10 Nov, 2014
What next LNF: Perspectives of fundamental physics at the Frascati Laboratory @ Frascati

# High-resolution hadronic atom X-ray spectroscopy with cryogenic detectors

Shinji OKADA (RIKEN)

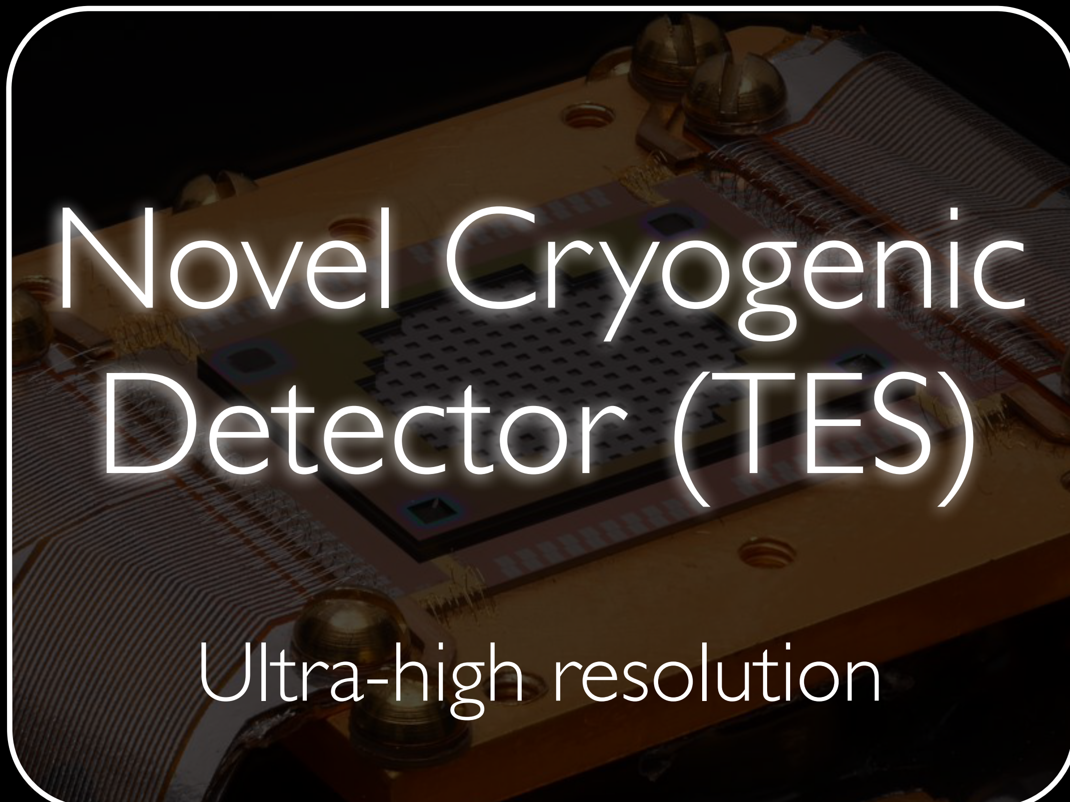
**The HEATES collaboration**

- **H**igh-resolution **E**xotic **A**tom x-ray spectroscopy with **TES** microcalorimeter -

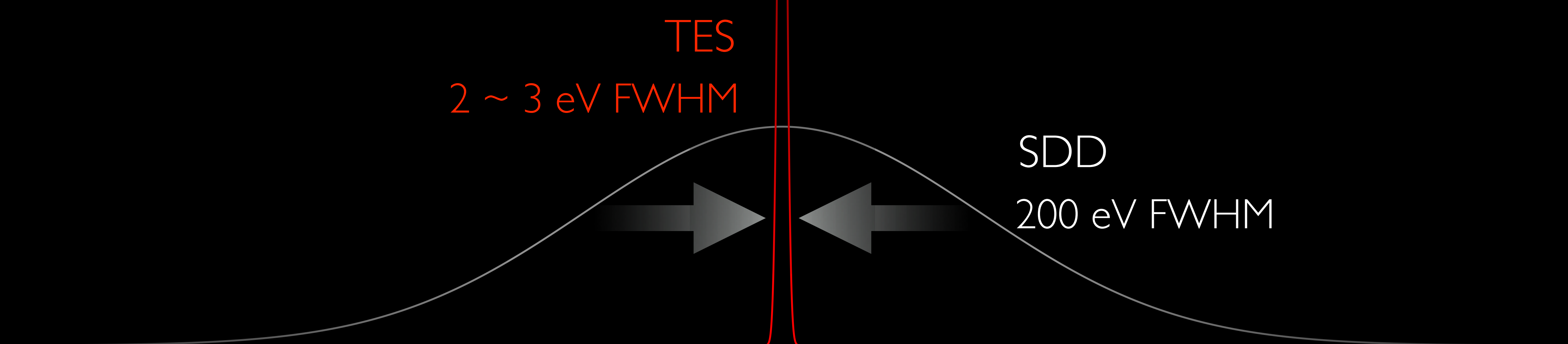
S. Okada[1], D.A. Bennett[2], C. Curceanu[3], W.B. Doriese[2], J.W. Fowler[2], F. Gustafsson[4], T. Hashimoto[1], R.S. Hayano[5], S. Hexi[3], M. Iliescu[3], S. Ishimoto[6], K. Itahashi[1], M. Iwasaki[1], K. Kuwabara[7], J. Marton[8], G.C. O'Neil[2], H. Noda[1], H. Outa[1], M. Sato[1], D.R. Schmidt[2], A. Scordo[3], K. Suzuki[8], T. Suzuki[5], D.S. Swetz[2], H. Tatsuno[2,6], J. Uhlig[4], J.N. Ullom[2], E. Widmann[8], S. Yamada[7], J. Zmeskal[8]

RIKEN[1], NIST[2], INFN-LNF[3], Lund Univ.[4], Univ. of Tokyo[5], KEK[6], Tokyo Metropolitan Univ.[7], Stefan Meyer Institut[8]

# New idea




×


*two orders of magnitude improved resolution*
*compared with the conventional semiconductor detector*

# Contents

1. **Introduction** - Missions at the DAFNE K-atom factory

2. **Detector** - Transition-Edge Sensor (TES)

3. **Experiment** - K-mass measurement at DAFNE

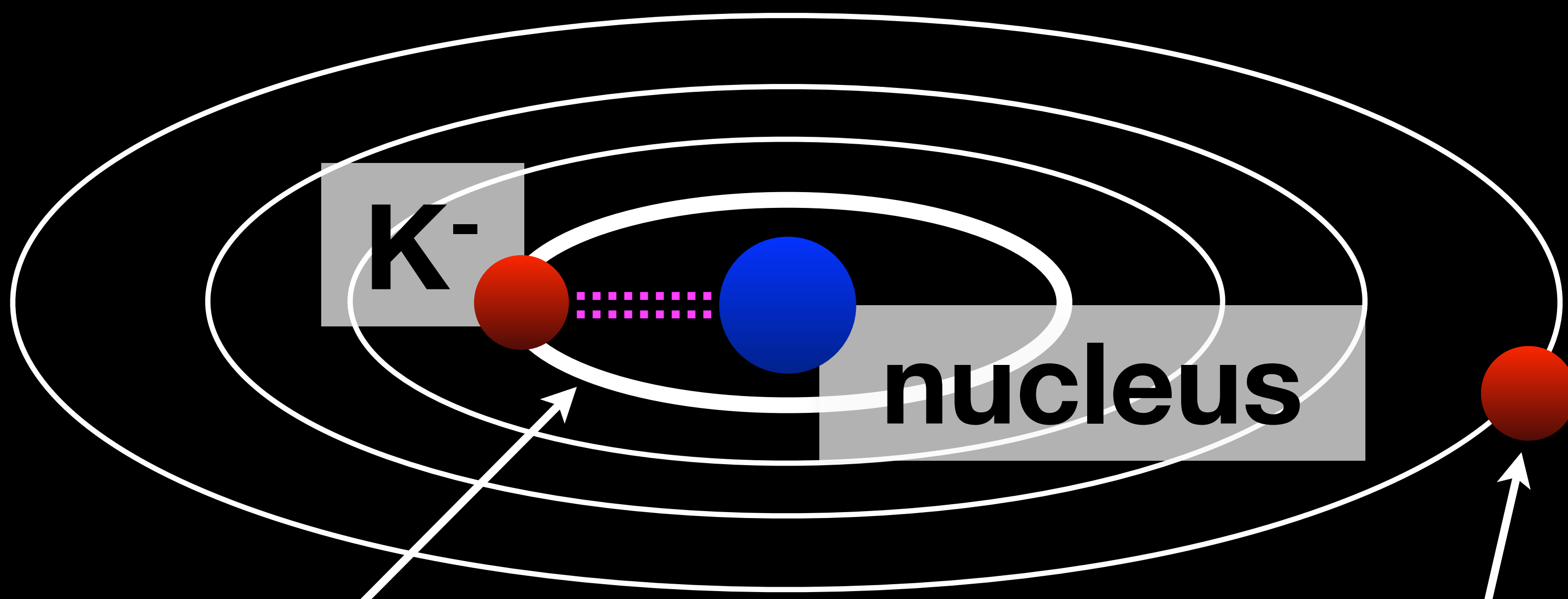
4. **Test experiment** - in-beam performance of TES

5. **Summary**

# 1. Introduction

Missions at the DAFNE K-atom factory

# Kaonic atom




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

# Two major puzzles on K-atom

## 1. K - nucleus potential puzzle

- Deep or Shallow? ( because of insufficient K-atom data )

## 2. K- mass puzzle

- The recent two measurements disagree by more than 5 sigma !

# Two major puzzles on K-atom

## 1. K - nucleus potential puzzle

- Deep or Shallow? ( because of insufficient K-atom data )

## 2. K- mass puzzle

- The recent two measurements disagree by more than 5 sigma !

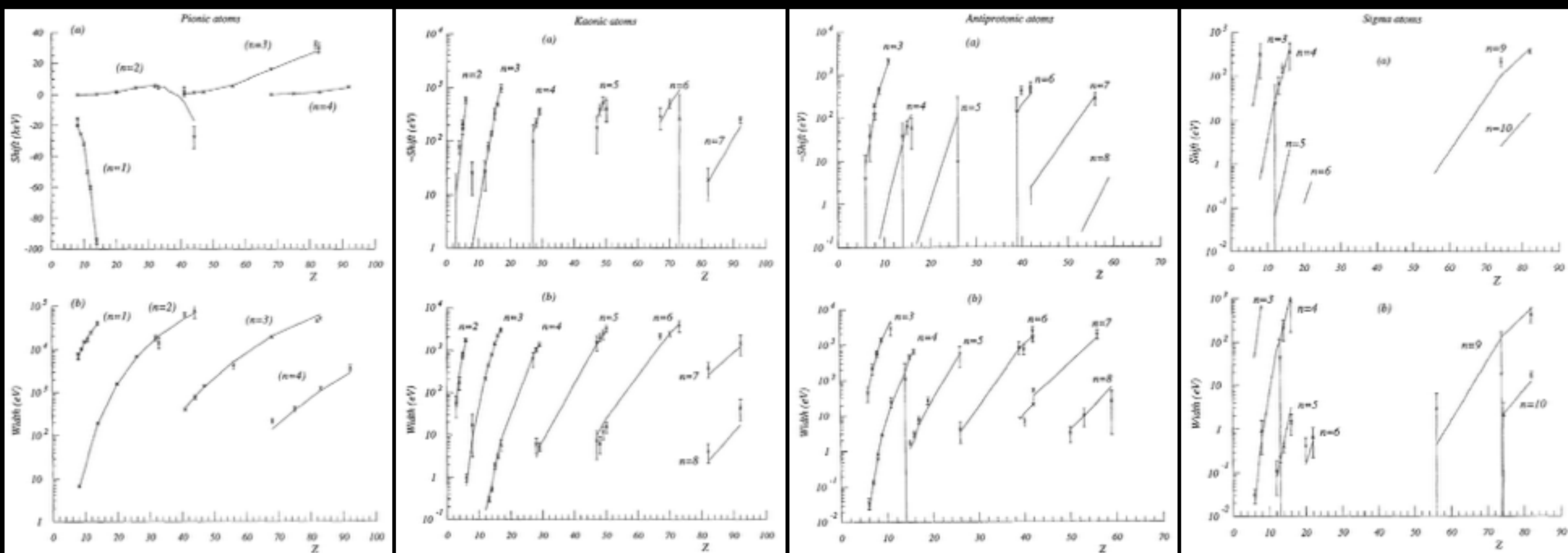
# Many measurements so far

## shift & width as a function of atomic number Z

$\pi^-$ atoms    $K^-$ atoms    $\bar{p}$ atoms    $\Sigma^-$ atoms

Shift [eV]

Width [eV]




