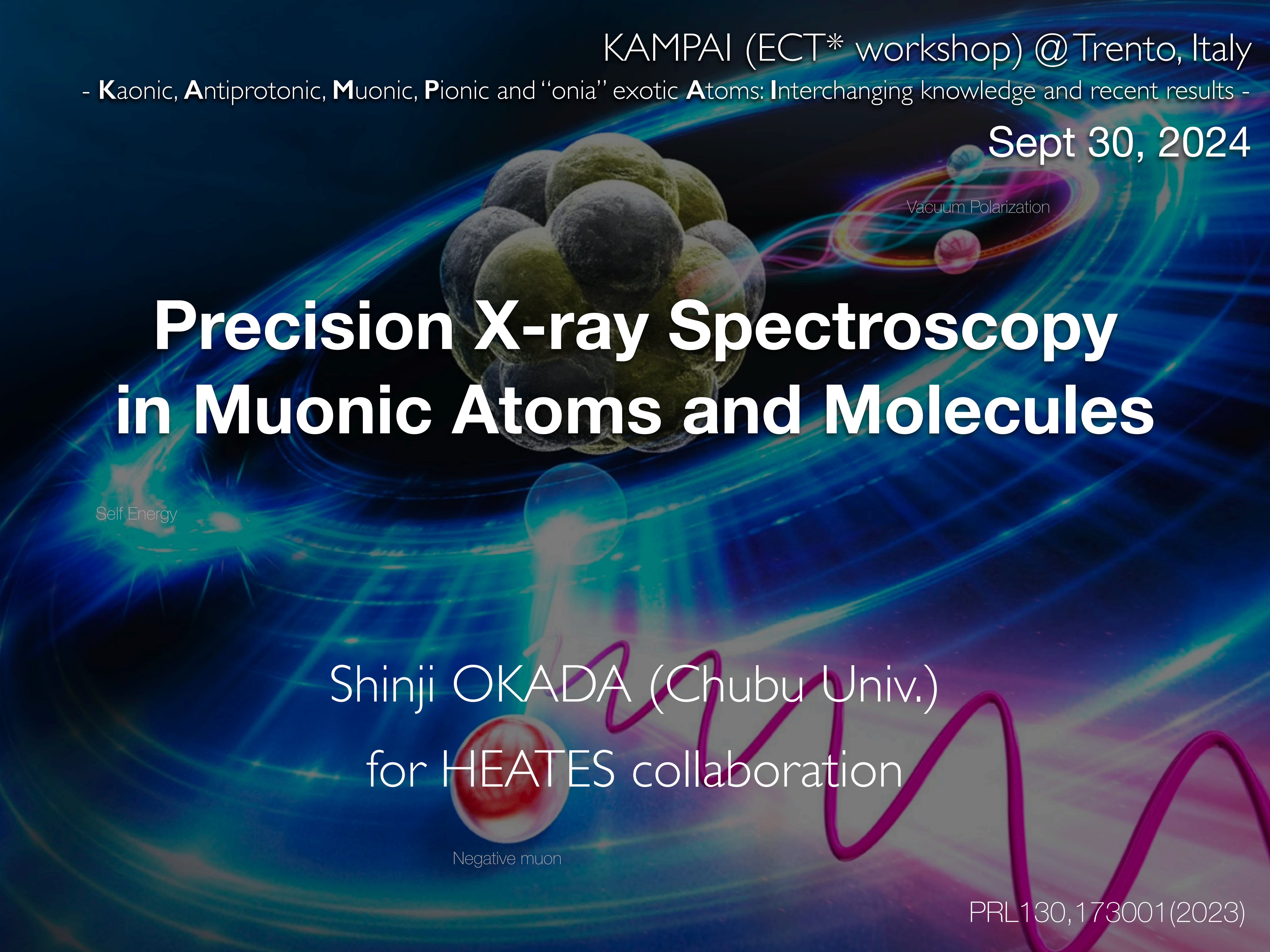
KAMPAI (ECT* workshop) @Trento, Italy

- **K**aonic, **A**ntiprotonic, **M**uonic, **P**ionic and "onia" exotic **A**toms: **I**nterchanging knowledge and recent results -

Sept 30, 2024



Precision X-ray Spectroscopy in Muonic Atoms and Molecules

Shinji OKADA (Chubu Univ.)

for HEATES collaboration

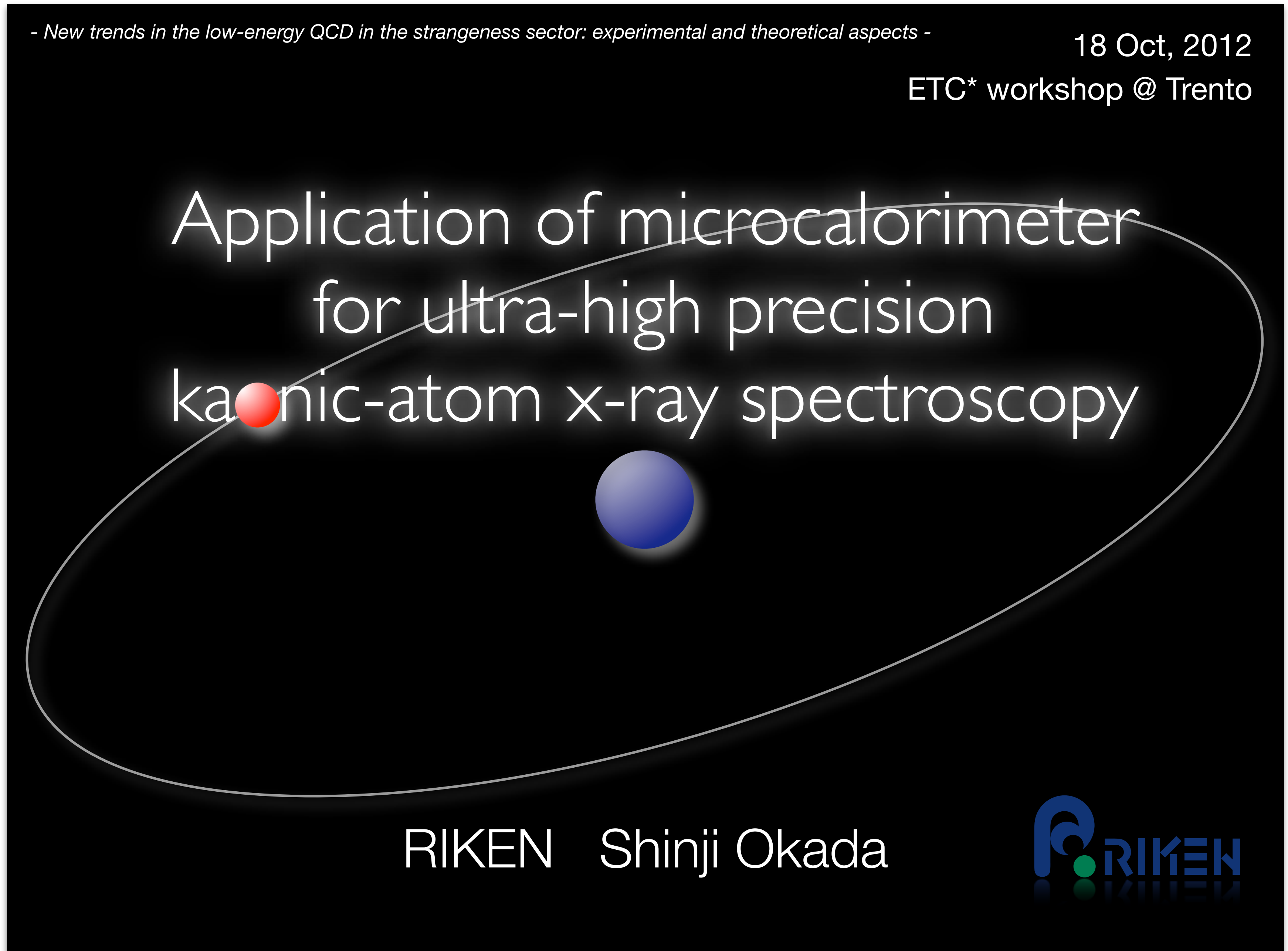
PRL130,173001(2023)

just 12 years ago here in ECT*

ECT* - Oct 2012


New trends in the low-energy QCD
in the strangeness sector :
experimental and theoretical aspects

My presentation 12 years ago



This was **“the idea stage”** of this project
before the “HEATES collaboration” with NIST began.

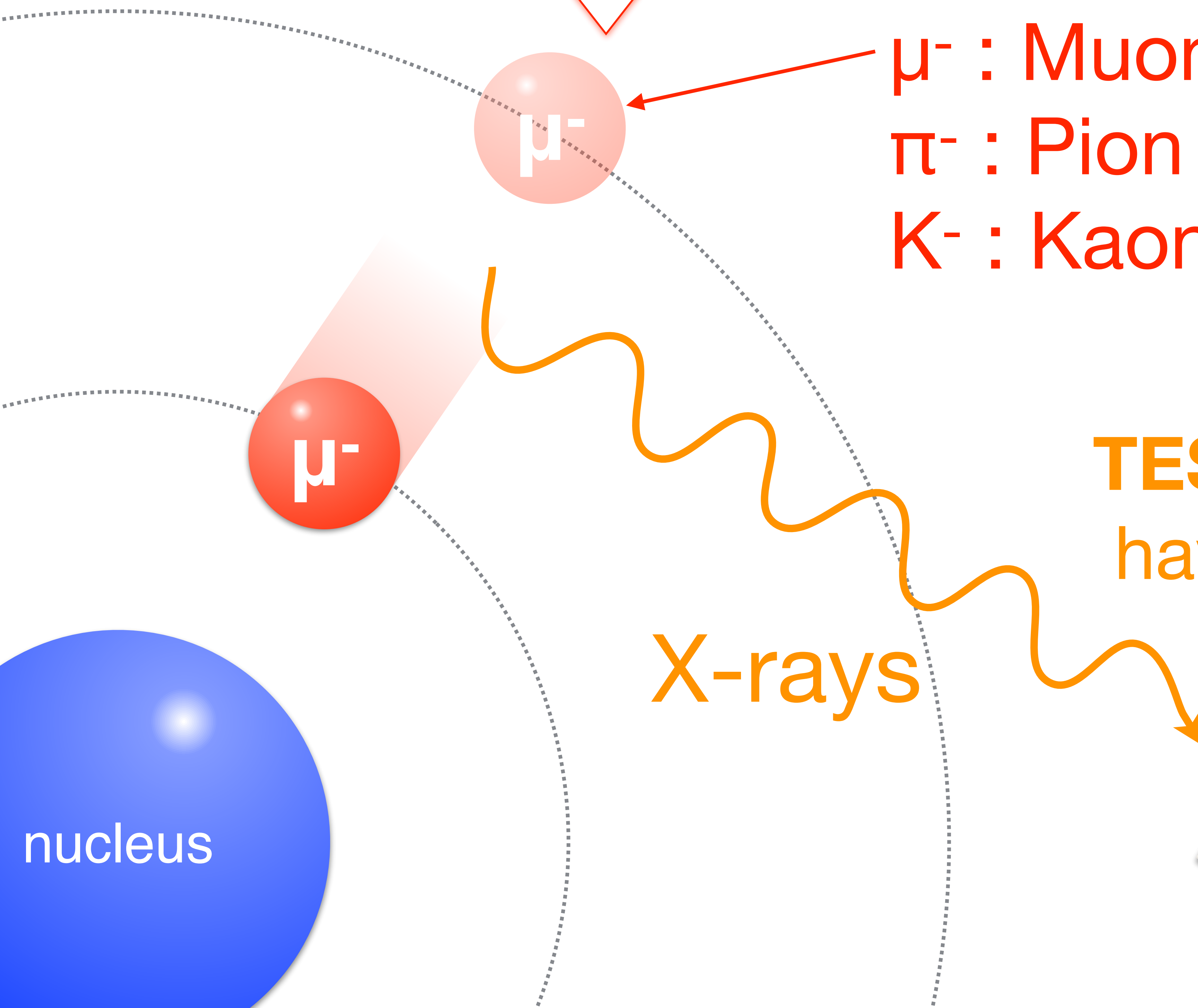
HEATES project

=

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

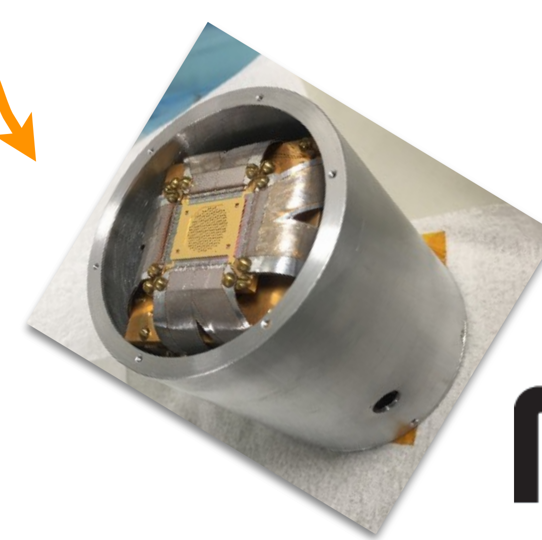
negative charged

μ⁻ : Muon
π⁻ : Pion
K⁻ : Kaon …



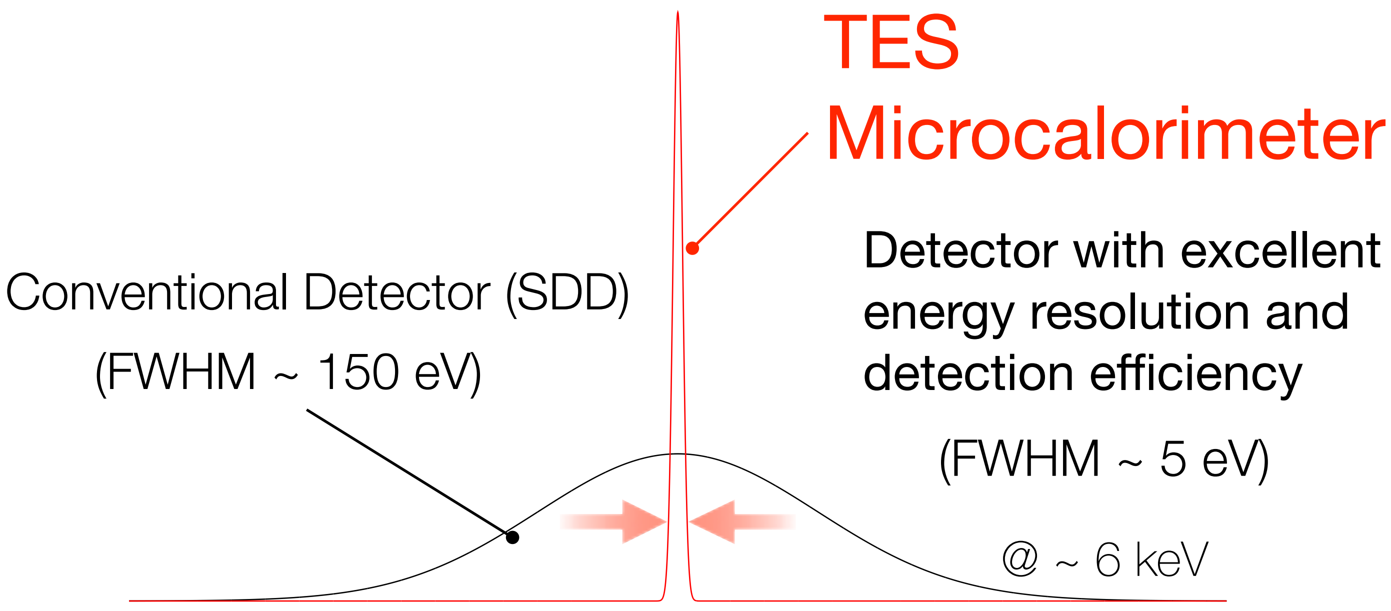
*named after microcalorimeter being a **heat** measuring device*

TES microcalorimeter
having high resolution



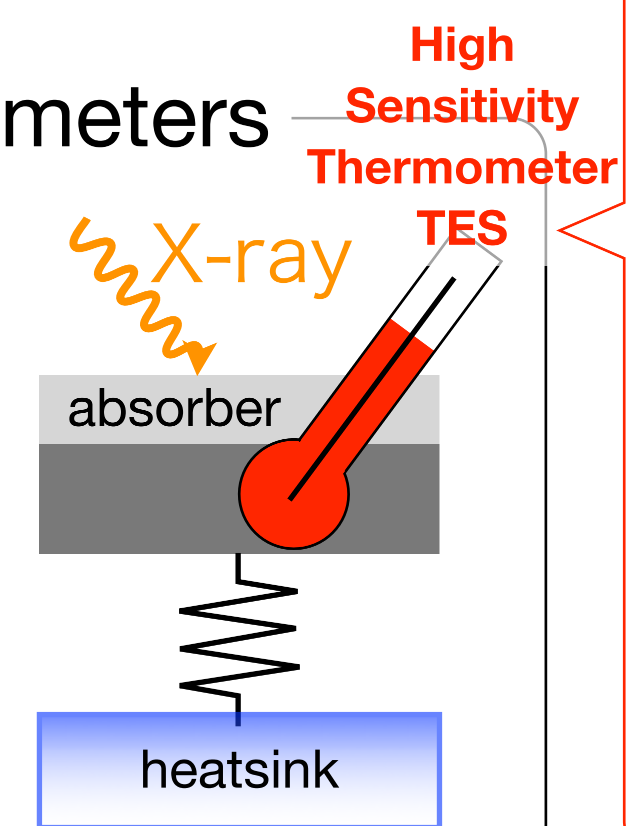
NIST

Innovative Spectroscopic Techniques

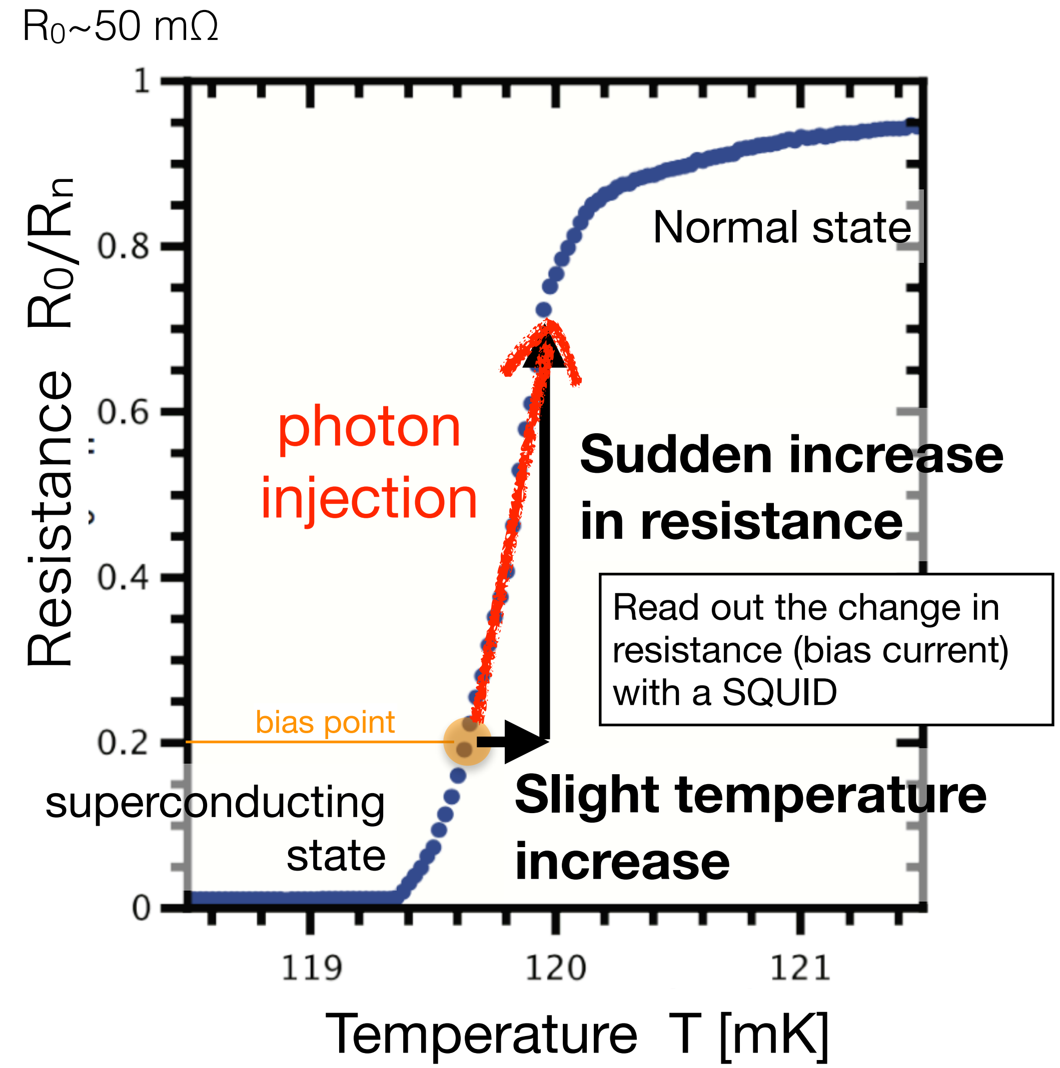


TES microcalorimeters

1. incident particles are absorbed by the absorber
2. energy ΔE is converted to phonons
3. **slight temperature rise** is measured with high sensitivity thermometer TES

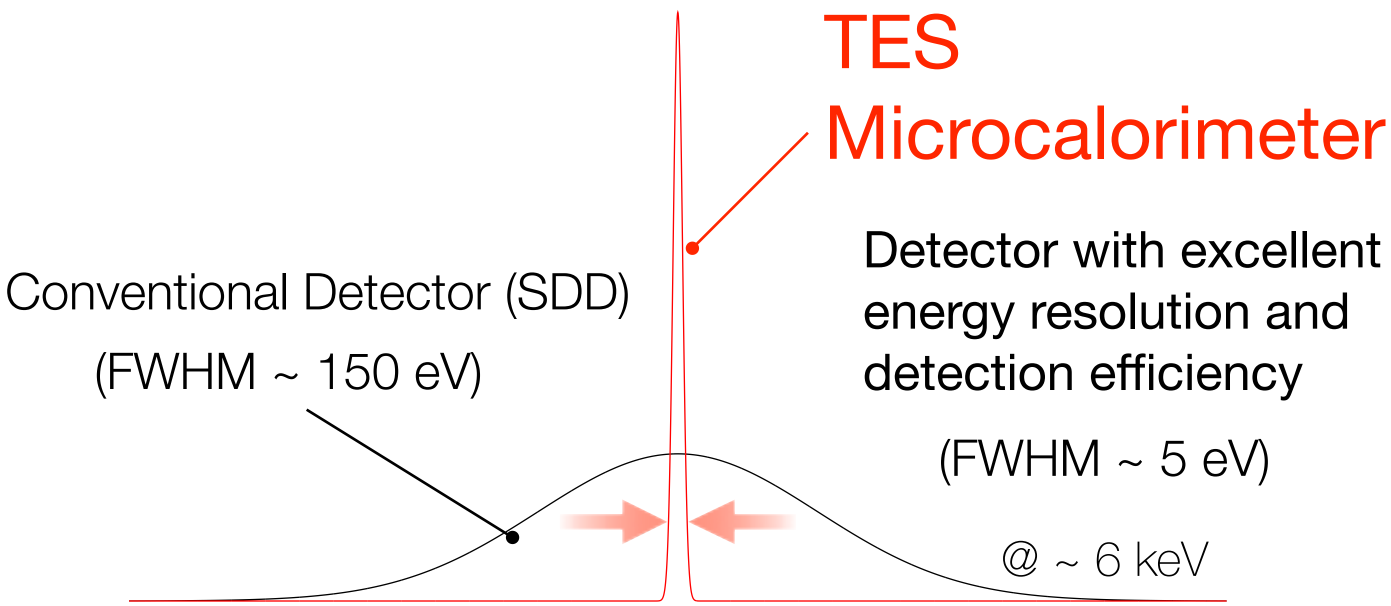


Transition Edge Sensor



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

Innovative Spectroscopic Techniques



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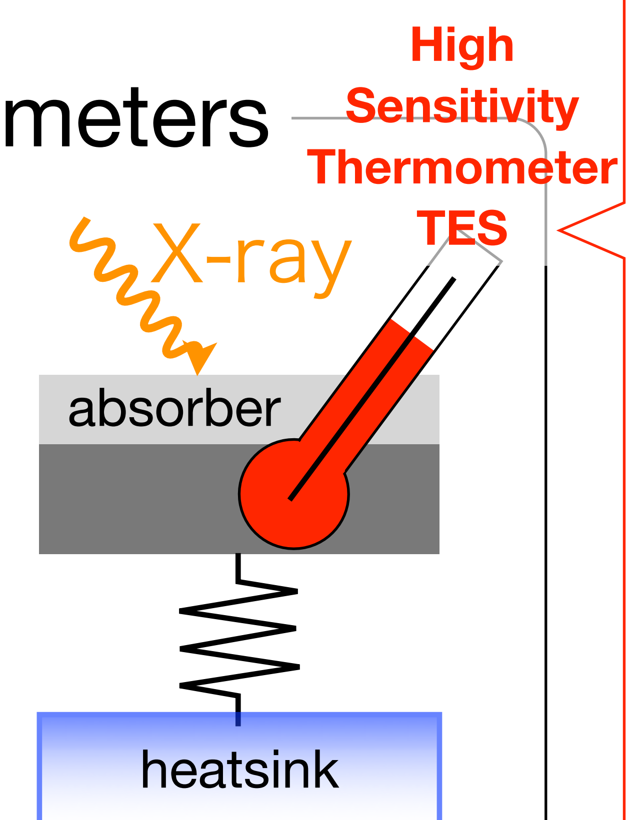
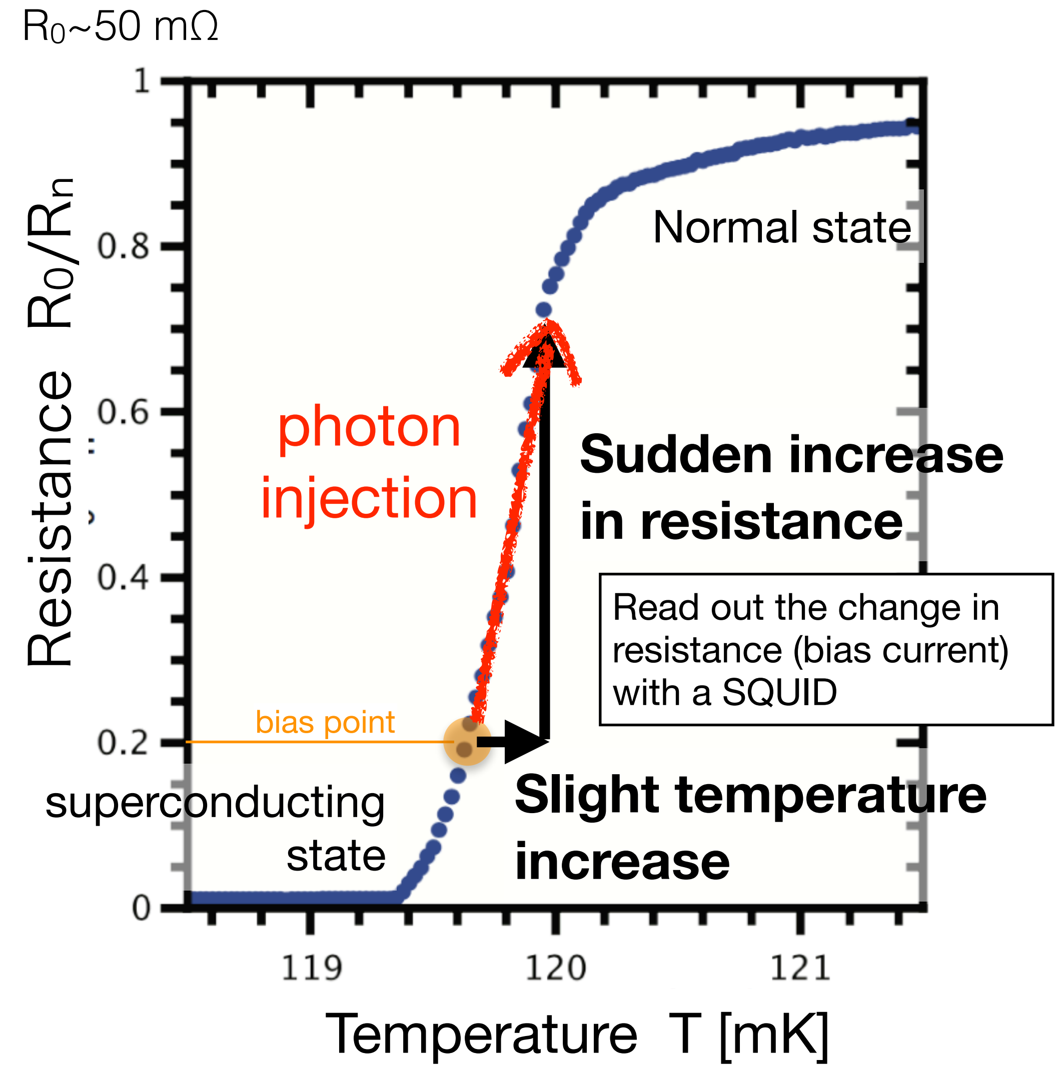


Transition Edge Sensor



High resolutio 0^{-3})

Please refer to presentation of Joel Ullom (NIST) tomorrow for further details !

