Precision X-ray spectroscopy of kaonic atoms as a probe of kaon-nucleon/nuclei interaction at low energy

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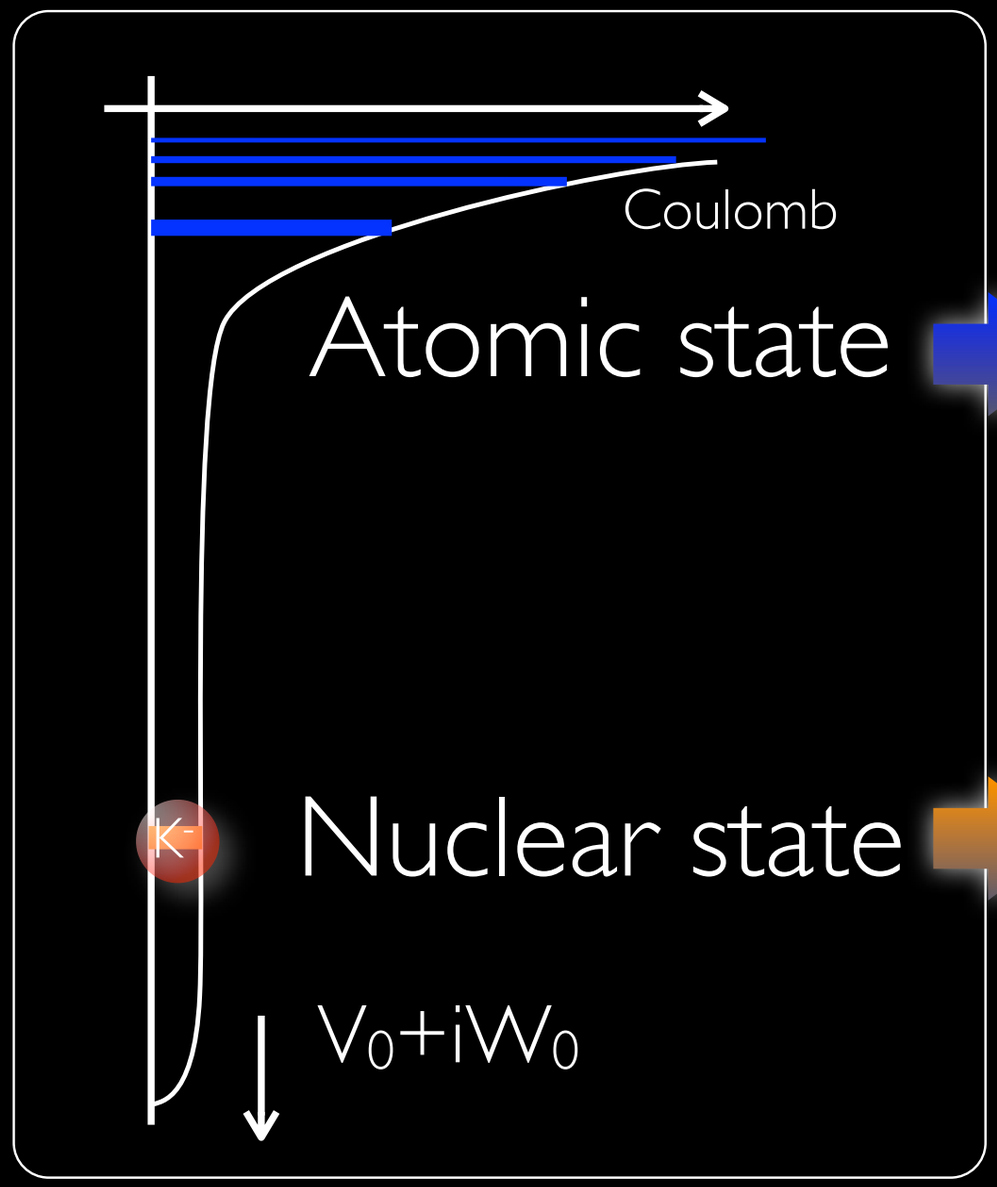
on behalf of SIDDHARTA Collaboration

27th, Aug. 2015
4th ICNFP conference,
Kolymbari, Greece

Introduction

Kaon - Nucleus Interaction

K^- - Nucl. potential



Precision measurement

SIDDHARTA
J-PARC E17
SIDDHARTA2
etc...

Peak search
- direct observation -

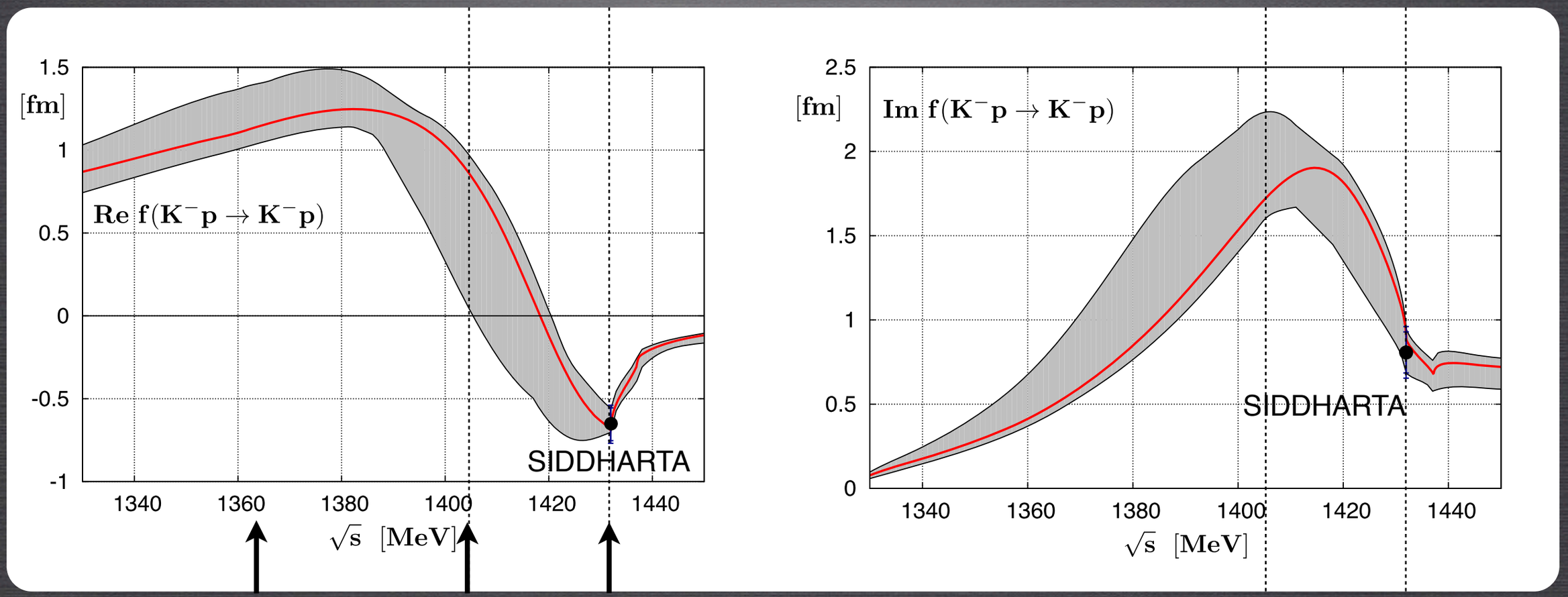
FOPI
J-PARC E15/E27/E31
AMADEUS
etc...

From Dr. S. Okada @ ECT* Trento 2011

QCD predictions near *K-p* threshold

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

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



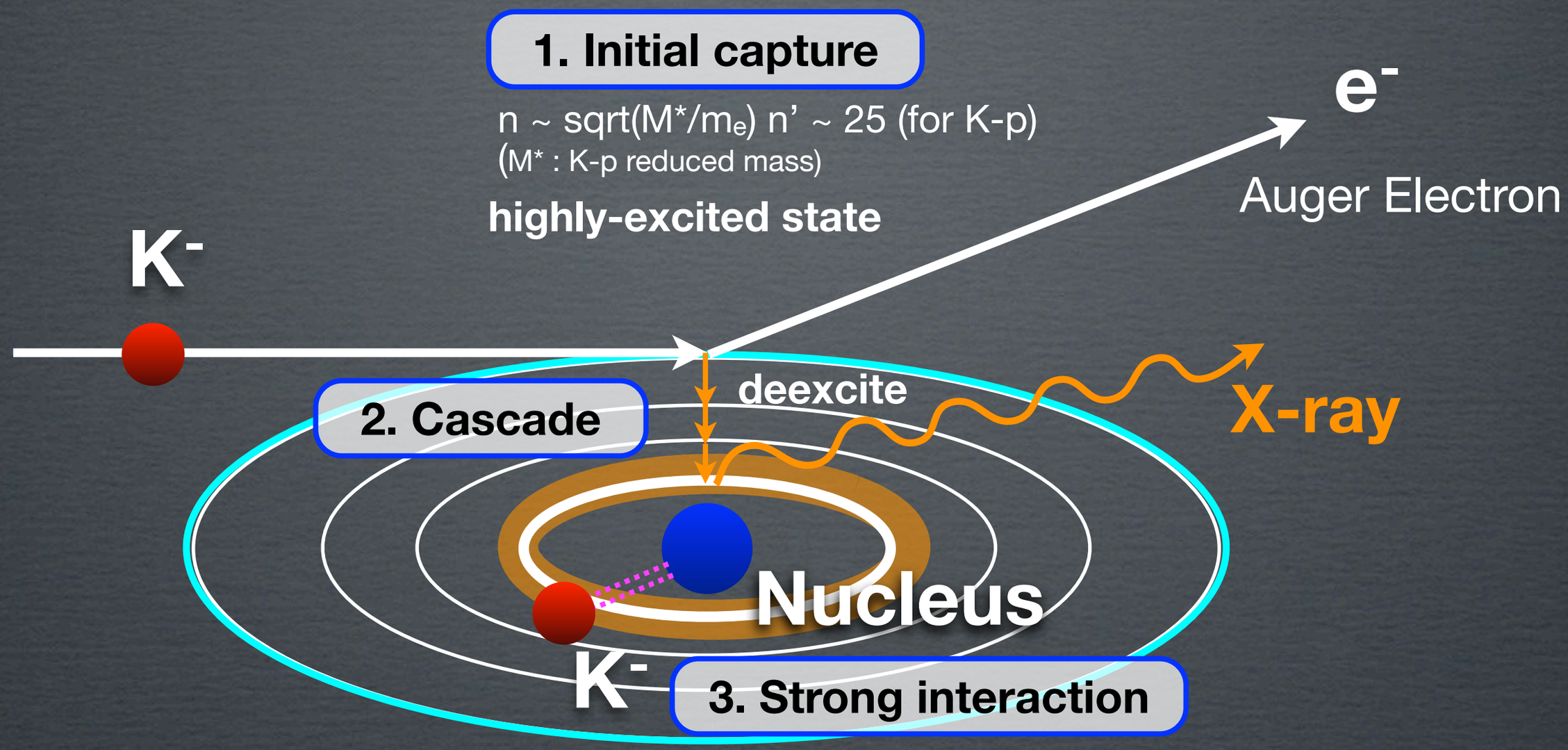
Σπ **Λ(1405)** **K-p threshold**

Kaon-nucleus deeply-bound state ?
-> Kaon condensation in dense matter.

Y. Ikeda et.al., PLB 706(2011)63-67

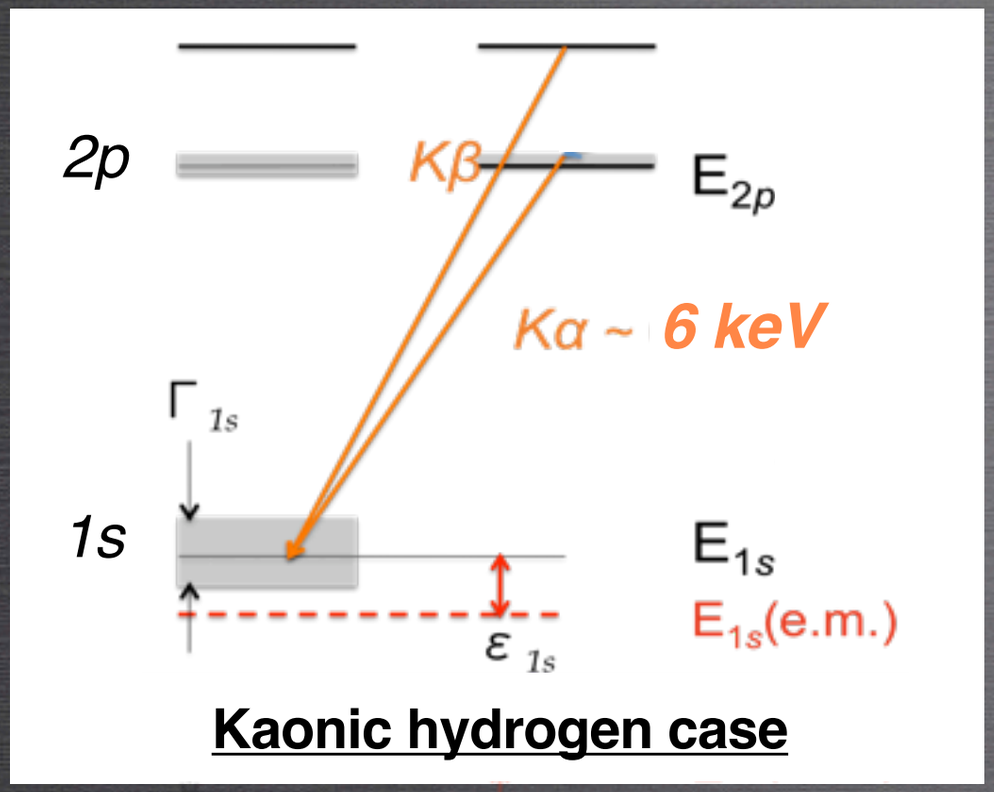
Chiral SU(3) effective theory with a relativistic coupled-channels approach:
Kp→Kp forward scattering amplitude obtained from the NLO calculation extrapolated to the sub-threshold region

Kaonic atom formation

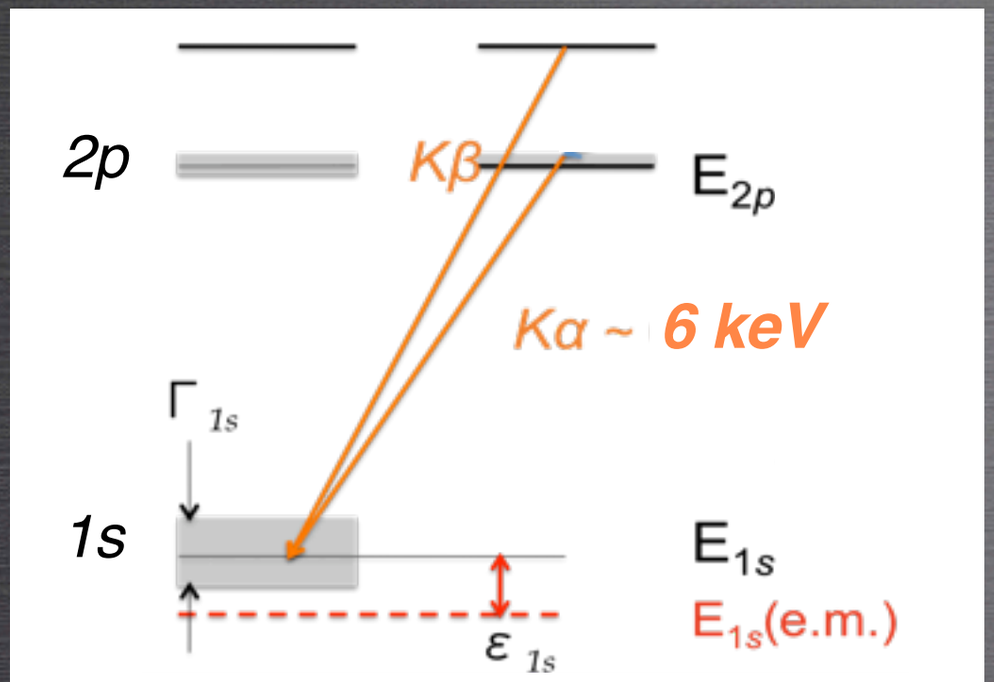


stopped in a target medium

Kaonic atoms



Kaonic atoms



Kaonic hydrogen case

Deser-Truman formula

$$\epsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3 \mu_c^2 a_{K^-p}$$

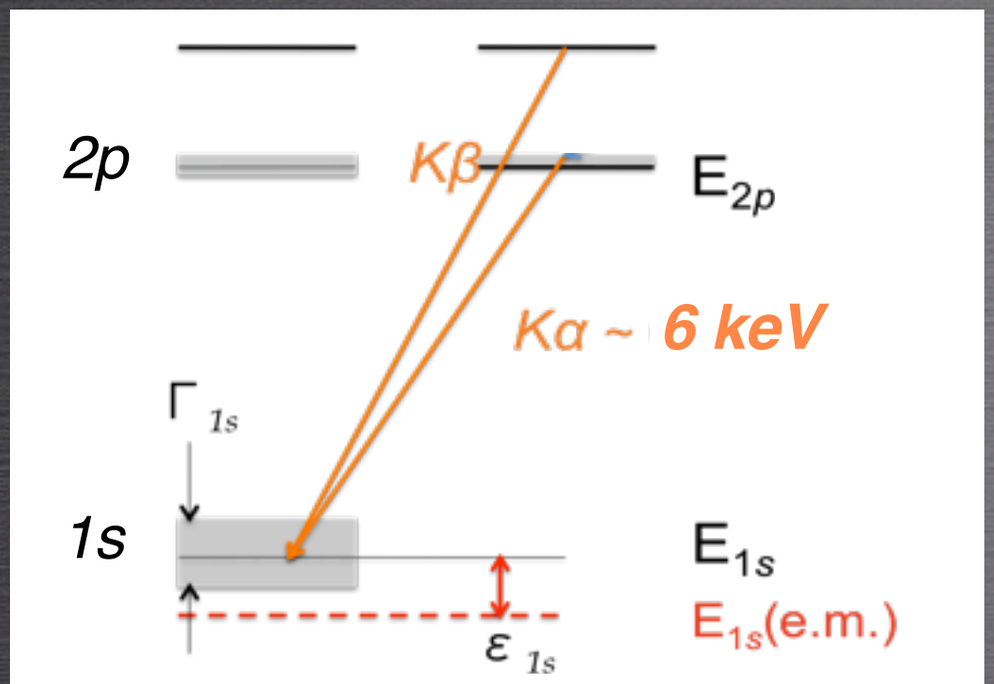
Kaonic hydrogen shift and width

s-wave scattering length using isospin I=0 and I=1 components a_0, a_1 :

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

μ_c : reduced mass of *K*-p

Kaonic atoms



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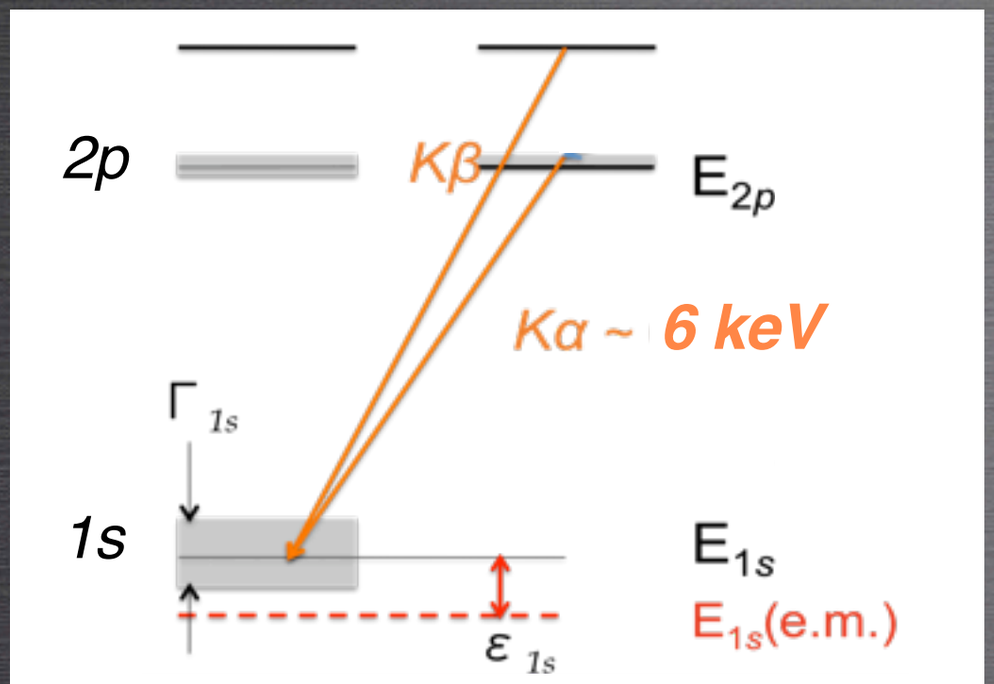
SIDDHARTA gaseous target & beam time

Z = 1, 2

target gas	transition	I.L. [pbarn^{-1}]	type of exp.	significance
Hydrogen	*2p-1s*	**350**	**precision**	best precision
Deuterium	*2p-1s*	**100**	***exploratory***	first time
Helium-4	*3d-2p*	55	**precision**	first gaseous
Helium-3	*3d-2p*	9	**precision**	first time

