

Development of a Nuclear Clock to Search for Variations in Fundamental Constants

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This research is a collaborative project.



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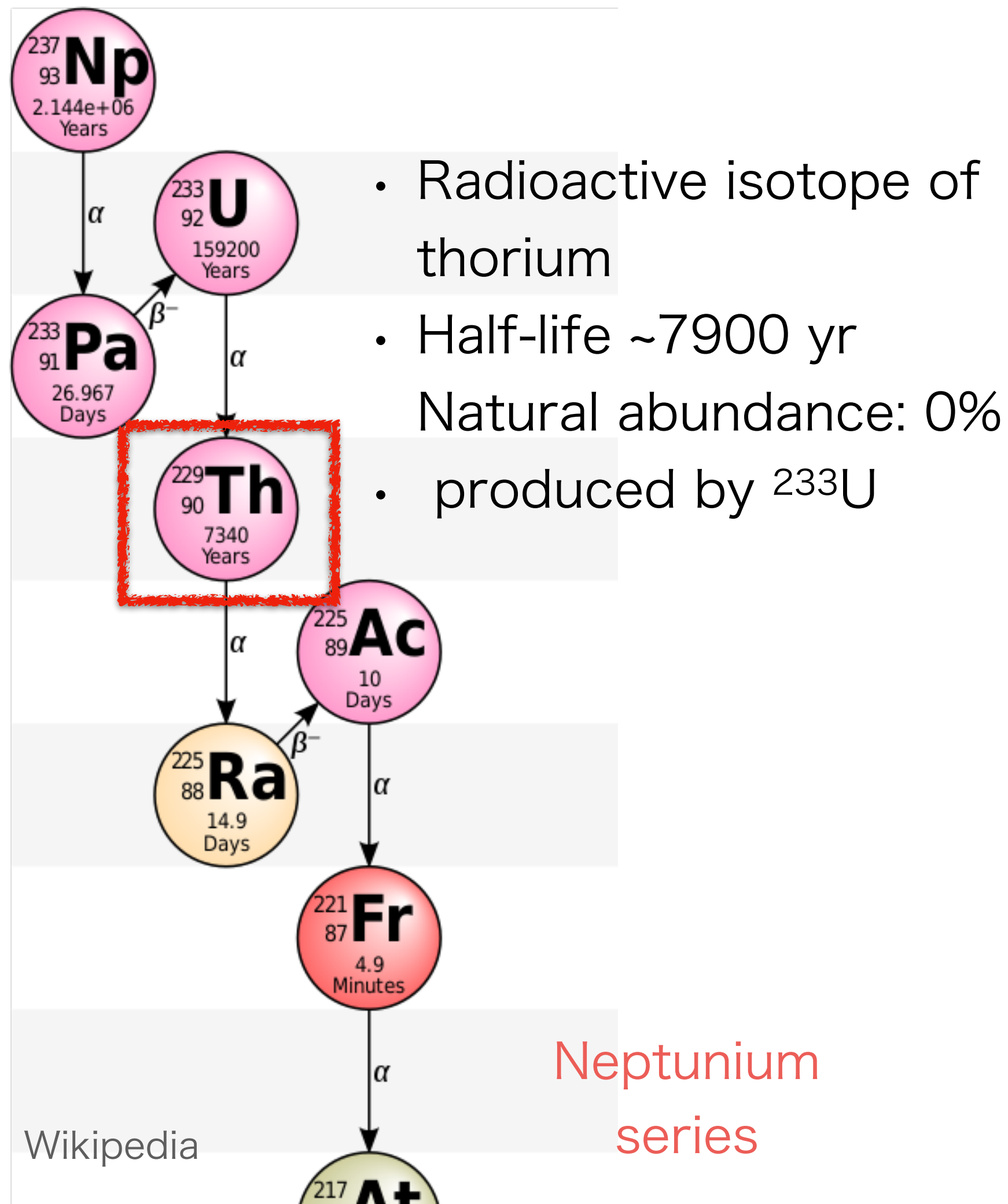
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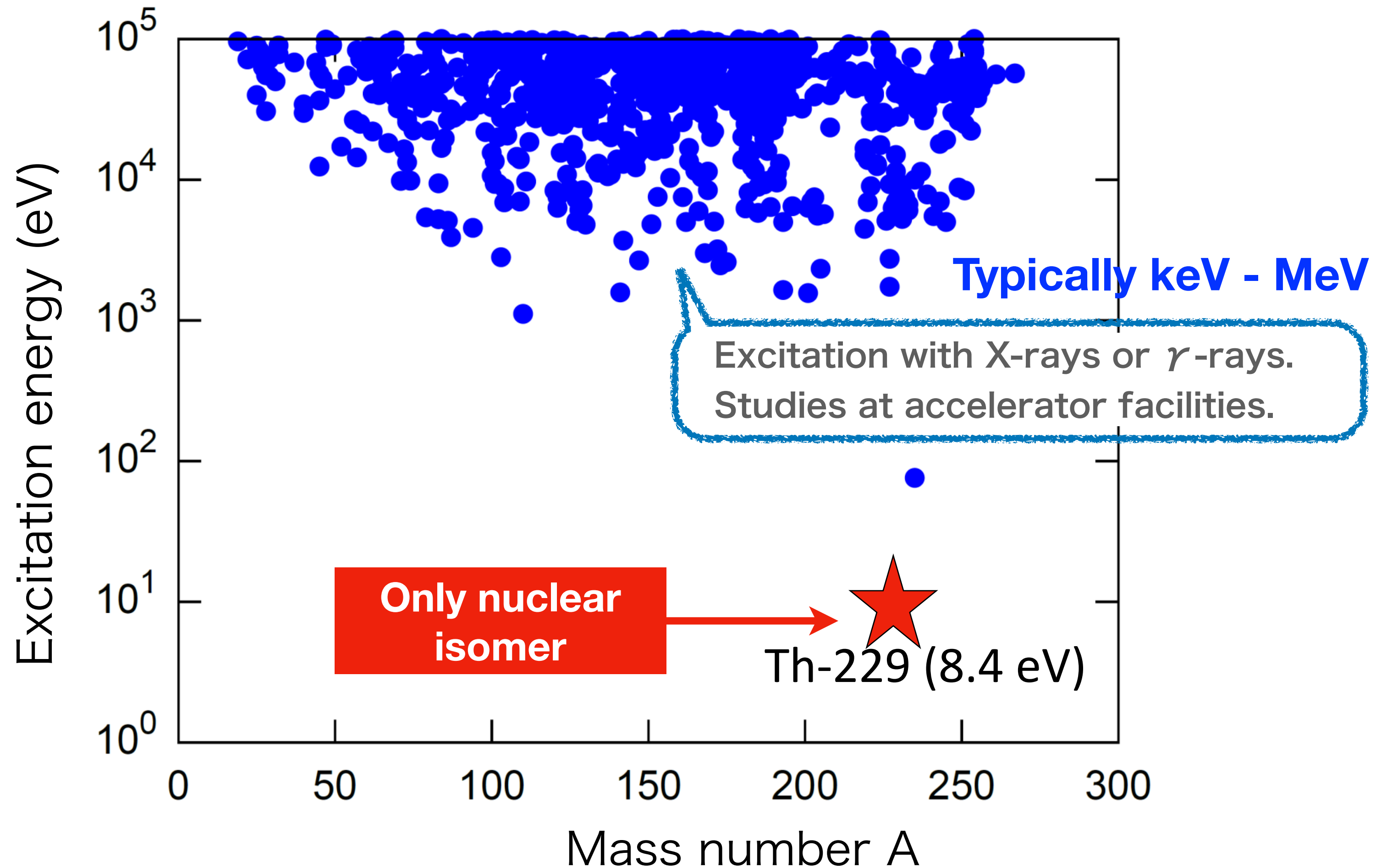
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Introduction — Thorium-229



- Radioactive isotope of thorium
- Half-life ~7900 yr
- Natural abundance: 0%
- produced by ²³³U