History (Study of exotic atoms using TES)

Launched in Feb. 2013 in collaborating with NIST (US)

2014	**π⁻ atom** @ PSI (Switzerland)	*Feasibility study*
2016–2018	**K⁻ atom** @ J-PARC hadron	*Study of **strong $\bar{K}N$ interaction***
2020	**μ⁻ atom** @ J-PARC MLF	*Study of **BSQED** under extremely strong electric fields* (**B**ound-**S**tate **Q**uantum **E**lectro**D**ynamics)
2022	**μ⁻ molecule** @ J-PARC MLF	*Study of **μCF** (muon catalyzed fusion)*
2024	*μ- atom (high-energy region: E ~ 50 keV and ~100 keV) @ J-PARC MLF*	

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)*	

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→ *Please refer to presentation of Tadashi Hashimoto (RIKEN) the day after tomorrow*

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→ *focusing on these two latest results*

Contents

a single sharp X-ray peak
(absolute energy)

1. Muonic atom (QED)

Collaboration (μNe)

J-PARC MLF 2019MS01 collaboration (for μNe)

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

Ryota		Hayakawa	Rikkyo Univ.	Japan
Yuto		Ichinohe		
Shinya		Yamada		
Yasushi		Kino	Tohoku Univ.	
Kenichi		Okutsu		
Takuma		Okumura	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		

(Nuclear & Hadron + Atomic & Muon + Astro) physicists + TES experts

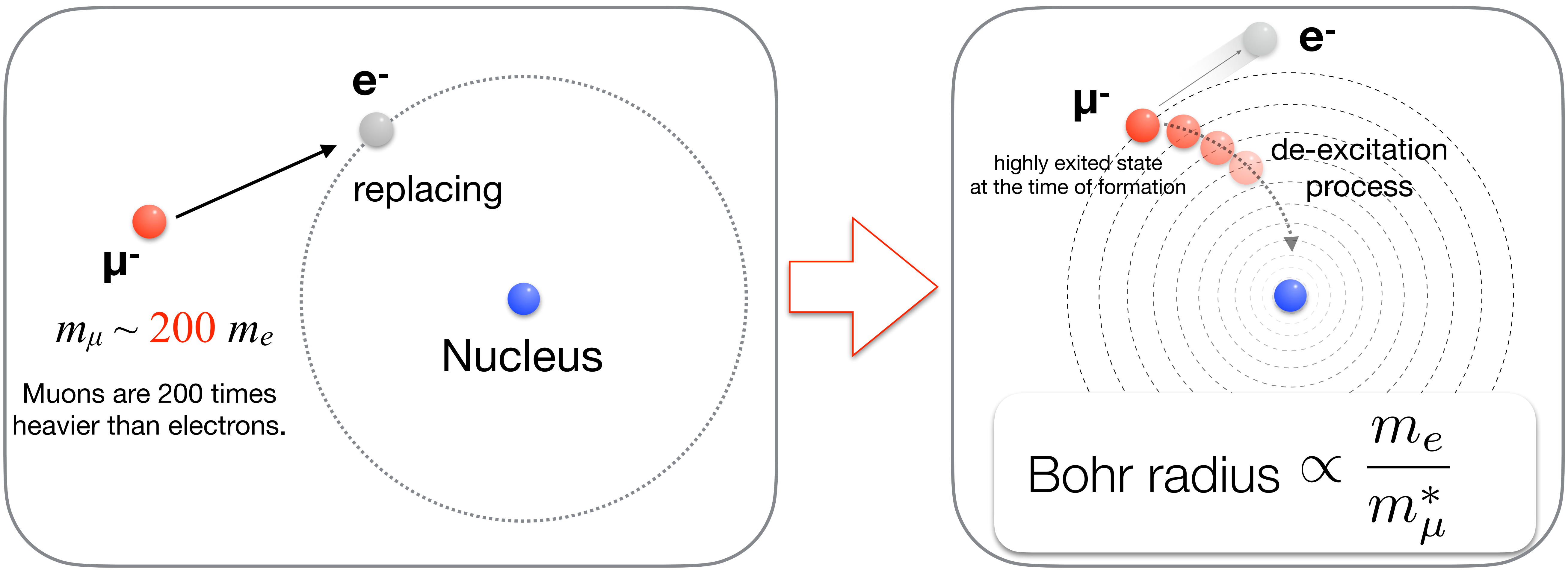
interdisciplinary team

Muonic atom

Muon atoms are formed when negative muons are replaced by electrons.

Normal atom

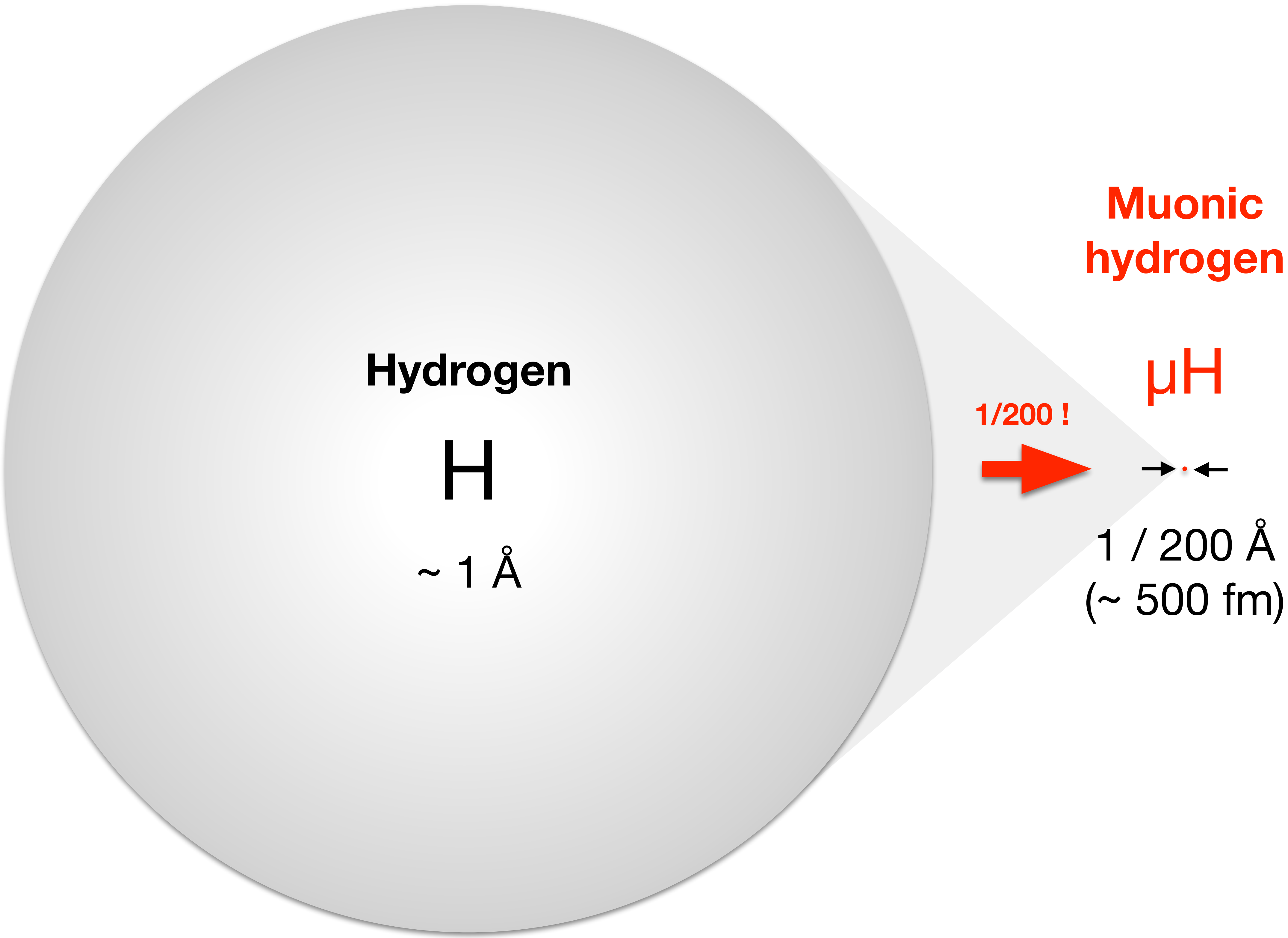
Muonic atom



(inversely proportional to their reduced mass)

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

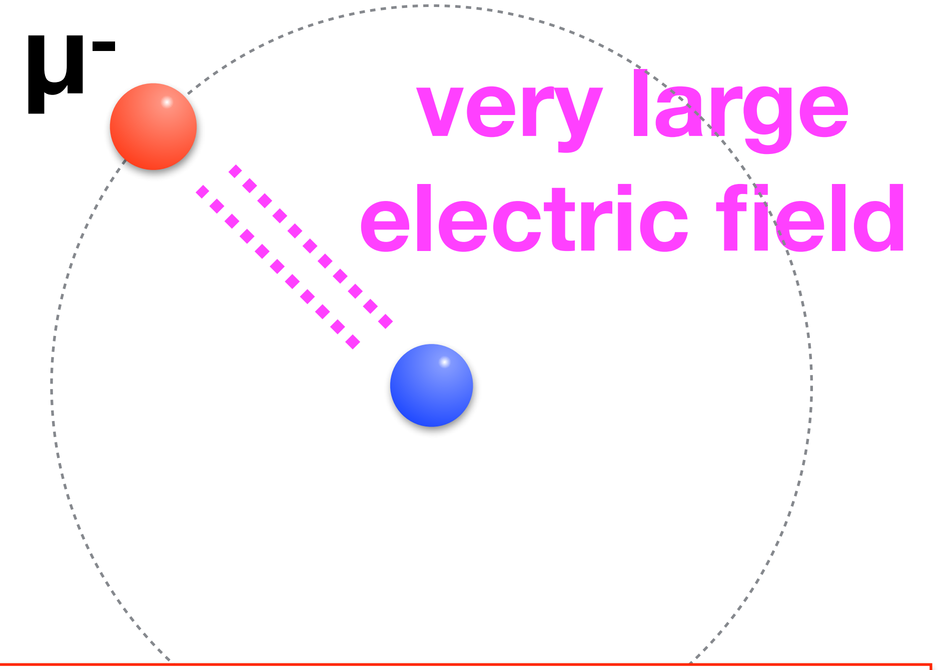
Image of the scale



Extremely close to the nucleus !

Bohr radius

R_{μ} ~ **1/200** R_e (μ⁻ atom)



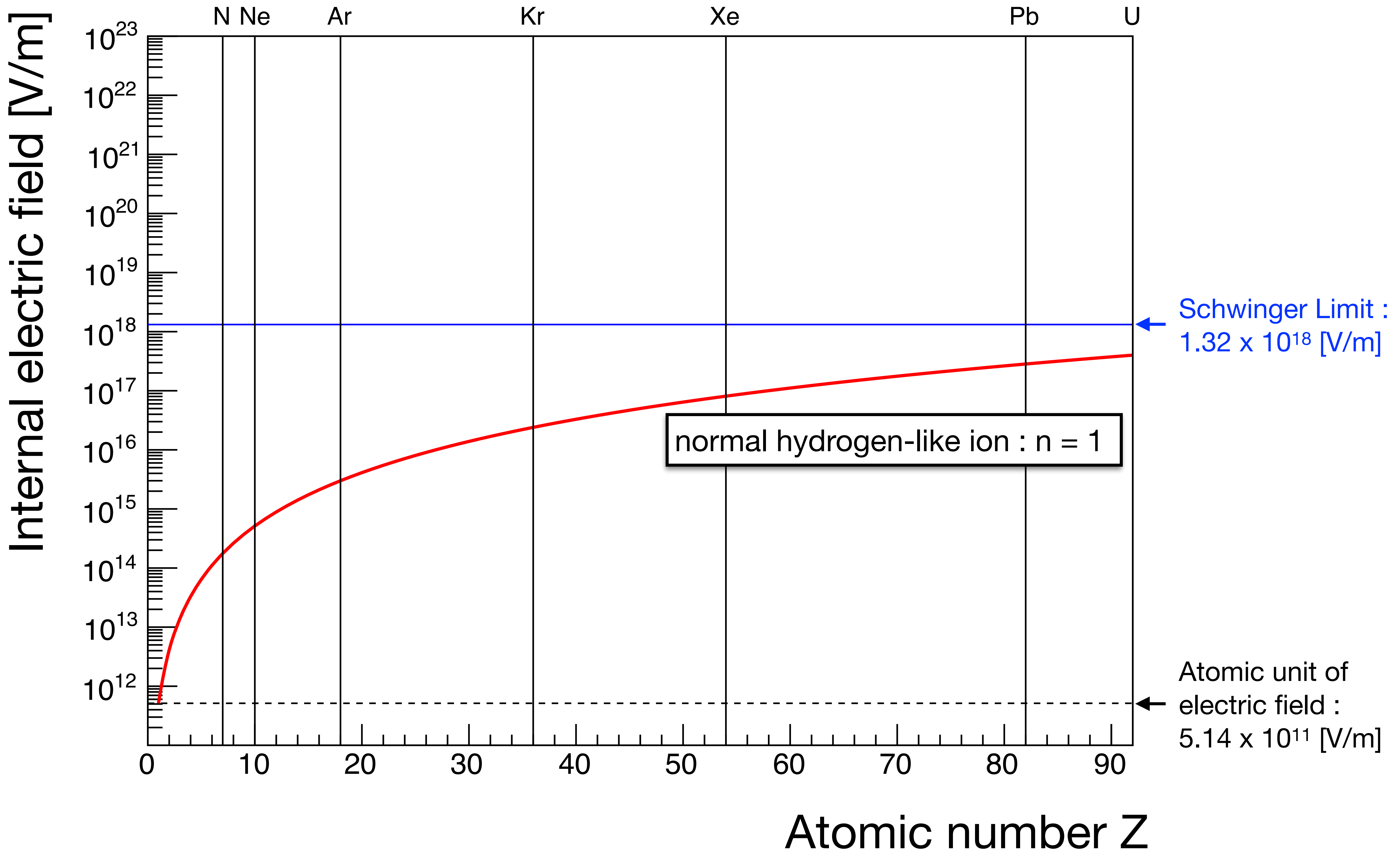
✓ μ⁻ feels an **extremely large electric field**

➡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**"

