28 June, 2013

LTD-15 @ Pasadena, California

High-resolution Kaonic-atom X-ray Spectroscopy with Transition-edge-sensor Microcalorimeters

RIKEN Shinji Okada

Collaboration

NIST (U.S.)	RIKEN (Japan)
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D.R. Schmidt	
J.N. Ullom	

KEK (Japan)

S. Ishimoto

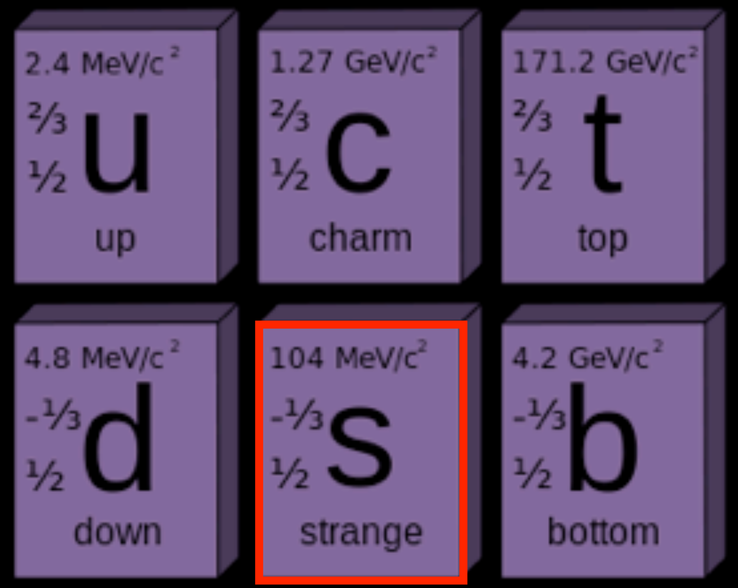
INFN - LNF (Italy)

H. Tatsuno

$I(J^P) = \frac{1}{2}(0^-)$

Kaon

- K meson -



the lightest hadron containing **strange quark**

anti-Kaon : $\overline{K}$

strange quark

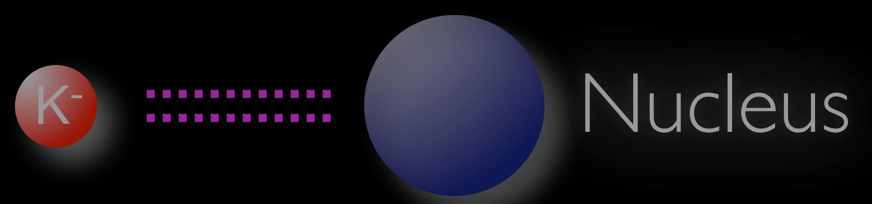
$$K^+ = u\bar{s},\ K^0 = d\bar{s},\ \overline{K}^0 = \bar{d}s,\ K^- = \bar{u}s,$$

Negative charged Kaon

For charged kaon :

mass	493.677(16) MeV	ex) ~1000 times heavier than electron
lifetime	~ 12 nsec	ex) ~1/200 times shorter than muon

$\bar{K}$ - Nucleus strong interaction at low energy



Why $\bar{K}$ - Nucl. interaction at low energy?

Quantum ChromoDynamics (QCD) becomes non-perturbative at low energy

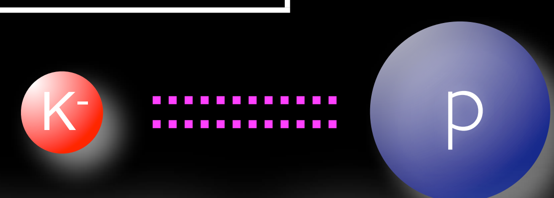
➡ impossible to use perturbative methods

➡ (approximative) symmetries are good guidelines to understand the hadron dynamics

quark	mass [MeV]	symmetry	
up	~ 2	**chiral symmetry**	*quark mass zero limit*
down	~ 5		
strange	~ 100	**intermediate**	
charm	~ 1,300	heavy-quark symmetry	*quark mass infinity*
bottom	~ 4,200		
top	~ 170,000	weak decay w/o forming hadrons	

*(**K^-** is the lightest hadron containing **strange** quark.)*

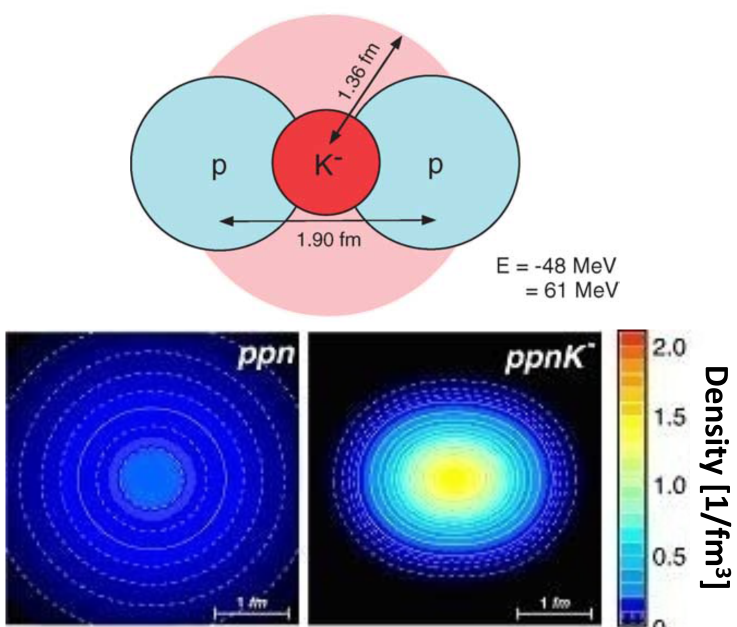
➡ "K^--Nucl." systems are suitable testing grounds for investigating the interplay between spontaneous and explicit **chiral symmetry breaking**.



Strongly attractive!

- ✓ **Dense matter :** higher density beyond normal nuclear-matter density?
- ✓ **Neutron star :** Kaon is a strong candidate of hadrons composing inside of neutron star.
- ✓ **Origin of mass :** the in-medium mass modification effect as a function of matter density?

Deeply bound K^- cluster



~3 times higher than the normal nuclear density!

Phys. Lett. B587, 167 (2004)

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*(... the lightest hadron containing **strange** quark.)*

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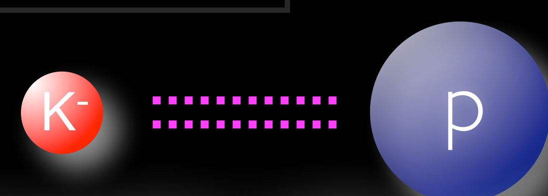
Depending on how much of K-nucl. potential depth

Deep or Shallow ?



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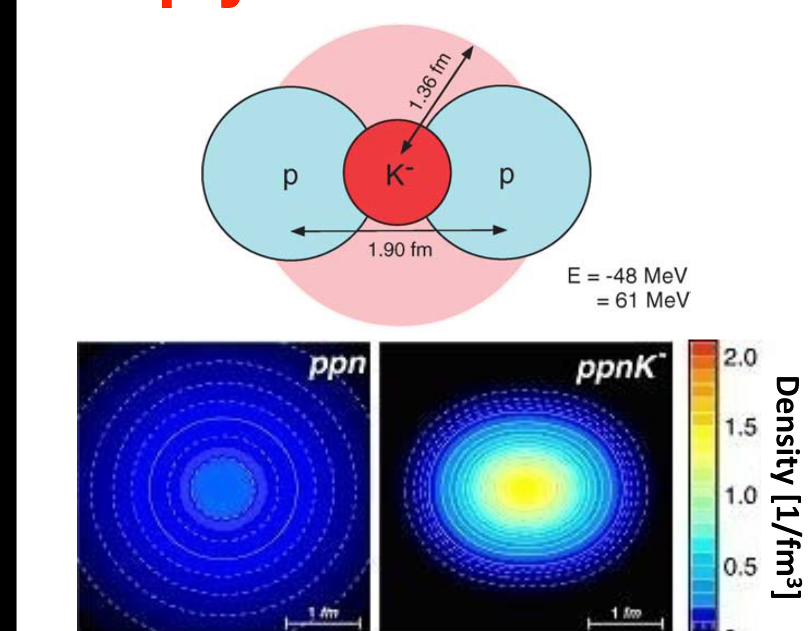

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Phys. Lett. B587, 167 (2004)

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

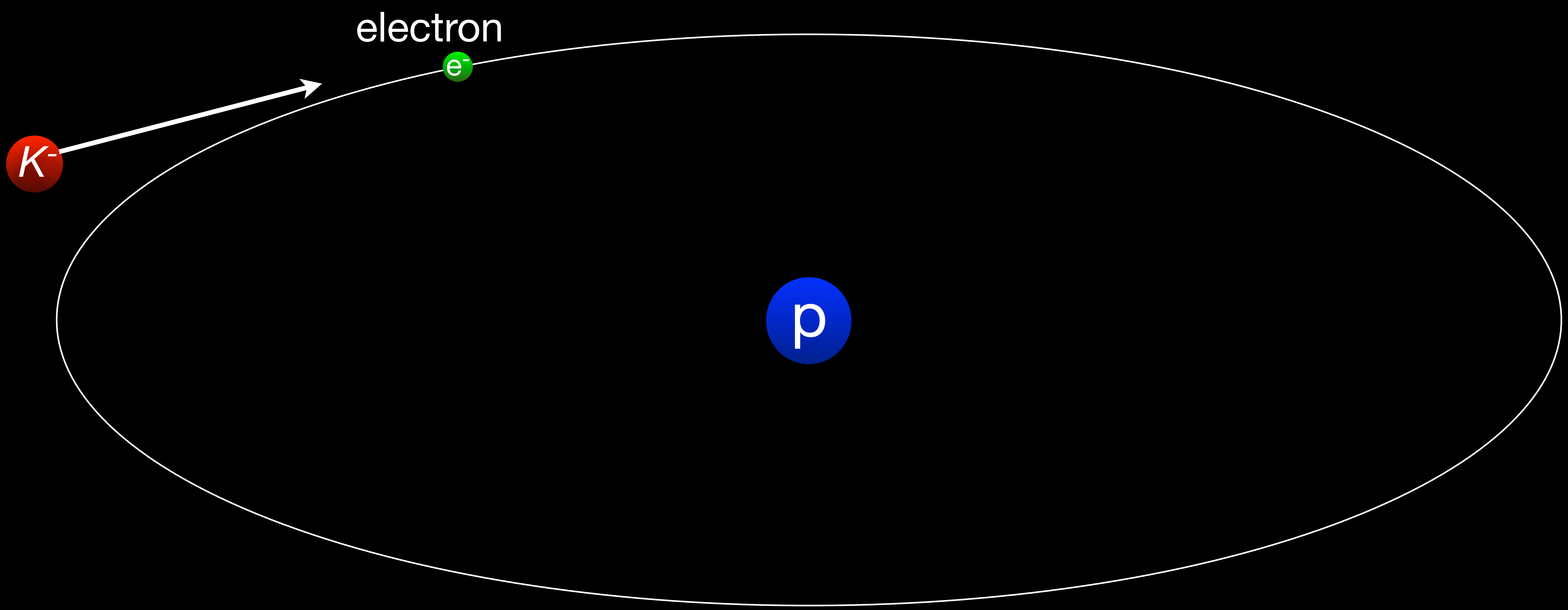
Kaon low-energy scattering experiment
is **difficult** due to the short lifetime (~12 nsec)

