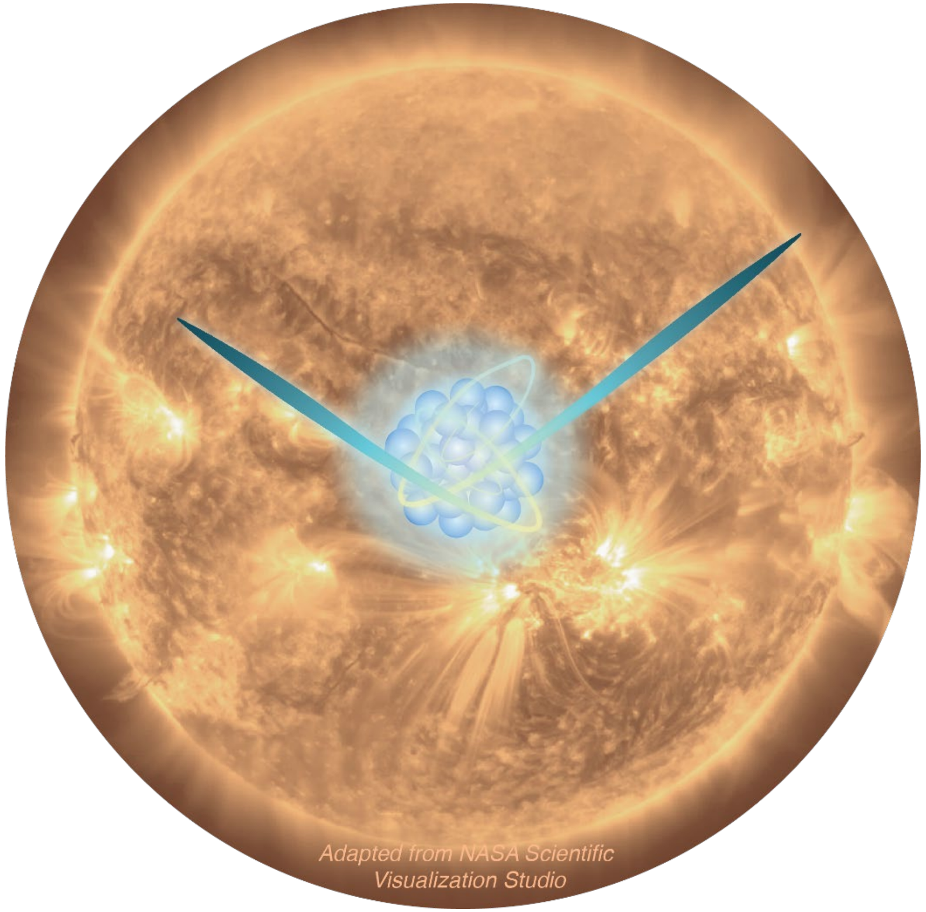
Sources for Ultraviolet Nuclear Spectroscopy of Thorium (SUNSPOT)



Dr. Mukund Vengalattore
Defense Sciences Office
DARPA

SUNSPOT Proposers Day

February 07, 2025

Proposers Day Agenda

SUNSPOT Proposers Day
February 7, 2025

Begin	End	Speaker
11:30 AM	11:35 AM	Welcome Mukund Vengalattore, DARPA/DSO PM
11:35 AM	11:50 AM	DSO Overview Jim Gimlett, DARPA/DSO Deputy Director
11:50 AM	12:05 PM	Contracting Overview Thao Phan, DARPA Contracting Officer
12:05 PM	12:45 PM	SUNSPOT Overview Mukund Vengalattore, DARPA/DSO PM
12:45 PM	1:15 PM	Break
1:15 PM	1:30 PM	Answers to submitted questions
1:30 PM	2:00 PM	Lightning Talks
2:00 PM	2:15 PM	Break
2:15 PM	4:15 PM	Sidebars

SUNSPOT Overview

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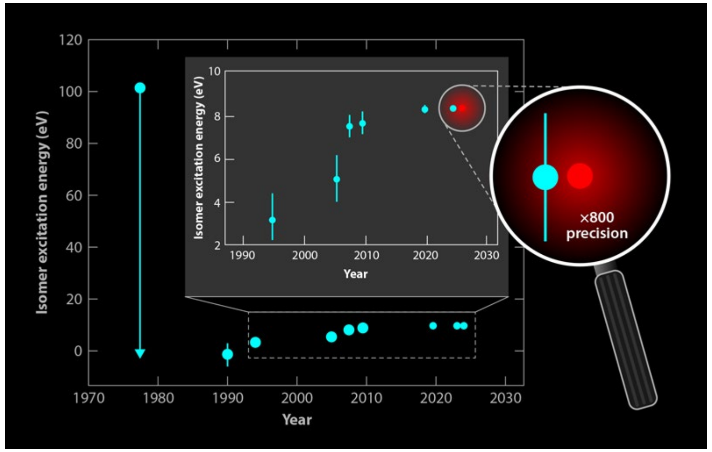
1. Background

Dawn of a nuclear clock: frequency ratio of the ^{229m}Th isomeric transition and the ^{87}Sr atomic clock

