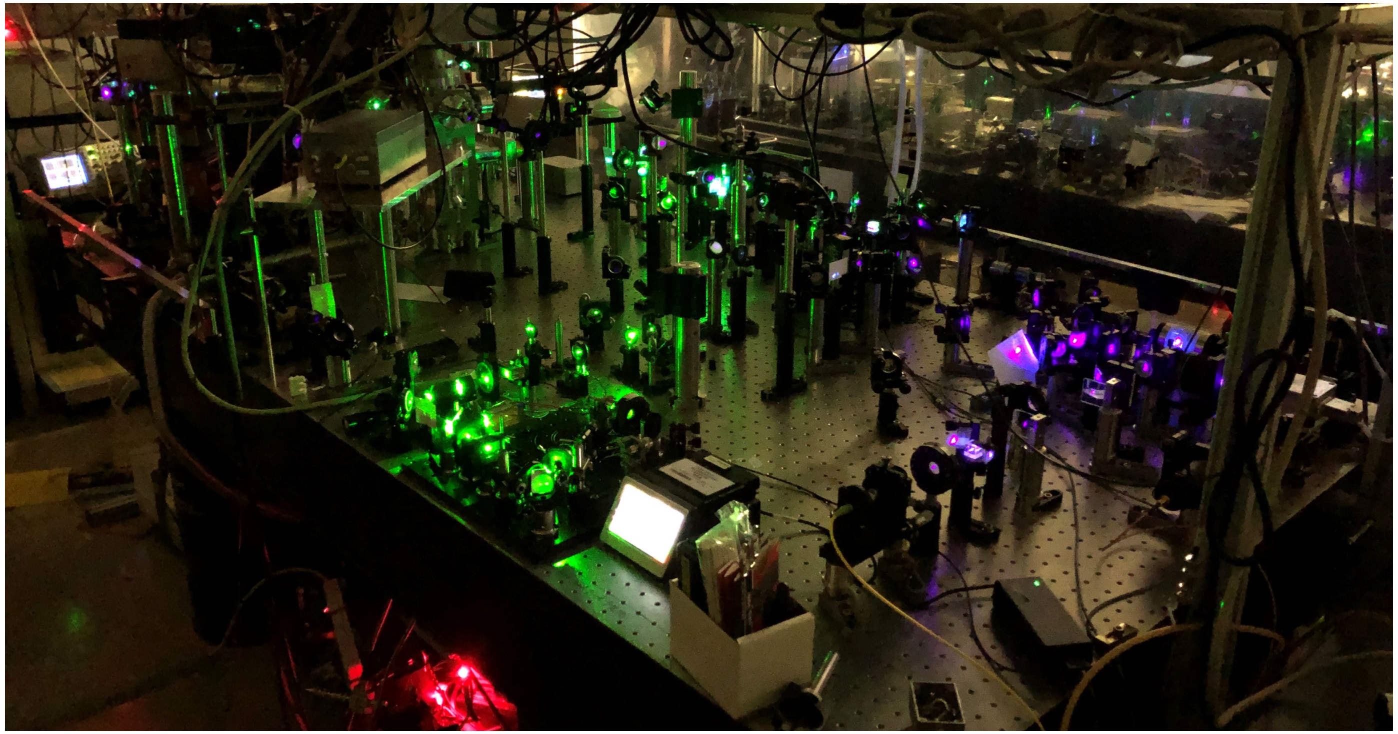
C01: Physics of Cosmogenesis Investigated with Atomic Clocks



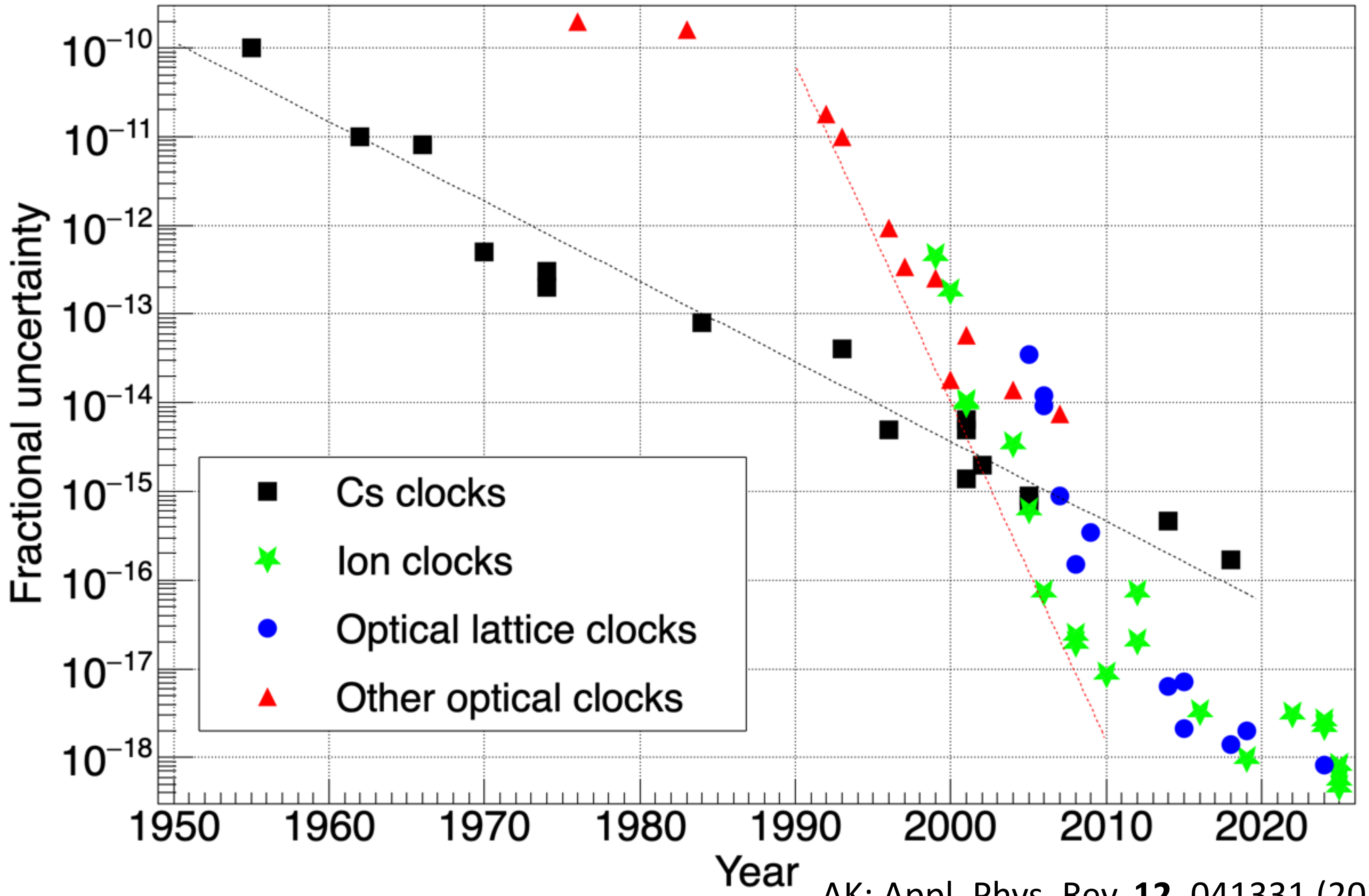
Akio Kawasaki

National Metrology Institute of Japan

National Institute of Advanced Industrial Science and Technology

Introduction to Fundamental Physics Searches Using Precision Spectroscopy

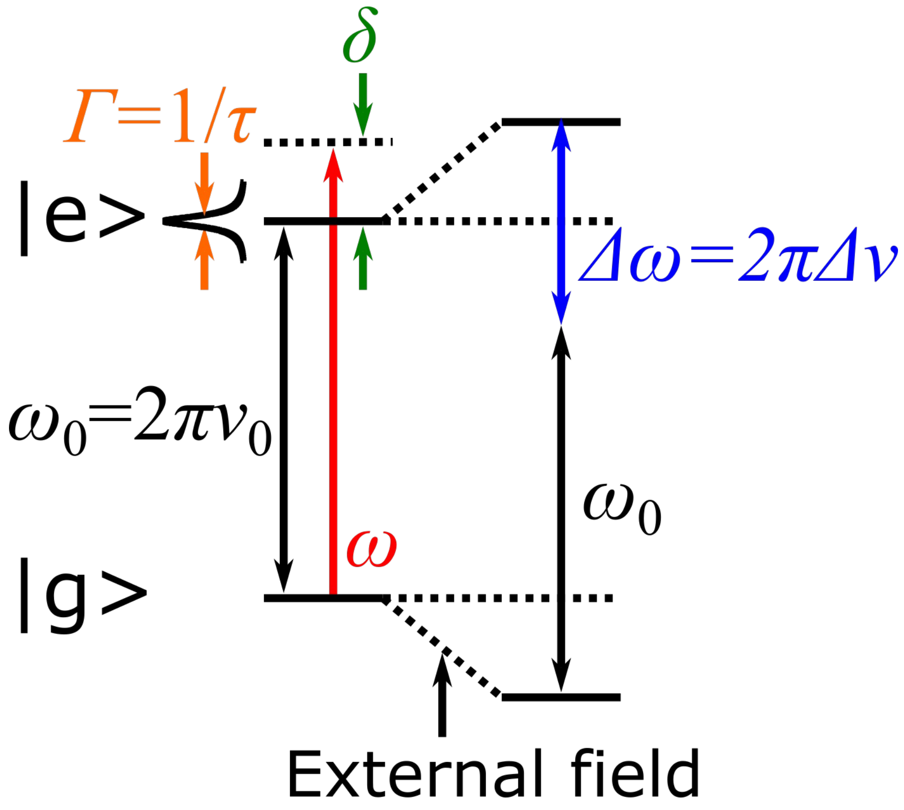
Accuracy of Atomic Clocks



AK: Appl. Phys. Rev. **12**, 041331 (2025)