Energy of the first nuclear excited state



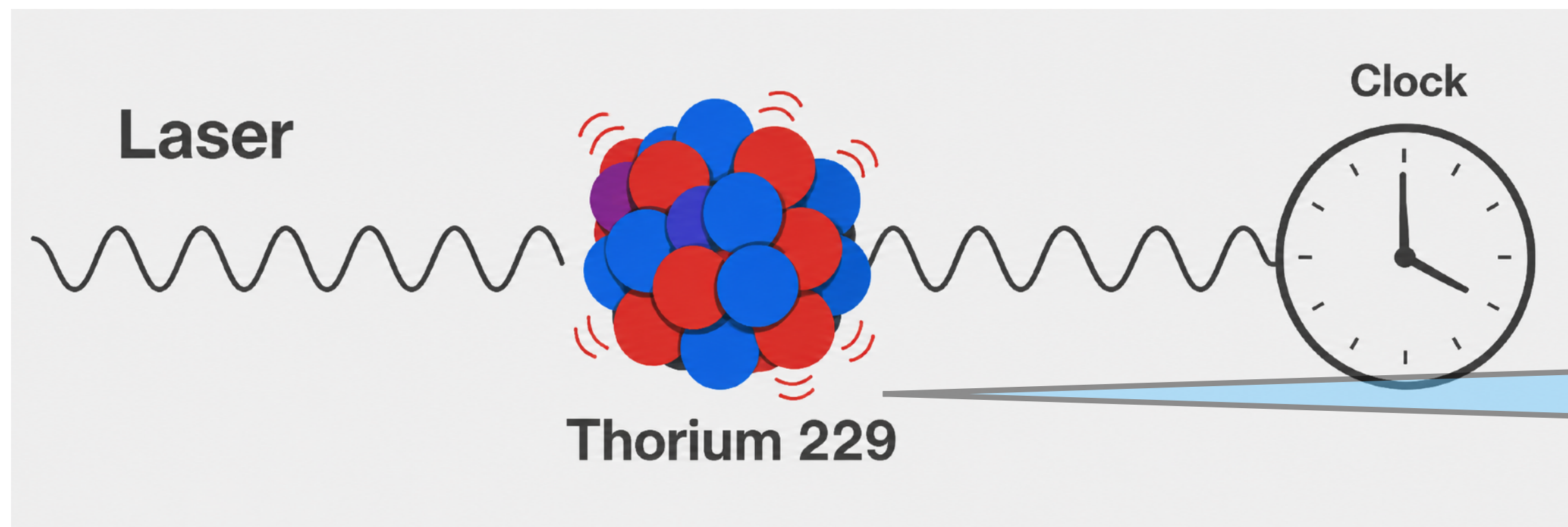
Thorium-229 has the lowest first nuclear-excited state ($\lambda \sim 148$ nm, $\tau \sim 10^3$ s)

→ **Direct laser excitation is possible, enabling its application to an optical nuclear clock.**

Introduction — Thorium-229 nuclear clock

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Use a **nuclear transition** as a frequency standard.

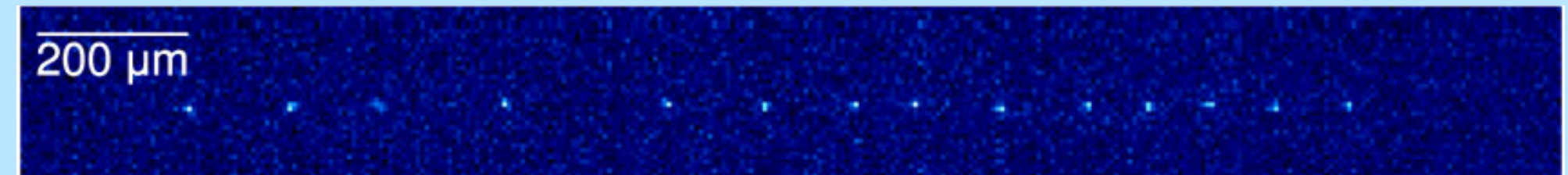


$$\frac{\delta f}{f} = K \frac{\delta \alpha}{\alpha}$$
$$K = \frac{\Delta E_c}{\Delta E_{IS}} \rightarrow \begin{matrix} \sim \text{MeV} \\ \sim 8 \text{ eV} \end{matrix}$$

Typically keV - MeV

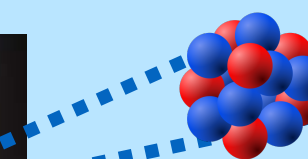
Type(1).Ion trap

C. J. Campbell et, al. PRL
102, 233004 (2009)



- trapped ^{229}Th ions
- Potential to achieve ultimate precision

Type(2).Doped into a crystal (solid-state nuclear clock)



$> 10^{18} / \text{cm}^3$

- Simultaneous excitation of many ^{229}Th nuclei
- Strong signal enhancement
- Compact

• Accuracy is expected to be $\Delta \nu / \nu \sim 10^{-19}$.

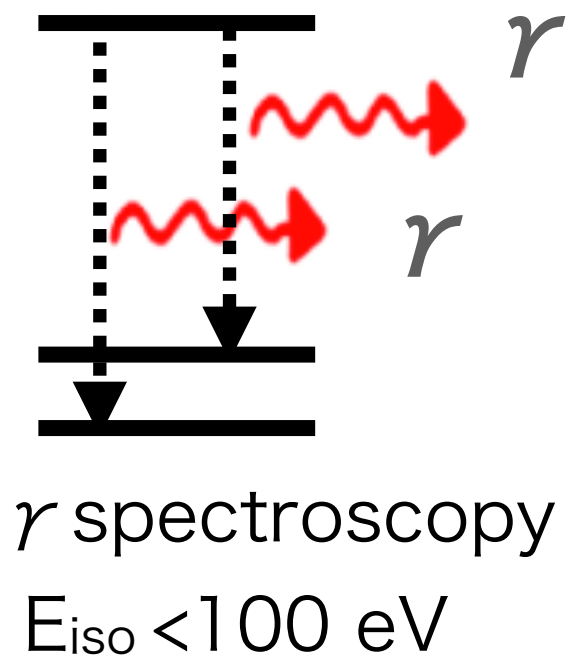
Since the nucleus is much smaller and less polarizable than the atom, it is less sensitive to external fields.

• Large sensitivity to variations in the fine-structure constant α : $K \sim 10^3 - 10^4$

• → These advantages make the nuclear clock promising for both fundamental physics and practical applications.

Background

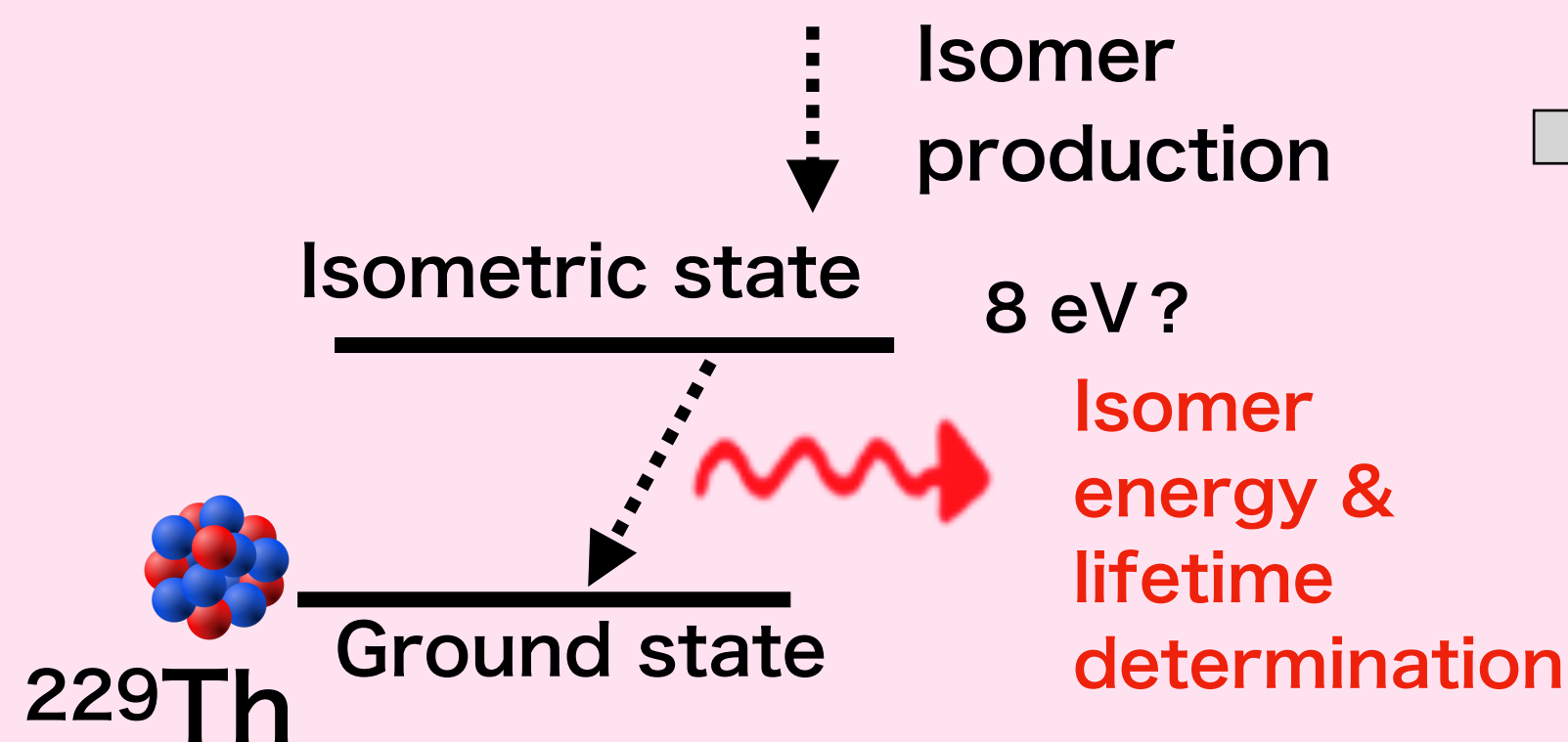
- 1976: The existence of a low-energy nuclear isomer was predicted by γ -spectroscopy
- However, its energy remained uncertain for many years.
- For direct laser excitation, precise determination of the isomer energy is essential.



