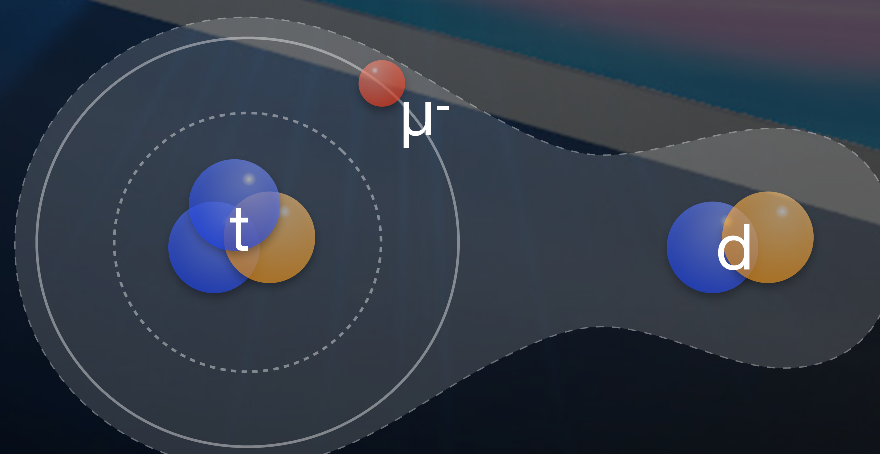
Interdisciplinary Science Conference in Okinawa
— Physics and Mathematics meet Medical Science —

ISCO 2023 @ OIST
Mar. 1, 2023

New Developments in Muon-Catalyzed Fusion Research by Precise X-ray Spectroscopy of Muonic Molecules



Shinji OKADA (Chubu Univ.)

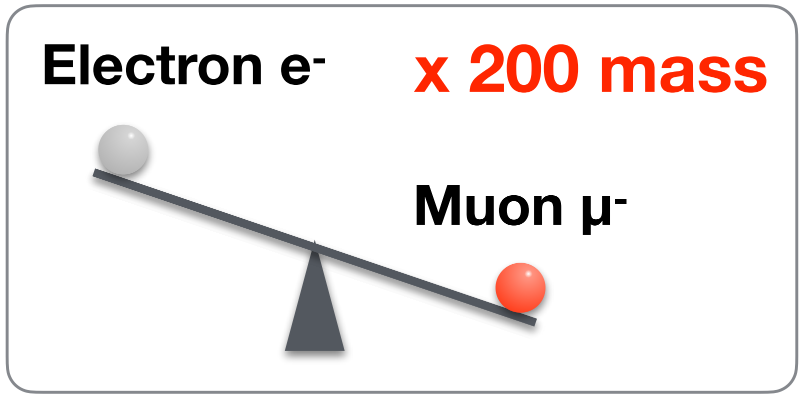
Contents

1. What’s muon-catalyzed fusion?

Muonic atom

What is muon?

- A member of the electron family
- ~200 times heavier than the mass of an electron
- short life time (~2.2 μsec)
- can be made into a beam using a particle accelerator



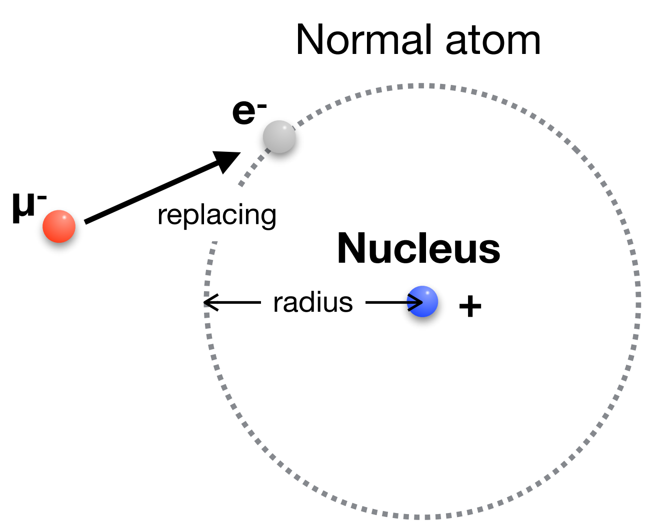
What is a muonic atom?

➡ When a negative-charged muon is stopped in a material, it can replace an electron to form a muonic atom

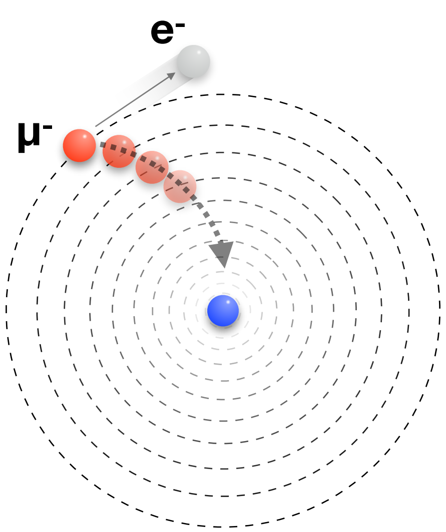
➡ Muons are 200 times heavier than electrons, so they form very compact atoms with a radius of 1/200 compared to ordinary atoms.

$$\text{Bohr radius} \propto \frac{m_e}{m_\mu^*}$$

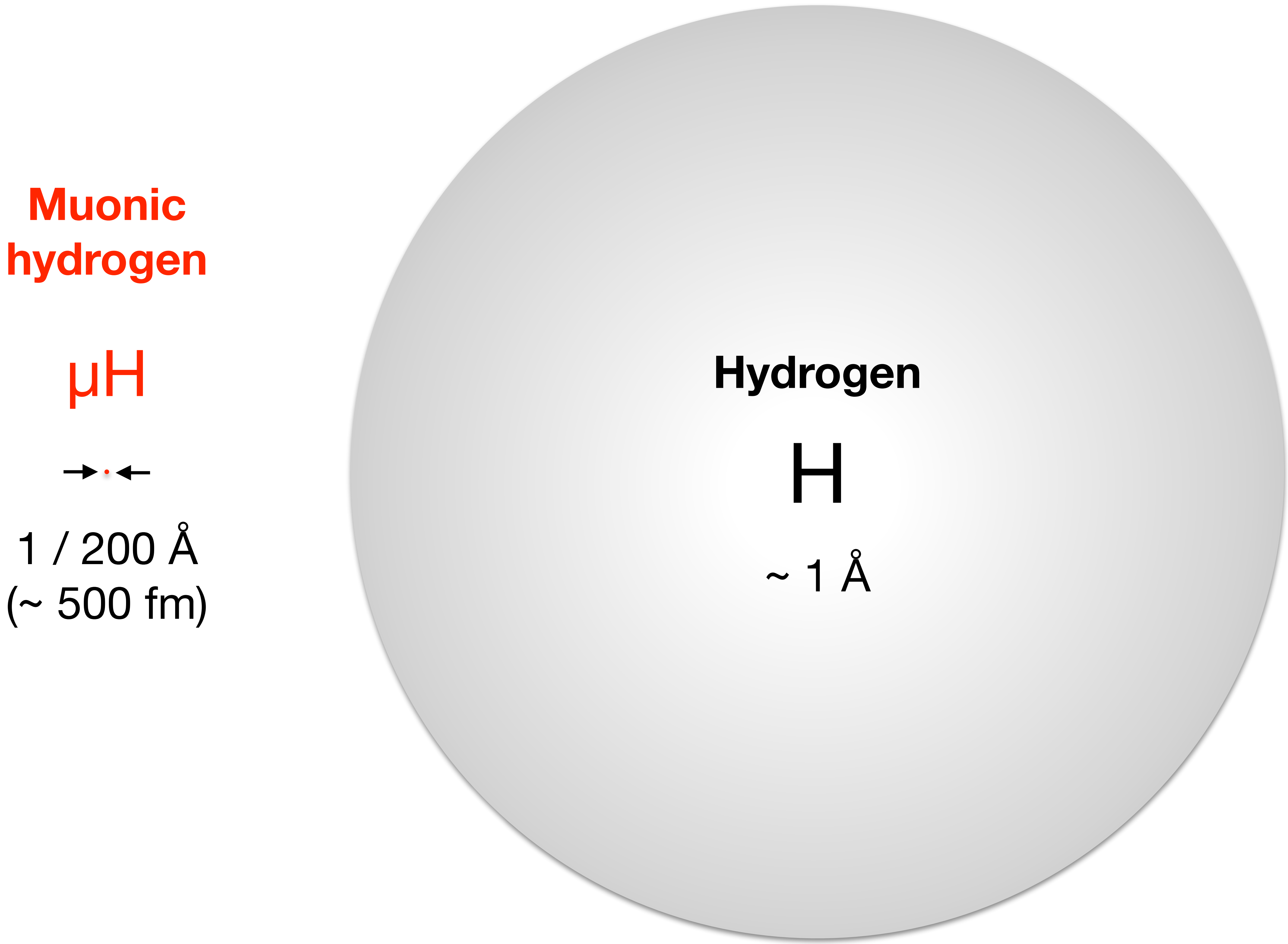
(inversely proportional to the muon reduced mass)



To a small "muon atom" with a **radius of 1/200**



Scaled image

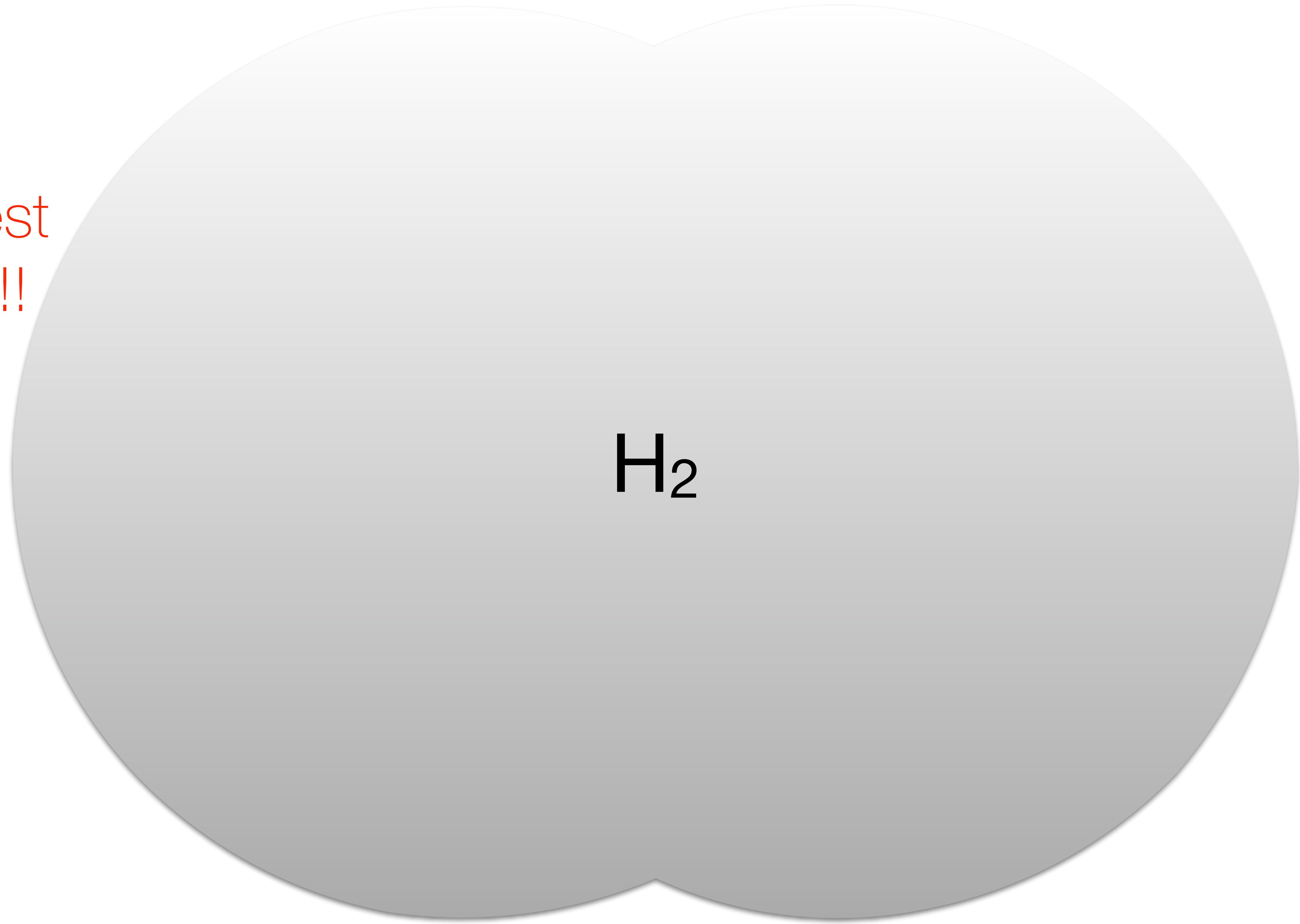


Scaled image

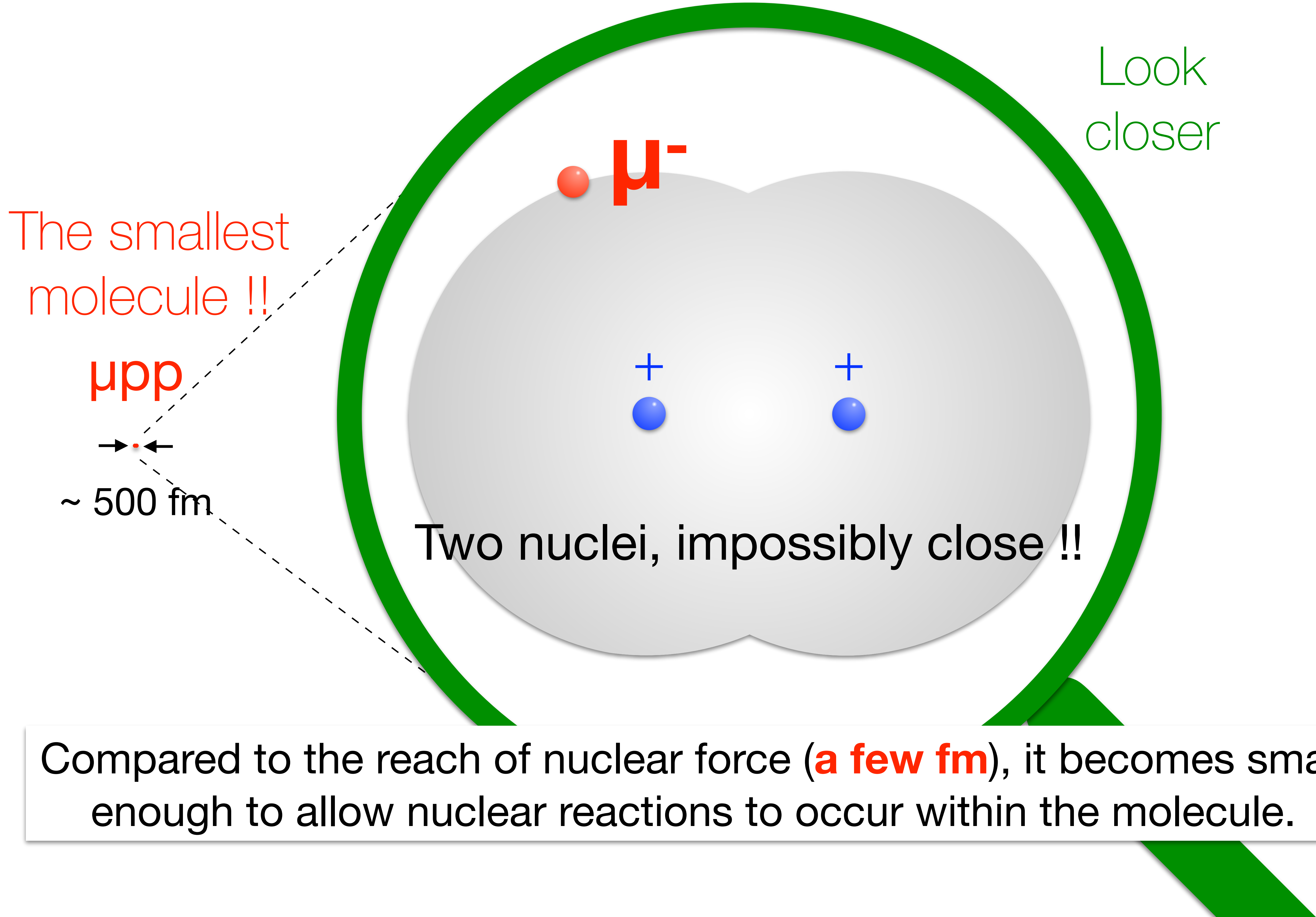
The smallest molecule !!

μpp

~ 500 fm



Muonic molecule

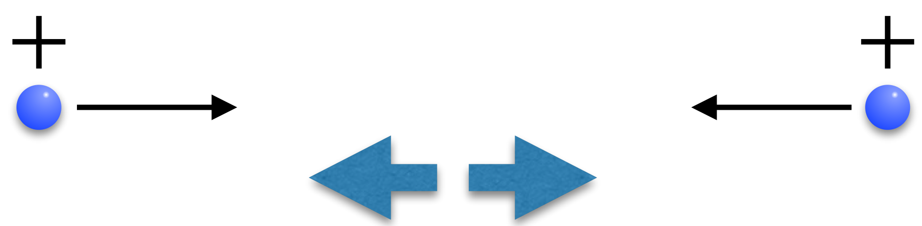


Compared to the reach of nuclear force (**a few fm**), it becomes small enough to allow nuclear reactions to occur within the molecule.

