26 Aug, 2014

PANIC14 @ Hamburg

High-resolution hadronic-atom x-ray spectroscopy with superconducting TES microcalorimeters

Shinji OKADA (RIKEN)

The HEATES collaboration

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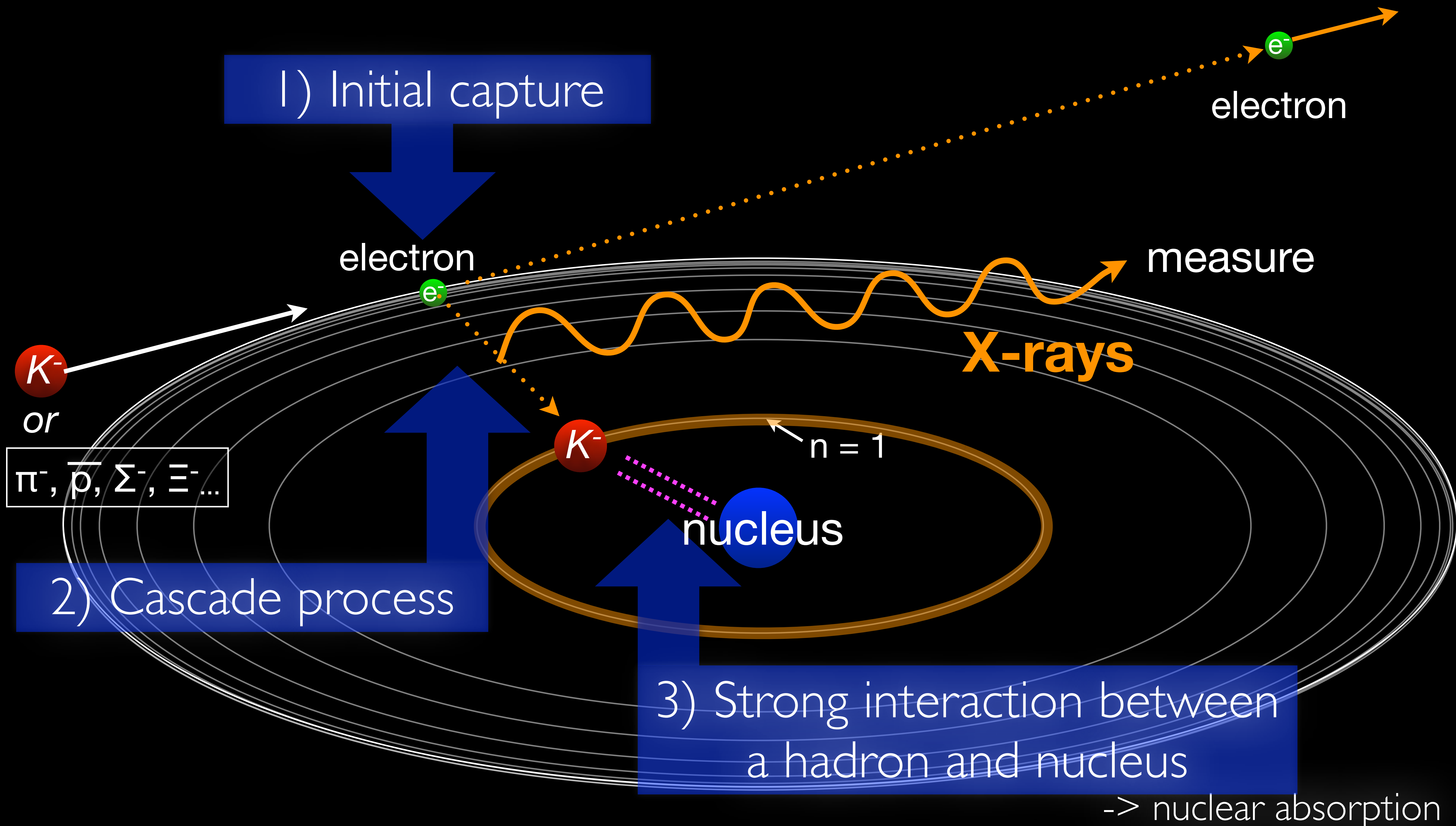
RIKEN[1], NIST[2], INFN-LNF[3], Univ. of Tokyo[4], KEK[5], Stefan Meyer Institut[6], Tokyo Metropolitan Univ.[7]

Contents

1. Introduction

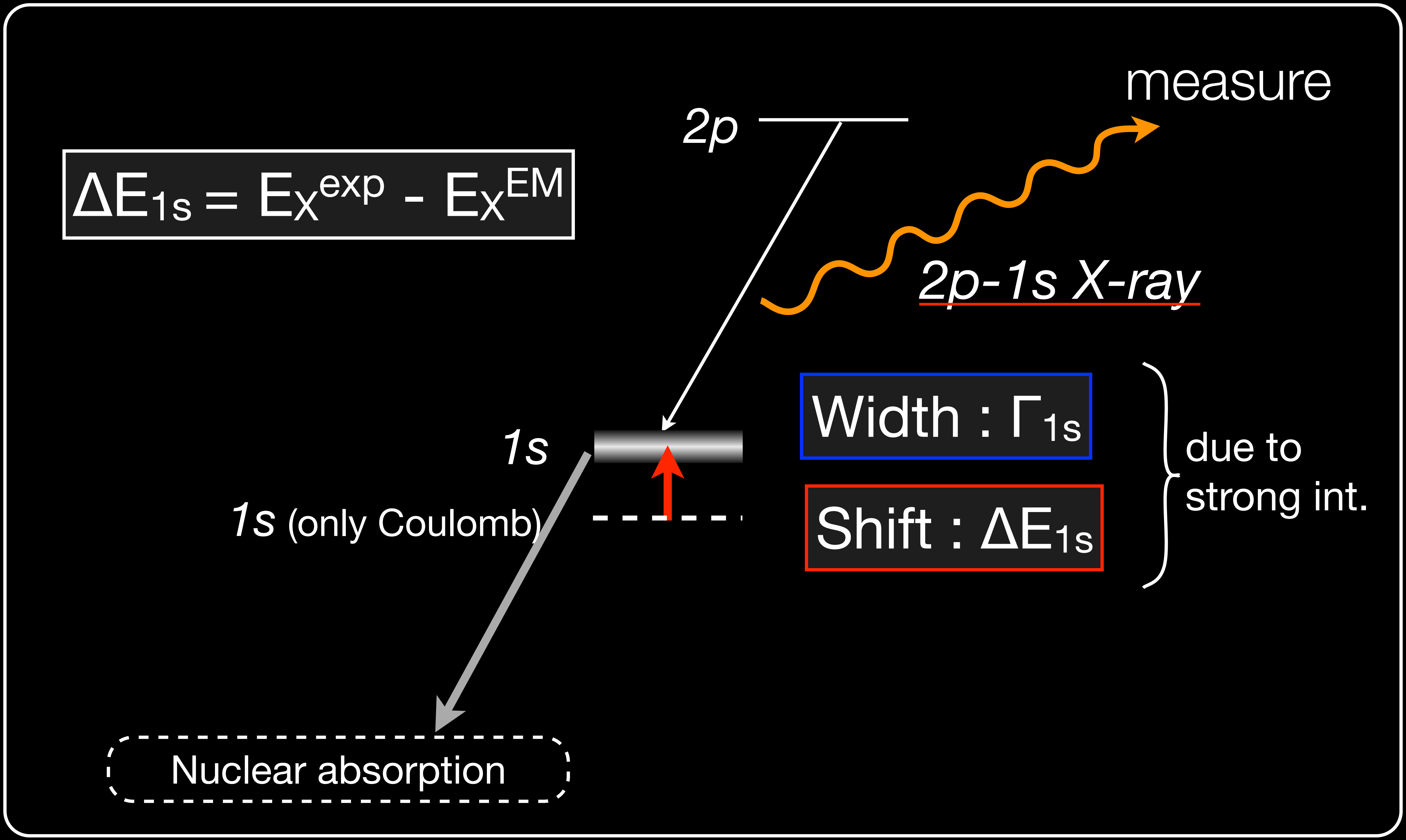
hadronic (kaonic) atom

Hadronic atom



A tool for studying strong interaction

Strong-interaction shift & width



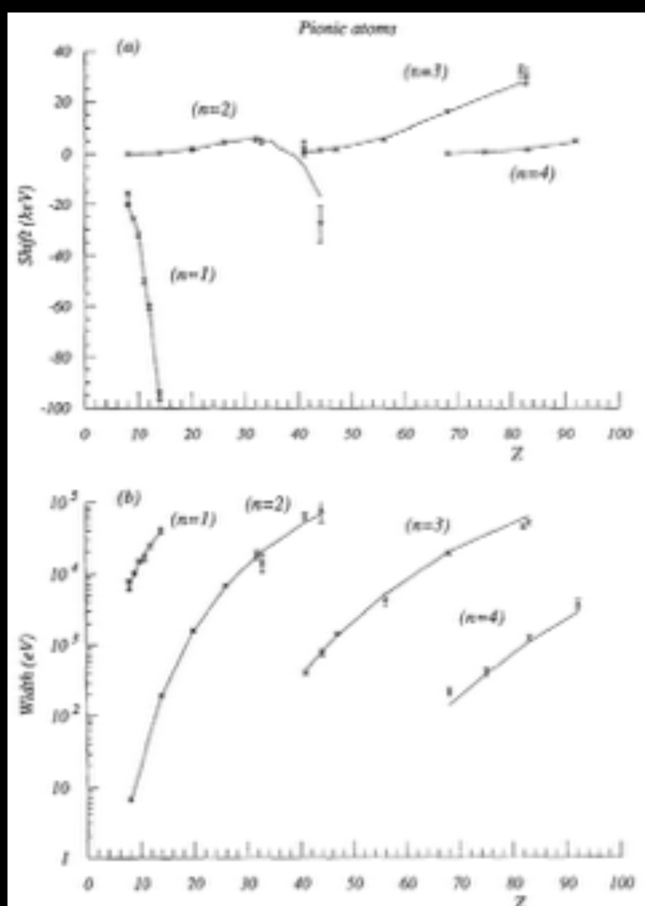
Many measurements so far

shift & width as a function of atomic number Z

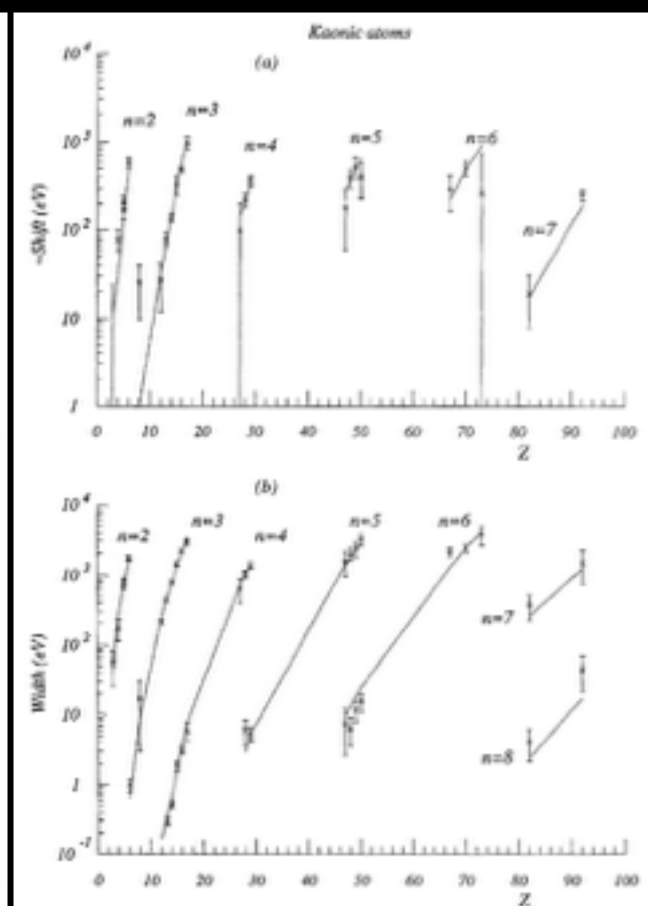
Shift [eV]

Width [eV]

