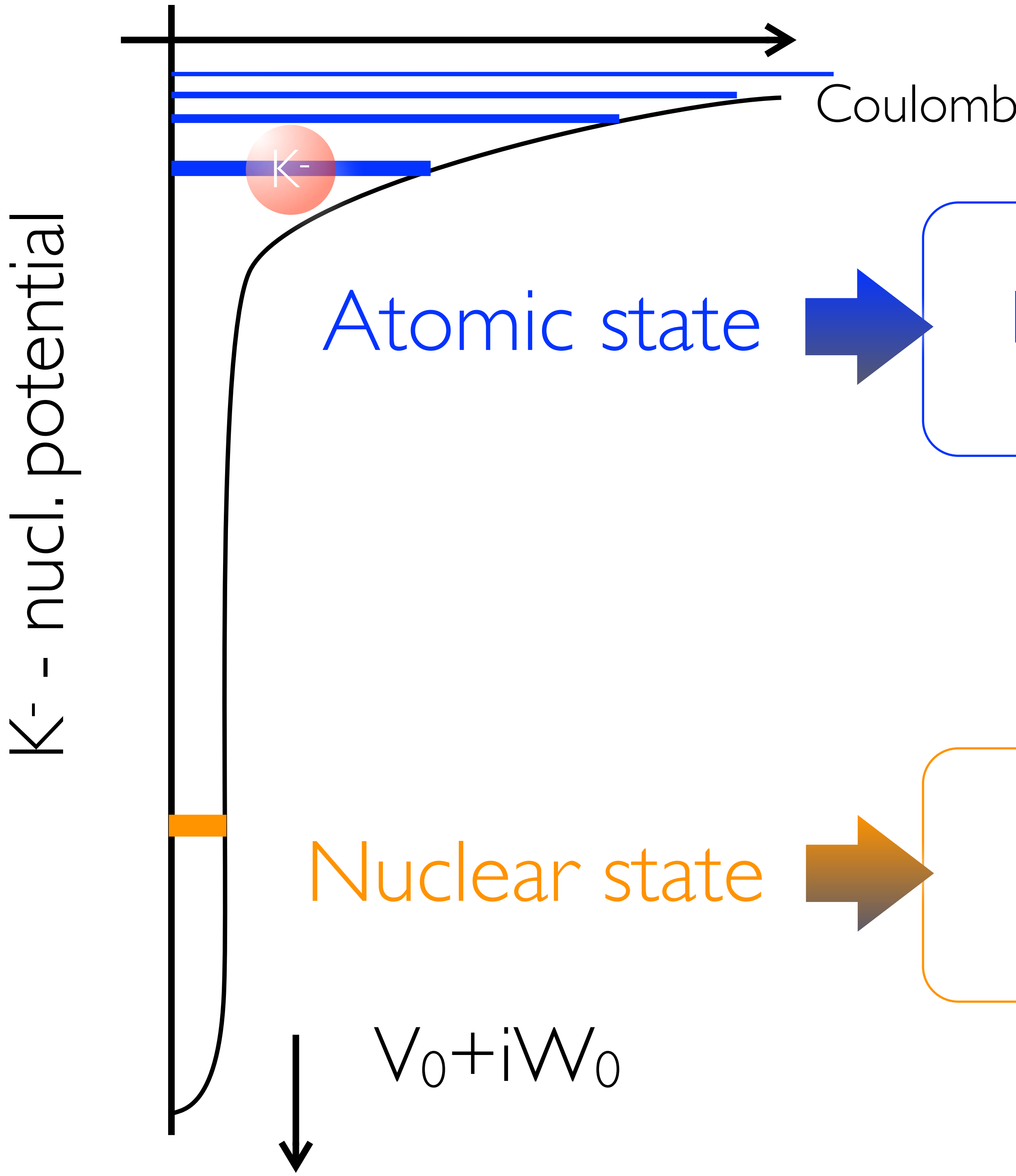
X-ray measurement of kaonic He-3,4 atoms with a high-resolution microcalorimeter

Tadashi Hashimoto (JAEA)
for the J-PARC E62 collaboration

Joint THEIA-STRONG2020 and JAEA/Mainz REIMEI Web-Seminar @ Apr. 15, 2021

Study of K-nucl. interaction



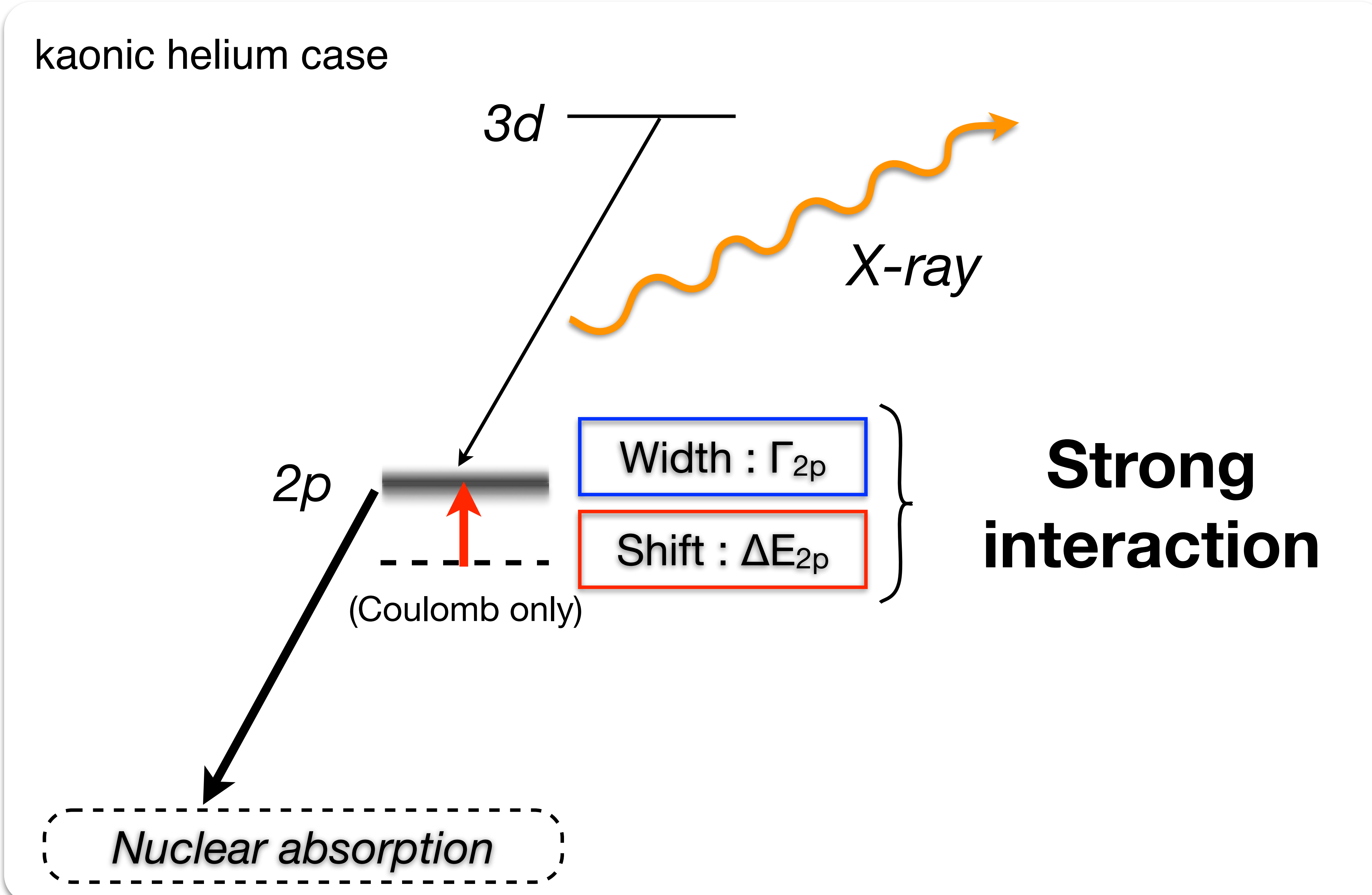
Precision x-ray measurement

complementary

Reaction formation
(Kaonic nuclear bound state)

cf. "K-pp" in J-PARC E15, etc…

Kaonic atom X-rays



Unique probe of the K^{bar}-nucleus strong interaction at the threshold energy

Kaonic atom X-rays

- Kaonic hydrogen, deuterium → K$^{\mathrm{bar}}$N scattering length

<u>Deser-Type relation</u> U.-G. Meißner, et al, Eur. phys. J. C35 (2004) 349

$$\varepsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu_c^2 \boxed{a_{K^-p}}\left(1 - 2\alpha\mu_c(\ln\alpha - 1)\boxed{a_{K^-p}}\right)$$

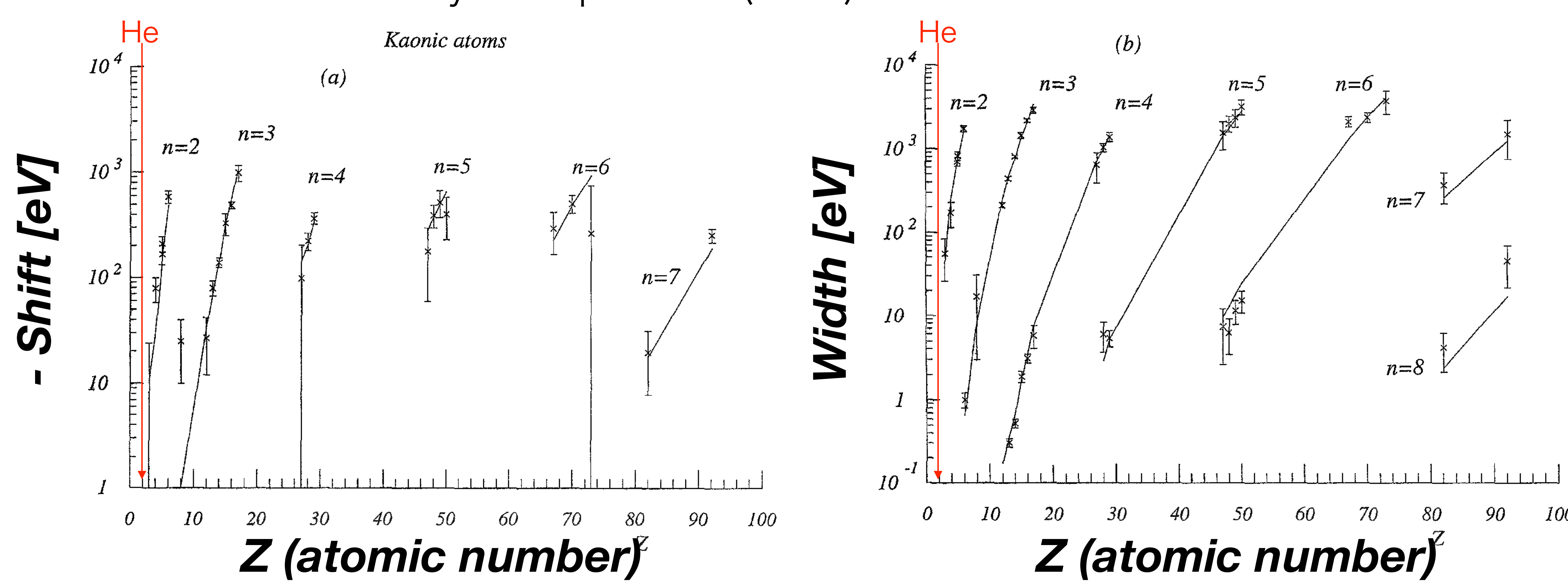
Shift **Width** **Scattering length**

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

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

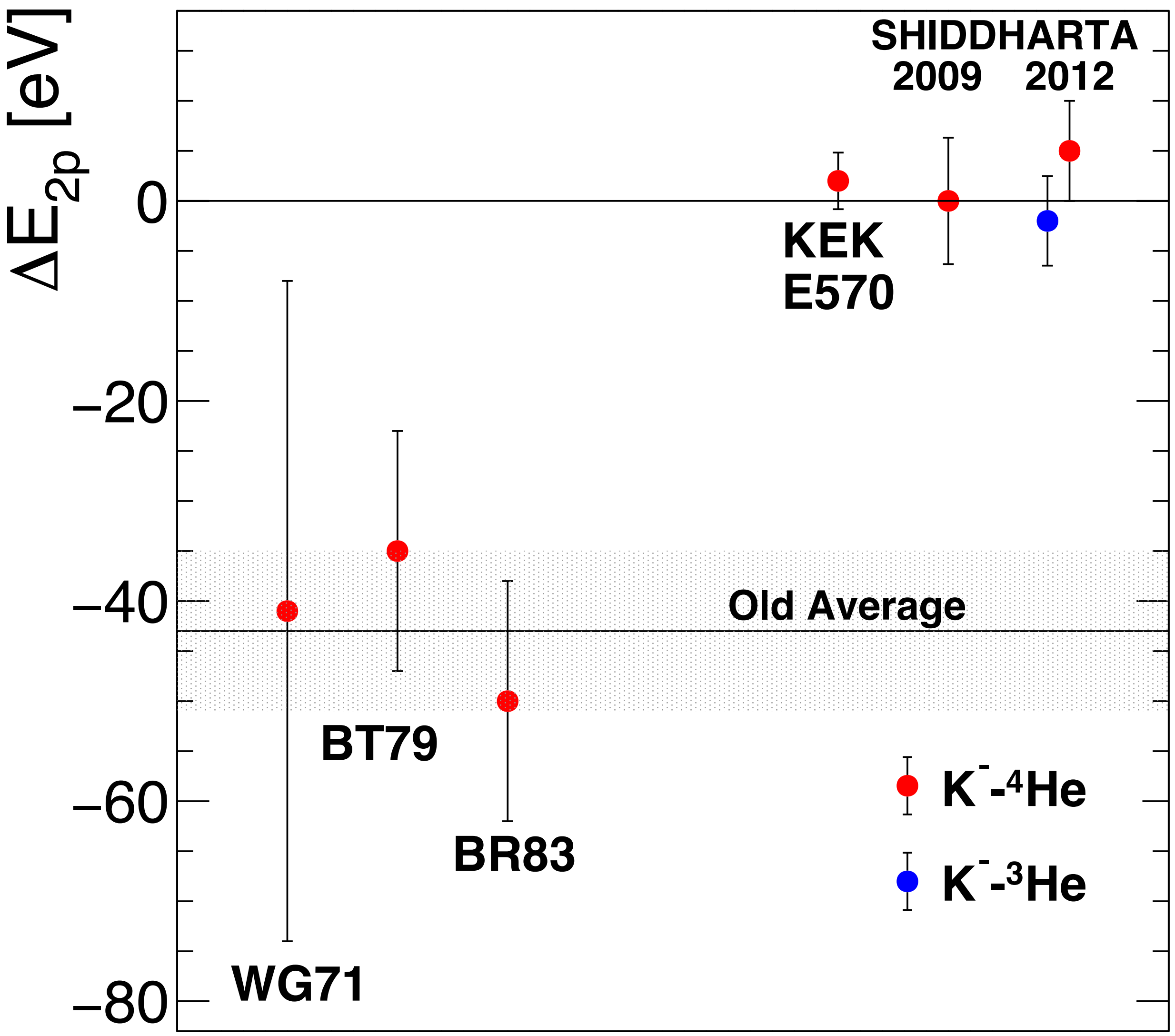
- Heavier atoms → Attractive optical potential
  global repulsion from a large imaginary part

