28 Dec, 2013
中性子星核物質研究会@理研

超伝導遷移端マイクロカロリメータを用いたハドロニック原子X線精密分光

A02班 公募研究：『K中間子原子X線分光に向けた
マイクロカロリメータのビーム環境下における性能評価』

理研　岡田信二

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

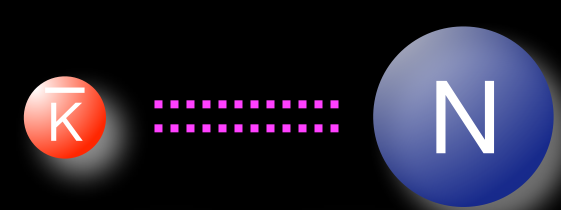
核物質中のK中間子実験

(研究分担者：応田)

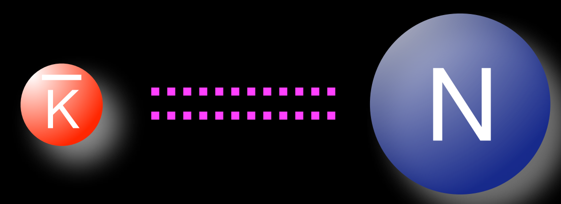
中性子星内部のK中間子発生領域の理解

--> $\bar{K}$-N 相互作用の理解が重要

Kaon condensation in neutron stars
--> Kaon dynamics in nuclear matter



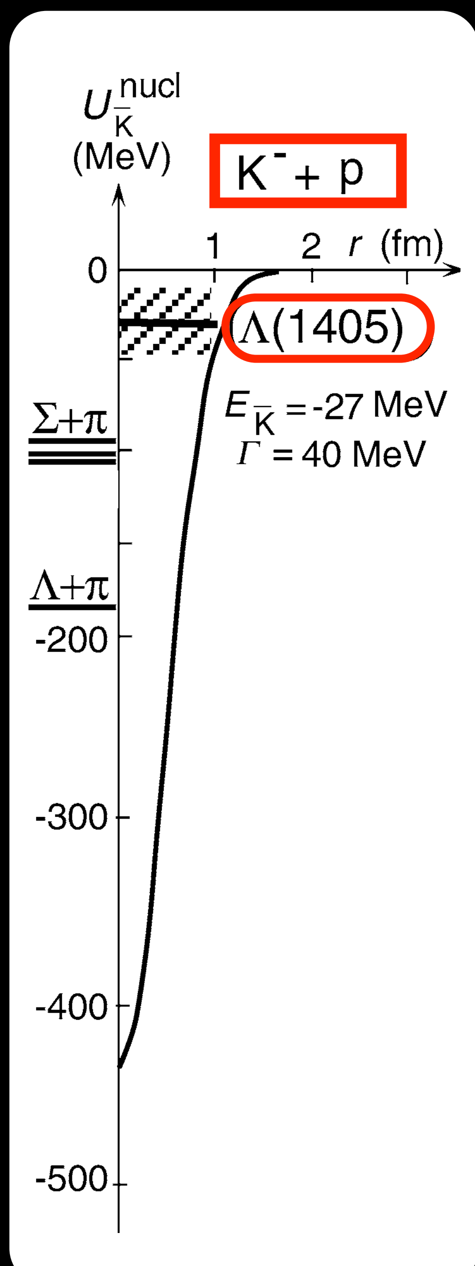
Strongly attractive!

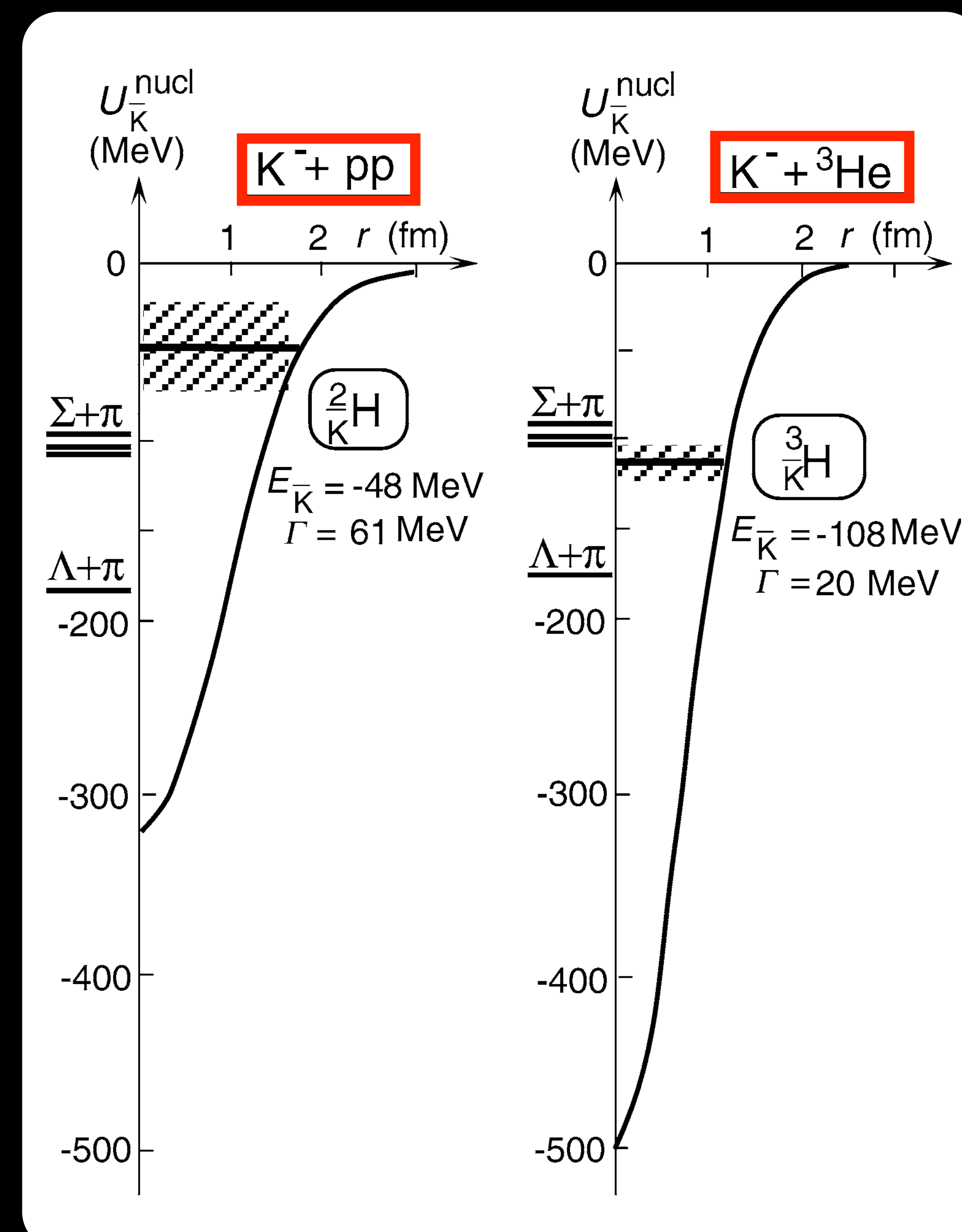


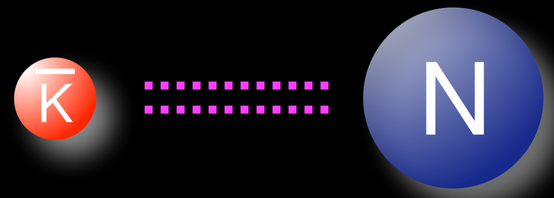
strongly attractive !

Λ(1405) is considered as a K-p nuclear bound state

leading a prediction of **deeply-bound kaonic nuclear cluster**







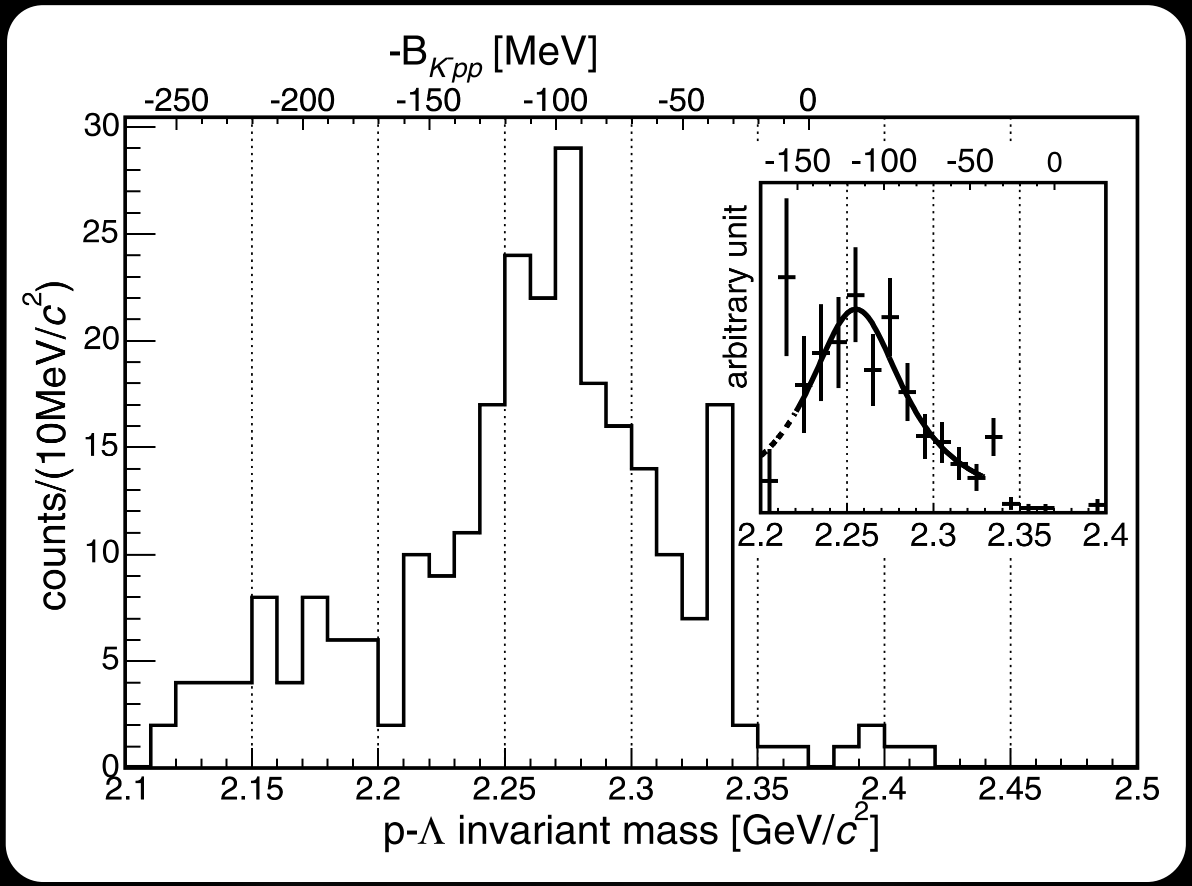
strongly attractive !

many experiments for searching the cluster

still not conclusive

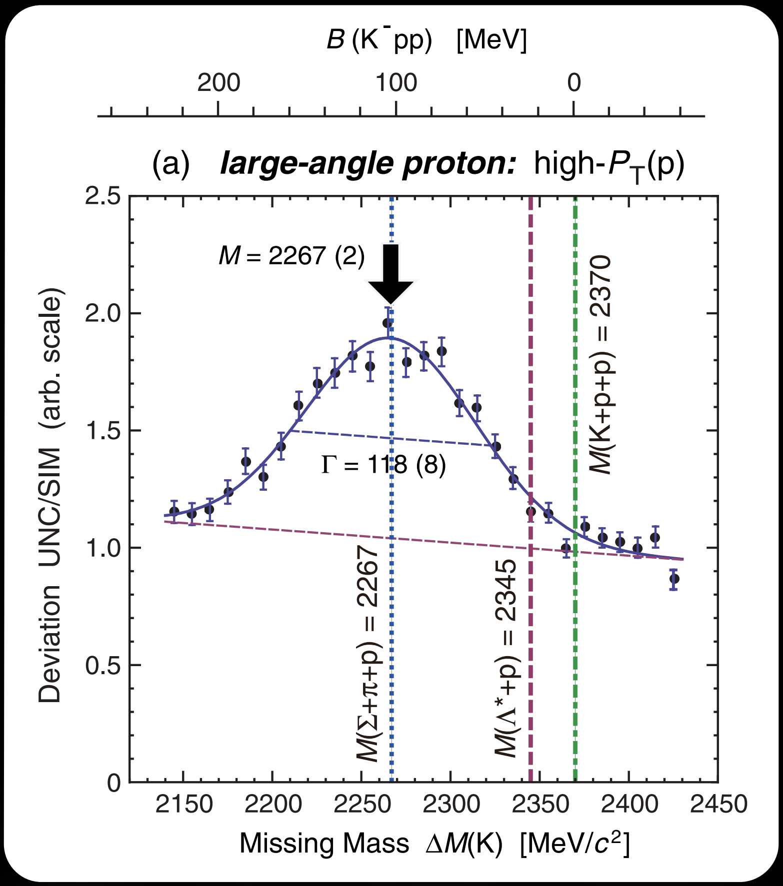
ex) for K-pp clusters

stopped-K^- + A → (Λ + p) + X

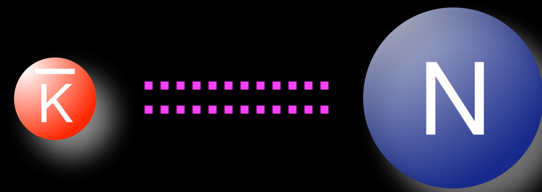


PRL 94, 212303 (2005)

2.85GeV-p + p → (Λ + p) + K^+

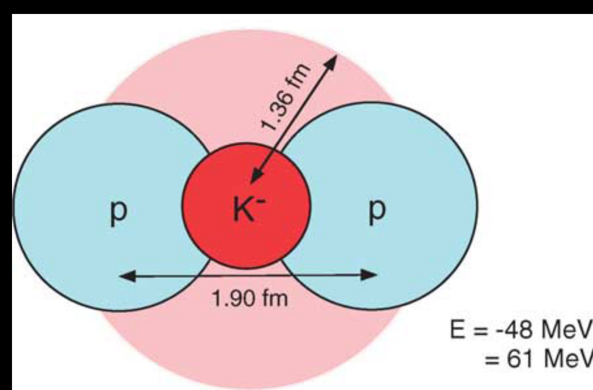


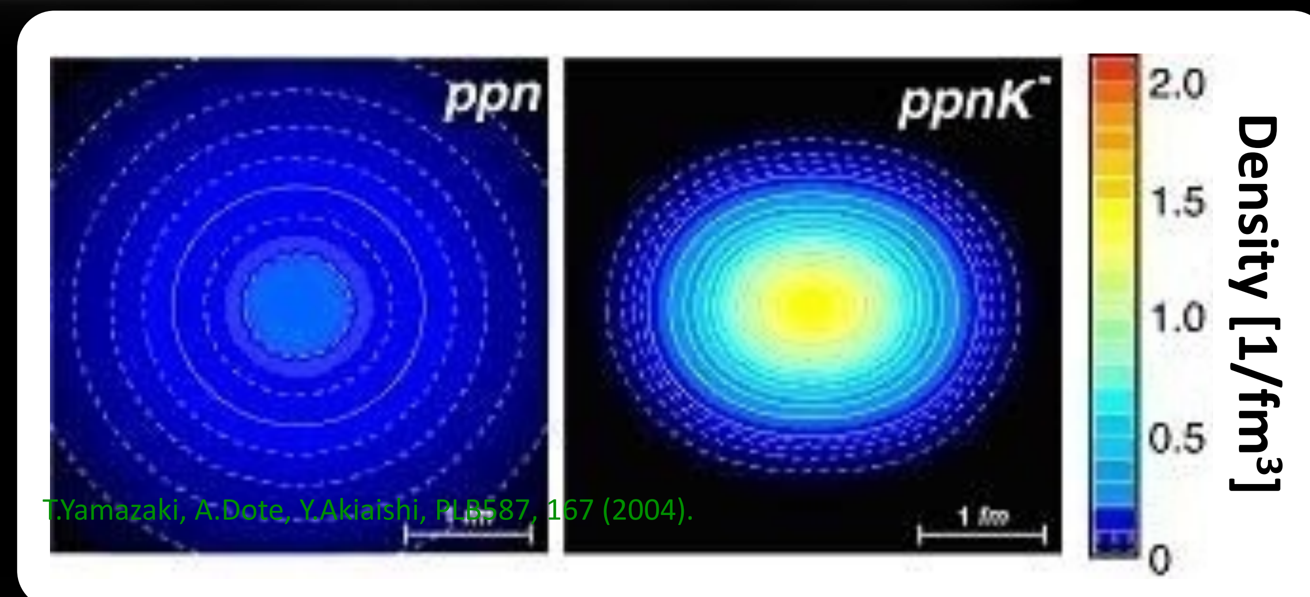
PRL 104, 132502 (2010)



strongly attractive !