⇩

Kaon-nucleus bound states

Coulomb bound state
- Kaonic atom -

Hydrogen

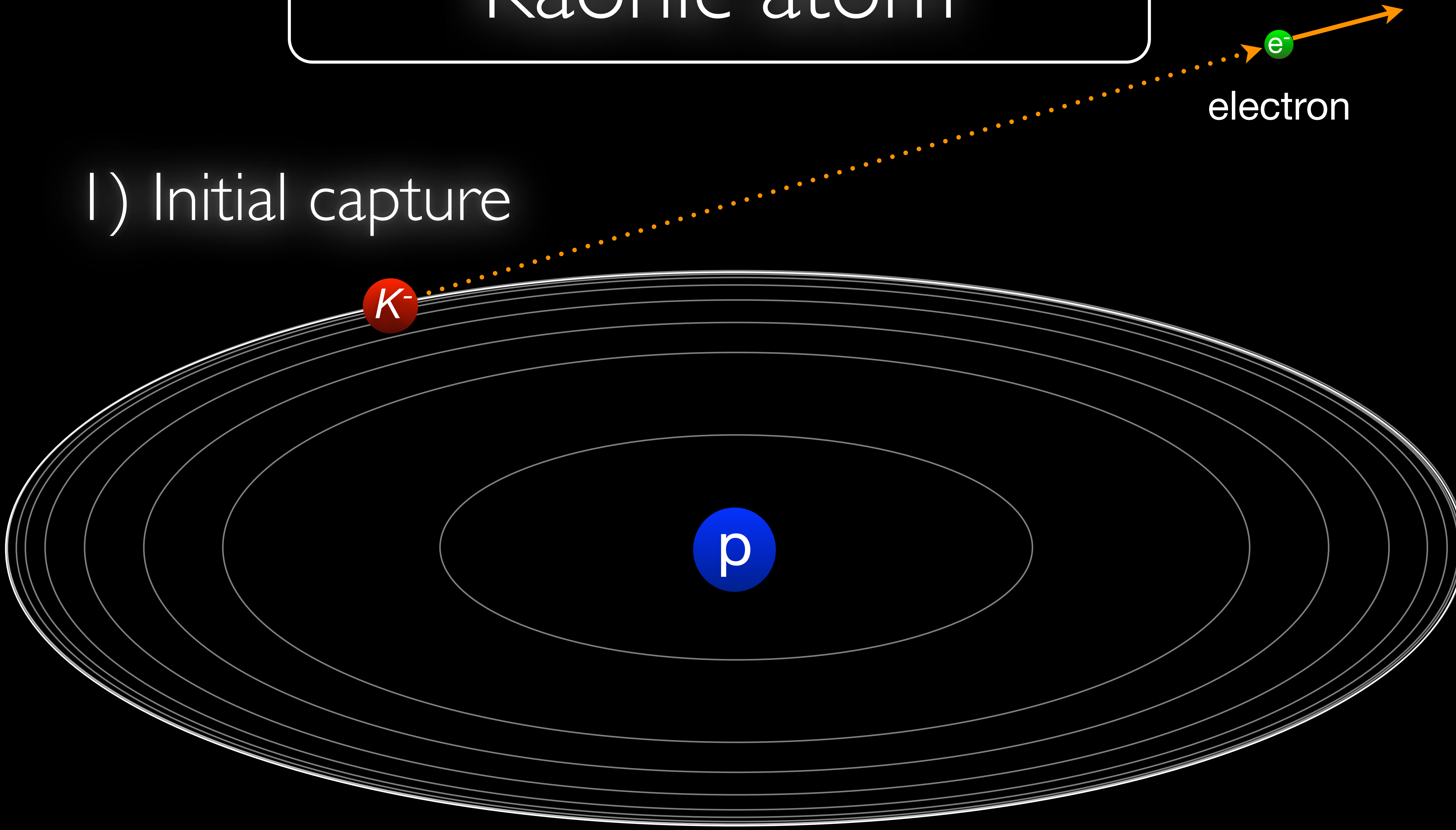


principal quantum number

$n = 1$

Kaonic atom

1) Initial capture



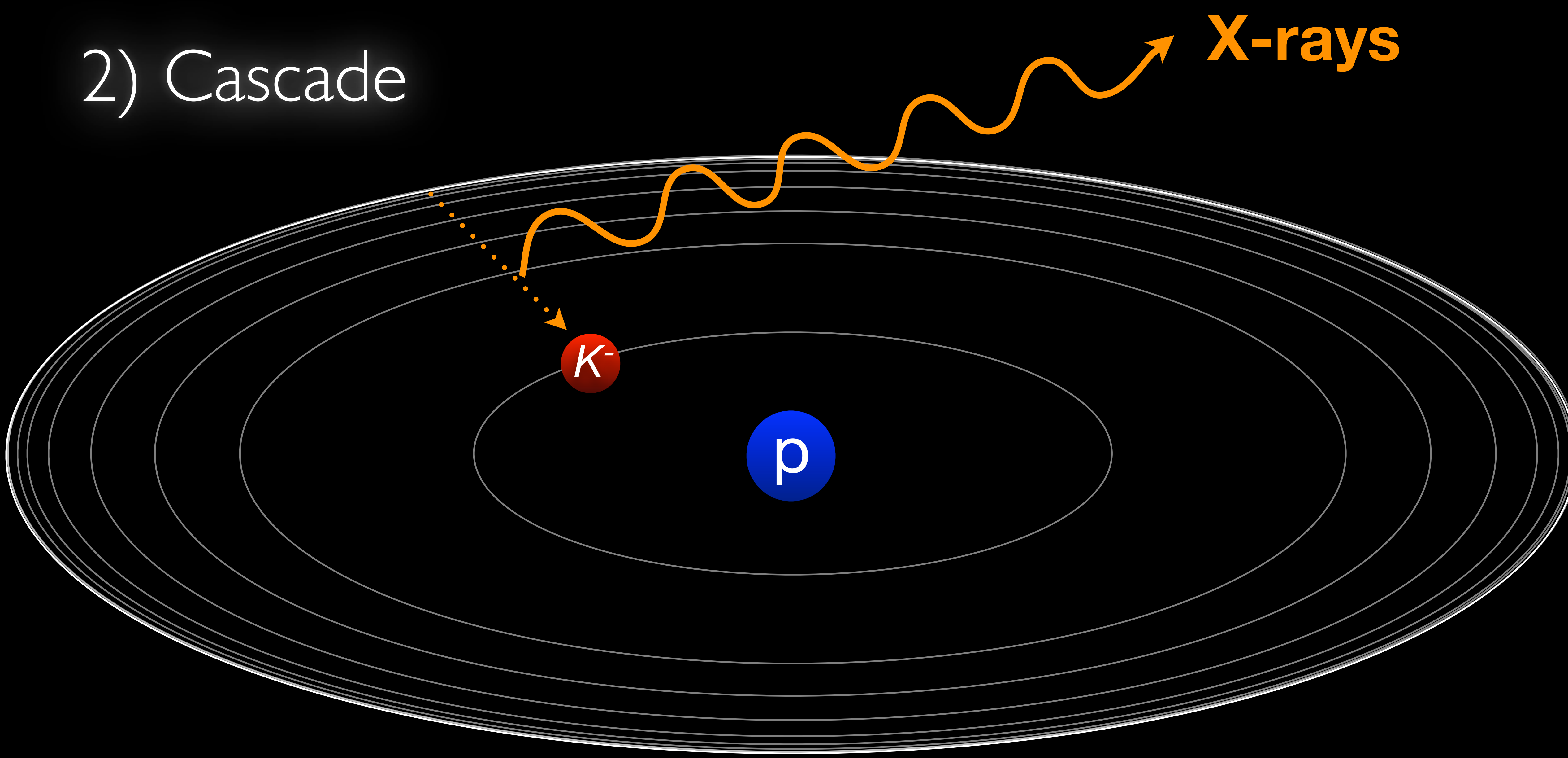
principal quantum number

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