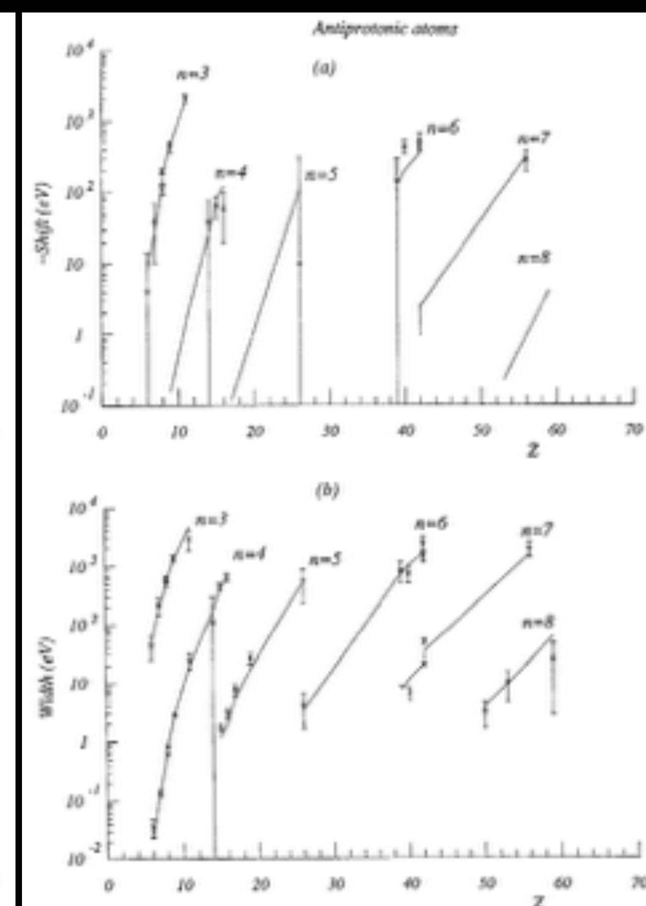
π^- atoms



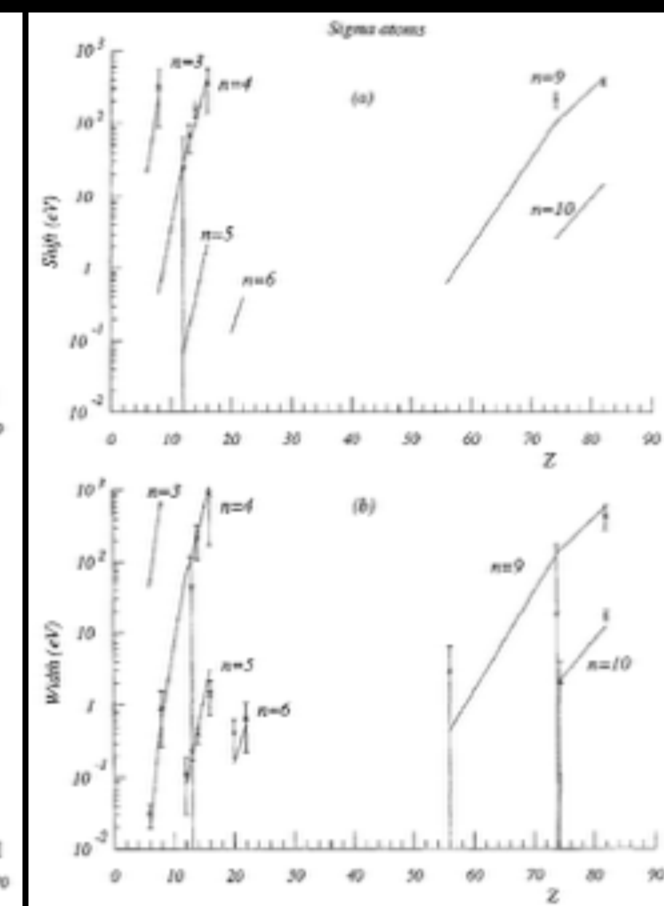
K^- atoms



$\bar{p}$ atoms



Σ^- atoms



Atomic number Z

dot : expt data
line : theo calc

Strong Interaction Physics From Hadronic Atoms

C.J. Batty, E. Friedman, A. Gal, Physics Reports 287 (1997) 385 - 445

Open problem on K-atom

Different scenarios for different exotic atoms

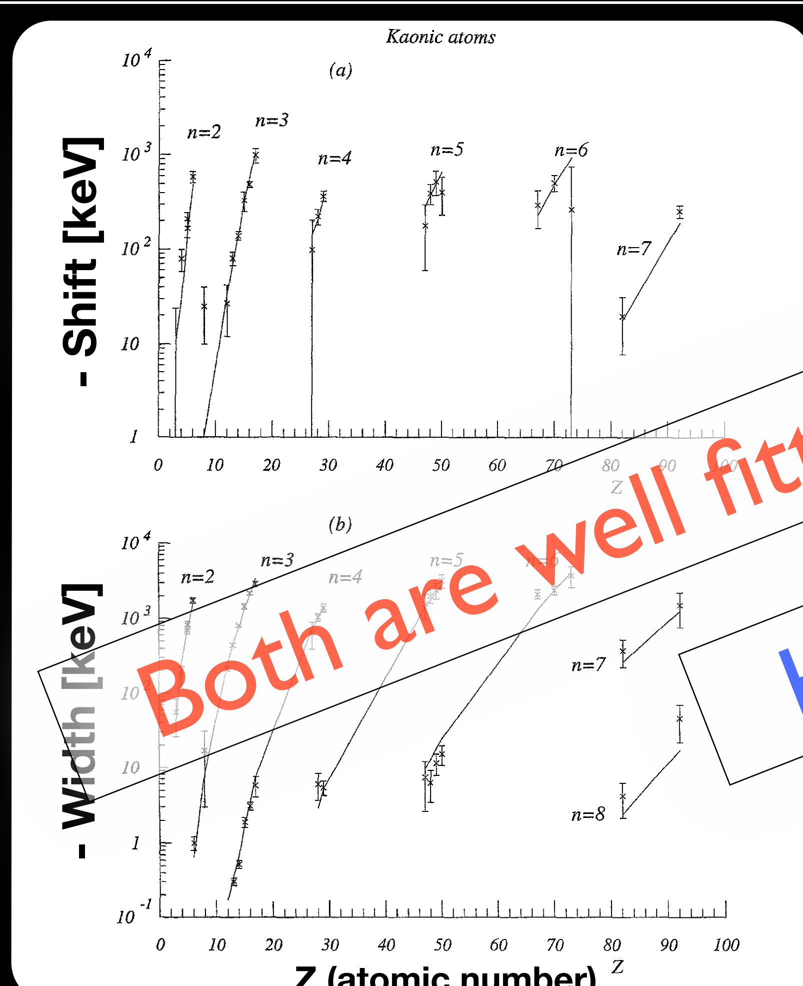
particle	real potl.	imaginary potl.	comments
π^-	repulsive in bulk	moderate	excellent data
	attractive on surface		well understood
K^-	attractive	moderate	good data
	deep or shallow?		open problems
$\bar{p}$	??	very absorptive	excellent data
			understood

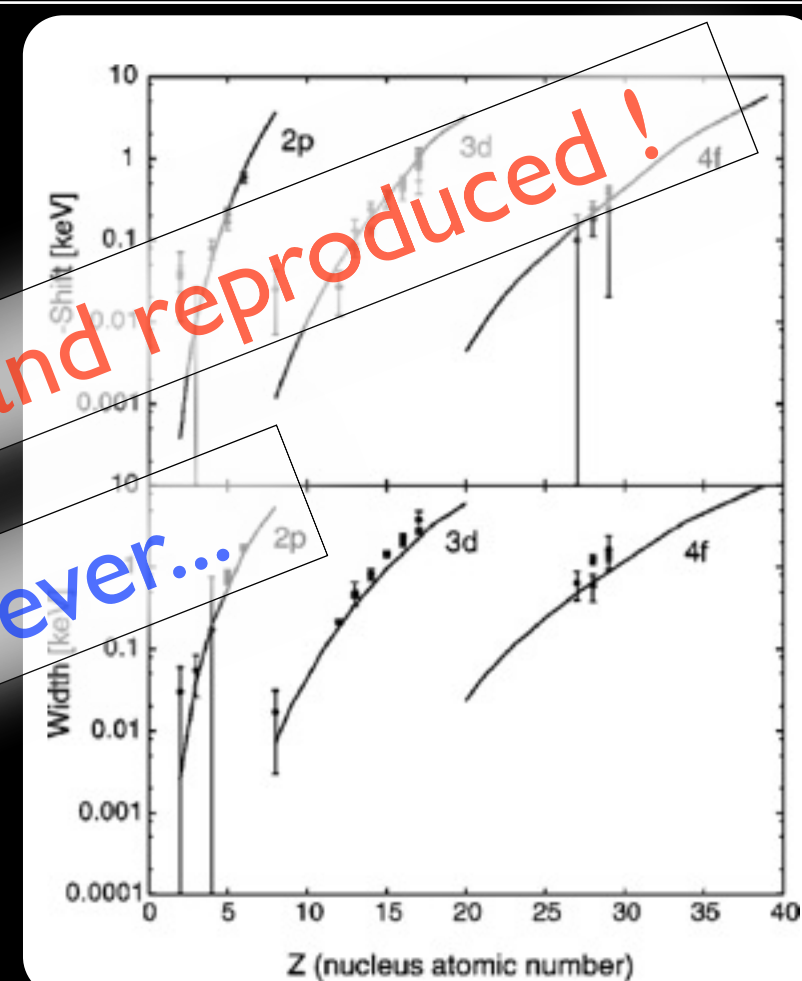
E. Friedman : MESON2010 conf.

K-atom : theoretical approaches

approach	Phenomenological	Fundamental
model	Density-dependent optical potential	SU(3) chiral unitary
	$V = -\frac{2\pi}{\mu}\left(1+\frac{\mu}{m}\right)\bar{a}\rho(r),$ $a \to a_0 + A_0[\rho(r)/\rho(0)]^{\alpha},$	$2\mu V_{opt}(r) = -4\pi\eta a_{eff}(\rho)\rho(r),$

exp. data
vs
calc. results





Both are well fitted and reproduced !

However...

deep or shallow ?

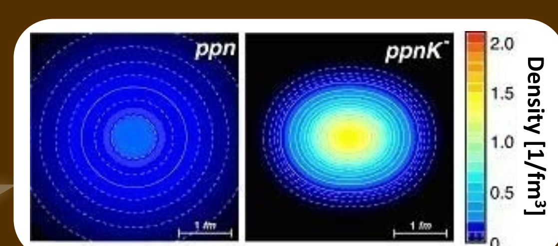
approach	Phenomenological	Fundamental
model	Density-dependent optical potential	SU(3) chiral unitary
	$V = -\frac{2\pi}{\mu}\left(1+\frac{\mu}{m}\right)\bar{a}\rho(r),$ $a \to a_0 + A_0[\rho(r)/\rho(0)]^{\alpha},$	$2\mu V_{opt}(r) = -4\pi\eta a_{eff}(\rho)\rho(r),$
potential depth	**deep** ($-V_{Real}$ = 150 ~ 200 MeV)	**shallow** ($-V_{Real}$ = 40 ~ 60 MeV)

Open problem

deep ⟷ **shallow**

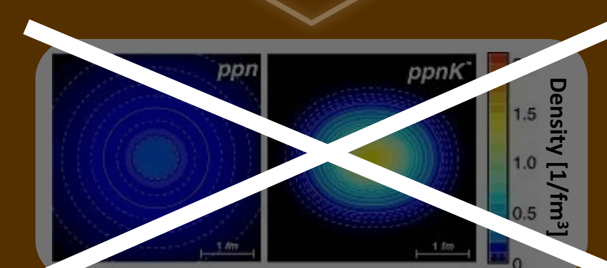
($-V_{Real}$ = 150 ~ 200 MeV)

($-V_{Real}$ = 40 ~ 60 MeV)

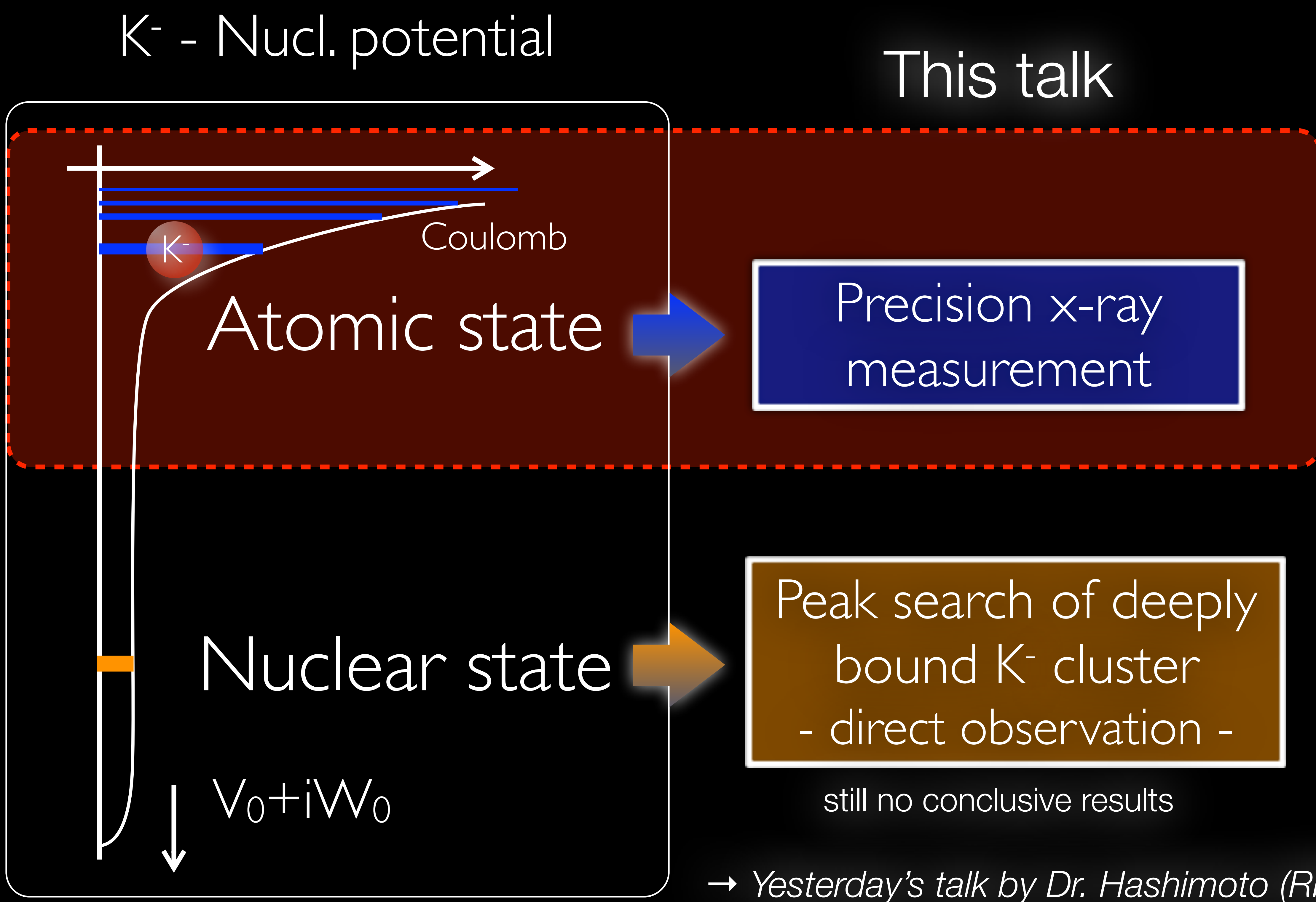


predicts deeply bound K^- clusters
(high density matter like neutron star)

unlikely



Experimental approaches



still no conclusive results

→ *Yesterday's talk by Dr. Hashimoto (RIKEN)*

Prediction

Kaonic Helium 2p level shift and width

S. Baird et al., NPA392(1983)297

30 years ago!

