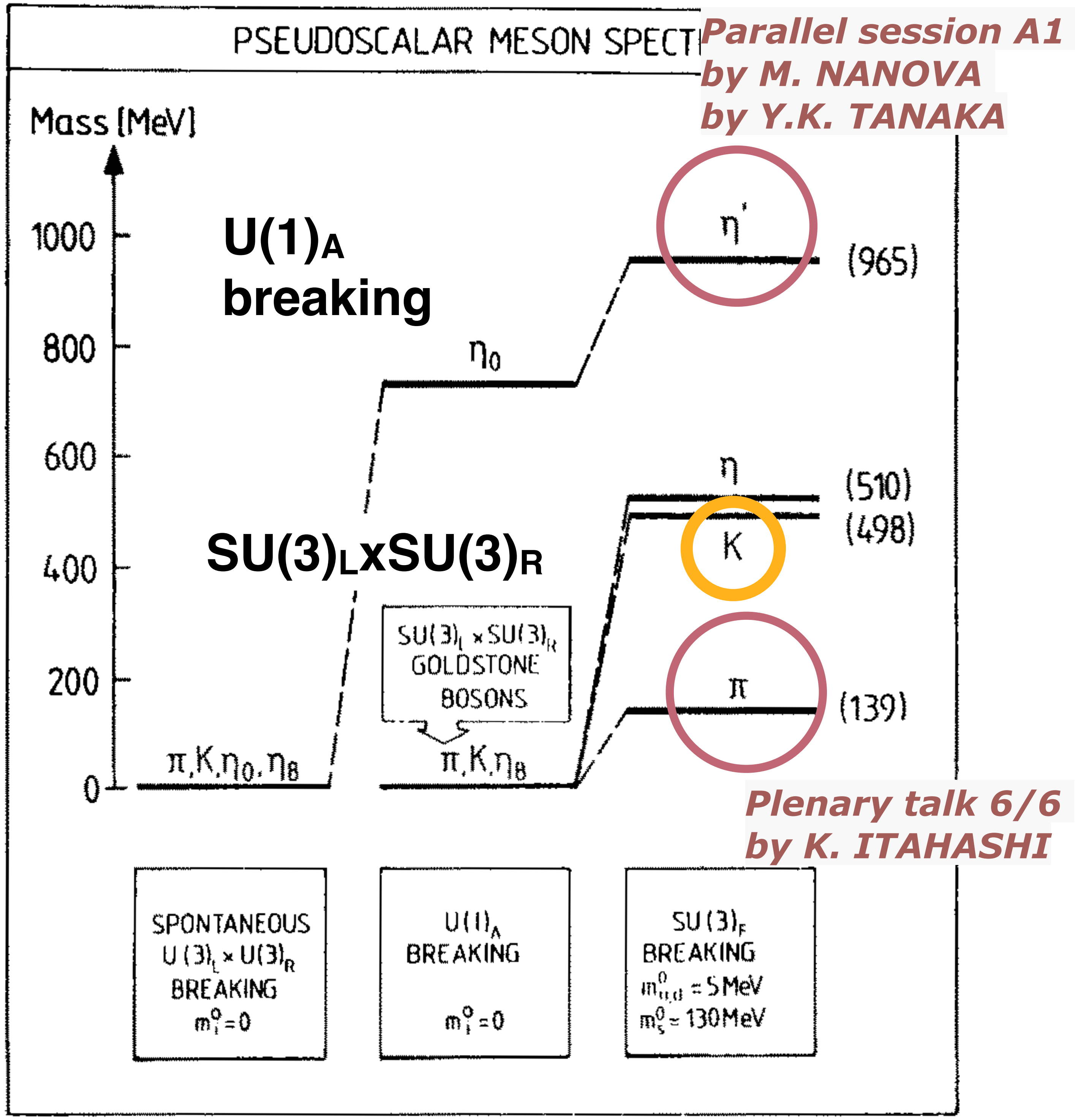
Light Kaonic Atoms

Hideyuki TATSUNO (Lund Univ.)

Shinji OKADA (RIKEN)

Kaon: pseudoscalar meson

S. Klimt, M. Lutz, U. Vogl and W. Weise, Nucl. Phys. A 516 (1990), 429.



Kaon: pseudoscalar meson

Spontaneous and **explicit** chiral symmetry breaking (*u,d,s*)

Low-energy QCD with **strangeness**

chiral SU(3)

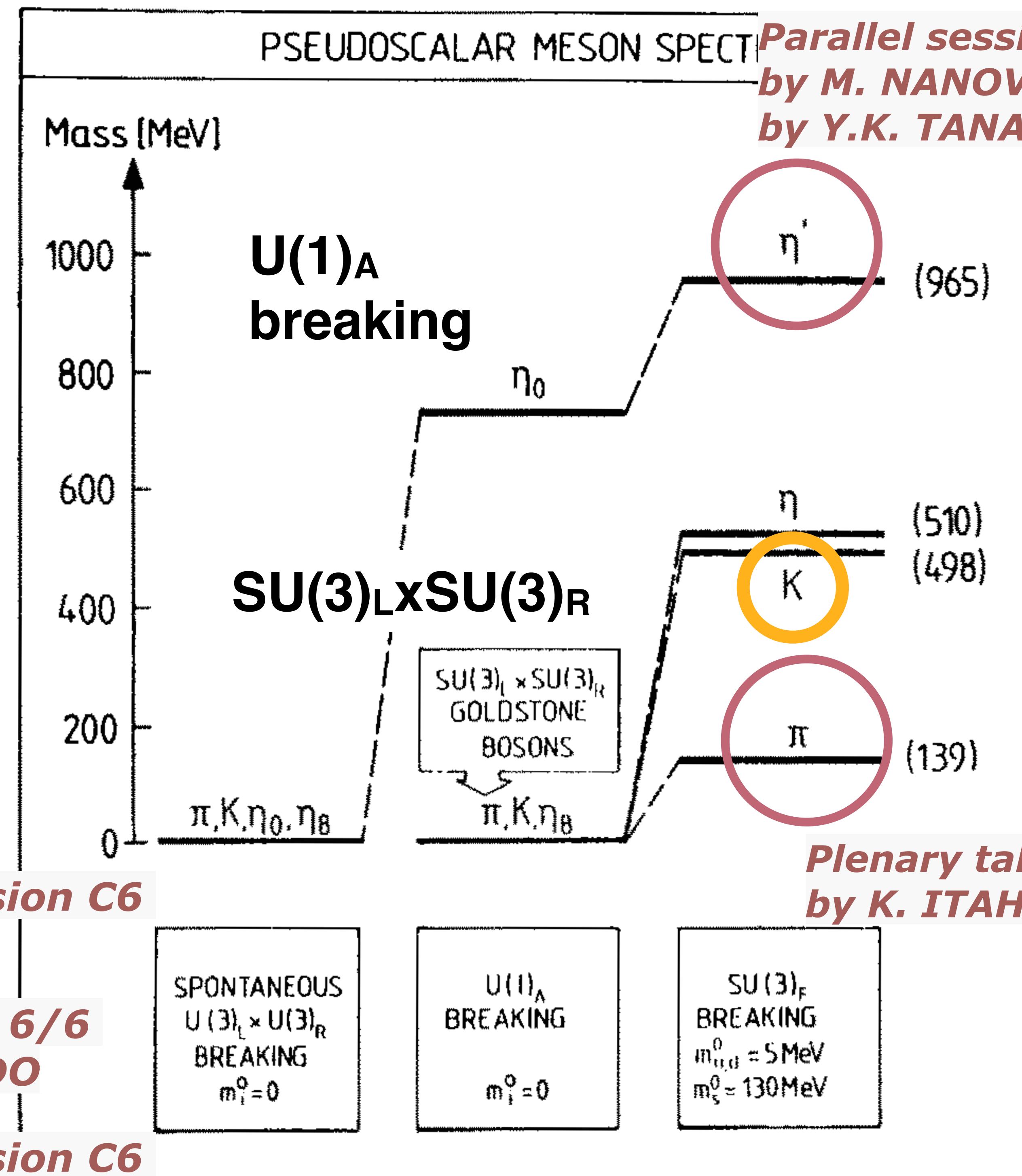
$\bar{K}N$ interaction

Exotic system

Λ(1405): K-p Σπ

K⁻ nucl. cluster

S. Klimt, M. Lutz, U. Vogl and W. Weise, Nucl. Phys. A 516 (1990), 429.



Parallel session A1 by M. NANOVA by Y.K. TANAKA

Plenary talk 6/6 by K. ITAHASHI

Parallel session C6 A. CIEPLY

Plenary talk 6/6 by A. SCORDO

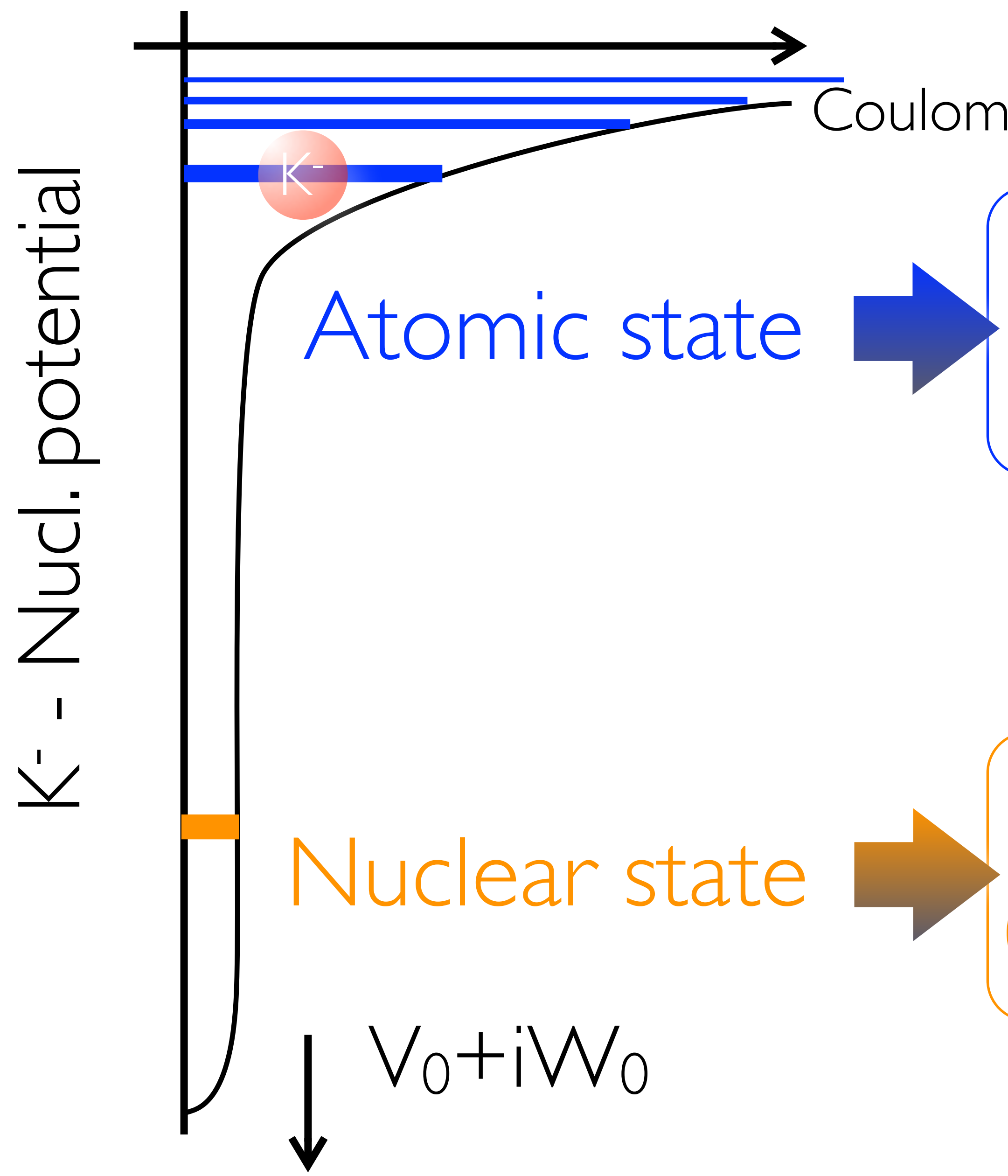
Parallel session C6 J. HRTANKOVA

Plenary talk 7/6 by M. IWASAKI

H.Tatsuno@MESON2016

Kaon-nucleus interaction

Two experimental approaches



Precision x-ray measurement
(strong interaction at threshold)

complementary

Reaction formation
(search for deeply bound K- cluster)

Experiments (past and future)

Target	Experiment	Physics
$K^- p$	KEK E228 DEAR SIDDHARTA	• Precise information of K^-p, K^-n scattering lengths • Essential inputs of chiral SU(3) dynamics • Understanding Λ(1405)
$K^- d$	SIDDHARTA2 J-PARC E57	
$K^- {}^4He$	KEK E570 SIDDHARTA J-PARC E62	• Kaon-nucleus potential depth • Chiral unitary vs Phenomenological model *'deep-or-shallow problem'* • Antikaon-nuclear cluster
$K^- {}^3He$	SIDDHARTA J-PARC E62	

“Light” Kaonic Atoms

explicit chiral
symmetry breaking

low-E QCD

chiral SU(3)

Λ(1405)

K-nucl

K-N interaction

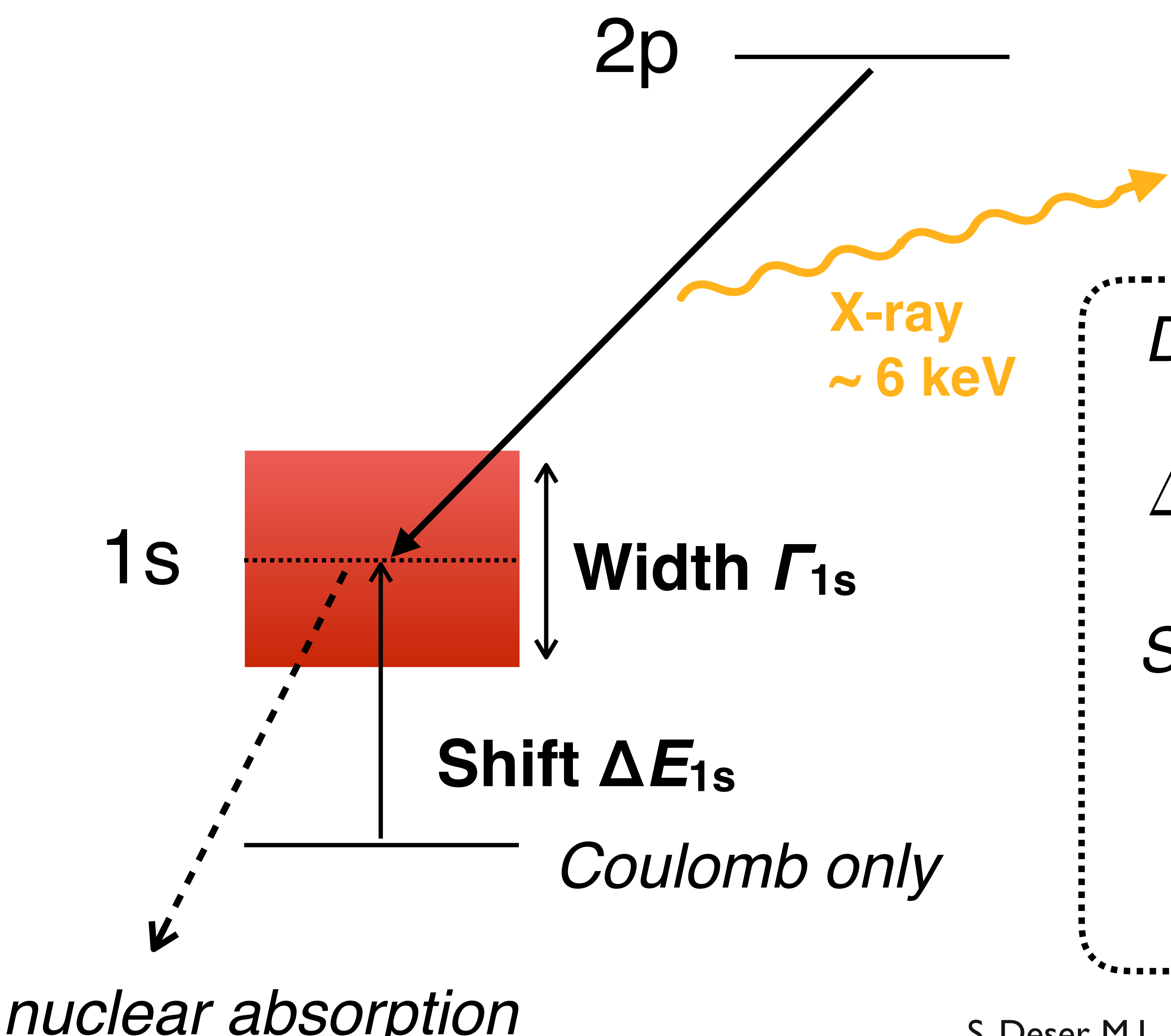
K^{-}

K-nucl potential

Kaonic atom spectroscopy

Kaonic atom spectroscopy

e.g., Kaonic hydrogen (*K-p*)



