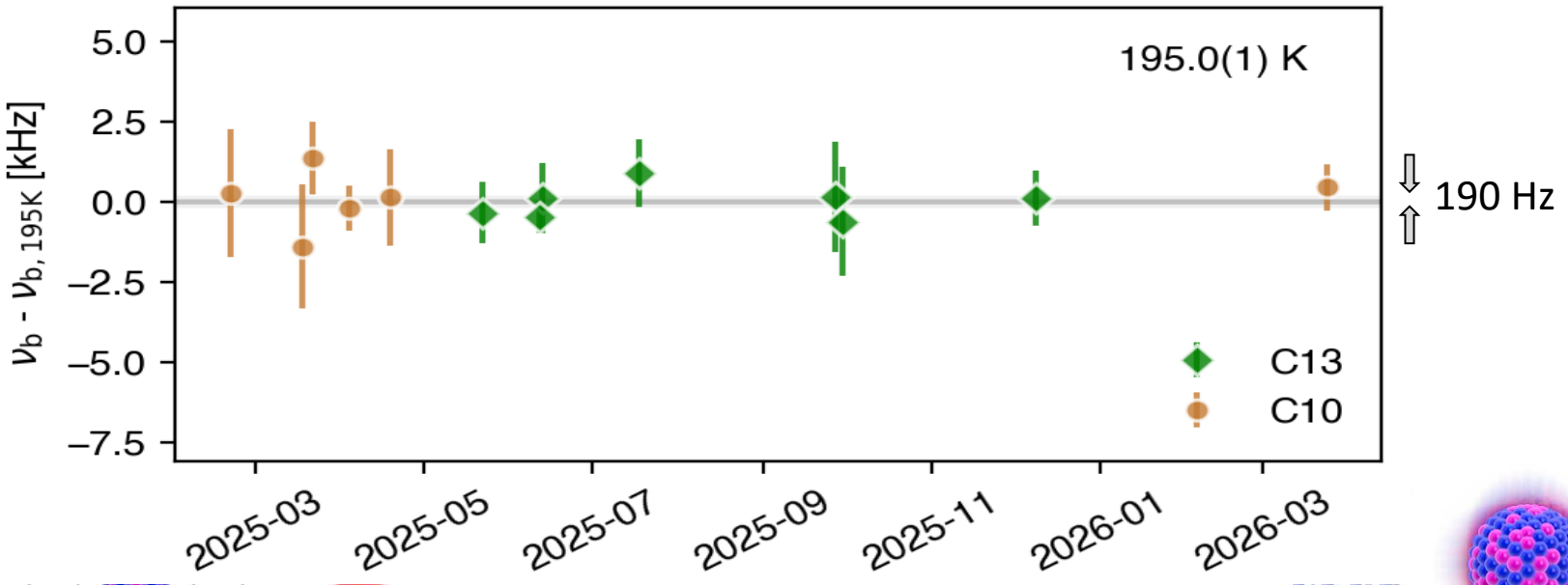
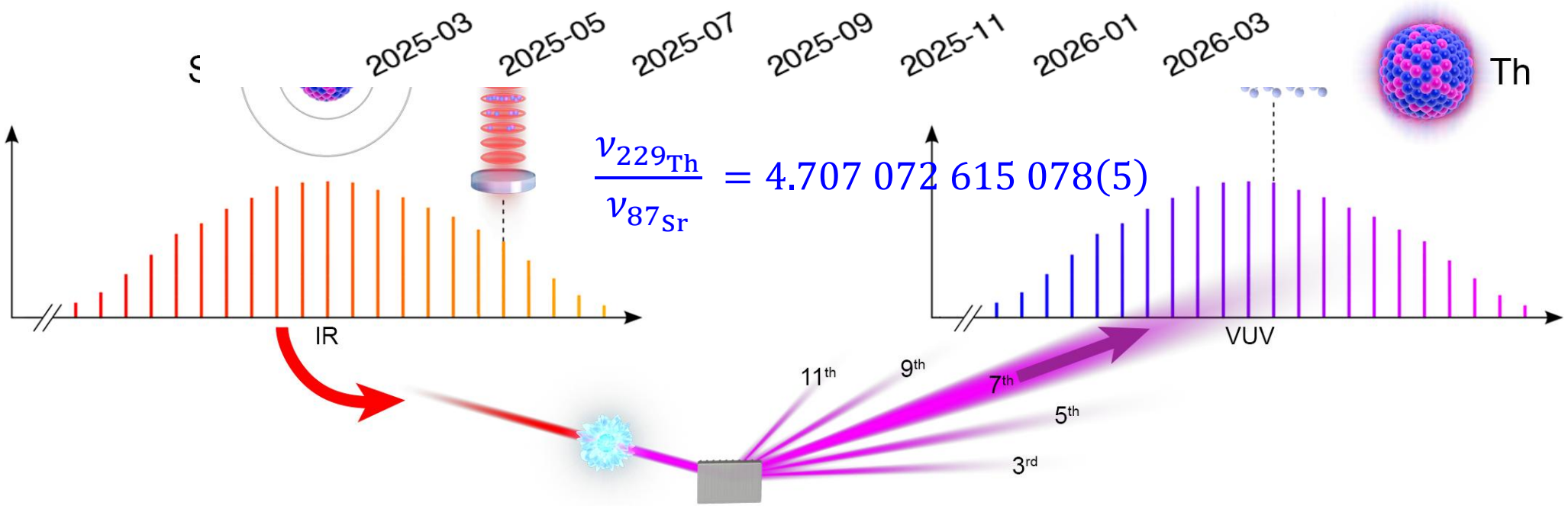
Laser-driven Mössbauer spectroscopy for nuclear clock





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

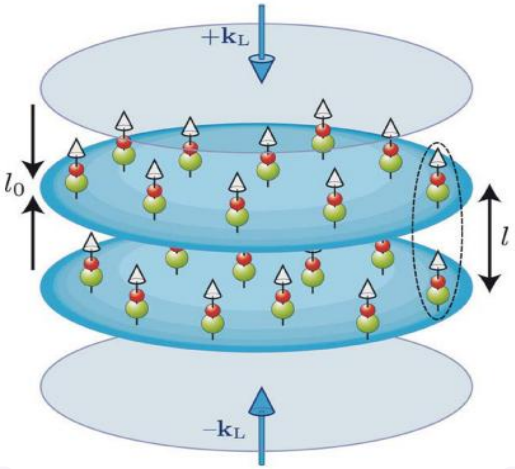
Junyu Lin

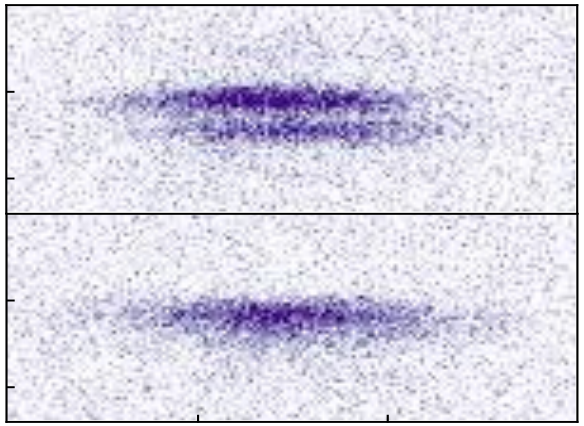
Young scientists

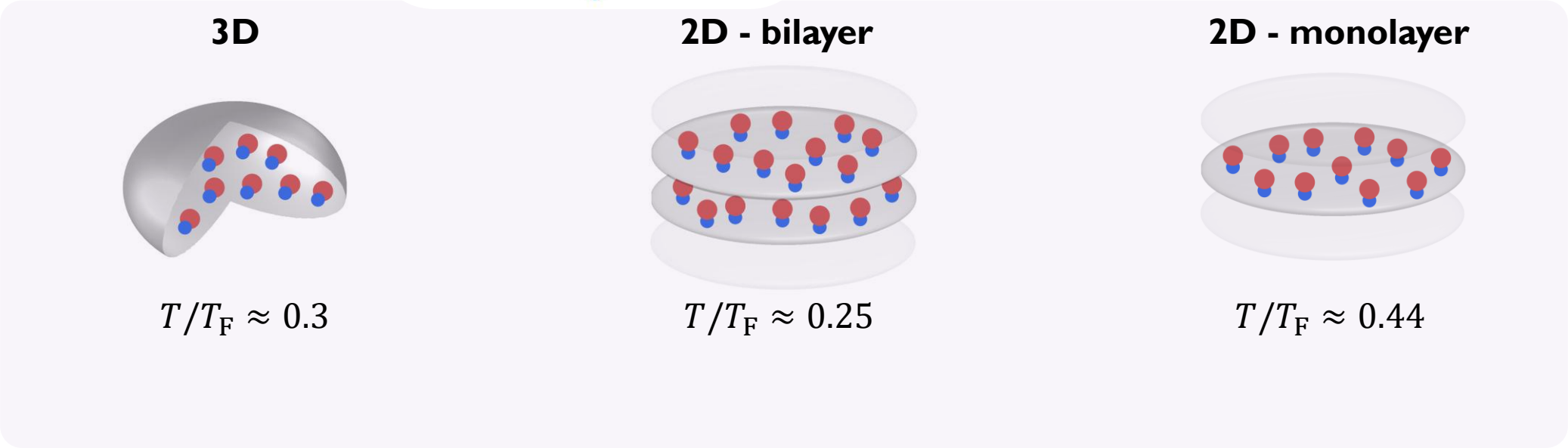
Fermi gas of dipolar molecules in 2D & 3D

Lin *et al.*, arXiv:2606.14135 (June 15, 2026).

Baranov … Zoller, *Chem. Rev* (2012)



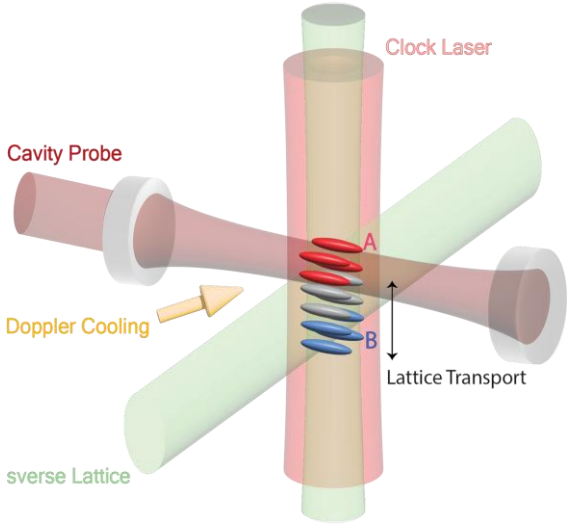


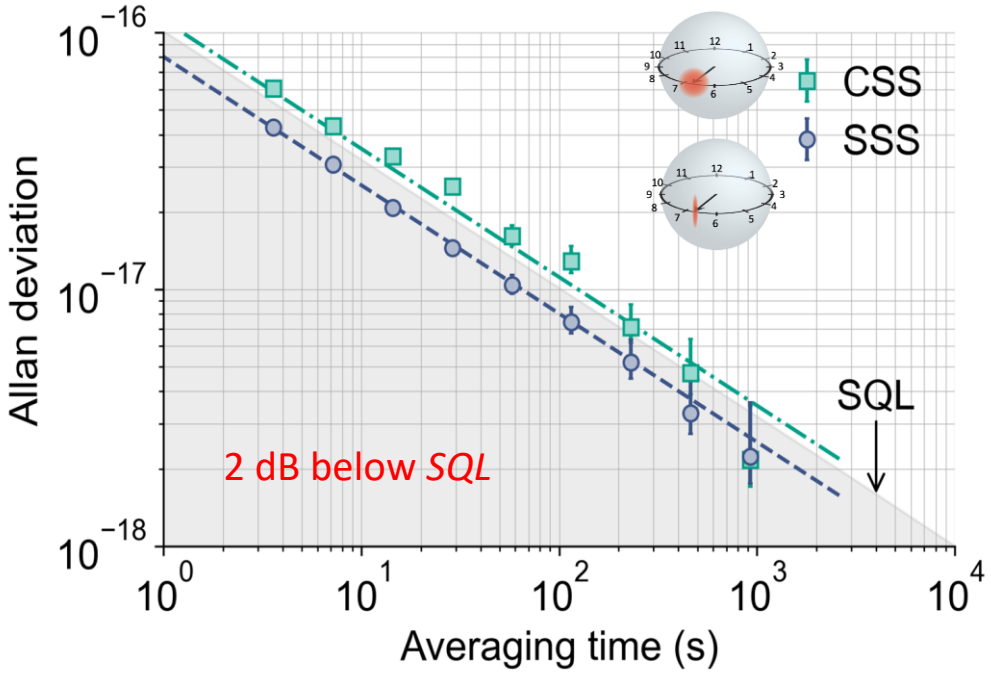


Young scientists

Quantum science & metrology

Yang Yang





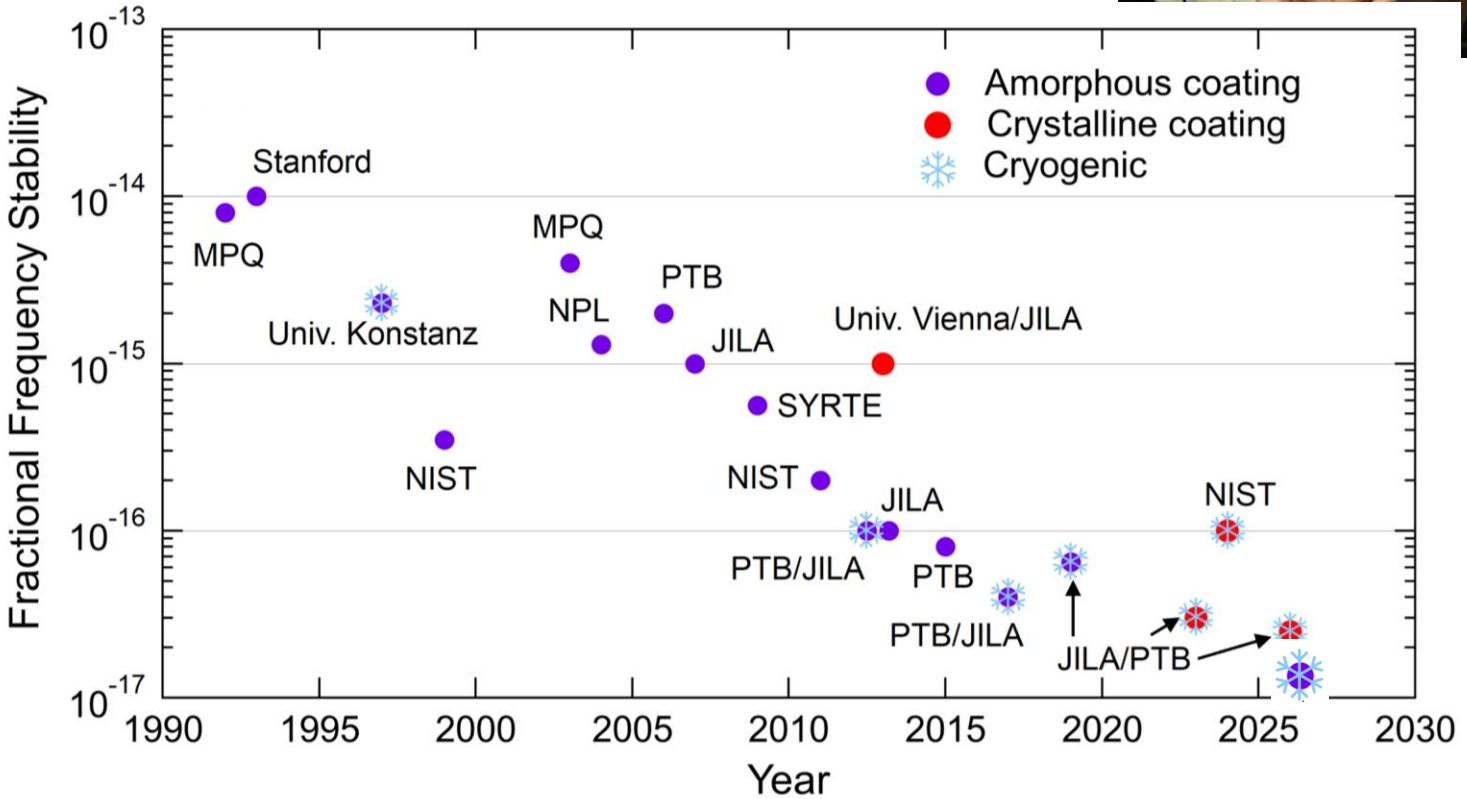
Yang … Ye, Phys. Rev. Lett. **135**, 193202 (2025).

Dahyeon Lee

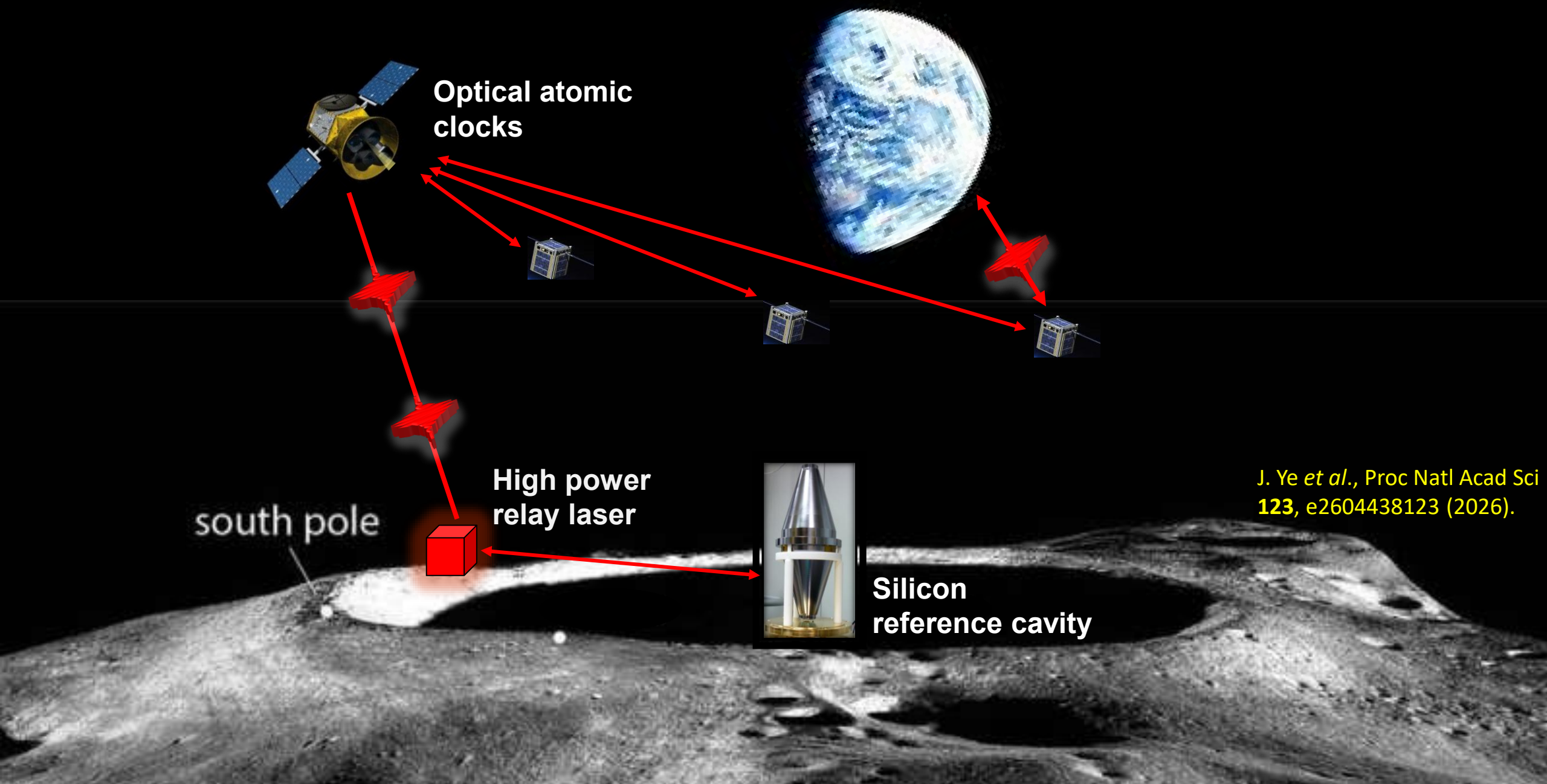
Ben Lewis

Lee *et al.*, Phys. Rev. Lett. **136**, 033801 (2026).