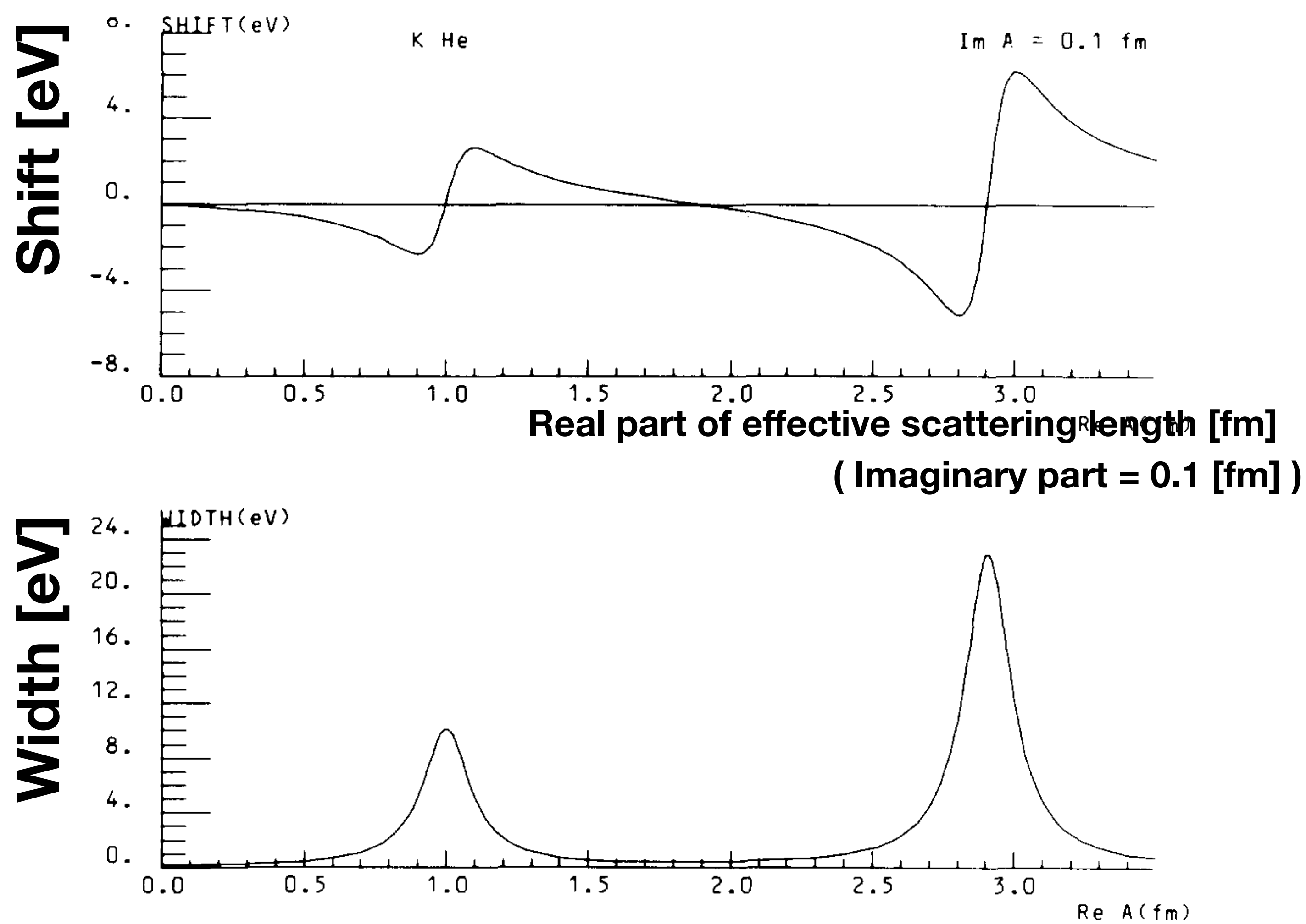
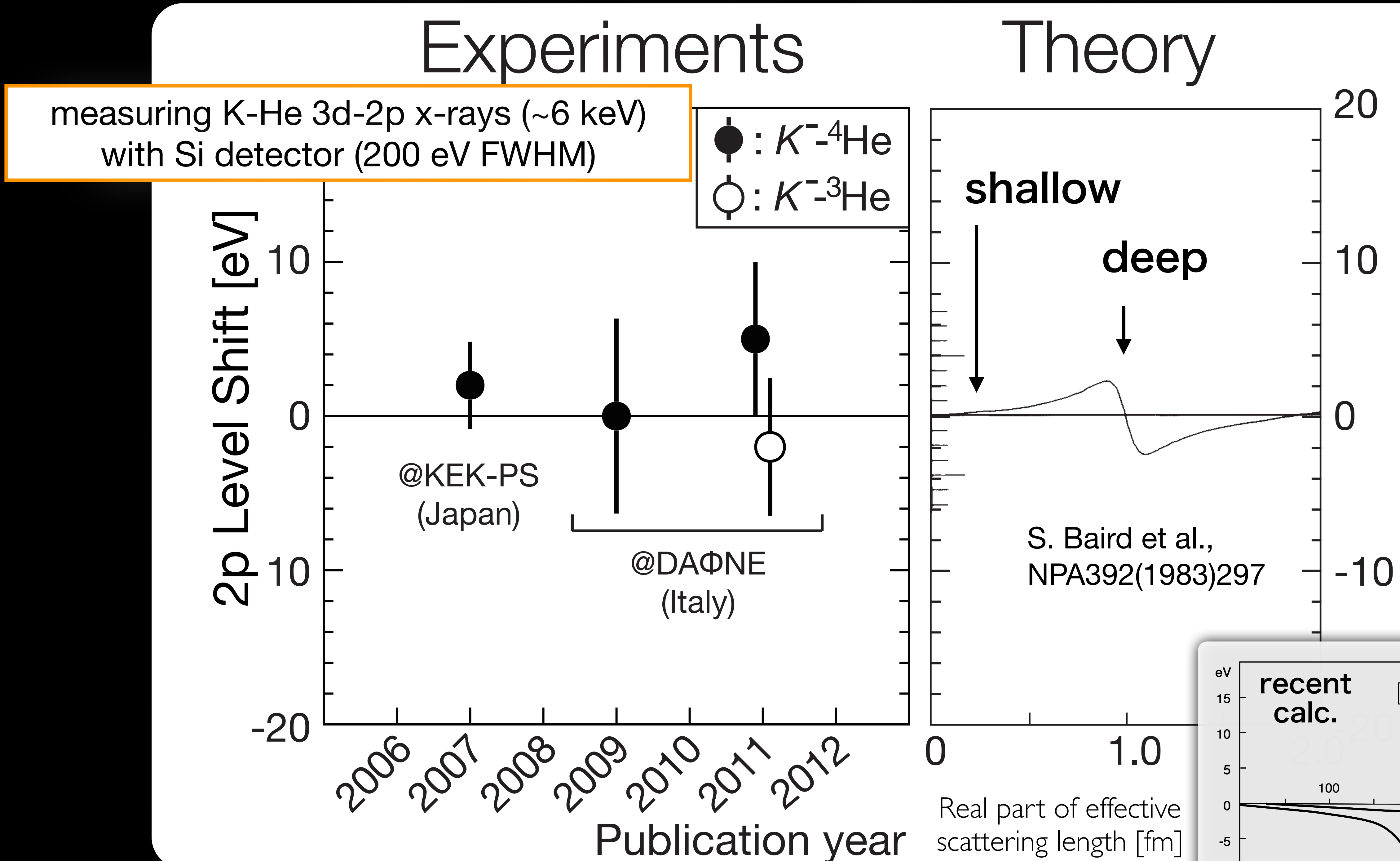


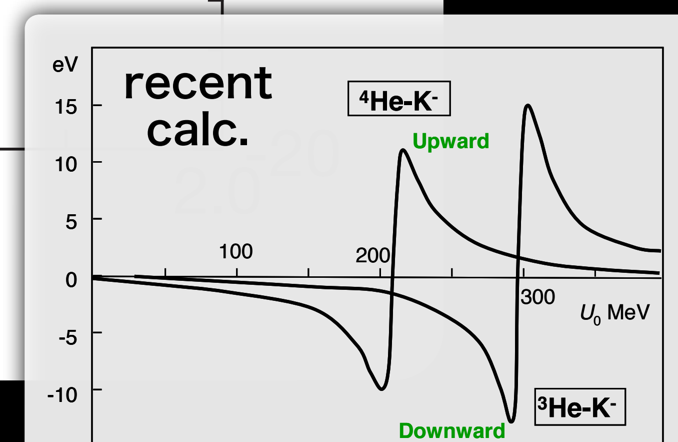
Fig. 5. Calculated strong interaction shift and width for kaonic helium as a function of the value of the real part of $\bar{a}$. The calculations used $a_I = 0.1$ fm.

precise measurement of shift & width → potential depth

Insufficient resolution

Kaonic helium 2p level shift

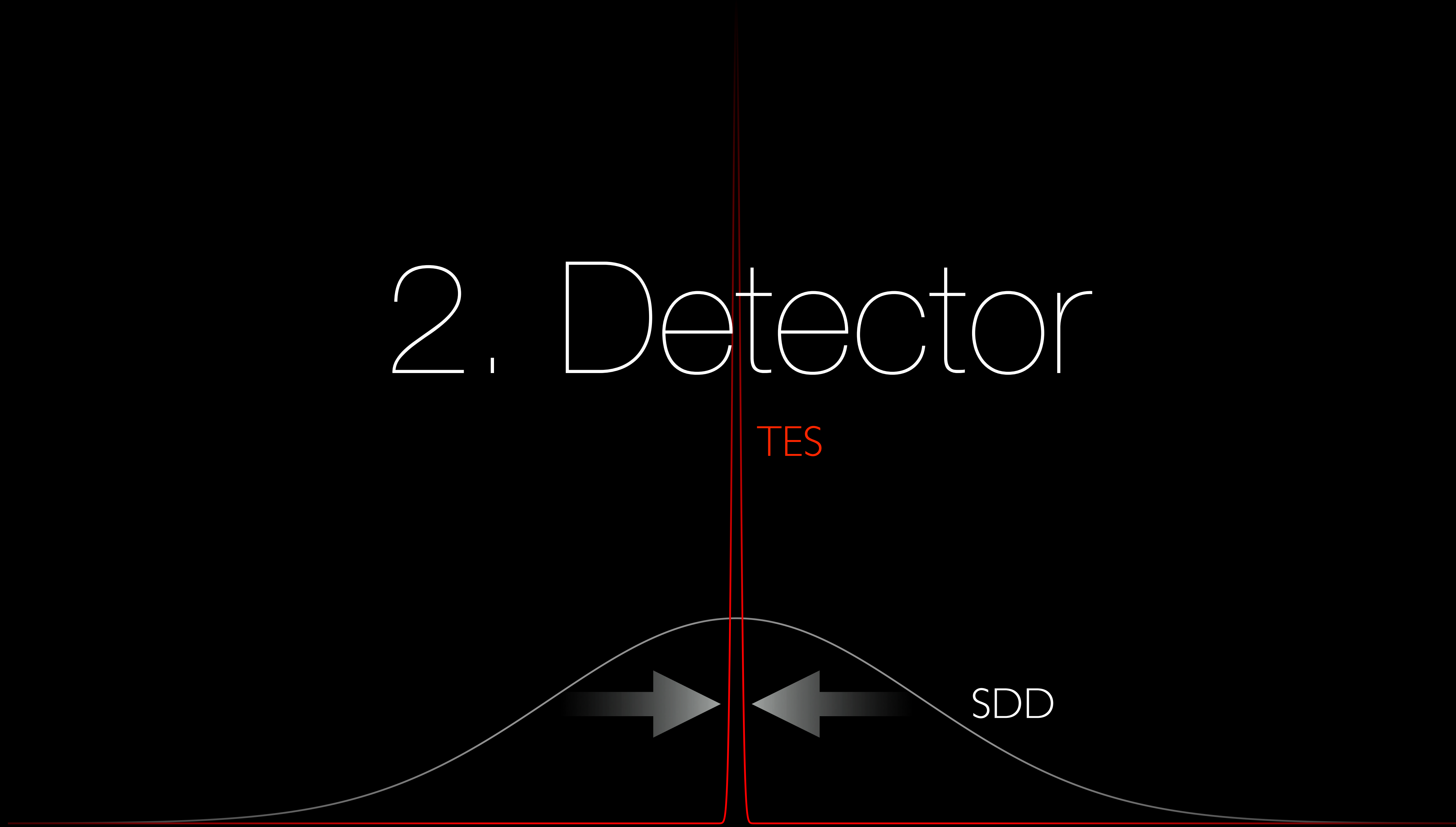




Y. Akaishi, Proceedings for International Conference on Exotic Atoms (EXA05), Austrian Academy of Sciences Press, Vienna, 2005, p. 45.

→ need a breakthrough

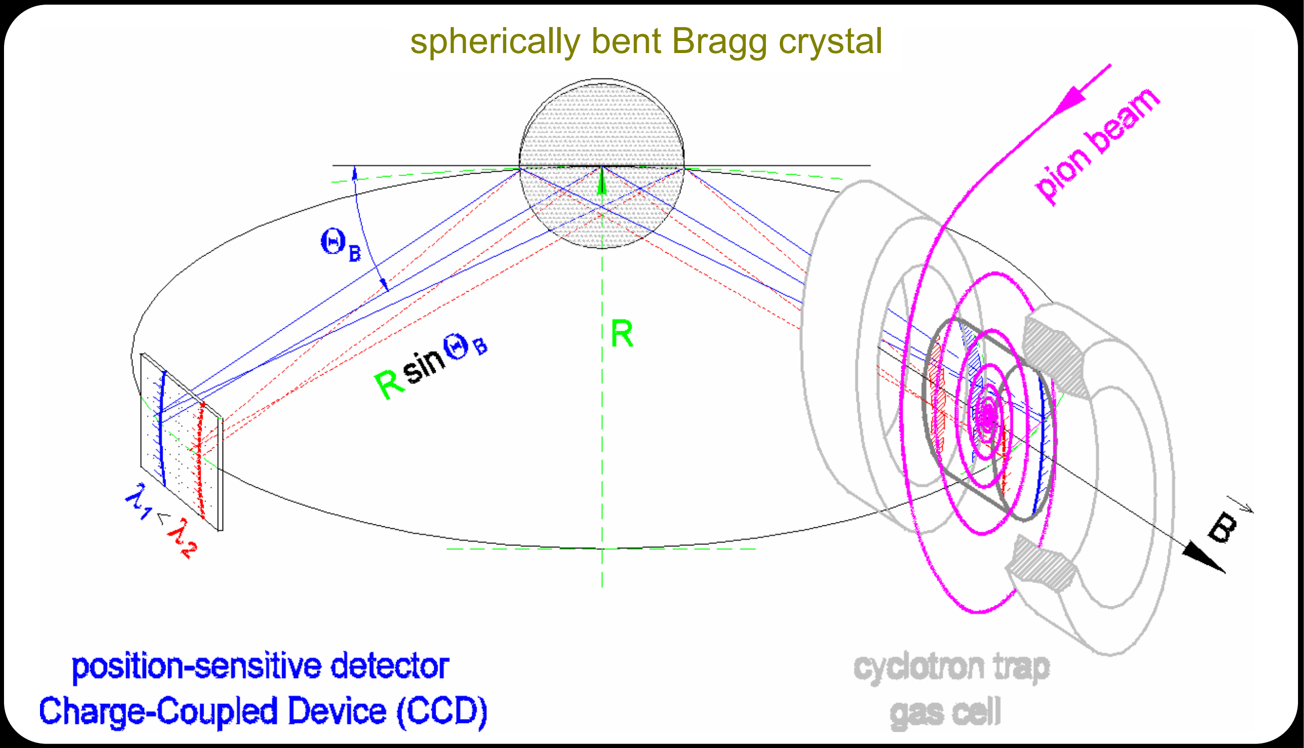
2. Detector



two orders of magnitude improved resolution
compared with the conventional semiconductor detector

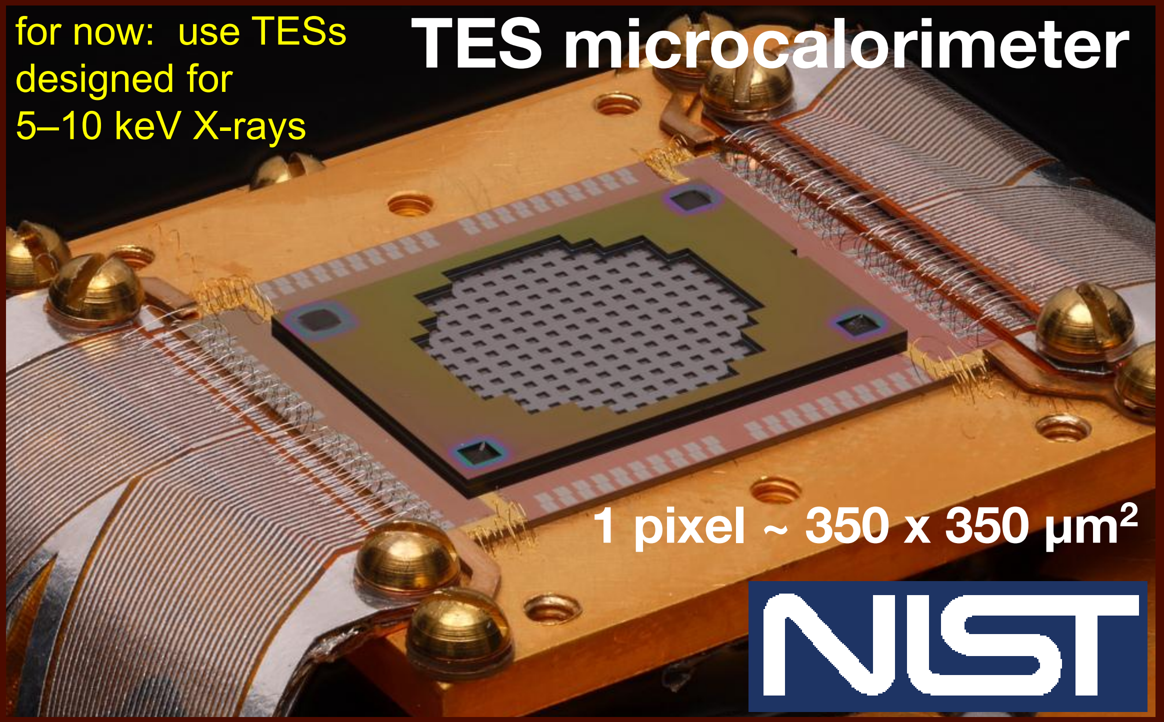
High-resolution detectors

1. Crystal spectrometer



pionic atom exp. : D. Gotta (Trento'06)

