IWASK2024 (**I**nterdisciplinary **W**orkshop for **A**dvanced **S**cience of **K**aon and related topics) @ RIKEN

March 5, 2024

Exotic-atom experiments pioneered by cryogenic detectors

（極低温検出器で拓くエキゾチック原子の物理）

Shinji OKADA (Chubu Univ.)

a project to apply TES
to accelerator experiments

自己紹介

岩崎研
13 年

氏名　：岡田 信二（オカダ シンジ）
現所属：中部大学 理工学部 数理・物理サイエンス学科
ミュオン理工学研究センター

1999 2000 2001 2002 2003	東京工業大学	修士・博士課程 **東工大岩崎研** (ほとんどKEKで過ごす)	**ハイパー核研究** @ KEK
2004 2005 2006 2007	理化学研究所	基礎科学特別研究員 ＋協力研究員 **(岩崎先端中間子研)**	**エキゾチック原子研究** (K中間子ヘリウム) @ KEK ー KEK 陽子シンクロトロン(PS) 最後の実験
2008 2009 2010 2011	イタリア国立 核物理研究機構 フラスカティ研究所	Postdoc Fellow for non-Italian citizens	**エキゾチック原子研究** (K中間子水素) @ イタリアINFN-LNF (e^+ e^- 衝突型加速器 DAΦNE)
2012 2013 2014 2015	理化学研究所	協力研究員 **(岩崎先端中間子研)**	**ミュオン研究** (muon g-2) @ 英国RAL, カナダTRIUMF **次世代エキゾチック原子超精密分光** @ スイスPSI, J-PARC
2016 2017 2018 2019	理化学研究所	協力研究員 (東原子分子物理研)	**超伝導検出器を用いた原子物理研究** @ J-PARC (ミュオン), RIKEN RICE (東研), SPring-8
2020 2021 2022 2023	中部大学	准教授 教授	**ミュオン触媒核融合研究** @ 中部大学, J-PARC

ハドロン

ミュオン

HEATES project

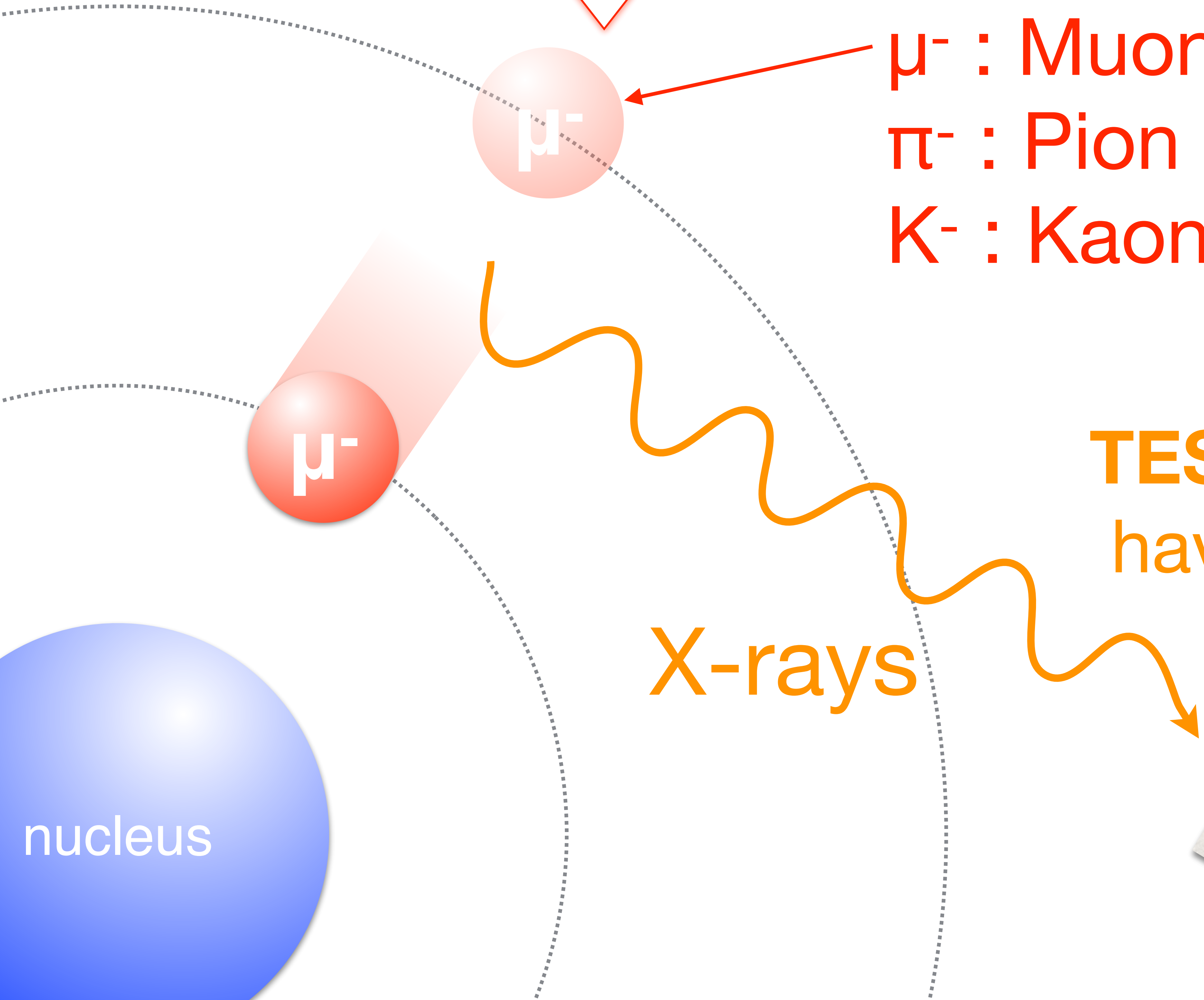
||

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

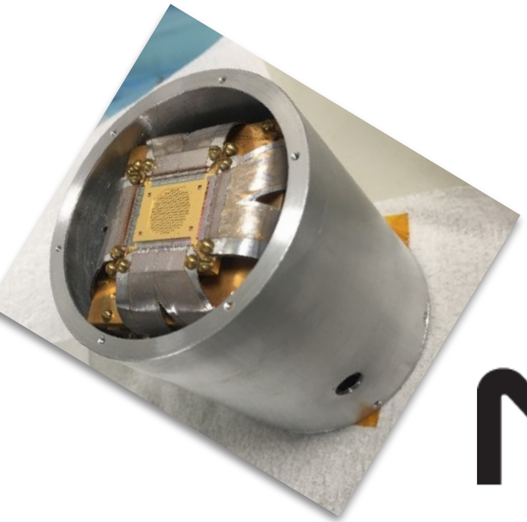
negative charged

μ⁻ : Muon
π⁻ : Pion
K⁻ : Kaon …

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

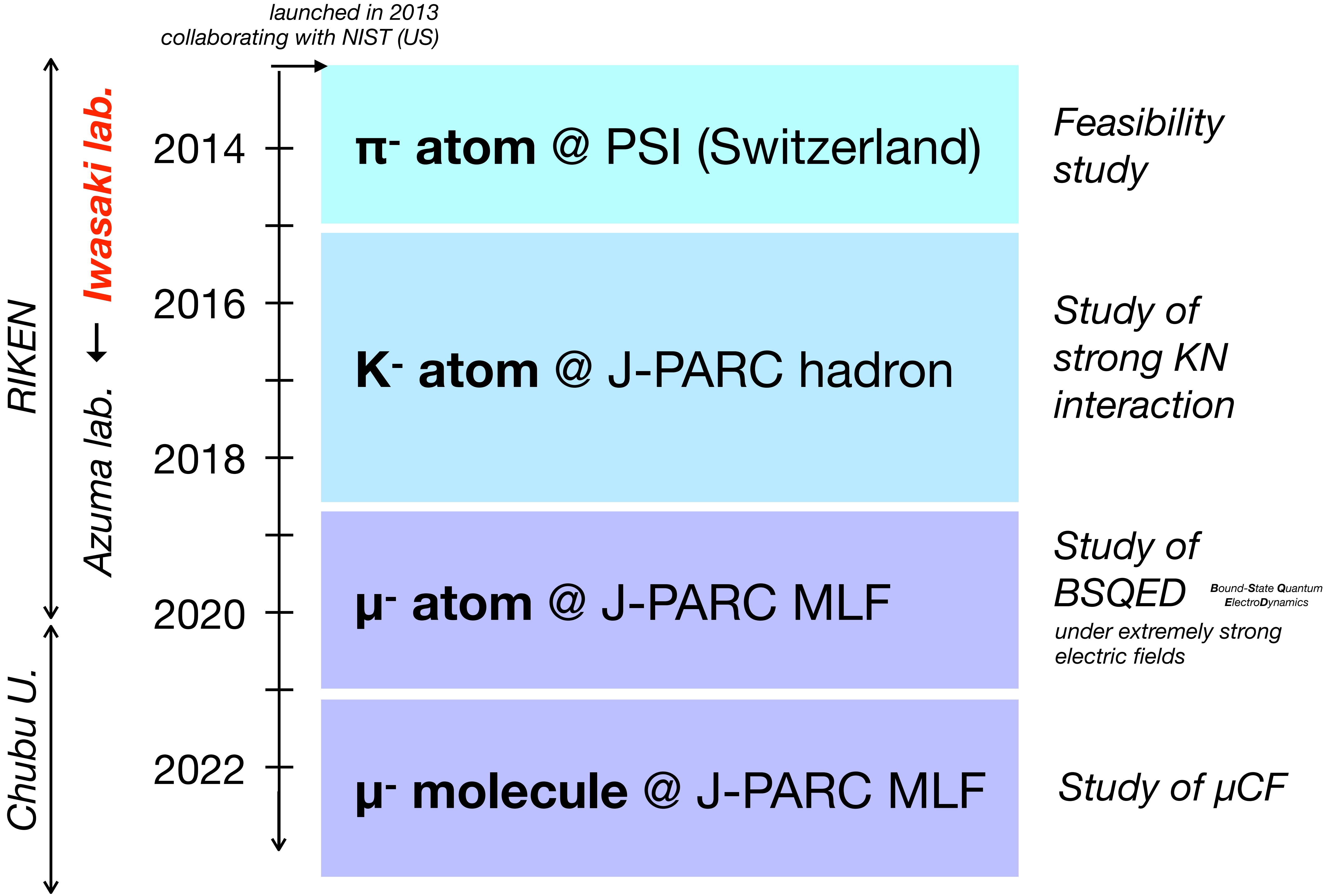


TES microcalorimeter
having high resolution



NIST

History



launched in 2013
collaborating with NIST (US)

RIKEN

Azuma lab. → ***Iwasaki lab.***

Chubu U.

2014

2016

2018

2020

2022

π^- atom @ PSI (Switzerland)

Feasibility study

K^- atom @ J-PARC hadron

Study of strong KN interaction

μ^- atom @ J-PARC MLF

Study of BSQED ***B****ound-****S****tate* ***Q****uantum* ***E****lectro****D****ynamics*

under extremely strong electric fields

μ^- molecule @ J-PARC MLF

Study of μCF

Results

3 publications & a new measurement

(a)	Kaonic atom	Phys. Rev. Lett. 128, 112503 (2022).	**a single sharp X-ray peak** (absolute energy)
(b)	Muonic atom	Phys. Rev. Lett. 130, 173001 (2023).	
(c)	Muonic atom *~Serendipity~*	Phys. Rev. Lett. 127, 053001 (2021).	**a broad structure** (complex of many X-ray lines)
(d)	Muonic molecule	New experiment *(to be published)*	

Results

3 publications & a new measurement

(a)	Kaonic atom	Phys. Rev. Lett. 128, 112503 (2022).	**a single sharp X-ray peak** (absolute energy)
(b)	Muo atom	Phys. Rev. Lett. 130, 173001 (2023).	
(c)	Mu atom *~Se ipity~*	Phys. Rev. Lett. 127, 053001 (2021).	**a broad structure** (complex of many X-ray lines)
(d)	Muonic molecule	New experiment *(to be published)*	

Kaon → μCF !

Contents

1. Exotic atoms

2. What’s TES microcalorimeter

3. Experiments

    (3-1) Kaonic atom

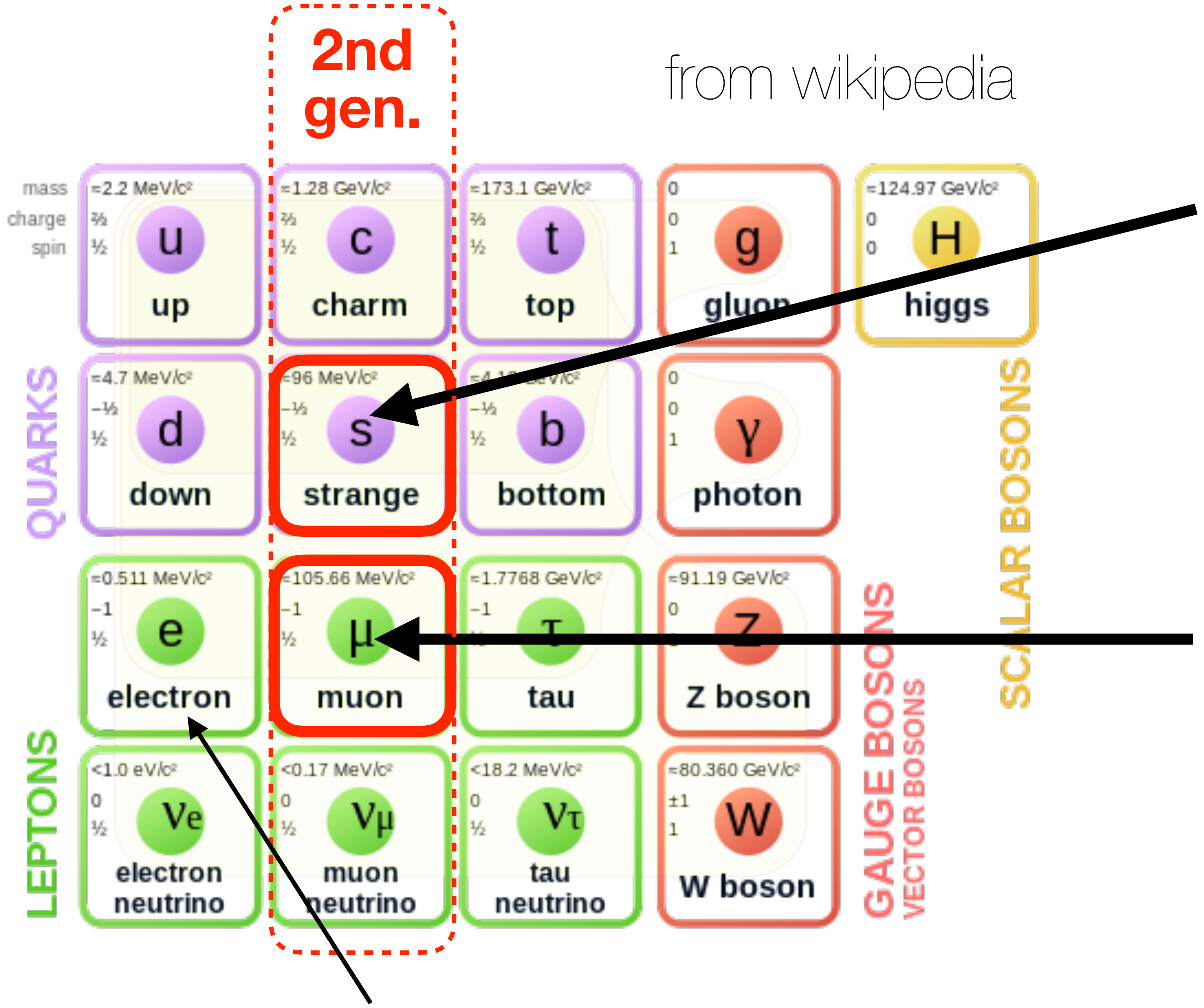
    (3-2) Muonic molecule

4. Summary & Outlook

1. Exotic atoms

Negatively-charged Kaon & Muon

having the **longest lifetimes** among the second-generation particles and composite particles in the Standard Model of particle physics.



from wikipedia

K^- (= s $\bar{u}$)

Lifetime ~ 12 nsec

Mass ~ 494 MeV

~ 1000 m_e

μ^-

Lifetime ~ 2.2 μsec

Mass ~ 106 MeV

~ 200 m_e

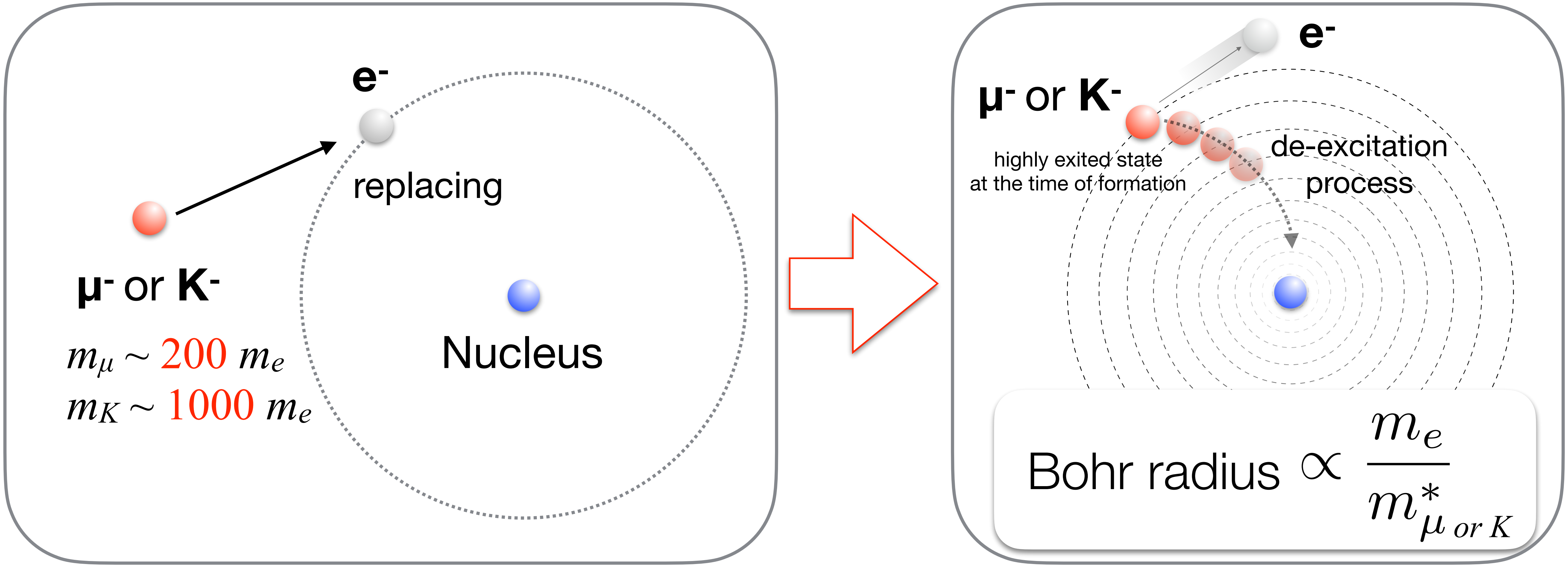
Electron mass : m_e ~ 0.511 MeV

What is exotic atom?

When a negative-charged particle is stopped in a material,
it can replace an electron to form a exotic atom

Normal atom

Exotic atom



$m_\mu \sim 200\ m_e$

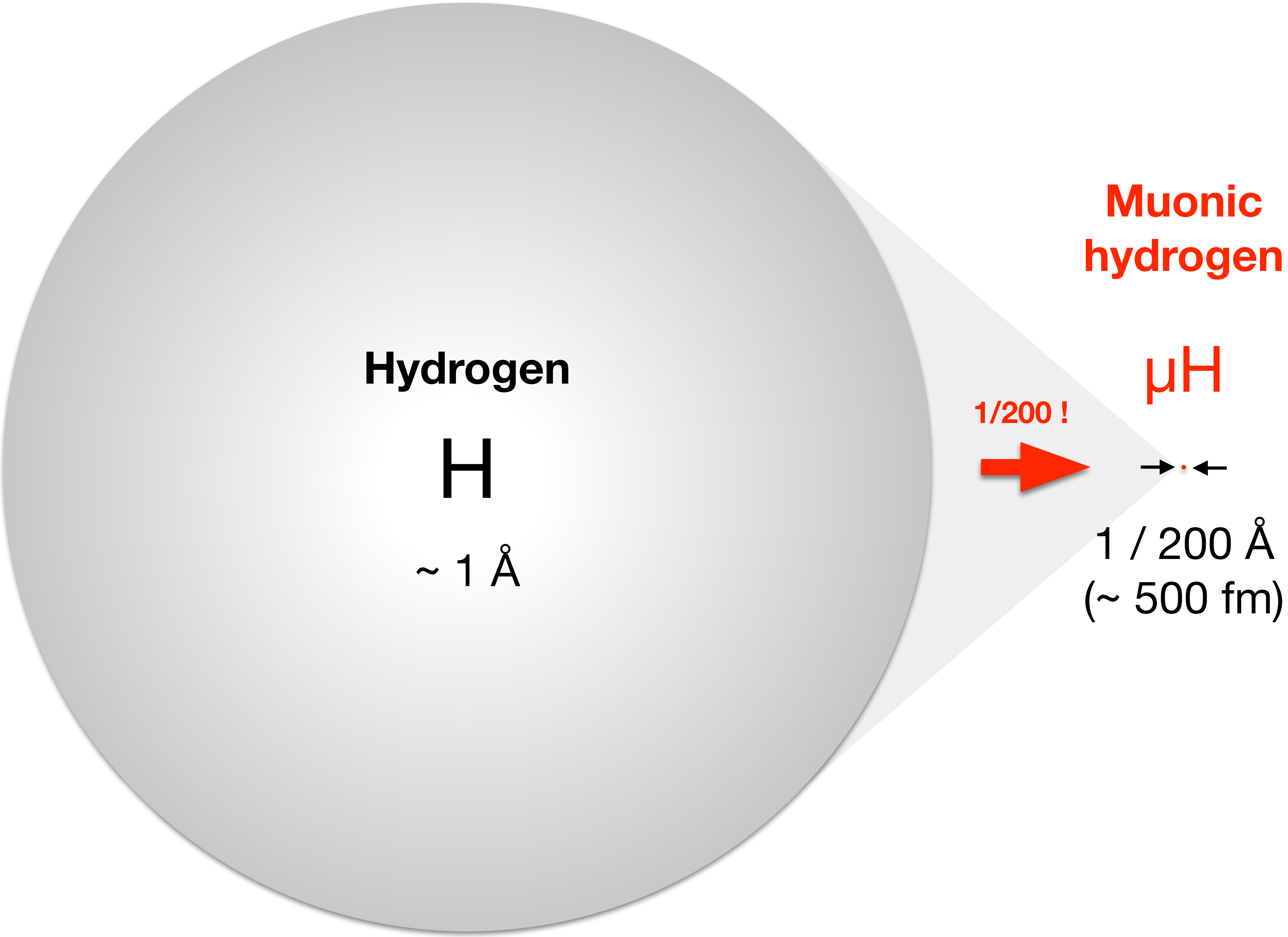
$m_K \sim 1000\ m_e$

$$\text{Bohr radius} \propto \frac{m_e}{m^*_{\mu\ or\ K}}$$

(inversely proportional to their reduced mass)

These radii are as small as **1/200 (μ- atom)** and **1/1000 (K- atom)** compared to the normal atoms.

Image of the scale



Hydrogen

H

~ 1 Å

1/200 !

Muonic hydrogen

μH

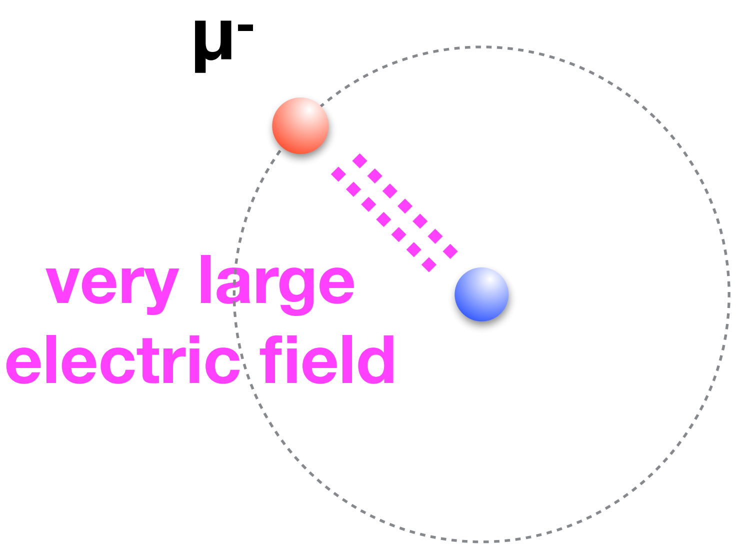
1 / 200 Å
(~ 500 fm)

Extremely close to the nucleus !

Bohr radius

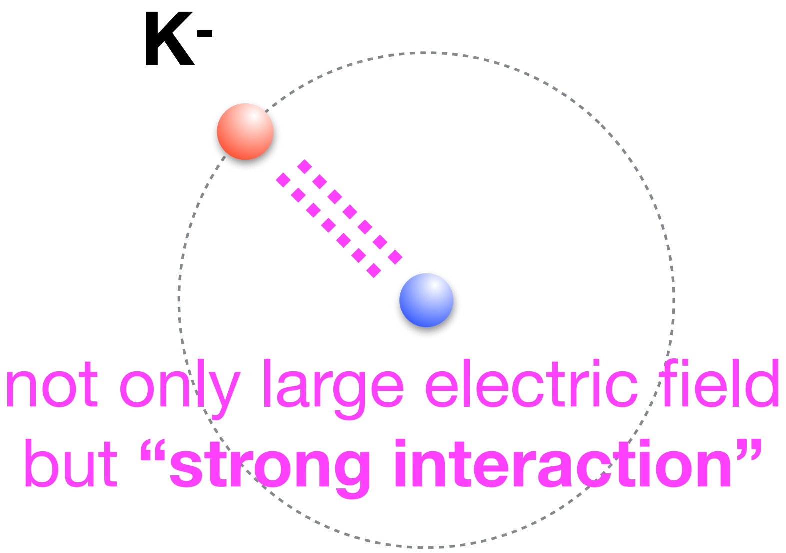
$R_\mu \sim$ **1/200** R_e (μ^- atom)

$R_K \sim$ **1/1000** R_e (K^- atom)



μ^-

very large electric field



K^-

not only large electric field but **“strong interaction”**

- ✓ μ^- feels an **extremely large electric field**
  - ➡ internal electric field strength is proportional to the squire of the mass ratio to atoms (→ being 200^2 (=40,000) times higher than that of normal H-like ions.)

Study of “**QED under strong field**”

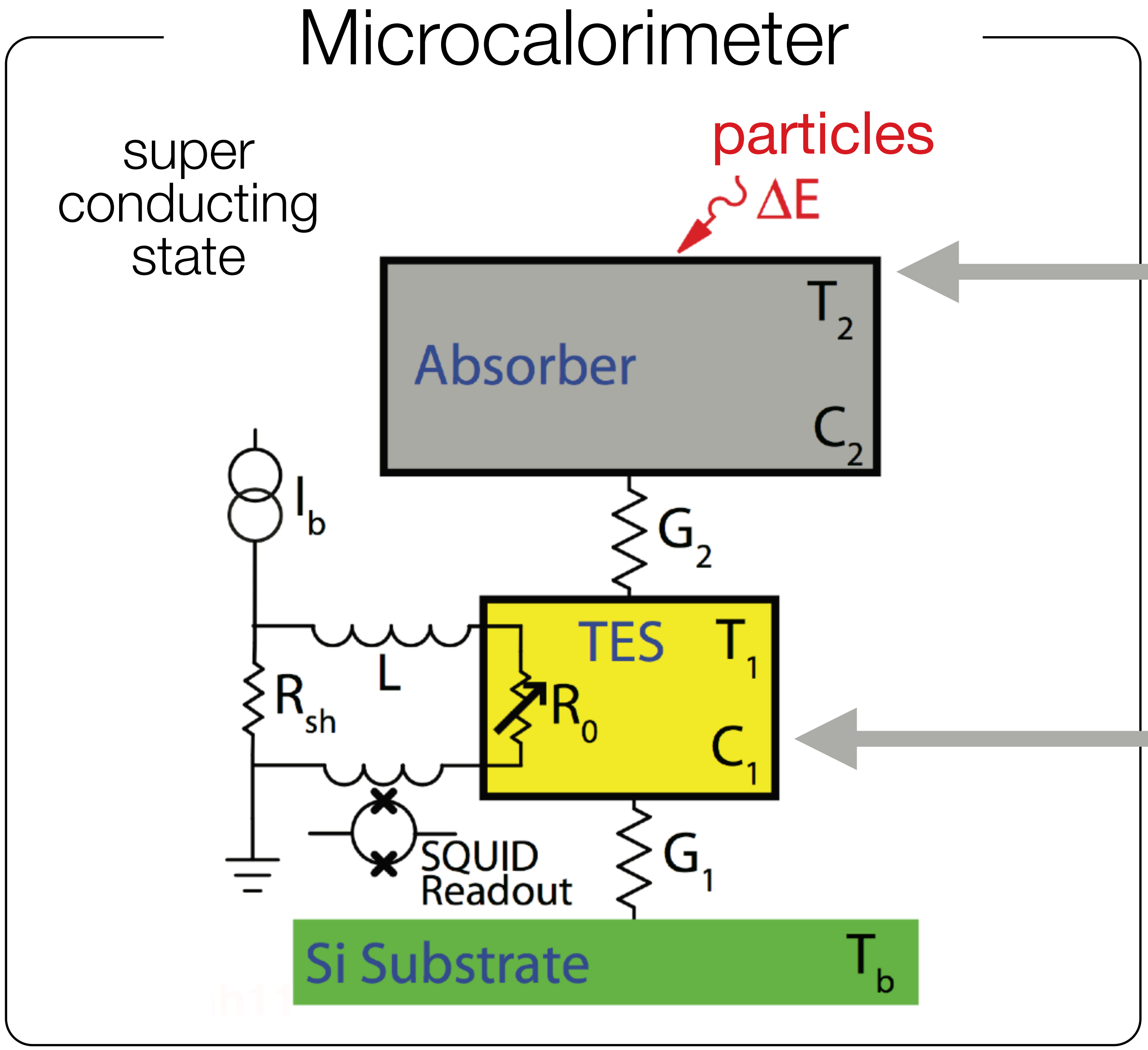
QED : Quantum ElectroDynamics

- ✓ Unlike μ^-, K^- feels an **"strong interactions"**.
  - ➡ The energy level of K- atoms shifts due to the strong interaction with the nucleus.

Study of “**Strong interaction**”

1. What’s TES

TES microcalorimeter



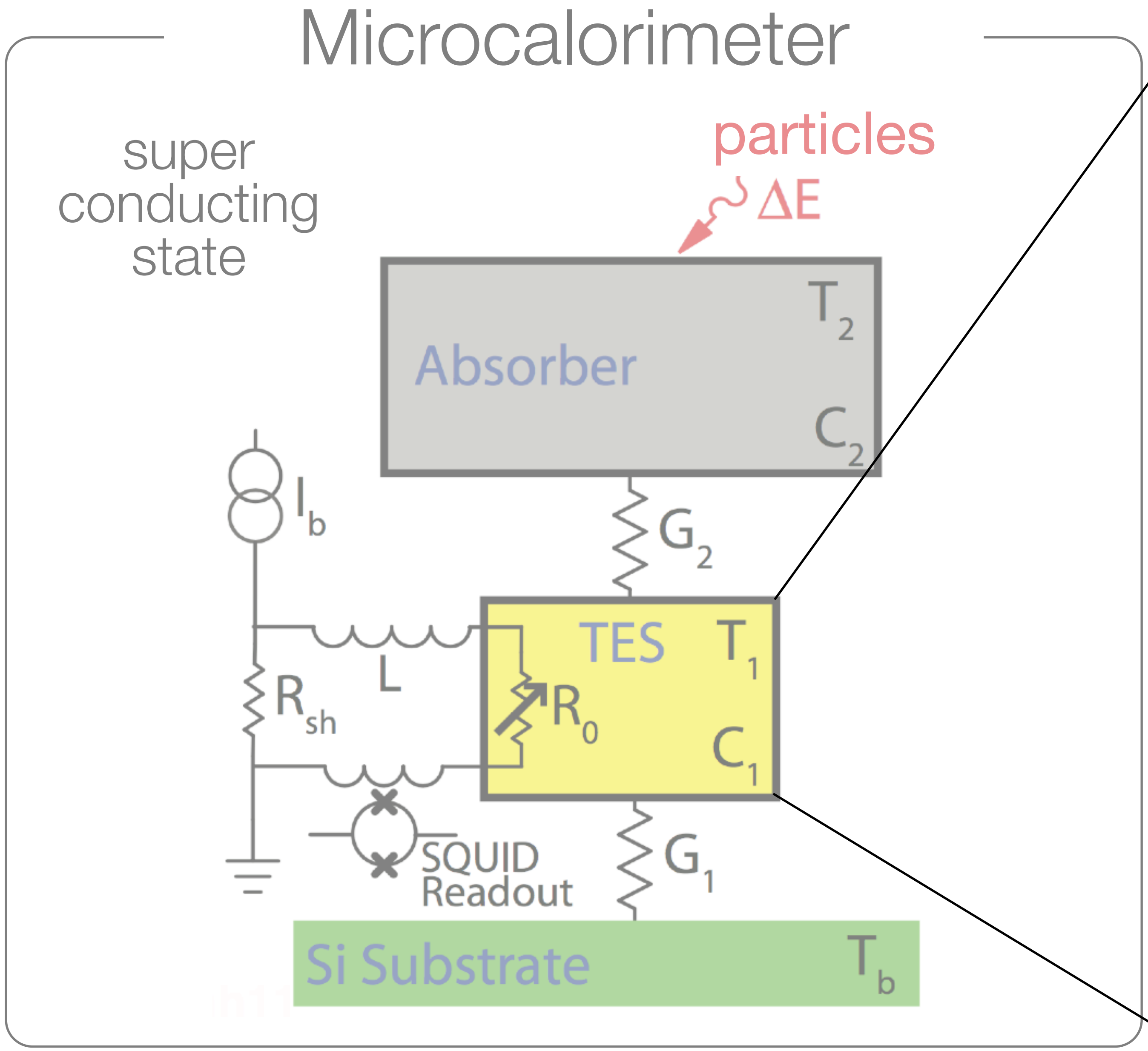
1. incident particles absorbed

2. Energy ΔE -> Phonon

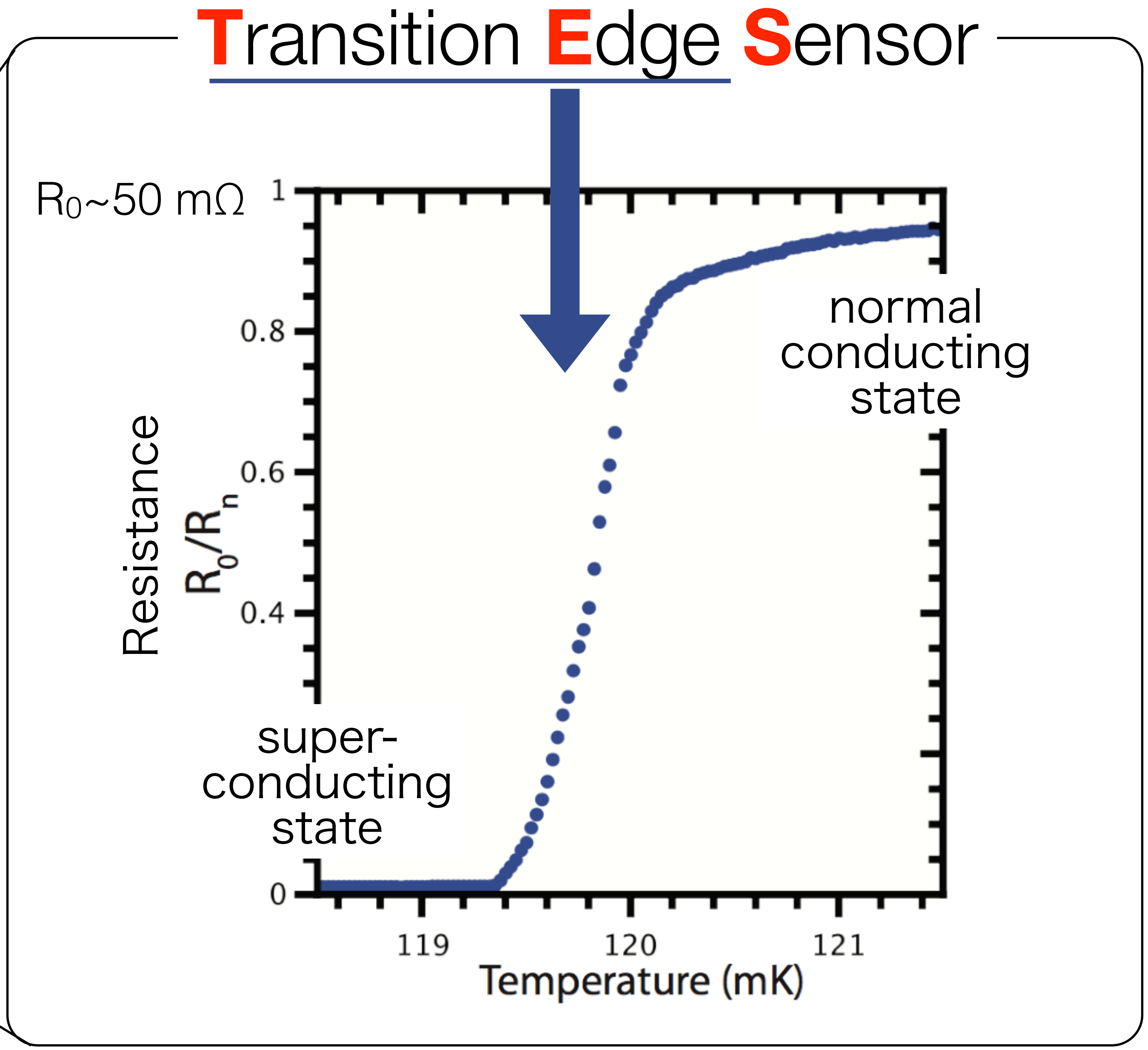
3. Tiny temperature rise is measured by a highly sensitive temperature sensor **TES**

