12 Sept, 2013

公募研究交流会＠東北大理学部

TES型マイクロカロリメータを用いた K中間子原子X線精密分光

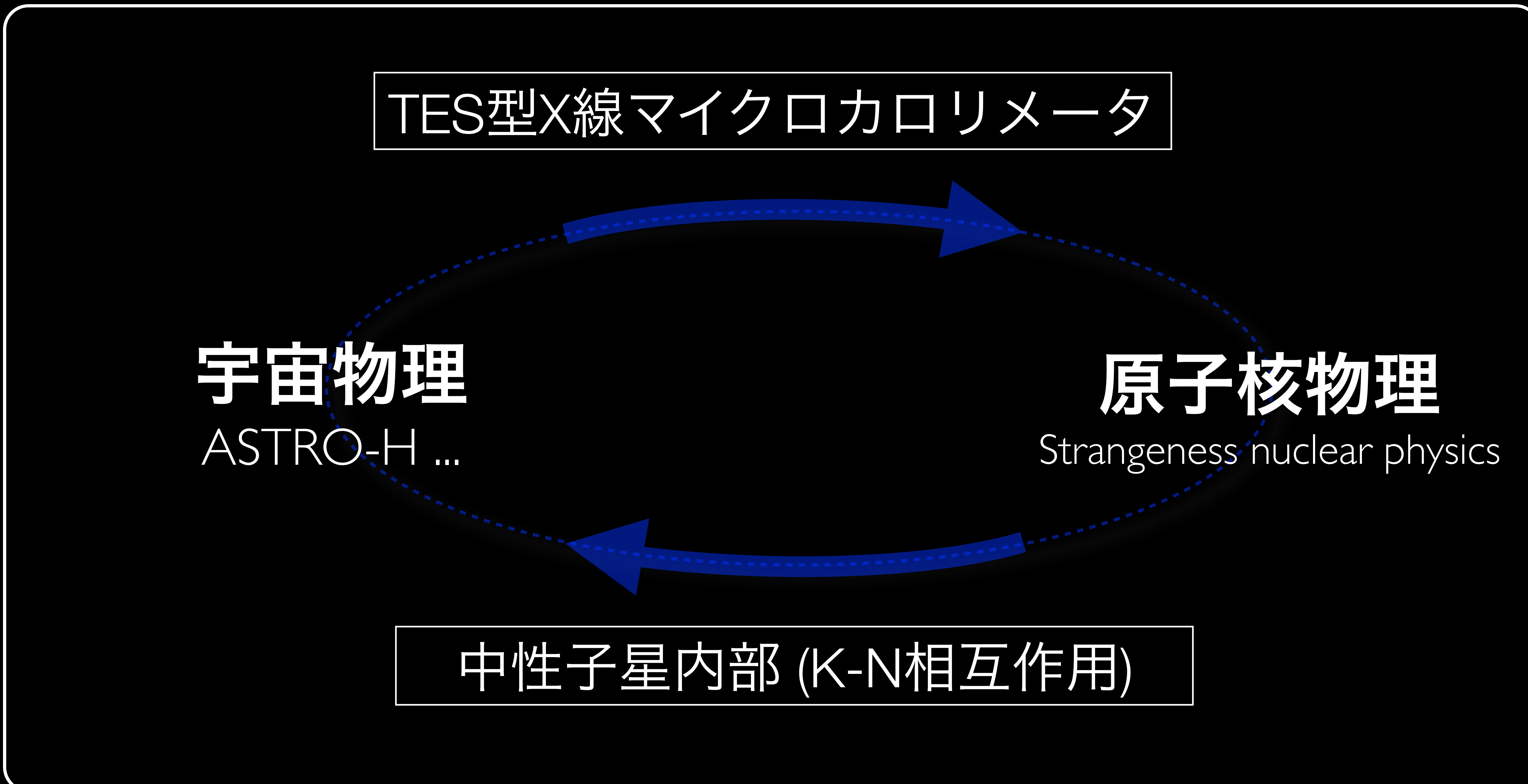
公募研究 (A02班)：『 K中間子原子X線分光に向けた

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

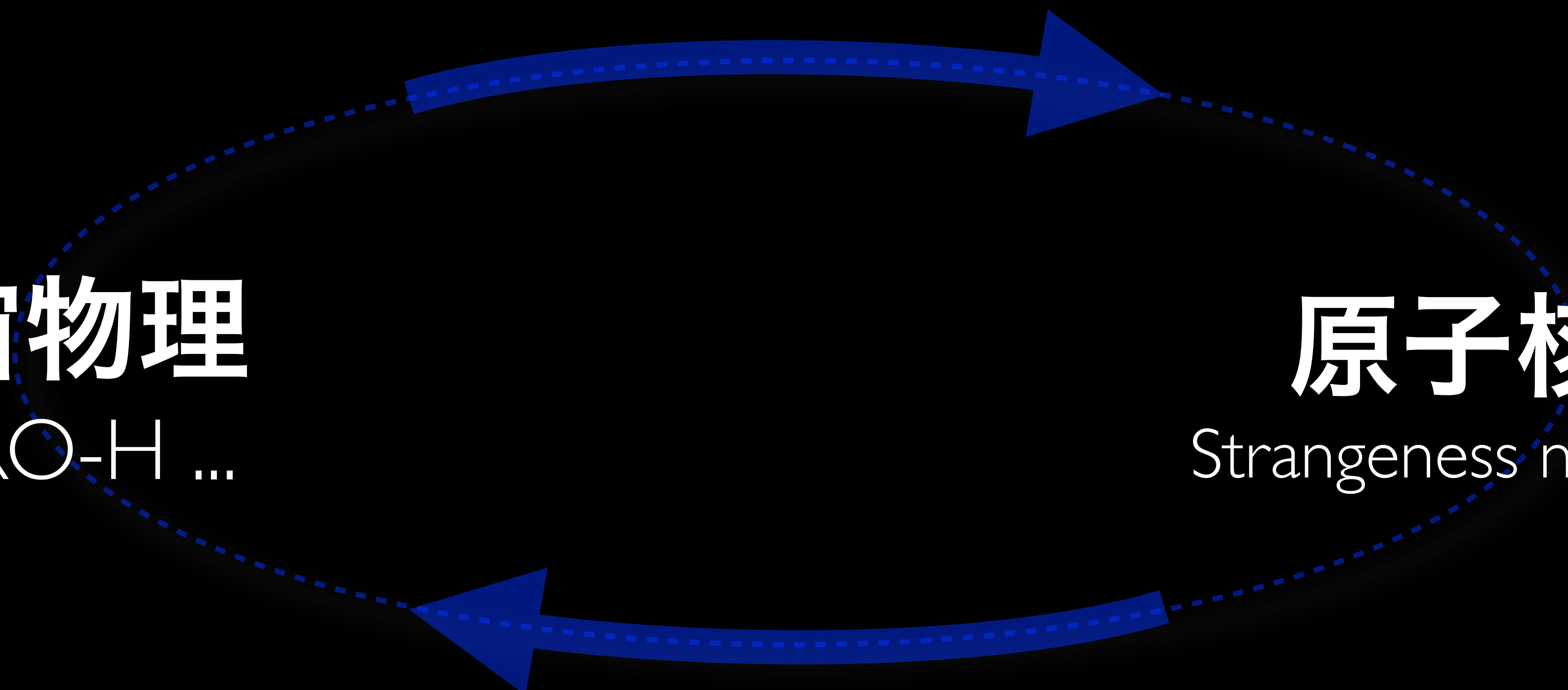
RIKEN

Collaboration



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)

公募研究申請後...

海外コラボレーション：**NIST** (アメリカ国立標準技術研究所)

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

公募研究申請後...

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 : 中性子過剰核物質中のストレンジネス

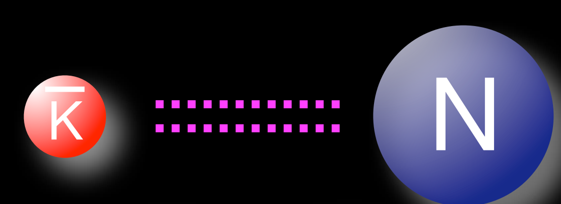
核物質中のK中間子実験

(研究分担者 : 応田)

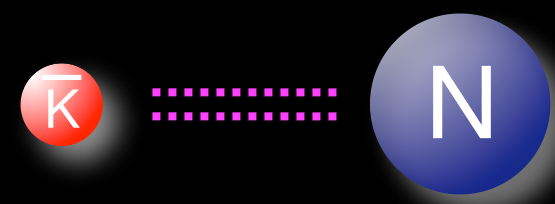
中性子星内部のK中間子発生領域の理解

--> $\bar{K}$-N 相互作用の理解が重要

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



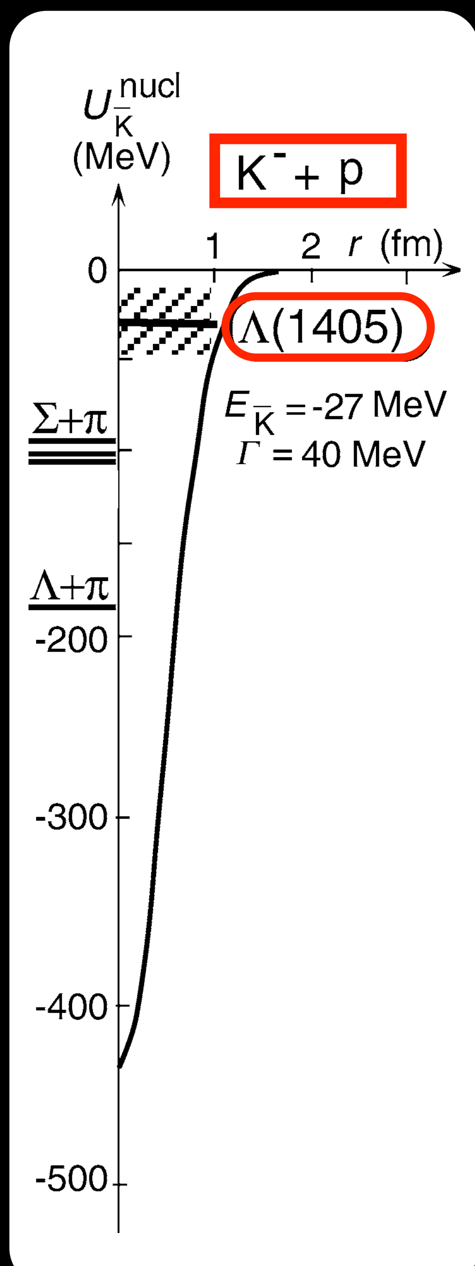
Strongly attractive!

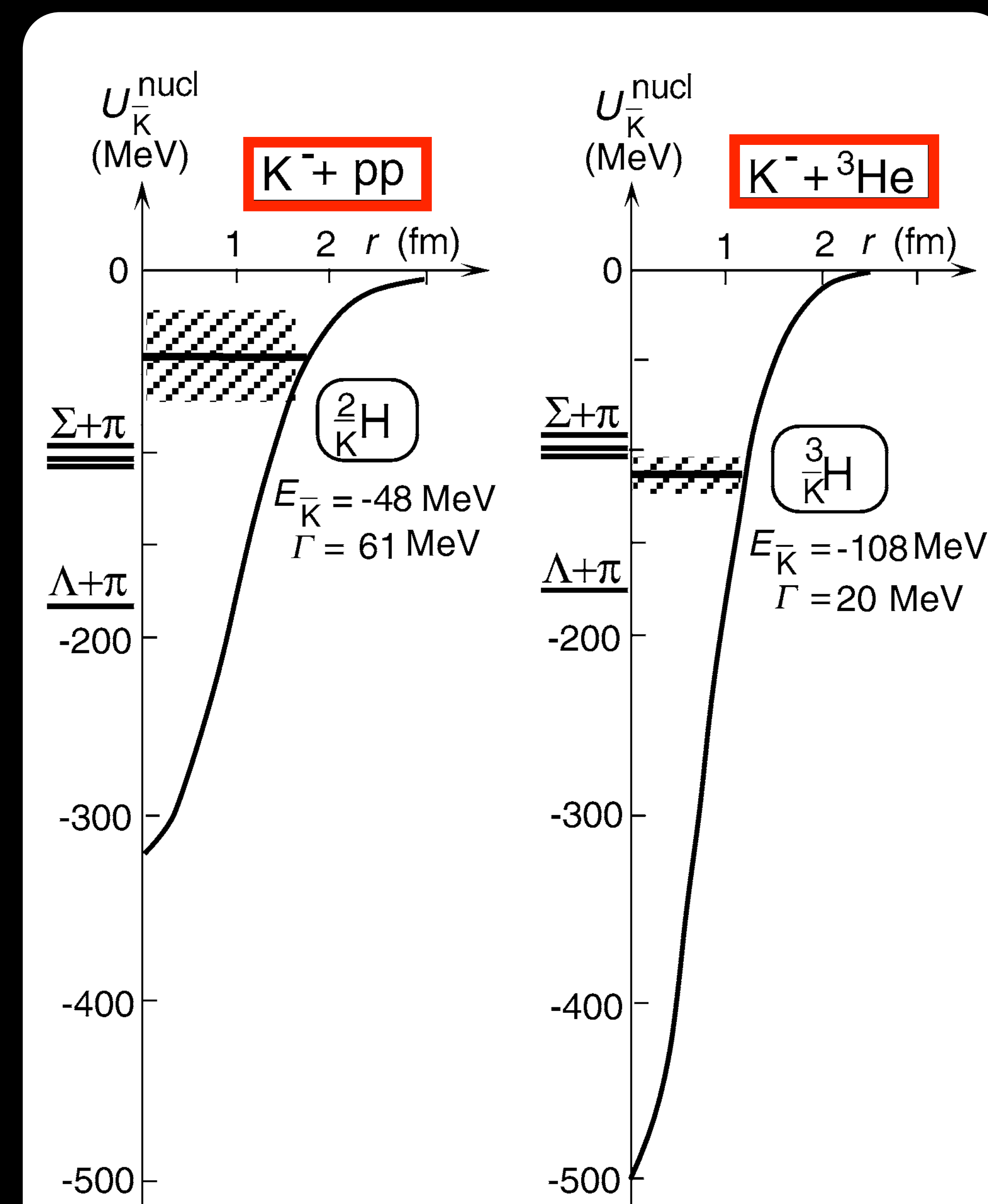


strongly attractive !

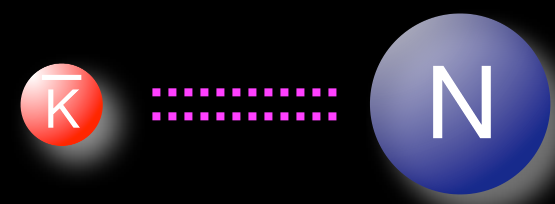
Λ(1405) is considered as a K-p nuclear bound state

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





Phys. Lett. B 535 (2002) 70

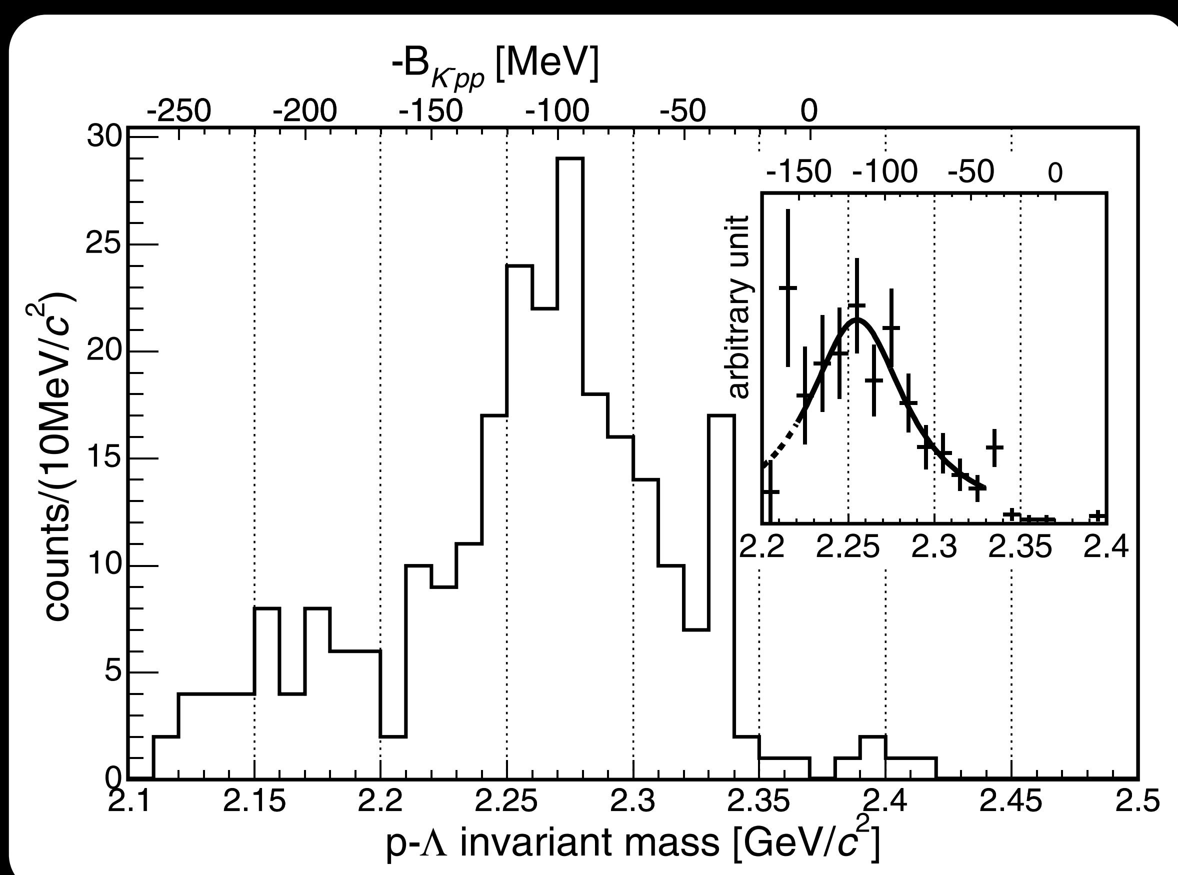


strongly attractive !

