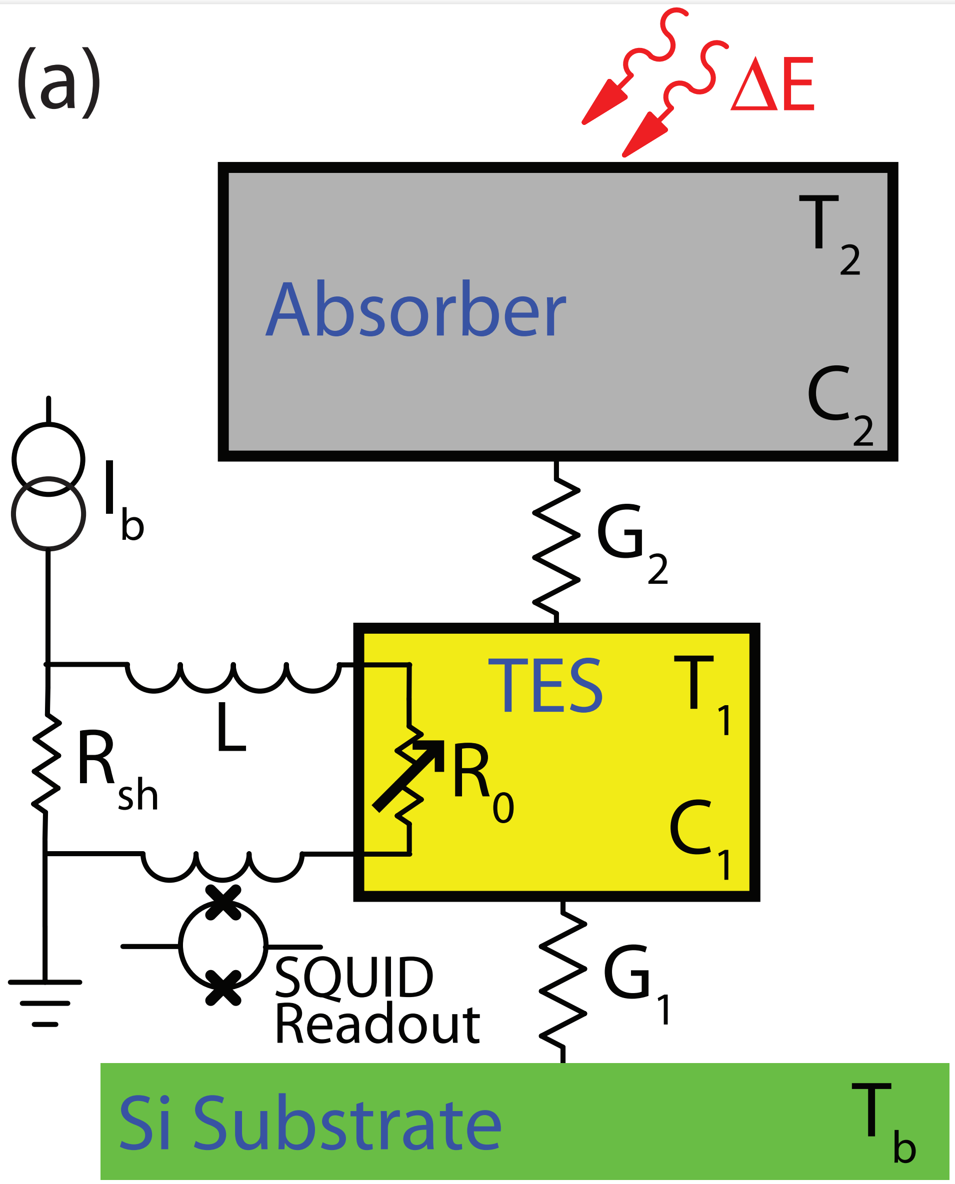
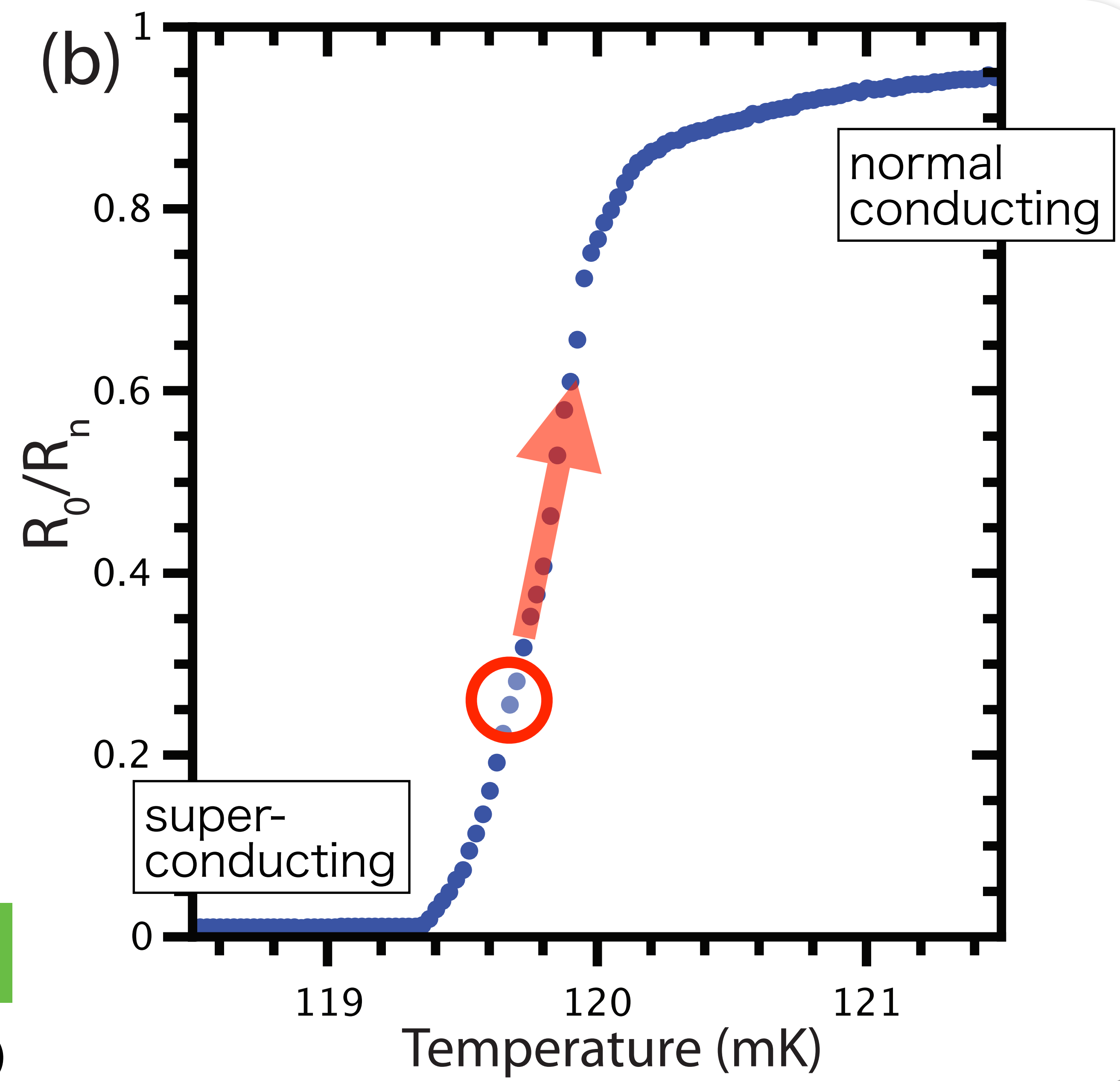
Kaonic atom experiments with TES microcalorimeters

Tadashi Hashimoto (JAEA)

High precision measurements of kaonic atoms, Laboratori Nazionali di Frascati, 9th February 2022

Transition-**E**dge-**S**ensor microcalorimeters



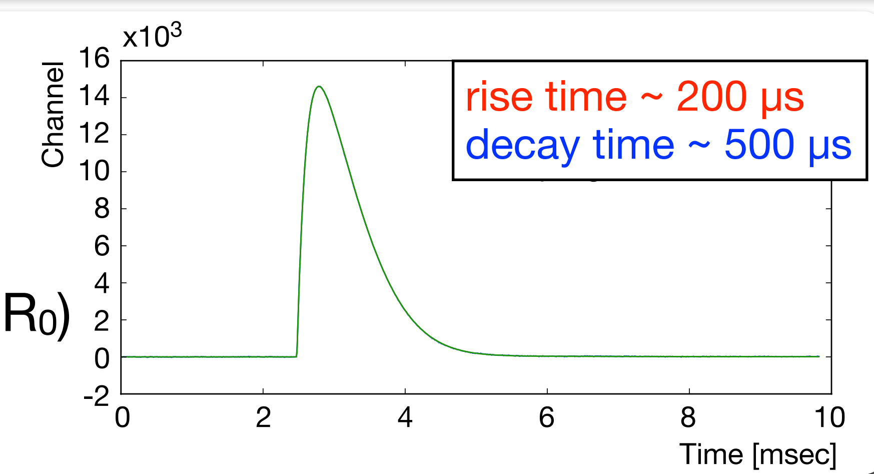


Rev. Sci. Instrum. **83**, 093113 (2012)