Deser-type formula

$$\Delta E_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu^2 a_{K^-p}$$

Scattering length

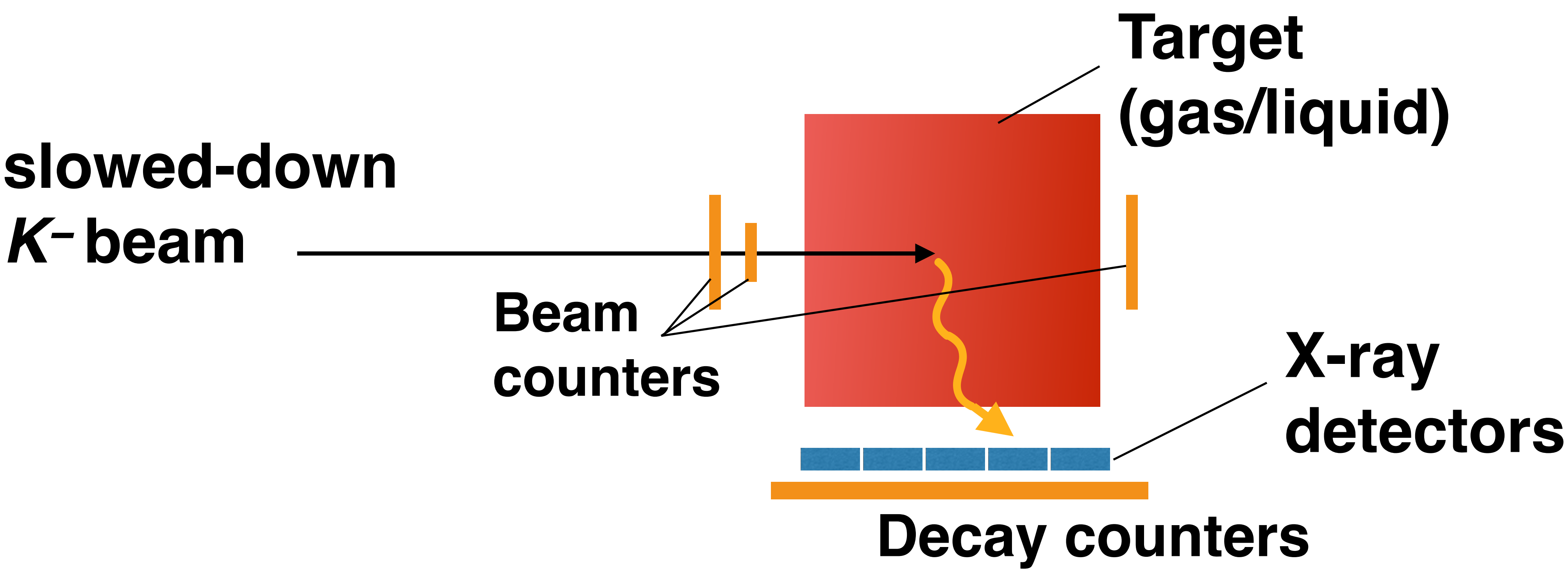
$$a_{K^-p} = \frac{1}{2}(a_0 + a_1)$$

[isospin 0 and 1]

S. Deser, M.L. Goldberger, K. Baumann and W. Thirring, Phys. Rev. 96 (1954) 774

modified by U.-G. Meißner, U. Raha, A. Rusetsky, Eur. Phys. J. C 35, 349 (2004)

How to measure x-rays



KEK–PS/J–PARC
(proton synchrotron), Japan

- secondary K– beam line
- high intensity beam

DAΦNE (e+e– collider), Italy

$\phi \rightarrow K^+ K^-$

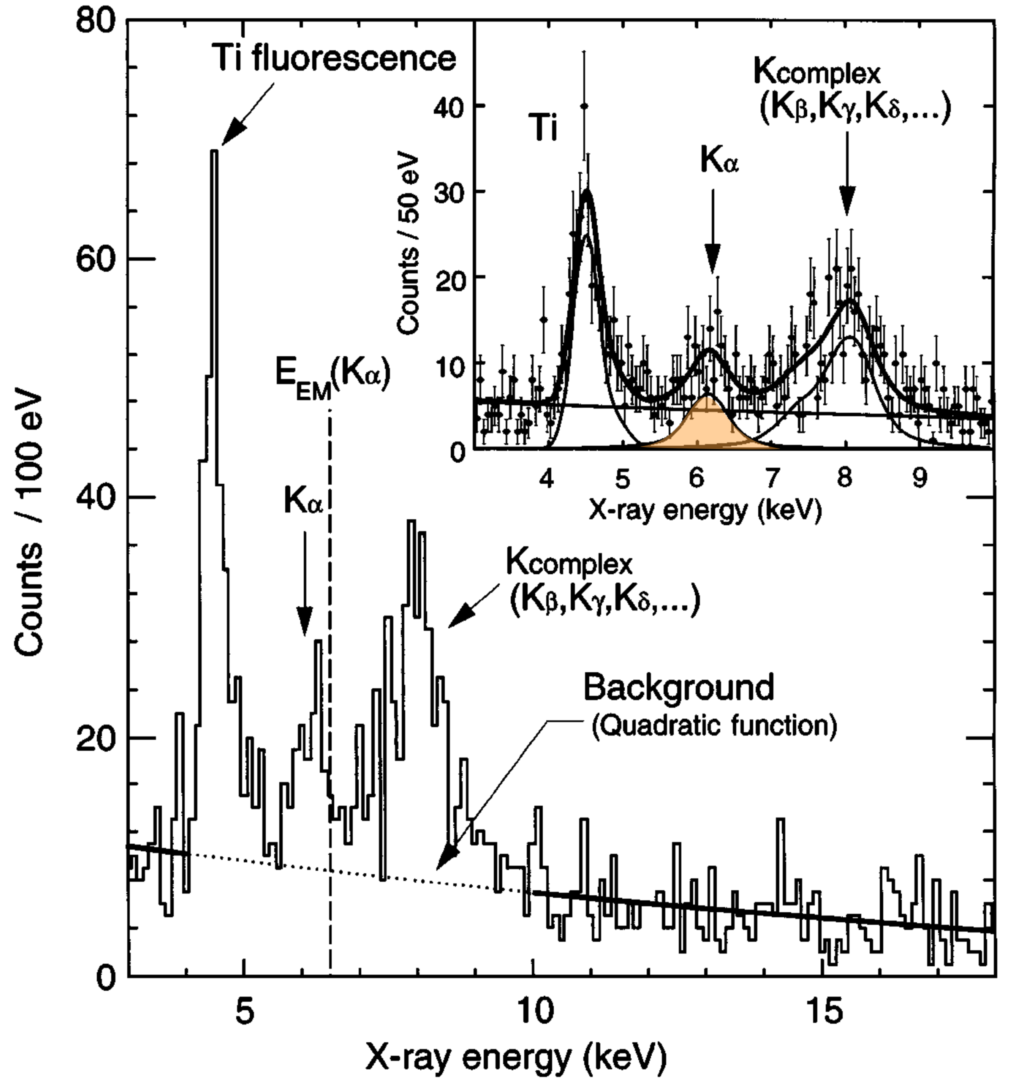
- slow and monochromatic K^-

Key points of experiment

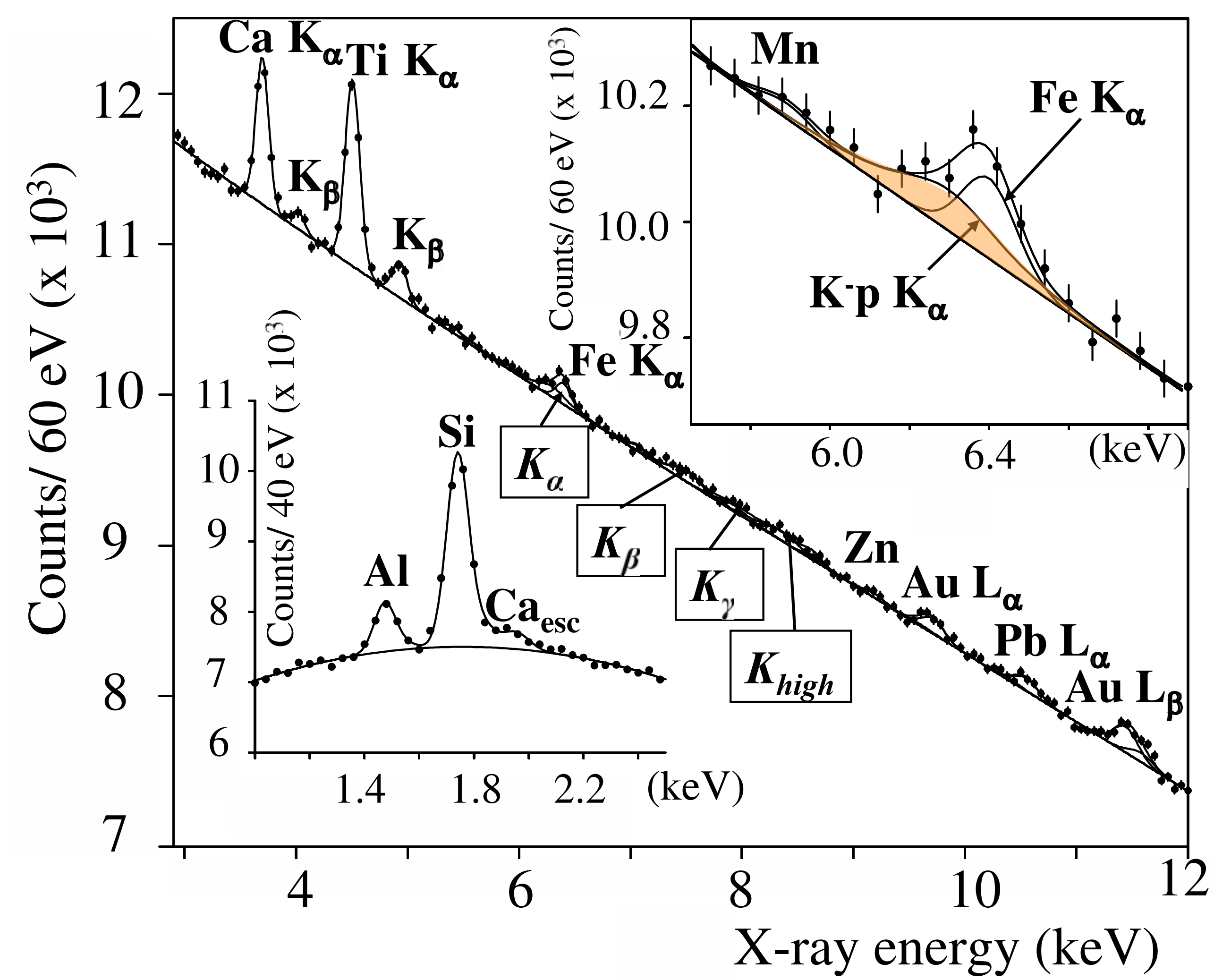
1. low absolute yield
   → long measurement / large area
2. high background
   (beam synchronous/asynchronous)
   → event selection / timing cuts
3. calibration
   → well-known characteristic x-rays
4. need high energy resolution

Kaonic hydrogen experiment (1)

M. Iwasaki et al., Phys. Rev. Lett. 78 (1997) 3067



G. Beer et al., Phys. Rev. Lett. 94 (2005) 212302



KEK-PS E228 (1997)

- Si(Li) x-ray detector (120 cm^2)
- 360 eV FWHM at 6 keV
- sub-μs timing information
- event selection (low BG)

DAΦNE DEAR (2005)

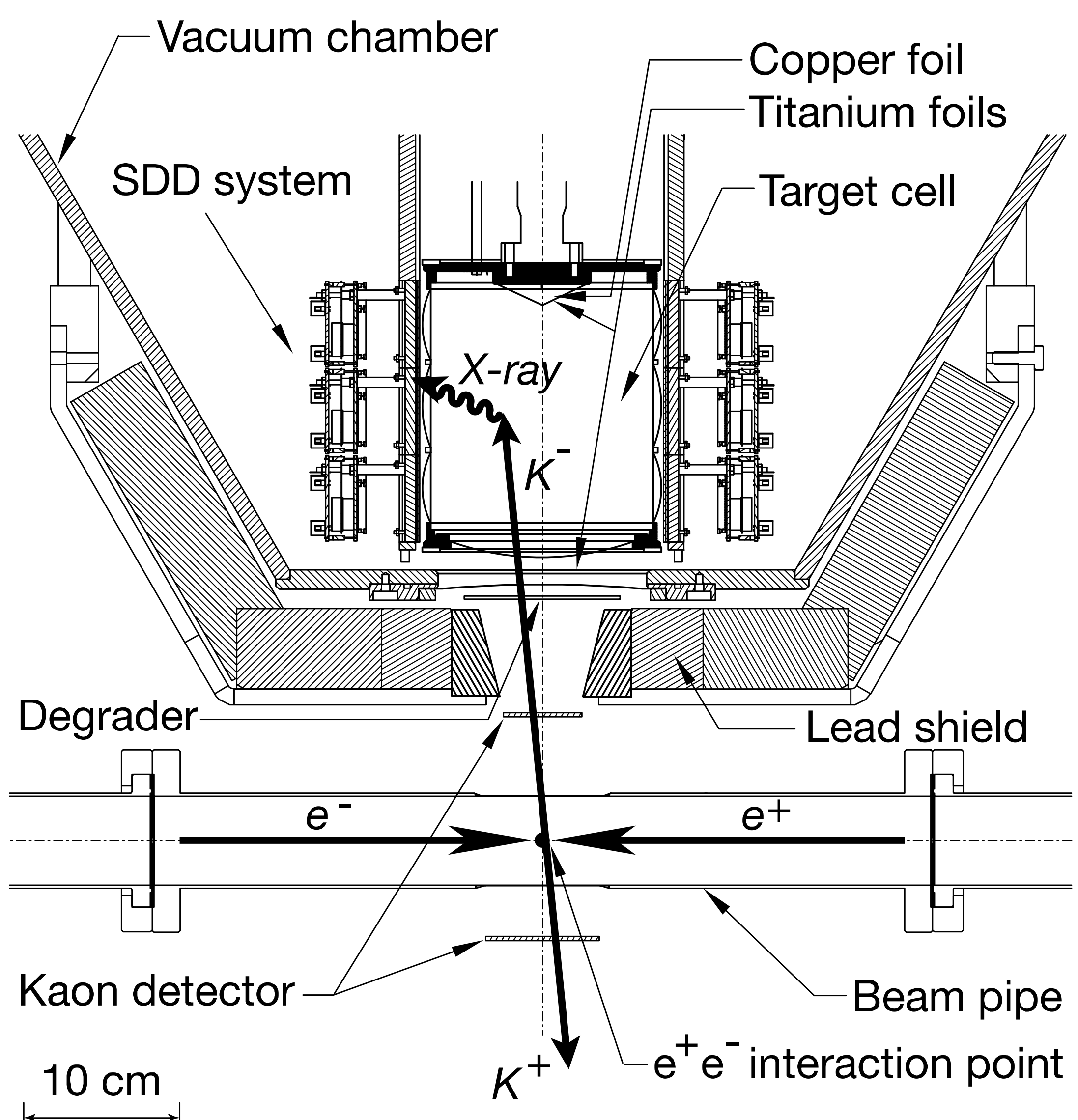
- CCD x-ray detector (116 cm^2)
- 180 eV FWHM at 6 keV
- no timing information (high BG)
- overlay with Mn and Fe peaks

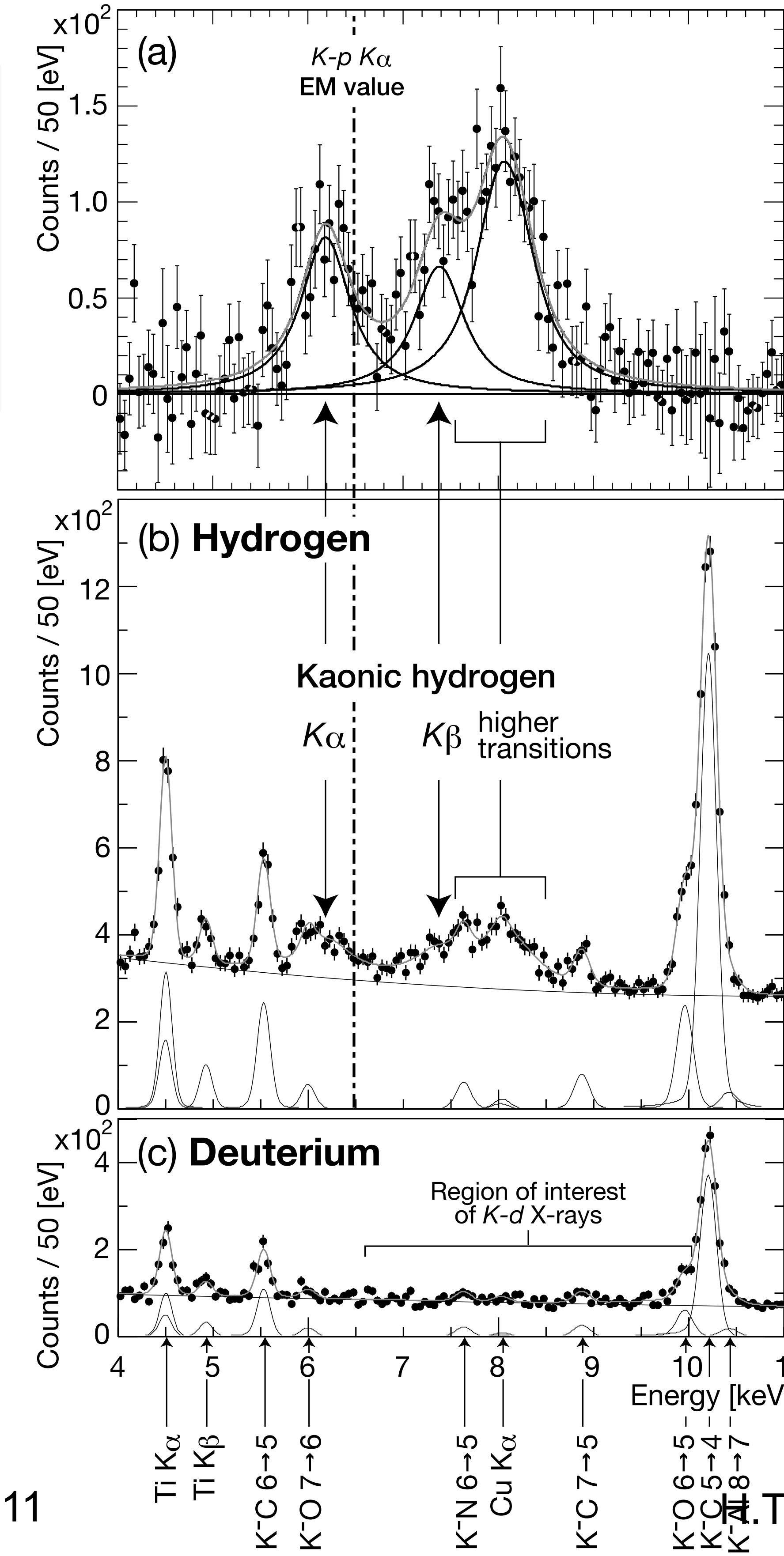
Kaonic hydrogen experiment (2)

