23 Sept, 2014

第三回研究会 @ 熱川

超伝導遷移端マイクロカロリメータ多ピクセルアレイを用いたK中間子原子X線精密分光

岡田 信二 (理研)

The HEATES collaboration

- **H**igh-resolution **E**xotic **A**tom x-ray spectroscopy with **TES** microcalorimeter -

S. Okada[1], D.A. Bennett[2], C. Curceanu[3], W.B. Doriese[2], J.W. Fowler[2], F. Gustafsson[4], T. Hashimoto[1], R.S. Hayano[5], S. Hexi[6], M. Iliescu[3], S. Ishimoto[7], K. Itahashi[1], M. Iwasaki[1], K. Kuwabawra[8], J. Marton[6], H. Noda[1], G.C. O'Neil[2], H. Outa[1], J. Uhlig[4], M. Sato[1], A. Scordo[3], K. Suzuki[6], T. Suzuki[5], D.R. Schmidt[2], D.S. Swetz[2], H. Tatsuno[2,7], J.N. Ullom[2], E. Widmann[6], S. Yamada[8], J. Zmeskal[6]

RIKEN[1], NIST[2], INFN-LNF[3], Lund Univ.[4], Univ. of Tokyo[5], SMI[6], KEK[7], Tokyo Metropolitan Univ.[8]

Collaboration

TES型X線マイクロカロリメータ

宇宙物理
ASTRO-H ...

原子核物理
Strangeness nuclear physics

中性子星内部 (K-N相互作用)

hadron - nucleus (nucleon) strong interaction

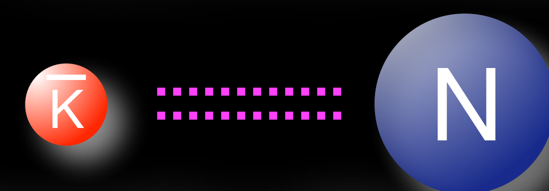
海外コラボレーション：**NIST** (アメリカ国立標準技術研究所)

A02班：核物質中のK中間子実験

（研究分担者：応田）

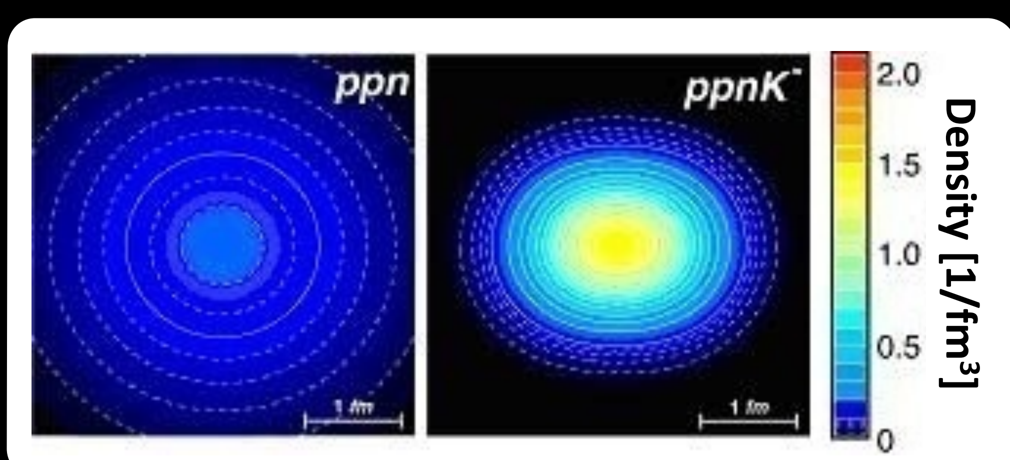
中性子星内部のK中間子発生領域の理解

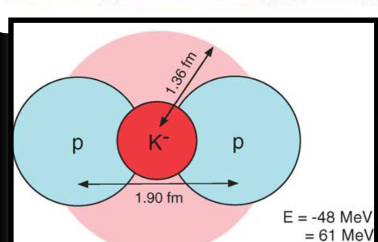
--> $\bar{K}$-N 相互作用の理解が重要



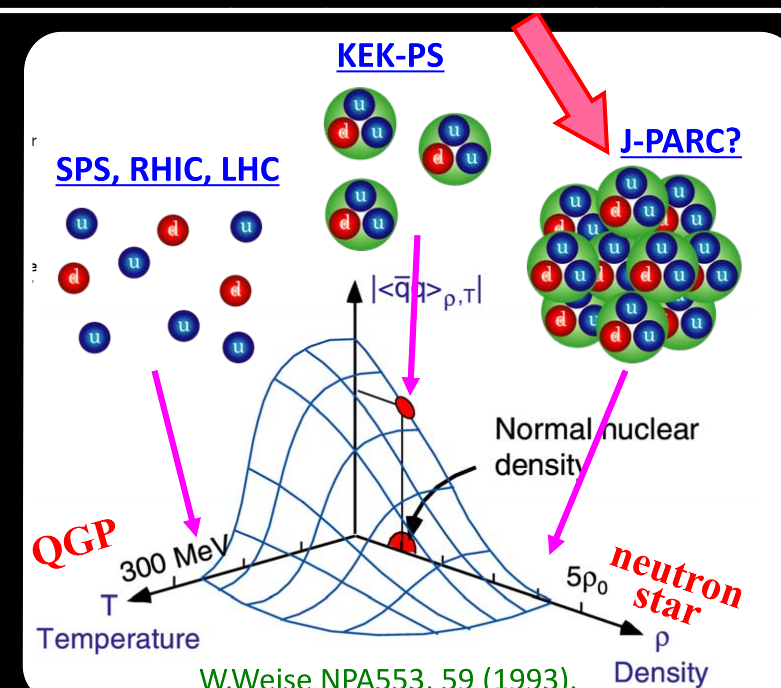
Strongly attractive!

a possibility of higher density
beyond normal nuclear-matter density





Phys. Lett. B587(2004)167



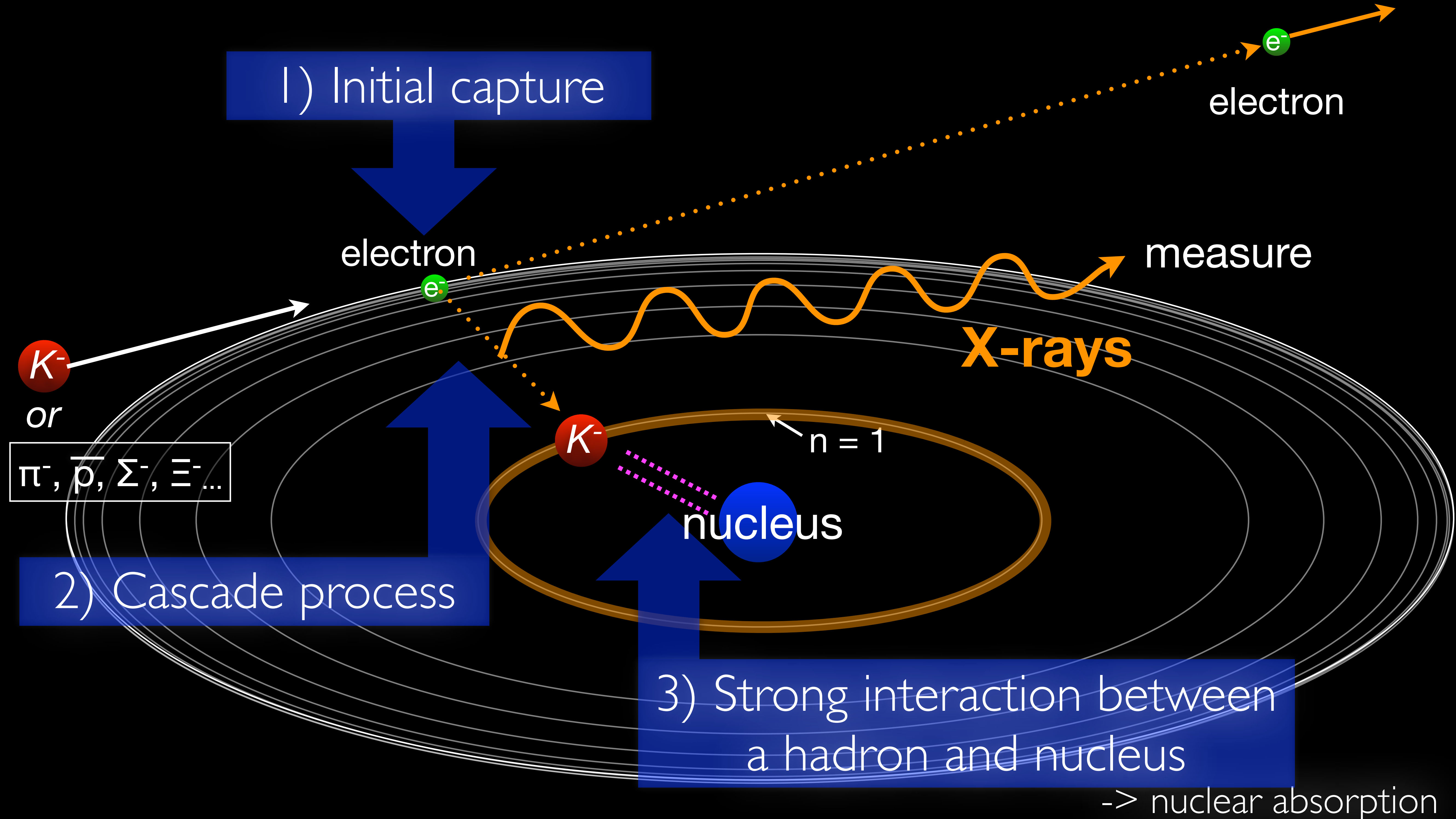
→ the in-medium **mass modification** effect ?
→ possibility of K- condensation in **neutron star** ?