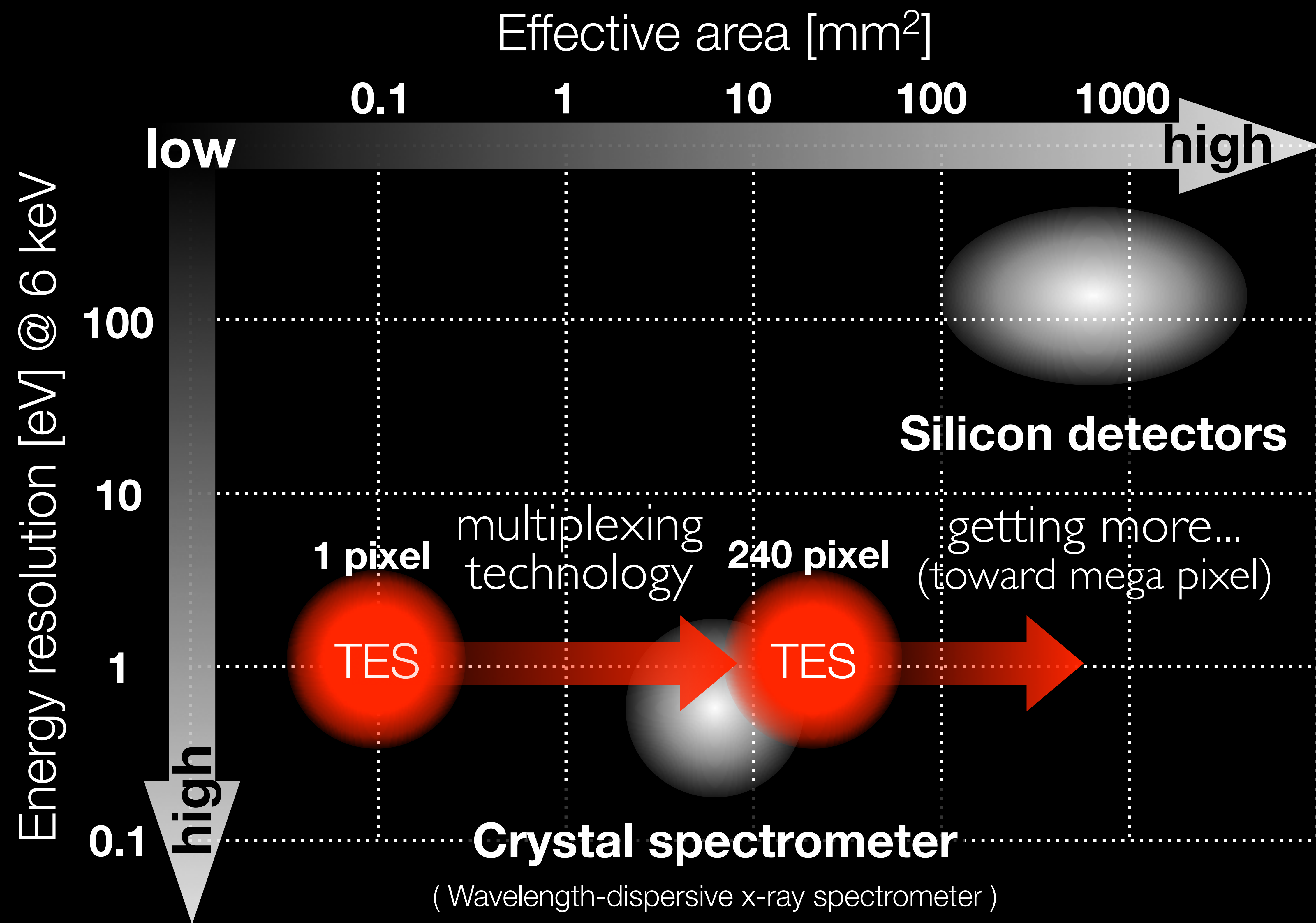
2. Cryogenic detector



W.B. Doriese, TES Workshop @ ASC (Portland), Oct 8, 2012

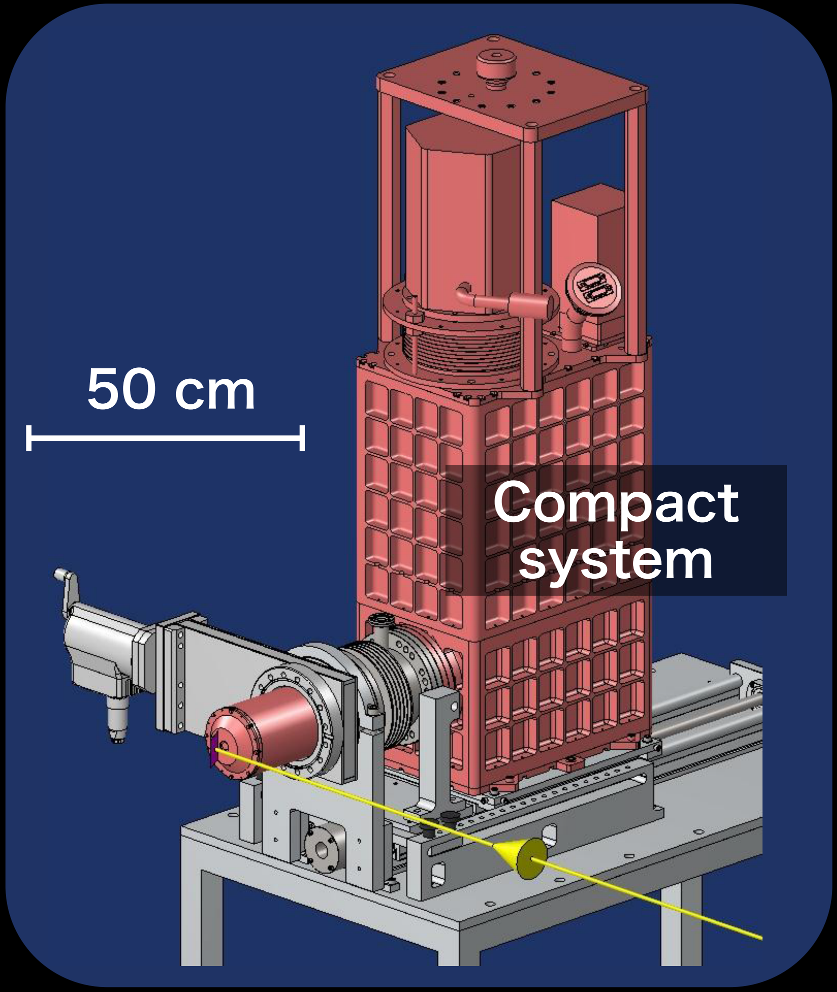
→ small acceptance

Why TES ?



The solid angle of a crystal spectrometer (PLB 416 (1998) 50) was converted to the equivalent effective area.

Why TES ? (cont')



✓ High collection efficiency

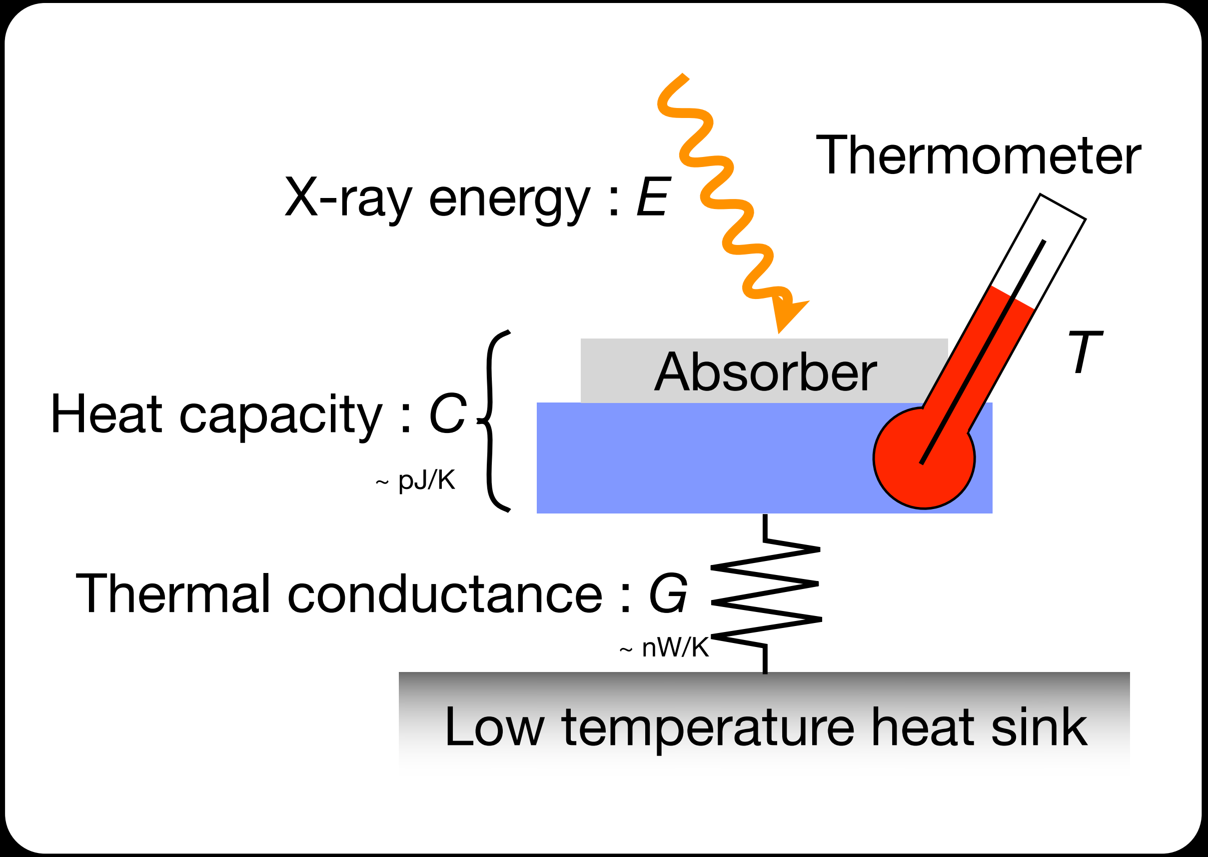
- Multi device (Array)
- Large absorber

✓ Compact and portable

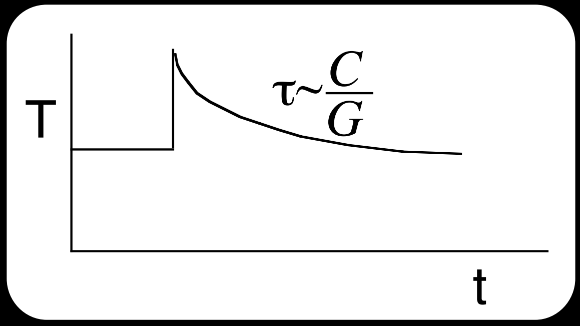
limited beam time, then need to remove

X-ray microcalorimeter

a thermal detector measuring the energy of an incident x-ray photon as a temperature rise (= E/C ~ 1 mK)



Decay time constant
= C / G (~ 500 μs)

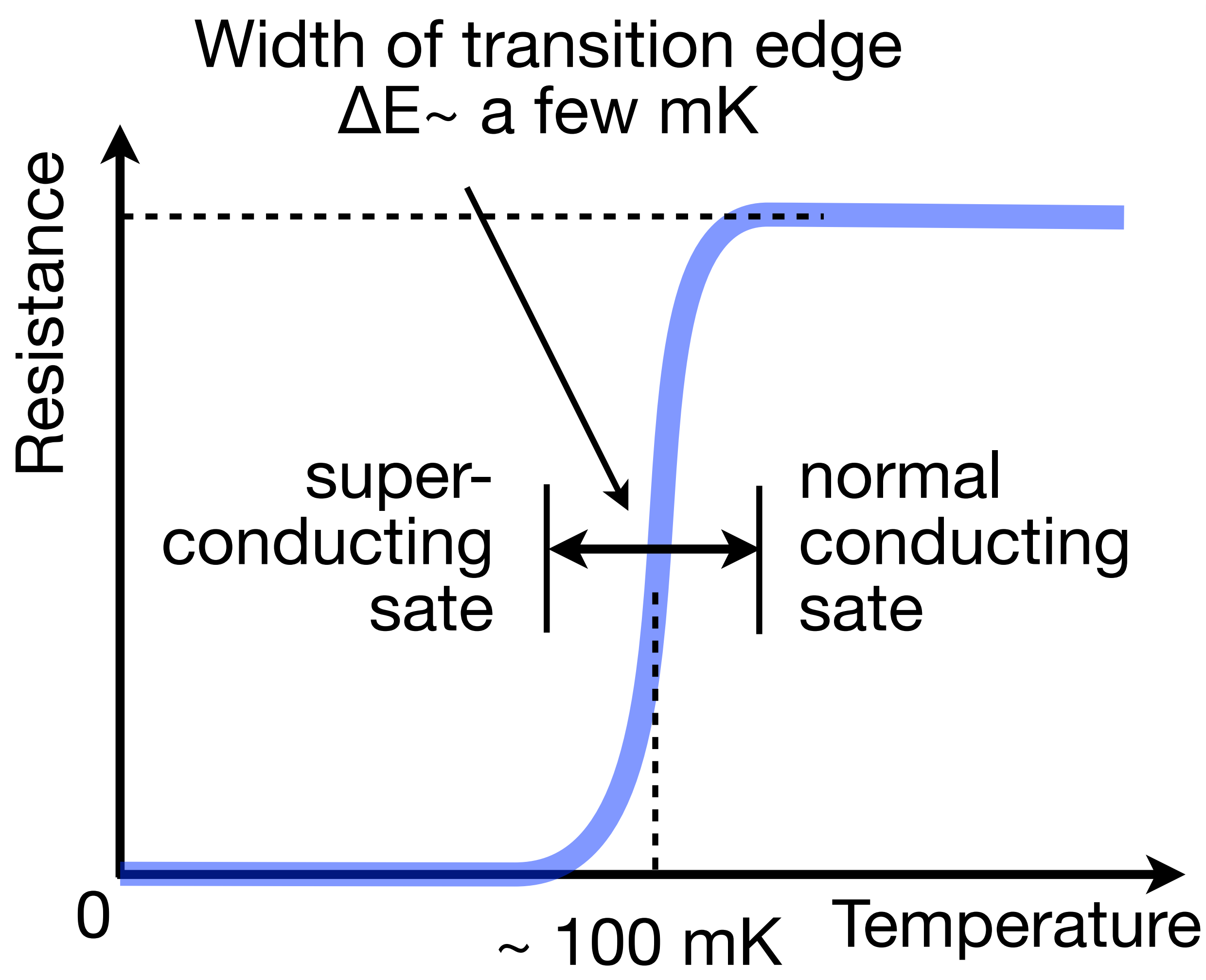


Absorber with larger “Z” (to stop the high energy x-rays)

e.g., Absorber : Bi (320 um × 300 um wide, ~ 3 um thick)
Thermometer : thin bilayer film of Mo and Cu (several 10s nm thick)

TES = Transition Edge Sensor

using the sharp transition between normal and superconducting state to sense the temperature



--> developed by Stanford / NIST at the beginning

Thermometer sensitivity

$$\alpha \equiv \frac{d \ \ln R}{d \ \ln T} \sim 10^{2\sim3}$$

Energy resolution (σ)

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

(Johnson noise and phonon noise are the most fundamental)