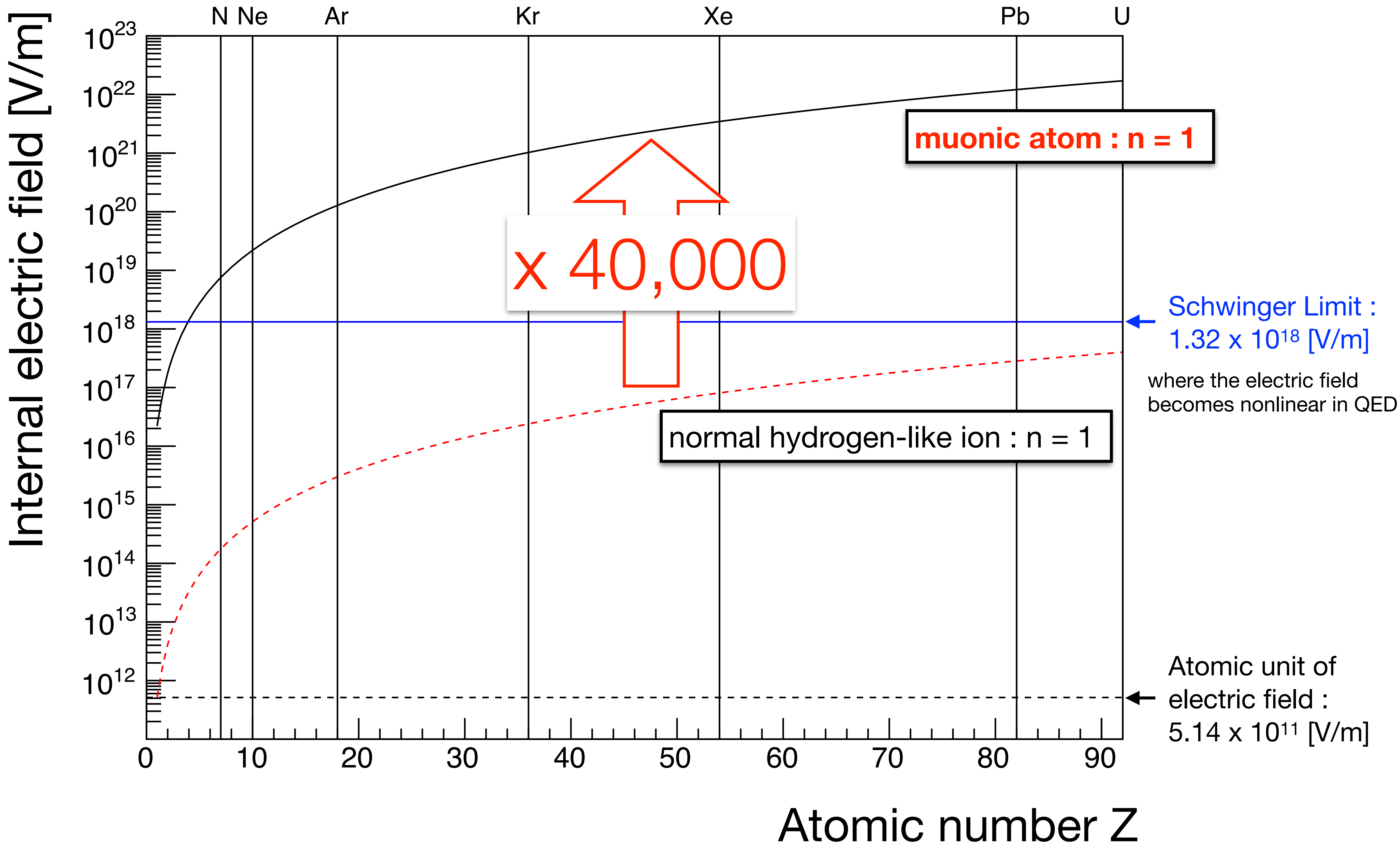
QED : Quantum ElectroDynamics

Internal electric field ∝ Z^3

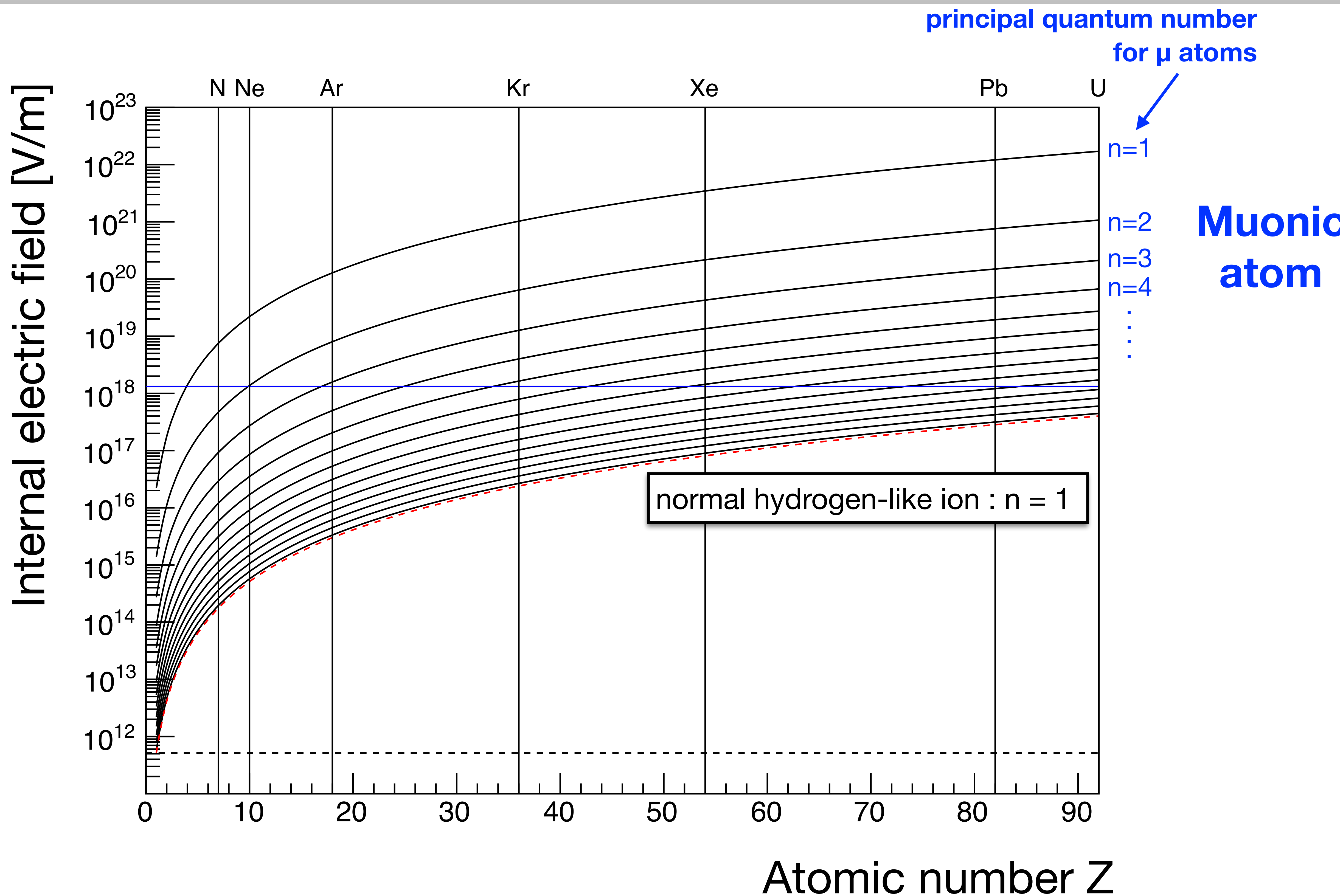


strong electric field @ heavier atoms

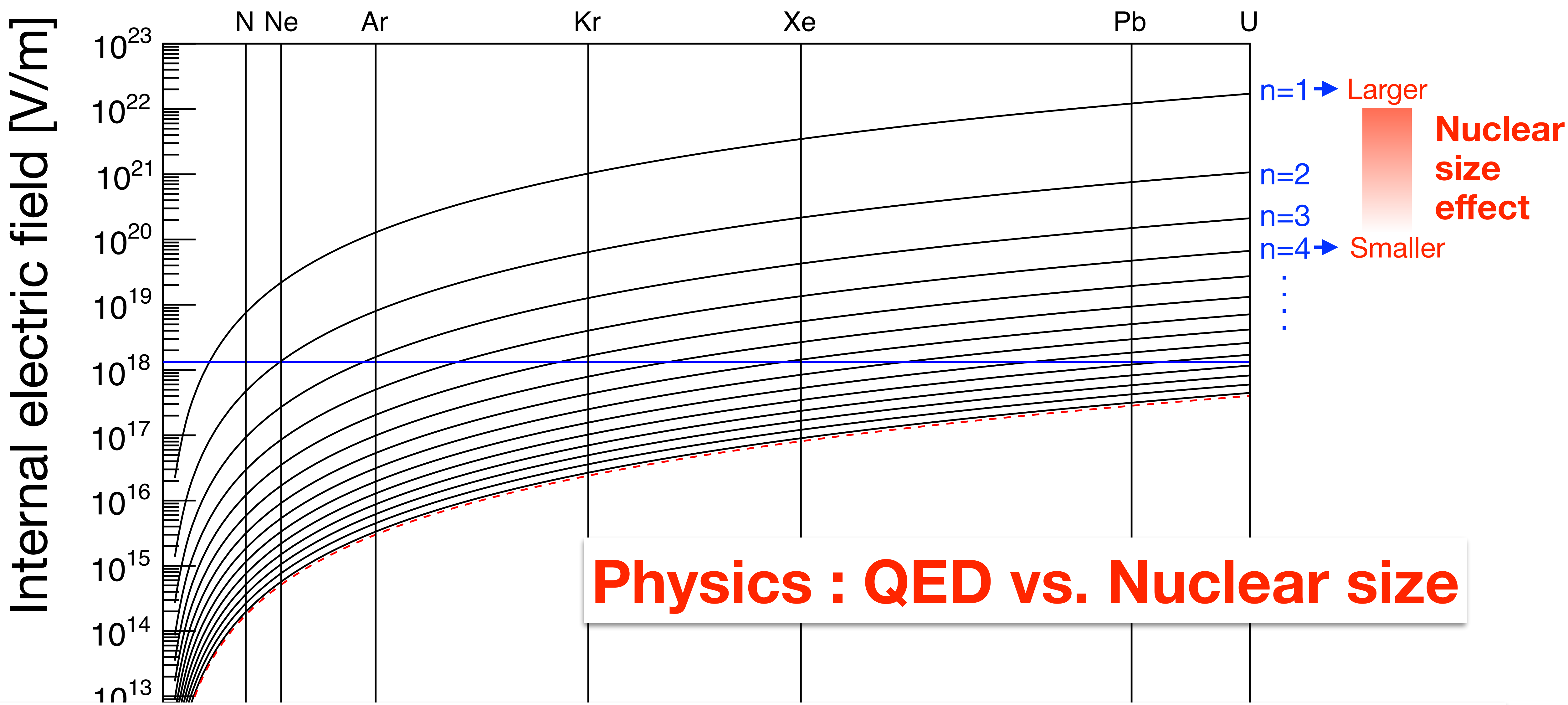
Internal electric field : x 200^2



Muonic atom : n = 1,2,3,4…



Avoiding nuclear-size effect



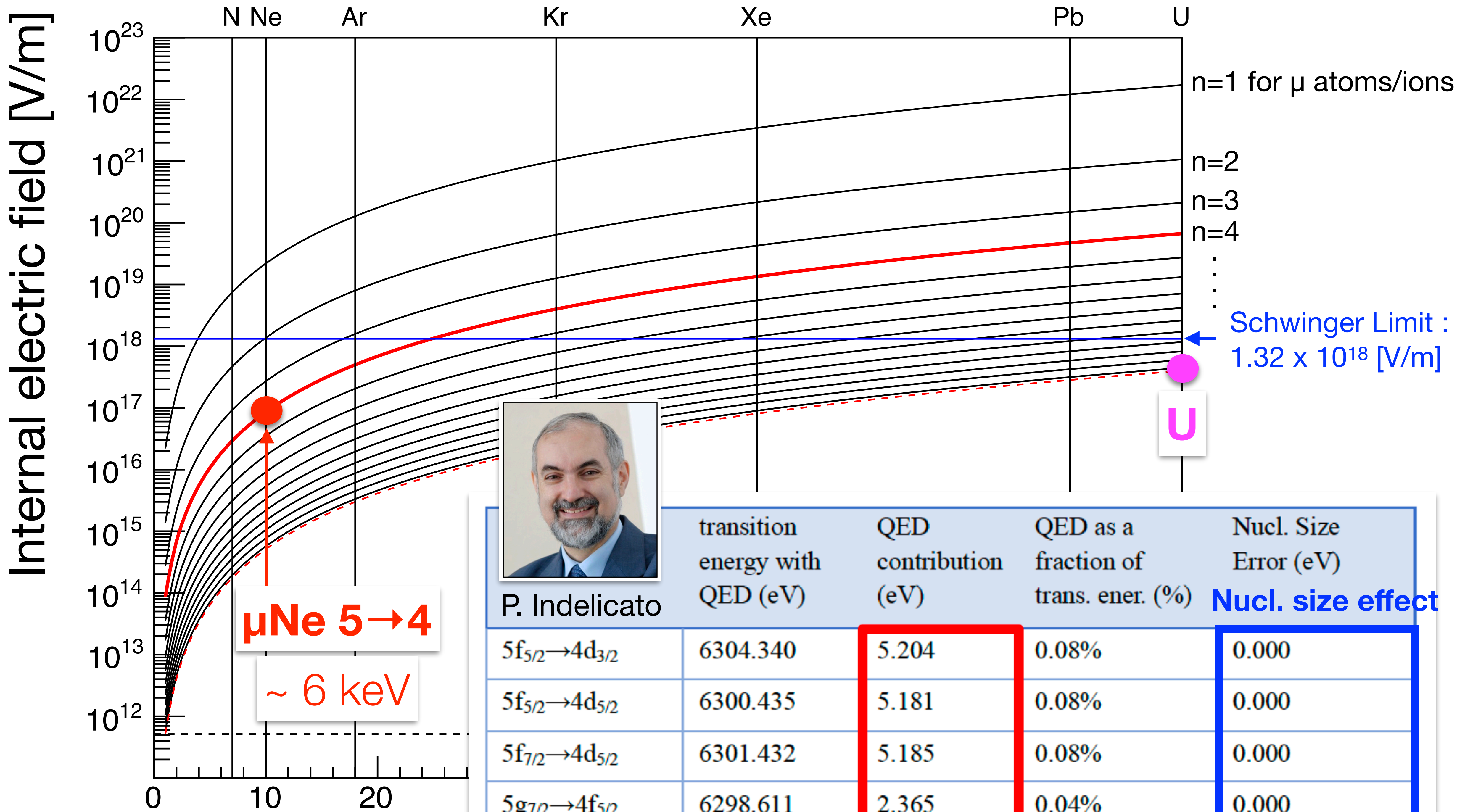
Physics : QED vs. Nuclear size

✓ 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

Proof-of-Principle Experiment with μNe 5→4

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



P. Indelicato

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

Nucl. size effect

PRL (2021)

PHYSICAL REVIEW LETTERS **126,** 173001 (2021)

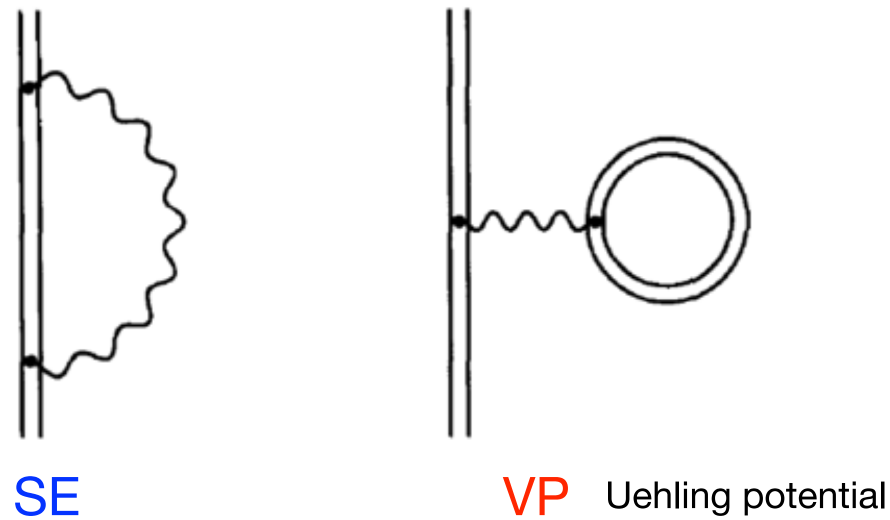
TABLE I. Transition energies, QED, and finite size corrections for transitions amenable to BSQED tests in muonic atoms and antiprotonic atoms, compared to transitions of similar energies in highly charged ions. All energies are given in eV.

Particle	Element	Initial state	Final state	Theoretical transition energy	1st order QED	2nd order QED	$g-2\ \bar{p}$	FNS	FNS/QED	Exp.	Ref.
e^-	^{40}Ar	$2p_{3/2}$	$1s_{1/2}$	3322.9931	−1.1238	0.0007		−0.0090	0.804%	3322.993(14)	[6]
μ^-	^{20}Ne	$6h_{11/2}$	$5g_{9/2}$	3419.6828	0.3845	0.0042		0.0001	0.013%		
$\bar{p}$	^{40}Ar	$17v_{33/2}$	$16u_{31/2}$	3522.9850	1.2209	0.0124	0.0618	0.0002	0.014%		
e^-	^{56}Fe	$2p_{3/2}$	$1s_{1/2}$	6973.1815	−3.8873	0.0042		−0.0527	1.357%	6972.73(24)	[50]
μ^-	^{20}Ne	$5g_{9/2}$	$4f_{7/2}$	6297.2616	2.3365	0.0229		0.0003	0.013%		
e^-	^{84}Kr	$2p_{3/2}$	$1s_{1/2}$	13 508.9648	−11.4244	0.0181		−0.2963	2.594%	13 508.95(50)	[66]
μ^-	^{20}Ne	$4f_{7/2}$	$3d_{5/2}$	13 616.0000	14.4762	0.1334		0.0034	0.023%		
$\bar{p}$	^{40}Ar	$11n_{21/2}$	$10m_{19/2}$	13 729.2333	24.6024	0.2198	0.9635	0.0080	0.032%		
e^-	^{132}Xe	$2p_{3/2}$	$1s_{1/2}$	31 283.9469	−43.0973	0.1068		−3.1806	7.380%	31 284.9(18)	[67]
$\bar{p}$	^{20}Ne	$6h_{11/2}$	$5g_{9/2}$	29 183.5476	106.3705	0.9818	4.7013	0.0719	0.068%		
$\bar{p}$	^{84}Kr	$13q_{25/2}$	$12o_{23/2}$	32 965.1496	85.8828	0.7744	5.4909	0.0606	0.071%		
e^-	^{238}U	$2p_{3/2}$	$1s_{1/2}$	102 175.0991	−257.2281	1.2278		−198.5110	77.173%	102 178.1(43)	[15]
μ^-	^{132}Xe	$6h_{11/2}$	$5g_{9/2}$	100 690.8984	246.5741	2.4873		0.2473	0.100%		
$\bar{p}$	^{40}Ar	$6h_{11/2}$	$5g_{9/2}$	97 106.9665	524.4471	5.1928	52.0324	1.0708	0.204%		
$\bar{p}$	^{84}Kr	$9l_{17/2}$	$8k_{15/2}$	105 534.2194	505.7241	4.8782	57.9787	1.0624	0.210%		
$\bar{p}$	^{132}Xe	$12o_{23/2}$	$11n_{21/2}$	95 937.8866	398.9032	3.7678	46.7550	0.7860	0.197%		
μ^-	^{84}Kr	$4f_{7/2}$	$3d_{5/2}$	178 245.9903	712.8101	7.1647		0.4179	0.059%		
μ^-	^{132}Xe	$5g_{9/2}$	$4f_{7/2}$	185 826.8188	664.5075	7.4047		1.1906	0.179%		
$\bar{p}$	^{84}Kr	$8k_{15/2}$	$7i_{13/2}$	154 113.2949	856.7465	8.5547	125.2672	2.6925	0.314%		
$\bar{p}$	^{132}Xe	$10m_{19/2}$	$9l_{17/2}$	170 796.0859	905.9163	8.9726	150.2826	3.2019	0.353%		
$\bar{p}$	^{184}W	$12o_{23/2}$	$11n_{21/2}$	180 885.6145	912.1929	8.9936	166.1718	3.5826	0.393%		
$\bar{p}$	^{238}U	$14r_{27/2}$	$13q_{25/2}$	172 808.8745	806.8144	7.9071	150.2331	3.2202	0.399%		

highly charged ion vs. muonic atom

The Lamb shift = QED + **nuclear size**

QED = Self Energy (SE) + Vacuum Polarization (VP)



muonic atom : VP > SE

highly charged ion : SE > VP

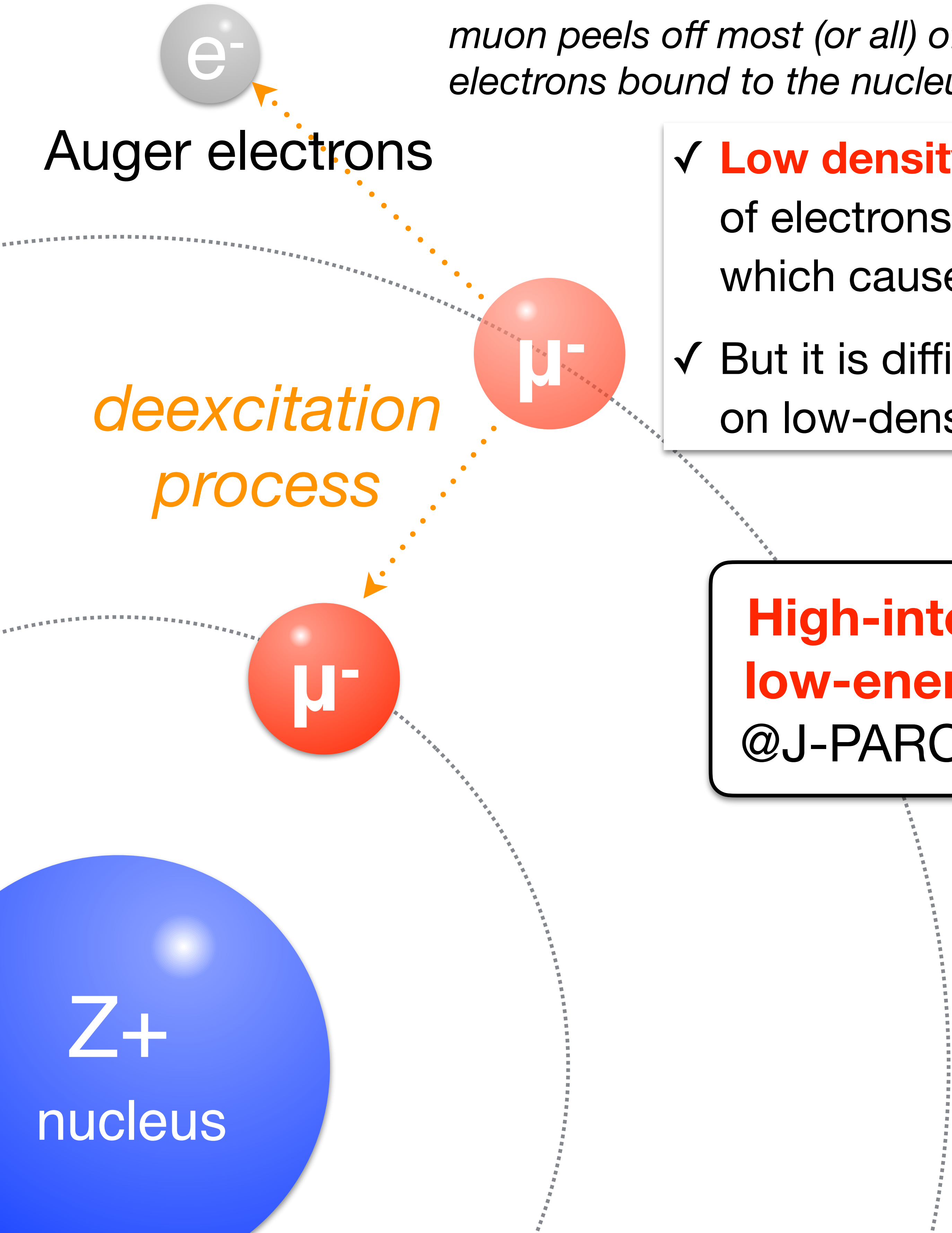
μ- would be **200 times closer** to the nucleus than electrons.
→ μ- **feel "bare" nuclear charge** freeing from "polarization" charge.
→ resulting in enhanced VP

observing different effects

⇒ complementary relationship

Low pressure gas target

muon peels off most (or all) of electrons bound to the nucleus



- ✓ **Low density gas target** is required to avoid rapid refilling of electrons into this system from surrounding atoms, which causes an energy shift.
- ✓ But it is difficult to efficiently stop muons experimentally on low-density targets. → **resulting low intensity**

High-intensity low-energy μ- @J-PARC MLF ⊗ TES detector having both "**high resolution**" and "**large effective area**"

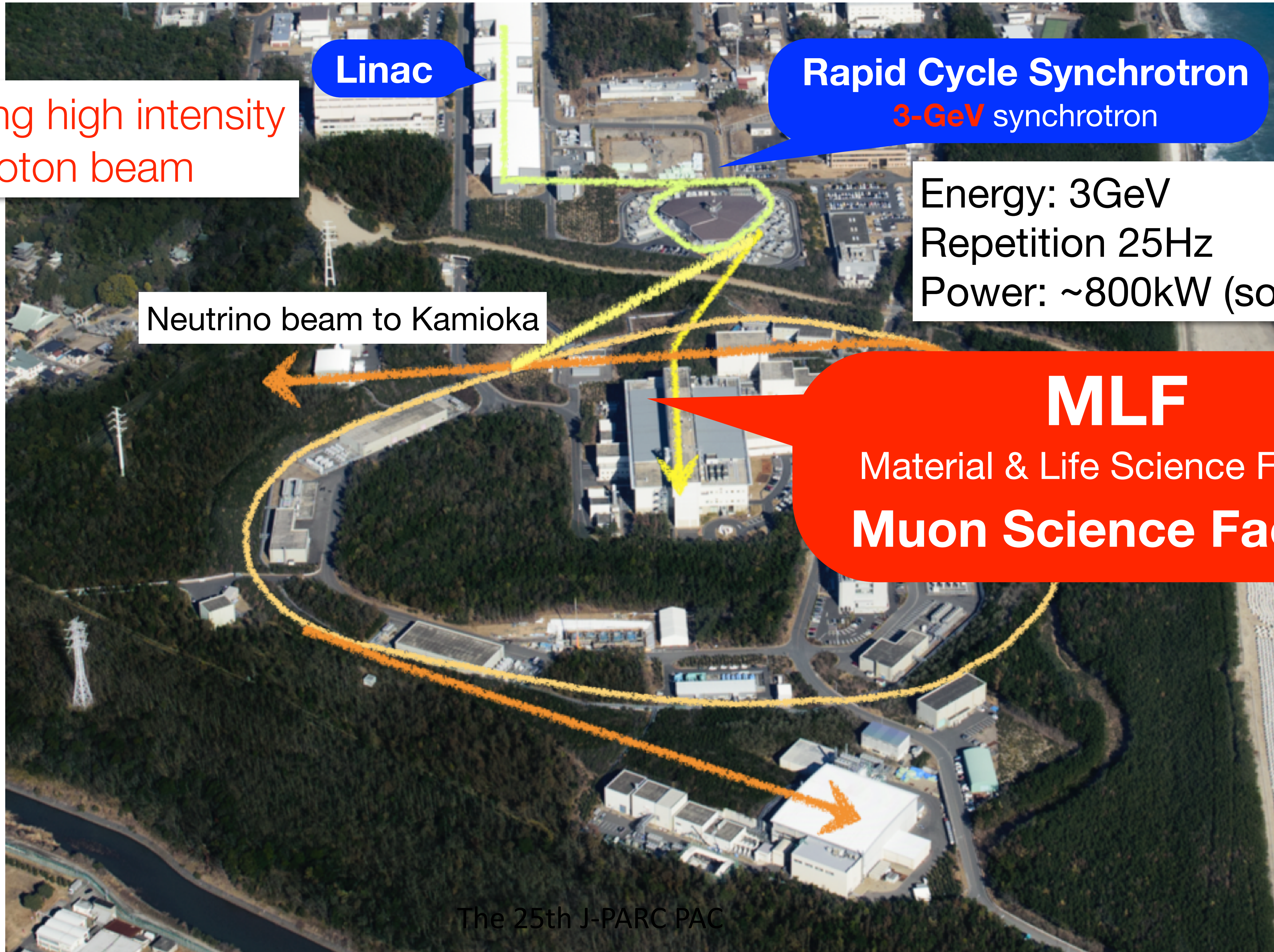
refilling → energy shift

e-

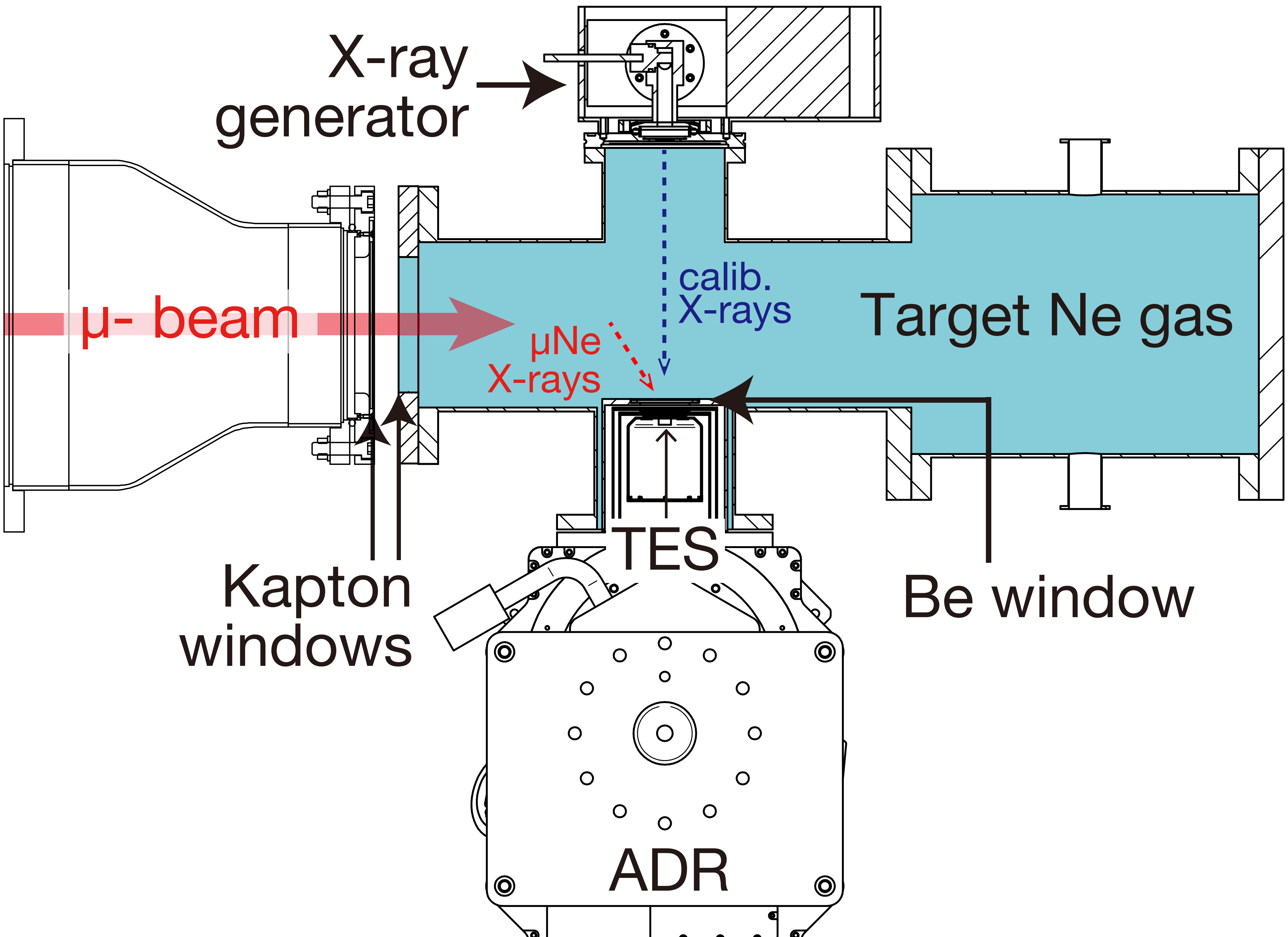
from surrounding atoms

J-PARC

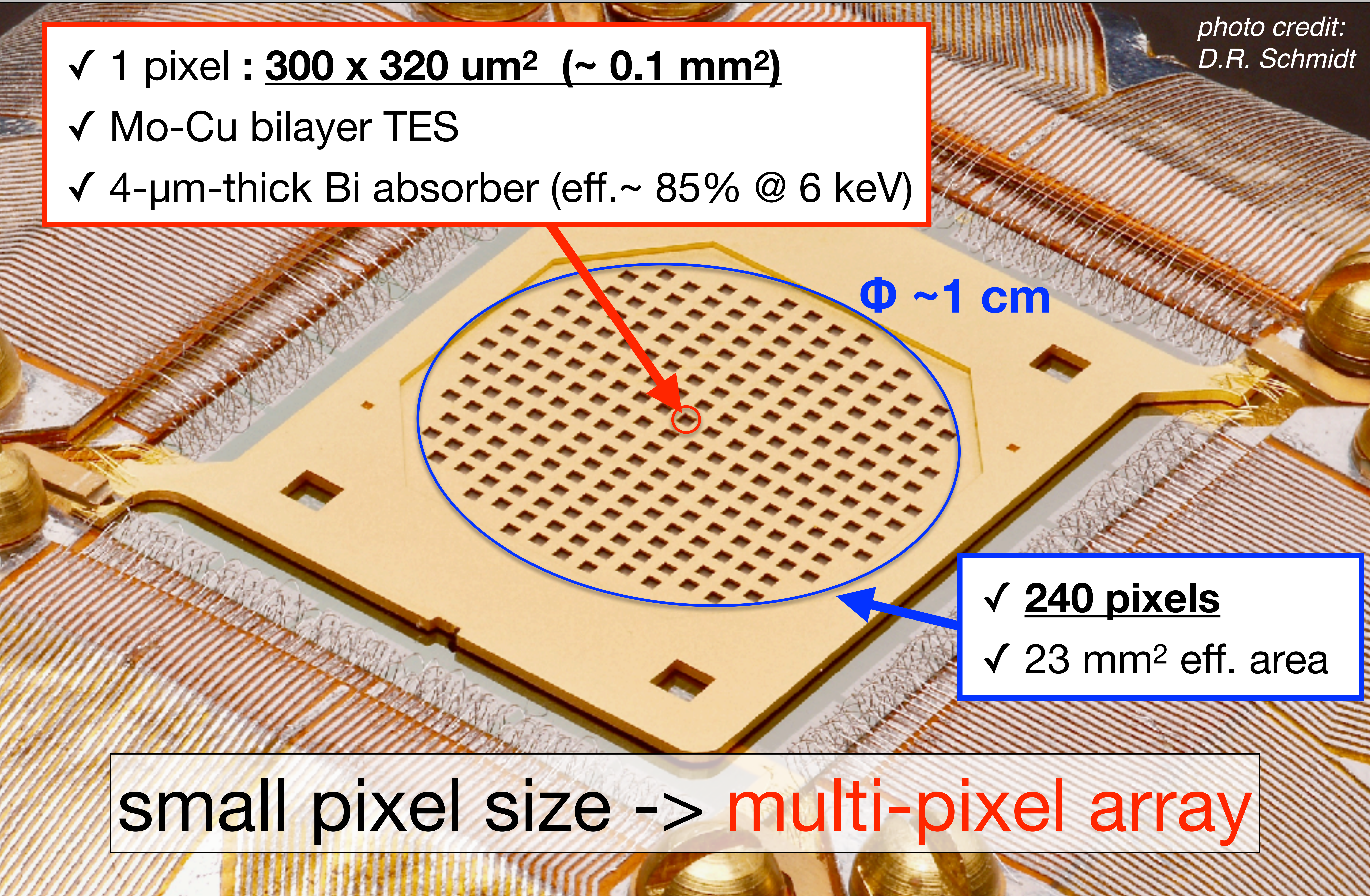
Japan **P**roton **A**ccelerator **R**esearch **C**omplex