Typical pulse

$\tau_{rise} \sim L/(R_{sh}+R_0)$

$\tau_{fall} \sim C/G$

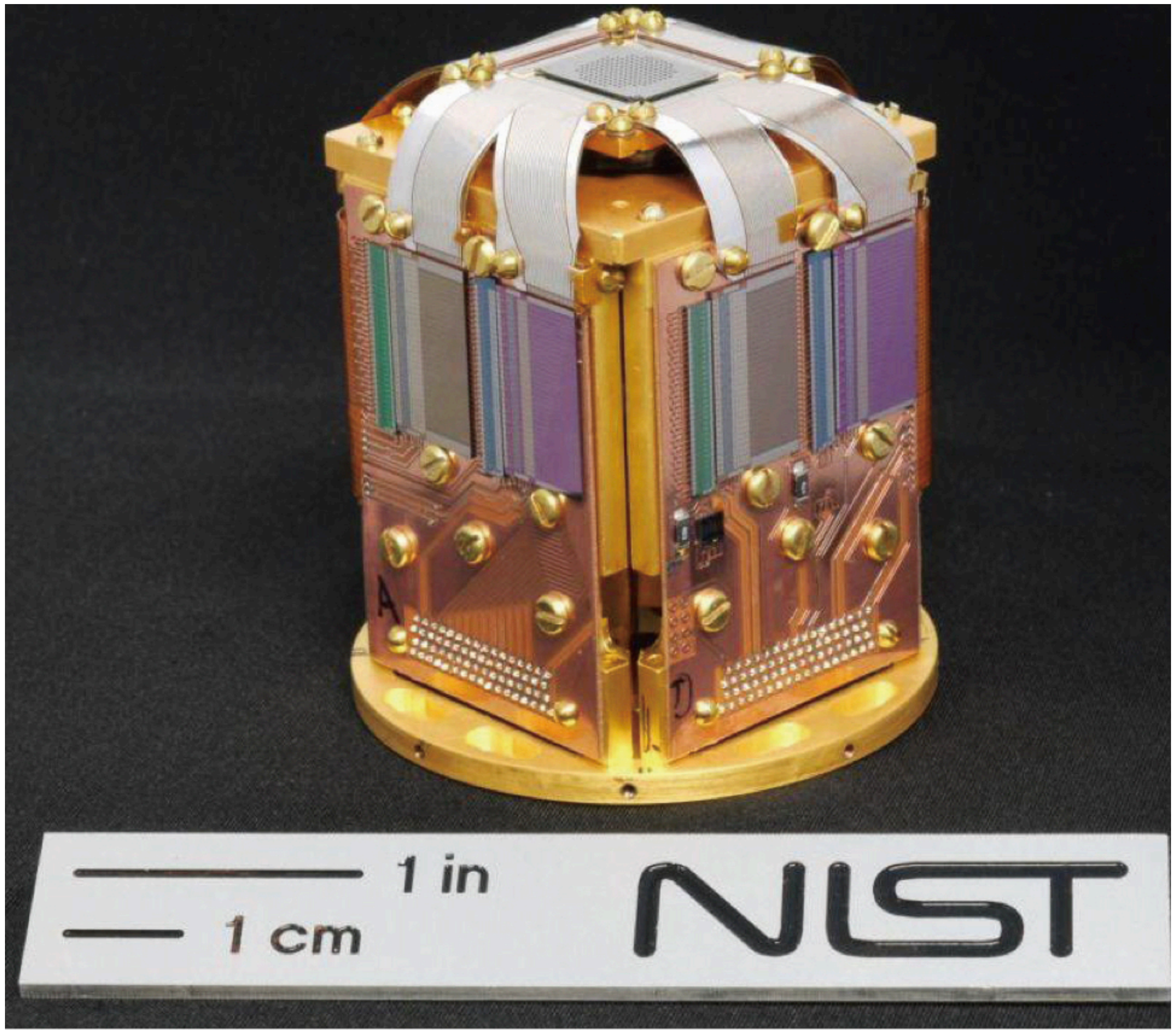


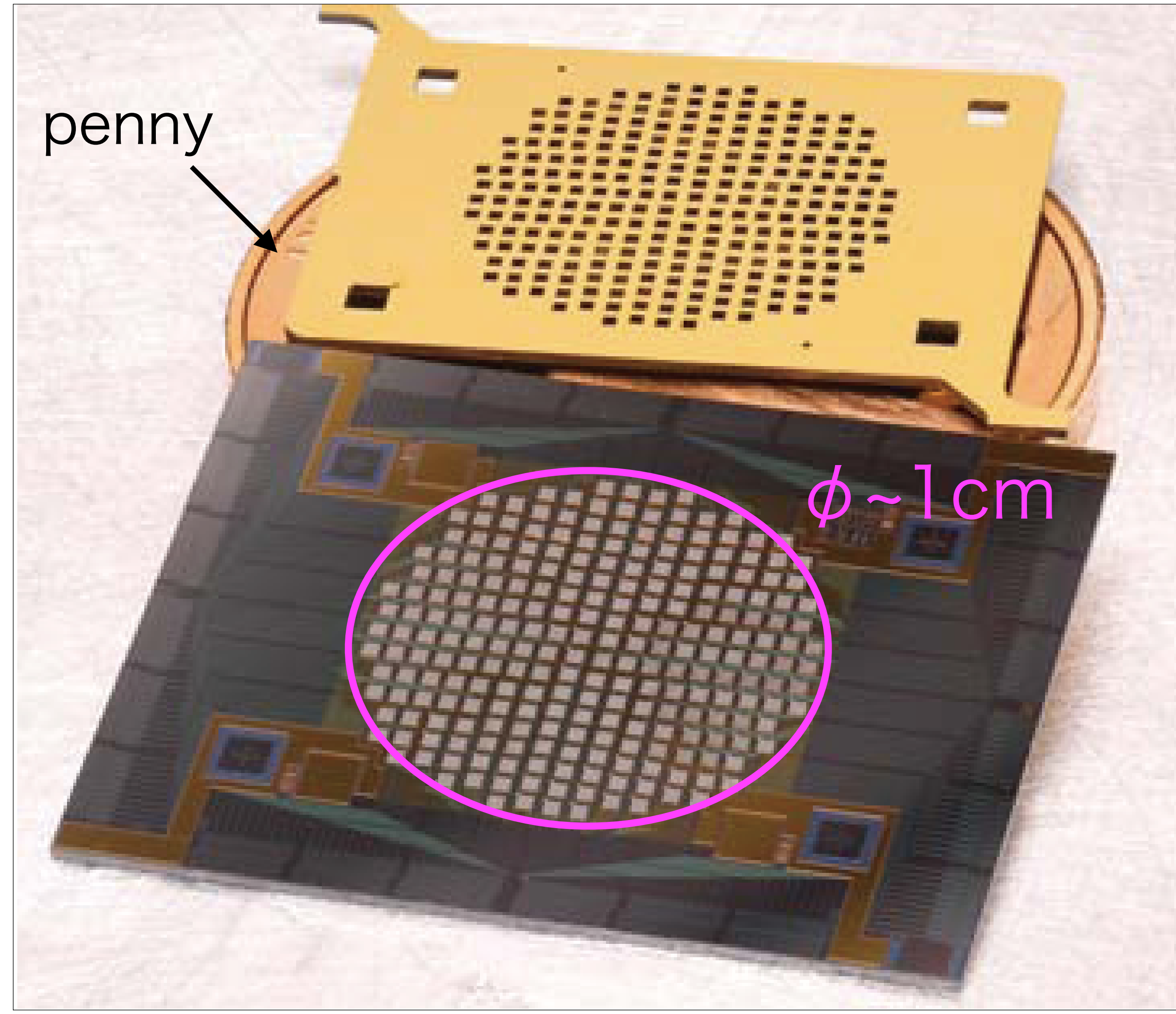
Resolution: ~ 5 eV FWHM @ 6 keV

Dynamic range: 4-15 keV

NIST(US) TES spectrometer for E62

Review of Scientific Instruments **88**, 053108 (2017)





- Cooled down to 70 mK with ADR & pulse tube.
- 240 pixel: 8 columns x 30 rows time-division multiplexing (TDM) readout
- ~23 mm^2, 85% eff.@6 keV (Mo/Cu + Bi 4um)
- First case to operate in a hadron beam environment.

History of the project

2013	Start collaboration with NIST
2014	**Demonstration experiment @ PSI (pionic atom)** *JLTP 184(3), 930-937, 2016; PTEP* ***2016****, 091D01, 2016.*
2015	Approved as J-PARC E62
2016	**Commissioning with K^- beam @ J-PARC** *IEEE Trans. Appl. Supercond. 27(4), 1-5, 2017.*
2017	
2018	**Physics data taking for K^- atom @ J-PARC, ~18 days** *J. Low Temp. Phys.* ***199****, 1018–1026 (2020)*
…	
2022	***PRL paper accepted !!***

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

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(J-PARC E62 collaboration)

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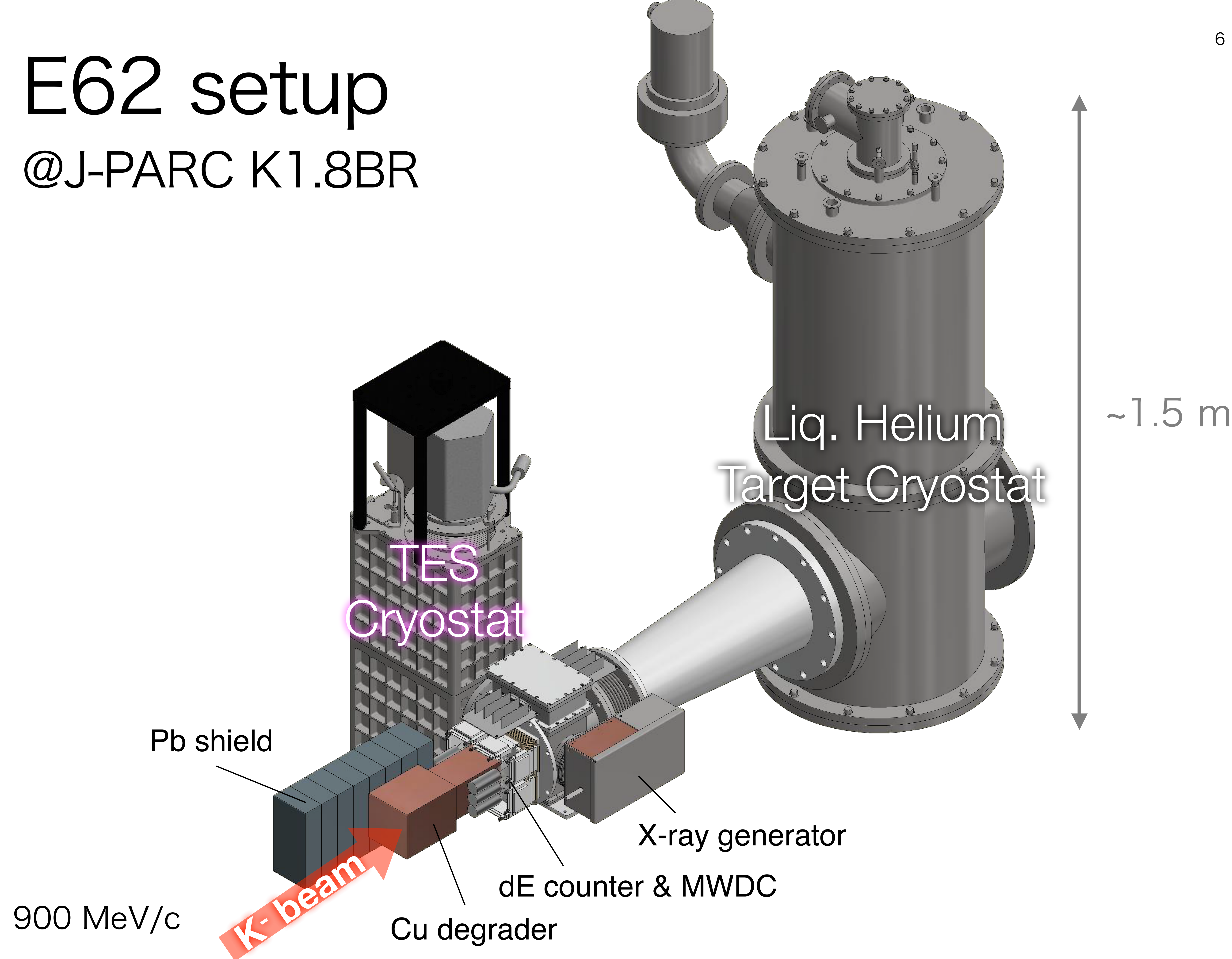
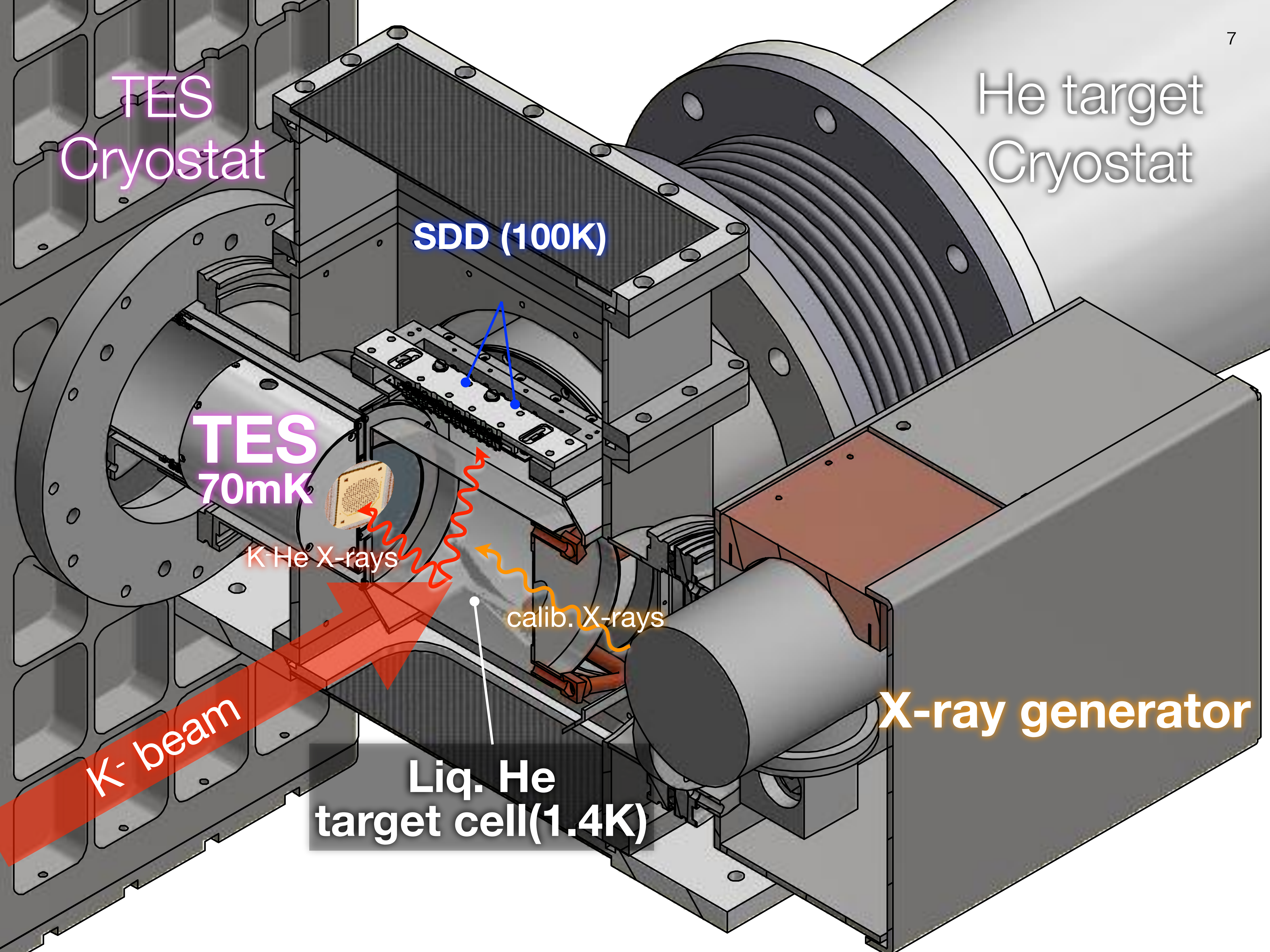
E62 setup