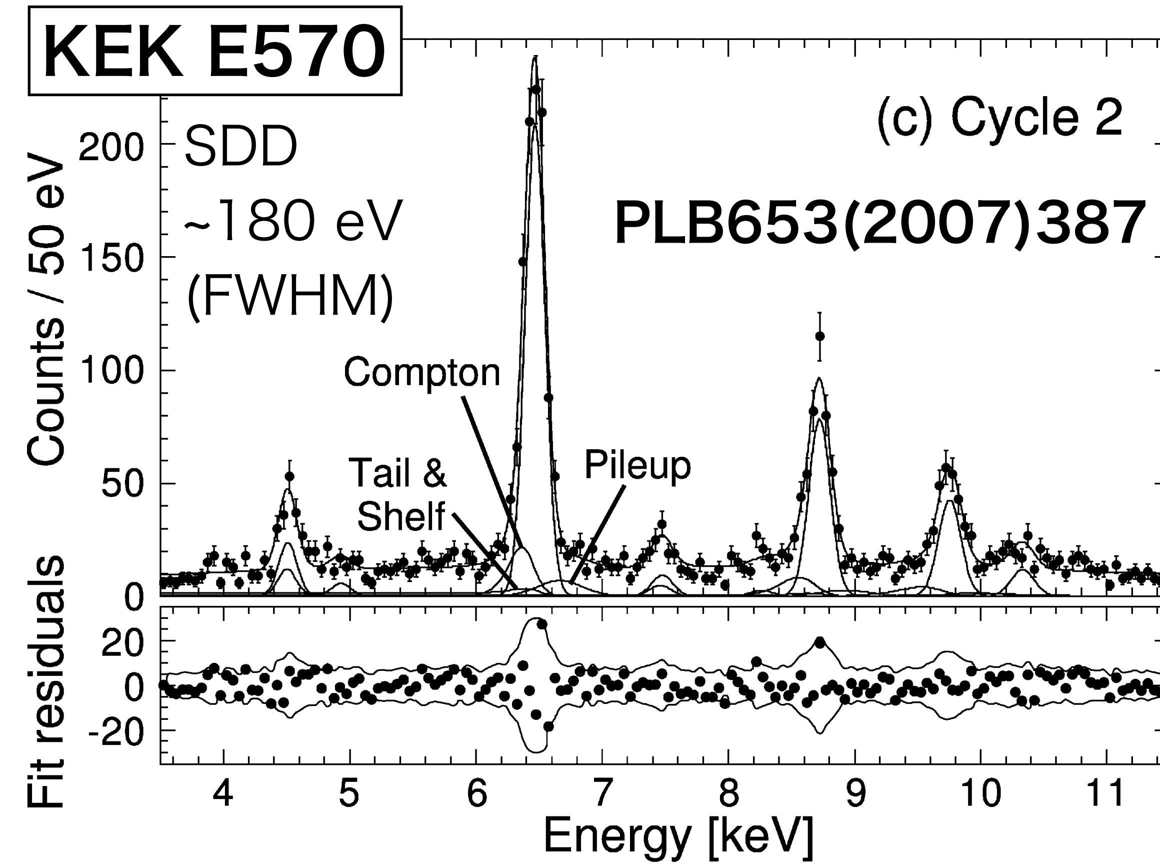
Physics report 287 (1997) 385-445

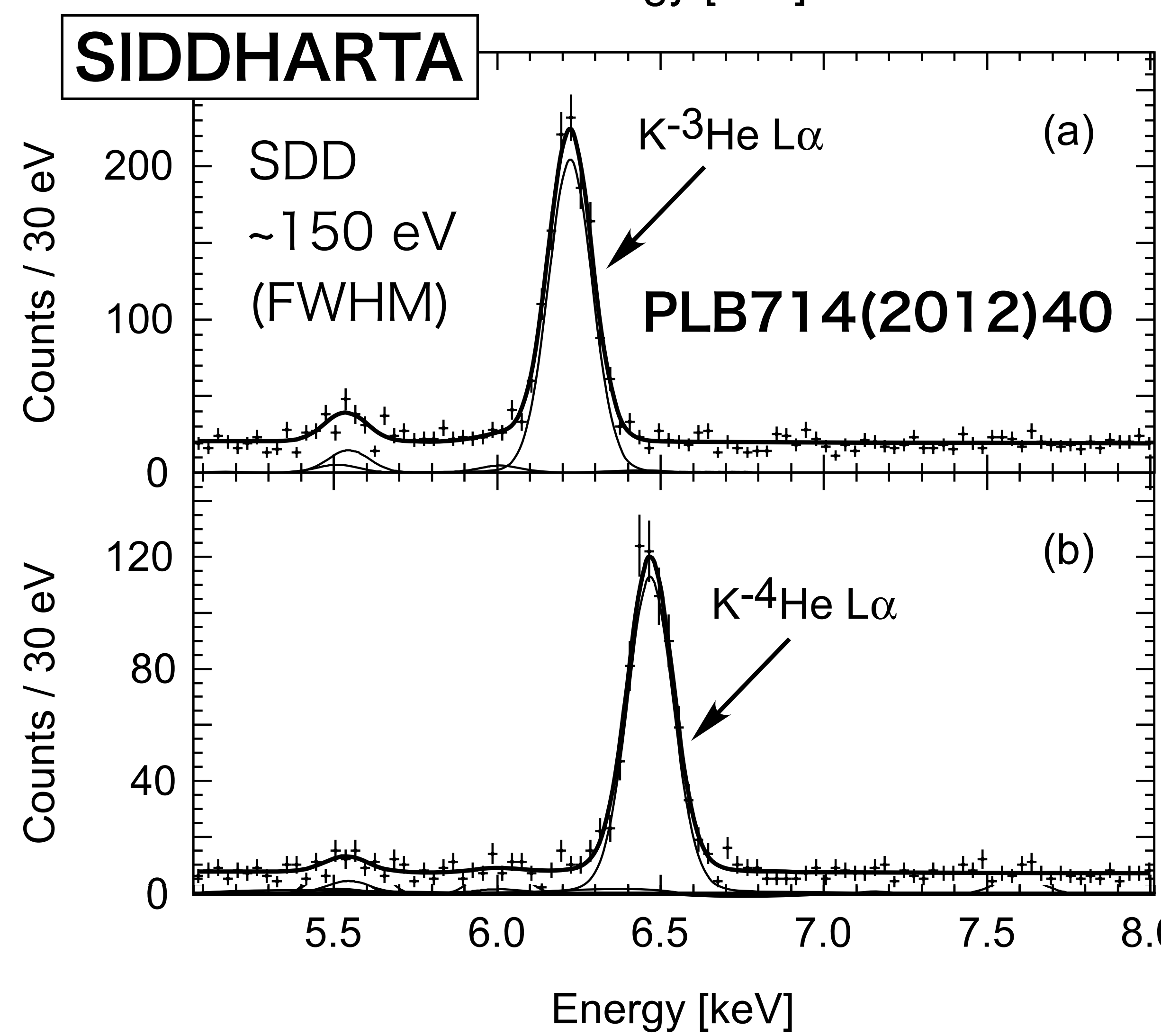


K$^-$He Experiments

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



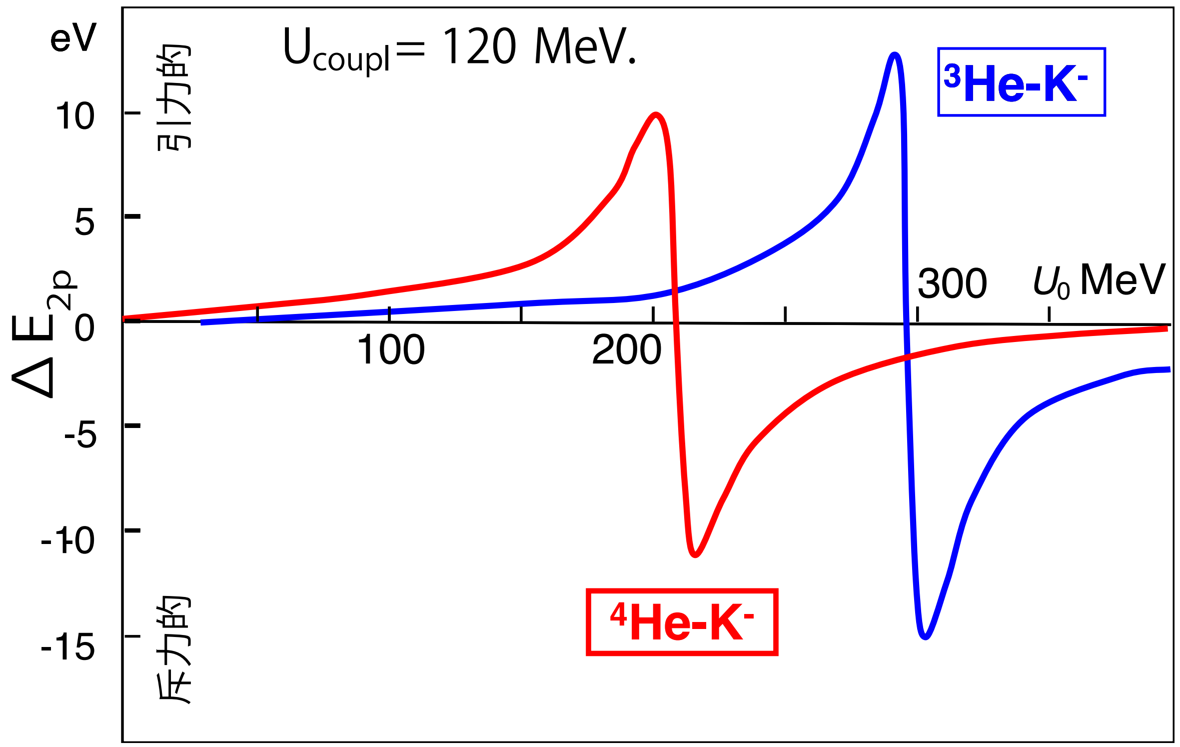




- Old “puzzle” has been solved
- Shift < 5 eV, Width < 20 eV
- Precision ~ 2 eV << Resolution 150 eV

K-He theoretical calculation

Y, Akaishi, EXA2005 proceedings



J. Yamagata-Sekihara, S. Hirenzaki
private communication

Width : ~2 eV

	deep	shallow
	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

	^{3}He	^{4}He
Shift (eV)	0.3	−0.2
Width (eV)	2.1	1.6

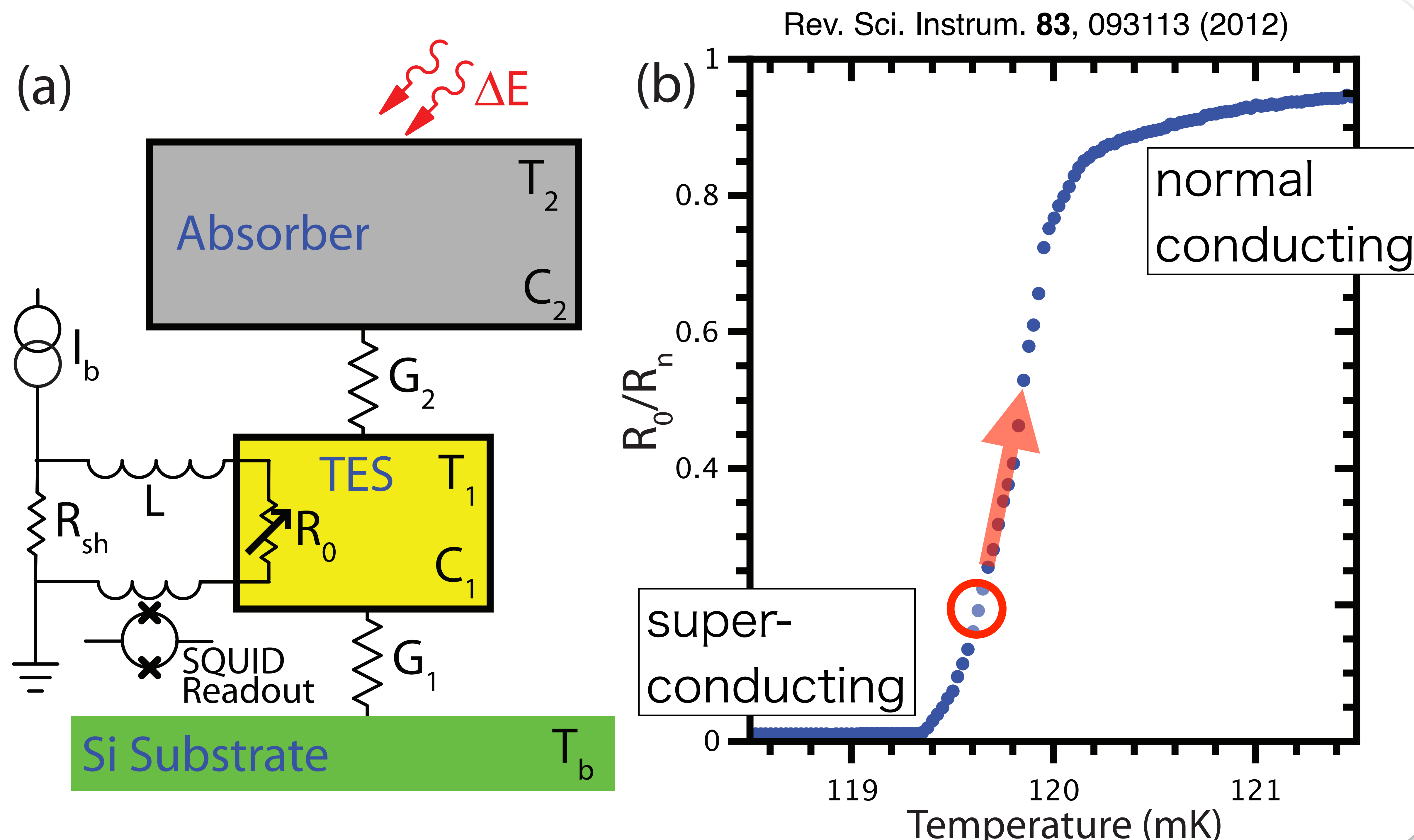
E. Friedman
Hyperfine Interactions
209, 127–132(2012)
TW1+ pheno. mN term

- Is there large shift > 1 eV, and width > 5 eV ?
    - if yes, optical potential models can not explain.
- Sign of the shift ?
    - attractive shift would suggest no p-wave nuclear bound state.