Fusion

Thermonuclear fusion

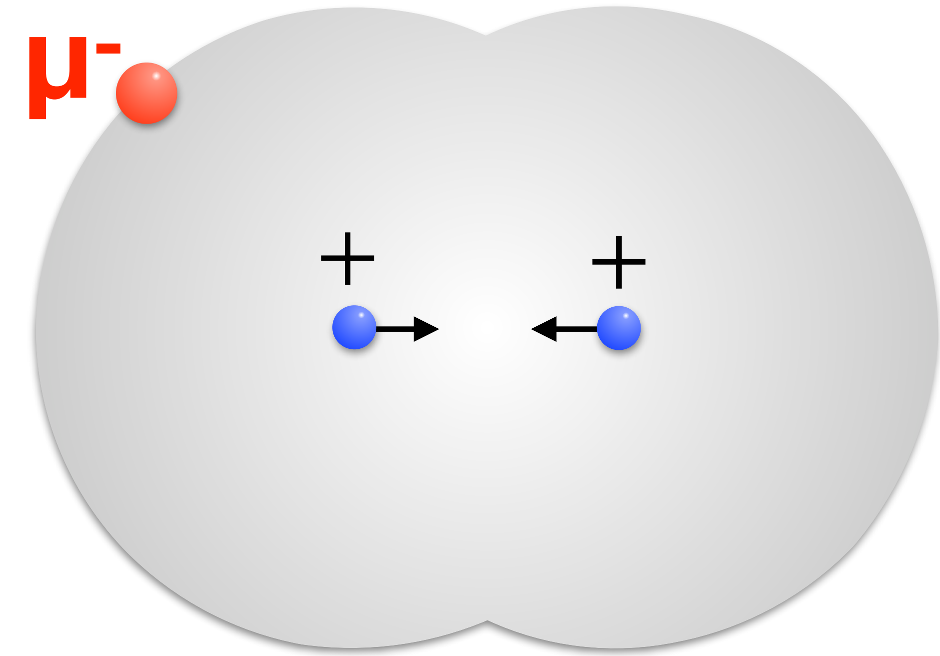
Vigorous collisions in plasma
at several hundred million
degrees Celsius



Large repulsion due to
electromagnetic force

Fusion with muons

Nuclei easily approach each other

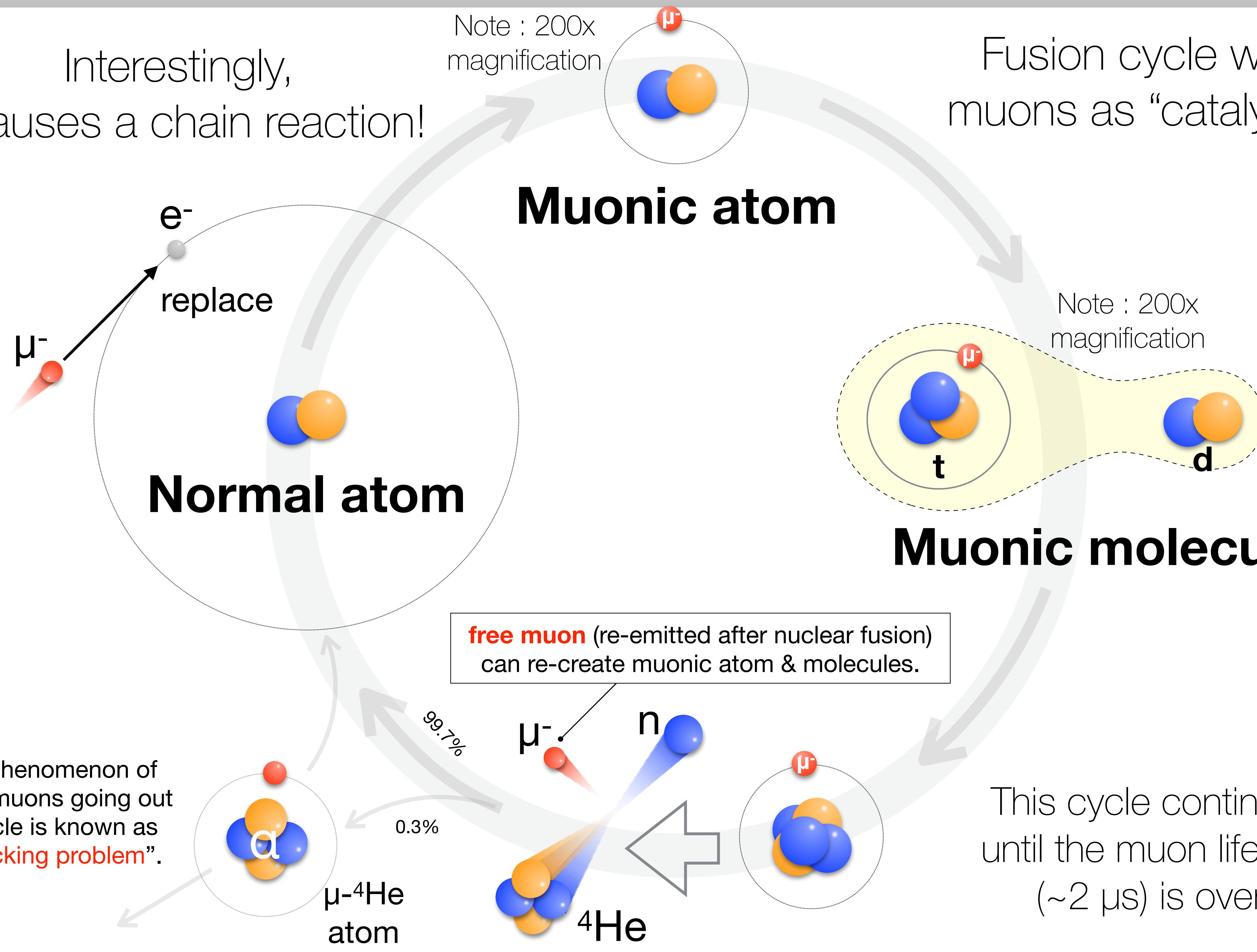


No repulsion by
electromagnetic forces
up to the size of a muonic
molecule

Muon-Catalyzed Fusion (μCF)

Interestingly,
it causes a chain reaction!

Fusion cycle with
muons as “catalysts"



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.

Brief history of μCF research

- 1947 F.C. Frank : Hypothesis of the μCF cyclic reaction
- 1957 L.W. Alvarez : **First observation** of the μCF cyclic reaction
- 1967 E.A. **Vesman** : Theory of Resonant Molecule Formation
- 1980 - 2000 Significant progresses in both experimental and theoretical studies
  - LAMPF (US, Los Alamos)
  - SIN, PSI (Swiss, Villigen)
  - TRIUMF (Canada, Vancouver)
  - KEK (Japan, Tsukuba)
  - RIKEN-RAL (UK, Chilton)

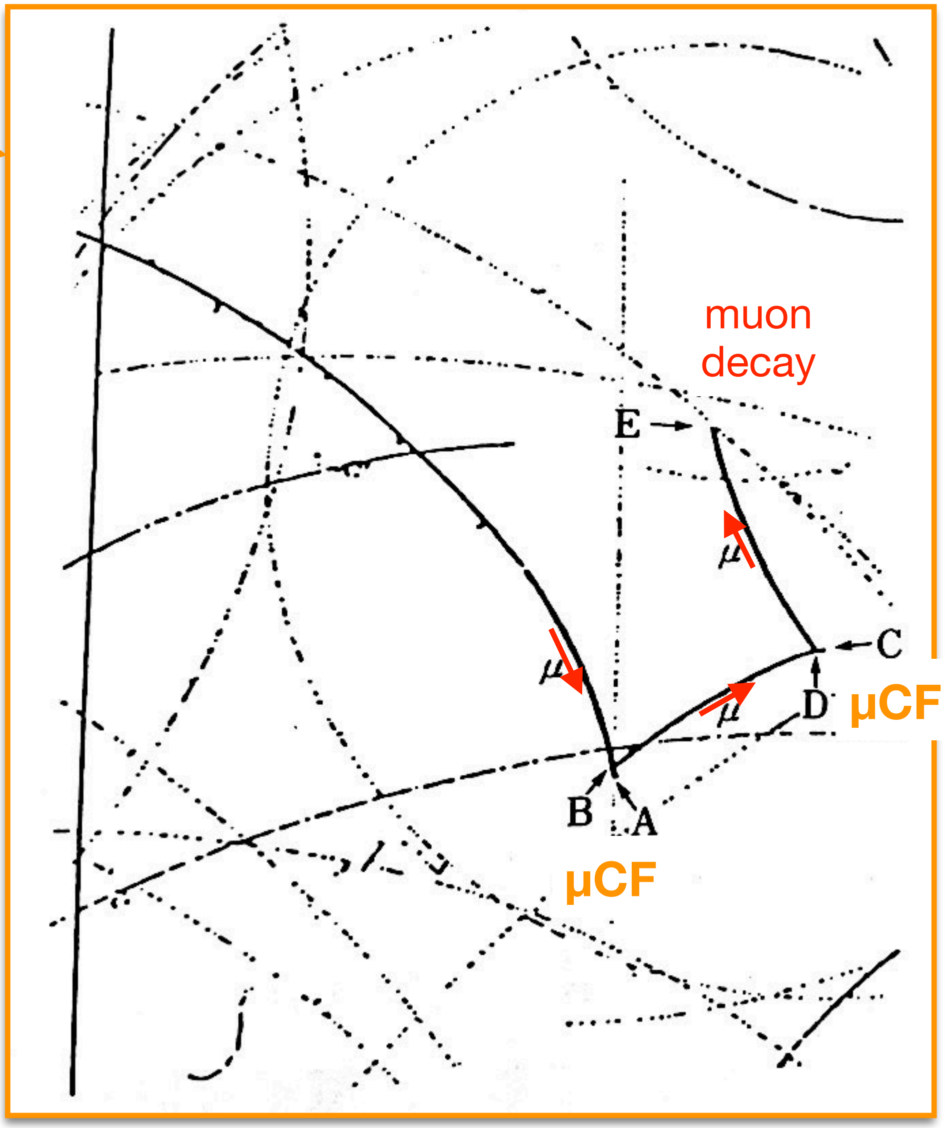
➡ found that the maximum number of μCF cycles is about 150

➡ Since it takes about 5 GeV of energy to make one muon, the scientific breakeven can be exceeded if more than 300 cycles/μ (~5000 MeV / 17.6 MeV) are performed.

➡ The bottlenecks are the molecular production rate and the α-sticking problem, and μCF research has not progressed since 2000.

- **2016 Reexamination has been initiated by Y. Kino (Tohoku Univ) and M. Sato (Chubu Univ).**

L.W. Alvarez et al., Phys Rev 105 (1957) 1127



μCF reaction in a bubble chamber
observed by Alvarez et al.
→ "AB", "CD" followed by μCF,
and Muons turn into electrons
and neutrinos at "E".

Since 2016

Two research funding programs :

(1) **ImPACT** (Impulsing Paradigm Change through Disruptive Technologies Program)

Substantial reduction and recycling of high-level radioactive waste through nuclear transmutation (PM : Reiko Fujita)

- Theoretical calculations of elementary processes of muon-catalyzed fusion reactions in high-temperature plasmas (Yasushi KINO)
- Application of fusion neutrons to the separation and transmutation of LLFPs (Motoyasu SATO)

(2) **Grant-in-Aid for Scientific Research on Innovative Areas** (2018-2022)

Toward new frontiers : Encounter and synergy of state-of-the-art astronomical detectors and exotic quantum beams (PI : **Tadayuki Takahashi**)

- Program B02 : **Basic research of in-flight muon catalyzed fusion** in the Mach shock wave interference region (Yasushi KINO)

New elementary process

⇒ μCF research is gaining momentum, again!

2. New developments on μCF research

New developments of μCF

①

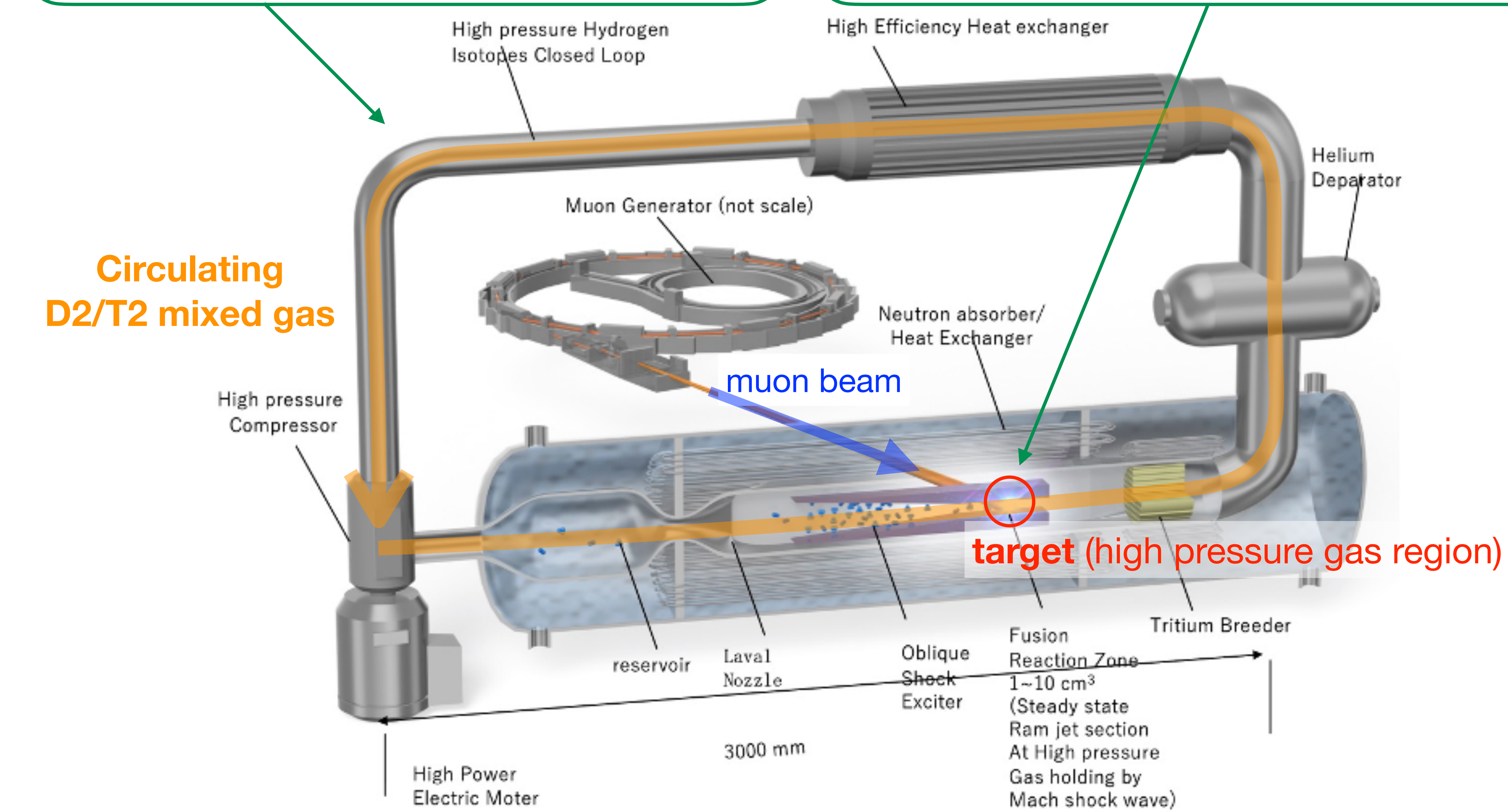
Proposed a "Muon Fusion Reactor"

→ This is a circulating μCF target, which is at a level that can be developed with existing technology.

②

Advances in our understanding of elementary processes

→ proposed a **new μCF elementary process** and took the first step toward its experimental verification



New development ①

μCF target development

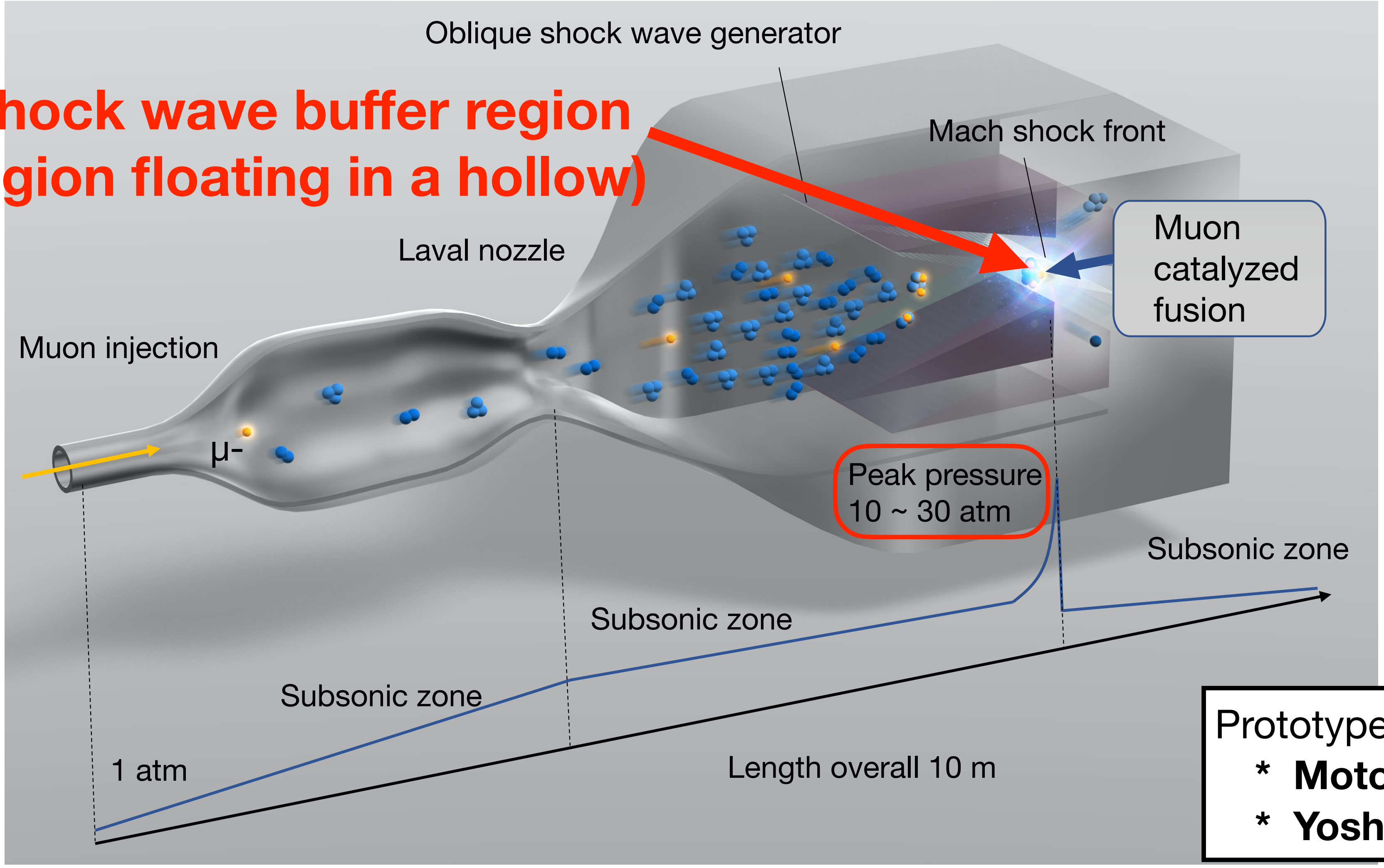
○ **Requirement of target for μCF :**

(1) Mixed deuterium and tritium targets
(2) High density (for efficient μ^- rest in the target)
(3) Removal of reaction products (^{4}He)

