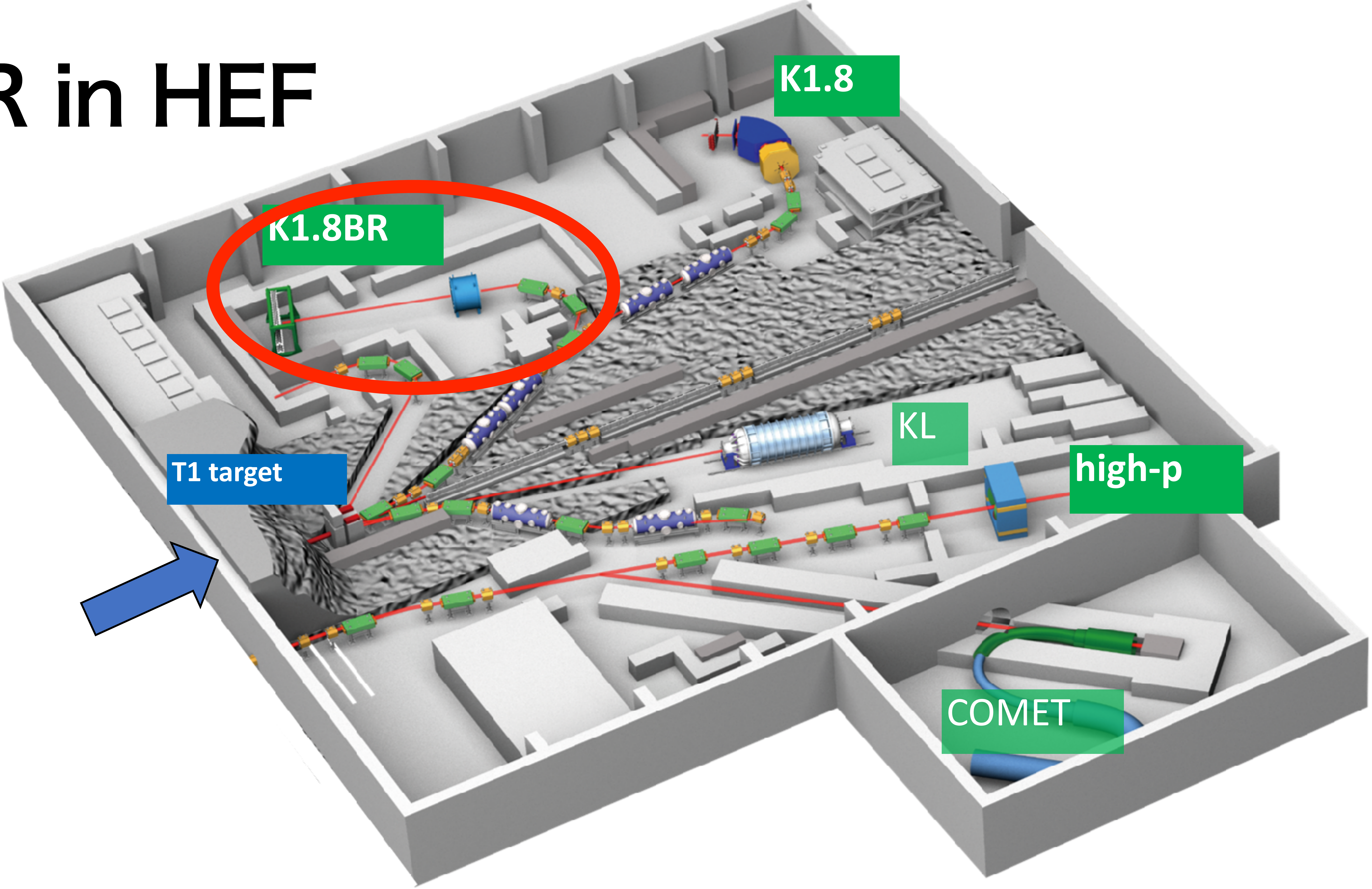
Alternative to a low-E scattering experiment

DAΦNE vs. J-PARC



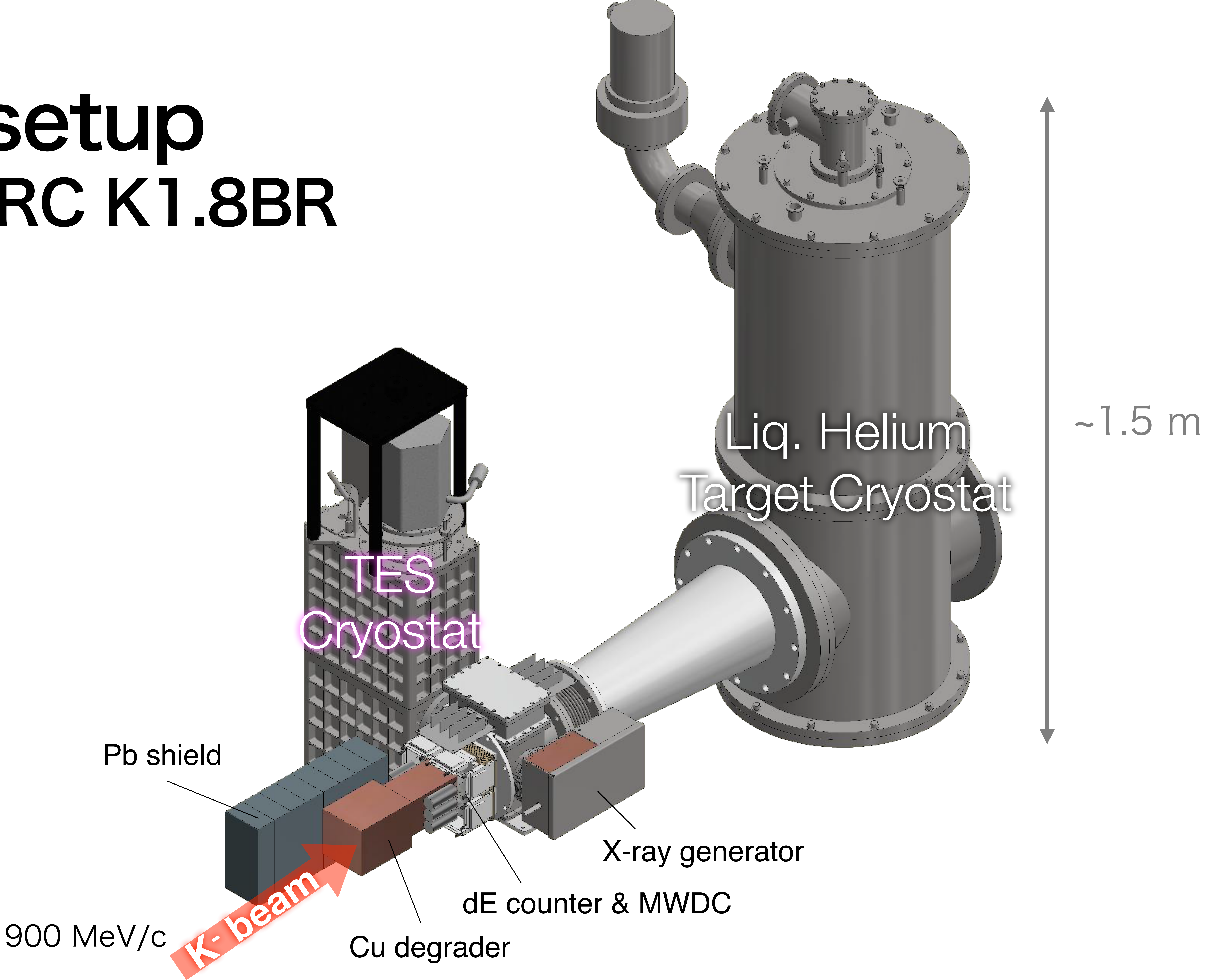
J-PARC provides higher intensity K- — advantage with liquid target.

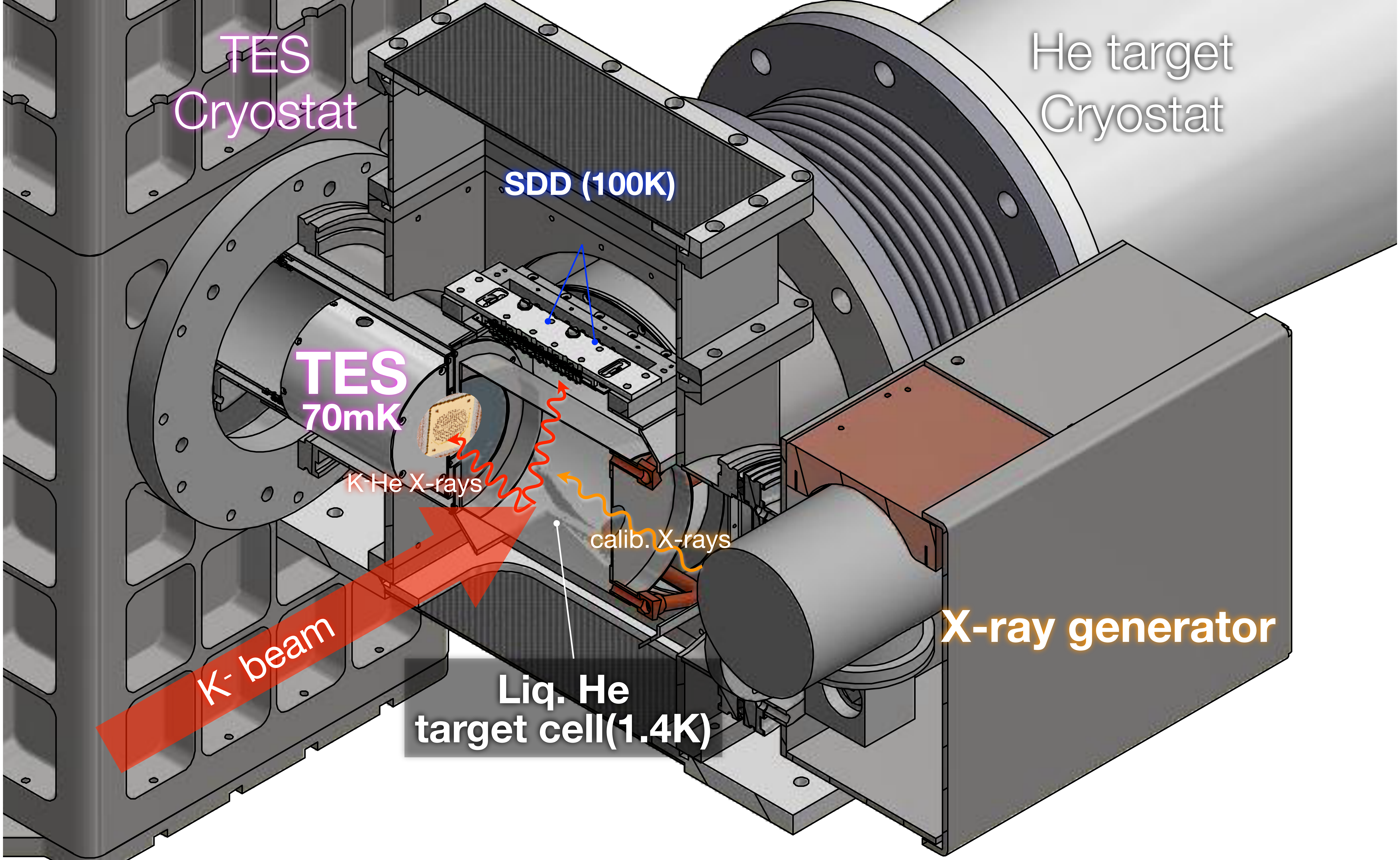
K1.8BR in HEF



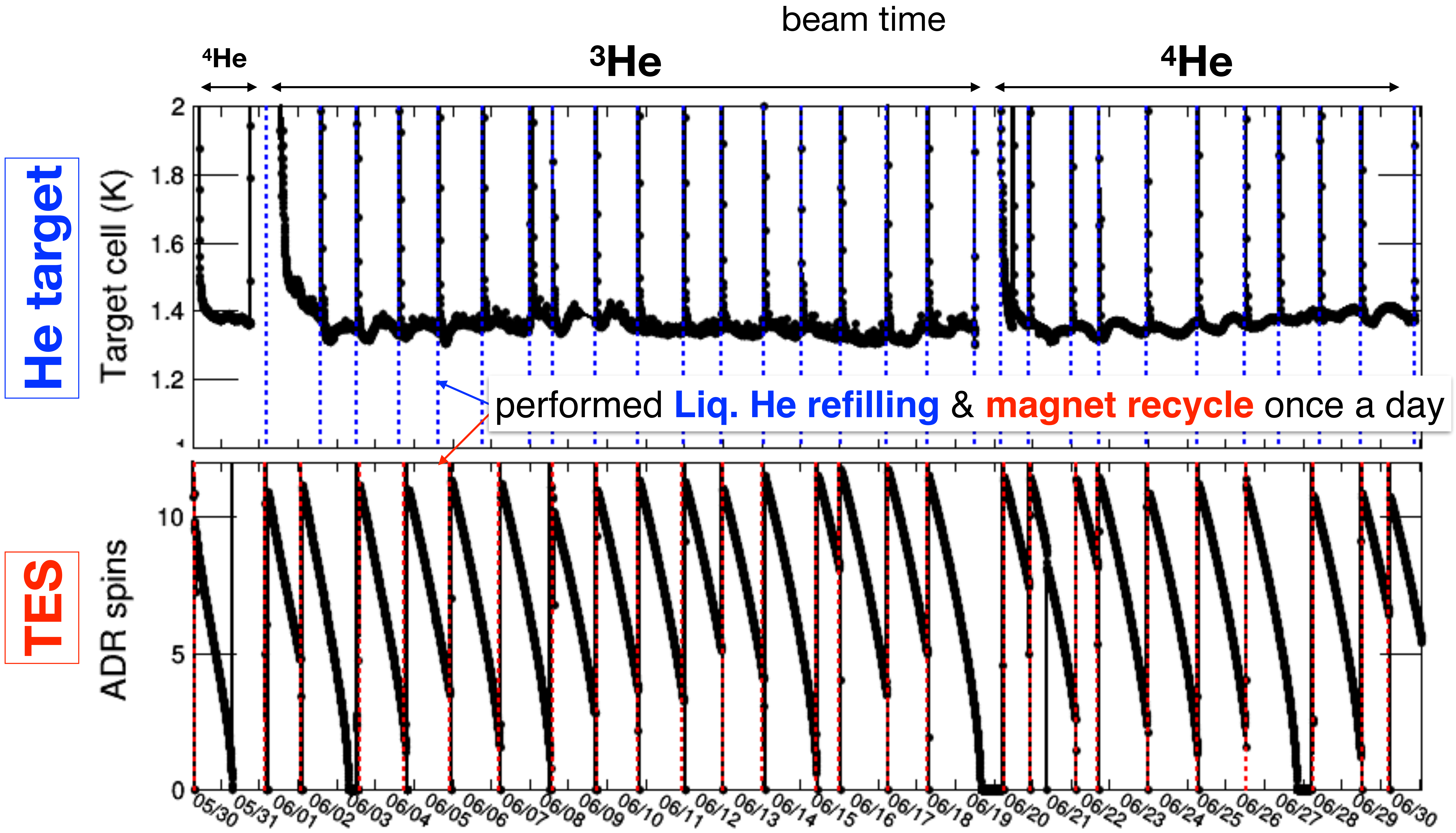
K1.8BR suitable for low-energy K^- beam below 1 GeV/c

E62 setup
@J-PARC K1.8BR



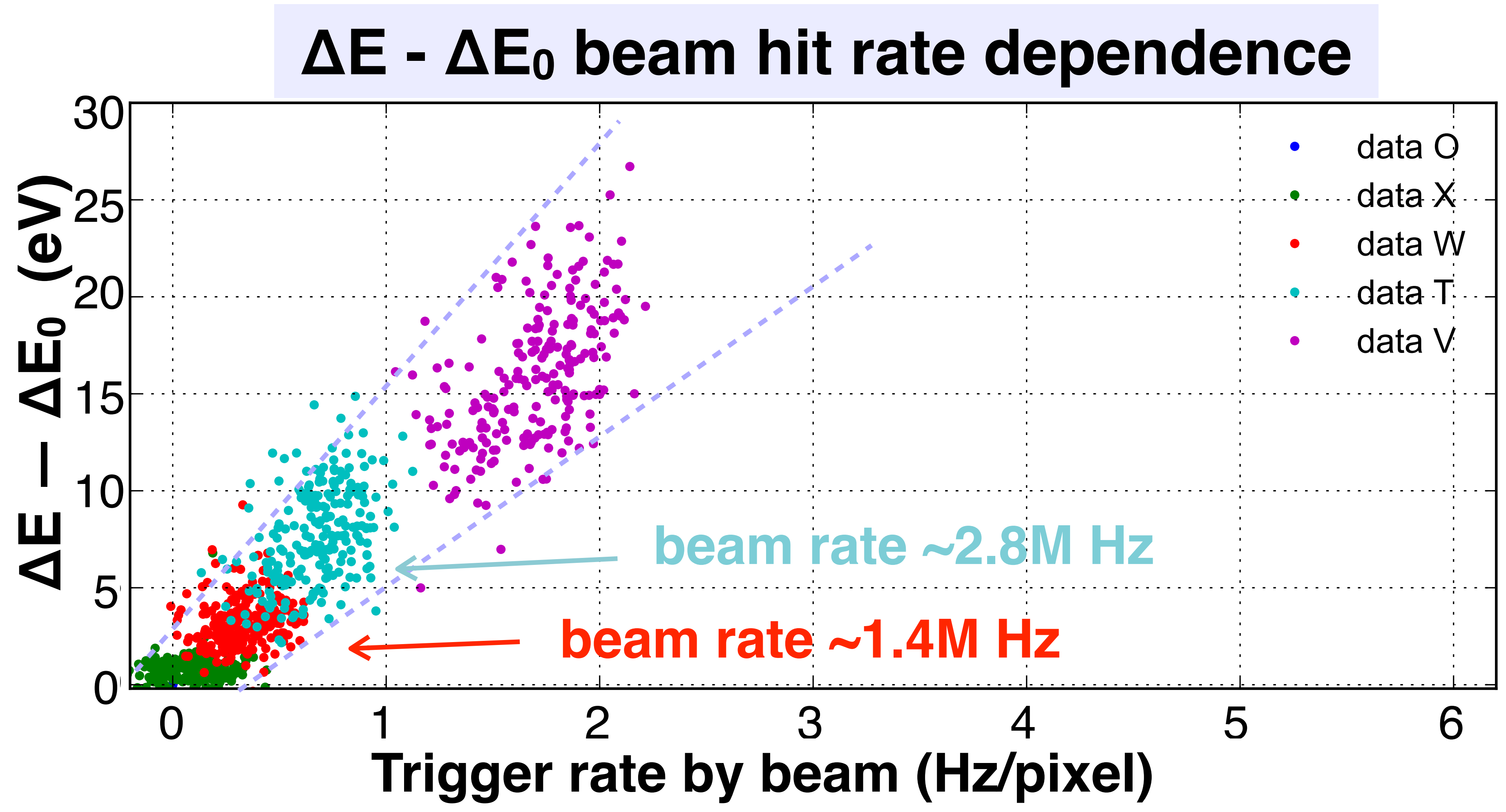

TES
Cryostat
He target
Cryostat
SDD (100K)
TES
70mK
K-He X-rays
calib. X-rays
K- beam
Liq. He
target cell(1.4K)
X-ray generator

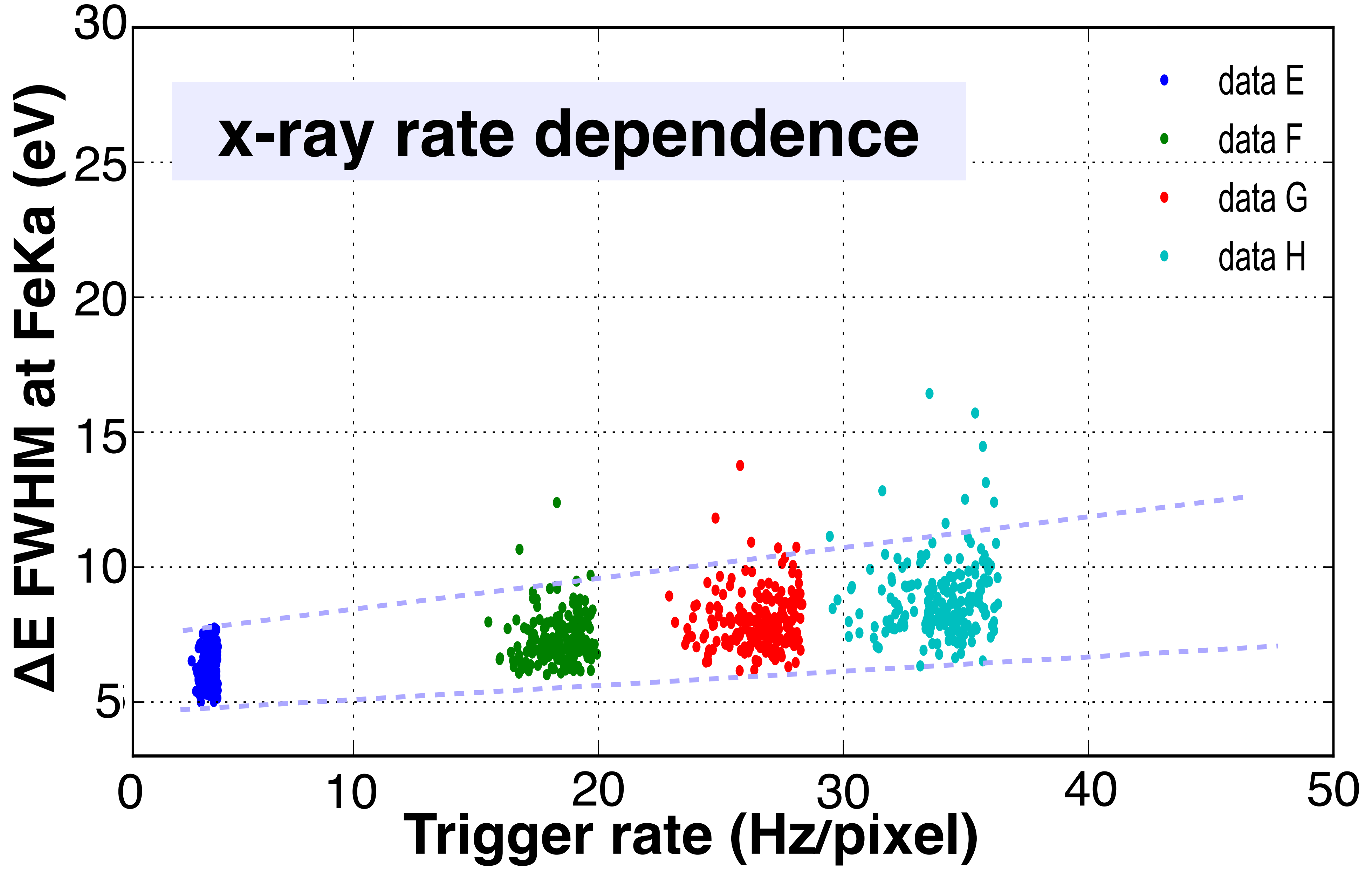
Long-term operation of cryogenic systems