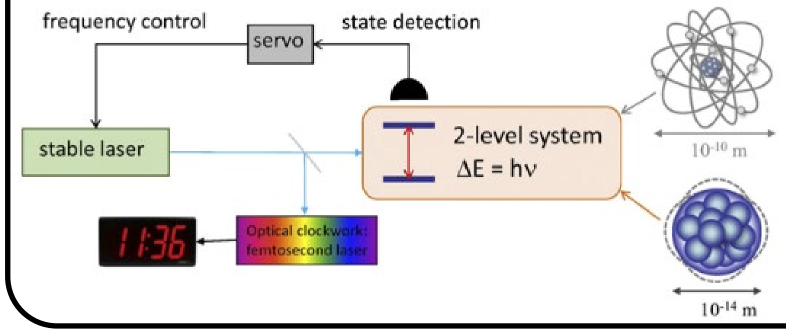
Chuankun Zhang[1], Tian Ooi[1], Jacob S. Higgins[1], Jack F. Doyle[1], Lars von der Wense[1], Kjeld Beeks[2], Adrian Leitner[2], Georgy Kazakov[2], Peng Li[3], Peter G. Thirolf[4], Thorsten Schumm[2], and Jun Ye[1]

(submitted to Nature, July 2024)

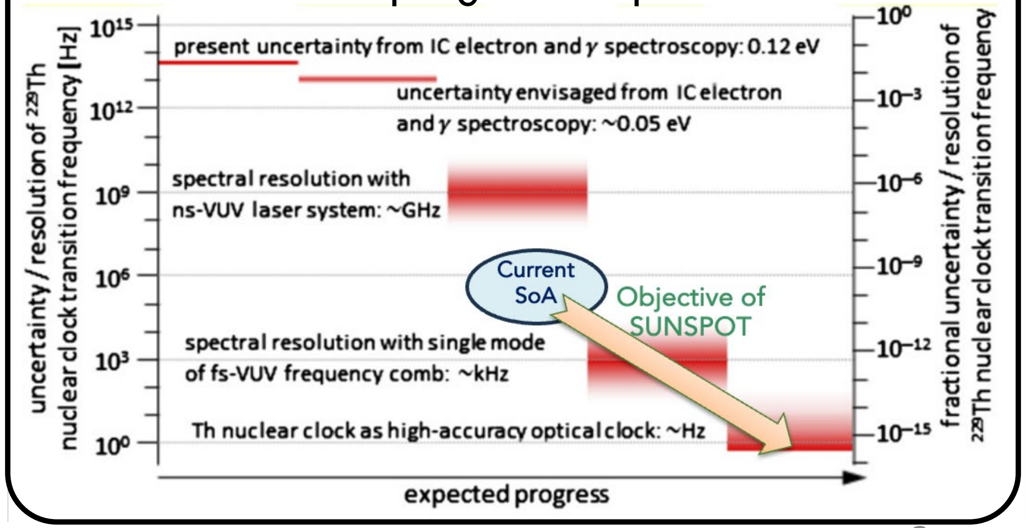


2. SUNSPOT

The SUNSPOT program will develop coherent VUV sources to enable high resolution spectroscopic studies of ^{229}Th



3. End-of-program Objective



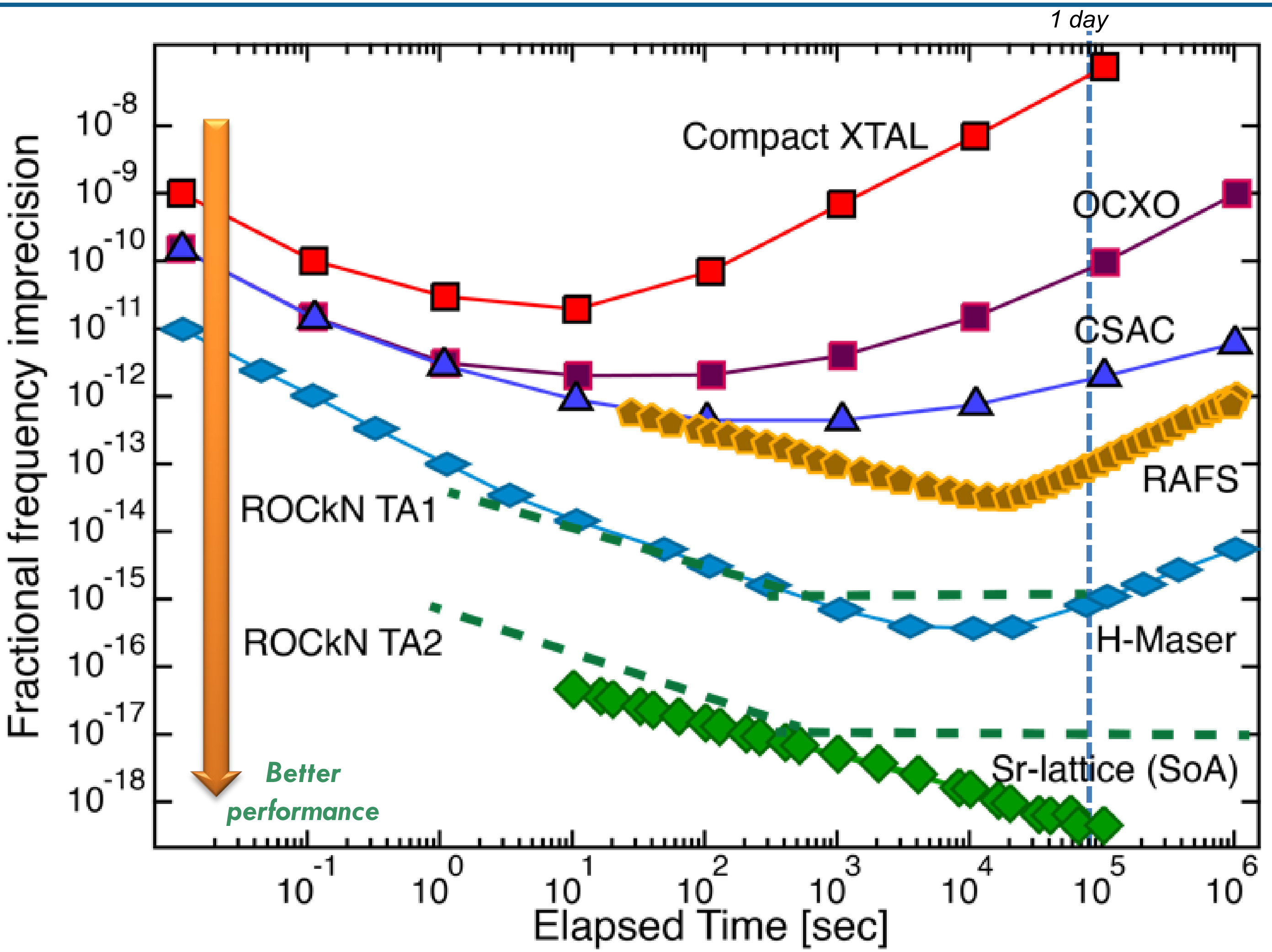
If there is any discrepancy between what is presented today and the Broad Agency Announcement (BAA), the BAA takes precedence.

