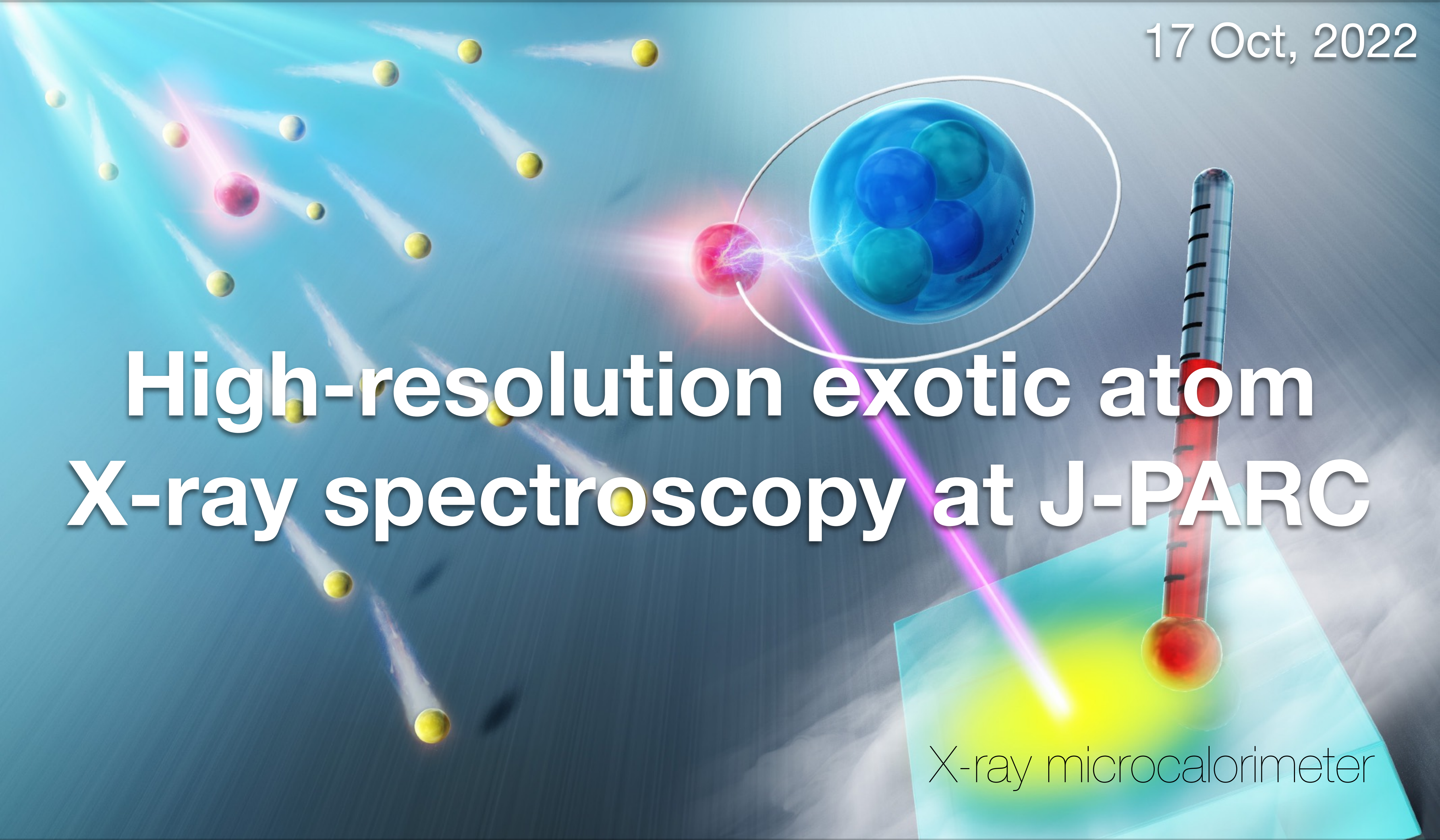
ECT* workshop EXOTICO @Trento, Italy

"EXOTIc atoms meet nuclear COllisions for a new frontier precision era in low-energy strangeness nuclear physics"

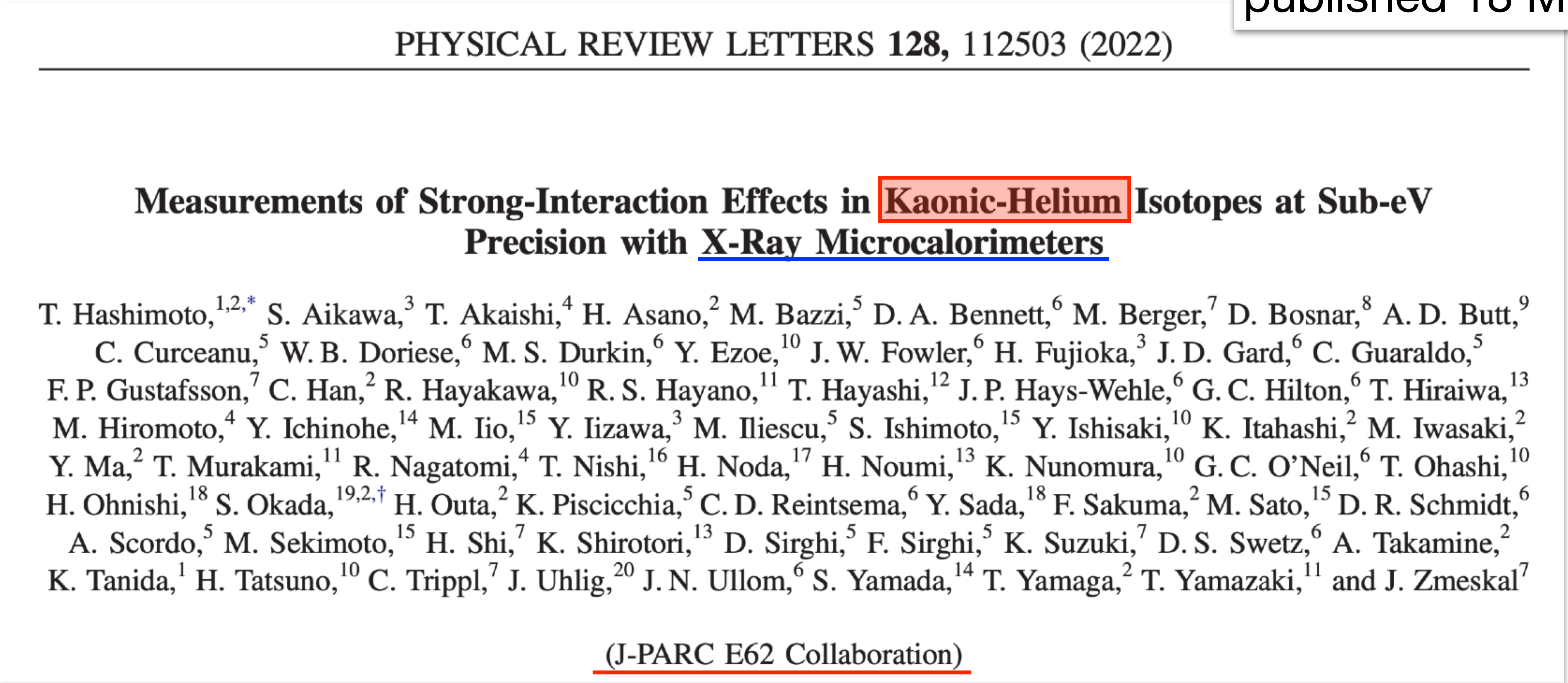
17 Oct, 2022

High-resolution exotic atom X-ray spectroscopy at J-PARC



Shinji OKADA (Chubu Univ.)
for HEATES / J-PARC E62 collaboration

published 18 Mar, 2022



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

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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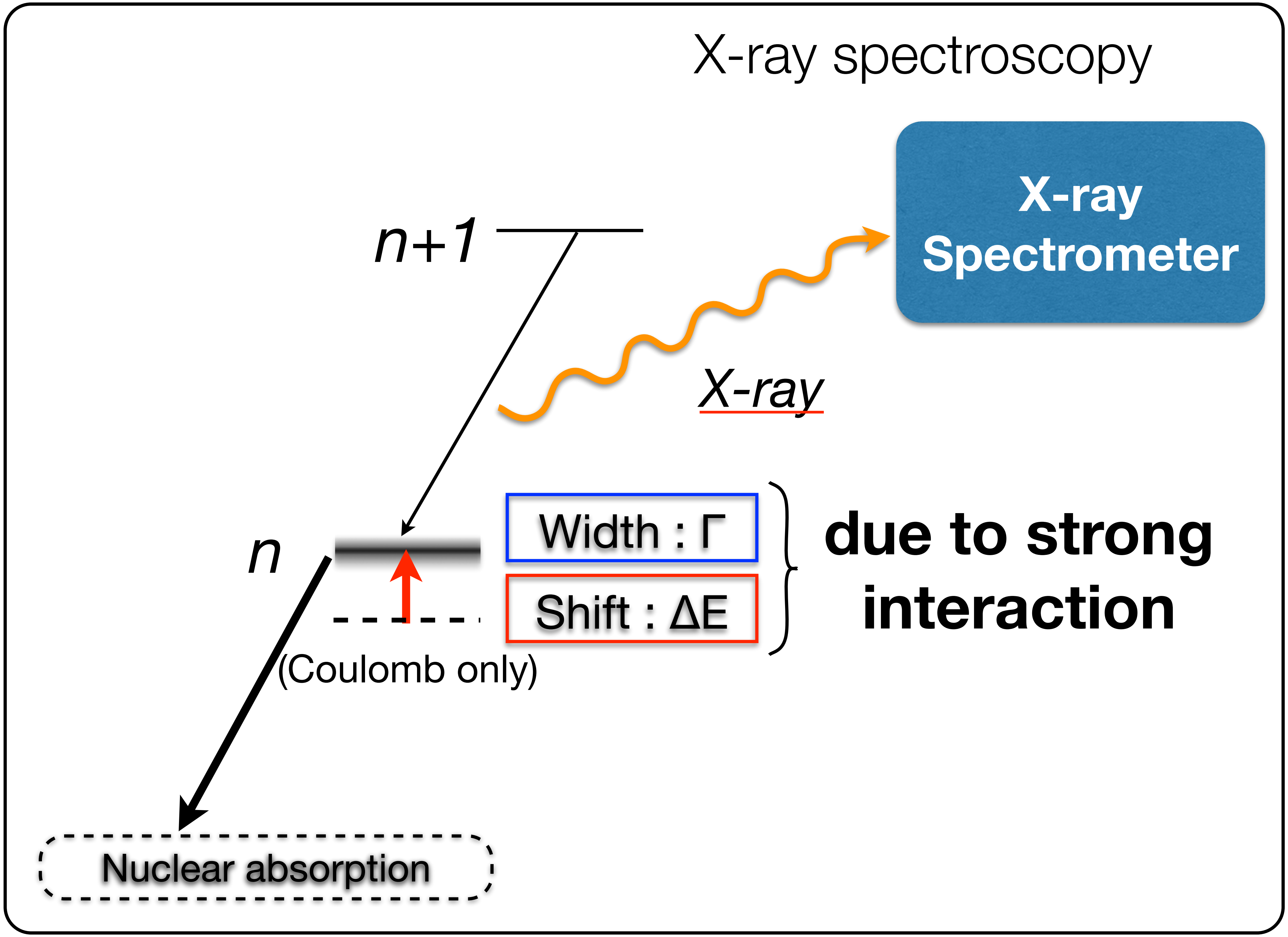
2. X-ray microcalorimeter
3. Experiment : J-PARC E62
4. Results
5. Summary & Outlook

1. Introduction

Kaonic atom X-rays



due to strong interaction

Scattering length & potential

Kaonic hydrogen & deuterium → **K^bar N scattering length**

$$\epsilon_{1s} + i\Gamma_{1s}/2 = 2\alpha^3\,\mu_r^2\,\boxed{a_{K^-p}}\,[1 + 2\alpha\,\mu_r\,(1 - \ln\alpha)\,\boxed{a_{K^-p}}]$$

Shift

Width

K-p Kα x-ray

Scattering length

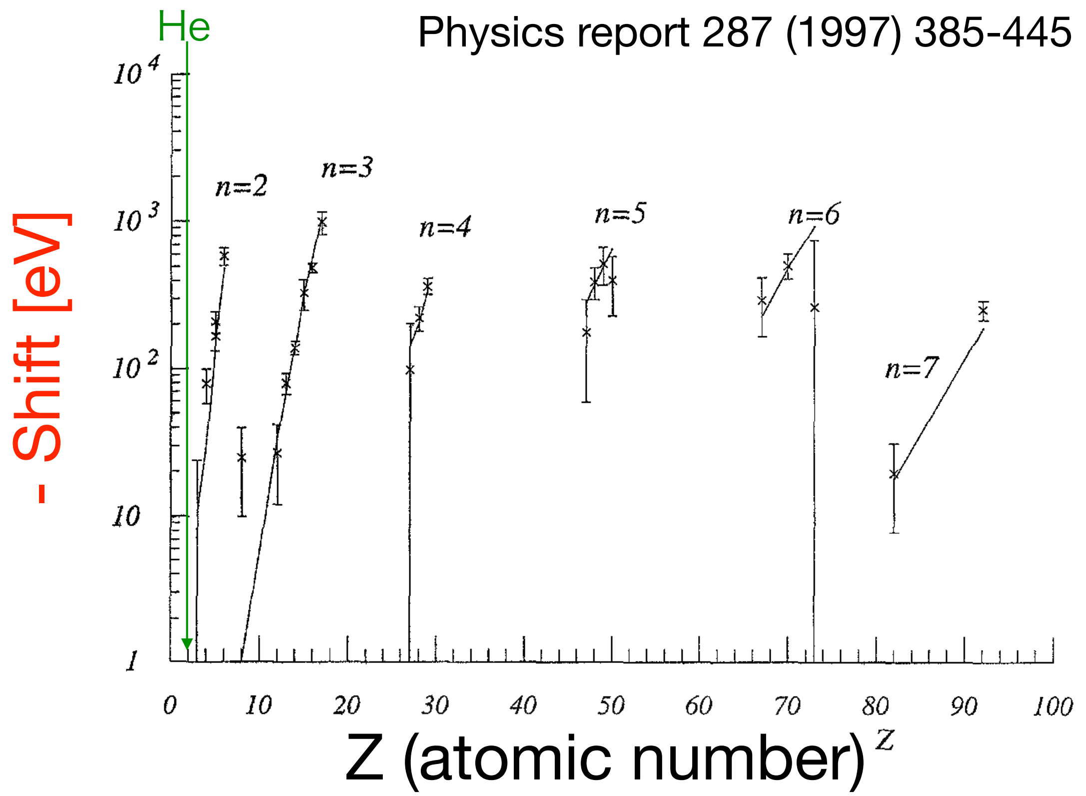
U.-G. Meißner et al, Eur Phys J C35 (2004) 349
(Deser-Type relation with isospin-braking correction)

$$a_{K^-p} = \frac{1}{2}(a_0 + a_1)$$

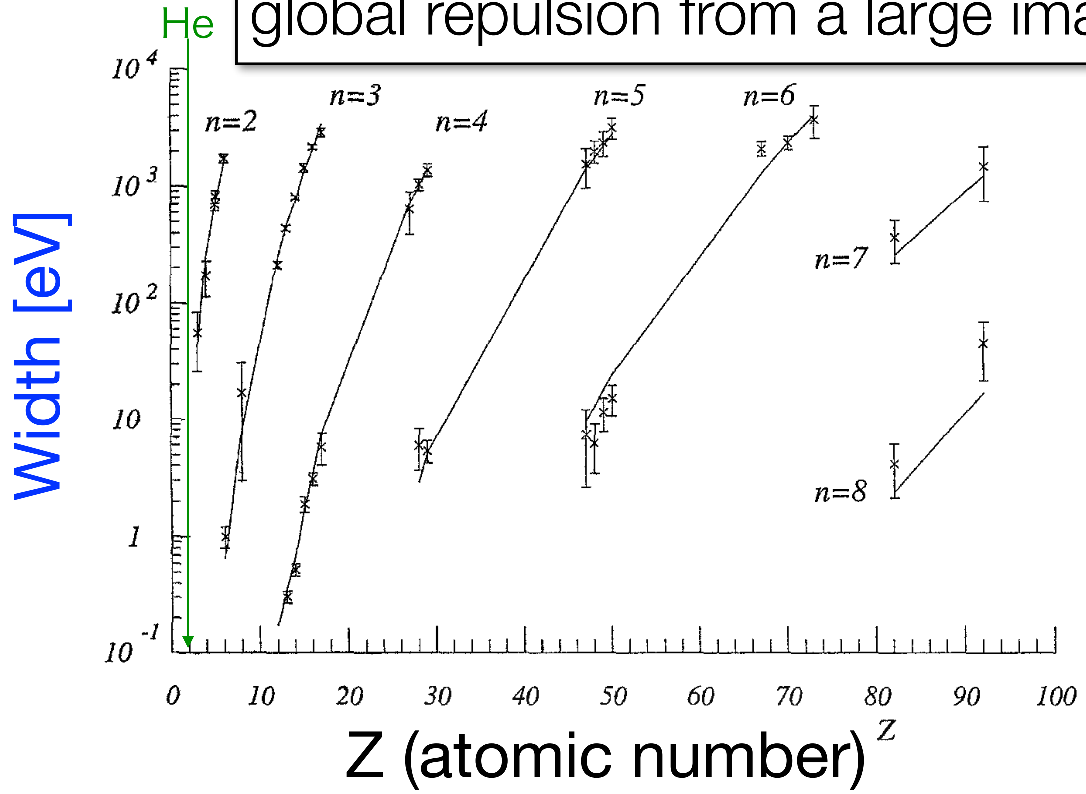
$$a_{K^-d} = \frac{k}{4}(a_0 + 3a_1) + C$$

Heavier kaonic atoms → **Attractive optical potential**

Physics report 287 (1997) 385-445

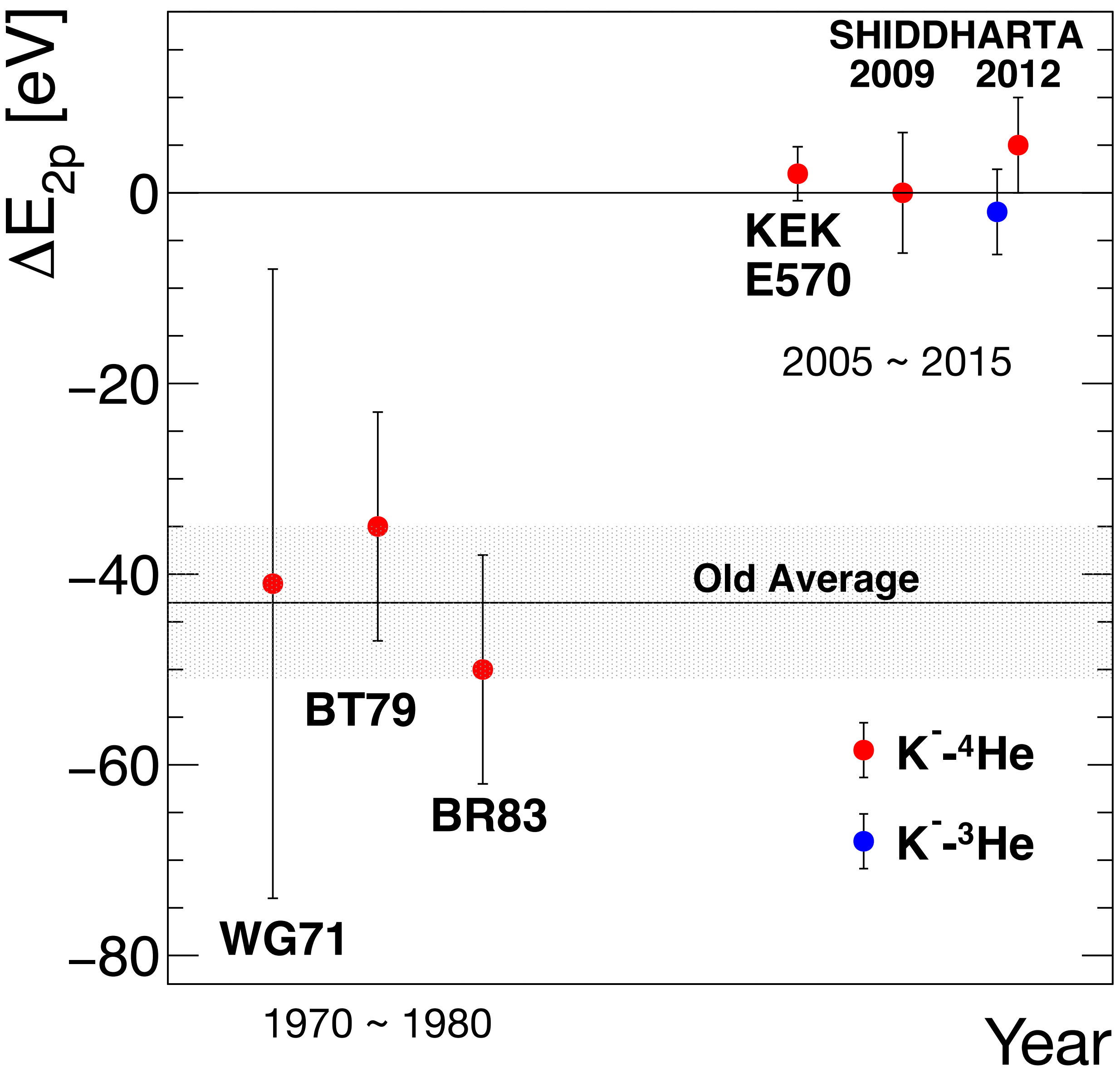


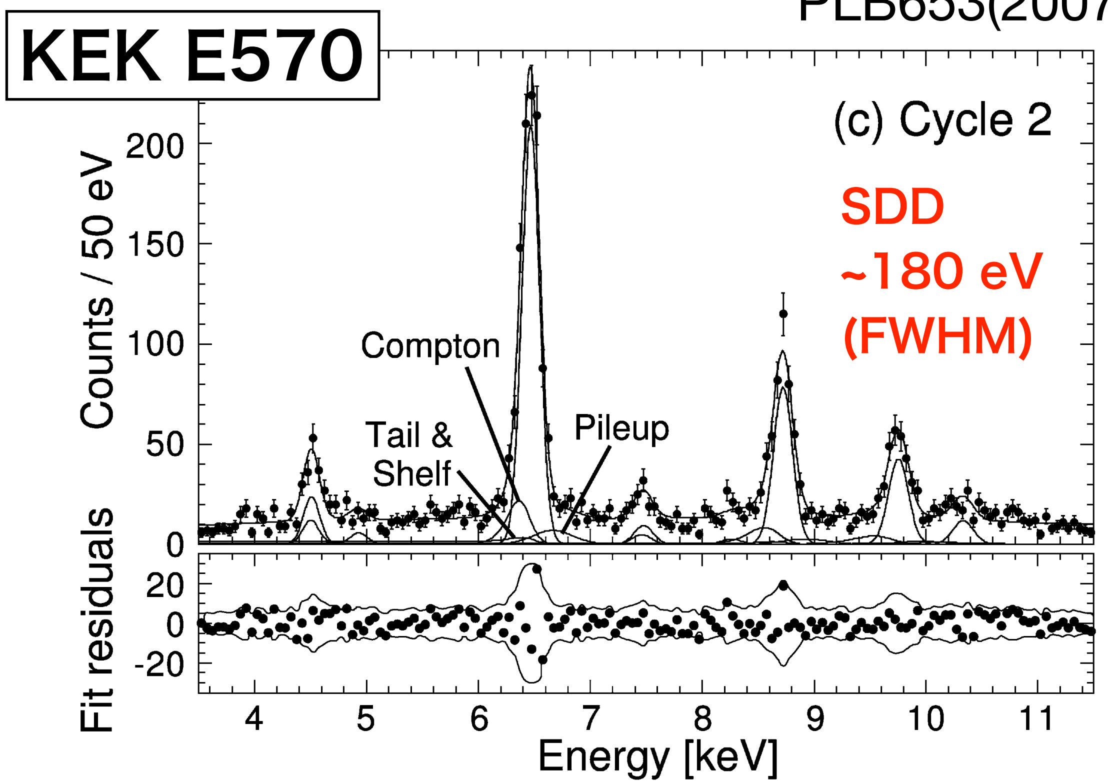
global repulsion from a large imaginary part



