2013年2月25日(月)
第９回ハドロンスクエア @ 理研

DAΦNE加速器における K中間子水素原子X線精密分光実験

SIDDHARTA実験の結果

Phys. Lett. B 704 (2011) 113

K-He X線分光 -> 次世代K原子実験

理研　岡田 信二

SIlicon Drift Detector
for Hadronic Atom Research
by Timing Application

SIDDHARTA

SIDDHARTA Collaboration

LNF-INFN, Italy

Univ. of Victoria, Canada

Politecnico di Milano, Italy

IFIN –HH, Romania

Stefan Meyer Institut, Austria

INFN Sez. di Roma I and Inst. Superiore di Sanita, Italy

Univ. of Tokyo, Japan

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Tech. Univ. München, Germany

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Campoleone
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Cori
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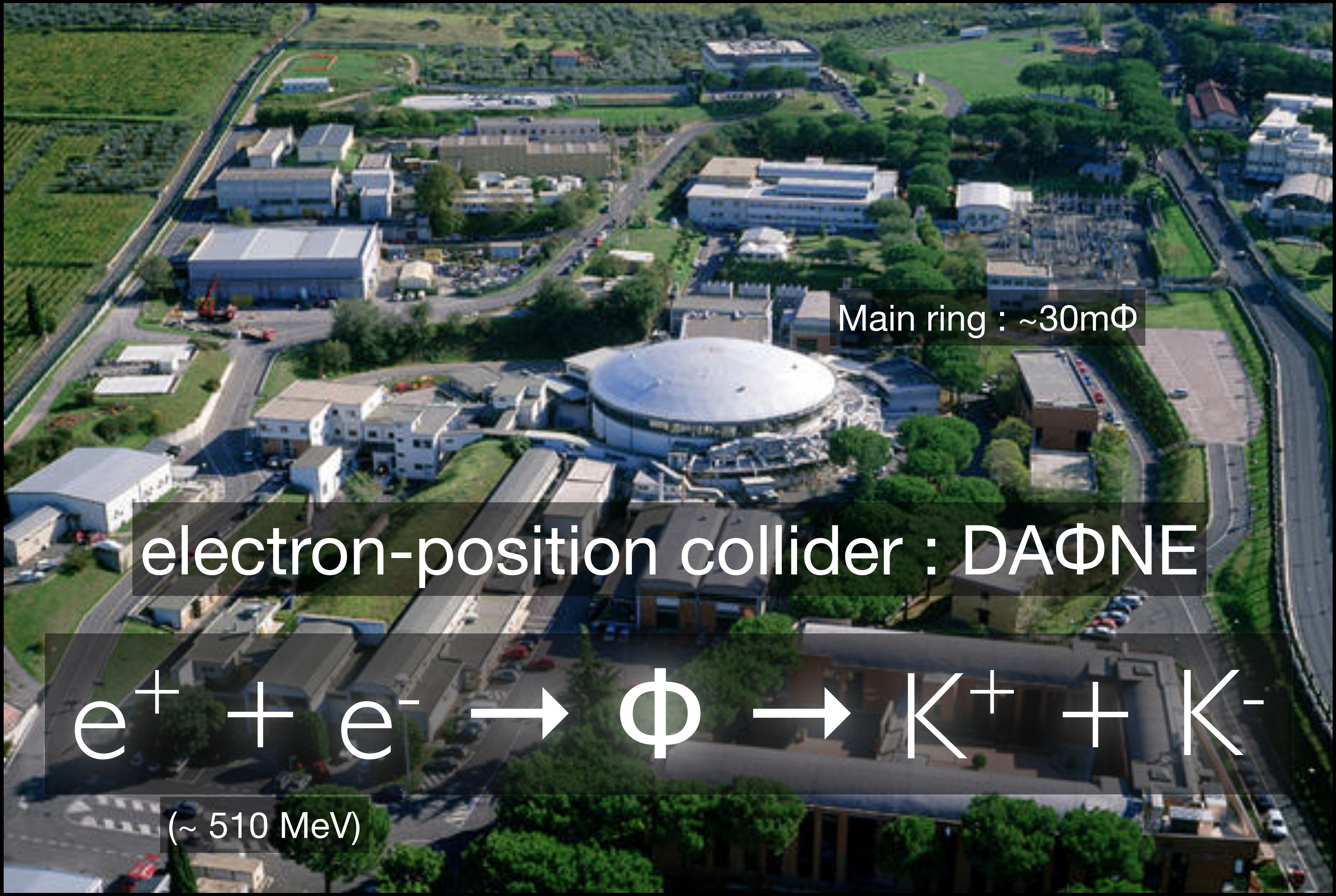
SS2
SS493
SS2bis
E35
E80
A12
SS1
SS4
SS5
A24
A90
SS6
A1
E821
SS7
SS217
SS215
SS600
SR207
SS148
SP601

Laboratori nazionali di Frascati (LNF-INFN)



Kaon

Kaon

- K meson -

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

the lightest particle containing **strange (anti-)quark**

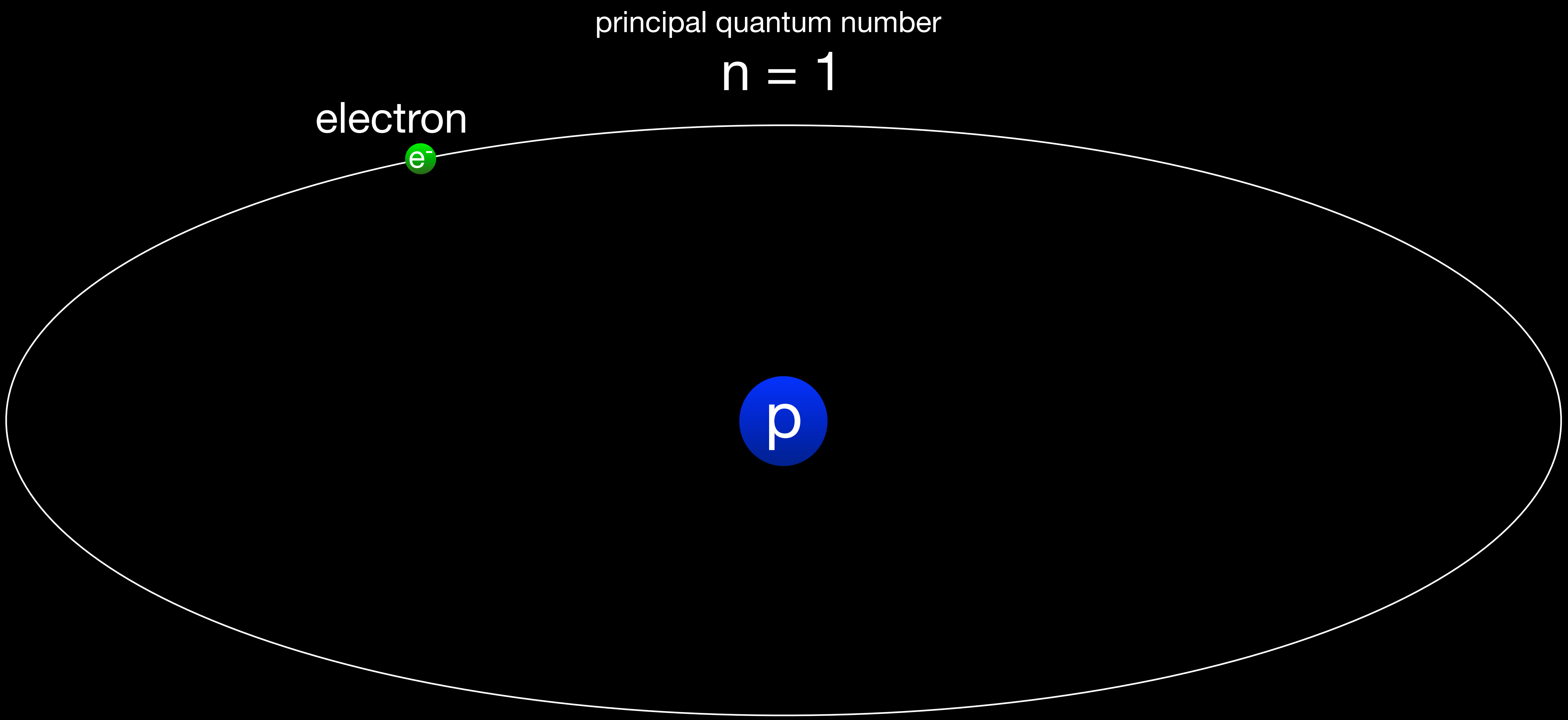
$$K^+ = u\bar{s},\ K^0 = d\bar{s},\ \overline{K}^0 = \bar{d}s,\ K^- = \bar{u}s,$$

strange anti-quark   strange quark

mass	493.677(16) MeV	ex) ~1000 times heavier than electron
lifetime	1.2380(21) x 10^{-8} sec	~ 12 nsec

What is Kaonic atom ?

Hydrogen atom

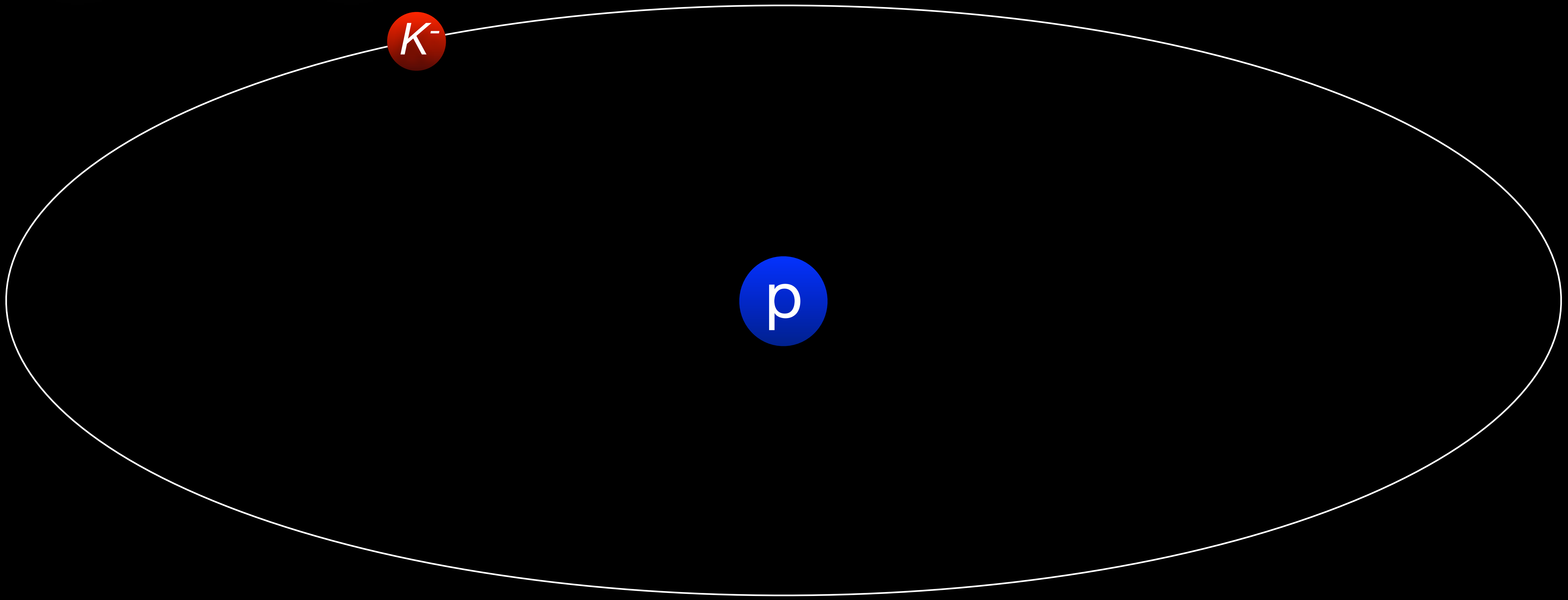


Kaonic hydrogen atom

1) Initial capture

principal quantum number

n = ?



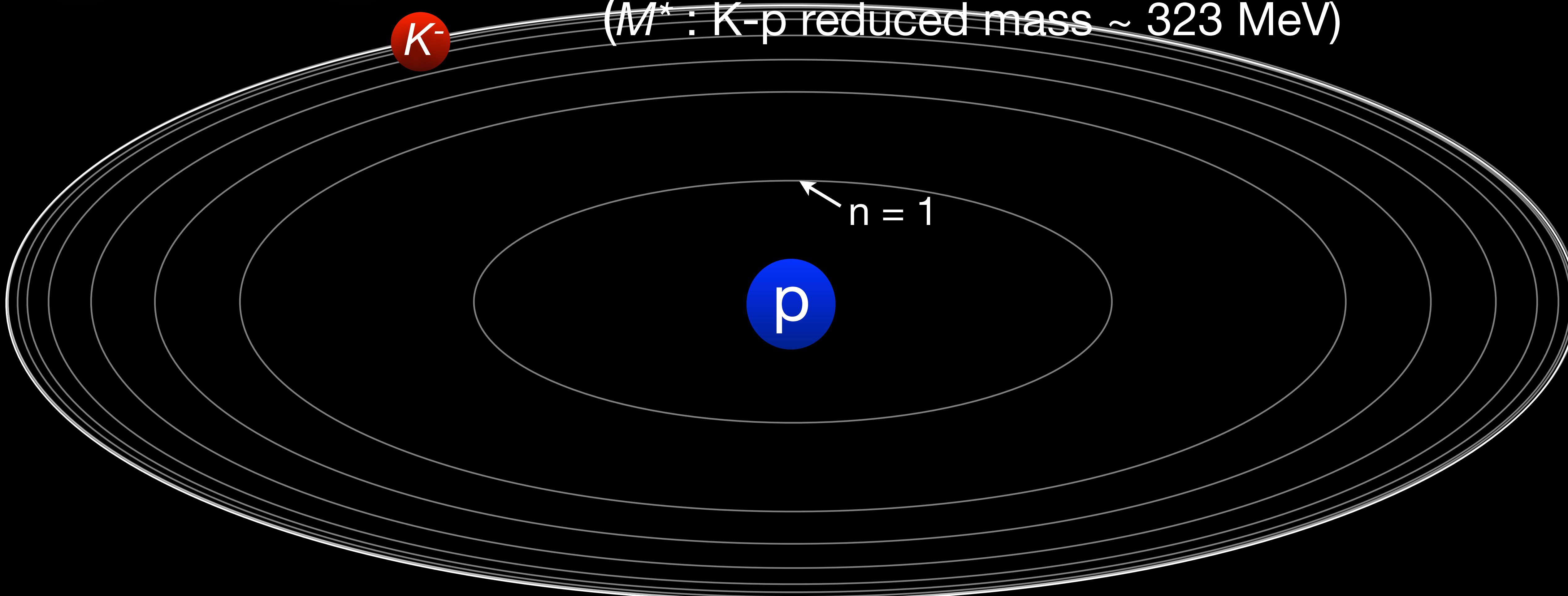
Kaonic hydrogen atom

1) Initial capture

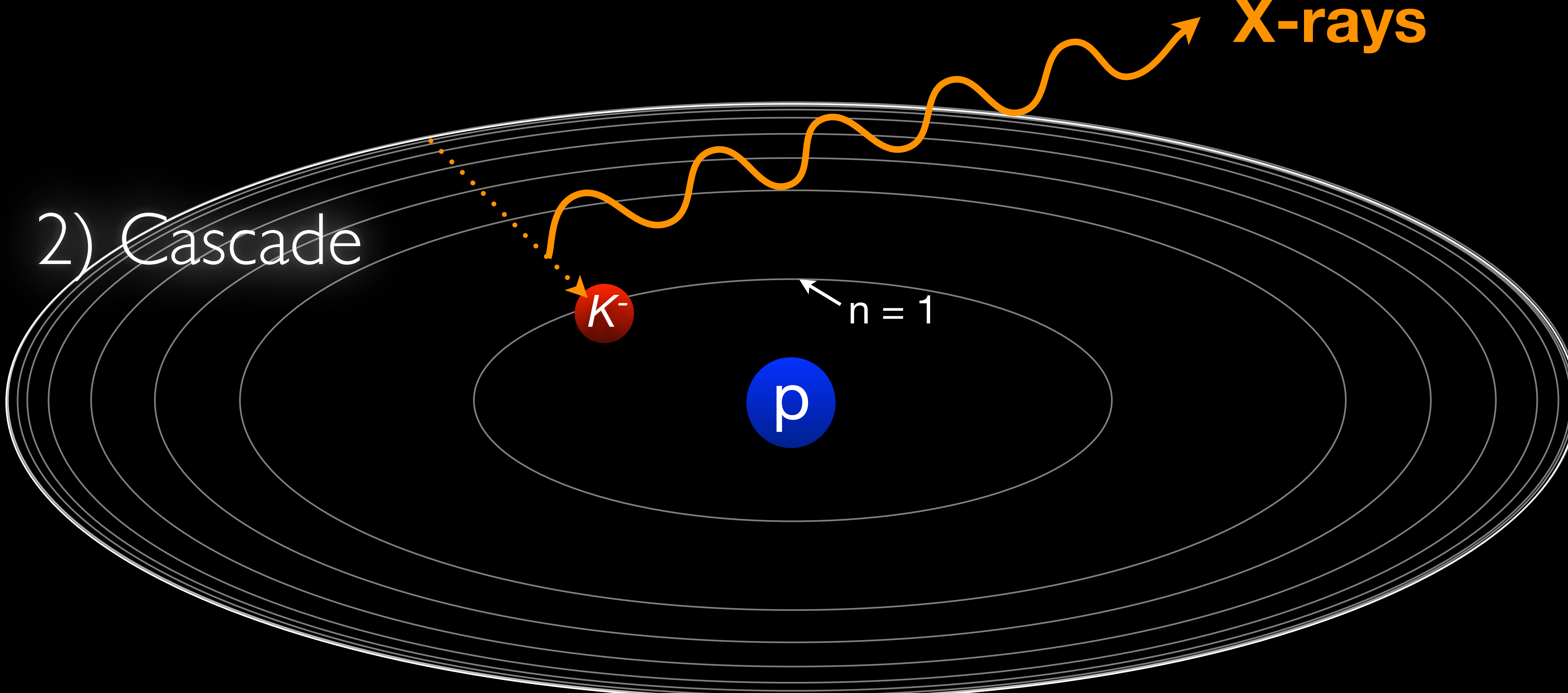
principal quantum number

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

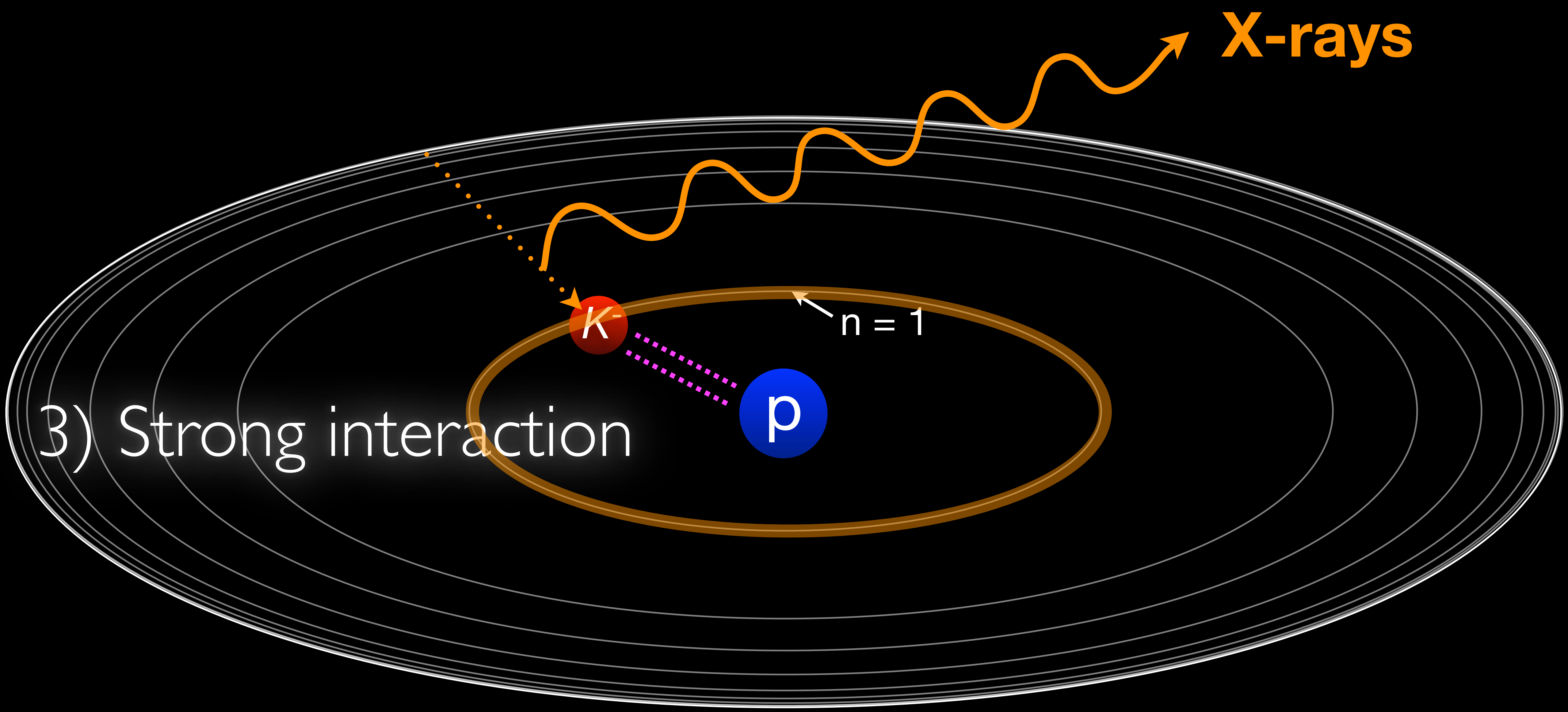
(M^* : K-p reduced mass ~ 323 MeV)



Kaonic hydrogen atom



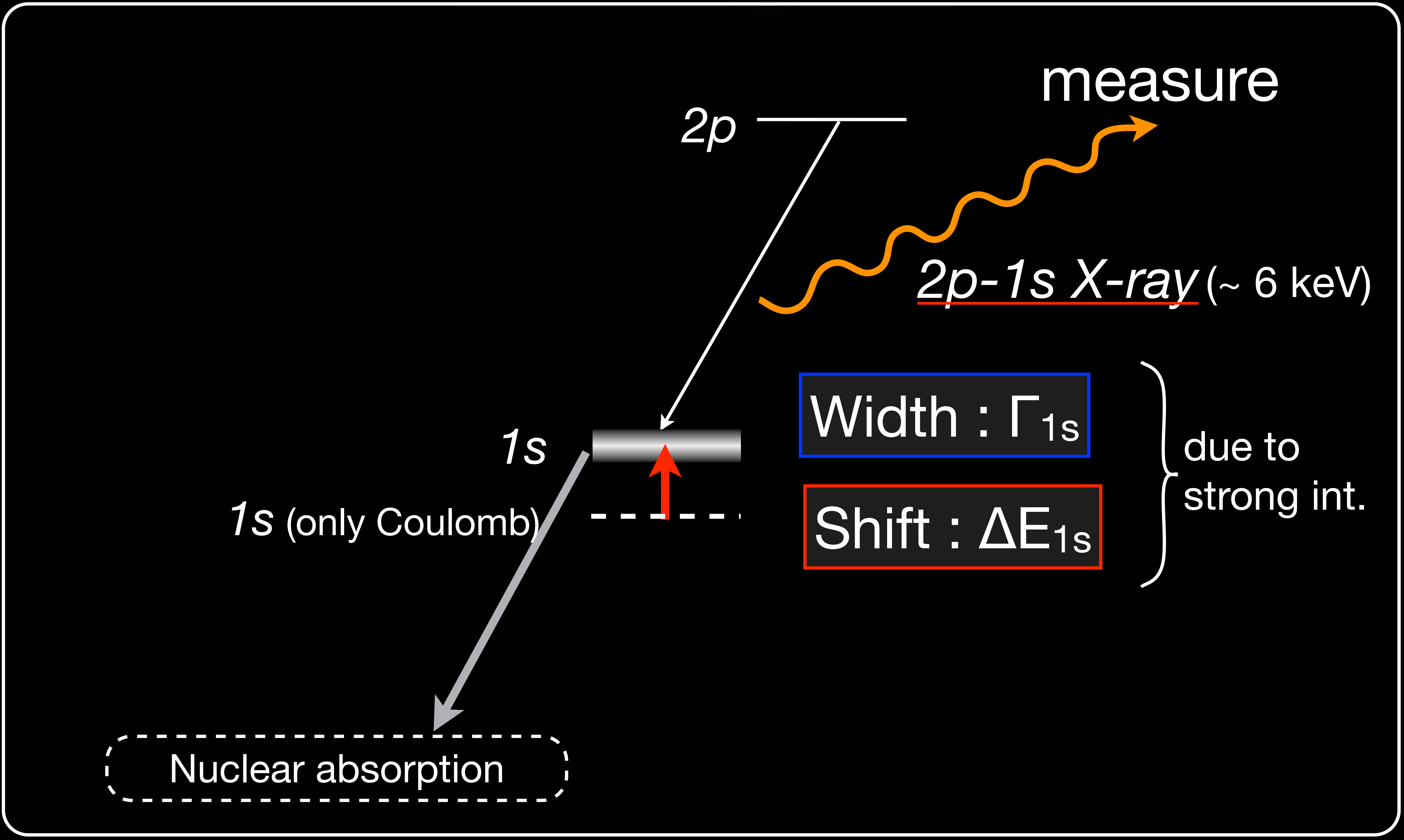
Kaonic hydrogen atom



How we observe the strong interaction ?

X-ray spectroscopy

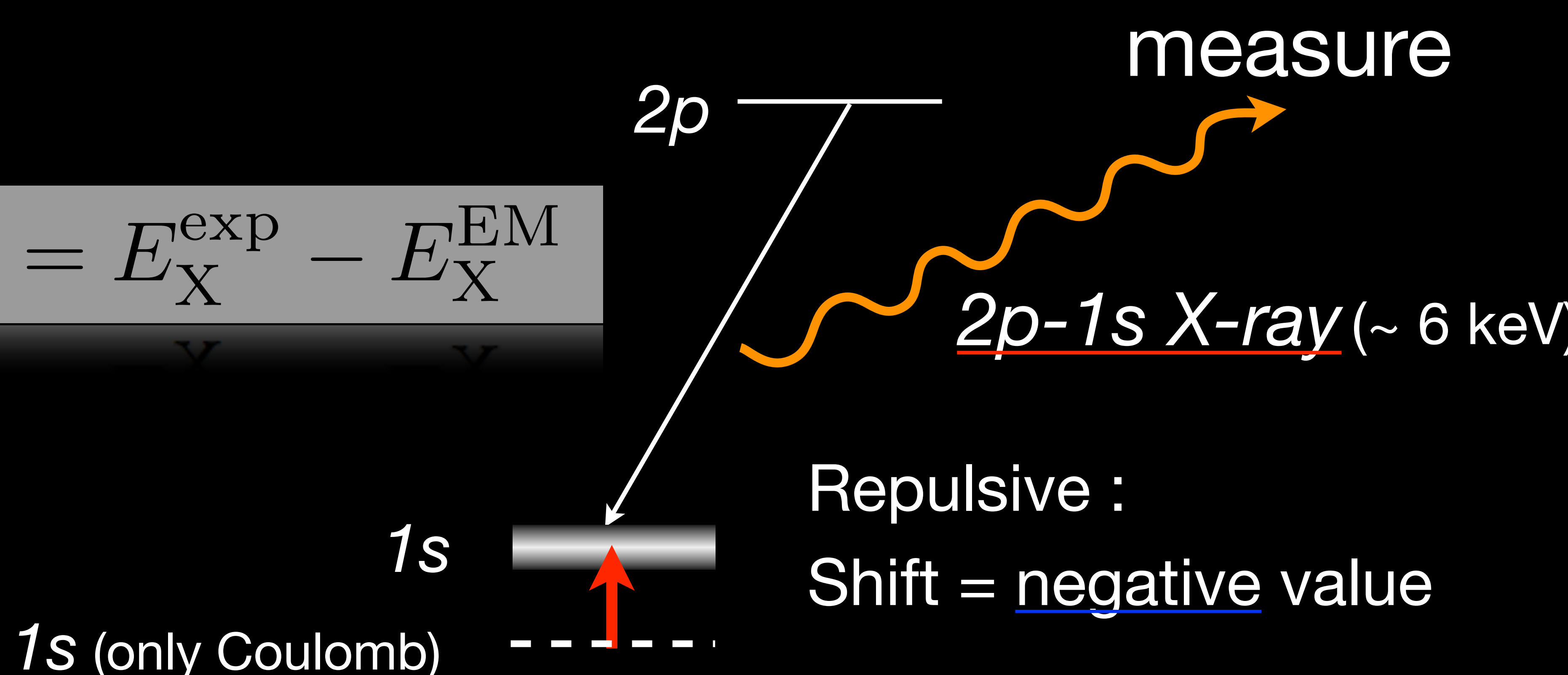
Kaonic hydrogen case



X-ray spectroscopy

Kaonic hydrogen case

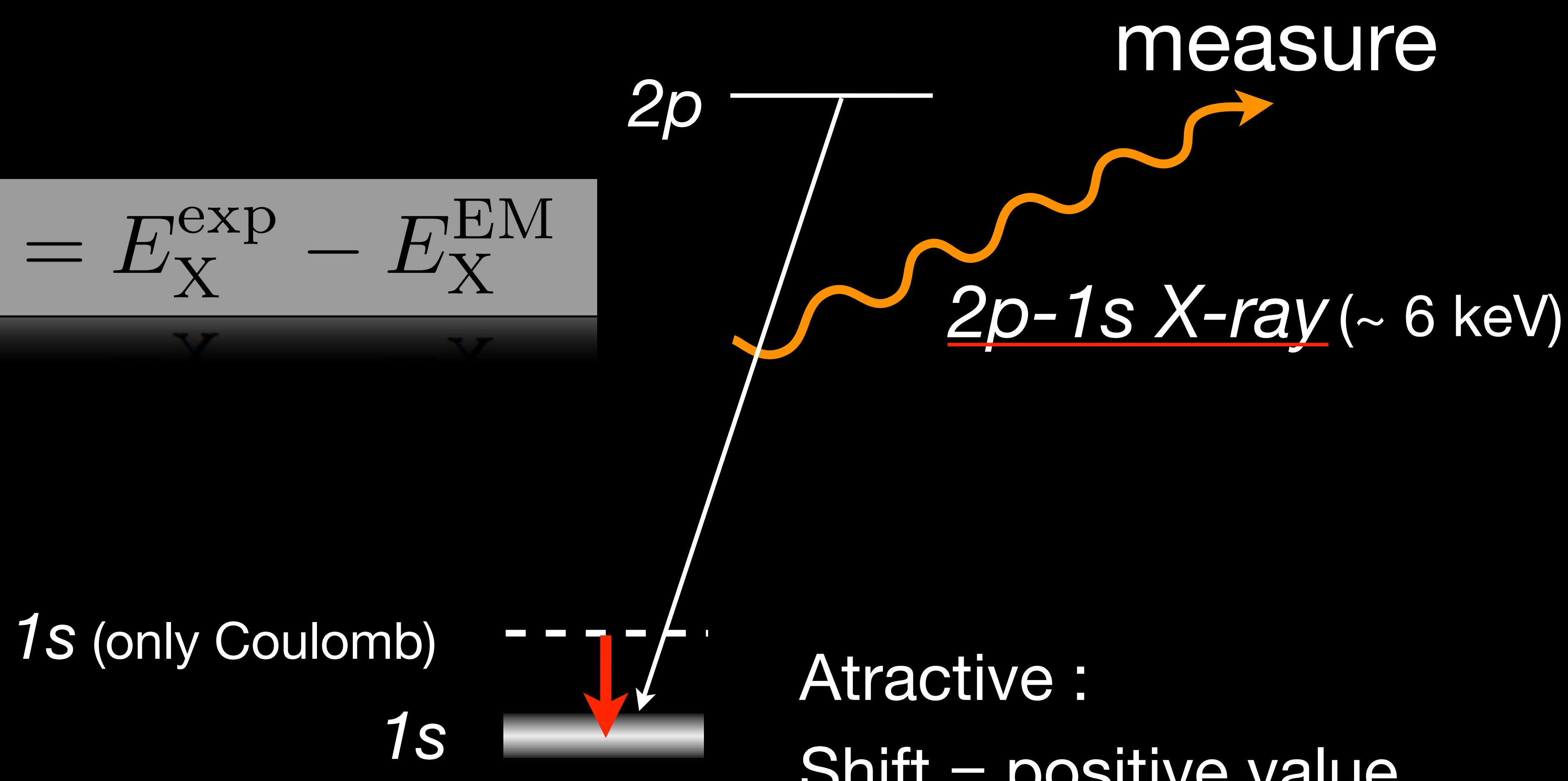
$$\Delta E_{2p} = E_{\mathrm{X}}^{\mathrm{exp}} - E_{\mathrm{X}}^{\mathrm{EM}}$$