VUV: Vacuum Ultra-Violet

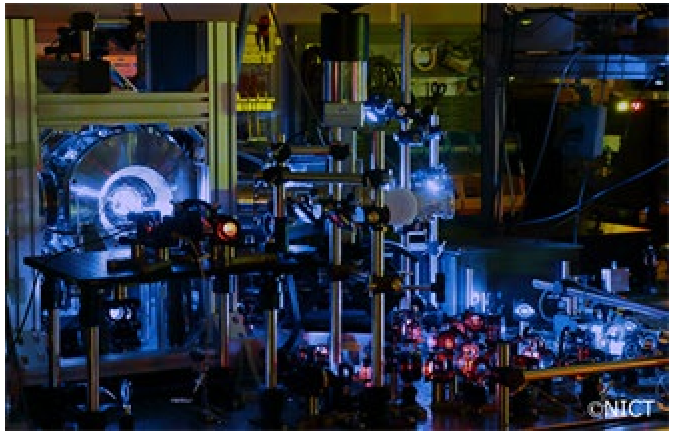
Comparison of clock technologies

CSAC
20 mL
22 ns @ 100 s

Excel-RAFS
4 L
10 ps @ 100 s



Hydrogen Maser
375 L
0.5 ps @ 100 s
100 ns @ 1 month

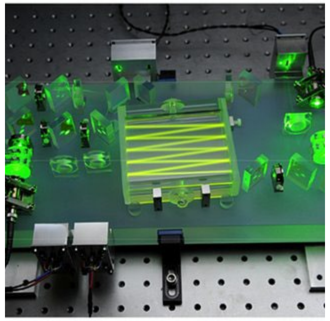


Strontium Lattice Clock
8000 L
1 fs @ 100 s

Current optical clock technologies have a fundamental SWaP-performance tradeoff

SWaP: Size, Weight, and Power
CSAC: Chip-scale Atomic Clock
RAFS: Rubidium Atomic Frequency Standard
OCXO: Oven-controlled Crystal Oscillator

