1 Nov, 2013

Hadron in Nucleus @ YITP

High-resolution hadronic-atom x-ray spectroscopy with transition-edge-sensor microcalorimeters

RIKEN Shinji Okada

Contents

1. Short introduction
 - Recent progress of light K-atom exp. -

2. NIST’s multi-pixel TES array

3. What do we measure ?

4. Experimental setup

5. Yield estimations

6. The first test exp. at NIST

7. Anti-coincidence system

8. Summary

1. Short introduction

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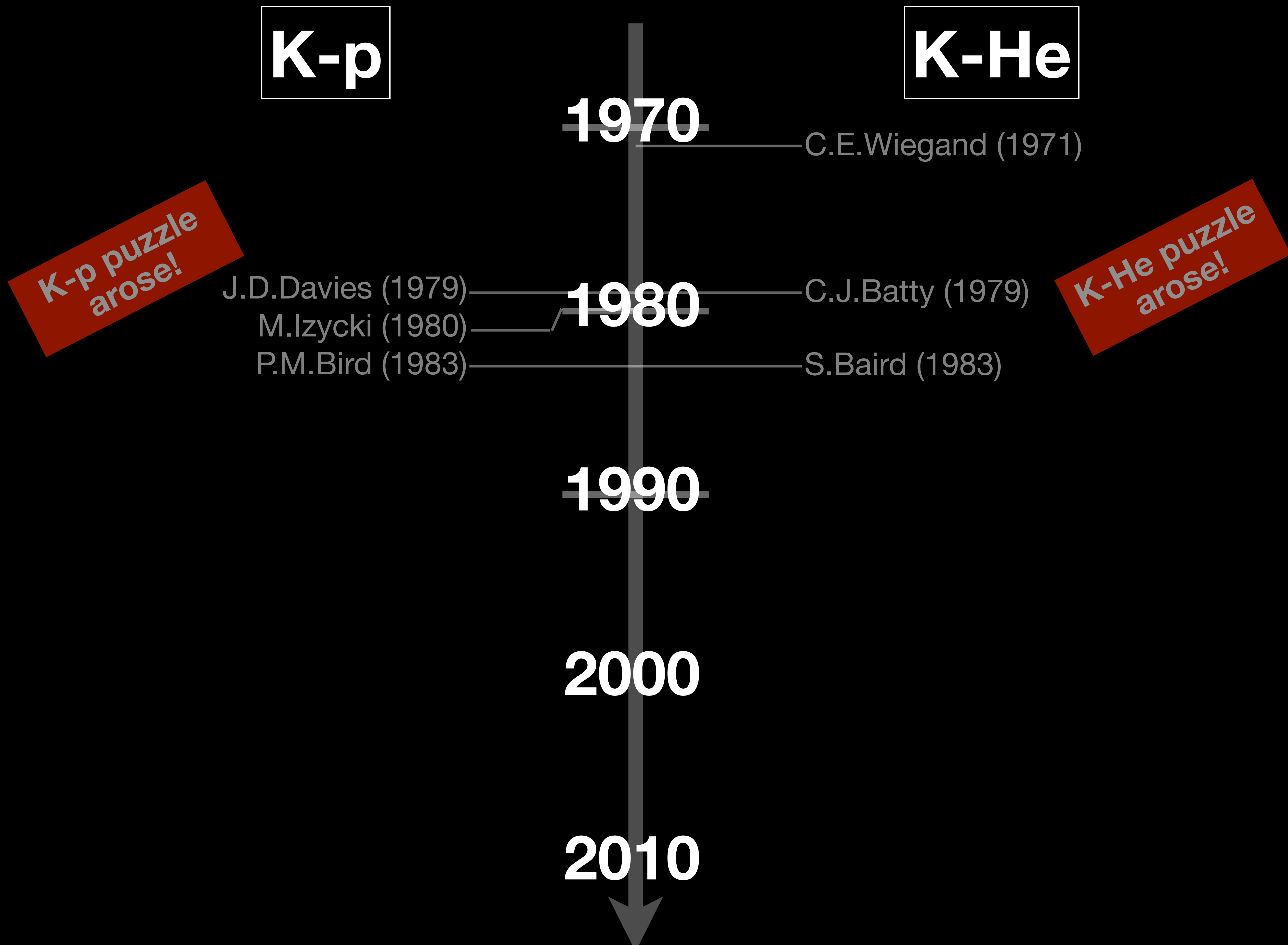
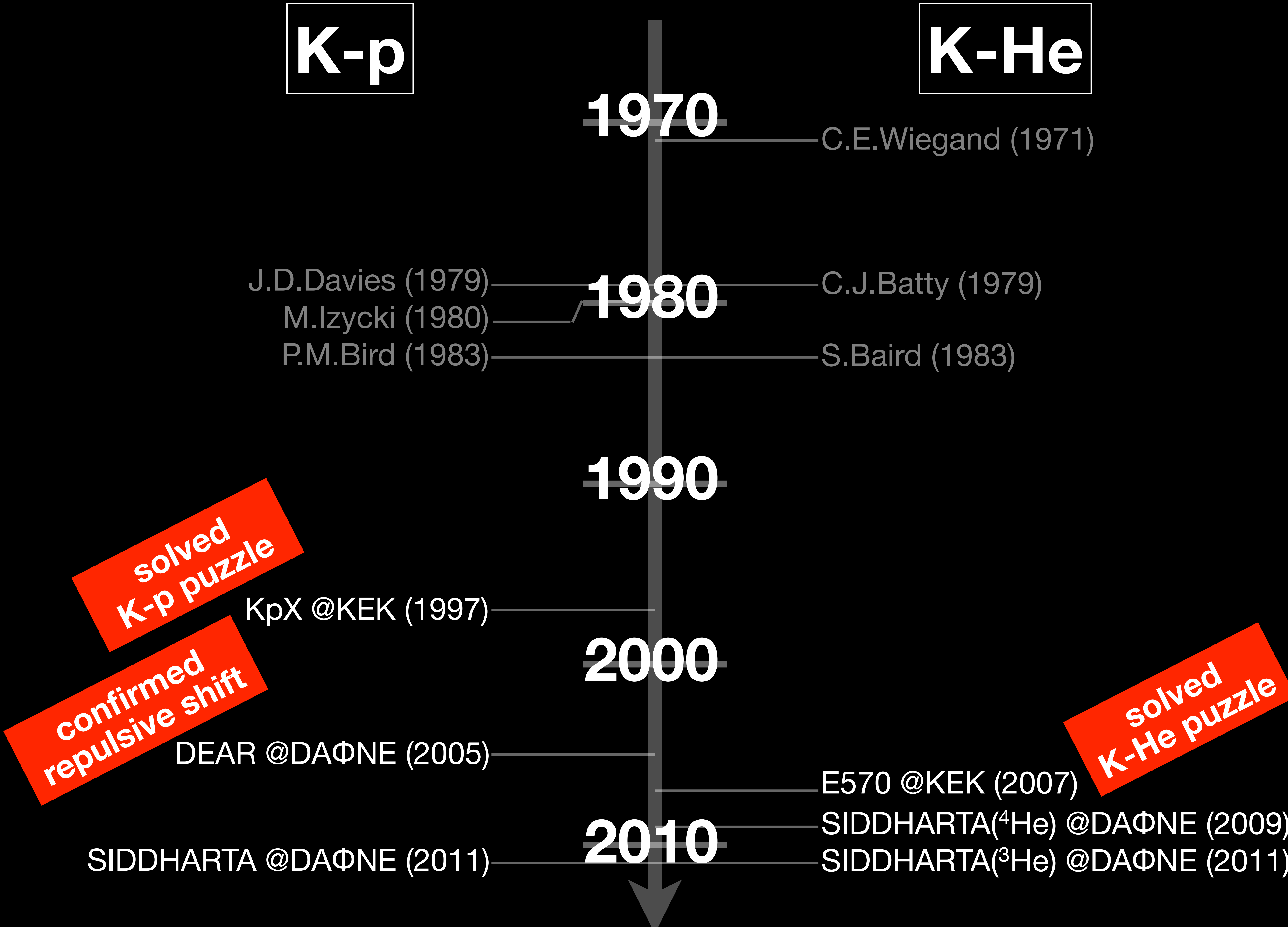
Recent progress of light K-atom exp.


K-p
K-He
1970
C.E.Wiegand (1971)
K-p puzzle arose!
K-He puzzle arose!
J.D.Davies (1979)
1980
C.J.Batty (1979)
M.Izycki (1980)
P.M.Bird (1983)
S.Baird (1983)
1990
2000
2010


K-p
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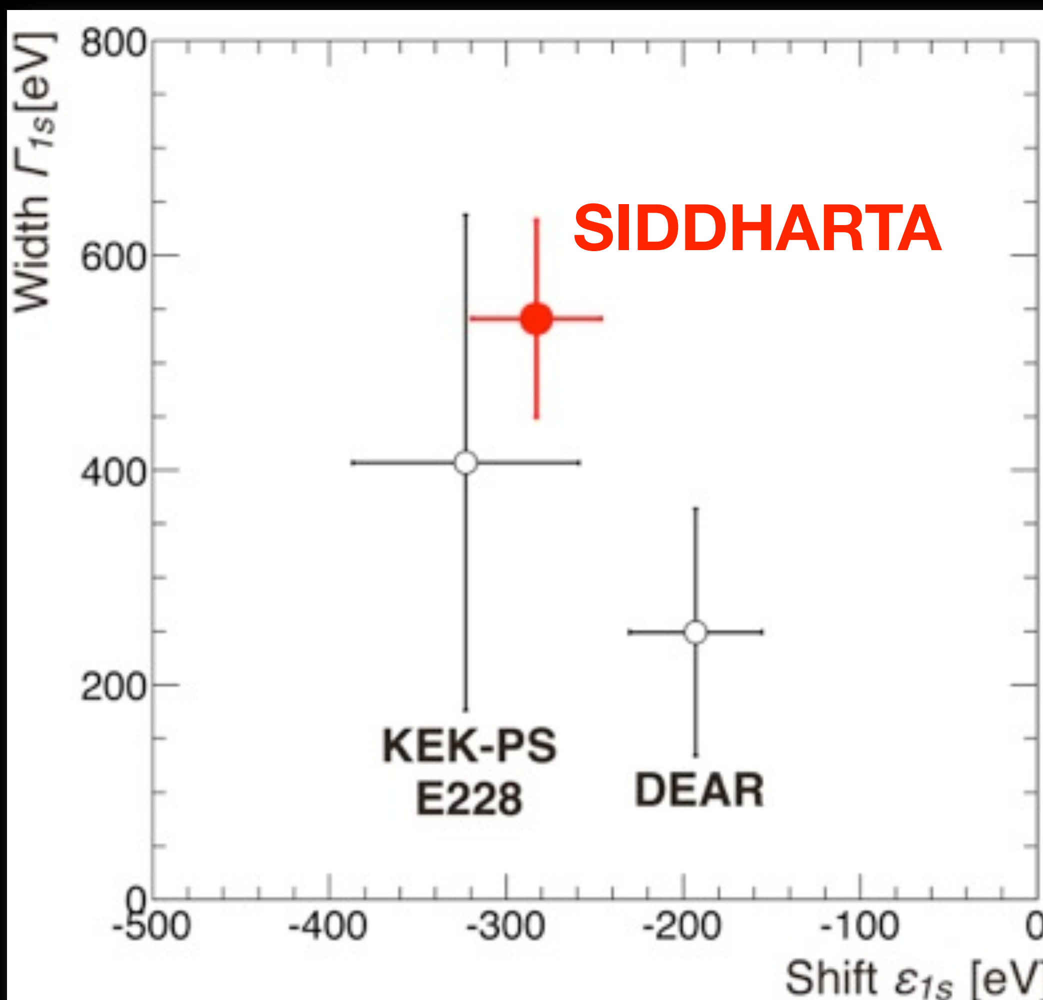
P.M.Bird (1983)
S.Baird (1983)
1990
solved K-p puzzle
KpX @KEK (1997)
2000
confirmed repulsive shift
DEAR @DAΦNE (2005)
solved K-He puzzle
E570 @KEK (2007)
SIDDHARTA(4He) @DAΦNE (2009)
2010
SIDDHARTA @DAΦNE (2011)
SIDDHARTA(3He) @DAΦNE (2011)

K-p		K-He
	1970	C.E.Wiegand (1971)
	1980	C.J.Batty (1979)
		S.Baird (1983)
	1990	
	2000	
DEAR @DAΦNE (2005)		
		E570 @KEK (2007)
		SIDDHARTA(^{4}He) @DAΦNE (2009)
SIDDHARTA @DAΦNE (2011)	2010	SIDDHARTA(^{3}He) @DAΦNE (2011)



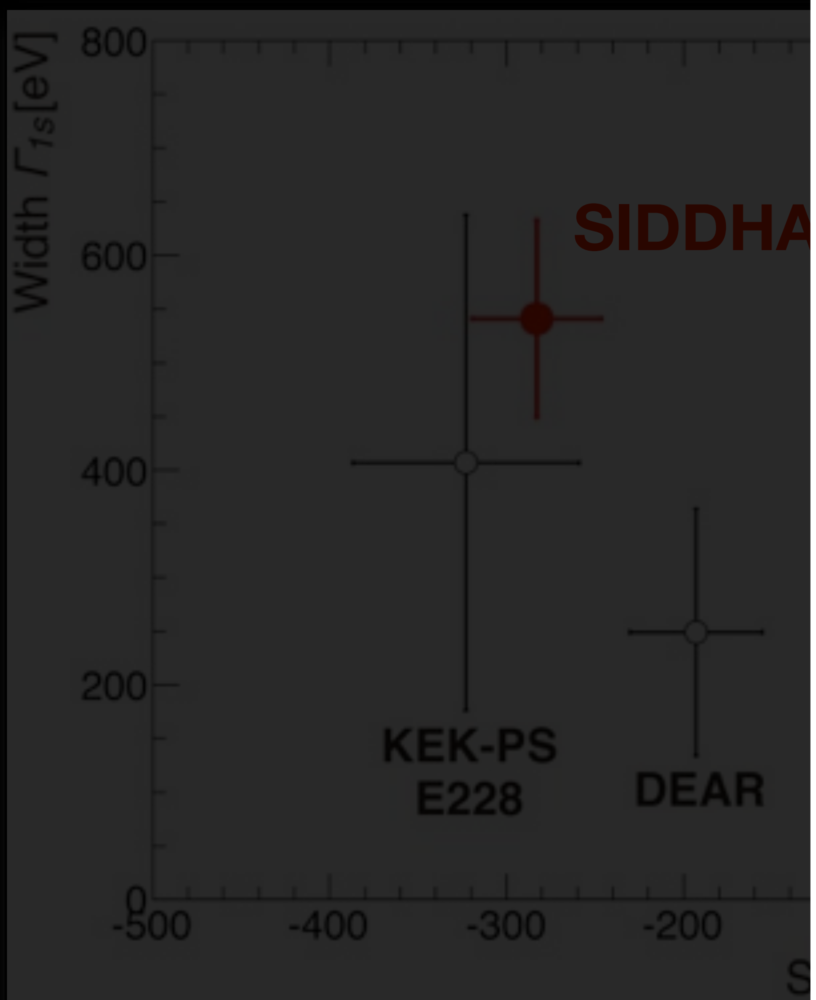
K-p

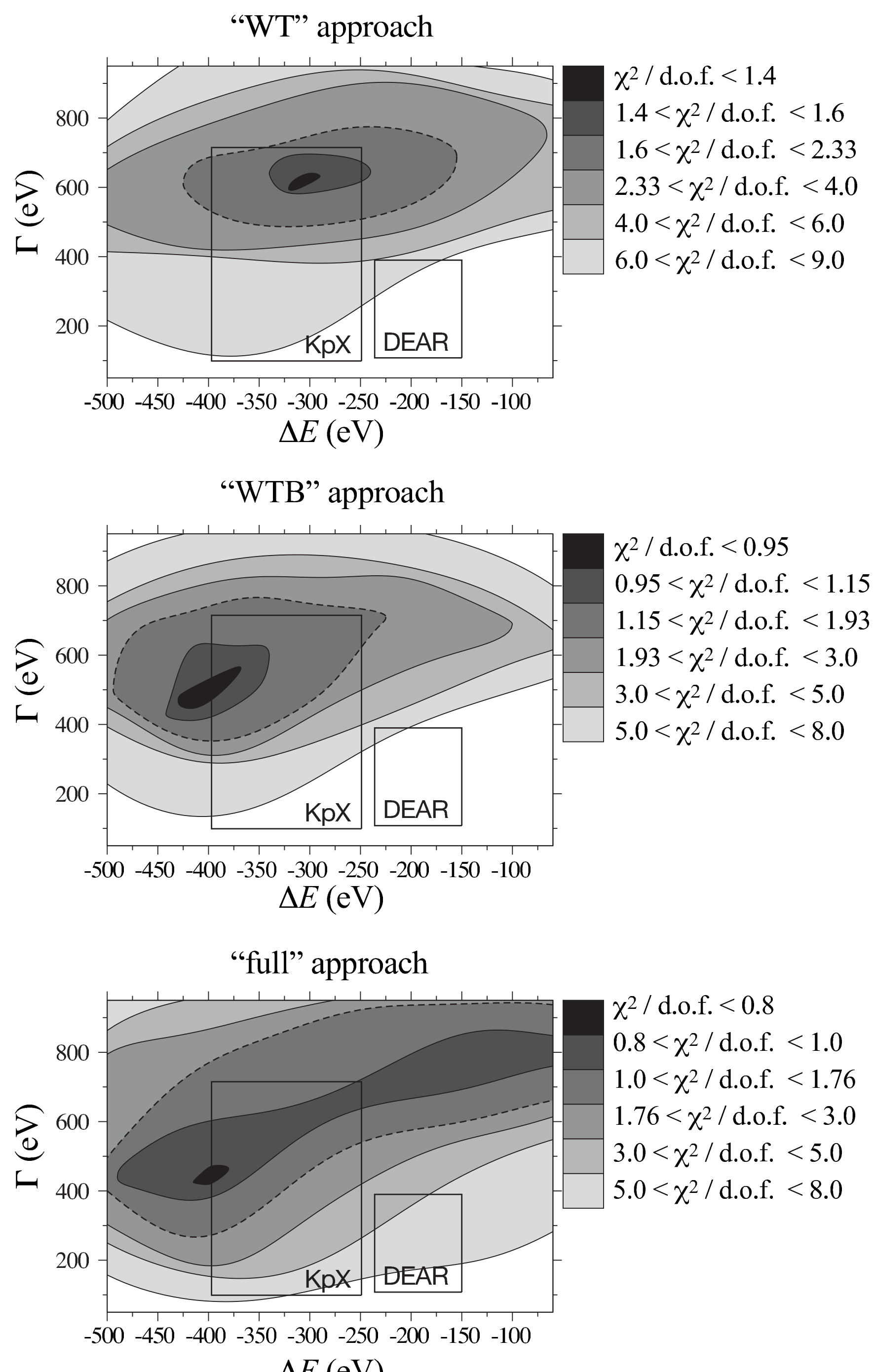
K-He

B. Borasoy et.al.,
PRC74, 055201 (2006)

Chiral SU(3) unitary approaches

solely from K-p scattering data !!