X-ray spectroscopy

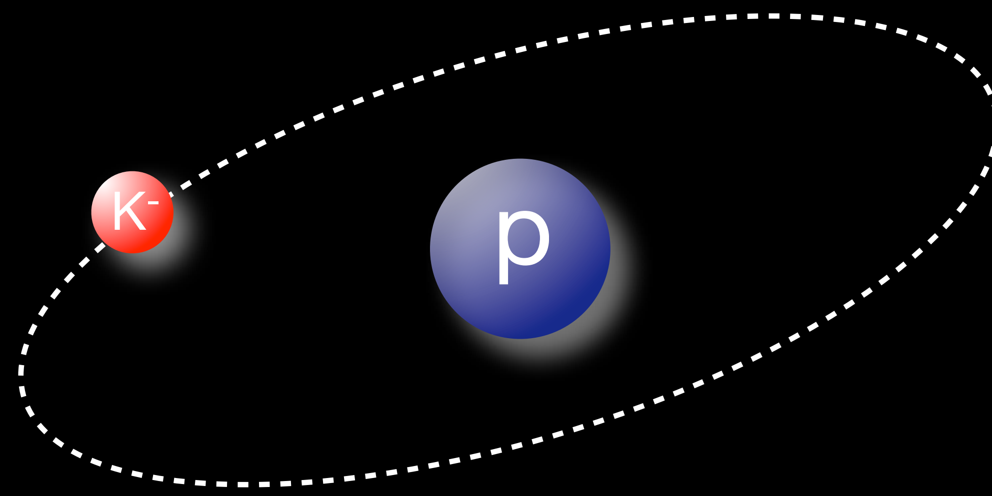
Kaonic hydrogen case

$$\Delta E_{2p} = E_{\mathrm{X}}^{\mathrm{exp}} - E_{\mathrm{X}}^{\mathrm{EM}}$$



Kaonic hydrogen

Kaonic hydrogen



-> the shift and width are basic information of K^{bar}-N strong interaction at low energy limit.

Kaonic hydrogen

U.-G. Meißner et al, Eur Phys J C35 (2004) 349

$$\epsilon_{1s} + \mathrm{i}\Gamma_{1s}/2 = 2\alpha^3 \mu_r^2 a_{K^-p} \left[1 + 2\alpha \mu_r (1 - \ln \alpha) a_{K^-p}\right]$$

Shift **Width**

Kaonic hydrogen
Kα x-ray

K$^-$p scattering length

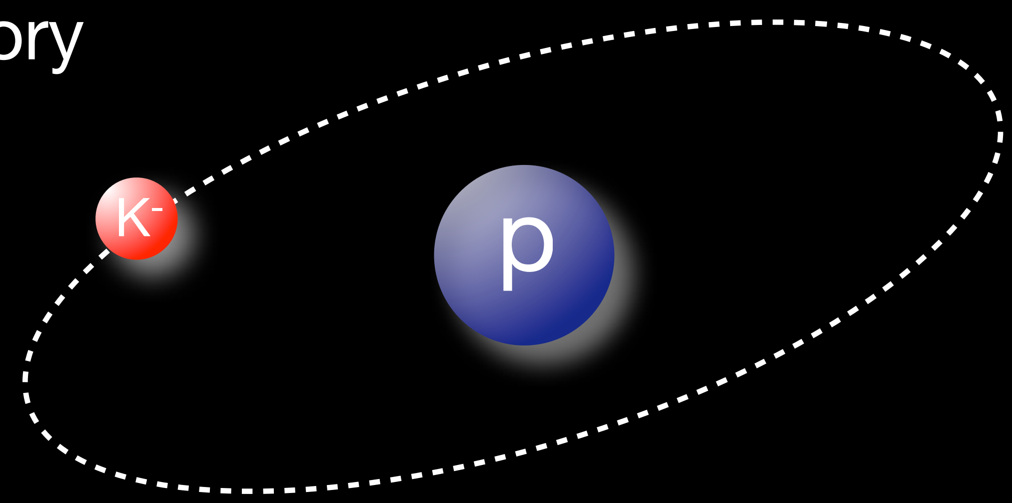
(= K$^-$p scattering amplitude at threshold)

can be directly deduced.

Kaonic hydrogen

QCD predictions

π-H system : successfully described by the chiral perturbation theory



but NOT with **K-H system**
due to the presence of Λ(1405) resonance only 25 MeV below threshold

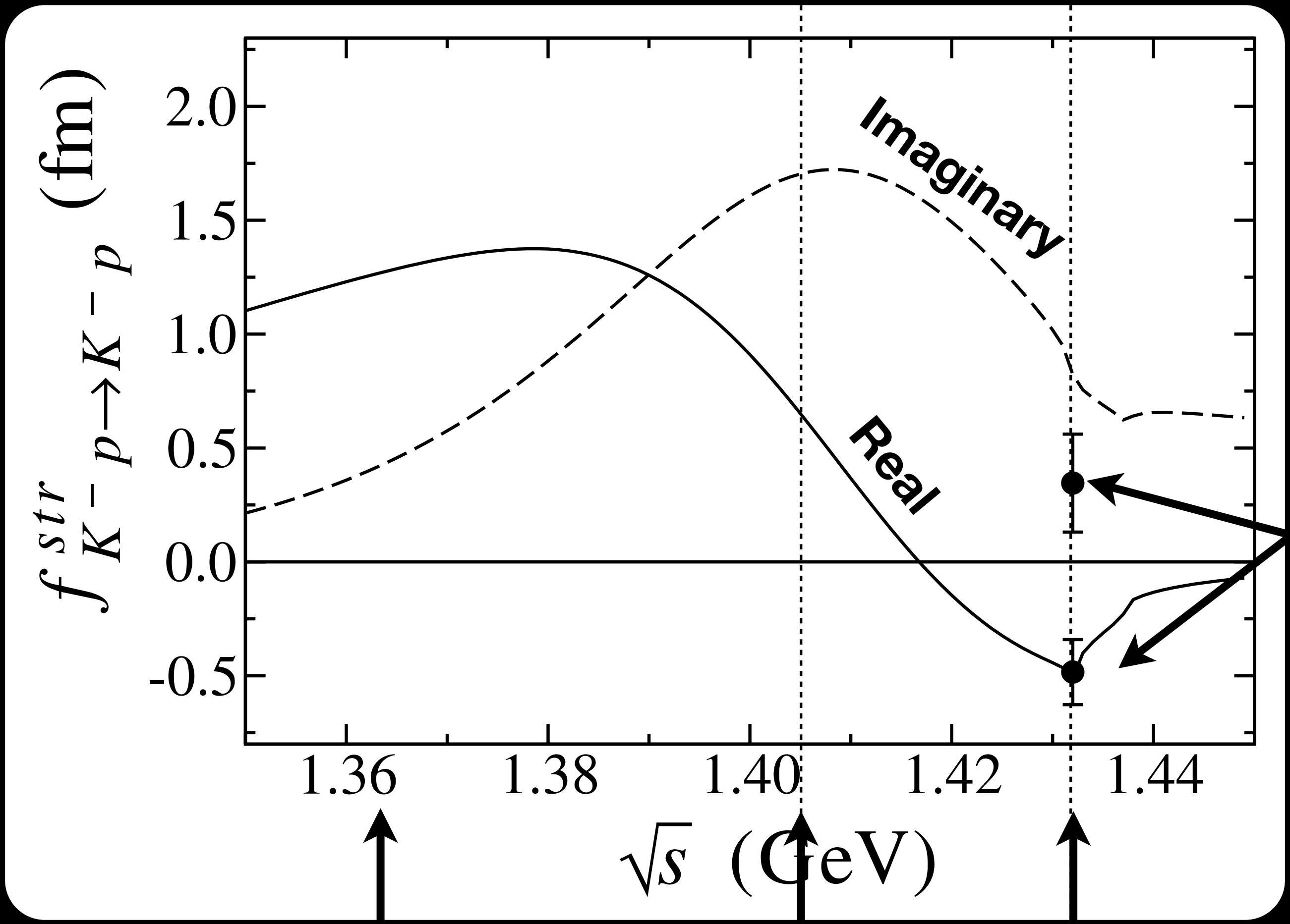
Kaonic hydrogen

inconsistency between data and theory

Chiral SU(3) effective theory
in combination with a relativistic coupled-channels approach

Strong elastic K-p amplitude

$$f^{\rm str}_{K^- p \to K^- p} = 1/(8\pi\sqrt{s})T^{\rm str}_{K^- p \to K^- p}.$$



Σπ

Λ(1405)

KN threshold

previous data

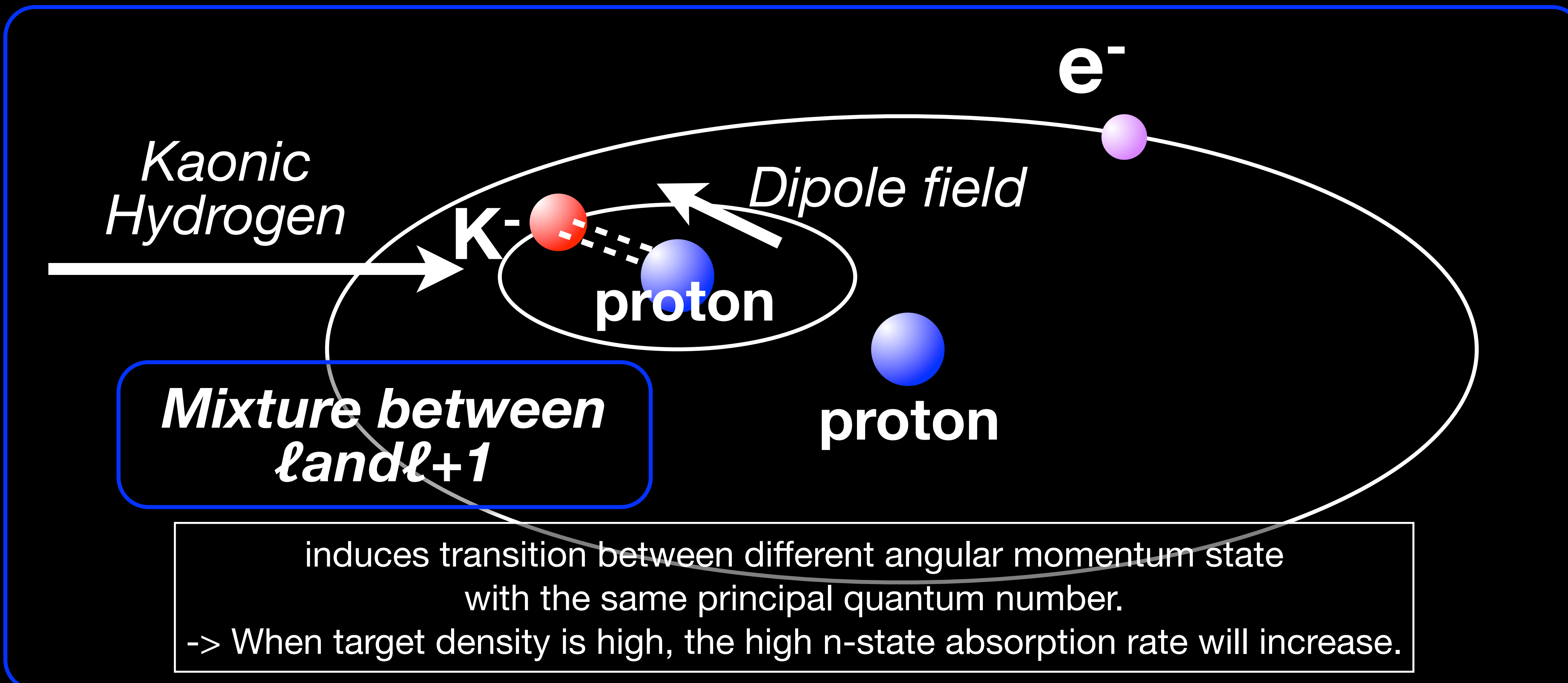
DEAR exp. ('95)

B. Borasoy, R. Nißler & W. Weise
PRL 94, 213401 (2005)

Experimental Difficulty

Difficulty of KH measurement

Density-dependent yield due to **Stark mixing**



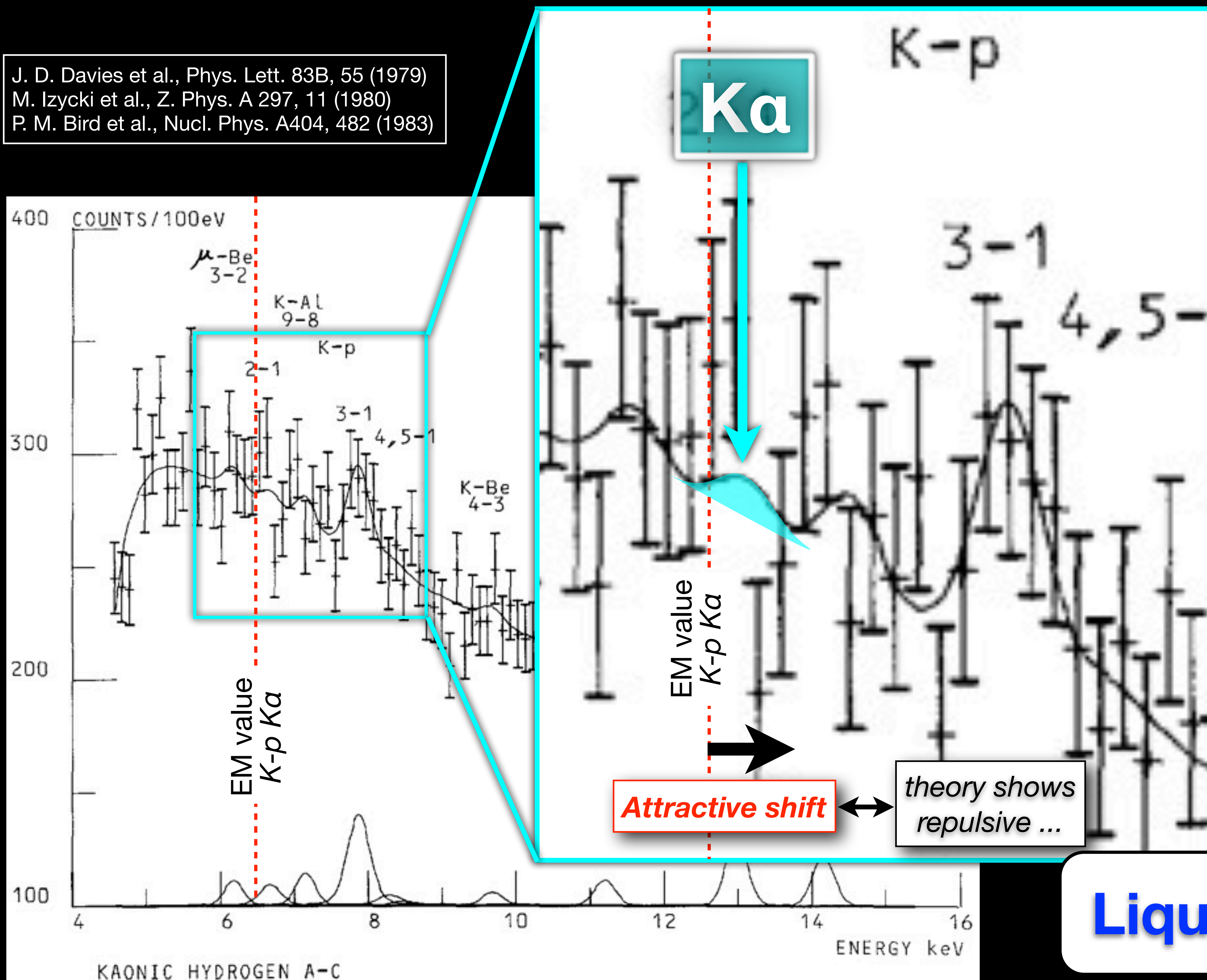
➡ Low density gaseous hydrogen target

➡ Low energy Kaon with small energy spread

History

70-80's : Kaonic hydrogen puzzle

J. D. Davies et al., Phys. Lett. 83B, 55 (1979)
M. Izycki et al., Z. Phys. A 297, 11 (1980)
P. M. Bird et al., Nucl. Phys. A404, 482 (1983)