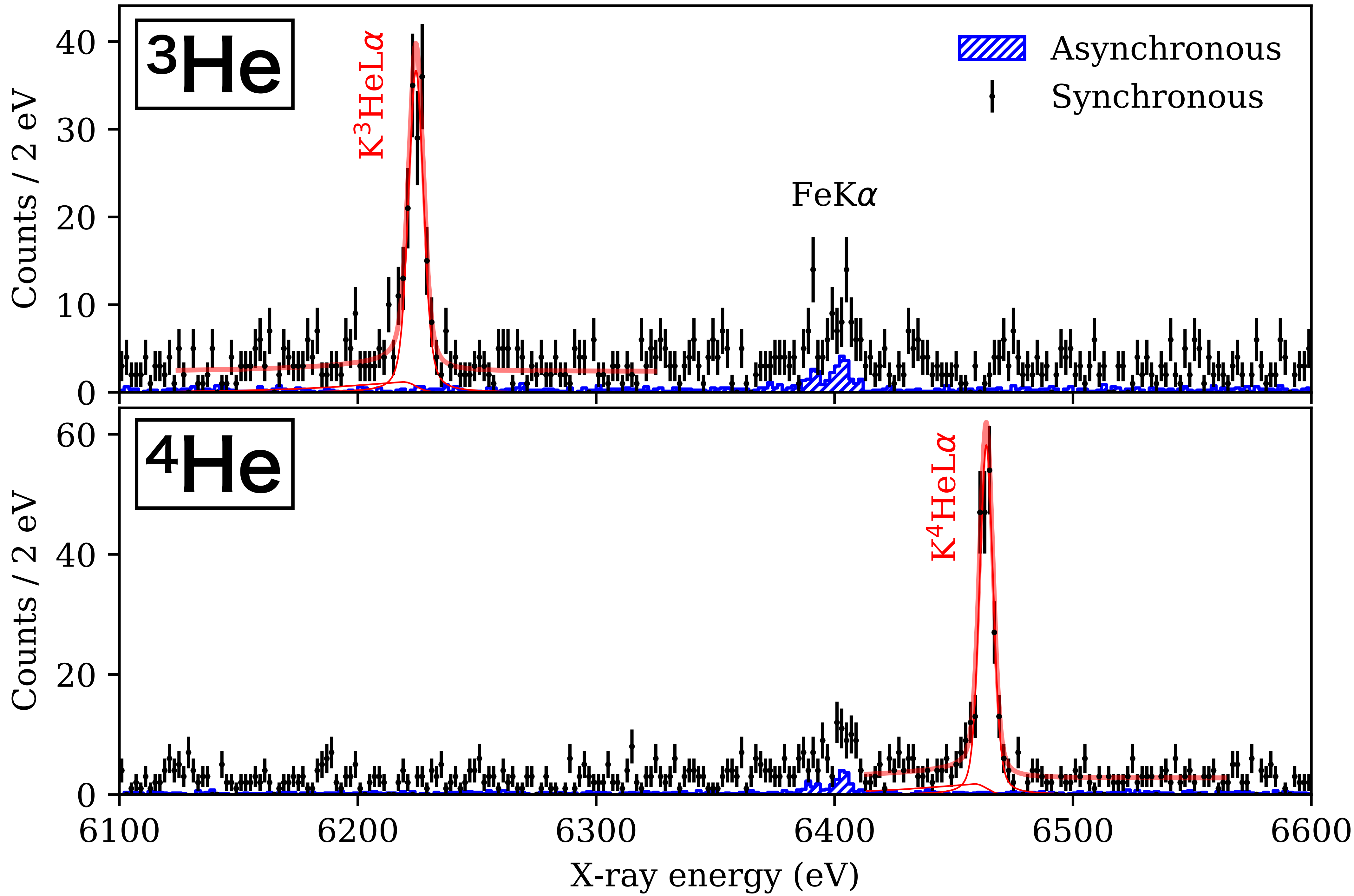
@J-PARC K1.8BR




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

J-PARC E62 results

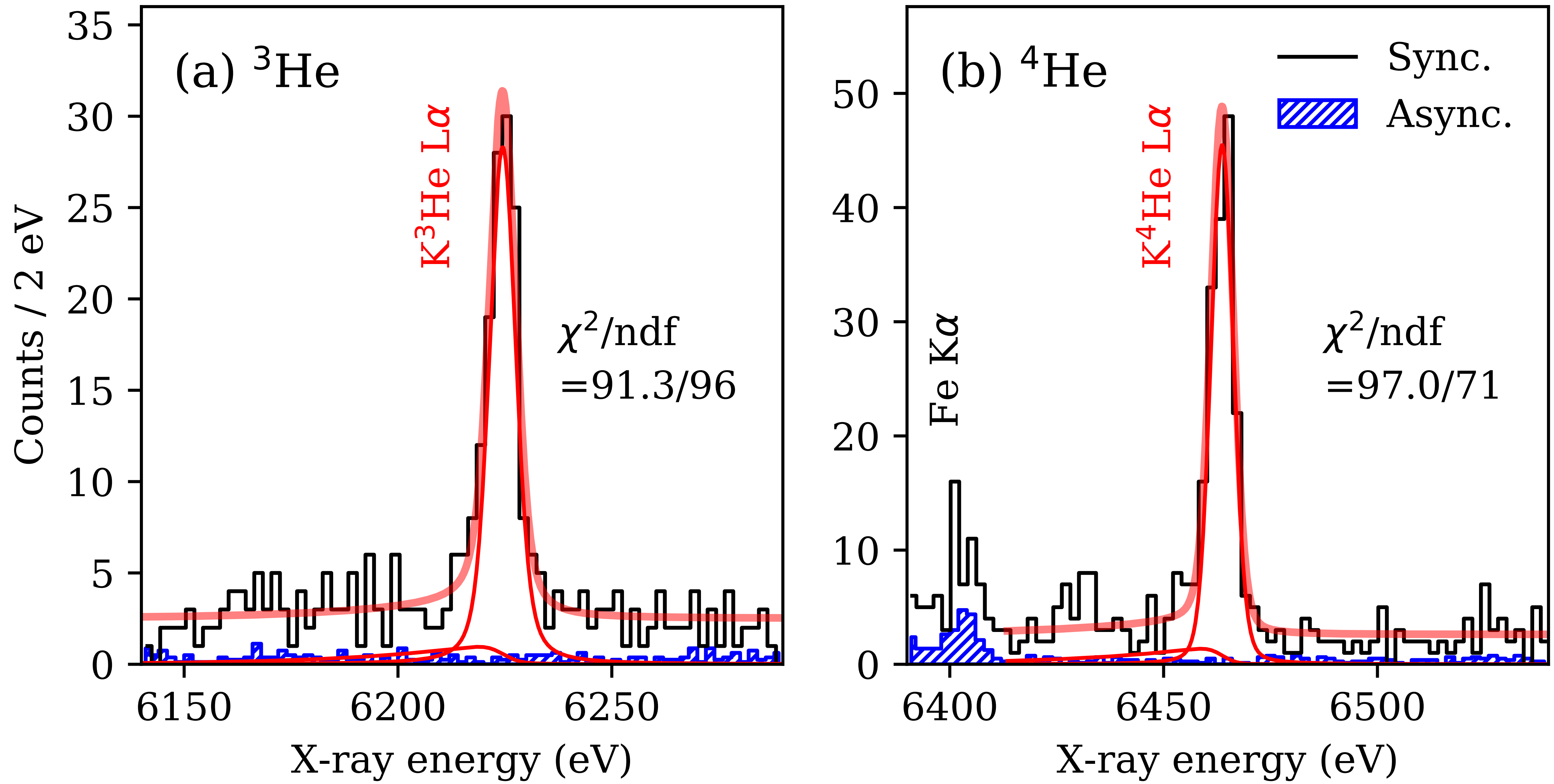
~14-day data taking



✓ Asynchronous background contribution is negligible

✓ Most of background come from stopped kaon absorptions

J-PARC E62 Fitting Results



$$E_{3d\to 2p}^{K^{-3}\mathrm{He}} = 6224.5 \pm 0.4(stat.) \pm 0.2(syst.)\ \mathrm{eV},$$

$$E_{3d\to 2p}^{K^{-4}\mathrm{He}} = 6463.7 \pm 0.3(stat.) \pm 0.1(syst.)\ \mathrm{eV},$$

$$\Gamma_{2p}^{K^{-3}\mathrm{He}} = 2.5 \pm 1.0(stat.) \pm 0.4(syst.)\ \mathrm{eV},$$

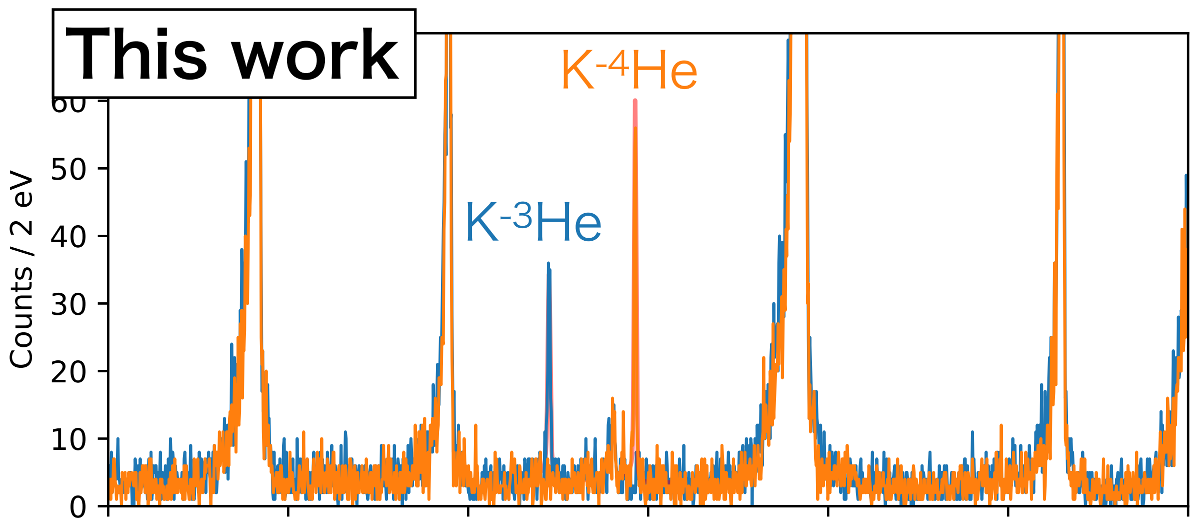
$$\Gamma_{2p}^{K^{-4}\mathrm{He}} = 1.0 \pm 0.6(stat.) \pm 0.3(syst.)\ \mathrm{eV}.$$