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

TES microcalorimeter



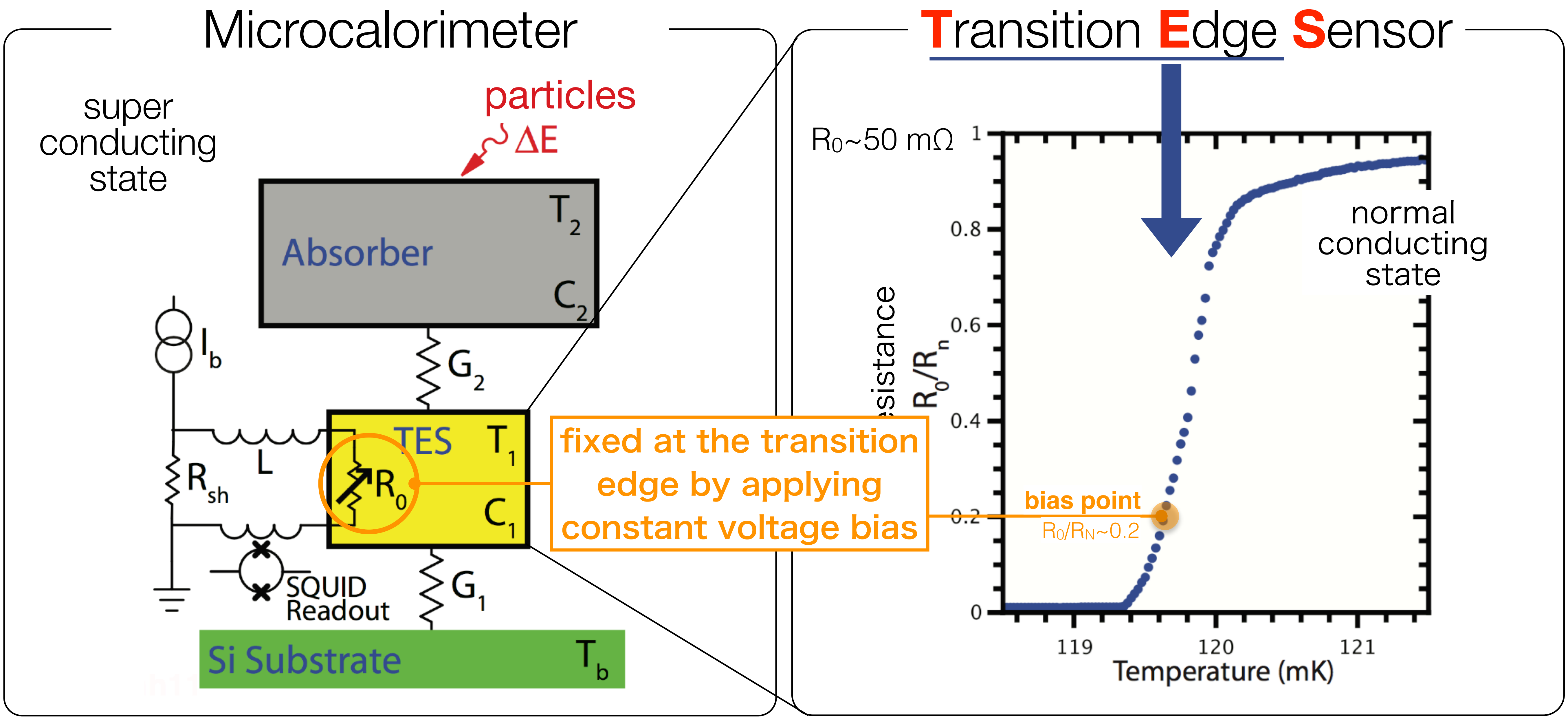
Microcalorimeter



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

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

TES microcalorimeter



Microcalorimeter

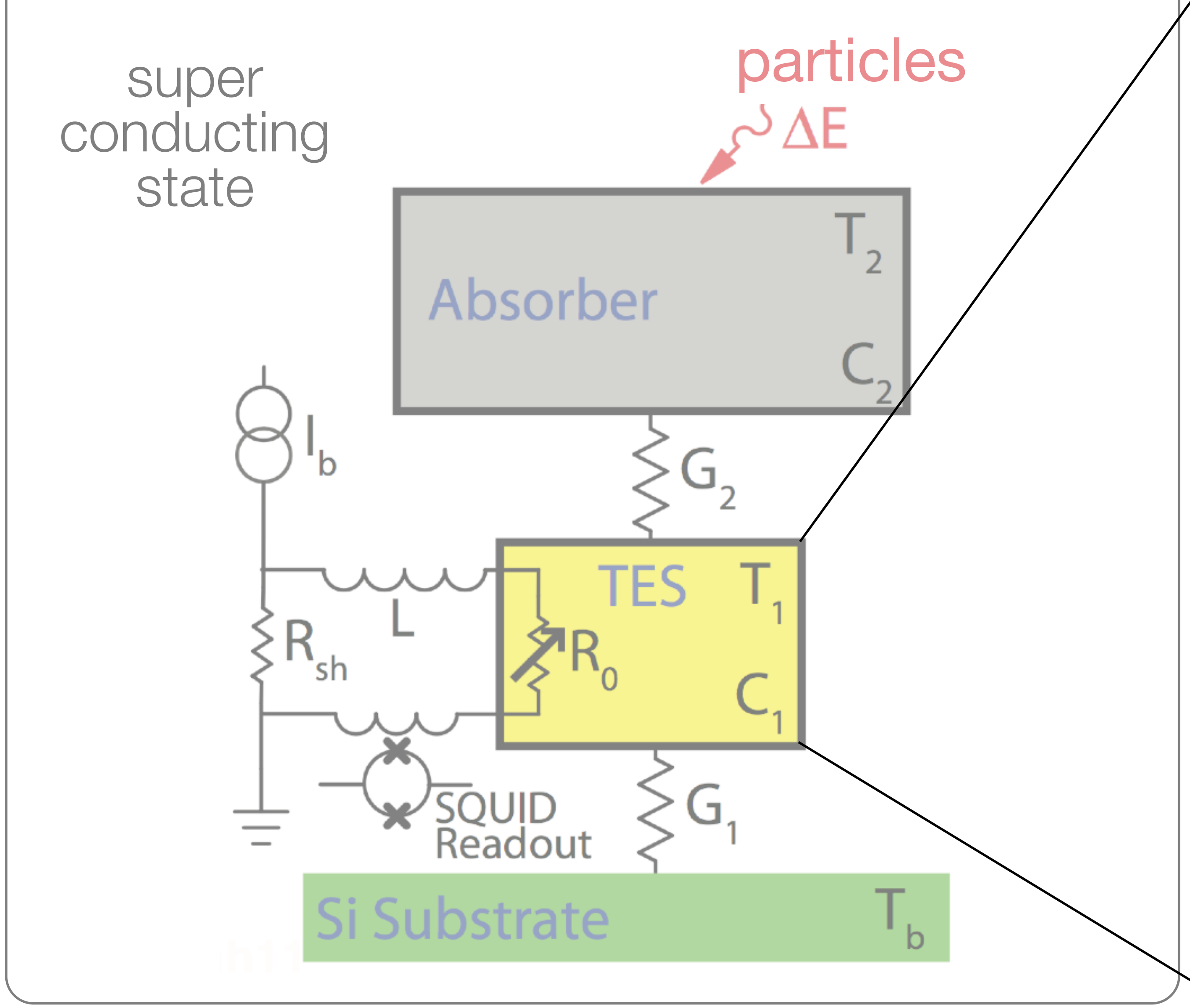
Transition **E**dge **S**ensor

fixed at the transition edge by applying constant voltage bias

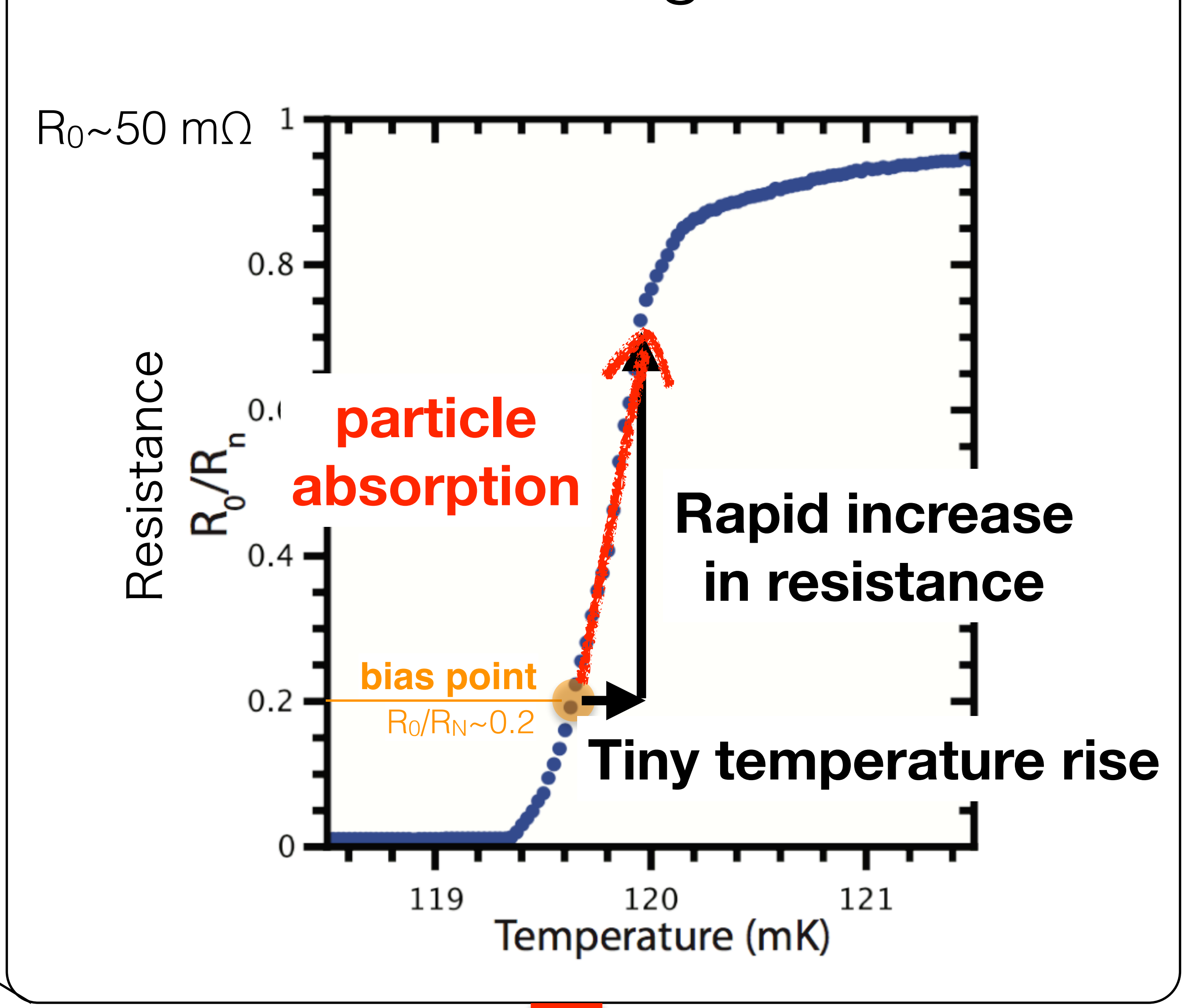
Reference : Bennet et al., Rev. Sci. Instrum. 83, 093113 (2012)

TES microcalorimeter

Microcalorimeter



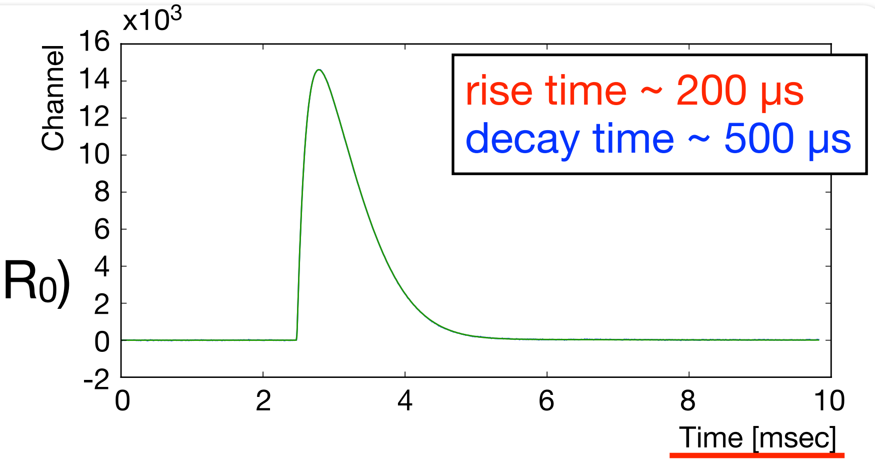
Transition Edge Sensor



Typical pulse

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

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



high energy resolution ($\Delta E / E \sim 10^{-3}$)

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)

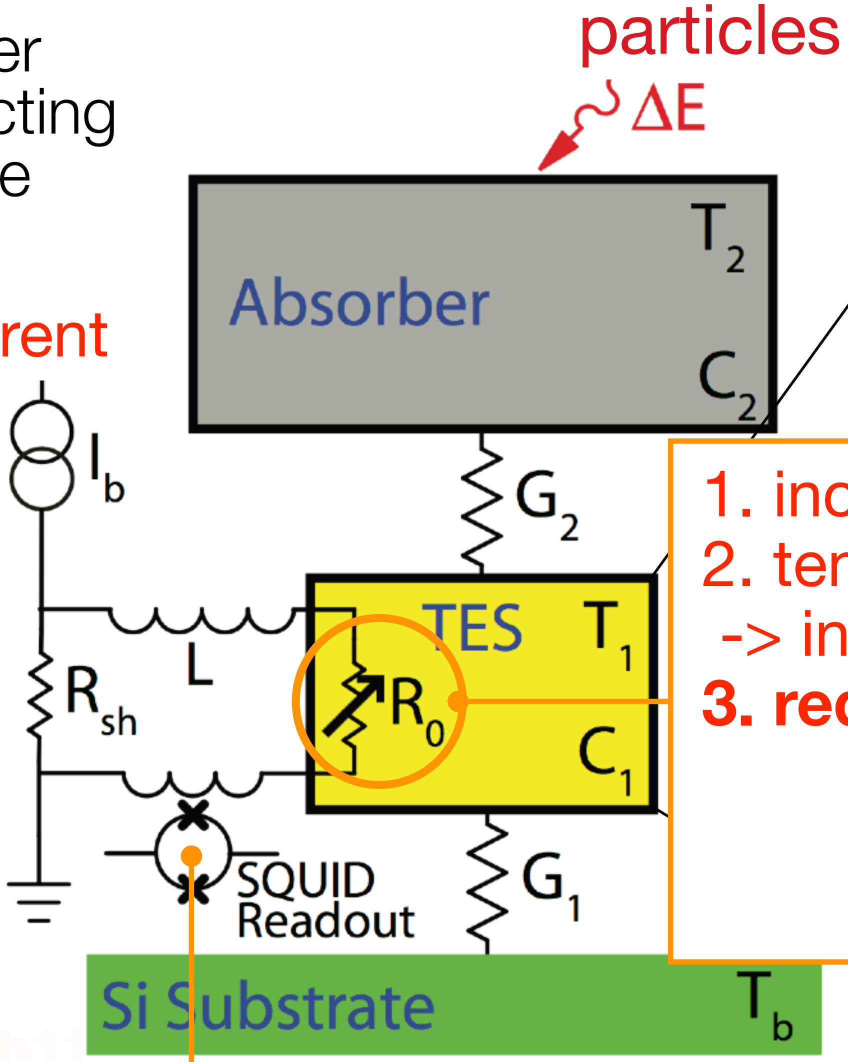
TES microcalorimeter

Microcalorimeter

super conducting state

bias current

constant bias

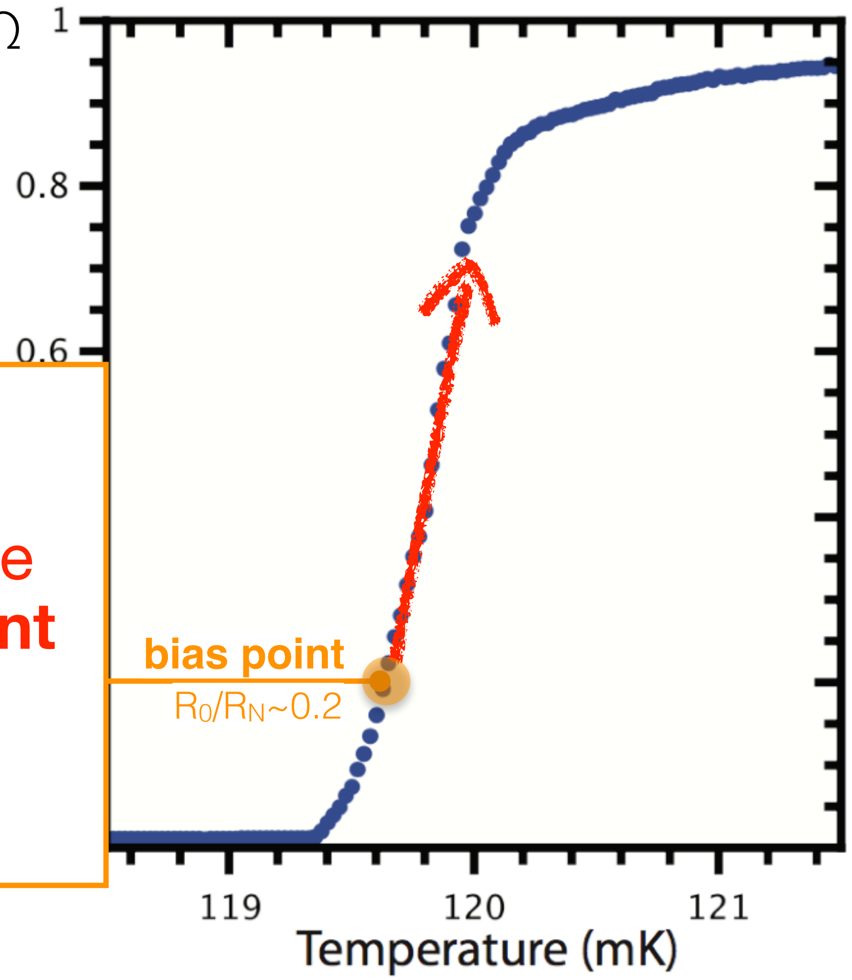


1. incoming radiation
2. temperature rise
 -> increasing resistance
3. **reducing bias current**

Read reduction of bias current using SQUID

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

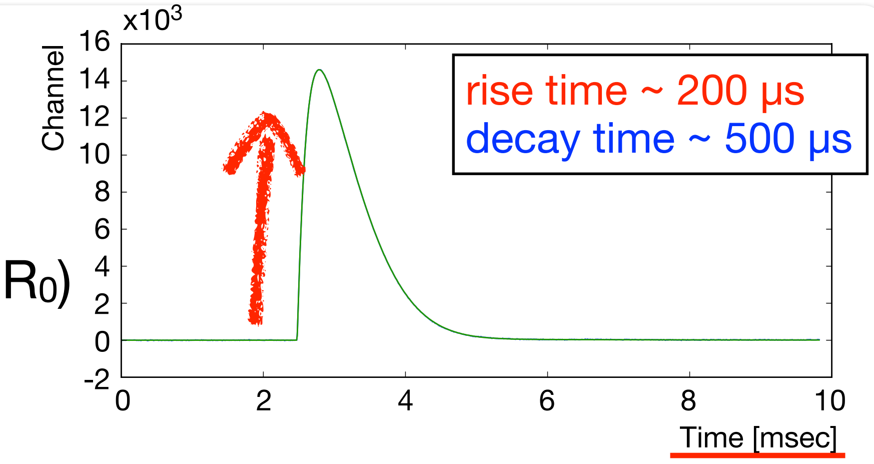
R_0~50 mΩ



Typical pulse

τ_{rise}~$L/(R_{sh}+R_0)$

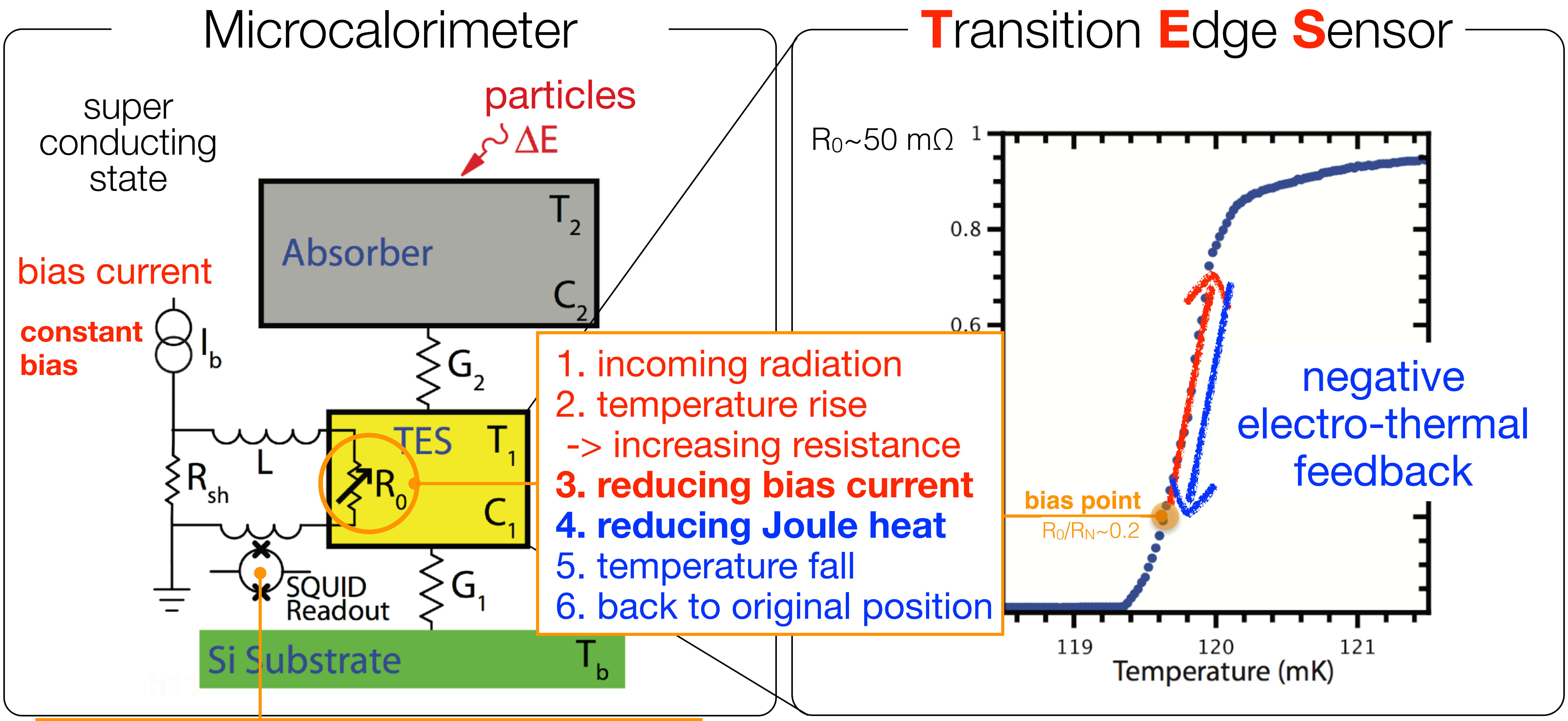
τ_{fall}~C/G



rise time ~ 200 μs

decay time ~ 500 μs

TES microcalorimeter



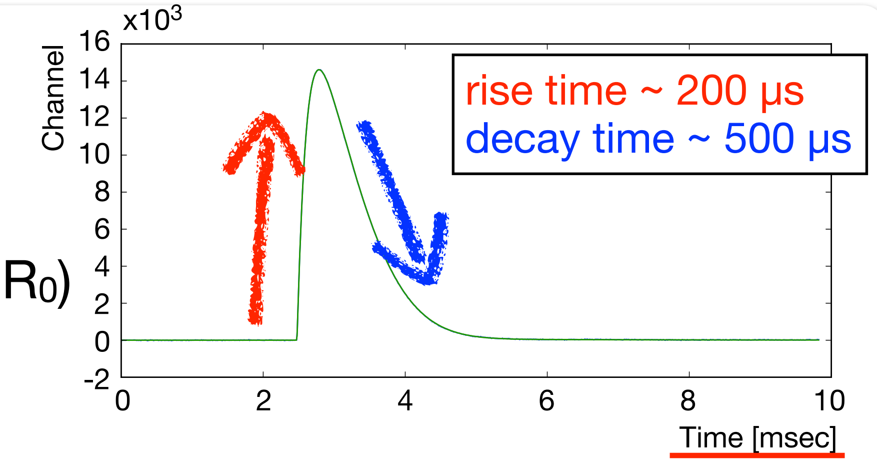
1. incoming radiation
2. temperature rise
   -> increasing resistance
3. **reducing bias current**
4. **reducing Joule heat**
5. temperature fall
6. back to original position

Read reduction of bias current using SQUID

Typical pulse

τ_{rise}~$L/(R_{sh}+R_0)$

τ_{fall}~C/G

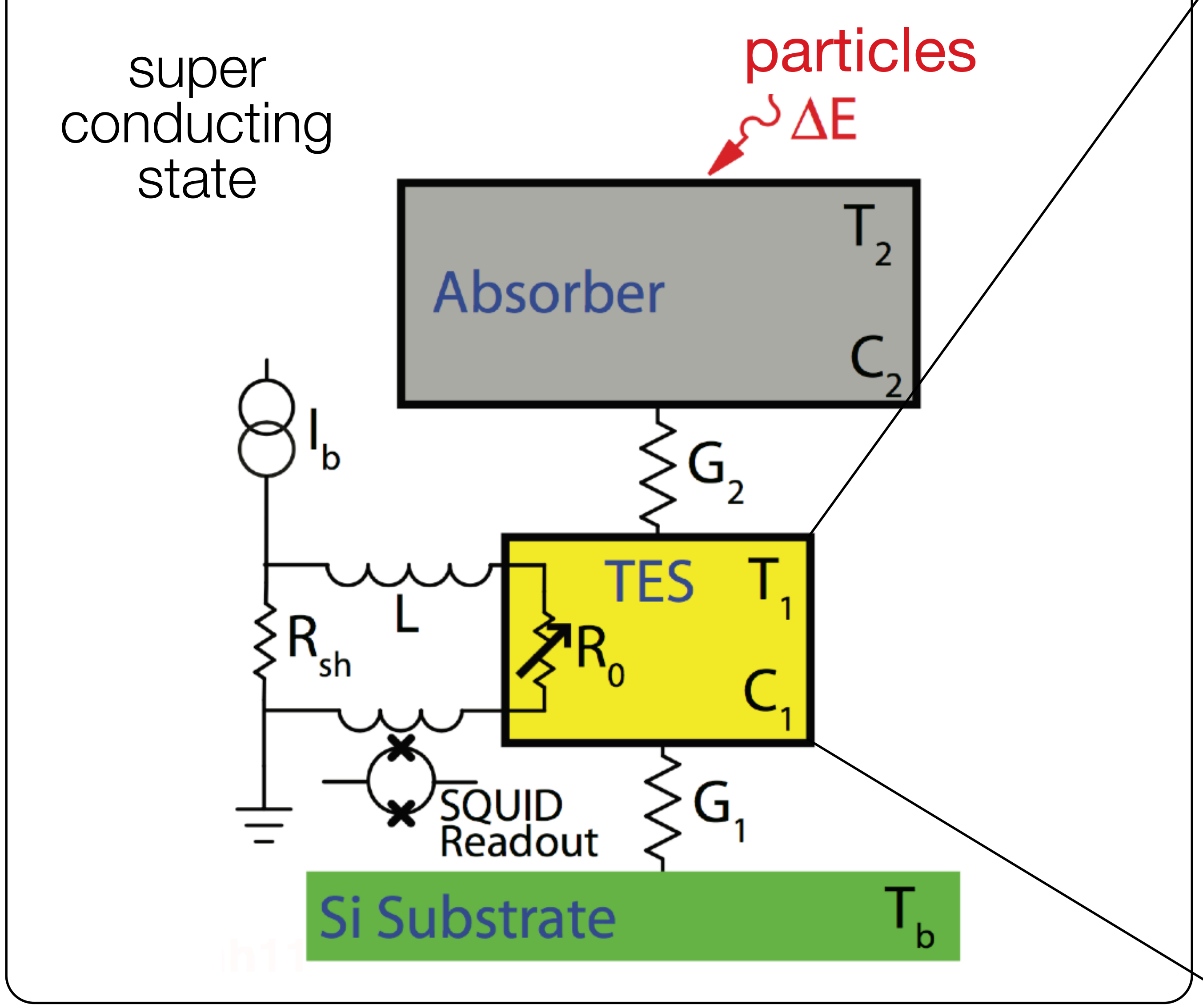


rise time ~ 200 μs

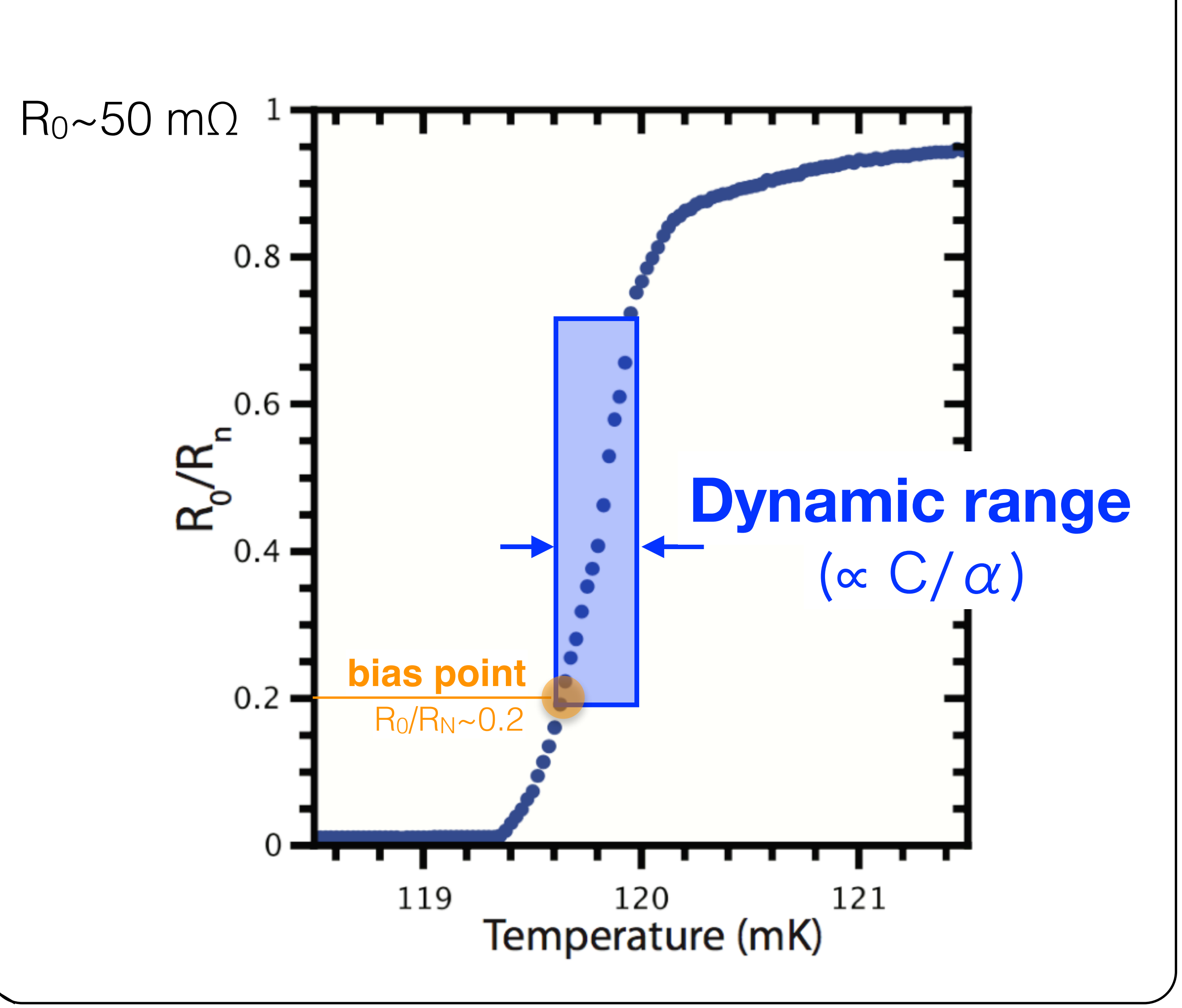
decay time ~ 500 μs

TES microcalorimeter

Microcalorimeter



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



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

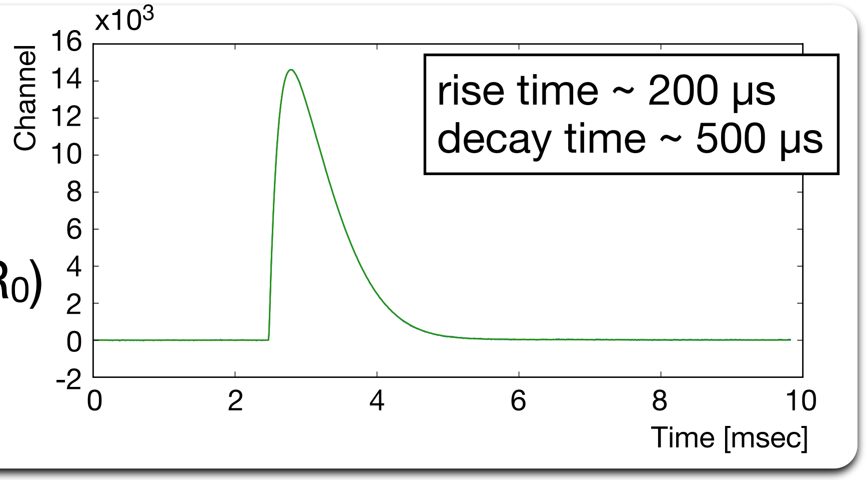
Energy resolution : $\Delta E \propto \sqrt{T_c^2 C/\alpha_I}$