many experiments for searching the cluster → still not conclusive

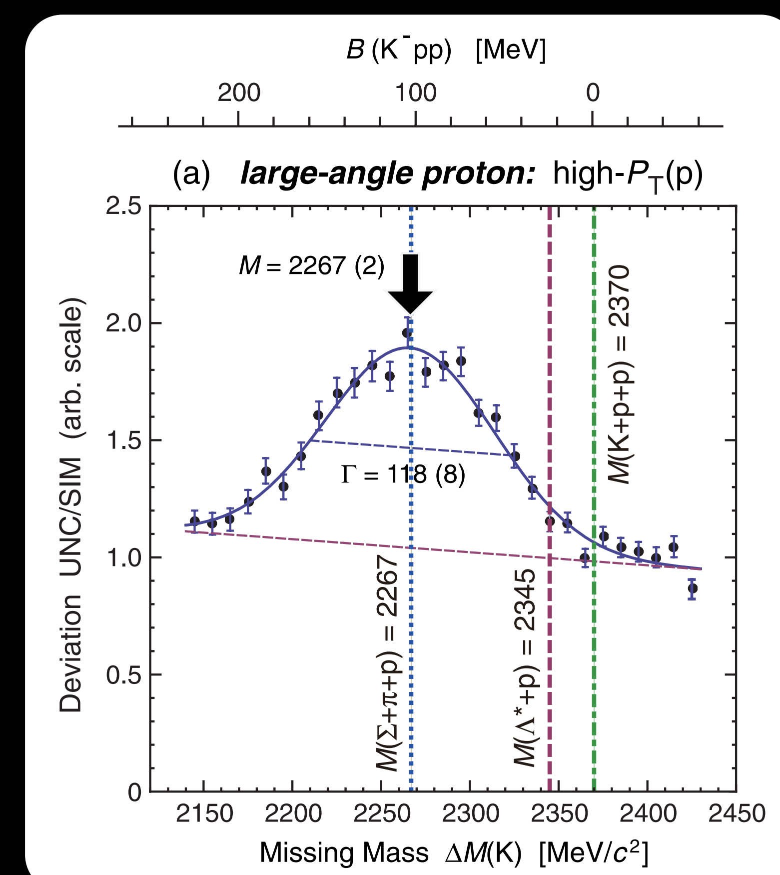
ex) for K-pp clusters

stopped-K⁻ + A → (Λ + p) + X

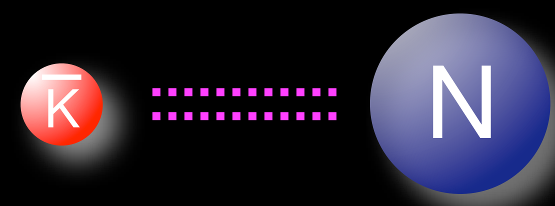


PRL 94, 212303 (2005)

2.85GeV-p + p → (Λ + p) + K⁺

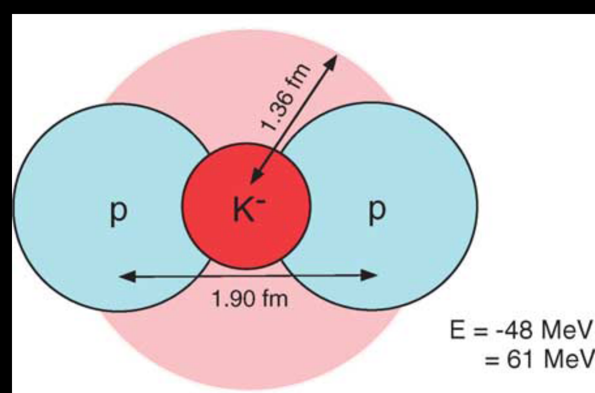


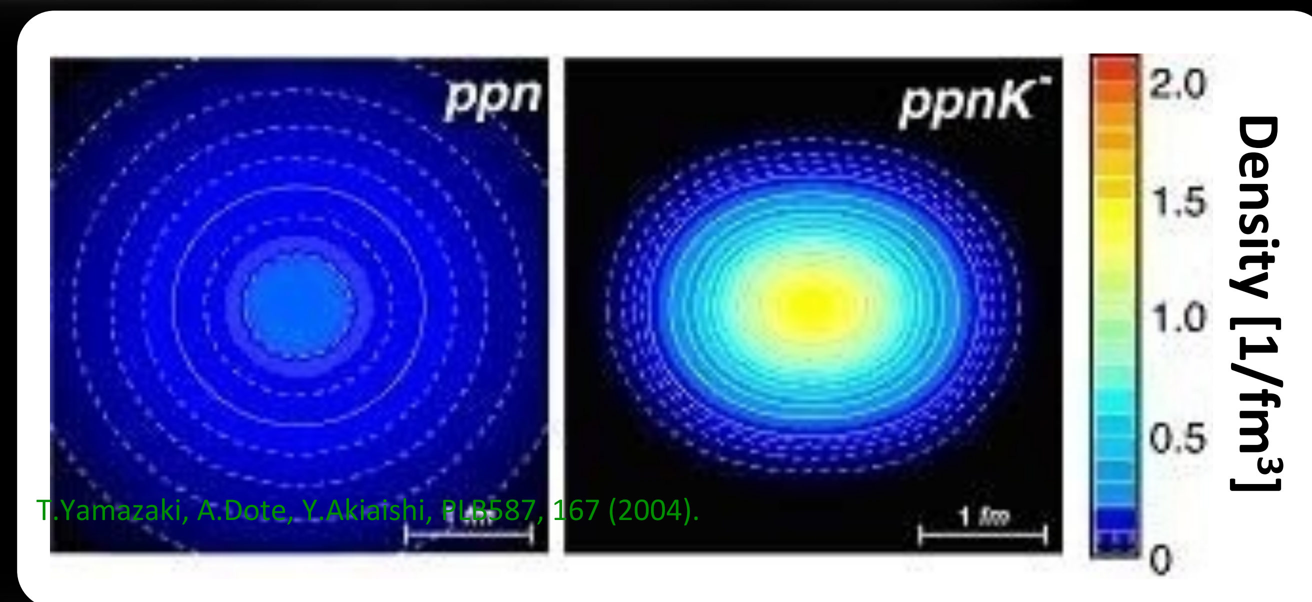
PRL 104,132502 (2010)



strongly attractive !

a possibility of higher density
beyond normal nuclear-matter density

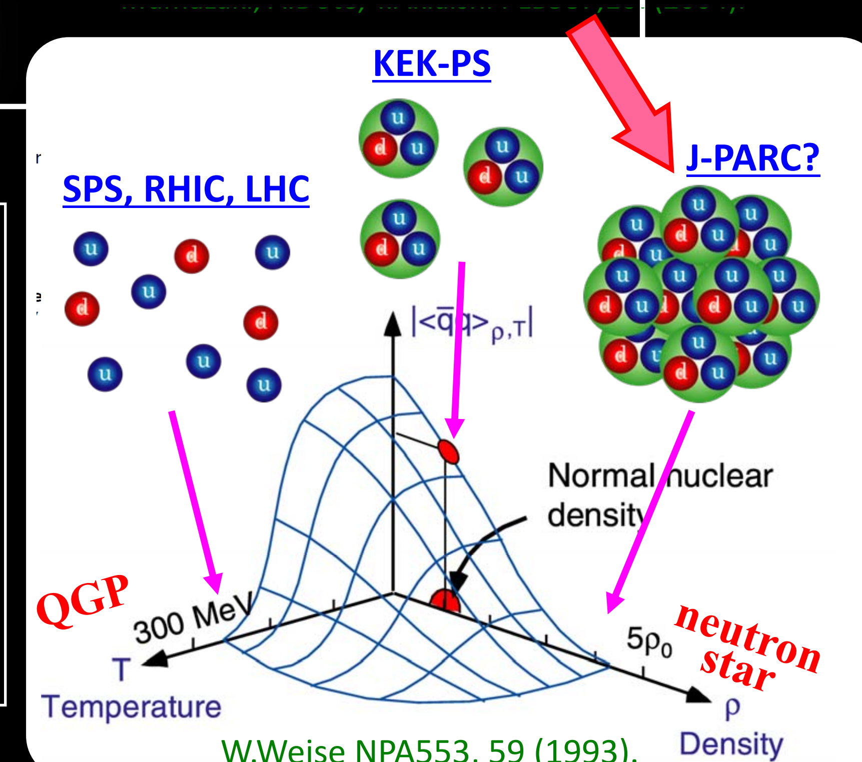




Phys. Lett. B587, 167 (2004)

→ 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?

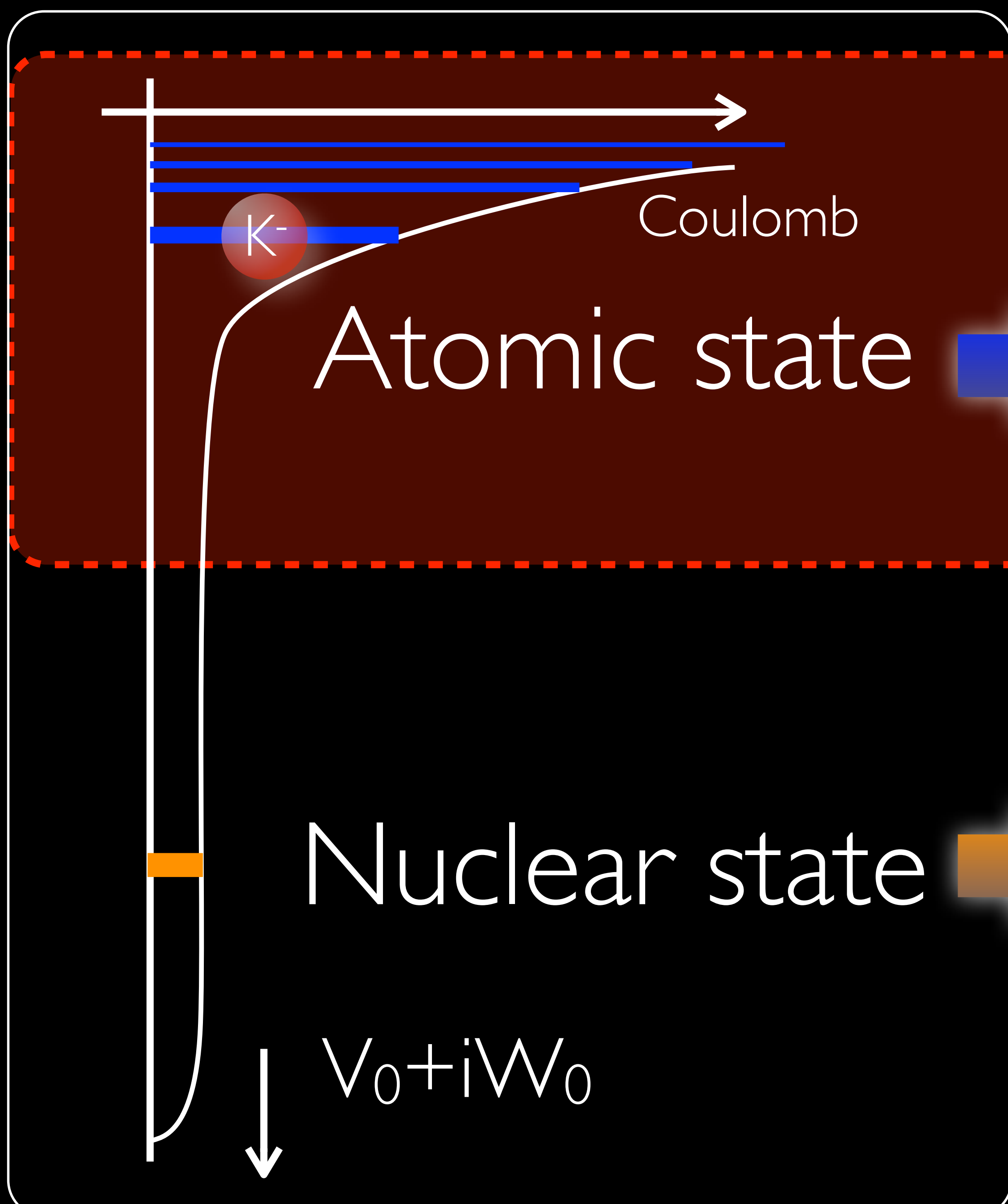
Kaon low-energy scattering experiment
is **difficult** due to the short lifetime (~12 nsec)

⇩

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

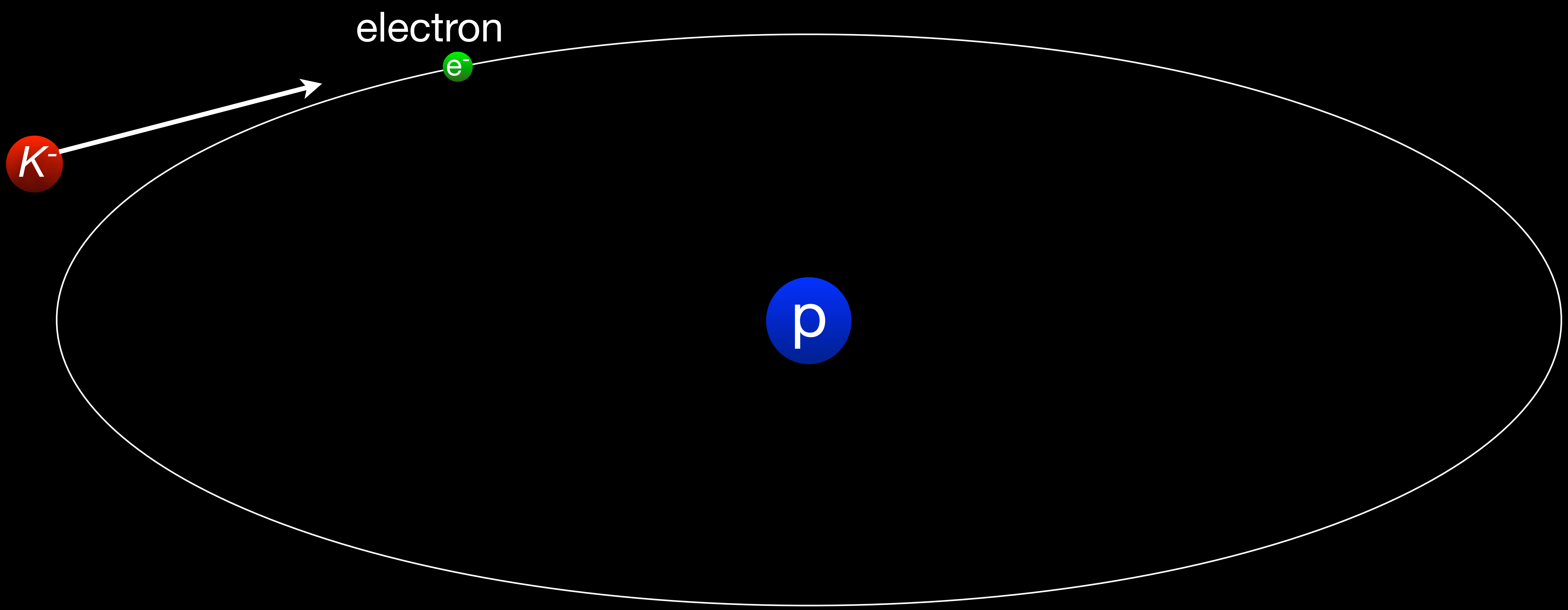
計画研究(A02)