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

Transition-Edge-Sensor microcalorimeters

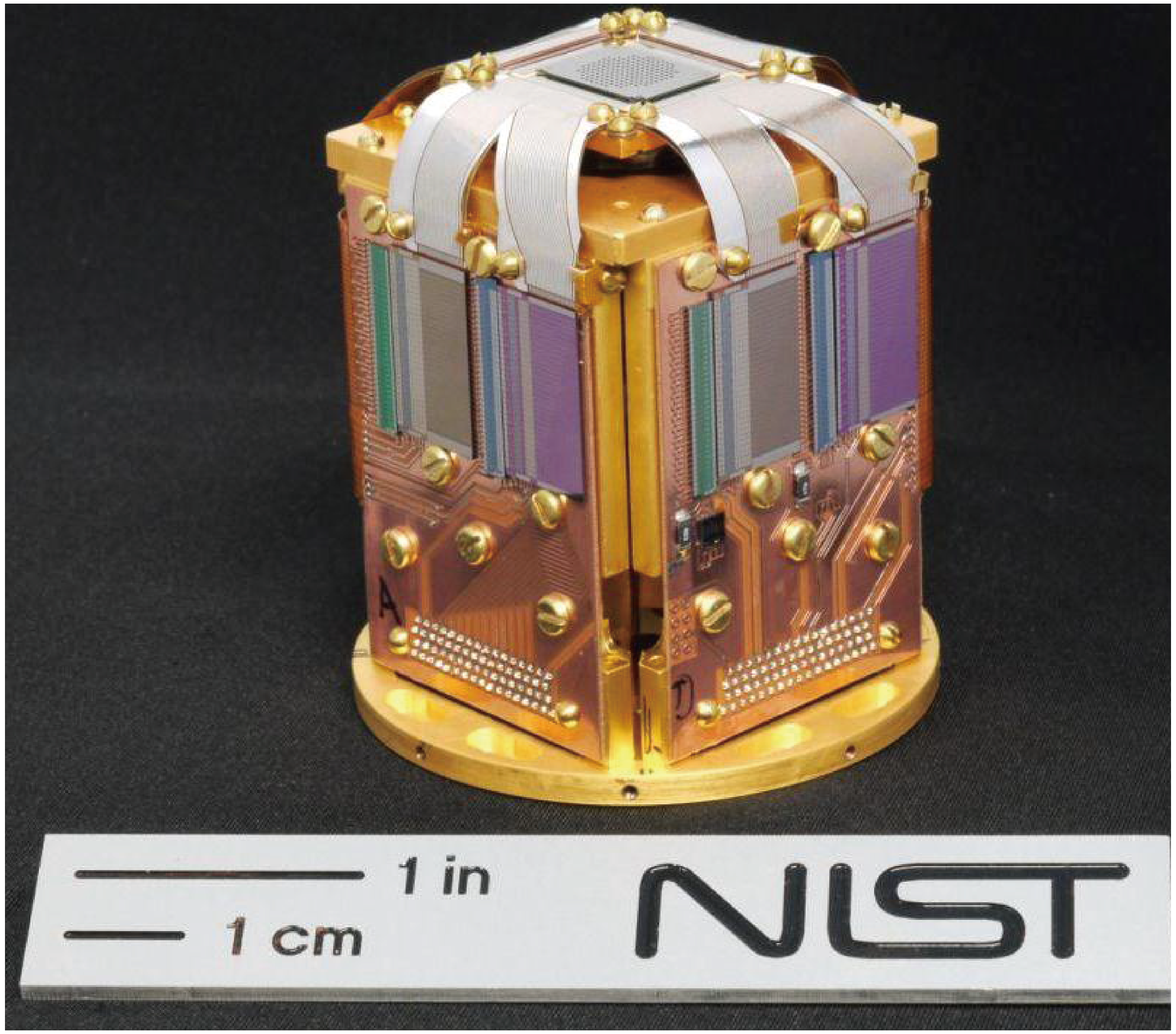


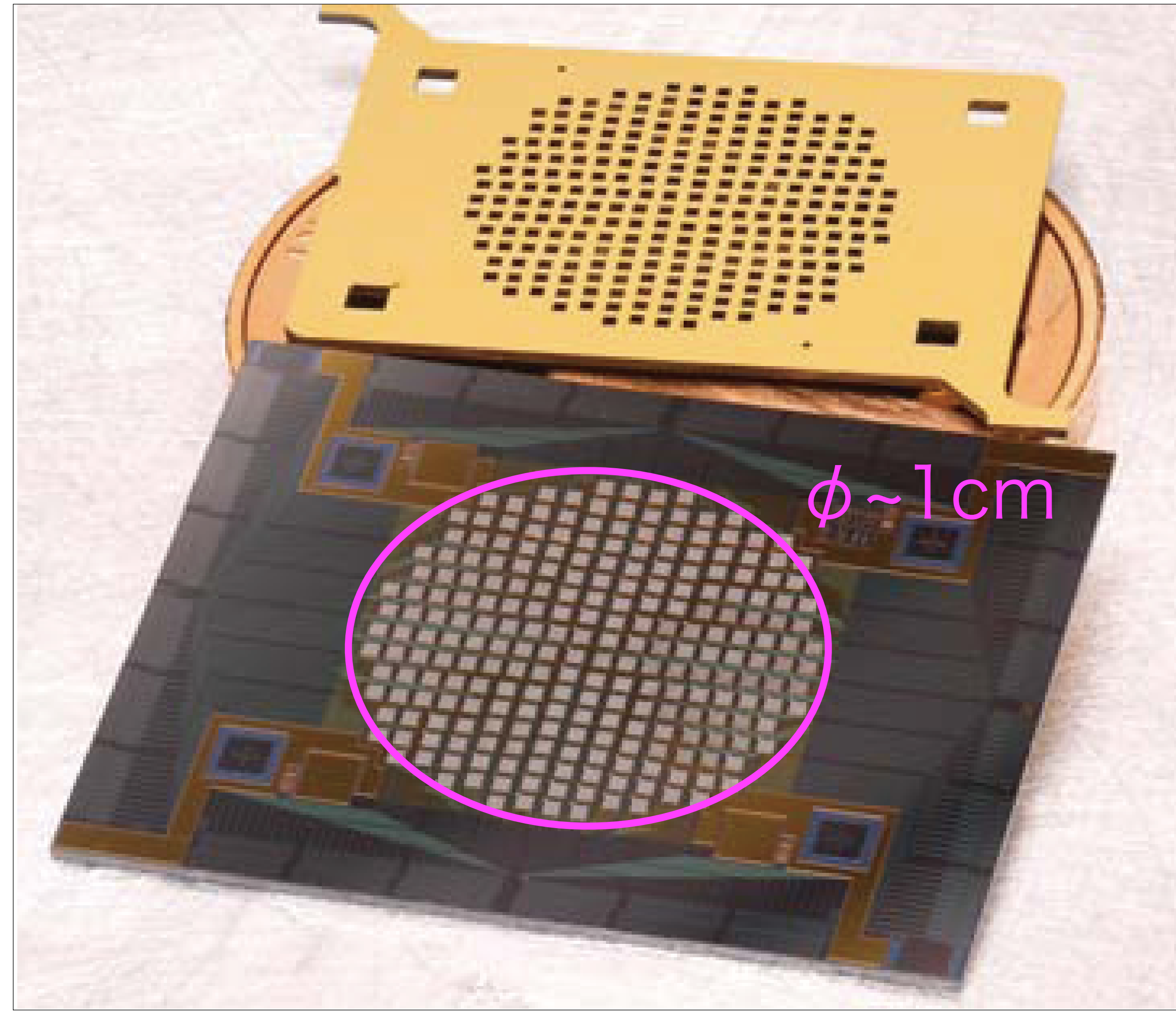
✓Excellent energy resolution with a reasonable dynamic range

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, Mo/Cu + Bi 4um (85% eff.@6 keV)
- First case to operate in a hadron beam environment.

HPD 102 DENALI

Date of Test Start: 12/29/15
Operator: David Hollander/Hans Bickling
Test ID: CD3MGA
Job Number: s13202
Customer:
QD Japan, Tokyo Metro University
Cryostat Model Number: 102
Cryostat Serial Number: p04102-50
Magnet Current: 20 Amps

De-Mag Start Temps:
FAA = 2.83 K
GGG = 2.76 K
1st Stage = 56.9 K
2nd Stage = 2.97 K

Base Temps after De-Mag:
FAA = 41 mK
GGG = 0.475 K

- Base temps:
  < 40 mK @ FAA
  < 500 mK@ GGG

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**
ADR Base Temperature   **< 50 mK**
FAA Cooling Capacity   **118 mJ @ 100 mK**

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** *J. Low Temp. Phys. **199**, 1018–1026 (2020)*
…	*physics paper in preparation…*

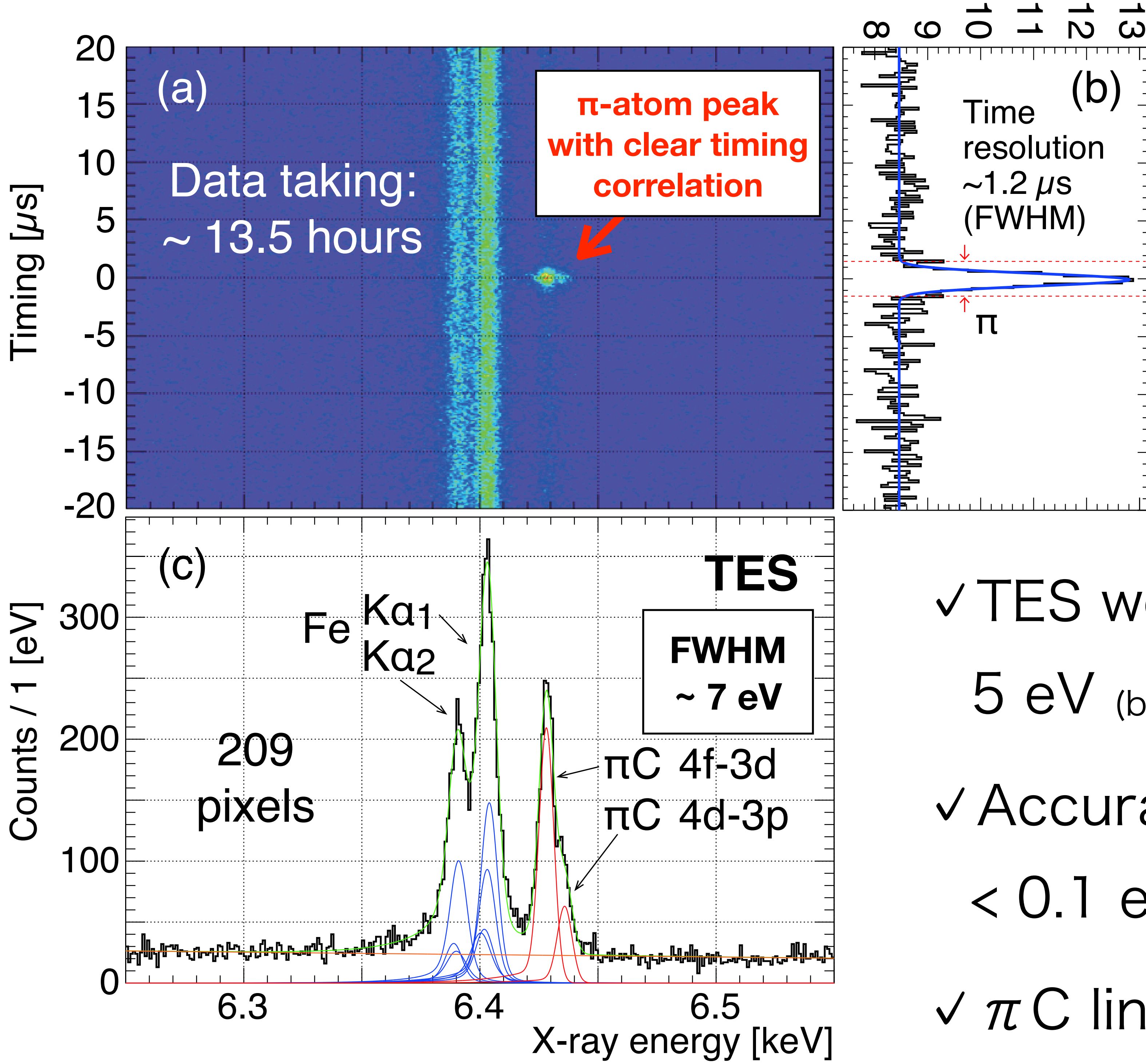
PSI v.s. J-PARC

	PSI	J-PARC
location	Villigen, Switzerland	Tokai, Japan
beam line	πM1	K1.8BR
particle	$\boldsymbol{\pi^-}$	$\mathbf{K^-}$
purity	~ 0.4	~ 0.2
momentum	170 MeV/c	900 MeV/c
intensity (sum of all particles)	1.4 ~ 2.8 * 10^6 cps	8 *10^5 / spill
X-rays from hadronic atom	$\pi\,^{12}$C 4-3: 6.4 keV	K^{3}He 3-2: 6.2 keV K^{4}He 3-2: 6.4 keV
science X-ray rate	~ 200 **/ hour**	~ 200 **/ week**

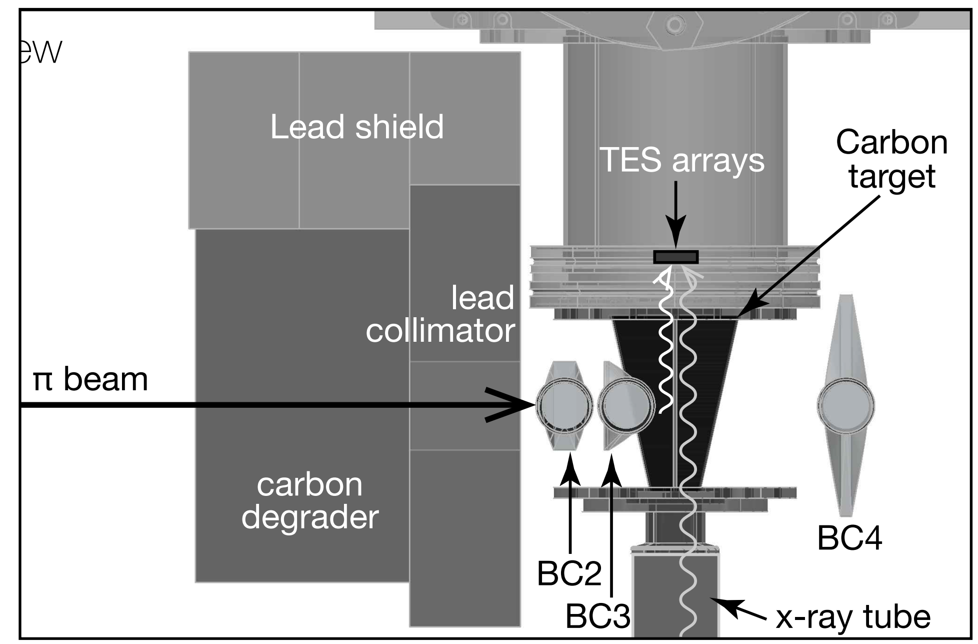
Easier to start with pion beam at PSI

πC 4-3 X rays at PSI πM1

S. Okada et al., PTEP. ***2016****, 091D01*



Oct./Nov. 2014



✓TES worked at a hadron beam line

5 eV (beam off) -> 7 eV (beam on) FWHM

✓Accurate energy calibration

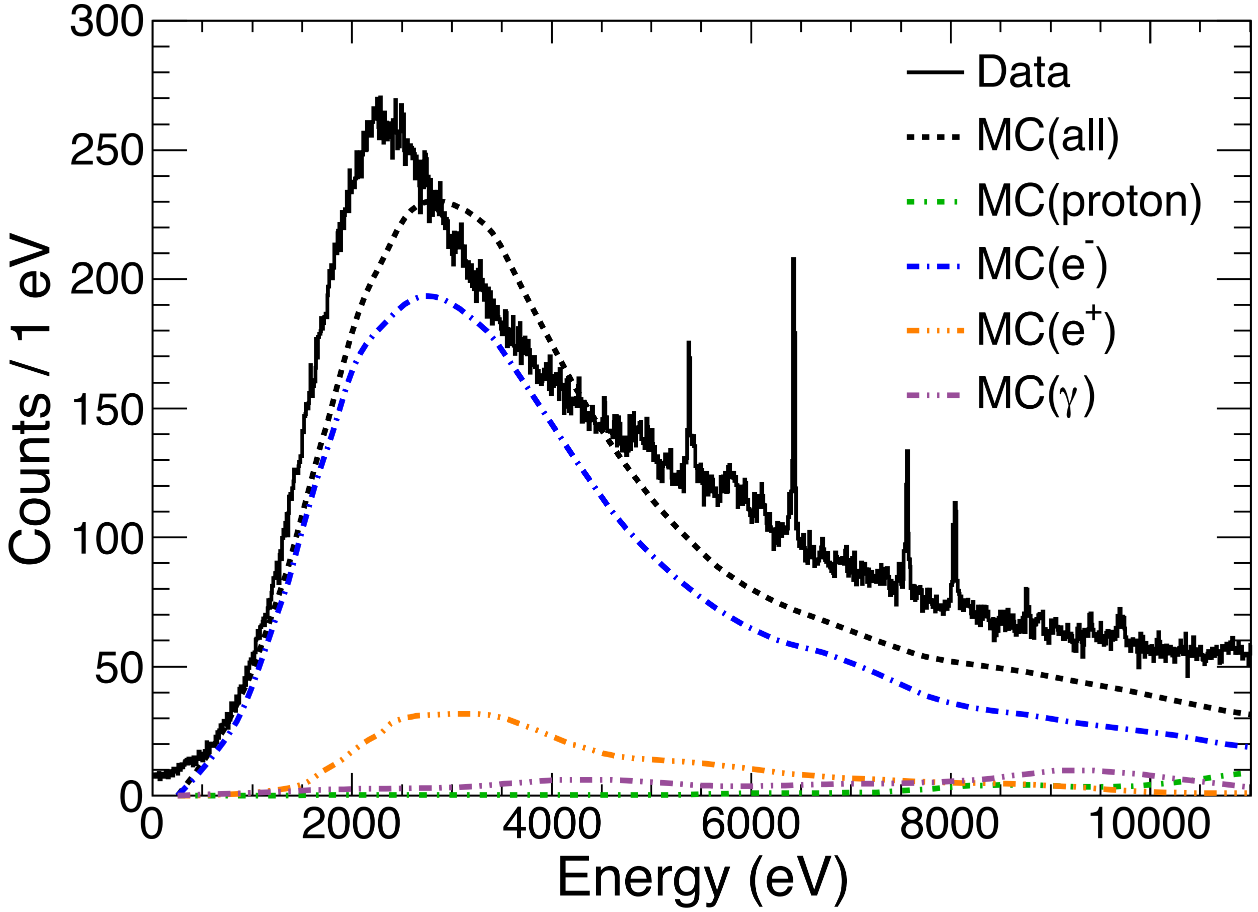
< 0.1 eV accuracy at FeKa

✓ πC lines at expected energies

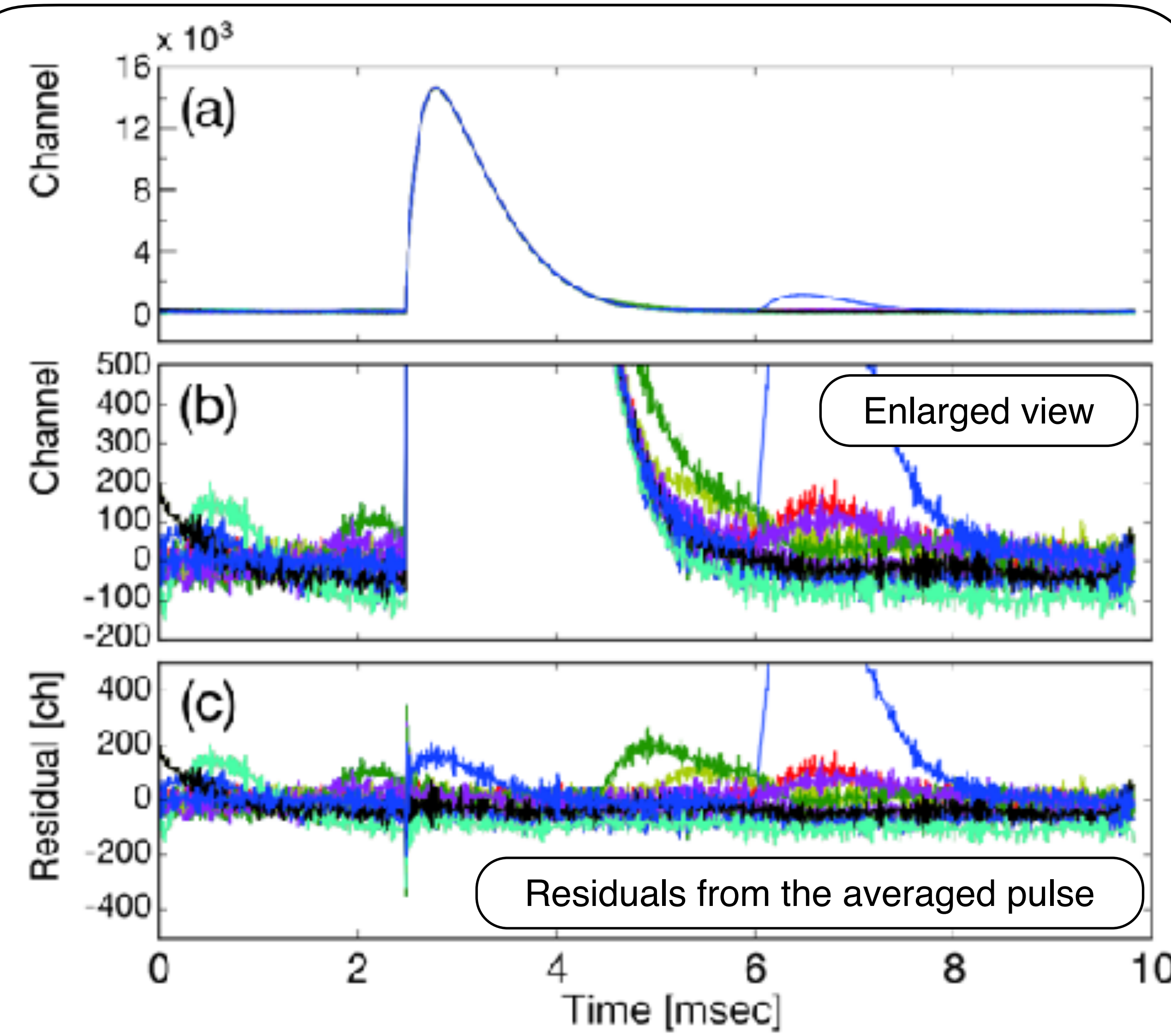
±0.13(stat.)±0.09(syst.) eV

Challenges in a hadron beam

In-beam spectrum
w/o photon source at PSI



Energetic charged particle deposits several keV energy on **4 um thick Bi** absorber



Charged particles on Si frame of TES chip.
→ thermal-crosstalk bumps
-→ degrade the energy resolution.