Atomic number Z

dot : expt data
line : theo calc

*Strong Interaction Physics From Hadronic Atoms*

*C.J. Batty, E. Friedman, A. Gal, Physics Reports 287 (1997) 385 - 445*

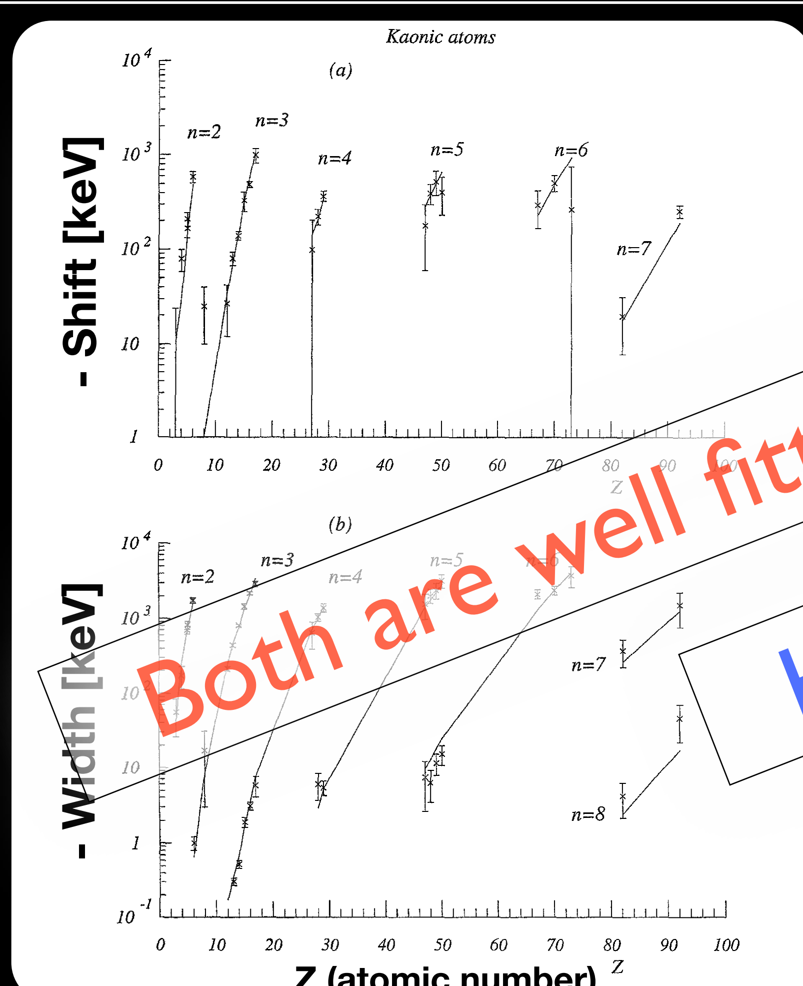
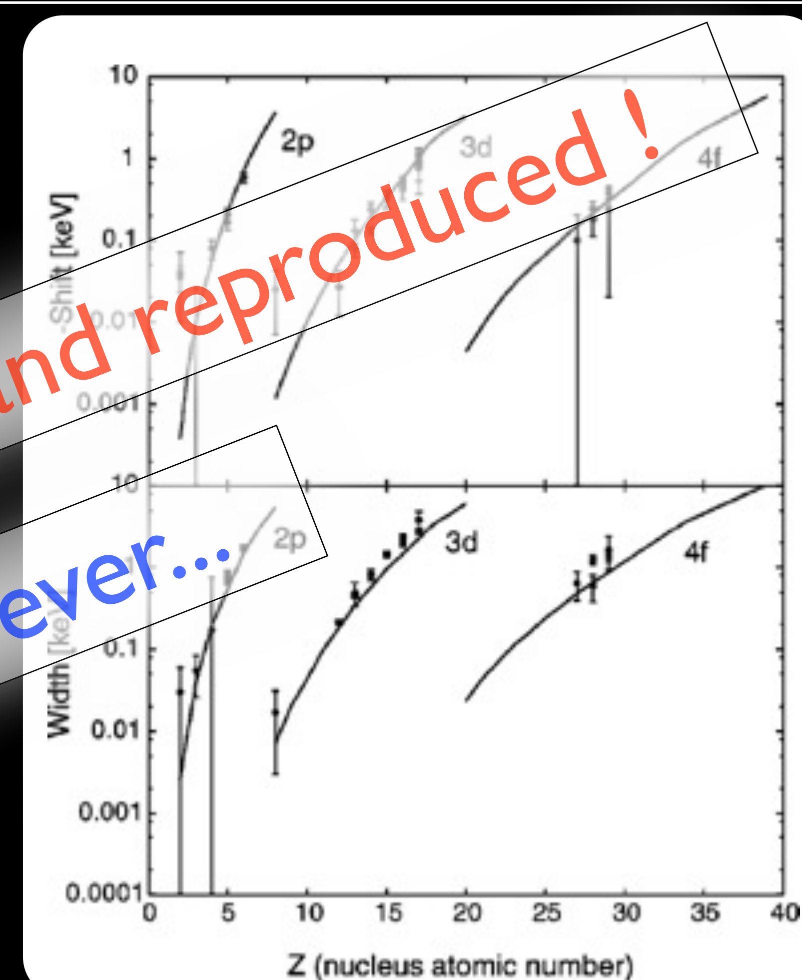
# Open problem on K-atom

Different scenarios for different exotic atoms

| particle | real potl. | imaginary potl. | comments |
|---|---|---|---|
| $\pi^-$ | repulsive in bulk | moderate | excellent data |
| | attractive on surface | | well understood |
| $K^-$ | attractive | moderate | good data |
| | deep or shallow? | | open problems |
| $\bar{p}$ | ?? | very absorptive | excellent data |
| | | | understood |

*E. Friedman : MESON2010 conf.*

# K-atom : theoretical approaches

| | Density-dep. optical potential | SU(3) chiral unitary |
|---|---|---|
| model | *C.J. Batty, E. Friedman, A. Gal, Phys. Reports 287 (1997) 385* | *Hirenzaki, Okumura, Toki, Oset, Ramos, PRC 61 (2000) 055205.* |
| | $V = -\frac{2\pi}{\mu}\left(1+\frac{\mu}{m}\right)\bar{a}\rho(r),$ <br> $a \to a_0 + A_0[\rho(r)/\rho(0)]^{\alpha},$ | $2\mu V_{opt}(r) = -4\pi\eta a_{eff}(\rho)\rho(r),$ |
| exp. data vs calc. results |  |  |





Both are well fitted and reproduced !

However...

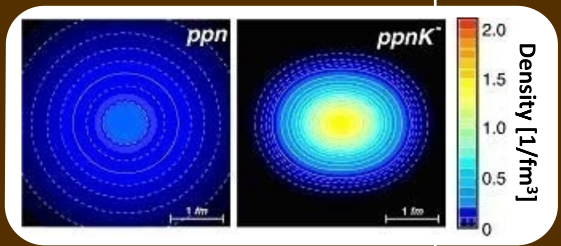
# deep or shallow ?

| | | |
|---|---|---|
| model | Density-dep. optical potential | SU(3) chiral unitary |
| | *C.J. Batty, E. Friedman, A. Gal, Phys. Reports 287 (1997) 385* | *Hirenzaki, Okumura, Toki, Oset, Ramos, PRC 61 (2000) 055205.* |
| | $V = -\frac{2\pi}{\mu}\left(1+\frac{\mu}{m}\right)\bar{a}\rho(r),$ <br> $a \rightarrow a_0 + A_0[\rho(r)/\rho(0)]^\alpha,$ | $2\mu V_{opt}(r) = -4\pi\eta a_{eff}(\rho)\rho(r),$ |
| potential depth | **deep** ($-V_{Real}$ = 150 ~ 200 MeV) | **shallow** ($-V_{Real}$ = 40 ~ 60 MeV) |

## Open problem

**deep** ⟷ **shallow**

**The number of the kaonic nuclear bound states would be different** (depending on the nucleus).




"deeply-bound" $K^-$ clusters ?

# deep or shallow ?

| | Density-dep. optical potential | SU(3) chiral unitary |
|---|---|---|
| model | *C.J. Batty, E. Friedman, A. Gal,* | *Hirenzaki, Okumura, Toki, Oset, Ramos,* |

**insufficient K-atom data**

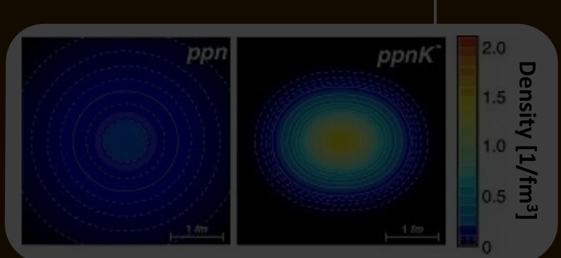
results in open problem in “K - nucl. potential”

need more high-precision K-atom measurements

Open problem

potential depth

**The number of the kaonic nuclear bound states would be different** (depending on the nucleus).




“deeply-bound” K⁻ clusters ?

# Two major puzzles on K-atom

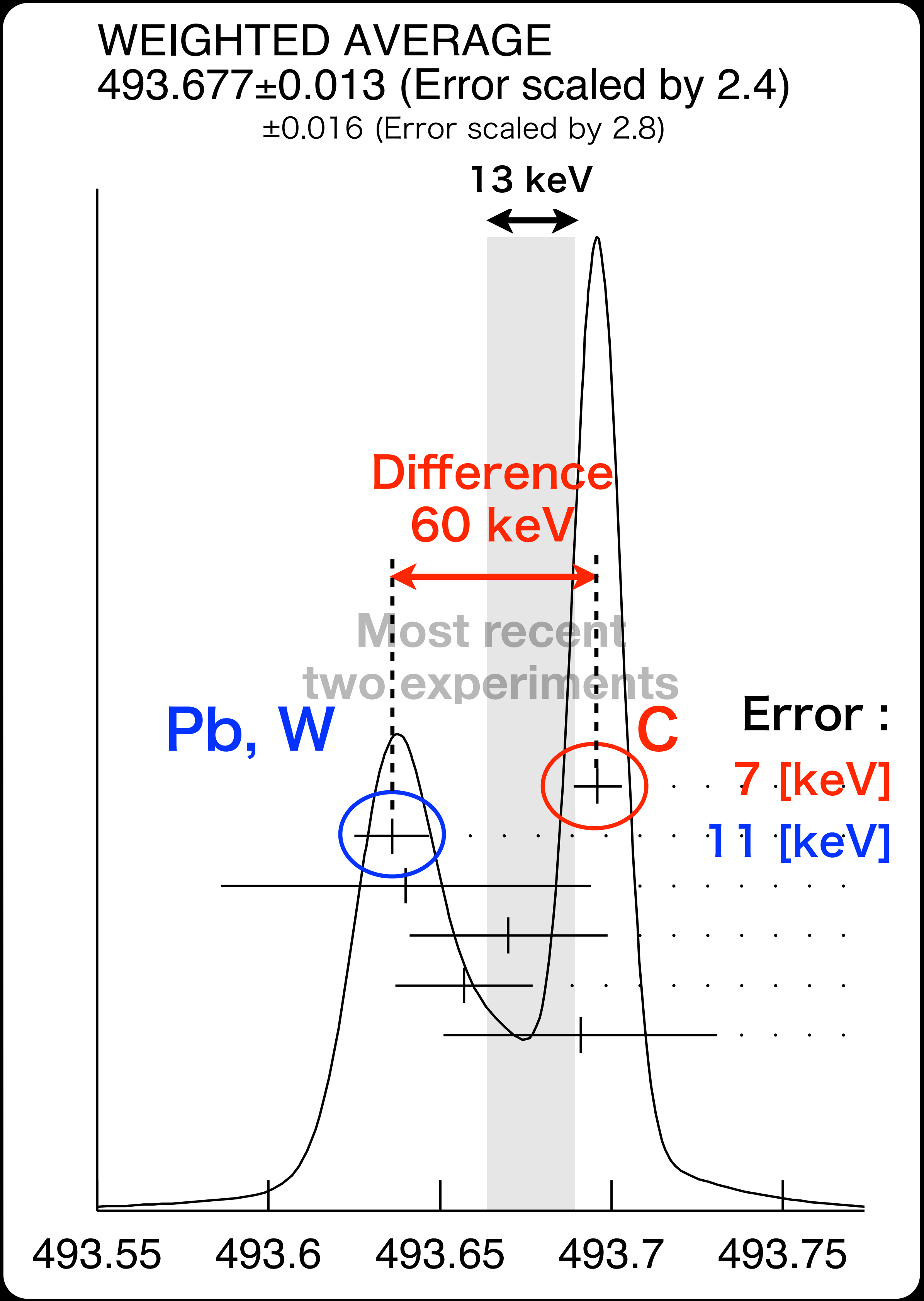
## 1. K - nucleus potential puzzle

- Deep or Shallow? ( because of insufficient K-atom data )

## 2. K- mass puzzle

- The recent two measurements disagree by more than 5 sigma !

