Kaonic atom experiments at J-PARC

Tadashi Hashimoto (RIKEN PRI/RNC)
for the J-PARC E62/E57 collaboration

Workshop on Fundamental Physics with Exotic Atoms, Frascati, Italy, June 23—25, 2025.

J-PARC E62

Kaonic ^{3}He/^{4}He 3d→2p

with **TES**

- RIKEN, KEK, JAEA, RCNP, JAXA, TMU, UTokyo, TokyoTech, OsakaU, RikkyoU, TohokuU
- NIST
- INFN-LNF, Politecnico di Milano
- Stefan Meyer Institut
- KU Leuven
- University of Zagreb
- Lund University

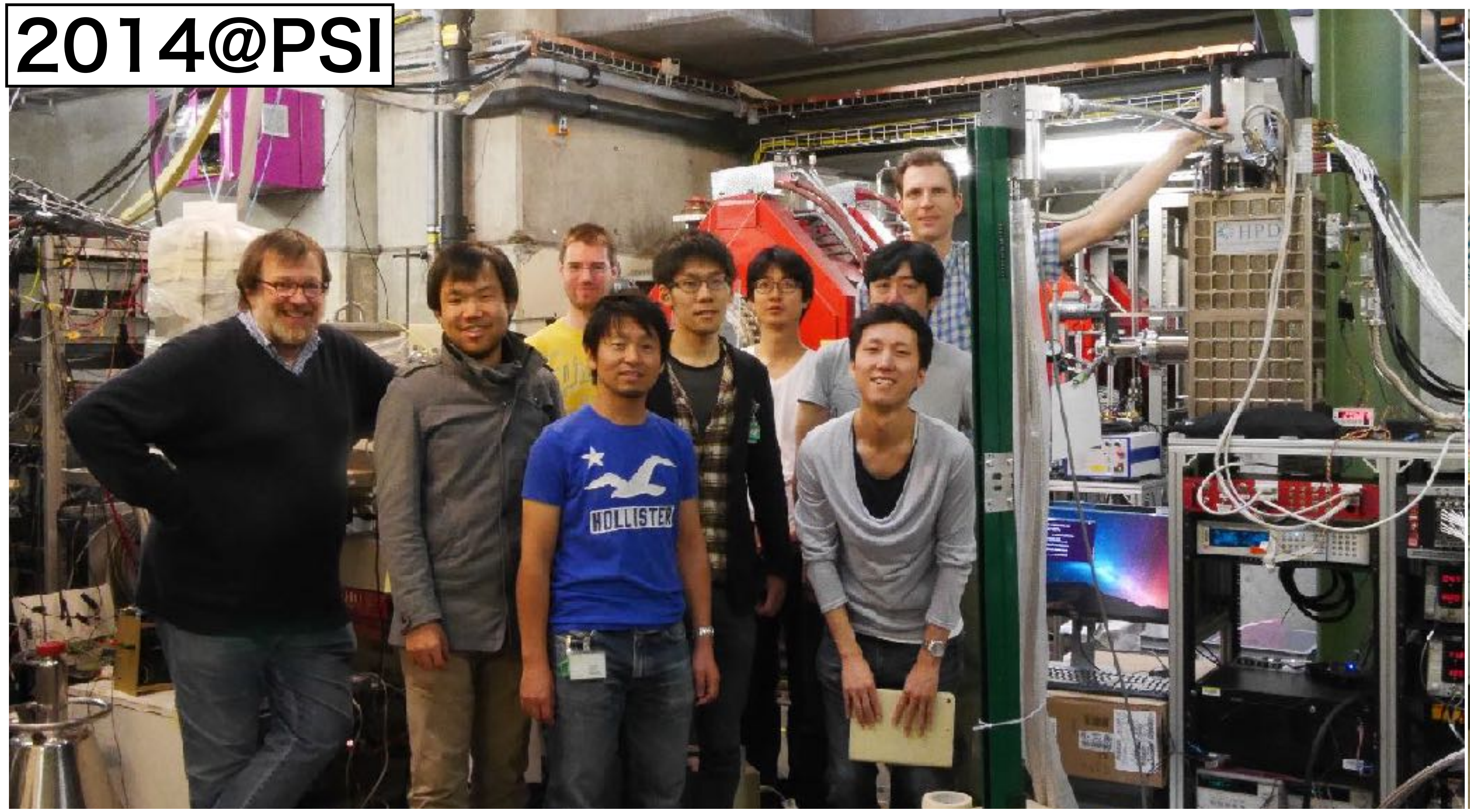
Nuclear physicists + TES experts (NIST+) + Astro-physicists

J-PARC E57

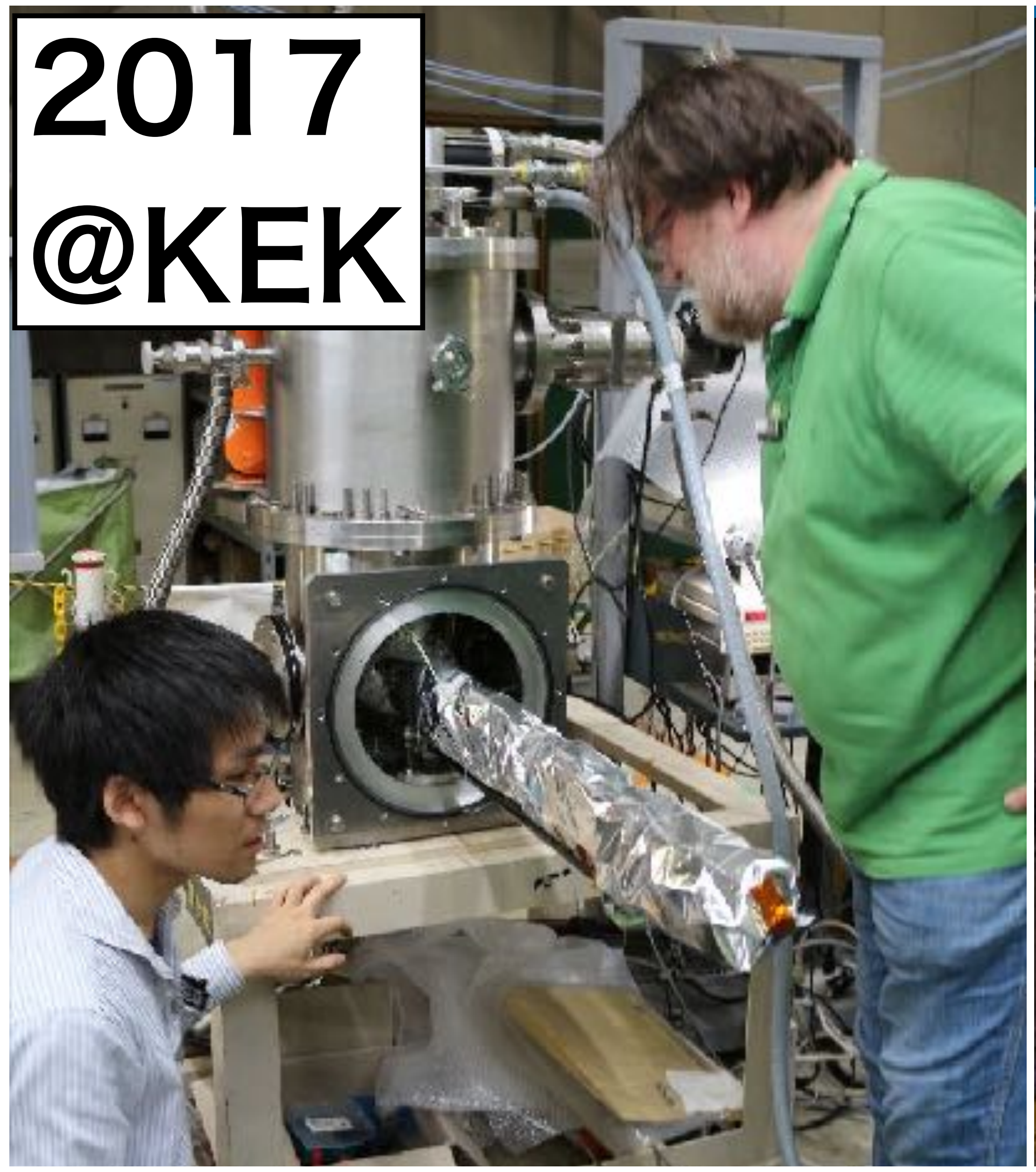
Kaonic Deuterium 2p→1s

with **SDDs**

lead by J. Zmeskal


2014@PSI
HOLLISTER


2023@RIKEN


2017
@KEK

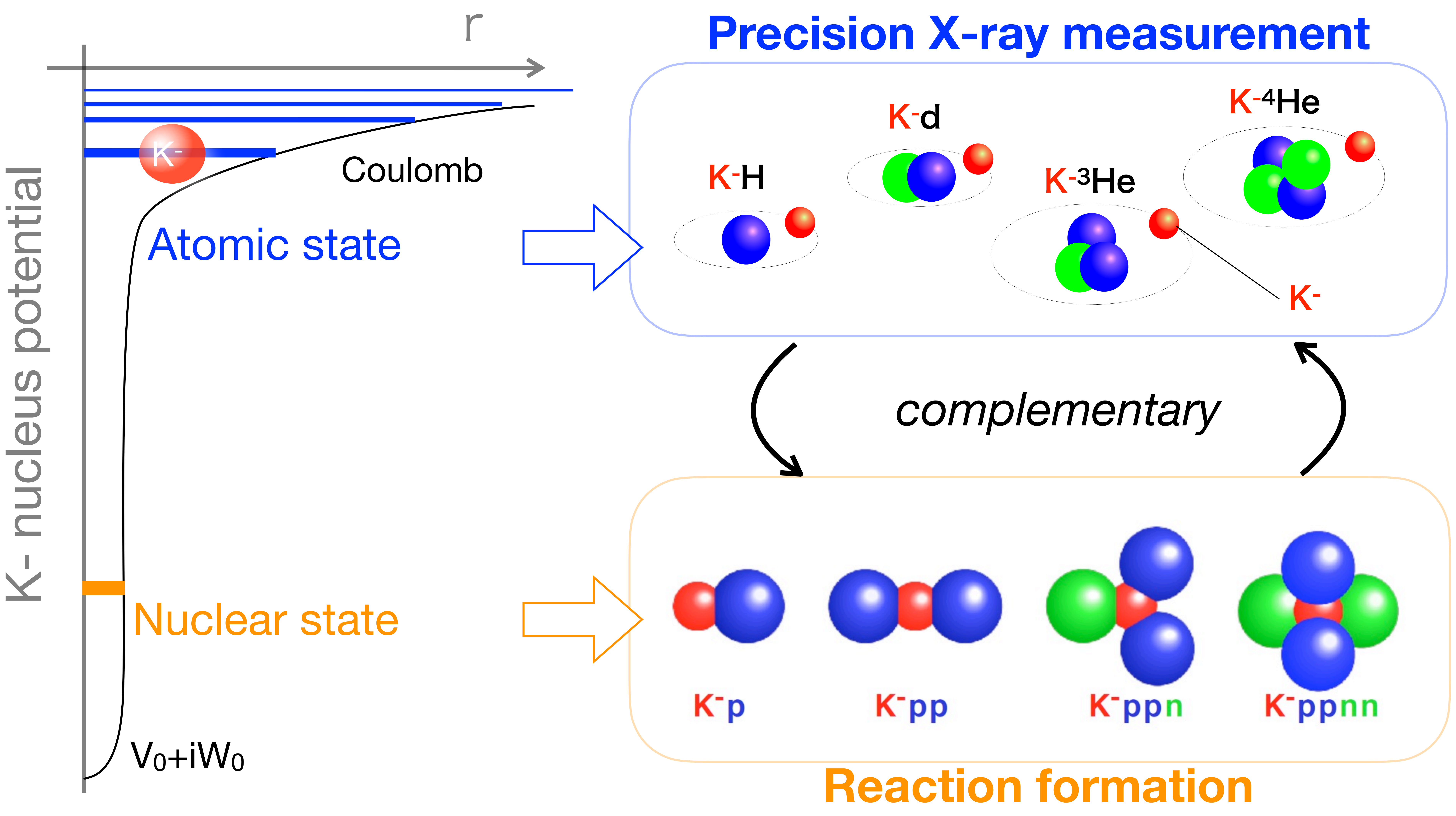

2018@J-PARC


2018 after E62

History

Year	E62	E57
2006	E17 proposal (1st PAC)	
・・・		
2014	TES demonstration @ PSI	E57 proposal (18th PAC)
2015	E62 proposal (20th PAC) →**stage-2** approval	updated proposal (20th PAC) →**stage-1** approval
2016	**Commissioning at K1.8BR**	
2017		
2018	**K-He Physics run**	SDD commissioning
2019		**K-H (+K-He) commissioning**
2020	Switch to lifetime measurement of hypernuclei…	

$\bar{K}$ meson in nuclei



F. Sakuma

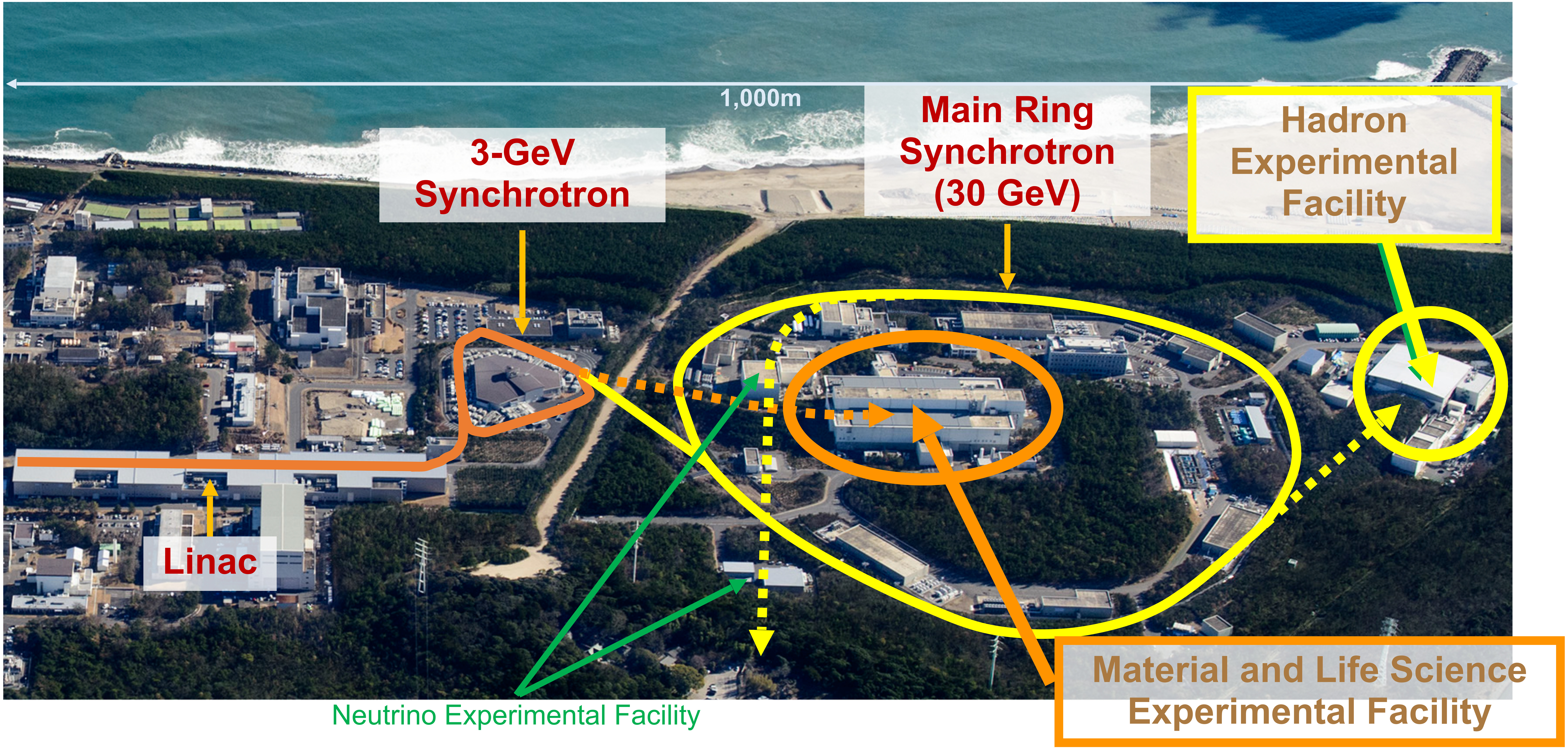
A series of experiments at J-PARC K1.8BR, probing different energy, density, and isospin

K-atom experiments @ J-PARC K1.8BR

		K-d (E57)	**K-$^{3/4}$He (E62)**
X-ray transition		2p → 1s	3d → 2p
	Energy	~ 8 keV	~ 6 keV
	Width	**~ 1000 eV**	**~ 2 eV**
	Yield (per stopped K-)	**~ 0.1 %** **(0.04% of liquid D2 density)**	~ 7 % (Liquid He)
X-ray detector		**SDD**	**TES**
	FWHM resolution	~ 150 eV	**~ 5 eV**
	Effective area	**~ 200 cm^2**	~ 0.2 cm^2
Physics		$K^{bar}N$ (I=1)	K^{bar}-nucleus potential

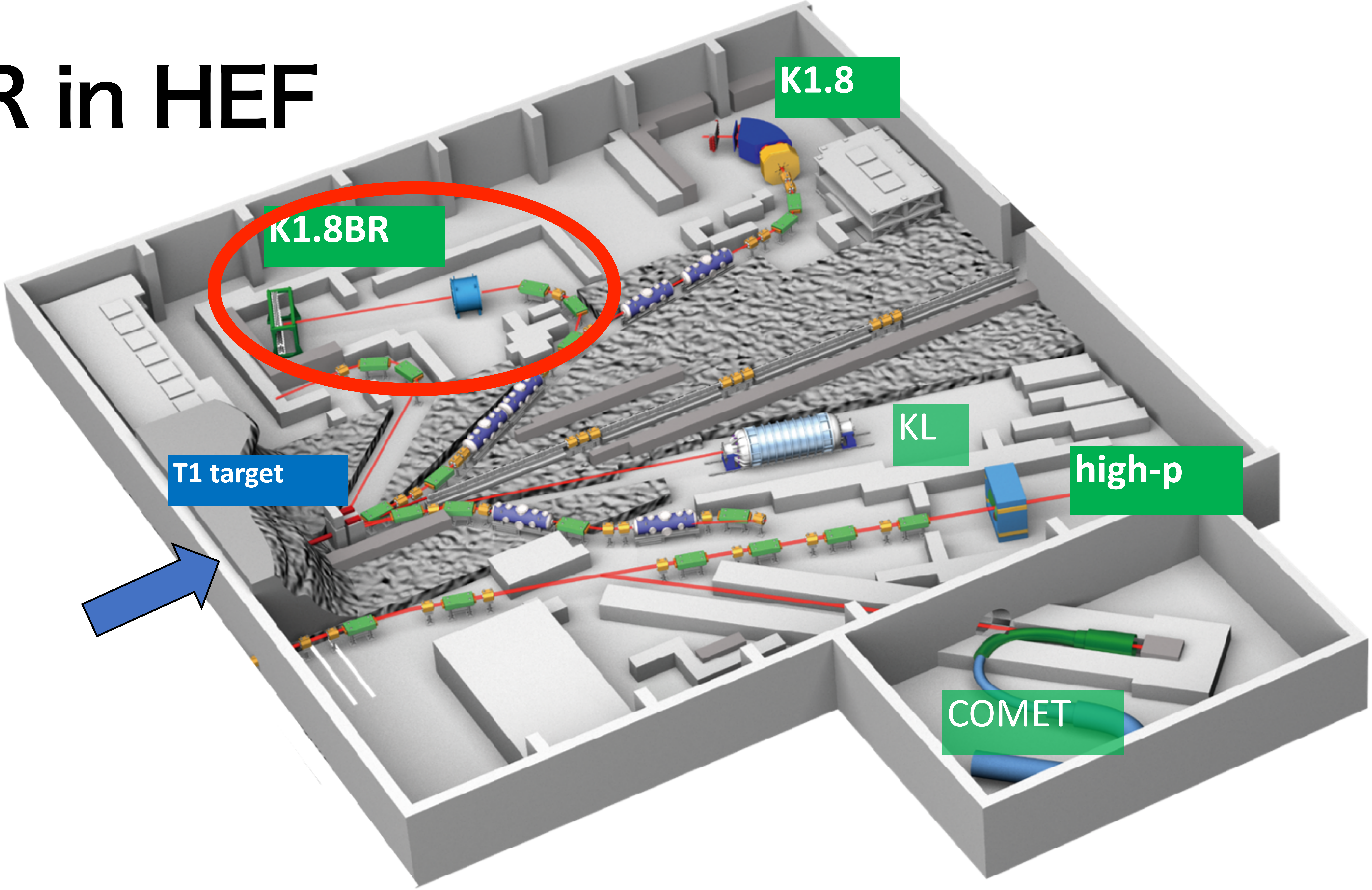
High sensitivity   High resolution

J-PARC Japan Proton Accelerator Research Complex



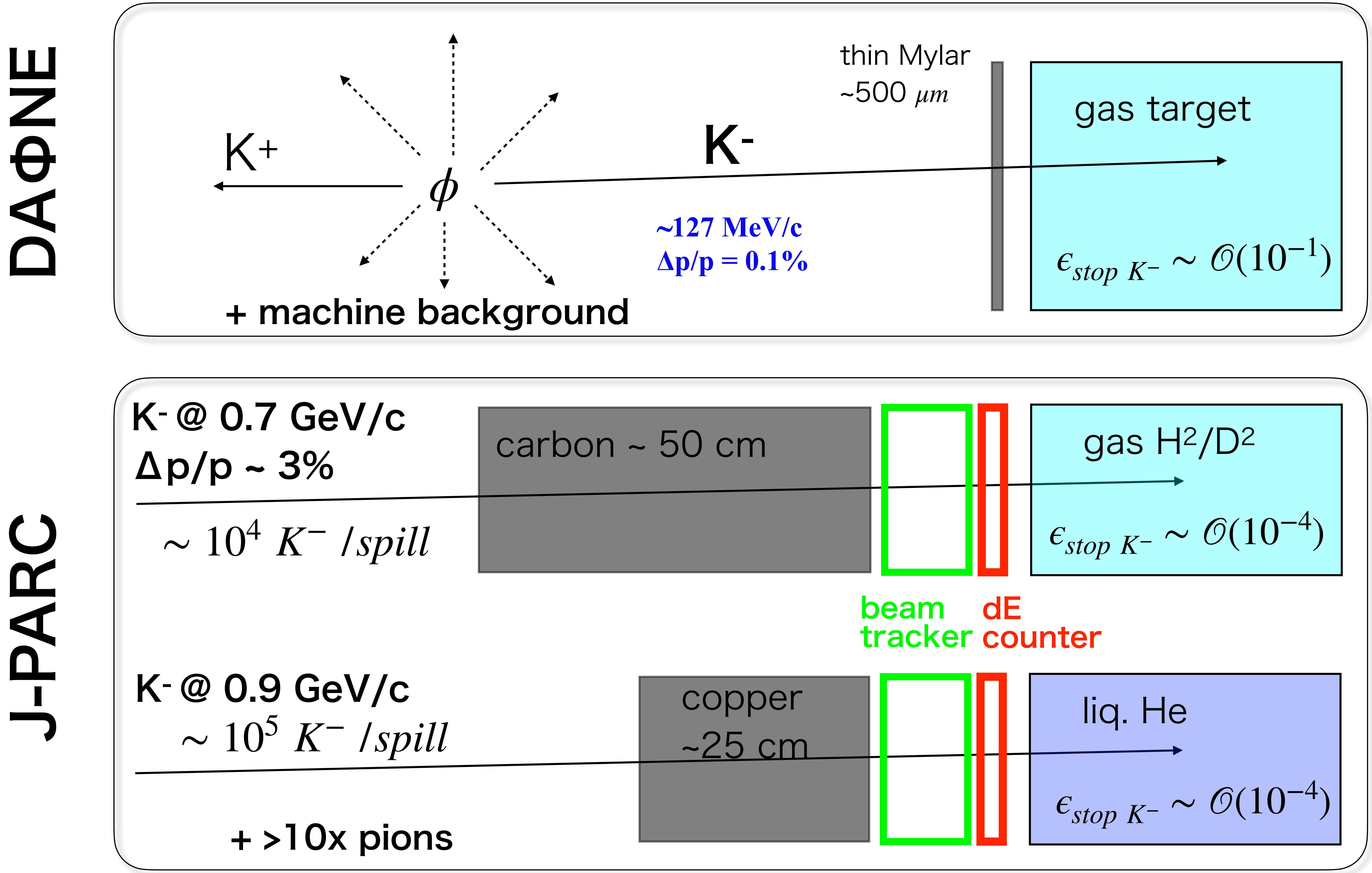
World's highest intensity proton driver→ high-intensity secondary K/μ beam

K1.8BR in HEF

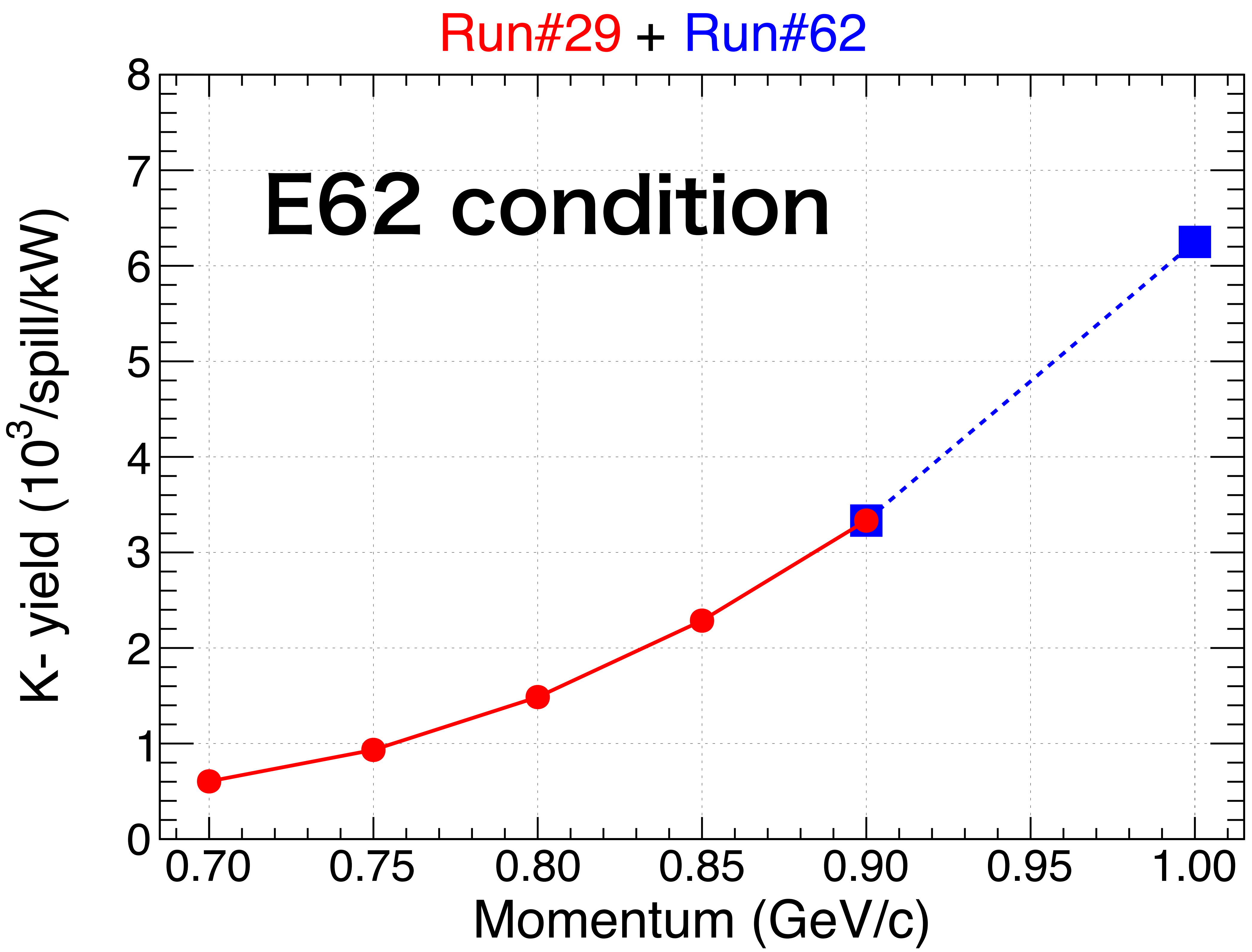


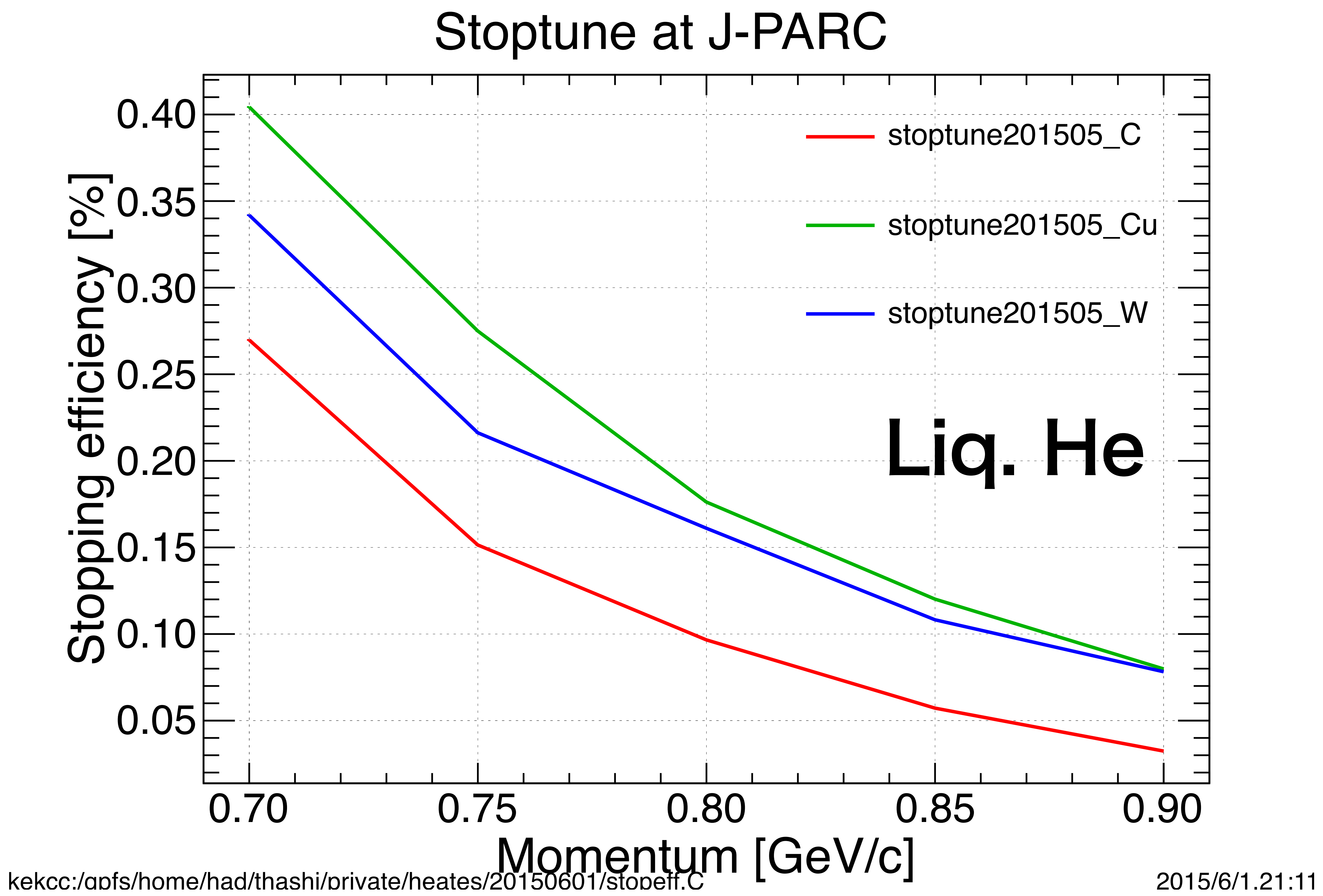
K1.8BR suitable for low-energy K^- beam below 1 GeV/c