Step for laser excitation of ^{229}Th isomer

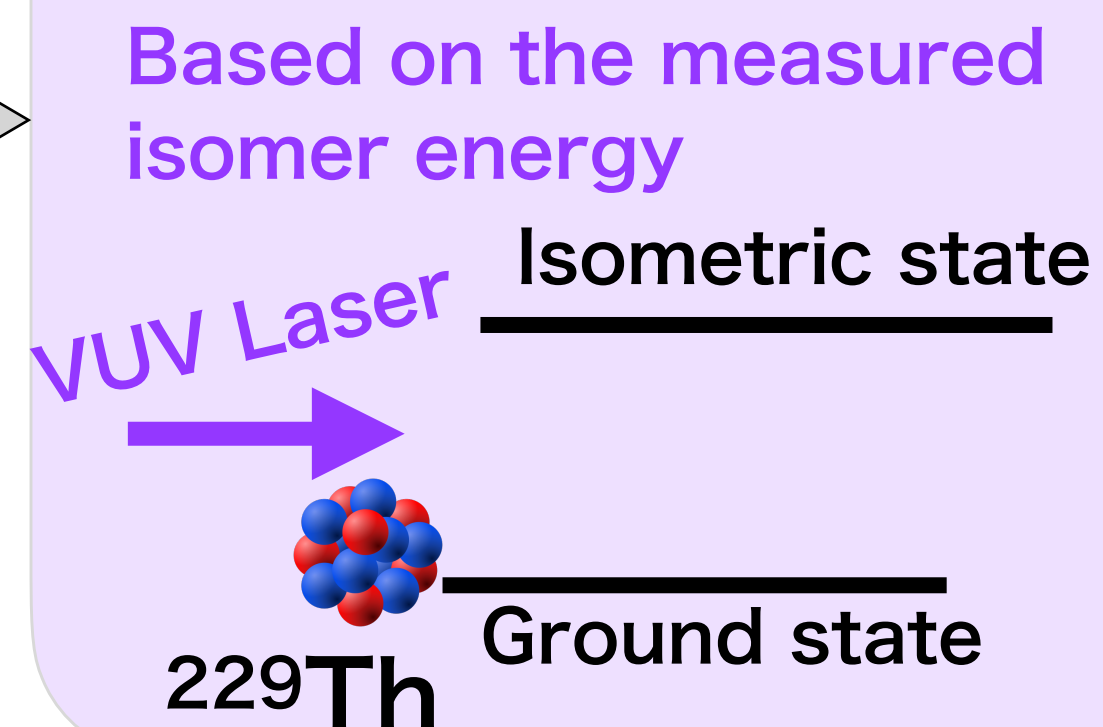
Step①

Isomer Production &
Direct VUV Observation



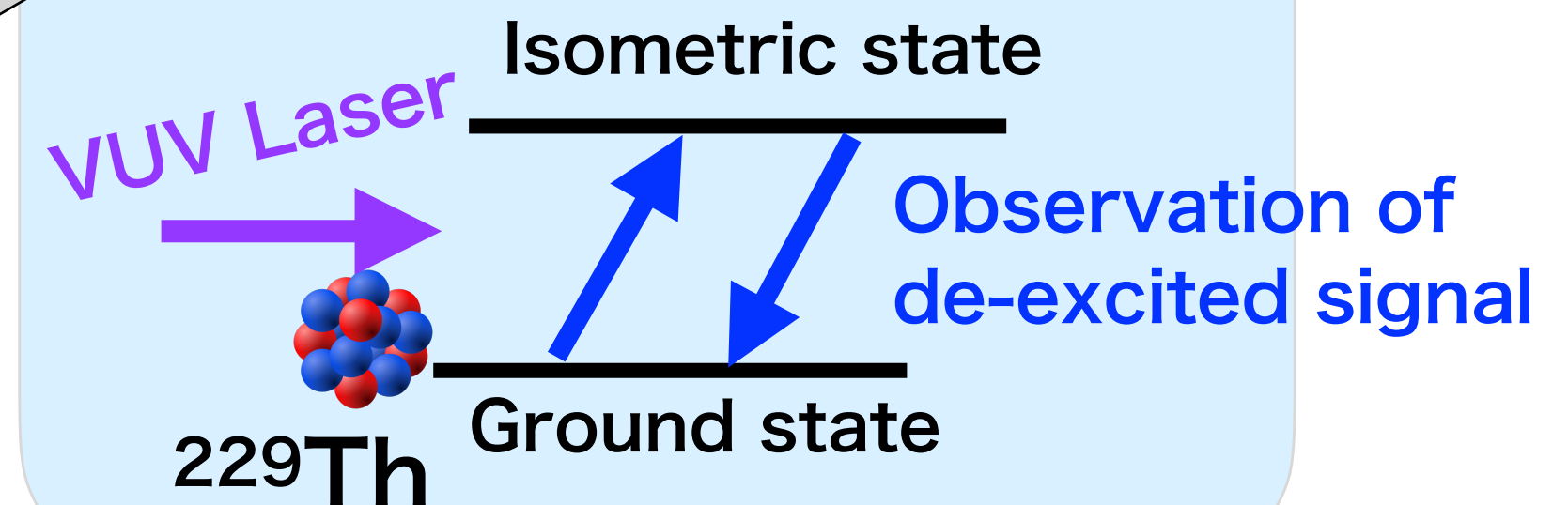
Step②

Development of a
Tunable VUV Laser



Step③

Direct Laser Excitation
of the Isomer

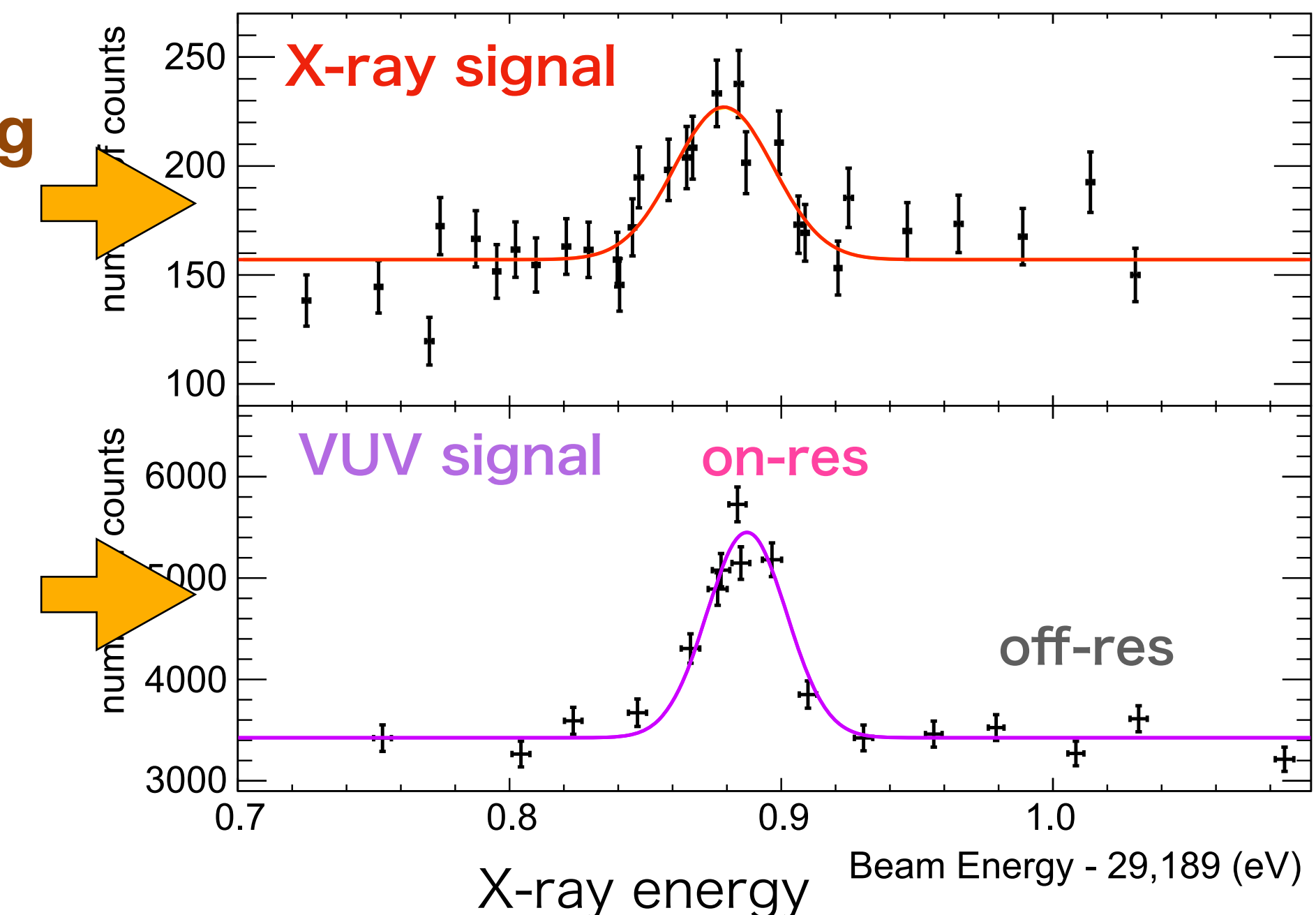