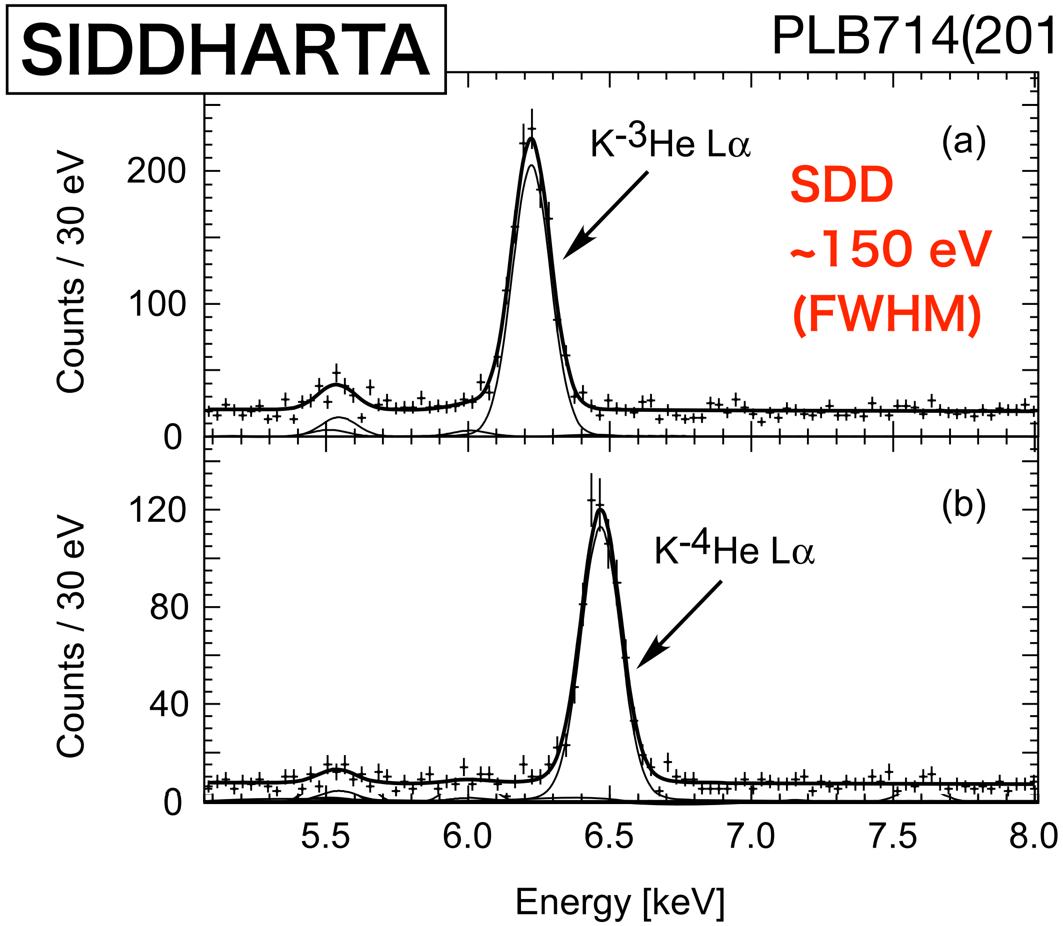
Kaonic helium : experiments

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





PLB653(2007)387



PLB714(2012)40

✓ Old “puzzle” has been solved

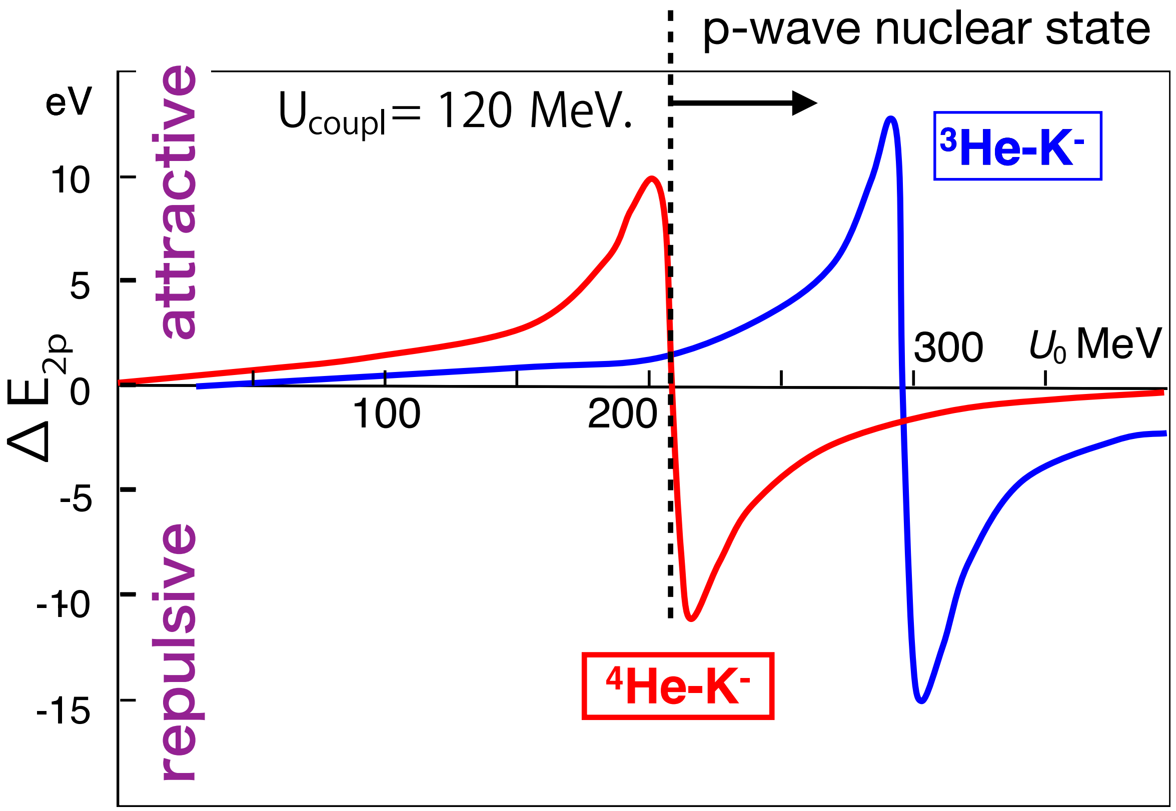
✓ Shift < 5 eV, Width < 20 eV

✓ **Precision ~ 2 eV << Resolution 150 eV**

Kaonic helium : theoretical values

Special interest in connection with light kaonic nuclei

Y. Akaishi (EXA2005 proceedings)



coupled-channel potential

J. Yamagata-Sekihara, S. Hirenzaki
(Private communication)

Width : ~2 eV

	Phenomenological $V_{opt}(r=0)$~ - (180+73i) MeV	**Chiral** $V_{opt}(r=0)$~ - (40+55i) MeV
K-^{4}He	-0.4 eV	-0.1 eV
K-^{3}He	0.2 eV	-0.1 eV

E. Friedman
(NPA959(2017)66)

KM (Kyoto-Munich) KN amplitudes within their sub-threshold kinematics model + a phenomenological term

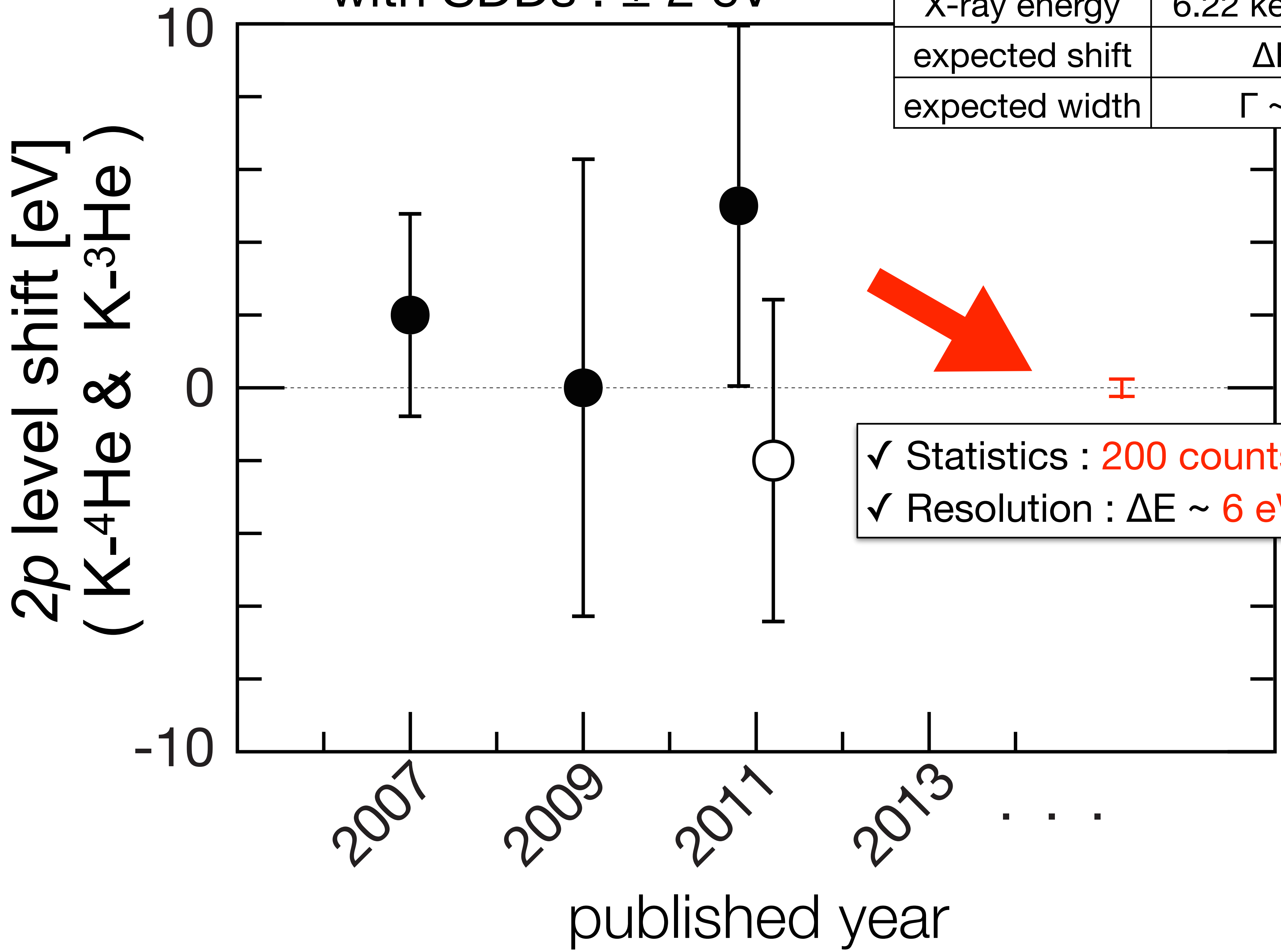
	Shift (eV)	Width (eV)
K-^{4}He	0.00	1.6
K-^{3}He	0.22	2.3

- ✓ Is there large shift > 1 eV, and width > 5 eV ?
- ✓ Sign of the shift ? (attractive shift → no p-wave nuclear bound state?)

→ eV-scale energy resolution is mandatory

Need one-order better precision

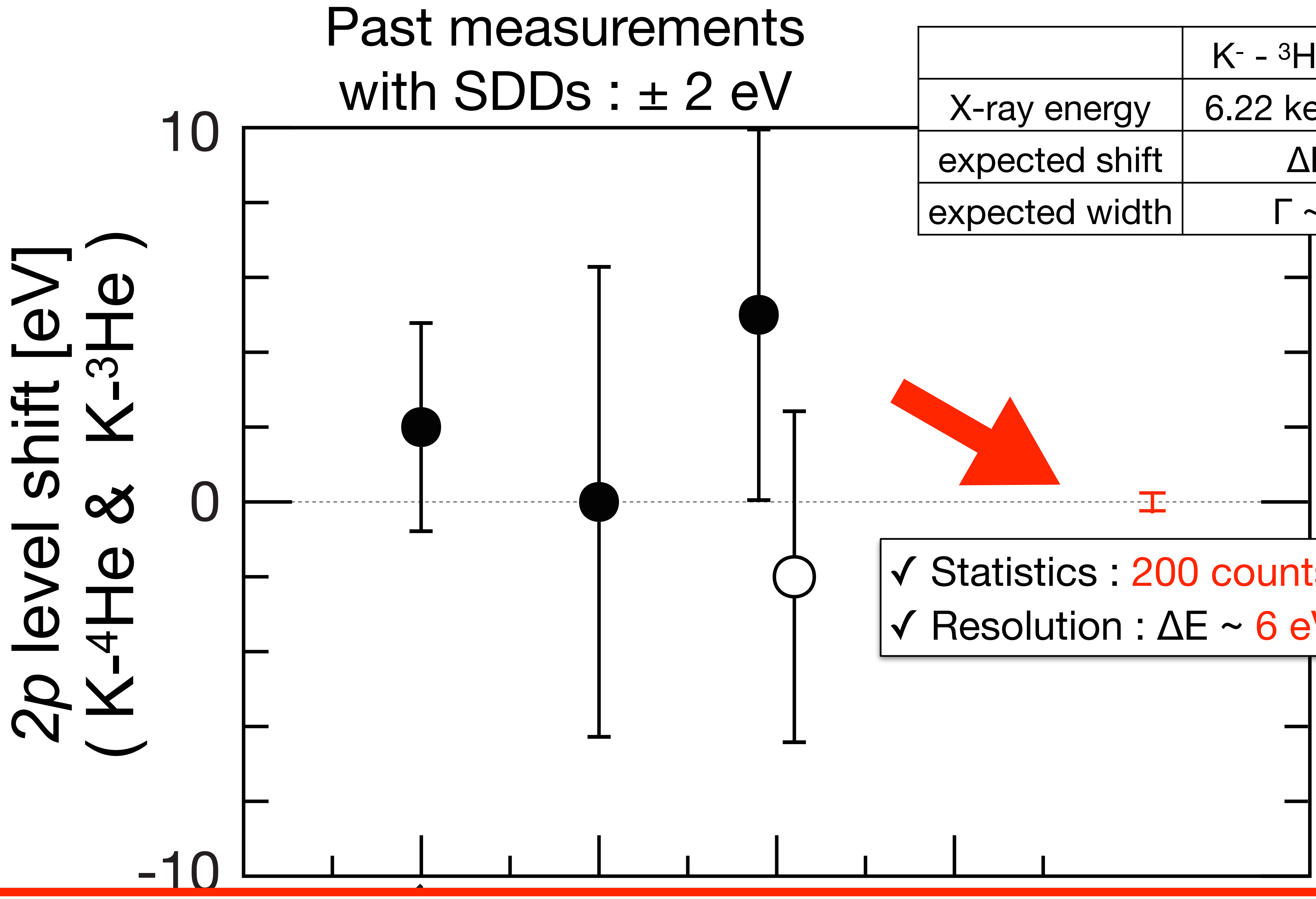
Past measurements with SDDs : ± 2 eV



	K^- - ^{3}He	K^- - ^{4}He
X-ray energy	6.22 keV	6.46 keV
expected shift	ΔE < 1 eV	
expected width	Γ ~ 2 - 5 eV	

✓ Statistics : 200 counts
✓ Resolution : ΔE ~ 6 eV FWHM

Need one-order better precision



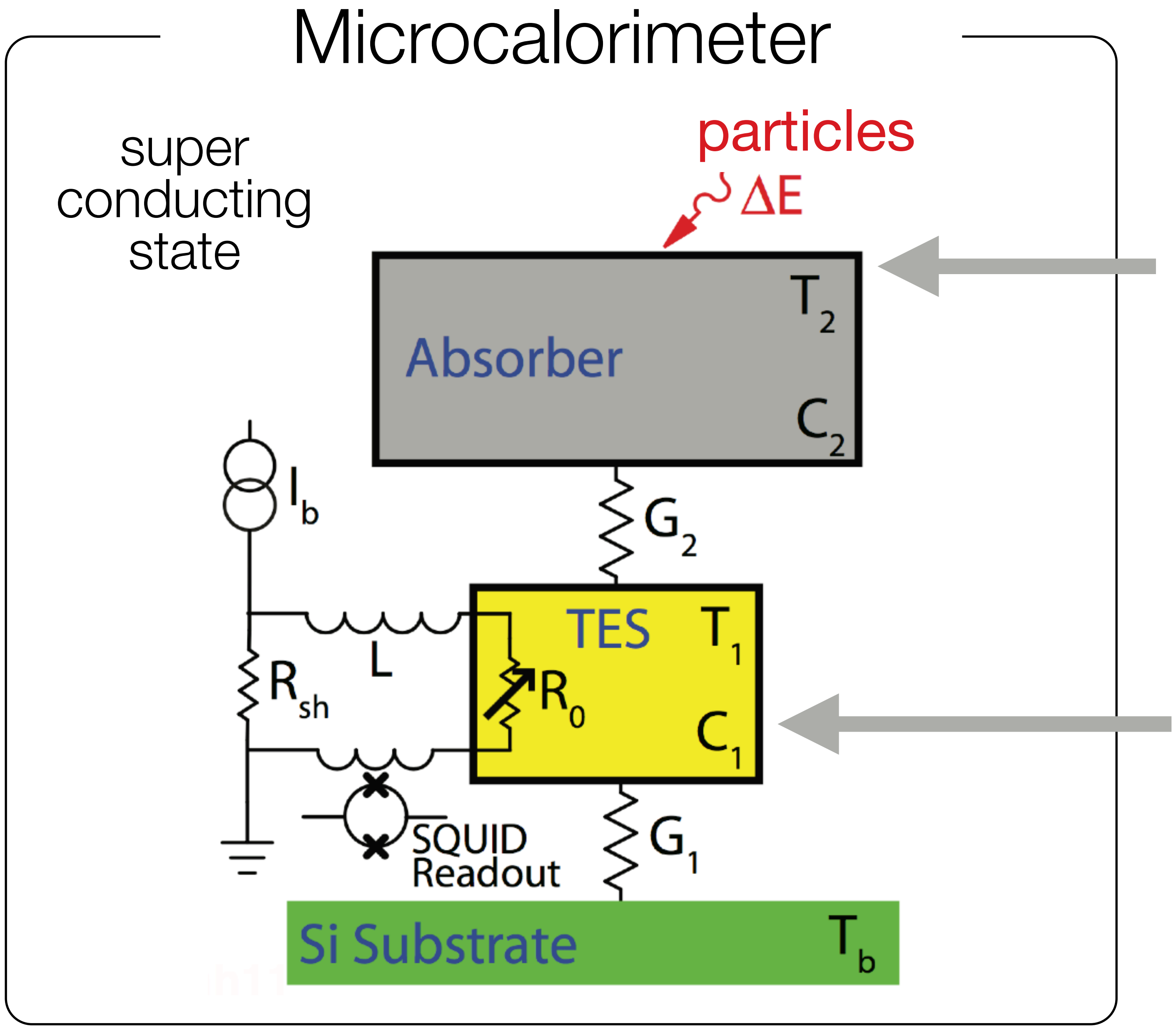
	K^- - ^{3}He	K^- - ^{4}He
X-ray energy	6.22 keV	6.46 keV
expected shift	ΔE < 1 eV	
expected width	Γ ~ 2 - 5 eV	