a possibility of higher density
beyond normal nuclear-matter density

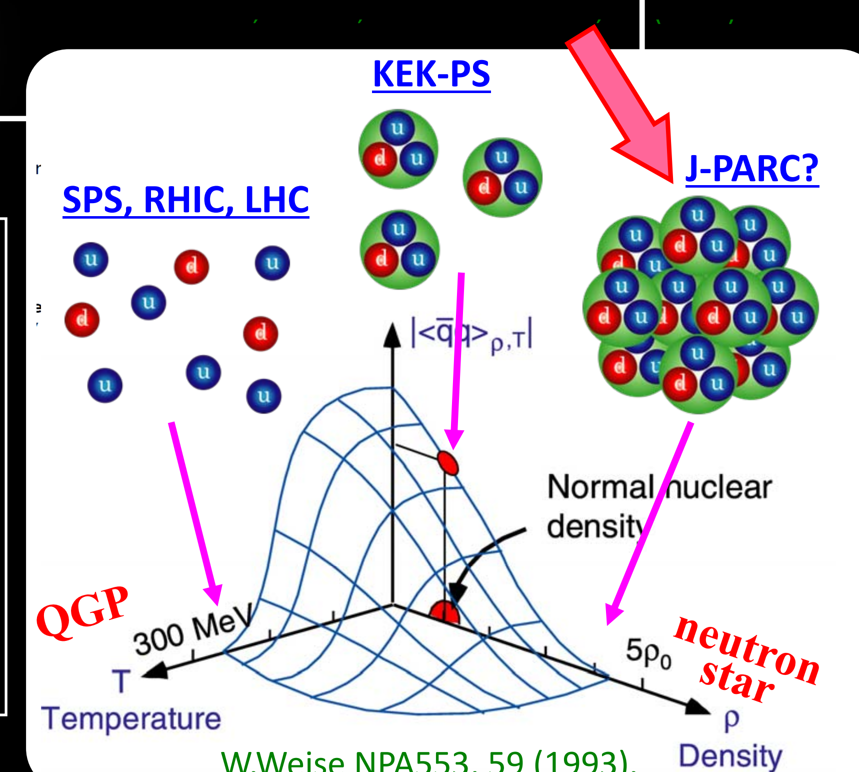




Phys. Lett. B587, 167 (2004)

→ the in-medium **mass modification** effect as a function of matter density?

→ the possibility of the kaon condensation in a **neutron star** ?



How do we study the $\bar{K}$ - Nucl. interaction at low energy?

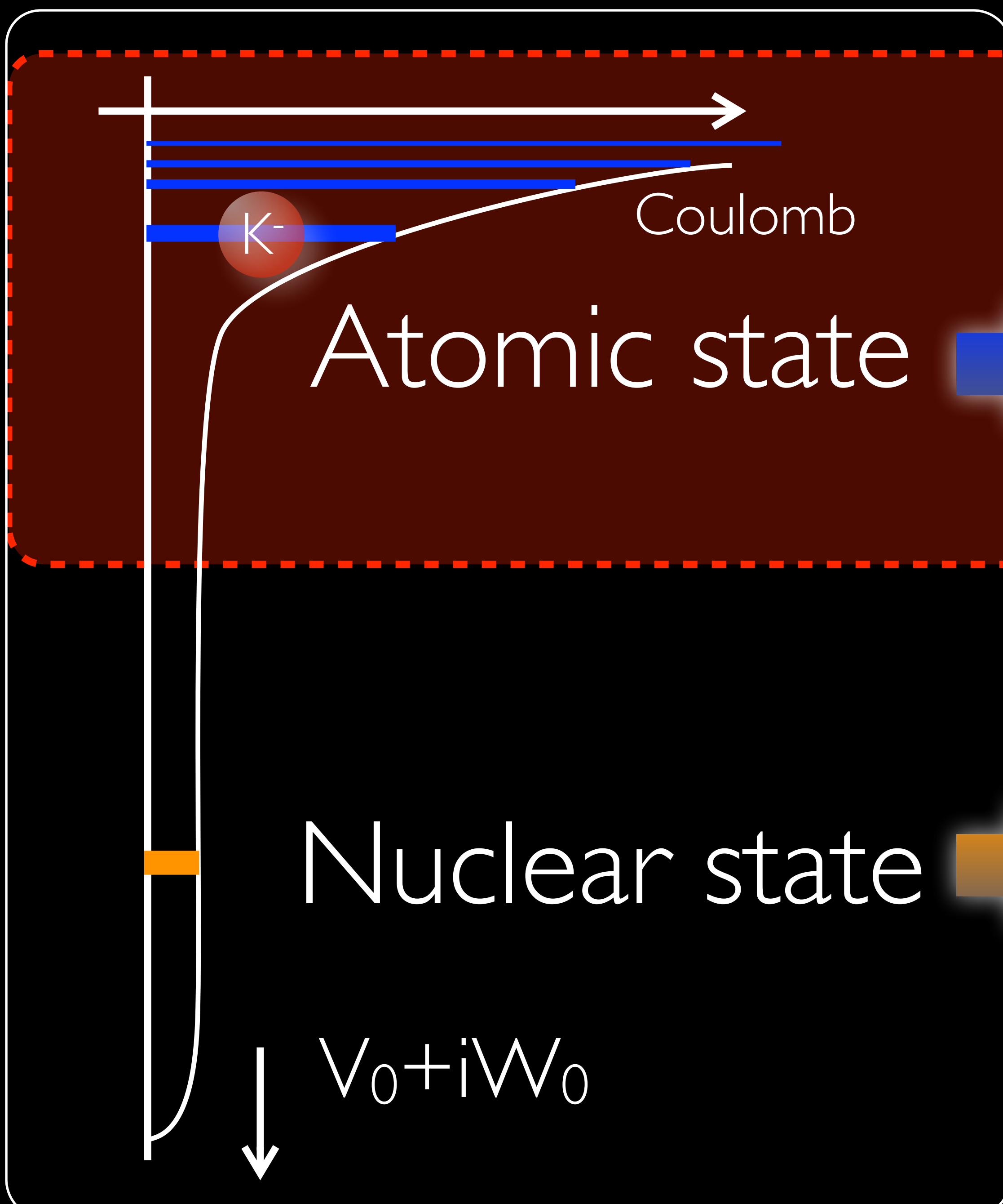
Kaon low-energy scattering experiment
is **difficult** due to the short lifetime (~12 nsec)

⇩

Kaon-nucleus **bound states**

How do we study the $\bar{K}$ - Nucl. interaction at low energy?

K^- - Nucl. potential



本公募研究(A02)

Precision x-ray measurement

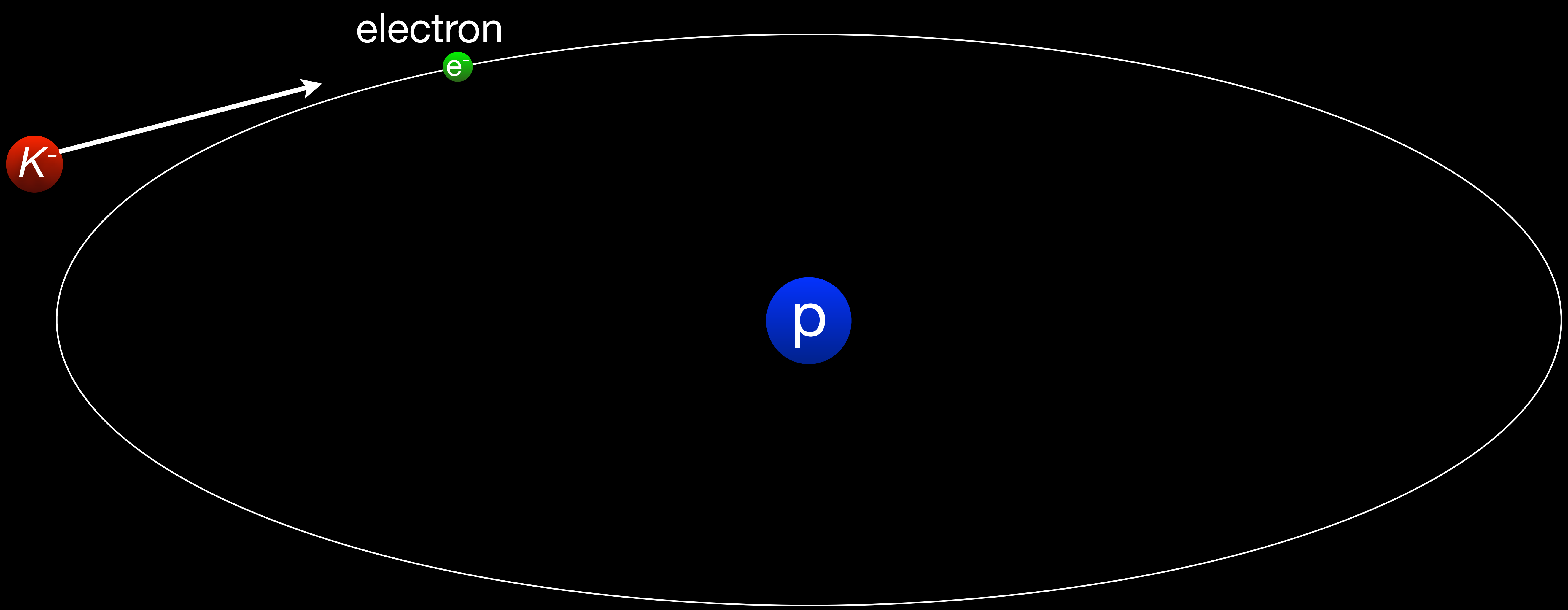
計画研究(A02)

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

-> still no conclusive results

Coulomb bound state
- Kaonic atom -

Hydrogen

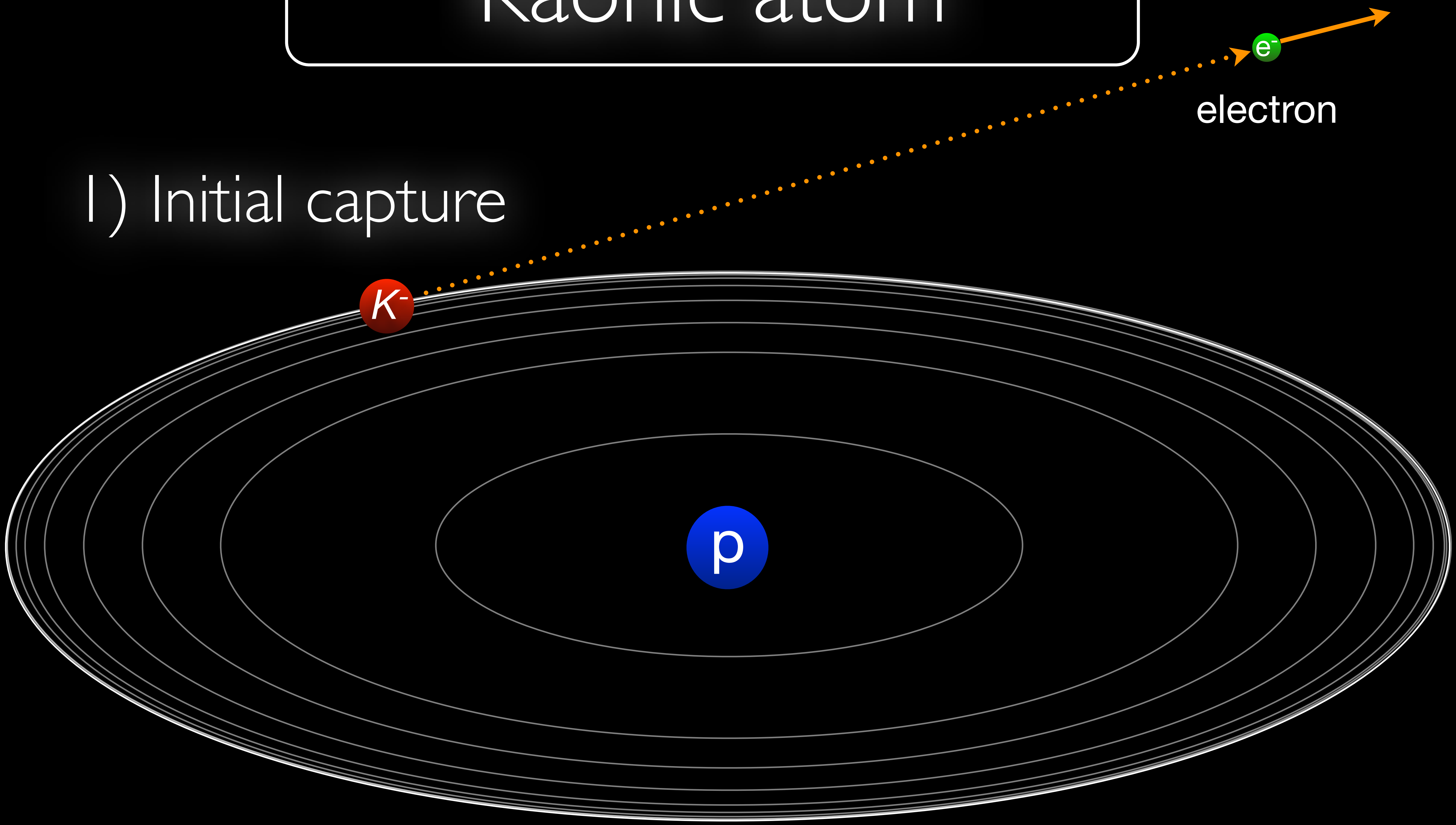


principal quantum number

$n = 1$

Kaonic atom

1) Initial capture



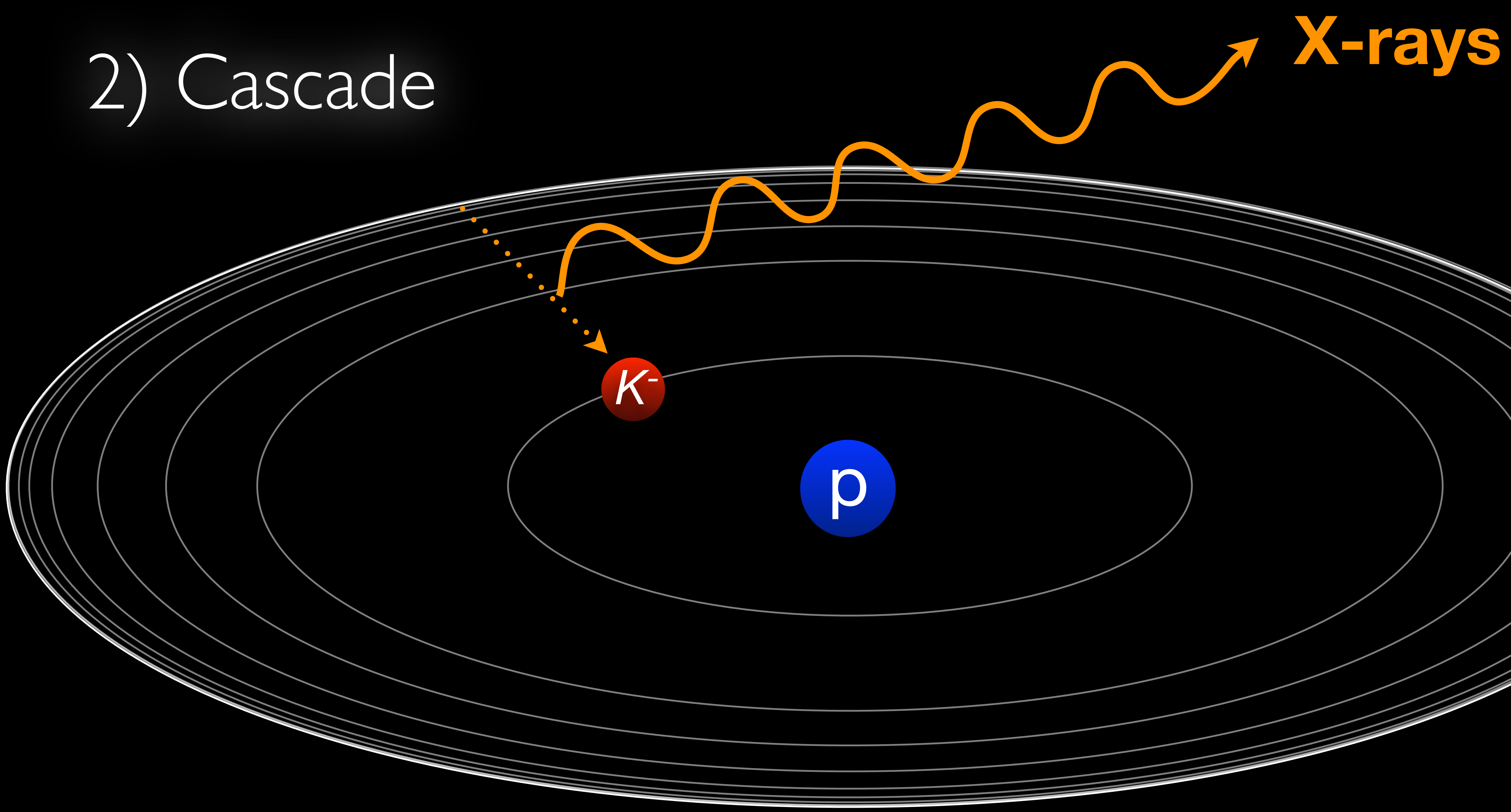
principal quantum number

$n \sim sqrt(M^*/m_e) \sim 25$

(M^* : K-p reduced mass ~ 323 MeV)

