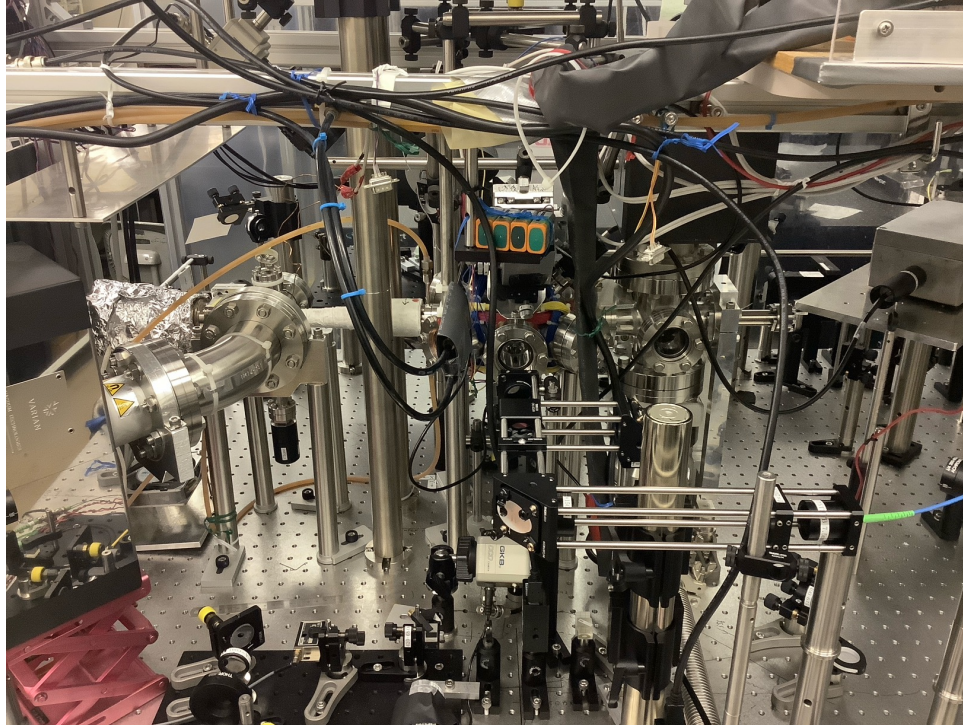


Searches for New Physics Using Ytterbium



Akio Kawasaki

National Metrology Institute of Japan

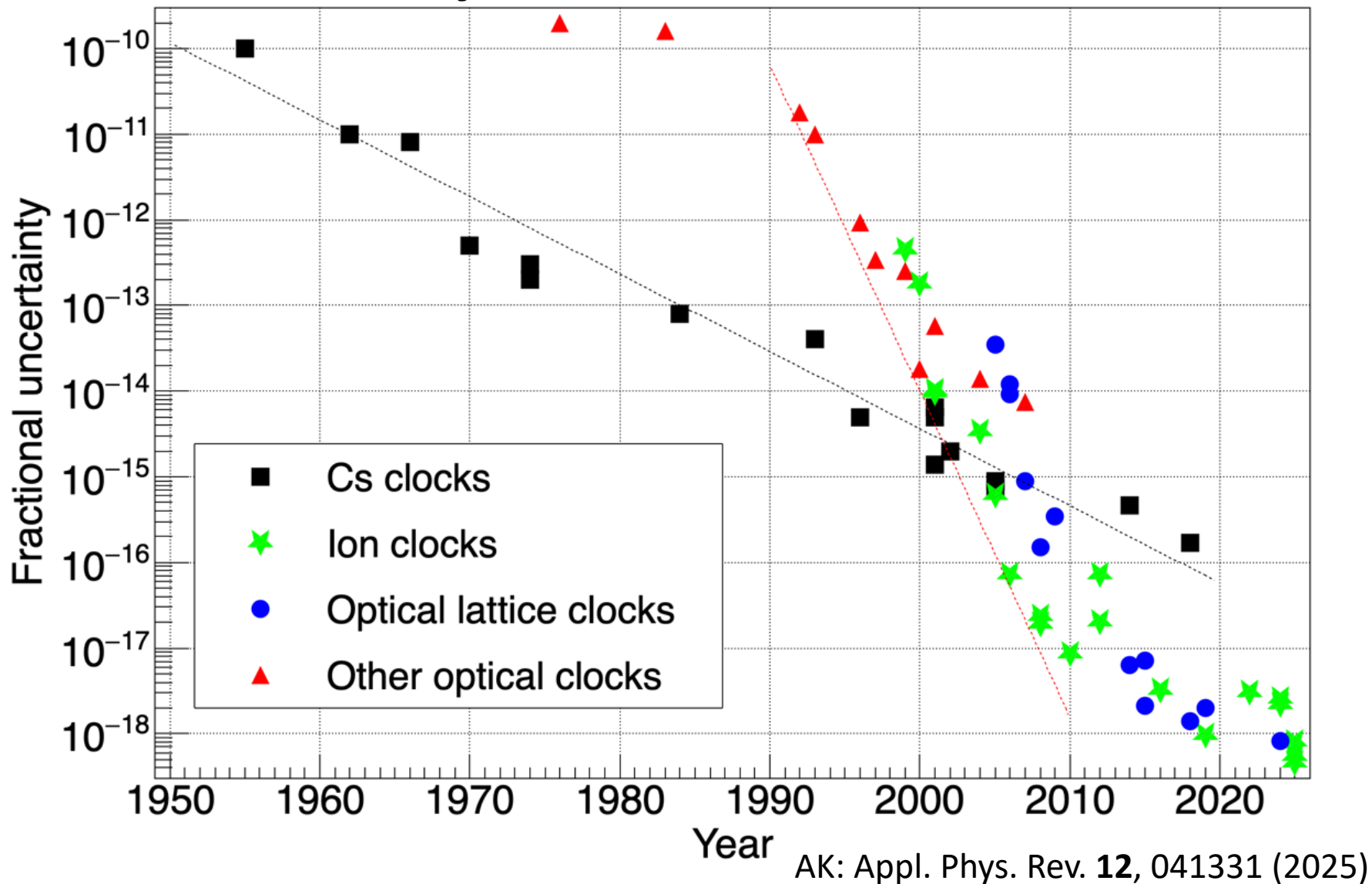
National Institute of Advanced Industrial Science and Technology

Outline

1. Introduction to new physics searches using precision spectroscopy
2. Precision spectroscopy of the 431 nm transition in ytterbium
3. Fifth force searches between an electron and a neutron
4. Search for variation of the fine structure constant