A new record:
laser stability 1.2 x 10^{-17}



Lunar Silicon Cavity: time & length standard for space

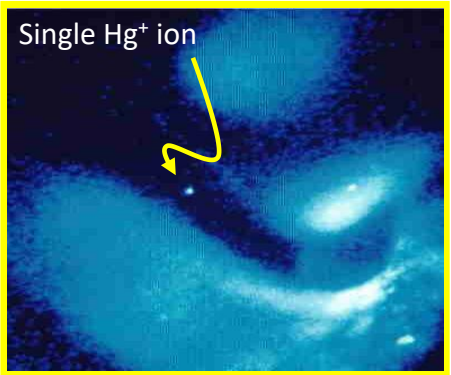


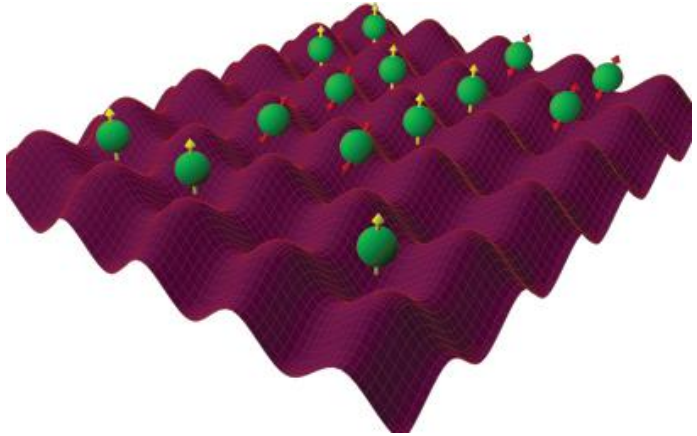
J. Ye *et al.*, Proc Natl Acad Sci **123**, e2604438123 (2026).

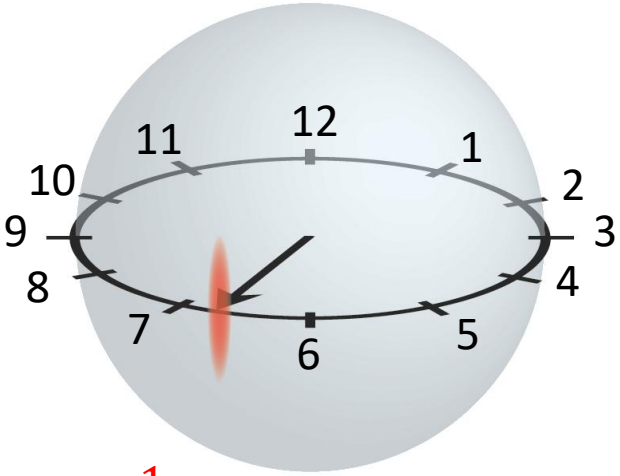
Quantum system scaling

Employing a macroscopic n

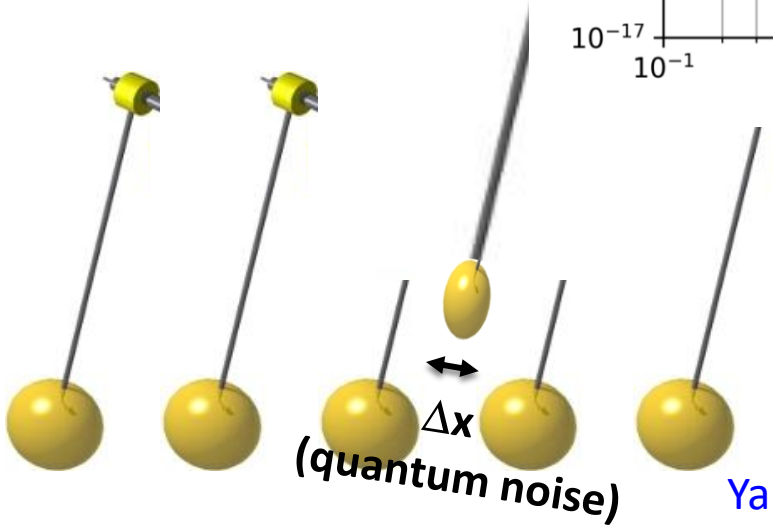
Atomic clocks



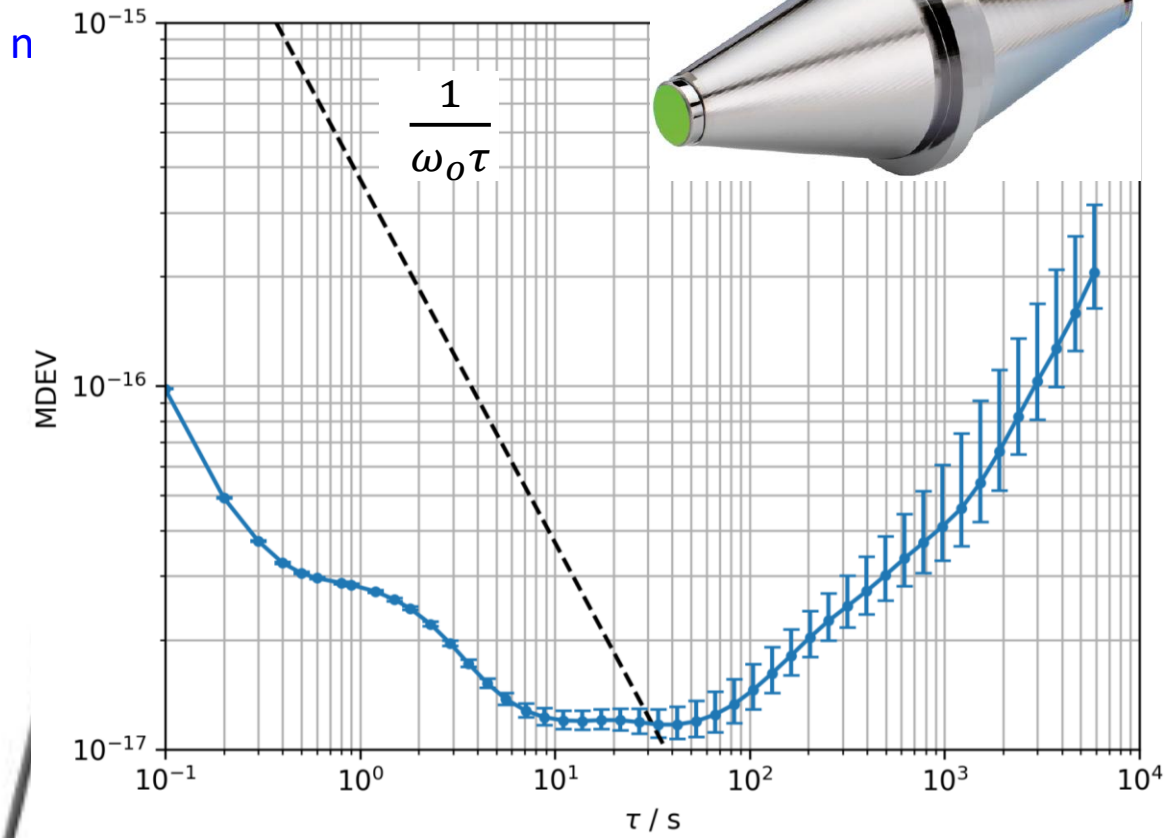




$$\frac{1}{\sqrt{2}}\left(e^{-iEt}|e\rangle + |g\rangle\right)$$



Silicon-7



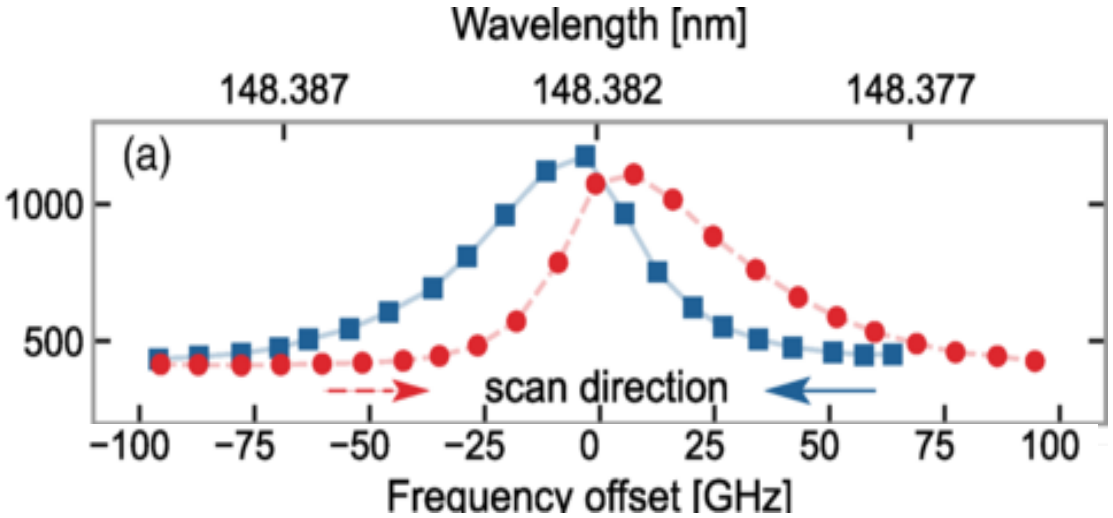
Kim *et al.*, Phys. Rev. Lett. **135**, 103601 (2025)

$$\Delta\varphi_{SQL} \sim \frac{1}{Q\sqrt{N}}$$

Yang … Ye, Phys. Rev. Lett. **135**, 193202 (2025).

Laser-based Mössbauer spectroscopy for nuclear clock

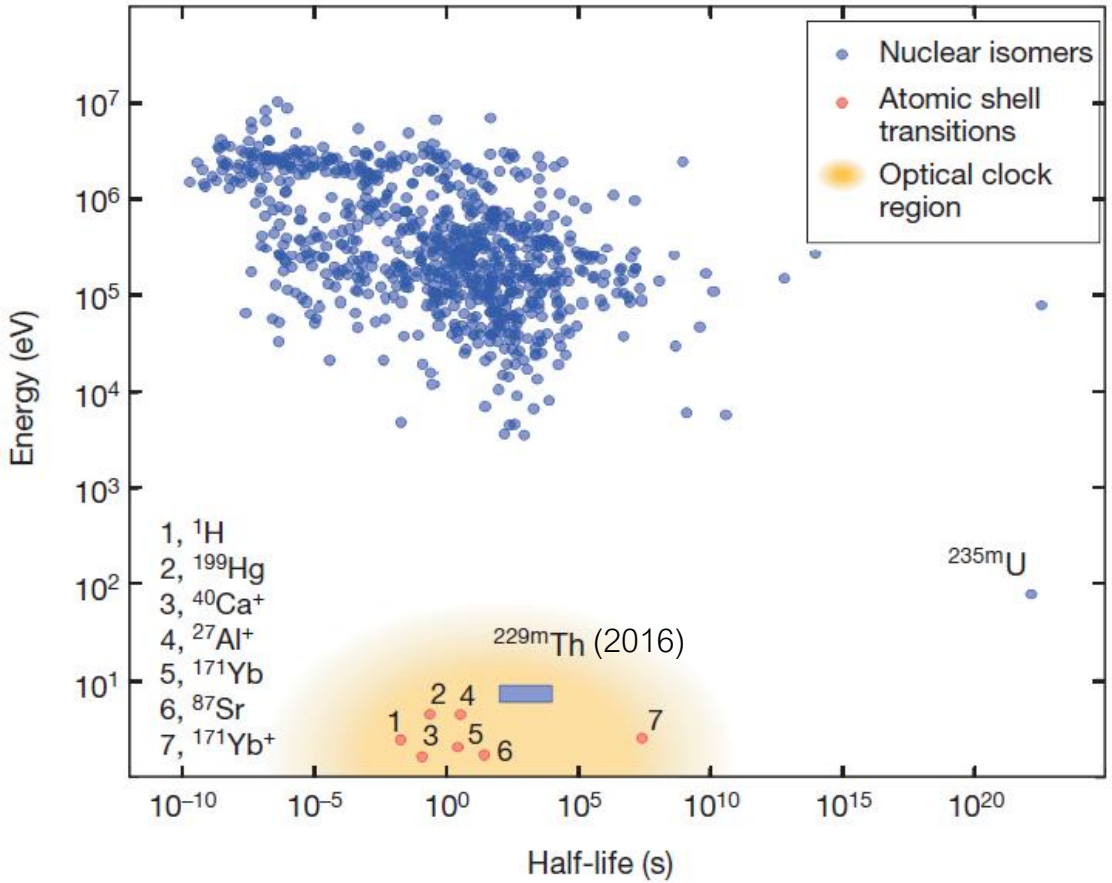
Tiedau ... Peik, PRL **132**,182501 (2024).



Urgent

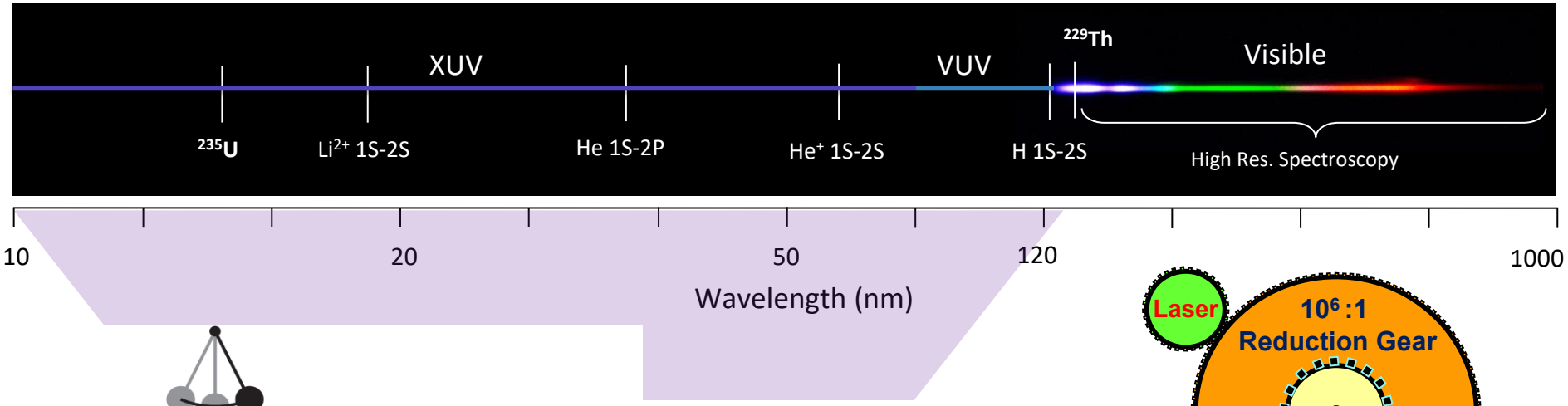
- **Hig**  **rrow l**  **UV laser**

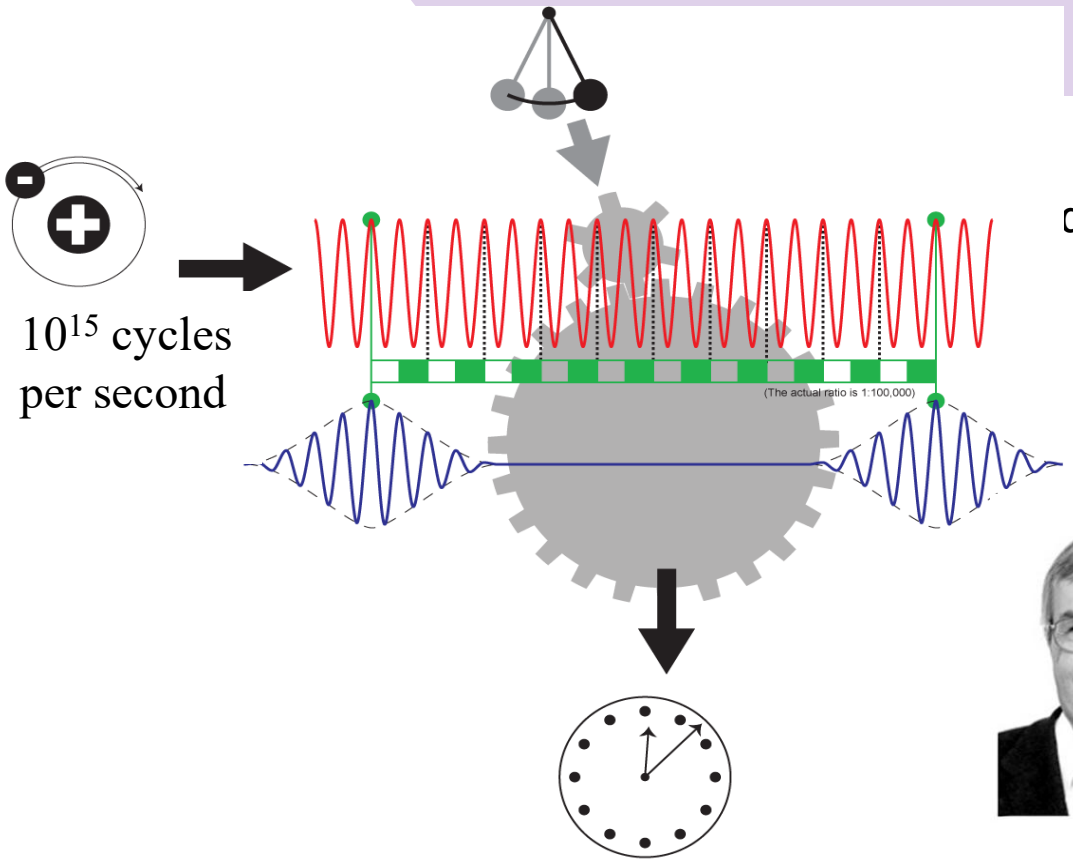
Uniquely low energy transition in ^{229}Th