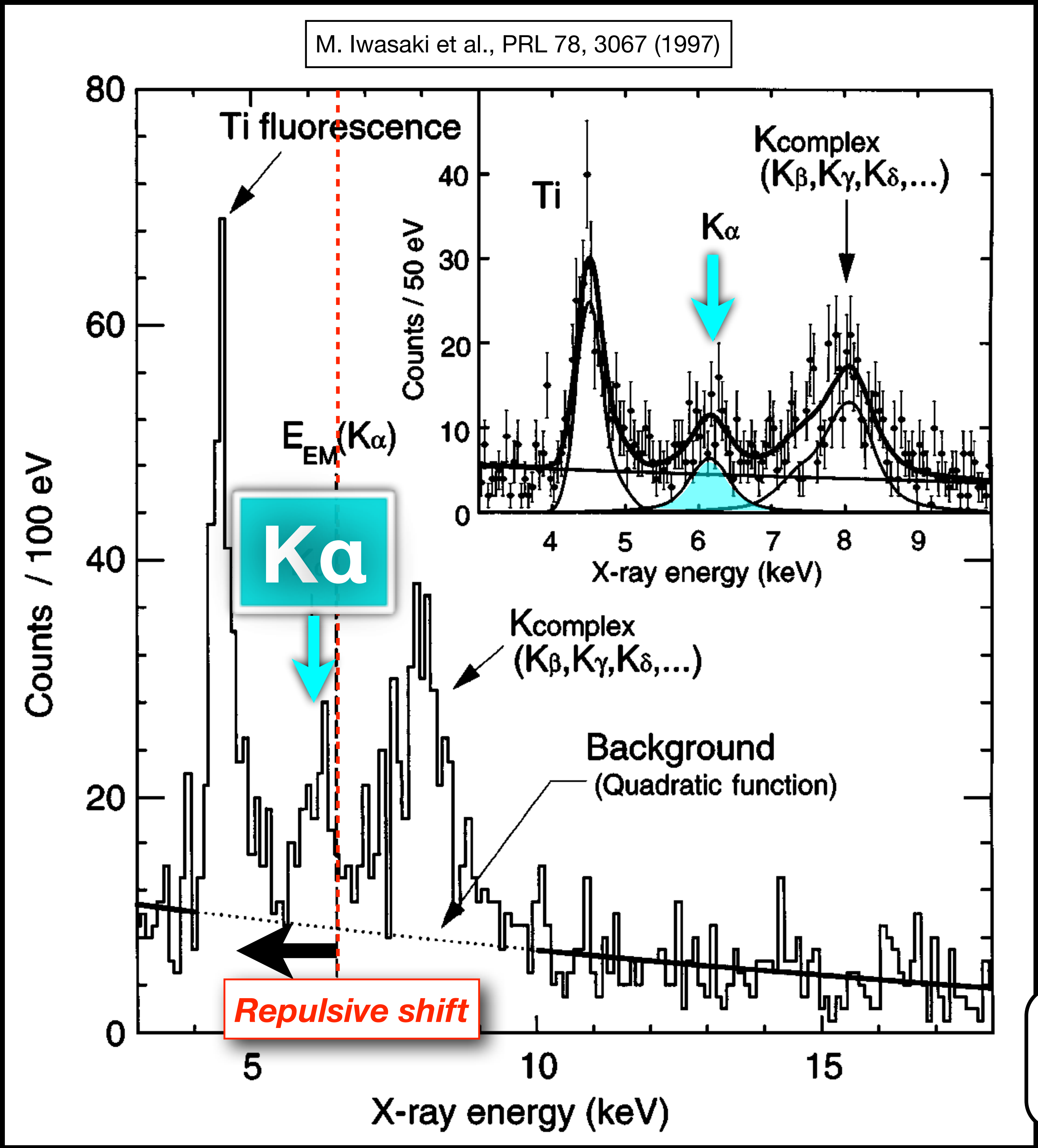


P. M. Bird (1983)

Liquid target

1997 : The first distinct peak @ KEK

KpX

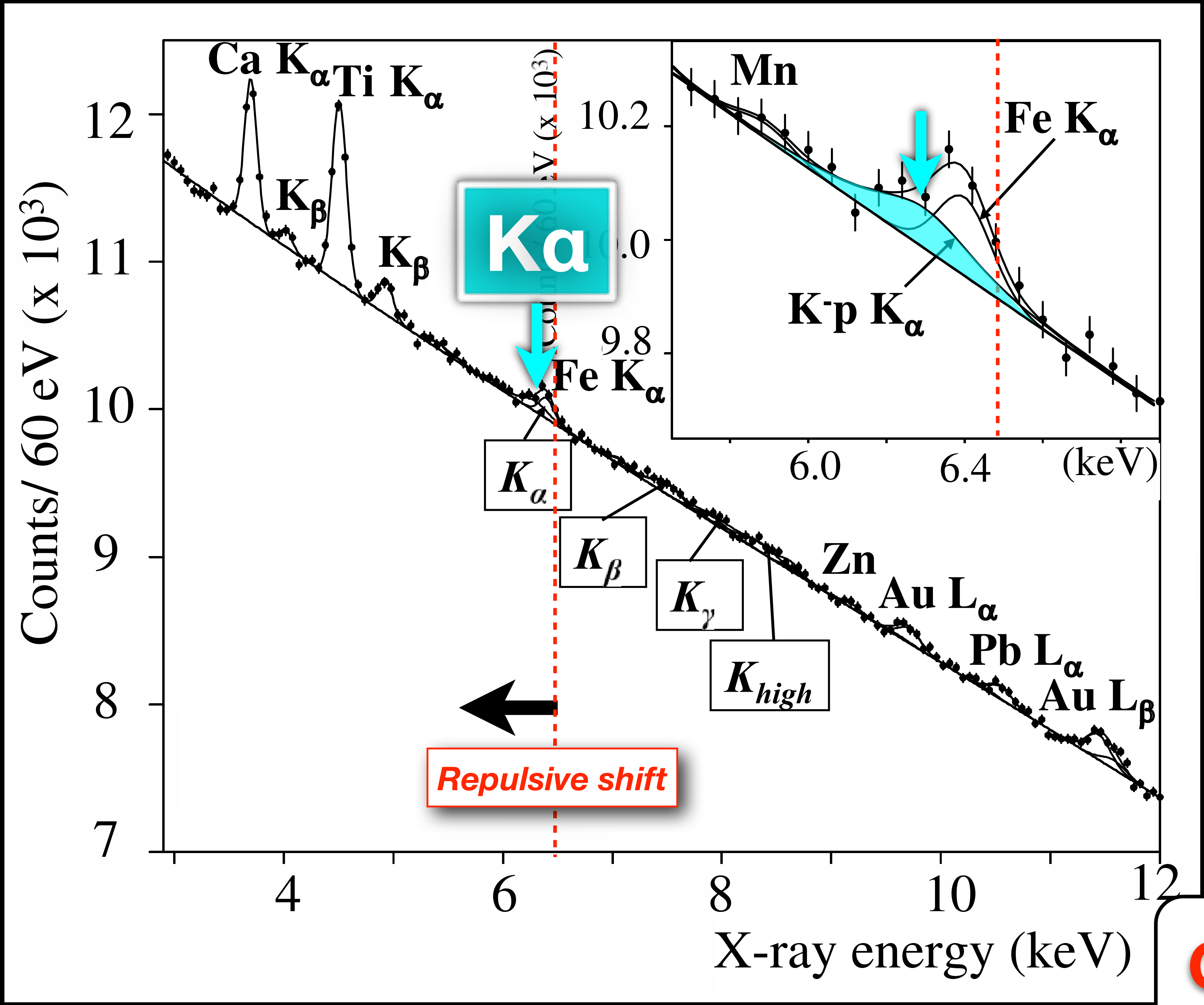


Gas target

2005 : Repulsive shift again @ LNF

DEAR

G. Beer et al., PRL 94, 212302 (2005)

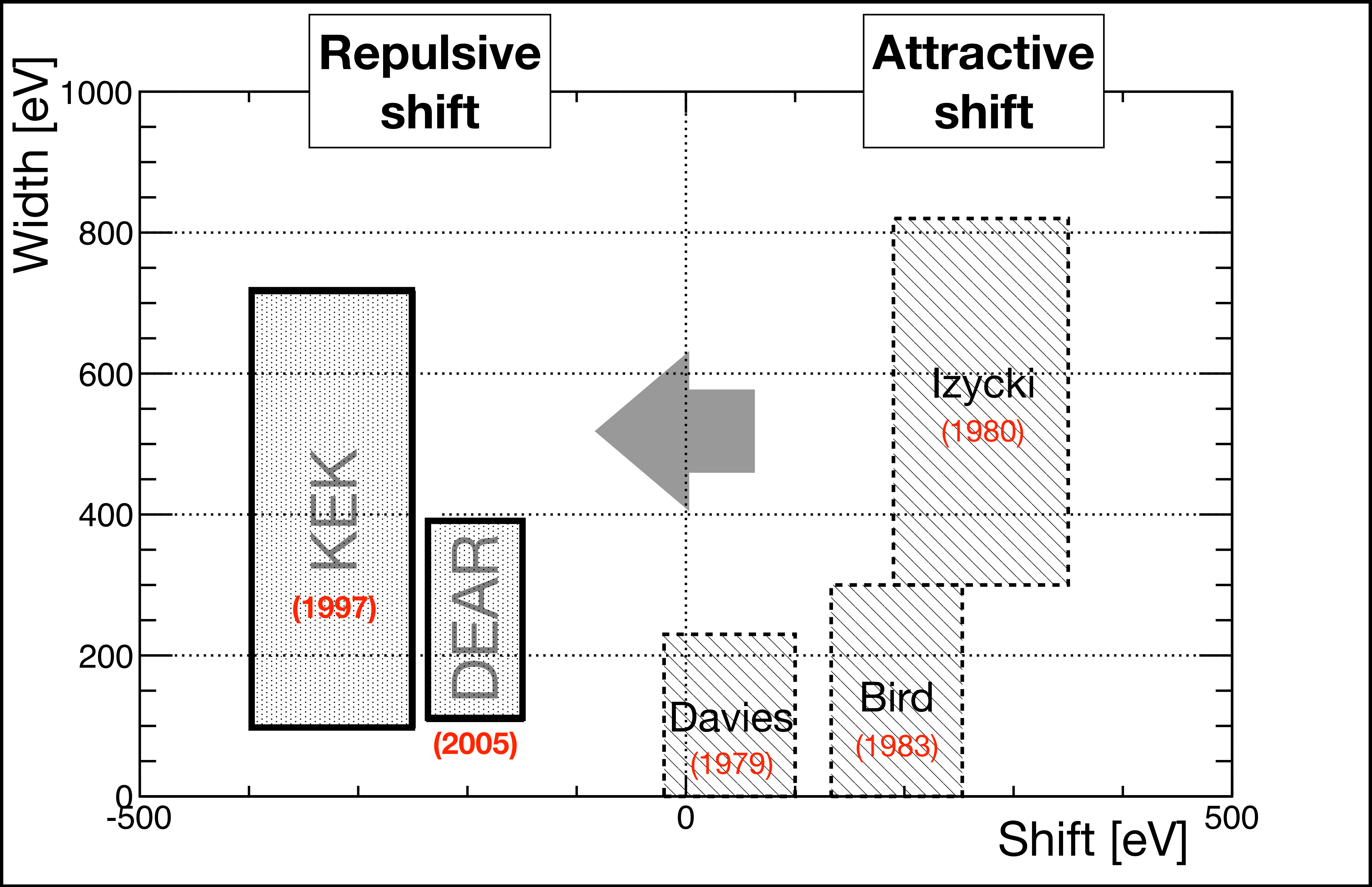


CCD has no timing capability

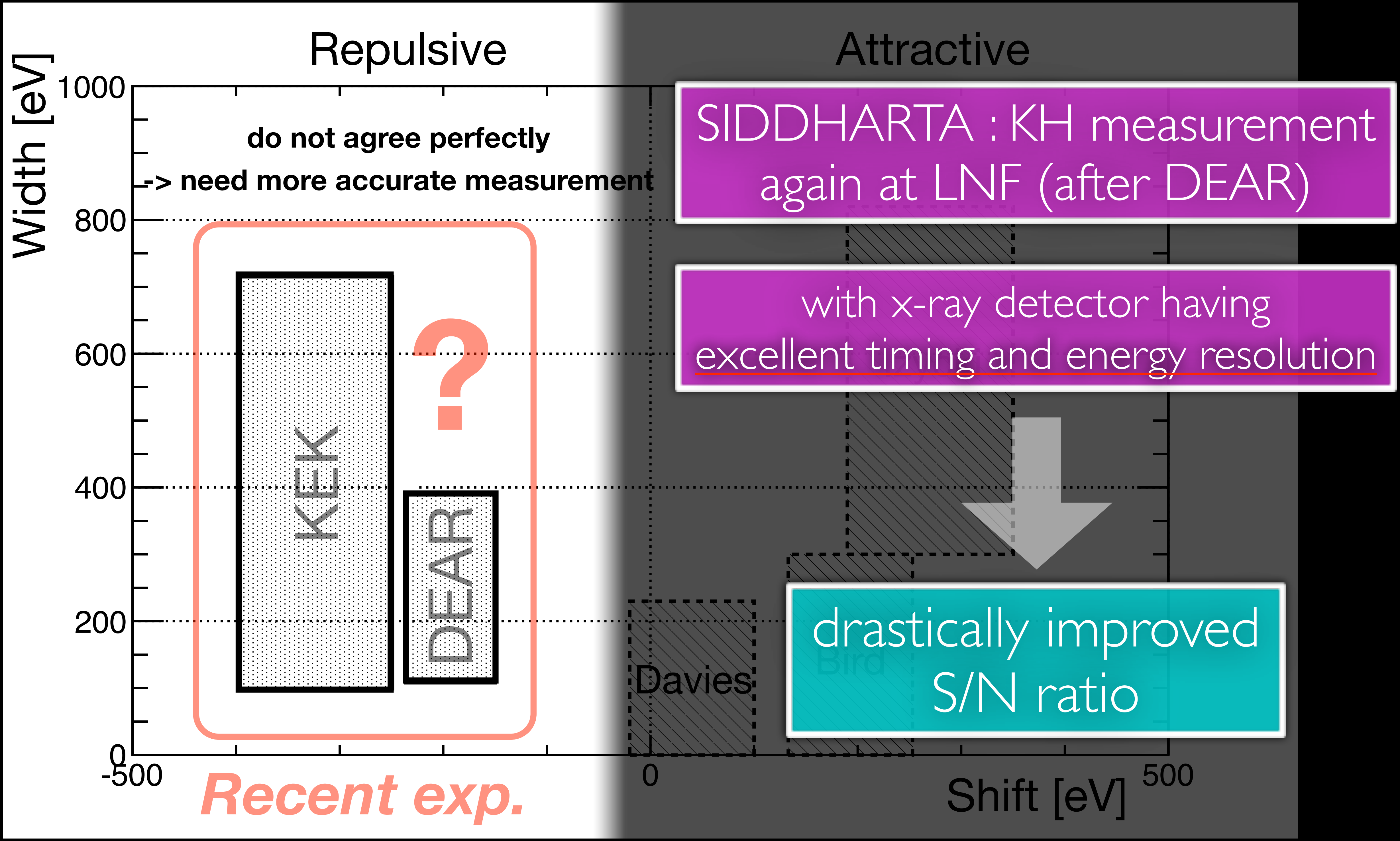
huge background

Gas target

Kaonic hydrogen : Shift vs. Width

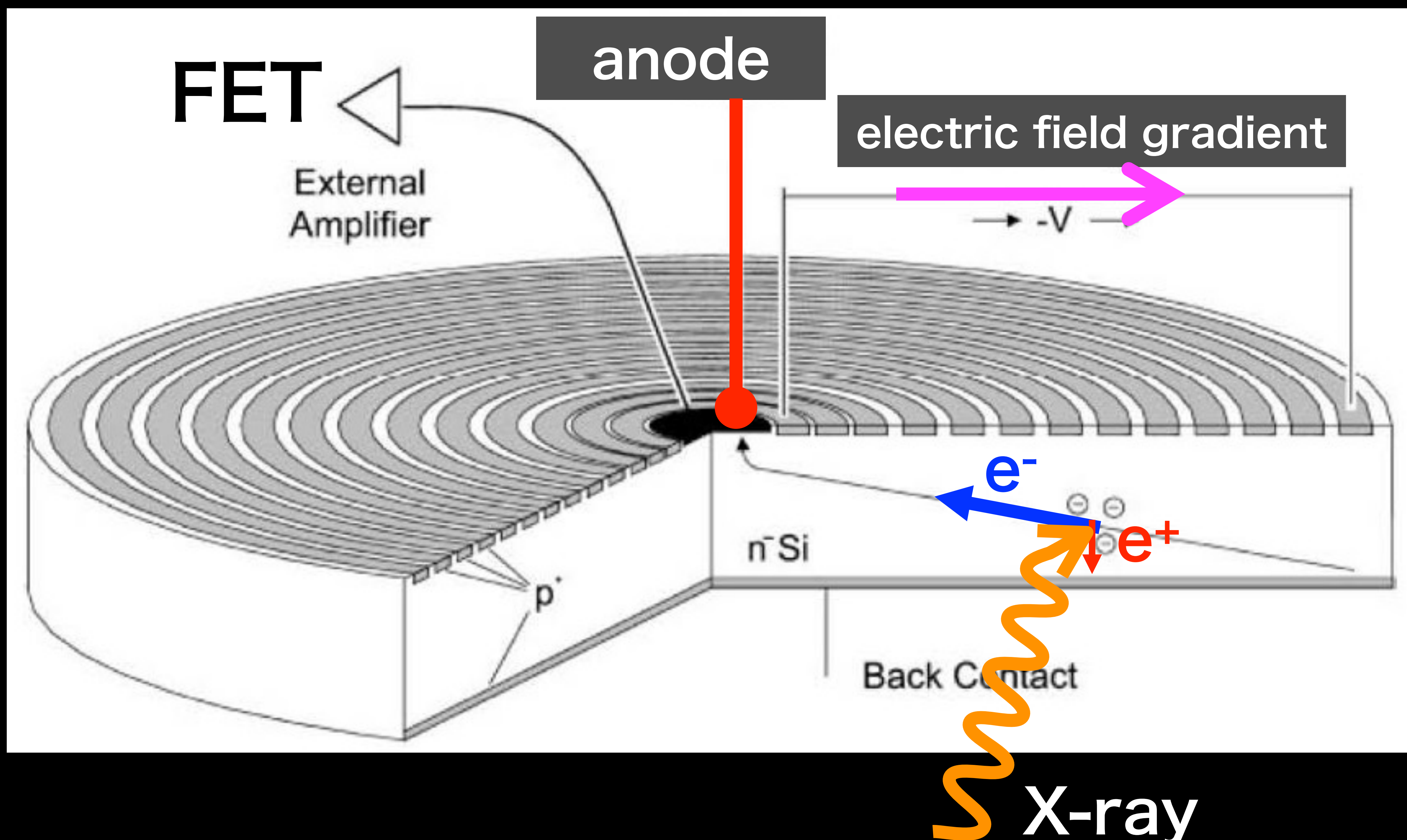


Kaonic hydrogen : Shift vs. Width



X-ray detector

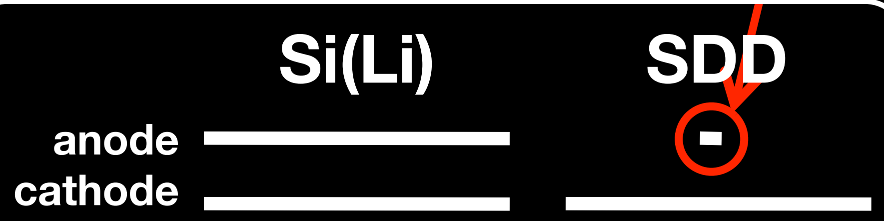
Silicon Drift Detector - SDD



Silicon Drift Detector - SDD

$(C = \varepsilon_0 S / d)$

electrode



parallel plate type
of silicon detector

small anode

↓

small capacitance

↓

High resolution
with thin depletion layer

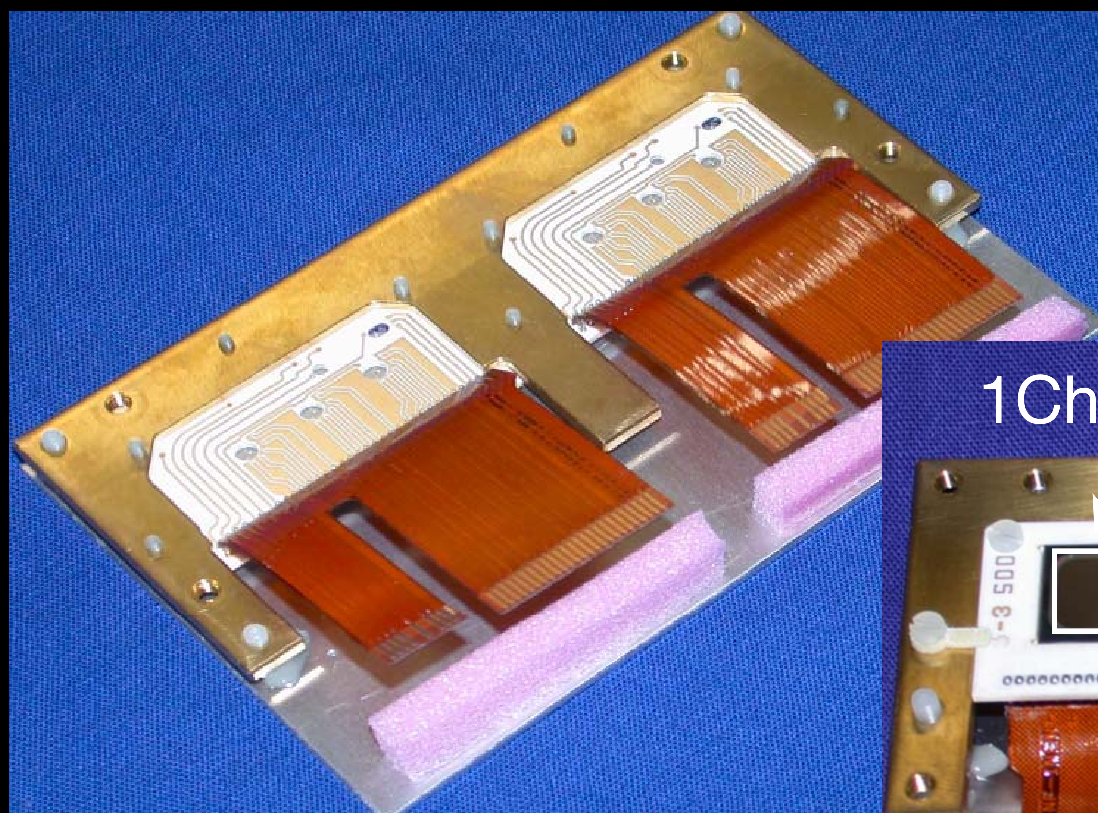
↓

Suppress a background
due to Compton scattering
inside the detector

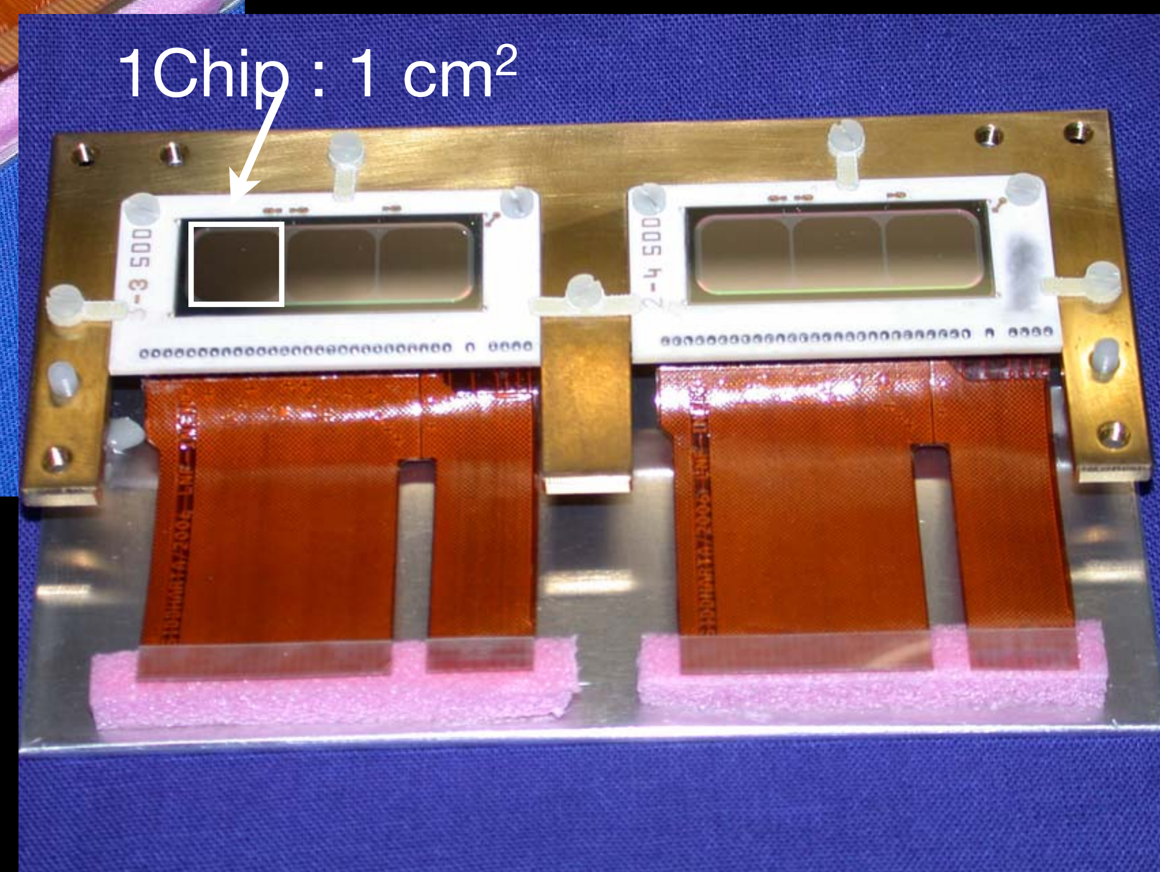
Silicon Drift Detector - SDD

	KpX, 1998	DEAR, 2005	SIDDHARTA
Detector	Si(Li)	CCD	**SDD**
Energy Resolution	360 eV	180 eV	150 eV
Thickness	sub 10 mm	sub mm	sub mm
Effective area	120 cm^2	116 cm^2	114 cm^2
Time resolution	sub μsec	~ 30 sec	sub μsec
Efficiency @ 6keV	~ 100 %	~ 60 %	~ 100 %

Silicon Drift Detector - SDD



Gluing and bonding at Fraunhofer Institut - Berlin

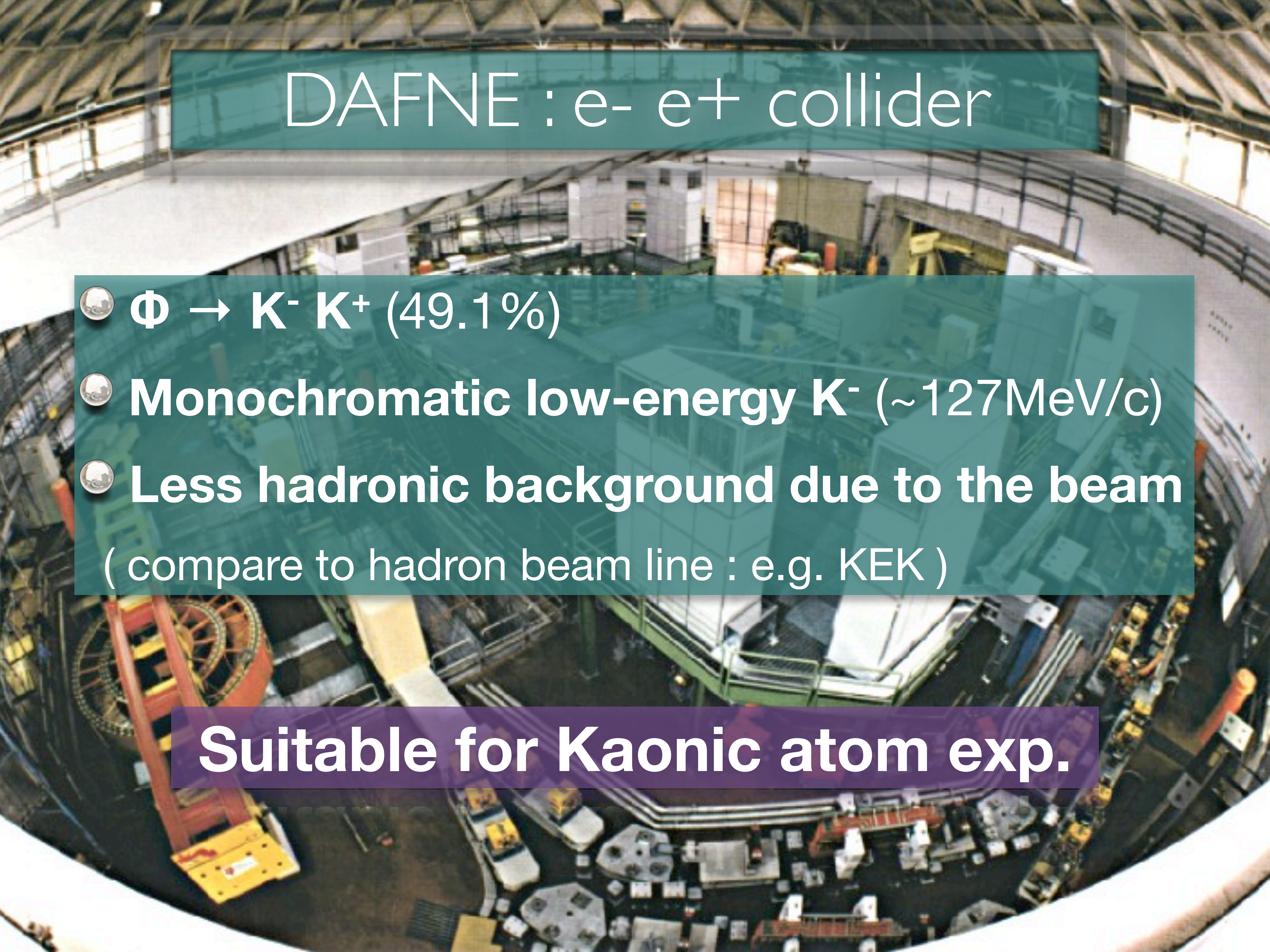


Final testing and assembling at SMI

DAΦNE

DAFNE : e- e+ collider

DAFNE : e- e+ collider

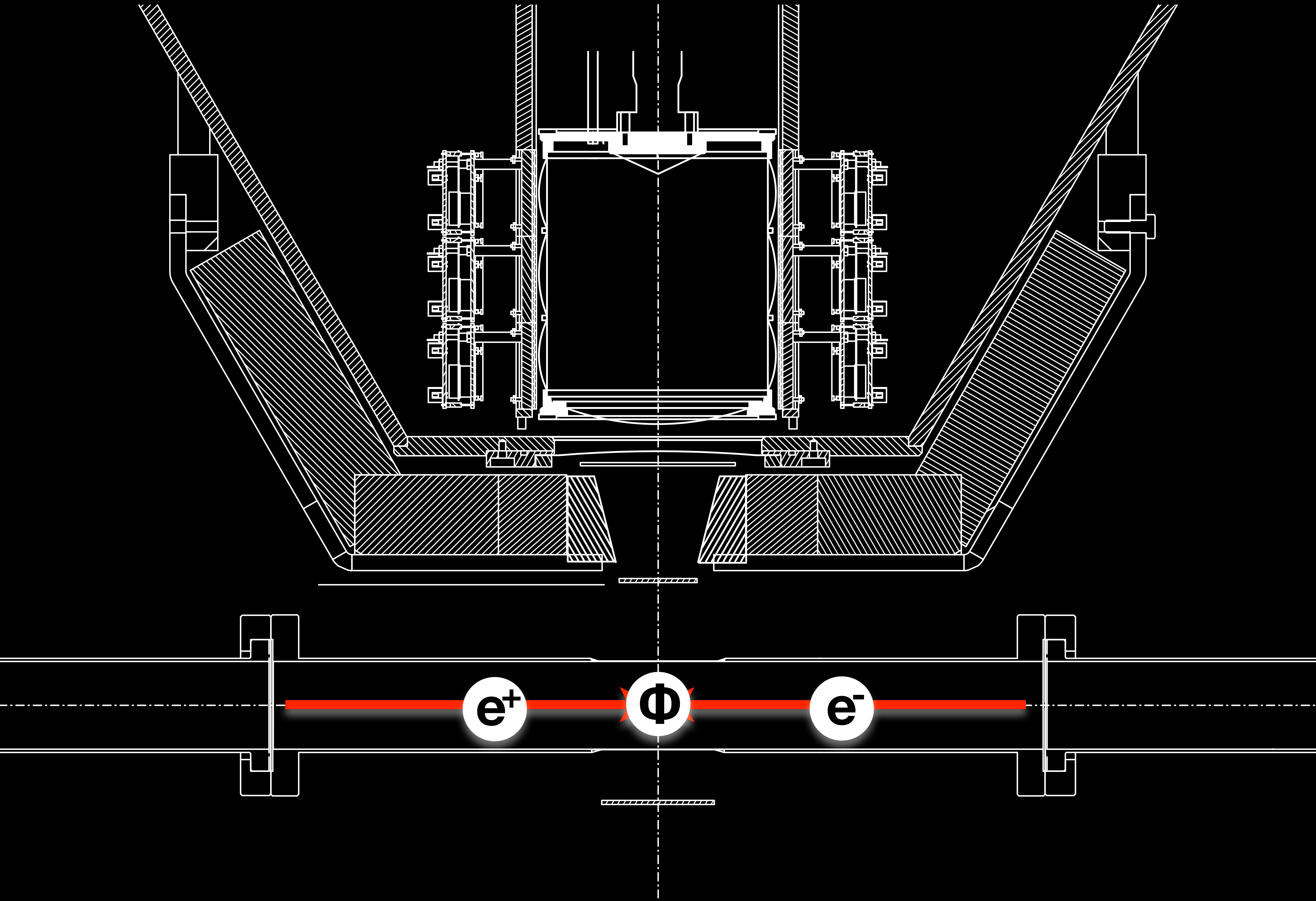


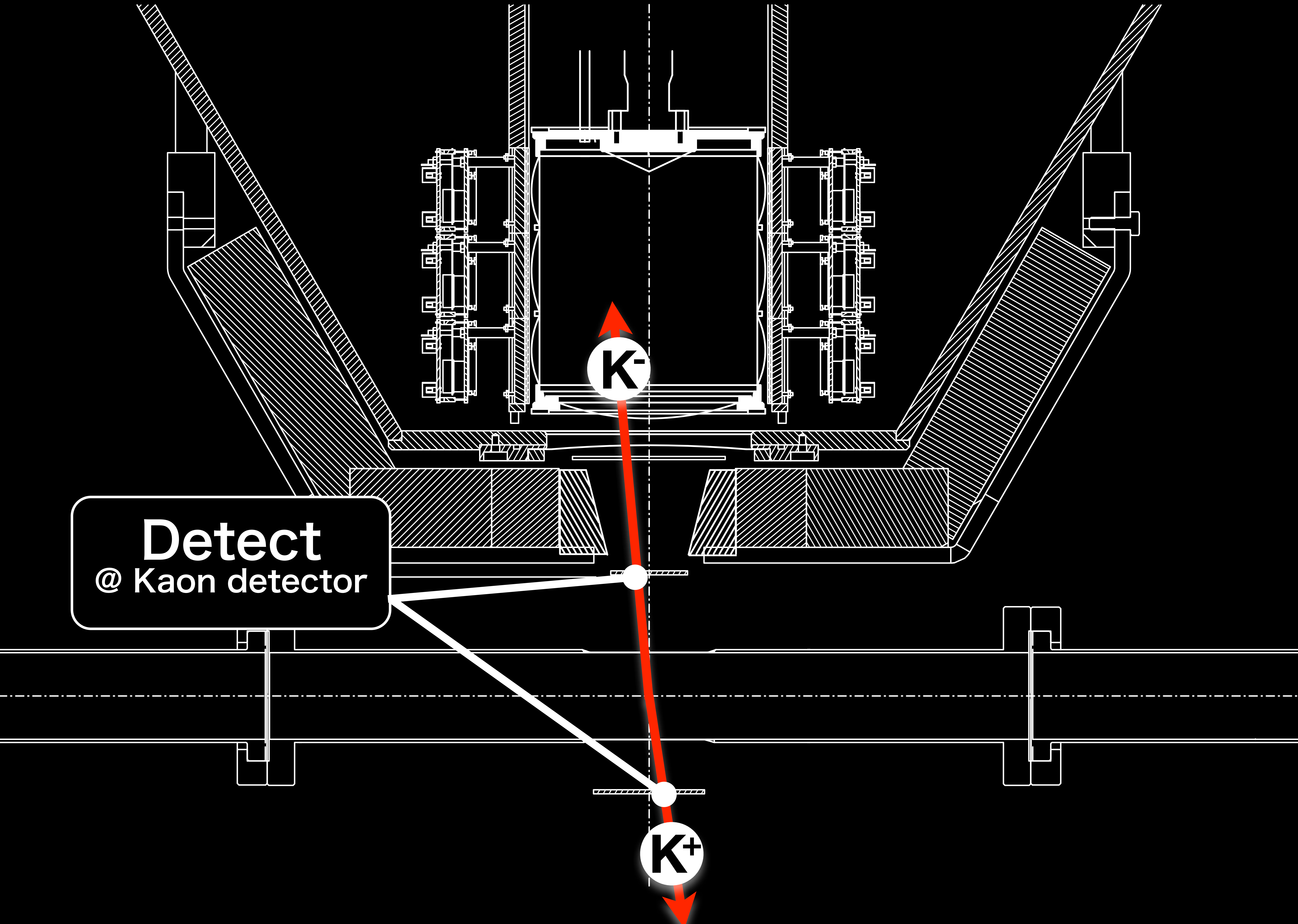
- **Φ → K^- K^+** (49.1%)
- **Monochromatic low-energy K^-** (~127MeV/c)
- **Less hadronic background due to the beam**

(compare to hadron beam line : e.g. KEK)

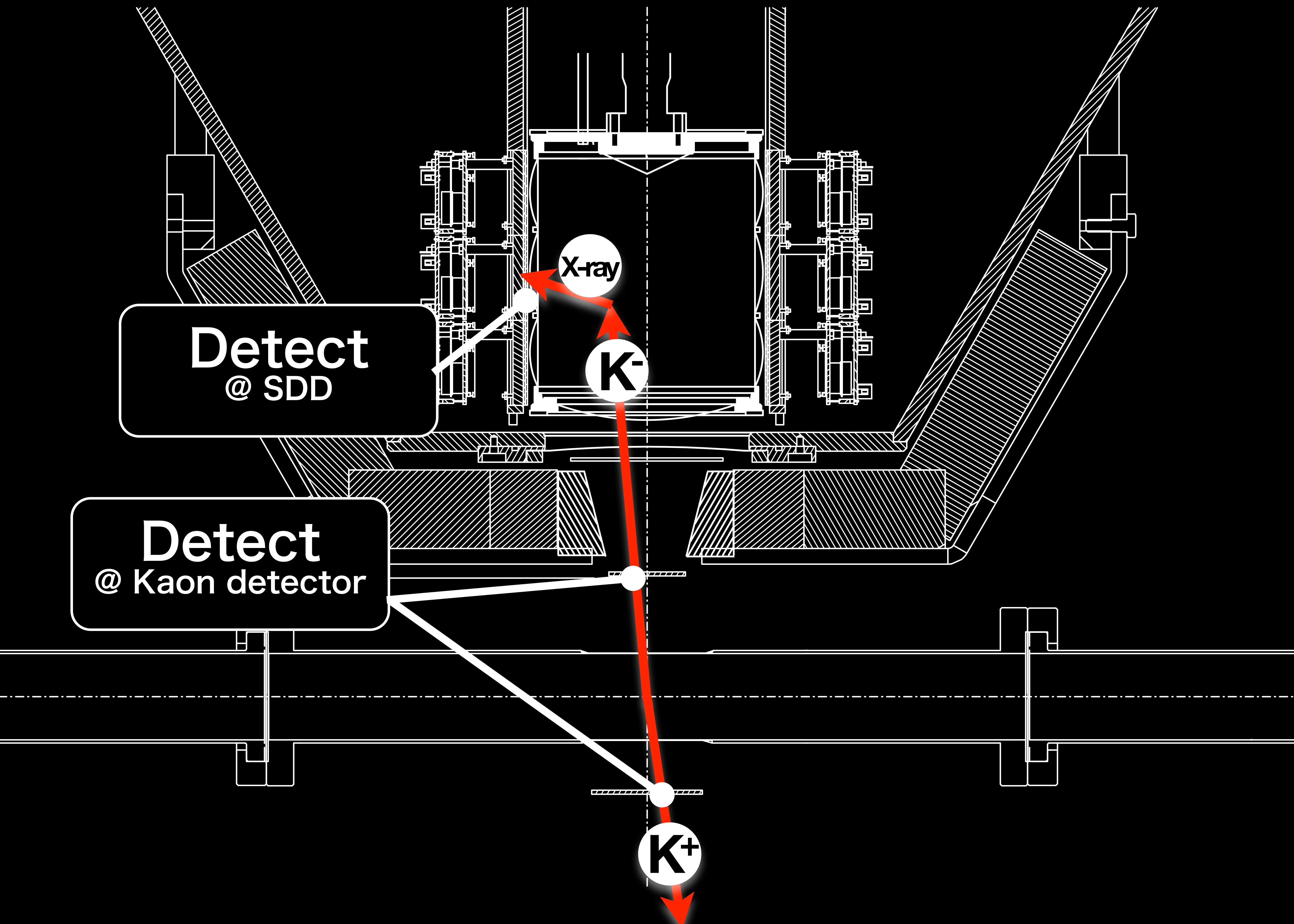
Suitable for Kaonic atom exp.

