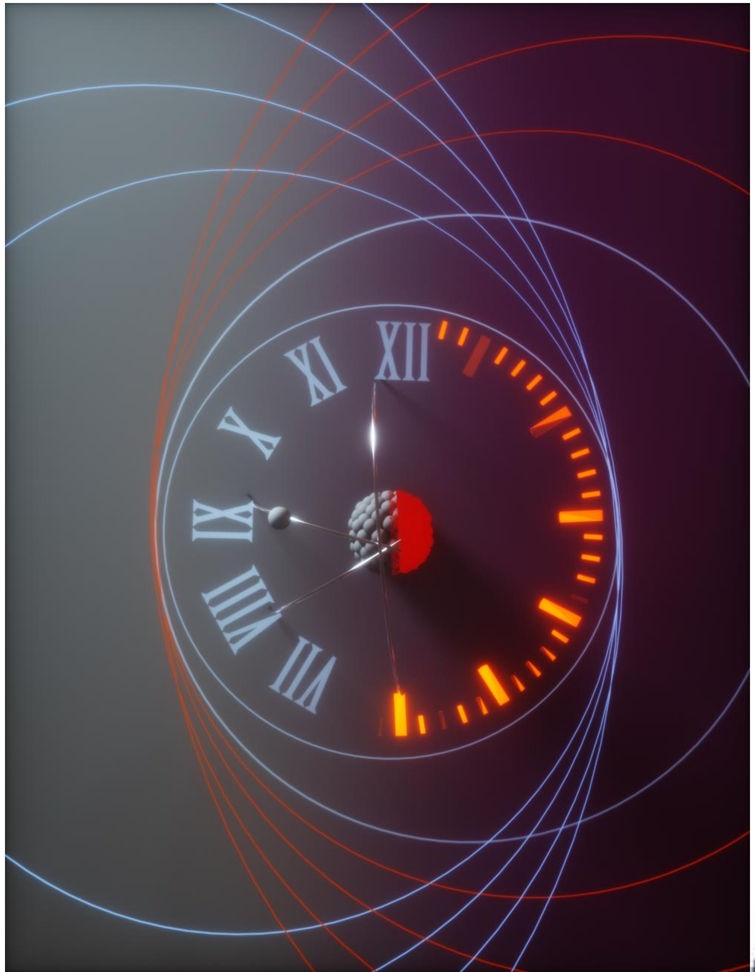
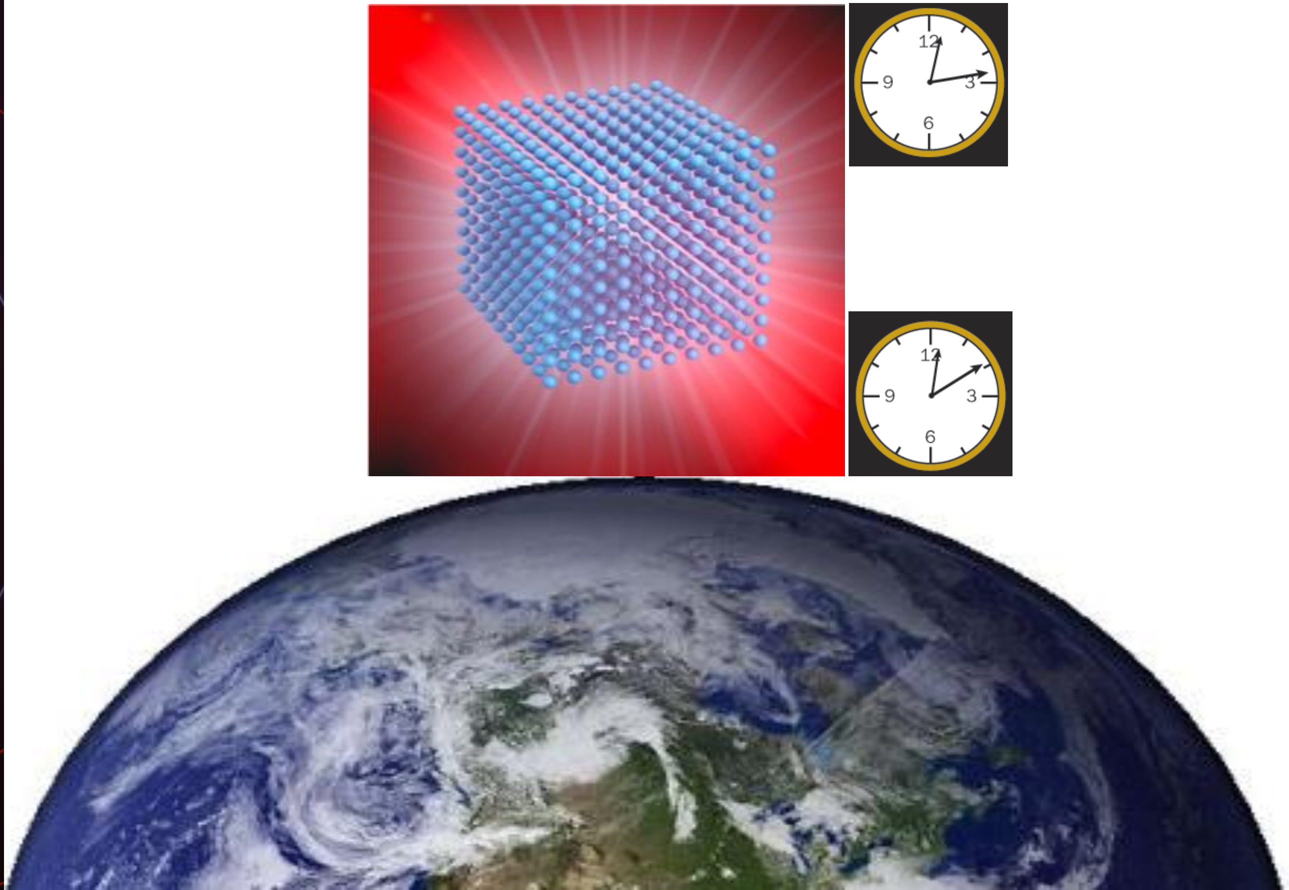
# Nuclear clock: scale up quantum systems for time

Jun Ye

JILA, NIST & Univ. Colorado

CAMOS Meeting, NAS, October 11, 2024



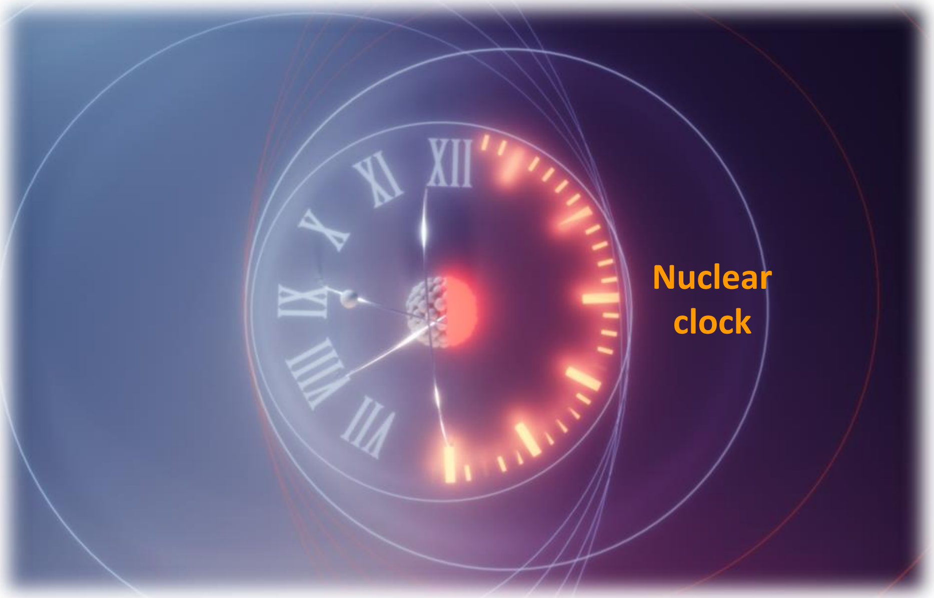


# Fusion of physics

Precision laser metrology

Nuclear and fundamental physics

Ultrafast science



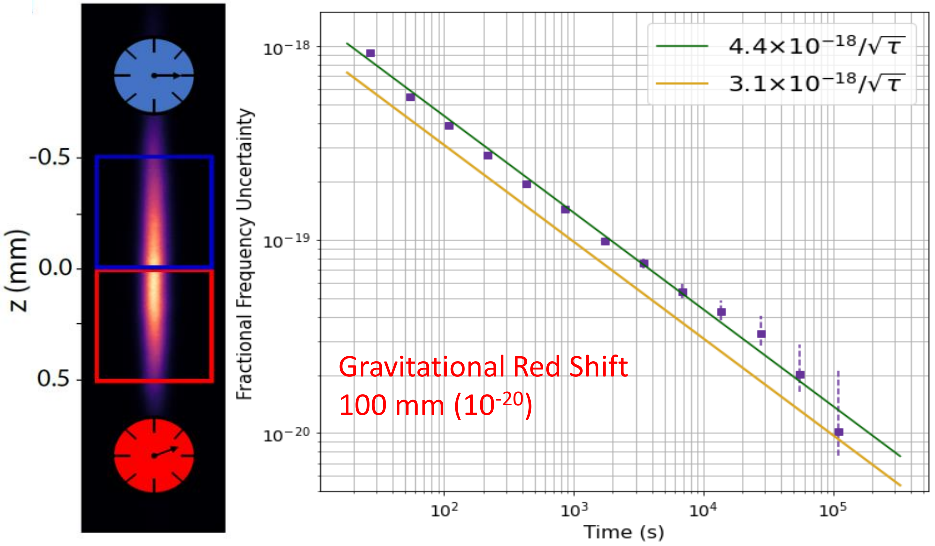

Scalable production & photonics integration

# Advancing atomic clocks

## Precision

Bothwell…Ye, Nature (2022)

Zheng… Kolkowiz, Nature (2022).




## Accuracy

Brewer…Wineland, Hume, Leibrandt, PRL (2019)

Aeppli…Ye, Phys. Rev. Lett. (2024)


PHYSICAL REVIEW LETTERS **133,** 023401 (2024)

Editors' Suggestion Featured in Physics


**Clock with $8\times10^{-19}$ Systematic Uncertainty**


Alexander Aeppli[1,*] Kyungtae Kim[1] William Warfield[1] Marianna S. Safronova[2] and Jun Ye[1,†]

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PHYSICAL REVIEW LETTERS **123,** 033201 (2019)

Editors' Suggestion Featured in Physics

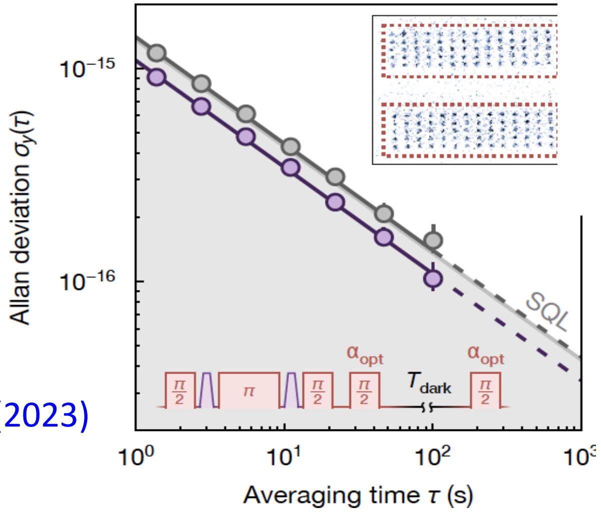

**$^{27}Al^{+}$ Quantum-Logic Clock with a Systematic Uncertainty below $10^{-18}$**


S. M. Brewer,[1,2,*] J.-S. Chen,[1,2,†] A. M. Hankin,[1,2,‡] E. R. Clements,[1,2] C. W. Chou,[1] D. J. Wineland,[1,2,3] D. B. Hume,[1] and D. R. Leibrandt[1,2,§]

[1] *Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA*

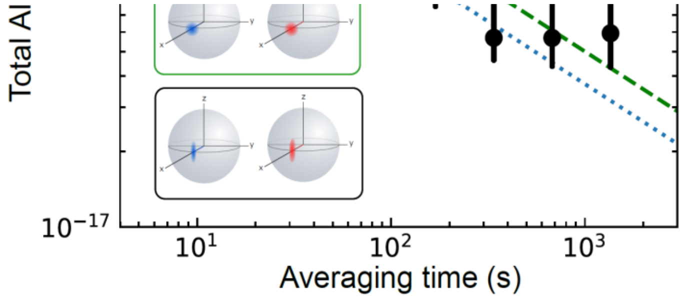
[2] *Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*

[3] *Department of Physics, University of Oregon, Eugene, Oregon 97403, USA*


Rydberg-squeezed clocks

Eckner…Ye, Kaufman, Nature (2023)