Dynamic range

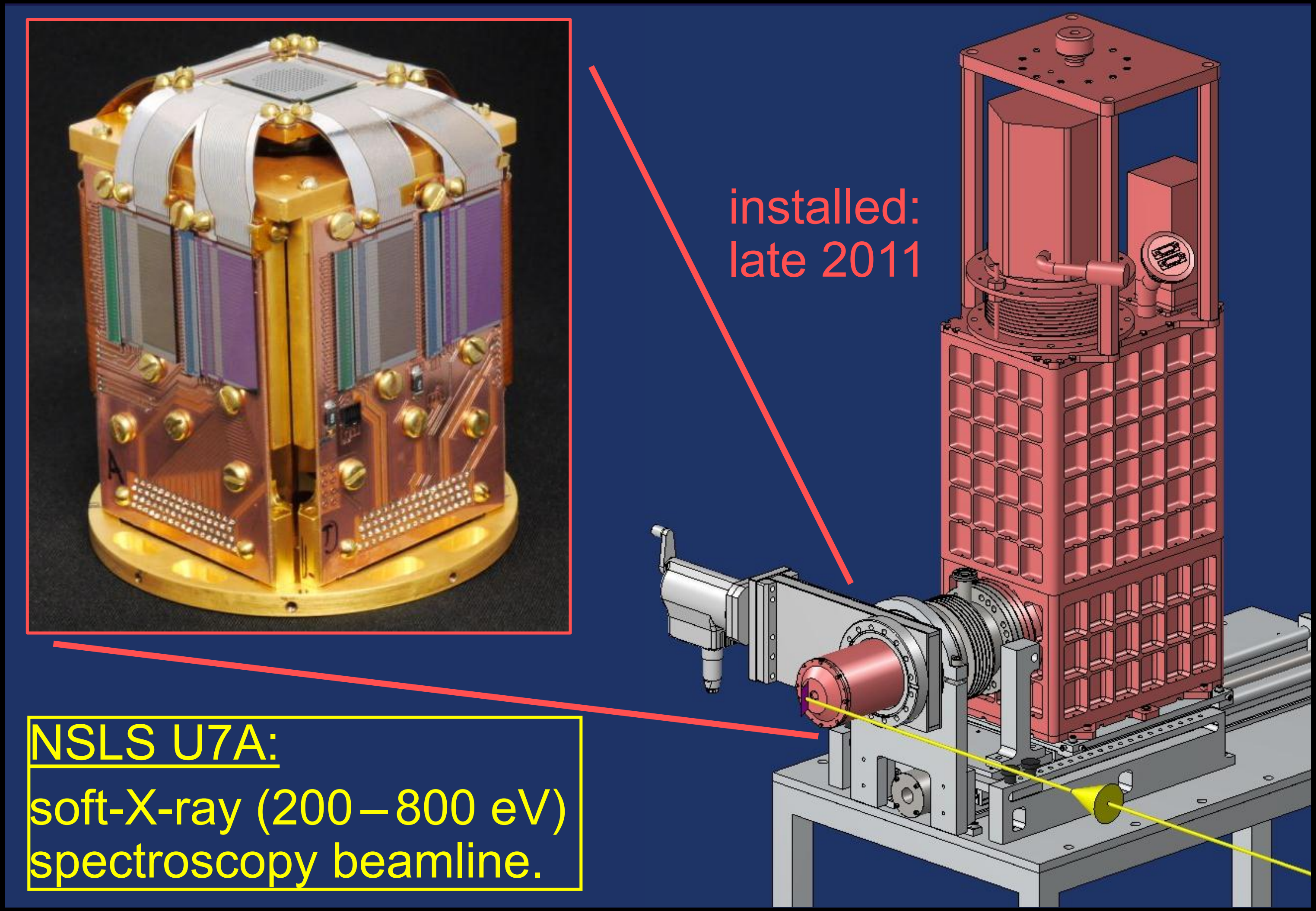
$$E_{max} \sim C T_C / \alpha$$

Trade-off between dynamic range and energy resolution : $\Delta E \sim \sqrt{E_{max}}$

applications : astrophysics (space satellite) etc.

NIST's TES array system for x-rays

e.g., soft-X-ray spectroscopy @ BNL



W.B. Doriese, TES Workshop @ ASC (Portland), Oct 8, 2012

NIST's standard TES

- 1 pixel : 300 x 320 μm^2
- 240 array : total ~ **23 mm^2**
- **2~3 eV (FWHM)** @ 6 keV

well established system!

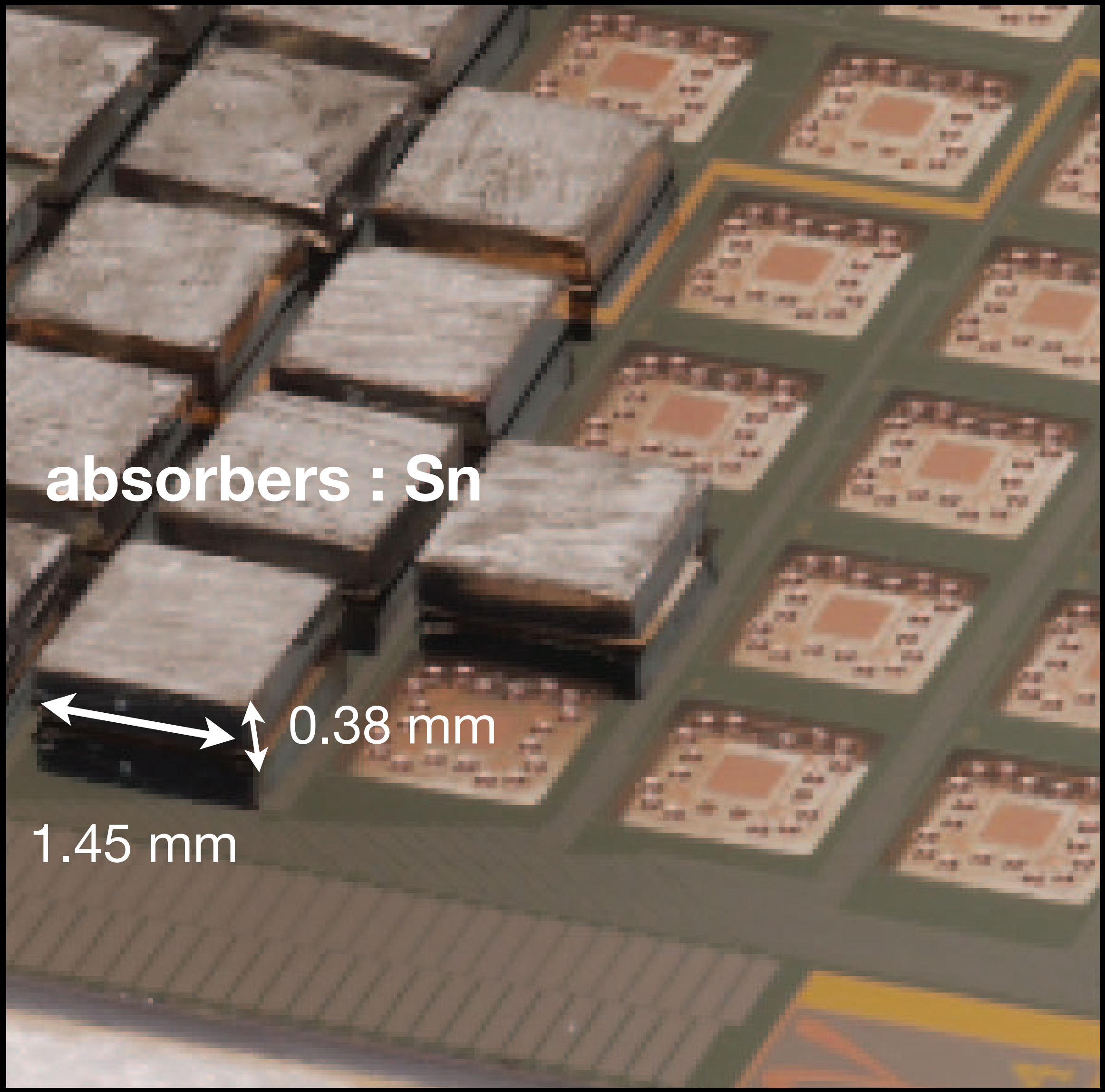
two-order improved resolution

~ 200 eV (FWHM) @ 6 keV
... a typical Silicon detector
used in the previous K-atom exp.

NIST's TES for gamma-rays

for 100 - 400 keV

e.g., hard-X-ray spectroscopy



NIST's standard TES

- 1 pixel : 1.45 x 1.45 mm^2
- 256 array : total ~ **5 cm^2**
- **53 eV (FWHM)** @ 97 keV

an order improved resolution

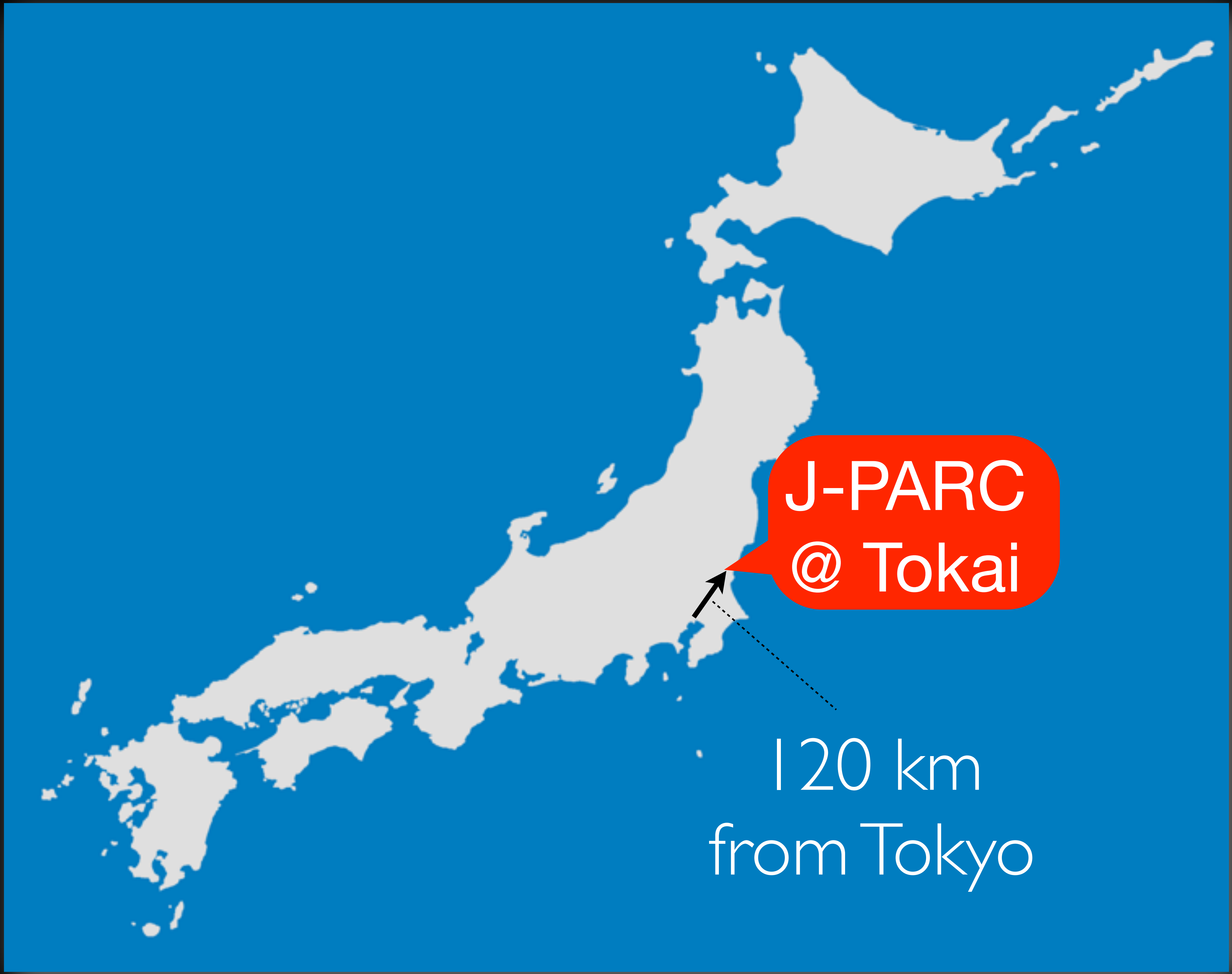
State-of-art high-purity germanium detectors