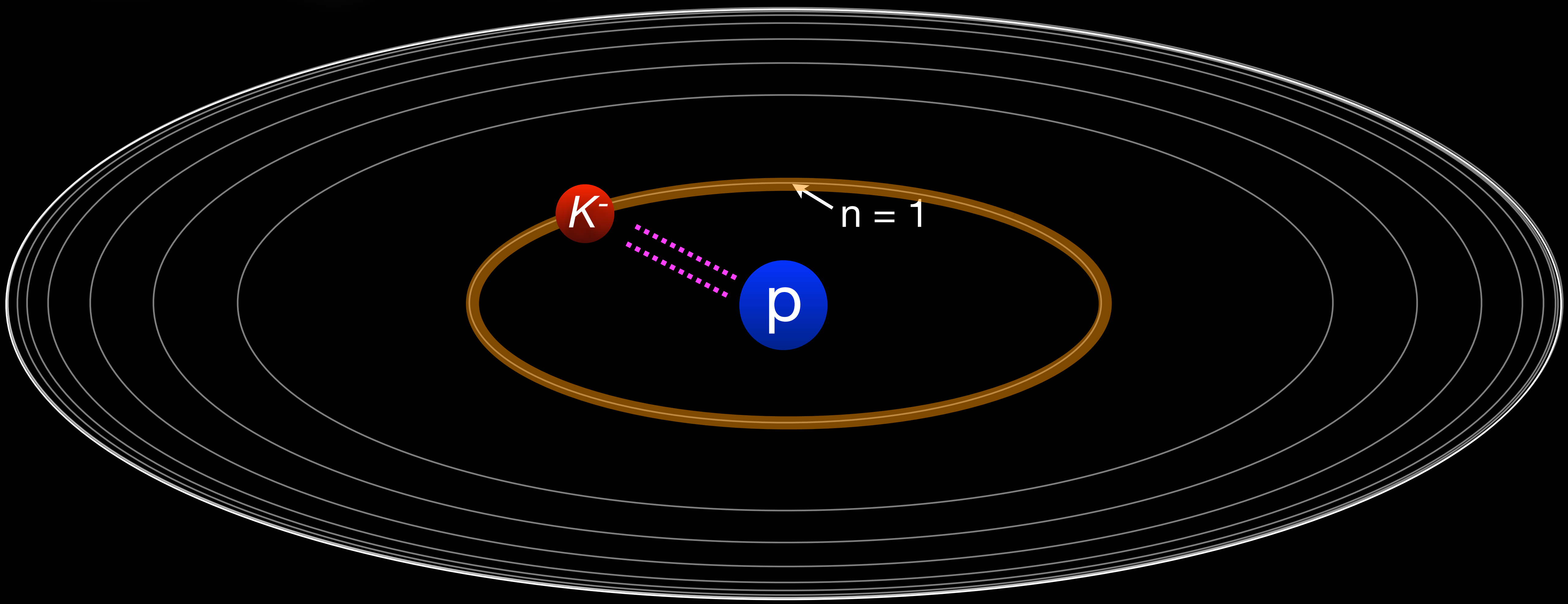
Kaonic atom

2) Cascade



Kaonic atom

3) Strong interaction



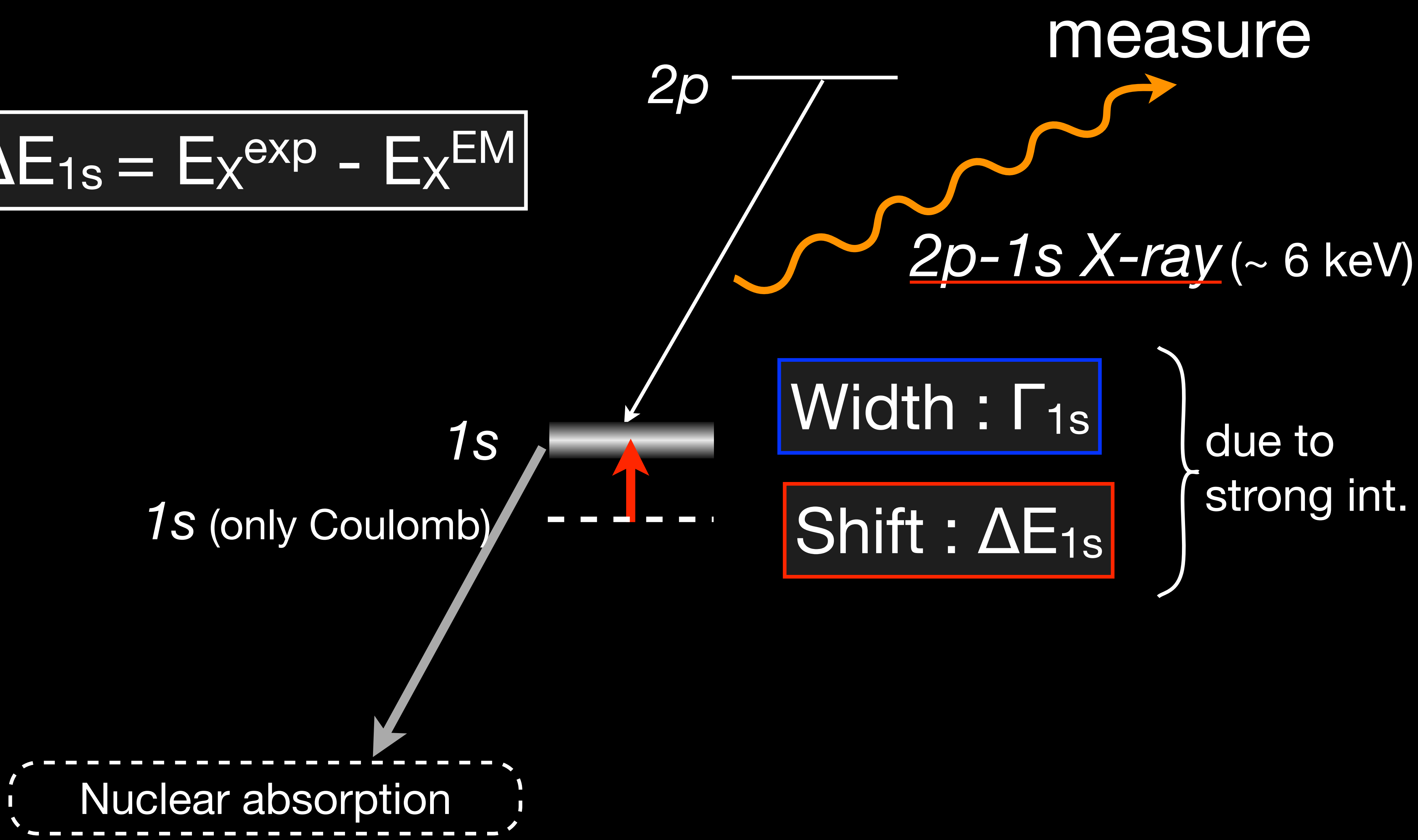
4) nuclear absorption

How we observe the strong interaction ?

K-atom x-ray spectroscopy

Z = 1 (Kaonic hydrogen)

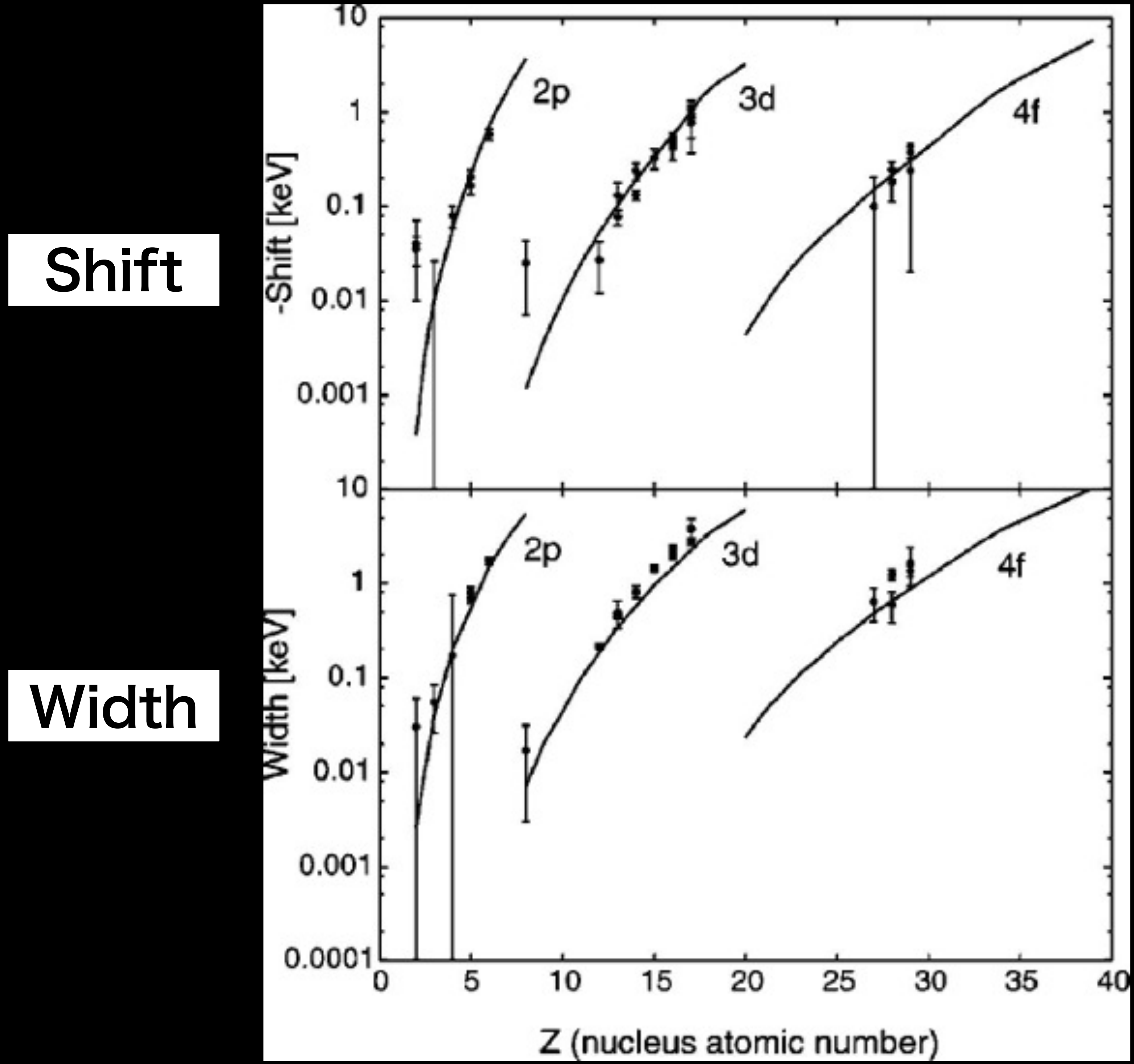
$\Delta E_{1s} = E_X^{exp} - E_X^{EM}$



Data & a theory for Z ≥ 2 K-atom

Shift and width for last orbit

SU(3) Chiral Unitary Model



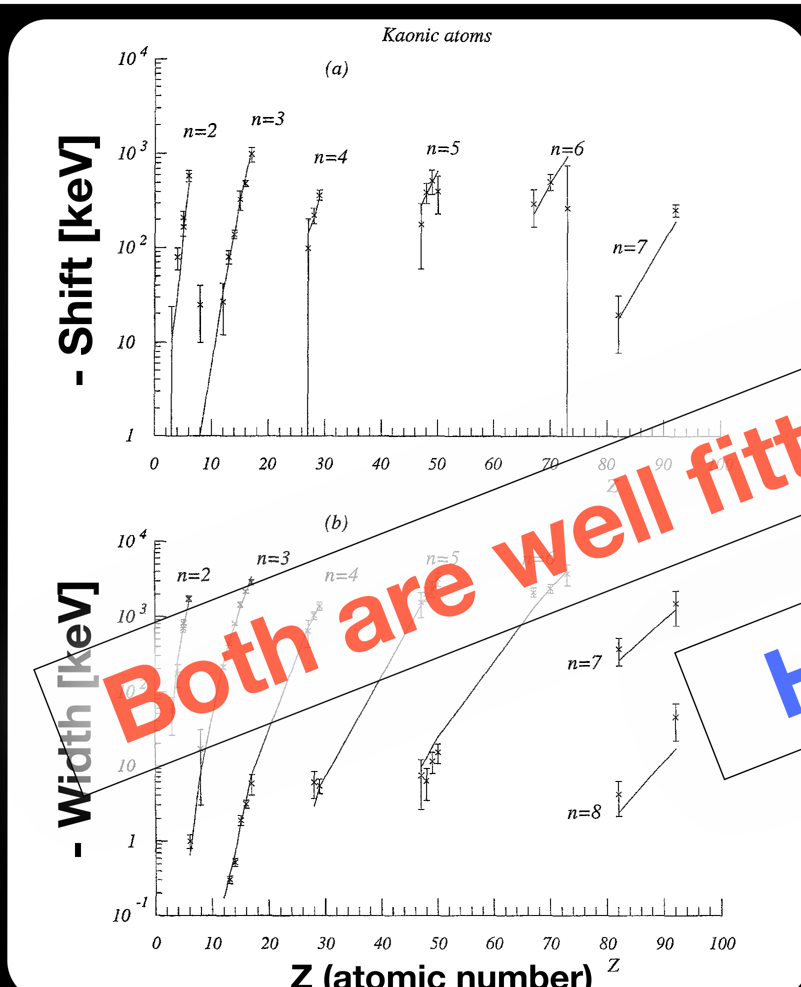
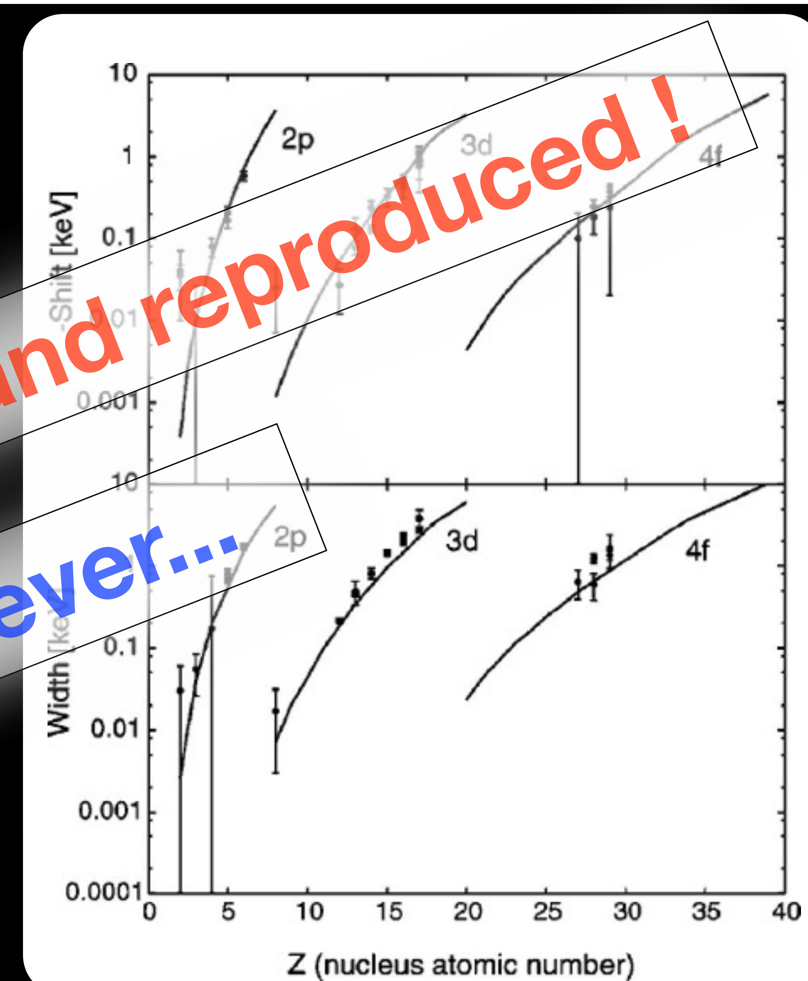
Plot w/error bar
... experimental data

Solid line
... a theoretical calc.