DAΦNE vs. J-PARC



Stop K^- optimization





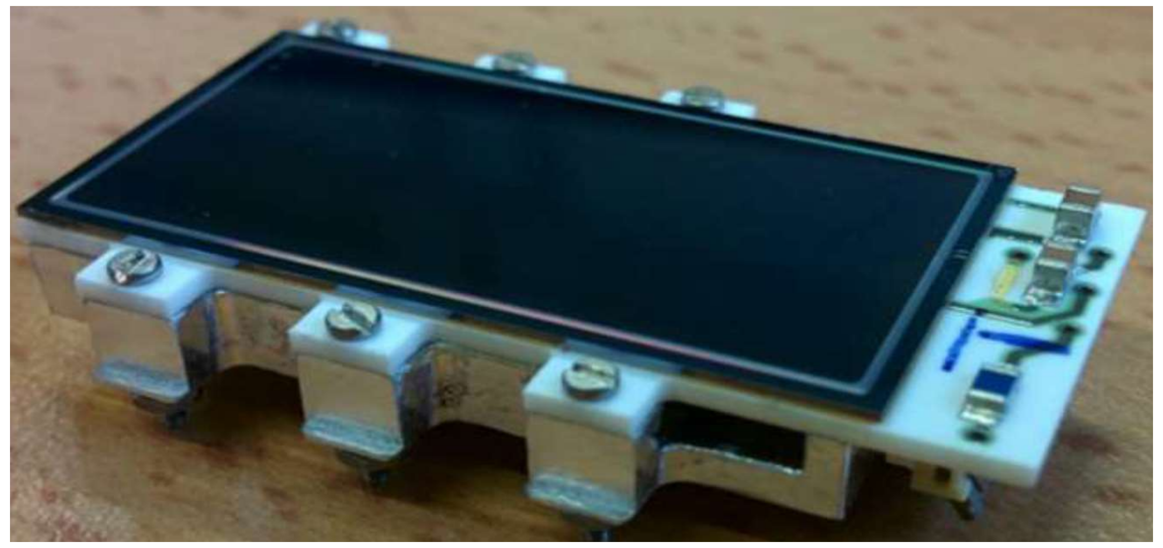
- The higher the momentum, the more kaons and the less stopping
- stopping efficiency is typically ~10^{-4}

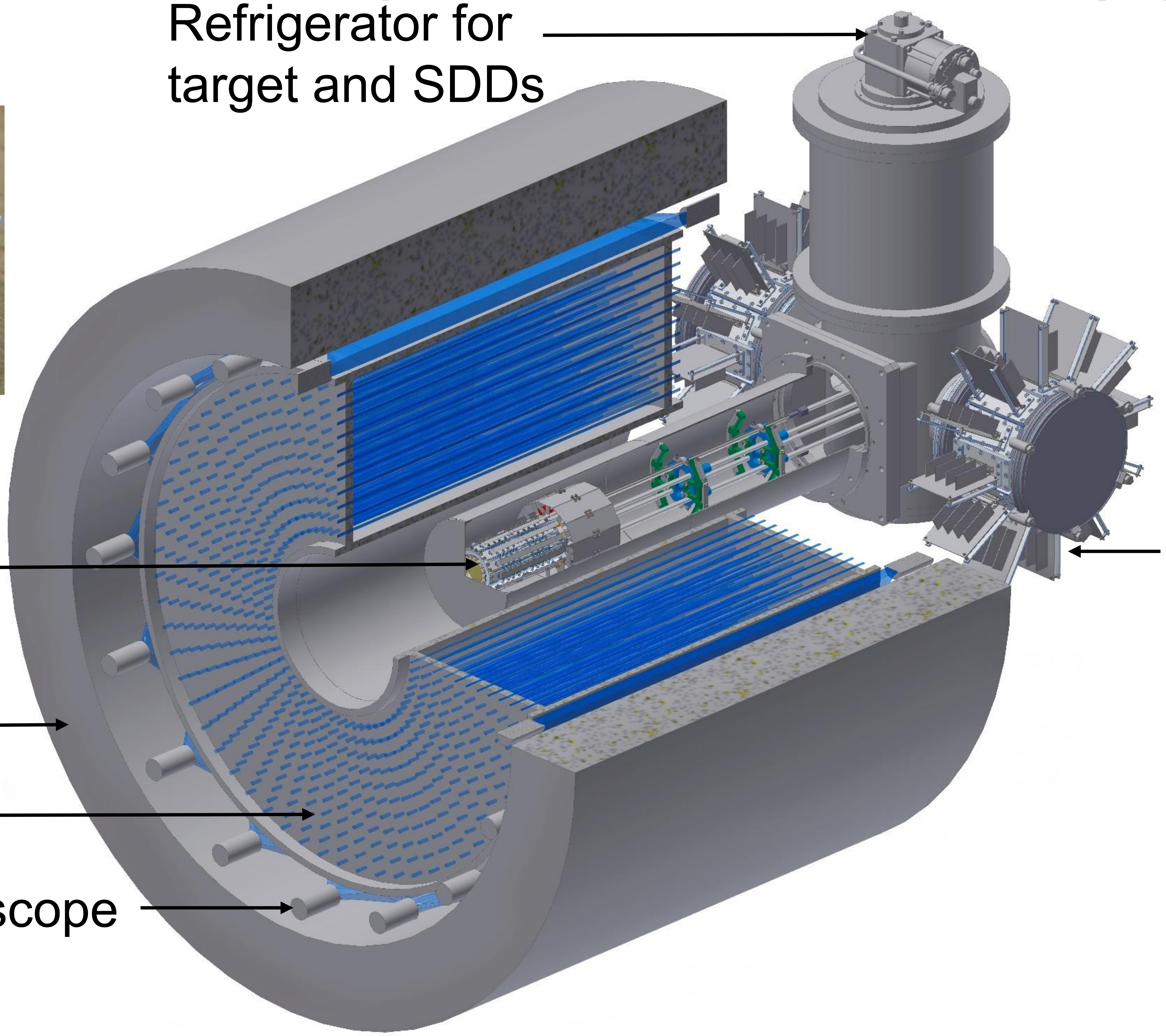
K-p/K-d 2p-1s (E57)

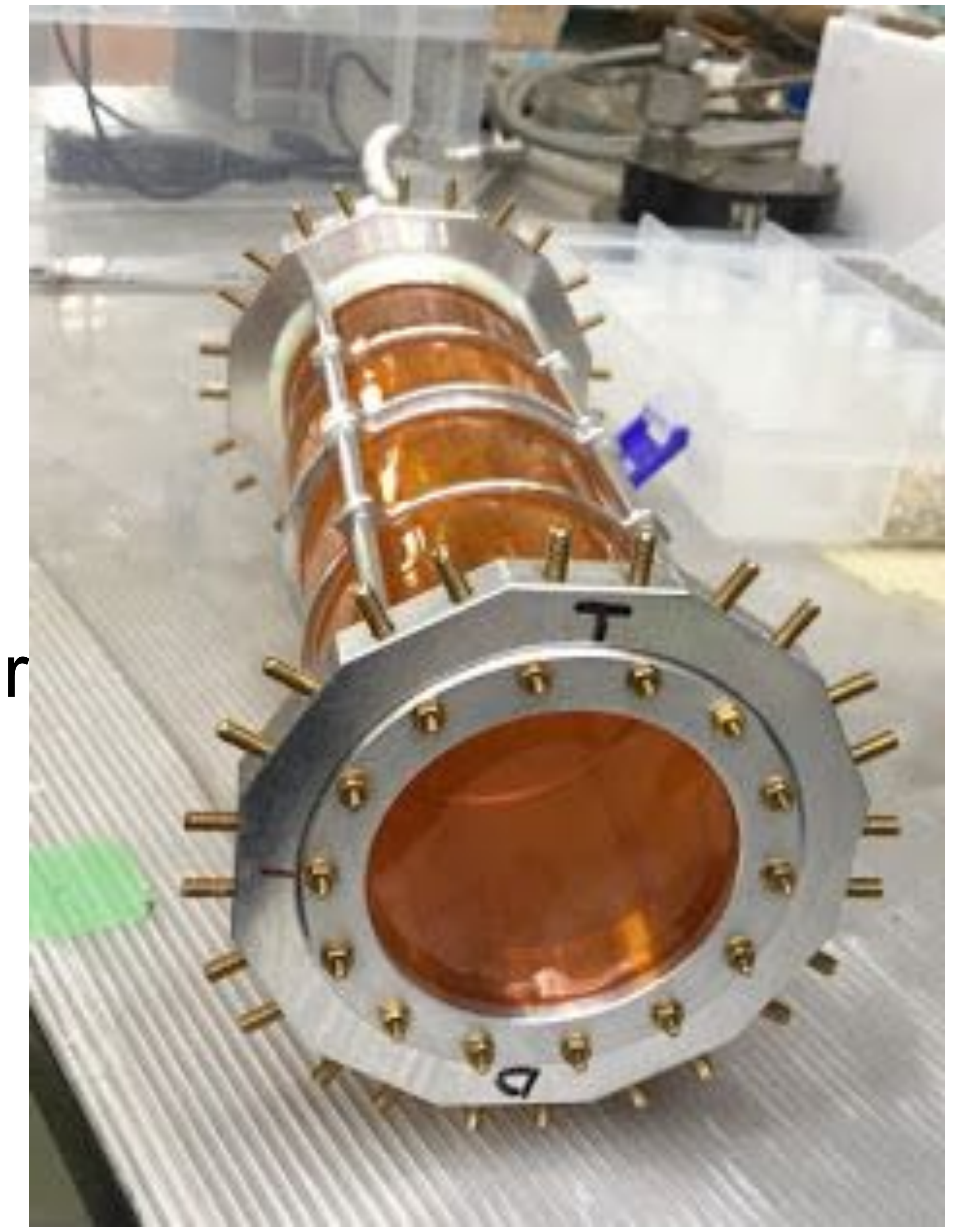
First test run was performed in Mar./Apr. 2019

J-PARC E57 original strategy

(CDS)



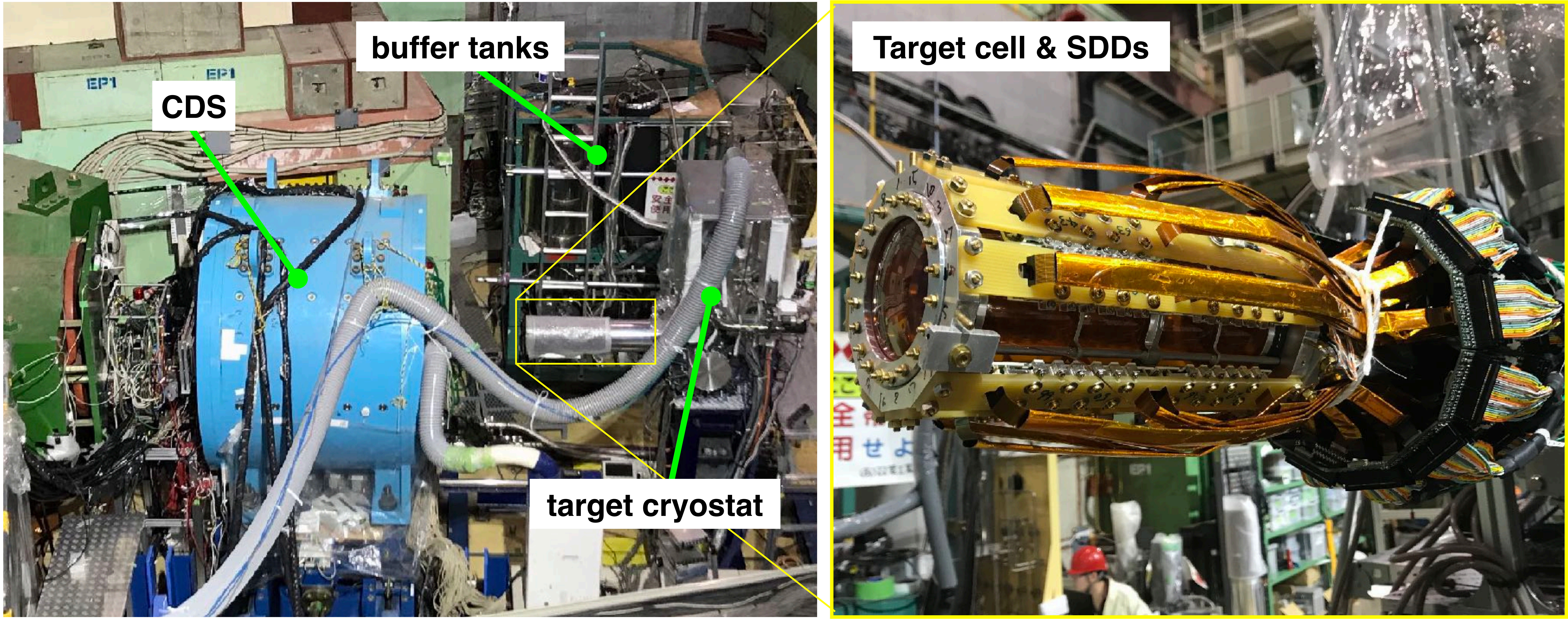




✓Target at 30K&3 bar, SDD down to 100K for better timing resolution

✓**Vertex cut & charged particle veto by using CDC**

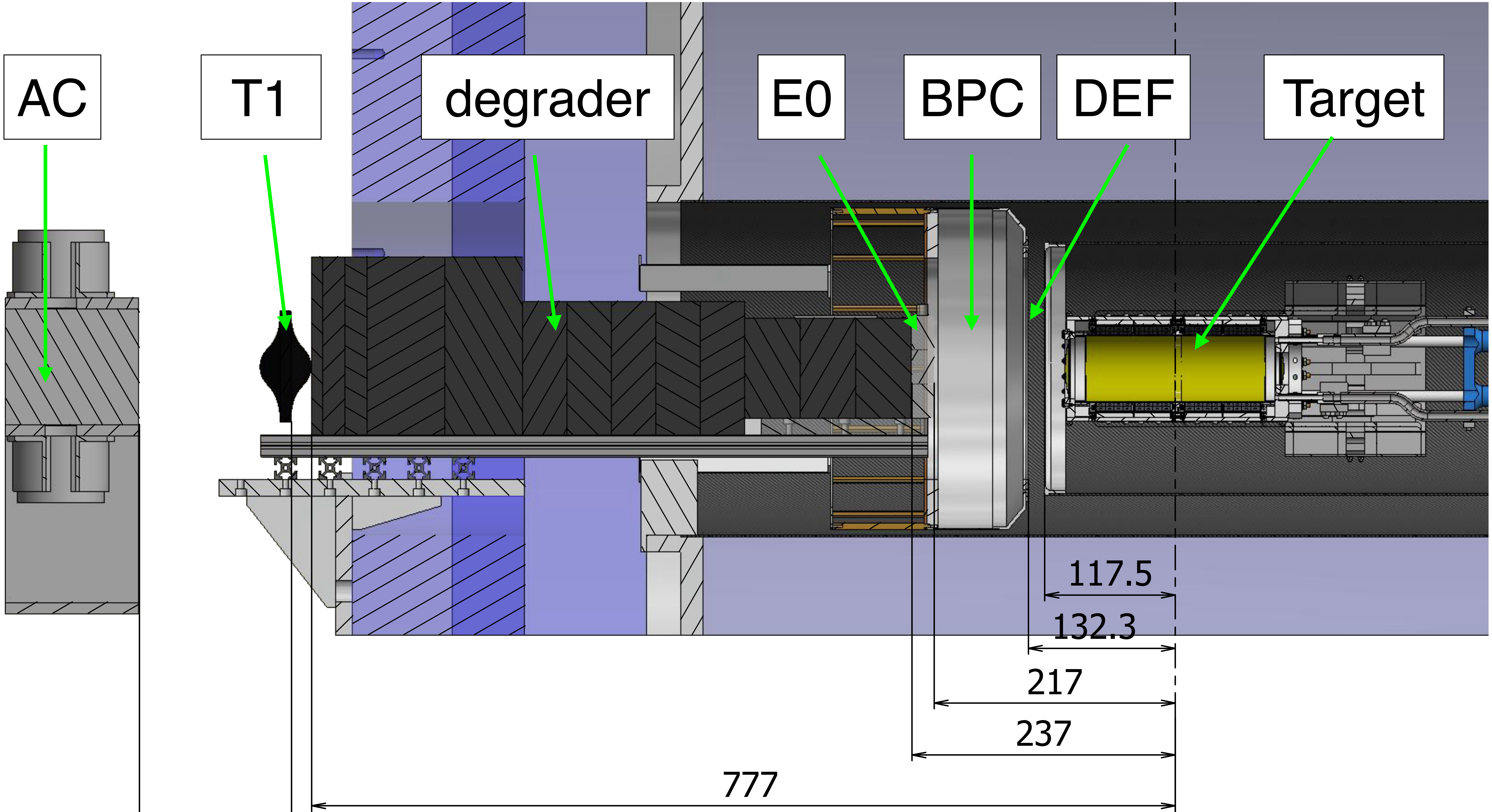
E57 test setup in 2019



✓ Hydrogen target is operated with the required safety measures.

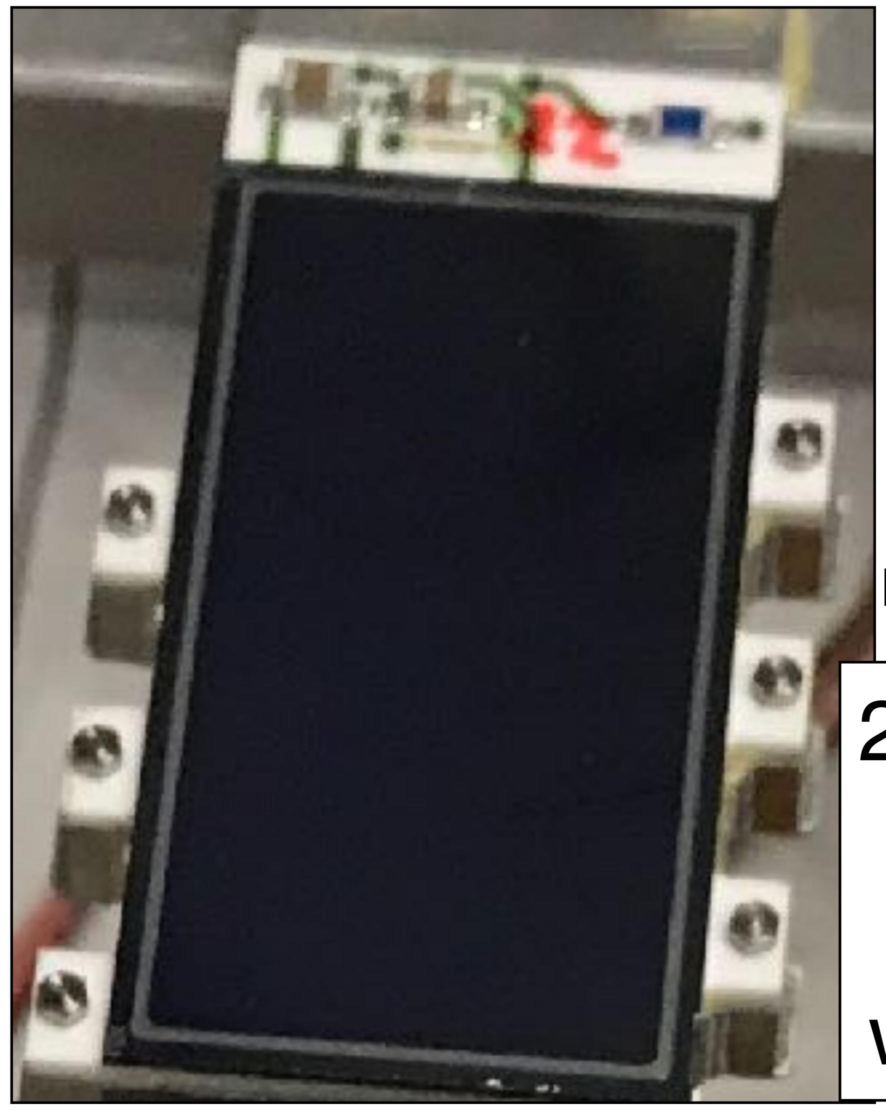
✓ 30 SDD units installed. ~150 ch in 26 units worked.

Setup for E57 pilot



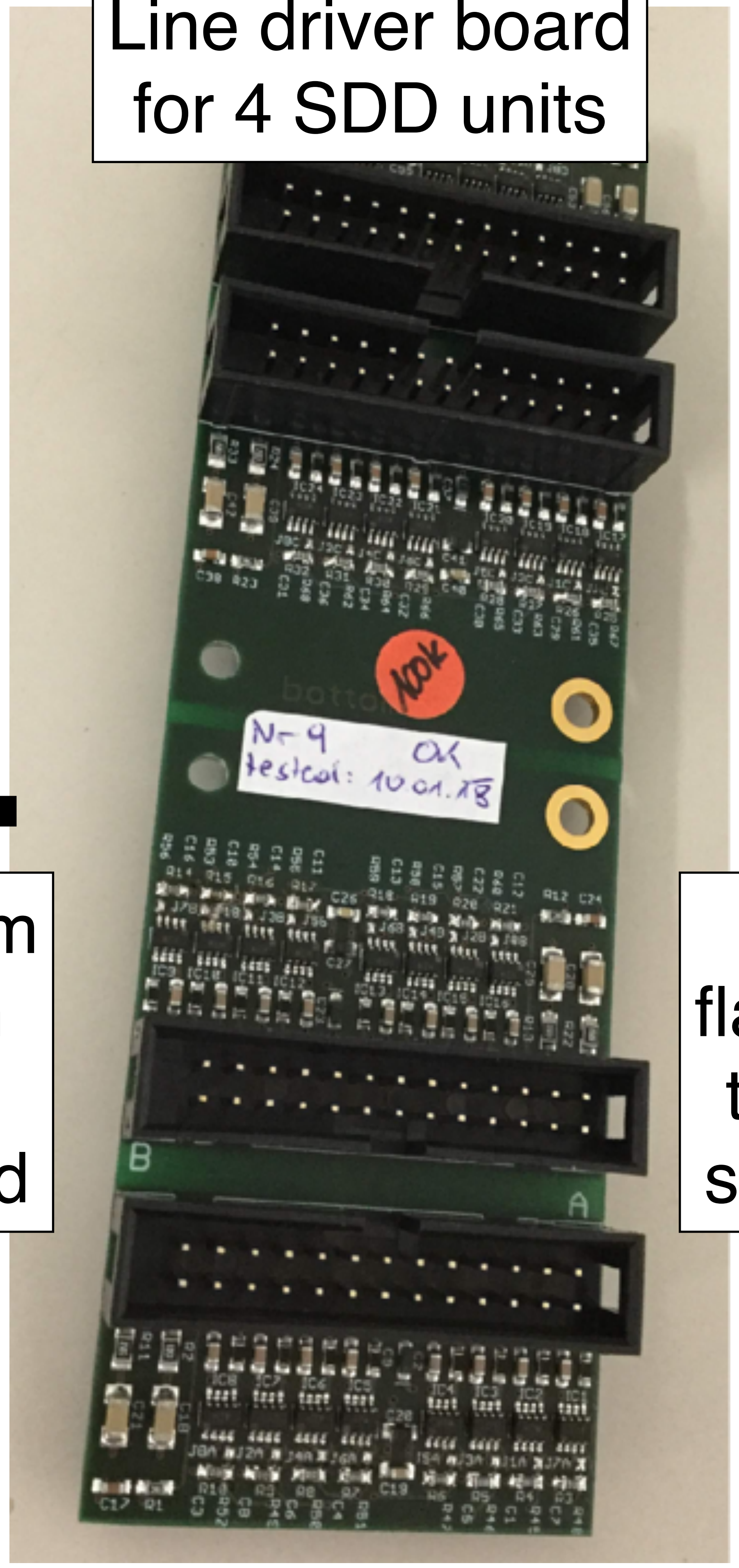
SDD Readout for J-PARC E57/E62

SDD with CUBE
exactly the same
as SIDDHARTA2



25~30cm
Kapton
cable
w/ shield

Line driver board
for 4 SDD units



~1m
flat cable
twisted
shielded

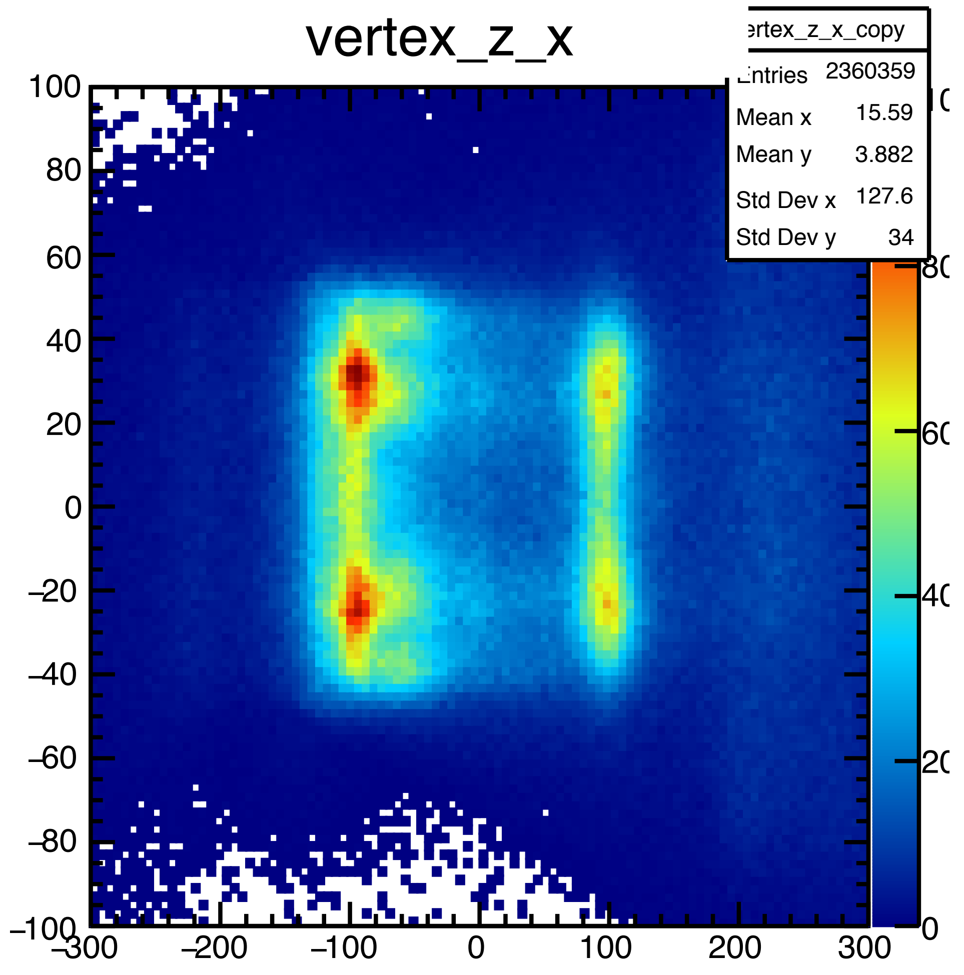
Vacuum

Shaping amplifier
for 2 SDD units

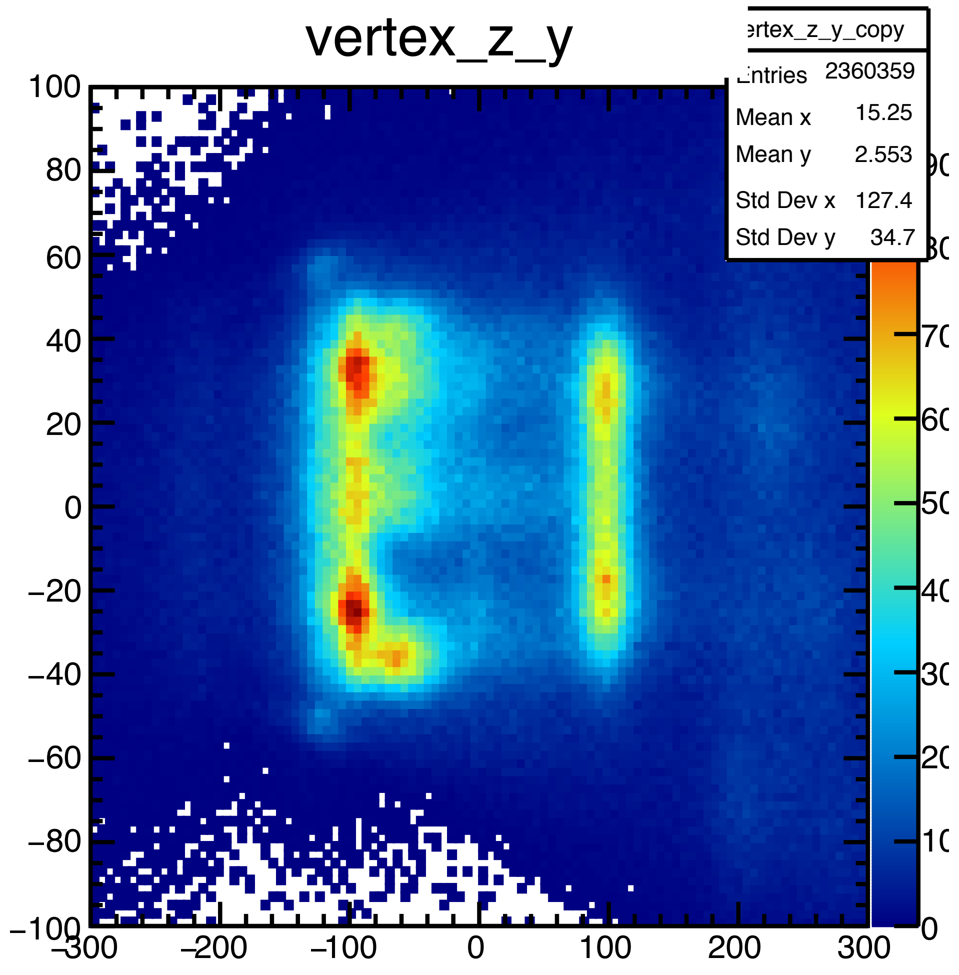
50m flat cable
to CAEN V785 PADC

Vertex reconstruction (BPC&CDC)