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

-> still no conclusive results

Coulomb bound state
- Kaonic atom -

Hydrogen

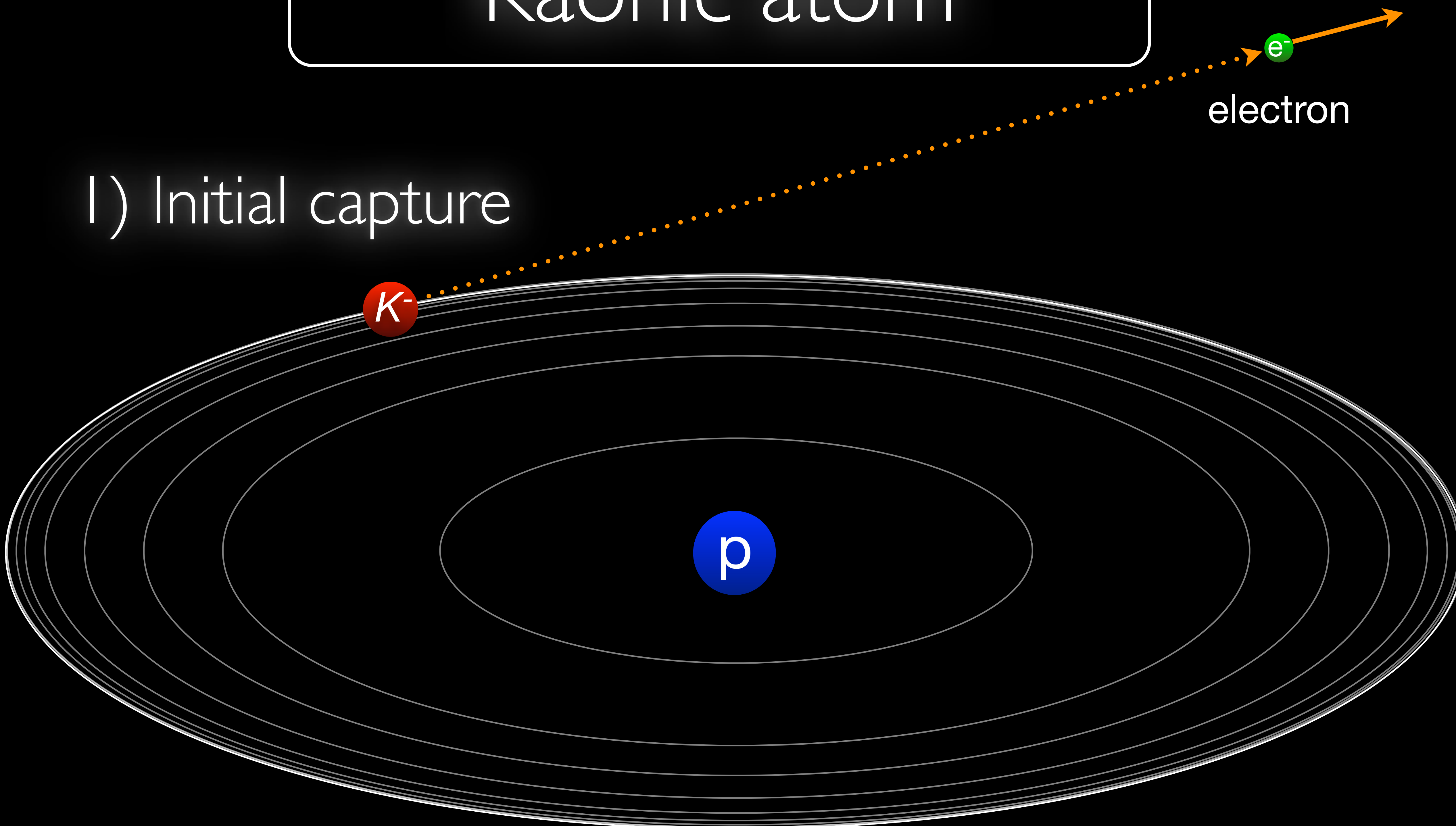


principal quantum number

$n = 1$

Kaonic atom

1) Initial capture



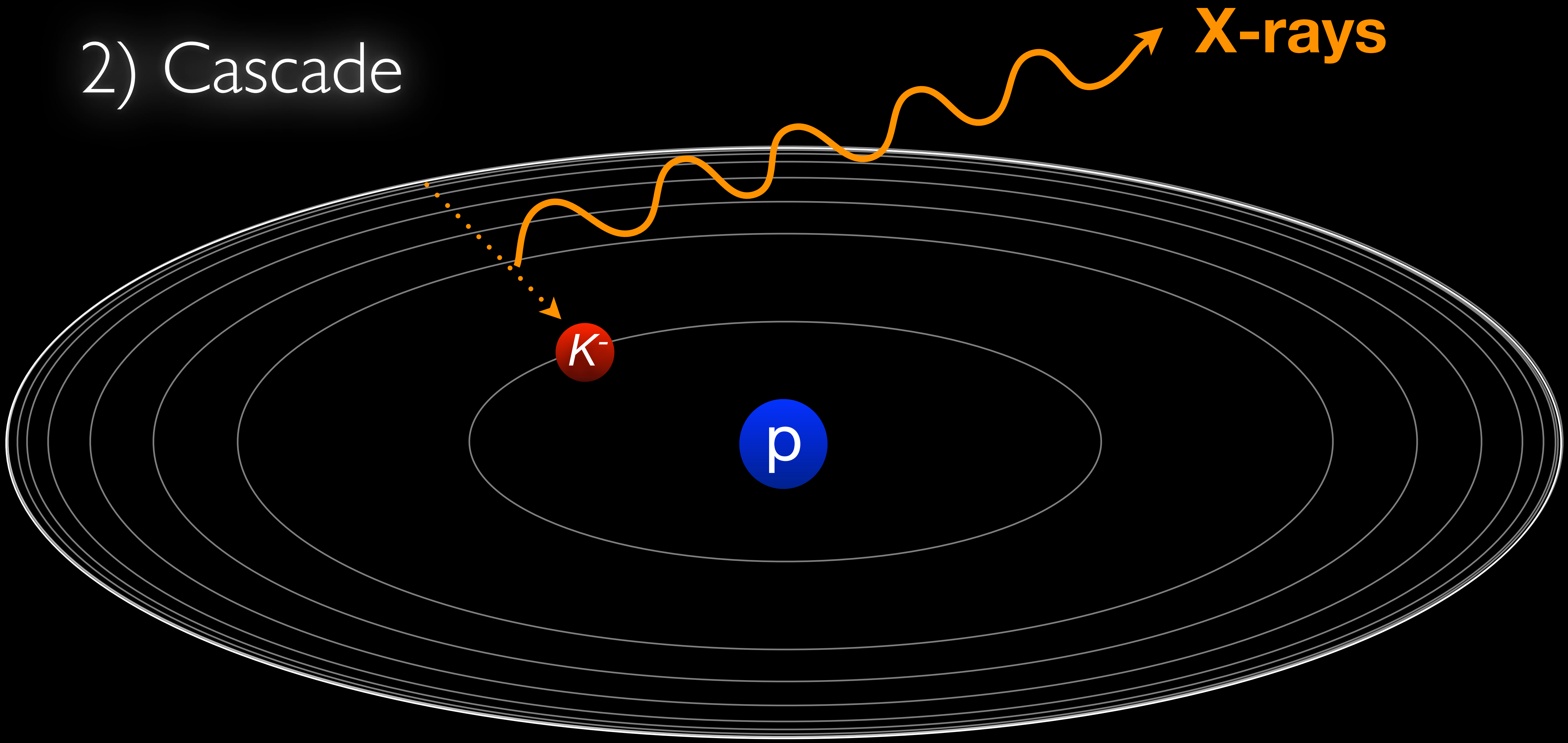
principal quantum number

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

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

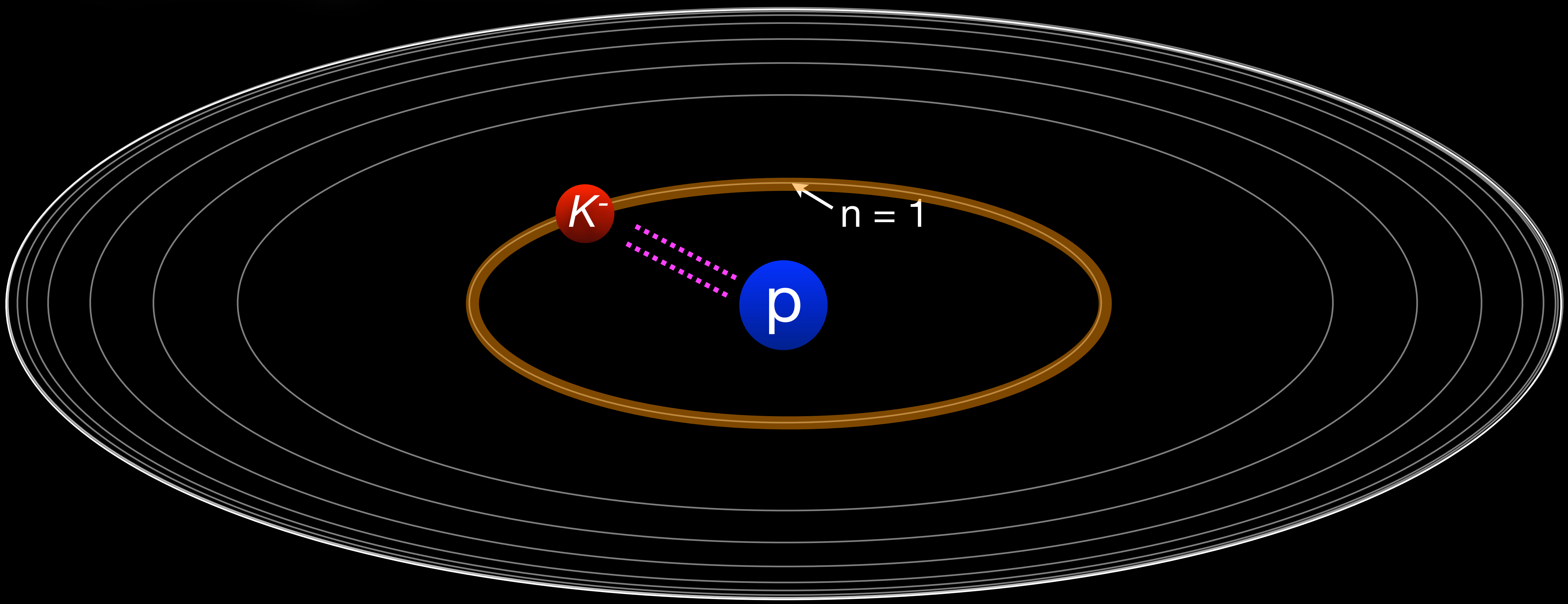
Kaonic atom

2) Cascade

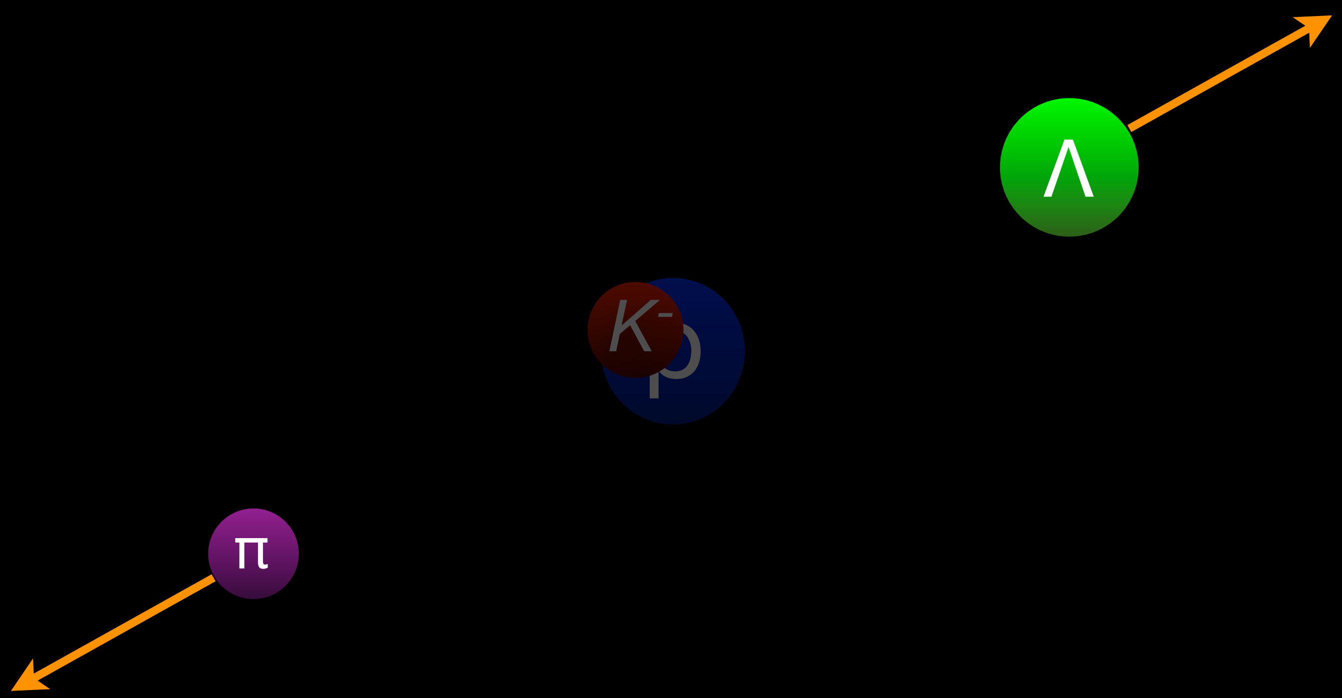


Kaonic atom

3) Strong interaction



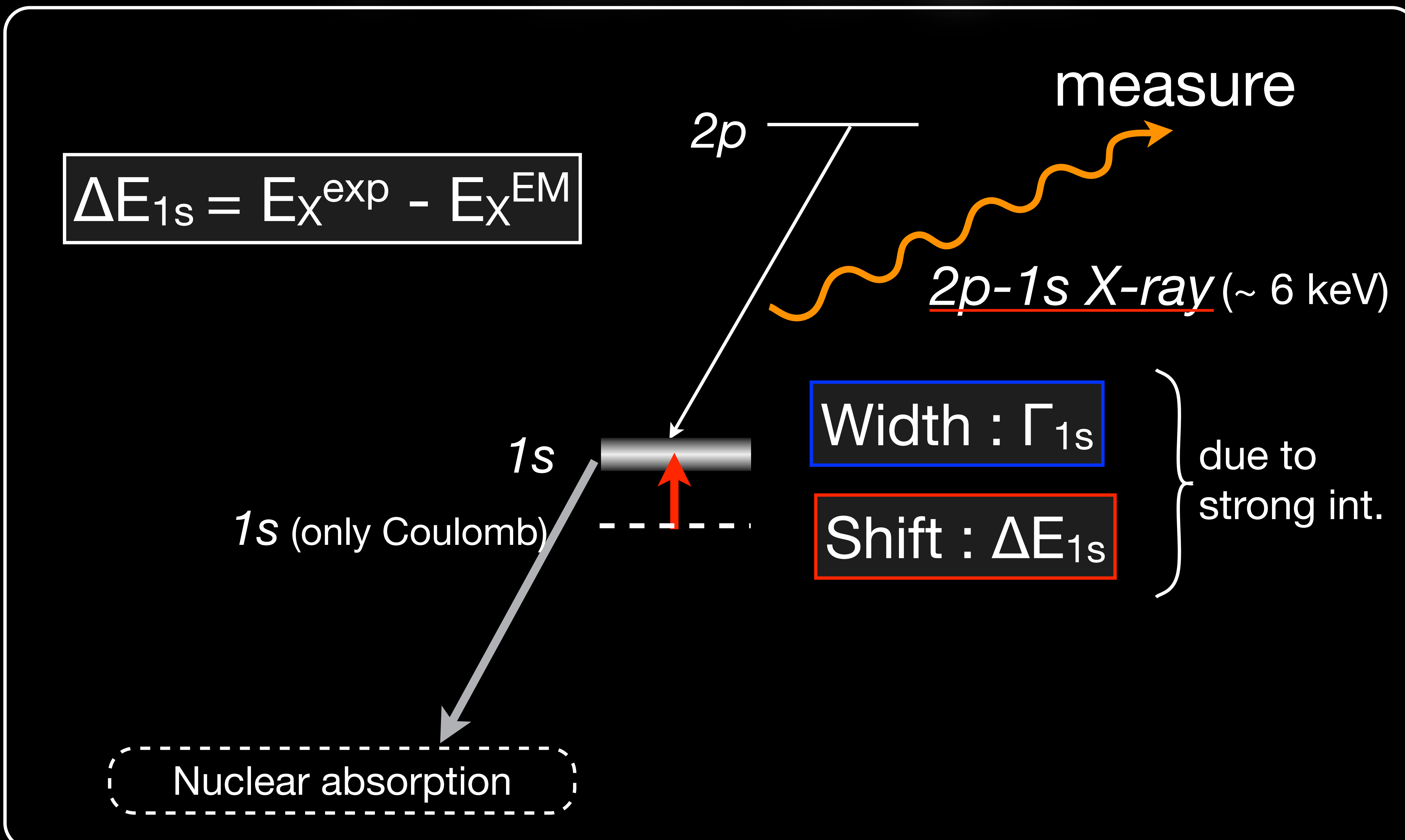
4) nuclear absorption



How we observe
the strong interaction ?