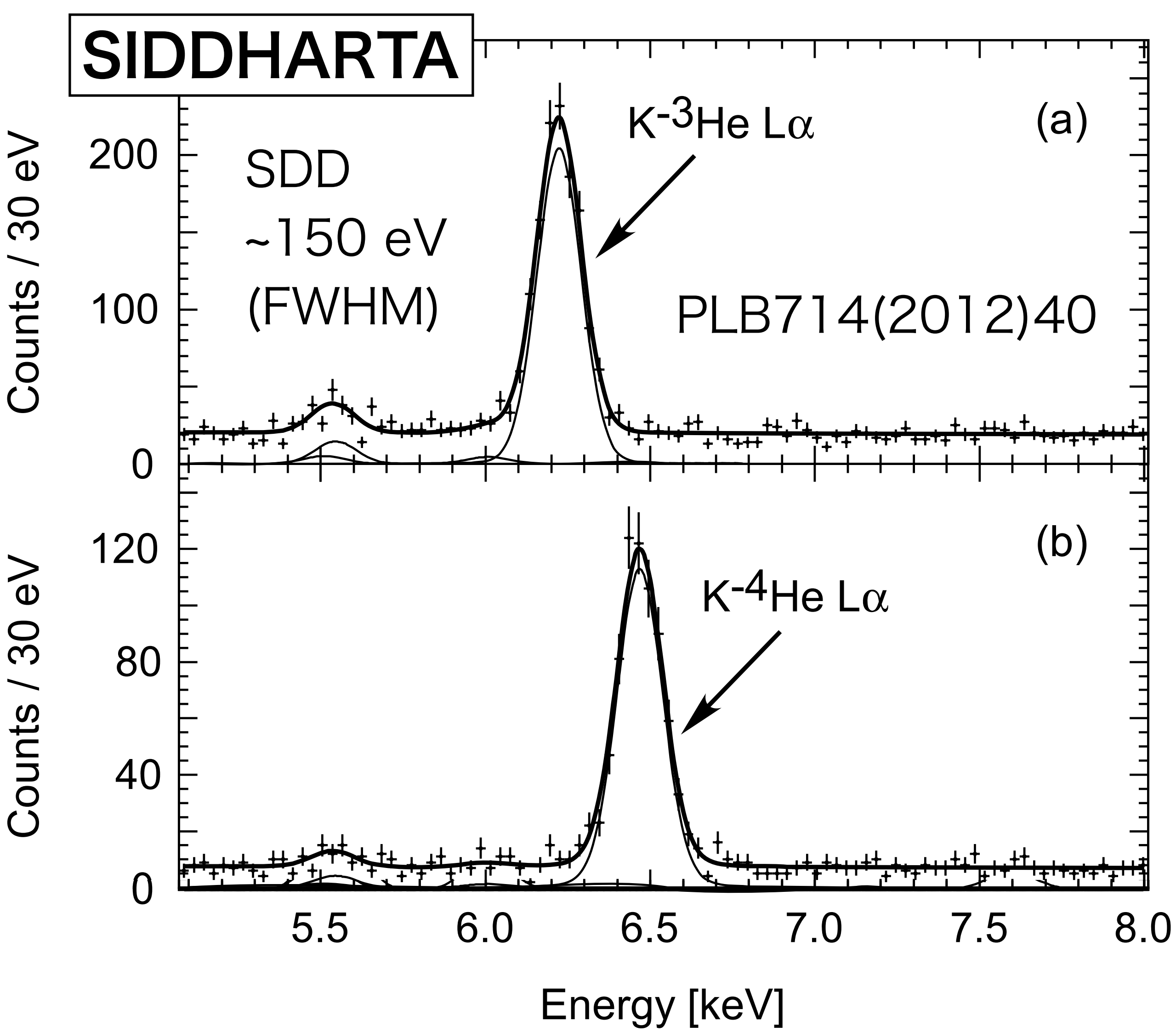
$$\Delta E_{2p}^{K^{-3}\mathrm{He}} = -0.2 \pm 0.4(stat.) \pm 0.3(syst.)\ \mathrm{eV},$$

$$\Delta E_{2p}^{K^{-4}\mathrm{He}} = 0.2 \pm 0.3(stat.) \pm 0.2(syst.)\ \mathrm{eV}.$$

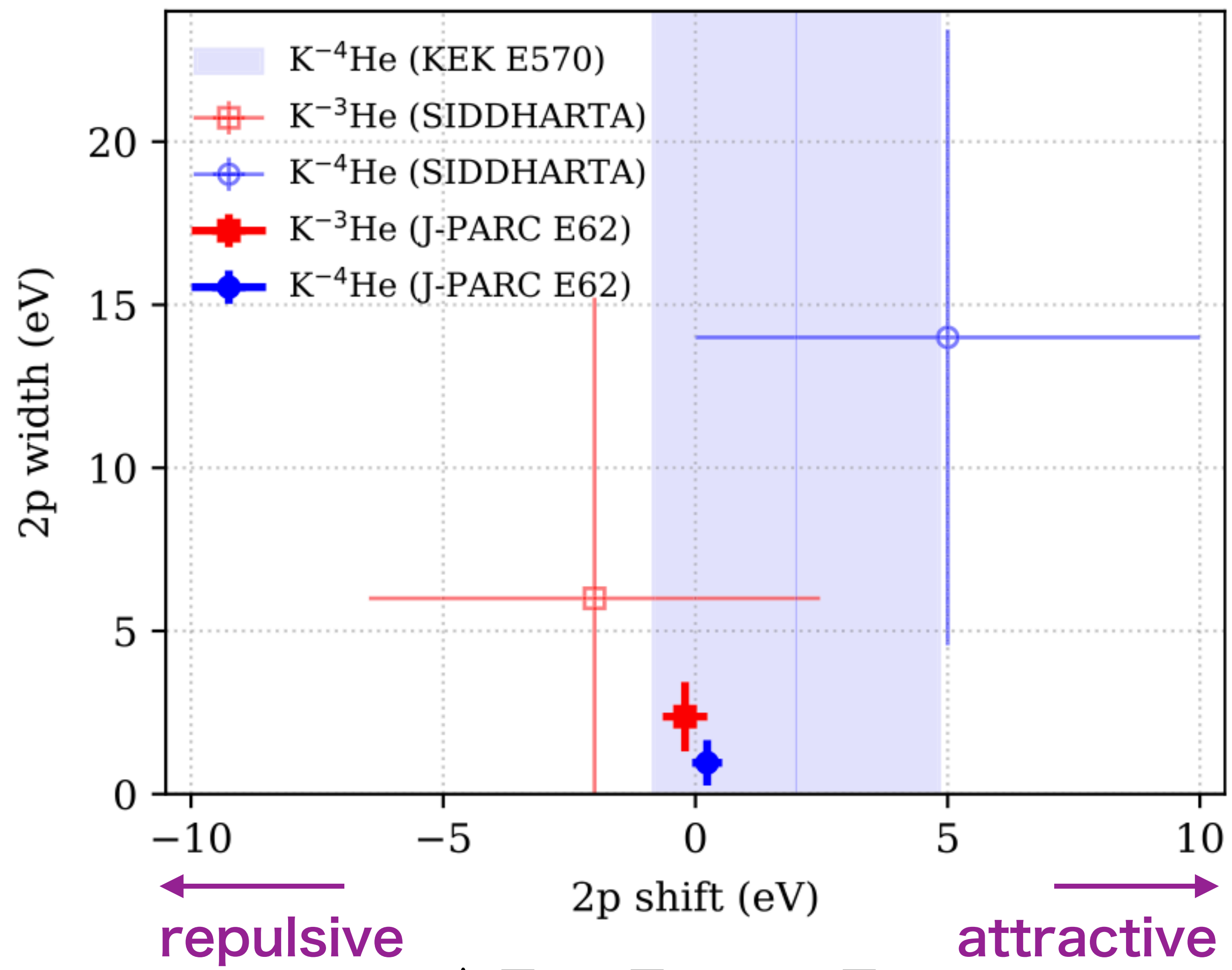
$$\Delta E_{2p}^{isotope} = -0.4 \pm 0.5(stat.) \pm 0.2(syst.)\ \mathrm{eV}.$$

Comparison with past experiments





Error bar: quadratic sum of stat. & sys.



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

x 25 energy resolution

x 10 precision (shift&width)

Exclude large shifts&widths

Systematics errors (20211018)

	^{3}He shift	^{3}He width	^{4}He shift	^{4}He width	
stat.	**0.40**	**0.99**	**0.27**	**0.63**	
syst.	**0.18**	**0.38**	**0.11**	**0.33**	quad. sum
calibration	**0.17**		**0.09**		
resolution	0.01	0.15	0.01	0.11	
tail	0.03	0.10	0.03	0.10	fraction ±10%, length ±20%
binning	0.05	0.10	0.05	0.10	0.5/1/2 eV bin, shift half a bin
background	0.01	0.10	0.02	0.20	compare pol0/pol1/pol2
fit range	0.01	0.30	0.01	0.20	min / max
robustness	0.05	0.33	0.05	0.30	binning + bg + fit range

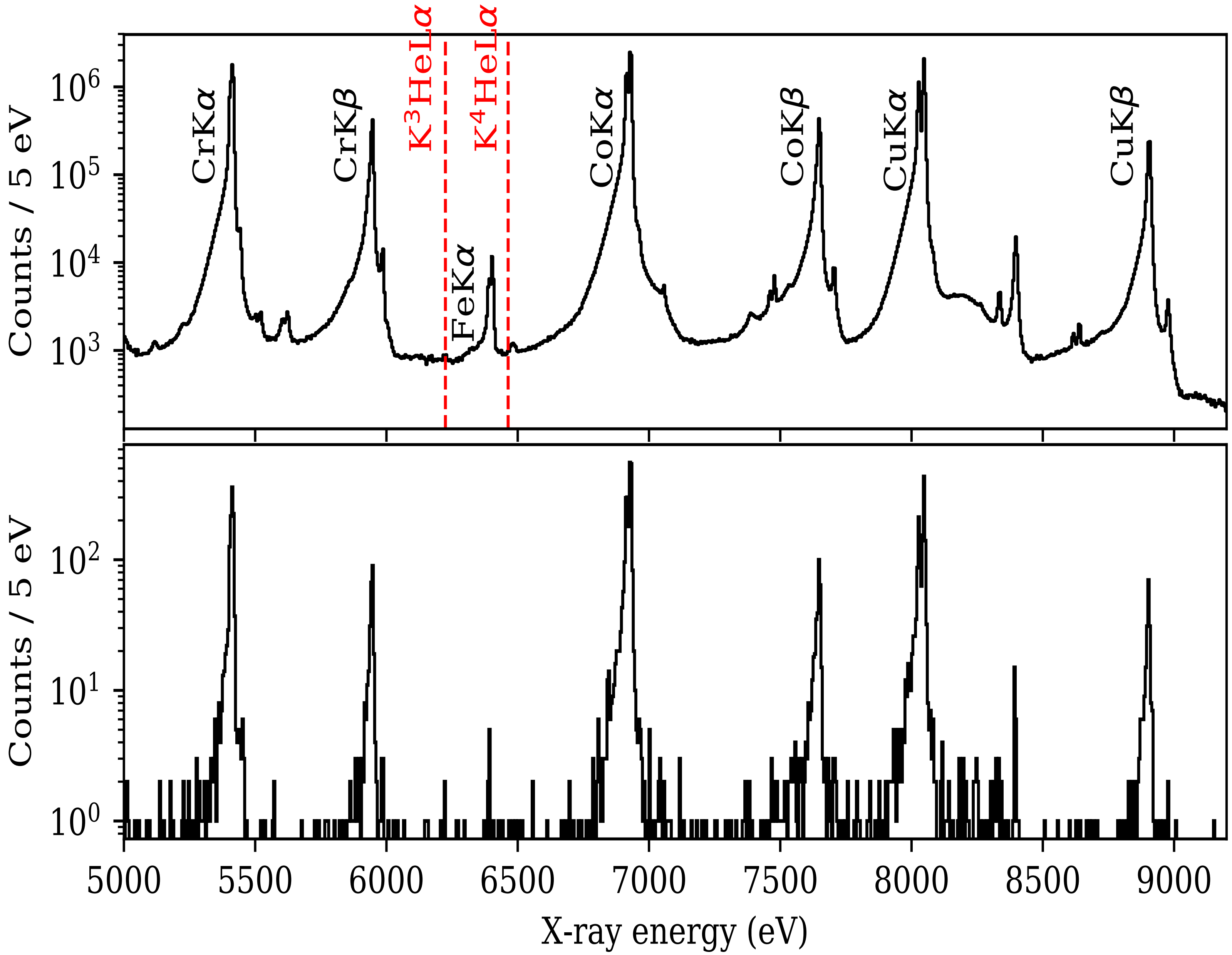
✓ Precision of the absolute energy scale is the dominant systematics

