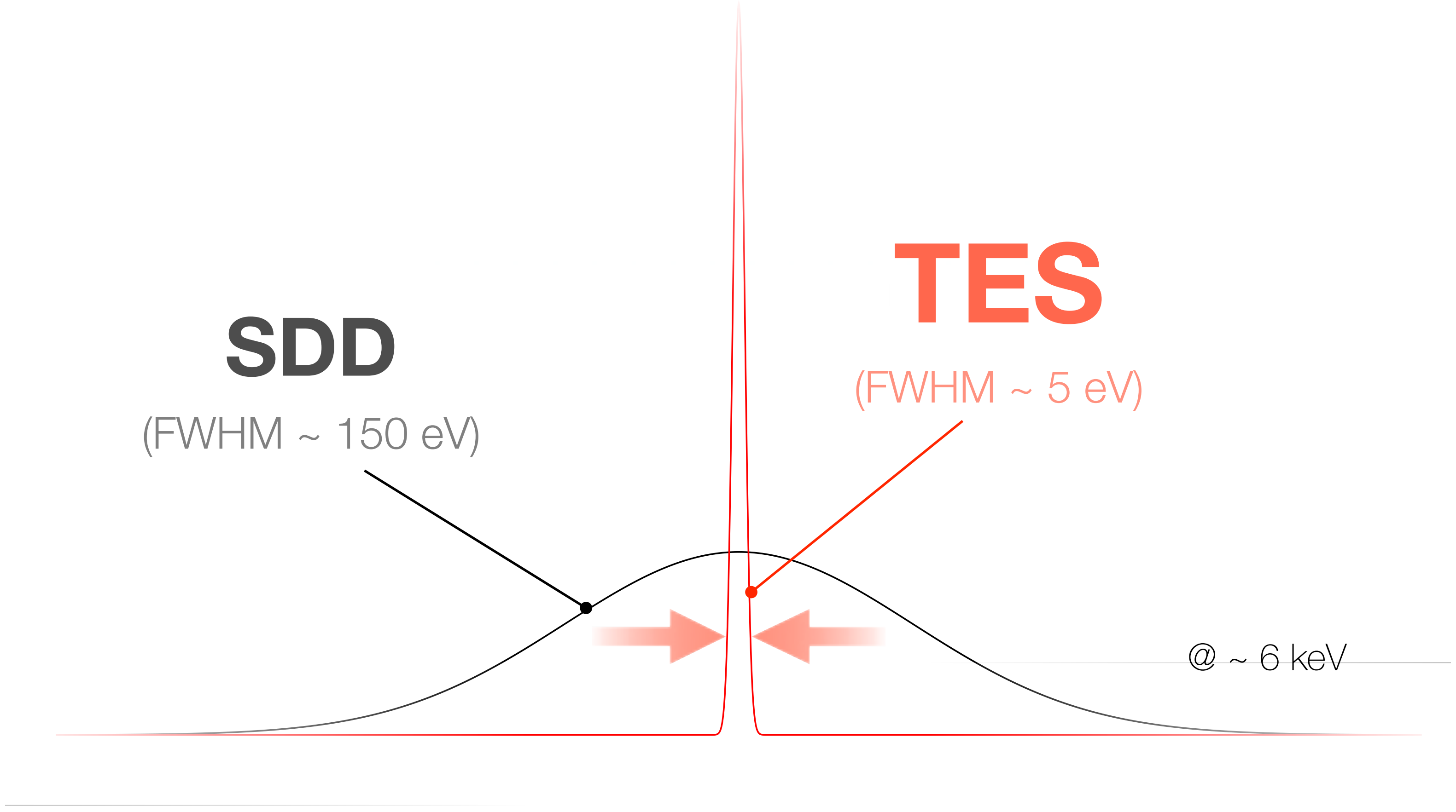
11 Sept, 2021

TGSW2021 (Universe Evolution and Matter Origin) @ Online

Accelerator-based physics experiments pioneered by superconducting TES microcalorimeters

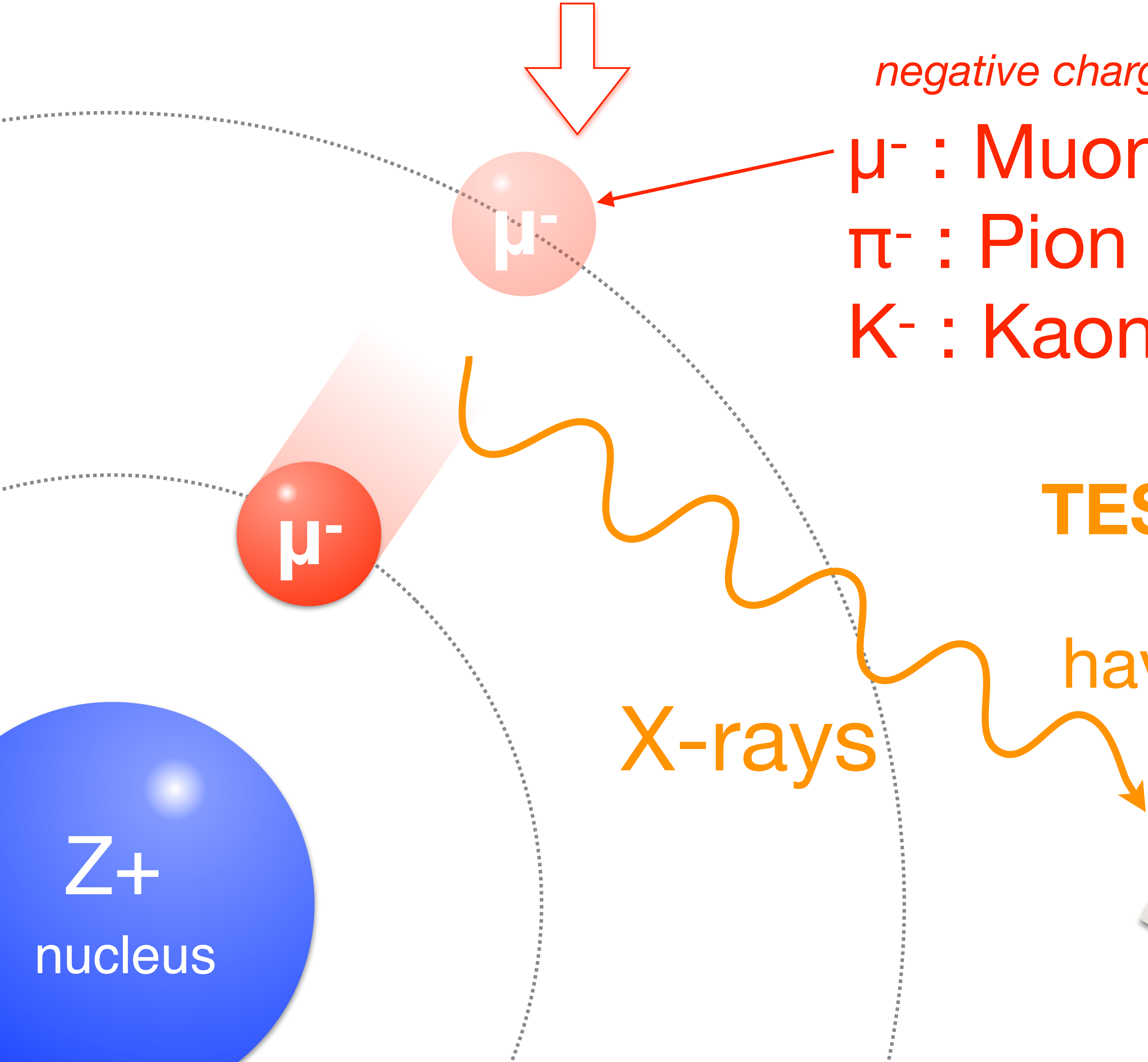


Shinji OKADA (Chubu Univ.)

HEATES project

||

High-resolution **E**xotic **A**tom x-ray spectroscopy with **TES**



negative charged

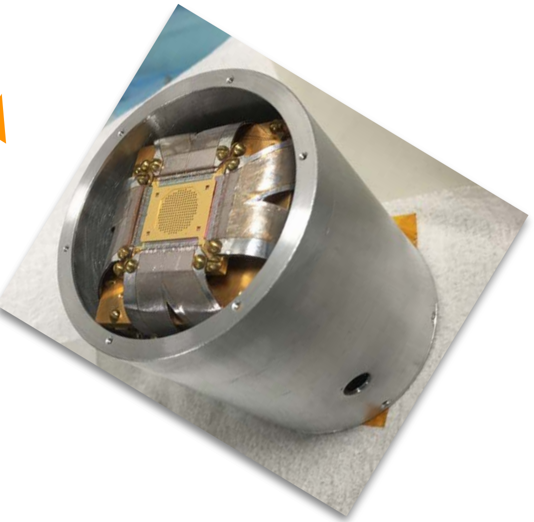
μ^- : Muon
π^- : Pion
K^- : Kaon …

named after microcalorimeter
*being a **heat** measuring device*

TES microcalorimeter

(Cryogenic detector)

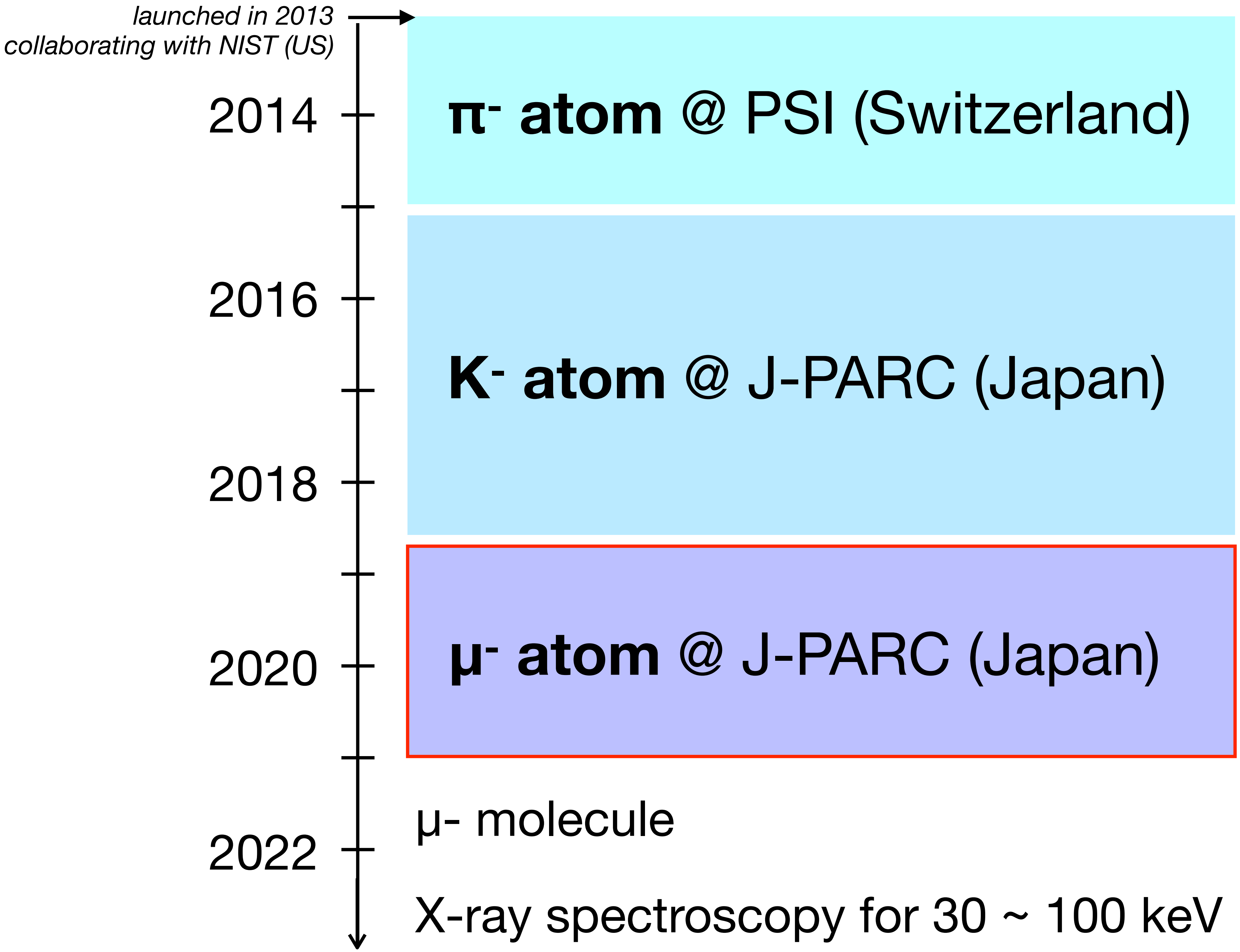
having high resolution



HEATES project

||

High-resolution **E**xotic **A**tom x-ray spectroscopy with **TES**



launched in 2013
collaborating with NIST (US)

2014

2016

2018

2020

2022

π^- atom @ PSI (Switzerland)

K^- atom @ J-PARC (Japan)

μ^- atom @ J-PARC (Japan)

μ- molecule

X-ray spectroscopy for 30 ~ 100 keV

Feasibility study

Study of strong KN interaction

Study of BSQED
***B**ound-**S**tate **Q**uantum **E**lectro**D**ynamics*
under extremely strong electric fields

future…

Collaboration (Muonic atom)

J-PARC MLF 2019MS01 collaboration (for 2020-Jan run)

Shinji	**Okada**	**Chubu Univ.**	**Japan**
Pietro	**Caradonna**	**IPMU**	
Miho	**Katsuragawa**		
Kairi	**Mine**		
Tadayuki	**Takahashi**		
Shinichiro	**Takeda**		
Tadashi	**Hashimoto**	**JAEA**	
Takahito	**Osawa**		
Shin	**Watanabe**	**JAXA**	
Naritoshi	**Kawamura**	**KEK**	
Yasuhiro	**Miyake**		
Kouichiro	**Shimomura**		
Patrick	**Strasser**		
Soshi	**Takeshita**		
I Huan	**Chiu**	**Osaka Univ.**	
Kazuhiko	**Ninomiya**		
Hirofumi	**Noda**		
Toshiyuki	**Azuma**	**RIKEN**	
TadaAki	**Isobe**		
Sohtaro	**Kanda**		
Takuma	**Okumura**		
Yasuhiro	**Ueno**		

Yuto		**Ichinohe**	**Rikkyo Univ.**	**Japan**
Shinya		**Yamada**		
Yasushi		**Kino**	**Tohoku Univ.**	
Kenichi		**Okutsu**		
Ryota		**Hayakawa**	**Tokyo Metropolitan Univ.**	
Hirotaka		**Suda**		
Hideyuki		**Tatsuno**		
Paul		**Indelicato**	**CNRS**	**France**
Nancy		**Paul**		
Douglas	**A.**	**Bennett**	**NIST**	**US**
William	**B.**	**Doriese**		
Malcolm	**S.**	**Durkin**		
Joseph	**W.**	**Fowler**		
Johnathon	**D.**	**Gard**		
Gene	**C.**	**Hilton**		
Kelsey	**M.**	**Morgan**		
Galen	**C.**	**O'Neil**		
Carl	**D.**	**Reintsema**		
Dan	**R.**	**Schmidt**		
Daniel	**S.**	**Swetz**		
Joel	**N.**	**Ullom**		

Particle, Nuclear, Hadron, Atomic physicists + Astro physicists + TES experts

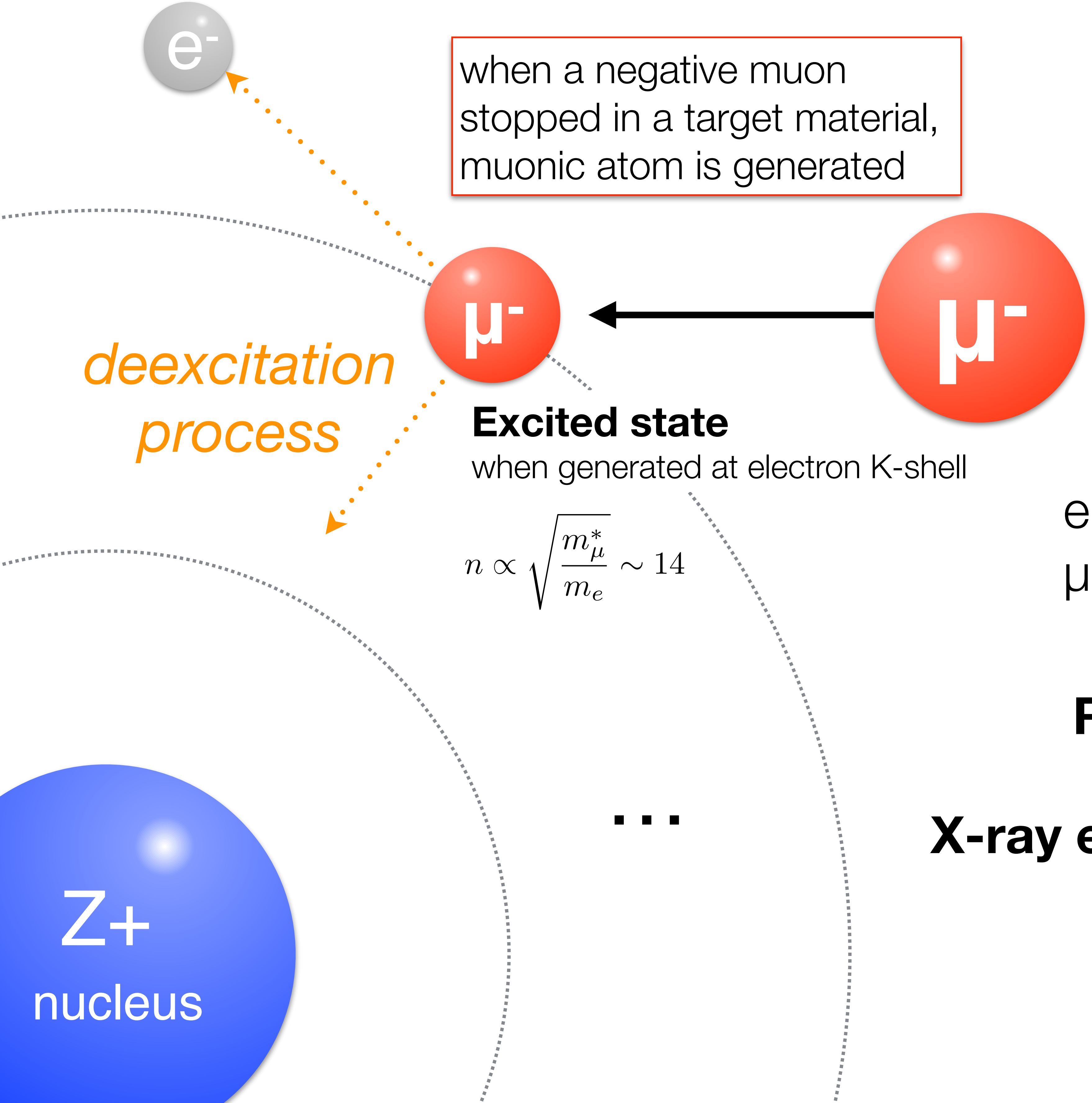
interdisciplinary team

Contents

1. Introduction
2. What’s TES microcalorimeter
3. Experiment
4. Results of muonic Neon experiment
5. Serendipity -> interesting phenomena discovered by chance during detector study
6. Summary

1. Introduction

Muonic atom



when a negative muon stopped in a target material, muonic atom is generated

Excited state
when generated at electron K-shell

$$n \propto \sqrt{\frac{m_\mu^*}{m_e}} \sim 14$$

muon (as heavy electron)

e^- mass : 0.511 MeV/c^2
μ^- mass : 105.7 MeV/c^2

Radius $\propto \frac{m_e}{m_\mu^*}$ **x 1/200**

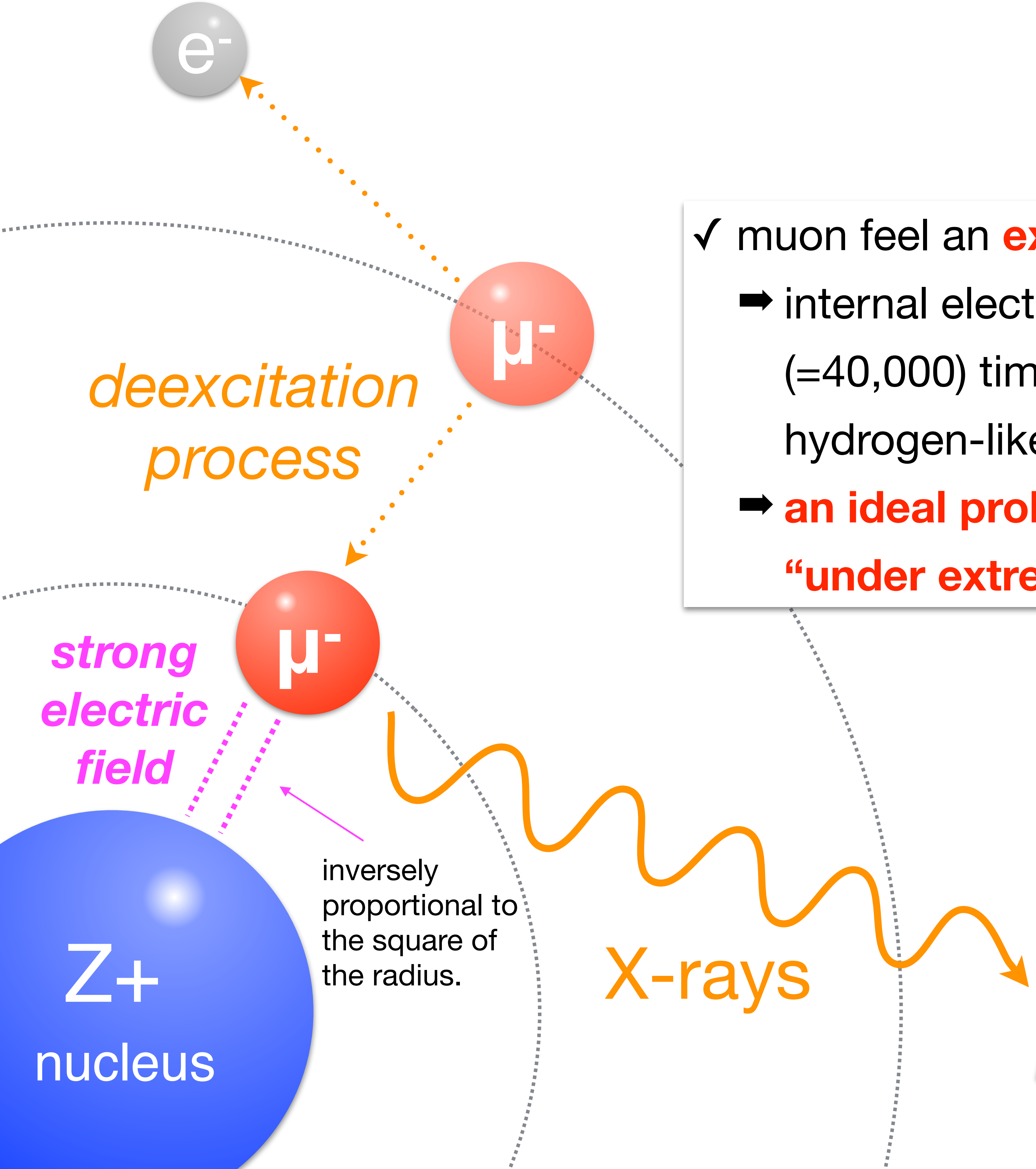
X-ray energy $\propto \frac{m_\mu^*}{m_e}$ **x 200**

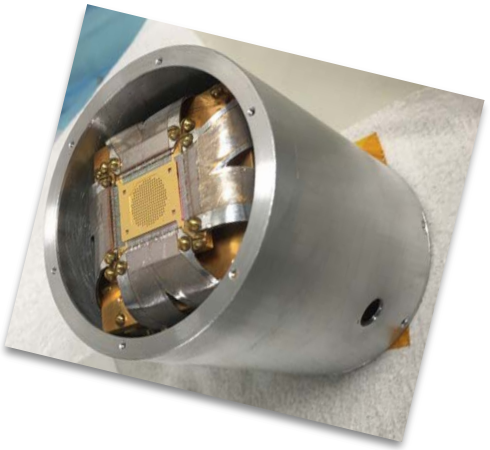
c.f. H atom (2p-1s) 122nm ~ 10 eV
μH atom (2p-1s) ~ 2 keV