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

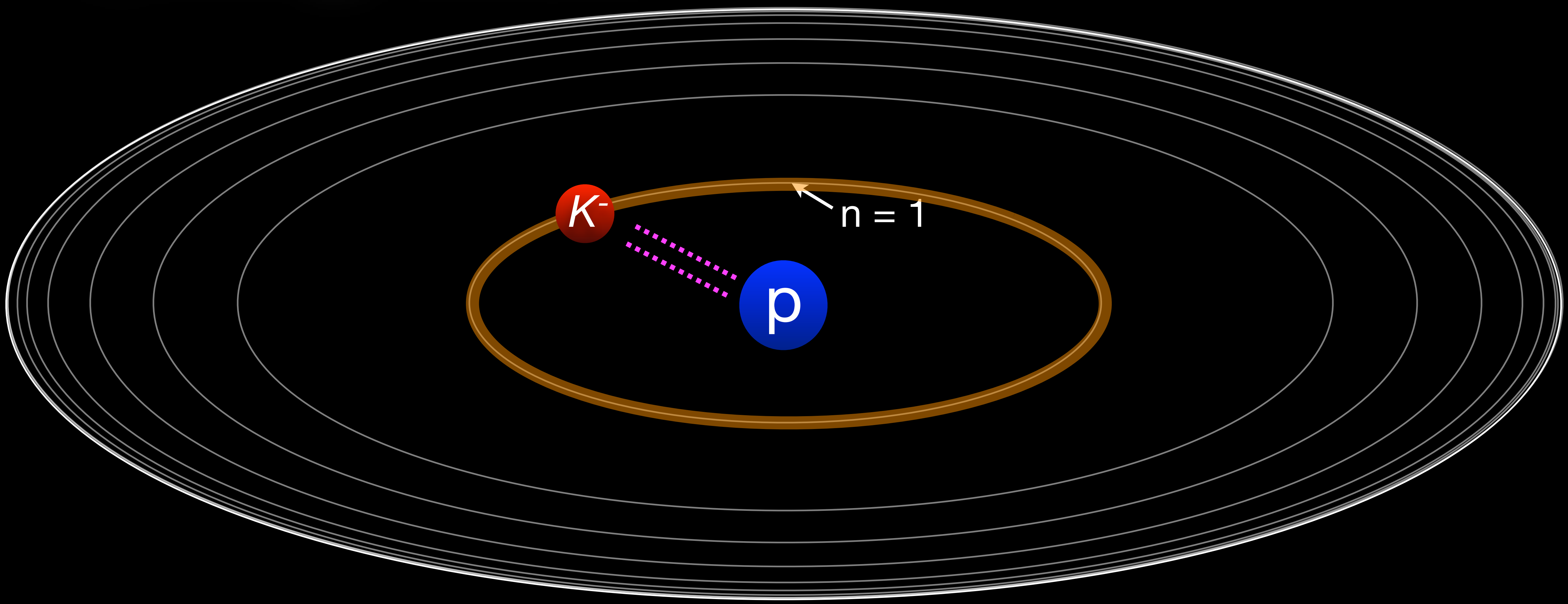
Kaonic atom

2) Cascade

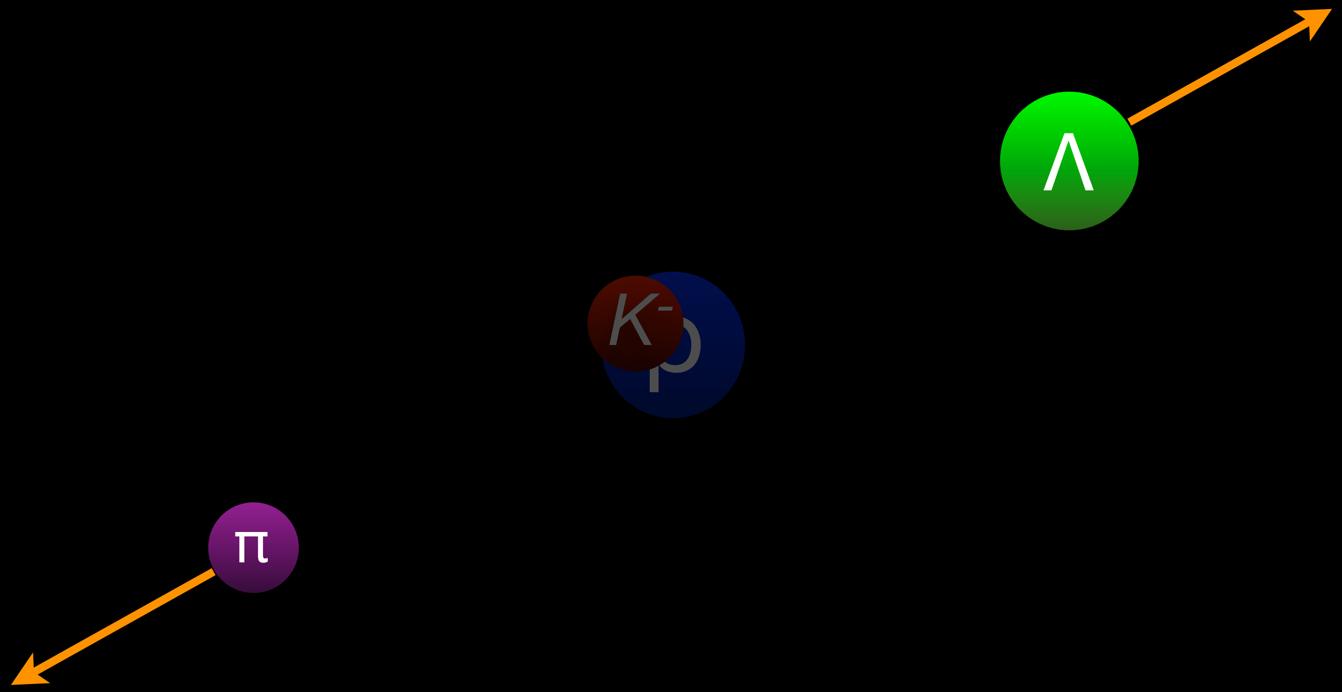


Kaonic atom

3) Strong interaction



4) nuclear absorption

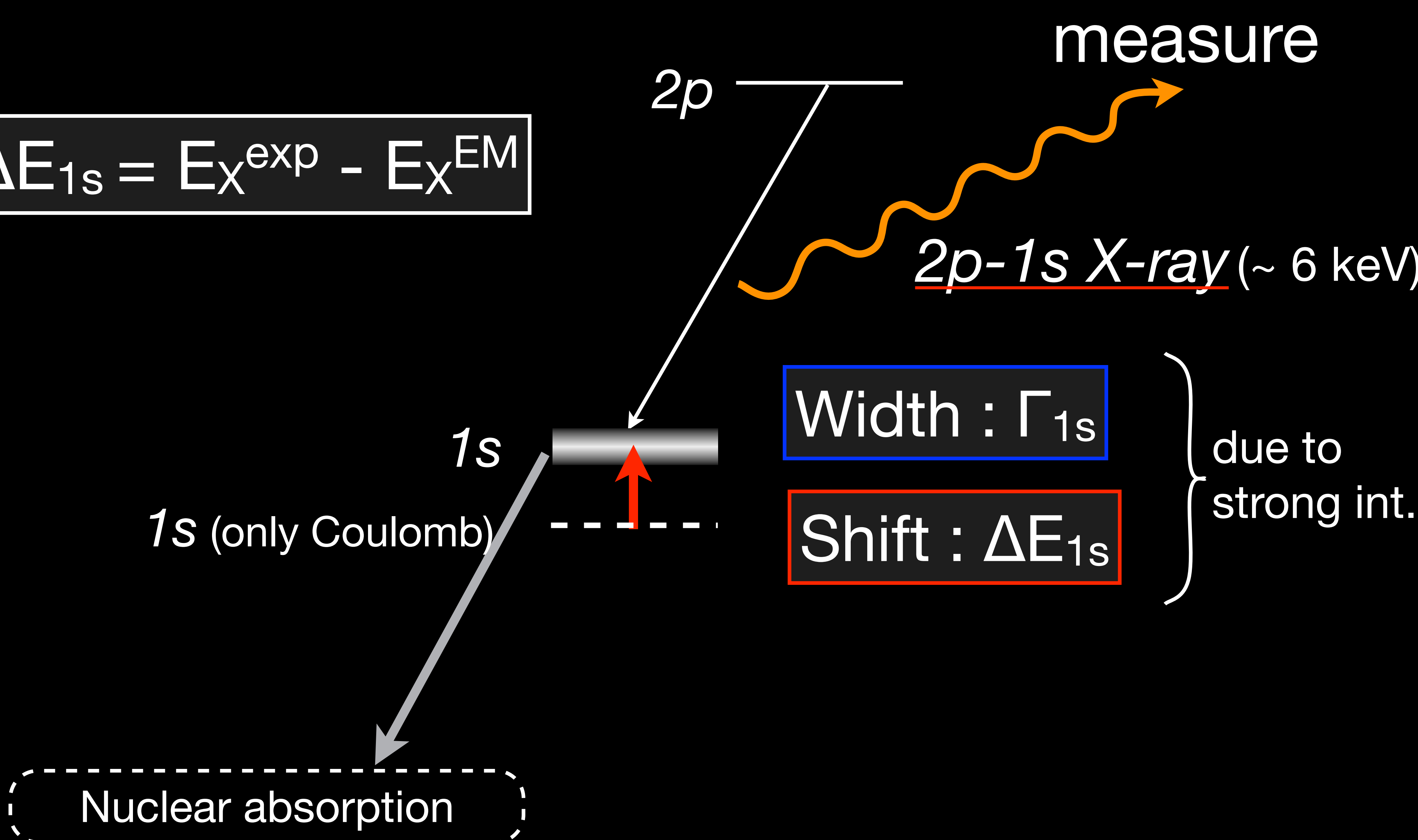


How we observe the strong interaction ?

K-atom x-ray spectroscopy

Z = 1 (Kaonic hydrogen)