Two-level under External Field

- In general, when an atomic system is under an external field, its energy levels are perturbed.
- Examples of external fields
  electric field = Stark shift
    Static electric field ⇒ DC Stark shift
    Oscillating electric field ⇒ AC Stark shift
  magnetic field = Zeeman shift
- These shifts are minimized in the state-of-art atomic clock.
- In this situation, the system is potentially sensitive to exotic external fields.



How to Observe a Change in α

- Energy level of hydrogen by Schrödinger equation (nonrelativistic):

$$E_n = -\frac{1}{2} m_e c^2 \alpha^2 \frac{1}{n^2}$$

  m_e: electron mass

  c: speed of light

  α: fine structure constant

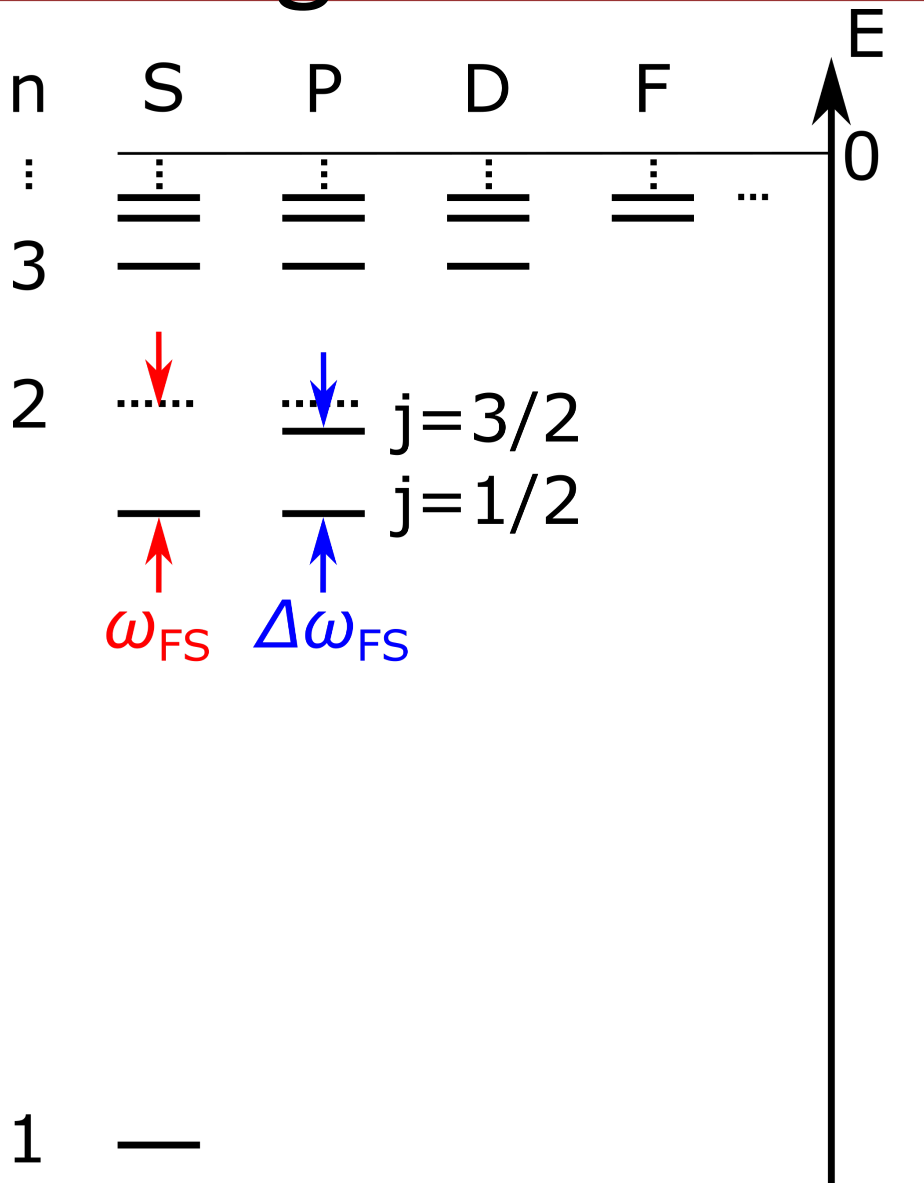
- By Dirac equation (relativistic):

$$\omega_{\mathrm{FS}} = -\frac{1}{2n^4} m_e c^2 \alpha^4 \left(\frac{n}{j+1/2} - \frac{3}{4}\right)$$

$$\Delta\omega_{\mathrm{FS}} = \frac{1}{32} m_e c^2 \alpha^4$$: fine structure

$$\frac{\Delta\omega_{\mathrm{FS}}}{E_2 - E_1} \sim \alpha^2$$

$$\alpha \rightarrow \alpha + \delta\alpha \Rightarrow \delta\left(\frac{\Delta\omega_{\mathrm{FS}}}{E_2 - E_1}\right) \sim 2\delta\alpha$$



Sensitivity to Variation of α

Atom	Transition	ν (THz)	K
^{87}Rb	Ground state hyperfine		0.34
^{133}Cs	Ground state hyperfine		0.83
Al^+	$3s^1\ ^1S_0$ - $3s3p\ ^3P_0$	1121	0.008
Ca^+	$4s\ ^2S_{1/2}$ - $3d\ ^2D_{5/2}$	411	0.15
Sr	$5s^2\ ^1S_0$ - $5s5p\ ^3P_0$	429	0.06
Sr^+	$5s\ ^2S_{1/2}$ - $4d\ ^2D_{5/2}$	445	0.43
Yb	$6s^2\ ^1S_0$ - $6s6p\ ^3P_0$	518	0.31
Yb	$6s^2\ ^1S_0$ - $4f^{13}5d6s$ (J=2)	695	-3.82
Yb^+	$4f^{14}6s\ ^2S_{1/2}$ - $4f^{14}5d\ ^2D_{3/2}$	688	1.00
Yb^+	$4f^{14}6s\ ^2S_{1/2}$ - $4f^{13}6s^2\ ^2F_{7/2}$	642	-5.95
Hg^+	$6s\ ^2S_{1/2}$ - $5d\ ^2D_{5/2}$	1065	-2.94
Y^+	$5s^2\ ^1S_0$ - $4d5s\ ^3D_1$	25.2	9.40
Ac^+	$7s^2\ ^1S_0$ - $6d7s\ ^3D_1$	142	9.73

$$\frac{\delta\nu}{\nu} = \frac{2q}{h\nu}\frac{\delta\alpha}{\alpha} = K\frac{\delta\alpha}{\alpha}$$