DAΦNE SIDDHARTA (2011)

- Silicon Drift Detector (114 cm^2)
- 150 eV FWHM at 6 keV
- sub-μs timing information

M. Bazzi et al., Phys. Lett. B 704 (2011) 113



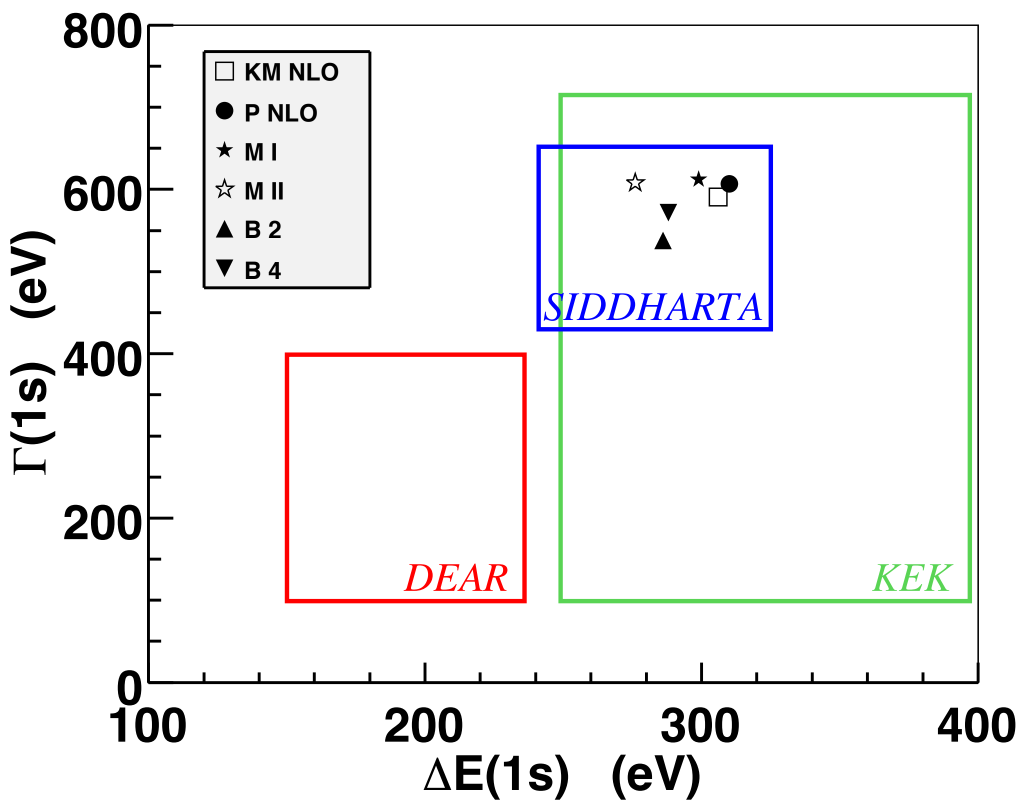


global fit with K-d spectrum

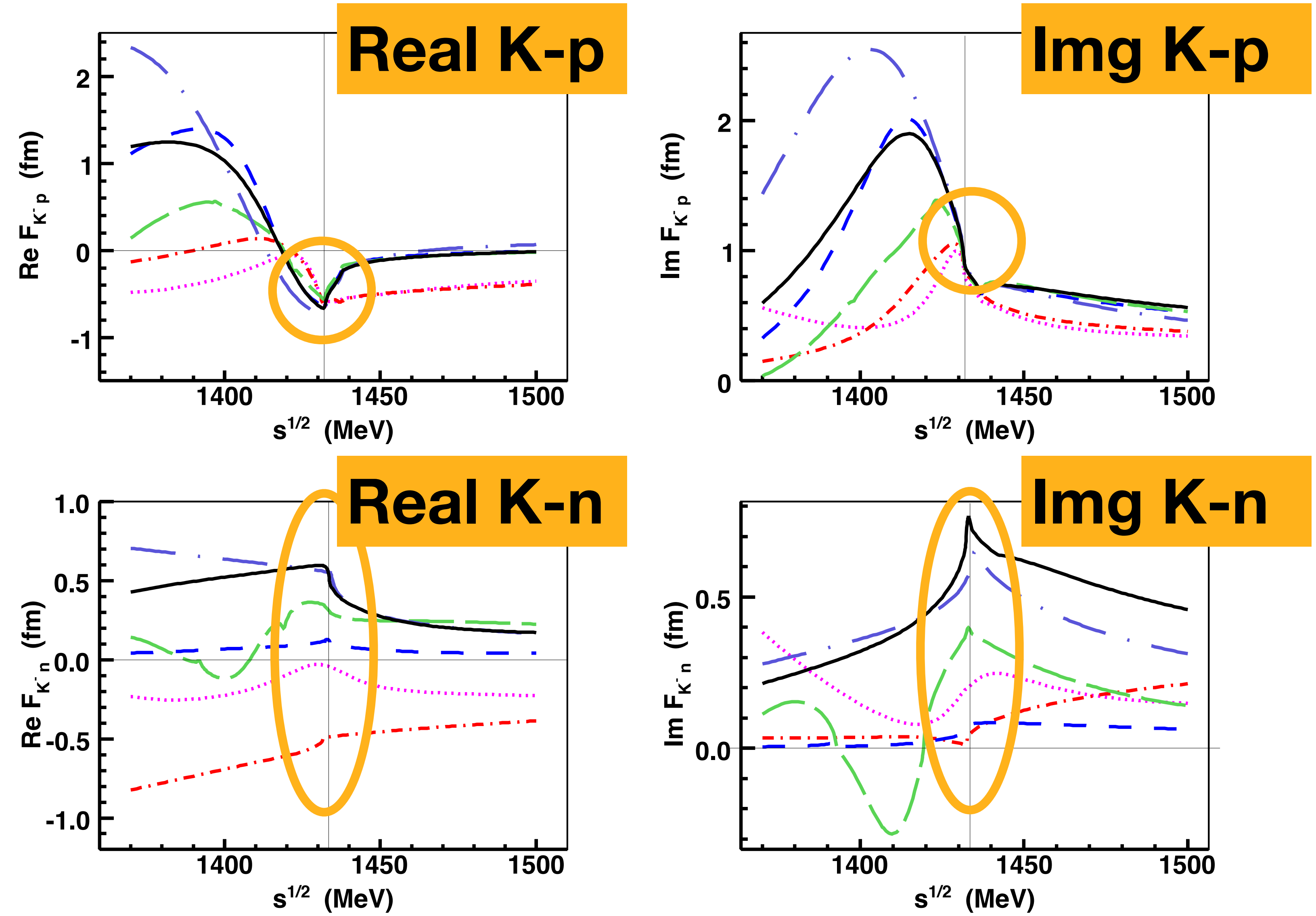
K-d x-ray yield ~1/10 of K-p

Kaonic hydrogen exp. and theory

Parallel session C6 by A. CIEPLY



A. Cieplý, M. Mai, Ulf-G. Meißner, J. Smejkal, https://arxiv.org/abs/1603.02531v2



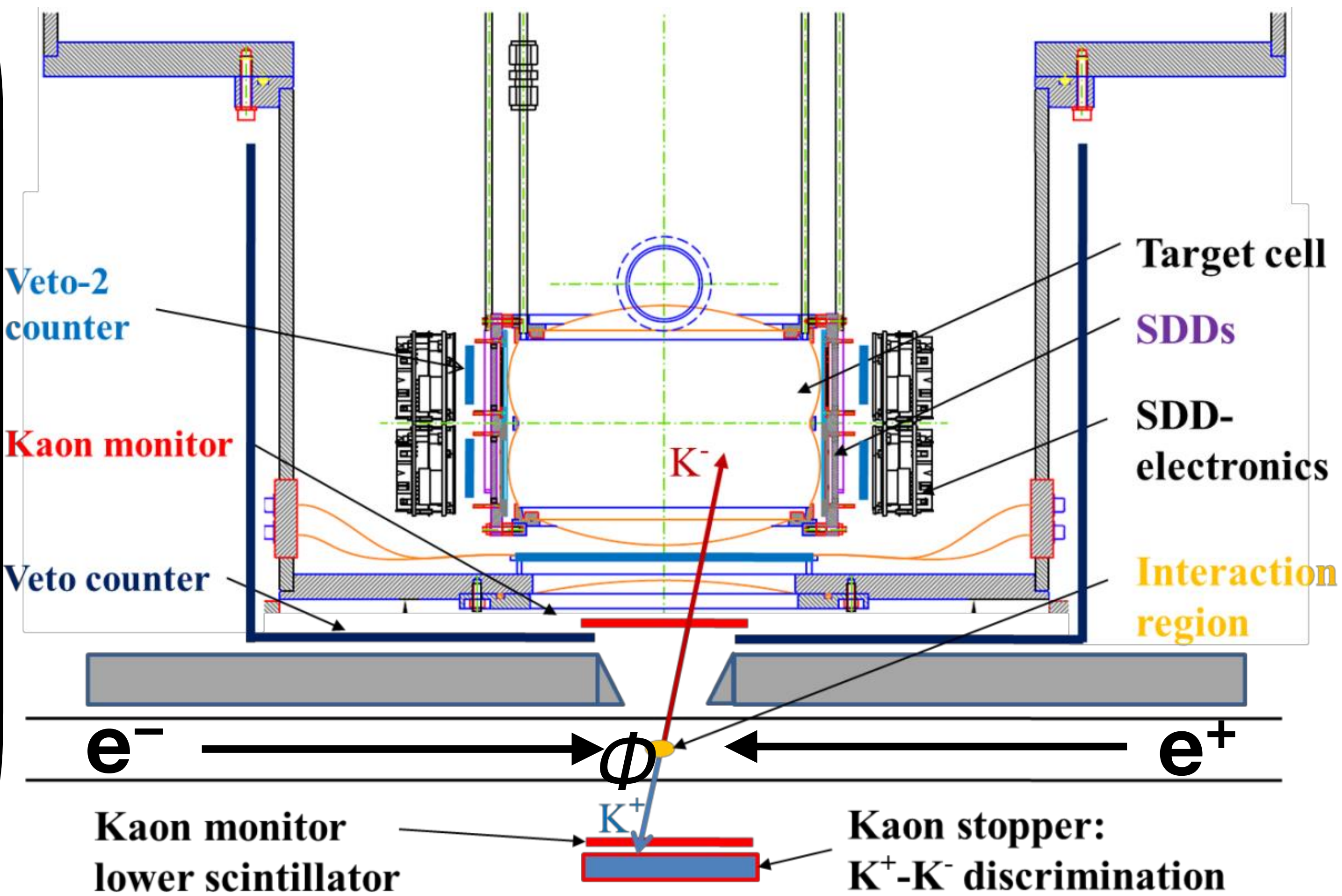
- theory reproduces the $K^{-}p$ results at threshold
- various predictions for $K^{-}n$ scattering length (pure isospin 1)
- K^{-} d result is awaited to determine the isospin dependence

Kaonic Deuterium (1)

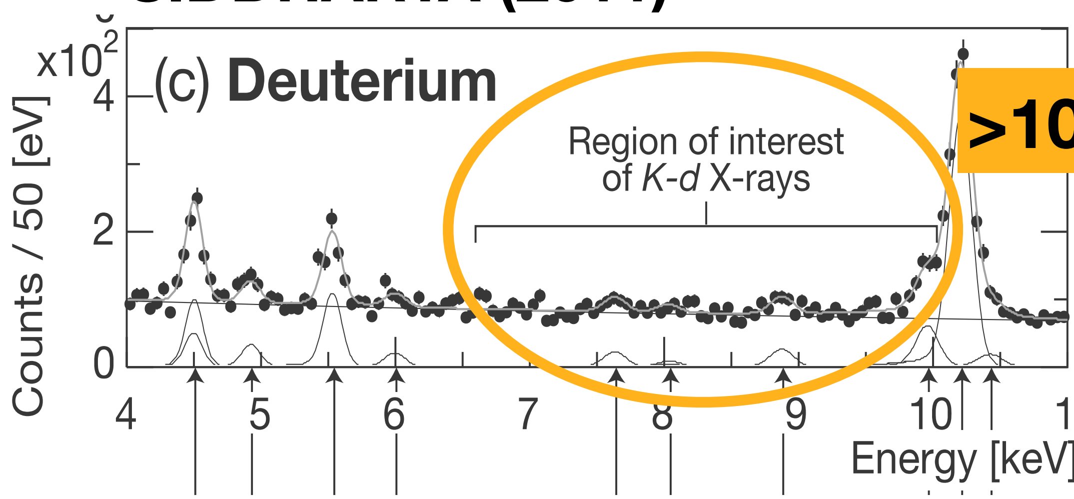
DAΦNE SIDDHARTA2

- gaseous deuterium target
- high geometrical efficiency
- new SDDs 200 cm^2
- 130 eV FWHM at 6 keV
- 400 ns timing resolution
- efficient trigger and event selection with K^+ tag and VETO

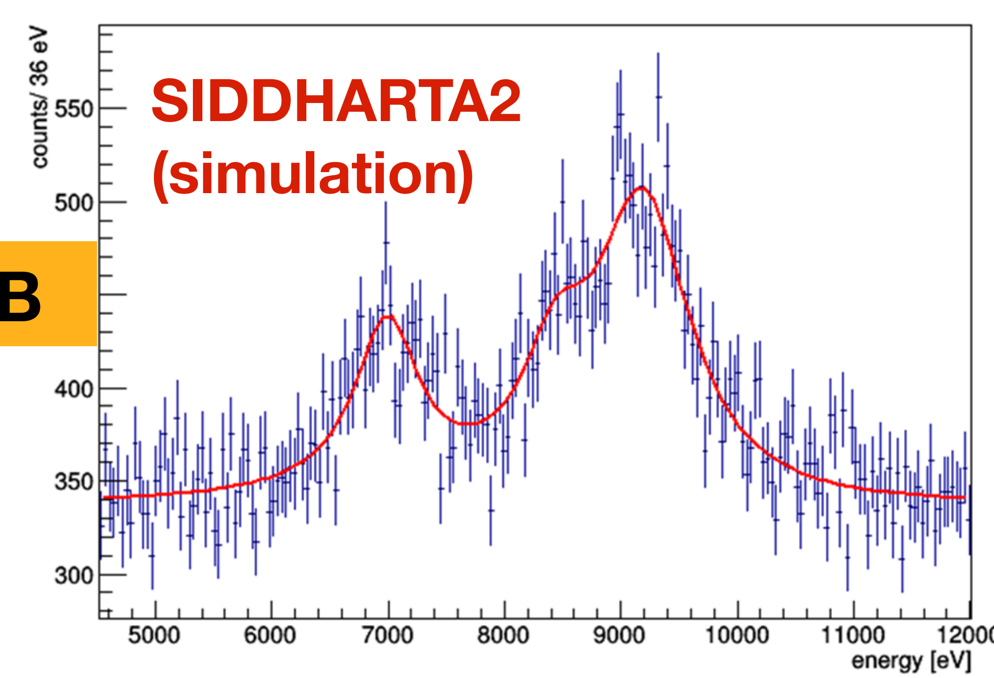
from LNF scientific committee SIDDHARTA2 status report (2016)



SIDDHARTA (2011)