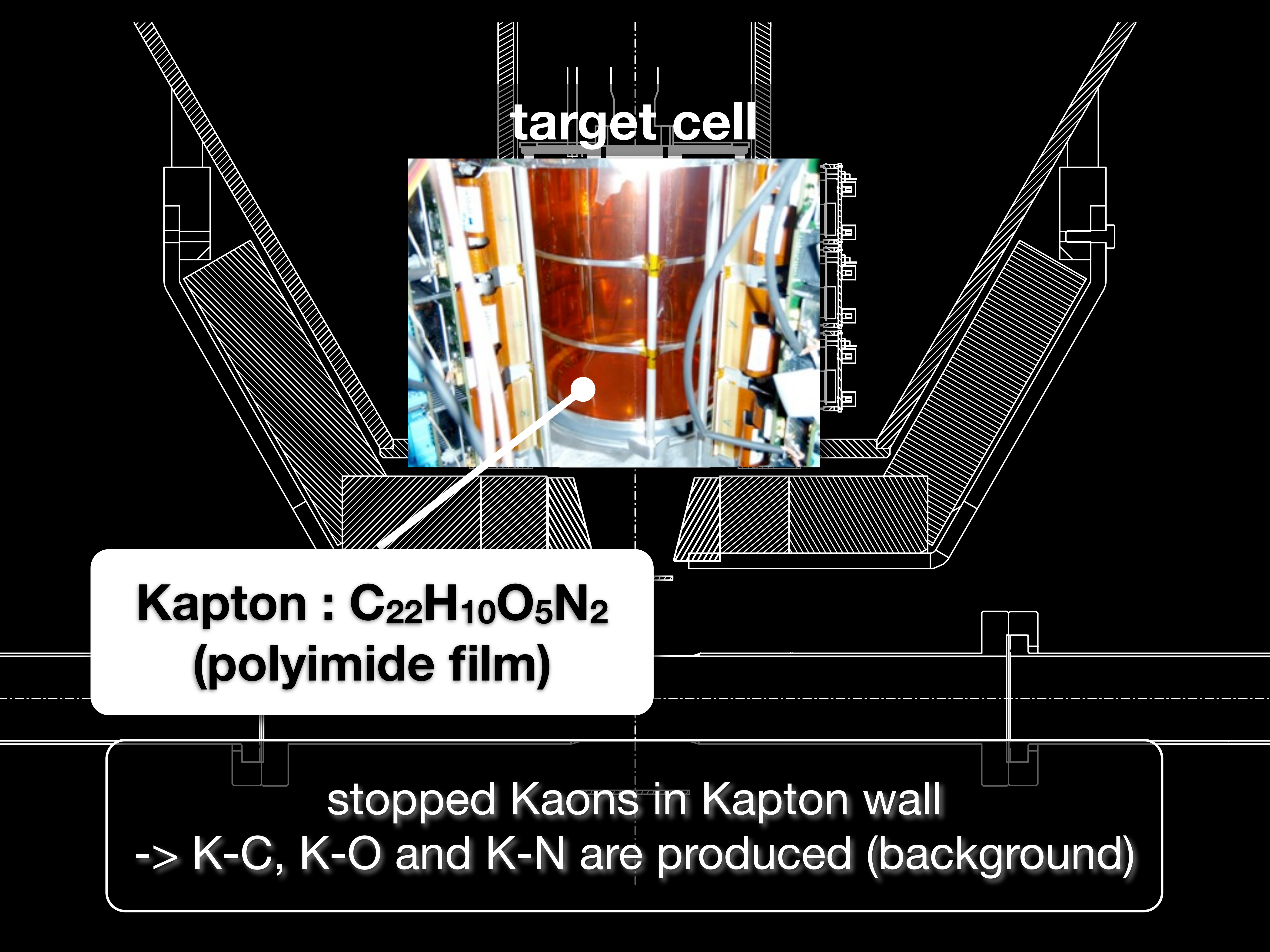
Experimental Setup


e+
Φ
e-



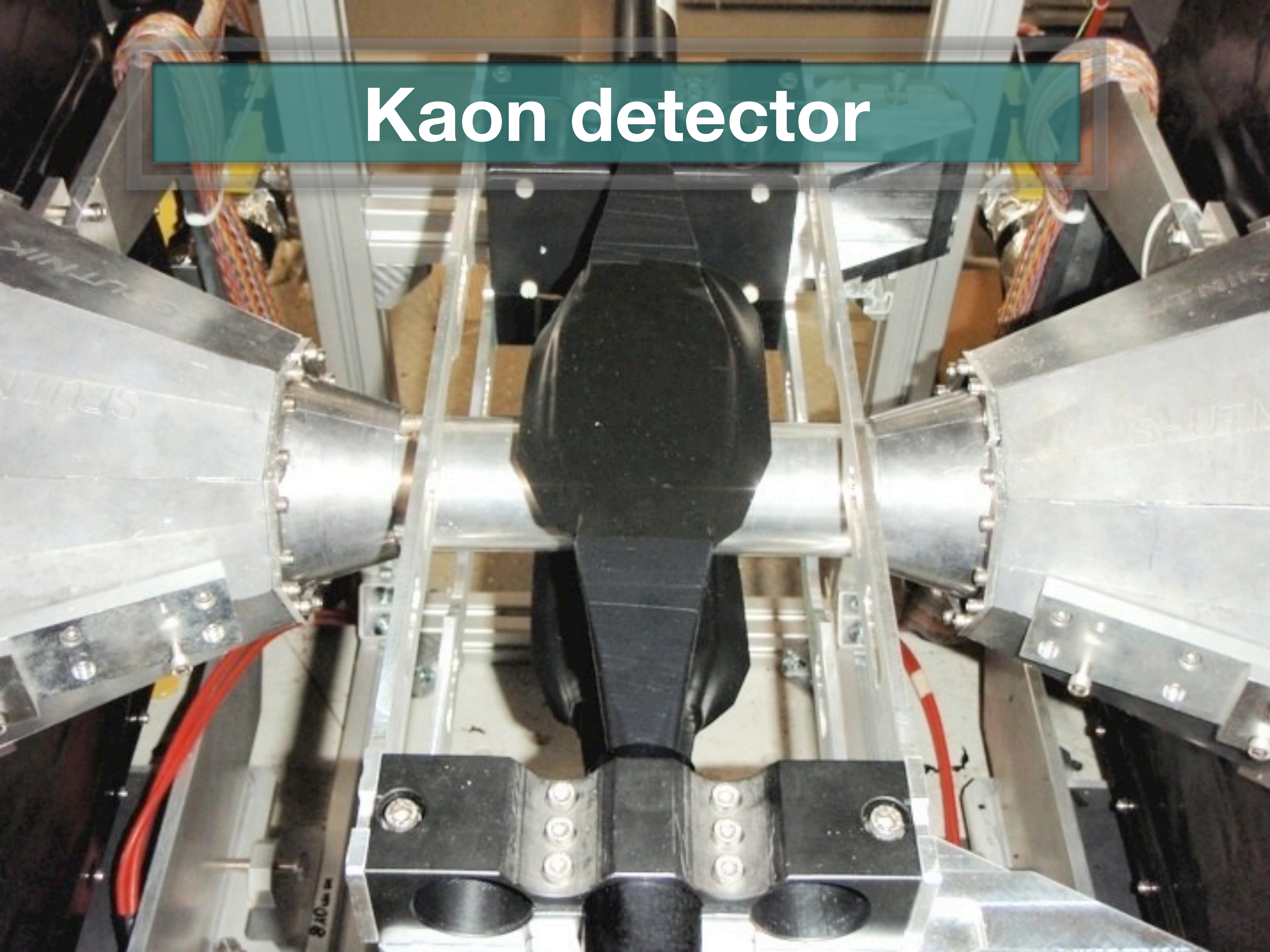
Detect
@ Kaon detector
K-
K+


X-ray
Detect
@ SDD
K-
Detect
@ Kaon detector
K+

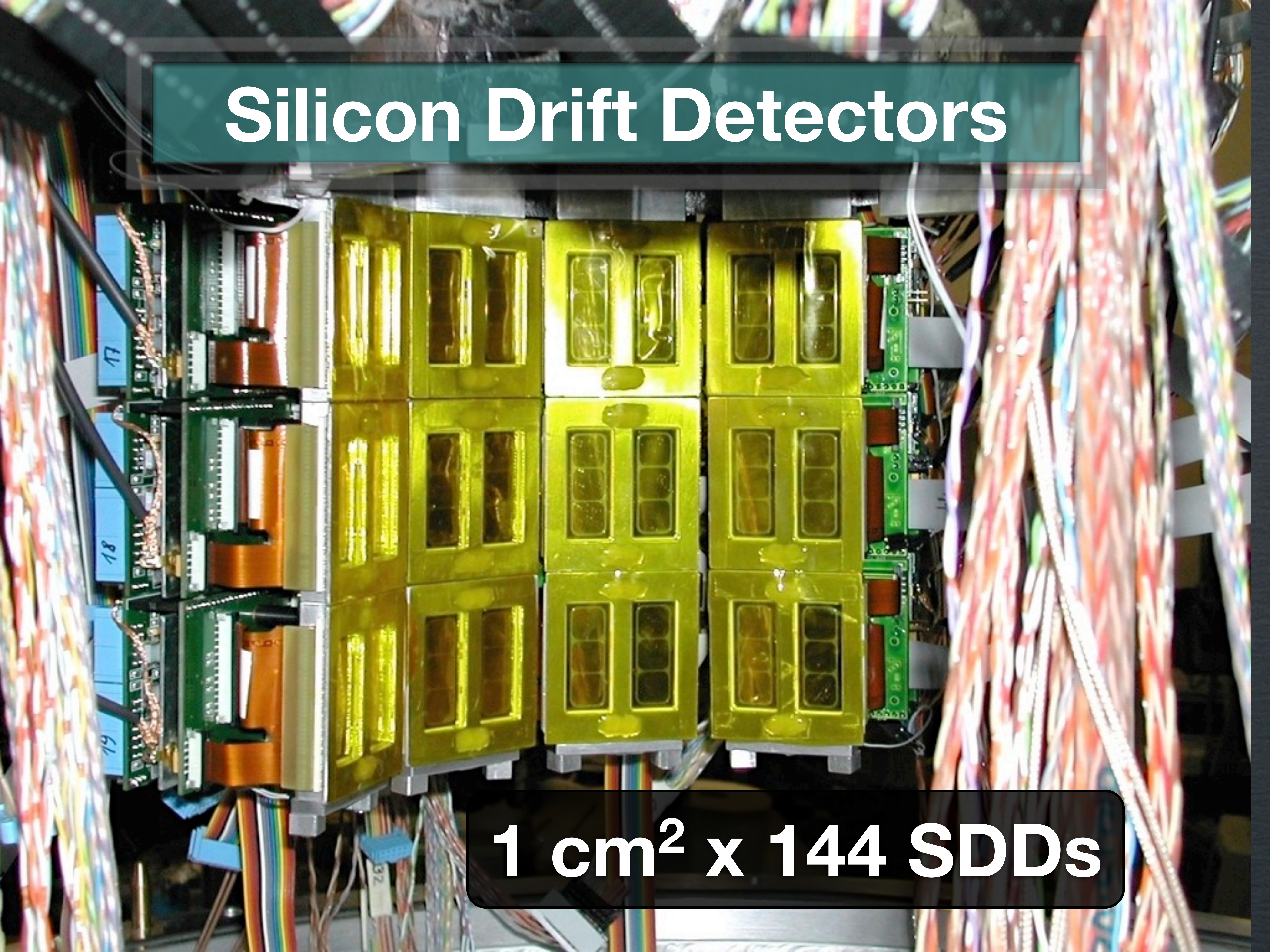

target cell
Kapton : C22H10O5N2
(polyimide film)
stopped Kaons in Kapton wall
-> K-C, K-O and K-N are produced (background)

SIDDHARTA setup

Kaon detector



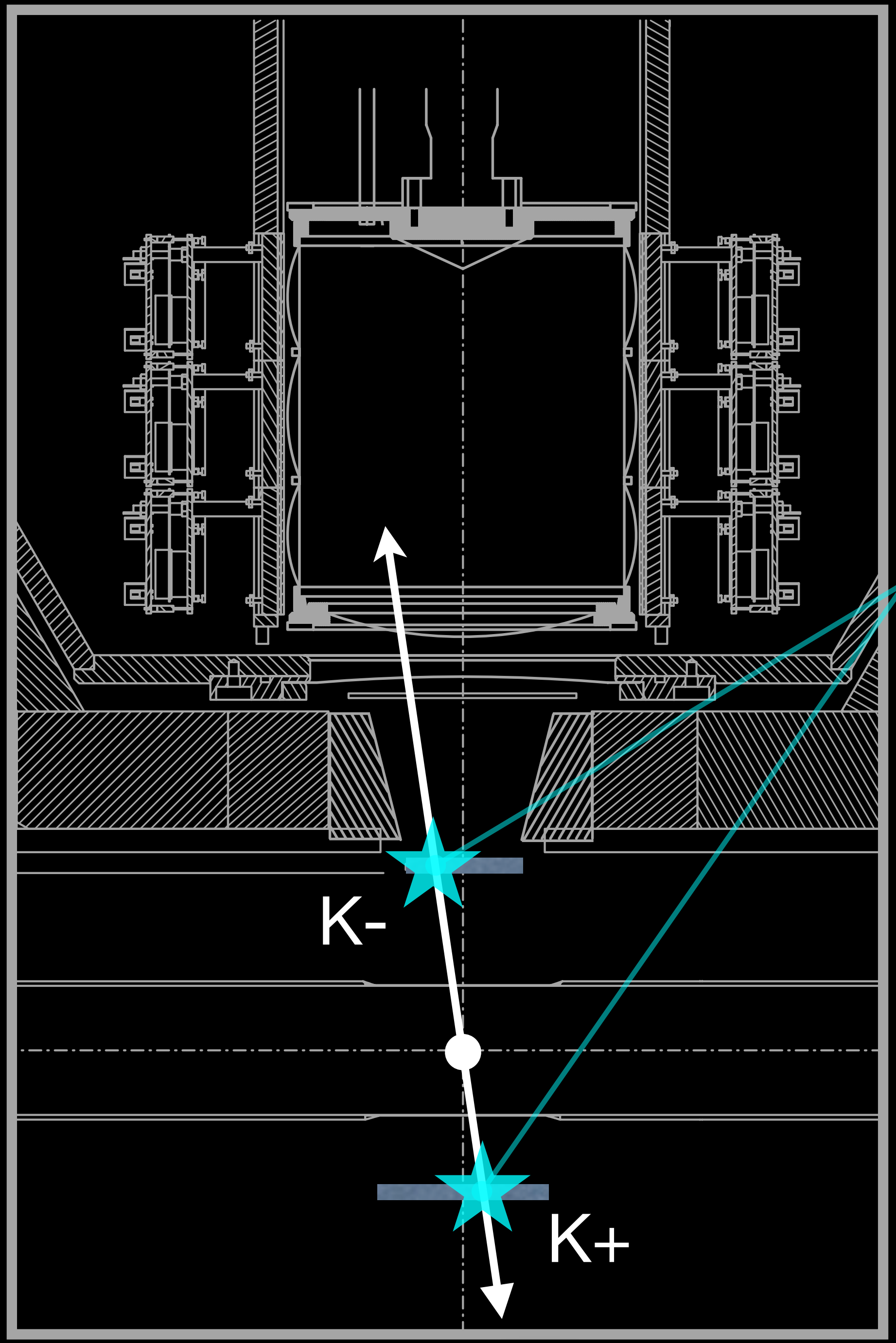
Silicon Drift Detectors



1 cm^2 x 144 SDDs

Analysis

Kaon identification

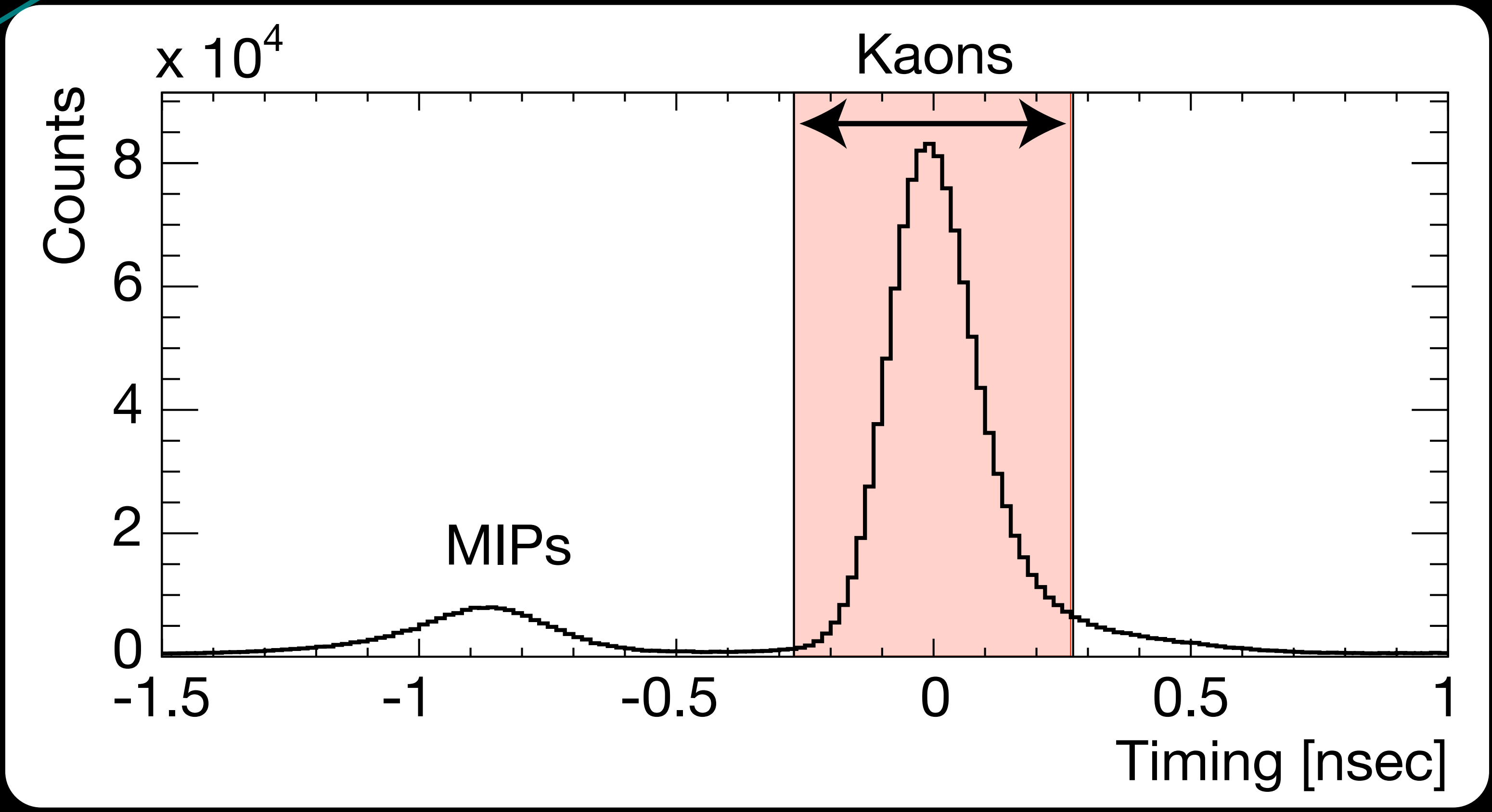


two scintillators

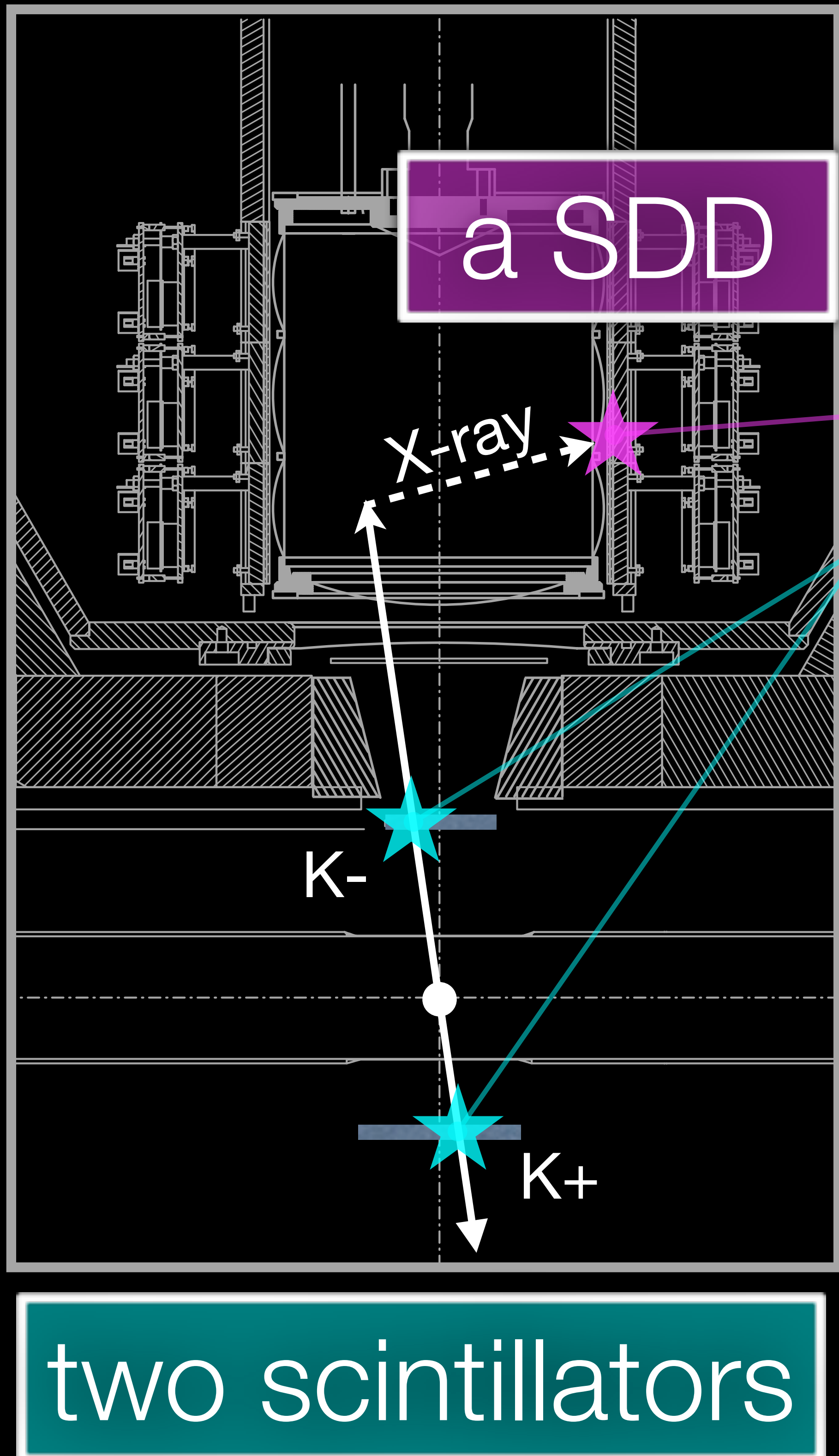
Timing of coincidence signals

with respect to the RF signal from DAFNE

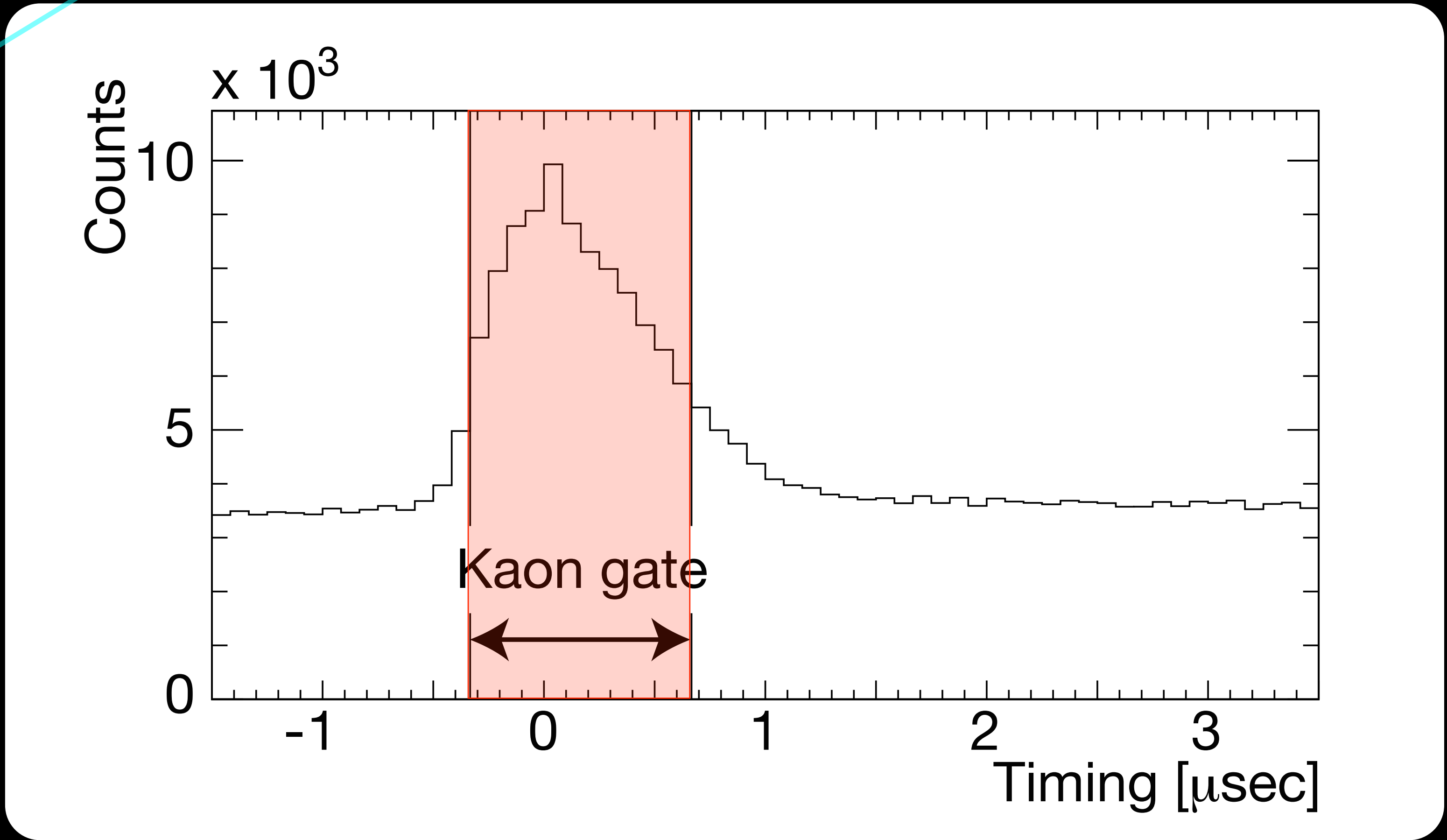
(~ 368.7 MHz)