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



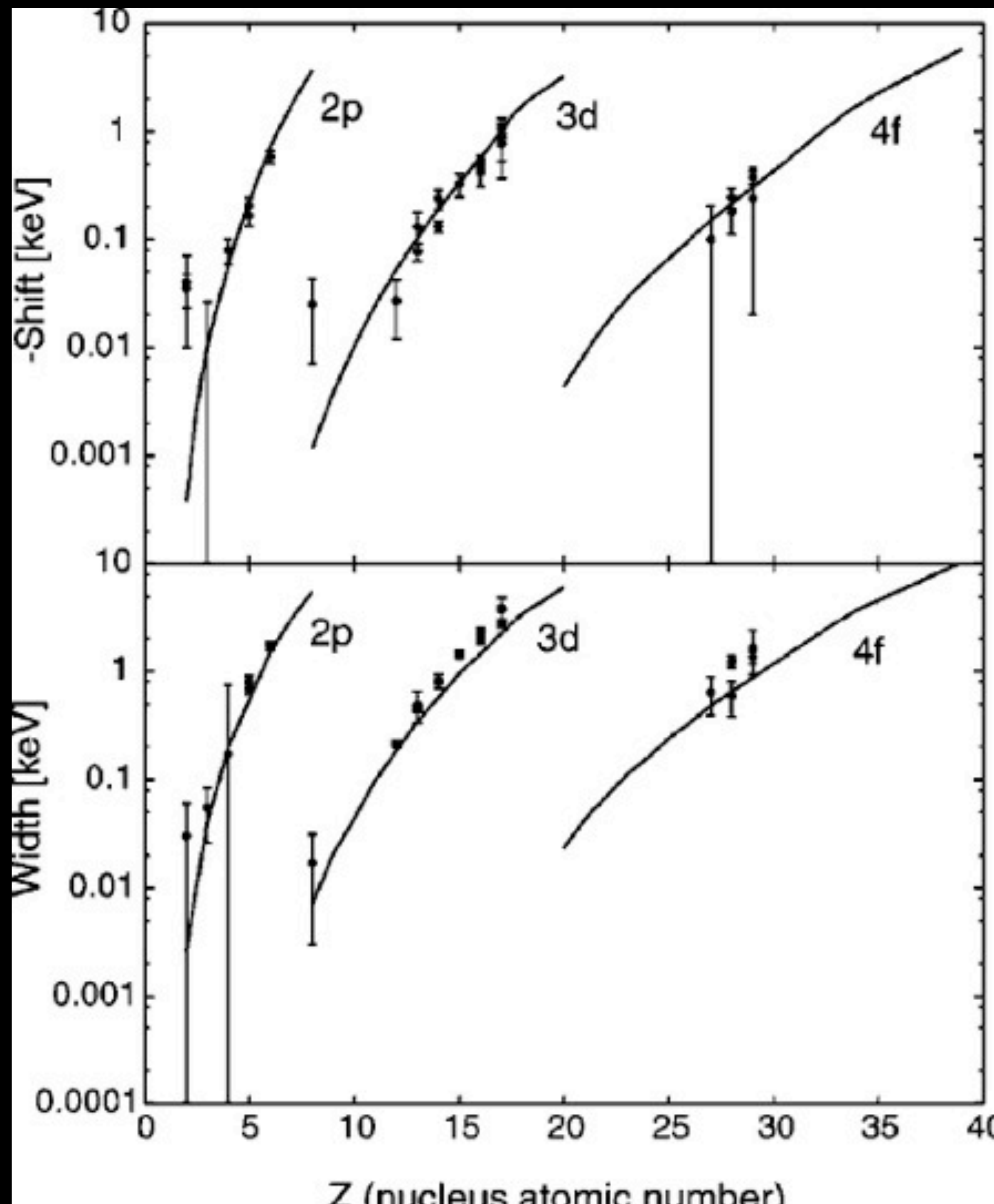
Data & a theory for Z ≥ 2 K-atom

Shift and width for last orbit

SU(3) Chiral Unitary Model

Shift

Width



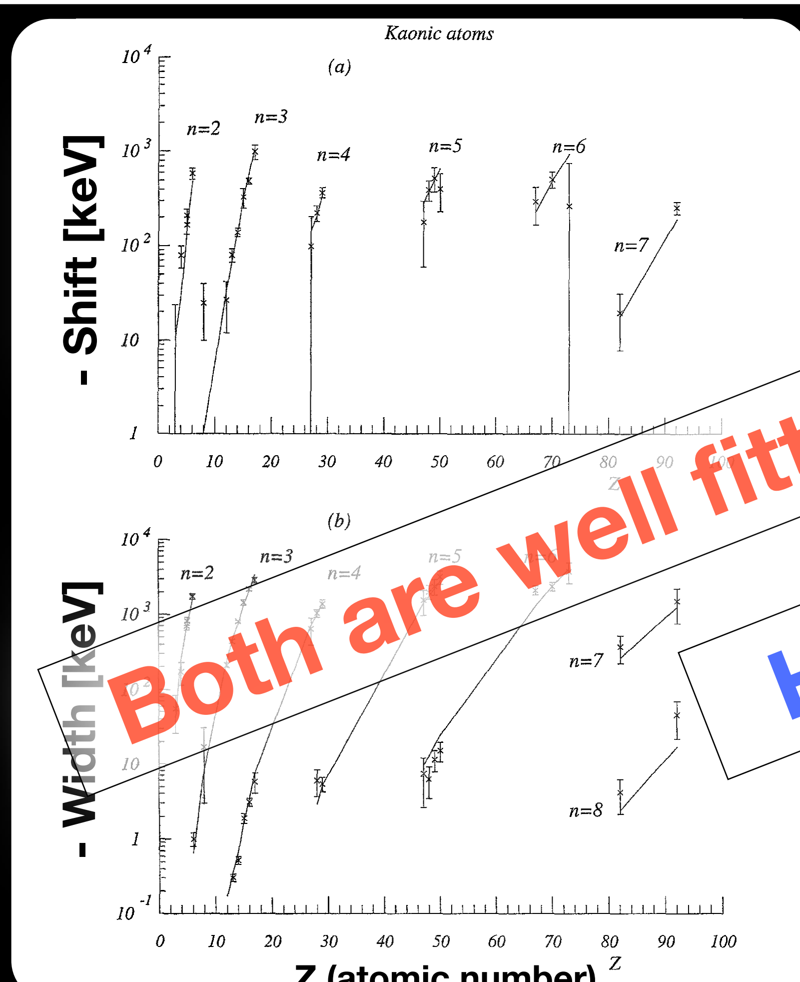
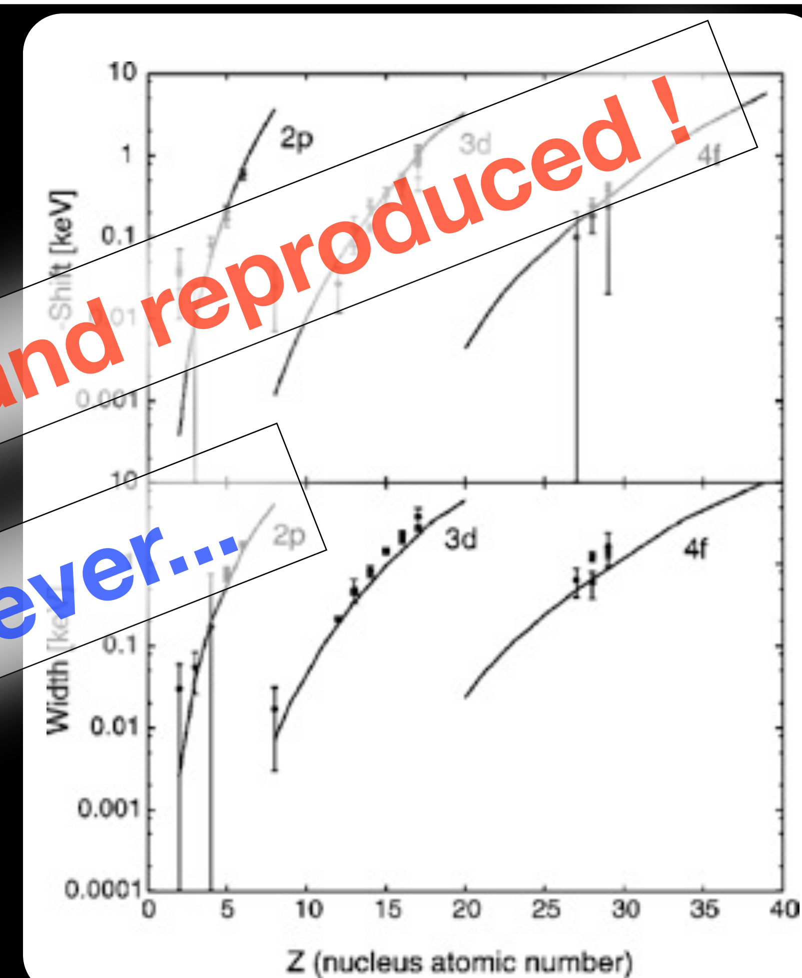
Plot w/error bar
... experimental data

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		

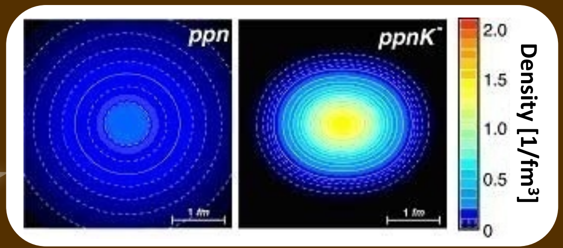
Both are well fitted and reproduced !

However...

Two theoretical approaches

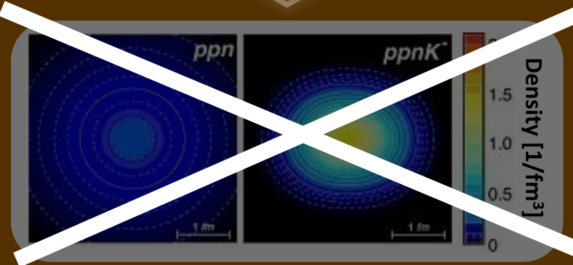
approach	Phenomenological	Fundamental
model	Density-dependent optical potential	SU(3) chiral unitary
	$V = -\frac{2\pi}{\mu}\left(1+\frac{\mu}{m}\right)\bar{a}\rho(r),$ $a \to a_0 + A_0[\rho(r)/\rho(0)]^{\alpha},$	$2\mu V_{opt}(r) = -4\pi\eta a_{eff}(\rho)\rho(r),$
potential depth	**deep** ($-V_{Real}$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

Open problem !



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

unlikely

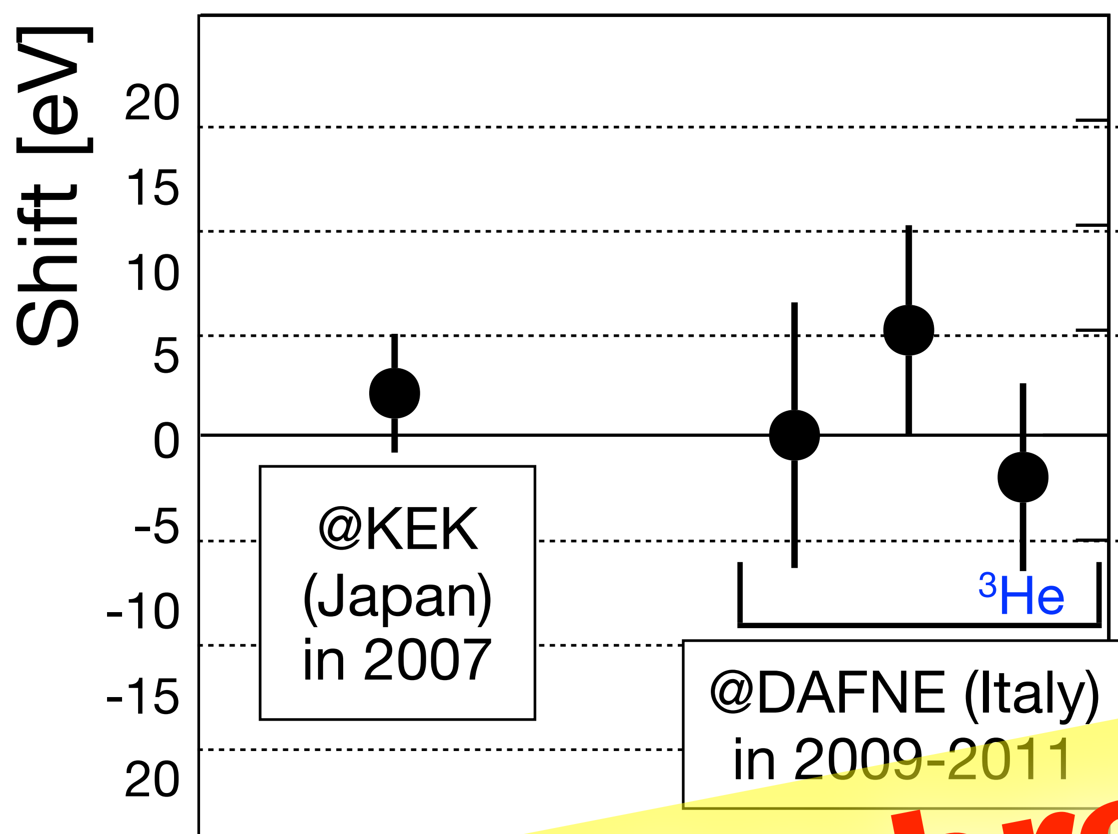


Experiments vs. Theories

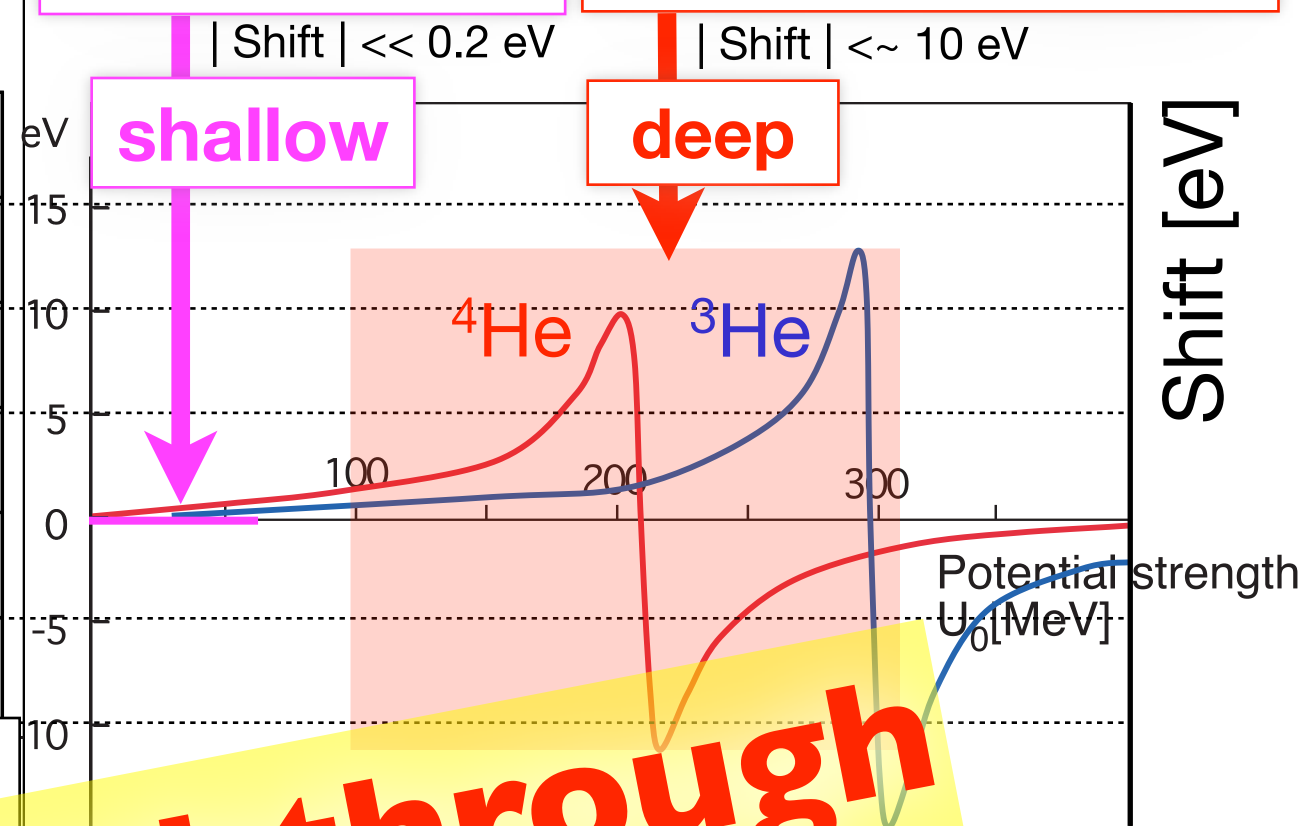
- Kaonic He atom case (for 6 keV x-rays) -