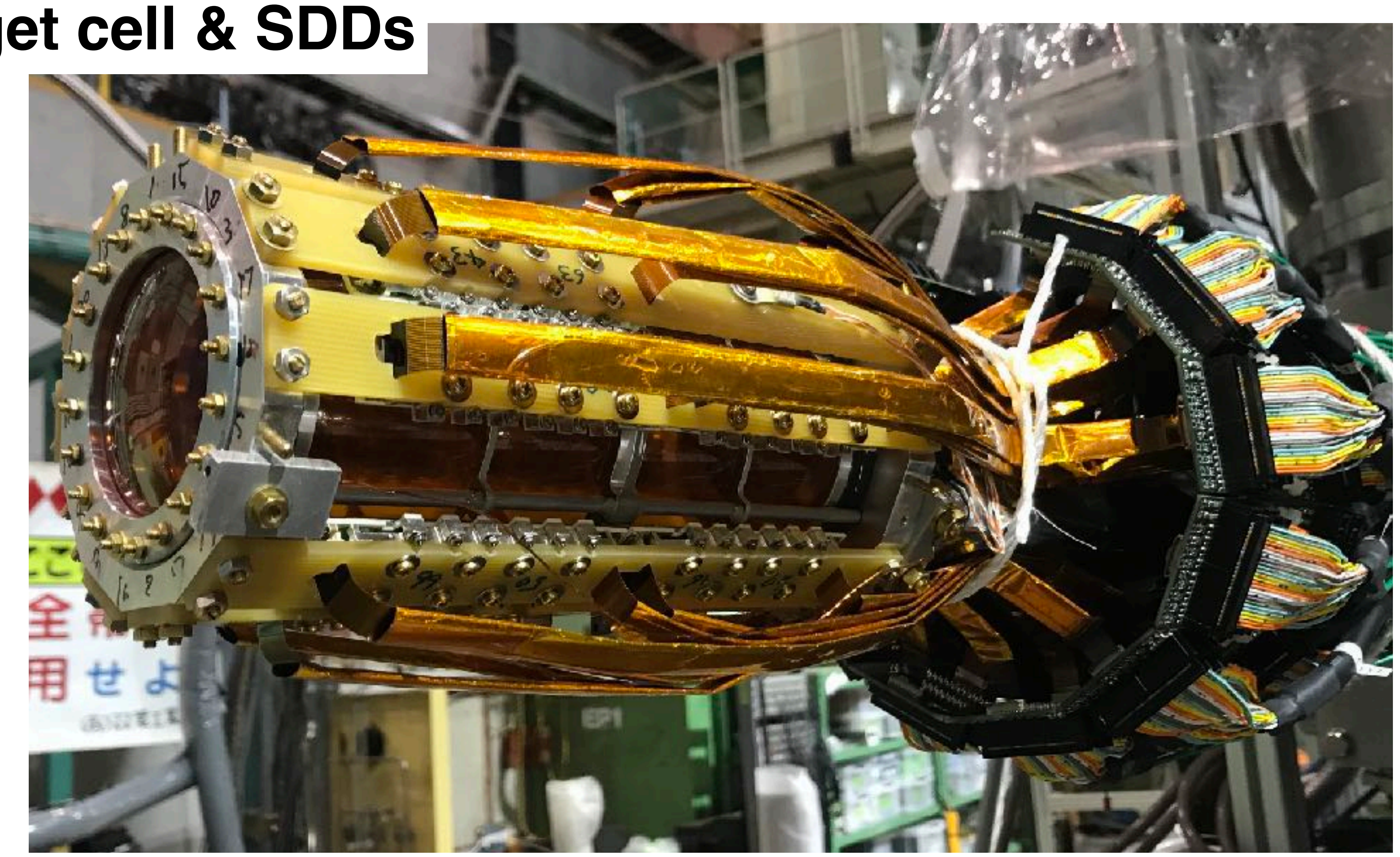
ZX



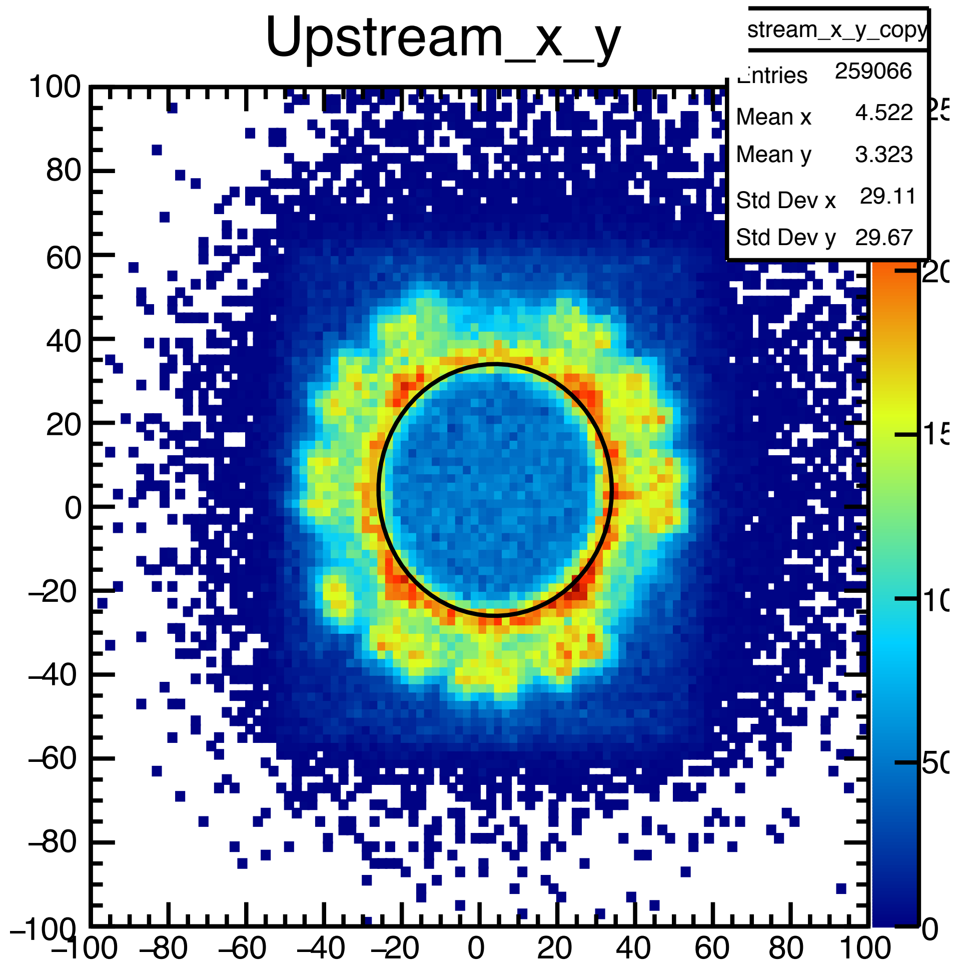
ZY



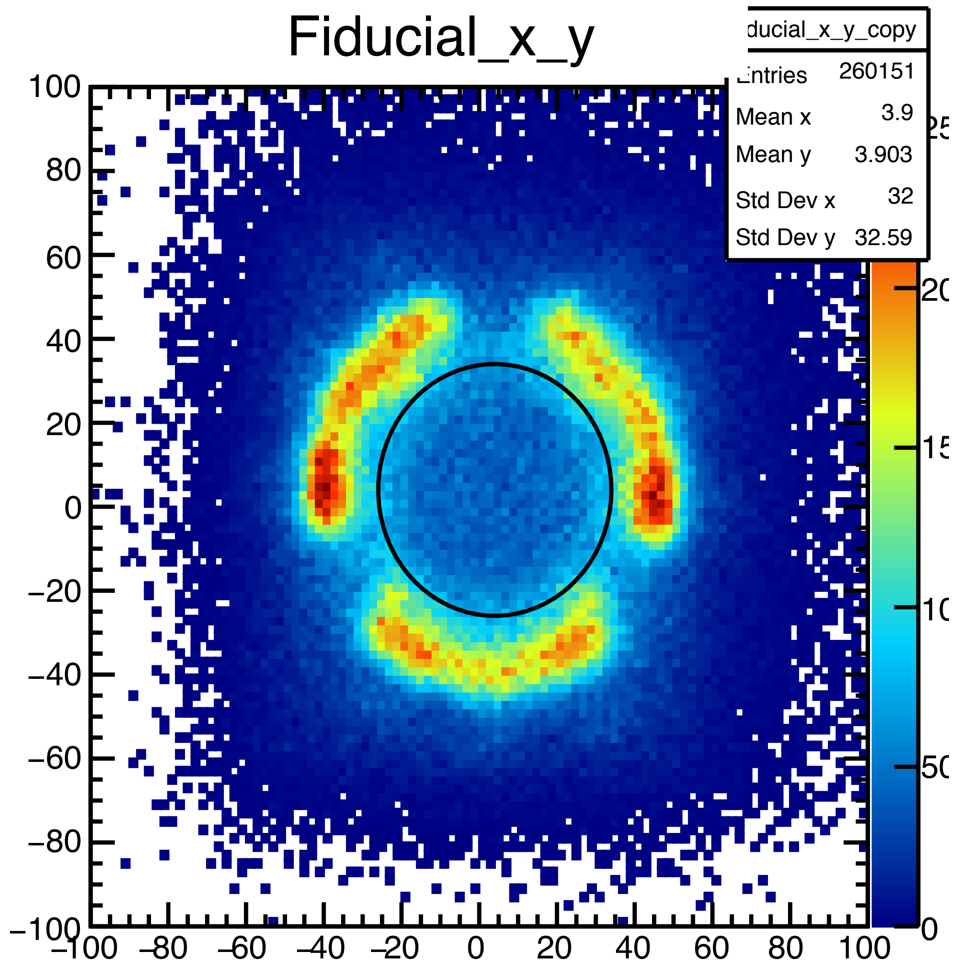
Target cell & SDDs



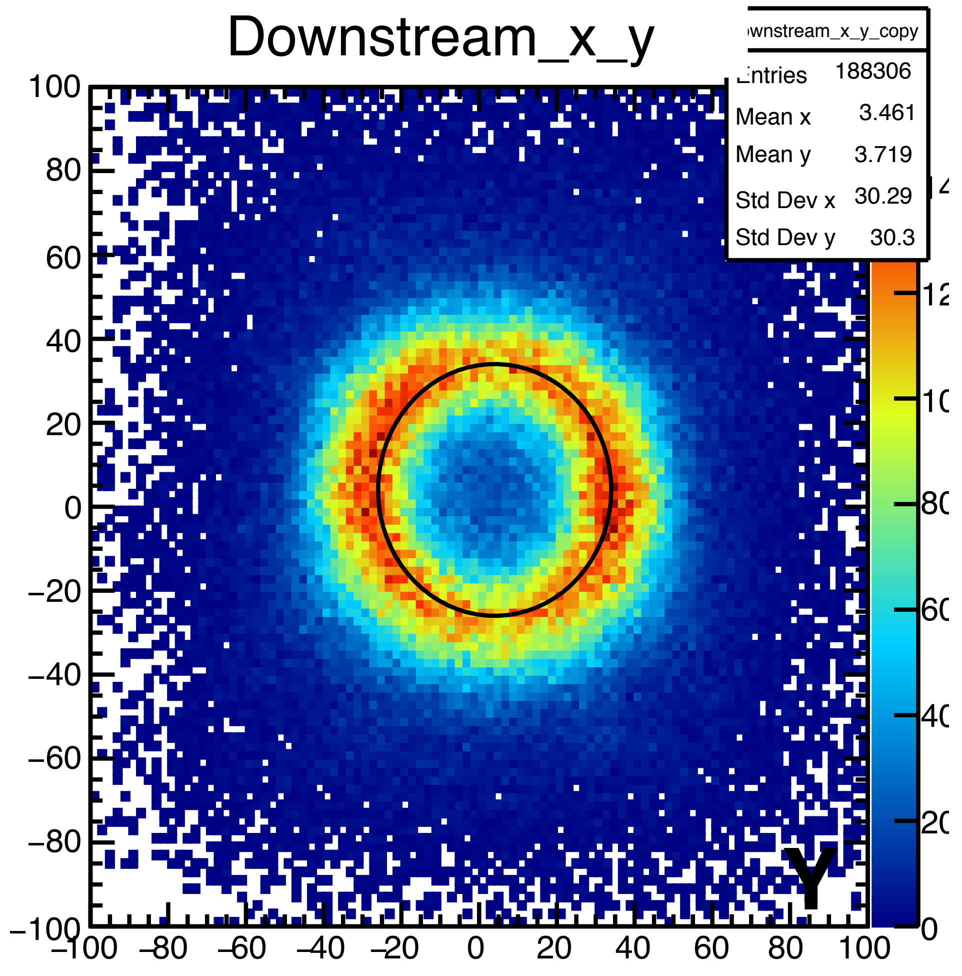
XY



-130<Z<-70

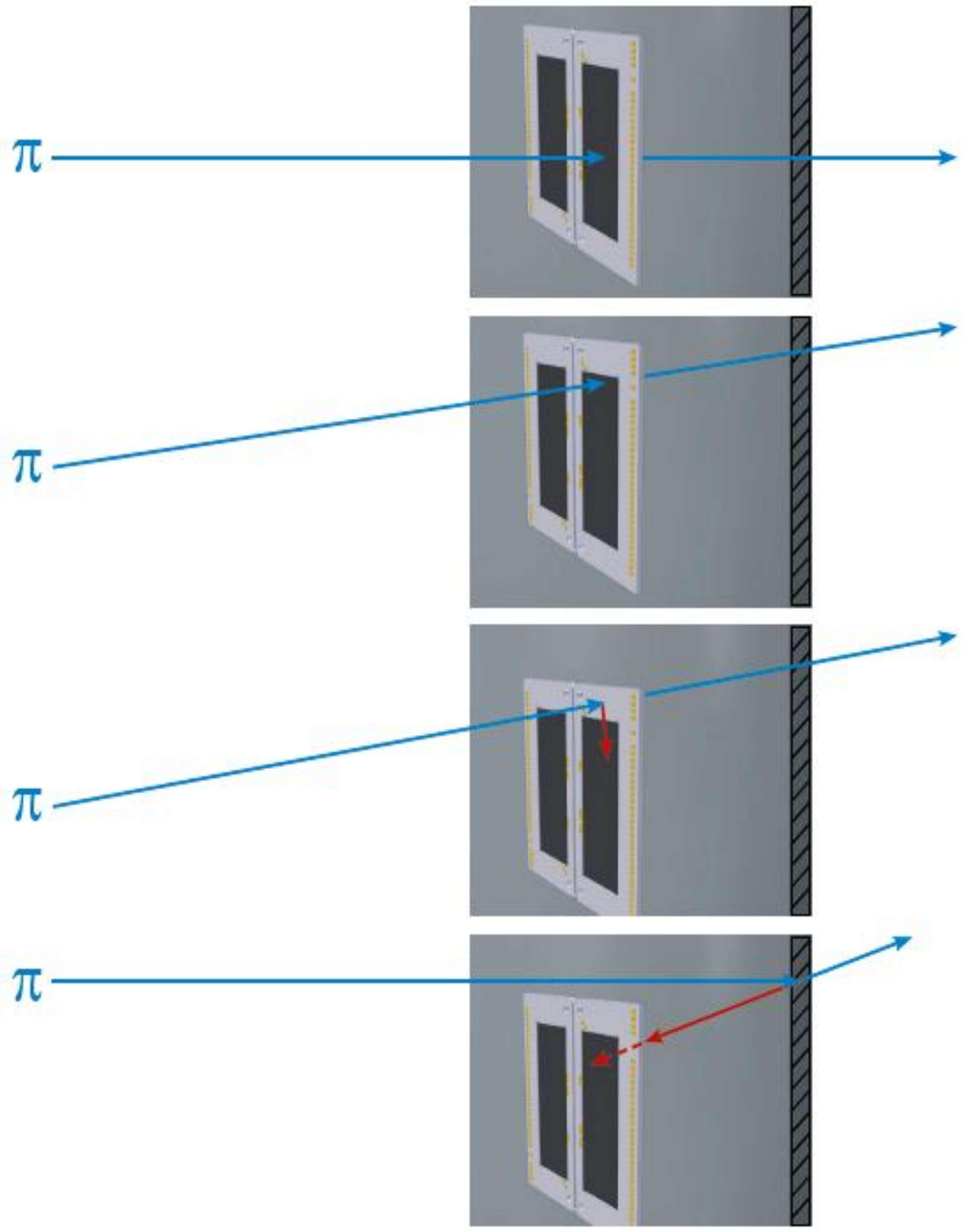


-60<Z<60



70<Z<130

Charged particle VETO on SDDs using CDC

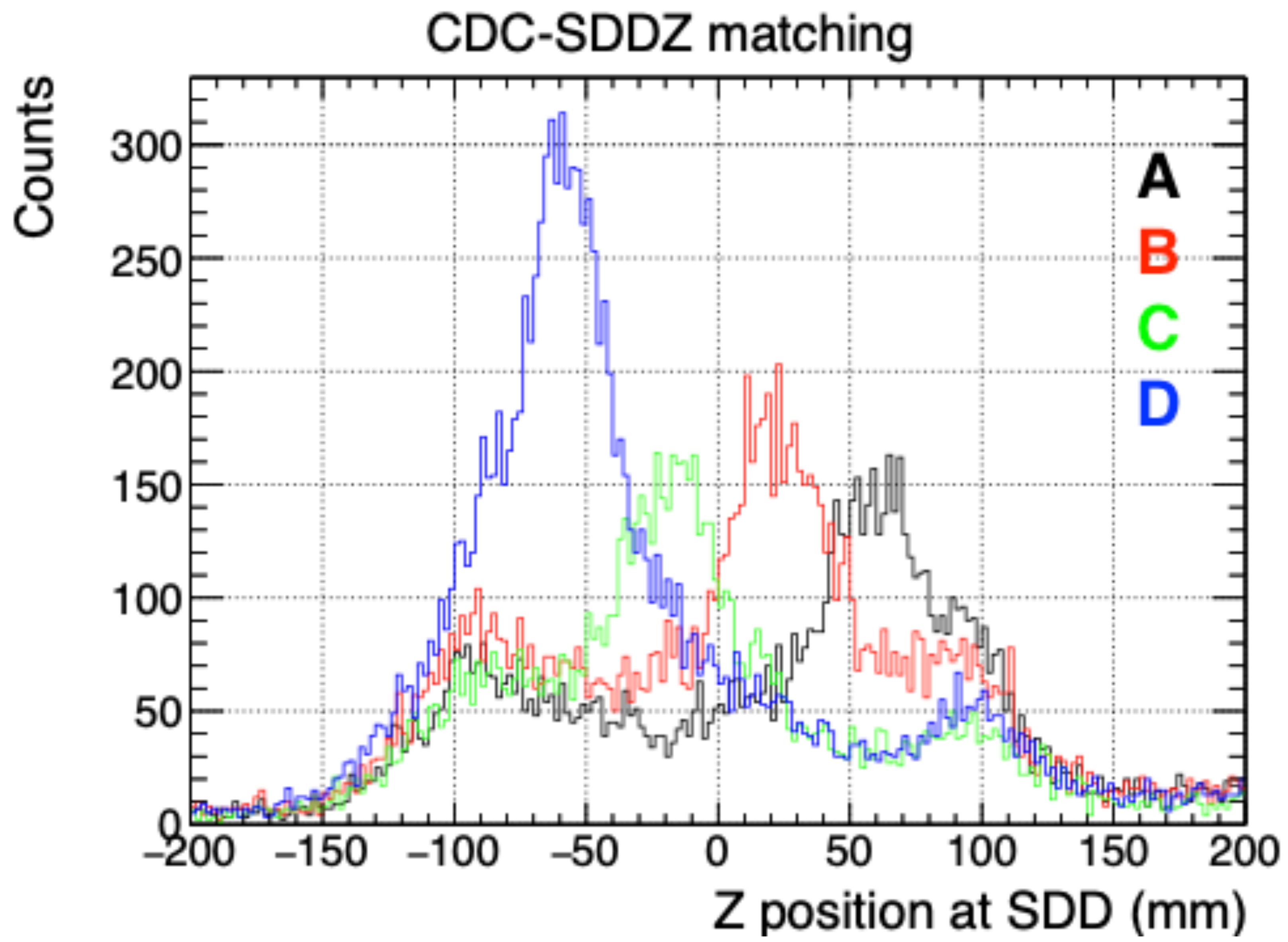


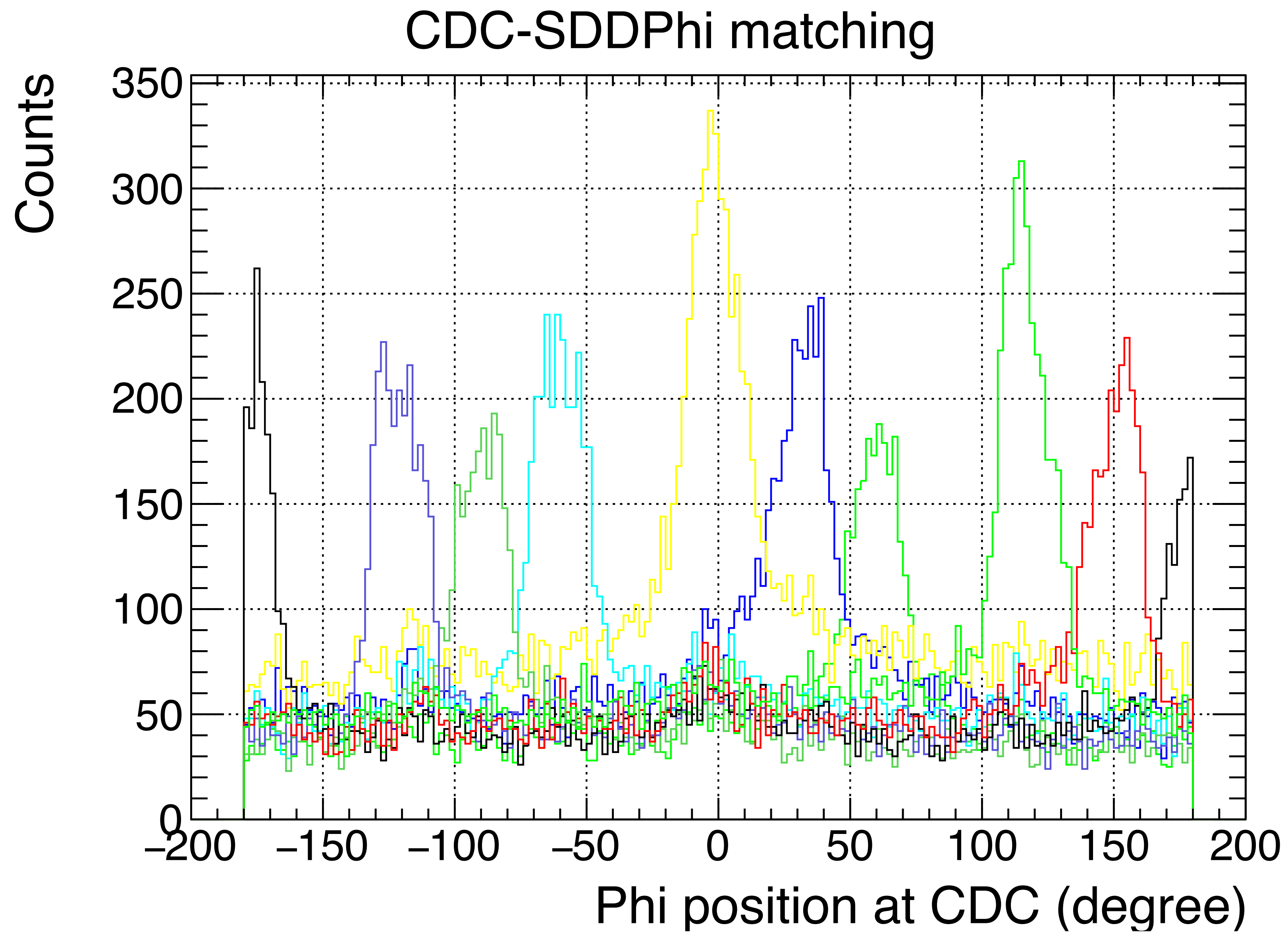
MIP traversing SDD at some distance from the edge → large signal > 150 keV

MIP traversing SDD at the edge of the active area → small signal

electron from secondary produced near the SDD

X-ray or electron from secondary produced in the setup



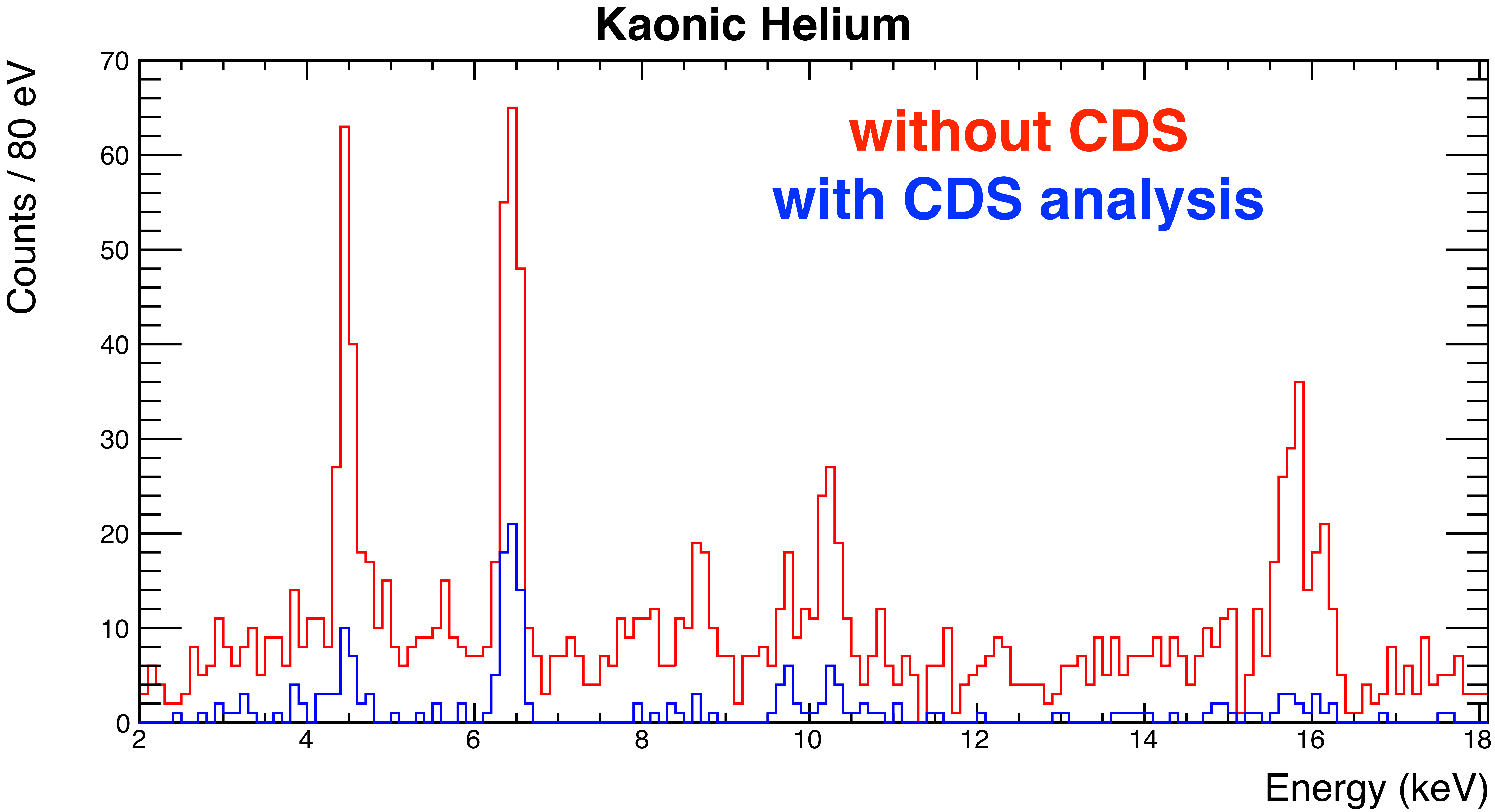


Correlation between the CDC charged track and the SDD position was clearly observed