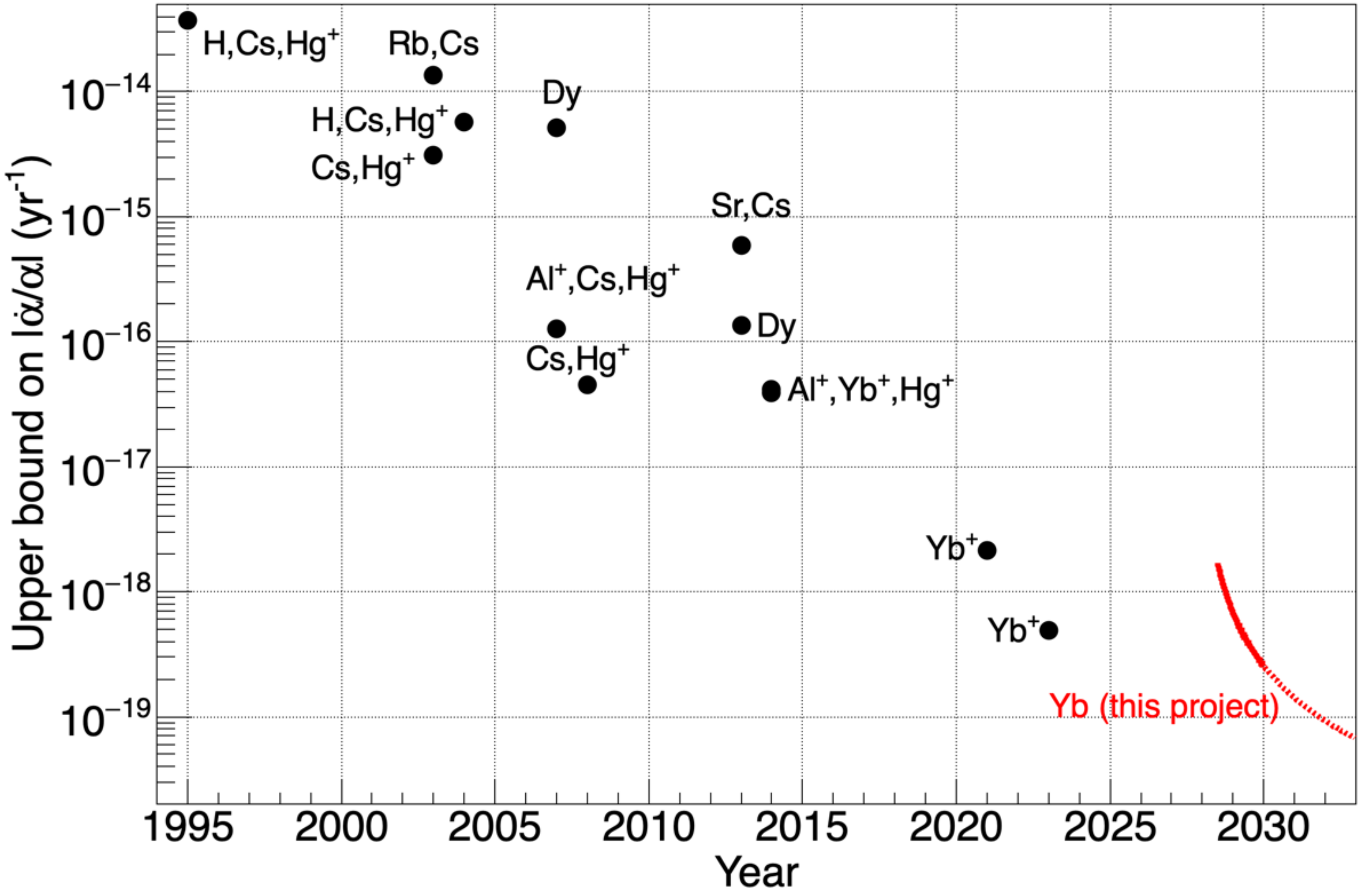
Dzuba, *et al.*: Phys. Rev. A **98**, 022501 (2018)
Safronova, *et al.*: Rev. Mod. Phys. **90**, 025008 (2018)

: New result from our project!

AK: arXiv:2606.29676 (2026)

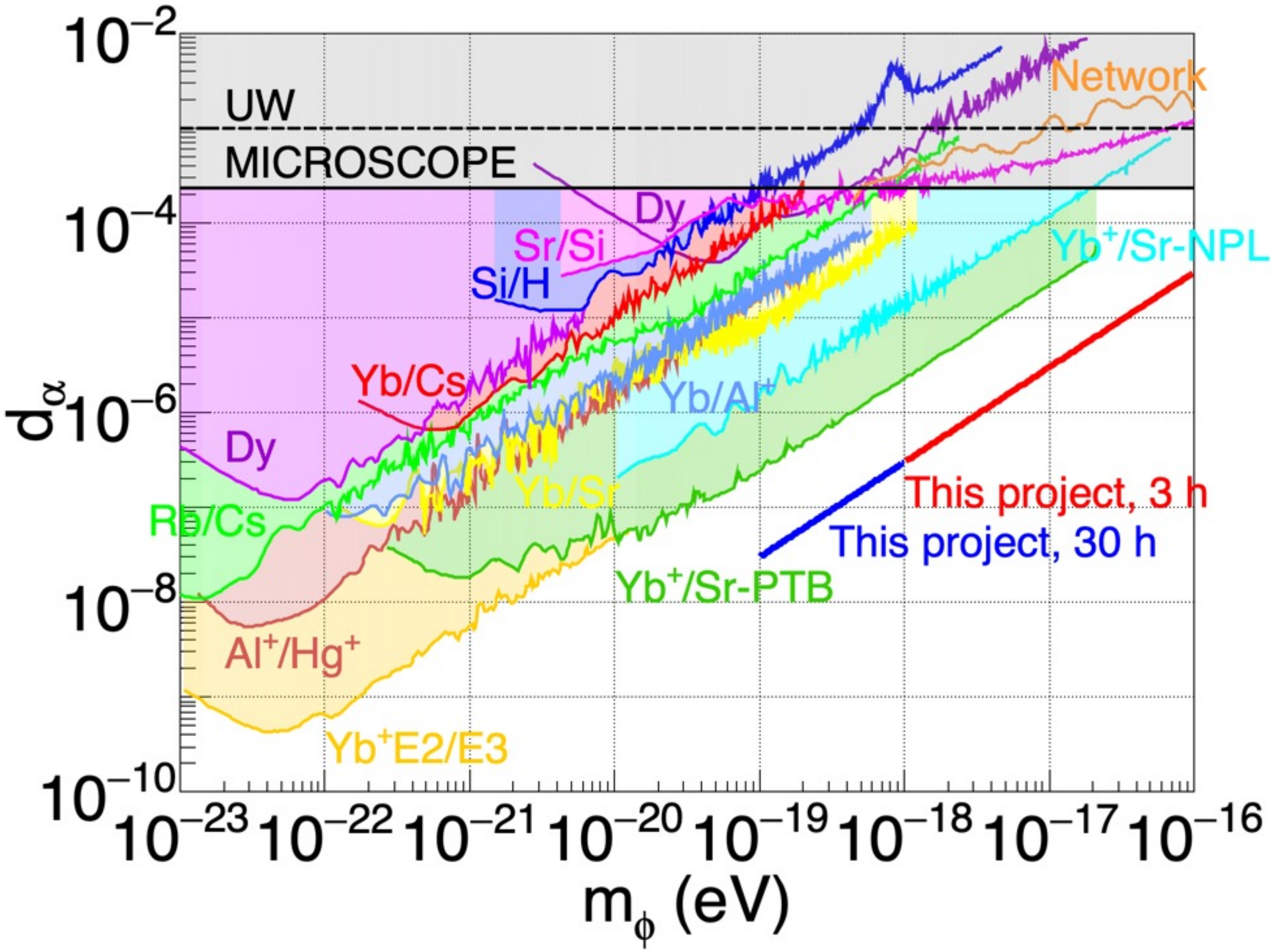
Expected Sensitivity in this Project

- Assuming stability of $10^{-16}/\sqrt{\tau}$ and 3h operation of the comparison between the 578 nm and 431 nm transition frequencies, we can expect the best constraint in a few years.



Expected Sensitivity in this Project

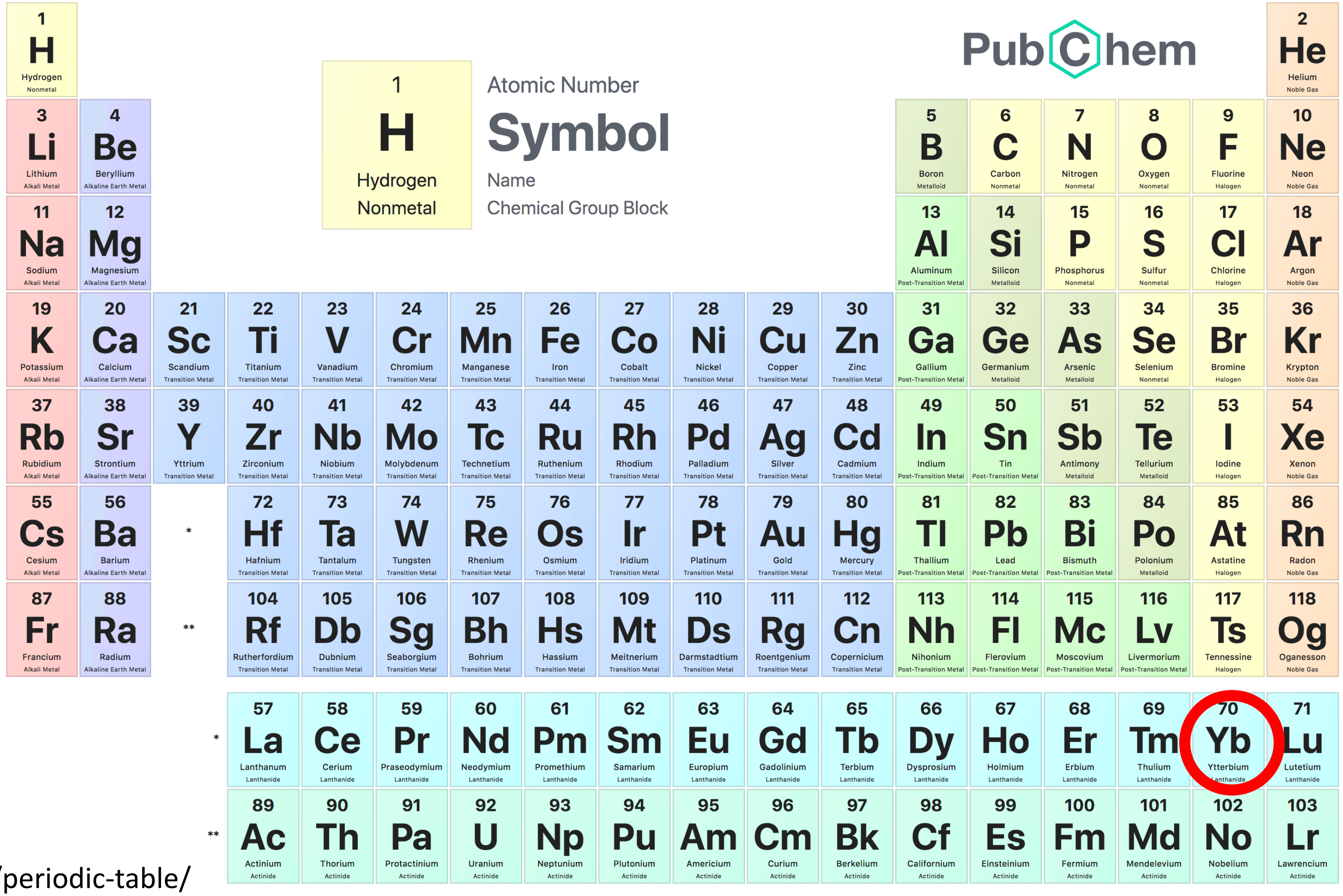
- Optical lattice clocks have an advantage of high short-term stability.
- Stability of $10^{-16}/\sqrt{\tau}$ is assumed.