Traditionally, **solid and liquid targets** have been used for μCF

Proposed a new concept of the "circulating" target

Utilizing Mach shock wave buffer region (high-density region floating in a hollow)



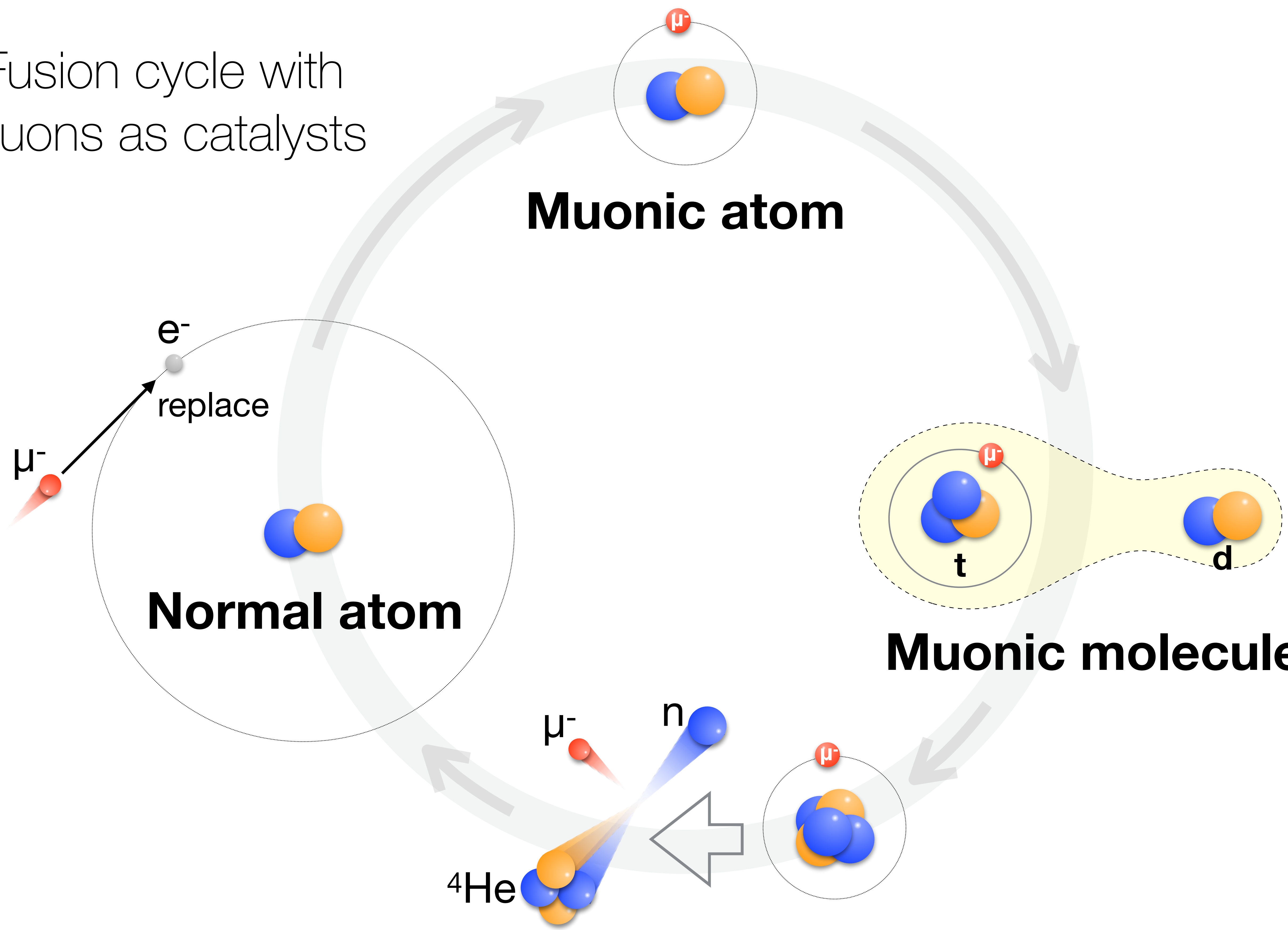
Prototypes will be built / tested.
* **Motoyasu SATO**
* **Yoshiharu TANAHASHI**

New development ②

new μCF process (IFμCF)

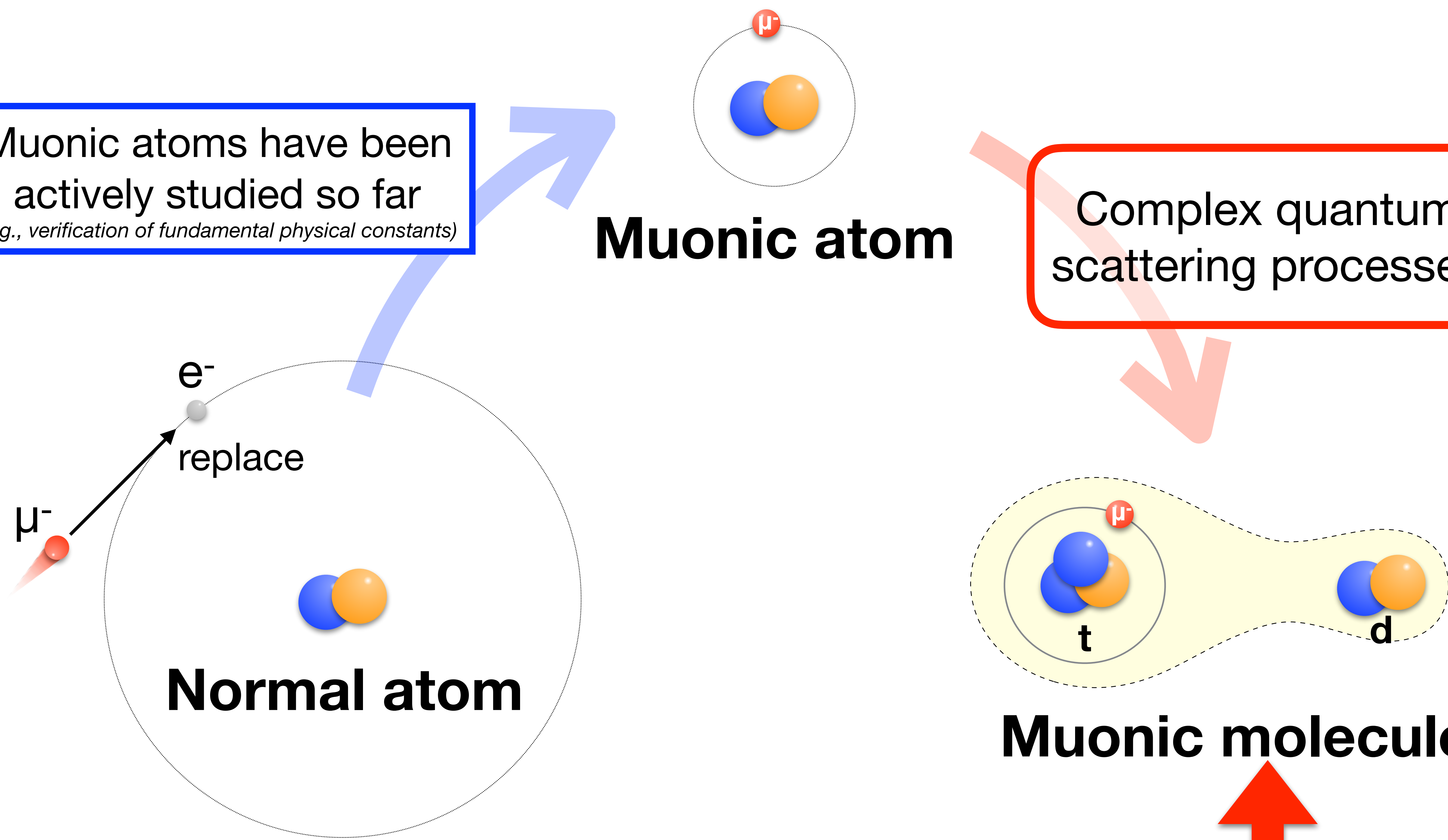
Muon-Catalyzed Fusion (μCF)

Fusion cycle with muons as catalysts



μ atomic & molecular process

Muonic atoms have been actively studied so far
(e.g., verification of fundamental physical constants)

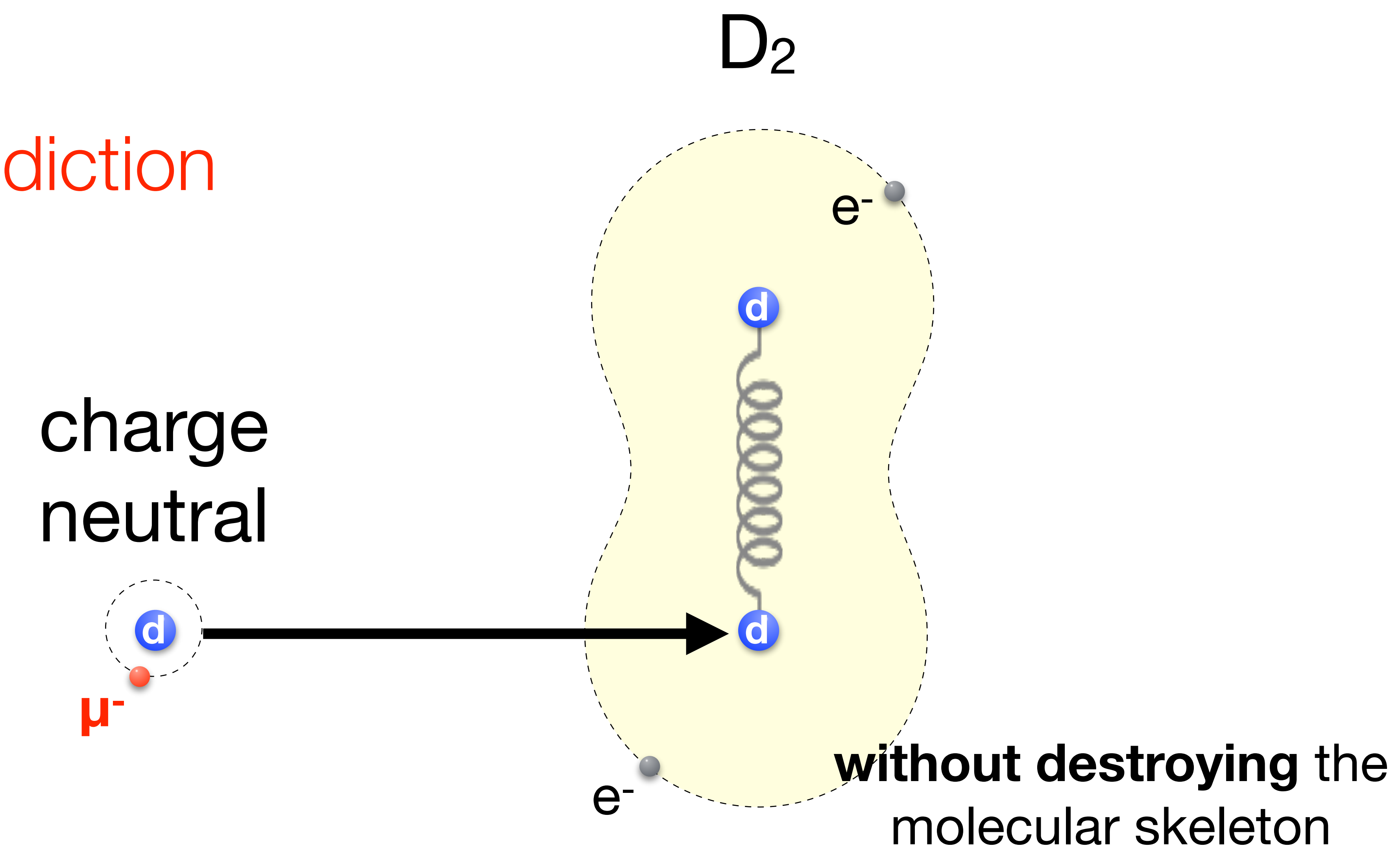


Complex quantum scattering processes

Almost no experimental knowledge of what quantum states are being generated.

How μ molecules are created ?

Theoretical Prediction



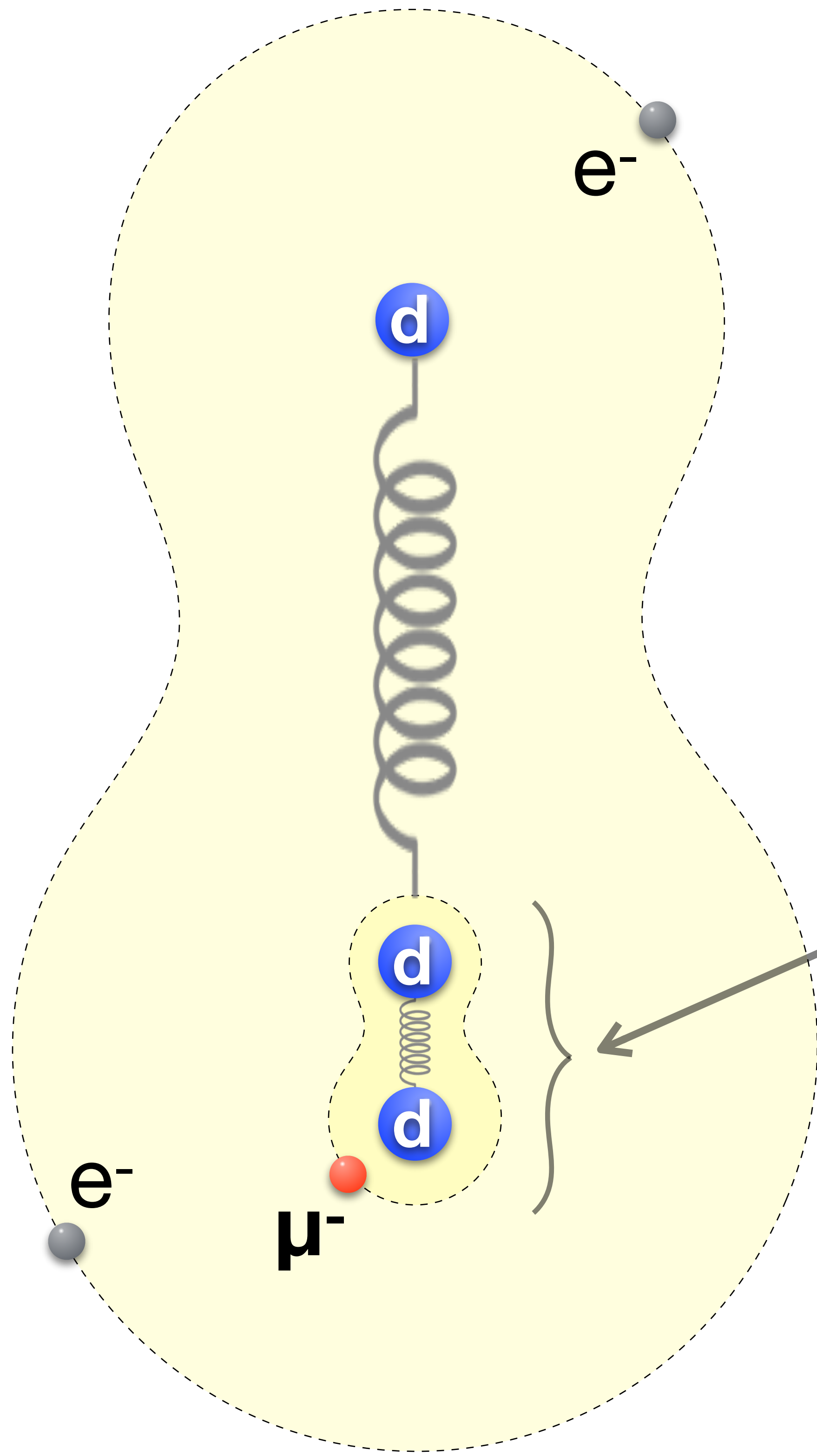
If the muonic atom collide "**gently**" to the normal molecule, the excess energy of ddμ molecule formation is passed to the rovibrational excitation energy of D_2 molecule.

⇒ Resonant generation (Vesman mechanism)

Molecule in molecule !