Contents

1. Introduction

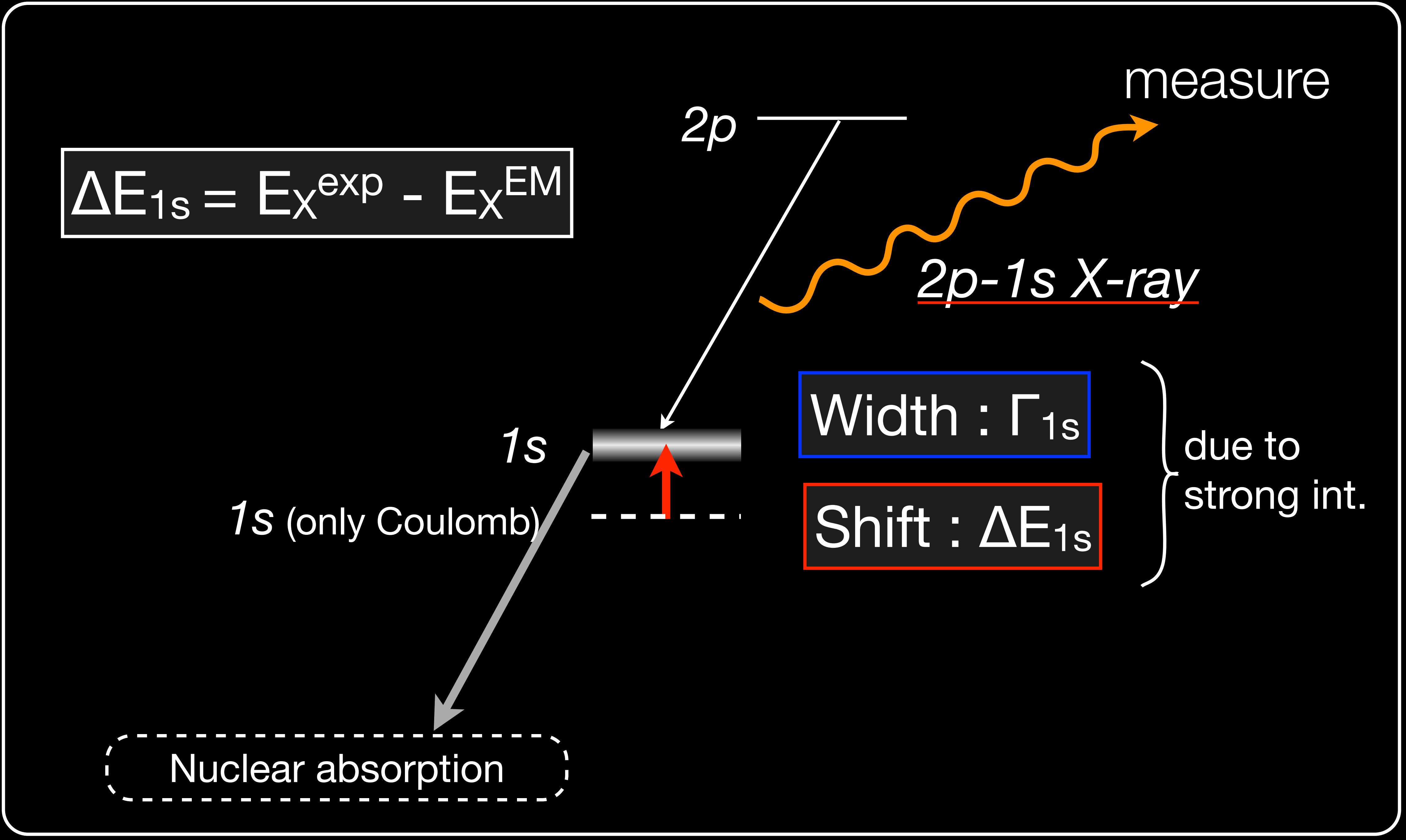
hadronic (kaonic) atom

Hadronic atom



A tool for studying strong interaction

Strong-interaction shift & width



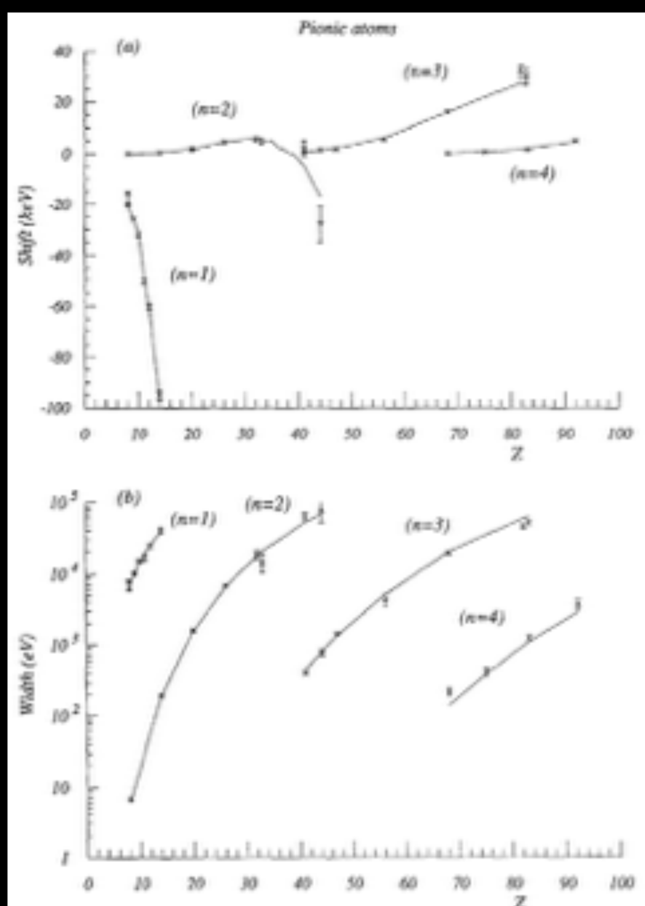
Many measurements so far

shift & width as a function of atomic number Z

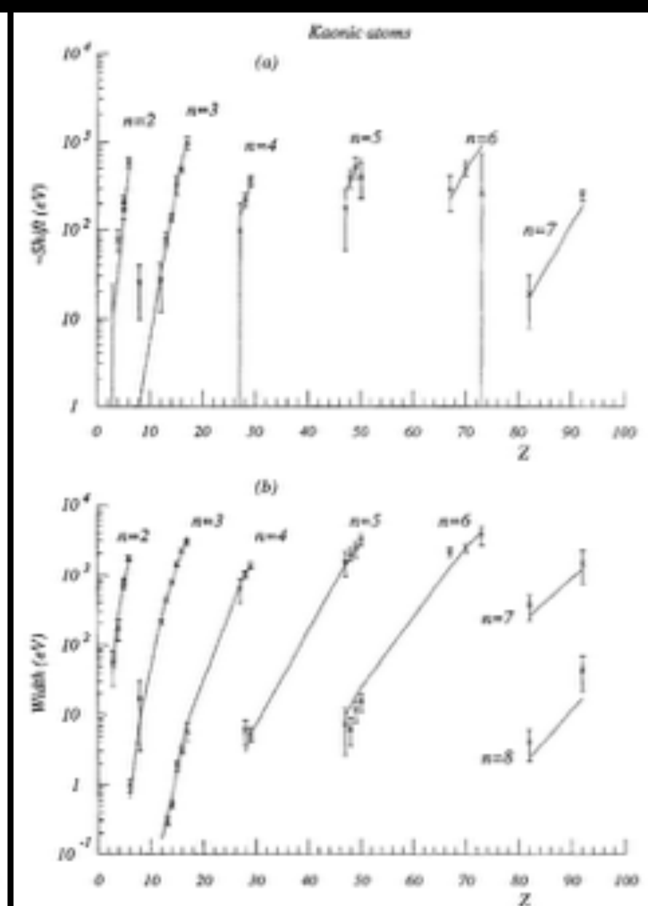
Shift [eV]

Width [eV]

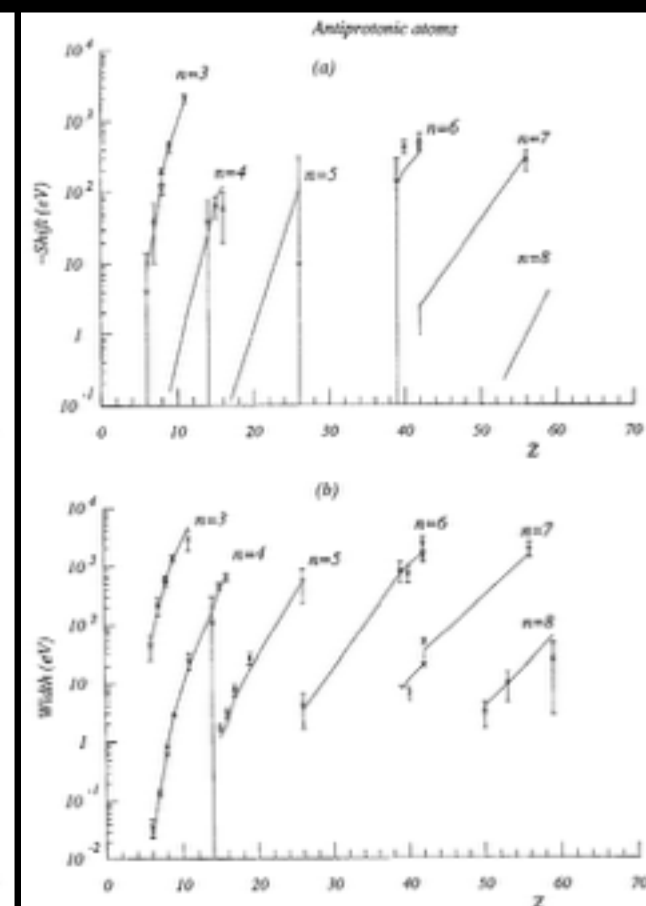
π^- atoms



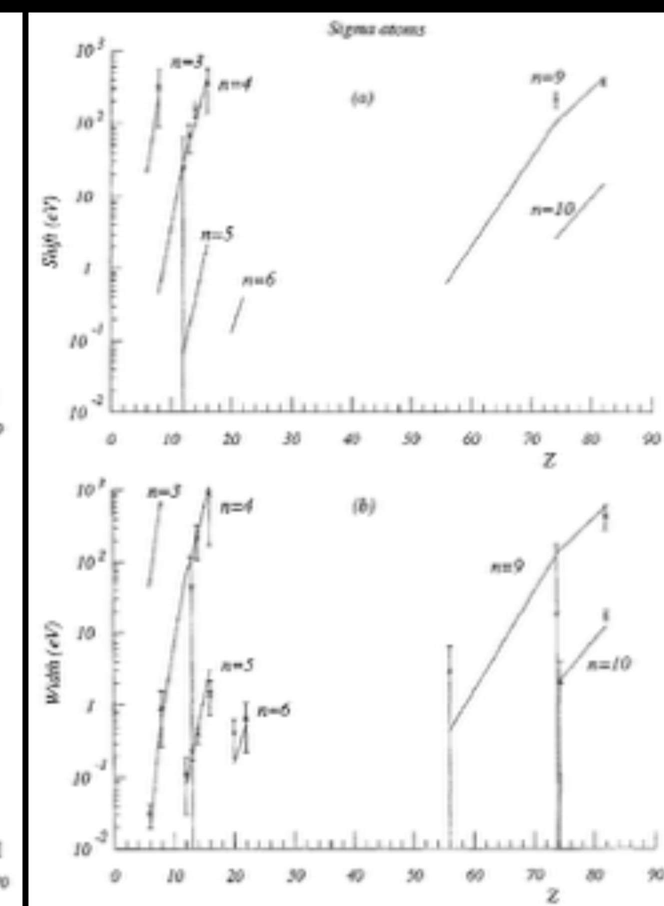
K^- atoms



$\bar{p}$ 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

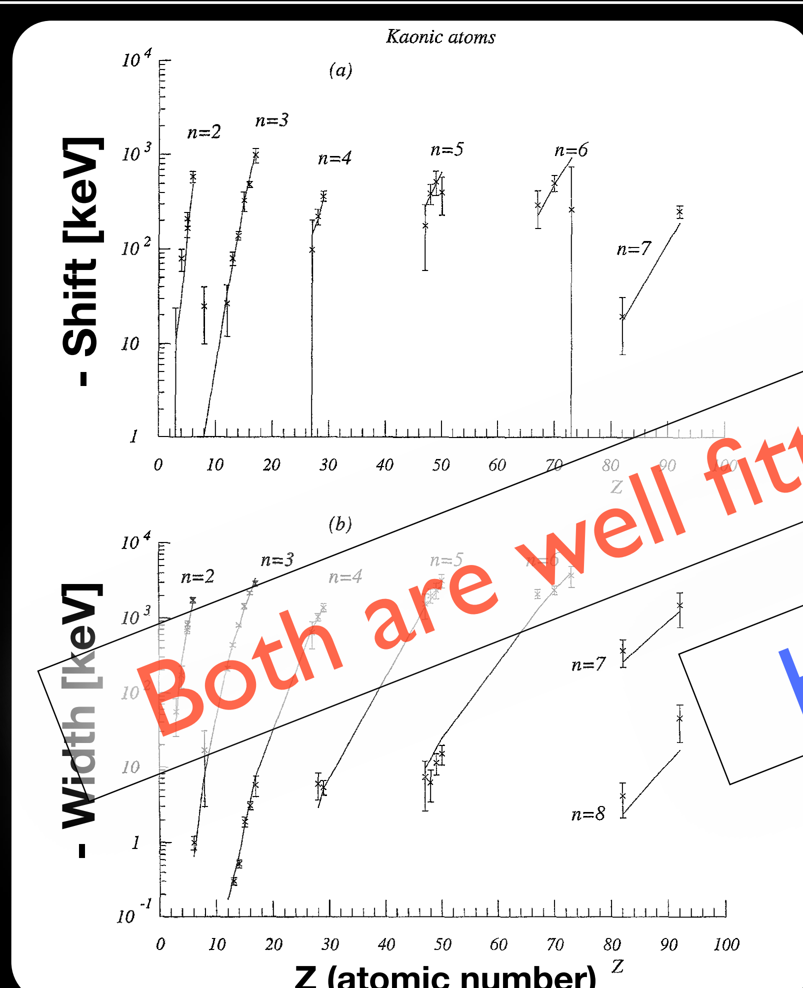
particle	real potl.	imaginary potl.	comments
π^-	repulsive in bulk	moderate	excellent data
	attractive on surface		well understood
K^-	attractive	moderate	good data
	deep or shallow?		open problems
$\bar{p}$	??	very absorptive	excellent data
			understood

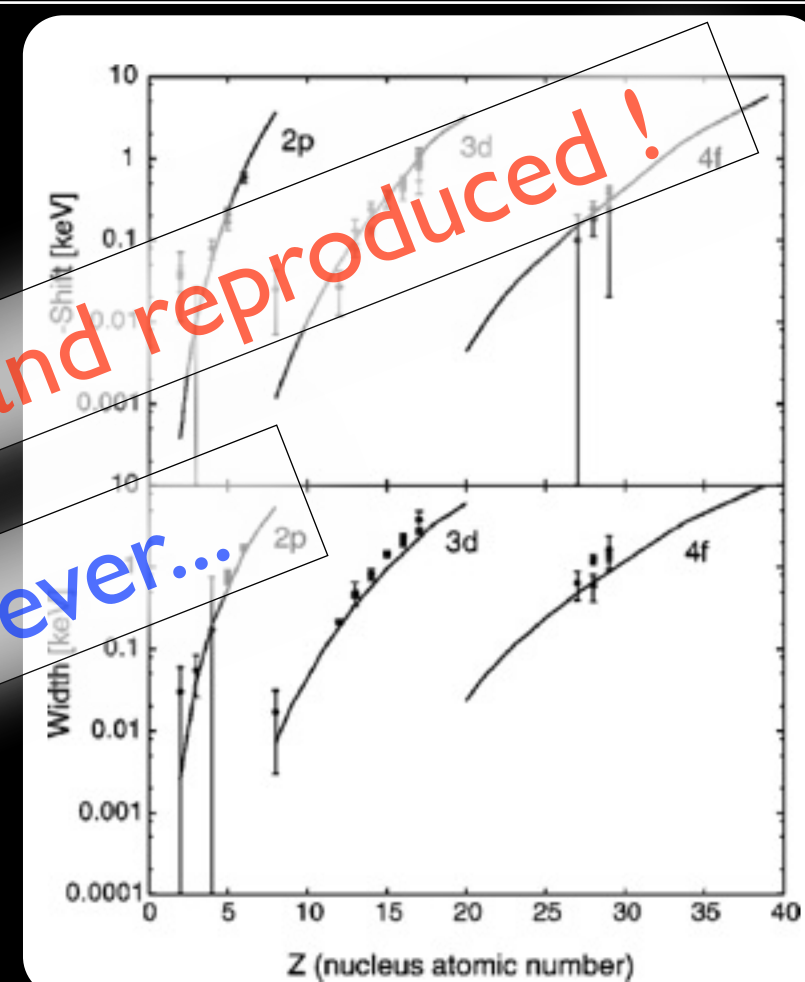
E. Friedman : MESON2010 conf.

K-atom : theoretical approaches

	Density-dep. optical potential	SU(3) chiral unitary
model	*C.J. Batty, E. Friedman, A. Gal, Phys. Reports 287 (1997) 385*	*Hirenzaki, Okumura, Toki, Oset, Ramos, PRC 61 (2000) 055205.*
	$V = -\frac{2\pi}{\mu}\left(1+\frac{\mu}{m}\right)\bar{a}\rho(r),$ $a \to a_0 + A_0[\rho(r)/\rho(0)]^{\alpha},$	$2\mu V_{opt}(r) = -4\pi\eta a_{eff}(\rho)\rho(r),$

exp. data
vs
calc. results





Both are well fitted and reproduced !

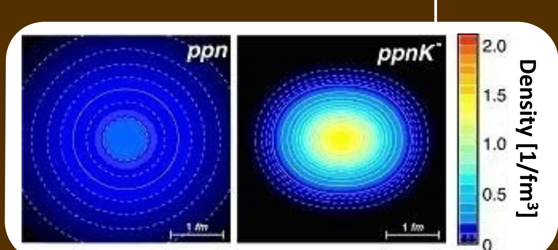
However...

deep or shallow ?