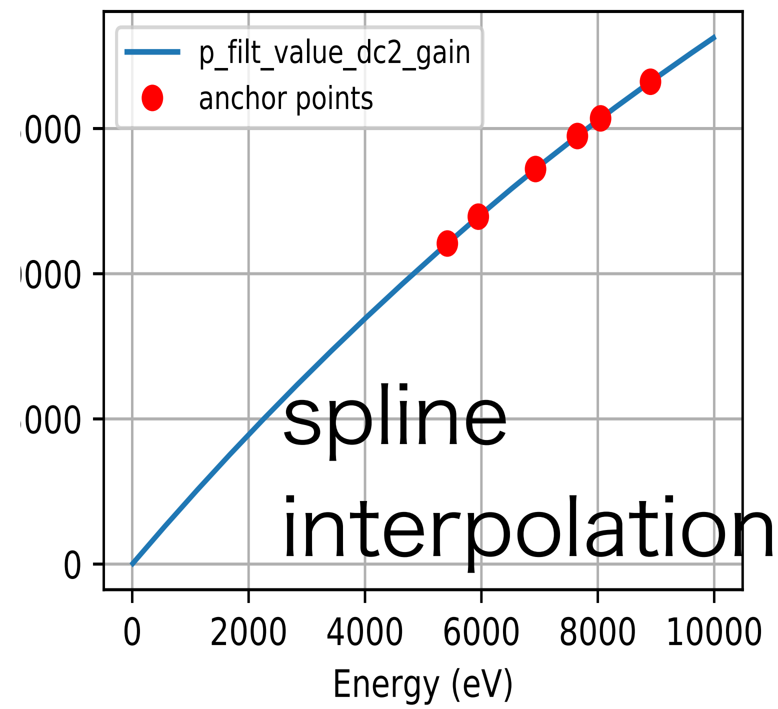
In-beam calibration

X-ray tube w/ Cr, Co, Cu

All dataset All channels

1 sub dataset 1 channel





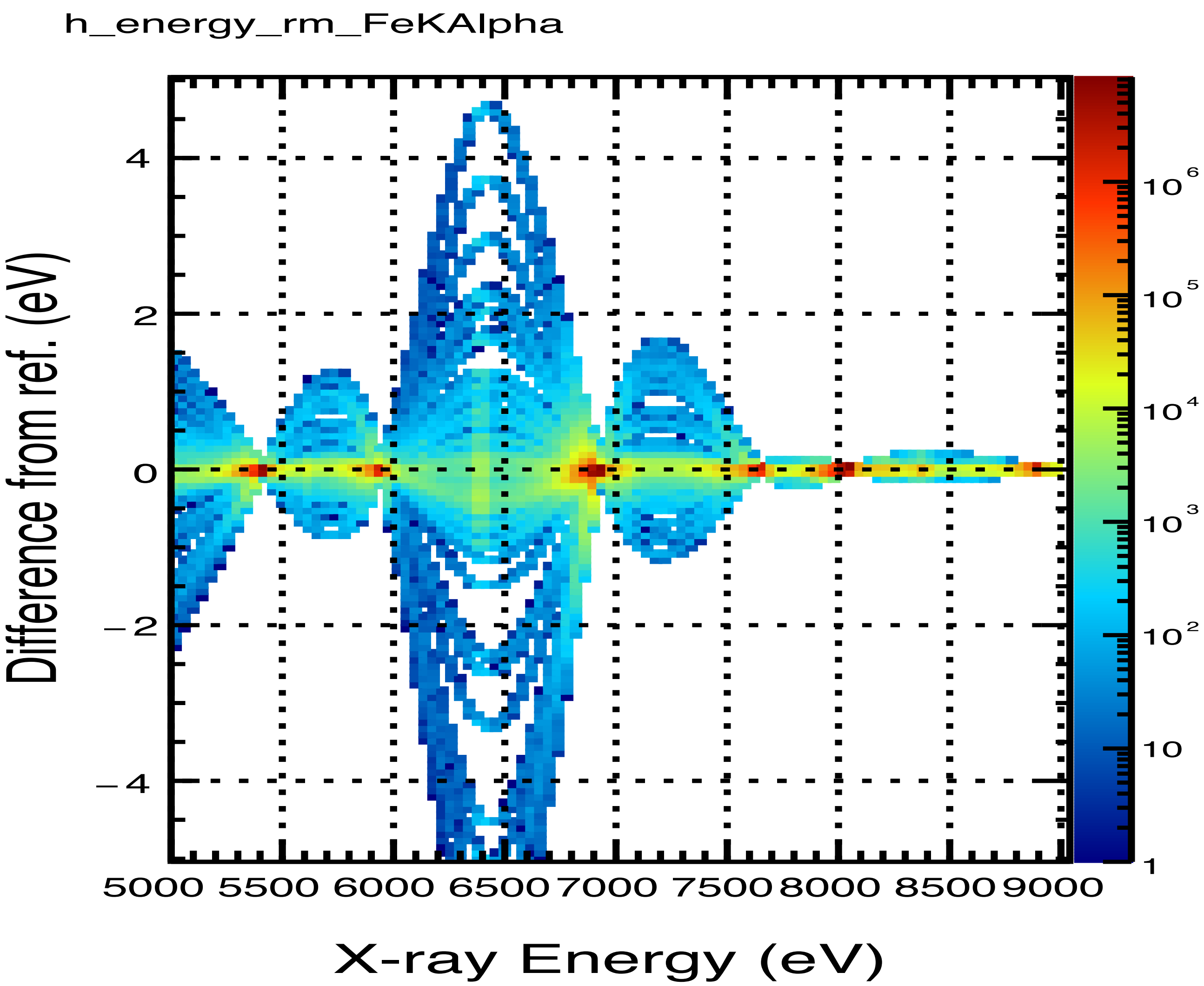
✓ X-ray tube was always ON during the experiment

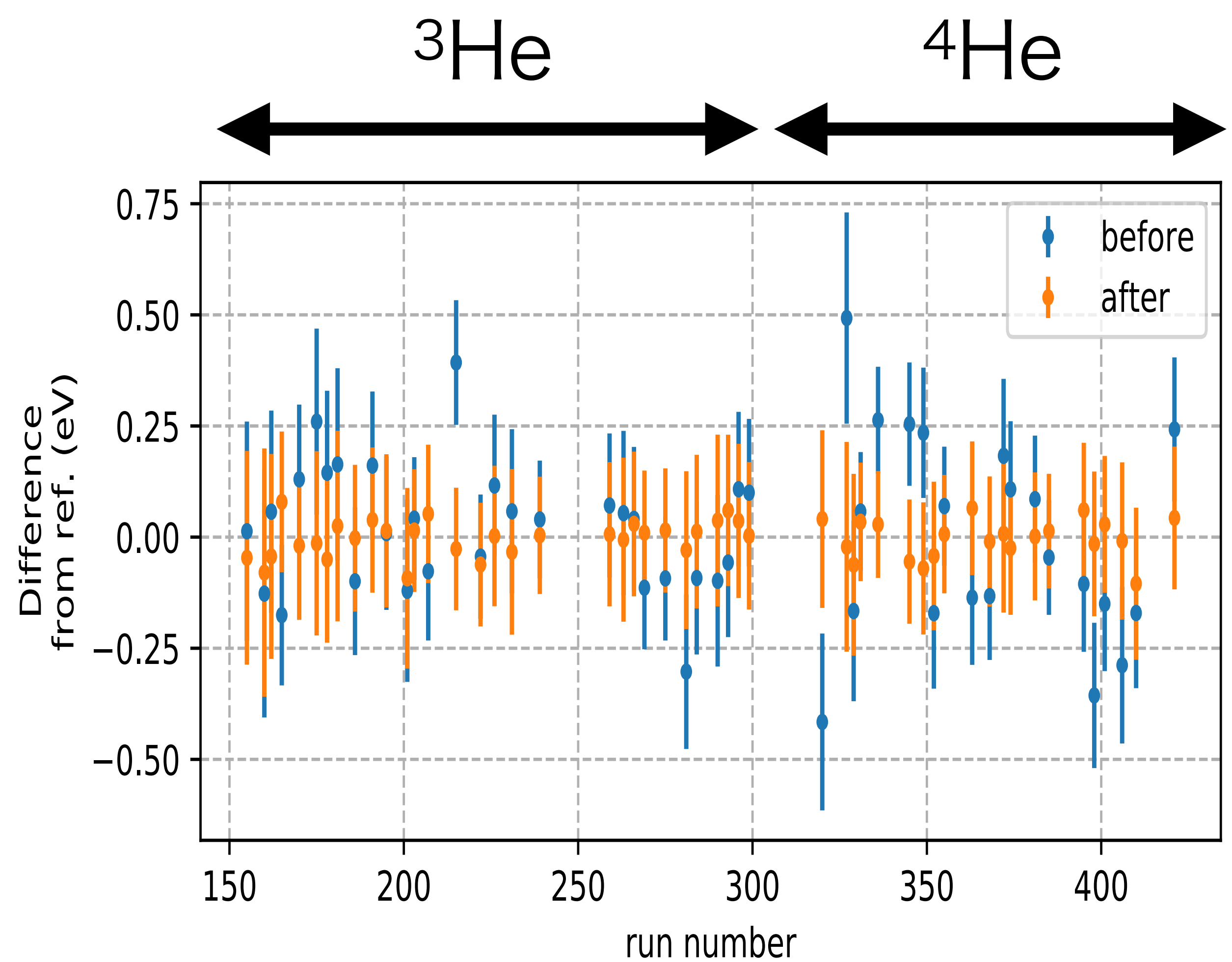
✓ Pixel-by-pixel calibration every 4~8 hours