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

Typical pulse

τ_{rise}~$L/(R_{sh}+R_0)$

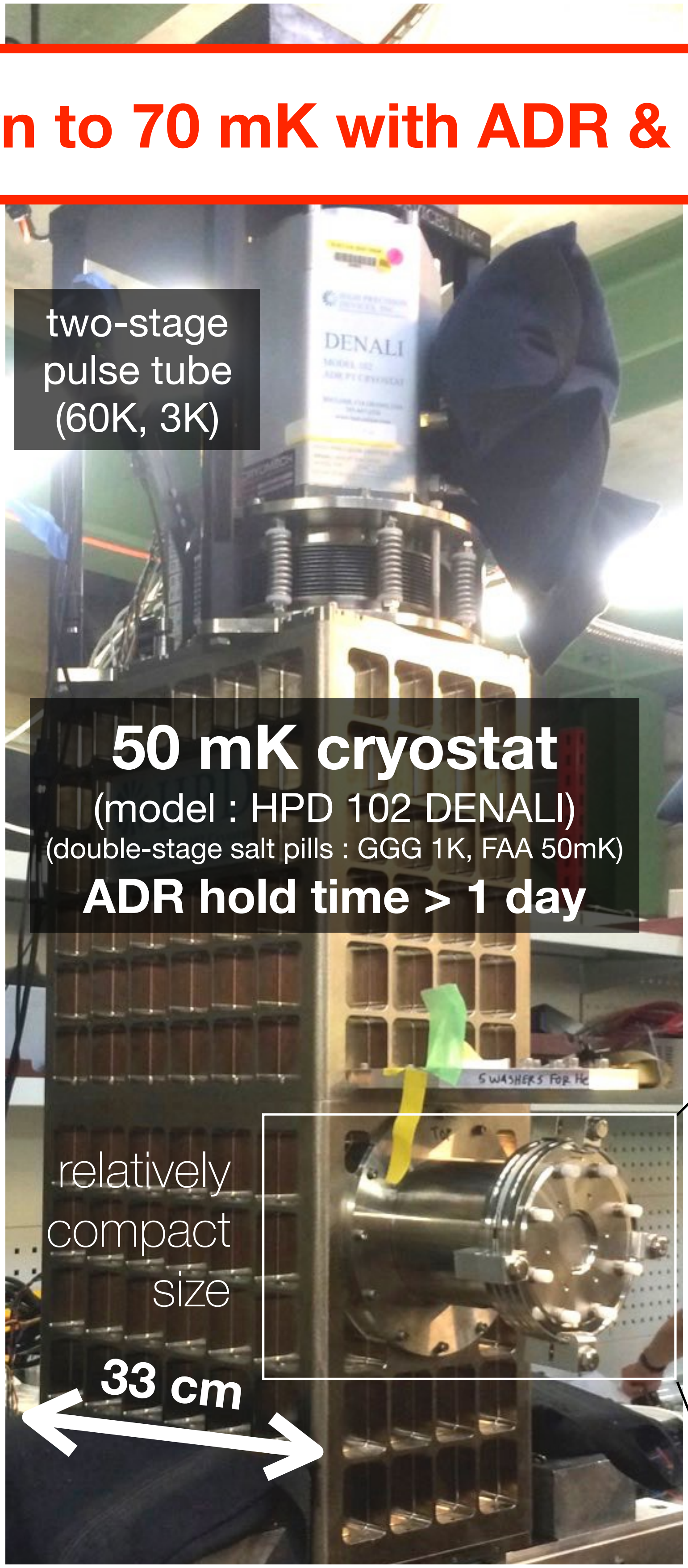
τ_{fall}~C/G



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

33 cm

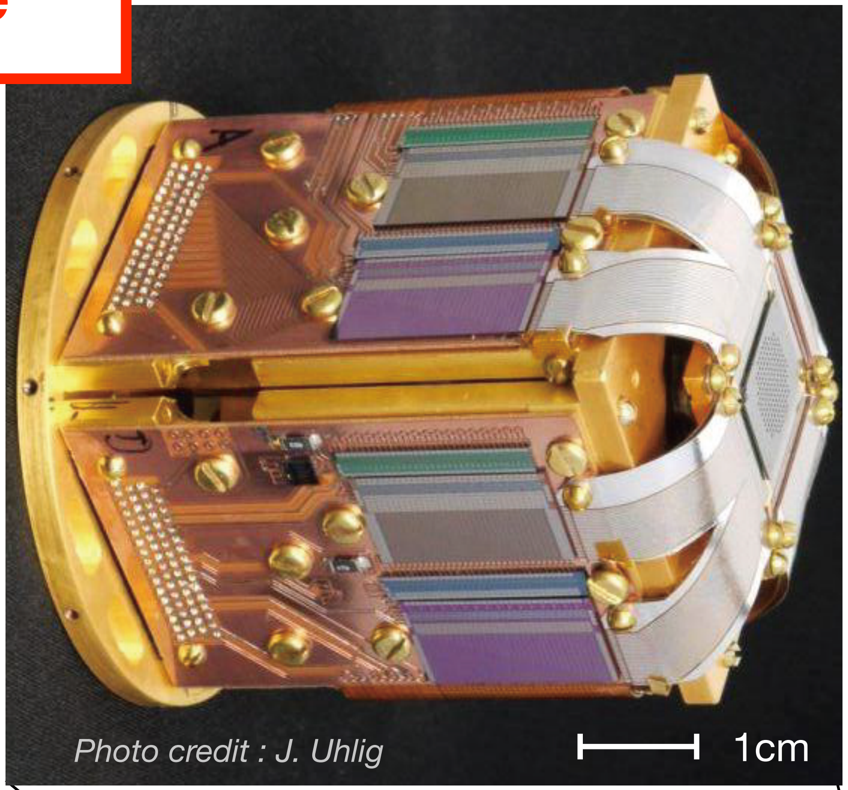
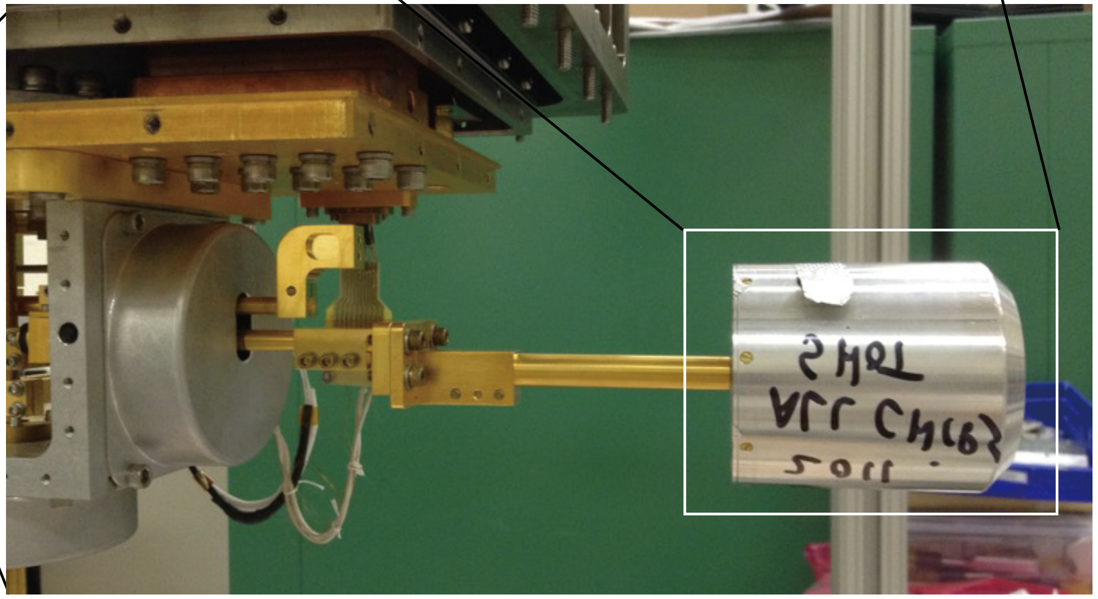


Photo credit : J. Uhlig

TES chip



TES array

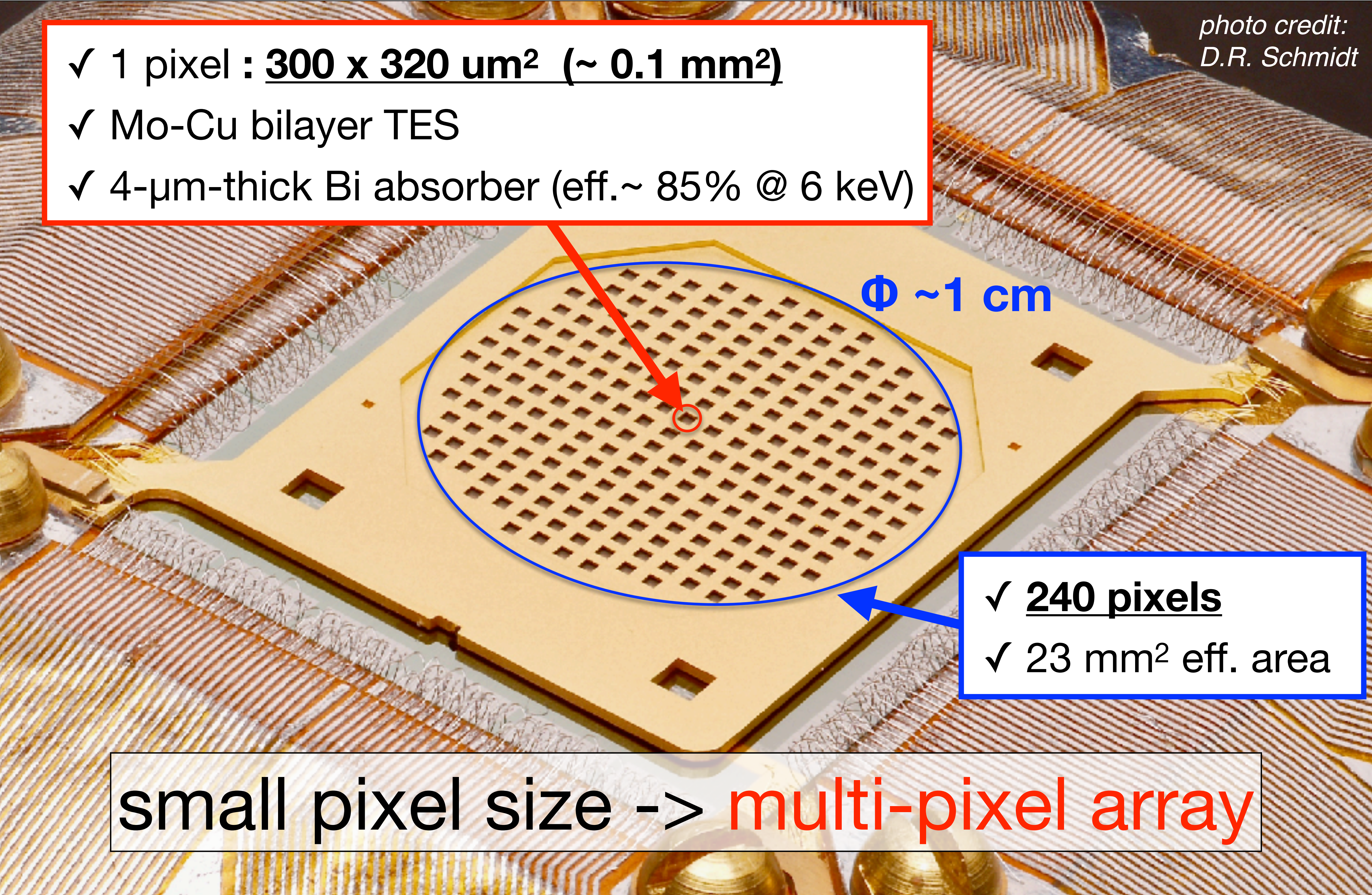


photo credit: D.R. Schmidt

- ✓ 1 pixel **: <u>300 x 320 um^2 (~ 0.1 mm^2)</u>**
- ✓ Mo-Cu bilayer TES
- ✓ 4-μm-thick Bi absorber (eff.~ 85% @ 6 keV)

Φ ~1 cm

- ✓ **<u>240 pixels</u>**
- ✓ 23 mm^2 eff. area

small pixel size -> multi-pixel array

TES array

- ✓ 1 pixel **: 300 x 320 um^2 (~ 0.1 mm^2)**
- ✓ Mo-Cu bilayer TES
- ✓ 4-µm-thick Bi absorber (eff.~ 85% @ 6 keV)

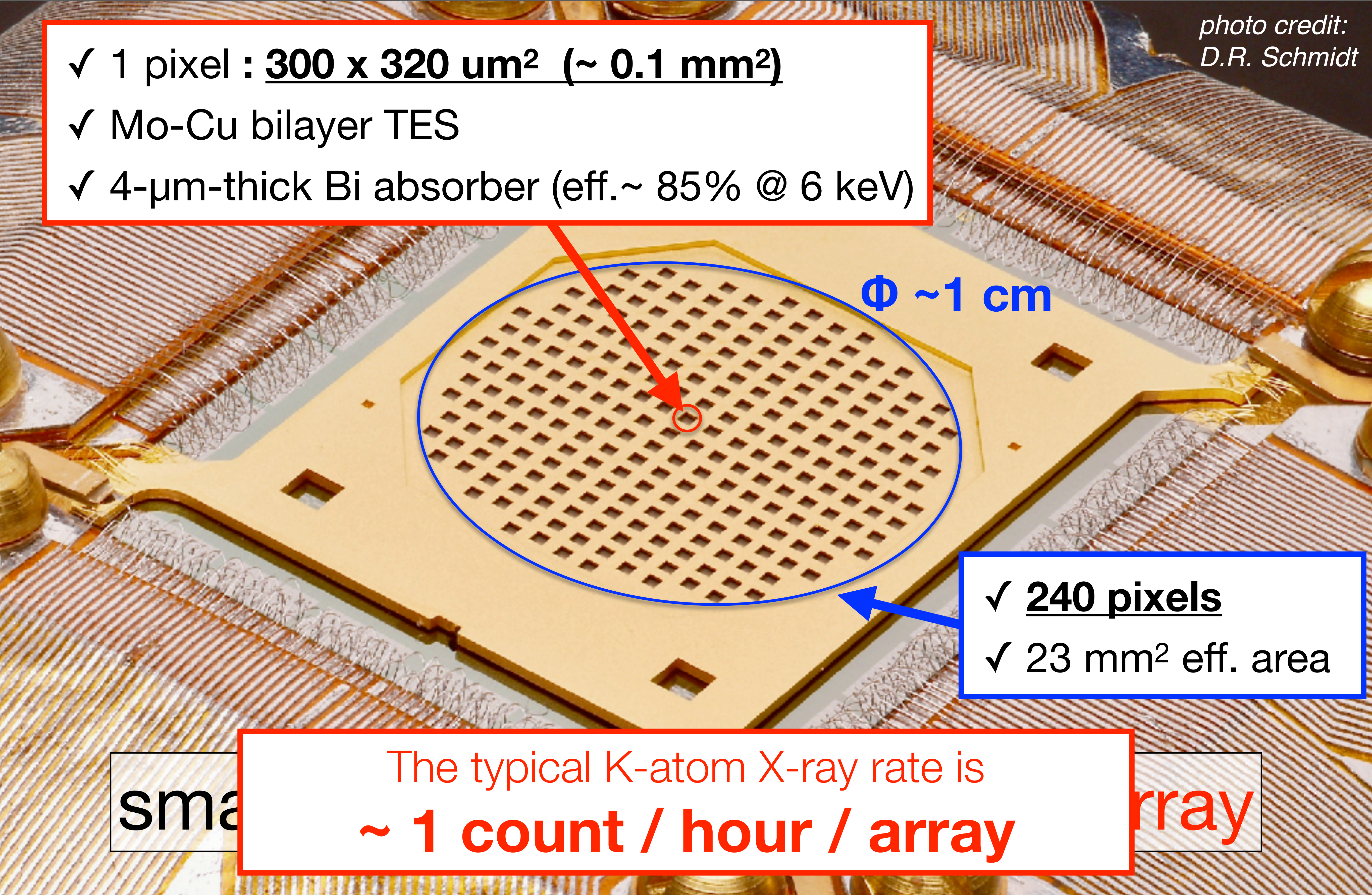


photo credit:
D.R. Schmidt

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

sma

rray

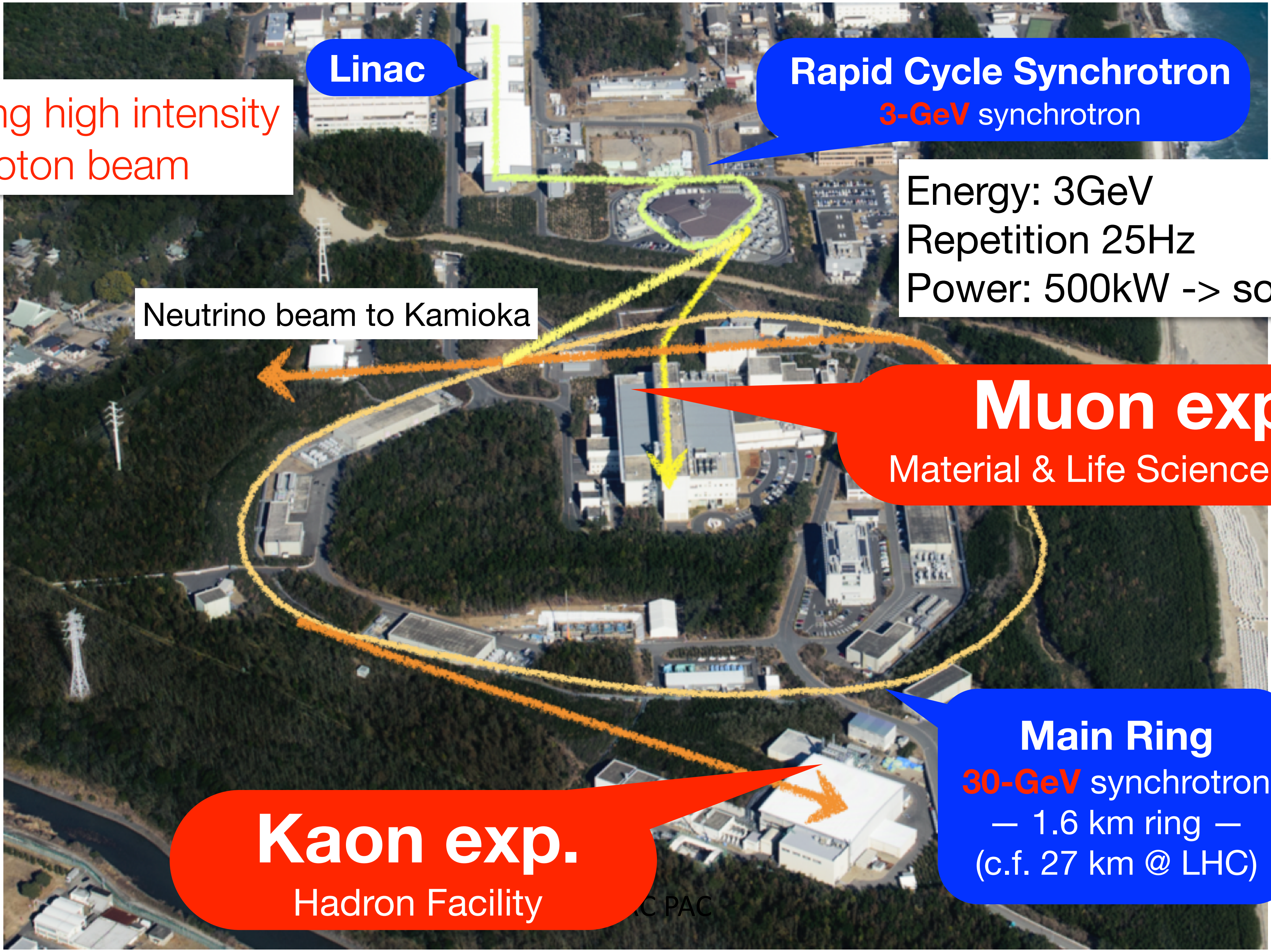
The typical K-atom X-ray rate is

~ 1 count / hour / array

3. Experiments

J-PARC

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



providing high intensity proton beam

Linac

Rapid Cycle Synchrotron
3-GeV synchrotron

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

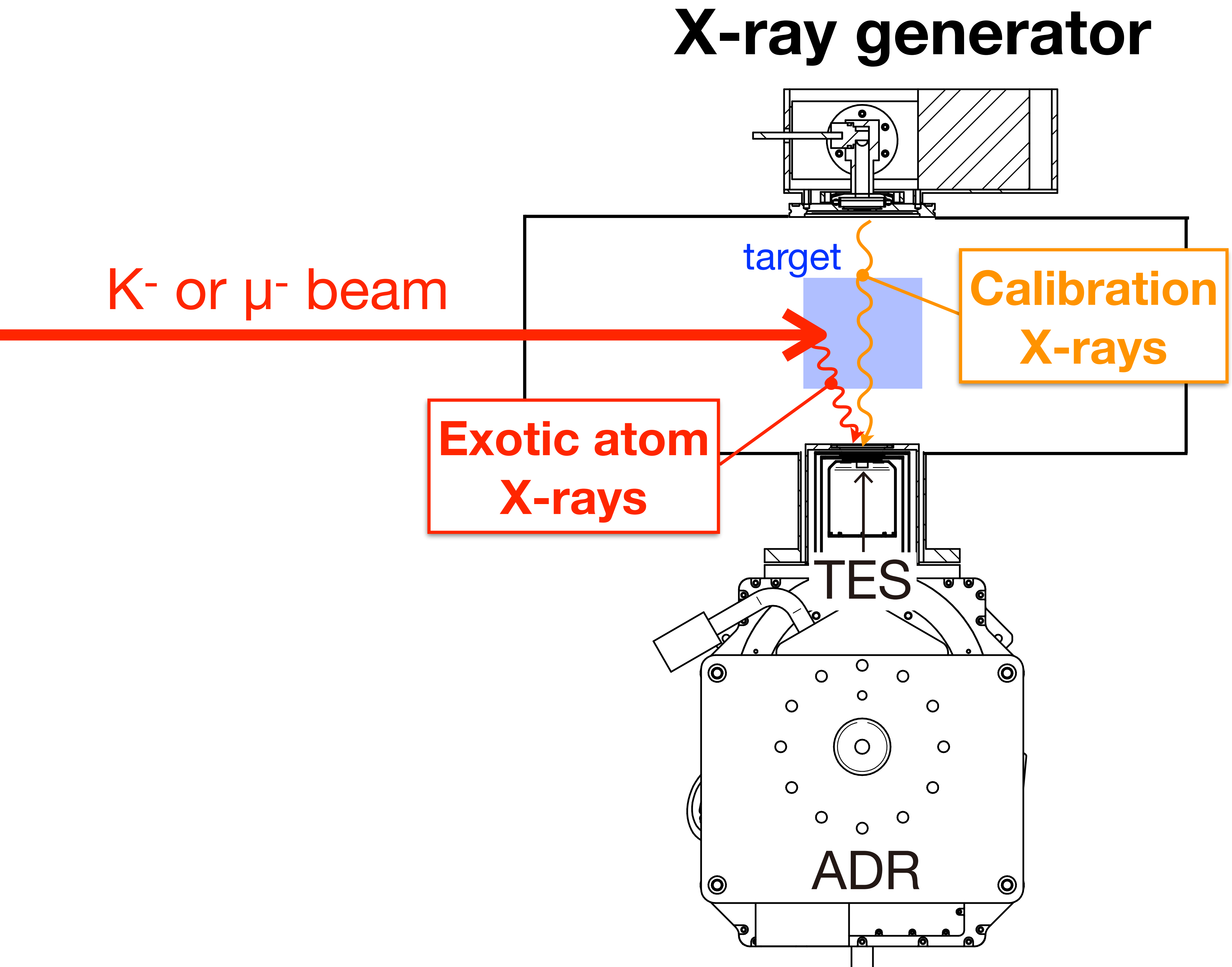
Neutrino beam to Kamioka

Muon exp.
Material & Life Science Facility

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

Kaon exp.
Hadron Facility

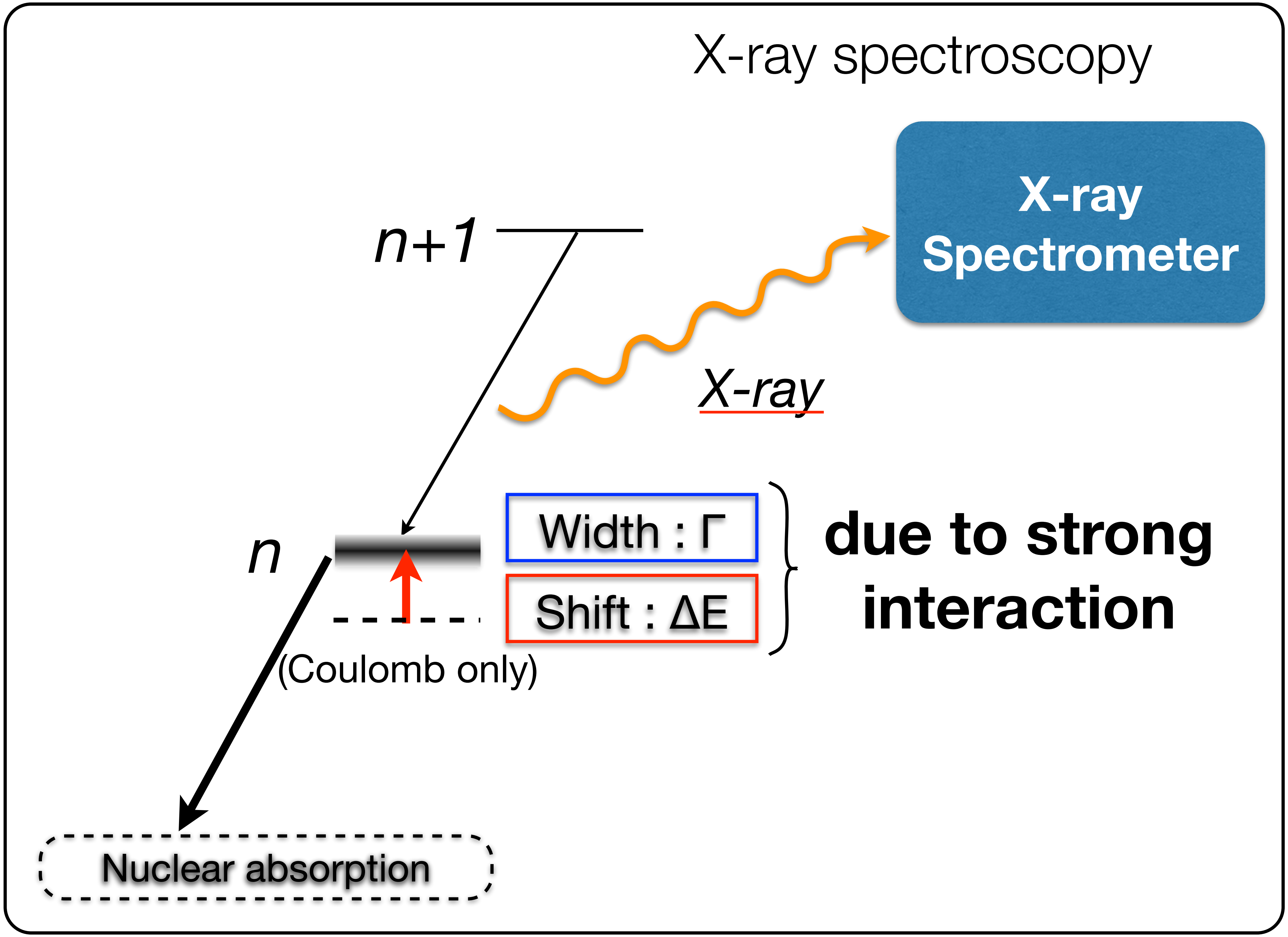
Experimental setup



observing a single sharp peak
to measure an absolute value of X-ray energy

(3-1) Kaonic atom

Kaonic atom X-rays



X-ray spectroscopy

X-ray Spectrometer

Width : Γ

Shift : ΔE

due to strong interaction

Nuclear absorption

Scattering length & potential

Kaonic hydrogen & deuterium → **$\bar{K}N$ scattering length**

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

Shift Width

K-p Kα x-ray

Scattering length

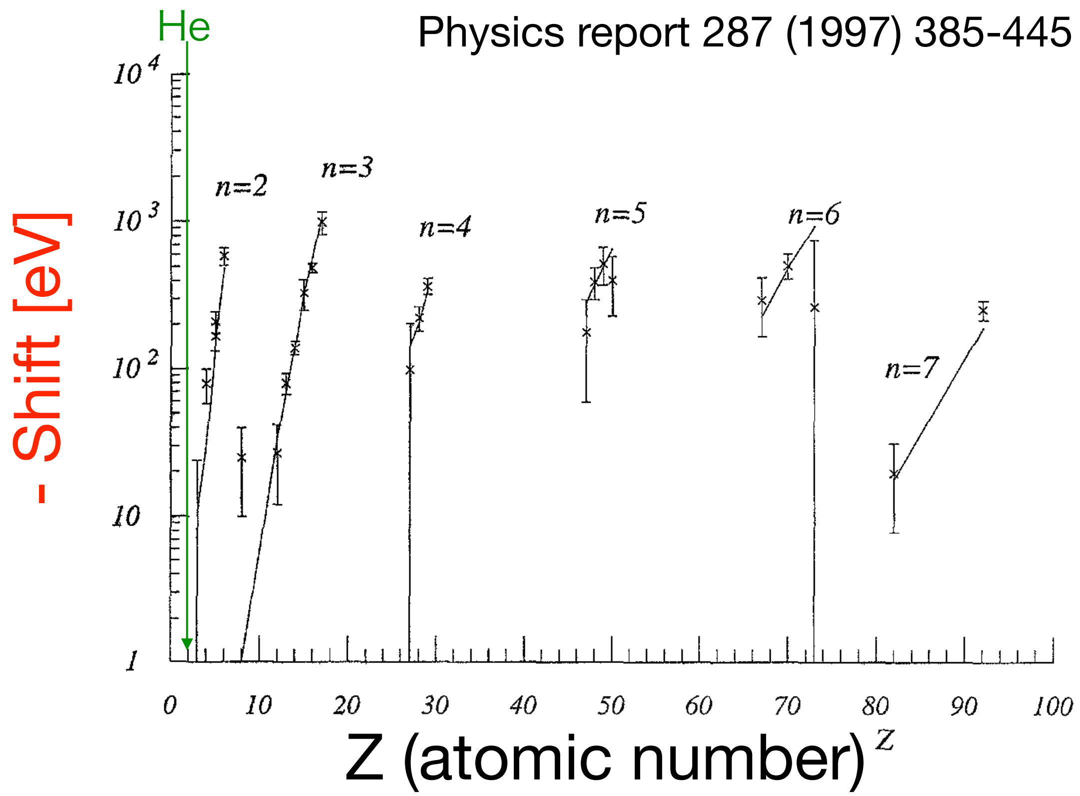
U.-G. Meißner et al, Eur Phys J C35 (2004) 349
(Deser-Type relation with isospin-braking correction)

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

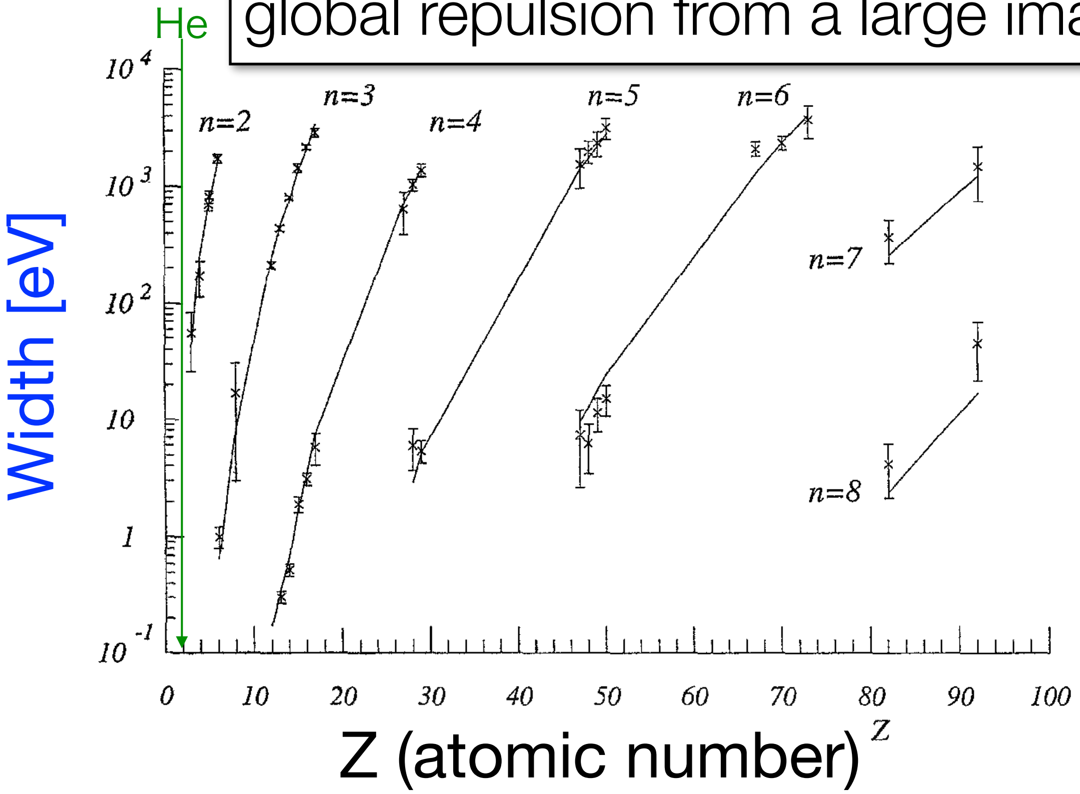
$$a_{K^-d} = \frac{k}{4}(a_0 + 3a_1) + C$$