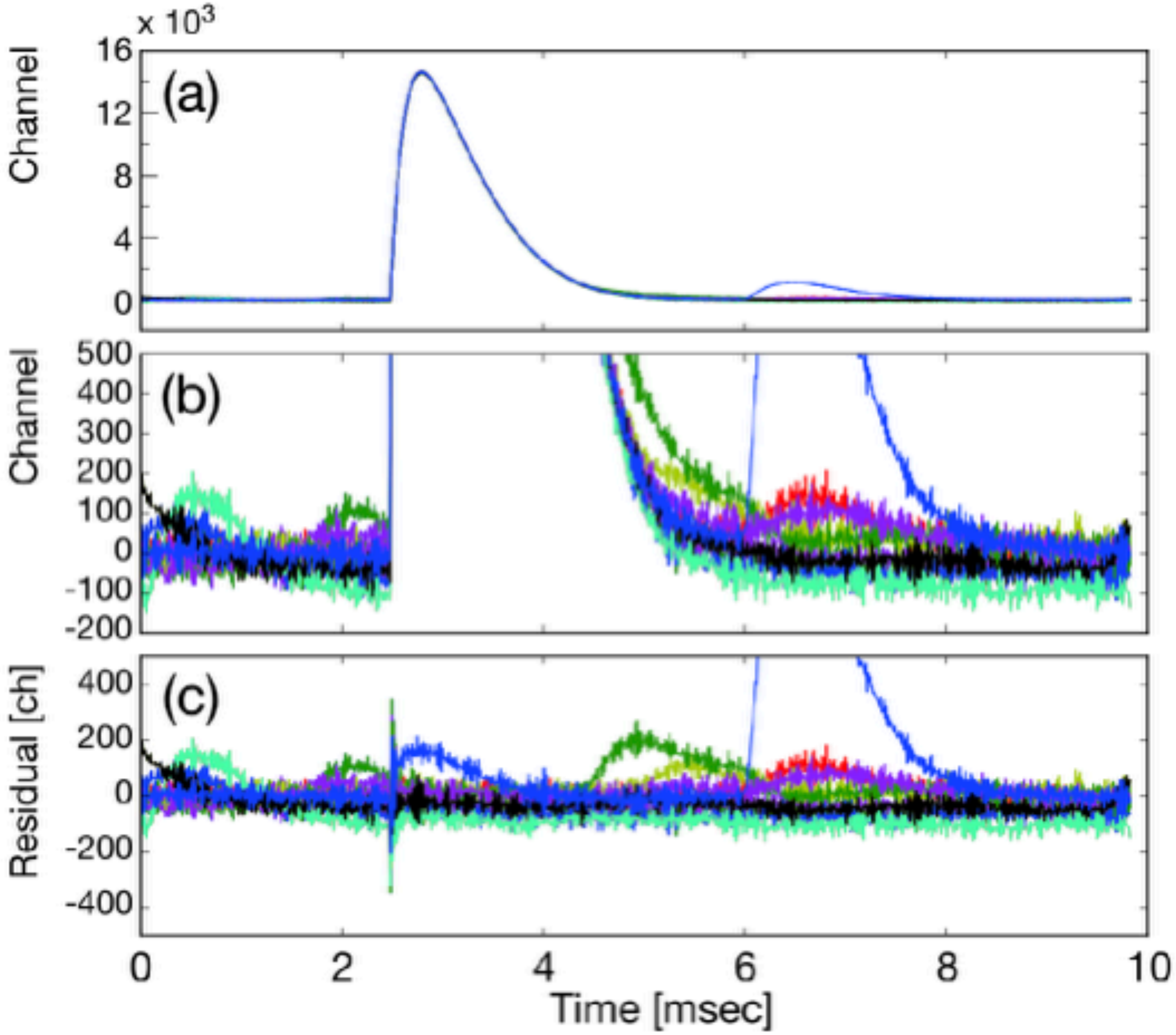


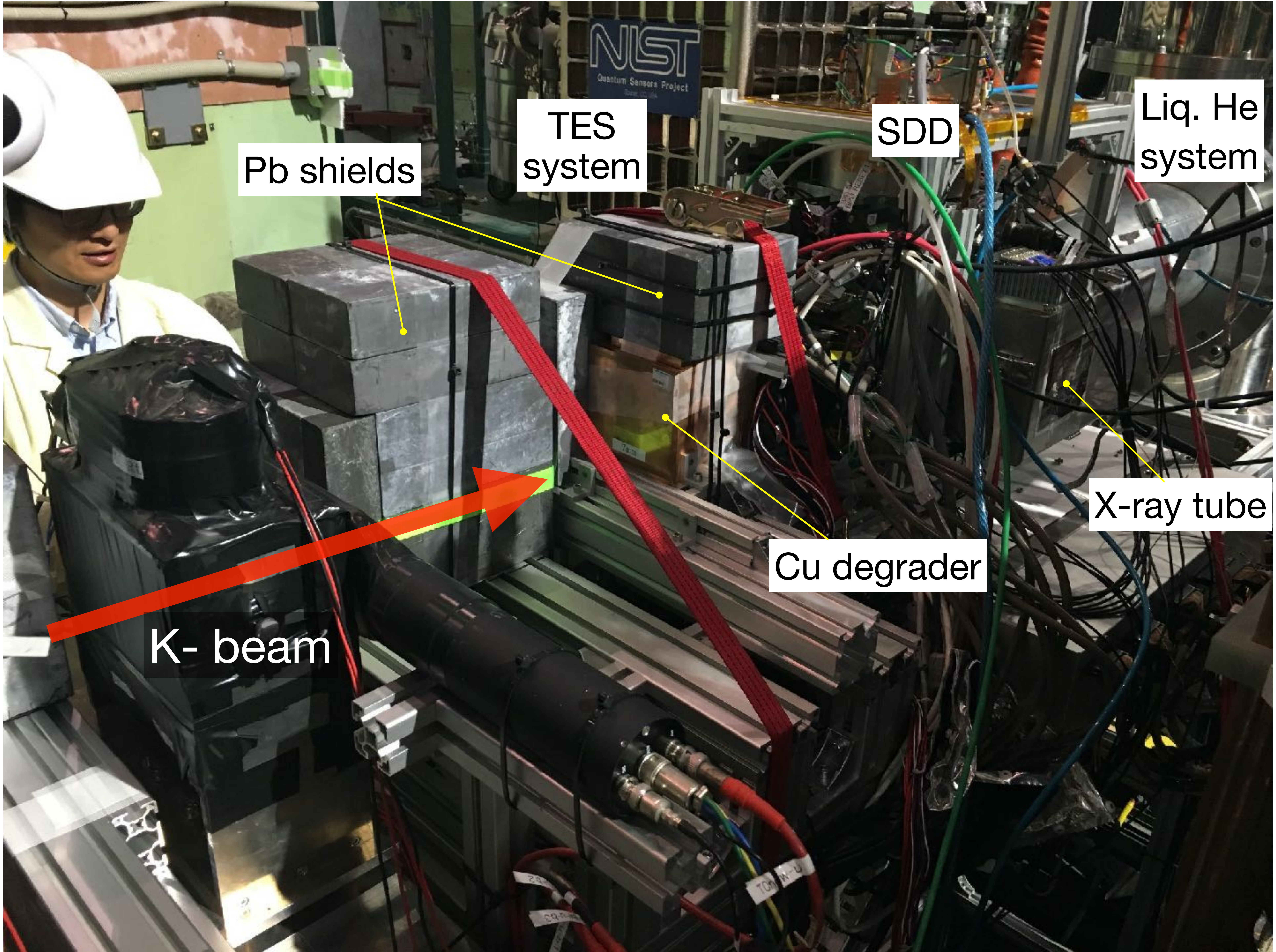
Stable operation for one month (28 He refills & 27 mag cycles)

In-beam energy deterioration







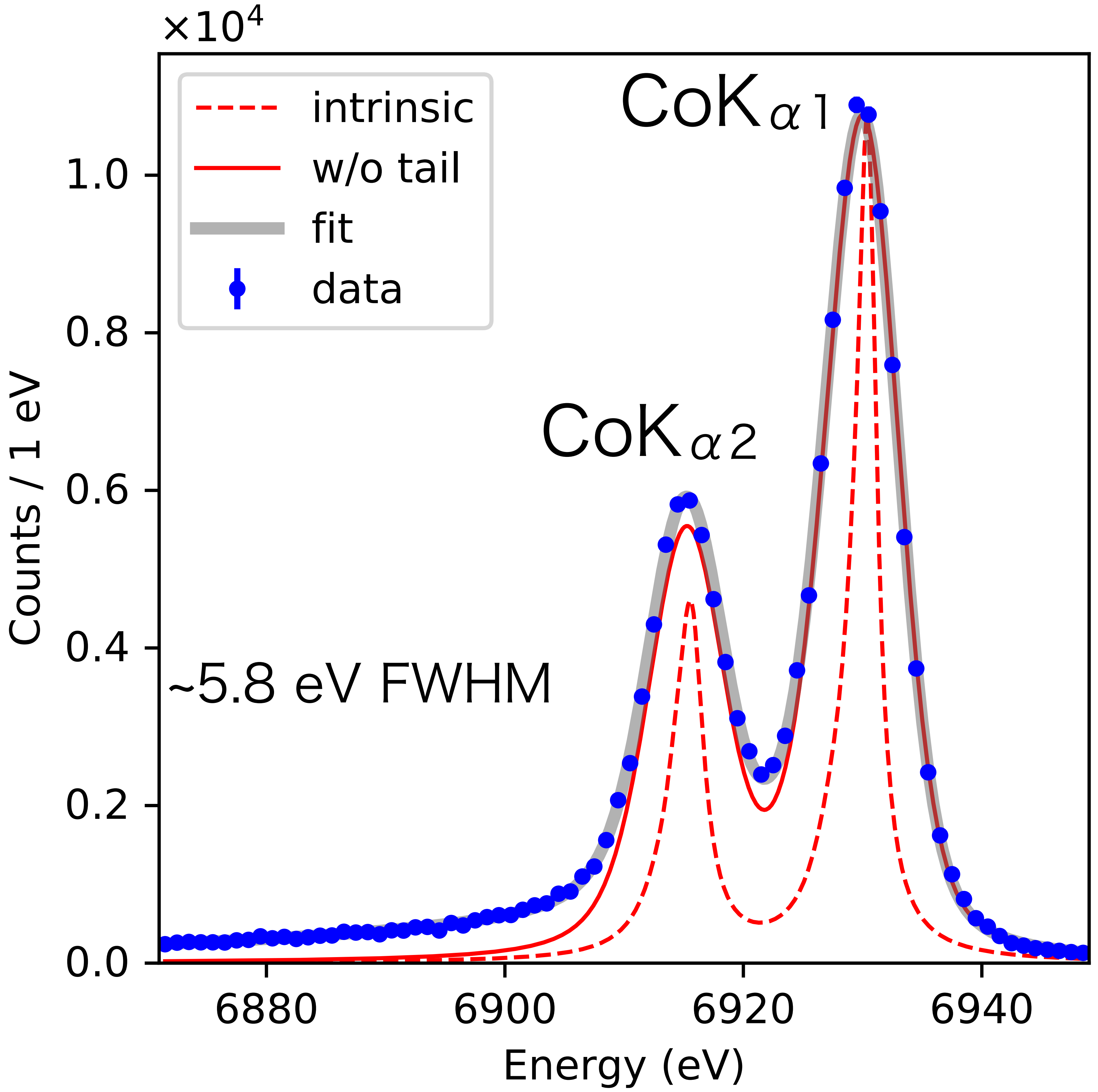


Pb shields
TES system
SDD
Liq. He system
X-ray tube
Cu degrader
K- beam
NIST
Quantum Sensors Project

Performance in the K- atom experiment

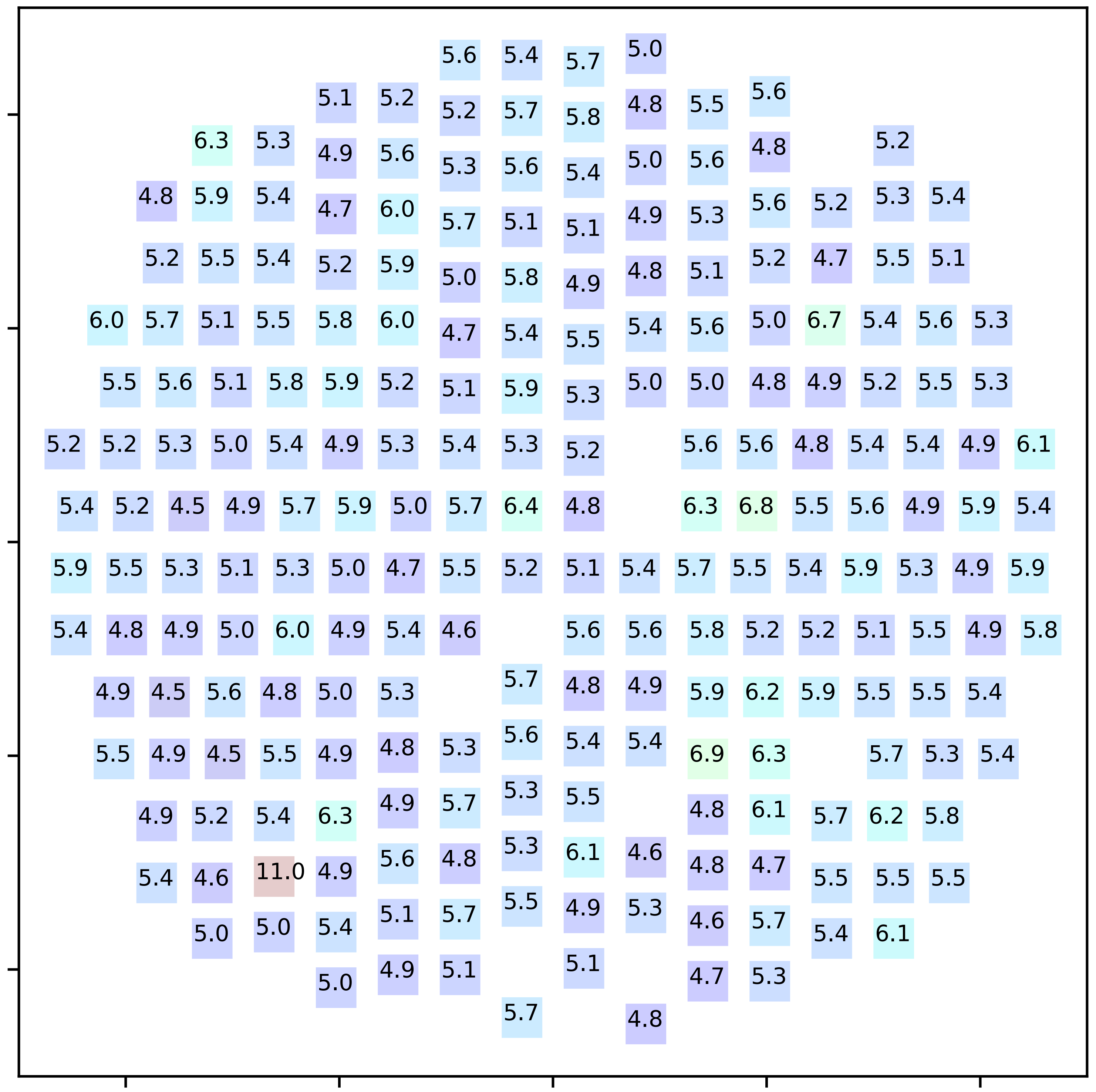
After all the analysis optimization (mainly reduction of charge-particle effects)

Response function



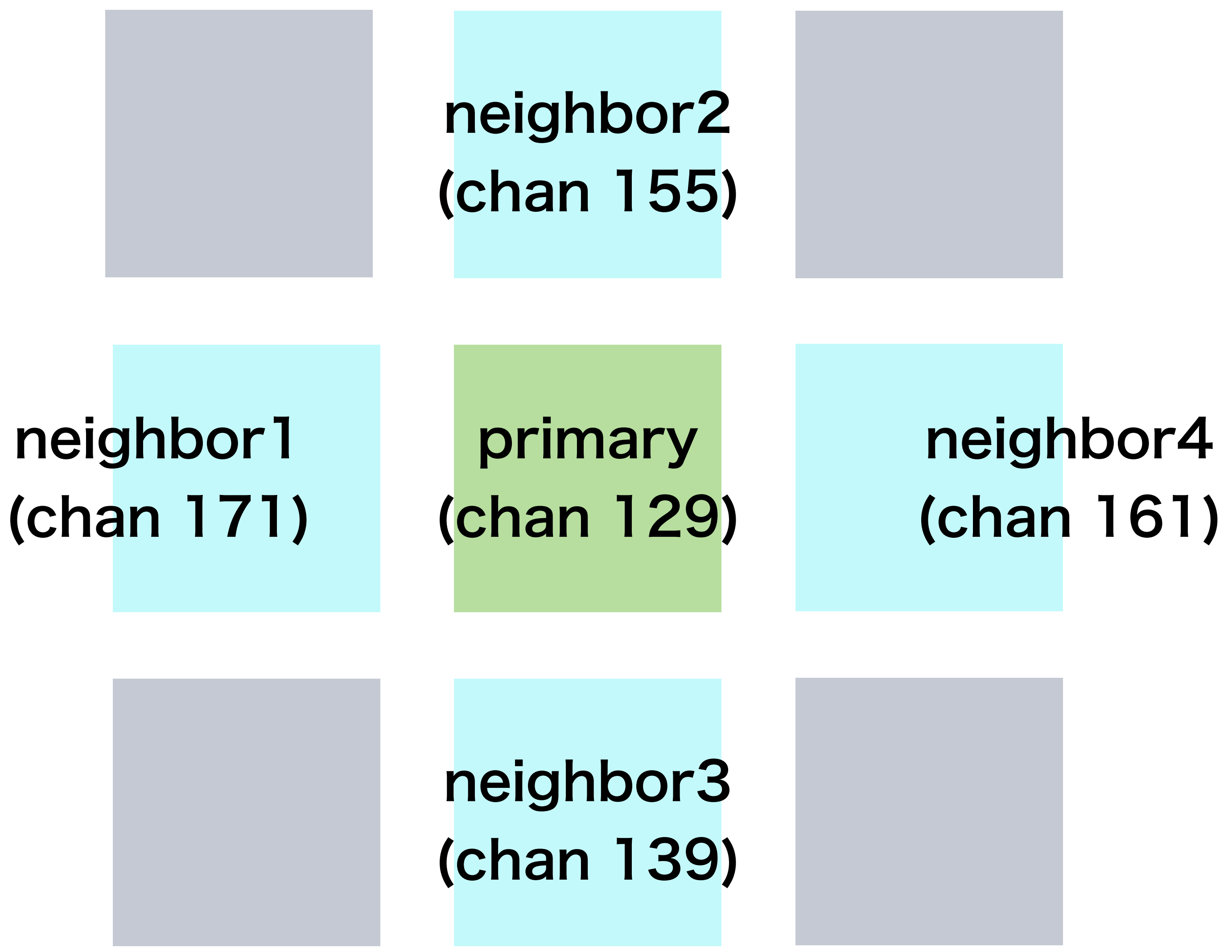
Detector response is well described
by a gaussian and a low-energy exponential tail

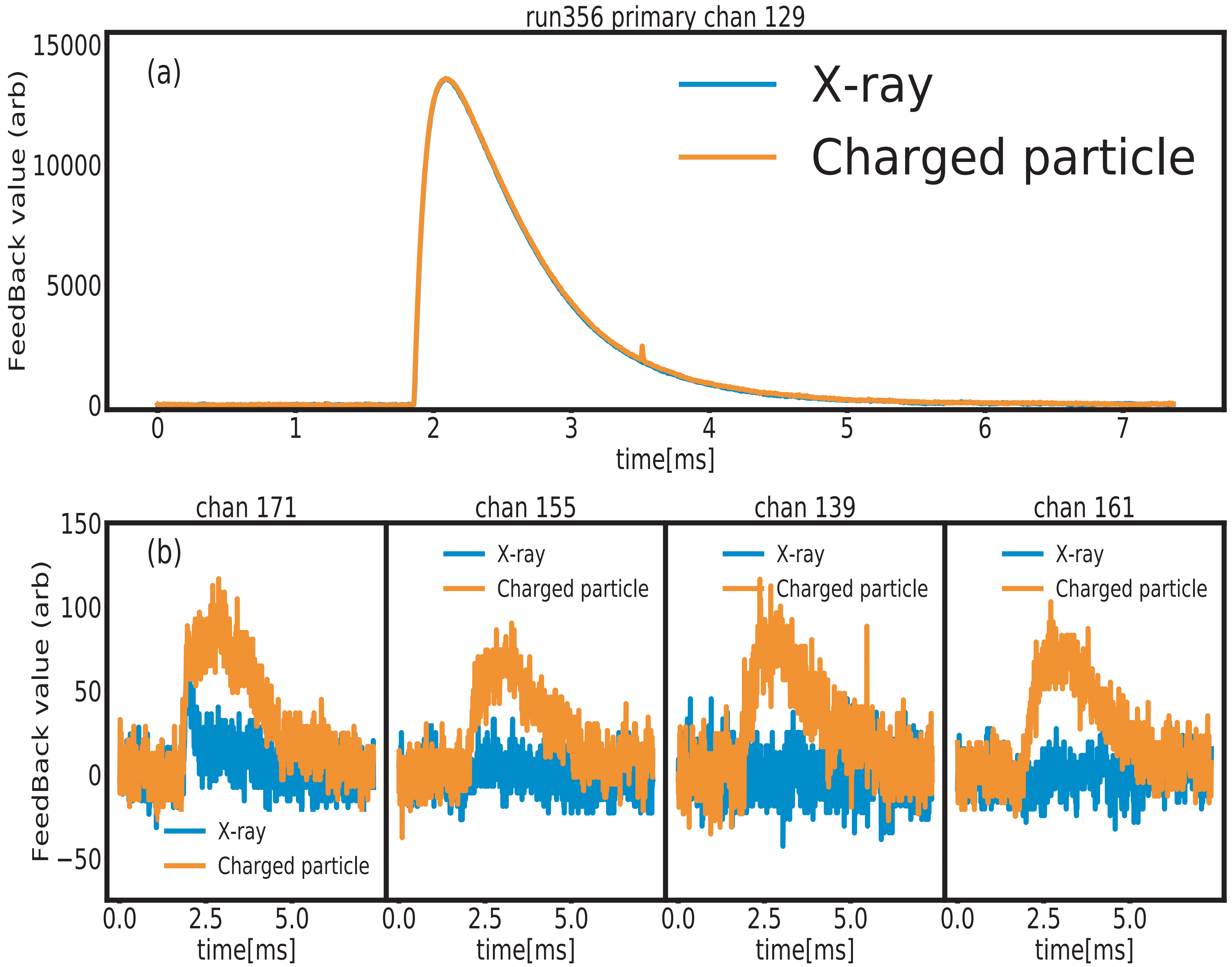
Resolution geometrical map



Resolution at CoKα
no box : doesn't work at all (12 pixel)