# K- mass puzzle




*K-mass : fundamental quantity*

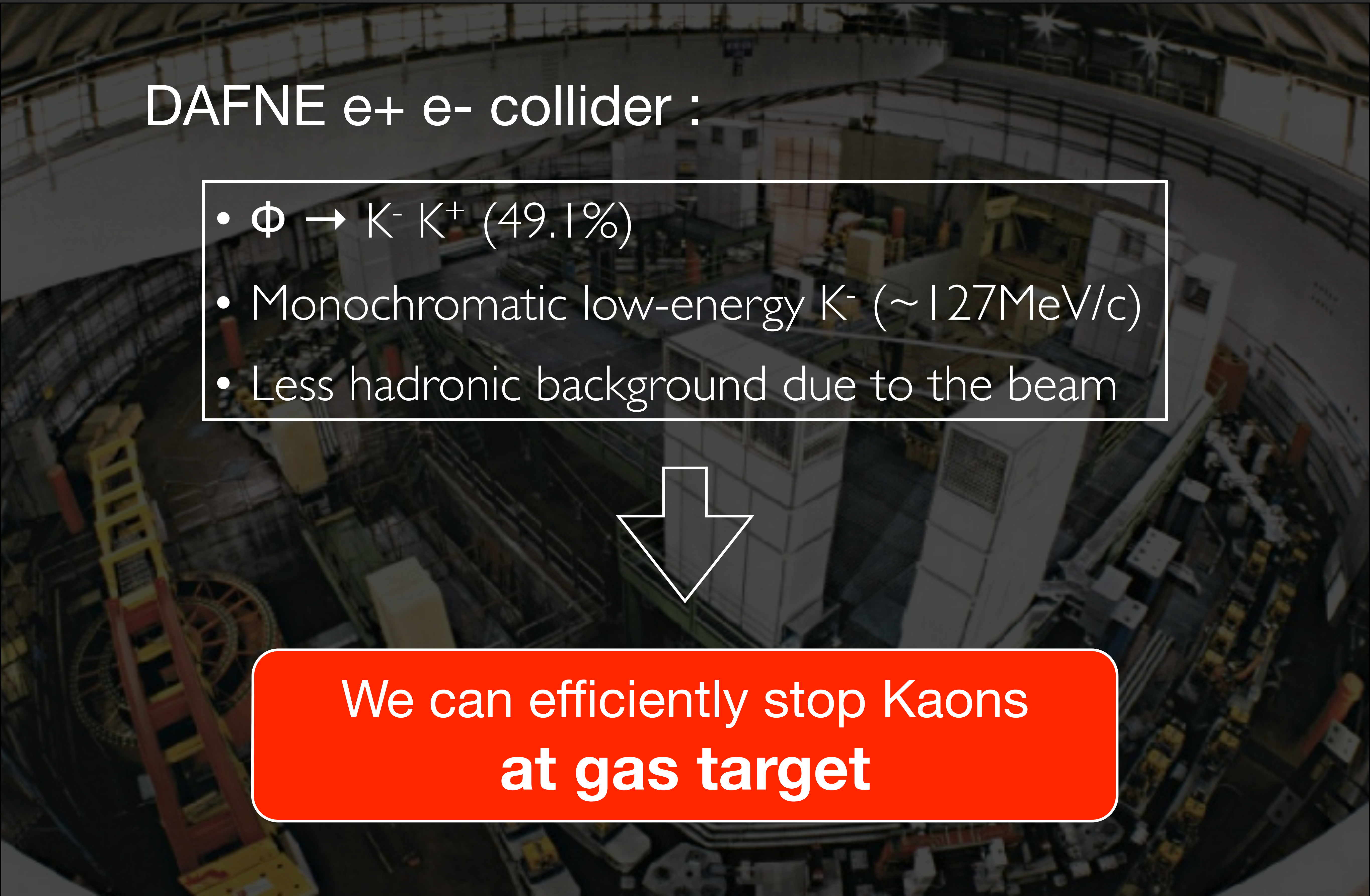
awaited for new measurement !

Requirements :

1. **high-resolution** detector
2. K-atom with low-Z **gas** target

to reduce the electron screening effects which could cause an uncertainty of K-mass value

# DAFNE : Unique facility for low-energy K-



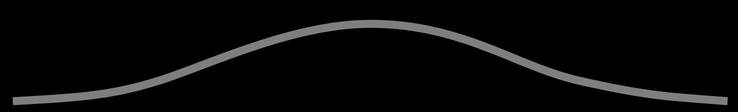
## DAFNE e+ e- collider :

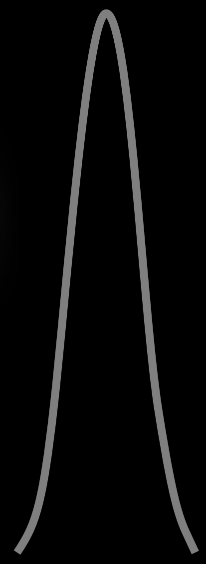
- $\Phi \rightarrow K^- K^+$ (49.1%)
- Monochromatic low-energy $K^-$ (~127MeV/c)
- Less hadronic background due to the beam

We can efficiently stop Kaons
**at gas target**

# Missions at DAFNE K-atom factory

## complete K-atom data acquisition





- large width
- low intensity

-> **SDD** etc.

- small width
- high intensity

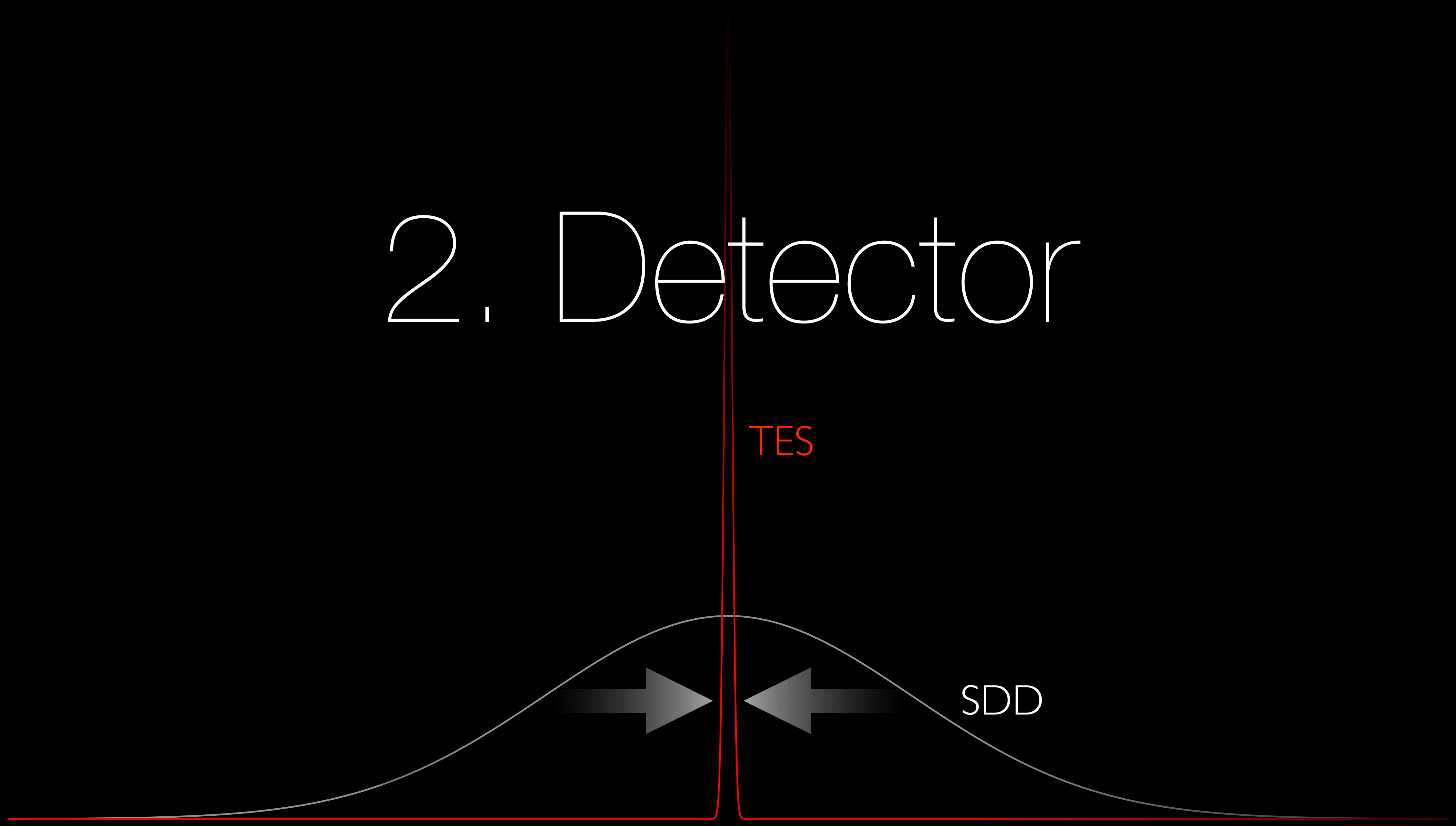
-> **TES**

✓ 1s level of K-p, **K-d** (K-He)
✓ other K atoms

SIDDHARTA-2

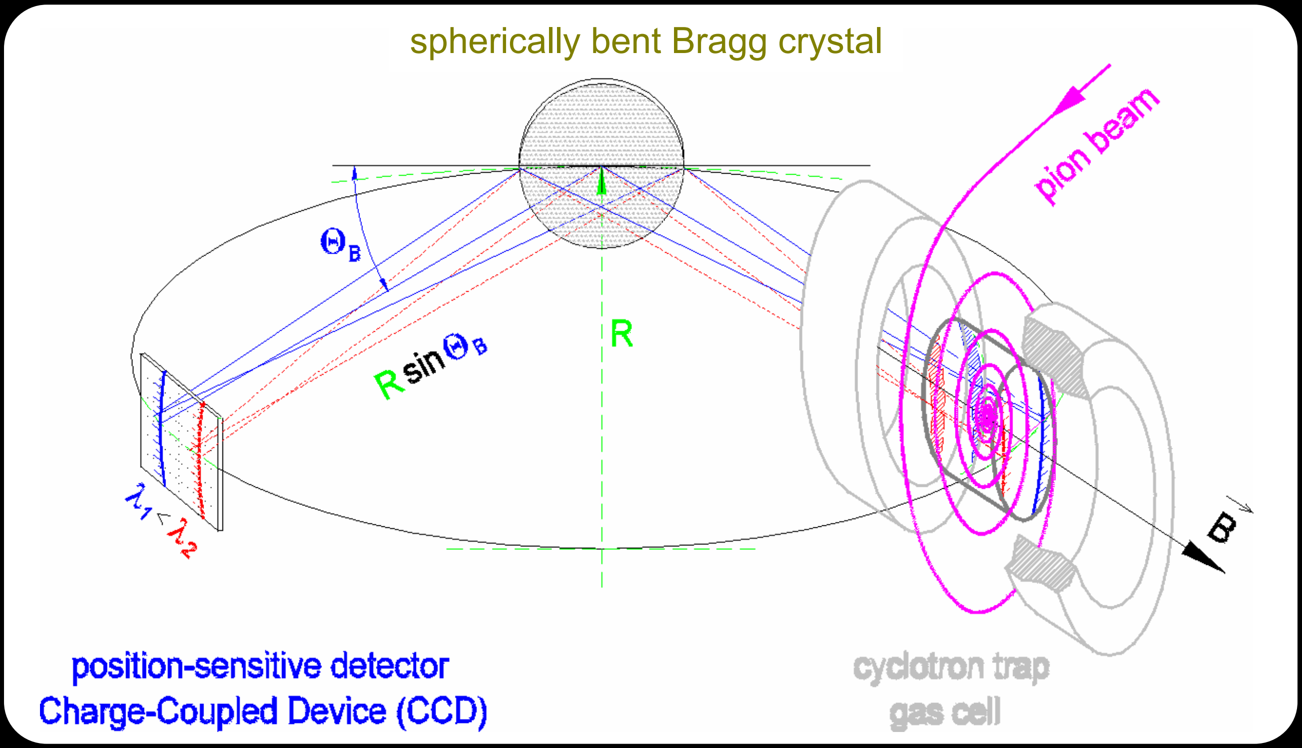
✓ **K-mass** measurement
✓ 2p level of K-He, K-Li etc…
✓ other higher level of K-atom