Heavier kaonic atoms → **Attractive optical potential**

Physics report 287 (1997) 385-445

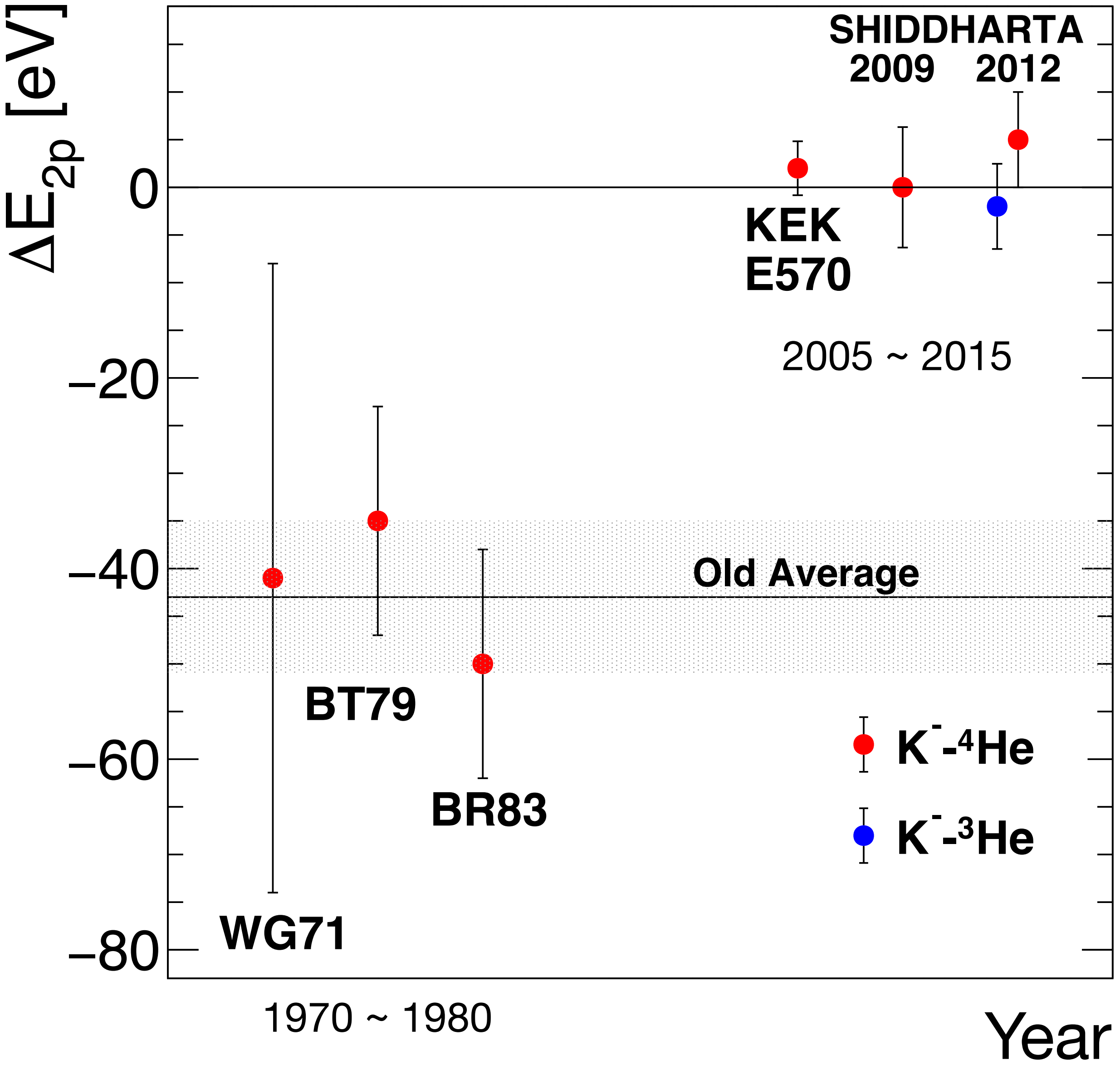


global repulsion from a large imaginary part

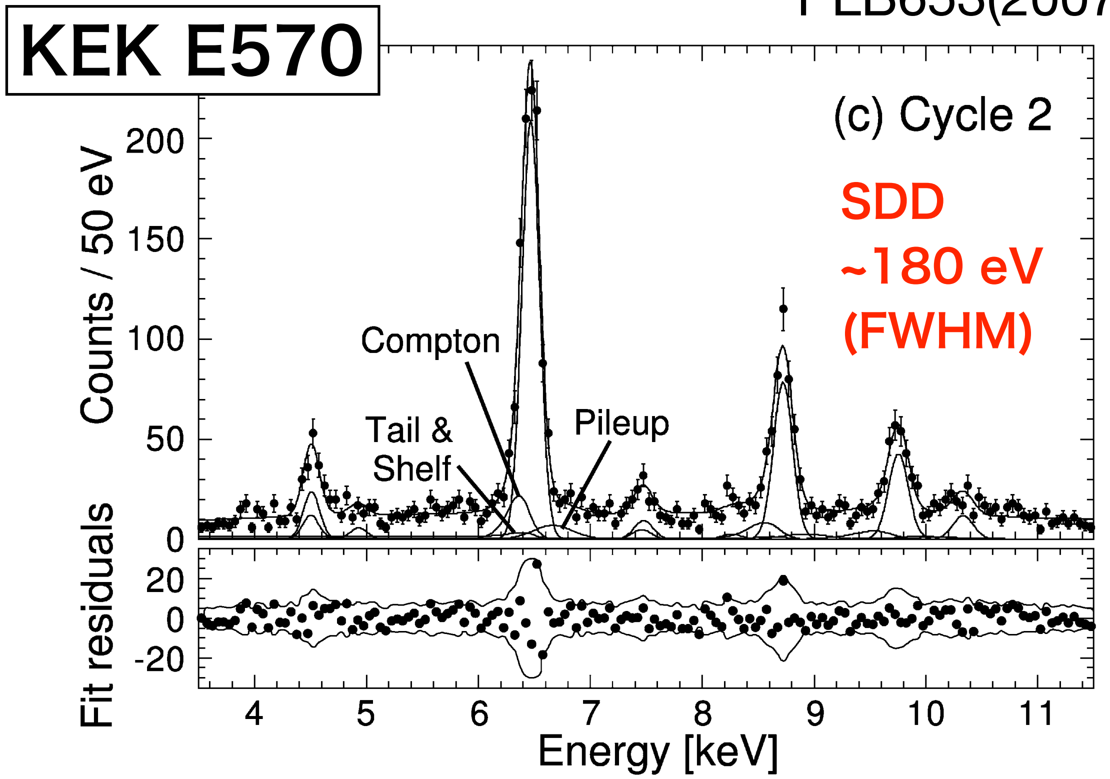


Kaonic helium : experiments

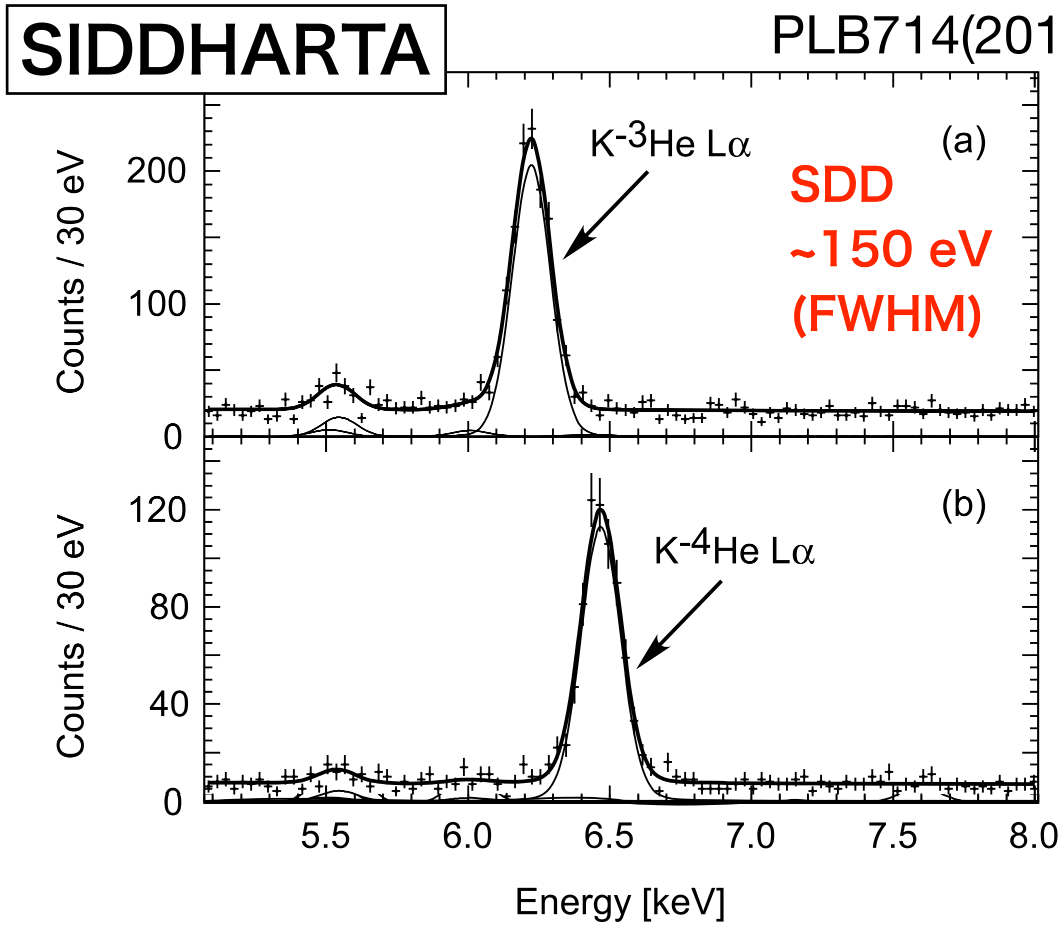
$$\Delta E = E_{exp.} - E_{EM}$$



PLB653(2007)387



PLB714(2012)40

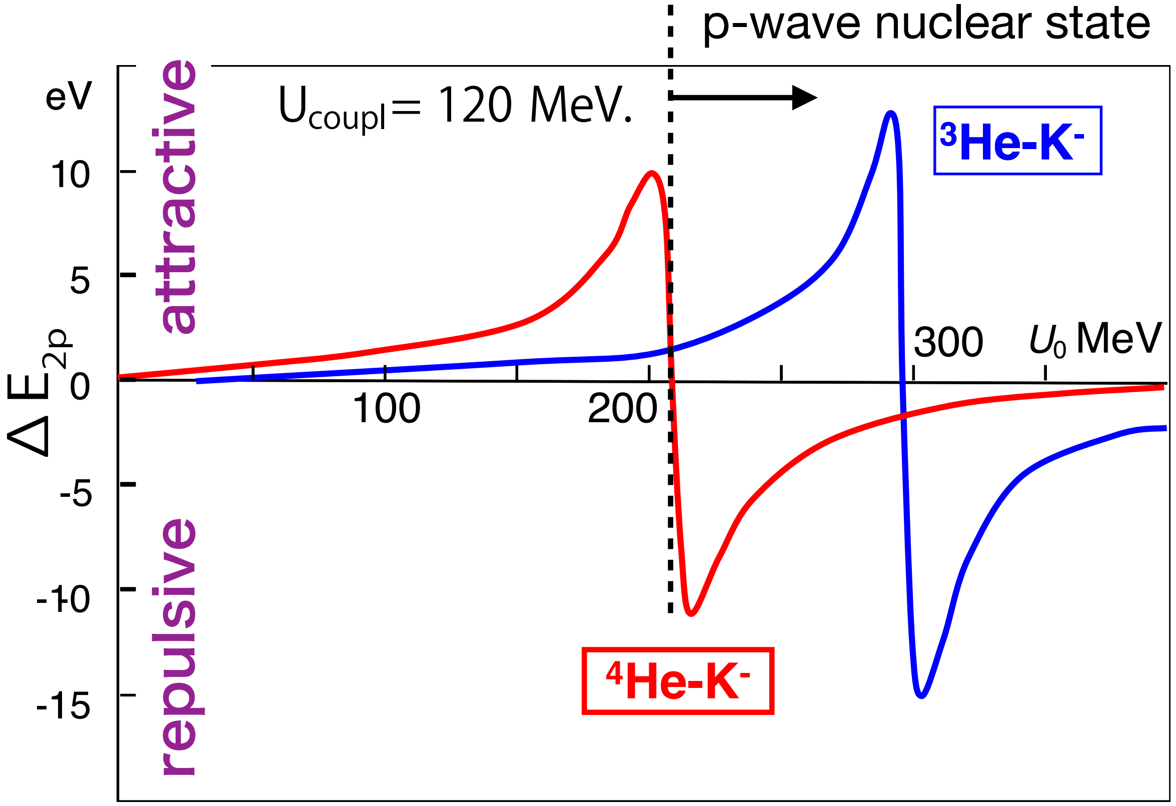


- ✓ Old "puzzle" has been solved
- ✓ Shift < 5 eV, Width < 20 eV
- ✓ **Precision ~ 2 eV << Resolution 150 eV**

Kaonic helium : theoretical values

Special interest in connection with light kaonic nuclei

Y. Akaishi (EXA2005 proceedings)



coupled-channel potential

J. Yamagata-Sekihara, S. Hirenzaki

(Private communication) Width : ~2 eV

	Phenomenological $V_{opt}(r=0)$~ - (180+73i) MeV	**Chiral** $V_{opt}(r=0)$~ - (40+55i) MeV
K-^{4}He	-0.4 eV	-0.1 eV
K-^{3}He	0.2 eV	-0.1 eV

E. Friedman

(NPA959(2017)66)

KM (Kyoto-Munich) KN amplitudes within their sub-threshold kinematics model + a phenomenological term

	Shift (eV)	Width (eV)
K-^{4}He	0.00	1.6
K-^{3}He	0.22	2.3

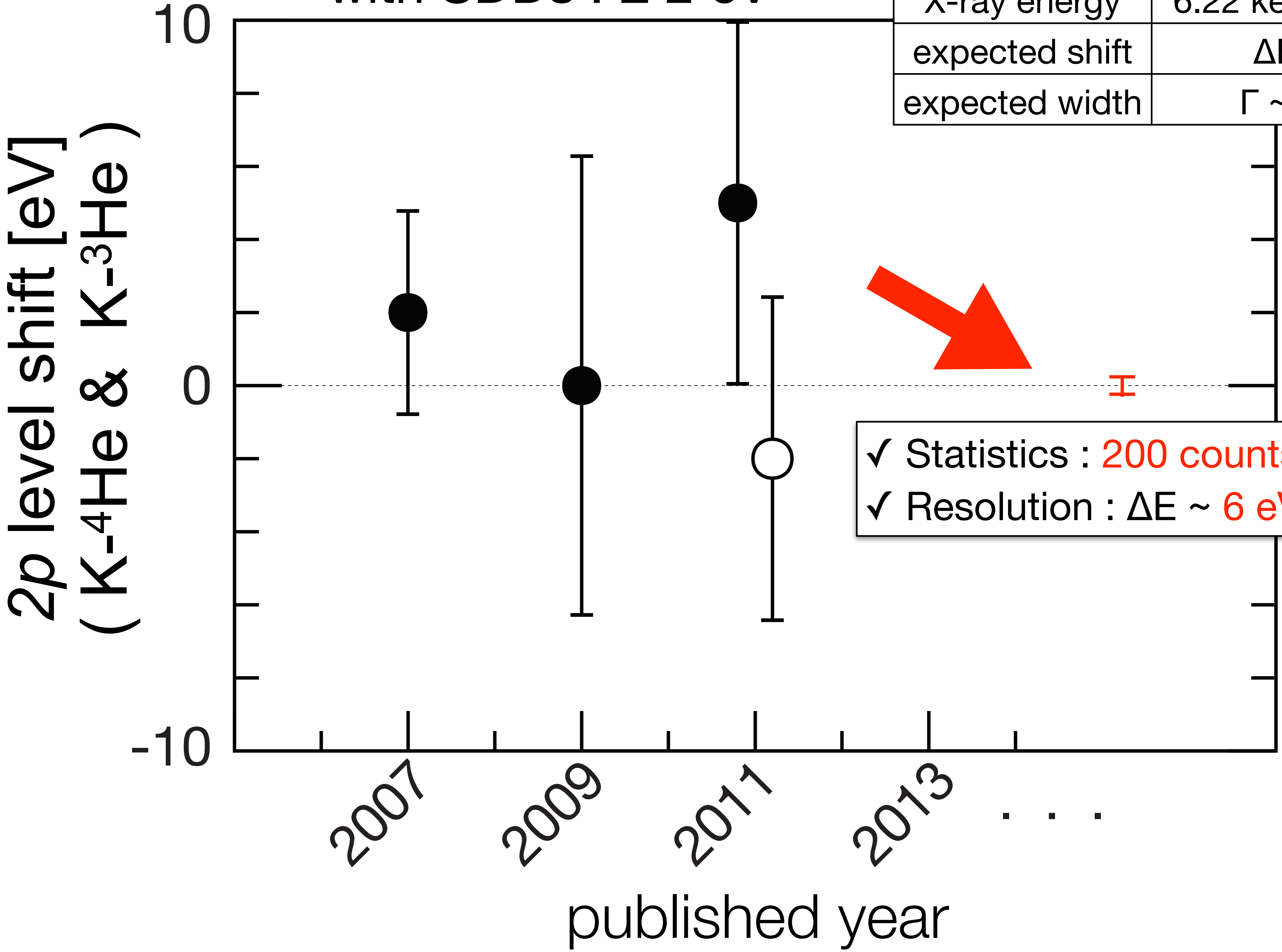
- ✓ Is there large shift > 1 eV, and width > 5 eV ?
- ✓ Sign of the shift ? (attractive shift → no p-wave nuclear bound state?)

→ eV-scale energy resolution is mandatory

Need one-order better precision

	K$^-$ - ^{3}He	K$^-$ - ^{4}He
X-ray energy	6.22 keV	6.46 keV
expected shift	ΔE < 1 eV	
expected width	Γ ~ 2 - 5 eV	

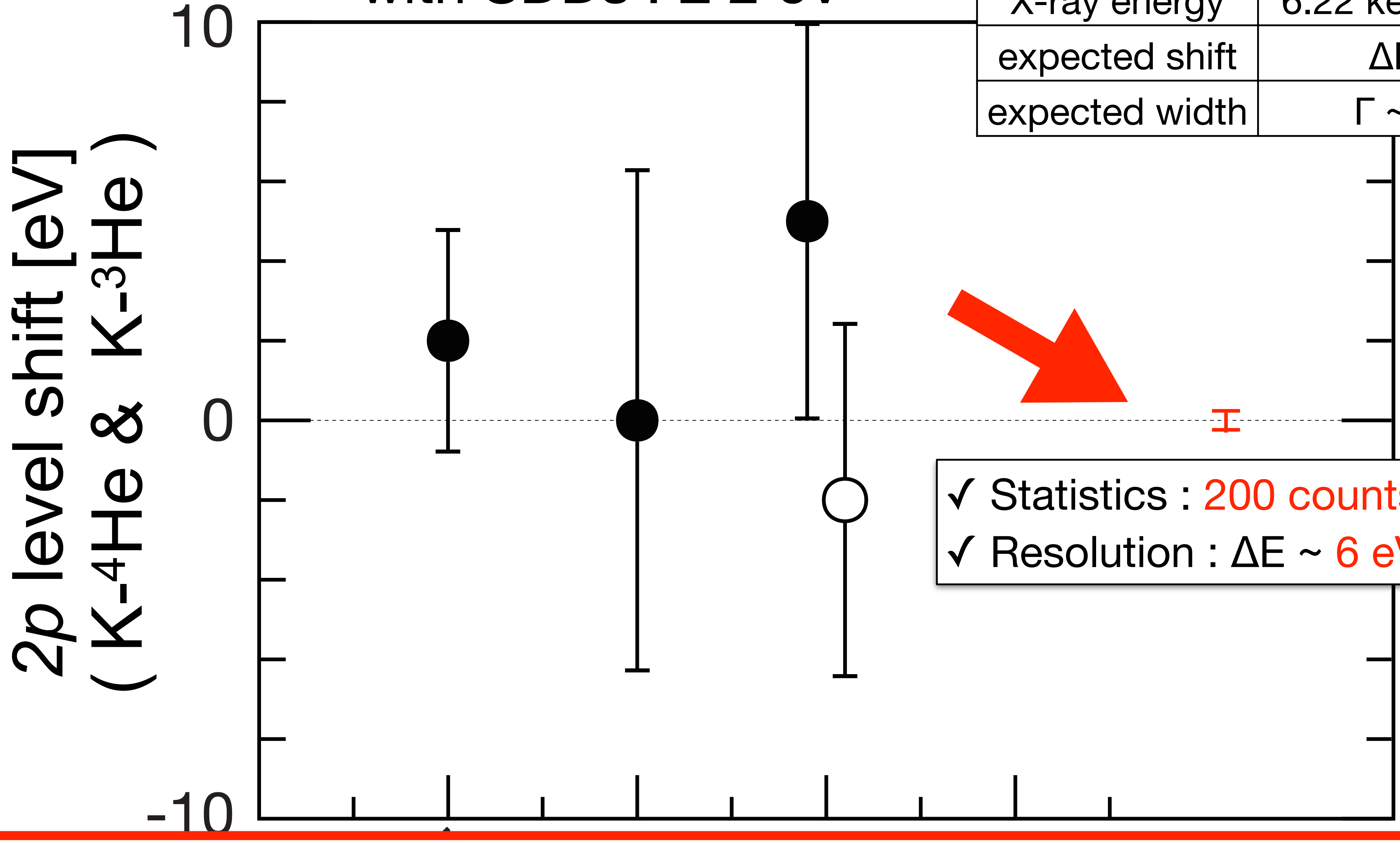
Past measurements
with SDDs : ± 2 eV



✓ Statistics : 200 counts

✓ Resolution : ΔE ~ 6 eV FWHM

Need one-order better precision



Past measurements with SDDs : ± 2 eV

	K^- - ^{3}He	K^- - ^{4}He
X-ray energy	6.22 keV	6.46 keV
expected shift	ΔE < 1 eV	
expected width	Γ ~ 2 - 5 eV	

✓ Statistics : 200 counts
✓ Resolution : ΔE ~ 6 eV FWHM

"**high resolution** + **Large detection area**" is essential

Operation of cryogenic systems

He target

keep ~1.4 K

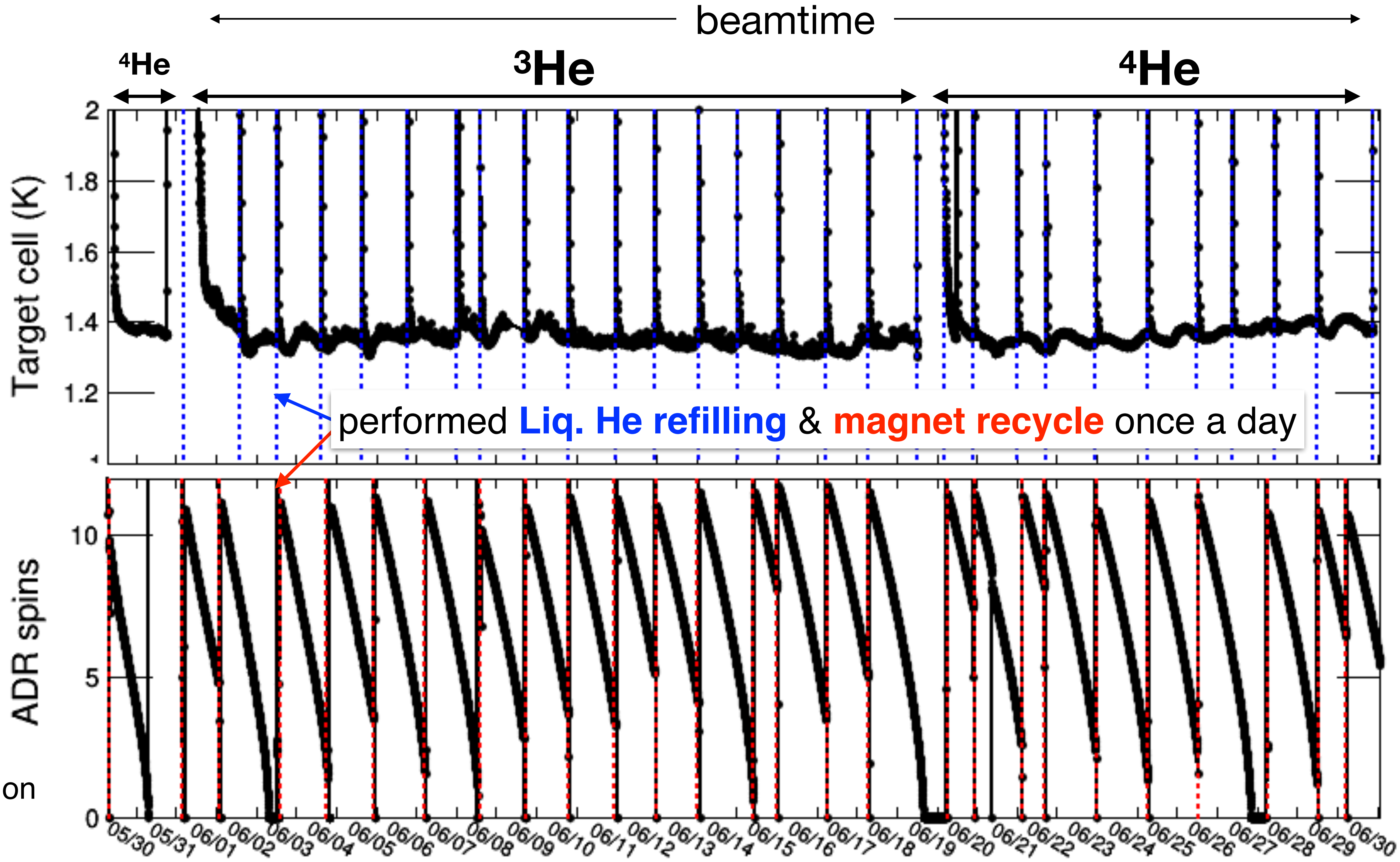
vacuum-cooled with Liq. ^{4}He

TES

keep 70 mK

Adiabatic
Demagnetization
Refrigerator

with pulse tube

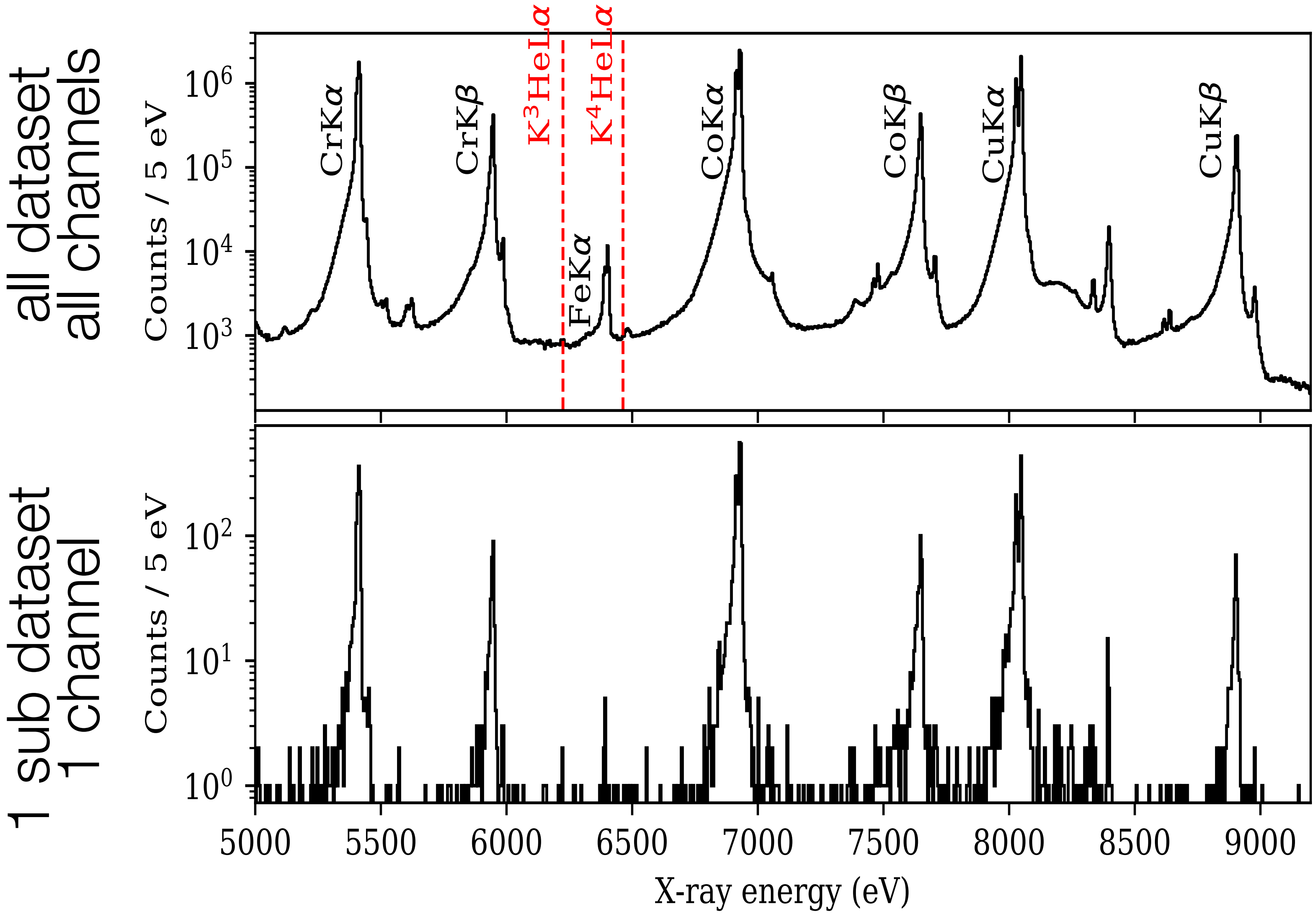


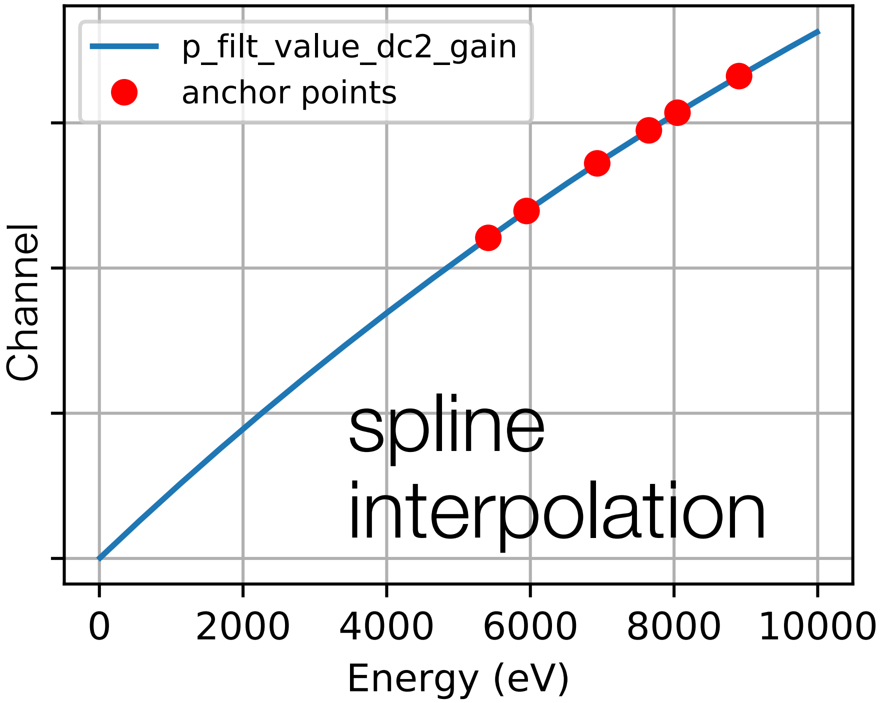
performed **Liq. He refilling** & **magnet recycle** once a day

Stable operation for one month

(28 He refills & 27 mag cycles)

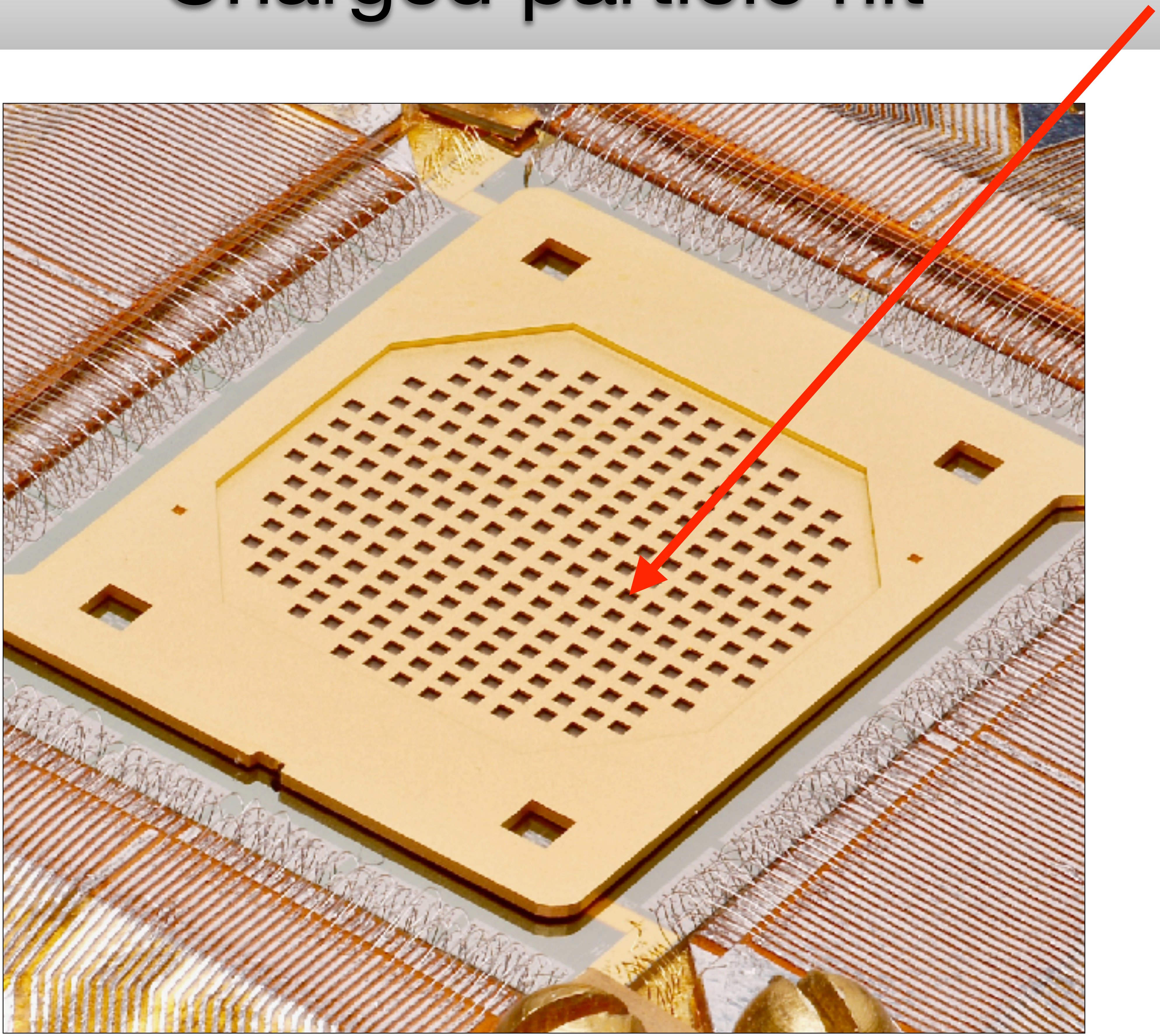
In-beam energy calib. (X-ray tube)



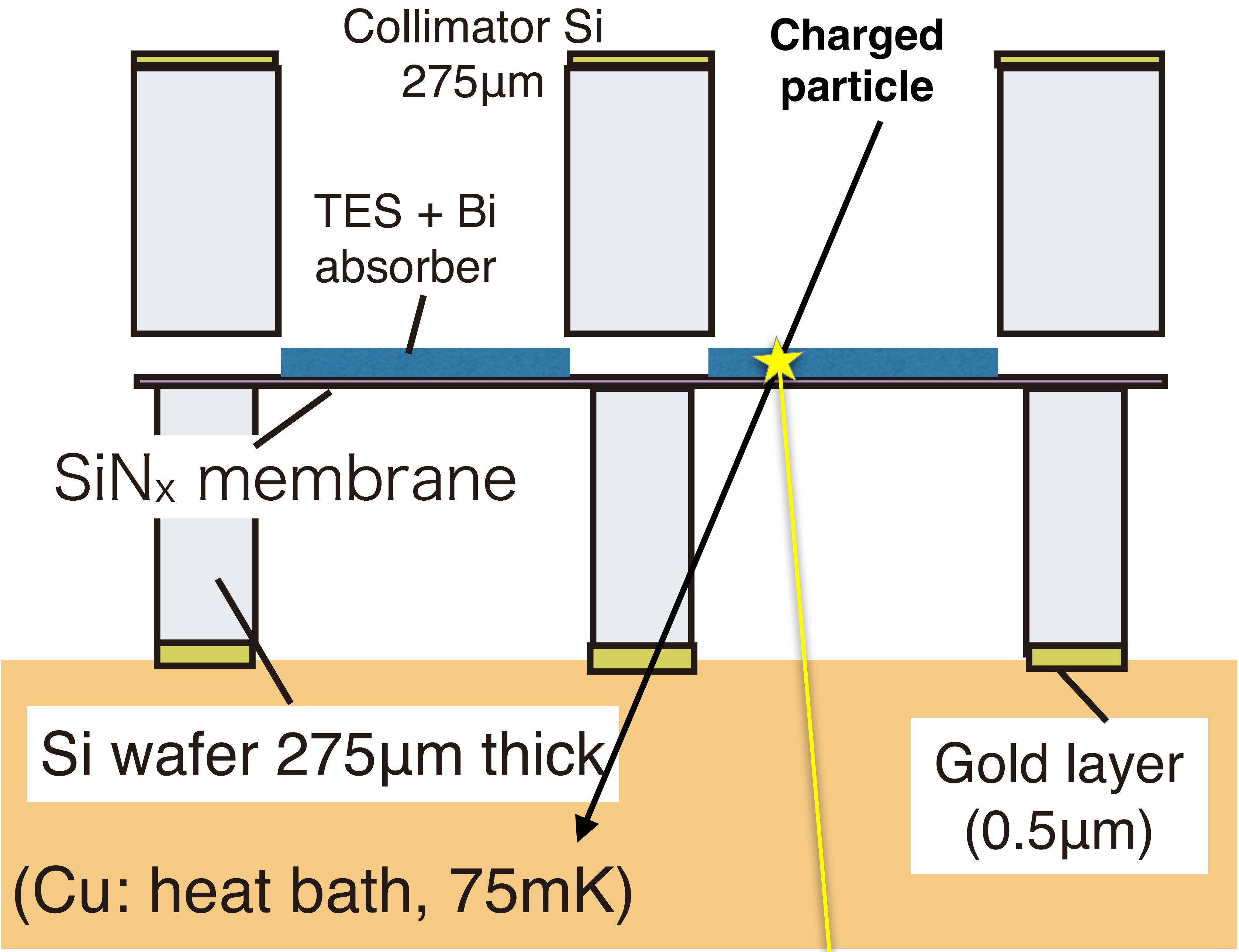


- ✓ X-ray tube was always ON during the experiment
- ✓ Pixel-by-pixel calibration every 4~8 hours