# of K : ~ 100 k [events / pbarn^{-1}]
# of KHe Lα : ~ 50 [events / pbarn^{-1}]

Kaonic atoms



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PLB 704 (2011)113

NPA 907 (2013) 69

PLB 681(2009)310

PLB 697(2011)99

# of K : ~ 100 k [events / pbarn^{-1}]

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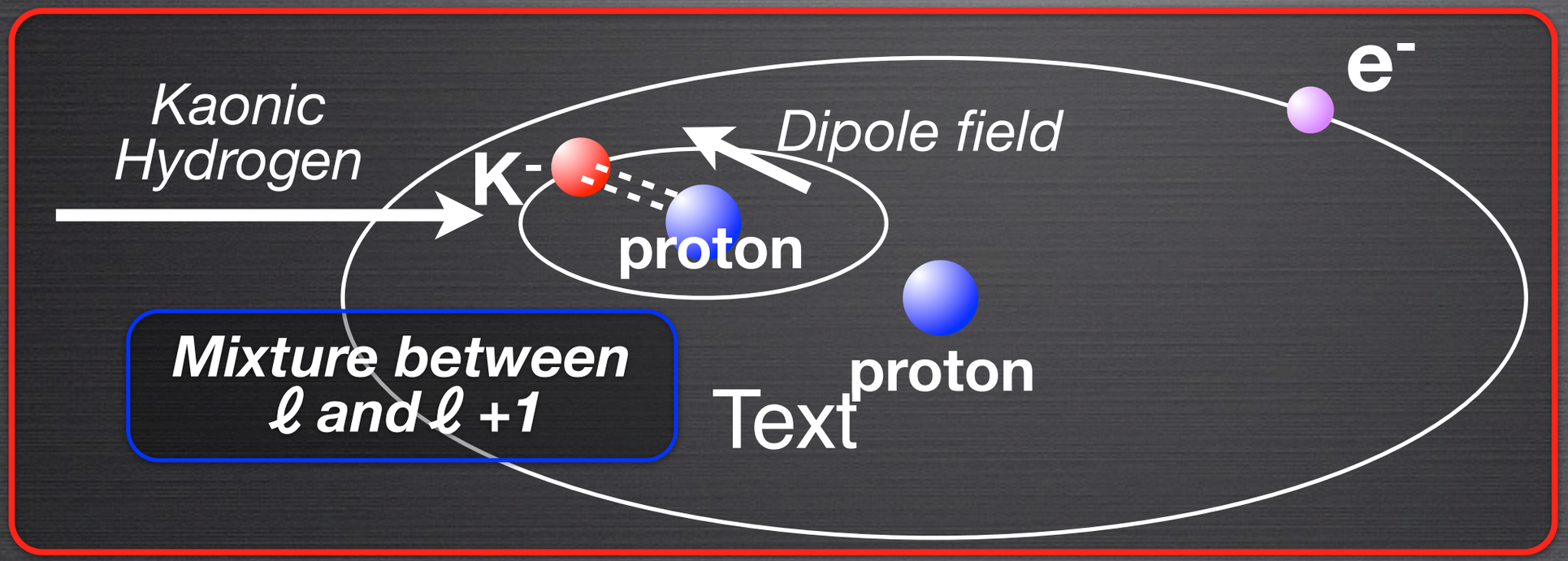
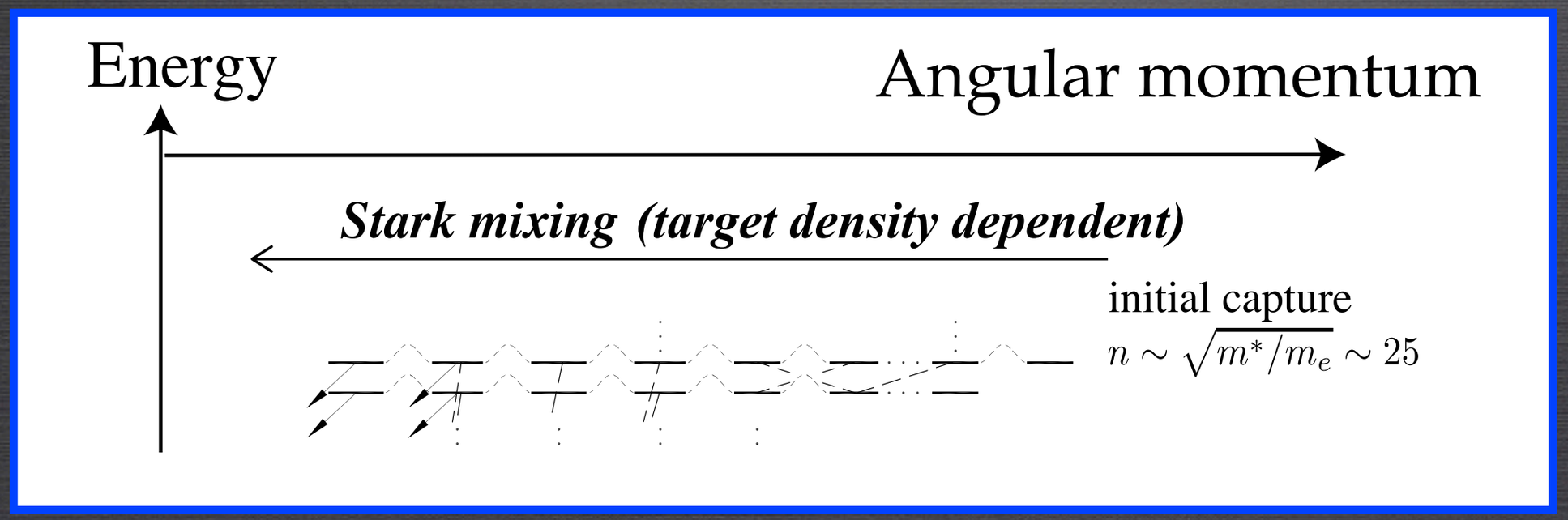
Experiment

Difficulty of Kp and Kd X-ray measurment

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





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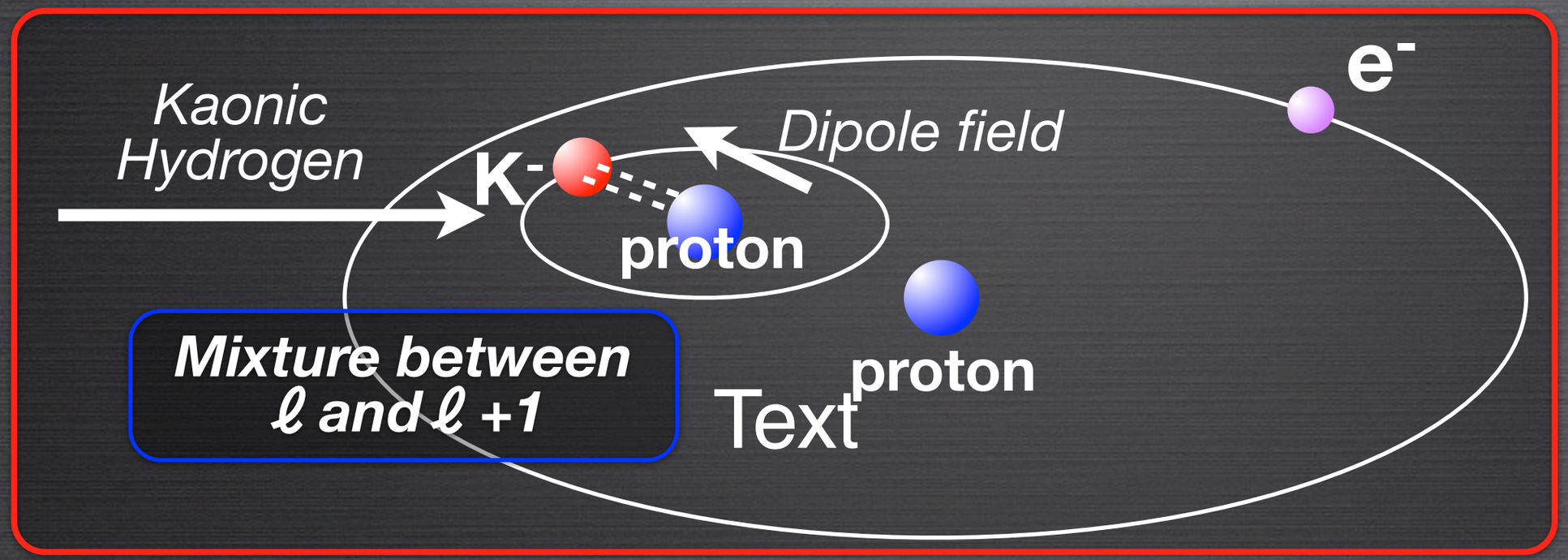

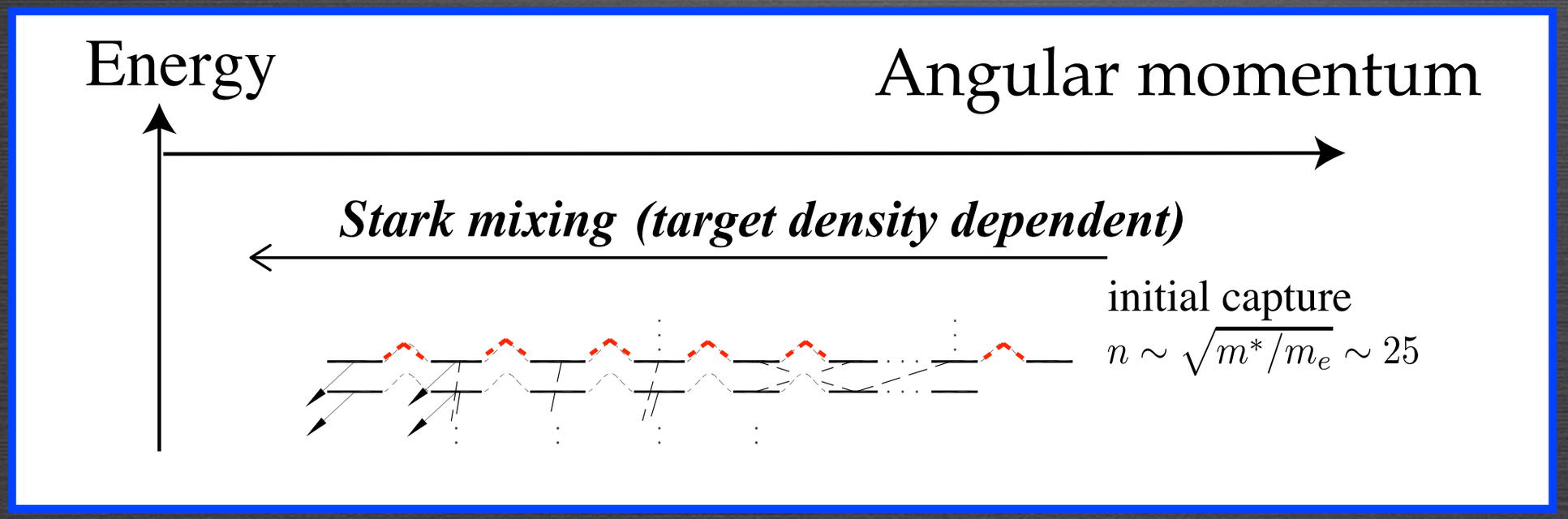

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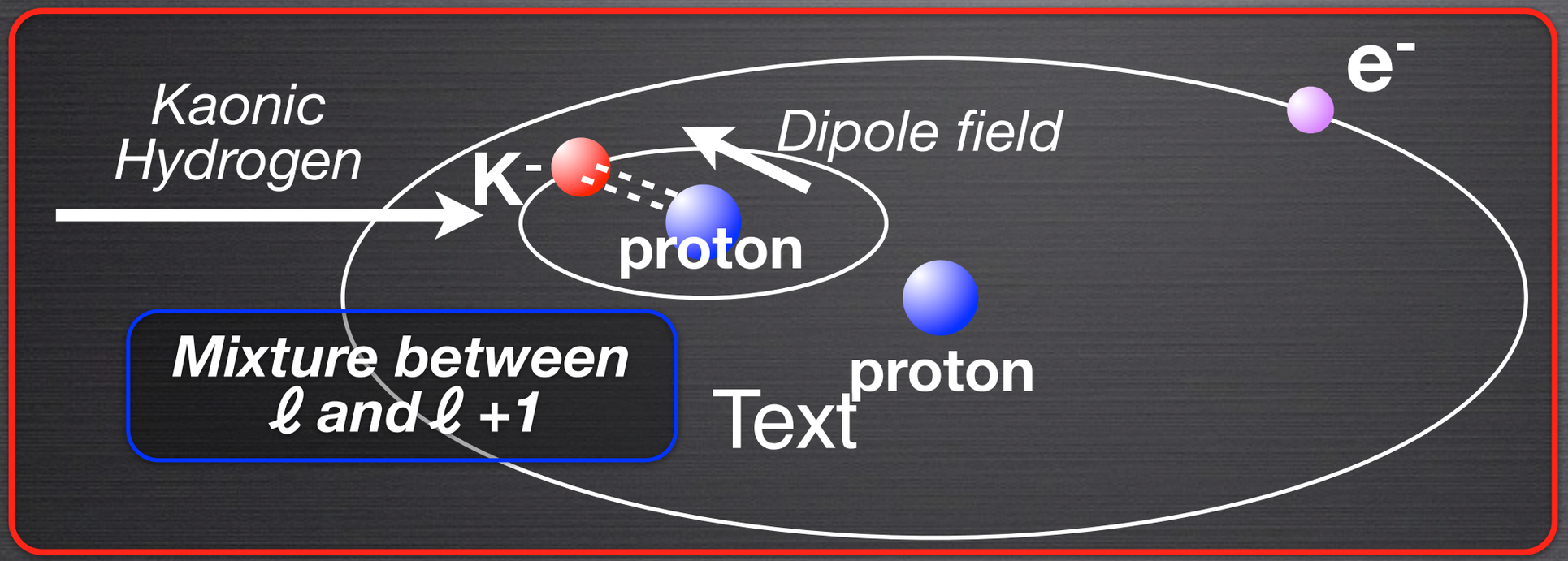
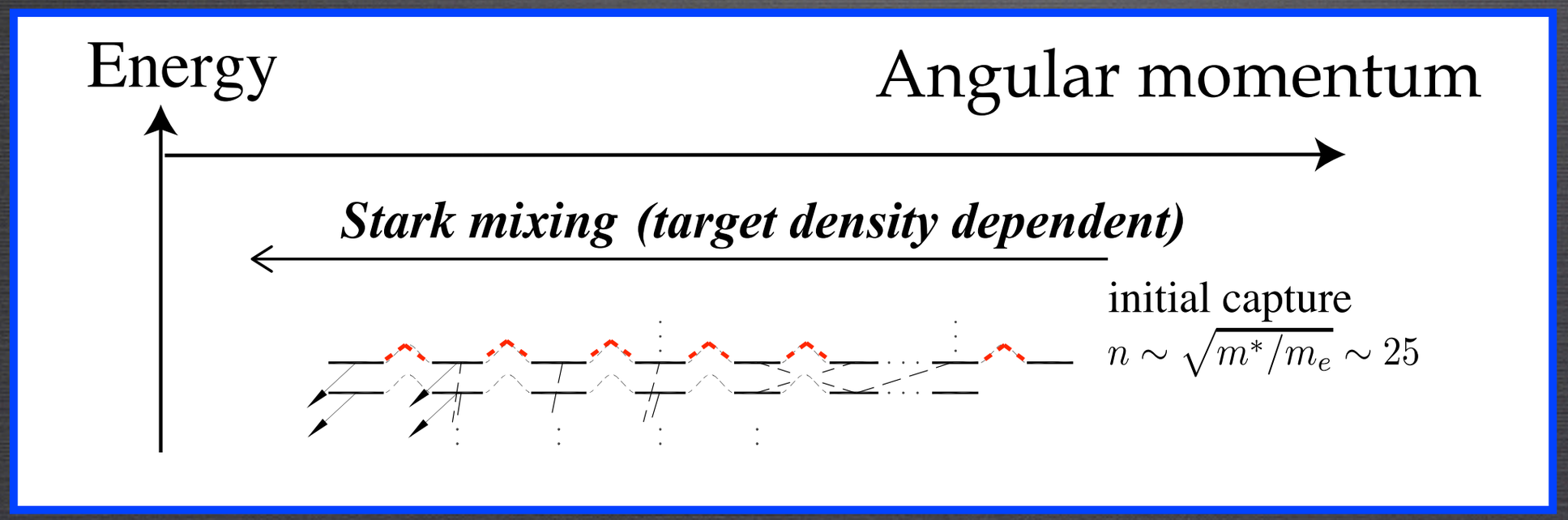
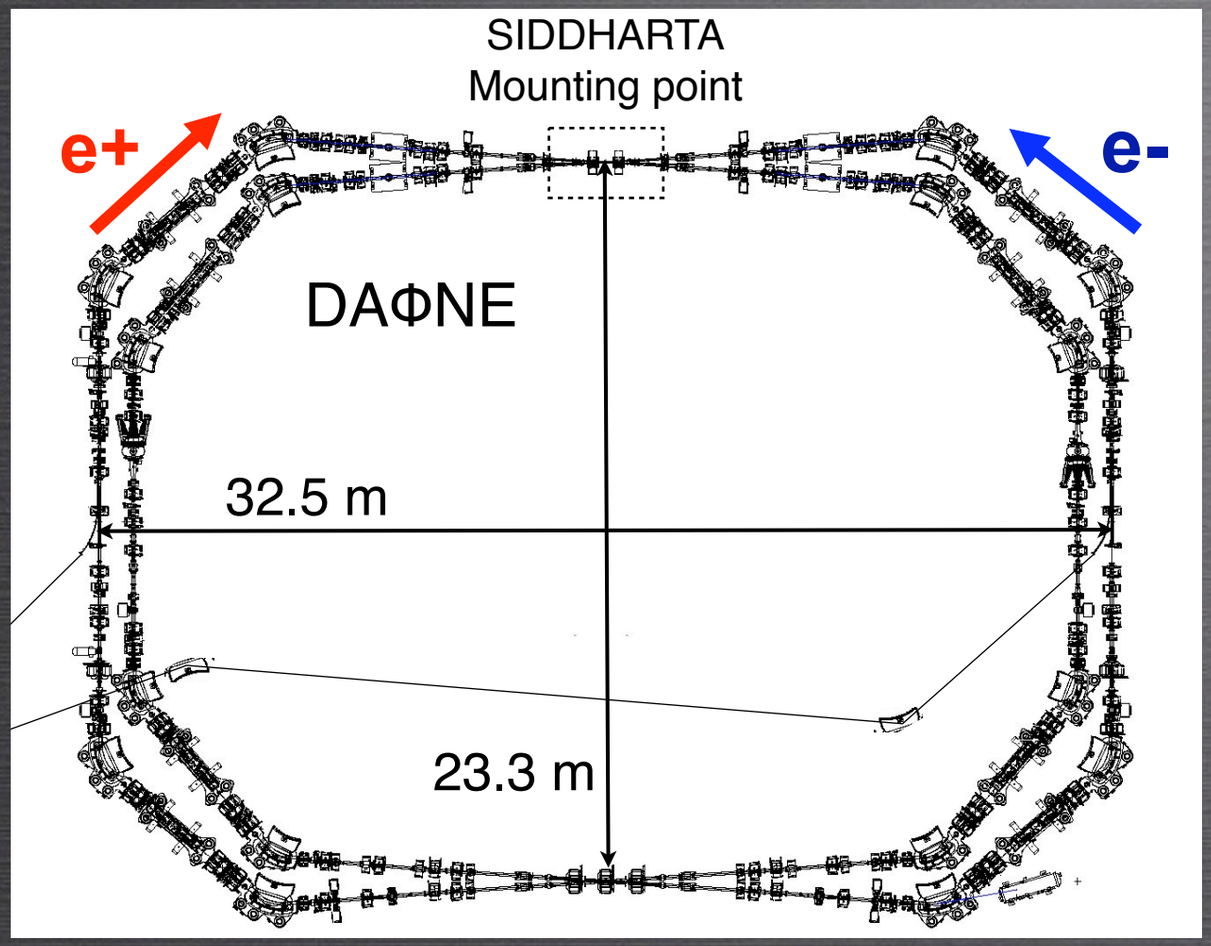




- ❖Low density gaseous target
- ❖ Low energy Kaon with small energy spread

SIDDHARTA experiment

DAFNE e^+e^- collider in Frascati



- $\phi \rightarrow K^+ K^-$ (49.1%)
- Monochromatic K^-
  (~127 MeV/c, 0.1% momentum bite)
- Low hadronic background comparing to secondary-particle beam line