Fundamental SWaP-Performance tradeoff

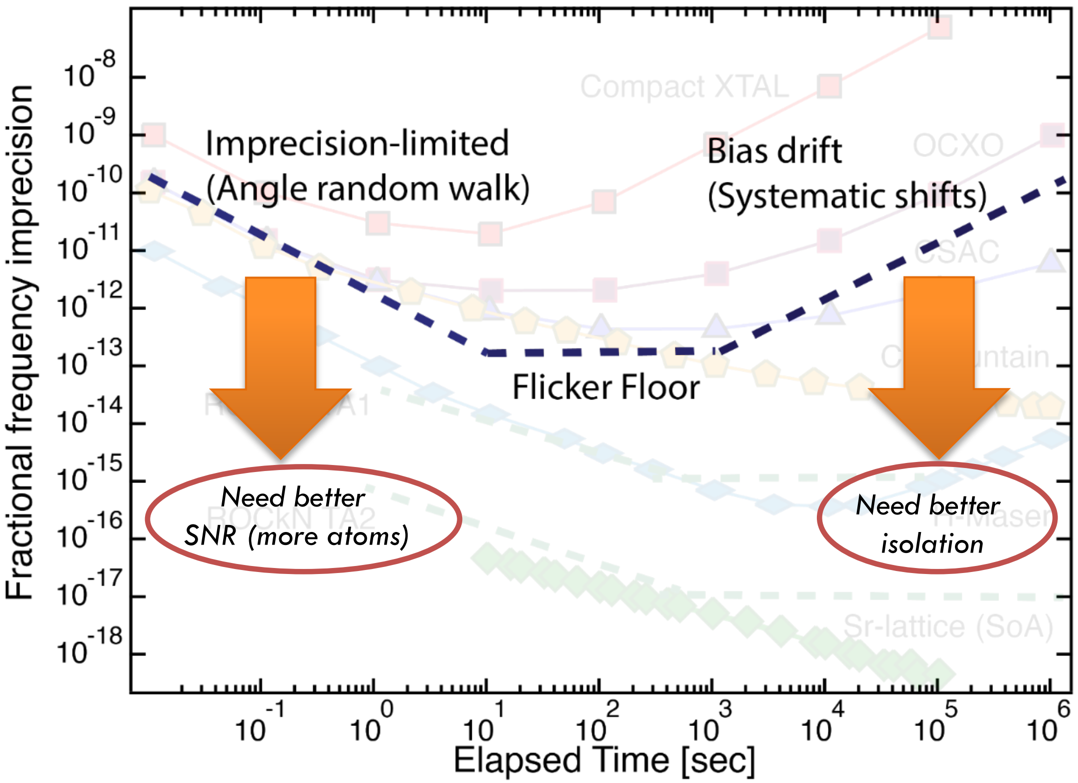


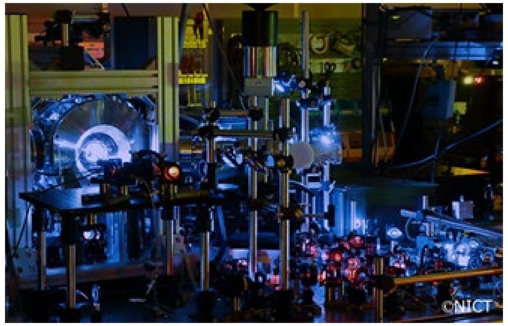
Thermal vapor clocks:

- ✓ Ambient temperature operation
- ✓ Minimal state preparation and control techniques required
- ✓ Large atomic ensembles (~10^{14} atoms)

- ❑ Poor isolation from environment
- ❑ Uncontrolled drifts
- ❑ Poorly understood systematic effects
- ❑ Poor long-term accuracy

Clock operating regimes

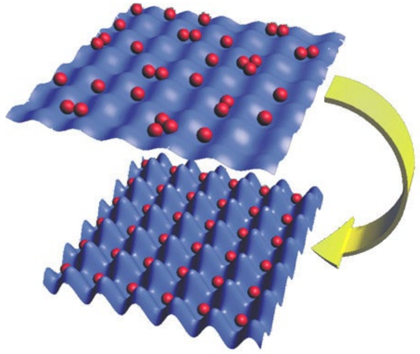




Ultracold atomic clocks:

- ✓ High levels of isolation
- ✓ Excellent long-term accuracy

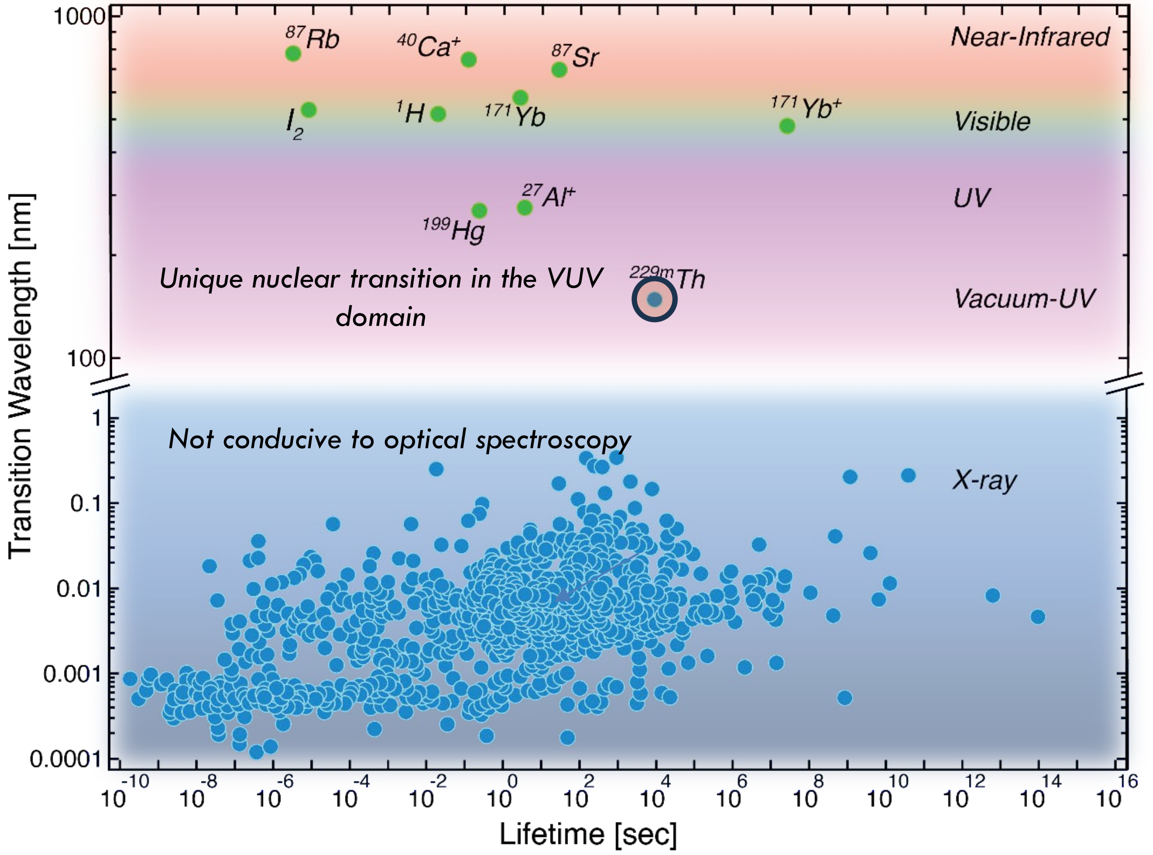
- ❑ Need ultrahigh vacuum for isolation from background gases
- ❑ Need laser cooling and all-optical trapping techniques
- ❑ Low atom number (~10^4 atoms)
- ❑ Need quantum many-body effects to mitigate atomic collisions