Experimental setup



TES array



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

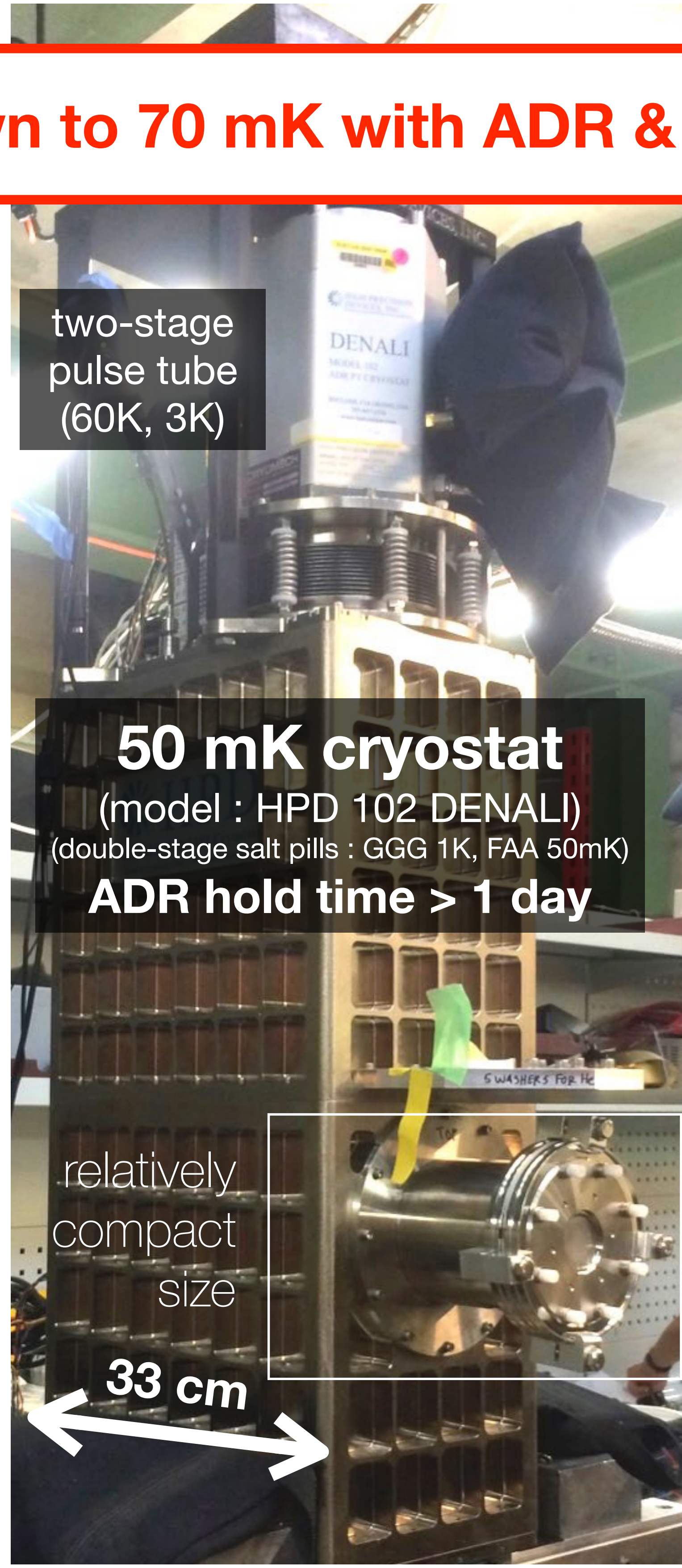
- ✓ **240 pixels**
- ✓ 23 mm² eff. area

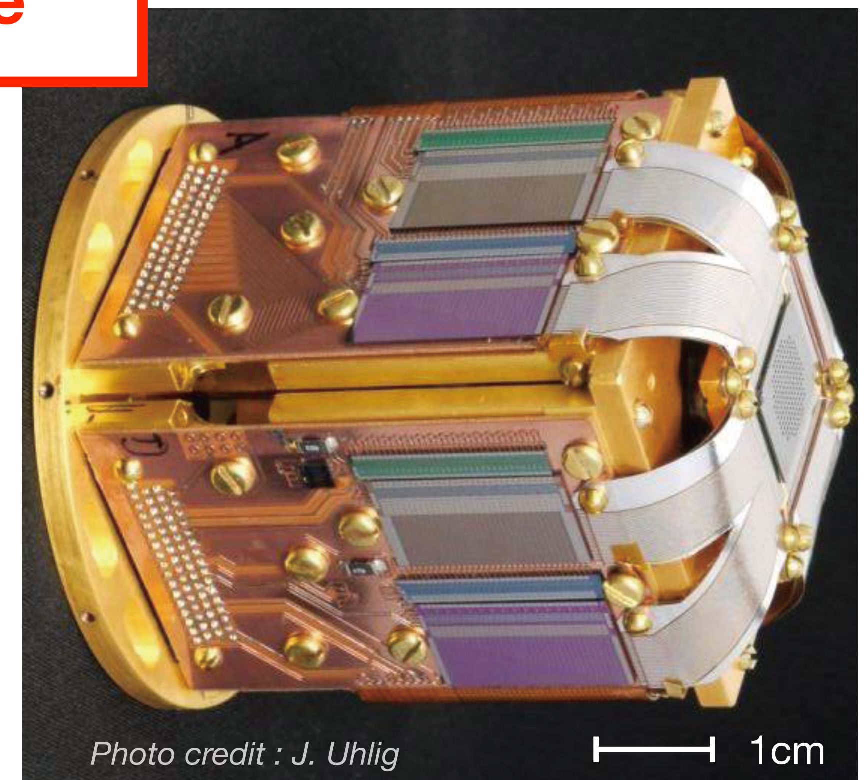
small pixel size -> multi-pixel array

Adiabatic Demagnetization Refrigerator (ADR)

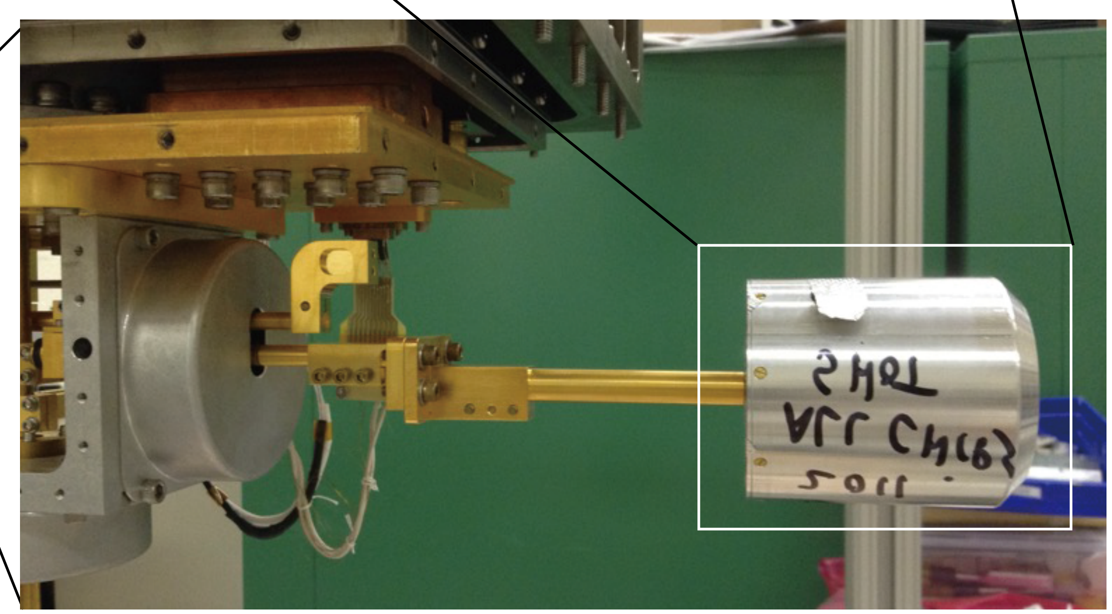
✓ Cooled down to 70 mK with ADR & pulse

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**

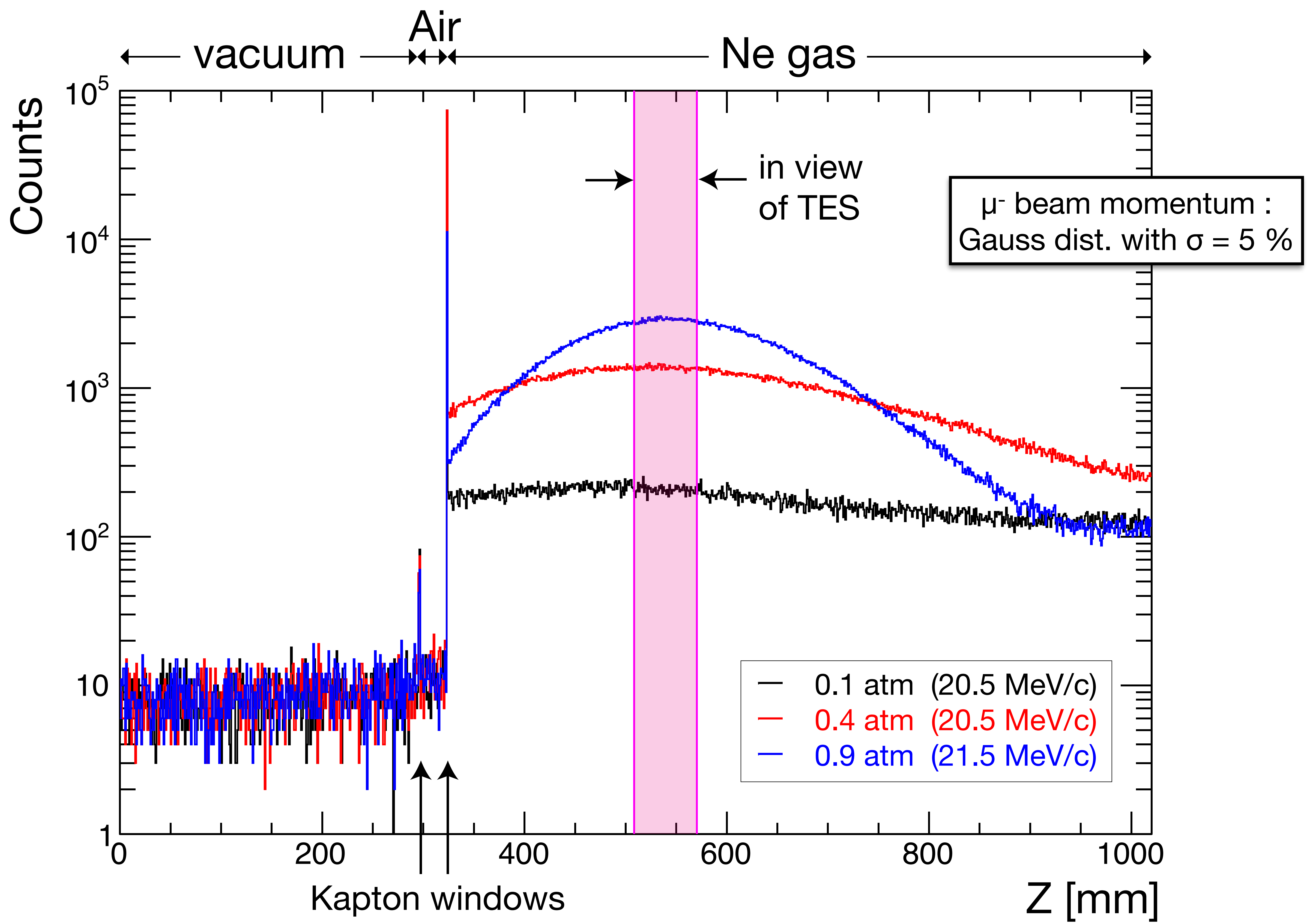




TES chip

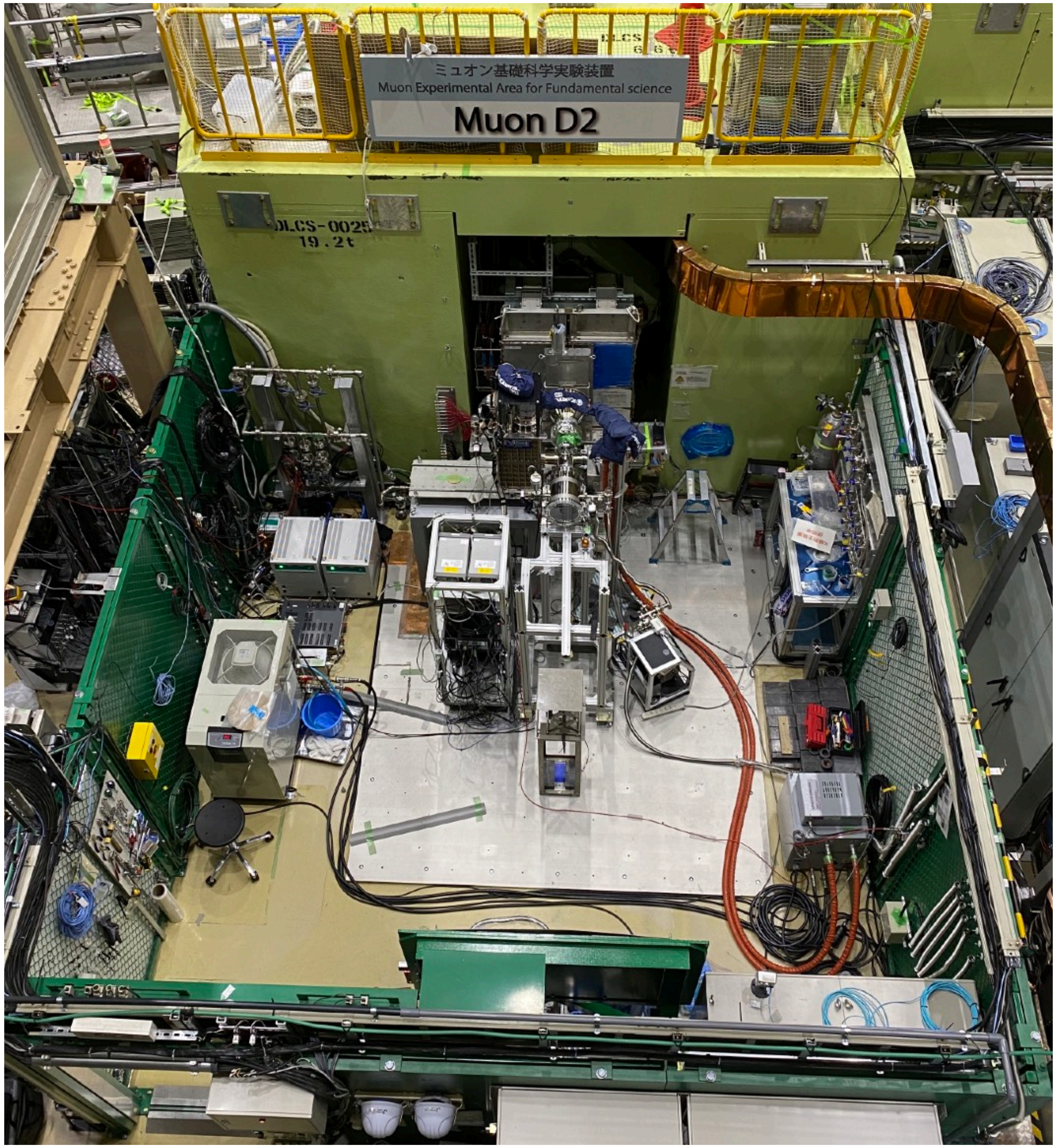


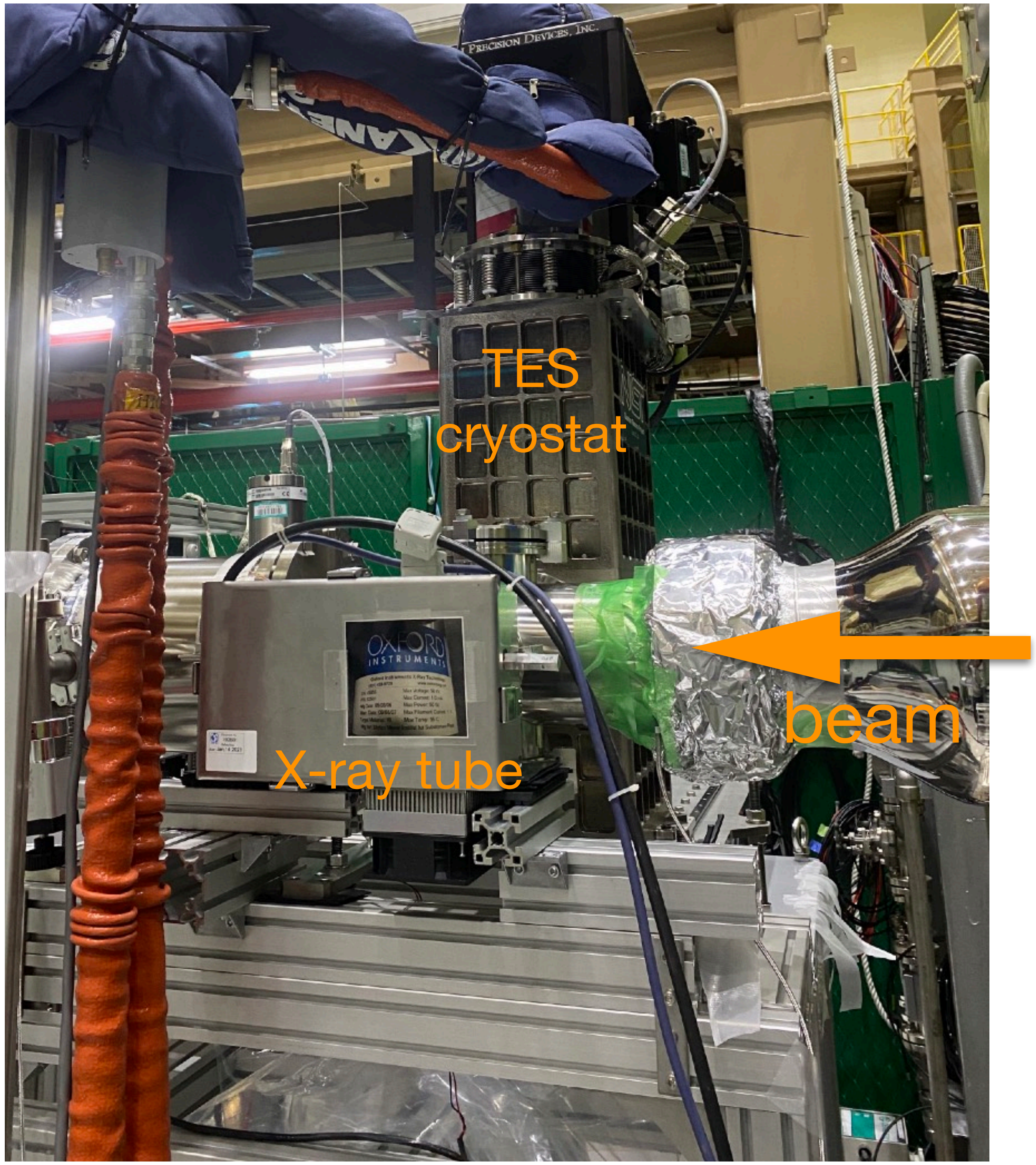
μ⁻ stopping distribution (sim)