S.Hirenzaki, Y.Okumura, H.Toki, E.Oset, and A.Ramos
Phys. Rev. C 61 055205 (2000)

Two theoretical approaches

Two theoretical approaches

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

Both are well fitted and reproduced !

However...

Two theoretical approaches

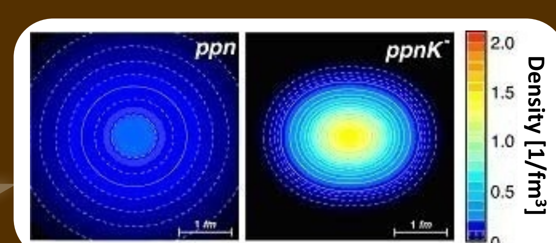
approach	Phenomenological	Fundamental
model	Density-dependent optical potential	SU(3) chiral unitary
	$V = -\frac{2\pi}{\mu}\left(1+\frac{\mu}{m}\right)\bar{a}\rho(r),$ $a \to a_0 + A_0[\rho(r)/\rho(0)]^{\alpha},$	$2\mu V_{opt}(r) = -4\pi\eta a_{eff}(\rho)\rho(r),$

potential depth

Open problem !

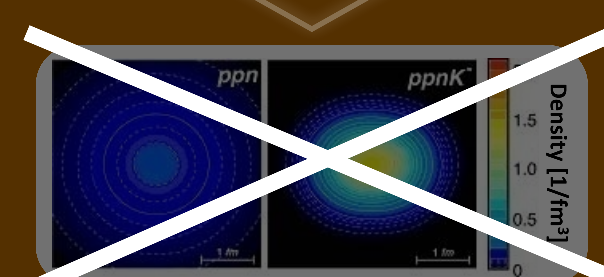
deep (-V_{Real} = 150 ~ 200 MeV)

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



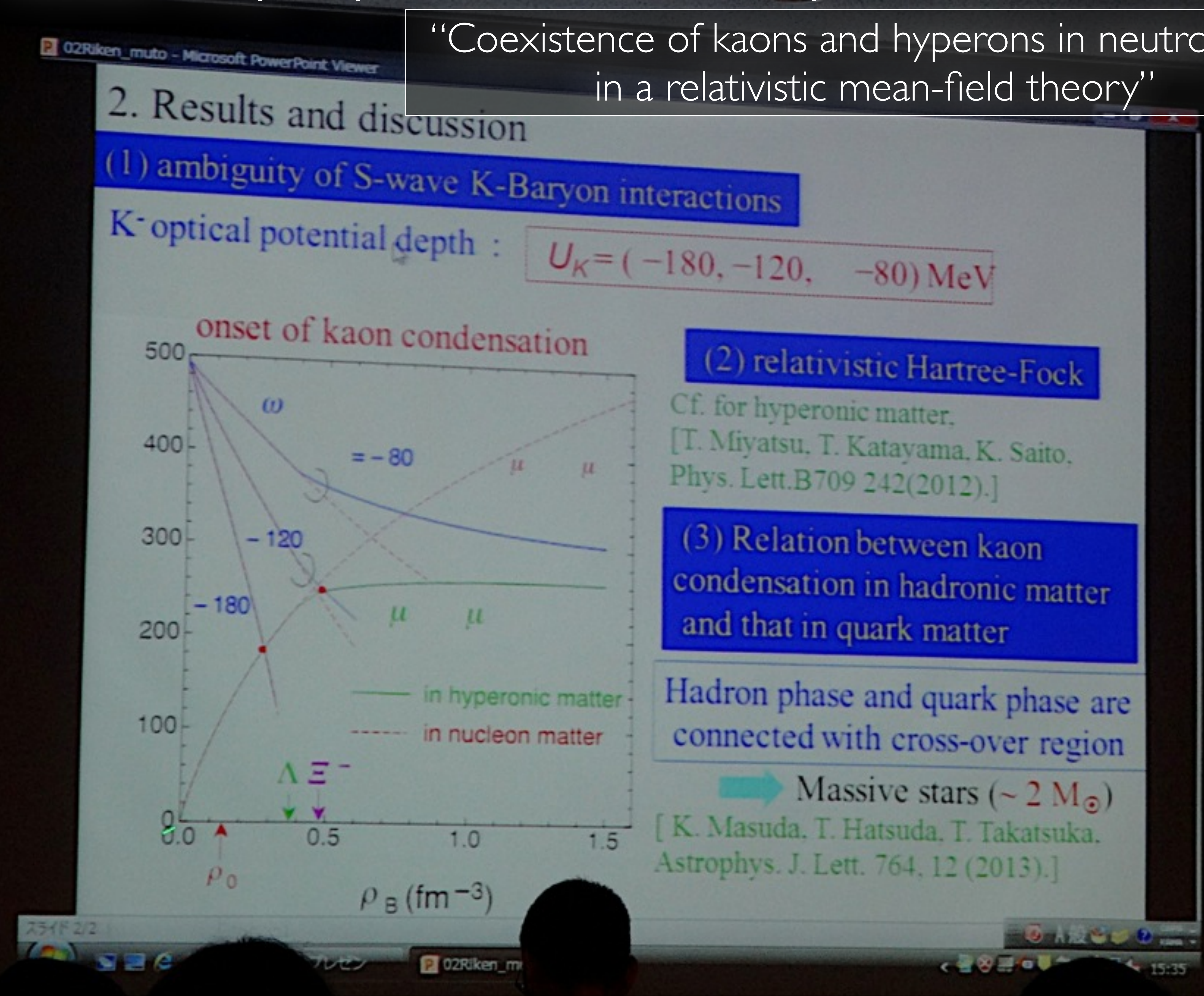
predicts ***deeply bound K- clusters***
(high density matter like ***neutron star****)*

unlikely



Yesterday's presentation by Prof. T. Muto

"Coexistence of kaons and hyperons in neutron stars in a relativistic mean-field theory"



Kaonic Helium 2p level

30 years ago!

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

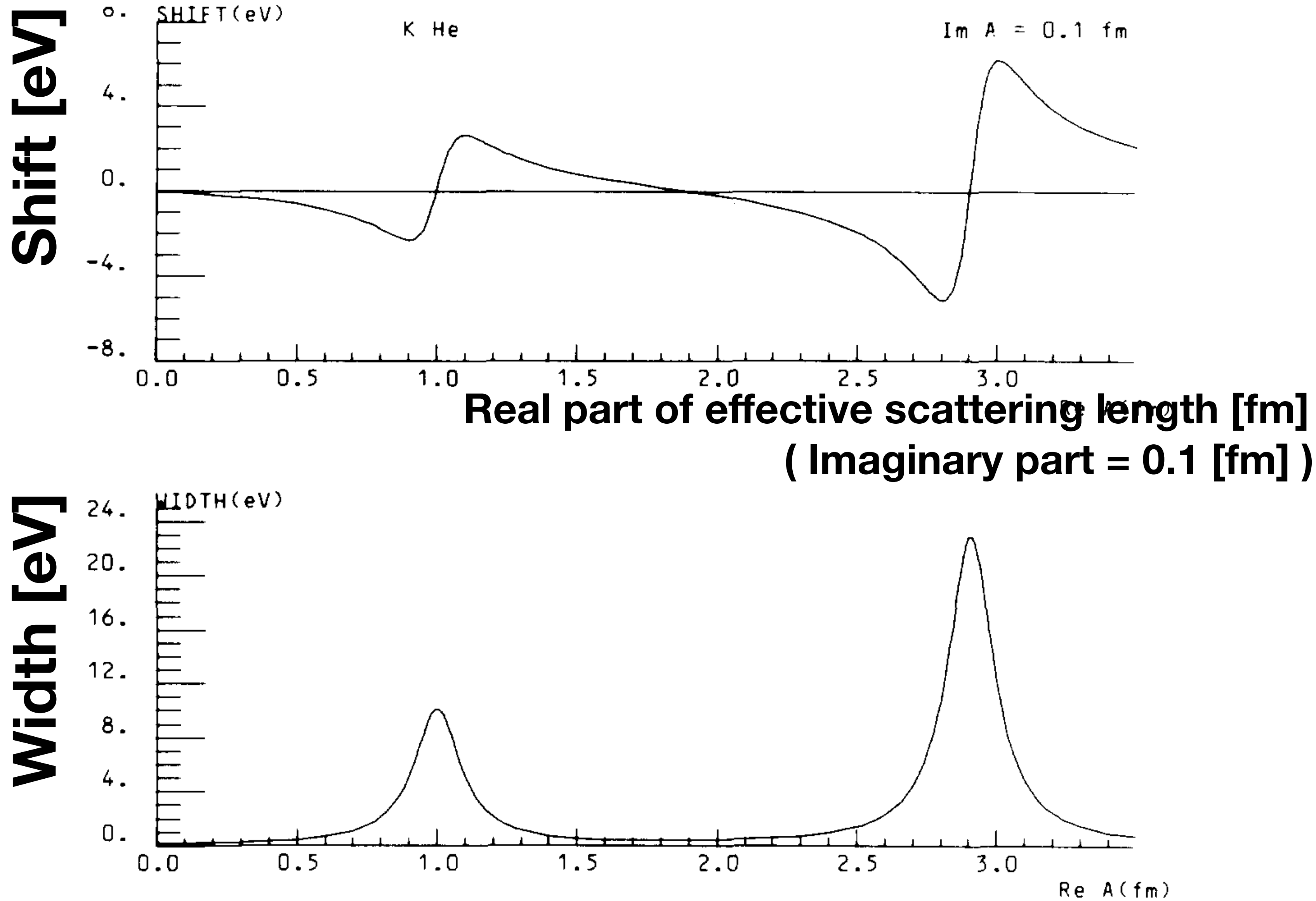
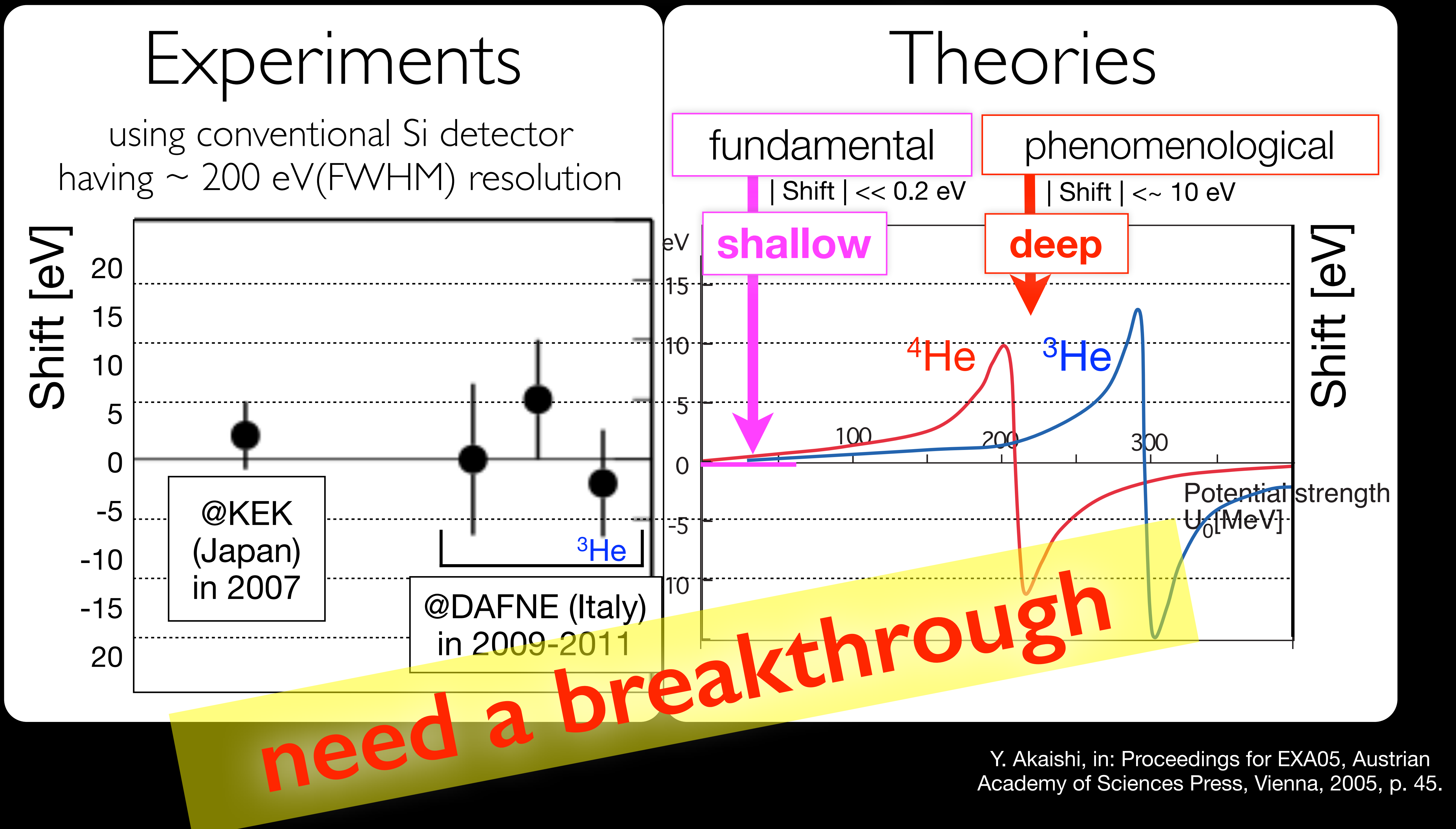


Fig. 5. Calculated strong interaction shift and width for kaonic helium as a function of the value of the real part of $\bar{a}$. The calculations used $a_{\rm I} = 0.1$ fm.