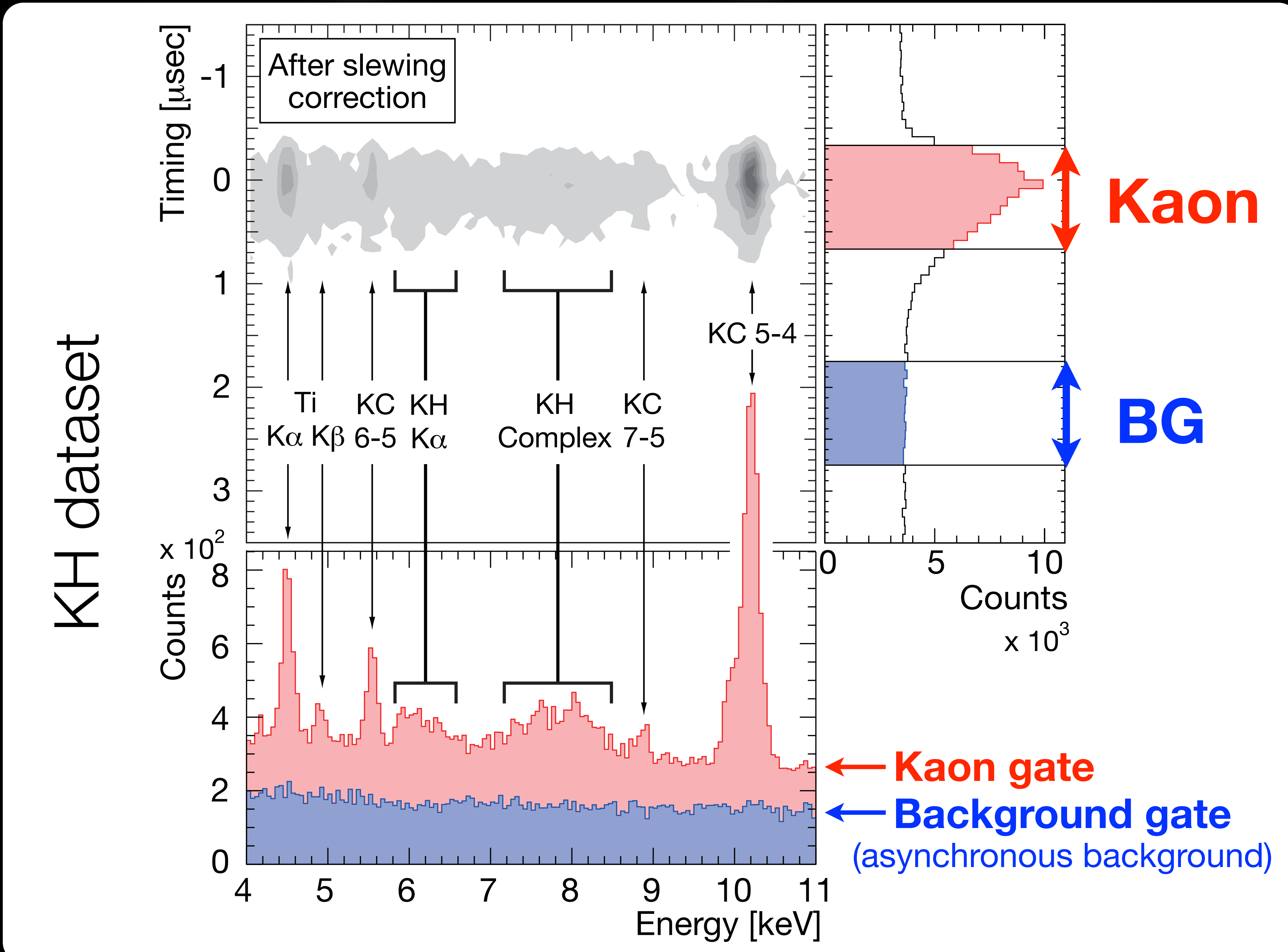
Timing on SDDs



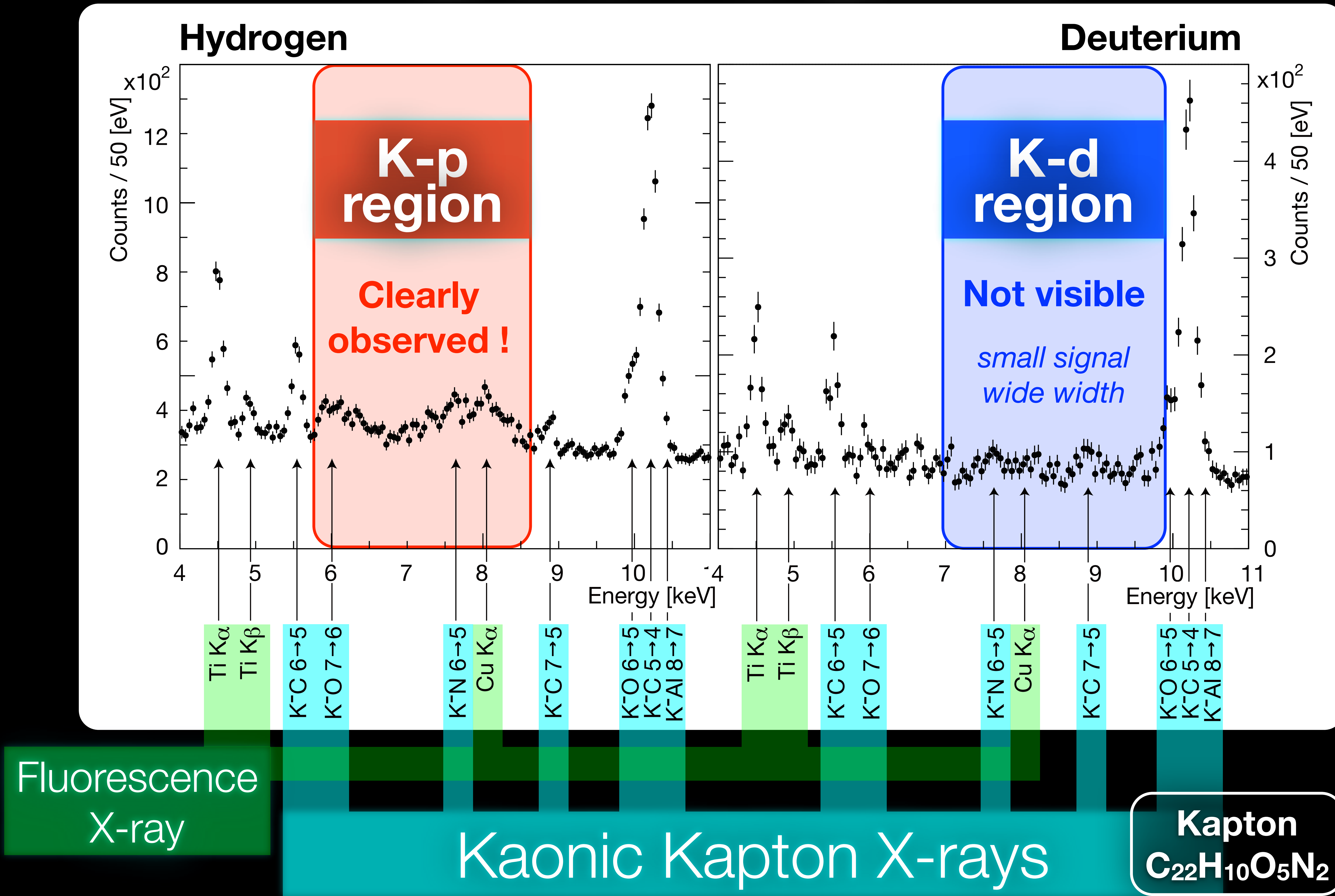
Time difference spectrum
between kaon arrival and x-ray detection



Energy vs. Timing on SDDs



K-p and K-d spectra

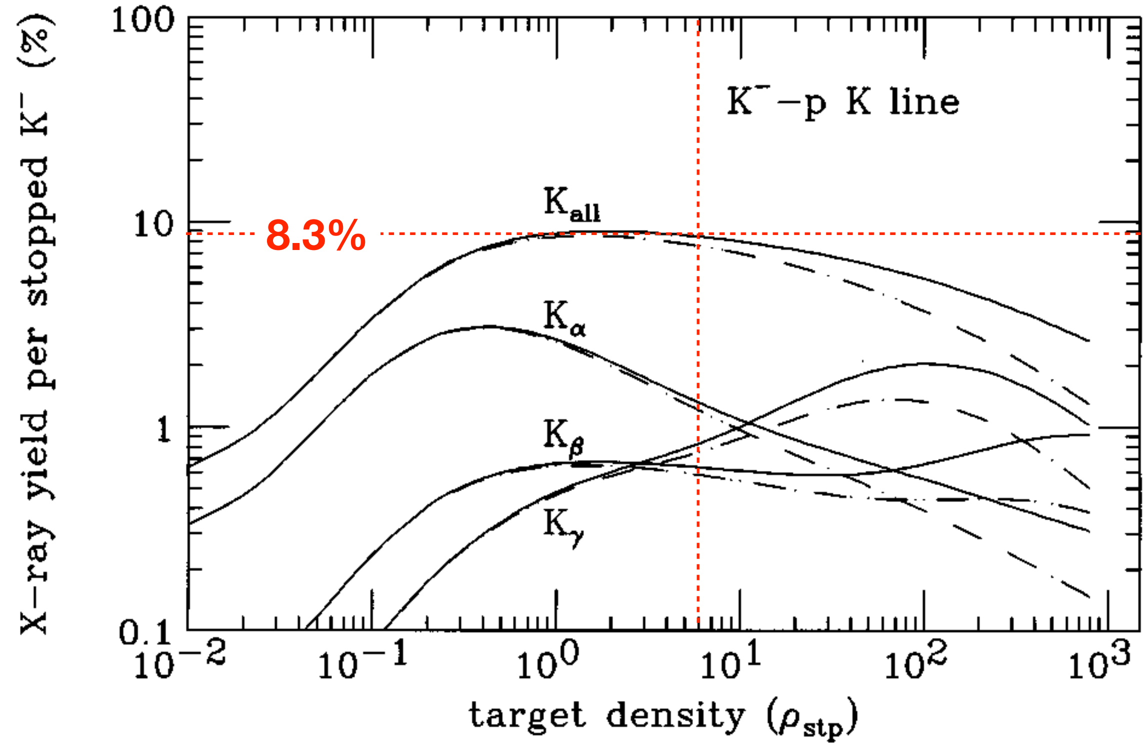


K-p and K-d spectra

Cascade calculation

Koike et al., PRC53(1996)79

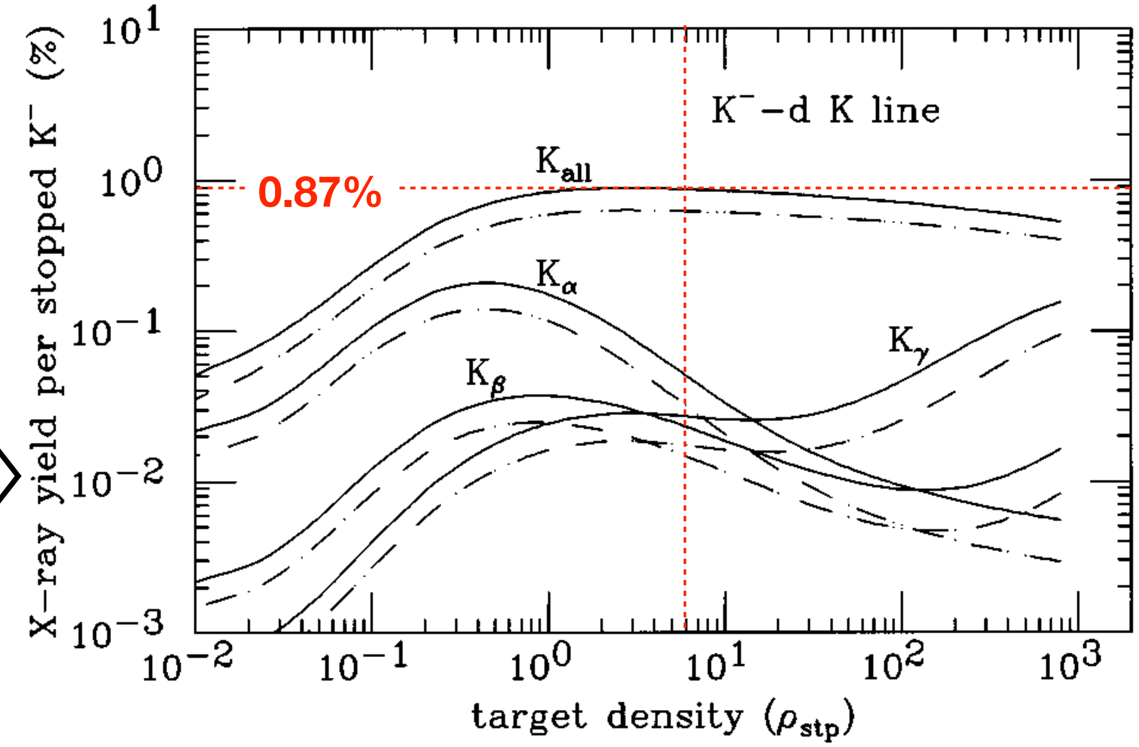
K-p



6 STP Kα/Kall ~ 15%

FIG. 5. Density dependence of K^--p atom x-ray yields with varying $(\delta E_{1s})_{\rm strong}$ and $\Gamma_{1s}^{\rm abs}$. The solid lines and the dashed lines are the cases which suffer the strongest (Conboy *et al.* [10]) and the weakest (Tanaka and Suzuki [11]) Stark effects among the parameters given in Table I, respectively. The other cases in Table I lie between these lines. The width $\Gamma_{2p}^{\rm abs}$ is taken to be 1 meV. The free parameter $k_{\rm stk}$ is fixed to 2.0.

K-d



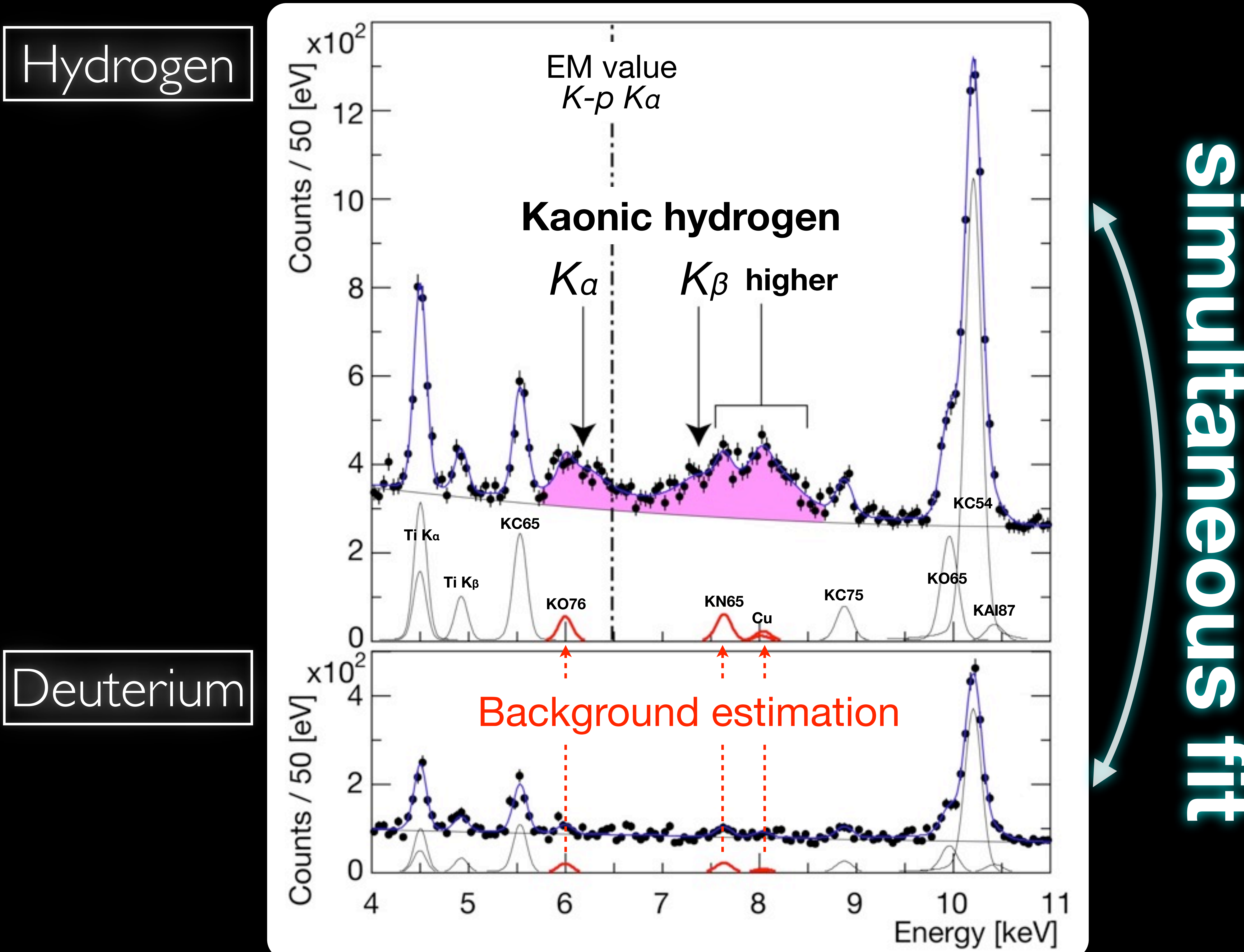
6 STP Kα/Kall ~ 5.8%

FIG. 10. Density dependence of K^--d atom x-ray yields with varying the strong-interaction parameters. The solid lines are the case of Martin's K matrix + Fermi average + binding effect. The dashed lines are for Batty's optical potential.

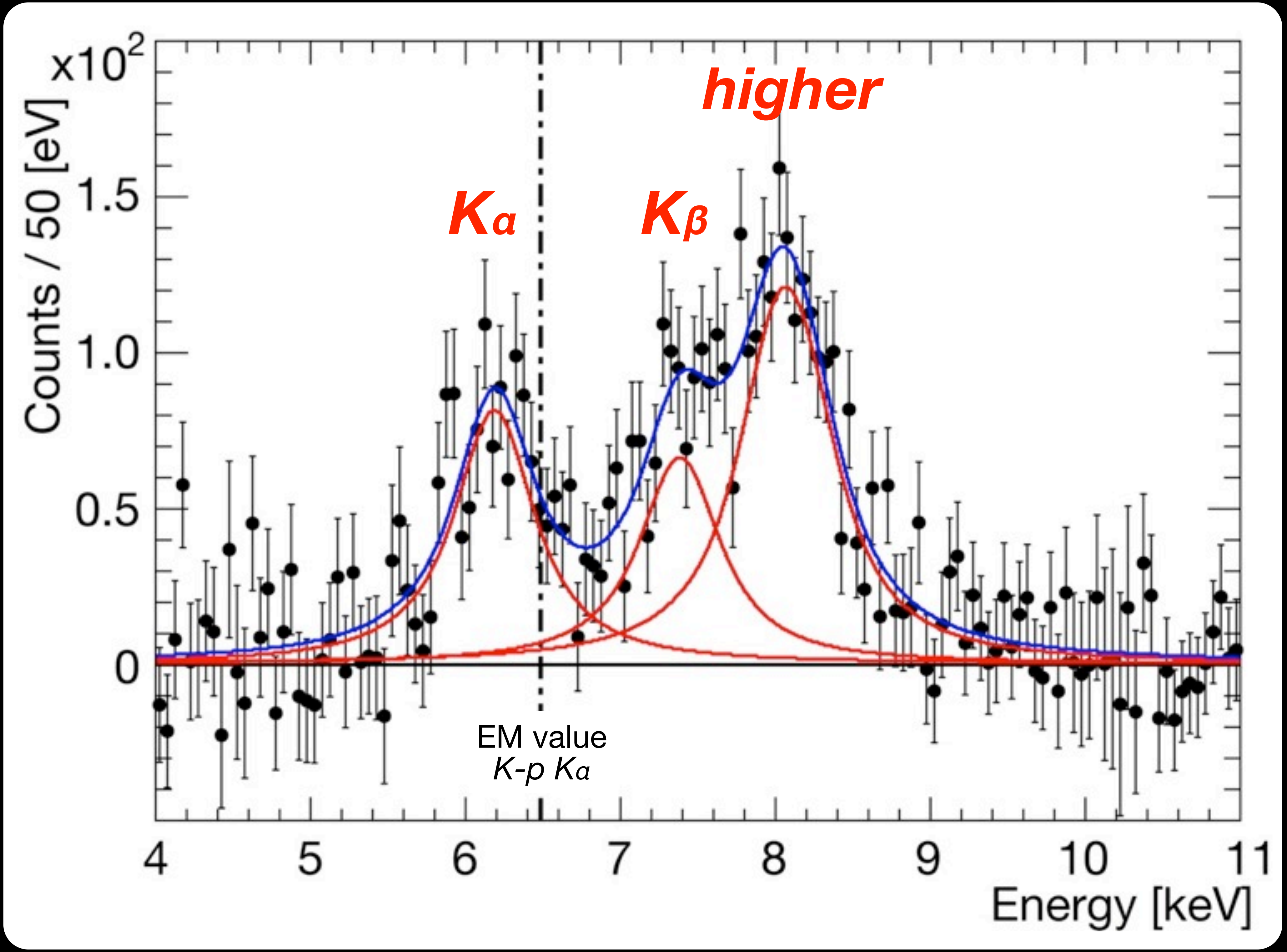
~ 1/10 yields

Kaonic Kapton X-rays

$C_{22}H_{10}O_5N_2$


Hydrogen
Deuterium
simultaneous fit
x10^2
Counts / 50 [eV]
EM value
K-p Kα
Kaonic hydrogen
Kα
Kβ
higher
Ti Kα
Ti Kβ
KC65
KO76
KN65
Cu
KC75
KO65
KC54
KAl87
Background estimation
Energy [keV]
4
5
6
7
8
9
10
11
0
2
4
6
8
10
12

Residuals of K-p x-ray spectrum after subtraction of fitted background



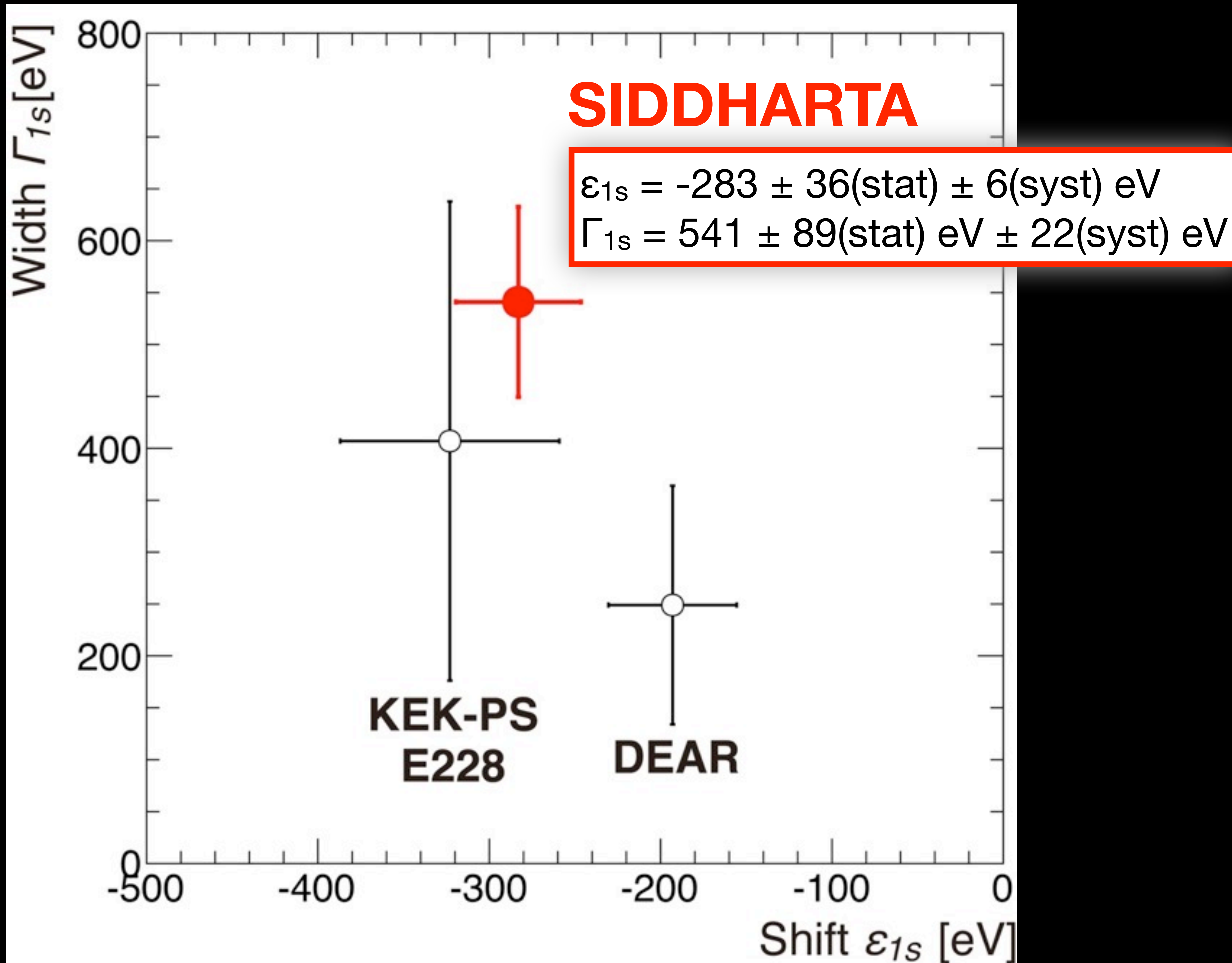
Systematic error of KH shift & width

- ✓ SDD rate dependence
- ✓ ADC linearity
- ✓ SDD response function **<- dominant for shift**
- ✓ Possible Kaonic deuterium x-rays
- ✓ Kaonic atom lines overlapped with KH x-rays

  (<-- including in the statistical error)
- ✓ Distribution of KH higher transitions
- ✓ Energy resolution (constant noise) **<- dominant for width**

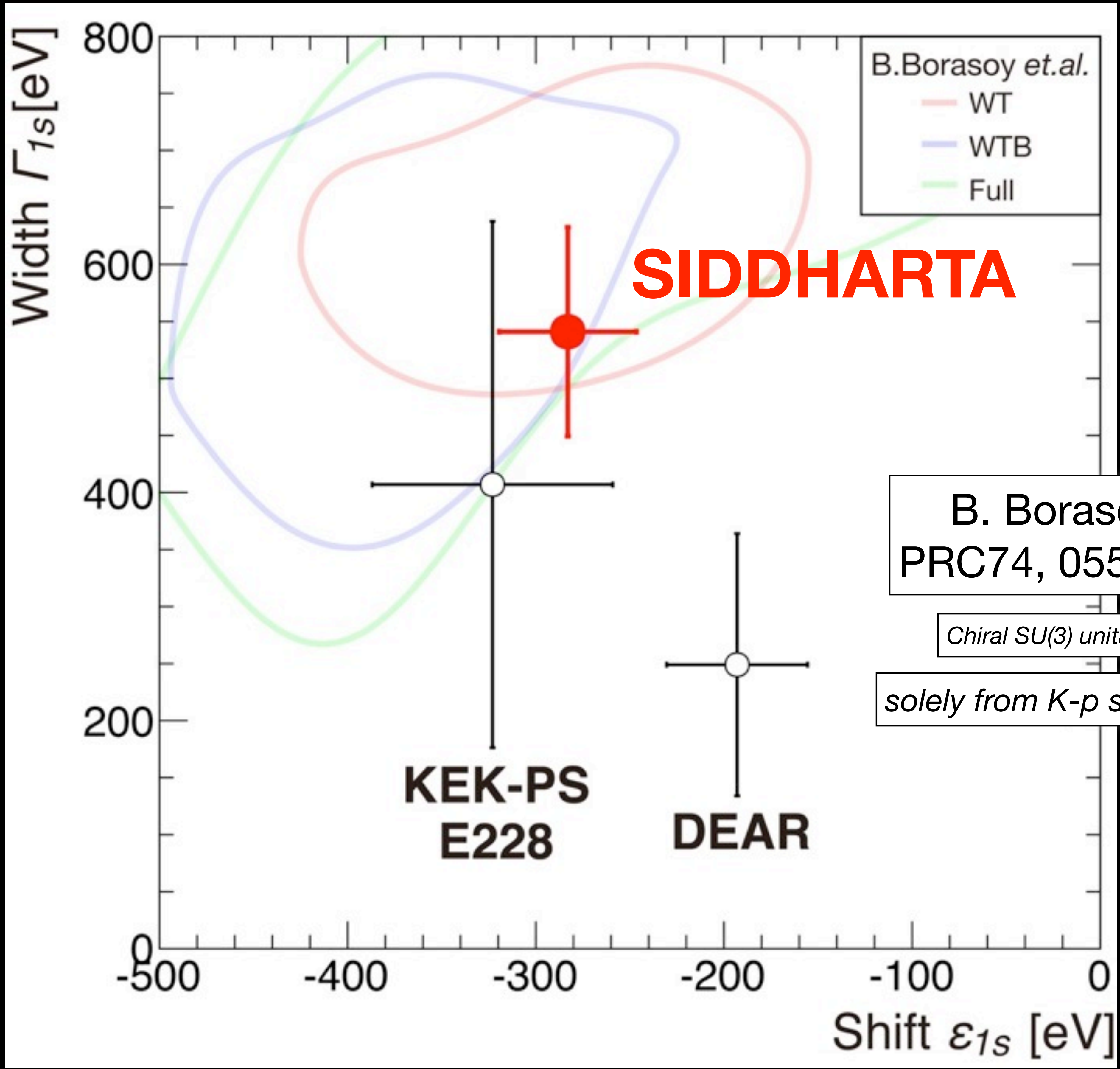
Result

Result



SIDDHARTA
ε1s = -283 ± 36(stat) ± 6(syst) eV
Γ1s = 541 ± 89(stat) eV ± 22(syst) eV
Width Γ1s[eV]
800
600
400
200
0
-500
-400
-300
-200
-100
0
Shift ε1s [eV]
KEK-PS
E228
DEAR

With a recent theoretical value

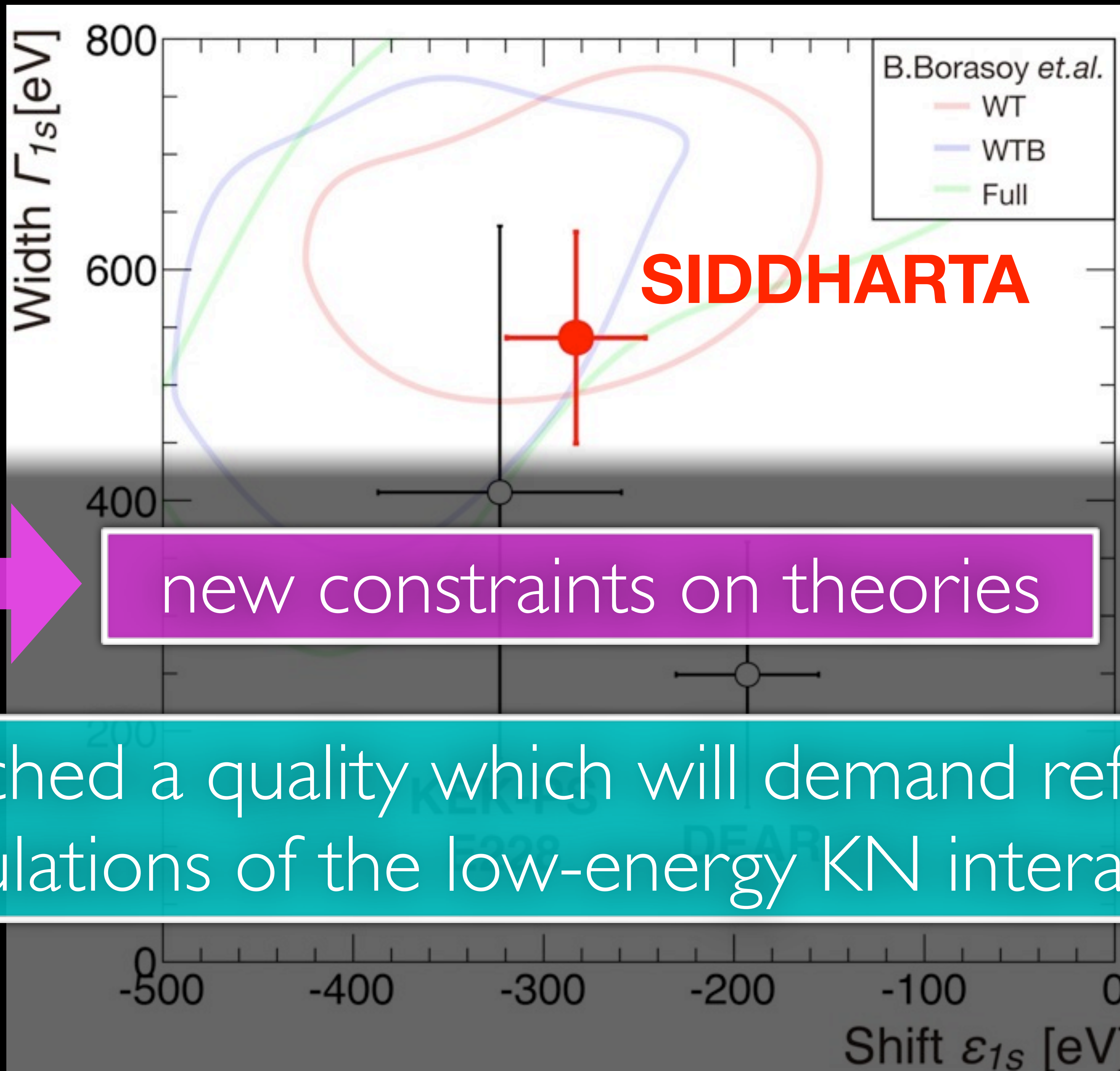


B. Borasoy et.al., PRC74, 055201 (2006)

Chiral SU(3) unitary approaches

solely from K-p scattering data !!