Difficulties in Calibration

Difference between calibration with all 7 points & calibration without FeKa

Run dependence of the FeKa peak position

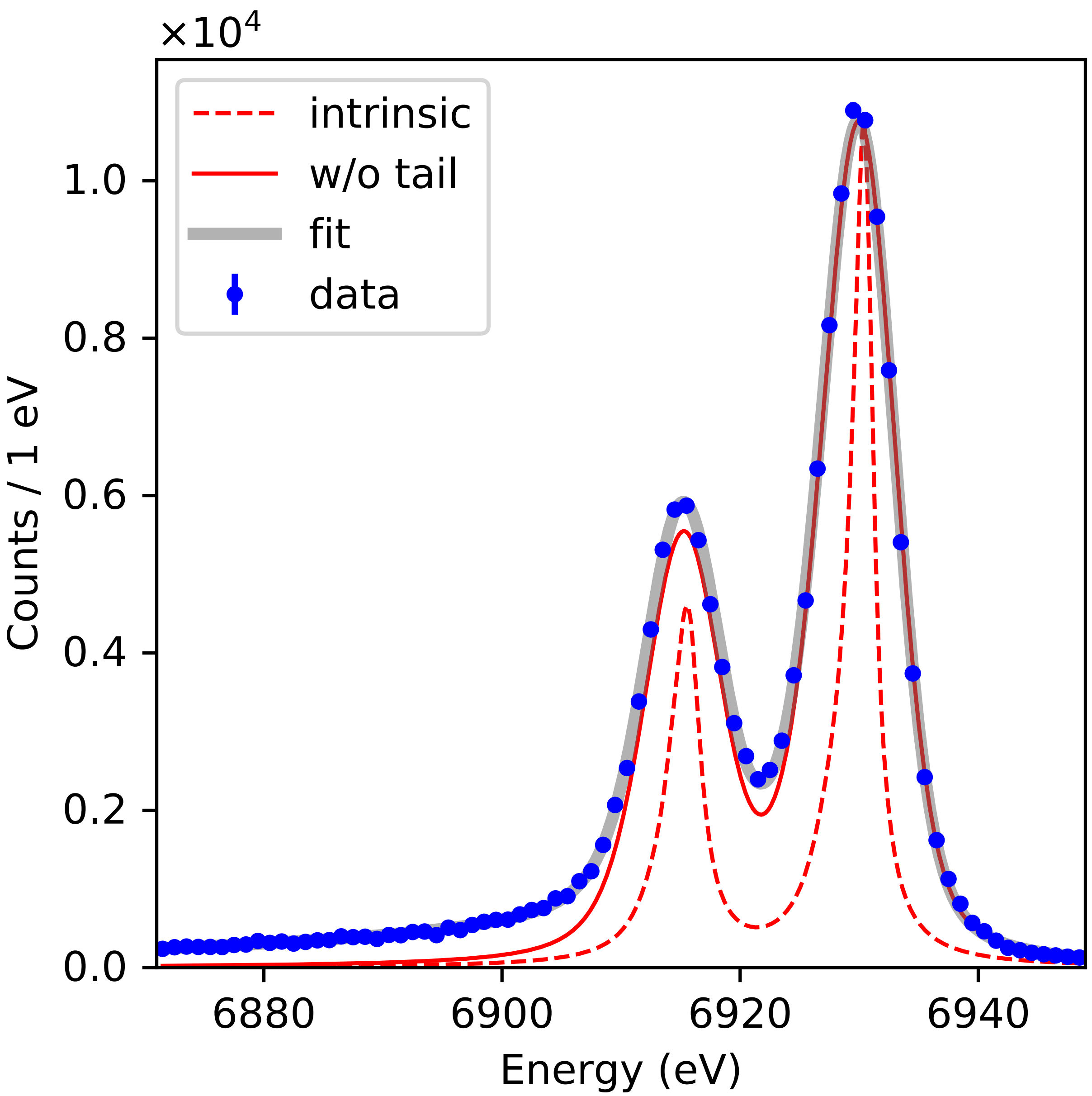




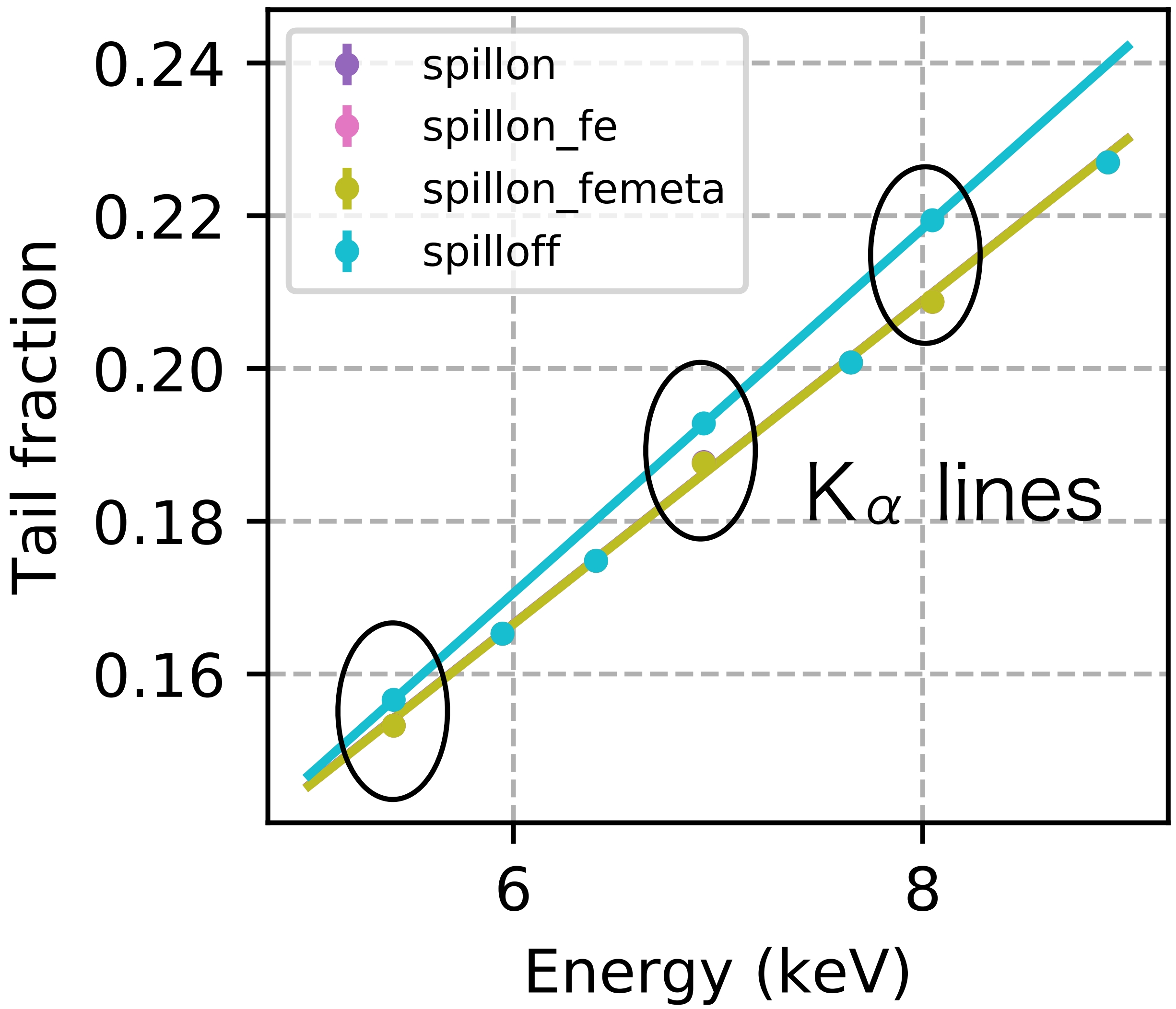
- Calibration curve = Non-linear energy response of the TES is not known precisely, differs by pixel, and changes in time.
  → **Interpolation uncertainty. need good calibration line near the science line**

Response function: not a problem

Gaussian plus a low-energy exponential tail



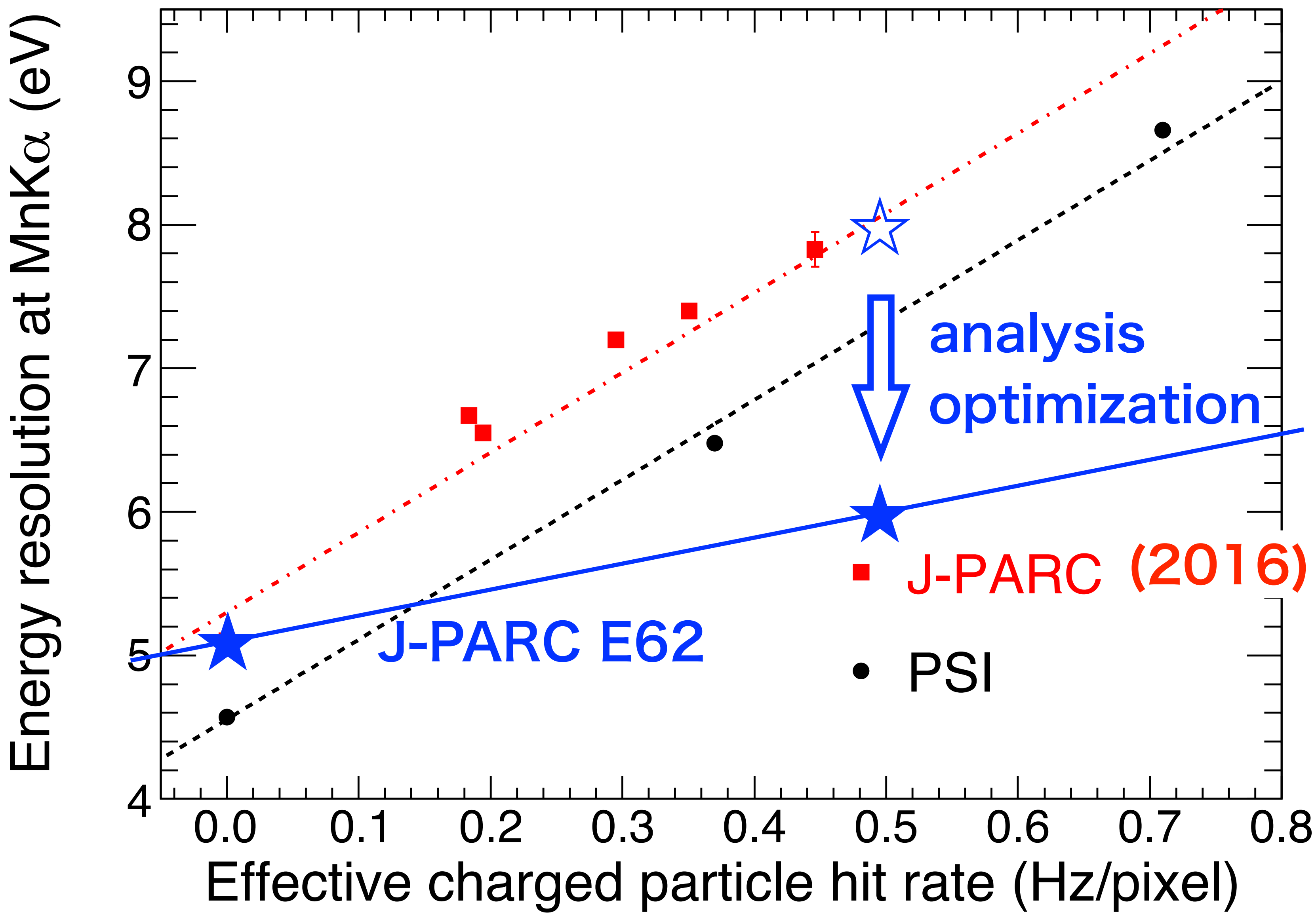
Energy dependence of the tail parameters is well under control

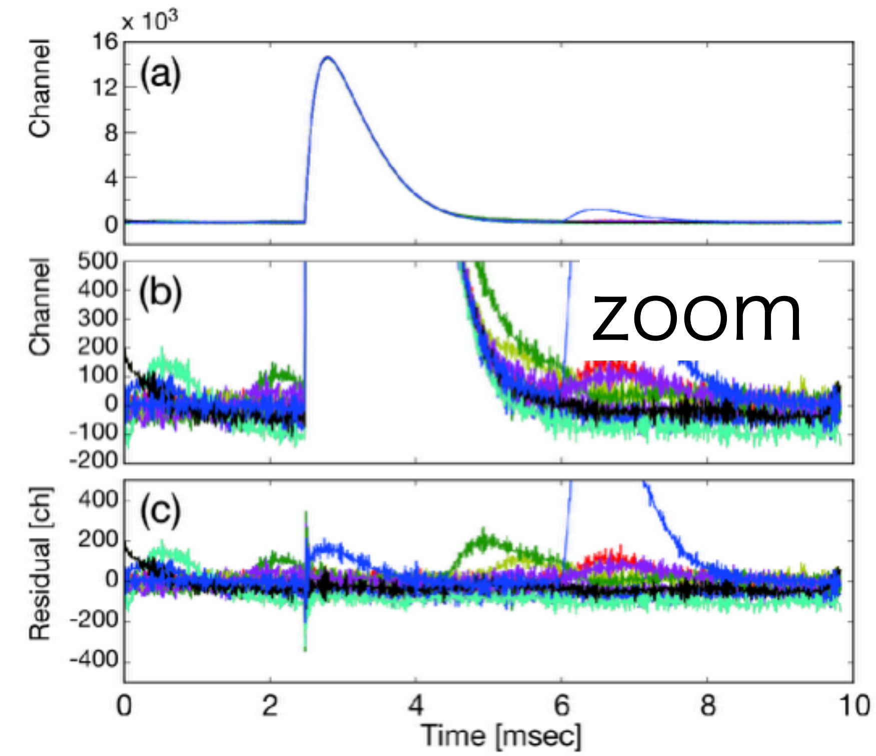


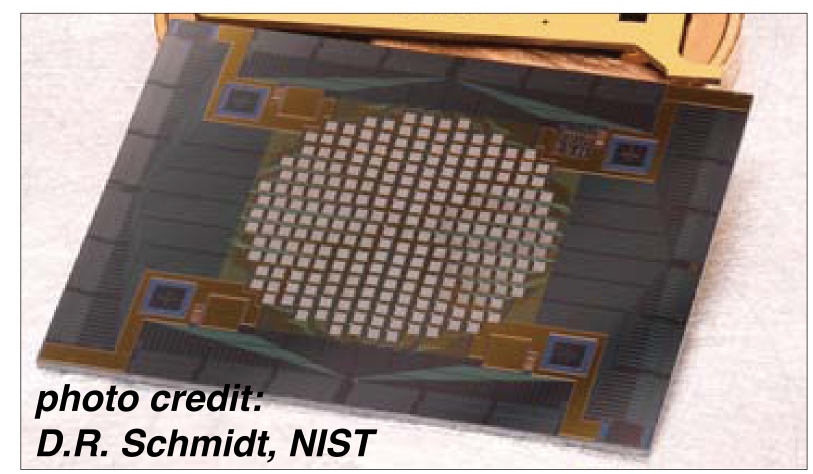
- We understand the response function rather well.
- Uncertainty of the tail parameters does not affect peak position so much (+-10% -> 0.03 eV)