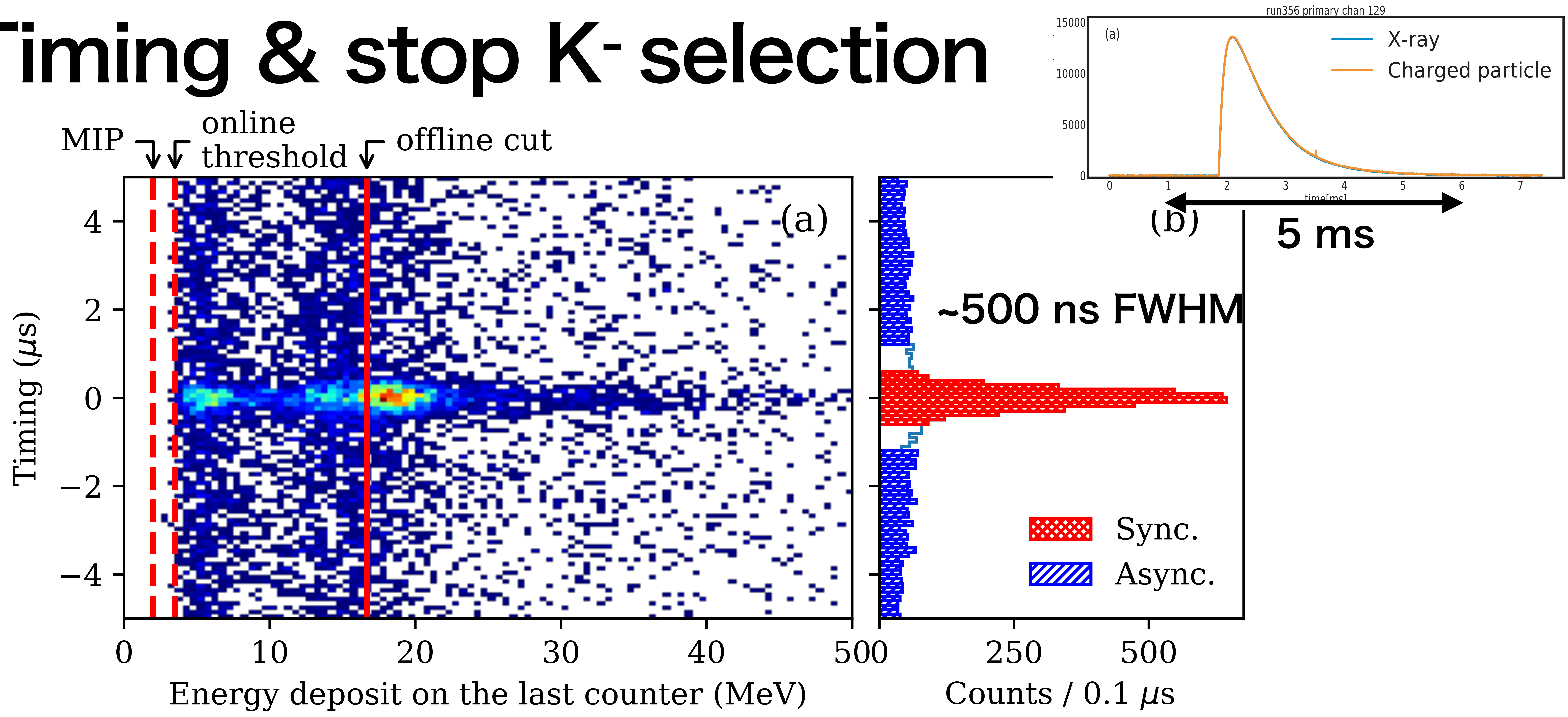
Charged particle identification





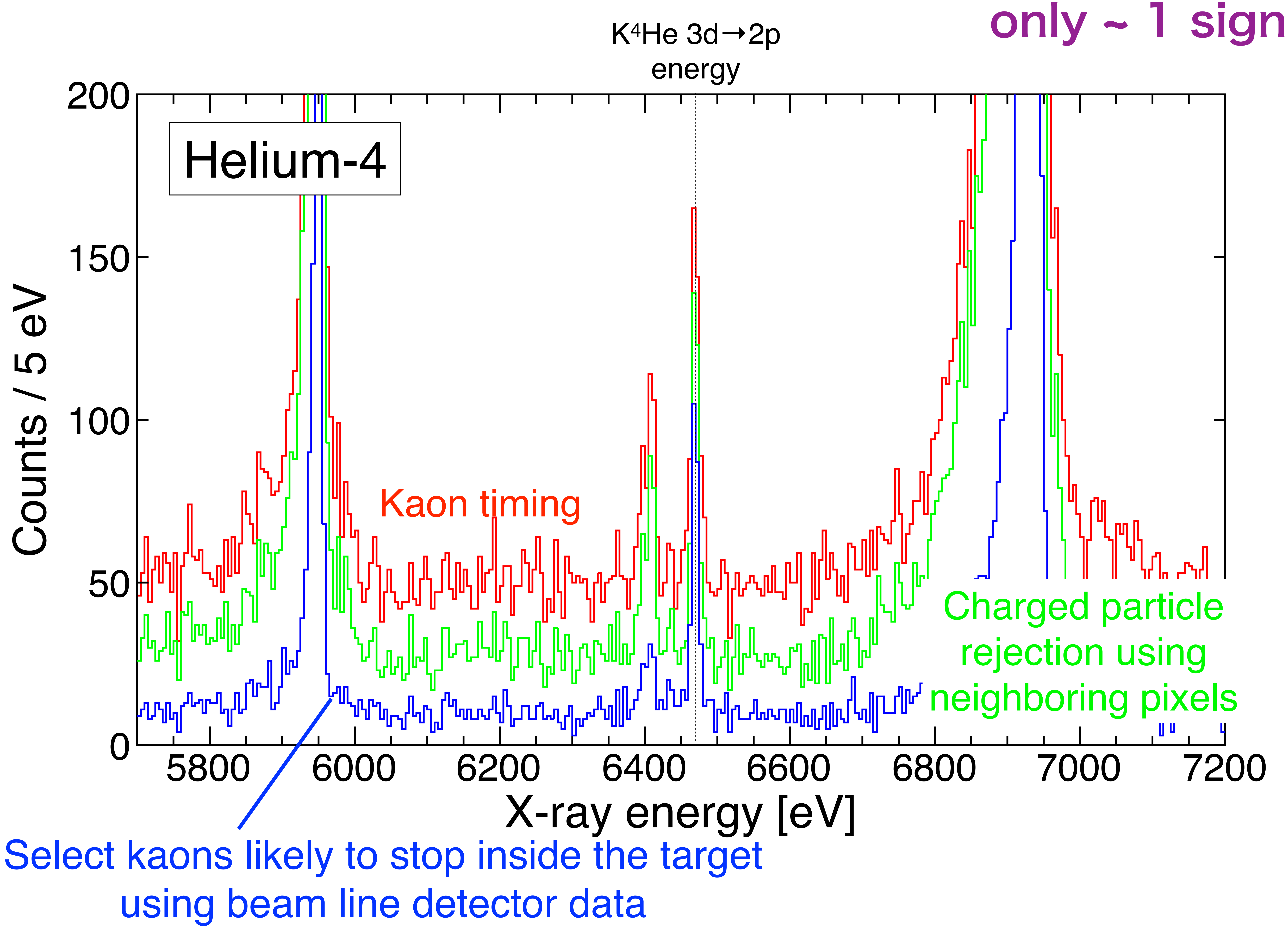
- No difference in the primary pulses between X-rays and charged particles
- If we look at neighboring pixels, we can reject half of the charged particles

Timing & stop K- selection



- Beamline data was offline synchronized based on timestamp
- **Time resolution ~ 500 ns FWHM is comparable to SDDs**

only ~ 1 signal / hour



TES (E62)

~6 eV (FWHM)

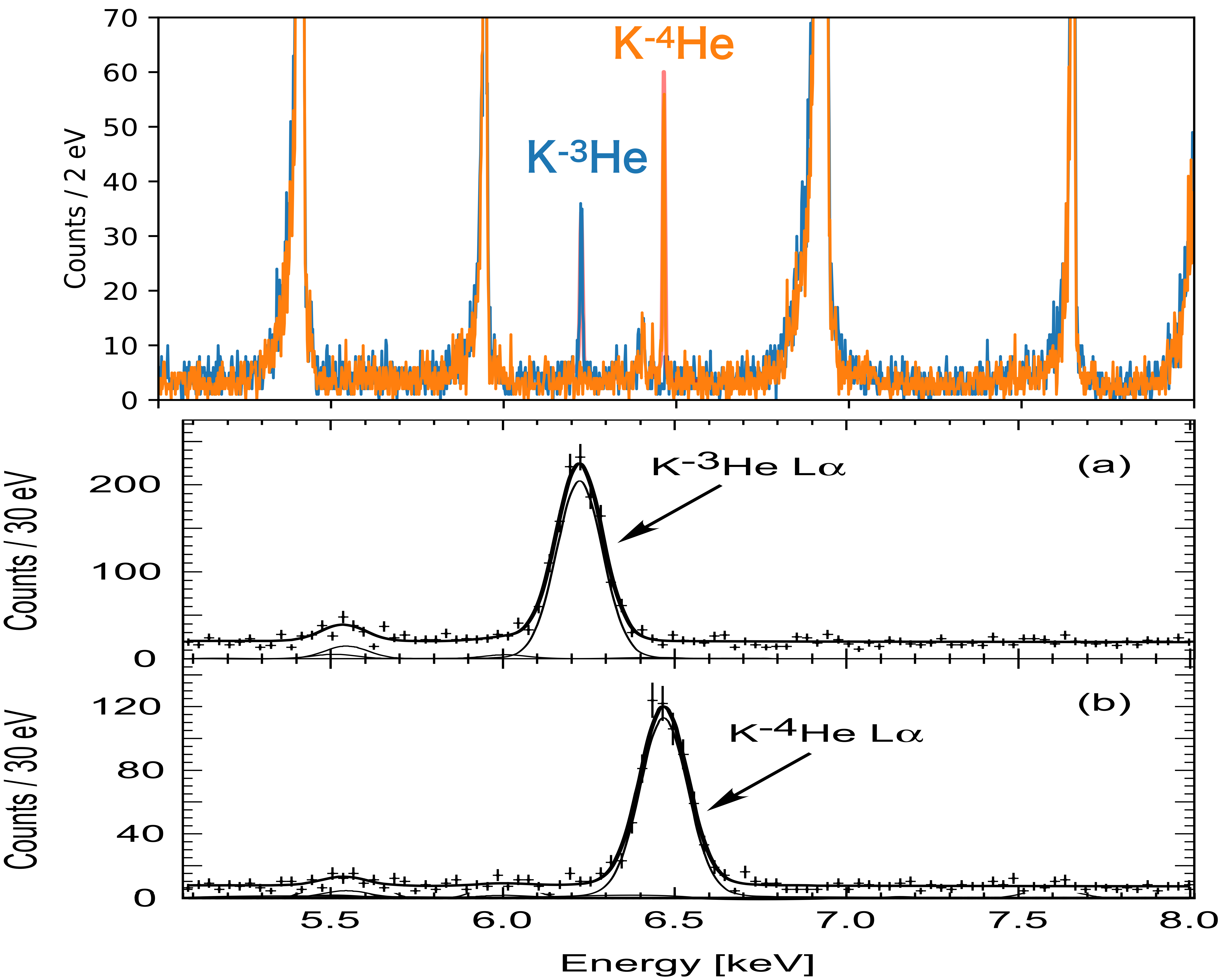
PRL128, 112503 (2022)

x25 better resolution

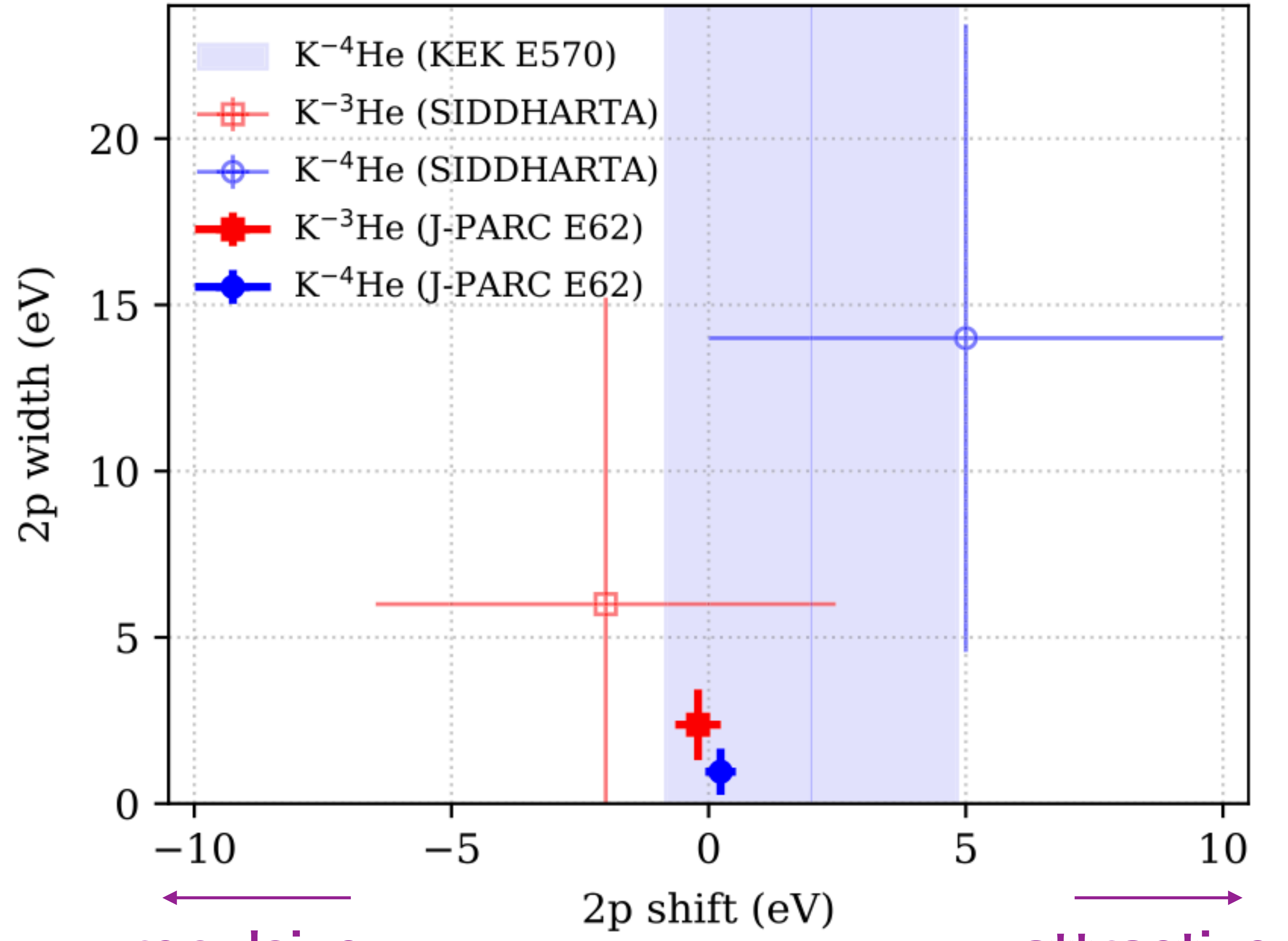
SDD (SIDDHARTA)

~150 eV (FWHM)

PLB714(2012)40



Theoretical study on the E62 results



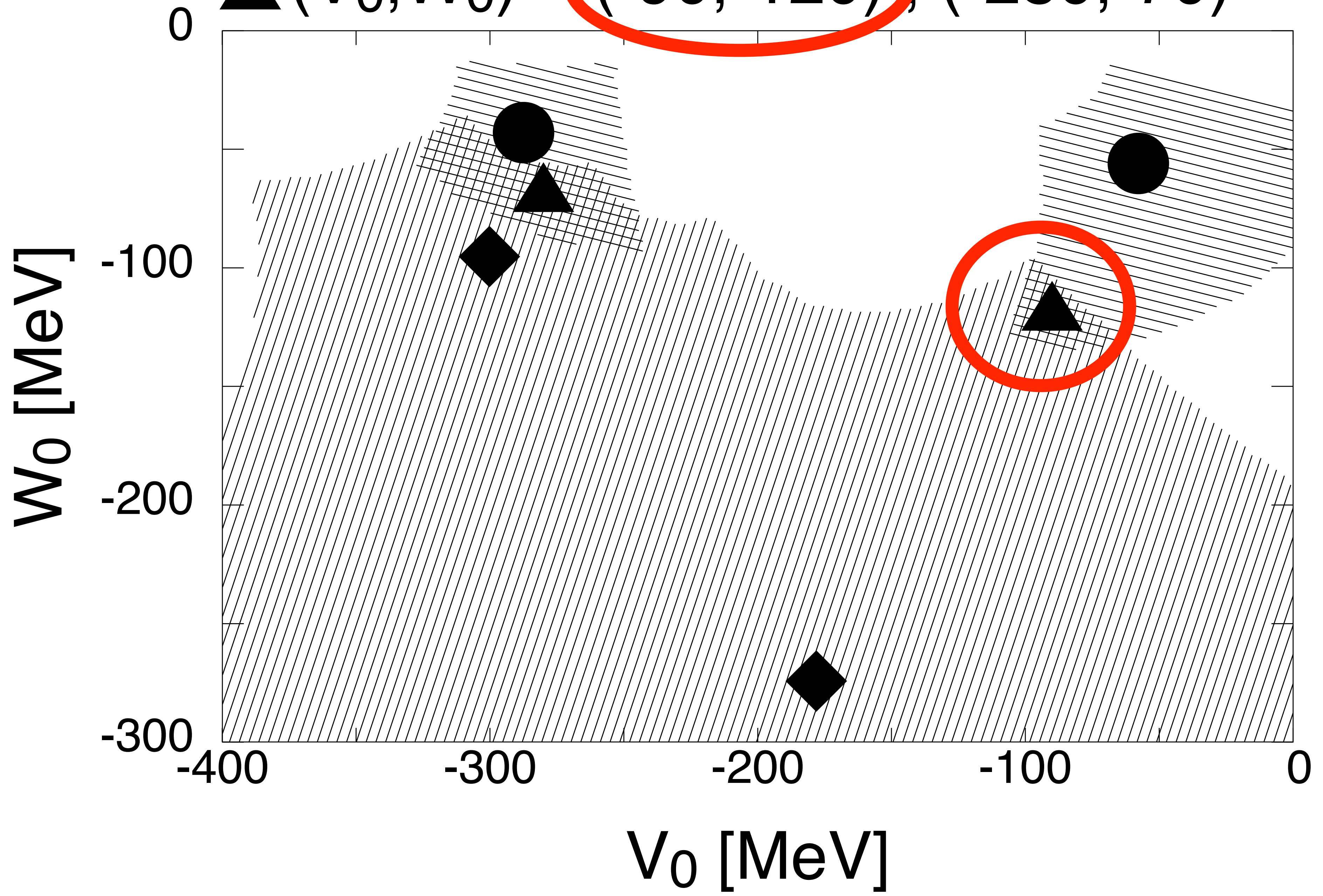
$$\Delta E = E_{exp.} - E_{EM}$$

J. Yamagata-Sekihara, et al., PTEP**2024,** 189 (2024).

$$U(r) = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$$

● ^{4}He ◆ ^{3}He

▲ (V_0, W_0) = (-90,-120), (-280,-70)



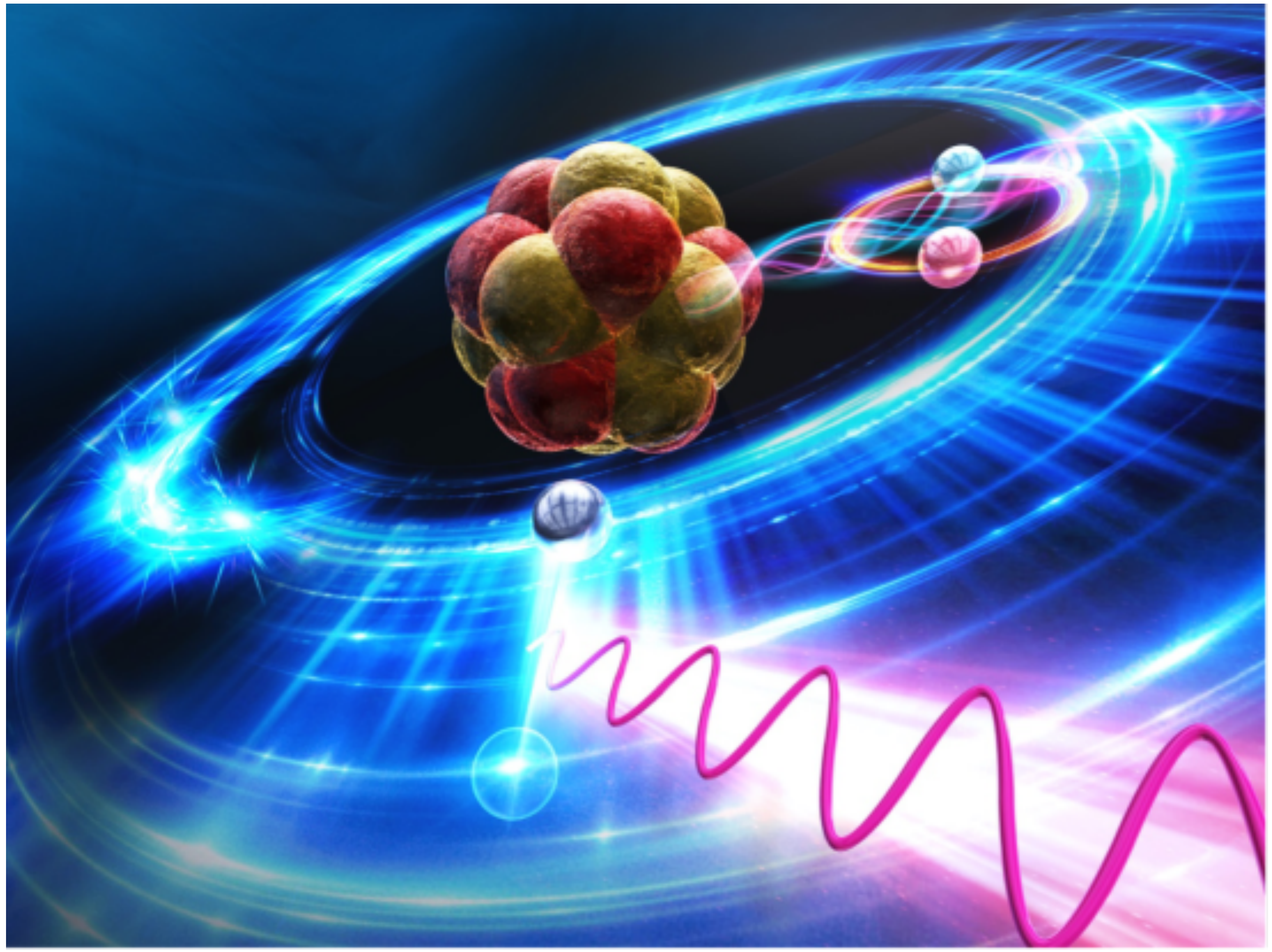
- Simple potential parameters constrained with the 4 observables well reproduce the global features of the kaonic-atom data

2. μNe 5g-4f: BSQED

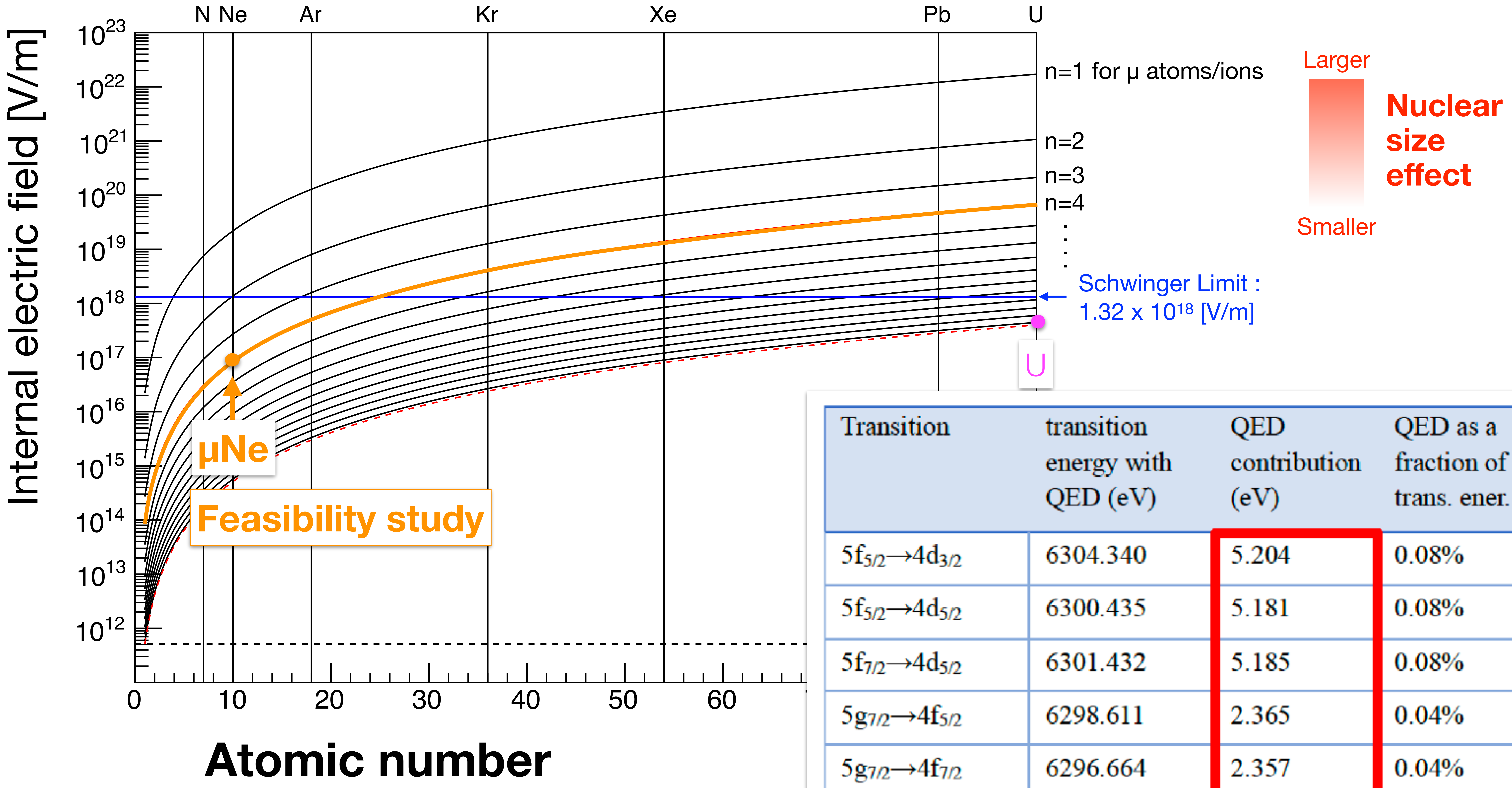
PHYSICAL REVIEW LETTERS **130,** 173001 (2023)