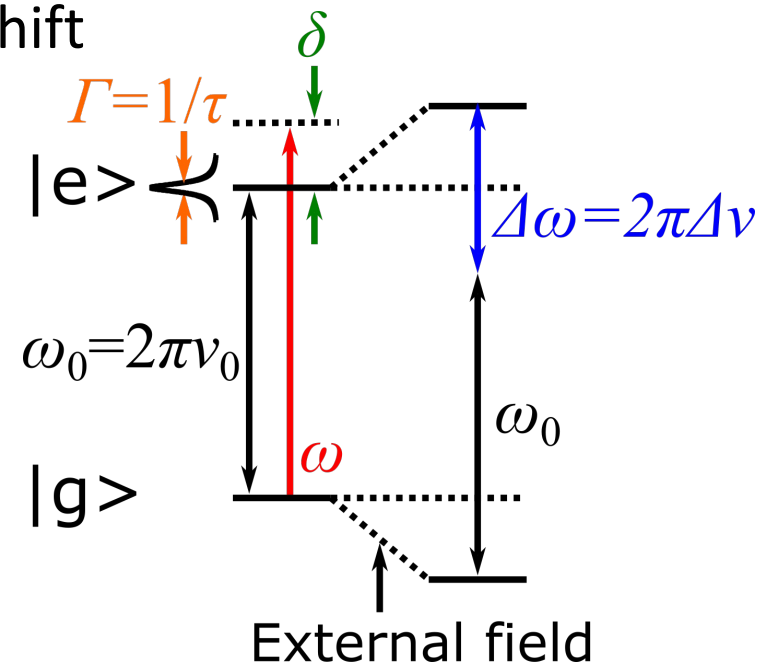
Introduction to Fundamental Physics Searches Using Precision Spectroscopy

Accuracy of Atomic Clocks

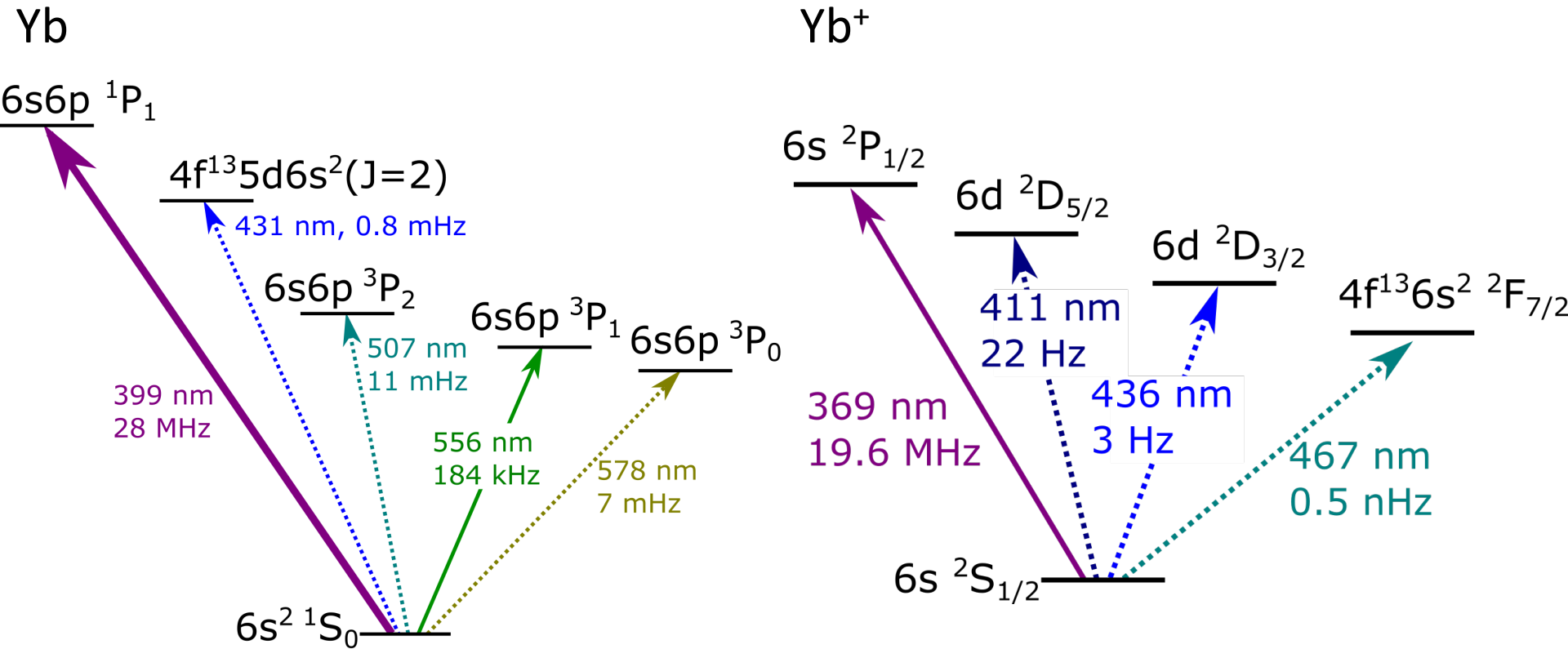


Two-level under External Field

- 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 \Rightarrow DC Stark shift
 - Oscillating electric field \Rightarrow 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.