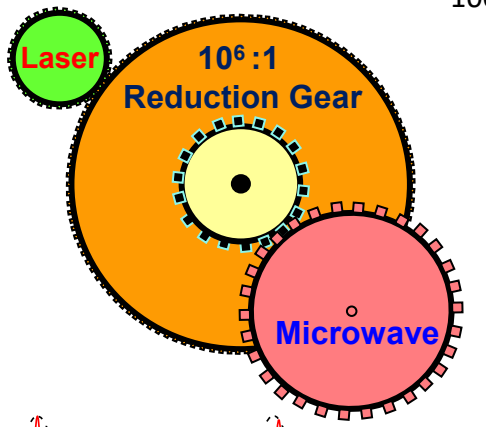
Peik & Tamm, Europhys. Lett. **61,** 181 (2003).
v.d.Wense ... Thirolf, Nature **533,** 47 (2016)

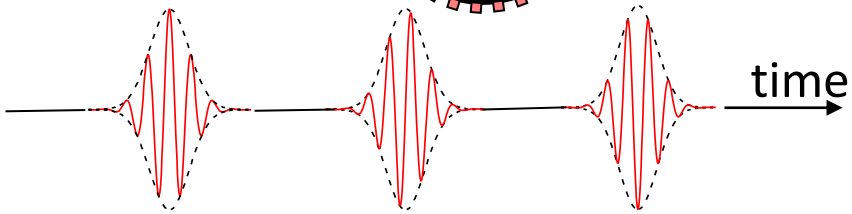
Need: Narrowline extreme ultraviolet light





diations broadband





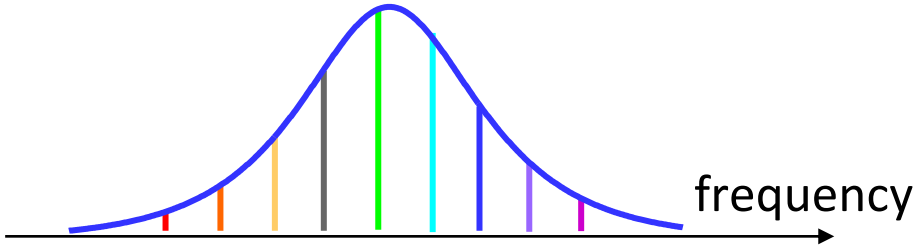
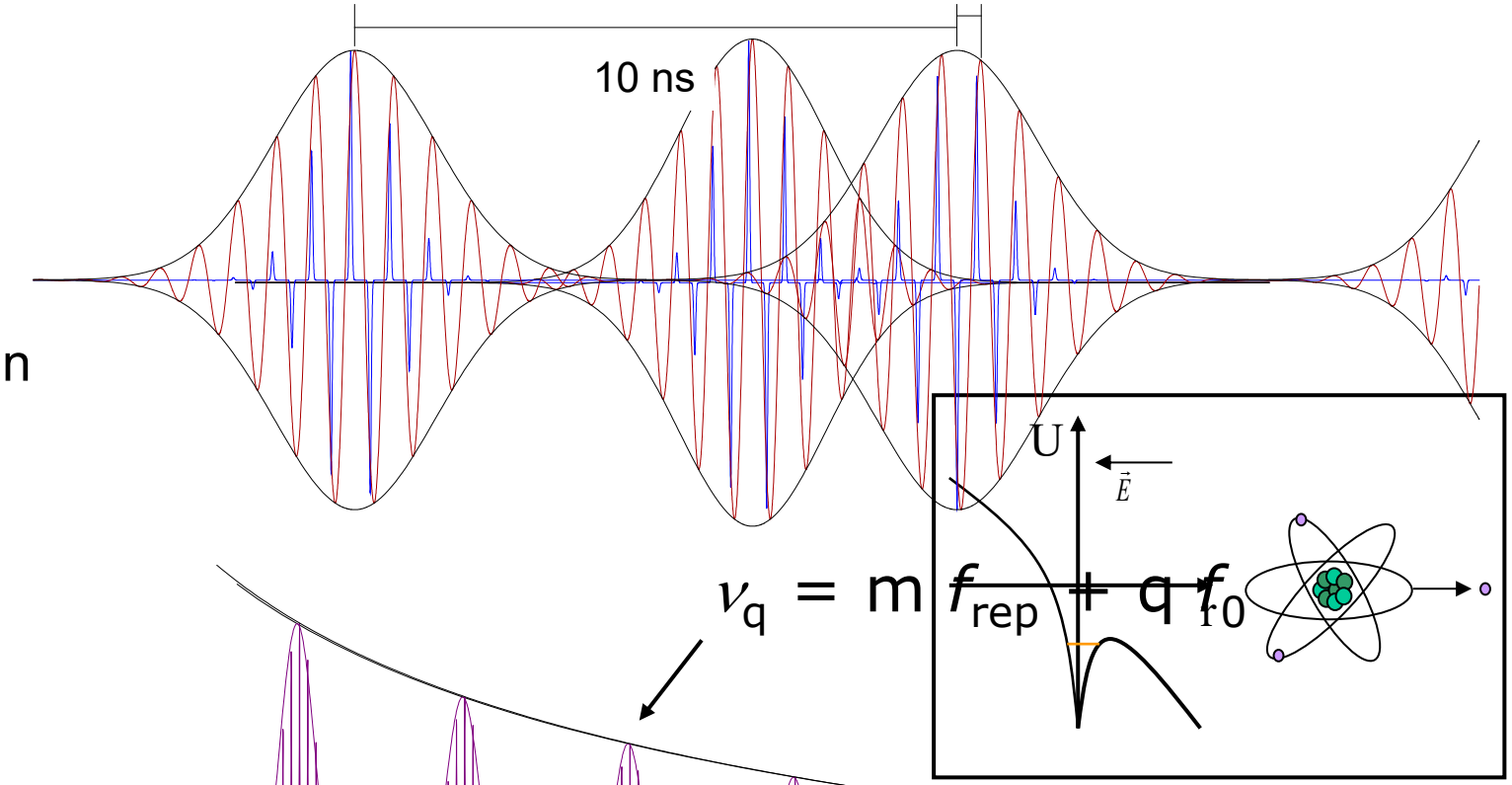


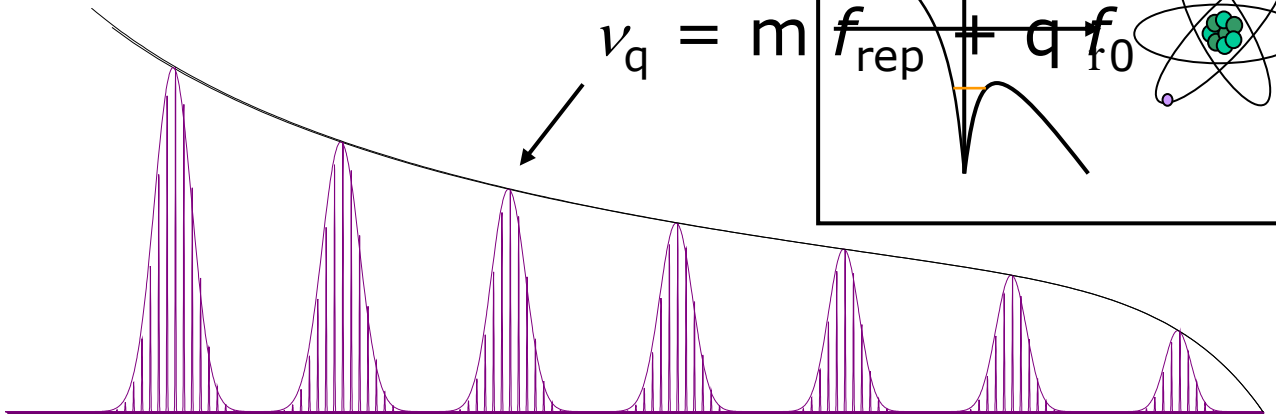
Table-top coherent VUV / XUV radiation

Harmonic Generation with a single IR pulse → attosecond dynamics

Time domain



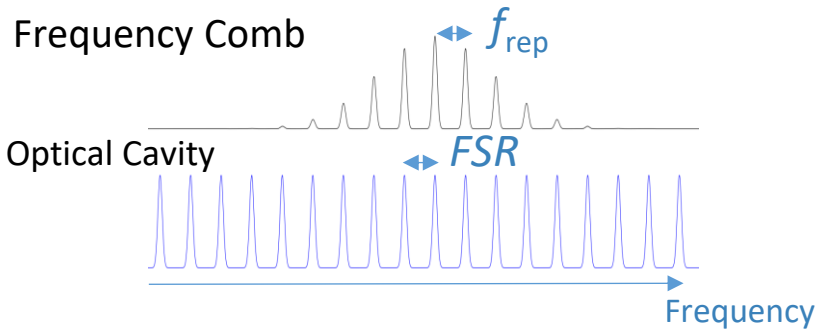
Frequency domain



ω_7 ω_9 ω_{11} ω_{13} ω_{15} ω_{17} ω_{19}

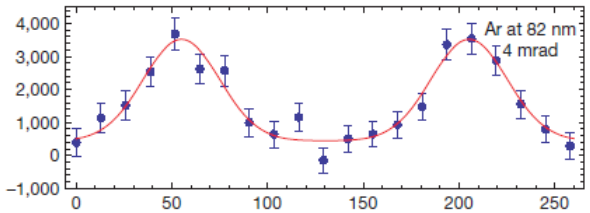
2 decades of development for XUV frequency comb

Femtosecond enhancement cavity



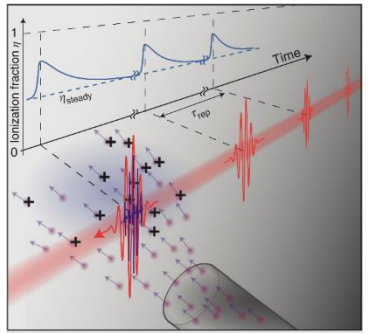
R. J. Jones & J. Ye, Opt. Lett. **27,** 1848 (2002)
R. J. Jones & J. Ye, Opt. Lett. **29,** 2812 (2004)