Proof-of-Principle Experiment for Testing Strong-Field Quantum Electrodynamics with Exotic Atoms: High Precision X-Ray Spectroscopy of Muonic Neon

T. Okumura,[1,*,†] T. Azuma,[1,‡] D. A. Bennett,[2] I. Chiu,[3] W. B. Doriese,[2] M. S. Durkin,[2] J. W. Fowler,[2] J. D. Gard,[2] T. Hashimoto,[4] R. Hayakawa,[5] G. C. Hilton,[2] Y. Ichinohe,[6] P. Indelicato,[7] T. Isobe,[8] S. Kanda,[9] M. Katsuragawa,[10] N. Kawamura,[9] Y. Kino,[11] K. Mine,[10] Y. Miyake,[9] K. M. Morgan,[2,12] K. Ninomiya,[3] H. Noda,[13] G. C. O'Neil,[2] S. Okada,[14,∥] K. Okutsu,[11] N. Paul,[7] C. D. Reintsema,[2] D. R. Schmidt,[2] K. Shimomura,[9] P. Strasser,[9] H. Suda,[5] D. S. Swetz,[2] T. Takahashi,[10] S. Takeda,[10] S. Takeshita,[9] M. Tampo,[9] H. Tatsuno,[5] Y. Ueno,[1] J. N. Ullom,[2] S. Watanabe,[15] and S. Yamada[6]



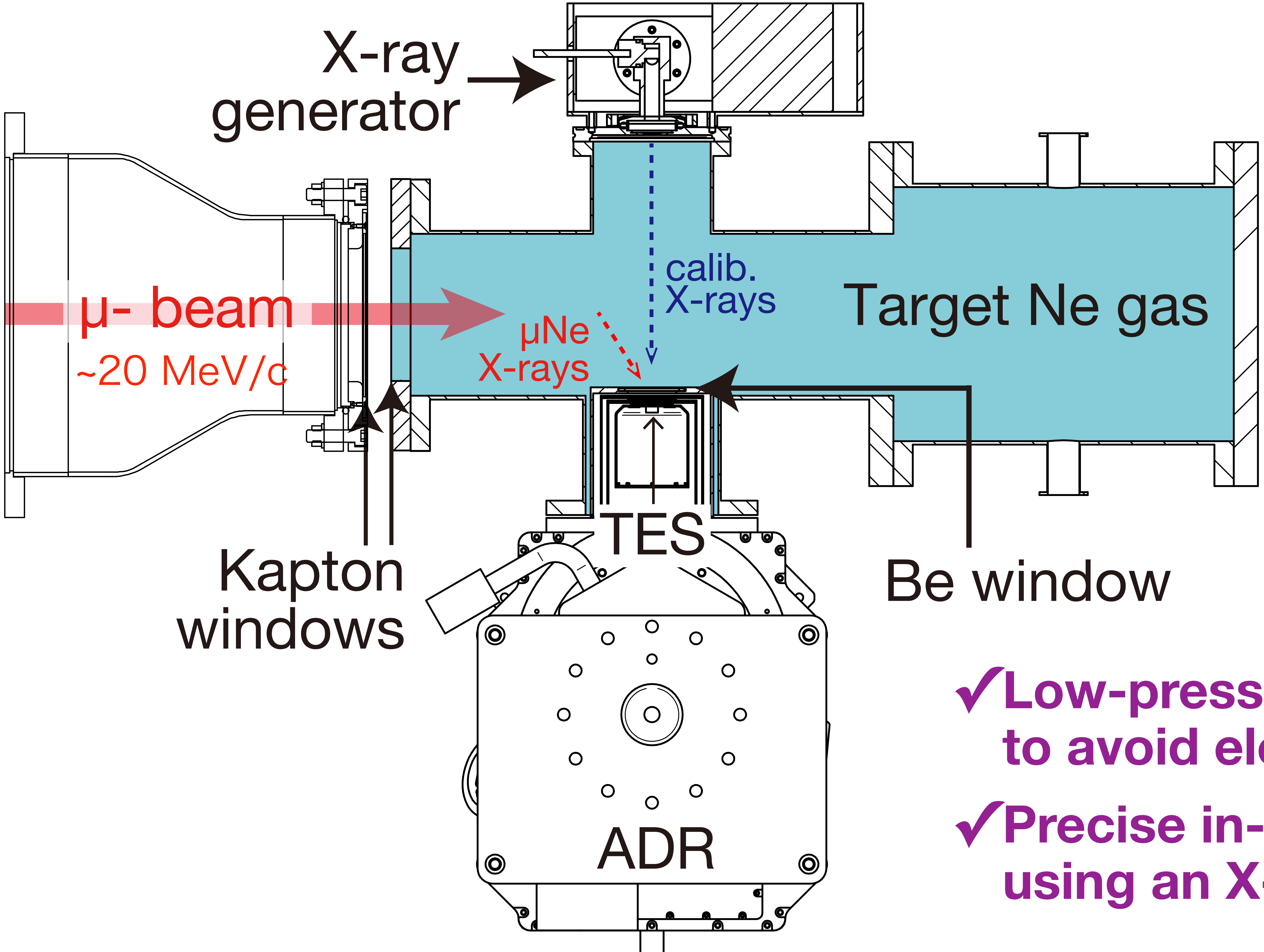
BSQED verification



P. Indelicato

Transition	transition energy with QED (eV)	QED contribution (eV)	QED as a fraction of trans. ener. (%)	Nucl. Size Error (eV)
$5f_{5/2} \to 4d_{3/2}$	6304.340	5.204	0.08%	0.000
$5f_{5/2} \to 4d_{5/2}$	6300.435	5.181	0.08%	0.000
$5f_{7/2} \to 4d_{5/2}$	6301.432	5.185	0.08%	0.000
$5g_{7/2} \to 4f_{5/2}$	6298.611	2.365	0.04%	0.000
$5g_{7/2} \to 4f_{7/2}$	6296.664	2.357	0.04%	0.000
$5g_{9/2} \to 4f_{7/2}$	6297.261	2.359	0.04%	0.000

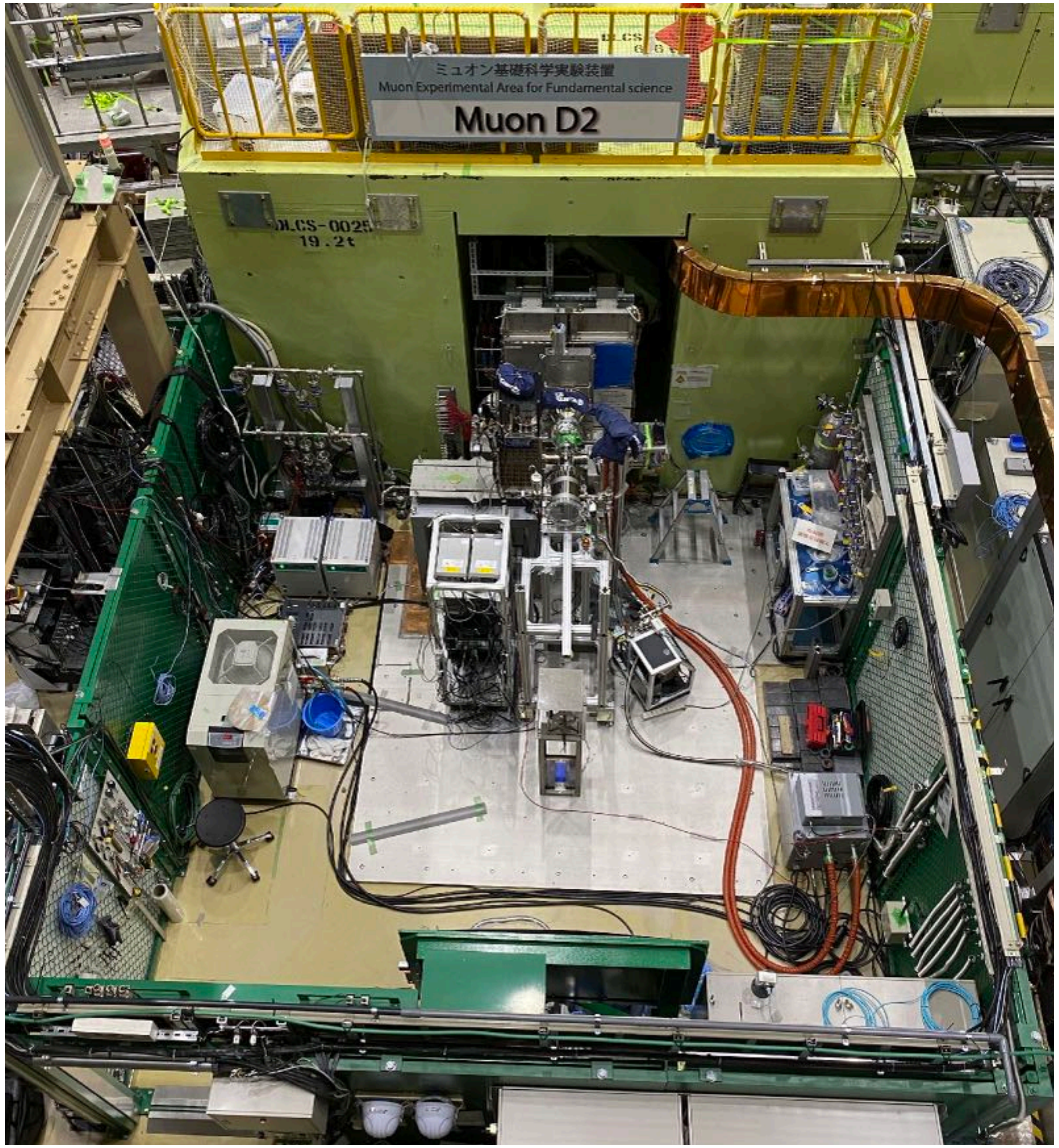
Experimental setup



✓**Low-pressure gas target to avoid electron refilling**

✓**Precise in-beam calibration using an X-ray generator**

Photos @ Muon D2



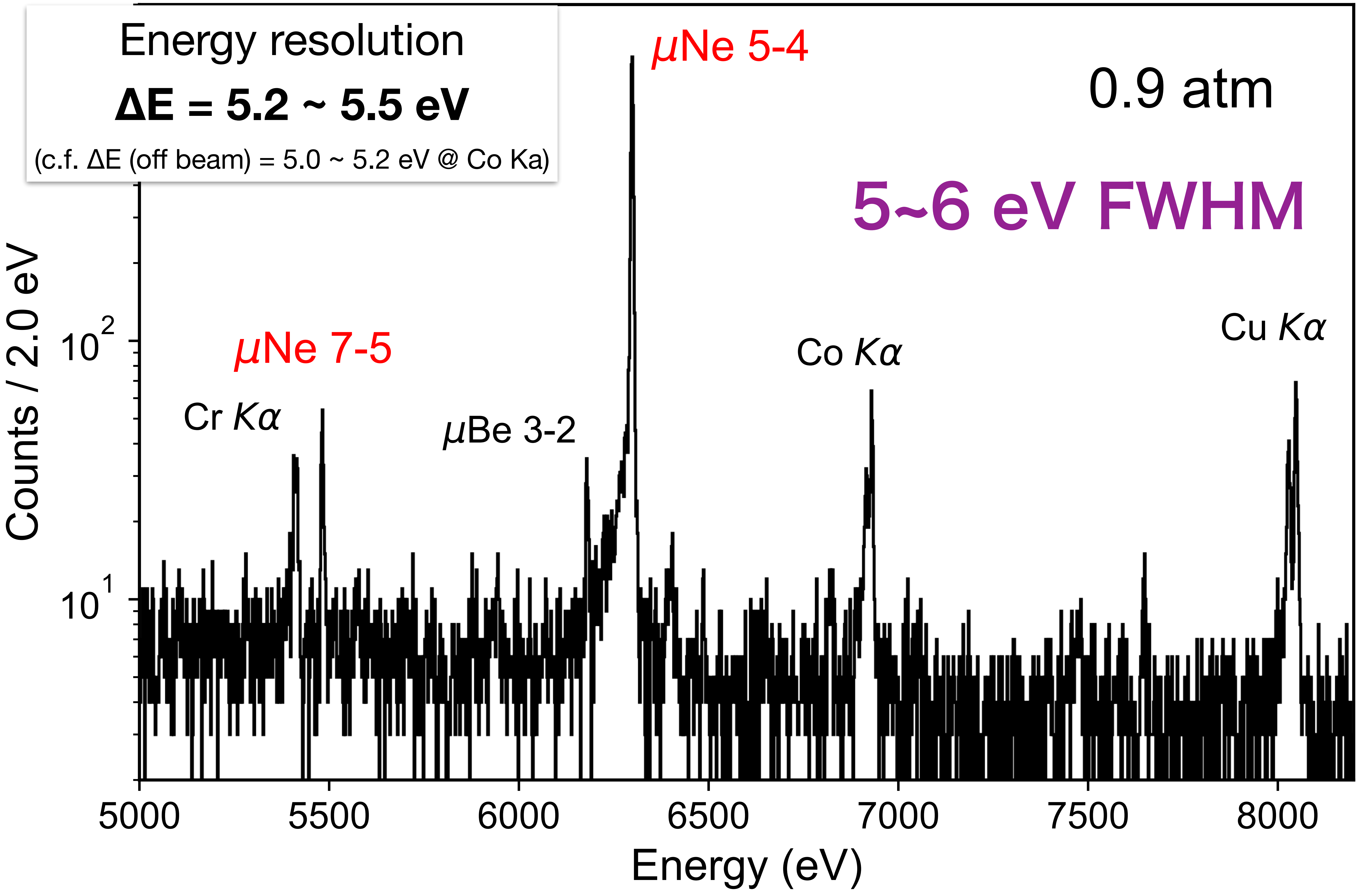
Muonic Ne atom 5→4

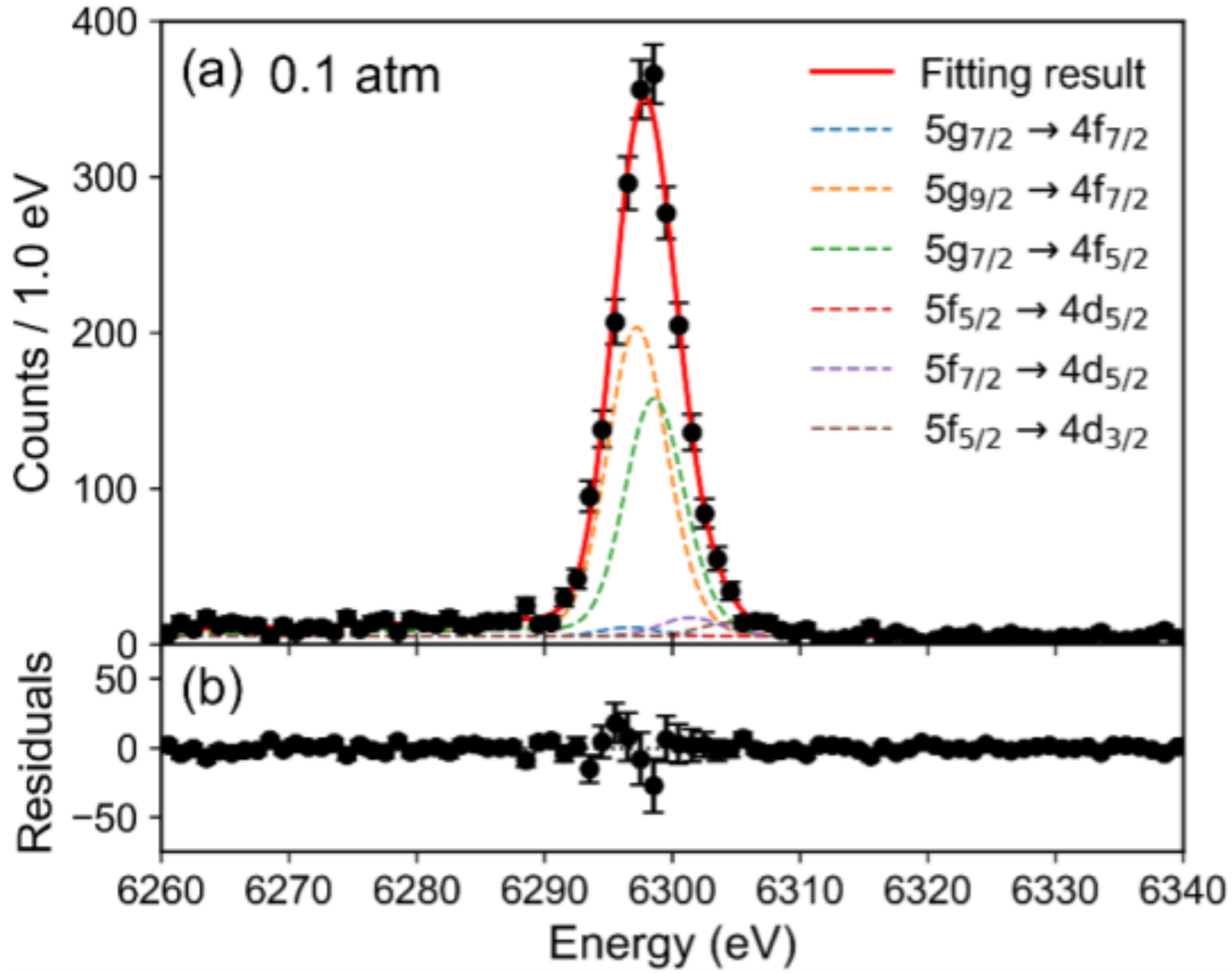
Phys. Rev. Lett. 130, 173001 (2023)

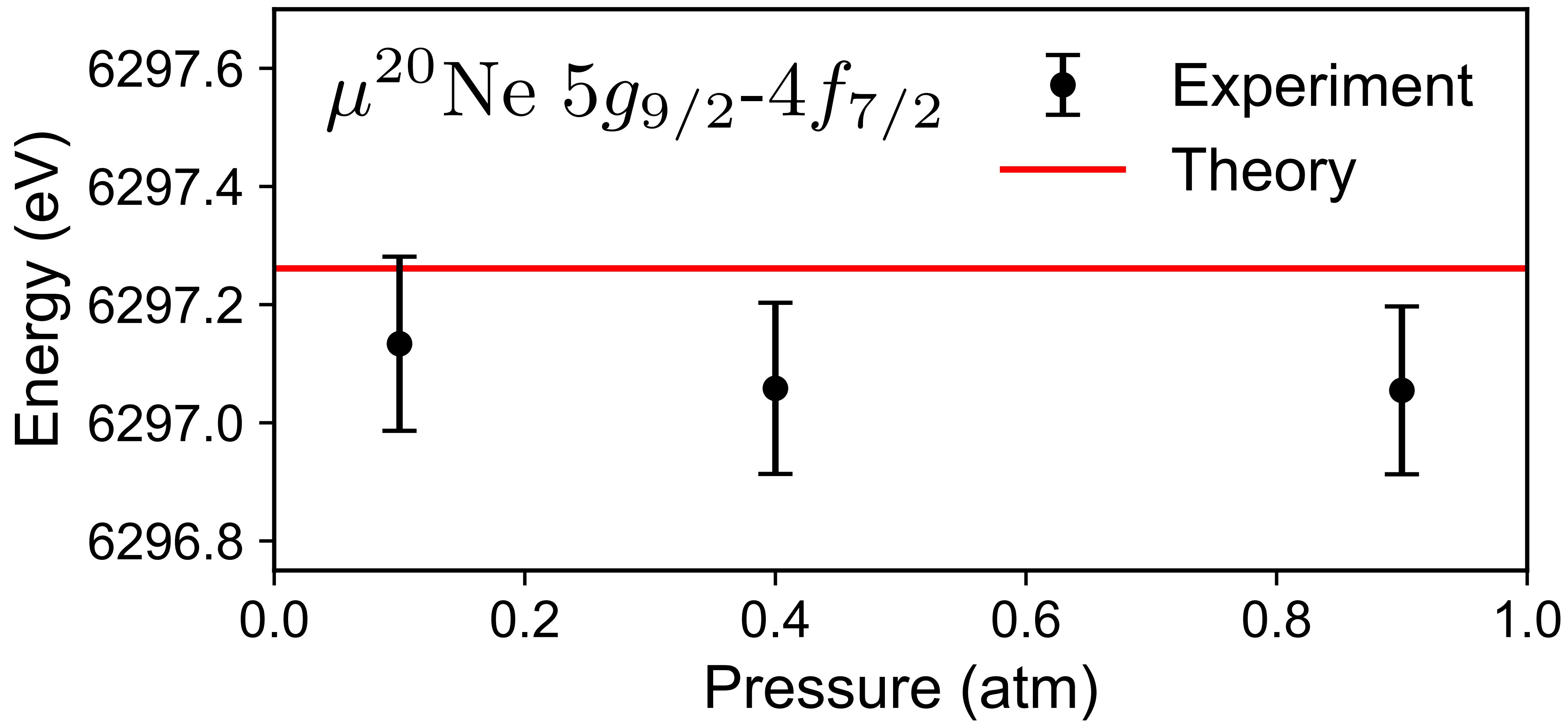
Energy resolution

ΔE = 5.2 ~ 5.5 eV

(c.f. ΔE (off beam) = 5.0 ~ 5.2 eV @ Co Ka)







Validated the BSQED calculation at ~6% level

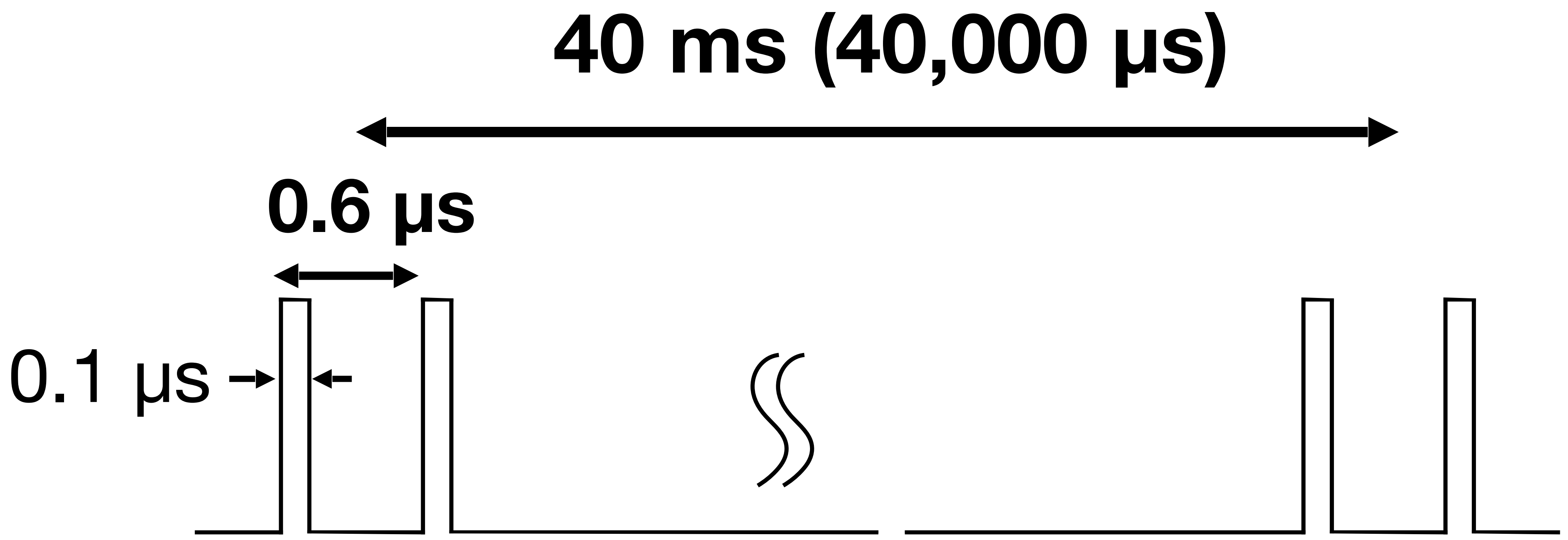
Systematic errors

Phys. Rev. Lett. 130, 173001 (2023)