.Wiegand (1971)

.Batty (1979)

Baird (1983)

DEAR @DAΦNE (2

70 @KEK (2007)

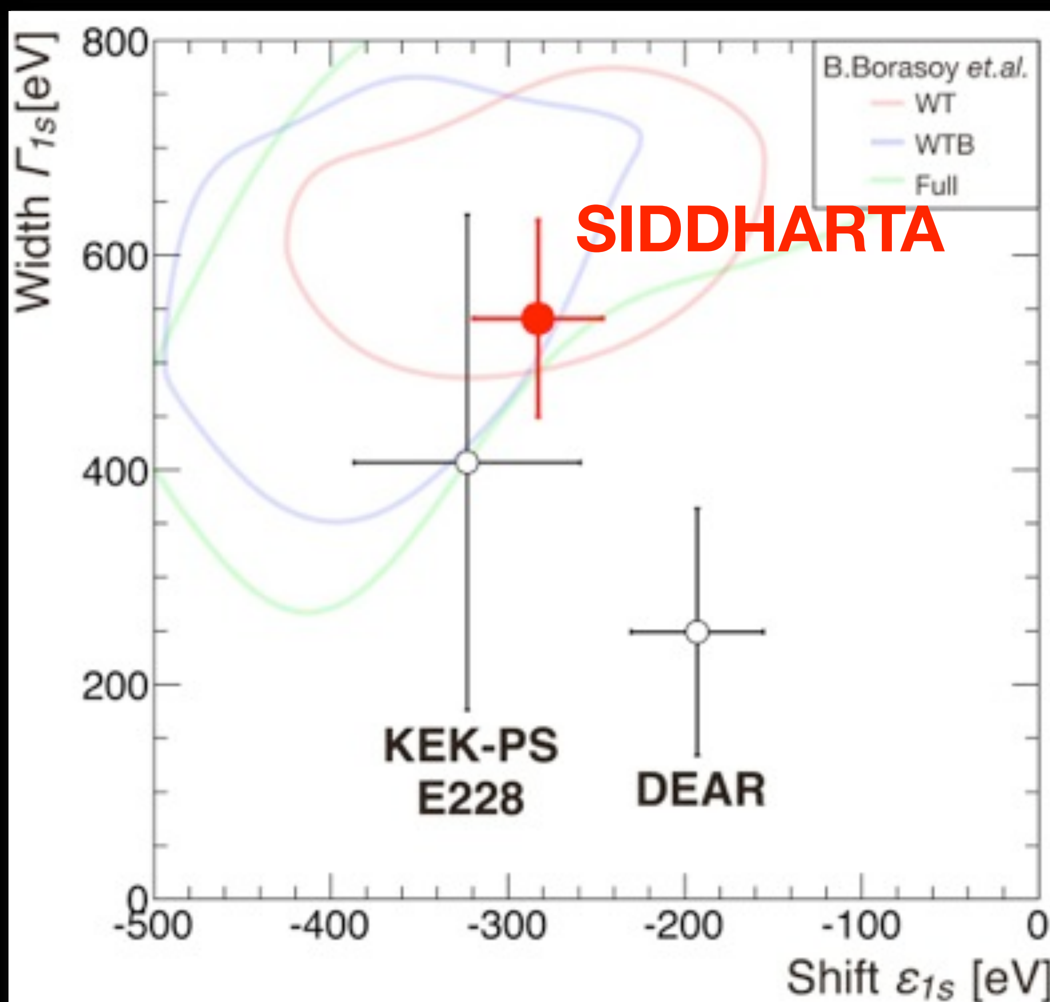
DDHARTA(^{4}He) @DAΦNE (2009)

SIDDHARTA @DAΦNE (2

DDHARTA(^{3}He) @DAΦNE (2011)

K-p

K-He



1970

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S.Baird (1983)

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2000

DEAR @DAΦNE (2005)

E570 @KEK (2007)

SIDDHARTA(^{4}He) @DAΦNE (2009)

2010

SIDDHARTA @DAΦNE (2011)

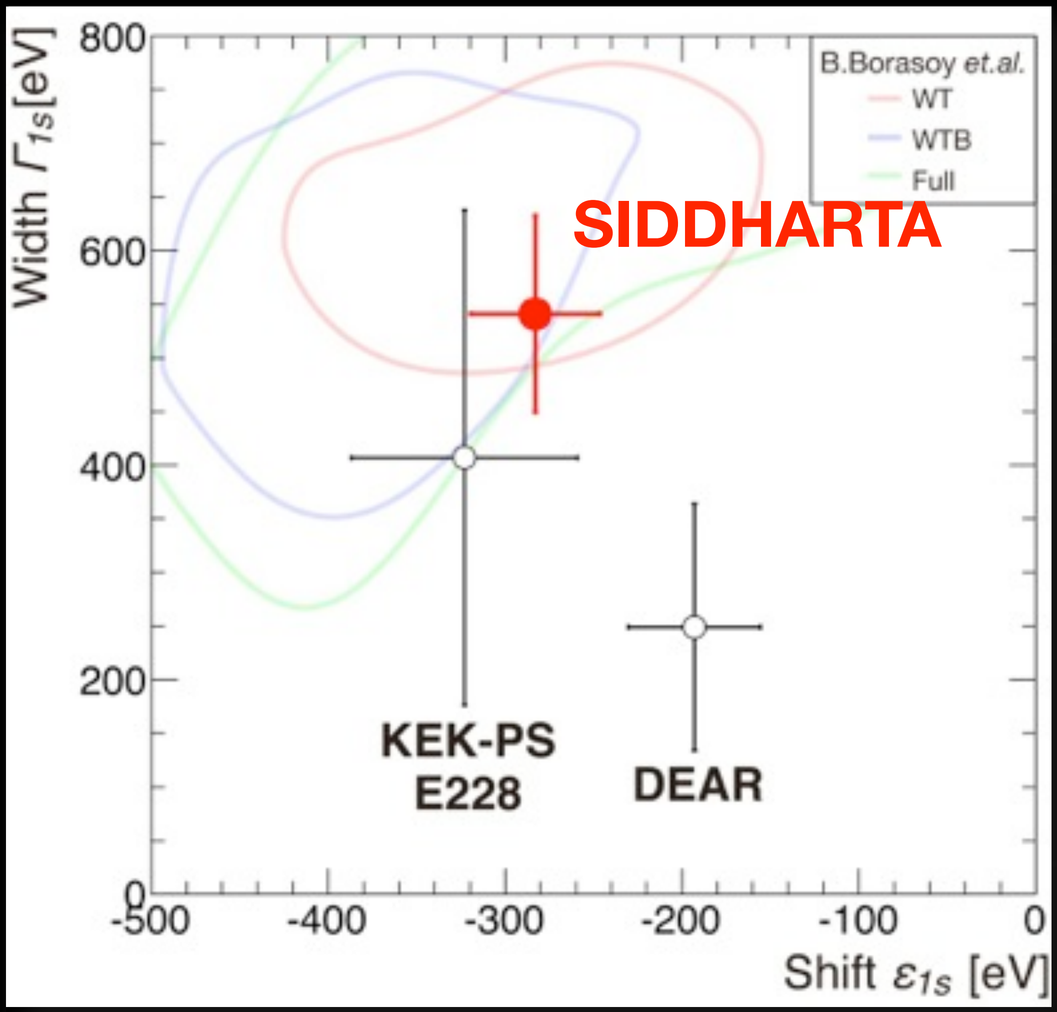
SIDDHARTA(^{3}He) @DAΦNE (2011)

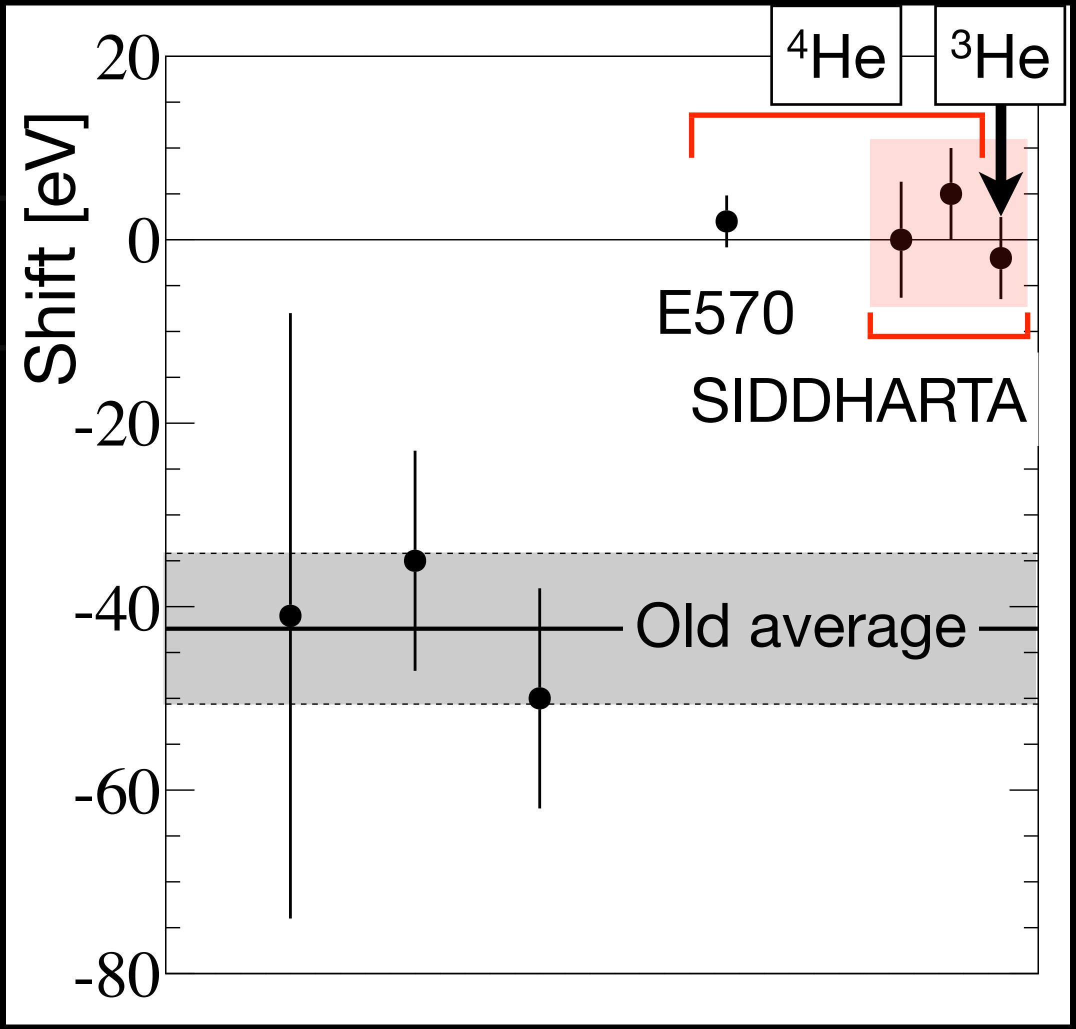
K-p

K-He

1970

C.E.Wiegand (1971)





1980

1990

2000

DEAR @DAΦNE (2005)

E570 @KEK (2007)

2010

SIDDHARTA(^{4}He) @DAΦNE (2009)

SIDDHARTA @DAΦNE (2011)

SIDDHARTA(^{3}He) @DAΦNE (2011)

K-p | **K-He**

1970

C.E.Wiegand (1971)

1980

J.D.Davies (1979) — C.J.Batty (1979)

M.Izycki (1980)

P.M.Bird (1983) — S.Baird (1983)

1990

Significant improvement !

KpX @KEK (1997)

2000

DEAR @DAΦNE (2005)

E570 @KEK (2007)

SIDDHARTA(^{4}He) @DAΦNE (2009)

2010

SIDDHARTA @DAΦNE (2011) — SIDDHARTA(^{3}He) @DAΦNE (2011)

K-p

K-He

1990

2000

2010

?

K-p

2010

K-He

SIDDHARTA

U.-G. Meißner et al, EPJ C35 (2004) 349

$$\Delta E - \mathrm{i}\Gamma/2 = -2\alpha^3\mu_r^2 a(K^-p)\left[1 + 2\alpha\mu_r(1-\ln\alpha)a(K^-p)\right],$$

scattering length by ***SIDDHARTA***

$$\mathrm{Re}\, a(K^-p) = -0.65 \pm 0.10 \text{ fm},$$
$$\mathrm{Im}\, a(K^-p) = 0.81 \pm 0.15 \text{ fm},$$

Y. Ikeda et al, NPA 881(2012)98

$$a(K^-p) = -0.93 + \mathrm{i}0.82 \text{ fm (TW)},$$
$$a(K^-p) = -0.94 + \mathrm{i}0.85 \text{ fm (TWB)},$$
$$a(K^-p) = -0.70 + \mathrm{i}0.89 \text{ fm (NLO)}.$$

now fully compatible

However ...

$$a(K^-p) = [a_0 + a_1]/2$$

average of I=0 and I=1 components

K-p

2010

K-He

SIDDHARTA

U.-G. Meißner et al, EPJ C35 (2004) 349

$$\Delta E - i\Gamma/2 = -2\alpha^3 \mu_r^2 a(K^- p)[1 + 2\alpha\mu_r(1 - \ln\alpha)a(K^- p)],$$

Now, we do need to determine the **I=1 component** of K^bar N scattering length

$$a(K^- p) = -0.93 + i0.82 \text{ fm (TW)},$$

$$a(K^- p) = -0.70 + i0.89 \text{ fm (NLO)}.$$

important to extract K⁻ n scattering length

However ...