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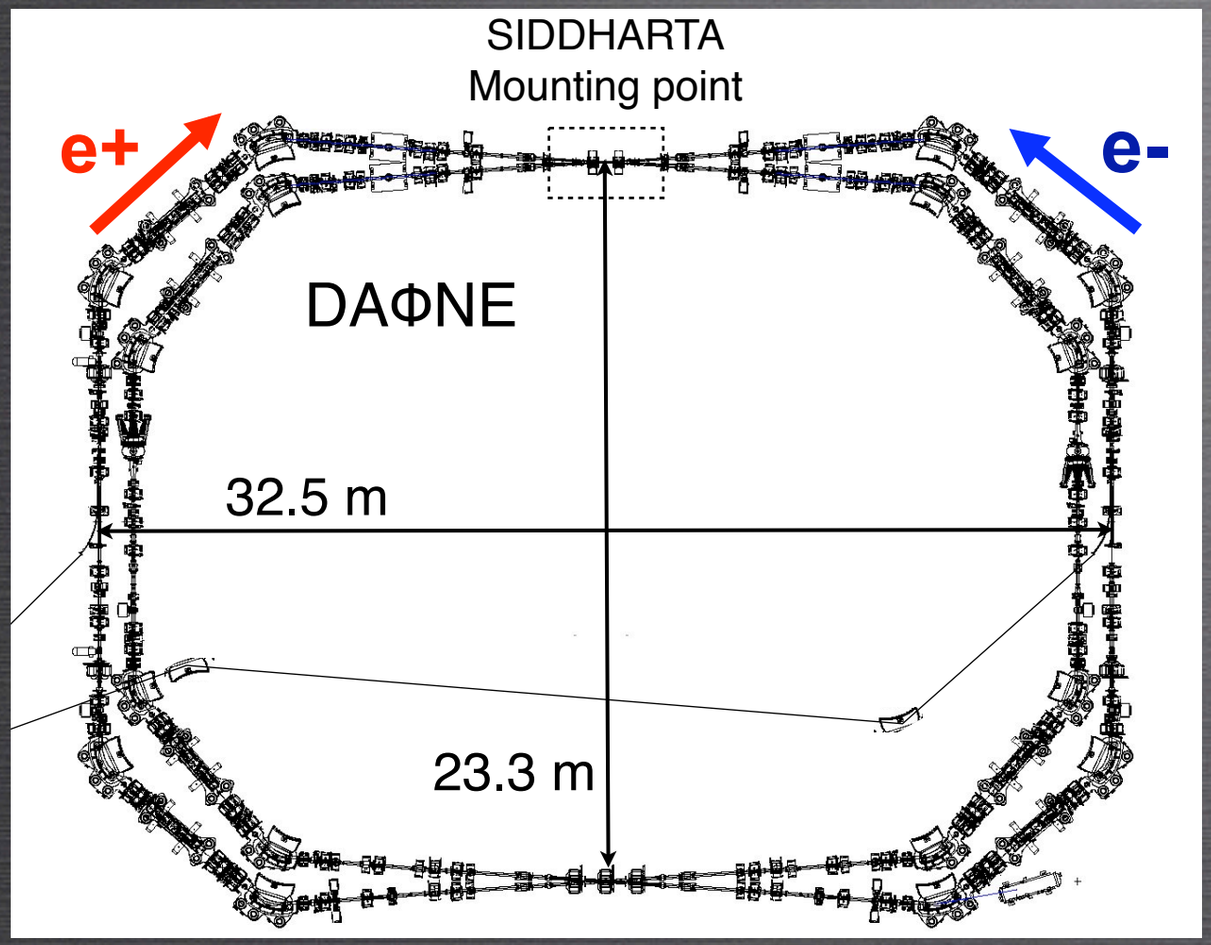
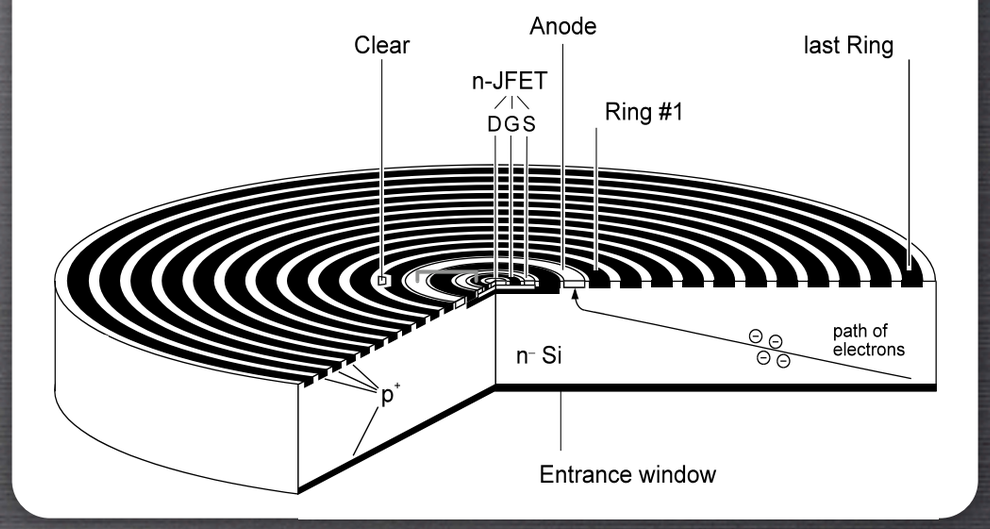


SDD features

➡ ~ 1 μs time resolution

➡ 1 cm² x 144 effective surface

➡ 150 eV FWHM @ 6 keV



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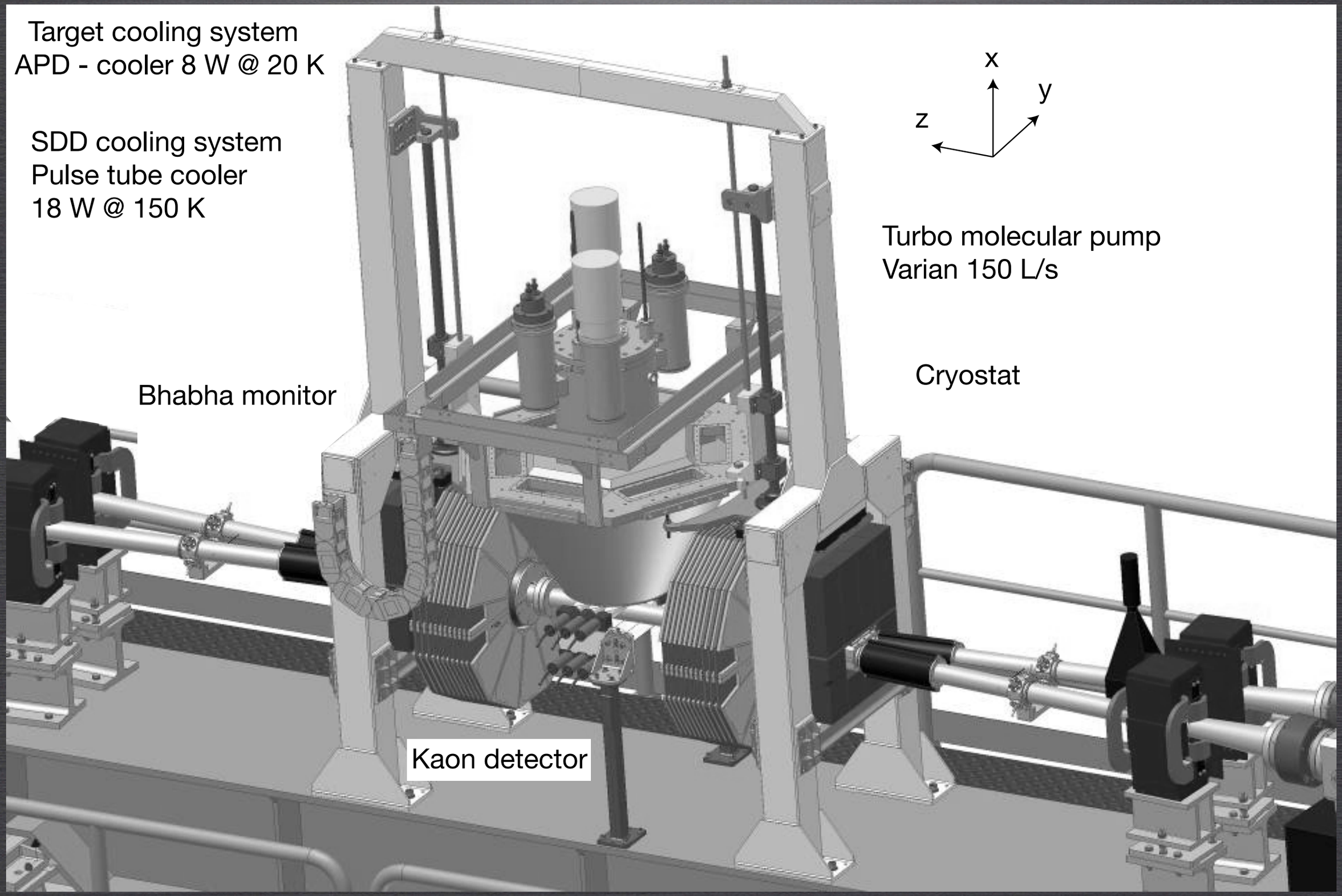
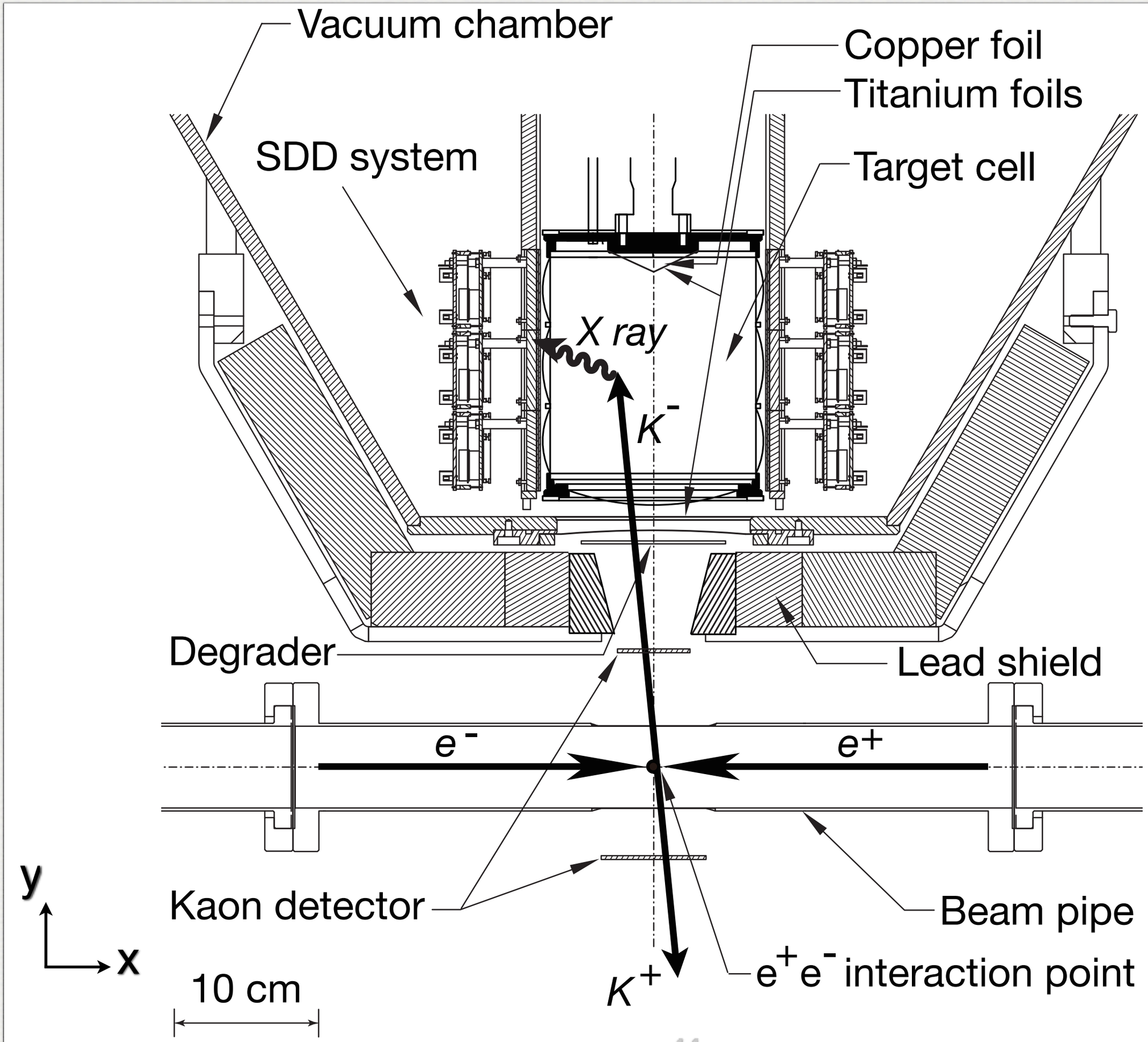
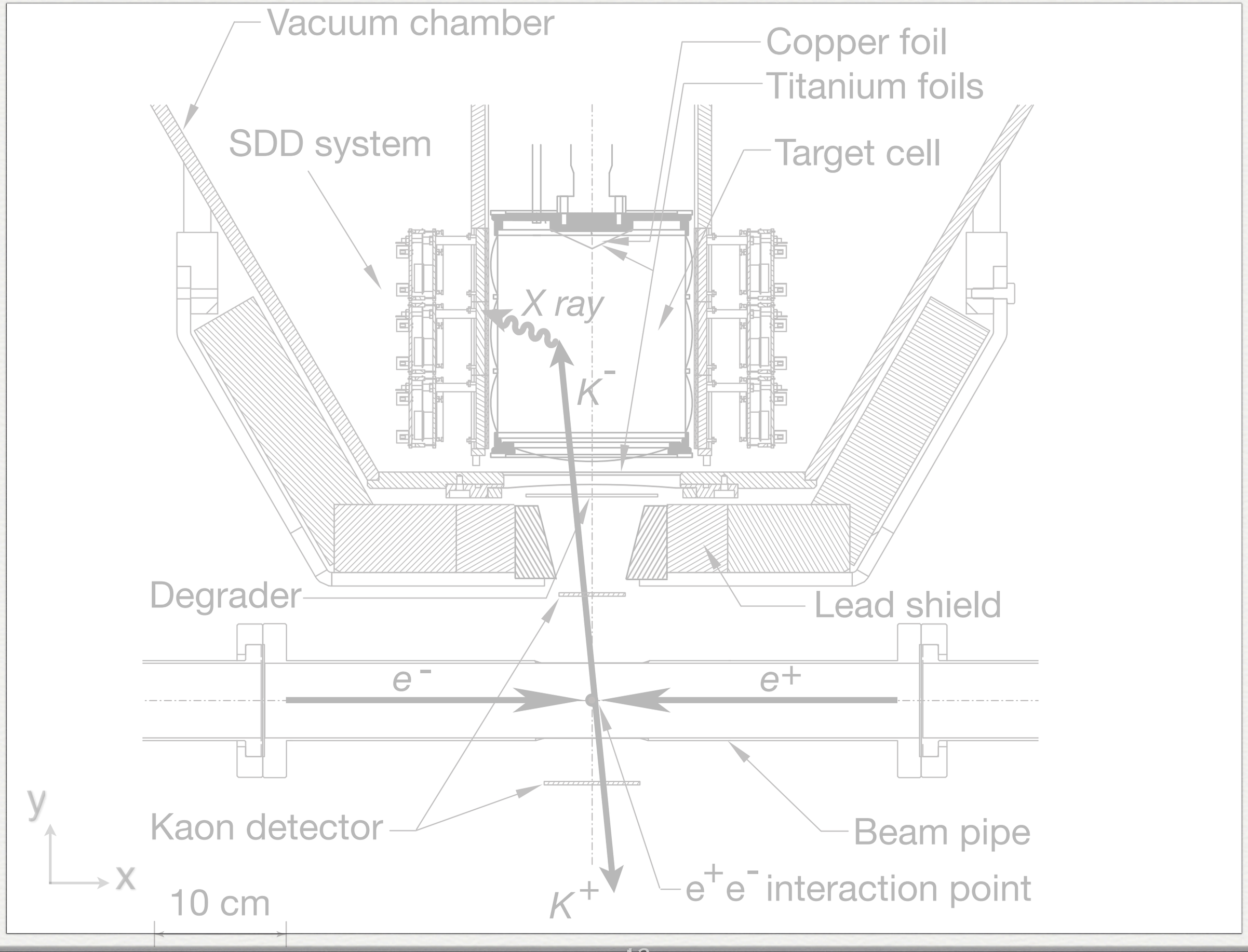
- Low hadronic background comparing to secondary-particle beam line