✓ Statistics : 200 counts
✓ Resolution : ΔE ~ 6 eV FWHM

“**high resolution** + **Large detection area**” is essential

2. X-ray microcalorimeter

TES microcalorimeter



1. incident particles absorbed

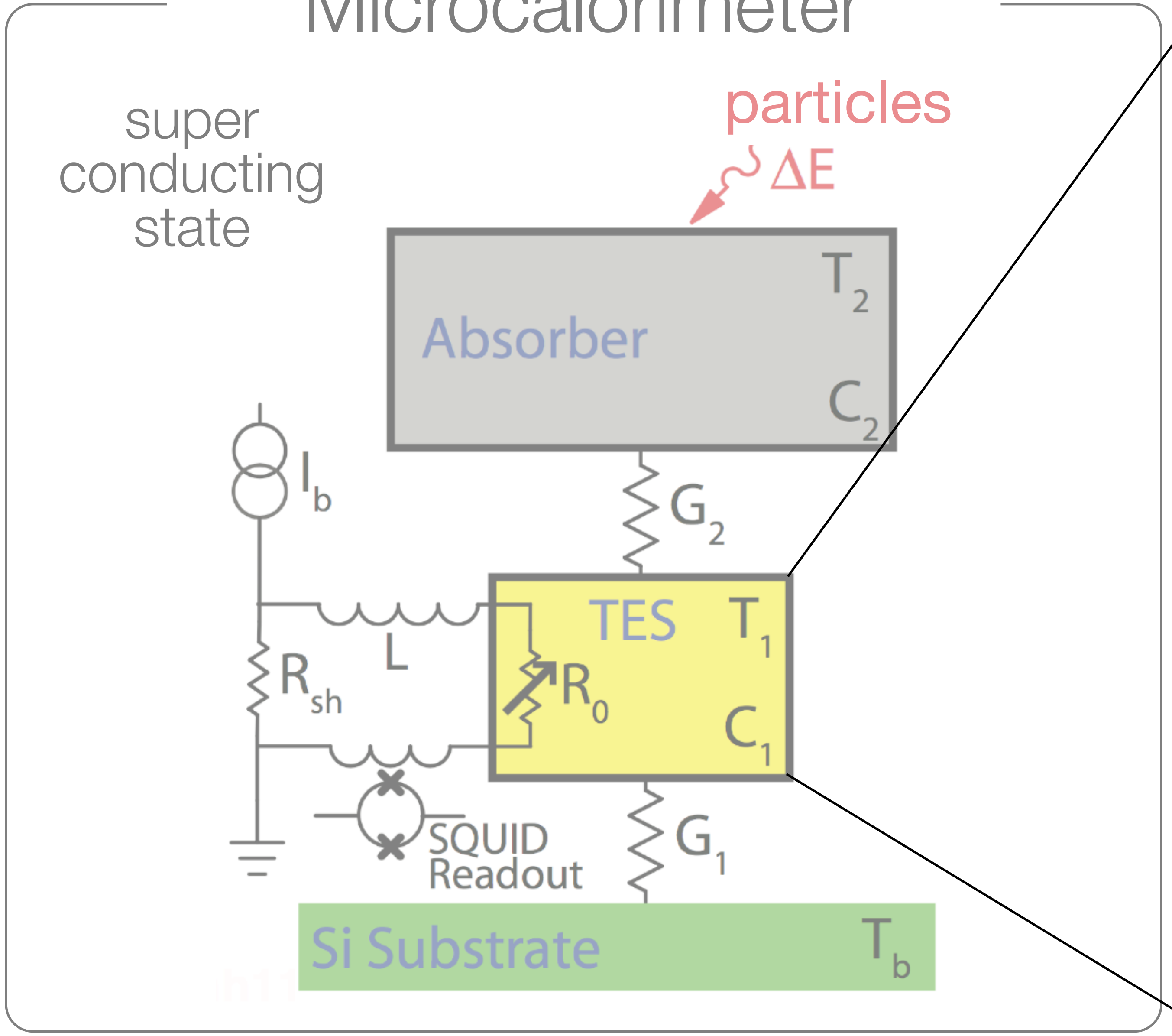
2. Energy ΔE -> Phonon

3. Tiny temperature rise is measured by a highly sensitive temperature sensor **TES**

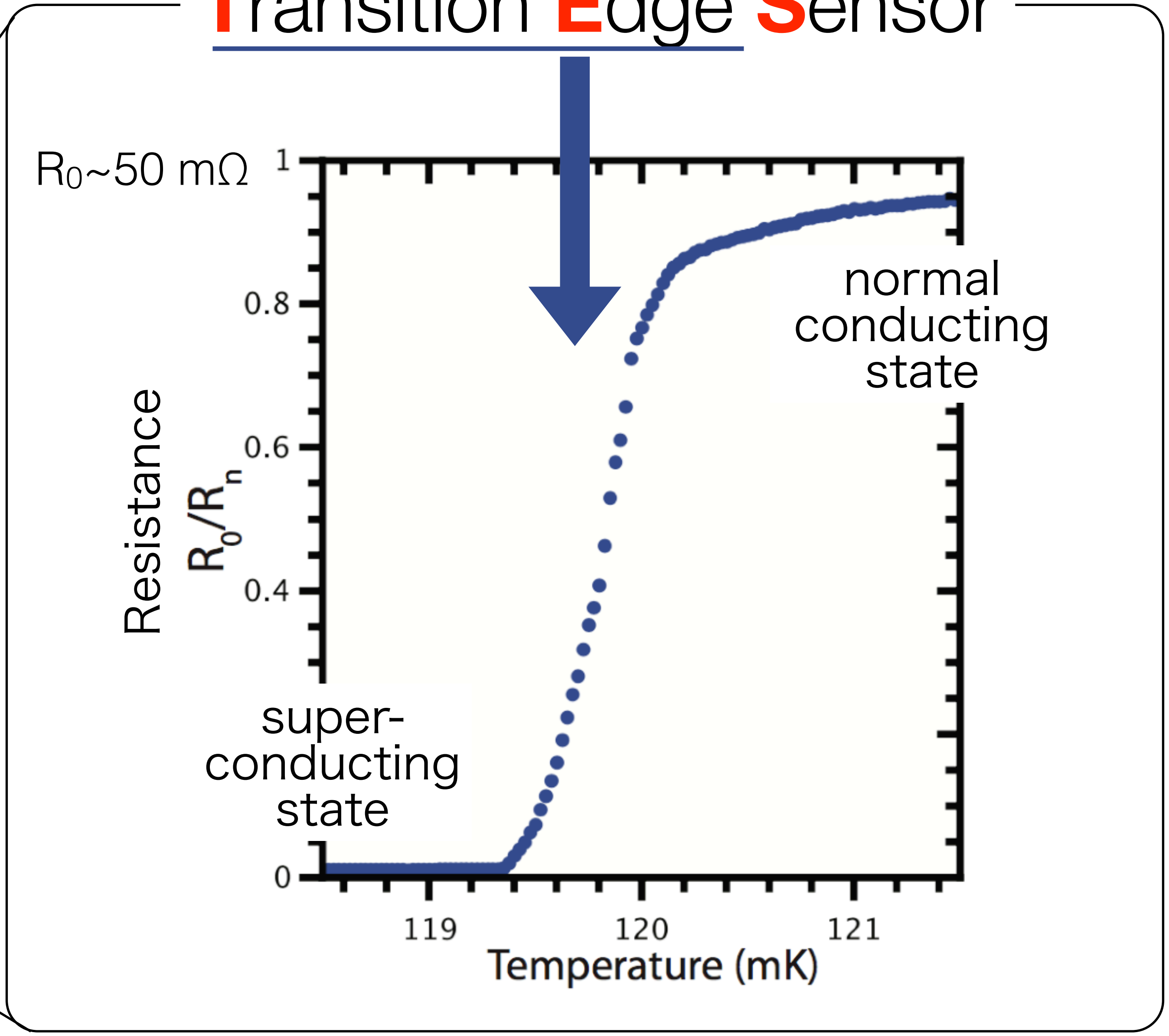
Reference : Bennet et al., Rev. Sci. Instrum. 83, 093113 (2012)

TES microcalorimeter

Microcalorimeter

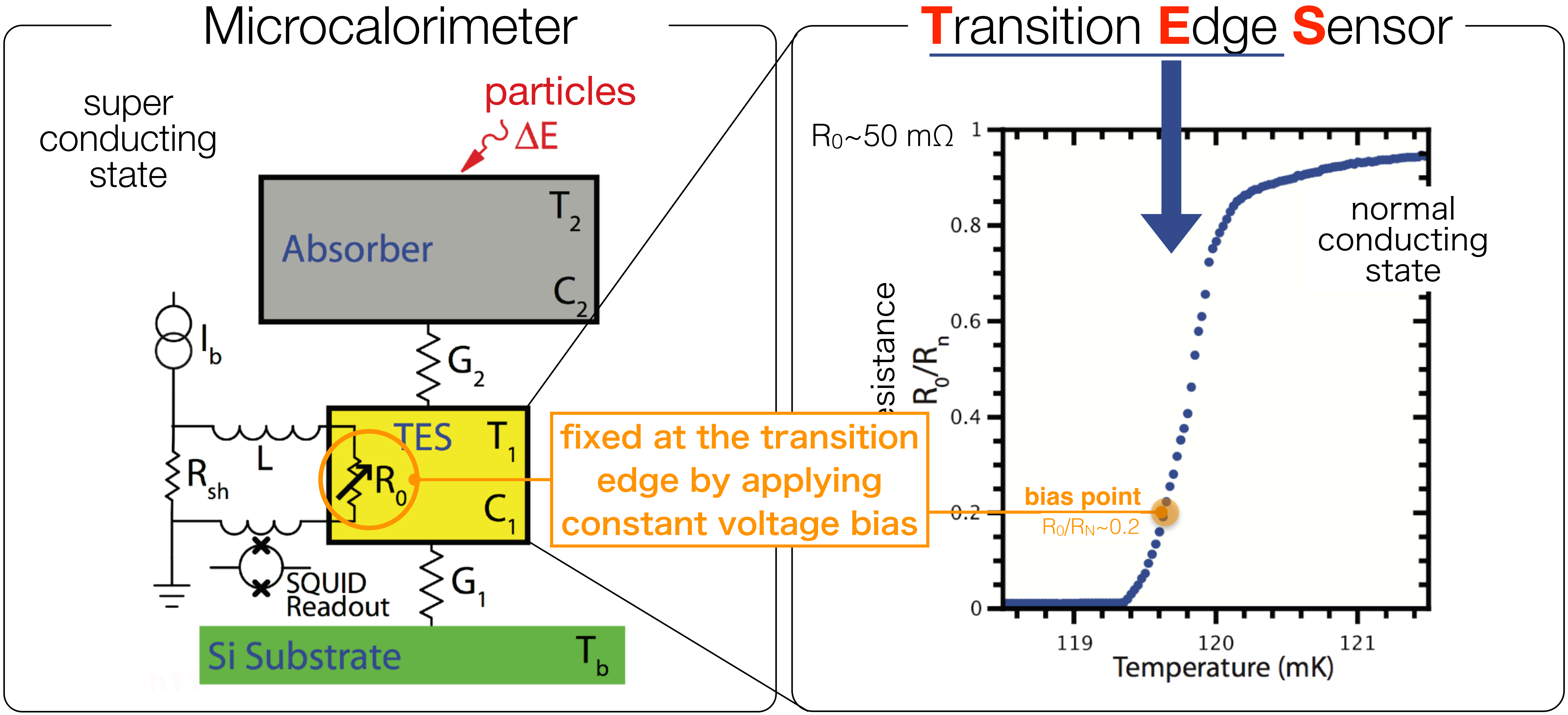


Transition **E**dge **S**ensor



Reference : Bennet et al., Rev. Sci. Instrum. 83, 093113 (2012)

TES microcalorimeter



Microcalorimeter

Transition Edge Sensor

super conducting state

particles

ΔE

fixed at the transition edge by applying constant voltage bias

bias point

R_0/R_N~0.2

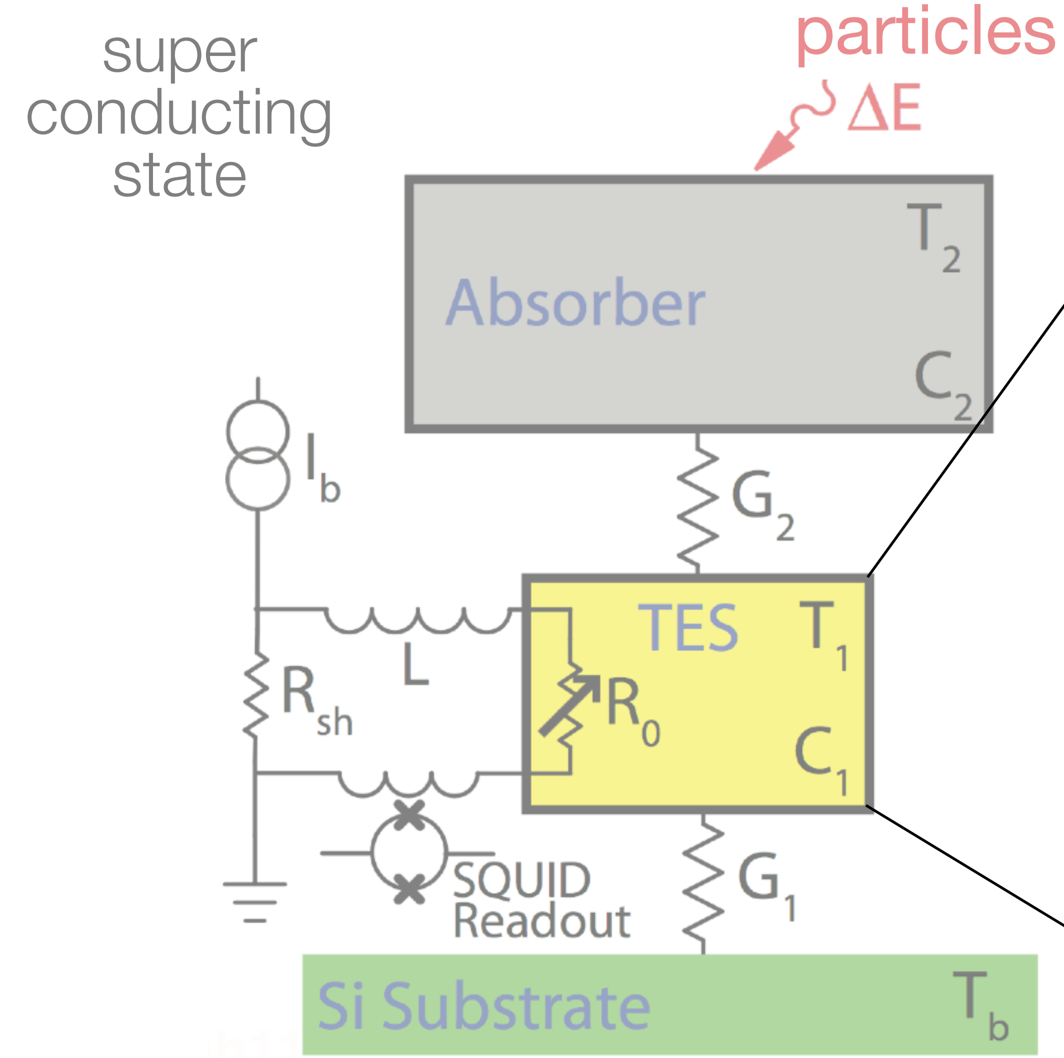
R_0~50 mΩ

normal conducting state

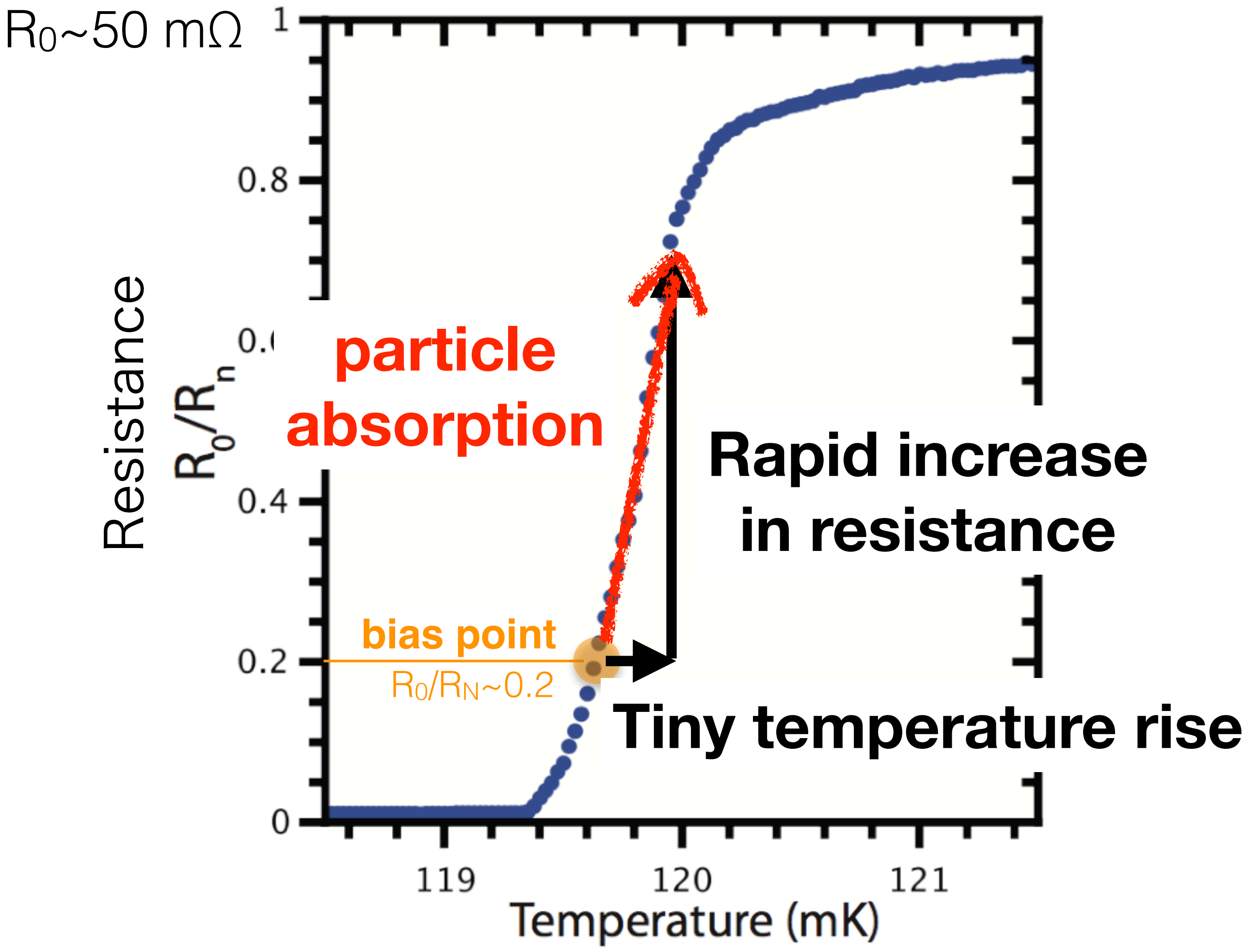
Reference : Bennet et al., Rev. Sci. Instrum. 83, 093113 (2012)

TES microcalorimeter

Microcalorimeter



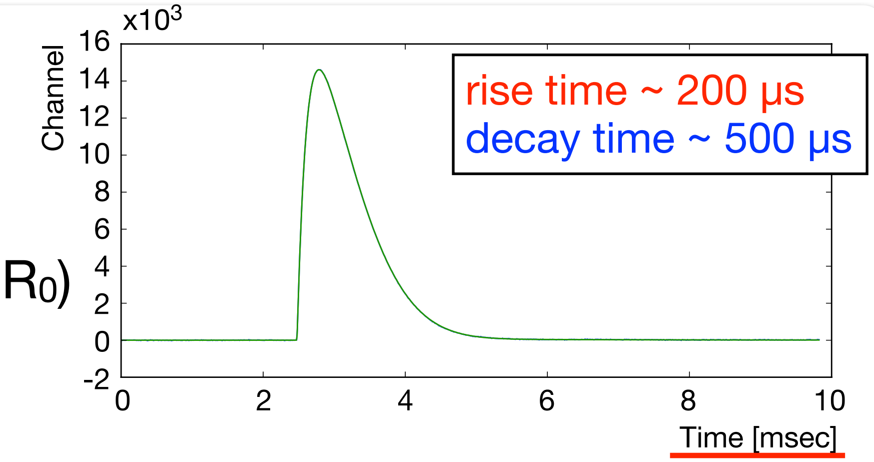
Transition **E**dge **S**ensor



Typical pulse

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

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



high energy resolution (ΔE / E ~ 10^{-3})

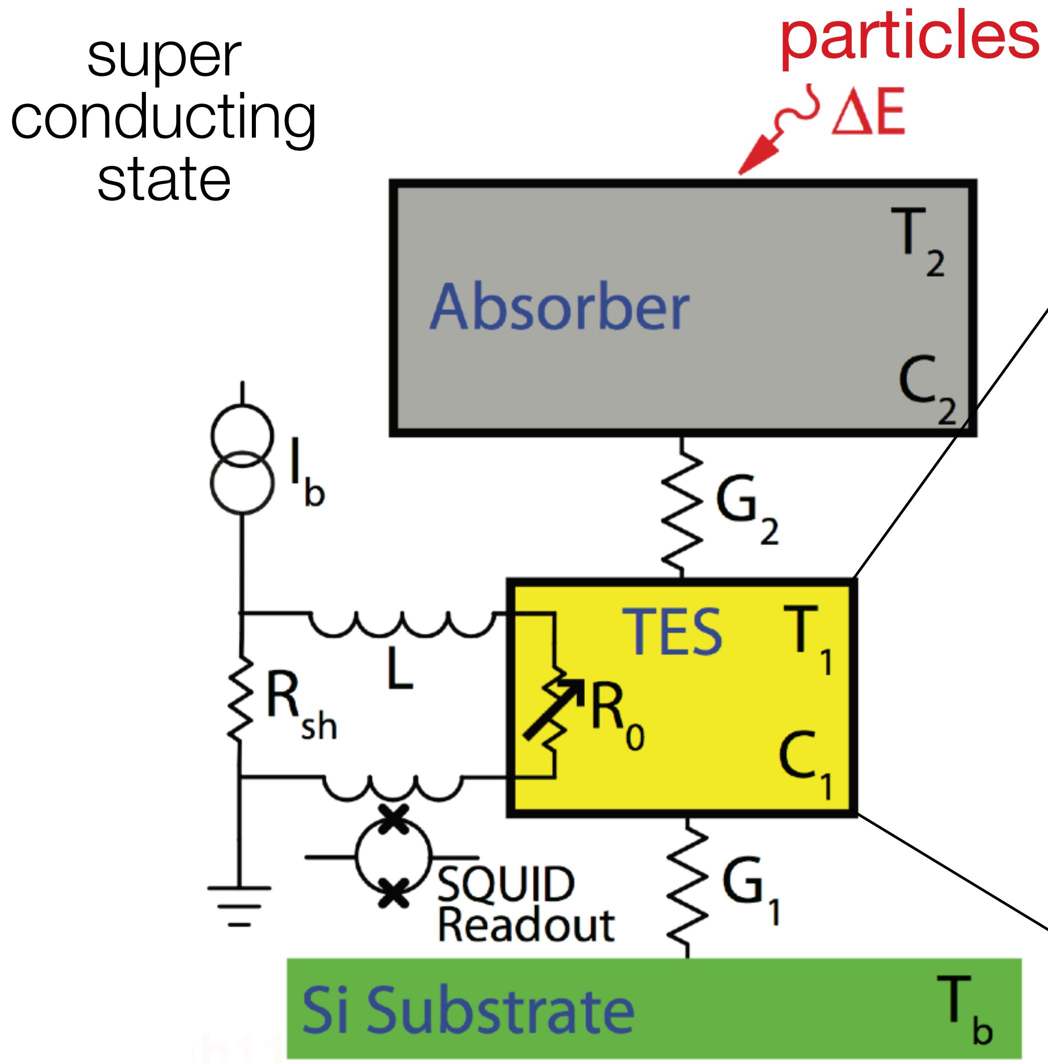
TES : ΔE (FWHM) ~ 5 eV @ 6 keV X-ray

(ref. SDD : ΔE (FWHM) ~ 150 eV @ 6 keV)