$$a(K^- p) = [a_0 + a_1]/2$$

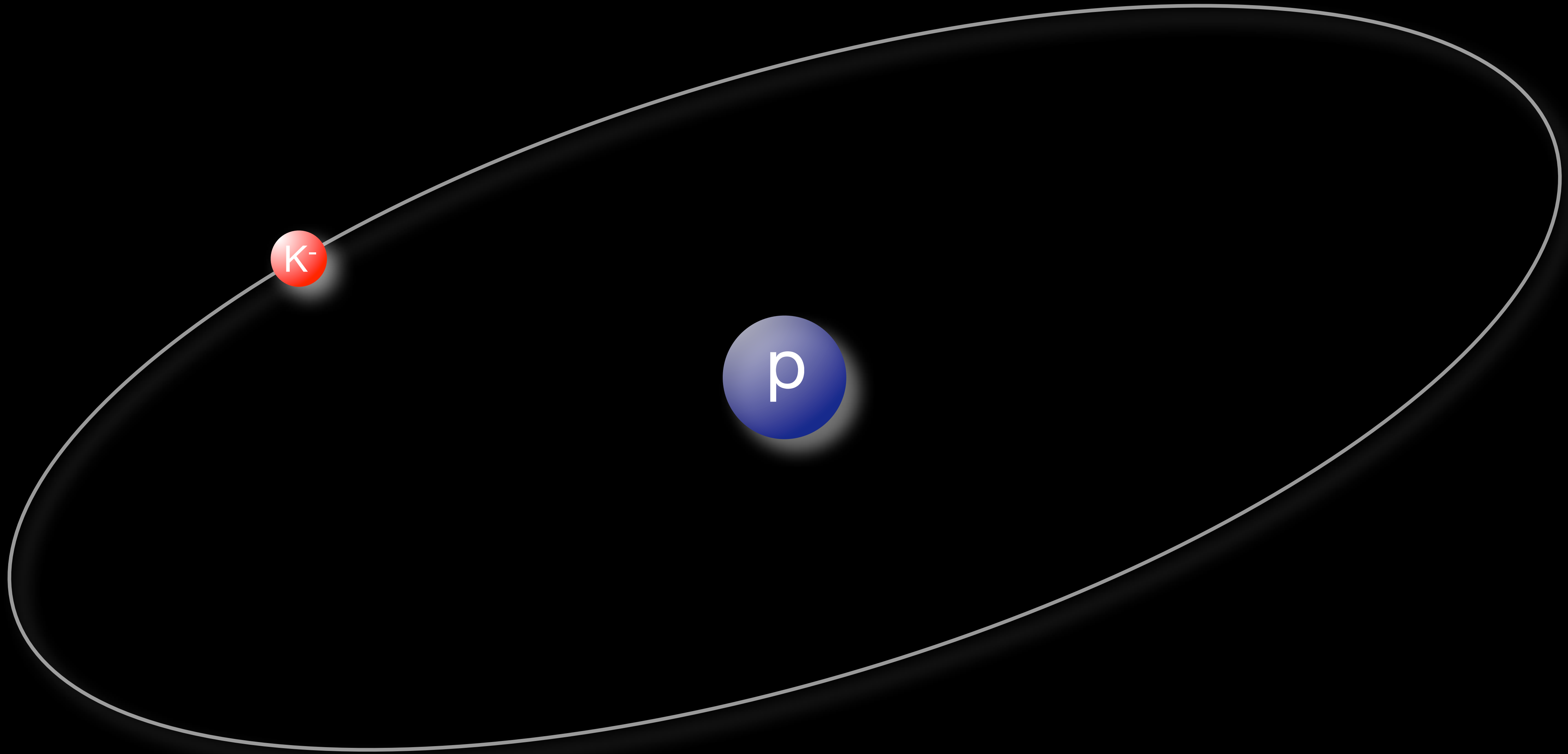
average of I=0 and I=1 components

K-p

2010

K-He

important to extract K^-n scattering length



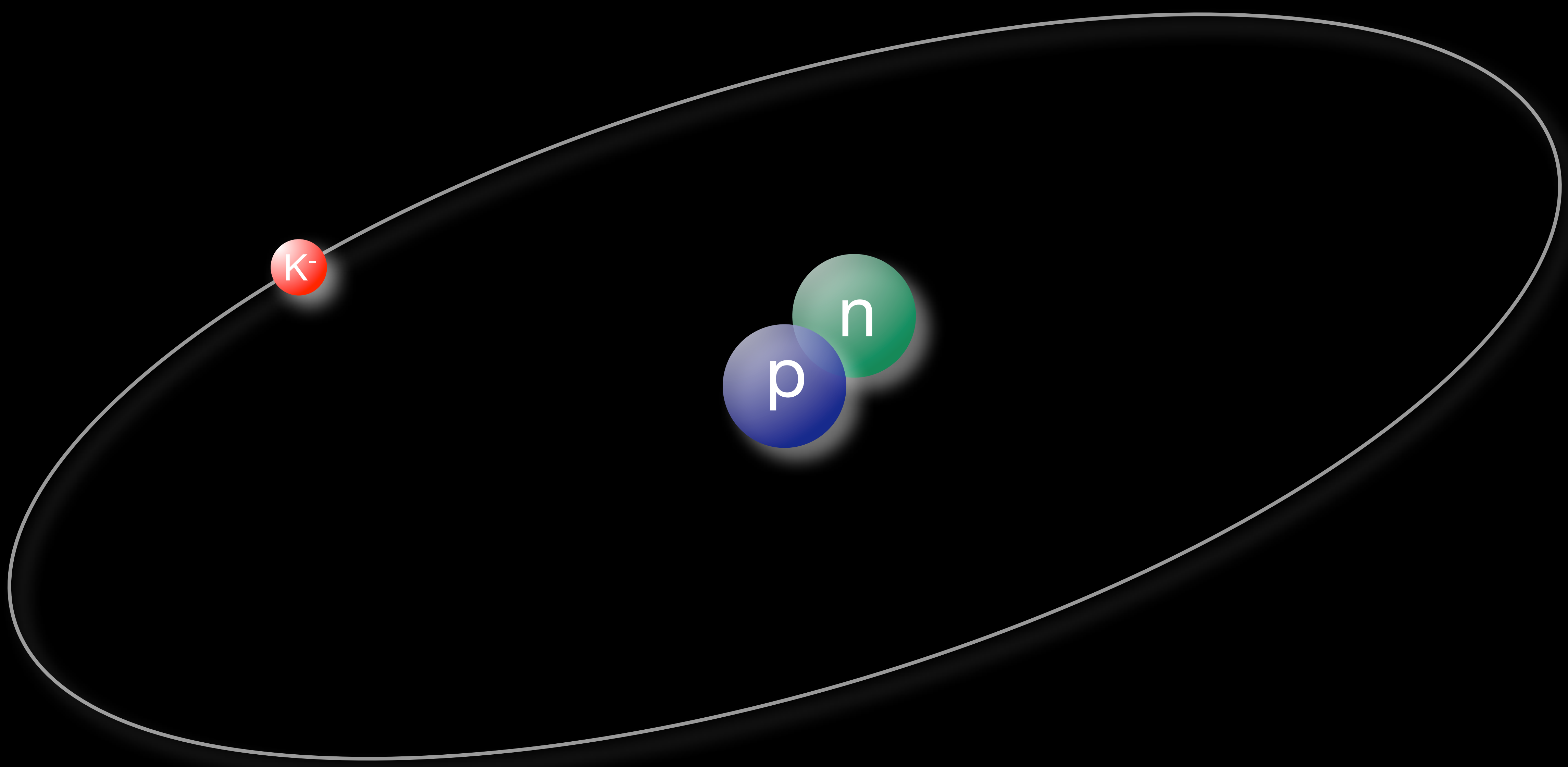
K-p

+

K-d

2010

K-He



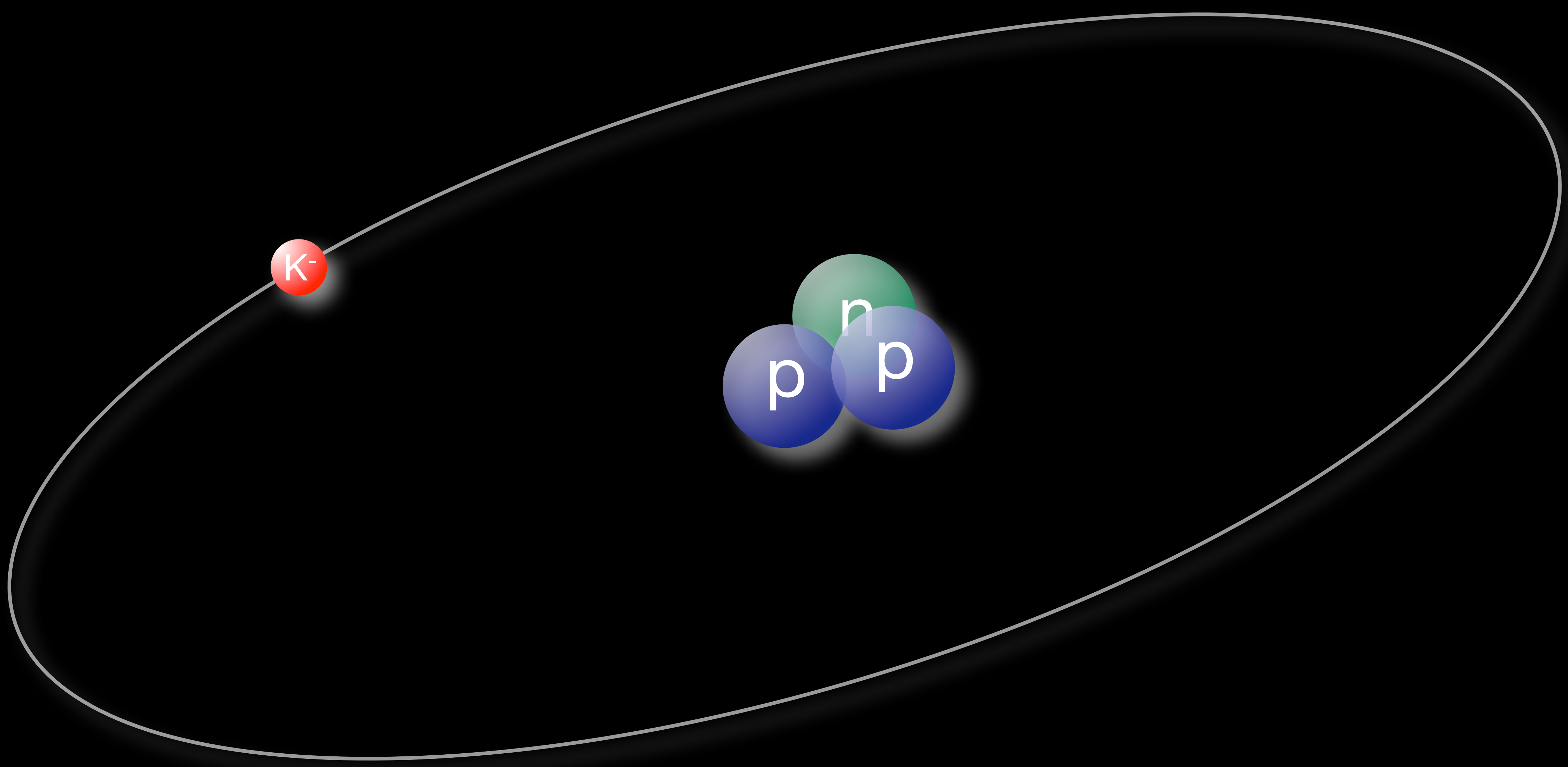
K-p

+

K-d

2010

K-^{3}He



K-p

+

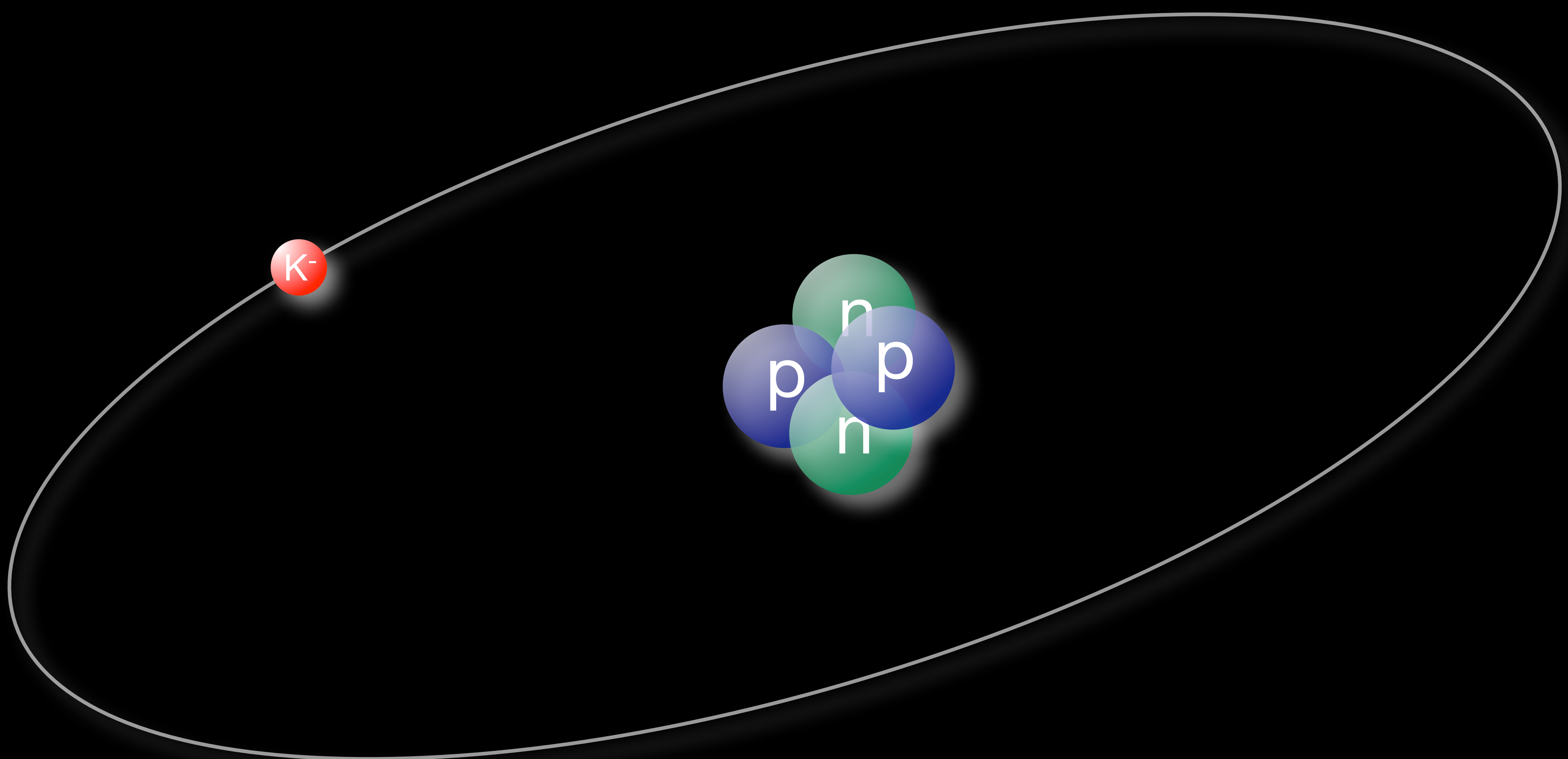
K-d

2010

$K\text{-}^3He$

+

$K\text{-}^4He$



Z=1	**K-p** + **K-d**	isotopic nucleus	**K-^{3}He** + **K-^{4}He**	Z=2

K-p

Z=1 +

K-d

2p-1s x-ray

~ 6 keV

K-^{3}He

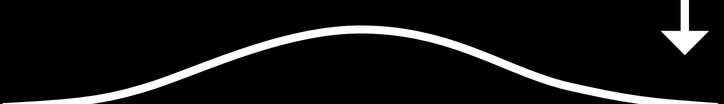
\+ Z=2

K-^{4}He

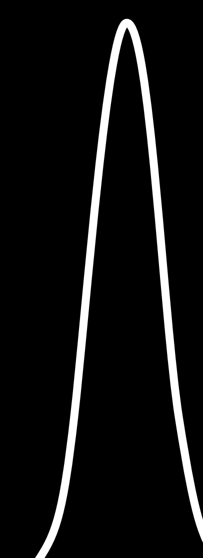
3d-2p x-ray

~ 6 keV

K-p + K-d		$K\text{-}^{3}He$ + $K\text{-}^{4}He$
Z=1 2p-1s x-ray		Z=2 3d-2p x-ray
Large	**Width**	Small
Low	**Yield**	High
↓		↓



High stat.
Improved S/N



High precision

K-p

Z=1 +

K-d

SIDDHARTA-2
or J-PARC

High stat.
Improved S/N

K-^{3}He

+ Z=2

K-^{4}He

+

Z=3

K-Li

more...

This talk

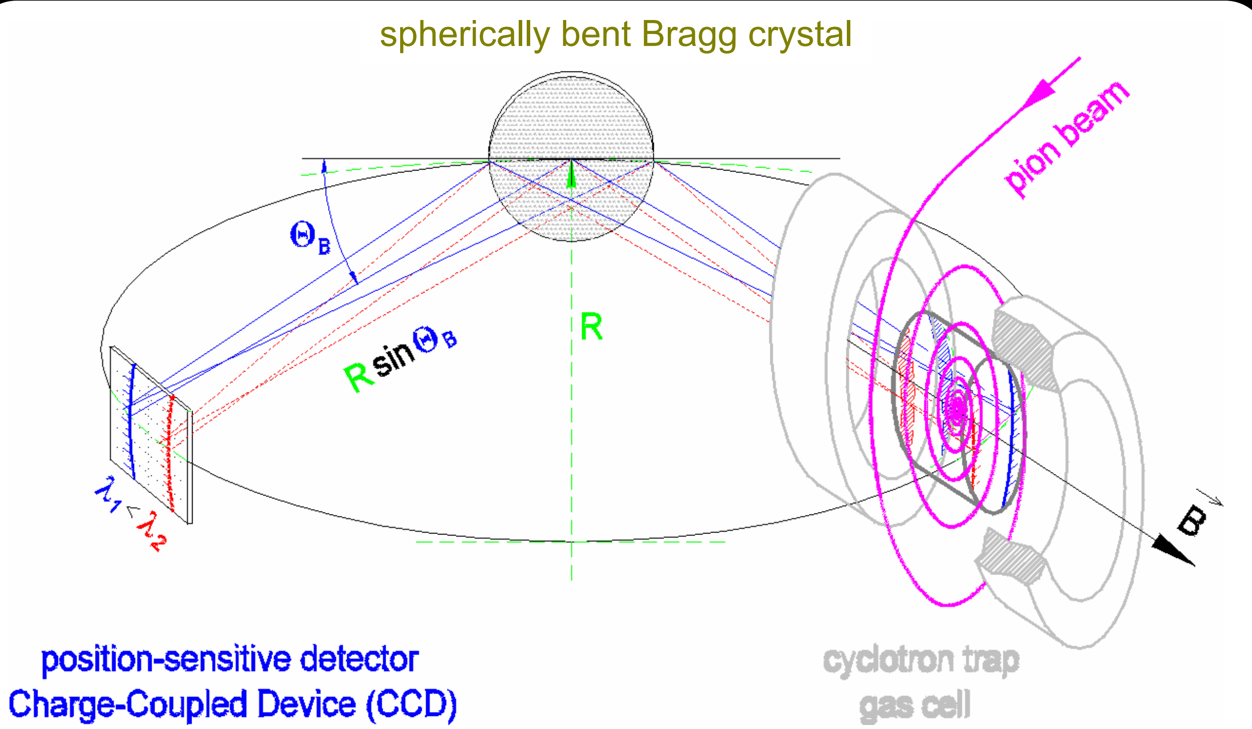
High precision

Next-generation K-atom exp.

for high-precision measurement

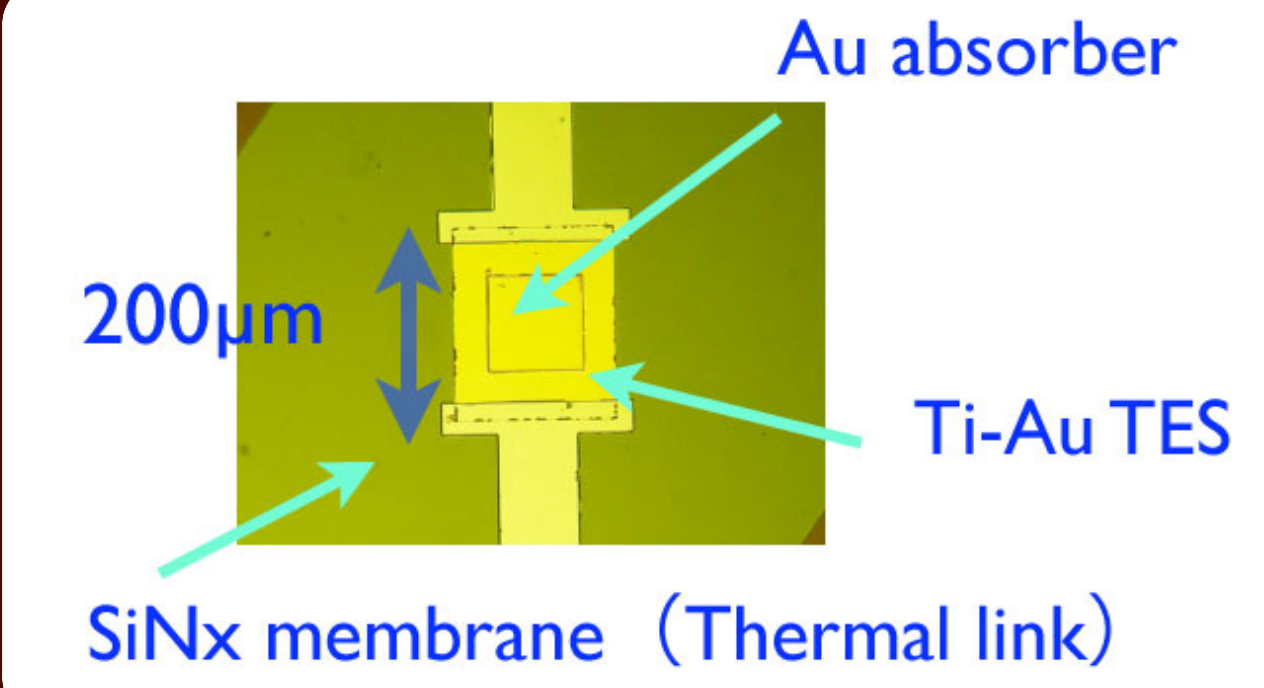
Next-generation K-atom exp.

1. Crystal spectrometer



pionic atom exp.@ PSI : D. Gotta et al.

2. Microcalorimeter

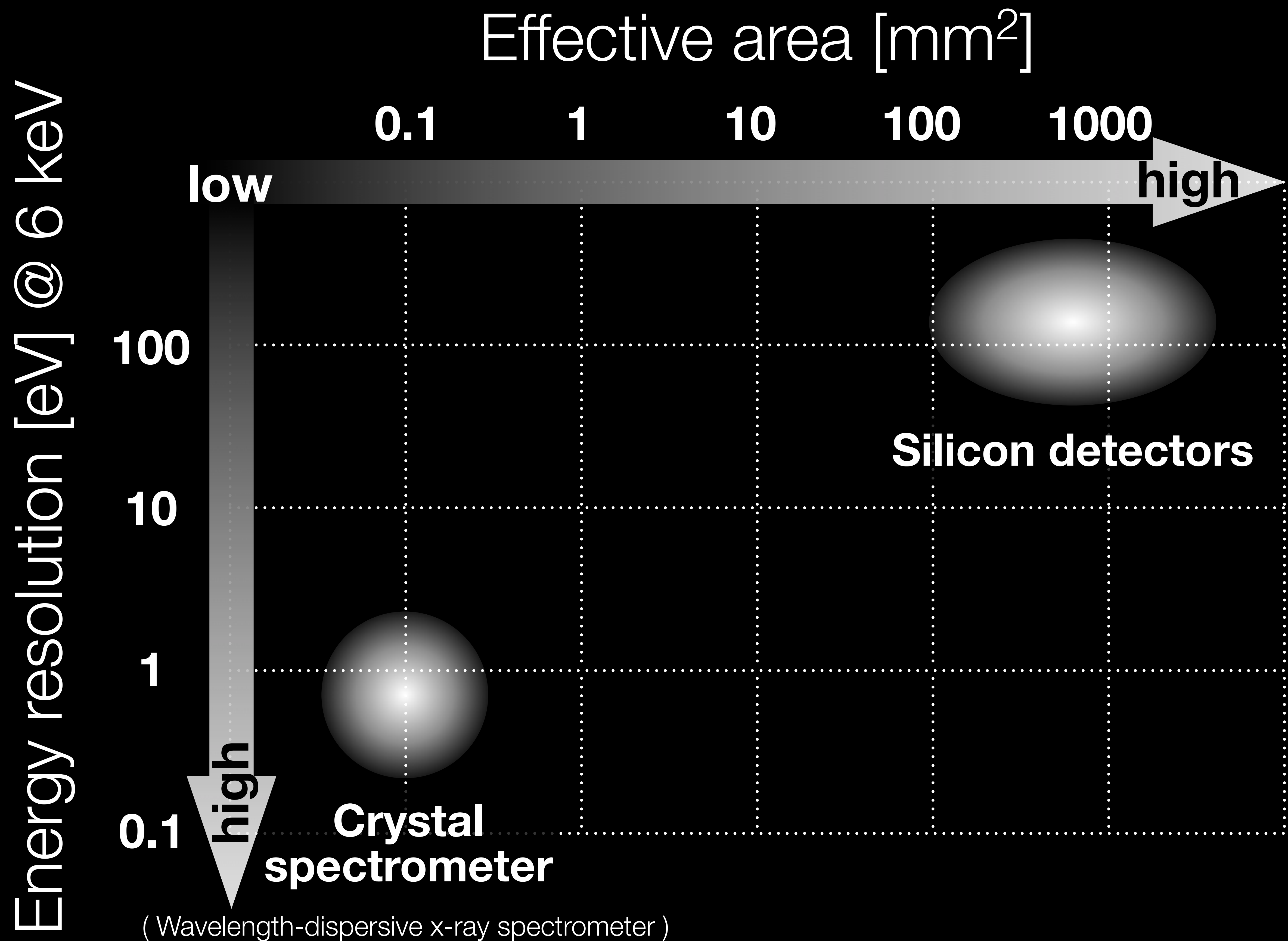


X-ray observation satellite (ASTRO-H)