Experiments

using conventional Si detector
having ~ 200 eV(FWHM) resolution



Theories



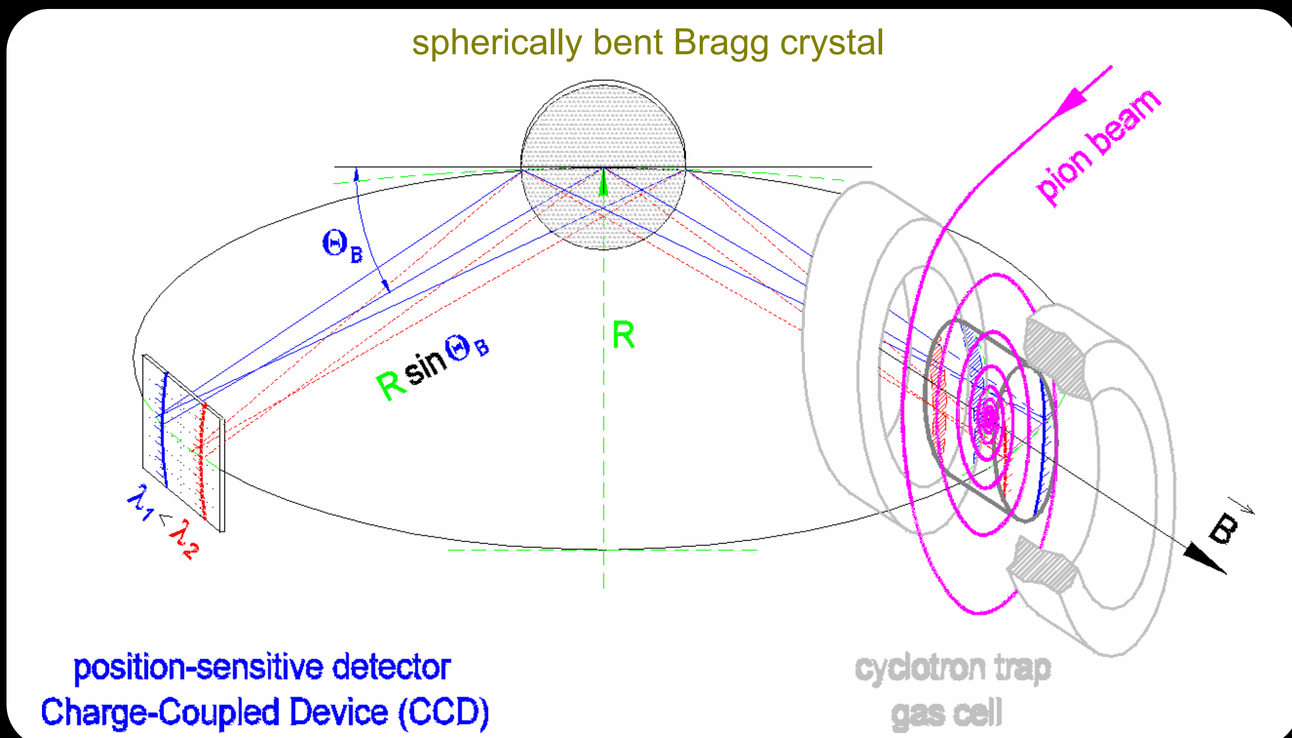
need a breakthrough

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

Next-generation K-atom experiment

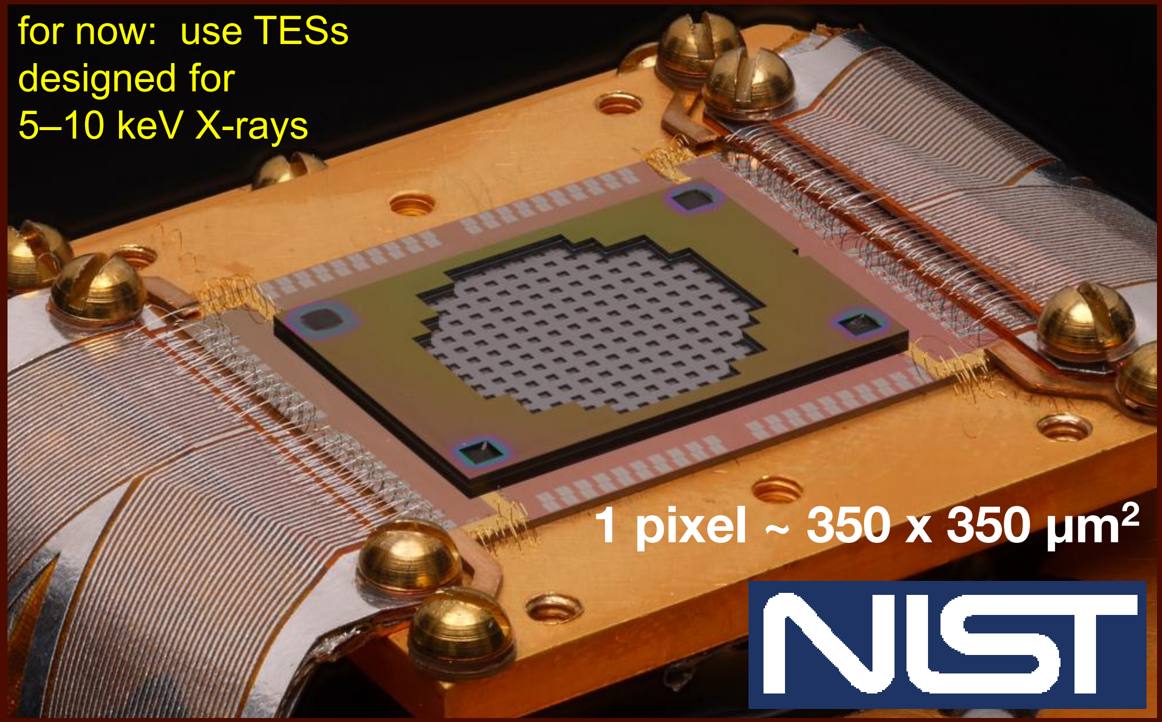
Next-generation K-atom exp.

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

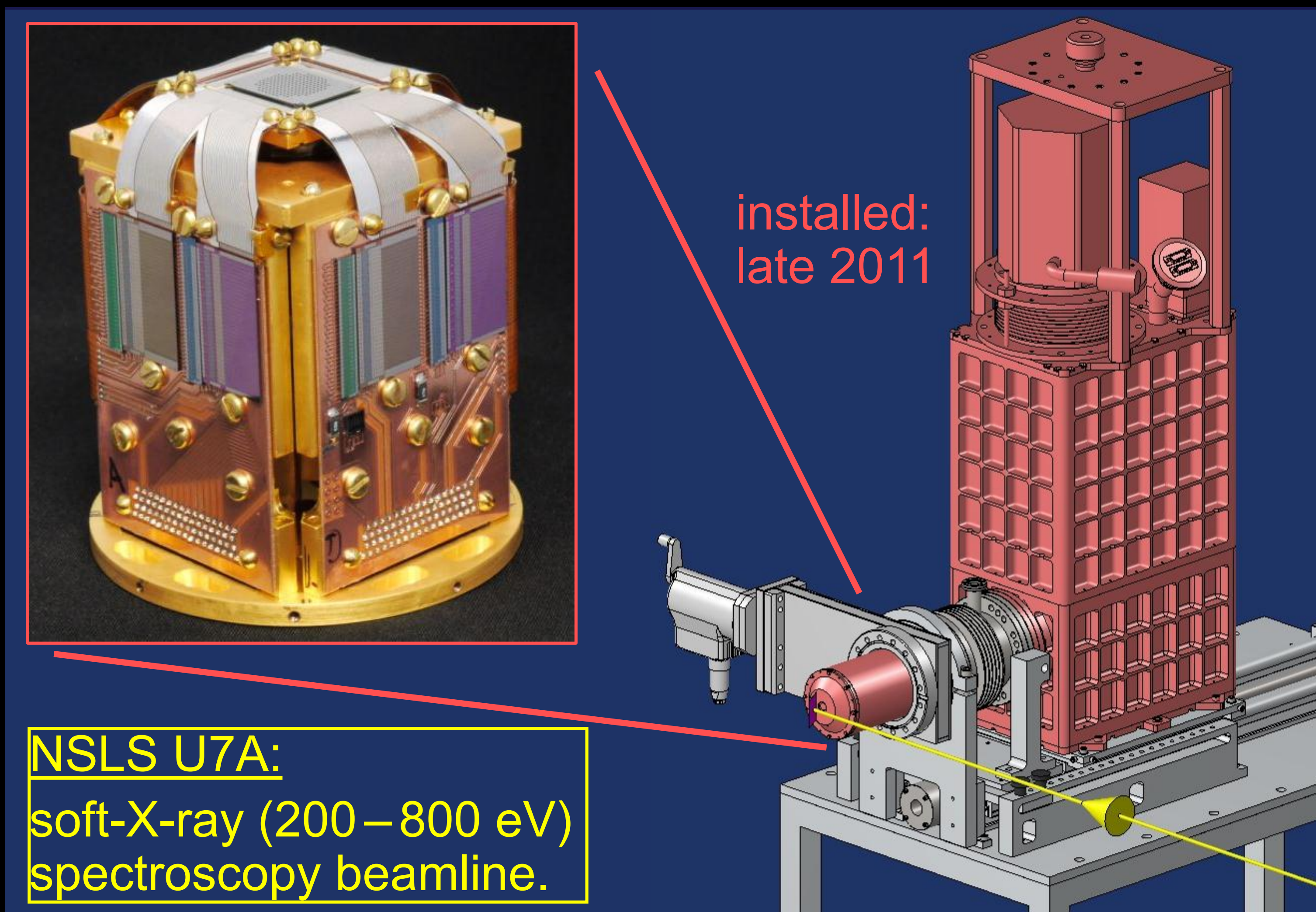
2. Compact and portable

limited beam time, then need to remove

(at J-PARC, DAΦNE etc.)

NIST TES array system

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



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

REF: talk by Daniel Swetz (NIST)
on Wednesday in this LTD-15 conf.

NIST's standard TES

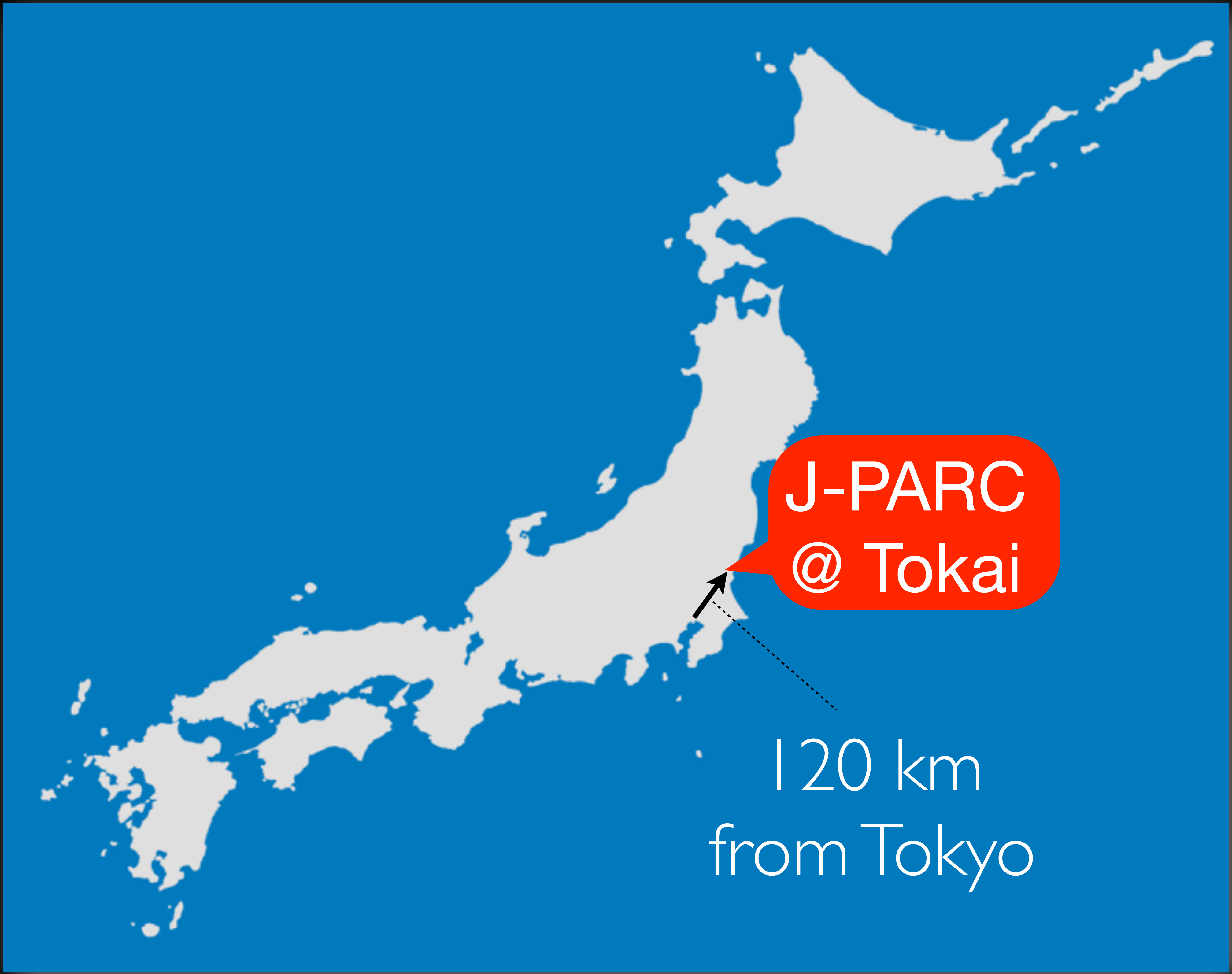
- 1 pixel : 350 x 350 μm^2
- 160 array : total ~ **20 mm^2**
- **2~3 eV (FWHM)** @ 6 keV

well established system!