- ✓ Reduction of the beam-particle hit is essentially important
- ✓ Analysis to distinguish X-ray/Charged particle hits, cross-talk events

J-PARC E62
K^{-} $^{3/4}$He 3d→2p with TES

completed in June 2018, ~18 days

J-PARC E62 collaboration

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

NIST

INFN-LNF, Politecnico di Milano

Stefan Meyer Institut

KU Leuven

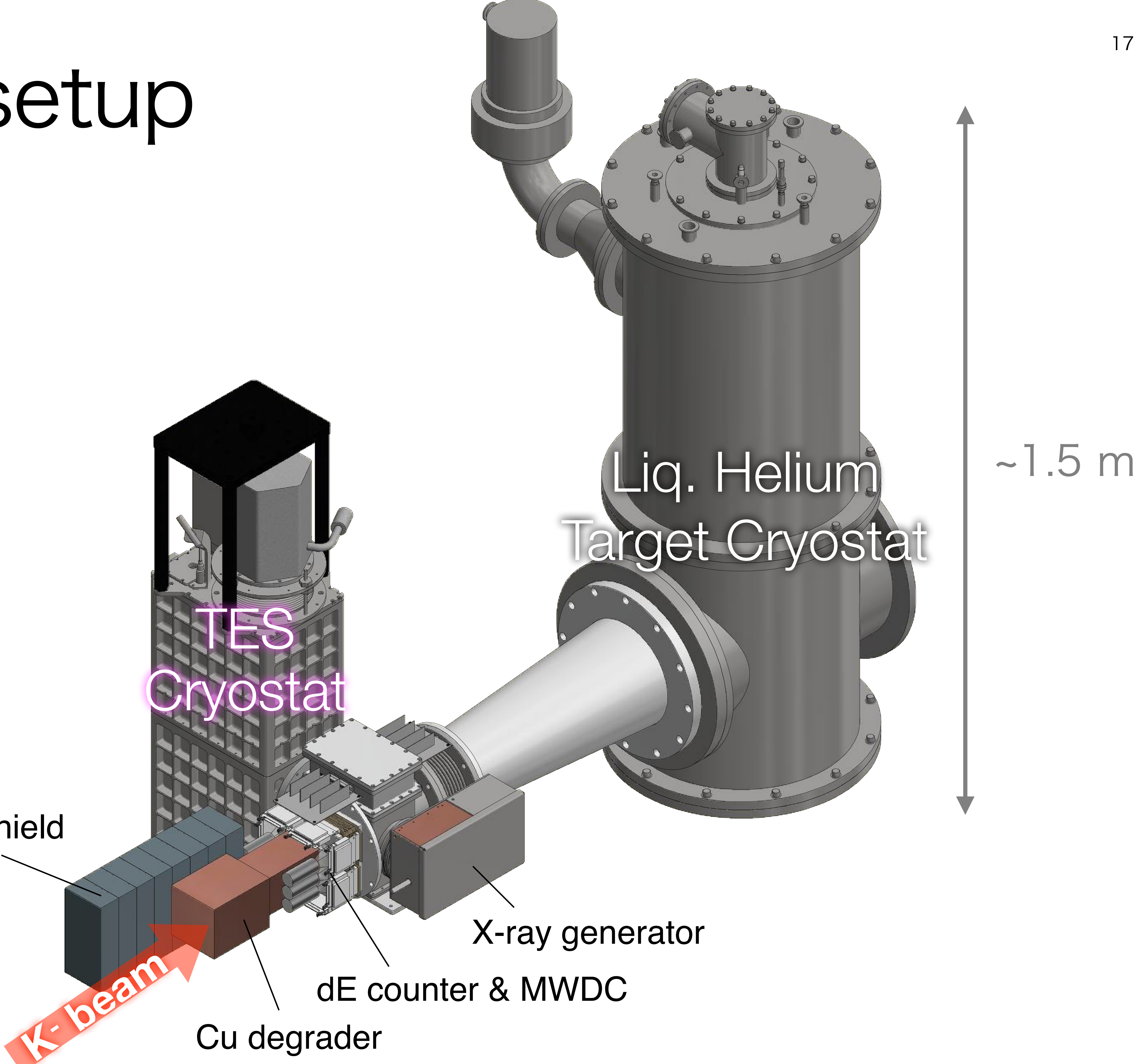
University of Zagreb

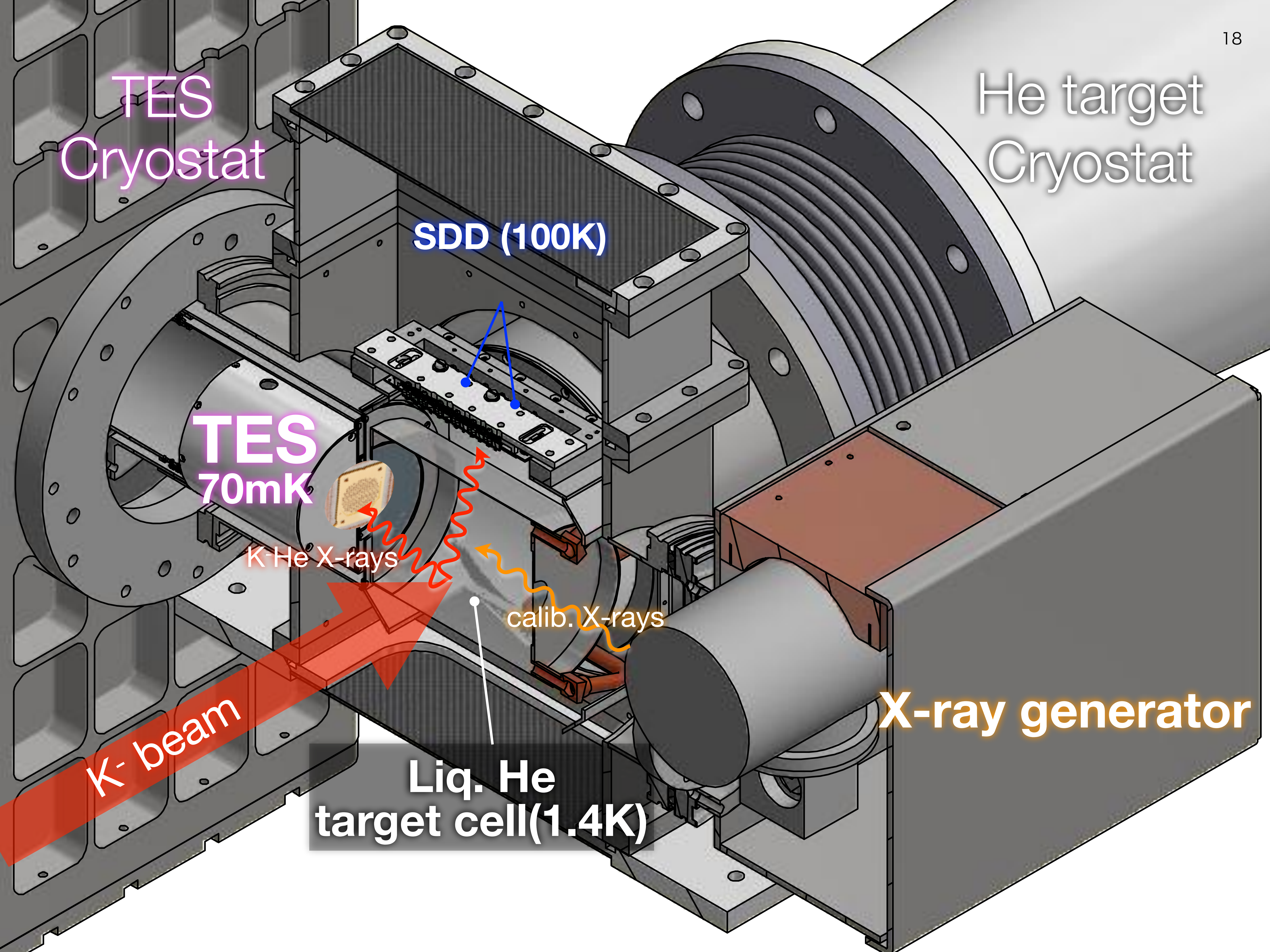
Lund University

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

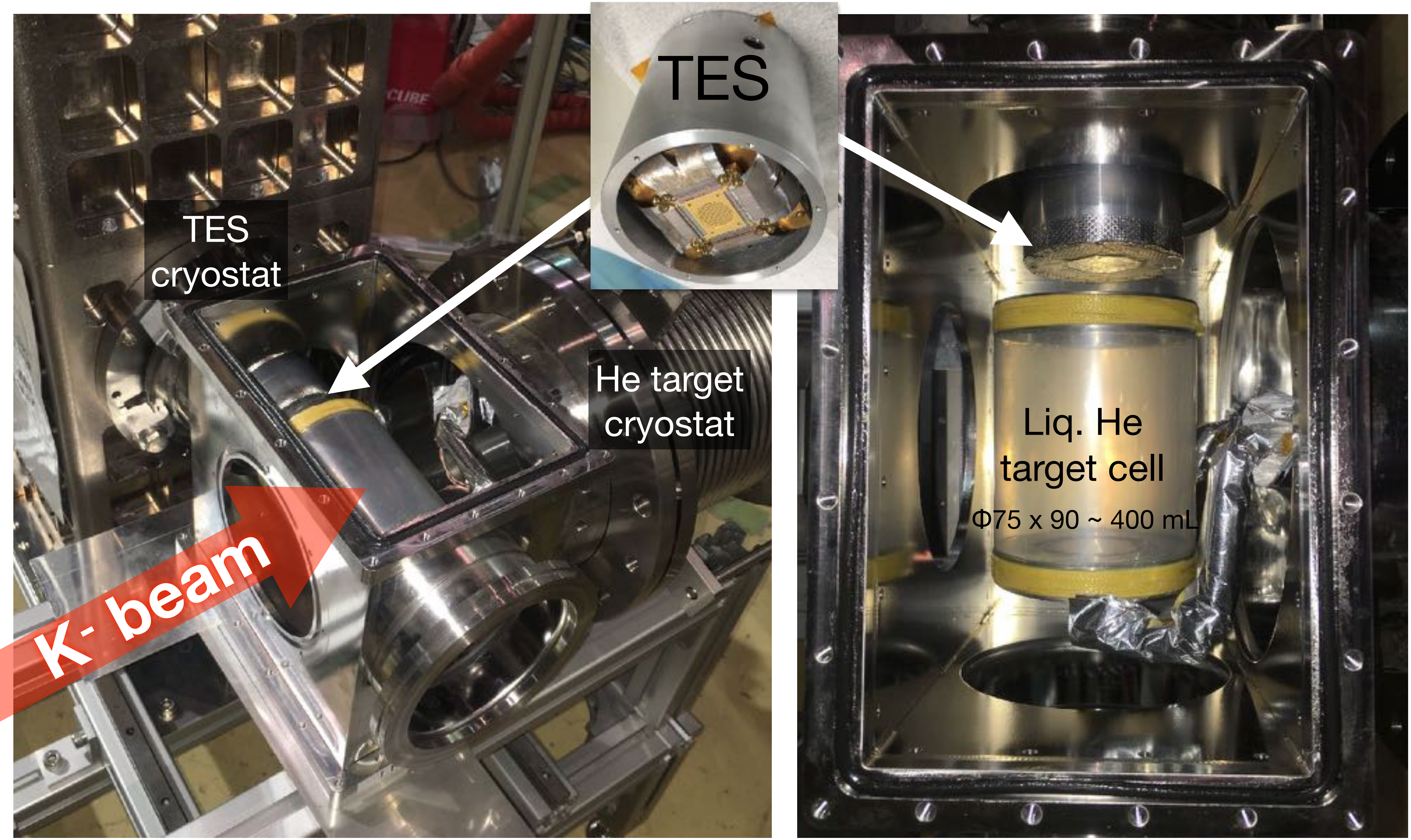
71 collaborators in total

E62 setup

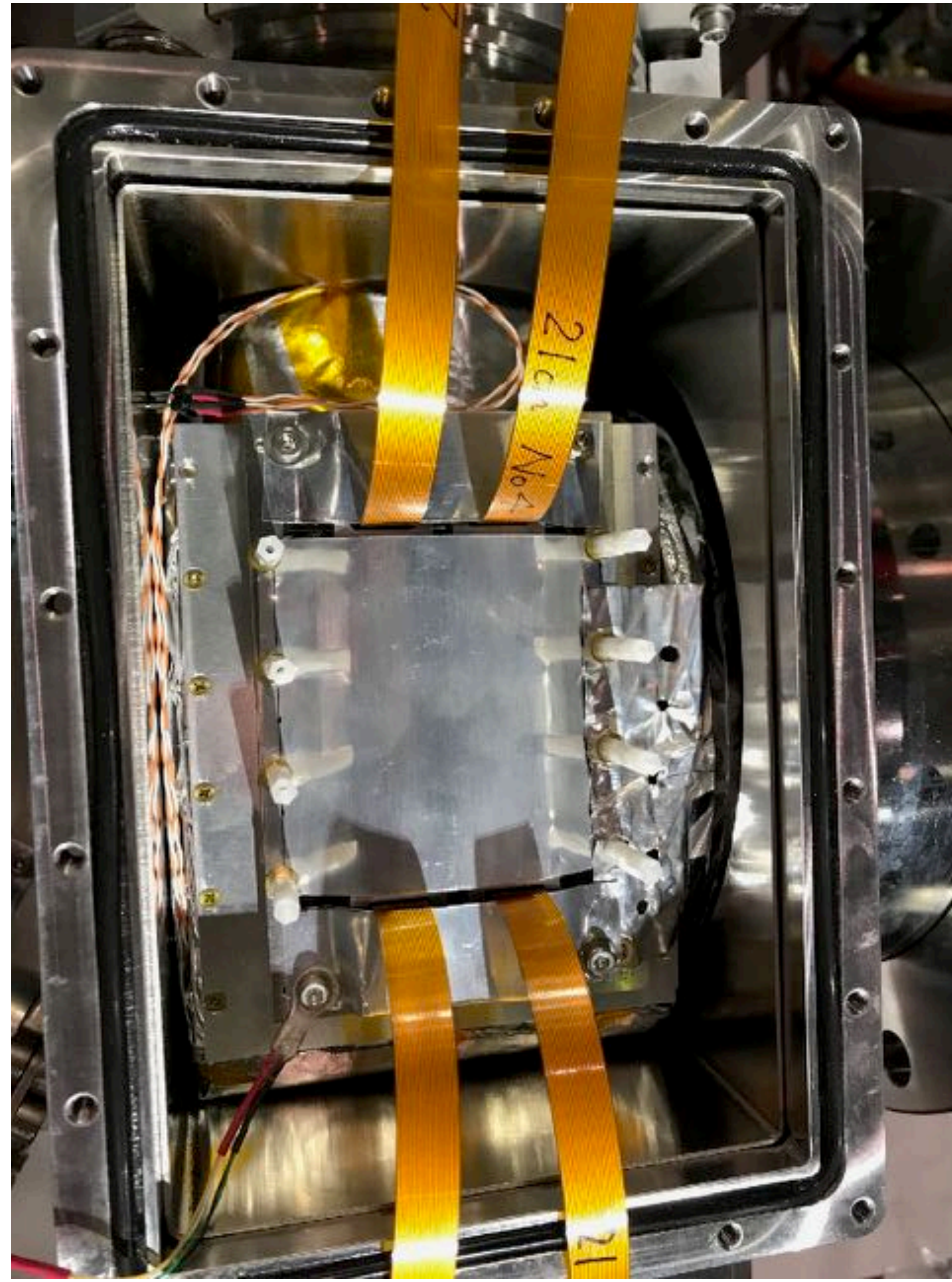

~1.5 m
Liq. Helium
Target Cryostat
TES
Cryostat
Pb shield
X-ray generator
dE counter & MWDC
Cu degrader
K- beam