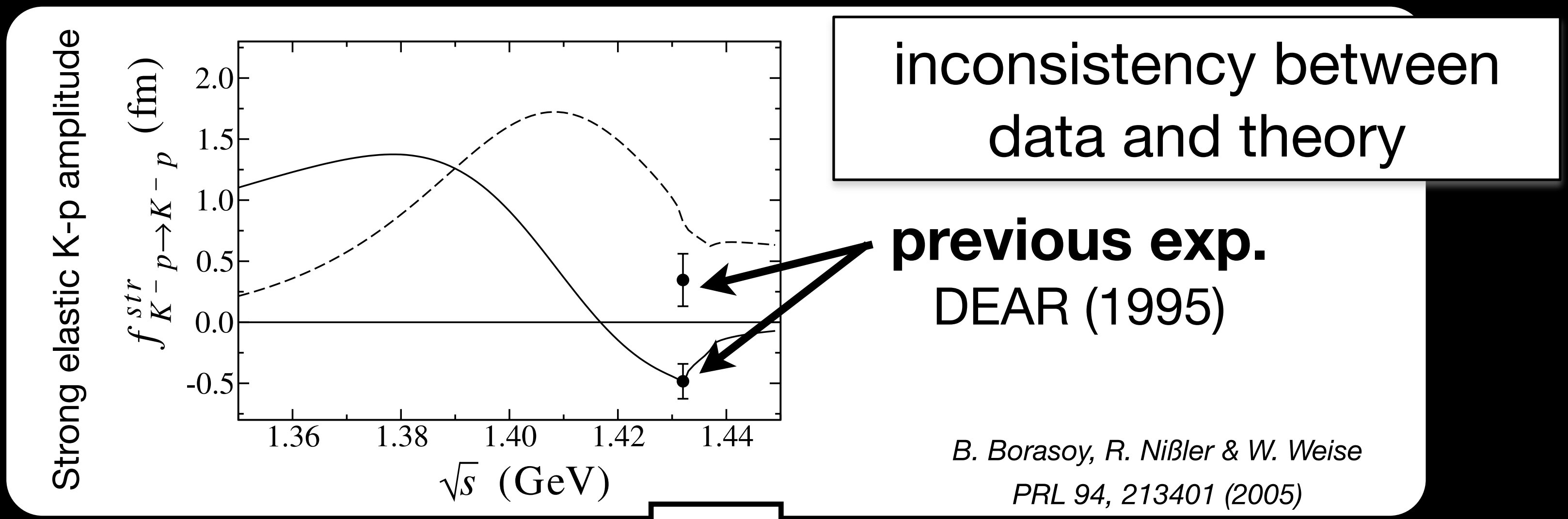
Conclusion

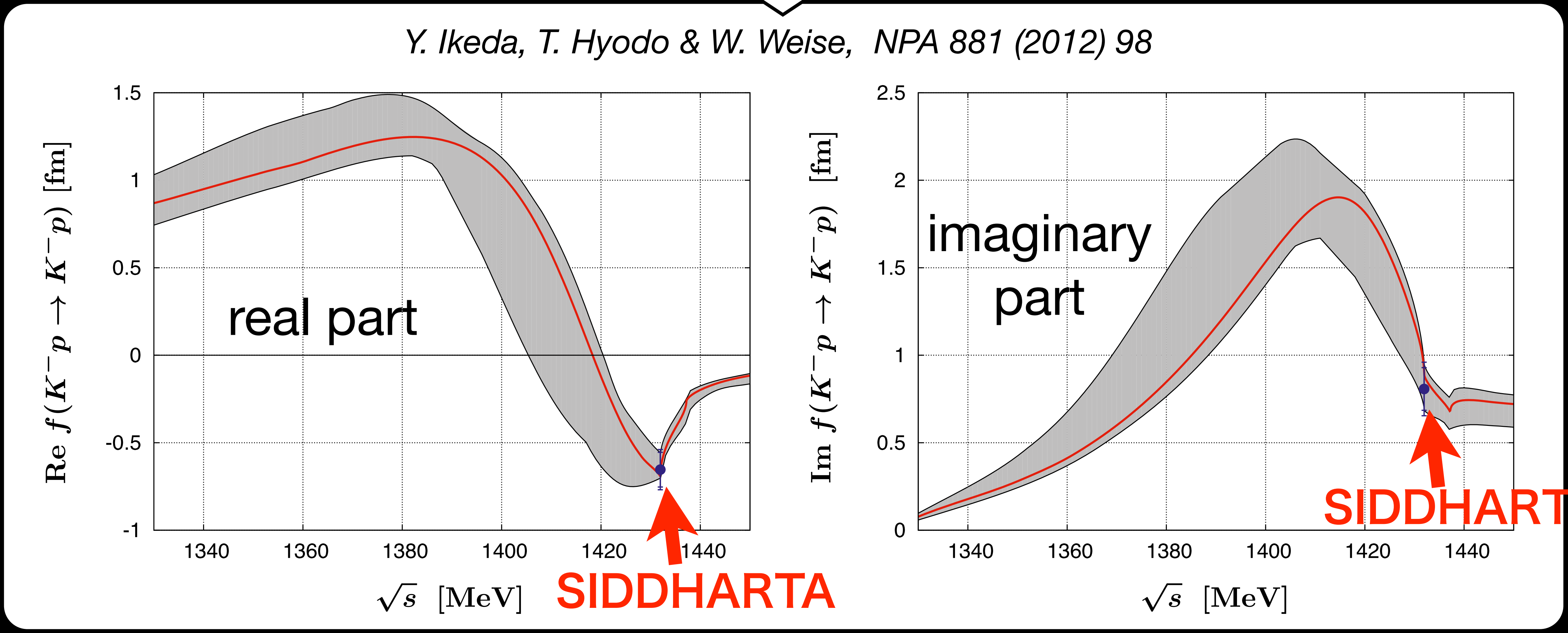


new constraints on theories

reached a quality which will demand refined calculations of the low-energy KN interaction

K-p amplitude





K-p scattering length by SIDDHARTA

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

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

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

$$a(K^- p) = -0.93 + i0.82 \text{ fm (TW)},$$
$$a(K^- p) = -0.94 + i0.85 \text{ fm (TWB)},$$
$$a(K^- p) = -0.70 + i0.89 \text{ fm (NLO)}.$$

now fully compatible

However ...

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

average of I=0 and I=1 components

Future experiment

Kaonic deuterium measurement

Now a precise KH data is available; however ...

$$a_{K^-p} = \frac{1}{2}[a_0 + a_1]$$

$$a_{K^-n} = a_1$$

impulse approximation term

larger than leading term

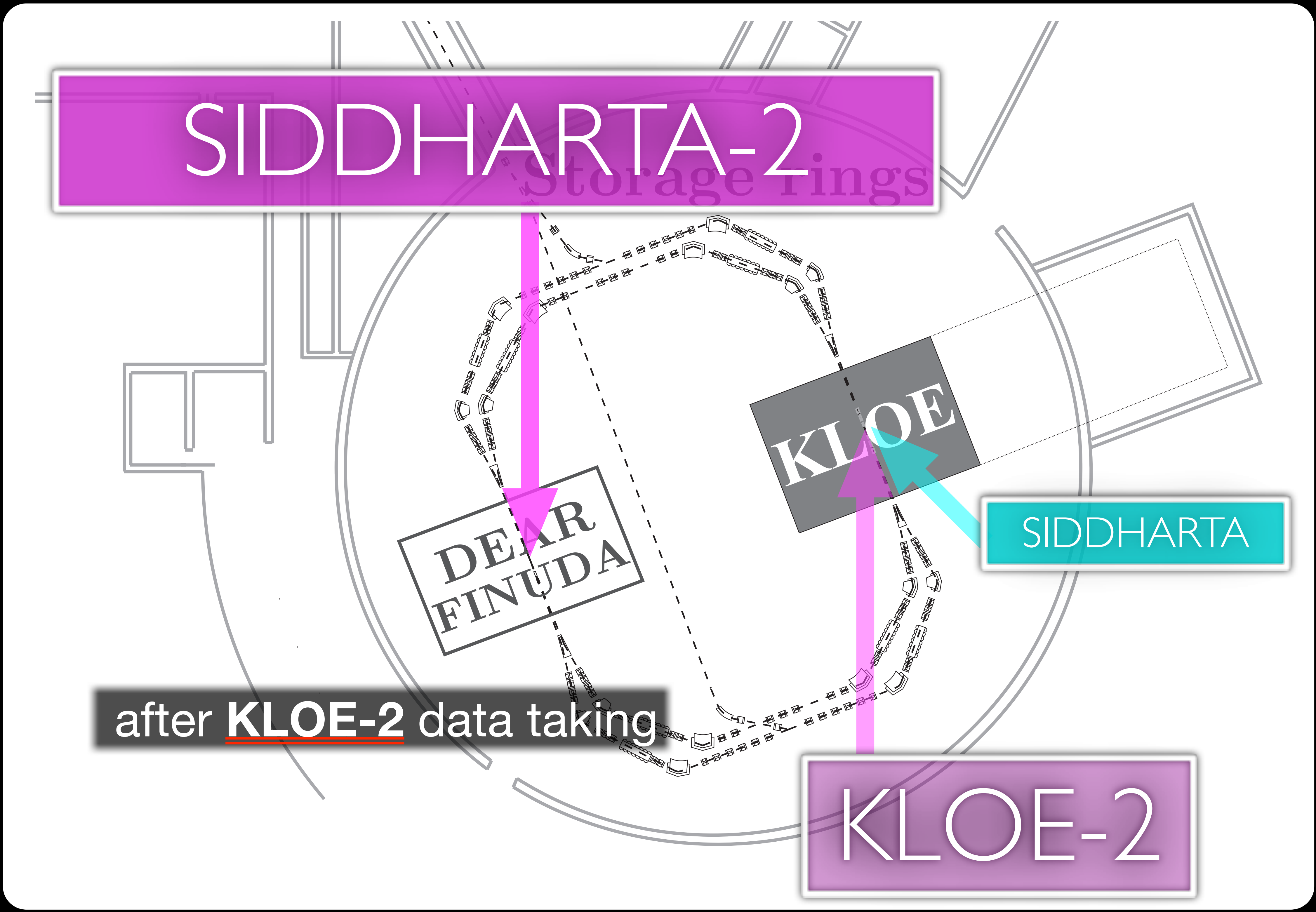
$$a_{K^-d} = \frac{4[m_N + m_K]}{[2m_N + m_K]} \cdot a^{(0)} + C$$

$$a^{(0)} = \frac{1}{2}[a_{K^-p} + a_{K^-n}] = \frac{1}{4}[a_0 + 3a_1]$$

⇨ **SIDDHARTA-2**

with one order better S/N

proposed new operation scheme



Feature

- Larger acceptance (changing geometry)
- Higher target gas density (new cryostat system)
- Discrimination of K+ (new detector)
- Active shielding (anti-coincidence counter)
- Better SDD time resolution (lower temperature)

Summary

Summary

✓ measured Kaonic x-ray spectra with several gas targets Z=1&2 :

- K-p : provided the most precise values (PLB704(2011)133)

$$\varepsilon_{1s} = -283 \pm 36(\text{stat}) \pm 6(\text{syst})\ \text{eV}$$
$$\Gamma_{1s} = 541 \pm 89(\text{stat})\ \text{eV} \pm 22(\text{syst})\ \text{eV}$$

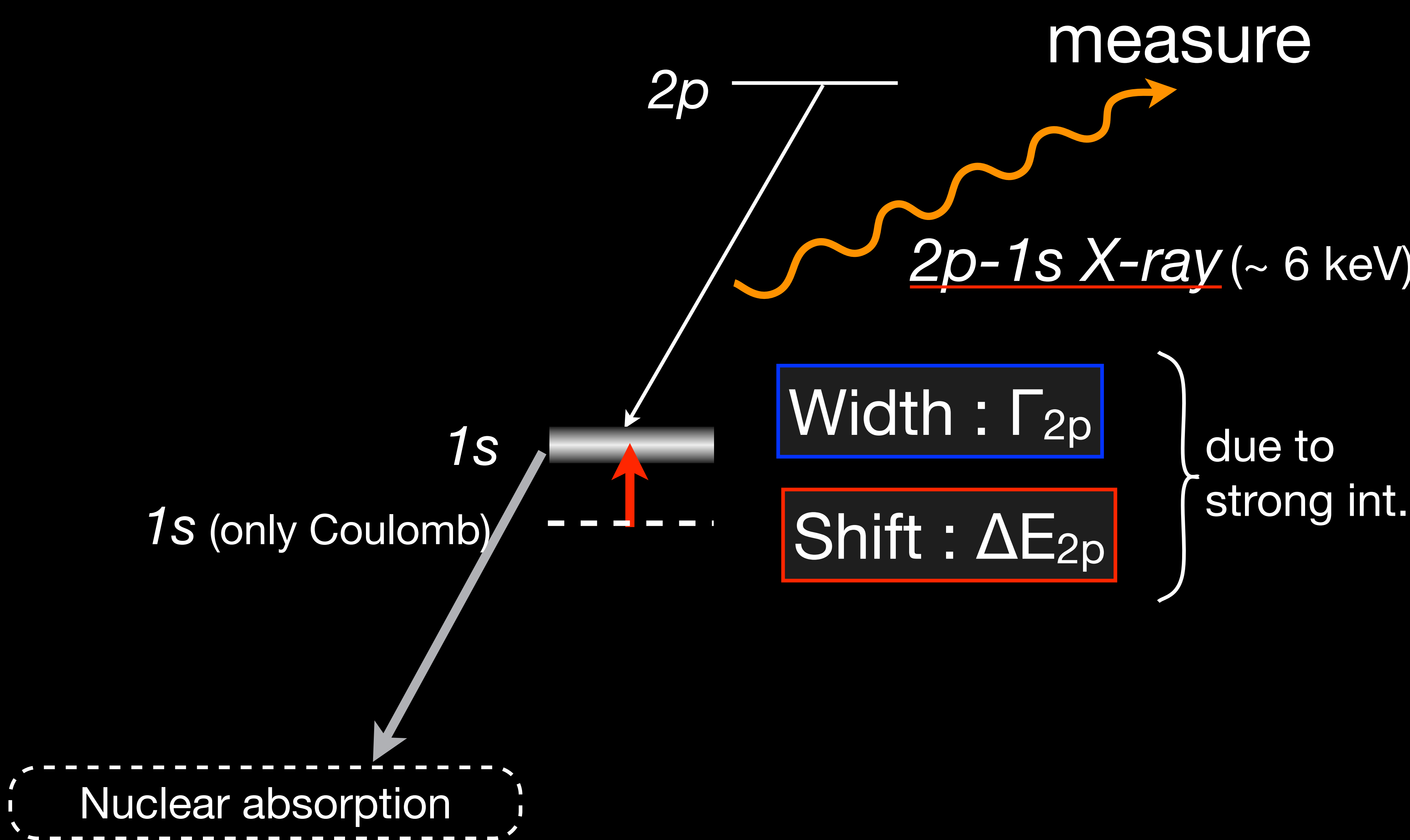
- K-d : first-time "exploratory" measurement -> small signal (large width)
- K-^{3}He (L-series) : first-time measurement (PLB697(2011)199)
- K-4He (L-series) : measured in gaseous target for the first time (PLB681(2009)310)

✓ future experiment : Kaonic deuterium @ SIDDHARTA-2

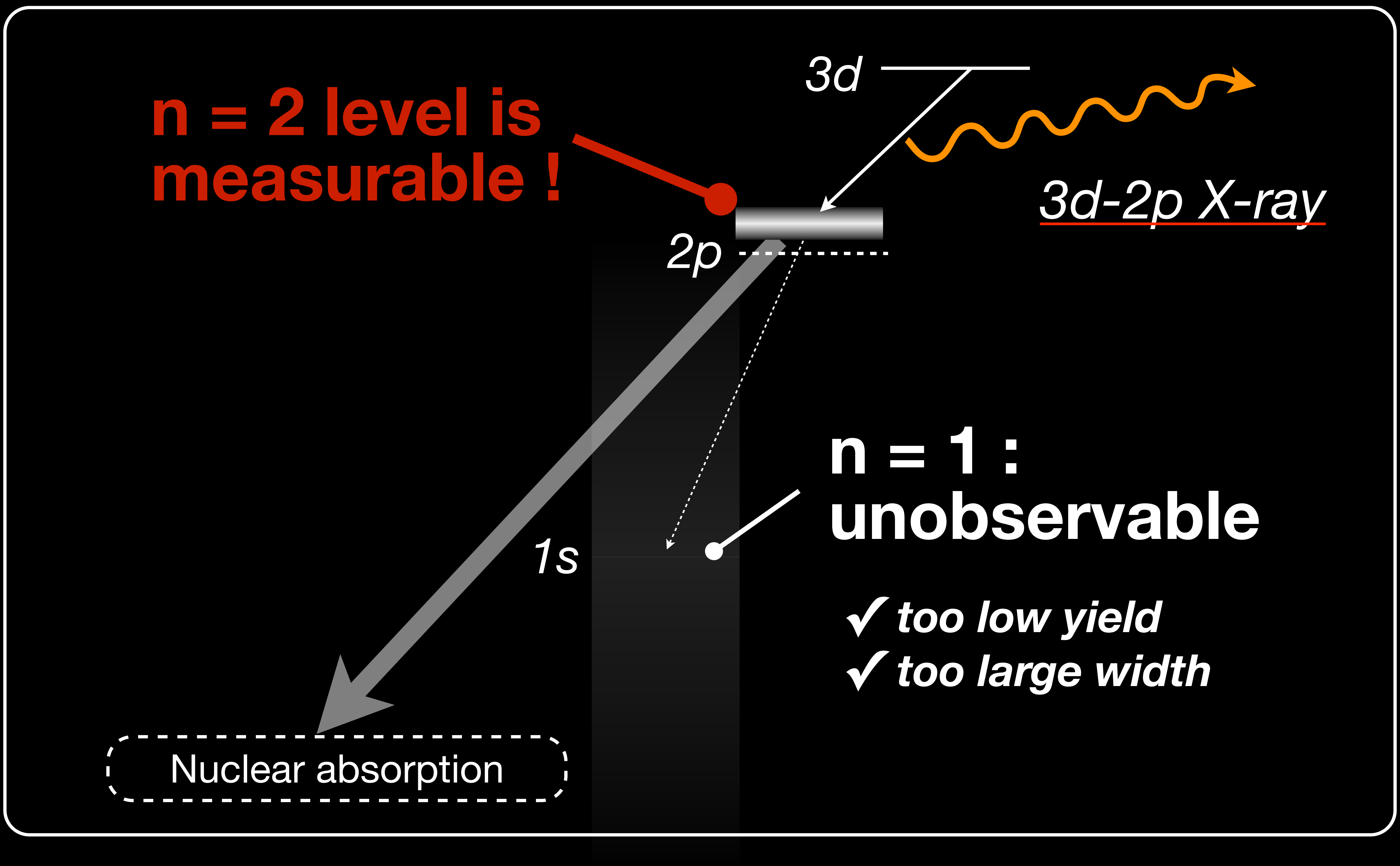
Kaonic helium

Kaonic helium

in the case of Kaonic hydrogen



Kaonic helium



Z=1

K-hydrogen

2p-1s x-ray

~ 6 keV

Z=2

K-helium

3d-2p x-ray

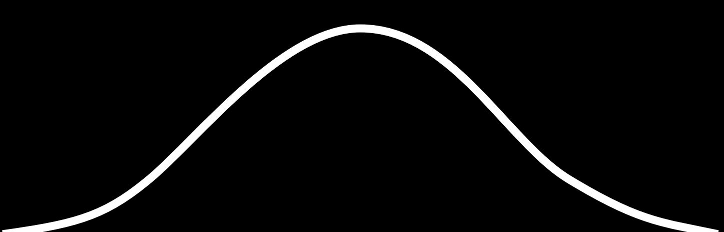
~ 6 keV

Z=1

K-hydrogen

2p-1s
x-ray

Large



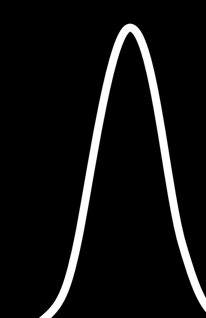
Width

Z=2

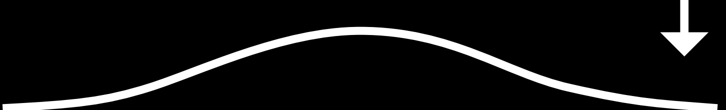
K-helium

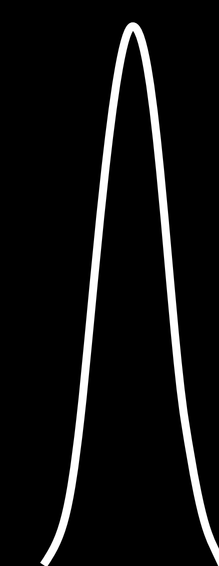
3d-2p
x-ray

Small

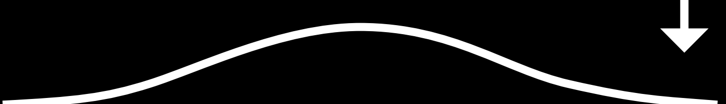


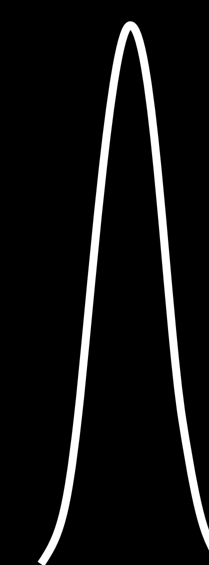
Z=1		Z=2
K-hydrogen		**K-helium**
2p-1s x-ray		3d-2p x-ray
Large	**Width**	Small
Low	**Yield**	High
↓		↓





Z=1		Z=2
K-hydrogen		**K-helium**
2p-1s x-ray		3d-2p x-ray
Large	**Width**	Small
Low	**Yield**	High
↓		↓
High stat. Improved S/N		**High precision**





Kaonic helium puzzle ...

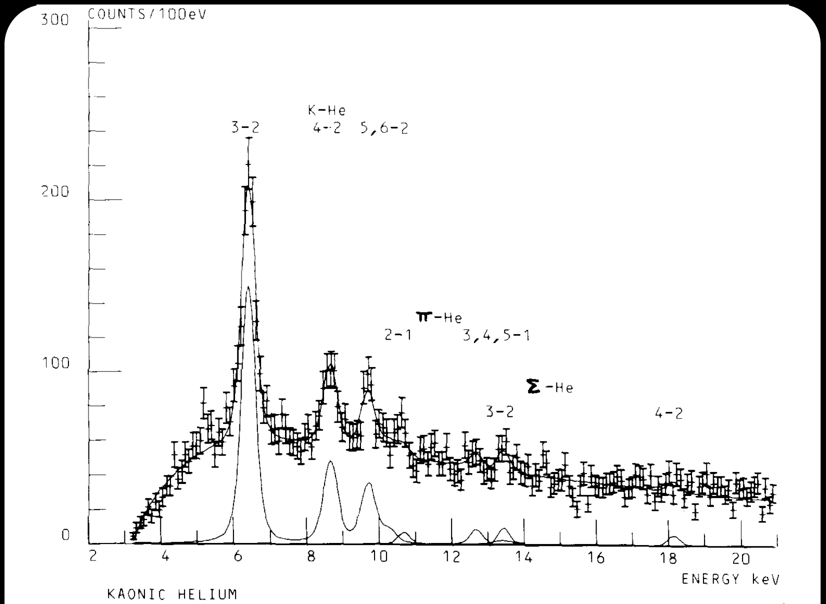
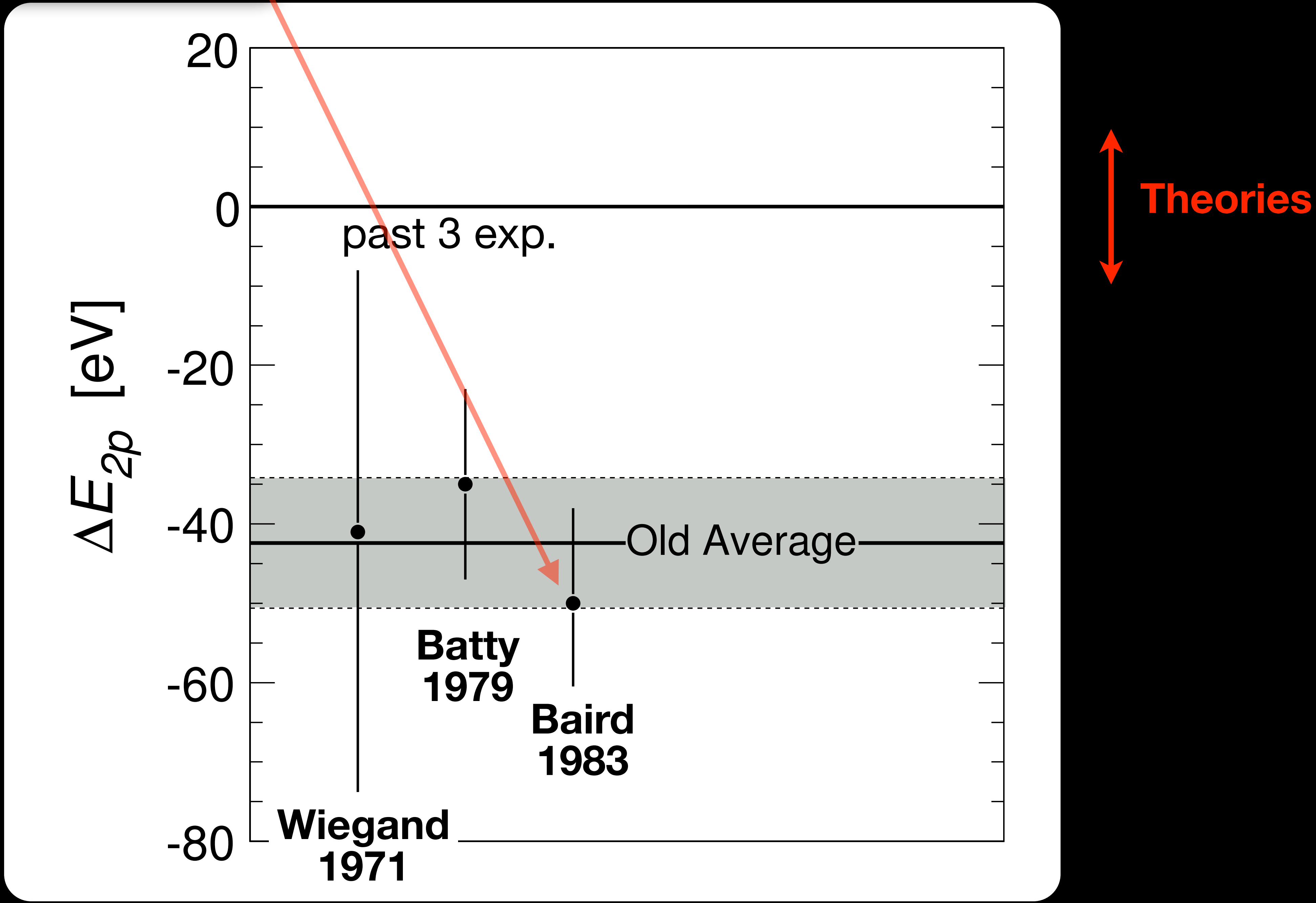


Fig. 3. X-ray spectrum measured with $(2.3 \pm 1.2) \times 10^7$ kaons stopping in liquid helium.