K-atom x-ray spectroscopy

Z = 1 (Kaonic hydrogen)



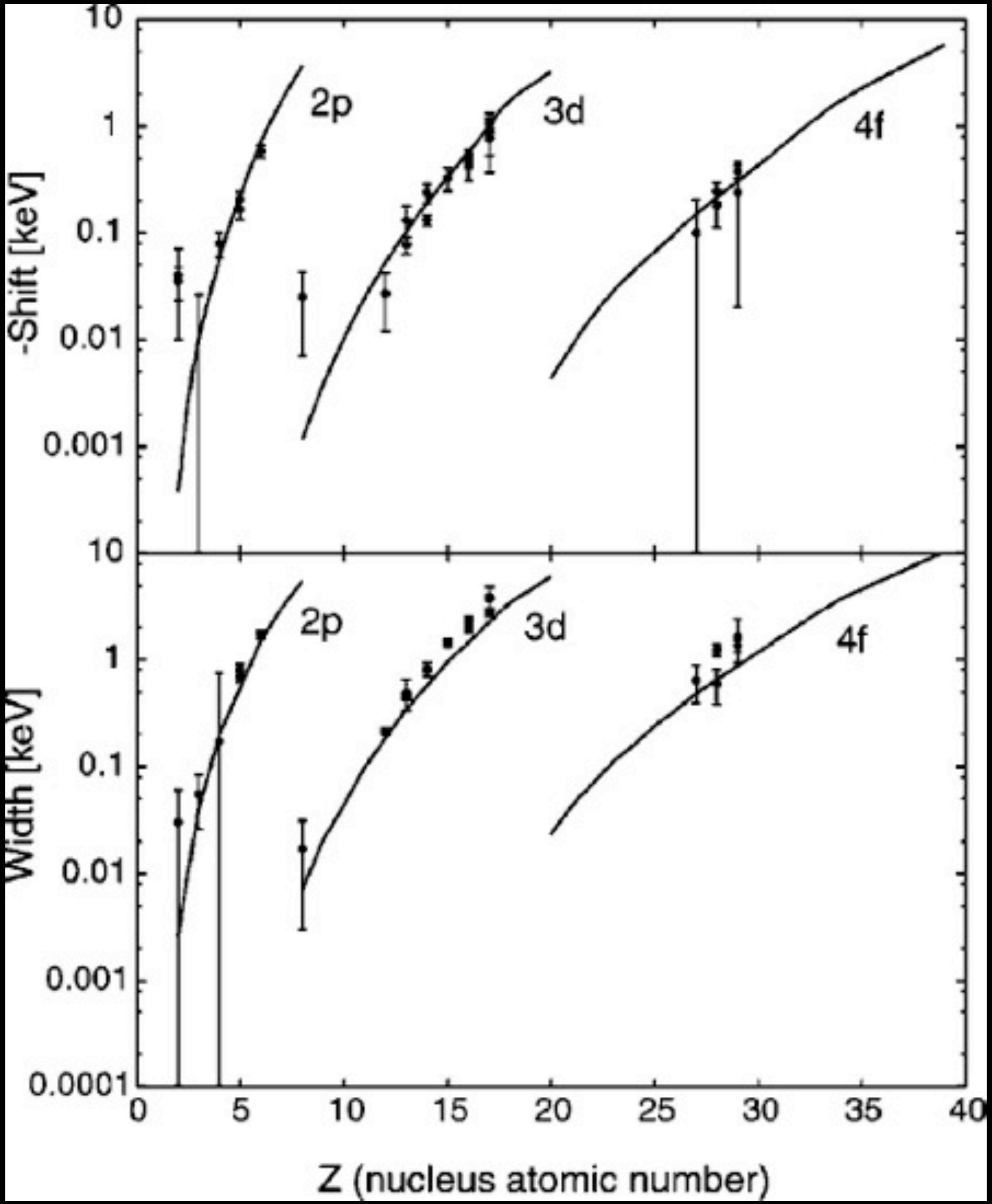
Data & a theory for Z ≥ 2 K-atom

Shift and width for last orbit

SU(3) Chiral Unitary Model

Shift

Width



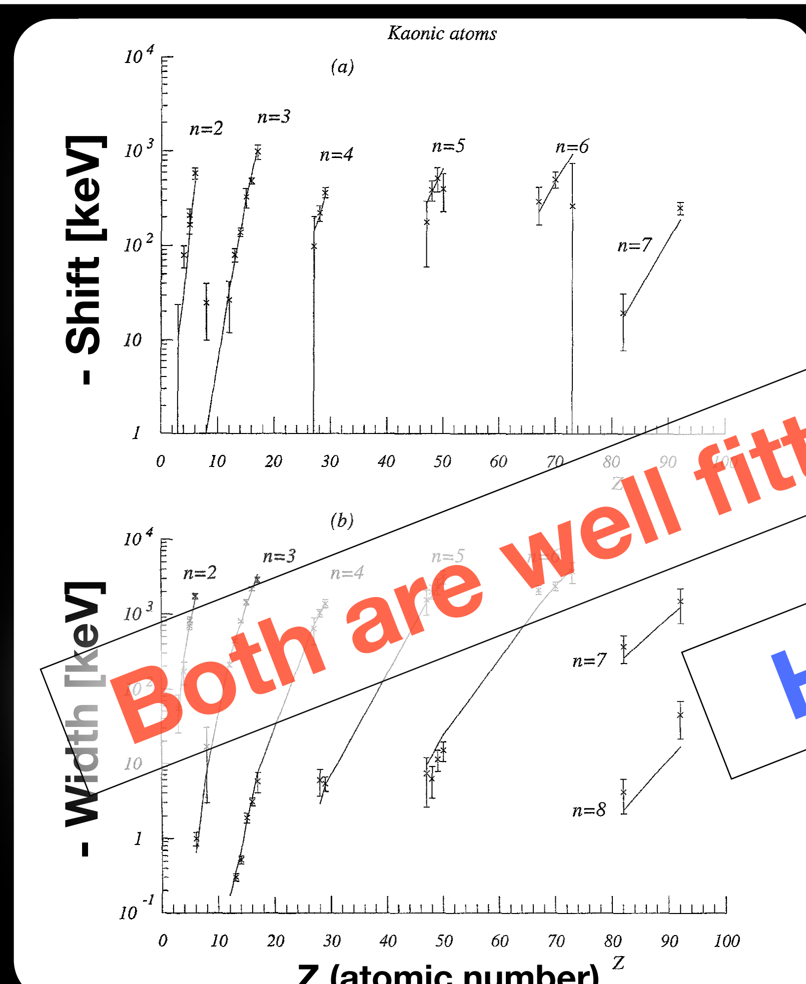
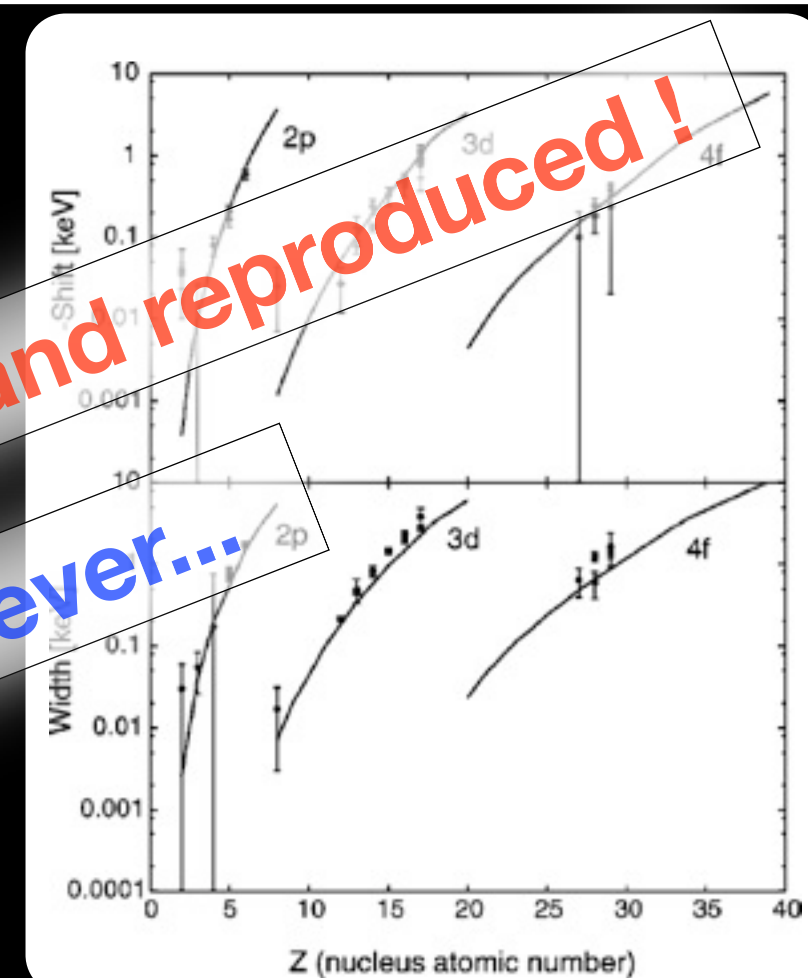
Plot w/error bar
… experimental data

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

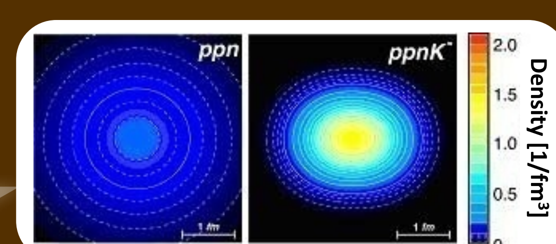
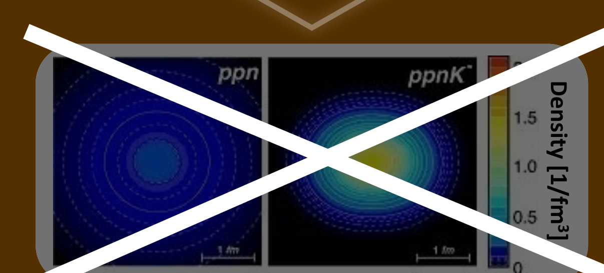
Two theoretical approaches

approach	Phenomenological	Fundamental
model	Density-dependent optical potential	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 !

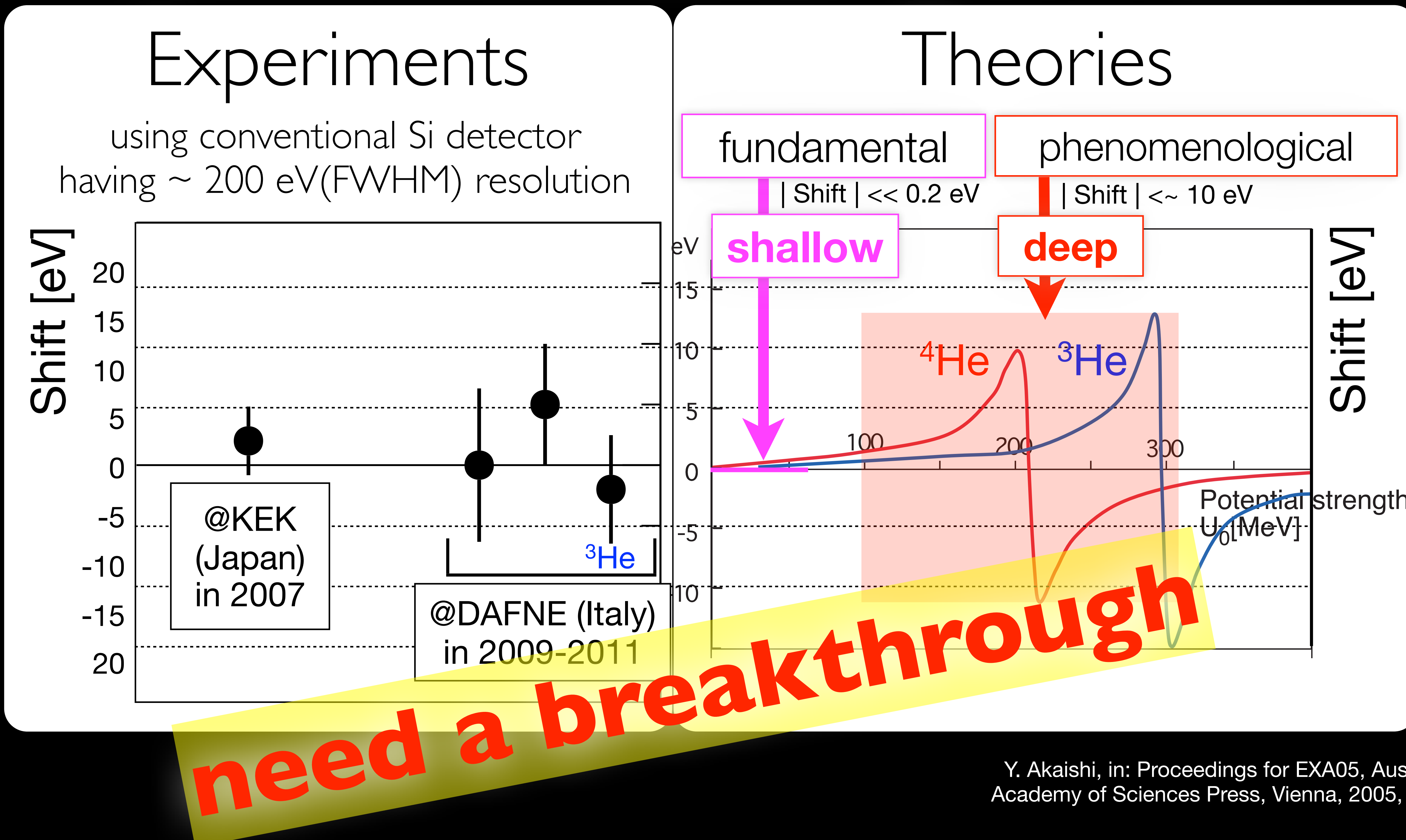
However...

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)  *predicts **deeply bound K^- clusters*** *(high density matter like **neutron star**)*	**shallow** (-V_{Real} = 40 ~ 60 MeV) *unlikely* 