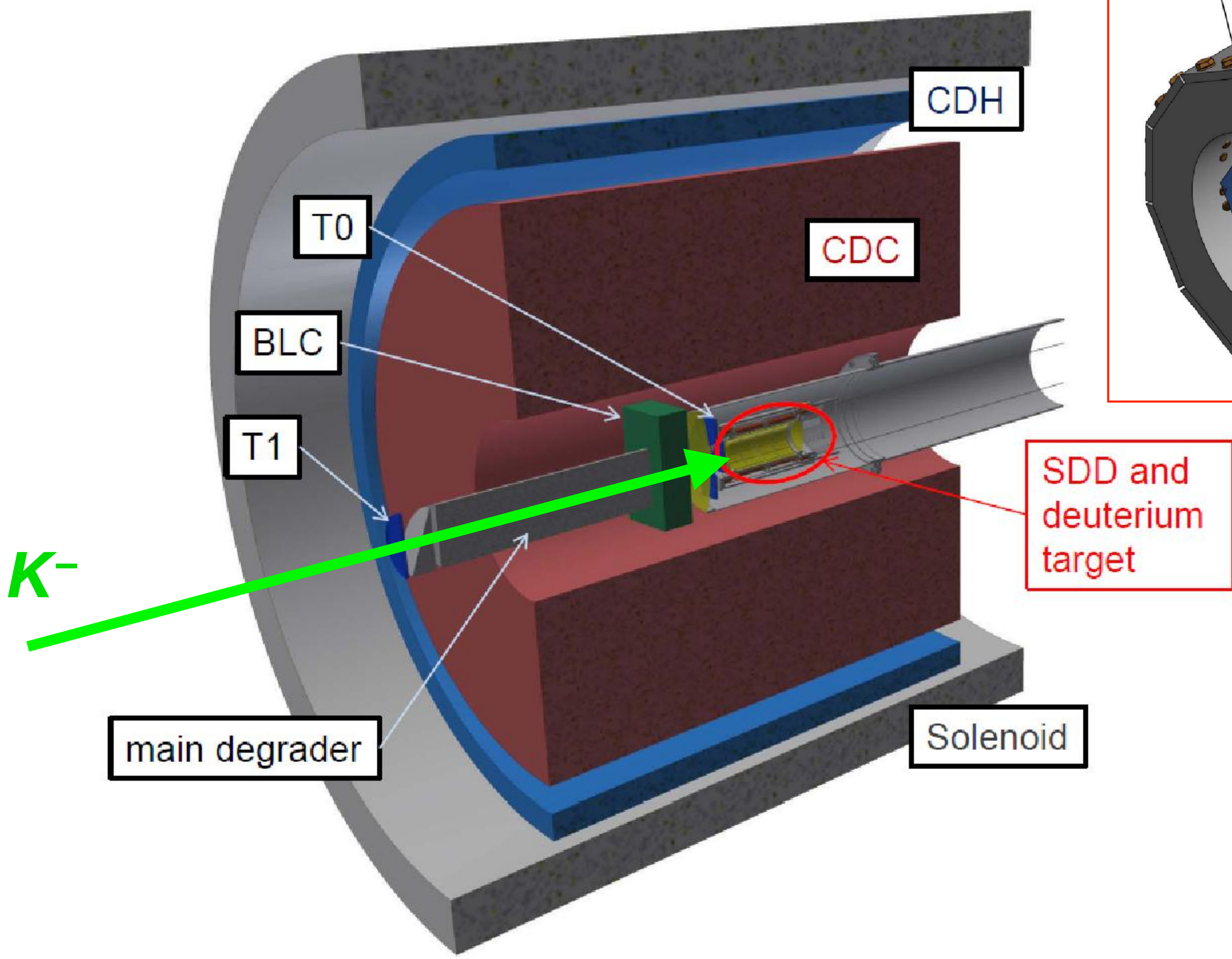
>10 times better S/B



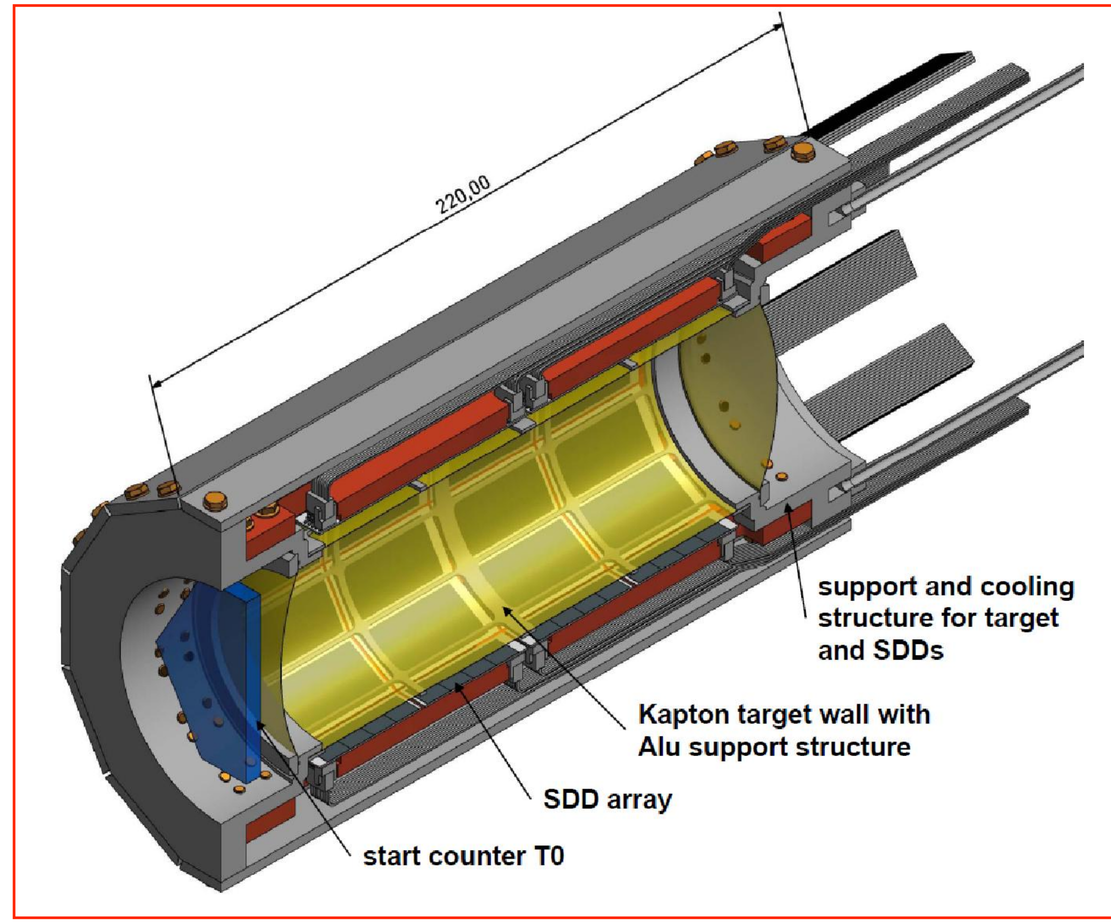
Kaonic Deuterium (2)

J-PARC E57

at K1.8 BR beam line



from J-PARC proposal E57, J. Zmeskal et al.

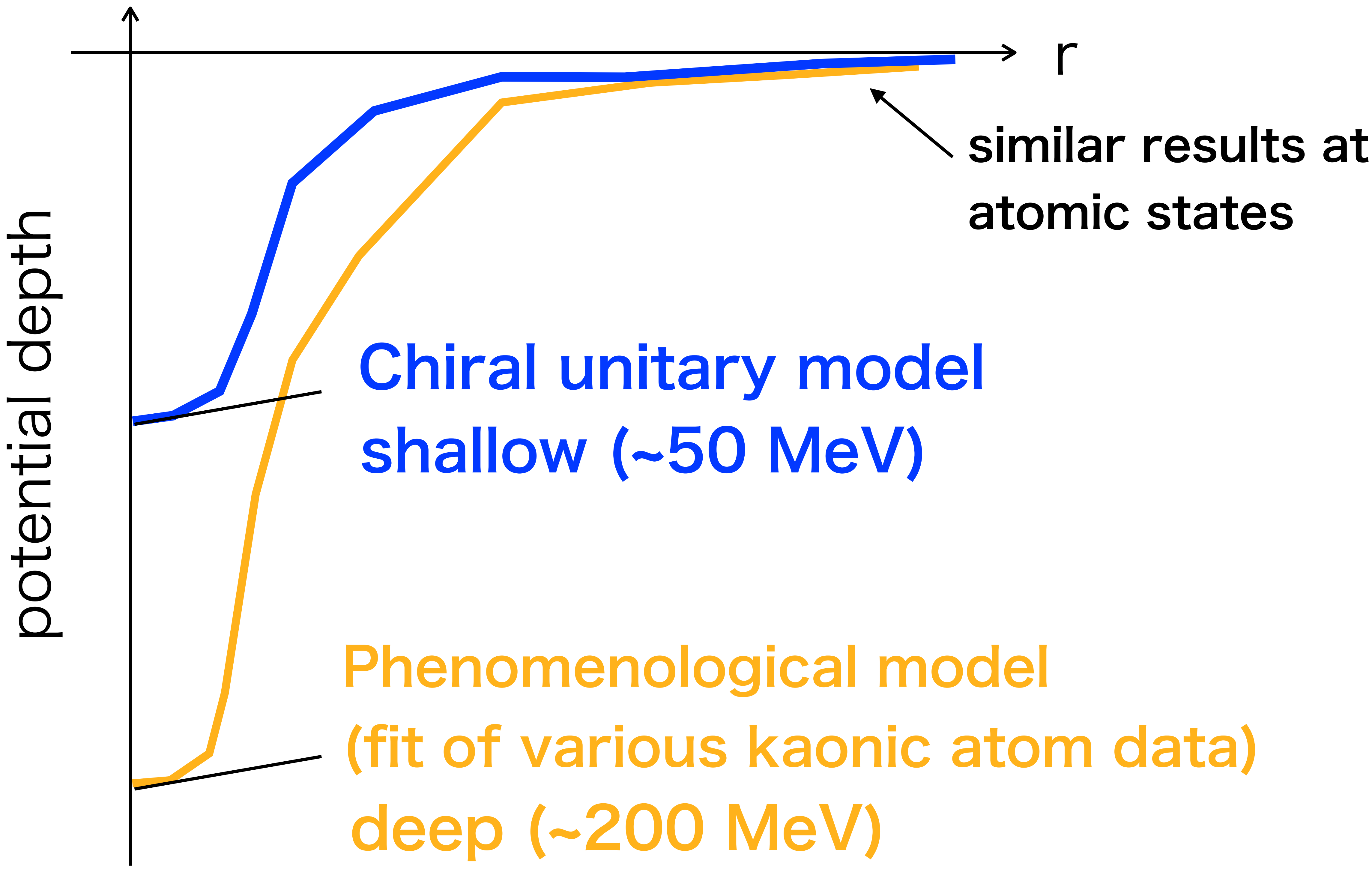


- **high beam intensity**
- **gaseous deuterium target**
- **new SDDs 246 cm^2**
- **130 eV FWHM at 6 keV**
- **400 ns timing resolution**
- **event selection with CDC**

Experiments (past and future)

Target	Experiment	Physics
$K^- p$	KEK E228 DEAR SIDDHARTA	• Precise information of K^-p, K^-n scattering lengths • Essential inputs of chiral SU(3) dynamics • Understanding Λ(1405)
$K^- d$	**SIDDHARTA2** **J-PARC E57**	
$K^- {}^4He$	KEK E570 SIDDHARTA **J-PARC E62**	• **Kaon-nucleus potential depth** • **Chiral unitary vs Phenomenological model** *'deep-or-shallow problem'* • **Antikaon-nuclear cluster**
$K^- {}^3He$	SIDDHARTA **J-PARC E62**	

“Deep-or-Shallow” problem



Kaonic helium strong interaction shift (theory)

A recent theoretical calculation

J. Yamagata-Sekihara and S. Hirenzaki :
— Strong-interaction Shift & Width calc.
E. Hiyama :
— Charge-density dist calc. for ^{4}He&^{3}He

two typical models : *[Pheno.] Mares, Friedman, Gal, NPA770(06)84* *[Chiral] Ramos, Oset, NPA671(00)481*	**deep** **Phenomenological** $V_{opt}(r=0)$ ~ - (180 + 73i) MeV	**shallow** **Chiral unitary** $V_{opt}(r=0)$ ~ - (40 + 55i) MeV
K-^{4}He *2p state*	-0.41 eV	-0.09 eV
K-^{3}He *2p state*	0.23 eV	-0.10 eV

preliminary

Width : 2 ~ 4 eV

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K-^{4}He *2p state*	-0.41 eV	-0.09 eV
K-^{3}He *2p state*	0.23 eV	-0.10 eV
Isotope shift (K-^{4}He - K-^{3}He)	**-0.64 eV**	**0.01 eV**

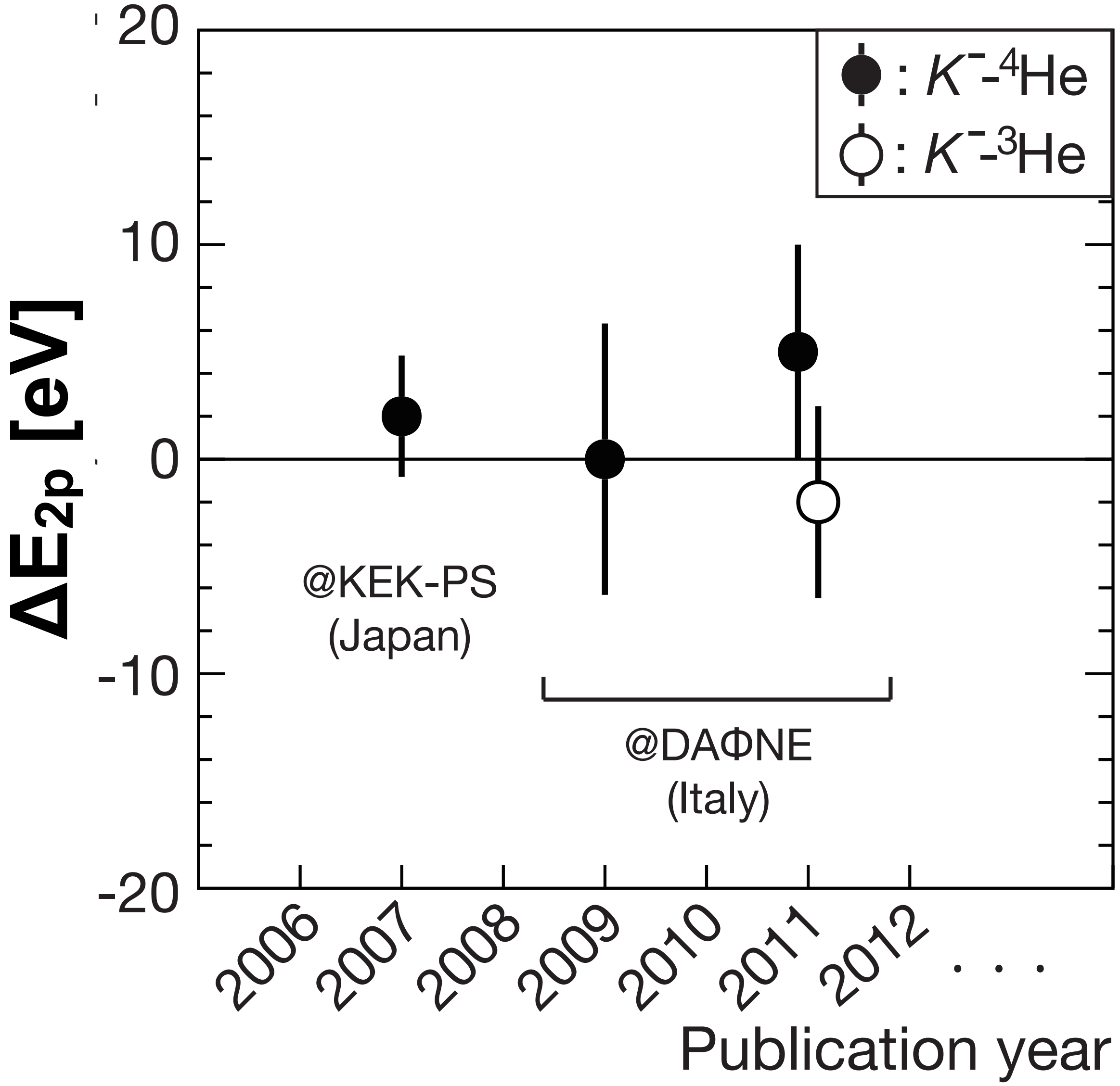
preliminary

Dominant systematic uncertainty (~0.15 eV)
due to kaon-mass uncertainty will be cancelled.

Width : 2 ~ 4 eV

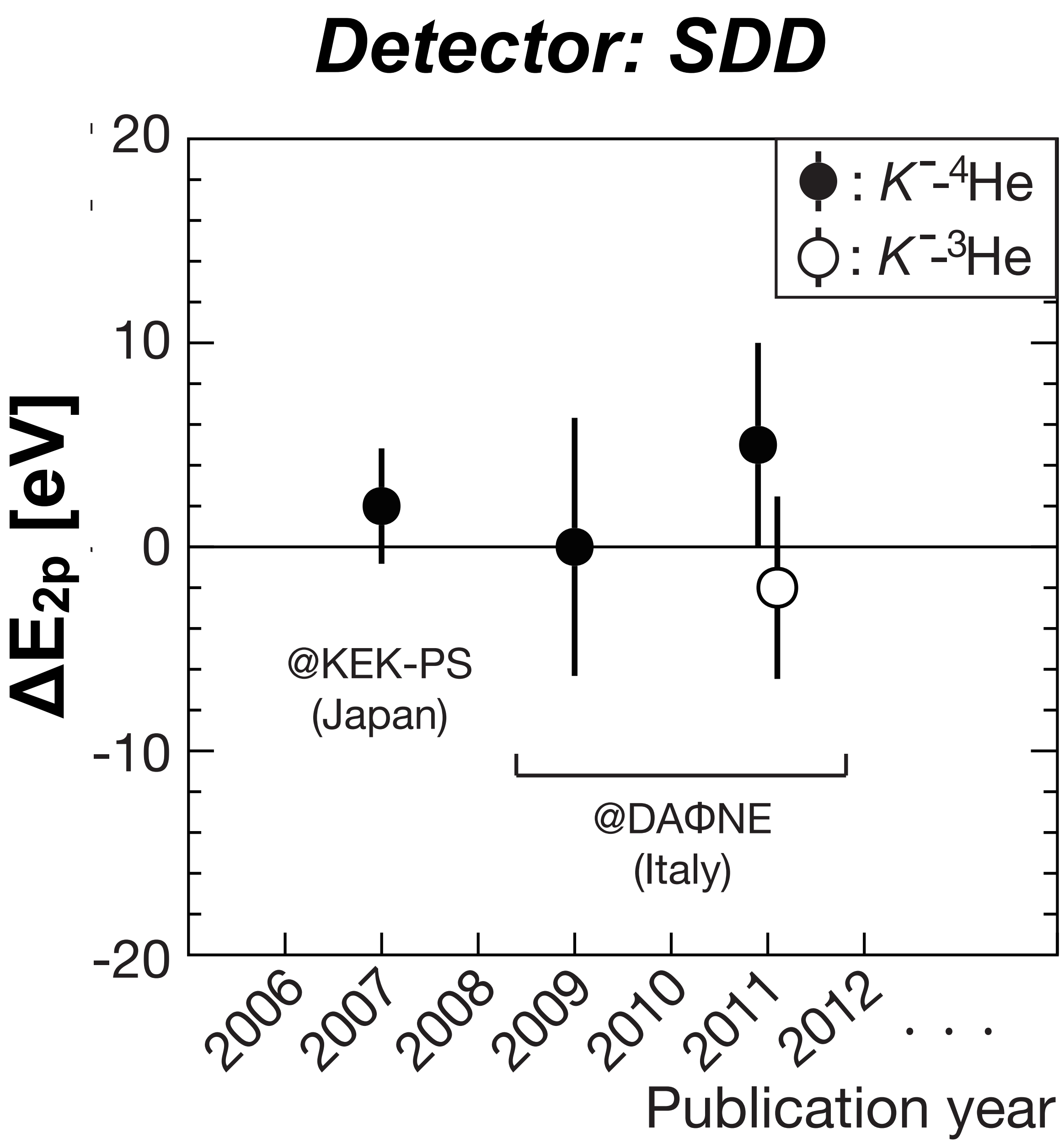
Kaonic helium strong interaction shift (exp.)

Detector: SDD



S.Okada et al., Phys. Lett. B 653, 387 (2007)
M.Bazzi et al., Phys. Lett. B 681, 310 (2009)
M.Bazzi et al., Phys. Lett. B 697, 199 (2011)

Kaonic helium strong interaction shift (exp.)