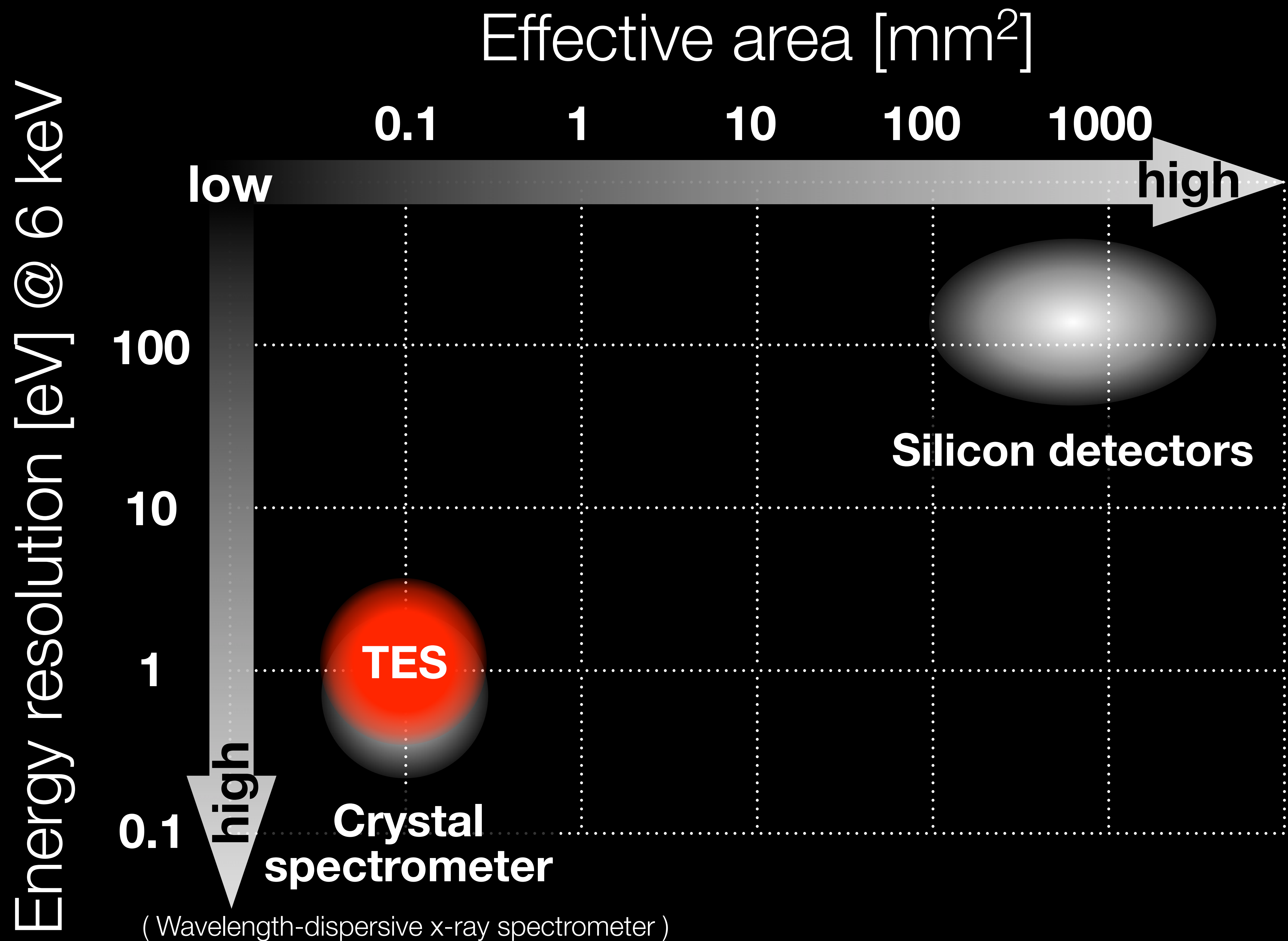
Compact and portable

limited beam time, then need to remove

Problem in both : **small acceptance**



Effective area [mm2]
0.1
1
10
100
1000
low
high
Energy resolution [eV] @ 6 keV
100
10
1
0.1
high
Silicon detectors
Crystal
spectrometer
(Wavelength-dispersive x-ray spectrometer)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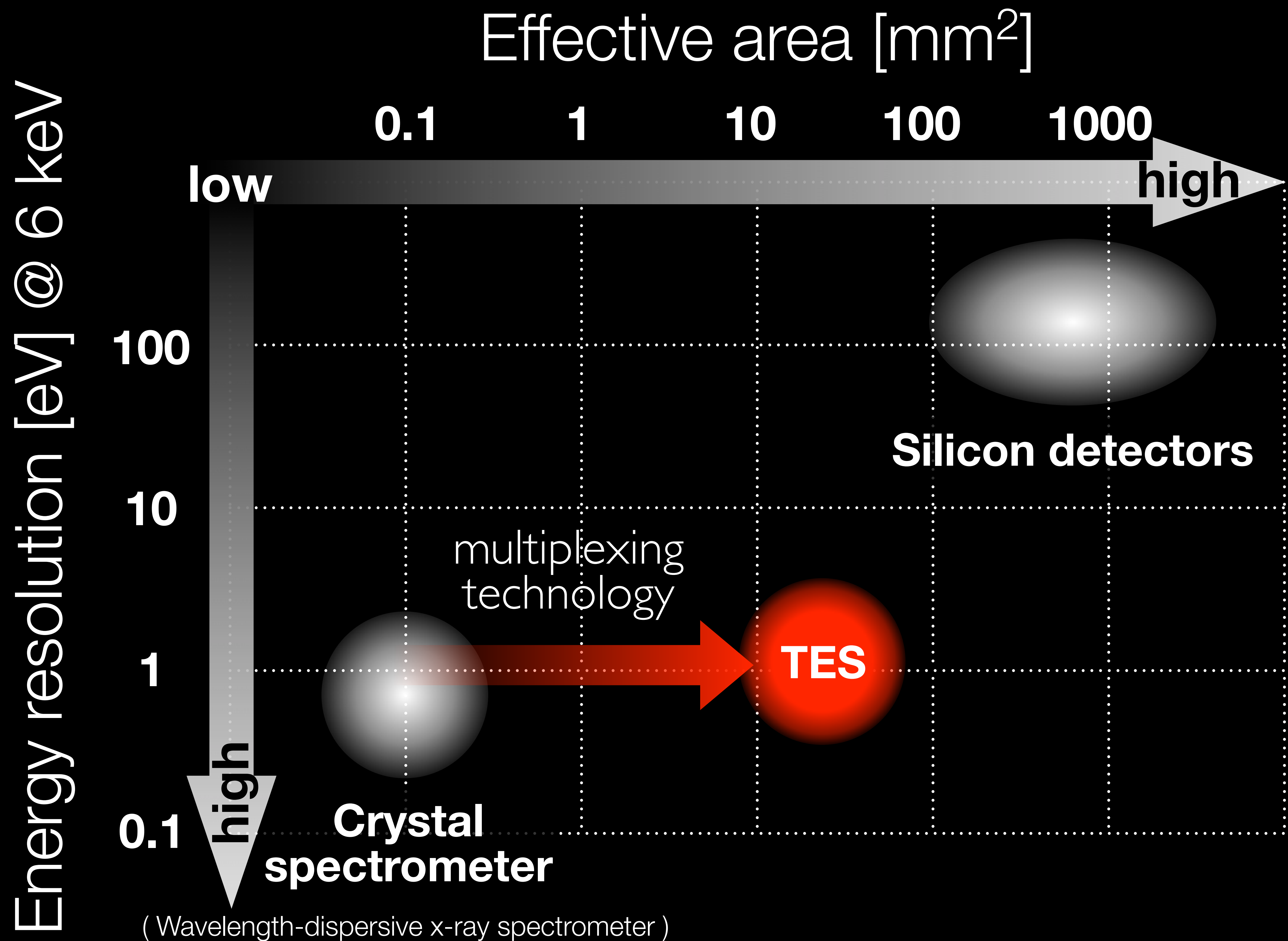
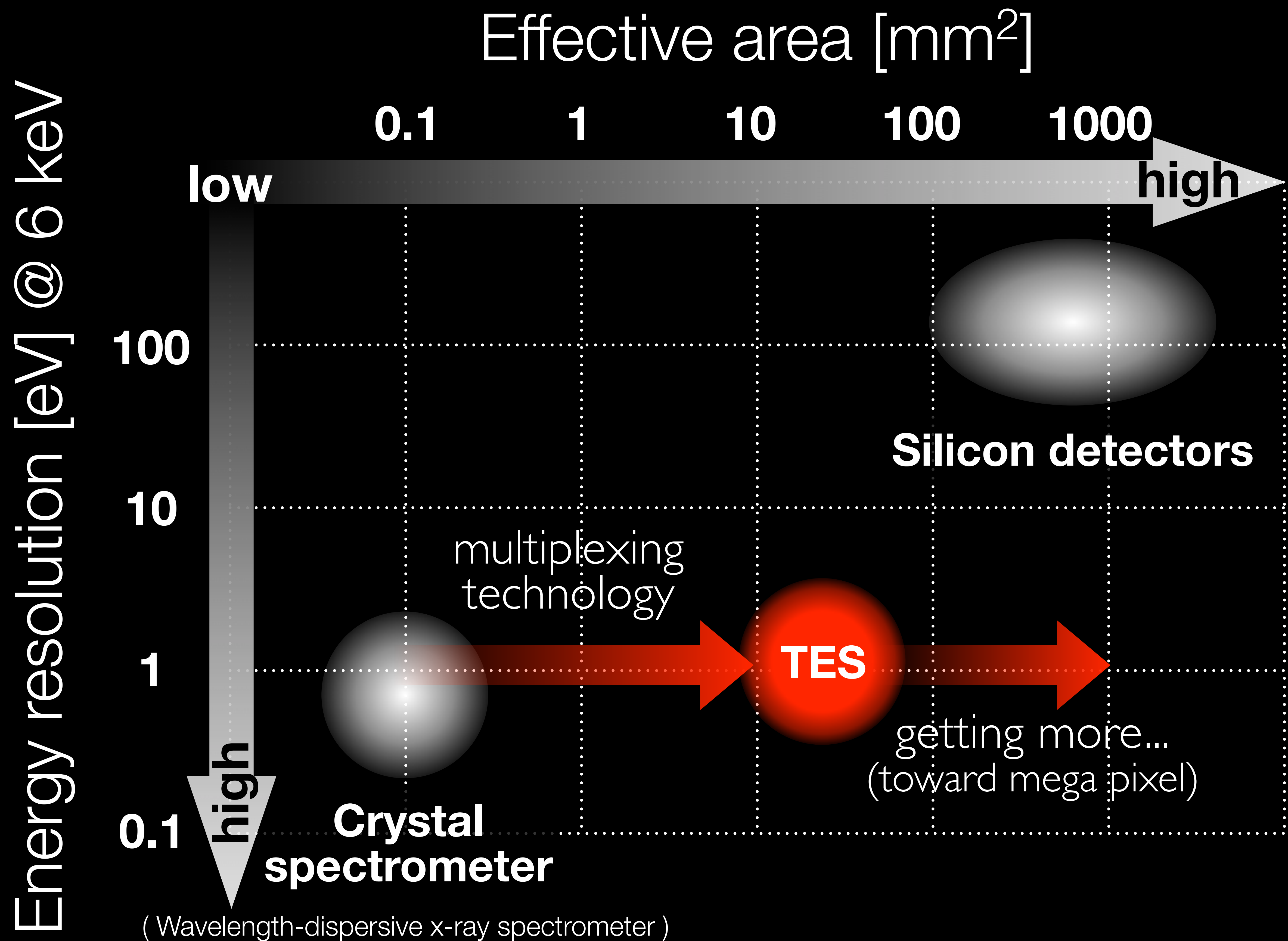
Silicon detectors
TES
Crystal
spectrometer
(Wavelength-dispersive x-ray spectrometer)



Effective area [mm²]
0.1
1
10
100
1000
low
high
Energy resolution [eV] @ 6 keV
100
10
1
0.1
high
Silicon detectors
multiplexing technology
TES
Crystal spectrometer
(Wavelength-dispersive x-ray spectrometer)



Effective area [mm2]
0.1
1
10
100
1000
low
high
Energy resolution [eV] @ 6 keV
100
10
1
0.1
high
Silicon detectors
multiplexing technology
TES
getting more...
(toward mega pixel)
Crystal spectrometer
(Wavelength-dispersive x-ray spectrometer)

Progress of this project in this year

1. get started a collaboration with NIST (in Feb.)

having the world's top-class technology of TES arrays (multiplexing readout technics)

2. performed a test experiment at lab. of NIST (in Aug.)

3. got two budgets

1) for a study of basic performance of TES in beam environment (as a part of the large research fund lead by Tamura-san)

2) for sending Japanese researchers to NIST (zuno-junkan)

2. NIST's multi-pixel TES array

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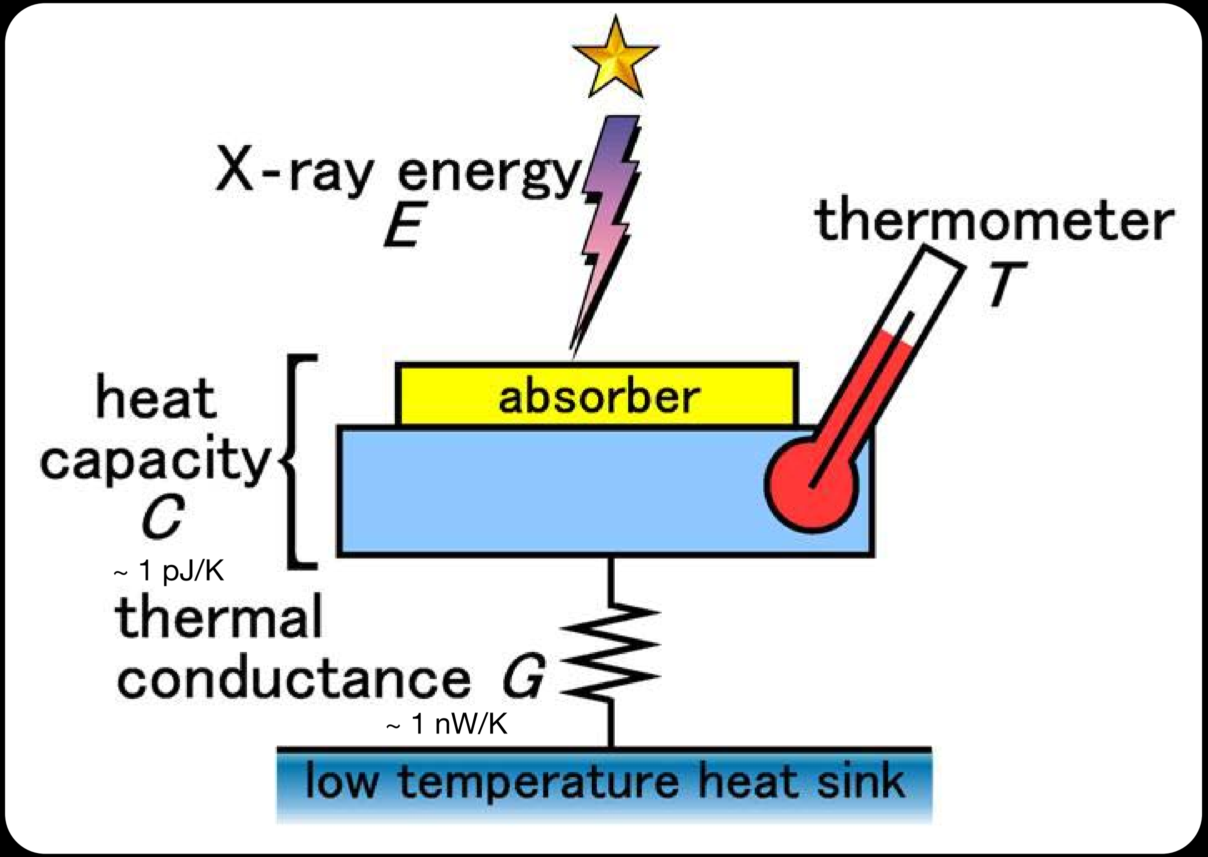
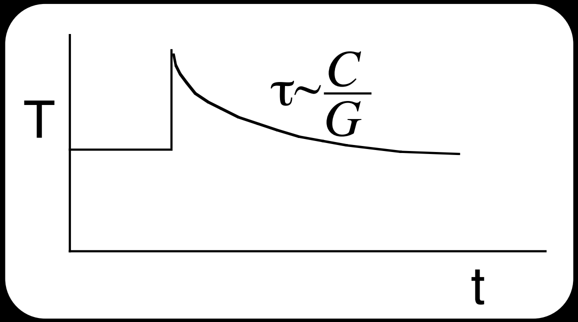
X-ray microcalorimeter

a thermal detector measuring the energy
of an incident x-ray photon as a temperature rise



Temperature rise
= E / C (~ 1 mK)

Decay time constant
= C / G (~ 100 μs)



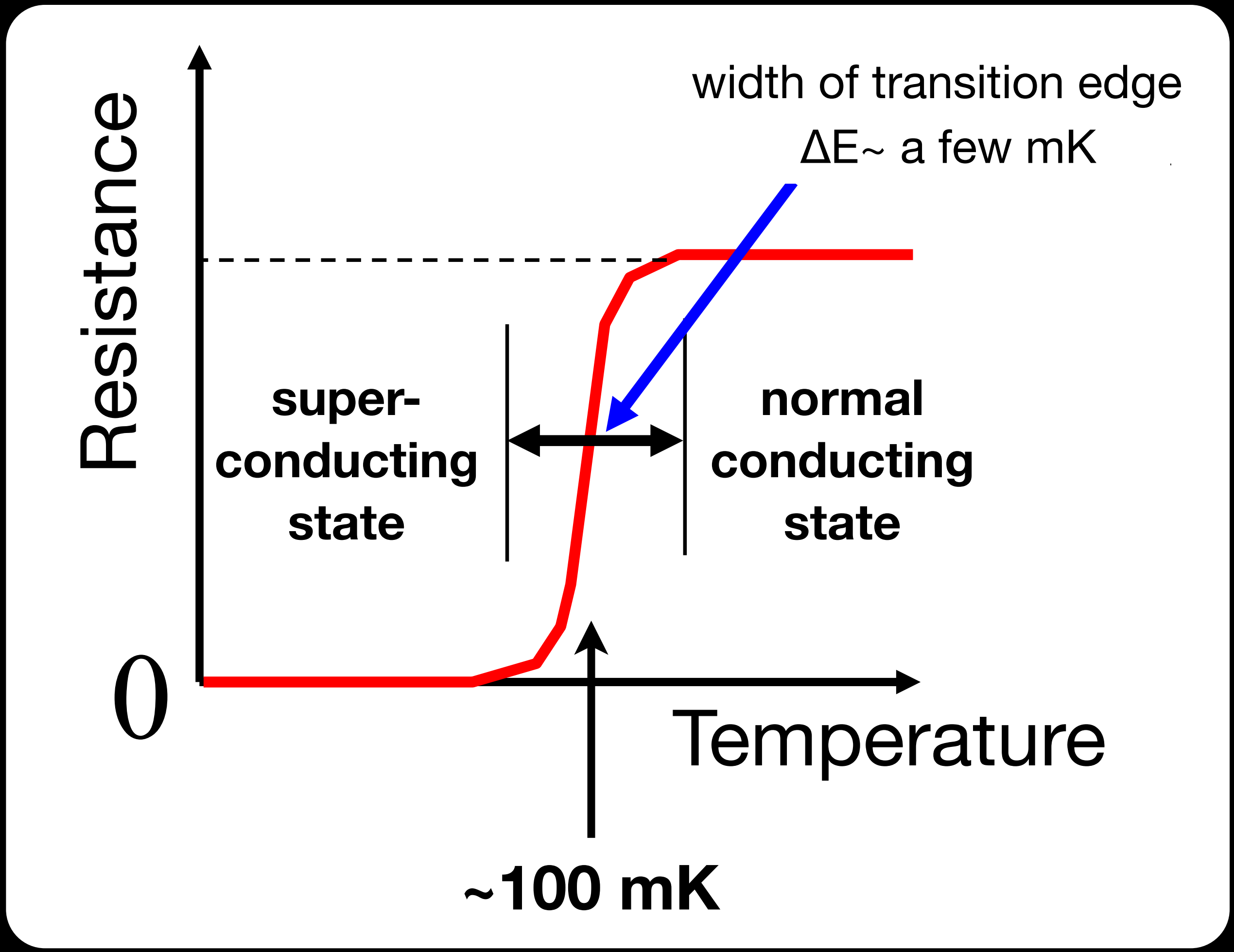
Absorber with larger "Z" (to stop the high energy x-rays)

e.g., Absorber : Au (0.3 mm×0.3 mm wide, 300 nm thick)
Thermometer : thin bilayer film of Ti (40nm) and Au(110 nm)