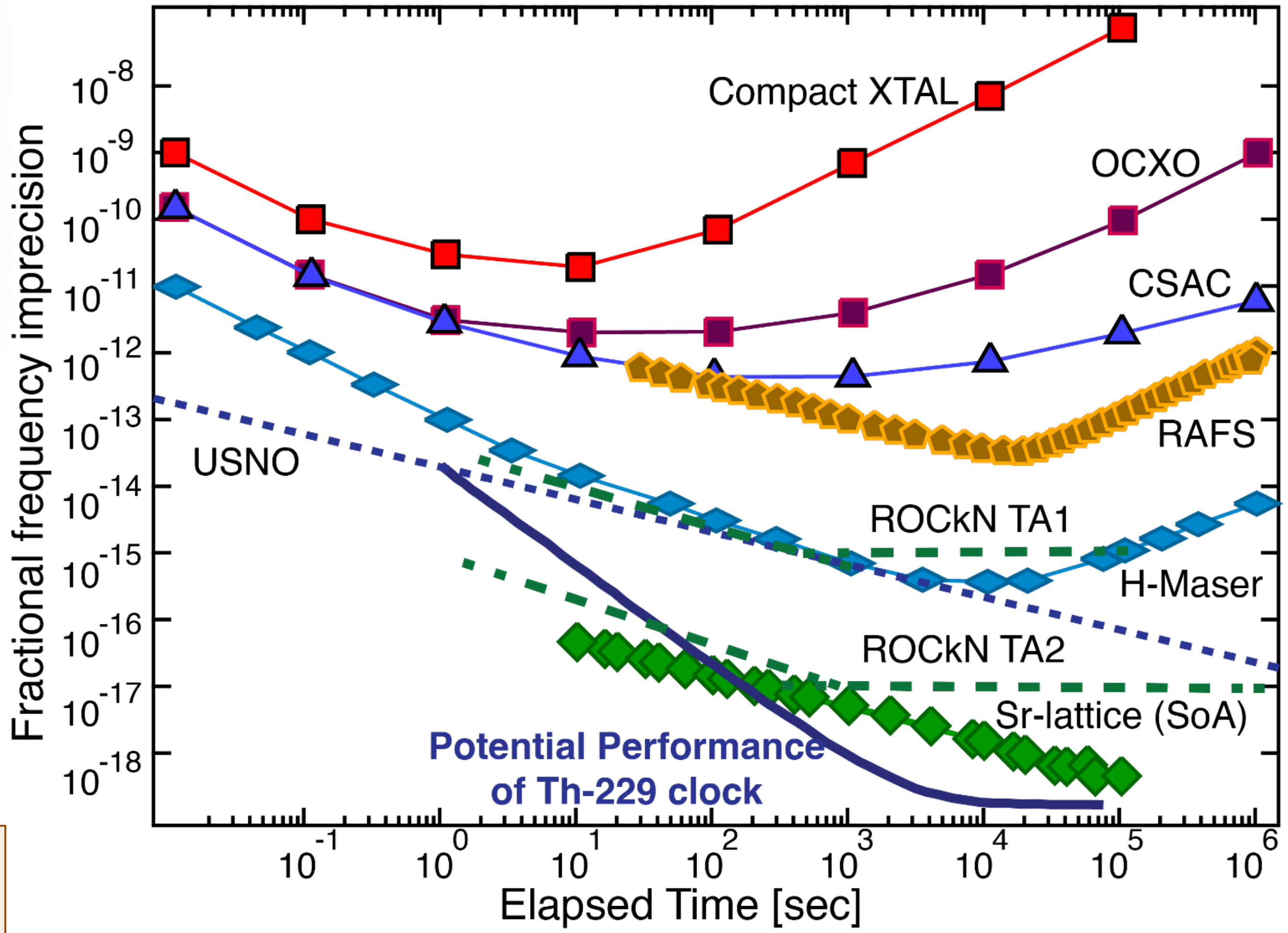


Current quantum state preparation techniques are incapable of combining large atom numbers, high levels of isolation and low SWaP

A new path towards compact, high-performance clocks

- The nucleus of large atoms is naturally isolated from the environment due to the presence of the surrounding electron cloud
- Nuclear transitions are extremely resilient to most perturbations due to 'nature-provided isolation'
- However, in most cases the nuclear transitions are at very high energies – not conducive to optical interrogation or time-transfer techniques



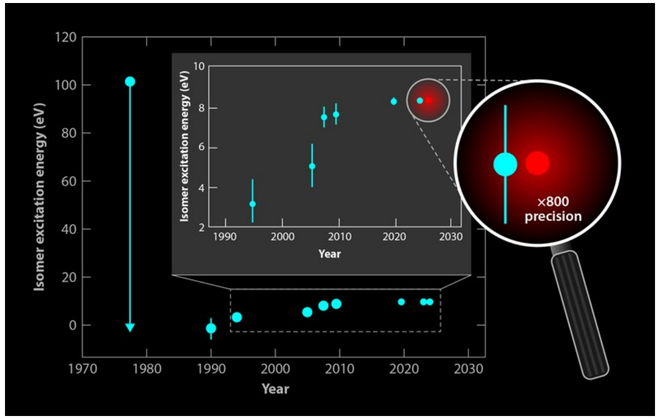


... except the Th-229 nuclear isomeric transition

- ✓ This transition was long predicted to be in the VUV range and uniquely conducive to ultrastable, low-SWaP clock operation

Preliminary spectroscopic measurements

Following decades of search, a long-lived VUV transition of Th-229 was finally measured precisely at 148.382 nm
Absolute frequency comparisons of the clock transition validates several predictions of potential clock performance (albeit at limited spectroscopic resolution)



Dawn of a nuclear clock: frequency ratio of the ^{229m}Th isomeric transition and the ^{87}Sr atomic clock