Experiments vs. Theories

- Kaonic He atom case (for 6 keV x-rays) -

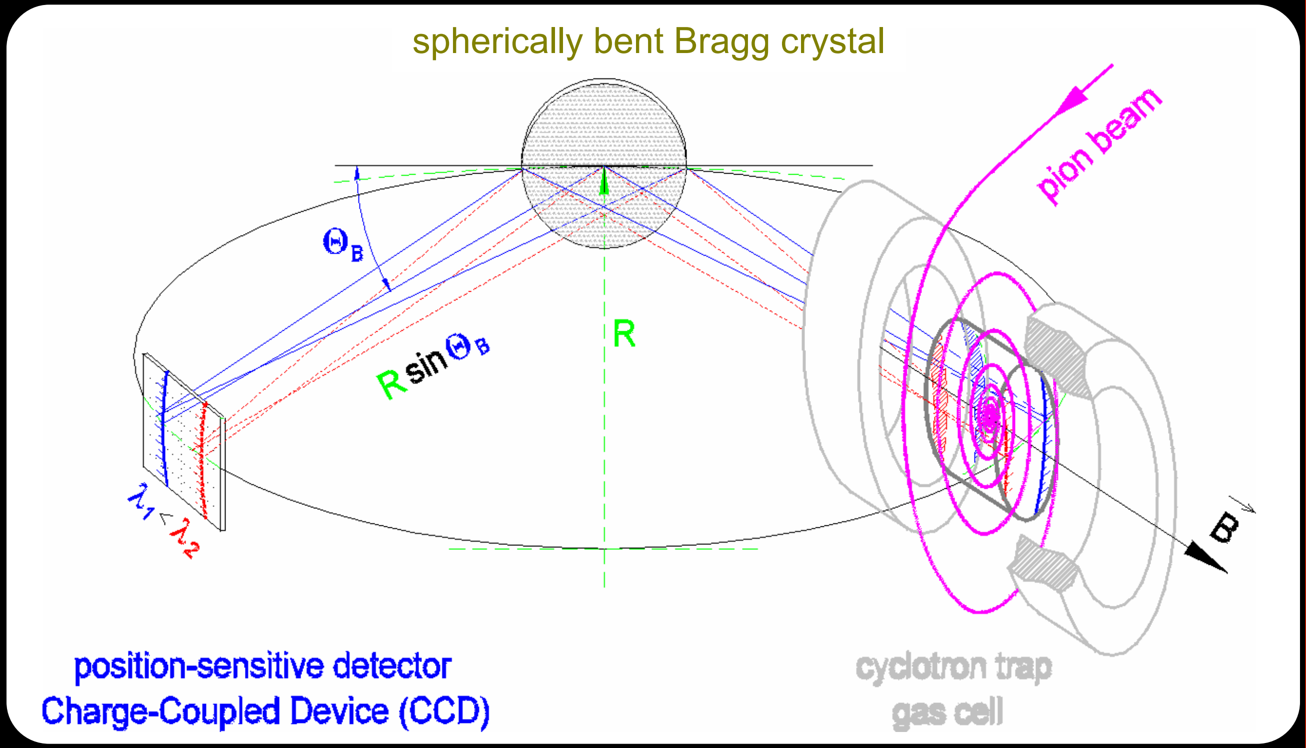


Y. Akaishi, in: Proceedings for EXA05, Austrian Academy of Sciences Press, Vienna, 2005, p. 45.

Next-generation K-atom experiment

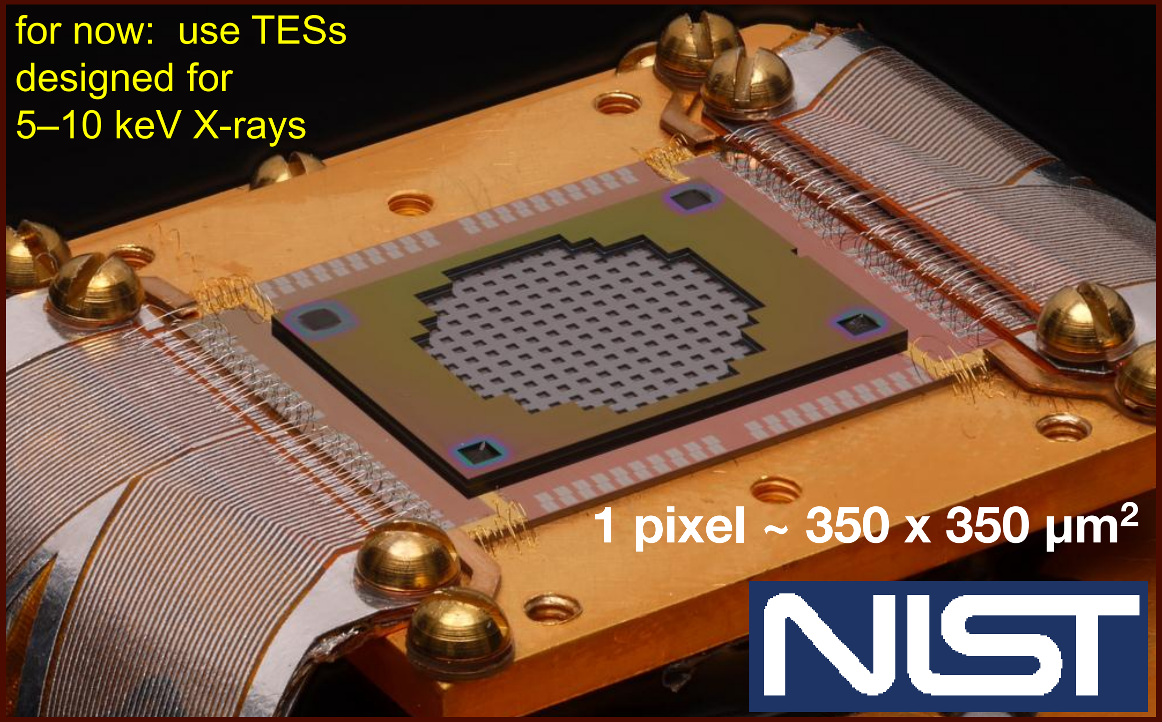
Next-generation K-atom exp.

1. Crystal spectrometer



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

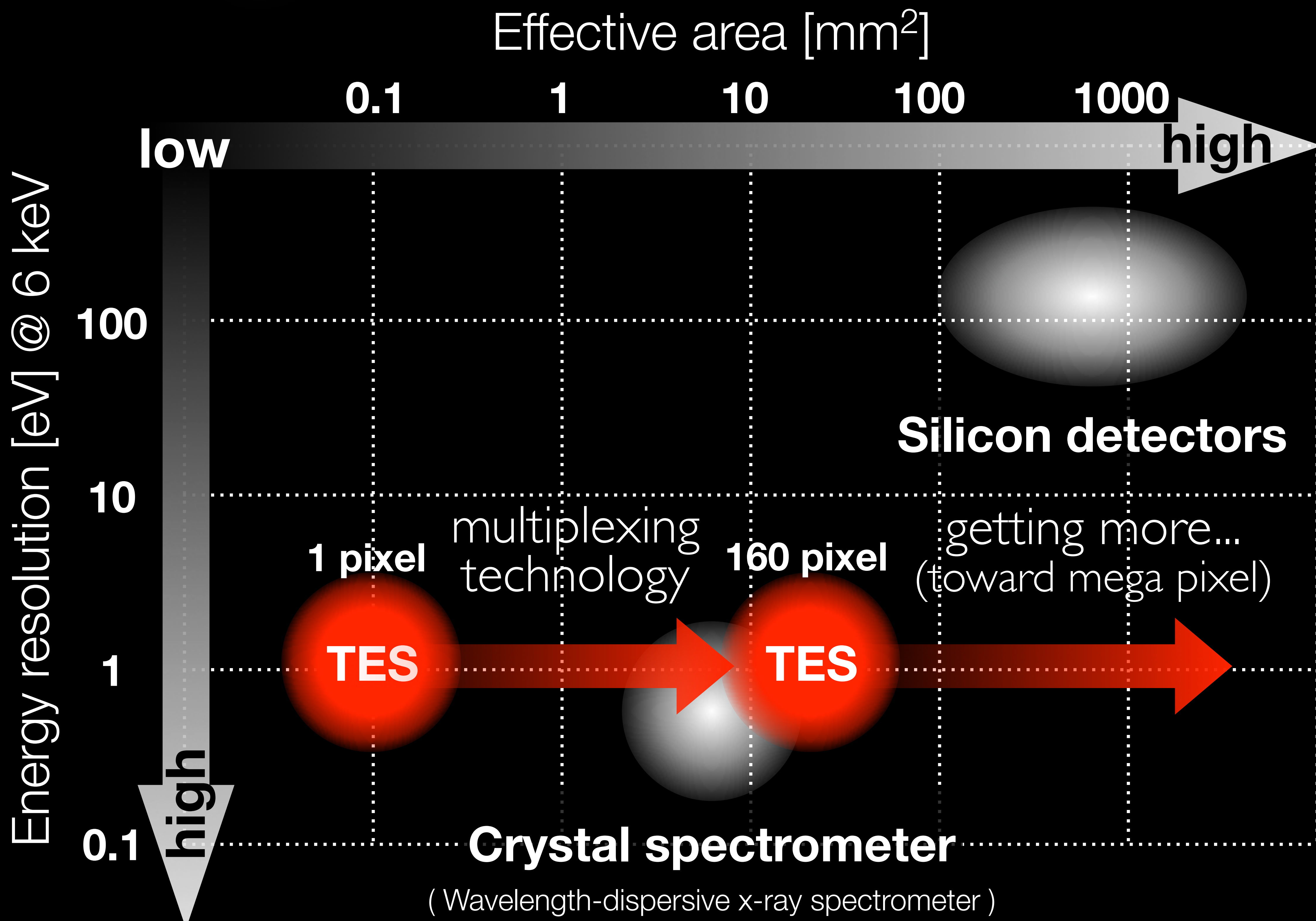
2. Microcalorimeter



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

-> small acceptance

Why TES Microcalorimeter ?



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

Why TES Microcalorimeter ?

1. High collection efficiency

- Multi device (Array)
- Large absorber

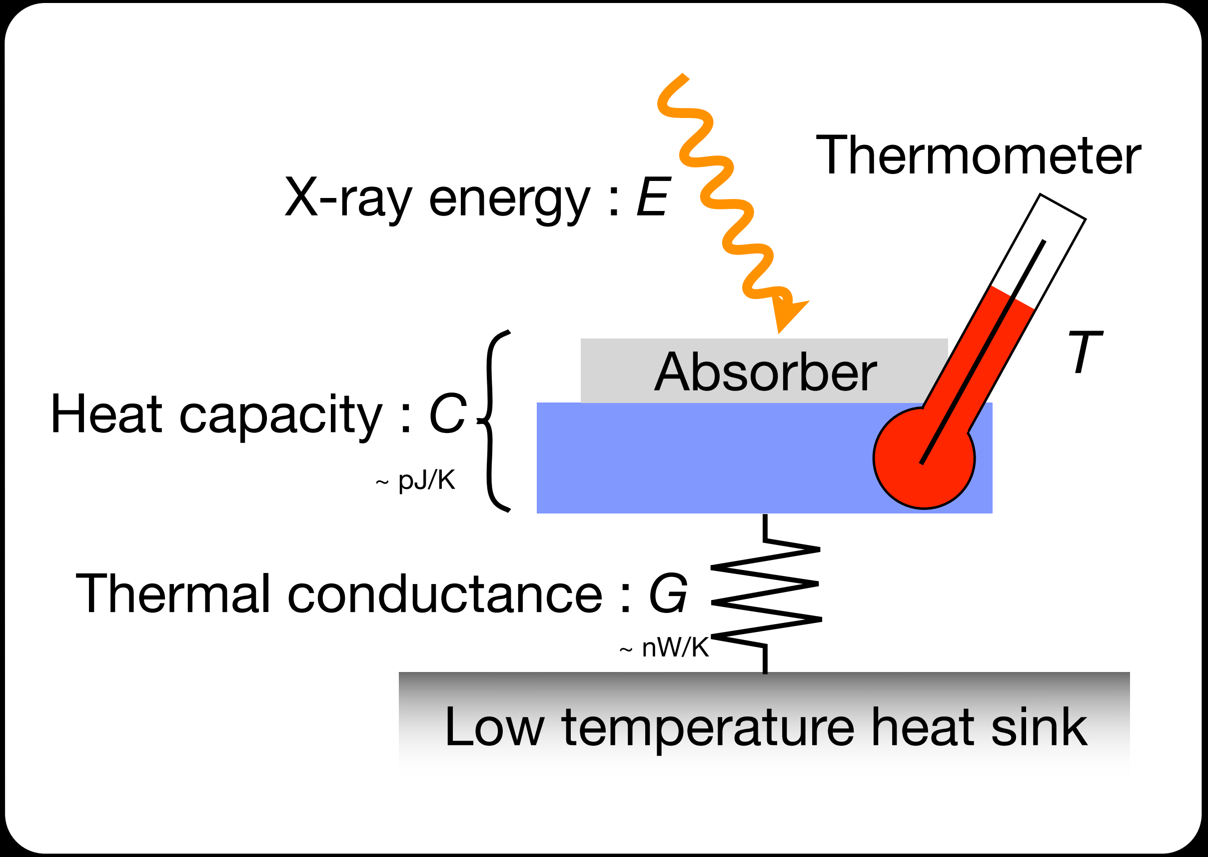
2. Compact and portable

limited beam time, then need to remove

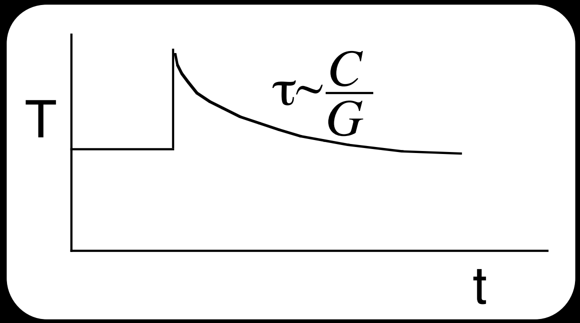
(at J-PARC, DAΦNE etc.)

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 (~ 100 μs)



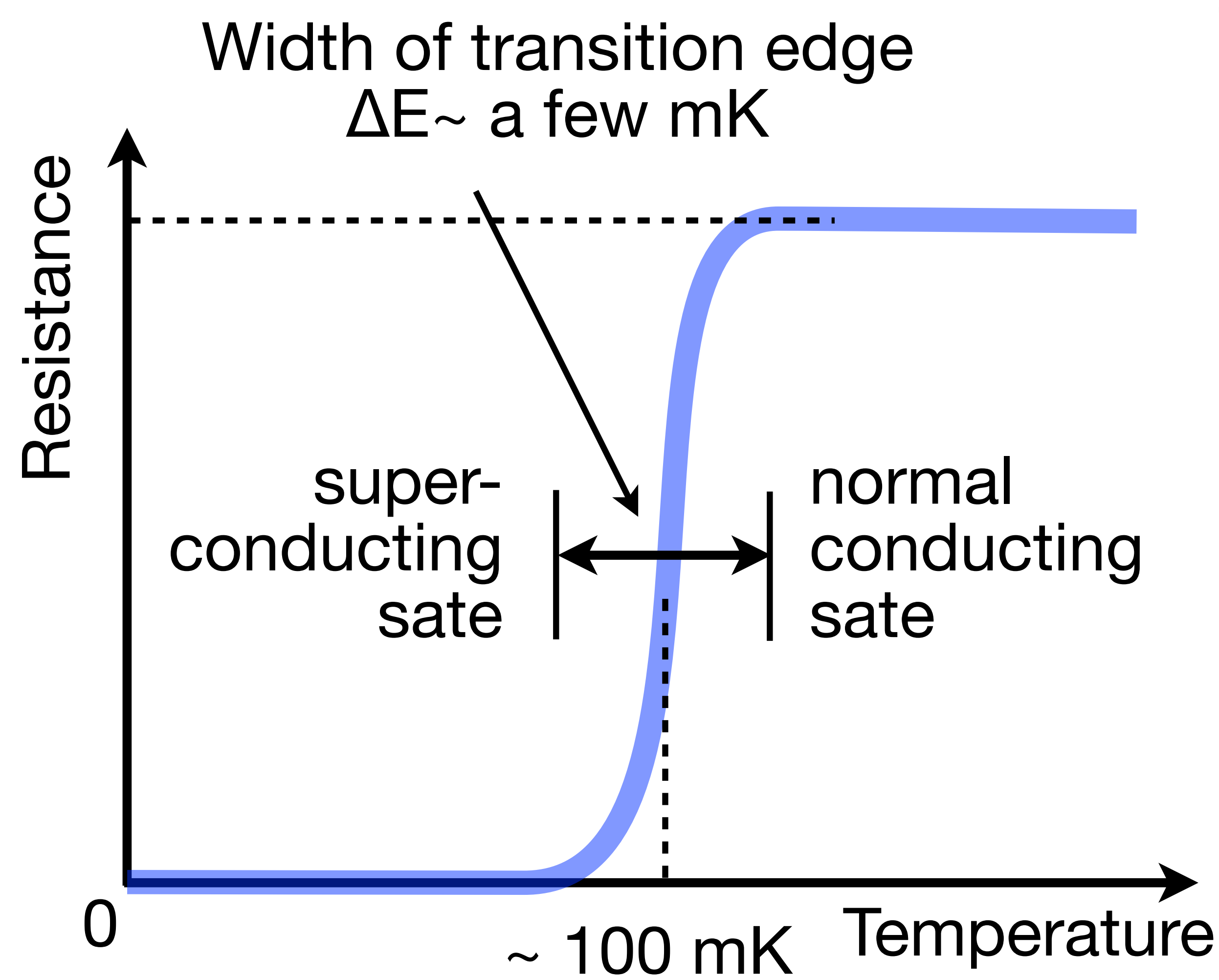
Absorber with larger "Z" (to stop the high energy x-rays)

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.