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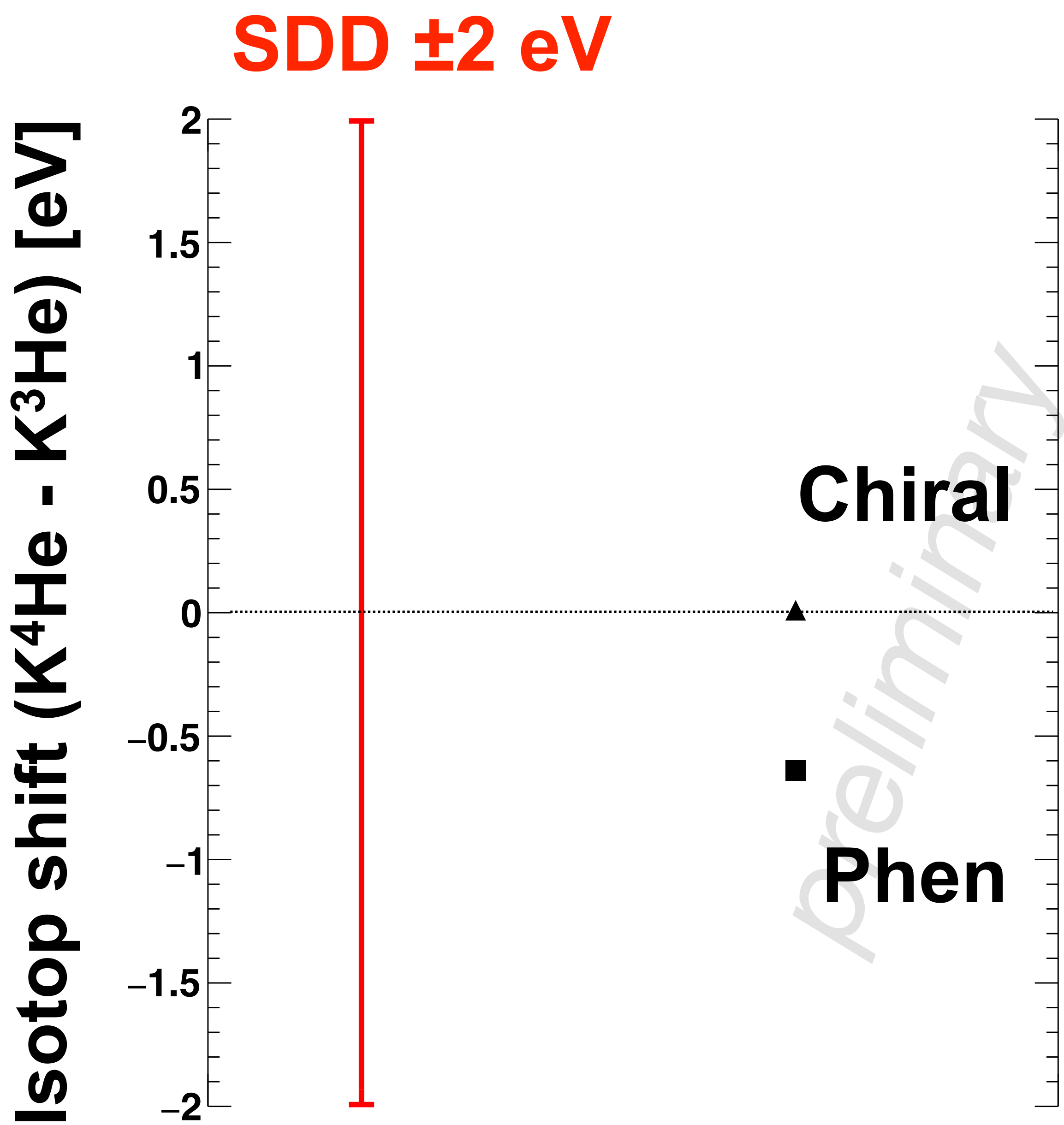
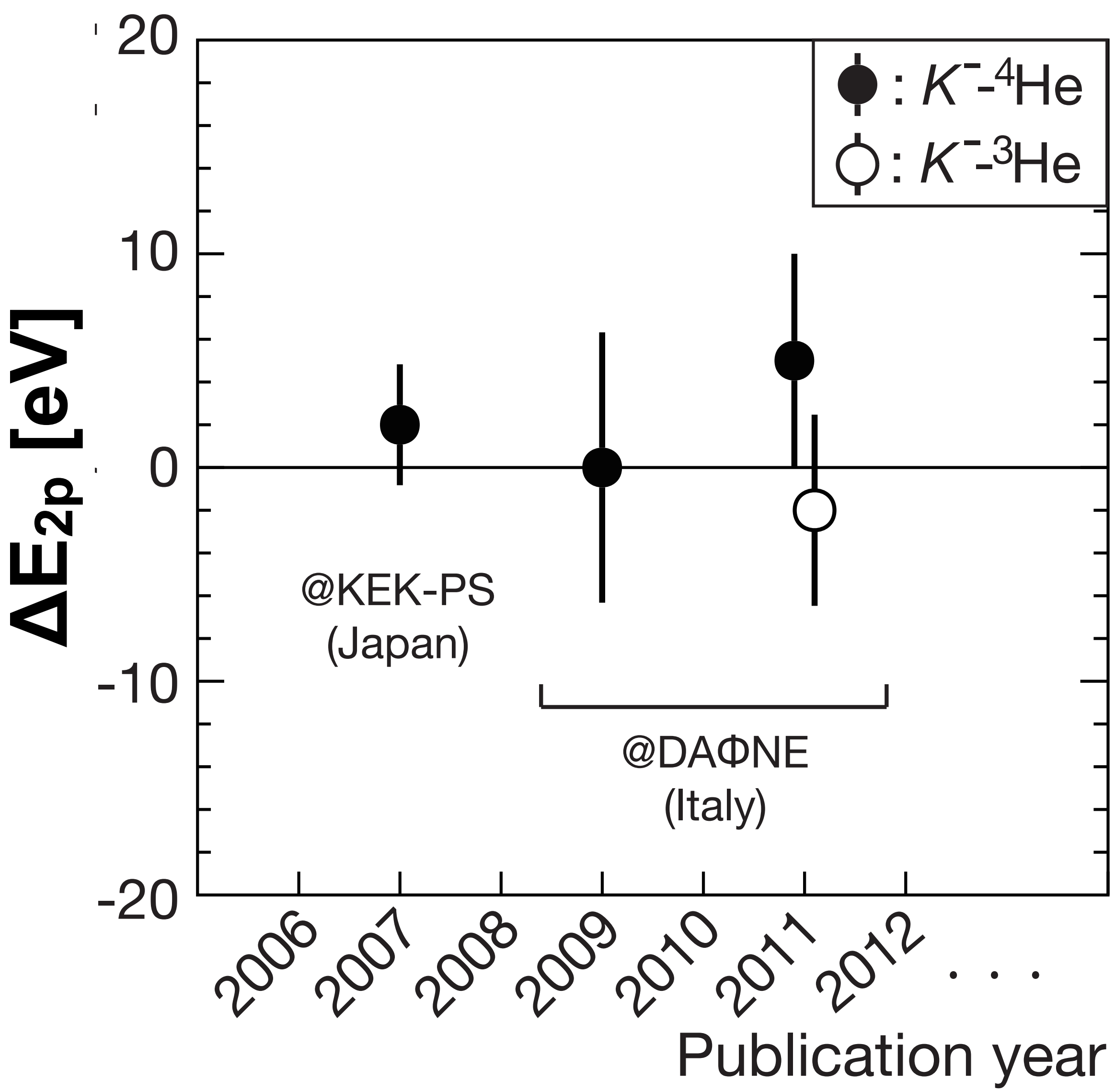


Kaonic helium strong interaction shift (exp.)

Detector: SDD



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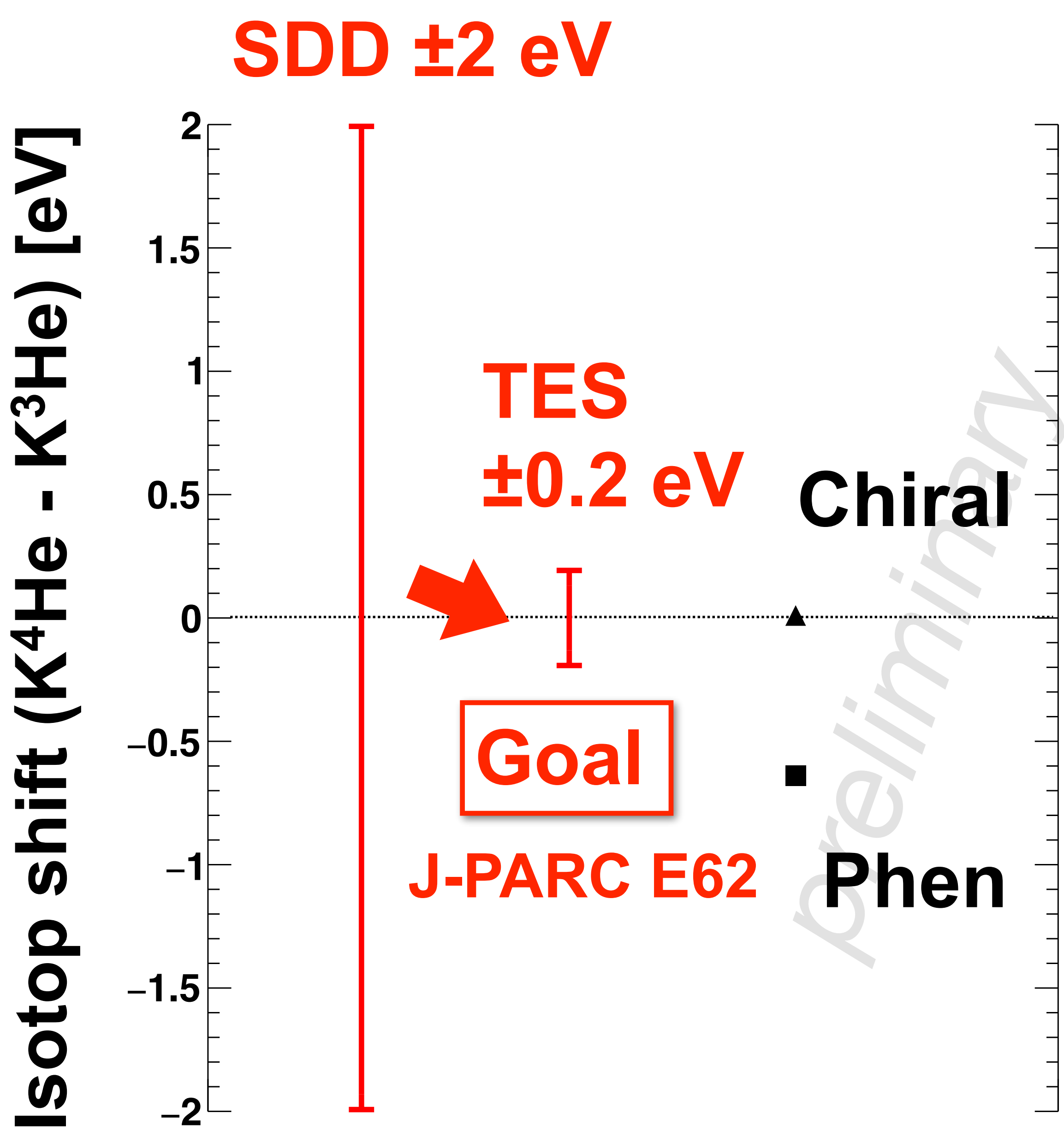
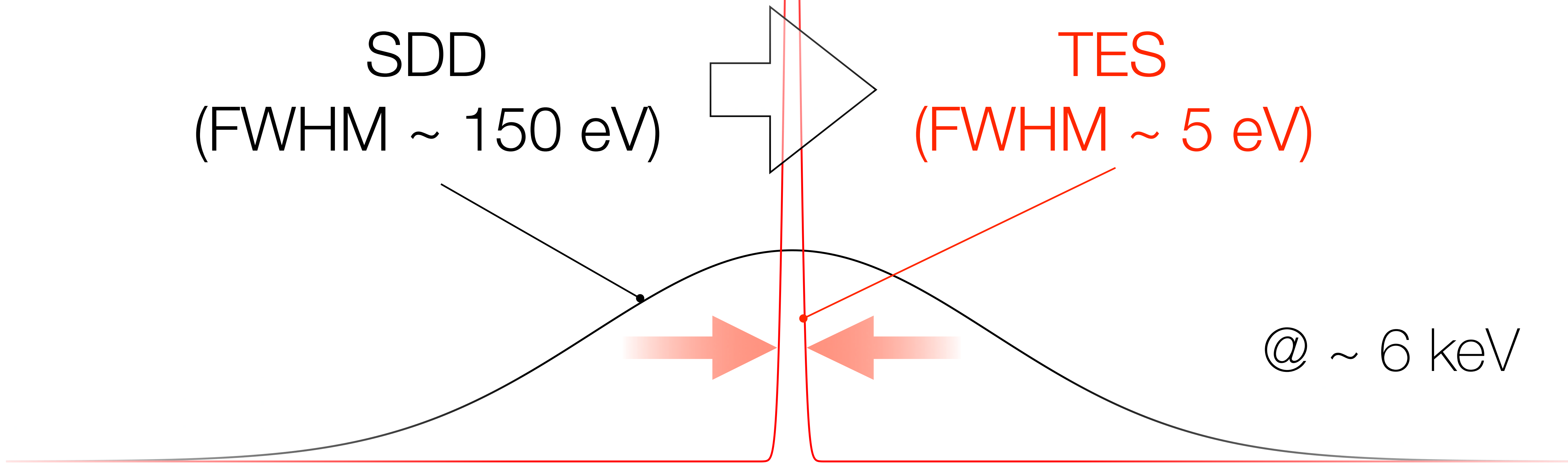


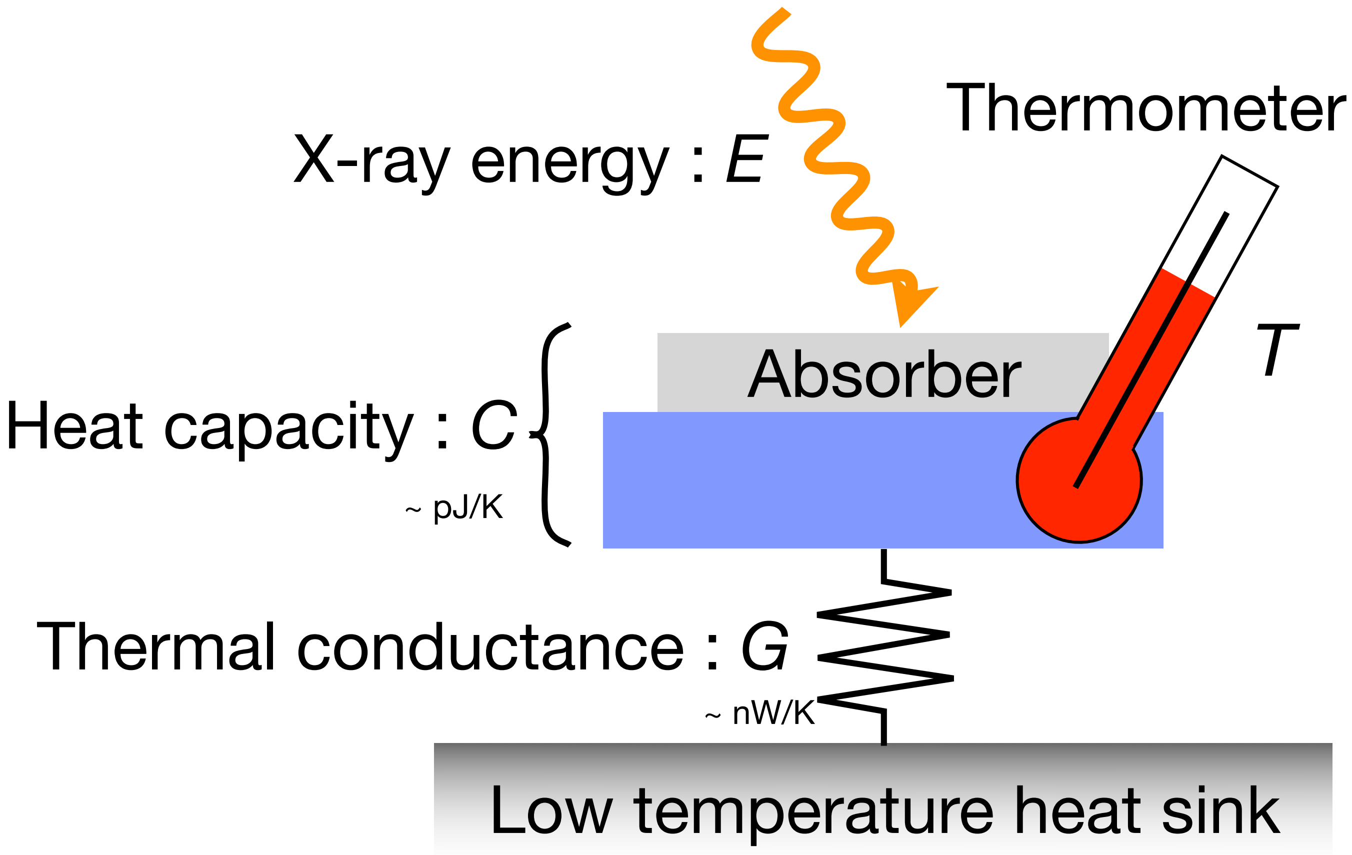
New measurement technique !