two-order
improved
resolution

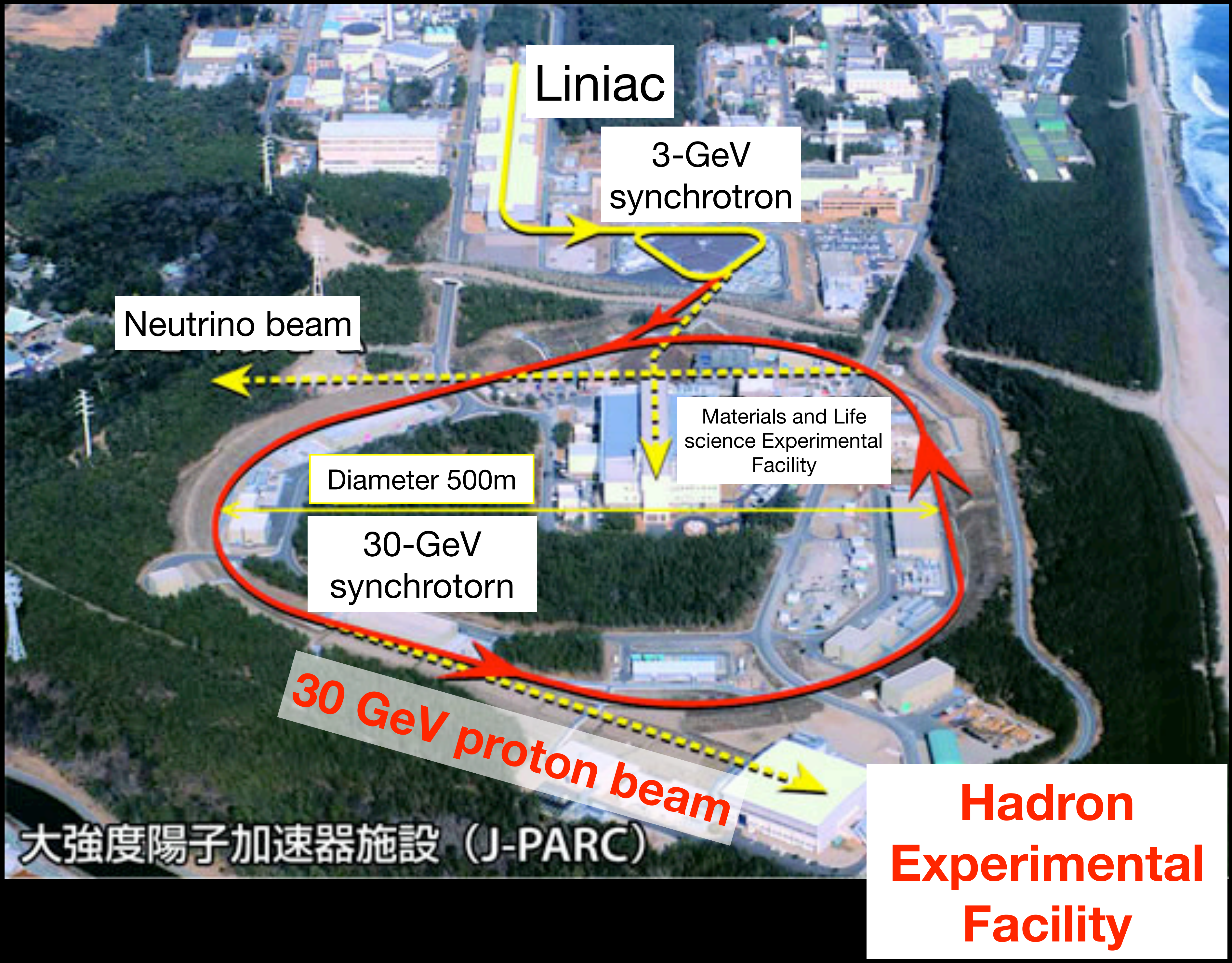
~ 200 eV (FWHM) @ 6 keV
... a typical Silicon detector
used in the previous K-atom exp.

J-PARC (Japan)



J-PARC (Japan)

Japan Proton Accelerator Research Complex = J-PARC



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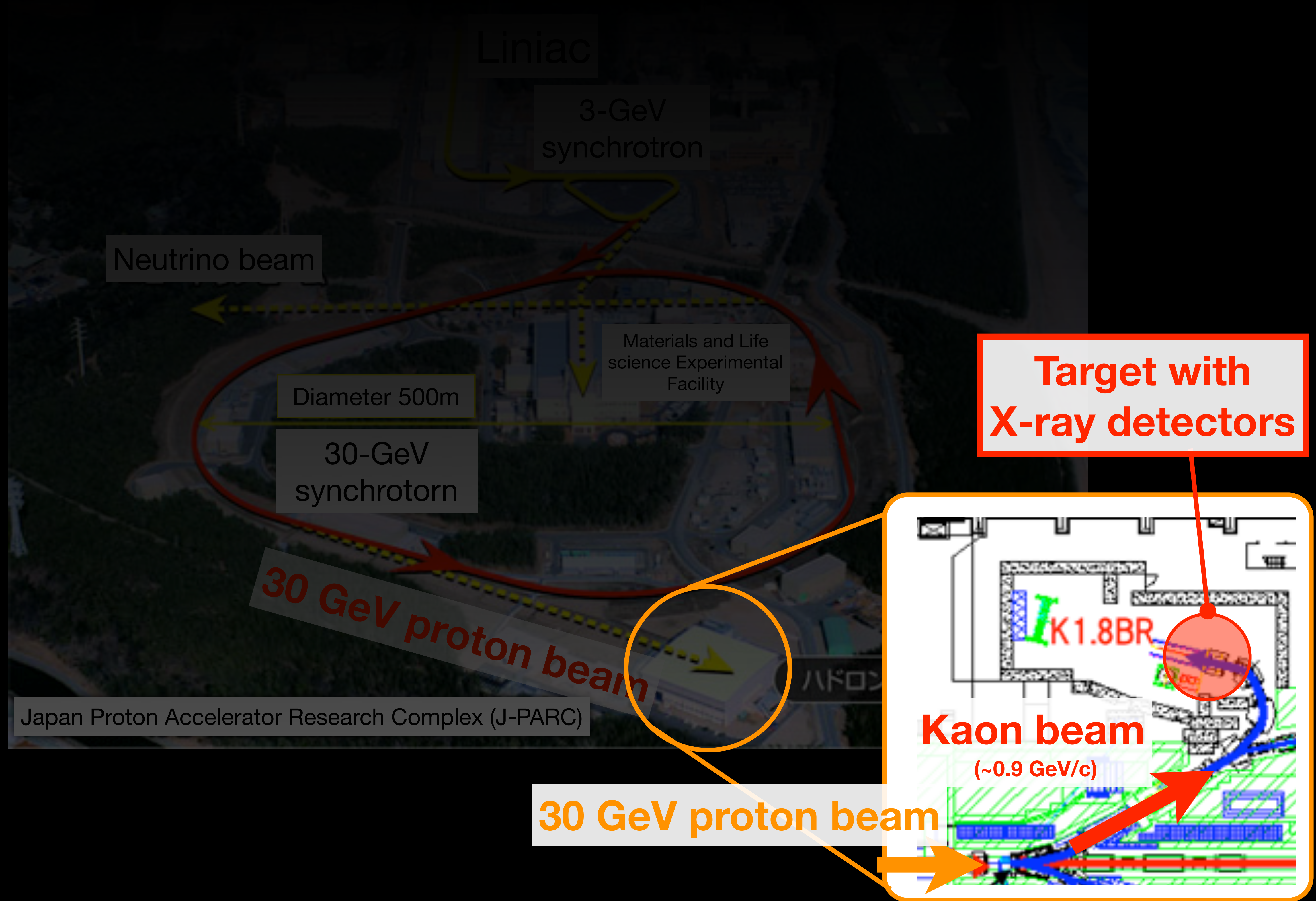
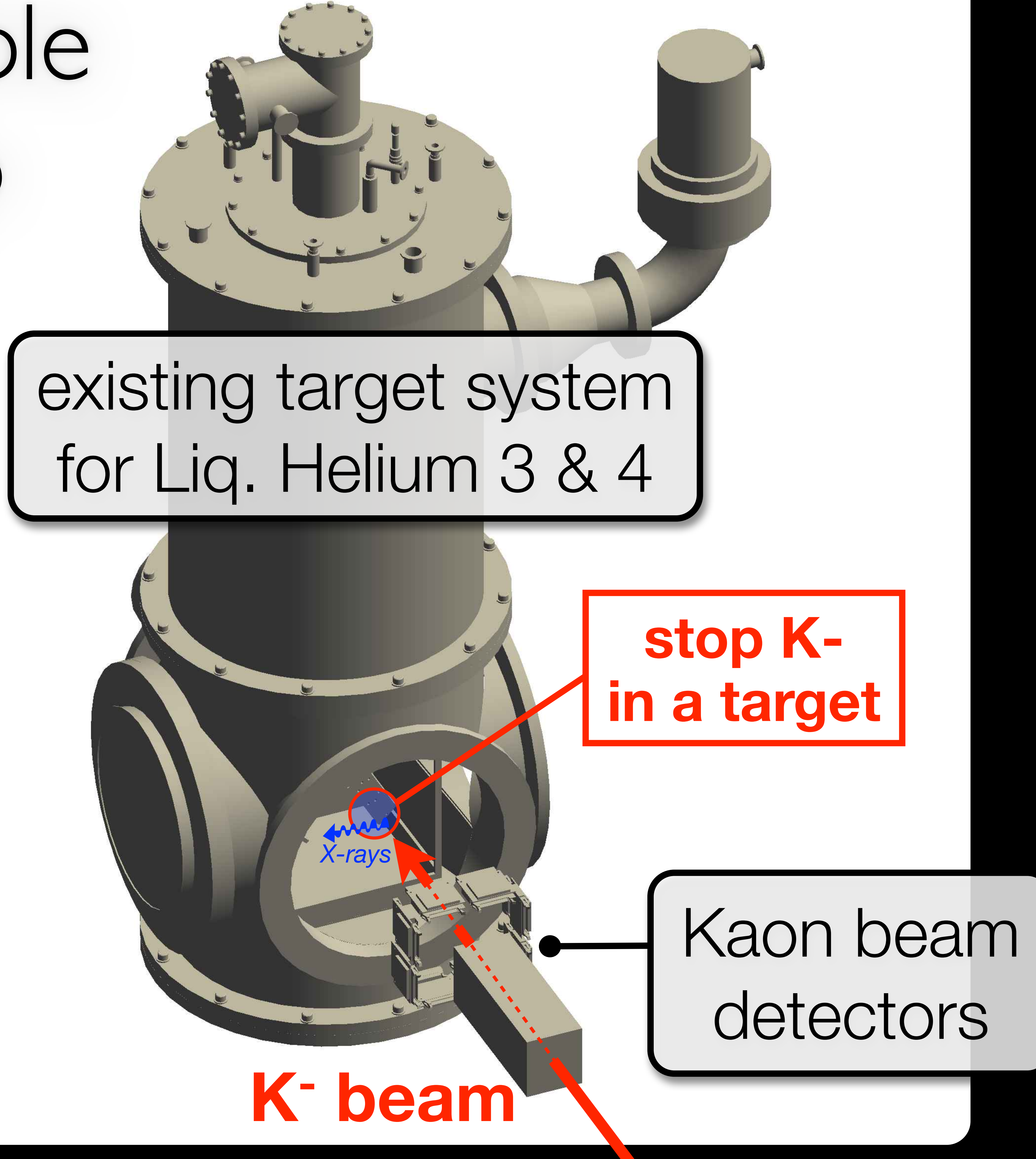
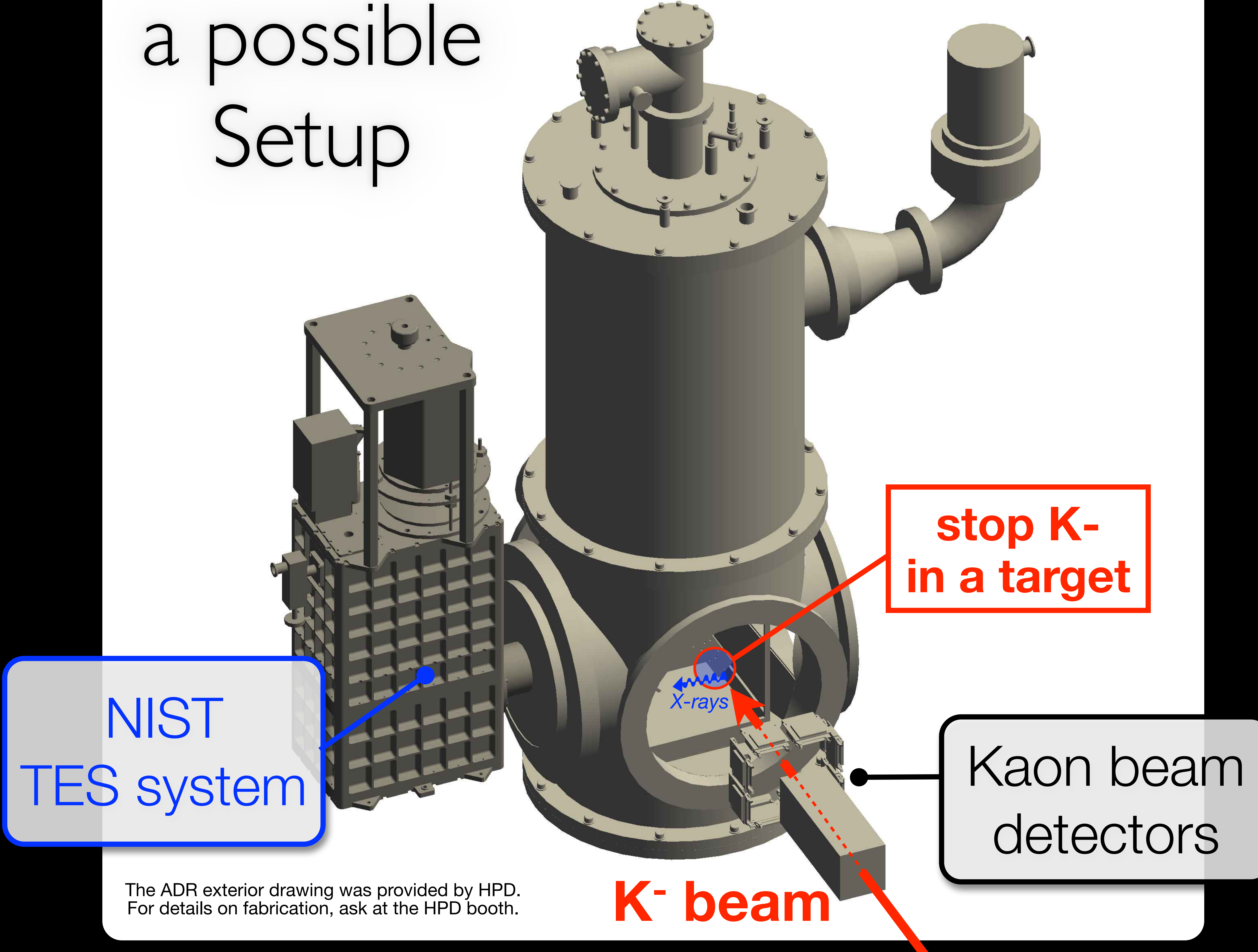