- Kaon origin X-ray by timing info. of SDD
- 144 SDDs : 10 % solid angle

Setup at interaction point




Vacuum chamber
Copper foil
Titanium foils
SDD system
Target cell
X ray
K-
Degrader
Lead shield
e-
e+
Kaon detector
Beam pipe
y
x
10 cm
K+
e+e- interaction point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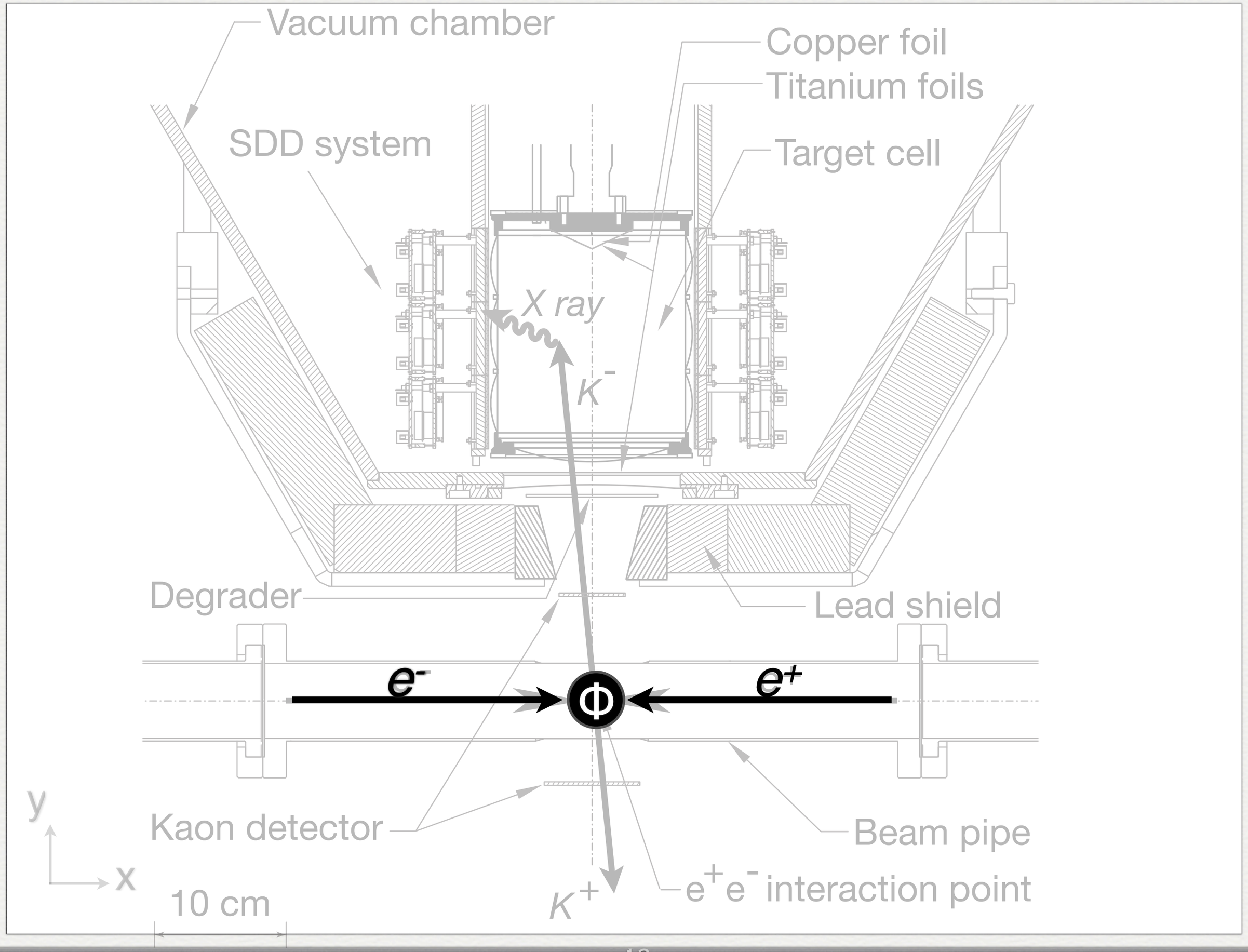
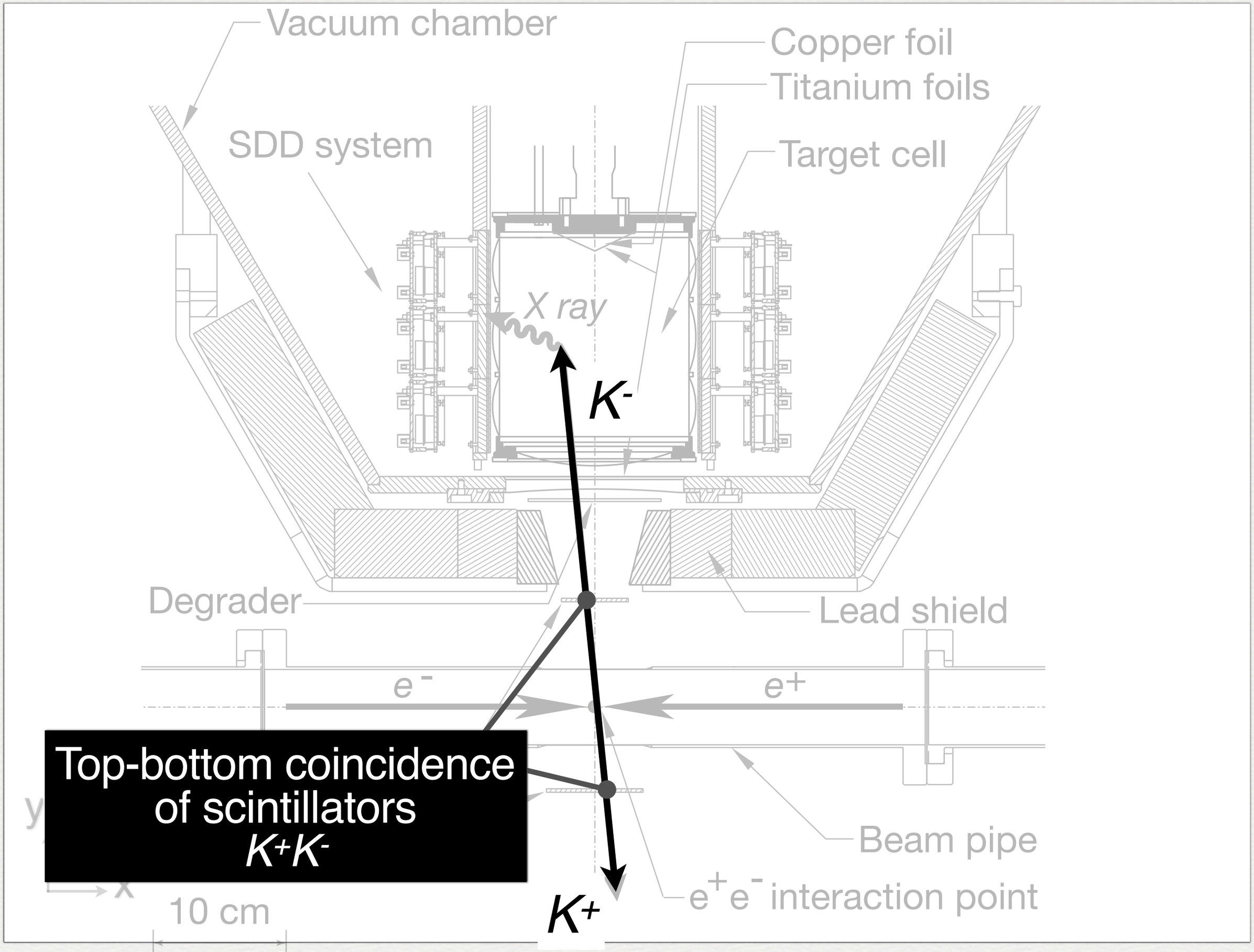
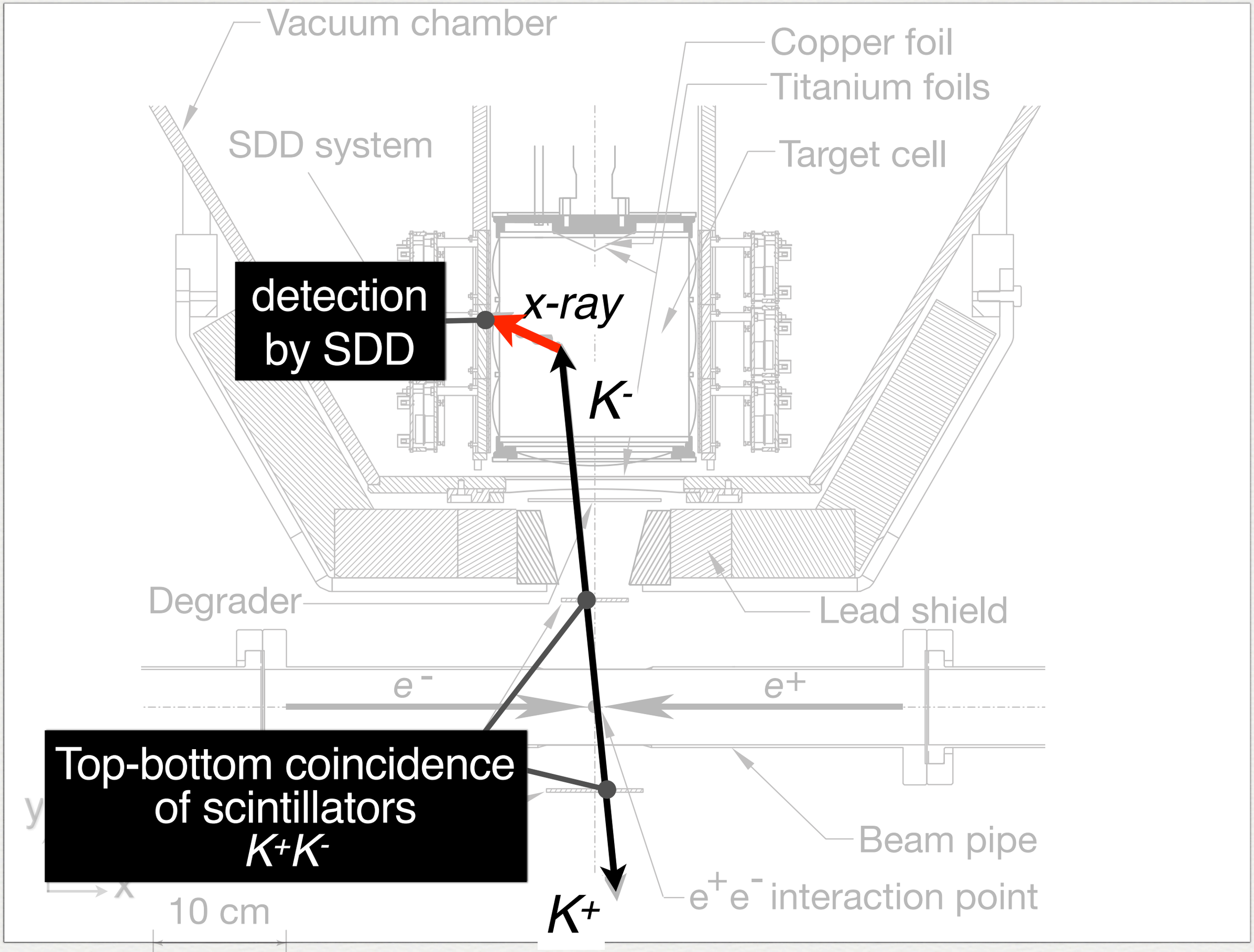
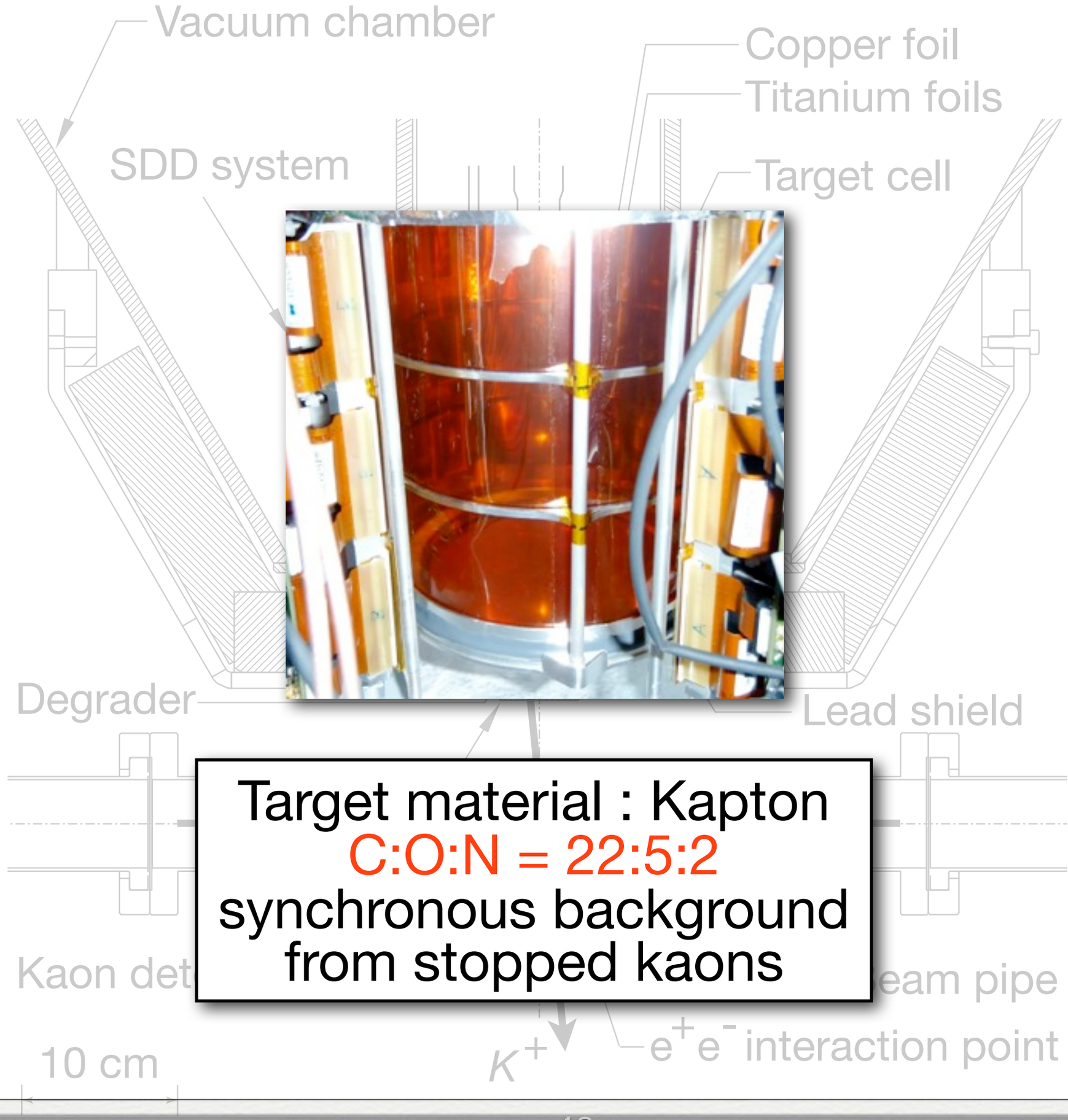
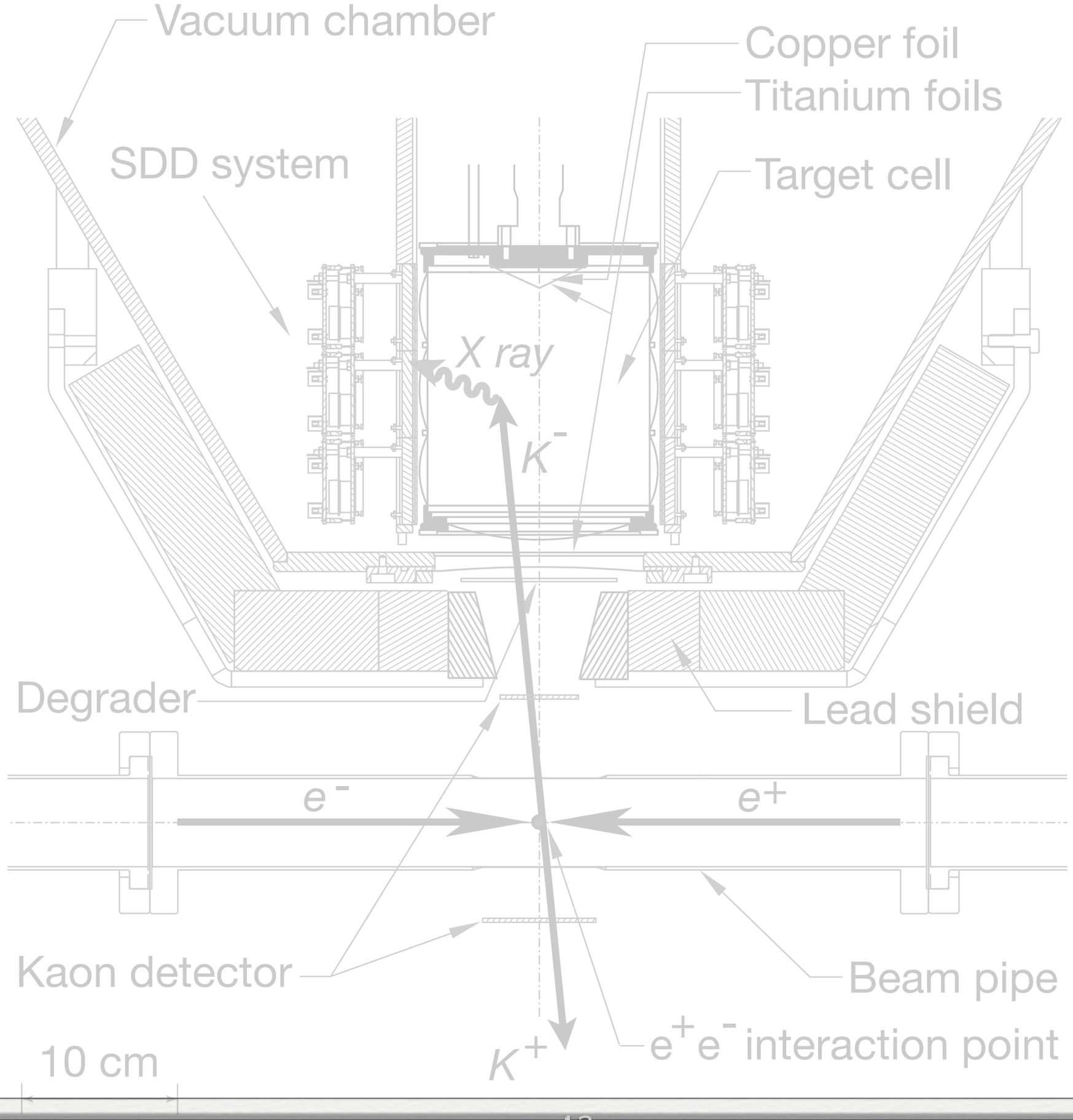

Vacuum chamber
Copper foil
Titanium foils
SDD system
Target cell
X ray
K-
Degrader
Lead shield
e-
e+
Φ
Kaon detector
Beam pipe
y
x
10 cm
K+
e+e- interaction point


Vacuum chamber
Copper foil
Titanium foils
SDD system
Target cell
X ray
K-
Degrader
Lead shield
e -
e+
Top-bottom coincidence
of scintillators
K+K-
Beam pipe
e+e- interaction point
10 cm
K+


Vacuum chamber
Copper foil
Titanium foils
SDD system
Target cell
detection by SDD
x-ray
K-
Degrader
Lead shield
e -
e+
Top-bottom coincidence of scintillators
K+K-
Beam pipe
e+e- interaction point
10 cm
K+



Target material : Kapton
C:O:N = 22:5:2
synchronous background
from stopped kaons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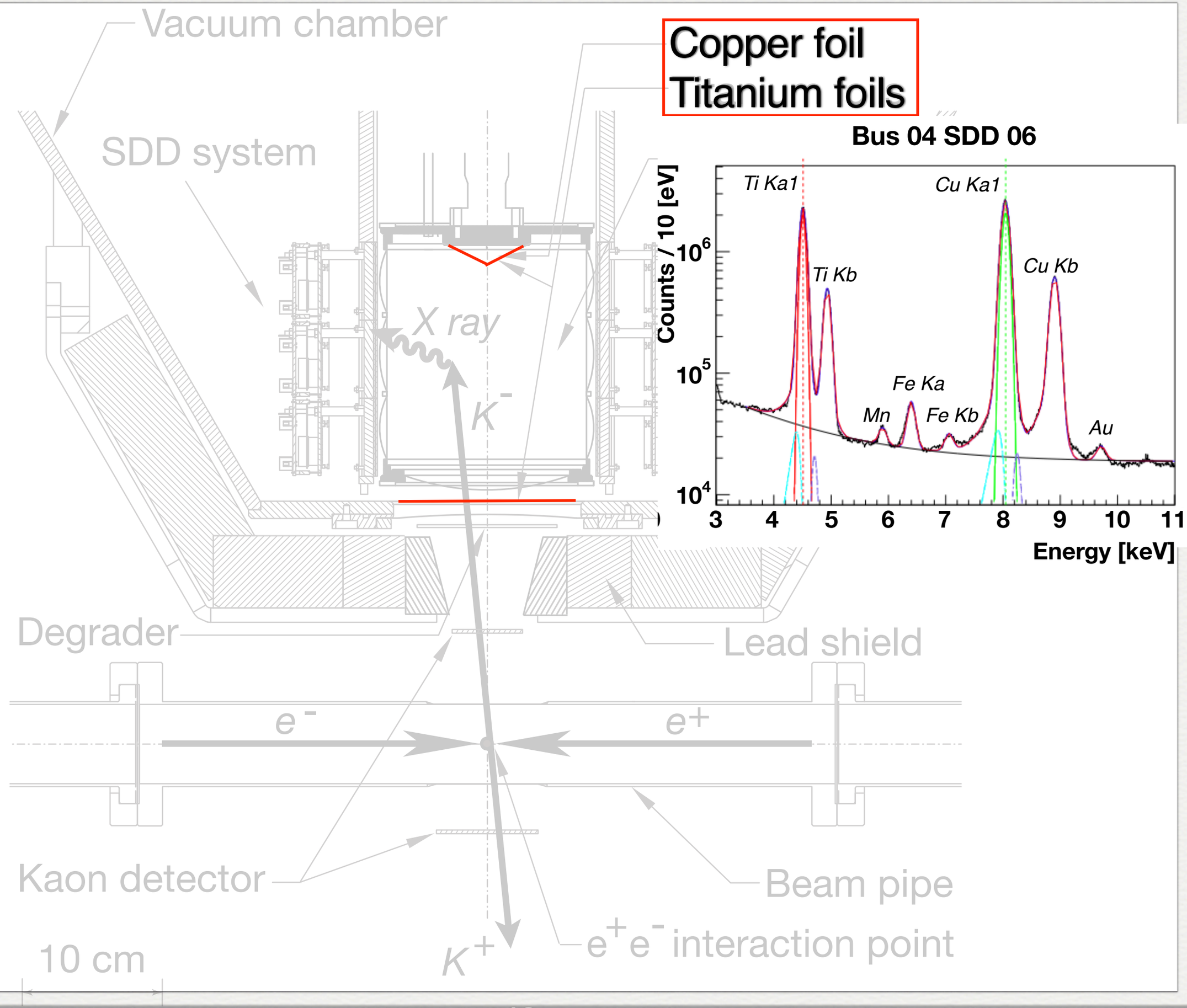
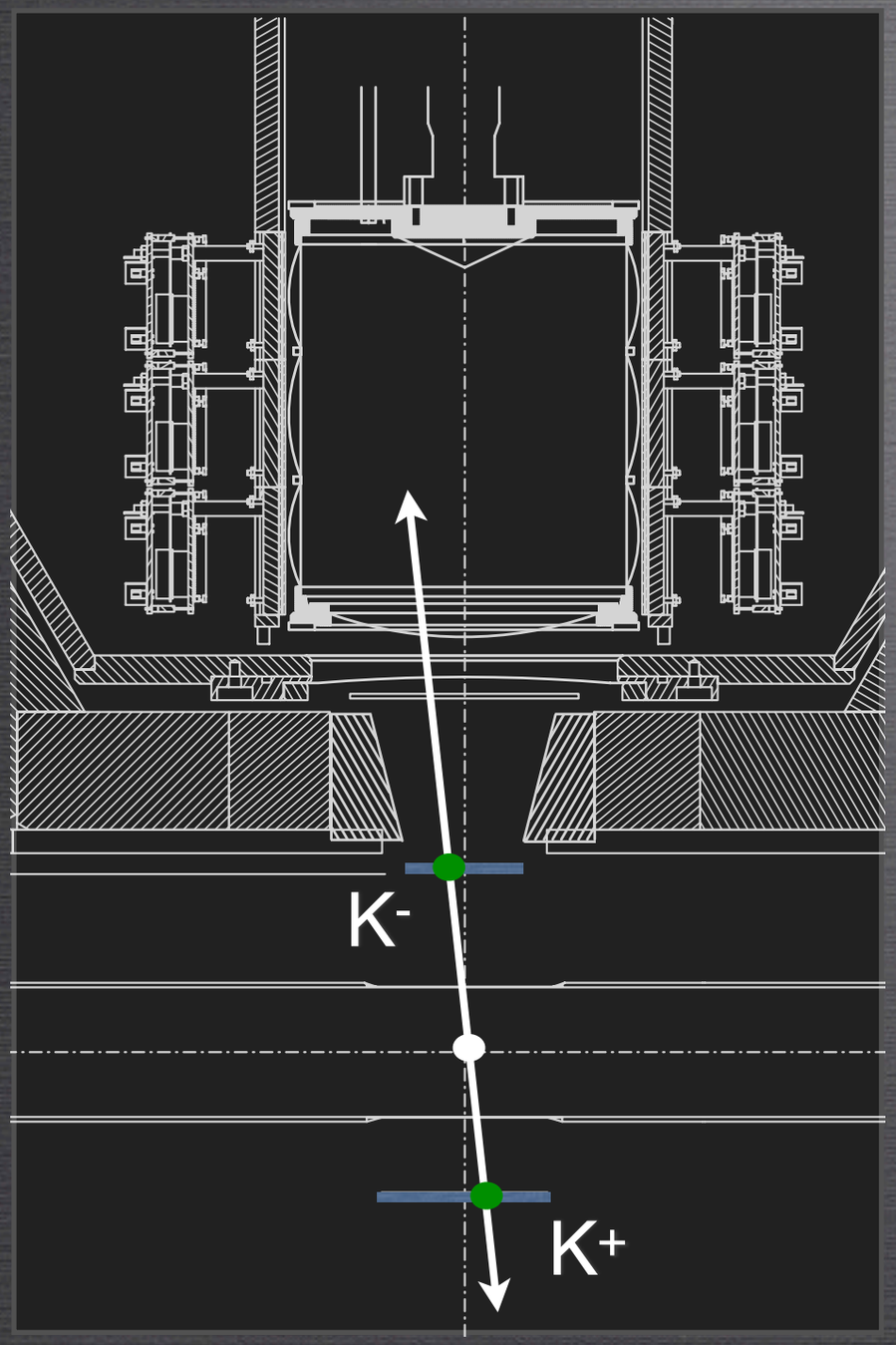
X ray
K-
Degrader
Lead shield
e-
e+
Kaon detector
Beam pipe
e+e- interaction point
K+
10 cm

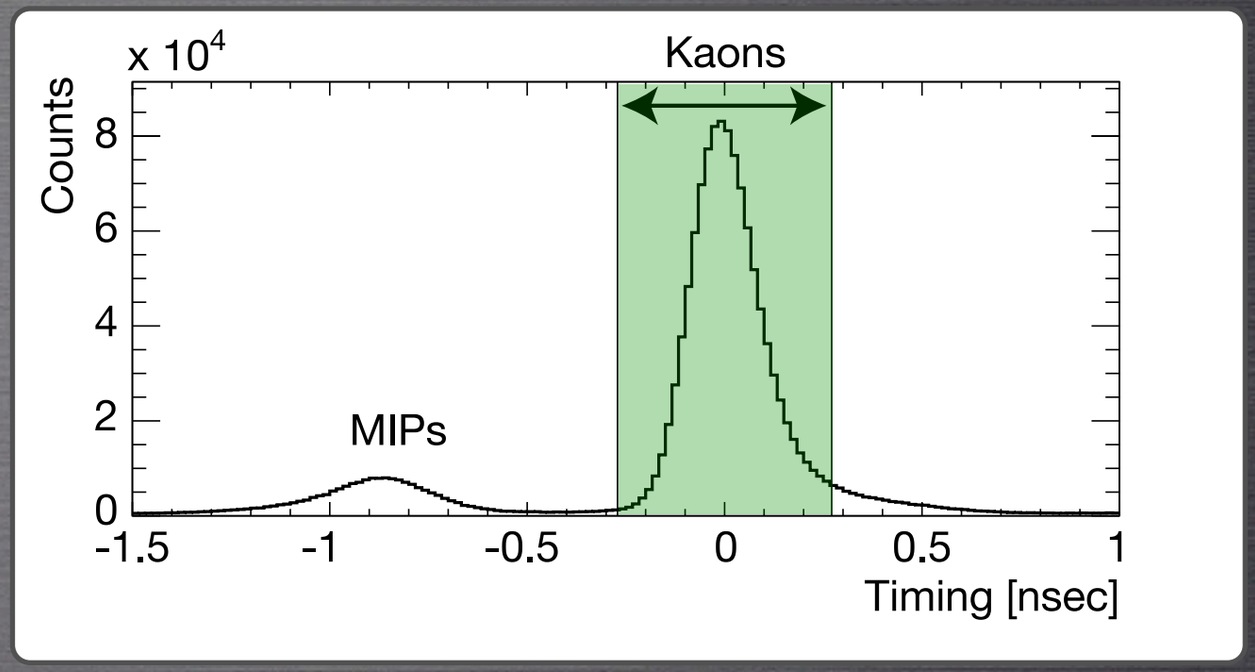

Vacuum chamber
Copper foil
Titanium foils
SDD system
X ray
K-
Bus 04 SDD 06
Counts / 10 [eV]
Ti Ka1
Ti Kb
Cu Ka1
Cu Kb
Fe Ka
Mn
Fe Kb
Au
Energy [keV]
Degrader
Lead shield
e-
e+
Kaon detector
Beam pipe
K+
e+e- interaction point
10 cm