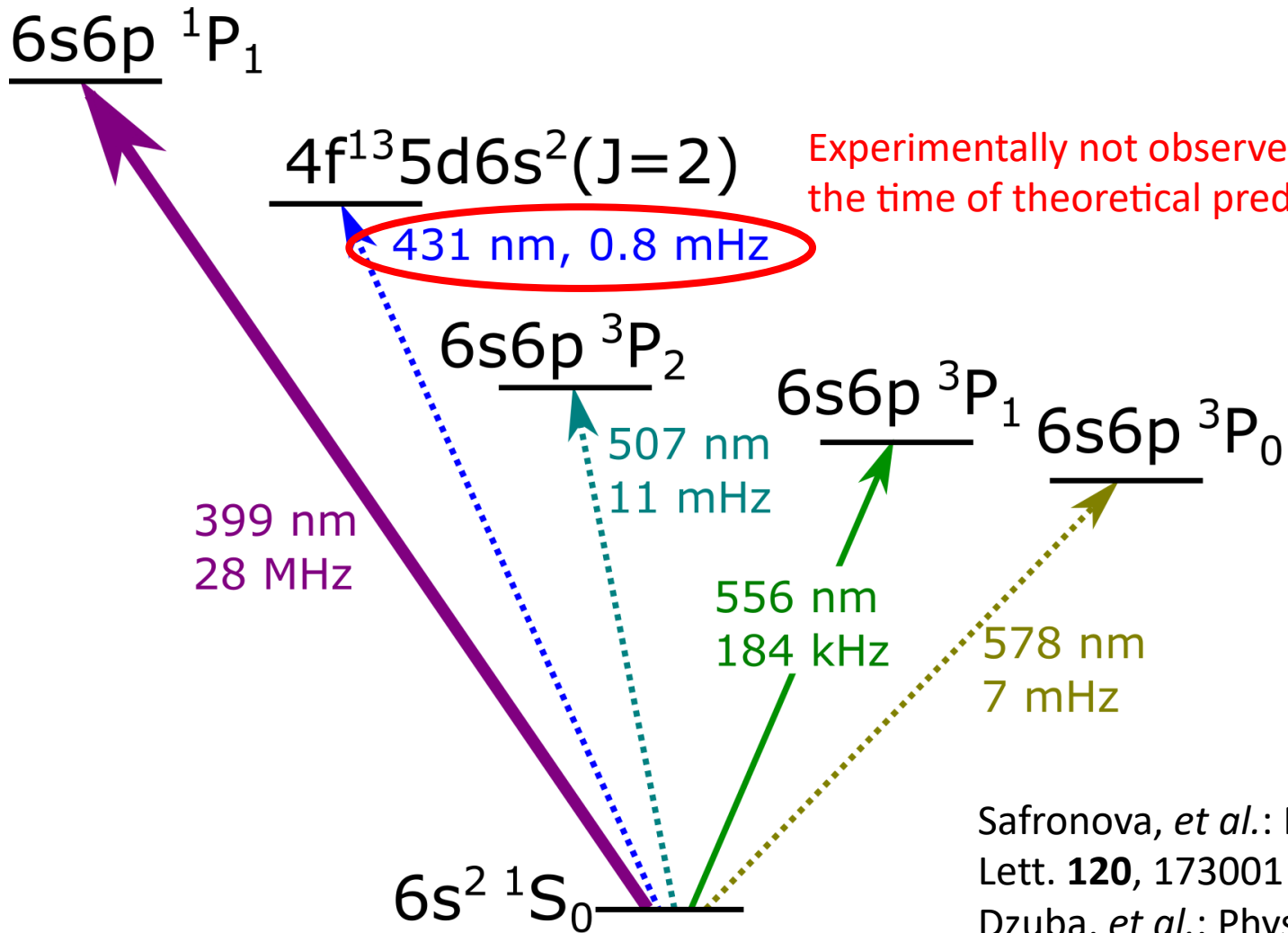
Transitions in Yb and Yb⁺



- The variety of narrow-linewidth transitions is attractive for precision spectroscopy.

Precision Spectroscopy of the 431 nm Transition in Ytterbium

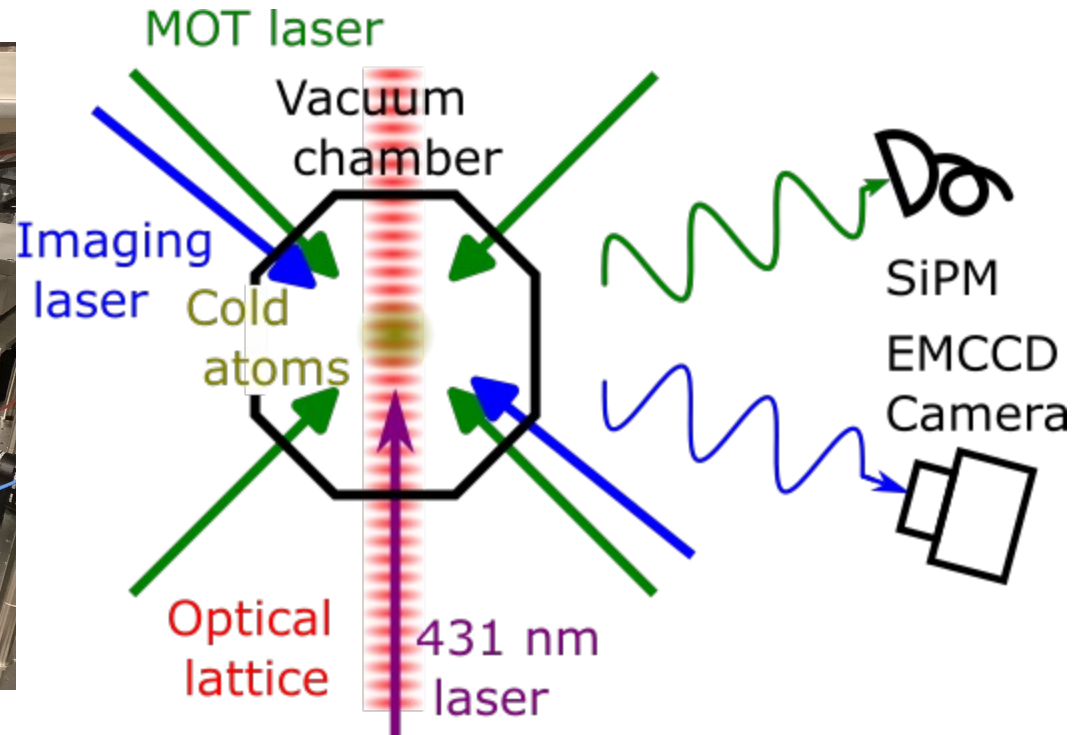
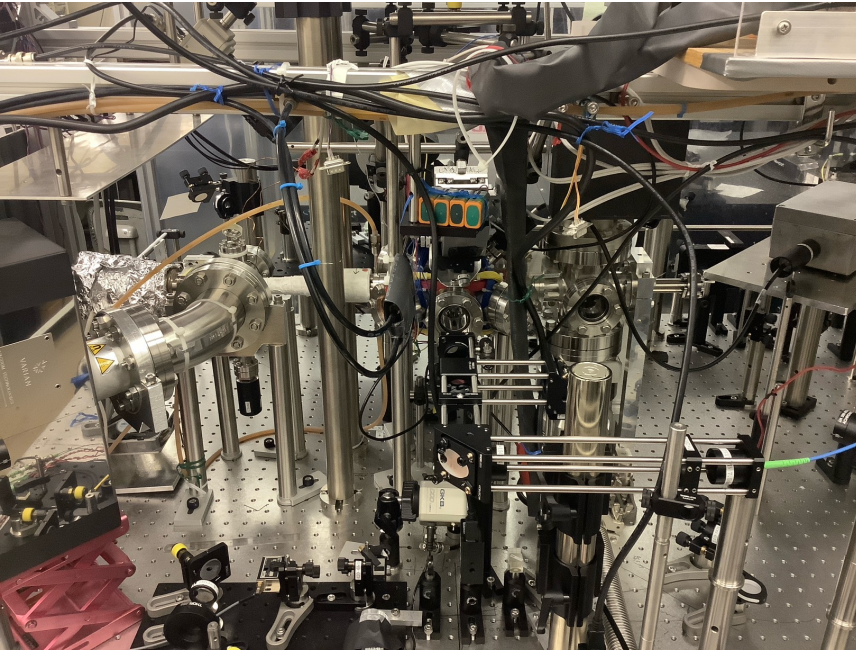
Transitions in Neutral Ytterbium



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

Experimental Setup

- Atoms are imaged by fluorescence imaging.



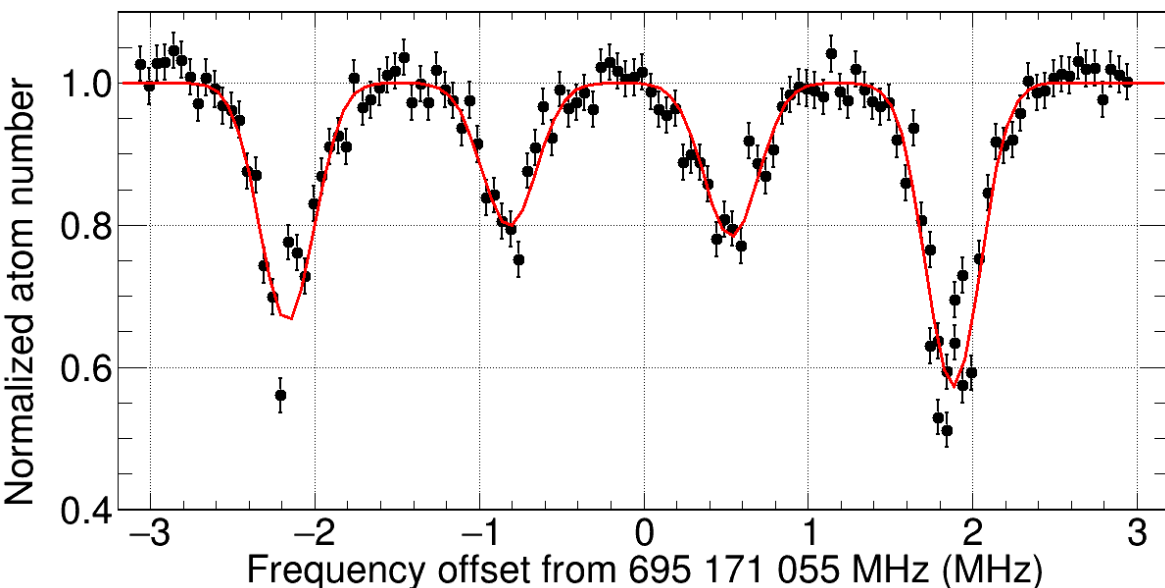
The vacuum chamber is the same as
Kohno, *et al.*: Appl. Phys. Express **2**, 072501 (2009)
Yasuda, *et al.*: Appl. Phys. Express **5**, 102401 (2012)