# 2. Detector



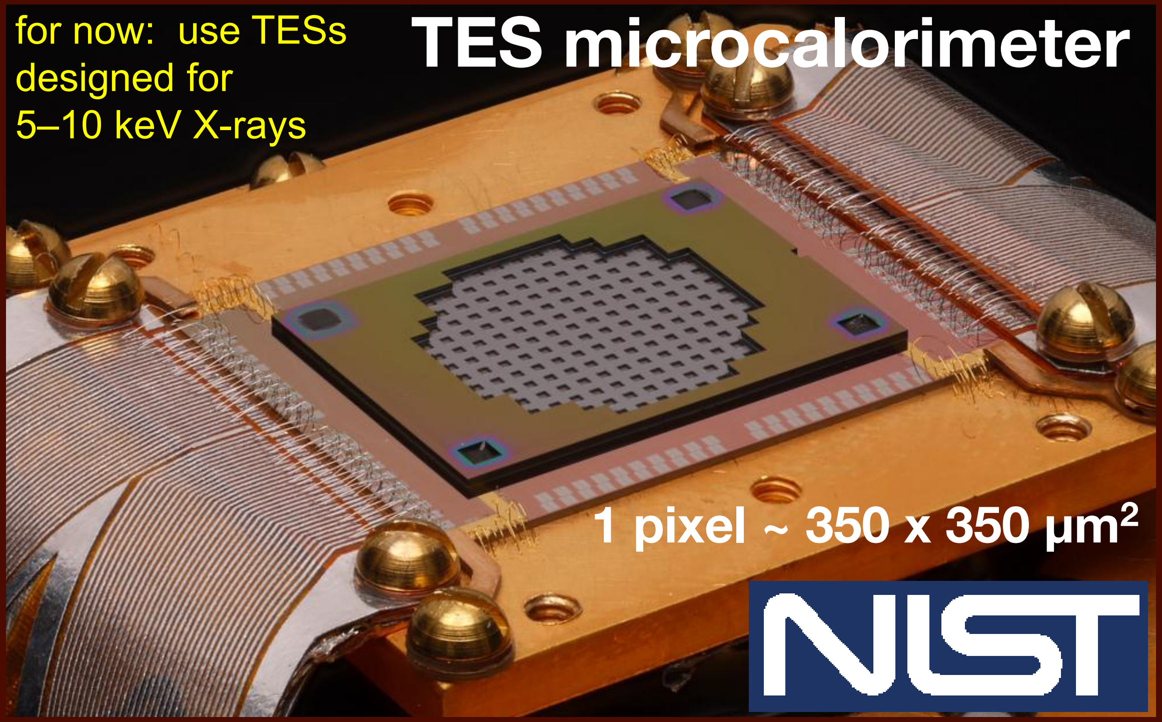
# High-resolution detectors

## 1. Crystal spectrometer




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

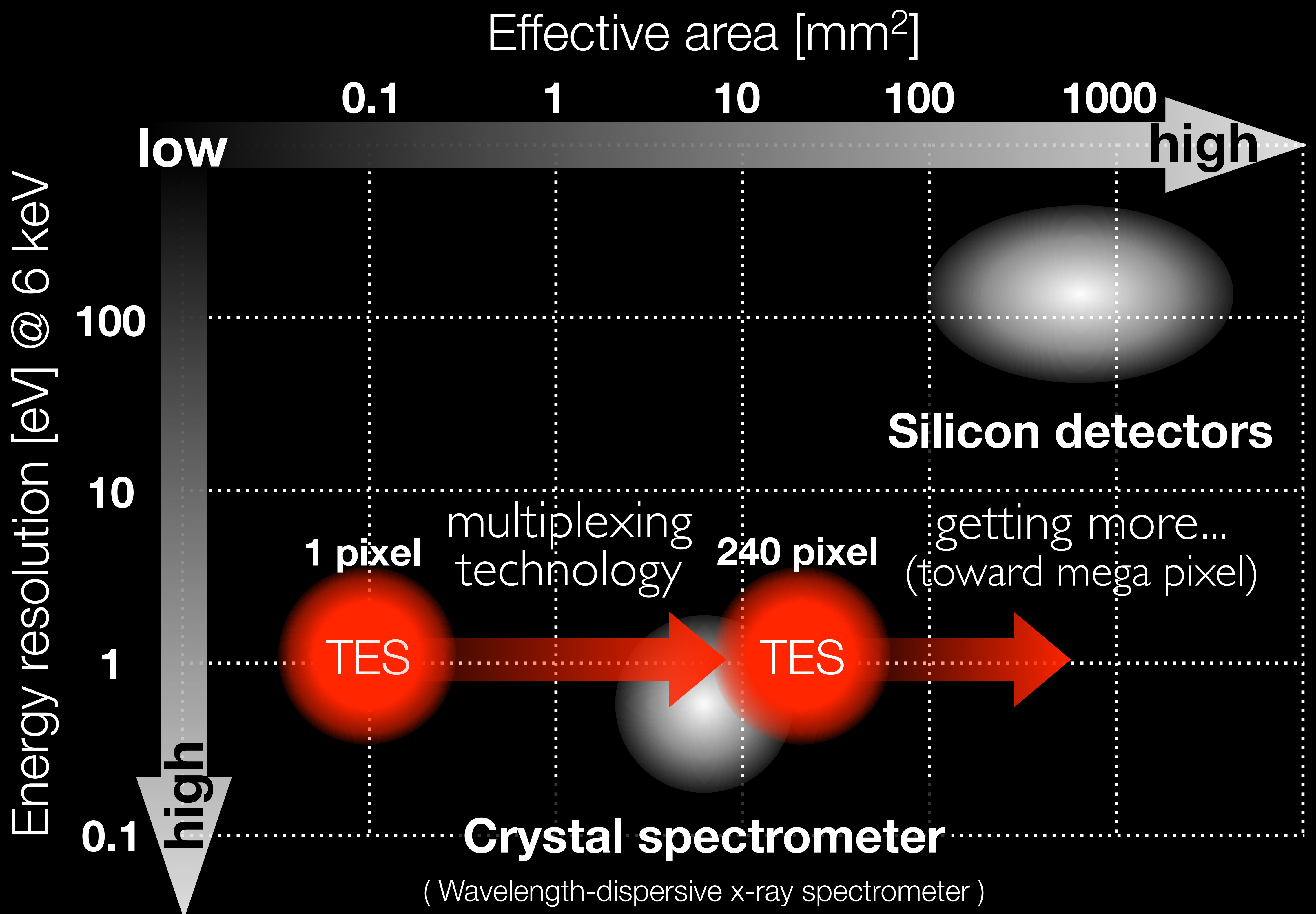
## 2. Cryogenic detector




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

→ small acceptance

# Why TES ? ( I )

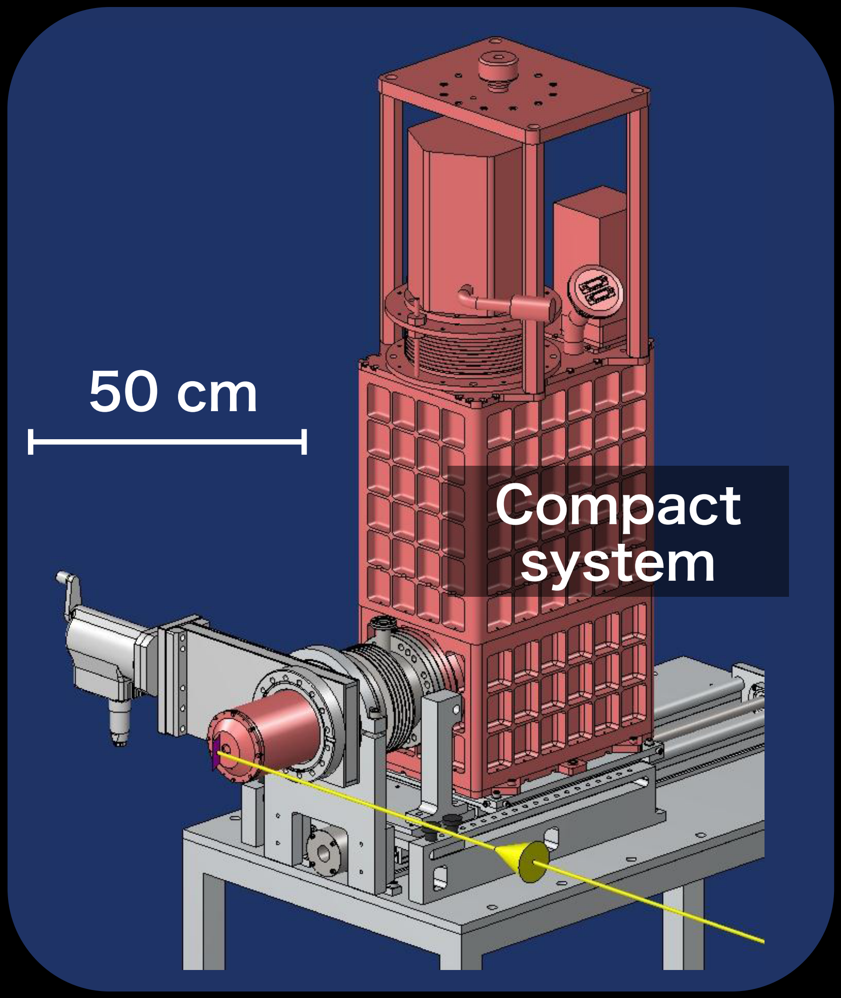



The solid angle of a crystal spectrometer (PLB 416 (1998) 50) was converted to the equivalent effective area.

# Why TES ? (2)

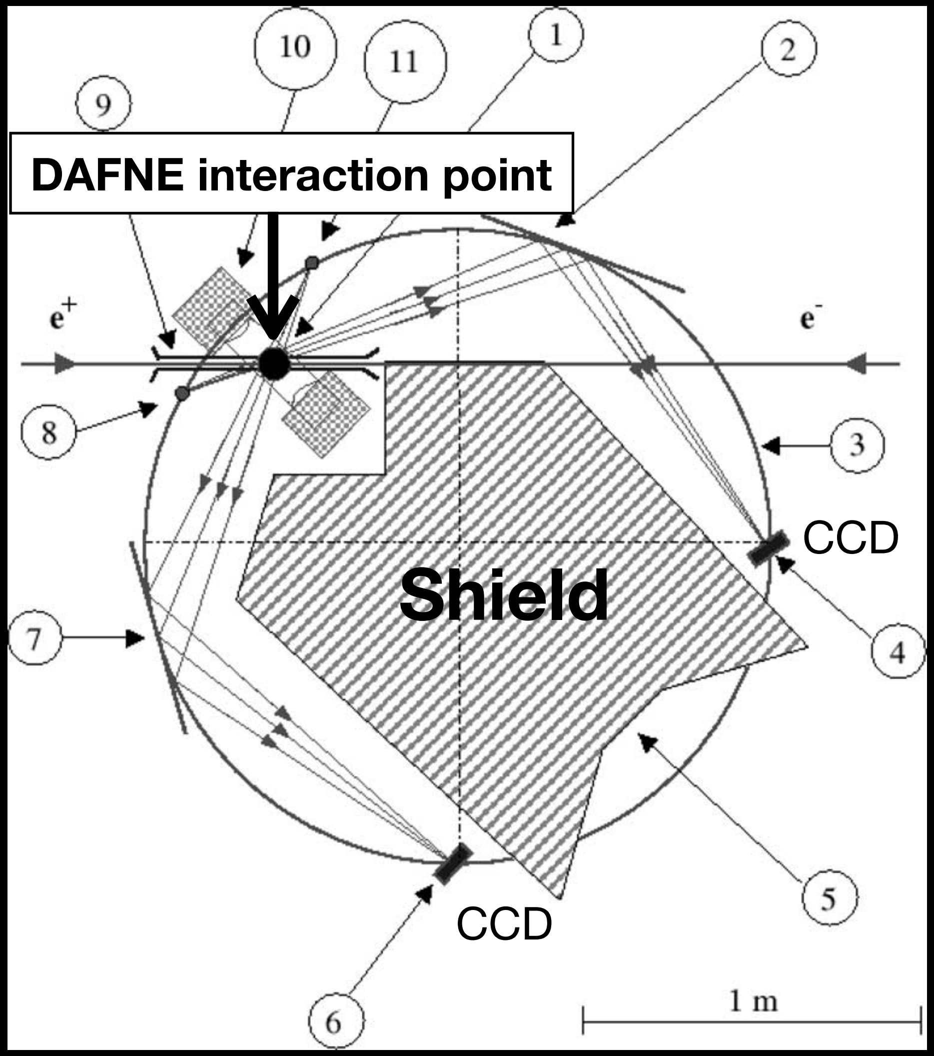
✓ Compact and portable

TES system




vs.

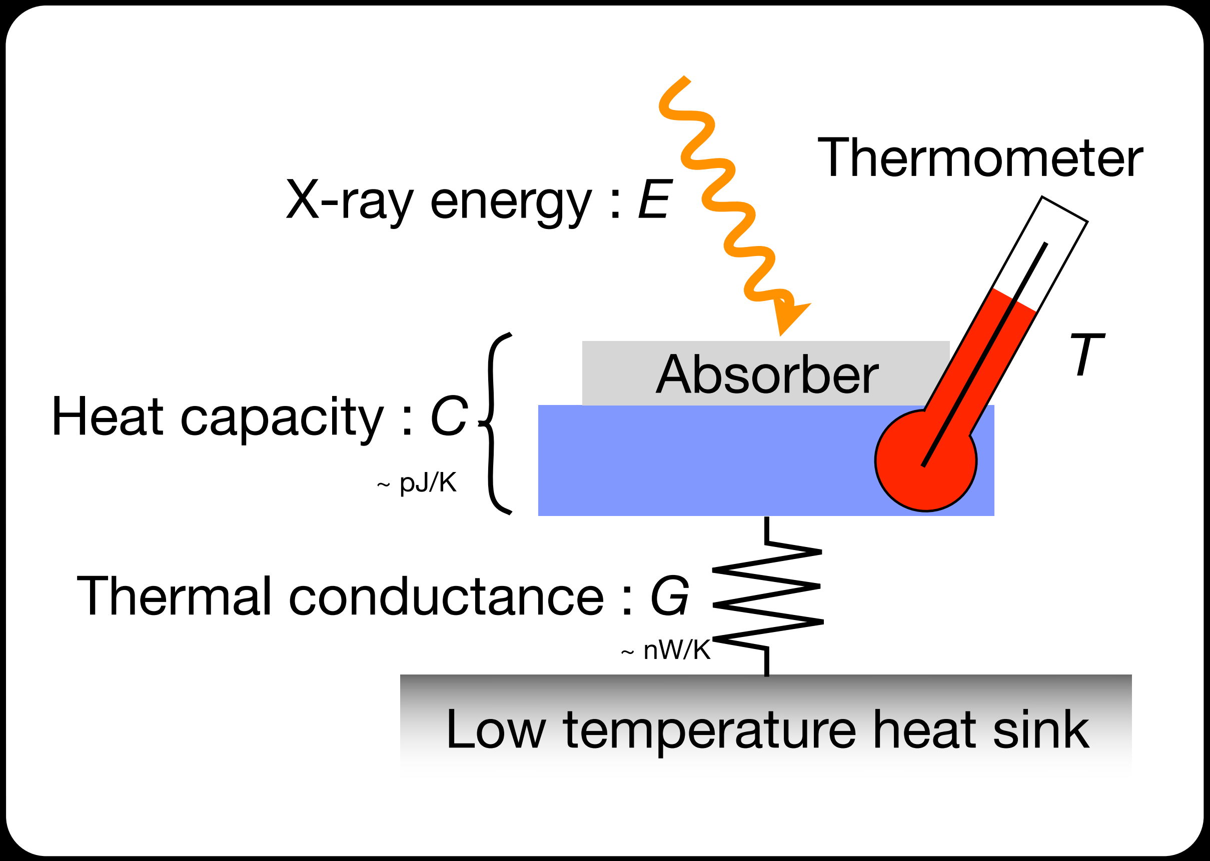
Crystal spectrometer



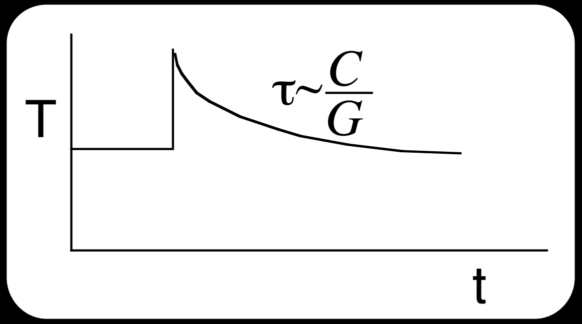

G. Beer et al., PLB 535 (2002) 52

# X-ray microcalorimeter

a thermal detector measuring the energy of an incident x-ray photon as a temperature rise (= E/C ~ 1 mK )