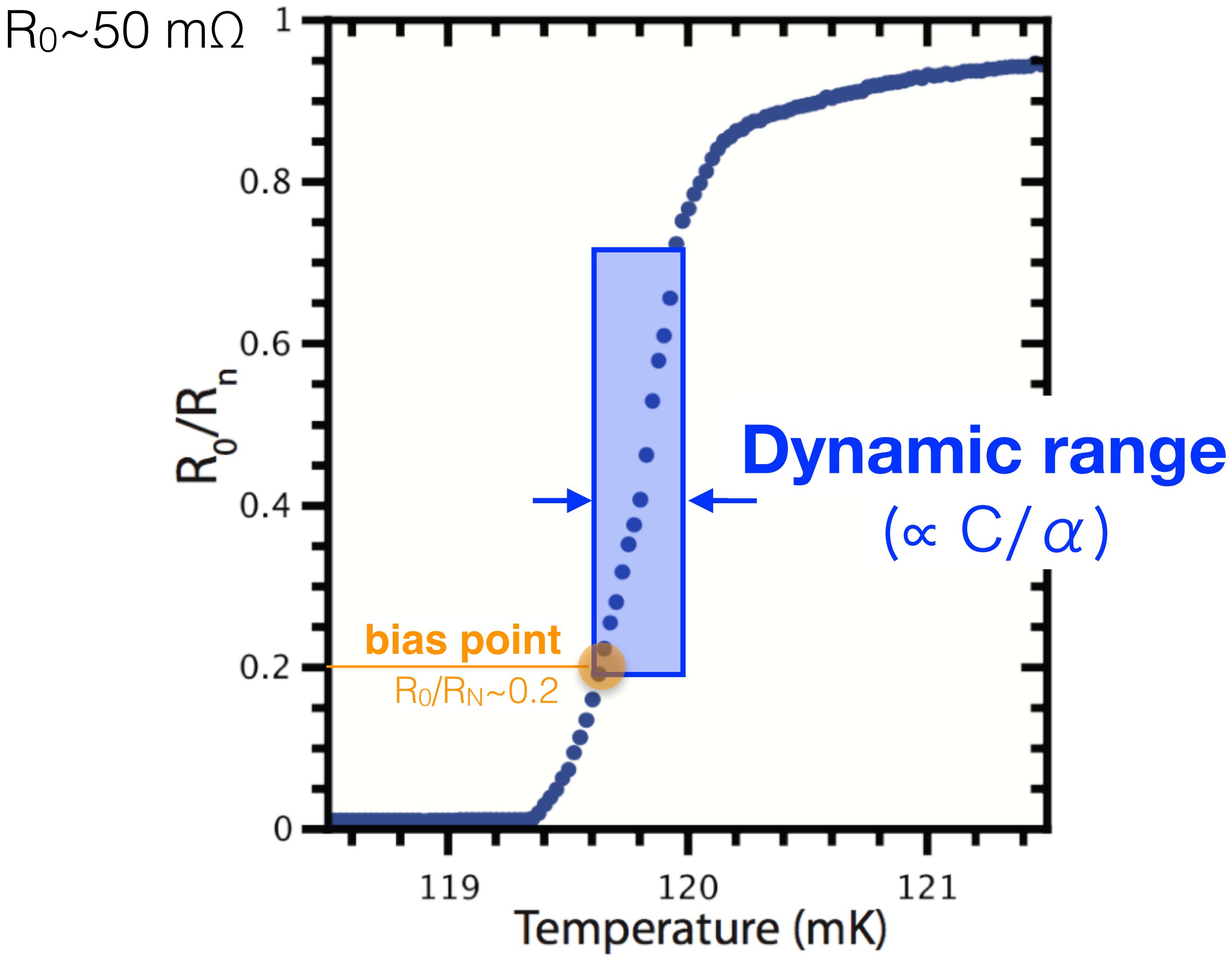
Reference : Bennet et al., Rev. Sci. Instrum. 83, 093113 (2012)

TES microcalorimeter

Microcalorimeter



Transition **E**dge **S**ensor



Temp. sensitivity : $\alpha_I = \left.\frac{\delta \log R}{\delta \log T}\right|_{I_0} = \frac{T_0}{R_0} \left.\frac{\delta R}{\delta T}\right|_{I_0}$

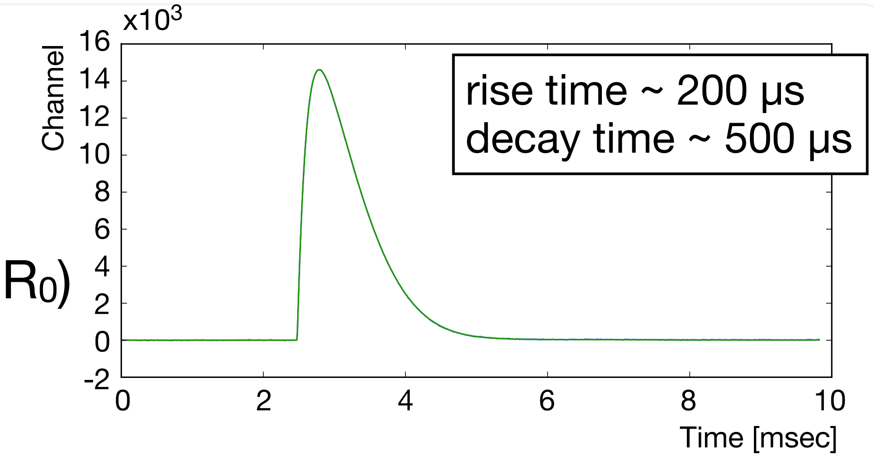
Energy resolution : $\Delta E \propto \sqrt{T_c^2 C / \alpha_I}$

Saturation energy : $E_{sat} \approx 4 T_C C / \alpha_I$

Typical pulse

τ_{rise}~$L/(R_{sh}+R_0)$

τ_{fall}~C/G

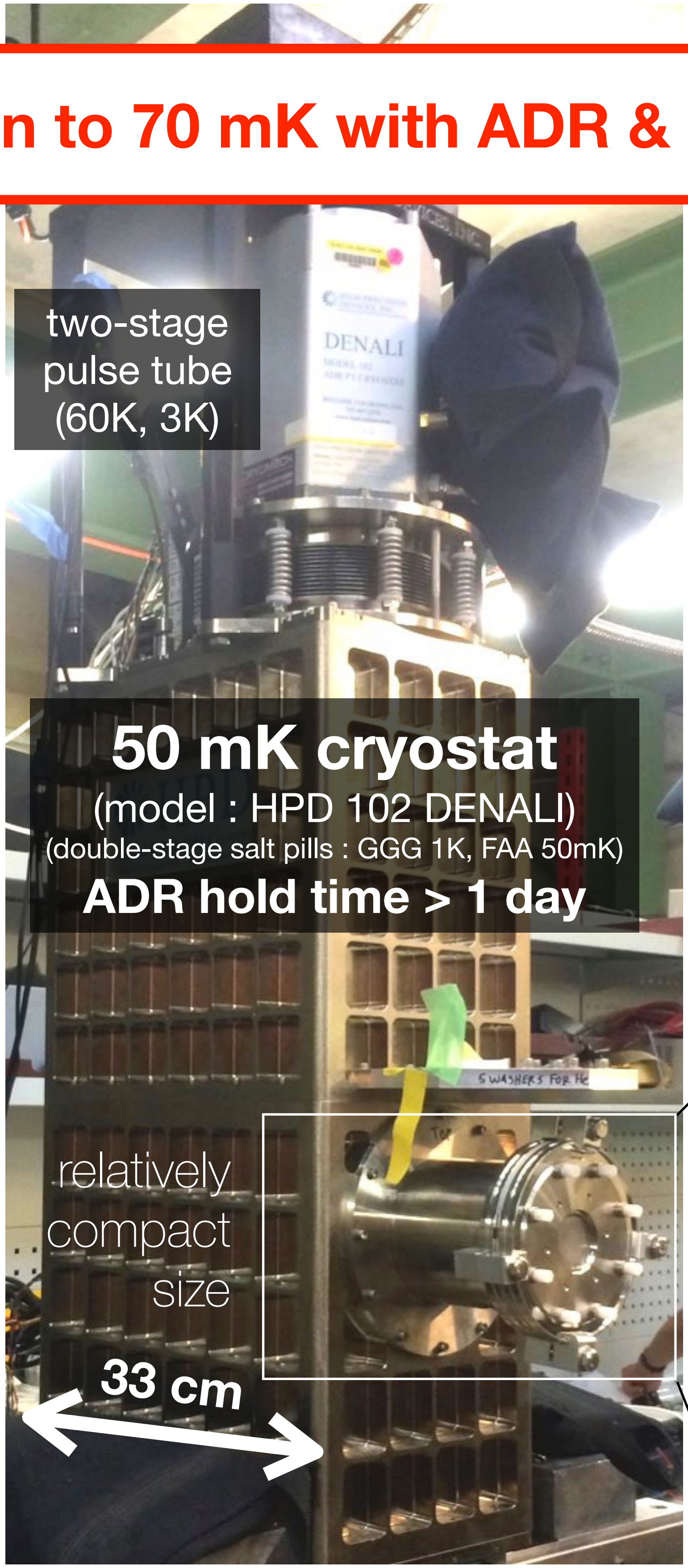


rise time ~ 200 μs
decay time ~ 500 μs

Adiabatic Demagnetization Refrigerator (ADR)

✓ **Cooled down to 70 mK with ADR & pulse**

102 DENALI **Pulse Tube ADR Cryostat**
Vacuum Jacket Size **33 cm X 22 cm X** **66 cm Tall**
Experimental Volume **24 cm X 15 cm X** **14 cm Tall**
1st Stage Cooling Power **25 W @ 55 K**
2nd Stage Cooling Power **0.7 W @ 4.2 K**
GGG Cooling Capacity **1.2 J @ 1 K** (< 500 mK @ GGG)
ADR Base Temperature **< 50 mK**
FAA Cooling Capacity **118 mJ @ 100 mK**



two-stage pulse tube (60K, 3K)

50 mK cryostat

(model : HPD 102 DENALI)

(double-stage salt pills : GGG 1K, FAA 50mK)

ADR hold time > 1 day

relatively compact size

33 cm

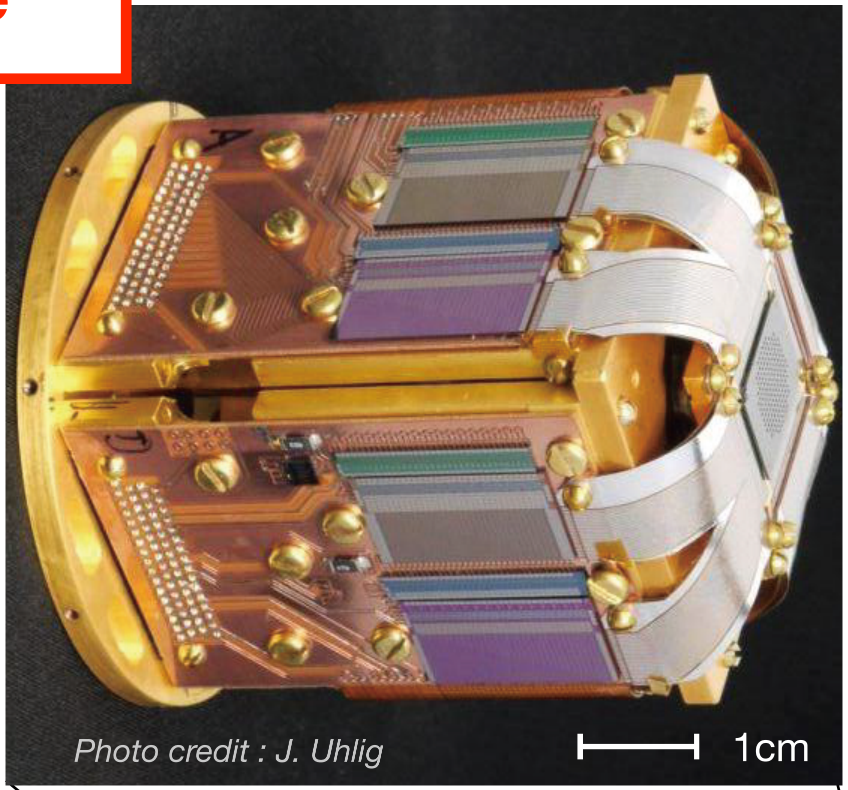
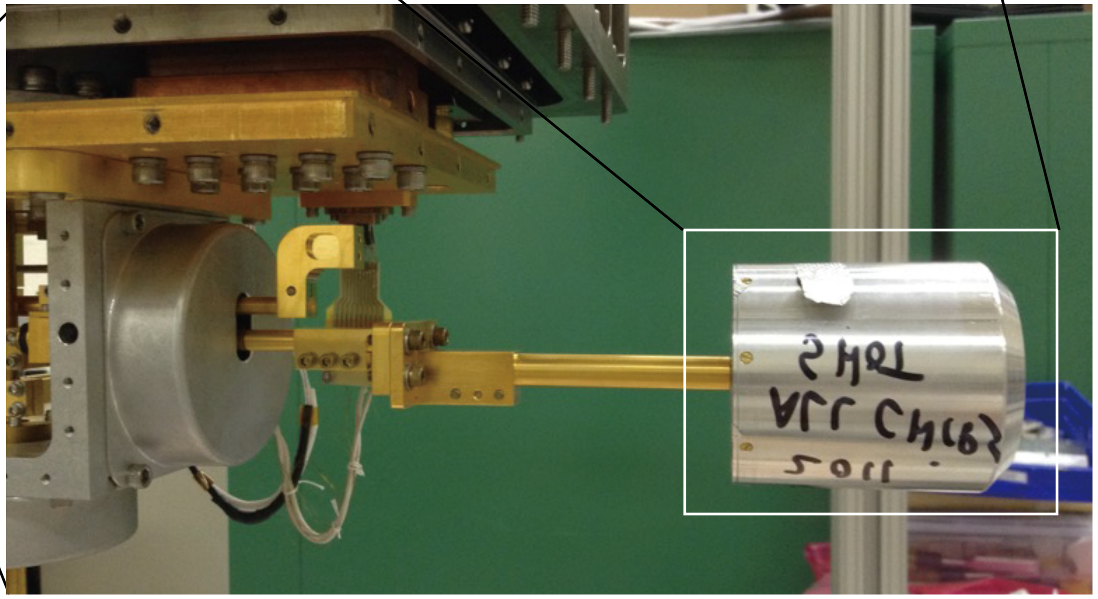


Photo credit : J. Uhlig

TES chip



TES array (NIST)

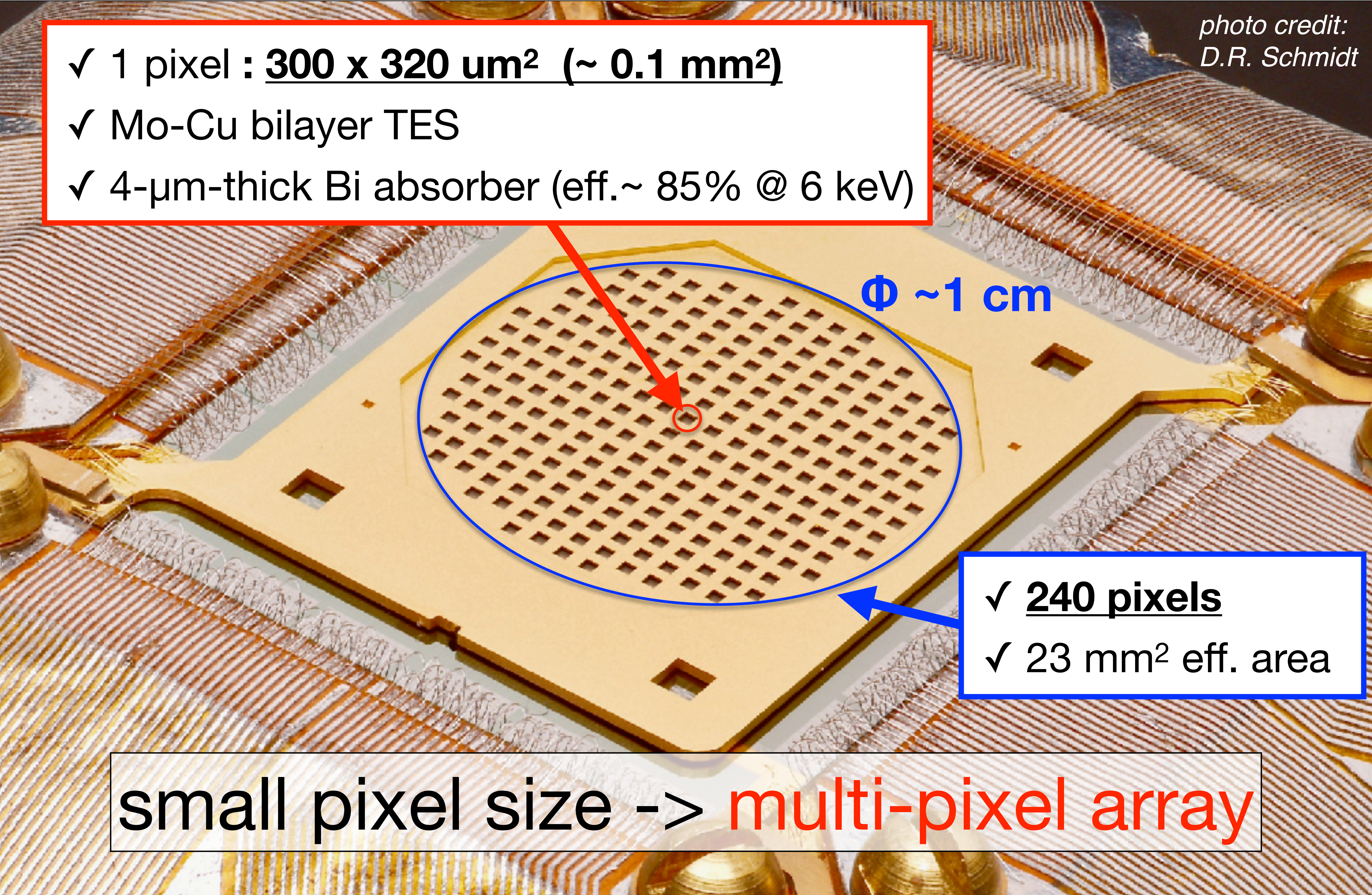


photo credit: D.R. Schmidt

- ✓ 1 pixel : **<u>300 x 320 um² (~ 0.1 mm²)</u>**
- ✓ Mo-Cu bilayer TES
- ✓ 4-μm-thick Bi absorber (eff.~ 85% @ 6 keV)

Φ ~1 cm

- ✓ **240 pixels**
- ✓ 23 mm² eff. area

small pixel size -> multi-pixel array

TES array (NIST)

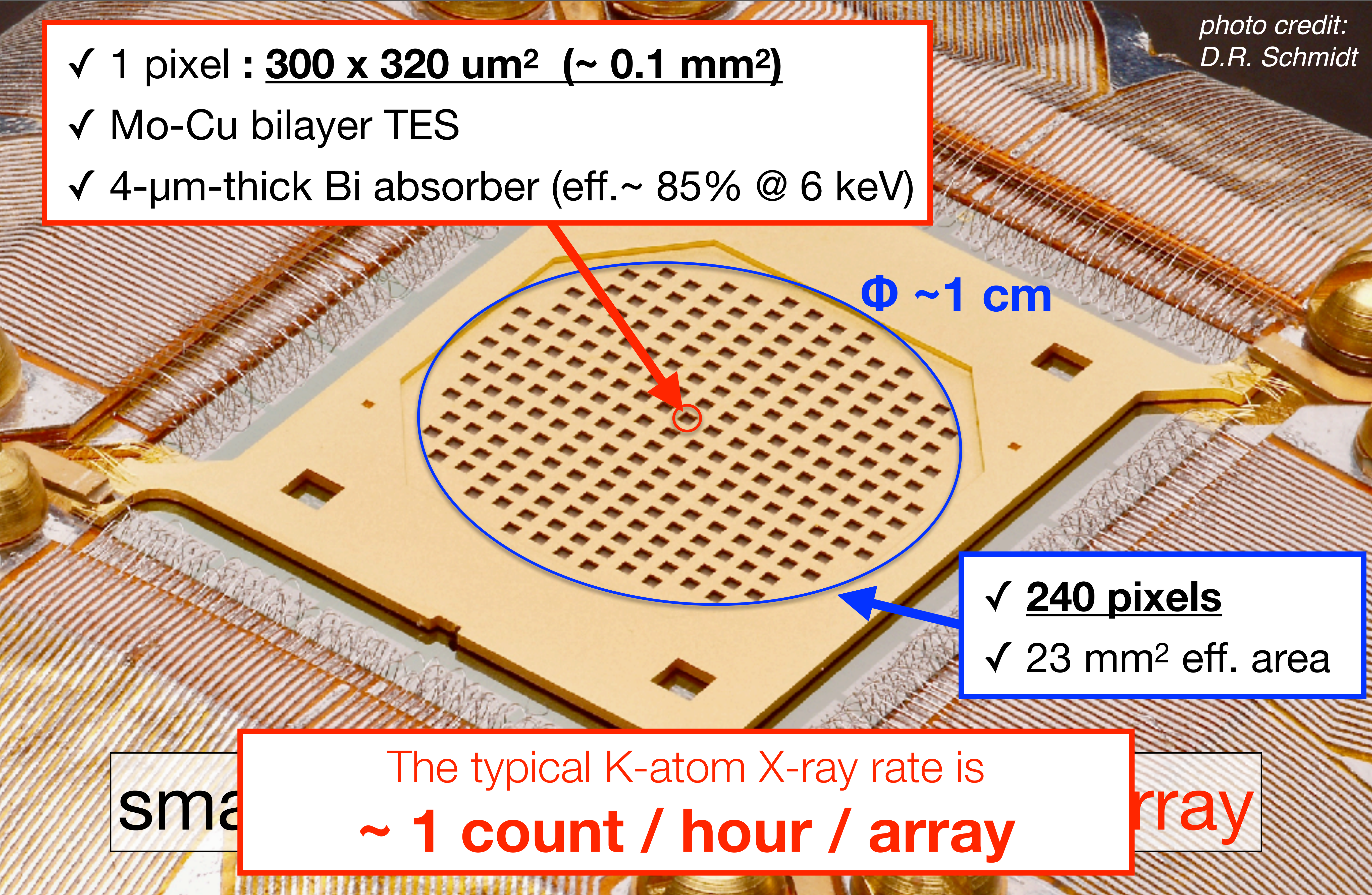


photo credit:
D.R. Schmidt

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- ✓ Mo-Cu bilayer TES
- ✓ 4-μm-thick Bi absorber (eff.~ 85% @ 6 keV)

- ✓ **<u>240 pixels</u>**
- ✓ 23 mm^2 eff. area

The typical K-atom X-ray rate is

~ 1 count / hour / array

sma

rray

Issue & solution

Requirement :

✓ Statistics : ~200 counts / week — **very low rate**

✓ Resolution : ~6 eV FWHM

in a large background of charged particles

⇐ large beam spot size (~several cm), π- contamination, K- decay, reaction …

issues	cause	solution
Poor S/B ratio	charged-particle hits on TES	✓ **timing cut** : selecting “K-stop events” ✓ **cross-talk cut** using neighboring pixel info
Deterioration of resolution		✓ installing **lead shield** to avoid direct hits of beam-caused background
Long-term stability	low rate science x-ray	✓ ***in-situ* energy calibration** using X-ray generator (to be accurate as good as 0.2 eV)

3. E62 experiment

First case to use TES in charged-particle rich environment

✓How the TES responses to a charge-particle hit ?