Photos

Muon beamline @ J-PARC

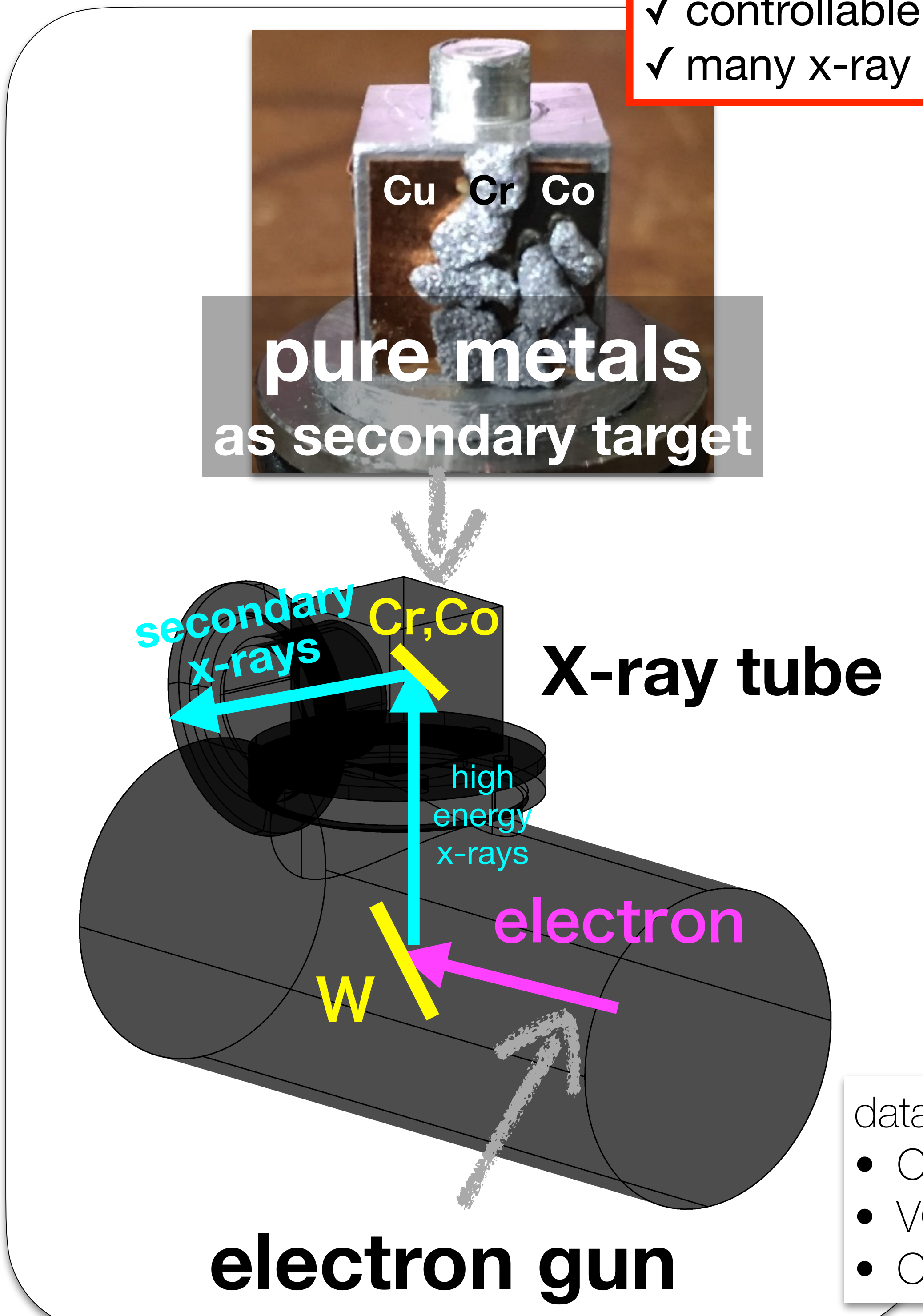




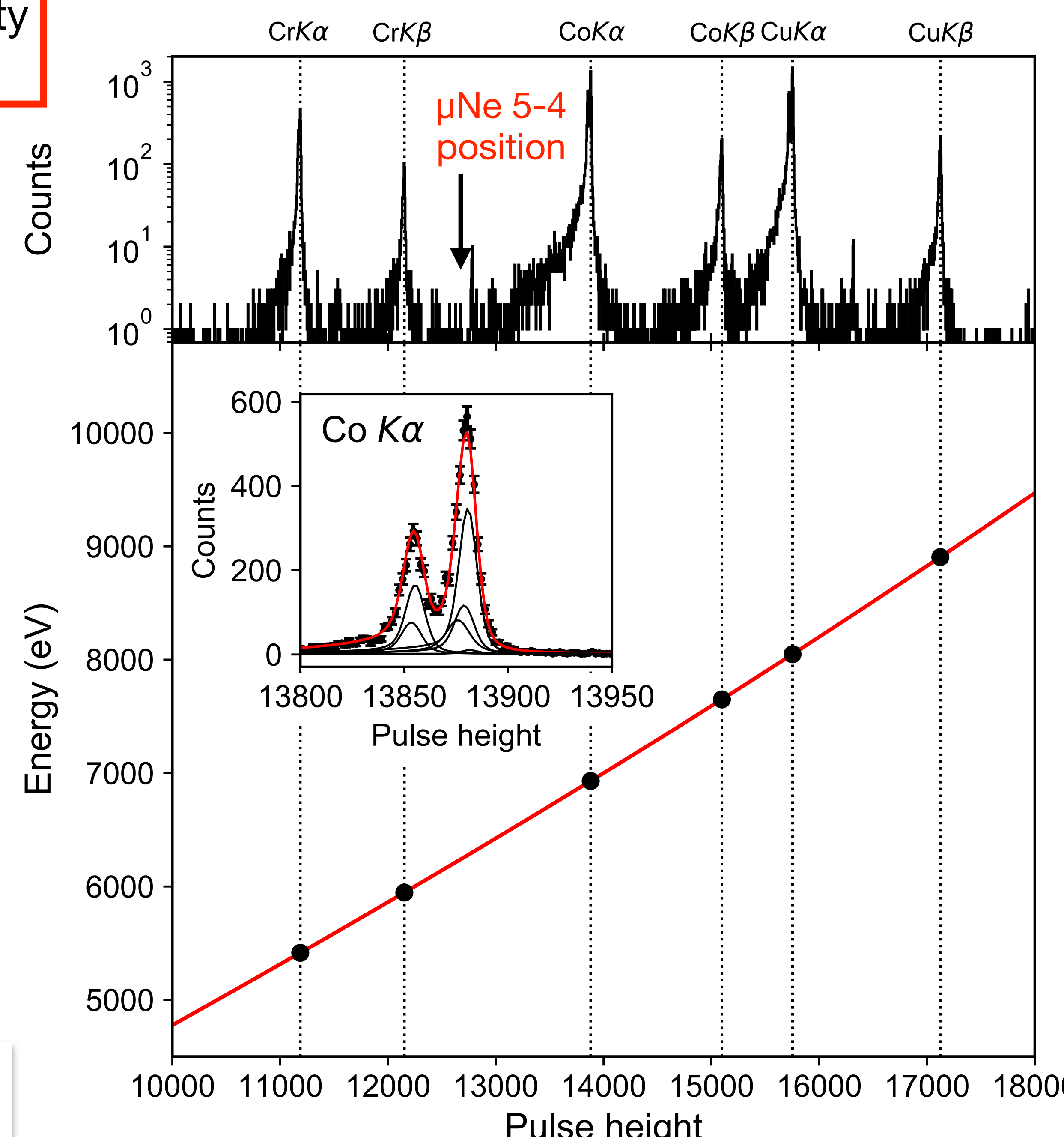
Energy calibration

Continuous X-ray irradiation during experiment

✓ controllable intensity
✓ many x-ray lines

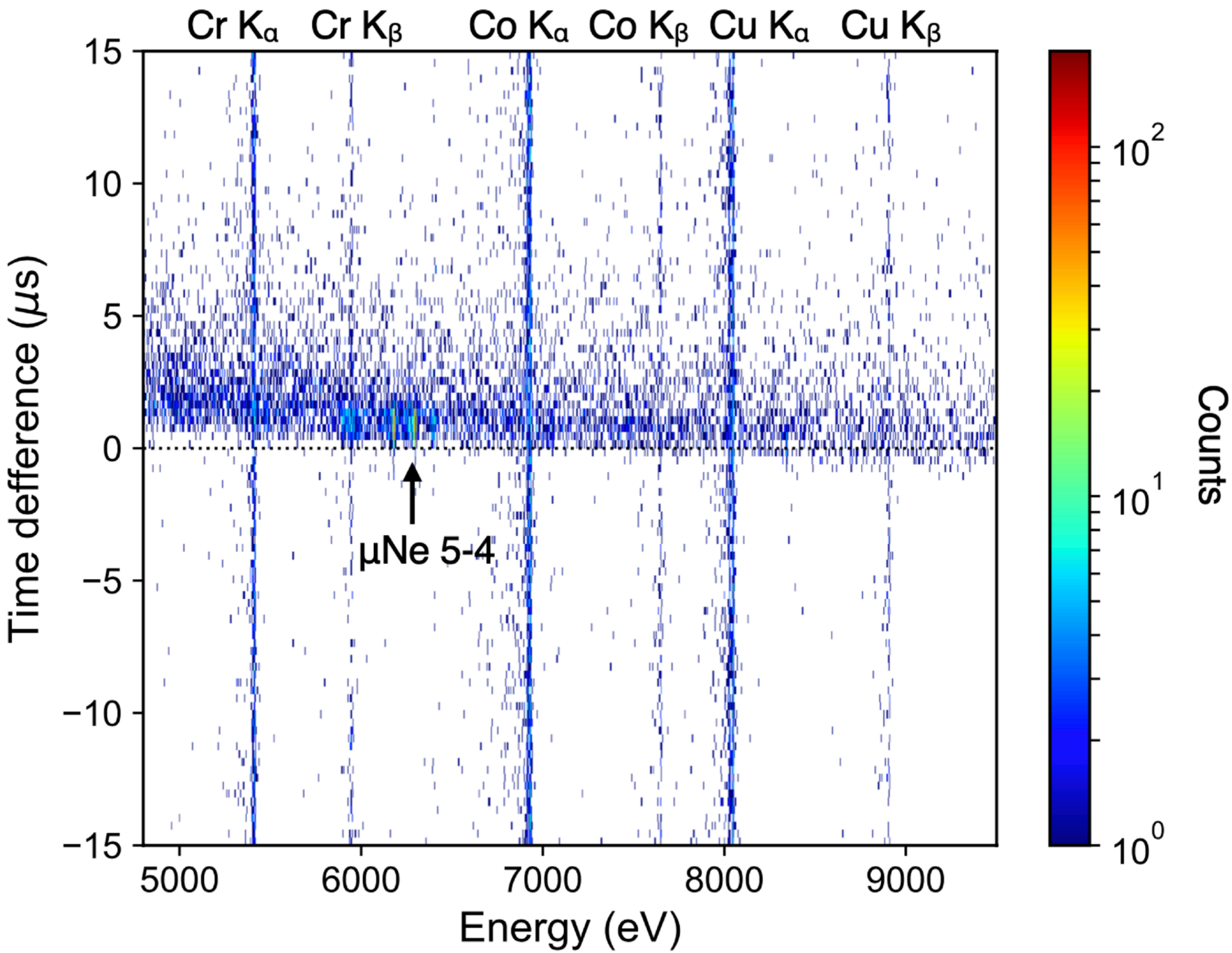


dataset :
- CrCoCu
- VCoCu
- CrNiZn

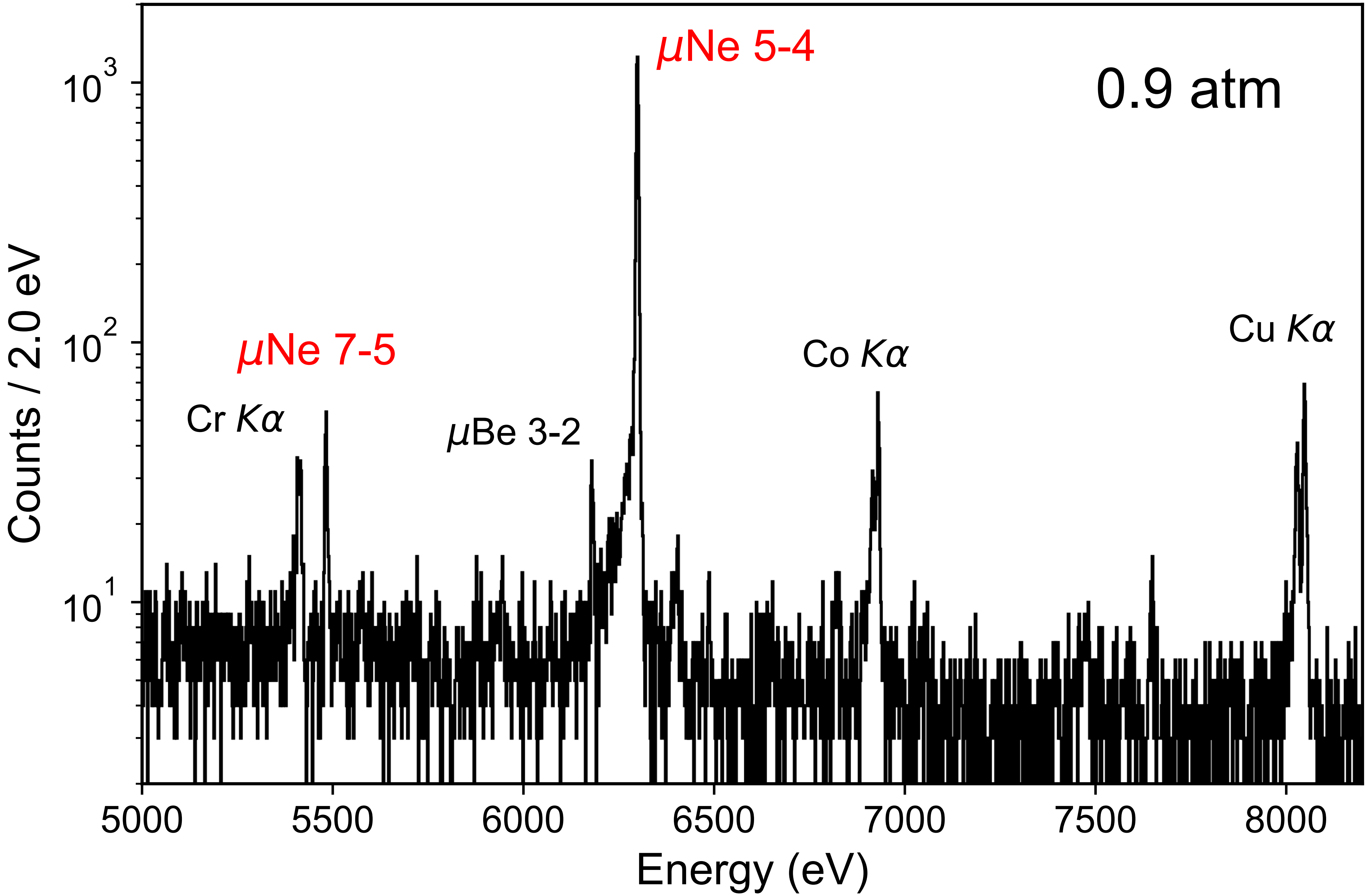


The low-energy tail originates from the trapping of heat carriers in the Bi absorber.

Energy vs. Timing (muon arrival time)



Muonic-atom X-ray spectrum

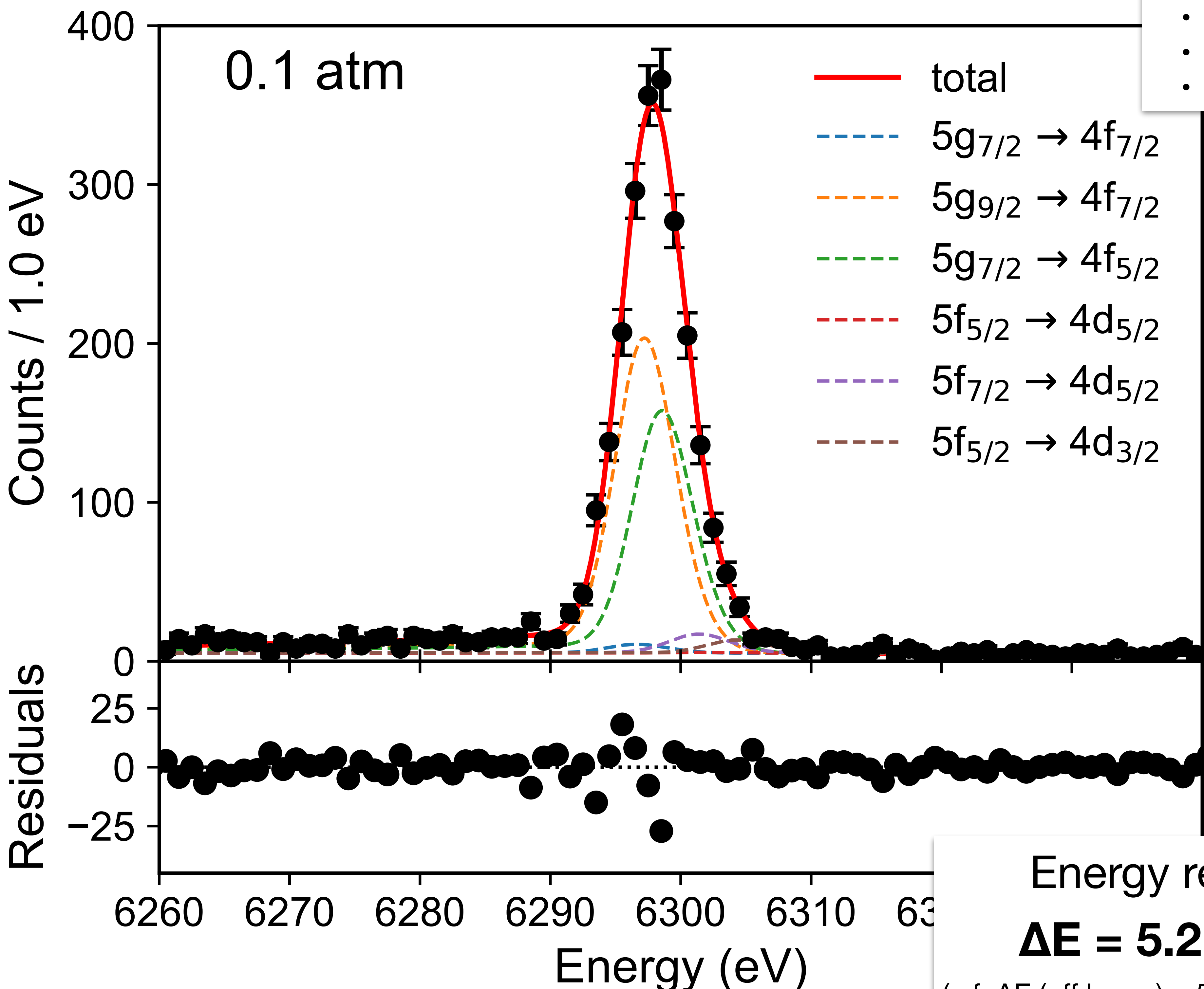


Typical count rates of muonic X-rays : 1-3 cps / TES array

(Calibration X-rays : ~ 400 cps / TES array)

Muonic Ne atom 5→4 @ 0.1 atm

Five fit parameters:
- $5g_{9/2}$ -$4f_{7/2}$ energy
- intensity ratio $R_{5f\text{-}4d}$
- total intensity
- constant BG level
- energy resolution

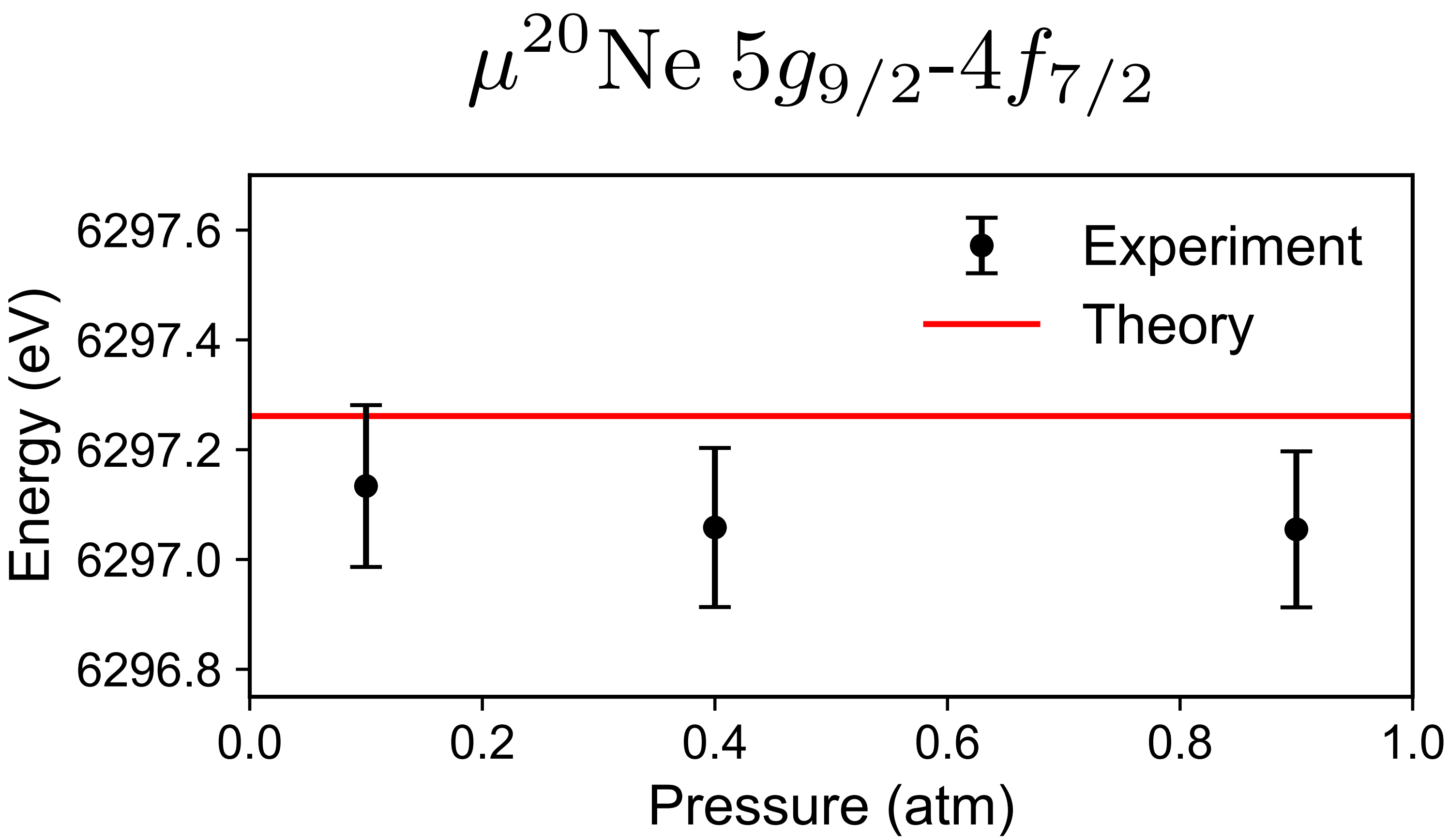


Energy resolution

ΔE = 5.2 ~ 5.5 eV

(c.f. ΔE (off beam) = 5.0 ~ 5.2 eV @ Co Ka)

Results (pressure dependence)



Stat. error ~ 0.04 eV
Syst. error ~ 0.13 eV

Breakdown of syst error

1. Thermal crosstalk : 0.11 eV
→ due to crosstalk correction

2. Calibration : 0.07 eV
→ evaluated by Fe Kα (as ref. line)

3. Low energy tail : 0.01 eV
→ response w/ & w/o beam

BSQED calculation (MCD-FGME code) includes :

- first- and second-order QED corrections
- the full Breit interaction
- all-order retardation effects
- the FNS contributions

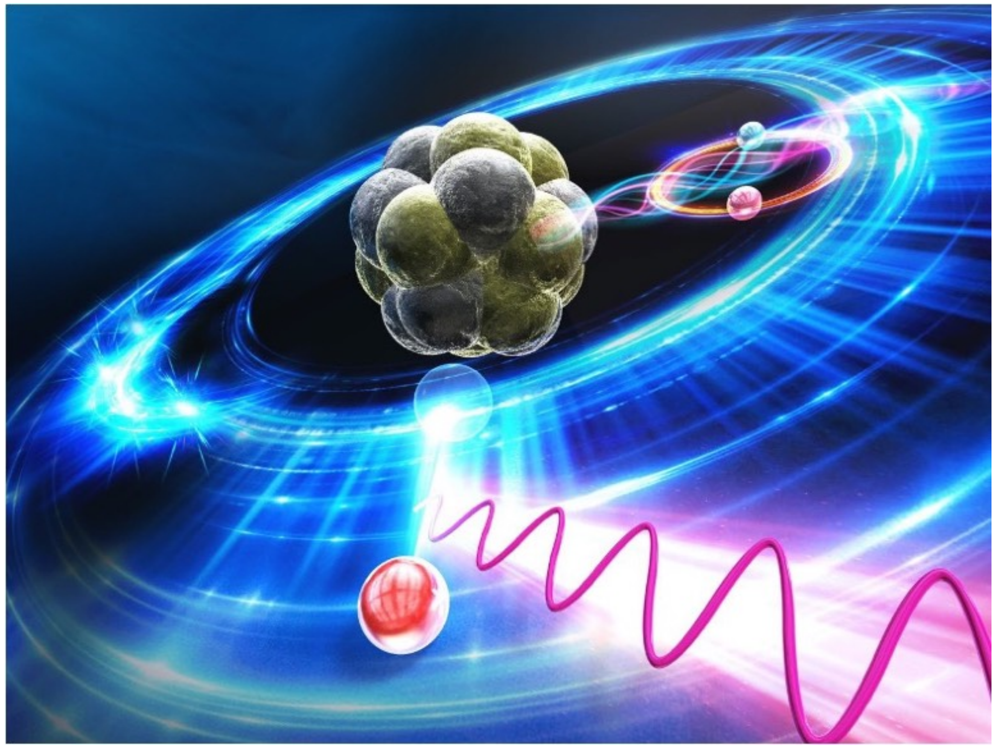
Published : PRL (2023)

PHYSICAL REVIEW LETTERS **130,** 173001 (2023)

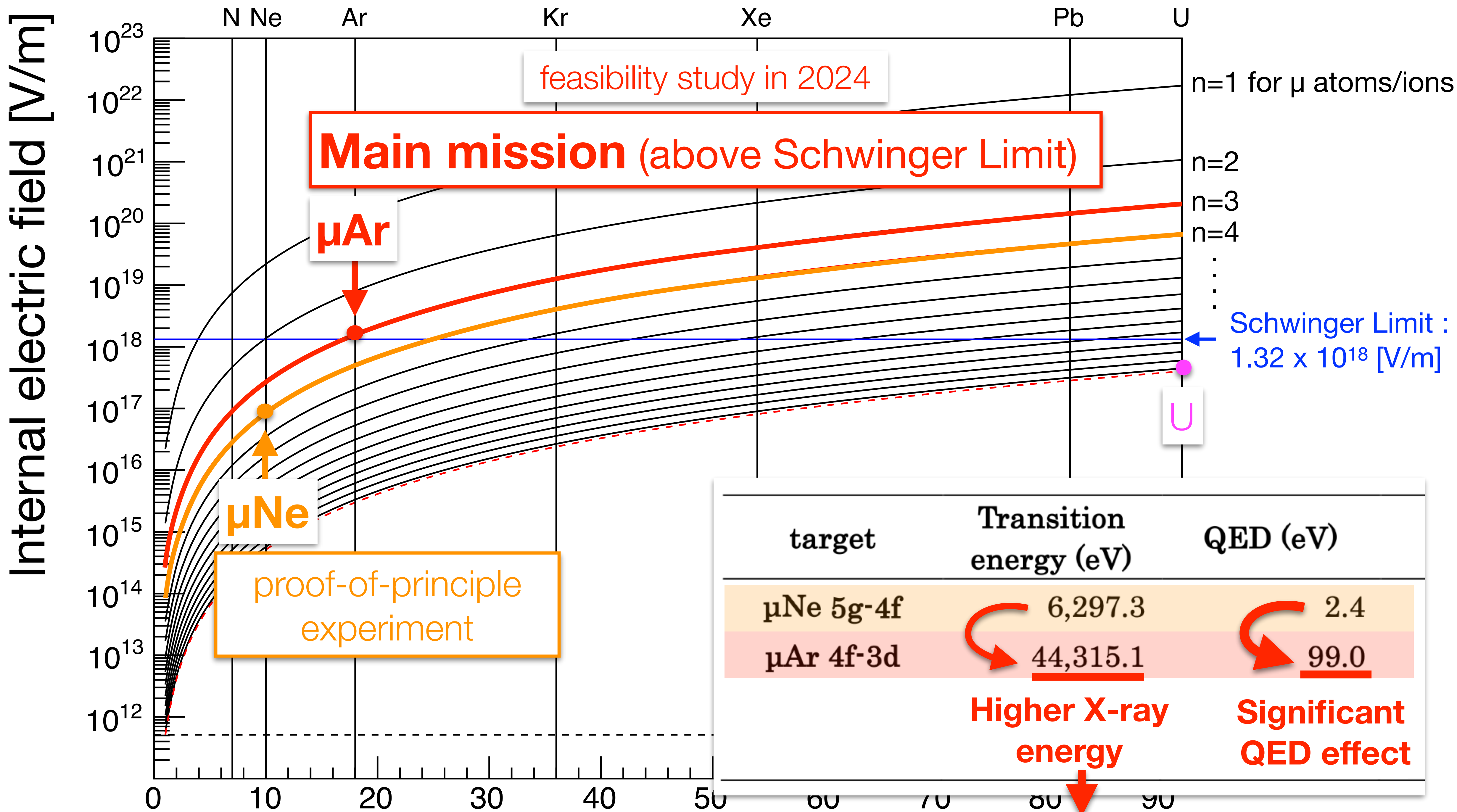
Proof-of-Principle Experiment for Testing Strong-Field Quantum Electrodynamics with Exotic Atoms: High Precision X-Ray Spectroscopy of Muonic Neon

T. Okumura,[1,*,†] T. Azuma,[1,‡] D. A. Bennett,[2] I. Chiu,[3] W. B. Doriese,[2] M. S. Durkin,[2] J. W. Fowler,[2] J. D. Gard,[2] T. Hashimoto,[4] R. Hayakawa,[5] G. C. Hilton,[2] Y. Ichinohe,[6] P. Indelicato,[7] T. Isobe,[8] S. Kanda,[9] M. Katsuragawa,[10] N. Kawamura,[9] Y. Kino,[11] K. Mine,[10] Y. Miyake,[9] K. M. Morgan,[2,12] K. Ninomiya,[3] H. Noda,[13] G. C. O'Neil,[2] S. Okada,[14,∥] K. Okutsu,[11] N. Paul,[7] C. D. Reintsema,[2] D. R. Schmidt,[2] K. Shimomura,[9] P. Strasser,[9] H. Suda,[5] D. S. Swetz,[2] T. Takahashi,[10] S. Takeda,[10] S. Takeshita,[9] M. Tampo,[9] H. Tatsuno,[5] Y. Ueno,[1] J. N. Ullom,[2] S. Watanabe,[15] and S. Yamada[6]

(Received 8 December 2021; revised 10 February 2023; accepted 10 March 2023; published 27 April 2023)



What's Next?



target	Transition energy (eV)	QED (eV)
μNe 5g-4f	6,297.3	2.4
μAr 4f-3d	44,315.1	99.0

Higher X-ray energy

Significant QED effect

Need new TES for high-energy X-rays

→ The feasibility study has been completed in this February.

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

2. Muonic molecule (μCF)

Collaboration (μdd*)

J-PARC MLF 2019MS01 collaboration (for μdd*)

Shinji Okada	Chubu Univ.	Japan
Yuichi Toyama	Chubu Univ.	Japan
Tadayuki Takahashi	IPMU	Japan
Tadashi Hashimoto	JAEA	Japan
Shin Watanabe	JAXA	Japan
Sohtaro Kanda	KEK	Japan
Naritoshi Kawamura	KEK	Japan
Yasuhiro Miyake	KEK	Japan
Hiroaki Natori	KEK	Japan
Kouichiro Shimomura	KEK	Japan
Patrick Strasser	KEK	Japan
Motonobu Tampo	KEK	Japan
Izumi Umegaki	KEK	Japan
Hirofumi Noda	Osaka Univ.	Japan
Toshiyuki Azuma	RIKEN	Japan
Katsuhiko Ishida	RIKEN	Japan
Ryota Hayakawa	Rikkyo Univ.	Japan
Yuto Ichinohe	Rikkyo Univ.	Japan
Toshiki Sato	Rikkyo Univ.	Japan
Shinya Yamada	Rikkyo Univ.	Japan

Yasushi		Kino	Tohoku Univ.	Japan
Ren		Konishi	Tohoku Univ.	Japan
Ryota		Nakashima	Tohoku Univ.	Japan
Kenichi		Okutsu	Tohoku Univ.	Japan
Kyosuke		Sasaki	Tohoku Univ.	Japan
Takuma		Yamashita	Tohoku Univ.	Japan
Takuma		Okumura	Tokyo Metropolitan Univ.	Japan
Hideyuki		Tatsuno	Tokyo Metropolitan Univ.	Japan
Douglas	A.	Bennett	NIST	US
William	B.	Doriese	NIST	US
Malcolm	S.	Durkin	NIST	US
Joseph	W.	Fowler	NIST	US
Johnathon	D.	Gard	NIST	US
Gene	C.	Hilton	NIST	US
Kelsey	M.	Morgan	NIST	US
Galen	C.	O'Neil	NIST	US
Carl	D.	Reintsema	NIST	US
Dan	R.	Schmidt	NIST	US
Daniel	S.	Swetz	NIST	US
Joel	N.	Ullom	NIST	US

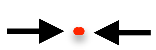
(Nuclear & Hadron + Atomic & Muon + Astro) physicists + TES experts

interdisciplinary team

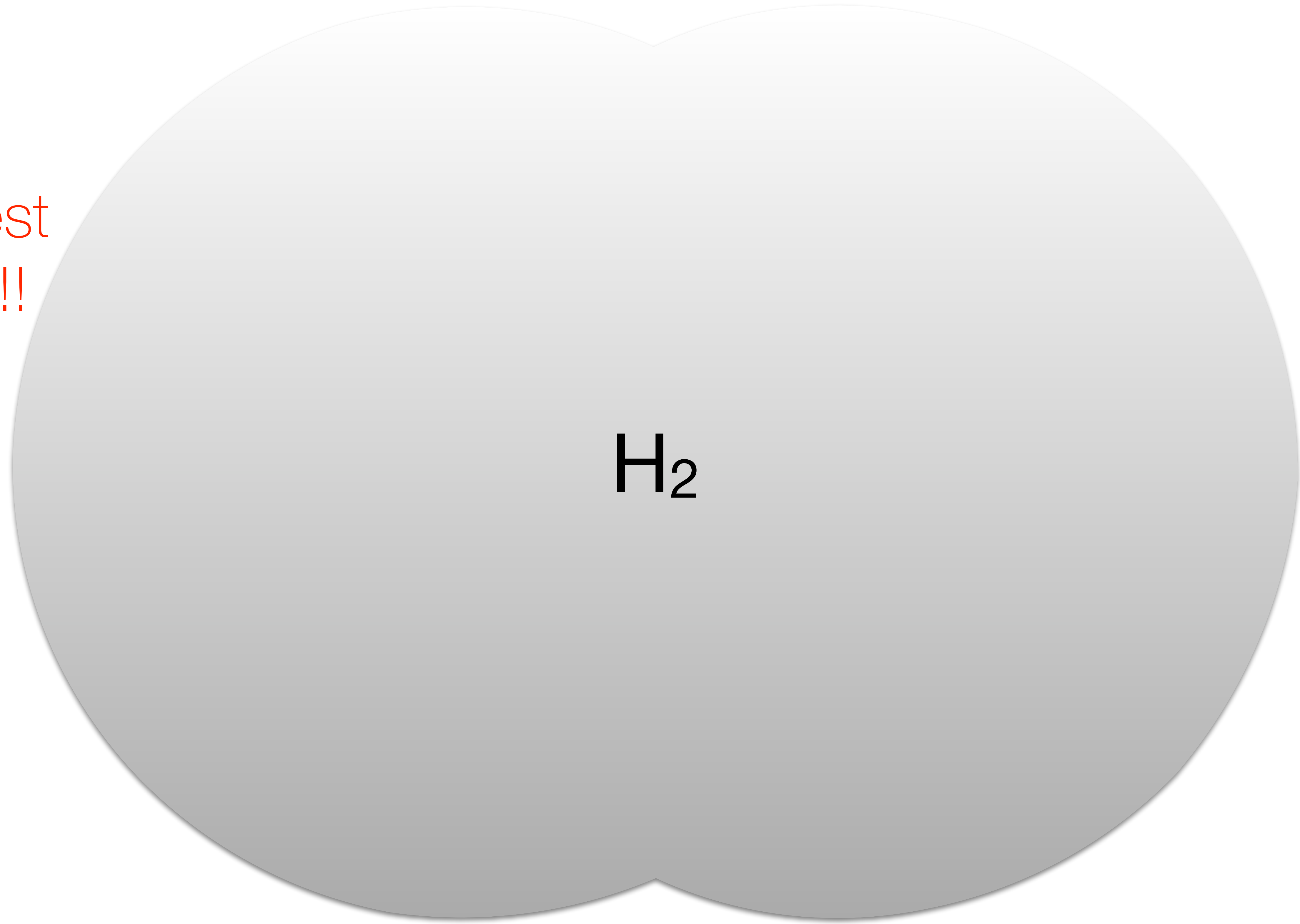
Scaled image, again

The smallest molecule !!