TES microcalorimeter

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

$$\alpha \equiv \frac{d \ln R}{d \ln T} \sim 100 - 1000$$

Energy resolution

$$\Delta E_{(FWHM)} = 2\sqrt{2\ln 2}\sqrt{\frac{k_B T^2 C}{\alpha}}$$

~ 2 eV @ 6 keV

(Johnson noise and phonon noise are the most fundamental)

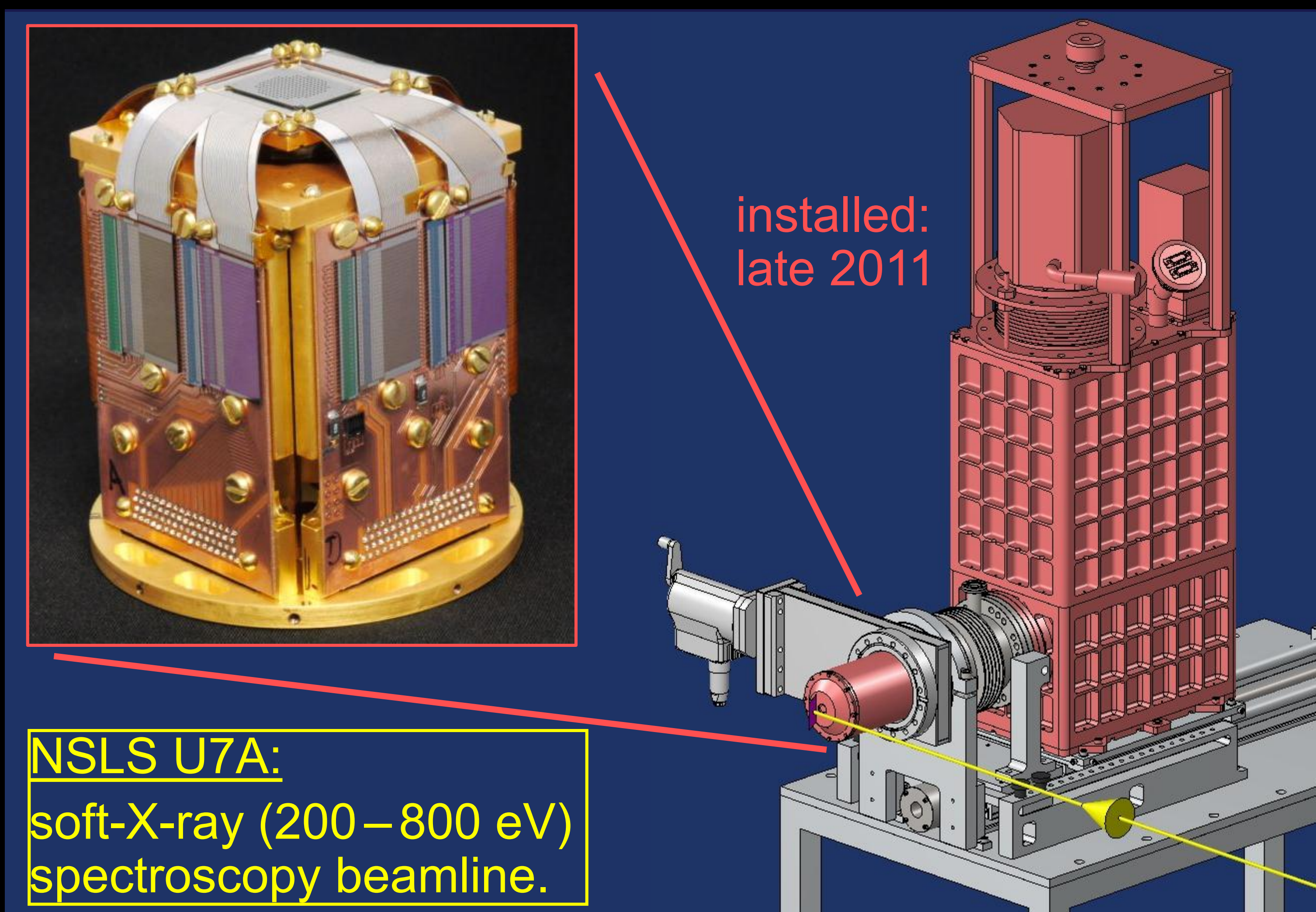
Dynamic range

$E_{max} \sim CT_C / \alpha$

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

NIST TES array system

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



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

NIST's standard TES

- 1 pixel : 350 x 350 μm^2
- 160 array : total ~ **20 mm^2**
- **2~3 eV (FWHM)** @ 6 keV

well established system!

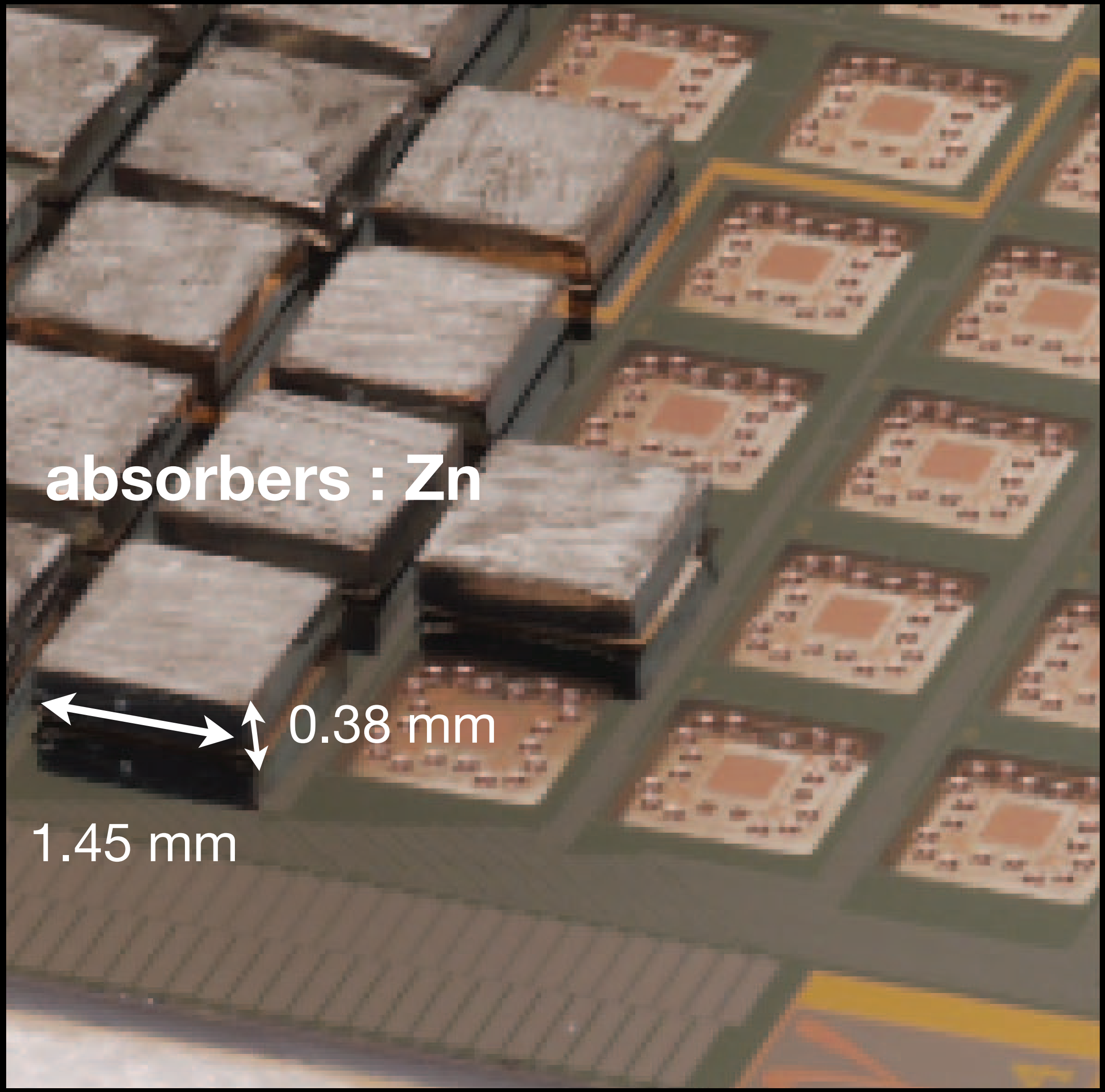
two-order improved resolution

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

NIST 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

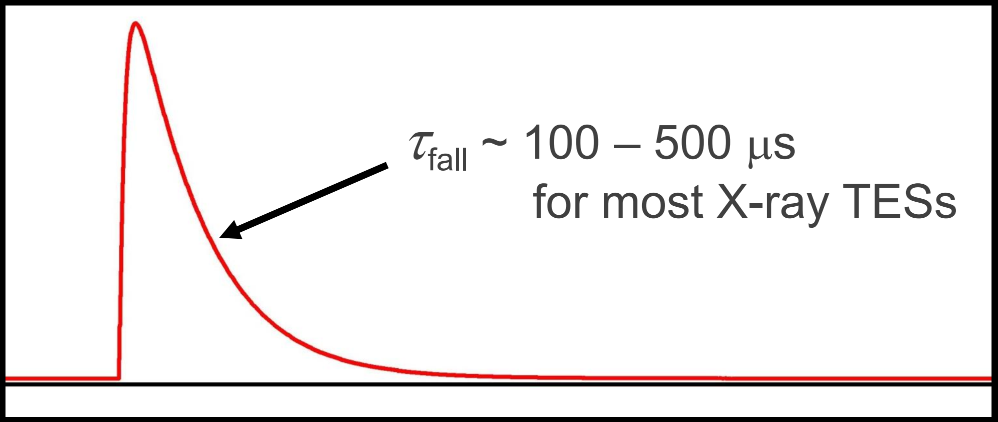
D. A. Bennett et al., Rev. Sci. Instrum. 83, 093113 (2012)

Is 160 pixel (= 20 mm^2) enough?

estimated K-^{4}He Kα yield (w/ realistic setup)
~ 25 events / day

	Energy resolution in FWHM	K-4He Kα events	Stat. accuracy of ene. determining (6 keV)
KEK-E570 with SDD	190 eV	1500 events	2 eV = 190 / 2.35 / sqrt(1500)
	TWO orders higher	**ONE order lower**	**ONE order better**
TES	2 ~ 3 eV	100 events (~ 4-day beam)	~ 0.1 eV = 2 ~ 3 / 2.35 / sqrt(100)

Count rate with TES



- Practical x-ray TES time constants ~ 100 - 500 μs
- **10s of Hz / TES** for 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. What do we measure?

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1) Kaonic helium 3 & 4
(& Pionic helium 3 & 4)

Original motivation

30 years ago!

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

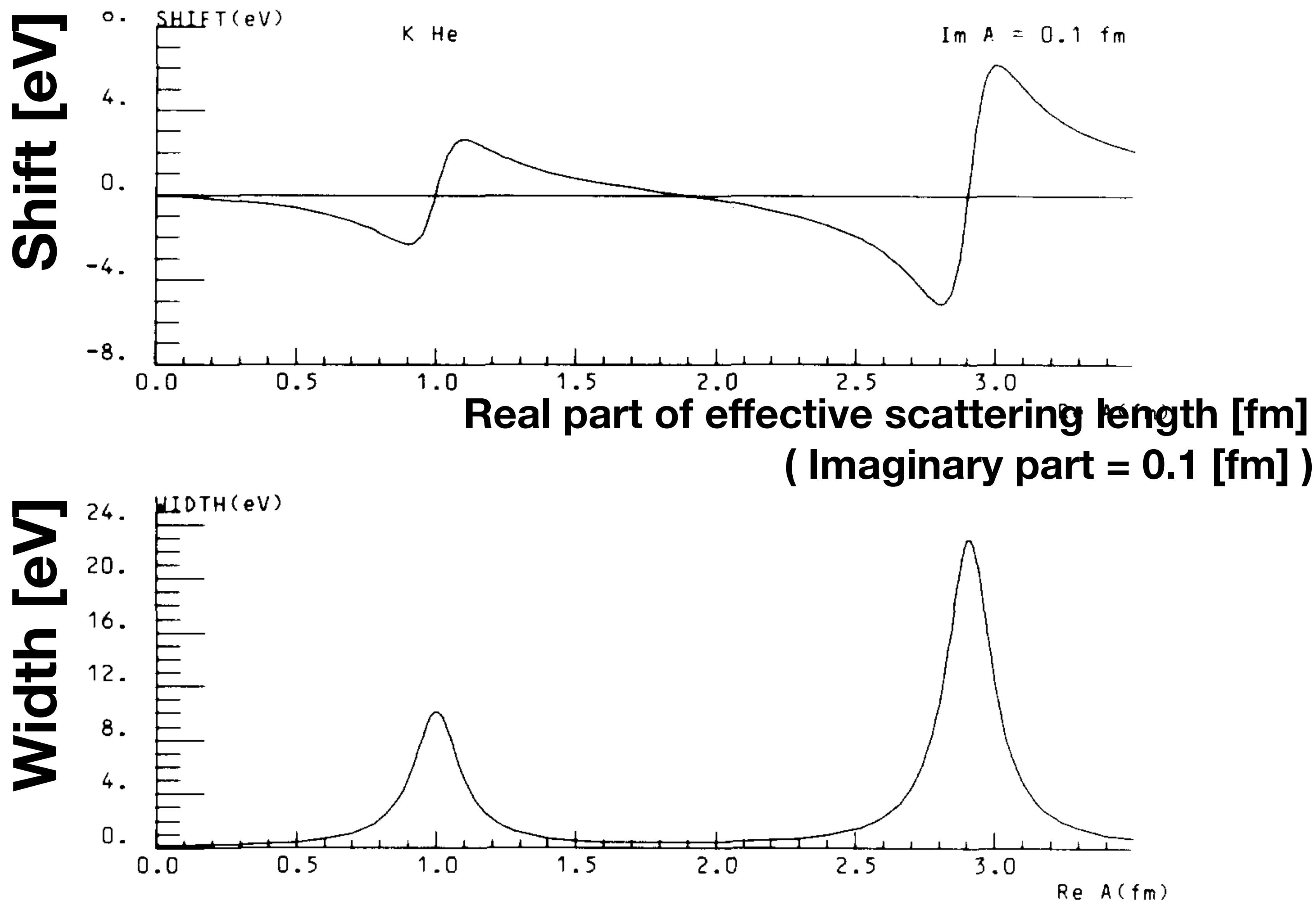
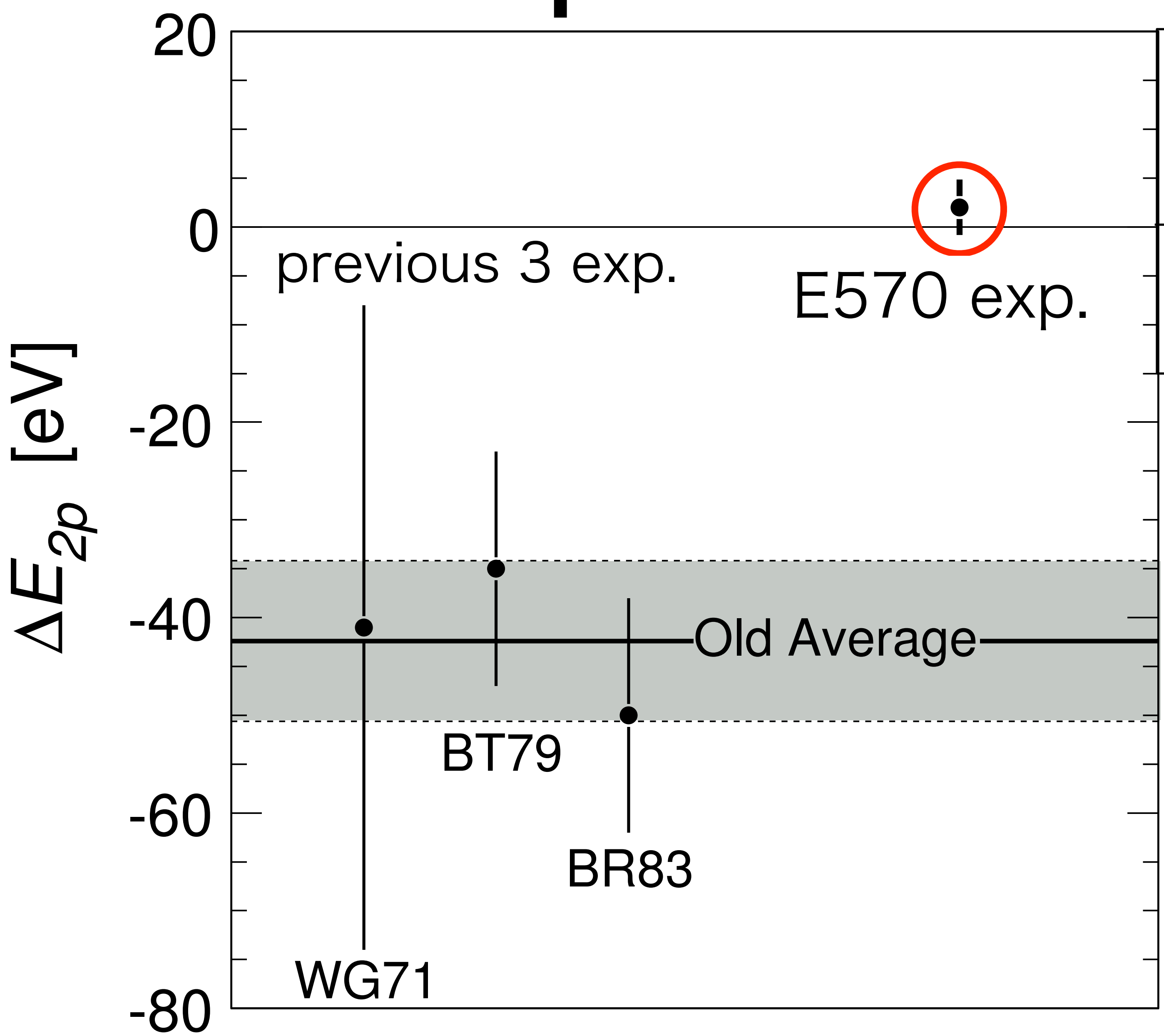


Fig. 5. Calculated strong interaction shift and width for kaonic helium as a function of the value of the real part of $\bar{a}$. The calculations used $a_I = 0.1$ fm.