Theoretical prediction

Matryoshka-like



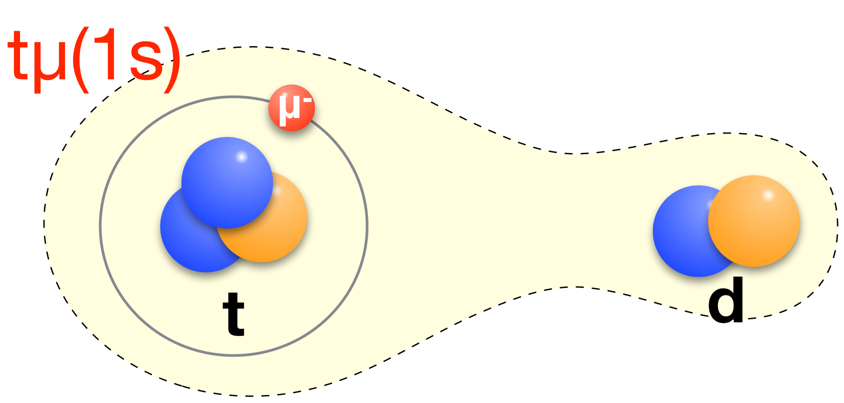
ddμ molecule

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

Key point of the new μCF process

Ground state

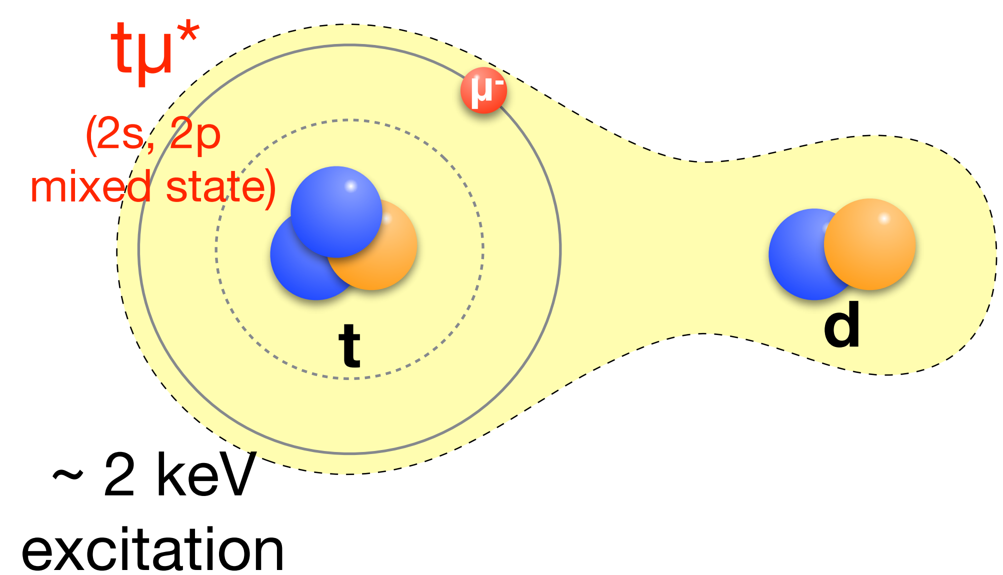
dtμ



Immediately leading to **nuclear fusion**

Excited state

dtμ*



No nuclear fusion, but **dissociates** quickly

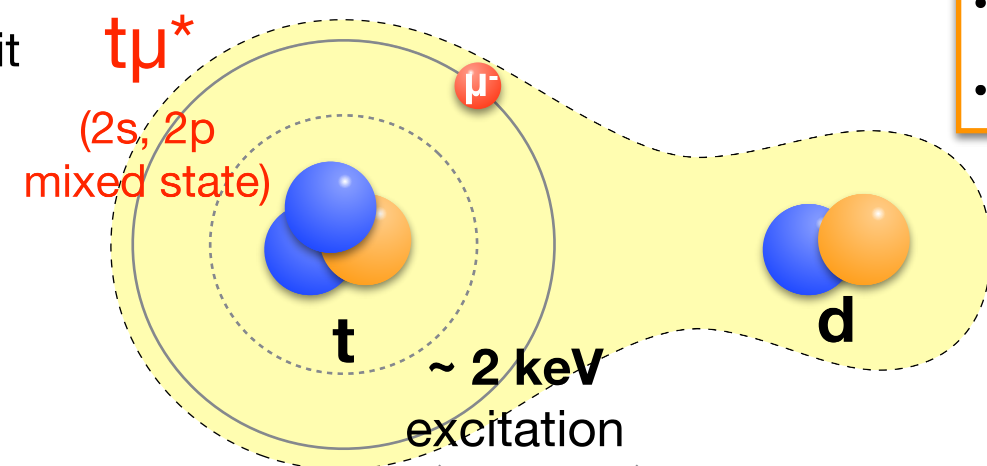
<- also will be created via Vesman mechanism

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**.

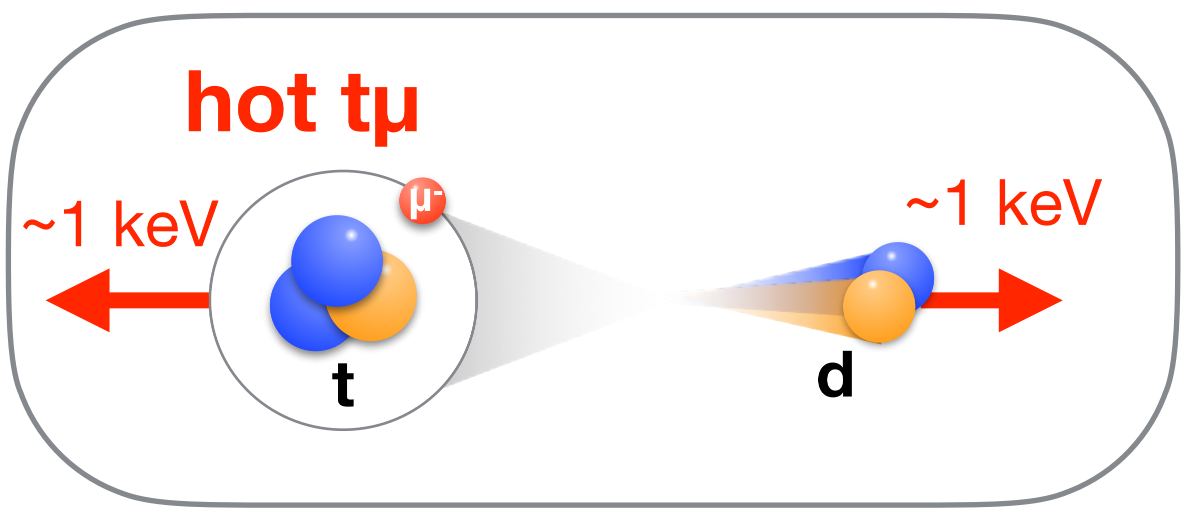


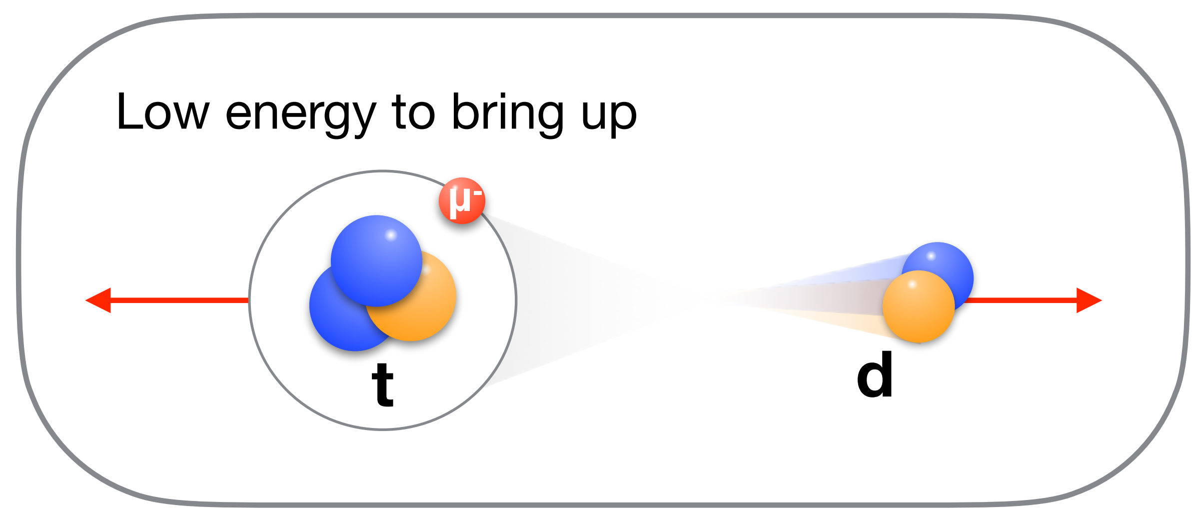
Precise measurement of X-rays enables the study of molecular resonance states.