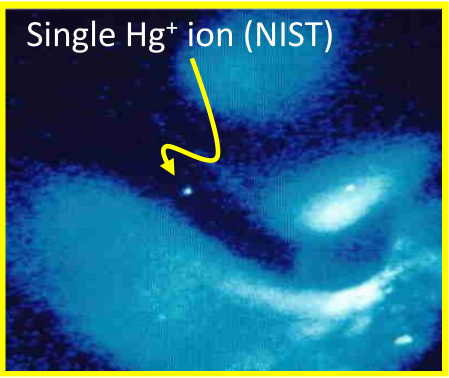



Entangled clock comparison

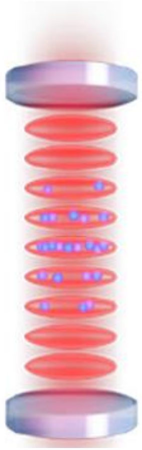
Robinson…Thompson, Ye, Nature Phys. (2024)

# Number scaling

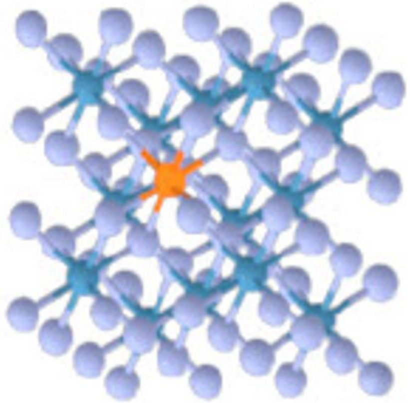
Doppler-free transition through motional state control:



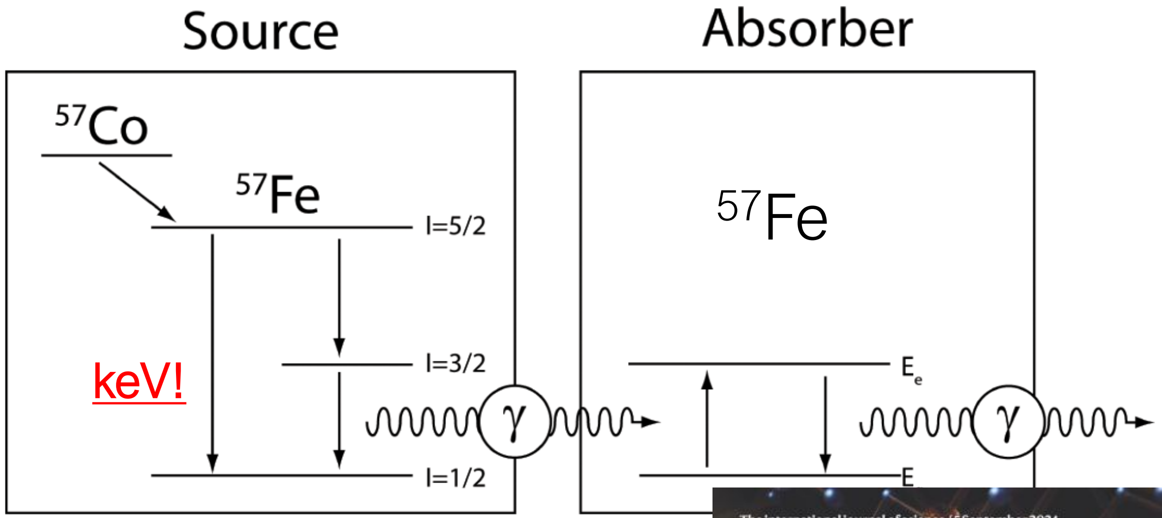

Atomic clocks
(coherent)



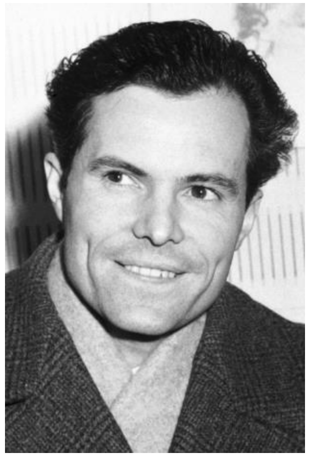
Mössbauer spectroscopy
(incoherent → coherent)



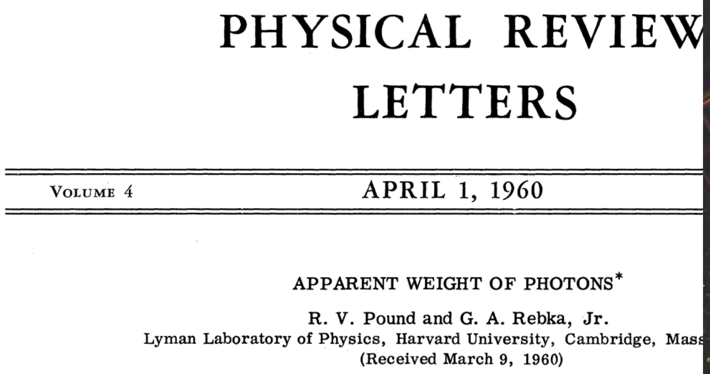
# Bring coherence to Mössbauer spectroscopy




Mössbauer spectroscopy
nuclear transitions



Gravitational red shift measured wit


PHYSICAL REVIEW
LETTERS

VOLUME 4 APRIL 1, 1960

APPARENT WEIGHT OF PHOTONS*

R. V. Pound and G. A. Rebka, Jr.
Lyman Laboratory of Physics, Harvard University, Cambridge, Mass
(Received March 9, 1960)

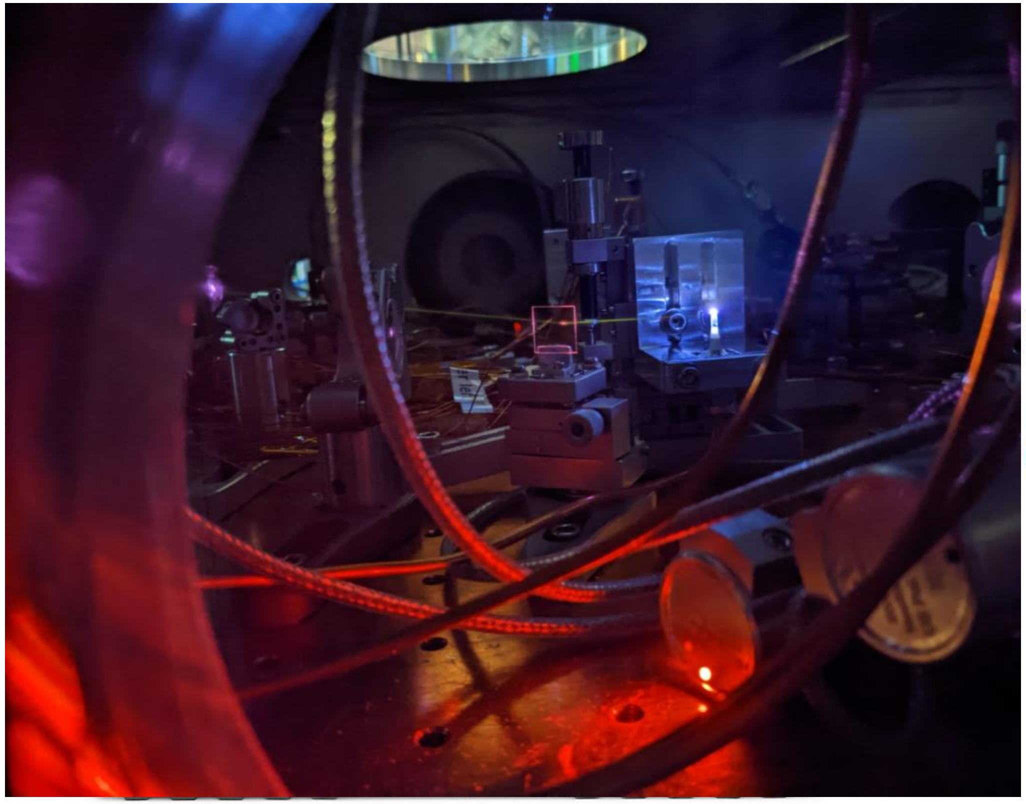

T. Bothwell et al., Nature **602** 420 (2022)
C. Zhang et al., Nature **633**, 63 (2024).

A nuclear-atomic connection

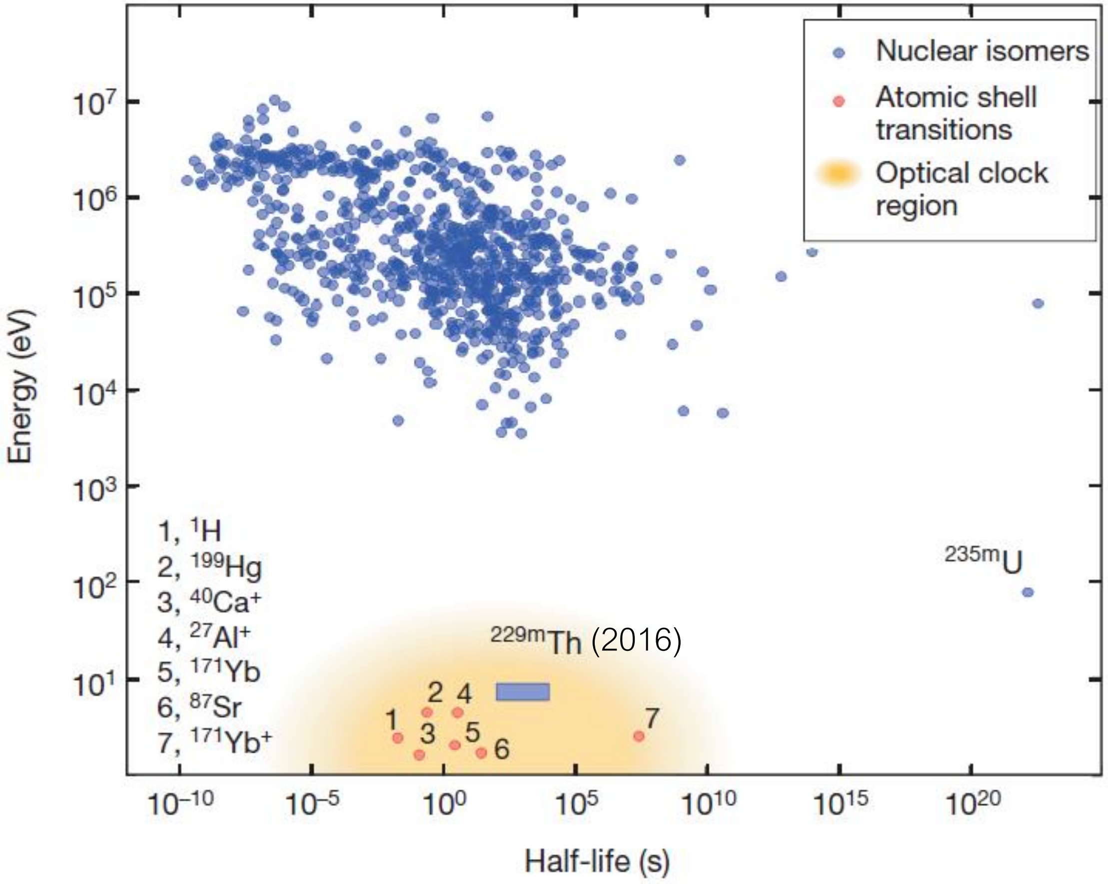
# Build a nuclear clock ?