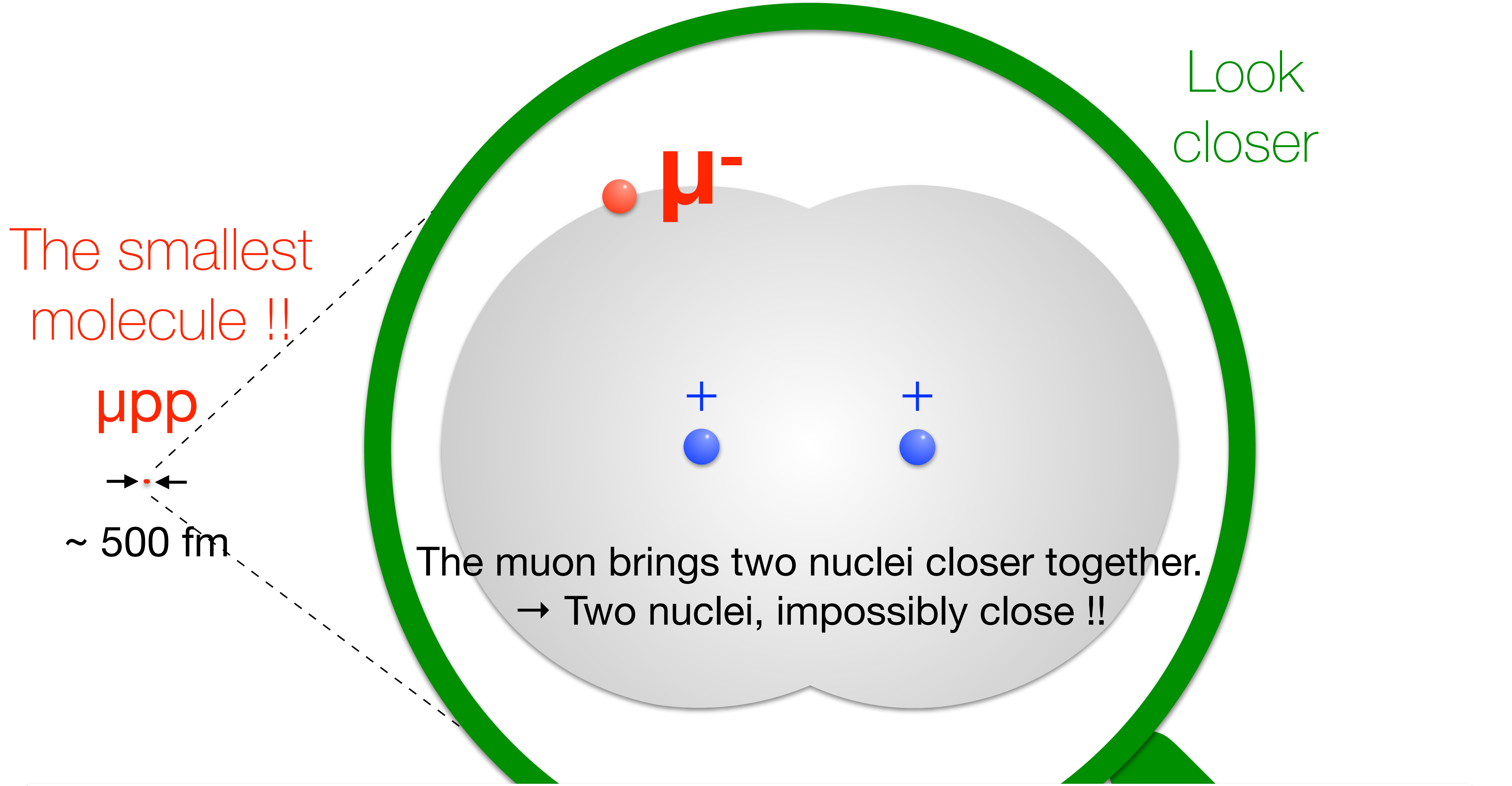
μpp



~ 500 fm



Muonic molecule

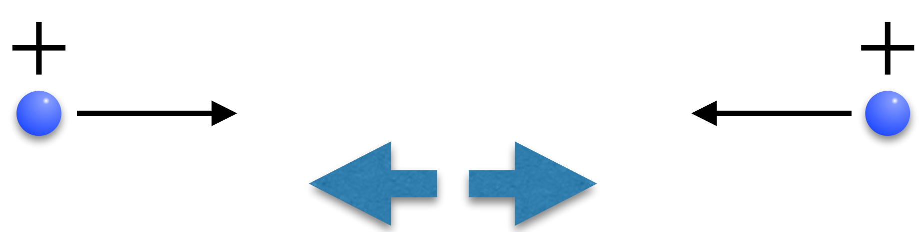


Compared to the reach of nuclear force (**a few fm**), it becomes small enough to allow nuclear reactions to occur within the molecule.

Fusion

Thermonuclear fusion

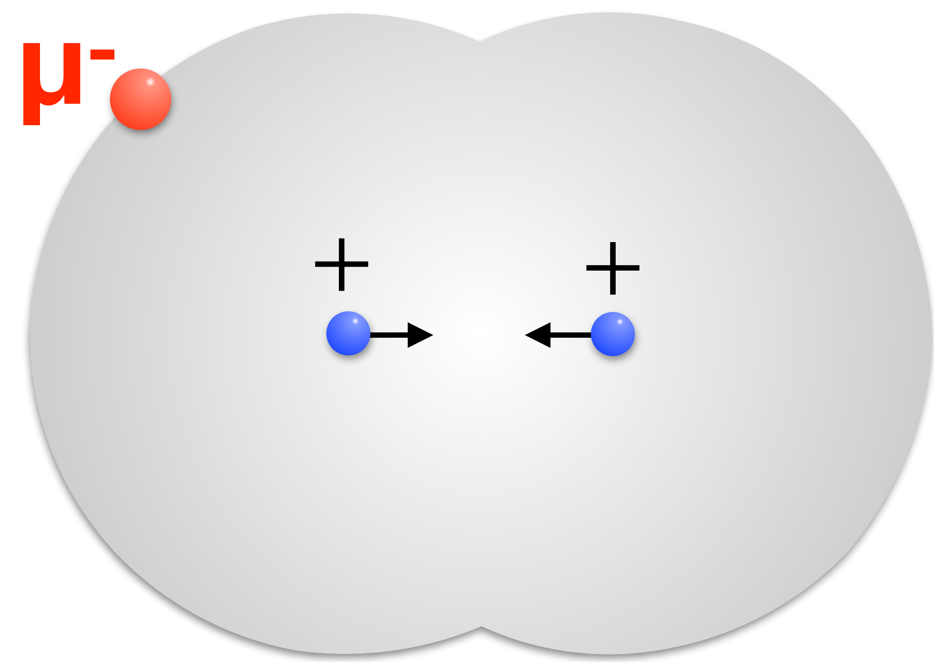
Vigorous collisions in plasma
at several hundred million
degrees Celsius



Large repulsion due to
electromagnetic force

Fusion with muons

Nuclei easily approach each other

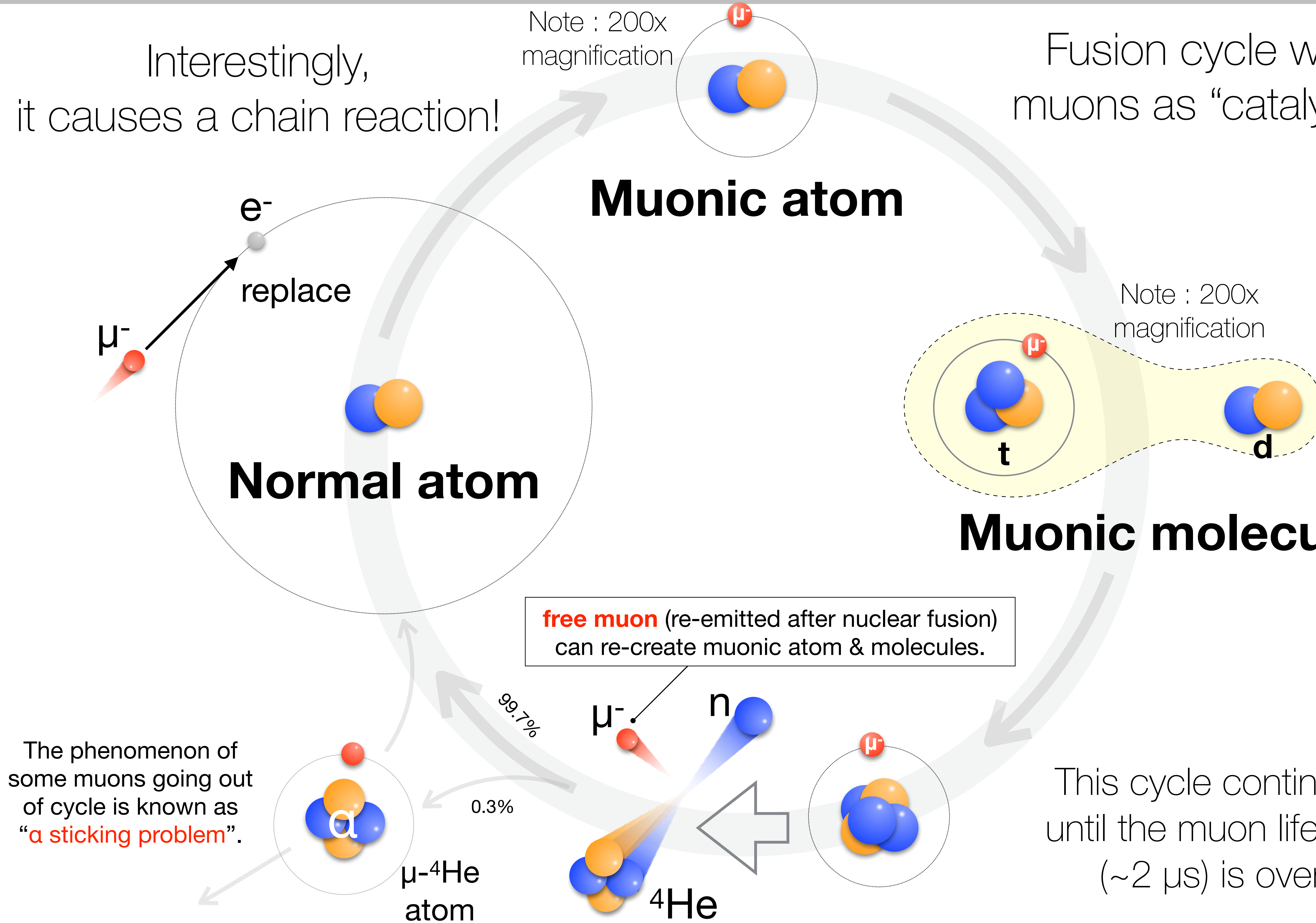


No repulsion by
electromagnetic forces
up to the size of a muonic
molecule

Muon-Catalyzed Fusion (μCF)

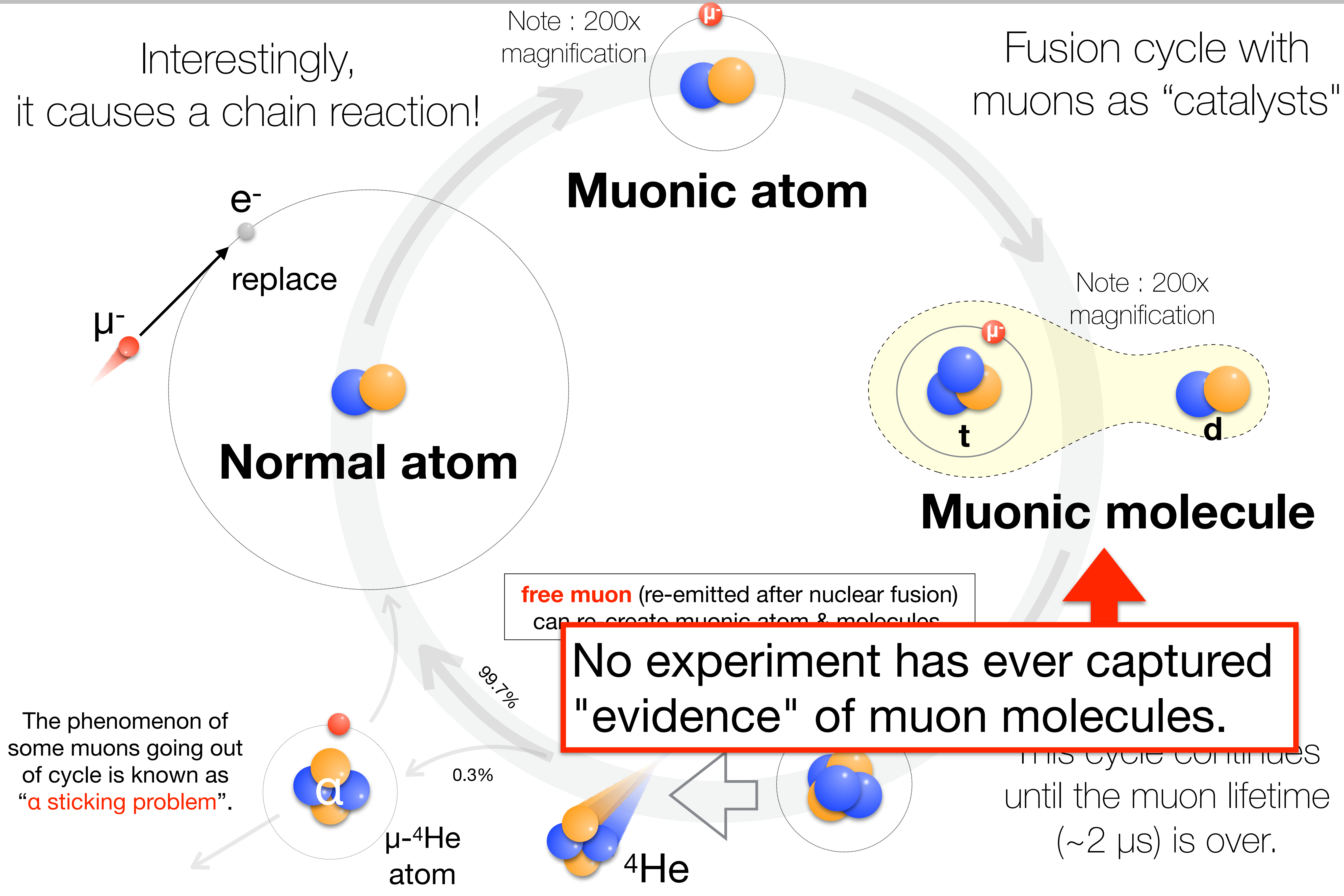
Interestingly,
it causes a chain reaction!

Fusion cycle with
muons as “catalysts"



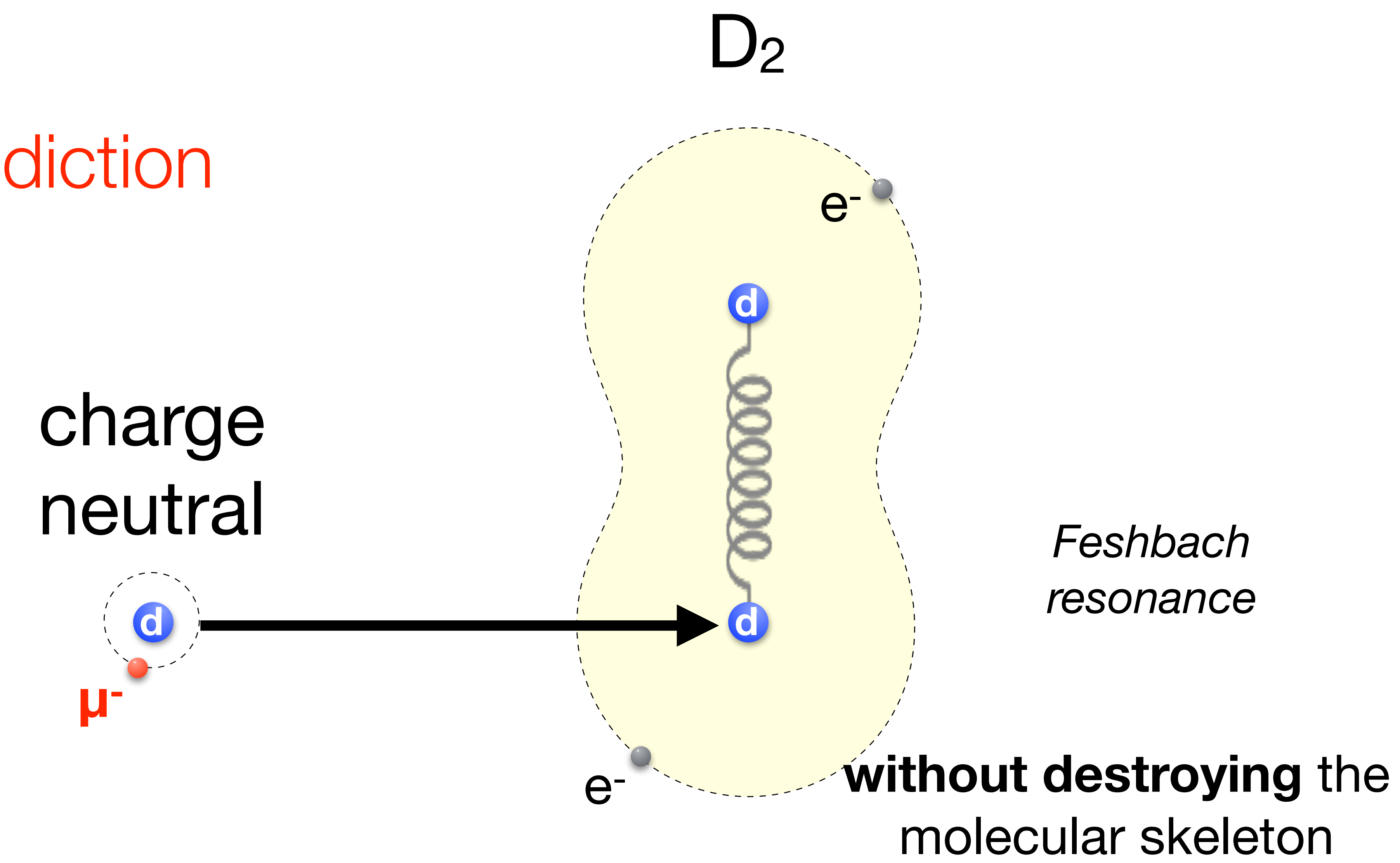
This cycle continues
until the muon lifetime
(~2 μs) is over.

Muon-Catalyzed Fusion (μCF)



How μ molecules are created ?

Theoretical Prediction



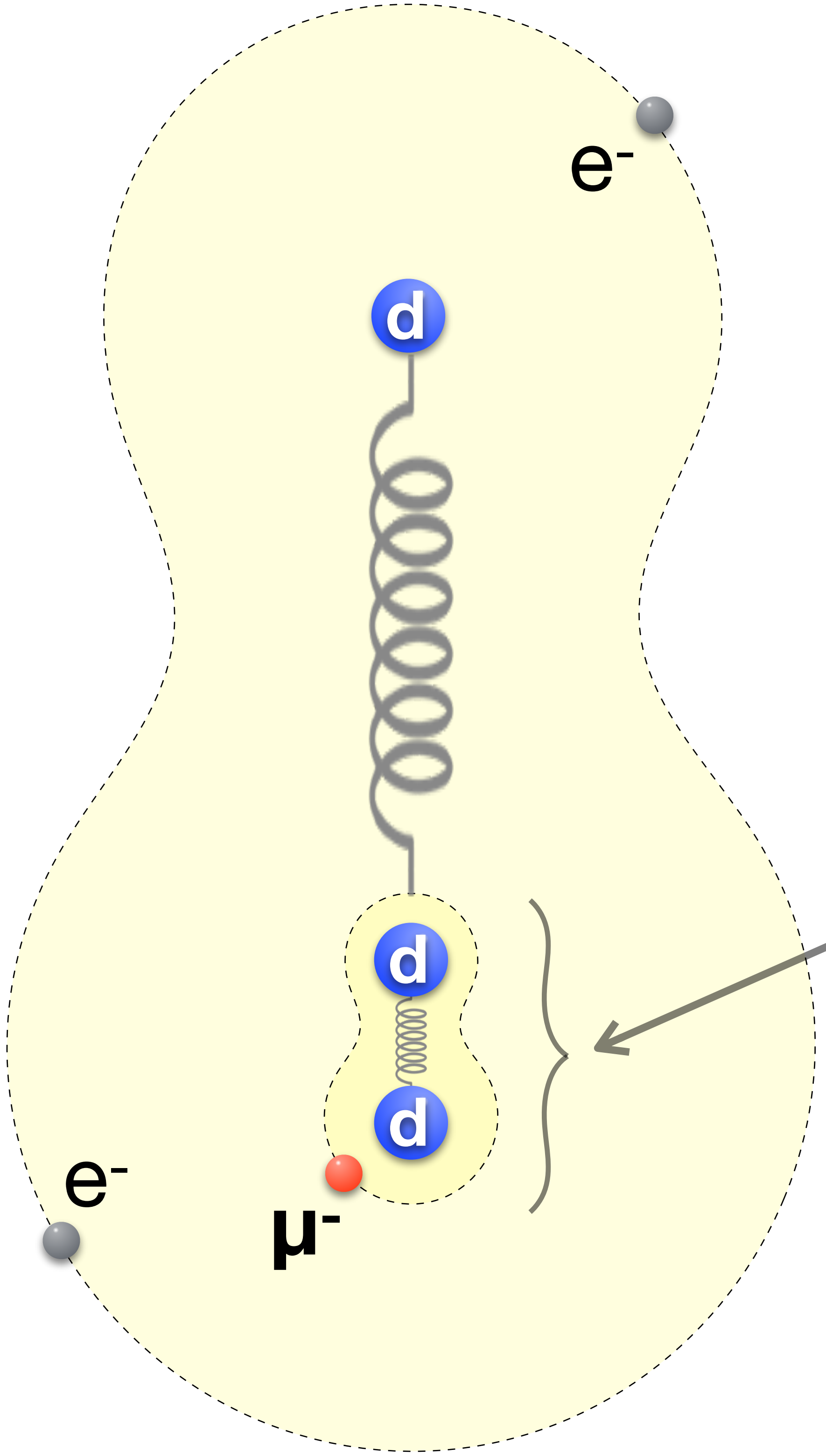
If the muonic atom collide “**gently**” to the normal molecule, the excess energy of ddμ molecule formation is passed to the rovibrational excitation energy of D_2 molecule.

⇒ Resonant generation (Vesman mechanism)

Molecule in molecule !