New μCF elementary processes

non-radioactive

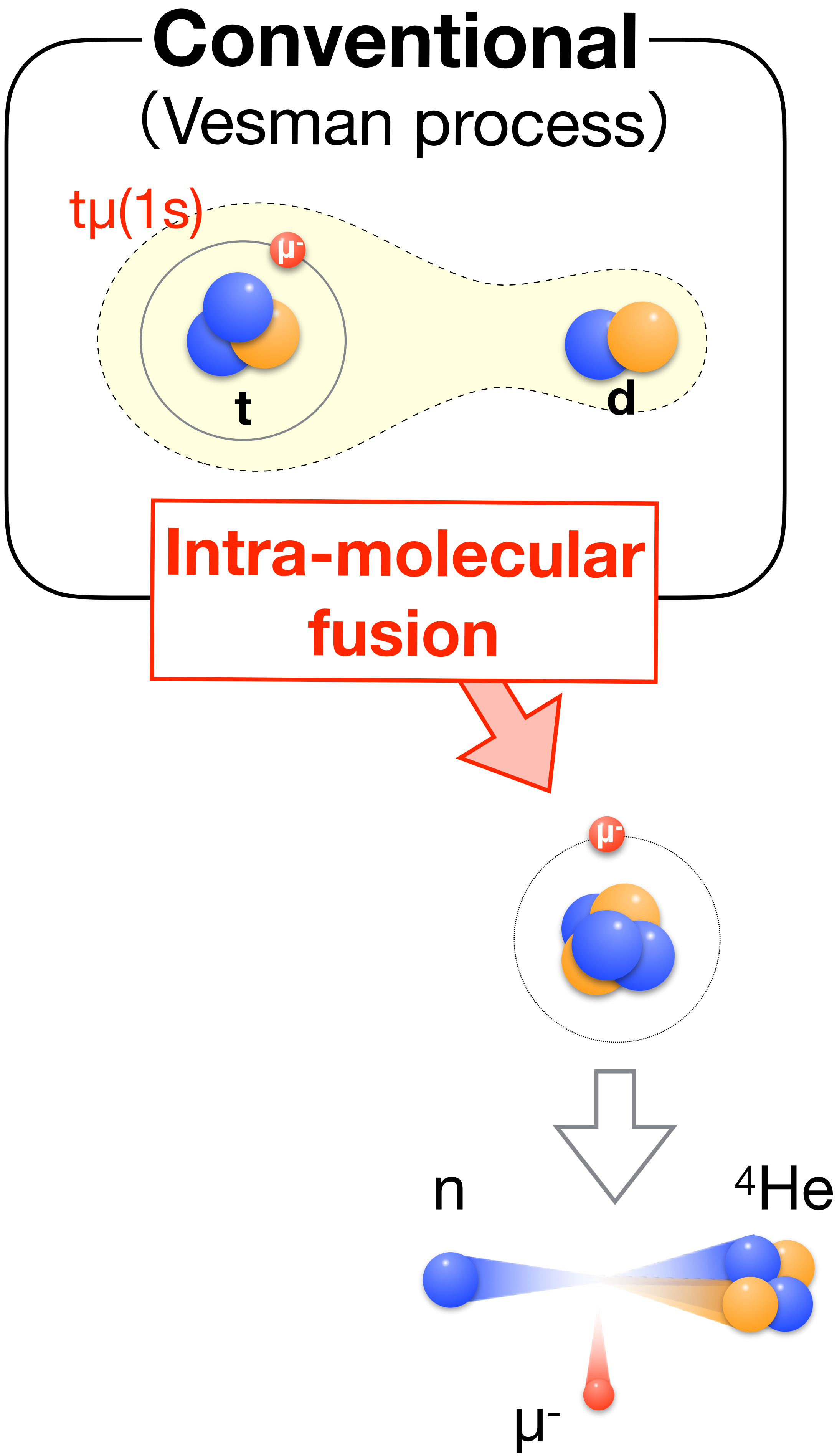
radioactive



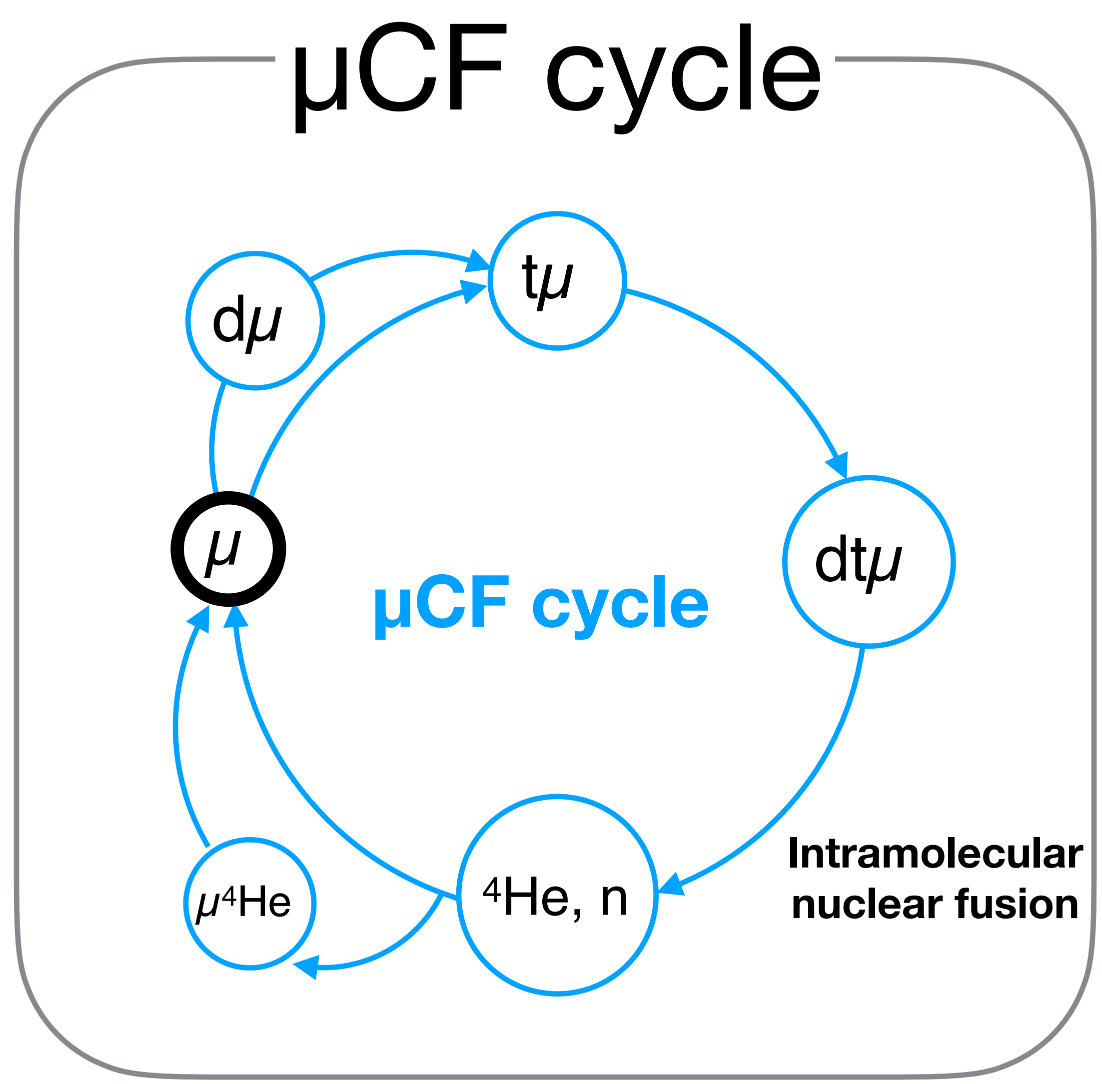


Inflight μCF study

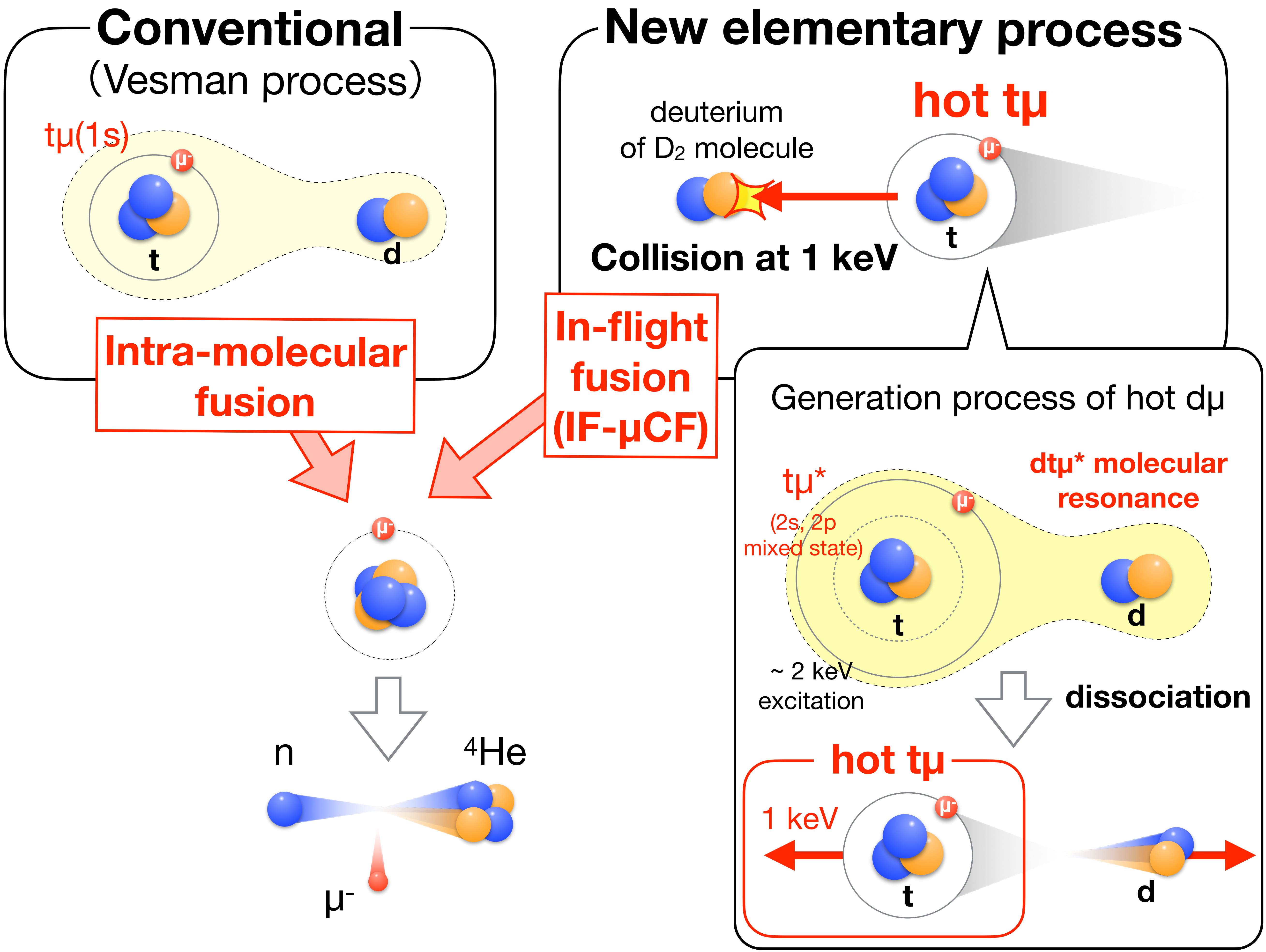
X-ray precision spectroscopy



Conventional
(Vesman process)
tμ(1s)
μ-
t
d
Intra-molecular fusion
μ-
n
4He
μ-

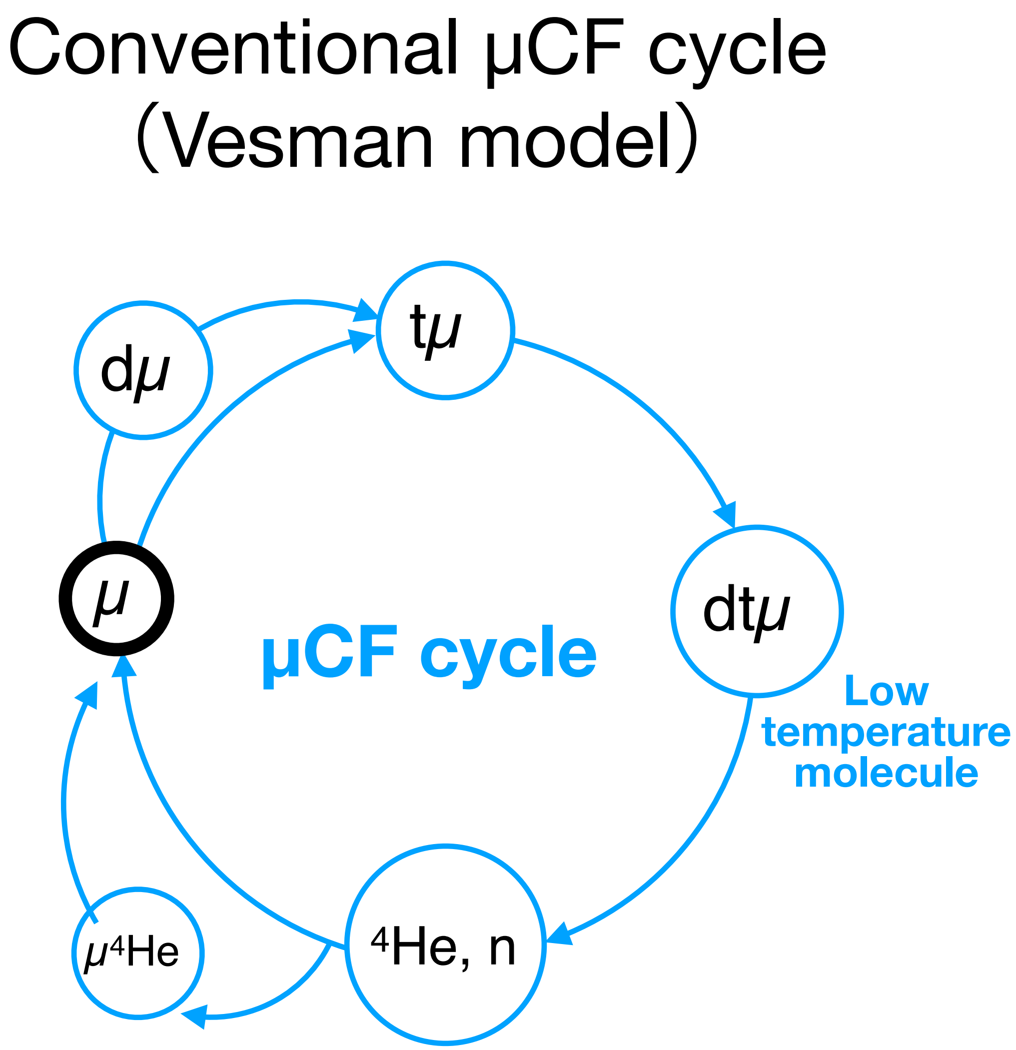


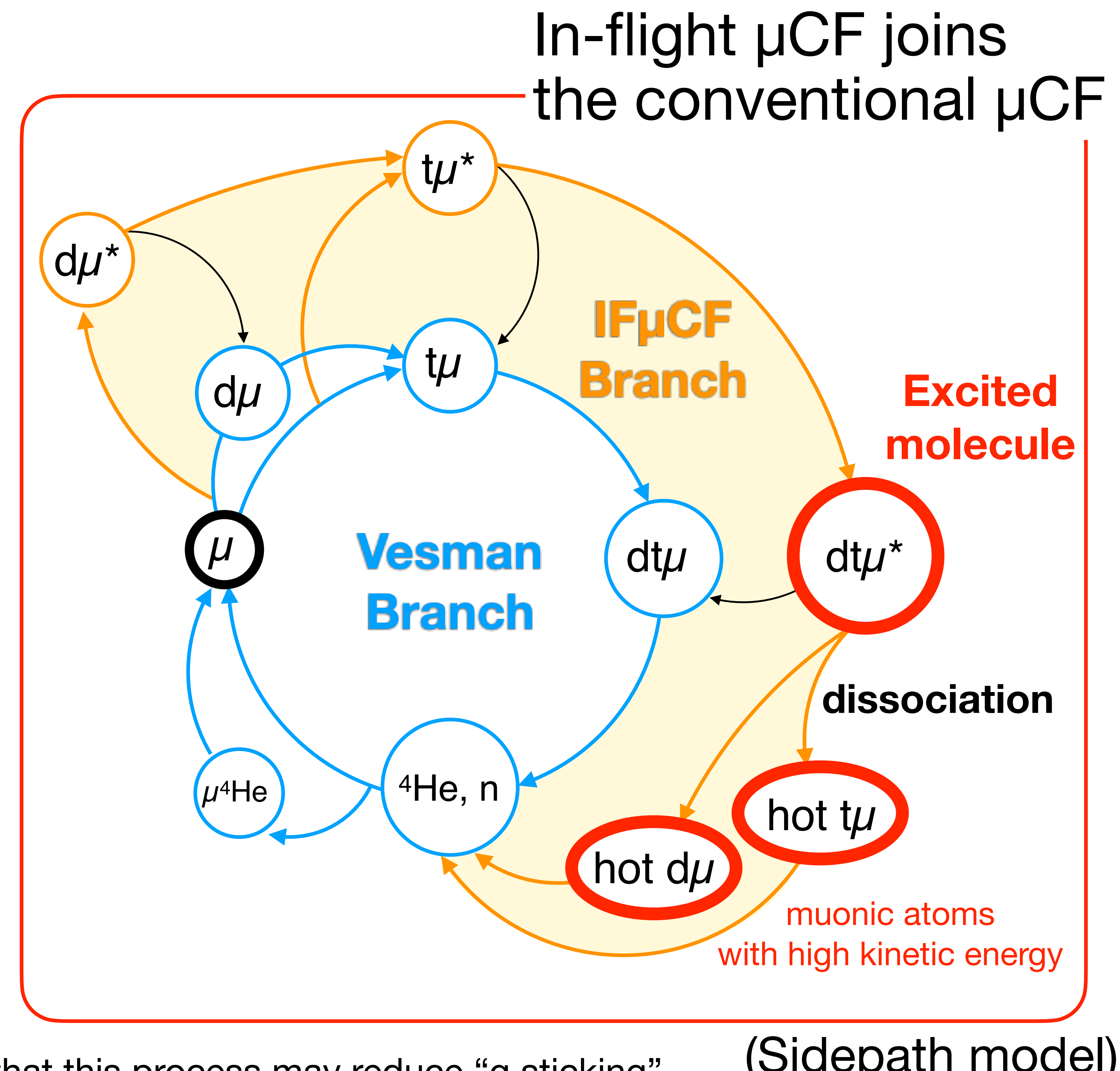
μCF cycle
dμ
tμ
μ
dtμ
μCF cycle
μ4He
4He, n
Intramolecular nuclear fusion



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

μCF cycle considering "excited molecules"

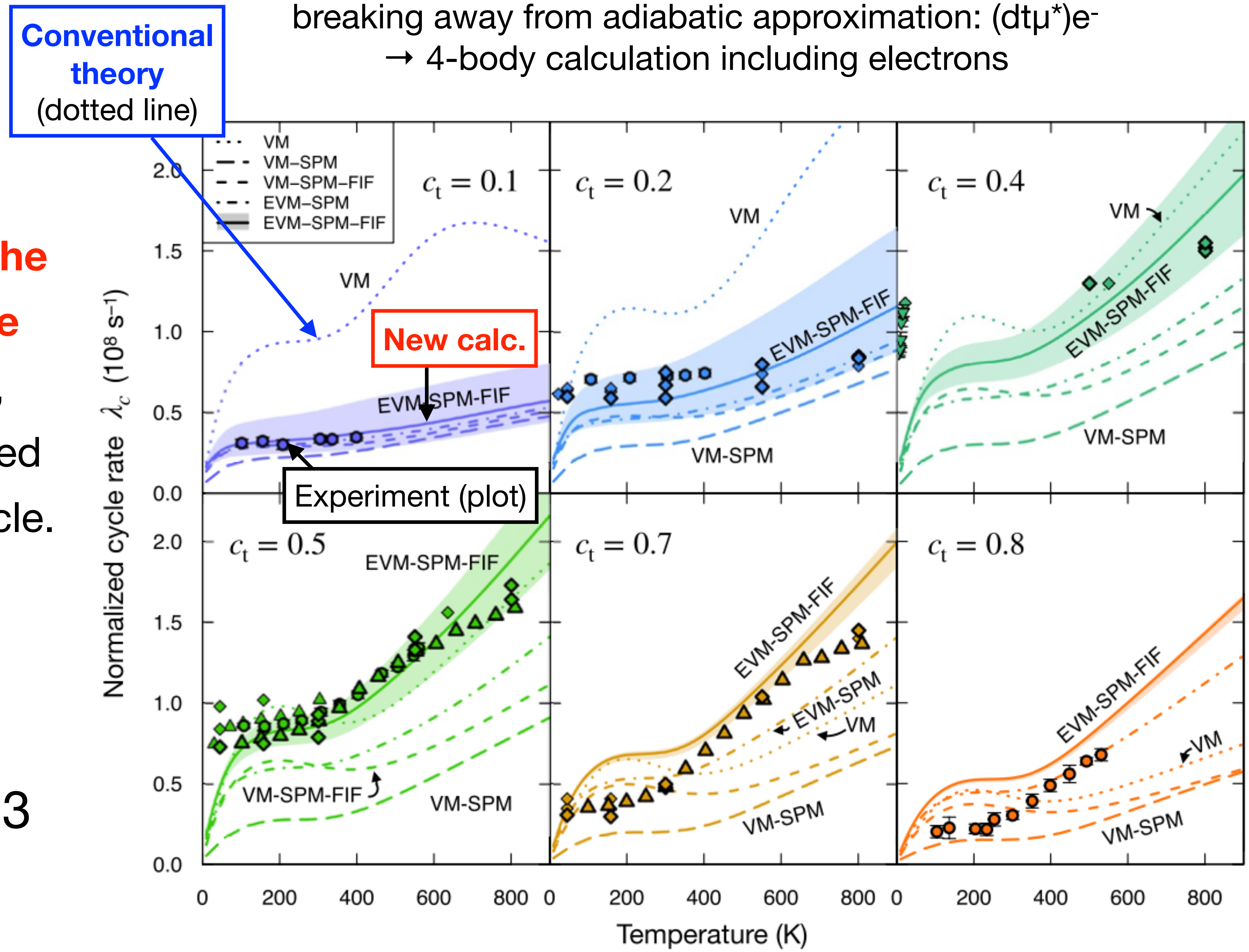




It has been suggested that this process may reduce “α sticking”,
and the formation rate is faster than the ordinary μCF process.
→ So it is important to study the mechanism to enhance the IFμCF process.

Importance of dtμ* was demonstrated

New few-body many-body calculation
breaking away from adiabatic approximation: (dtμ*)e⁻
→ 4-body calculation including electrons

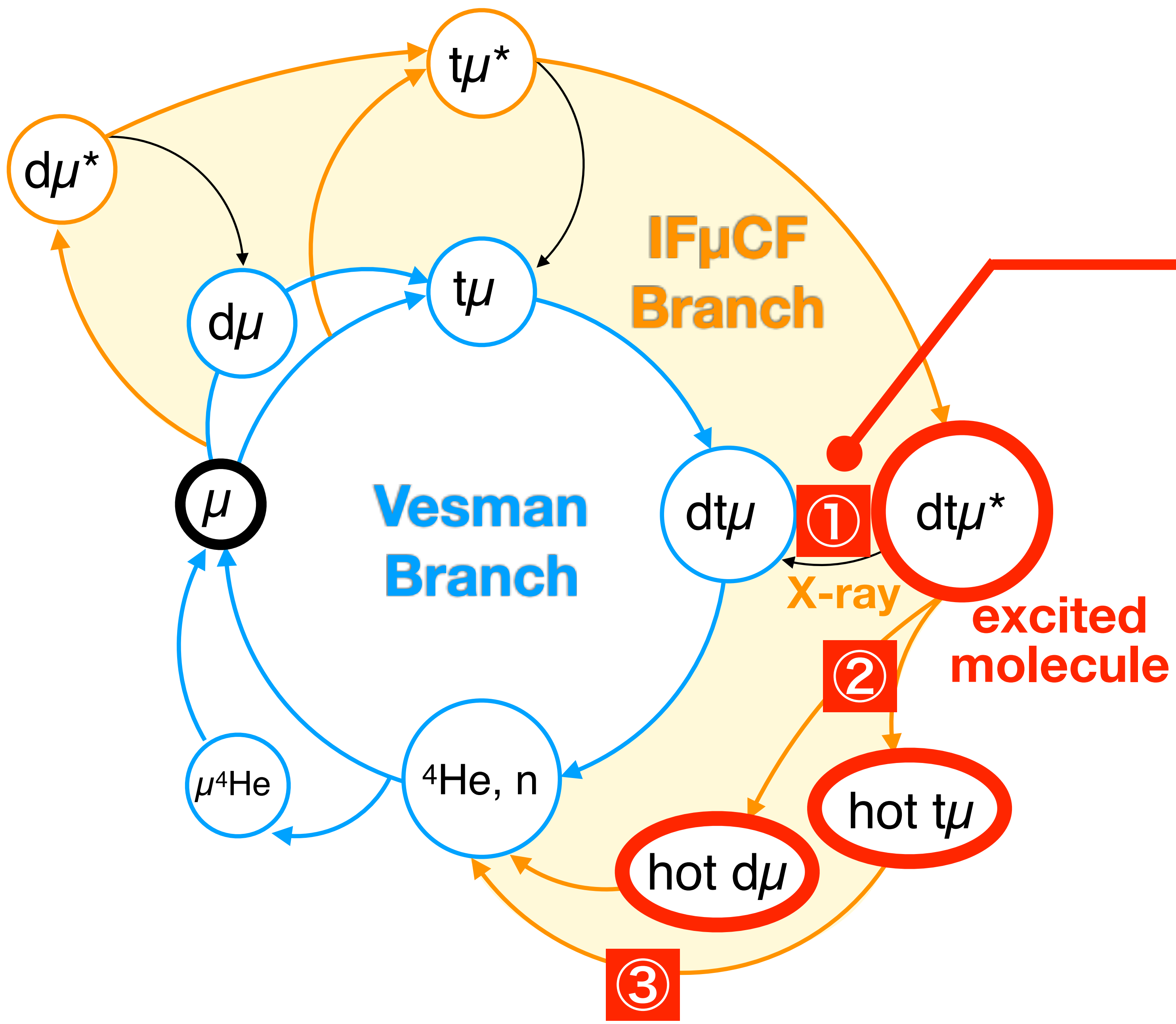


Succeeded in explaining the temperature dependence of the μCF reaction rates, which could not be explained by the conventional μCF cycle.