E. Peik and C. Tamm, Europhys. Lett. **61,** 181 (2003)

Phase-coherent vacuum-ultraviolet frequency comb



Uniquely low energy transition in $^{229}$Th

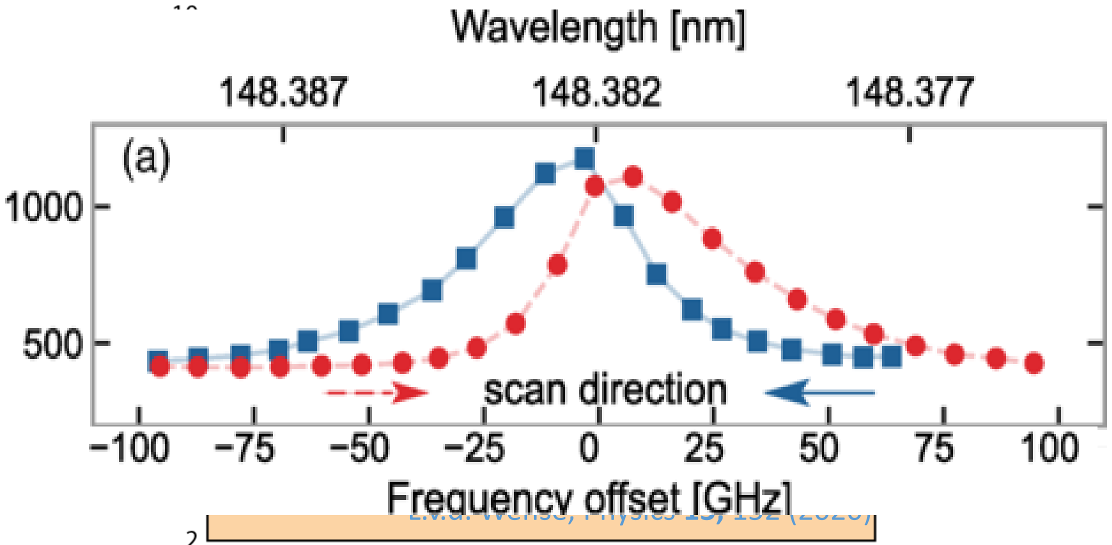



R. J. Jones *et al*., Phys. Rev. Lett. **94**, 193201 (2005)
C. Gohle *et al*., Nature **436**, 234 (2005)

L. v.d.Wense *et al*., Nature **533,** 47 (2016)

# $^{229m}$Th excitation

**Until last year…**



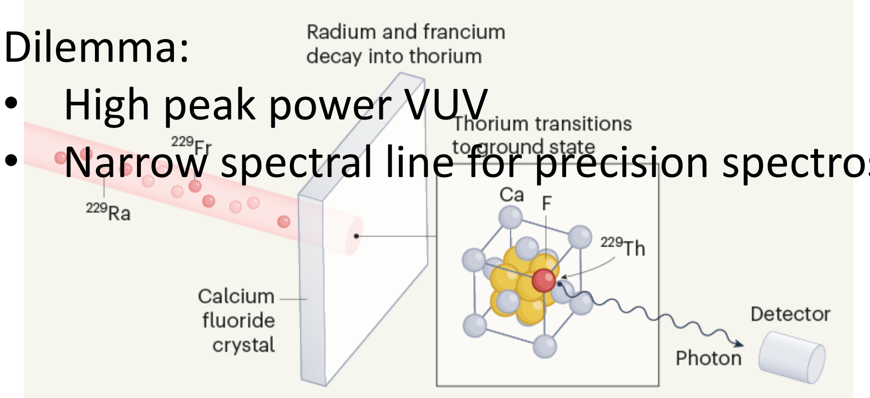

Experimental measurements

**First observation of radiative decay photons**

**148.71 ± 0.06 (stat.) ± 0.41 (syst.) nm**

Dilemma:

- High peak power VUV
- Narrow spectral line for precision spectroscopy




S. Kraemer et al., Nature **617,** 706 (2023)

**Broadband laser excitation of $^{229m}$Th**

PTB TU WIEN


PHYSICAL REVIEW LETTERS **132,** 182501 (2024)

Editors' Suggestion Featured in Physics


**148.3821(5) nm**

**Laser Excitation of the Th-229 Nucleus**


J. Tiedau,* M. V. Okhapkin,* K. Zhang,* J. Thielking, G. Zitzer, and E. Peik†
*Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany*

F. Schaden,* T. Pronebner, I. Morawetz, L. Toscani De Col, F. Schneider, A. Leitner, M. Pressler, G. A. Kazakov, K. Beeks, T. Sikorsky, and T. Schumm‡
*Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, 1020 Vienna, Austria*



(Received 5 February 2024; revised 12 March 2024; accepted 14 March 2024; published 29 April 2024)


UCLA

**148.38219(4)$_{stat}$(20)$_{svs}$ nm**


PHYSICAL REVIEW LETTERS **133,** 013201 (2024)

Editors' Suggestion Featured in Physics


**Laser Excitation of the $^{229}$Th Nuclear Isomeric Transition in a Solid-State Host**


R. Elwell,[1] Christian Schneider,[1] Justin Jeet,[1] J. E. S. Terhune,[1] H. W. T. Morgan,[2] A. N. Alexandrova,[2] H. B. Tran Tan,[3,4] Andrei Derevianko,[3] and Eric R. Hudson[1,5,6]
[1]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA*
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[3]*Department of Physics, University of Nevada, Reno, Nevada 89557, USA*
[4]*Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, New Mexico 87545, USA*
[5]*Challenge Institute for Quantum Computation, University of California Los Angeles, Los Angeles, California 90095, USA*
[6]*Center for Quantum Science and Engineering, University of California Los Angeles, Los Angeles, California 90095, USA*



(Received 22 March 2024; revised 19 April 2024; accepted 17 May 2024; published 2 July 2024)

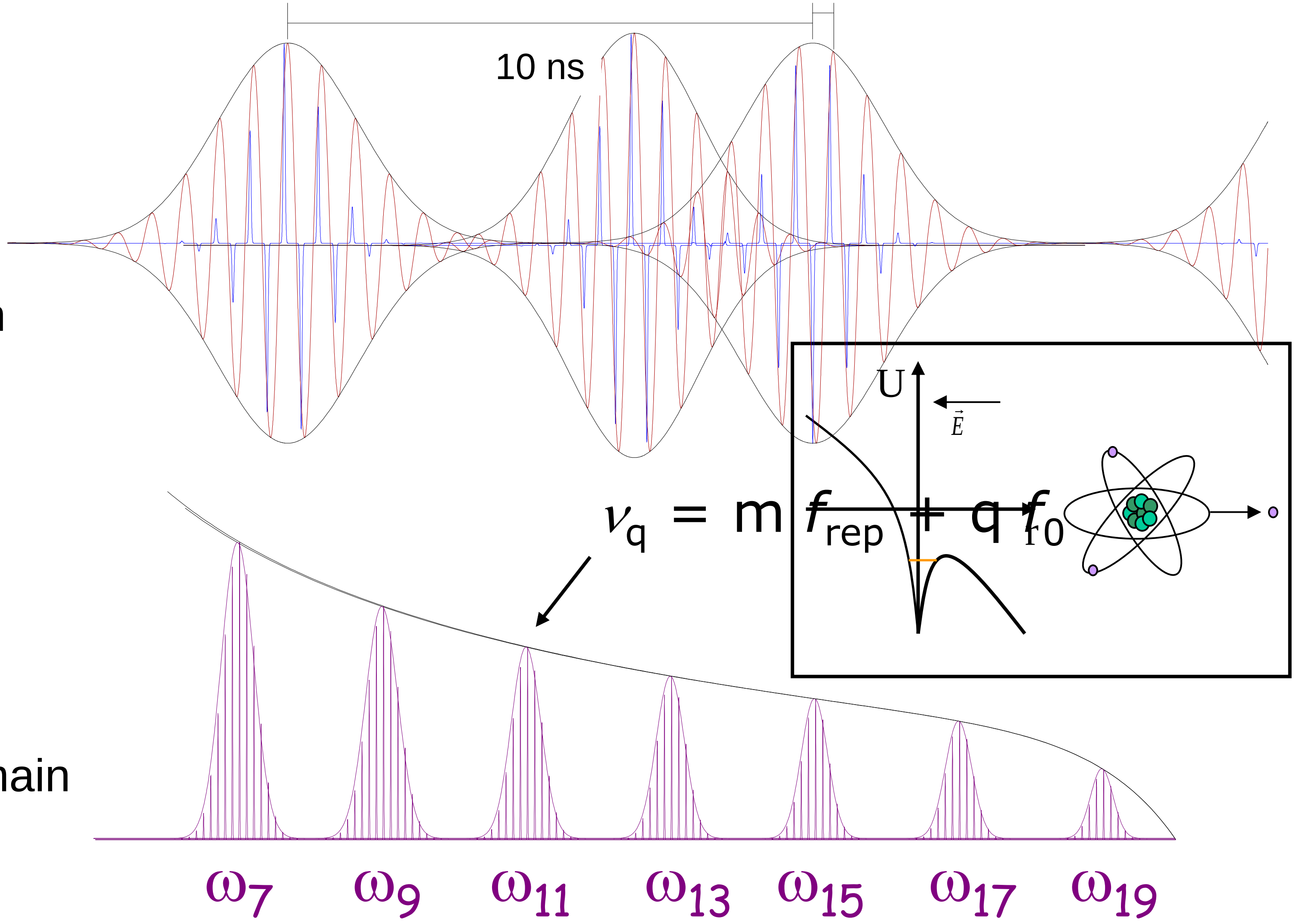
# Coherent VUV and XUV radiation

Harmonic Generation with a train of IR pulses → *train of attosecond pulses*

Harmonic Generation with a single IR pulse → *XUV attosecond pulse*

Time domain

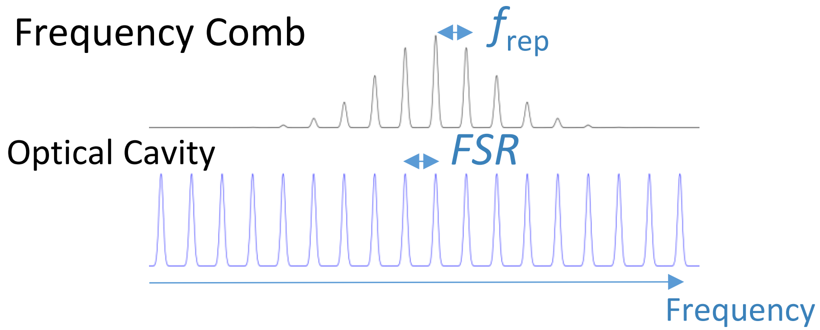
Frequency domain




$$\nu_q = m\, f_{rep} + q\, f_0$$

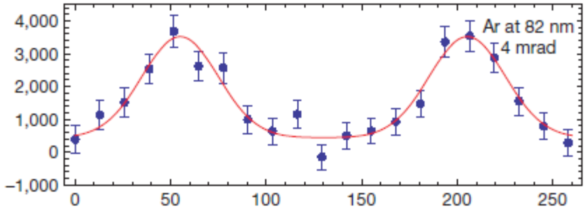
# 2 decades of development for XUV frequency comb