	Density-dep. optical potential	SU(3) chiral unitary
model	*C.J. Batty, E. Friedman, A. Gal, Phys. Reports 287 (1997) 385*	*Hirenzaki, Okumura, Toki, Oset, Ramos, PRC 61 (2000) 055205.*
	$V = -\frac{2\pi}{\mu}\left(1+\frac{\mu}{m}\right)\bar{a}\rho(r),$ $a \to a_0 + A_0[\rho(r)/\rho(0)]^{\alpha},$	$2\mu V_{opt}(r) = -4\pi\eta a_{eff}(\rho)\rho(r),$
potential depth	**deep** ($-V_{Real}$ = 150 ~ 200 MeV)	**shallow** ($-V_{Real}$ = 40 ~ 60 MeV)

Open problem

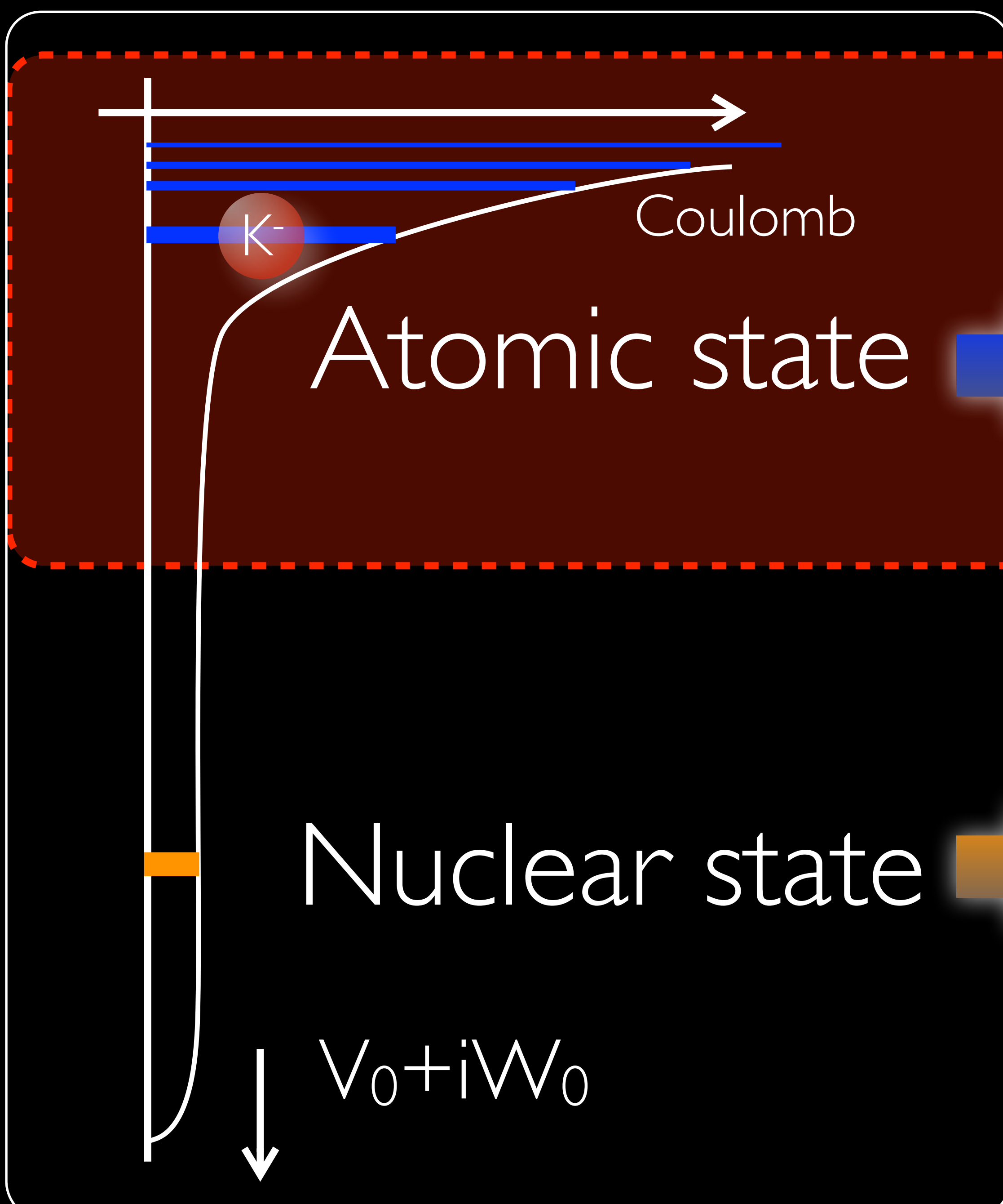
The number of the kaonic nuclear bound states would be different (depending on the nucleus).



"deeply-bound" K^- clusters ?

Experimental approaches

K^- - Nucl. potential



本公募研究(A02)

Precision x-ray measurement

計画研究(A02)

Peak search of deeply bound K^- cluster
- direct observation -

still no conclusive results

-> H. Outa's talk on 25 Sept. (afternoon)

Prediction

Kaonic Helium 2p level shift and width

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

30 years ago!

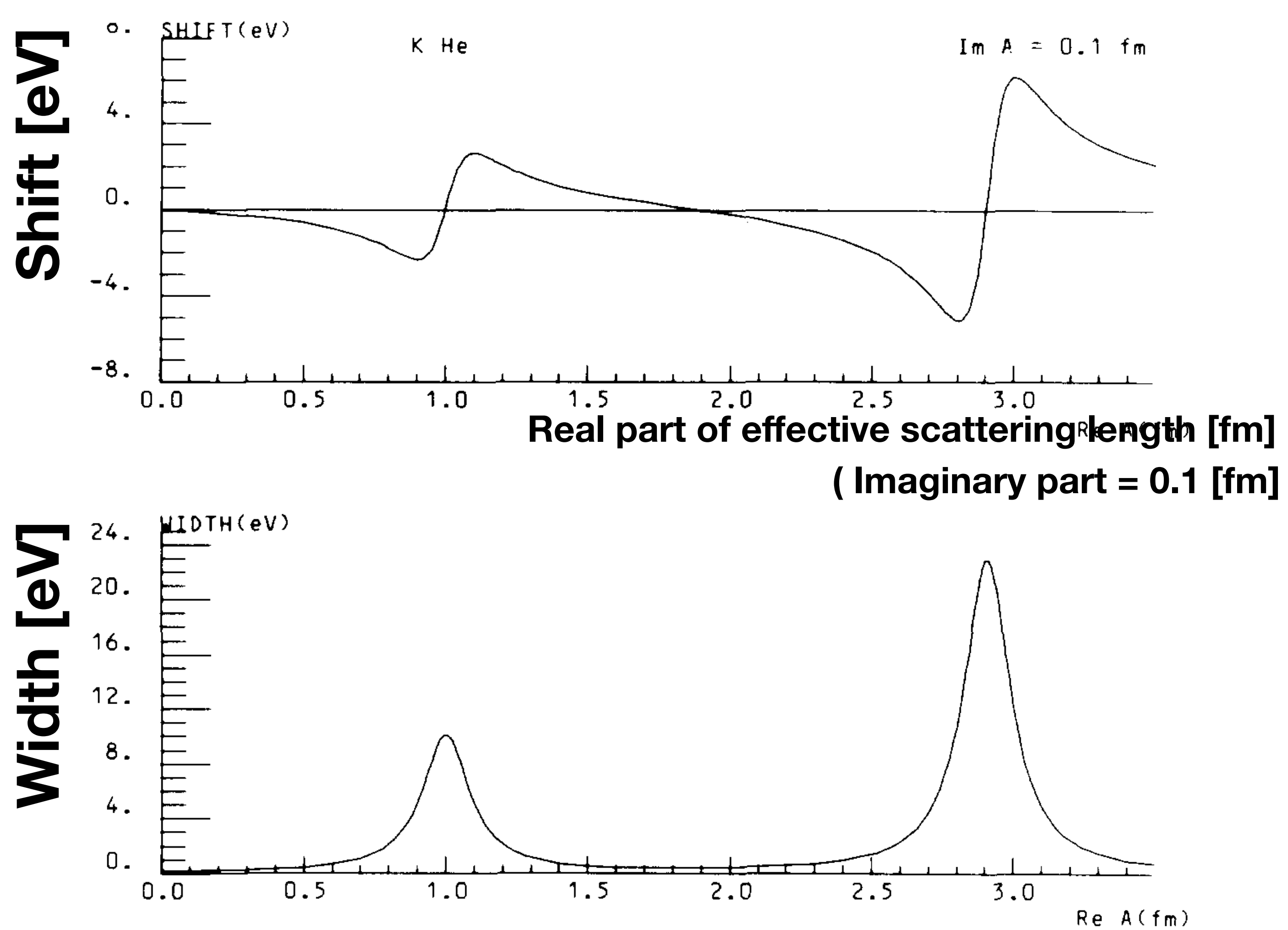


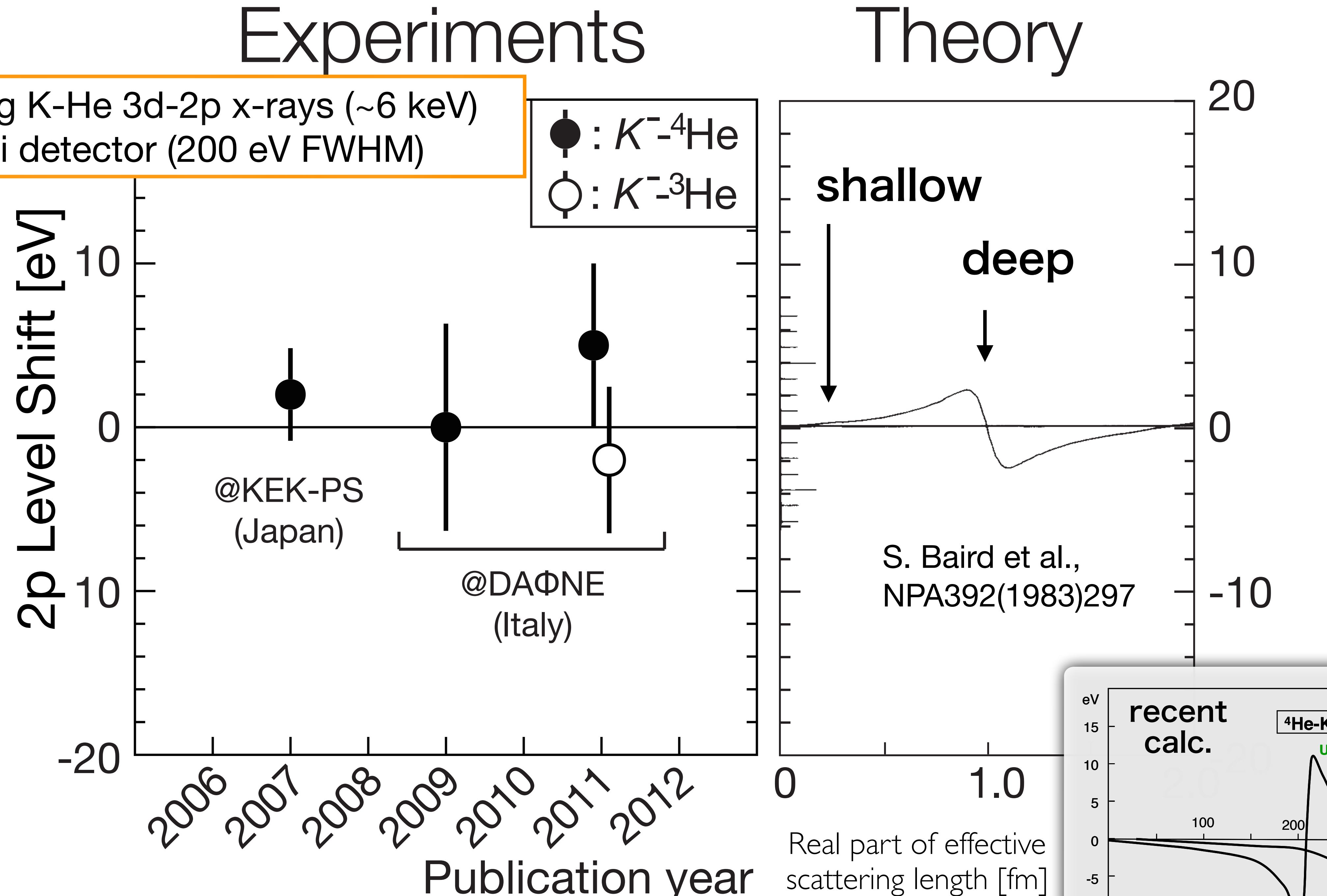
Fig. 5. Calculated strong interaction shift and width for kaonic helium as a function of the value of the real part of $\bar{a}$. The calculations used $a_I = 0.1$ fm.

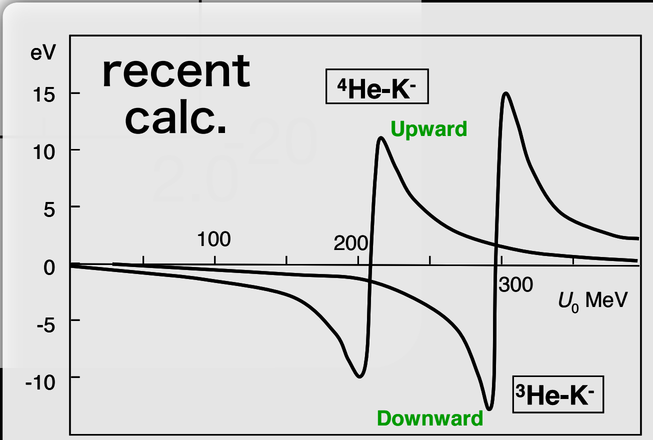
precise measurement of shift & width → potential depth

Insufficient resolution

Kaonic helium 2p level shift

measuring K-He 3d-2p x-rays (~6 keV) with Si detector (200 eV FWHM)