Theoretical prediction

Matryoshka-like



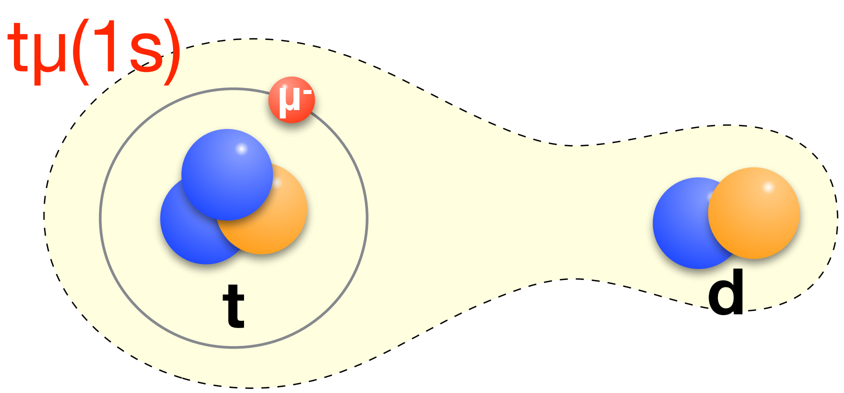
ddμ molecule

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

Exited state of muonic molecule

Ground state

dtμ

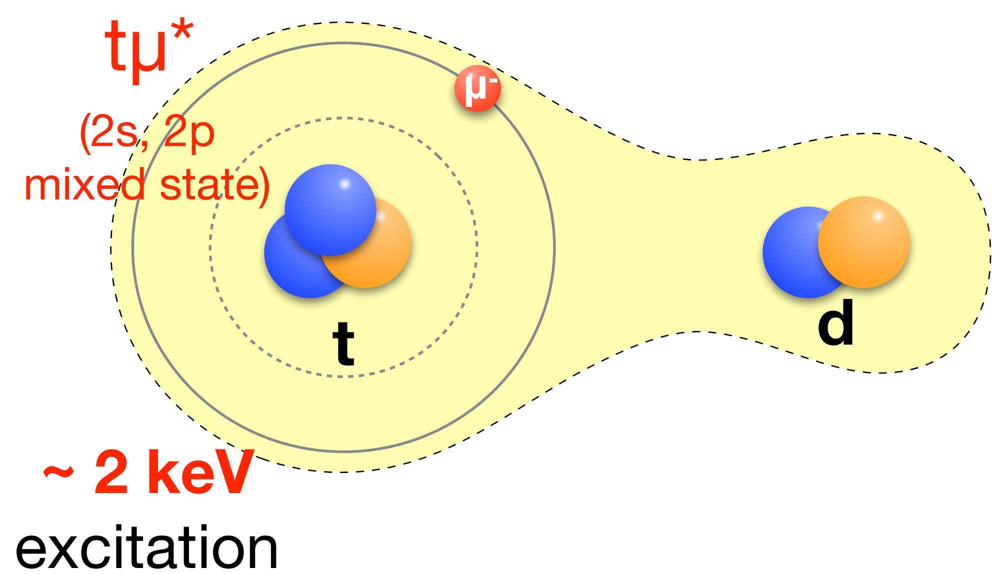


Immediately leading to **nuclear fusion**

No chance to measure ↑

Excited state

dtμ*



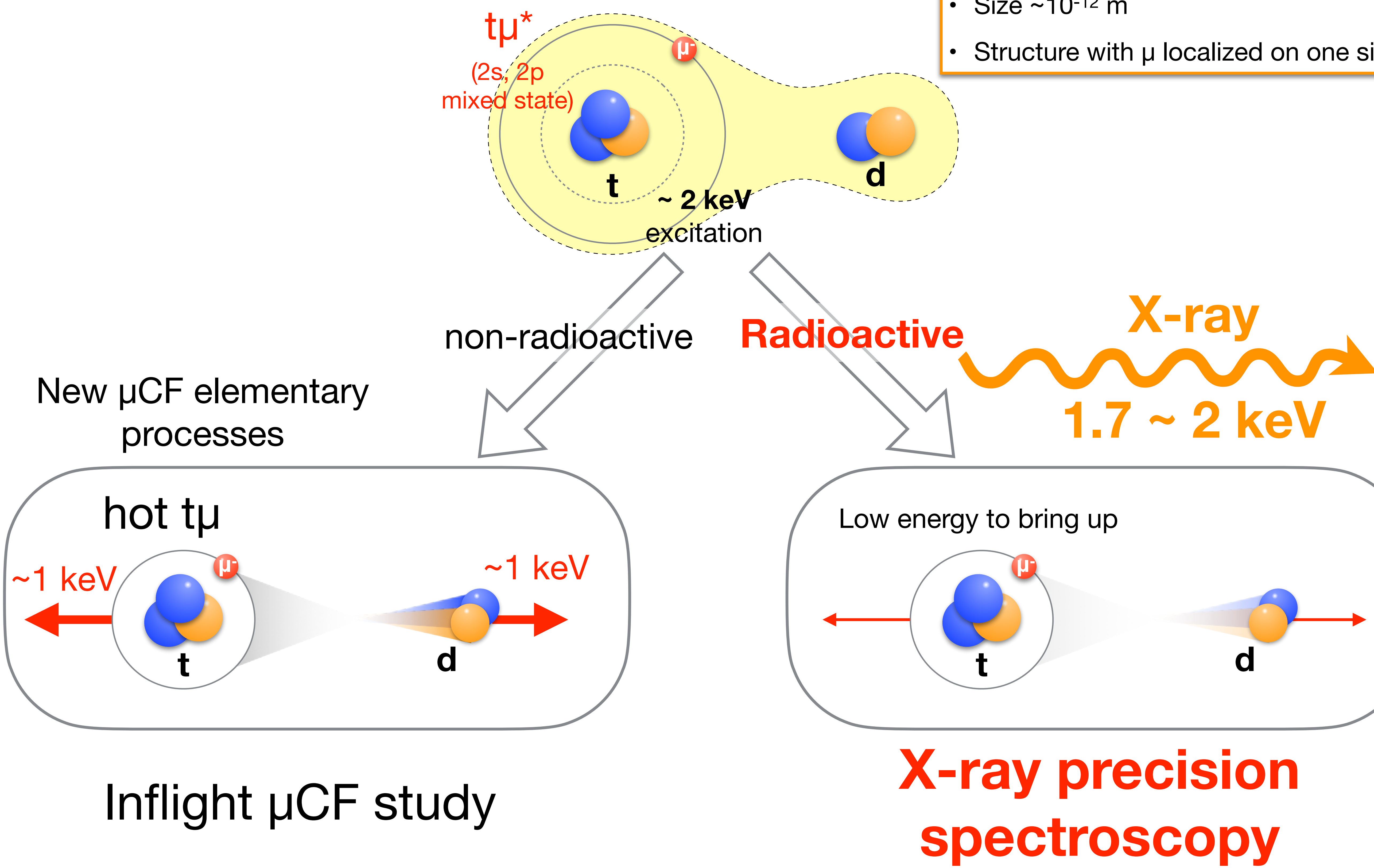
No nuclear fusion, but dissociates while **emitting X-rays**

Measure this ↑

to determine what quantum states are being produced and how.

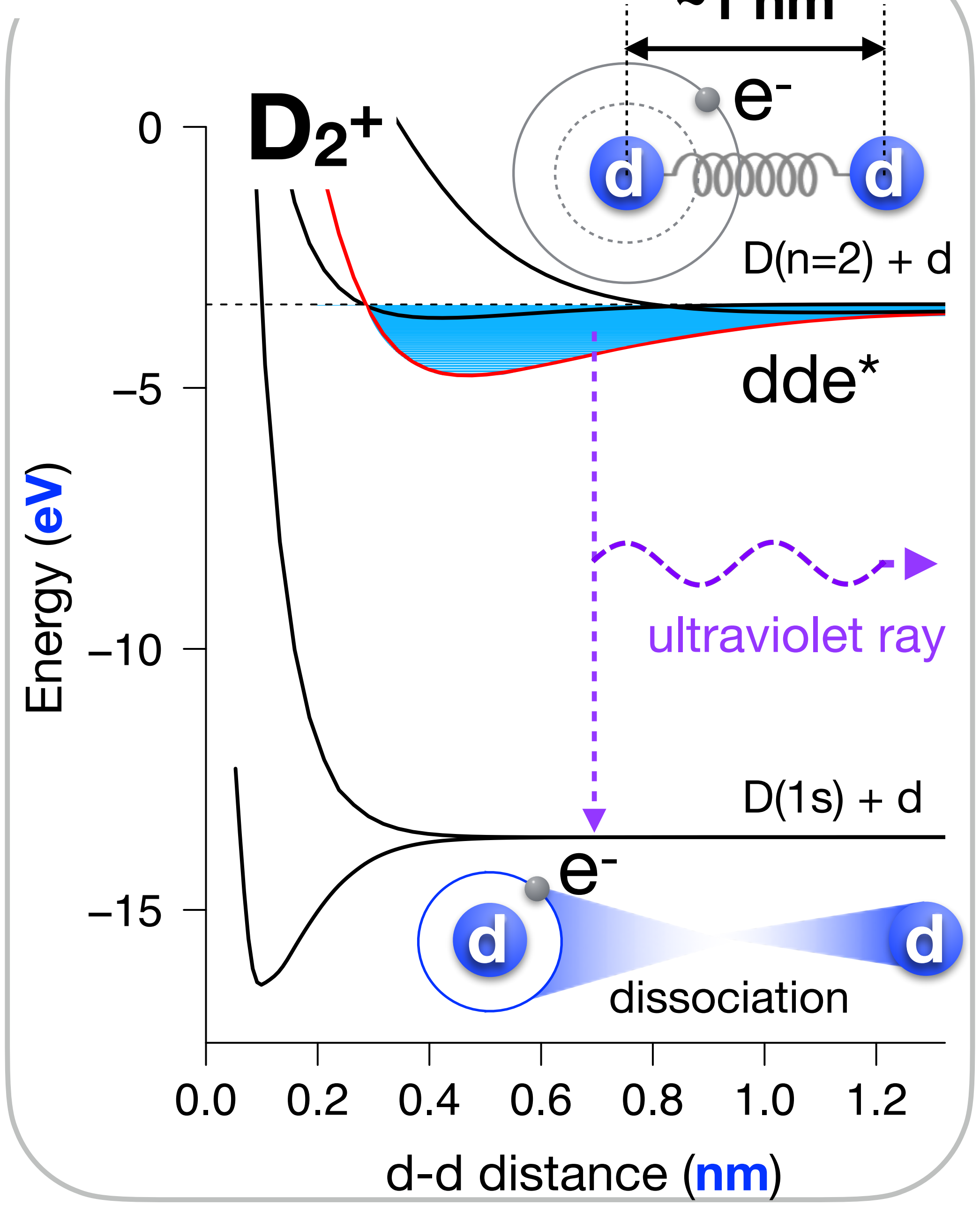
Dissociation of excited molecules

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

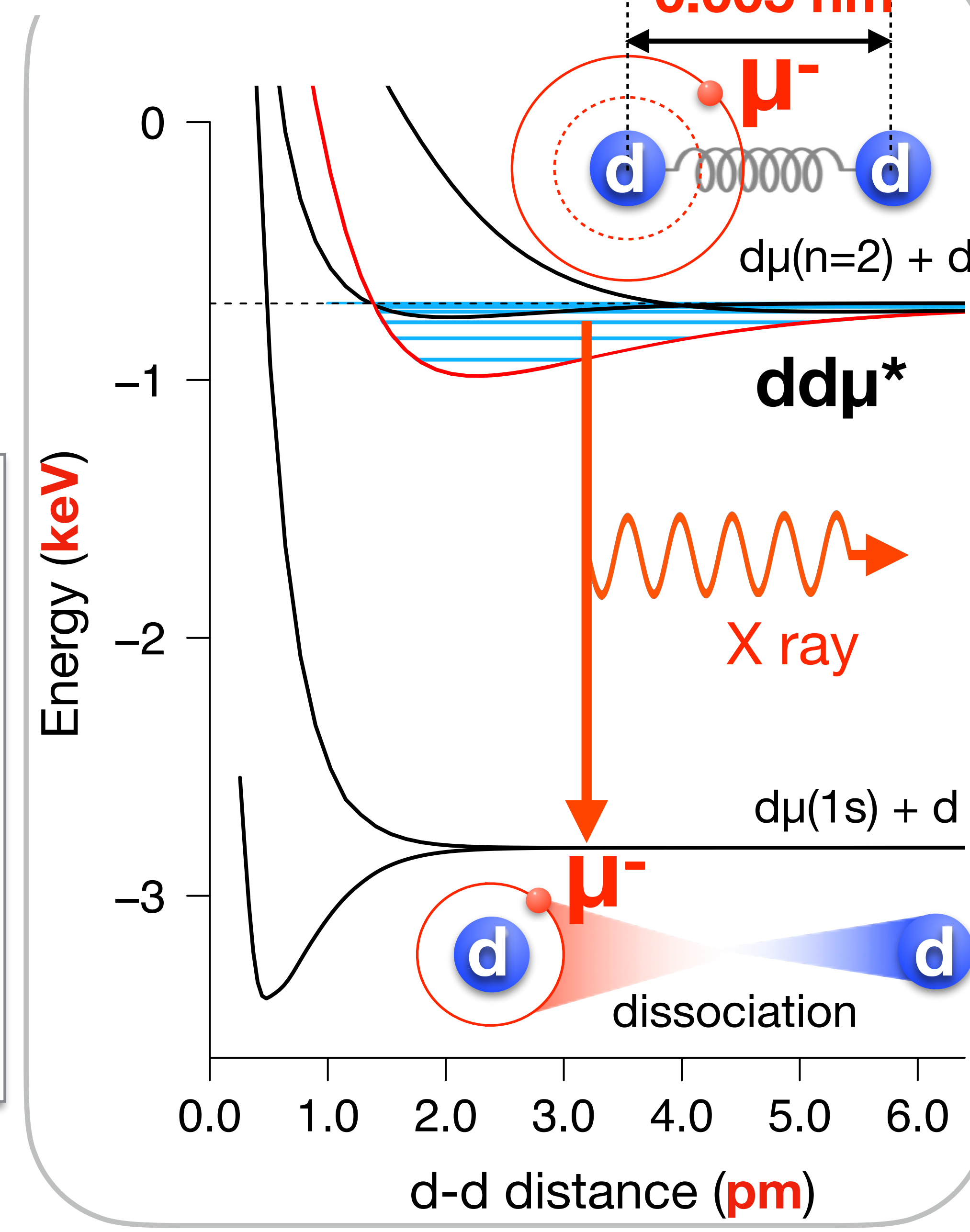


High Precision Spectroscopy of **Muonic Molecules**

Normal molecule



Muonic molecule

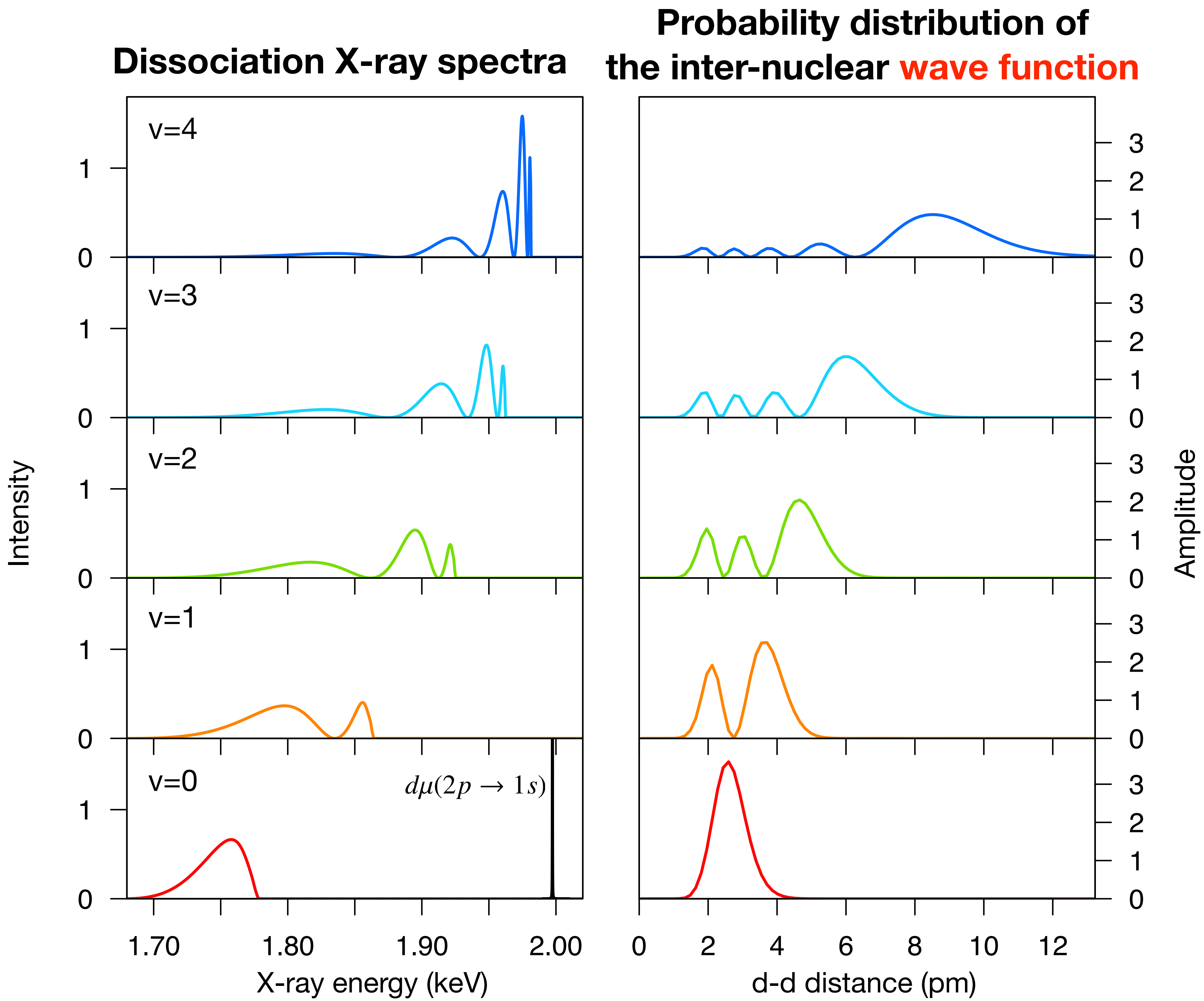


- Distance between nuclei : **x 1/200**
- Energy : **x 200**
- **Adiabatic approximation is not valid** due to close masses of d and μ
- ddμ* has large zero-point motion and **sparse level spacing**

Note that this is a figure of convenience.
(In fact, such adiabatic approximate potentials cannot be fully understood.)

Requires a **few-body calculation** that simultaneously solves for the motion of nuclei and heavy negatively charged particles. → **Y. Kino & T. Yamashita**

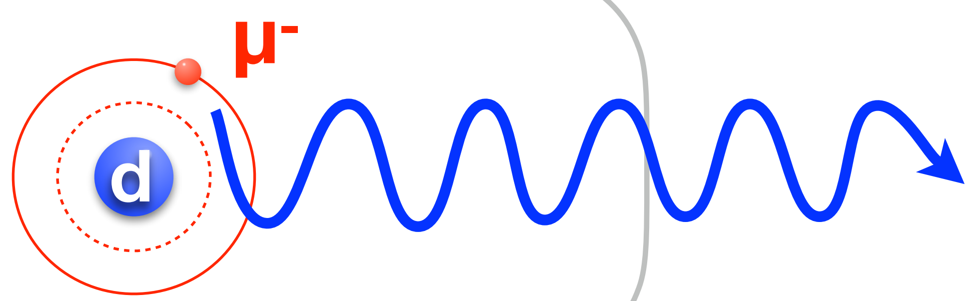
Radiation dissociation spectra of excited μ molecules



The X-ray energy spectrum is expected to have a very characteristic structure **reflecting the shape of the wavefunction !!**

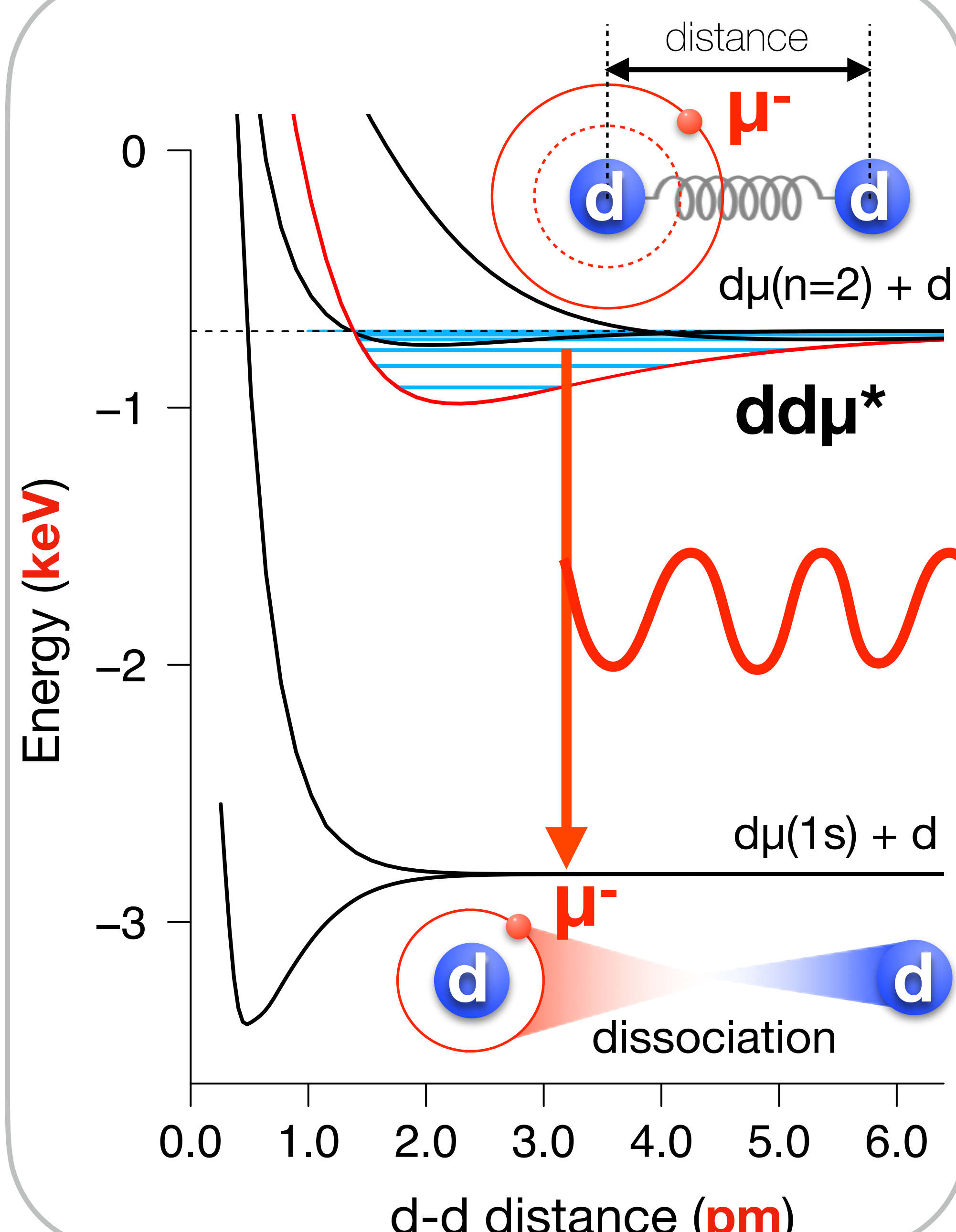
Difficulty of the measurement

Muonic atom



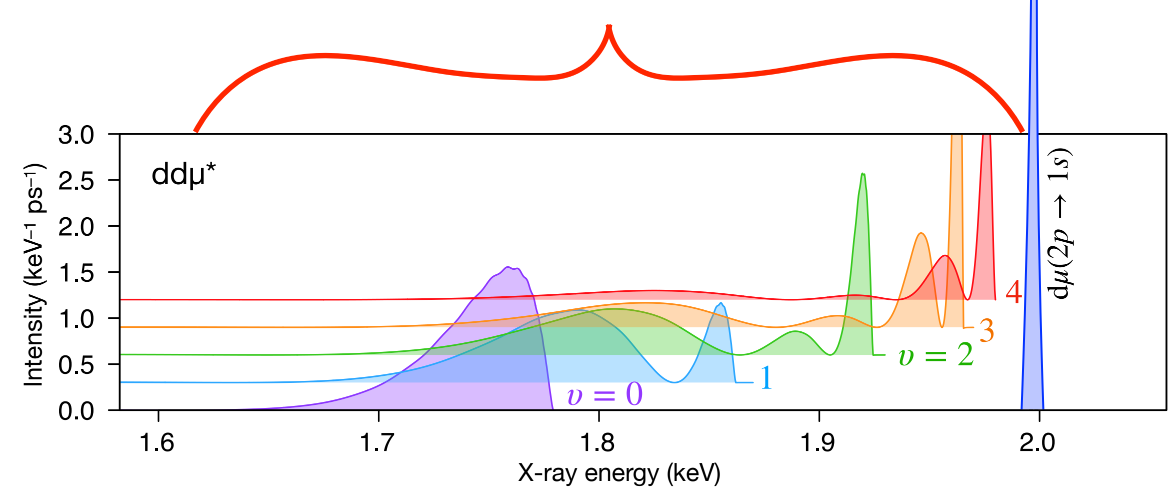
X-ray : 2 keV
intense & sharp peak

Muonic molecule

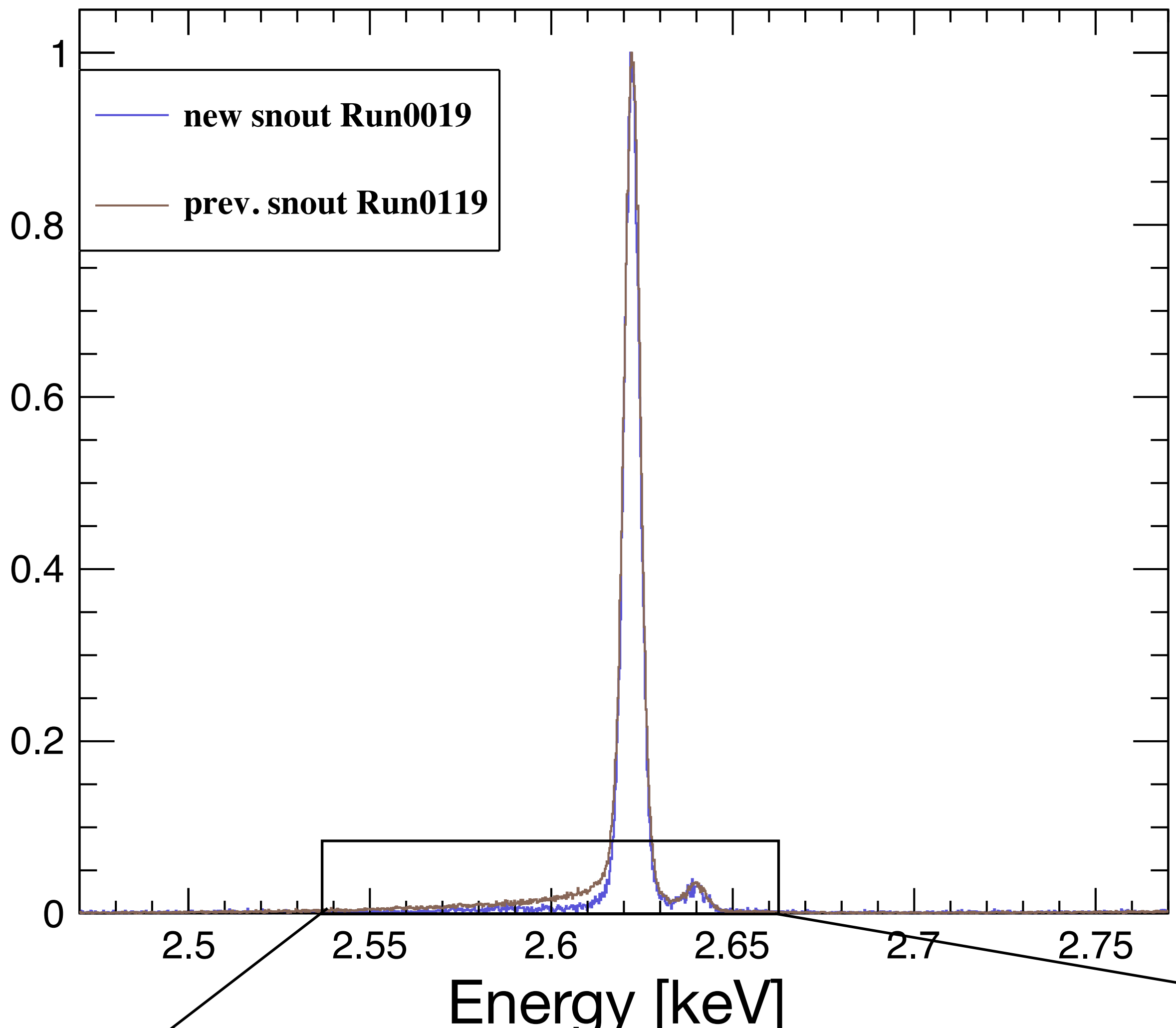


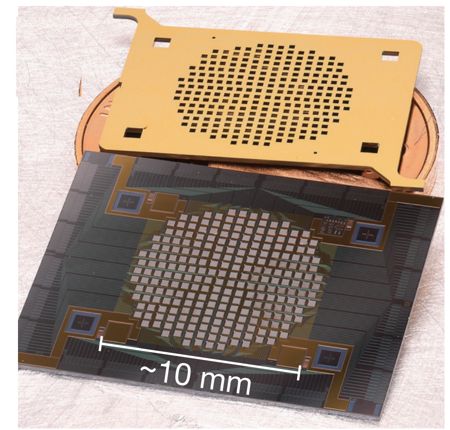
→ **cannot be separated** with the resolution of conventional semiconductor detectors (~several 100 eV)