## Femtosecond enhancement cavity



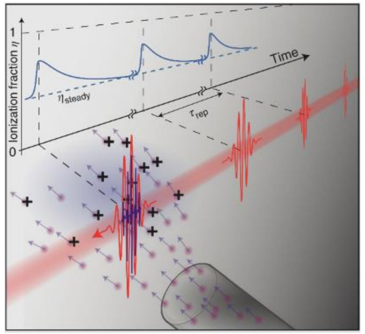

R. J. Jones & J. Ye, Opt. Lett. **27,** 1848 (2002)
R. J. Jones & J. Ye, Opt. Lett. **29,** 2812 (2004)

## XUV comb spectroscopy

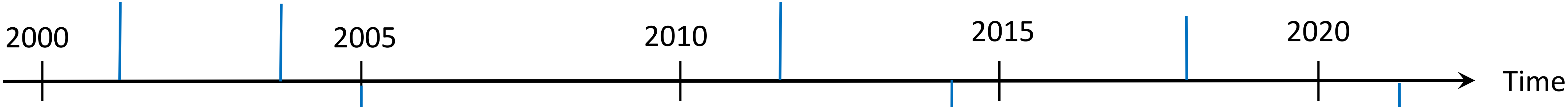



A. Cingöz et al., Nature **482**, 68 (2012)

## Phase-matched XUV comb generation

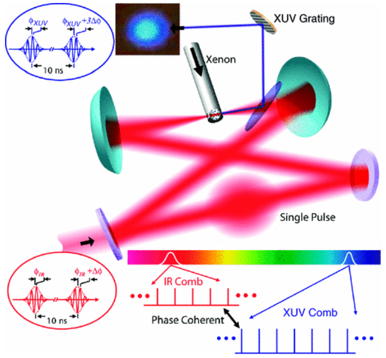



G. Porat et al., Nat. Photon. **12**, 387 (2018)



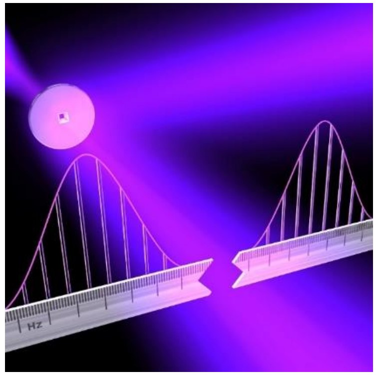

## XUV comb

~100 pW




R. J. Jones et al., Phys. Rev. Lett. **94**, 193201 (2005)
C. Gohle et al., Nature **436**, 234 (2005)

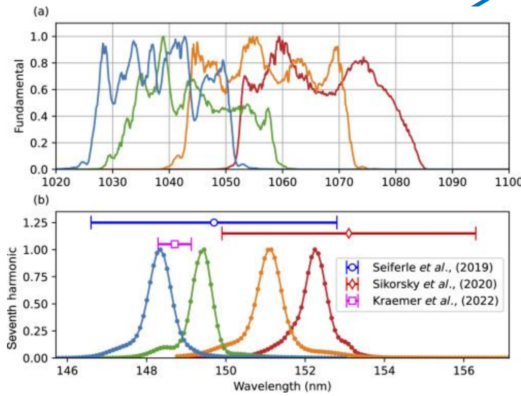
## Coherence times > 1s



C. Benko et al., Nat. Photon. **8**, 530 (2014)

## Tunable VUV comb

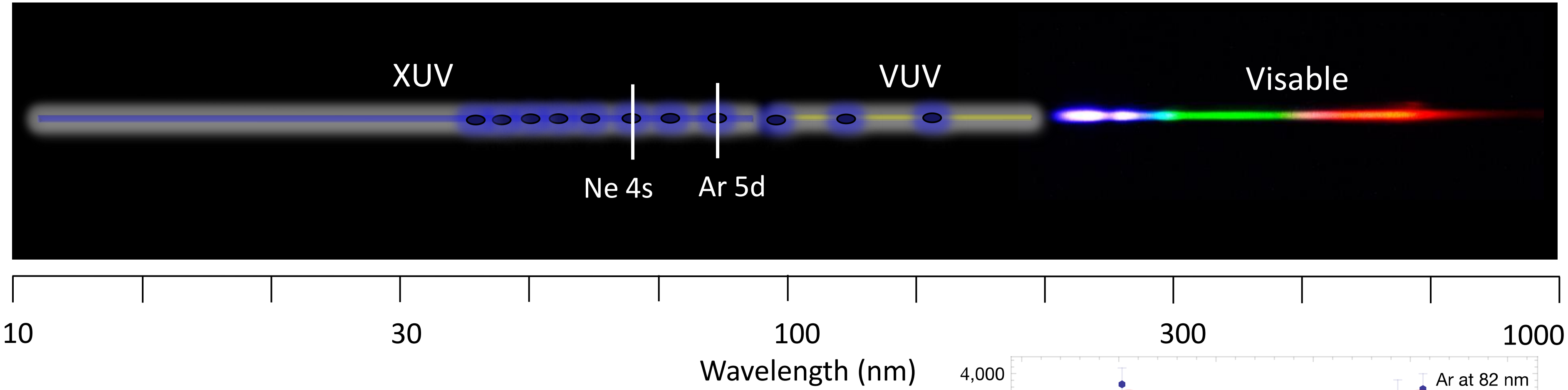
>1 mW

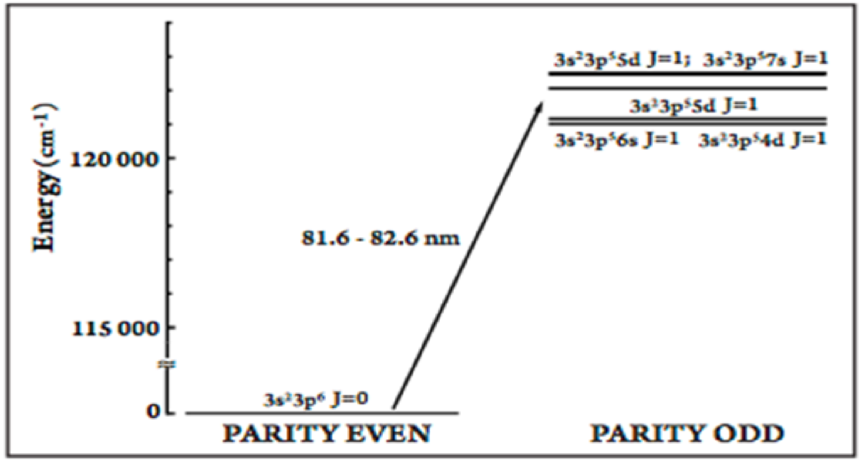



C. Zhang et al., Opt. Lett. **47**, 5591 (2022)

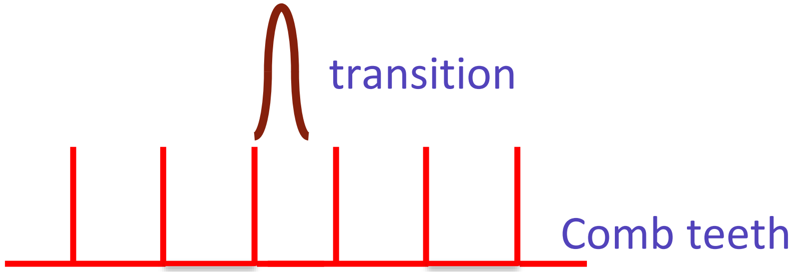
# XUV frequency comb spectroscopy

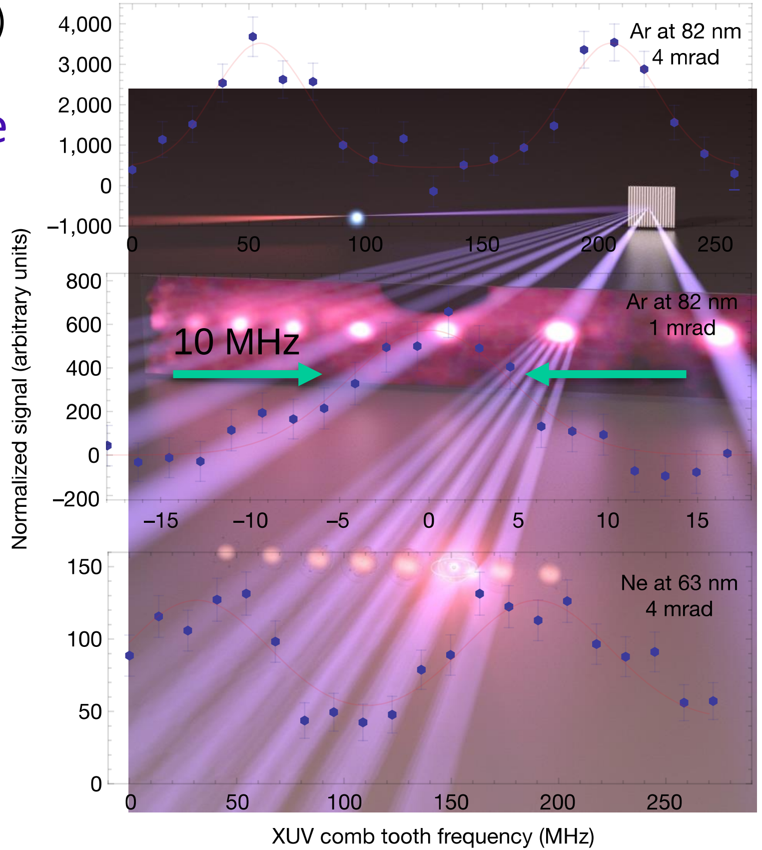
Cingöz, Yost … Ye, Nature **482**, 68 (2012).




resonance



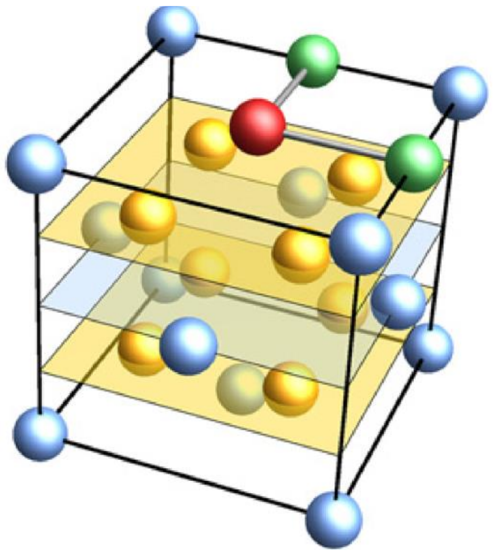




Ar at 82 nm

Ne at 63 nm

# Solid-state host: $^{229}\mathrm{Th{:}CaF_2}$

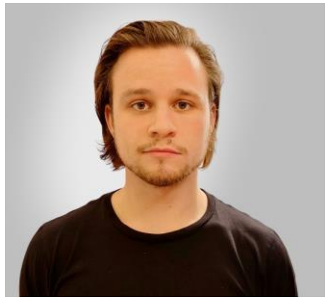
W.G. Rellergert *et al*., Phys. Rev. Lett. **104,** 200802 (2010)
G A Kazakov *et al*., New J. Phys. **14,** 083019 (2012)

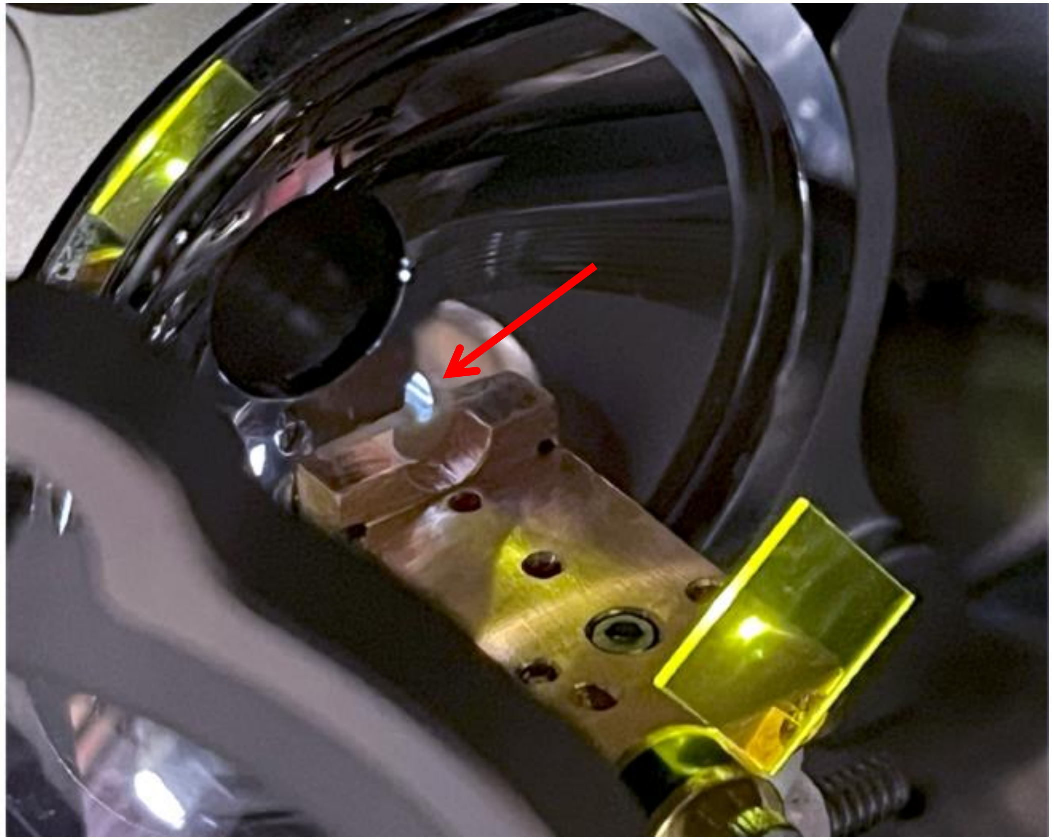


| Parameters | Values |
|---|---|
| Dimensions | 1.8×1.4×0.7 mm |
| Doping concentration | $4\times10^{18}/\mathrm{cm}^3$ |
| Transmission @150 nm | 45% |