Decay time constant
= C / G ( ~ 500 μs )

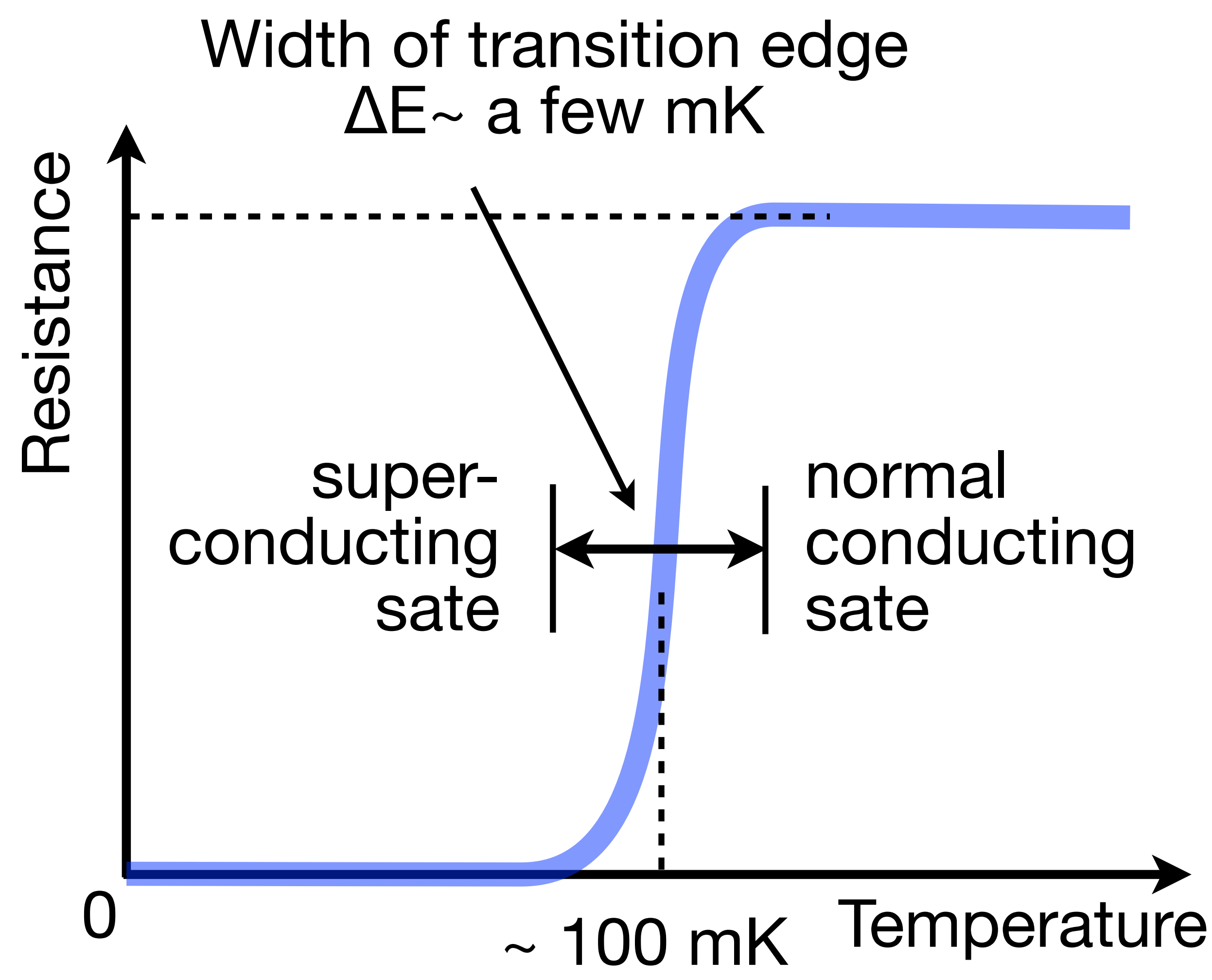



Absorber with larger "Z" (to stop the high energy x-rays)

e.g., Absorber : Bi (320 um × 300 um wide, 4 um thick)
Thermometer : thin bilayer film of Mo (~65nm) and Cu (~175nm)

# 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

$$\alpha \equiv \frac{d \ \ln R}{d \ \ln T} \sim 10^{2\sim3}$$

### Energy resolution (σ)

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

( Johnson noise and phonon noise are the most fundamental )

### Dynamic range

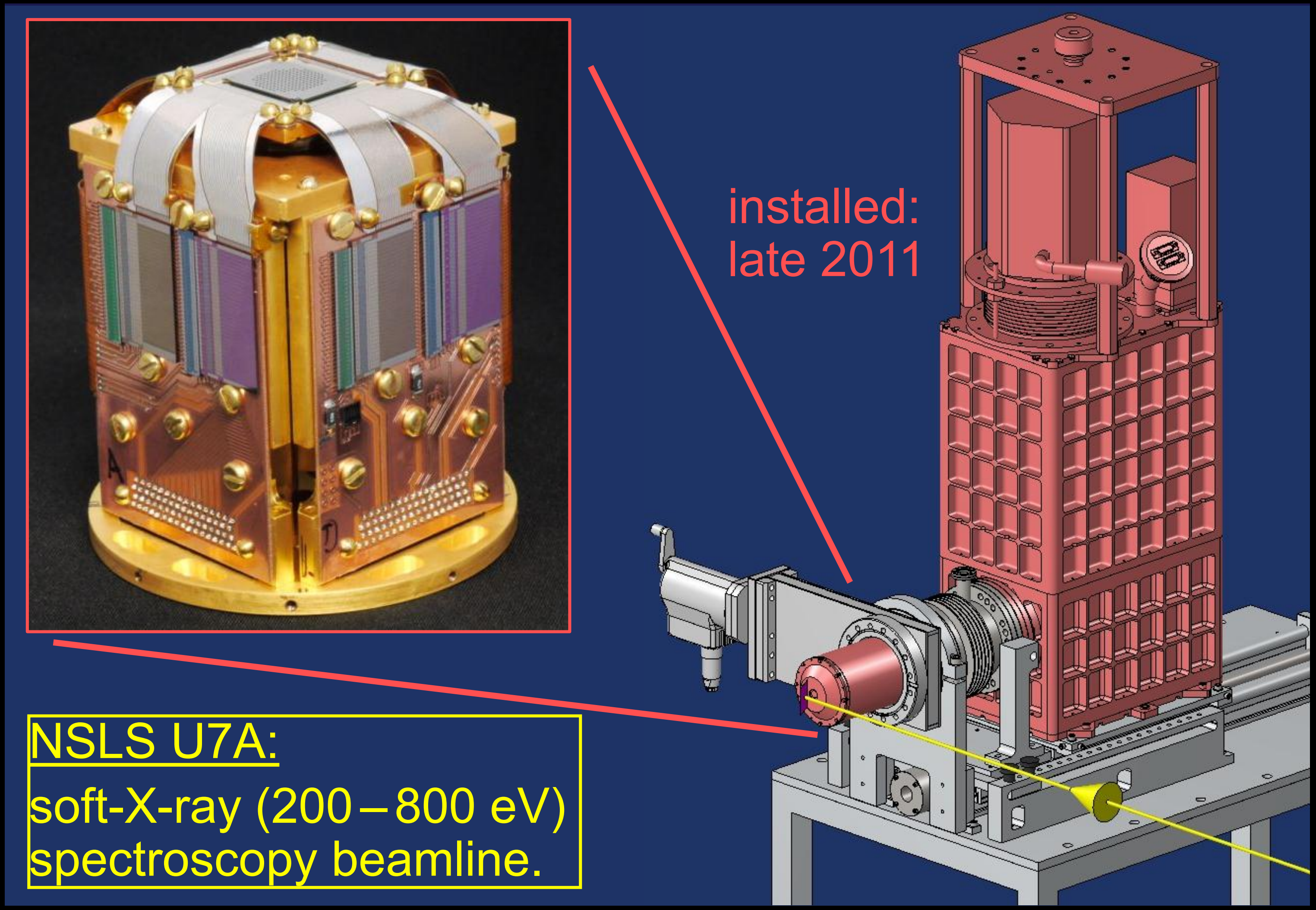
$$E_{max} \sim CT_C/\alpha$$

Trade-off between dynamic range and energy resolution : $\Delta E \sim \sqrt{E_{max}}$

applications : astrophysics (space satellite) etc.

# NIST's TES array system for x-rays

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




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

## NIST's standard TES

- 1 pixel : 300 x 320 $\mu m^2$
- 240 array : total ~ **23 $mm^2$**
- **2~3 eV (FWHM)** @ 6 keV

well established system!

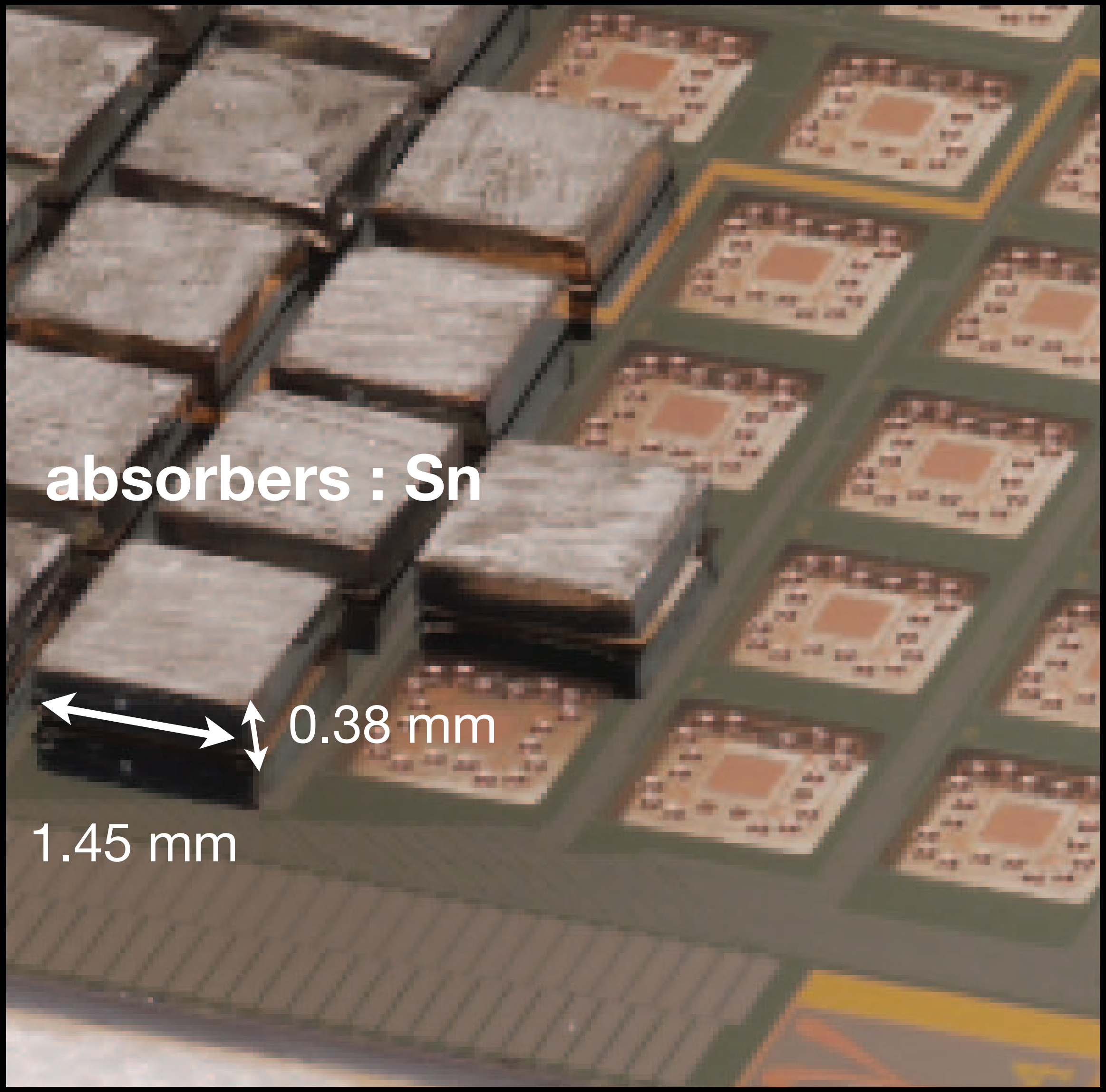
**two-order improved** resolution

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

# NIST's TES for gamma-rays

for 100 - 400 keV

e.g., hard-X-ray spectroscopy




## NIST's standard TES

- 1 pixel : 1.45 x 1.45 $mm^2$
- 256 array : total ~ **5 $cm^2$**
- **53 eV (FWHM)** @ 97 keV