XUV comb spectroscopy



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

Phase-matched XUV comb generation

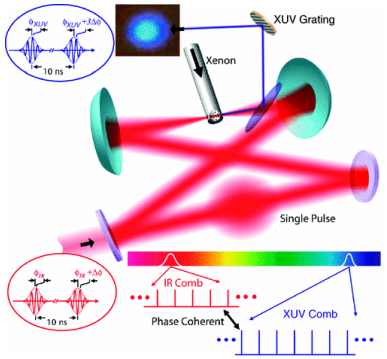


G. Porat et al., Nat. Photon. **12**, 387 (2018)

2000 | 2005 | 2010 | 2015 | 2020 — Time

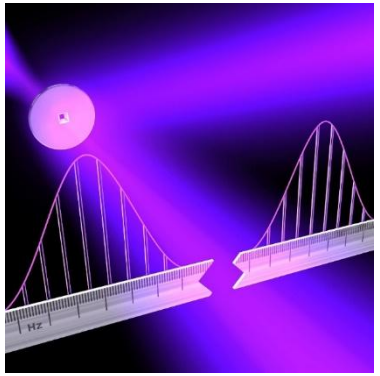
XUV comb

~100 pW



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

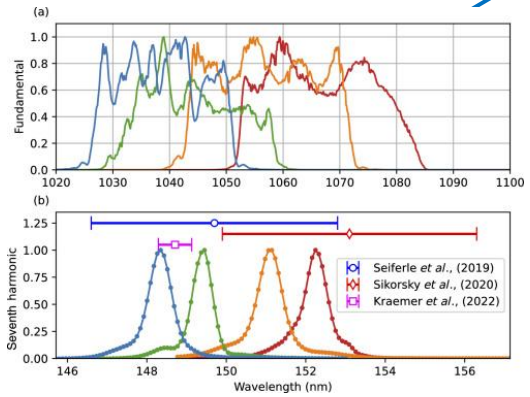
Coherence times > 1s



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

Tunable VUV comb

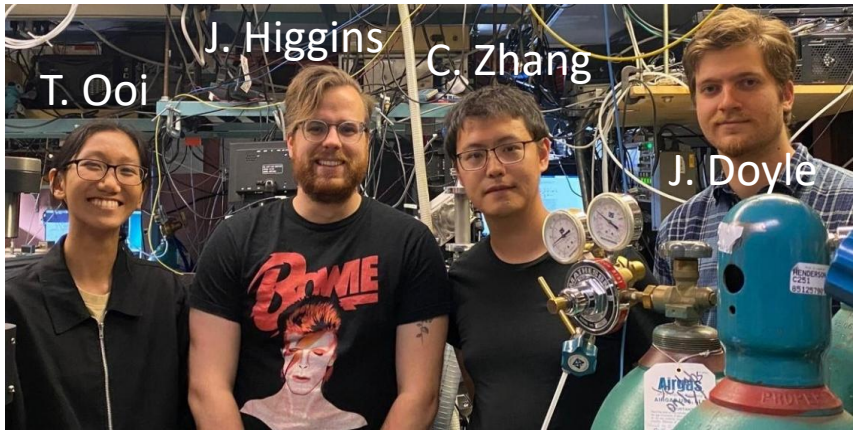
>1 mW

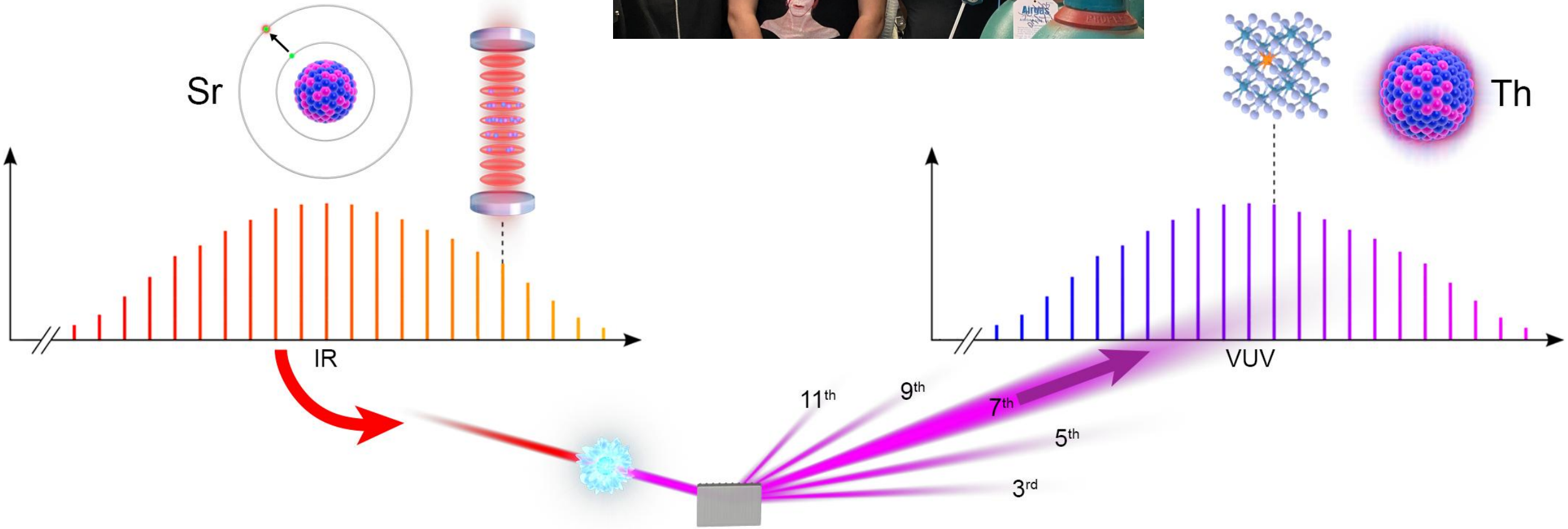


C. Zhang et al., Opt. Lett. **47**, 5591 (2022)

VUV/XUV frequency comb

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





Comb parallelism – high resolution, broad bandwidth

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

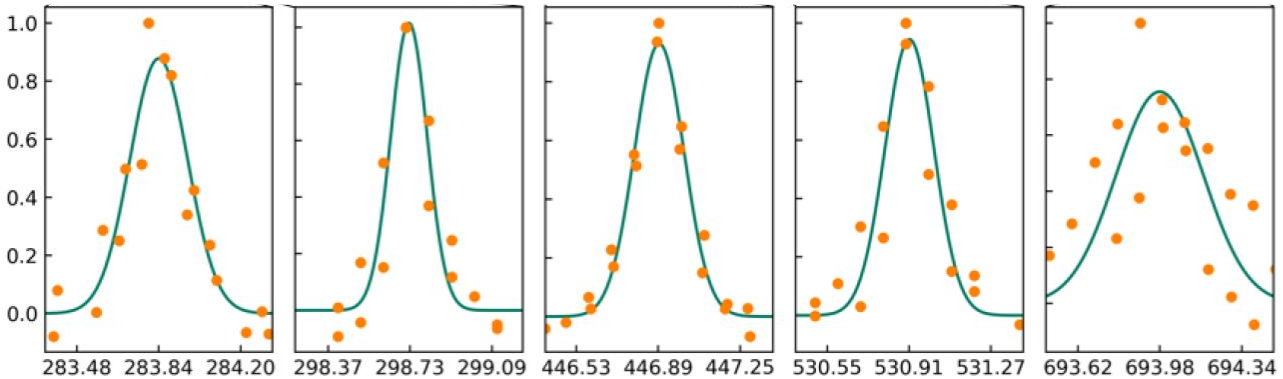
Thorsten Schumm

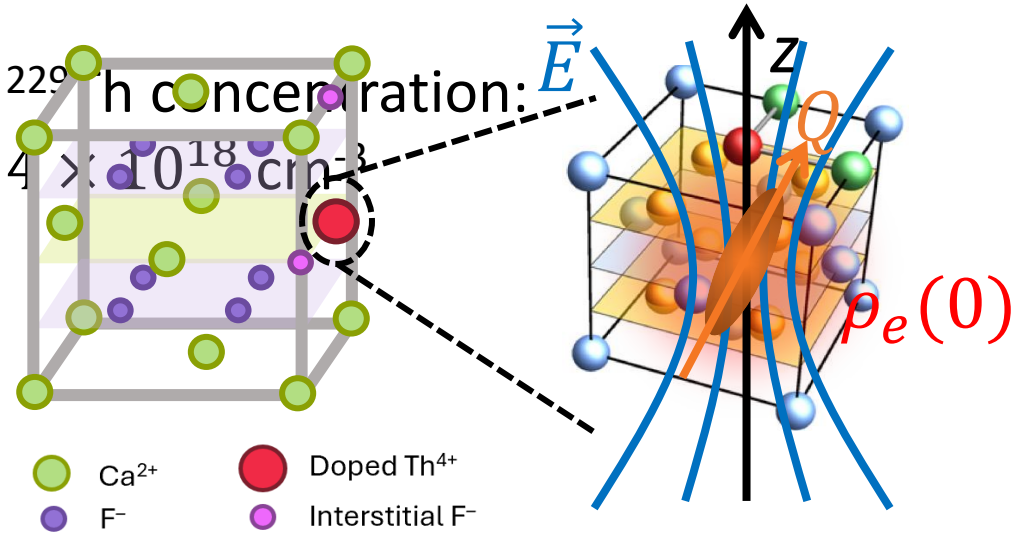
Nuclear quadrupole moment

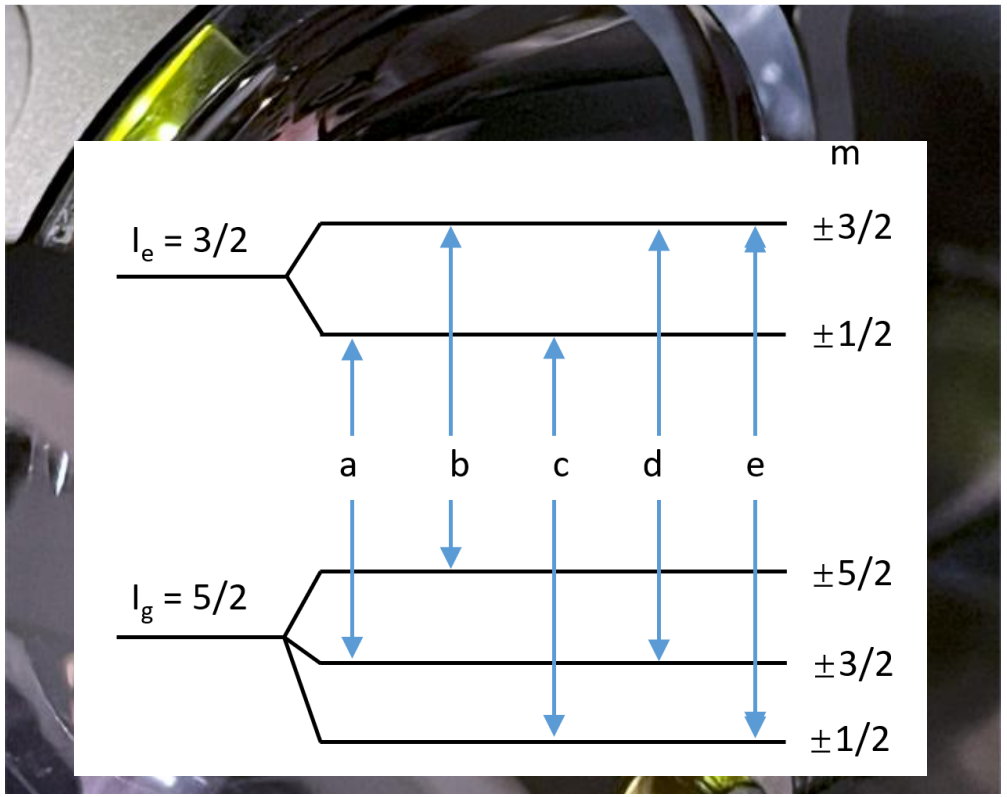
$\nabla\vec{E}$

$\nabla\vec{E}$ asymmetry

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

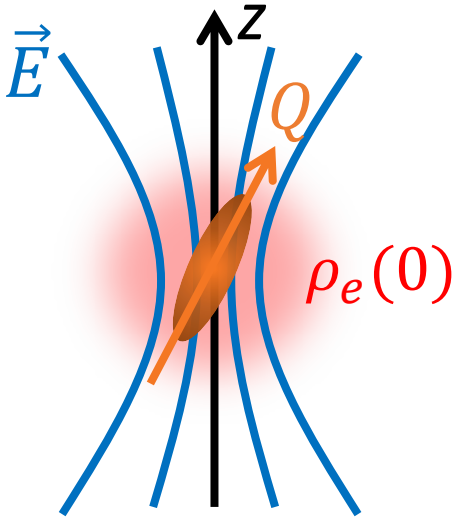


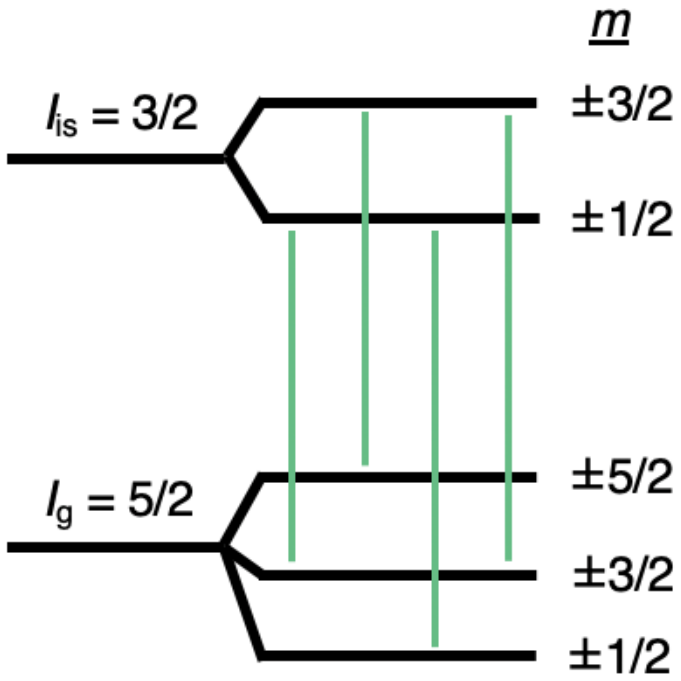




^{229}Th:CaF_2 : system parameters

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





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

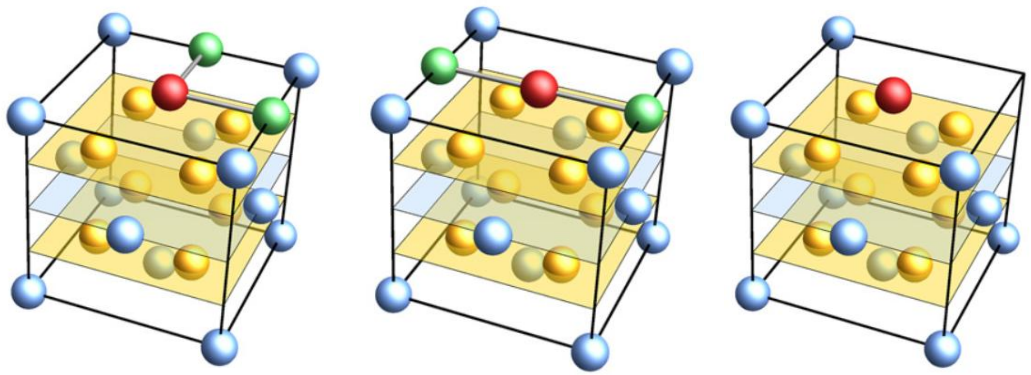
$$H_{E2} = \frac{QV_{zz}}{4I(2I-1)}\left[3I_z^2 - \boldsymbol{I}^2 + \eta(I_x^2 - I_y^2)\right]$$

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

Doping configuration in Th:CaF2

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

Th^{4+}
F^- interstitial
Ca^{2+}
F^-



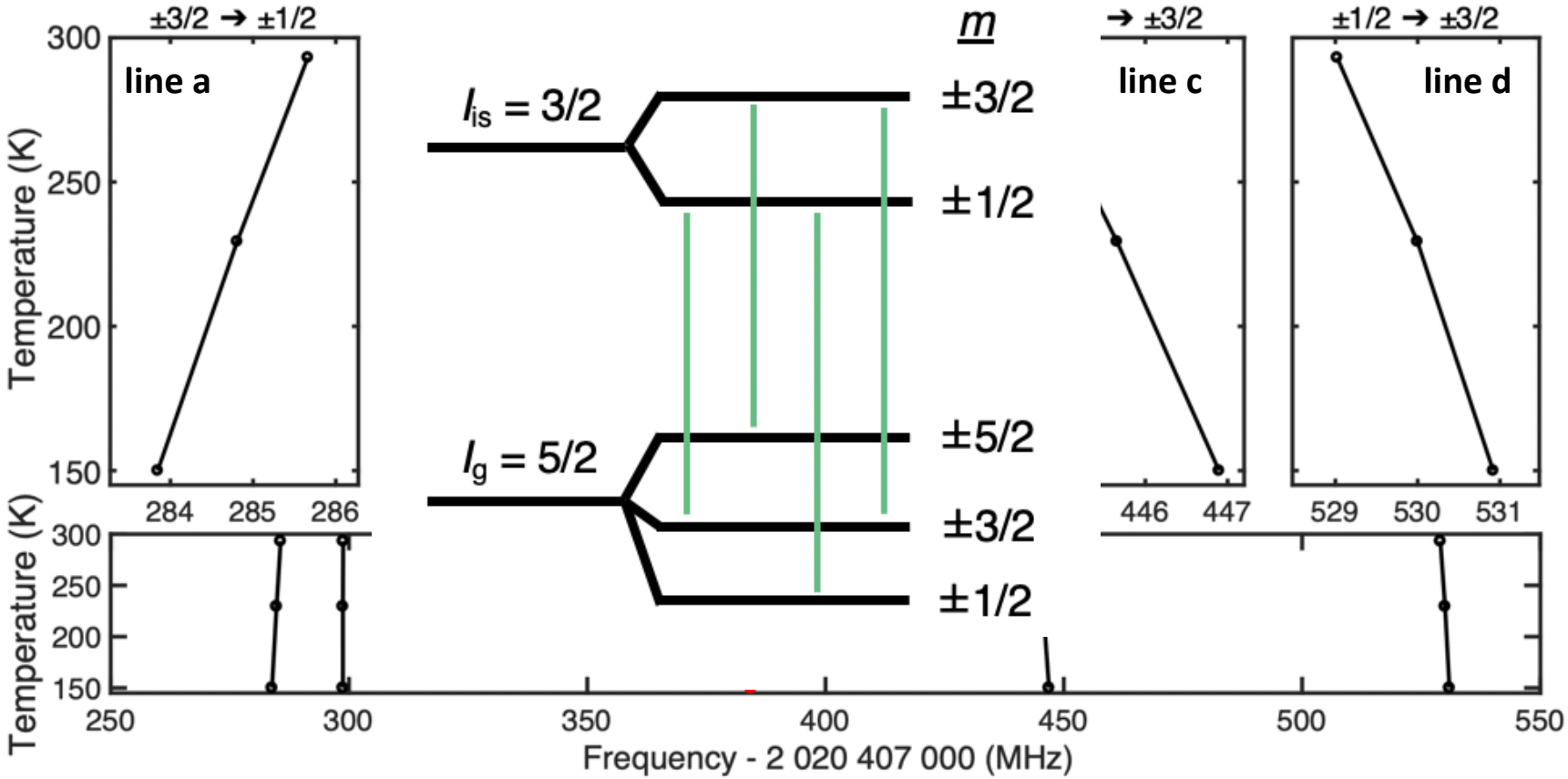
Simulations [Dessovic 2014]	F^- interstitials (90°)	F^- interstitials (180°)	Ca^{2+} vacancy
V_{zz} [V/Å^2]	223	-296.7	68.3
$\eta = \frac{V_{xx} - V_{yy}}{V_{zz}}$	0.48	0	0
Solution energy per defect (eV)	0.32	0.47	1.67

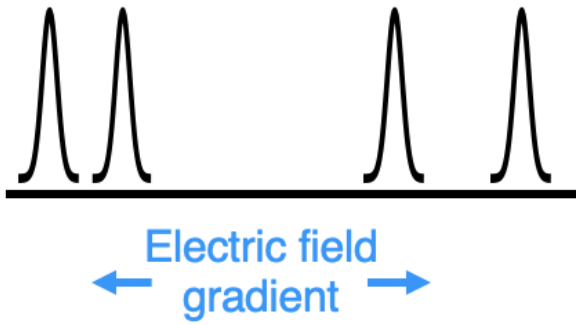
Most energetically favorable!

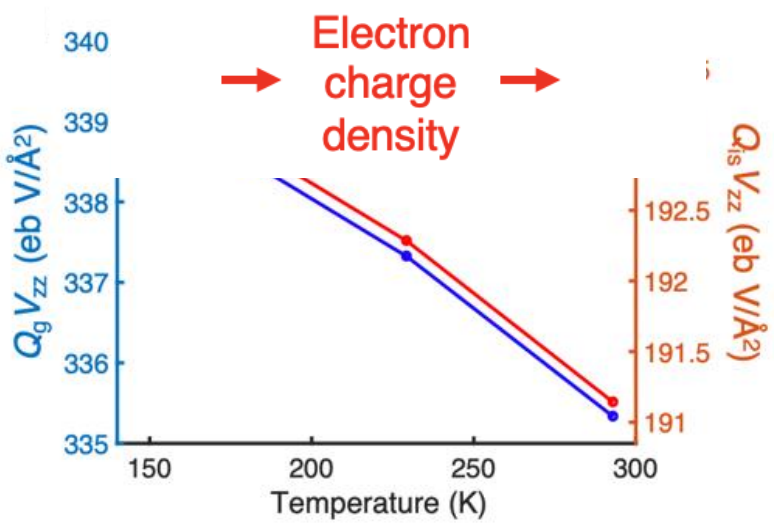
Dessovic, P. et al. *J. Phys.: Condens. Matter* **26**, 105402 (2014).
Zhang, C. et al. Nature 633, 63–70 (2024).
Hiraki, T. et al. arxiv:2509.00041 (2025).

Temperature dependent line frequency

Higgins … Schumm, Ye, Phys. Rev. Lett. **134**, 113801 (2025).







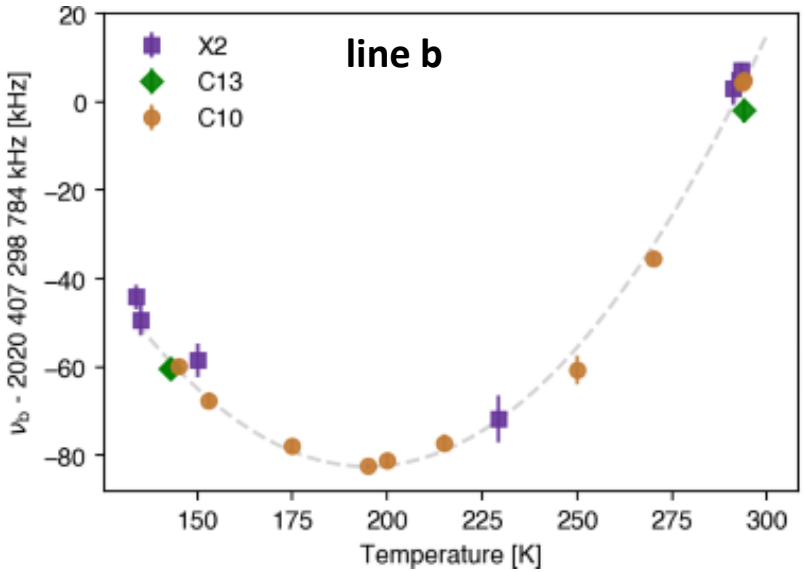
$$H_{E2} = \frac{QV_{zz}}{4I(2I-1)}\left[3I_z^2 - \boldsymbol{I}^2 + \eta(I_x^2 - I_y^2)\right]$$

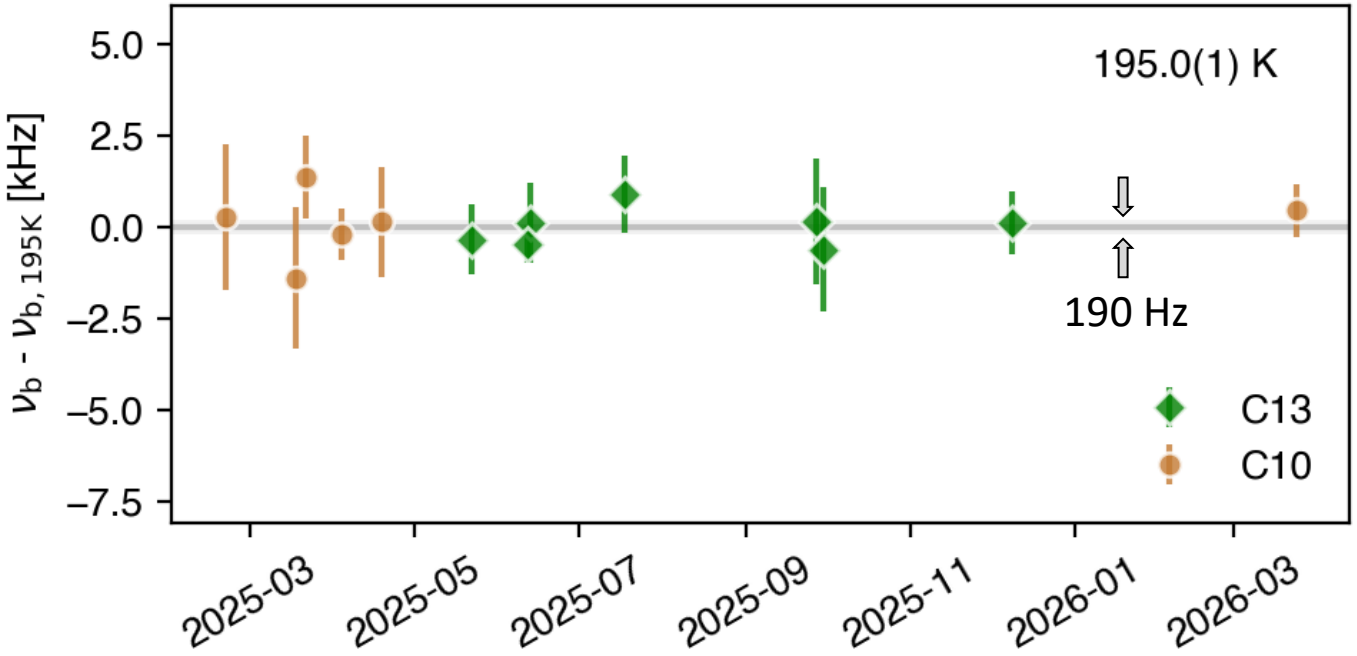
$$H_{E0} = \frac{2}{3}\pi Z e^2 \rho_e(0)\langle r^2\rangle$$

$$\Rightarrow \delta\rho_e(0) \sim 10^{-3}/(\text{Å}^3 \cdot \text{K})$$

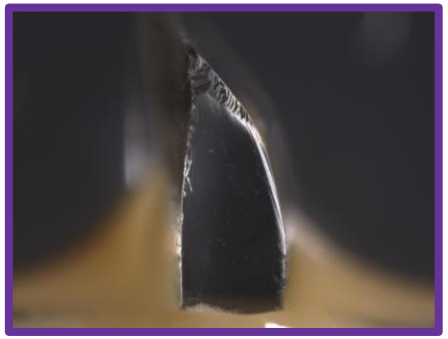
^{229}Th:CaF_2 : Frequency reproducibility (independent of doping)

Ooi ... Schumm, Ye, Nature **650**, 72 (2026).