Precision Spectroscopy of the 431 nm Transition in Ytterbium

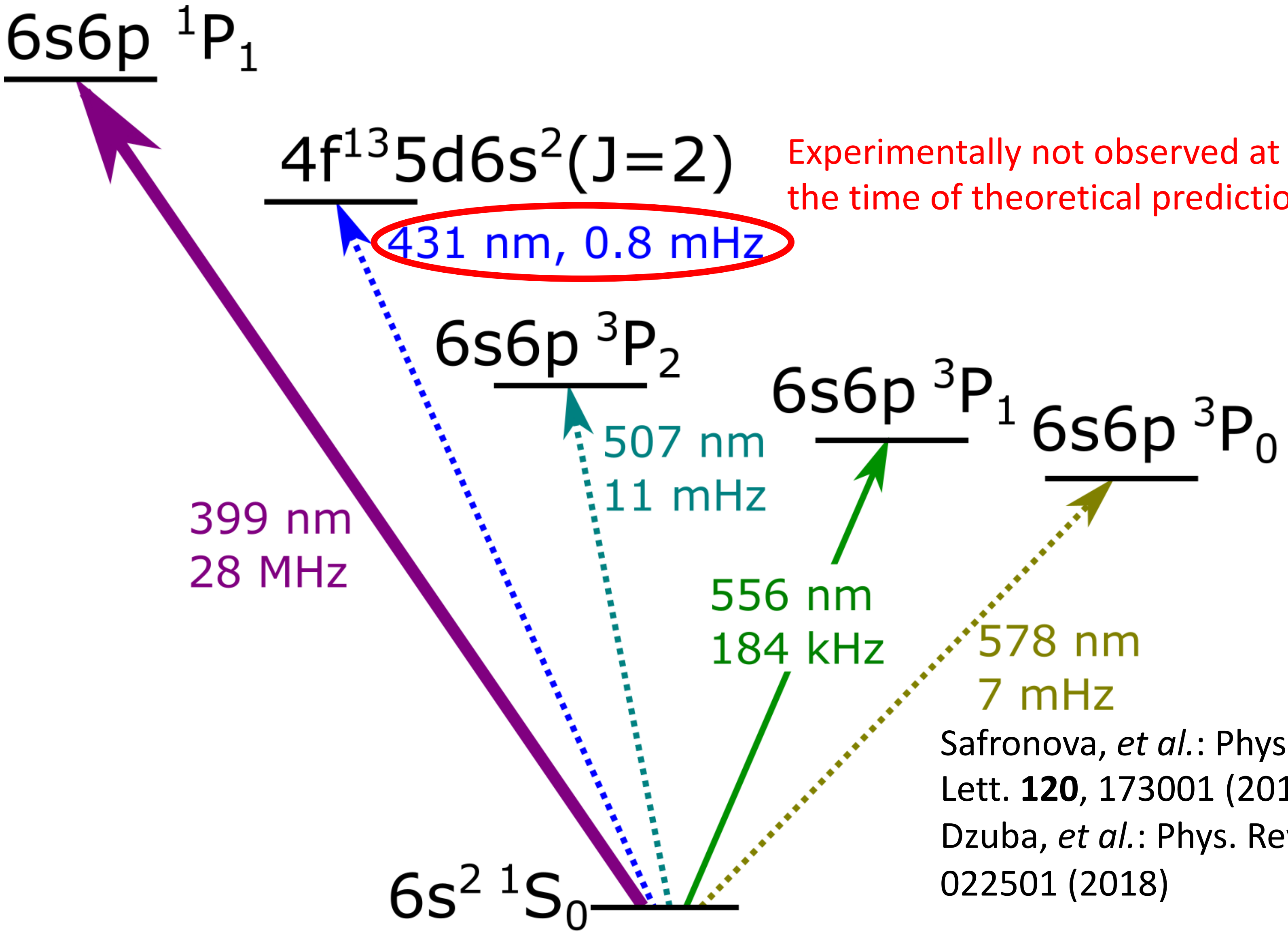
Ytterbium

- Z=70
- 7 stable isotopes (168, 170, 171, 172, 173, 174, 176)
- [Xe] $4f^{14}\ 6s^2$



https://pubchem.ncbi.nlm.nih.gov/periodic-table/

Transitions in Neutral Ytterbium



Experimentally not observed at the time of theoretical prediction.

Safronova, *et al.*: Phys. Rev. Lett. **120**, 173001 (2018)
Dzuba, *et al.*: Phys. Rev. A **98**, 022501 (2018)