→ **We can remove charged particle events on SDDs**

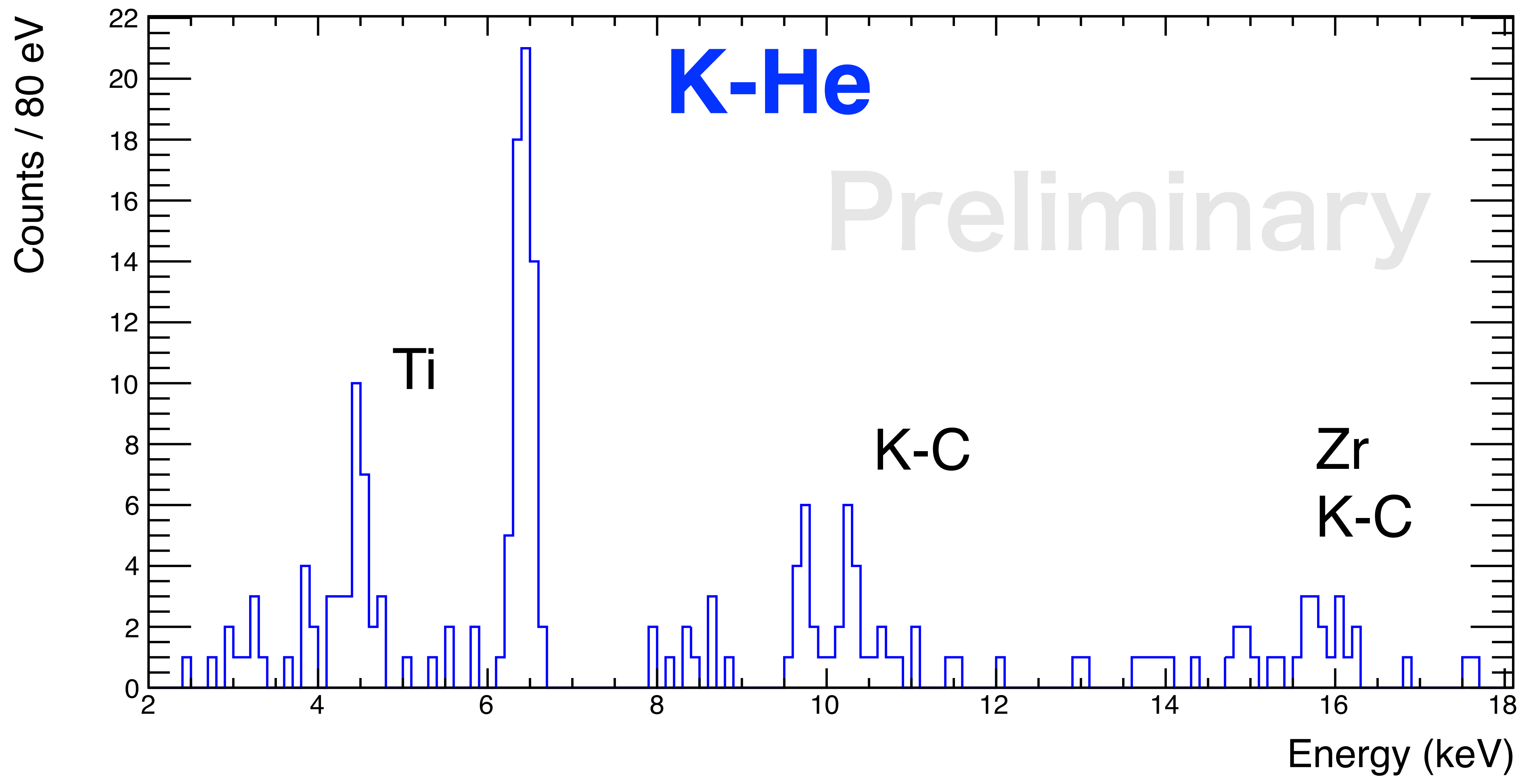
Helium data in E57

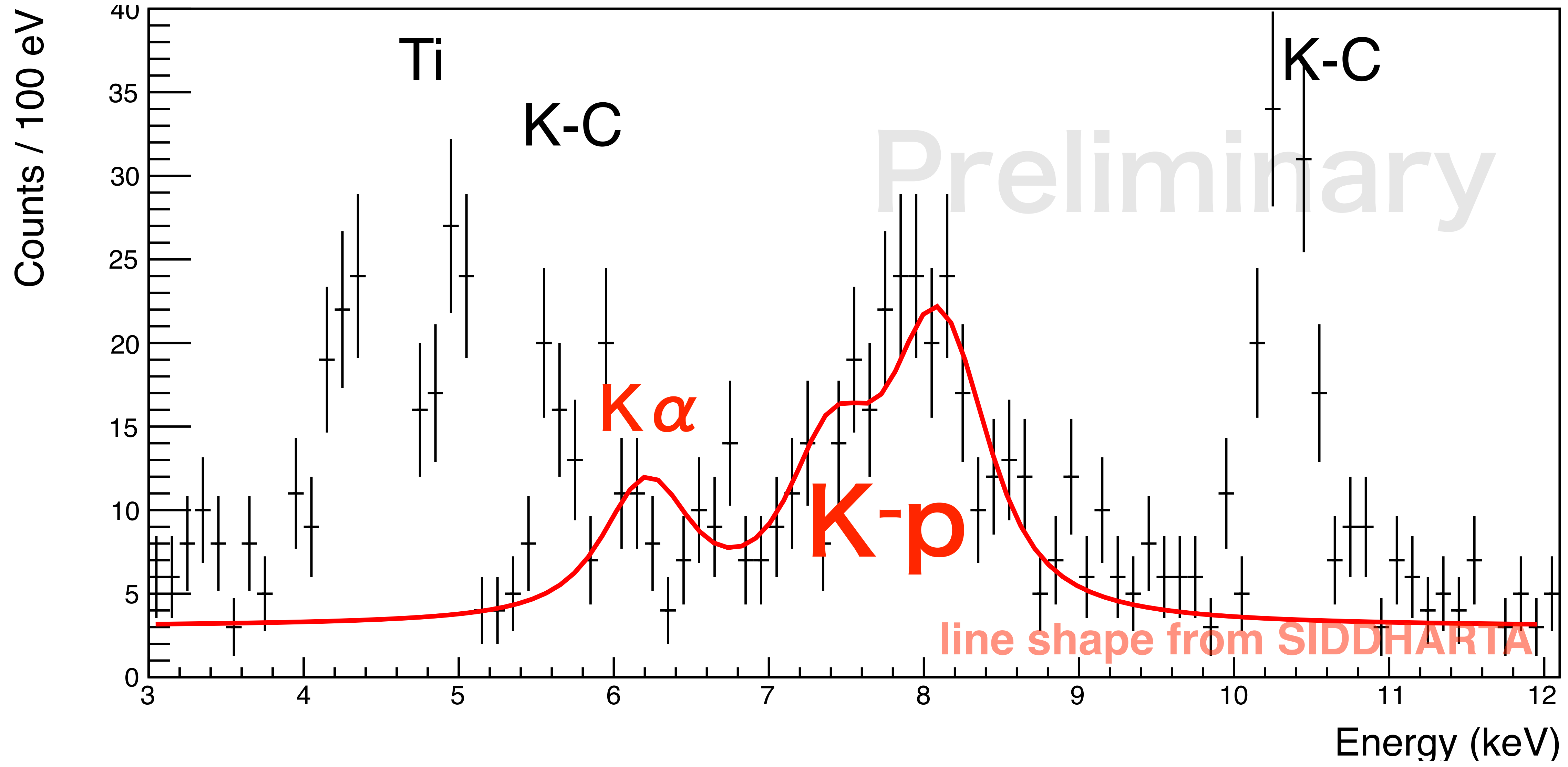
~6 hour data taking



- Almost all background are rejected with a reasonable signal loss

Results of E57 test run in 2019





He target: ~6 hours

✓ almost background free as designed

H_2 target: ~4 days

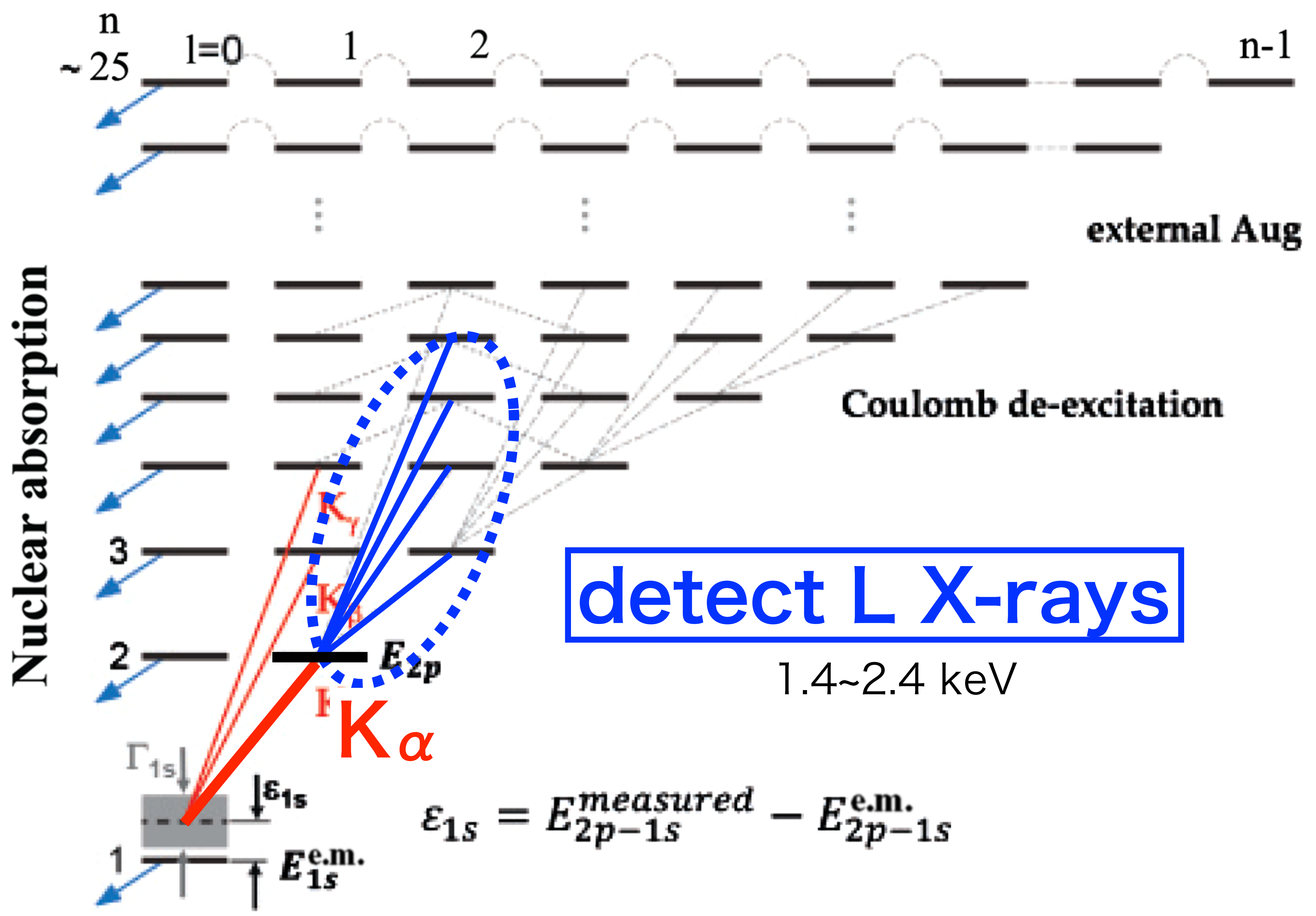
✓ Higher transitions are observed.

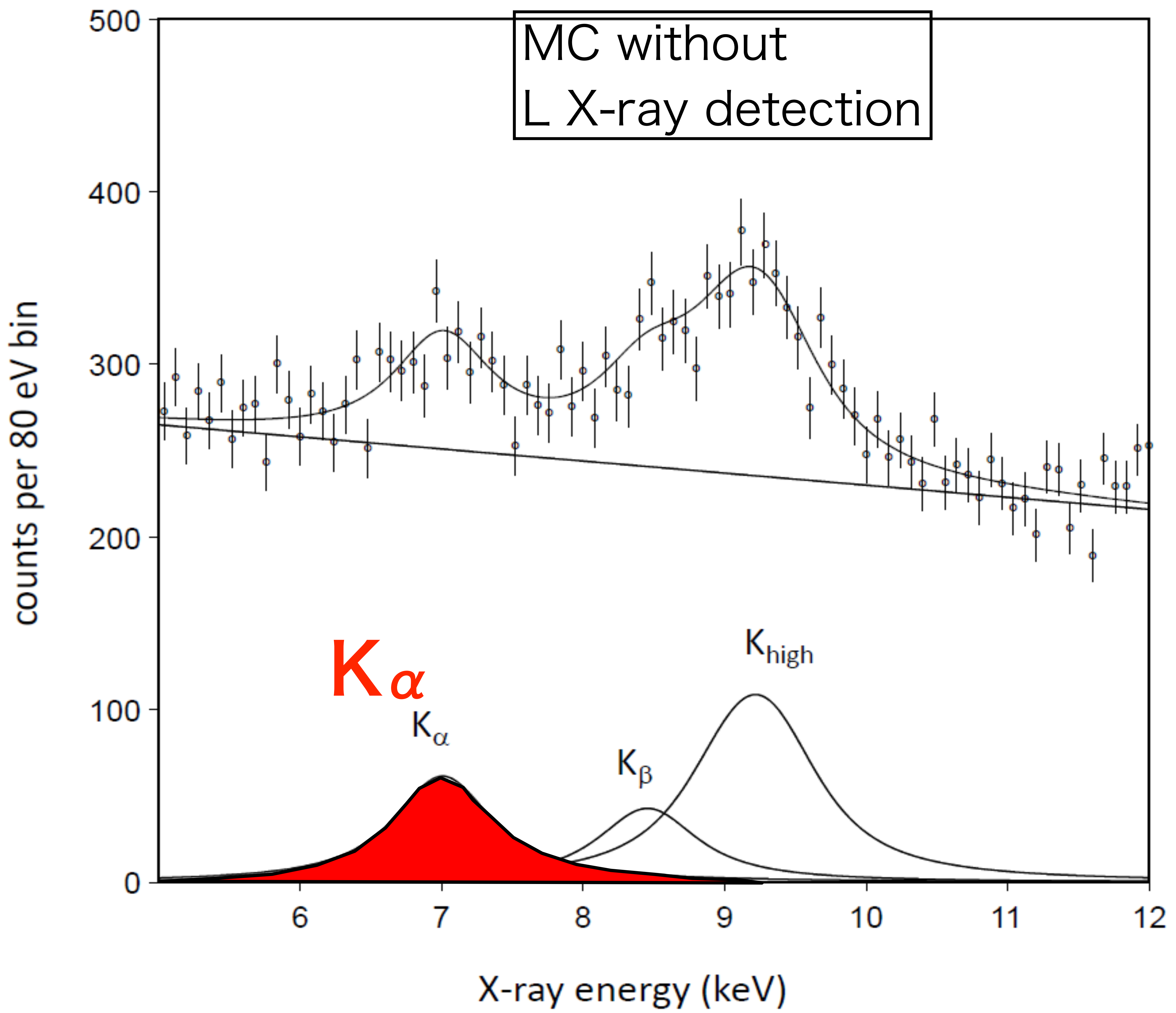
x no clear Kα peak

x Low yields

Meanwhile, SIDDHARTA2 started data taking

Updated strategy: X-ray coincidence

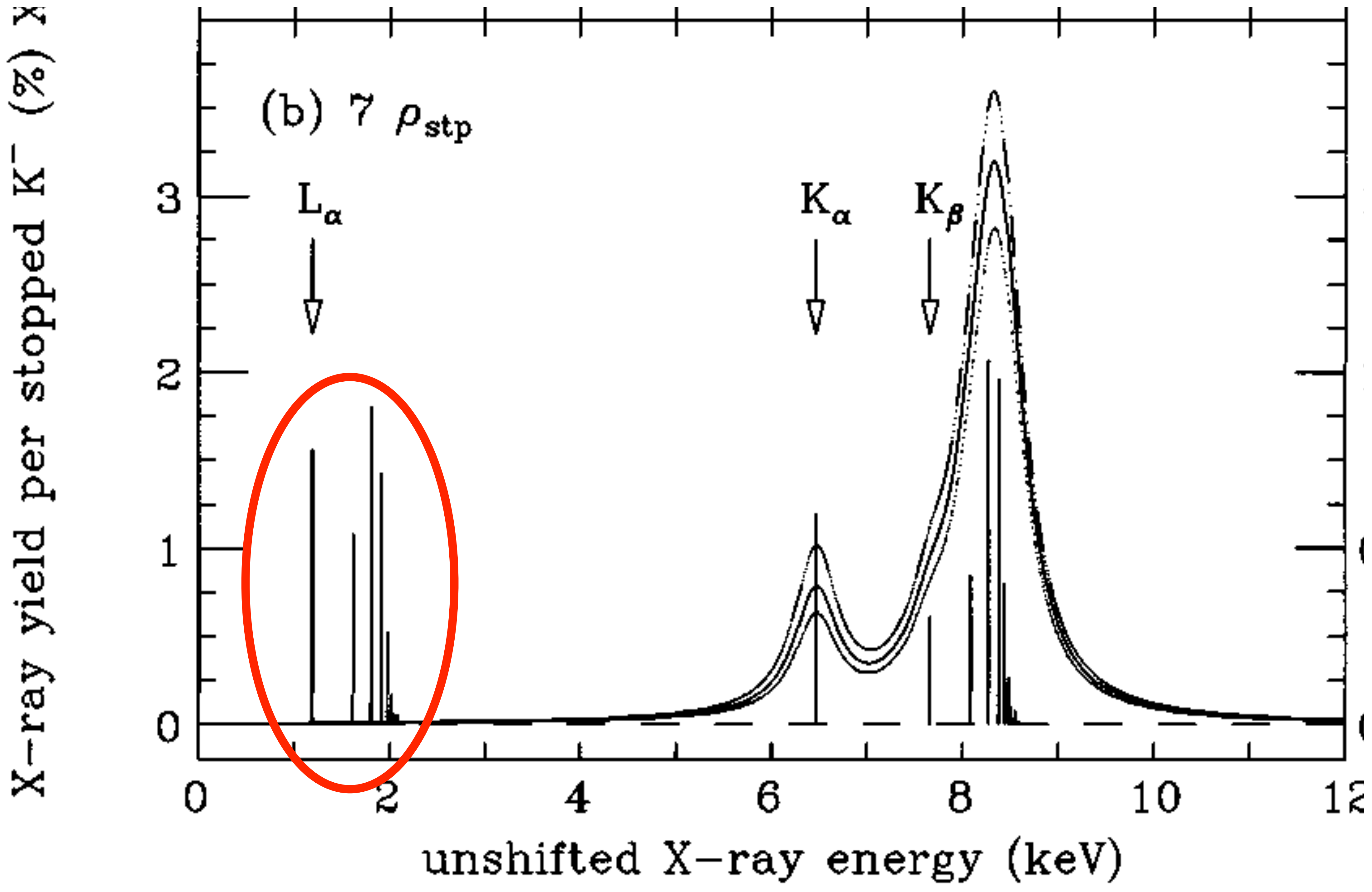


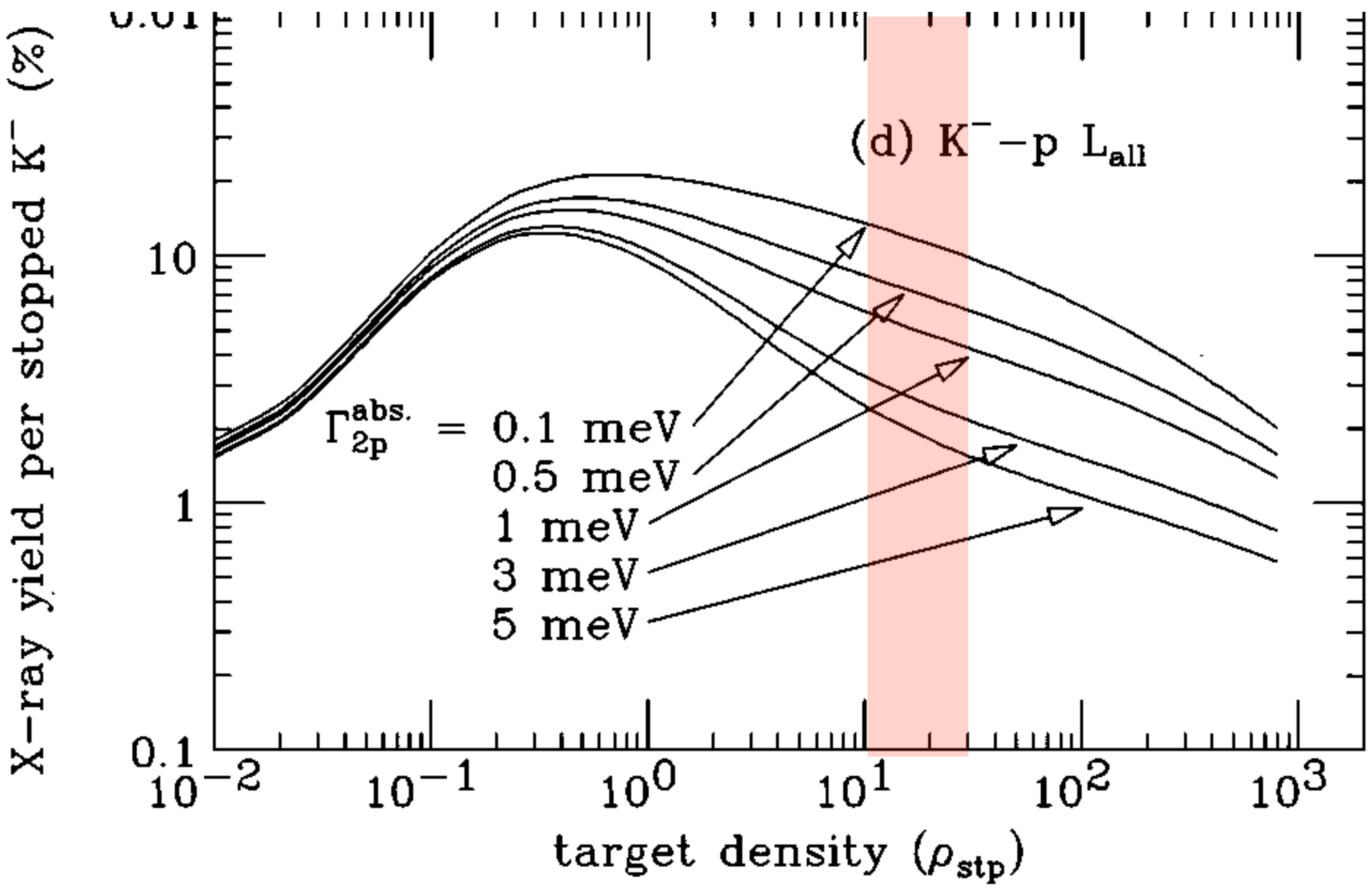


✓ Drastic background reduction
by detecting K and L X-rays in coincidence

L X-rays in kaonic hydrogen

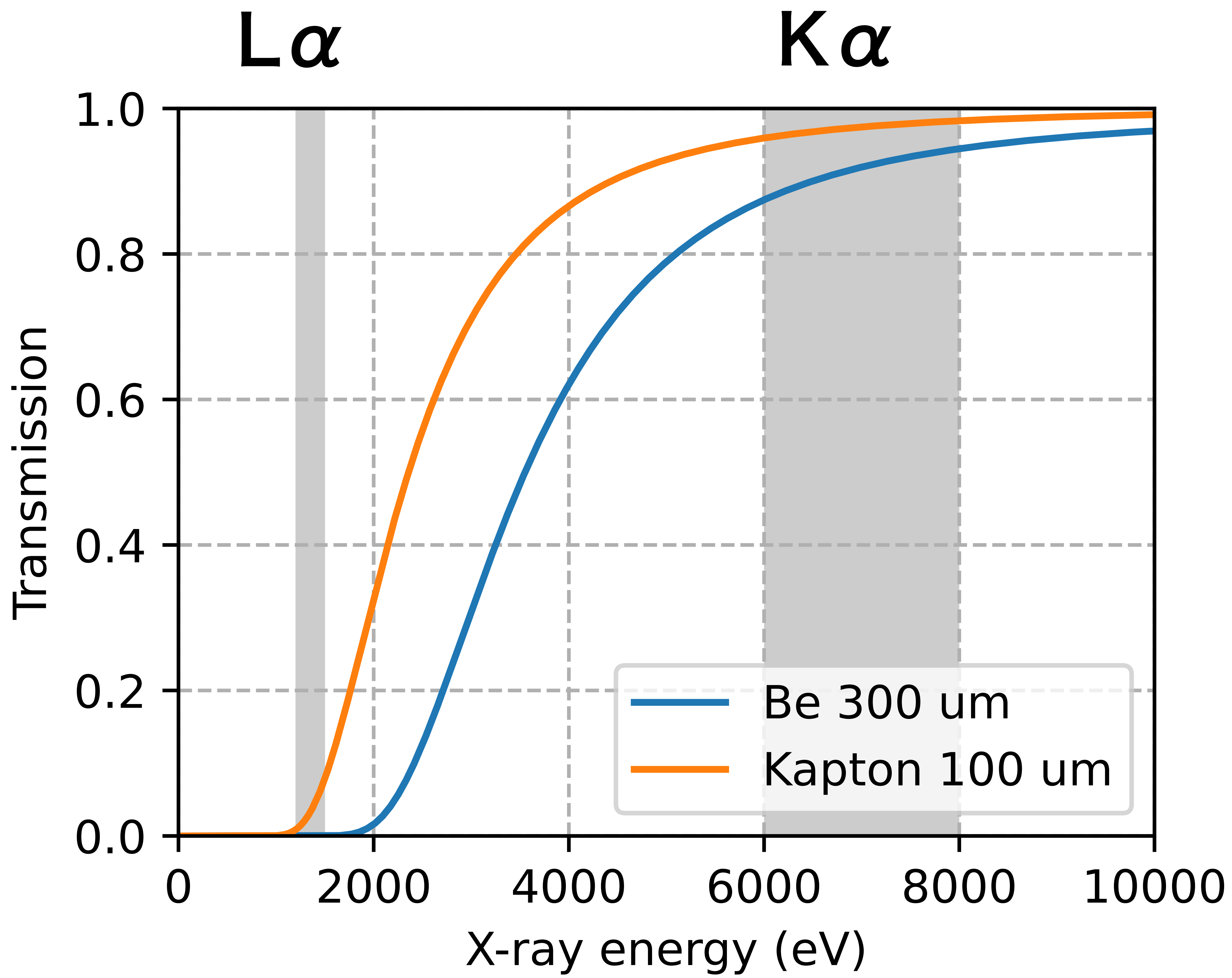
T. Koike PRC(1996)



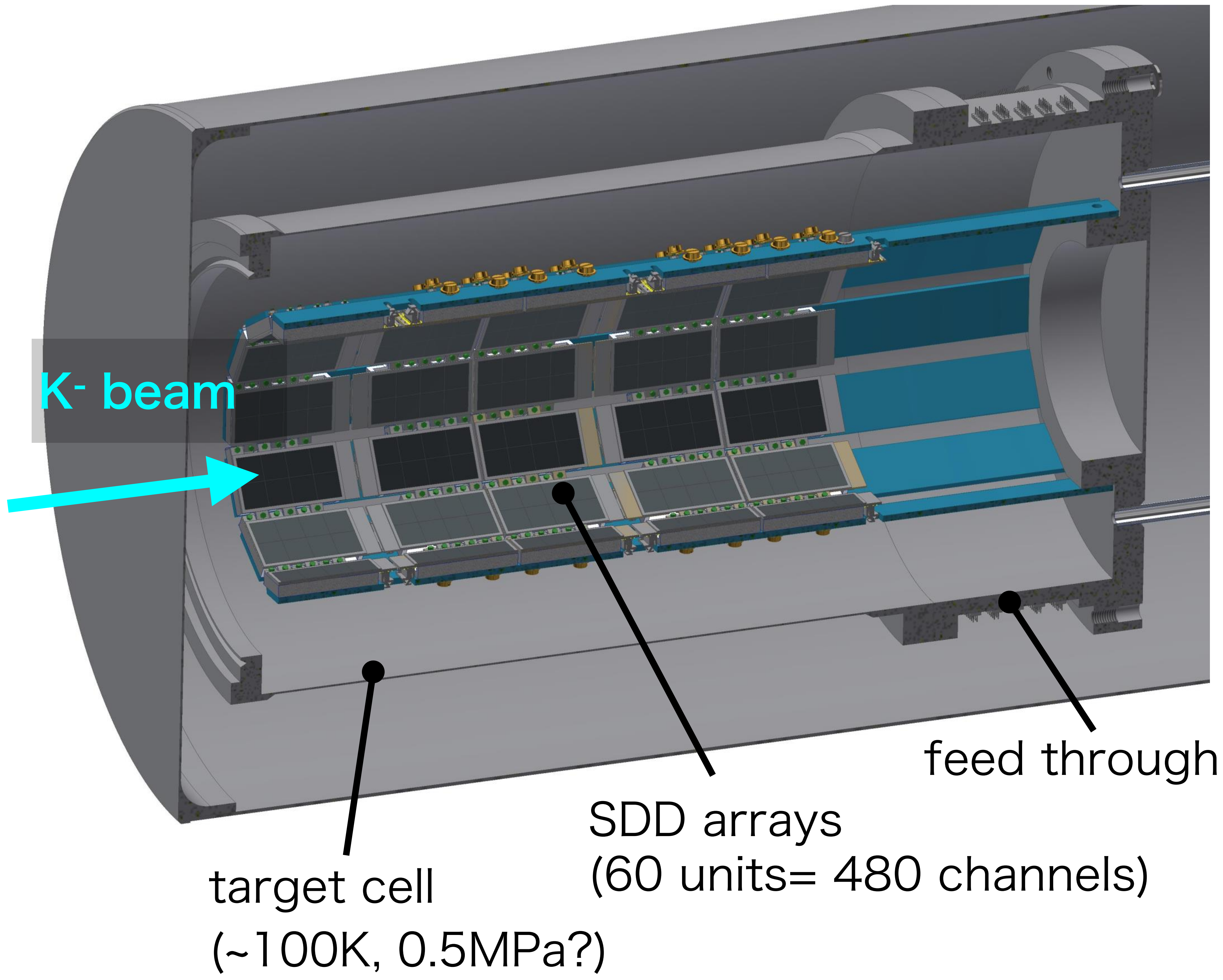


- L X-rays yield ~ 10% at most
- S/N at Kα can be improved at least by factor 10
- L X-ray measurement alone gives additional information (Γ_{2p}, cascade …)