Charged particle hit

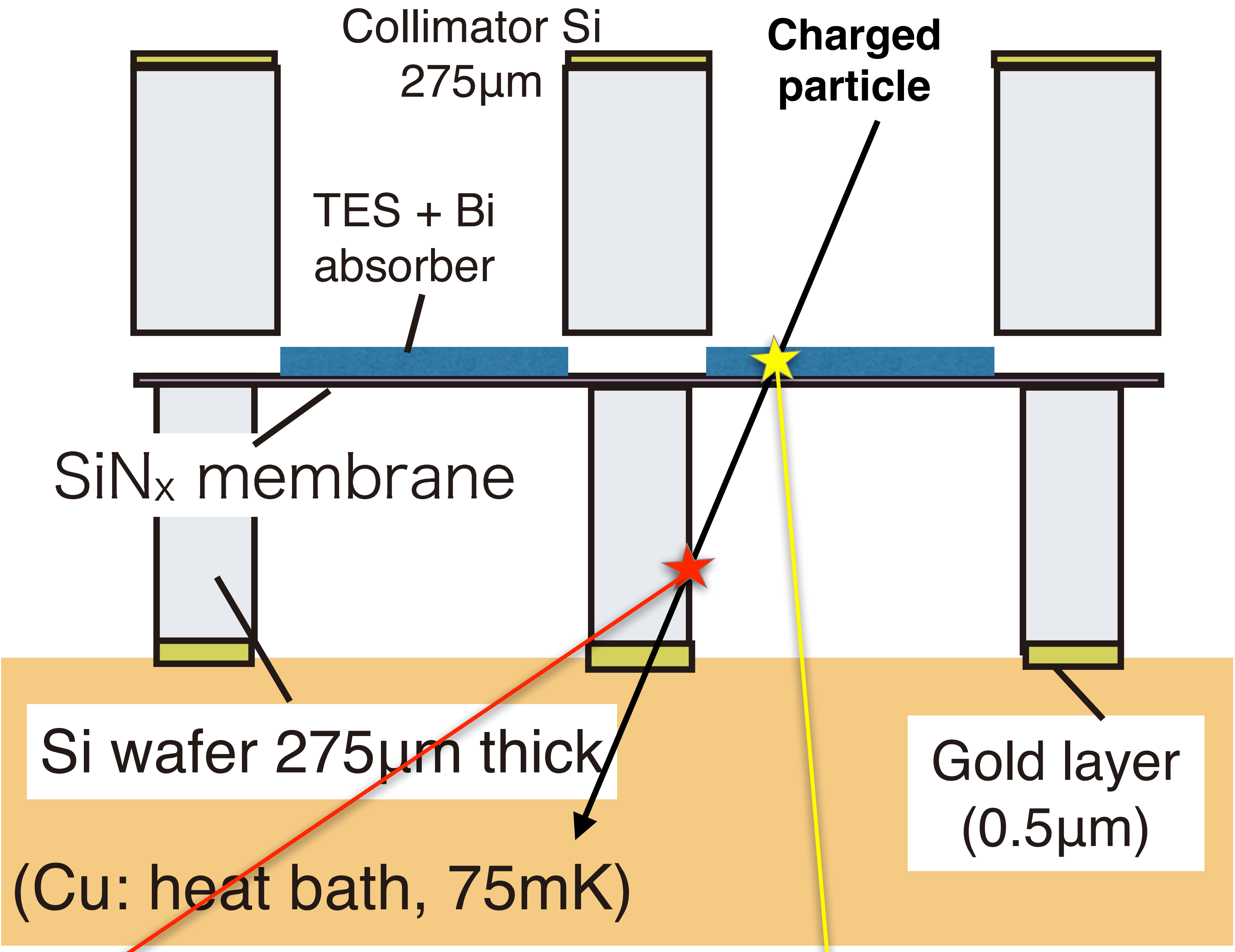


Charged particle hit



If charged particle hit on the detector pixel, it deposits ~10 keV energy (Bi 4um), which become severe background in the spectrum

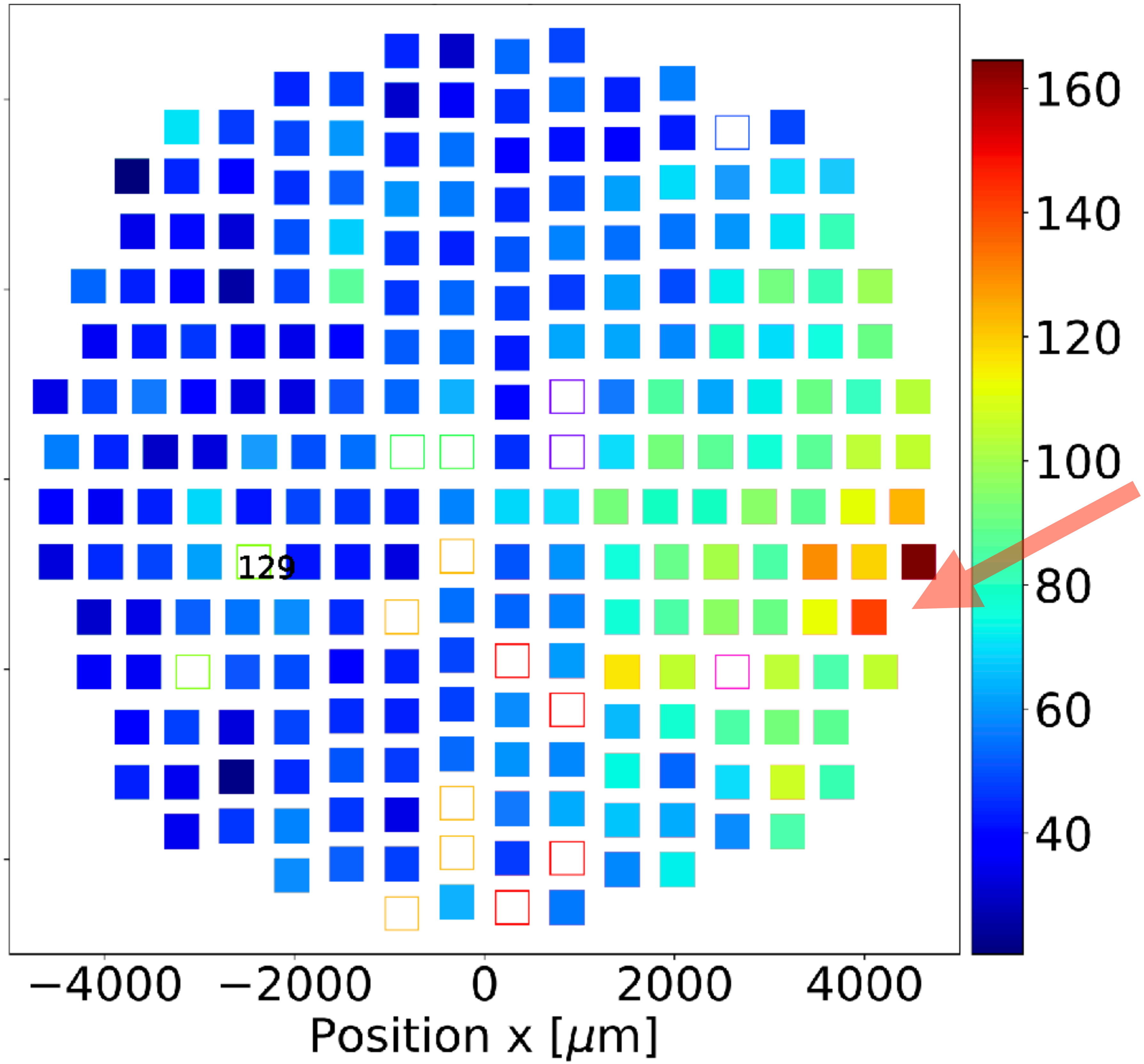
Charged particle hit



If charged particle hit on the Si substrate, heat will spread out throughout the array, making small bump signals in many pixels

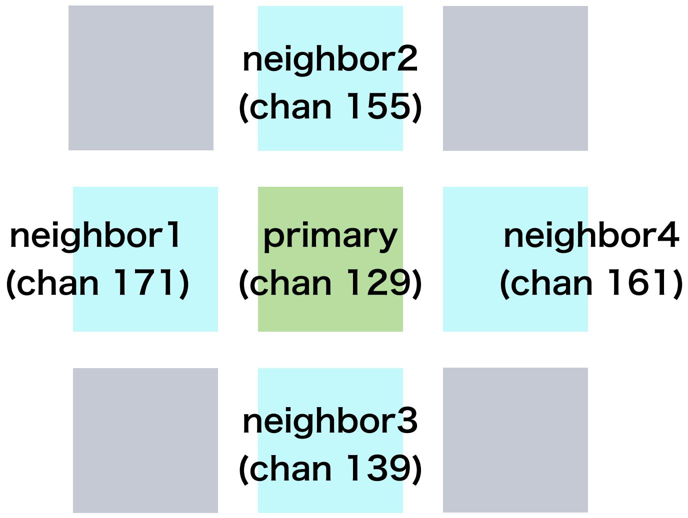
If charged particle hit on the detector pixel, it deposits ~10 keV energy (Bi 4um), which become severe background in the spectrum

Pulse height distribution in array



Charged particle hit

Charged particle identification



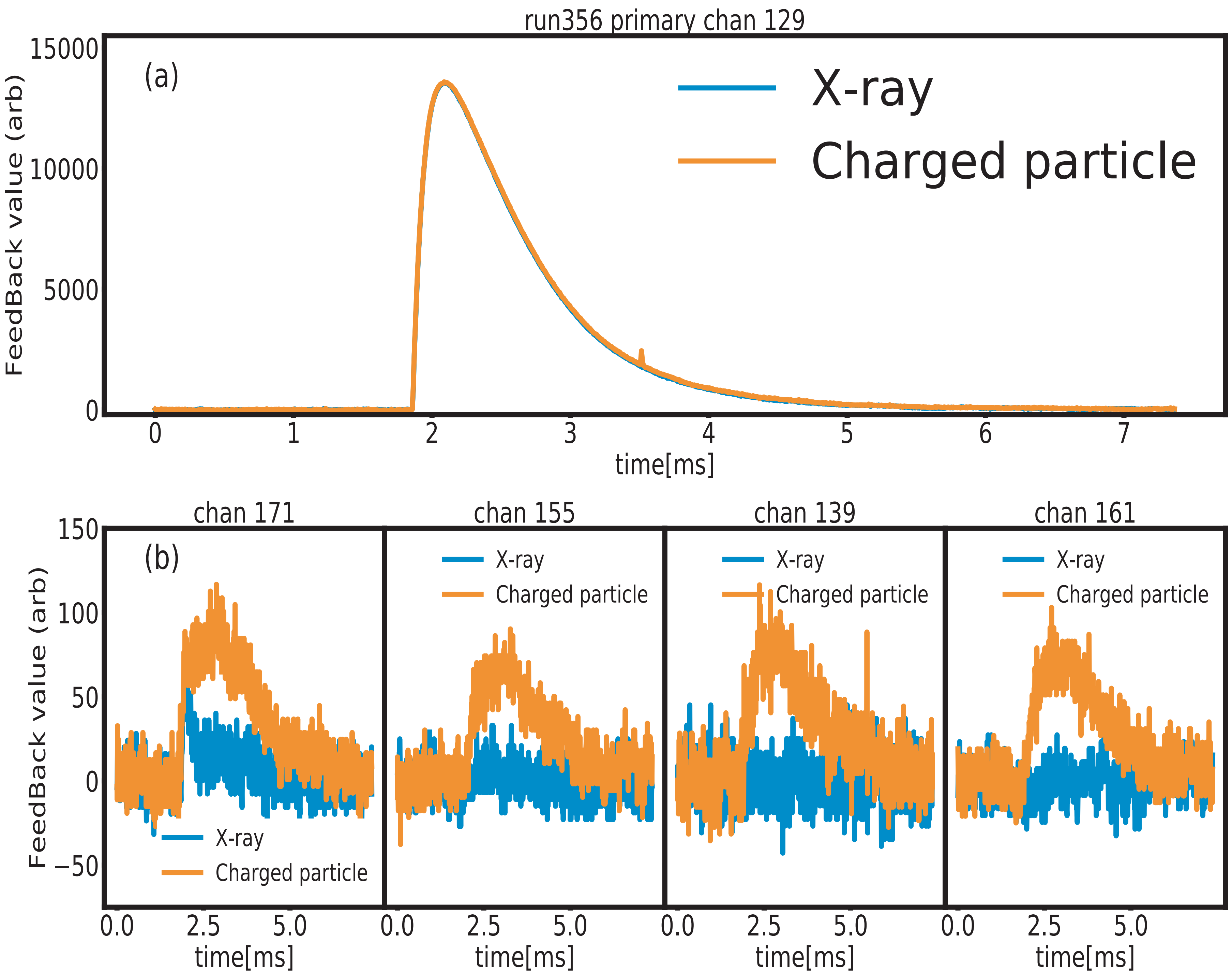
neighbor2 (chan 155)

neighbor1 (chan 171)

primary (chan 129)

neighbor4 (chan 161)

neighbor3 (chan 139)



- No difference in the primary pulses between X-rays and charged particles
- If we look at neighboring pixels, we can reject half of the charged particles

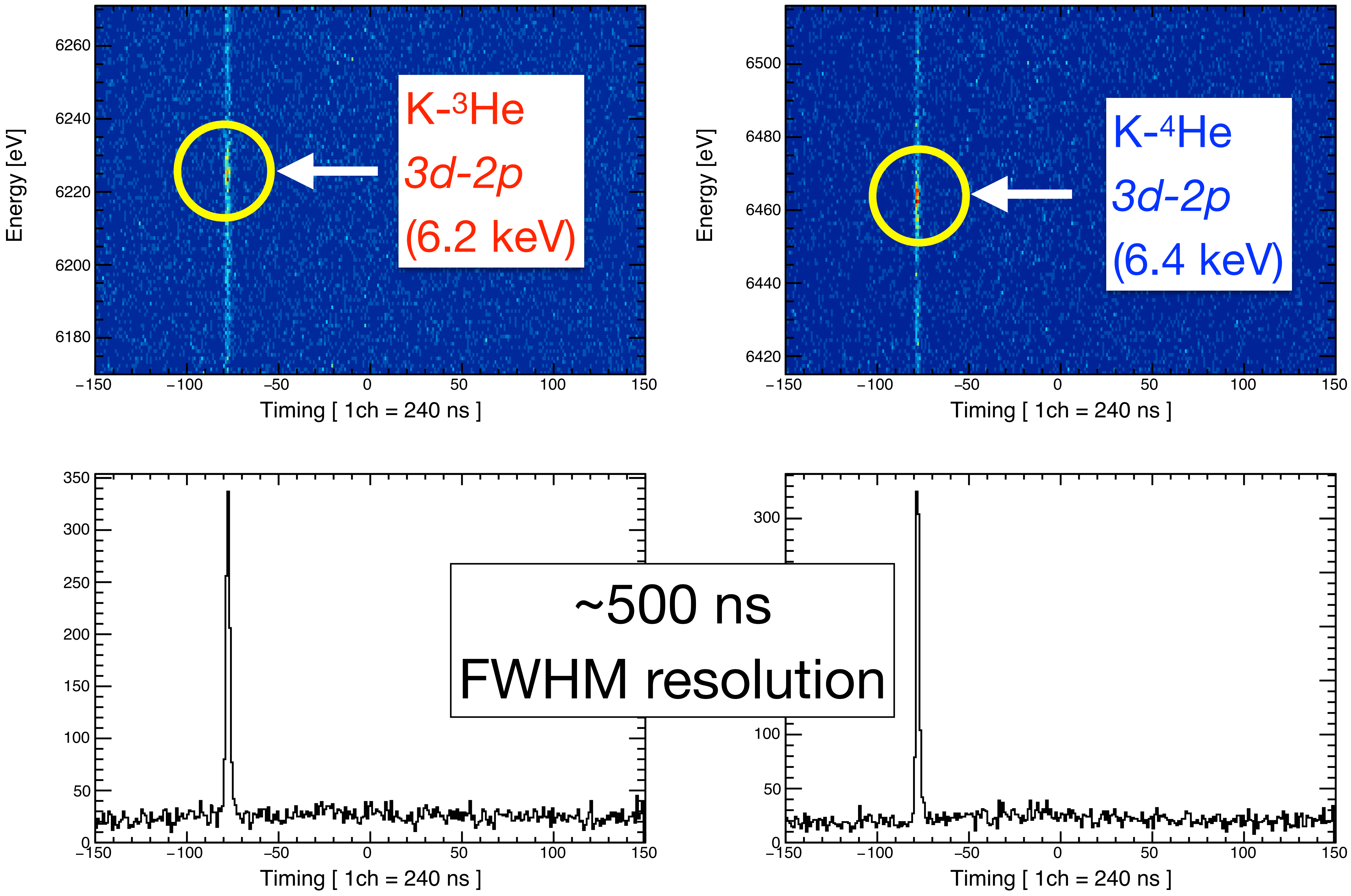
Timing resolution

^{3}He target

^{4}He target

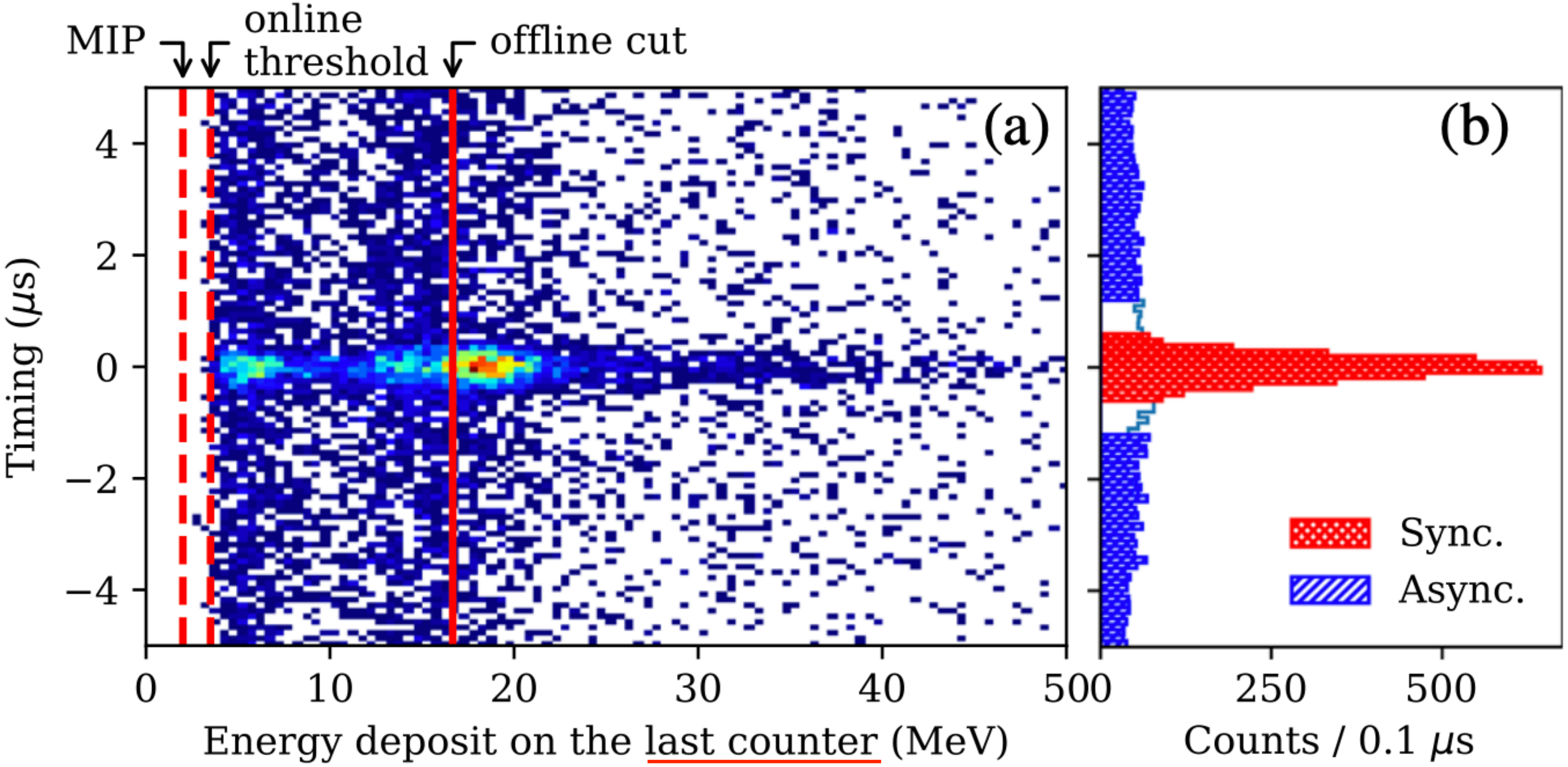
Time vs. energy

Time to K_{stop} trigger



~500 ns
FWHM resolution

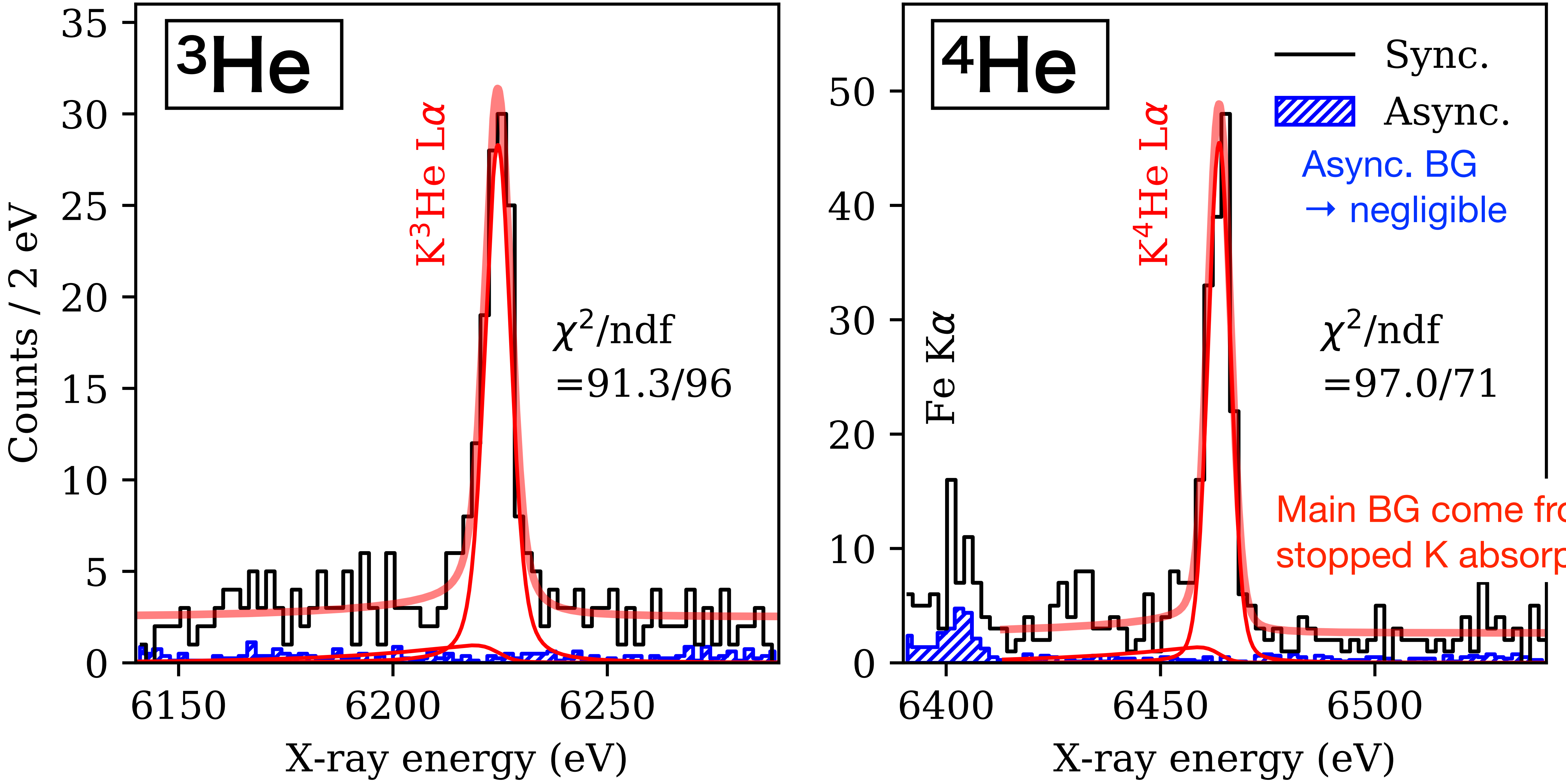
Timing vs. dE (energy deposit)



a thin scintillator just in front of the target

requiring the energy deposit to be larger than 16 MeV
to select low momentum kaons which are likely to stop in the target.

Kaonic X-ray spectra



Async. BG
→ negligible

Main BG come from stopped K absorption

$$E_{3d\to 2p}^{K^{-3}\mathrm{He}} = 6224.5 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{syst})\ \mathrm{eV}$$

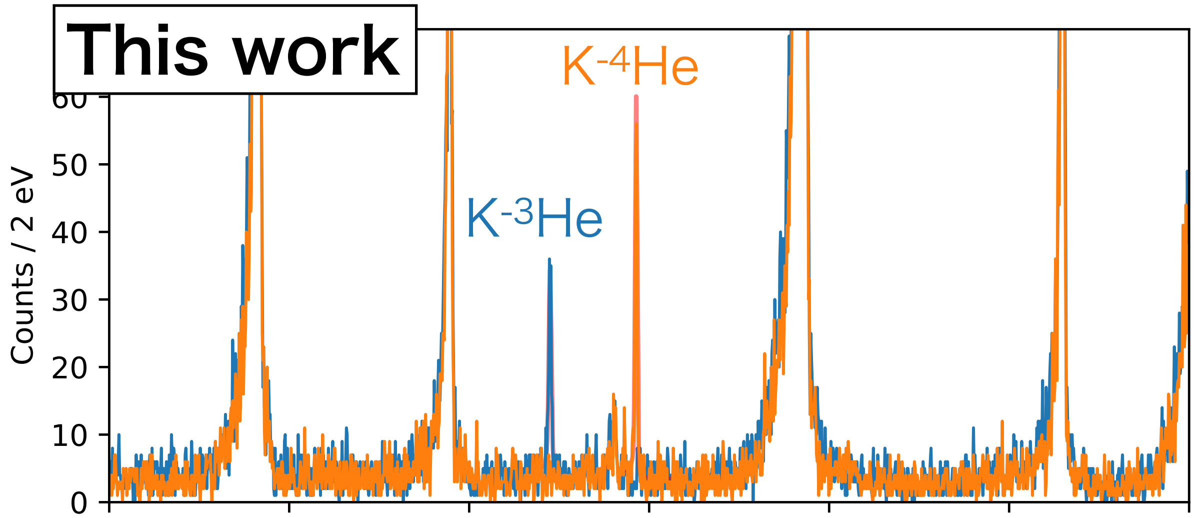
$$\Gamma_{2p}^{K^{-3}\mathrm{He}} = 2.5 \pm 1.0(\mathrm{stat}) \pm 0.4(\mathrm{syst})\ \mathrm{eV}$$

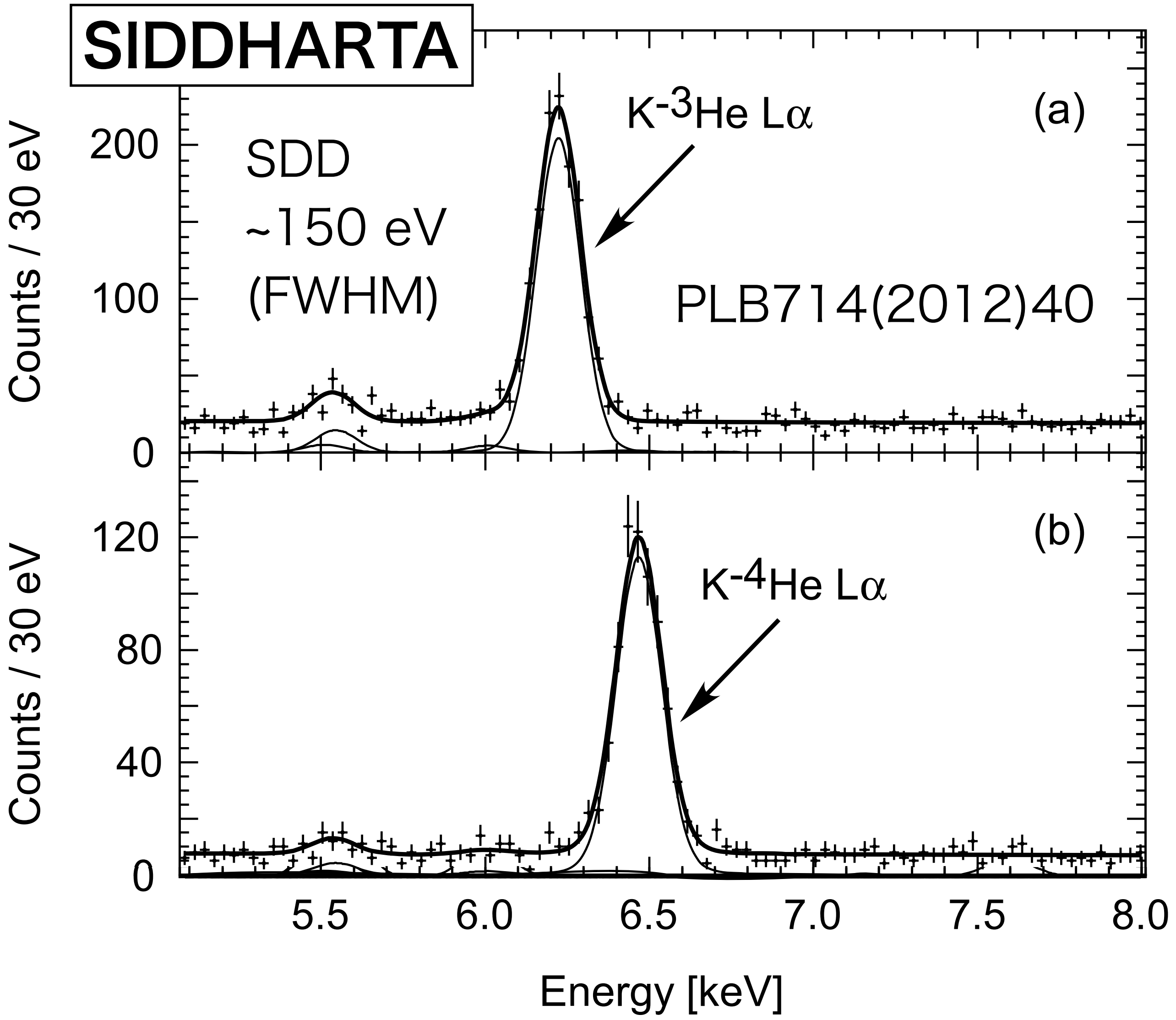
$$E_{3d\to 2p}^{K^{-4}\mathrm{He}} = 6463.7 \pm 0.3(\mathrm{stat}) \pm 0.1(\mathrm{syst})\ \mathrm{eV}$$

$$\Gamma_{2p}^{K^{-4}\mathrm{He}} = 1.0 \pm 0.6(\mathrm{stat}) \pm 0.3(\mathrm{syst})\ \mathrm{eV}$$

Syst. error : mainly from the uncertainty in absolute energy scale

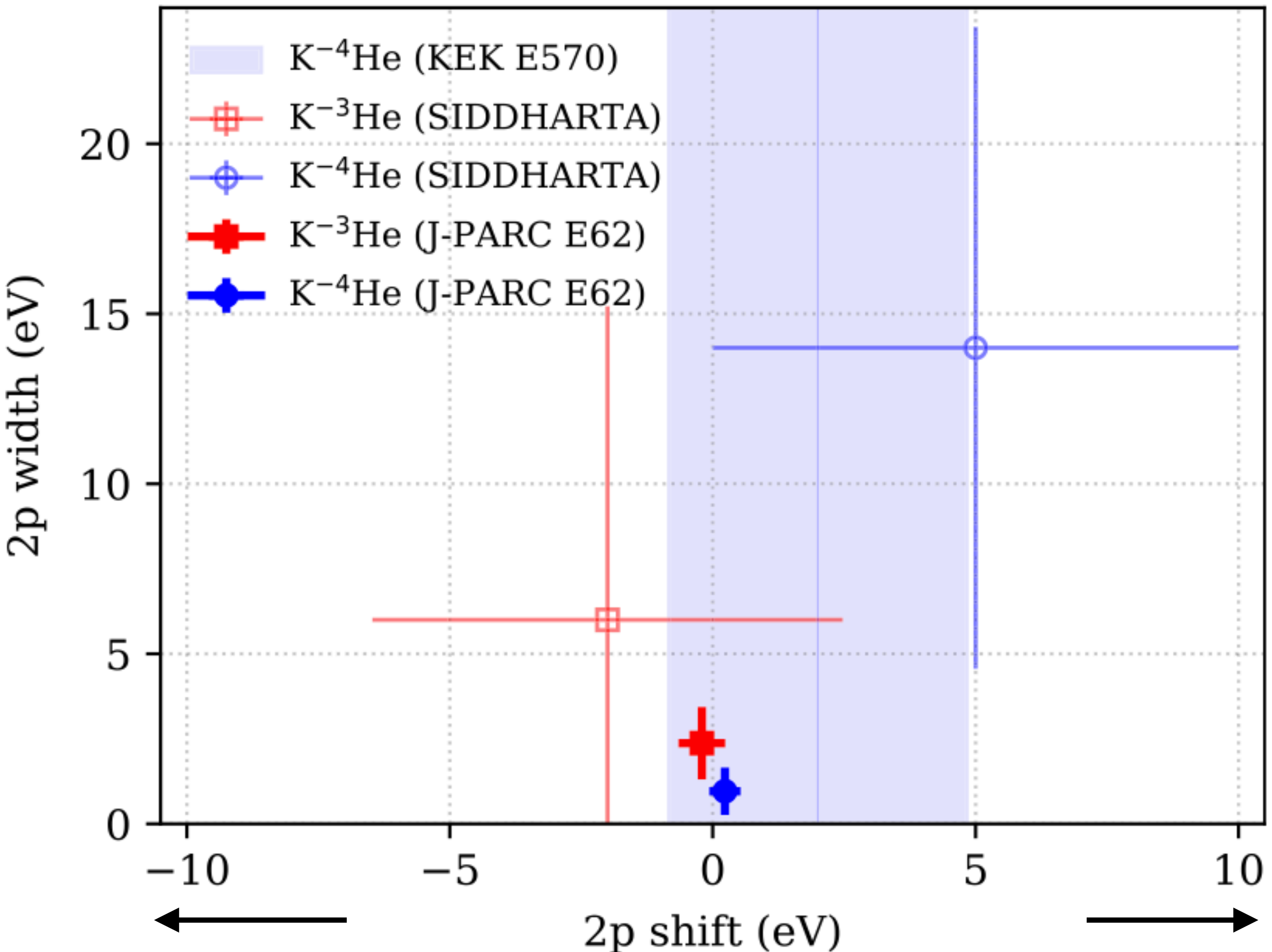
Comparison with past experiments





x 25 energy resolution
x 10 precision (shift&width)

Error bar: quadratic sum of stat. & sys.