D. A. Bennett et al., Rev. Sci. Instrum. 83, 093113 (2012)

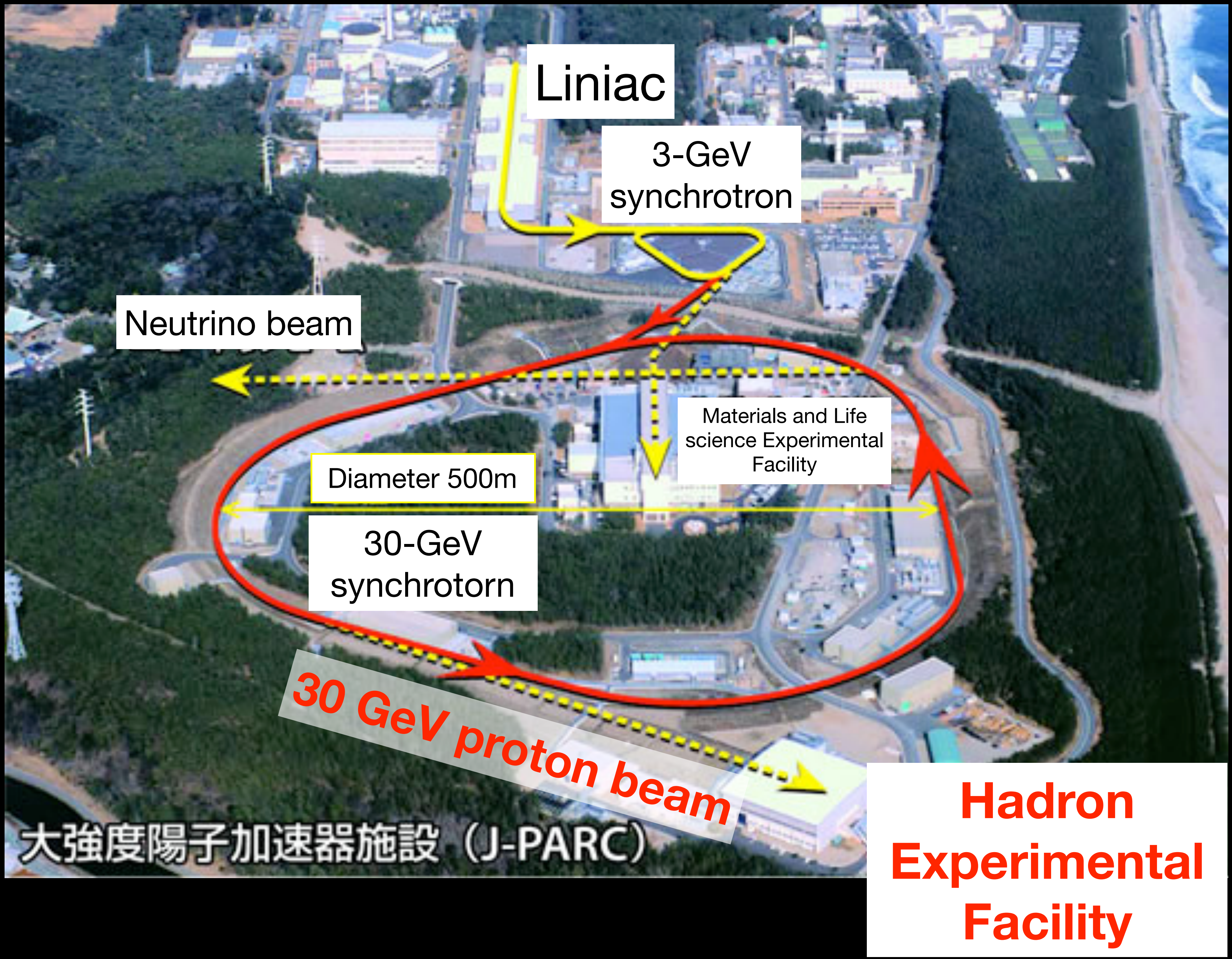
3. Experiment

a proposed K-atom experiment at J-PARC

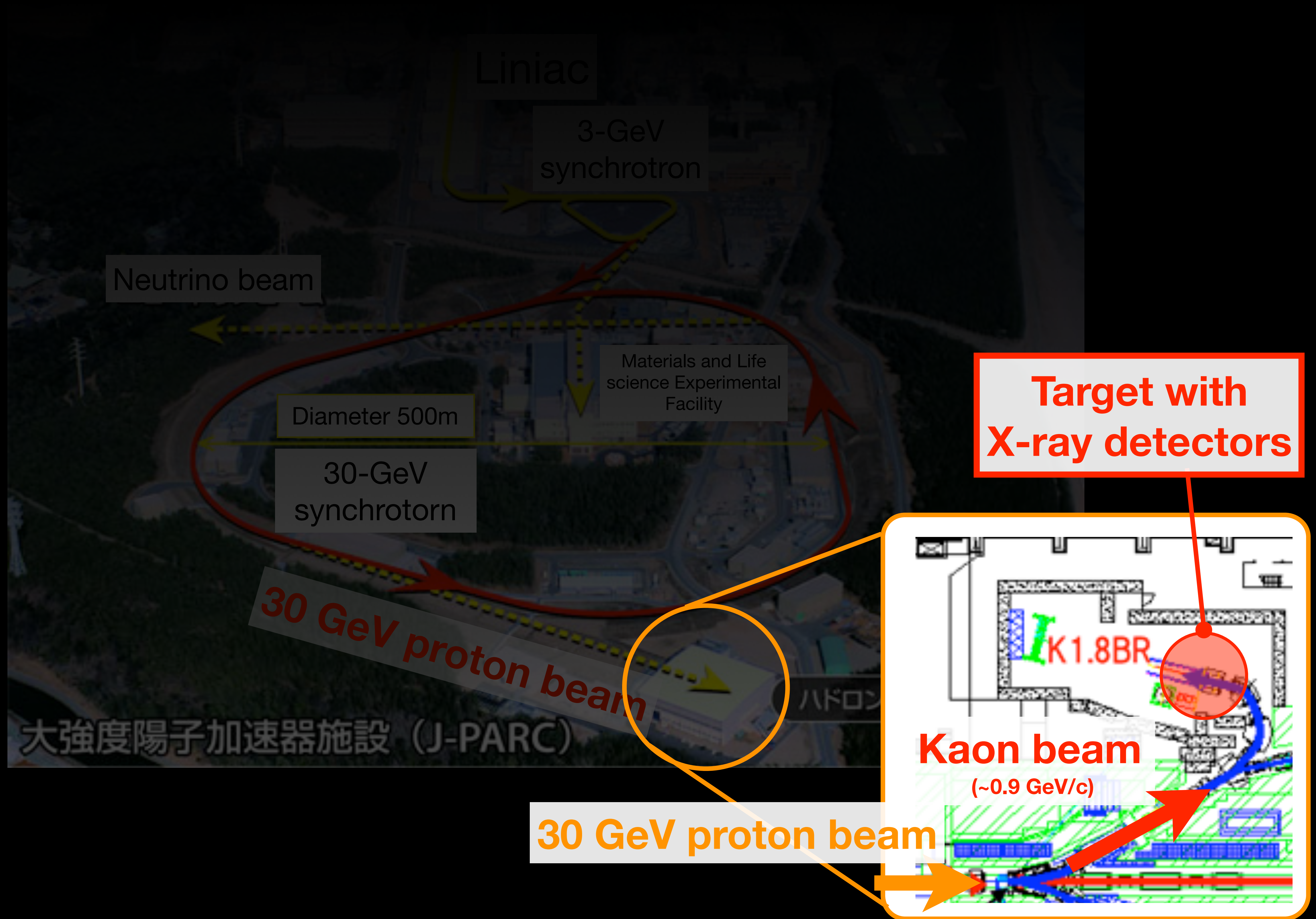
J-PARC (Japan)



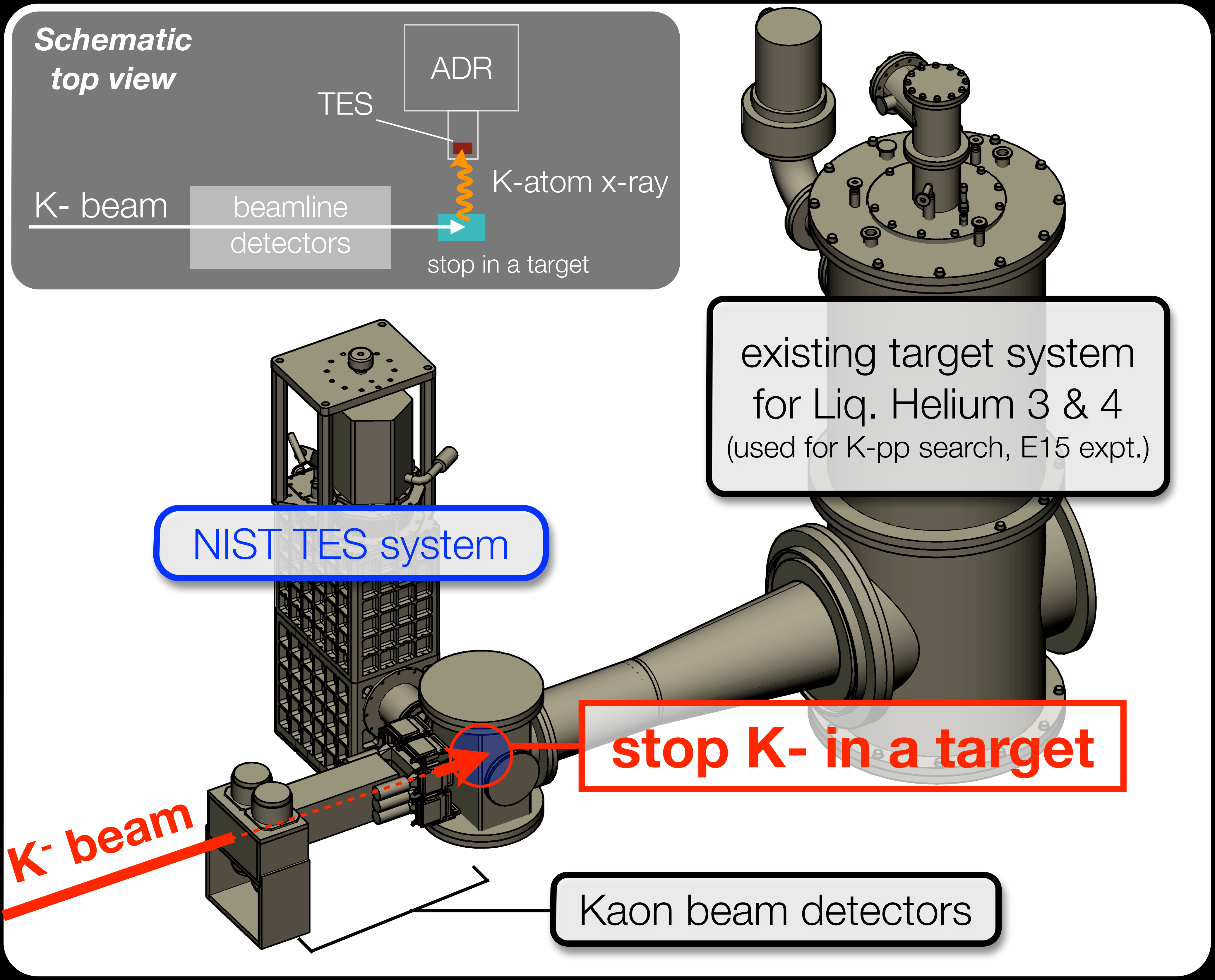
J-PARC : Japan Proton Accelerator Research Complex



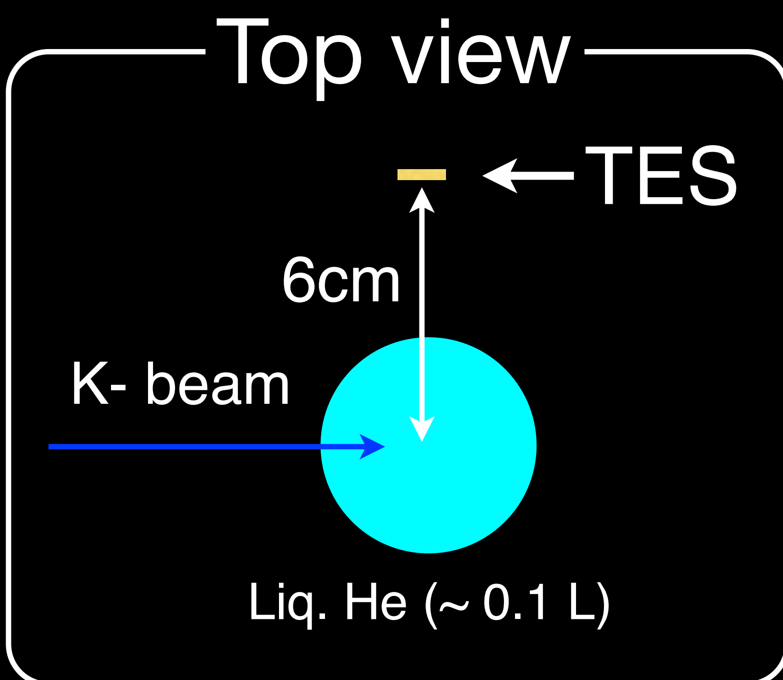
J-PARC hadron beamline



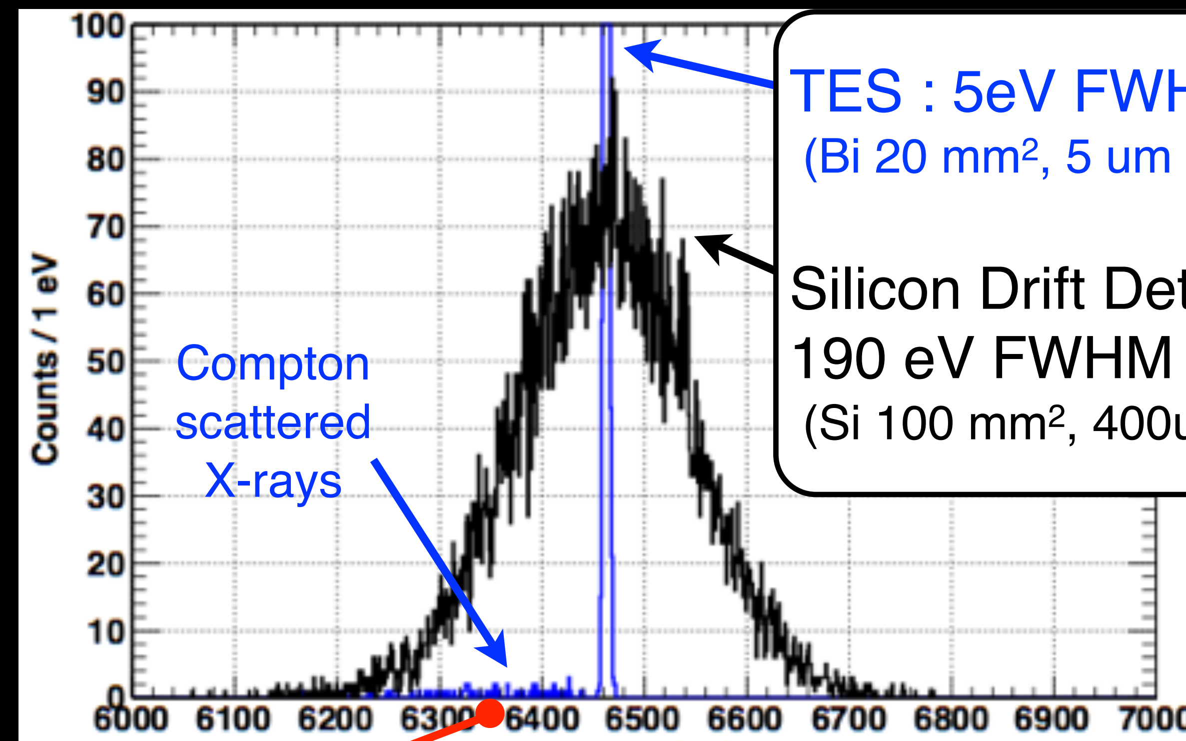
Experimental setup



A simple simulation

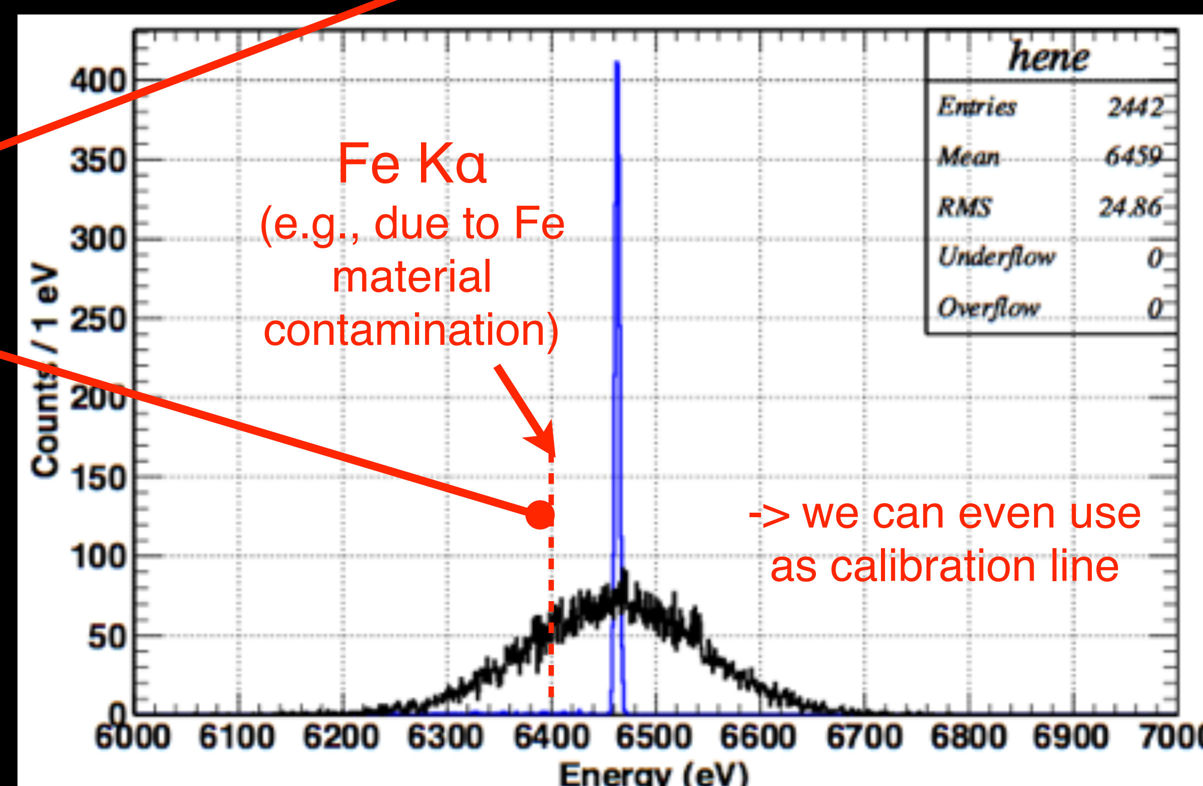


K-^{4}He x-rays from Liq. ^{4}He w/ GEANT4



TES : 5eV FWHM
(Bi 20 mm², 5 um thick)