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

	mF	-3/2	-1/2	1/2	<u>3/2</u>
$4f^{13}5d6s^2(J=2)$				—	—
F=3/2		—	—		
$6s^2\ ^1S_0$	F=1/2		—	—	

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

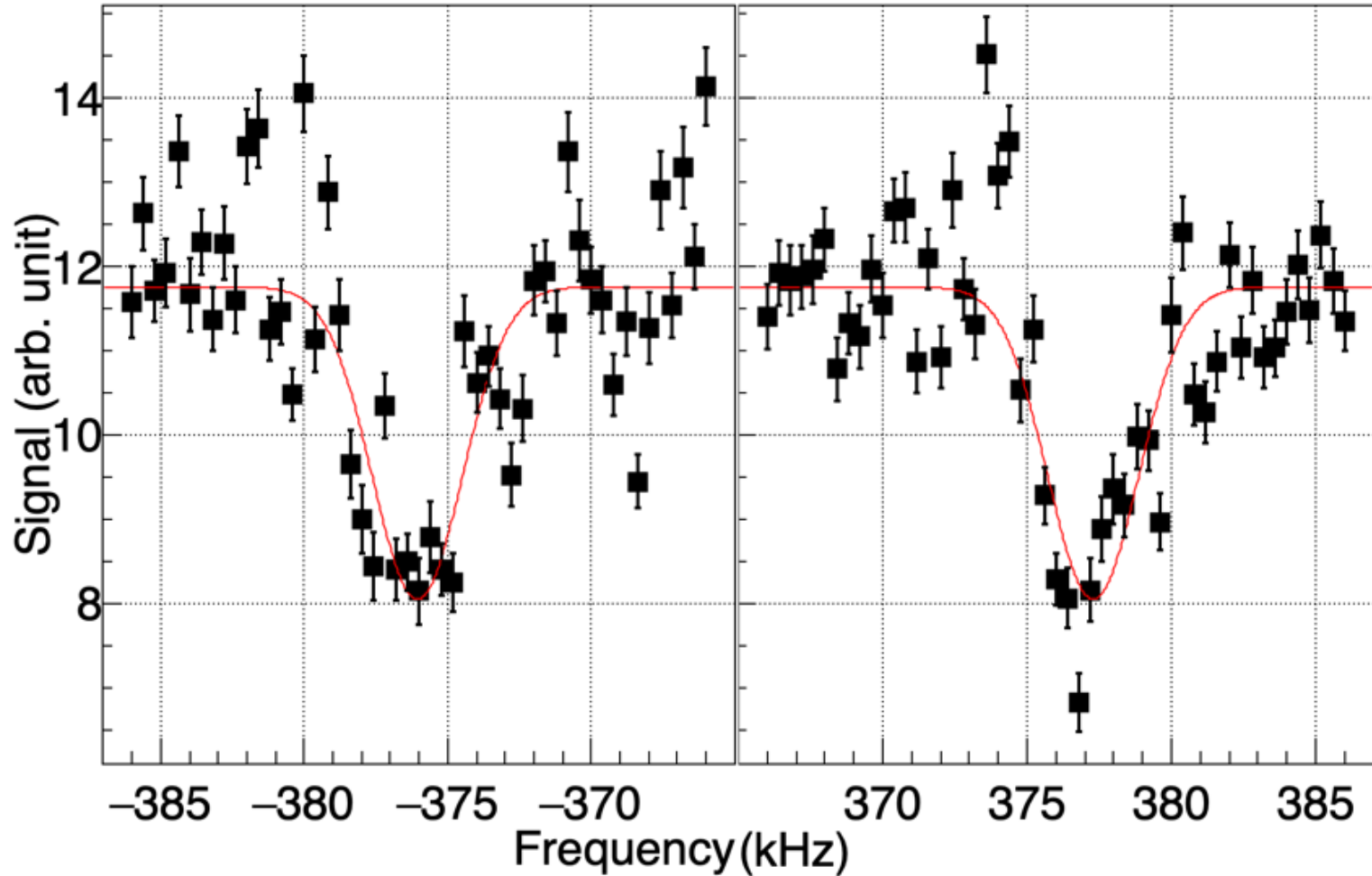
Full List of Absolute Frequencies

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)

Early Spectroscopy in the Lattice

- 0.36 G bias field is applied.
- Linewidth is around 1.5 kHz.



Fifth Force Searches between an Electron and a Neutron

Isotope shifts

Isotope shift within the Standard Model

$$\nu_{\alpha}^{AA'} = F_{\alpha} \langle r^2 \rangle^{AA'} + K_{\alpha} \mu^{AA'} + G_{\alpha}^{(4)} \langle r^4 \rangle^{AA'} + G_{\alpha}^{(2)} [\langle r^2 \rangle^2]^{AA'}$$

- 1st term: field shift, $\langle r^2 \rangle^{AA'}$: difference of RMS nuclear radii
- 2nd term: mass shift, $\mu^{AA'}$: difference of inverse mass
- Higher order nuclear deformation
 - 3rd terms: 4th moment shift
 - 4th term: quadratic field shift

Isotope shifts

Isotope shift beyond the Standard Model

$$\nu_{\alpha}^{AA'} = F_{\alpha} \langle r^2 \rangle^{AA'} + K_{\alpha} \mu^{AA'} + G_{\alpha}^{(4)} \langle r^4 \rangle^{AA'} + G_{\alpha}^{(2)} [\langle r^2 \rangle^2]^{AA'} + v_{ne} N^{AA'} D_{\alpha}$$

- 1st term: field shift, $\langle r^2 \rangle^{AA'}$: difference of RMS nuclear radii
- 2nd term: mass shift, $\mu^{AA'}$: difference of inverse mass
- Higher order nuclear deformation
 - 3rd terms: 4th moment shift
 - 4th term: quadratic field shift
- 5th term: effect of new bosons mediating forces between an electron and a neutron

$$V_{ne}(r) = (-1)^{s+1} \frac{y_n y_e}{4\pi} \frac{e^{-m_{\phi} cr/\hbar}}{r}, \quad v_{ne} = (-1)^{s+1} \frac{y_n y_e}{4\pi \hbar c}$$

$y_{n,e}$: coupling constant with neutron, electron

m_{ϕ} : mass of the boson

s : spin of the boson

Linearity in King Plot

- Eliminating $\langle r^2 \rangle^{AA'}$, we obtain the following approximately linear relation.

$$\frac{v_{\beta}^{AA'}}{\mu^{AA'}} = \frac{F_{\beta}}{F_{\alpha}} \frac{v_{\alpha}^{AA'}}{\mu^{AA'}} + K_{\beta,\alpha} + \frac{\langle r^4 \rangle^{AA'}}{\mu^{AA'}} G_{\beta,\alpha}^{(4)} + \frac{[\langle r^2 \rangle^2]^{AA'}}{\mu^{AA'}} G_{\beta,\alpha}^{(2)} + \frac{v_{ne} N^{AA'}}{\mu^{AA'}} D_{\beta,\alpha}$$

$$X_{\beta,\alpha} = X_{\beta} - X_{\alpha} F_{\beta} / F_{\alpha}$$

- For better uncertainty management, we normalize this with $v_{\alpha}^{AA'} / \mu^{AA'}$.