SDDs inside the target gas



typical X-ray window materials
absorb all L X-rays…

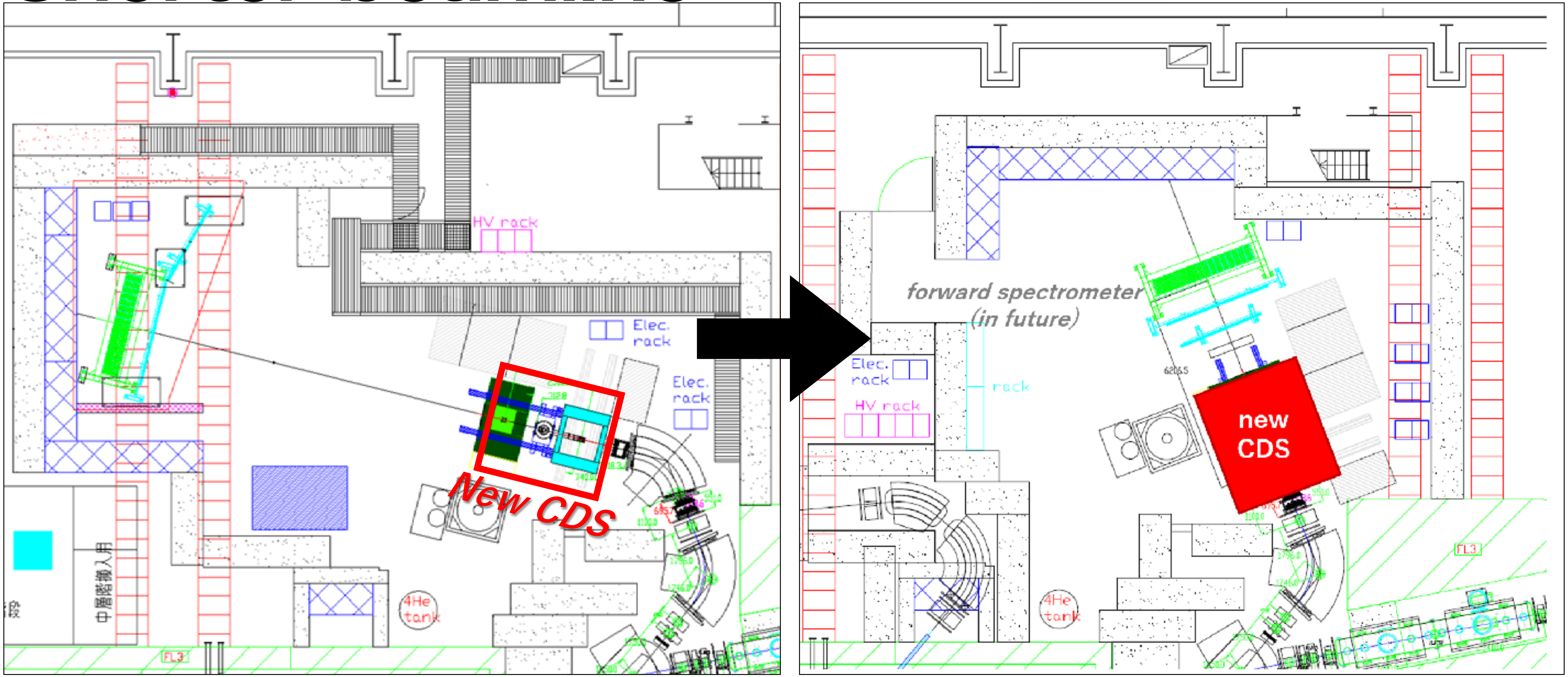


~40% single X-ray acceptance

~20% coincidence acceptance

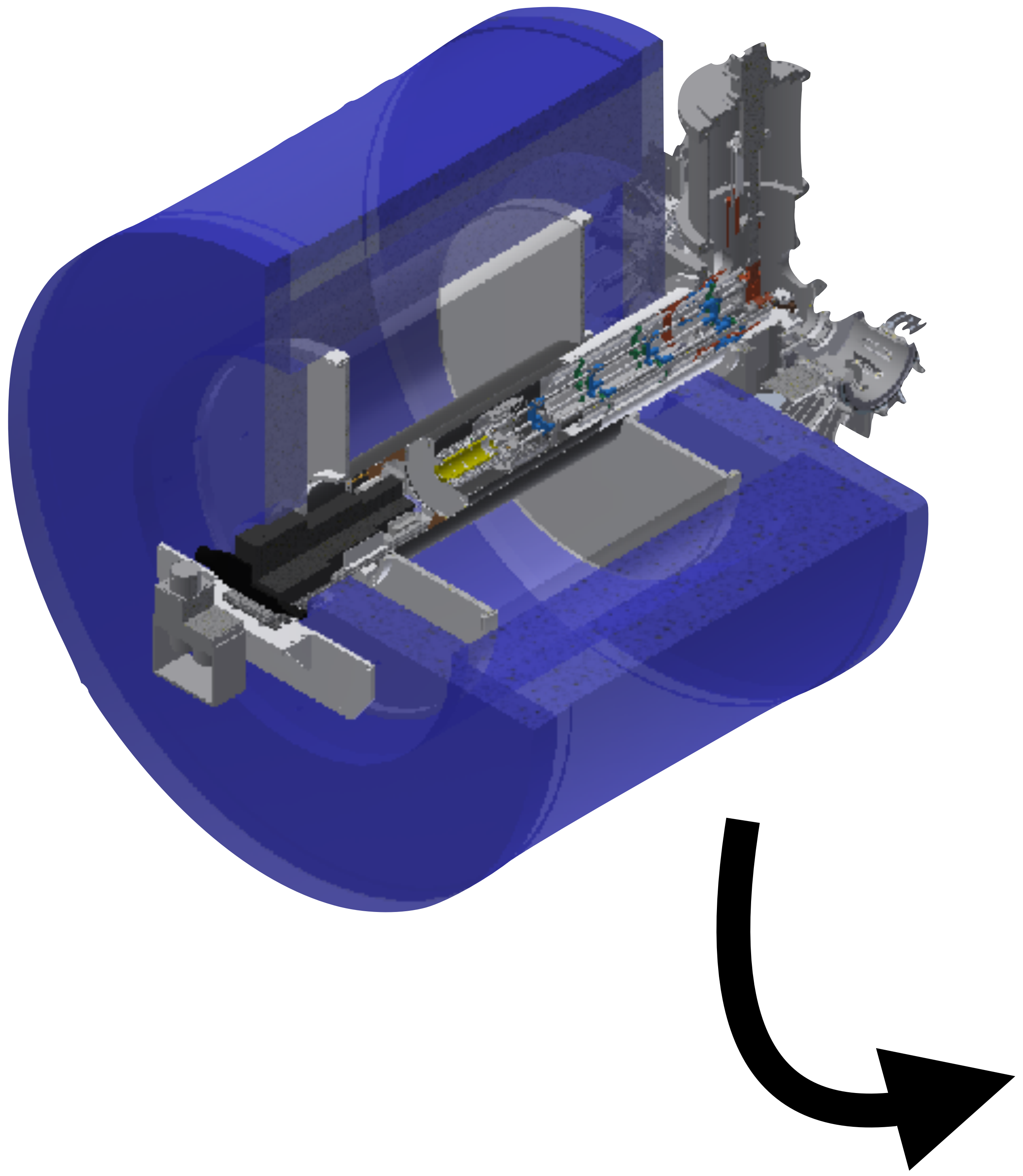
We have already succeeded in operating SDDs in a hydrogen (<10bar, 135K)
We started the discussion for new development of the active target cell

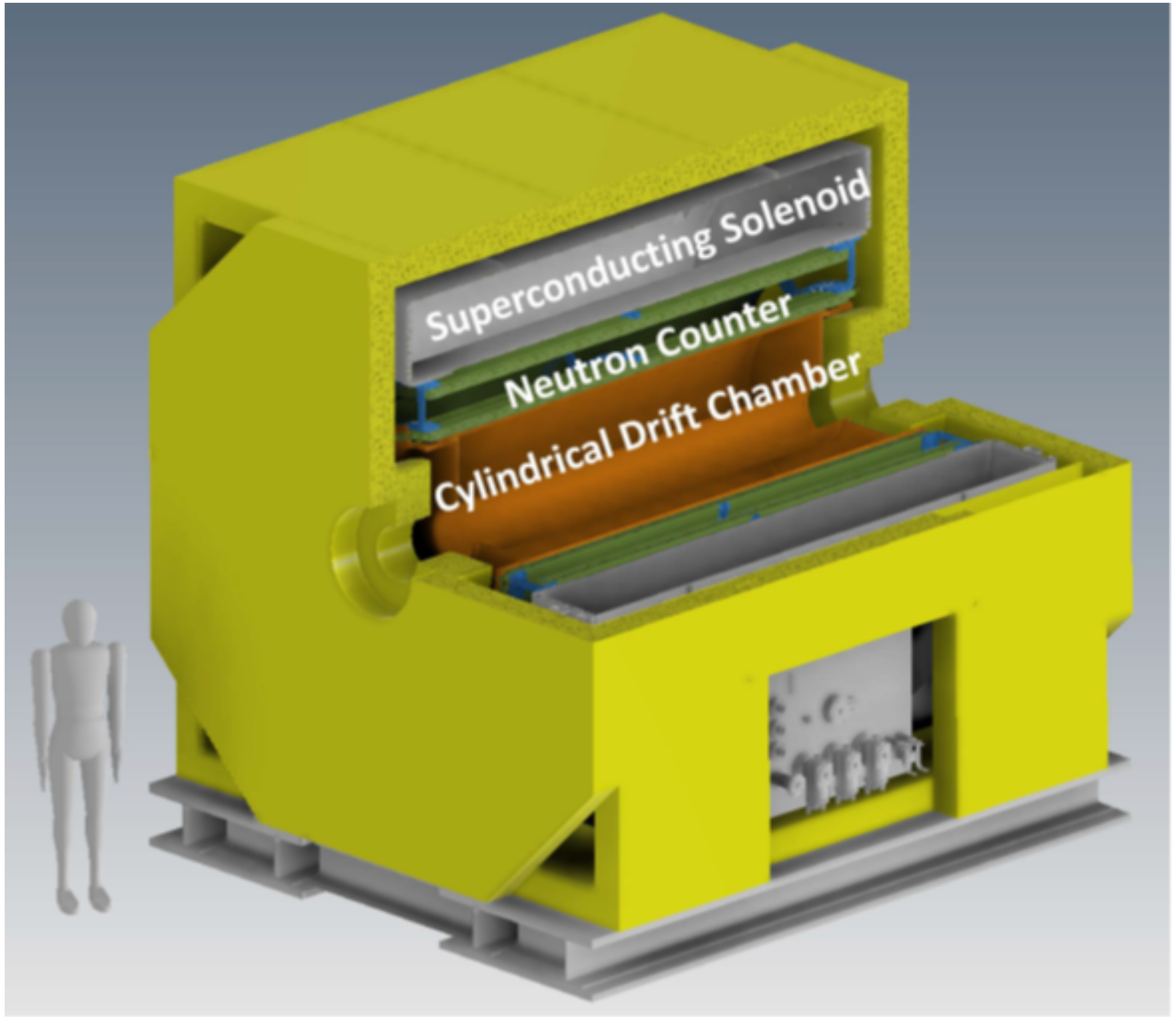
Shorter beamline



- ~4m shorter beamline can provide ~2x K^- @ 0.7 GeV/c

New CDS





- Need to extend the horizontal part of the target&SDD system
- 59%→93% solid angle for the secondary particles

Gain factors

D5 removal: shorter beam line, beam focus

new target configuration: target size R, L, target density, X-ray window

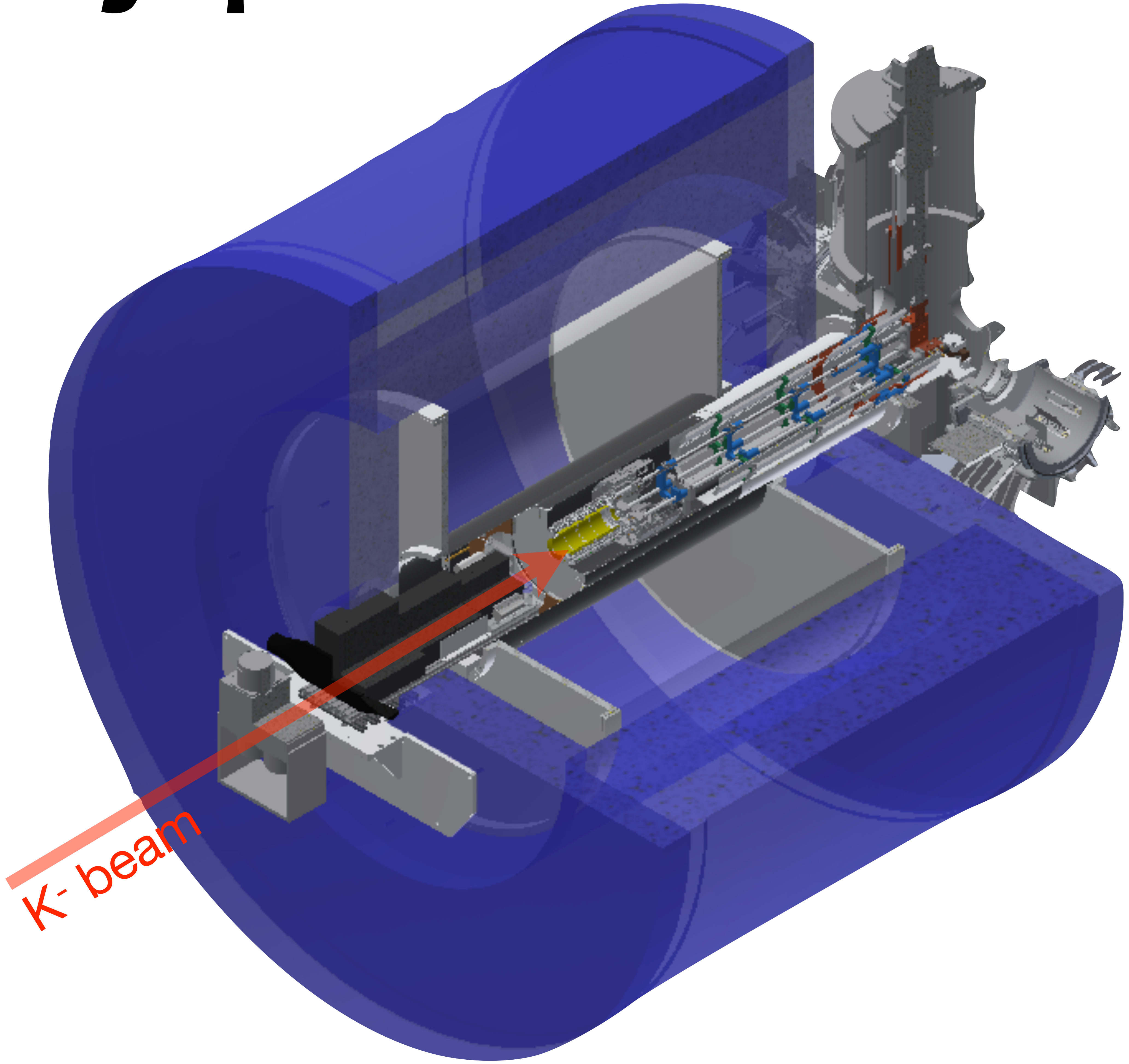
	present	upgrade	gain
shorter beam line	1.0	2.0	2.00
beam focus	1.0	1.5	1.50
target size R	625.0	1225.0	1.96
L	160.0	250.0	1.56
target density	4.0	2.0	0.50
beam intensity	50.0	80.0	1.60
beam time	3.2	4.0	1.25
X-ray yield	0.7	1.0	1.43
X-ray window	0.8	1.0	1.25
total			16.41

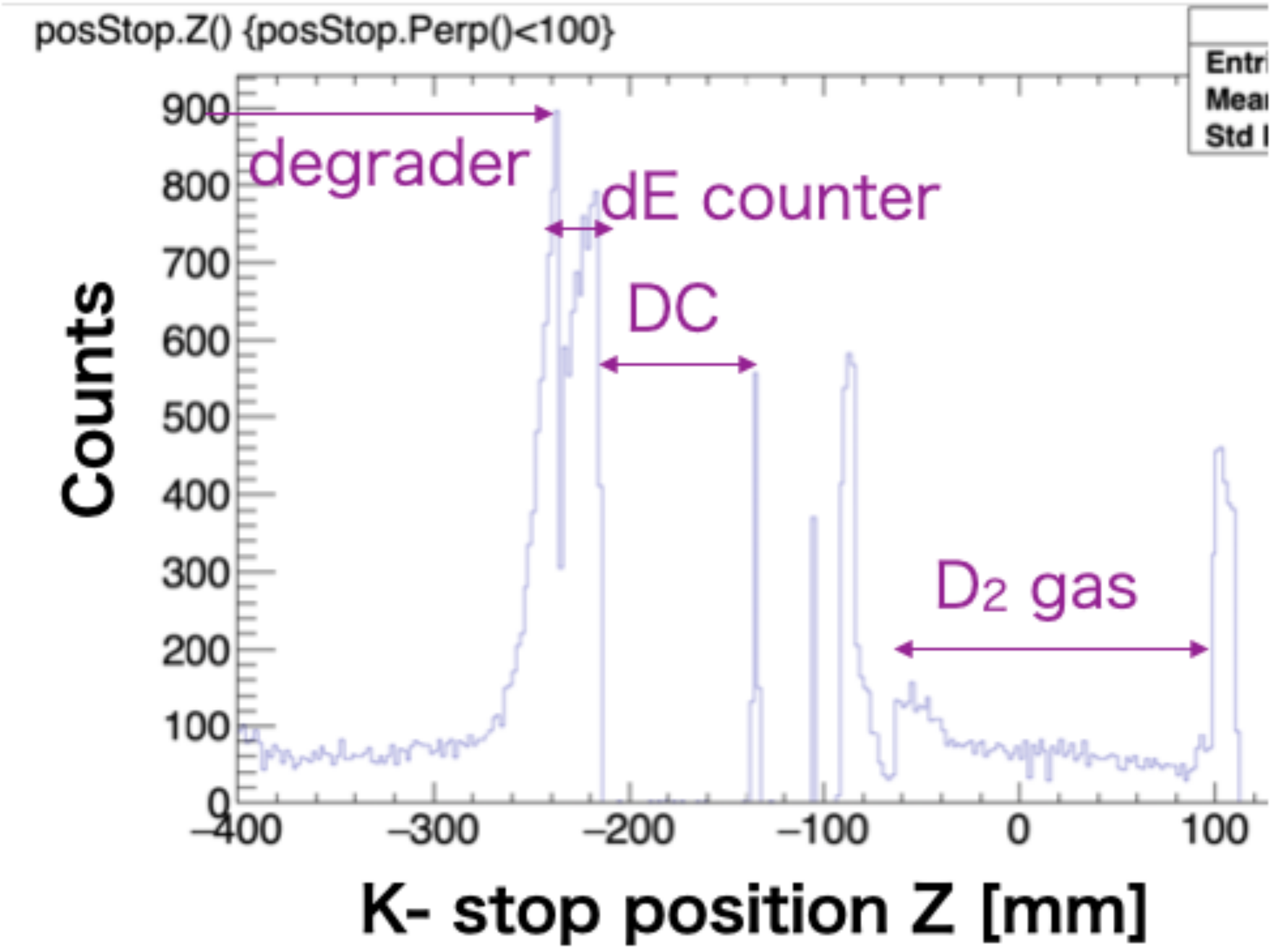
combined factor
rough estimation
1.9

this MC:
<u>1.4 ~ 2.4</u>
with 2019
beam profile

- 1000 events / 1 month beamtime is feasible for 0.1% X-ray yield

by-product with CdZnTe





- put CdZnTe detectors surrounding the degrader
- Kaonic C, S, Al, …

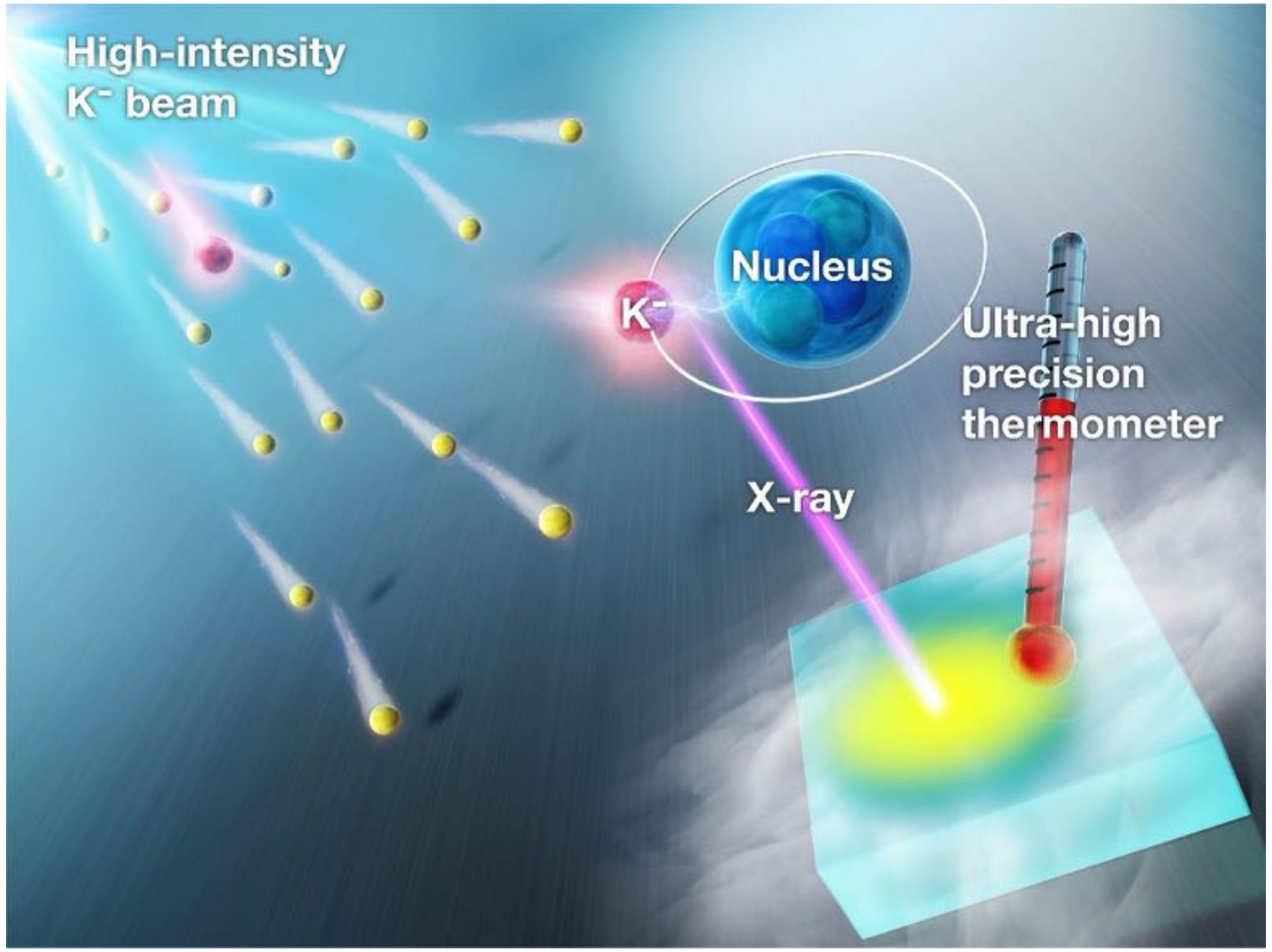
$K^{-3/4}$He X-rays with TES

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)

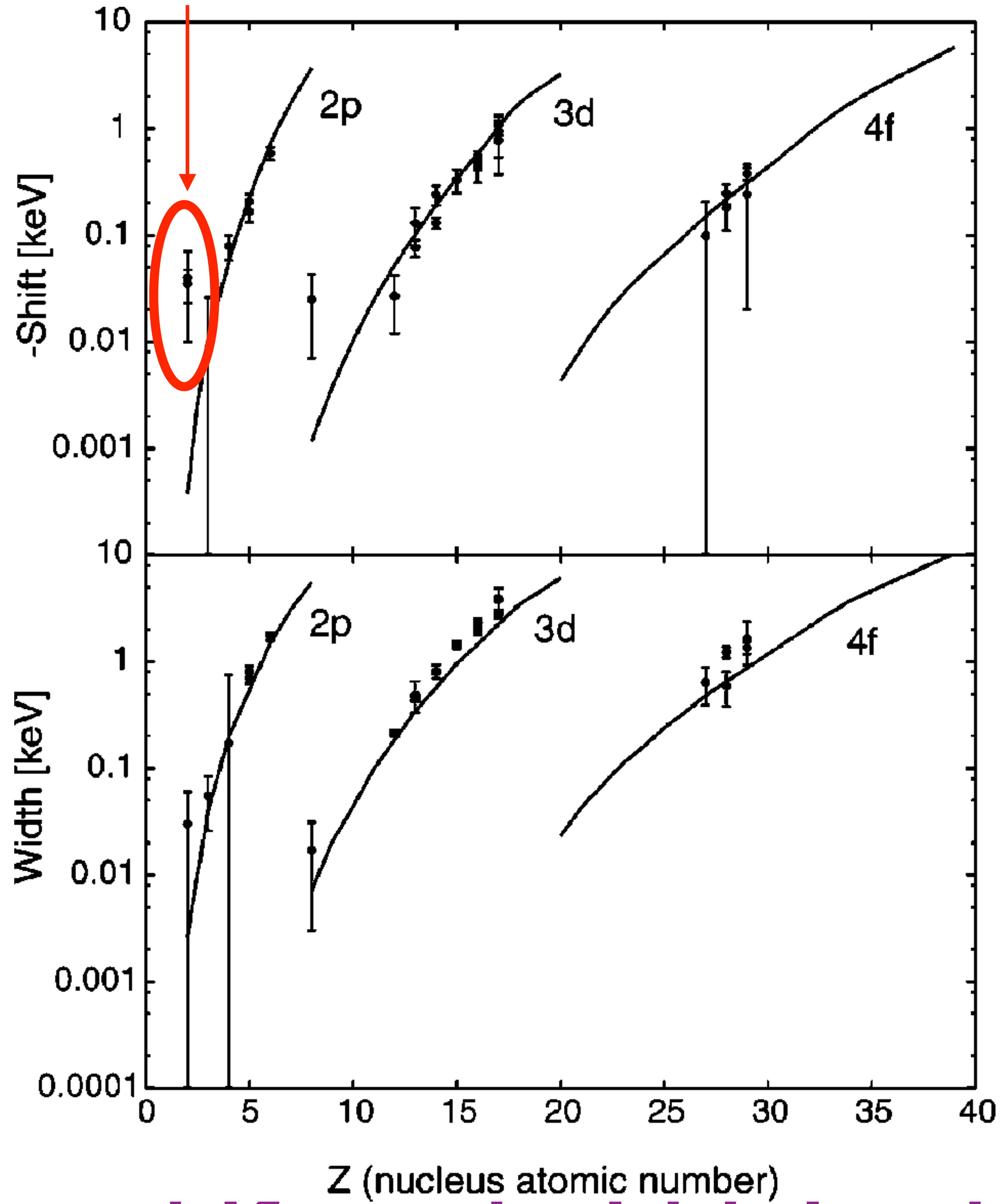


Hadoron physicists + TES experts + Astro physicists

“Kaonic helium puzzle”