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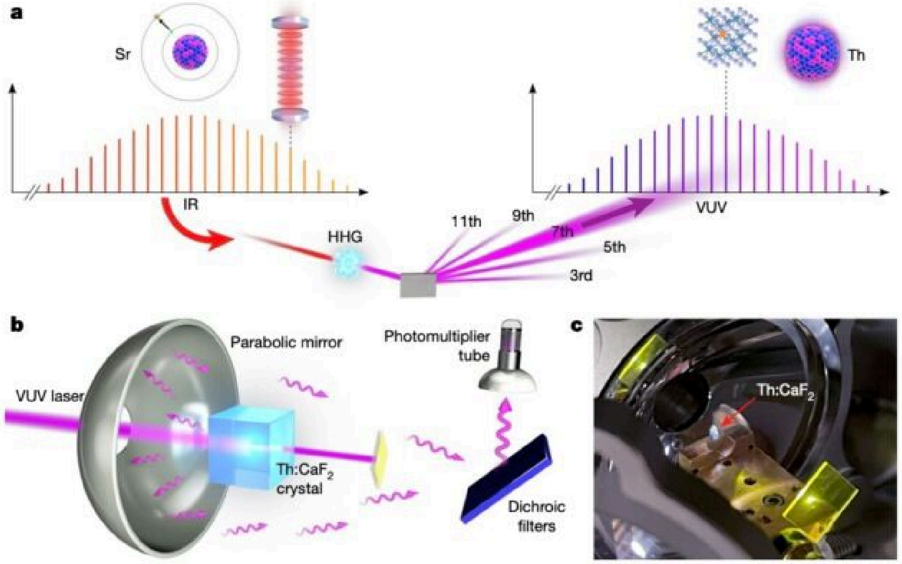
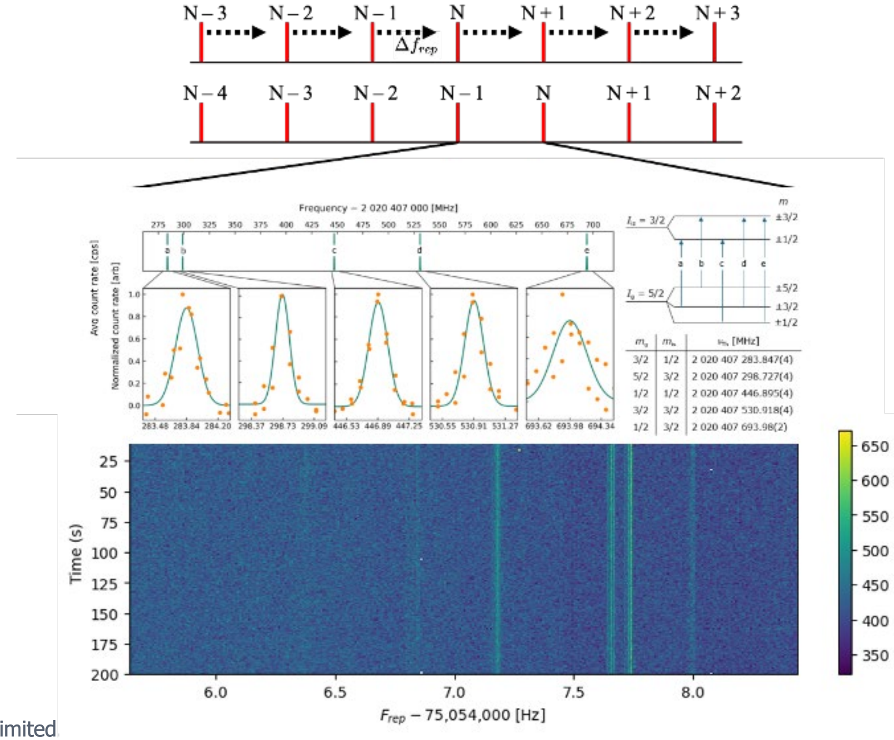
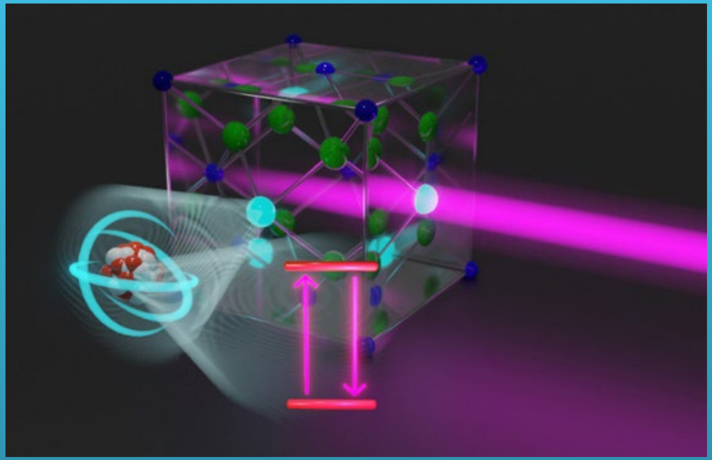




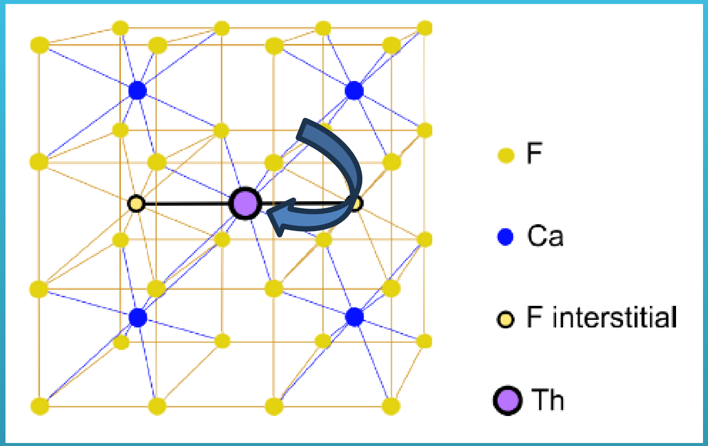
Open Questions

Several open questions remain before an all solid-state nuclear clock can be developed

What is the effect of the crystal host on the clock transition?