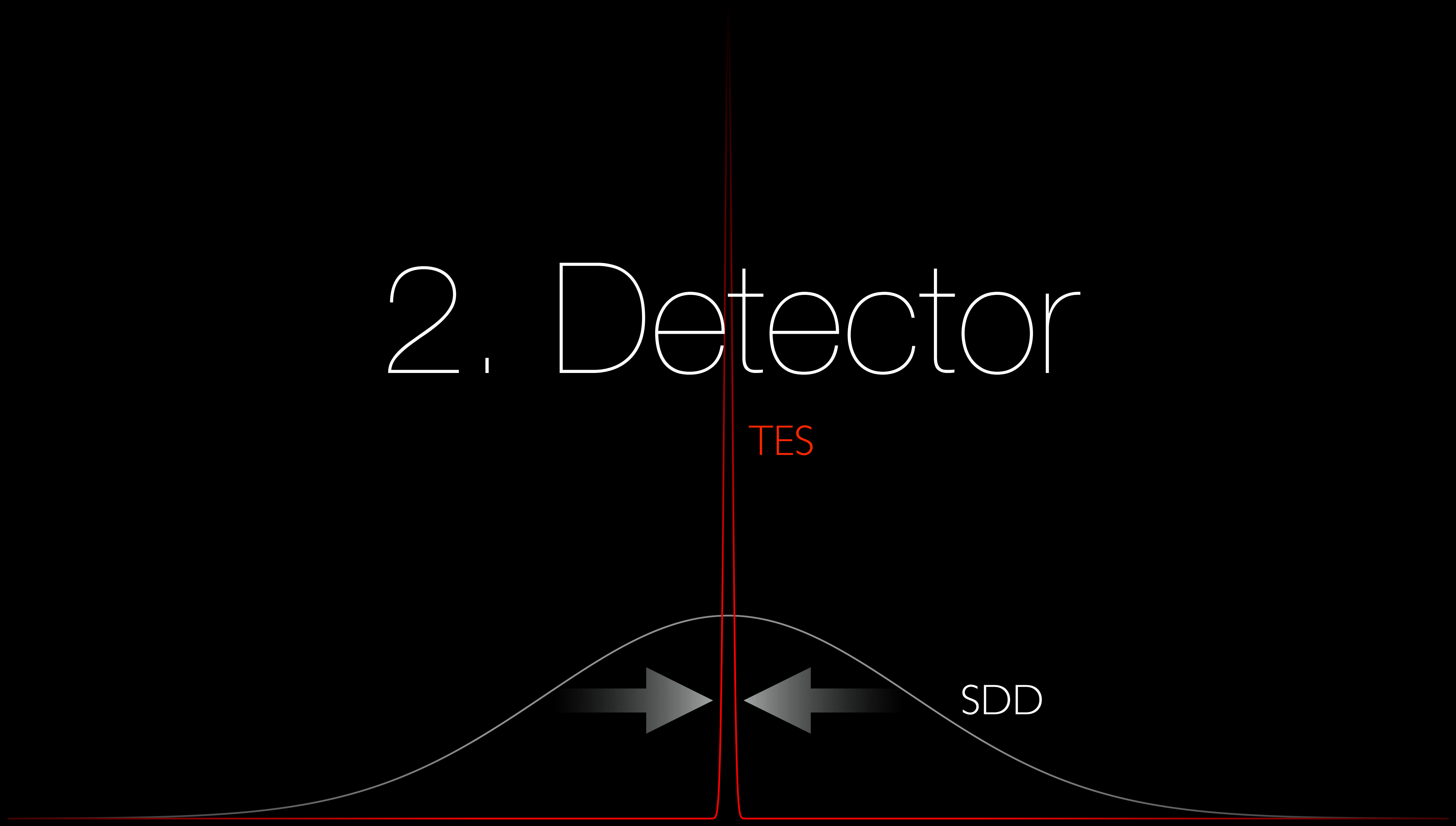




Y. Akaishi, Proceedings for International Conference on Exotic Atoms (EXA05), Austrian Academy of Sciences Press, Vienna, 2005, p. 45.

→ need a breakthrough

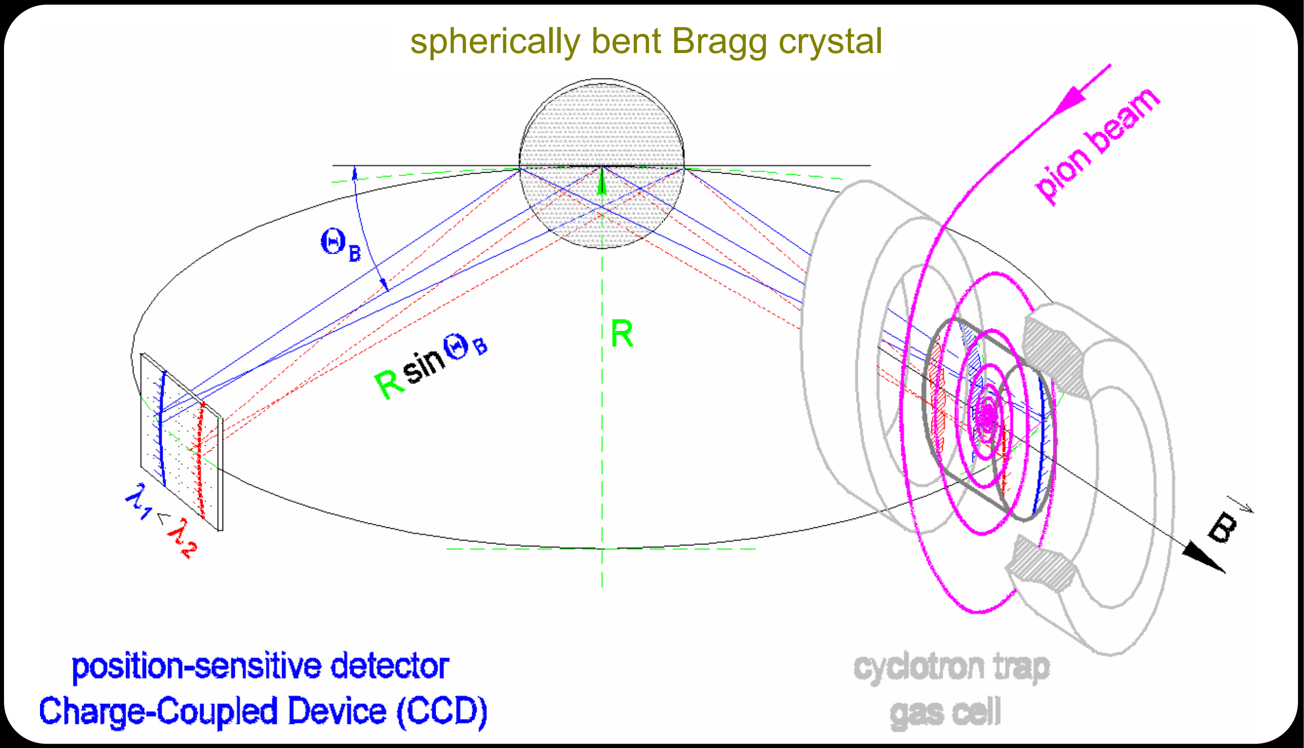
2. Detector



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

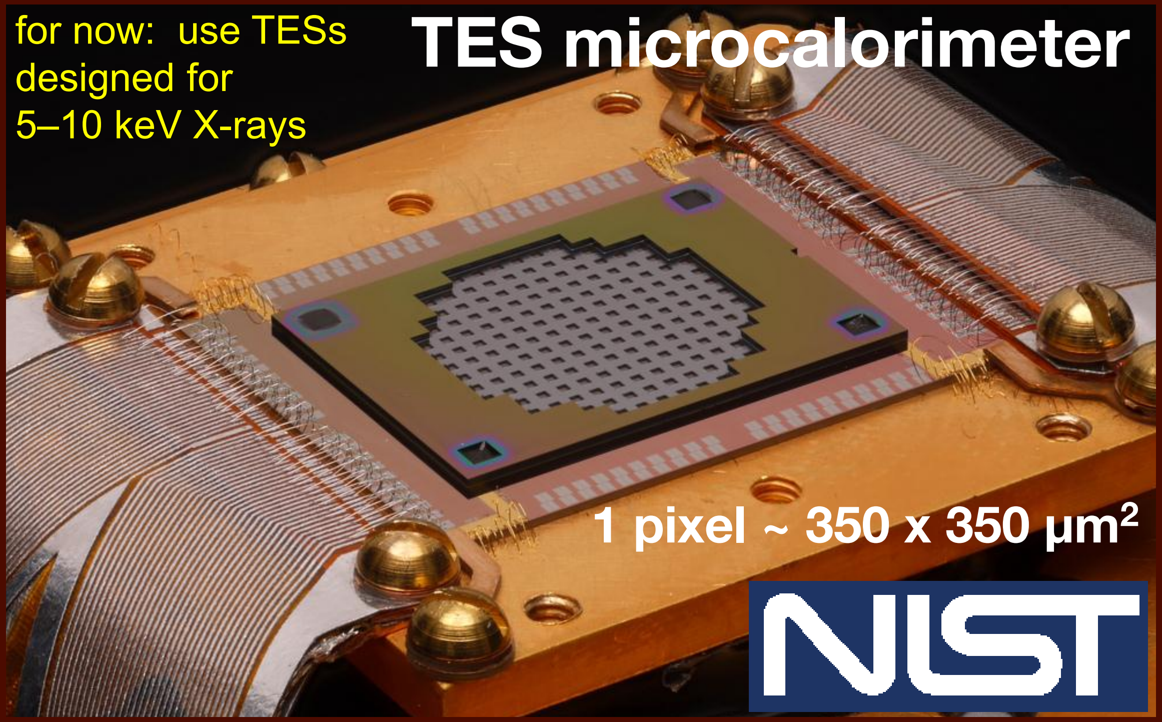
High-resolution detectors

1. Crystal spectrometer



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

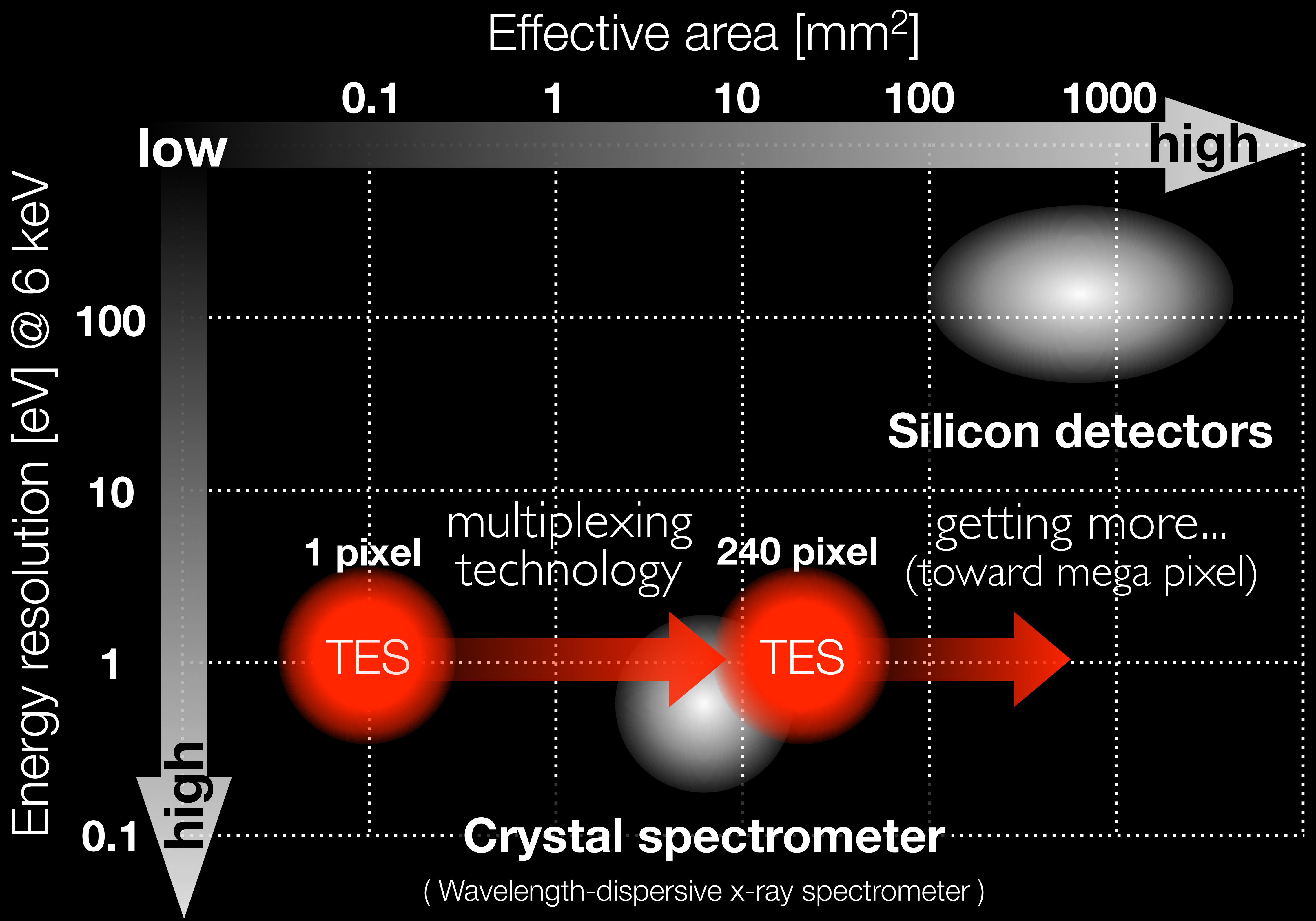
2. Cryogenic detector



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

→ small acceptance

Why TES ? (I)

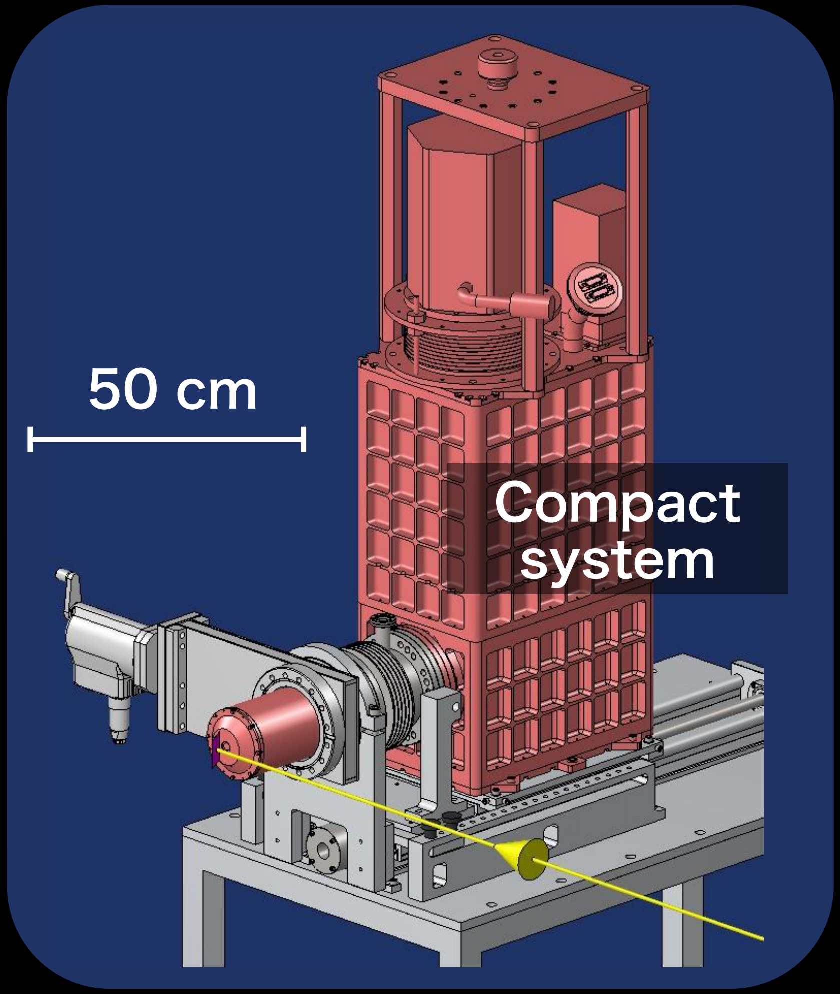


The solid angle of a crystal spectrometer (PLB 416 (1998) 50) was converted to the equivalent effective area.