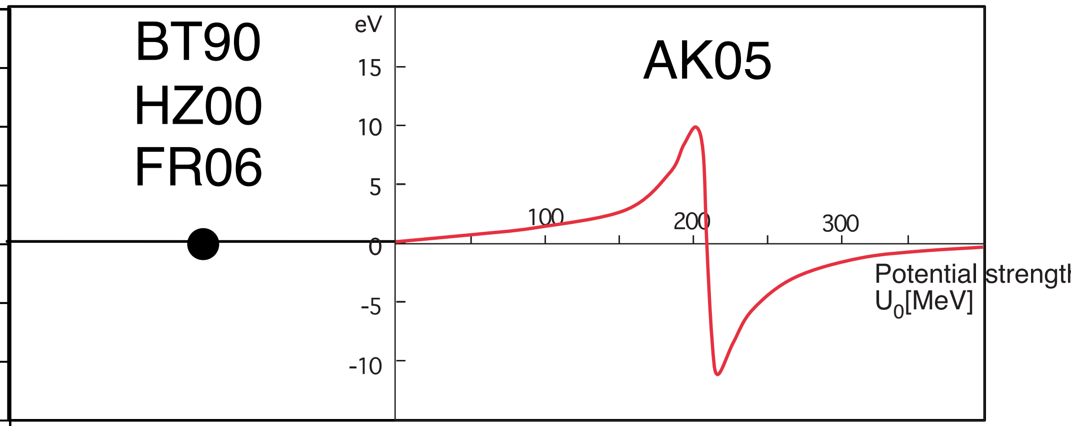
Original motivation

Experiment



stat. and syst. errors are quadratically added

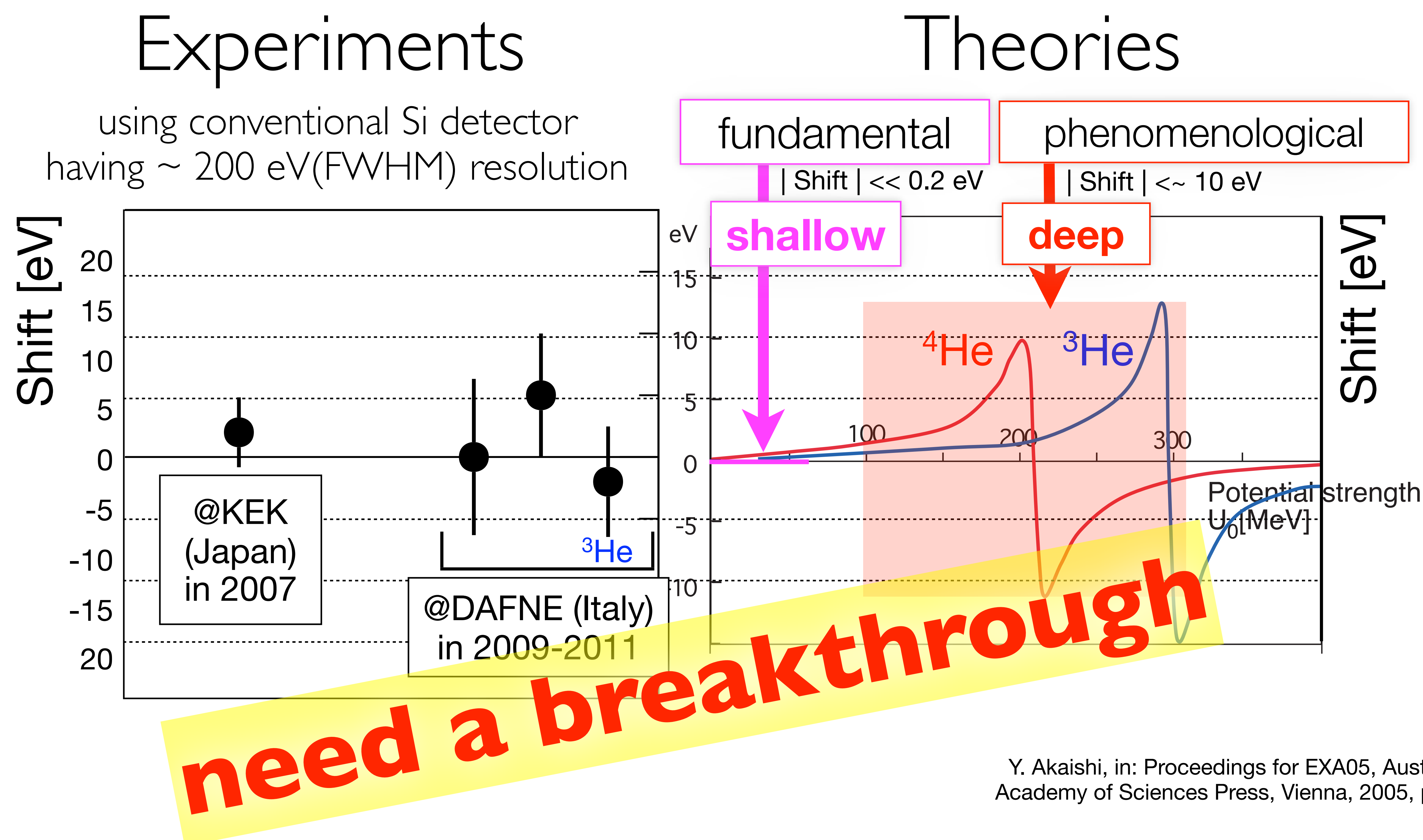
Theory



(U_{coupl} = 120 [MeV])

WG71 : C.E. Wiegand and R. Pehl, PRL27,1410 (1971).
BT79 : C.J. Batty et al., NPA326, 455 (1979).
BR83 : S. Baird et al., NPA392, 297 (1983).
BT90 : C.J. Batty, NPA 508, 89c (1990).
HZ00 : S. Hirenzaki et al., PRC 61, 055205 (2000).
FR06 : E. Friedman, private communication (2006).
AK05 : Y.Akaishi, EXA05 proceedings (2005).

Original motivation



Y. Akaishi, in: Proceedings for EXA05, Austrian Academy of Sciences Press, Vienna, 2005, p. 45.

Advanced motivation

High accuracy measurement
- Shift accuracy : < 0.1 eV
- Width accuracy: < 2~3 eV

↓

including nuclear excitation effects etc.

To compare the data, need more precise calc.
-> **Few-body calculation** (e.g., Hiyama-san)

↓ *motivated*

started theoretical calc. for K-d
by S. Ohnishi et al.

Advanced motivation

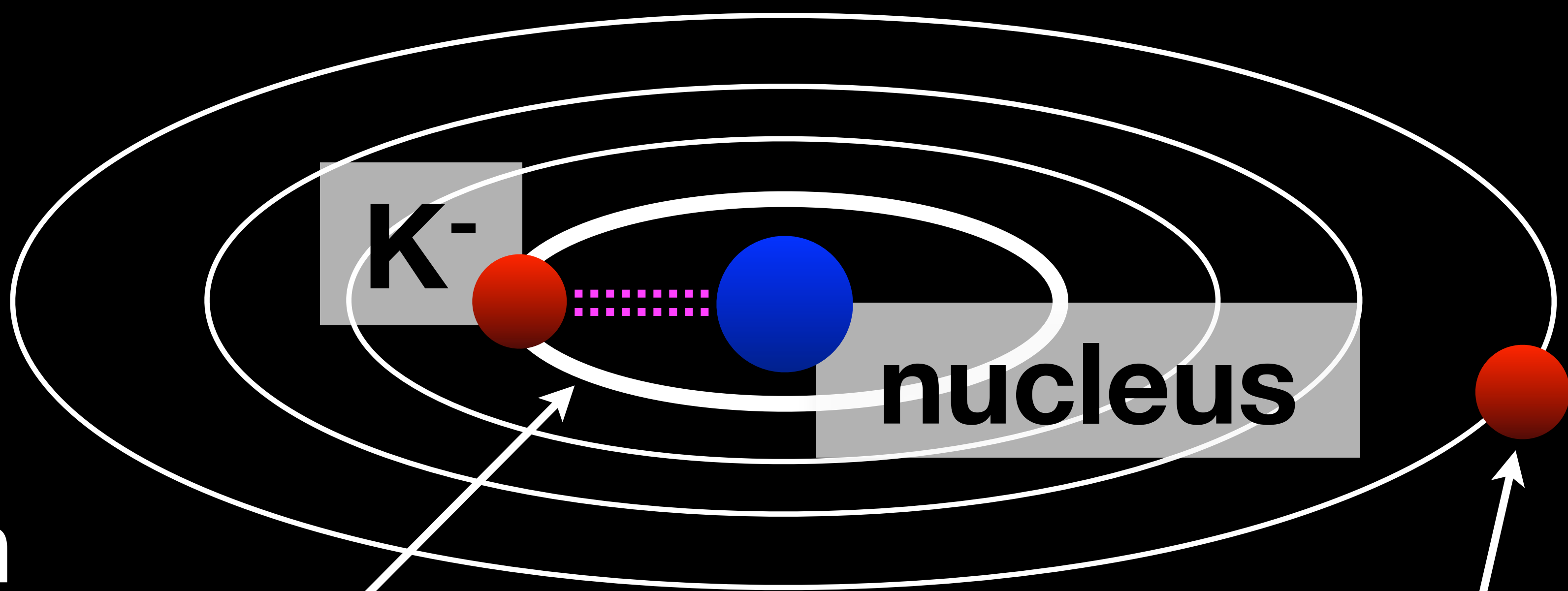
Comparison with few body calculations

K^--^3He & K^--^4He	*3d-2p* : 6 keV	**KN poorly known**
π-^3He & π-^4He	*3d-2p* : 2 keV *2p-1s* : 11 keV	**πN well known**

so far, **no accurate data** using crystal spectrometer

2) Kaon mass

Summary of Kaonic atom study



Small n

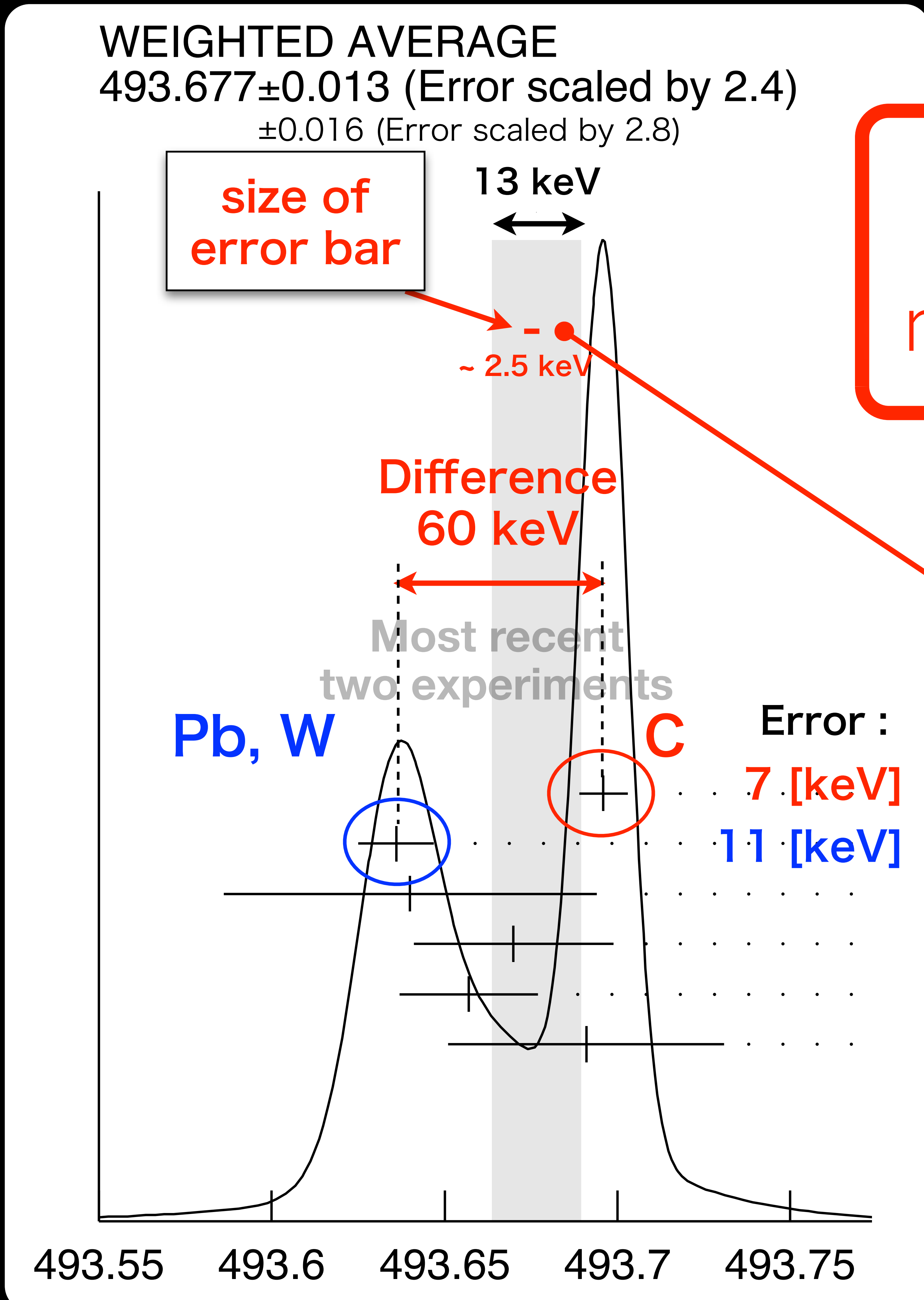
strong-interaction study

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



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)

3) Investigation of multi-nucleon process of $\bar{K}$ in nucleus

Available online at www.sciencedirect.com
SciVerse ScienceDirect
Nuclear Physics A 915 (2013) 170–178
NUCLEAR PHYSICS A
www.elsevier.com/locate/nuclphysa

Feasibility guidelines for kaonic atom experiments with ultra-high-resolution X-ray spectrometry

E. Friedman[a,*], S. Okada[b]

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Available online 30 July 2013

Abstract

Recent studies of strong-interaction effects in kaonic atoms suggest that analysing so-called ‘lower’ and ‘upper’ levels in the same atom could separate one-nucleon absorption from multinucleon processes. The present work examines the feasibility of direct measurements of upper level widths in addition to lower level widths in future experiments, using superconducting microcalorimeter detectors. About ten elements are identified as possible candidates for such experiments, all of medium-weight and heavy nuclei. New experiments focused on achieving good accuracy for widths of such pairs of levels could contribute significantly to our knowledge of the K^-–nucleon interaction in the nuclear medium.

Keywords: Kaonic atoms; Antikaon–nucleon interaction; Microcalorimeter

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Table 1
rms radii of various terms of the K^-–nucleus potential (in fm). r_m is the rms radius of the nucleus.

	r_m	Re(full)	Re(1N)	Re(mN)	Im(full)	Im(1N)	Im(mN)
Ni	3.72	3.34	3.82	2.86	3.73	4.46	3.12
Pb	5.56	5.21	5.71	4.78	5.46	6.23	5.00

Analysing so-called ‘lower’ and ‘upper’ levels in the same atom could separate one-nucleon (1N) absorption from multinucleon (mN) processes.

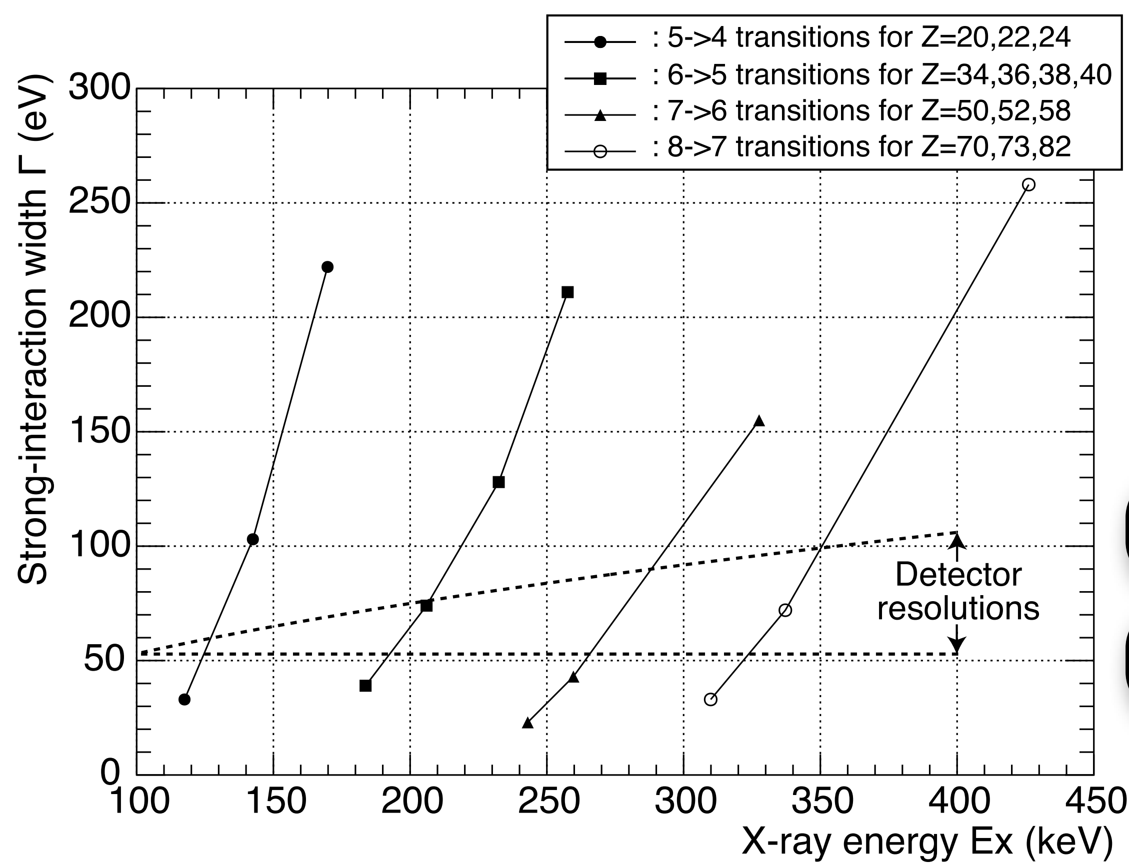


Fig. 5. Summary of upper-level results and the feasibility guideline due to the detector resolution.

utilizing ρ^2 dependence in high-Z K-atoms

$$\Delta E = 53 \times \sqrt{E_X/100}\ \mathrm{eV}$$

$$\Delta E = 53\ \mathrm{eV}$$

Table 2
Absolute and relative yields of the relevant transitions for kaonic atoms indicated in the figures. Also listed are the (n, l) values of the various levels, see text.