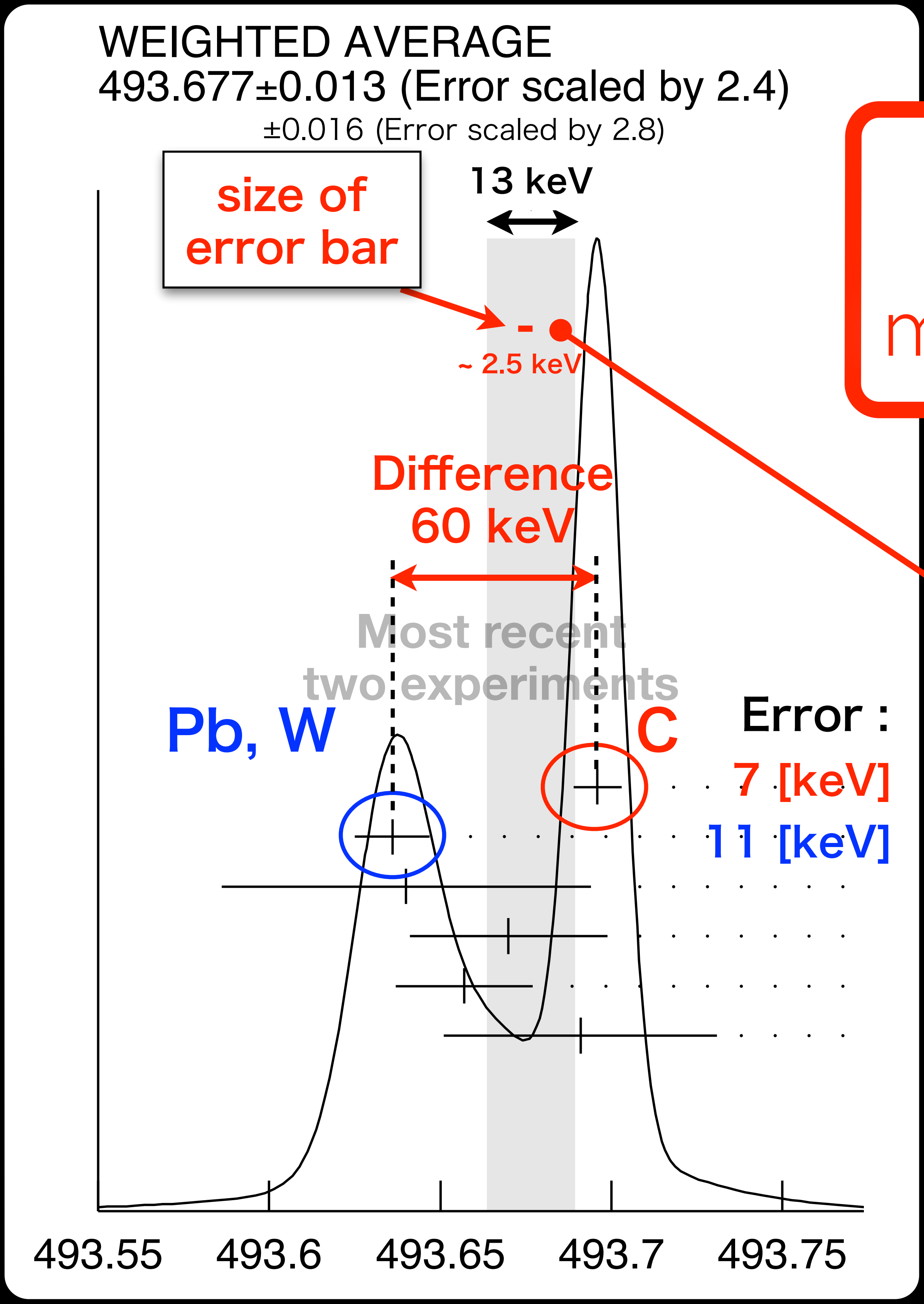
Silicon Drift Detector(SDD) :
190 eV FWHM
(Si 100 mm², 400um thick)



well separated from
"Compton scattered X-rays"
and "Fe Ka energy".

Both have been serious problems
in the prev. experiments.

Moreover ...



most fundamental quantity

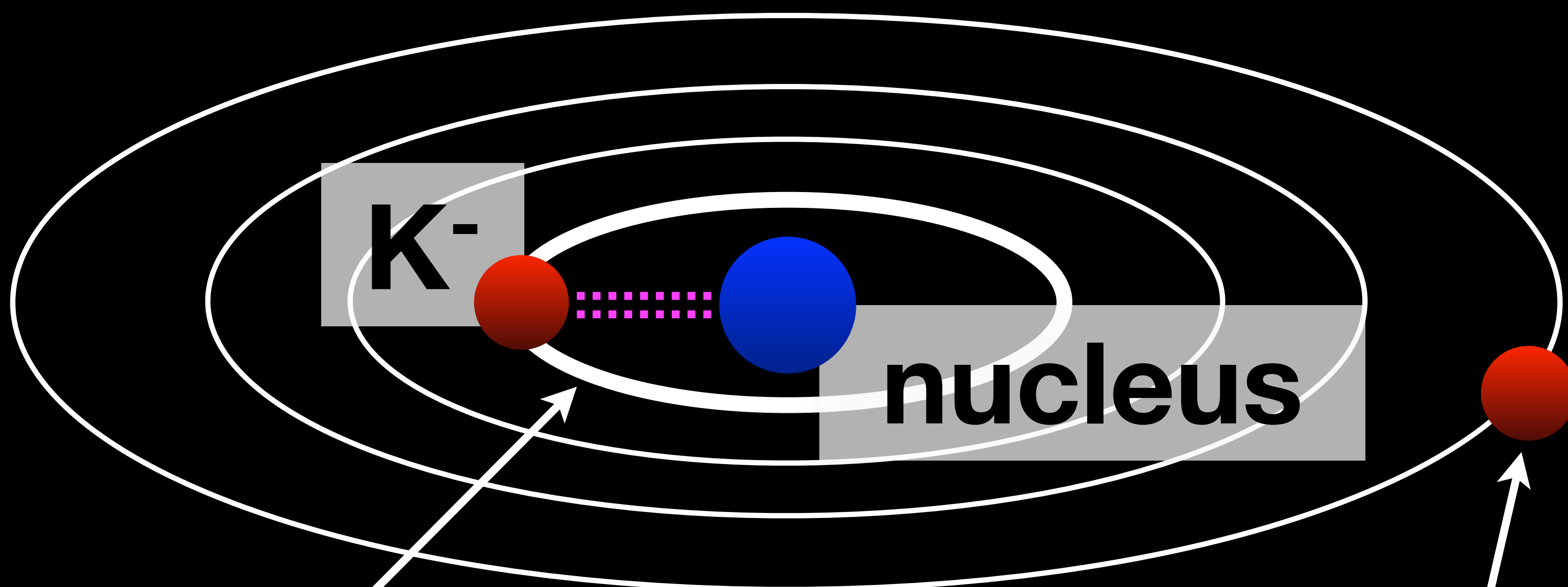
Charged Kaon mass measurement with TES

Rough estimation

- K-^{12}C 5→4 x-ray : 10.2 keV
- 2000 events & ΔE=5eV(FWHM)
  - ➡ ΔE (x-ray energy) ~ ± 0.05 eV
  - ➡ Δm (K-mass) ~ **± 2.5 keV**

Kaon mass is essential to determine the strong-interaction shift with 0.1-eV order of magnitude.
(Δm = 16 keV --> EM value for K-He Lα = 0.15eV)
(Δm = 2.5 keV --> EM value for K-He Lα = 0.03eV)

Summary of Kaonic atom study



Small n

strong-interaction study

the most tightly bound energy levels that are the most perturbed by the strong force

Large n

Kaon mass

the higher orbit having almost no influence on the strong interaction

Rough yield estimation

		Acceptance (including x-ray attenuation)	Number of stopped kaon	Absolute x-ray yield / stopped K	Time	X-ray counts
prev. experiment (KEK-PS E570 2nd cycle)		0.126% / 7SDDs	~300/spill (2sec)	~8%	272 hours	1700 w/o cuts (including trigger condition ~40%)
TES J-PARC (30kW)	**He**	0.024%	~300?/spill (2sec) duty ~45%	~8%	**~ 4 days**	130
	C	~0.01% self attenuation	~2000?/spill (2sec) duty ~45%	~17%	**~ 1 weeks**	2500

very preliminary

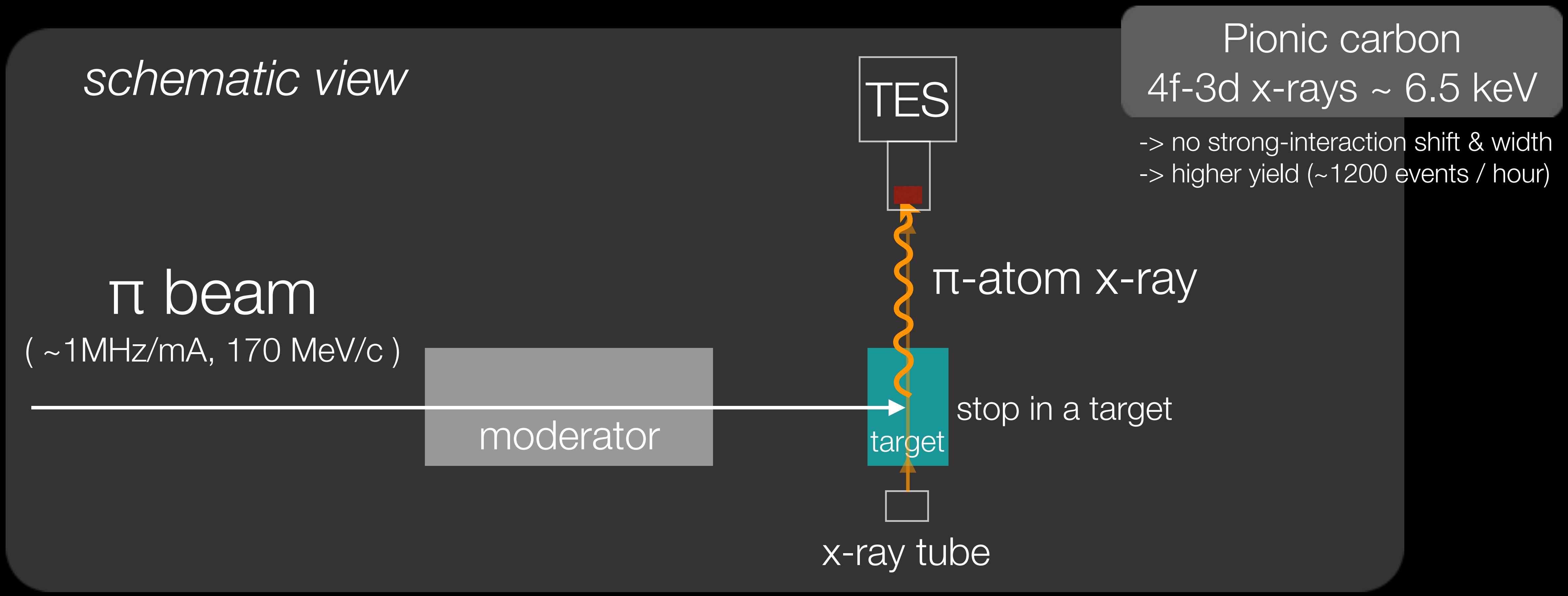
-> reasonable beam time

4. Test experiment

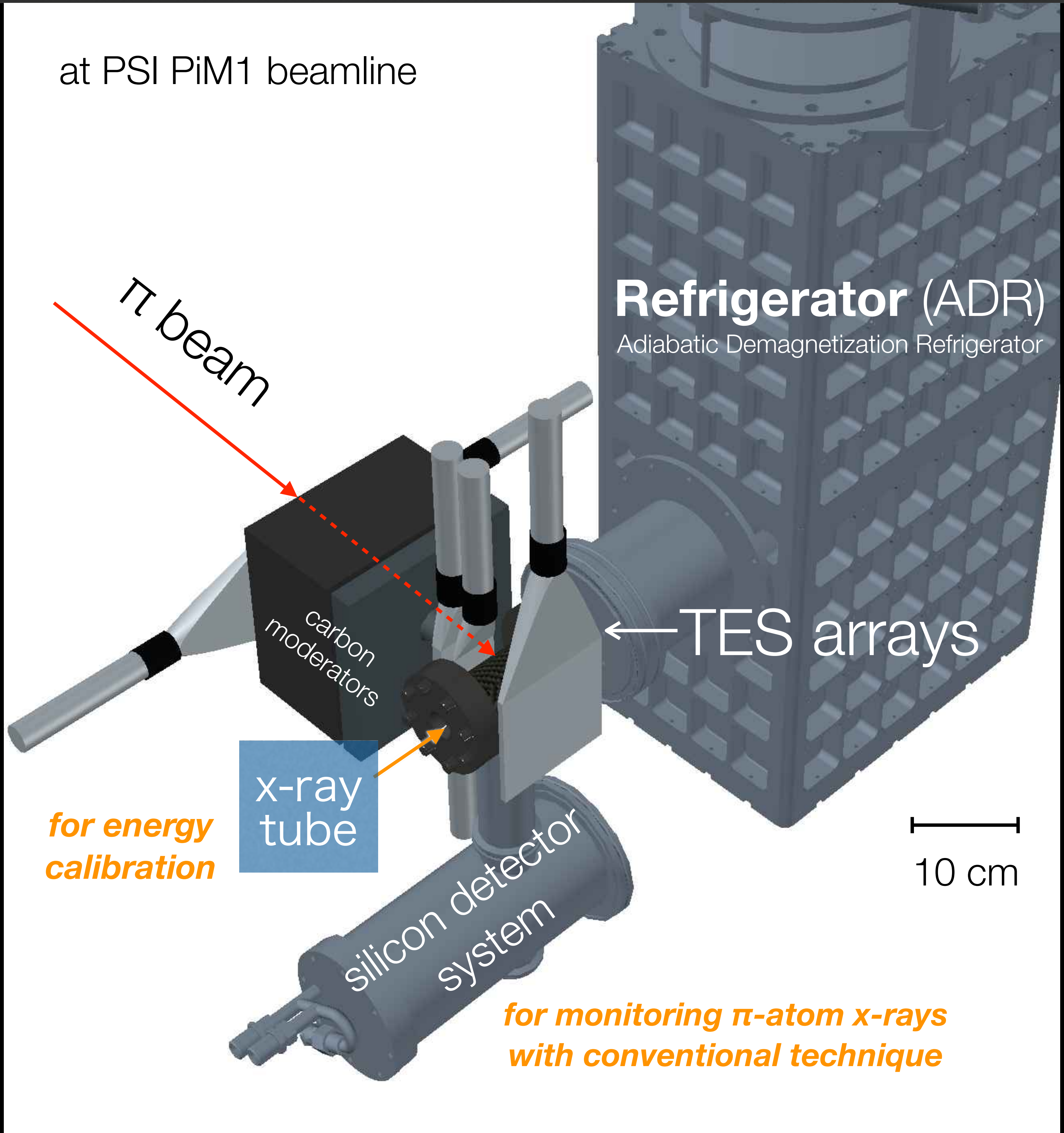
study of in-beam performance of TES at PSI

Feasibility test towards J-PARC expt.