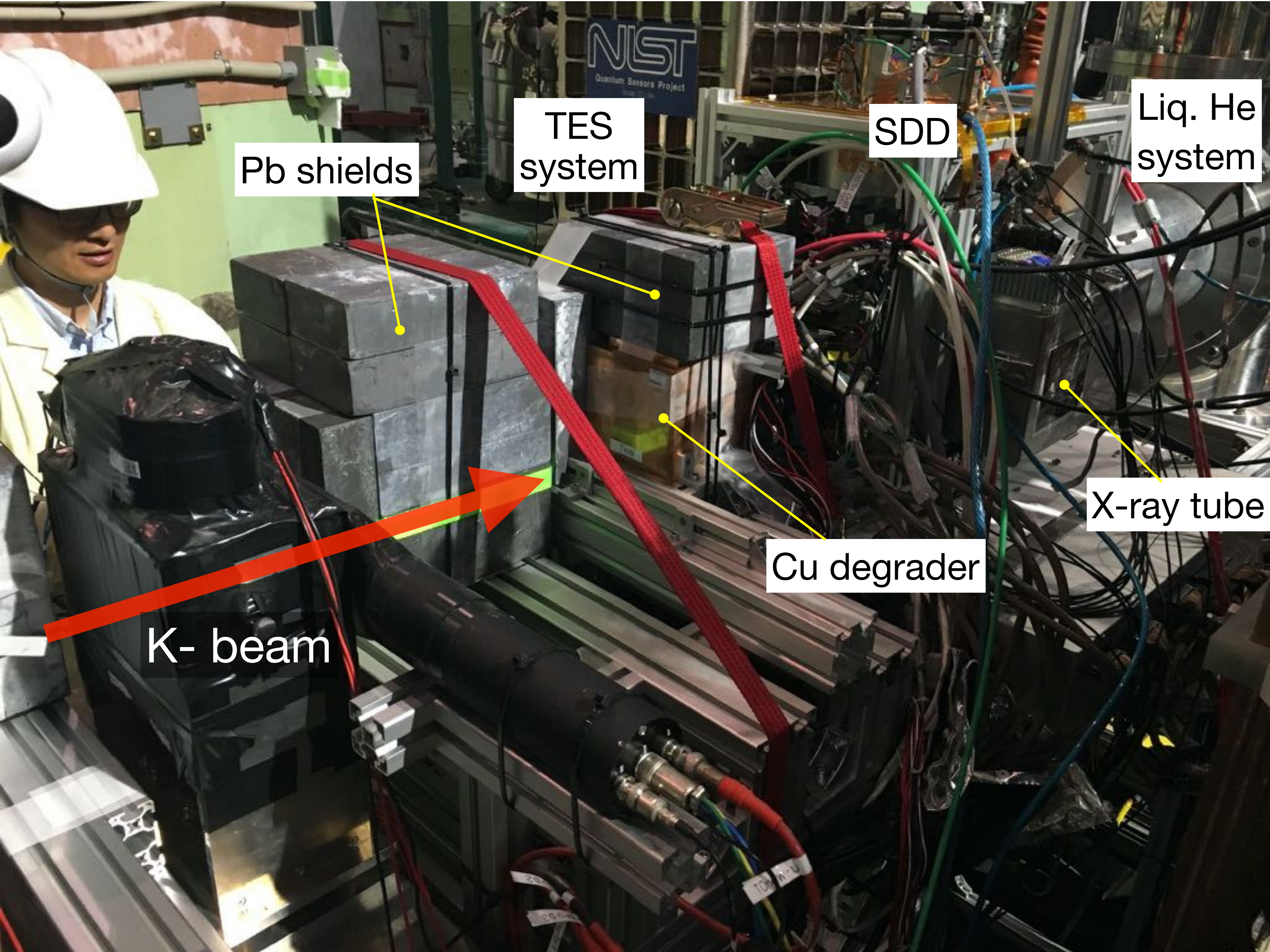

TES
Cryostat
He target
Cryostat
SDD (100K)
TES
70mK
K-He X-rays
calib. X-rays
X-ray generator
K- beam
Liq. He
target cell(1.4K)

TES & He target cell



Target region with shield, MLI, SDDs




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

Operation of cryogenic systems

He target

keep ~1.4 K

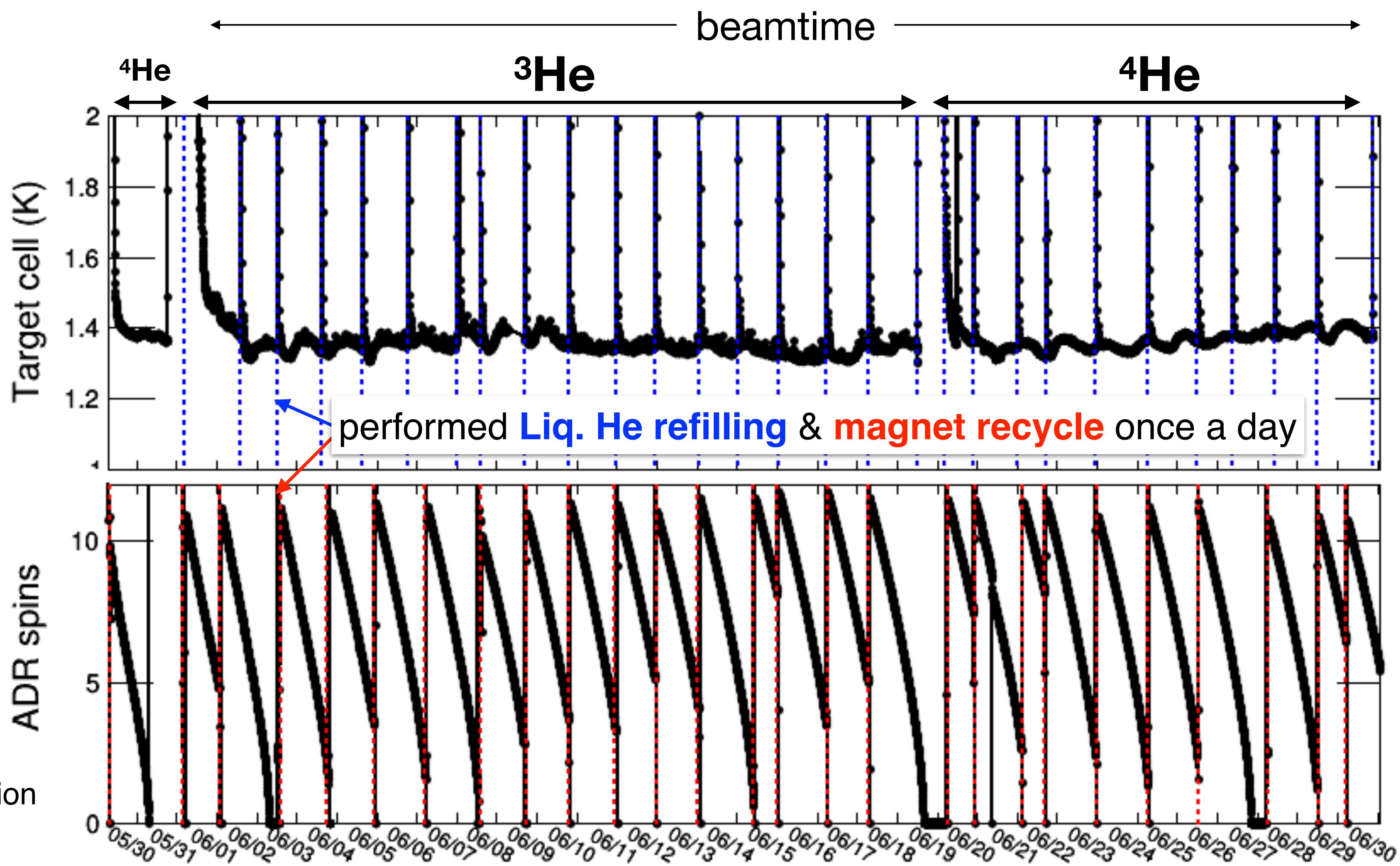
vacuum-cooled with Liq. ^{4}He

TES

keep 70 mK

Adiabatic
Demagnetization
Refrigerator

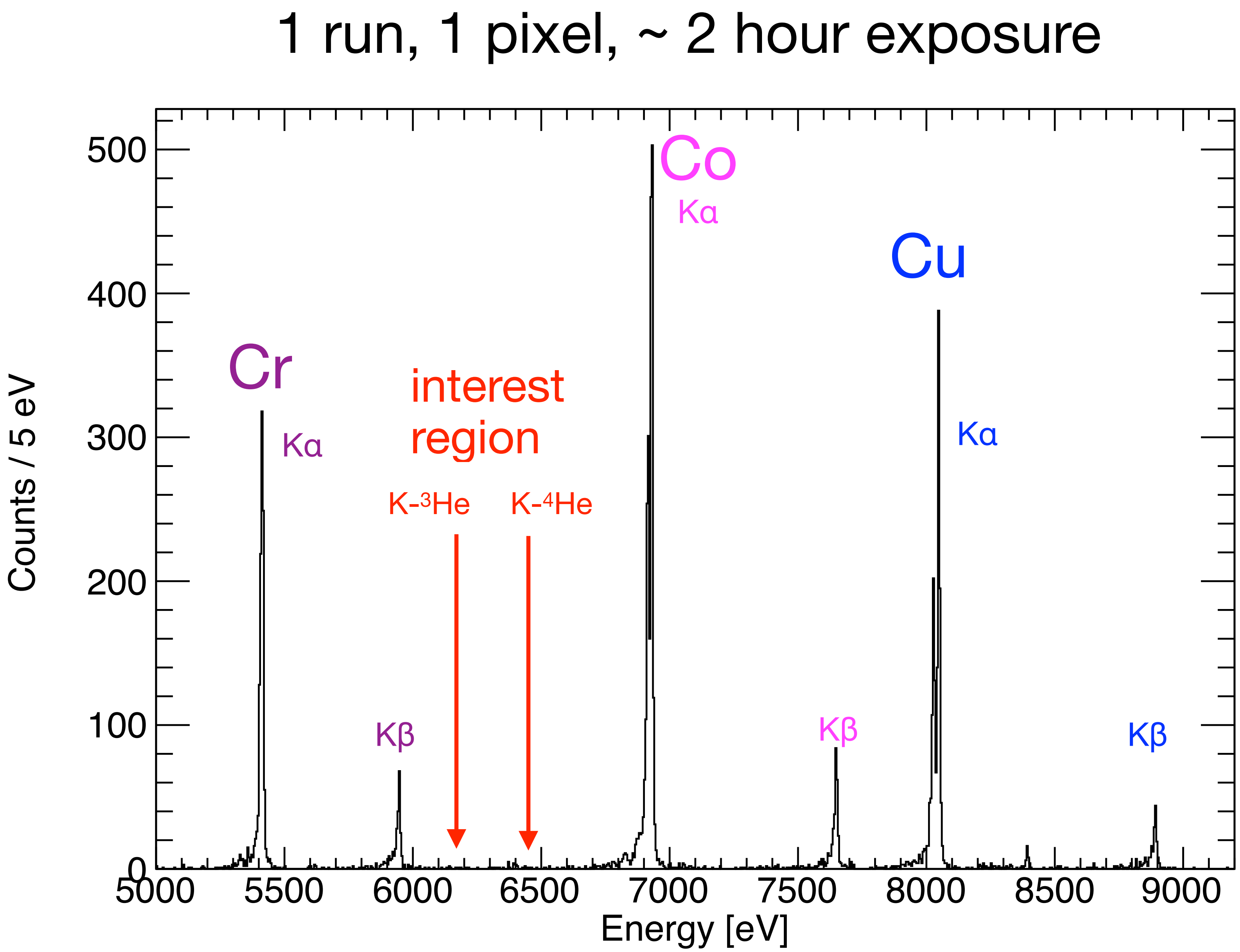
with pulse tube

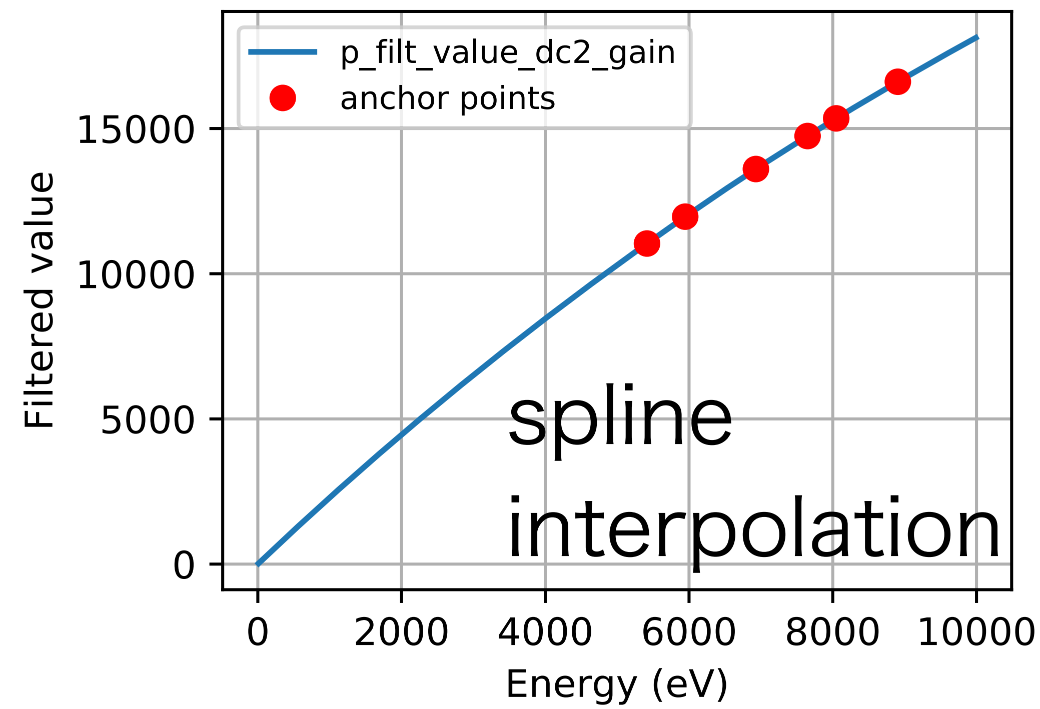


Stable operation for one month

(28 He refills & 27 mag cycles)

In-beam calibration



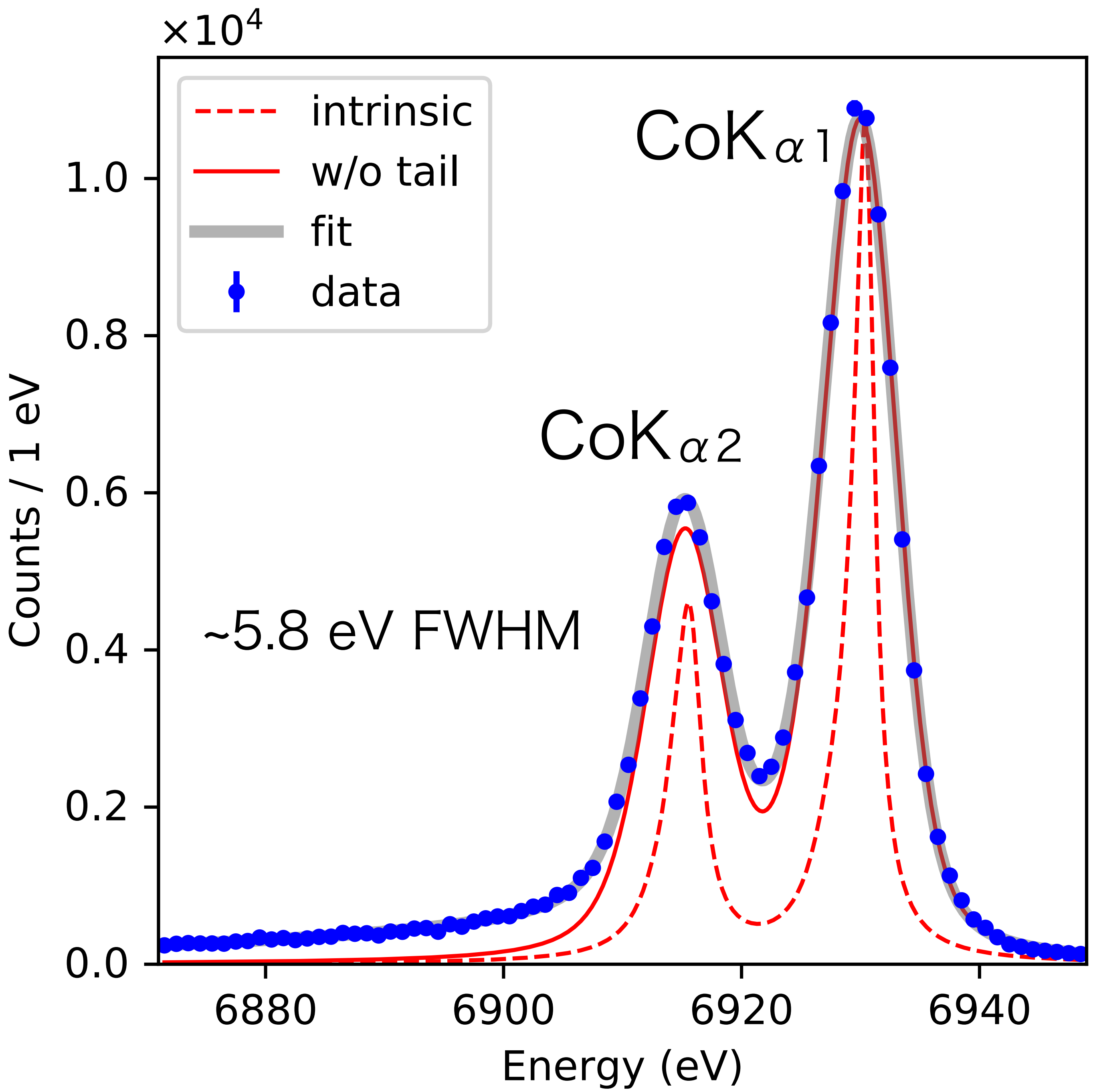


- ✓ X-ray tube was always ON during the experiment
- ✓ Run-by-run (2 hours), pixel-by-pixel calibration