Strong electric field

✓ muon feel an **extremely strong electric field**

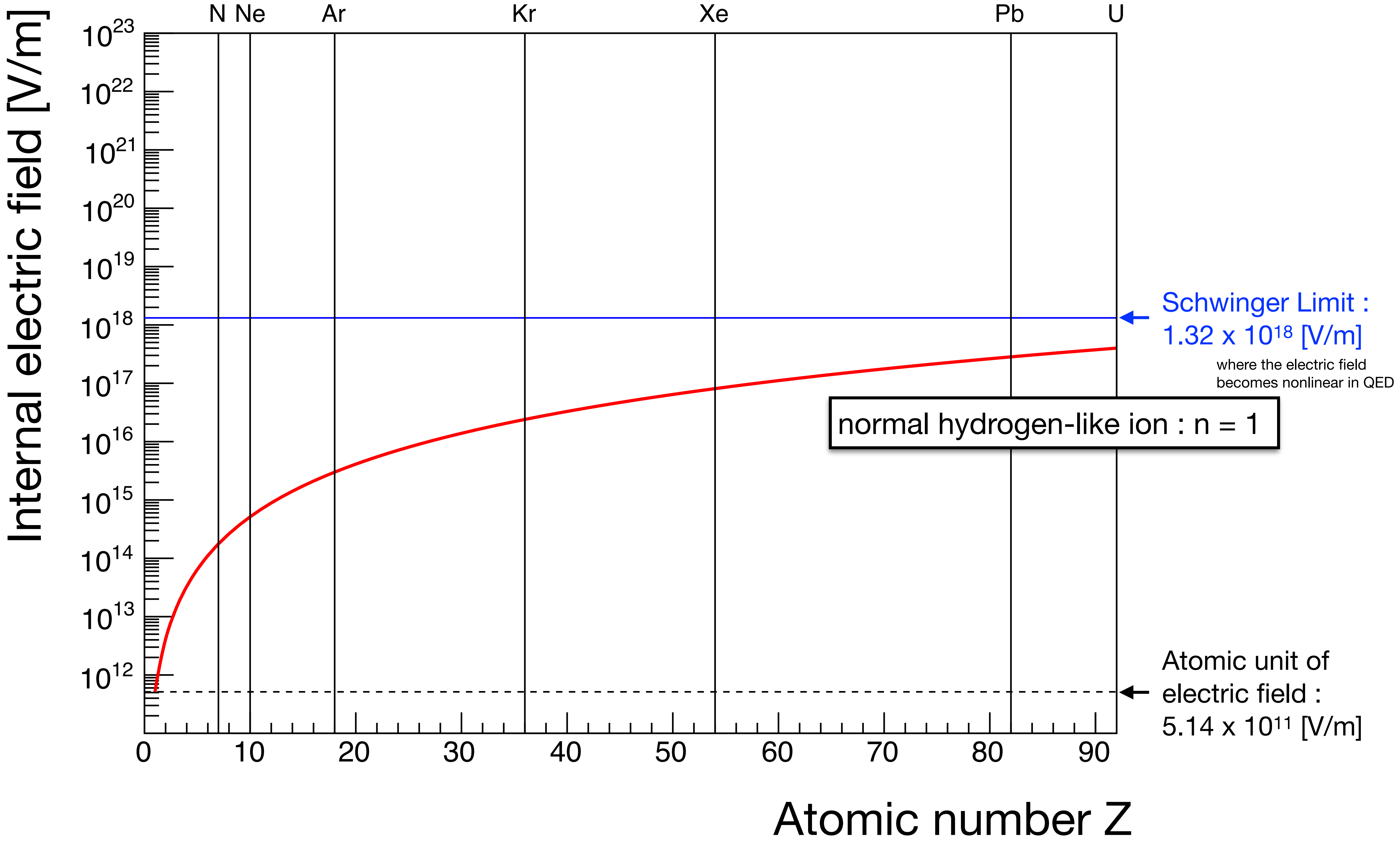
- ➡ internal electric field strength is to be 200^2 (=40,000) times higher than that of normal hydrogen-like ions.
- ➡ **an ideal probe to explore QED "under extremely strong electric fields"**





high-precision spectroscopy

Internal electric field $\propto Z^3$

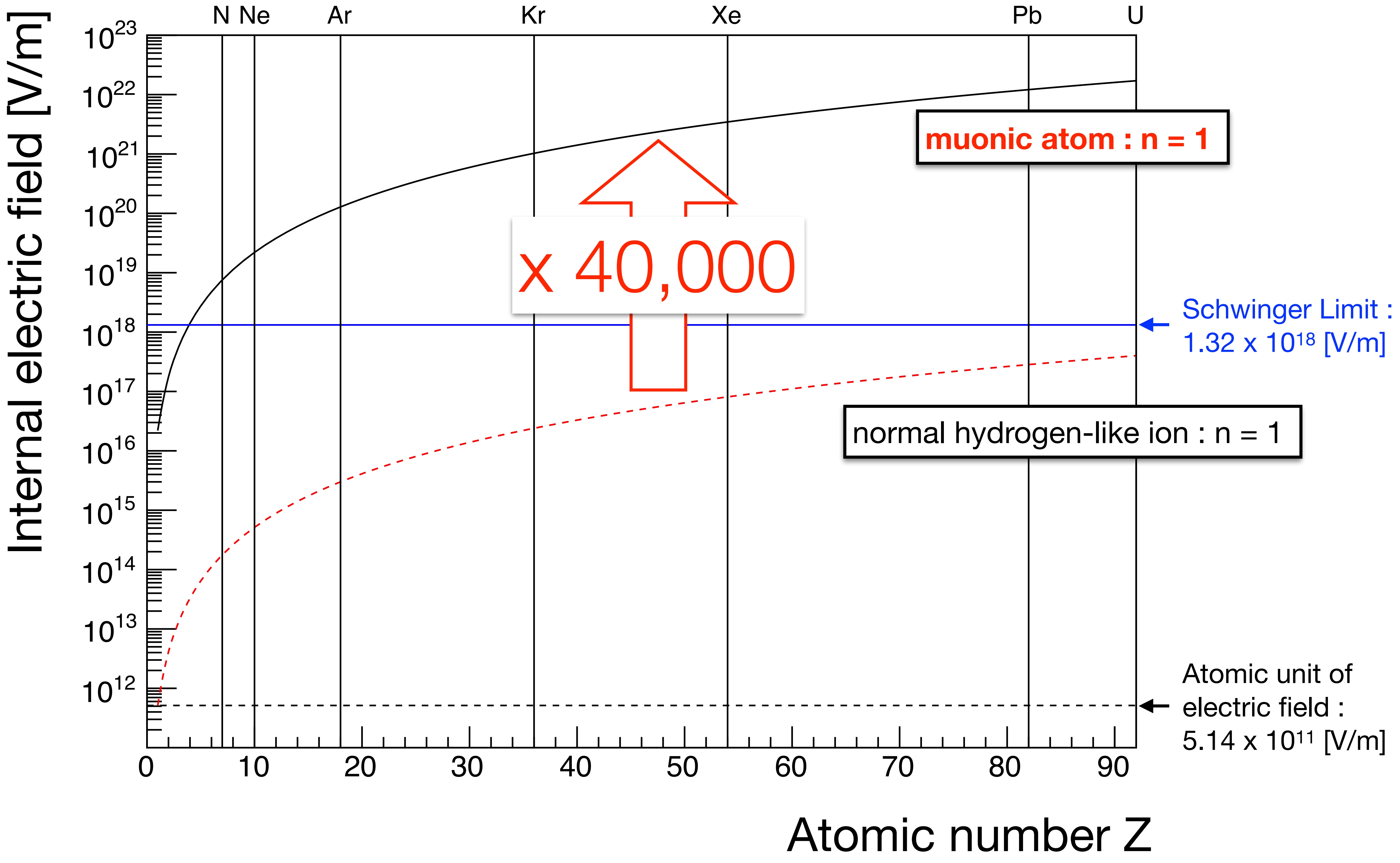


Schwinger Limit :
1.32 x 10^{18} [V/m]
where the electric field
becomes nonlinear in QED

Atomic unit of
electric field :
5.14 x 10^{11} [V/m]

strong electric field @ heavier atoms → still lower than Schwinger limit

Internal electric field : x 200^2



muonic atom : n = 1

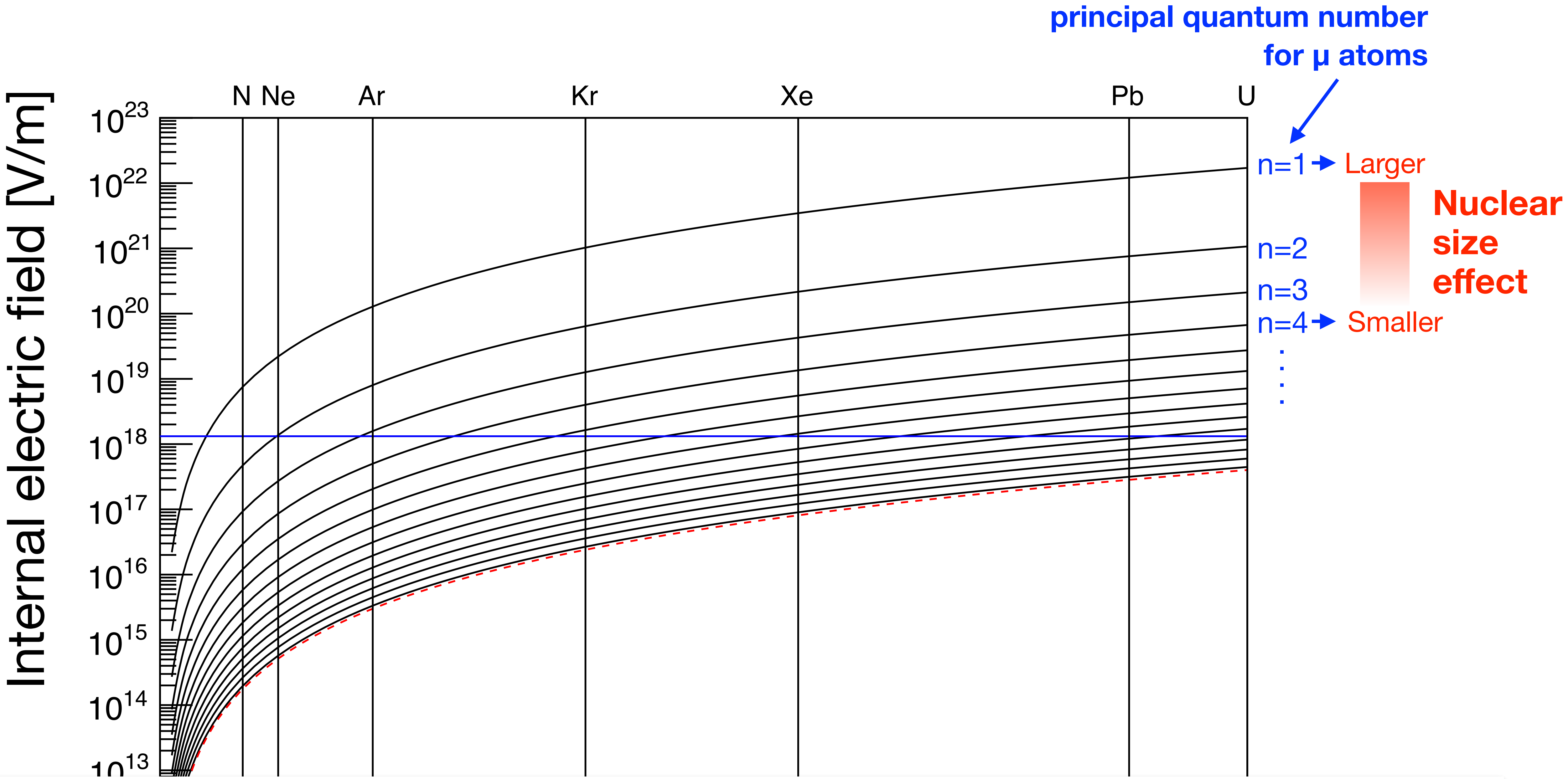
x 40,000

Schwinger Limit : 1.32×10^{18} [V/m]

normal hydrogen-like ion : n = 1

Atomic unit of electric field : 5.14×10^{11} [V/m]

Avoiding nuclear-size effect

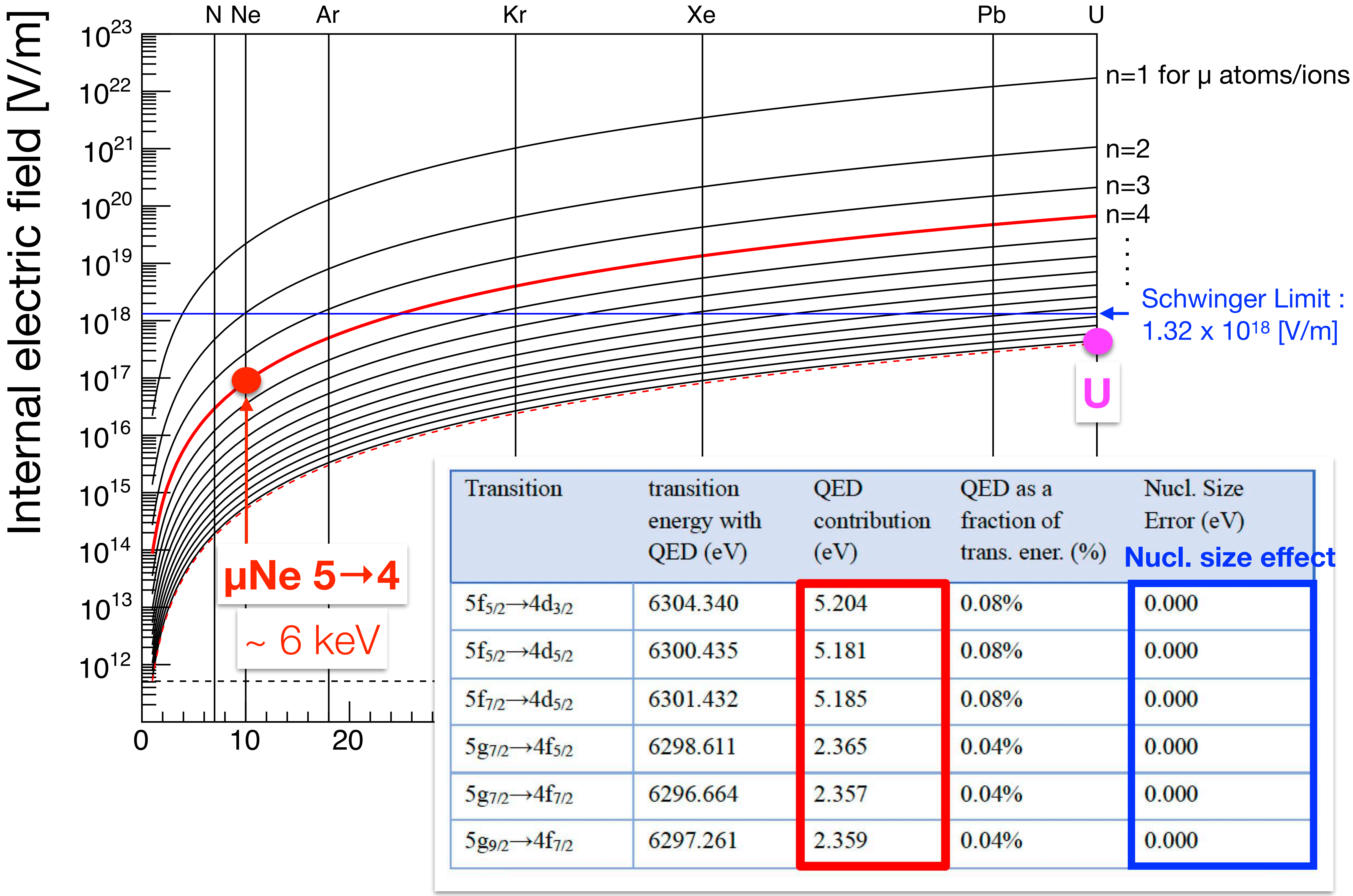


✓ But, in the Lower "n" (principal quantum number) state, nuclear size effect (overlapping with nucleus) become dominant.

➡ **Carefully choose** X-ray transition into the energy level where **the nuclear size effect is negligible** but having significant QED effect

Muonic Ne 5→4 X-ray

The first experiment (with ~10 keV X-ray region)



Schwinger Limit : 1.32 x 10^{18} [V/m]

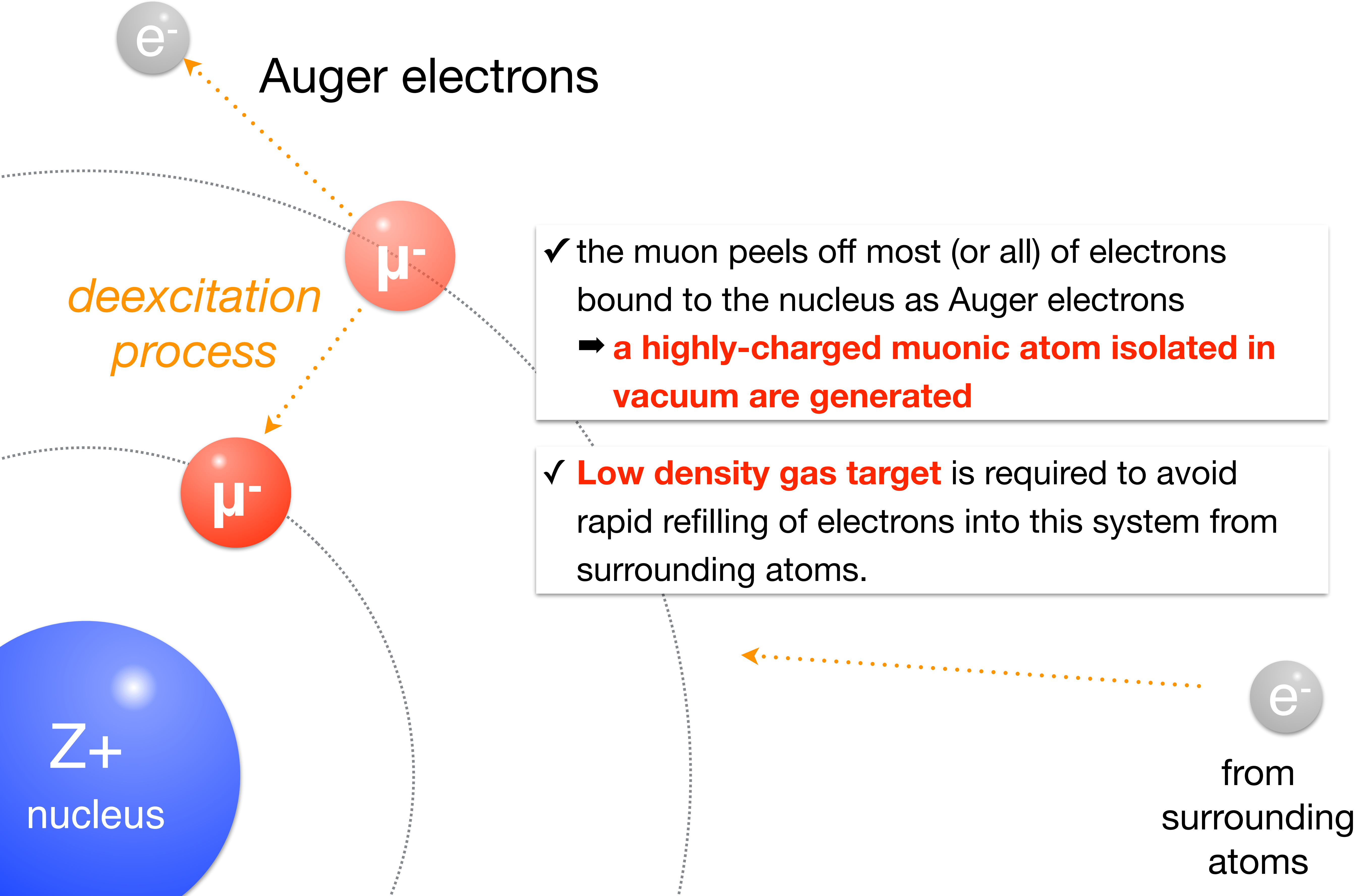
μNe 5→4

~ 6 keV

Nucl. size effect

Transition	transition energy with QED (eV)	QED contribution (eV)	QED as a fraction of trans. ener. (%)	Nucl. Size Error (eV)
$5f_{5/2}\to 4d_{3/2}$	6304.340	5.204	0.08%	0.000
$5f_{5/2}\to 4d_{5/2}$	6300.435	5.181	0.08%	0.000
$5f_{7/2}\to 4d_{5/2}$	6301.432	5.185	0.08%	0.000
$5g_{7/2}\to 4f_{5/2}$	6298.611	2.365	0.04%	0.000
$5g_{7/2}\to 4f_{7/2}$	6296.664	2.357	0.04%	0.000
$5g_{9/2}\to 4f_{7/2}$	6297.261	2.359	0.04%	0.000

Low pressure gas target



✓ the muon peels off most (or all) of electrons bound to the nucleus as Auger electrons
➡ **a highly-charged muonic atom isolated in vacuum are generated**

✓ **Low density gas target** is required to avoid rapid refilling of electrons into this system from surrounding atoms.

Problems so far

1. **Electron refill** ：
   - ➡ To avoid rapid refilling of electrons from the surrounding atoms, a low-density gas target (e.g., as low as 0.1 atom) is essential
   - ➡ However, it is experimentally **difficult to efficiently stop muons in a low-density target** due to their large momentum distribution (Δp/p ~ several %) via traveling pion decay.

2. **X-ray detector :**
   - ➡ need **both** “high resolution” and “large effective area”

This project

1. High-intensity low-energy negative muon

➡ world strongest pulse low-energy μ- source @ **J-PARC MUSE (muon facility)**

➡ isolated muonic atoms in vacuum is available by using **low-density gas target**

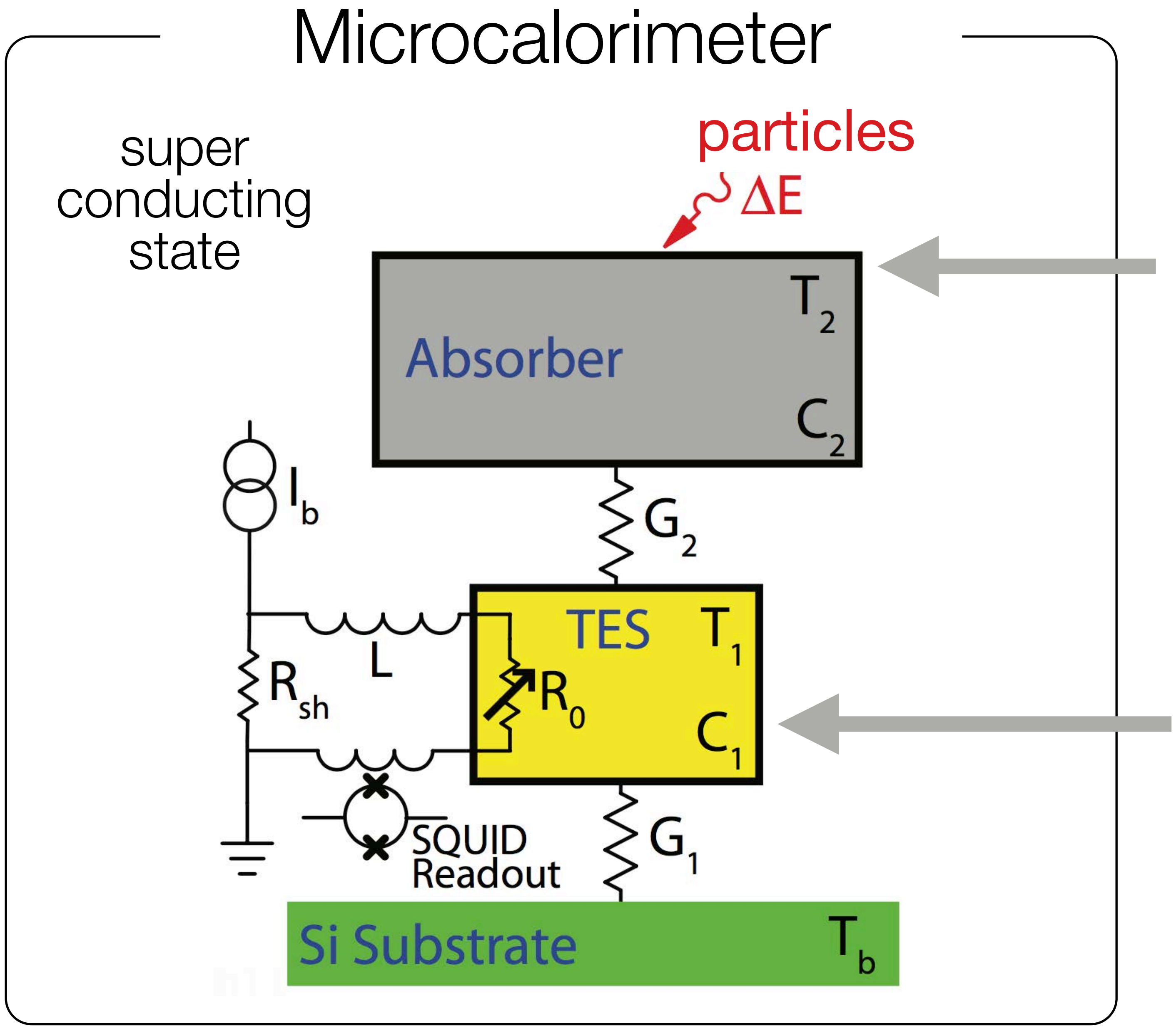
2. Novel superconducting detector

➡ an array of NIST’s multi-pixel TES microcalorimeters

➡ combining both “high resolution” and “large effective area”

2. What’s TES

TES microcalorimeter



1. incident particles absorbed

2. Energy ΔE -> Phonon

3. Tiny temperature rise is measured by a highly sensitive temperature sensor **TES**

Reference : Bennet et al., Rev. Sci. Instrum. 83, 093113 (2012)