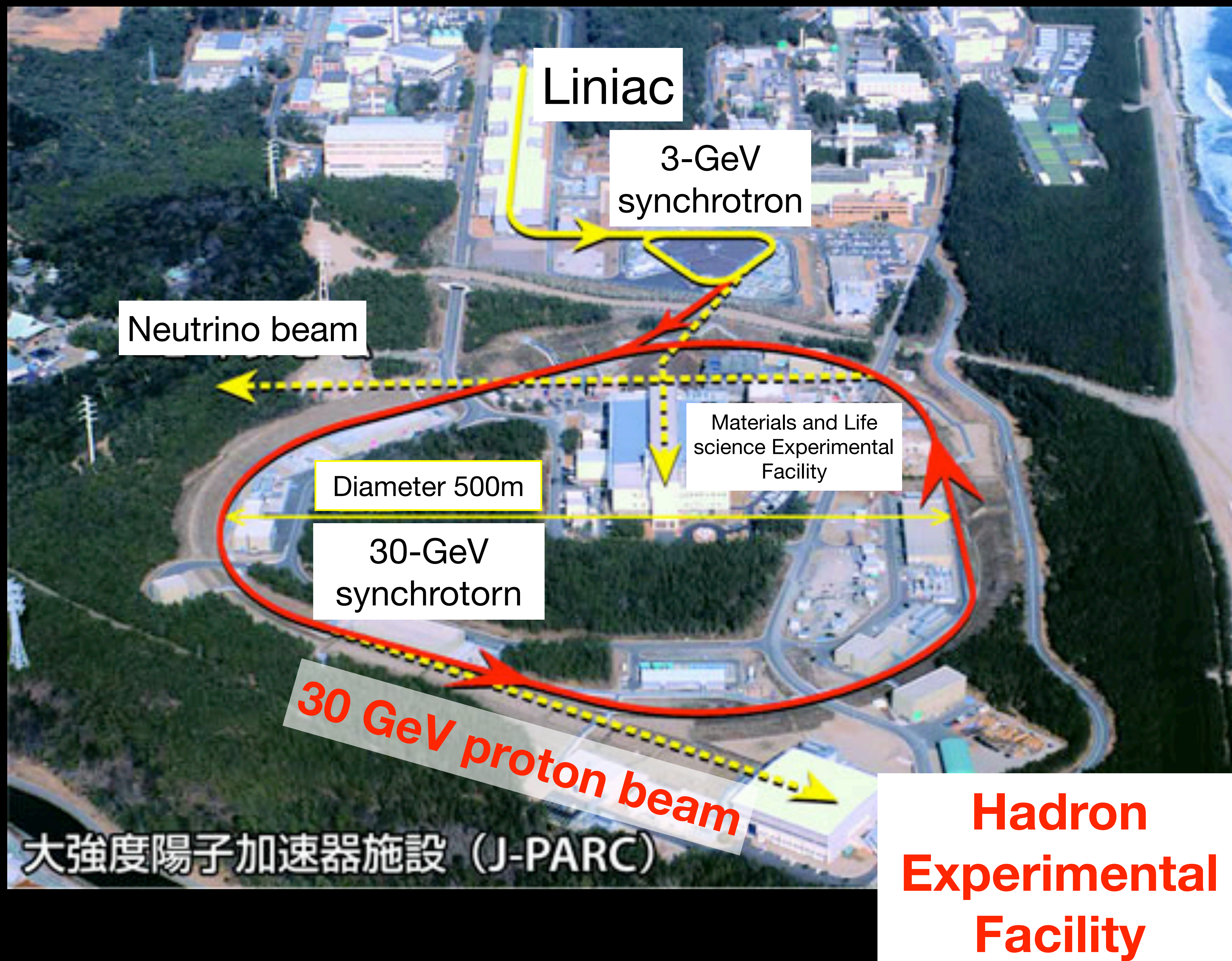
Target	U + 1	U	L	$Y^{abs}_{U+1\to U}$	$Y^{abs}_{U\to L}$	$Y^{rel}_{U\to L}$
Ca	(5, 4)	(4, 3)	(3, 2)	0.665	0.044	0.061
Ti	(5, 4)	(4, 3)	(3, 2)	0.627	0.019	0.029
Cr	(5, 4)	(4, 3)	(3, 2)	0.570	0.012	0.019
Se	(6, 5)	(5, 4)	(4, 3)	0.705	0.091	0.121
Kr	(6, 5)	(5, 4)	(4, 3)	0.689	0.061	0.083
Sr	(6, 5)	(5, 4)	(4, 3)	0.663	0.043	0.062
Zr	(6, 5)	(5, 4)	(4, 3)	0.628	0.031	0.047
Sn	(7, 6)	(6, 5)	(5, 4)	0.706	0.218	0.292
Te	(7, 6)	(6, 5)	(5, 4)	0.696	0.152	0.207
Ba	(7, 6)	(6, 5)	(5, 4)	0.651	0.069	0.101
Yb	(8, 7)	(7, 6)	(6, 5)	0.674	0.236	0.331
Ta	(8, 7)	(7, 6)	(6, 5)	0.655	0.147	0.212
Pb	(8, 7)	(7, 6)	(6, 5)	0.601	0.067	0.107

4. Experimental setup

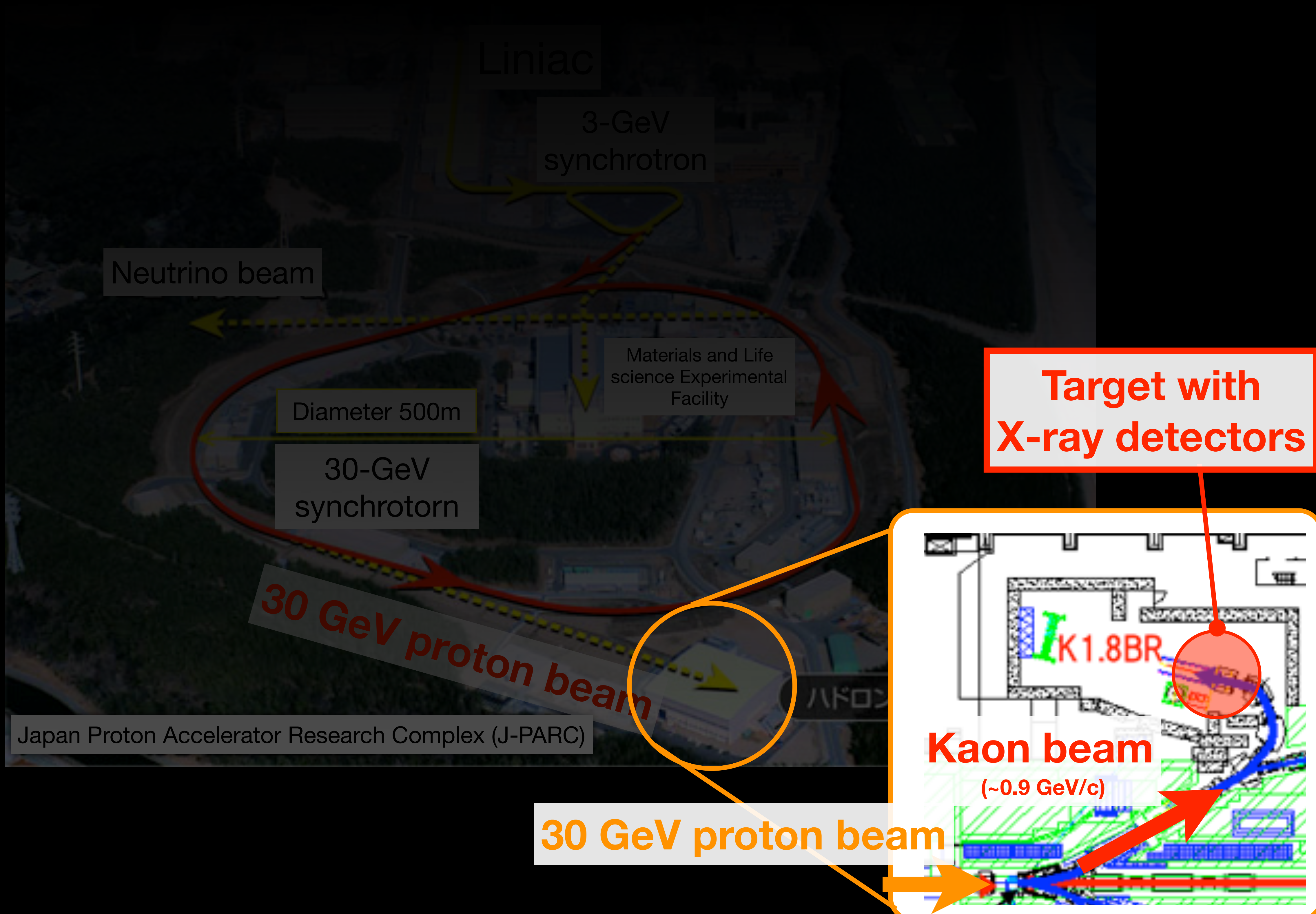
1. Short introduction
2. NIST’s multi-pixel TES array
3. What do we measure ?
4. Experimental setup
5. Yield estimations
6. The first test exp. at NIST
7. Anti-coincidence system
8. Summary

J-PARC (Japan)

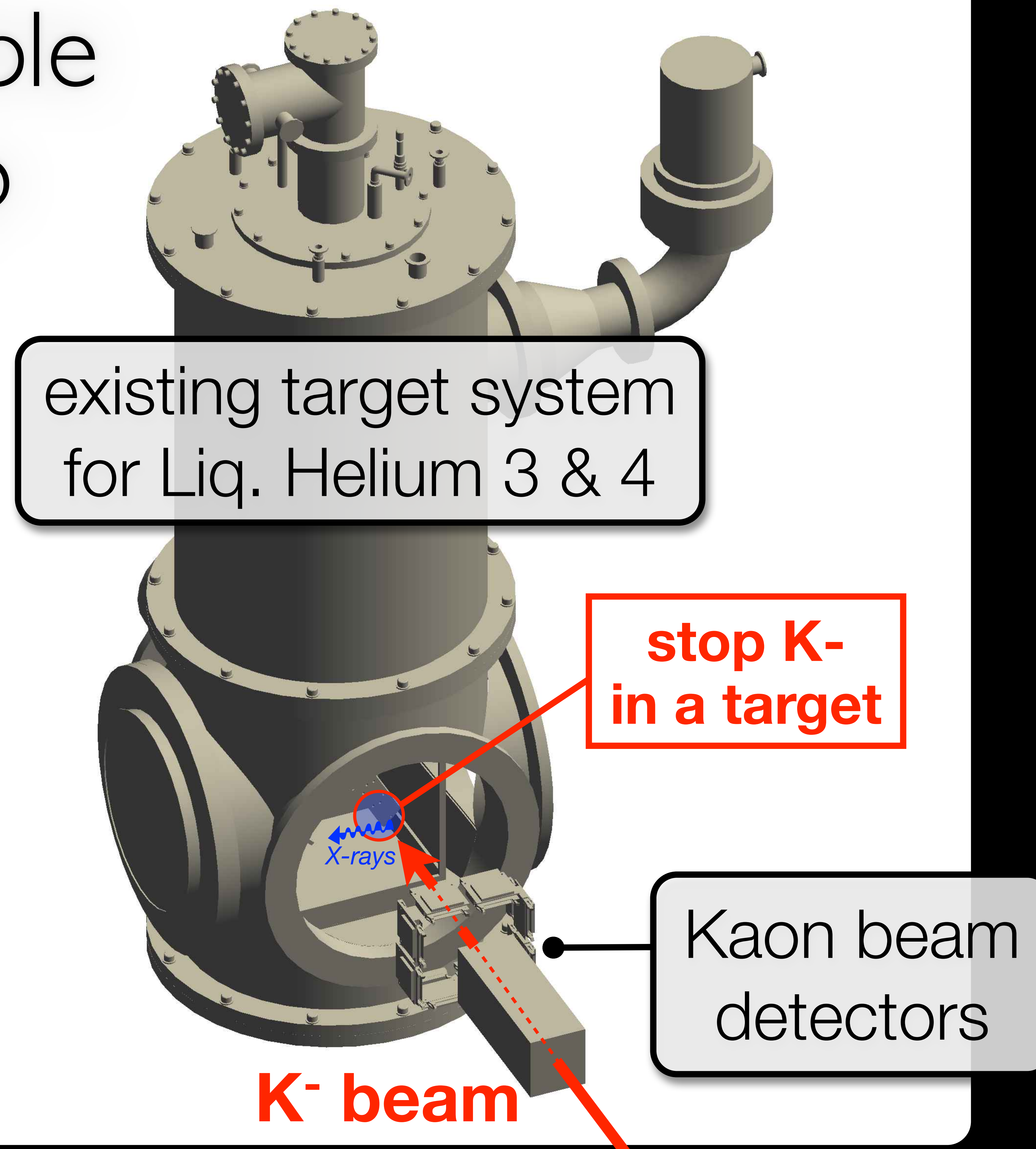
Japan Proton Accelerator Research Complex = J-PARC



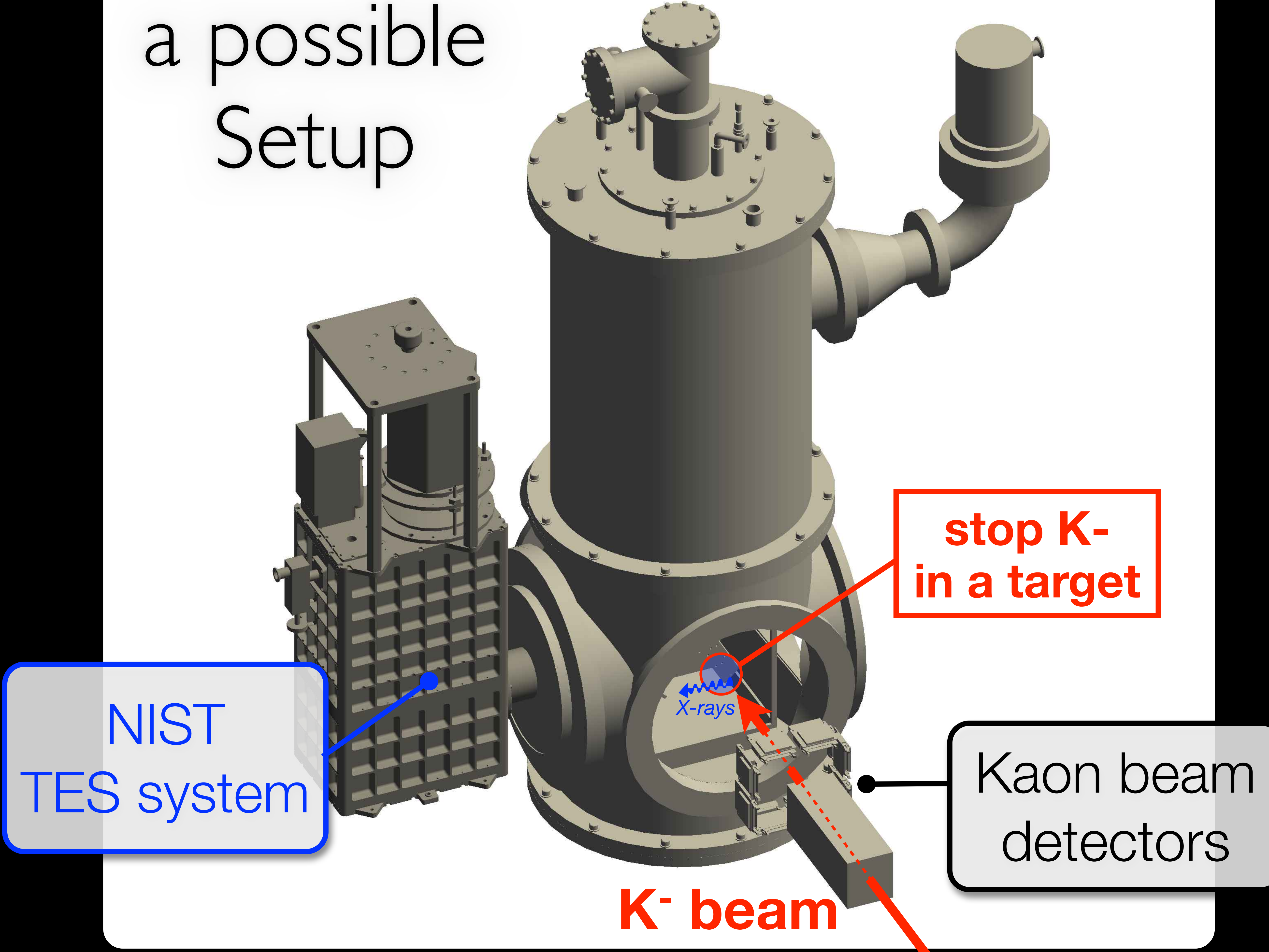
J-PARC (Japan)


Liniac
3-GeV synchrotron
Neutrino beam
Materials and Life science Experimental Facility
Diameter 500m
30-GeV synchrotorn
30 GeV proton beam
Japan Proton Accelerator Research Complex (J-PARC)
Target with X-ray detectors
K1.8BR
Kaon beam
(~0.9 GeV/c)
30 GeV proton beam

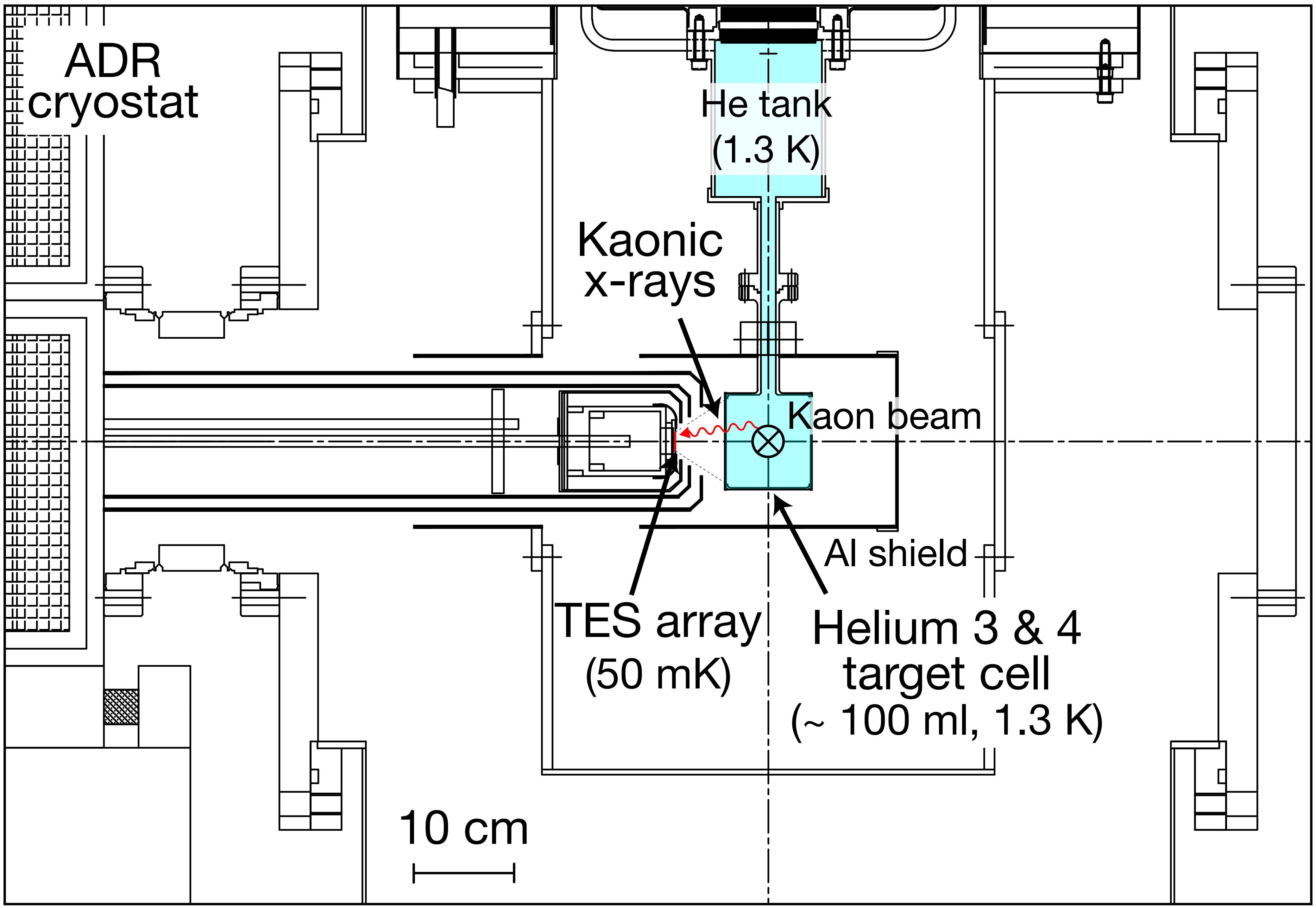
a possible Setup



a possible Setup



Cross section (front view)