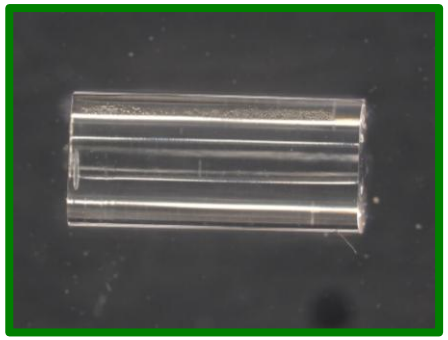




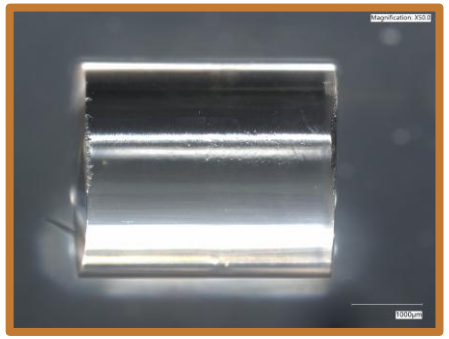
X2: 4×10^{18} cm^{-3}
19 May 2021



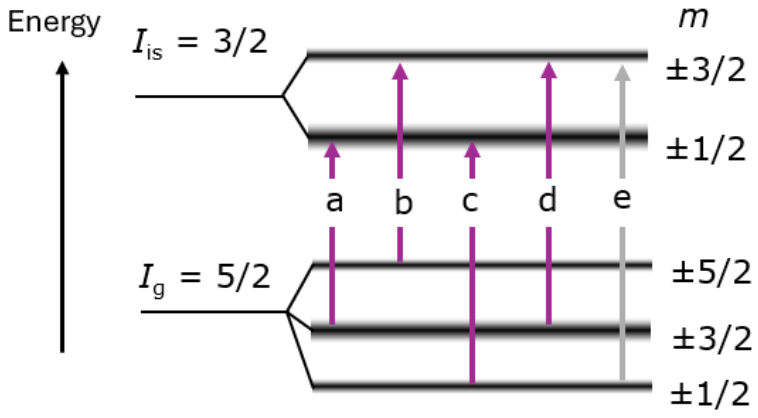
C13: 0.8×10^{18} cm^{-3}
7 Dec 2020

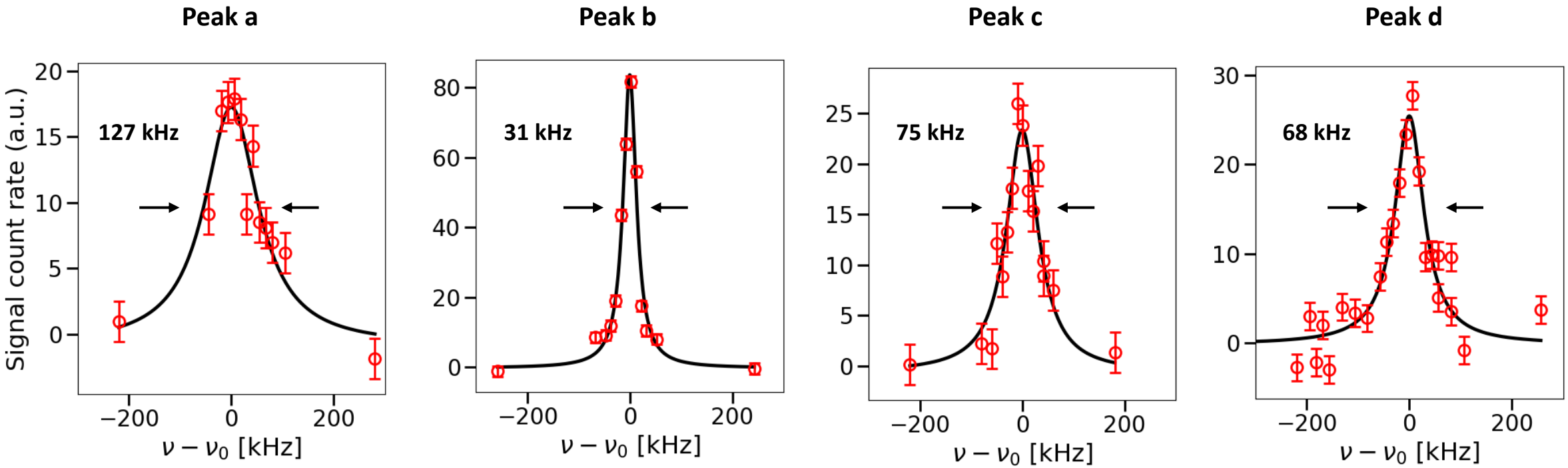


C10: 0.3×10^{18} cm^{-3}
23 Nov 2020



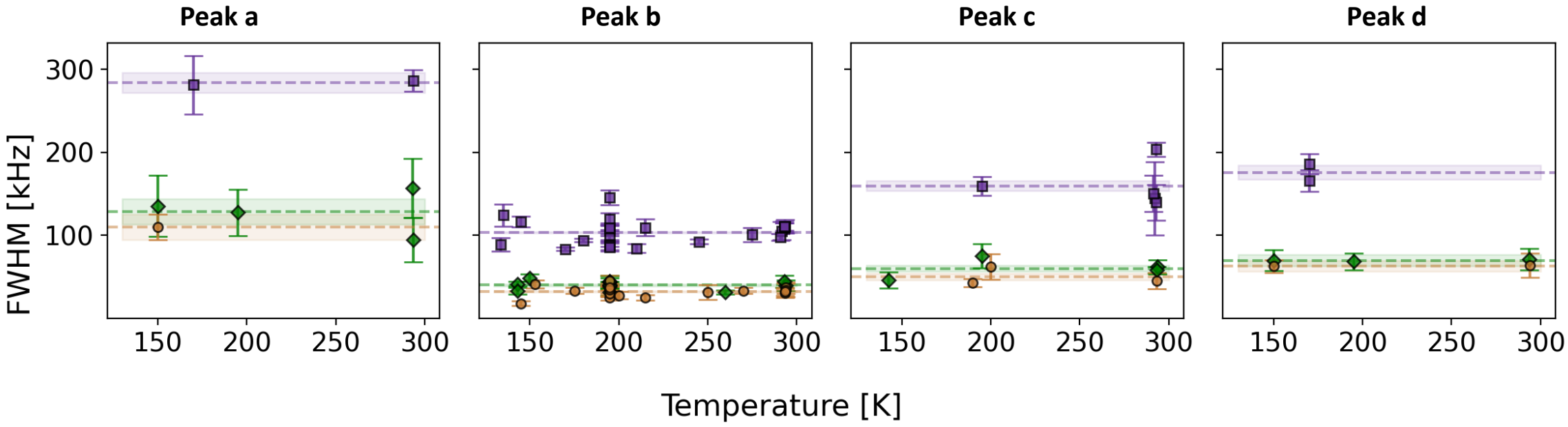
High resolution line shape and width





Linewidth of $^{229}Th:CaF_2$

Independent of temperature



Line-center & linewidth – "napkin" model

Line center: (Zhang *et al*. *Nature* (2024))

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

$$V_{zz} = 109.1\, V/A^2$$

$$\eta = \frac{V_{xx} - V_{yy}}{V_{zz}} = 0.59163$$

$$V_{xx} + V_{yy} + V_{zz} = 0$$

=>

$$V_{yy} = \frac{\eta + 1}{-2} V_{zz} = -86.82\, V/A^2$$

$$V_{xx} = -V_{yy} - V_{zz} = -22.28\, V/A^2$$

Linewidth:

δV_{zz} & δV_{yy} => inhomogeneous broadening

$$dv(V_{zz}, V_{yy}) = \frac{\partial v}{\partial V_{zz}} \Delta V_{zz} + \frac{\partial v}{\partial V_{yy}} \Delta V_{yy}$$

Linewidth of transition i:

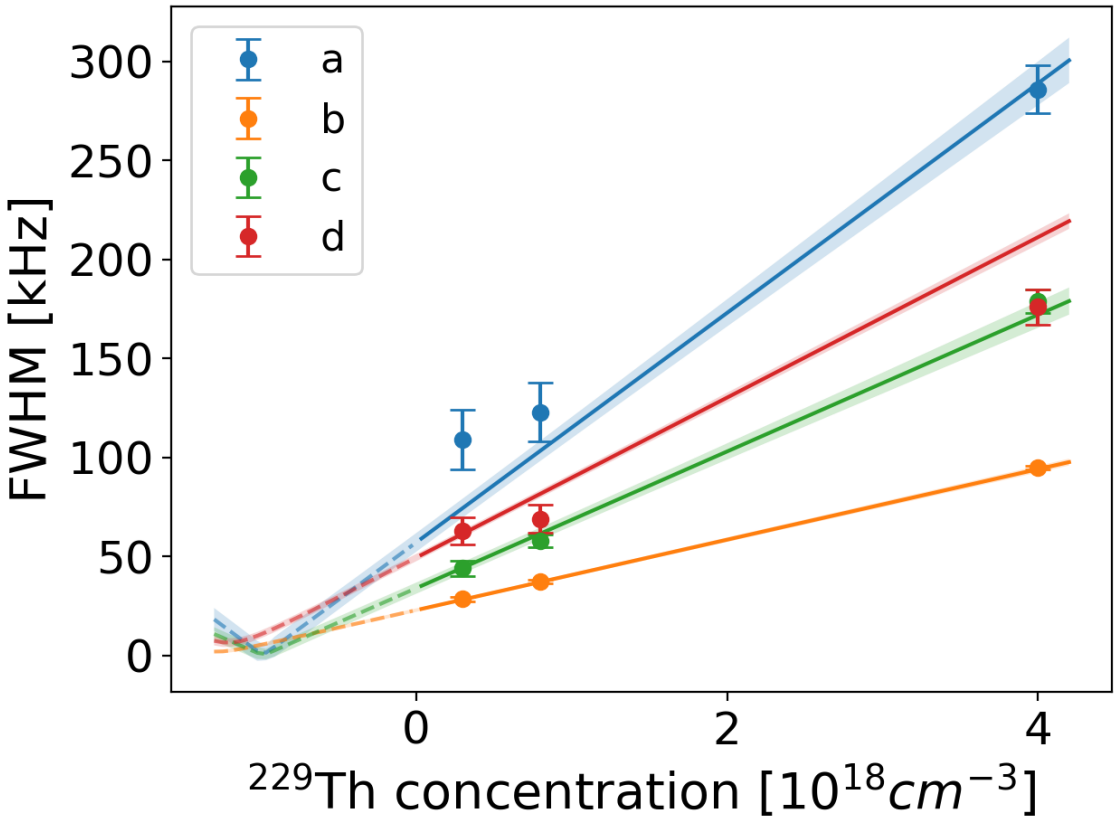
$$\mathrm{FWHM}^i = \sqrt{\left(\frac{\partial v_i}{\partial V_{zz}}\right)^2 \delta V_{zz}^2 + \left(\frac{\partial v_i}{\partial V_{yy}}\right)^2 \delta V_{yy}^2}$$

Minimize: $\chi^2 = \sum_{i=a}^{d} \left(\frac{FWHM_{measure}^i - FWHM_{fit}^i}{\delta FWHM_{measure}^i}\right)^2$

δV_{yy} / δV_{zz} $\approx$ 2 for all crystals

Reduced χ_v^2~ 2.28

Linewidth of $^{229}Th:CaF_2$ – "napkin" model

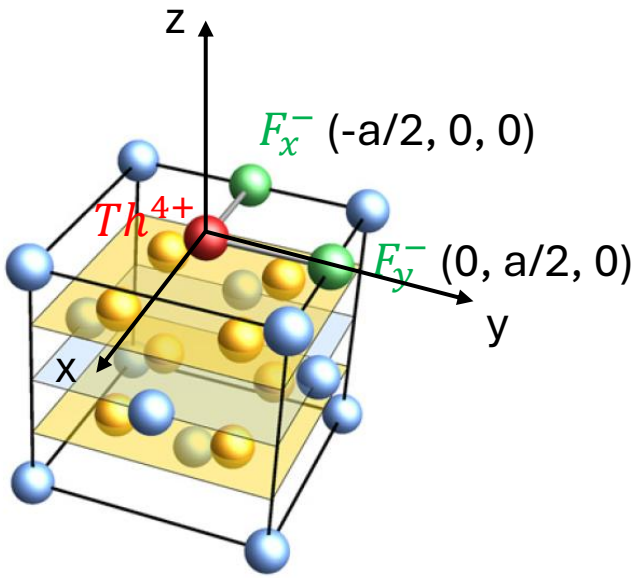


- E-field gradient inhomogeneous broadening fits data well
- A specific ratio of δV_{yy} / δV_{zz} (~2) across all 3 crystals
- δV_{zz} & δV_{yy} scale linearly with ^{229}Th doping concentration

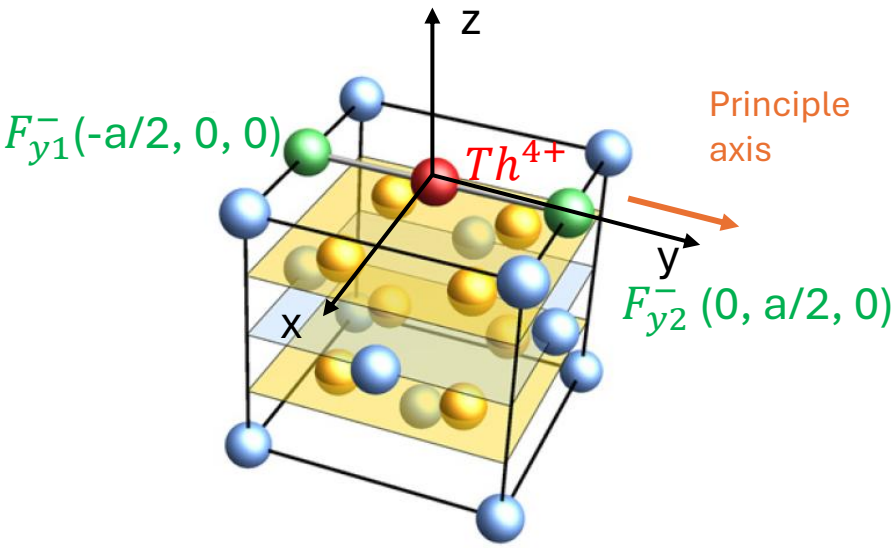
- Extrapolations to a single point, suggests "zero-doping" linewidth also ~ δV_{yy} / δV_{zz}
- Linewidth at the crossing point ~5 kHz, suggests homogeneous broadening

“napkin” model for doping configuration

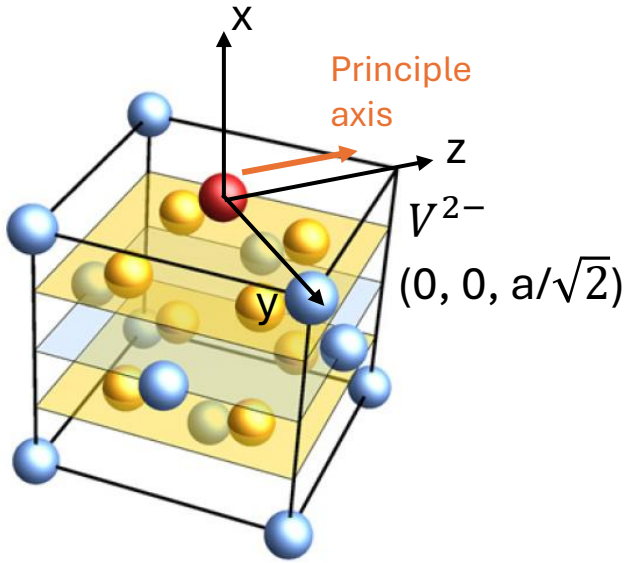
$(\delta V_{yy}/\delta V_{zz})$



$$\frac{\delta V_{yy}}{\delta V_{zz}} = \sqrt{\frac{5}{2}} \sim 1.6$$



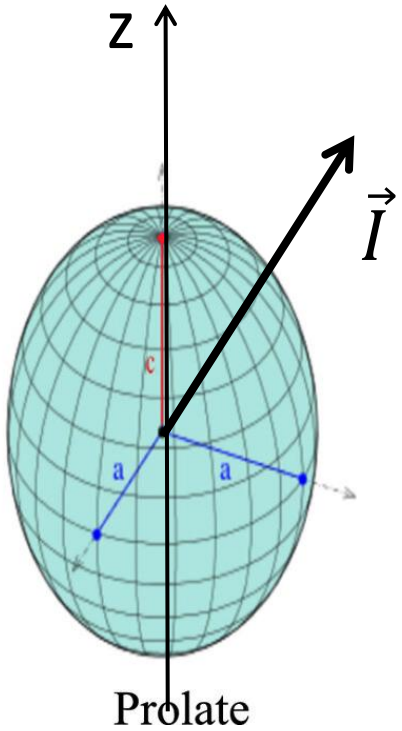
$$\frac{\delta V_{yy}}{\delta V_{zz}} = 0.5$$



$$\frac{\delta V_{yy}}{\delta V_{zz}} = 0.5$$

Nuclear structure to probe new physics beyond standard model

Beeks … Schumm, Ye, Safronova, Nature Comm. **16**, 9147 (2025).