SDD to TES

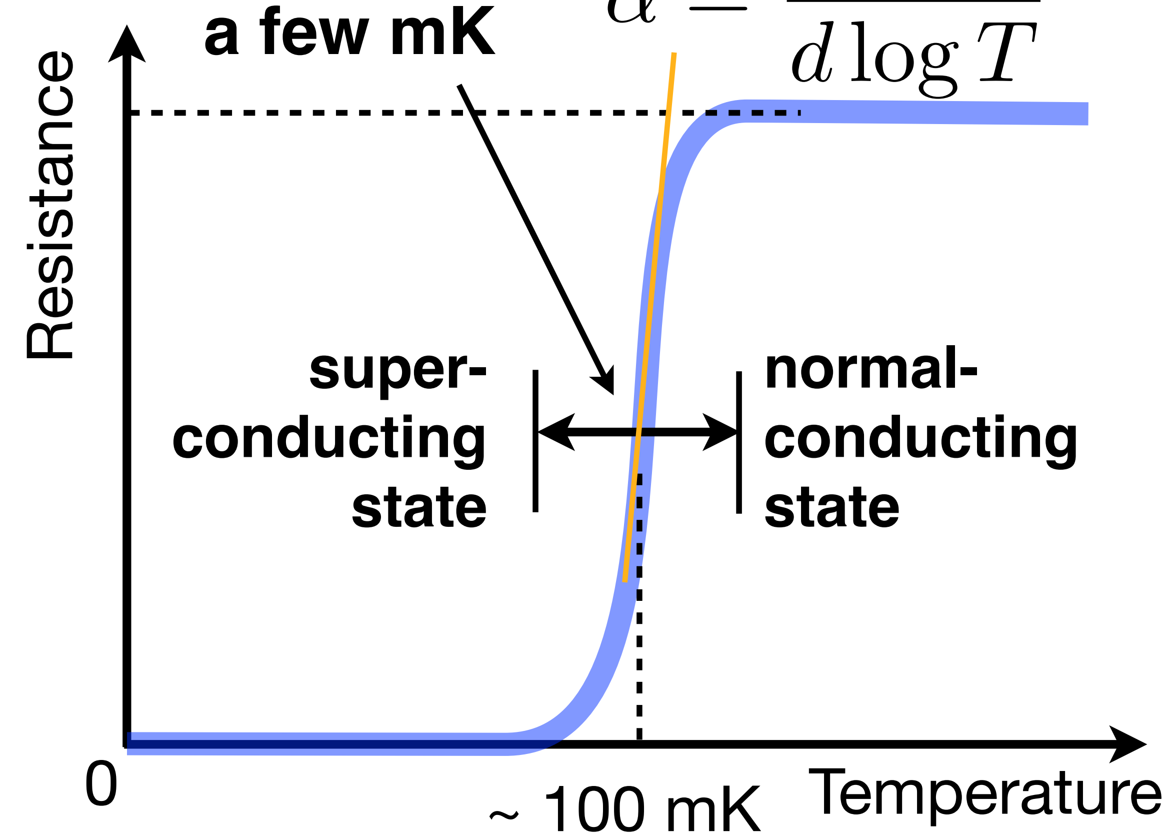
- ✓ Shift : precision goal “2eV → 0.2 eV”
- ✓ Width : sensitive for Γ_{2p} > ~2eV



Transition edge sensors

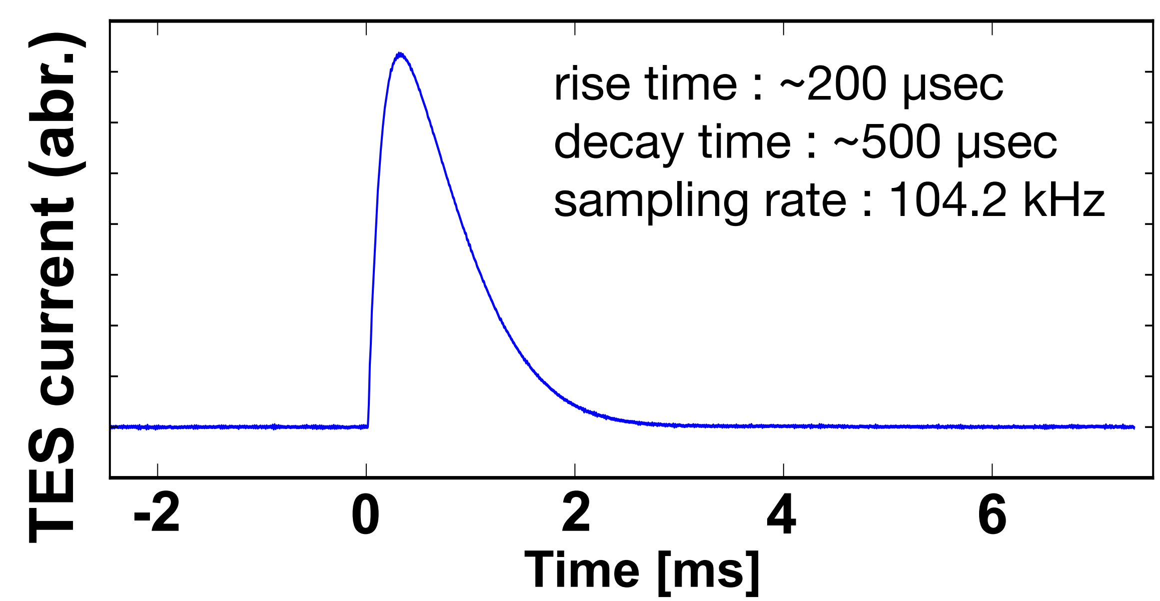


$$\alpha = \frac{d \log R}{d \log T}$$

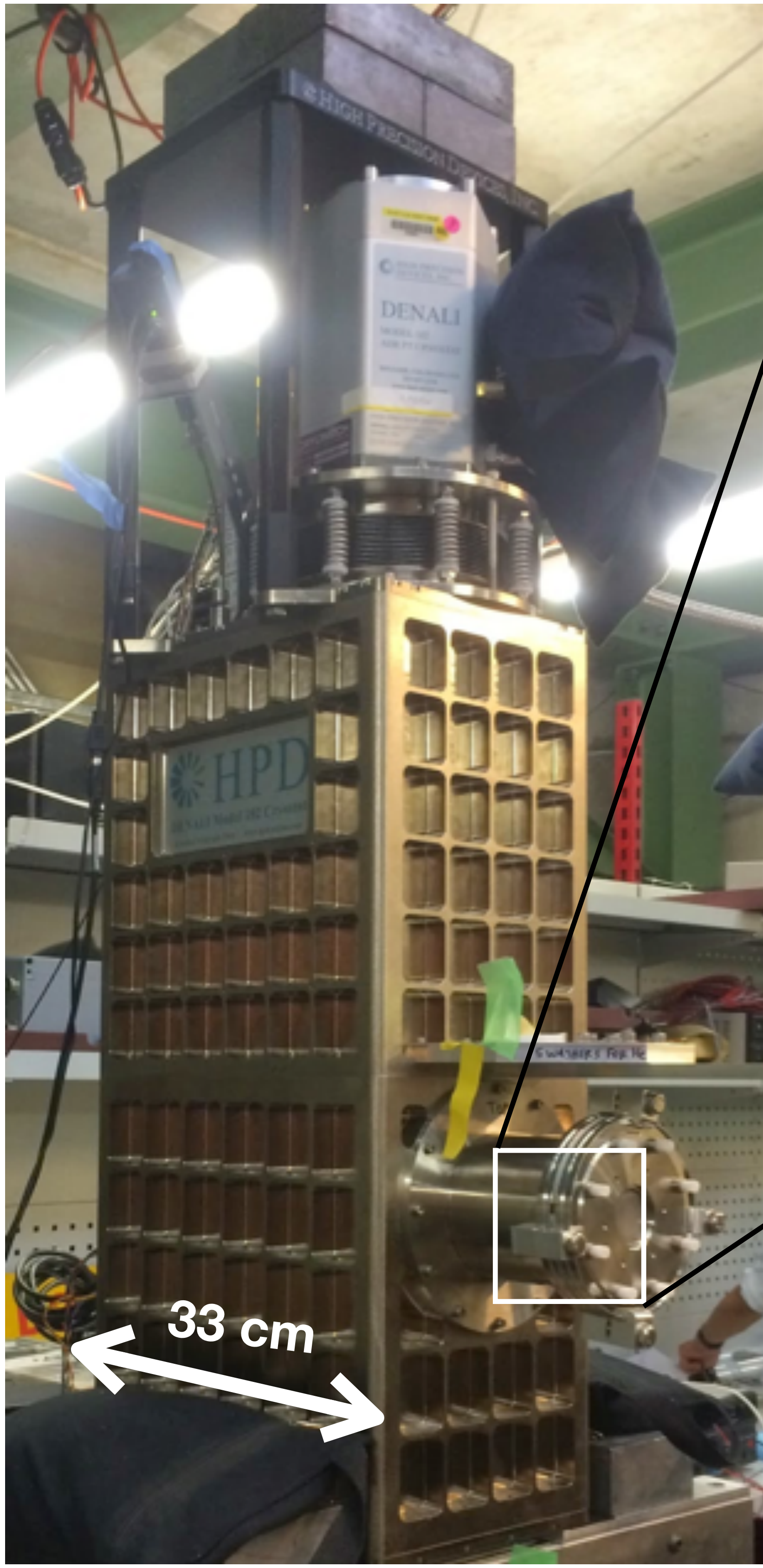


$$\Delta E_{\mathrm{FWHM}} = 2.355 \sqrt{\frac{k_B T^2 C}{\alpha}} \quad E_{max} \propto \frac{C}{\alpha}$$

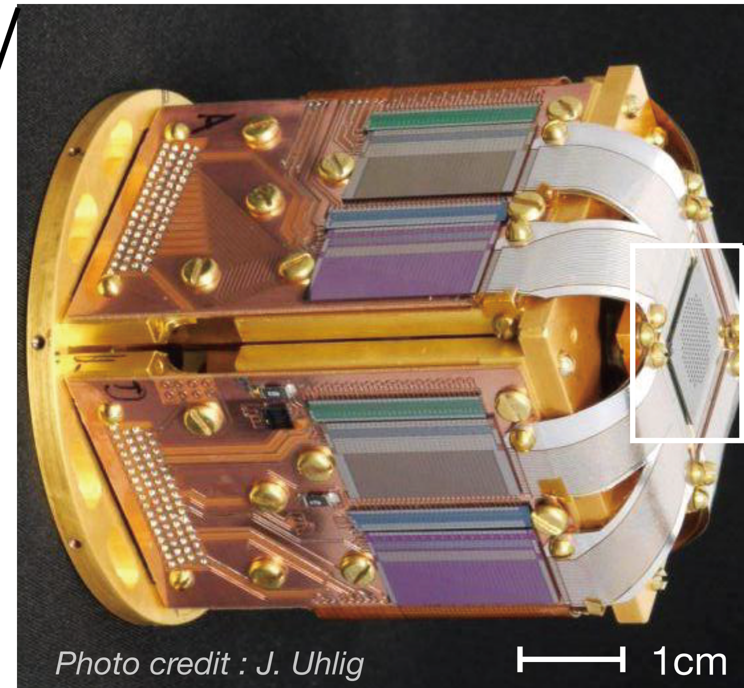
- ✓ **Excellent energy resolution < ~ 5eV@6 keV**
- ✓ **Large active area with multiplexing (240 ch)**
- ✓ **Compact detector package**

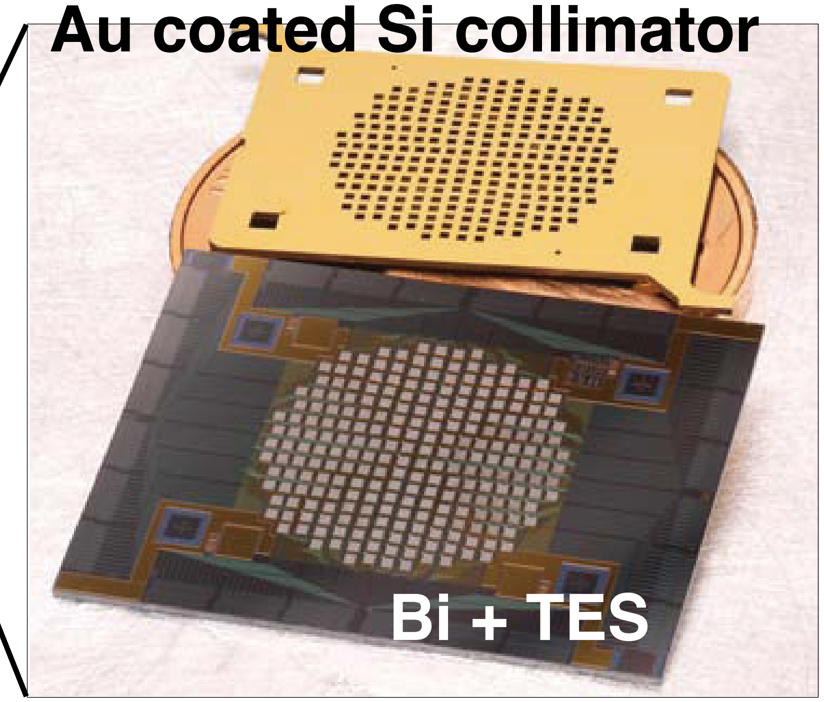


TES spectrometer



J.N. Ullom et al., Synchrotron Radiation News, Vol. 27, 24 (2014)



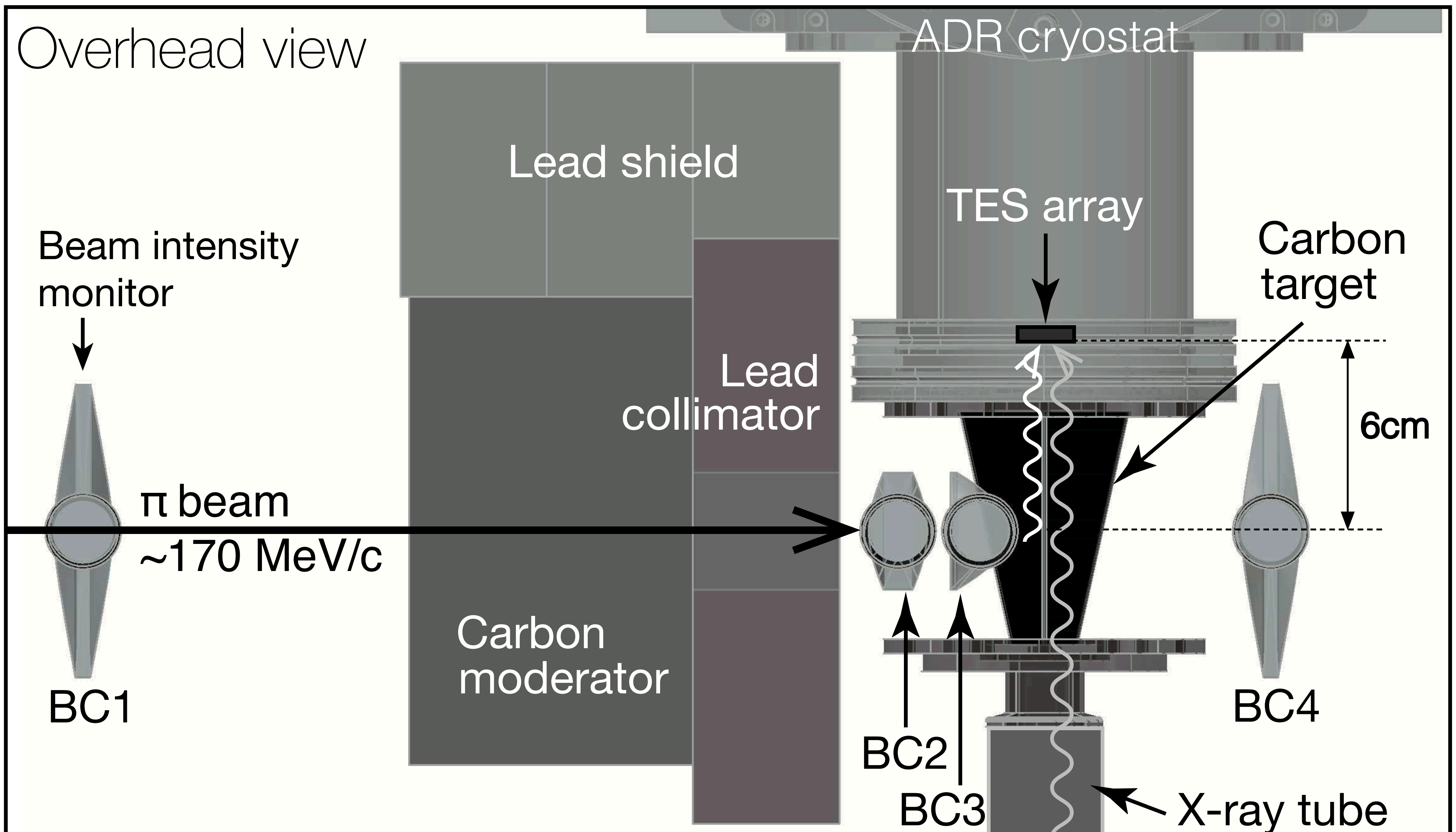


Cryostat
- Pulse tube (50K, 3K) + ADR (1K, 50mK)
- Temp regulation (75mK) hold time 36 hours
- Manufactured by HPD, designed at NIST