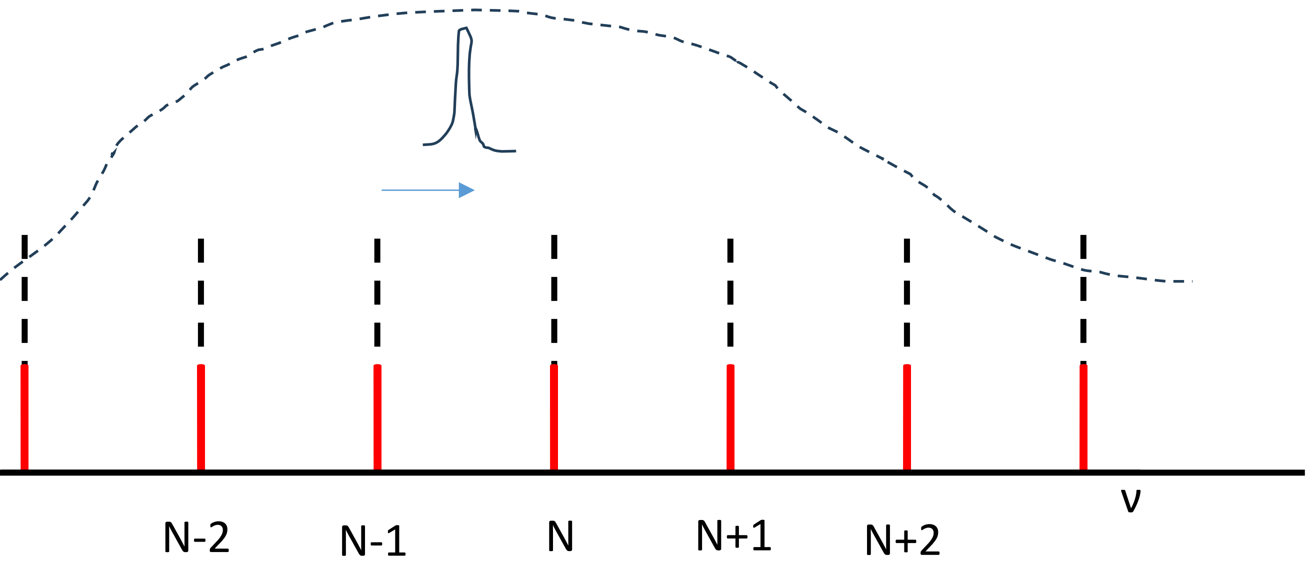
Thorsten Schumm

Kjeld Beeks

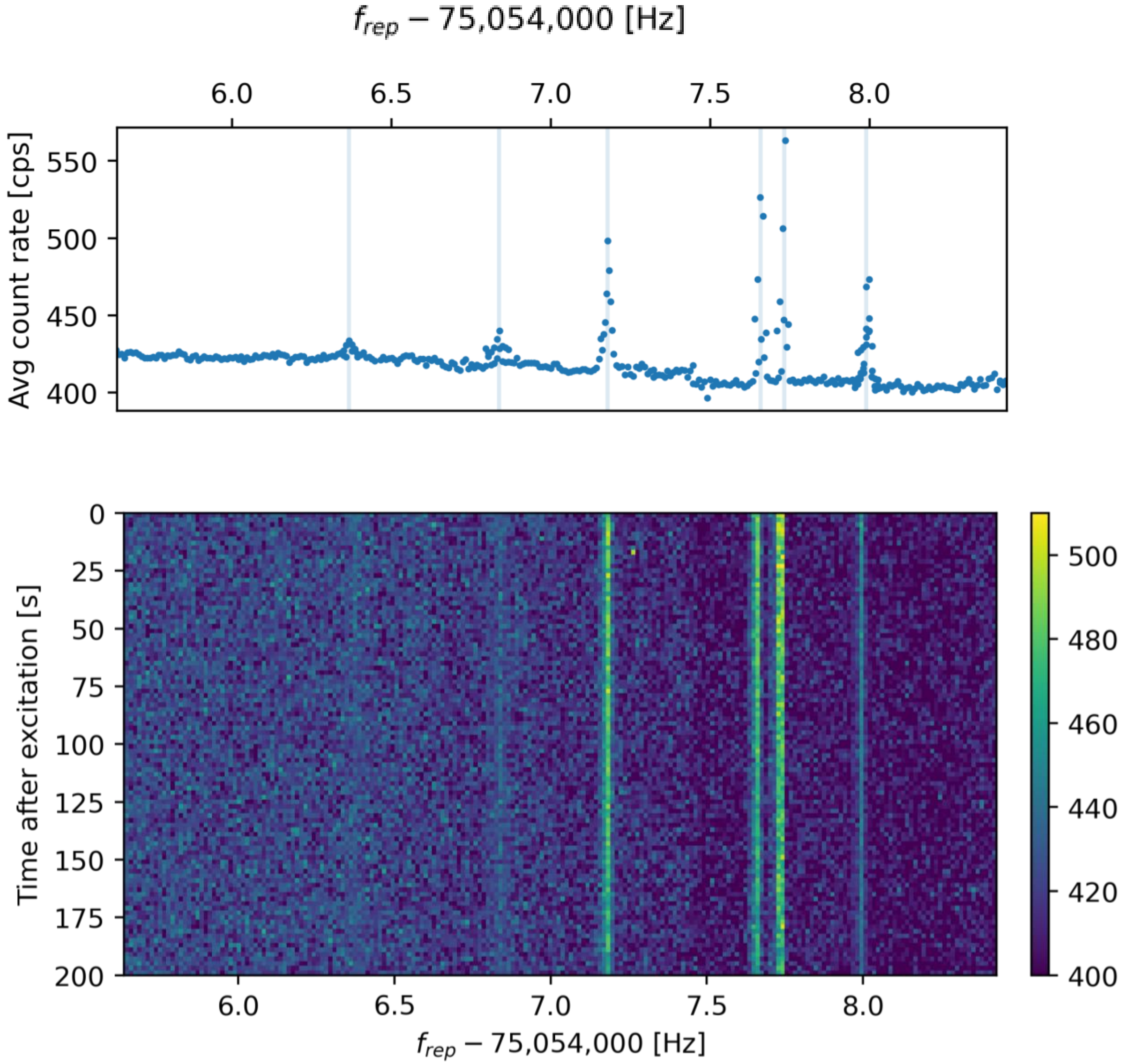


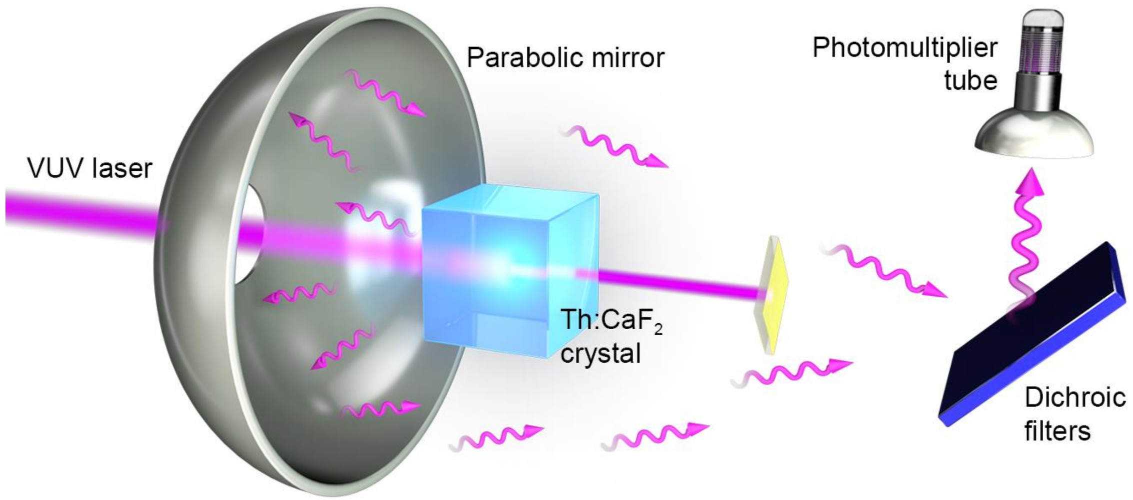


# Parallel scan of comb lines: precision + speed

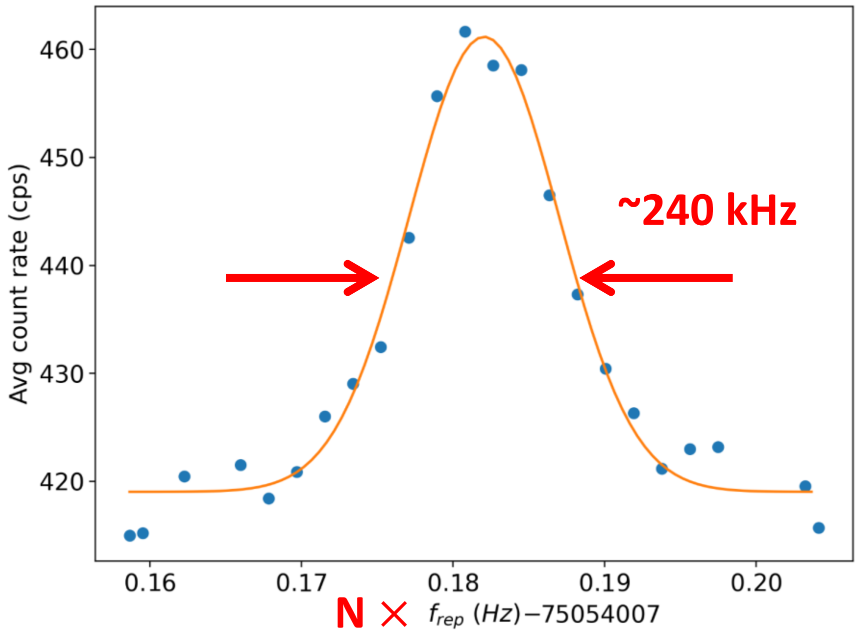


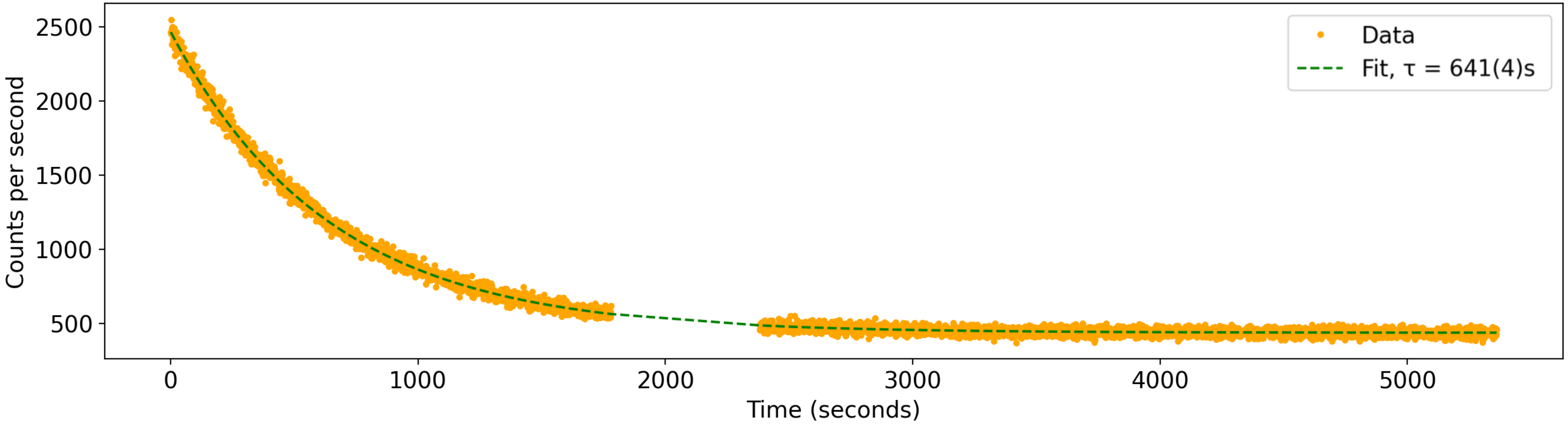

$$\nu_{\mathrm{comb}} = f_0 + N \times f_{\mathrm{rep}}$$



# High resolution line-shape and decay lifetime

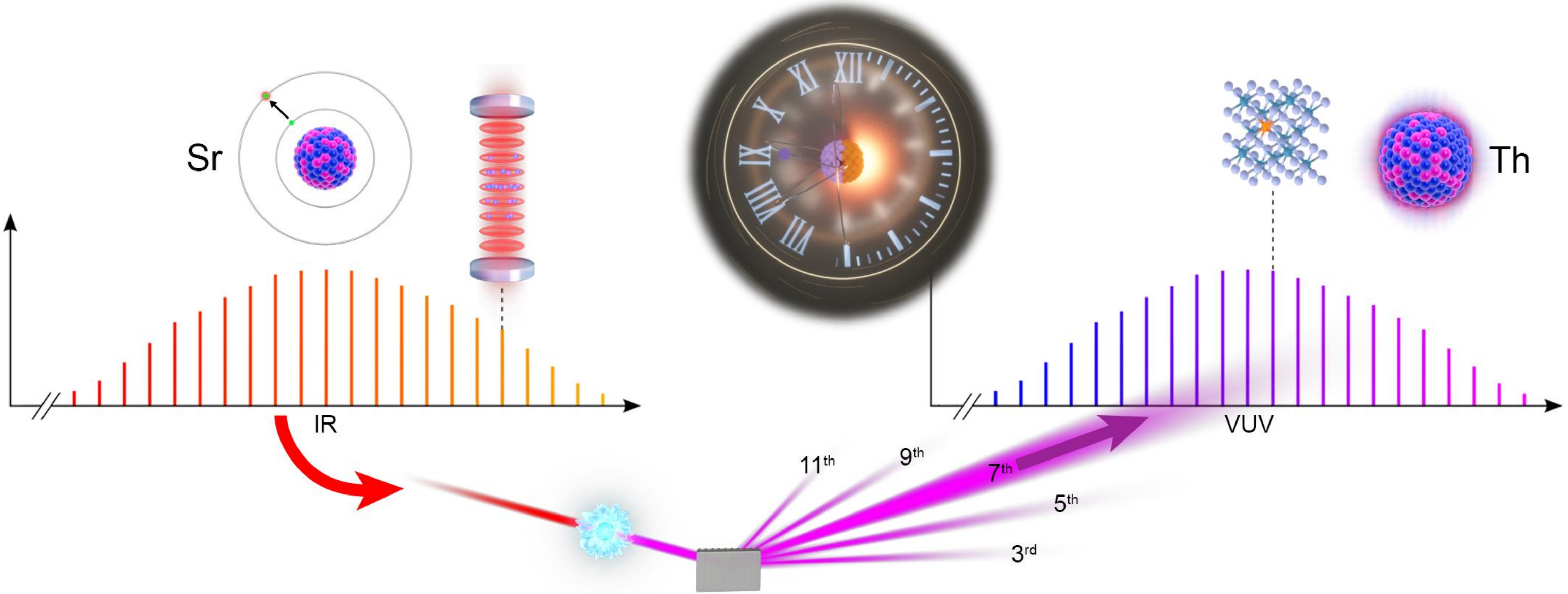


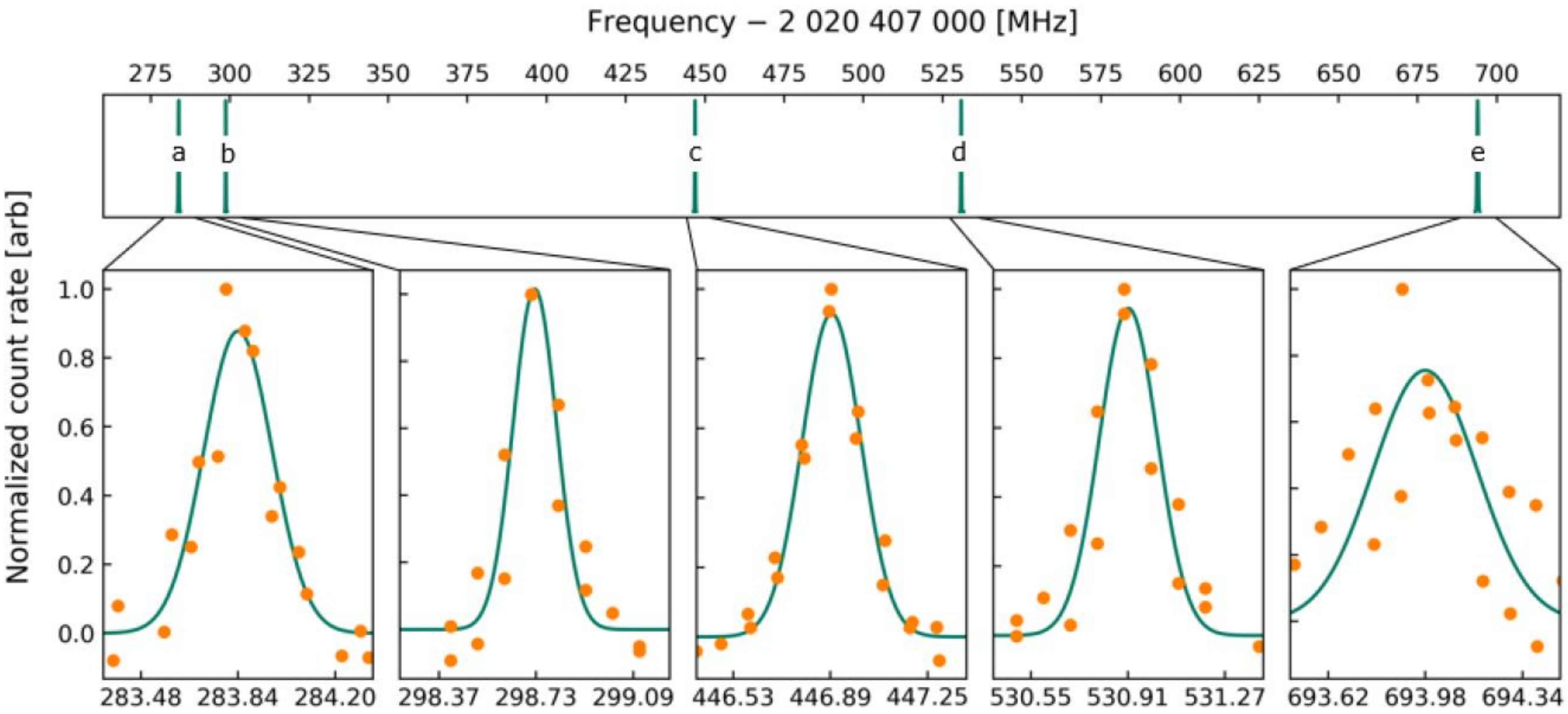
# Connecting $^{229m}$Th isomeric frequency to $^{87}$Sr atomic clock

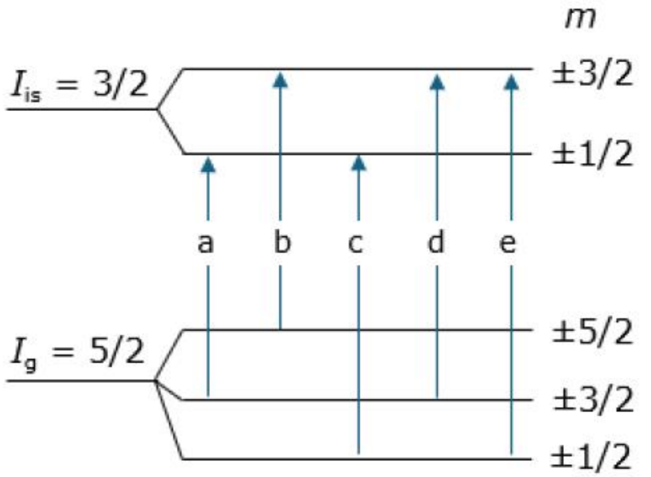
Zhang … Thirolf, Schumm, Ye, Nature **633**, 63 (Sept. 5, 2024).

$$\frac{\nu_{^{229}\mathrm{Th}}}{\nu_{^{87}\mathrm{Sr}}} = 4.707\,072\,615\,078(5)$$



# Quantum state resolved nuclear electric quadrupoles




| $m_g$ | $m_{is}$ | $\nu_{Th}$ [MHz] |