✓Can the TES keep its excellent performance ?

2013	Start collaboration with NIST
2014	**Demonstration experiment @ PSI (pionic atom)** → J. Low. Temp. Phys. **184**, 930 (2016) → PTEP **2016**, 091D01 (2016)
2015	Approved as J-PARC E62
2016	**Commissioning with K^- beam @ J-PARC** → IEEE Trans. Appl. Supercond. **27** (4) 2100905 (2017)
2017	
2018	**Physics data taking for K^- atom @ J-PARC, ~18 days** → J. Low Temp. Phys. **199**, 1018 (2020) **→ Phys. Rev. Lett. 128, 112503 (2022)**

Collaboration

HEATES / J-PARC E62 collaboration

ChubuU, JAEA, JAXA, KEK,
OsakaU, RCNP, RIKEN, RikkyoU,
UTokyo, TohokuU, TMU, TokyoTech

INFN-LNF, Politecnico di Milano

NIST

Stefan Meyer Institut

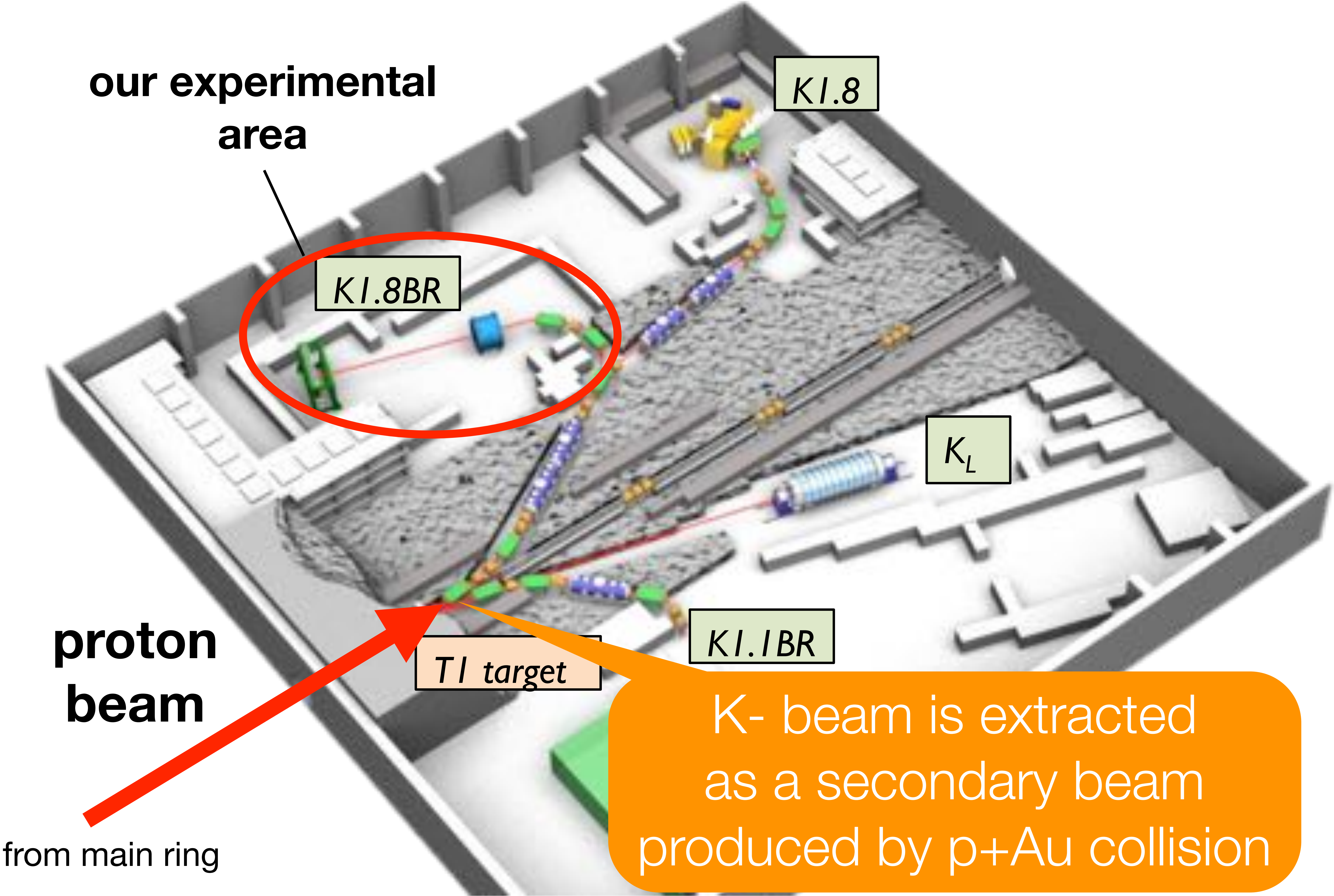
University of Zagreb

Lund University

Nuclear/hadron physicists + TES experts + Astro physicists

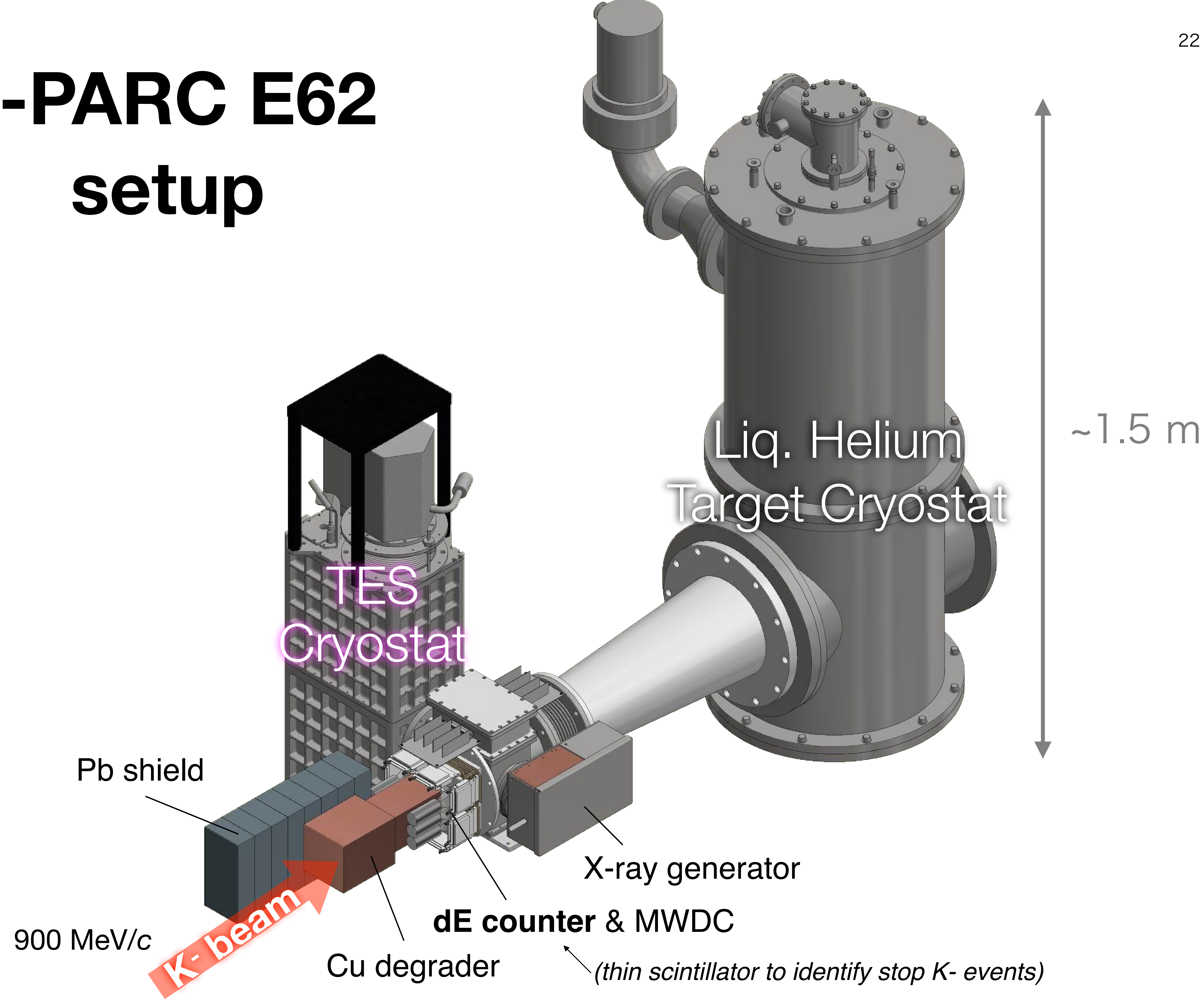
70 collaborators in total

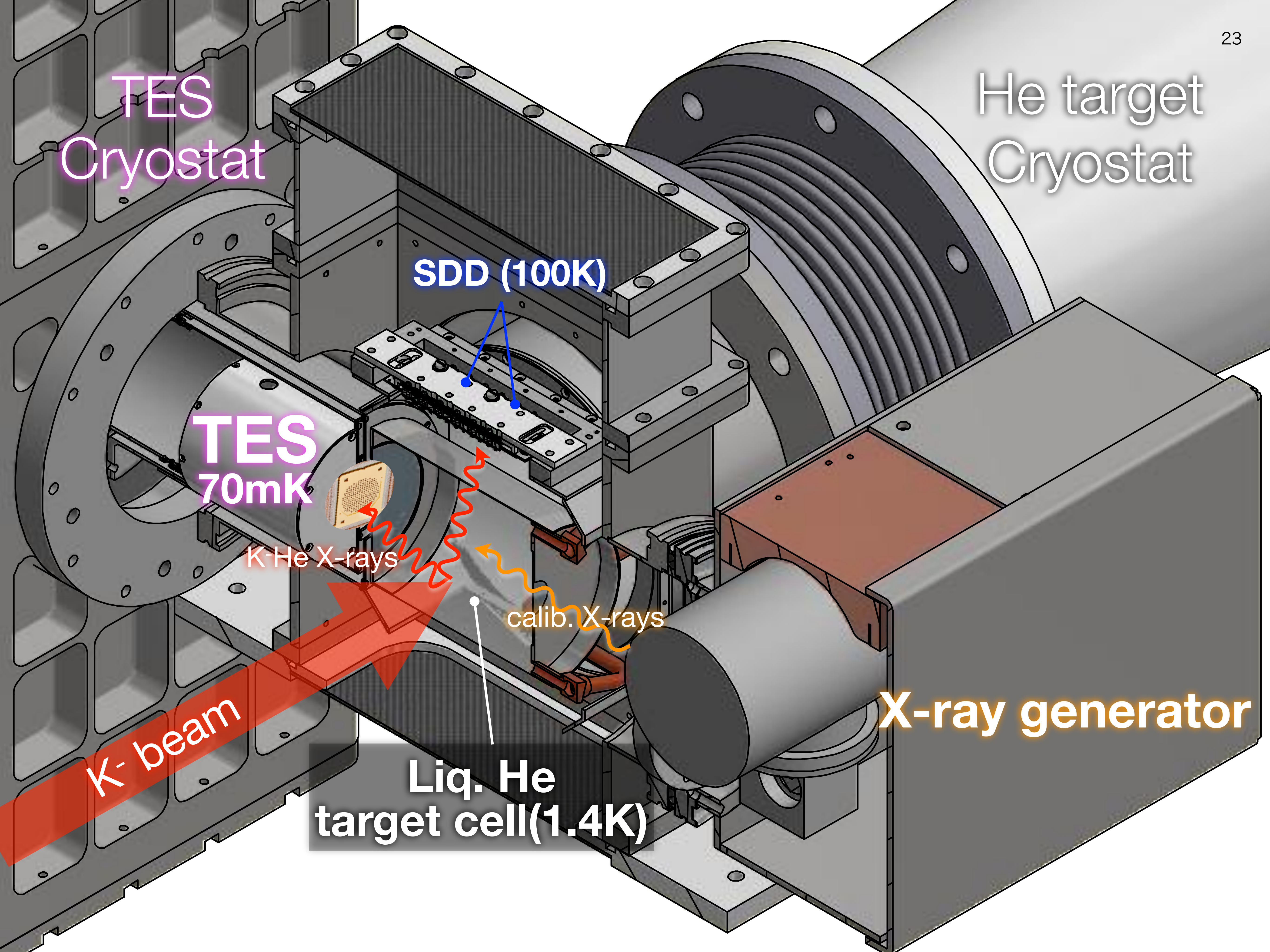
J-PARC hadron experimental facility



K- beam is extracted as a secondary beam produced by p+Au collision

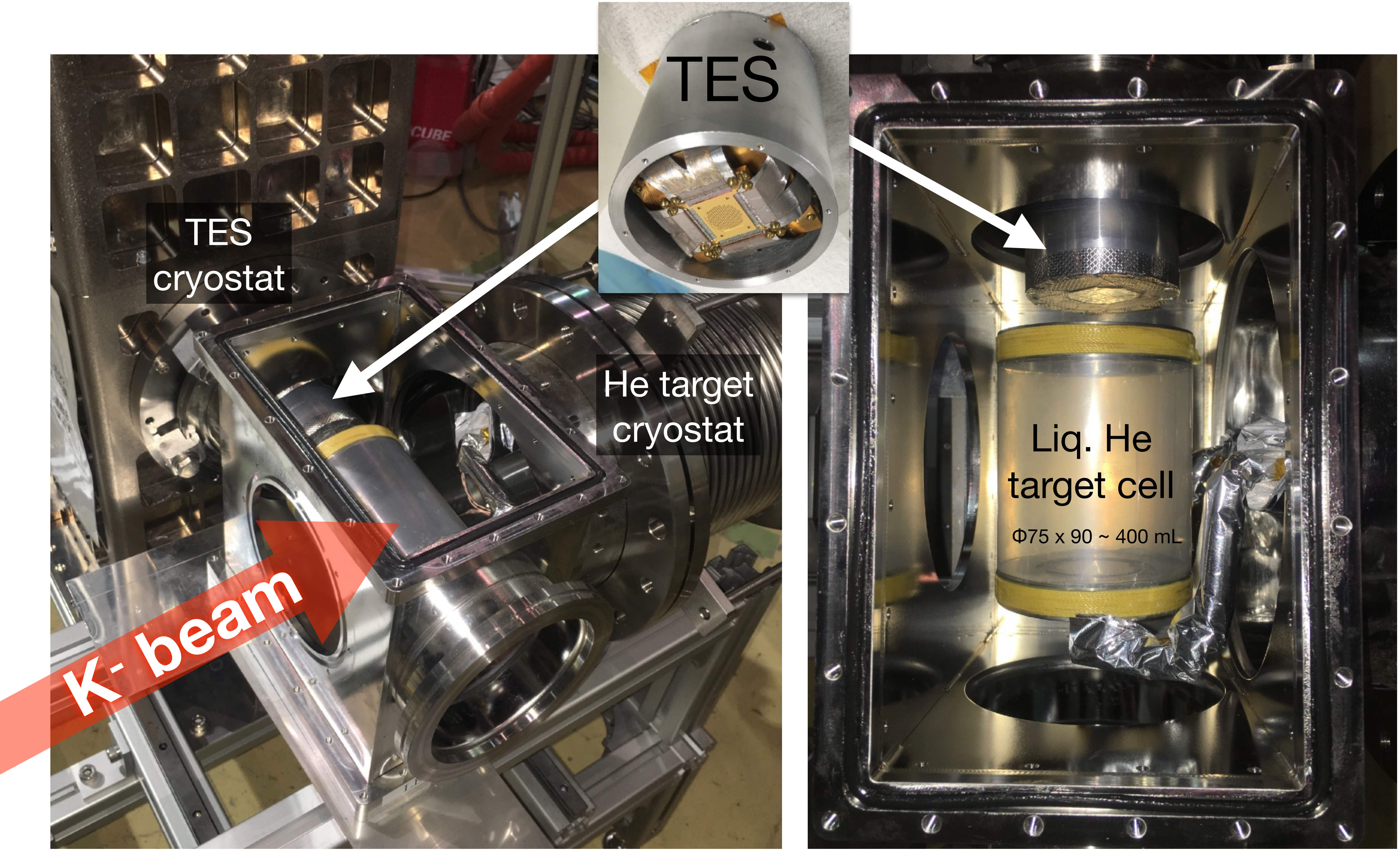
J-PARC E62 setup



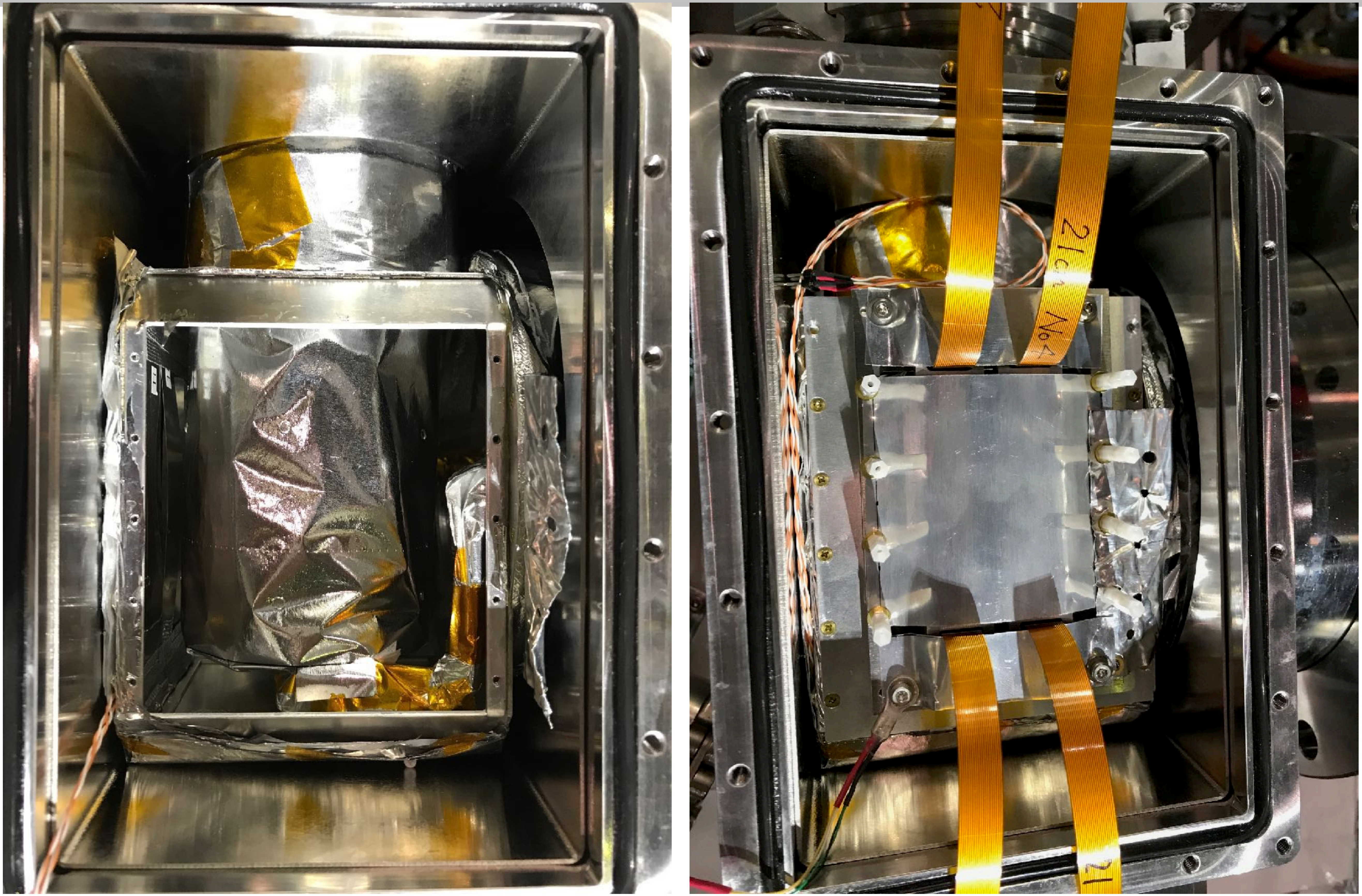


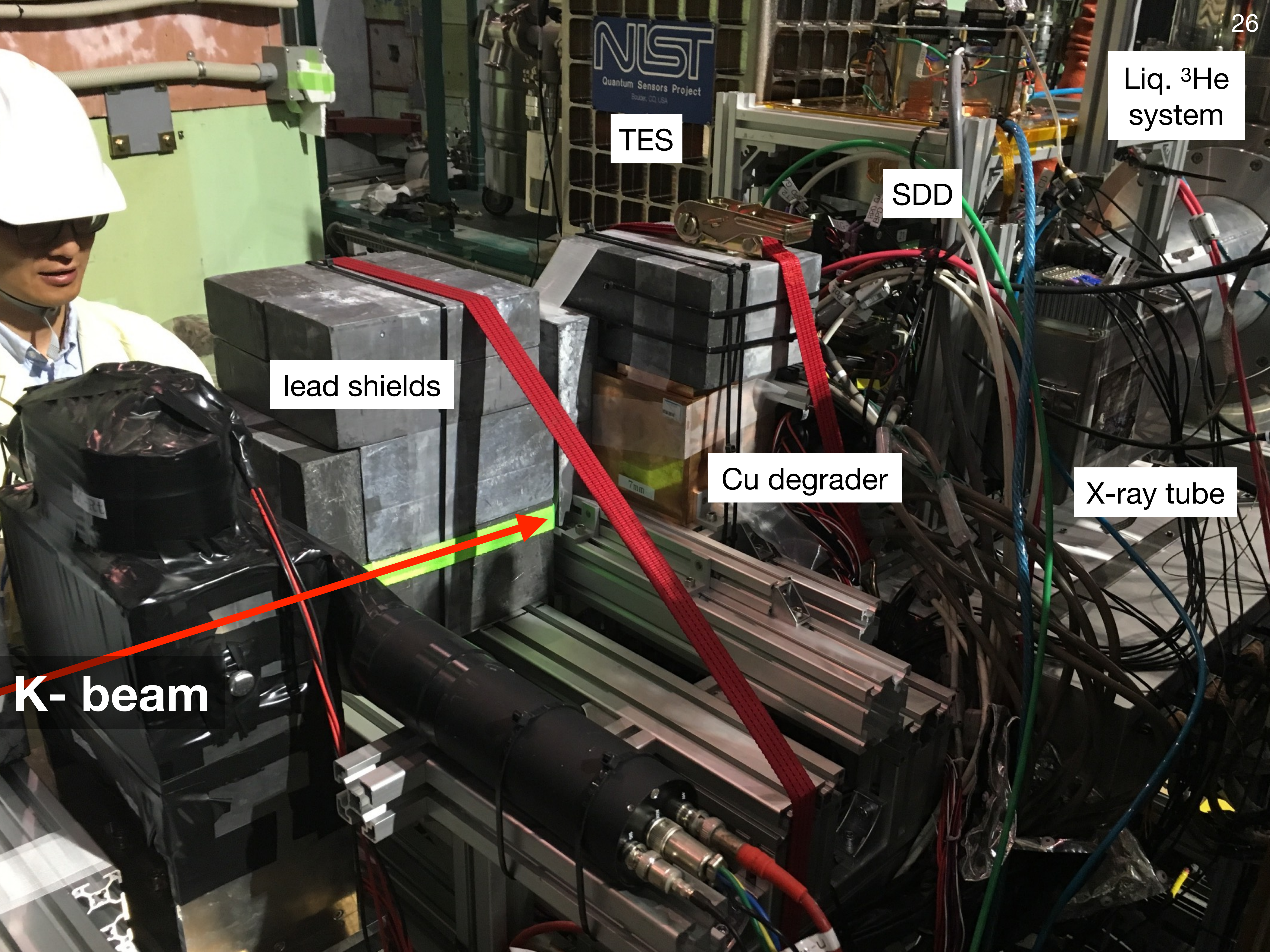
TES Cryostat
He target Cryostat
SDD (100K)
TES
70mK
K-He X-rays
calib. X-rays
X-ray generator
K- beam
Liq. He
target cell(1.4K)