X-ray : 1.7 ~ 2 keV
low-intense & broad structure



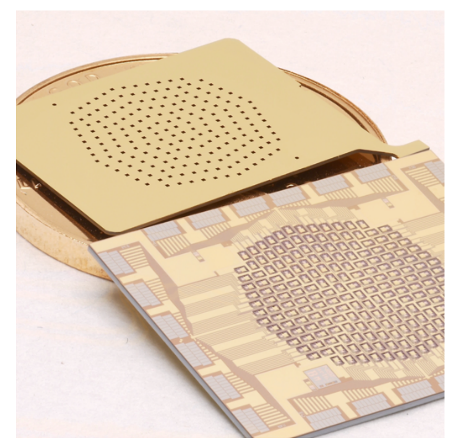
New TES : Less tail component





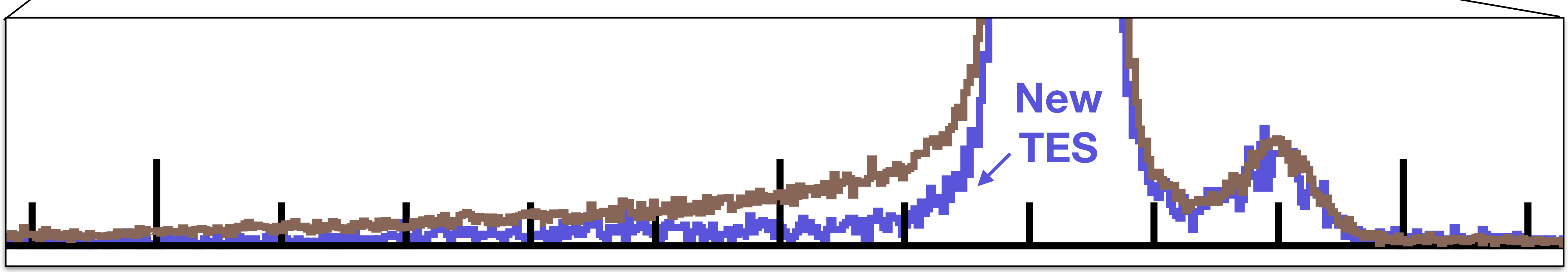
Original TES

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



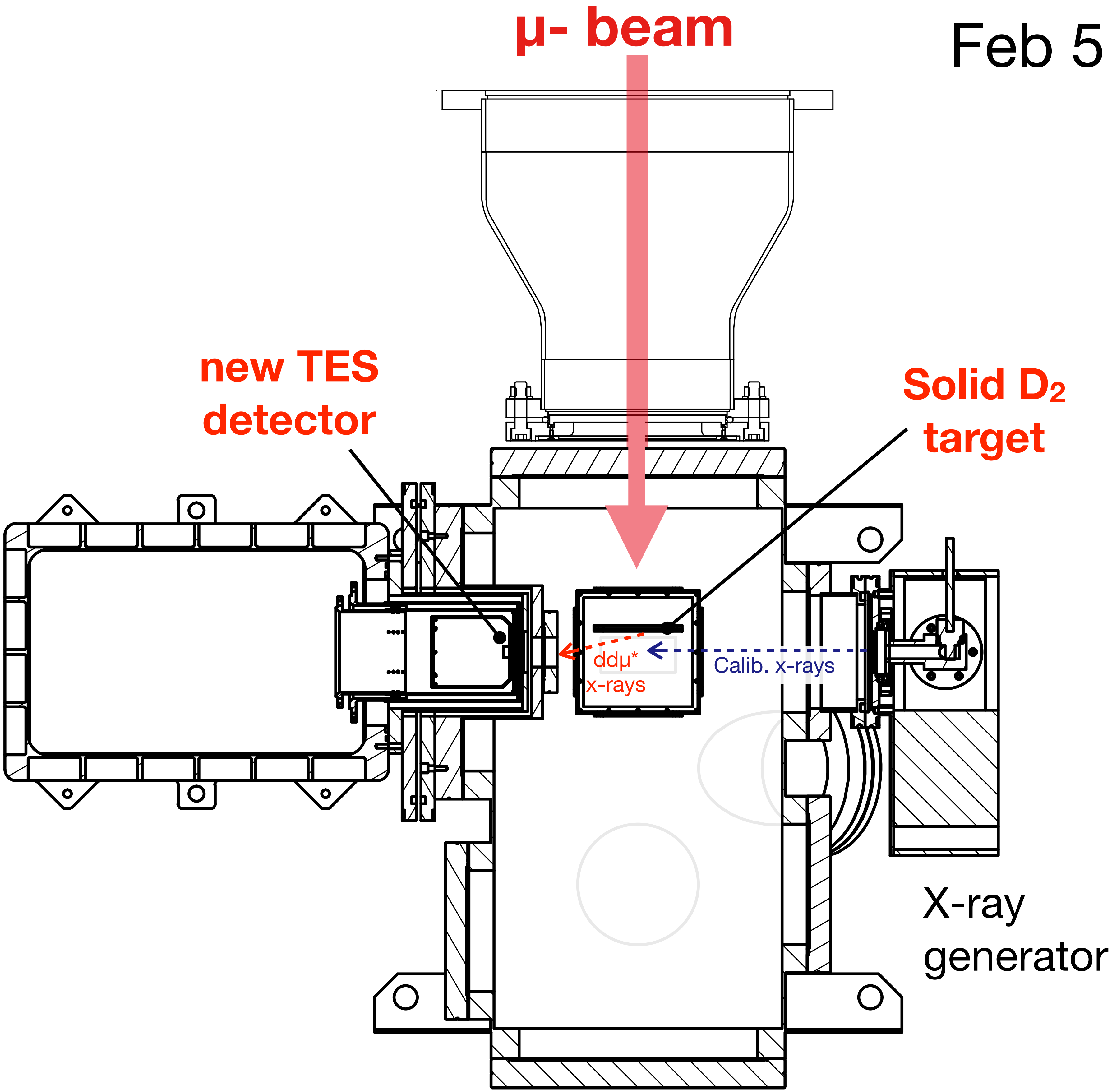
New TES
for Low energy X-ray

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



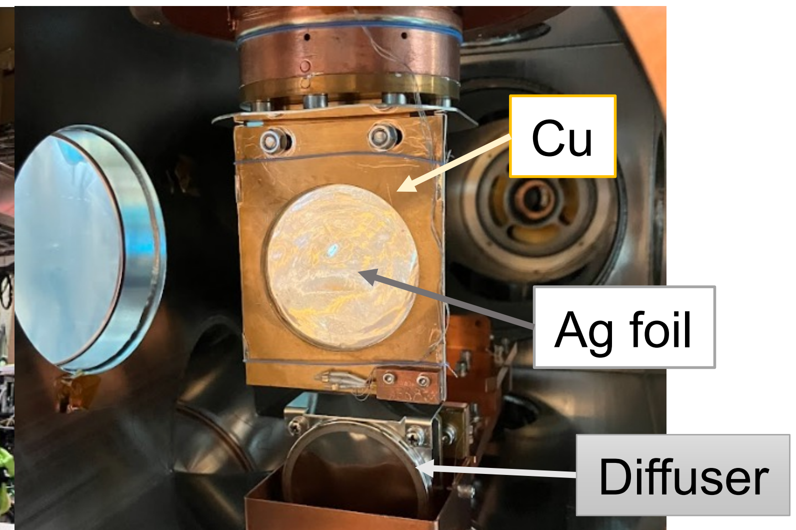
Experimental setup

Feb 5 - 11, 2023



Solid deuterium system

P. Strasser et al. NIMA 460, 451 (2001)



Al thermal shield
(before attaching window)

Solid deuterium target system

- Base: Ag foil (100 μm)
- Target size: Φ60
- Thickness: 1 mm
- Temperature: ~3 K (Liq. He coolant)
- Chamber pressure: 1x10^{-6} Pa

✓ Stable operation during the measurement.

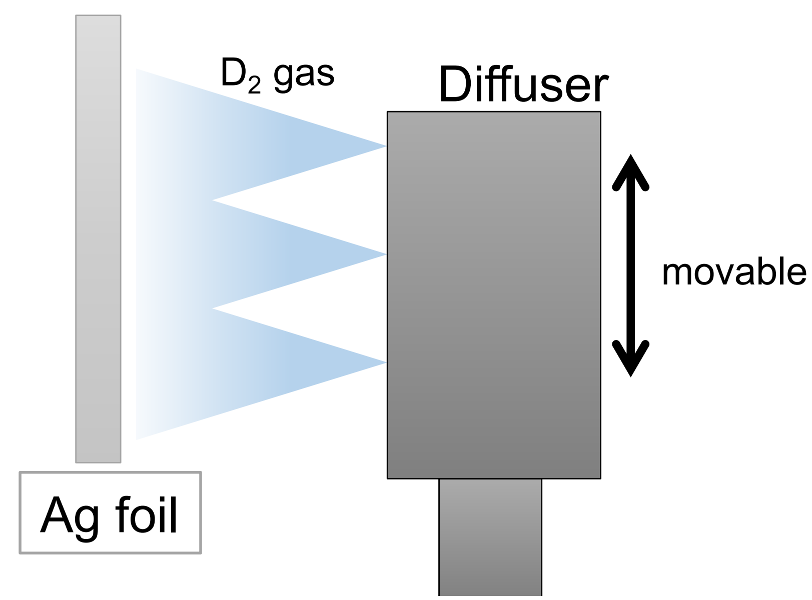
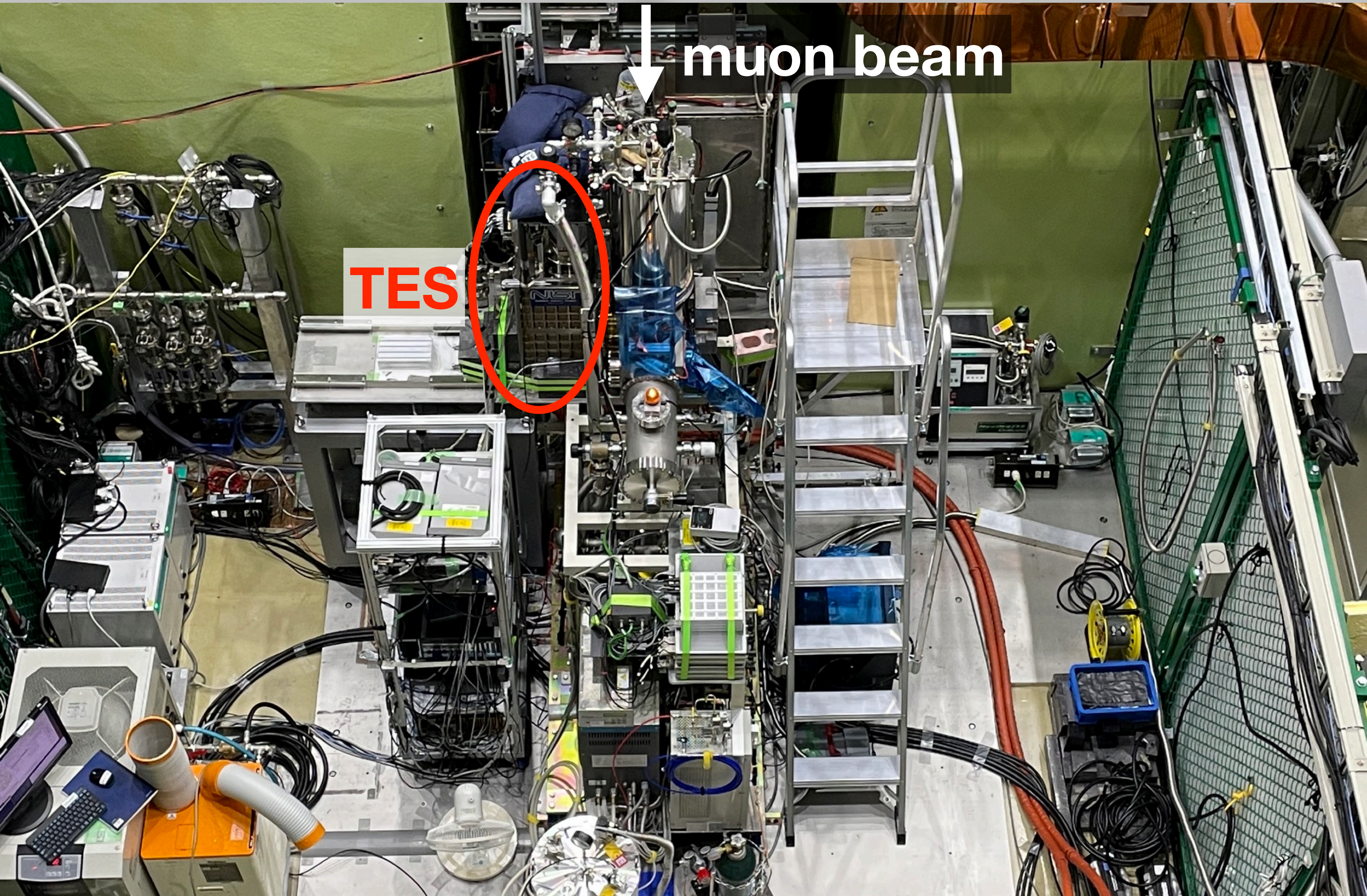
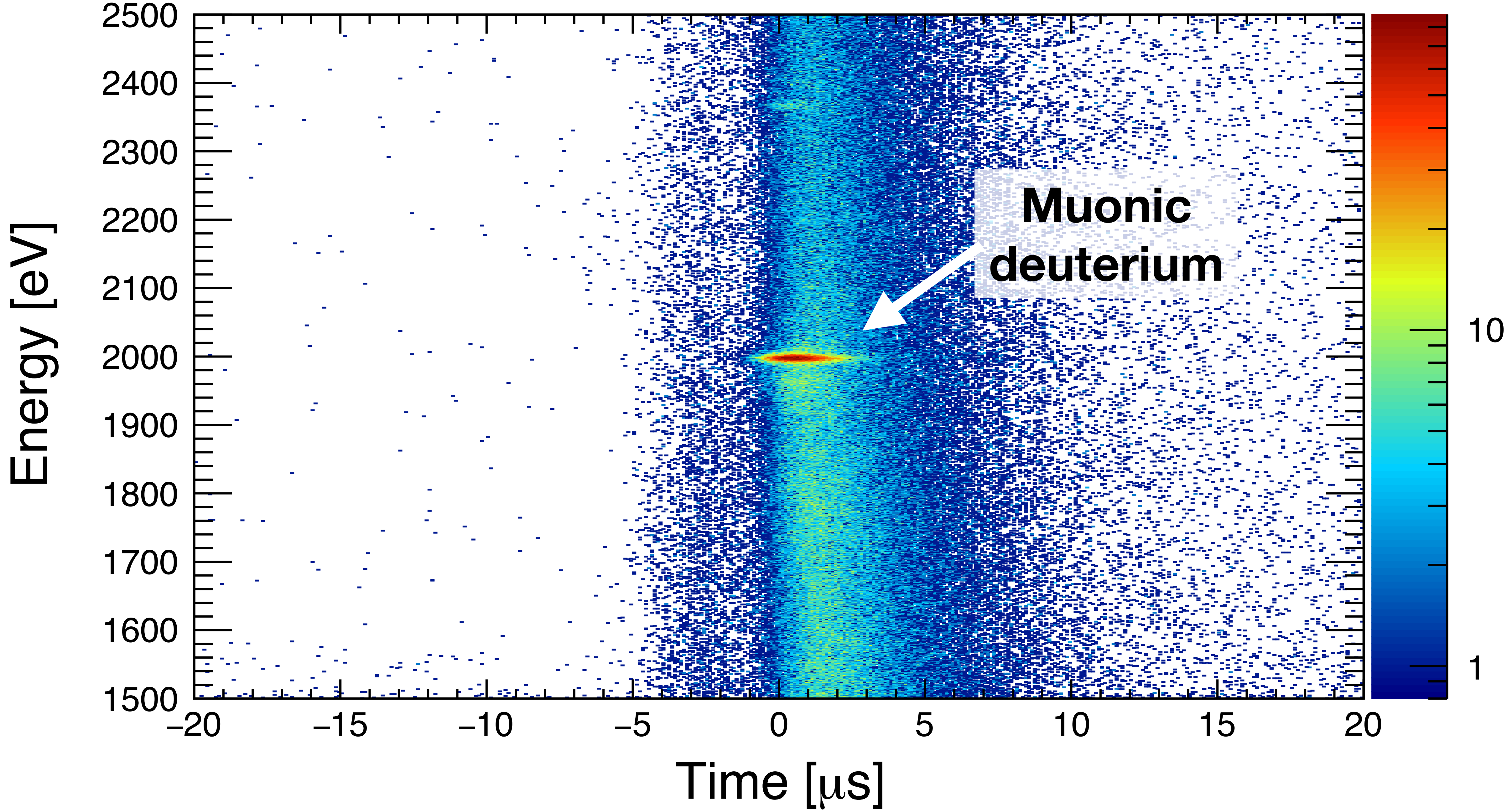


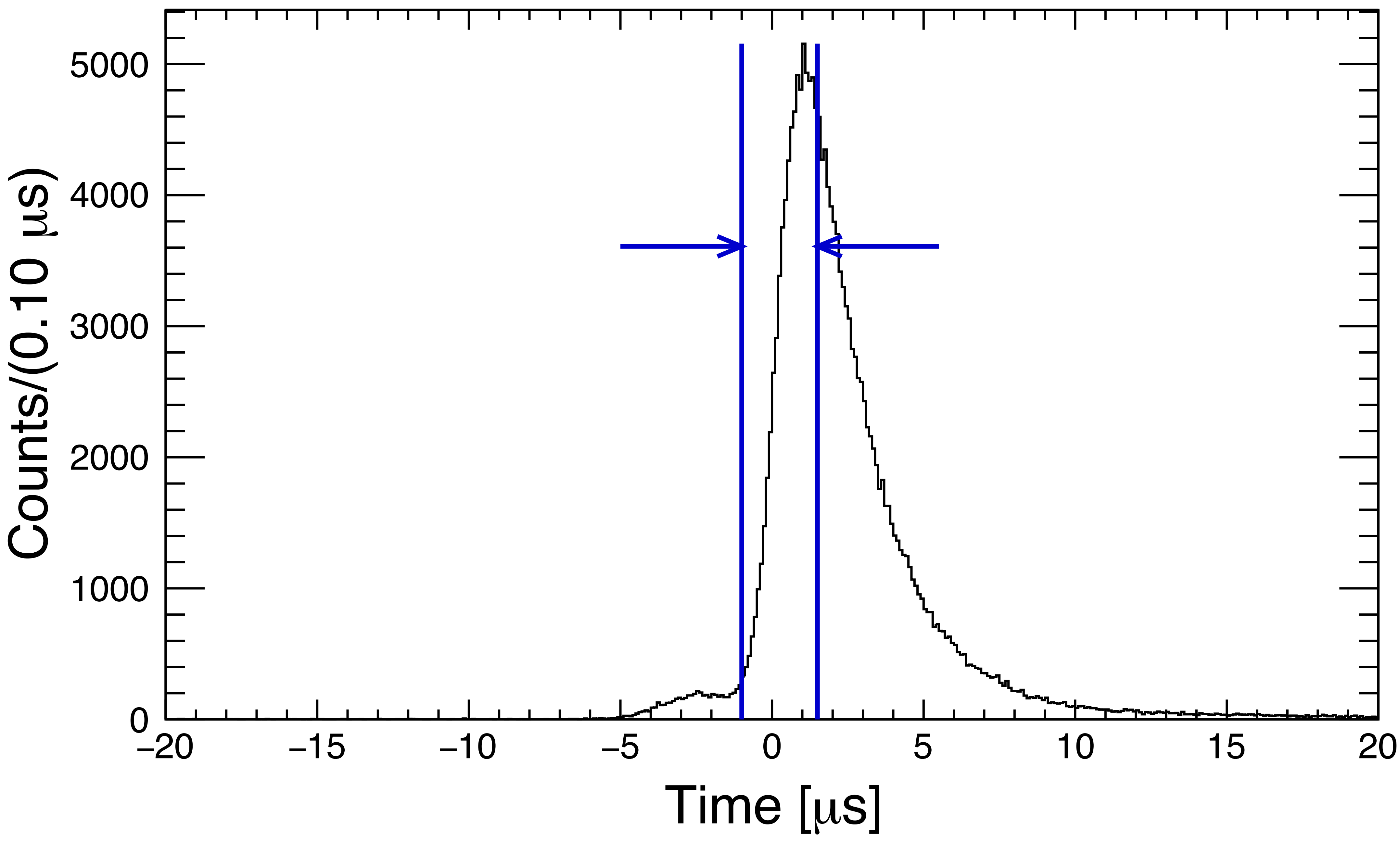
Photo at beamline



Energy vs. Time



Timing cut


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

3. 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)

Muonic atoms

➡ High-precision absolute energy measurement for rare events

2. Covering a wide energy range with high resolution

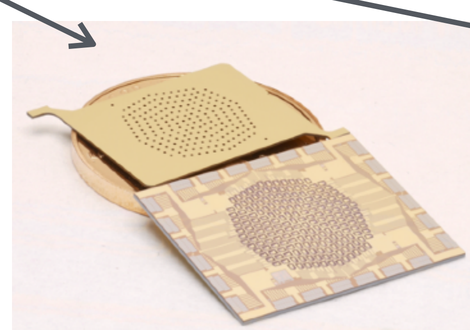
Muonic molecule

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

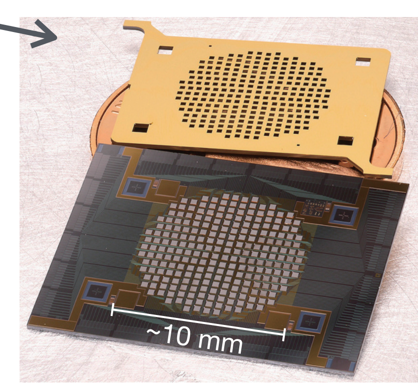
Developed TES for high-energy X-rays

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

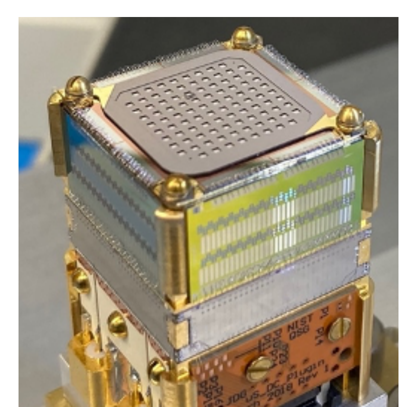
Existing TES
(have been using since 2016)

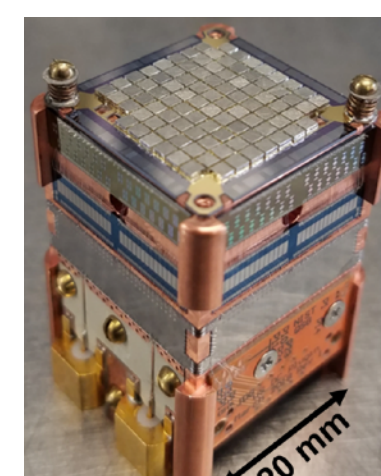


Rev. Sci. Instrum. 90, 123107 (2019)



Brand-new TES detector
(brought from NIST this January)



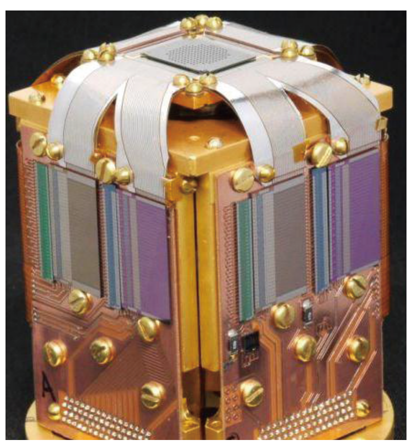


Outlook

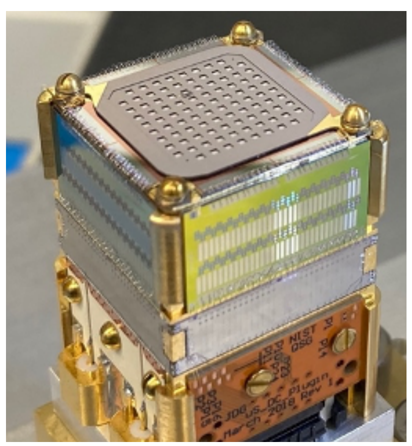
◉ **A new proposal application** (muon S1 type) are being submitted for various experiments using this new TES system, very recently.

Next generation X-ray detector
covering a wide energy range

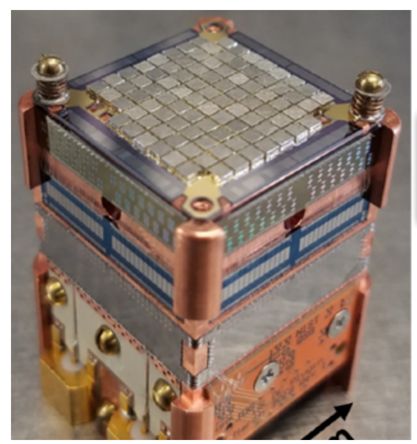
10 keV



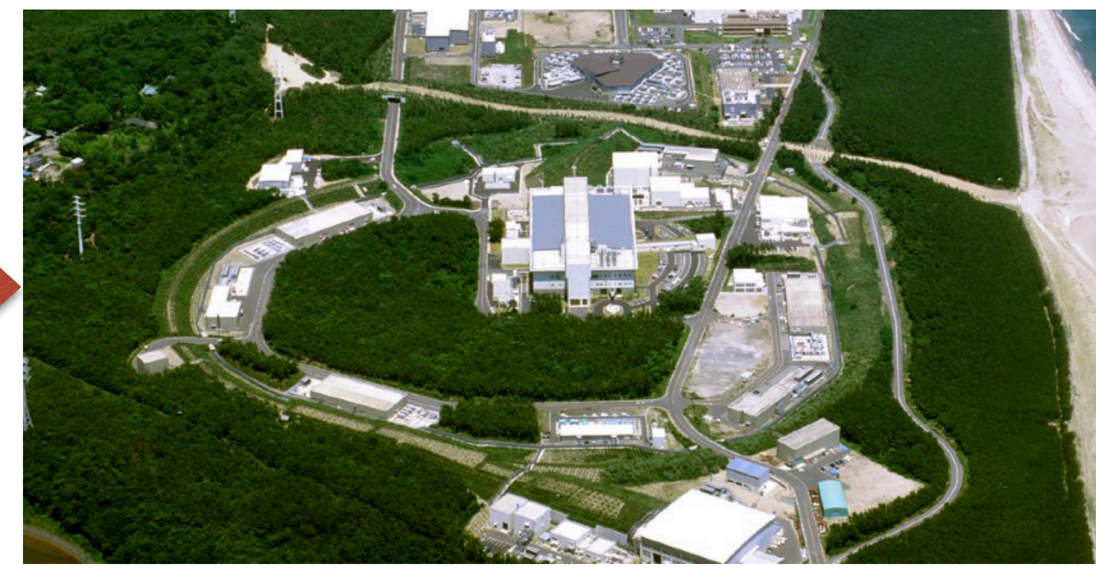
50 keV



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

Thank you for your attention.