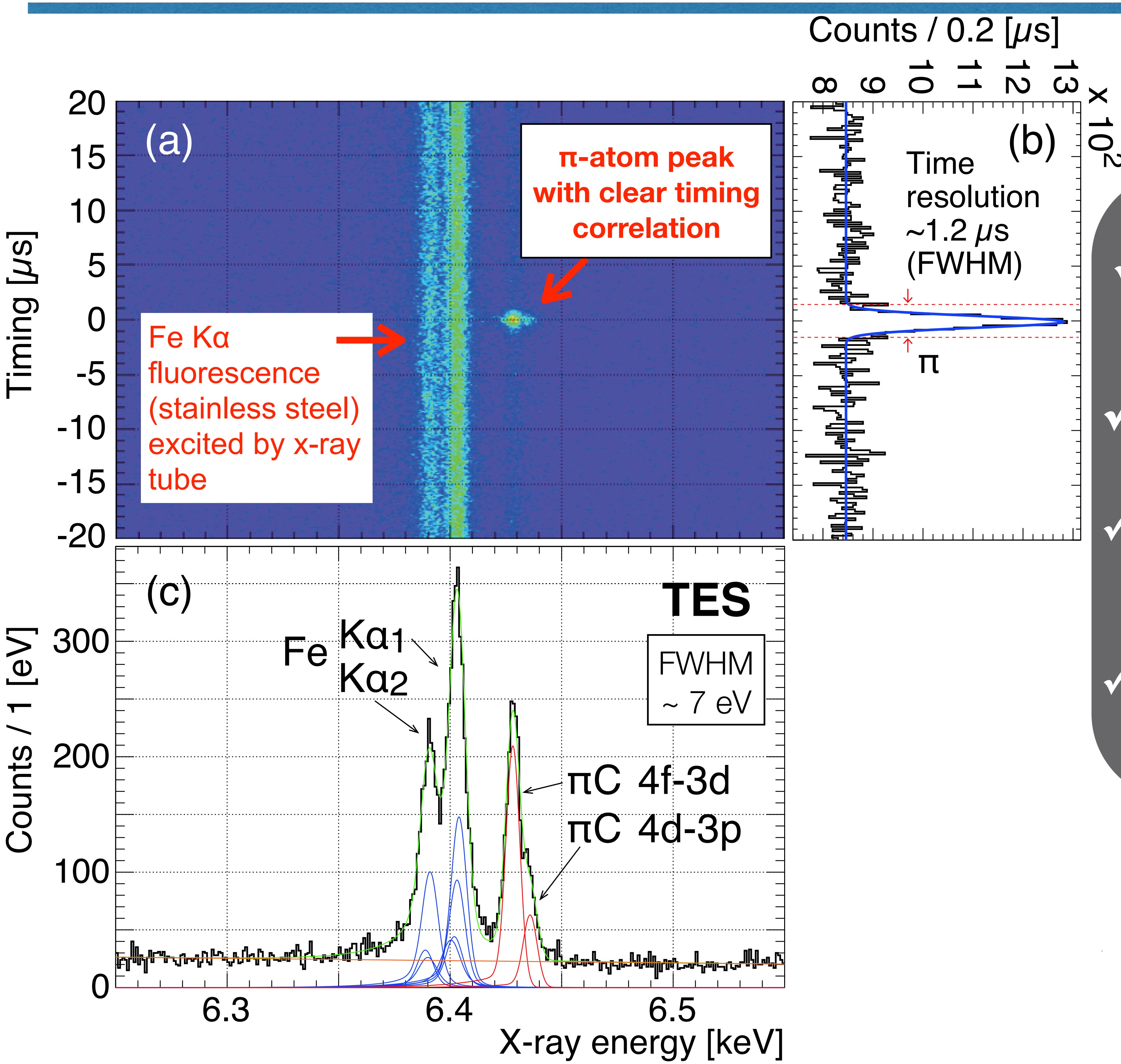
TES array
- 240 pixel Mo-Cu bilayer TESs
- 4-μm thick Bi absorber → 85% efficiency at 6 keV
- pixel area: 305 μm x 320 μm → total 23mm^2

Feasibility test at the PSI πM1 beam line

- ✓ TES in-beam performance study
- ✓ measured πC 4-3 transition x-rays ~6.4 keV
- ✓ in-situ energy calibration (Cr and Co fluorescence)



π-C 4f→3d, 4d→3p x-rays measurement at PSI

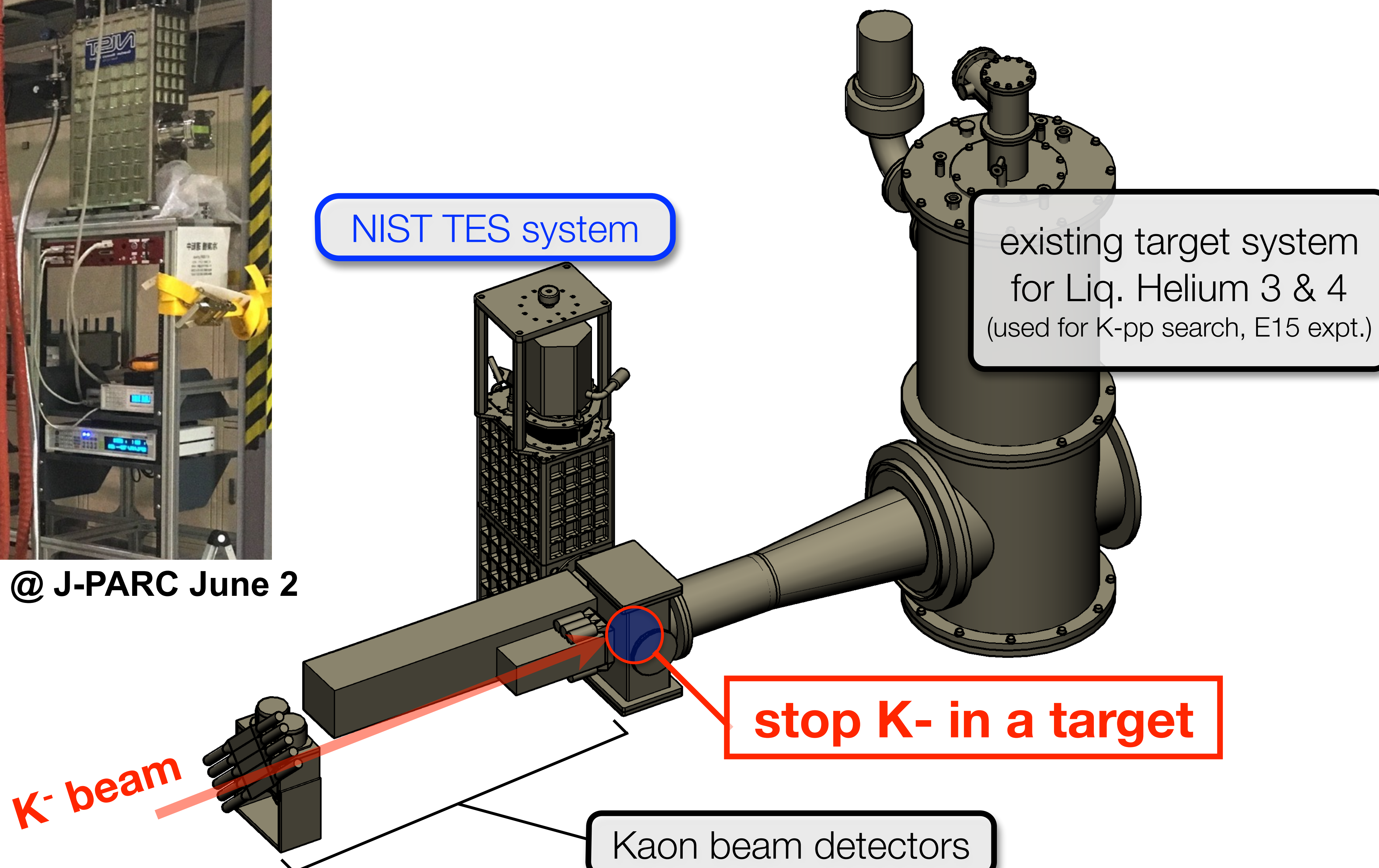


- ✓ ΔE_{FWHM} ~ 7eV (beam on) at 6.4 keV
- ✓ Δt_{FWHM} =1.2 μs
- ✓ FeKα energy uncertainty ±0.04 eV
- ✓ πC 4f-3d syst uncertainty~ ±0.1 eV

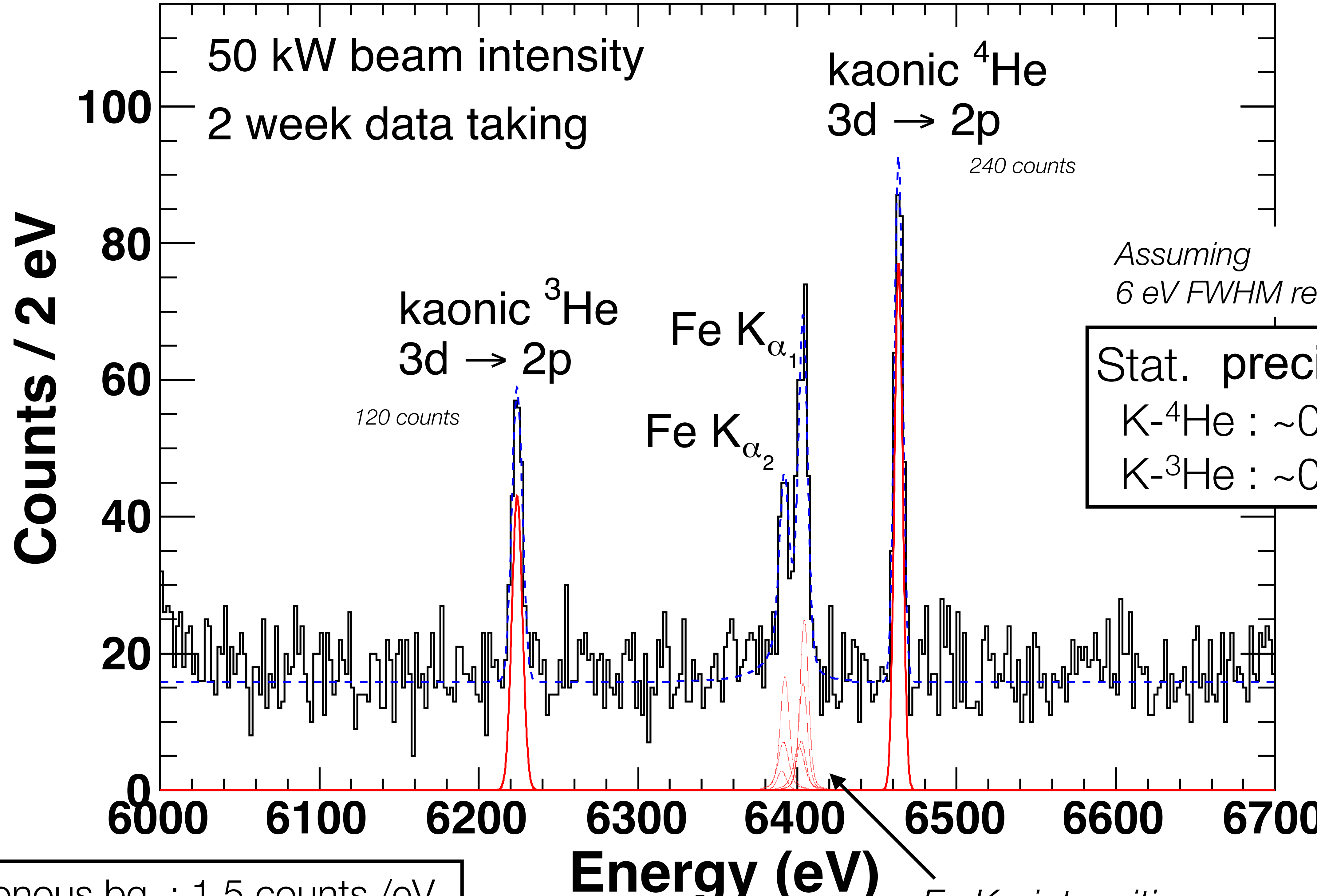
TESs work!!

J-PARC E62 setup at K1.8 BR beam line

Our TES system @ J-PARC June 2



Expected J-PARC E62 x-ray spectrum



Assuming
6 eV FWHM resolution

Stat. precision
K-^{4}He : ~0.2 eV
K-^{3}He : ~0.35 eV

Asynchronous bg. : 1.5 counts /eV
Synchronous bg. : 6 counts /eV

Fe Ka intensities are controllable with applied voltage of x-ray tube

Summary

$\overline{\mathrm{K}}$N interaction

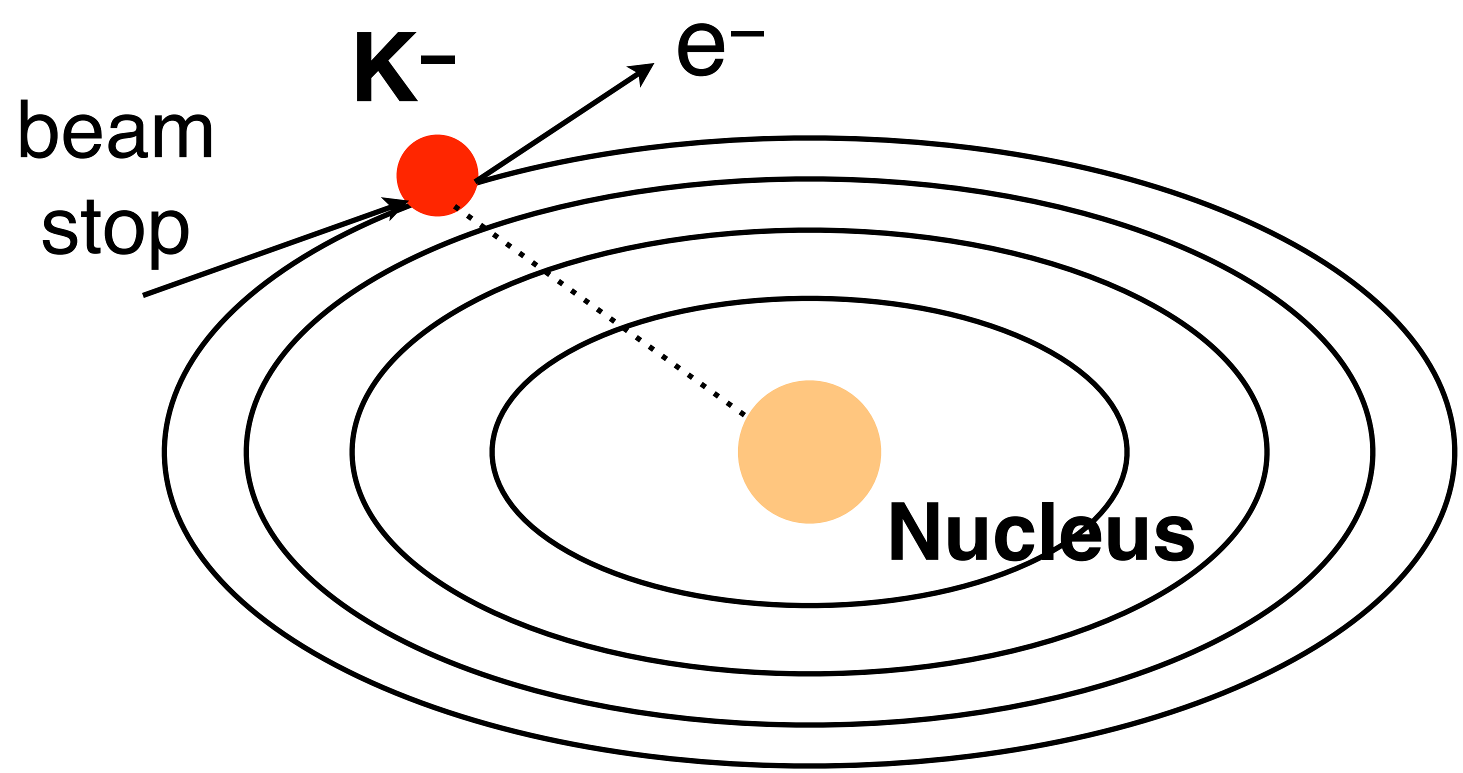
- available the precise results of SIDDHARTA $K^{-}p$
- various predictions of $K^{-}n$ (isospin 1)
- $K^{-}d$ $2p \rightarrow 1s$ x-ray measurement is awaited
- SIDDHARTA2 and J-PARC E57 with new SDDs (2017)

K^{-}nucleus potential depth

- deep-or-shallow problem
- strong interaction shift of K^{-} ^{3}He and ^{4}He $2p$ state
- precision goal ΔE_{2p} ±0.2 eV
- J-PARC E62 with TESs (2017)