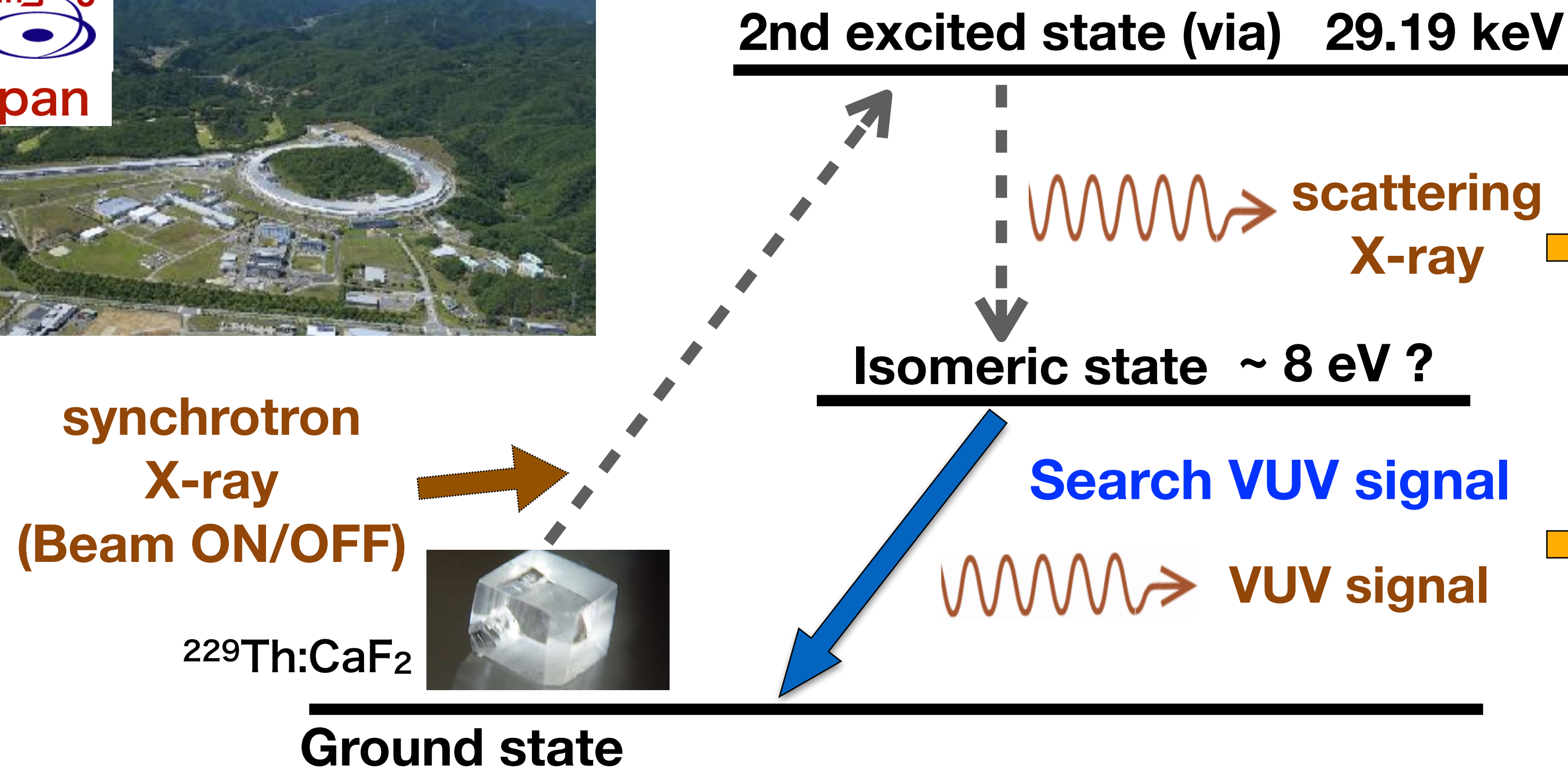


① Isomer Production & Direct VUV Observation

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T. Masuda et al., Nature 573, 238-242 (2019). T. Hiraki et al. Nature Com 15, 5536 (2024).

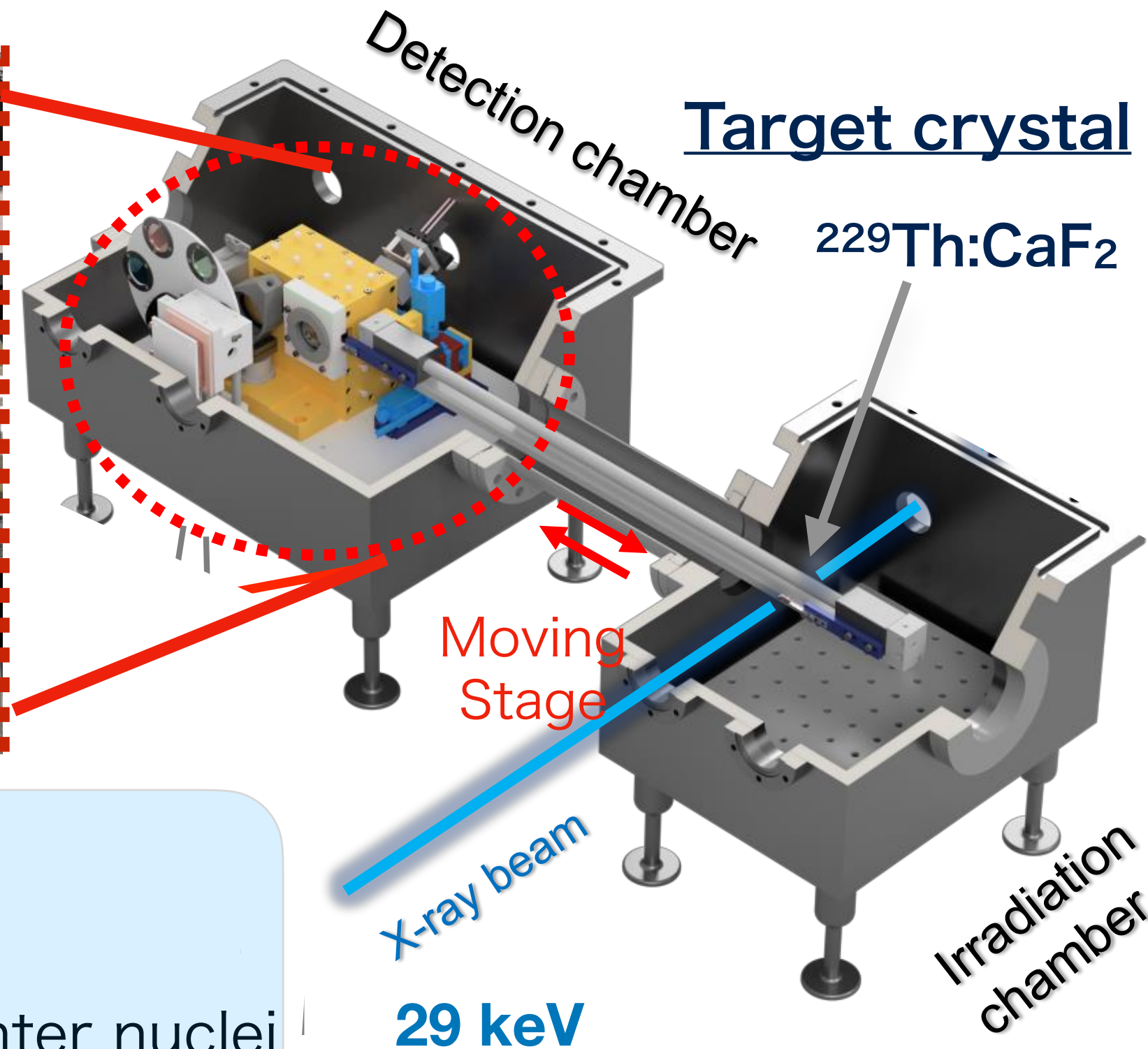
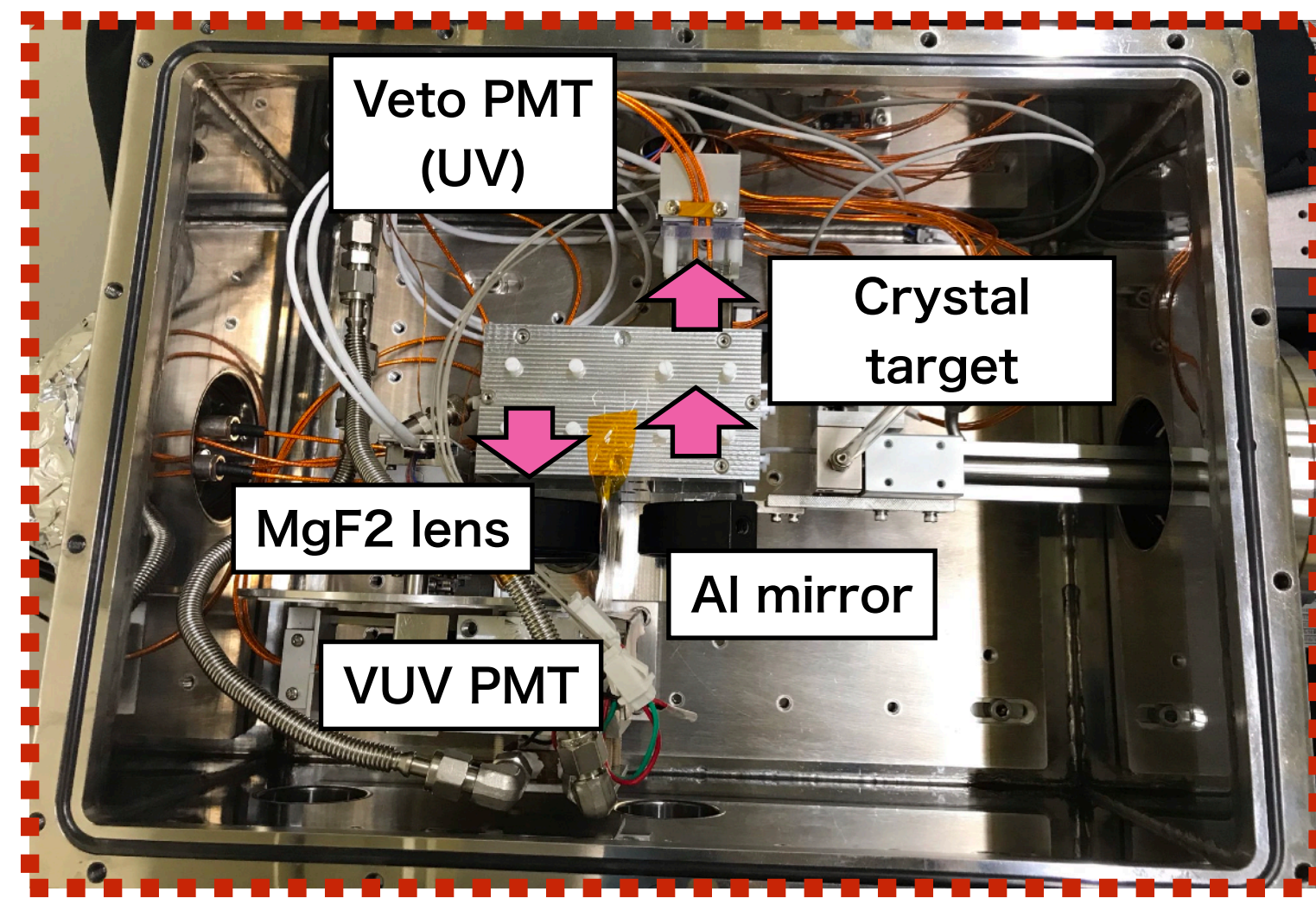