TES & He target cell



Target region with shield, MLI, SDDs




NIST
Quantum Sensors Project
Boulder, CO, USA
TES
Liq. ^{3}He system
SDD
lead shields
Cu degrader
X-ray tube
K- beam

4. Results

Operation of cryogenic systems

He target

keep ~1.4 K

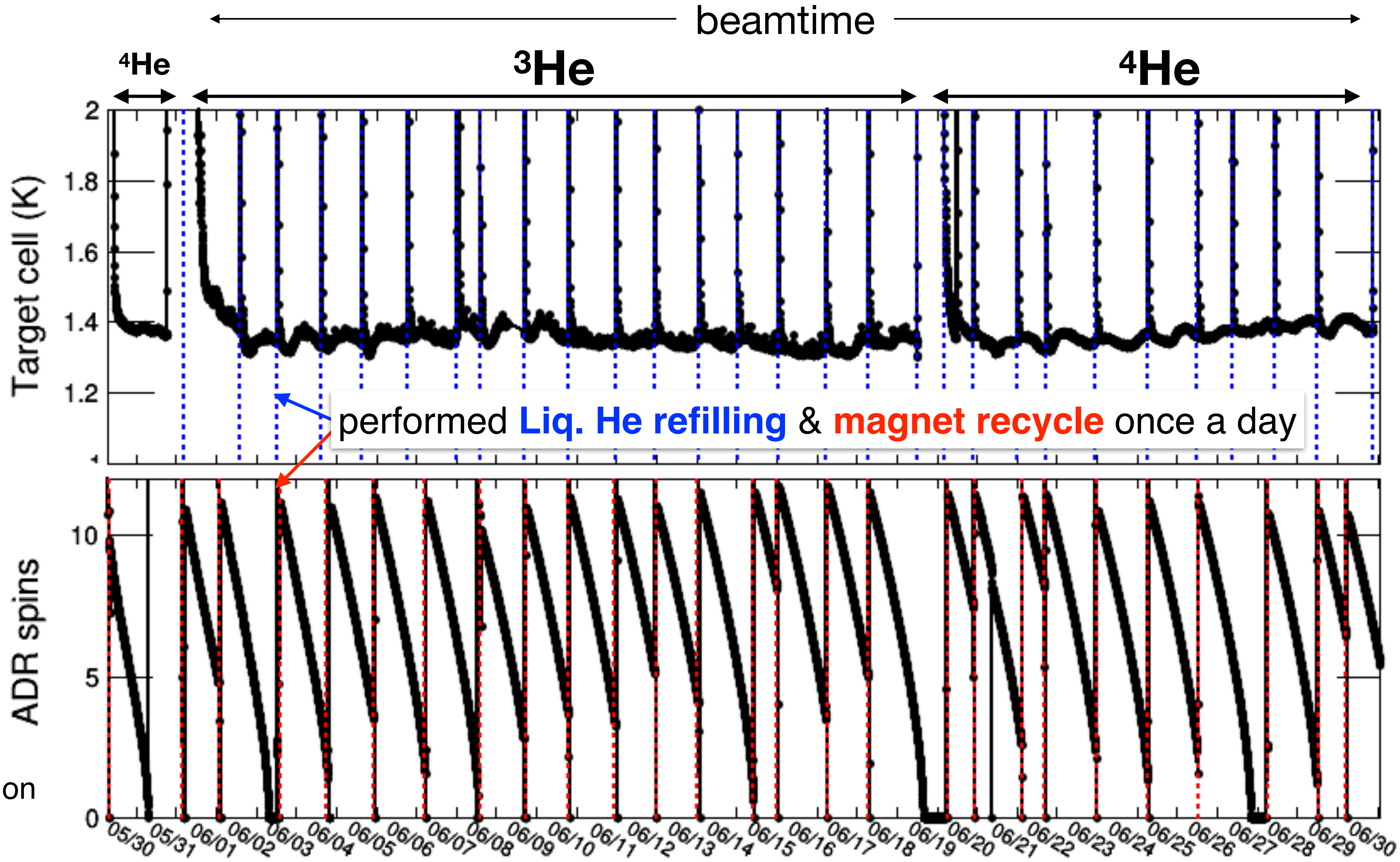
vacuum-cooled with Liq. ⁴He

TES

keep 70 mK

Adiabatic
Demagnetization
Refrigerator

with pulse tube

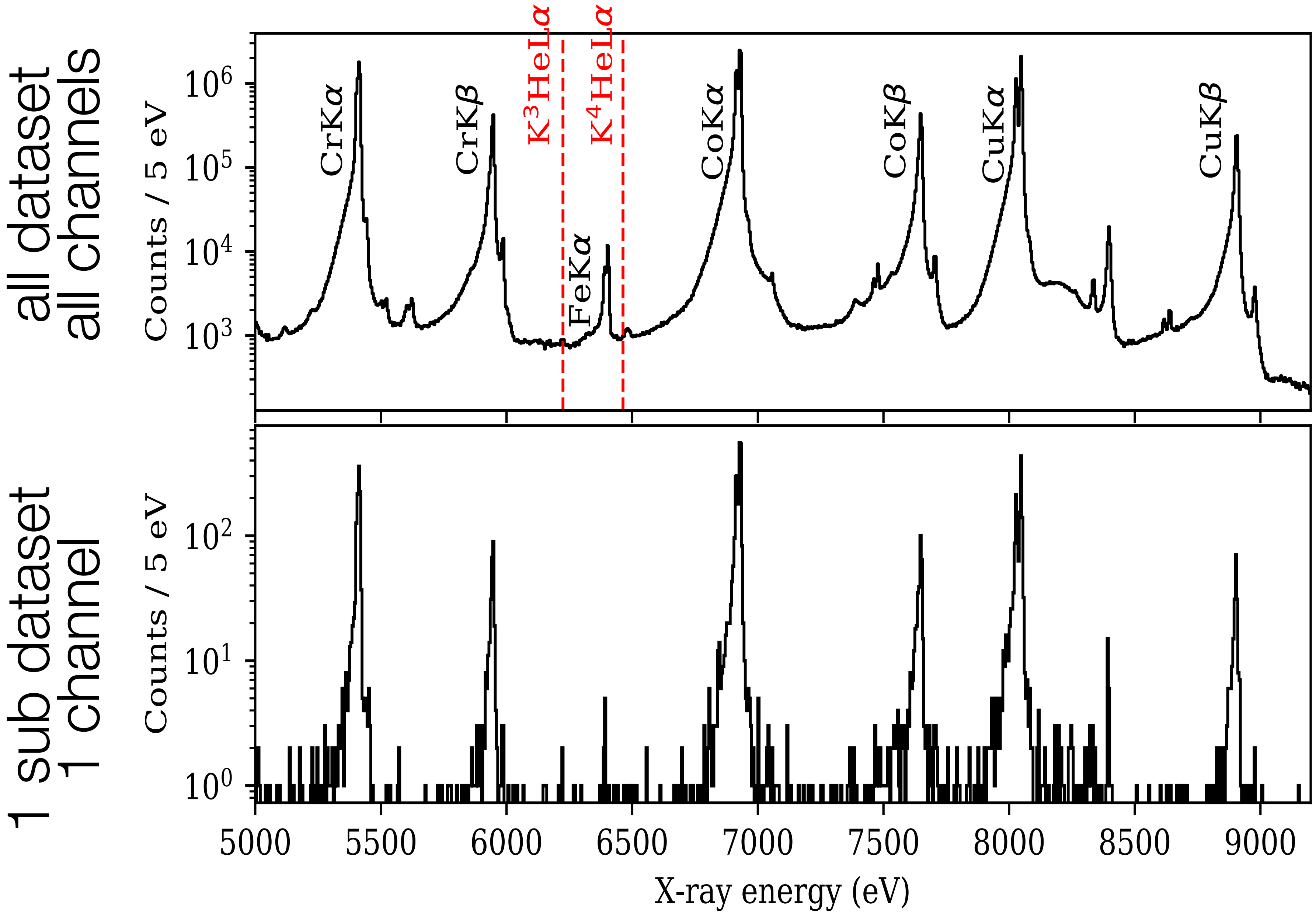


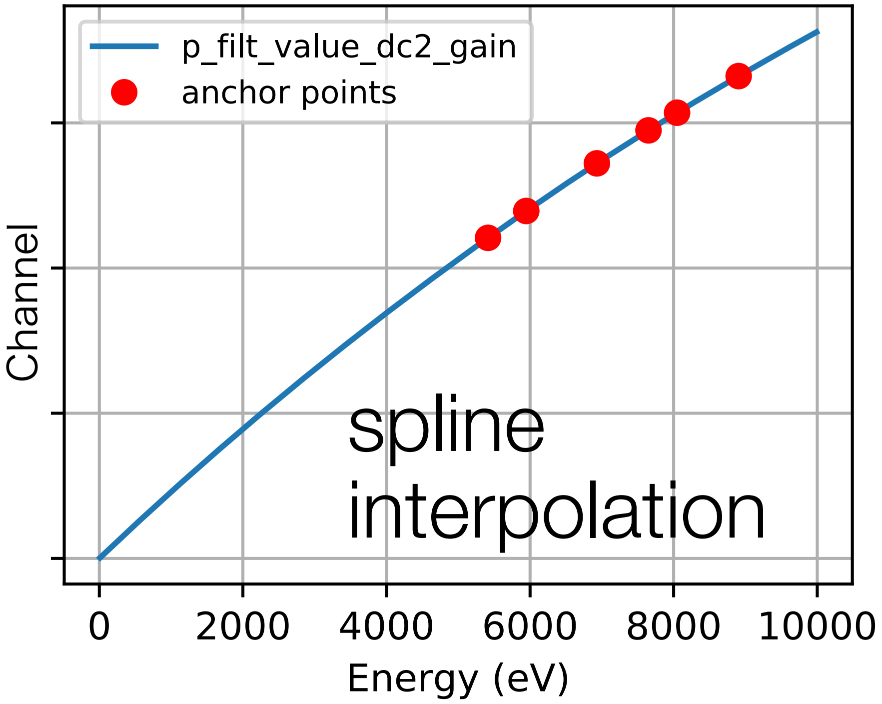
performed **Liq. He refilling** & **magnet recycle** once a day

Stable operation for one month

(28 He refills & 27 mag cycles)

In-beam energy calib. (X-ray tube)



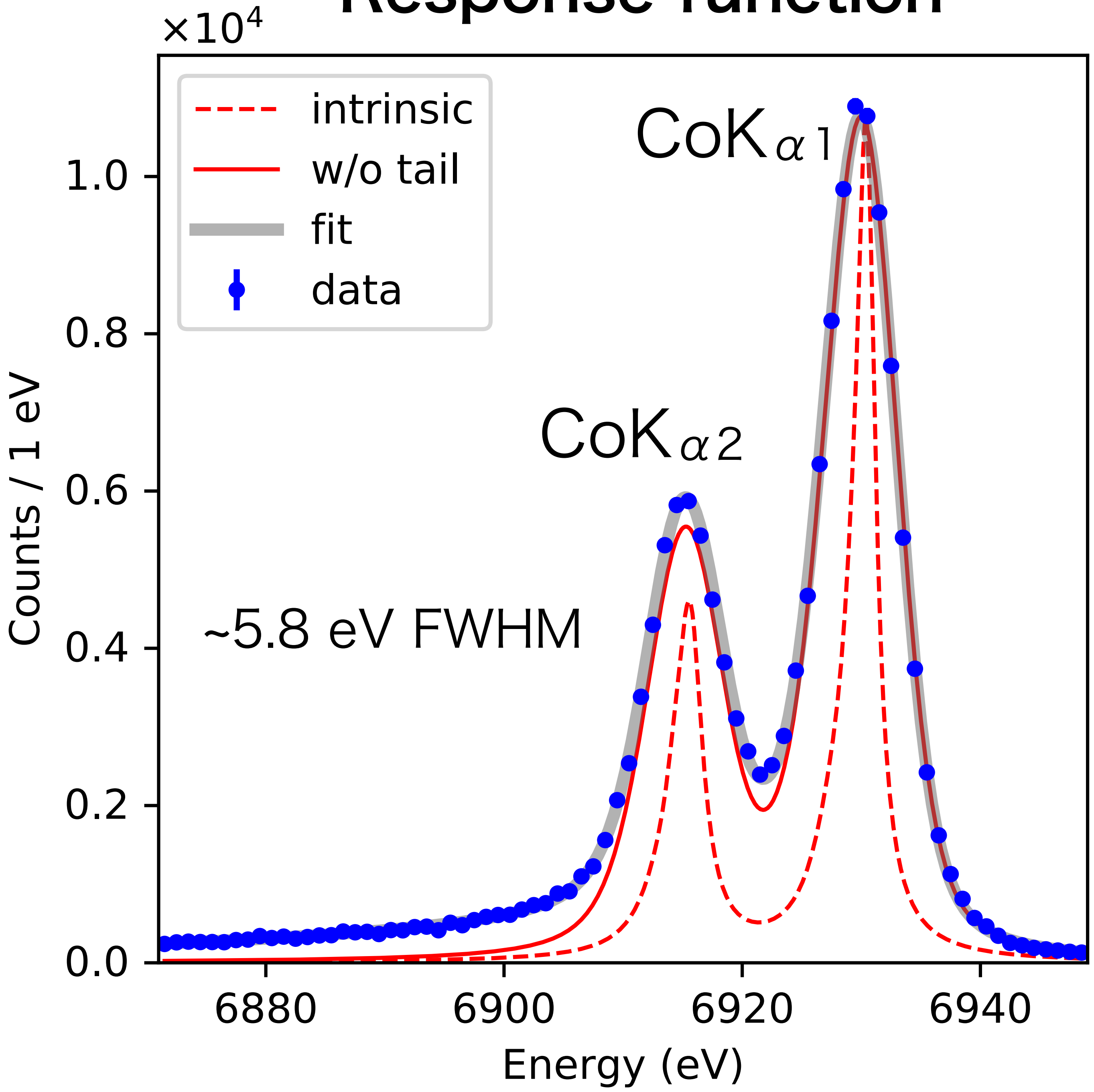


- ✓ X-ray tube was always ON during the experiment
- ✓ Pixel-by-pixel calibration every 4~8 hours

TES in-beam performance

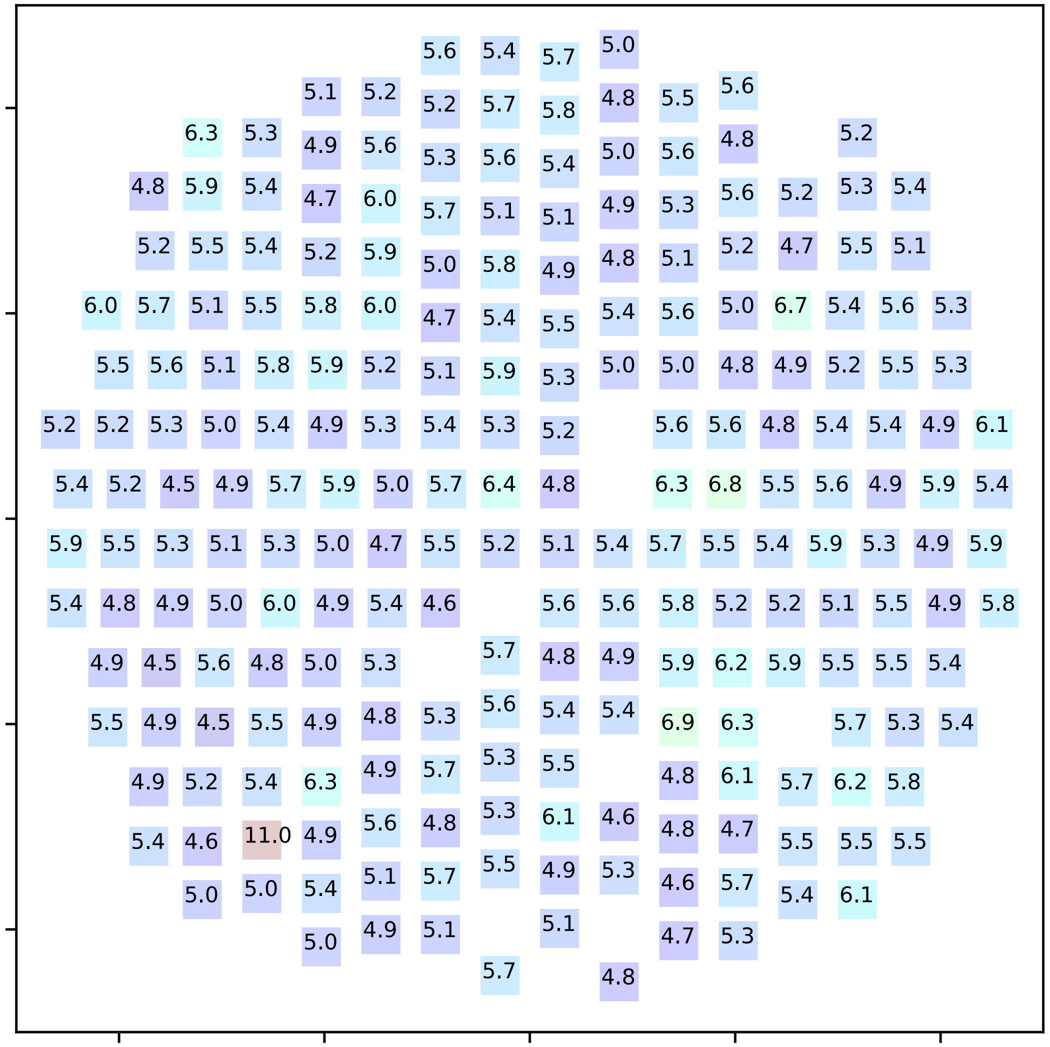
After all the analysis optimization (mainly reduction of charge-particle effects)

Response function



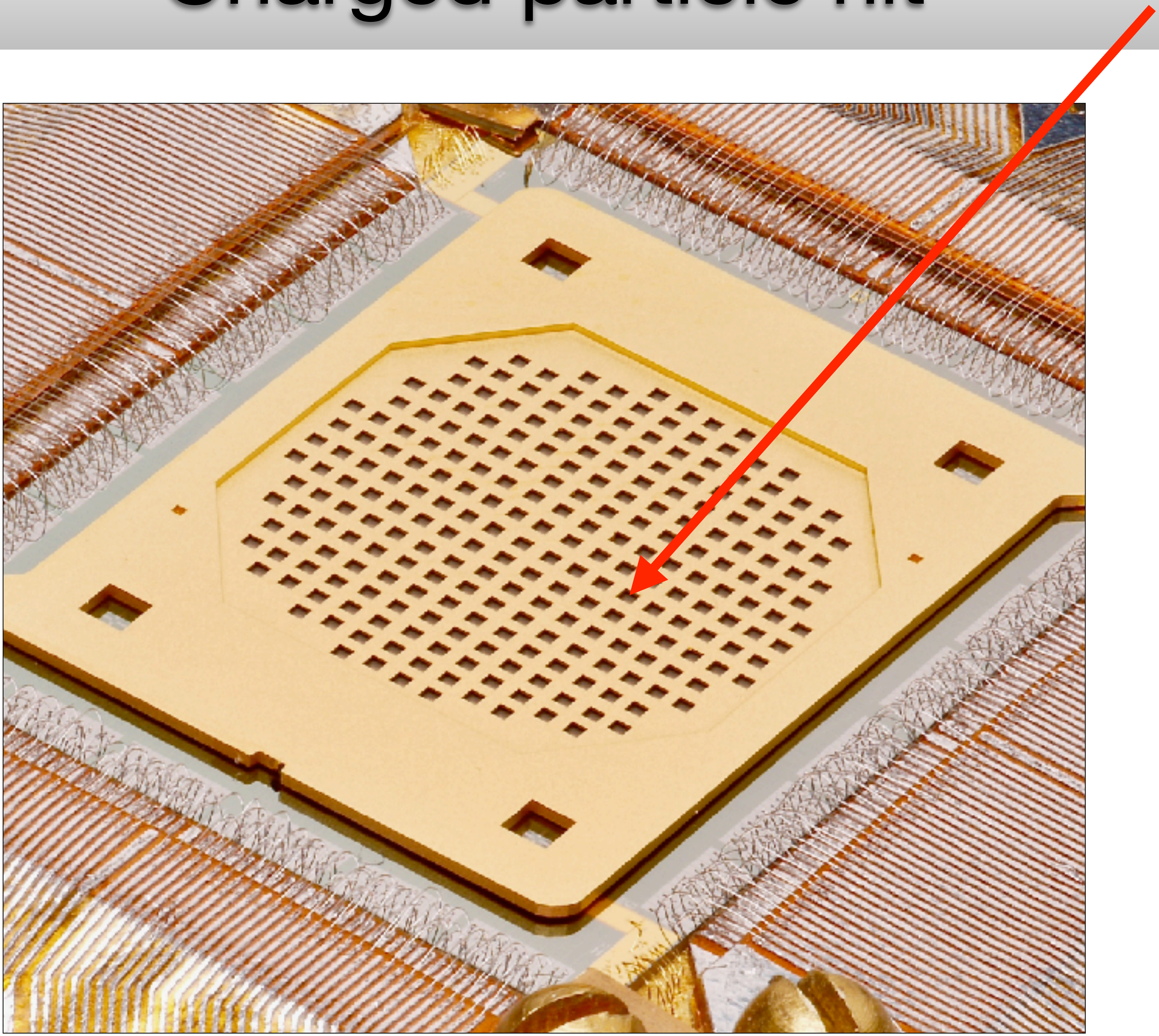
Detector response is well described
by a gaussian and a low-energy exponential tail