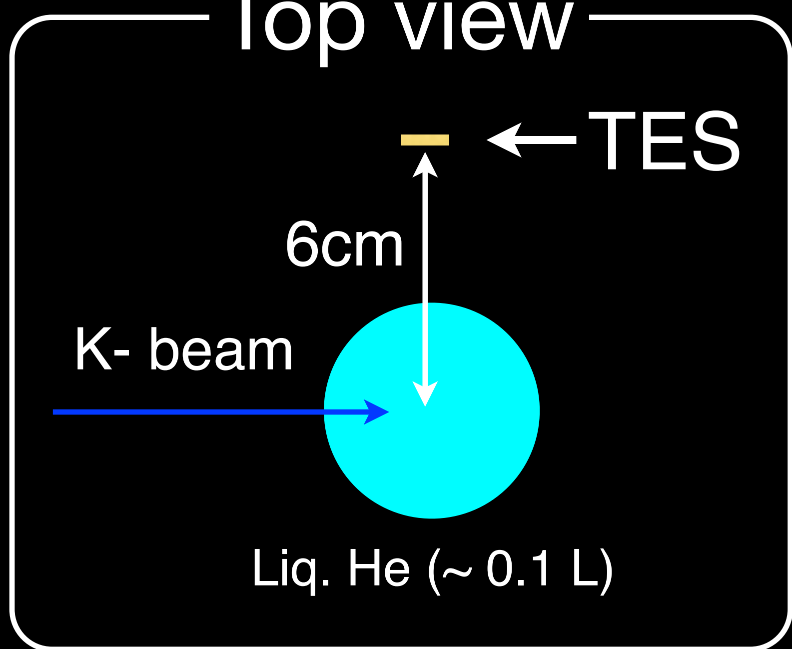


by S. Ishimoto

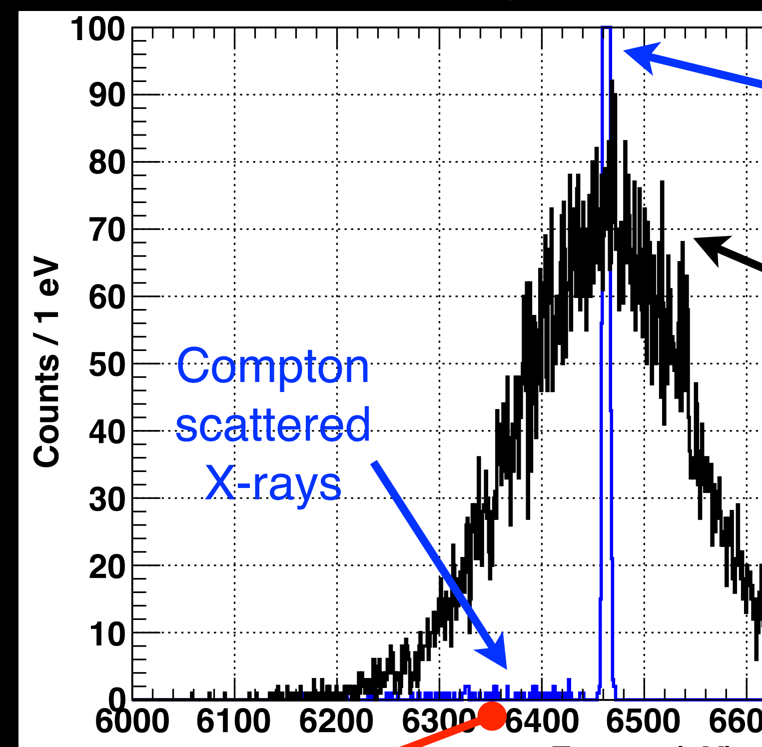
A simple simulation

w/ GEANT4

by H.Tatsuno

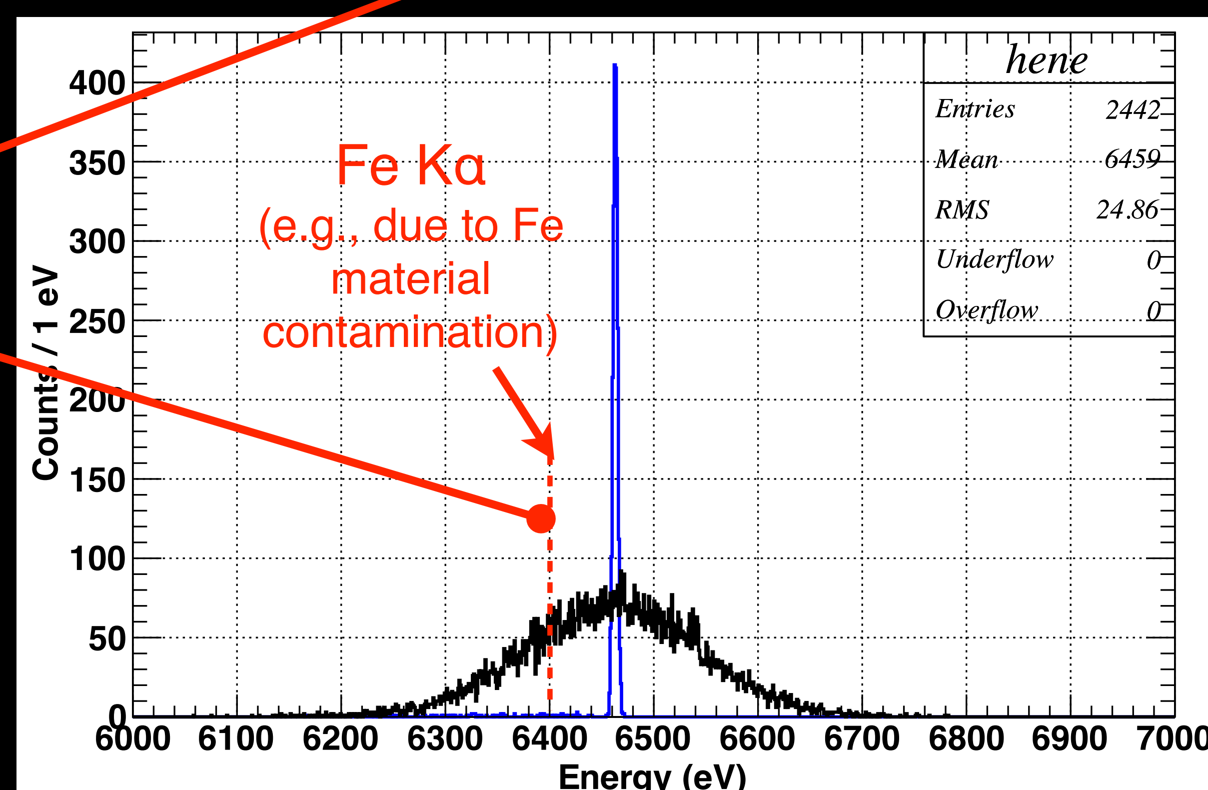


K-^{4}He x-rays from Liq. ^{4}He



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.

5. Yield estimations

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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

6. The first test exp. at NIST

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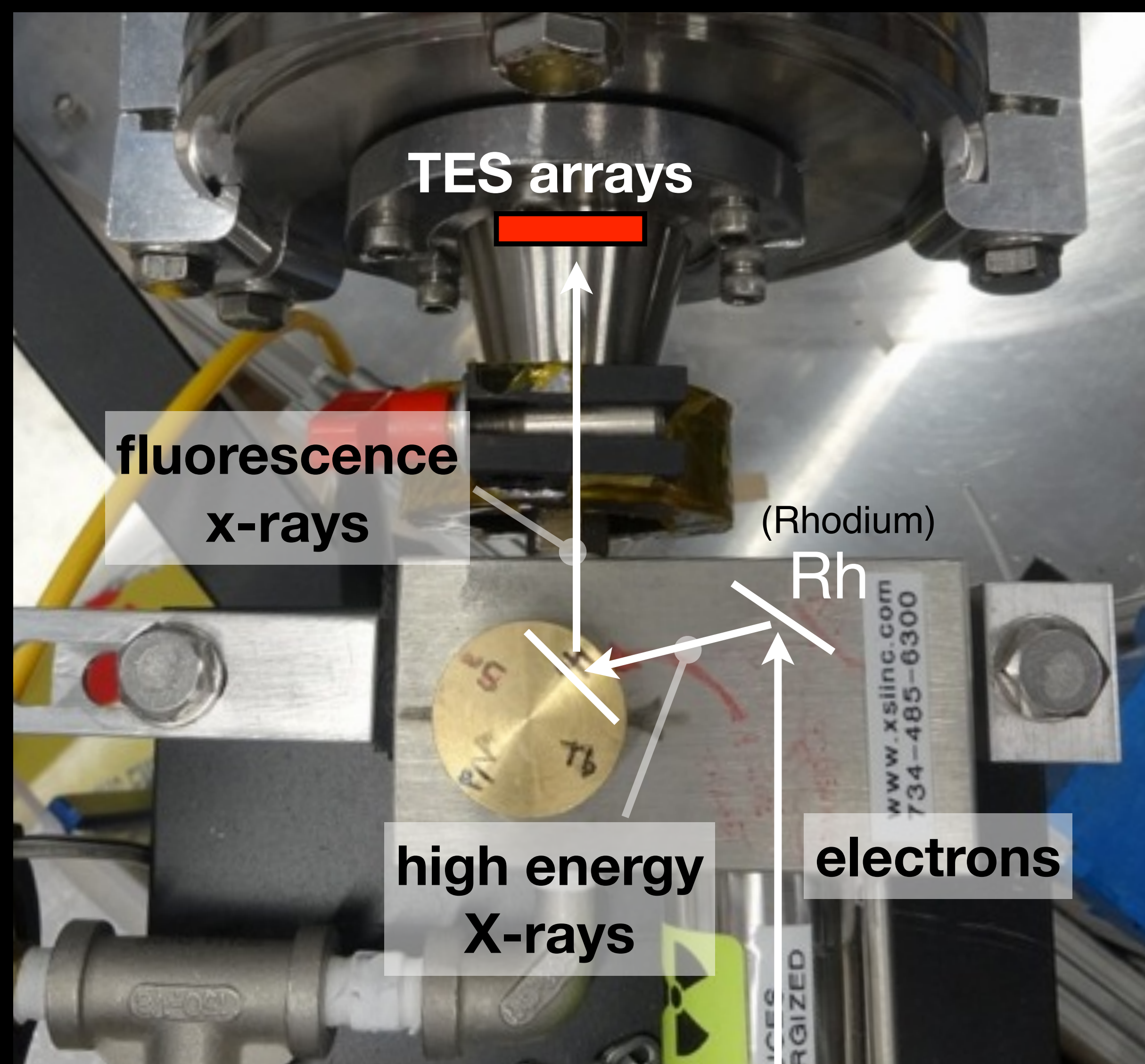
Line calib. experiment @ NIST

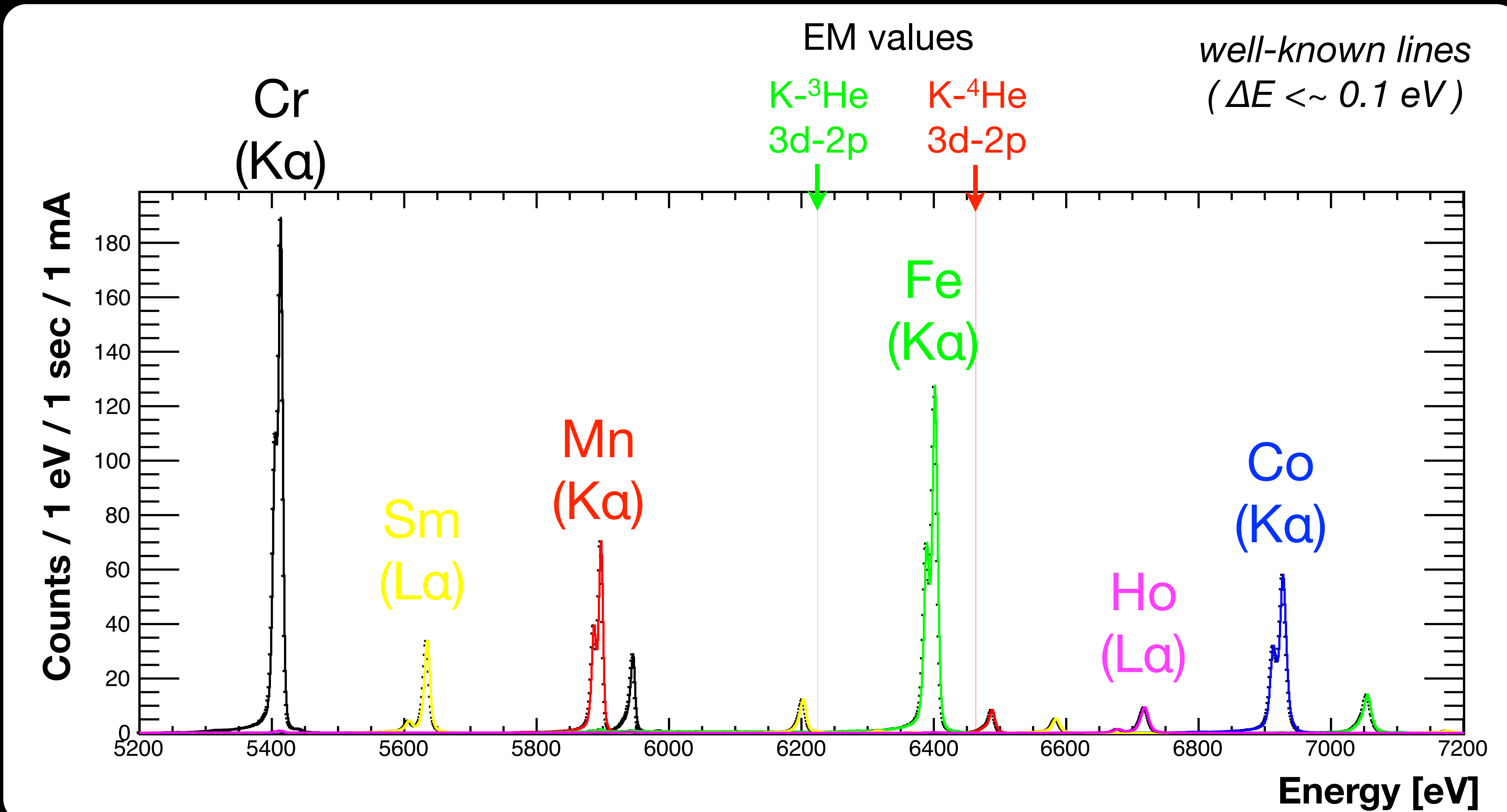
26 Aug. - 6 Sept., 2013



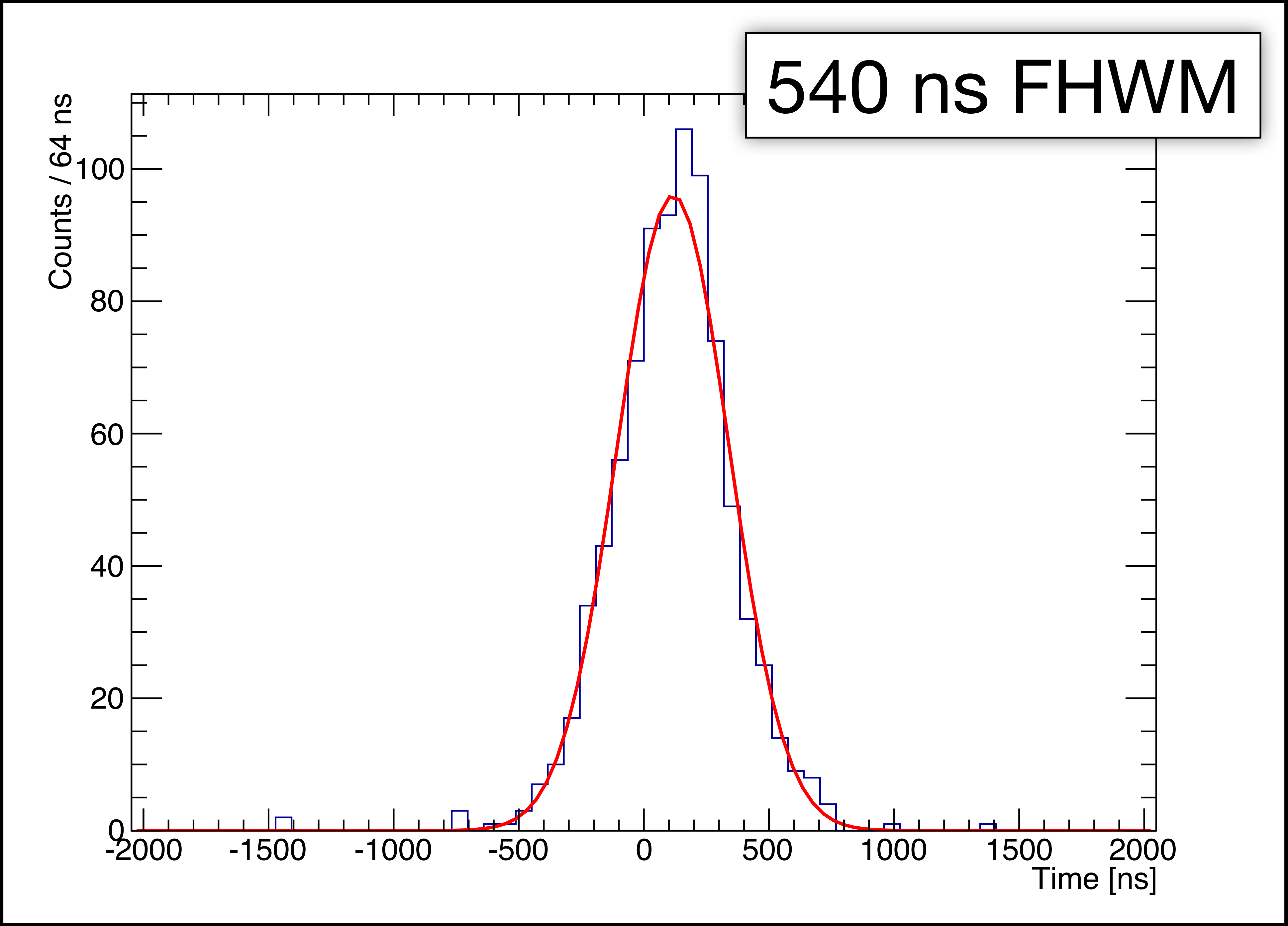
electron gun

Line calib. experiment @ NIST

26 Aug. - 6 Sept., 2013



Timing resolution



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Summary

◉ Next-generation hadronic-atom exp. with **NIST TES array** having great performance of 2~3 eV (FWHM) resolution @ 6keV

◉ π^- ^{3,4}He , K^- ^{3,4}He --> comparison with few-body calc.

◉ new accurate **charged kaon mass**

◉ multi-nucleon process of $\bar{K}$ in nucleus (w/ ‘upper’ & ‘lower’ levels)

in future ◉ w/ k/M-pixel TES : other hadronic atom (Σ-, Ξ-) x-ray spectroscopies

◉ Test experiment without beam was done. (evaluation of basic performance)

◉ future perspective

- 2014 : test experiment with beam (at PSI / TRIUMF / J-PARC ?)
- --> and preparation of LoI / proposal to J-PARC

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- **Tokyo Metropolitan Univ.** : Y. Ezoe, Y. Ishizaki, T. Ohashi
- **KEK** : S. Ishimoto, M. Hazumi
- **Univ. of Tokyo** : M. Ohno