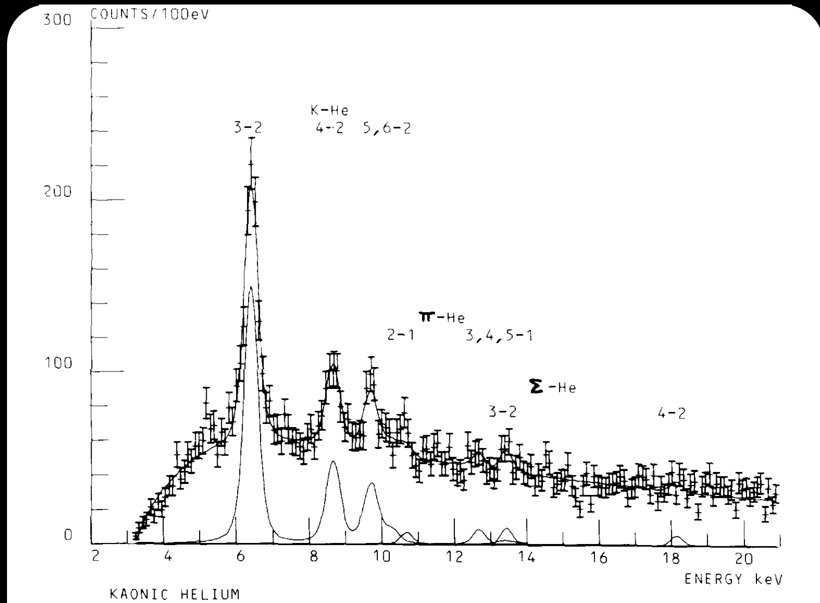
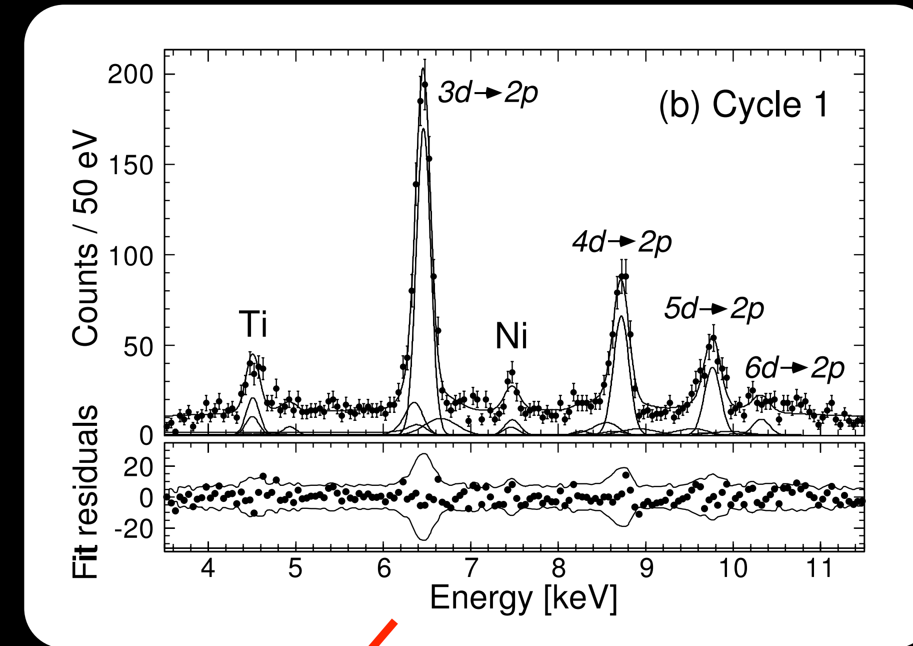
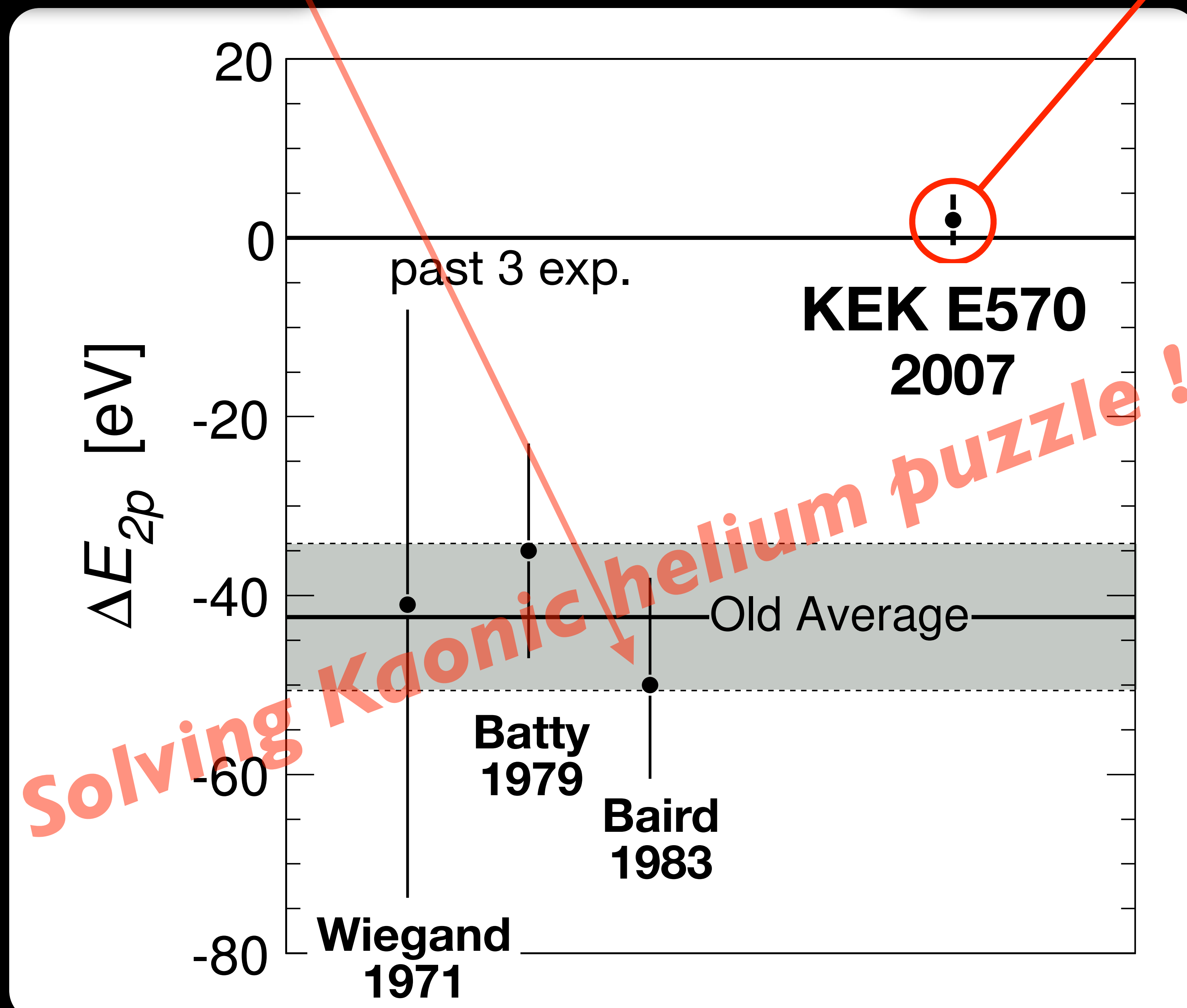


Fig. 3. X-ray spectrum measured with $(2.3 \pm 1.2) \times 10^7$ kaons stopping in liquid helium.

1) Silicon drift detector
2) In-beam energy calib.
3) Low background
(by tracking the secondary particles)



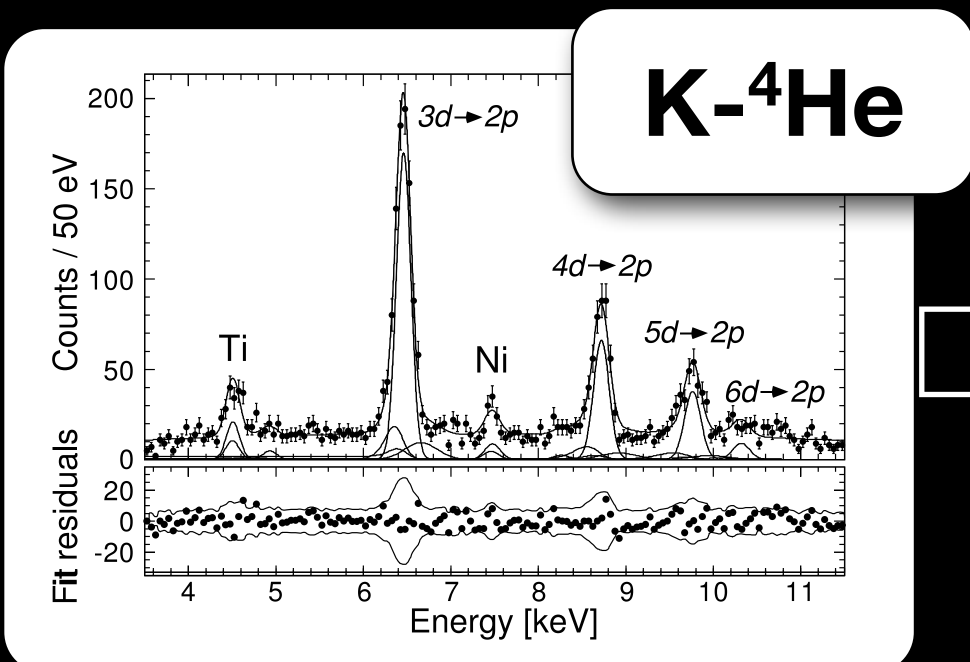


Theories

S. Okada et al.,
PLB 653(2007)387

KEK E570

using 8 SDDs

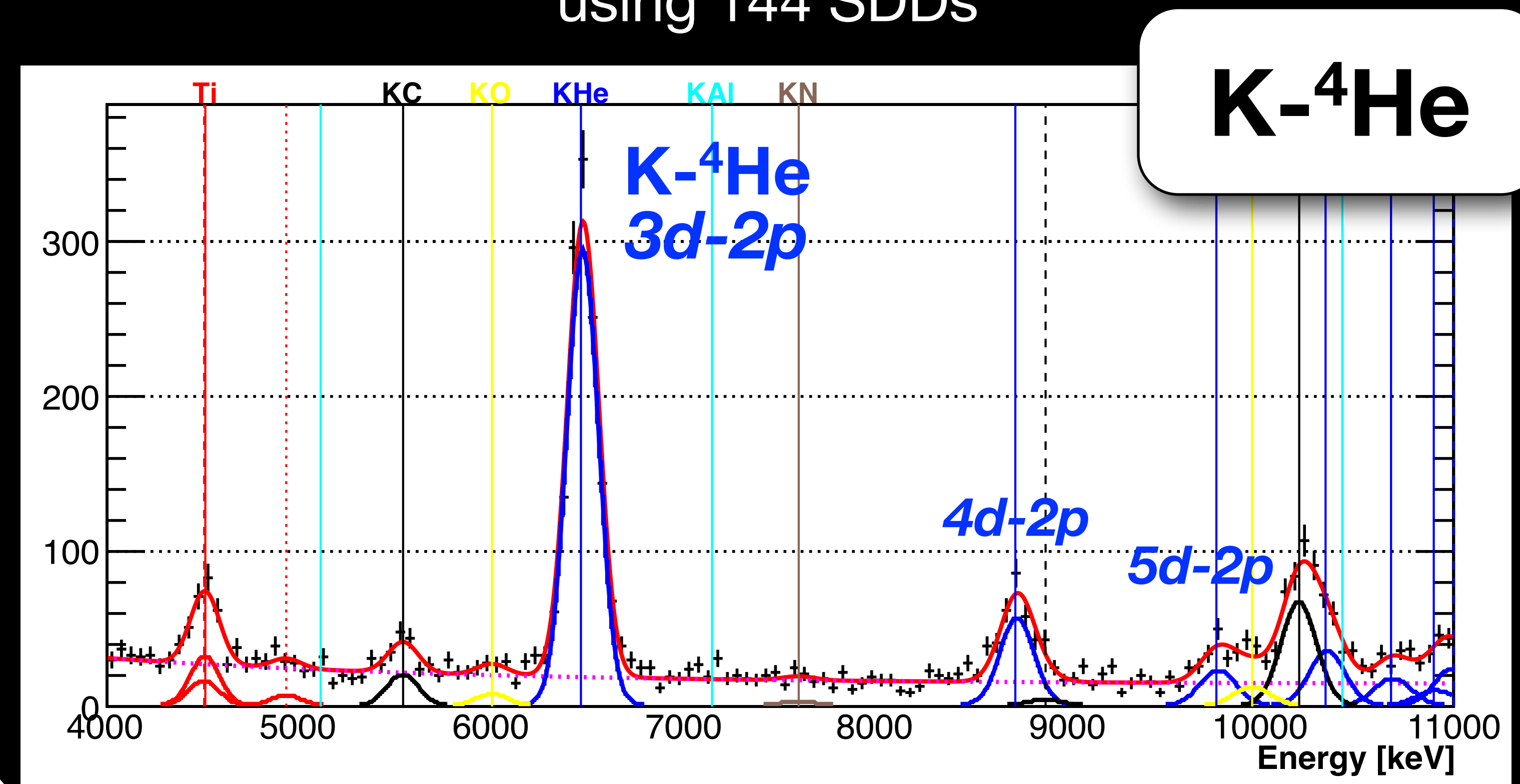


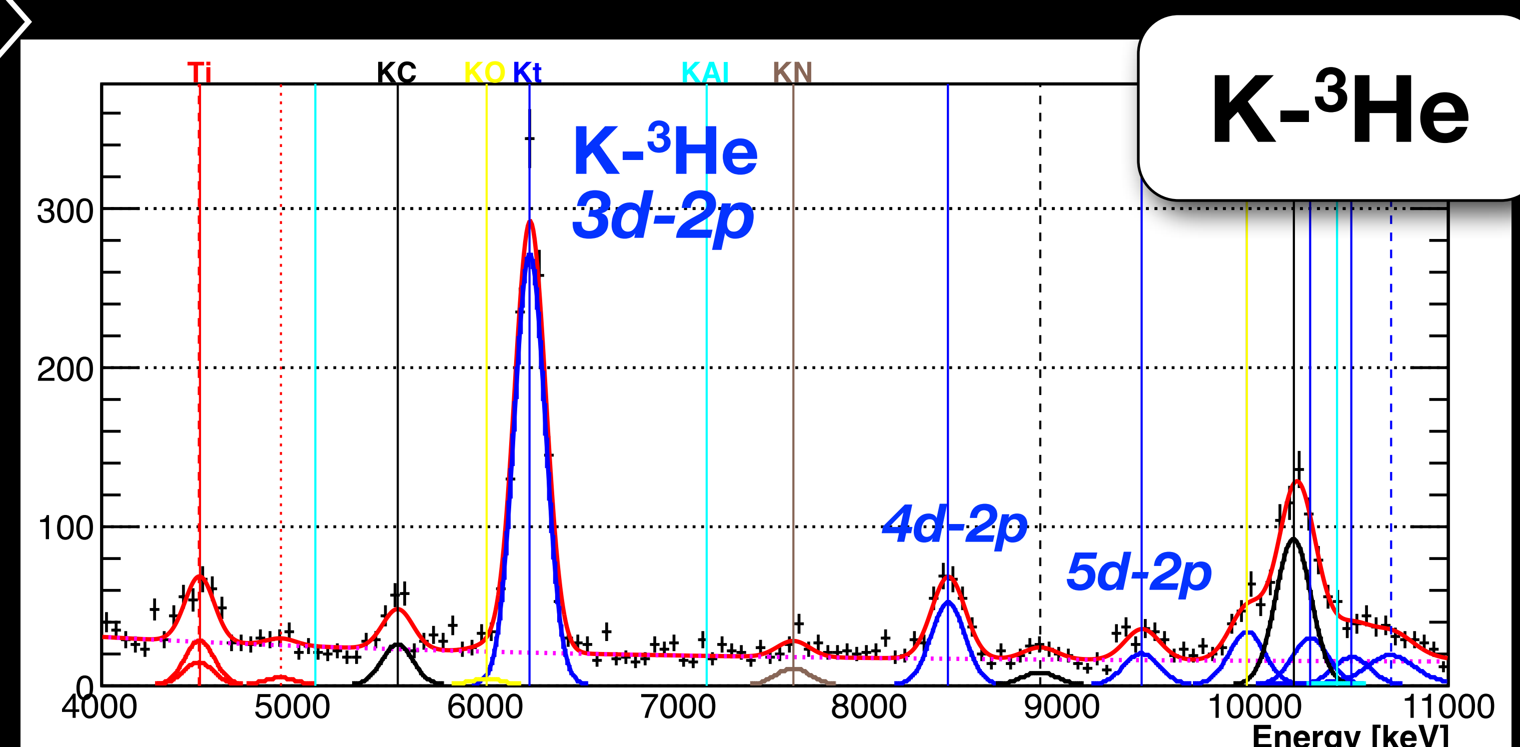
accumulated data

~ 1 month

SIDDHARTA

using 144 SDDs



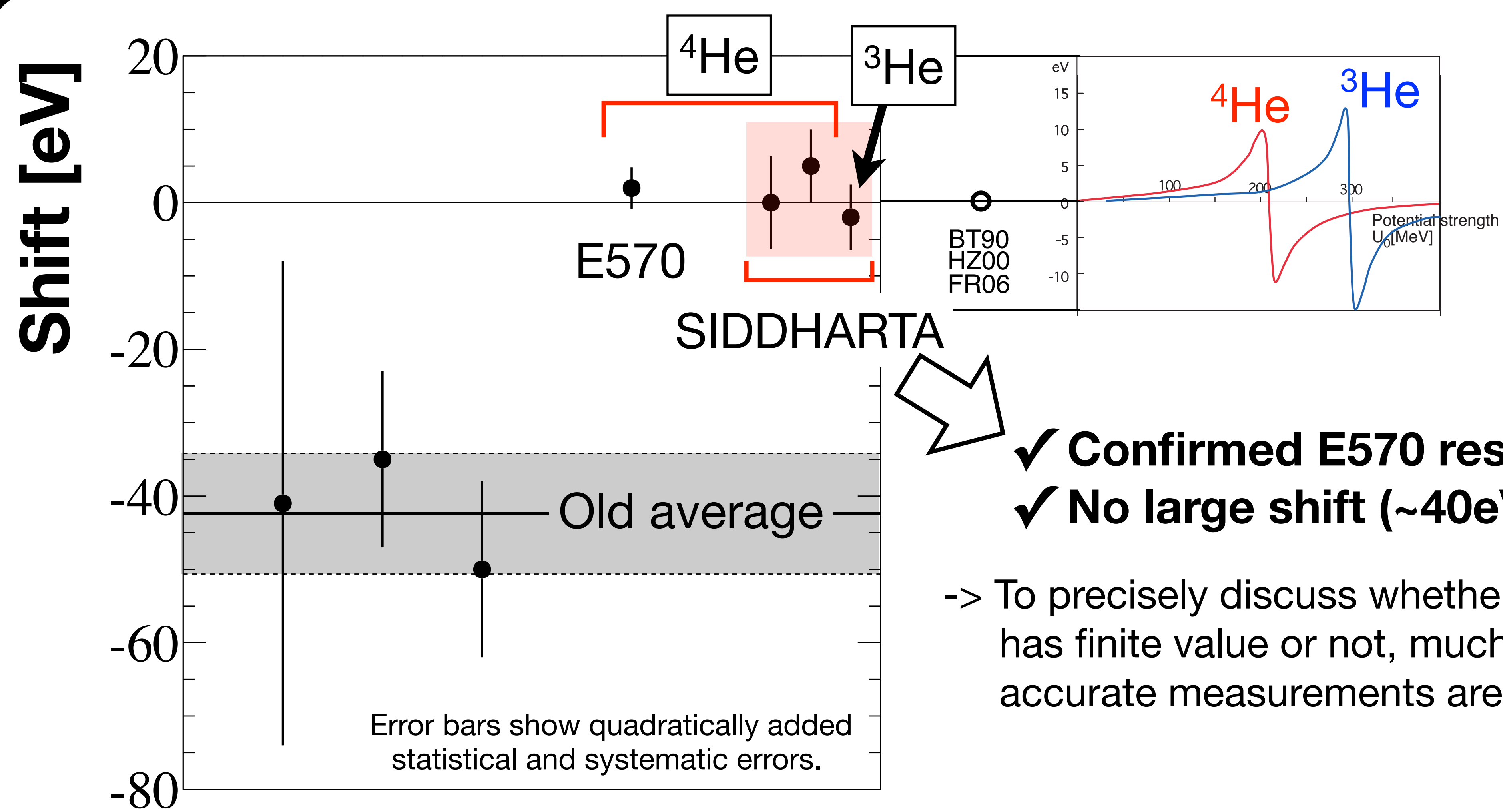


accumulating data

a few days !

Summary of Kaonic helium results

			Shift [eV]	Publication
KEK-E570	K^4He		+2 ± 2(stat) ± 2(syst)	PLB 653(2007)387
SIDDHARTA	K^4He	a part of dataset	0 ± 6(stat) ± 2(syst)	PLB 681(2009)310
		increased statistics	+5 ± 3(stat) ± 4(syst)	*Preliminary* (*PLB 697(2011)199*)
	K^3He		-2 ± 2(stat) ± 4(syst)	PLB 697(2011)199



✓ **Confirmed E570 result**

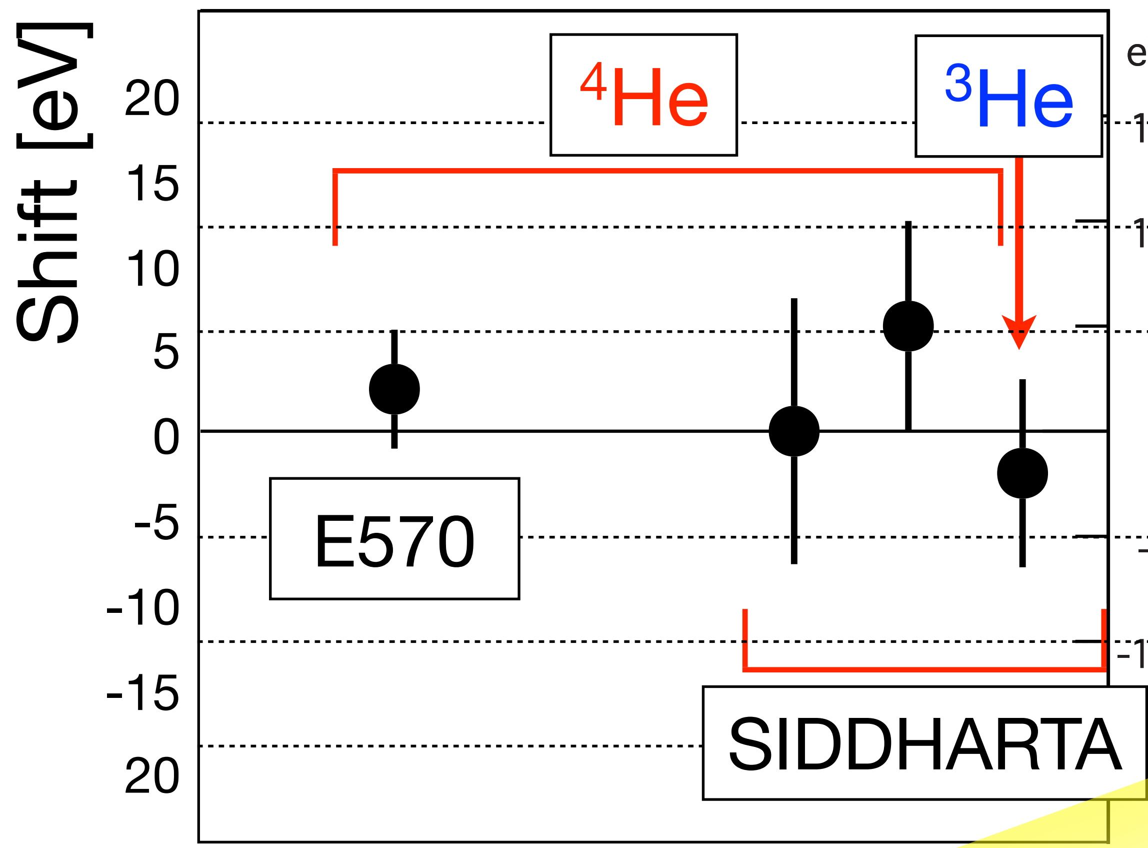
✓ **No large shift (~40eV) any more.**

-> To precisely discuss whether the shift has finite value or not, much more accurate measurements are necessary

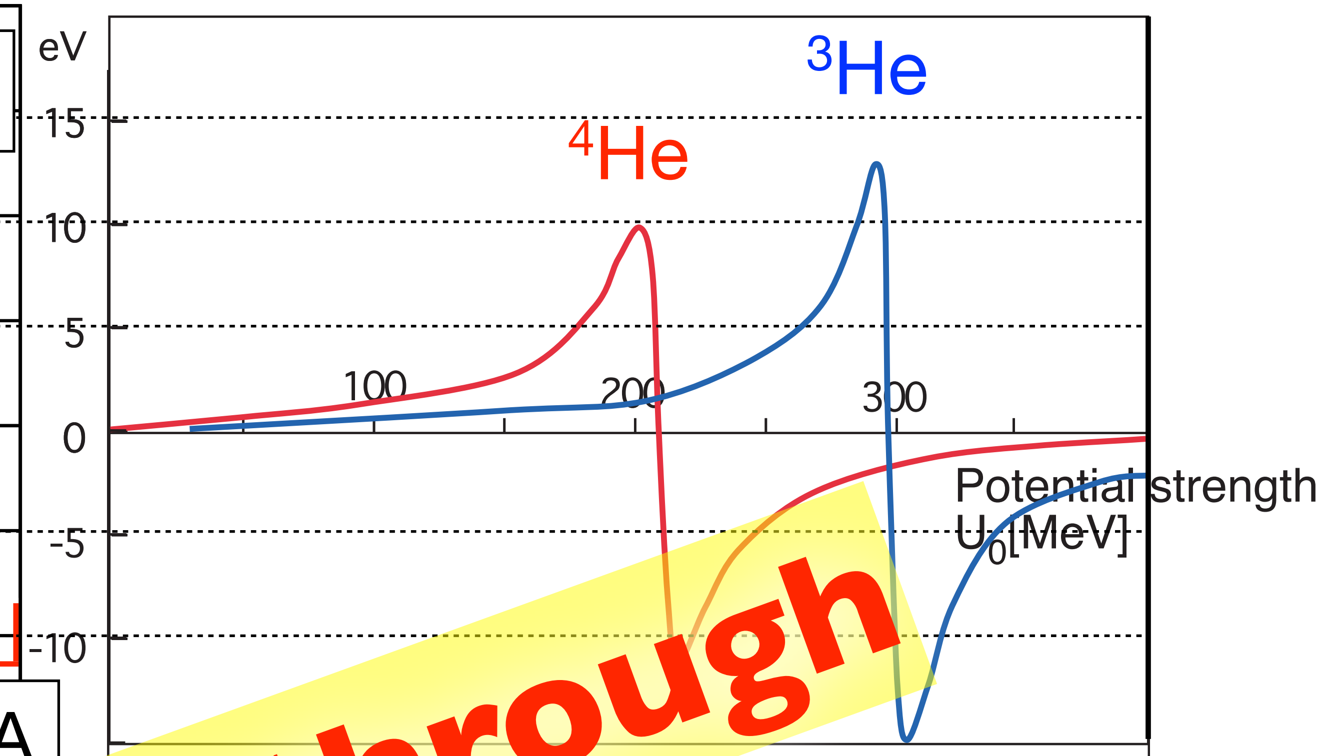
Summary of Kaonic helium results

		Shift [eV]	Publication

Experiments



Theories



need a breakthrough

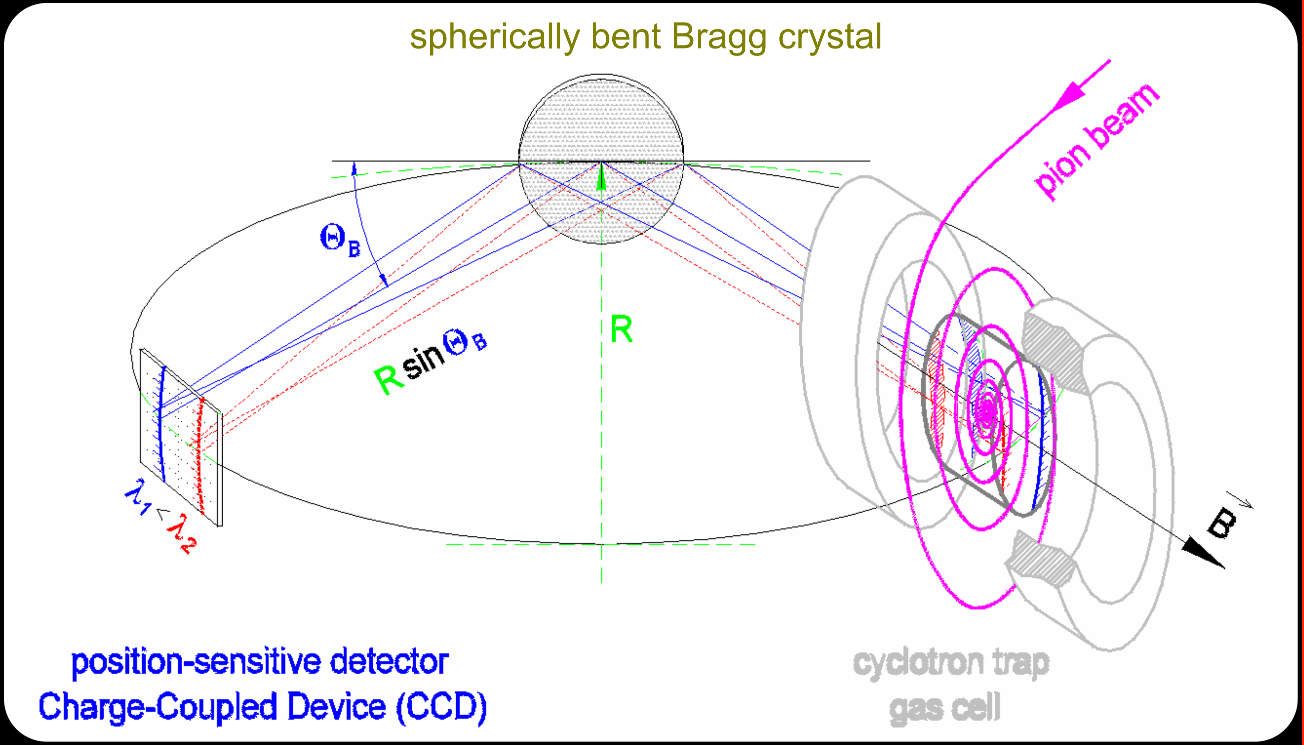
-> To precisely discuss whether the shift has finite value or not, much more accurate measurements are necessary

Error bars show quadratically added statistical and systematic errors.

Next-generation K-atom exp.

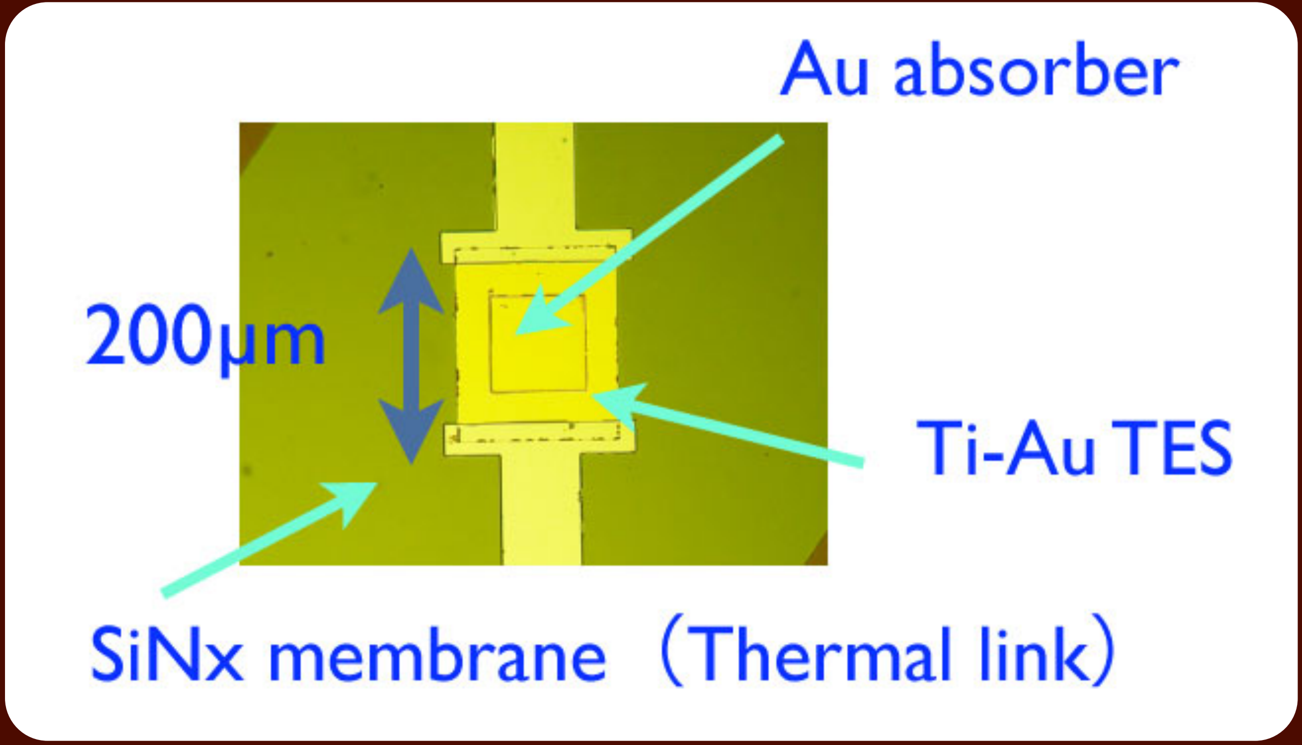
Next-generation K-atom exp.