Resolution geometrical map

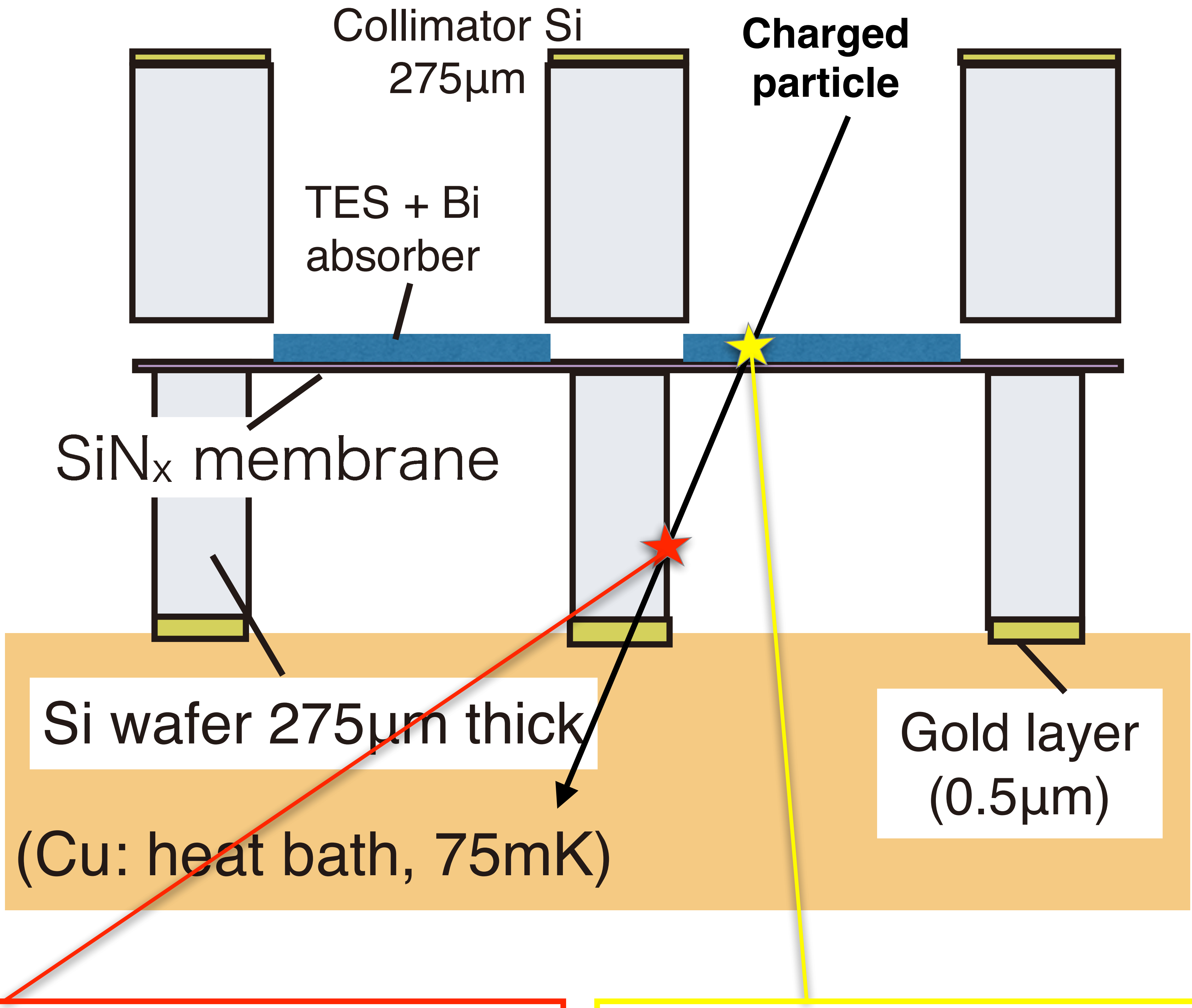


Resolution at CoKα
no box : doesn't work at all (12 pixel)

Charged particle hit



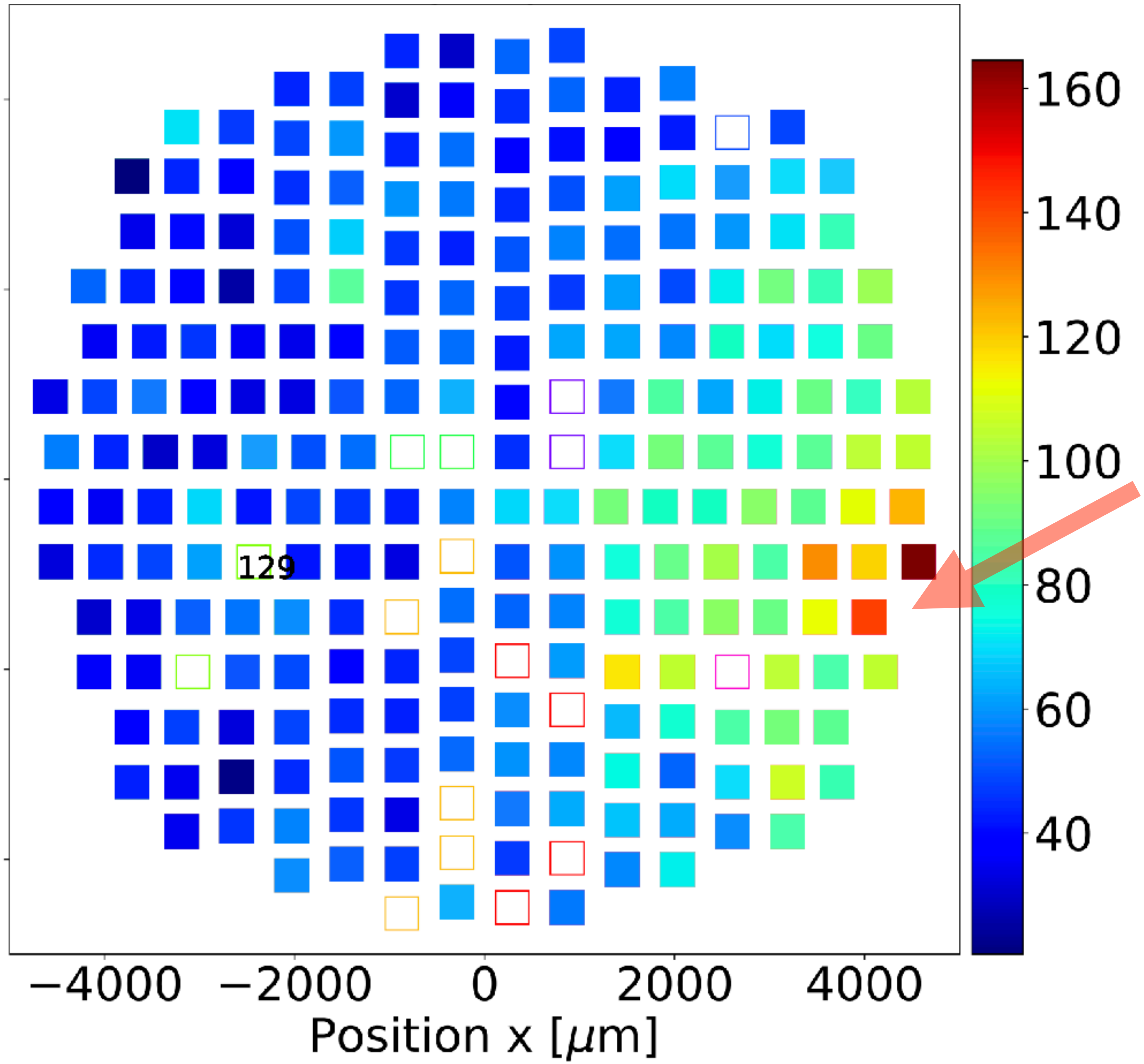
Charged particle hit



If charged particle hit on the Si substrate, heat will spread out throughout the array, making small bump signals in many pixels

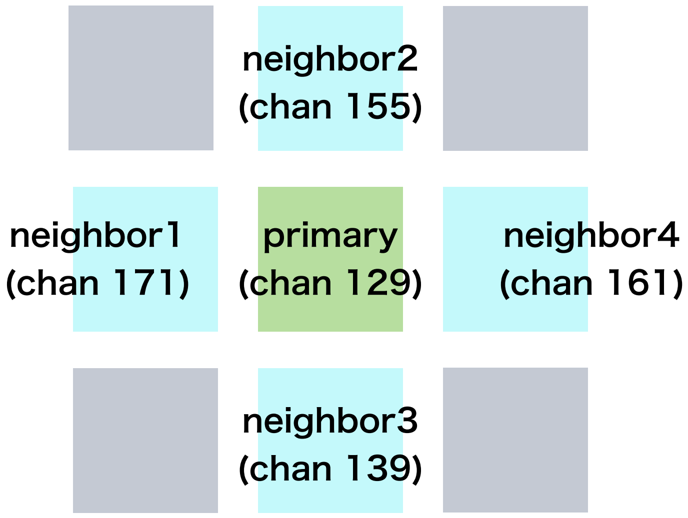
If charged particle hit on the detector pixel, it deposits ~10 keV energy (Bi 4um), which become severe background in the spectrum

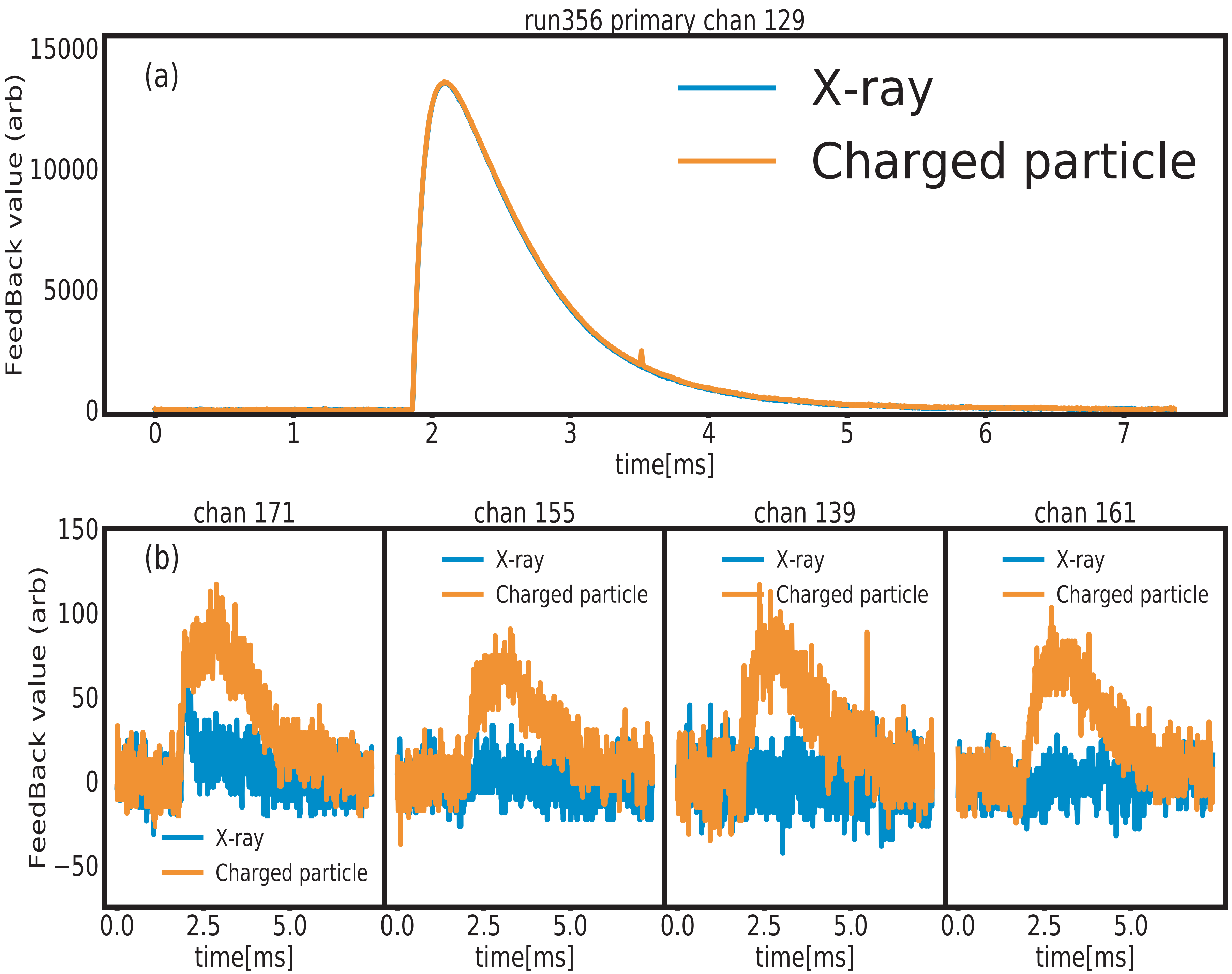
Pulse height distribution in array



Charged particle hit

Charged particle identification





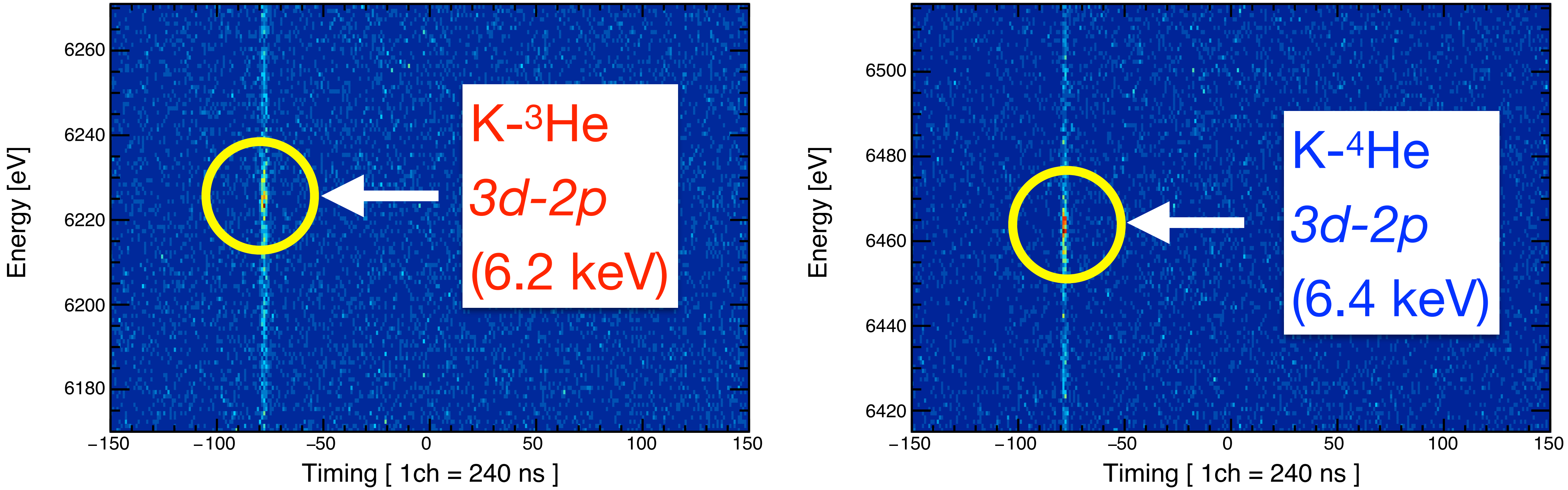
- No difference in the primary pulses between X-rays and charged particles
- If we look at neighboring pixels, we can reject half of the charged particles

Timing resolution

^{3}He target

^{4}He target

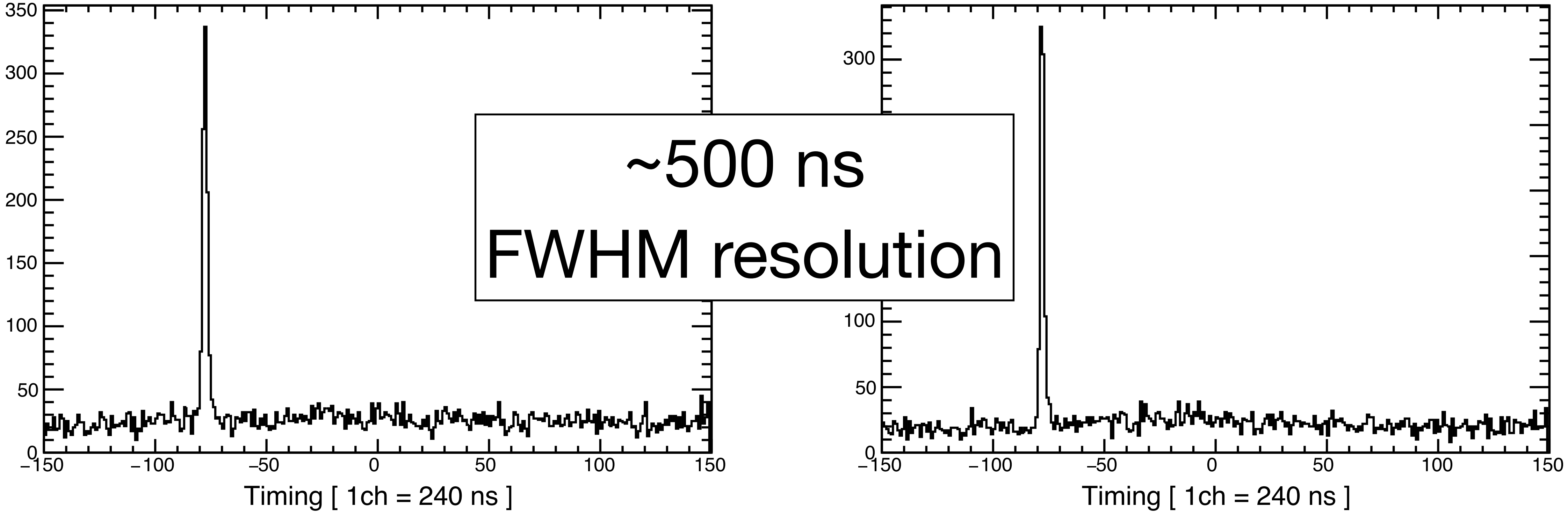
Time vs. energy



K-^{3}He
3d-2p
(6.2 keV)

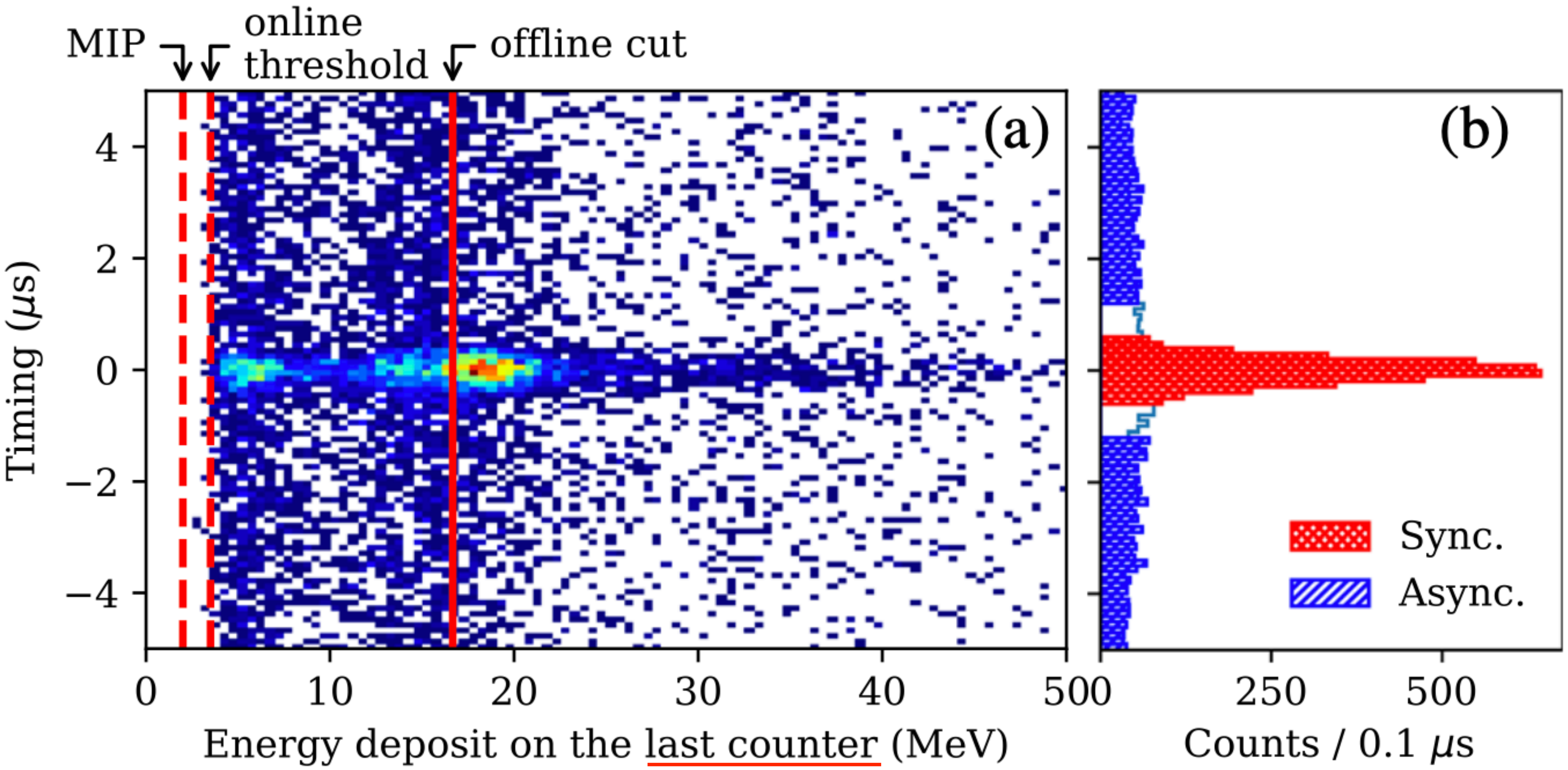
K-^{4}He
3d-2p
(6.4 keV)