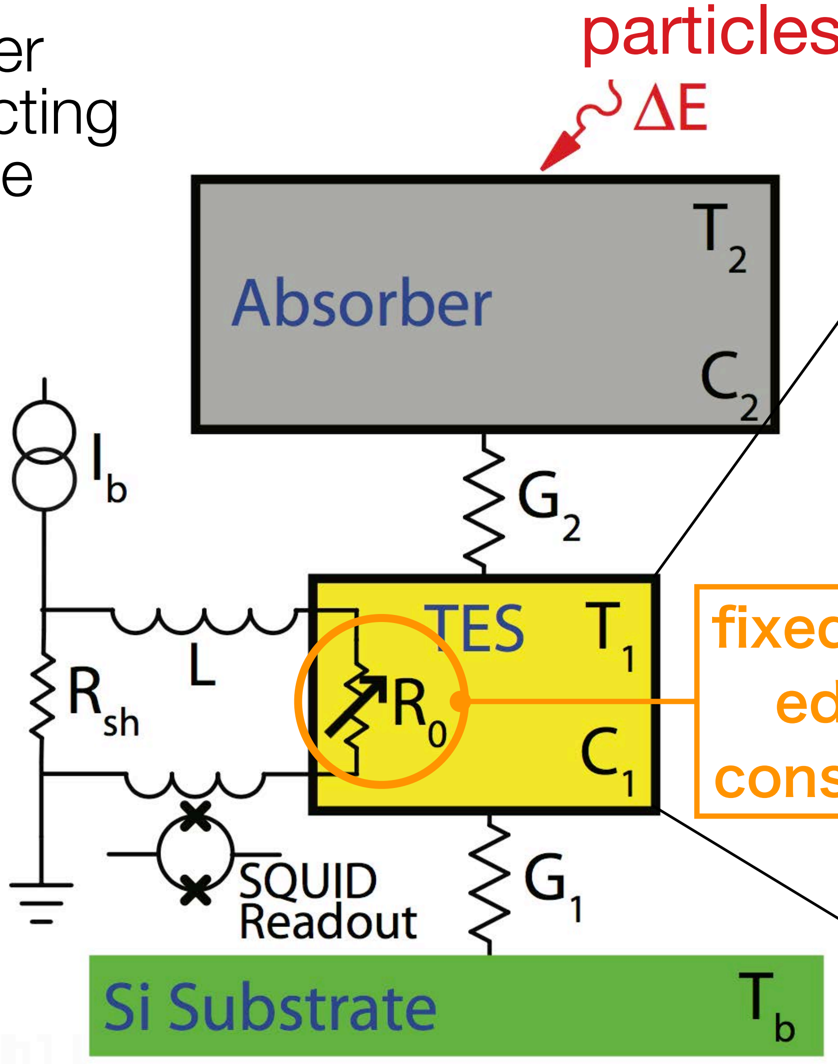
TES microcalorimeter

Microcalorimeter

super conducting state

particles

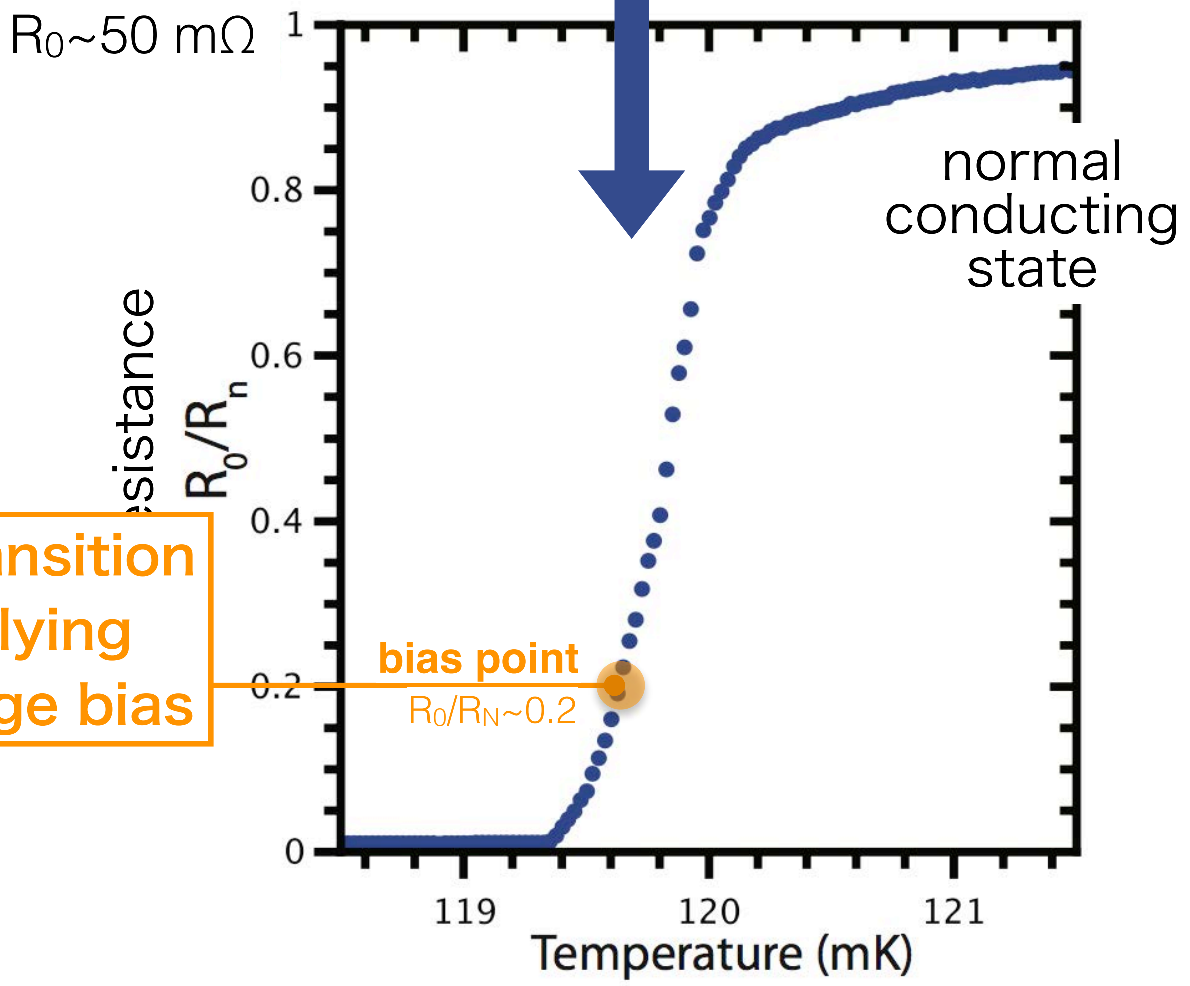
ΔE



fixed at the transition edge by applying constant voltage bias

Transition **E**dge **S**ensor

R_0~50 mΩ



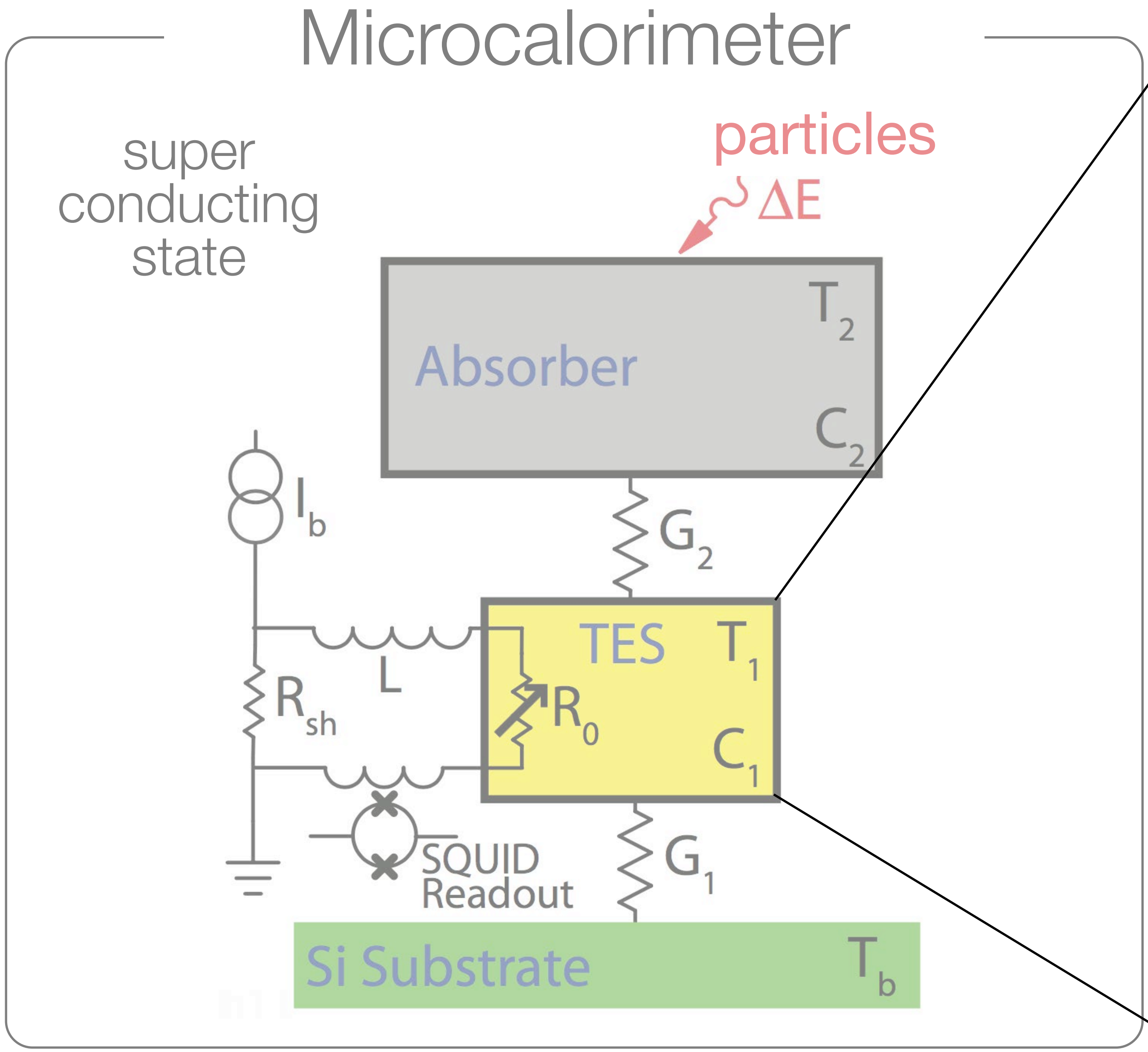
normal conducting state

bias point

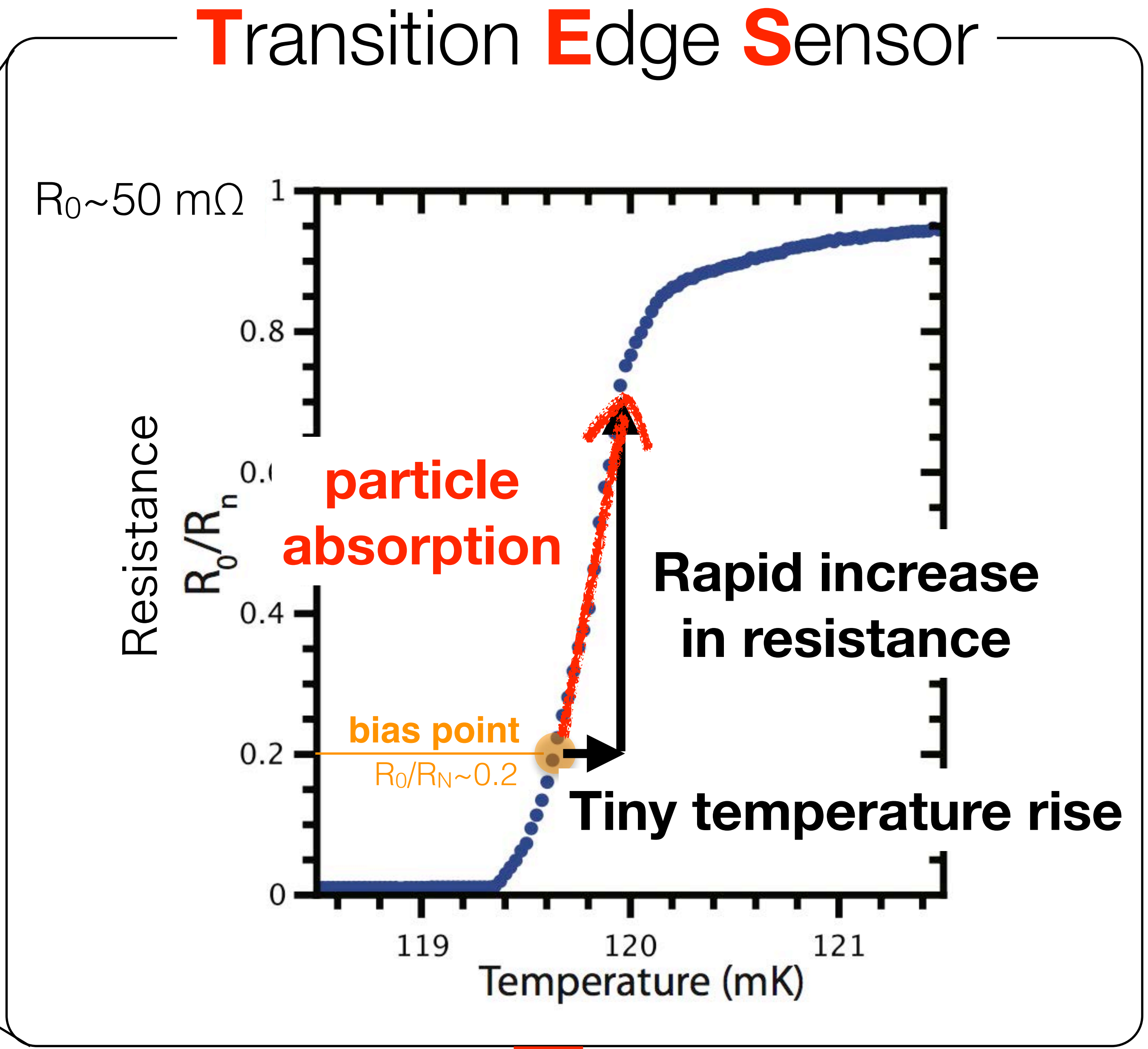
R_0/R_N~0.2

Reference : Bennet et al., Rev. Sci. Instrum. 83, 093113 (2012)

TES microcalorimeter



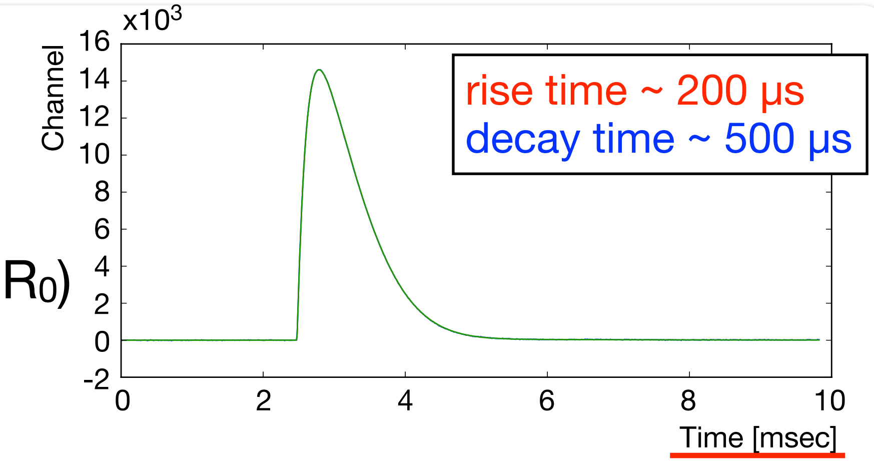
Transition Edge Sensor



Typical pulse

$\tau_{rise} \sim L/(R_{sh}+R_0)$

$\tau_{fall} \sim C/G$



rise time ~ 200 μs

decay time ~ 500 μs

high energy resolution (ΔE / E ~ 10^{-3})

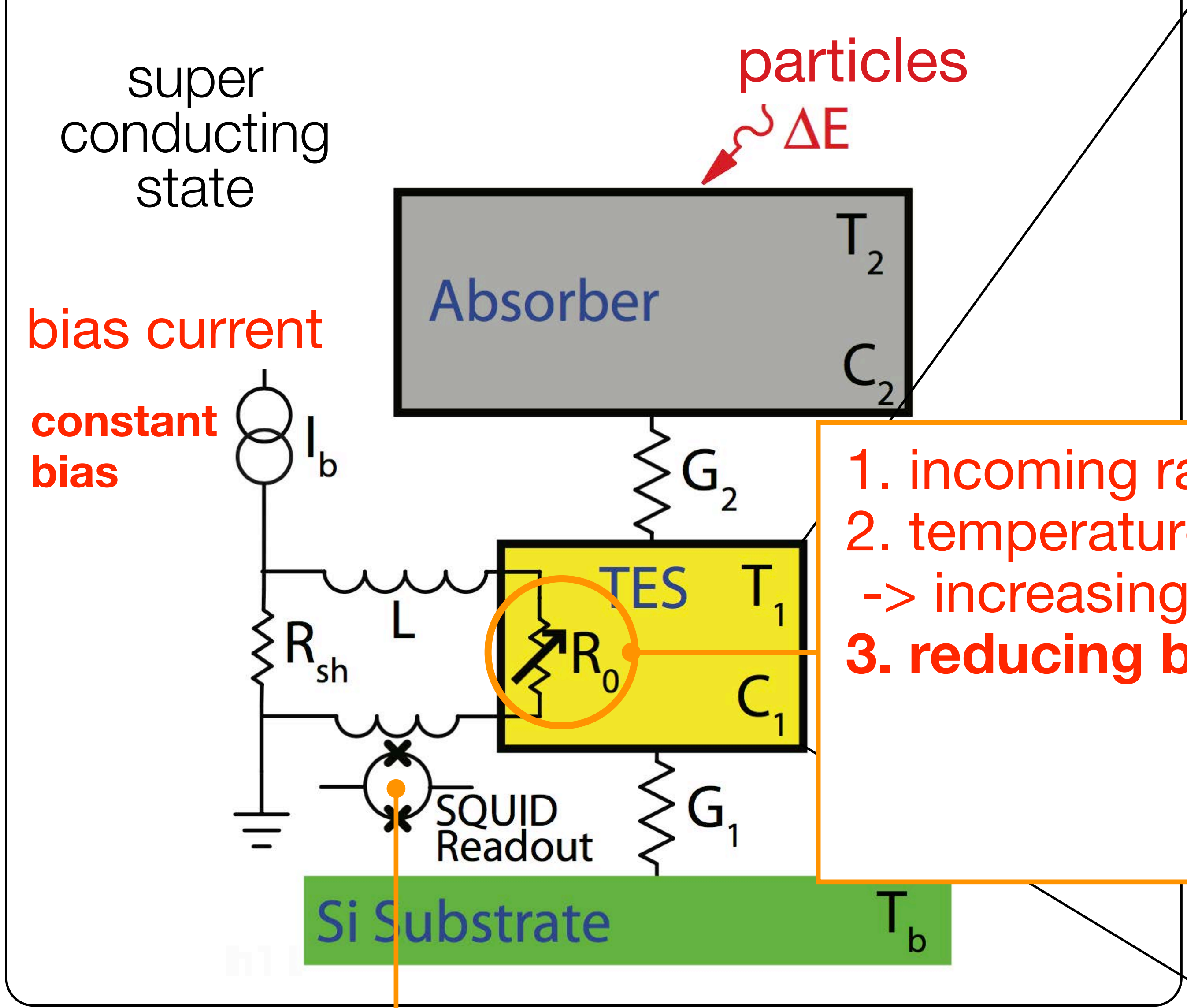
TES : ΔE (FWHM) ~ 5 eV @ 6 keV X-ray

(ref. SDD : ΔE (FWHM) ~ 150 eV @ 6 keV)

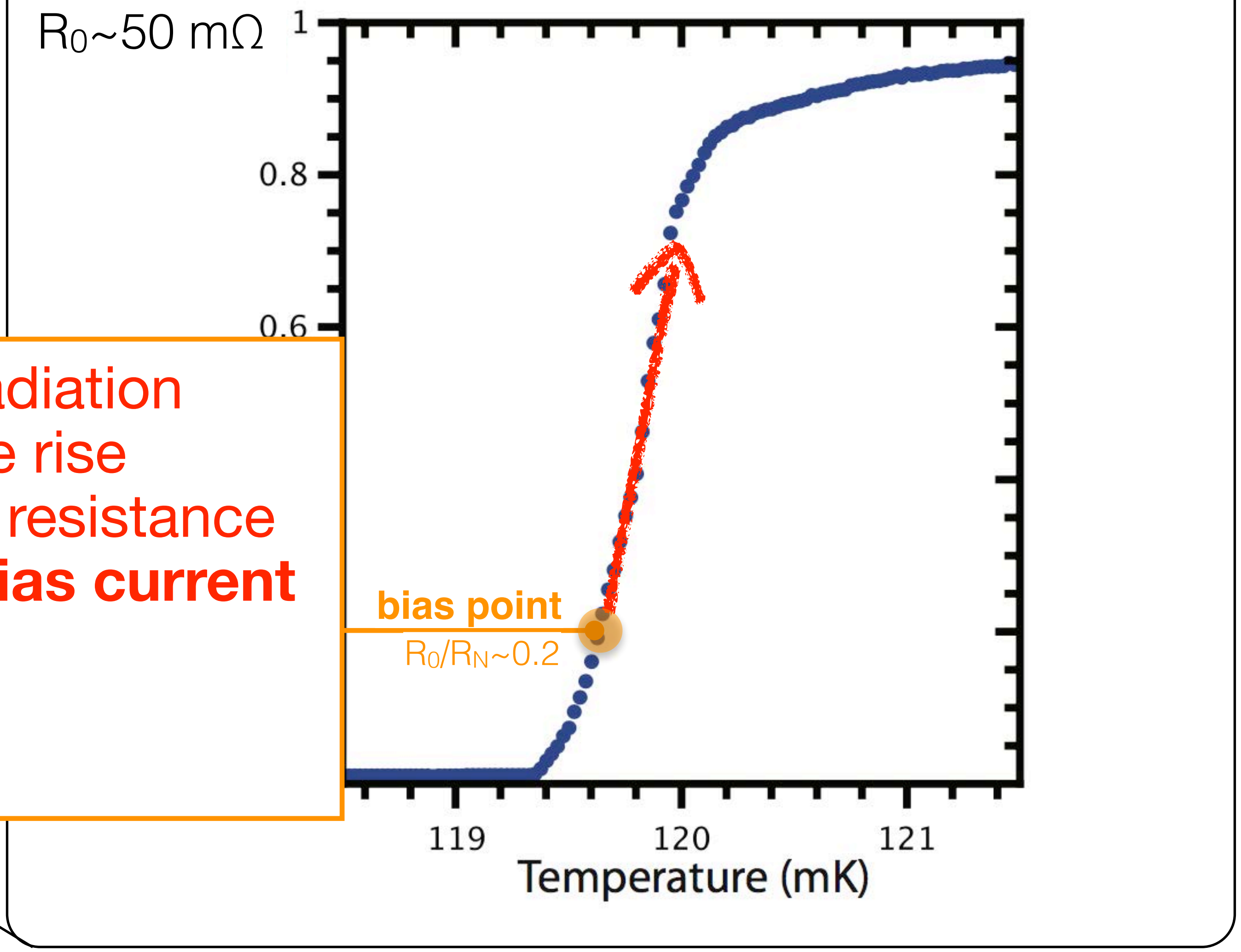
Reference : Bennet et al., Rev. Sci. Instrum. 83, 093113 (2012)

TES microcalorimeter

Microcalorimeter



Transition **E**dge **S**ensor



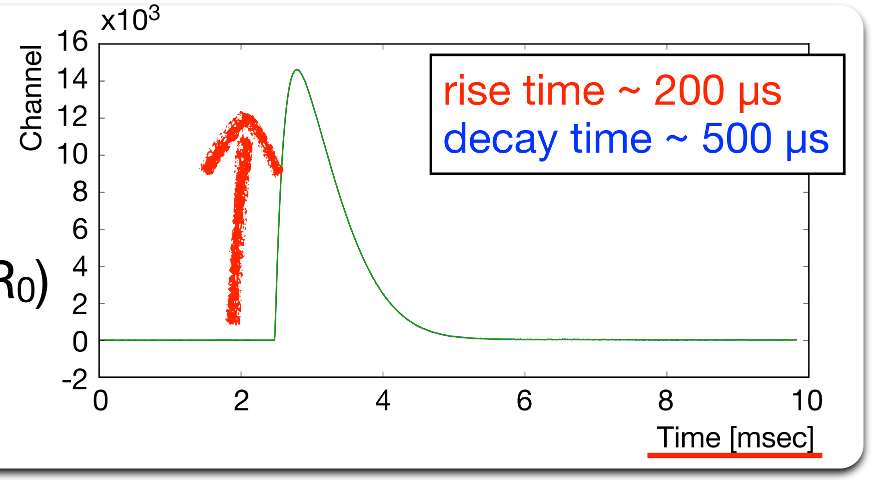
1. incoming radiation
2. temperature rise
 -> increasing resistance
3. **reducing bias current**

Read reduction of bias current using SQUID

Typical pulse

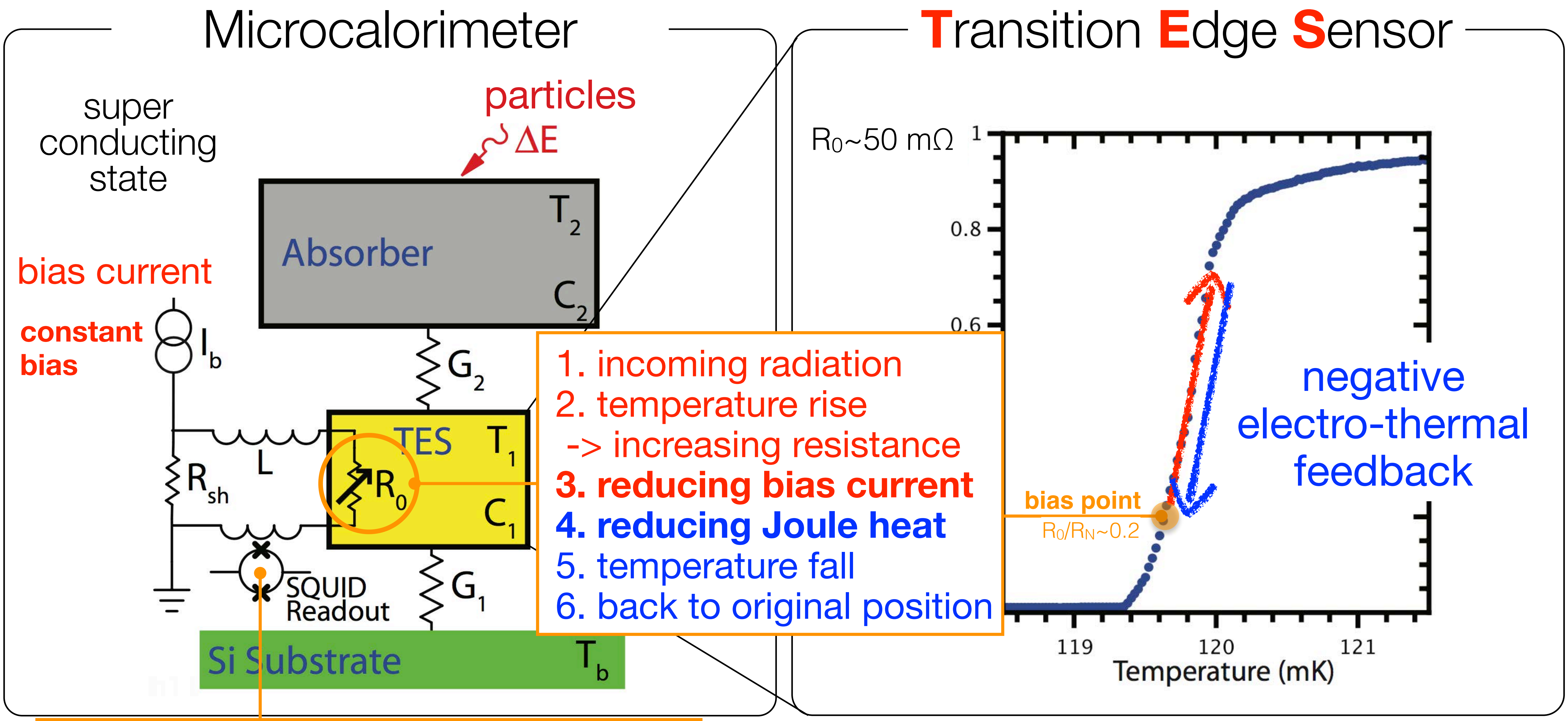
$\tau_{rise} \sim L/(R_{sh}+R_0)$

$\tau_{fall} \sim C/G$



rise time ~ 200 μs
decay time ~ 500 μs

TES microcalorimeter



Microcalorimeter

Transition Edge Sensor

1. incoming radiation
2. temperature rise
   -> increasing resistance
3. **reducing bias current**
4. **reducing Joule heat**
5. temperature fall
6. back to original position