repulsive ← → attractive

$$\Delta E = E_{exp.} - E_{EM}$$

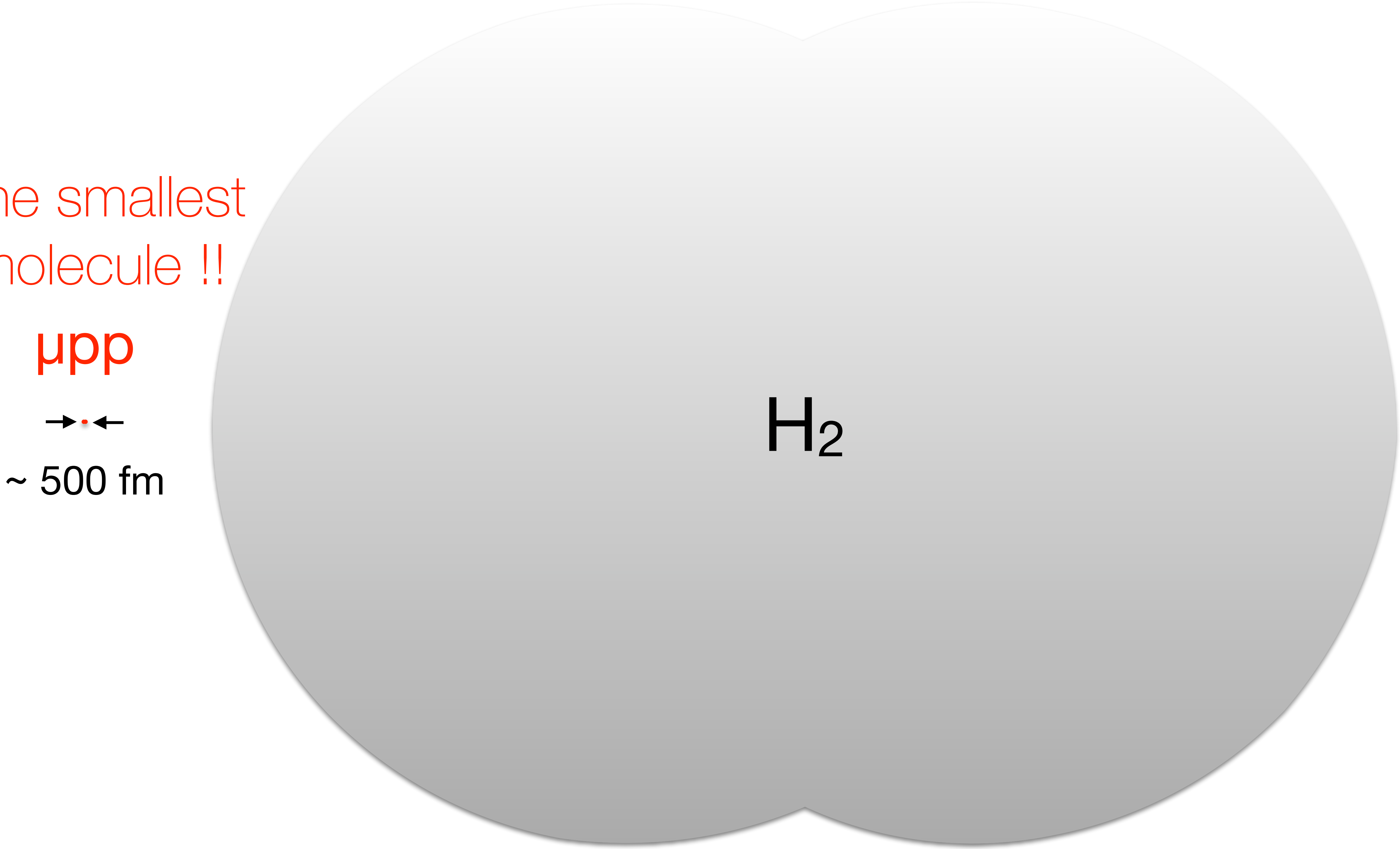
Excluded large shifts & widths

Detailed investigation of the optical potentials is under way by **Yamagata-san** *et al*.

observing a broad structure
(being complex of many X-ray lines)

(3-2) Muonic molecule

Scaled image, again

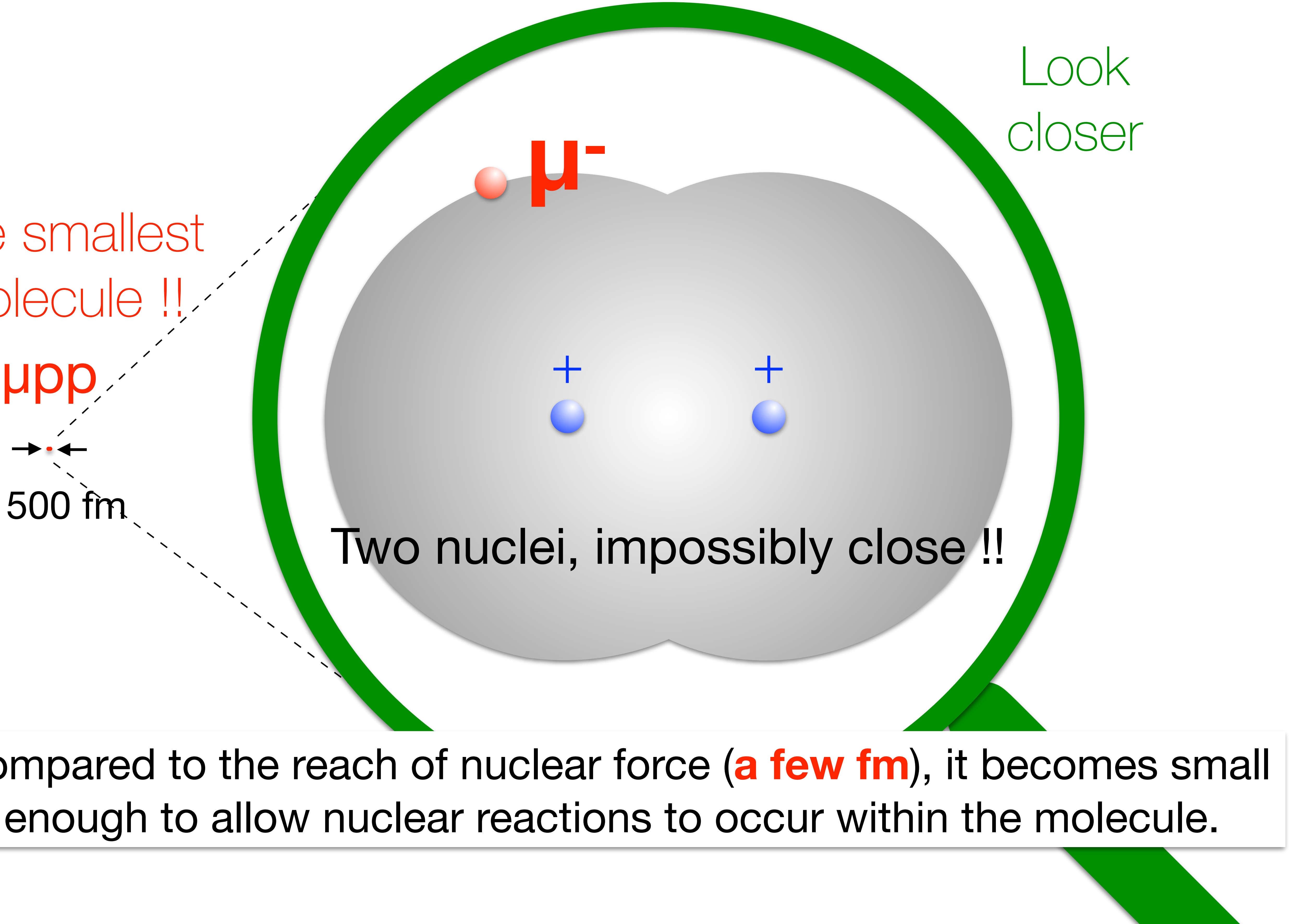


The smallest molecule !!

μpp

~ 500 fm

Muonic molecule



The smallest
molecule !!

μpp

~ 500 fm

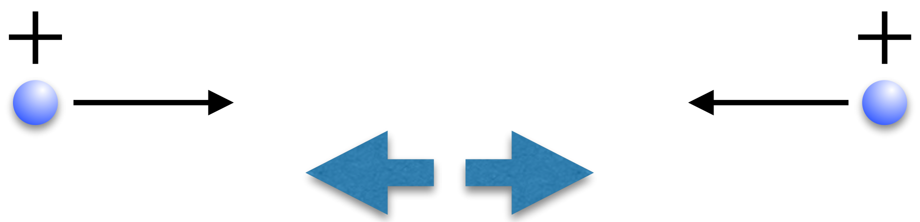
Two nuclei, impossibly close !!

Compared to the reach of nuclear force (**a few fm**), it becomes small enough to allow nuclear reactions to occur within the molecule.

Fusion

Thermonuclear fusion

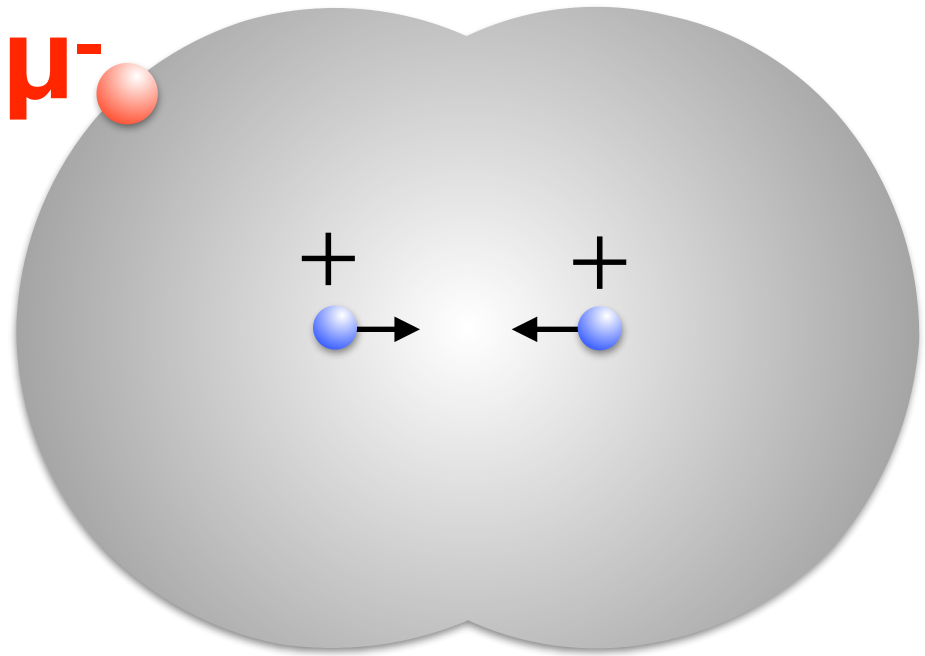
Vigorous collisions in plasma
at several hundred million
degrees Celsius



Large repulsion due to electromagnetic force

Fusion with muons

Nuclei easily approach each other

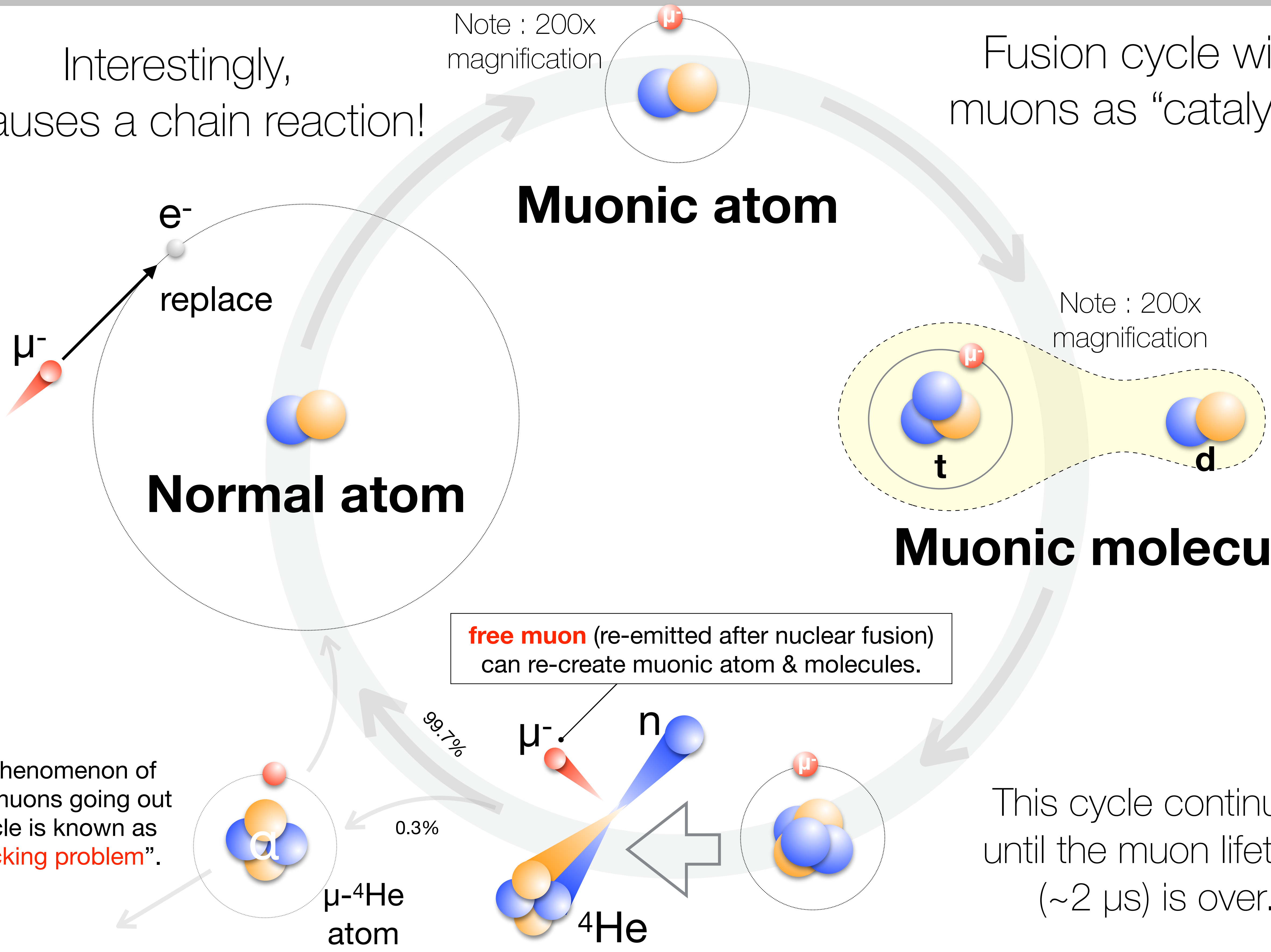


No repulsion by electromagnetic forces up to the size of a muonic molecule

Muon-Catalyzed Fusion (μCF)

Interestingly,
it causes a chain reaction!

Fusion cycle with
muons as “catalysts"



free muon (re-emitted after nuclear fusion)
can re-create muonic atom & molecules.

The phenomenon of
some muons going out
of cycle is known as
“α sticking problem”.

This cycle continues
until the muon lifetime
(~2 μs) is over.

Muon-Catalyzed Fusion (μCF)

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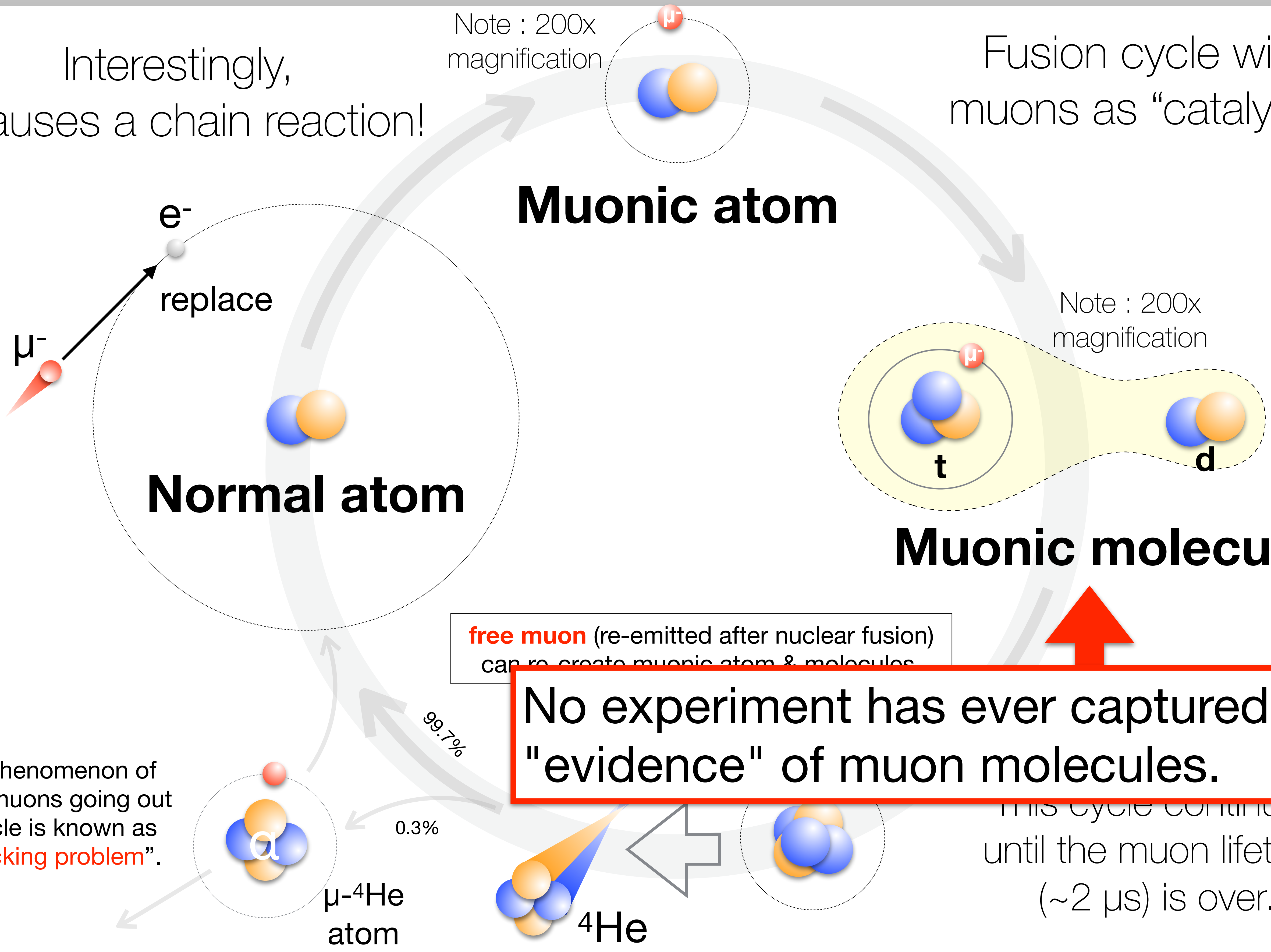


free muon (re-emitted after nuclear fusion)
can re-create muonic atom & molecules

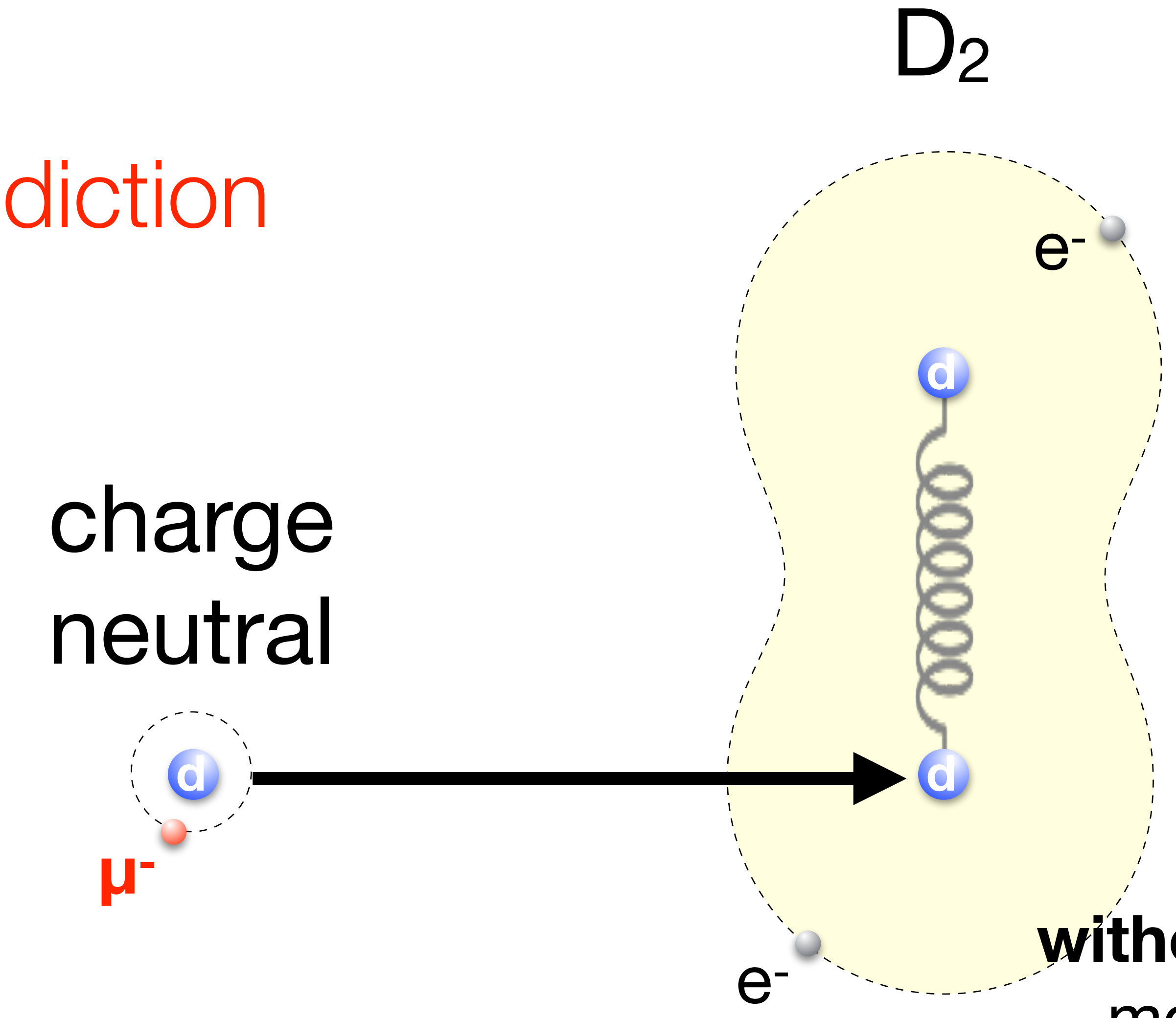
No experiment has ever captured "evidence" of muon molecules.

The phenomenon of
some muons going out
of cycle is known as
“α sticking problem”.

This cycle continues
until the muon lifetime
(~2 μs) is over.

How μ molecules are created ?

Theoretical Prediction



without destroying the molecular skeleton

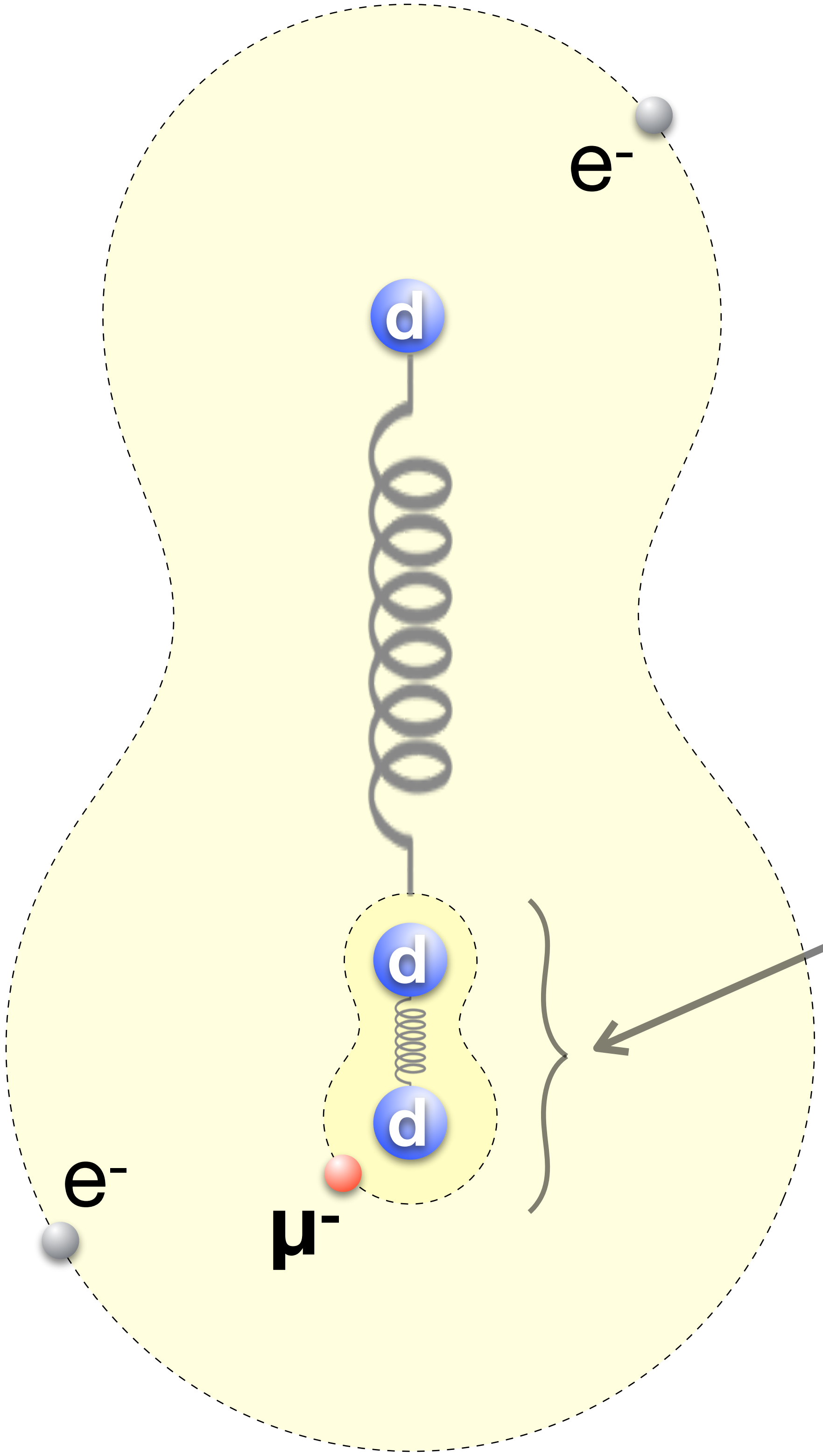
If the muonic atom collide "**gently**" to the normal molecule, the excess energy of ddμ molecule formation is passed to the rovibrational excitation energy of D_2 molecule.

⇒ Resonant generation (Vesman mechanism)

Molecule in molecule !

Theoretical prediction

Matryoshka-like



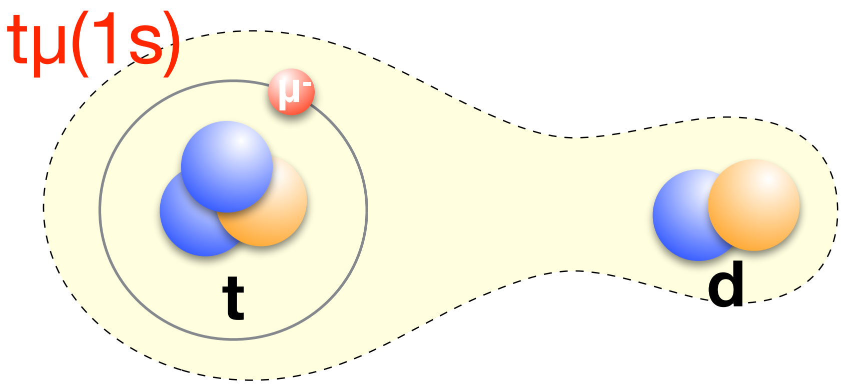
ddμ molecule

Forms a molecule within a molecule by acting as a **pseudo-nucleus** with charge +1

Key point of the new μCF process

Ground state

dtμ

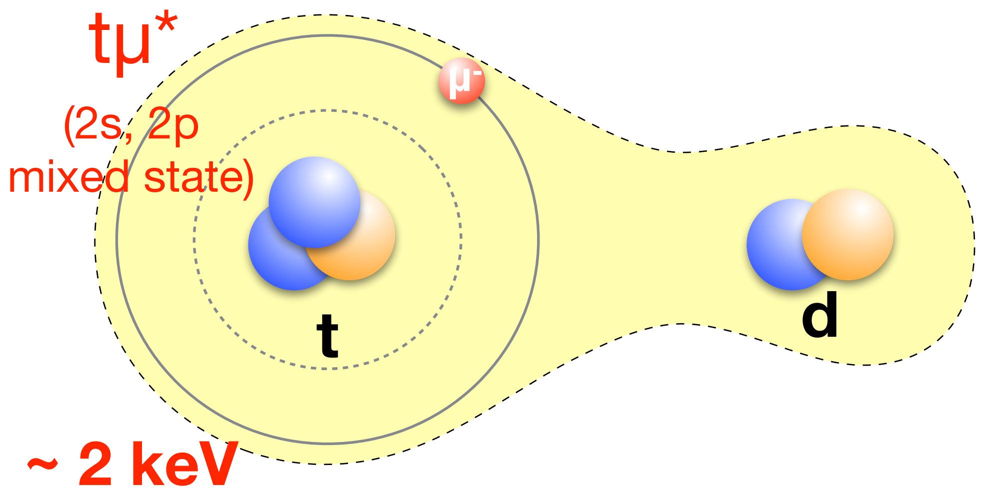


Immediately leading to **nuclear fusion**

No chance to measure ↑

Excited state

dtμ*



~ 2 keV excitation

No nuclear fusion, but dissociates while **emitting X-rays**

Measure this ↑

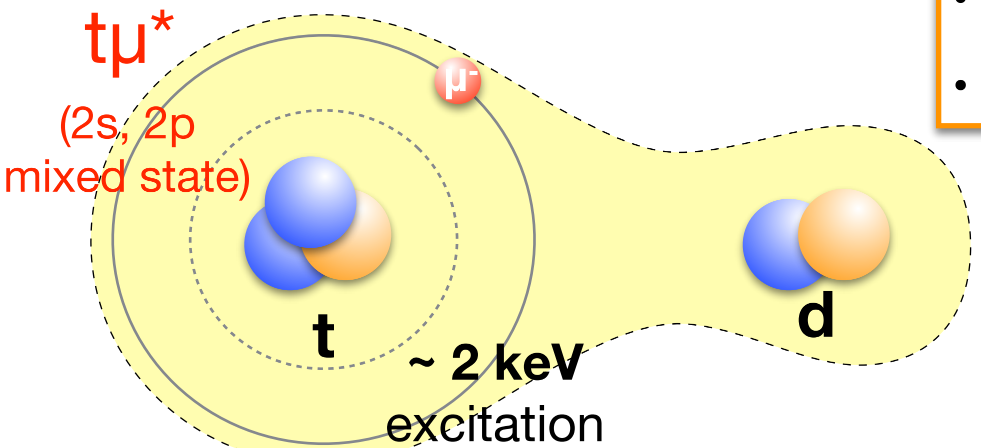
to determine what quantum states are being produced and how.

Dissociation of excited molecules

- Metastable Excited Molecule
- Size ~10^{-12} m
- Structure with μ localized on one side

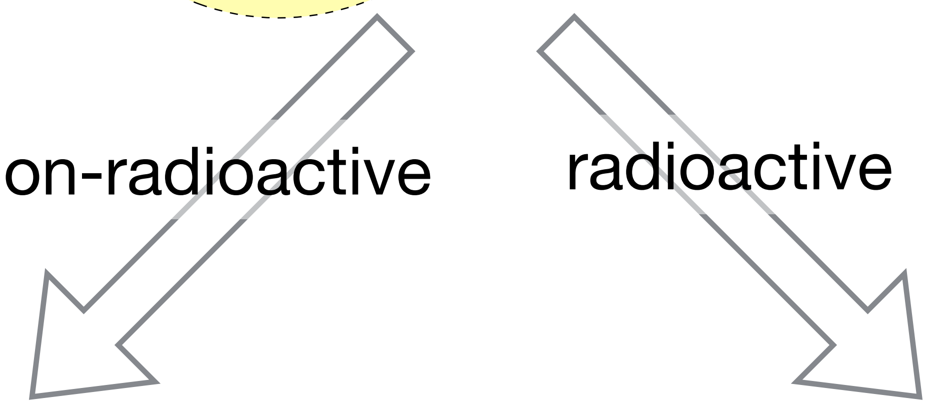
At first glance, it appears to have nothing to do with fusion because it dissociates.

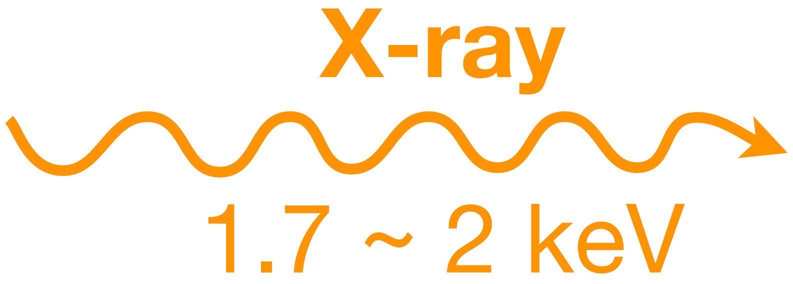
But, the high-energy **“electrically neutral”** muonic hydrogen atoms after the dissociation suggest the possibility of **direct fusion**.

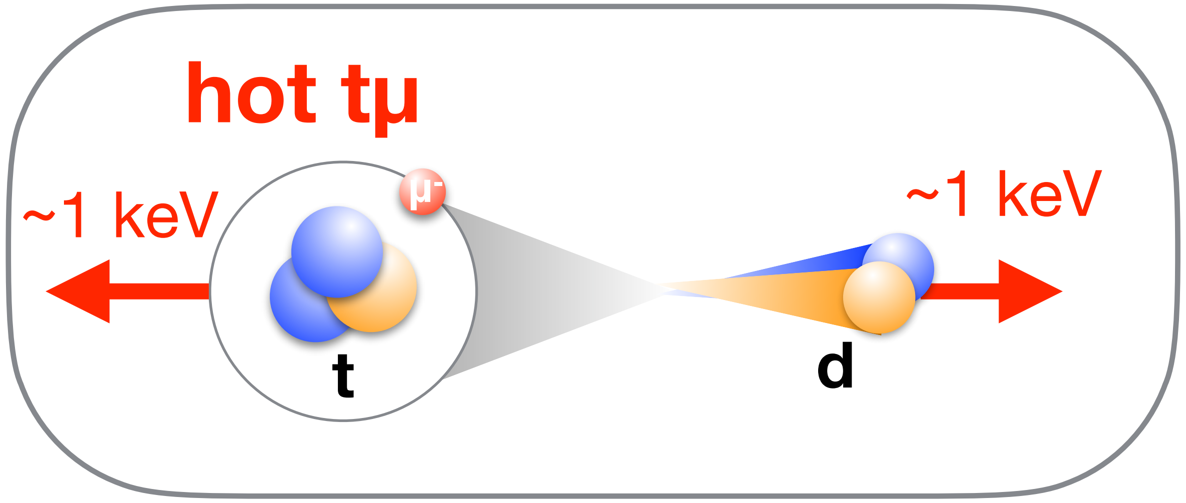


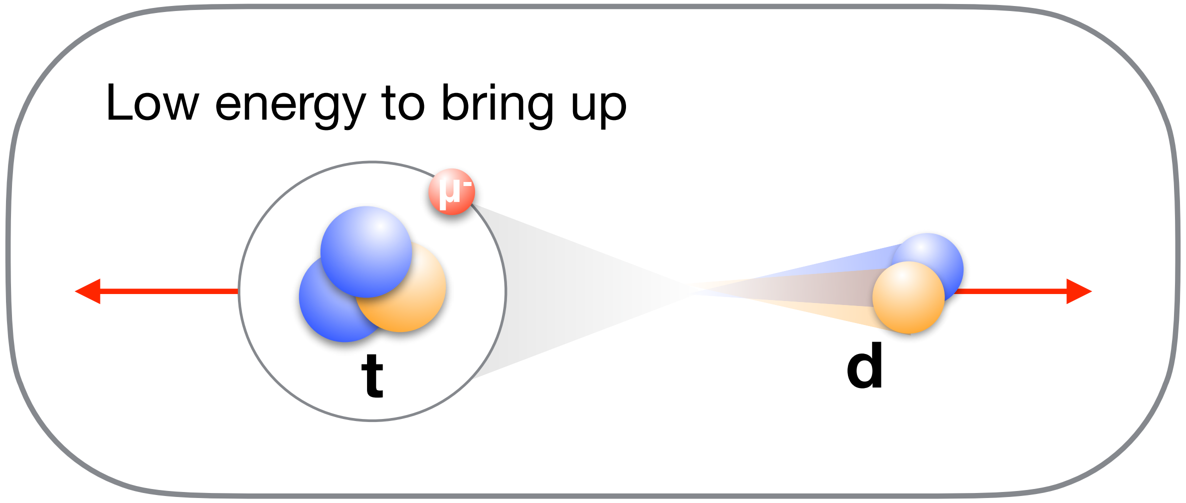
Precise measurement of X-rays enables the study of molecular resonance states.