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

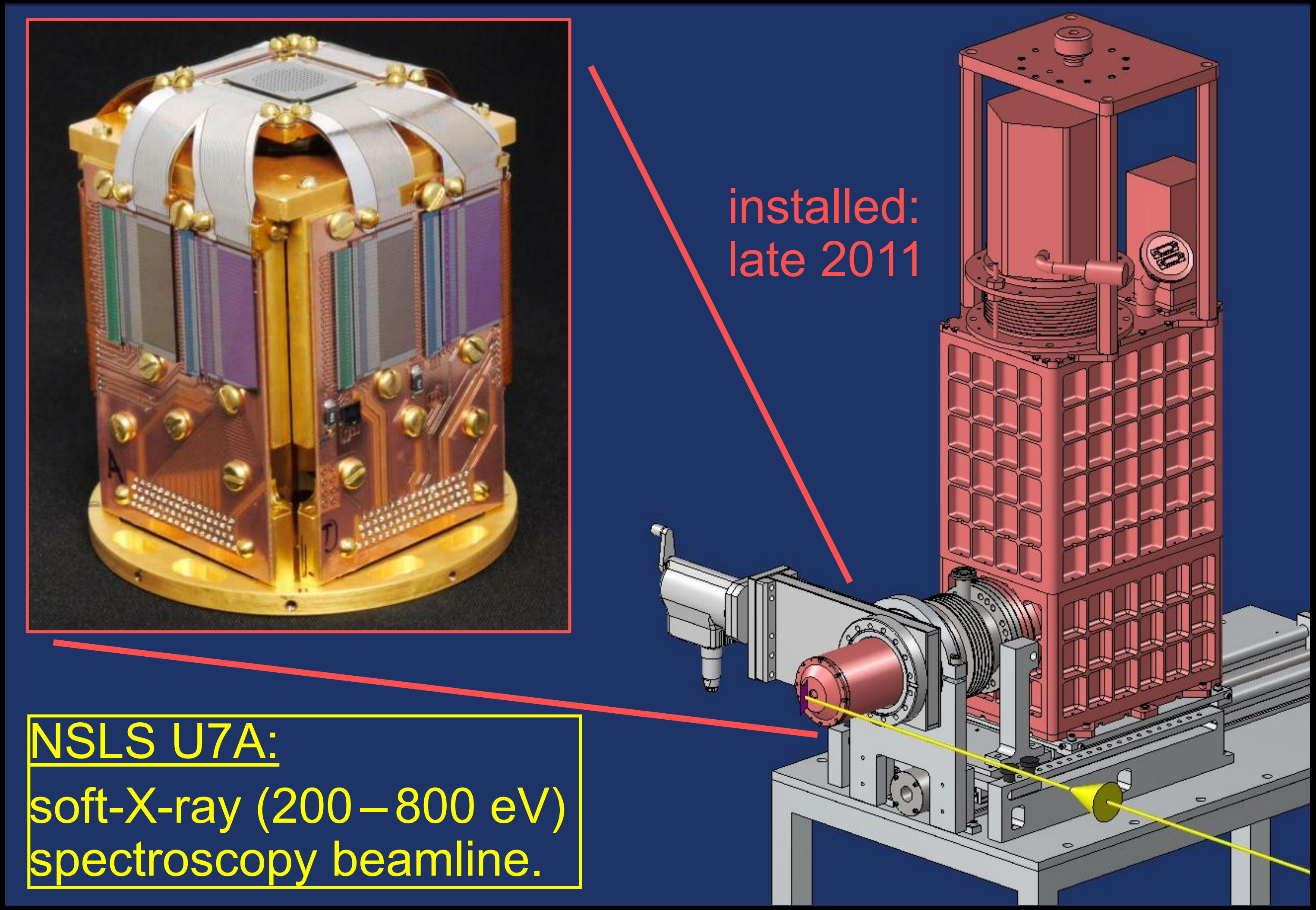
$$E_{max} \sim C T_C / \alpha$$

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

--> developed by Stanford / NIST at the beginning

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!

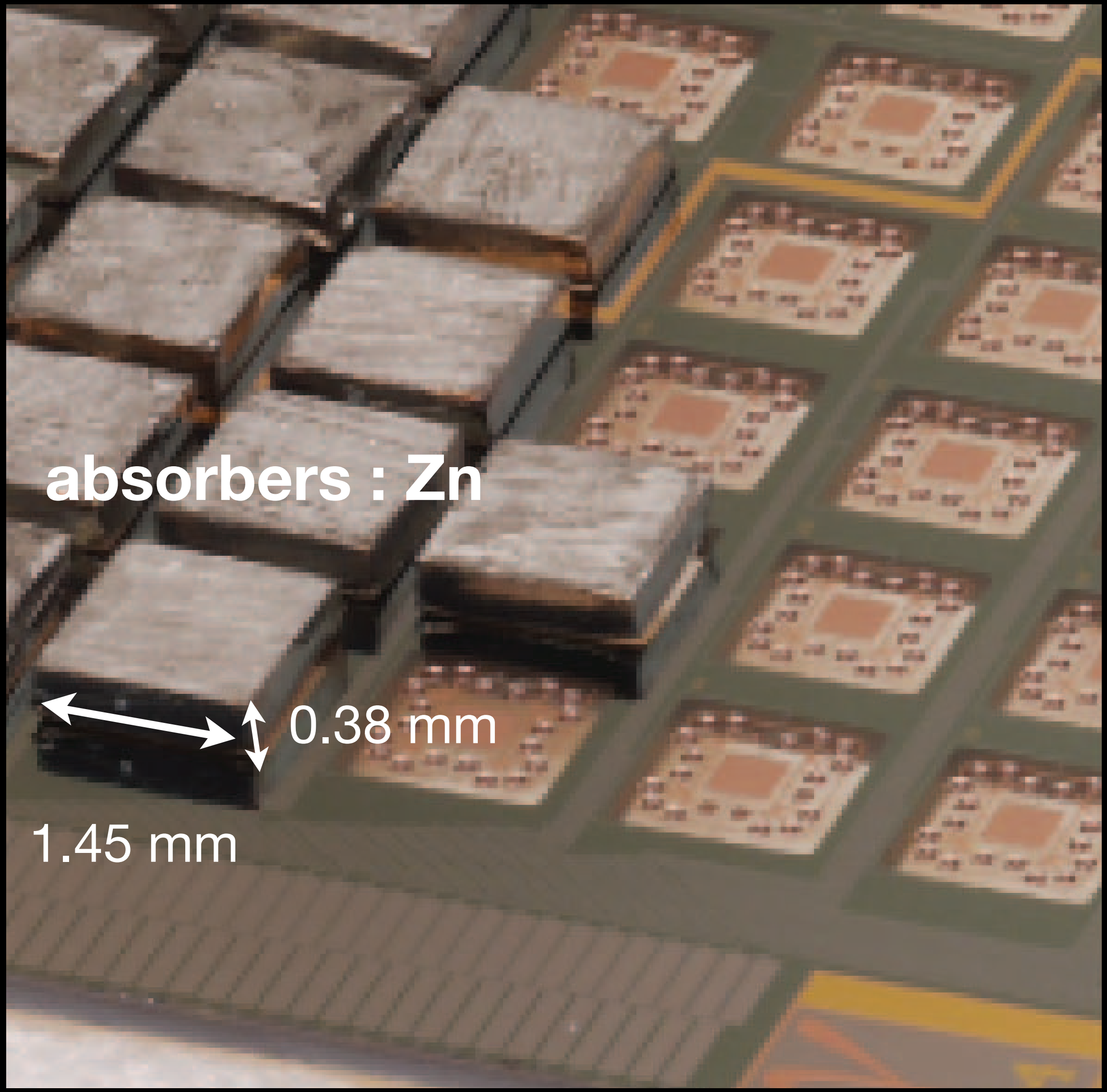
two-order improved resolution

~ 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

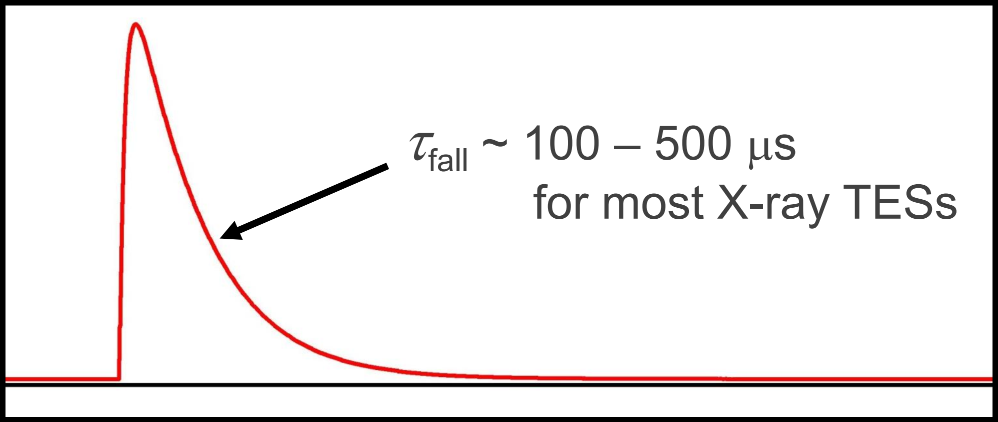
D. A. Bennett et al., Rev. Sci. Instrum. 83, 093113 (2012)

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

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

	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	100 events (~ 4-day beam)	2 ~ 3 eV	~ 0.1 eV = 2 ~ 3 / 2.35 / sqrt(100)

Count rate with TES



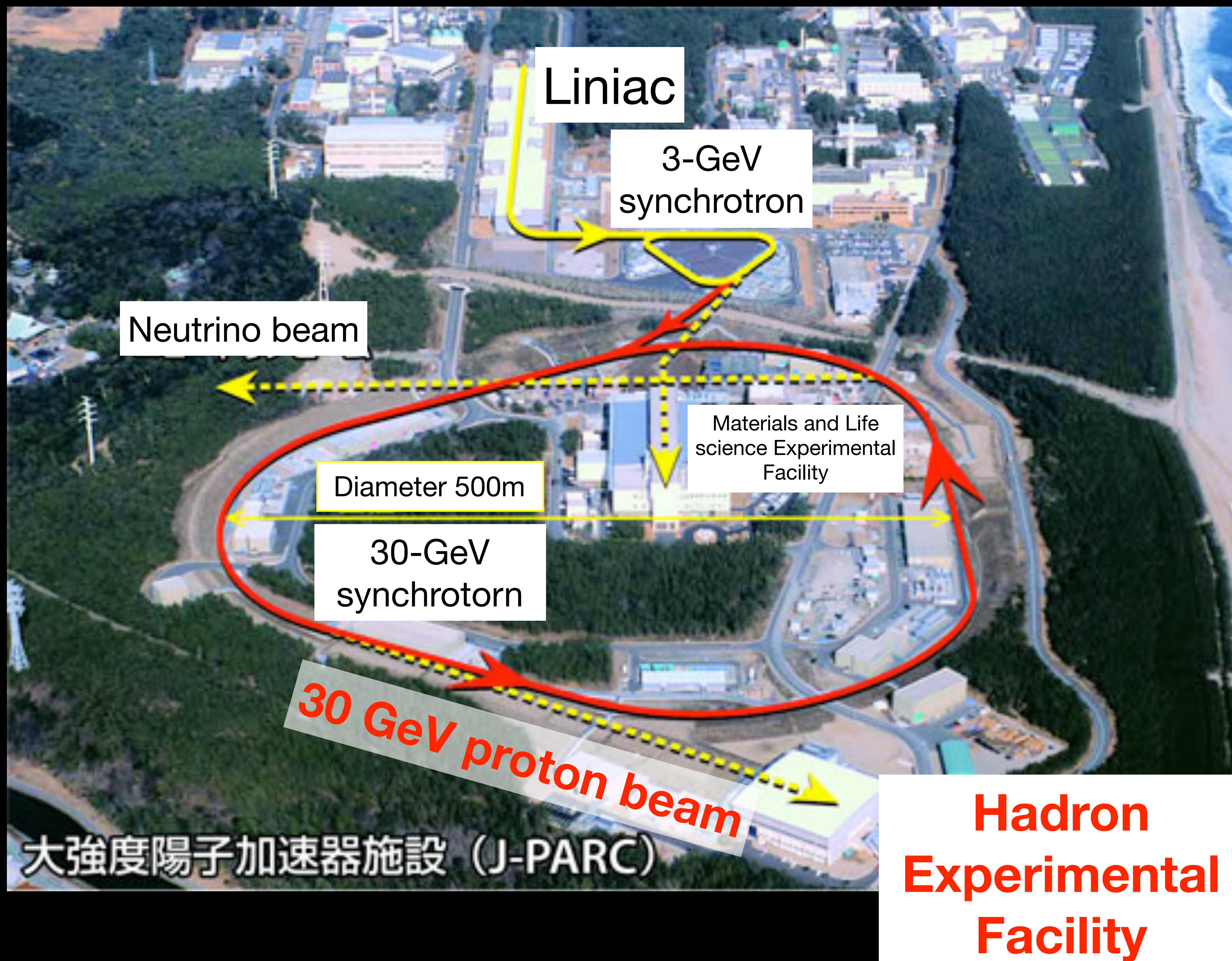
- Practical x-ray TES time constants ~ 100 - 500 μs
- **10s of Hz / TES** for highest resolution

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

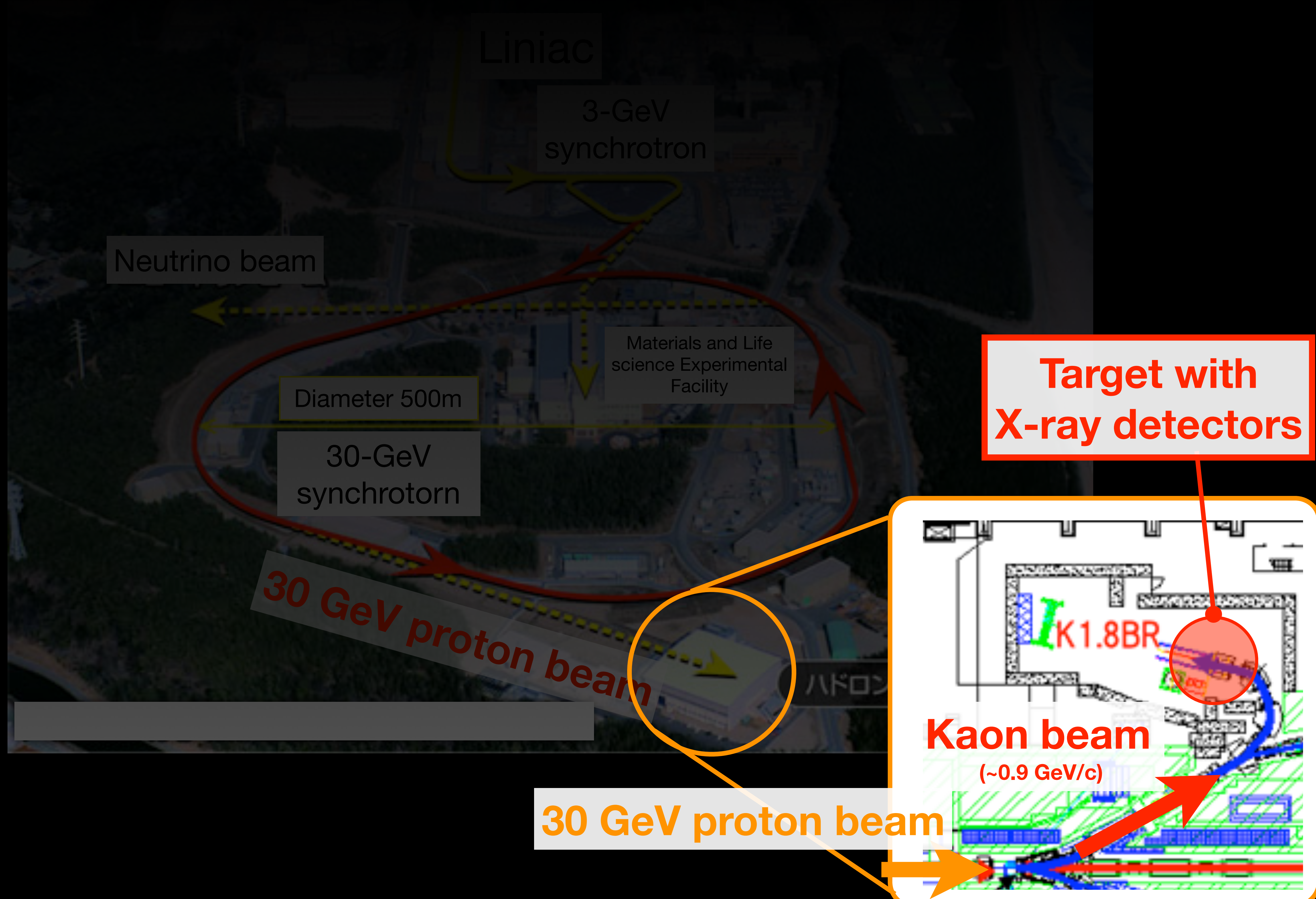
--> acceptable even 10 times higher count rate

J-PARC (Japan)