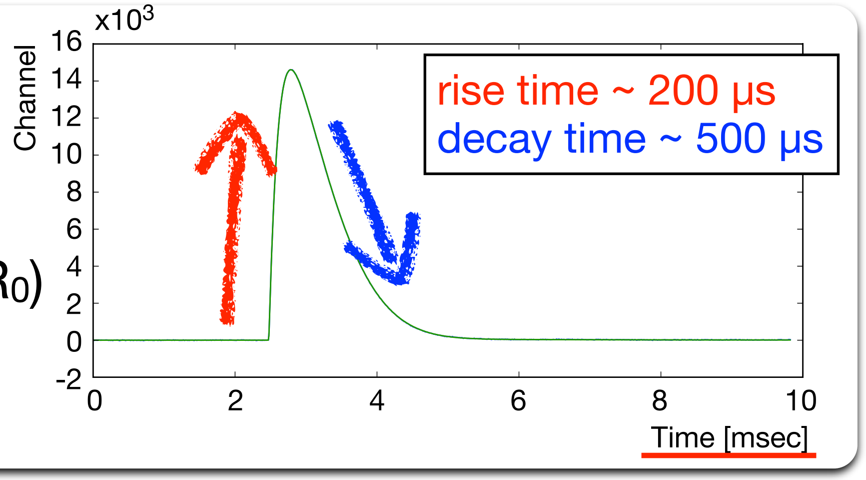
negative electro-thermal feedback

Read reduction of bias current using SQUID

Typical pulse

τ_{rise}~$L/(R_{sh}+R_0)$

τ_{fall}~C/G

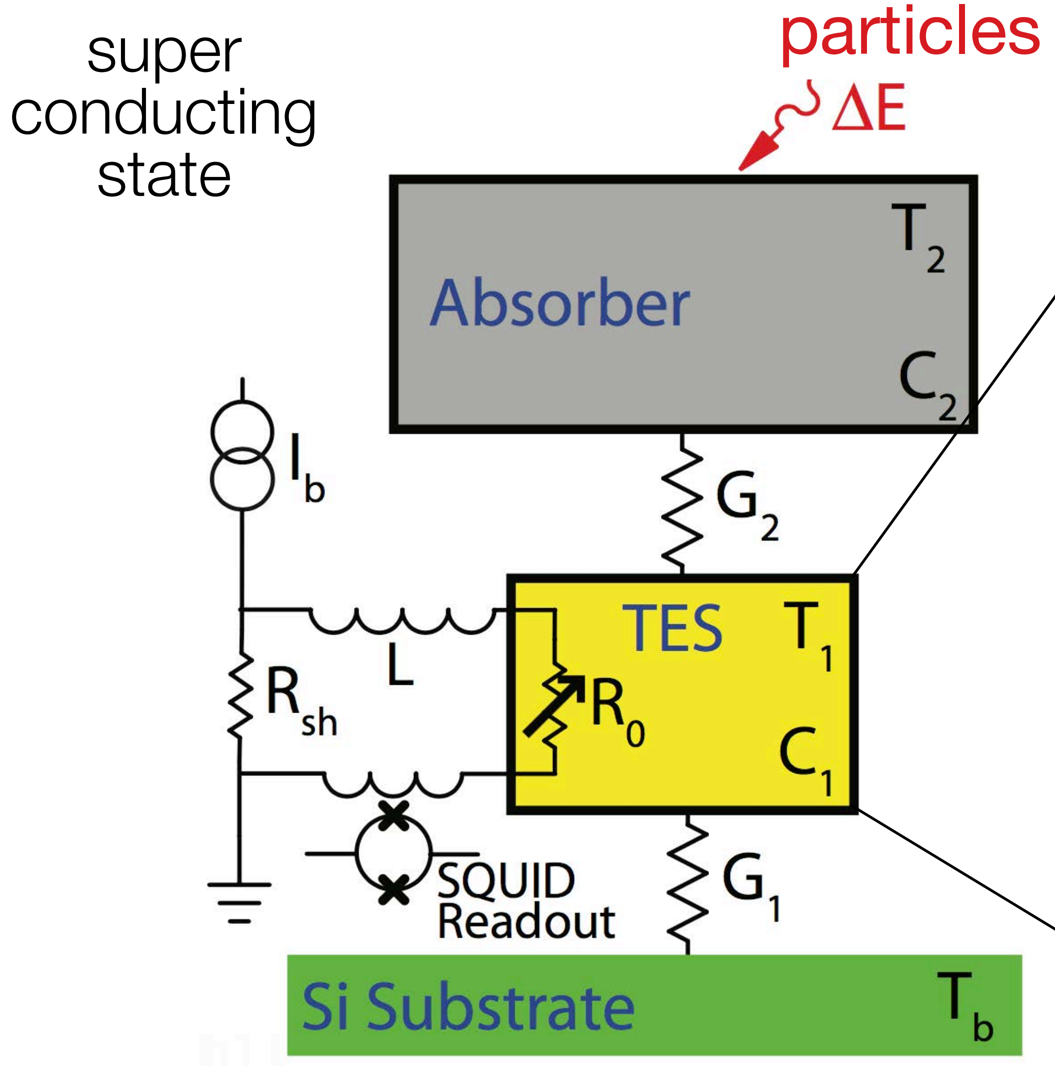


rise time ~ 200 μs

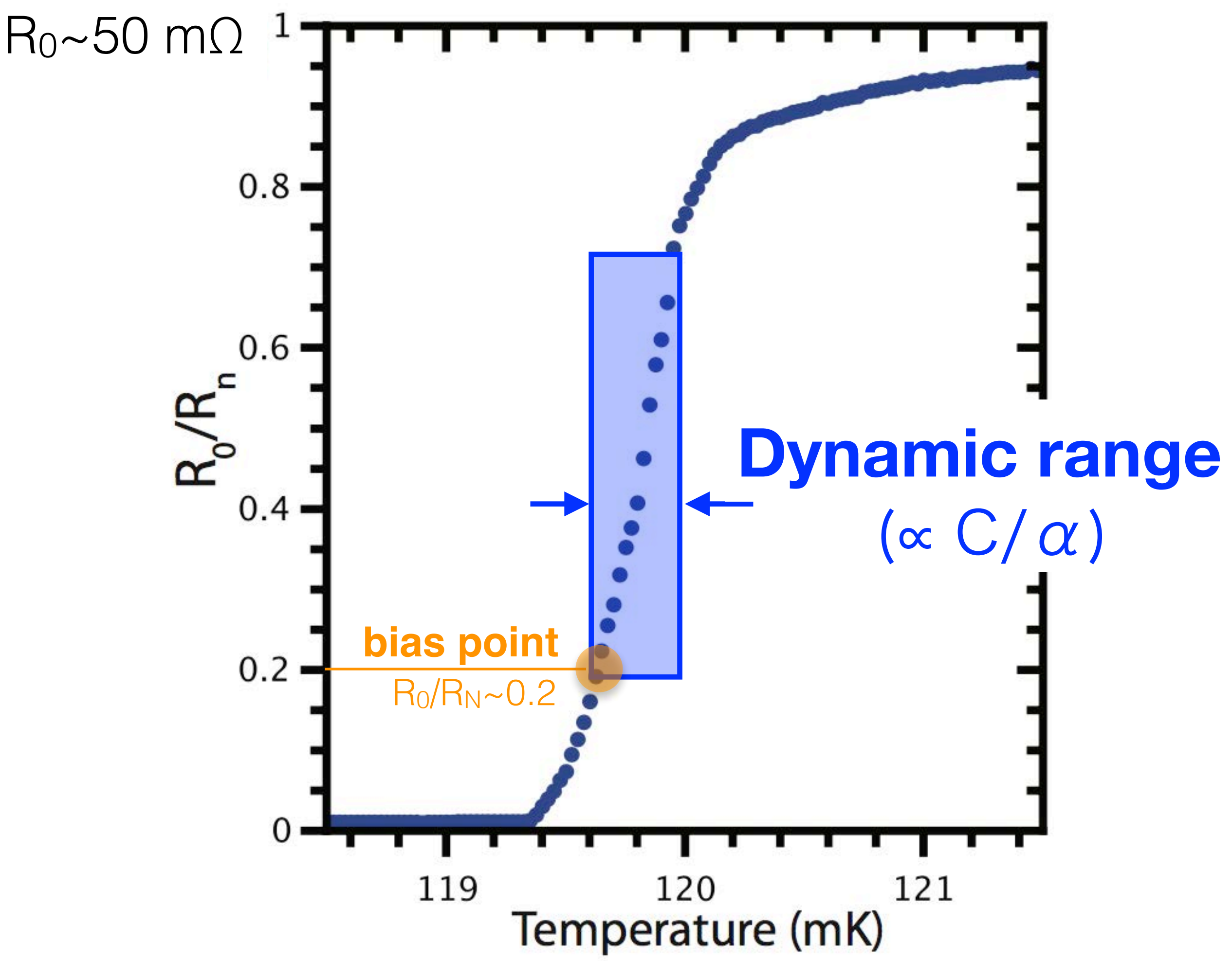
decay time ~ 500 μs

TES microcalorimeter

Microcalorimeter



Transition Edge Sensor



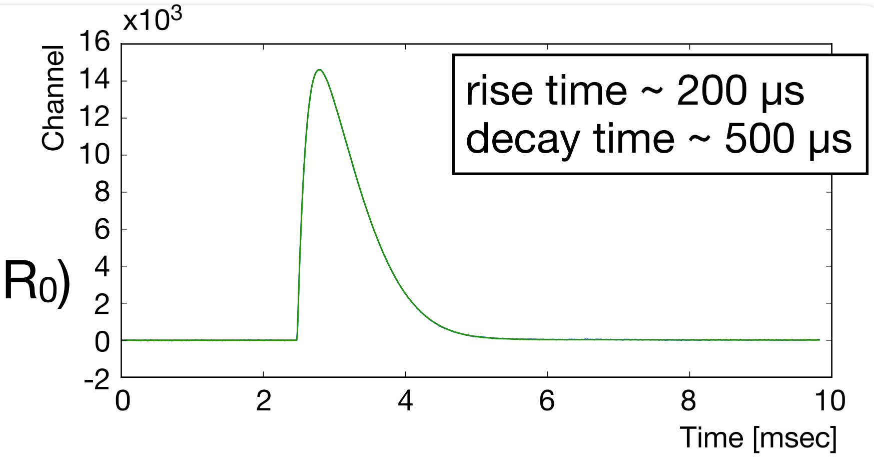
Temp. sensitivity : $\alpha_I = \left.\frac{\delta \log R}{\delta \log T}\right|_{I_0} = \frac{T_0}{R_0}\left.\frac{\delta R}{\delta T}\right|_{I_0}$

Energy resolution : $\Delta E \propto \sqrt{T_c^2 C/\alpha_I}$

Saturation energy : $E_{sat} \approx 4T_C C/\alpha_I$

Typical pulse

τ_{rise}~$L/(R_{sh}+R_0)$
τ_{fall}~C/G

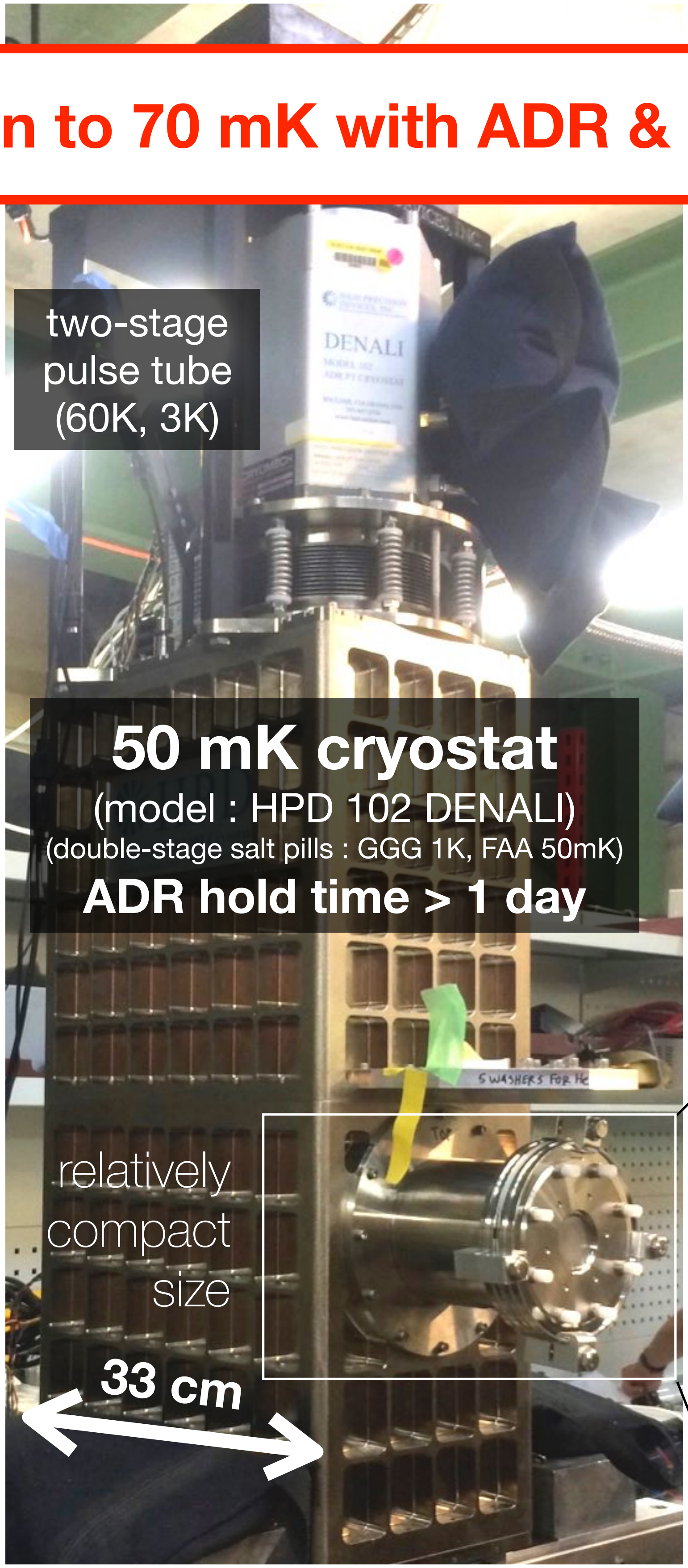


rise time ~ 200 μs
decay time ~ 500 μs

Adiabatic Demagnetization Refrigerator (ADR)

✓ Cooled down to 70 mK with ADR & pulse

102 DENALI **Pulse Tube ADR Cryostat**
Vacuum Jacket Size **33 cm X 22 cm X 66 cm Tall**
Experimental Volume **24 cm X 15 cm X 14 cm Tall**
1st Stage Cooling Power **25 W @ 55 K**
2nd Stage Cooling Power **0.7 W @ 4.2 K**
GGG Cooling Capacity **1.2 J @ 1 K** (< 500 mK @ GGG)
ADR Base Temperature **< 50 mK**
FAA Cooling Capacity **118 mJ @ 100 mK**


two-stage pulse tube (60K, 3K)

50 mK cryostat
(model : HPD 102 DENALI)
(double-stage salt pills : GGG 1K, FAA 50mK)
ADR hold time > 1 day

relatively compact size

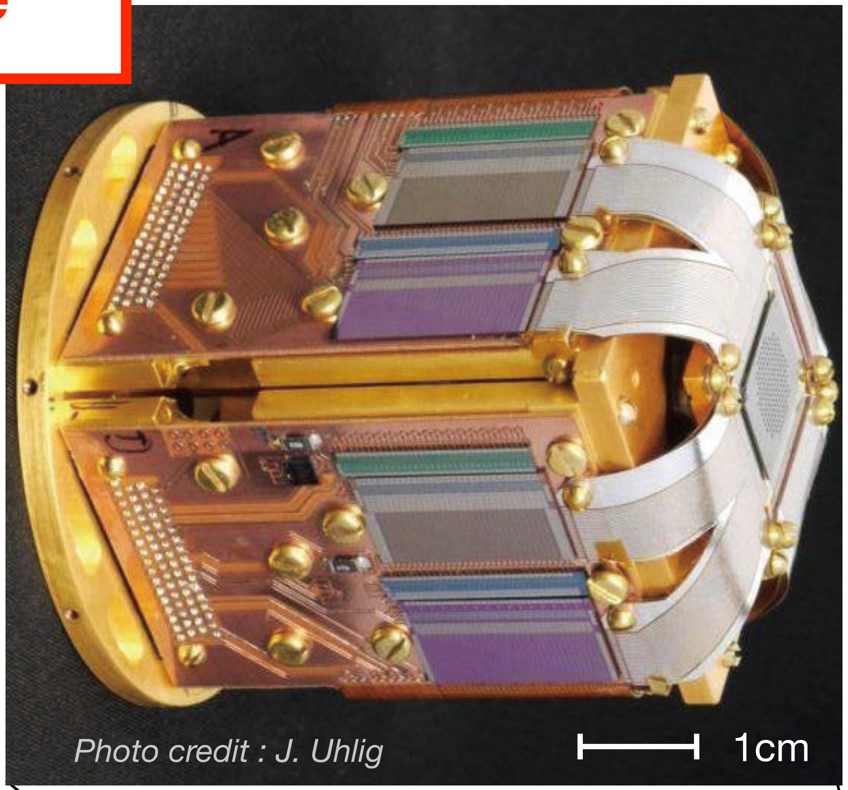
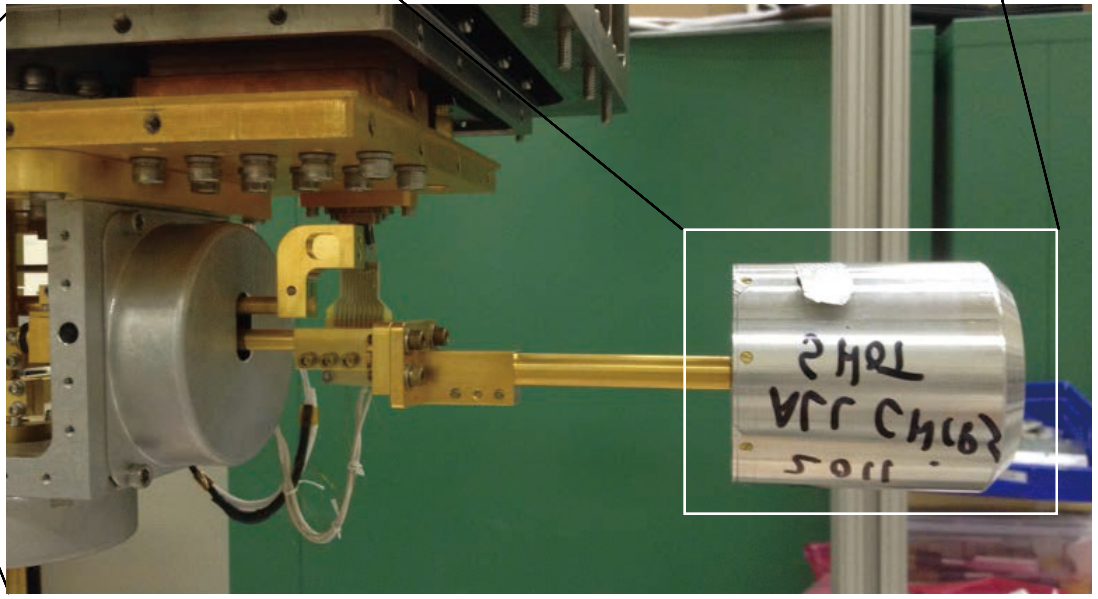


Photo credit : J. Uhlig

TES chip



TES array (NIST)

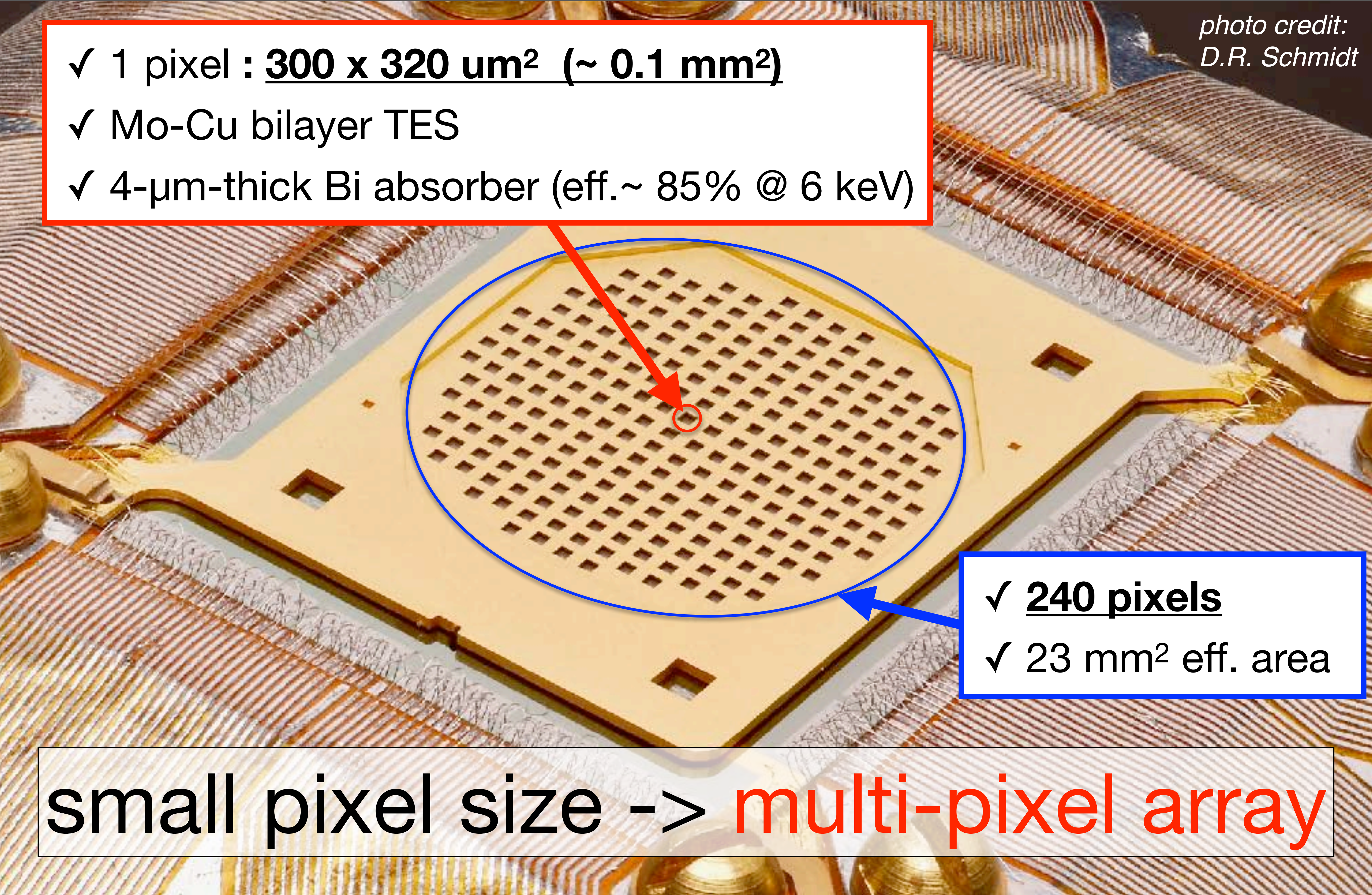


photo credit: D.R. Schmidt

- ✓ 1 pixel **:** **300 x 320 um² (~ 0.1 mm²)**
- ✓ Mo-Cu bilayer TES
- ✓ 4-µm-thick Bi absorber (eff.~ 85% @ 6 keV)

- ✓ **240 pixels**
- ✓ 23 mm^2 eff. area

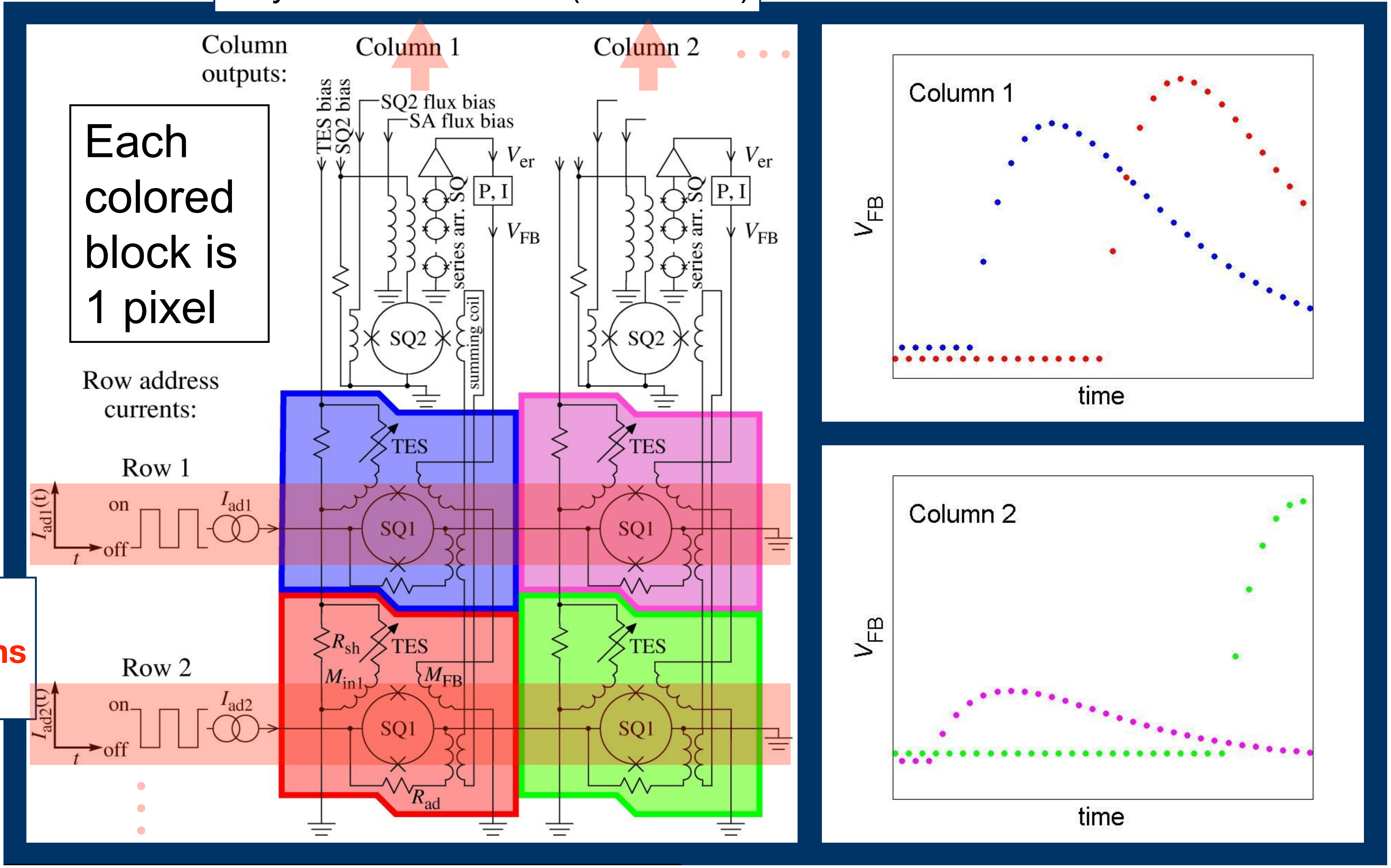
small pixel size -> multi-pixel array

Time division SQUID multiplexing (TDM)

to reduce the number of wires running to the low-temperature stages of the cryocooler