- We developed an excitation scheme to populate the ^{229}Th isomer via the well-known 2nd excited state using synchrotron X-ray irradiation.
- We then directly detected VUV photons from isomer decay, enabling a precise determination of the isomer energy and lifetime.

① Isomer Production & Direct VUV Observation

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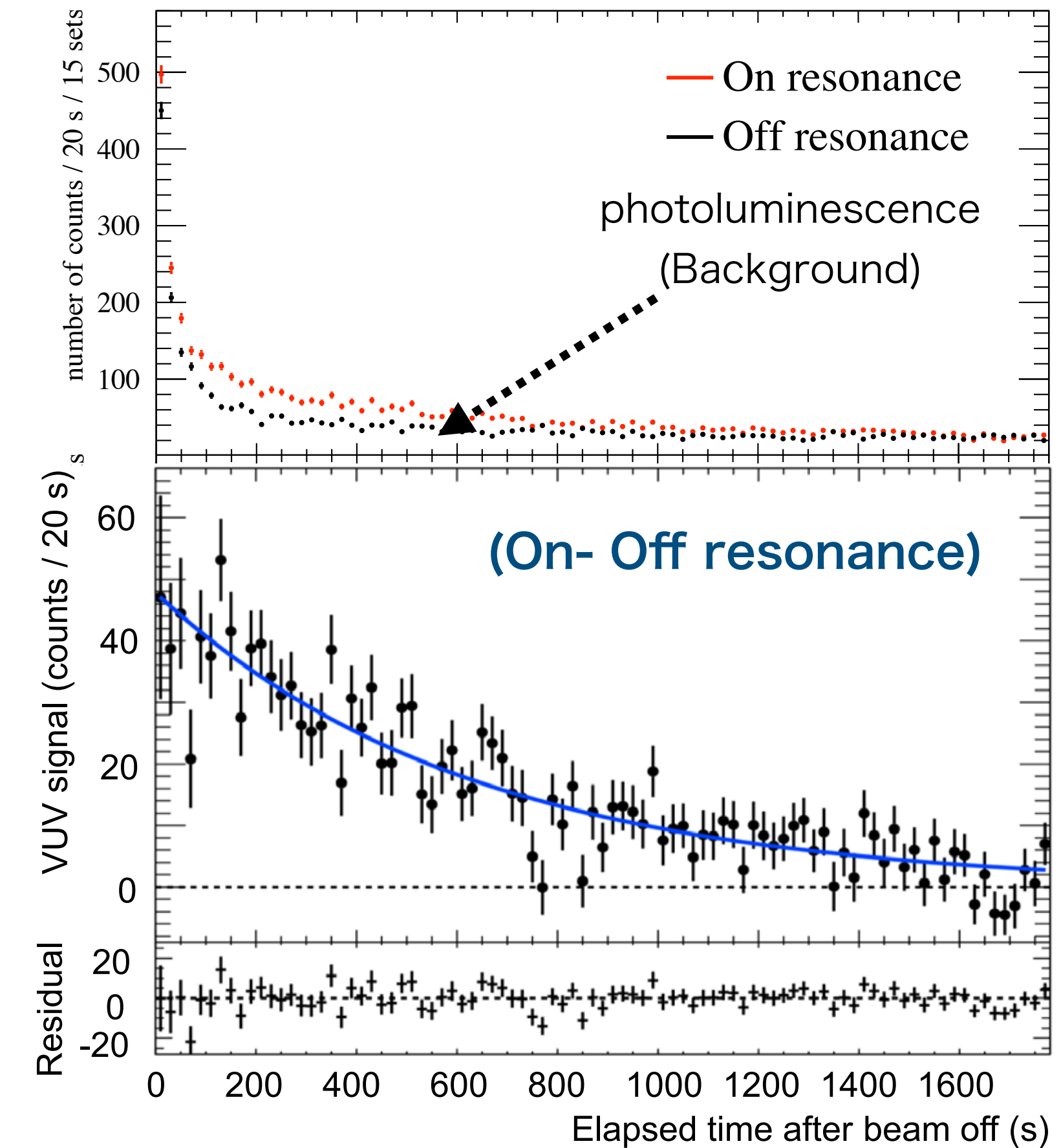
Experimental setup



Subtracting the background

- Radio-luminescence
from α/β decays of ^{229}Th and daughter nuclei
- Photoluminescence
from X-ray irradiation of crystals