**an order improved** resolution

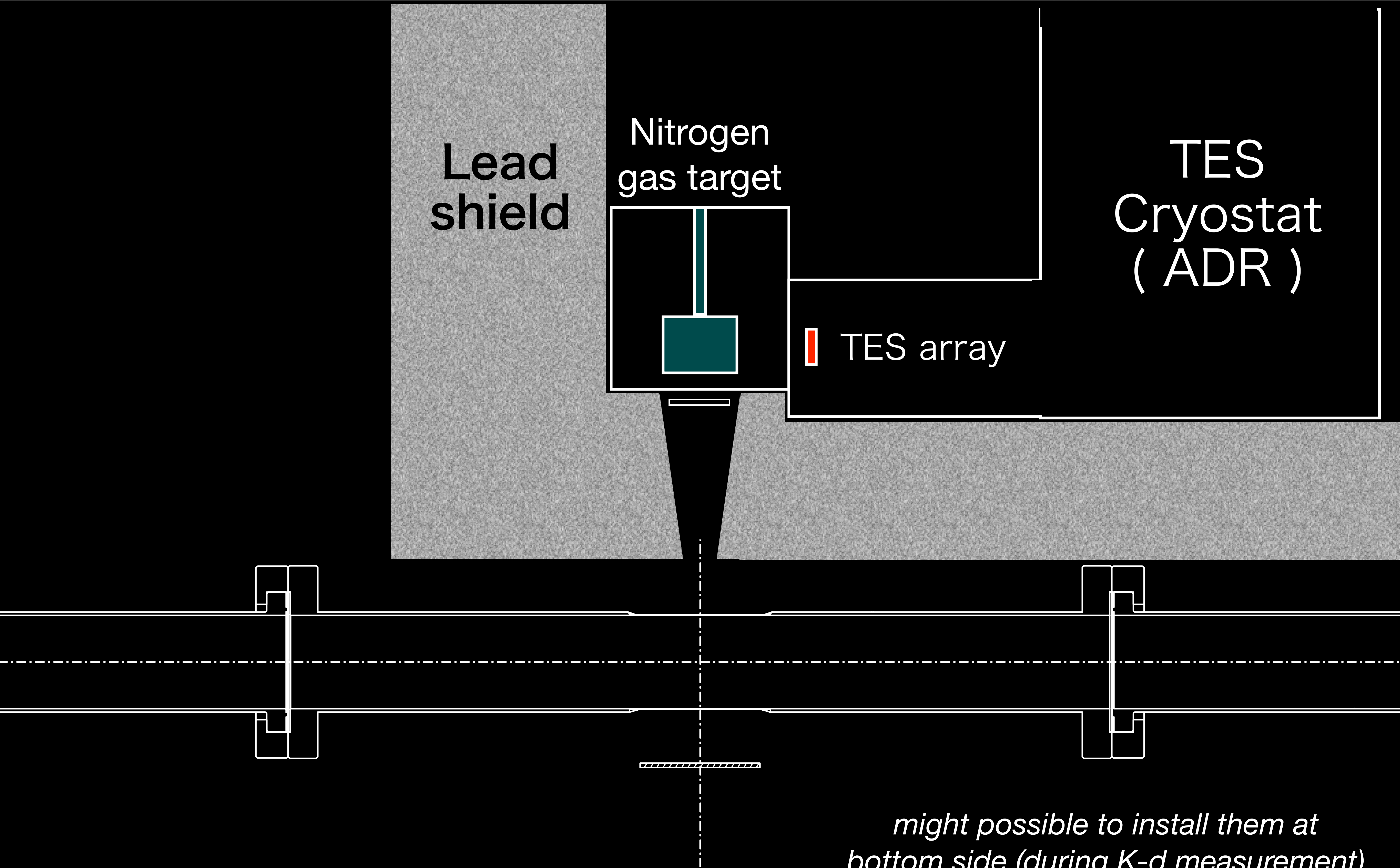
State-of-art high-purity germanium detectors