1. Crystal spectrometer



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

2. Microcalorimeter



X-ray observation satellite (ASTRO-H)

-> small acceptance

Why Microcalorimeter ?

1. Possibility of large acceptance

- Multi device (Array)
- Large absorber

2. High mobility

available only short term of occupancy (at J-PARC, DAΦNE etc.)

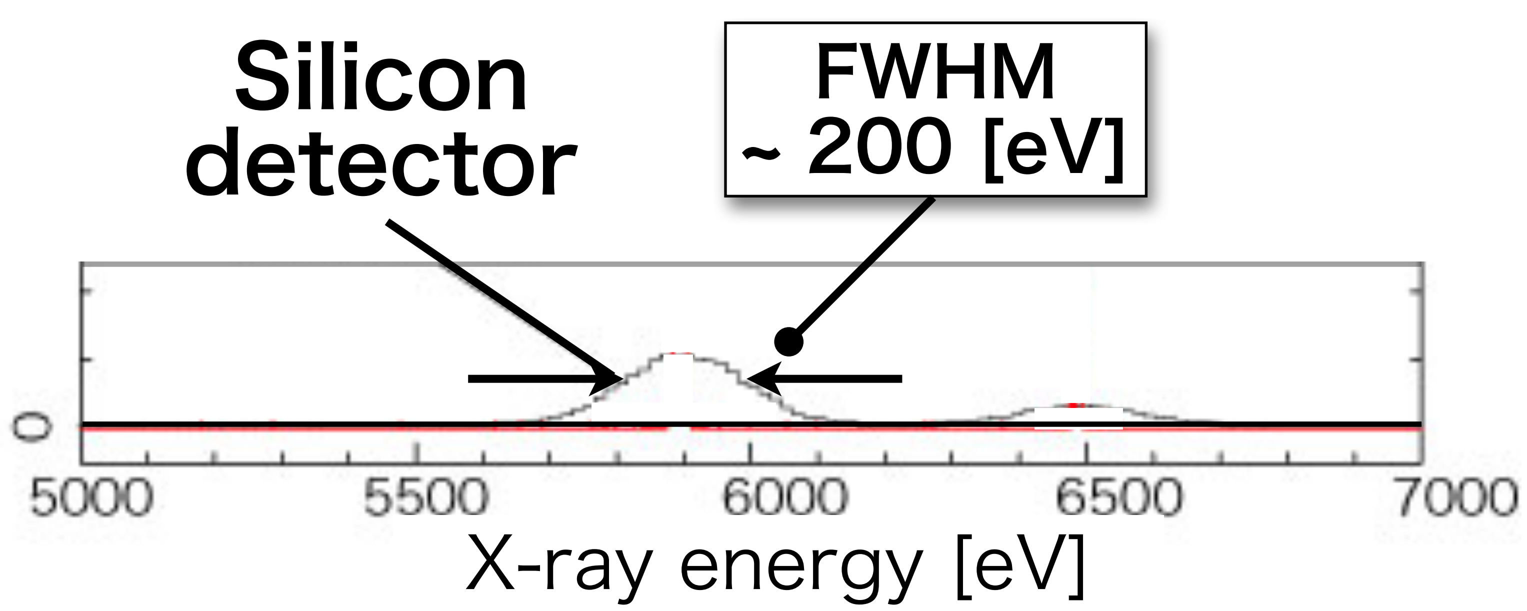
Energy resolution

@ 6 keV (FWHM)

difficult to determine

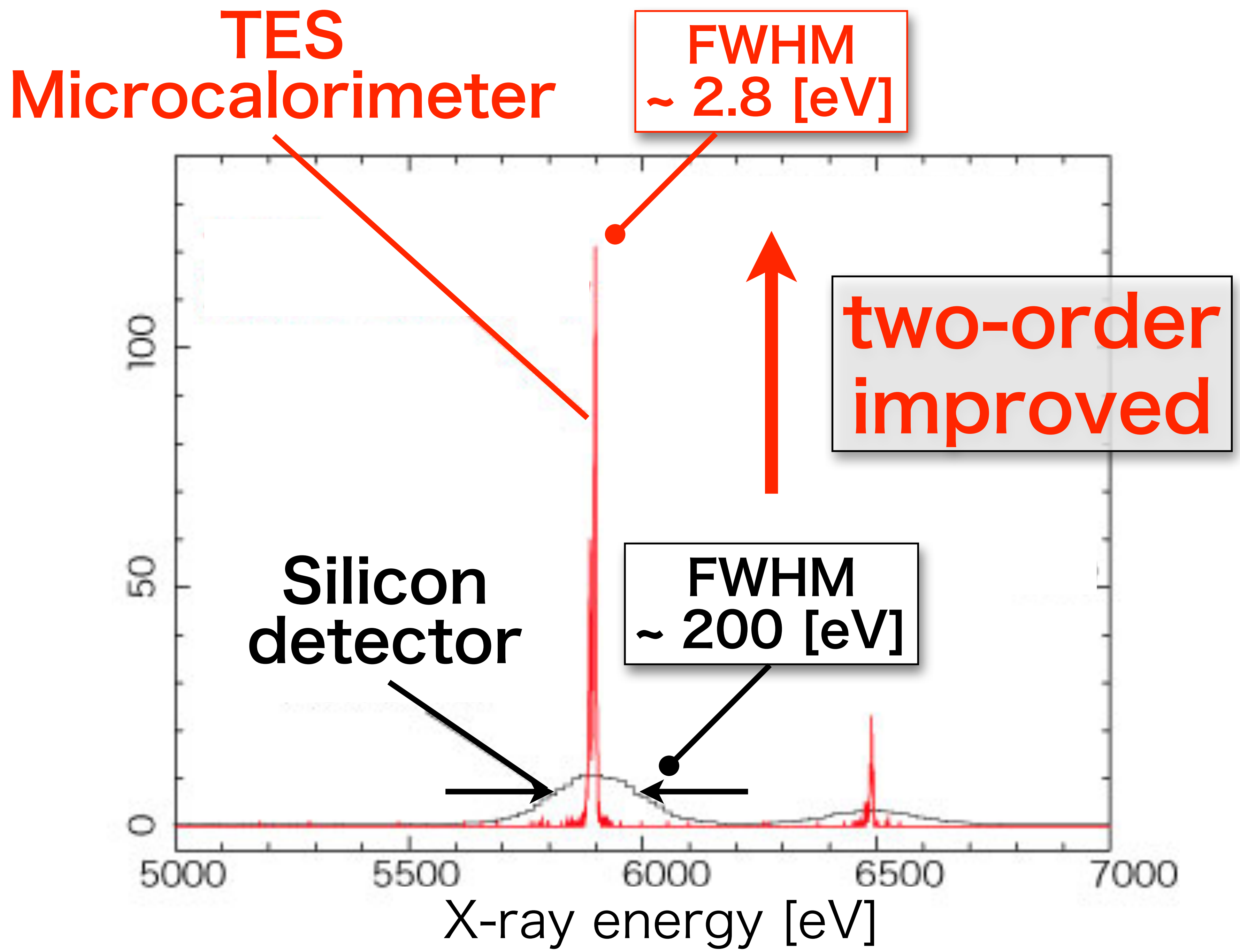
the energy and width

with ~ eV order



Energy resolution

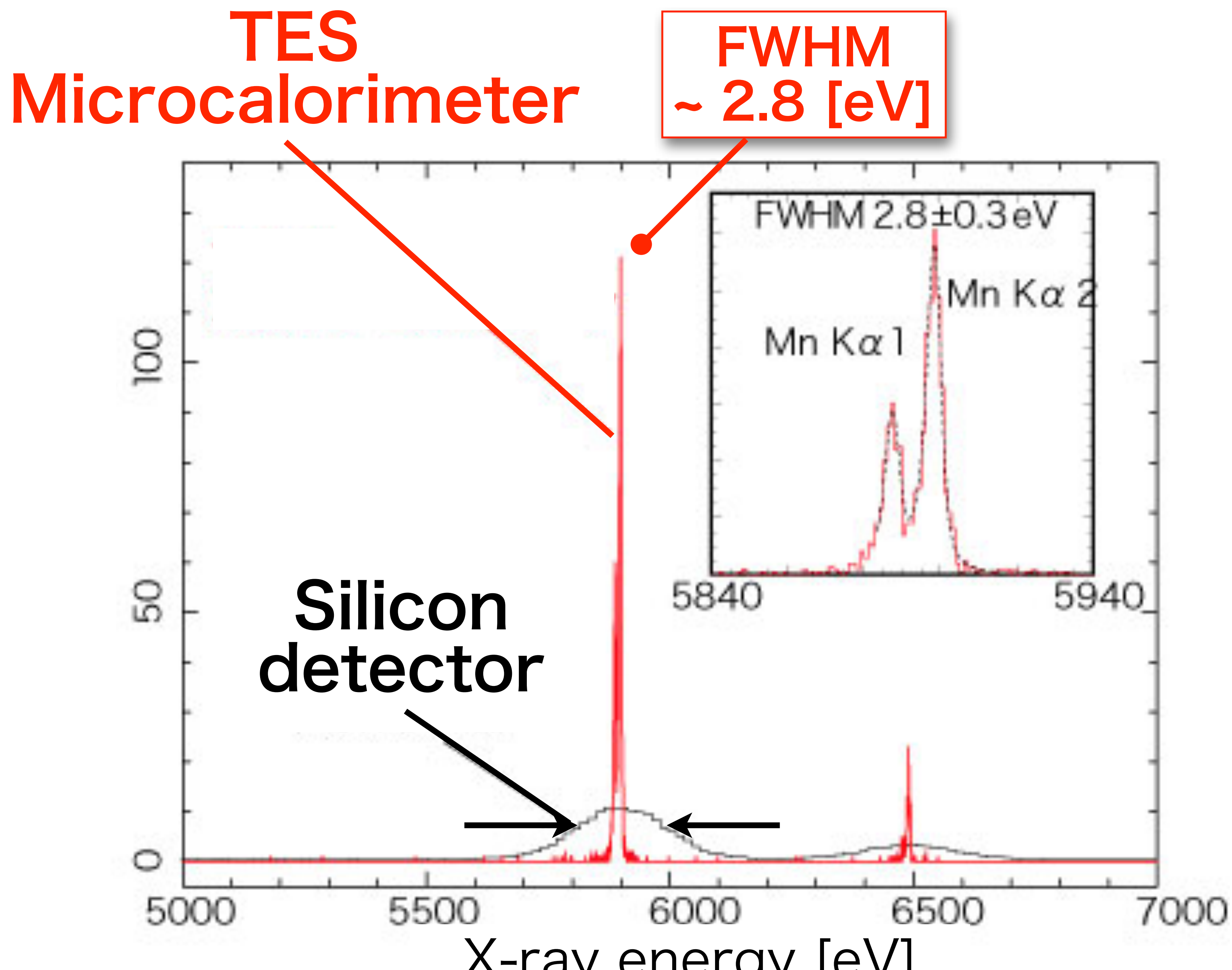
@ 6 keV (FWHM)



Ref : http://www.astro.isas.jaxa.jp/~tes/

Energy resolution

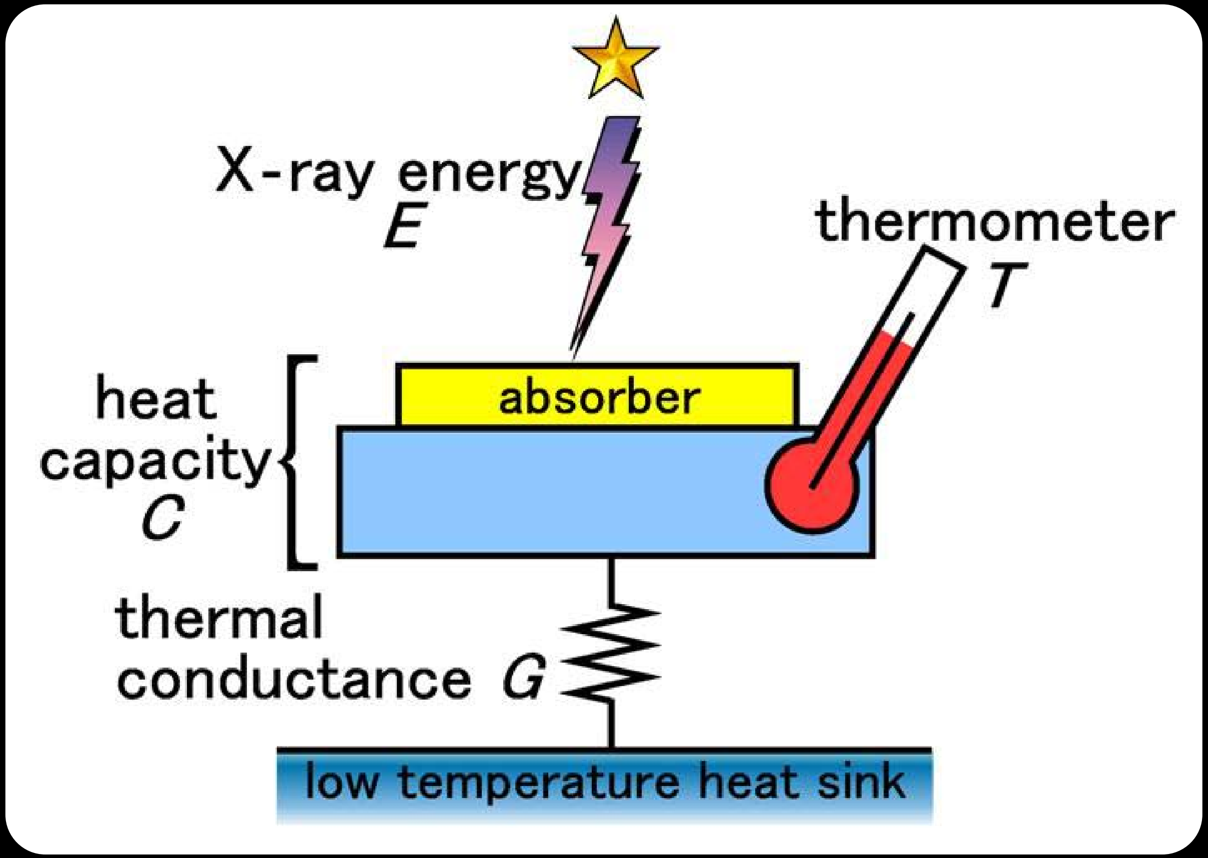
@ 6 keV (FWHM)



Ref : http://www.astro.isas.jaxa.jp/~tes/

X-ray microcalorimeter

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

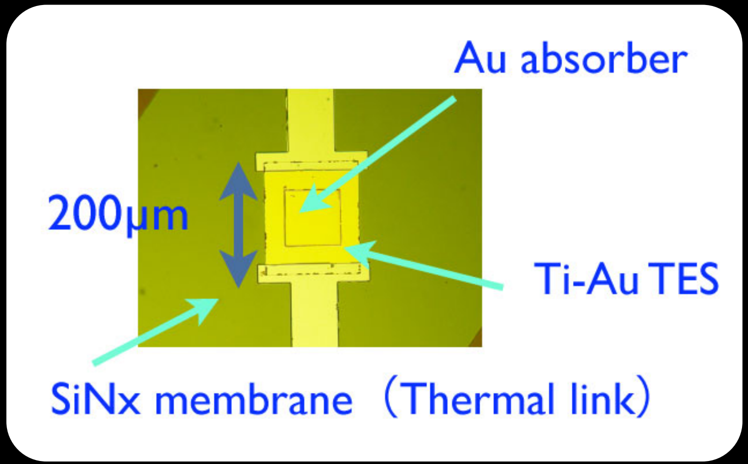


Temperature rise
= E / C (~ 1 mK)

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

Absorber size : e.g.,
0.2 x 0.2 [mm^2] ...

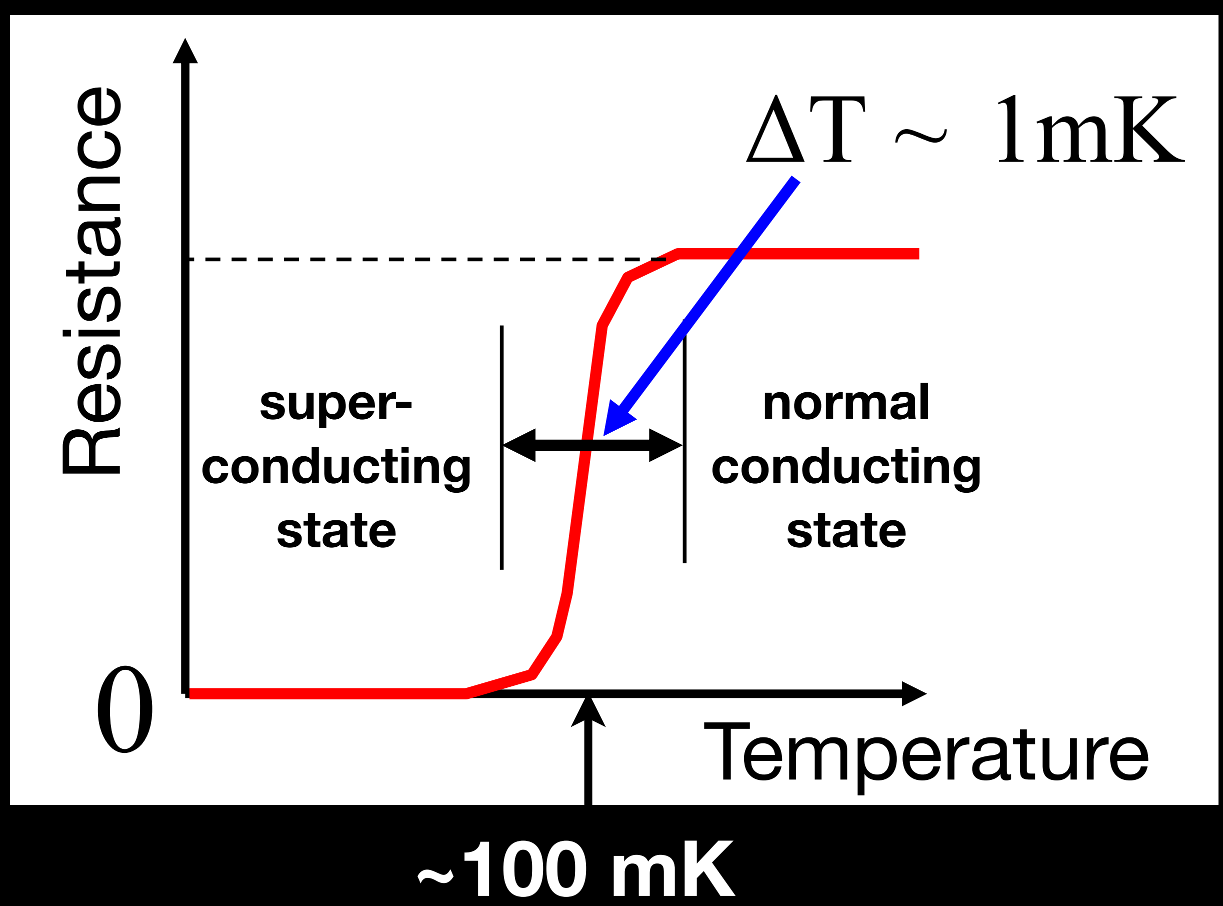
e.g., Absorber : Au (0.3 mm×0.3 mm wide, 300 nm thick)
Thermometer : thin bilayer film of Ti (40nm) and Au(110 nm)



TES microcalorimeter

TES = Transition **E**dge **S**ensor

--> using the sharp transition between normal and superconducting state to sense the temperature.



Thermometer sensitivity

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

Energy resolution

$$\Delta E \propto \sqrt{\frac{T^2 C}{\alpha}}$$

Energy resolution ~ 1 eV at most
(Johnson noise and phonon noise are the most fundamental.)

started the investigation

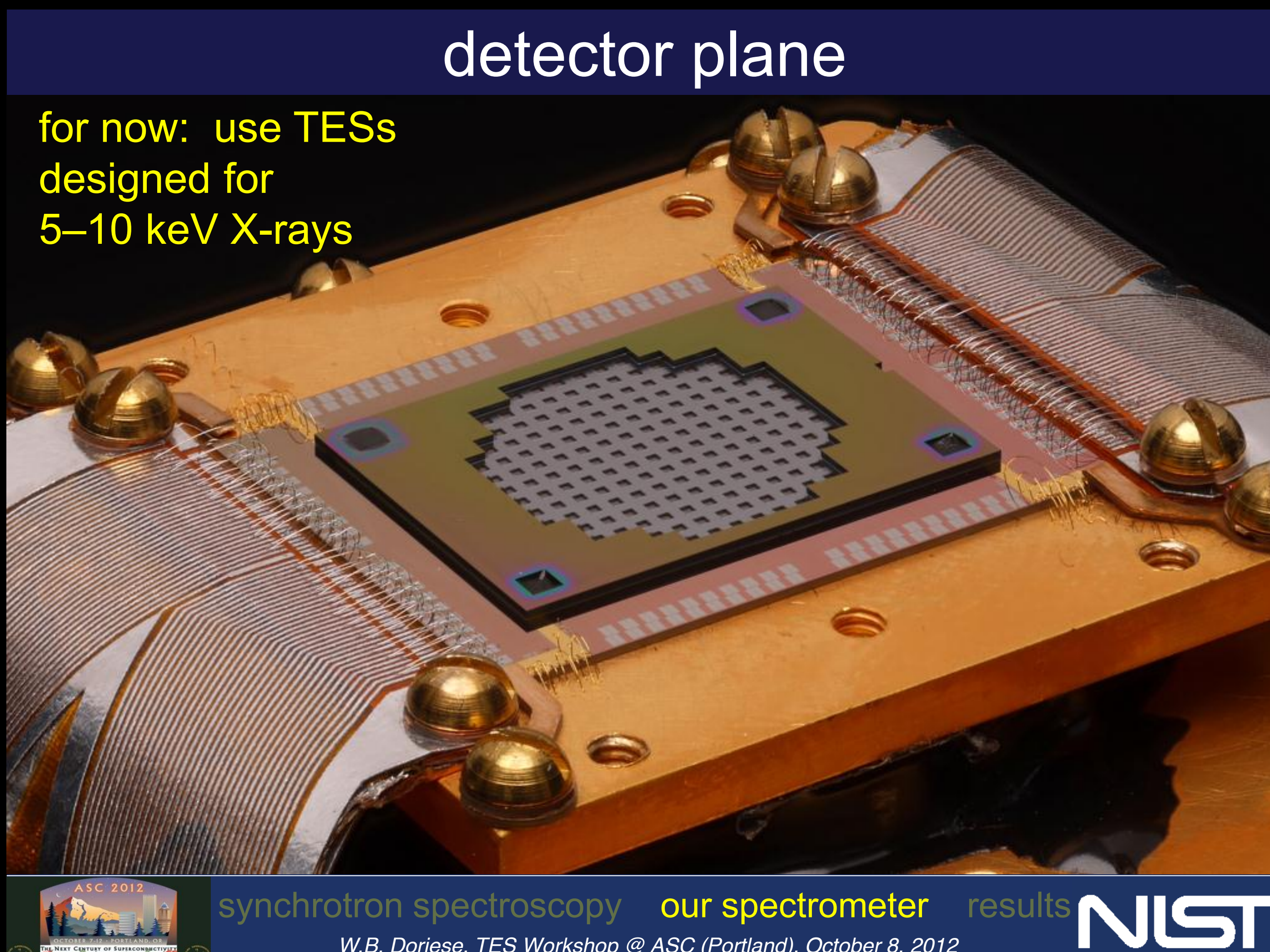
funding status

- got a small research fund in RIKEN for R&D
- applying another funding now...

enhancing partnerships

- RIKEN (Tamagawa-lab. : Dr. Yamada)
- Tokyo Metropolitan University (Ohashi-lab.)
- NIST

NIST microcalorimeter



NIST's standard TES sensor

350 x 350 μm^2, 160 array

--> ~20 [mm2]

(2~3 eV (FWHM)@ 6 keV)

(4~5 eV (FWHM)@ 10 keV)

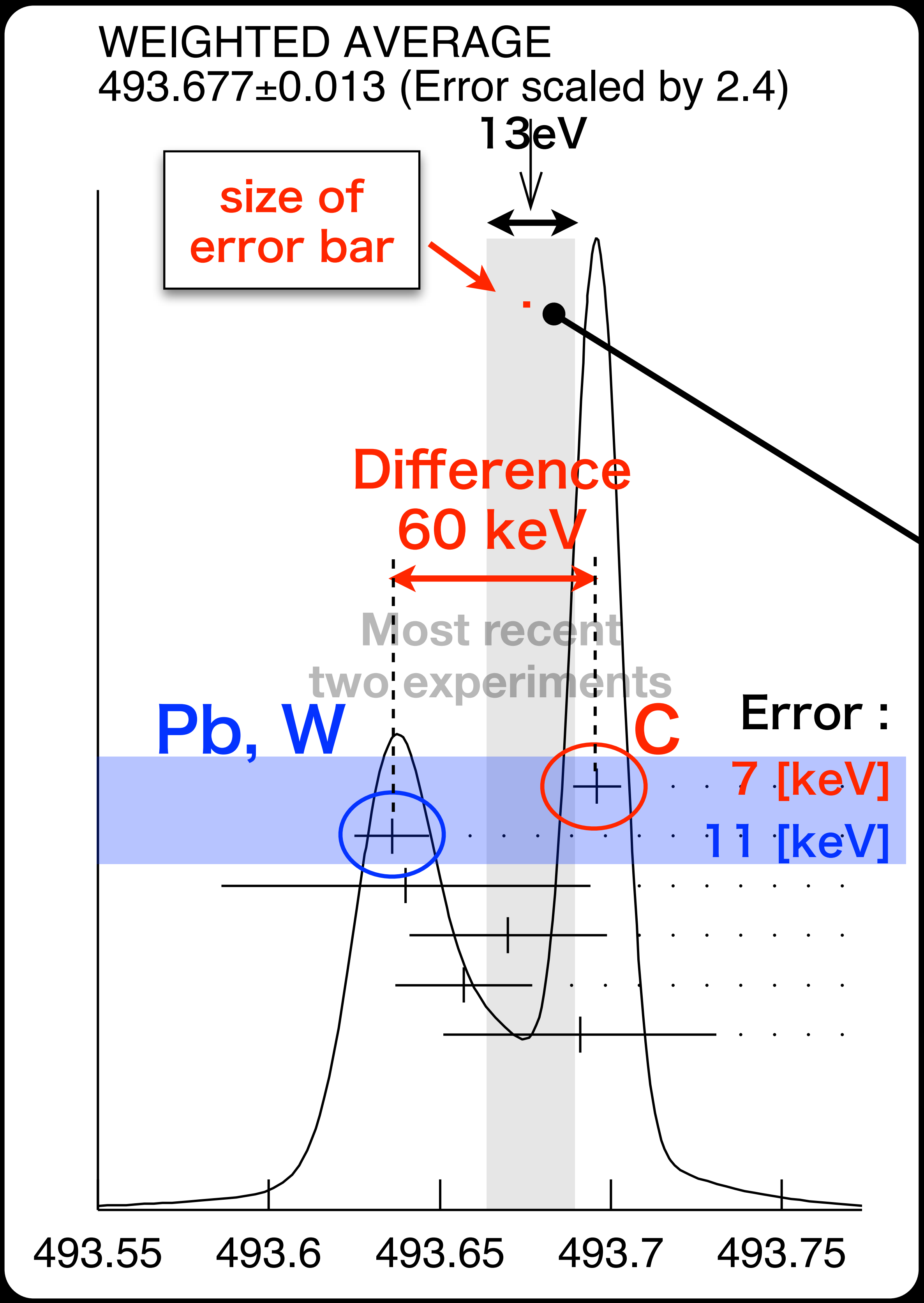
(6~8 eV (FWHM)@ 15 keV)

60 kW operation :

K-He La 3-days data acquisition : 300 events

K-C 5-4 (K-mass) 7-days data acquisition : 7000 events

Kaon mass measurement



"Assuming K-C 5-4 yield = K-He Lα yield x 10",
--> ~ 7000 [events/1week] with NIST MC array whose resolution is 4~5 eV (FWHM)@ 10 keV.
--> ΔE = 4 / 2.35 / sqrt(7000)~ 0.02 [eV]

ΔE (for x-ray energy) ~ 0.02 [eV]
--> Δm (for K- mass) ~ **1 [keV]**

will improve one order of magnitude in accuracy of K-mass
(~ 1 month data accumulation w/60kW)

Summary

Summary

- K-Helium and K^- mass -

✓ measured Kaonic helium x-ray spectra :

- K-^3He (L-series) : first-time measurement (PLB697(2011)199)
- K-^4He (L-series) : measured in gaseous target for the first time (PLB681(2009)310)

✓ get started to investigate the next-generation of K-atom exp.

✓ TES Microcalorimeter : high mobility and a large acceptance

✓ open new door to investigate K-nucleus strong interaction

✓ provide new accurate charged kaon mass value, which would be the first measurement in this project

Thank you