^{229}Th isomer decay curve



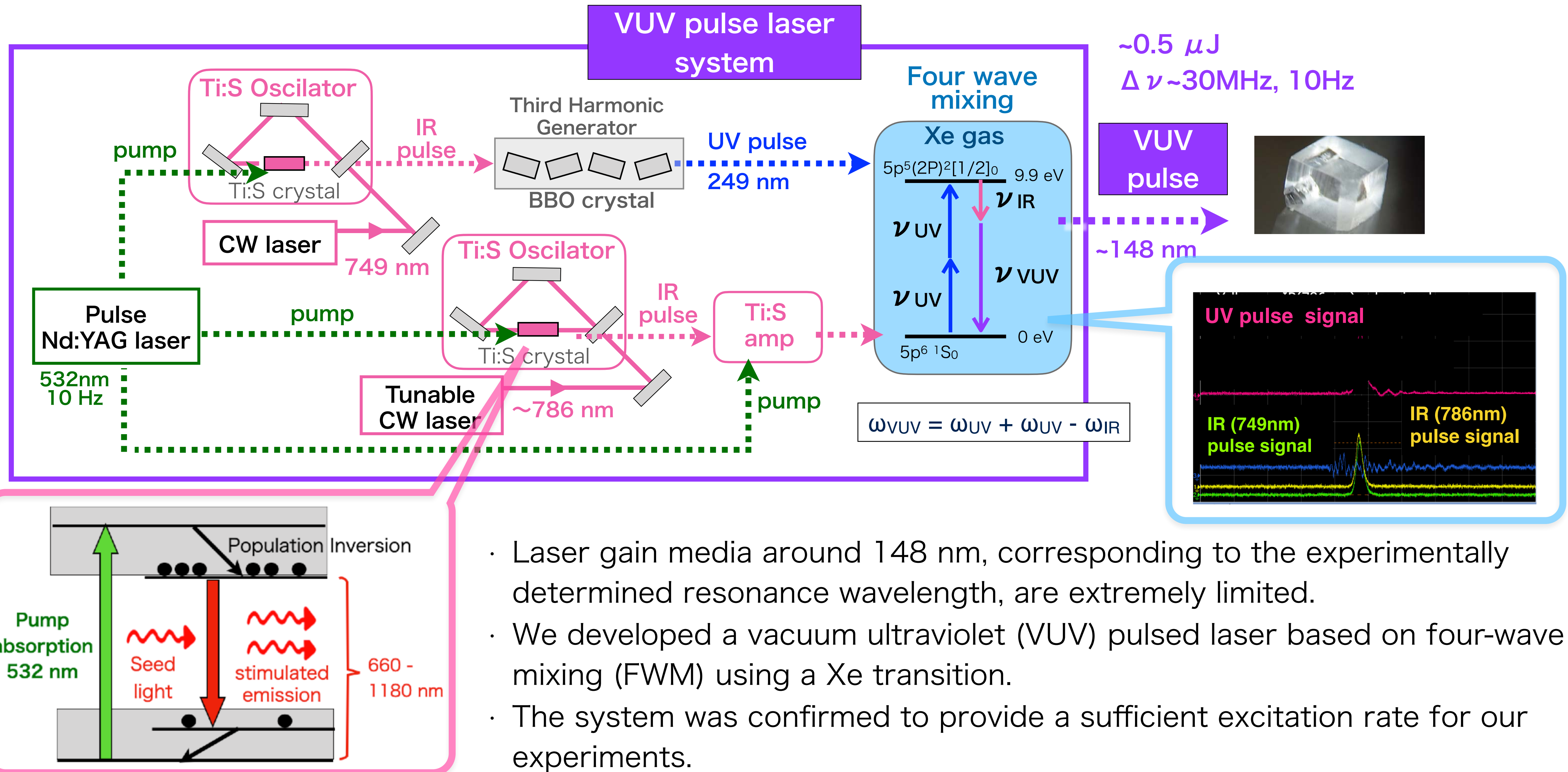
Observation results (w/BPF)

$$\begin{aligned} E_{\text{iso}} &= 8.368 \pm 0.024 \text{ eV} \\ \tau &= 645(23) \text{ s} \end{aligned}$$

The precise determination of the isomer energy and lifetime has contributed to nuclear clock research.

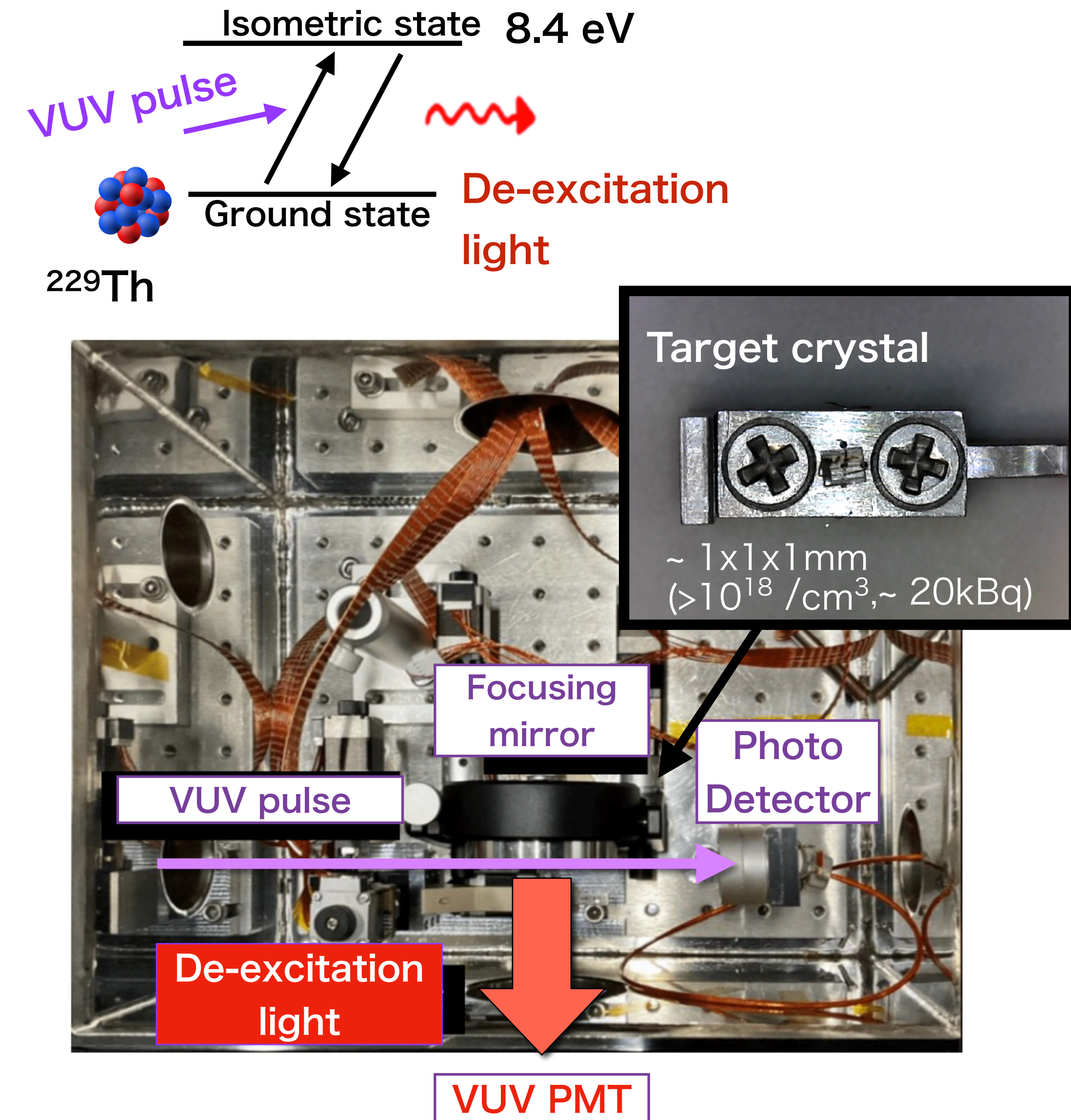
② VUV laser system development

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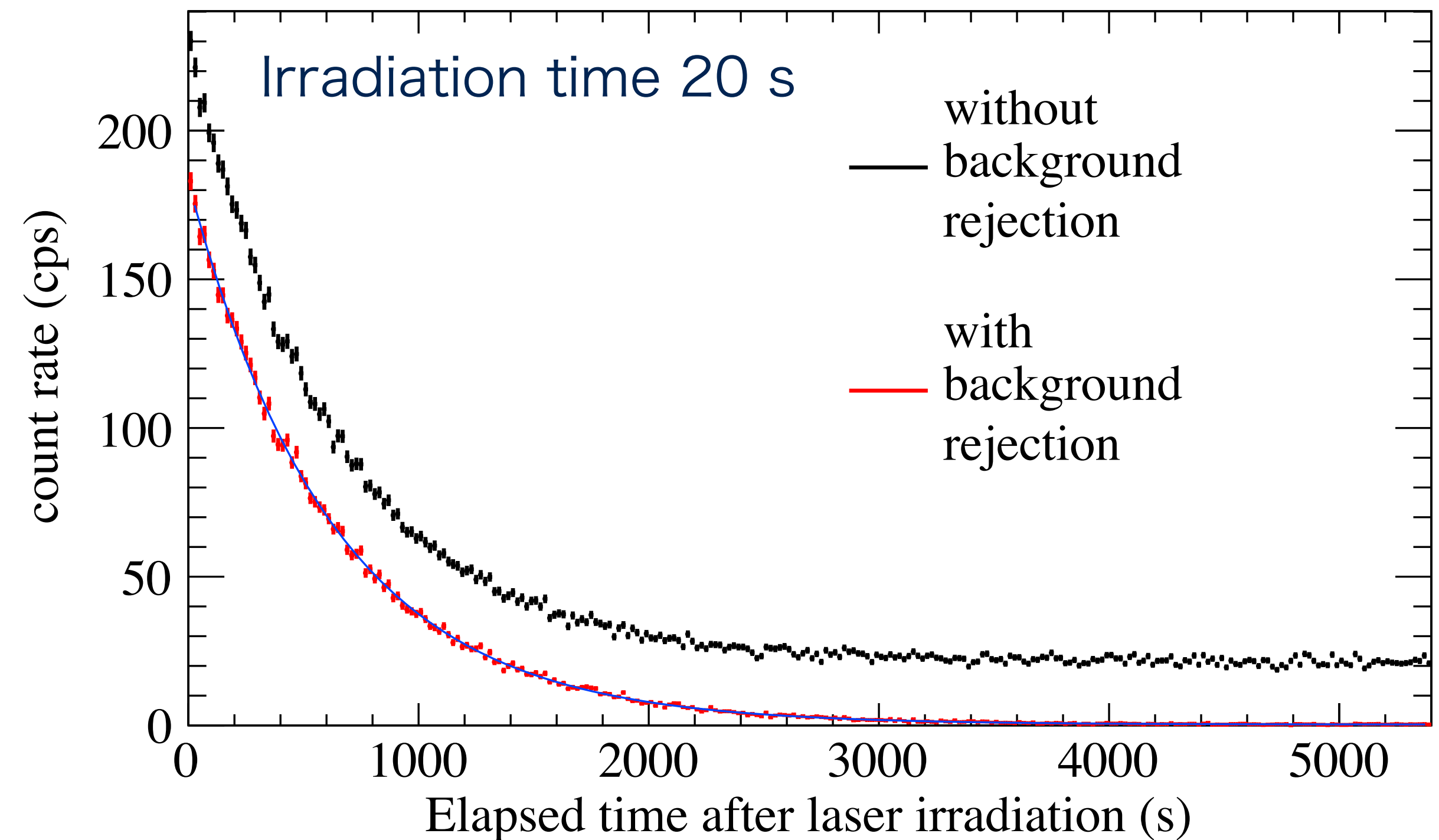