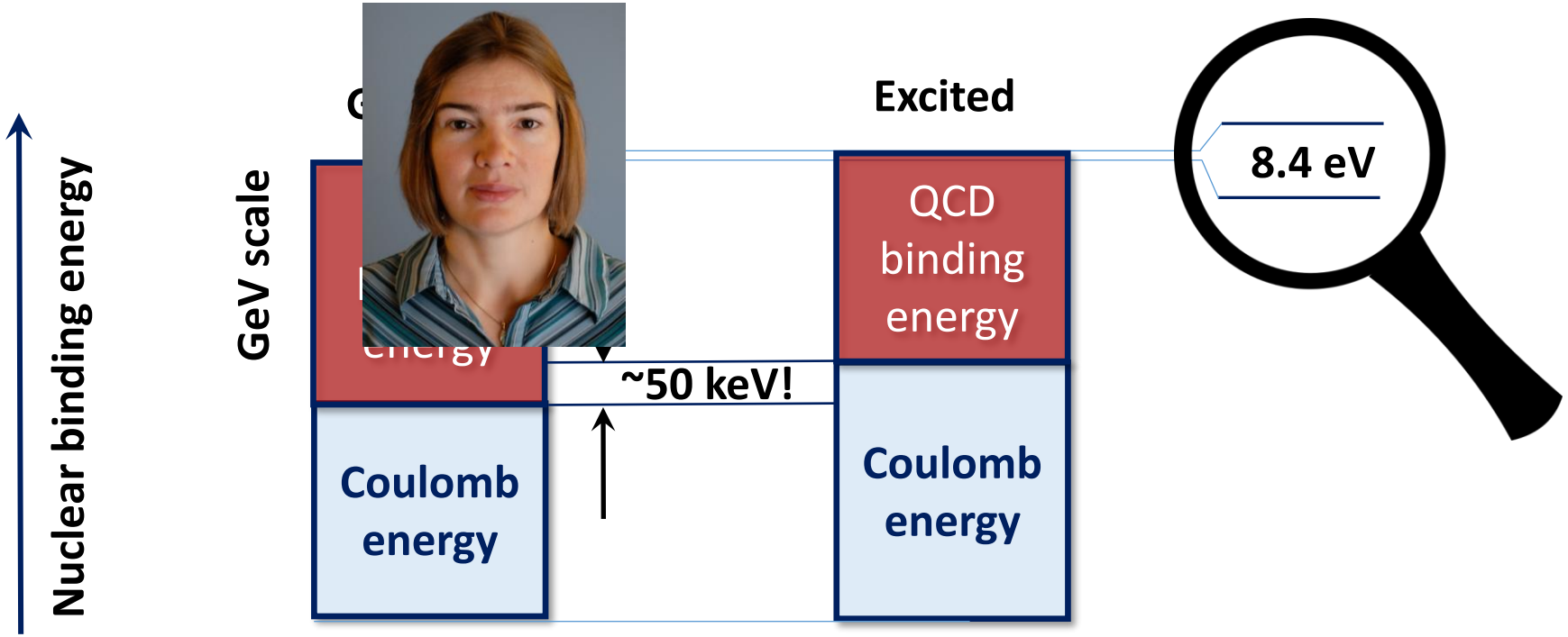
Quadrupole moment ratio

$$\frac{Q_{\rm is}}{Q_{\rm g}} = 1.01791(2)$$

$\Rightarrow$

Nuclear volume:

$$\frac{V_{\rm is}}{V_{\rm g}} = 1.00055$$



Coulomb interaction $\sim \alpha$

Strong force

Sensitivity to variation of α

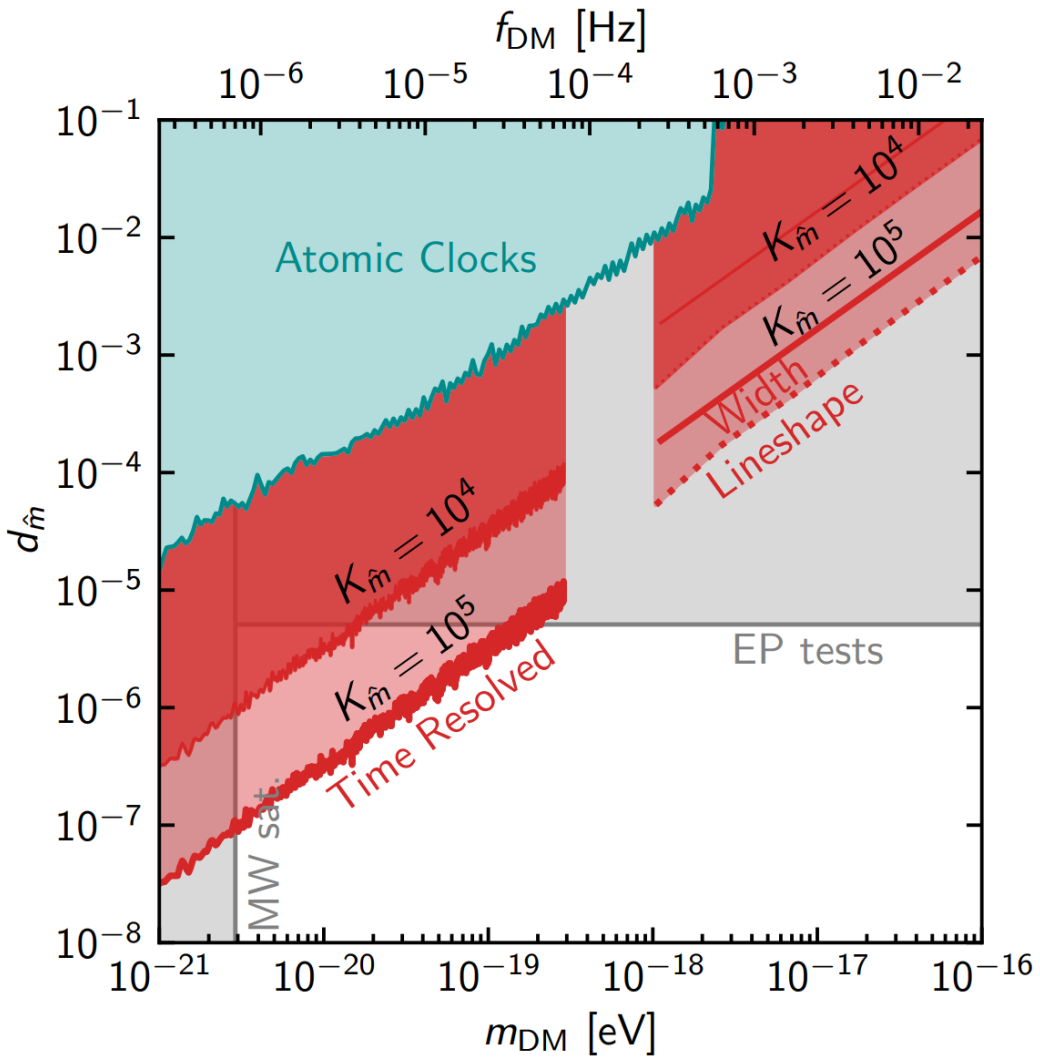
$$\frac{49(19)\ \text{keV}}{8.4\ \text{eV}} \sim 5900(2300)$$

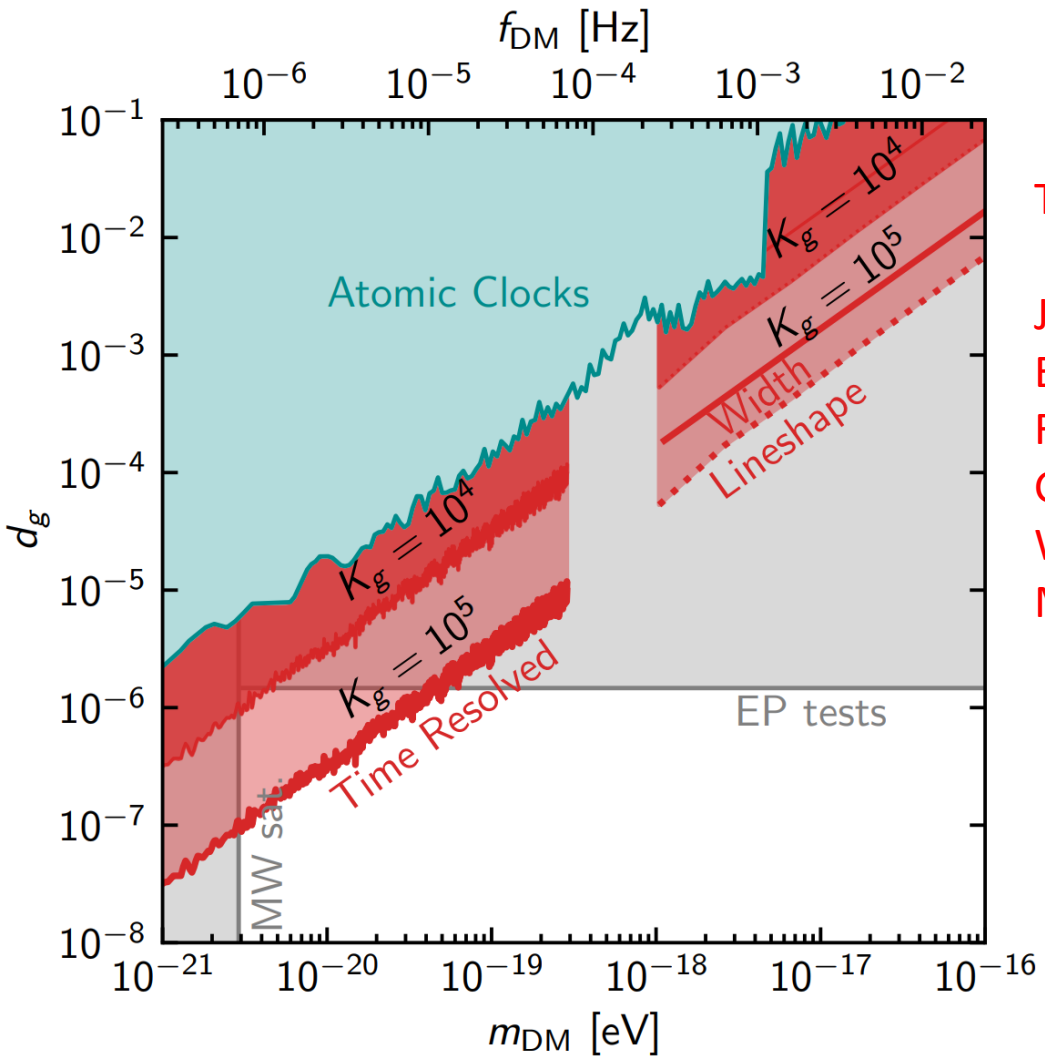
Probe of new physics

Arakawa *et al.*, Nature Comm. (2026)

Variation of α or QCD scale upsets cancellation between Coulomb & QCD → Enhanced sensitivity to new physics

Coupling of scalar DM to quark masses (left) and gluons (right).

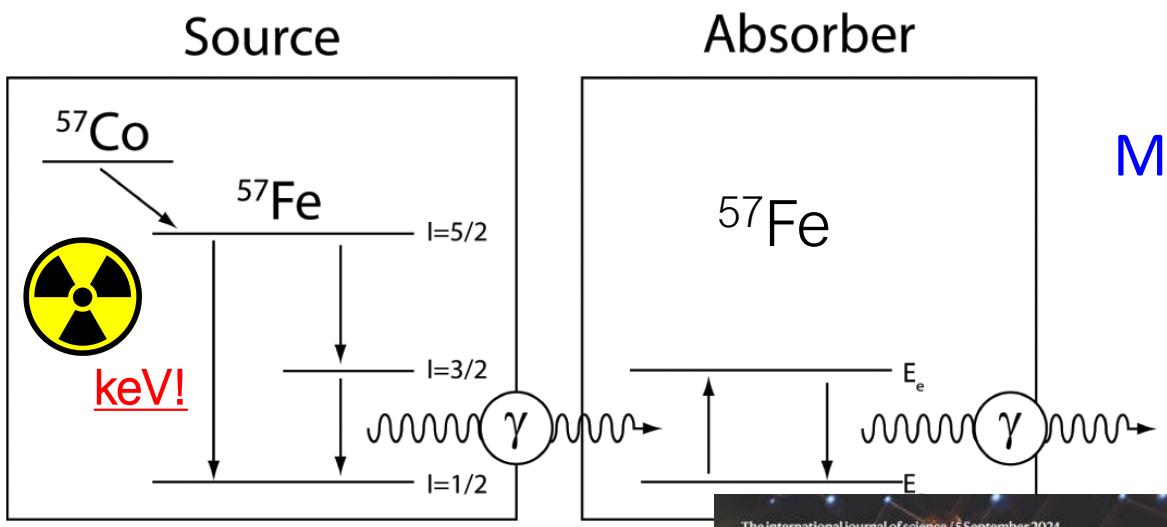




Theorists:

Jason Arakawa
Elina Fuchs
Fiona Kirk
Gilad Perez
Wolfram Ratzinger
Marianna Safronova

Precision sensing for fundamental physics



Mössbauer spectroscopy
nuclear transitions

Gravitational red shift measured with

PHYSICAL REVIEW LETTERS

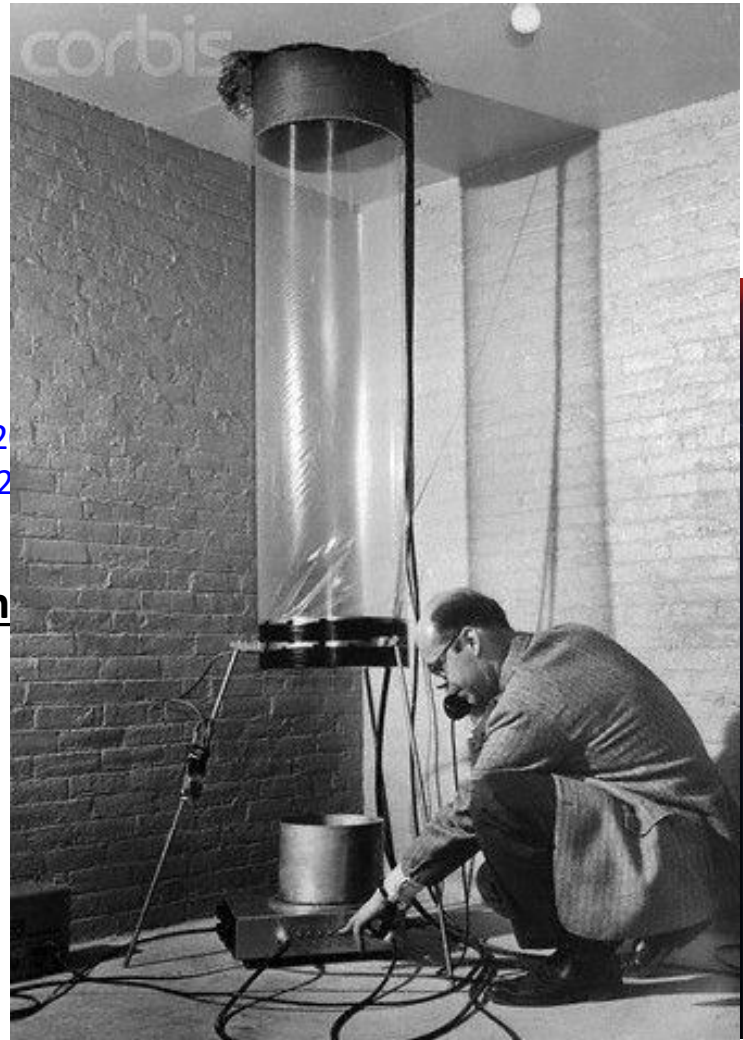
VOLUME 4 APRIL 1, 1960

APPARENT WEIGHT OF PHOTONS*

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

Bothwell *et al.*, Nature **602** 42
Zhang *et al.*, Nature **633**, 63 (2

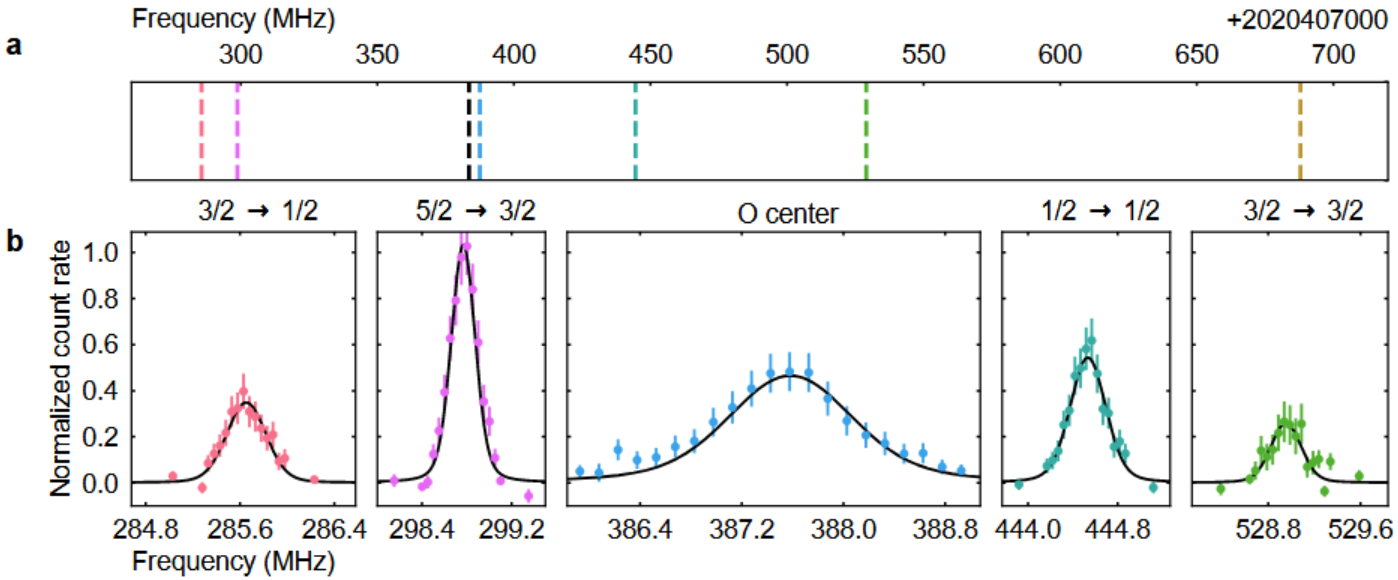
A nuclear-atomic conn



CW laser spectroscopy of ^{229}Th

Morawetz *et al.*, arXiv.2604.16640 (2026)

First cw laser absorption spectroscopy: Peik & Schumm collaboration



Hot off press on cw spectroscopy & laser lock:
Peik &Schumm, arXiv: 2606.04997v2
S. Ding, arXiv:2606.08870

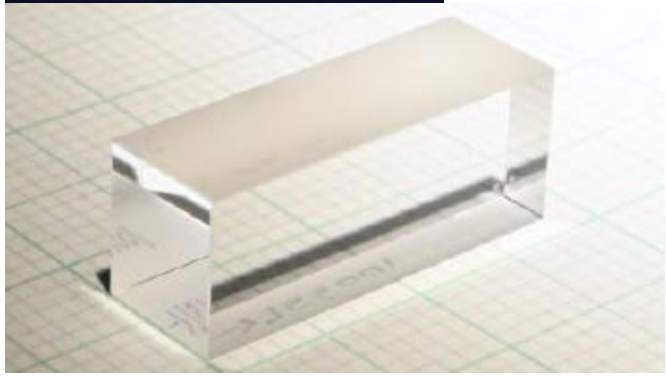
Morawetz 2026

2024 JILA data for comparison
Zhang … Ye, Nature **633**, 63 (2024).

All lineshapes are X2 at room temperature except for line d (green, 170 K)