*D. A. Bennett et al., Rev. Sci. Instrum. 83, 093113 (2012)*

# 3. Experiment

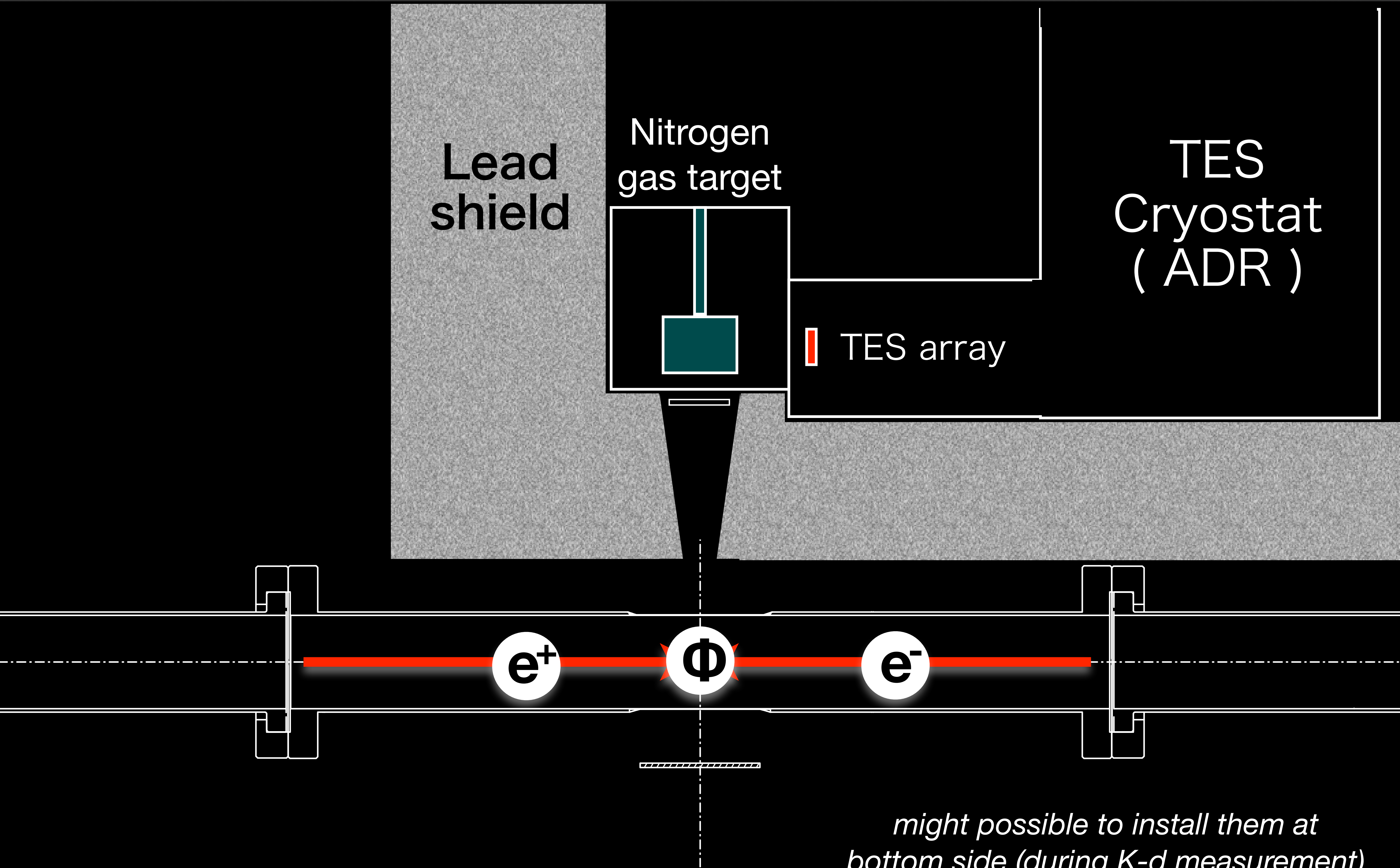
K-mass measurement at DAFNE

# Possible simple experimental setup



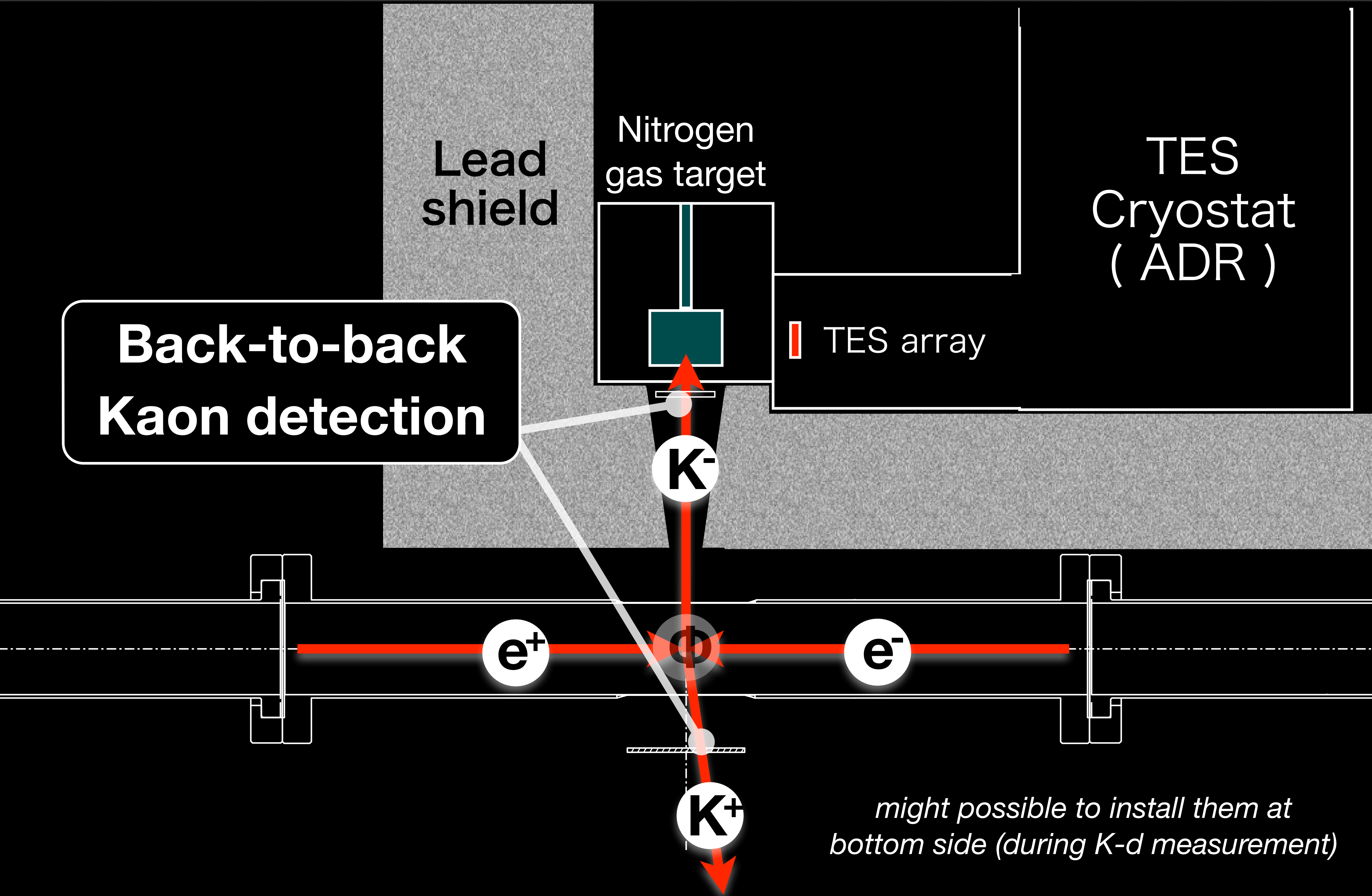

*might possible to install them at bottom side (during K-d measurement)*

# Possible simple experimental setup

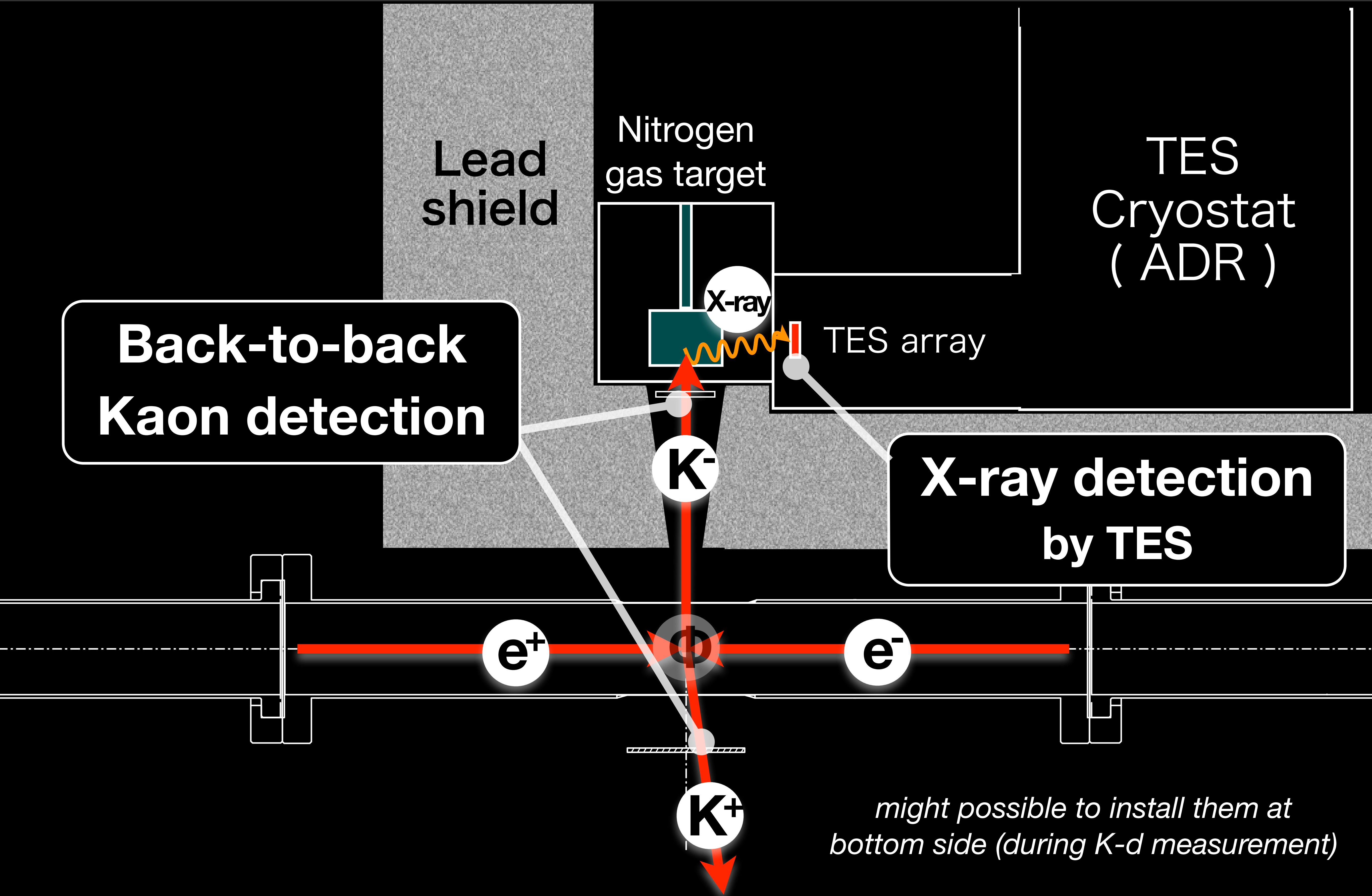



*might possible to install them at bottom side (during K-d measurement)*

# Possible simple experimental setup



# Possible simple experimental setup




*might possible to install them at bottom side (during K-d measurement)*

# Rough yield estimation : K-N 6-5 x-ray (7.6 keV)

Estimated based on DEAR / SIDDHARTA data (just scaled) :

- **TES array : 240 pixel ~ 23 $mm^2$ effective area**
- TES located the same position as SDD's at SIDDHARTA
- Target cell located the same position as that of SIDDHARTA
- Nitrogen gas density : 3.4 $\rho_{STP}$

➡ KN 6-5 x-ray ~ 3 events / day (4.5 $pb^{-1}$)

assumed improvements

✓ bring TES close to target ( x ~3 )
✓ bring target close to interaction point ( x ~3)
✓ higher Nitrogen gas density ( x ~2)

⇩

~ 50 events / day (4.5 $pb^{-1}$)

# Estimated stat. accuracy of K-mass

assuming :

- K-N 6-5 x-ray ~ **1500 events / month** (135 $pb^{-1}$)
- Energy resolution **~ 6.5 eV (FWHM)**
- No background

⇩

Stat. accuracy : ΔE (x-ray energy) ~ ± 0.07 eV

Δm (K-mass) = ΔE / E x m ~ ± 4.6 keV

possible improvements for more yield :

✓ weak magnetic lens to collect K- at small target

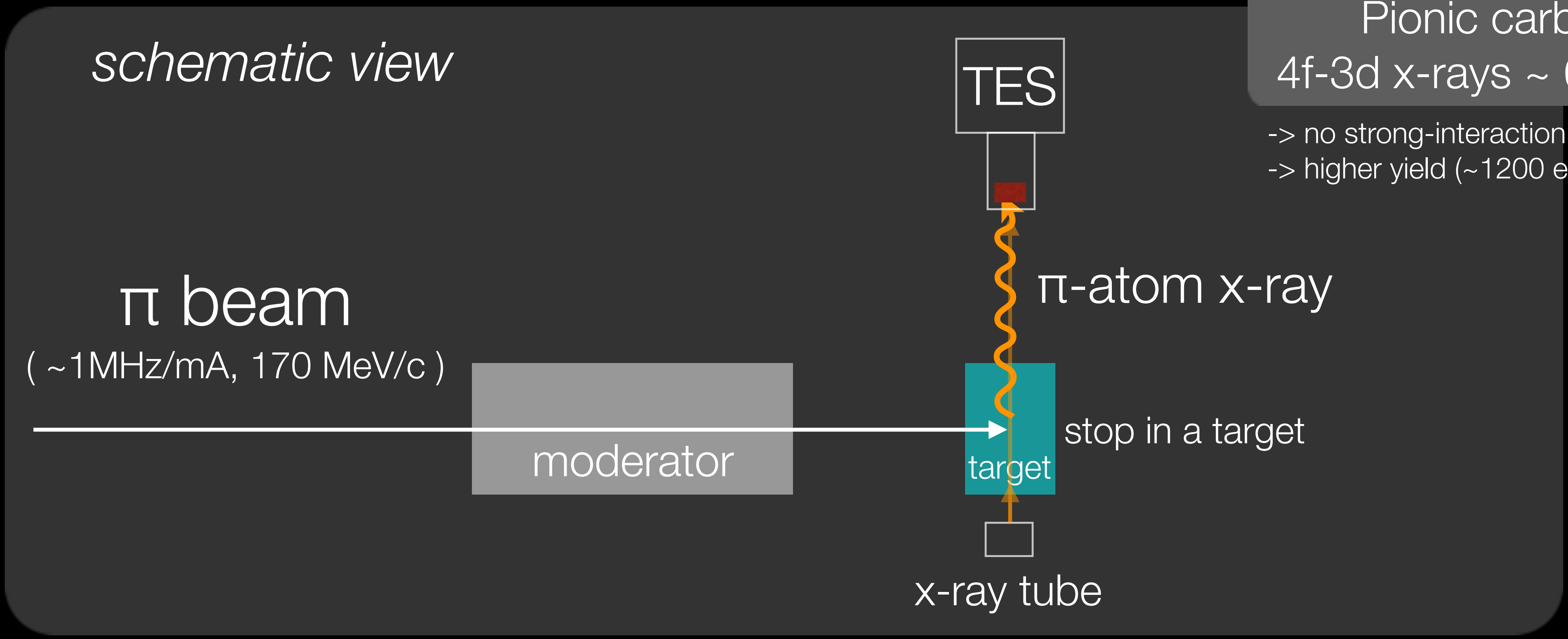
✓ polycapillary X-ray lens …

# 4. Test experiment

in-beam performance of TES

# Feasibility test towards K-atom expt.

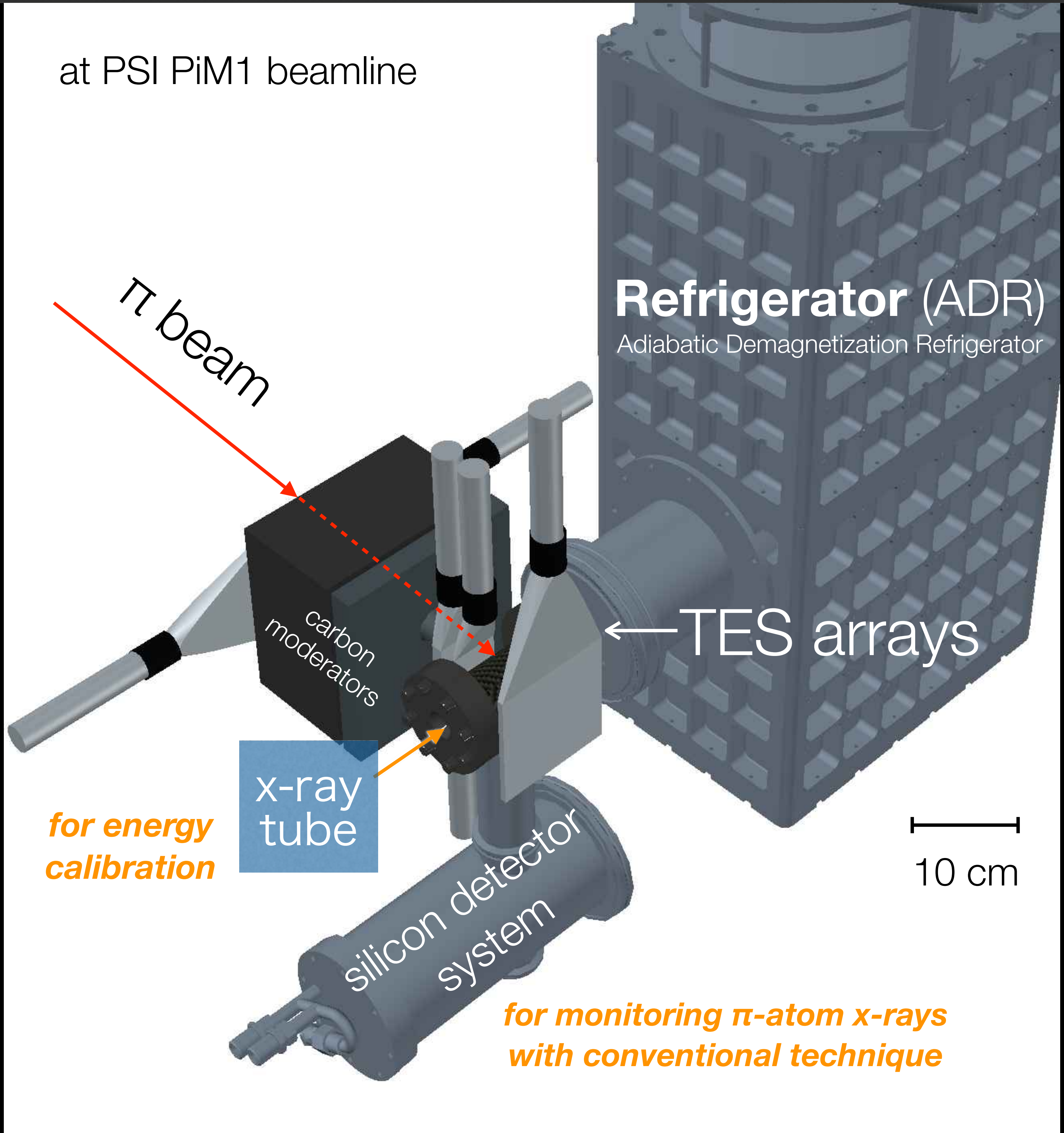
- aim : studying in-beam performance of TES
  ➡ the first measurement of hadronic-atom x-rays with TES
- when? : 27 Oct - 5 Nov, 2014 (just finished last week!)
- where? : Paul Scherrer Institute (PSI), PiM1 beamline