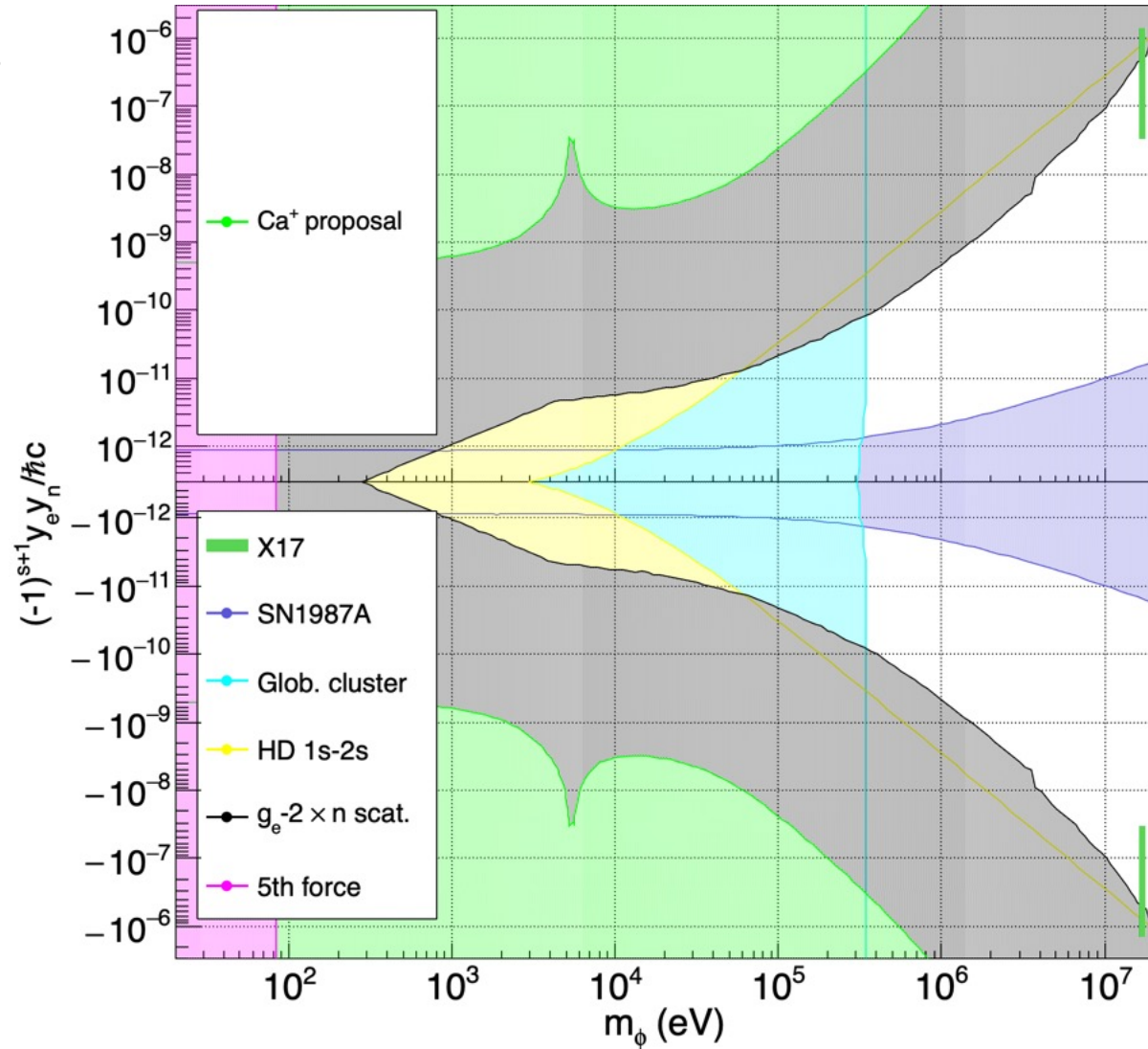
$$\frac{v_{\beta}^{AA'}}{v_{\alpha}^{AA'}} = \frac{F_{\beta}}{F_{\alpha}} + K_{\beta,\alpha} \frac{\mu^{AA'}}{v_{\alpha}^{AA'}} + \frac{\langle r^4 \rangle^{AA'}}{v_{\alpha}^{AA'}} G_{\beta,\alpha}^{(4)} + \frac{[\langle r^2 \rangle^2]^{AA'}}{v_{\alpha}^{AA'}} G_{\beta,\alpha}^{(2)} + \frac{v_{ne} N^{AA'}}{v_{\alpha}^{AA'}} D_{\beta,\alpha}$$

- The nonlinearity is the potential signature of the new bosons (only if the higher order term is properly cancelled).

Historical Development

- Initial proposal (2018)

Berengut, et al.: Phys. Rev. Lett.
120, 091801 (2018)