Analysis & results

Kaon ID and timing information of X-ray events



Kaon event : coincidence of two scintillators



Kaon coincidence timing w.r.t. DAFNE RF (~ 368.7 MHz) clock

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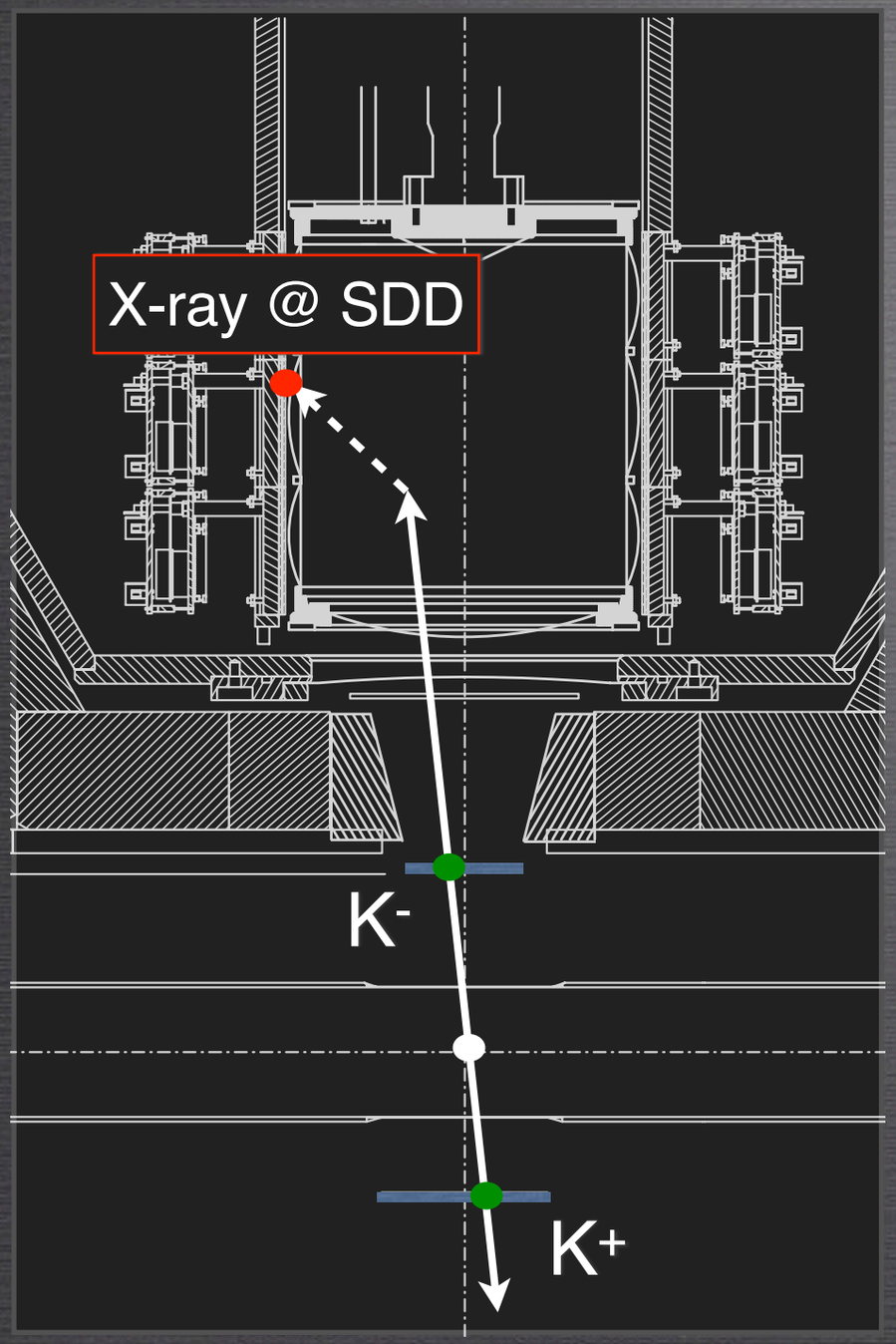

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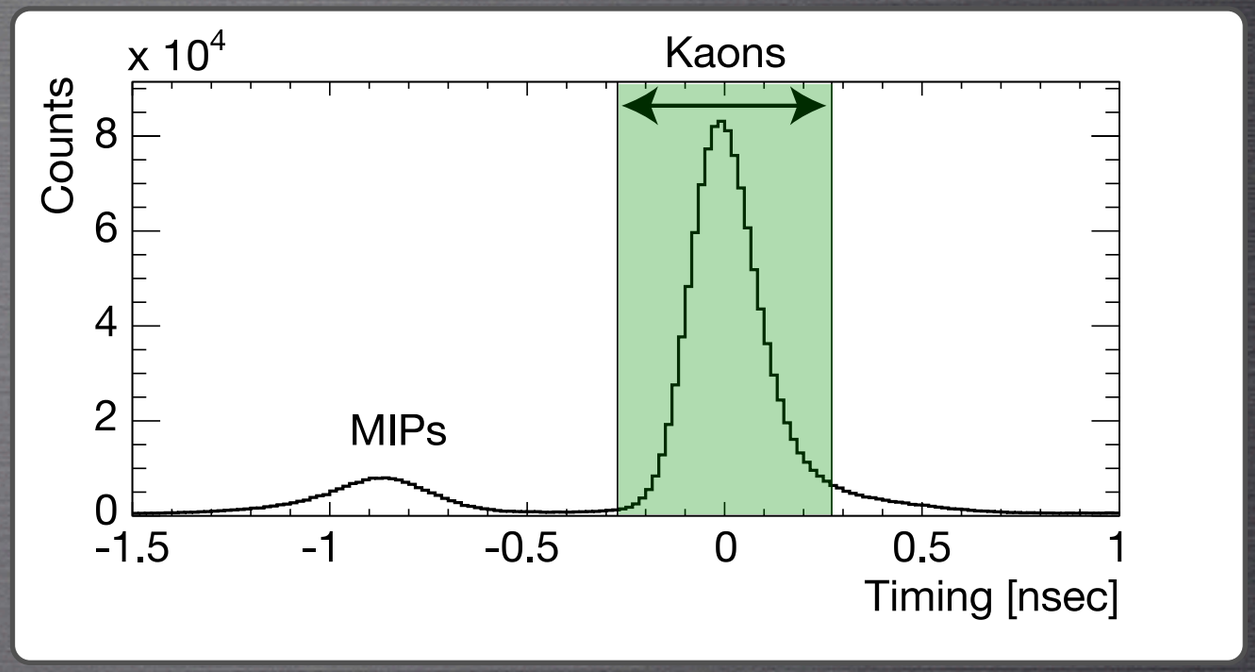

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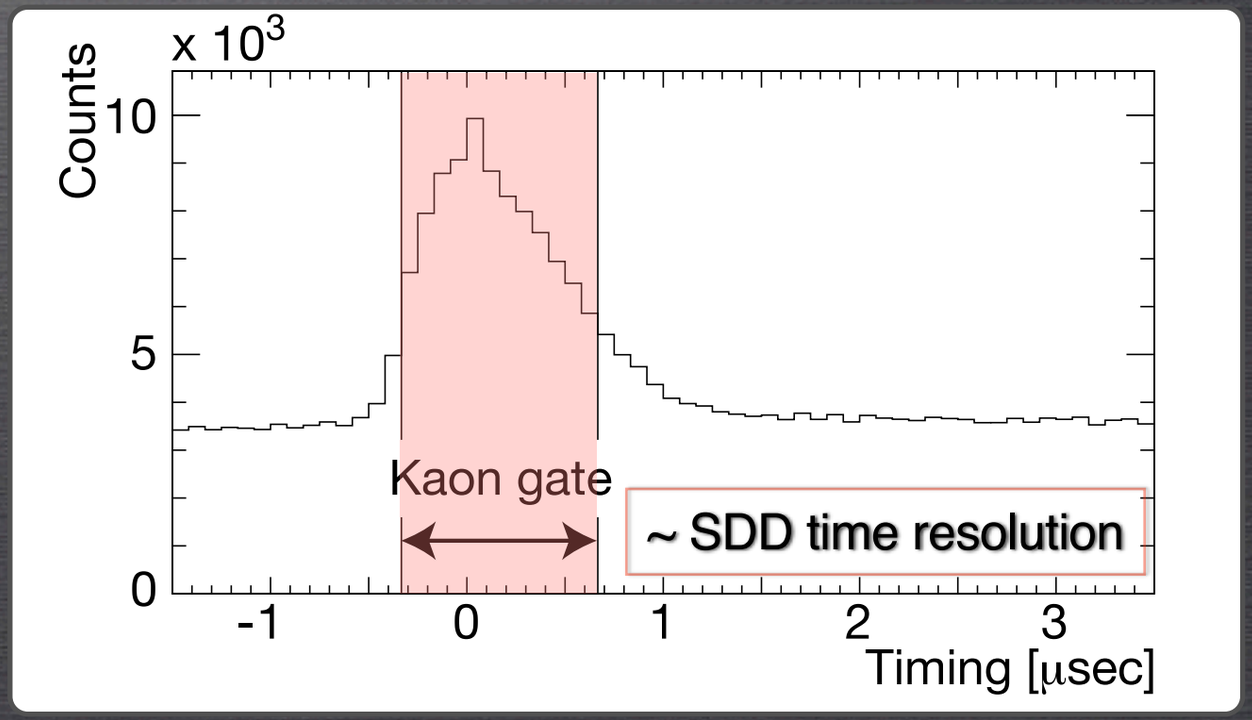
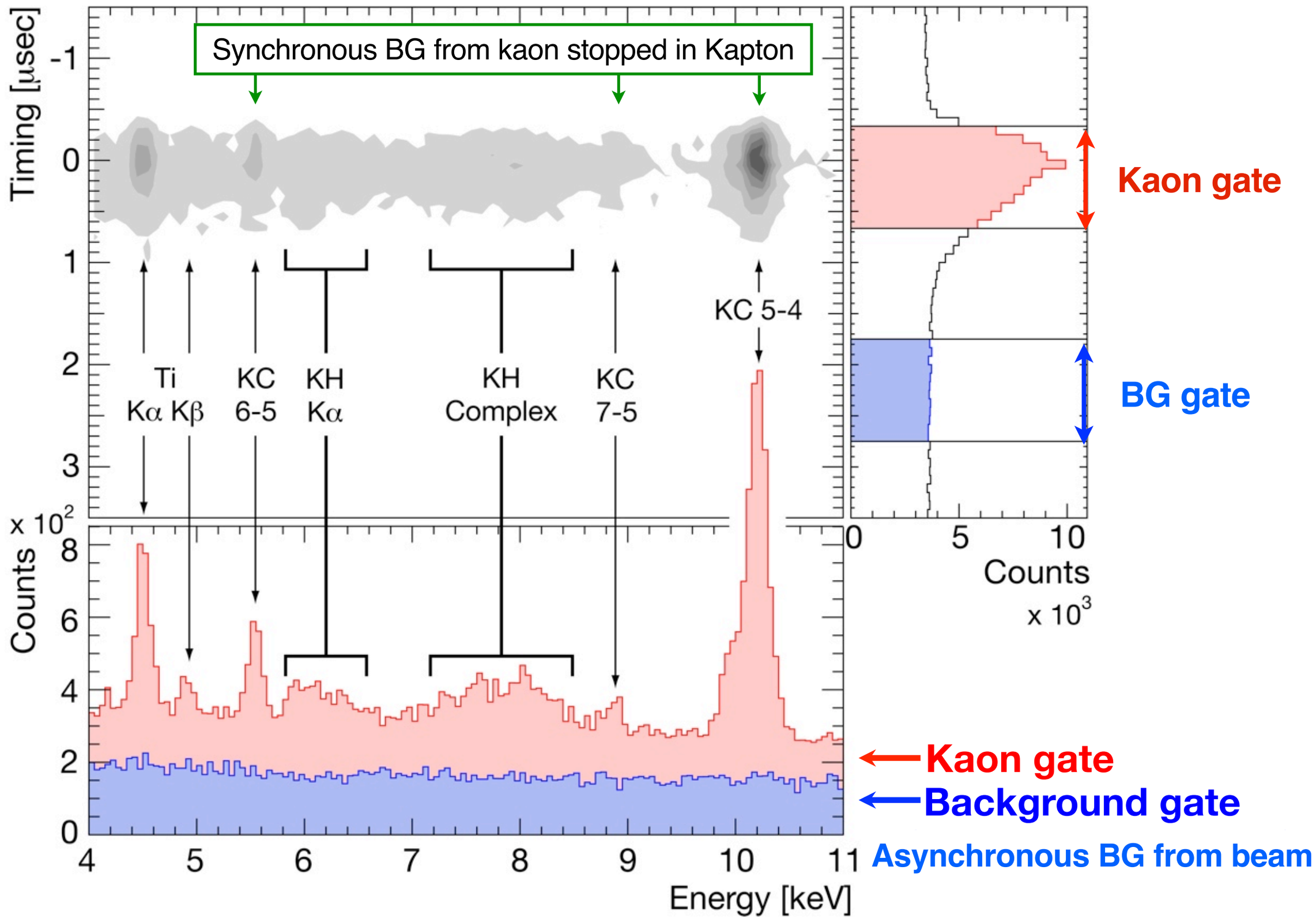


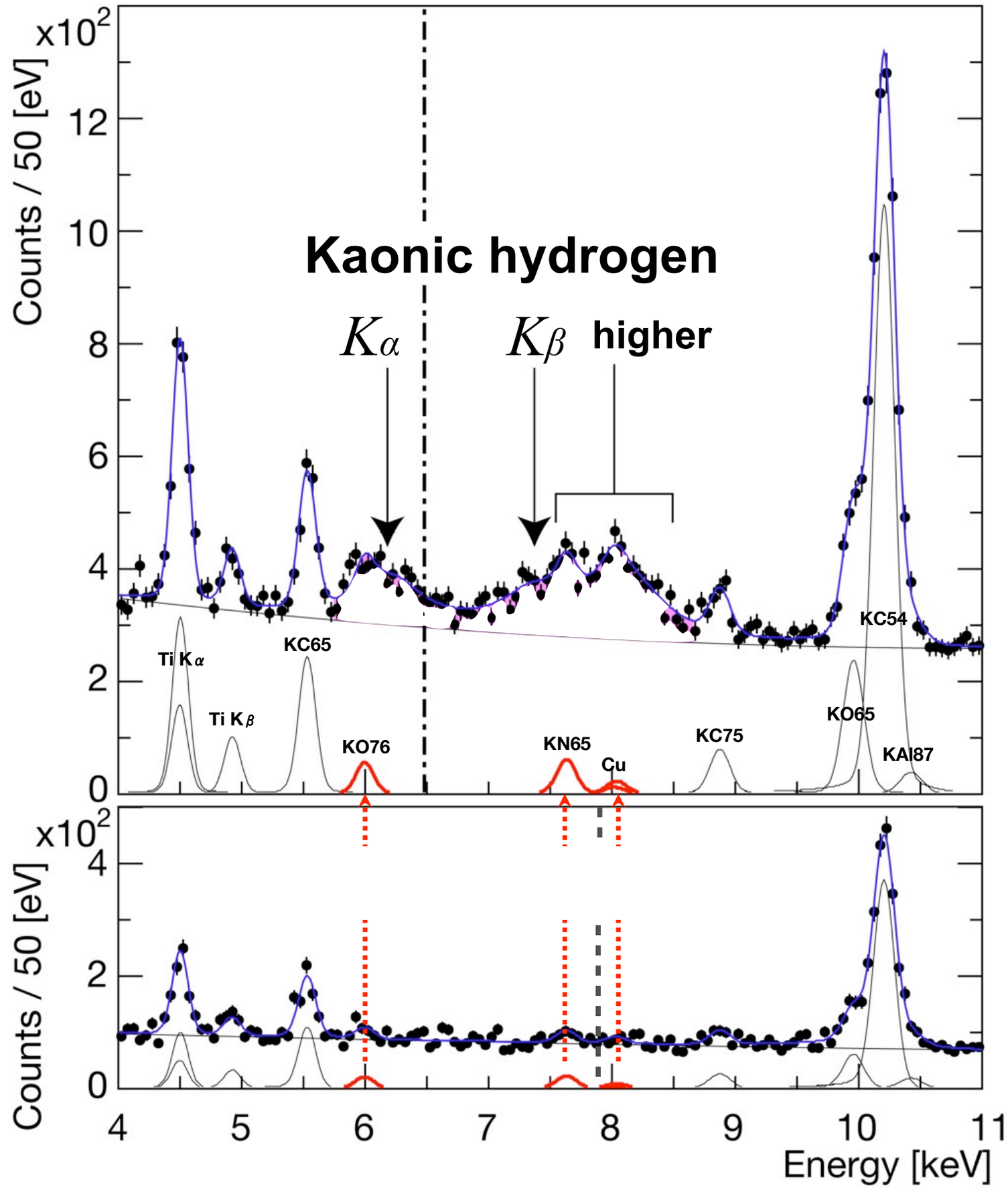
Time difference between X-ray and kaon events

Energy to timing correlation of SDD events



Hydrogen

Deuterium



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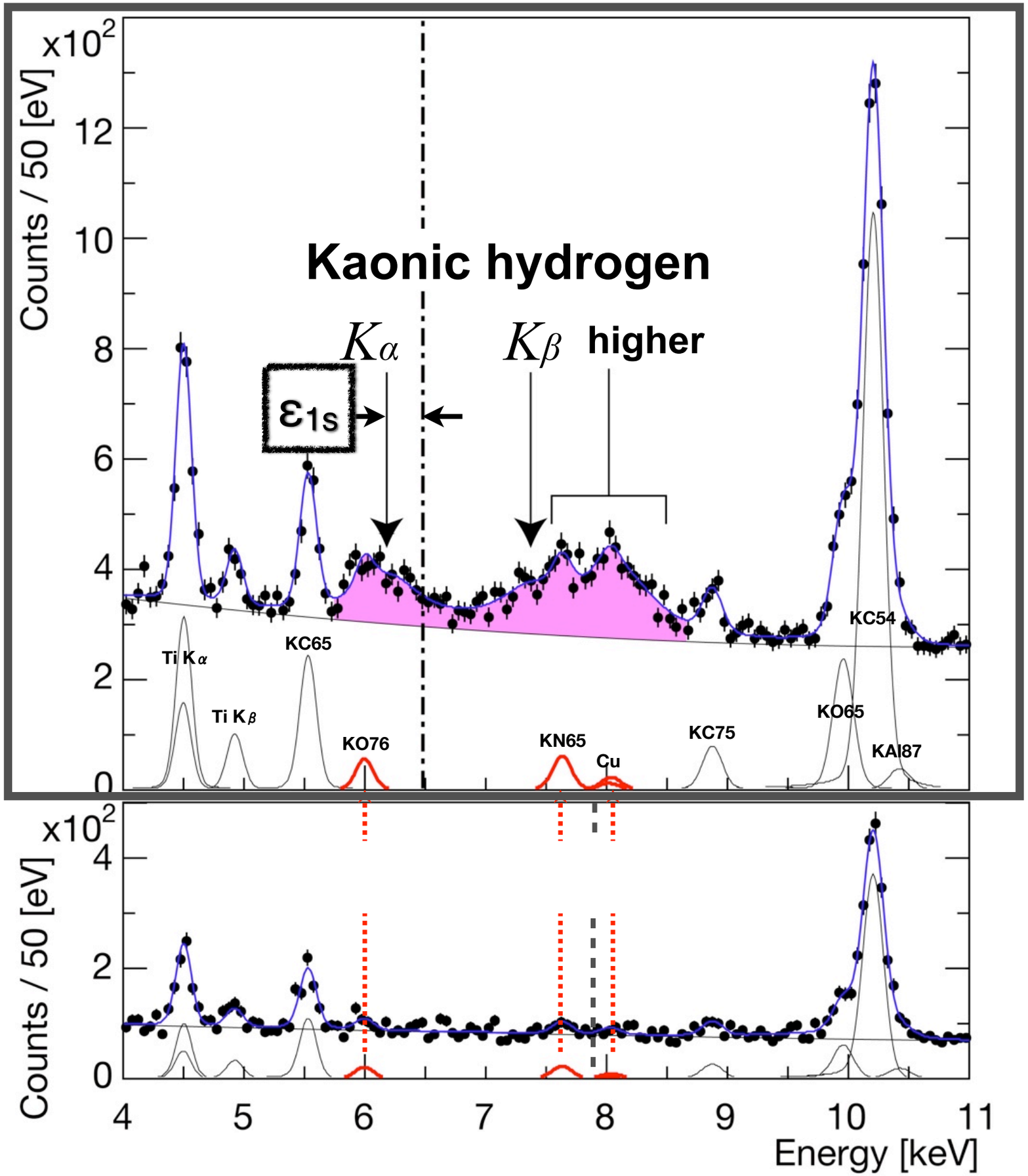