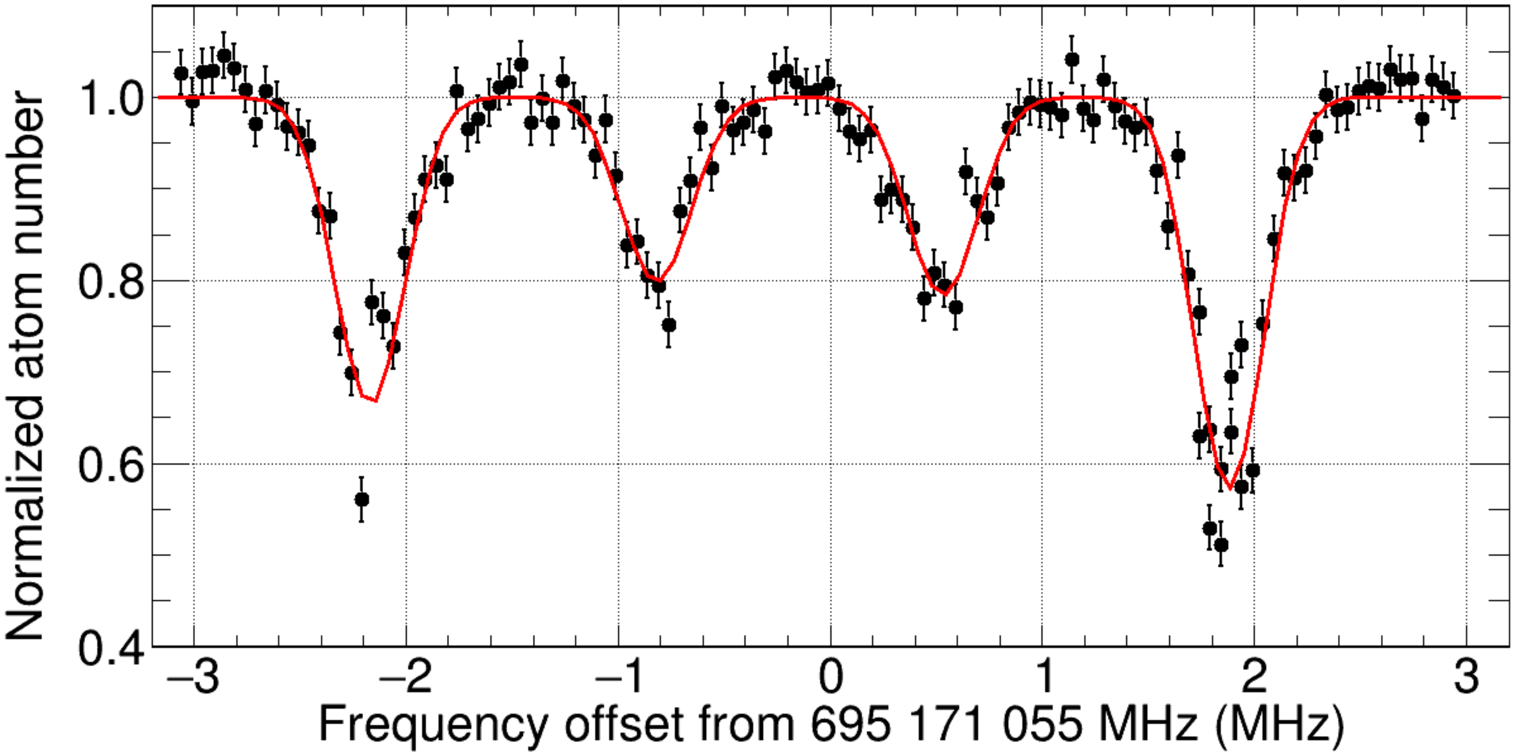
Progress So Far

Absolute Frequency Measurement

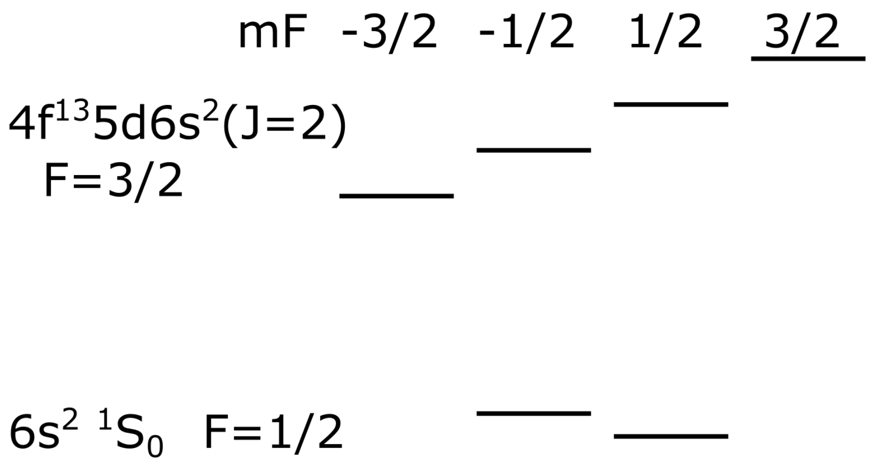
Obtained absolute frequency for F=3/2 state in ^{171}Yb:

695 171 054 858.1 (8.2) kHz

--This is the world's first report.



Energy level



AK, *et al.*: Phys. Rev. A **107**, L060801 (2023)

Full List of Absolute Frequencies

A	F	Absolute frequency [kHz]	
168		695 170 466 295(17)	[3]
170		695 172 220 247(19)	[2]
171		695 172 739 827(24)	
	3/2	695 171 054 858.1(8.2)	[1]
	5/2	695 173 863 243(30)	[1]
172		695 173 850 275(18)	[2]
173		695 174 348 875(19)	
	1/2	695 175 324 560(47)	[2]
	3/2	695 175 625 655(17)	[2]
	5/2	695 175 702 427(13)	[2]
	7/2	695 174 916 888(12)	[2]
	9/2	695 172 376 487(17)	[2]
174		695 175 030 891(17)	[2]
176		695 176 146 678(17)	[2]

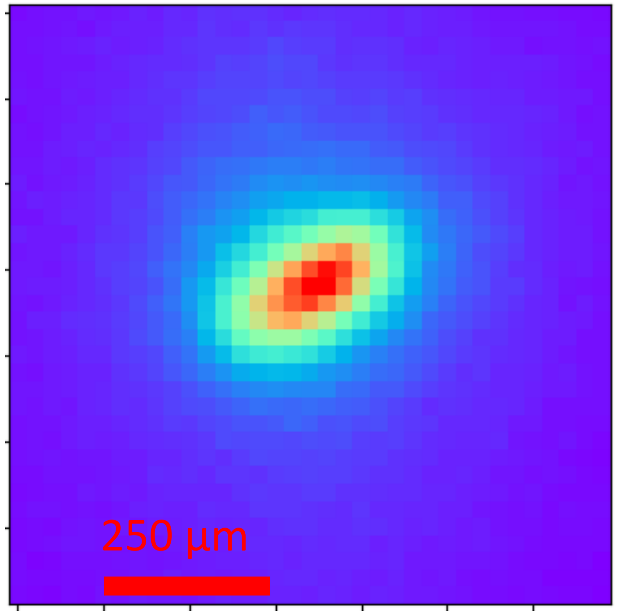
[1] AK, *et al.*: Phys. Rev. A **107**, L060801 (2023)

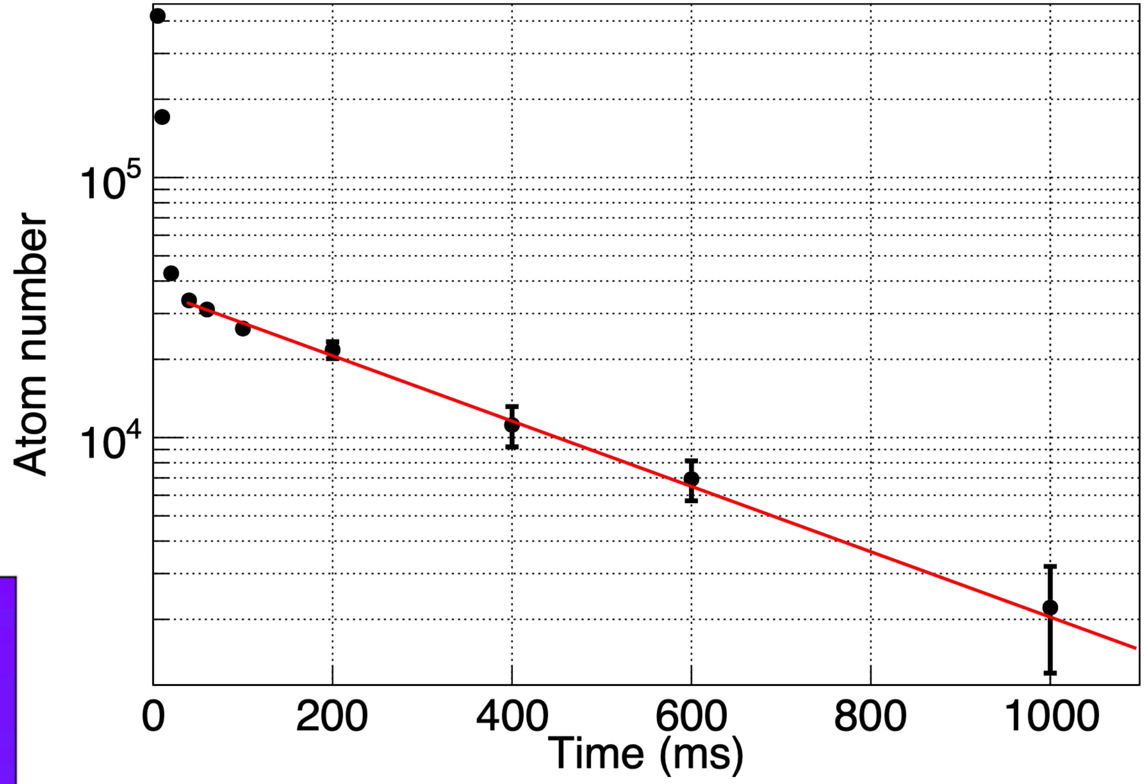
[2] AK, *et al.*: Phys. Rev. A **109**, 062806 (2024)

[3] Ishiyama, *et al.*: Phys. Rev. Lett. **130**, 153402 (2023)