③ Laser excitation experiment

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^{229}Th isomer decay curve



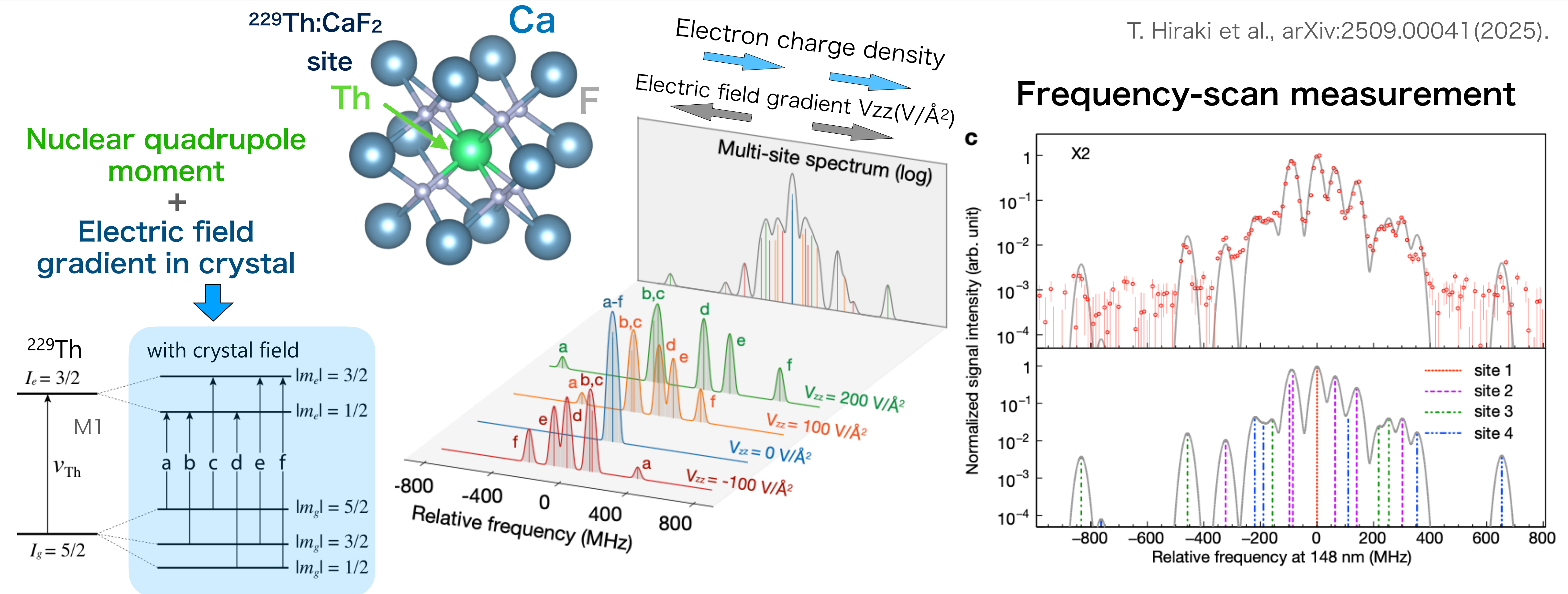
- Successful observation of radiative decay from the isomeric state ($\tau \sim 630 \text{ s}$)
- **We demonstrated ^{229}Th laser excitation and detection of de-excitation signal.**

③ Laser spectroscopy

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T. Hiraki et al., arXiv:2509.00041 (2025).

Frequency-scan measurement



- We achieved spectroscopy of the crystal-field splitting in the host crystal.
- The observed spectrum can be consistently explained as a sum of contributions from 4 different sites. (Confirmed weak peaks (site3, 4) that had not been observed in previous studies.)

Recent Status of ^{229}Th Nuclear Clock Research

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Major Progress in Recent Years

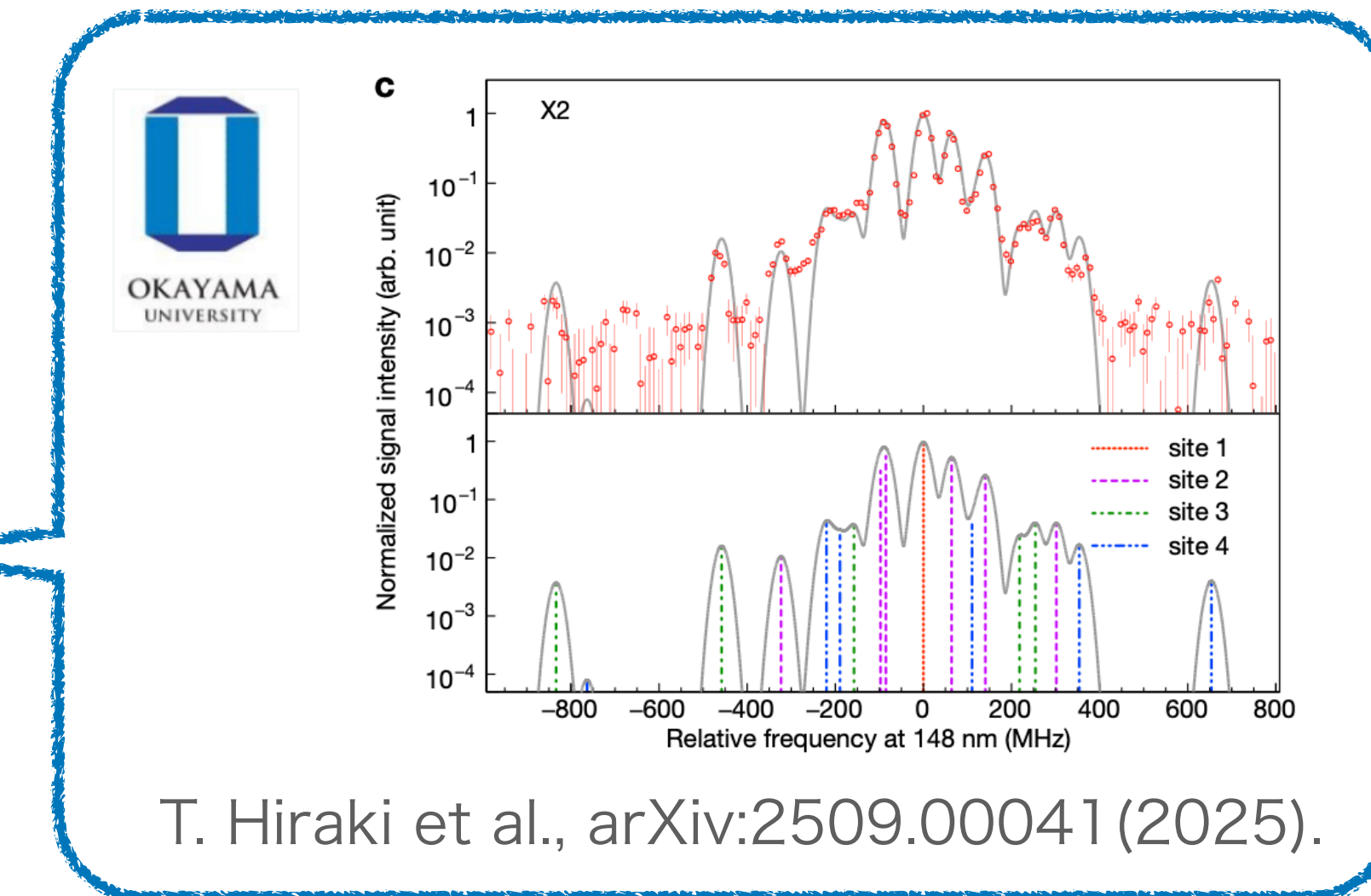
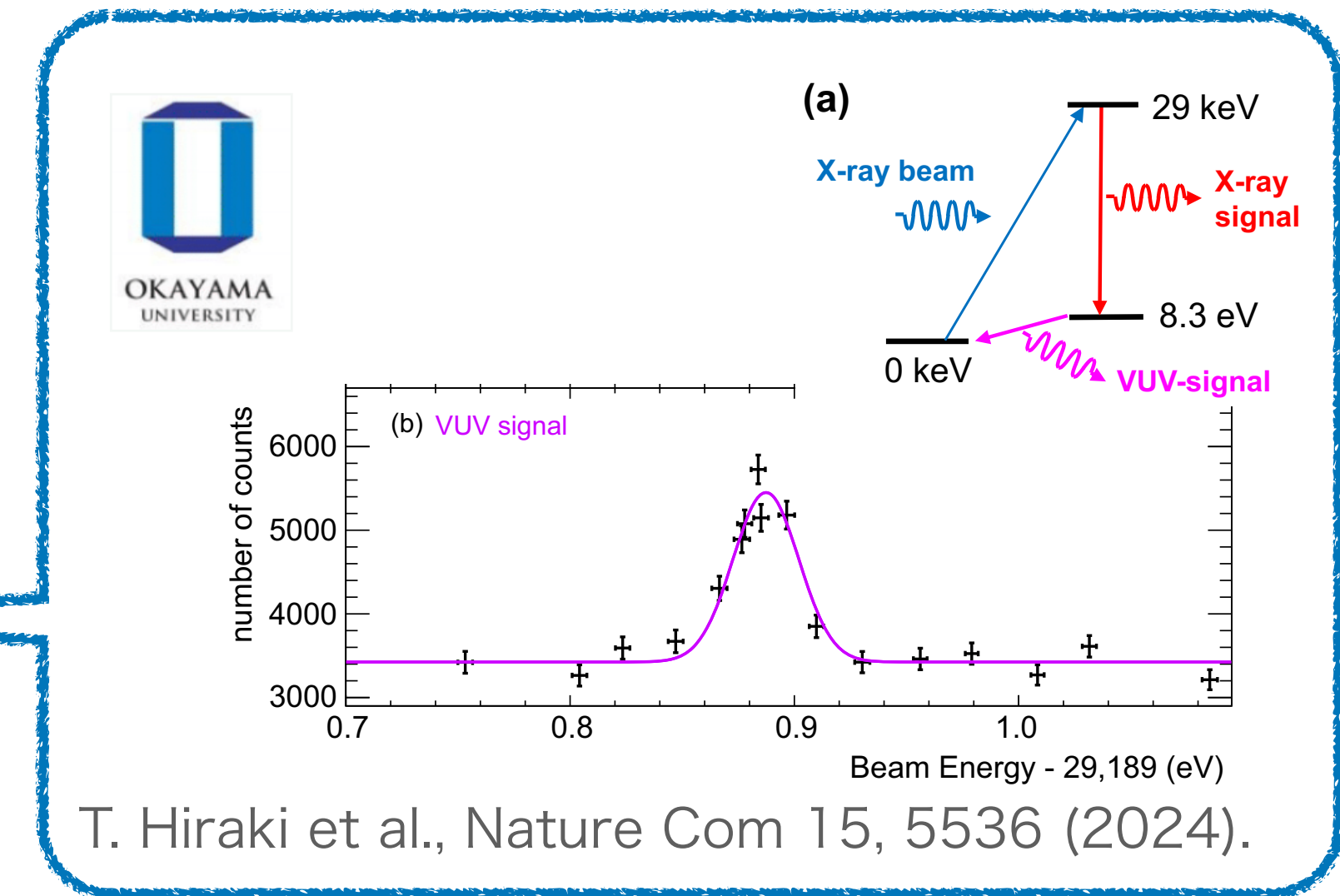
2023~ Precise determination of the isomer energy