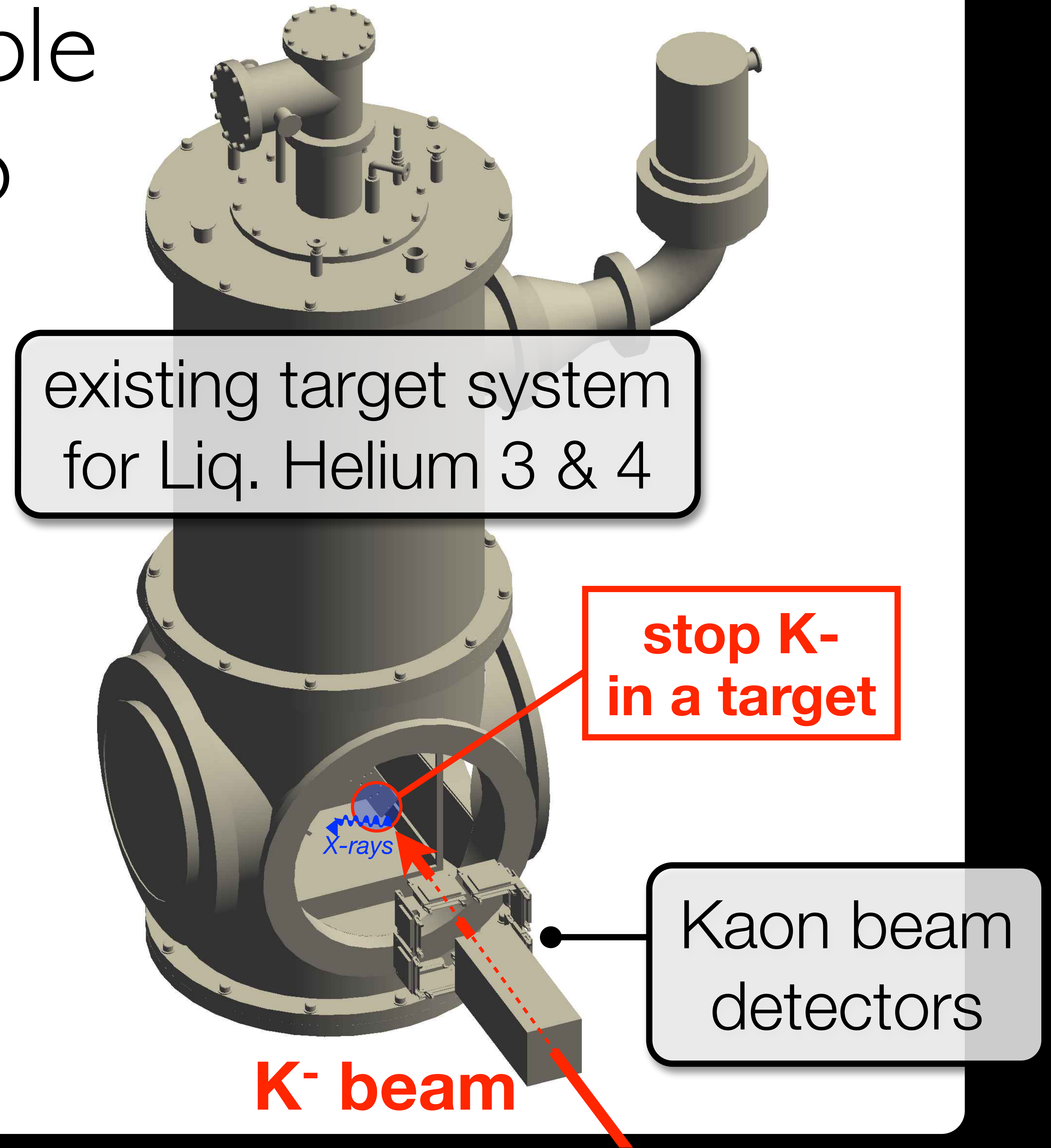
Japan **P**roton **A**ccelerator **R**esearch **C**omplex = J-PARC



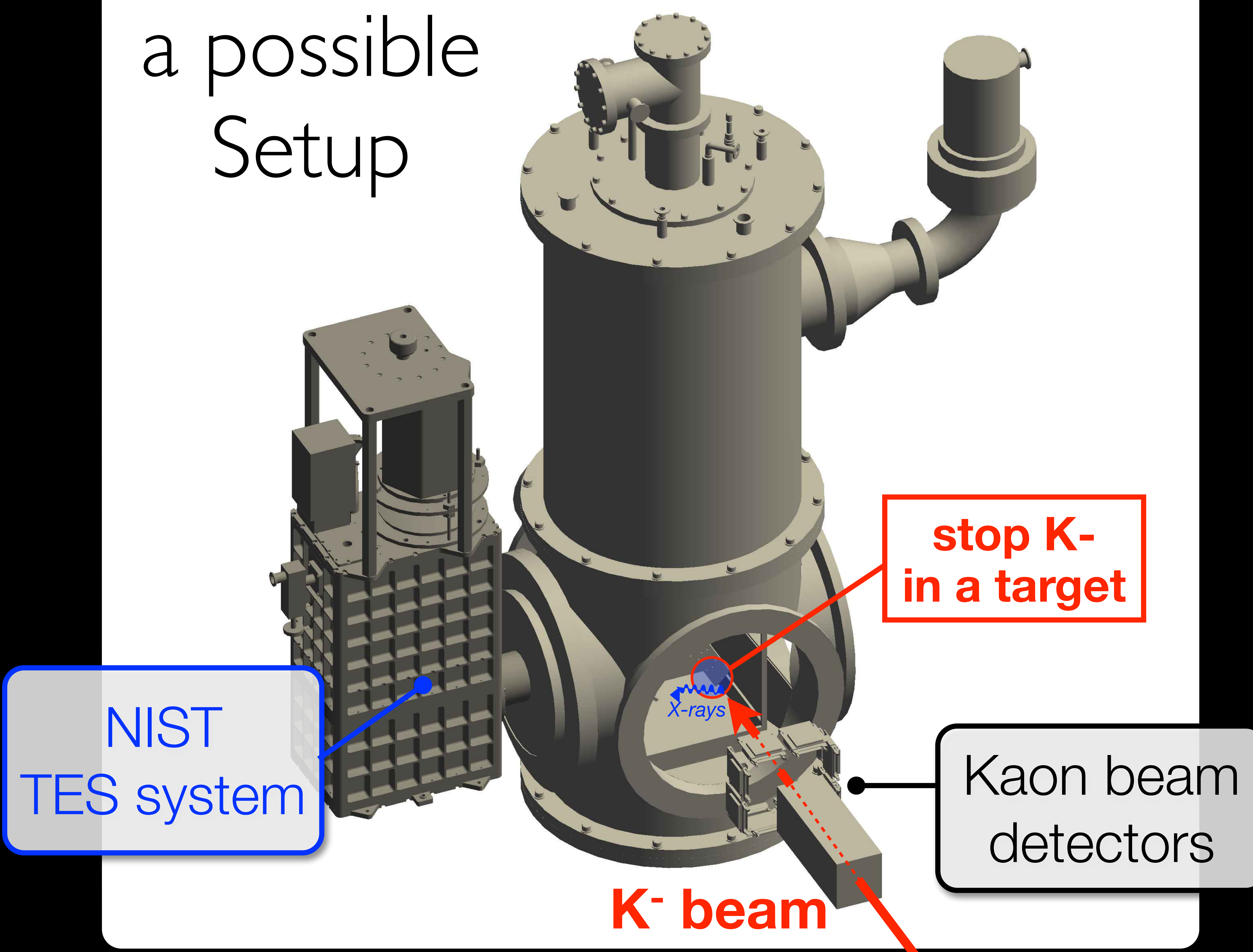
J-PARC (Japan)


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

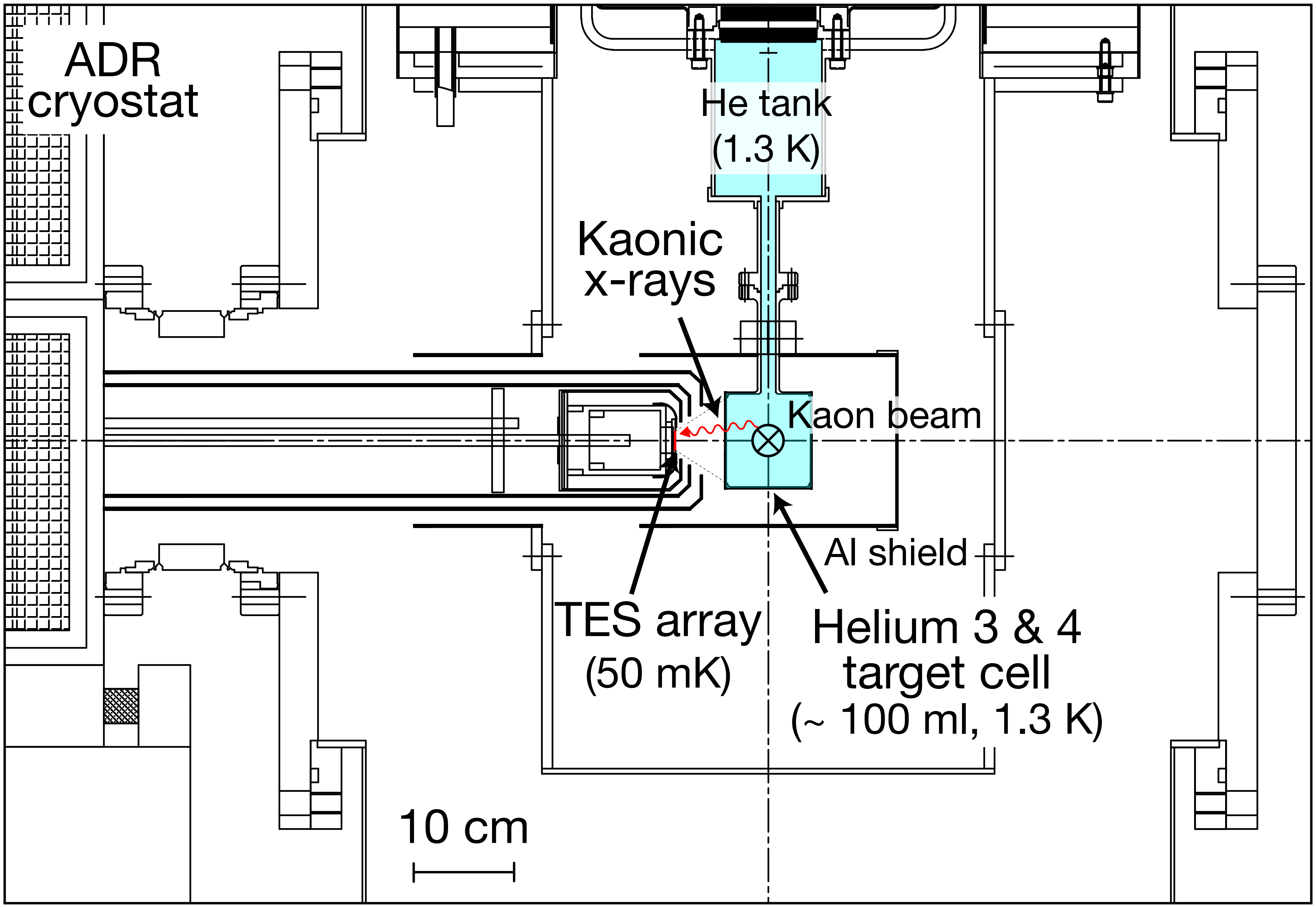
a possible Setup



a possible Setup



Cross section (front view)