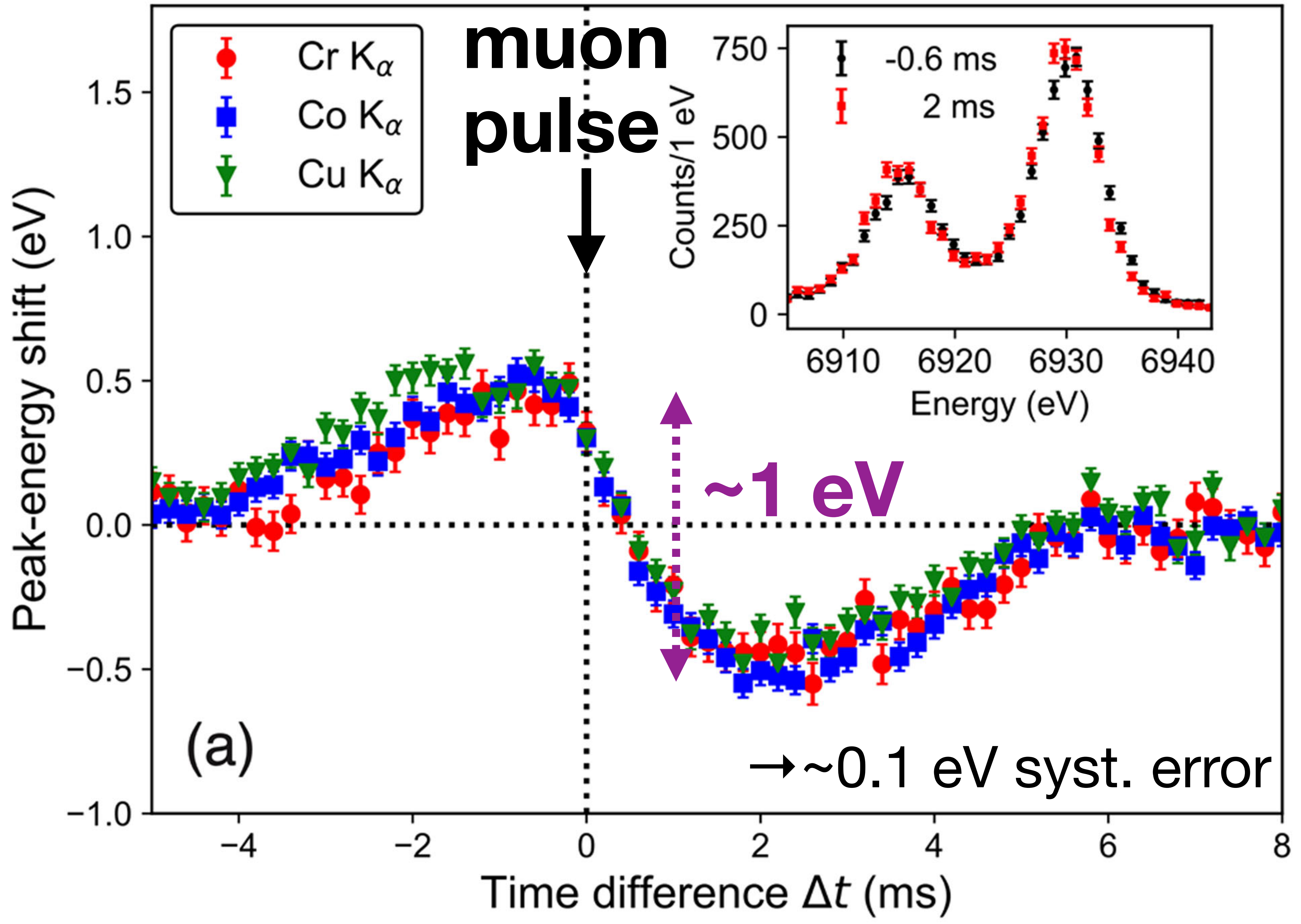
Transition energy and uncertainties (eV)	$5g_{9/2}-4f_{7/2}$ 0.1 atm	0.4 atm	0.9 atm
Measured energy	6297.13	6297.06	6297.05
Statistical error	0.07	0.06	0.06
Systematic error: Total	0.13	0.13	0.13
(1) Calibration	0.07	0.07	0.07
(2) Low-energy tail	0.01	0.02	0.01
(3) Thermal crosstalk	0.11	0.11	0.11

cf. quasi-DC beam in K$^-$ experiment

25 Hz pulse beam



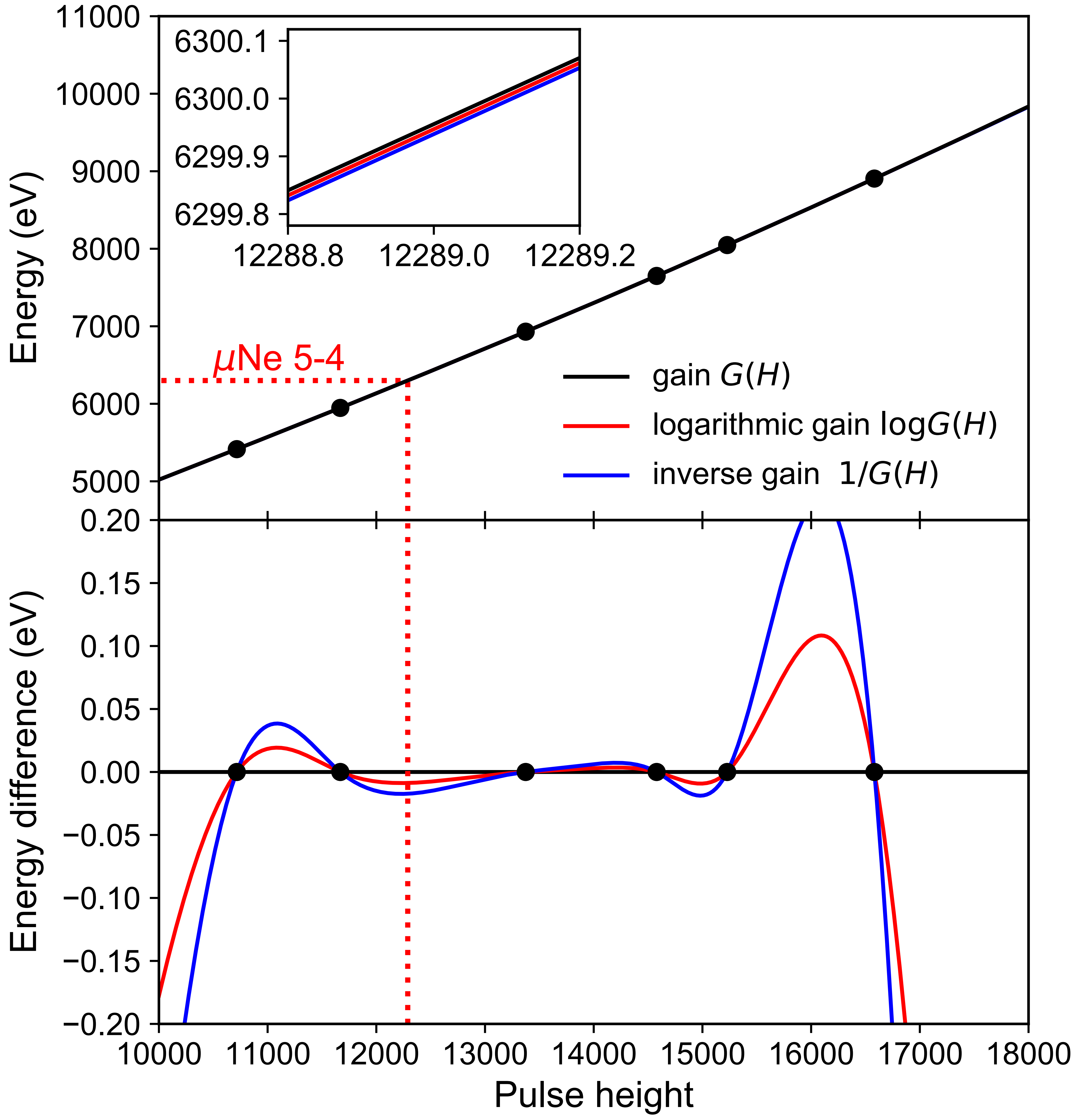
double pulse structure



Systematic errors

Phys. Rev. Lett. 130, 173001 (2023)

Transition energy and uncertainties (eV)	$5g_{9/2}-4f_{7/2}$ 0.1 atm	0.4 atm	0.9 atm
Measured energy	6297.13	6297.06	6297.05
Statistical error	0.07	0.06	0.06
Systematic error: Total	0.13	0.13	0.13
(1) Calibration	0.07	0.07	0.07
(2) Low-energy tail	0.01	0.02	0.01
(3) Thermal crosstalk	0.11	0.11	0.11



3. Muonic atom cascade

So far, we assumed all electrons are stripped out. Is it true?

PHYSICAL REVIEW LETTERS **127,** 053001 (2021)

Editors' Suggestion

Deexcitation Dynamics of Muonic Atoms Revealed by High-Precision Spectroscopy of Electronic K X rays

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EDITORS' SUGGESTION

Few-Electron Highly Charged Muonic Ar Atoms Verified by Electronic K X Rays

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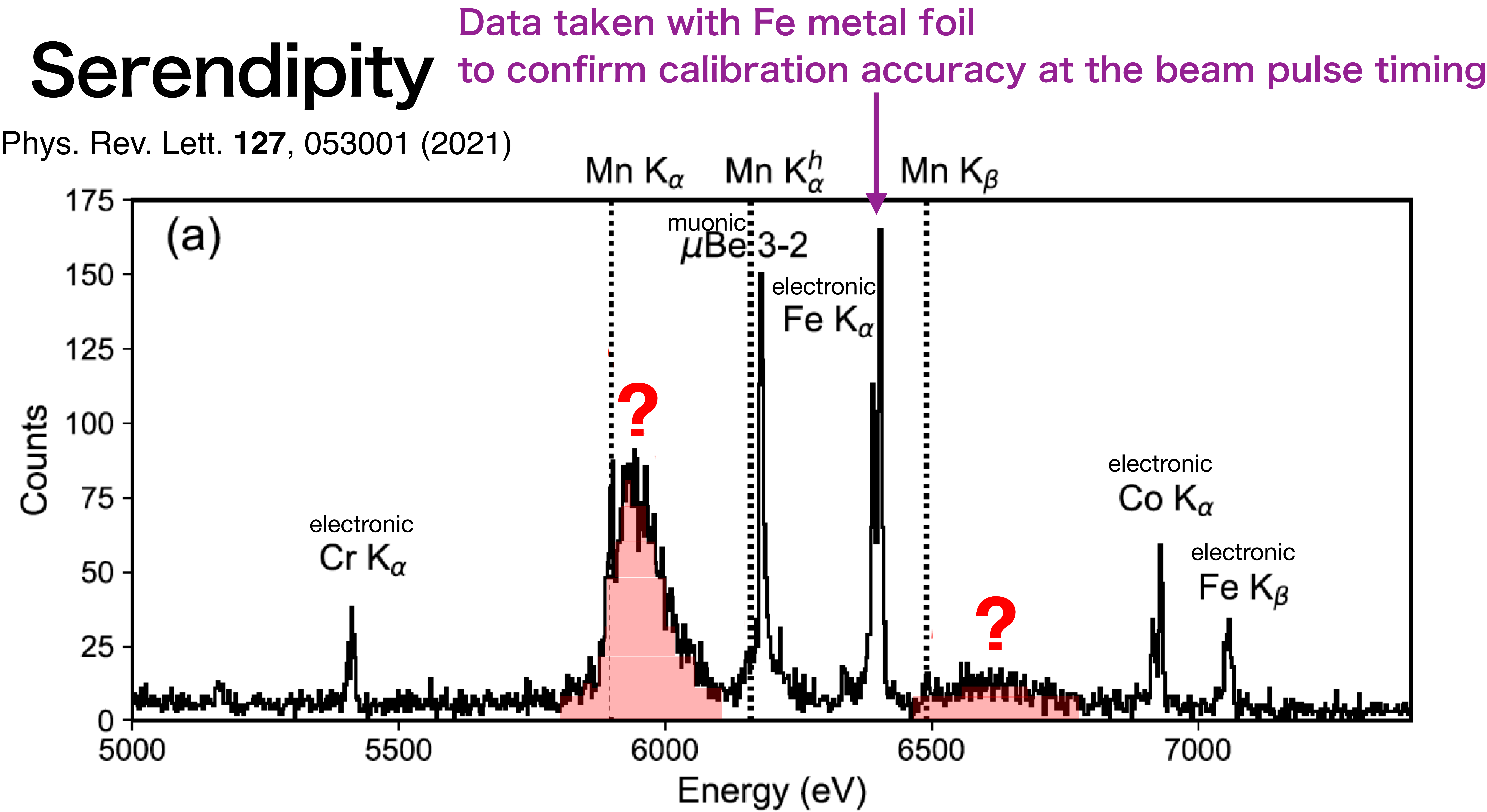
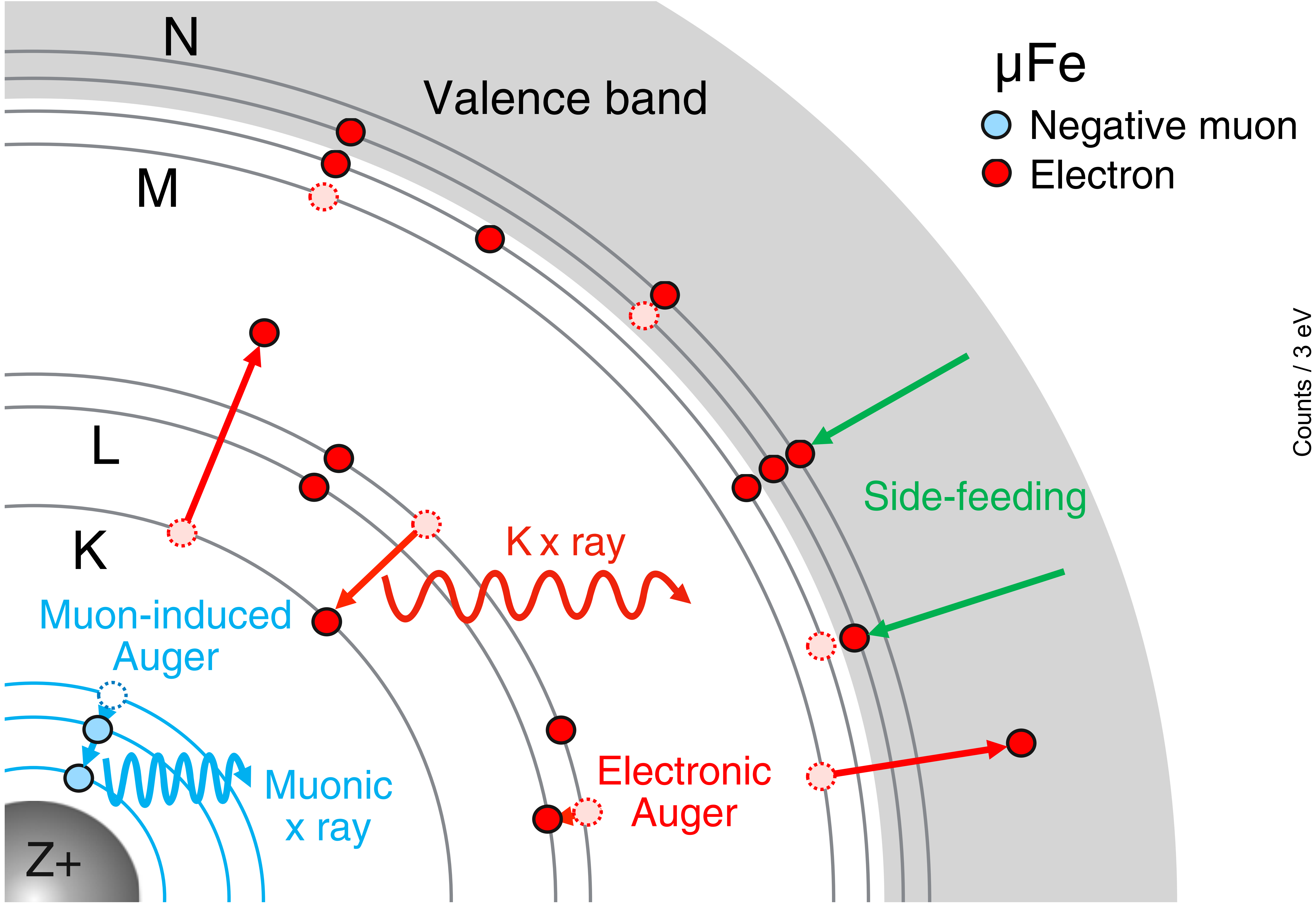
Serendipity

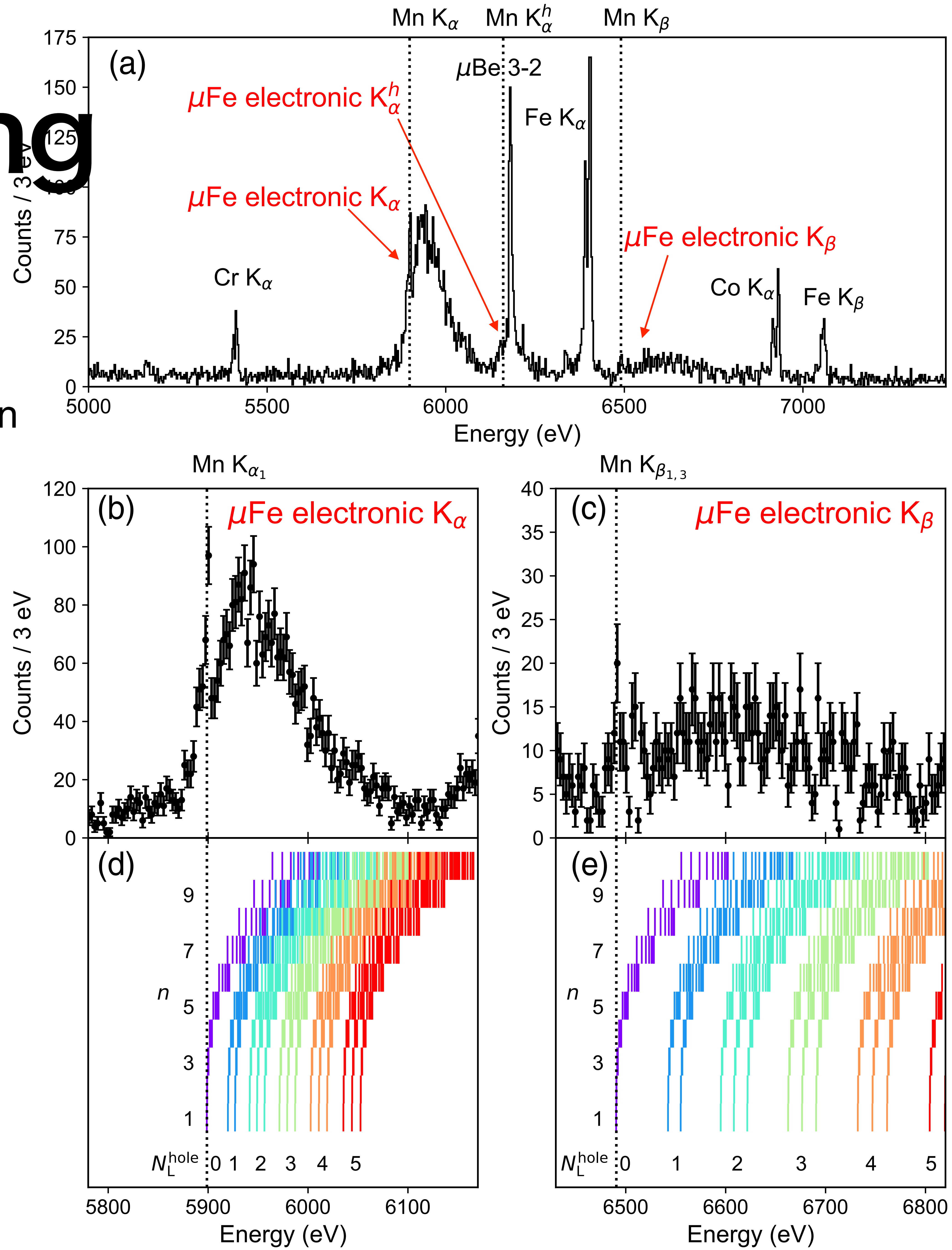
Phys. Rev. Lett. **127**, 053001 (2021)



Cascade with e- feeding

Phys. Rev. Lett. **127**, 053001 (2021)