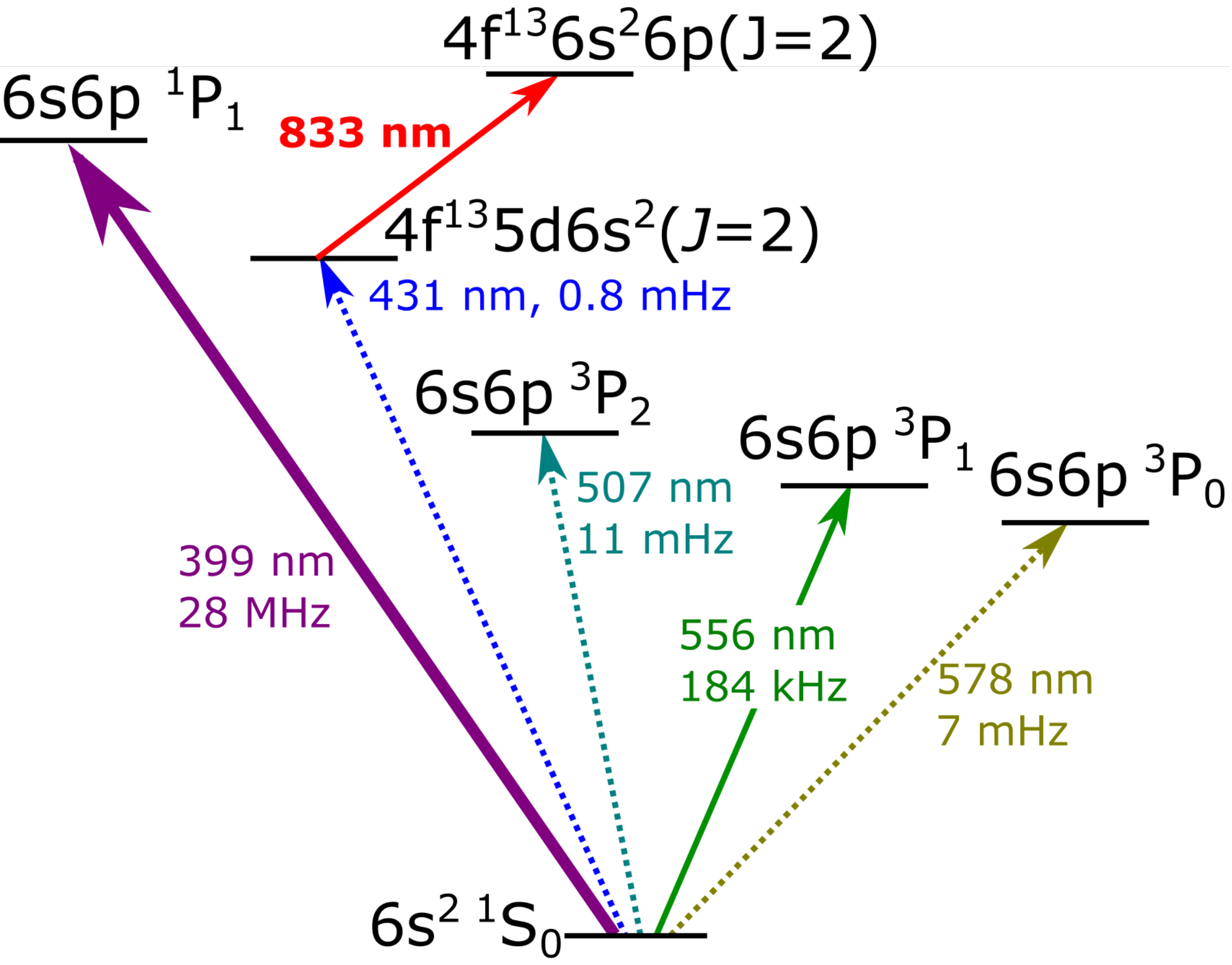
Lattice Configuration

- Horizontal 1D lattice
- laser power: <0.85 W
- waist size: w_0=26 µm
- atom number: 2.7×10^4
- atom lifetime: ~350 ms
- probe beam size: w_0=120 µm
- probe beam power: 8 mW

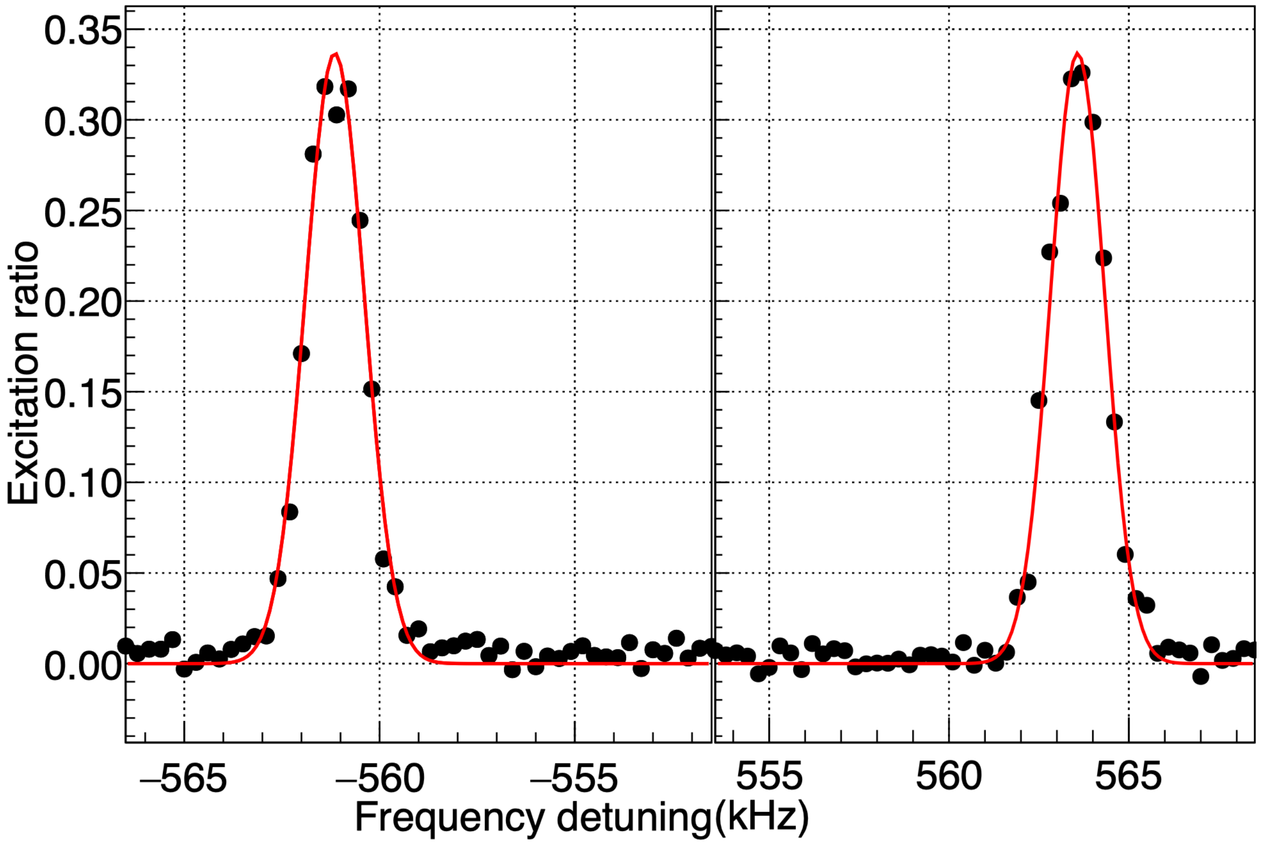




Measurement of Excited State Population



- Linewidth is ~800 Hz.



Magic Frequency

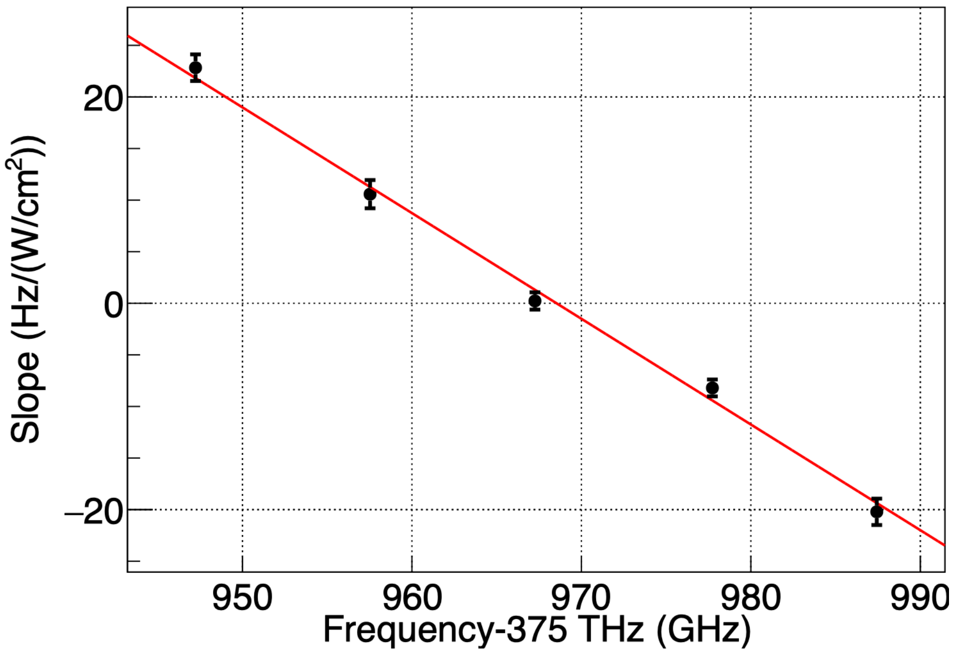
At a magic frequency, energy shifts for the ground and excited states due to the optical lattice is the same.