Difficulties
in charged-beam environments

Resolution deterioration by beam





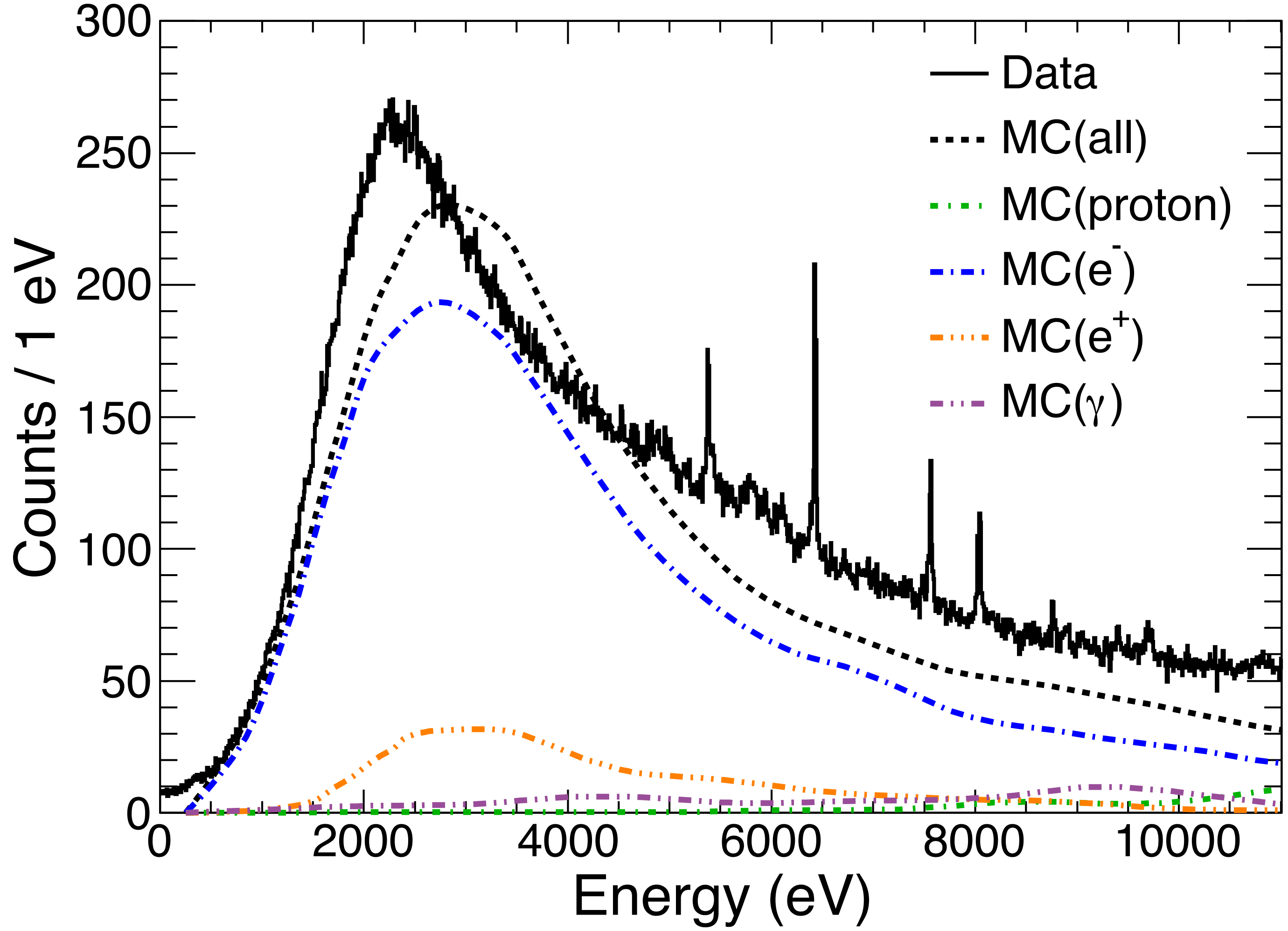


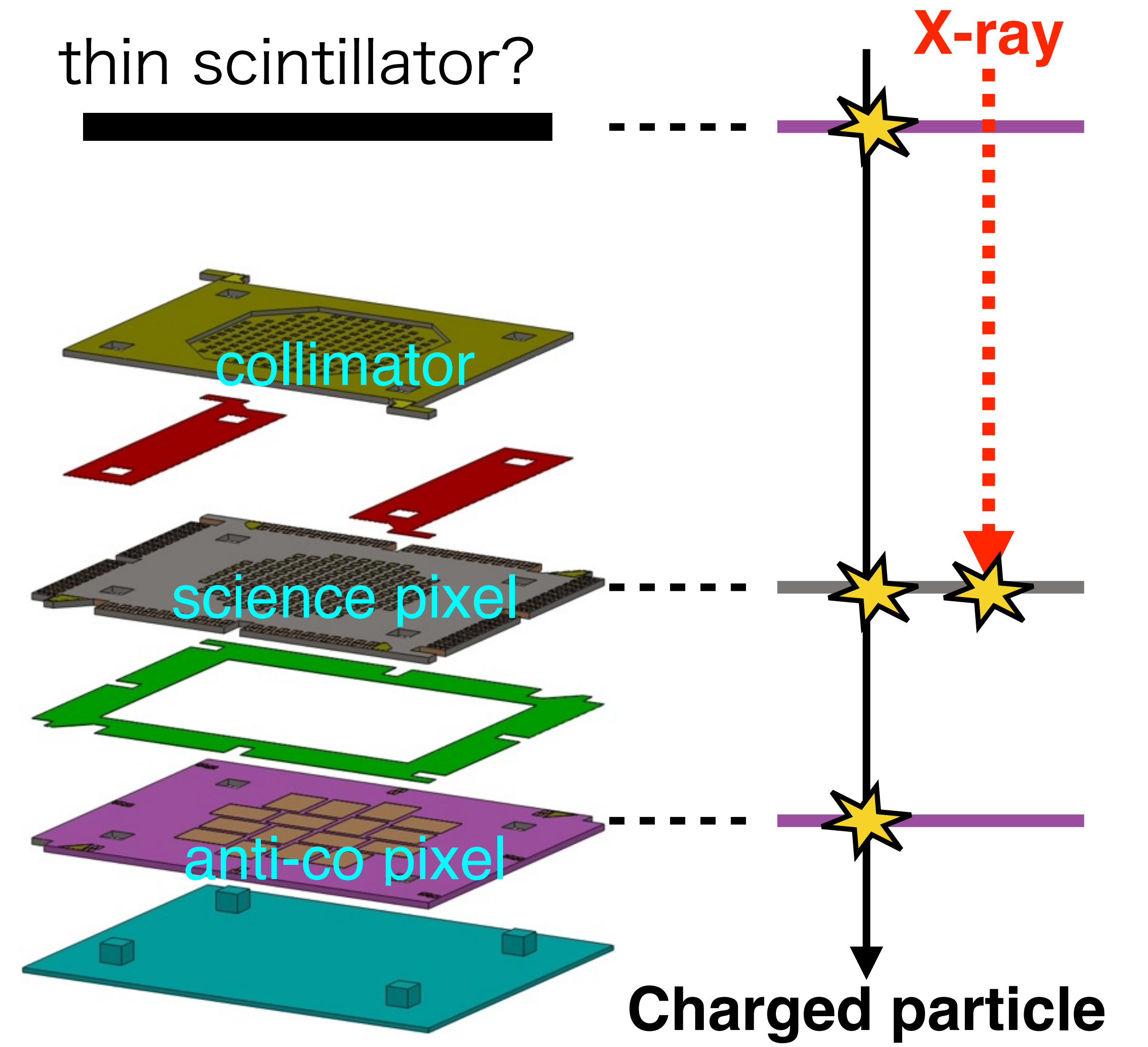
- Small bumps by charged-particle hits on array deteriorate resolution
- In E62: 180 cps from X-ray tube + 20 cps (triggered pulses) from Beam
  -> 100 count /spill / array ~ effectively **0.5 cps/pixel from beam**
- We partically recovered the resolution at a cost of 1/3 event loss.
- Important to shield from charged particles as much as possible.

Charged-particle background

90% transmission
@ 6 keV, 0.1 mm plastic

In-beam spectrum w/o photon source at PSI





- MIP particles give keV energies on 4um-thick Bi absorber -> main background in the final X-ray spectrum
- I would like to consider VETO counter in front of the TES.

Future propescts

K$^-$ atom with TES: Future propescts

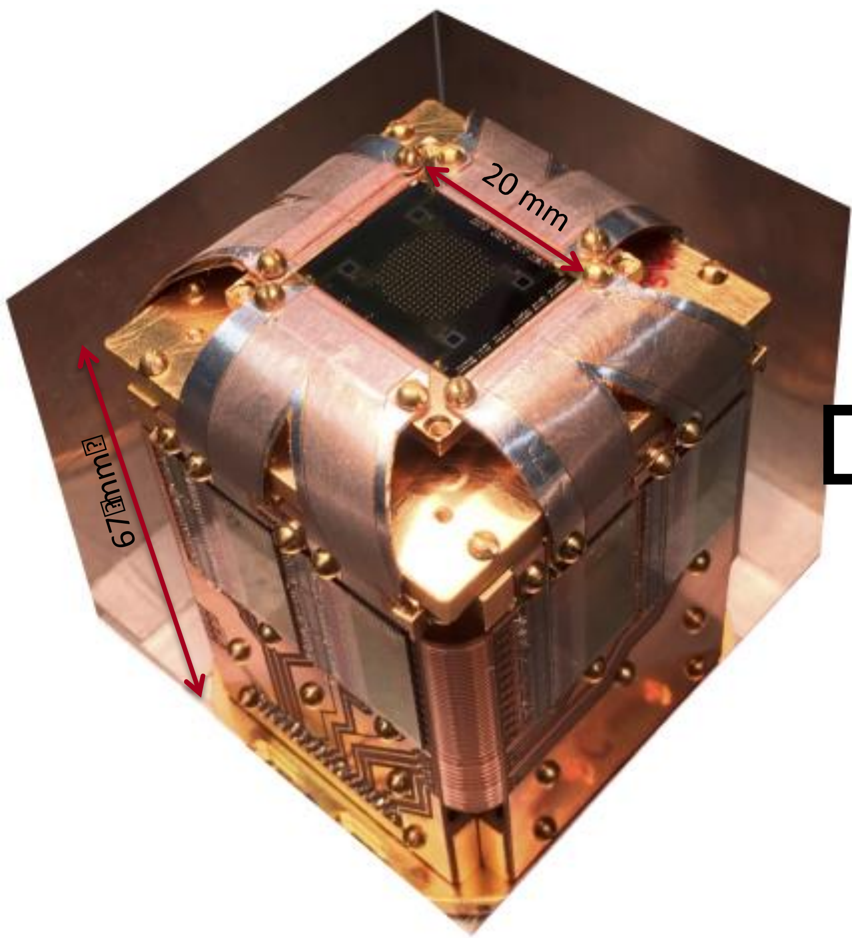
- Present system is applicable **up to 15 keV**, limited by TES saturation and stopping power of 4 um thick Bi absorber
    - Strong interaction in light kaonic atoms (K$^-$ $^{6/7}$Li, …)
    - Charged kaon mass (K$^-$N, K$^-$O, K$^-$Ne, …)

- New system for higher energy **up to 100 keV** region is under development for a muonic atom project
(QED test under strong electric field)
    - Upper level of high-Z kaonic atoms to separate 1N/mN contributions (proposed in NPA 915 (2013) 170–178)
    - Σ-atoms, Ξ-atoms etc…
    - Many unknown technical issues:
    detector performance, calibration lines, …