H. Tatsuno et al., Jour. Low Temp. Phys., 184(3), 930-937, 2016.

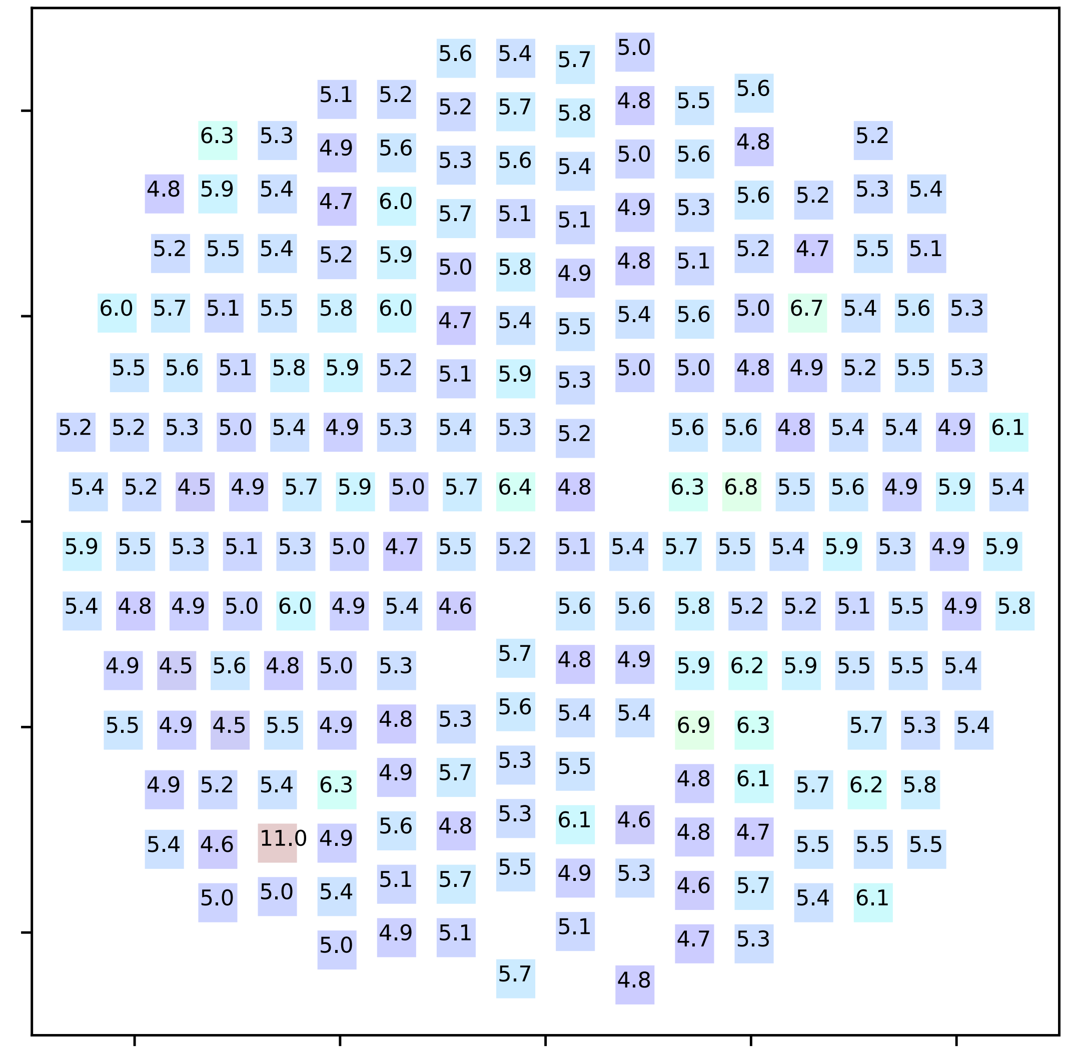
TES in-beam performance

run424, coadded 218 pixels



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

Resolution geometrical map

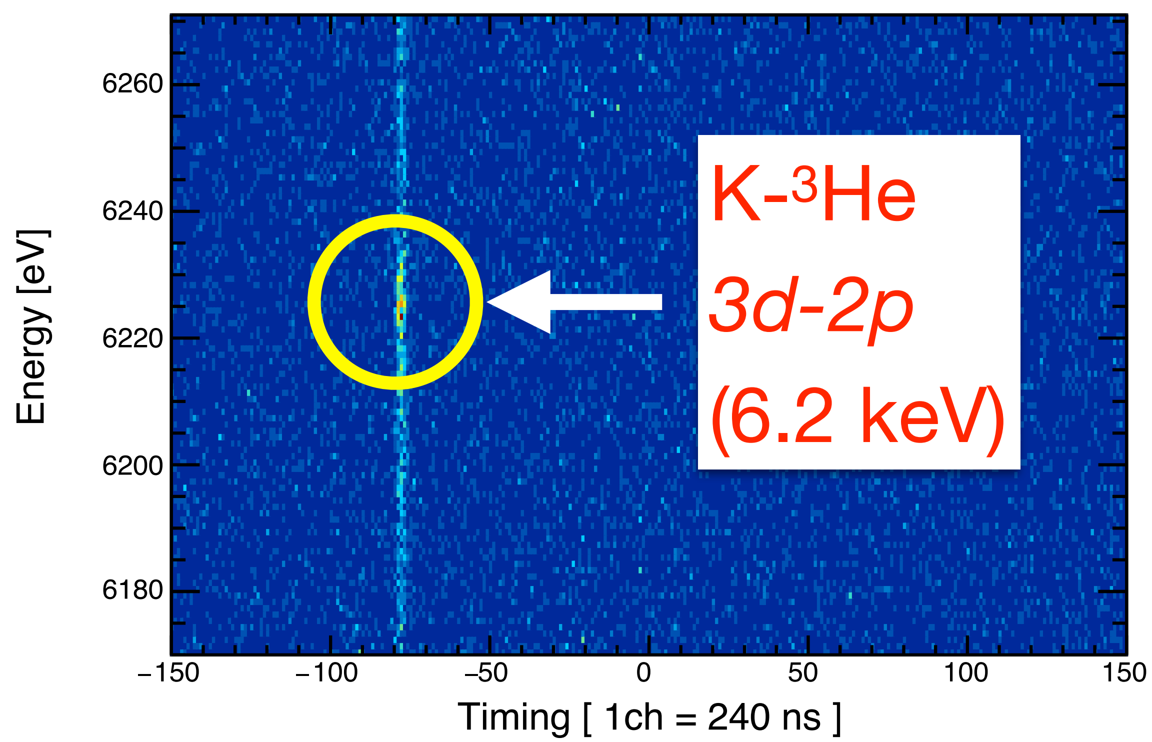


Resolution at CoKα
no box : doesn't work at all (12 pixel)