Experiments vs. Theories

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

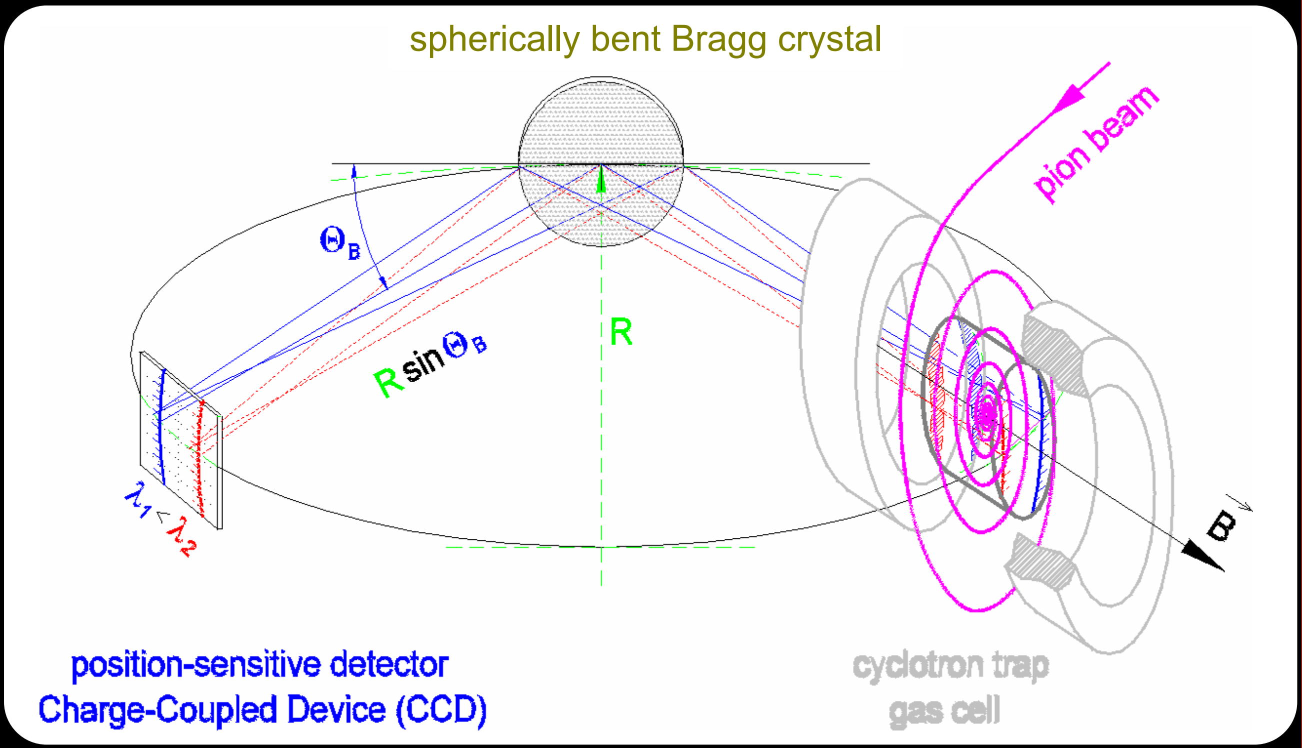


Y. Akaishi, in: Proceedings for EXA05, Austrian Academy of Sciences Press, Vienna, 2005, p. 45.

Next-generation K-atom experiment

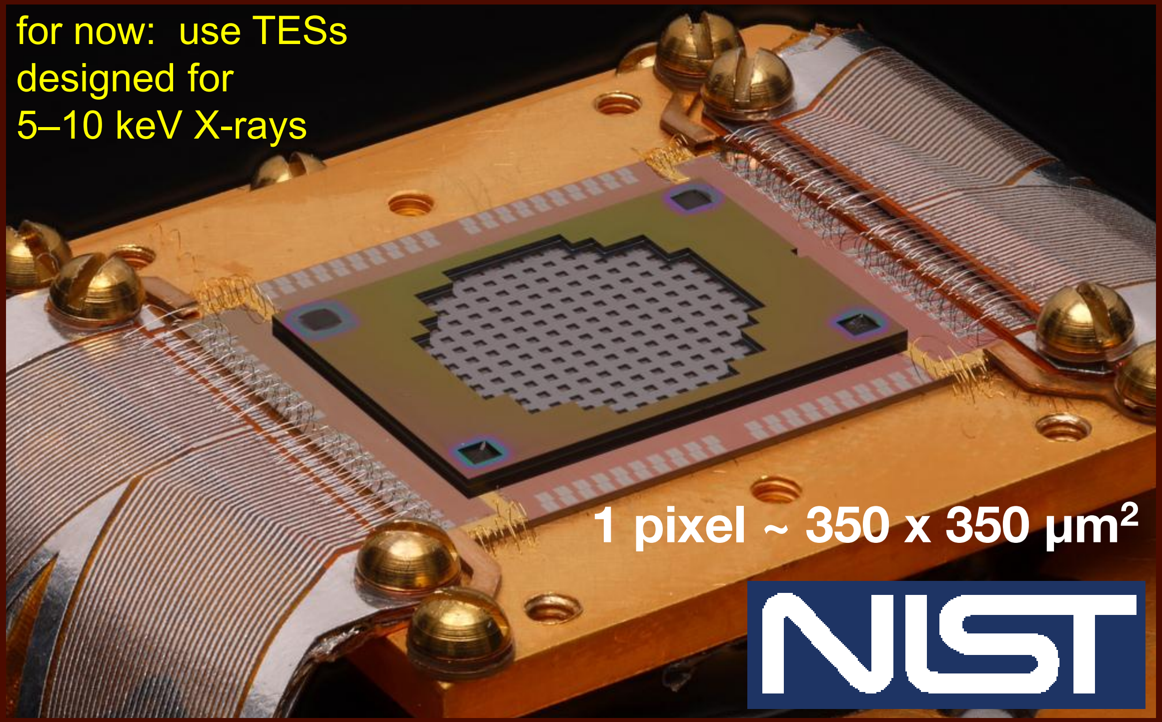
Next-generation K-atom exp.

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 ?

1. High collection efficiency

- Multi device (Array)
- Large absorber

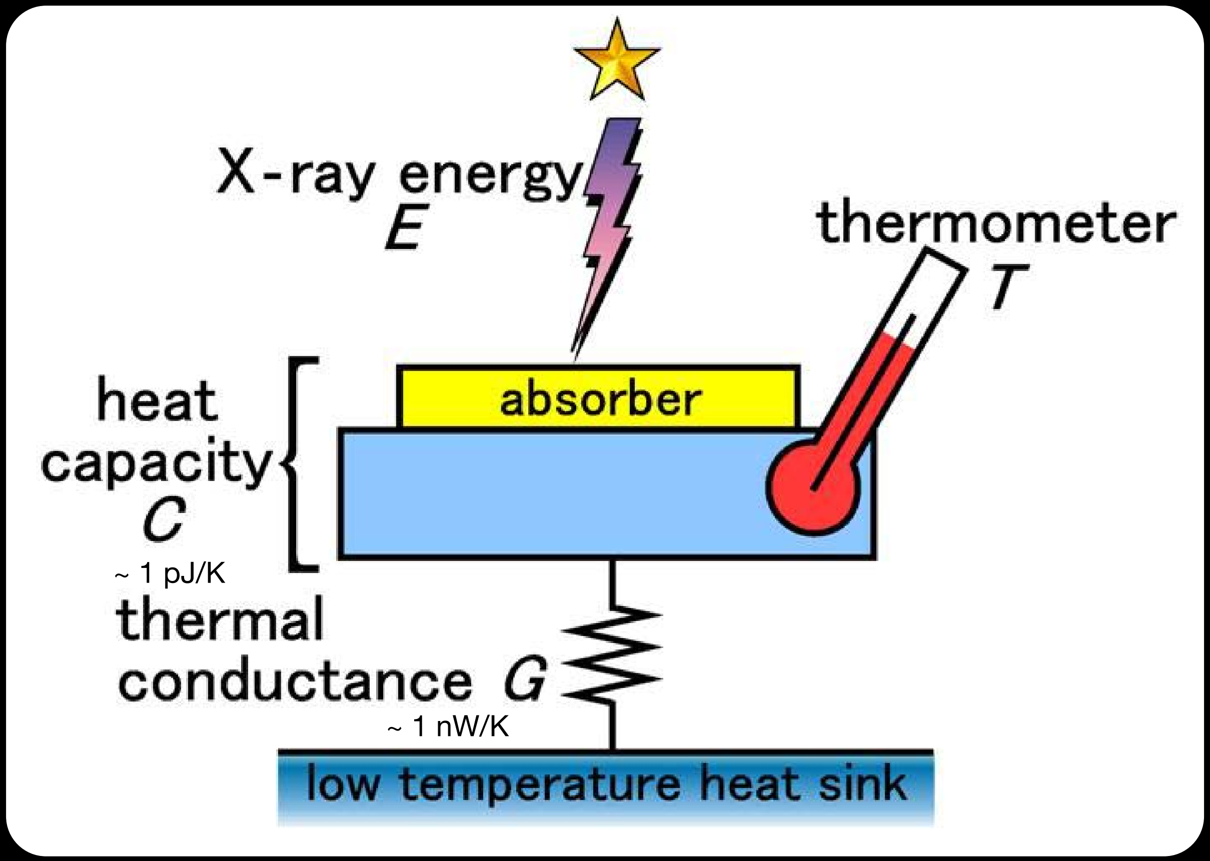
2. Compact and portable

limited beam time, then need to remove

(at J-PARC, DAΦNE etc.)

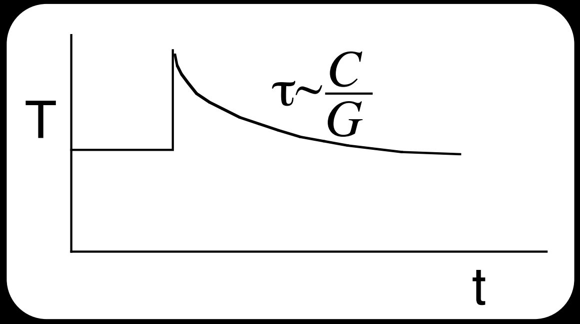
X-ray microcalorimeter

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



Temperature rise
= E / C (~ 1 mK)

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



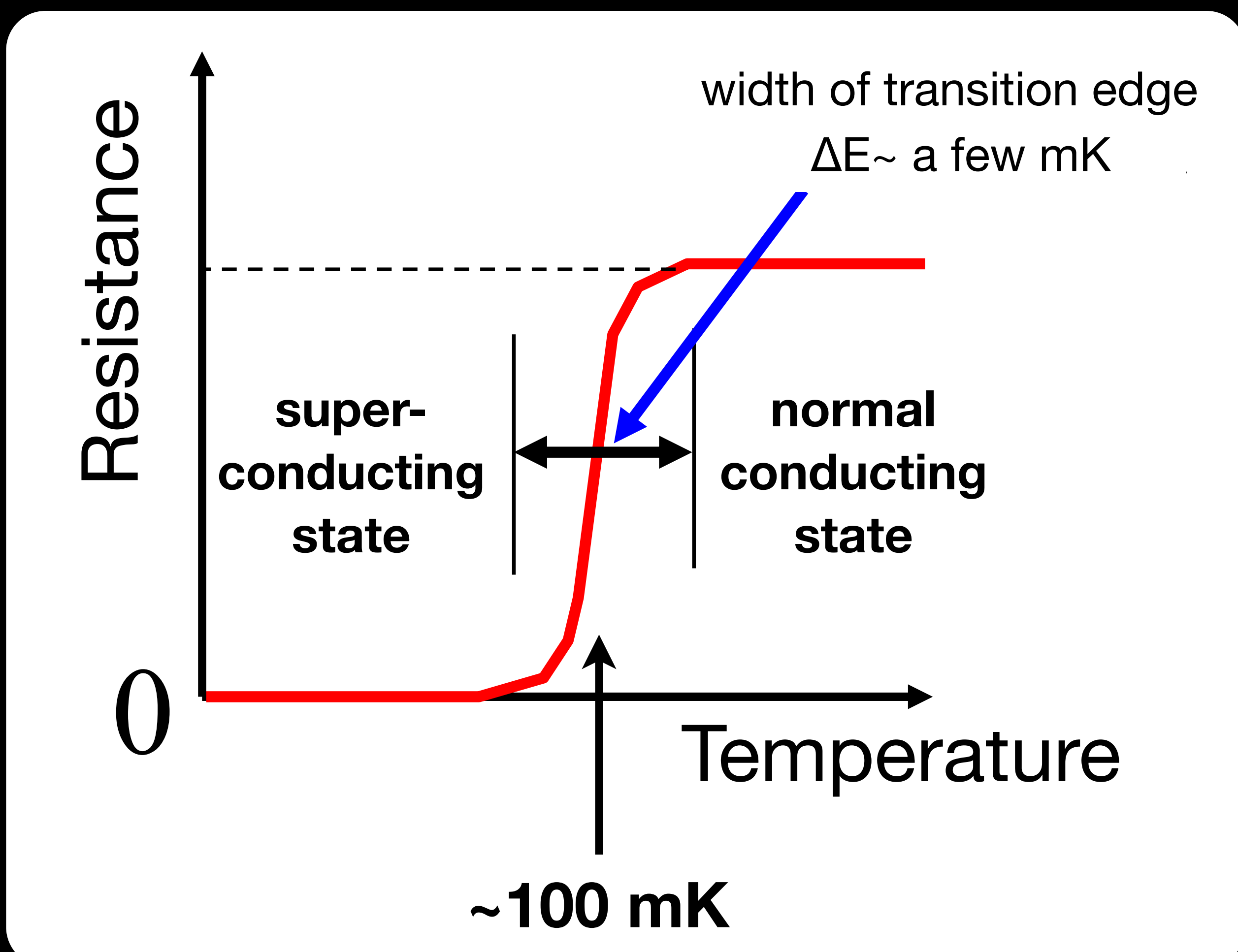
Absorber with larger "Z" (to stop the high energy x-rays)

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)

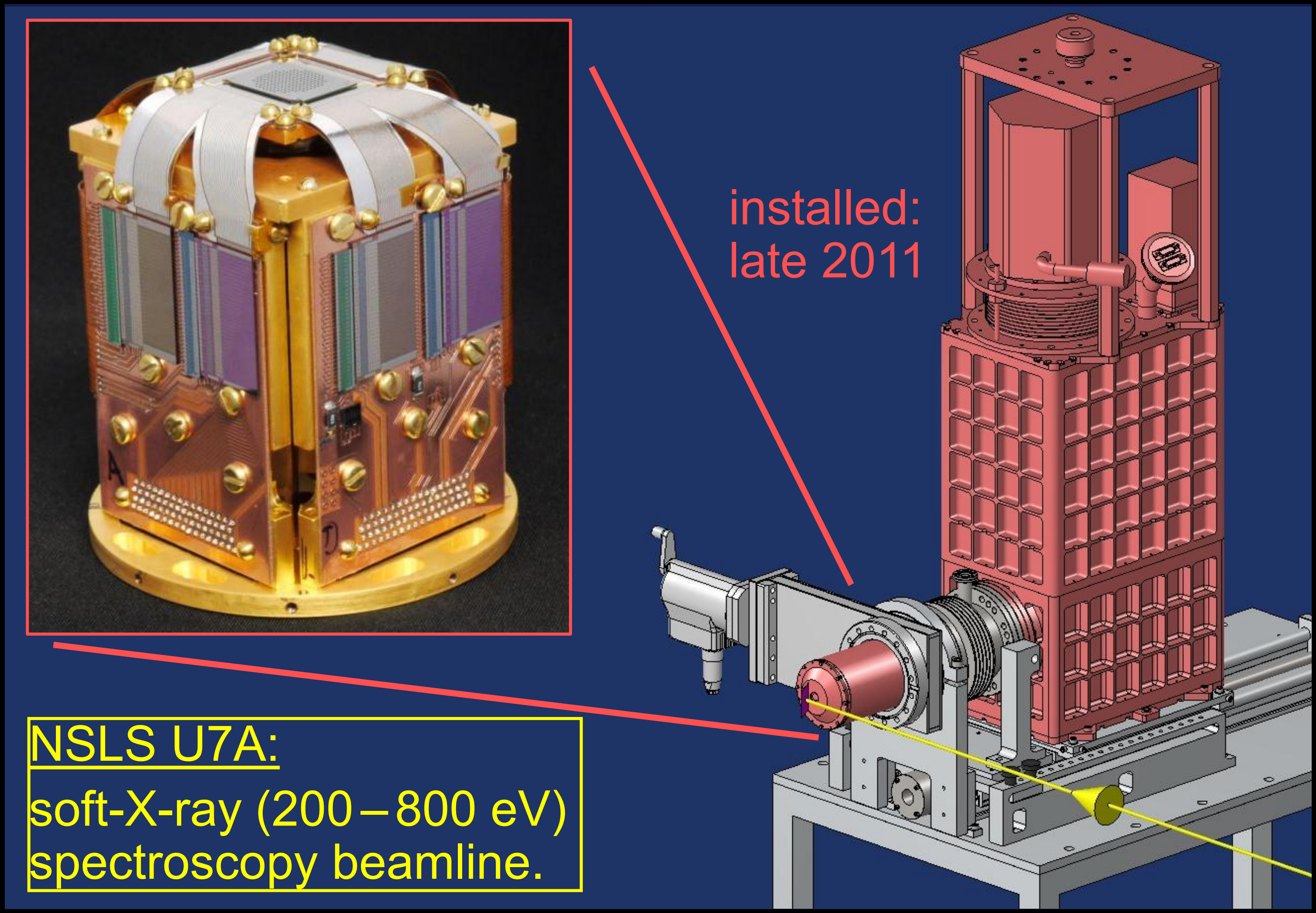
Dynamic range

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

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

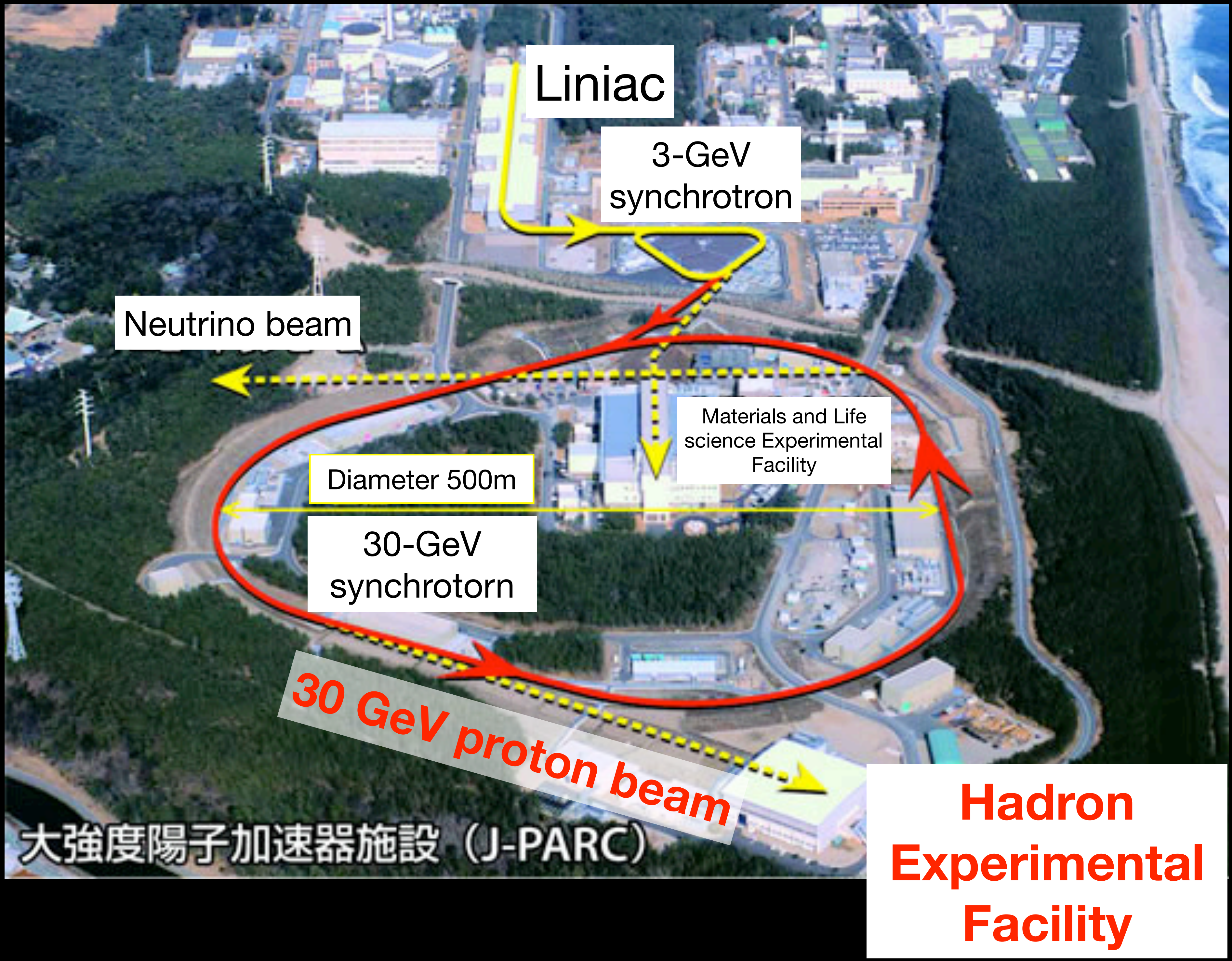
well established system!