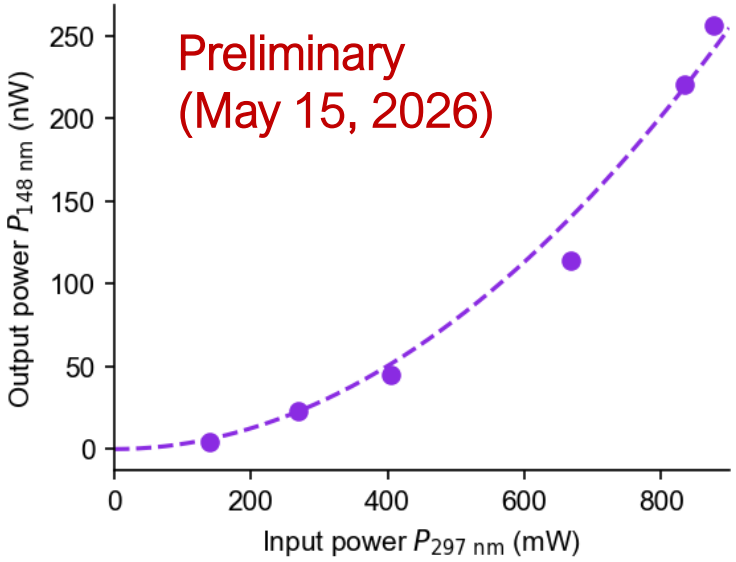
CW laser at 148 nm: 967 nW (JILA, May 29, 2026)

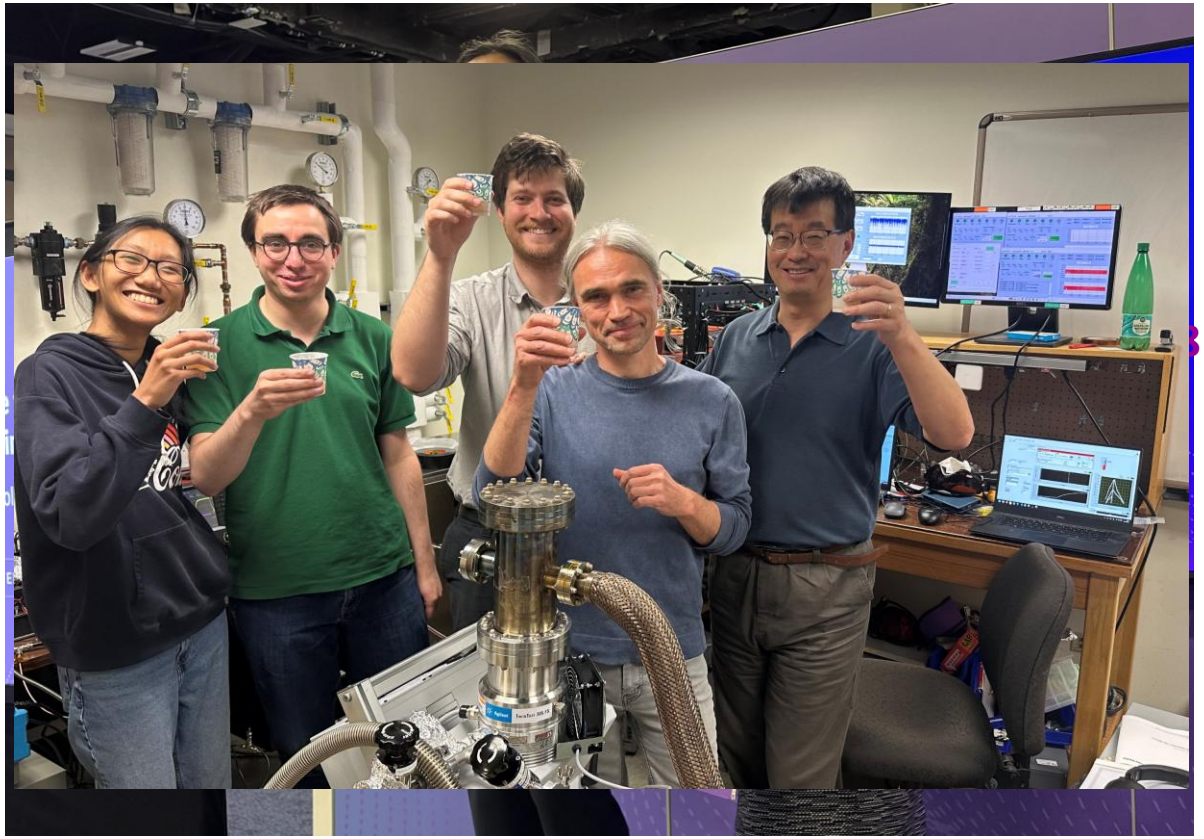
IPG Photonics: high $\chi^{(2)}$ QPM crystal (VUV transparency to 130 nm)



Vasilyev, Moskalev, Ooi, Mirov ... Ye, Photonics West, January 2026, Paper 13877-61
Ooi, Vasilyev, …, Mirov, Ye, CLEO Post-deadline paper, May 17-21, 2026

Tian Ooi, CLEO 2026 Science Slam Winner

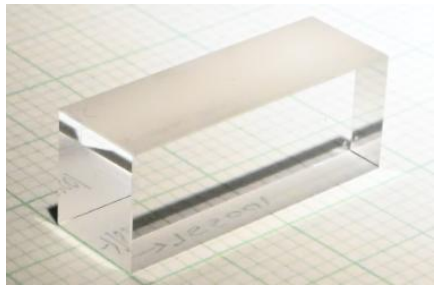




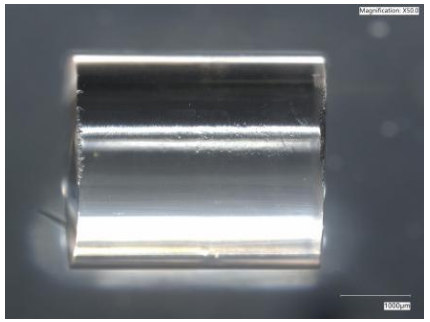
3 nm

Future of nuclear clocks

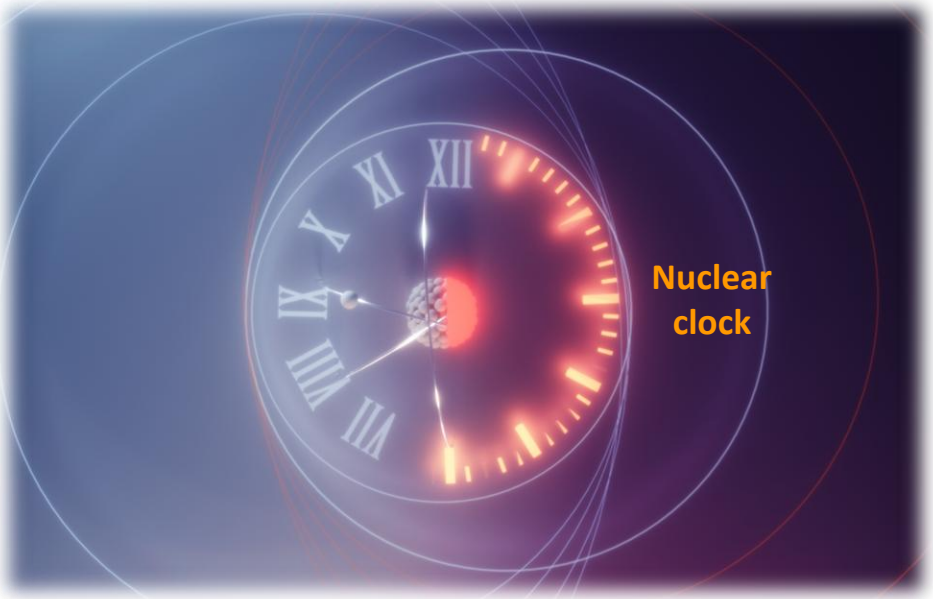
New 148 nm VUV laser
(1 μW CW)



+



^{229}Th:CaF_2 crystal
~10^{15} ^{229}Th nuclei!

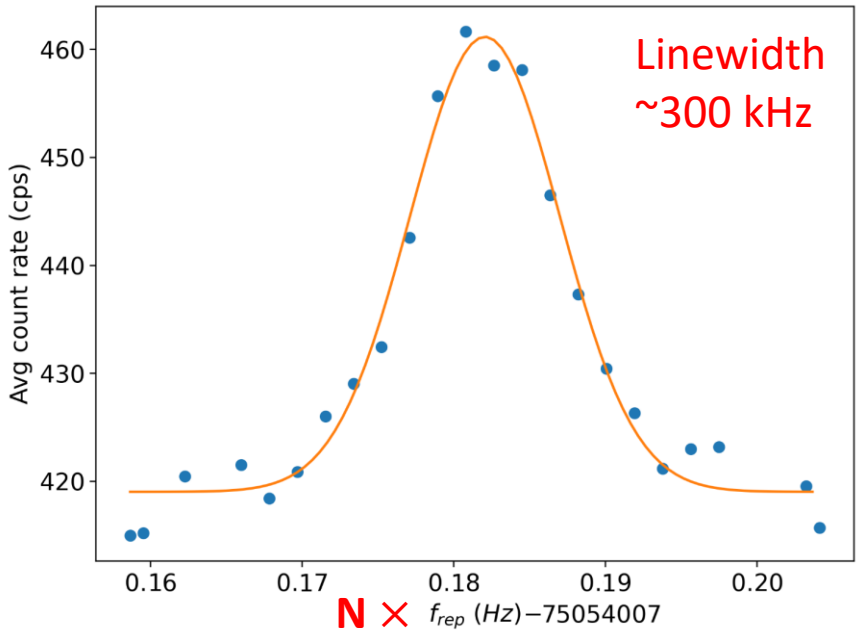


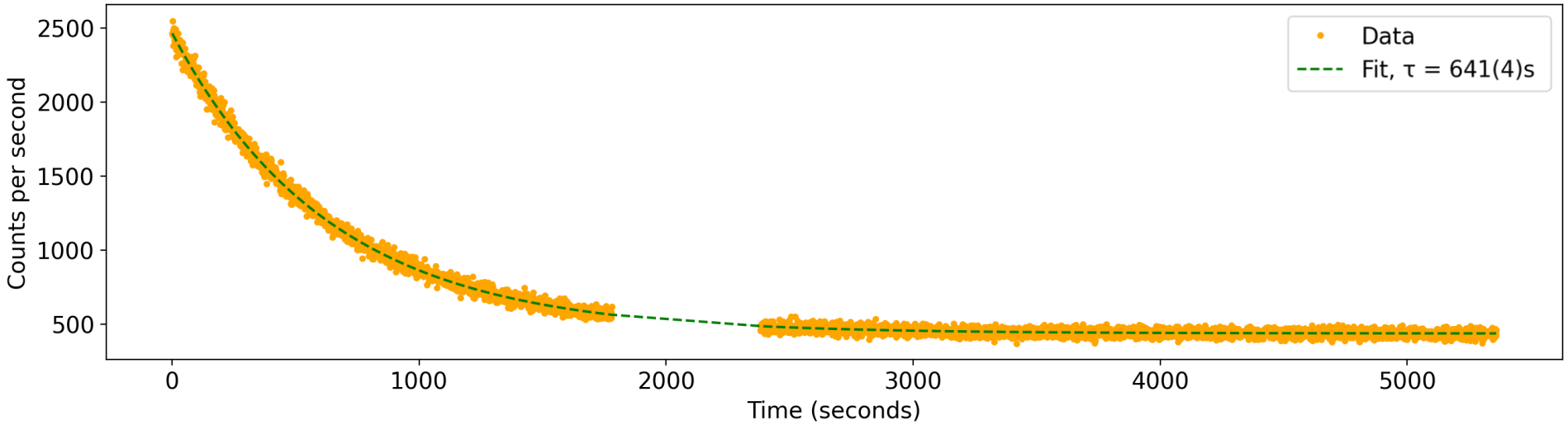
- Next-generation compact, fieldable optical clock
- Coherent control of the nucleus
- Fundamental physics

A NIST video on nuclear clock

(Sean Kelley, Gabe Popkin, Jose Garcia, Ben Stein, Jun Ye)

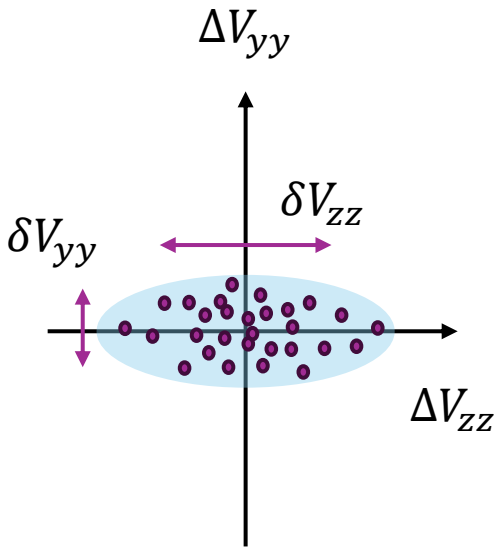
High resolution line-shape and decay lifetime

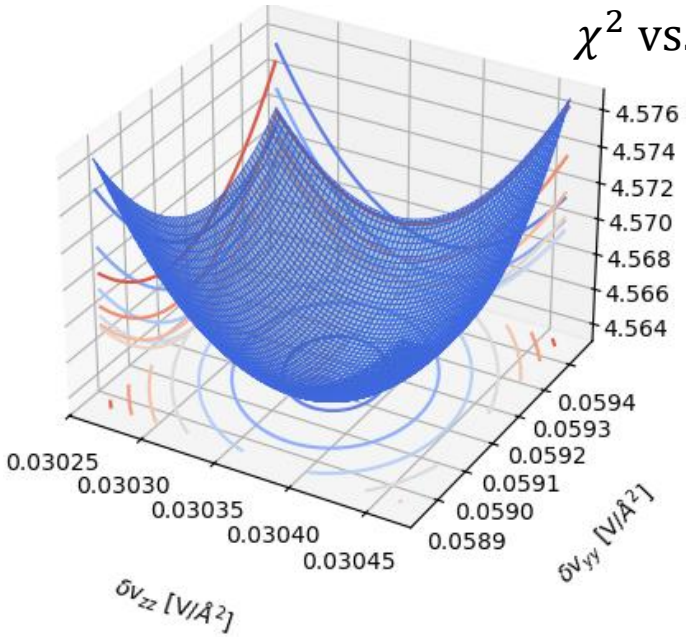




Linewidth of ^{229}Th:CaF_2 – "napkin" model

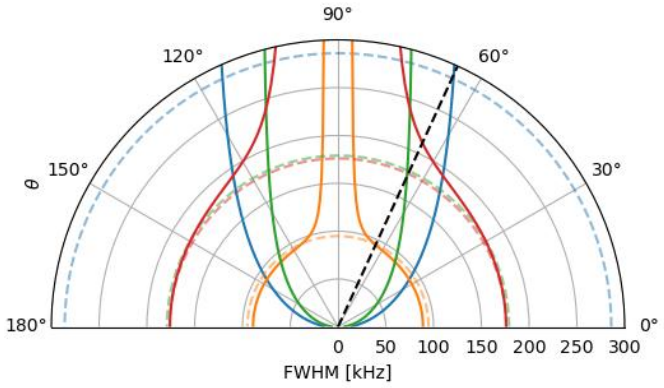
δV_{yy} / δV_{zz} ≈ 2 for all crystals



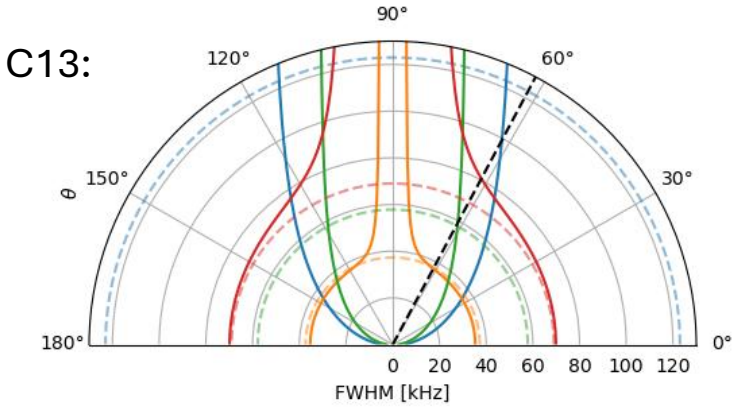


Reduced χ_v^2~ 2.28

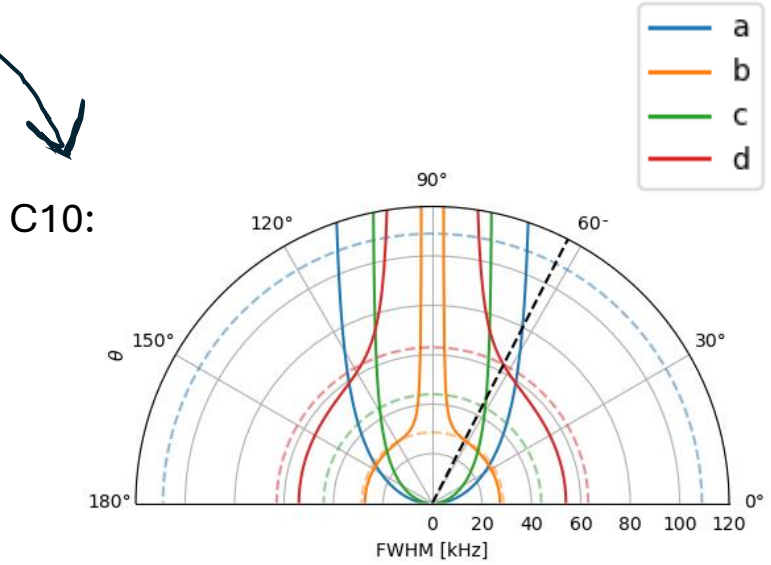
$$\mathrm{FWHM} = \sqrt{\left(\left(\frac{\partial v}{\partial V_{zz}}\right)^2 + \left(\frac{\partial v}{\partial V_{yy}}\right)^2 \tan\theta^2\right)\delta V_{zz}^{opt.2}}$$