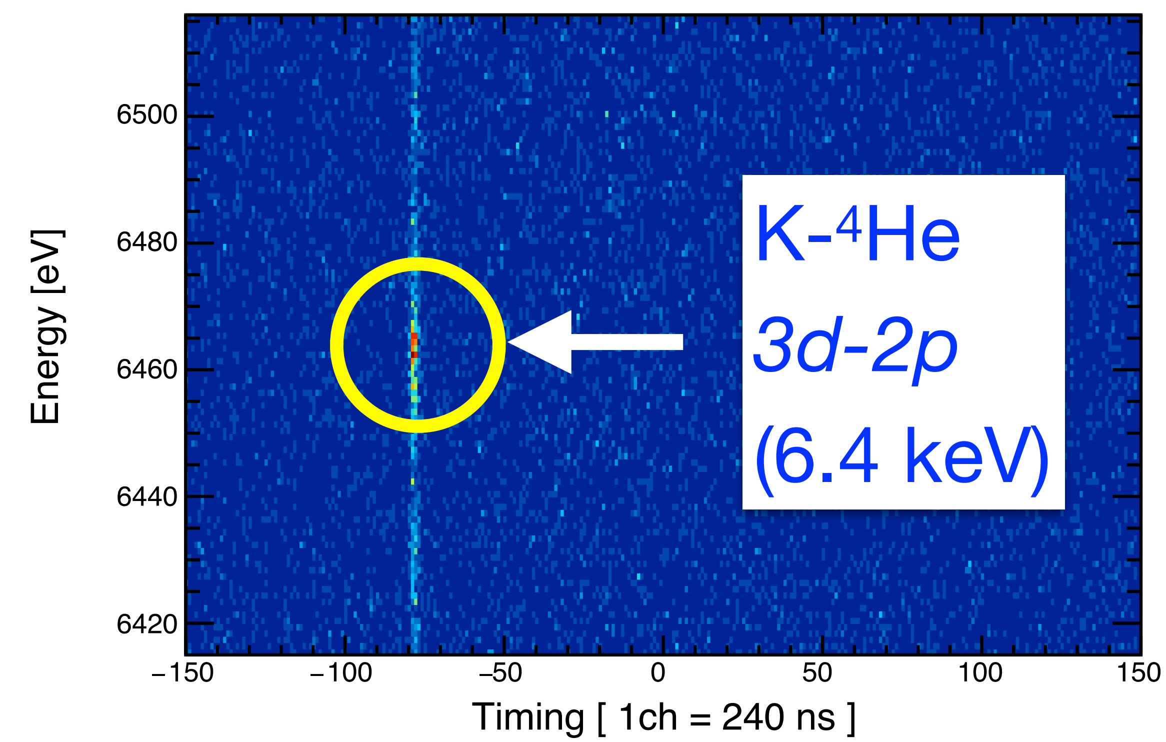
Preliminary result : time vs. energy

Time vs. energy

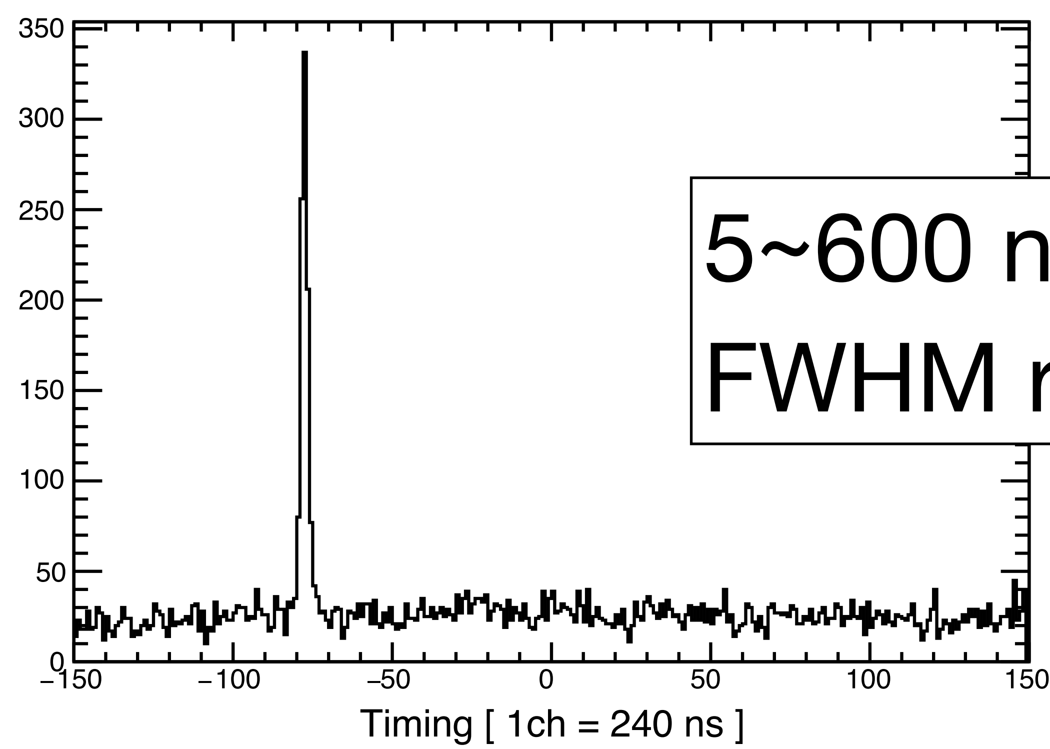
^{3}He target

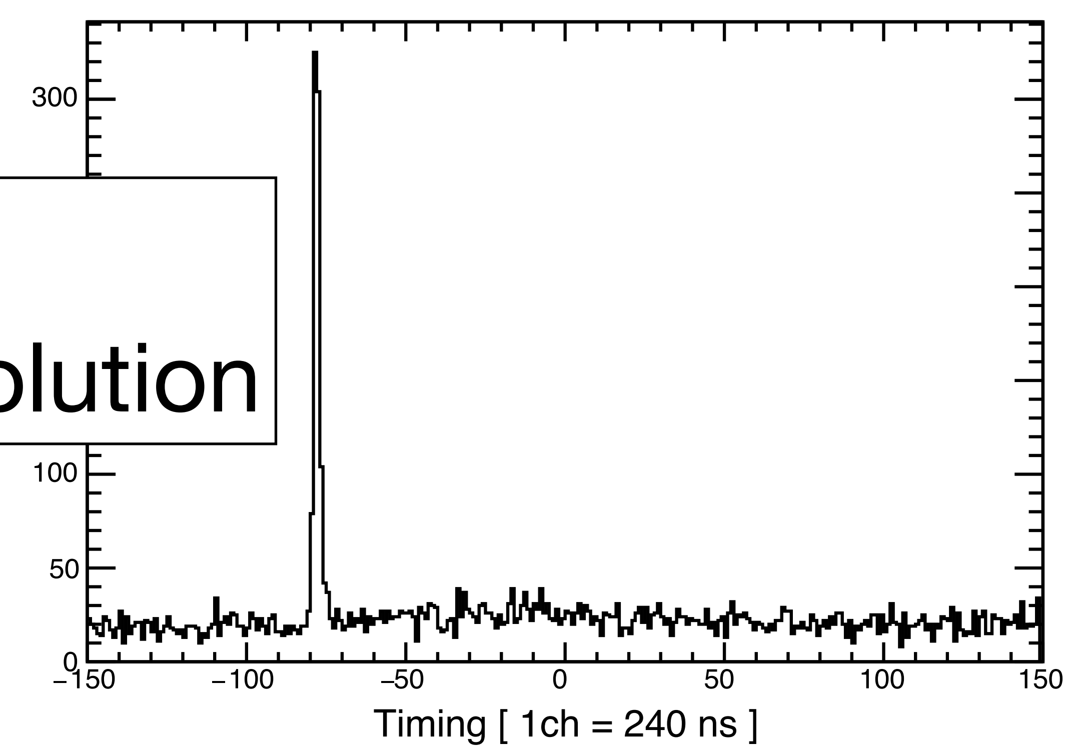


^{4}He target



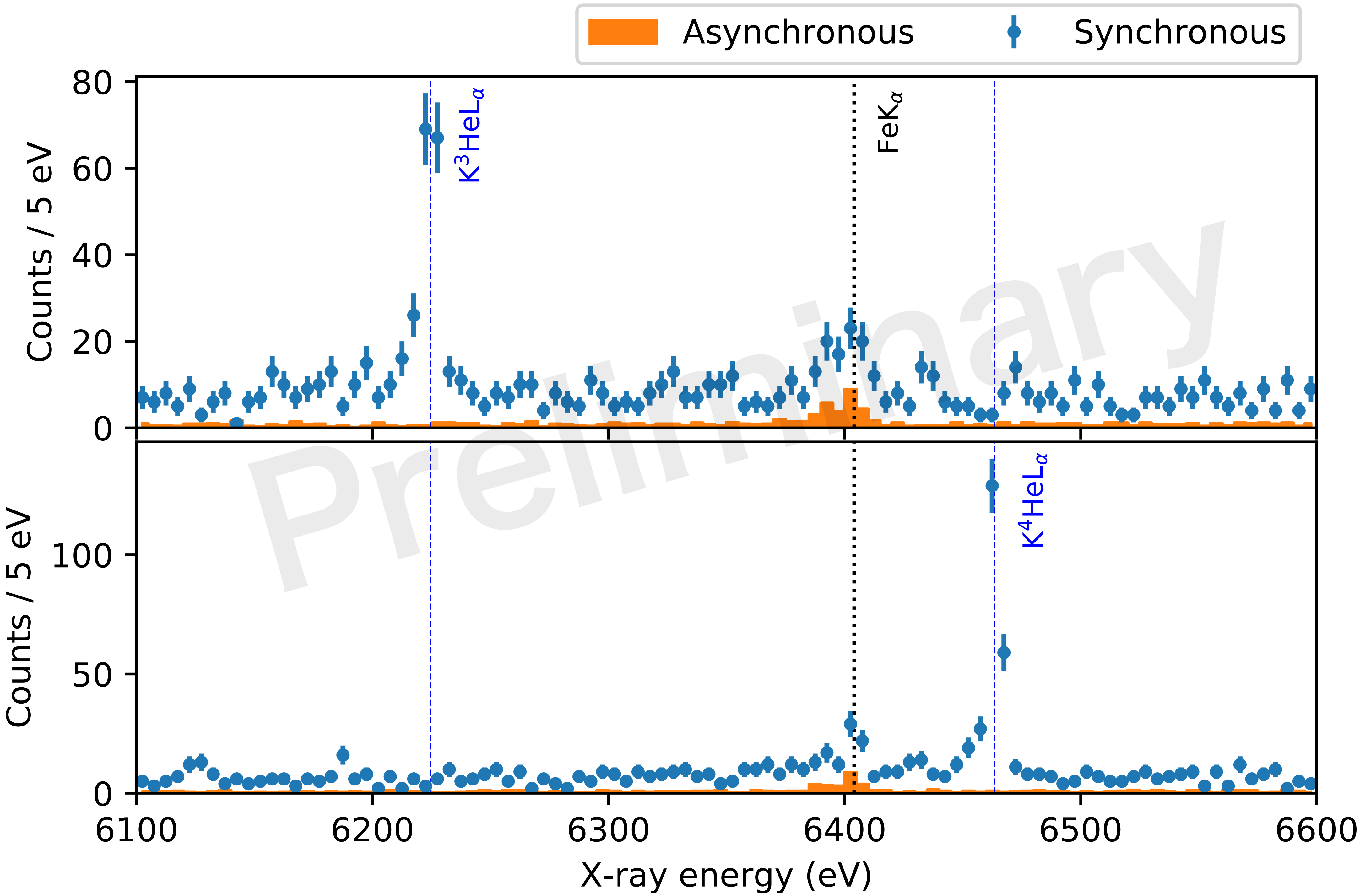
Time to K_{stop} trigger





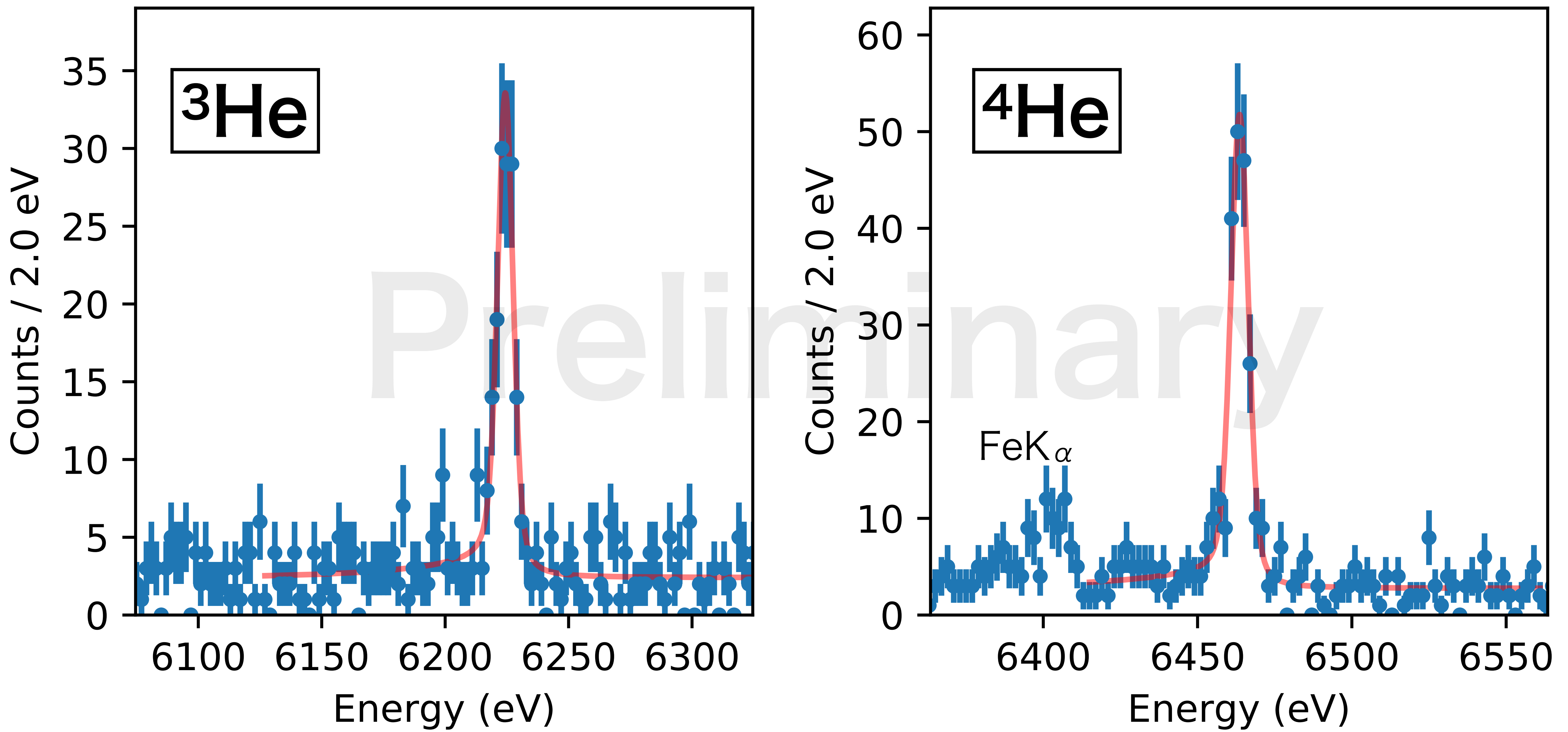
5~600 ns
FWHM resolution

Preliminary result: final spectra



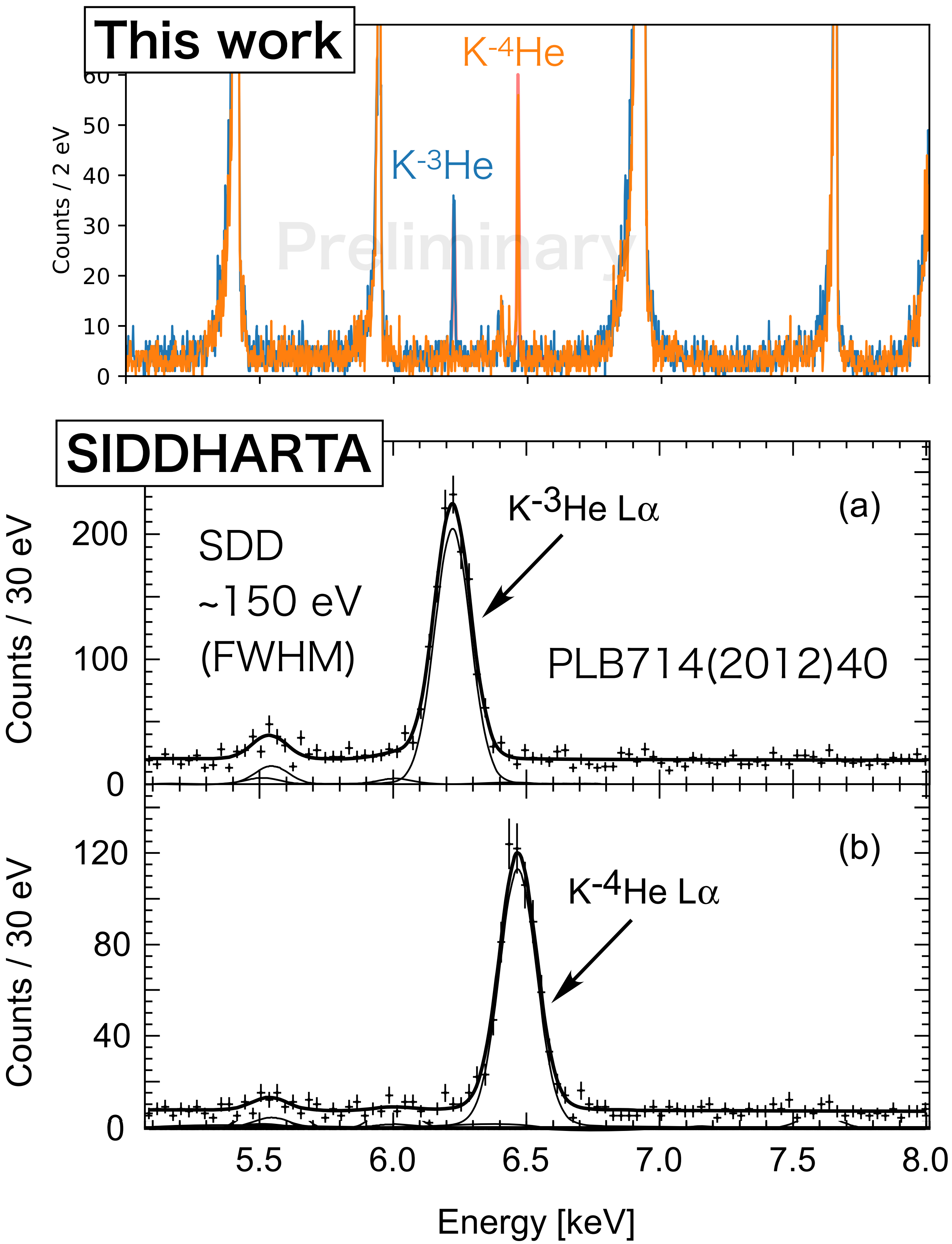
- Asynchronous background contribution is negligible
- Most of background come from stopped kaon absorptions

Preliminary result: fitting

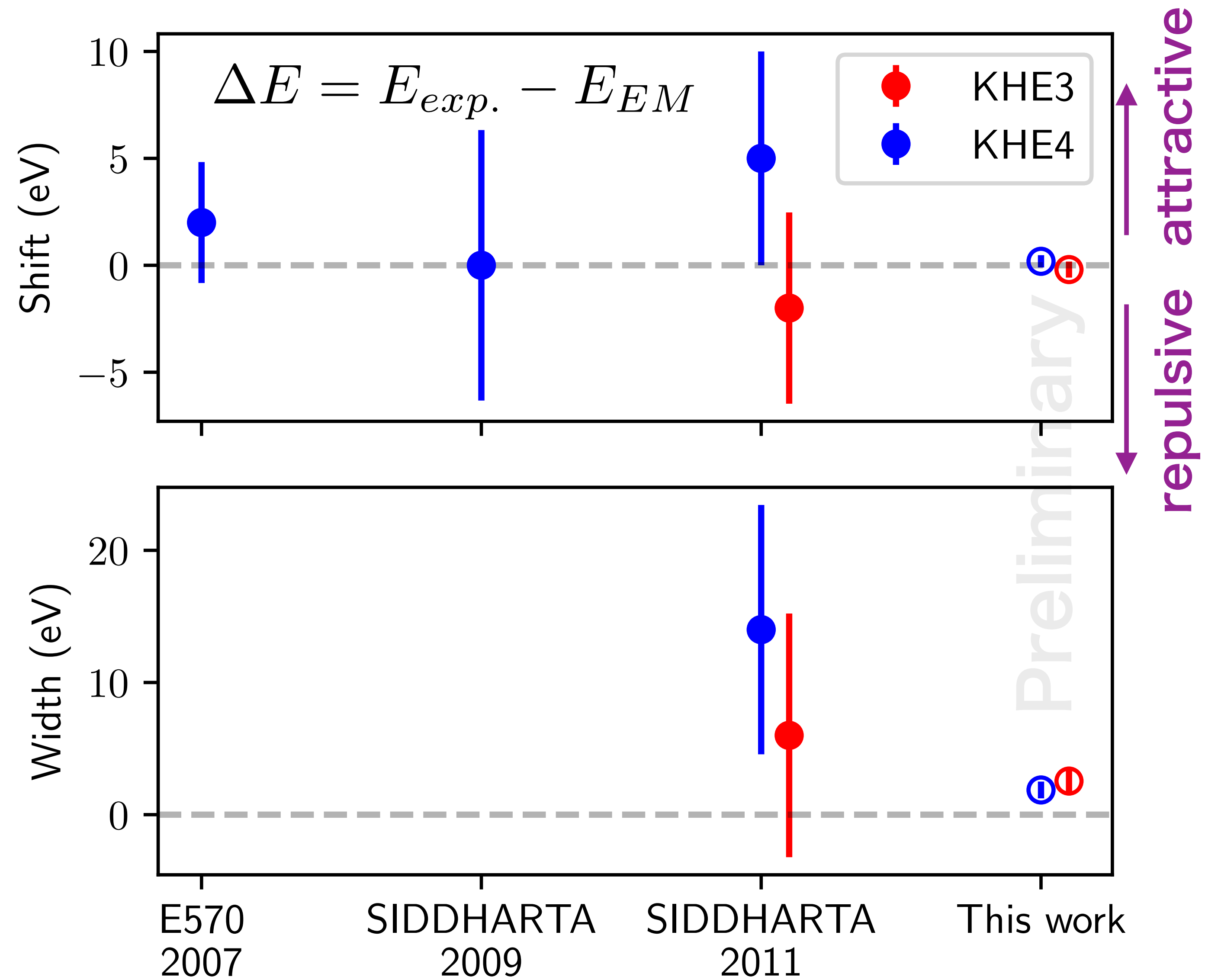


- Voigt (Gaussian*Lorentzian) + Low-energy tail + Background
  - Resolution, Tail parameters are estimated from Ka lines
  - 4 free parameters: mean, gamma, amplitude, background

Comparison with past experiments



Error bar
Past exp: quadratic sum of stat. & sys.
This work: stat. only



x 25 energy resolution
x 10 precision (shift&width)

Systematic errors

[eV]	^{3}He shift	^{3}He width	^{4}He shift	^{4}He width	
stat.	**0.37**	**0.90**	**0.28**	**0.65**	
syst.	**0.19**	**0.44**	**0.11**	**0.42**	quad. sum
absolute calib.	0.17		0.09		energy dependent
resolution	0.01	0.30	0.01	0.20	energy dependent
timing cut	0.05		0.05		0.1/0.2 eV error for resolution
tail	0.03	0.10	0.01	0.10	fraction ±10%, length ±20%
background	0.02	0.20	0.02	0.20	compare pol0/pol1/pol2
fit range	0.01	0.20	0.01	0.01	min / max
binning	0.05	0.10	0.03	0.30	0.5/1/2 eV bin, shift half a bin