-> 240 pixel readout

only **8 read-out lines** (8 columns)



Each colored block is 1 pixel

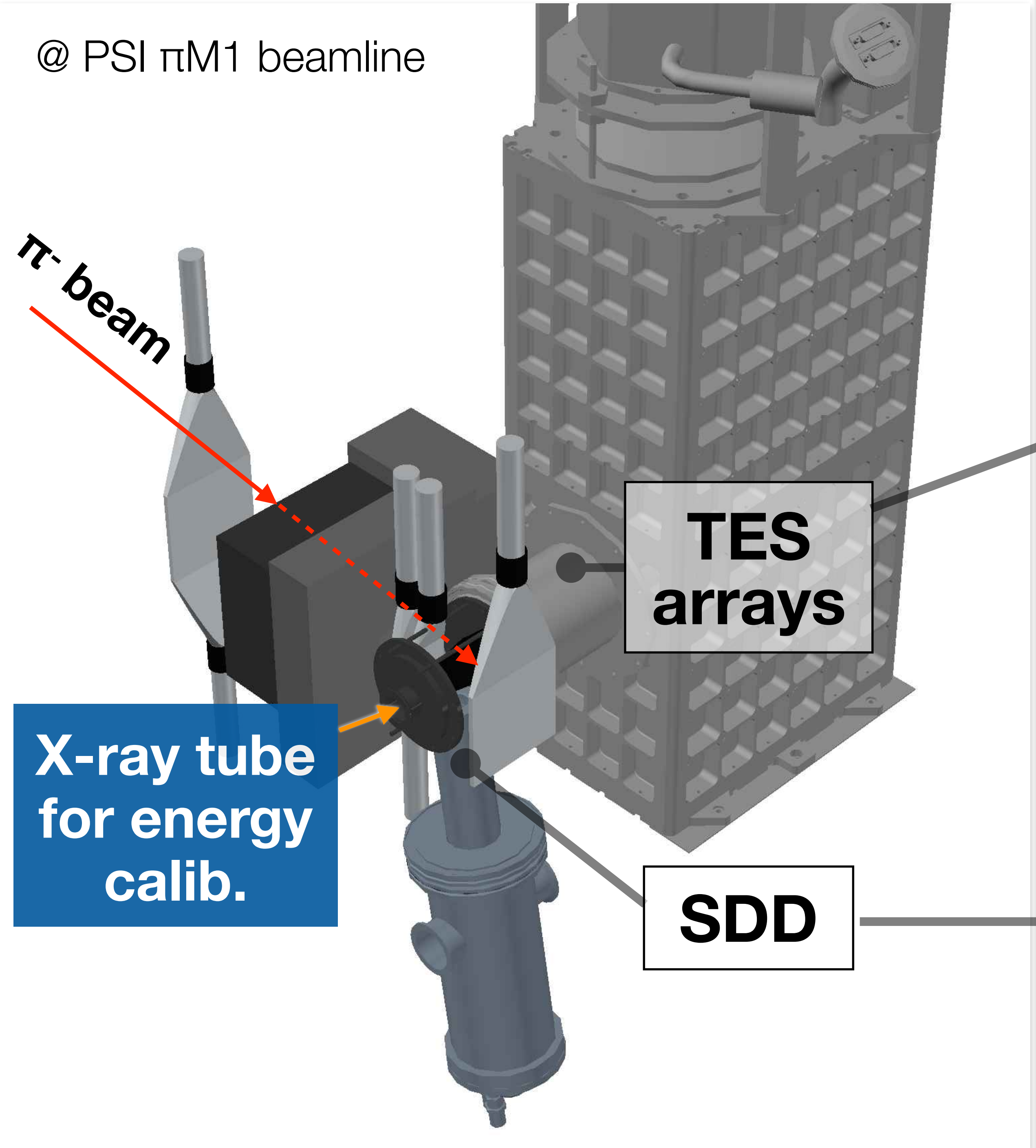
independent 30ch switching each 240ns
(30 rows)

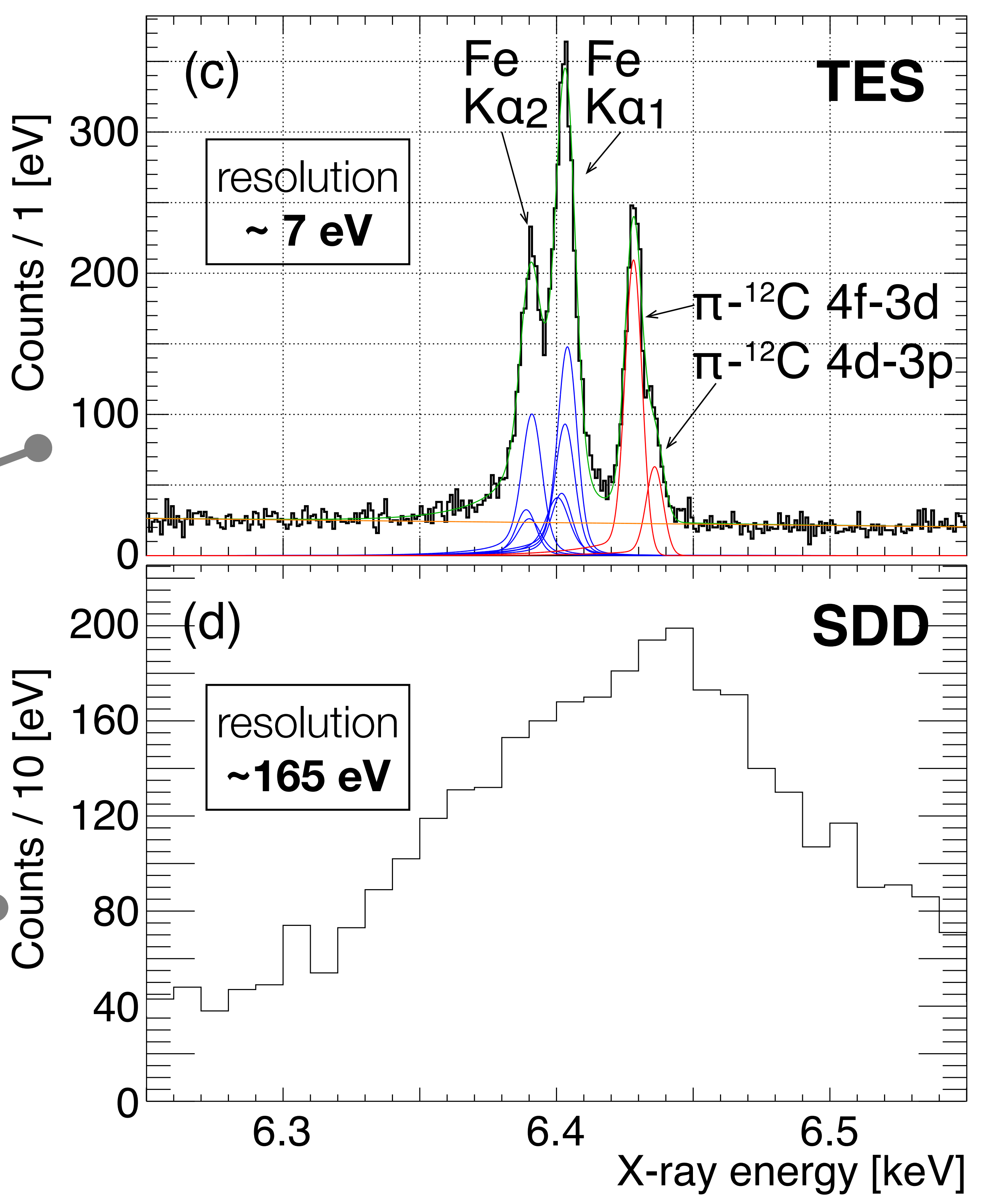
master clock
125 MHz

multiplexing flame time : 7.2 [μs] (=240 ns x 30 ch) -> **sampling rate=139 [kHz]**

Randy Doriese (NIST), NSLS Users Meeting: May 21, 2008

Example of pionic atom experiment



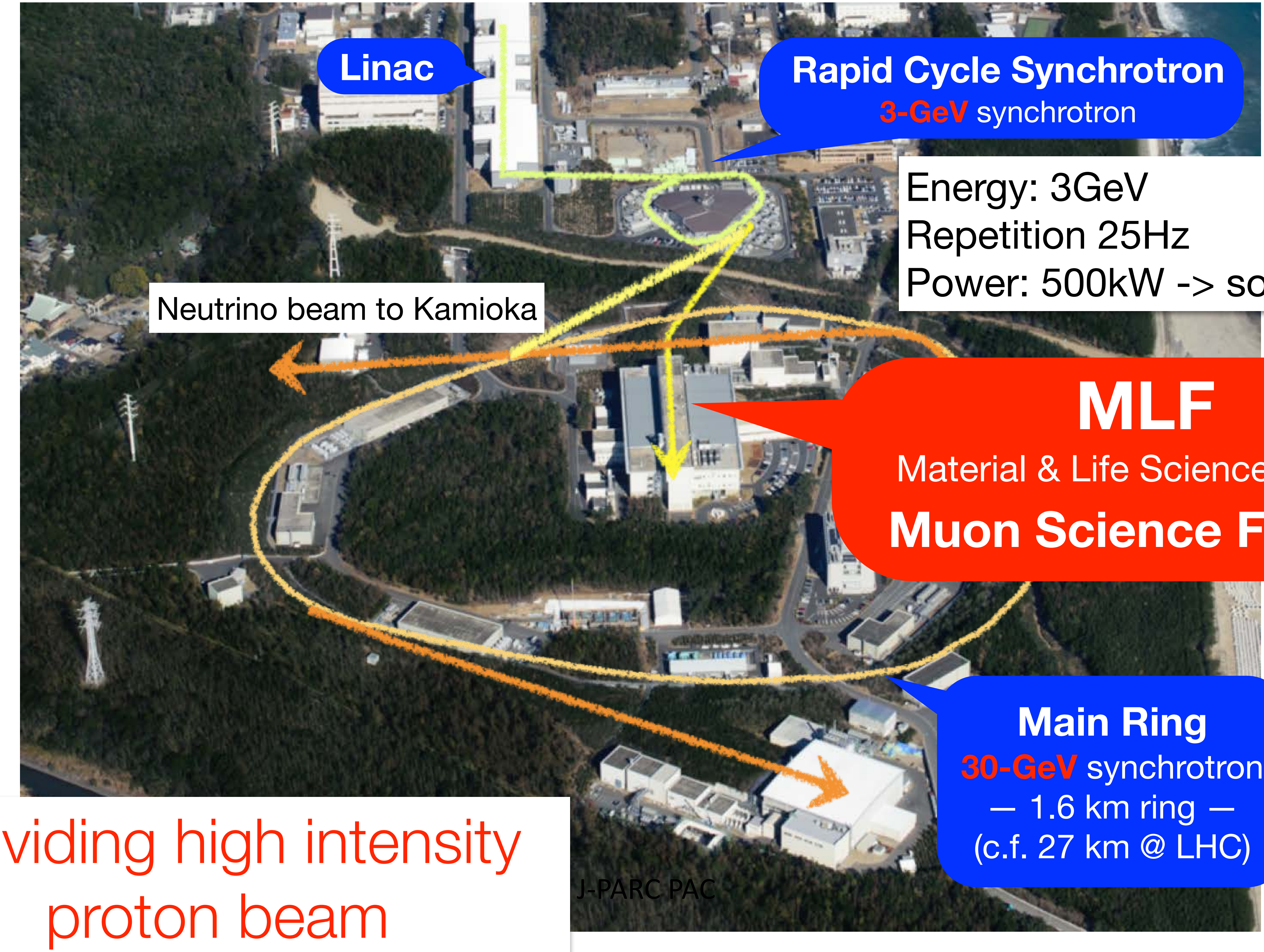


S. Okada et al., PTEP 2016, 091D01 (2016)

3. Experiment

J-PARC

Japan **P**roton **A**ccelerator **R**esearch **C**omplex



Rapid Cycle Synchrotron
3-GeV synchrotron

Energy: 3GeV
Repetition 25Hz
Power: 500kW -> soon 1MW

MLF
Material & Life Science Facility
Muon Science Facility

Main Ring
30-GeV synchrotron
— 1.6 km ring —
(c.f. 27 km @ LHC)

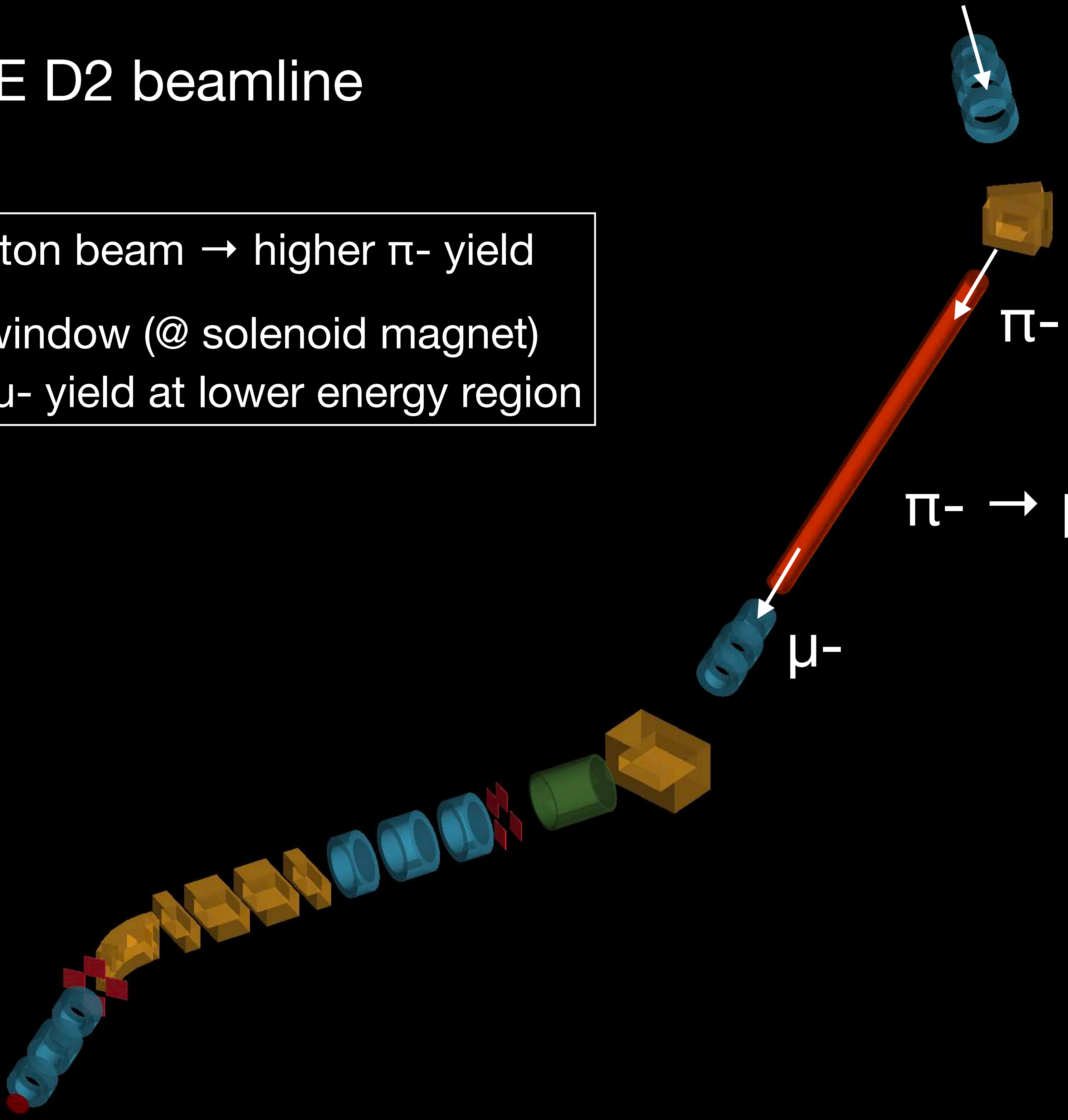
J-PARC PAC

providing high intensity proton beam

Muon beamline

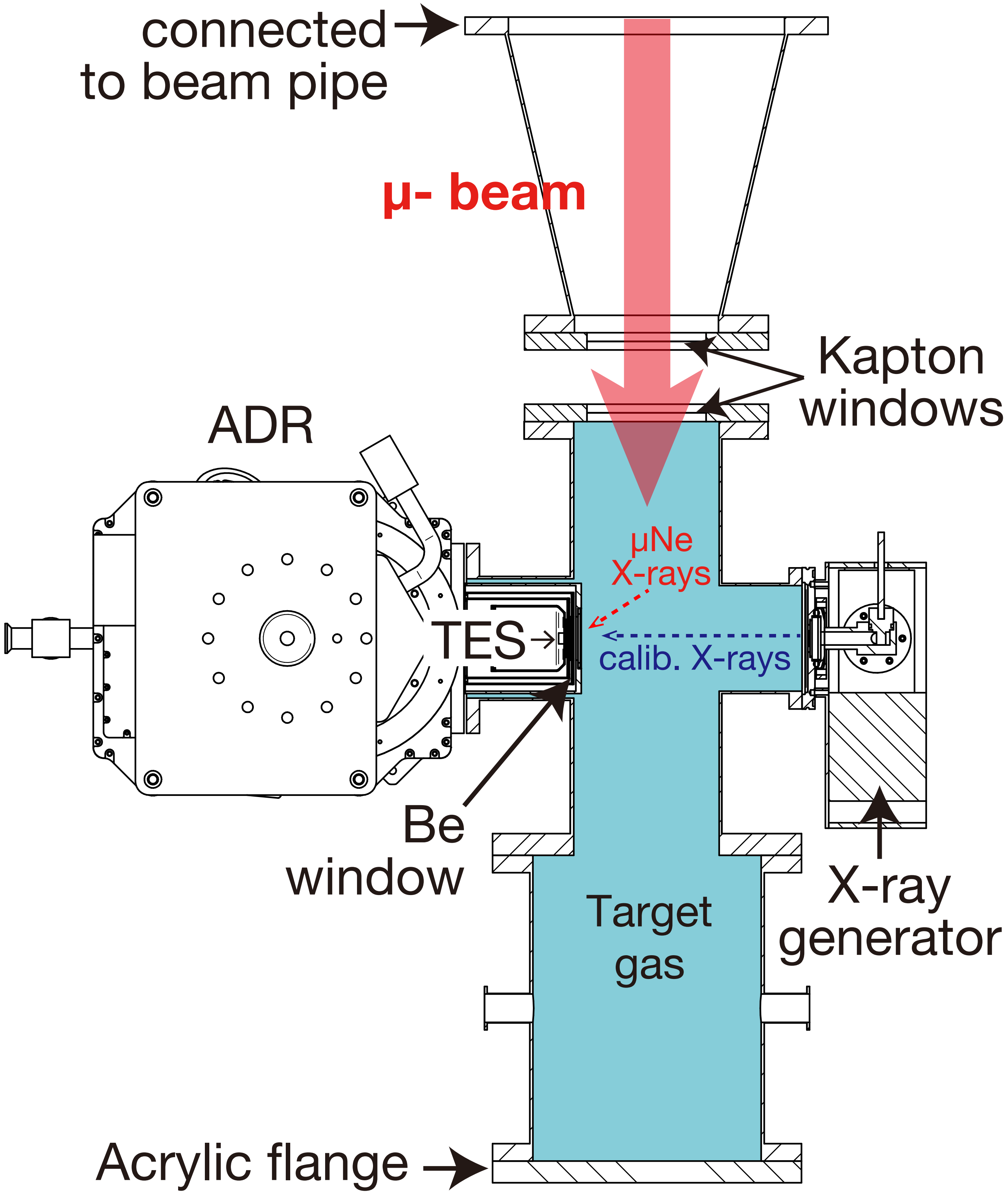
J-PARC MUSE D2 beamline

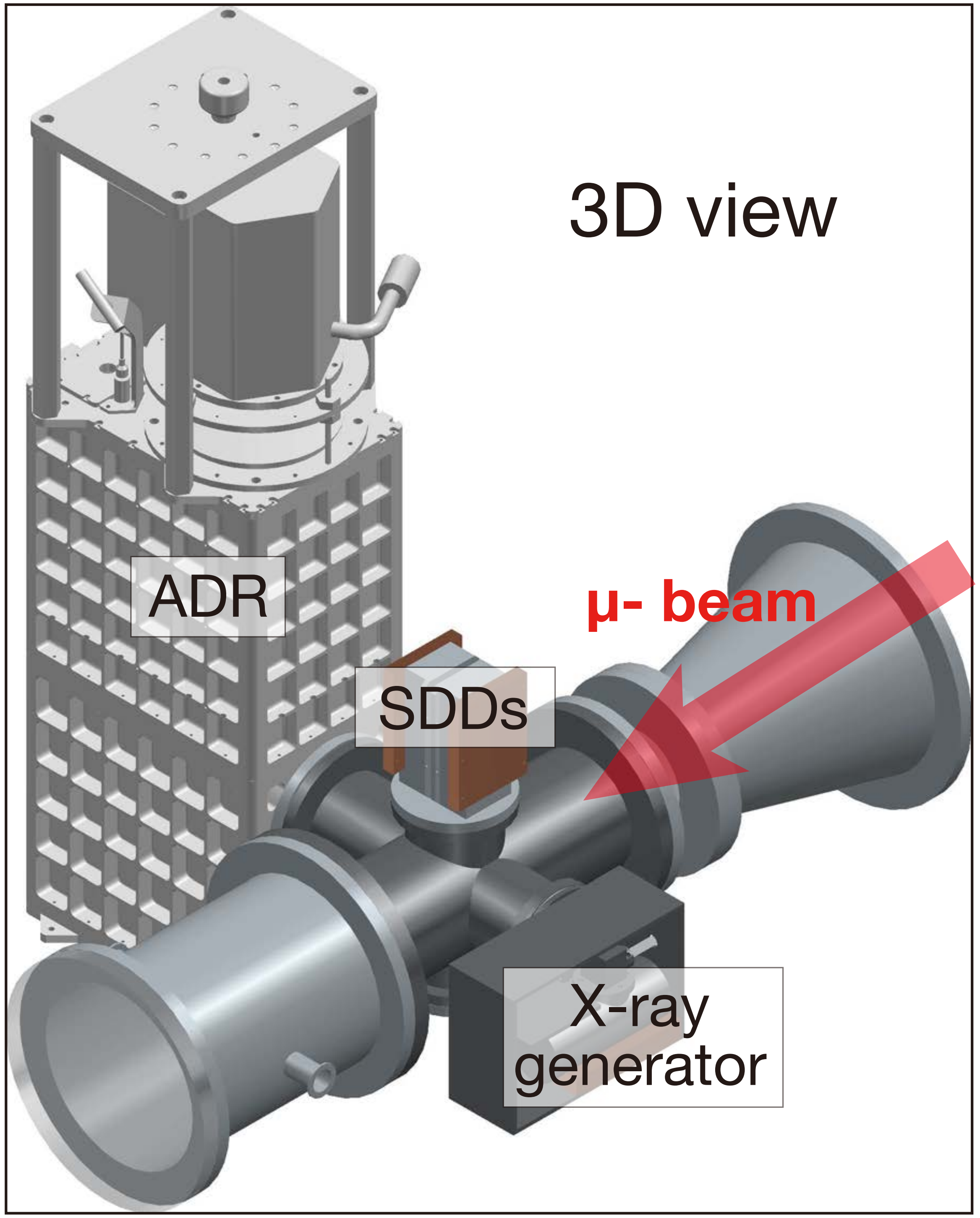
- 3 GeV proton beam → higher π- yield
- avoiding window (@ solenoid magnet)
  → higher μ- yield at lower energy region