Why TES ? (2)

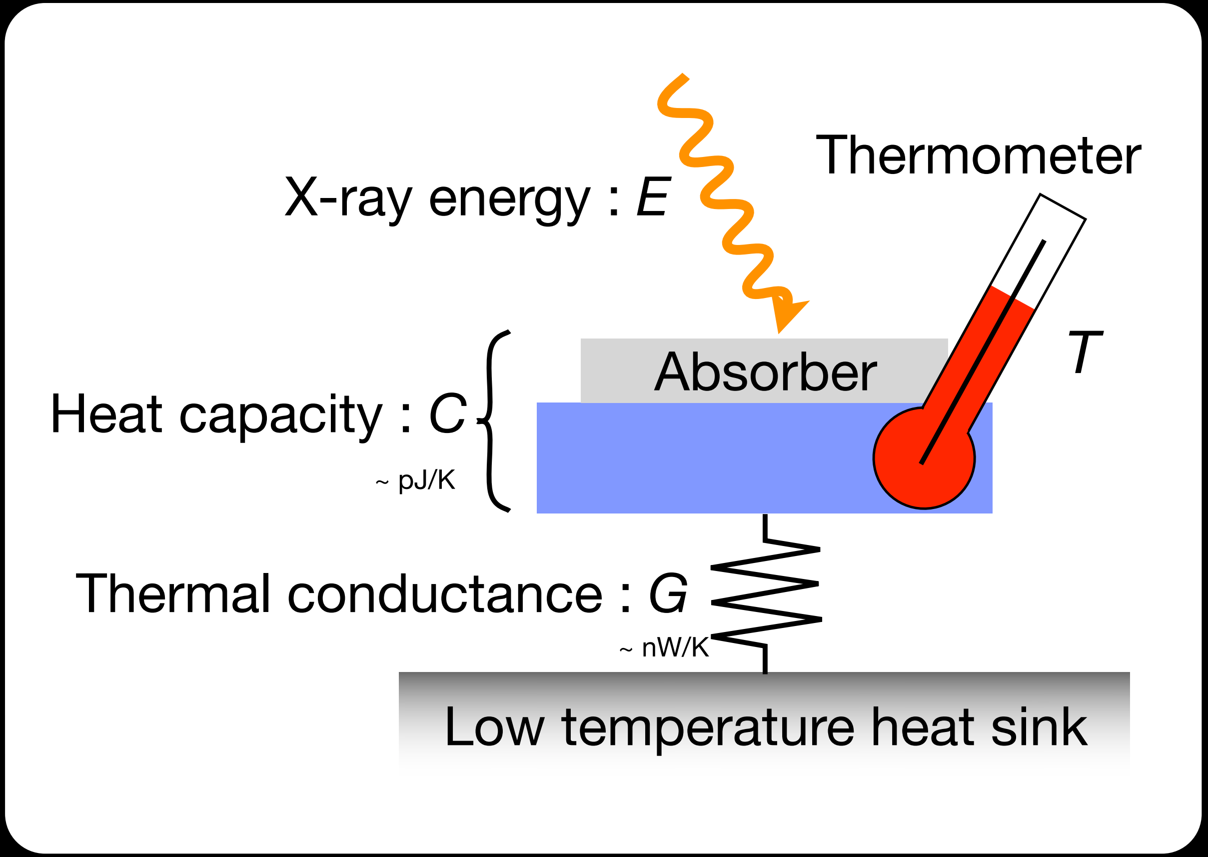
✓ Compact and portable

limited beam time, then need to remove

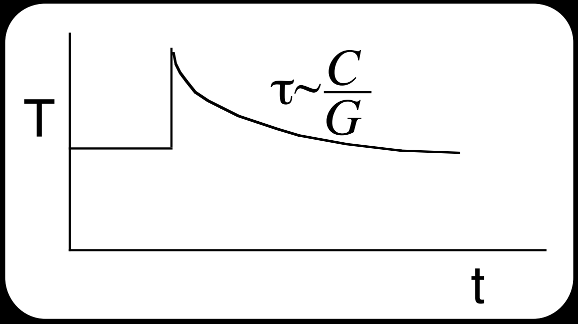


X-ray microcalorimeter

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)

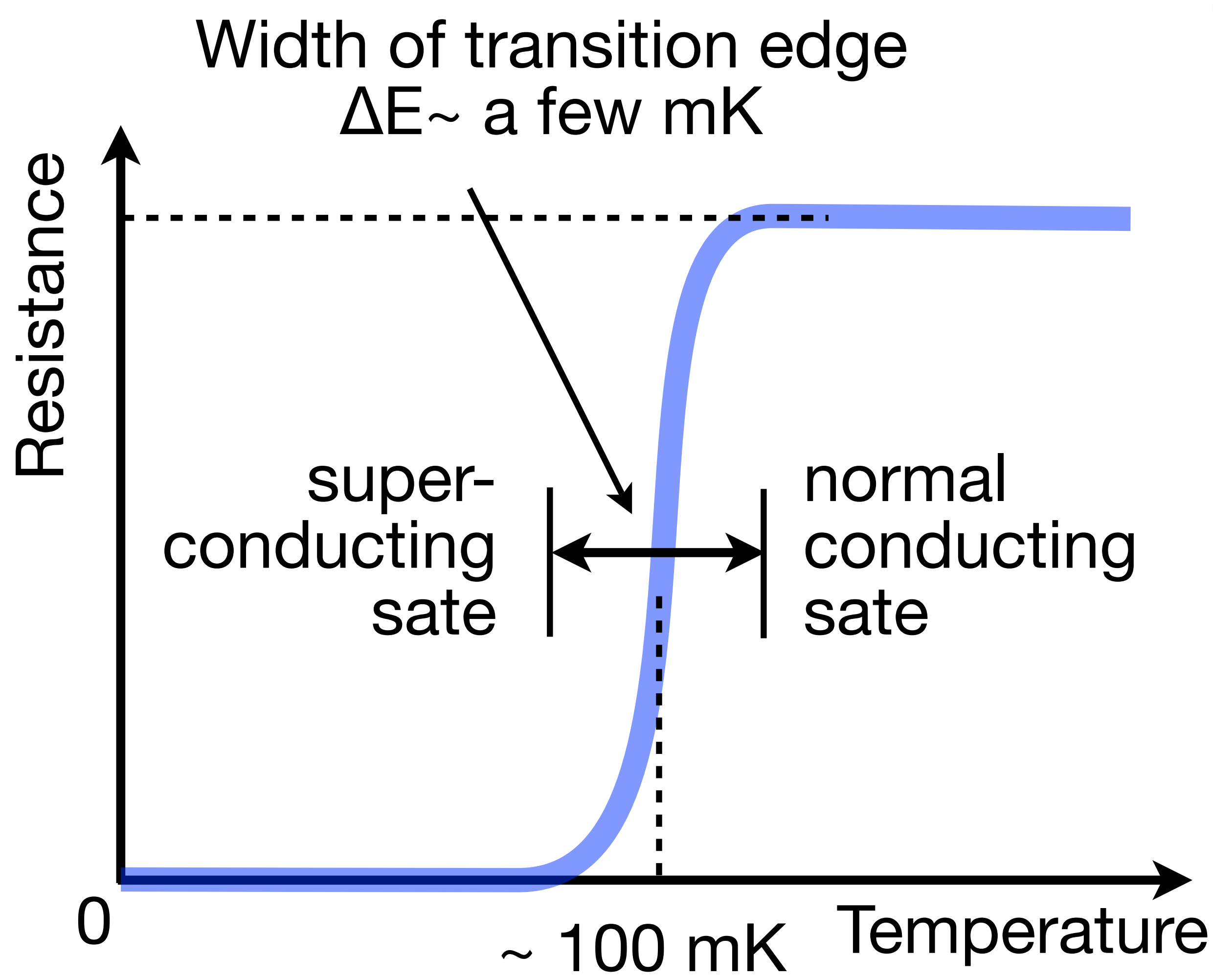


Absorber with larger “Z” (to stop the high energy x-rays)

e.g., Absorber : Bi (320 um × 300 um wide, 4 um thick)
Thermometer : thin bilayer film of Mo (~65nm) and Cu (~175nm)

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

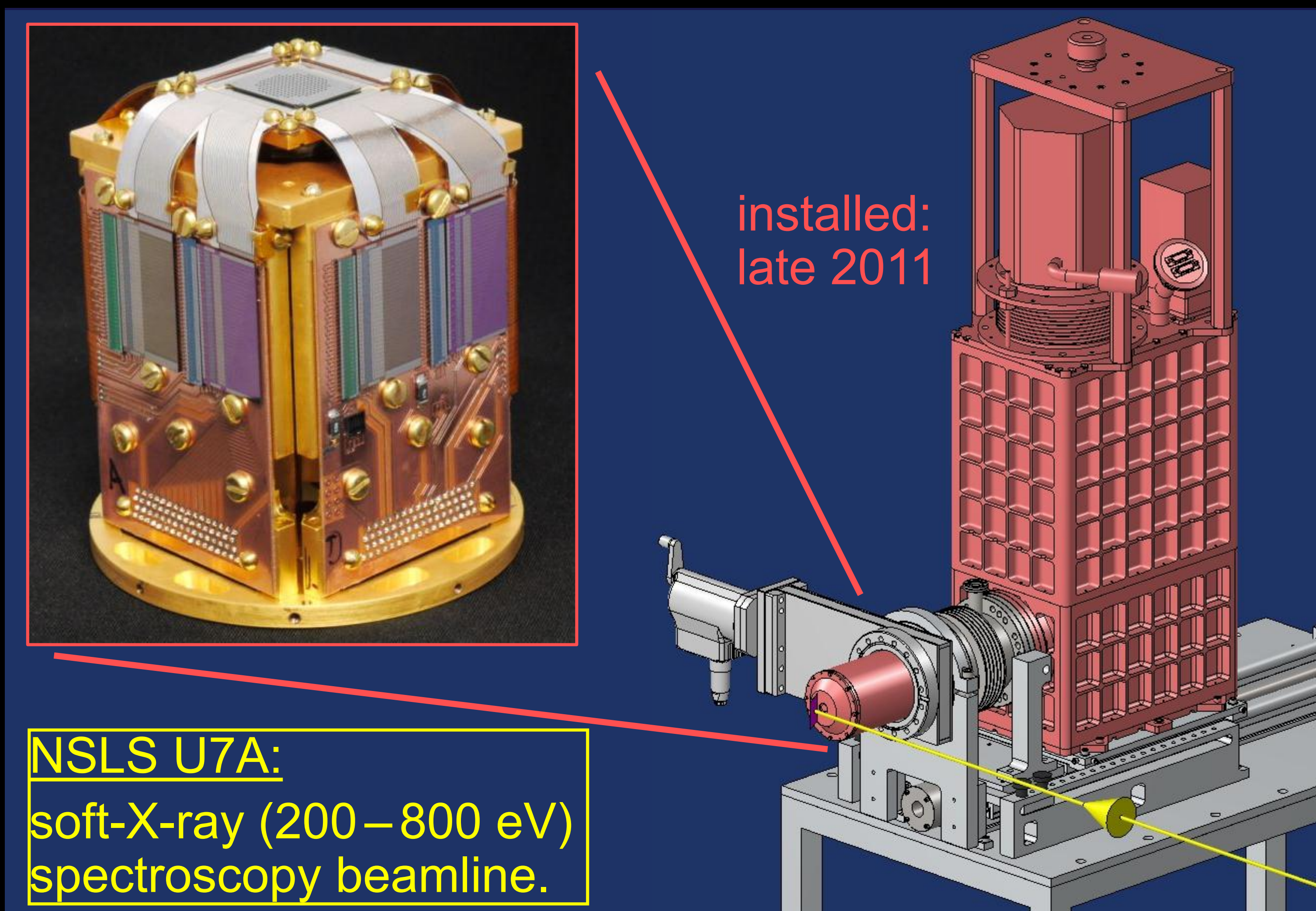
$$E_{max} \sim C T_C / \alpha$$

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!