- aim : studying in-beam performance of TES
  ➡ the first measurement of hadronic-atom x-rays with TES
- when? : October 2014
- where? : Paul Scherrer Institute (PSI), PiM1 beamline



Experimental setup



Moreover …

High-precision measurement of π^--^{3,4}He 2p-1s x-rays

π-p, π-d : high accuracy data w/ crystal spectrometer

-> but no high-precision data for π-He yet

		past measurements	
	x-ray energy	shift	width
π - 3He atom 2p-1s	10.64 [keV]	+32 ± 4 [eV]	28 ± 7 [eV]
π - 4He atom 2p-1s	10.77 [keV]	-75.7 ± 2.0 [eV]	45 ± 3 [eV]

G. Backenstoss et al., Nuclear Phys. A 232 (1974) 519.
I. Schwanner et al., Nuclear Phys. A 412 (1984) 253.

aiming to measure π-He shift & width
with one-order better accuracy than past one

- Target : gas helium-3 & 4 (room temperature, ~10 atom)
- Yield estimation : ~ 5000 events for 3-days data acquisition

5. Summary

Summary

- Next-generation hadronic-atom experiment with TES
- NIST's TES : large area ~20 mm^2, high resolution ~3 eV FWHM @ 6 keV
- Kaonic atom at J-PARC (in future years)
  - a potential to resolve a long-standing deep-shallow problem
  - providing new accurate charged kaon mass value
- Pionic atom at PSI (soon!)
  - feasibility test towards K-atom expt. at J-PARC
  - the first hadronic-atom expt. with TES (aiming high-accuracy π-He data)
- Future w/ k/M-pixel TES : other hadronic atom (Σ-, Ξ-) x-ray spectroscopies

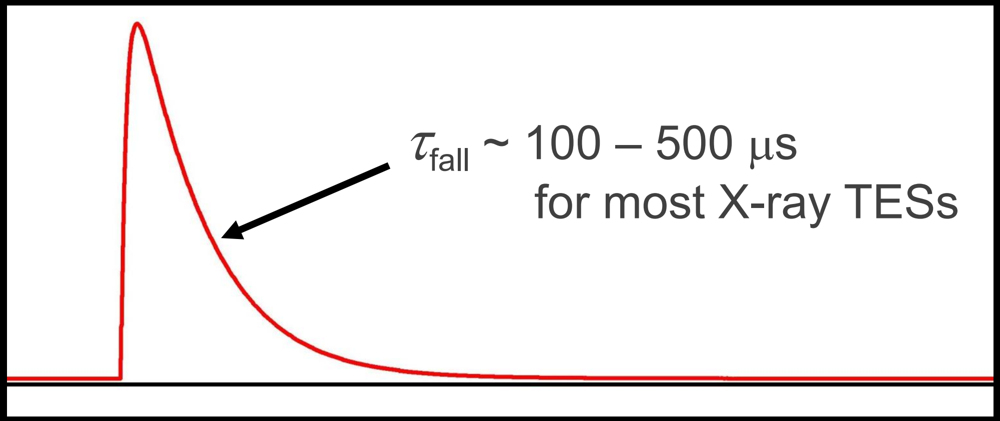
Appendix

Is 240 pixel (~23 mm^2) enough?

estimated K-^{4}He Kα yield w/ realistic setup
~ 30 events / day

	K-4He Kα events	Energy resolution in FWHM	Stat. accuracy of ene. determining (6 keV)
KEK-E570 with SDD	1500 events	190 eV	2 eV = 190 / 2.35 / sqrt(1500)
	ONE order lower	TWO orders higher	ONE order better
TES	120 events (~ 4-day beam)	2 ~ 3 eV	~ 0.1 eV = 2 ~ 3 / 2.35 / sqrt(120)

Count rate with TES



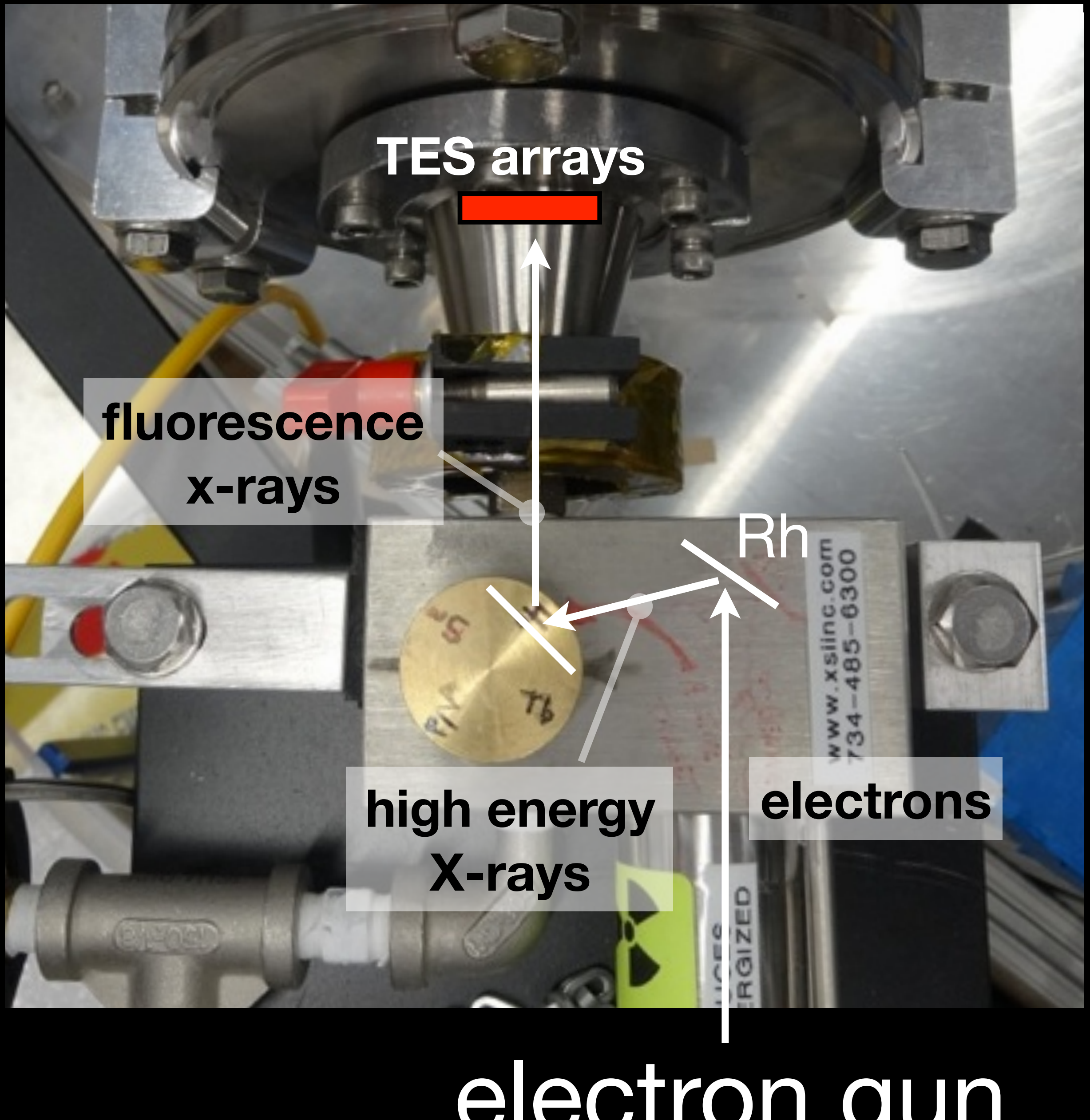
- Practical x-ray TES time constants ~ 100 - 500 μs
- **10s of Hz / TES** for the highest resolution

- Prev. exp : single count rate (incl. bg) ~ 1000 Hz for 100 mm^2
- Effective area ~ 0.1 mm^2 / TES -> **~ 1 Hz / TES**

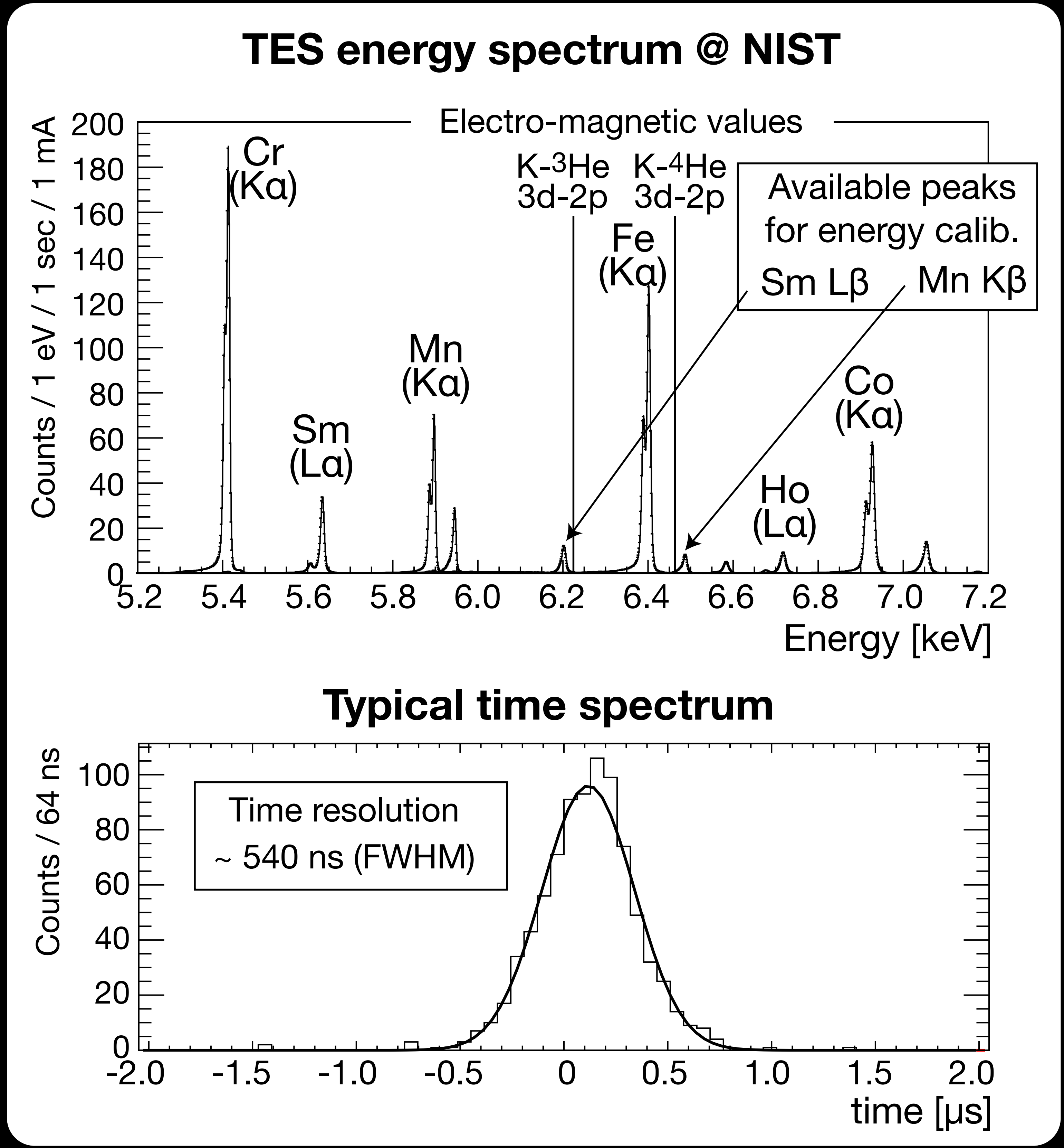
-> acceptable even 10 times higher count rate

Line calib. experiment @ NIST

26 Aug. - 6 Sept., 2013

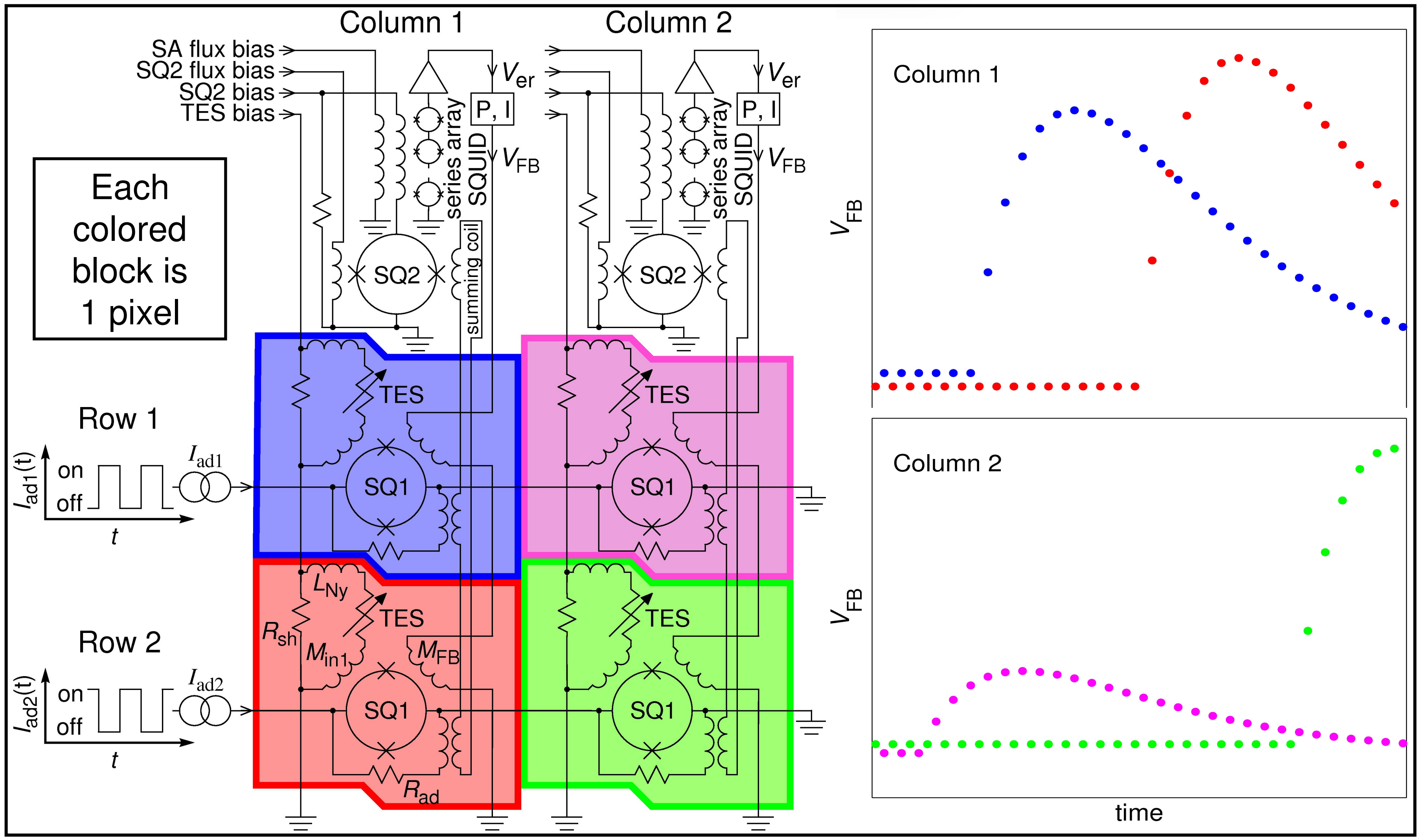


Line calib. experiment @ NIST



well-known lines
(ΔE <~ 0.1 eV)

NIST's 240 pixel TES array



Time-division SQUID multiplexer

W.B. Doriese, LTD-13 @ Stanford, 2009