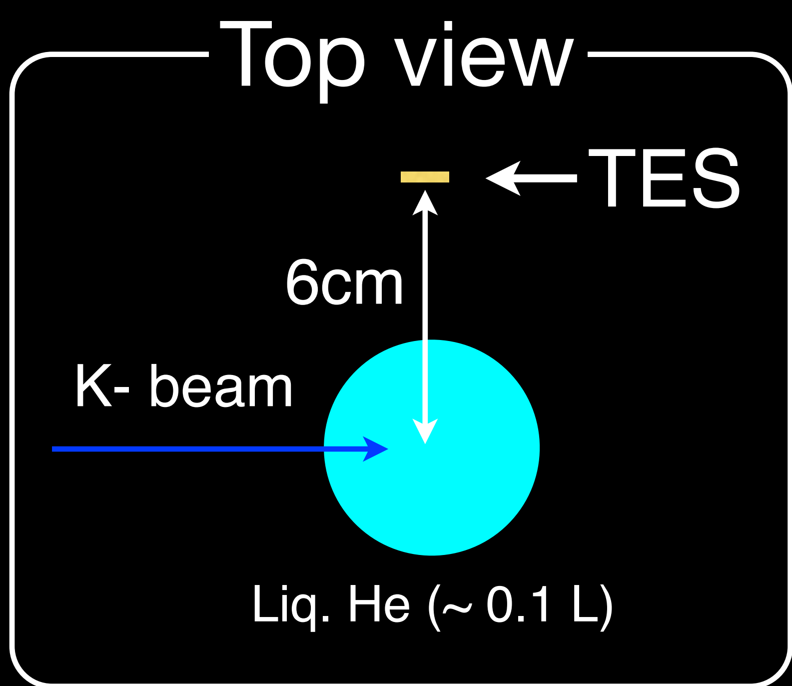


by S. Ishimoto

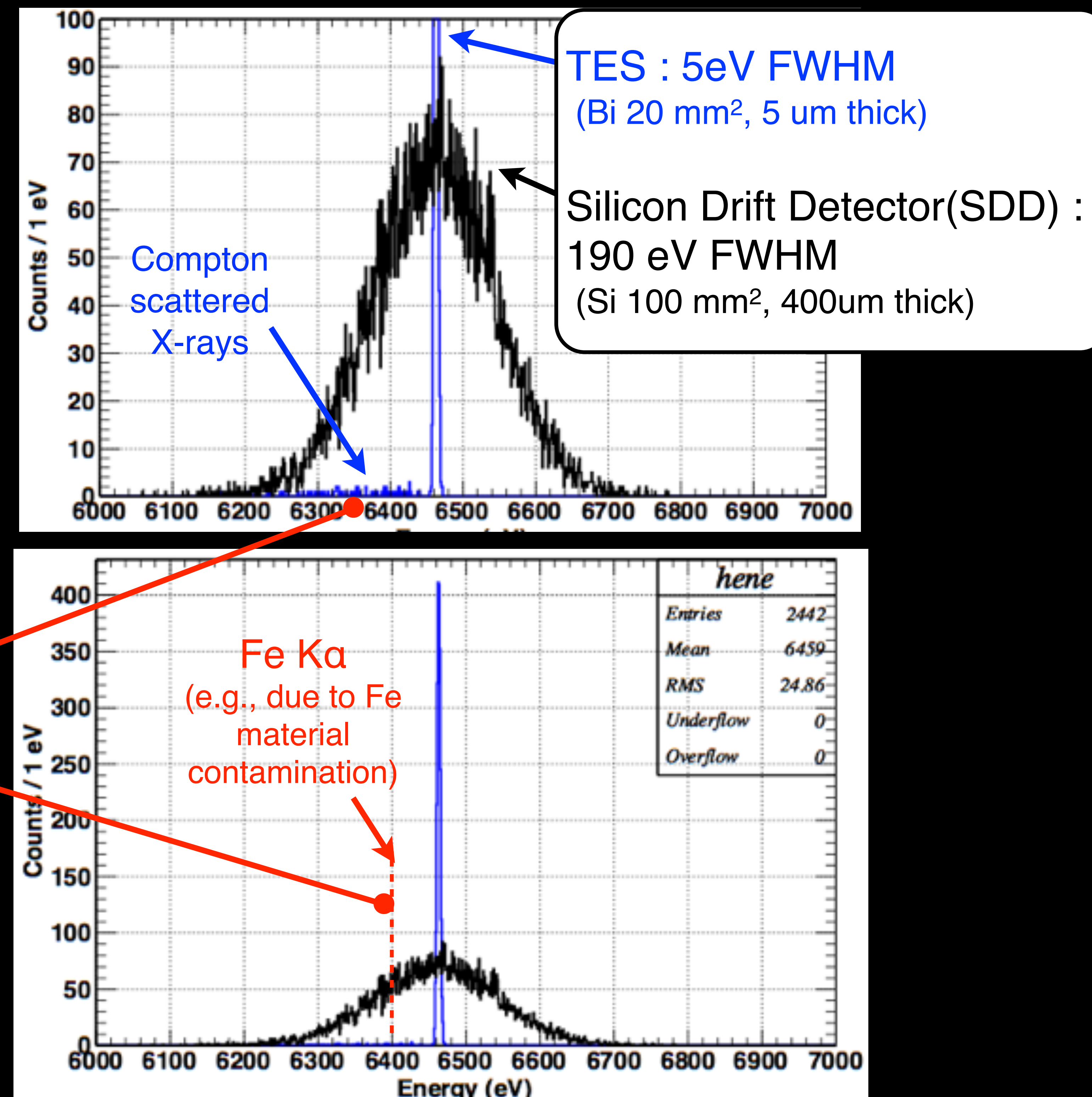
A simple simulation

w/ GEANT4

by H. Tatsuno

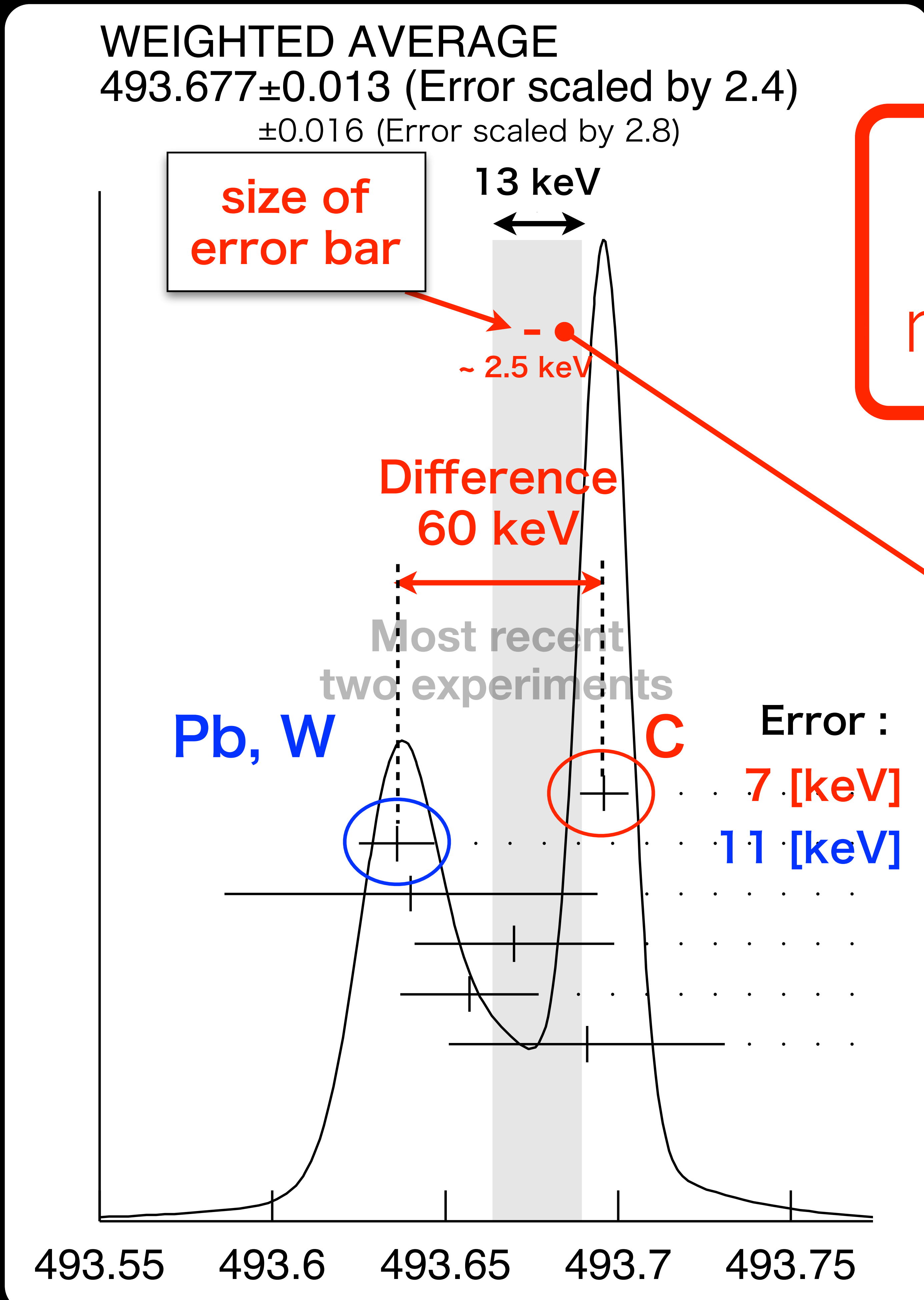


K-^{4}He x-rays from Liq. ^{4}He



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

Both have been serious problems
in the prev. experiments.



most fundamental quantity

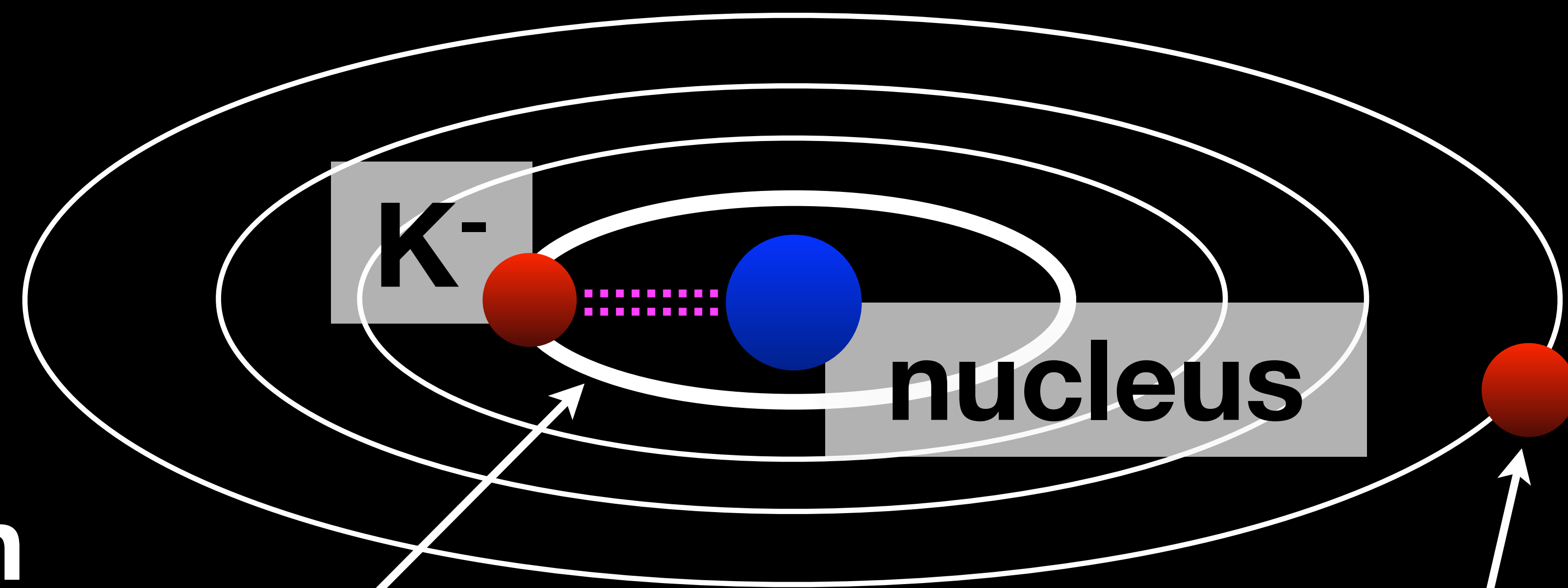
Charged Kaon mass measurement with TES

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

- 公募研究 (A02) -

“ K中間子原子X線分光に向けたマイクロカロリメータのビーム環境下における性能評価 ”

Original plan

Single pixel (TMU)

J-PARC test beamline

measuring **fluorescence x-rays** from charged particle hits on pure-metal foils

Modified plan

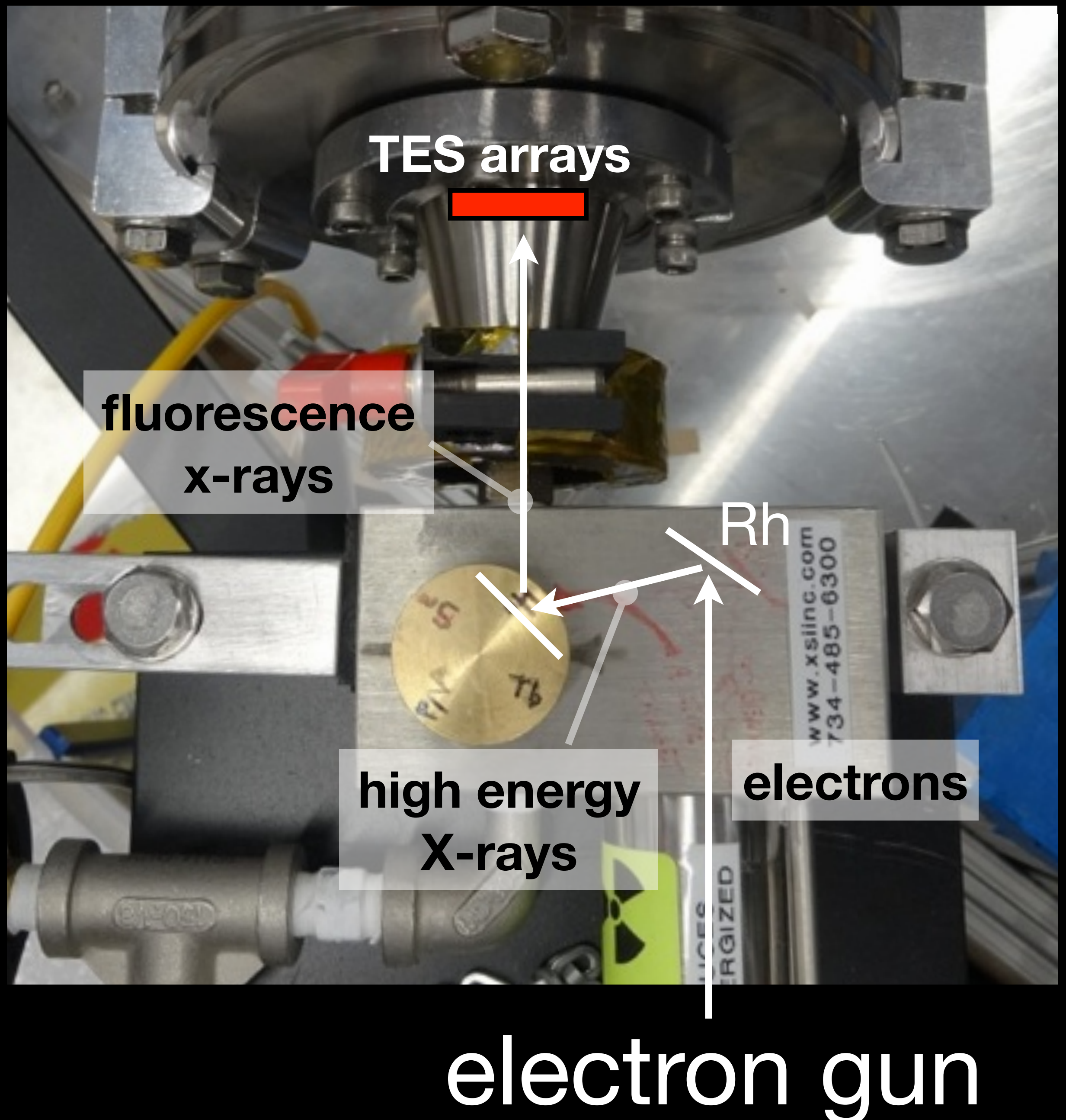
160 pixel (NIST)

PSI π beamline (piM1)

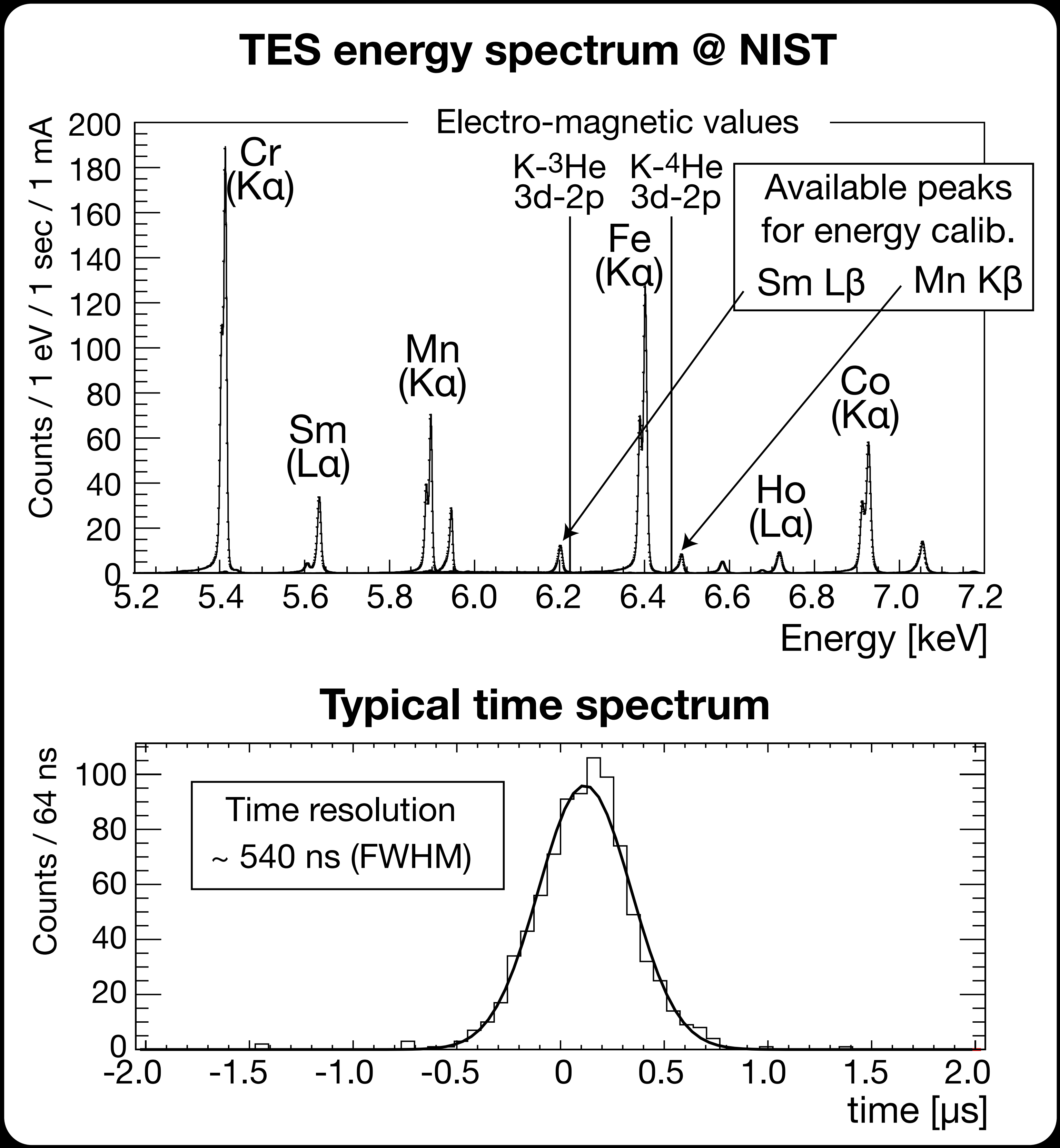
1. measuring pionic carbon (4-3) x-rays ~6.5 keV
   - the first exotic-atom exp. with TES
   - good demonstration (for J-PARC proposal)
2. checking the direct hit of charged particle
   - with low-intensity pion beam
   - test for anti-coincidence system
3. measuring pionic-^{3}He and ^{4}He 2p-1s x-rays
   - no precise data so far
   - —> physics result

Line calib. experiment @ NIST

26 Aug. - 6 Sept., 2013



Line calib. experiment @ NIST



well-known lines
(ΔE <~ 0.1 eV)

Summary

Summary

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

◉ open new door to investigate K-nucleus strong interaction

◉ has potential to resolve a long-standing **“deep” or “shallow” problem** of the K-atom optical potential depth

◉ provide new accurate **charged kaon mass** value (being also essential to determine the energy shift of K-^{4}He atom)

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

in future

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

◉ future perspective

- 2014 (fall or winter) : test experiment with beam at PSI (piM1 beamline)
- --> and preparation of LoI / proposal to J-PARC

Thanks to

- **J-PARC E15/E17 collaborators**
- **RIKEN** : T. Tamagawa, S. Yamada (ASTRO-H)
- **NIST(Boulder)** : D.A. Bennett, W.B. Doriese, G.C. O'Neil,

J.W. Fowler, K.D. Irwin, D.S. Swetz, D.R. Schmidt, J.N. Ullom

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