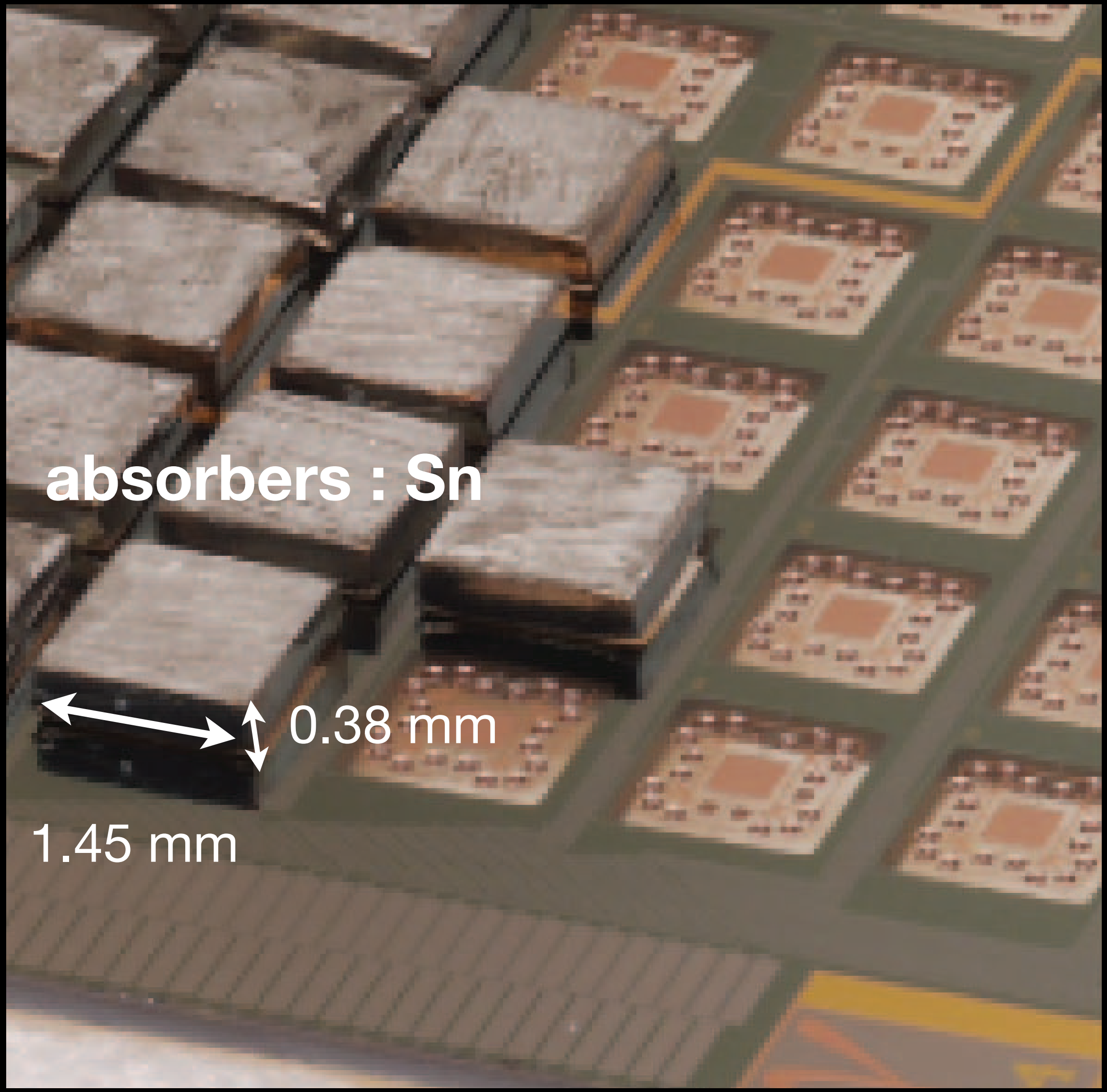
two-order improved resolution

~ 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

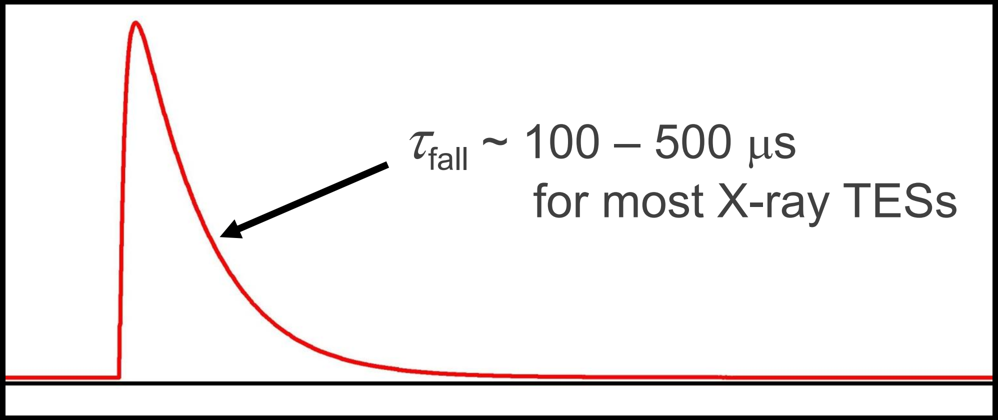
- 1 pixel : 1.45 x 1.45 mm^2
- 256 array : total ~ **5 cm^2**
- **53 eV (FWHM)** @ 97 keV

an order improved resolution

State-of-art high-purity germanium detectors

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

Count rate with TES



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

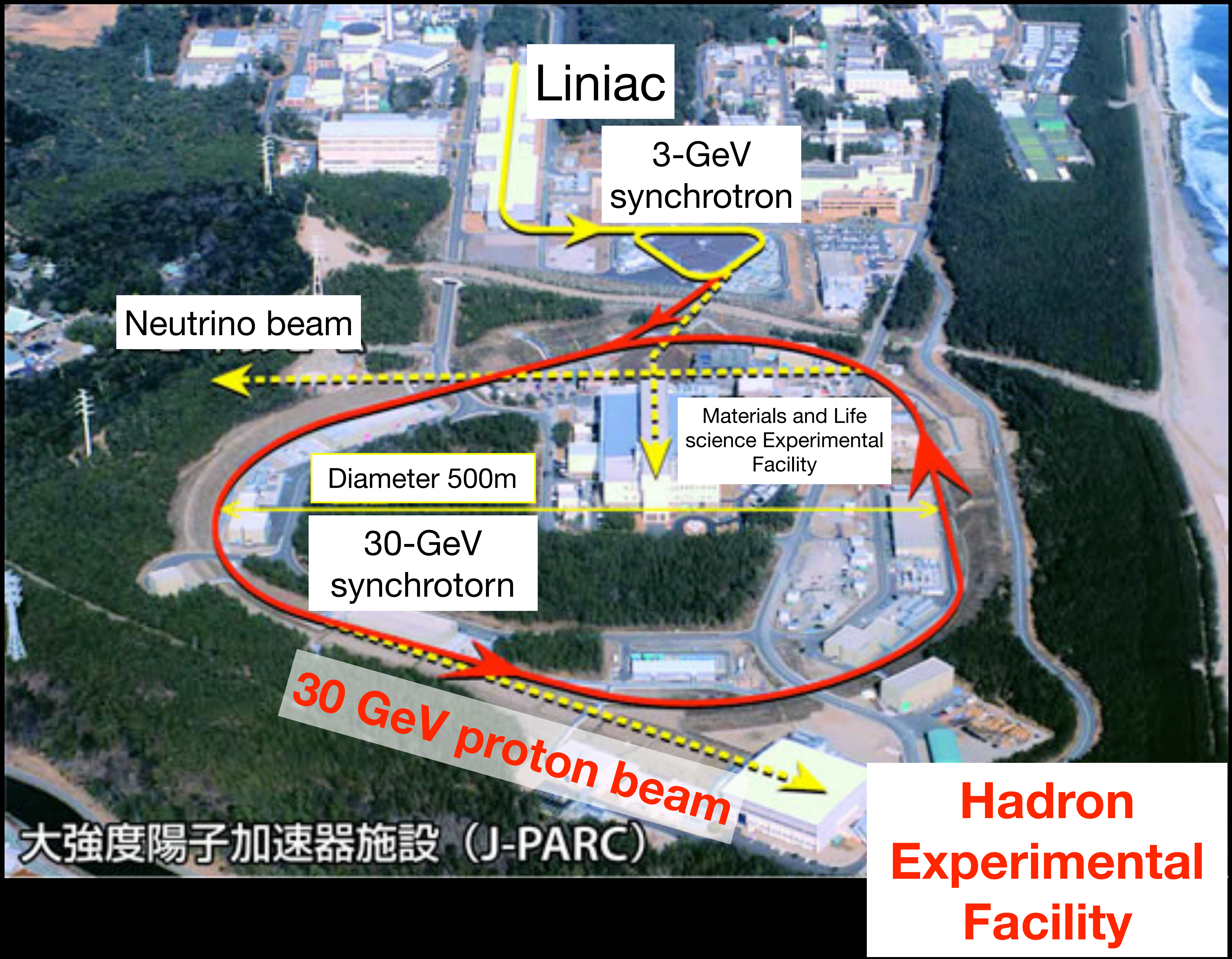
- Prev. exp : single count rate (incl. bg) ~ 1000 Hz for 100 mm^2
- Effective area ~ 0.1 mm^2 / TES -> **~ 1 Hz / TES**

-> acceptable even 10 times higher count rate

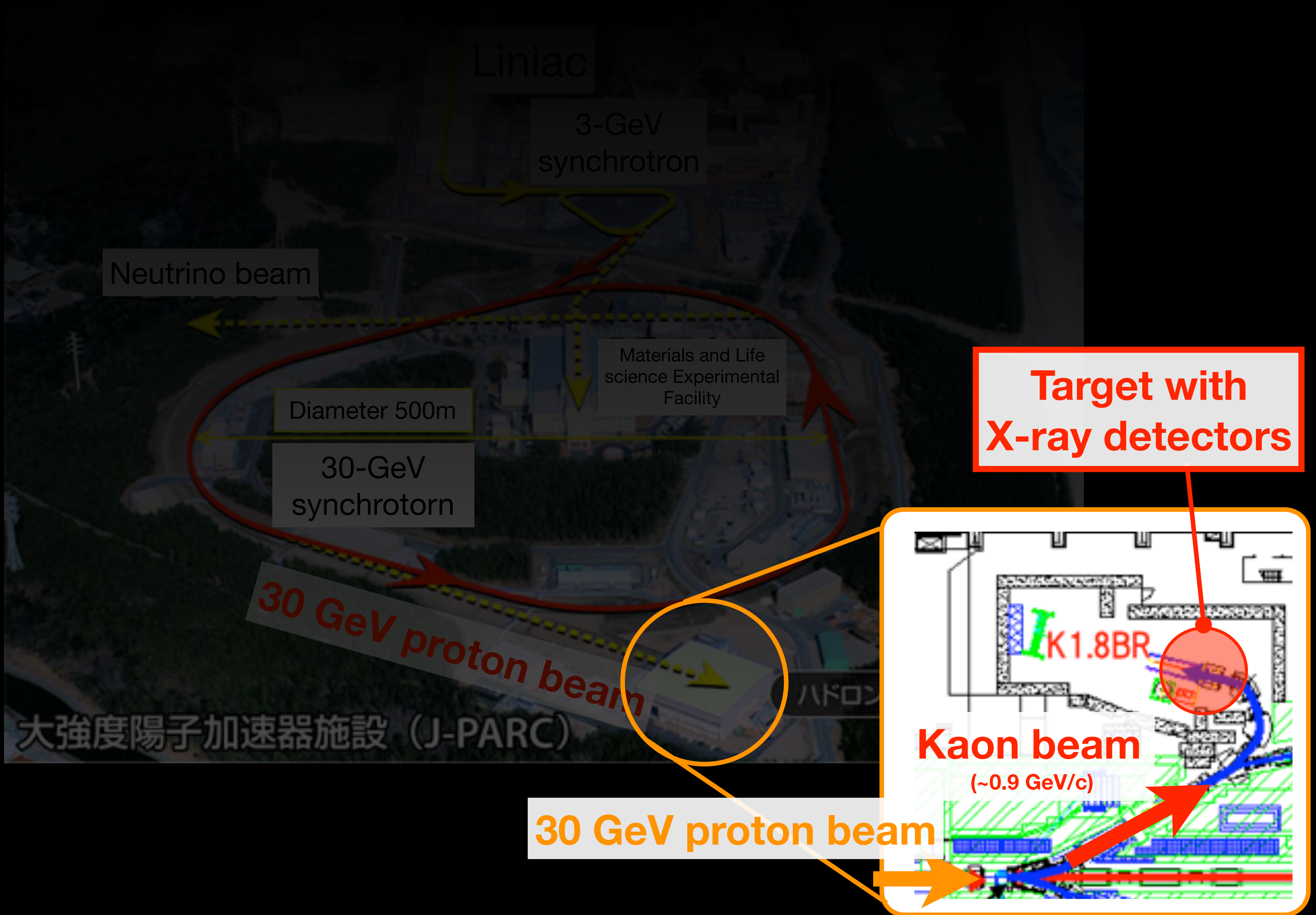
3. Experiment

a proposed K-atom experiment at J-PARC

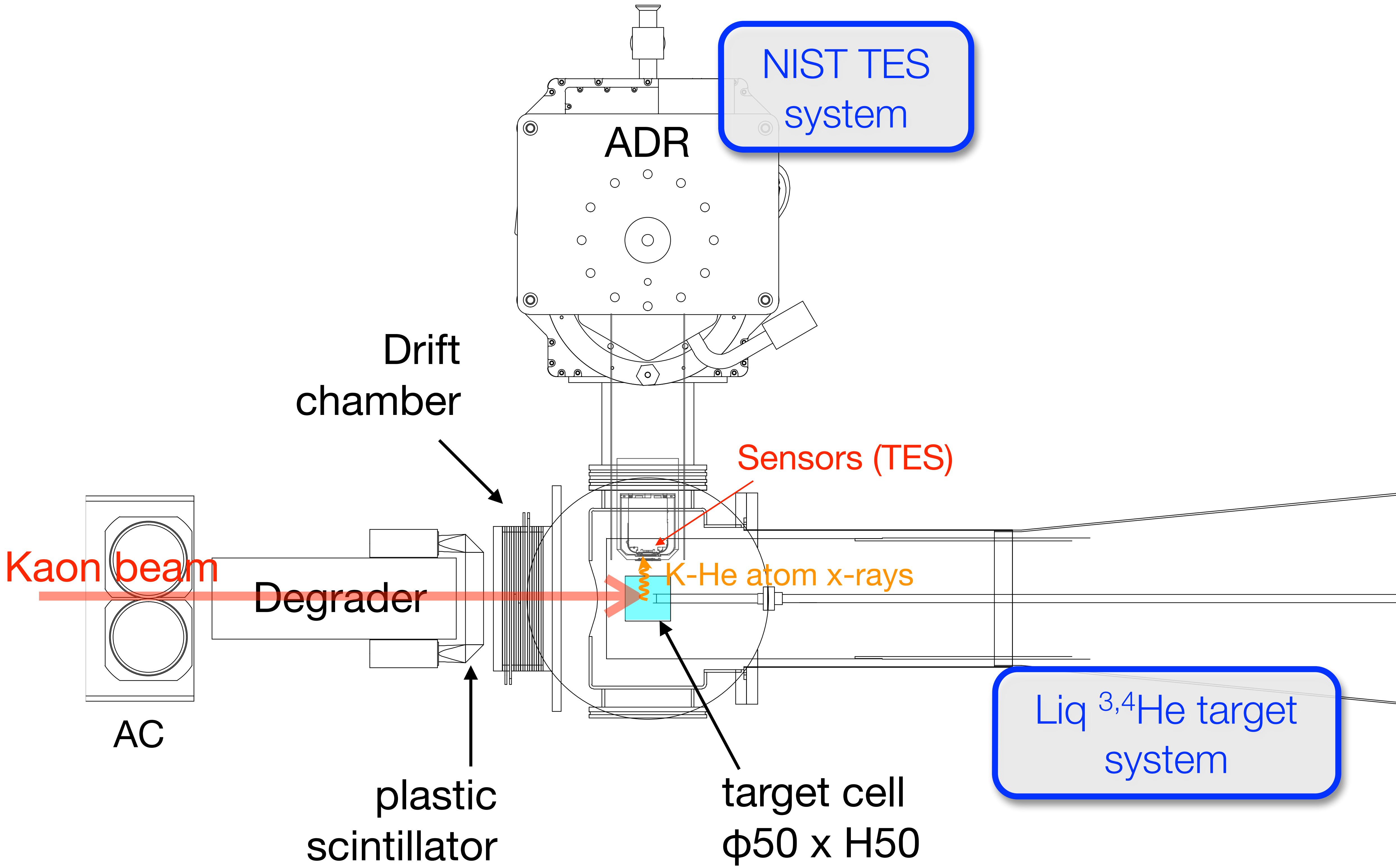
J-PARC : Japan Proton Accelerator Research Complex