|---|---|---|
| 3/2 | 1/2 | 2 020 407 283.847(4) |
| 5/2 | 3/2 | 2 020 407 298.727(4) |
| 1/2 | 1/2 | 2 020 407 446.895(4) |
| 3/2 | 3/2 | 2 020 407 530.918(4) |
| 1/2 | 3/2 | 2 020 407 693.98(2) |

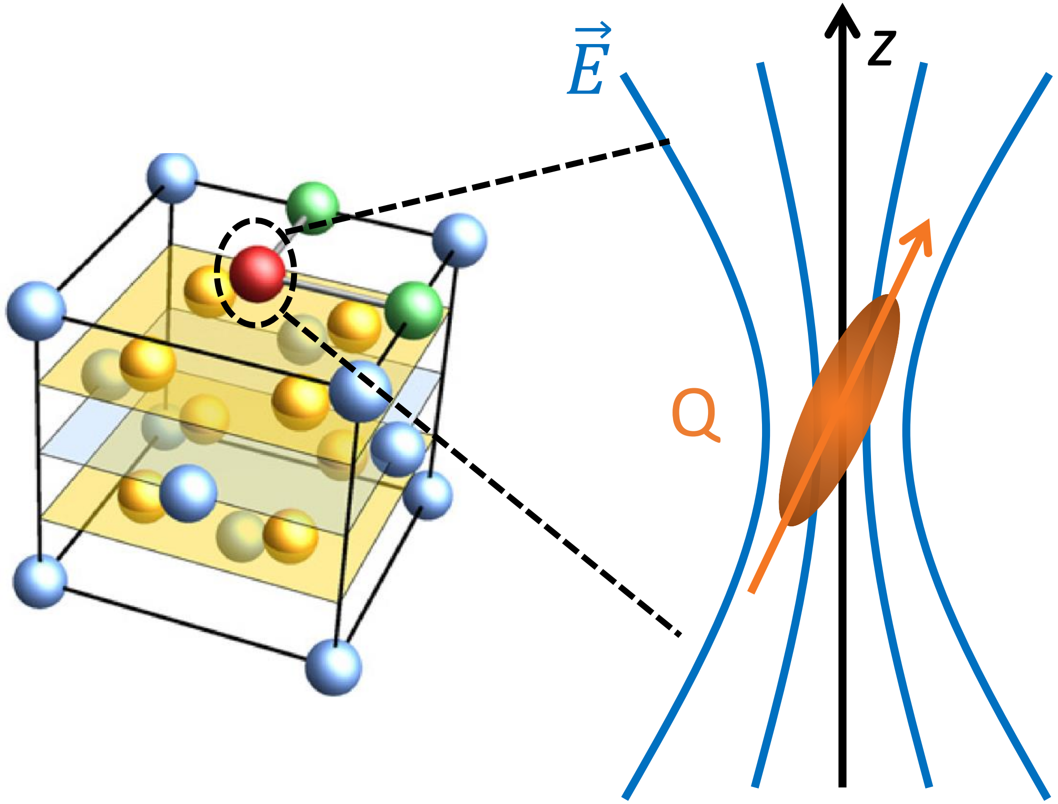
# Understanding of the quadrupole splitting

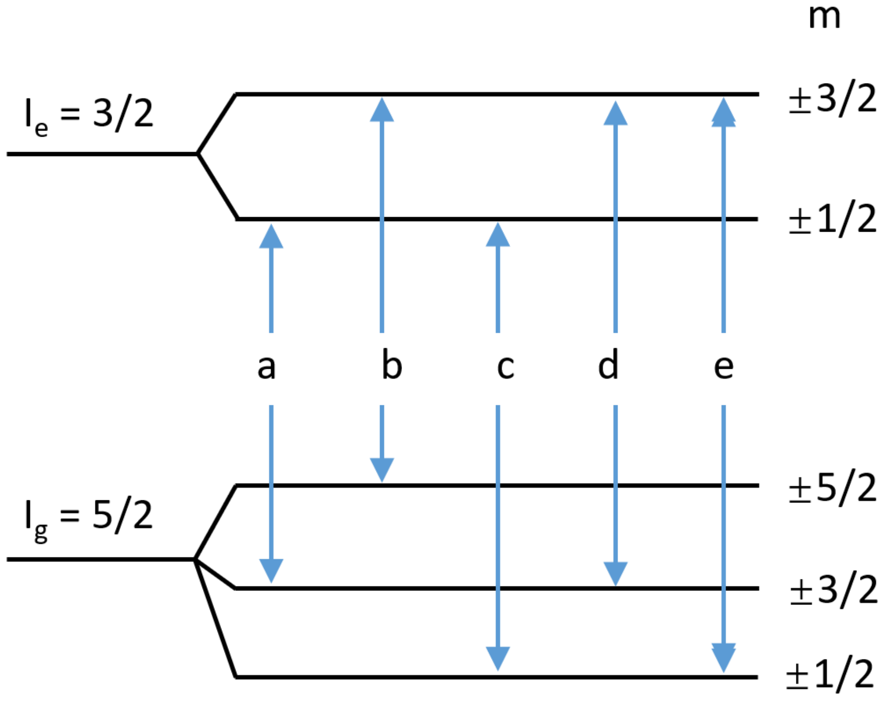
Nuclear quadrupole moment

$\nabla\vec{E}$ component

$\nabla\vec{E}$ asymmetry

$$H_{E2} = \frac{QV_{zz}}{4I(2I-1)}[3I_z^2 - \boldsymbol{I}^2 + \eta(I_x^2 - I_y^2)]$$

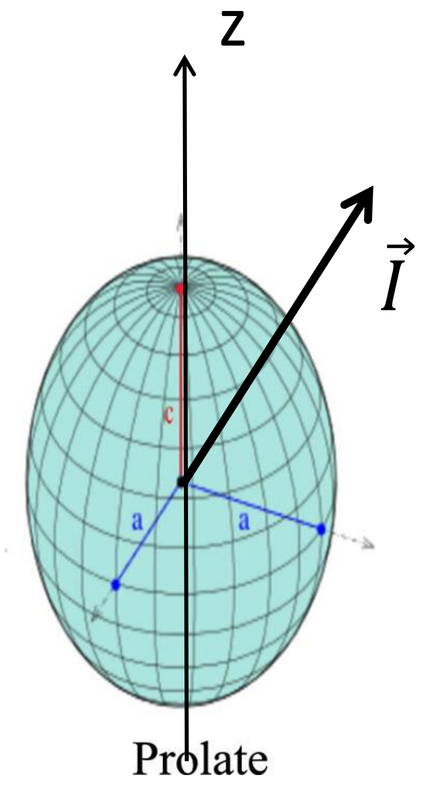



| Parameter | Value |
|---|---|
| $\eta$ | 0.59163(5) |
| $Q_{is}V_{zz}$ | 339.258(7) eb V/Å$^2$ |
| $Q_g V_{zz}$ | 193.387(5) eb V/Å$^2$ |
| $Q_{is}/Q_g$ | 0.57003(1) |

# New insight to nuclear structure

Beeks … Ye, Safronova, Schumm, arXiv:2407.17300 (2024).