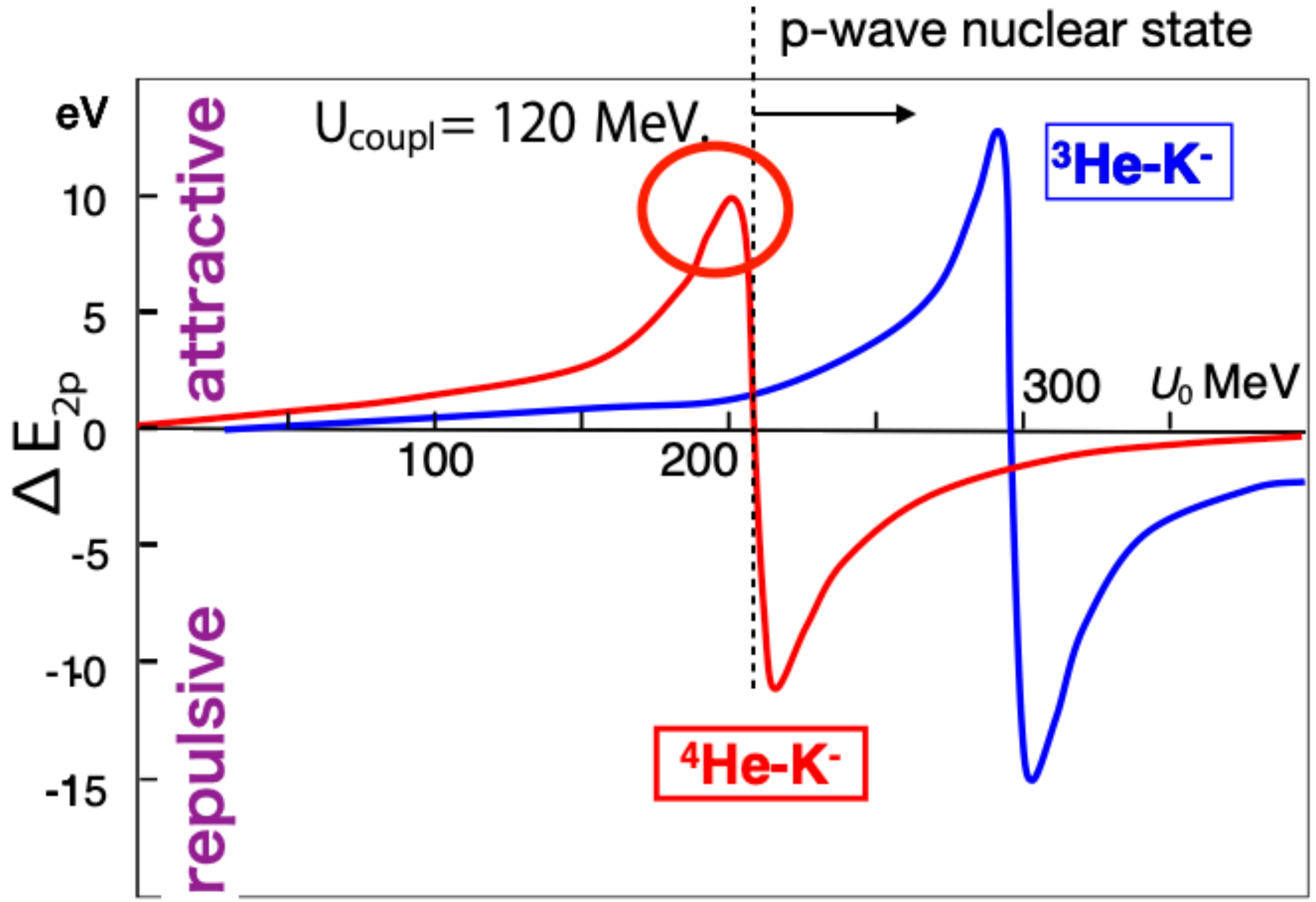
S. Hirenzaki et al., PRC 61, 055205 (2000)

anomalous shift   < 1 eV shift expected



Y. Akaishi, EXA2005 proceedings

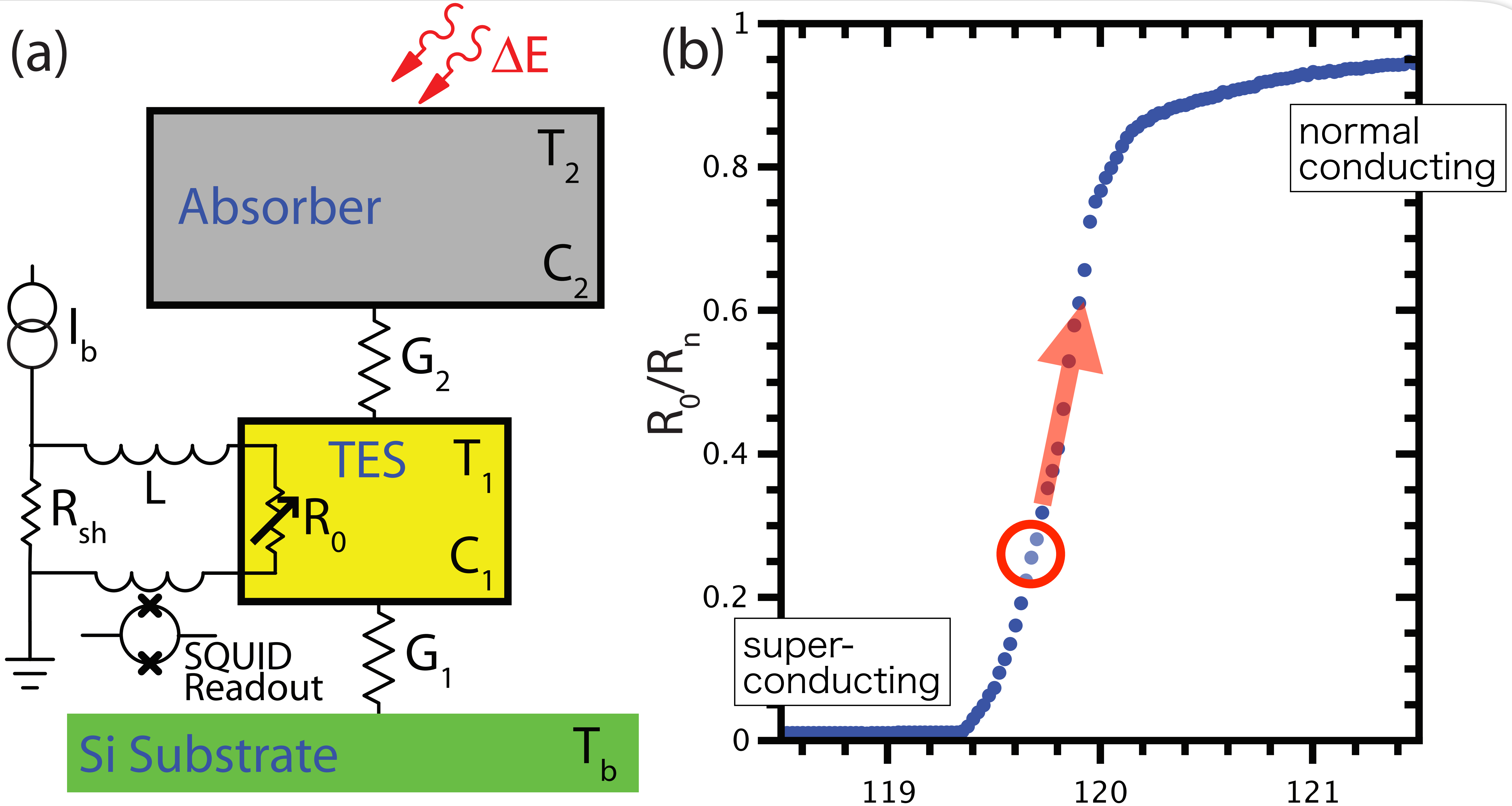
Possible explanation for the large shift



coupled-channel potential

- Large shift and width imply the generation of a p-wave nuclear state
- Need precision below 1 eV to draw a conclusion

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

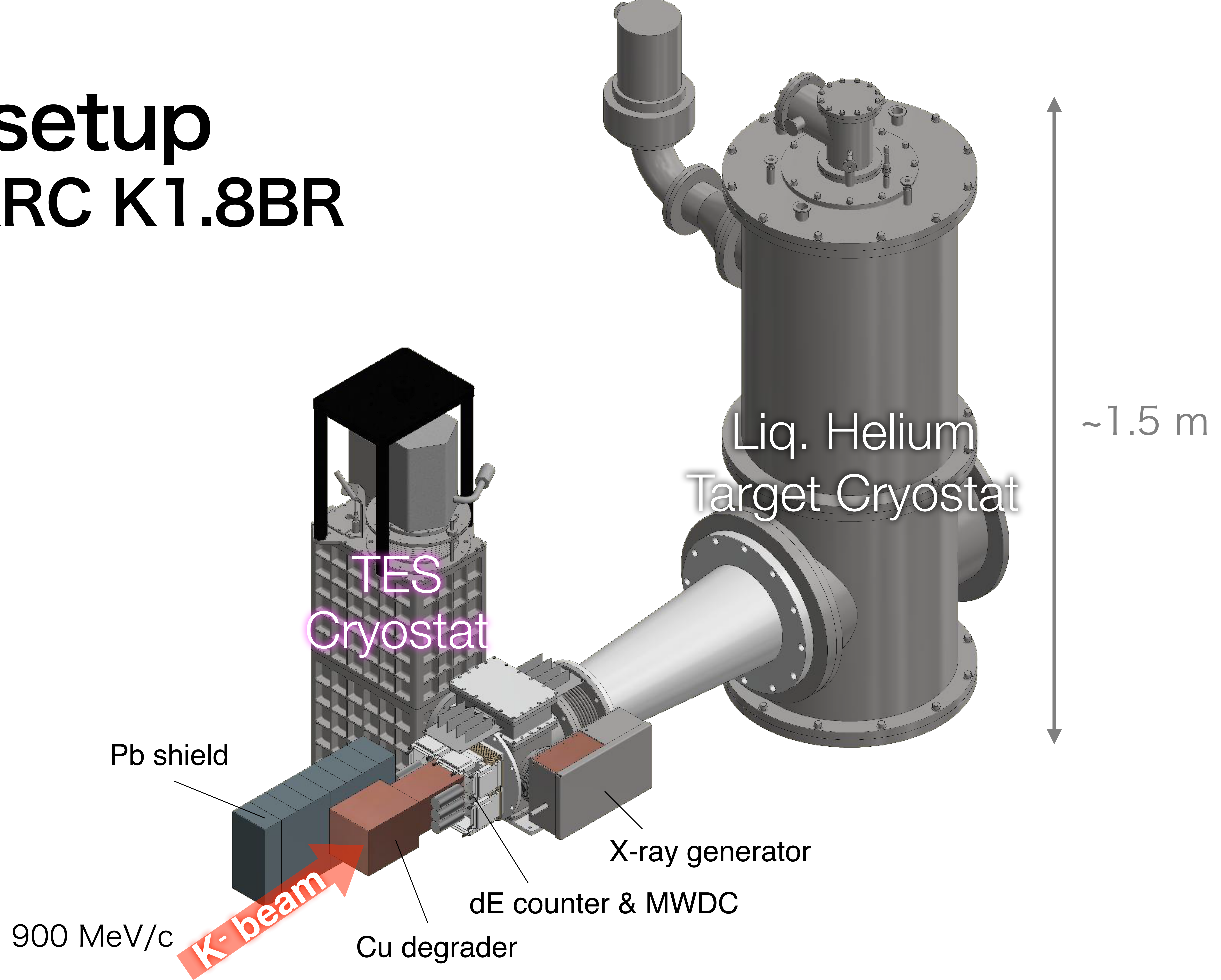
Variety of applications dependent on the detector parameters

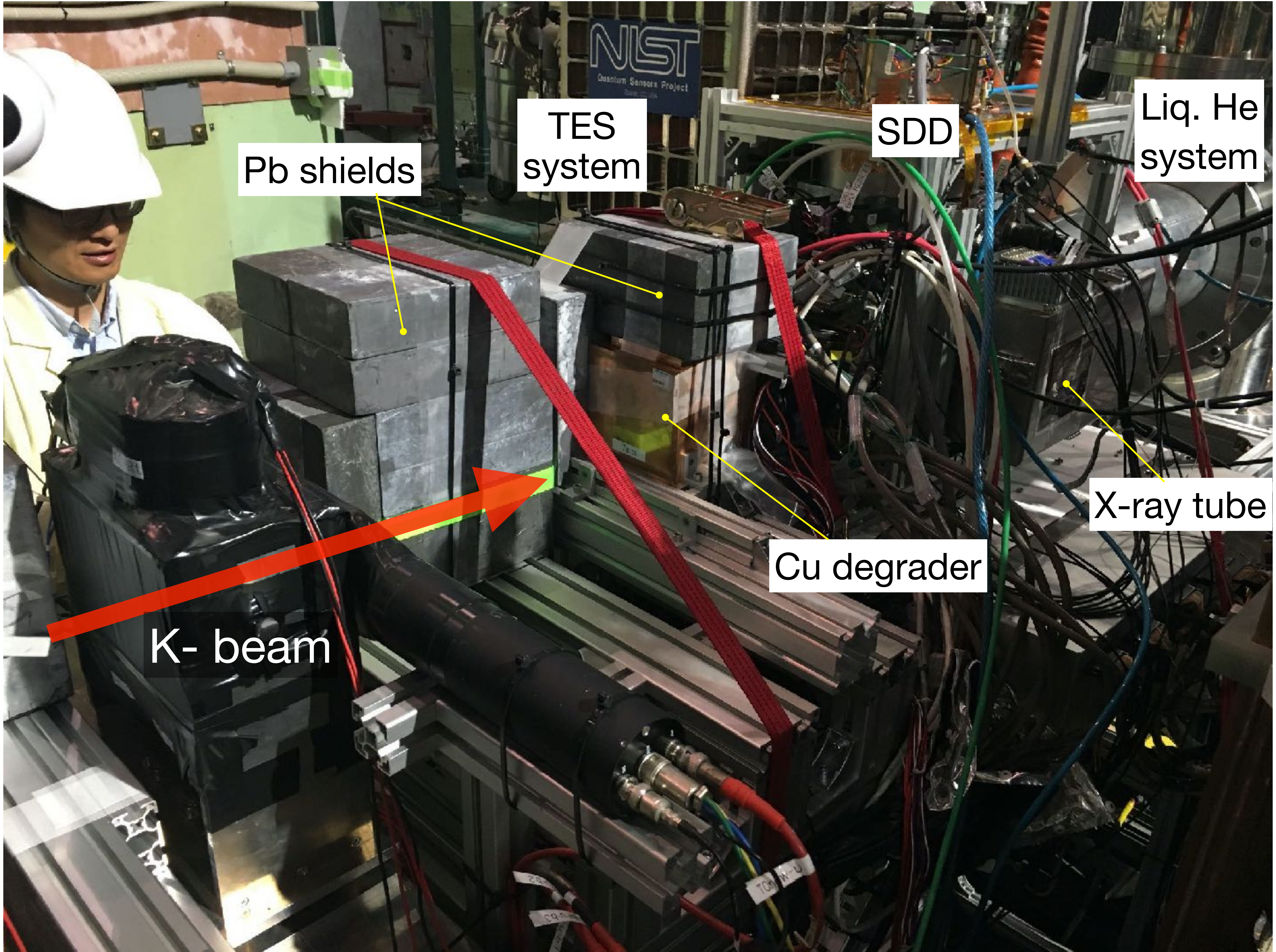

✓ 1 pixel : 300 x 320 um² (~ 0.1 mm²)
✓ Mo-Cu bilayer TES
✓ 4-μm-thick Bi absorber (eff.~ 85% @ 6 keV)
Φ ~1 cm
✓ 240 pixels
✓ 23 mm² eff. area
NIST
photo credit:
D.R. Schmidt


J-PARC K1.8BR
beam dump
γ, n
p
beam sweeping magnet
15m
Liq. H2/D2/3/4He target system
neutron counter
charge veto counter
proton counter
CDS
K- beam
beam line spectrometer

E62@J-PARC K1.8BR

E62 setup
@J-PARC K1.8BR




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

TES (E62)

~6 eV (FWHM)

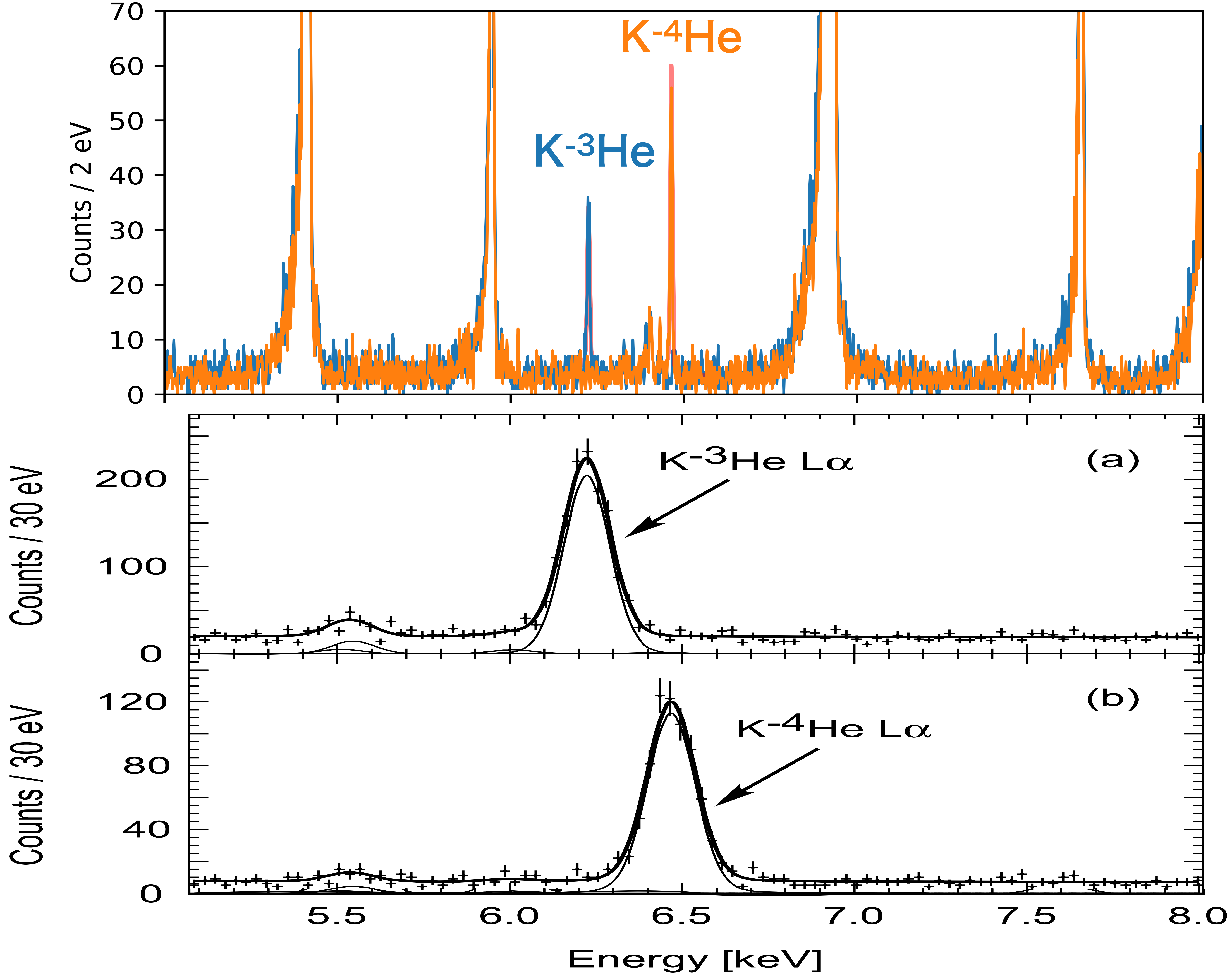
PRL128, 112503 (2022)

x25 better resolution

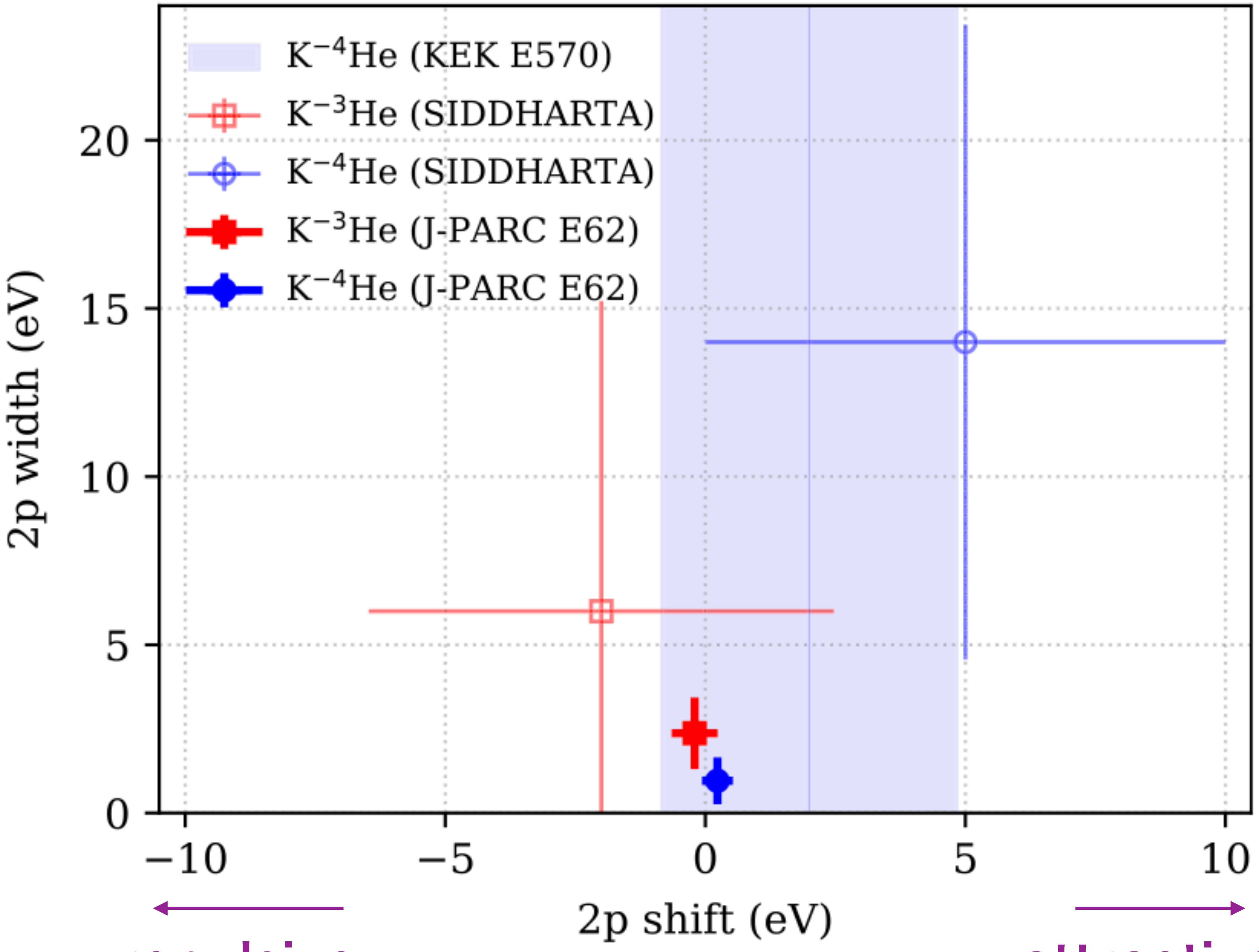
SDD (SIDDHARTA)

~150 eV (FWHM)