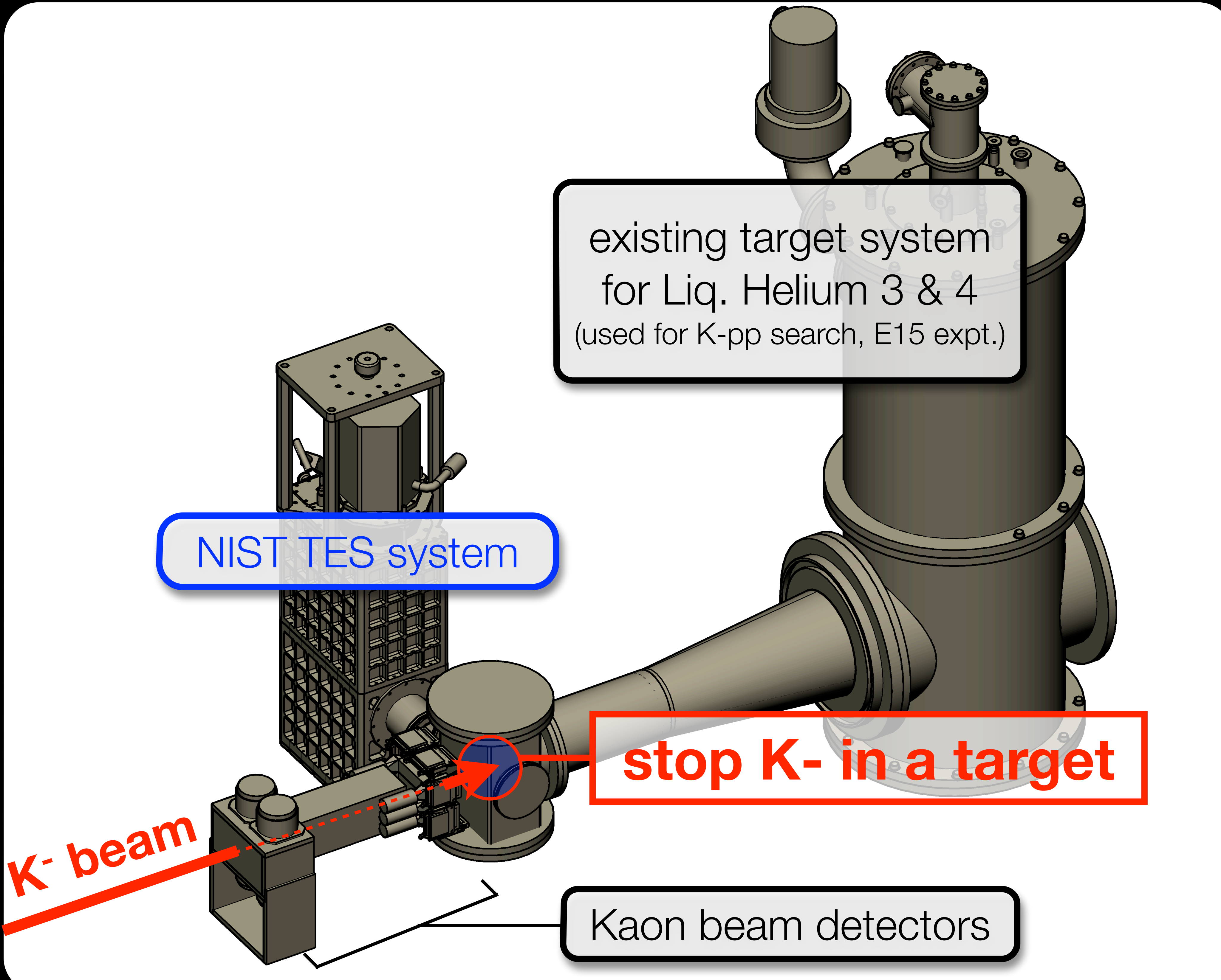
J-PARC hadron beamline



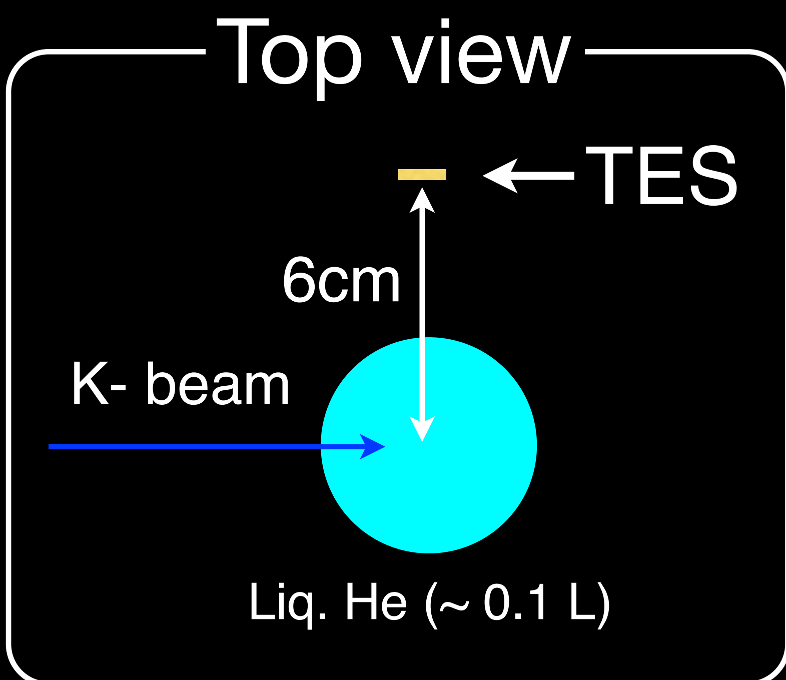
Experimental setup (top view)



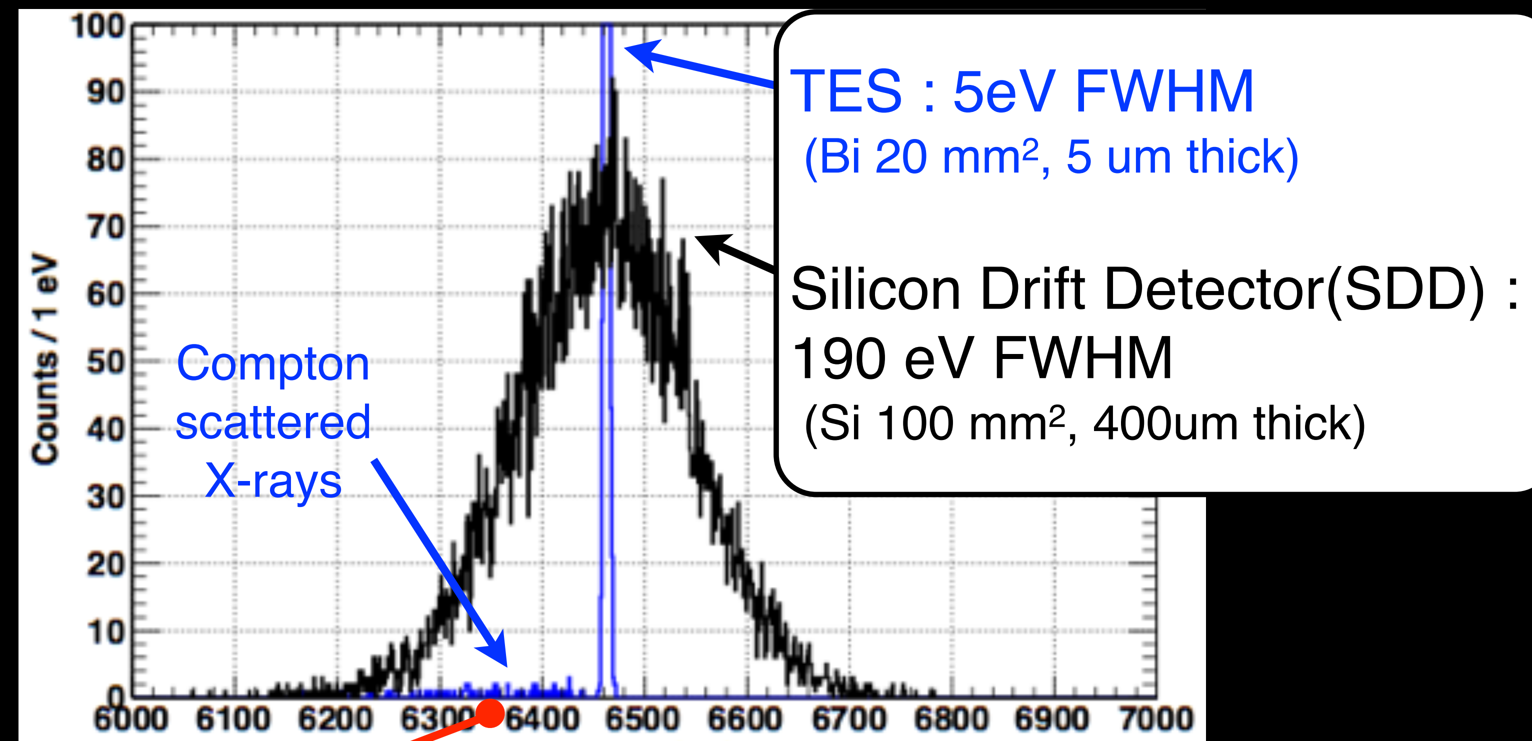
Experimental setup (bird's-eye view)



A simple simulation

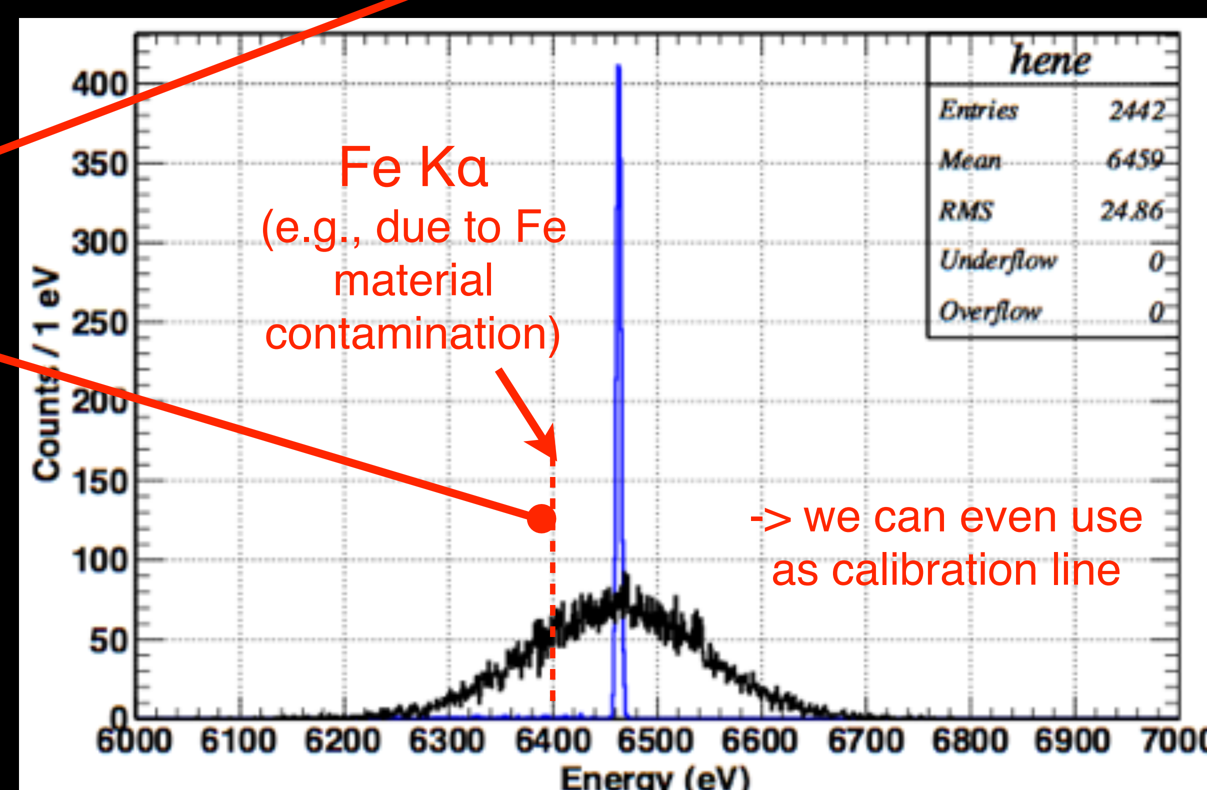


K-^{4}He x-rays from Liq. ^{4}He w/ GEANT4



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

Both have been serious problems in the prev. experiments.