Liniac
3-GeV synchrotron
Neutrino beam
Materials and Life science Experimental Facility
Diameter 500m
30-GeV synchrotorn
30 GeV proton beam
Japan Proton Accelerator Research Complex (J-PARC)
Target with X-ray detectors
K1.8BR
Kaon beam
(~0.9 GeV/c)
30 GeV proton beam

a possible Setup

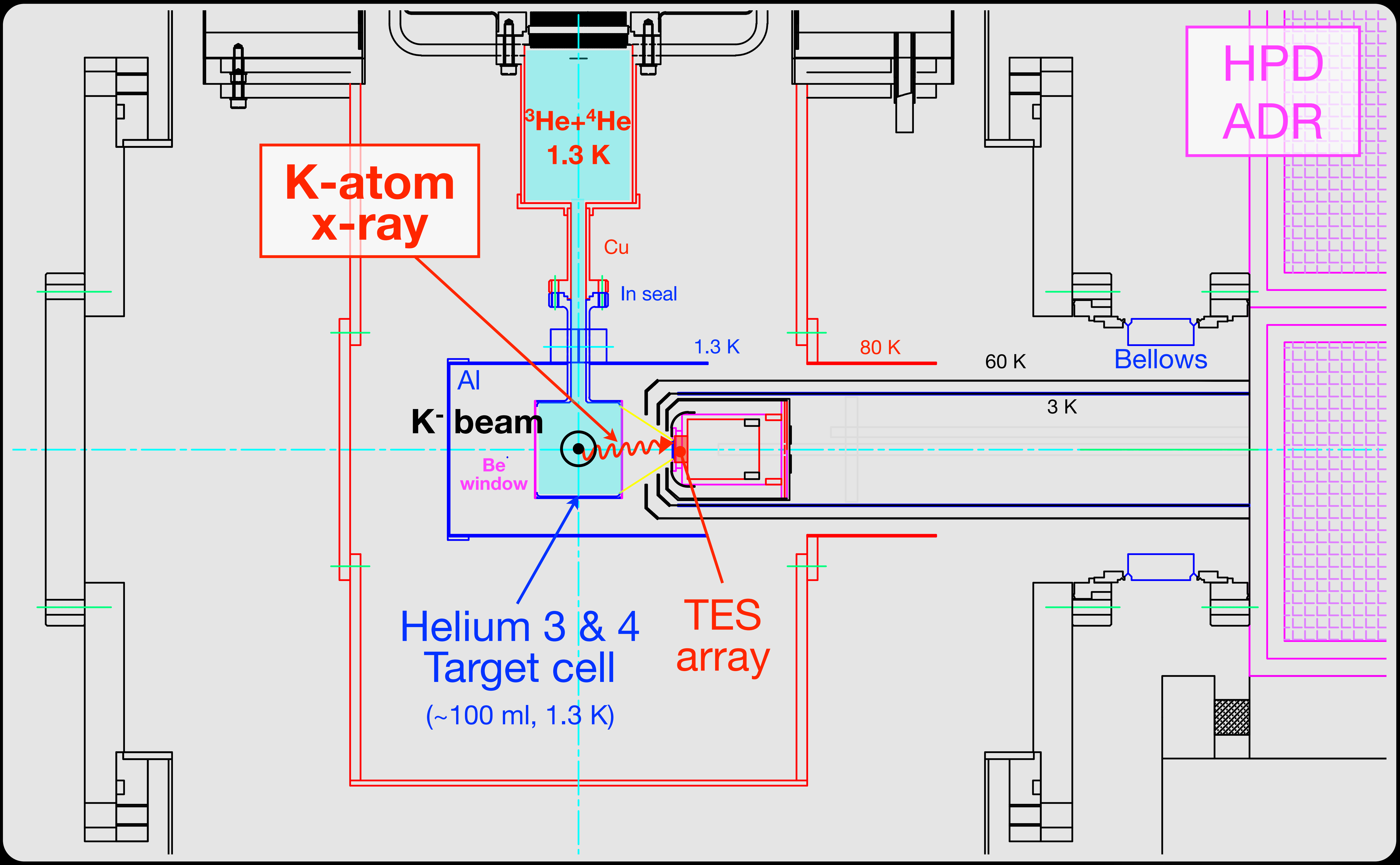


a possible Setup



The ADR exterior drawing was provided by HPD.
For details on fabrication, ask at the HPD booth.

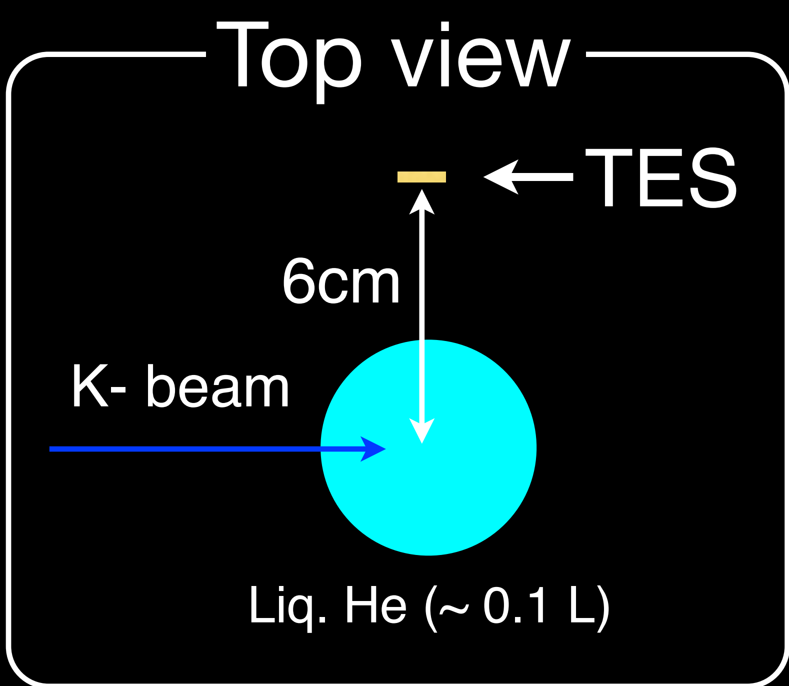
Side view (from downstream)