Experimental area

Experimental setup

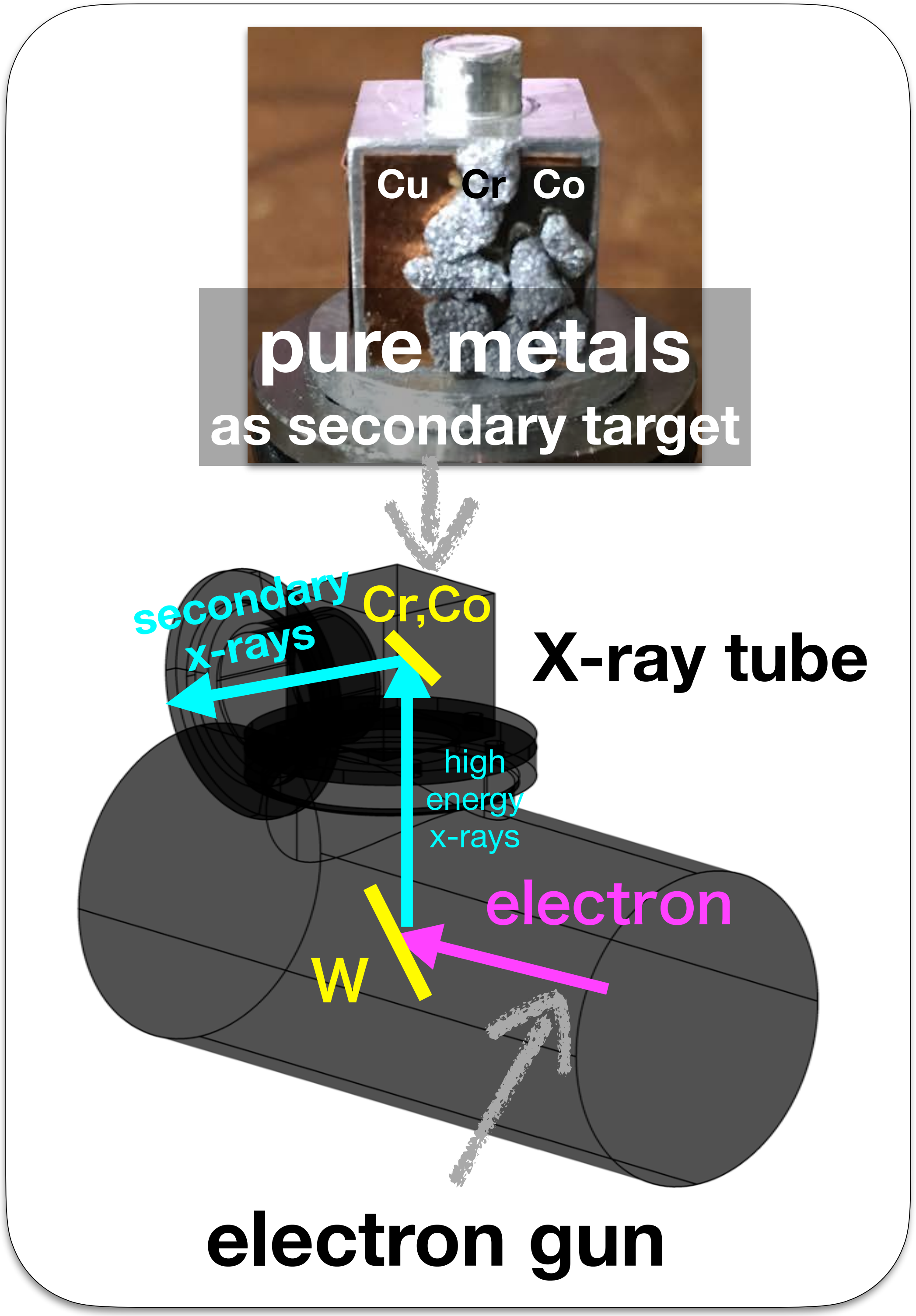




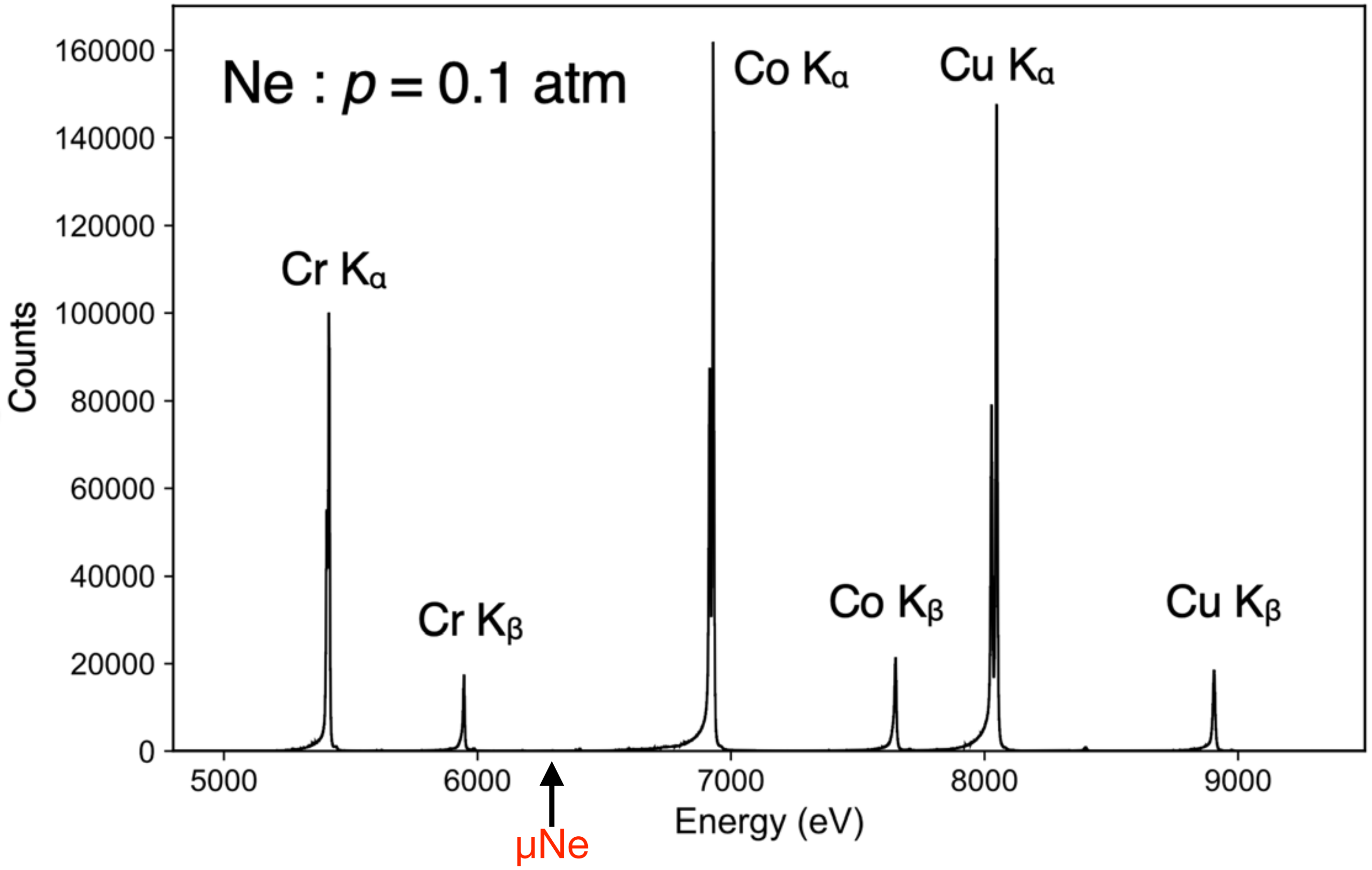
4. Results

Energy calibration

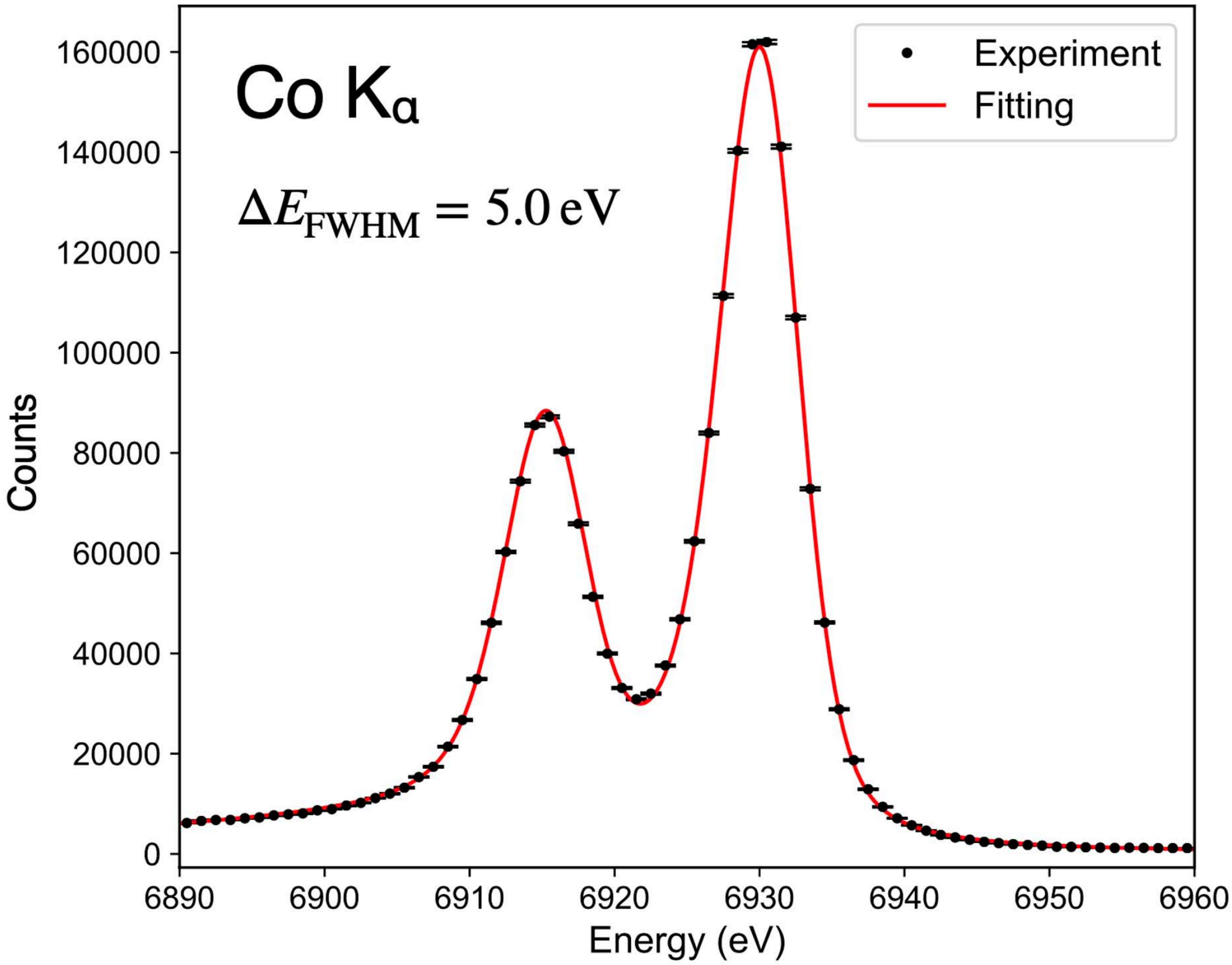
Continuous X-ray irradiation during experiment



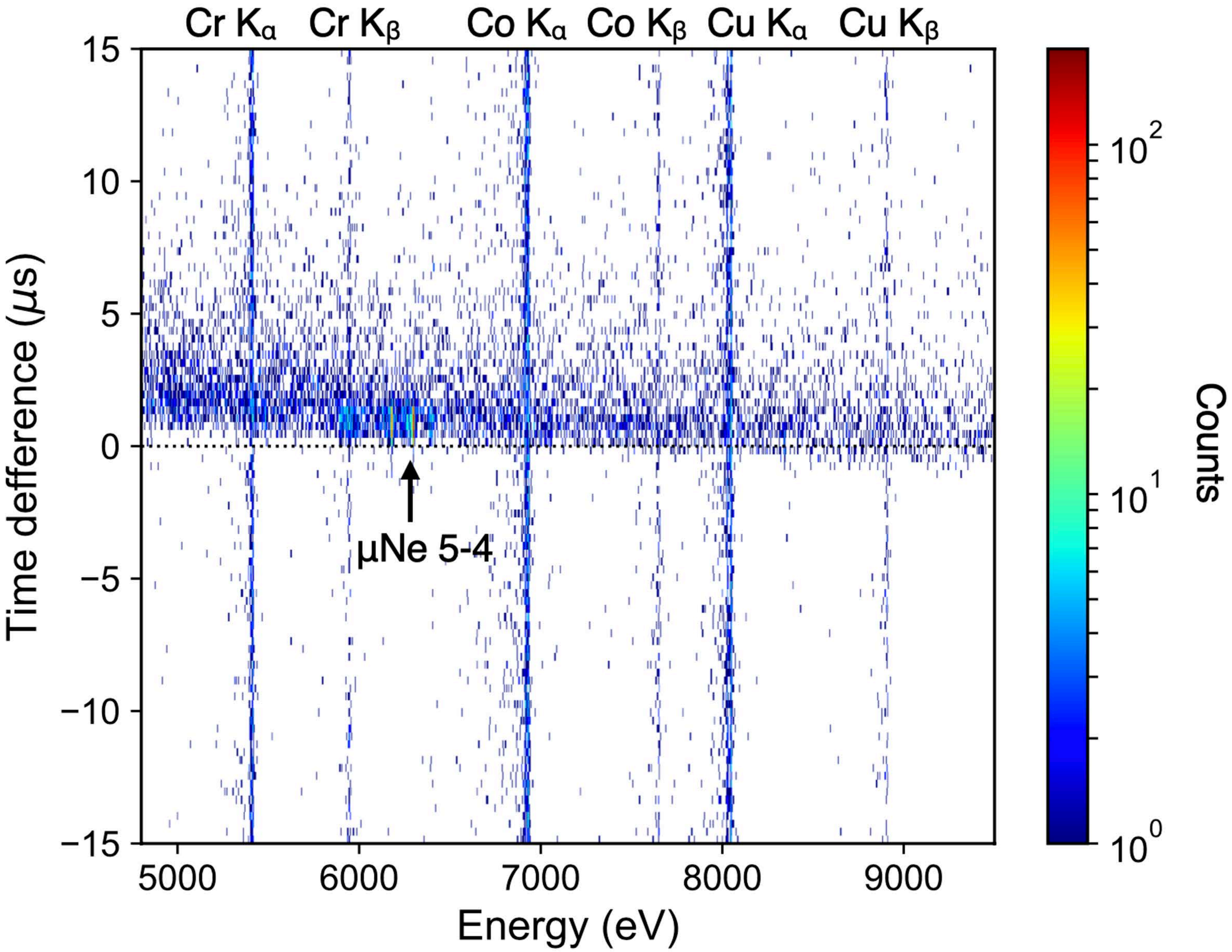
✓controllable intensity
✓many x-ray lines



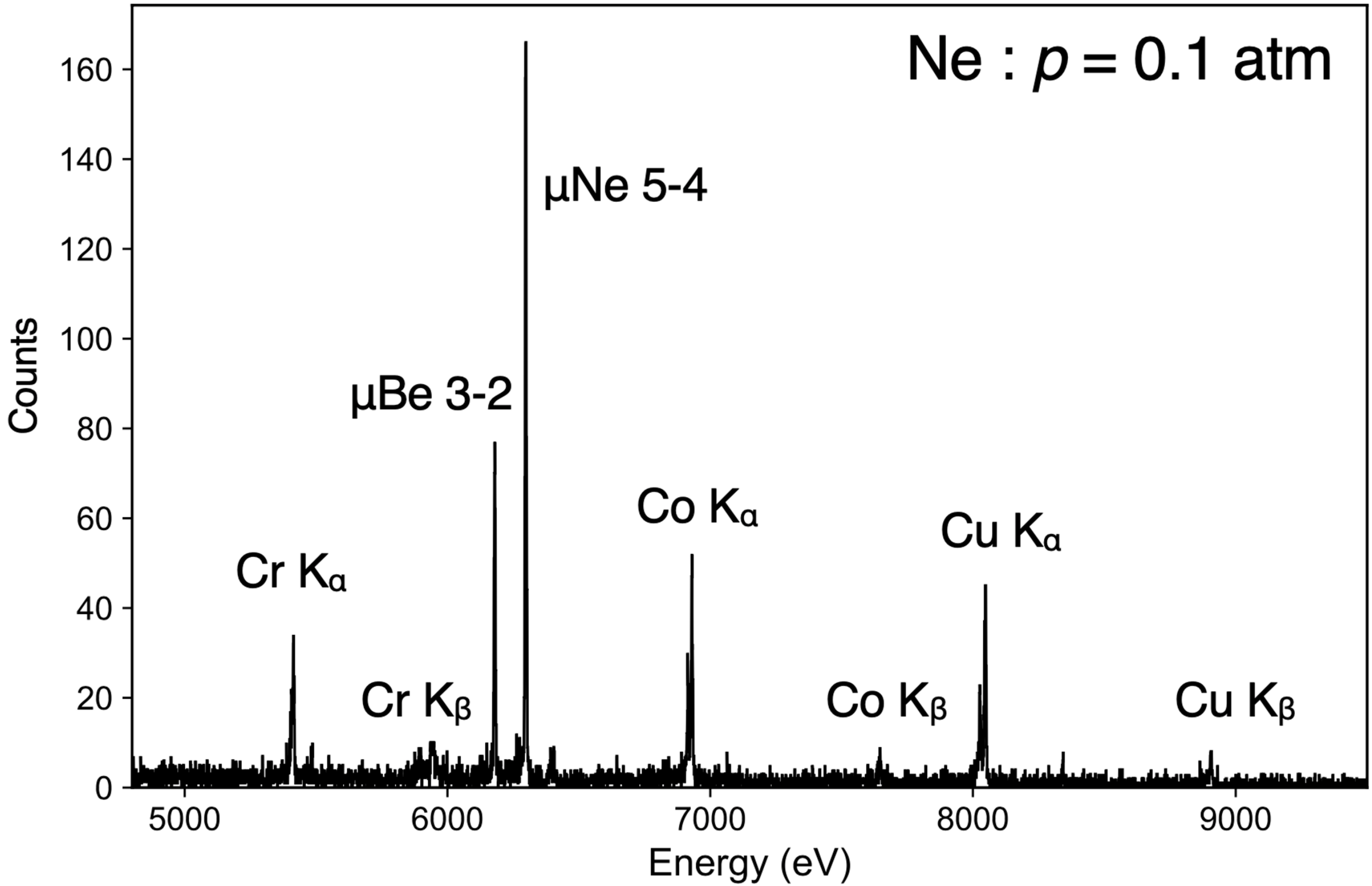
Energy resolution ~ 5 eV @ 6.9 keV



Energy vs. Timing (muon arrival time)



Muonic-atom X-ray spectrum



Effect of charged particle

Charged particles scattered at the timing of the muon beam may hit the detector.

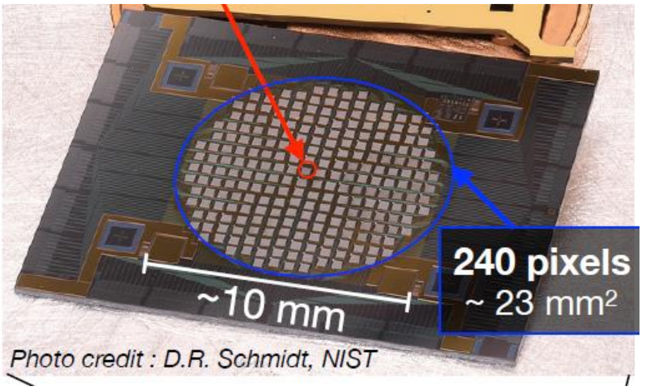
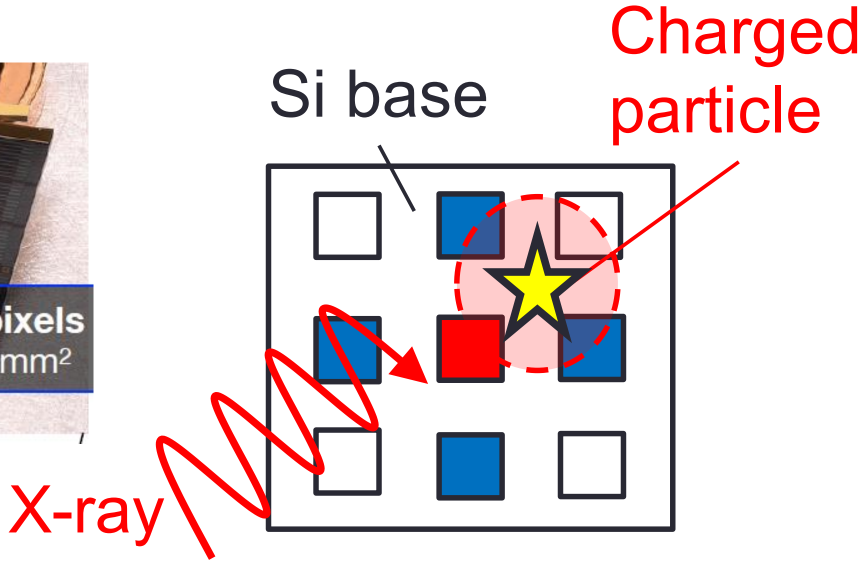
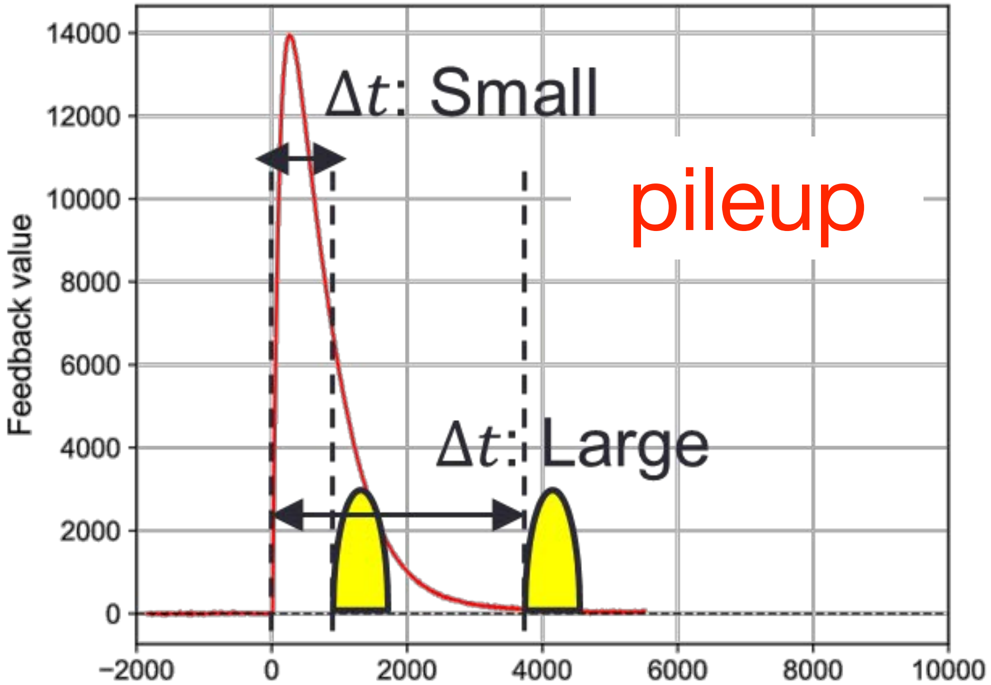
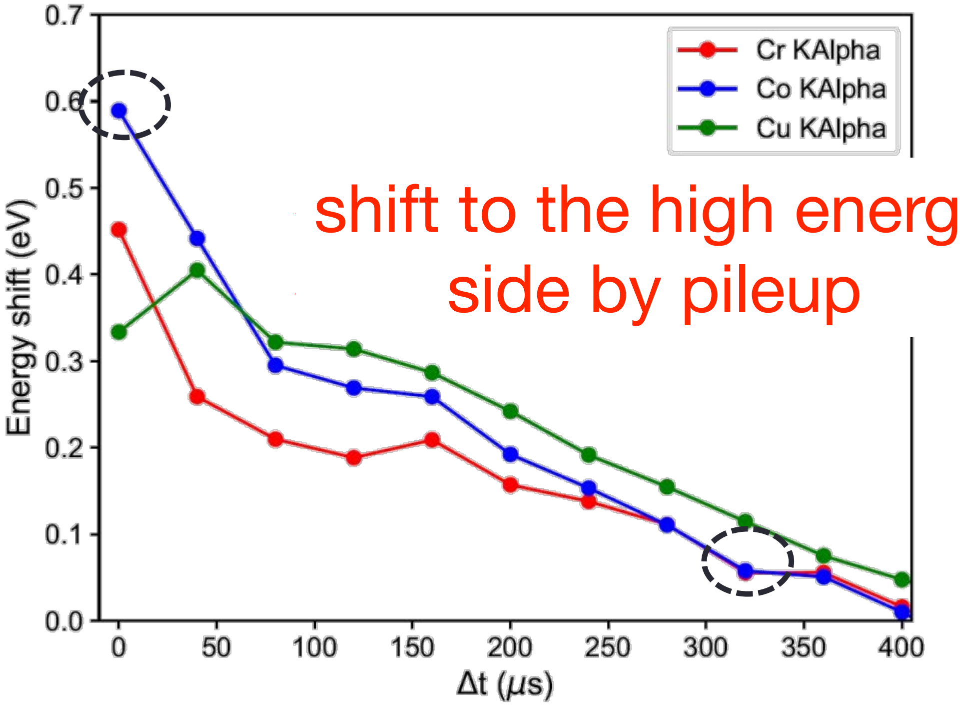