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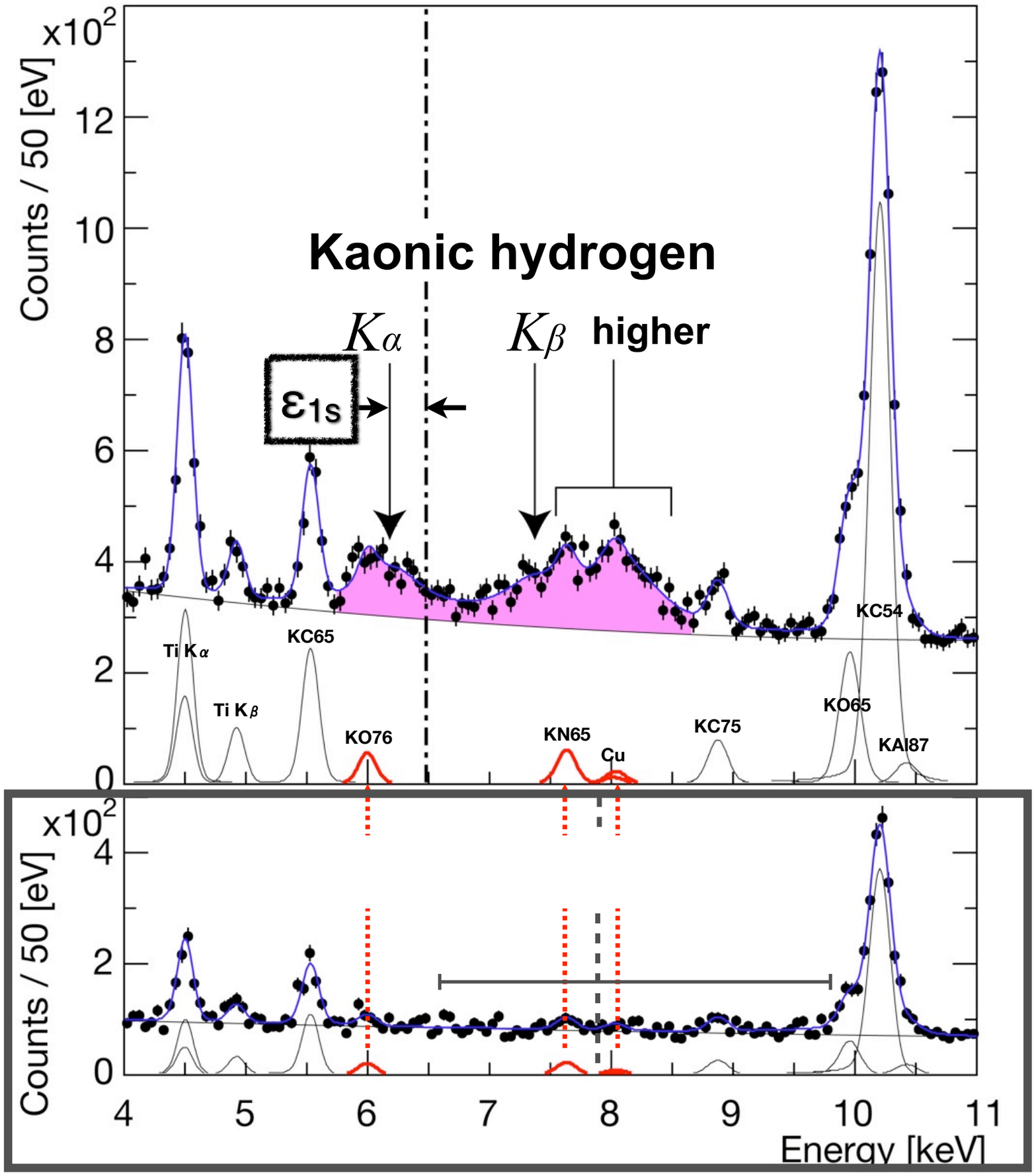

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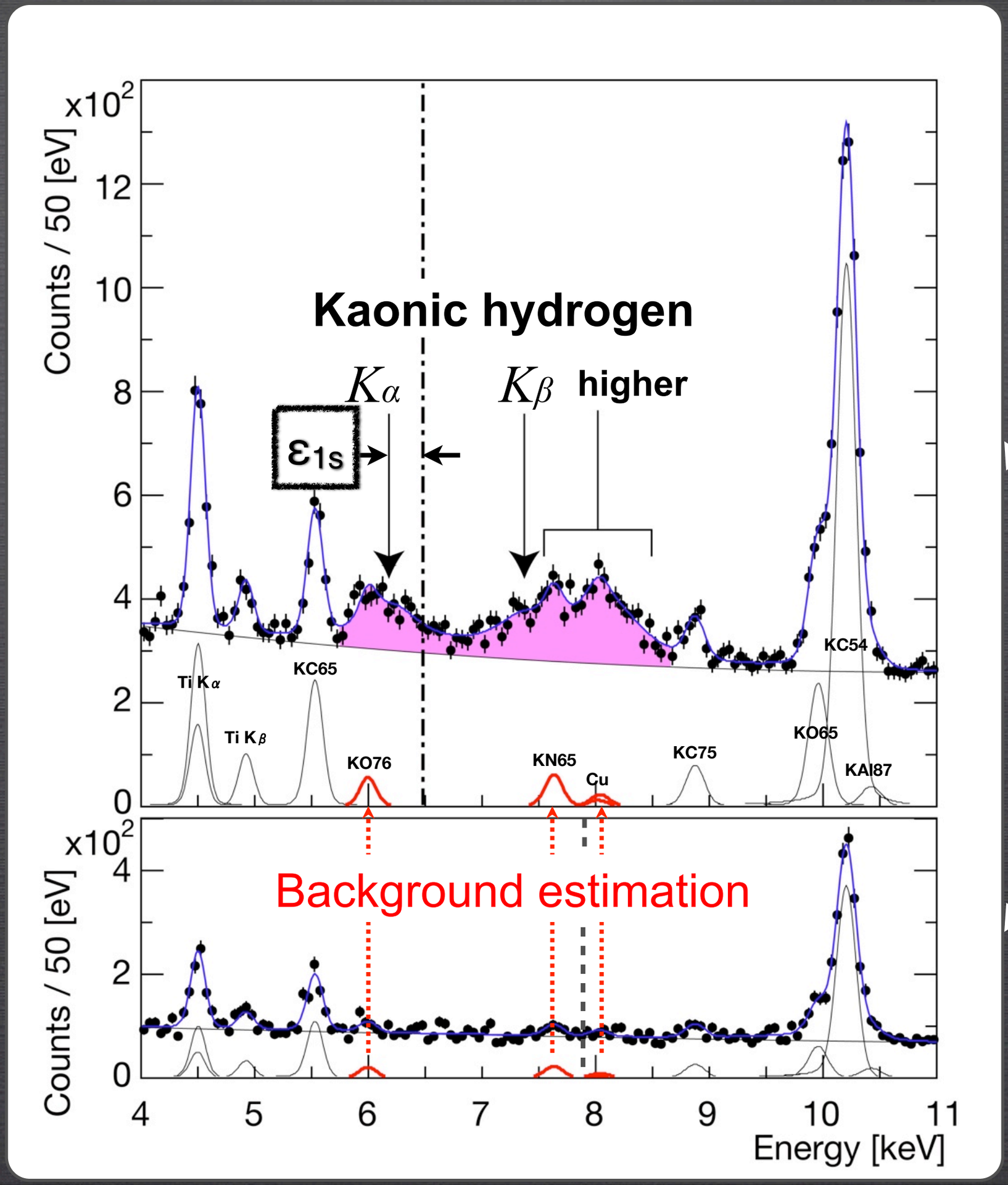
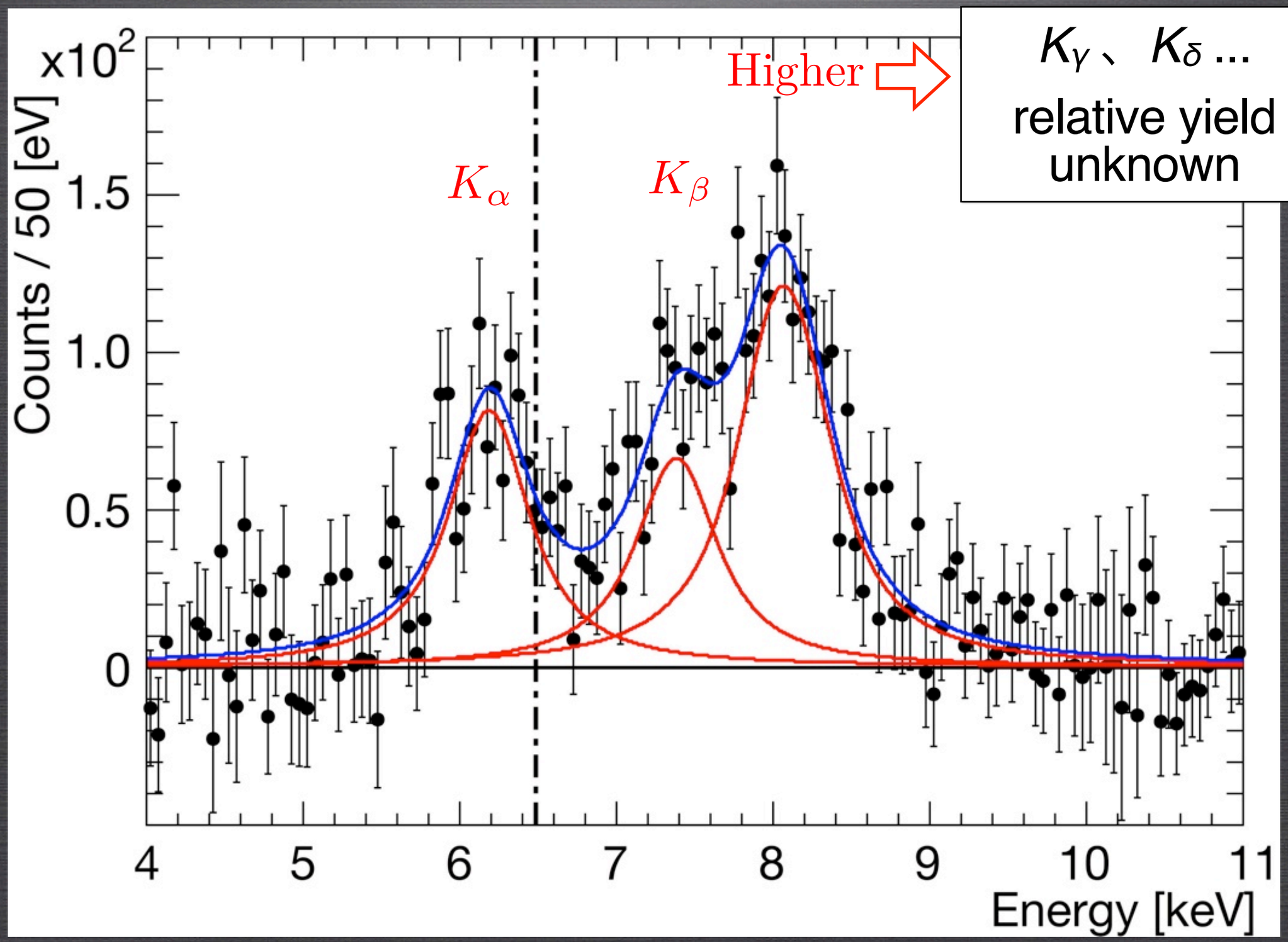


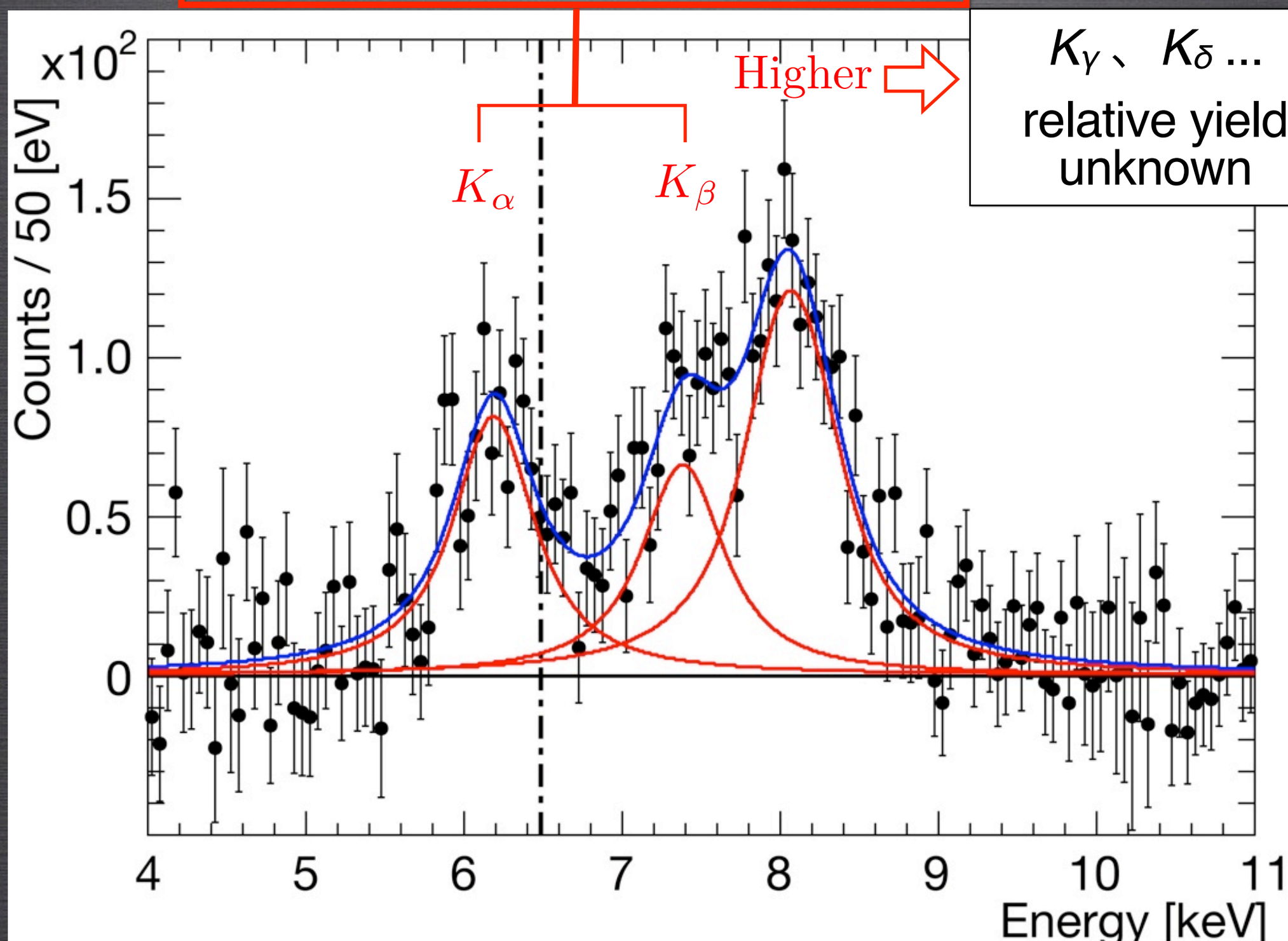
Simultaneously fit

Residuals of *K-p* spectrum after the subtraction of the fitted background



Residuals of *K-p* spectrum after the subtraction of the fitted background

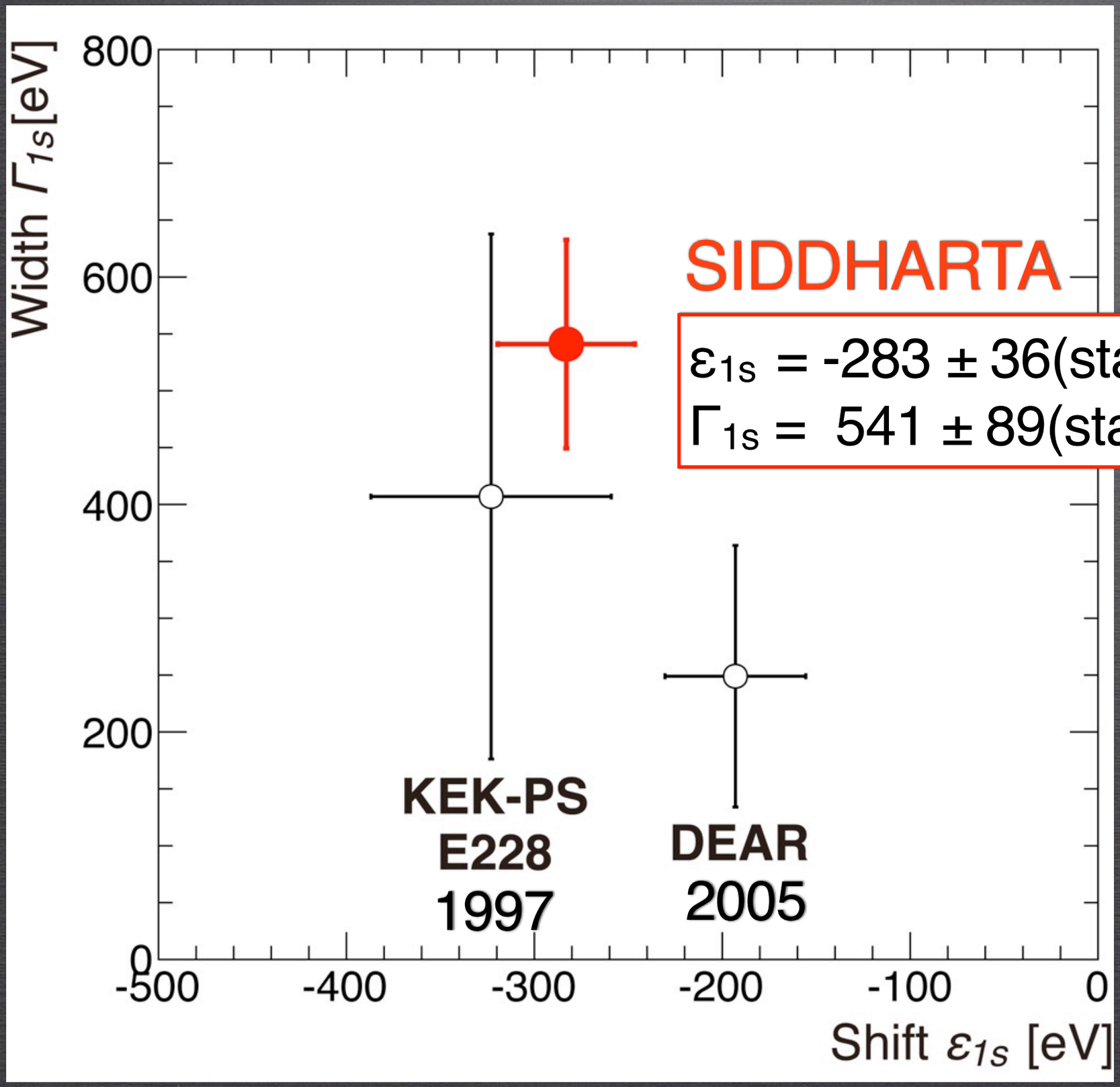
shift and width determined by Kα, Kβ



K_γ 、 K_δ ...

relative yield unknown

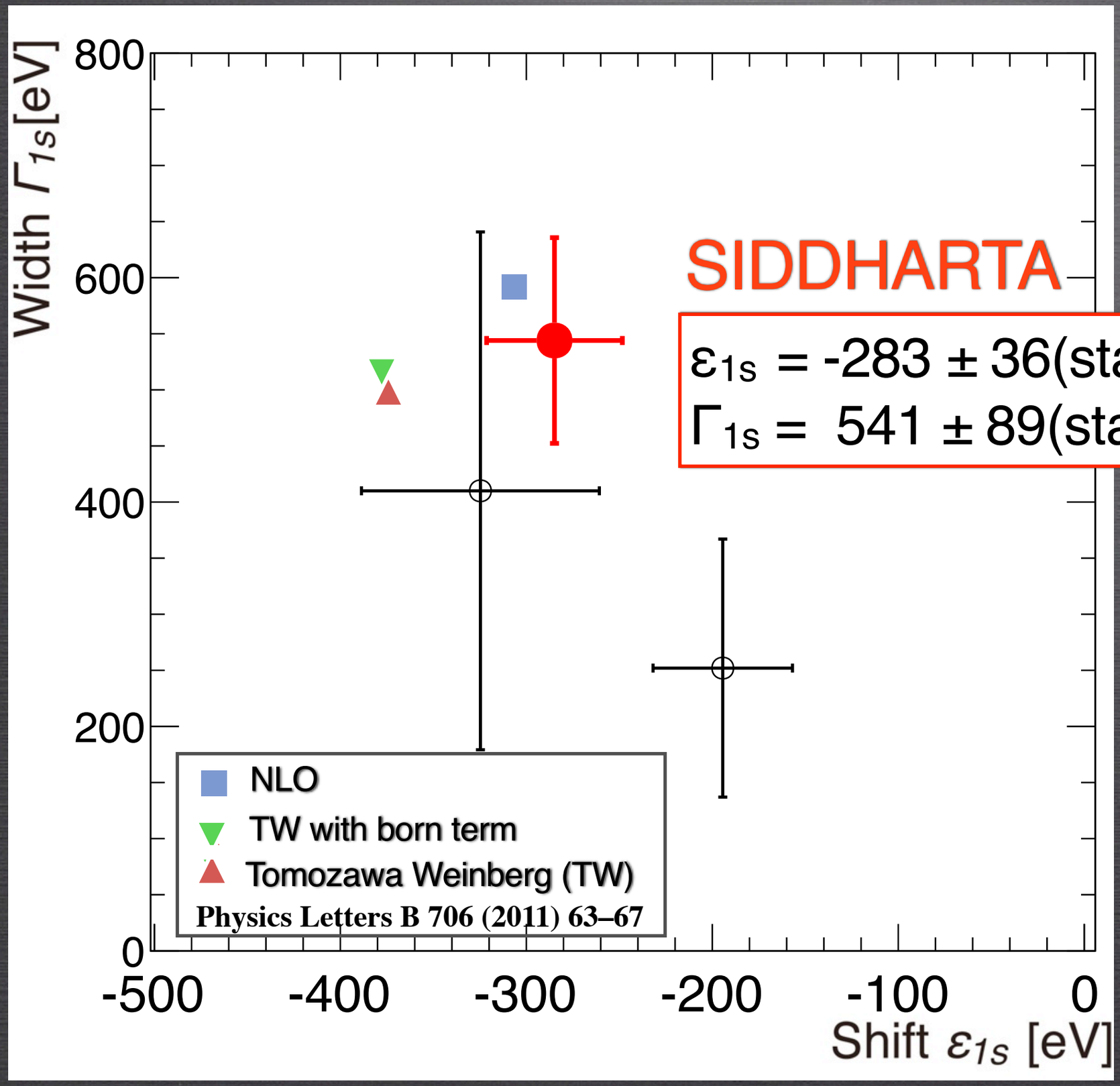
Results on *K*-p *1s* state shift and width