- ISOLDE (Belgium): 148.7(4) nm (2023)
- **Okayama**: 148.18(42) nm (2024)
 - Direct observation enabled precise energy determination, leading to laser development, and nuclear excitation.

2024~ Laser excitation achieved

- PTB: linewidth 6 GHz (2024) $^{229}\text{Th}:\text{CaF}_2$
- UCLA: linewidth 15 GHz (2024) $^{229}\text{Th}:\text{LiSrAlF}_6$
- JILA: linewidth 300 kHz (2024) $^{229}\text{Th}:\text{CaF}_2$
- **Okayama**: linewidth 30 MHz (2025) $^{229}\text{Th}:\text{CaF}_2$
 - High-sensitivity spectroscopy of the nuclear resonance
- TU Wien: CW excitation (2026) $^{229}\text{Th}:\text{CaF}_2$

→ All laser excitation so far has been achieved in solid-state targets.
Laser spectroscopy of trapped ions is the next major milestone.



Summary & Future work

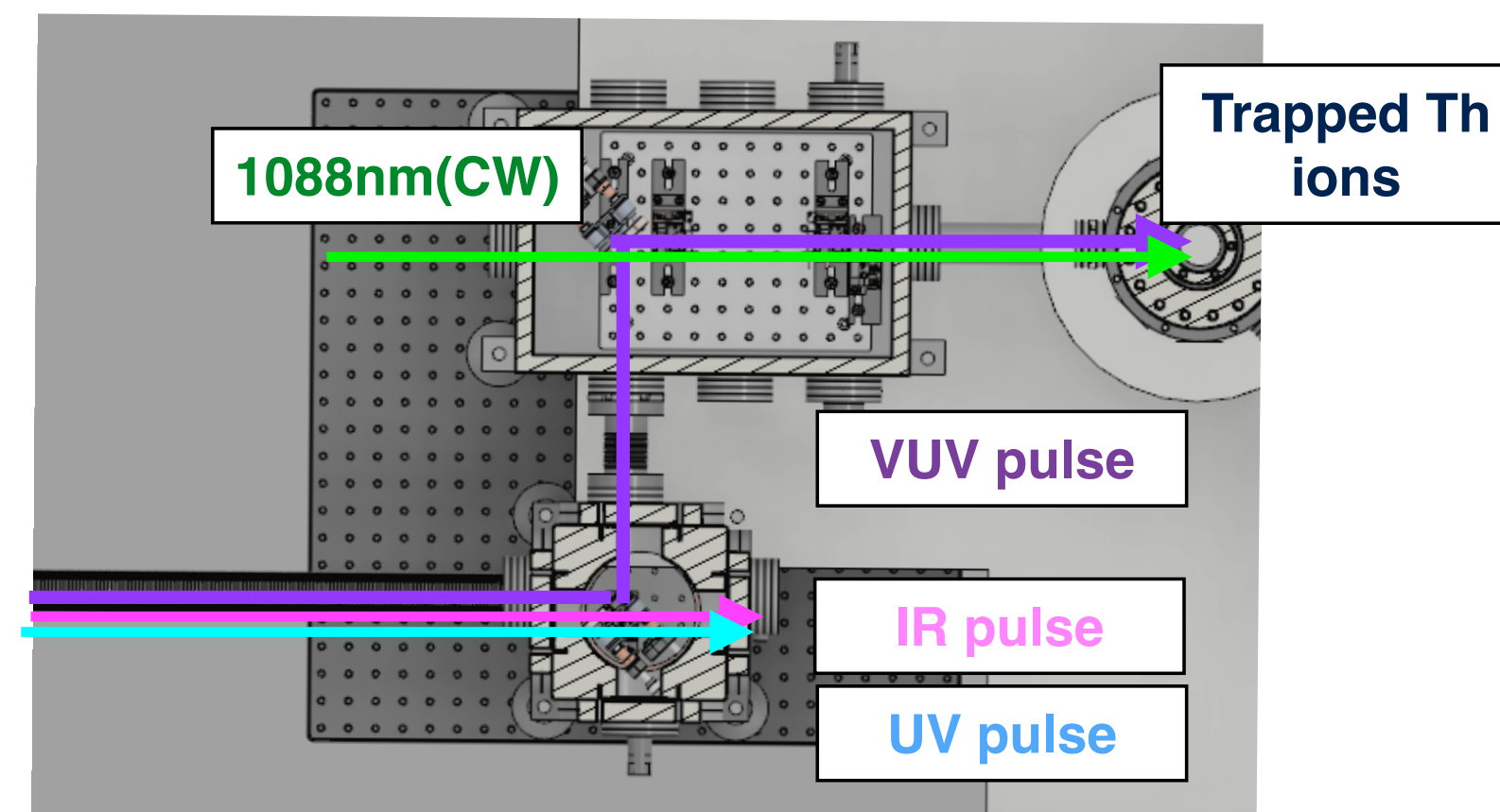
- ^{229}Th has an isomeric state with exceptionally low energy, and is expected to be applied to a precise nuclear clock.
- In this study, ① precisely determined the isomer energy through direct detection of de-excitation photons, ② developed a VUV pulsed laser based on four-wave mixing, and ③ demonstrated laser excitation and precision spectroscopy of the ^{229}Th isomeric transition in a $^{229}\text{Th}:\text{CaF}_2$ crystal.

Developing solid-state nuclear clock

- Laser quenching study and temperature dependence study are ongoing.
- Development of ^{229}Th new samples and Evaluation by Laser-Based Mössbauer spectroscopy
- Development of CW VUV laser etc...



Developing ion trap nuclear clock



Upgrades to the VUV laser and preparations for ion trap experiments are ongoing.