More pixels with new readout

Douglas Bennett @ NIST

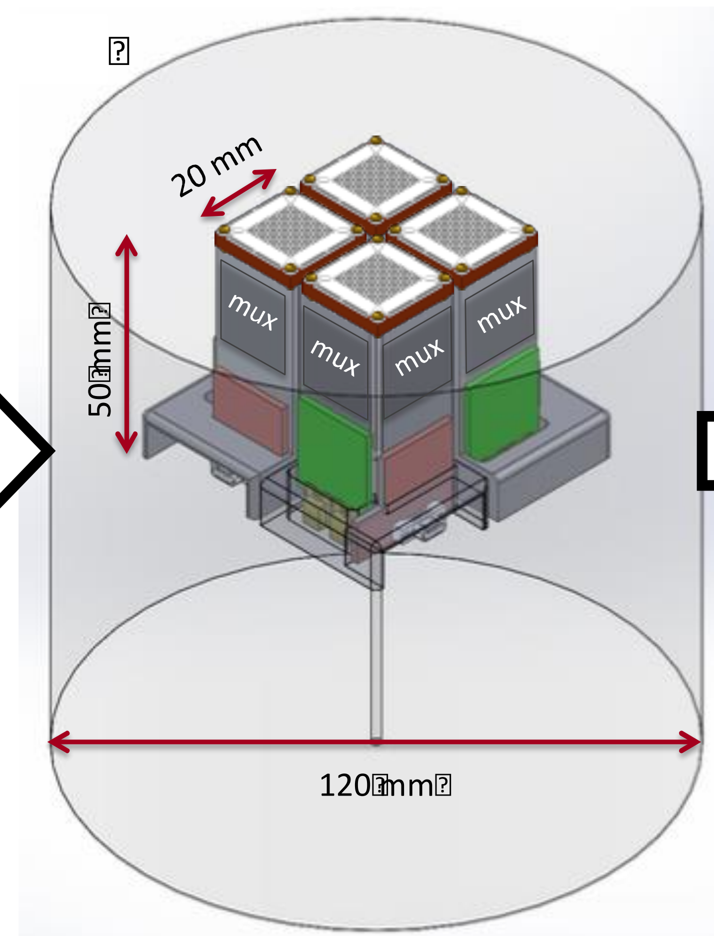
TDM “snout”



240 TESs readout with TDM

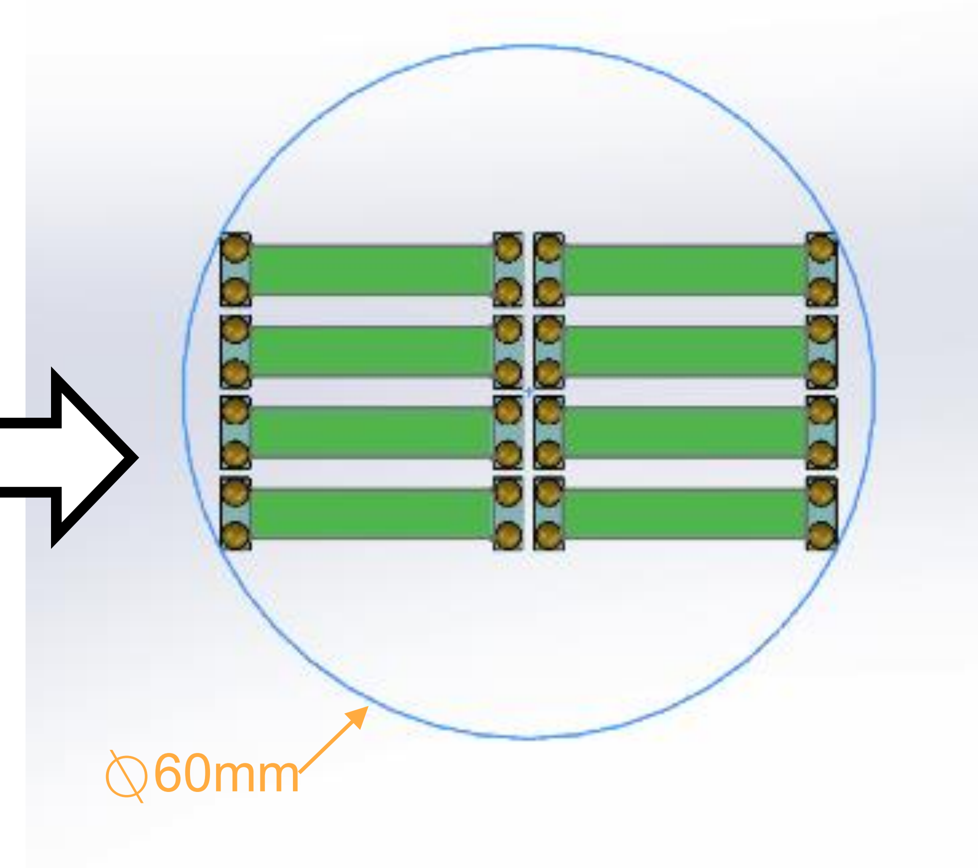
2010~

“microsnouts”



1024 TESs readout with μMUX

2020~



1260 TESs per microsnout
8 microsnouts
10,080 TESs

in a few years?

- Rapidly improving scalability using the new readout technology.

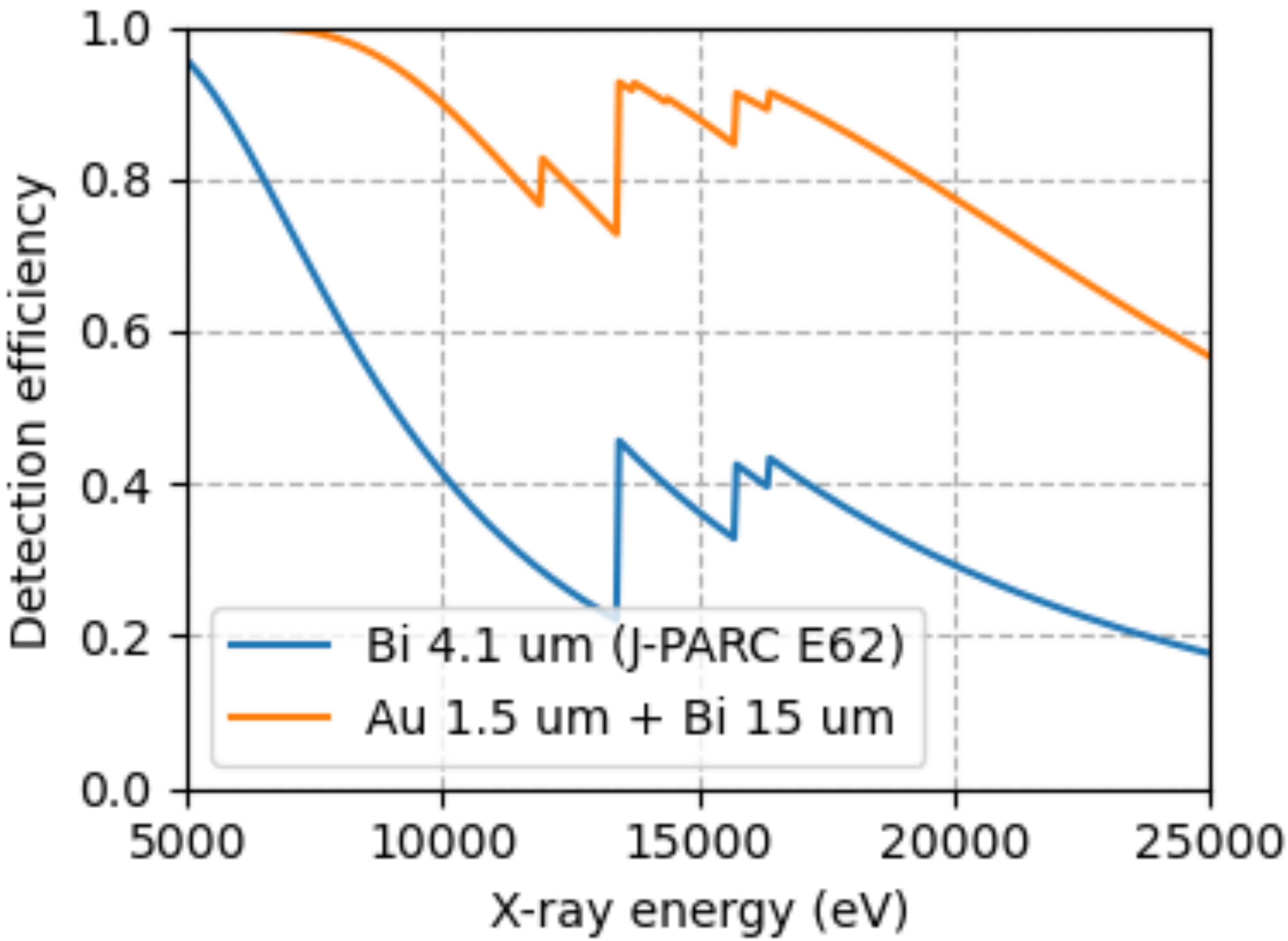
TES under development

Douglas Bennett @ NIST

	J-PARC E62	Gamma-ray	50 keV	20 keV
Saturation energy	20 keV	150 keV	70 keV	50 keV
Absorber material	Bi	Sn	Au/ Bi	Au/Bi
Absorber thickness	4 um	120~250 um	3 um / 15 um	1.5 um / 15 um
Absorber area	320 x 305 um	1.3 x 1.3 mm	700 x 700 um	700 x 700 um
Pixel number	240	96	150	150
Total collection area	**23 mm²**	**160 mm²**	**70 mm²**	**70 mm²**
ΔE (FWHM)	**5 eV @ 6 keV**	**40 eV @ 130 keV**	**20 eV @ 40 keV**	**8 eV @ 20 keV**

- ✓ New cryostat, new readout system
- ✓ Available soon (for μ-atoms)
- ✓ Multiple units can be installed

(Near) future low-E TES



- 80% efficiency upto 20 keV with 8 eV FWHM resolution

X-ray line candidates for low-E TES

	Z	ρ g/L @STP	boiling point	9-8	8-7	7-6	6-5	5-4	4-3	3-2
He	2	0.1785	4.2							done 6.2 6.4
Li	3	534								**15.1 15.3**
K- N	7	1.250	78			4.6	**7.6**	**14**	30	
K- O	8	1.429	90.2			**6**	**10**	**18**	40	
K- Ne	10	0.900	27	4.2	**6.1**	**9.4**	**15.6**	28.8	62	

- Kaon mass: N_2, O_2, Ne, ···
  - multiple lines, targets, densities should be measured
- Strong interaction: K-$^{6/7}$Li 3d-2p
  - shift 6~15 eV, width 30~40 eV depending on potential models

Rough yield, precision at DAFNE

- E62 TES array (**Bi 4um, 23 mm²**) at 6 cm from target center
- N_2 target, ϕ10cm x L10cm, at -15cm from IP
  - 0.15MPa, 120K (or 0.375MPa@300K)

X-ray energy (keV)	6	10	15
stopped K / day (5 pb^{-1})		50000	
X-ray yield		50%	
TES acceptance		**0.03%**	
X-rays on detector	7.5	7.5	7.5
Efficiency	85%	40%	35%
X-ray count / day	6.375	3	2.625
X-ray count / month(20d)	**127.5**	**60**	**52.5**
resolution (FWHM)	6	8	10
statistical error (eV)	0.23	0.44	0.59
K mass error (keV)	**18.58**	**21.67**	**19.30**

PDG error: 13keV

Rough yield, precision at DAFNE

- new TES array (**Bi 15um, 70 mm²**) at 6 cm from target center
- N_2 target, ϕ10cm x L10cm, at 15cm from IP
  - 0.15MPa, 120K (or 0.375MPa@300K)

X-ray energy (keV)	6	10	15
stopped K / day (5 pb^{-1})		50000	
X-ray yield		50%	
TES acceptance		**0.09%**	
X-rays on detector	22.5	22.5	22.5
Efficiency	99%	85%	80%
X-ray count / day	22.275	19.125	18
X-ray count / month(20d)	**445.5**	**382.5**	**360**
resolution (FWHM)	8	8	8
statistical error (eV)	0.16	0.17	0.18
K mass error (keV)	**13.25**	**8.58**	**5.90**

PDG error: 13keV

Summary

- TES microcalorimeters are unique detector to realize both an eV-scale energy resolution & reasonable collecting efficiency.

- We have successfully measured kaonic helium 3d→2p X-rays with TES in J-PARC E62. Letter was recently accepted by PRL.

- Challenges to use TES in kaonic-atom experiments.
  - Absolute energy calibration
  - Energy resolution deterioration by charged-particle hits
  - Charged particle background

- TES detector technology is rapidlly advancing.
  More pixels and for higher energies.

- TES at DAFNE would be feasible. (in terms of X-ray yield)