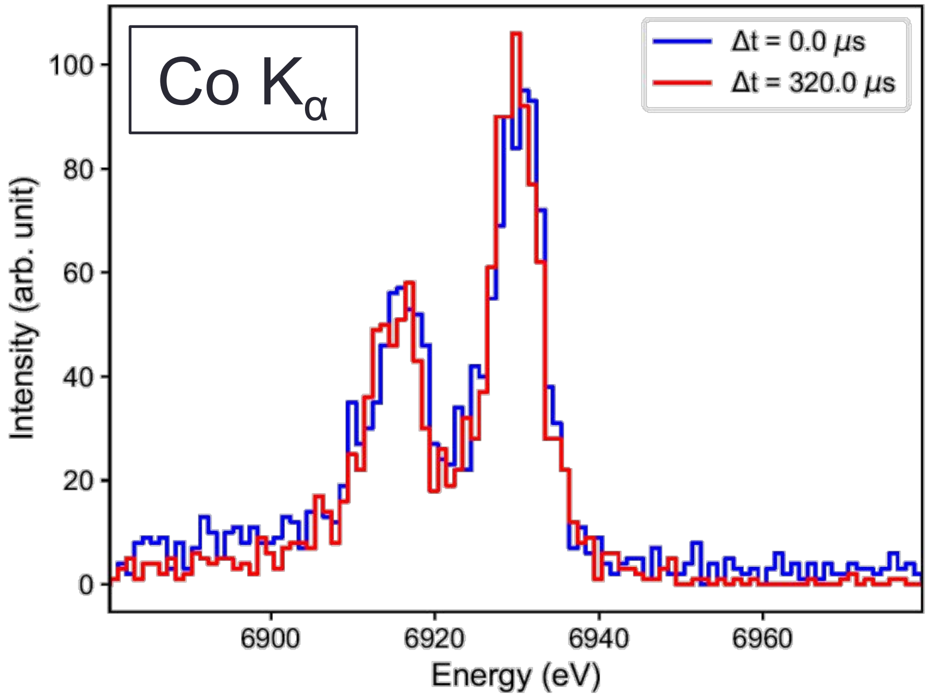
Photo credit : D.R. Schmidt, NIST



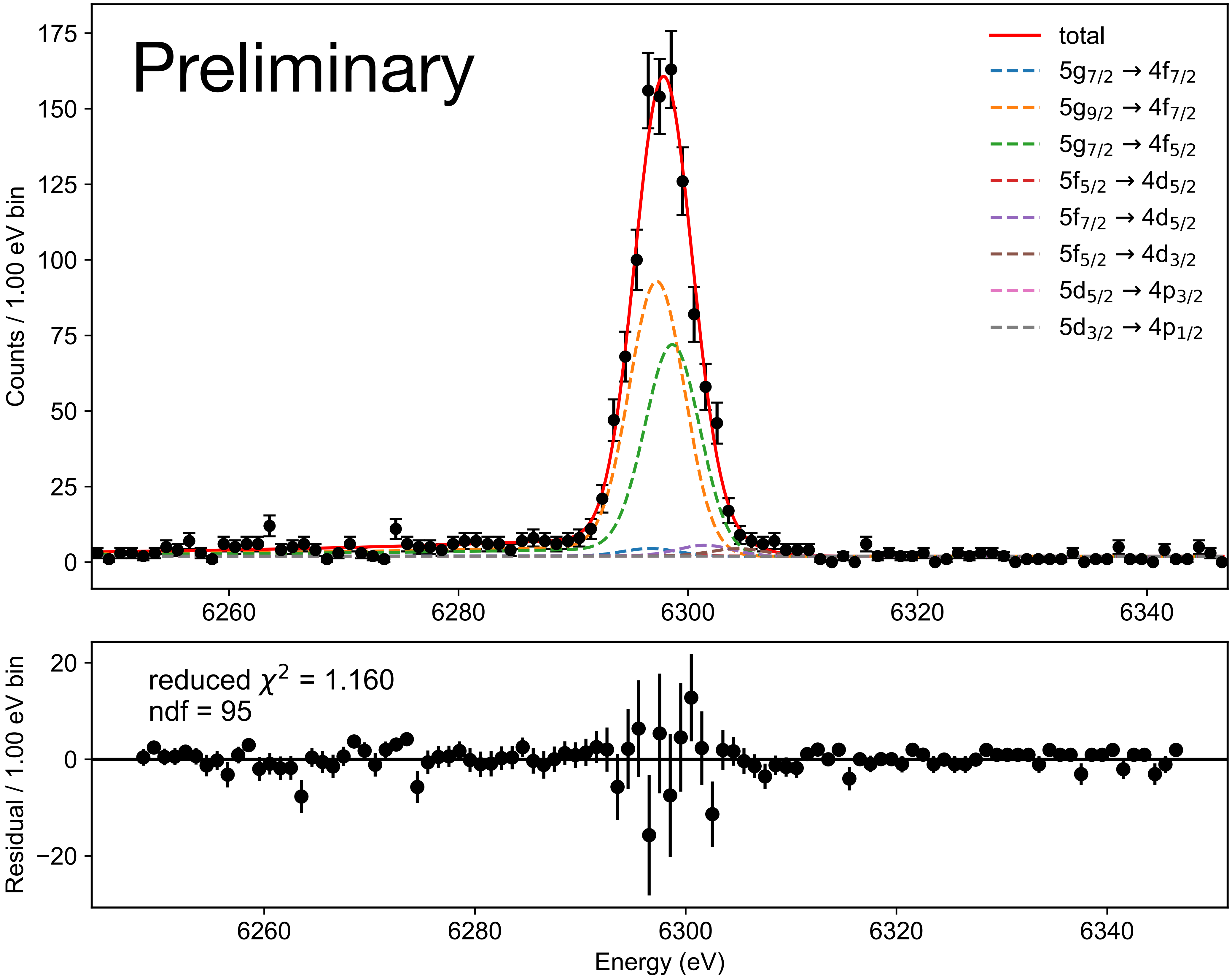




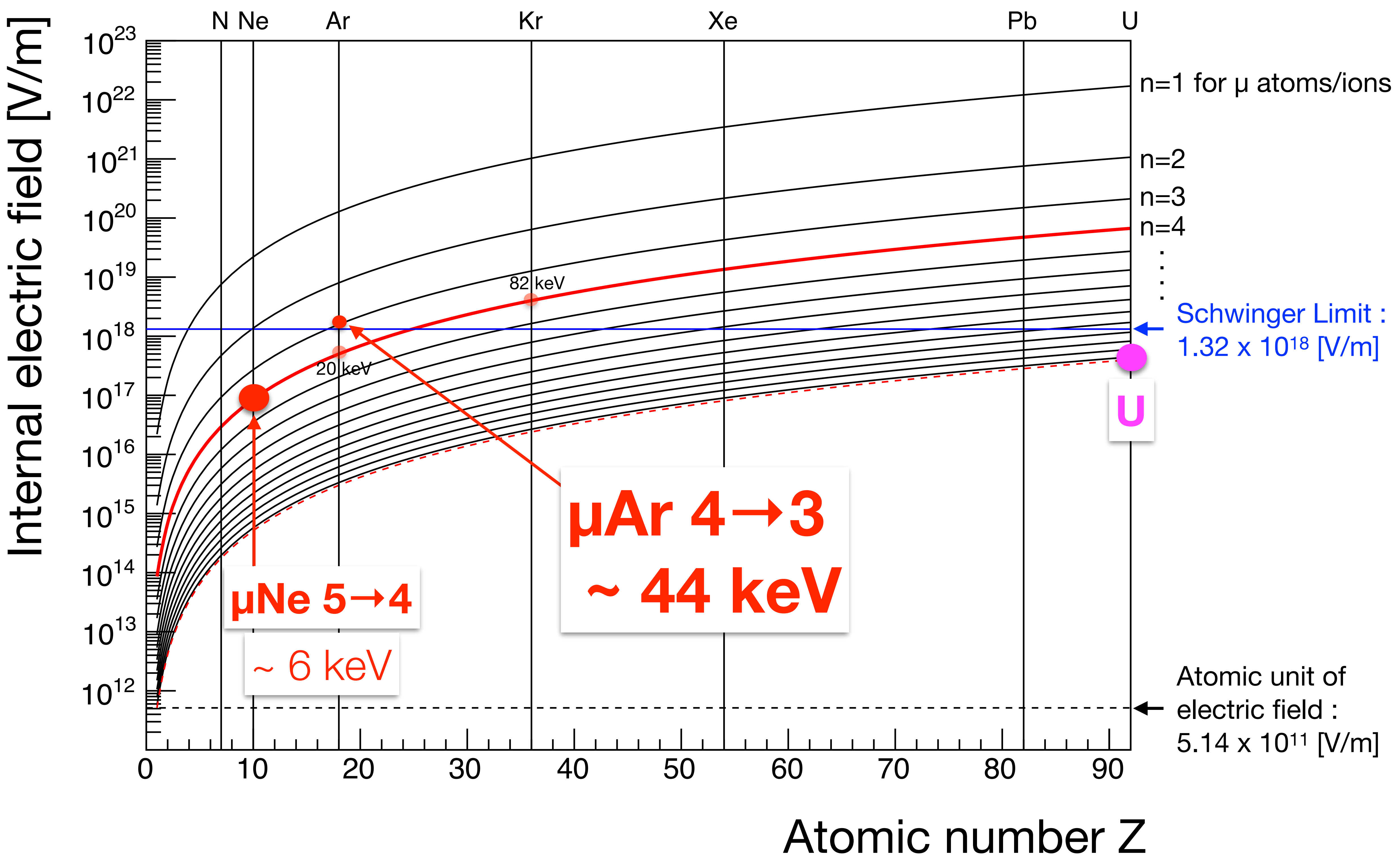
shift to the high energy side by pileup



Muonic Ne atom 5→4 @ 0.1 atm



Next target?



Schwinger Limit : 1.32 x 10^{18} [V/m]

Atomic unit of electric field : 5.14 x 10^{11} [V/m]

μNe 5→4

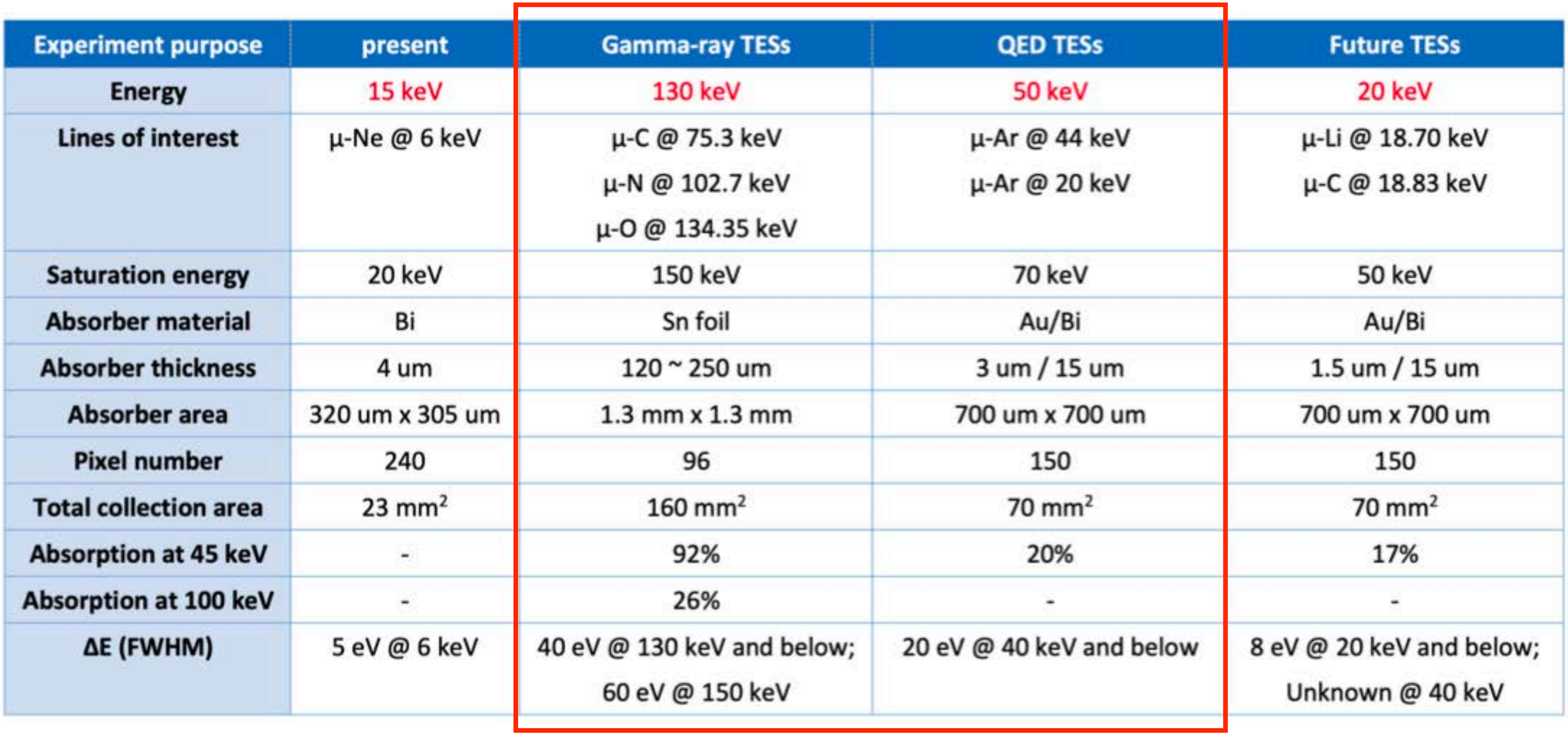
~ 6 keV

μAr 4→3

~ 44 keV

TES under development

$$\alpha \equiv \frac{d\ \ln R}{d\ \ln T} \qquad \Delta E = \sqrt{\frac{k_B T^2 C}{\alpha}} \qquad E_{max} \sim C T_C / \alpha$$



Experiment purpose	present	Gamma-ray TESs	QED TESs	Future TESs
Energy	15 keV	130 keV	50 keV	20 keV
Lines of interest	μ-Ne @ 6 keV	μ-C @ 75.3 keV μ-N @ 102.7 keV μ-O @ 134.35 keV	μ-Ar @ 44 keV μ-Ar @ 20 keV	μ-Li @ 18.70 keV μ-C @ 18.83 keV
Saturation energy	20 keV	150 keV	70 keV	50 keV
Absorber material	Bi	Sn foil	Au/Bi	Au/Bi
Absorber thickness	4 um	120 ~ 250 um	3 um / 15 um	1.5 um / 15 um
Absorber area	320 um x 305 um	1.3 mm x 1.3 mm	700 um x 700 um	700 um x 700 um
Pixel number	240	96	150	150
Total collection area	23 mm^2	160 mm^2	70 mm^2	70 mm^2
Absorption at 45 keV	-	92%	20%	17%
Absorption at 100 keV	-	26%	-	-
ΔE (FWHM)	5 eV @ 6 keV	40 eV @ 130 keV and below; 60 eV @ 150 keV	20 eV @ 40 keV and below	8 eV @ 20 keV and below; Unknown @ 40 keV

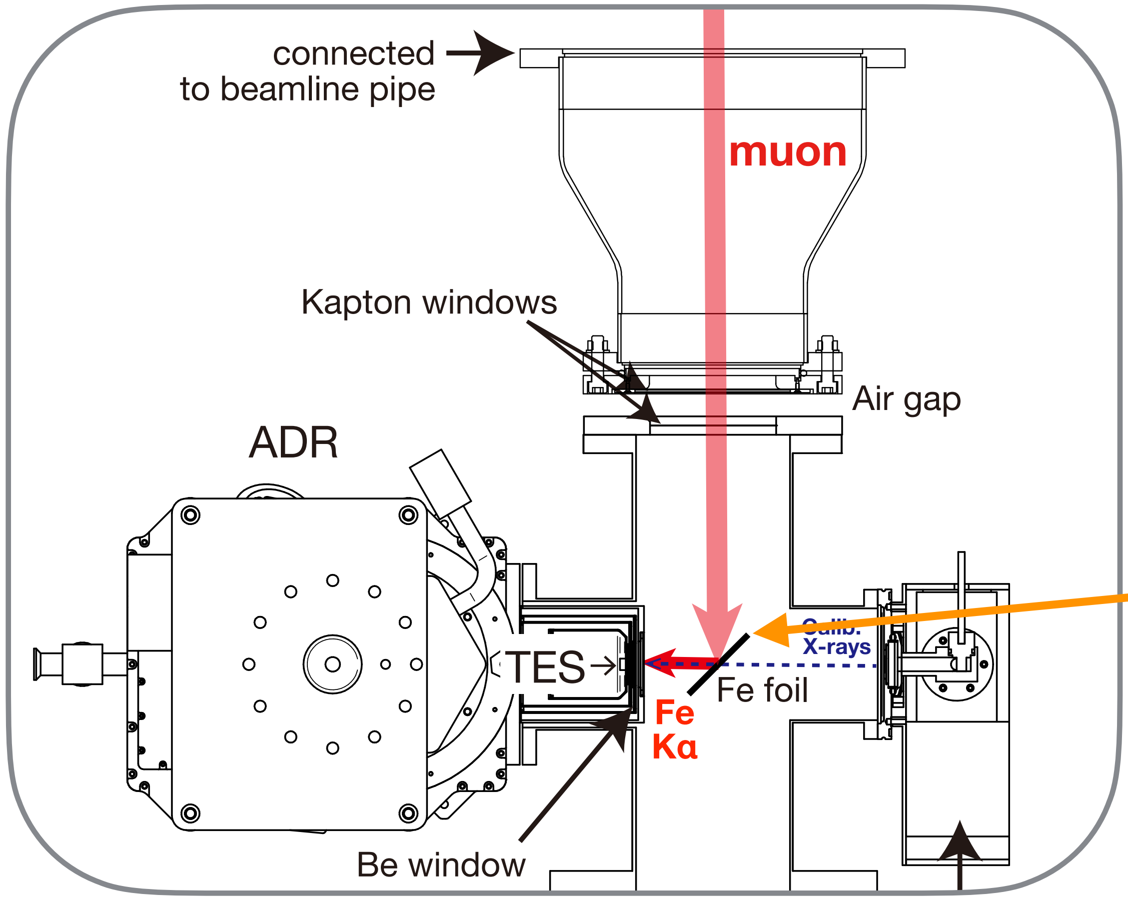
✓New cryostat, readout system

✓Available in a few years (for μ-atoms)

✓Multiple units can be installed

5. Serendipity

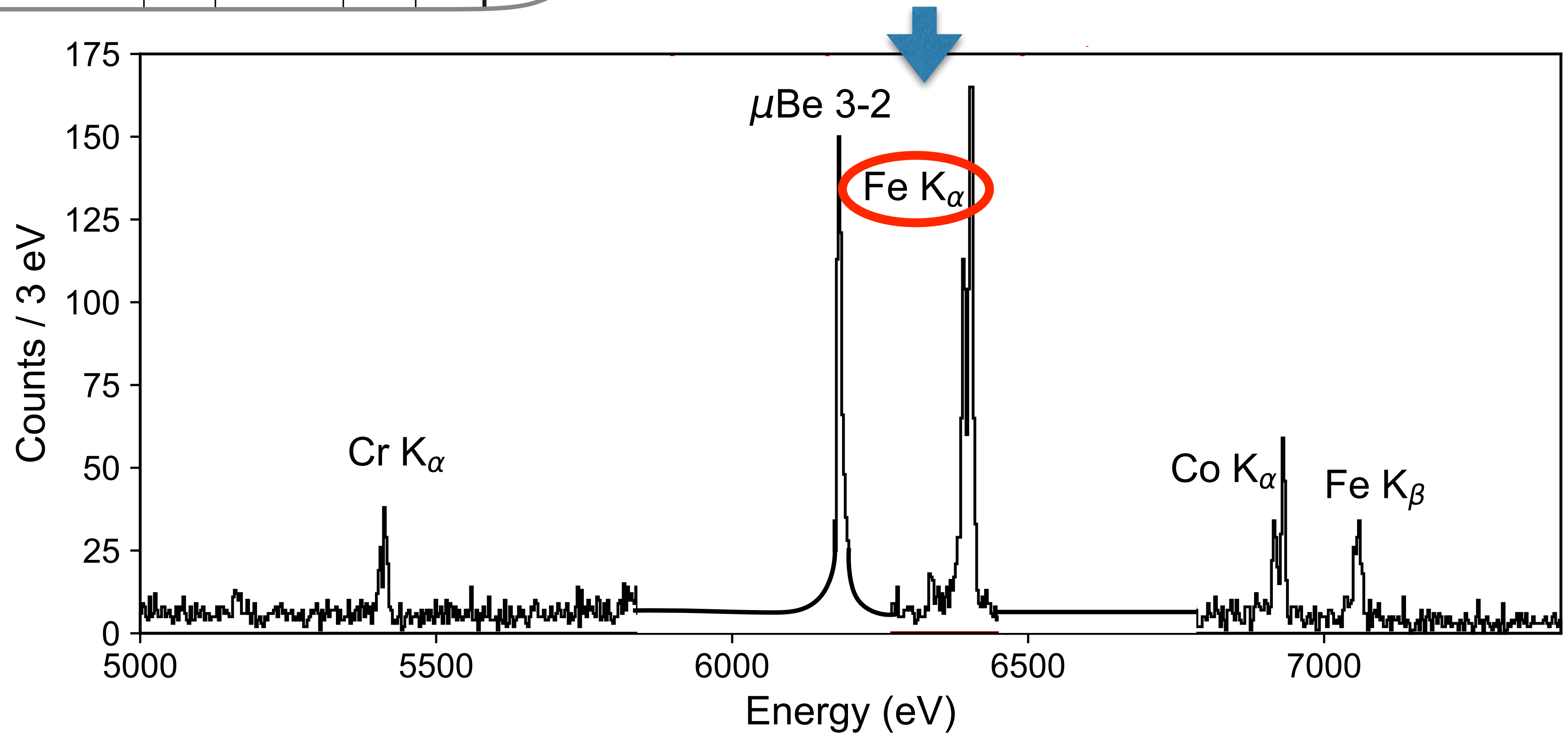
during TES detector study



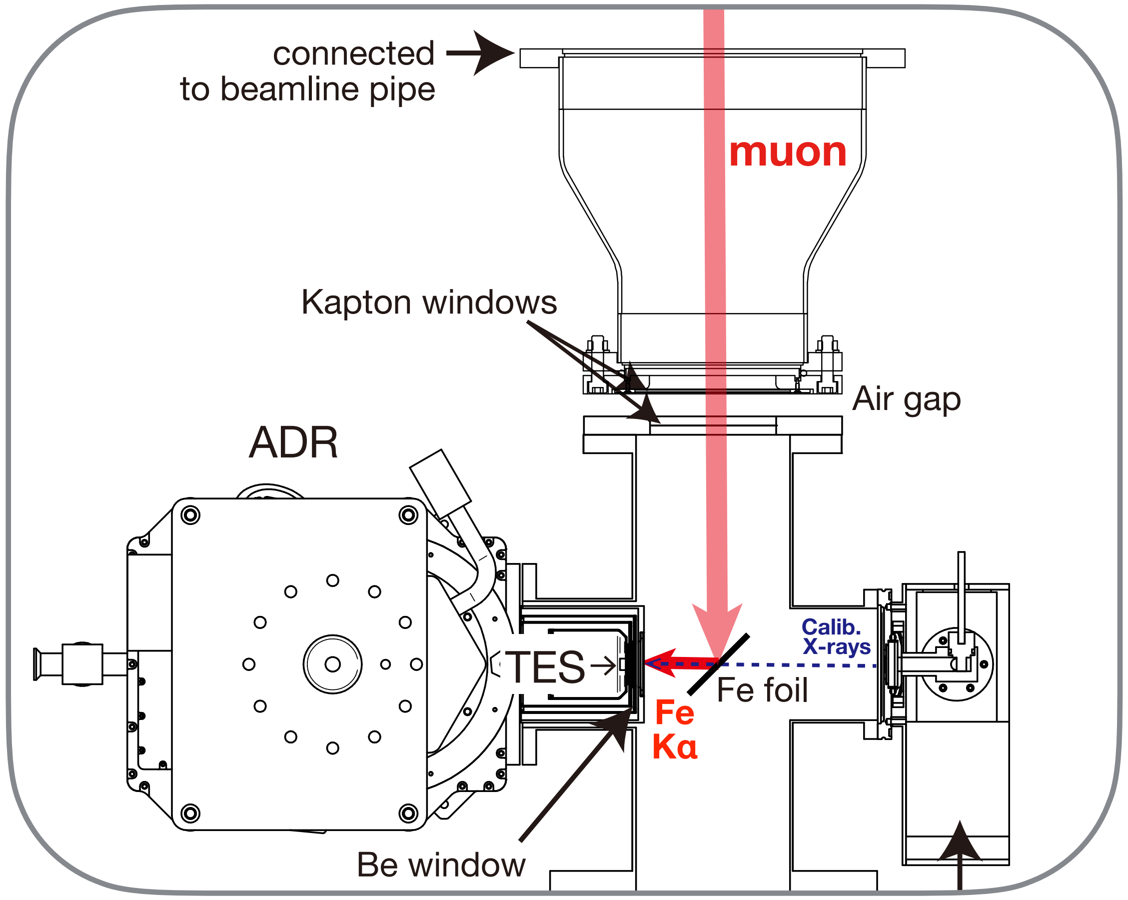
Just for a study of energy shifts at beam timing :

Observing characteristic X-rays from **pure metal (Fe)** excited by the charged particles of the beam

This is what we expected

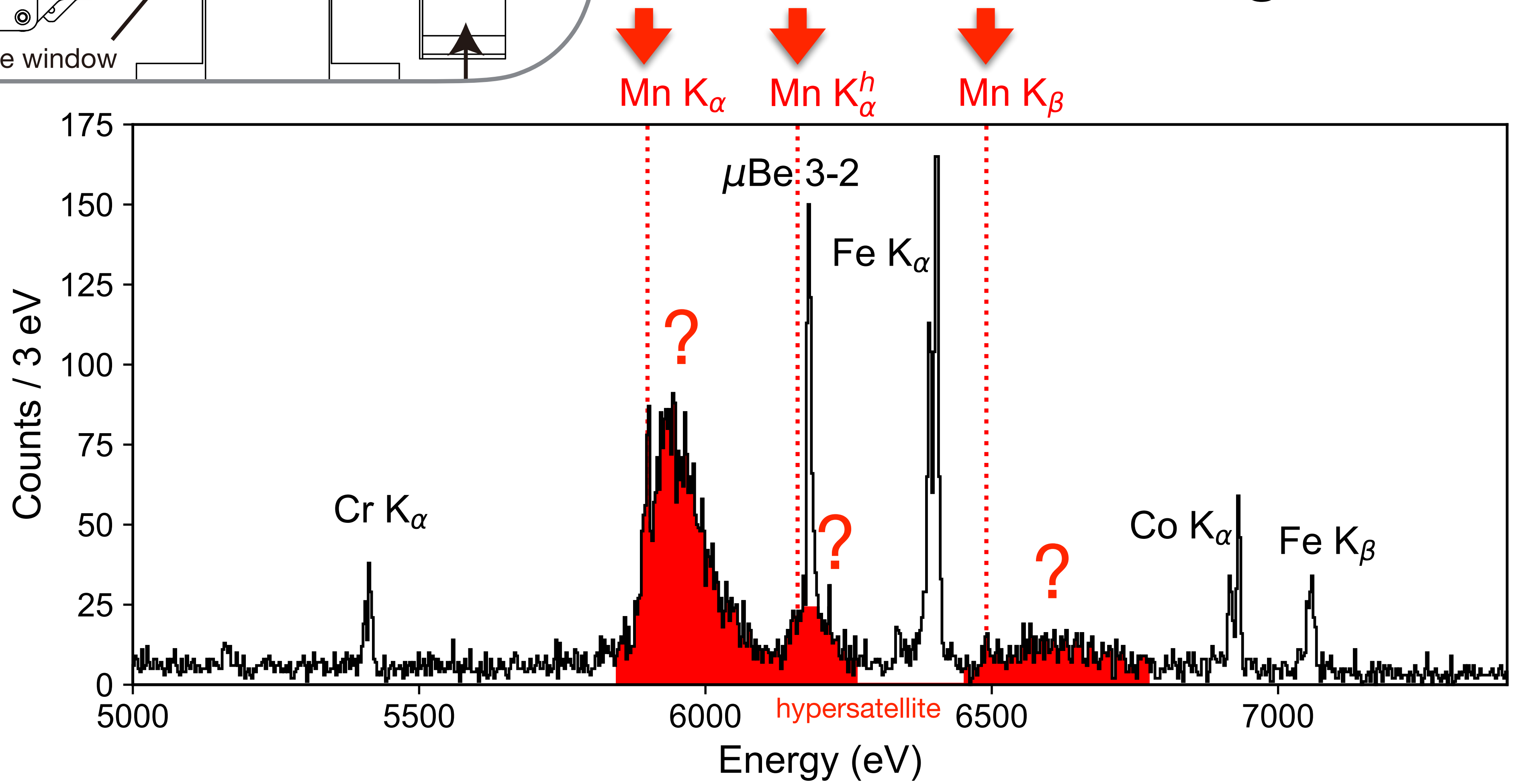


Serendipity !