ε_{1s} = -283 ± 36(stat.) ± 6(syst.) eV
Γ_{1s} = 541 ± 89(stat.) ± 22(syst.) eV

Best precision

Results on *K*-p *1s* state shift and width



SIDDHARTA

ε_{1s} = -283 ± 36(stat.) ± 6(syst.) eV
Γ_{1s} = 541 ± 89(stat.) ± 22(syst.) eV

Best precision

coupled-channels method with for chiral SU(3) dynamics;
best fit to together with scattering data

SIDDHARTA-2

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

μ_c : reduced mass of *K*-p

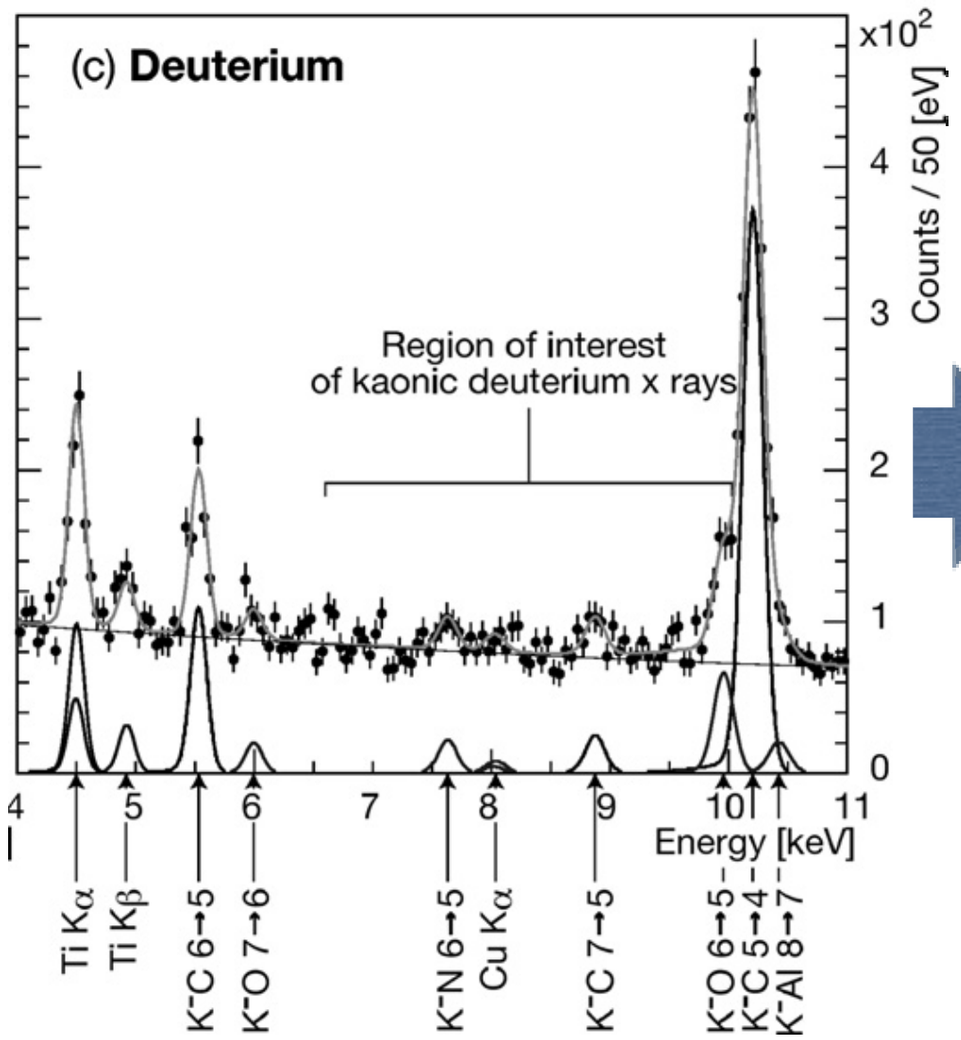
Kaonic deuterium

X-ray measurement: key to obtain the isospin-dependent antikaon-nucleon scattering lengths at threshold.

➡ breakthrough in the low energy QCD.

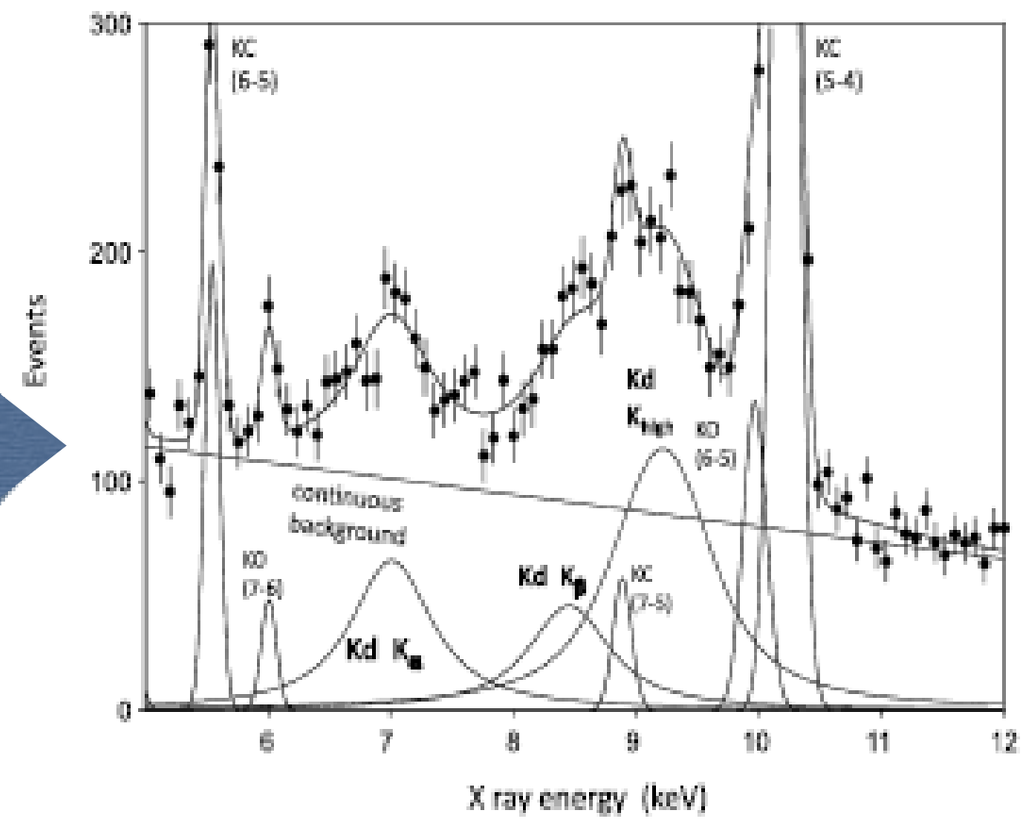
SIDDHARTA-2 goal

SIDDHARTA(2009)



~100 pb^{-1}

SIDDHARTA2 (expected spectrum)



assuming

0.1% yield (1/10 of Kp)

800 pb^{-1}

K-d yield upper limit :
Y (Kα) < 0.39 % (CL 90%).
NPA 907 (2013) 69

fit result (all intensities free) sample 1
shift = -556+-86 eV width= 1284+-145 eV

Improvement factors

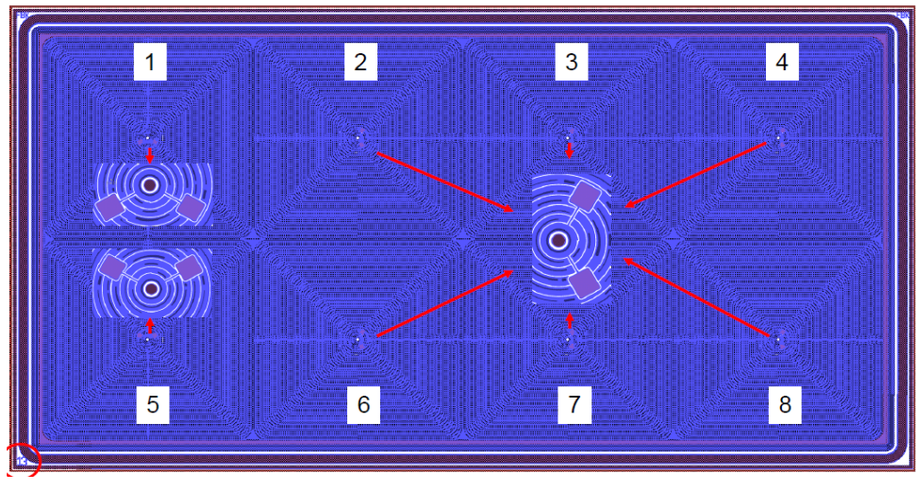
MC simulation - summary

	new geometry & gas density	timing resolution	$K^{\pm}$ dis-crimination	del'd anti-coinc.	prompt anti-coinc.	total impr. factor
Signal	**2.5**		**0.8**			**2.0**
kaonic X-rays wall stops	**20**					**20**
continuous background / Signal /keV	**3.8** ratio of gasstops vs. decay+wallstops		**2** events due to decay of K^{+} removed		**2** charged particle veto	**15.2**
beam background (asynchron)	**4.8** less trigger per signal	**1.5** smaller coincidence gate		**3** „active shielding“		**21.6**

From Dr. C. Curceanu, presentation at 45th LNF-INFN Scientific Committee, November 2012

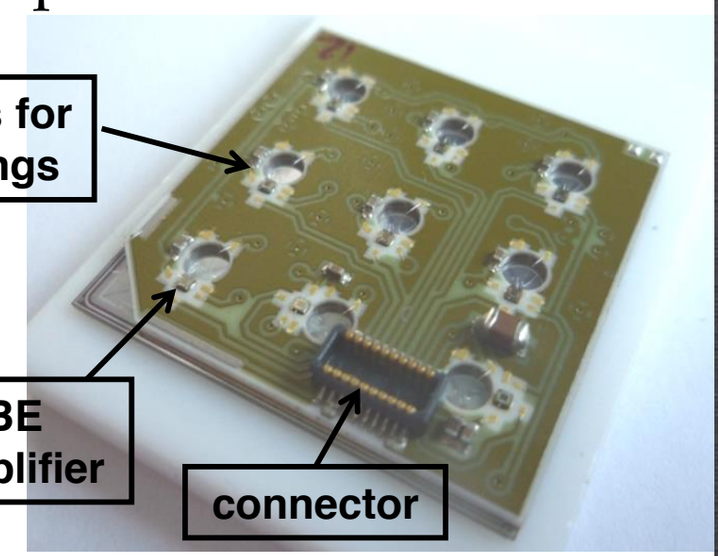
New SDD development

Prototype of the new 4x2 SDD array



SDD-chip back side with bonding pads

SDD-chip glued to ceramic board, bonded to CUBE preamplifier



Summary

❖ kaonic atom X-rays successfully measured with gaseous targets of Z = 1 & 2

- K-p : *1s* shift and width determined to the best precision
- K-d : first exploratory measurement
- K-^{3}He : strong-shift of *2p* state determined for the first time
- K-^{4}He : measured for the first-time with a gaseous target
- K-Kapton : yield of X-rays for KO and KN

❖ SIDDHARTA-2 is planning the *first precision measurement* of the K-d X-ray

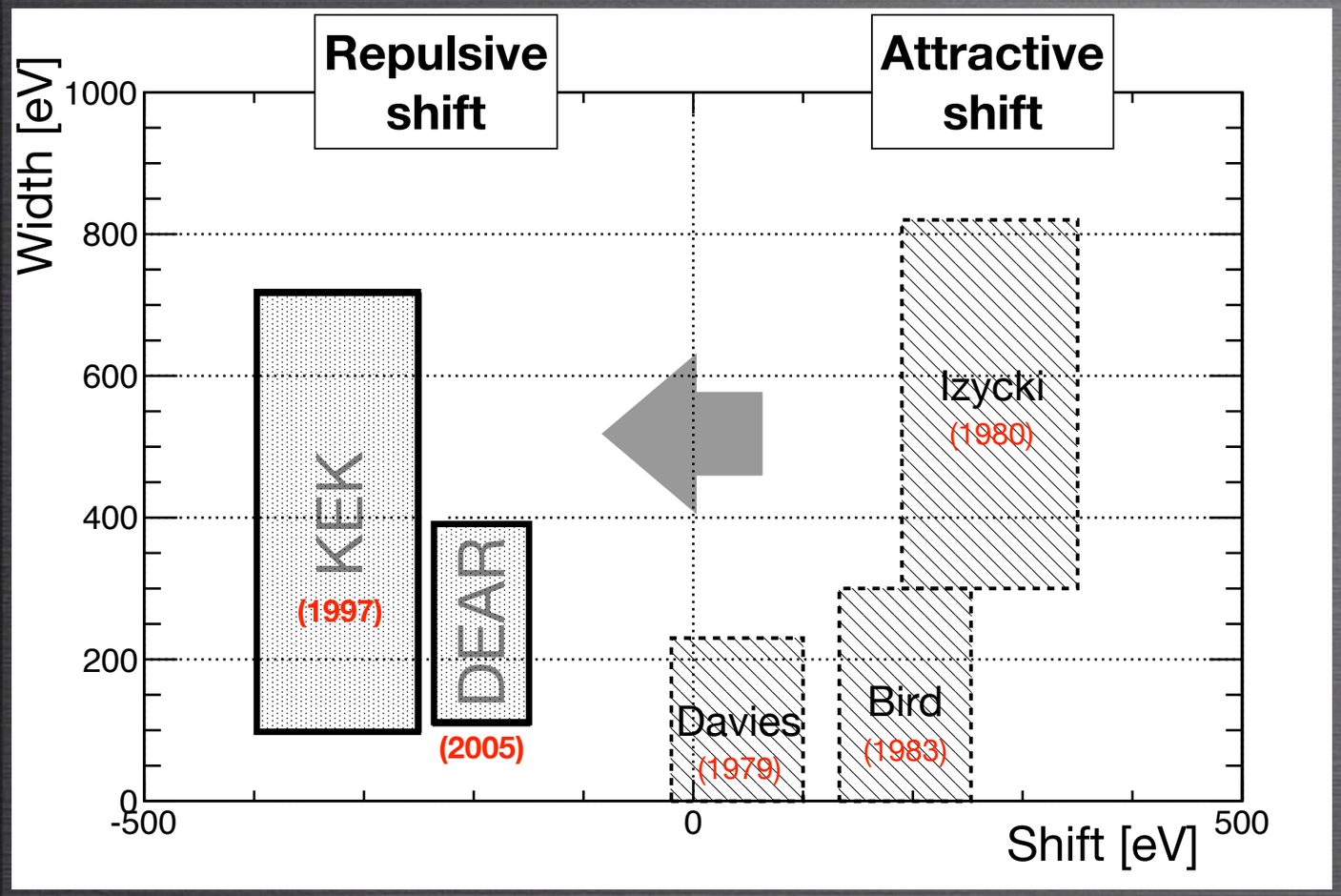
SIDDHARTA Collaboration

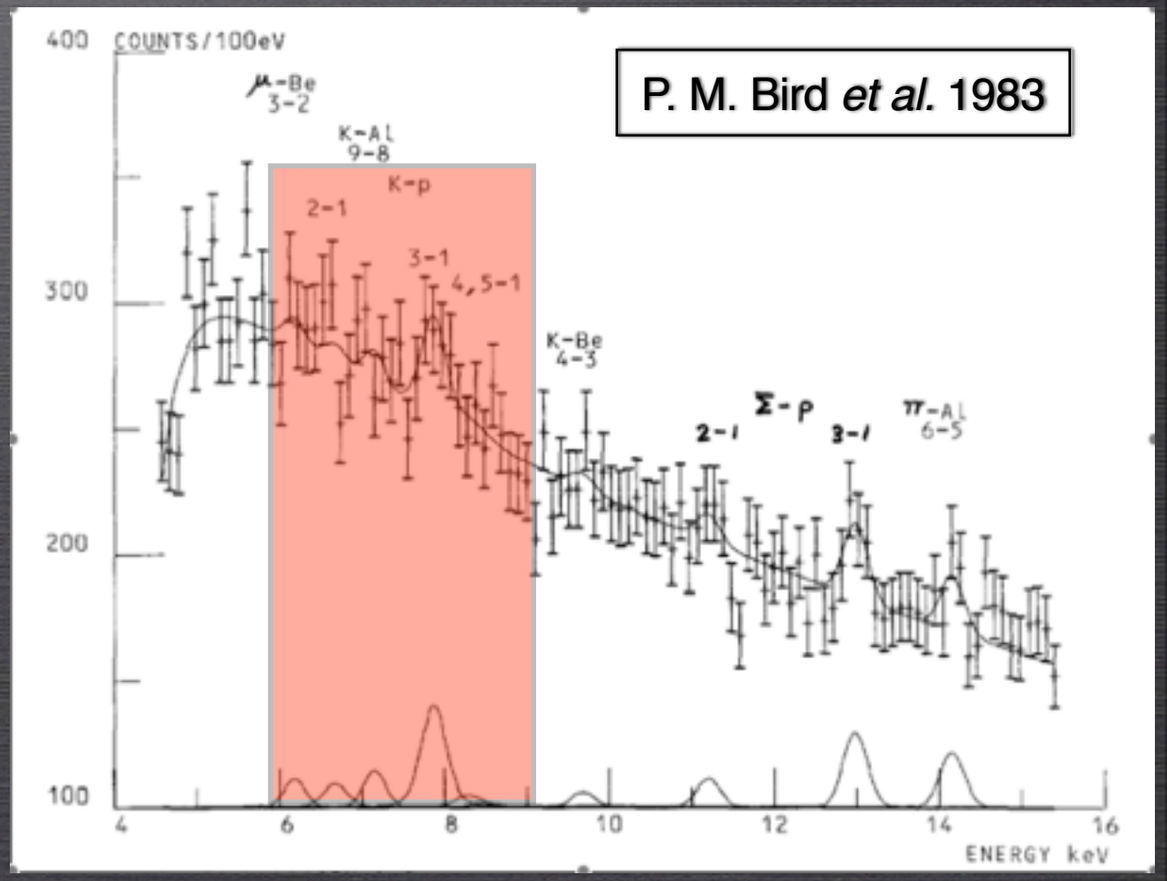
M. Bazzi [A], G. Beer [B], L. Bombelli [C], A.M. Bragadireanu [A,D], M. Cargnelli [E], G. Corradi [A], C. Curceanu (Petrascu) [A], A. d'Uffizi [A], C. Fiorini [C], T. Frizzi [C], F. Ghio [F], B. Girolami [F], C. Guaraldo [A], R. S. Hayano [G], M. Iliescu [A,D], T. Ishiwatari [E], M. Iwasaki [H], P. Kienle [E,I], P. Levi Sandri [A], A. Longoni [C], V. Lucherini [A], J. Marton [E], S. Okada [A], D. Pietreanu [A], T. Ponta [D], A. Rizzo [A], A.Romero [A], A. Scordo [A], H. Shi [G], D.L. Sirghi [A,D], F. Sirghi [A,D], H. Tatsuno [A], A. Tudorache [D], V. Tudorache [D], O. Vazquez Doce [A], E. Widmann [E], J. Zmeskal [E]

INFN(LNF) [A], Univ. Victoria [B], Politecnico Milano [C], IFIN-HH [D], SMI [E], INFN Sezione di Roma I and Istituto Superiore di Sanita' [F], Univ. Tokyo [G], RIKEN [H], TUM [I]