two-order improved resolution

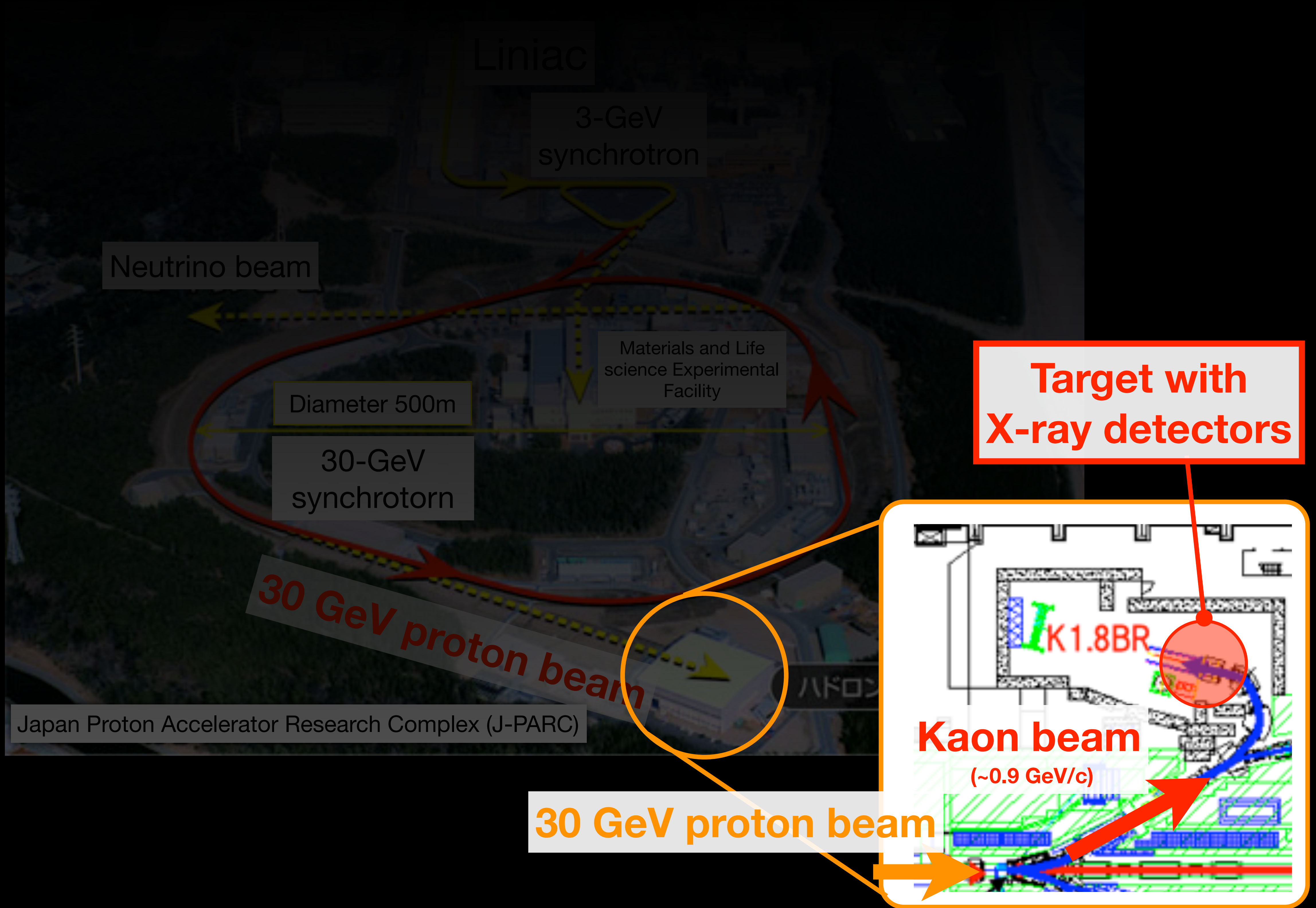
~ 200 eV (FWHM) @ 6 keV
... a typical Silicon detector
used in the previous K-atom exp.

J-PARC (Japan)

Japan Proton Accelerator Research Complex = J-PARC

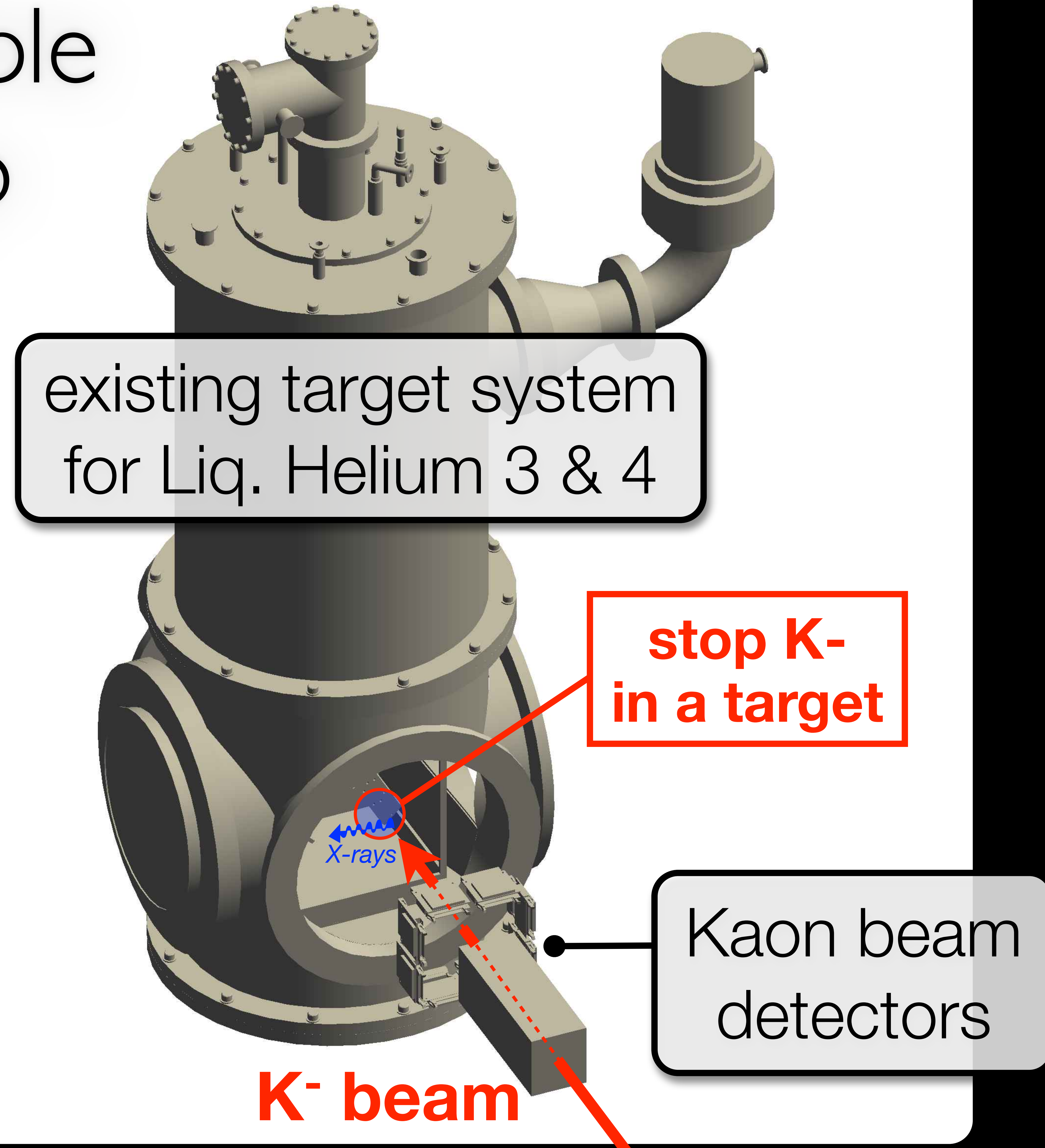


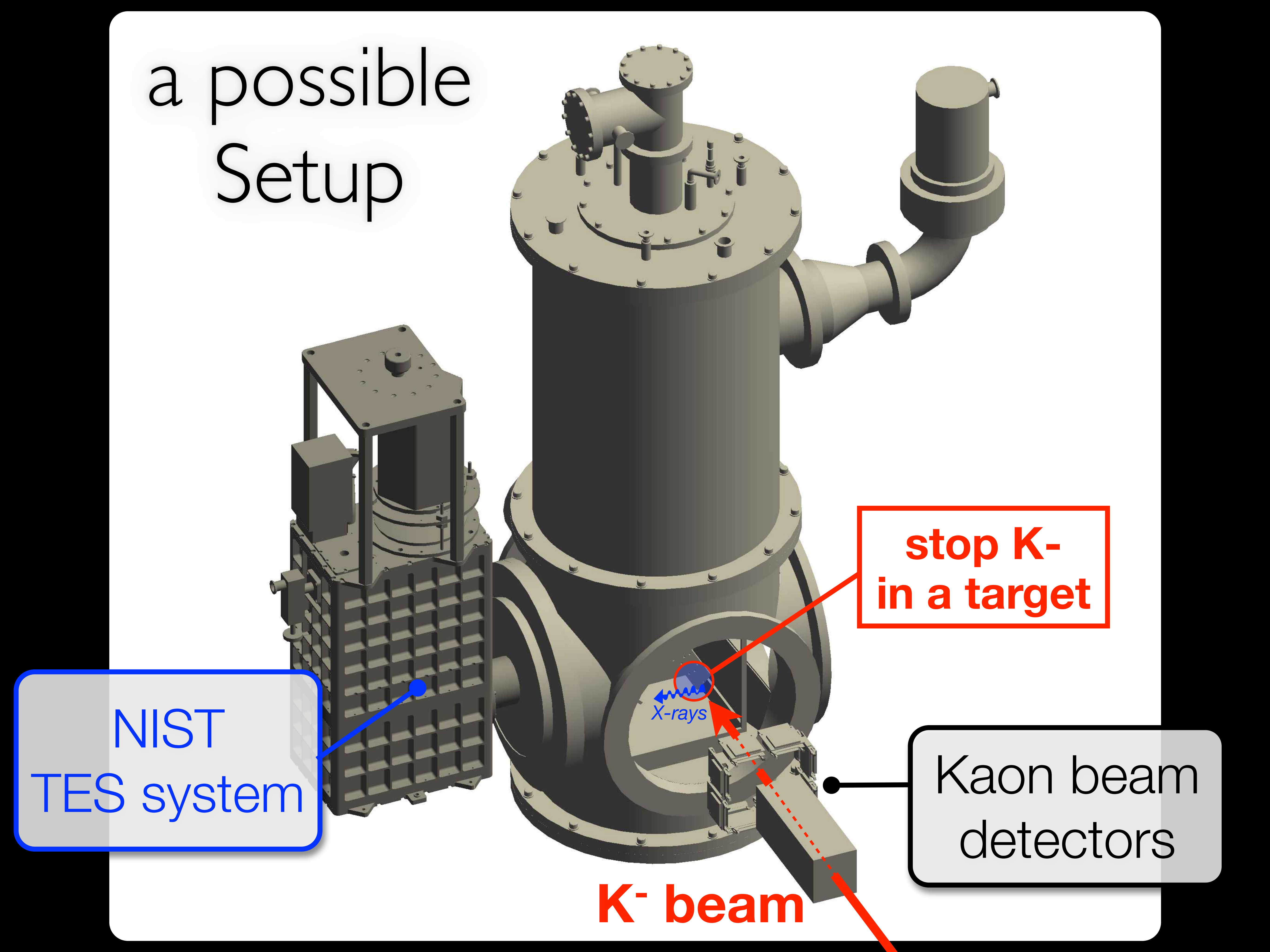
J-PARC (Japan)



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

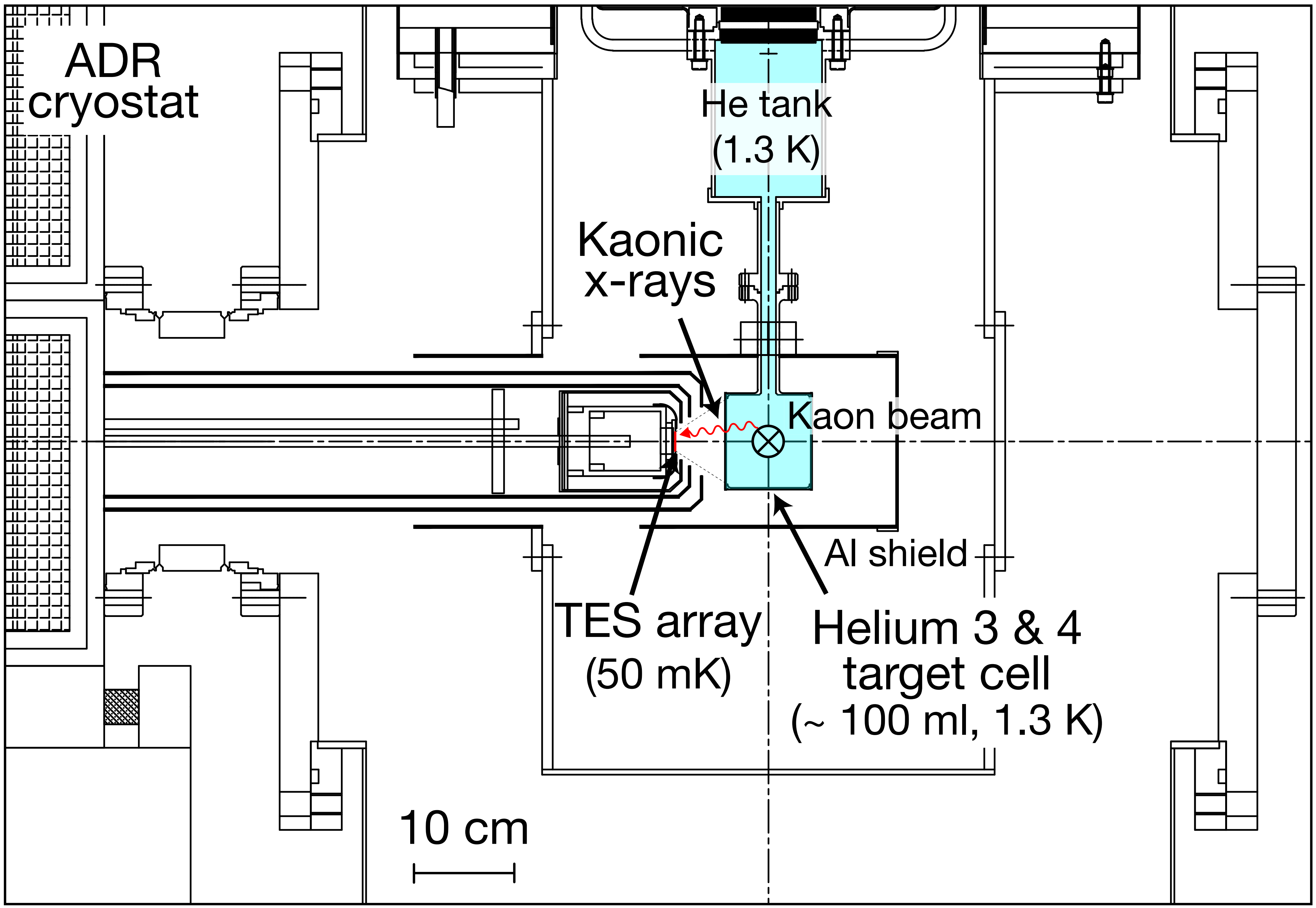
a possible Setup





a possible Setup
stop K- in a target
X-rays
NIST TES system
Kaon beam detectors
K- beam