Time to K_{stop} trigger



~500 ns
FWHM resolution

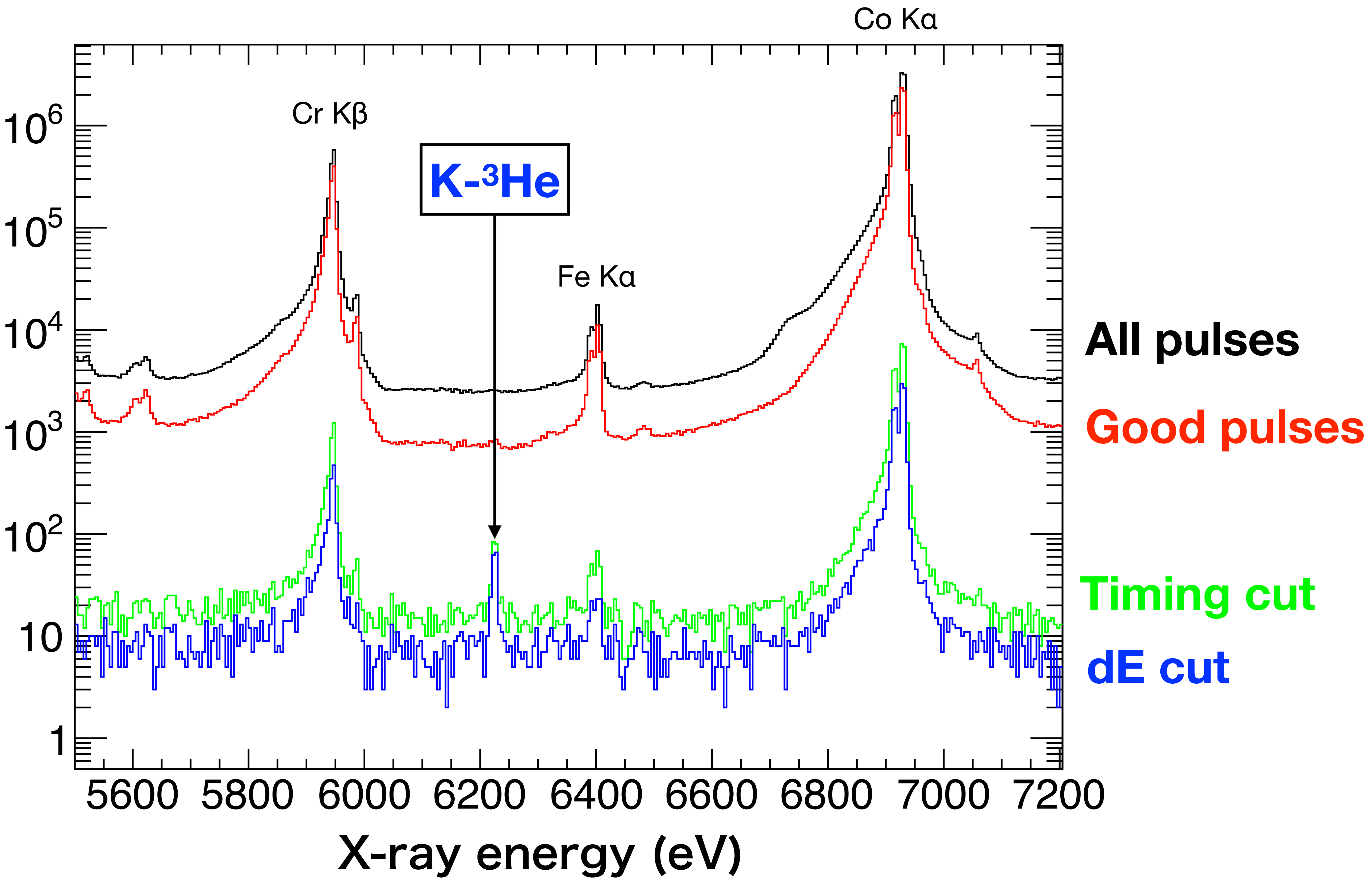
Timing vs. dE (energy deposit)



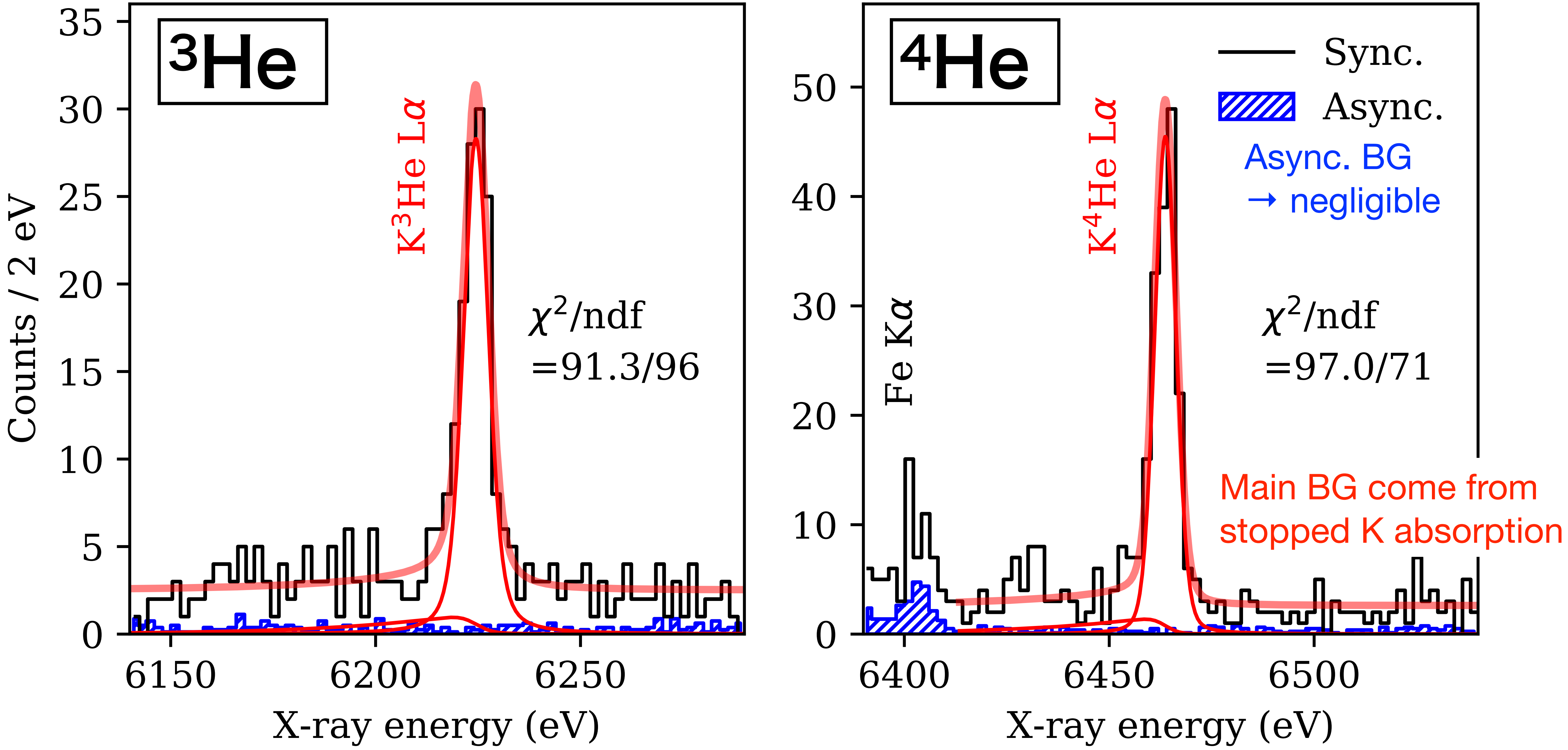
a thin scintillator just in front of the target

requiring the energy deposit to be larger than 16 MeV
to select low momentum kaons which are likely to stop in the target.

Background reduction



Kaonic X-ray spectra



Async. BG
→ negligible

Main BG come from stopped K absorption

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

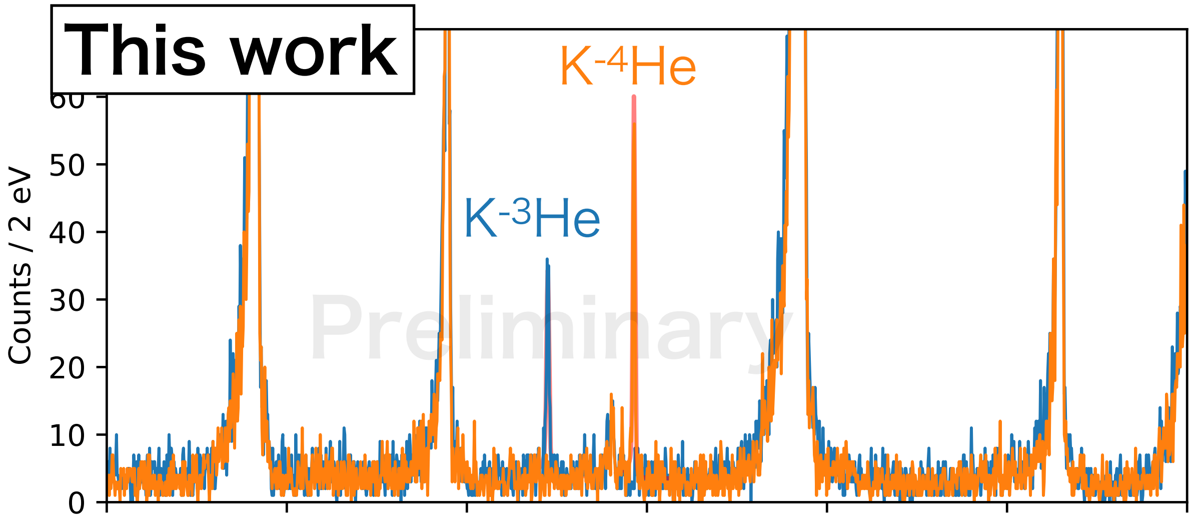
$$\Gamma_{2p}^{K-^3\mathrm{He}} = 2.5 \pm 1.0(\mathrm{stat}) \pm 0.4(\mathrm{syst})\ \mathrm{eV}$$

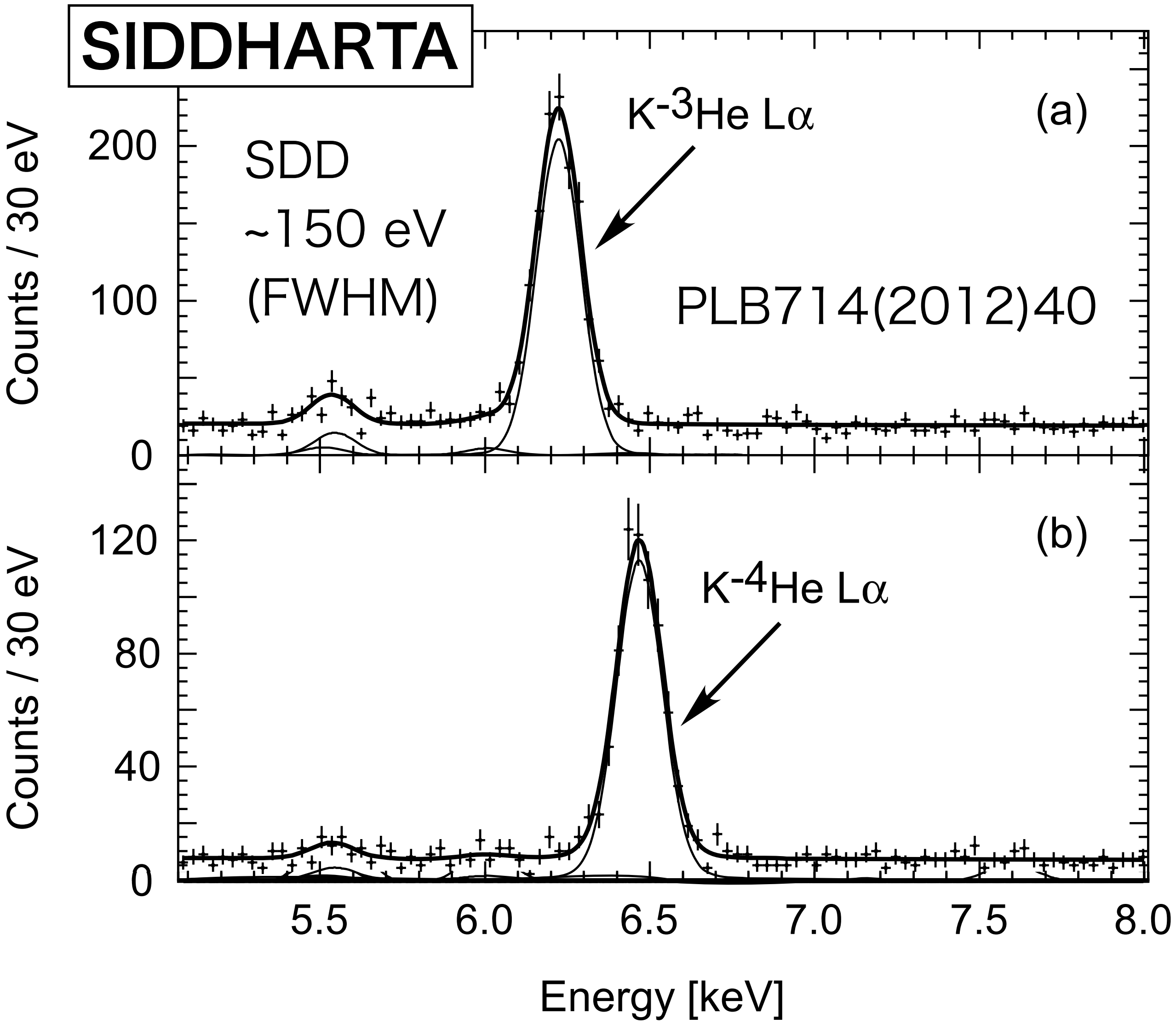
$$E_{3d\to 2p}^{K-^4\mathrm{He}} = 6463.7 \pm 0.3(\mathrm{stat}) \pm 0.1(\mathrm{syst})\ \mathrm{eV}$$

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

Syst. error : mainly from the uncertainty in absolute energy scale

Comparison with past experiments

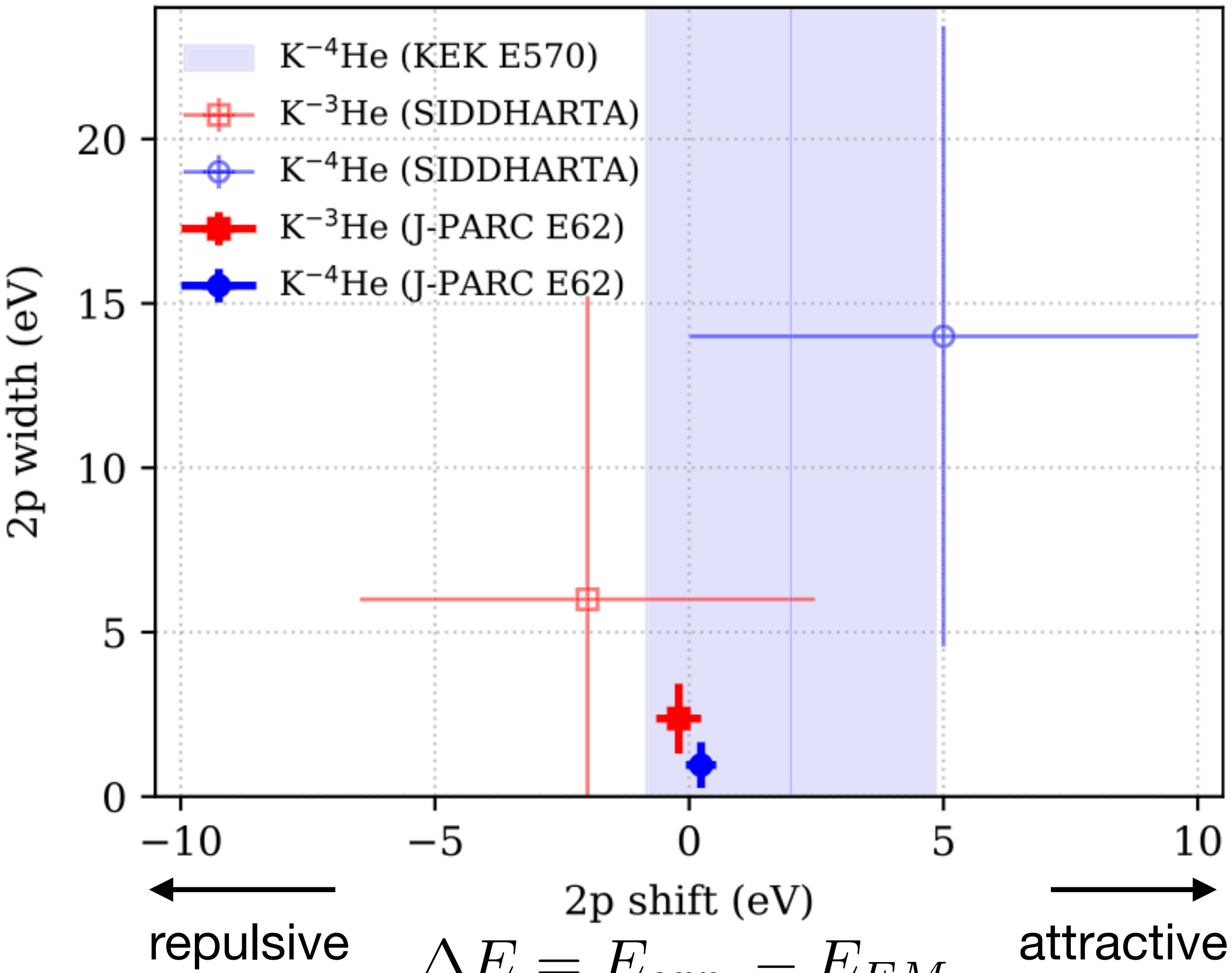




x 25 energy resolution

x 10 precision (shift&width)

Error bar: quadratic sum of stat. & sys.



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

Excluded large shifts & widths

Detailed investigation of the optical potentials is under way by Yamagata-san.

Outlook with TES

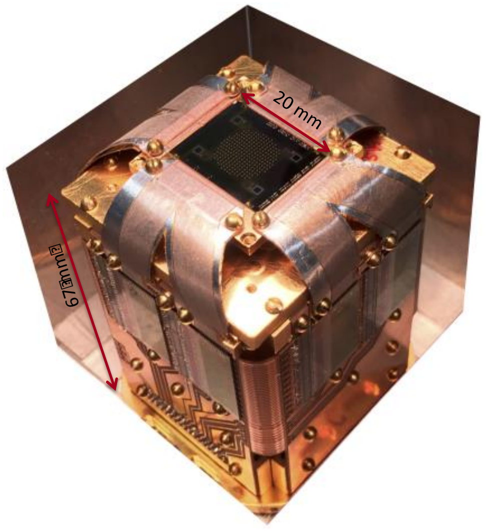
- Present system is applicable **up to 15 keV**, limited by TES saturation and stopping power of 4 um thick Bi absorber
  - Strong interaction in light kaonic atoms (K^{-} $^{6/7}$Li)
  - Charged kaon mass (K-N, K-O, K-Ne, …)

- New system for higher energy up to **100 keV** region is under development for 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)
  - Ξ-atoms (Ξ^{-}C) etc…

TES under development

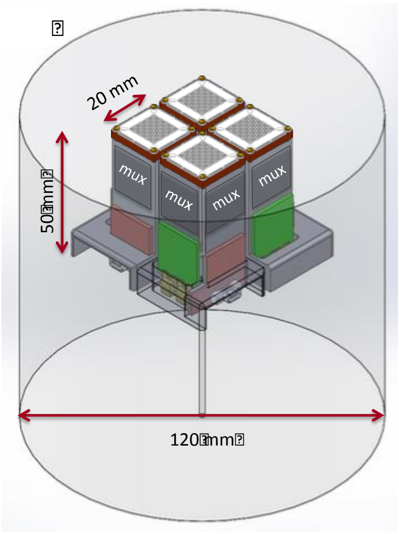
	J-PARC E62	Gamma-ray	50 keV	20 keV
Saturation energy	20 keV	150 keV	70 keV	50 keV
Absorber material	Bi	Sn	Au/ Bi	Au/Bi
Absorber thickness	4 um	120~250 um	3 um / 15 um	1.5 um / 15 um
Absorber area	320 x 305 um	1.3 x 1.3 mm	700 x 700 um	700 x 700 um
Pixel number	240	96	150	150
Total collection area	**23 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**

TDM “snout”



240 TESs readout with TDM

“microsnouts”



1024 TESs readout with μMUX

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

Douglas Bennett @ NIST

Summary & Outlook

J-PARC E62

✓ precision spectroscopy of kaonic ^{3}He & ^{4}He 3d→2p X-rays

✓ ~ 6 eV FWHM resolution (@ 6 keV) with a cryogenic detector TES

✓ realized sub-eV precision for 2p shifts and width

✓ large shift and width were excluded: $|\Delta E_{2p}| < 1$ eV, $\Gamma_{2p} < 5$ eV

✓ published the final results in 2022

Outlook (TES)

✓ New projects (μ-atom/molecule) following E62 success is launched

✓ ~30 keV region TES, ~100 keV region TES system will be available in next year → further μ-, K- Σ-, Ξ- atoms, K- mass etc.

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