PLB714(2012)40



Theoretical study on the E62 results



repulsive ← → attractive

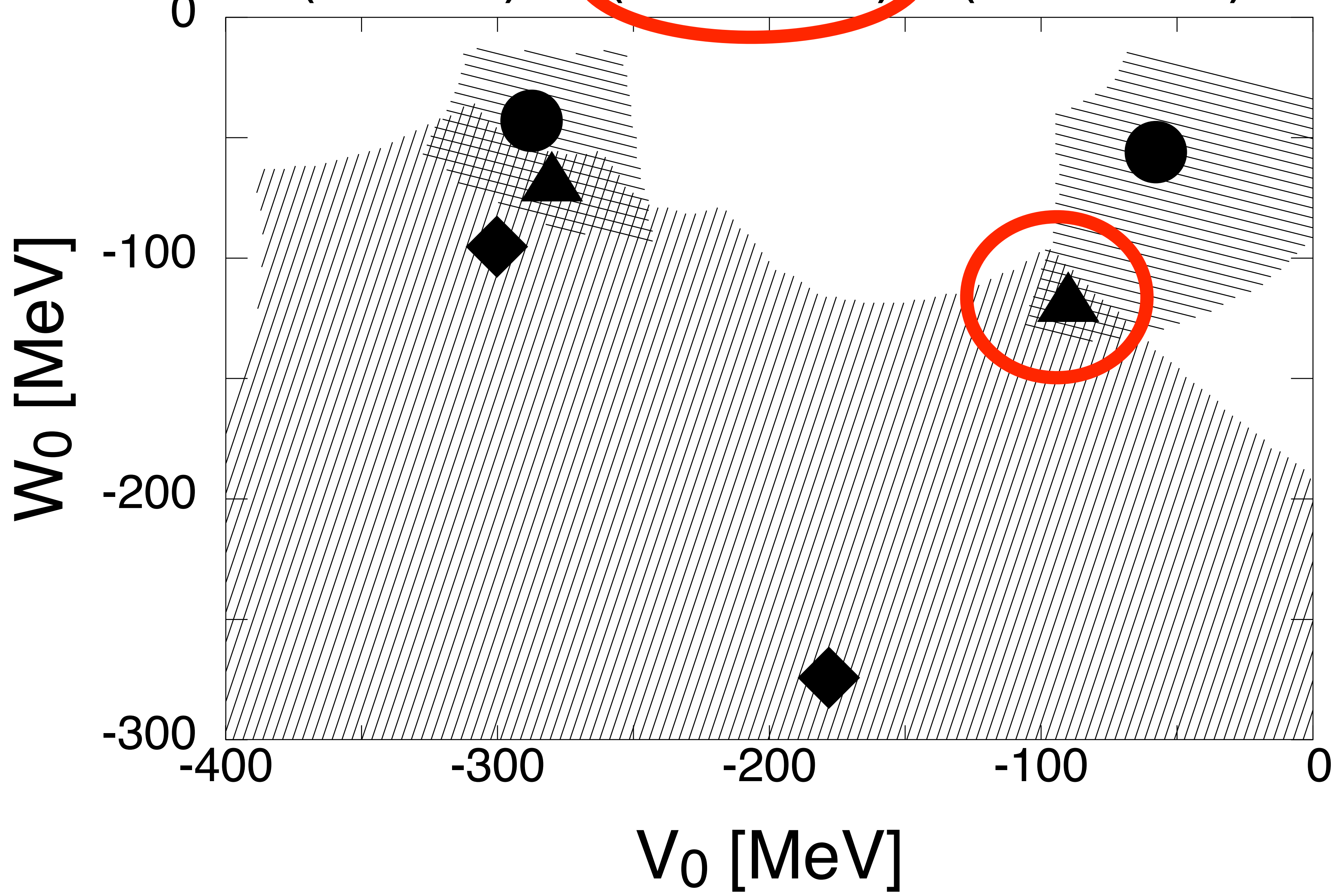
$$\Delta E = E_{exp.} - E_{EM}$$

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

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

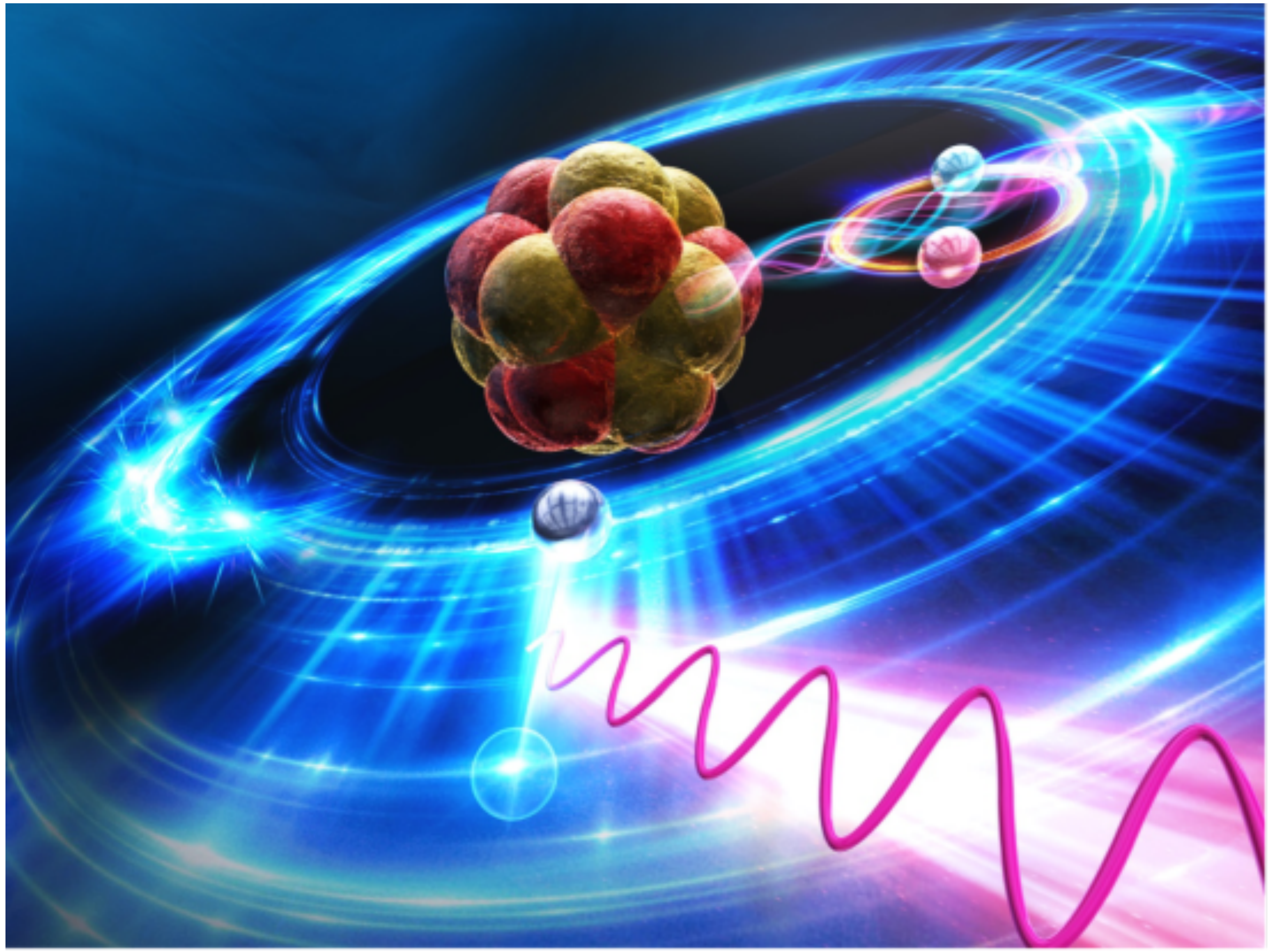
● ^{4}He ◆ ^{3}He

▲ (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

Muonic atoms with TES



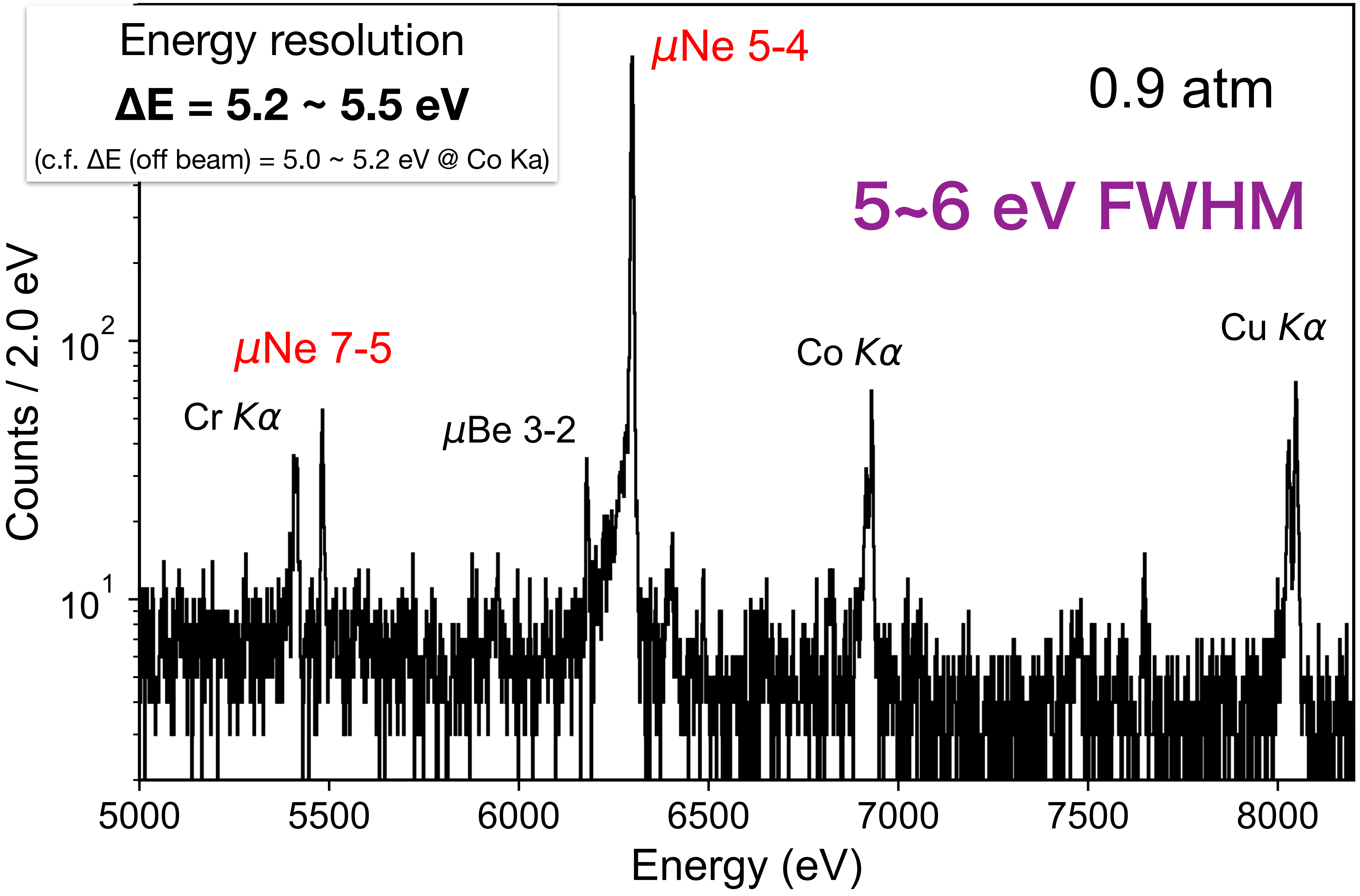
Muonic Ne atom 5→4

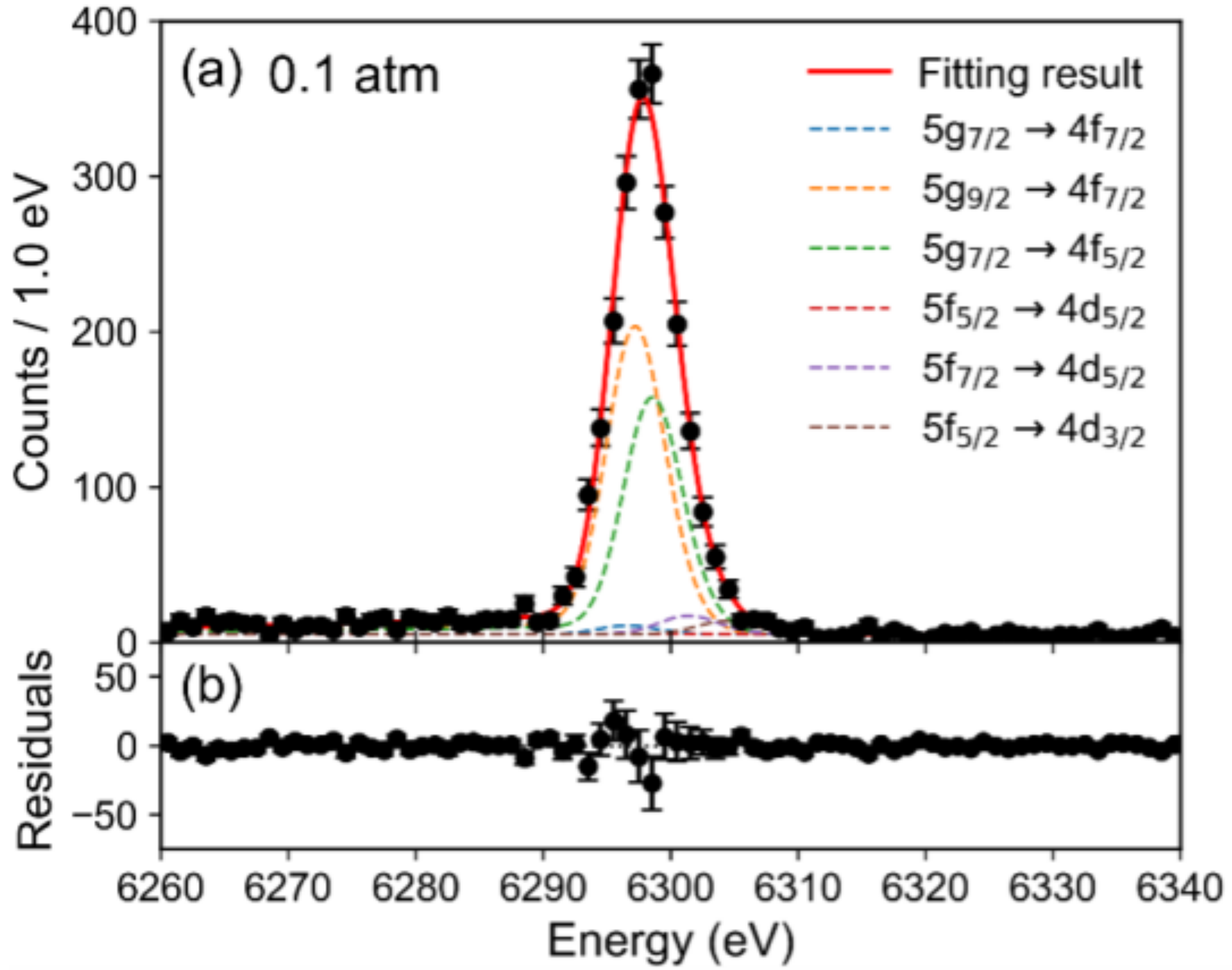
Phys. Rev. Lett. 130, 173001 (2023)

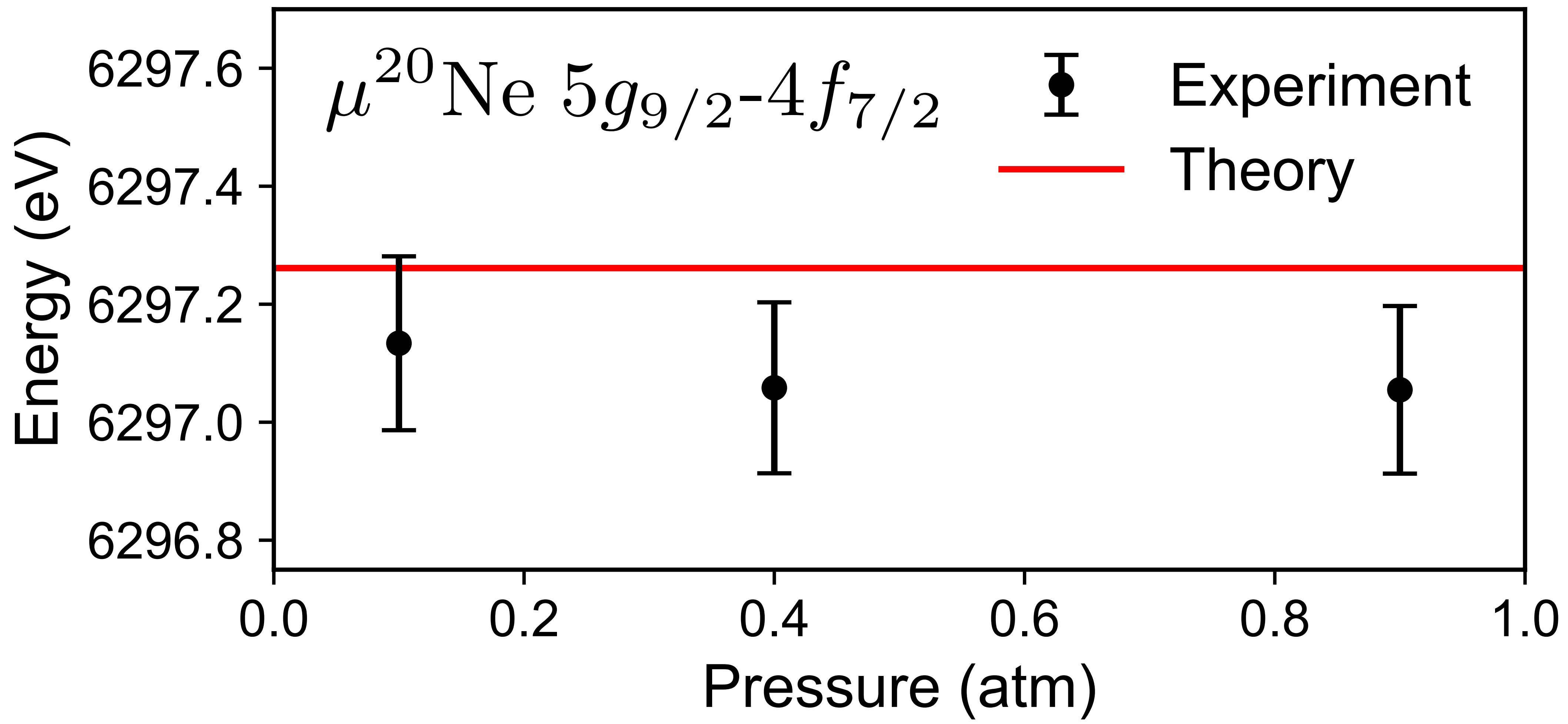
Energy resolution

ΔE = 5.2 ~ 5.5 eV

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



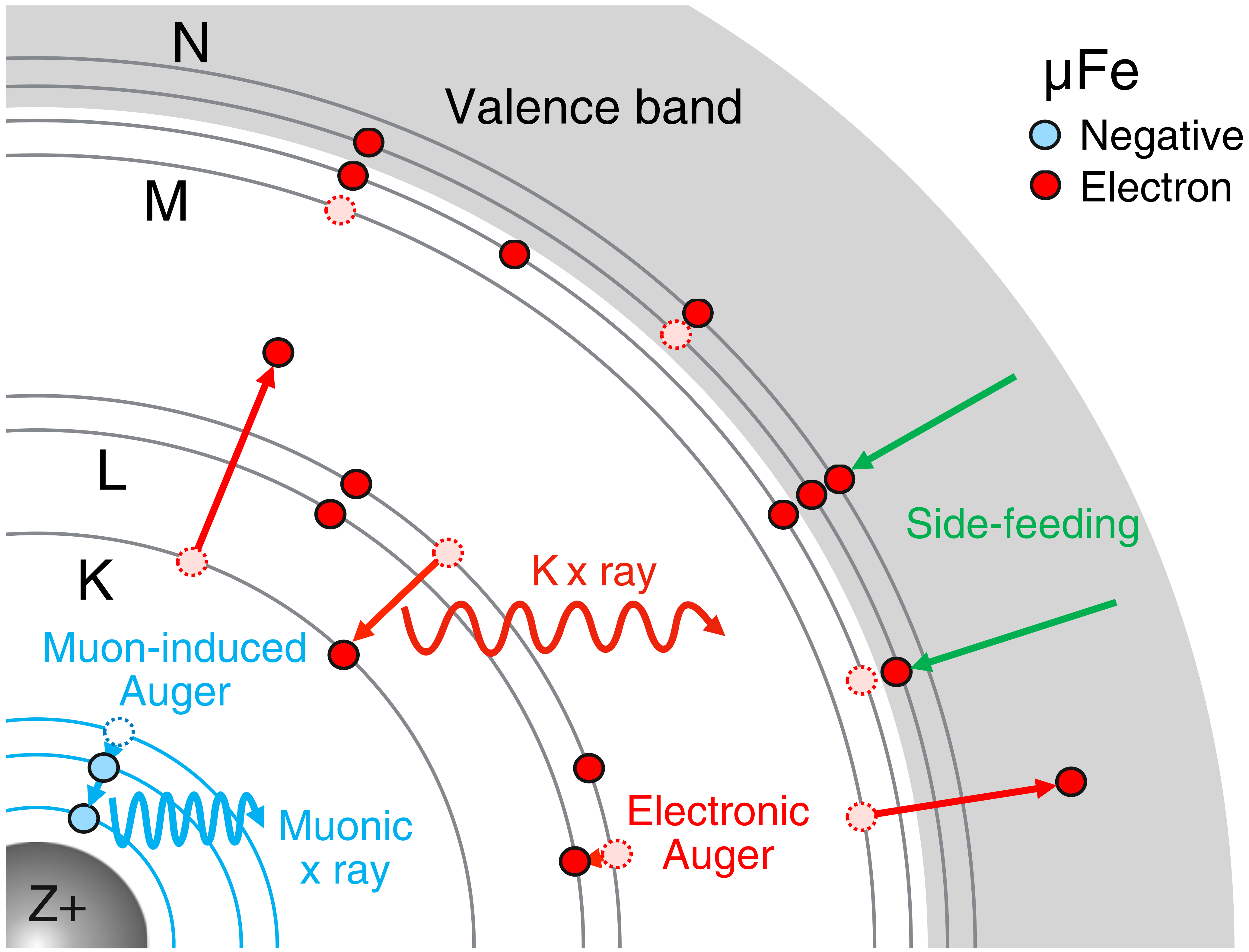


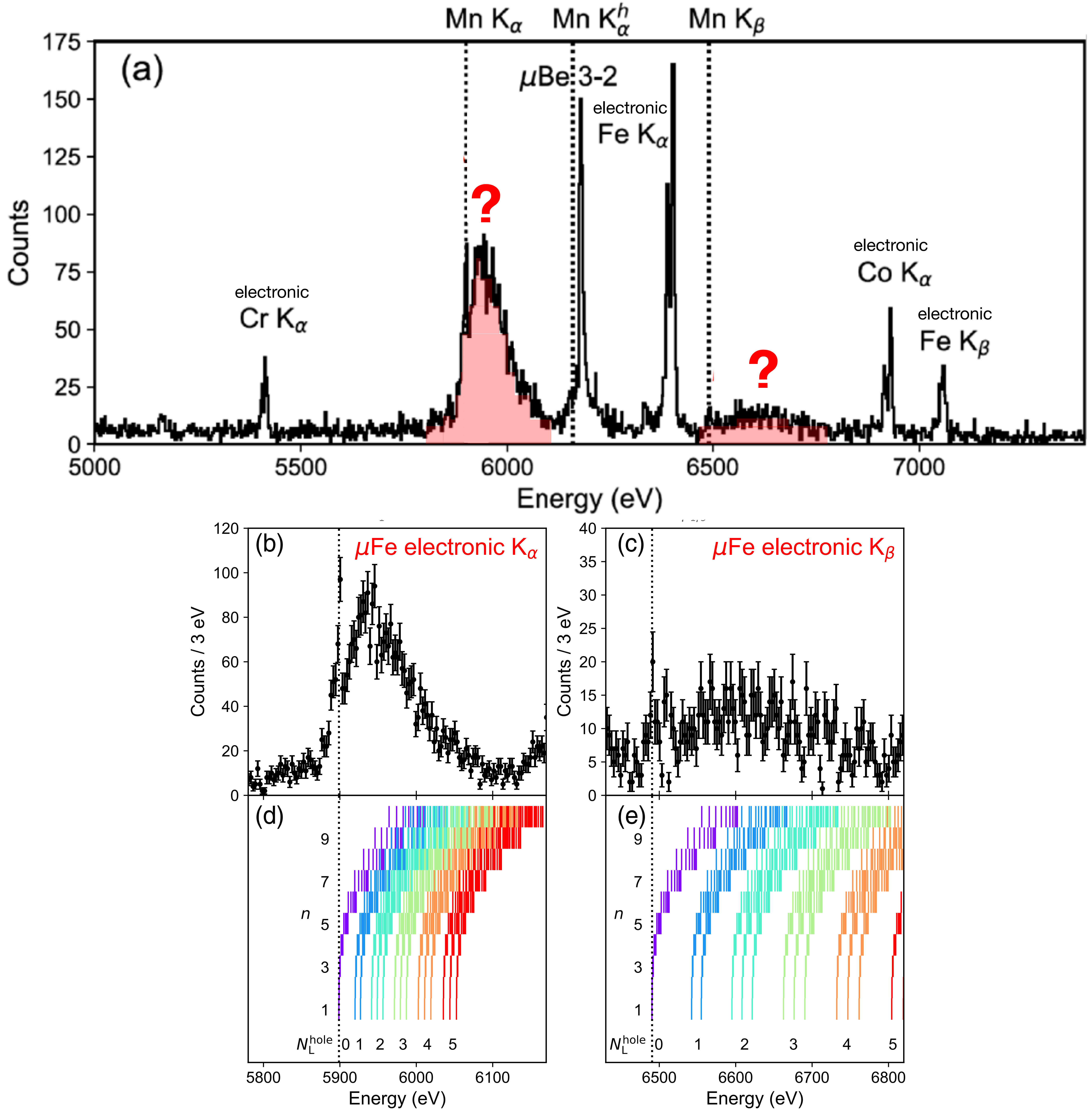


Validated the BSQED calculation at ~6% level

muFe cascade

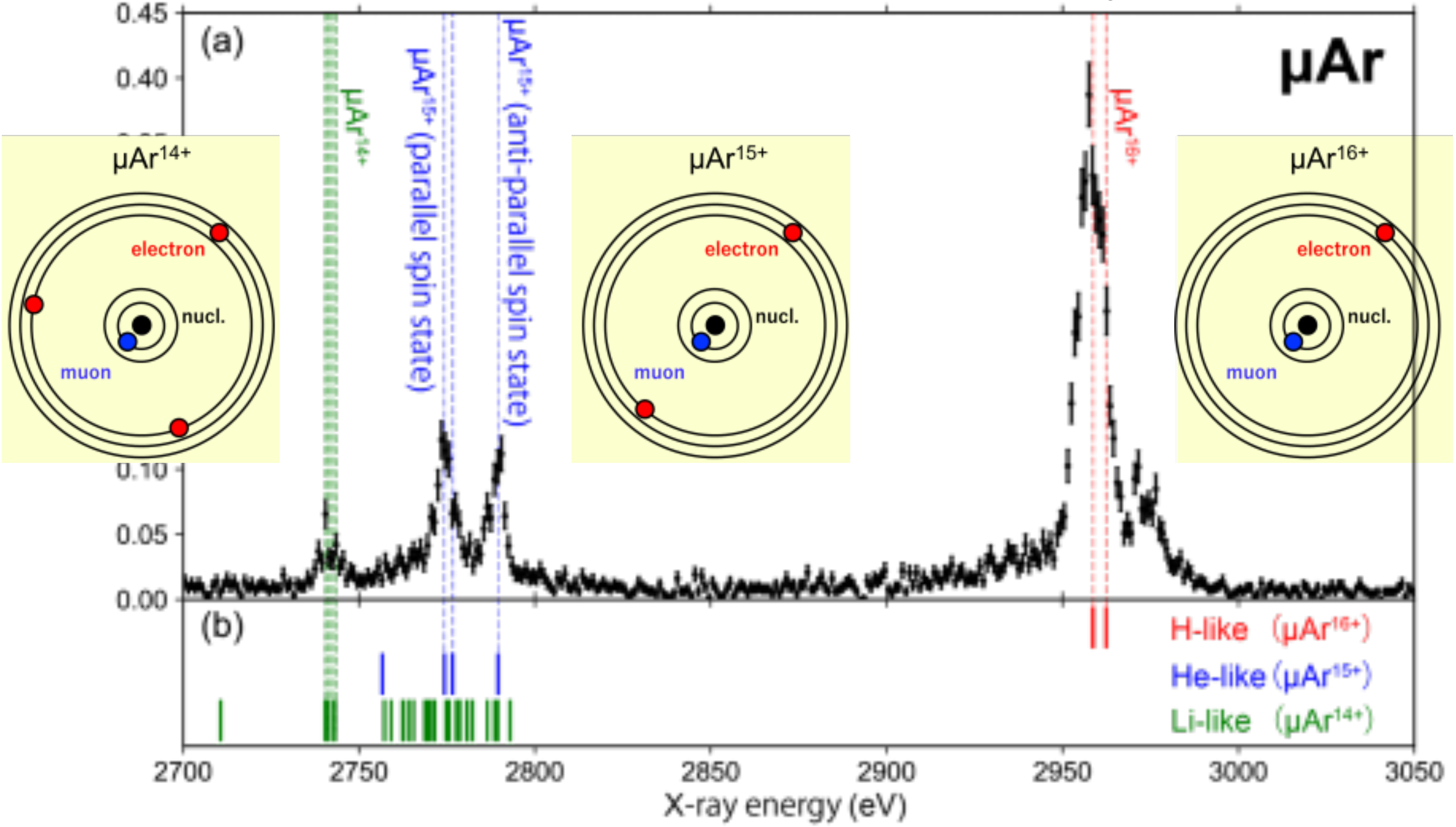
Phys. Rev. Lett. **127**, 053001 (2021)