$m_F = \pm 3/2$ 375 628(6) GHz

$m_F = \pm 1/2$ 375 969(10) GHz

(Numbers are preliminary)

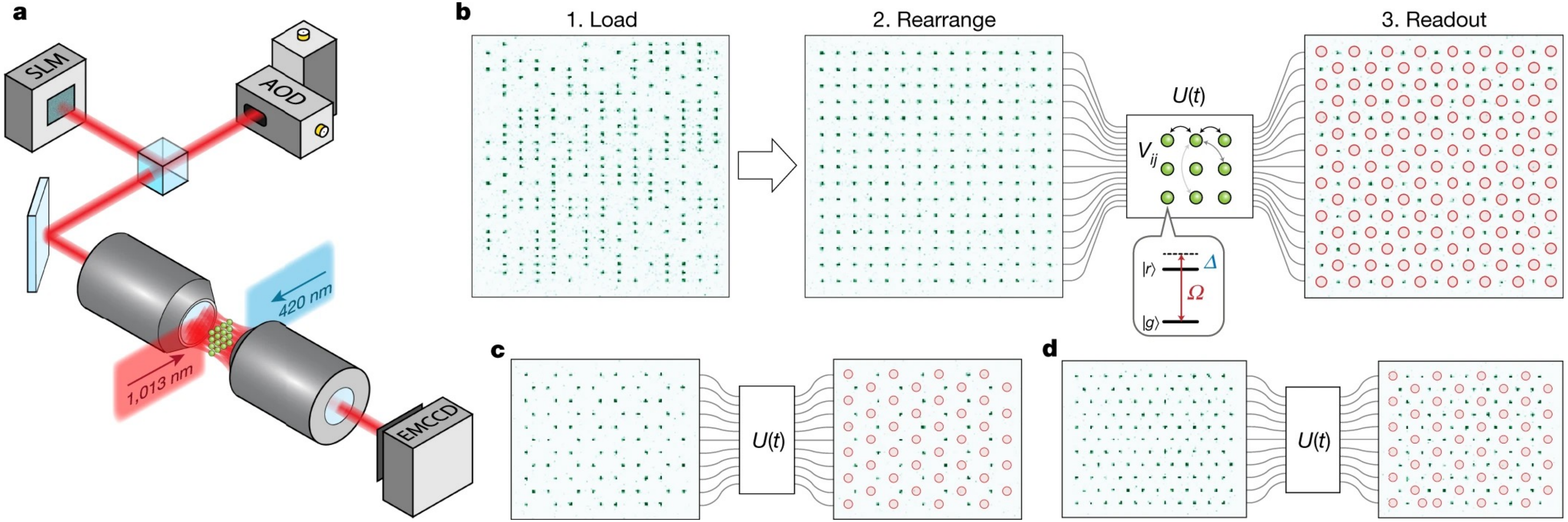
- In reality, using $m_F = \pm 1/2$ for precision spectroscopy makes the most sense, because of narrower linewidths.
- More precise determination for $m_F = \pm 1/2$:
  375 968.53(60) GHz.



Future Direction: Search for Variation of the Fine Structure Constant

Tweezer Array Clock

- An optical tweezer is a tightly focused laser that can trap a single atom.
- An array of optical tweezer can trap 10-100 atoms.
- This system is very popular in the field of quantum computation.
- I can make use of this to avoid any scattering and have magnetic field insensitivity.

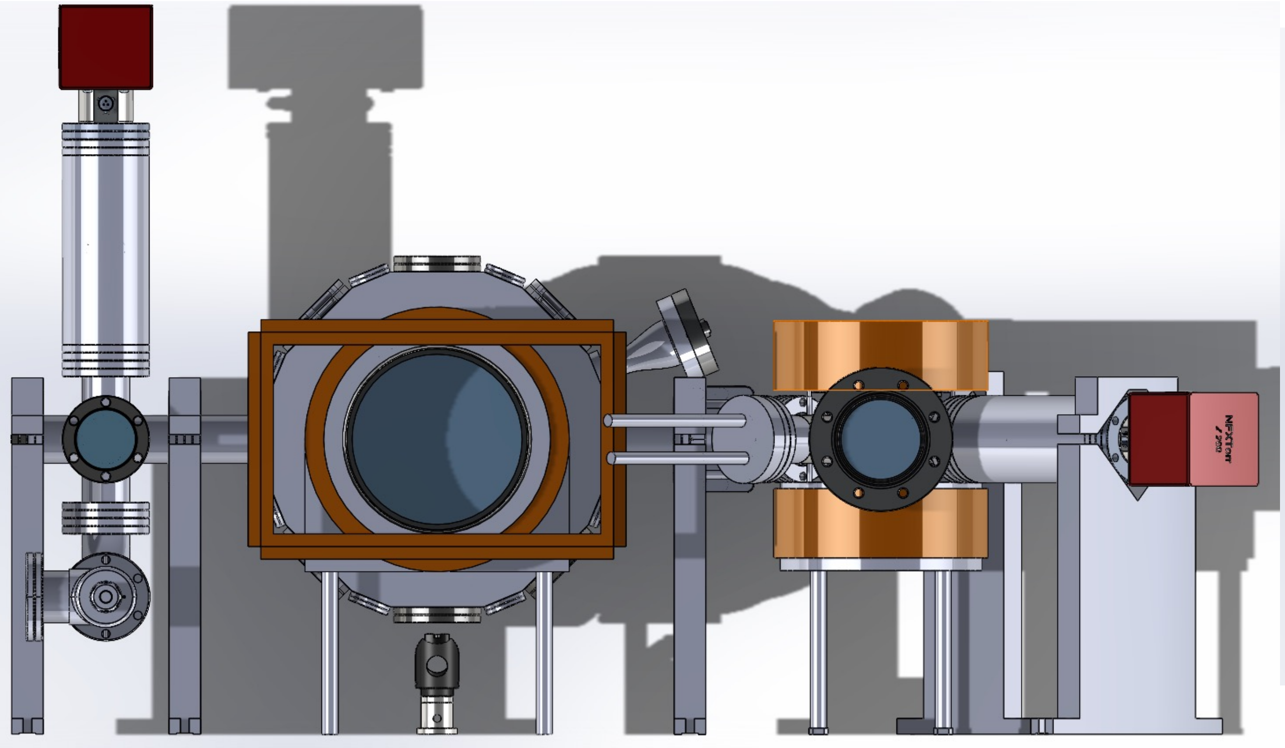


Ebadi, *et al.*: Nature 595, 227 (2021)

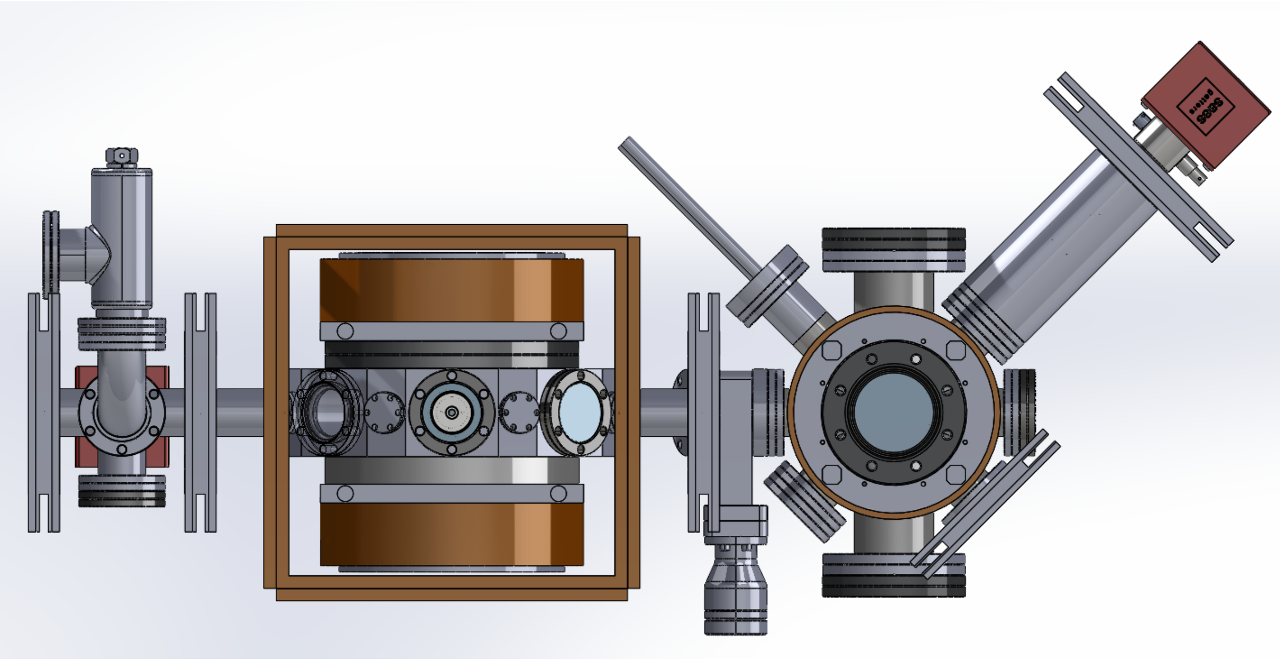
New Vacuum System

- A new multi-purpose vacuum chamber for the state-of-the-art optical lattice clock system and potential other experiments is designed.
- The system is currently under procurement.