Cross section (front view)

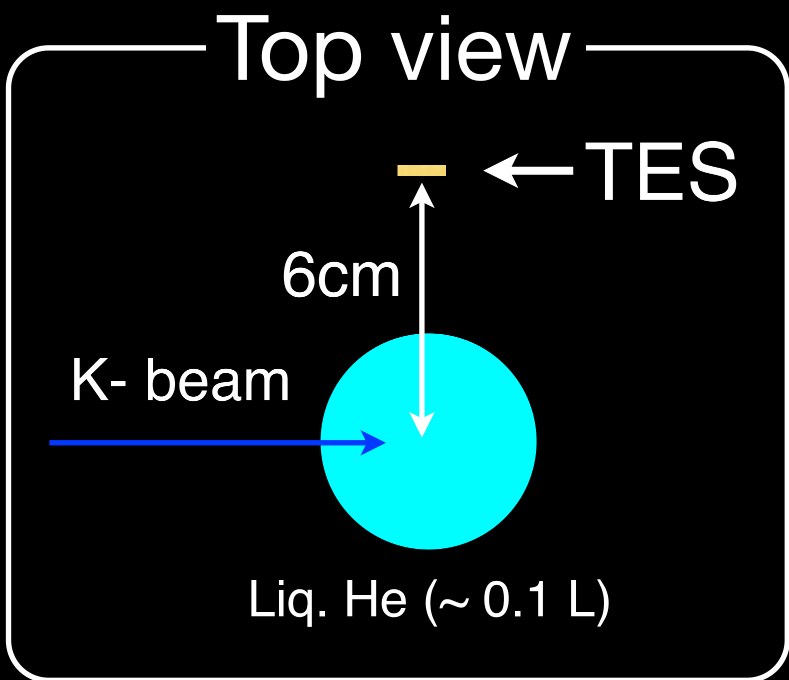


by S. Ishimoto

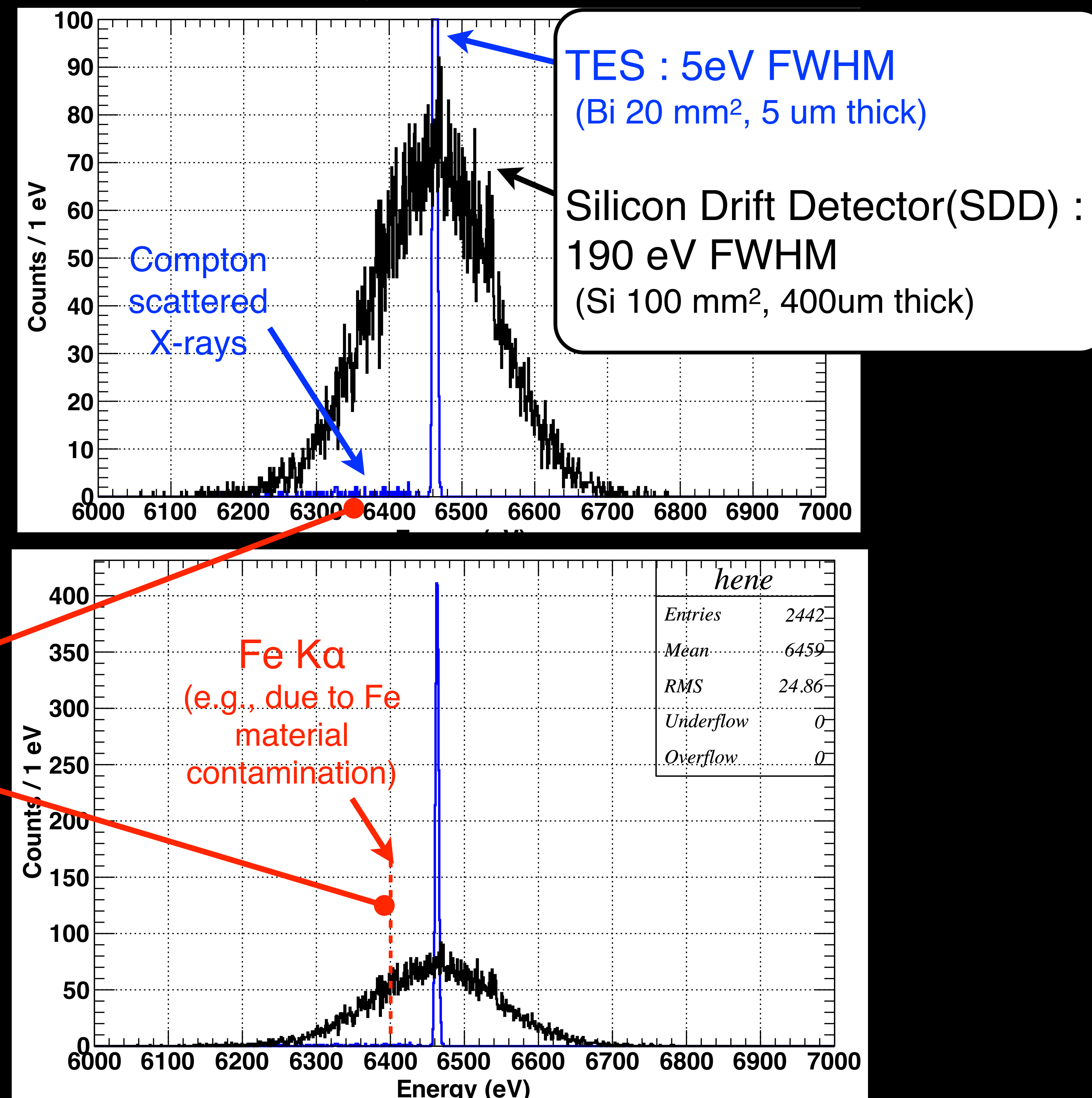
A simple simulation

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".

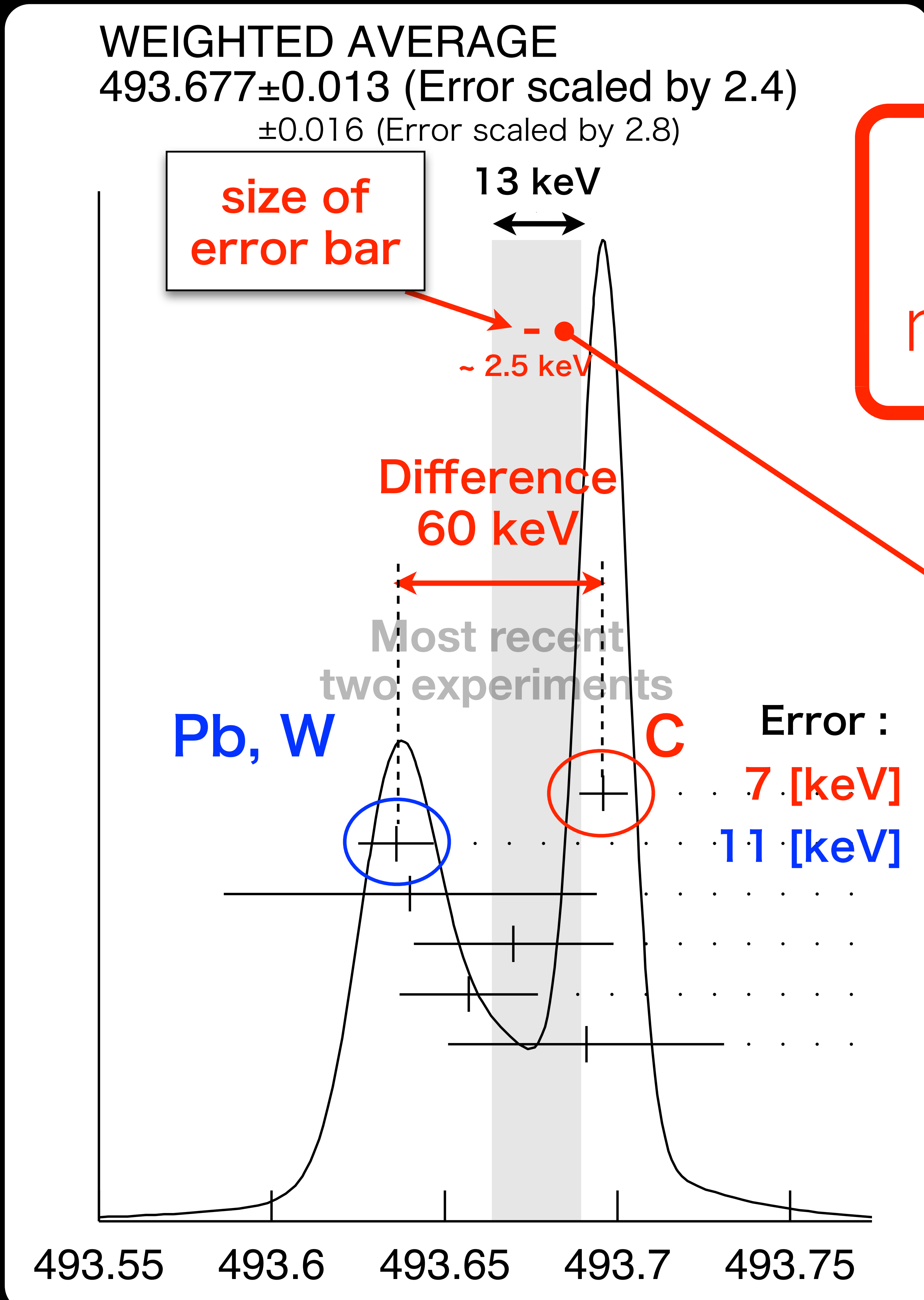
Both have been serious problems
in the prev. experiments.

Rough estimation of stat. accuracy

	K-4He Kα events	detector resolution (FWHM)	stat. accuracy of determining the central value of 6 keV
KEK-E570 with SDD	1500 events	190 eV	**2 eV** = 190 / 2.35 / sqrt(1500)
TES Microcalorimeter	100 events (~ 4-day beam)	2 eV	**0.09 eV**
		3 eV	**0.13 eV** = 3 / 2.35 / sqrt(100)
		4 eV	**0.17 eV**

most fundamental quantity

Charged Kaon mass measurement with TES



Rough estimation

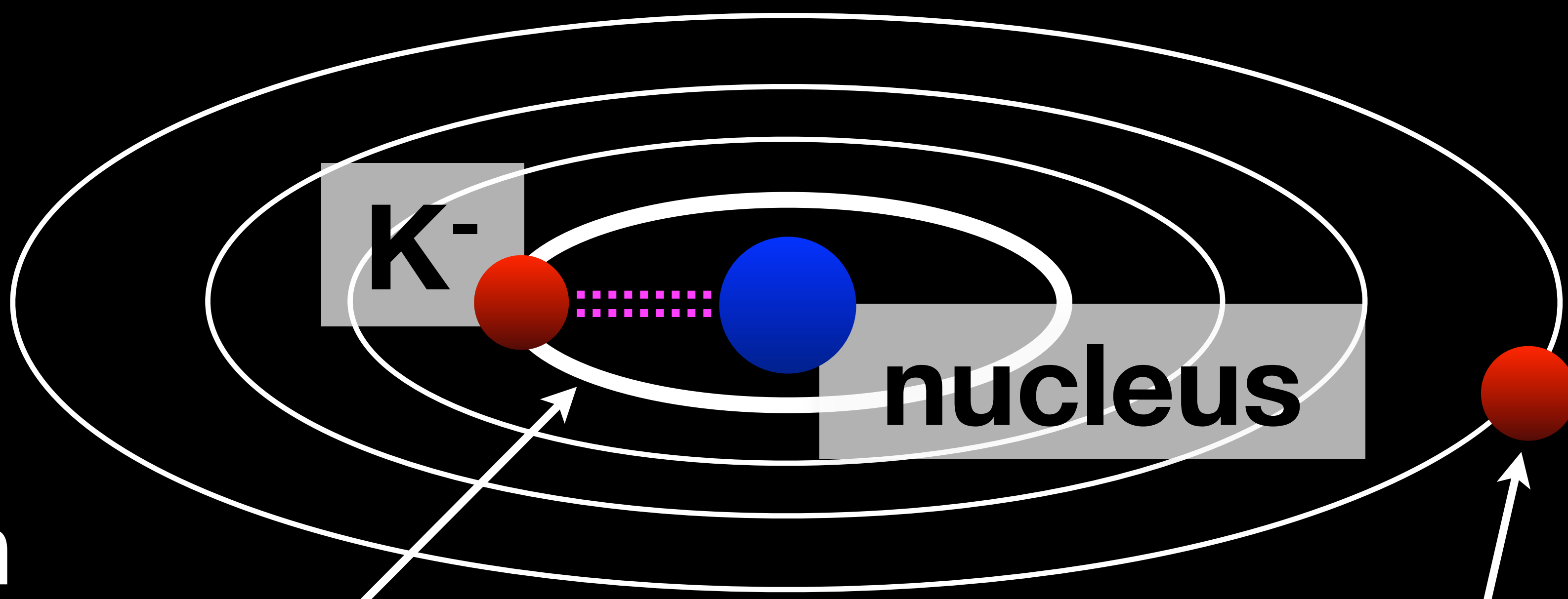
- K-^{12}C 5→4 x-ray : 10.2 keV
- 2000 events & ΔE=5eV(FWHM)
  - ➡ ΔE (x-ray energy) ~ ± 0.05 eV
  - ➡ Δm (K-mass) ~ **± 2.5 keV**

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

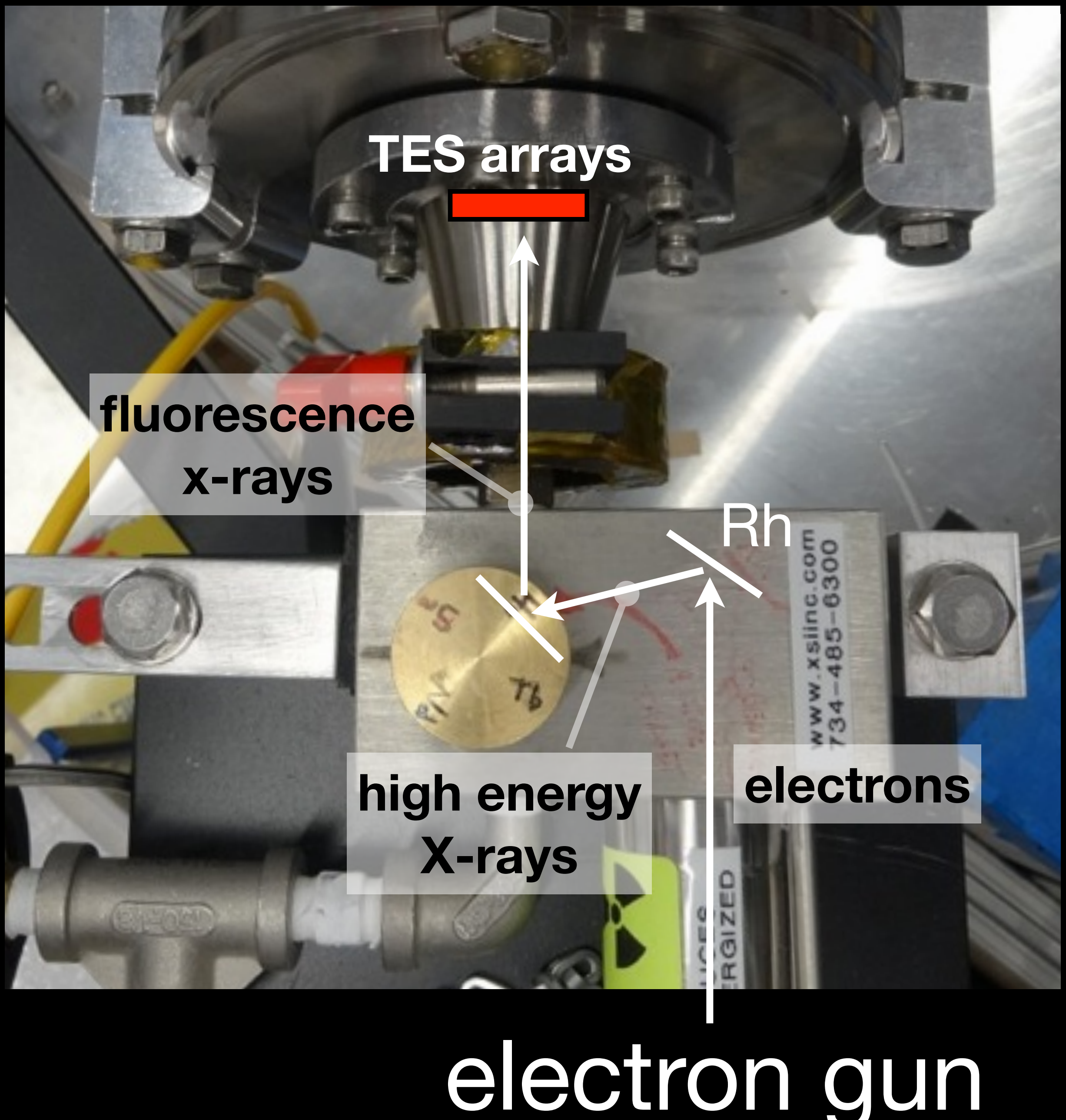
- 公募研究 (A02) -

“ 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	**Modified plan**
Single pixel (TMU)	160 pixel (NIST)
J-PARC test beamline	TRIUMF π beamline
measuring **fluorescence x-rays** from charged particle hits on pure-metal foils	measuring **pionic atom x-rays** (e.g., π-C 4-3 : ~ 6.5 keV) ‣ the first exotic-atom exp. with TES ‣ good demonstration (for J-PARC proposal) *test for anti-coincidence system with low-intensity pion beam*