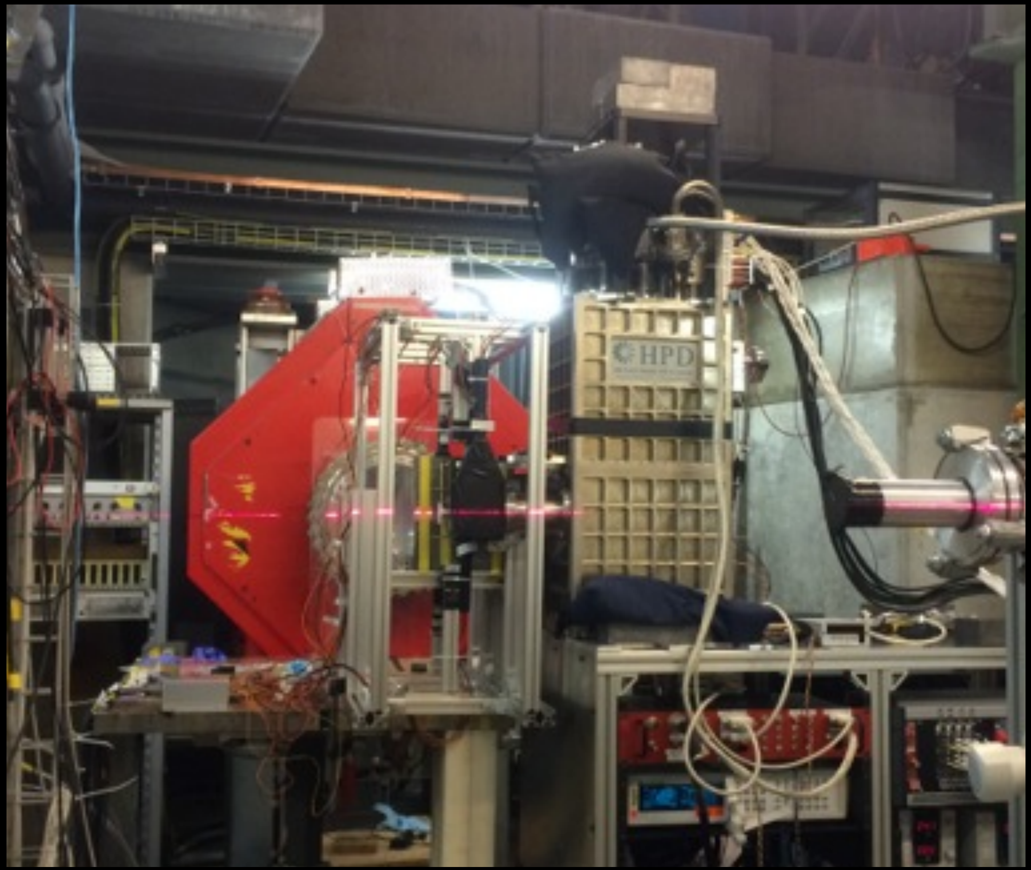

Pionic carbon
4f-3d x-rays ~ 6.5 keV

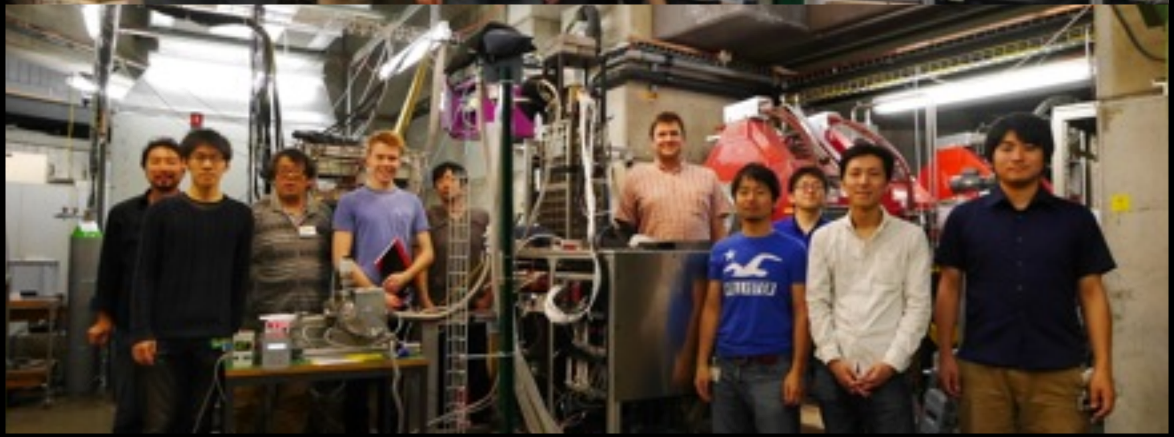
-> no strong-interaction shift & width
-> higher yield (~1200 events / hour)

# Experimental setup

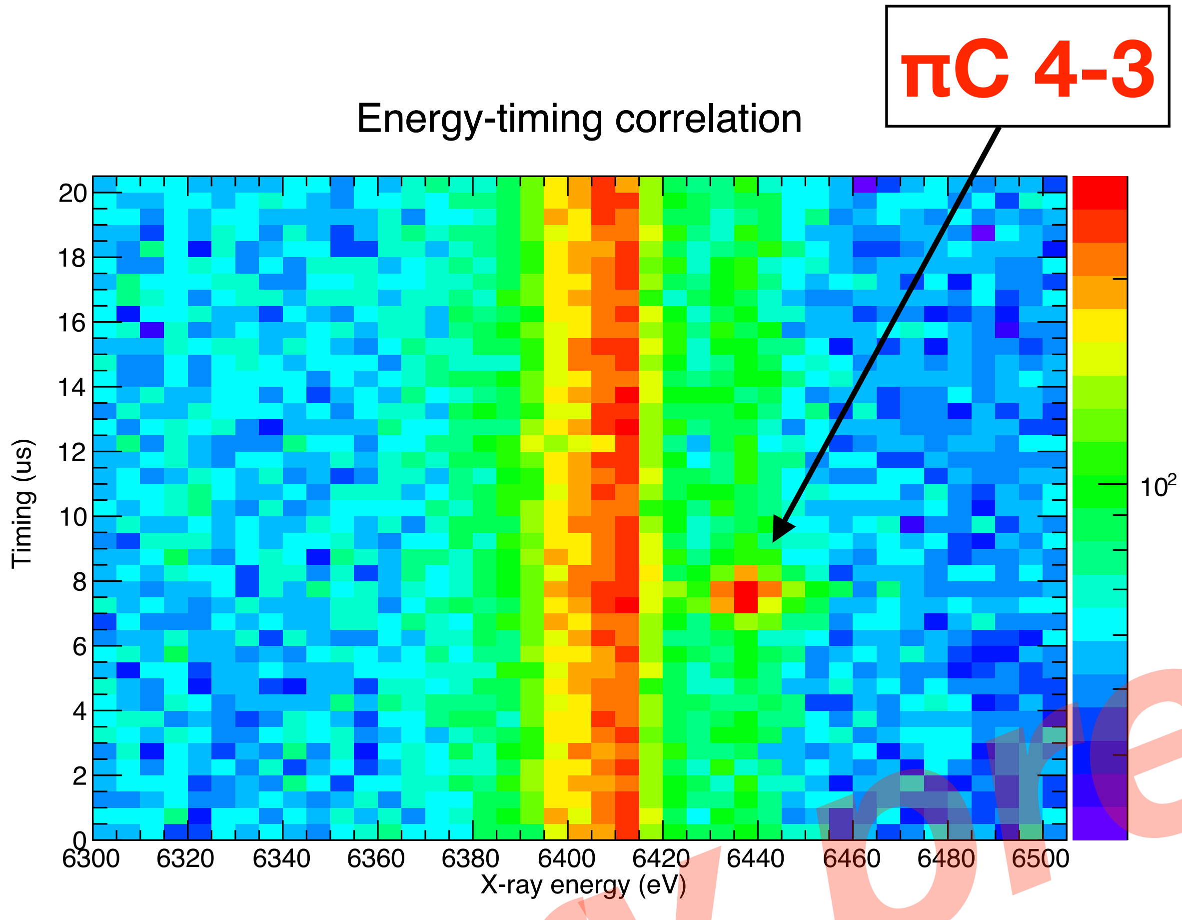


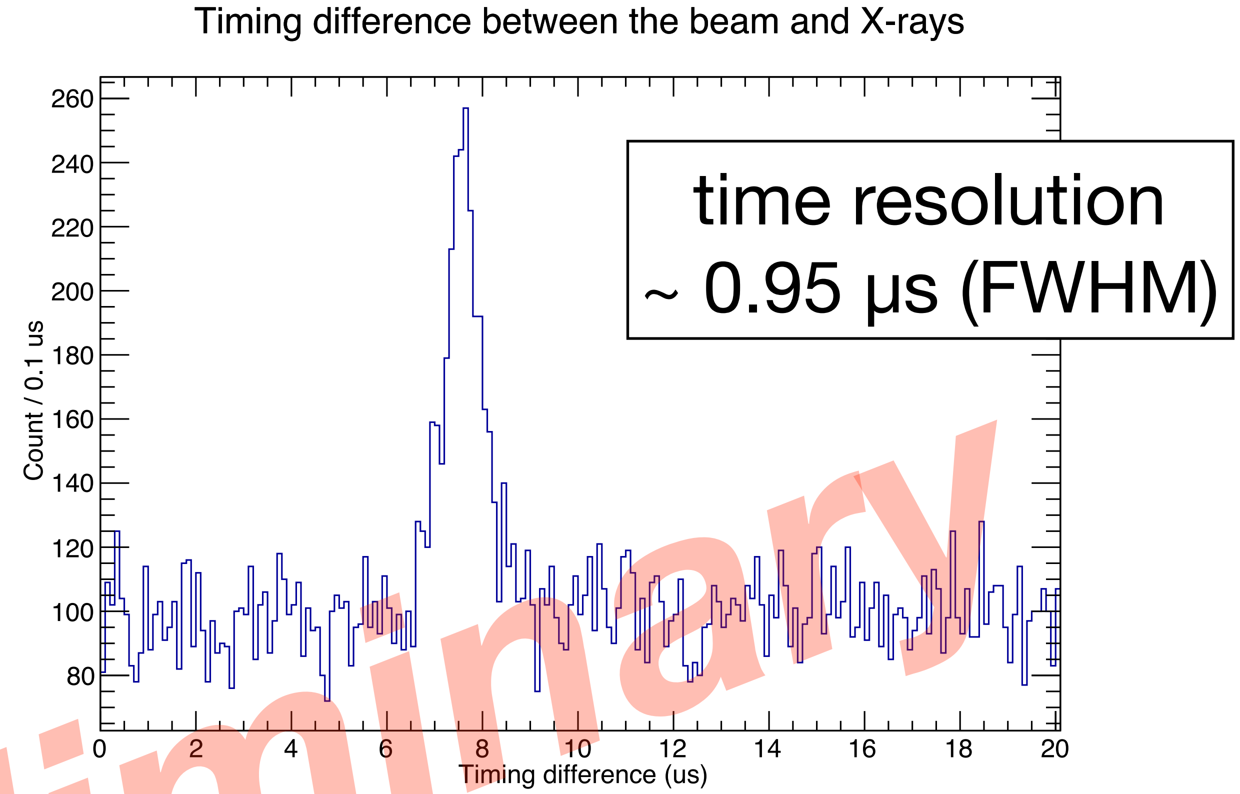
# Photos

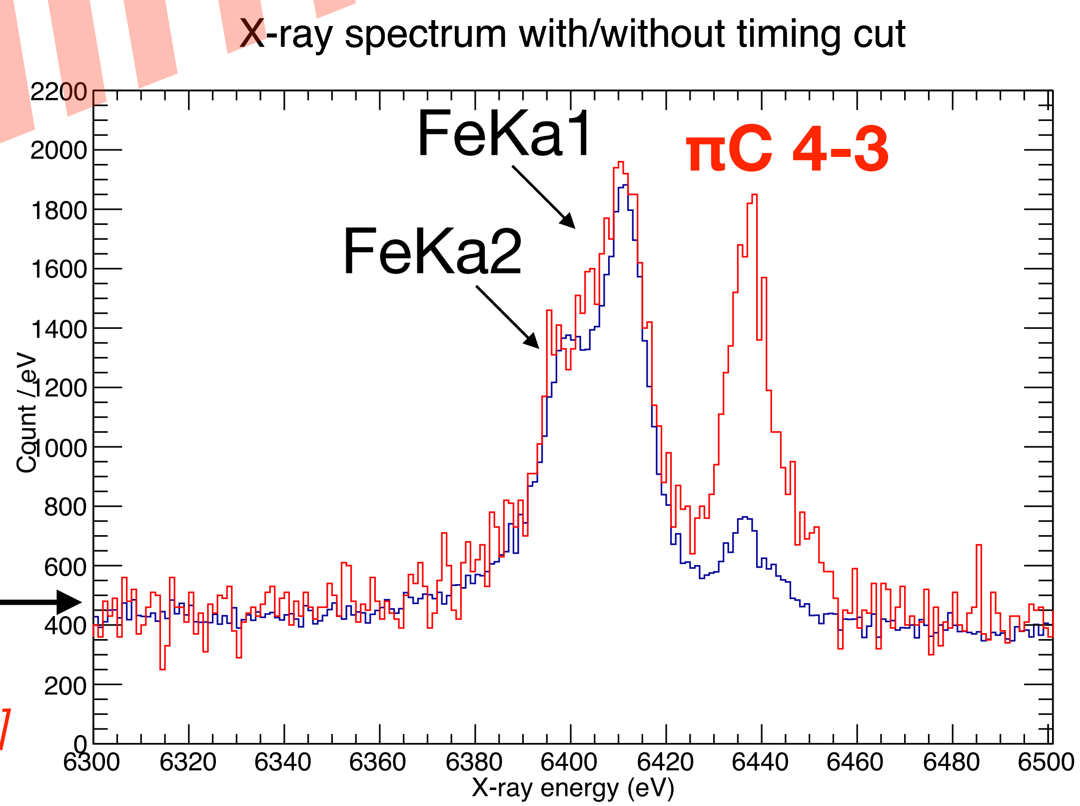





# Exotic-atom x-rays with TES for the first time !




blue : without timing cut
red : with timing cut (scaled x10)

*6.5 < t < 8.5 [μs]*

Very preliminary

# 5. Summary

# take-home messages

1. Ultra-high-resolution x-ray spectrometer "TES microcalorimeter" is now available as a powerful tool for exotic-atom research

2. "TES x DAFNE" could provide valuable physics outputs related Kaonic atoms