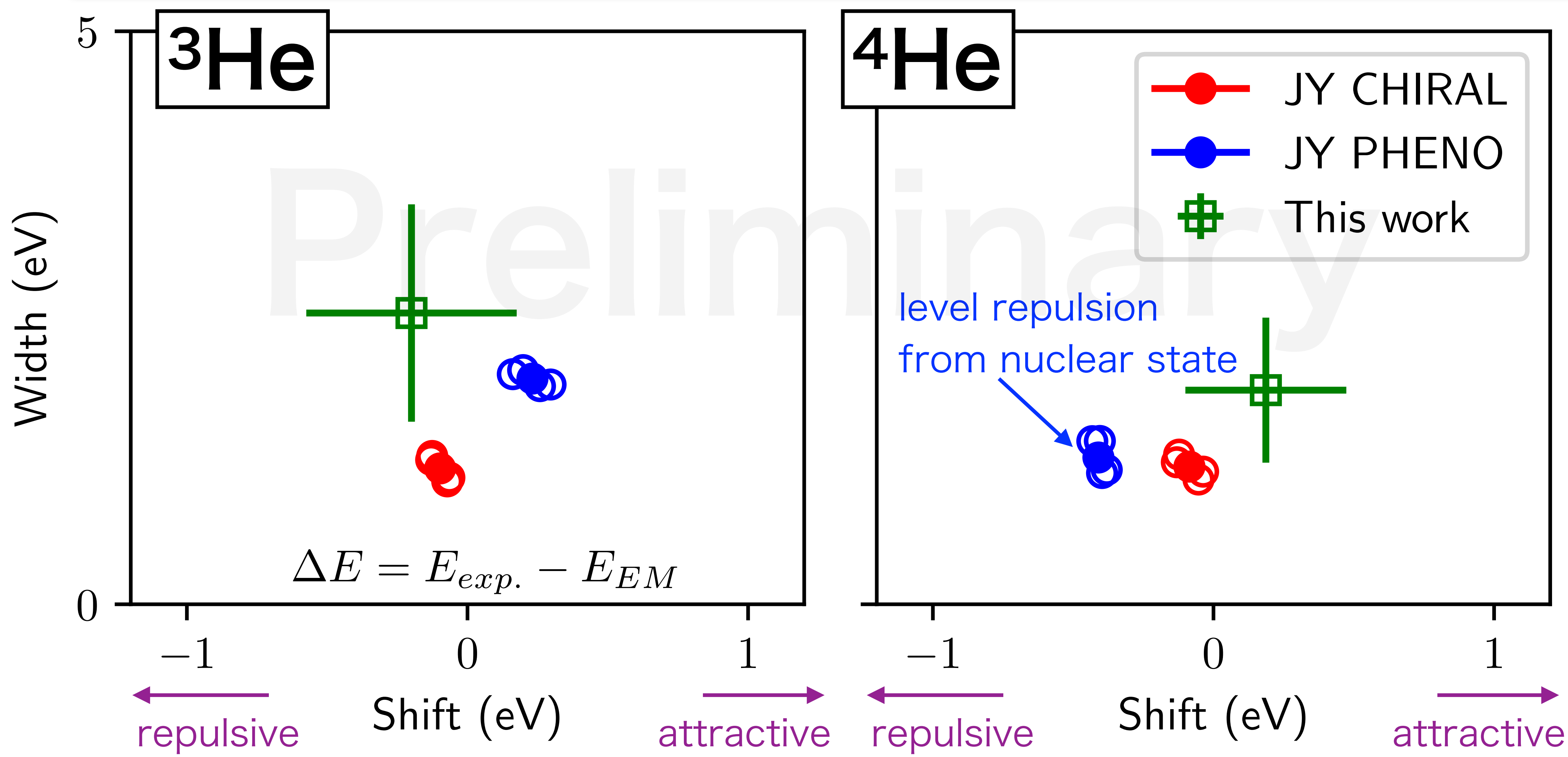
Preliminary

- Precision of the absolute energy scale is the dominant systematics
- Systematical error < Statistical error

Comparison with a theoretical calc.

by J. Yamagata-Sekihara and S. Hirenzaki

- Chiral potential [Ramos, Oset, NPA671(2000)481]
  Phenomenological potential [Mares, Friedman, Gal, NPA770(2006)84]
- Realistic charge density distribution for ^{3}He&^{4}He by E. Hiyama

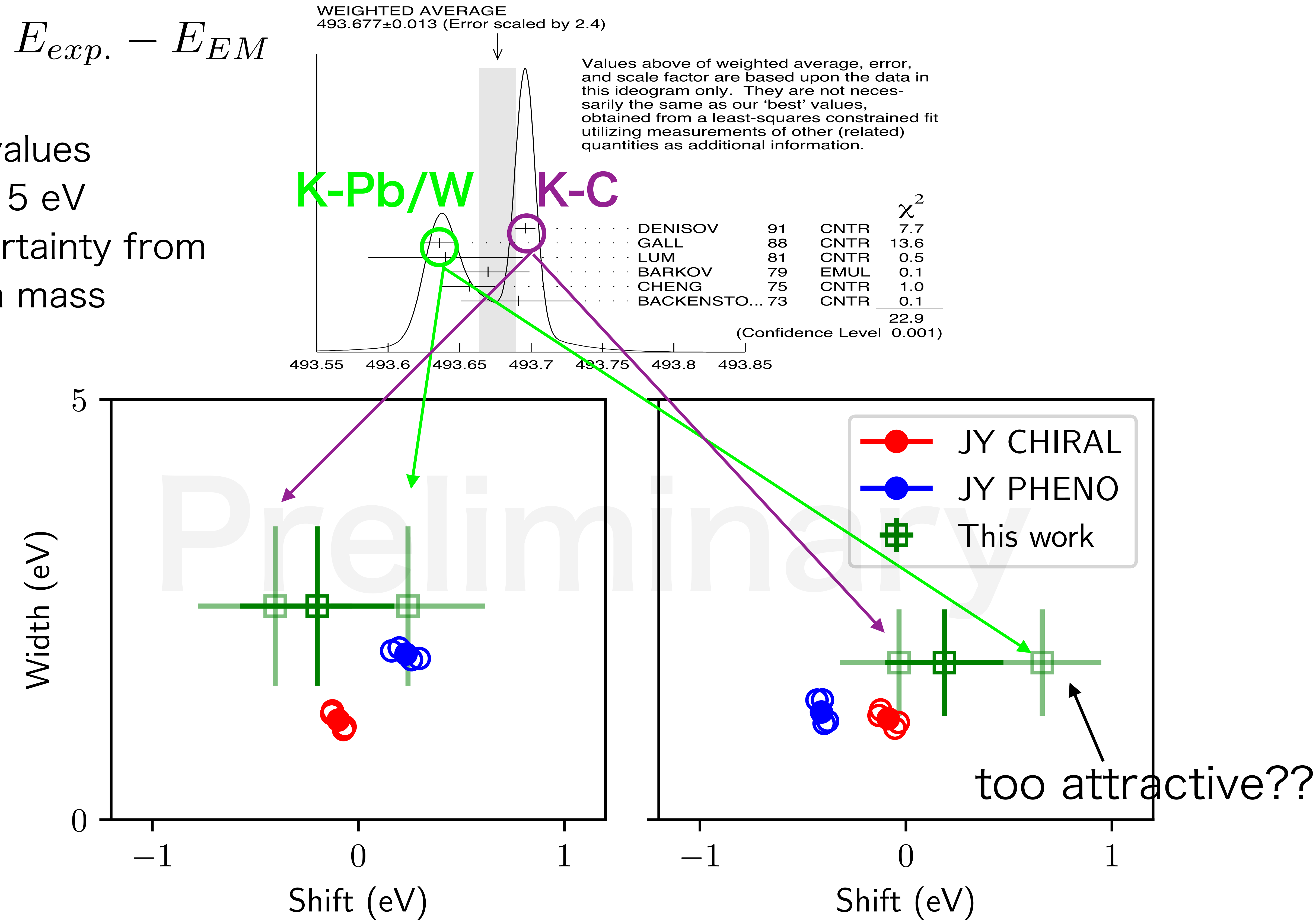


- Our result is comparable to the values based on optical potentials
- Zero or attractive shift in K^{4}He would support no p-wave nuclear state

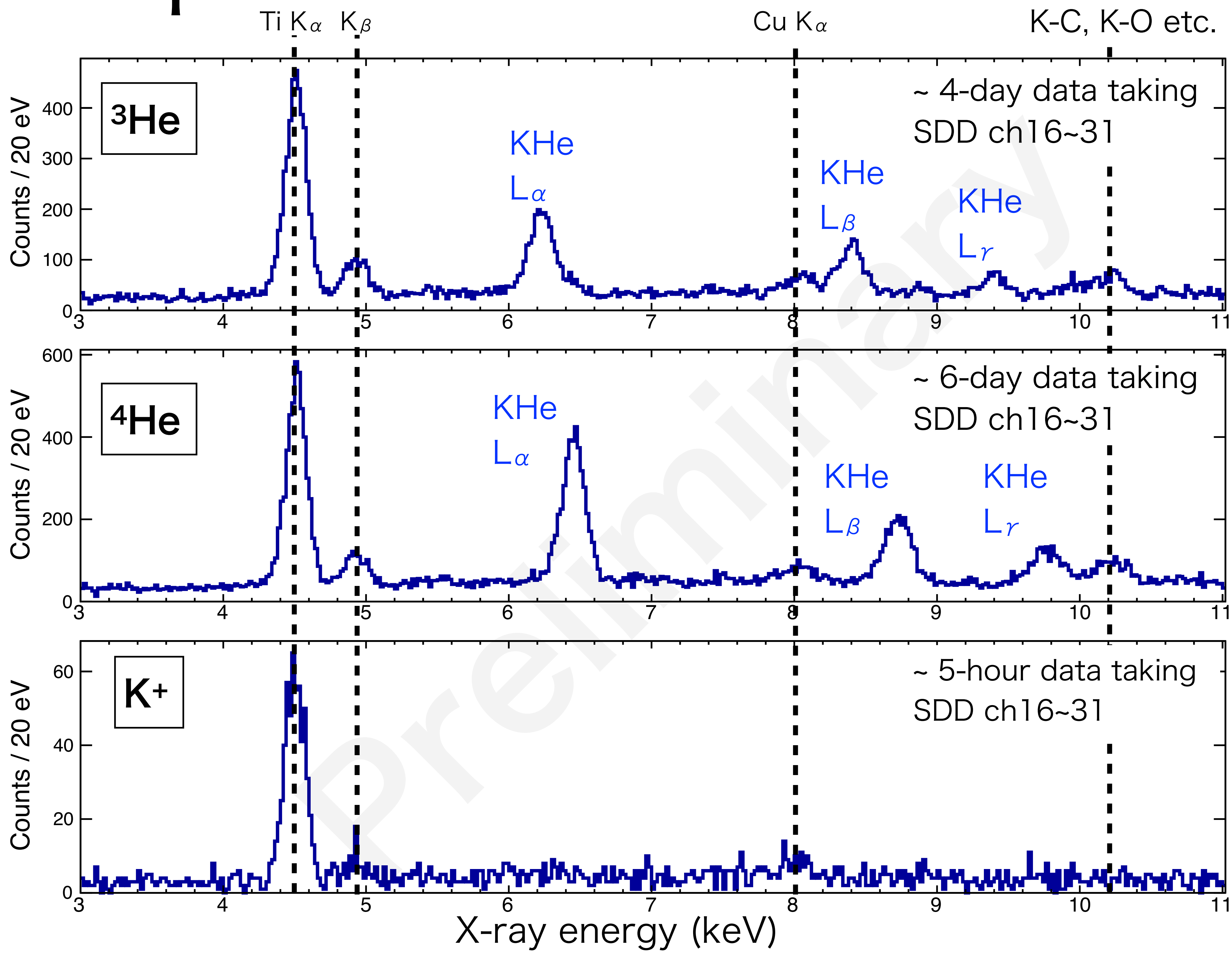
Systematics from Kaon mass

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

EM values
+-0.15 eV
uncertainty from
Kaon mass



SDD spectra in E62 < 200 eV FWHM @ 6 keV



- SDDs were installed as a reference and test for E57(K-d)
- Relative yield of $L\alpha/L\beta/L\gamma$ will be extracted

Outlook: TES

- Present system is applicable **up to 15 keV**, limited by TES saturation and stopping power of 4 um thick Bi absorber
  - Light kaonic atoms (K^- Li 6/7)
  - Kaon mass (K-N, 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

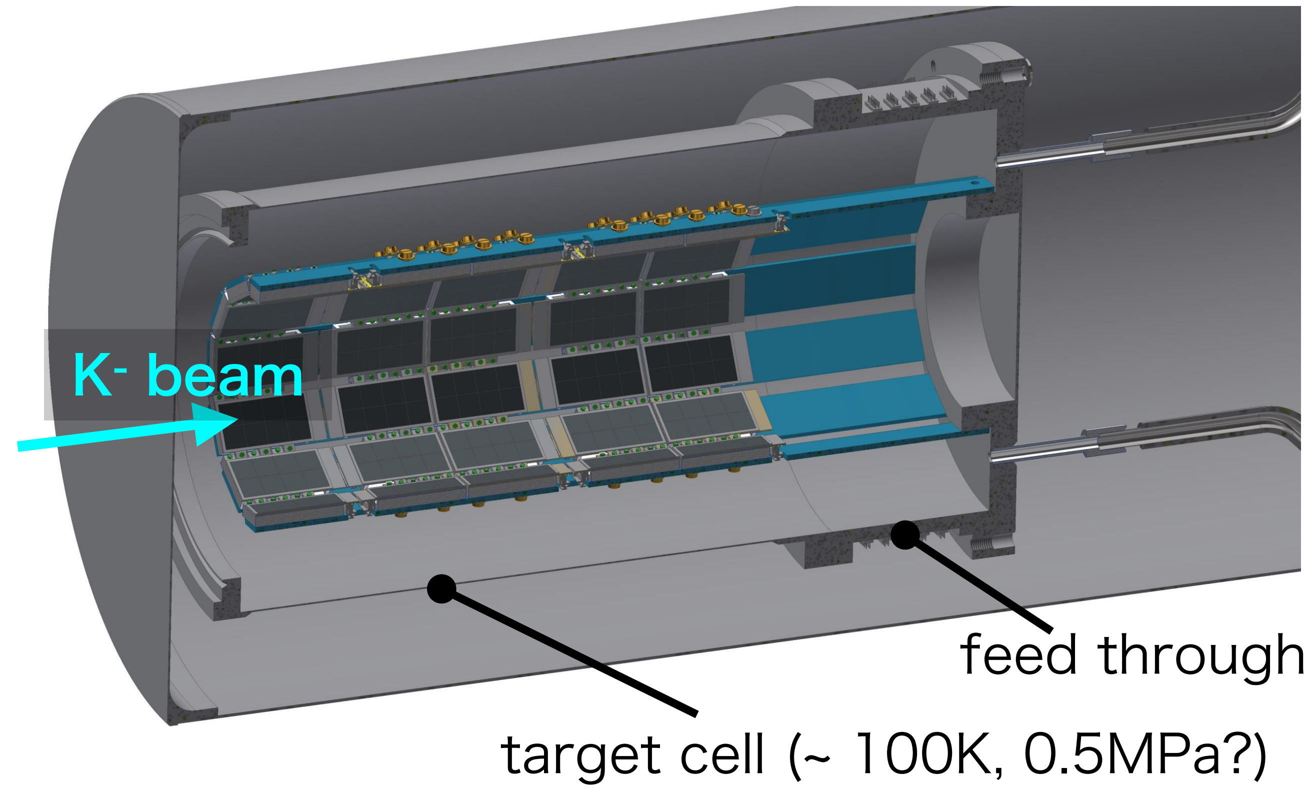
$$\alpha \equiv \frac{d\ \ln R}{d\ \ln T} \qquad \Delta E = \sqrt{\frac{k_B T^2 C}{\alpha}} \qquad E_{max} \sim C T_C / \alpha$$

Experiment purpose	present	Gamma-ray TESs	QED TESs	Future TESs
Energy	15 keV	130 keV	50 keV	20 keV
Lines of interest	μ-Ne @ 6 keV	μ-C @ 75.3 keV μ-N @ 102.7 keV μ-O @ 134.35 keV	μ-Ar @ 44 keV μ-Ar @ 20 keV	μ-Li @ 18.70 keV μ-C @ 18.83 keV
Saturation energy	20 keV	150 keV	70 keV	50 keV
Absorber material	Bi	Sn foil	Au/Bi	Au/Bi
Absorber thickness	4 um	120 ~ 250 um	3 um / 15 um	1.5 um / 15 um
Absorber area	320 um x 305 um	1.3 mm x 1.3 mm	700 um x 700 um	700 um x 700 um
Pixel number	240	96	150	150
Total collection area	23 mm^2	160 mm^2	70 mm^2	70 mm^2
Absorption at 45 keV	-	92%	20%	17%
Absorption at 100 keV	-	26%	-	-
ΔE (FWHM)	5 eV @ 6 keV	40 eV @ 130 keV and below; 60 eV @ 150 keV	20 eV @ 40 keV and below	8 eV @ 20 keV and below; Unknown @ 40 keV

- ✓ New cryostat, readout system
- ✓ Available in a few years (for μ-atoms)
- ✓ Multiple units can be installed

Outlook: K^- atom with SDDs

- **Kaonic hydrogen/deuterium 2p→1s** in J-PARC E57
  - 1% / 0.1% yield with a gas target. (~4% LD)
  - SDDs inside target gas
  - detect L X rays in coincidence
  - re-start in 2023?



- **Kaonic Helium 2p→1s**
  - Small 2p width measured in E62 suggests it is feasible.
    > 0.1% yield relative to 3d→2p, absolute yield ~0.05%?
  - X-ray coincidence with a large solid acceptance
  - at DAΦNE? or with liquid target at J-PARC?
  - need some detector development for ~ 30 keV

Summary

- **Kaonic helium 3d→2p X-rays in J-PARC E62**
  - Physics data taking was completed in 2018
  - Preliminary results
    - ~ 6 eV FWHM resolution with a cryogenic detector **TES**
    - Large shift and width were excluded
      - $|\Delta E_{2p}| < 1$ eV, $\Gamma_{2p} < 5$ eV
    - Attractive shift
      → non-existence of p-wave nuclear state?
    - Final numbers & publication will come soon

- **Outlook**
  - TES for higher energy will be available in a few years
  - K-p/K-d (J-PARC E57/SIDDHARTA2), K-He 2p→1s with SDDs