Optimum angle:
$\theta = \tan^{-1}(\delta V_{yy}/\delta V_{zz})$ ~ 65°



Optimum angle:
$\theta = \tan^{-1}(\delta V_{yy}/\delta V_{zz})$ ~ 62°

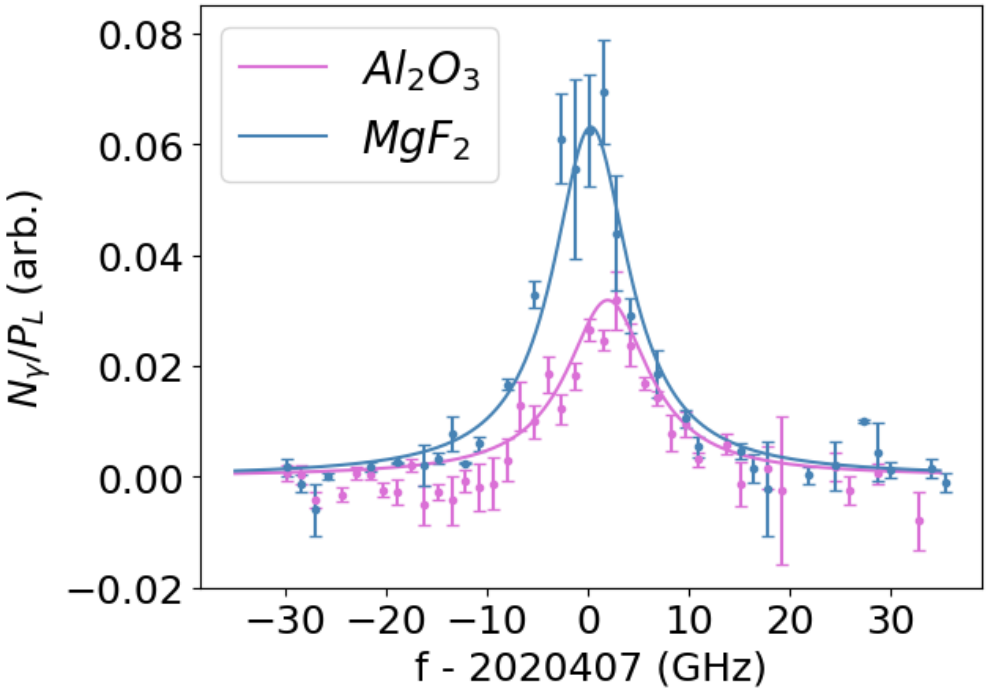


Optimum angle:
$\theta = \tan^{-1}(\delta V_{yy}/\delta V_{zz})$ ~ 63°

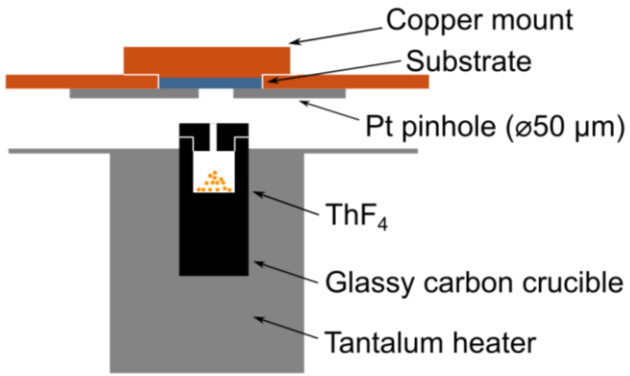
JILA ThF_4 thin film-based nuclear transition

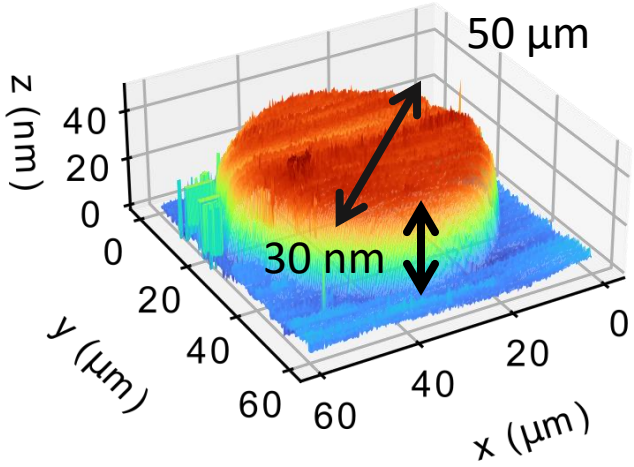
Zhang, von der Wense, … , Ye, Derevianko, Hudson, Nature **636**, 603 (2024).

Eric Hudson (UCLA)



Pure $^{229}ThF_4$ vapor deposition

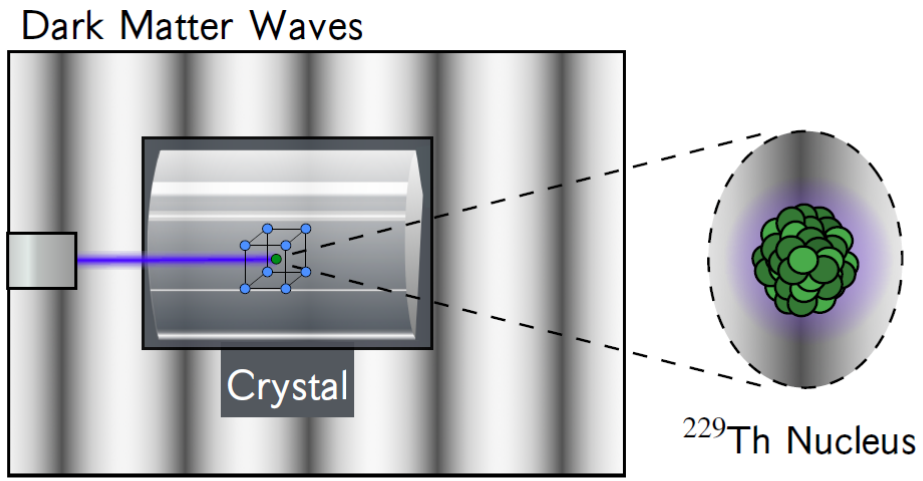


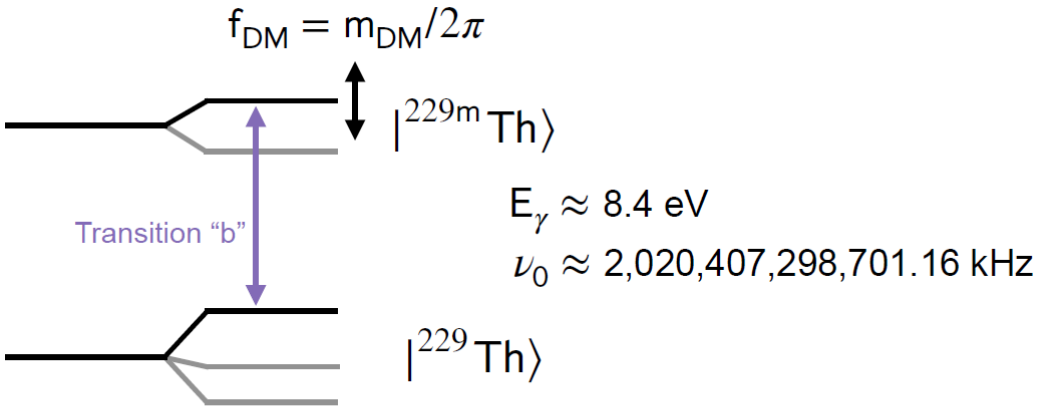


✓ Efficient use of material! (µg)

? Narrow line transition not yet observed

Probe of new physics





$E_\gamma \approx 8.4$ eV

$\nu_0 \approx 2{,}020{,}407{,}298{,}701.16$ kHz

Linewidth of the ^{229}Th transitions - model

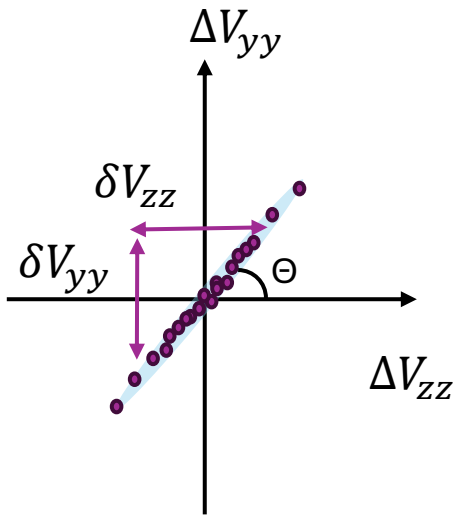
$$dv(V_{zz}, V_{yy}) = \frac{\partial v}{\partial V_{zz}} \Delta V_{zz} + \frac{\partial v}{\partial V_{yy}} \Delta V_{yy} \quad \Rightarrow \quad \mathrm{FWHM} = \left\| \left(\frac{\partial v}{\partial V_{zz}} + \frac{\partial v}{\partial V_{yy}} \tan\theta \right) \delta V_{zz} \right\|$$

$$\tan\theta = \delta V_{yy} / \delta V_{zz}$$

Minimize: $\chi^2 = \sum_{i=1}^{4} \left(\frac{FWHM^i_{measure} - FWHM^i_{fit}}{\delta FWHM^i_{measure}} \right)^2$

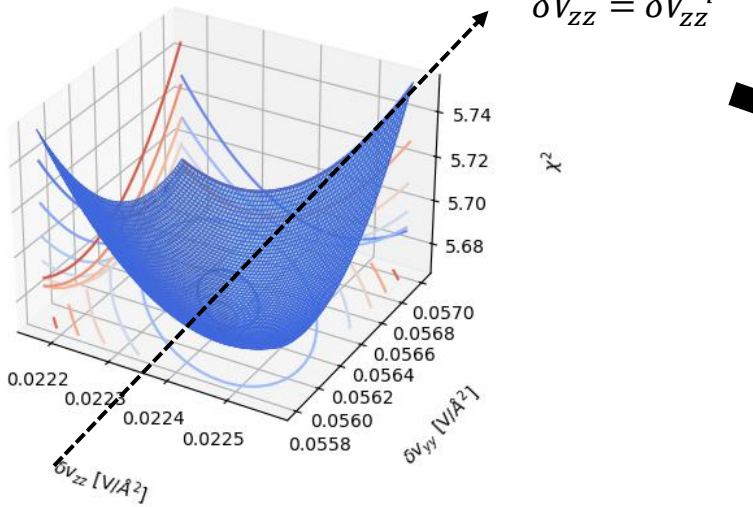
FWHM along optimized δV_{zz}

$$\mathrm{FWHM} = \left\| \left(\frac{\partial v}{\partial V_{zz}} + \frac{\partial v}{\partial V_{yy}} \tan\theta \right) \delta V_{zz}^{opt.} \right\|$$

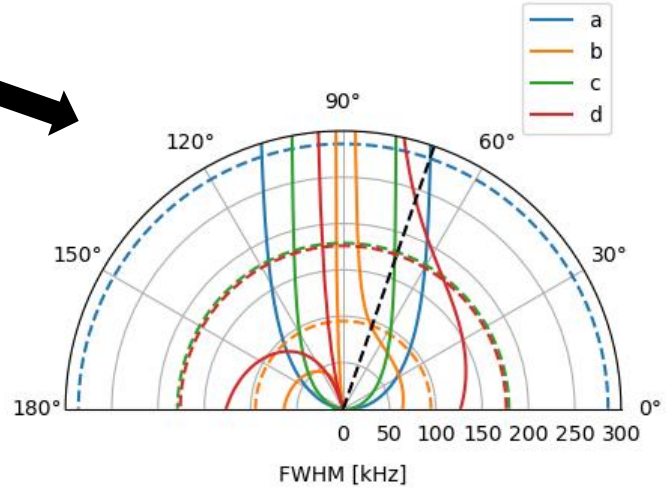


δV_{zz} & δV_{yy} correlated model

C10: χ^2 VS δV_{zz} & δV_{yy}



Minimum χ^2 ~ 5.67
Reduced χ^2_v ~ 2.83



Optimum angle:
Θ=arctan(δV_{zz} / δV_{yy}) ~ 71°

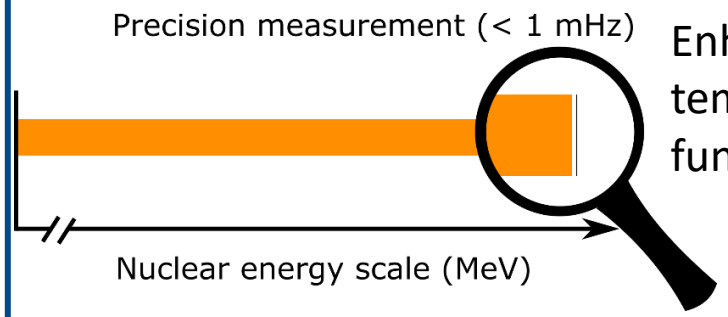
New opportunities with a ^{229m}Th nuclear clock

Accurate nuclear-based optical clock

Quality factor Q~10^{19}
Resistent to external perturbations
10^{-19} potential clock accuracy

E. Peik et al., Europhys. Lett. **61,** 181 (2003)
C. J. Campbell et al., Phys. Rev. Lett. **108,** 120802 (2012)

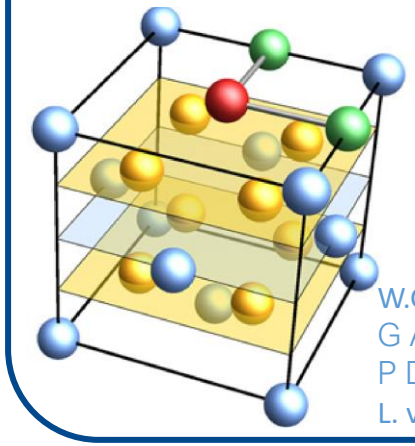
Sensitive probe for fundamental physics



Enhanced sensitivity for temporal variation of fundamental constants

V. V. Flambaum, Phys. Rev. Lett. **97,** 092502 (2006)
P, Fadeev et al., Phys. Rev. A **102,** 052833 (2020)

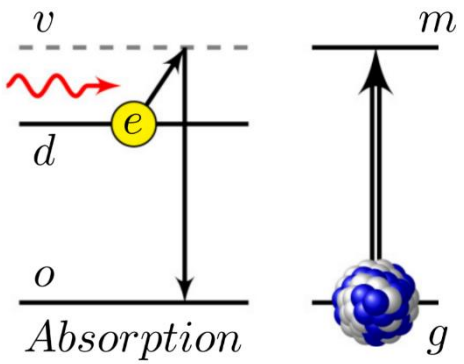
Solid-state optical clock



Decoupled from electronic states
Good statistics for high performance
Portable clock

W.G. Rellergert et al., Phys. Rev. Lett. **104,** 200802 (2010)
G A Kazakov et al., New J. Phys. **14,** 083019 (2012)
P Dessovic et al J. Phys.: Condens. Matter **26** (2014)
L. v.d.Wense et al., Eur. Phys. J. D **74,** 146 (2020)

A new quantum degree of freedom



New probe for coupling between nuclear and electronic states

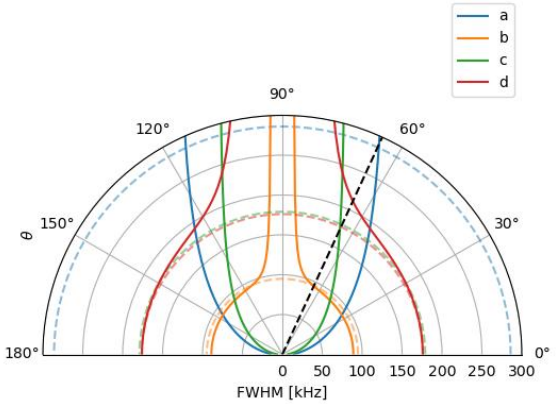
B. S. Nickerson et al., Phys. Rev. A **103,** 053120 (2021)

Fit FWHM with δV_{zz} & δV_{yy} uncorrelated model

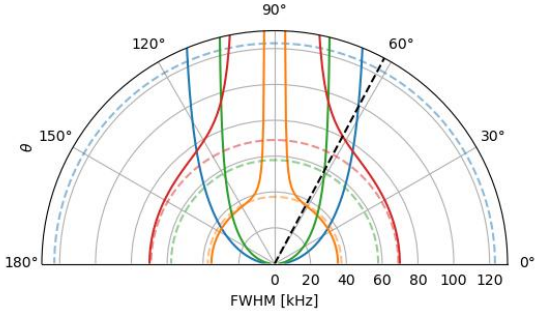
Optimized solution

FWHM equation plotted

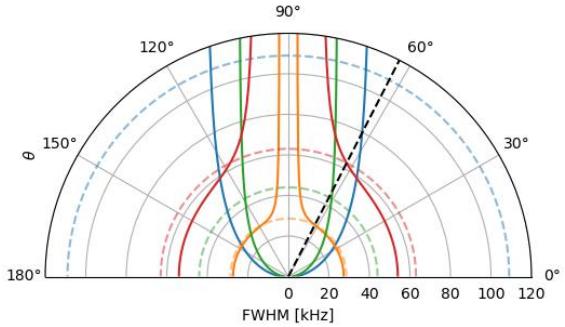
X2:



C13:



C10:



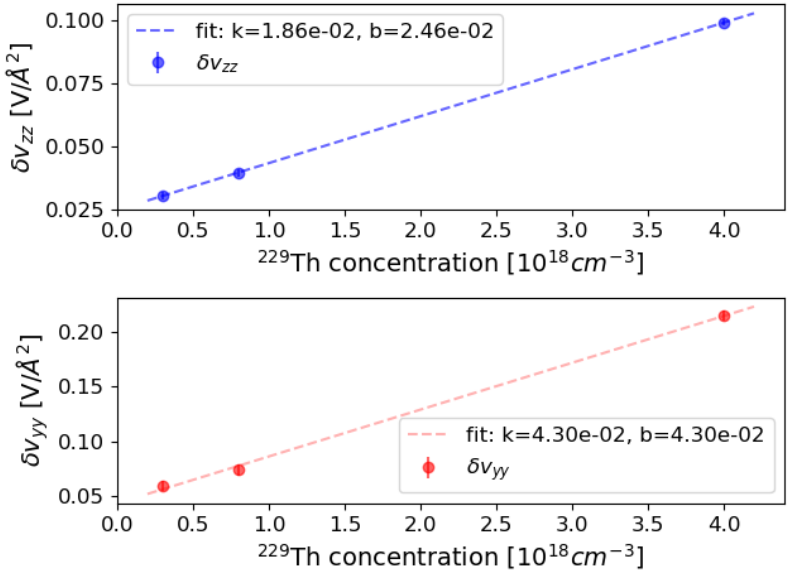
For X2, C13, C10 crystal:

Optimized Θ=[65, 62, 63] deg.

Minimized χ^2 = [17.30, 5.59, 4.56]

Reduced χ_v^2 = [8.65, 2.79, 2.28]

$$\mathrm{FWHM} = \sqrt{\left(\frac{\partial v}{\partial V_{zz}}\right)^2 \delta V_{zz}^2 + \left(\frac{\partial v}{\partial V_{yy}}\right)^2 \delta V_{yy}^2}$$



Model prediction VS data