T. Yamashita et al.,
Sci. Rep.12 (2022) 6393

⇒ Aiming for direct experimental verification

Strategy for IFμCF Demonstration Experiment



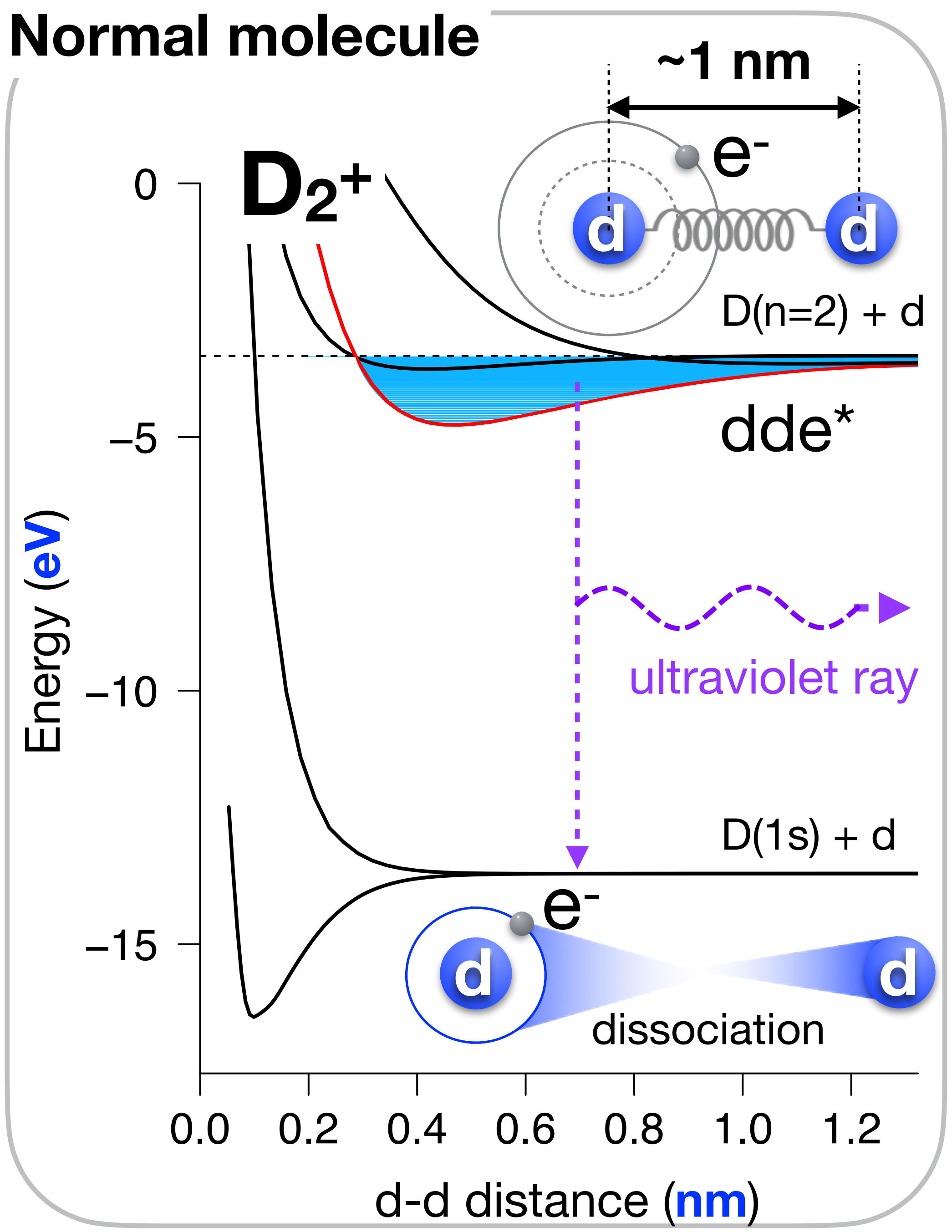
Step-by-step development of demonstration experiments

① Measurement of excited molecular X-rays

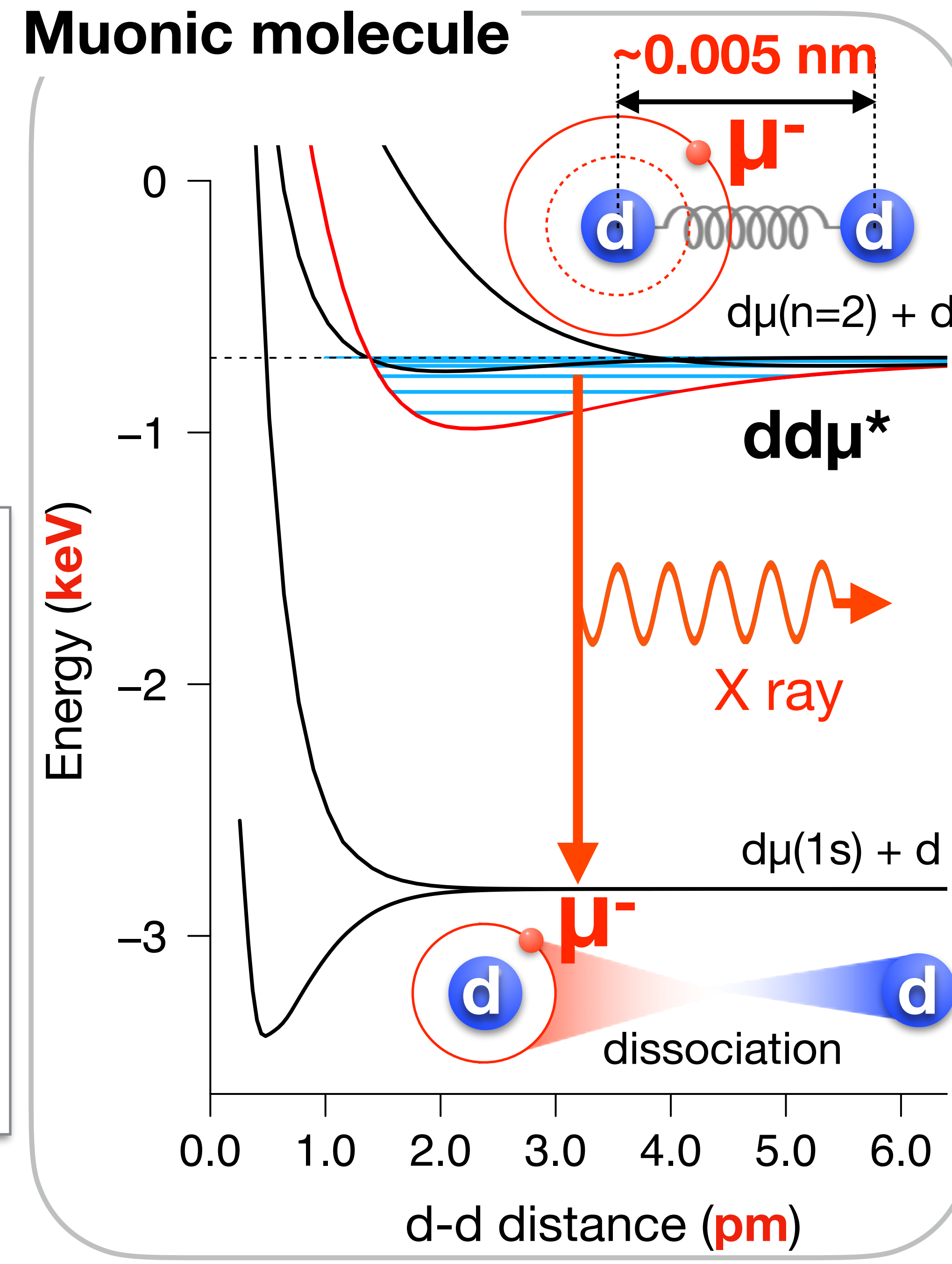
② Observation of hot dμ

③ IFμCF experiment

High Precision Spectroscopy of **Muonic Molecules**



- 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**



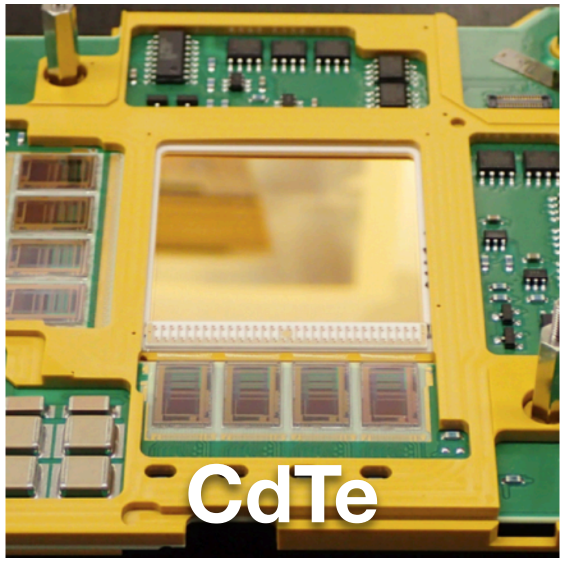
✤ Theory : **Few-body calculations** simultaneously solving for the motion of nuclei and heavy negatively charged particles

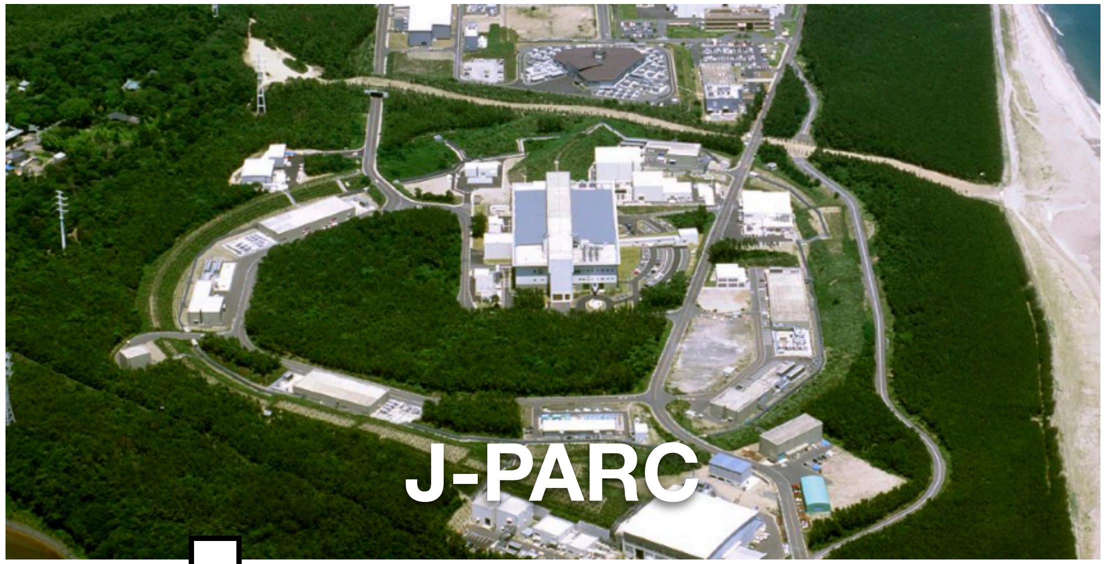
✤ Experimental : **High energy resolution** in X-ray measurements in muon beams

Scientific Research on Innovative Areas (2018-2022)

Encounter and Synergy of

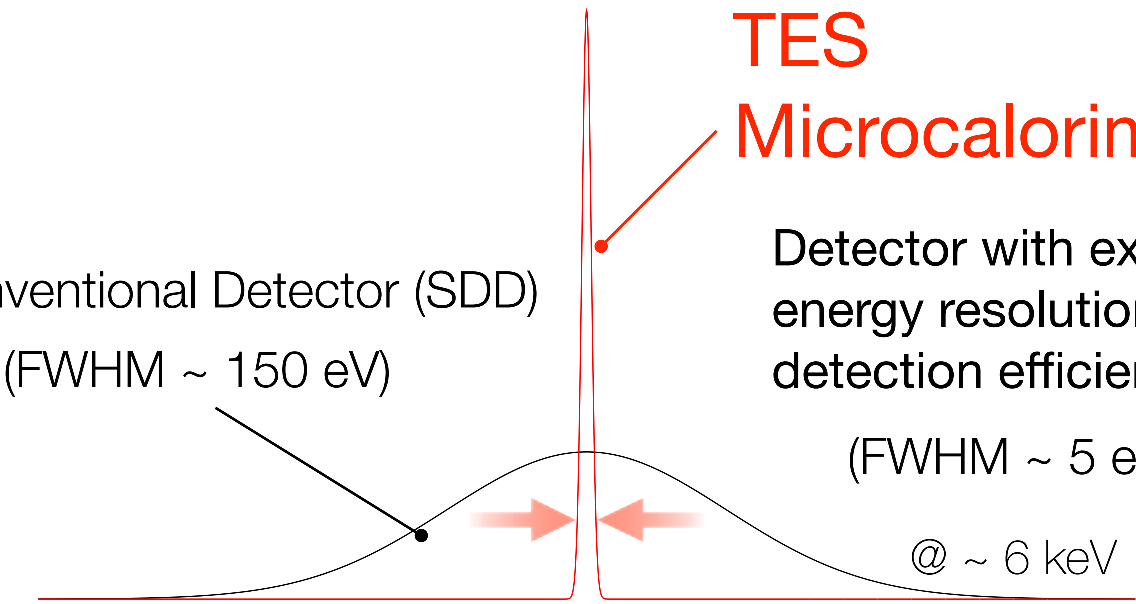
State-of-the-art Astronomical Detectors and **Exotic Quantum Beams**





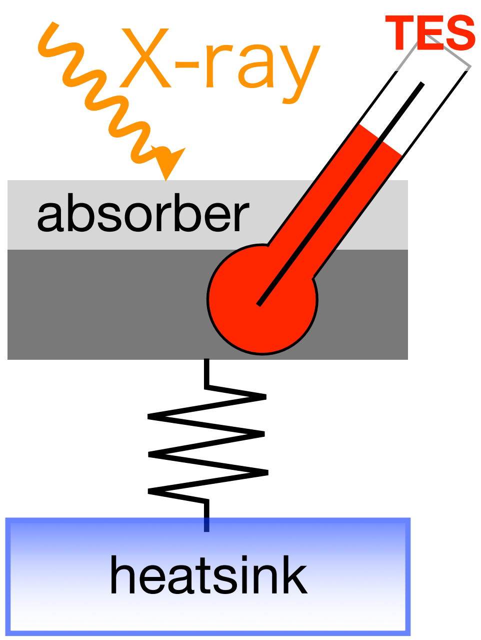
We brought the detector to the muon beam experiment !