**Lab frame** → **Body-fixed frame**

$$\frac{Q_{is}}{Q_g} = 0.57003(1) \Rightarrow \frac{Q_{\mathrm{is},0}}{Q_{\mathrm{g},0}} = 1.01791(2)$$

Nuclear volume: $\frac{V_{is}}{V_g} = 1.00055$

PHYSICAL REVIEW VOLUME 121, NUMBER 4 FEBRUARY 15, 1961

**Liquid-Drop Nuclear Model with High Angular Momentum***

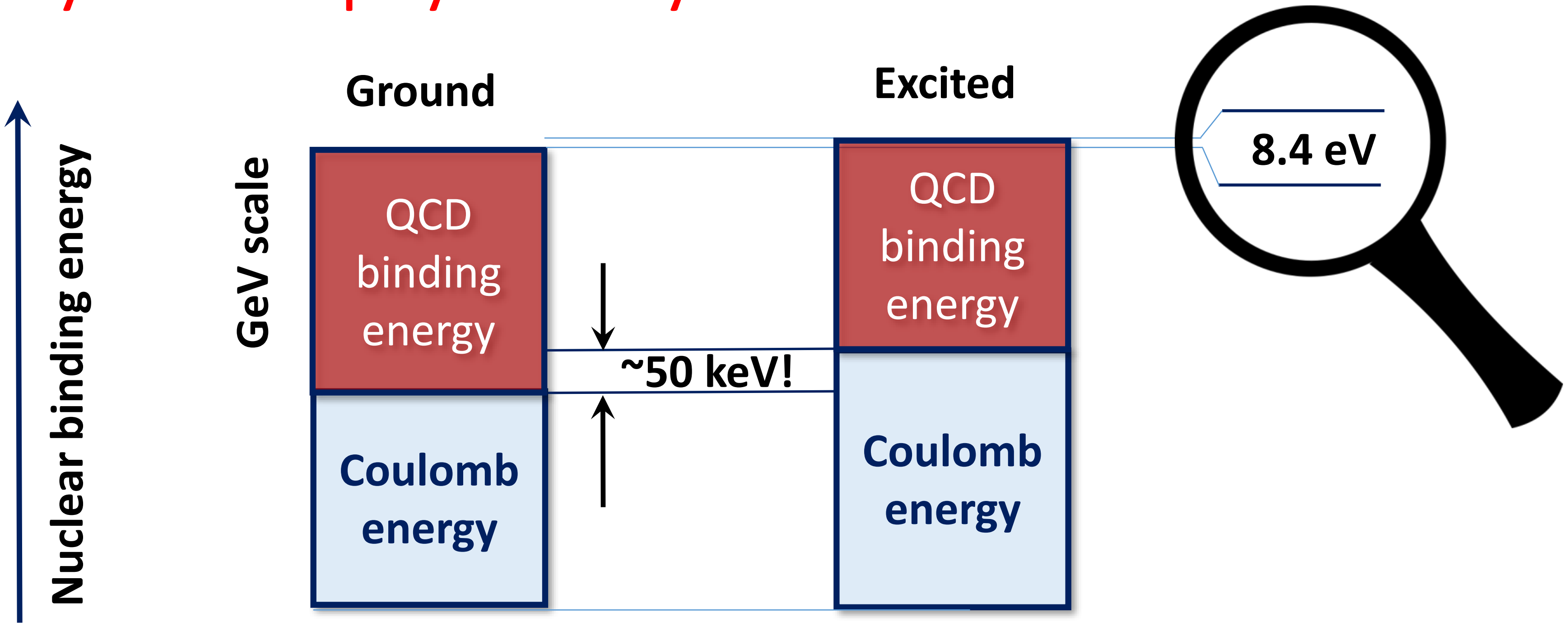
ROBERT BERINGER AND W. J. KNOX
*Department of Physics, Yale University, New Haven, Connecticut*
(Received October 10, 1960)

The equilibrium shapes of rotating liquid drops are calculated in the spheroidal approximation. The solutions are prolate forms for high angular momenta such as are produced in compound nuclei resulting from heavy-ion bombardments. This is thought to account for the angular and energy distributions observed in heavy-ion-induced fission and light-particle evaporation.

# Sensitivity to new physics beyond standard model

Coulomb repulsion $\sim \alpha$

Strong force binding

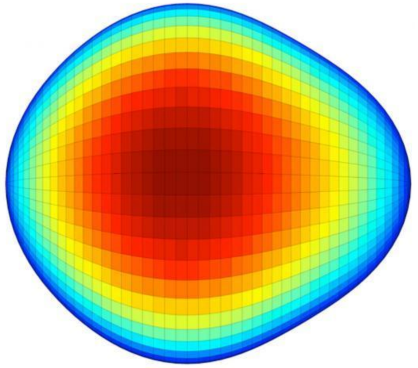



**Sensitivity to α variation**

$$\boxed{\frac{49(19)\ \mathrm{keV}}{8.4\ \mathrm{eV}} \sim 5900(2300)}$$

Beeks et al., arXiv:2407.17300v1 (2024)

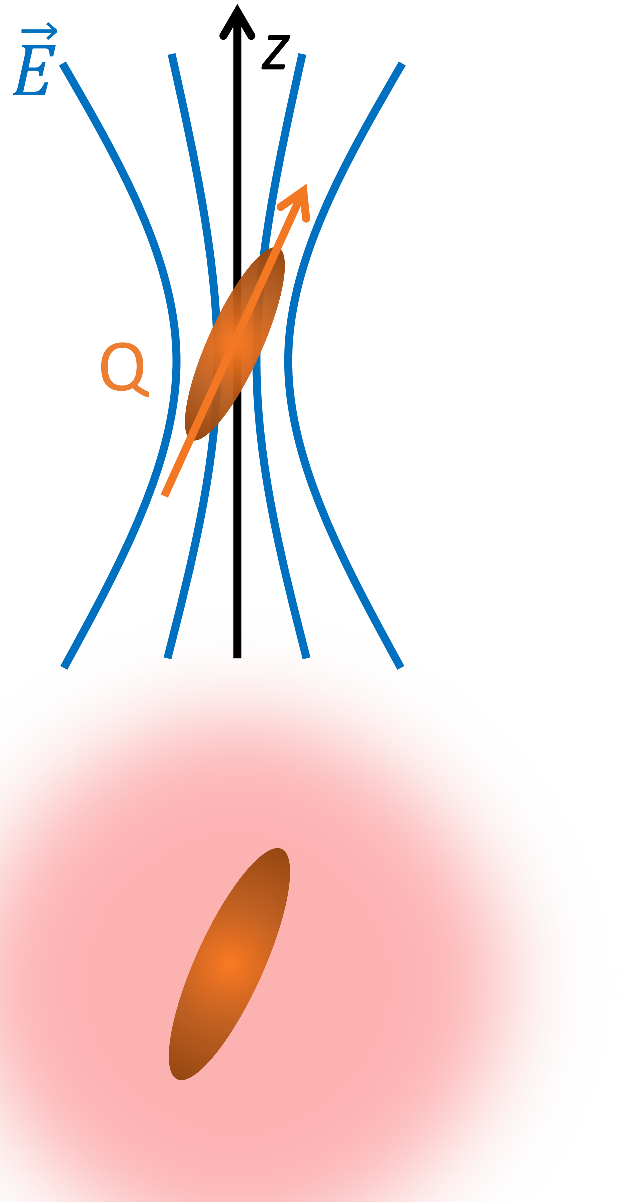
**Higher order moments?**

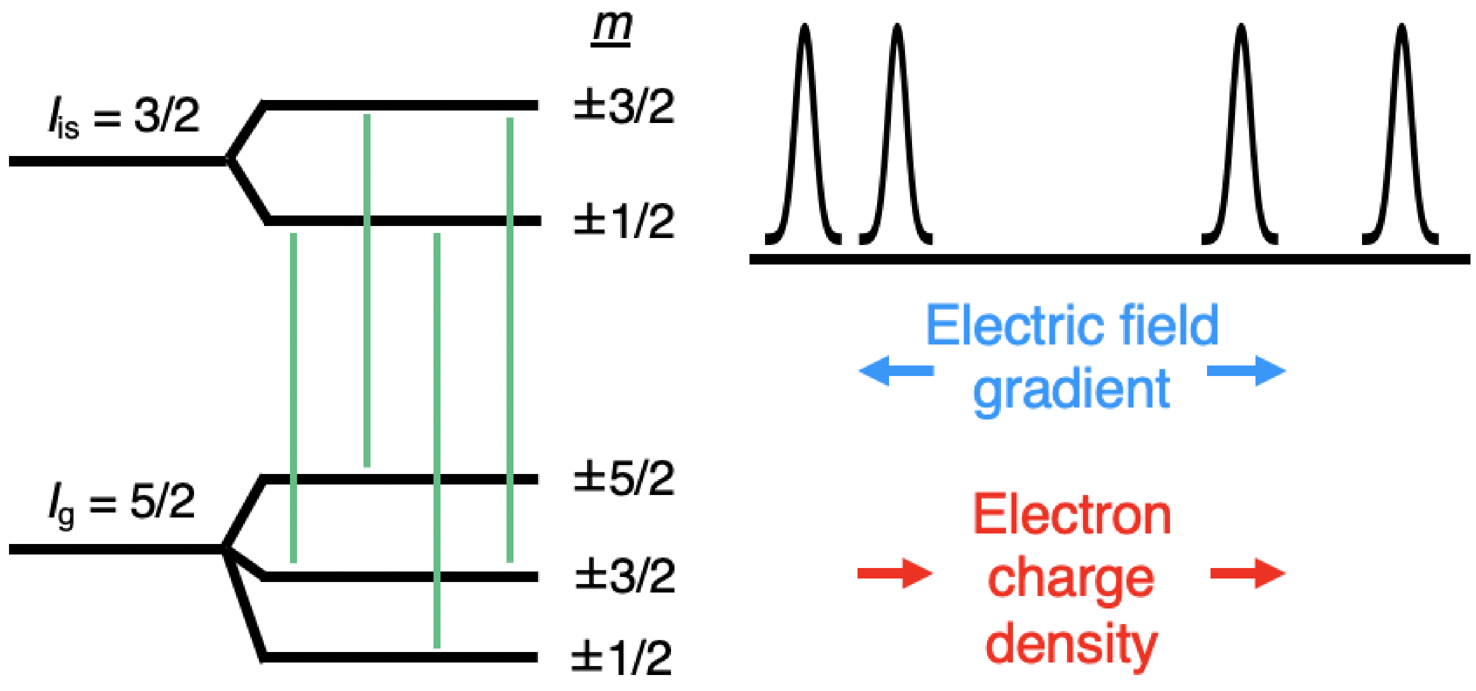


Gaffney et al., Nature **497**, 199 (2013)

# Temperature shift → crystal structure

Higgins … Schumm, Ye, arXiv:2409.11590 (2024).