What is the requisite environmental stability to realize a solid-state clock?



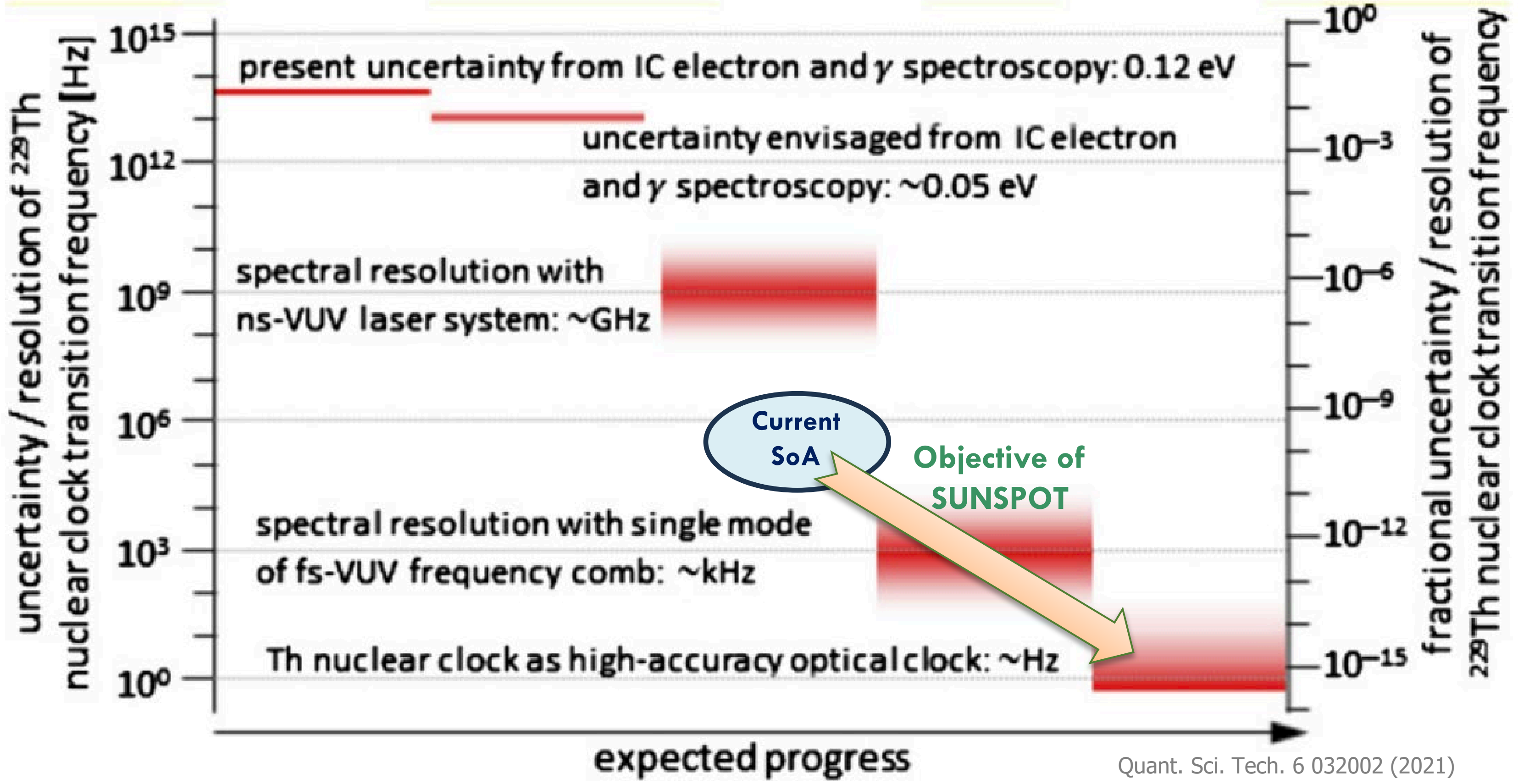
What is the effect of weak electron-nuclear interactions on the clock transition?

Other questions relevant to clock operation include

- Crystal-specific shifts and line-broadening effects on the clock transition
- Optimal interrogation and stabilization protocols for an eventual clock
- Development of techniques to enable frequency comb locking, synchronization, and time sharing

These questions require high resolution spectroscopic measurements and improved modeling of the nuclear clock transition.
Current measurements are severely limited by the lack of appropriate VUV lasers with the required coherence/linewidth and power at the clock transition

Objective of the SUNSPOT program



Quant. Sci. Tech. 6 032002 (2021)

The proposed VUV sources should enable high-resolution spectroscopic studies to

- Quantify effects of crystal host and lattice structure on the clock frequency
- Quantify systematic shifts and uncertainties to validate potential operation at the predicted levels of performance
- Investigate more optimal clock interrogation protocols for continuous and accurate measurement of the clock transition

VUV: Vacuum Ultra-Violet

What is in scope of the SUNSPOT program?