Backup

Kaonic atoms

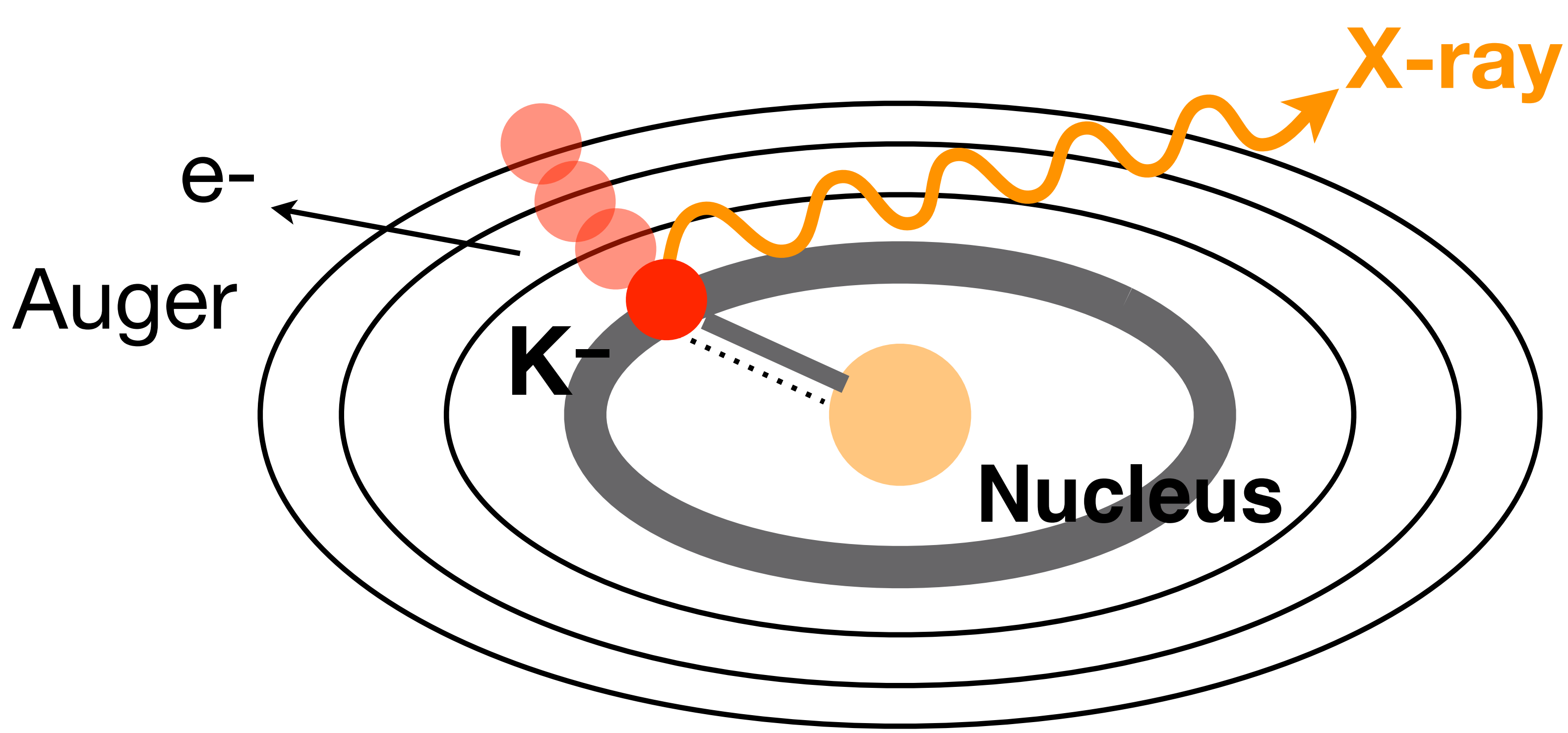


Coulomb capture

- ~10³ times reduced mass
- keV order energy levels
- highly excited states

$$n^{*} \sim n_e \sqrt{\frac{m_K^{*}}{m_e}}$$

m_K^{*} reduced kaon mass

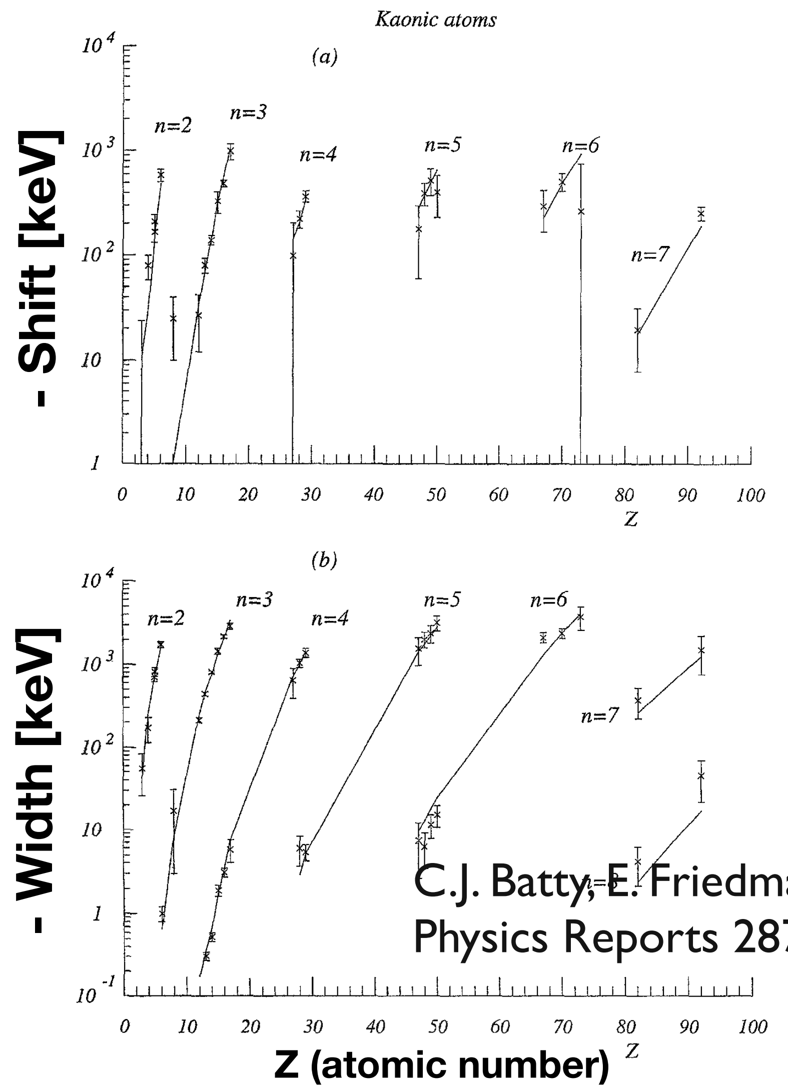


Cascade down (de-excitation)

- Auger & radiative
- nuclear absorption

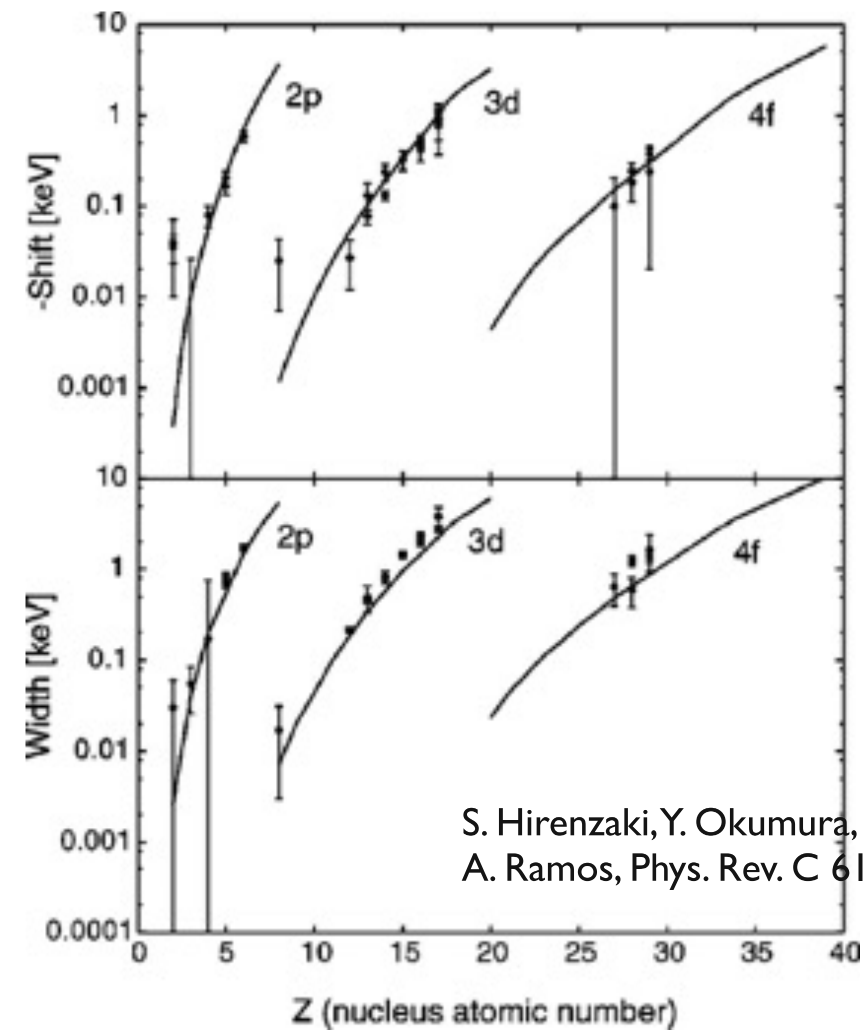
“Deep-or-Shallow” problem

Phenomenological Model
— **deep potential** —
typically 180 MeV deep



C.J. Batty, E. Friedman, and A. Gal, Physics Reports 287 (1997) 385

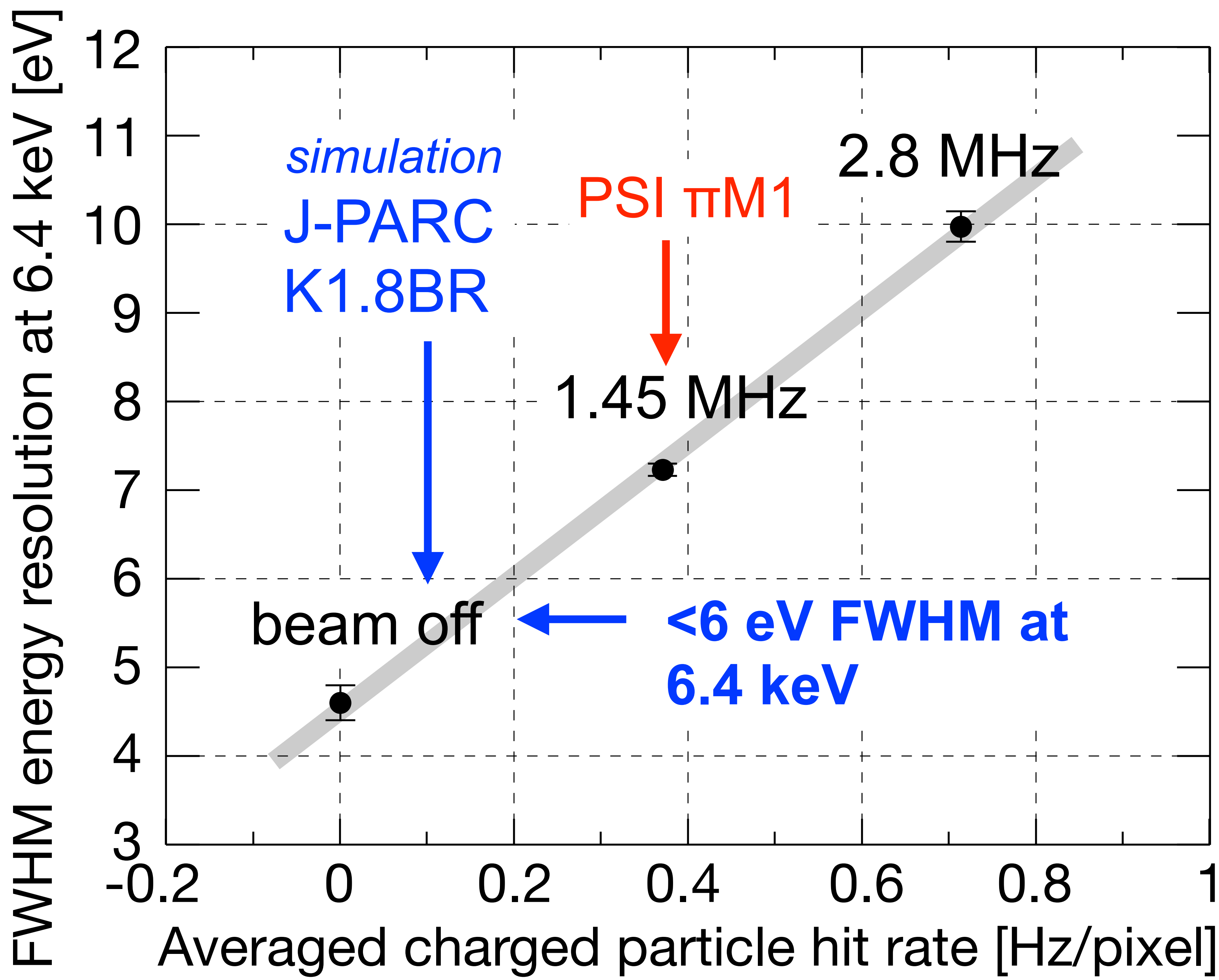
Chiral Unitary Model
— **shallow potential** —
typically 50 MeV deep



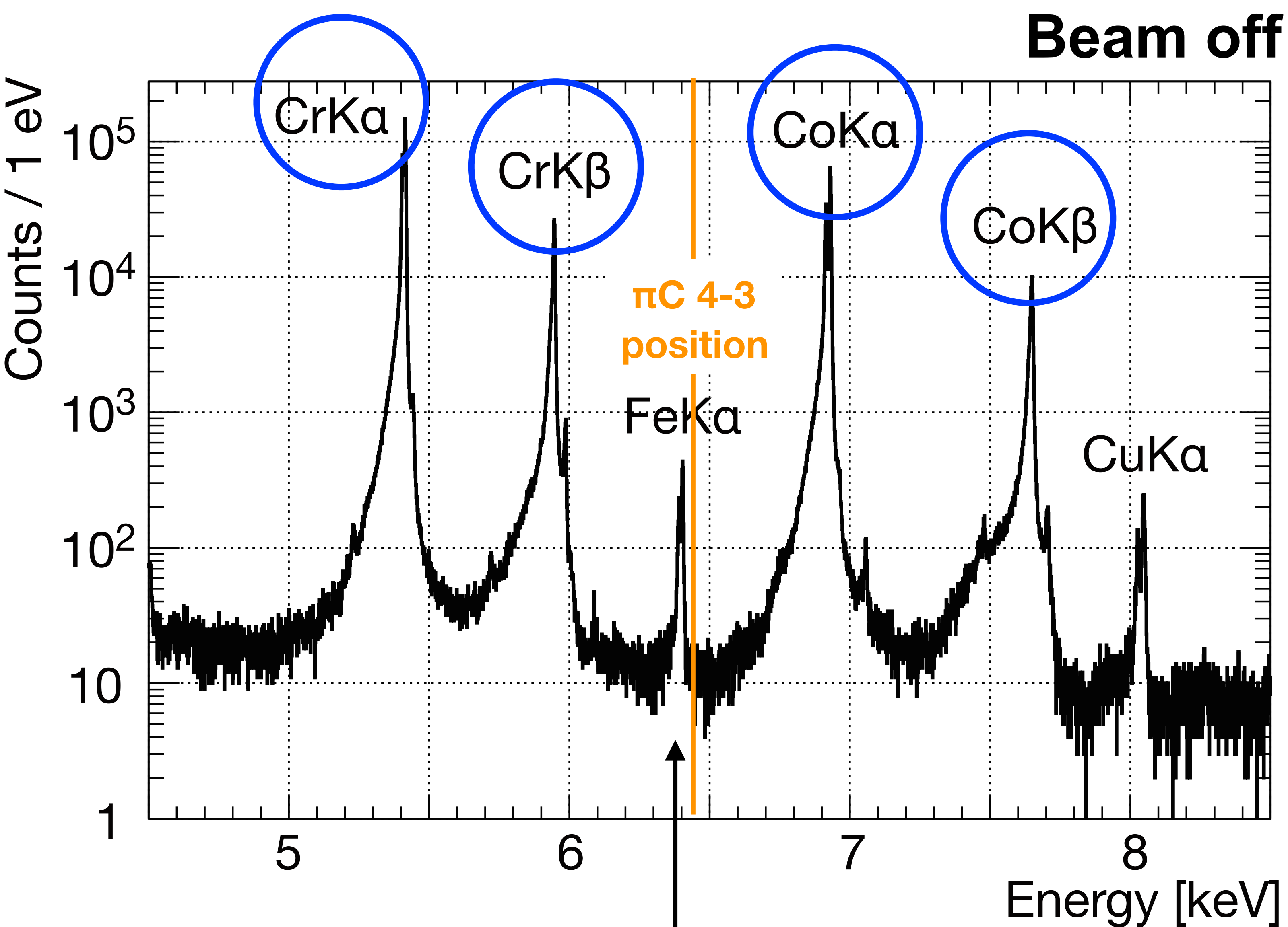
S. Hirenzaki, Y. Okumura, H. Toki, E. Oset, and A. Ramos, Phys. Rev. C 61 (2000) 055205

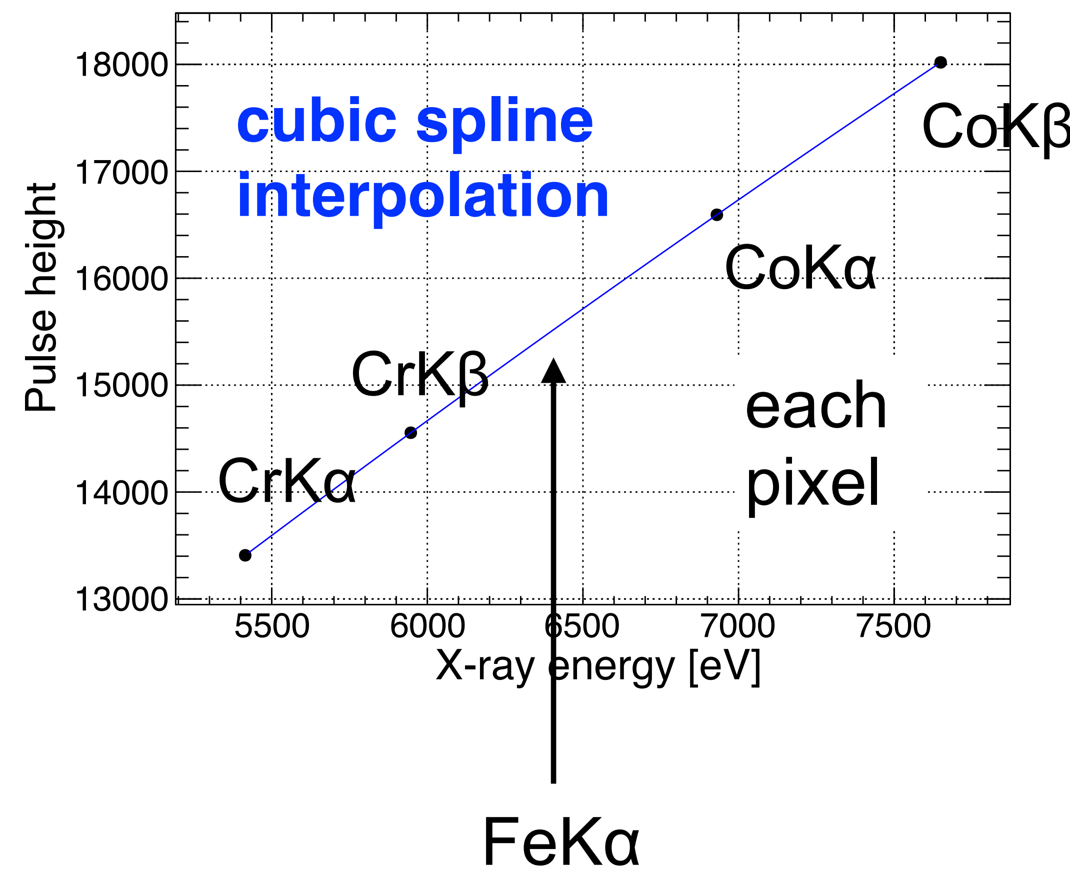
→ Closely related to **K^- nuclear cluster** study
→ **Current data quality is not good enough** to determine K-nucl. potential strength

Estimated energy resolution at J-PARC K1.8 BR



Energy calibration lines





FeKα (from stainless steal):
useful to verify the energy
calibration

✓ ΔE_{FWHM} ~ 5 eV (beam off)
at 6.4 keV