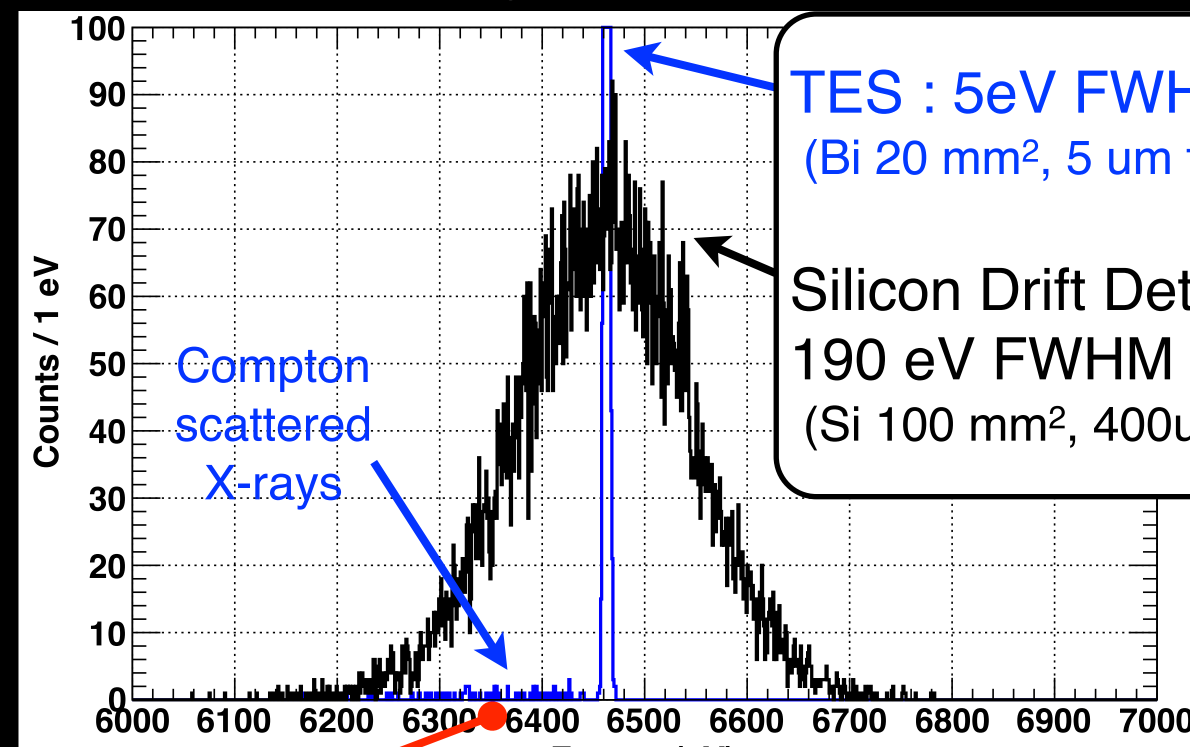
by S. Ishimoto

A simple simulation
w/ GEANT4

by H. Tatsuno

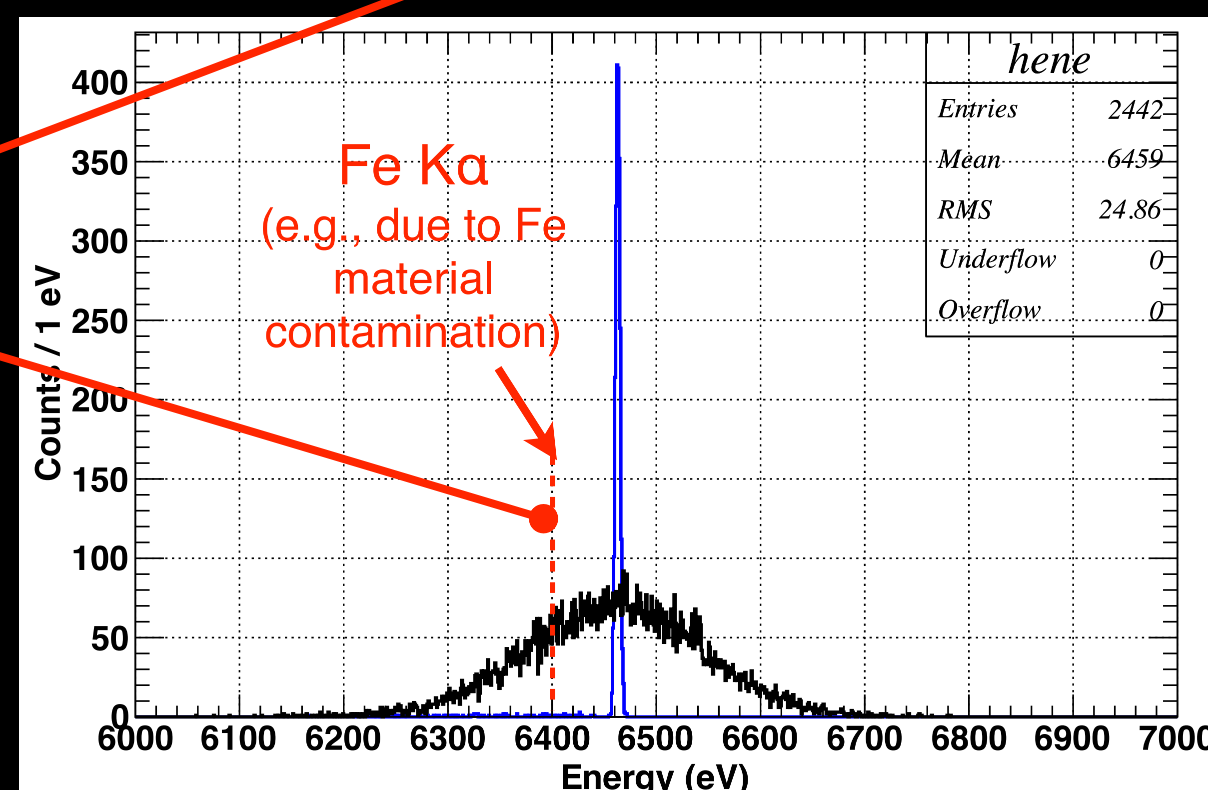


K-^{4}He x-rays from Liq. ^{4}He



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".

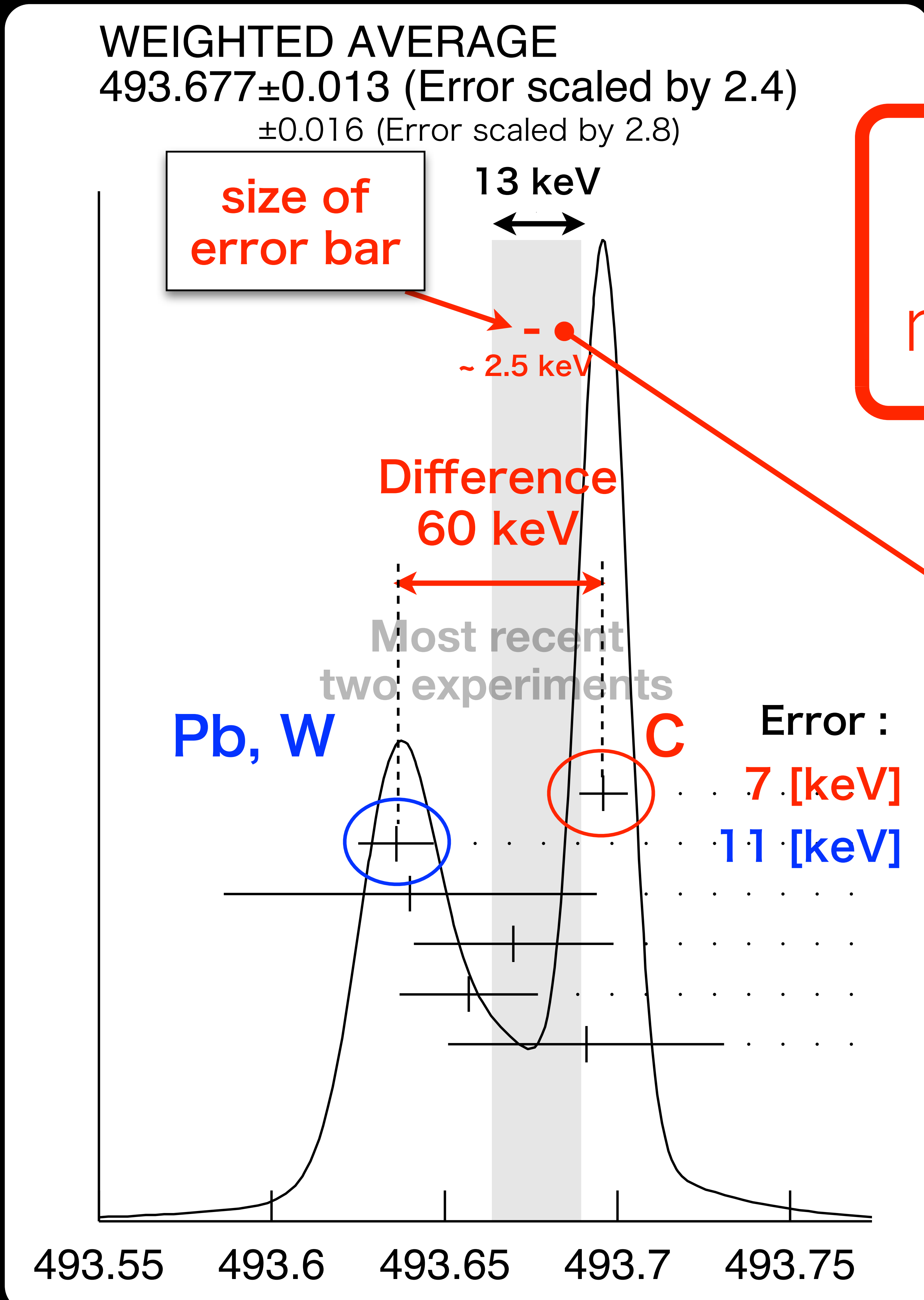
Both have been serious problems
in the prev. experiments.

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

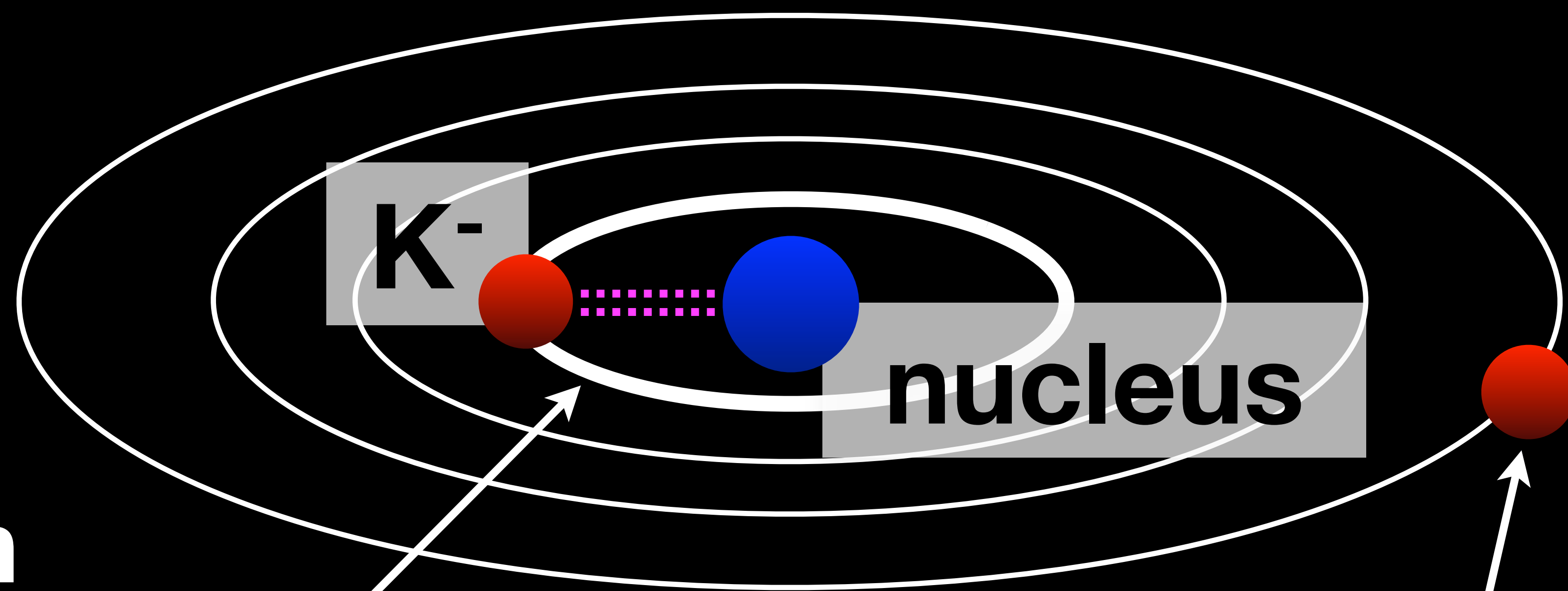
- K-^{12}C 5→4 x-ray : 10.2 keV
- 2000 events & ΔE=5eV(FWHM)
  - ➡ ΔE (x-ray energy) ~ ± 0.05 eV
  - ➡ Δm (K-mass) ~ **± 2.5 keV**

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

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)

◉ future perspective

- 2013 : test experiment without beam (evaluation of basic performance)
- 2014 : test experiment with beam and preparation of LoI / proposal
- 2015 or later : the first experiment