New μCF elementary processes







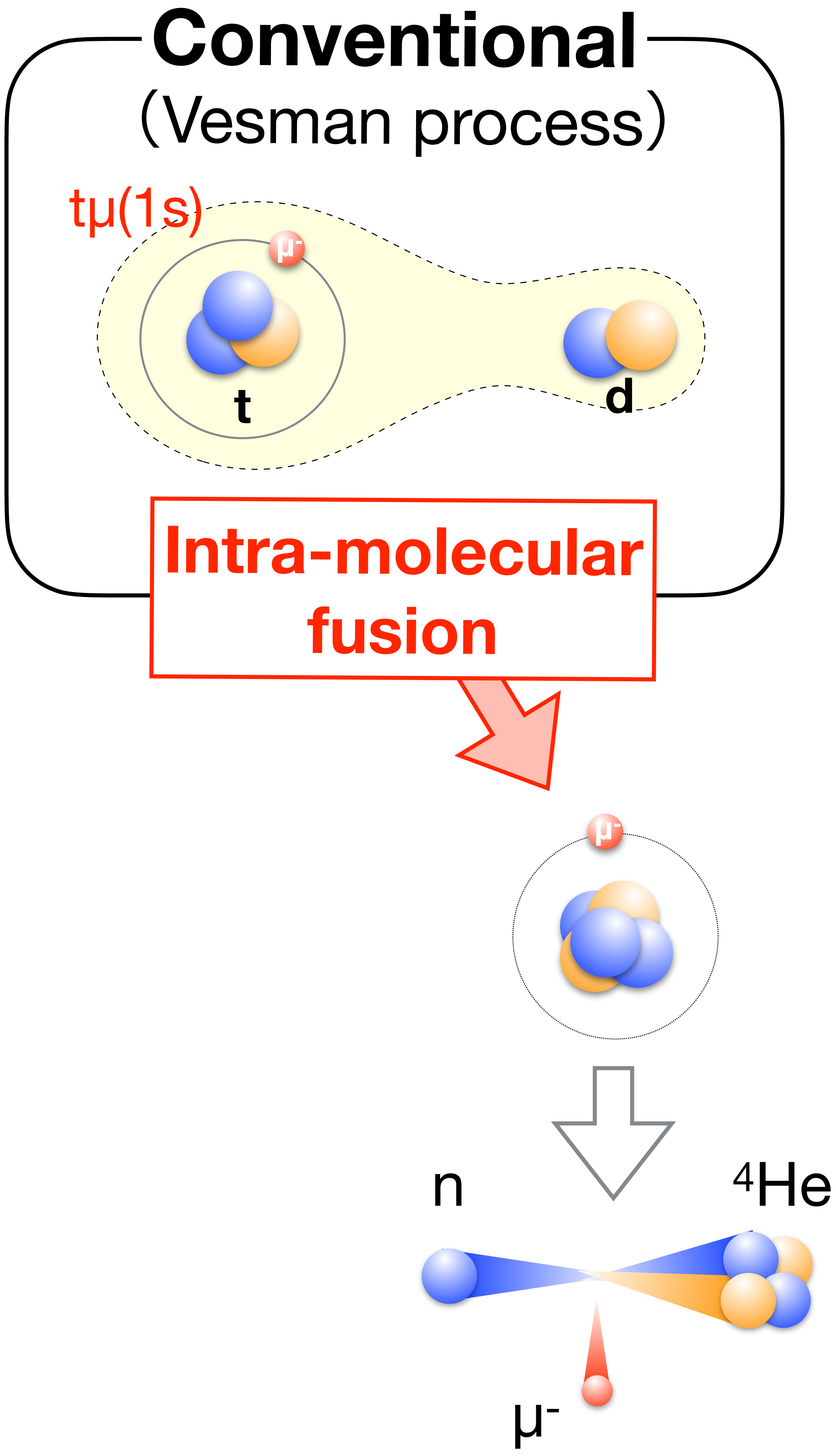


Inflight μCF study

X-ray precision spectroscopy

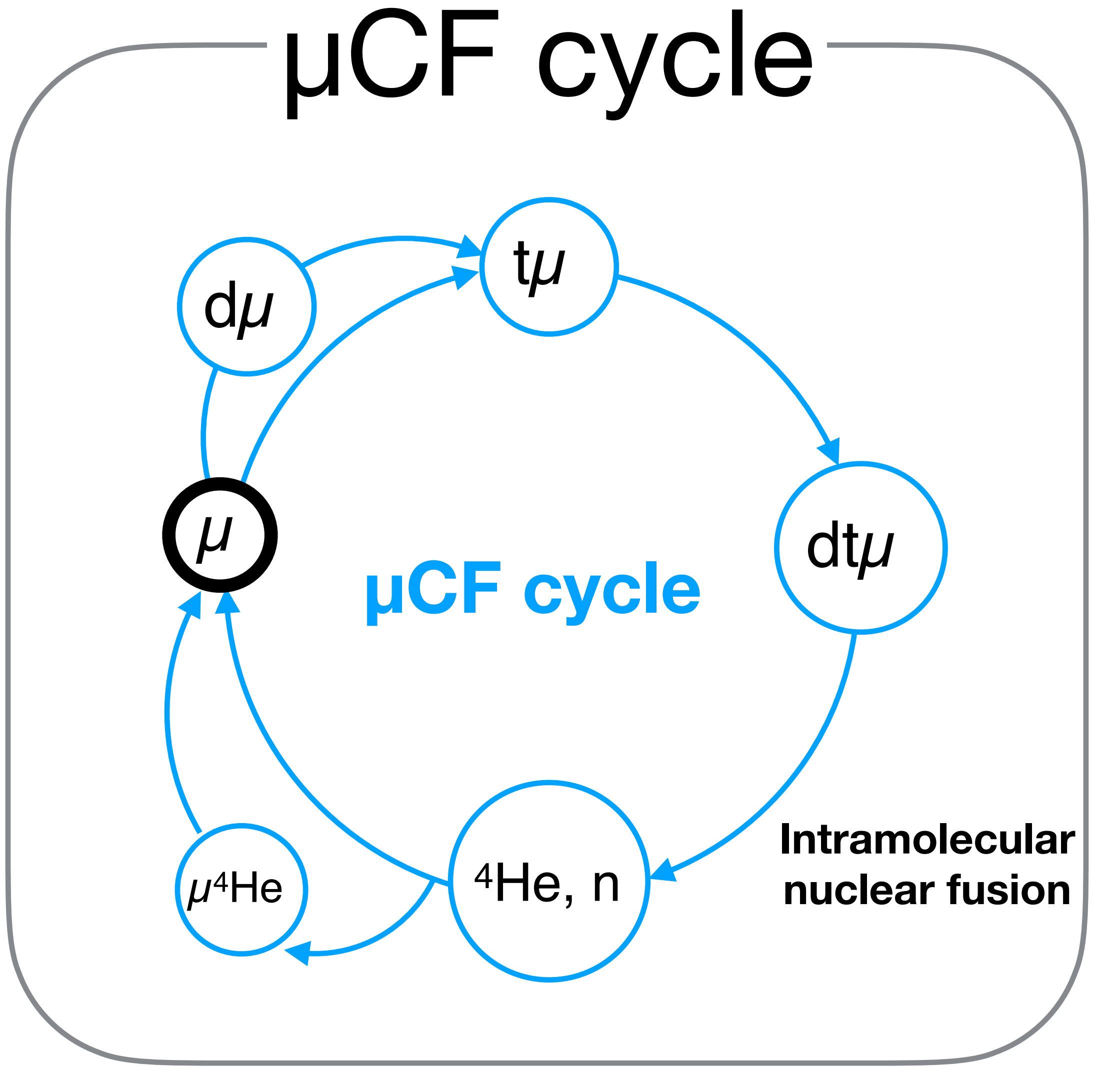
Conventional

(Vesman process)

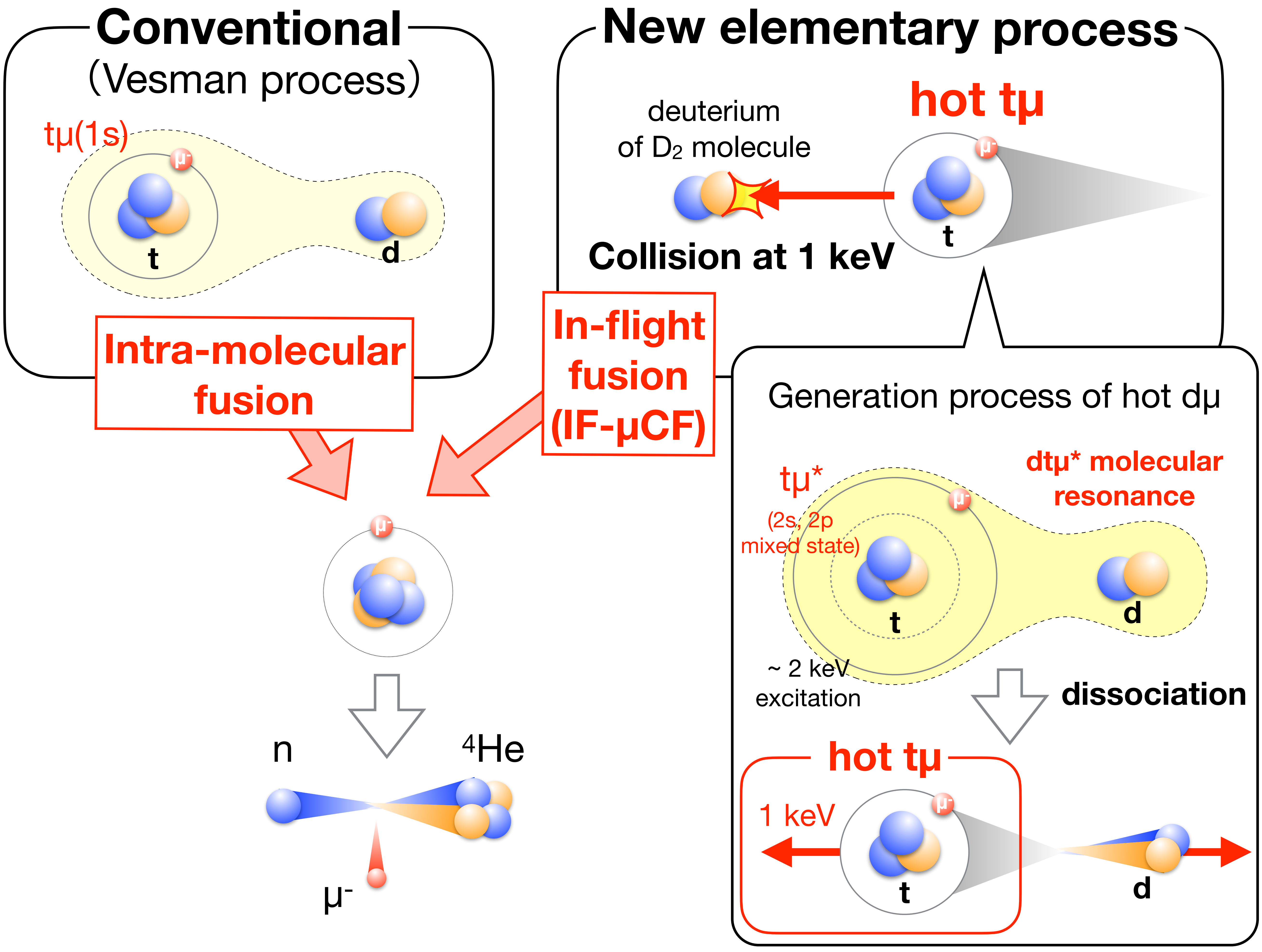


Intra-molecular fusion

μCF cycle



Intramolecular nuclear fusion

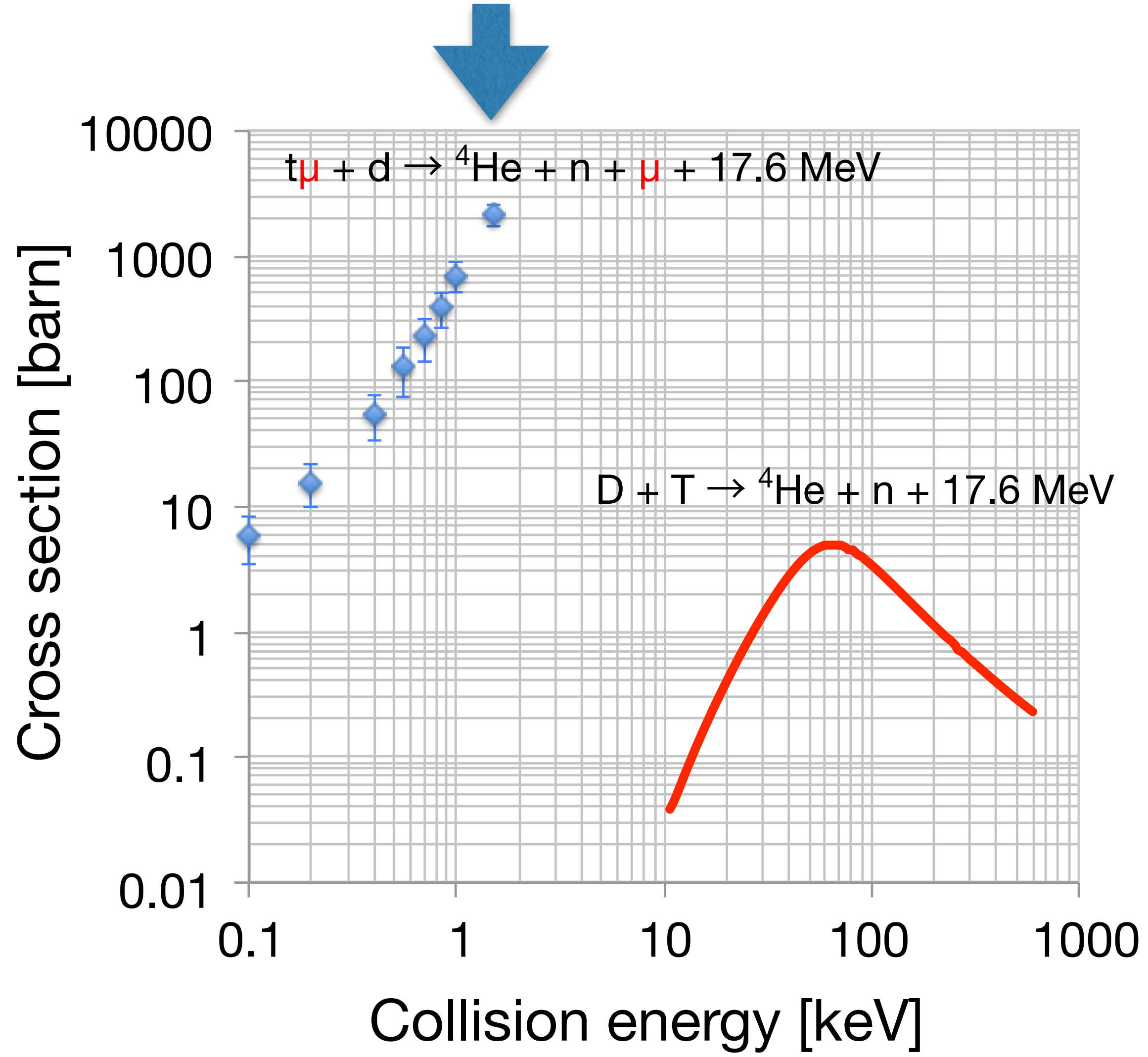

Conventional
(Vesman process)
tμ(1s)
μ-
t
d
Intra-molecular fusion
New elementary process
deuterium of D2 molecule
hot tμ
μ-
t
Collision at 1 keV
In-flight fusion (IF-μCF)
Generation process of hot dμ
tμ*
(2s, 2p mixed state)
μ-
dtμ* molecular resonance
t
d
~ 2 keV excitation
dissociation
hot tμ
1 keV
μ-
t
d
μ-
n
4He
μ-

Conventional

(Vesman process)

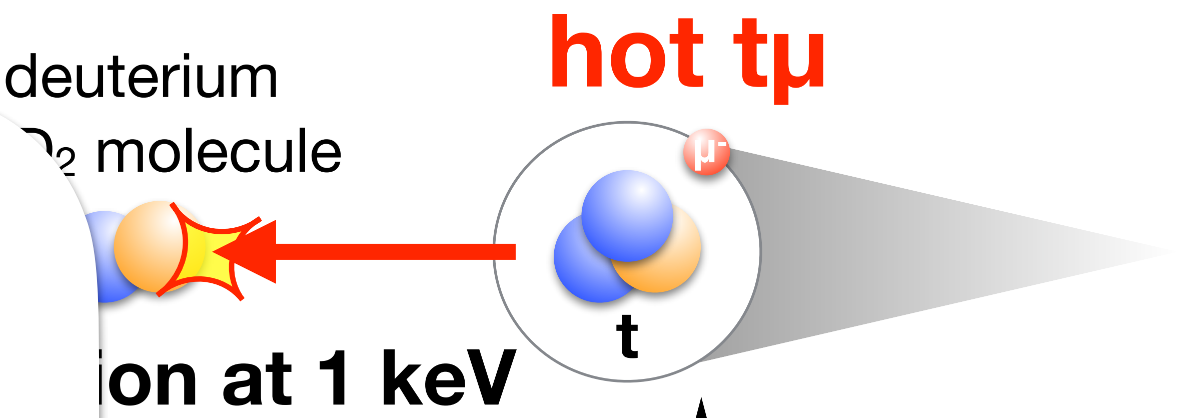
tμ(1

In-flight μCF : higher cross-section



AIP Conference Proceedings 2179, 020010 (2019)

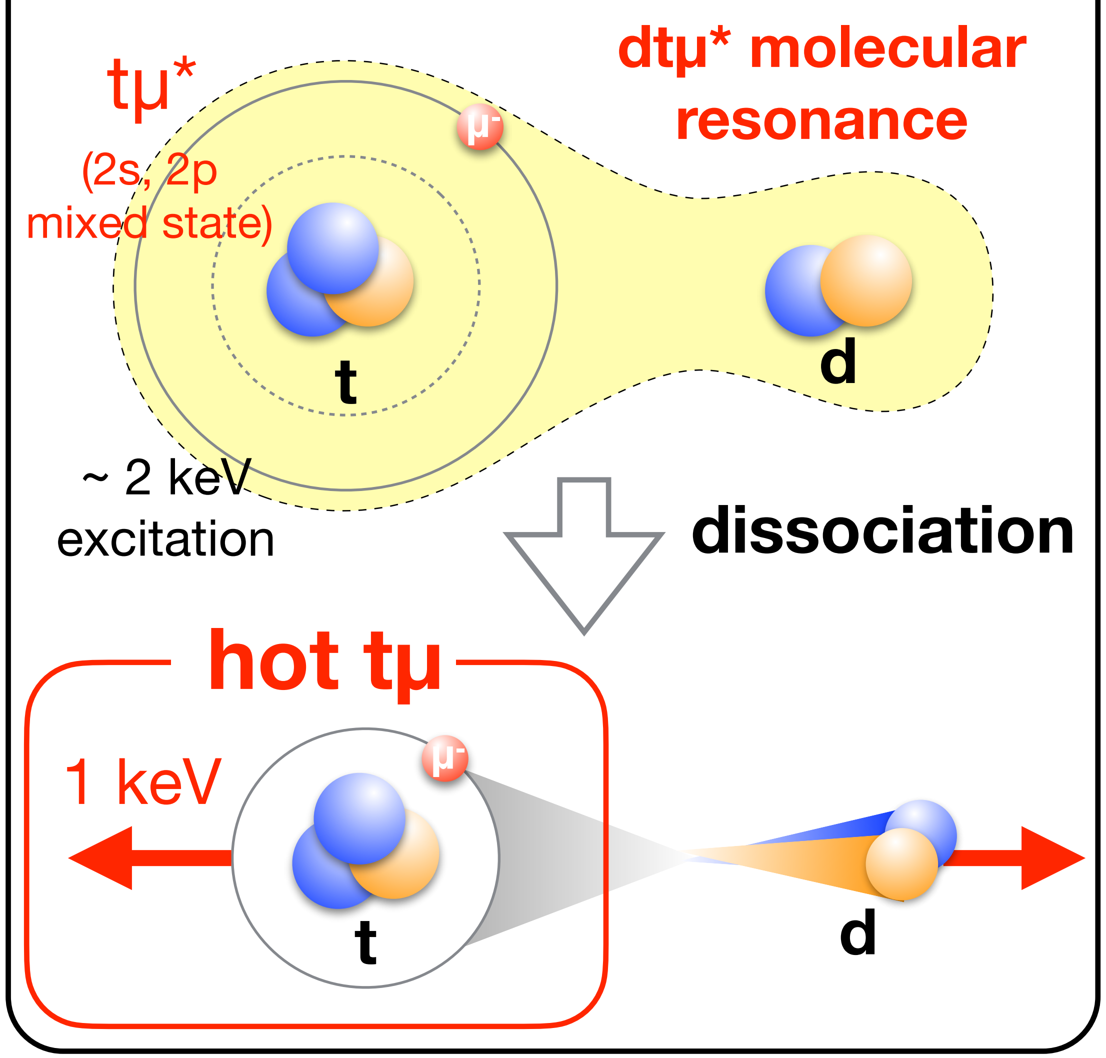
New elementary process



t

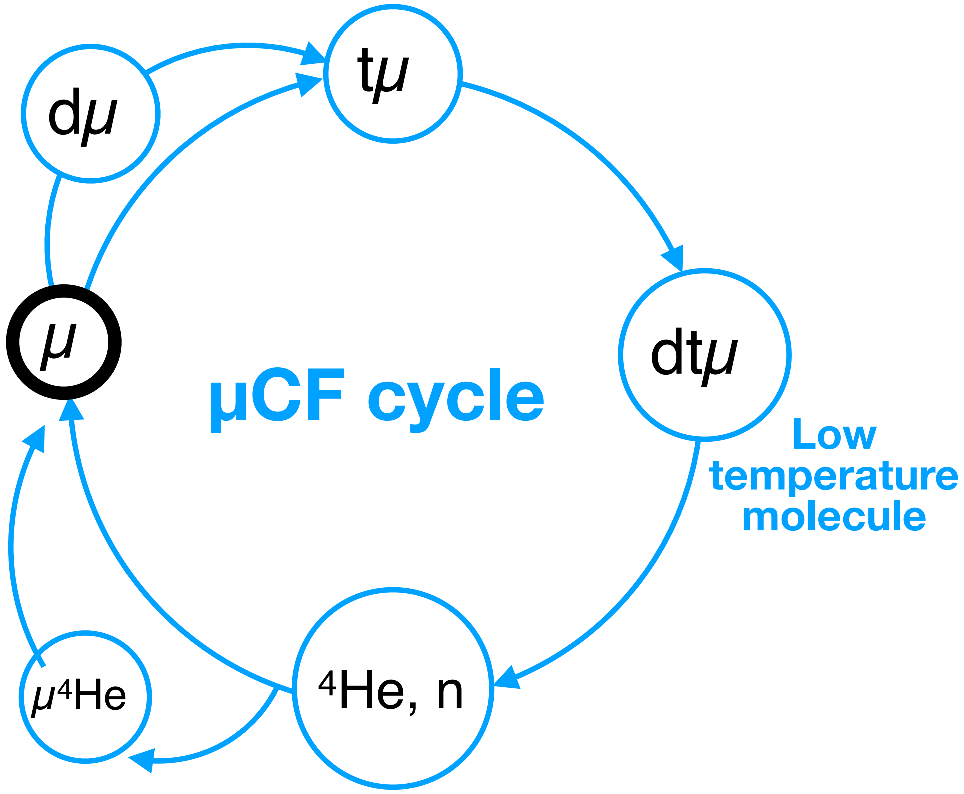
)

Generation process of hot dμ

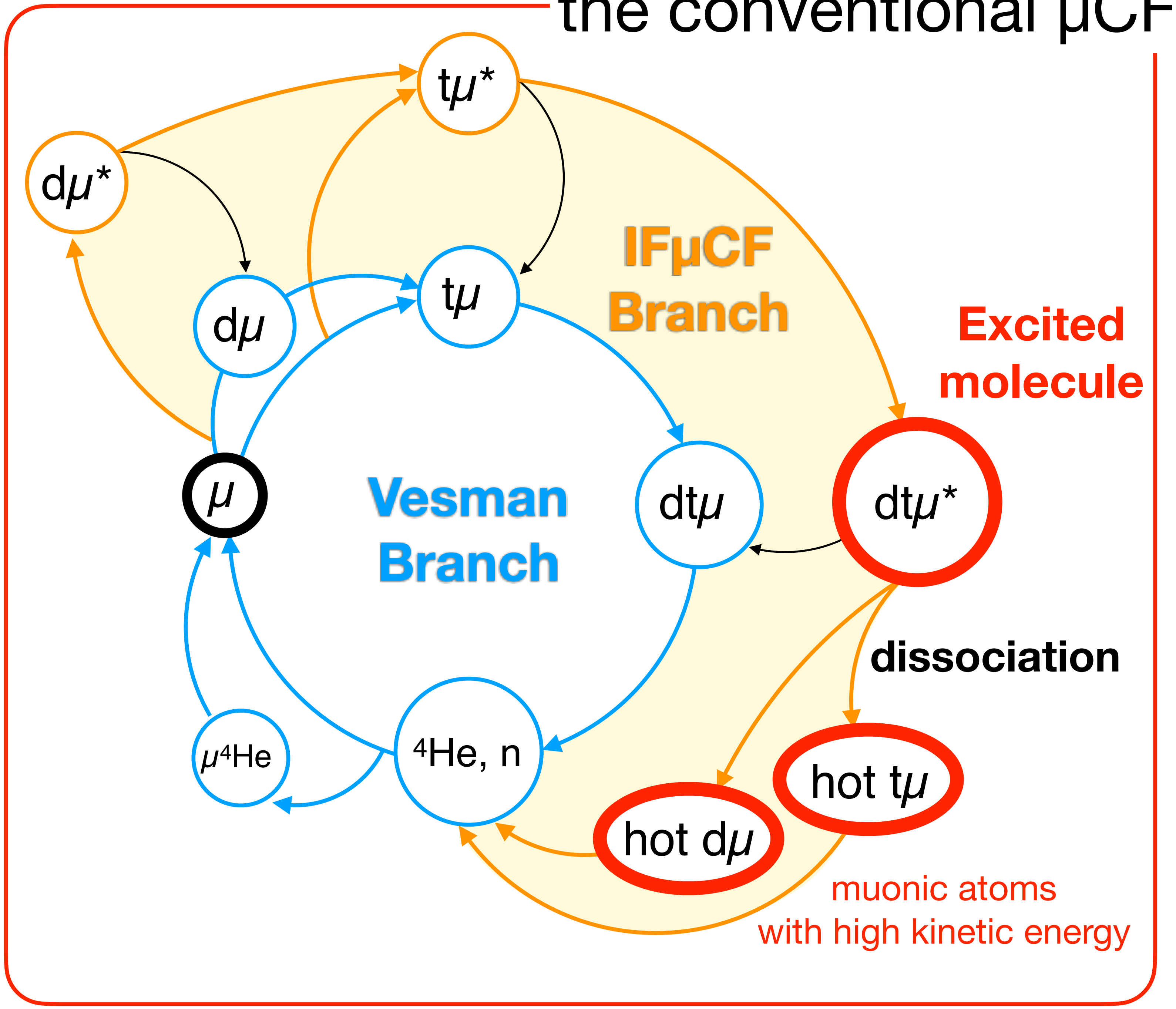


μCF cycle considering "excited molecules"

Conventional μCF cycle
(Vesman model)



In-flight μCF joins
the conventional μCF



(Sidepath model)

It has been suggested that this process may reduce "α sticking",
and the formation rate is faster than the ordinary μCF process.
→ So it is important to study the mechanism to enhance the IFμCF process.

Importance of dtμ* was demonstrated

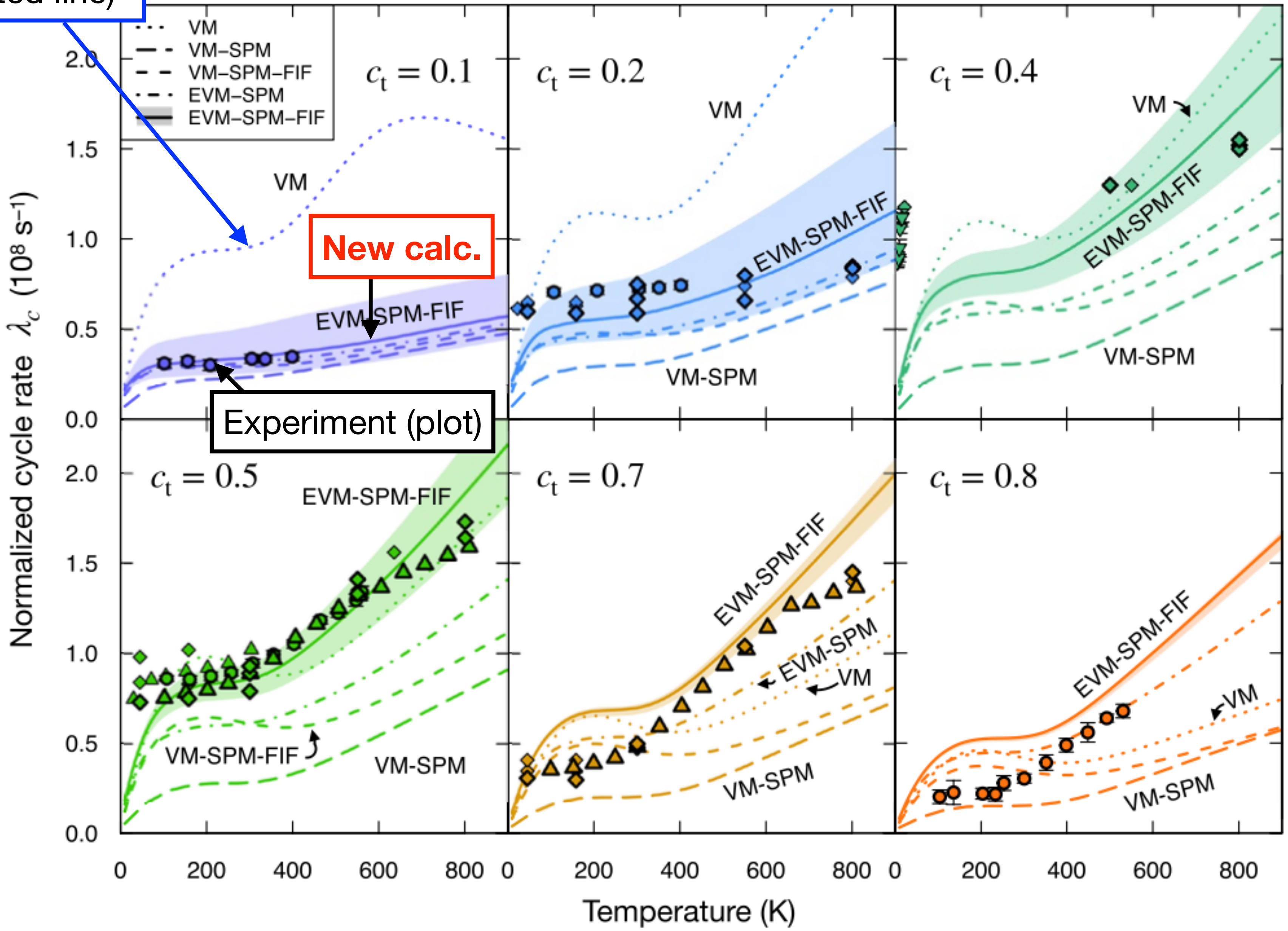
New few-body many-body calculation

breaking away from adiabatic approximation: (dtμ*)e-

→ 4-body calculation including electrons

Conventional theory

(dotted line)



New calc.

Experiment (plot)

Succeeded in explaining the temperature dependence

of the μCF reaction rates,

which could not be explained

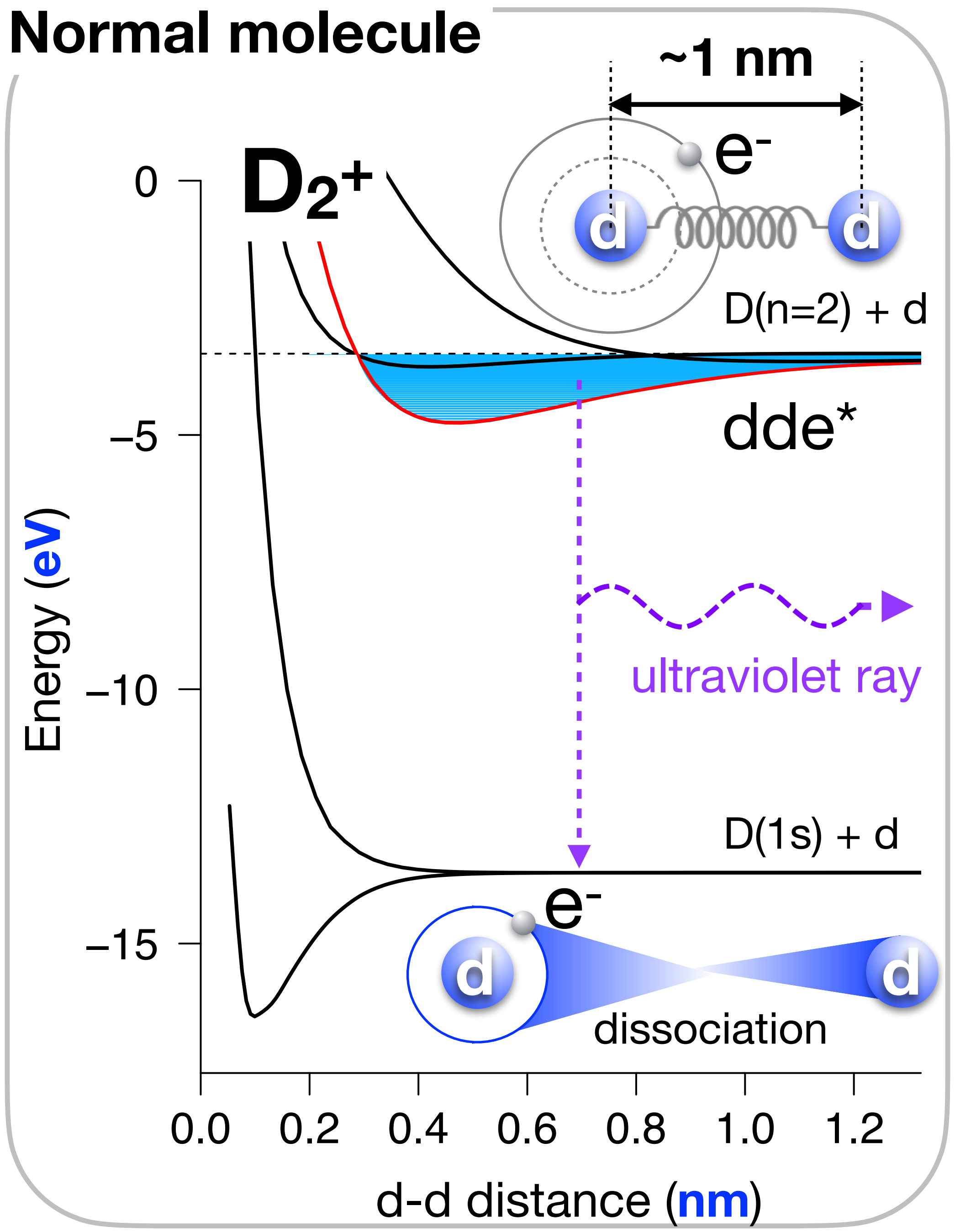
by the conventional μCF cycle.