Simulated dynamics of energy distribution of K X-rays

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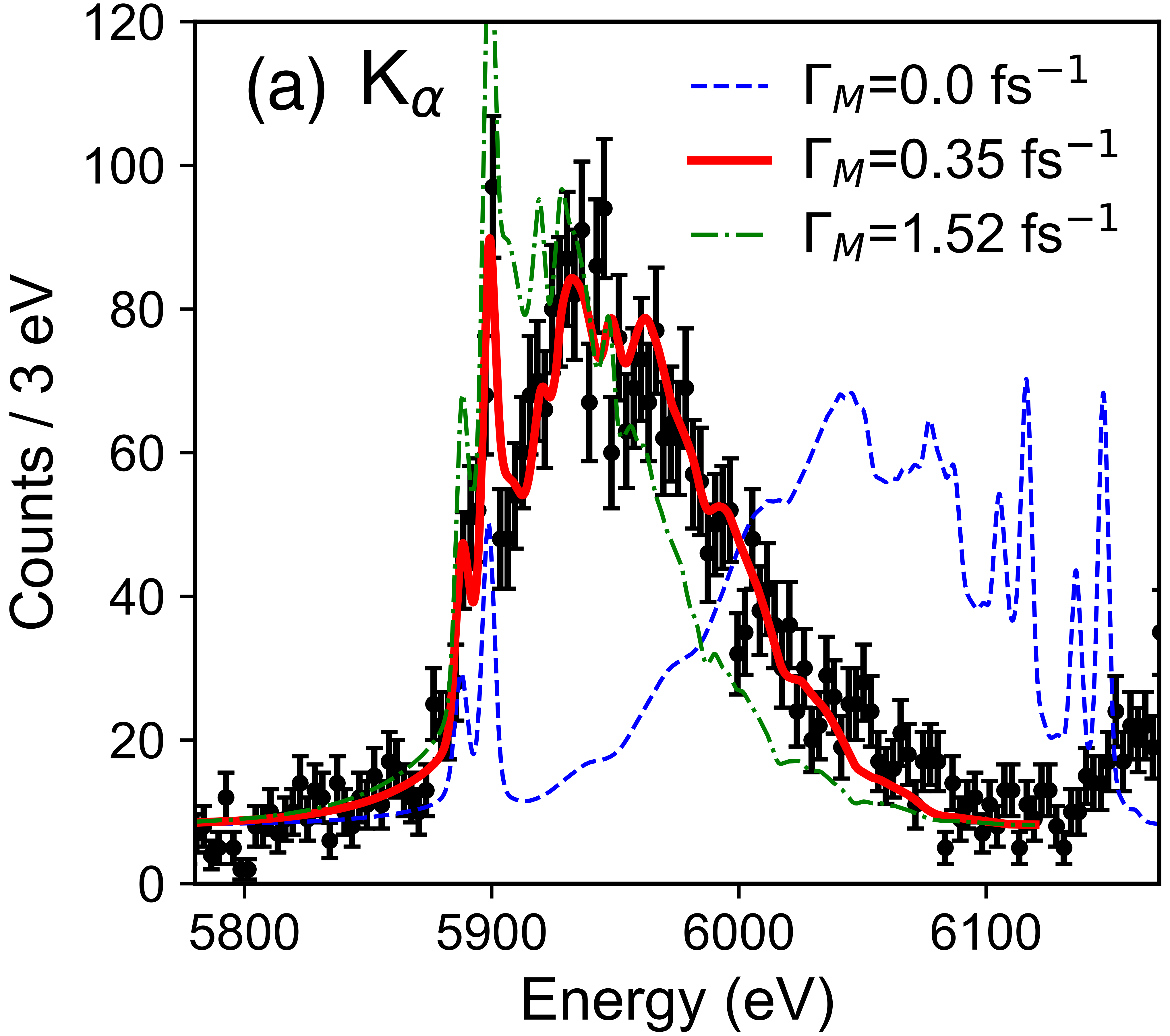
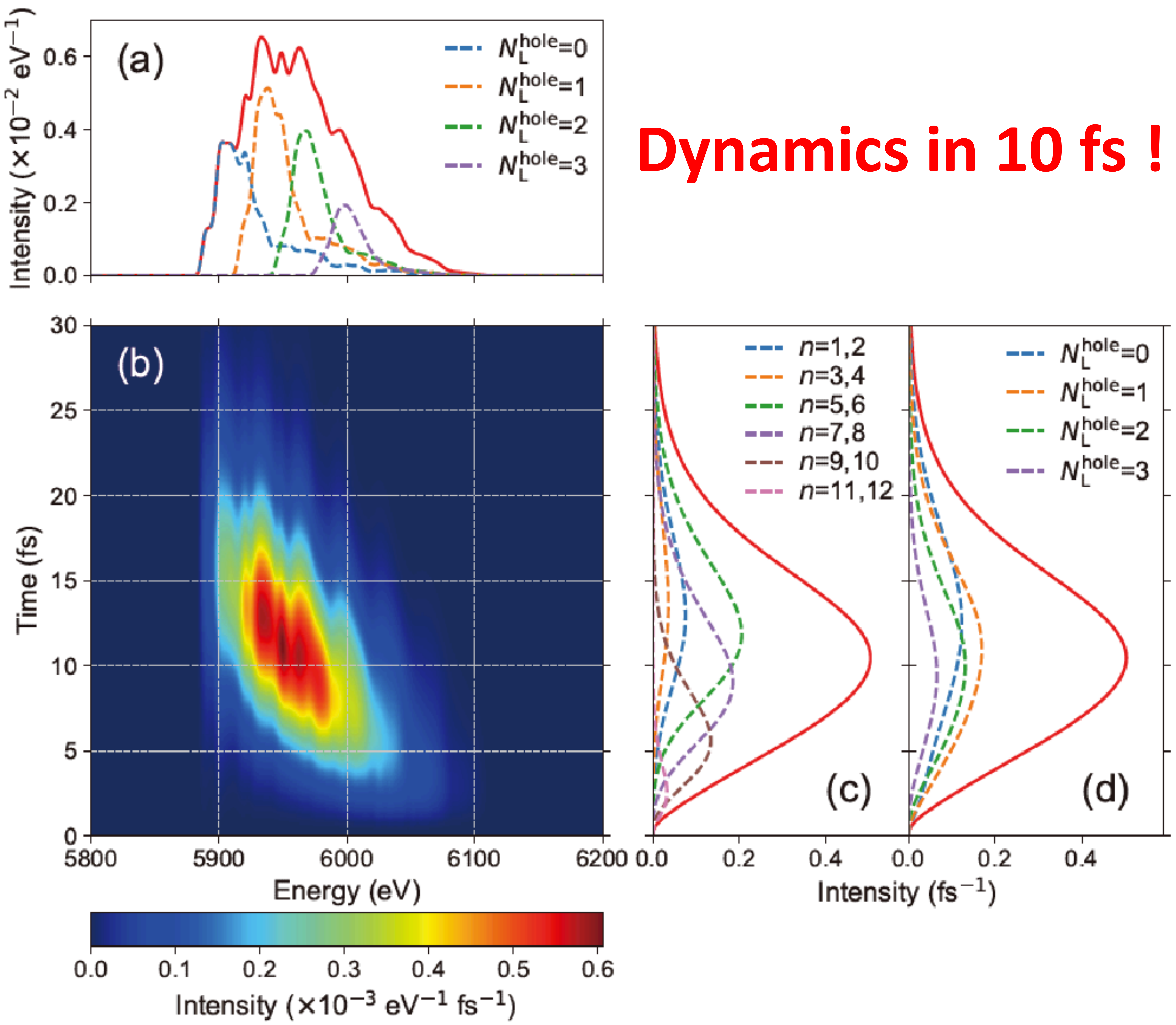


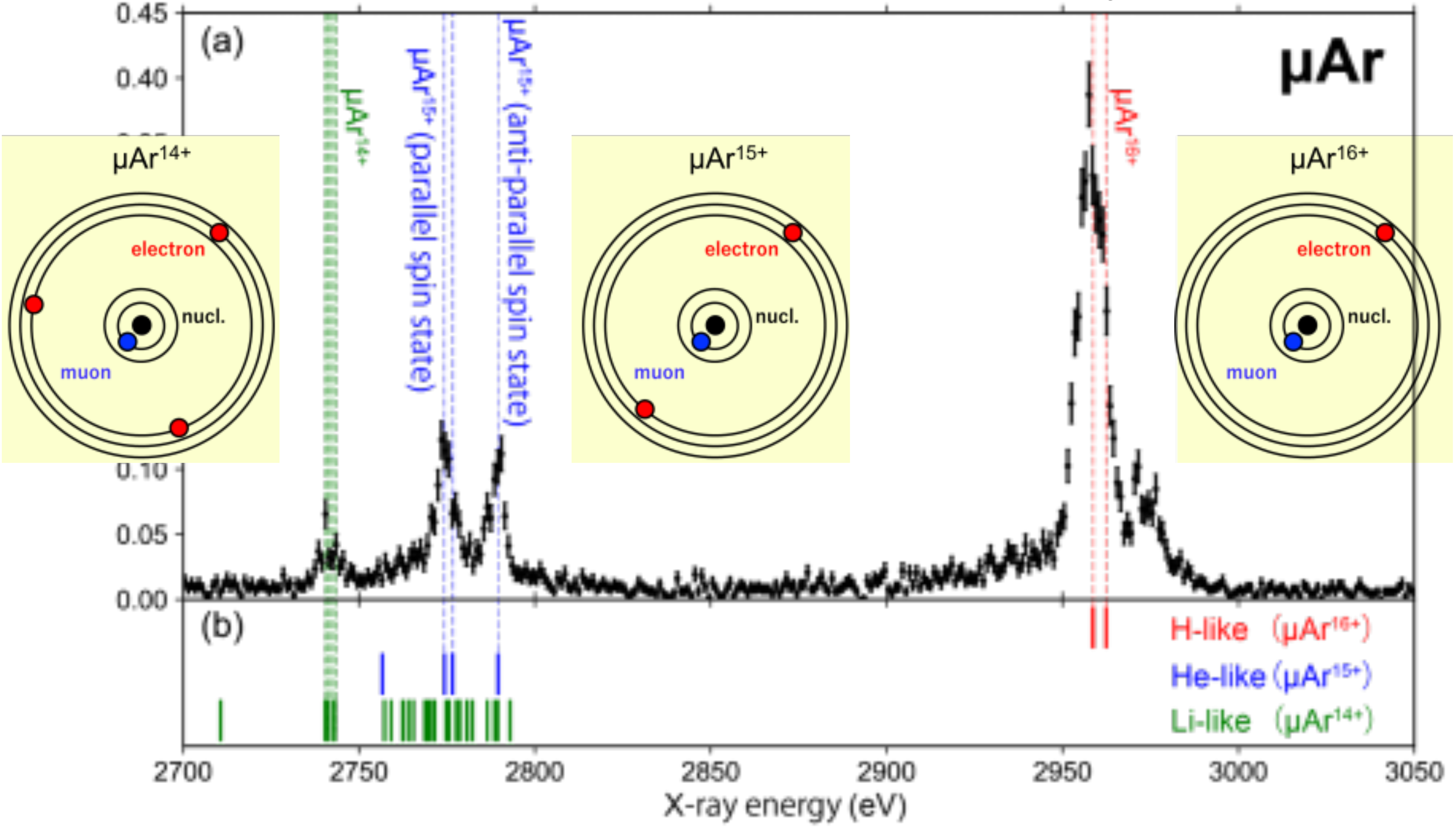


Dynamics in 10 fs !

M-shell side-feeding rate is only the fit parameter!

What happens with a gas target?

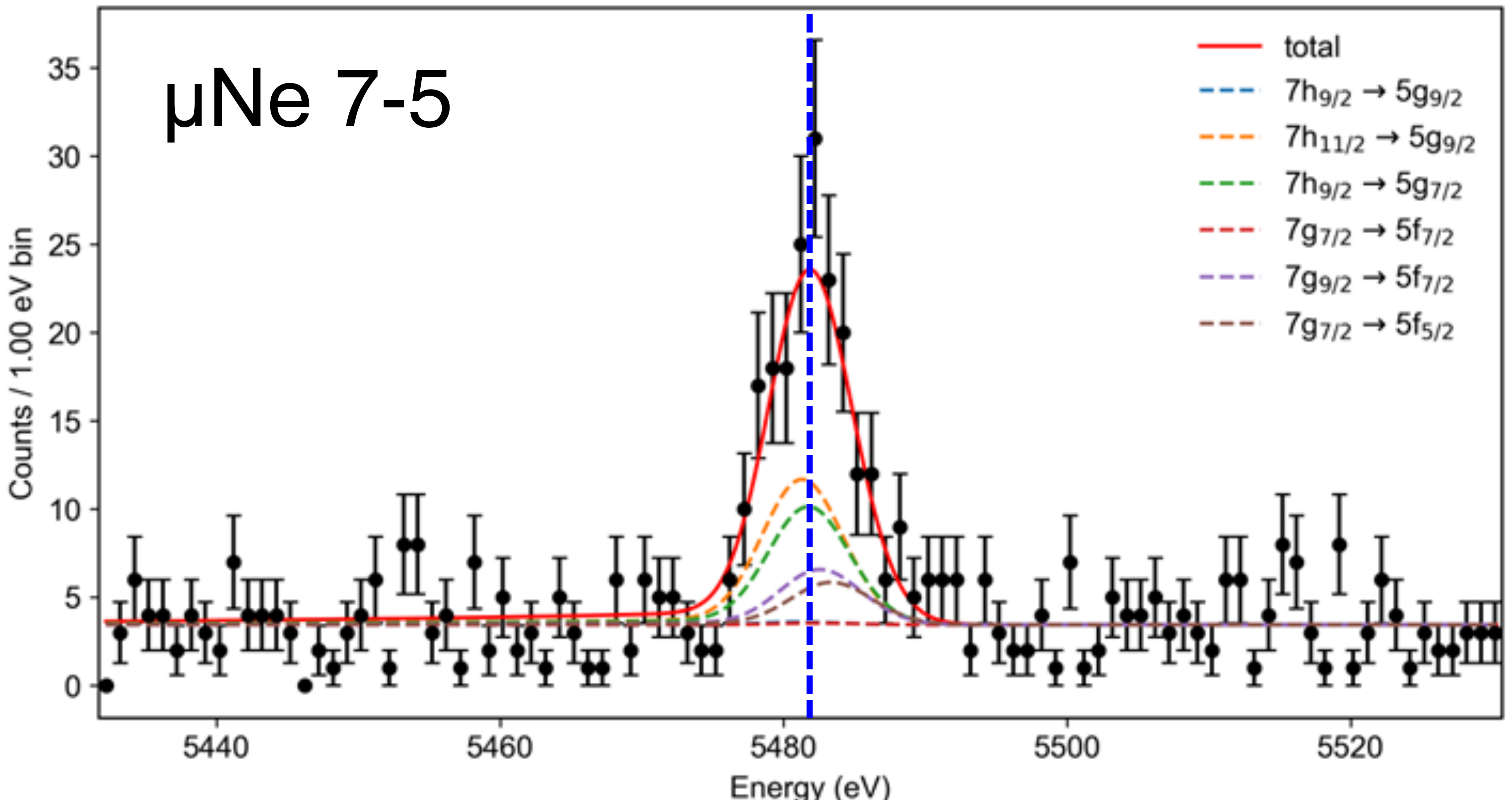
Phys. Rev. Lett. **134**, 243001 (2025)



μNe: Is there electron screening?

Initial state	Final state	Transition energy (eV)			K-shell e$^-$ energy shift (eV)
		Total	Vacuum polarization	FNS	
$5g_{9/2}$	$4f_{7/2}$	6297.26191	2.33803	0.00031	-1.25198
$5g_{7/2}$	$4f_{7/2}$	6296.66427	2.33775	0.00031	-1.25163
$5g_{7/2}$	$4f_{5/2}$	6298.61192	2.34051	0.00031	-1.25196
$7h_{11/2}$	$5g_{9/2}$	5481.26622	0.39899	0.00003	-6.93382
$7h_{9/2}$	$5g_{9/2}$	5481.12106	0.39896	0.00003	-6.93326
$7h_{9/2}$	$5g_{7/2}$	5481.71870	0.39924	0.00003	-6.93361

We can estimate the number of K-shell electrons from the energy shift of 7-5 transition



fraction of μNe with one K-shell electron

$$f_{1e} = 0.00^{+0.08}_{-0.00}$$

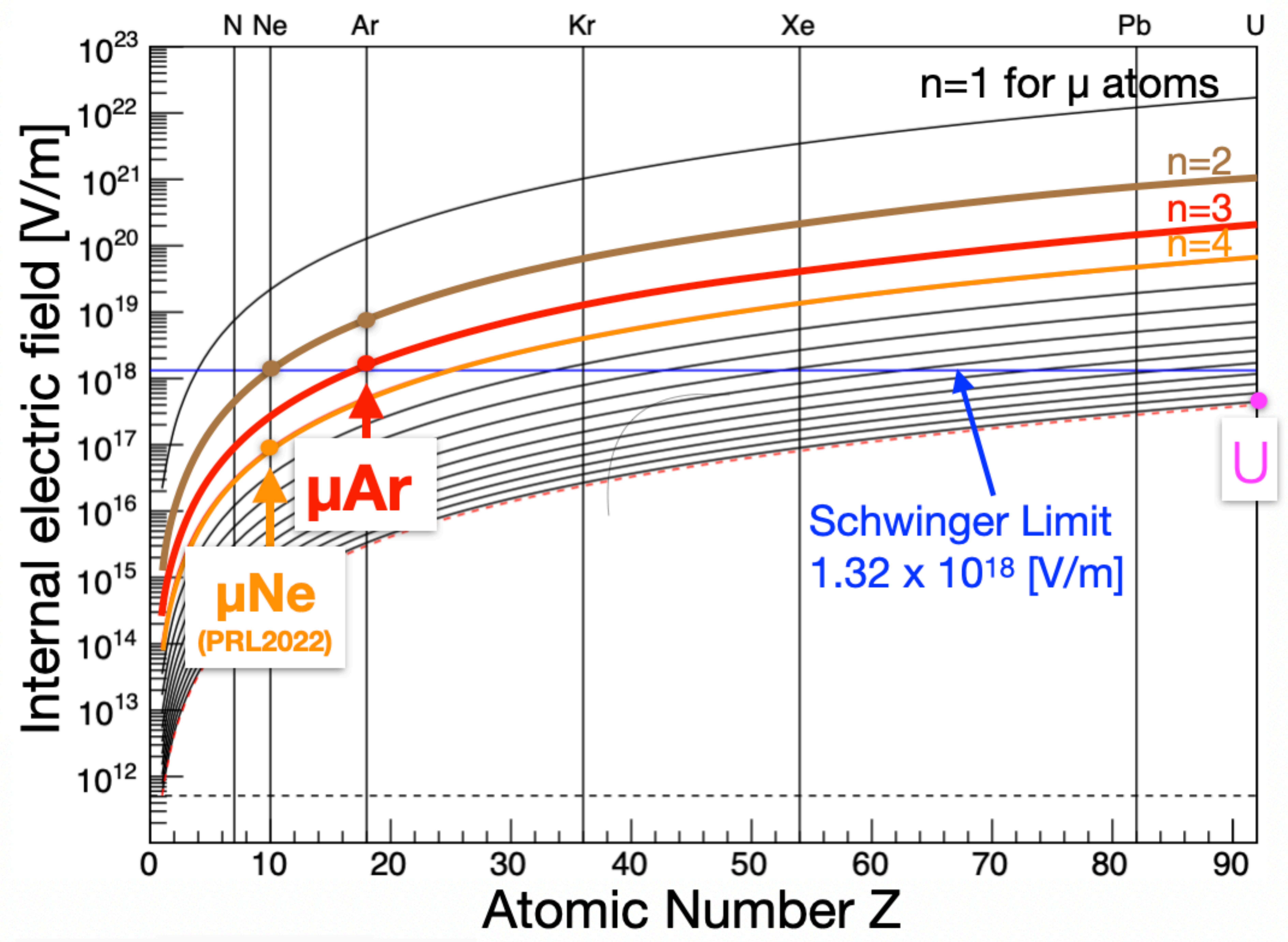
Electrons are fully stripped off !

4. Preliminary results with high-E TES system

Candidate lines for BSQED study

[eV]	transition	Energy	QED effect	QED/ transition	FNS	Screening 2e	remaining electron
μ-Ne	5→4	6,297	-2.4	0.04%	0	2.32	~0
	4→3	13,616	-14.6	0.11%	0	1.23	
	3→2	**38,976**	**-105.8**	**0.27%**	**0.23**	**0.52**	
μ-Ar	5→4	20,482	-22.6	0.11%	-0.01	5.05	~0
	4→3	**44,315**	**-99**	**0.22%**	**-0.05**	**2.71**	
	3→2	**126,963**	**-543.3**	**-0.43%**	**14.18**	**1.16**	
μ-Kr	7→6	26,880	-24.9	0.09%	-0.01	29.01	~5
	6→5	44,624	-70	0.16%	-0.03	20.11	
	5→4	82,278	-210.1	0.26%	-0.17	12.64	
μ-Xe	8→7	39,302	-42.5	0.11%	-0.02	69.88	many
	7→6	60,618	-100.5	0.17%	-0.07	53.36	
	6→5	100,691	-249	0.25%	-0.25	37.95	

← done

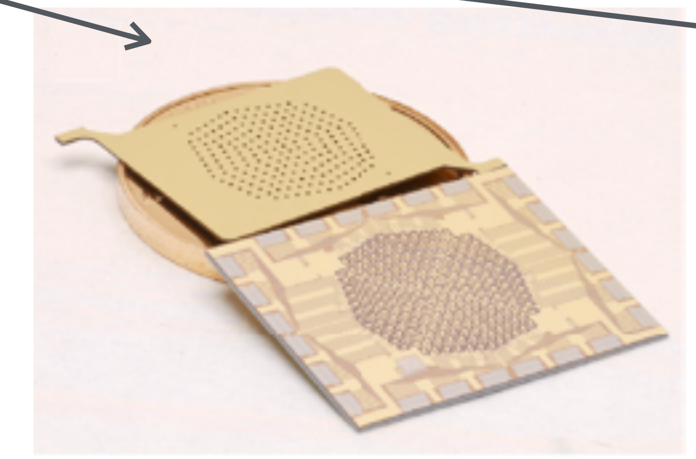
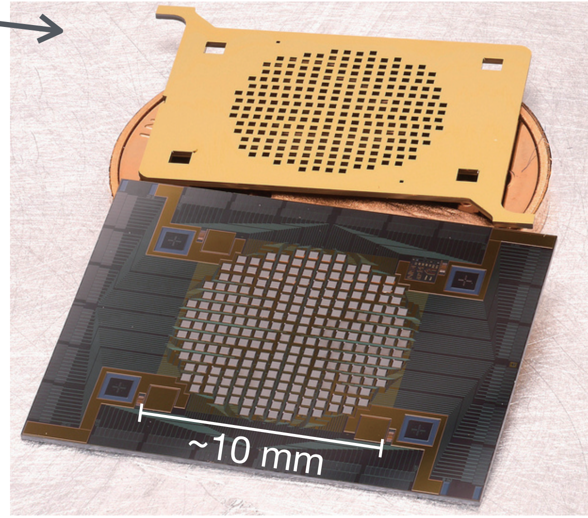


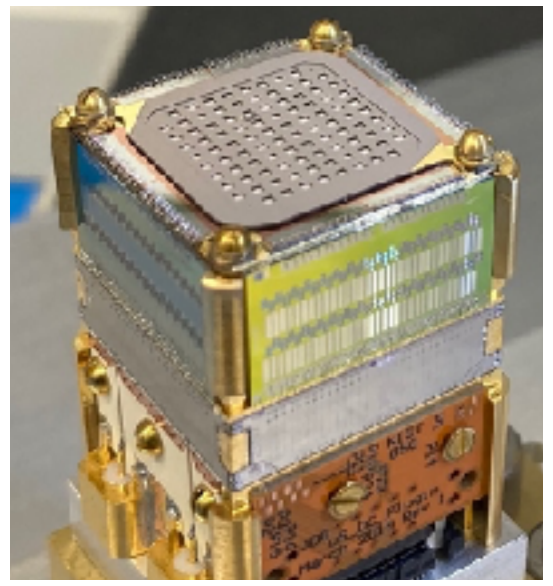
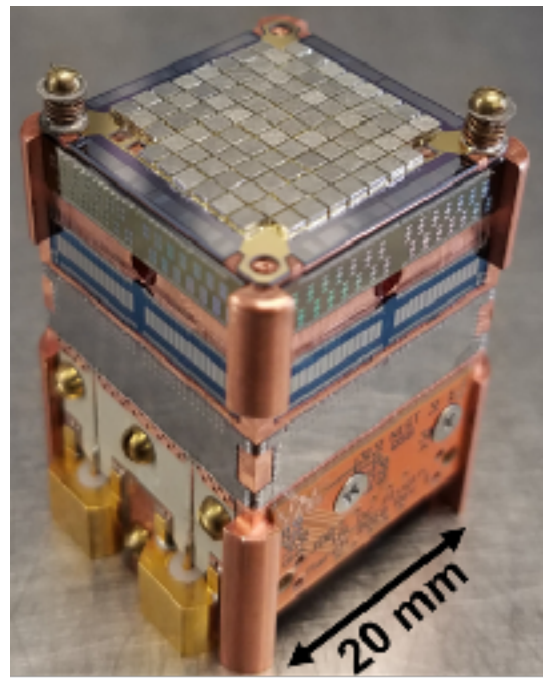
N
Ne
Ar
Kr
Xe
Pb
U
n=1 for μ atoms
n=2
n=3
n=4
μAr
μNe
(PRL2022)
U
Schwinger Limit
1.32 x 10^18 [V/m]
Internal electric field [V/m]
Atomic Number Z