Line calib. experiment @ NIST

26 Aug. - 6 Sept., 2013



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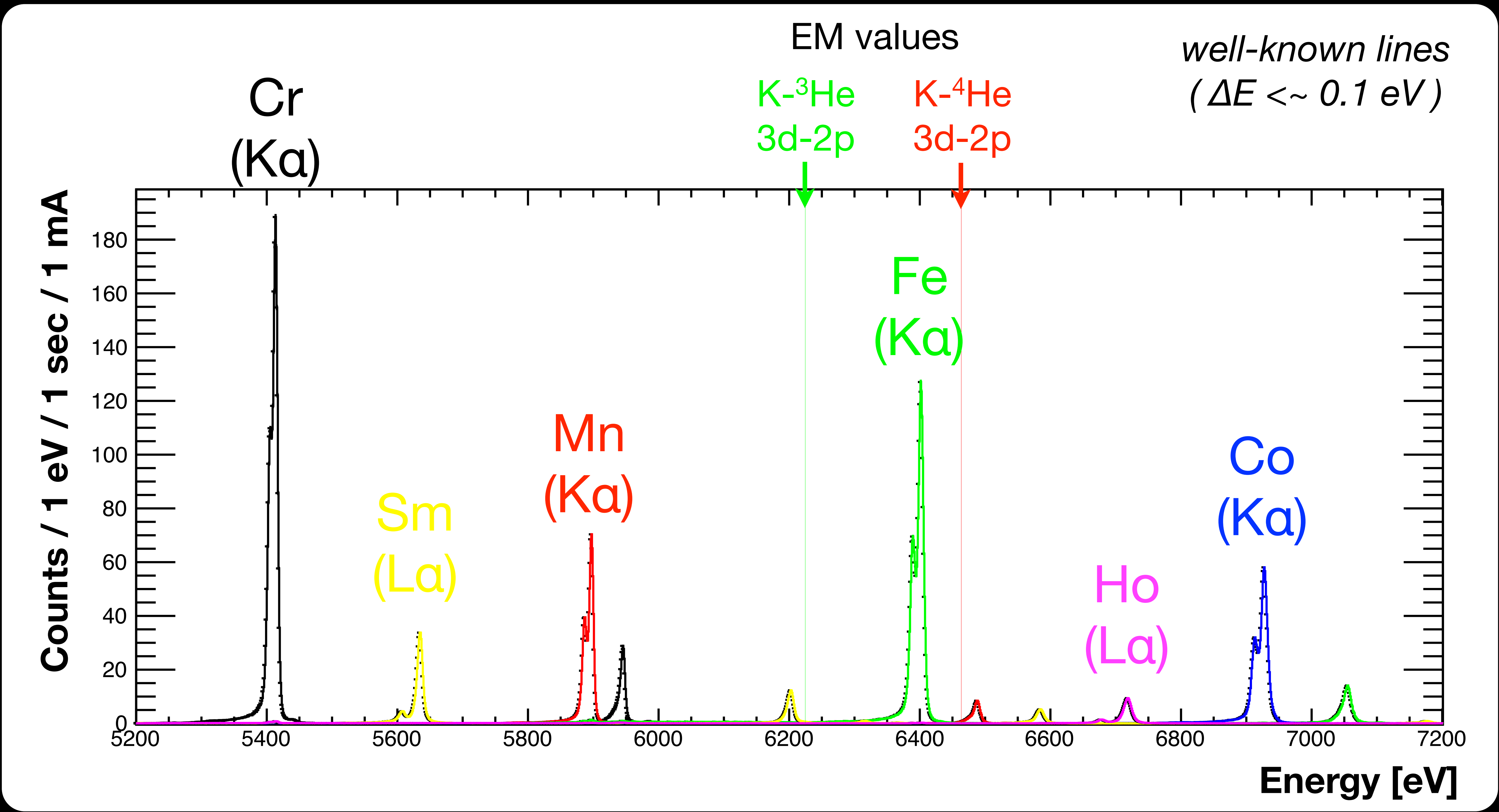
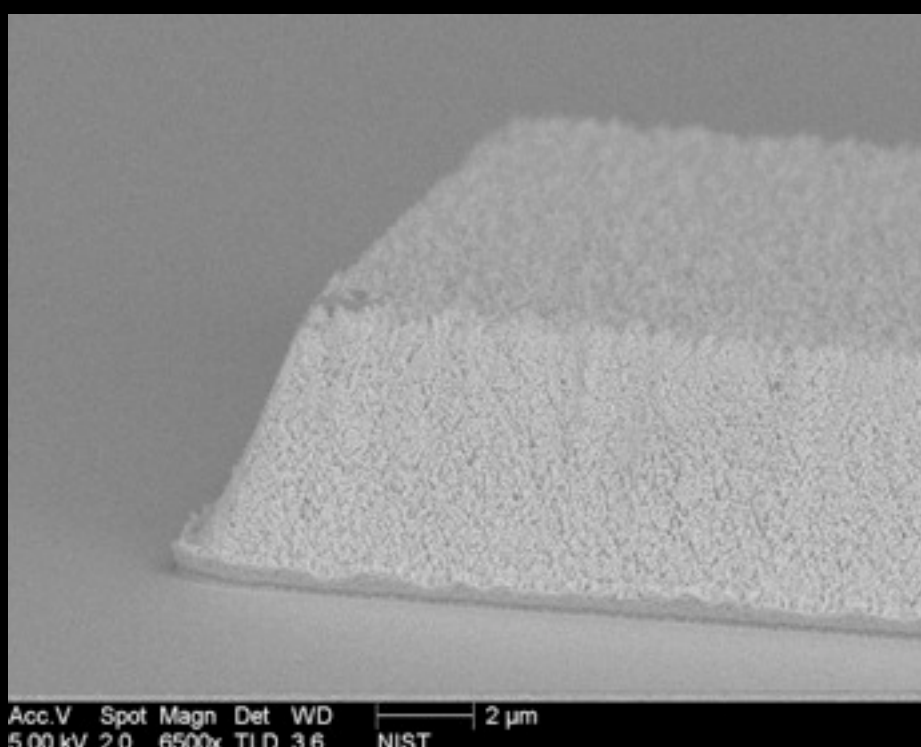


Thicker Bi absorber

First try of 5-um Bi absorber --> successfully done



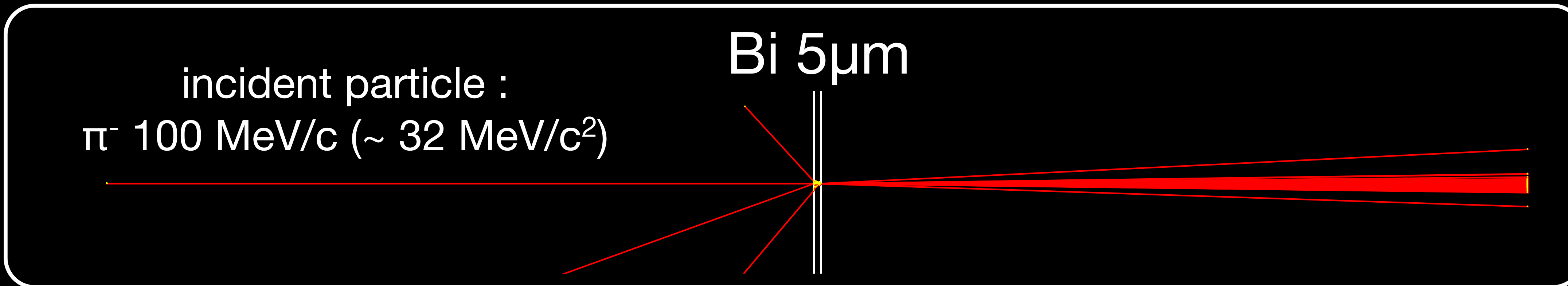
X-ray transmission factor for various Bi absorber

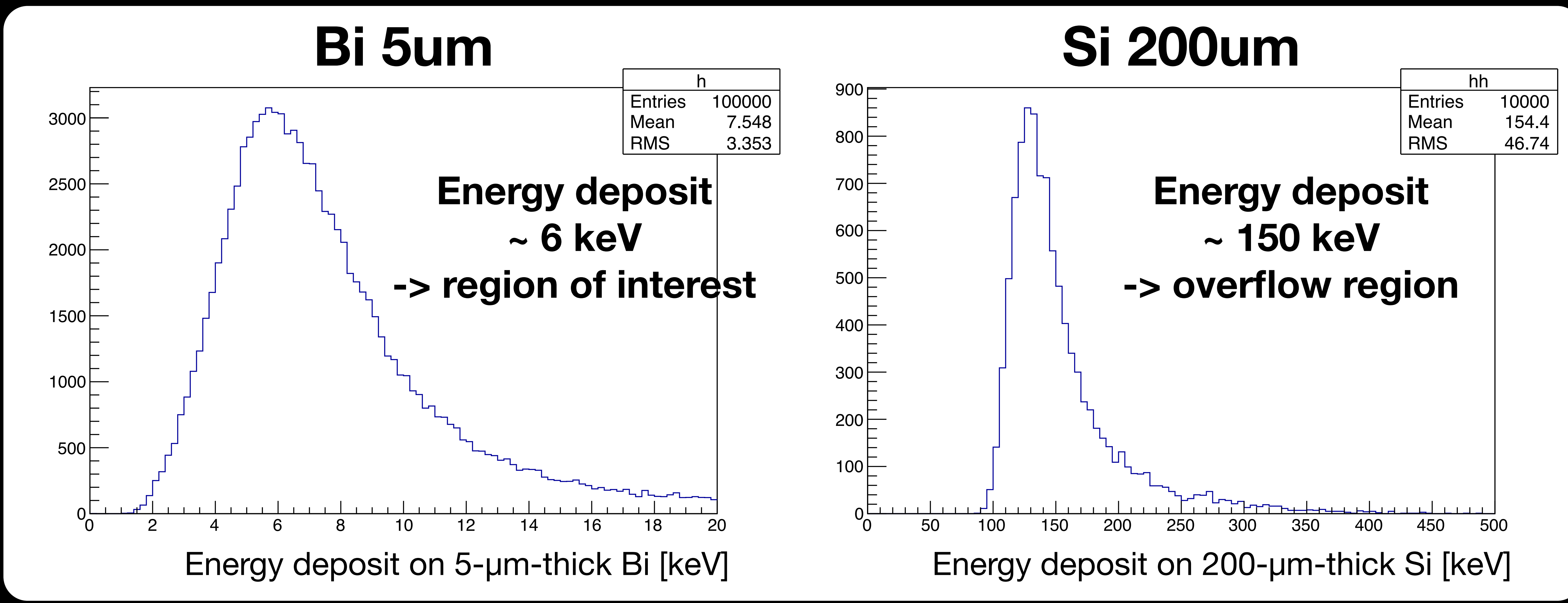
Bi thickness	Transmission x-rays	
	for 6 keV	for 10 keV
2 um	38.4%	77.1%
5 um	9.1%	52.2%
10 um	0.8%	27.3%

⇦ typical (now) 2 ~ 3 um

~ 5.5 um thick (measured by a profilometer (~ a simplified AFM))

Anti-coincidence system

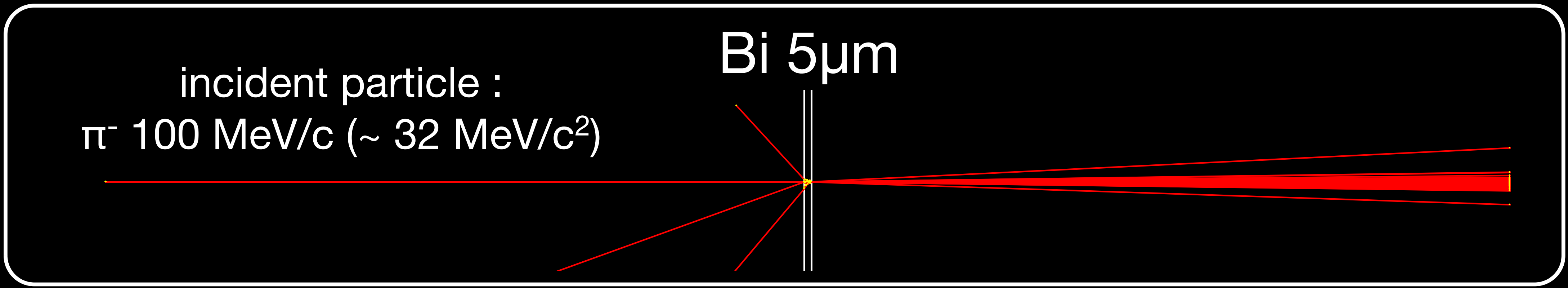


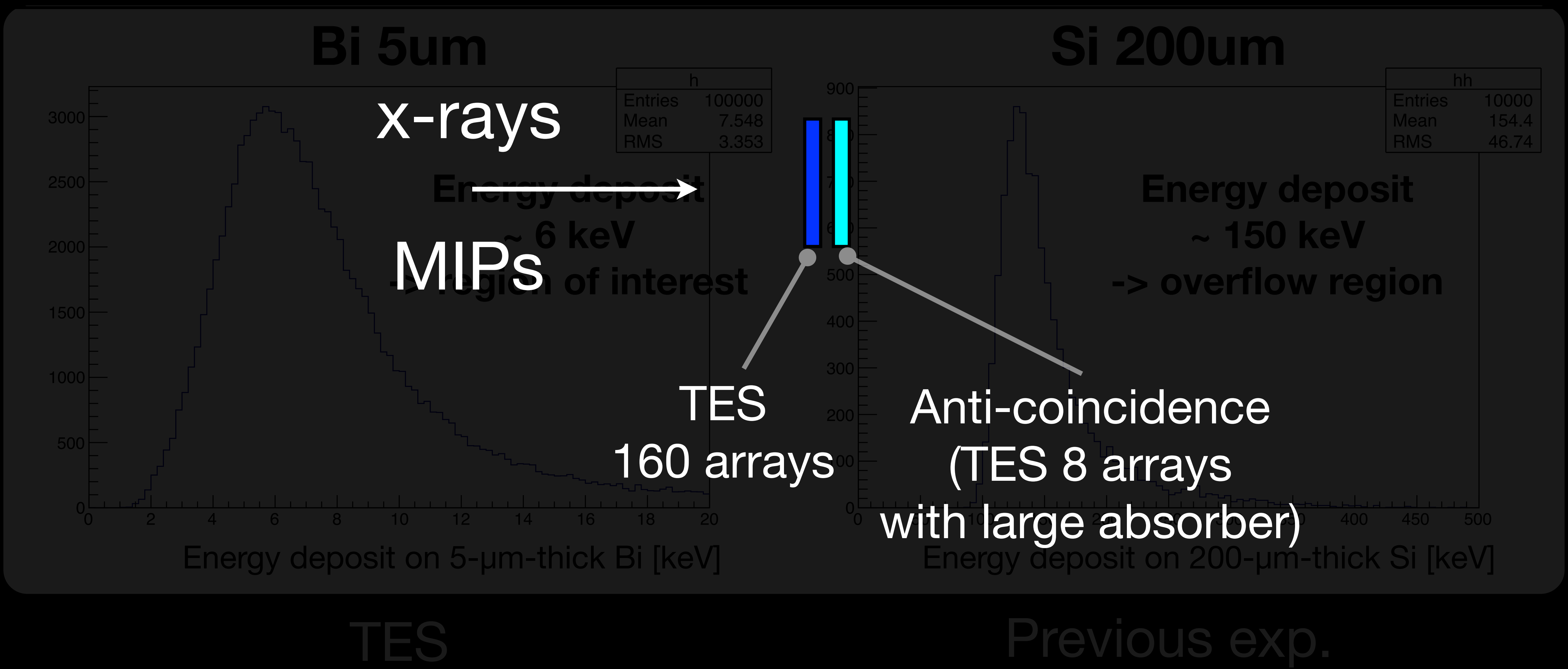


TES

Previous exp.

Anti-coincidence system





Summary

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◉ 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)

◉ future perspective

- 2013 : test experiment without beam (evaluation of basic performance)
- 2014 : test experiment with beam (and preparation of LoI / proposal)

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