T. Yamashita et al.,

Sci. Rep.12 (2022) 6393

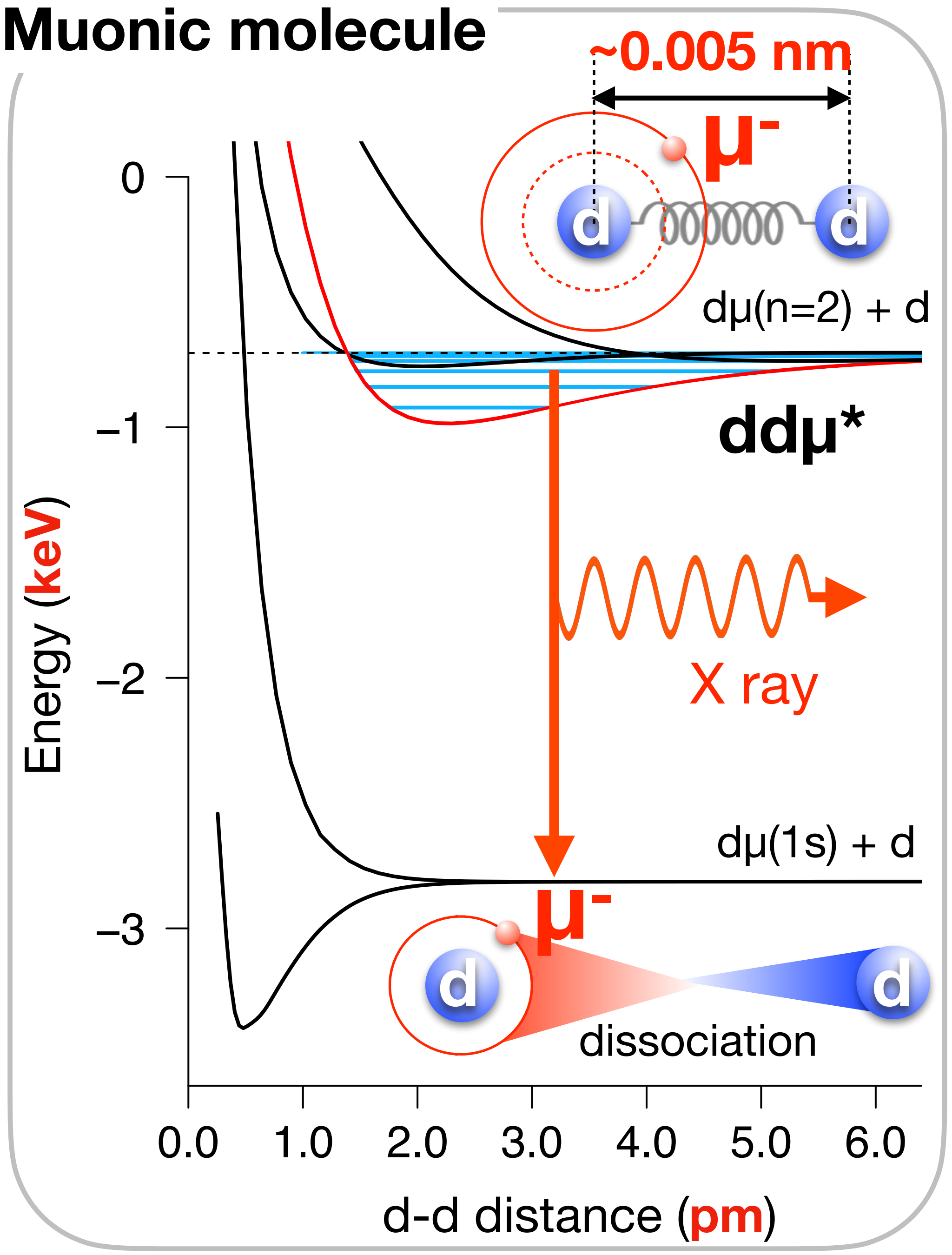
⇒ Aiming for direct experimental verification

High Precision Spectroscopy of **Muonic Molecules**



Normal molecule

- Distance between nuclei : x 1/200
- Energy : x 200
- **Adiabatic approximation is not valid** due to close masses of d and μ
- ddμ* has large zero-point motion and **sparse level spacing**

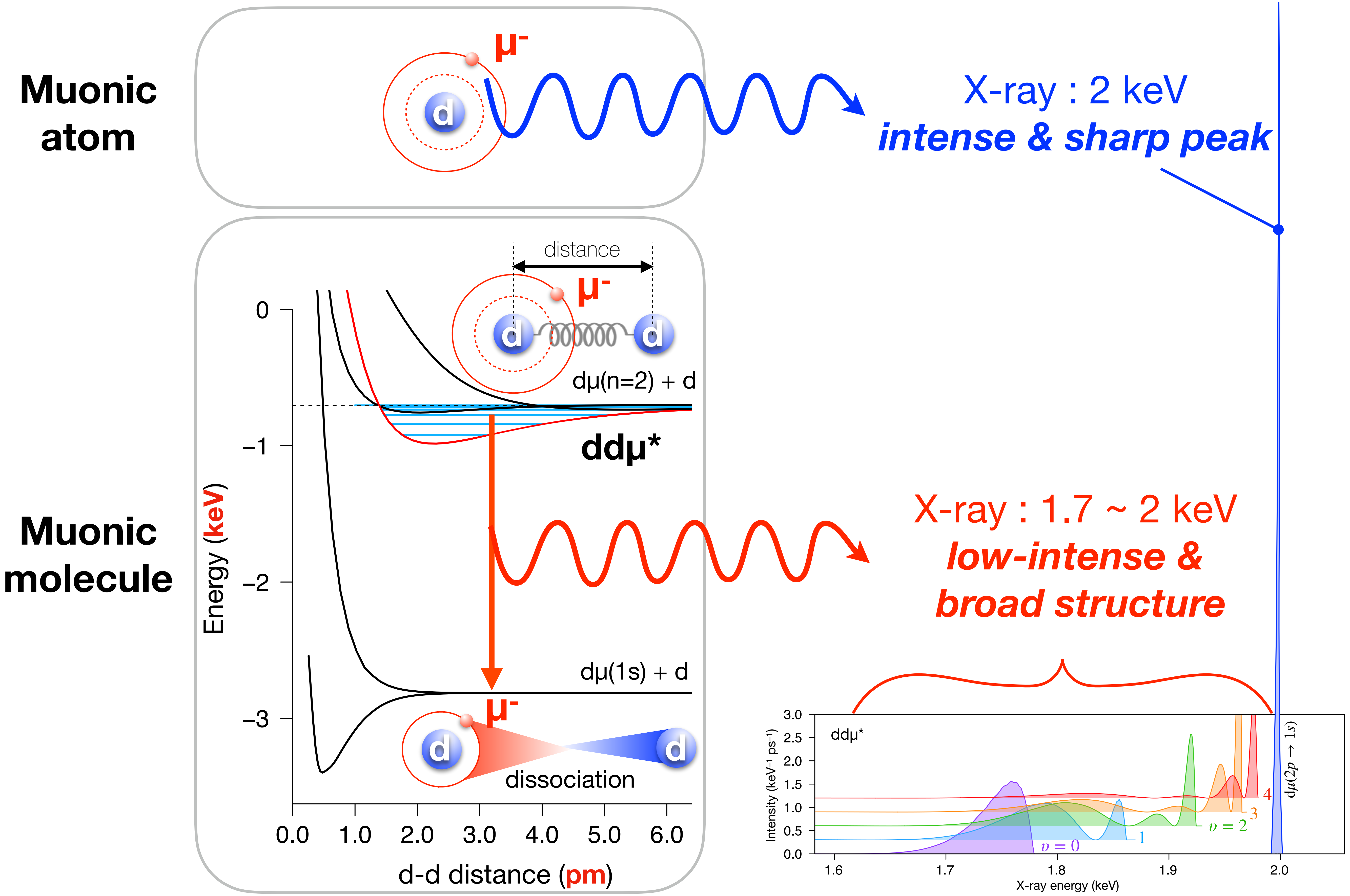


Muonic molecule

✤ Theory : **Few-body calculations** simultaneously solving for the motion of nuclei and heavy negatively charged particles

✤ Experimental : **High energy resolution** in X-ray measurements in muon beams

Difficulty of the measurement



Muonic atom

X-ray : 2 keV

intense & sharp peak

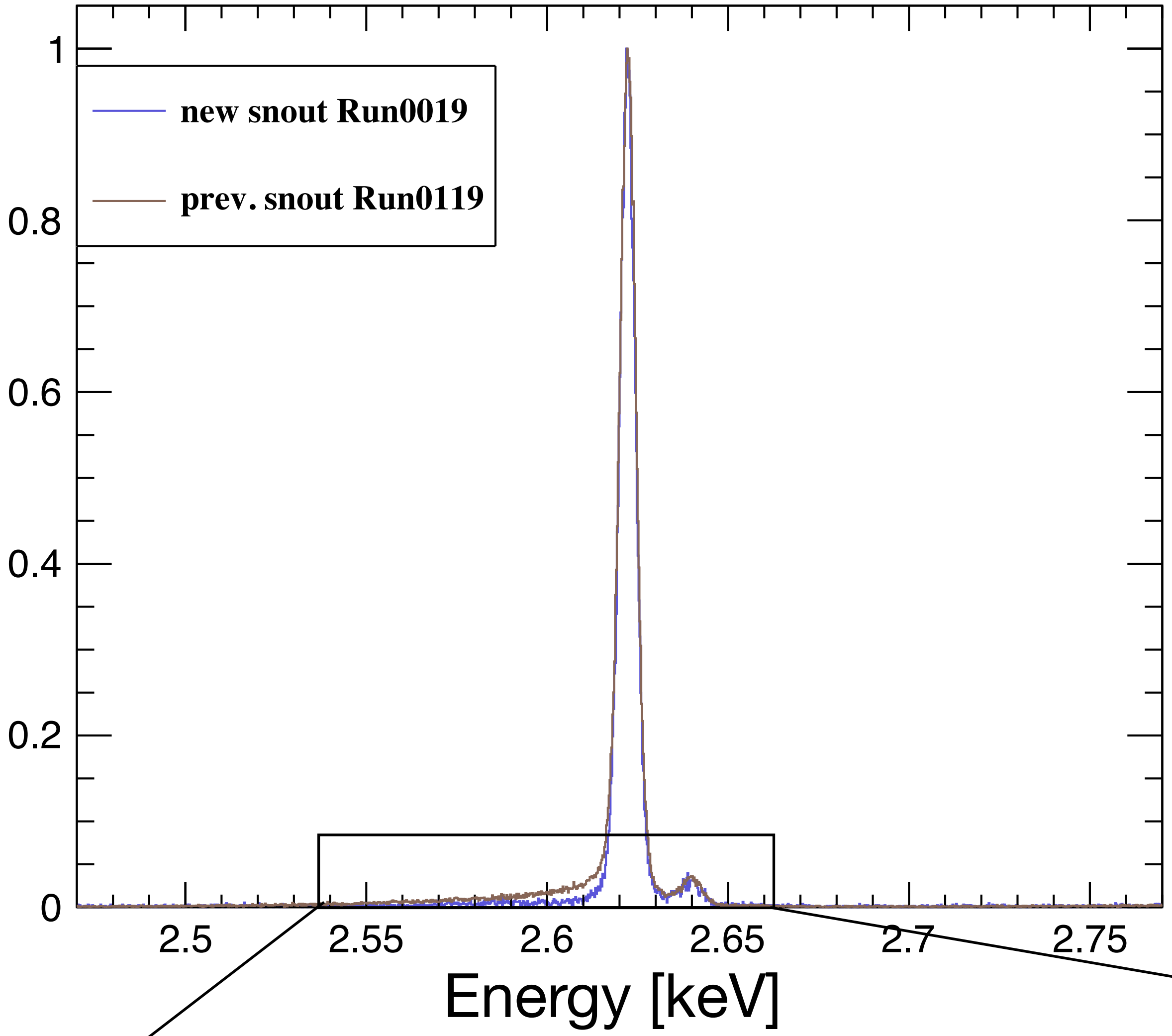
Muonic molecule

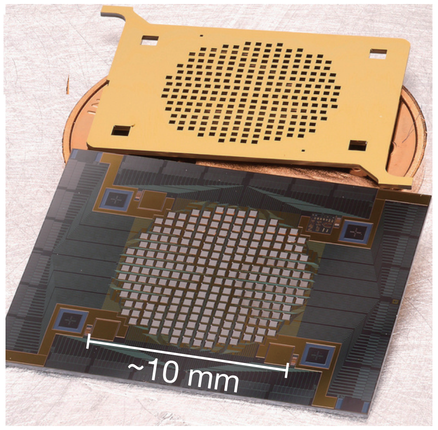
ddμ*

X-ray : 1.7 ~ 2 keV

low-intense & broad structure

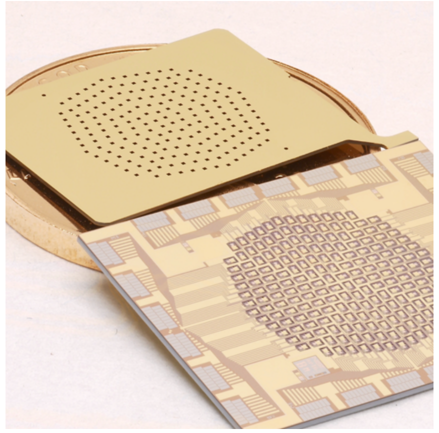
New TES : Less tail component





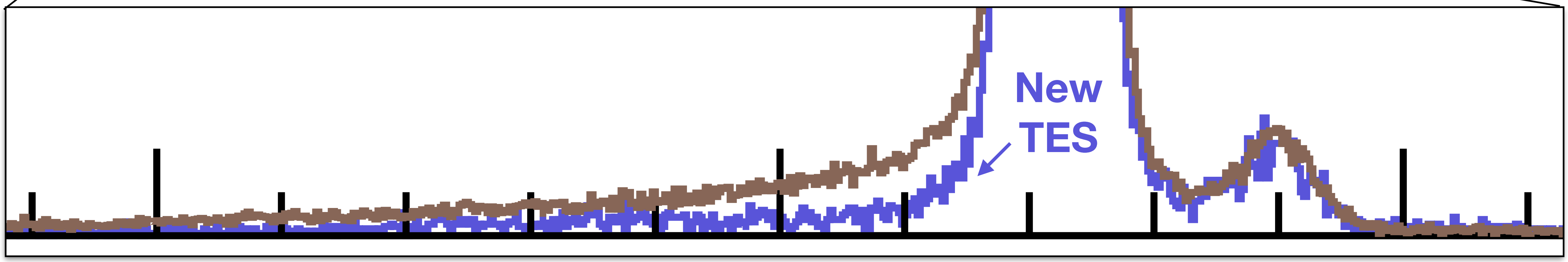
Original TES

Absorber : **Bi** (4.1 um)
# of Pixel : 240
(61% for 8 keV)



New TES
for Low energy X-ray

Absorber : **Au** (965 nm)
# of Pixel : 192
(32% for 8 keV)



Experimental setup

Feb 5 - 11, 2023

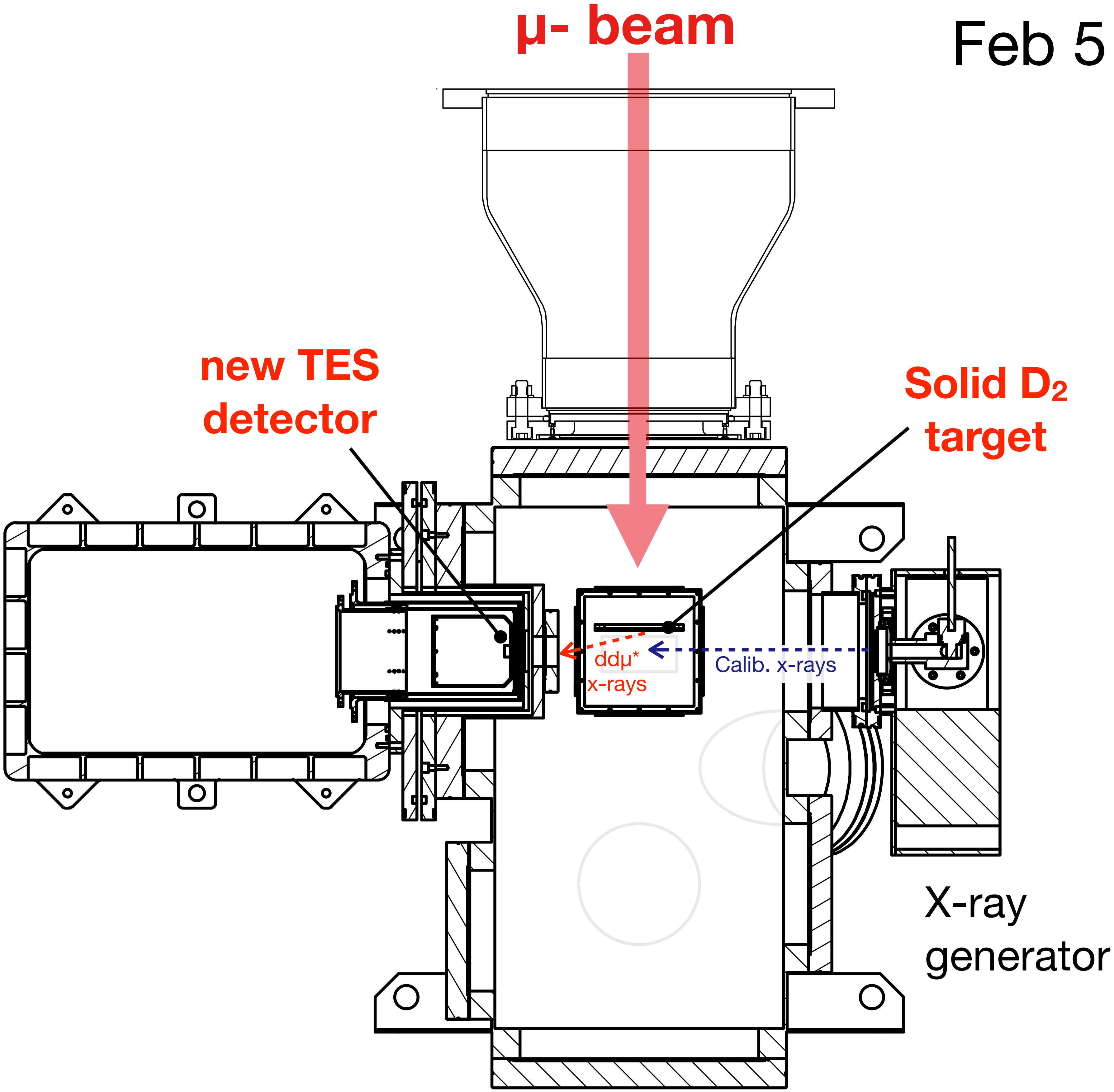
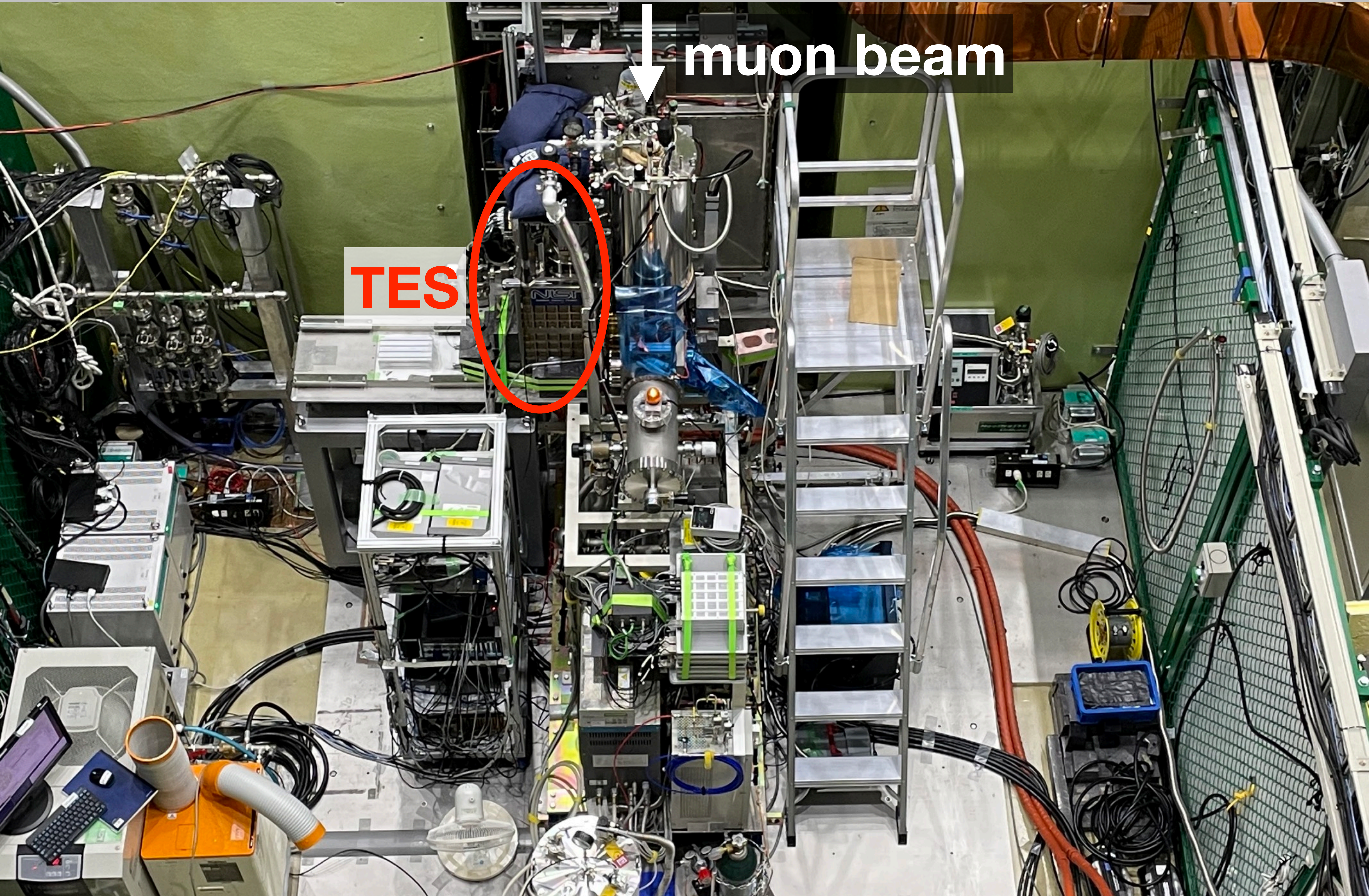
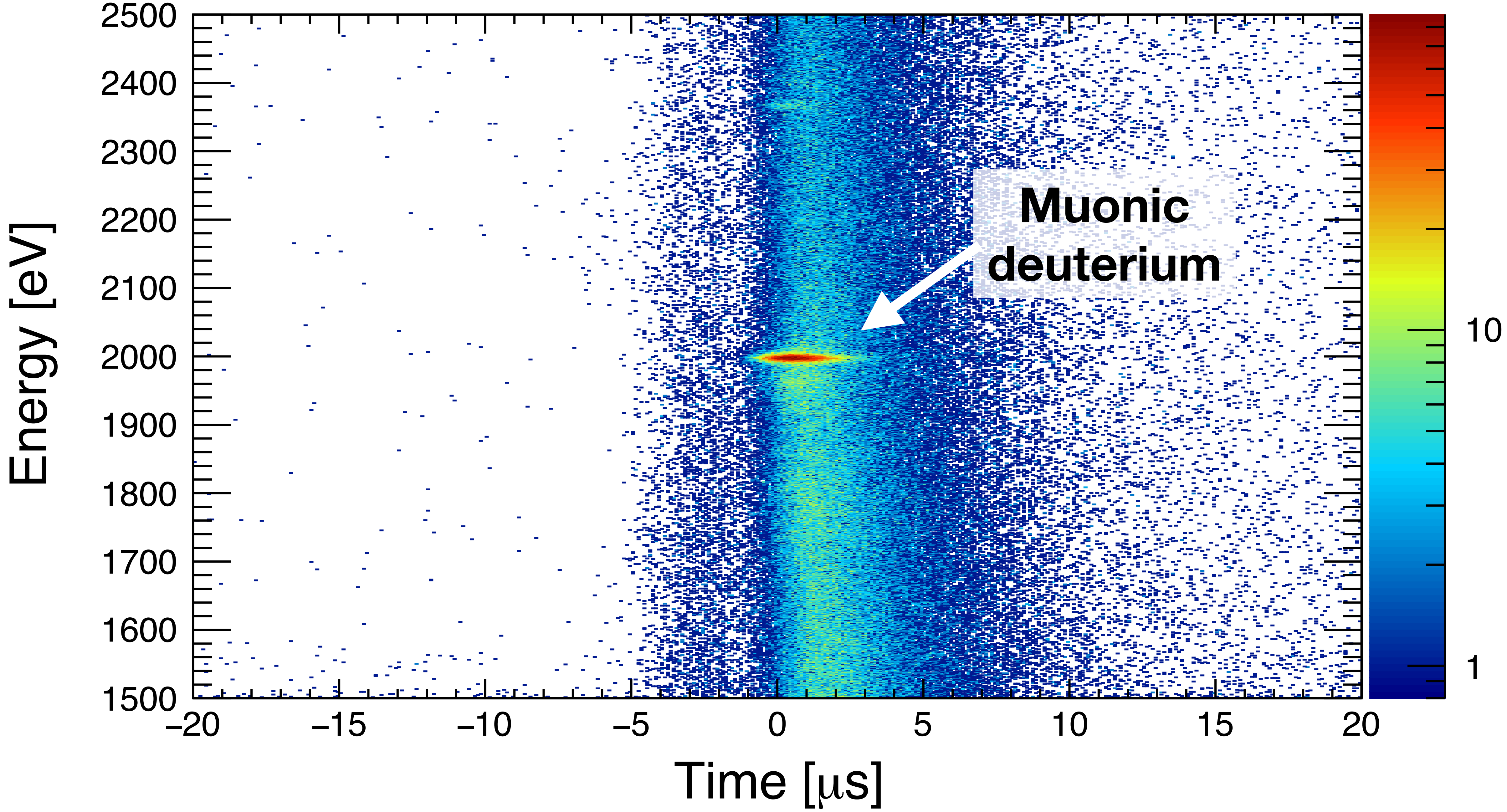


Photo at beamline

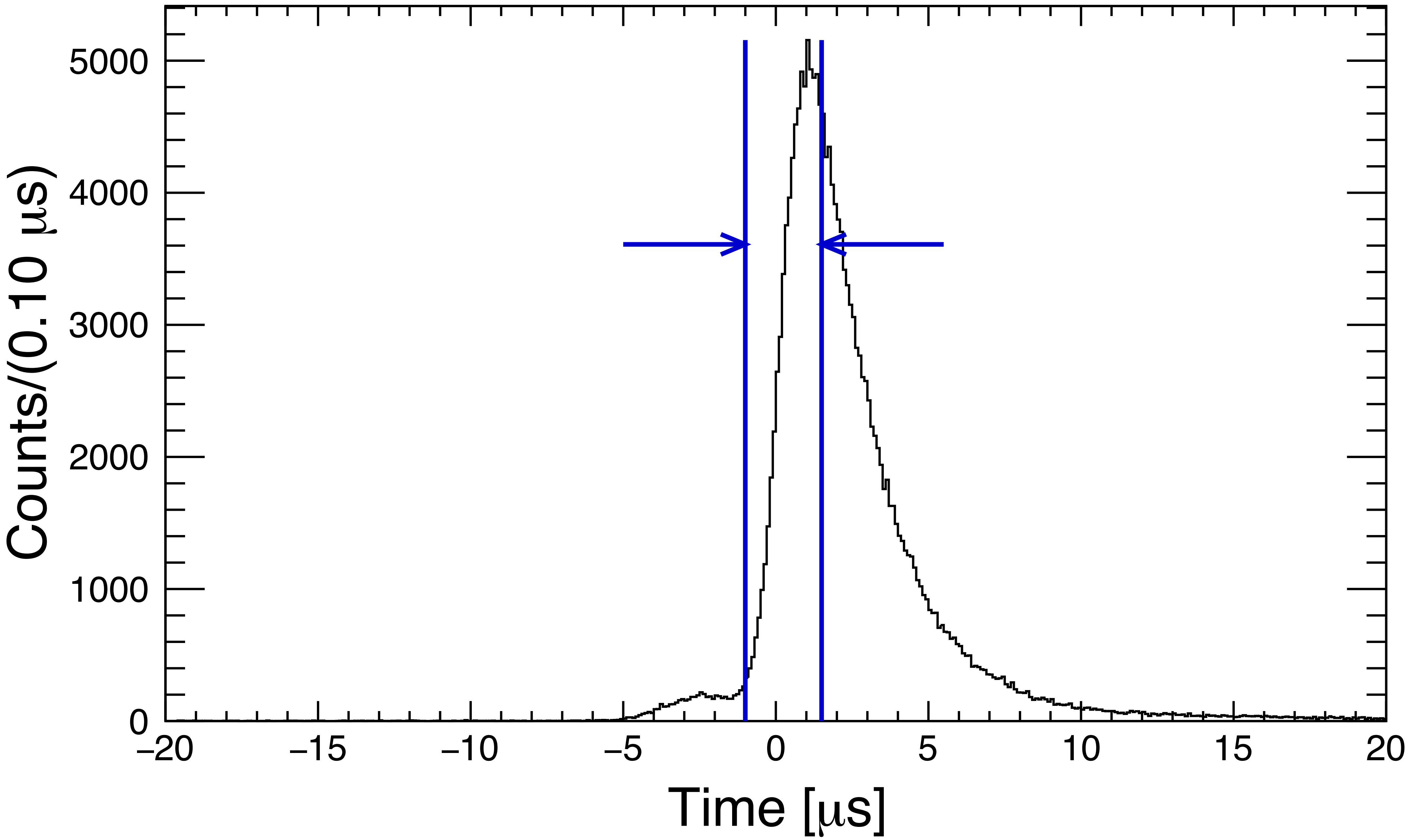


Energy vs. Time



Muonic deuterium

Timing cut


Counts/(0.10 μs)
5000
4000
3000
2000
1000
0
–20
–15
–10
–5
0
5
10
15
20
Time [μs]

4. Summary & Outlook

Summary

◉ The following **advantages of TES** have made it possible to conduct accelerator experiments that were not possible before

1. Combination of energy resolution and detection efficiency (multi-pixel)

   Kaonic atoms

   ➡ High-precision absolute energy measurement for very rare events

2. Covering a wide energy range with high resolution

   Muonic molecule

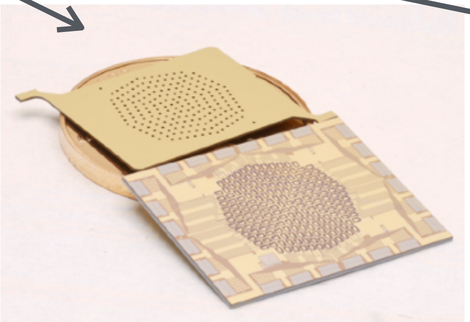
   ➡ Interesting broad structures are now visible in detail. This was not possible with the crystal spectrometer.

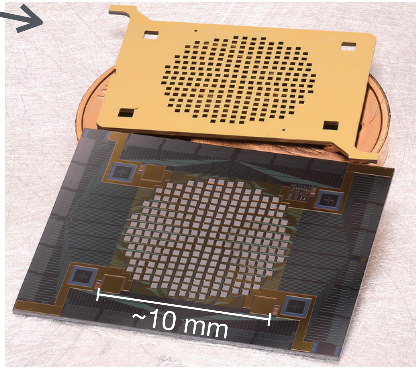
Developed TES for high-energy X-rays

Name	5 keV TES	10 keV TES	50 keV TES	100 keV TES
Saturation energy	10 keV	20 keV	70 keV	150 keV
Readout system	TDM	TDM	microwave	microwave
Absorber thickness (material)	0.965 μm (Au)	4.1 μm (Bi)	1.85 μm (Au) & 20 μm (Bi)	0.5 mm (Sn)
Absorber area	0.34 x 0.34 mm^2	0.320 x 0.305 mm^2	0.73 x 0.73 mm^2	1.3 x 1.3 mm^2
Absorber collimated area	0.28 x 0.28 mm^2	0.305 x 0.290 mm^2	0.67 x 0.67 mm^2	(no collimator)
Number of pixel	192	240	96	96
Total collection area	15.1 mm^2	21.2 mm^2	43.1 mm^2	162 mm^2
ΔE (FWHM)	5 eV @ 6 keV	5 eV @ 6 keV	20 eV @ 40 keV (8 eV @ 17 keV)	60~70 eV @ 130 keV

Existing TES

(have been using since 2016)





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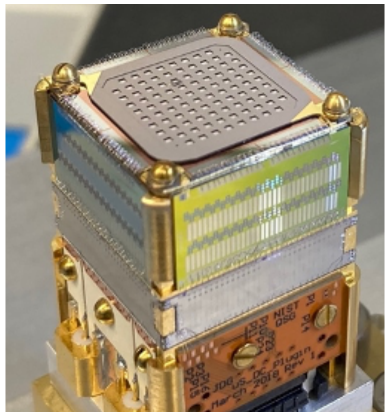
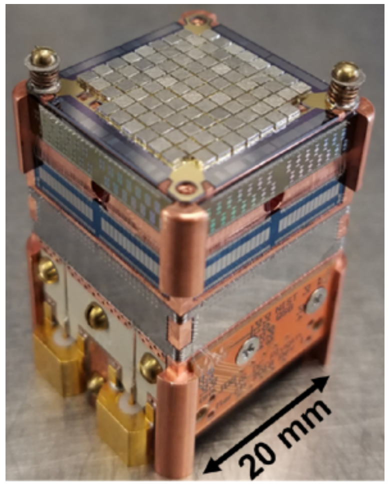
Brand-new TES detector

(brought from NIST this January)



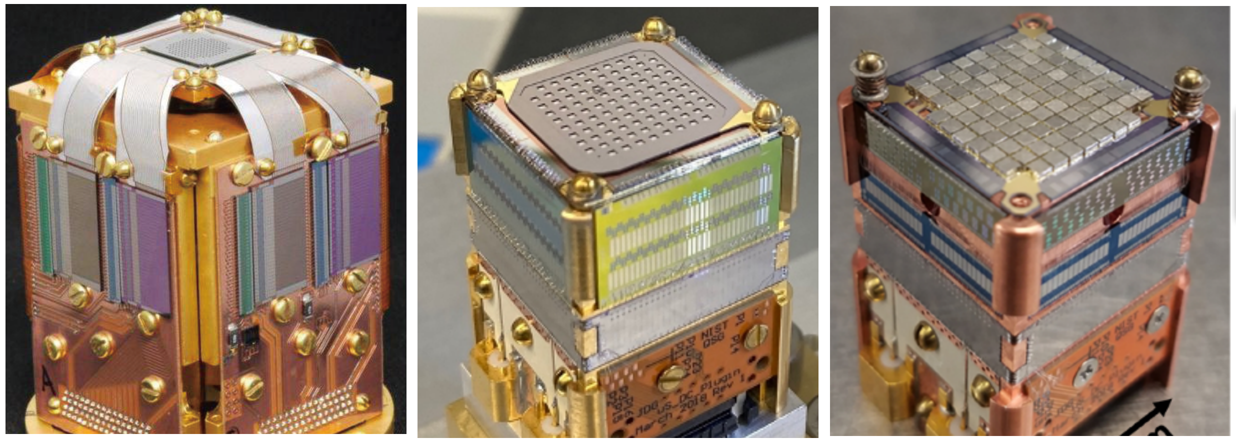


Outlook

◉ **A new proposal application** (muon S1 type) are being submitted for various experiments using this new TES system, very recently.

Next generation X-ray detector

covering a wide energy range

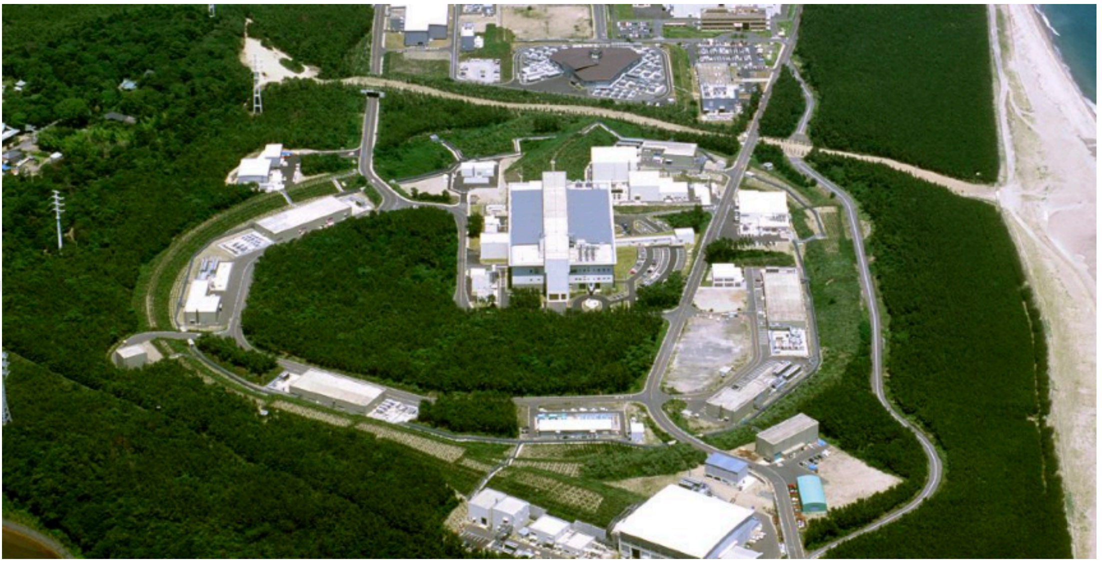


10 keV

50 keV

100 keV

J-PARC High-intensity μ^- source



From basic physics study to applications in non-destructive elemental analysis

- ✓ QED verification under strong electric field
- ✓ Metastable muonic molecules (related to μCF study)
- ✓ Nuclear radius
- ✓ Non-destructive analysis

I was allowed **to research freely** and our research is blossoming from **Kaon to Muon**.
Thank you very much, Prof. Iwasaki-san. **Happy retirement !**