Innovative Spectroscopic Techniques

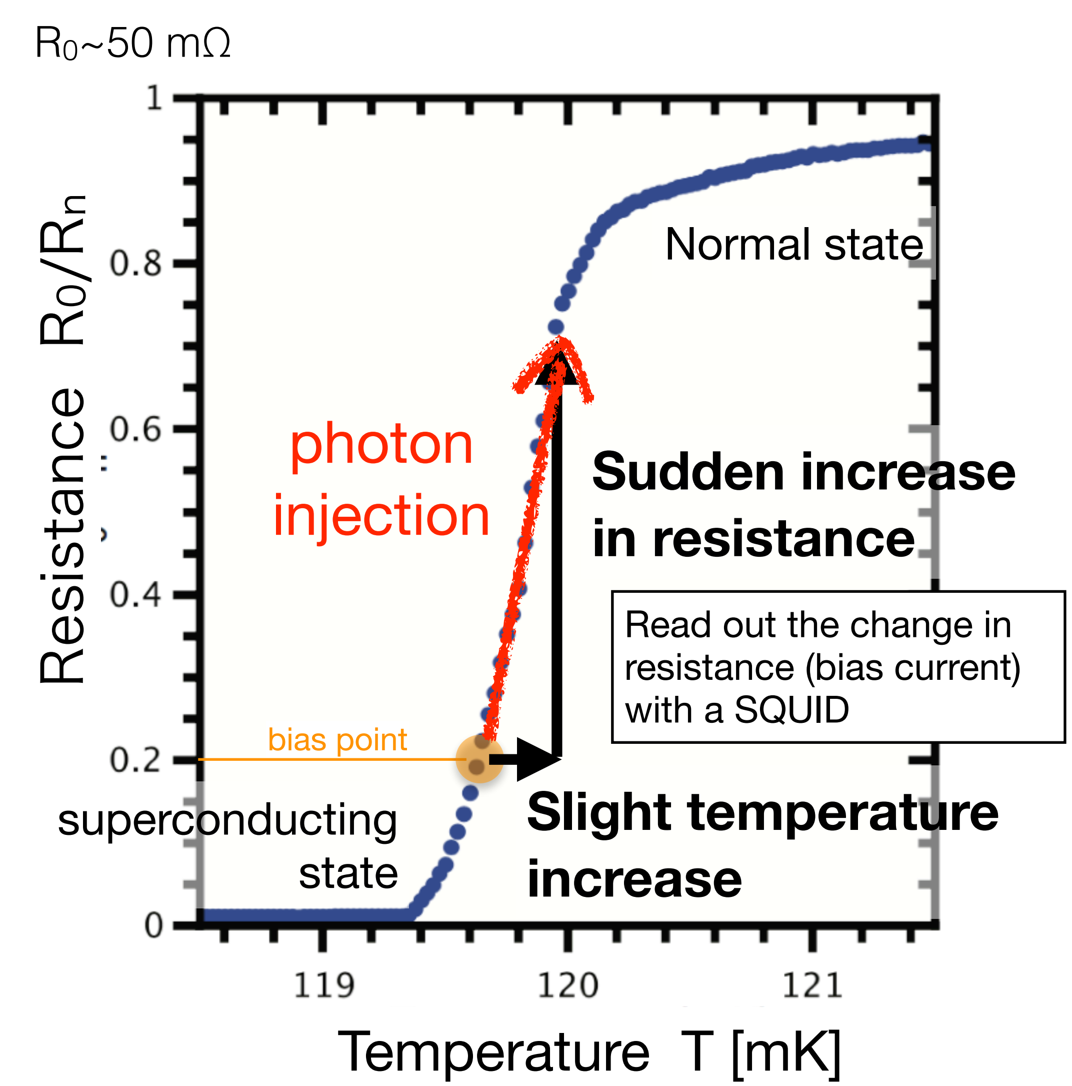


TES microcalorimeters

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

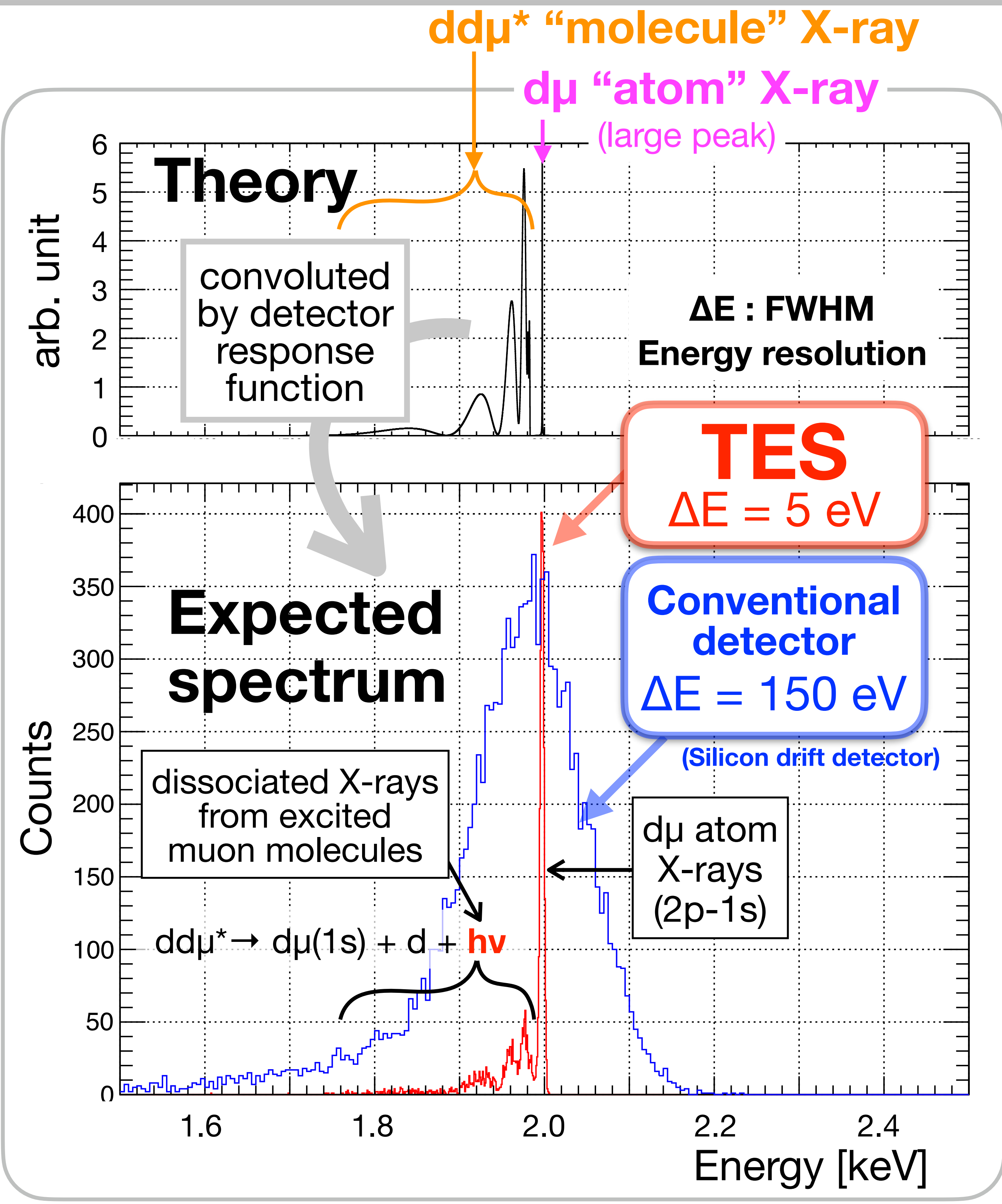


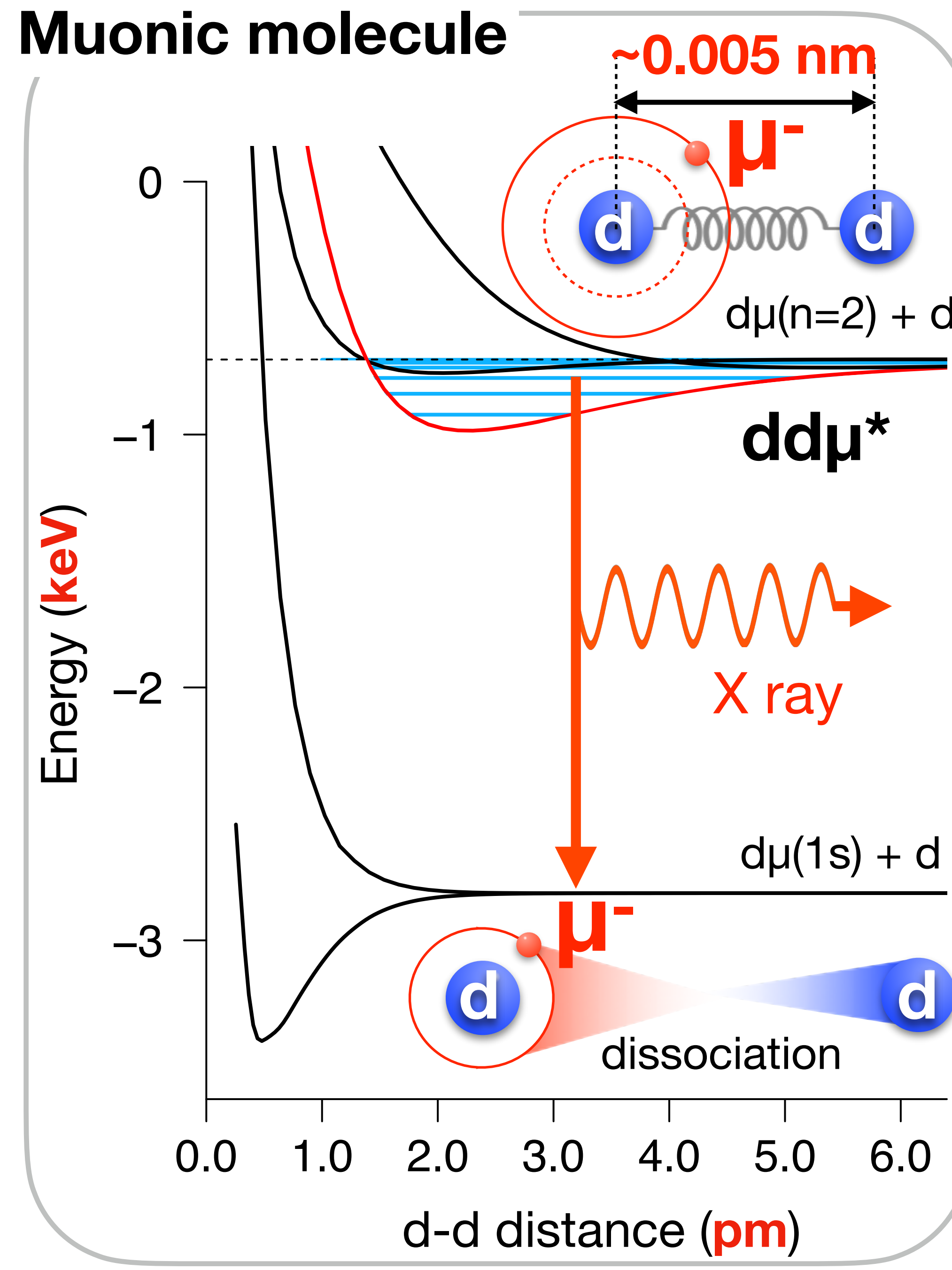
Transition Edge Sensor

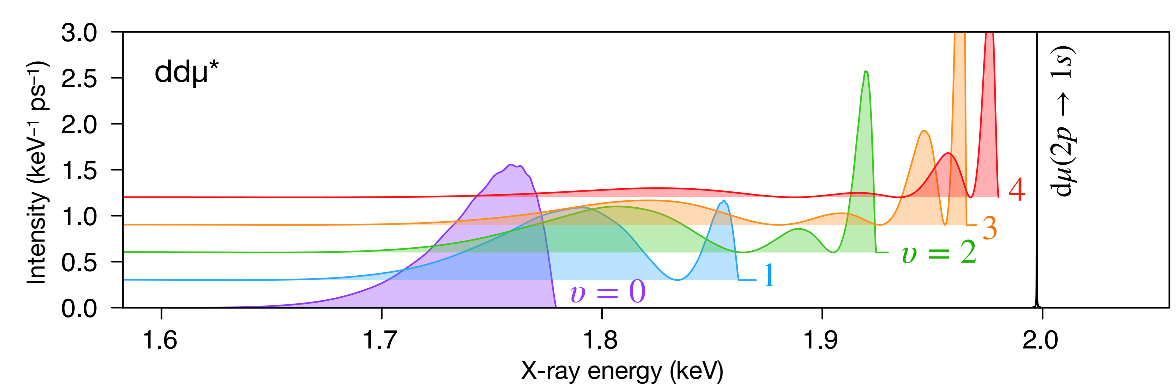


High resolution ($\Delta E / E \sim 10^{-3}$)