side view

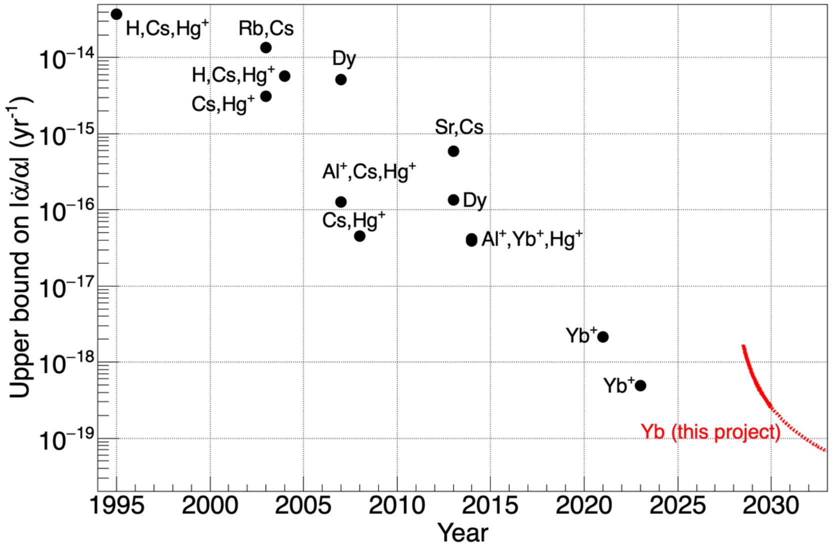


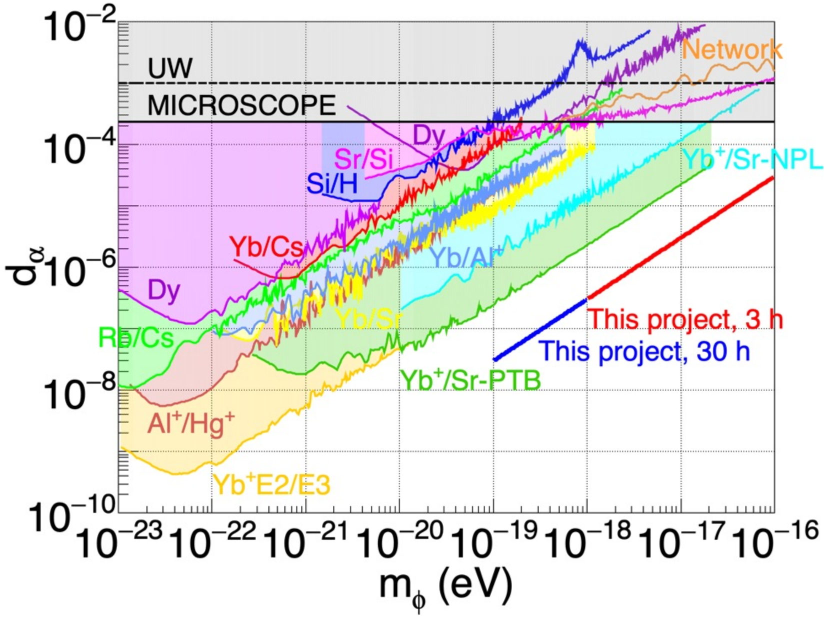
bottom view

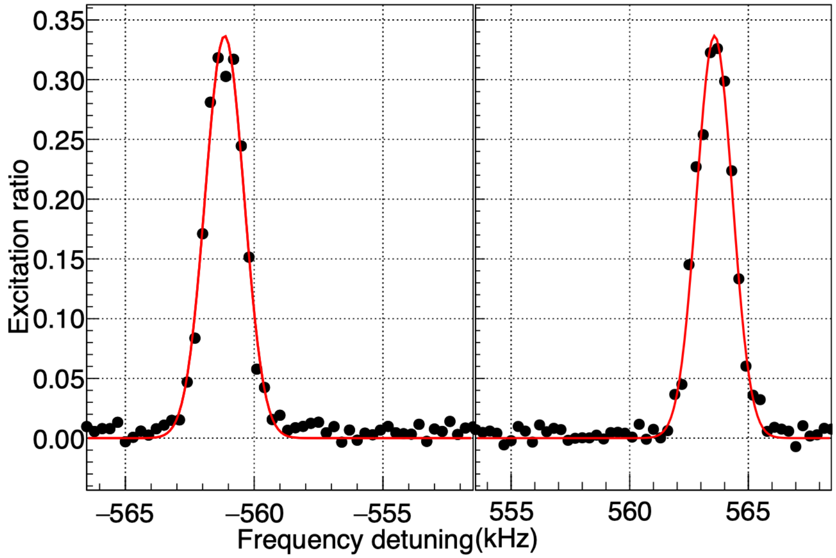


Summary

- Precise comparison of two clocks can be utilized for fundamental physics searches.
- We are working on precision spectroscopy of the 431 nm transition in Yb.
- The transition is highly sensitive to variation of the fine structure constant and ultralight scalar dark matter coupling to the fine structure constant.



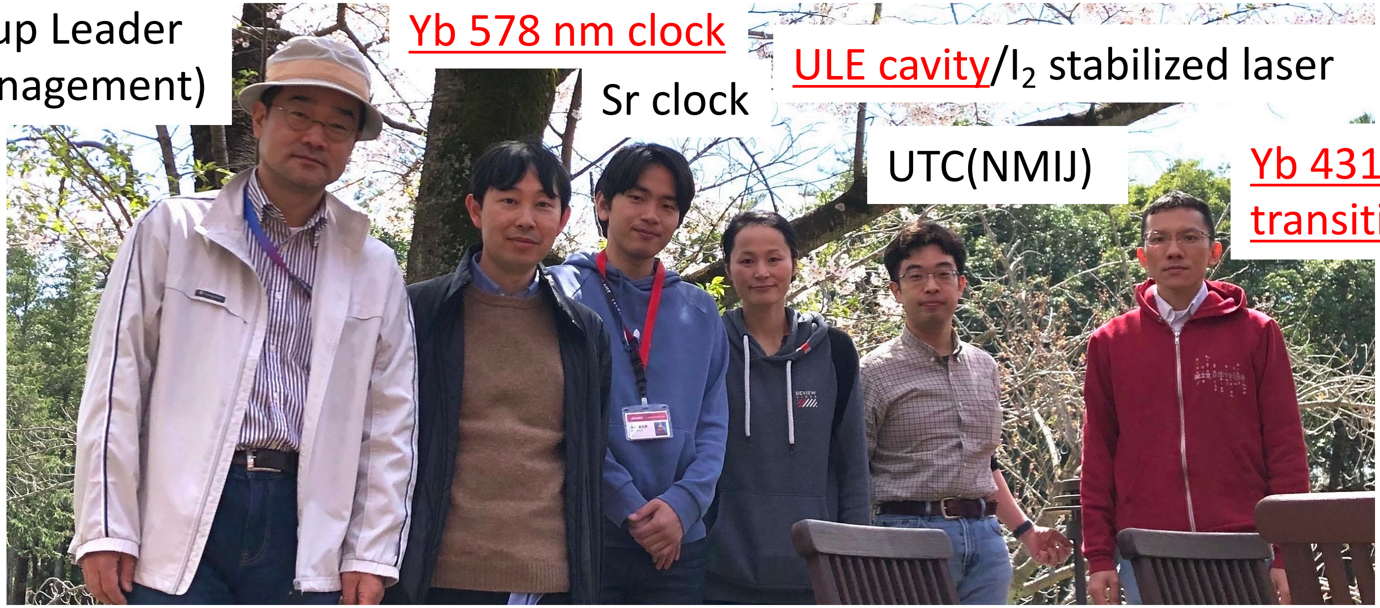




Acknowledgments

Time Standards Group at AIST

Masami Yasuda	Takumi Kobayashi	Shintaro Nagase	Akiko Nishiyama	Takehiko Tanabe	AK
Group Leader (Management)	Yb 578 nm clock	Sr clock	ULE cavity/I_2 stabilized laser	UTC(NMIJ)	Yb 431 nm transition



A postdoc and a grad student position are available!

Funding:

科研費 KAKENHI

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Positions are Available!

Postdoc

- See the following official job posting, or you can Google Akio Kawasaki's personal webpage and go to Available Positions page.
  https://unit.aist.go.jp/deihrd07/keiyaku_koubo/2026-ripm_0002.html#ttl

Graduate student

- 200k JPY/month stipend is guaranteed for doctoral students.
  Please contact Akio for more details, as AIST is not a university.