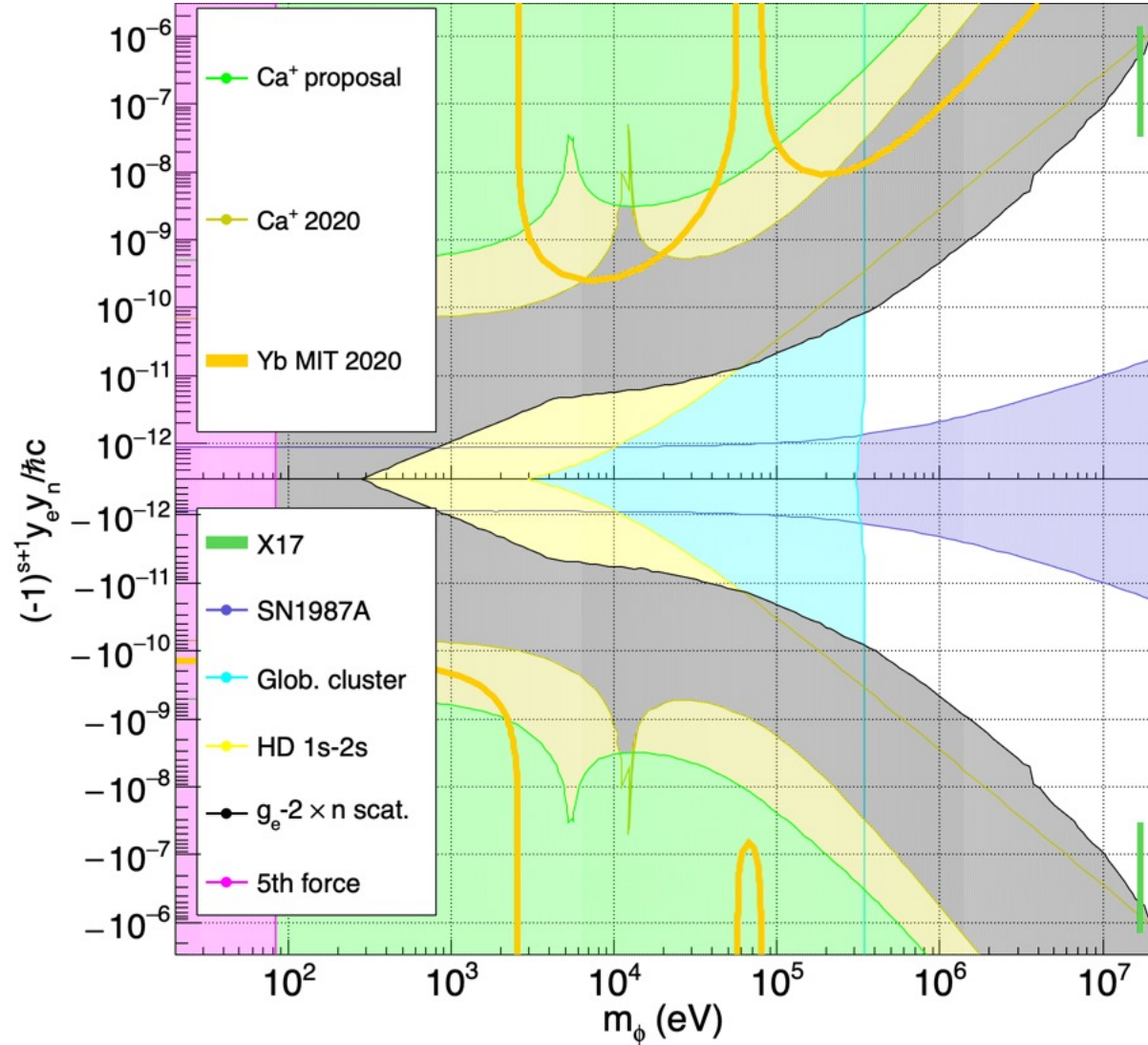
Historical Development

- First dedicated experiments (2020)

- Ca^+ observed linearity.
- Yb^+ observed nonlinearity.

Yb^+ : Counts, ..., AK, ...: Phys. Rev. Lett. **125**, 123002 (2020)

Ca^+ : Solaro, *et al.*: Phys. Rev. Lett. **125**, 123003 (2020)



Historical Development

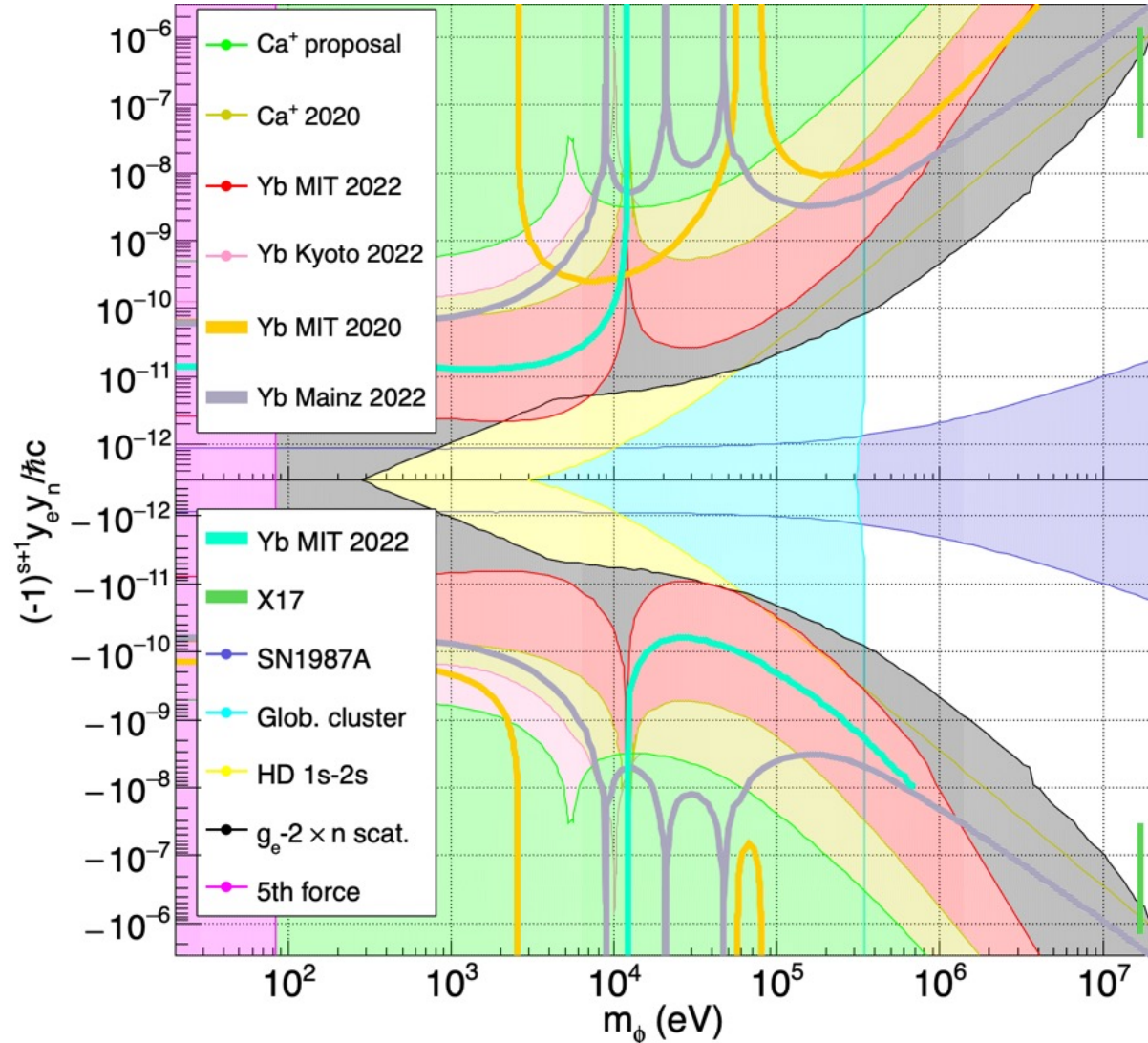
- Multiple reports using Yb (2022)

- 578 nm transition in Yb (Kyoto)
- 361 nm transition in Yb (Mainz)
- 469 nm transition in Yb⁺ (MIT)

MIT: Hur, ..., AK, ...: Phys. Rev. Lett. **128**, 163201 (2022)