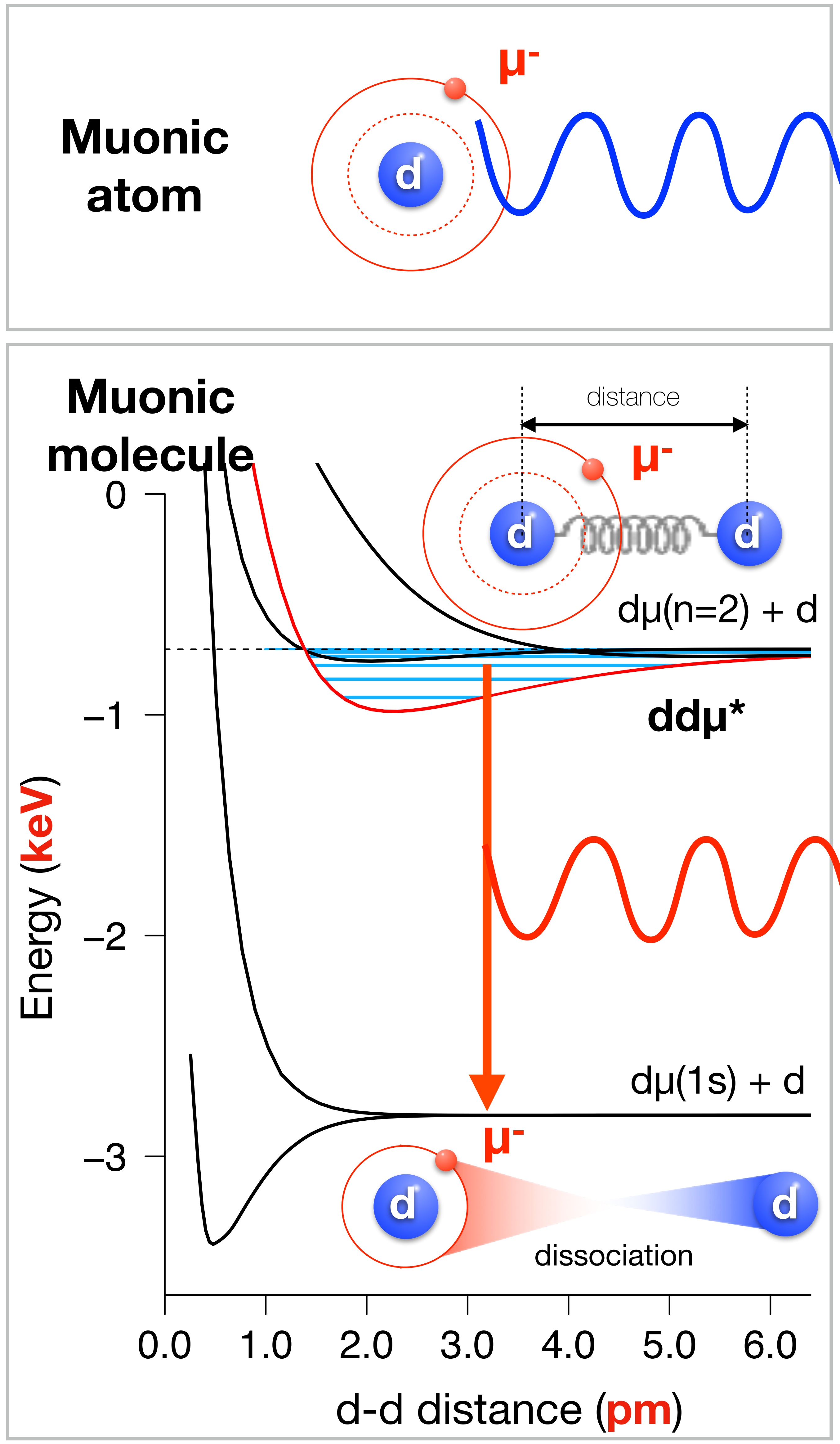


Gas Argon target

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



Muonic molecule ddμ*



X-ray : 2 keV

intense & sharp peak

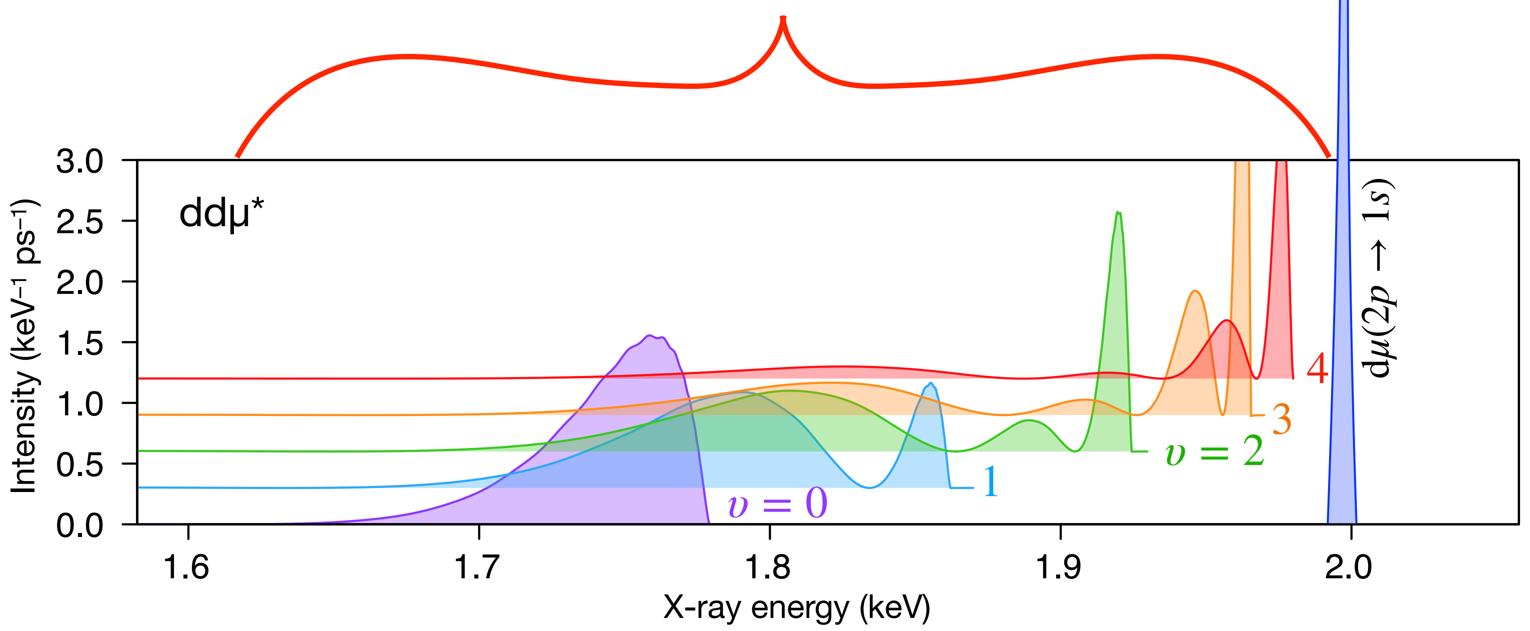
→ **cannot be separated**

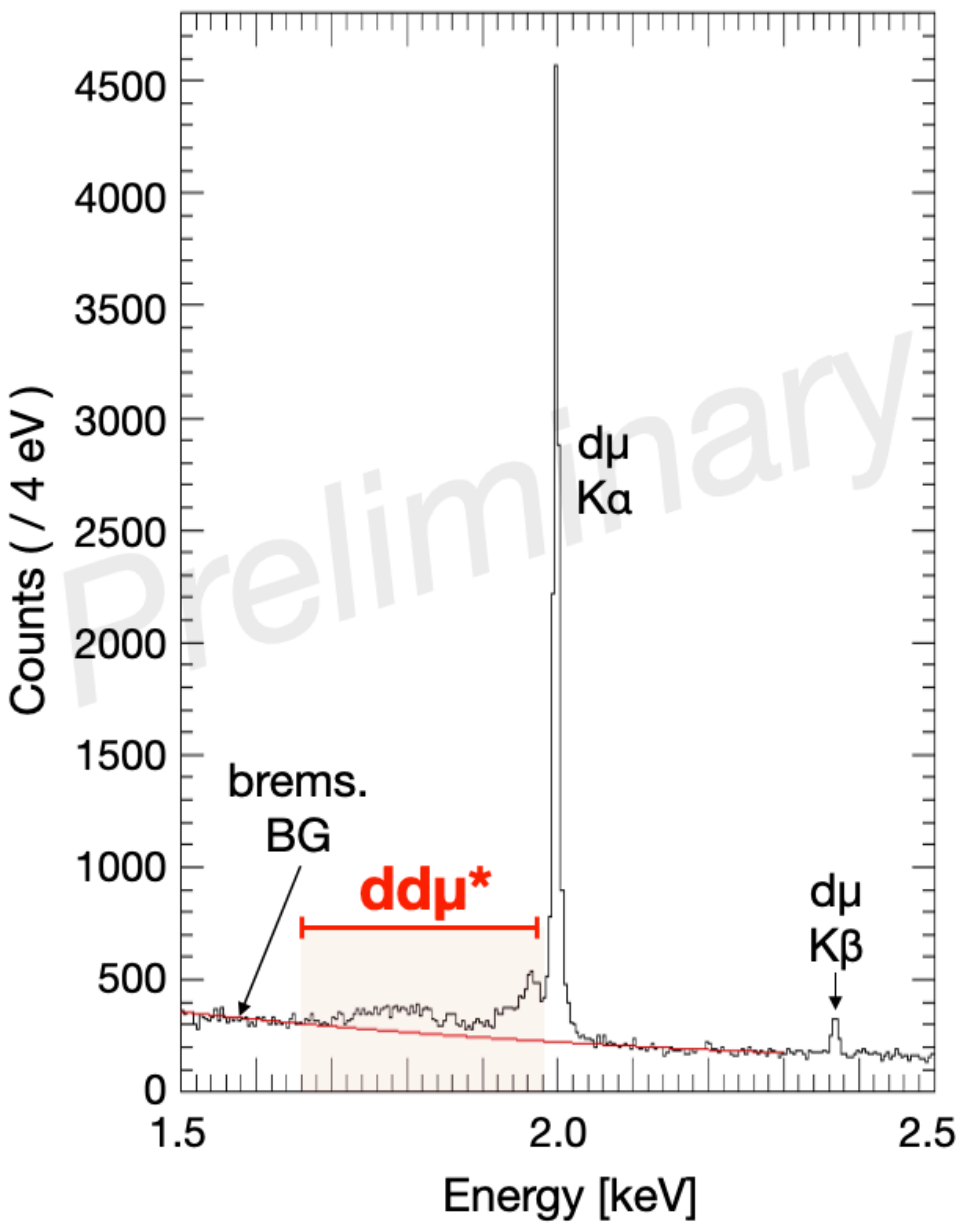
with the ~100 eV resolution

X-ray : 1.7 ~ 2 keV

low-intense &

broad structure



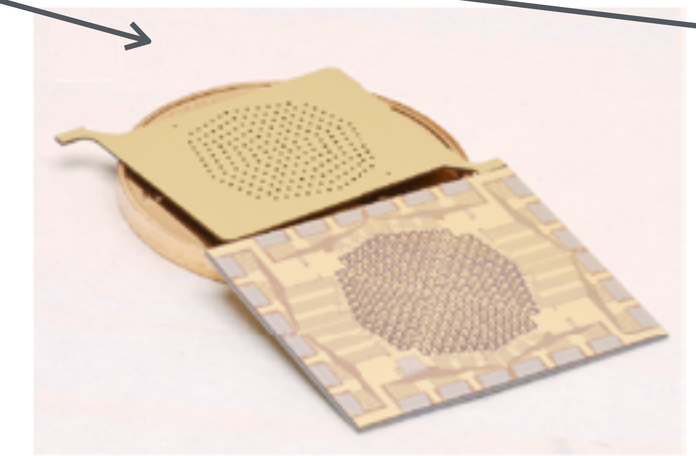


to be submitted soon…

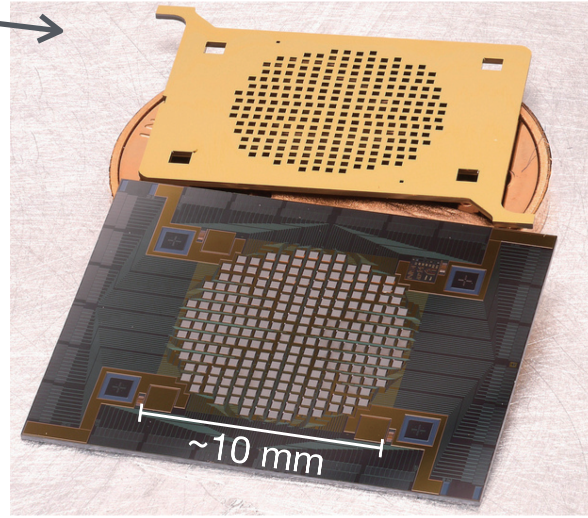
TES detectors from NIST

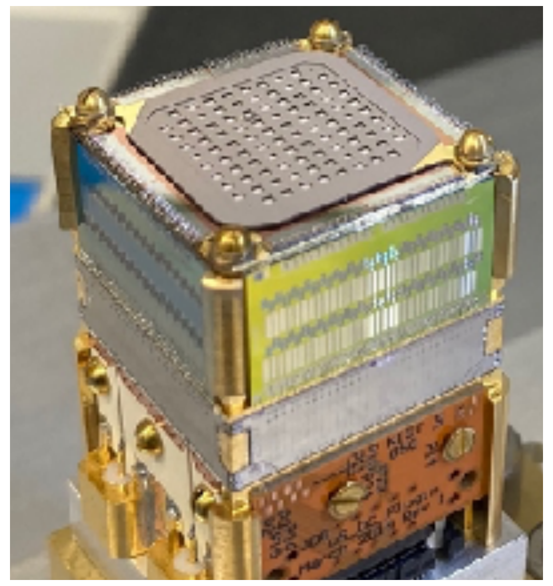
new since 2024

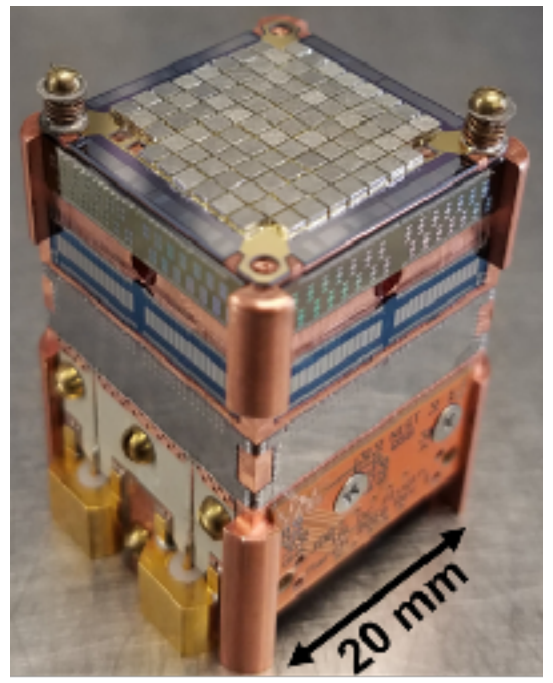
	10 keV TES	20 keV TES	50 keV TES	100 keV TES
Saturation energy	10 keV	20 keV	70 keV	150 keV
Readout system	TDM	TDM	microwave	microwave
Absorber thickness (material)	0.965 μm (Au)	4.1 μm (Bi)	1.85 μm (Au) & 20 μm (Bi)	0.5 mm (Sn)
Absorber area	0.34 x 0.34 mm^2	0.320 x 0.305 mm^2	0.73 x 0.73 mm^2	1.3 x 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



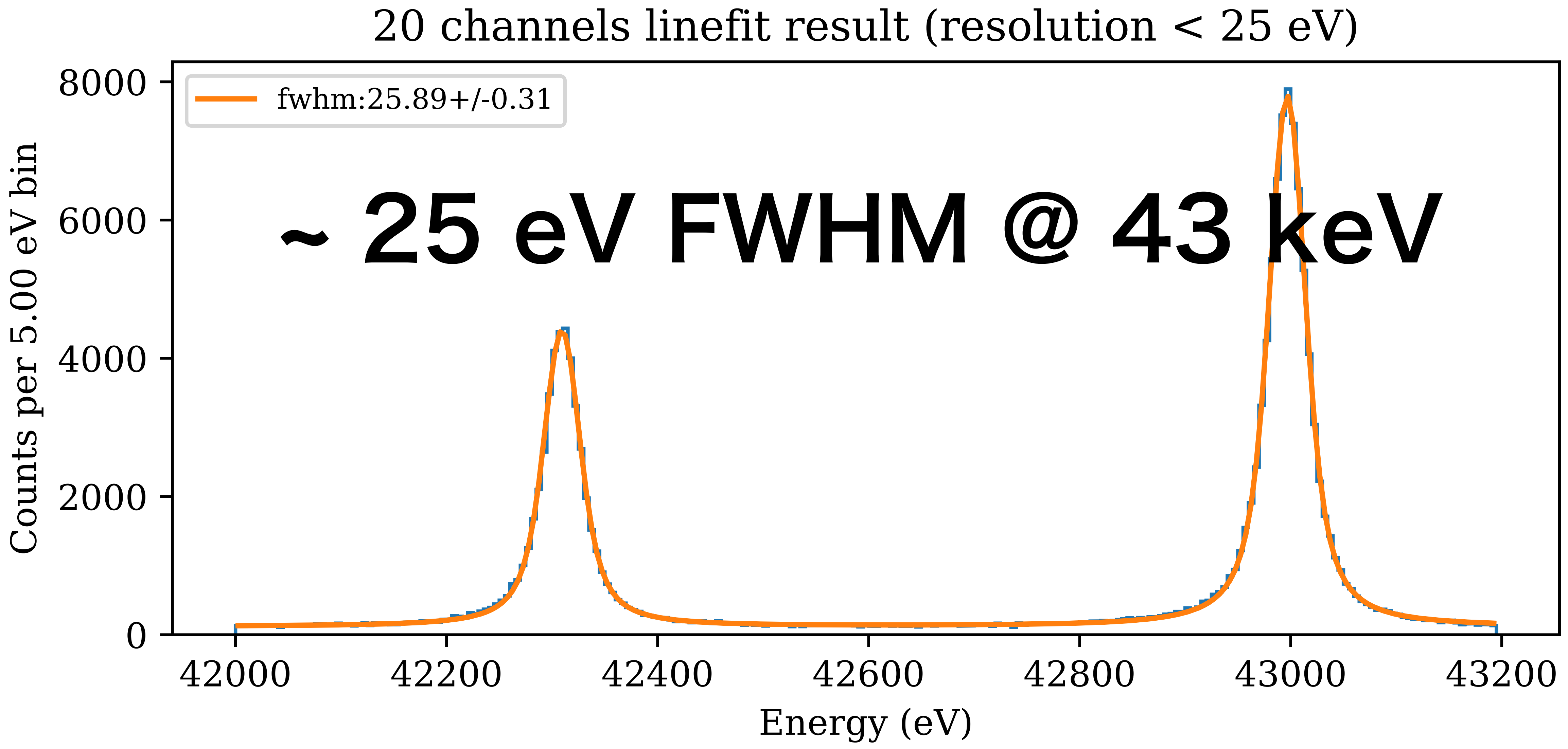
Rev. Sci. Instrum. 90, 123107 (2019)

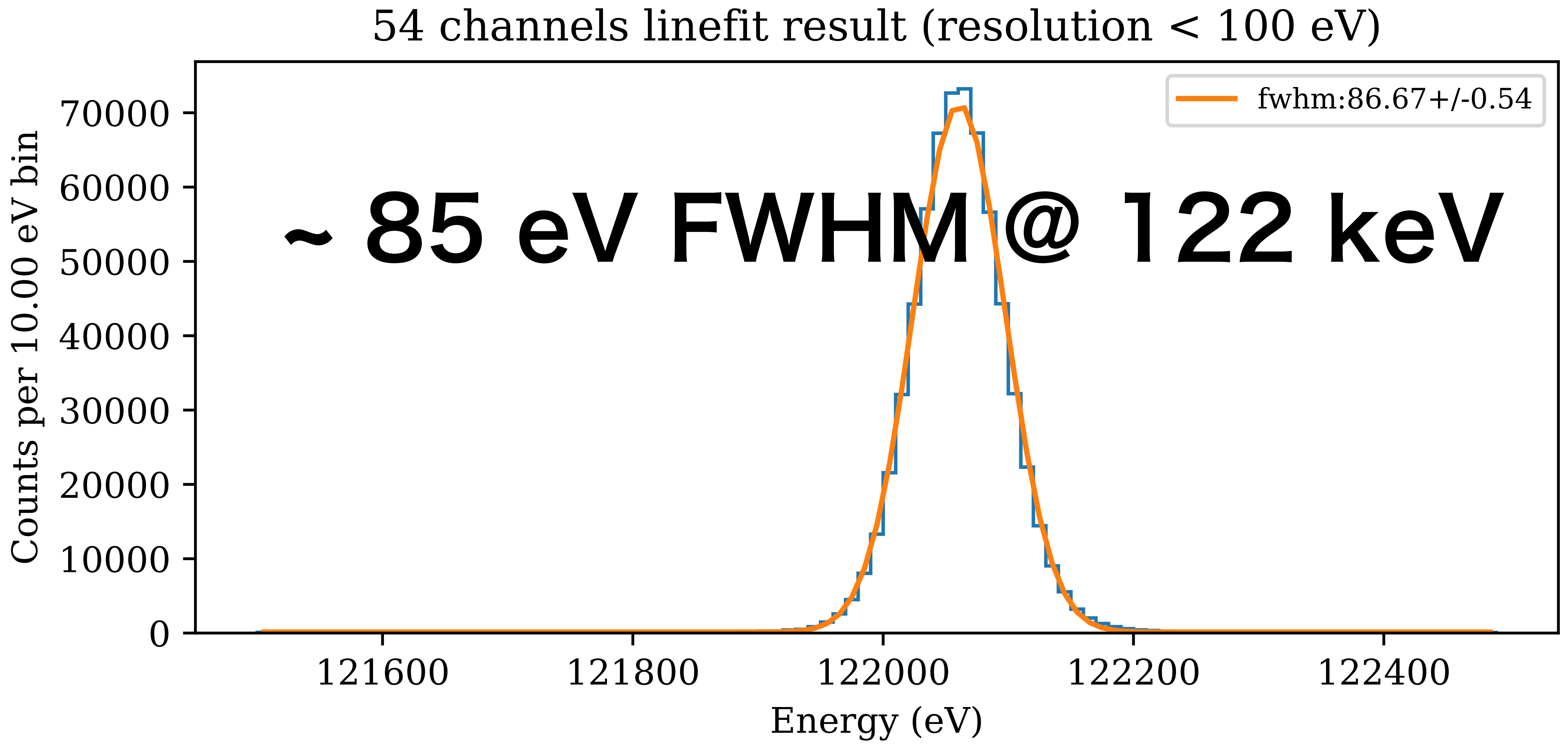


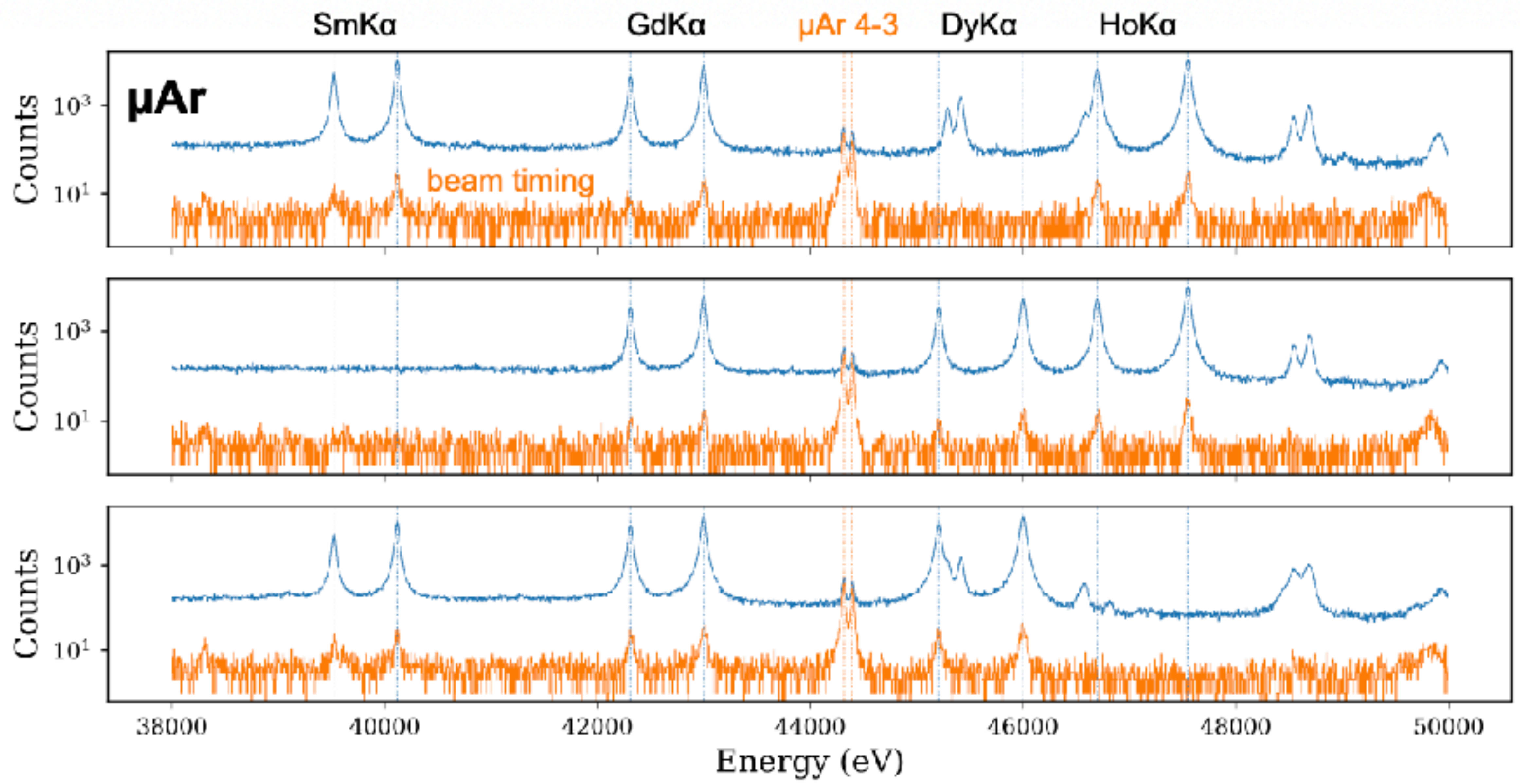


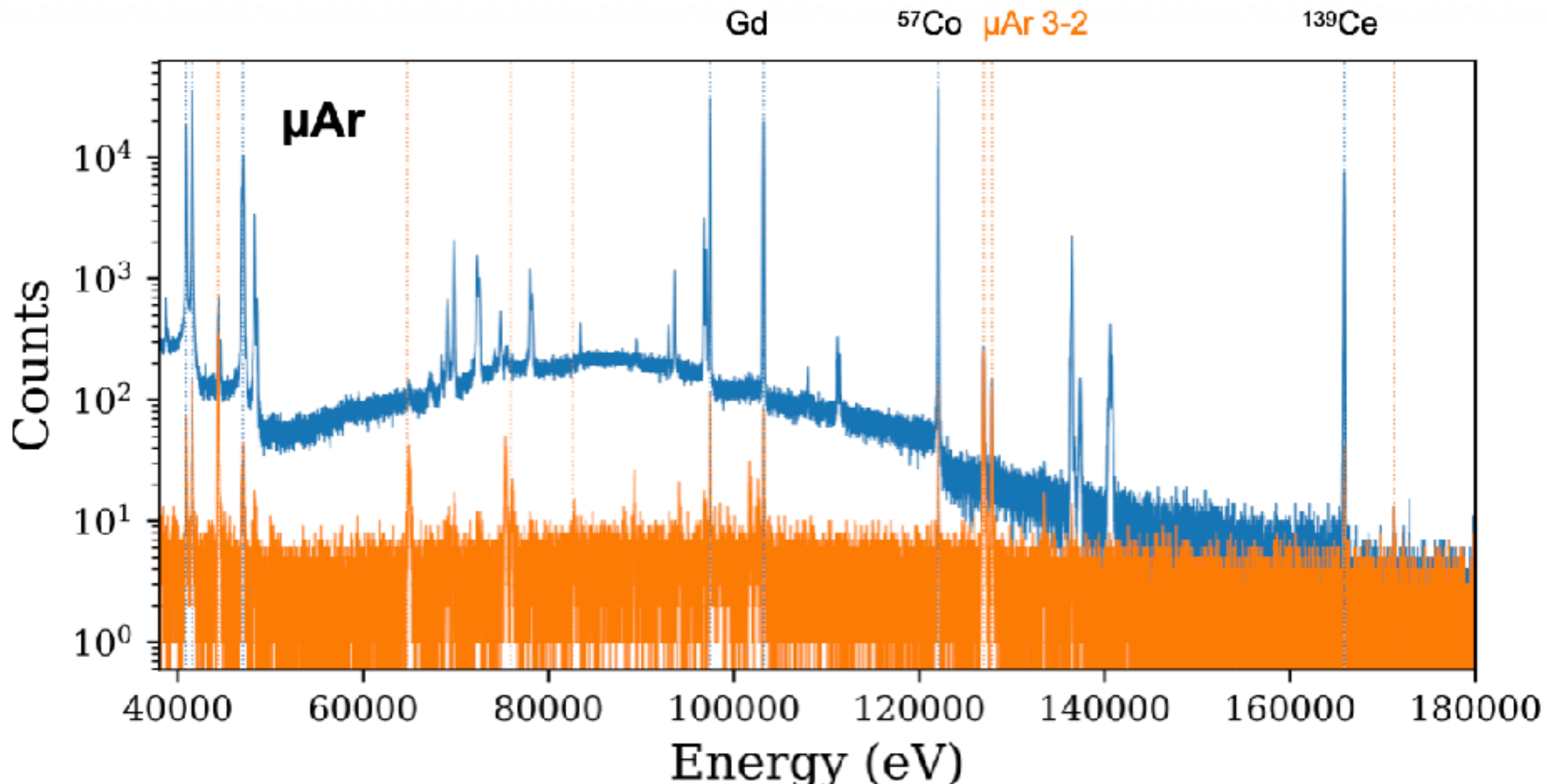


Preliminary spectra



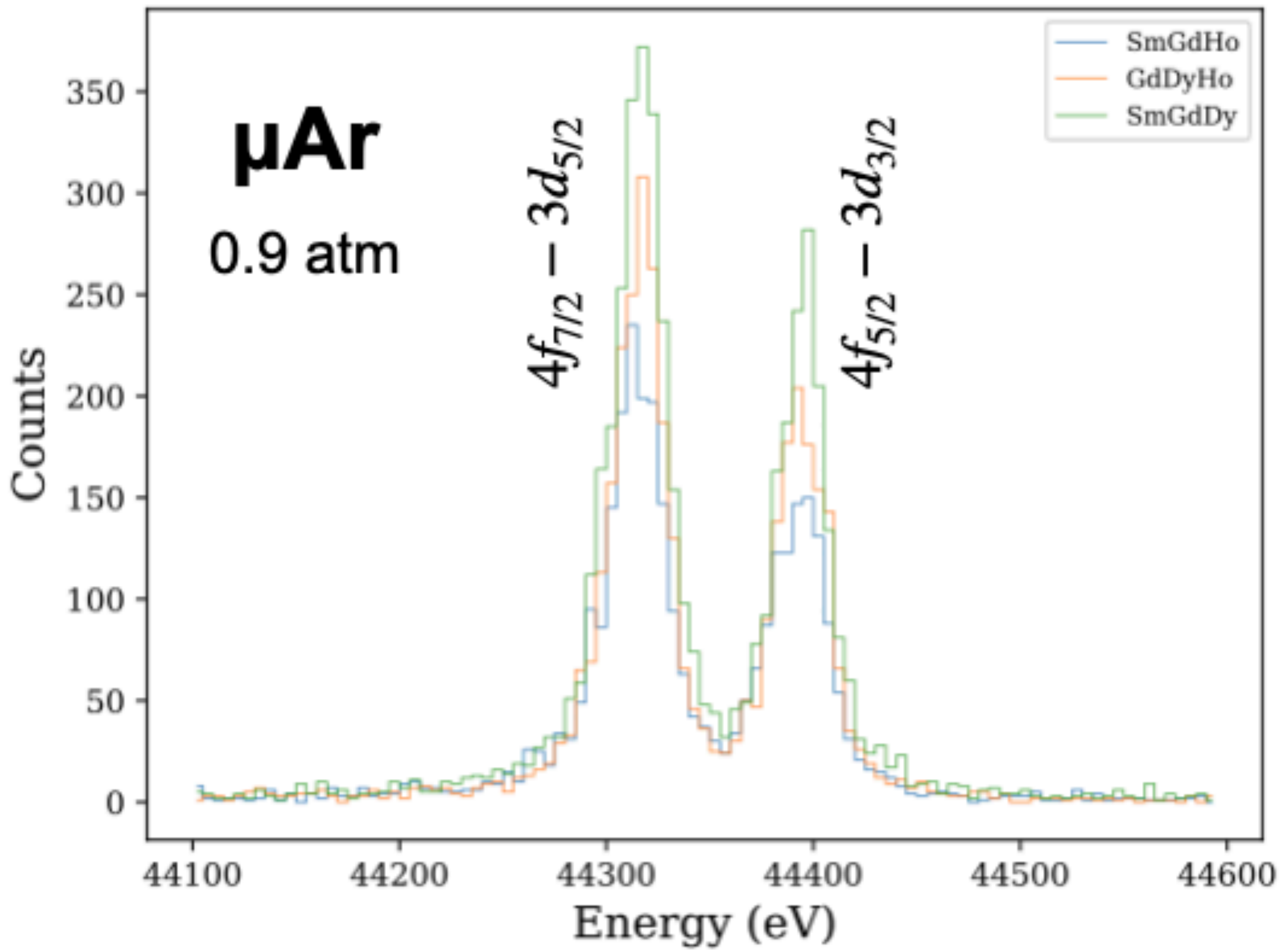


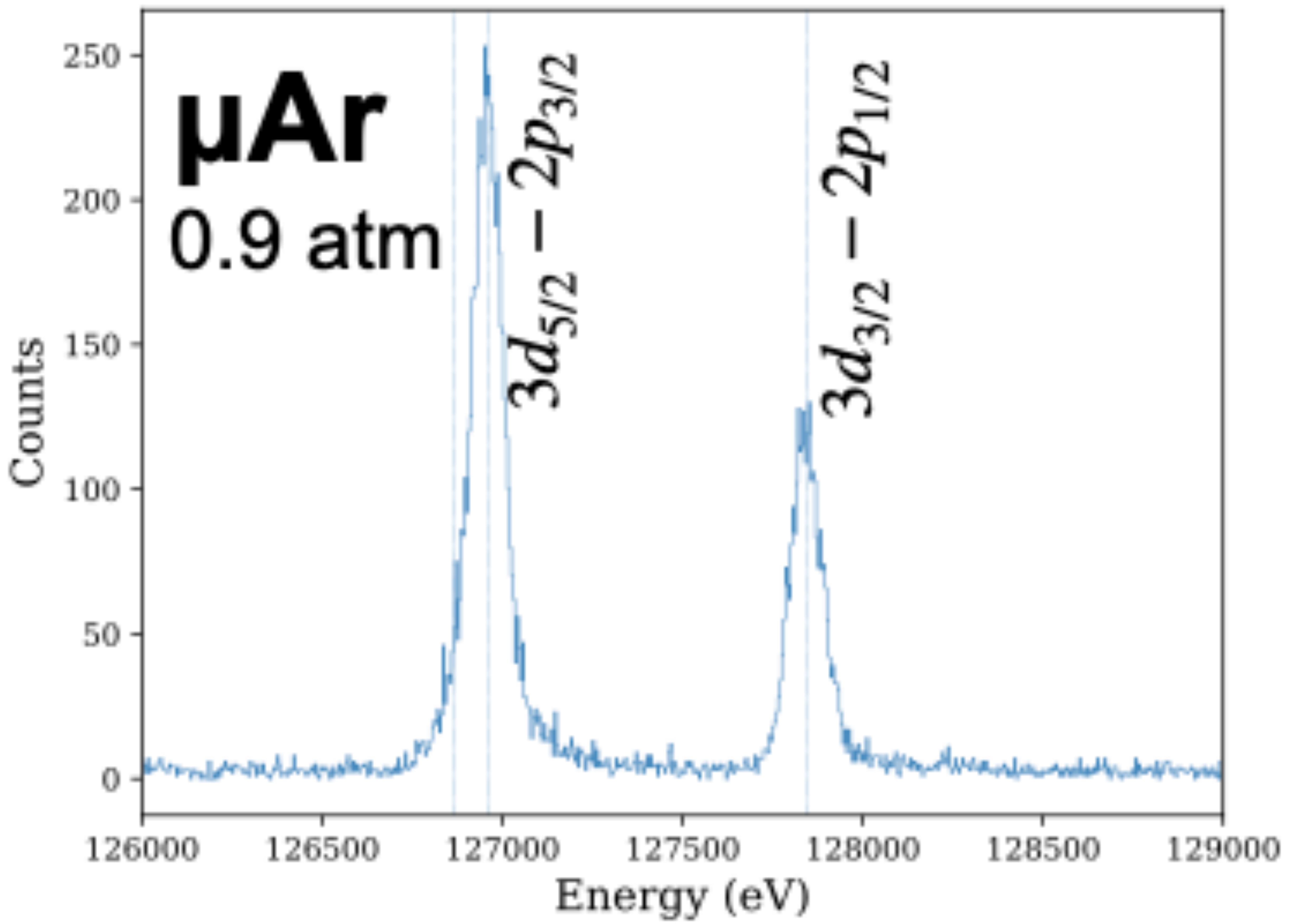




Preliminary spectra

~ 1 day data-taking for each data set





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

Summary

- **Kaonic deuterium X-rays should be confirmed and improved at J-PARC**
  - X-ray coincidence measurement
  - Aiming to start from 2027
  - Similar technique can be employed for K-He 1s, Σ atom,⋯

- **Successful application of the TES microcalorimeter to kaonic-atom X-rays**
  - Helium-3/4 2p states to exclude large shifts/widths
  - Kaon mass measurement?
  - Isotope shift? ($Li^{6/7}$ 2p, $Na^{20/22}$ 3d, $Ca^{40\sim48}$ 4f)

- **Many outputs from muonic atom X-rays with TES**