High Precision Spectroscopy of **Muonic Molecules**



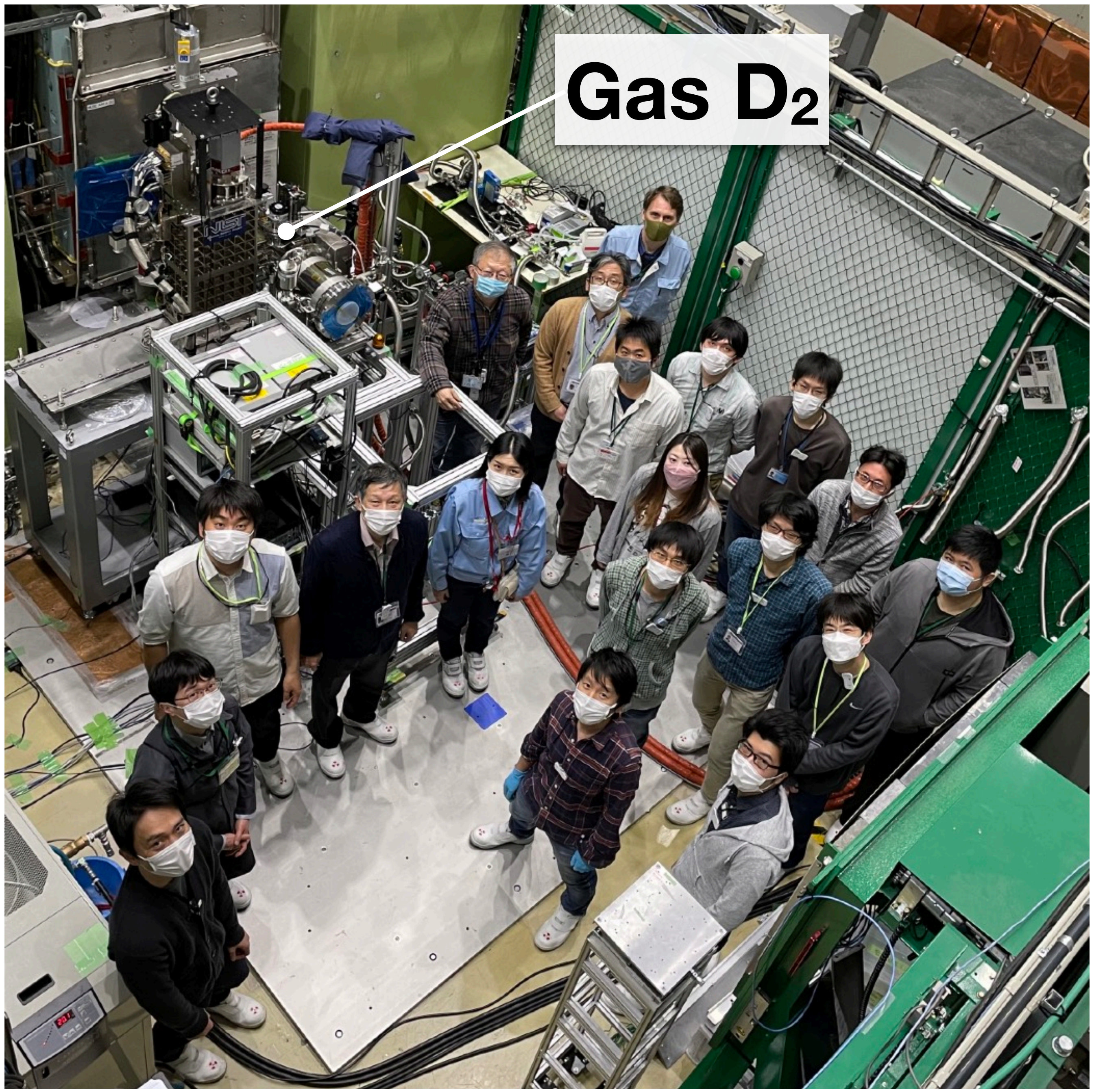


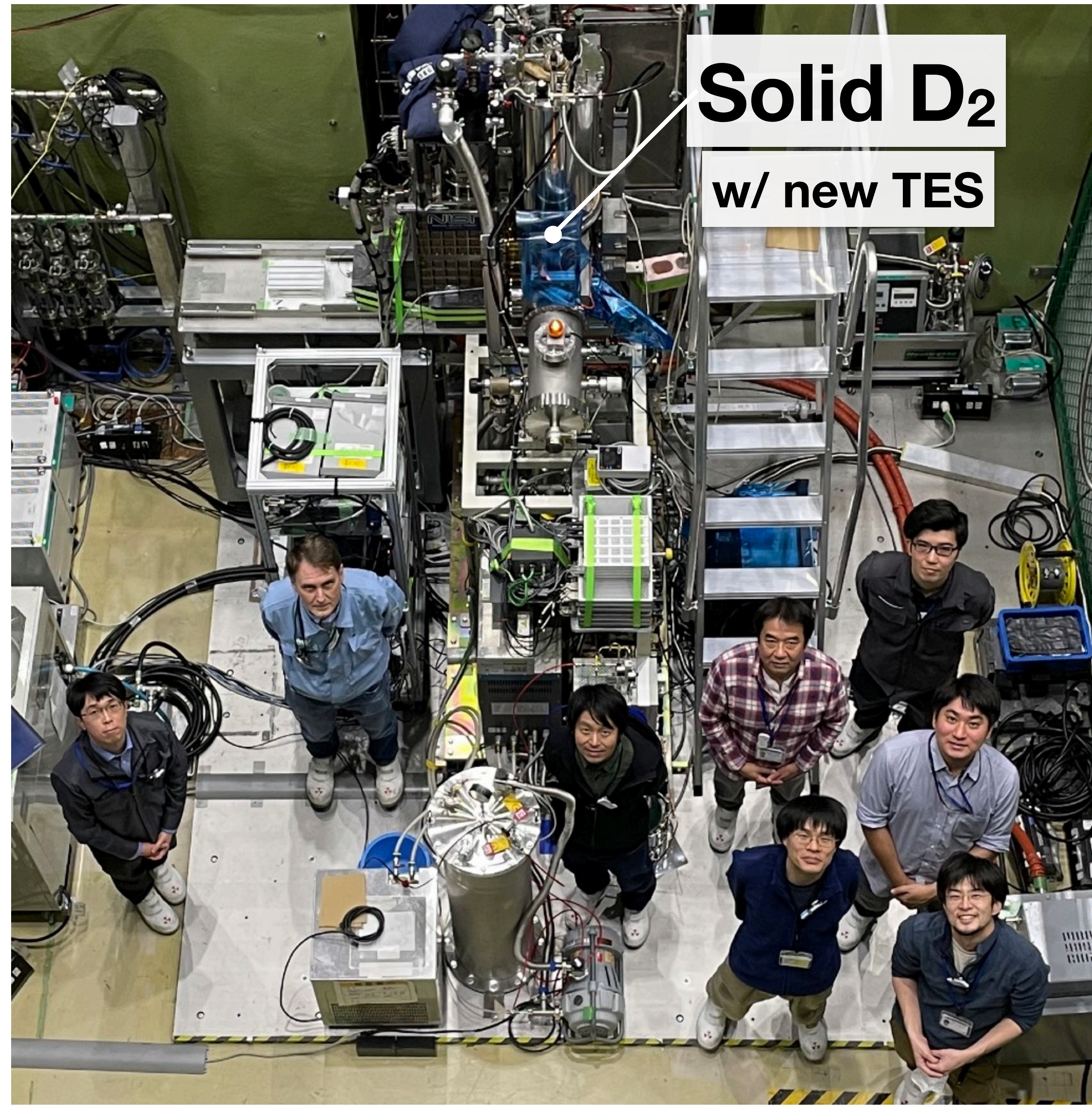


2019MS01 : "μ molecule" experiment

Mar 9 - 19, **2022**

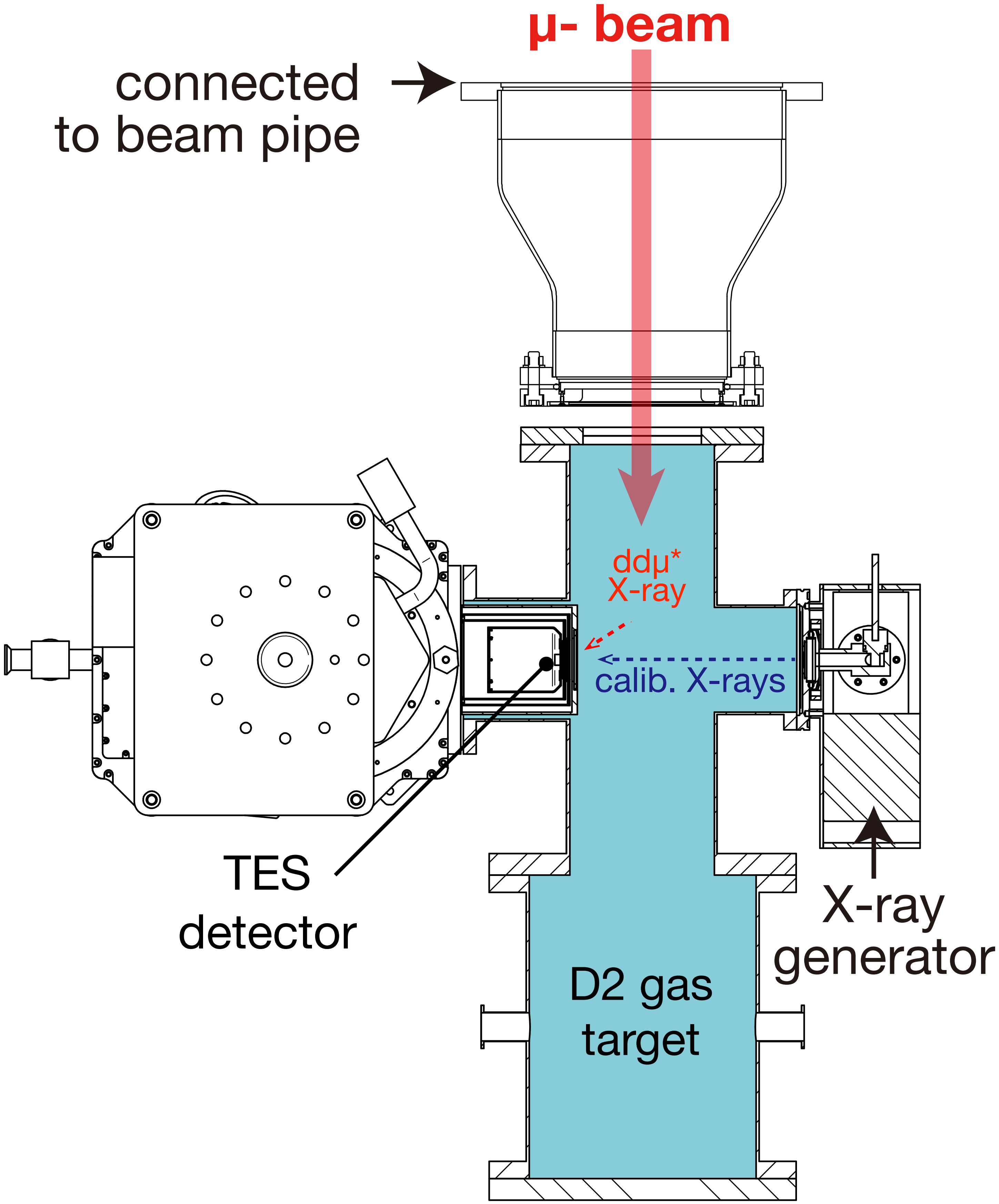
Feb 5 - 11, **2023**



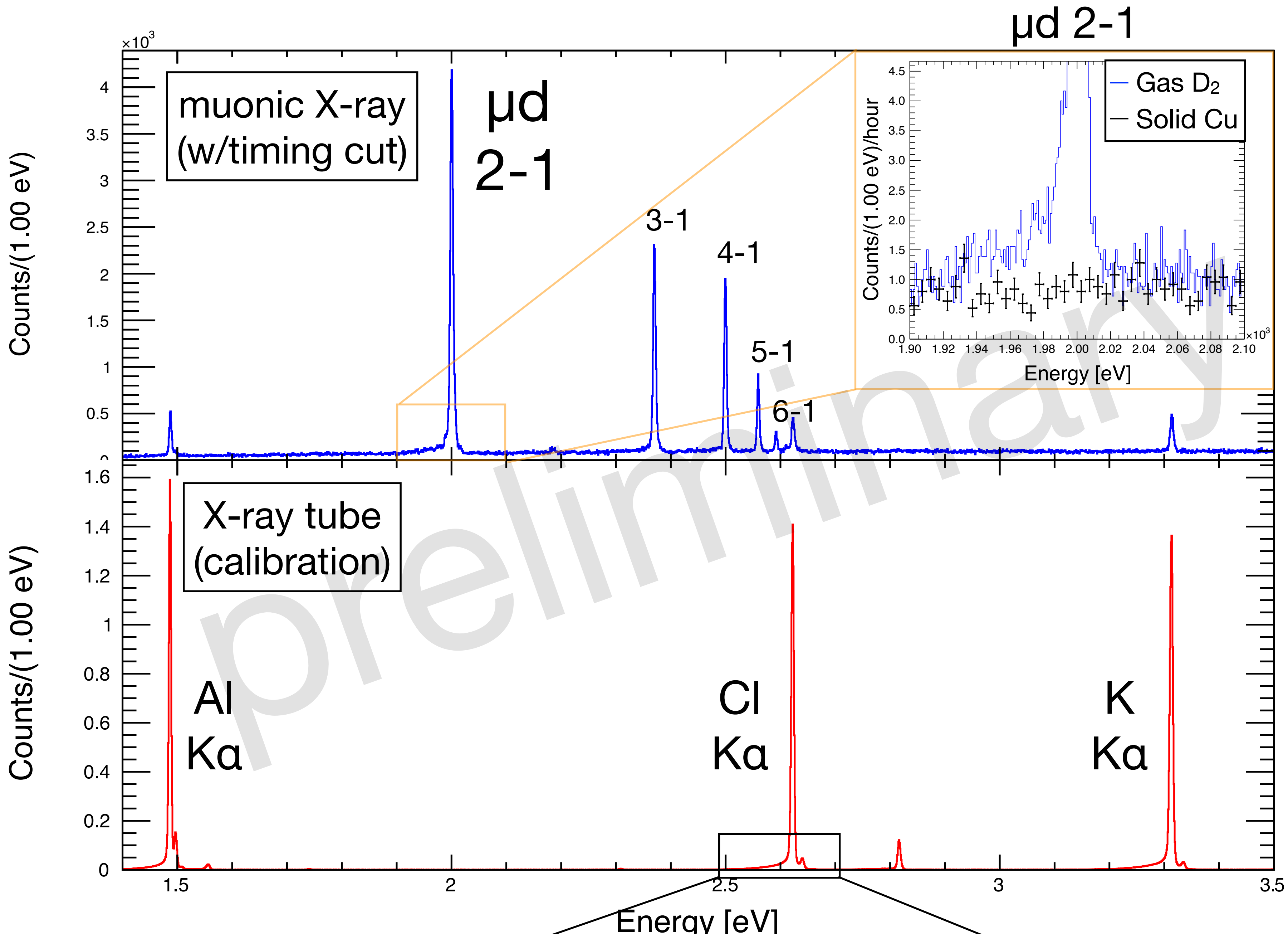


Experiment with gas D_2

March, 2022



Experiment with gas D_2



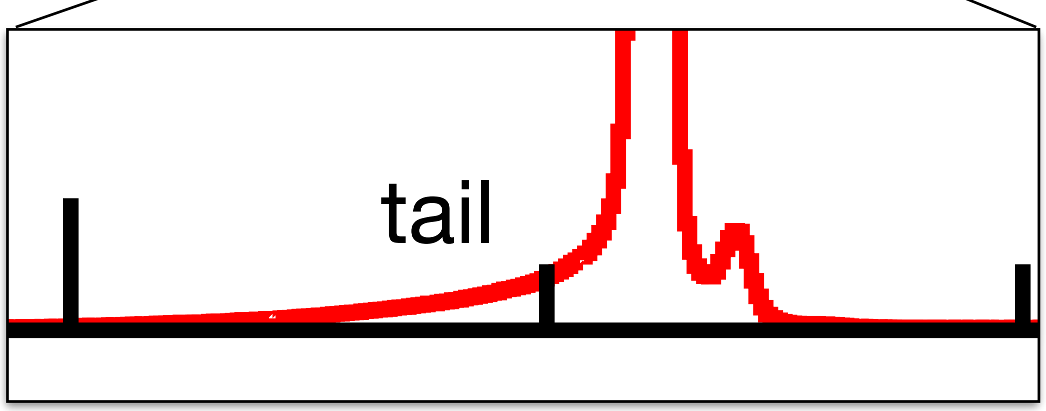
March, **2022**

- ✓ Precise energy calib. in ~2 keV
- ✓ Clear Lyman series dμ X-rays
- ✓ **No significant signal of μ molecules**
- ✓ "Vesman mechanism" requires that μ atoms collide "**gently**" to the normal molecule.

➡ expecting that the Vesman mechanism did not work well in the low-density gas environment due to **insufficient thermalization**

➡ Moreover, the present TES is known to have a **tail component** in the detector response function.

Response function :

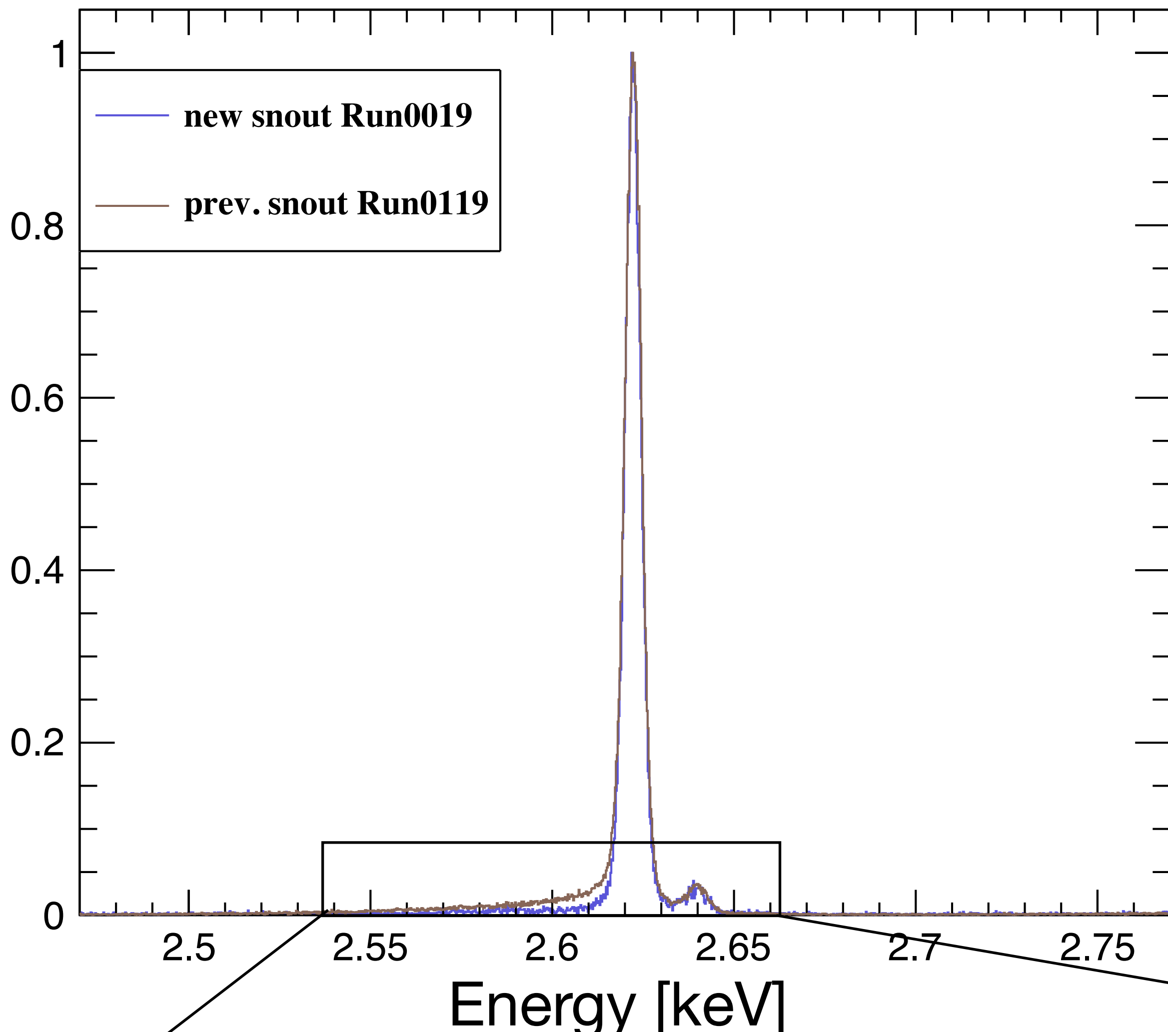


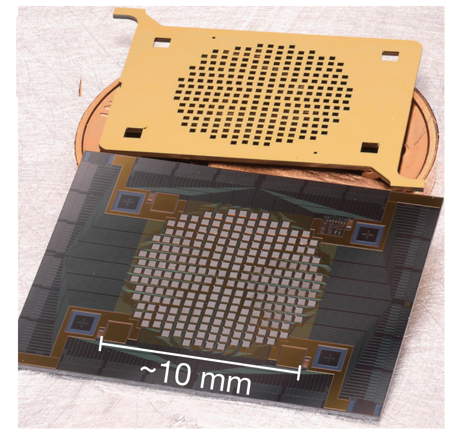
Next :

➡ **Low tail TES**

➡ **Solid D_2 target**

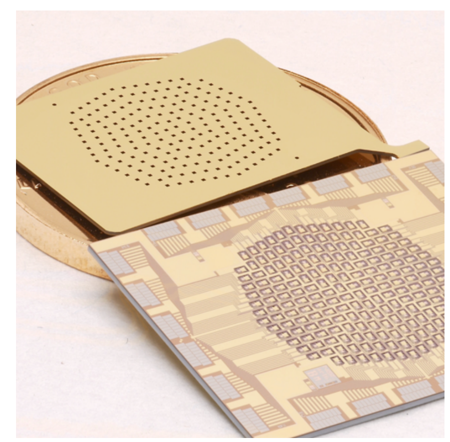
New TES : Less tail component





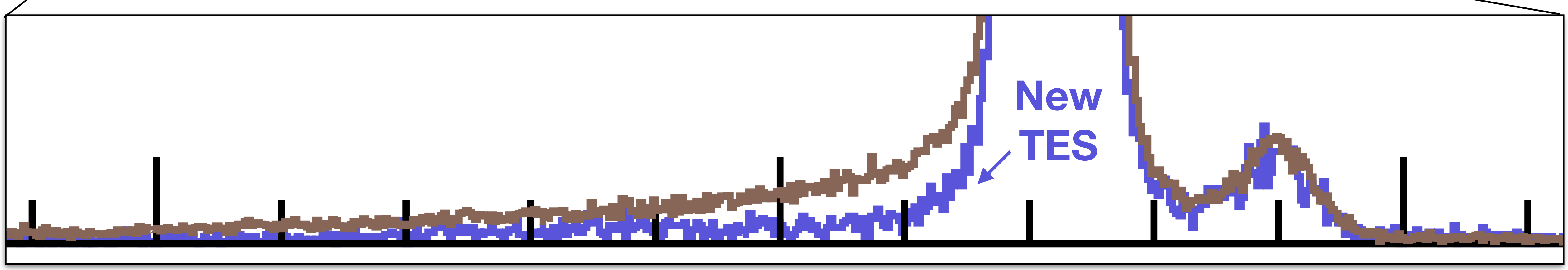
Original TES

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



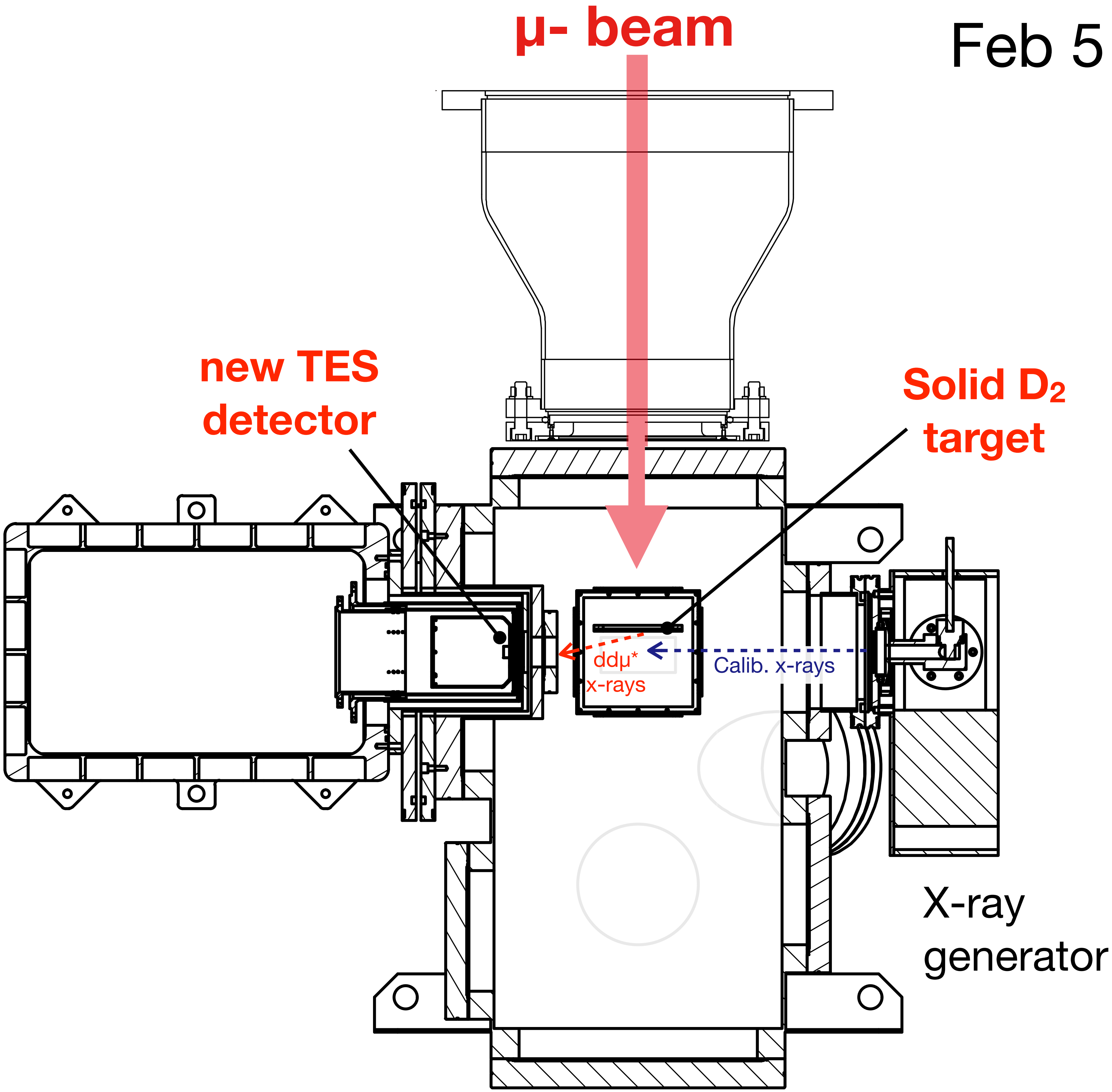
New TES
for Low energy X-ray

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



Experiment with solid D_2 (2023)

Feb 5 - 11, 2023



Summary

take-home message

- ✓ Muon-catalyzed fusion, **μCF**, research is **entering a new phase**
- ✓ Concept of **circulating gas target** for μCF is ready for practical use
- ✓ A **new elementary process** of μCF was proposed and indirect evidence was obtained.
- ✓ The first direct evidence for the existence of “resonant **Matryoshka molecules**” (= intramolecular molecules) is provided.
  - ➡ opens a complex and diverse black box leading to μCF
  - ➡ marks the beginning of a new quantum few-body study in the field of "exotic molecules".

Collaborators

many researchers from different fields

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THE UNIVERSITY OF TOKYO
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P. Caradonna

JAEA
T. Osawa,
T. Hashimoto

T. Saito,
Y. Ueno

大阪大学
OSAKA UNIVERSITY
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K. Terada, H. Noda

ICU
Expanding Potential
K. Kubo

RIKEN
T. Azuma,
K. Ishida,
T. Isobe,
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KEK
J-PARC
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H. Natori, S. Nagatani, K. Shimomura,
P. Strasser, S. Takeshita, I. Umegaki,
M. Tampo

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