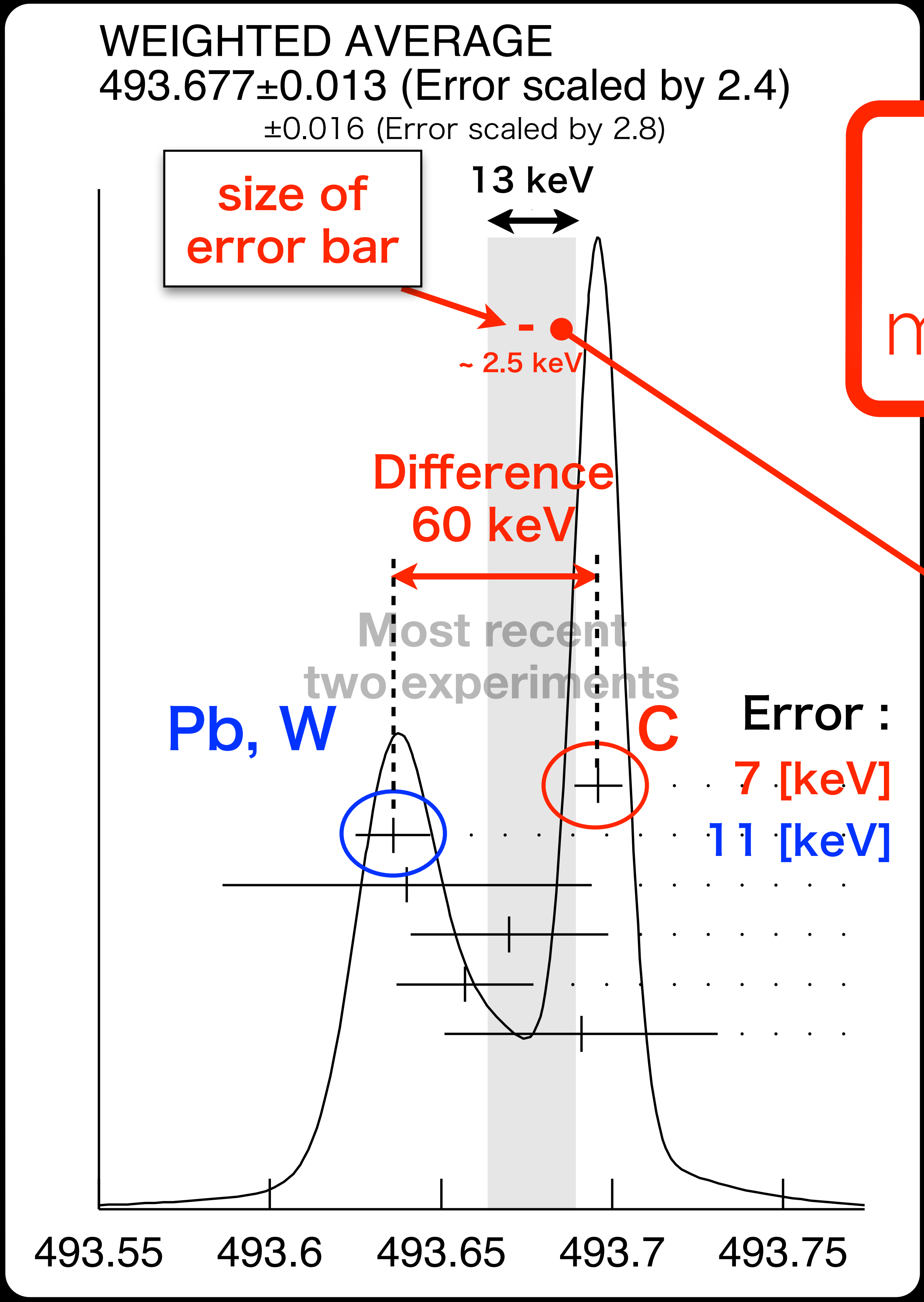


Is 240 pixel (~23 mm^2) enough?

estimated K-^{4}He Lα yield w/ realistic setup
~ 20 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	150 events (~ a-week beam)	2 ~ 3 eV	~ 0.1 eV = 2 ~ 3 / 2.35 / sqrt(150)

Moreover ...



fundamental quantity

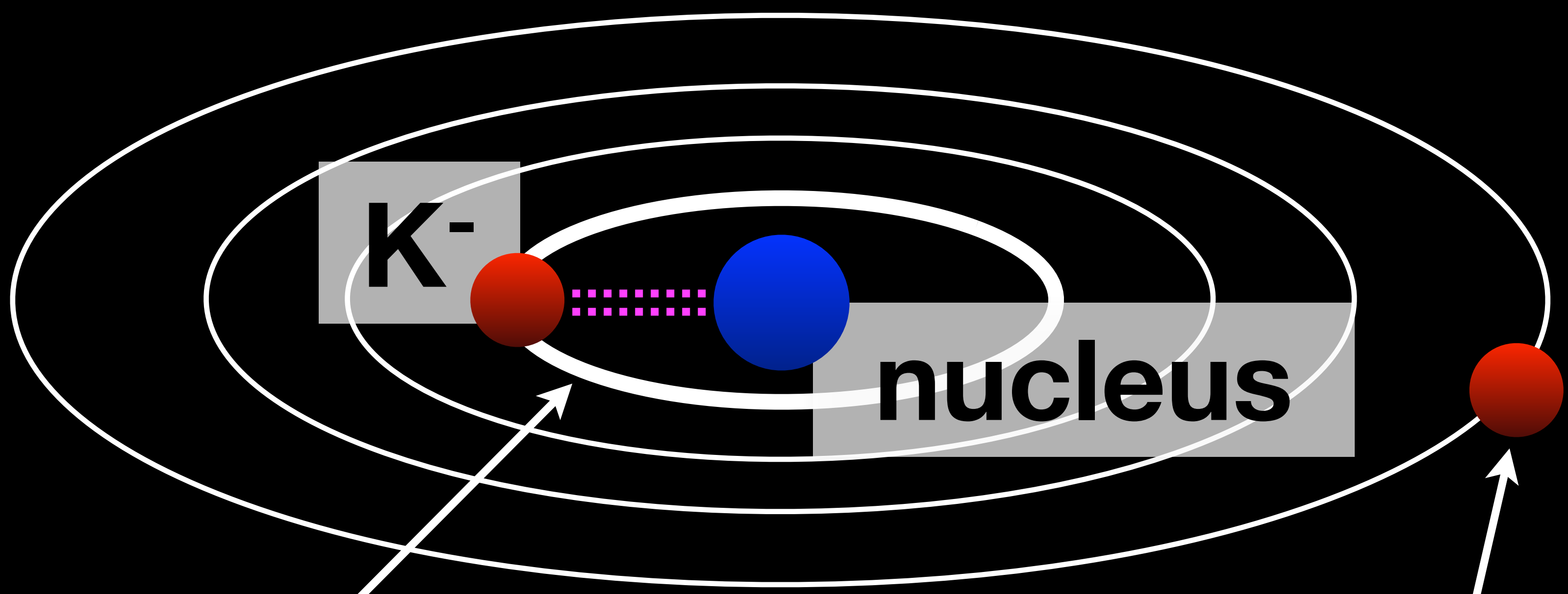
Charged Kaon mass measurement with TES

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%	~ 1 weeks	150
	C	~0.01% self attenuation	~2000?/spill (2sec) duty ~45%	~17%	~ 2 weeks	2500

very preliminary

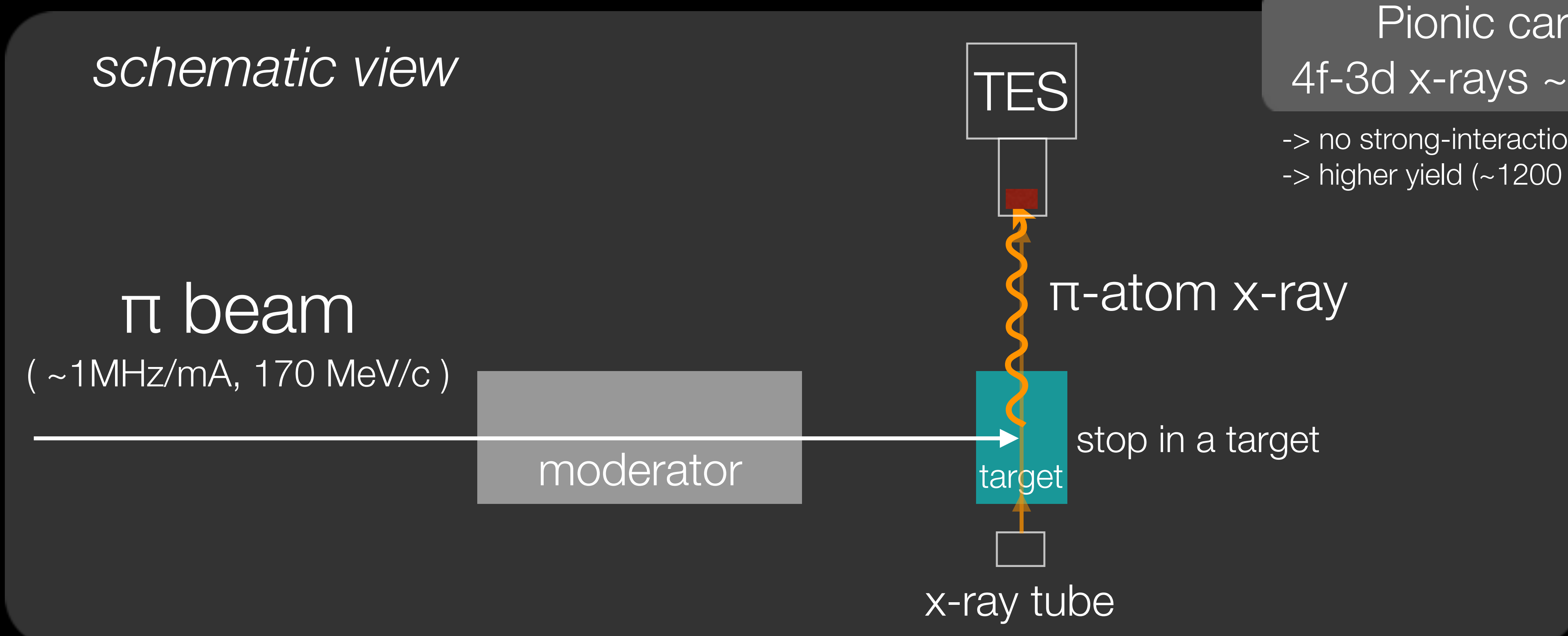
-> reasonable beam time

4. Test experiment

study of in-beam performance of TES at PSI

Feasibility test towards J-PARC expt.

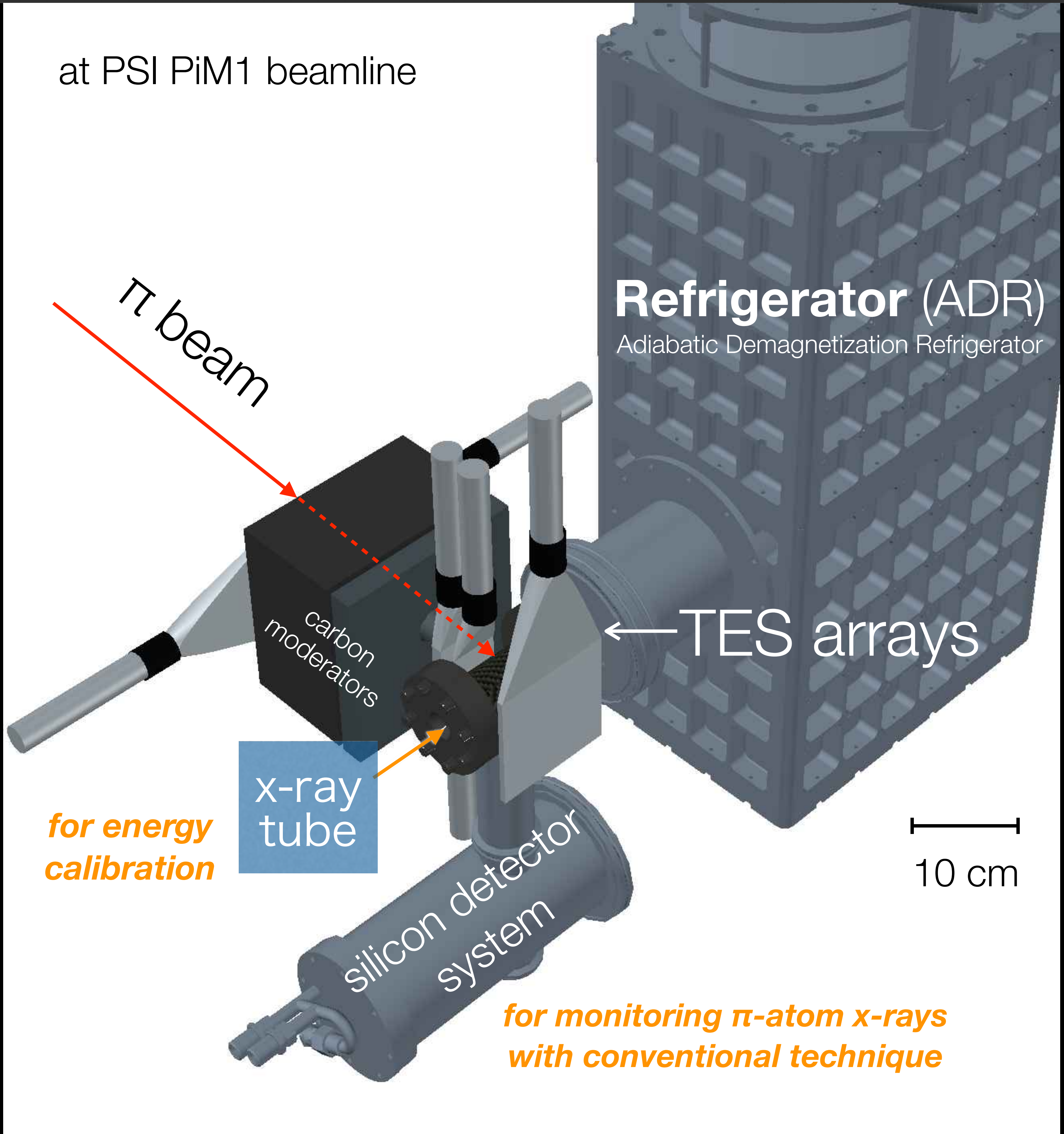
- aim : studying in-beam performance of TES
  ➡ the first measurement of hadronic-atom x-rays with TES
- when? : October 2014
- where? : Paul Scherrer Institute (PSI), PiM1 beamline



Pionic carbon
4f-3d x-rays ~ 6.5 keV

-> no strong-interaction shift & width
-> higher yield (~1200 events / hour)

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
- Pionic atom at PSI - very soon!
  - feasibility test towards K-atom expt. at J-PARC
  - the first hadronic-atom expt. with TES (aiming high-accuracy π-He data)
- Kaonic atom at J-PARC - in future years
  - a potential to resolve a long-standing deep-shallow problem (K-^{3,4}He)
  - providing new accurate charged kaon mass value
- Further …
  - further study of K-atom (K-^{6}Li, K-^{7}Li, … 'lower' and 'upper' levels in the same K-atom (E.Friedman))
  - other hadronic atom (Σ-, Ξ-) x-ray spectroscopies
  - application for nuclear gamma-ray spectroscopy