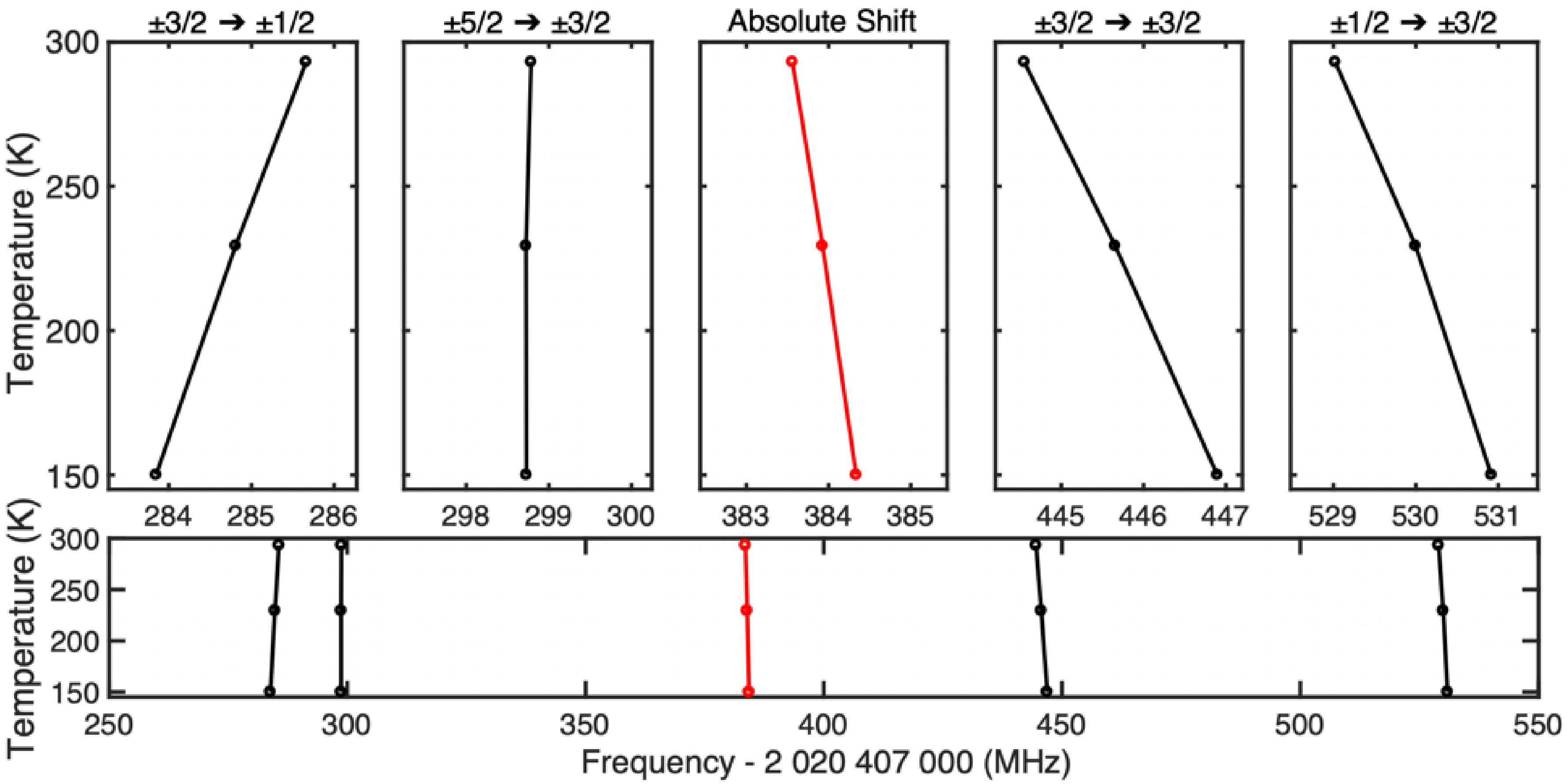


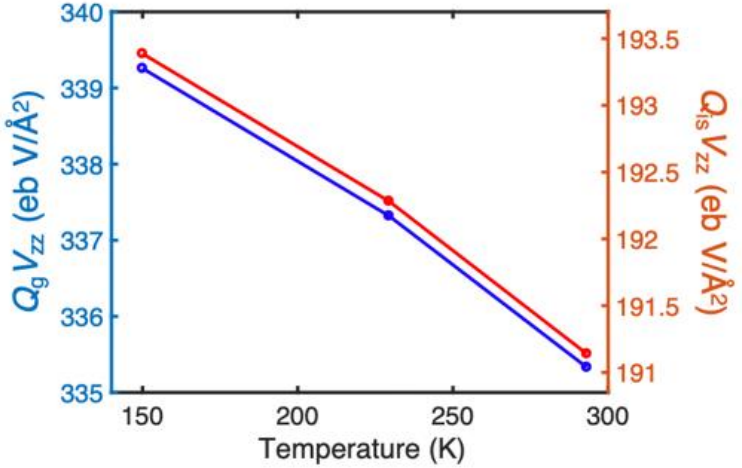



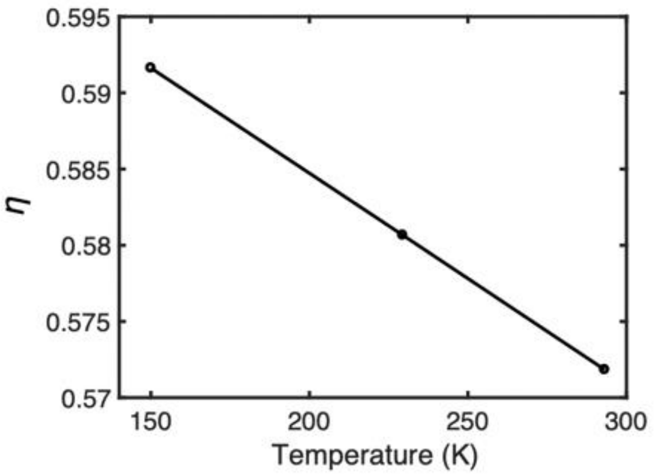

$$H_{E2} = \frac{QV_{zz}}{4I(2I-1)}\left[2I_z^2 - \boldsymbol{I}^2 + \eta\left(I_x^2 - I_y^2\right)\right]$$

$$H_{E0} = \frac{2}{3}\pi Z e^2 \rho_e(0)\langle r^2\rangle$$

# Temperature shift → crystal structure



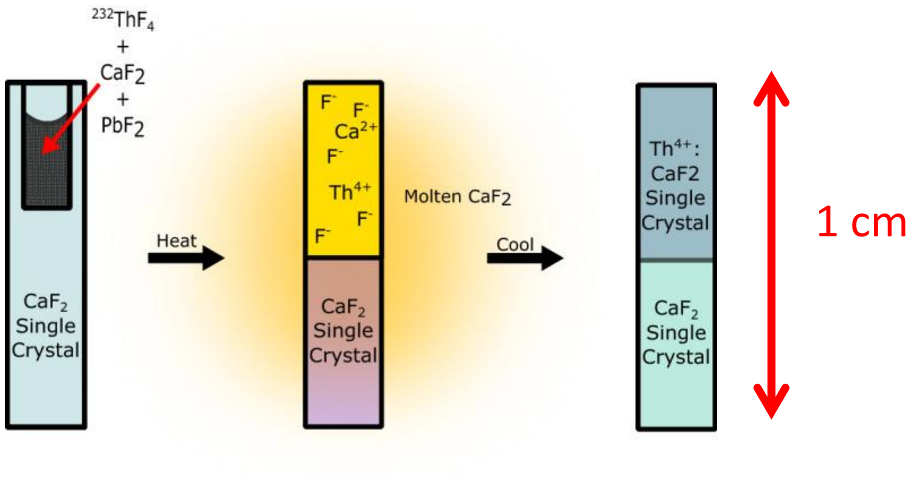

$$H_{E2} = \frac{QV_{zz}}{4I(2I-1)}\left[2I_z^2 - \boldsymbol{I}^2 + \eta(I_x^2 - I_y^2)\right]$$

$$H_{E0} = \frac{2}{3}\pi Z e^2 \rho_e(0)\langle r^2\rangle \Rightarrow \delta\rho_e(0) \sim 10^{-3}/(\text{Å}^3\cdot\text{K})$$

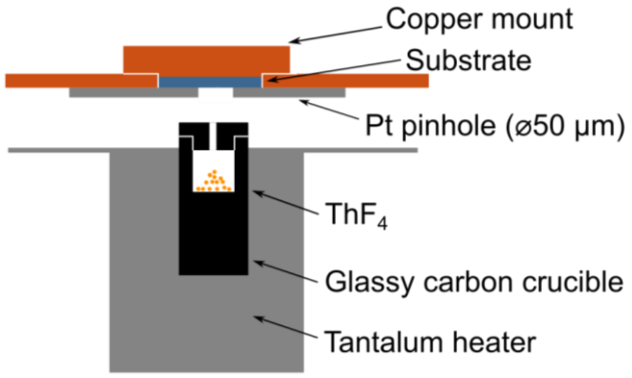
# Vapor deposition for future solid-state nuclear clocks

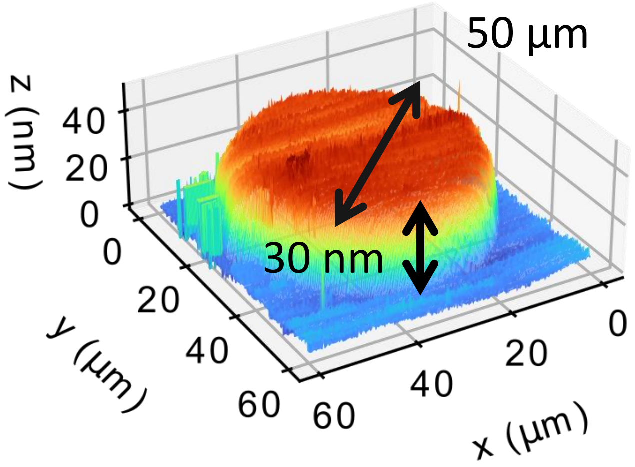
Zhang … Alexandrova, Derevianko, Hudson, Ye, Nature, in press (2024), arXiv:2410.01753

**$^{229}Th:CaF_2$**




**Pure $^{229}ThF_4$ vapor deposition**




- ✓ Works! Narrow spectral feature observed
- ? mg material required

- ✓ Efficient use of material! (µg)
- ? Narrow line transition not yet observed

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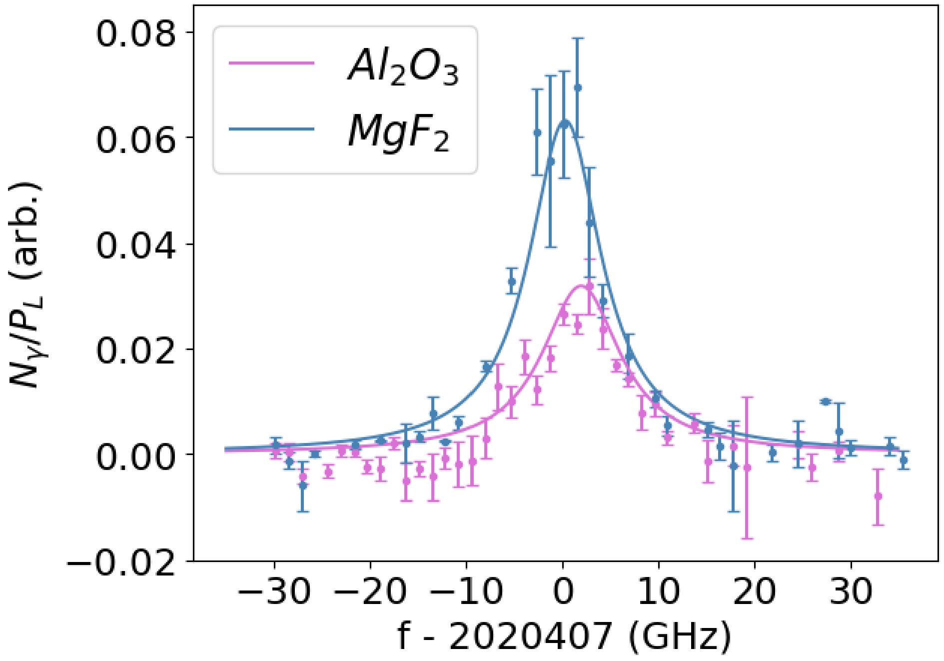
# Nuclear transition observed in JILA $ThF_4$ thin film

Zhang … Alexandrova, Derevianko, Hudson, Ye, Nature, in press (2024), arXiv:2410.01753


Eric Hudson

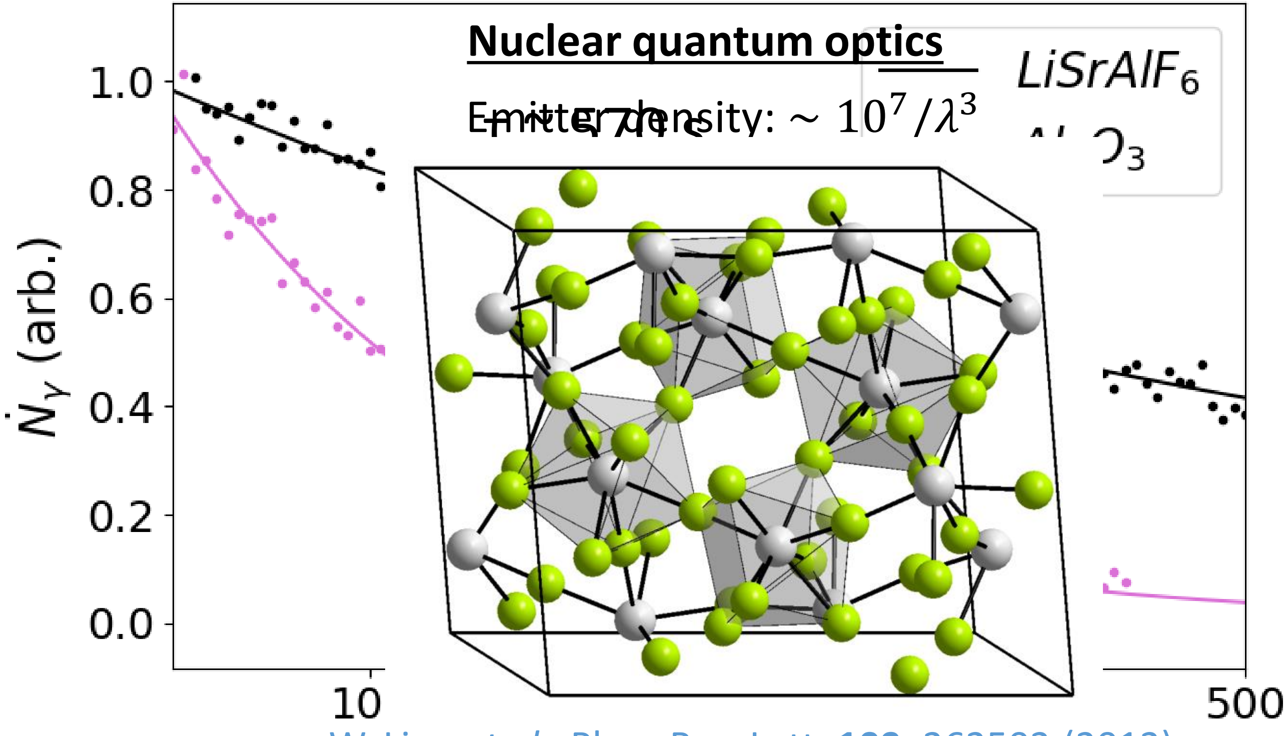
Ricky Elwell

James Terhune




**Nuclear quantum optics**

Emitter density: $\sim 10^7/\lambda^3$




W. Liao *et al.*, Phys. Rev. Lett. **109**, 262502 (2012)

# $^{229}$Th nuclear clock

Many JILA scientists and staff members

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JILA

NIST