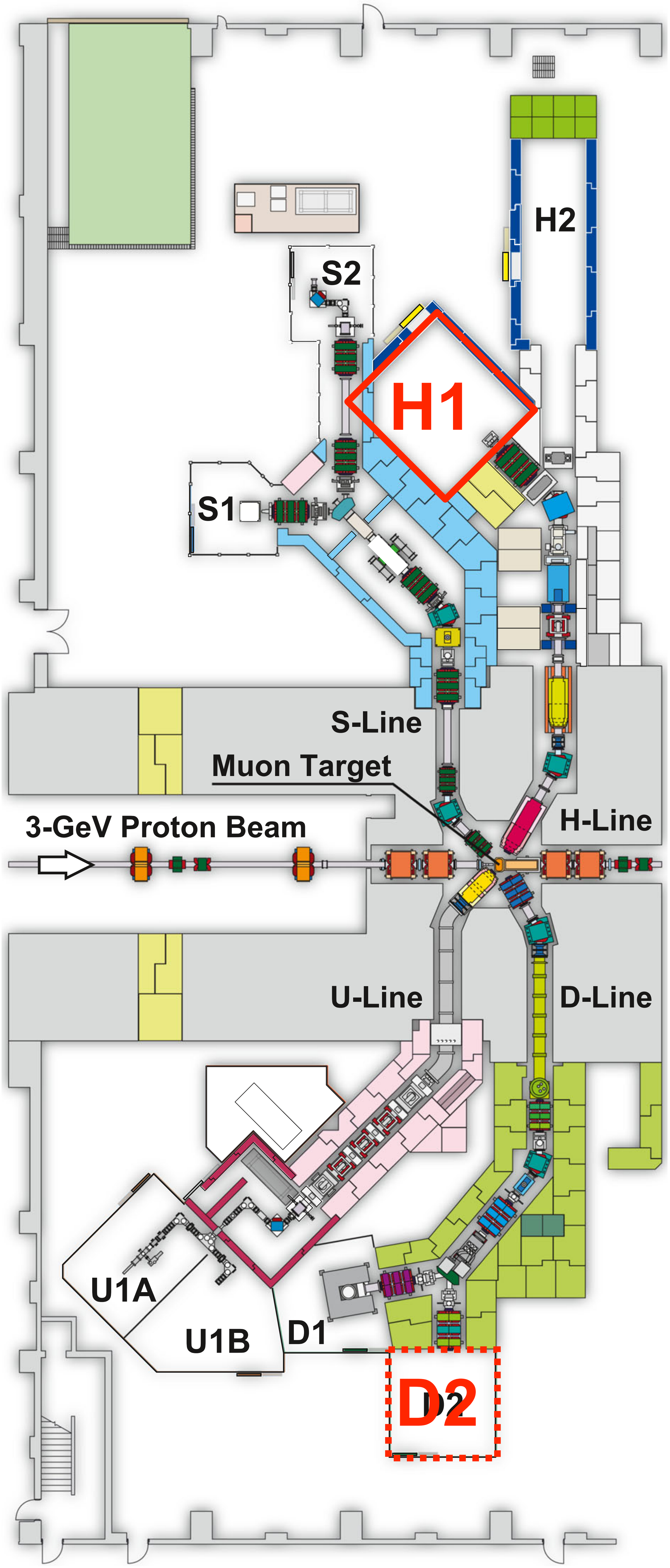
TES detectors from NIST

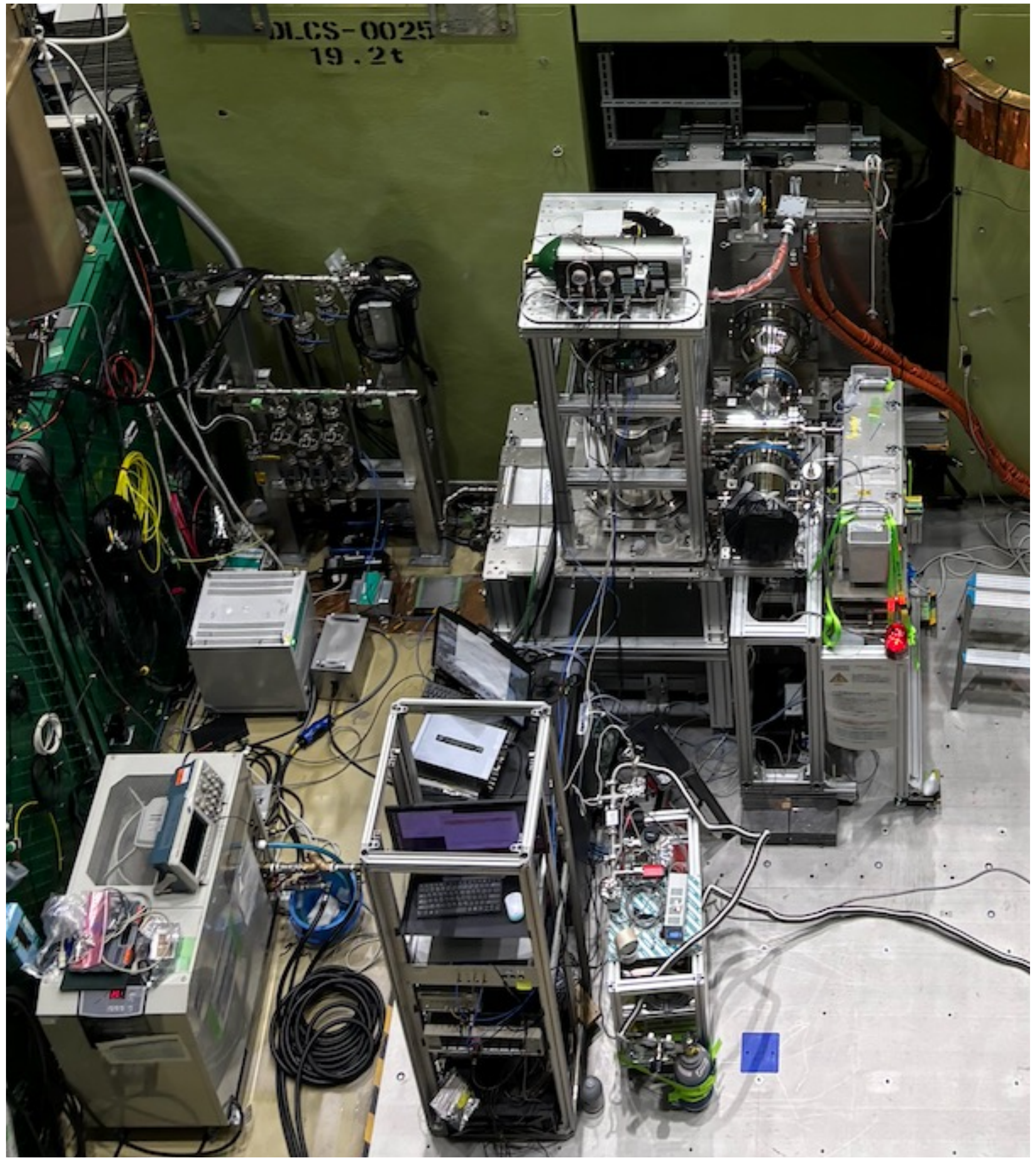
new since 2024

	10 keV TES	20 keV TES	50 keV TES	100 keV TES
Saturation energy	10 keV	20 keV	70 keV	150 keV
Readout system	TDM	TDM	microwave	microwave
Absorber thickness (material)	0.965 μm (Au)	4.1 μm (Bi)	1.85 μm (Au) & 20 μm (Bi)	0.5 mm (Sn)
Absorber area	0.34 x 0.34 mm^2	0.320 x 0.305 mm^2	0.73 x 0.73 mm^2	1.3 x 1.3 mm^2
Absorber collimated area	0.28 x 0.28 mm^2	0.305 x 0.290 mm^2	0.67 x 0.67 mm^2	(no collimator)
Number of pixel	192	240	96	96
Total collection area	15.1 mm^2	21.2 mm^2	43.1 mm^2	162 mm^2
ΔE (FWHM)	5 eV @ 6 keV	5 eV @ 6 keV	20 eV @ 40 keV	80 eV @ 100 keV



Rev. Sci. Instrum. 90, 123107 (2019)



H2
S2
H1
S1
S-Line
Muon Target
3-GeV Proton Beam
H-Line
U-Line
D-Line
U1A
U1B
D1
D2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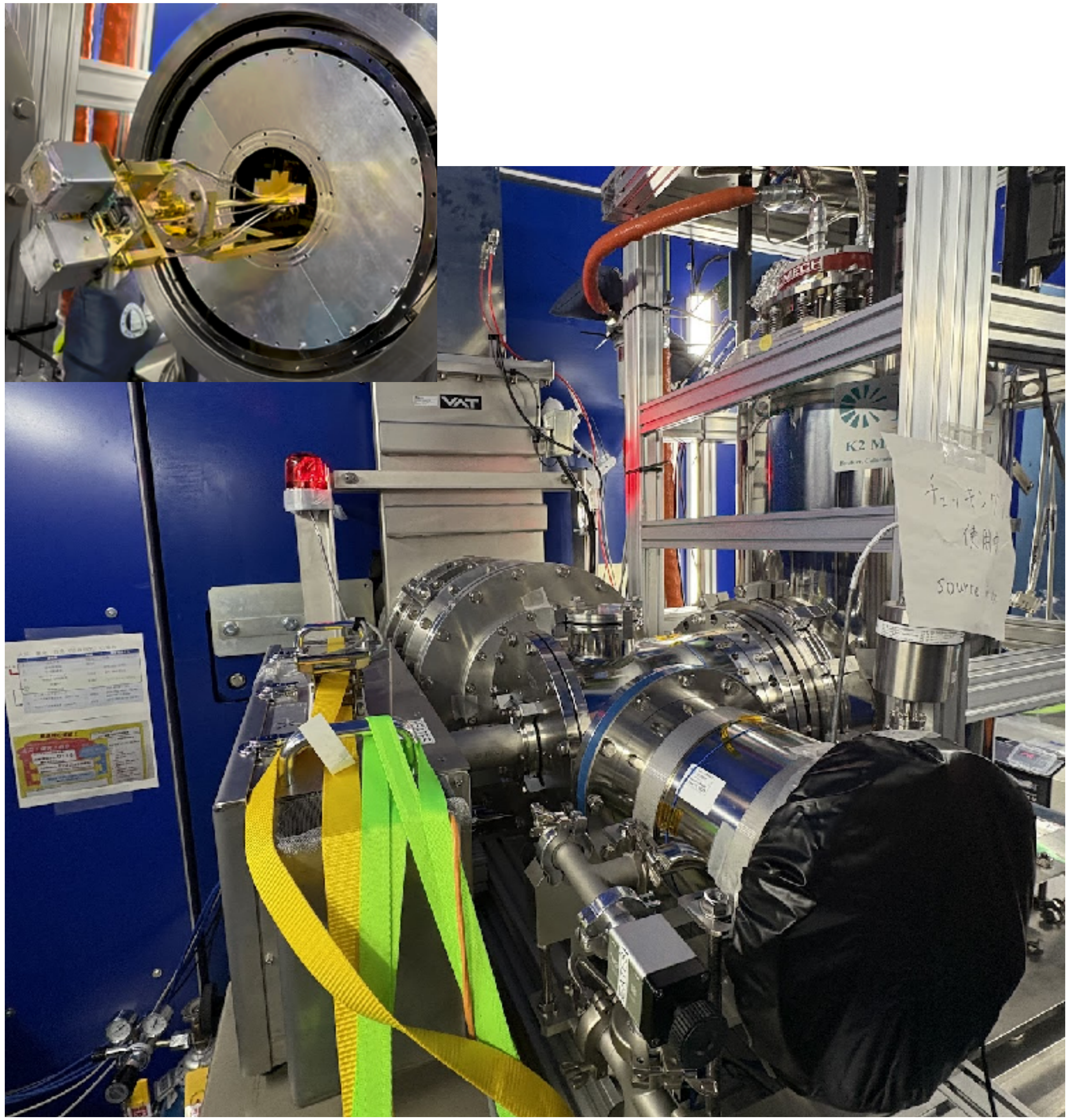
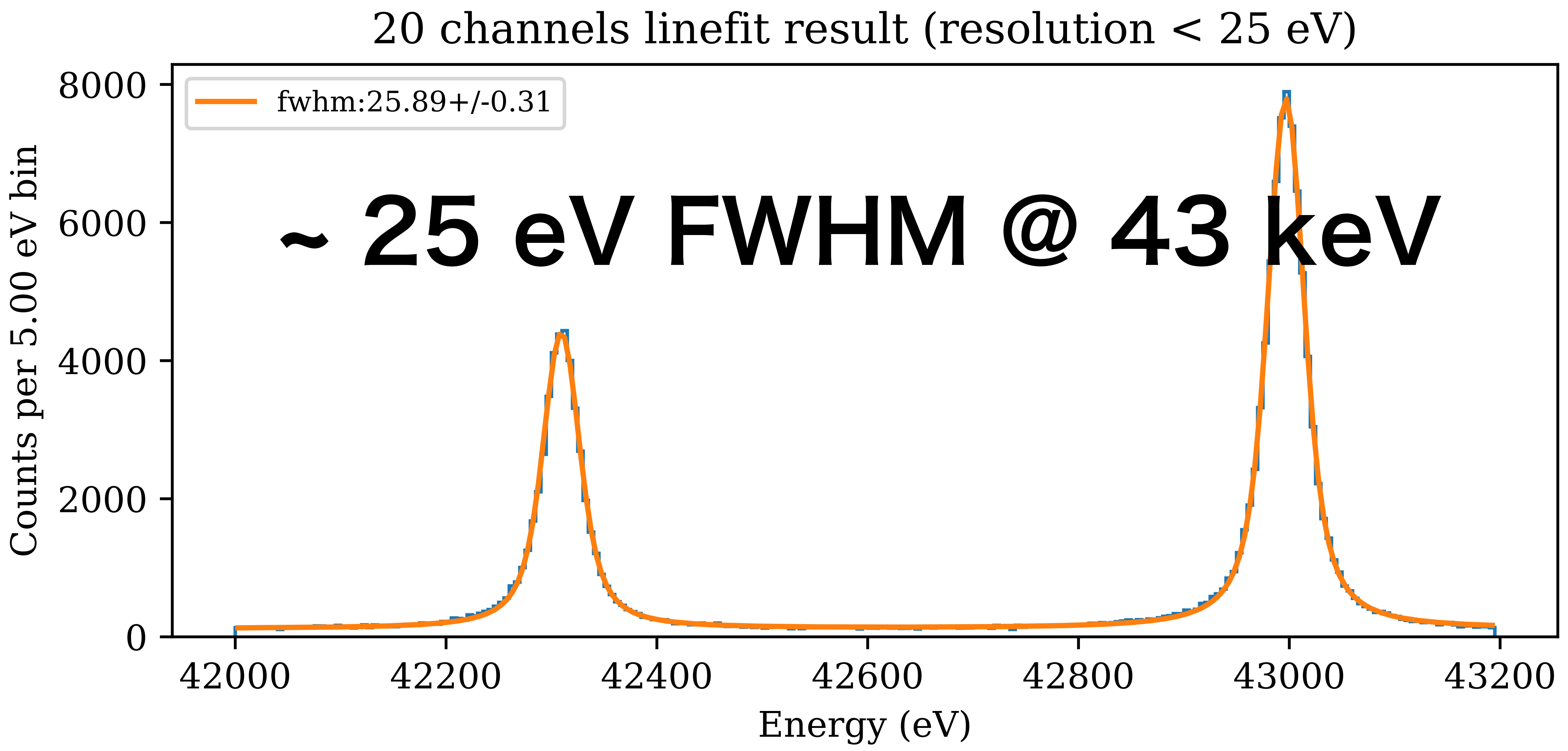
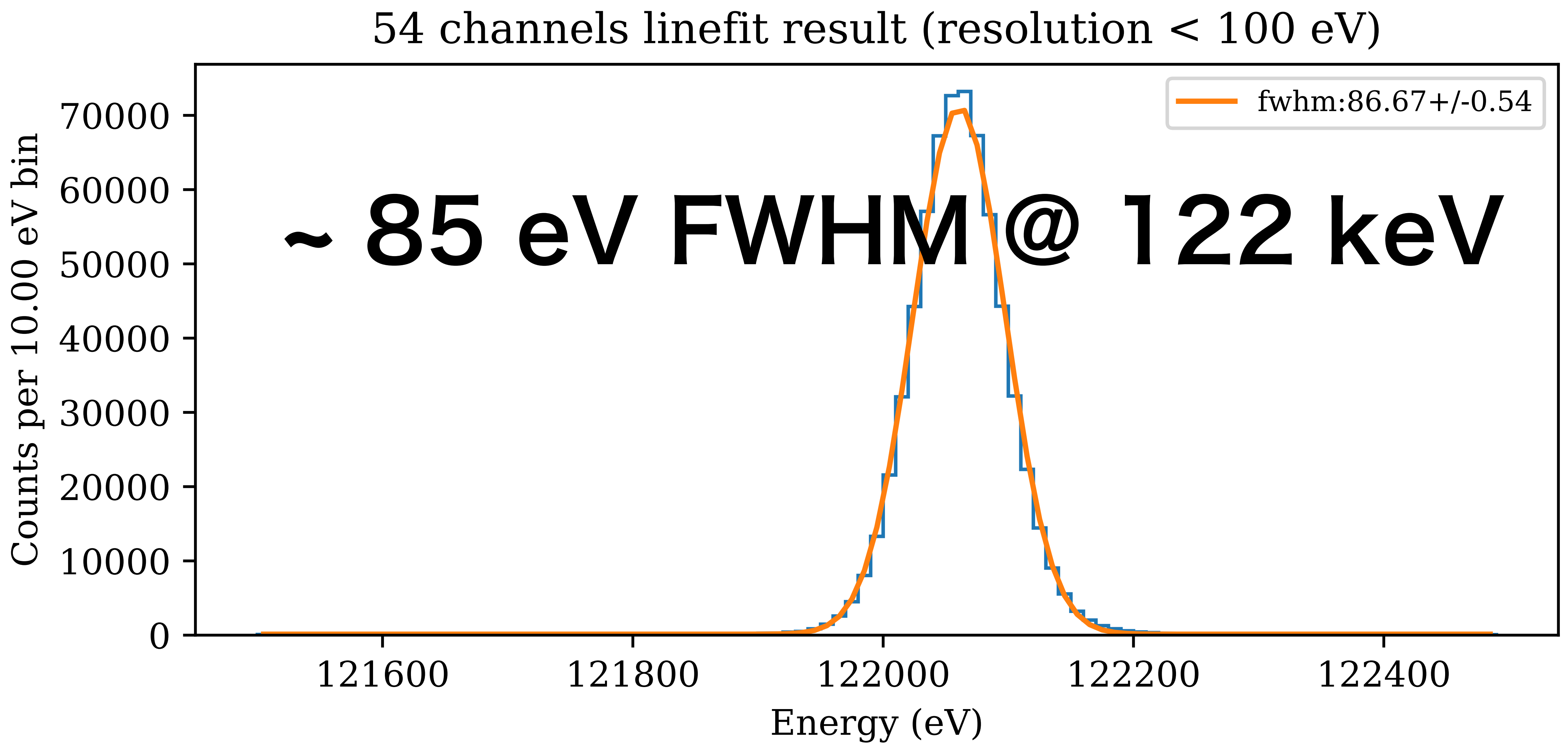
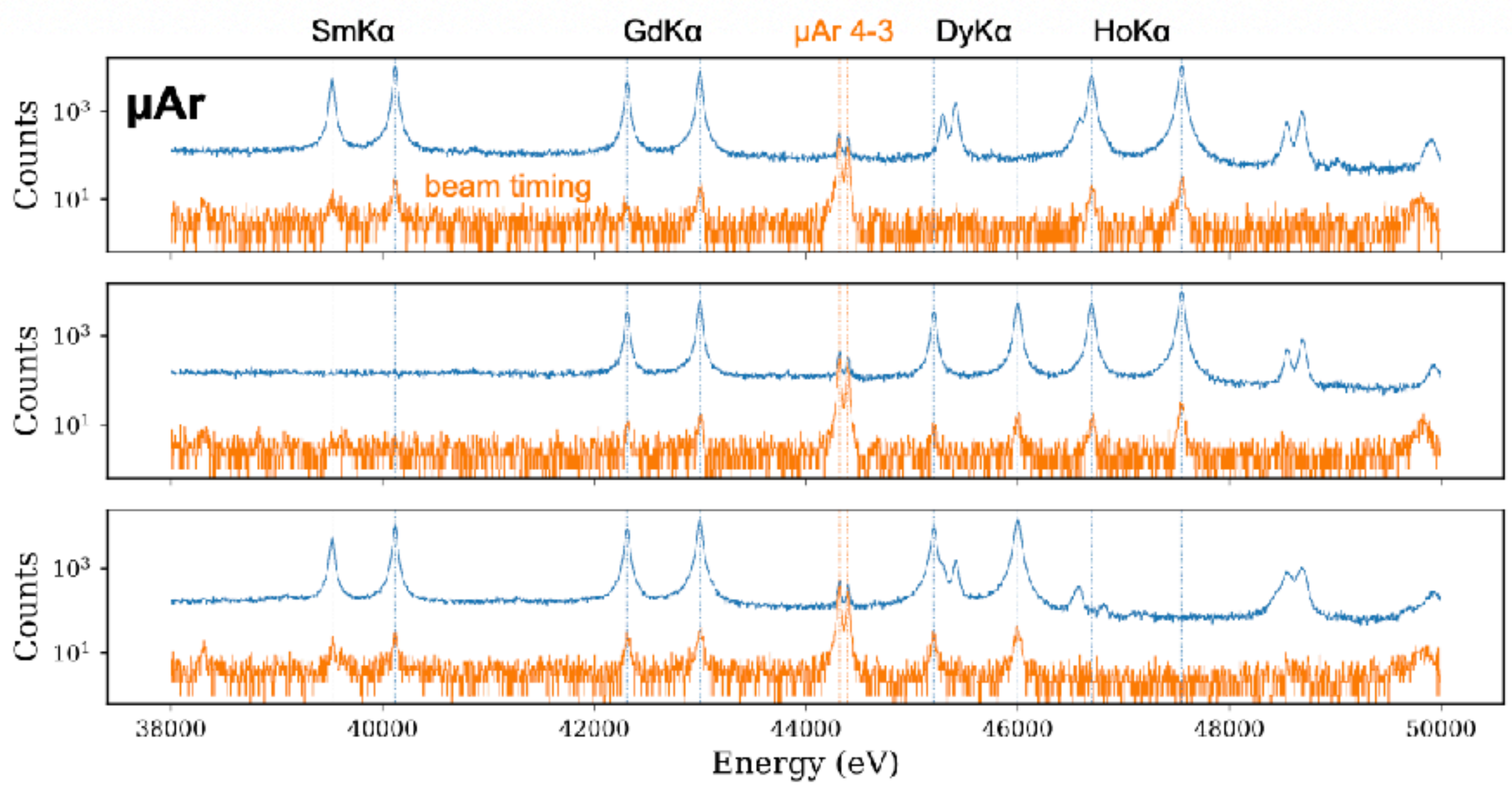
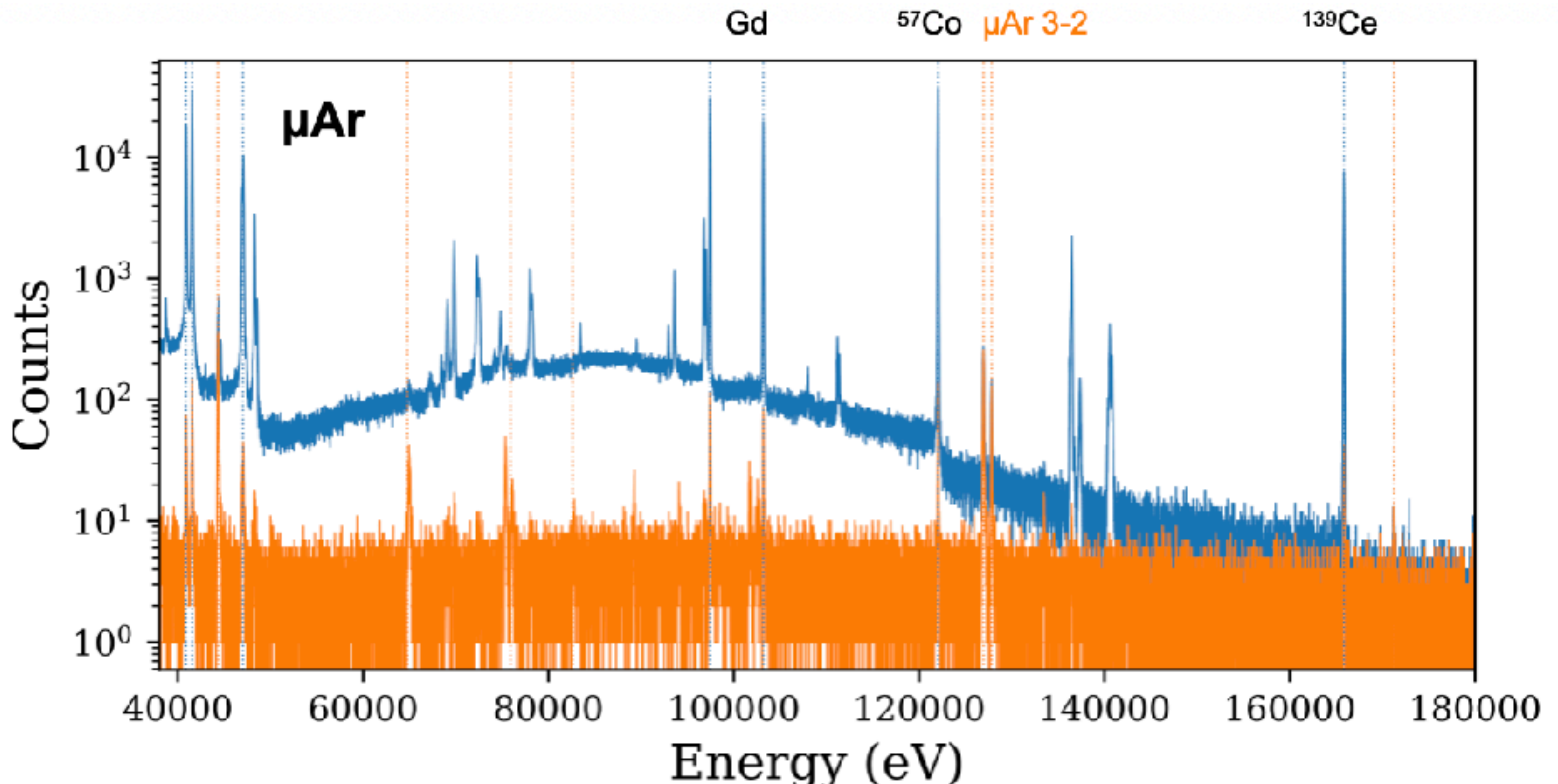