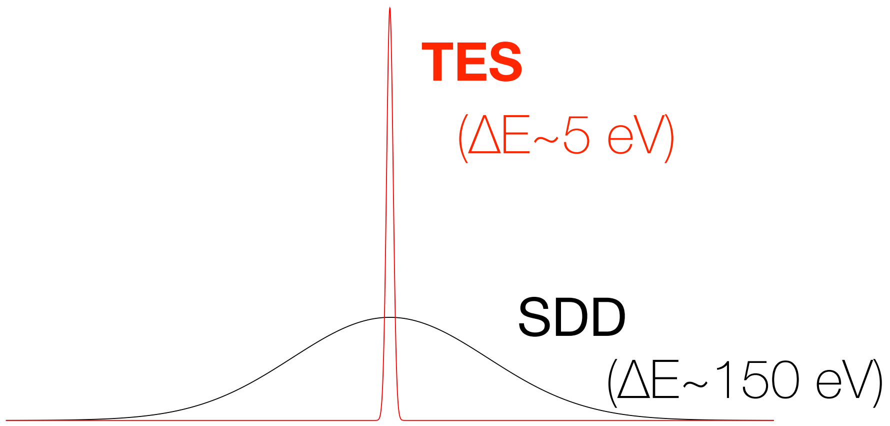
Surprisingly,
other than Fe Kα and Kβ,
an **unexpected and very broad structure** was discovered.

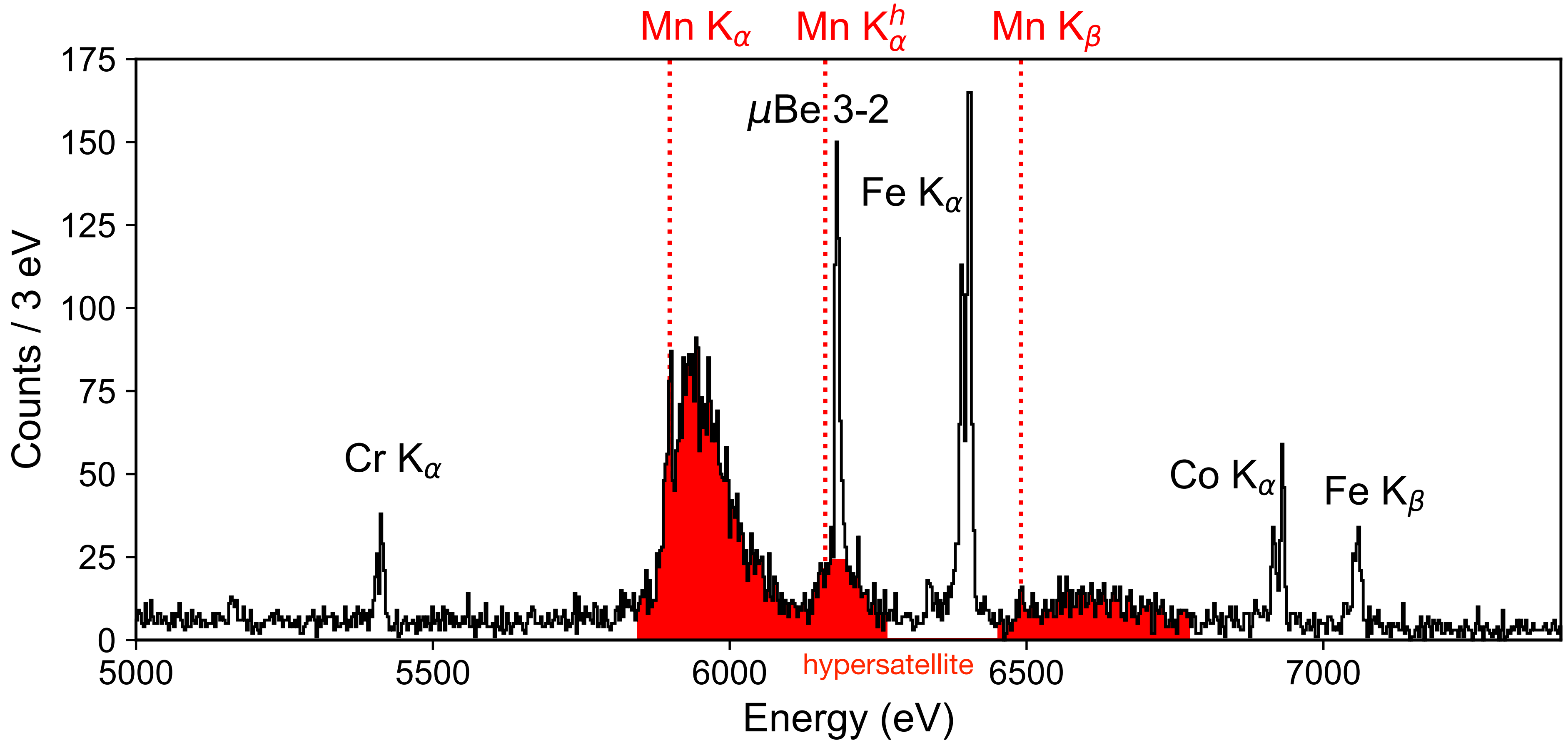
Structure is starting from **Mn line**?



Serendipity !

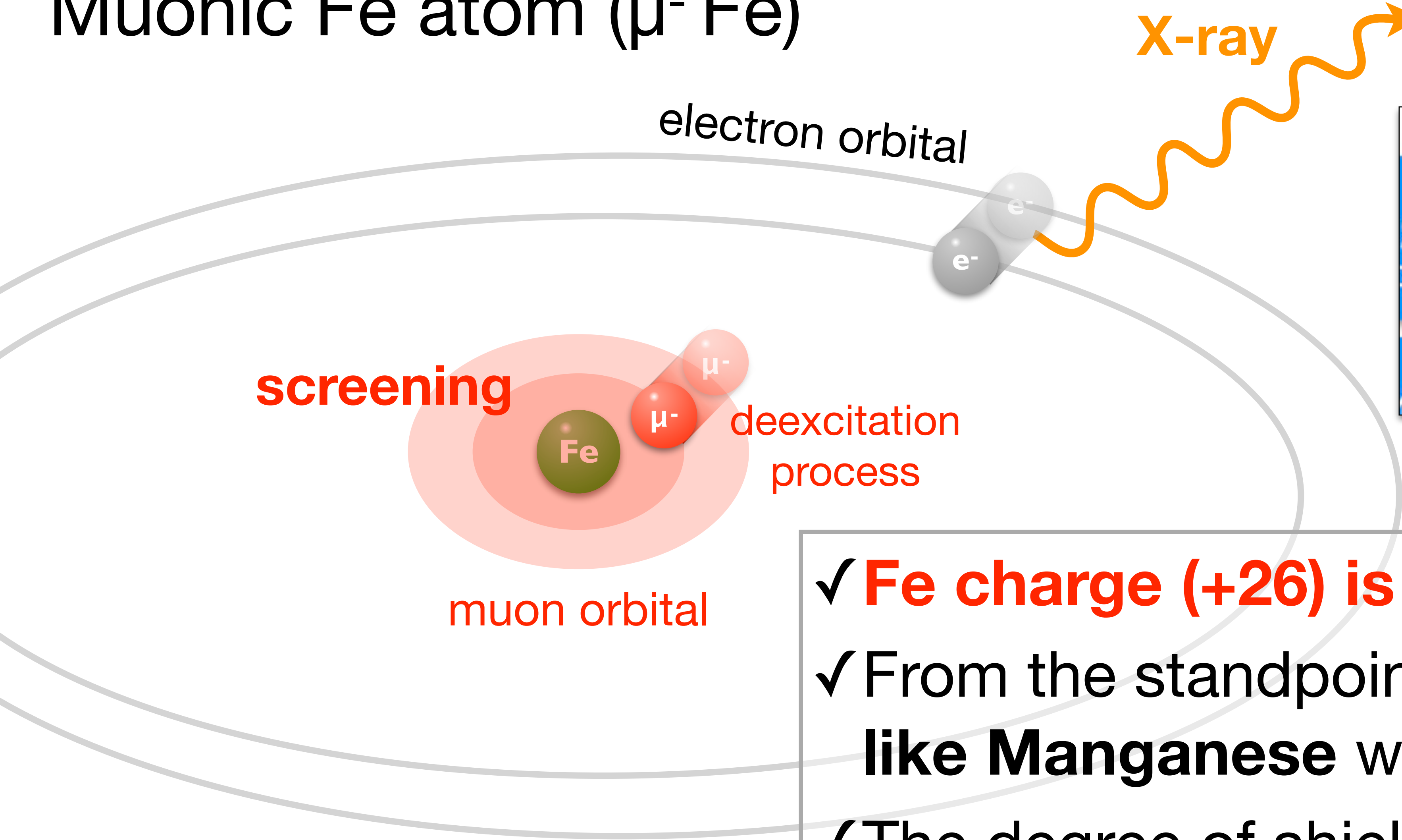
Thanks to the high-resolution detector,
this structure could be observed.



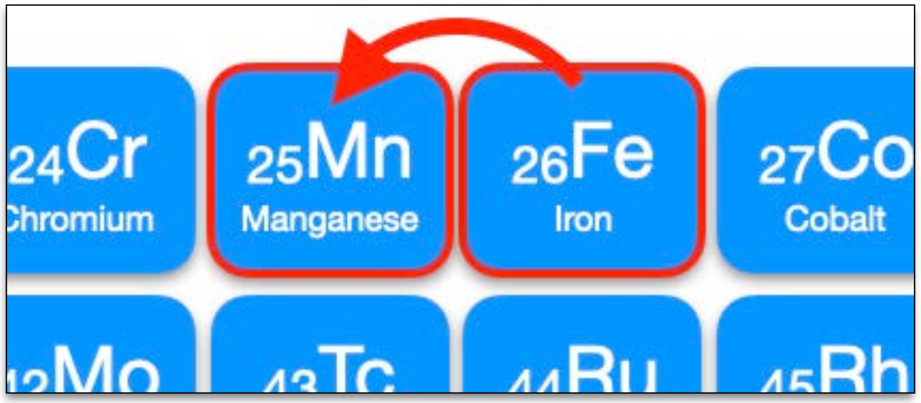


Fe behaves like Mn with a charge of -1

Muonic Fe atom (μ^- Fe)



Periodic table



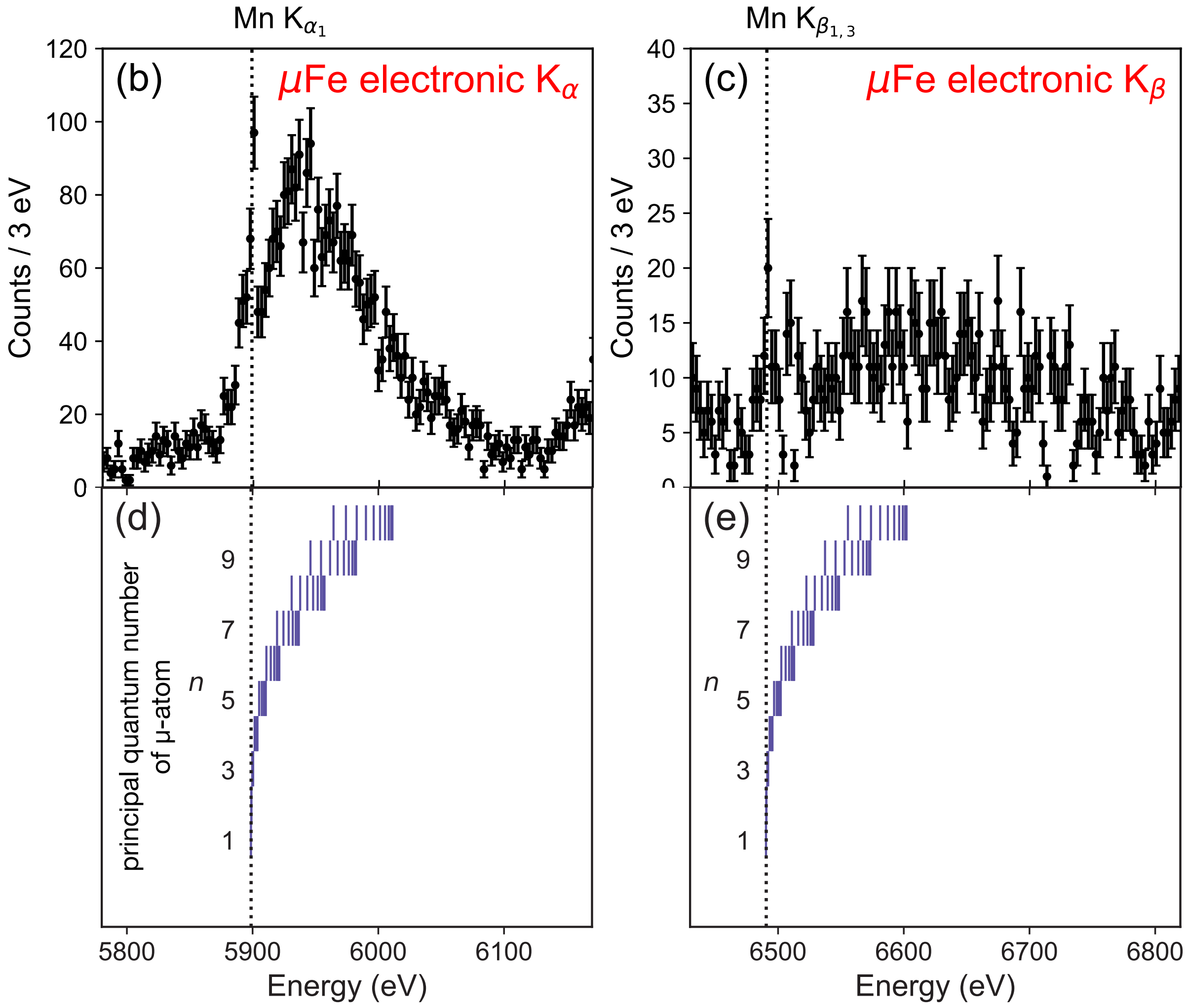
✓**Fe charge (+26) is shielded by μ^- (-1)**

✓From the standpoint of an electron, it looks **like Manganese** with atomic number **+25**.

✓The degree of shielding changes during the deexcitation of muon atoms

✓This precise spectroscopy of electron X-ray energy captured the whole picture of muon's atomic formation process.

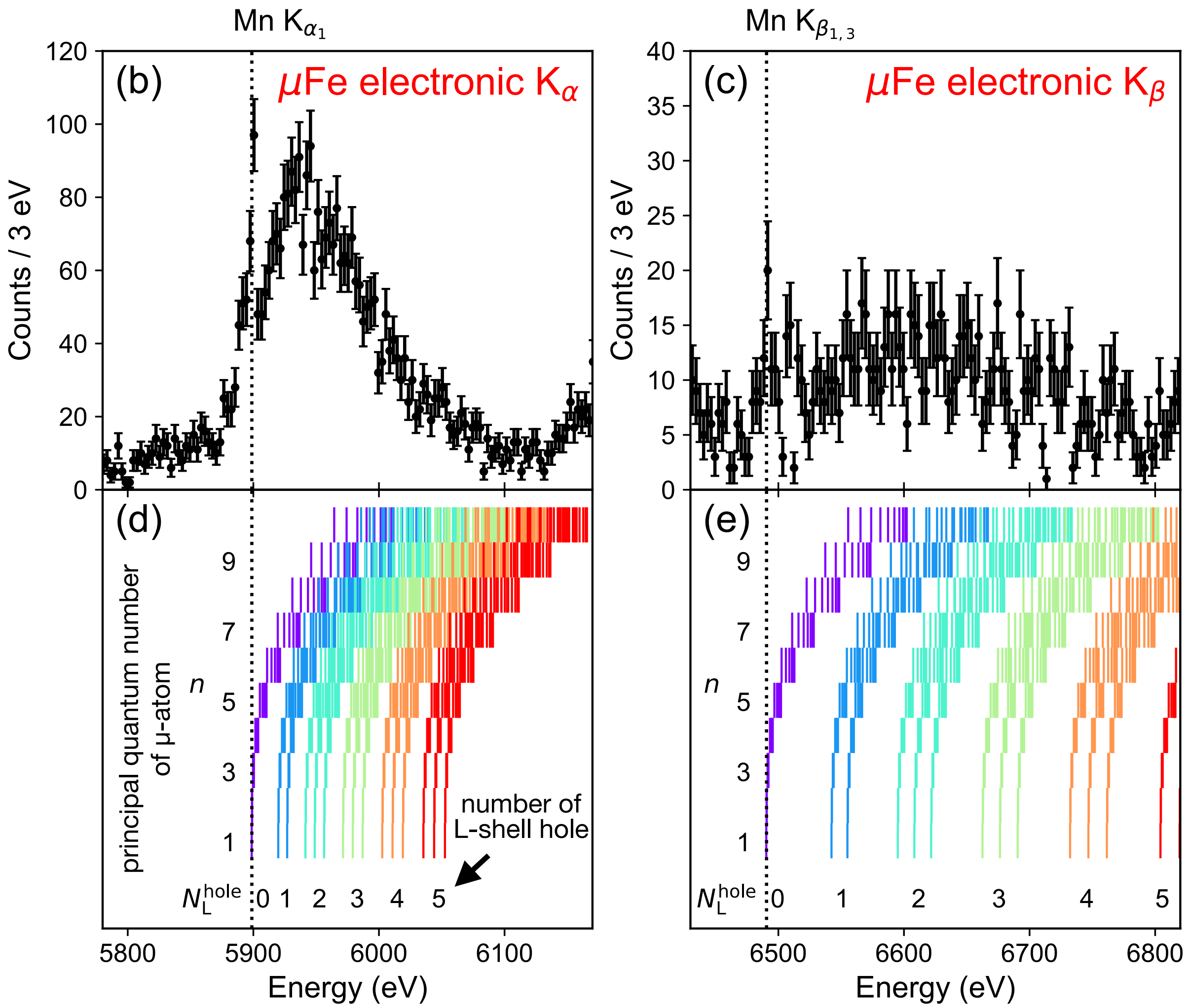
Results (PRL 127(2021) 053001)



X-ray energy changes depending on:

1. Shielding effect by muons (-> principal quantum number of μFe)

Results (PRL 127(2021) 053001)

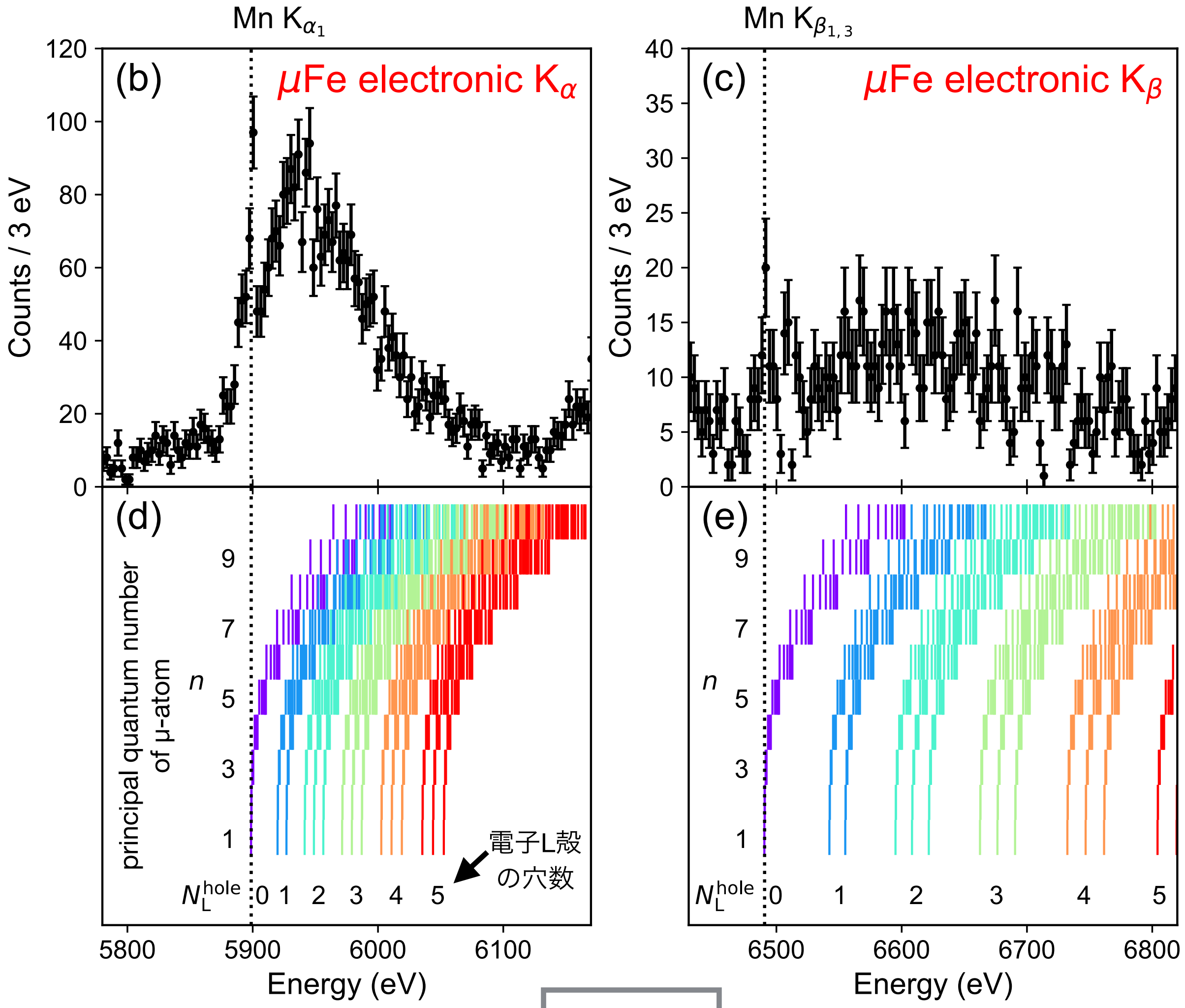


X-ray energy changes depending on:

1. Shielding effect by muons
   (-> principal quantum number of μFe)

2. Electron configuration
   (-> number of L-shell hole)

Results (PRL 127(2021) 053001)



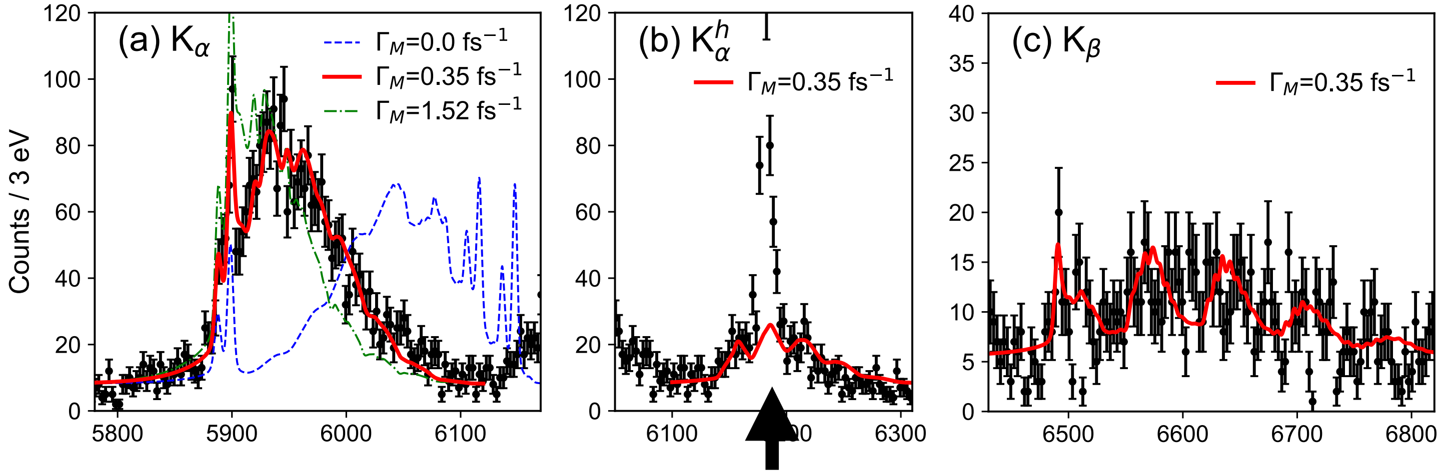
X-ray energy changes depending on:

1. Shielding effect by muons (-> principal quantum number of μFe)
2. Electron configuration (-> number of L-shell hole)

Cascade calculation reproduces spectrum

with ONLY one fit parameter, Γ_M

(Speed of side-feeding of electrons from the metal band to the M shell)



also reproduces "**hyper-satellite** x-ray"
from the double K-hole state

6. Summary

Summary & Outlook

◉ Muonic atom is an ideal probe to explore QED under extremely strong electric fields

◉ Introduced TES microcalorimeters

◉ Successfully conducted muonic Ne X-ray measurement with 0.1 atm gas target under an intense pulsed muon beam

◉Towards further measurements of higher atomic number Z (having a larger contribution of QED effect), a new TES spectrometer having the energy range of < 50 keV and < 130 keV is developing.

◉ [Serendipity] fortunately observed dynamics of the muon atom formation process for the first time