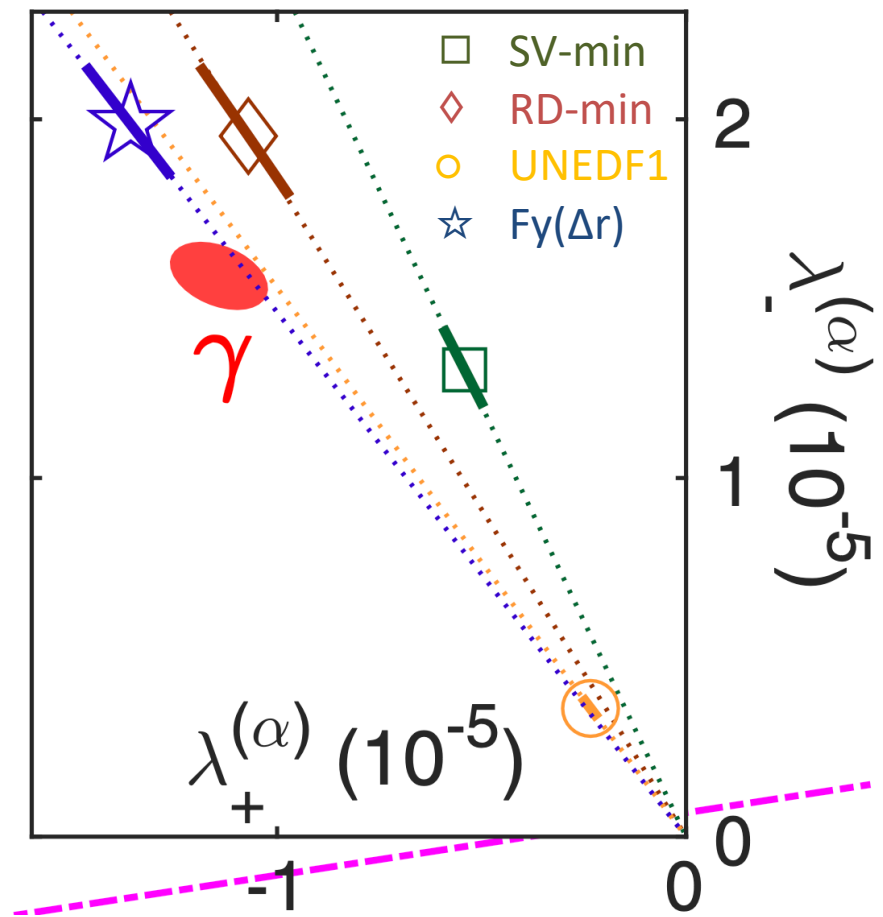
Kyoto: Ono, *et al.*: Phys. Rev. X **12**, 021033 (2022)

Mainz: Figueroa, *et al.*: Phys. Rev. Lett. **128**, 073001 (2022)



Historical Development

- Multiple reports using Yb (2022)
 - 578 nm transition in Yb (Kyoto)
 - 361 nm transition in Yb (Mainz)
 - 469 nm transition in Yb⁺ (MIT)
- The MIT report addressed favored nuclear models.



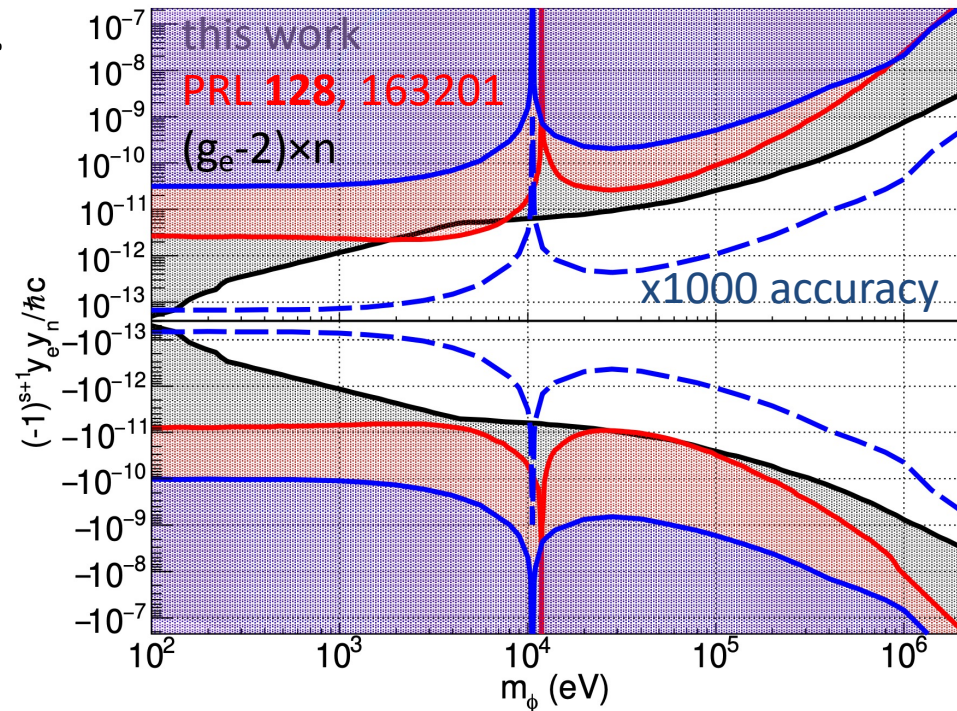
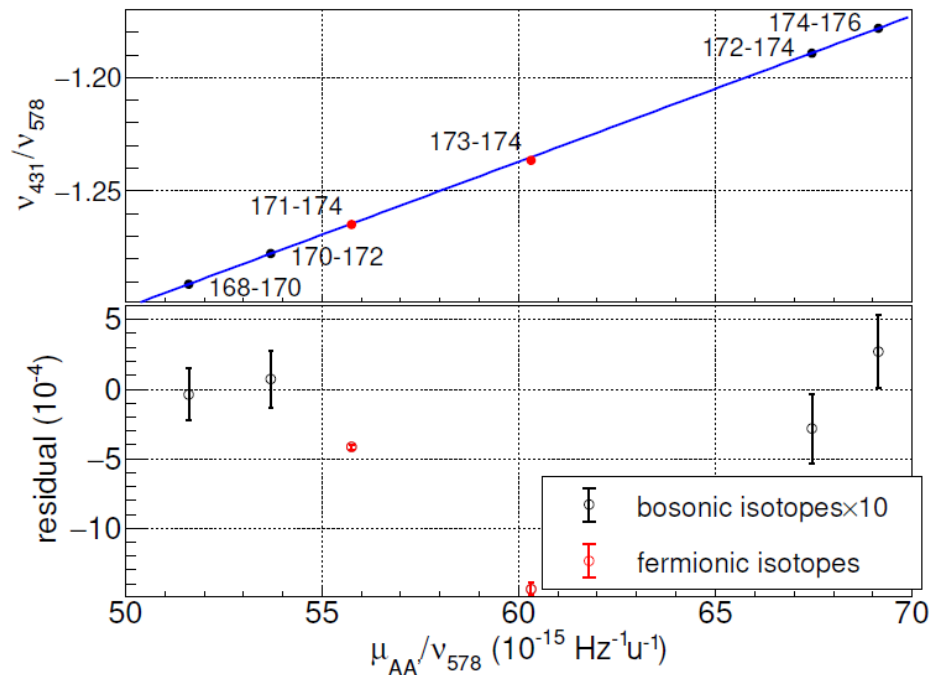
Hur, ..., AK, ...: Phys. Rev. Lett. **128**, 163201 (2022)