VAT

Preliminary spectra



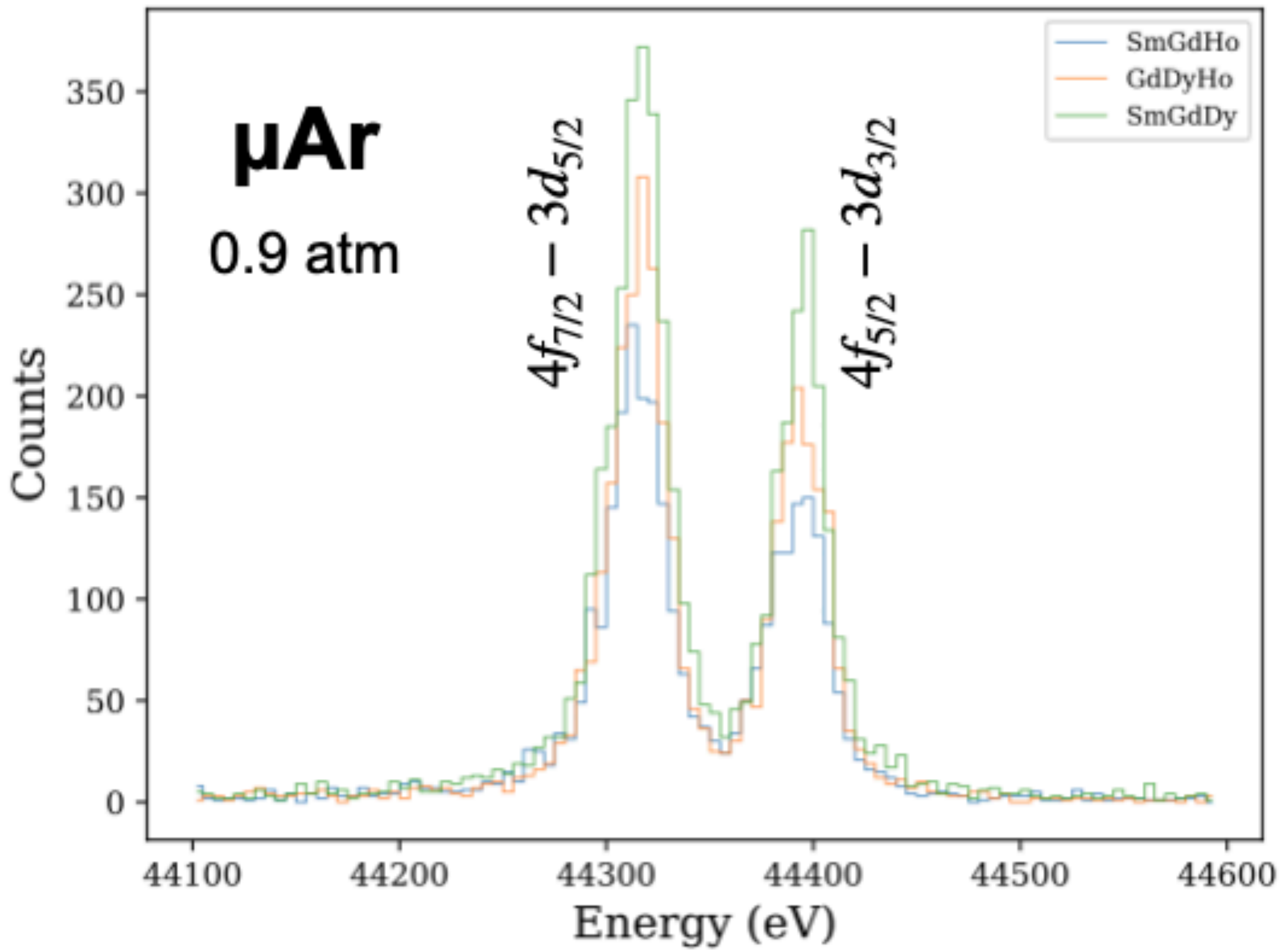


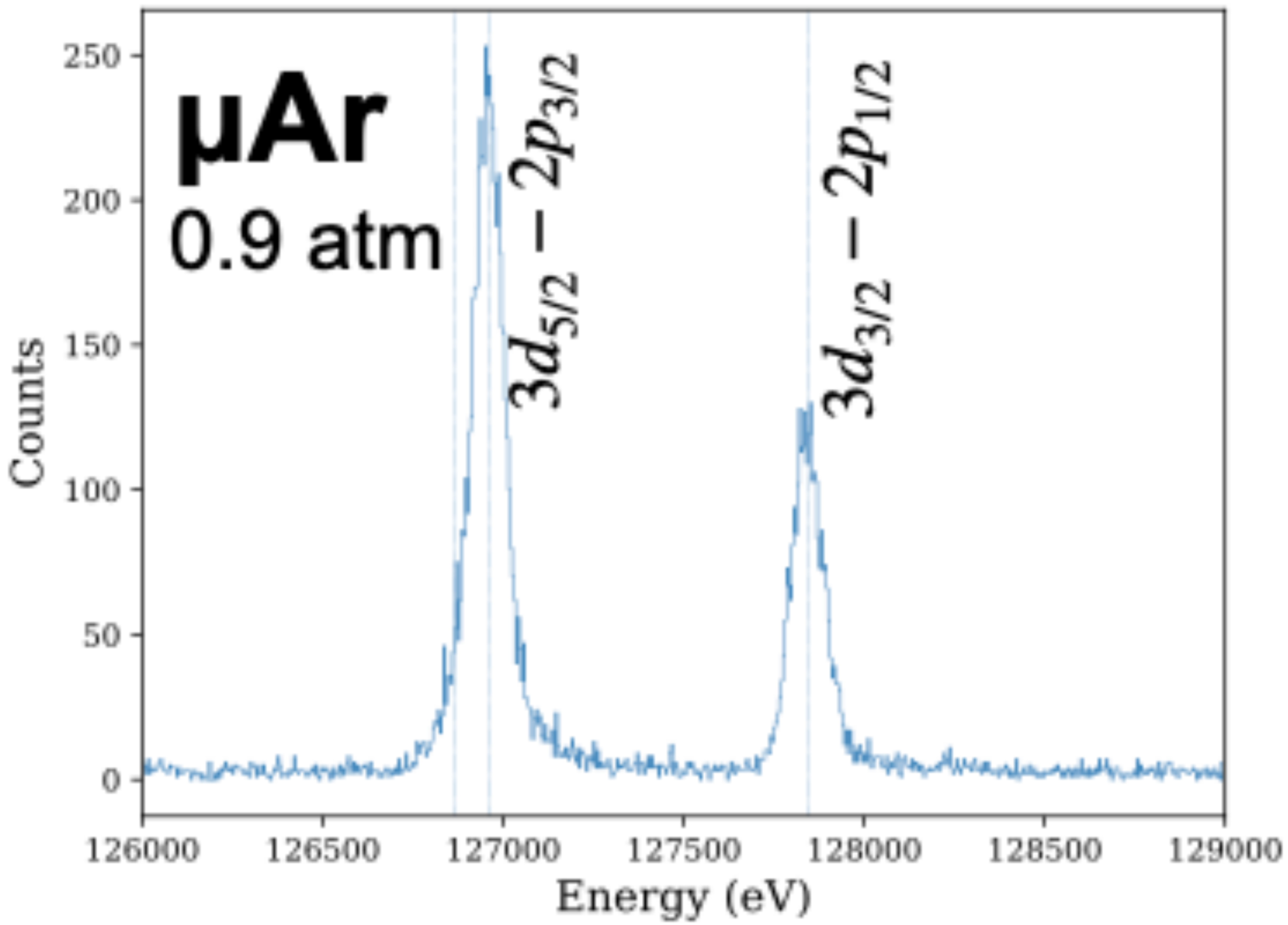




Preliminary spectra

~ 1 day data-taking for each data set





Precision goal: 1eV for 44 keV line→ Validate QED effect at 1% level

Summary

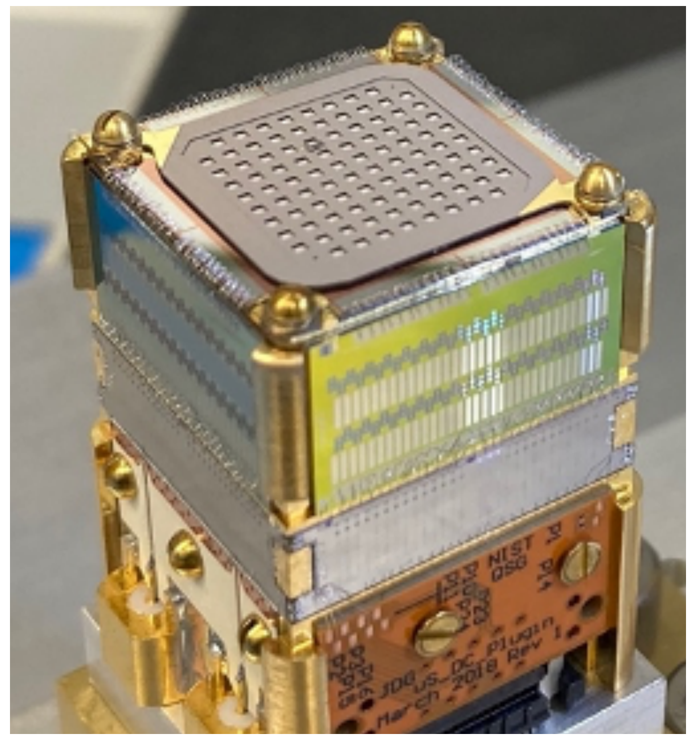
- **We explored the TES application in the charged-particle beam lines, and demonstrated that microcalorimeter is a powerful tool for exotic-atom X-ray spectroscopy**
  - Strong interaction study
  - Strong E-field QED
  - Cascade dynamics

Excellent resolution + collection area

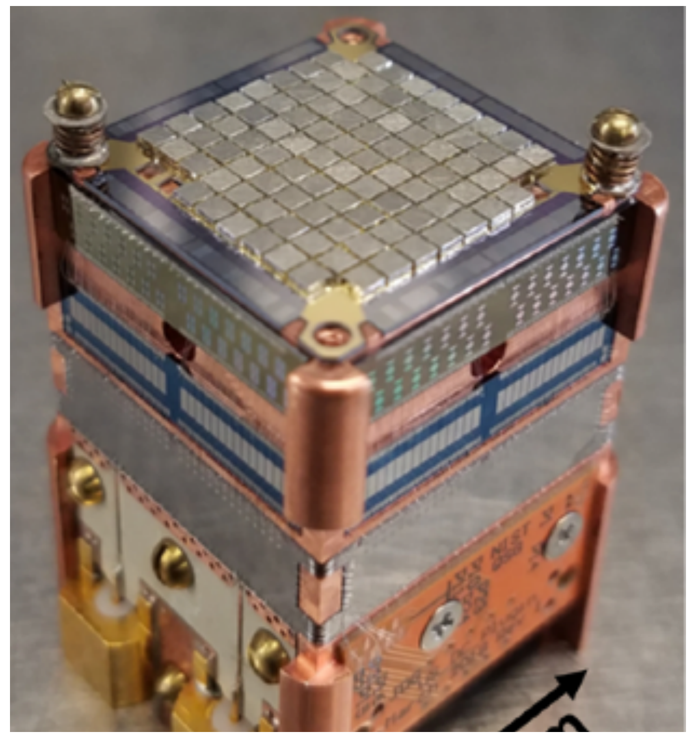
broad energy range

10 keV

50 keV



100 keV



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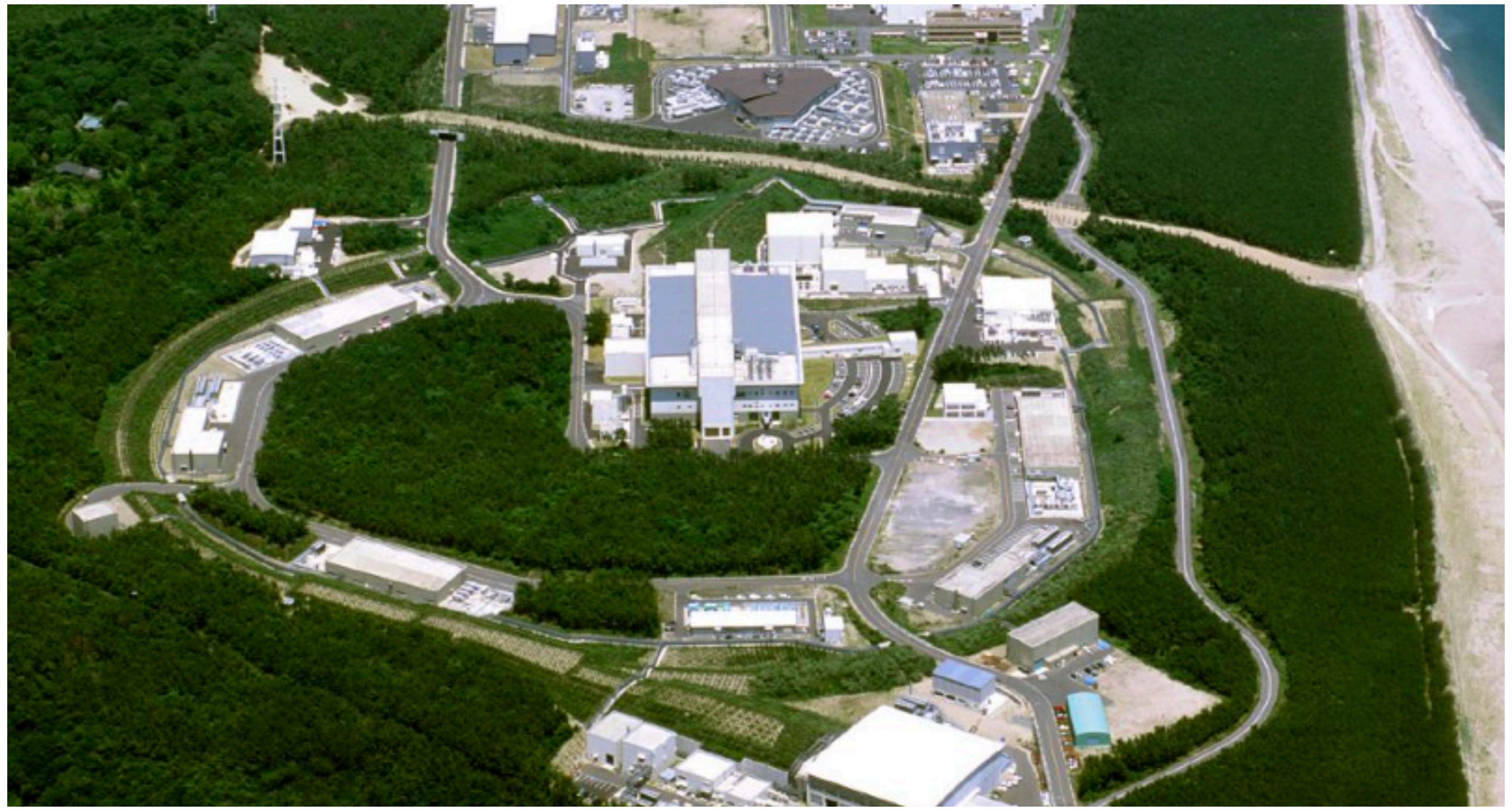

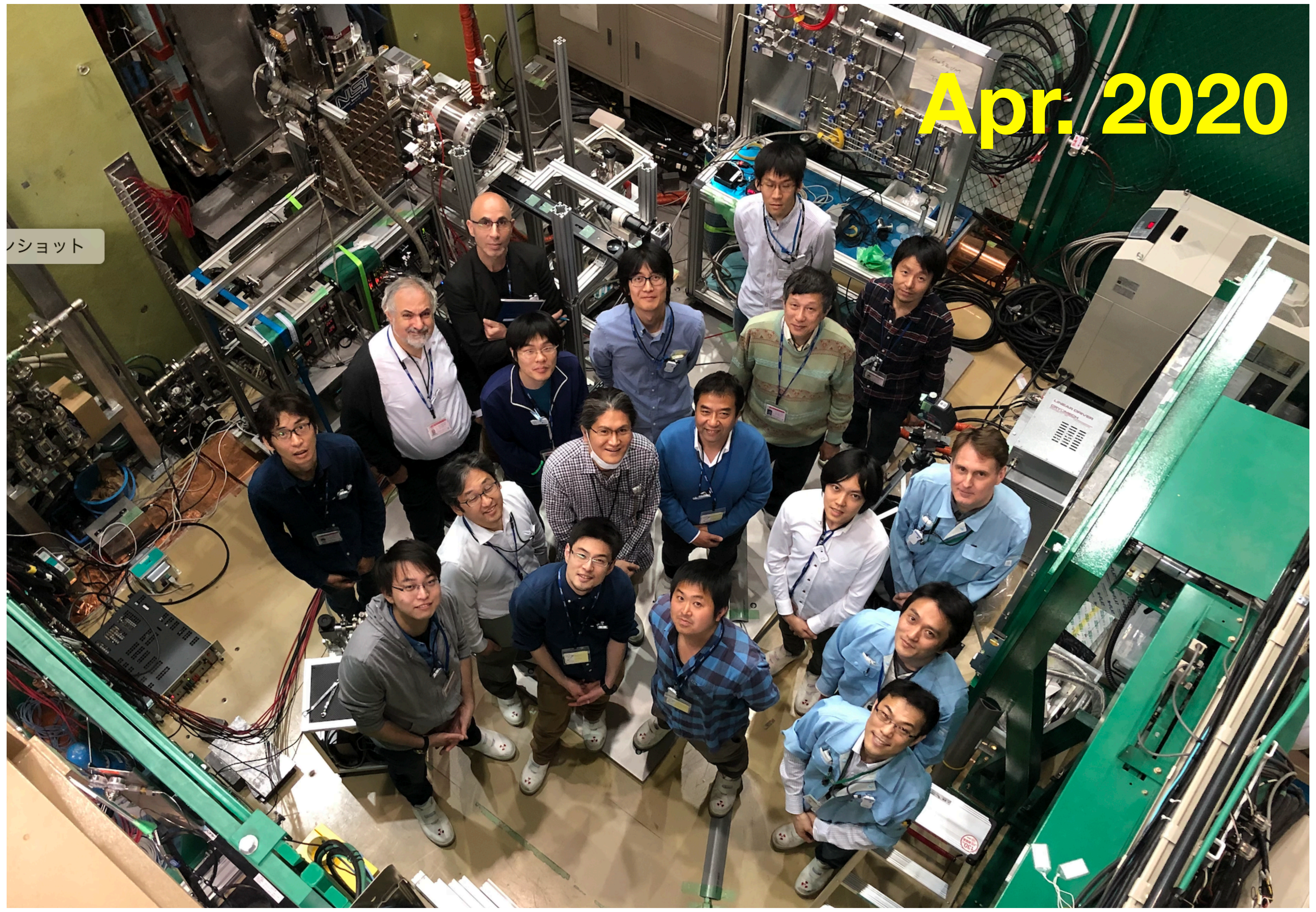

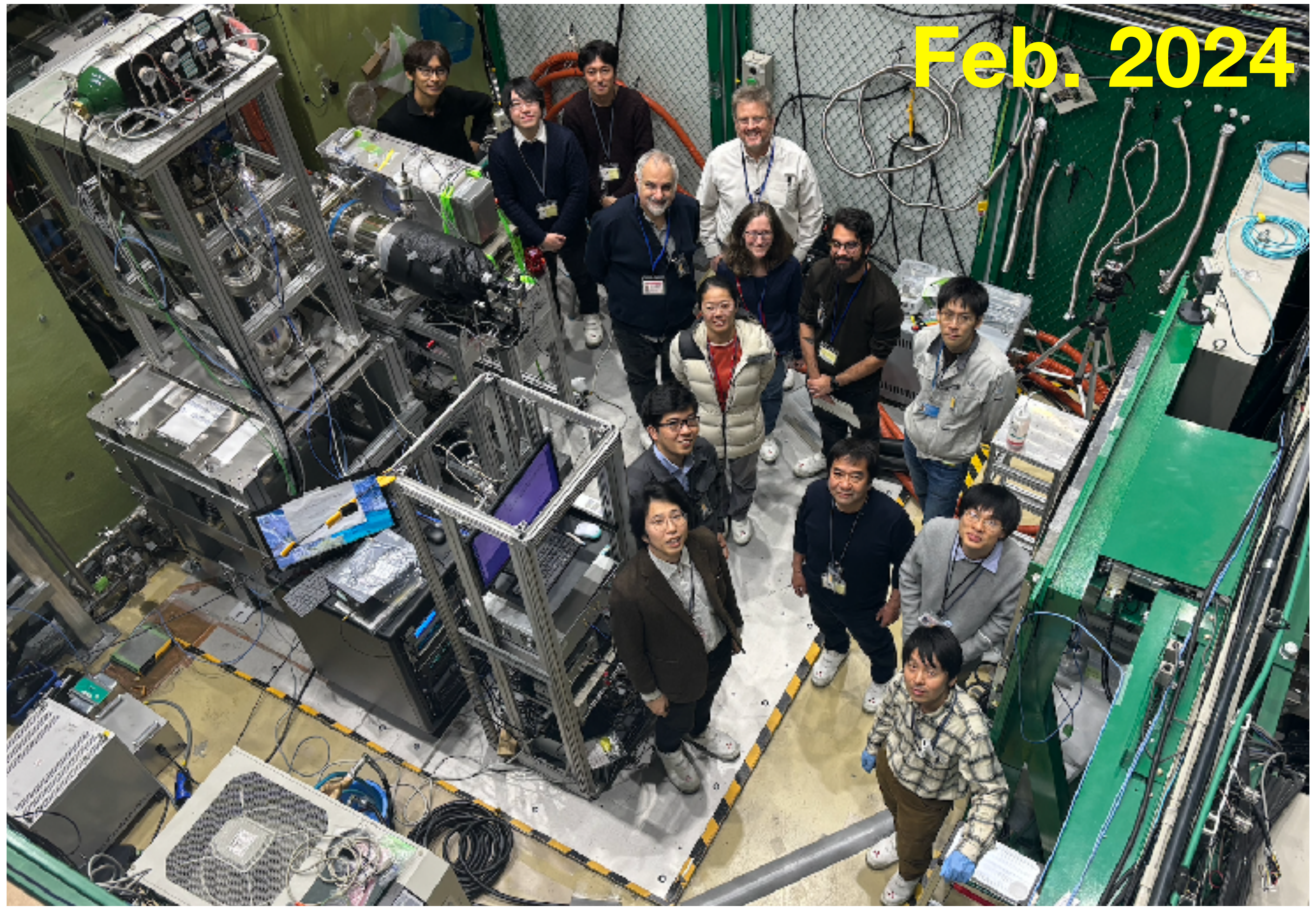

Thank you for your attention !