Appendix

Past experiments-1

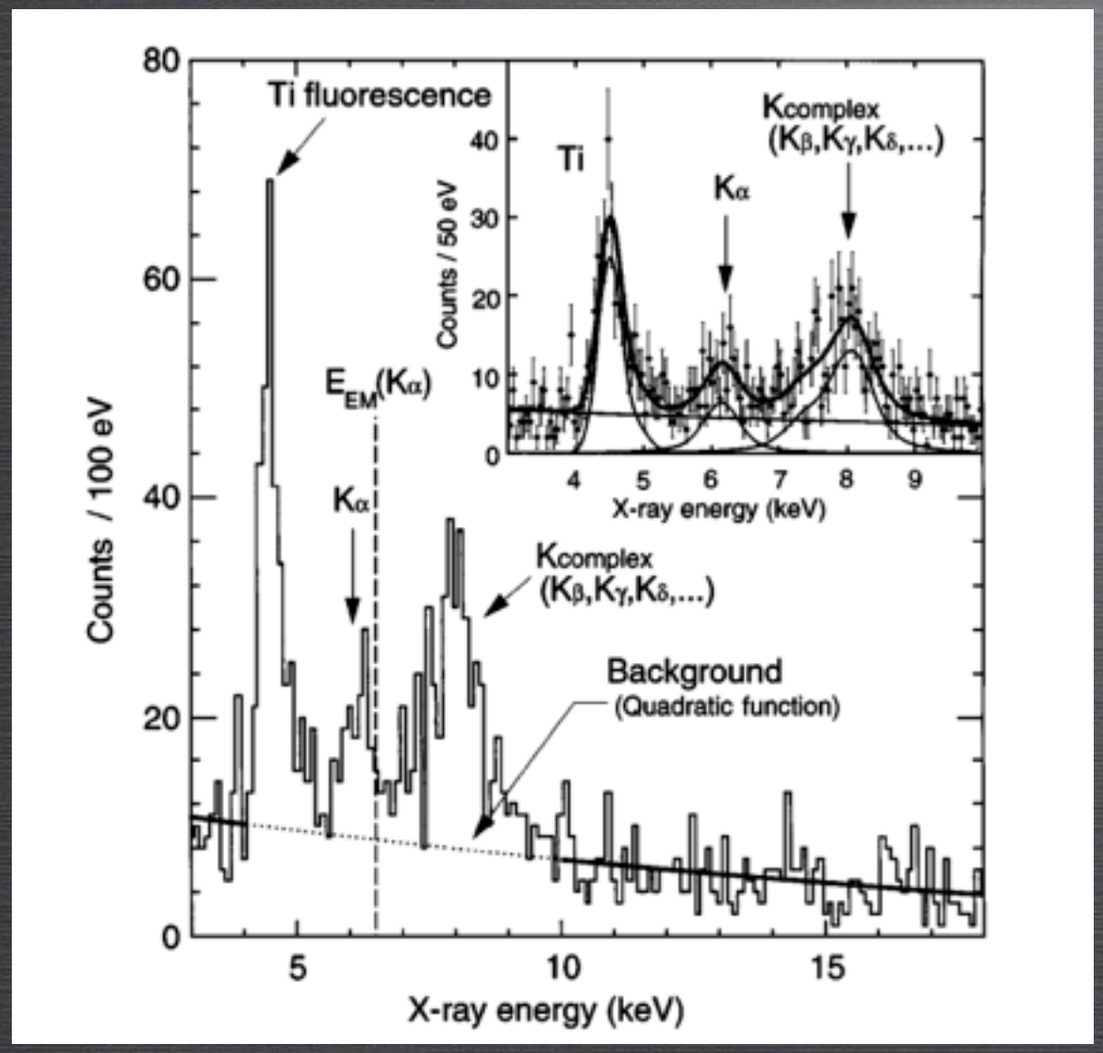




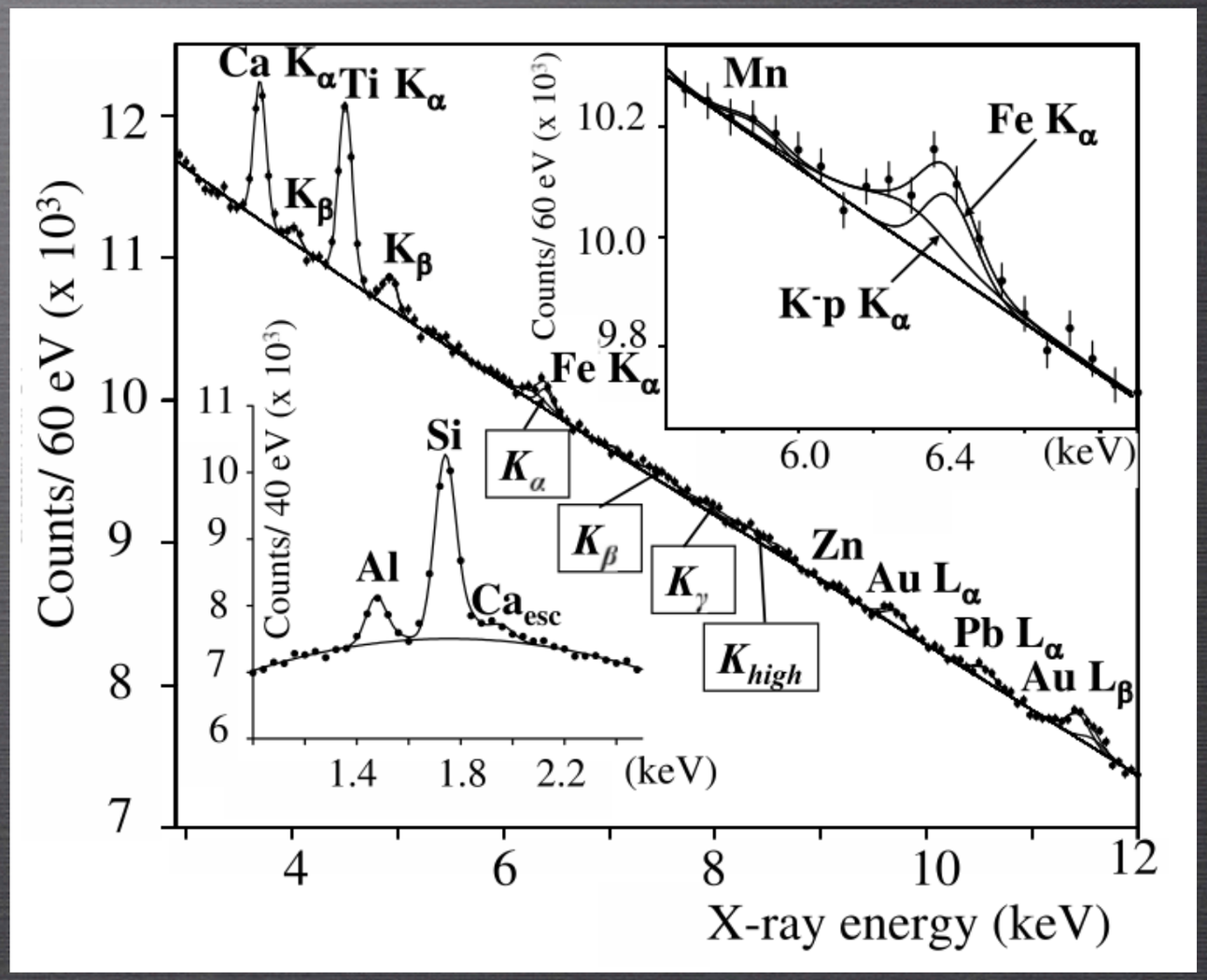
liquid target

Past experiments-2

KEK-PS E228 (KpX) 1997



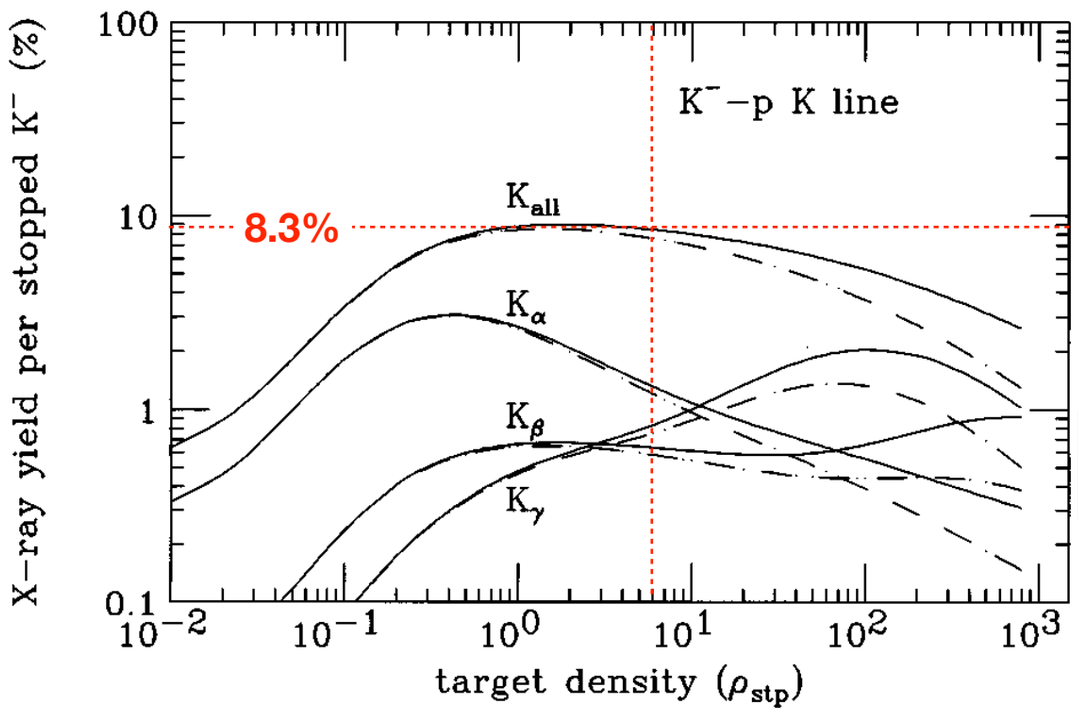
DEAR DAFNE 2005



Cascade calculation

Koike et al., PRC53(1996)79

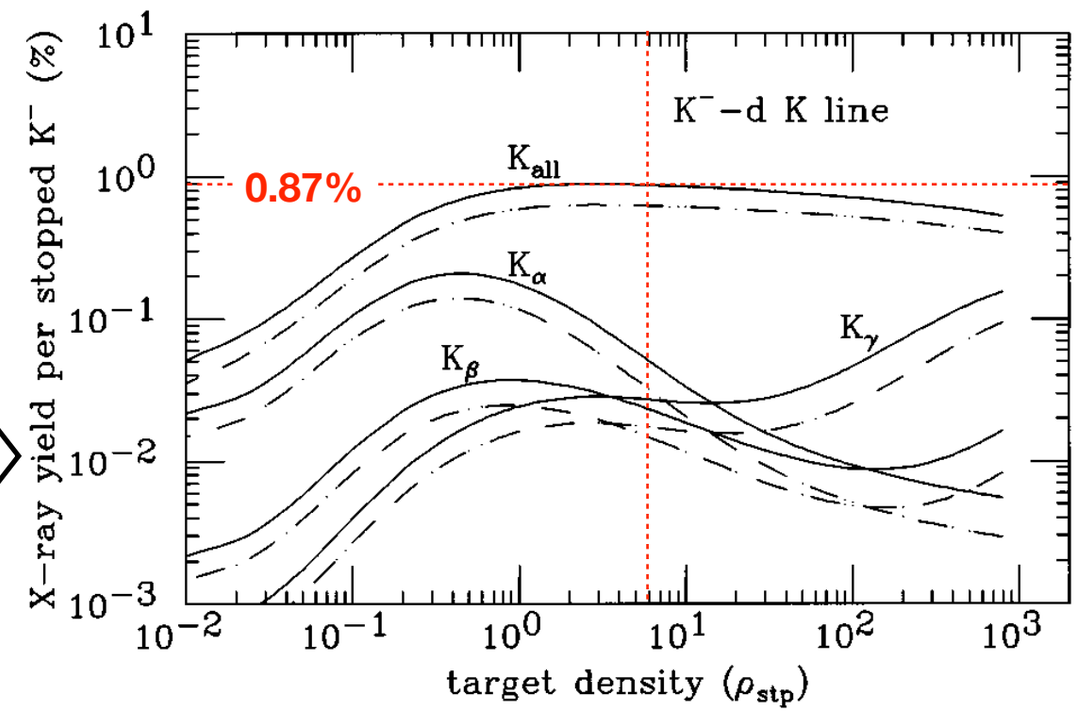
K-p



6 STP Kα/Kall ~ 15%

FIG. 5. Density dependence of K^--p atom x-ray yields with varying $(\delta E_{1s})_{\rm strong}$ and $\Gamma^{\rm abs}_{1s}$. 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 $\Gamma^{\rm abs}_{2p}$ 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 helium *2p* shift results

	2p shift [eV]	Reference
KEK E570	+2 ± 2 ± 2	PLB653(2007)387
SIDDHARTA (He4)	0 ± 6 ± 2	PLB681(2009)310
SIDDHARTA (He3)	-2 ± 2 ± 4	PLB697(2011)199

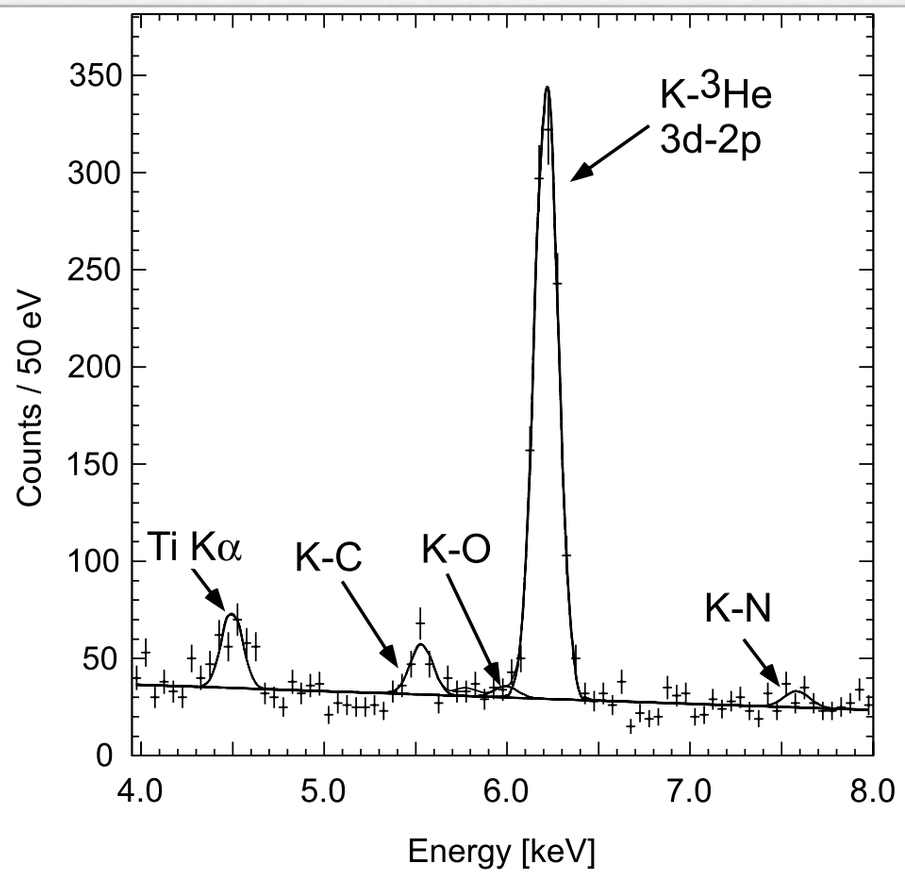


Fig. 5. Energy spectrum of the kaonic ^{3}He X-rays in coincidence with the K^+K^- events. The kaonic ^{3}He $3d \rightarrow 2p$ transition is seen at 6.2 keV. Together with this peak, small peaks are seen, which are the kaonic atom X-ray lines produced by kaons stopping in the target window made of Kapton (polyimide), and the Ti Kα line at 4.5 keV.

PLB 681(2009)310

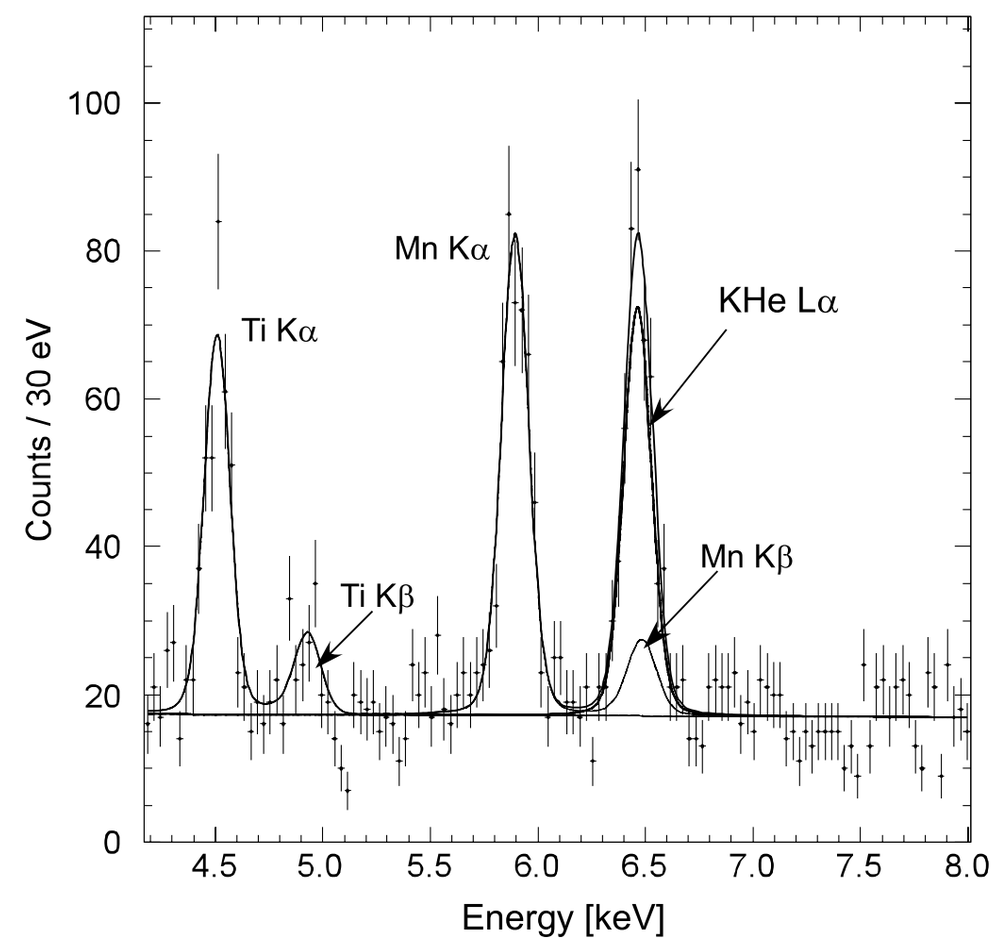
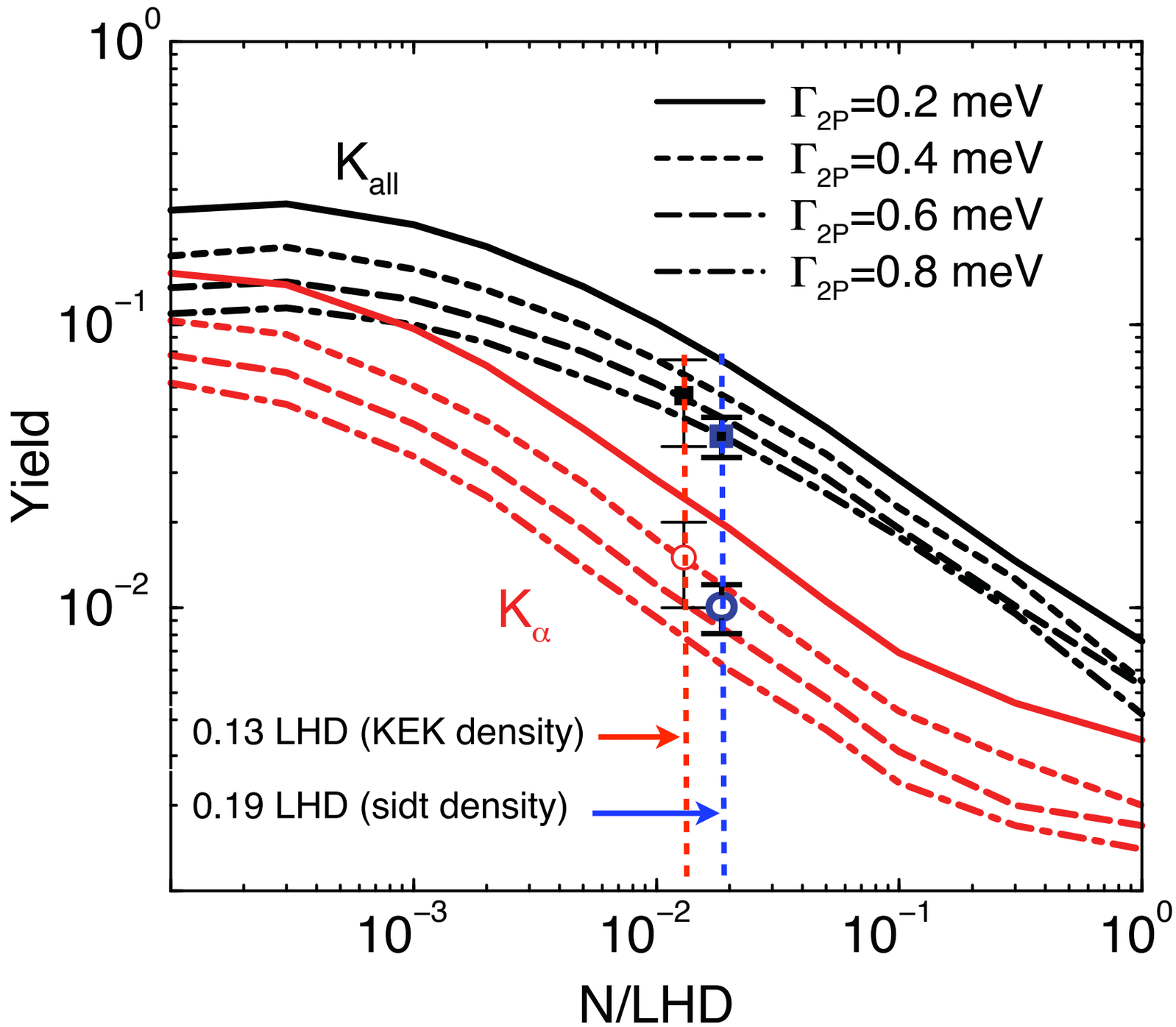


Fig. 5. Energy spectrum of the kaonic ^{4}He X-rays in coincidence with the K^+K^- events. Together with the accidental coincidence events of the Ti and Mn X-rays, the kaonic ^{4}He Lα line is seen at 6.4 keV.

PLB 697(2011)99

preliminary kaonic hydrogen yield

Kp *Ka* yield with comparison to cascade calculation



T.S. Jensen and V.E. Markushin, LNP 627, (2003) 37-57

K_{all}

0.043 + 0.011- 0.012.

K_a

0.012 + 0.003 - 0.004.

However, experimentally, instead of K_{all}, systematic error for $K_{complex}$ is easier to assign, and the result is:

$K_{complex}$

0.029 + 0.008 - 0.009.