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- The primary focus of SUNSPOT is the development of high coherence VUV sources for Thorium spectroscopy.
- While proposers should keep the program objective (quantification of clock-related systematic and statistical errors; assessment of potential Th-based nuclear clock performance) in mind, proposers need not include these objectives as part of their proposed statement of work.
- It is anticipated that DARPA will arrange for the proposed VUV sources to be calibrated and tested against appropriate Th-doped crystals. However, proposers are also encouraged to suggest potential collaborators who can aid in the spectroscopic evaluation of their VUV sources.

What is NOT in scope of the SUNSPOT program?

- Thorium spectroscopy with existing VUV laser sources
- Exploration of crystal growth, doping, synthesis for Thorium hosts
- Clock concepts based on laser cooled atomic or ionic Thorium
- Modeling and analysis of Thorium clock systematics
- Explorations of novel non-linear optical materials for VUV generation

The SUNSPOT program metrics

VUV source parameter	Program Metric
Avg. Output power (at ^{229m}Th transition wavelength of 148.382 nm)	> 1μW
Linewidth	< 30 Hz

- These metrics were obtained based on projected spectroscopic resolution comparable to estimates of the crystal-induced decoherence rate ($\gamma_{coh} \sim 2\pi$ (150 Hz)), an excitation rate of ~50 Γ_{rad}, and a fractional frequency instability in the $10^{-16} – 10^{-17}$ range over 1 hour of measurement.

- Size, Weight, and Power (SWaP) metrics are not included in the SUNSPOT program metrics. However, proposers should include an analysis of the projected SWaP of the proposed laser source, and a discussion of how future systems-level integration may reduce the SWaP to enable compact, portable VUV sources.

Guidelines for a successful proposal

- **Read the BAA**
- **Understand DARPA's objectives for this program**
- **If there is reasonable doubt that your proposed effort may not be in scope of SUNSPOT, reach out to us for clarification before investing effort into the proposal**
- **Required attachments, budgets, cost proposals etc are NOT placeholders**

Required technical discussion

- A description of the proposed approach, the required research and development efforts, and a description of what will be developed and demonstrated during the period of the program. This description should be accompanied by a schedule of tasks and milestones that will be accomplished during the period of performance.
- Substantiation of the proposed VUV source and a detailed justification based on theoretical analysis, modeling, and proof-of-concept data (as applicable) that the proposed source can meet the program metrics.
- An identification of risks associated with the fabrication, development, and demonstration of the proposed VUV source in meeting program metrics. Risk mitigation strategies must be adequately described with clear statements of how the proposed research plan addresses the dominant risks early in the program.

Proposal Evaluation Criteria (See Section II of BAA)

- **Overall Scientific and Technical Merit**: The proposed technical approach is innovative, feasible, achievable, and complete. The proposed technical team has the expertise and experience to accomplish the proposed tasks. Task descriptions and associated technical elements provided are complete and in a logical sequence with all proposed deliverables clearly defined such that a final outcome that achieves the goal can be expected as a result of award. The proposal identifies major technical risks and planned mitigation efforts are clearly defined and feasible.
- **Potential Contribution and Relevance to the DARPA Mission**: The potential contributions of the proposed effort bolster the national security technology base and support DARPA's mission to make pivotal early technology investments that create or prevent technological surprise.
- **Cost and Schedule Realism**: The proposed costs are realistic for the technical and management approach and accurately reflect the technical goals and objectives of the solicitation. The proposed costs are consistent with the proposer's Statement of Work and reflect a sufficient understanding of the costs and level of effort needed to successfully accomplish the proposed technical approach. The costs for the prime proposer and proposed sub-awardees are substantiated by the details provided in the proposal (e.g., the type and number of labor hours proposed per task, the types and quantities of materials, equipment and fabrication costs, travel and any other applicable costs and the basis for the estimates). It is expected that the effort will leverage all available relevant prior research in order to obtain the maximum benefit from the available funding. For efforts with a likelihood of commercial application, appropriate direct cost sharing may be a positive factor in the evaluation. DARPA recognizes that undue emphasis on cost may motivate proposers to offer low-risk ideas with minimum uncertainty and to staff the effort with junior personnel in order to be in a more competitive posture. DARPA discourages such cost strategies.

Schedule and Deliverables

- The SUNSPOT program is a 24-month effort. Proposers may assume a target start date of September 2025 for planning purposes.
- Proposers should specify the research and technology development schedule for the full period of performance. The Statement of Work (SoW) must provide a detailed task breakdown, citing specific tasks and their connection to interim milestones and metrics, as applicable. Proposers should provide a technical and programmatic strategy conforming to the entire program schedule and present an aggressive plan to fully address all program goals, metrics, milestones, and deliverables. The task structure must be consistent across the proposed schedule, SoW, and cost volume.

Deliverables:

- Comprehensive quarterly technical reports due within ten days of the end of the given quarter, describing progress made on the specific milestones as laid out in the SOW.
- A phase completion report submitted within 30 days of the end of each phase, summarizing the research done.
- Other negotiated deliverables specific to the objectives of the individual efforts. These may include registered reports; experimental protocols; publications; data management plan; intermediate and final versions of software libraries, code, and APIs, including documentation and user manuals; and/or a comprehensive assemblage of design documents, models, modeling data and results, and model validation data.
- Performers will be required to arrange for their VUV sources to be tested by DARPA's government team to ensure that program metrics are satisfied.

Important Dates

- **Posting Date (PD):** January 27, 2025
- **Proposers Day:** February 07, 2025
- **FAQ Submission Deadline:** March 03, 2025
- **Full Proposal Due Date:** March 13, 2025