Excluded Region Based on my Work

$$\frac{v_{\beta}^{AA'}}{v_{\alpha}^{AA'}} = \frac{F_{\beta}}{F_{\alpha}} + K_{\beta,\alpha} \frac{\mu^{AA'}}{v_{\alpha}^{AA'}} + \frac{\langle r^4 \rangle^{AA'}}{v_{\alpha}^{AA'}} G_{\beta,\alpha}^{(4)} + \frac{[\langle r^2 \rangle^2]^{AA'}}{v_{\alpha}^{AA'}} G_{\beta,\alpha}^{(2)} + \frac{v_{ne} N^{AA'}}{v_{\alpha}^{AA'}} D_{\beta,\alpha}$$

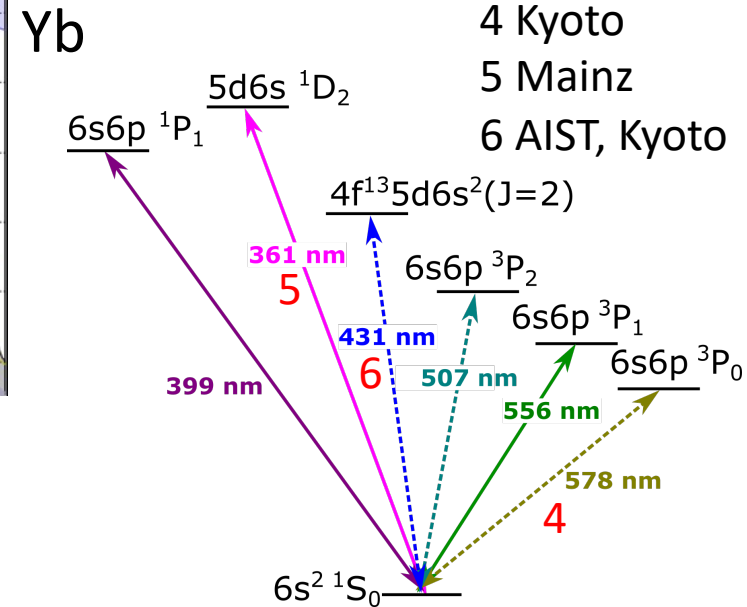
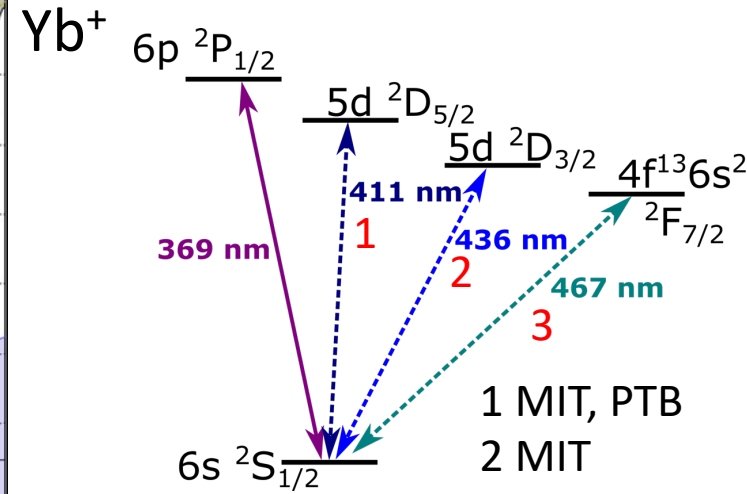
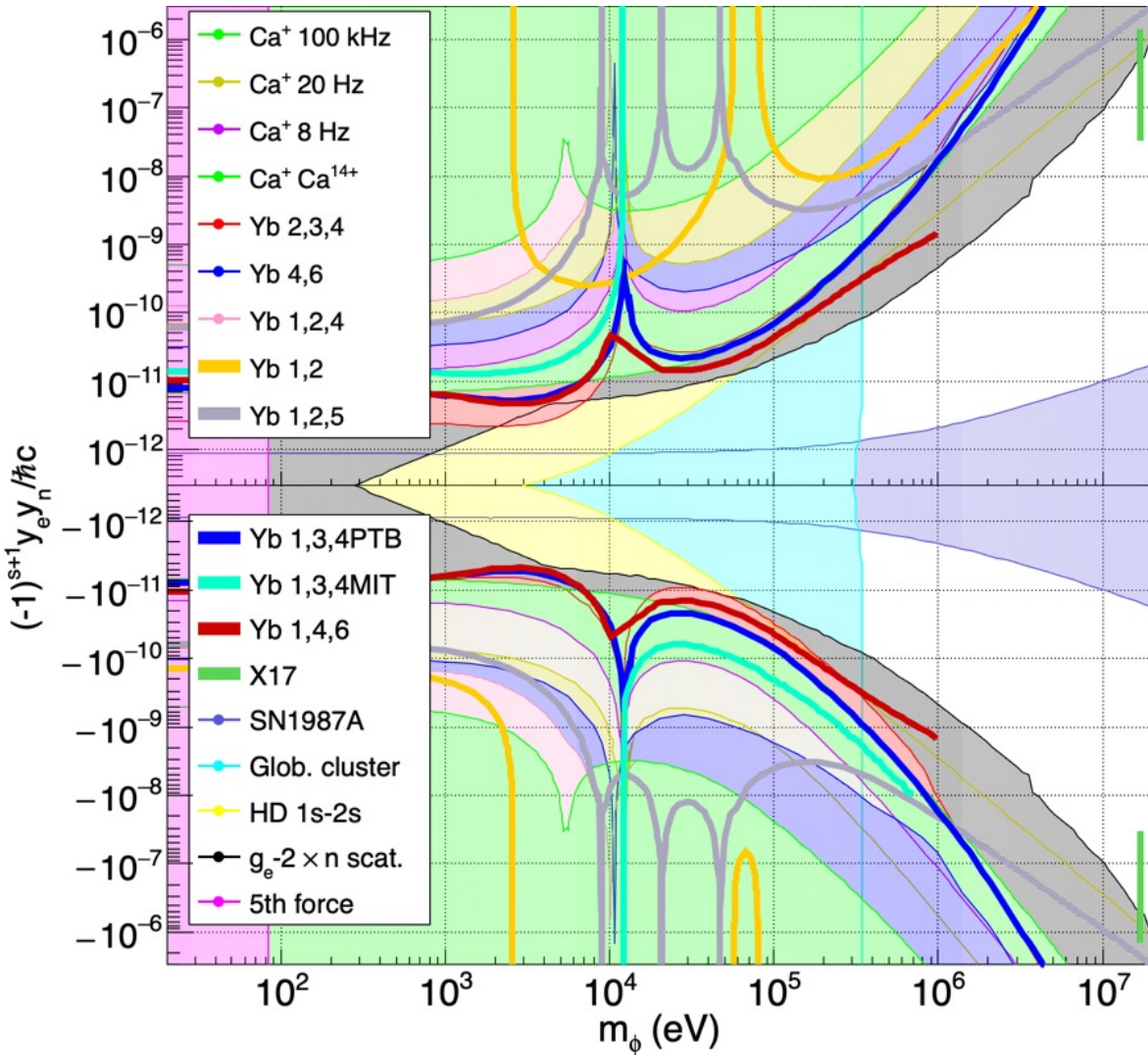
is plotted for $\alpha=431$ nm and $\beta=578$ nm transitions.

Residual for bosons are analyzed to obtain the constraint on new forces between an electron and a neutron.



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

Status of the Search



Search for Variation of the Fine Structure Constant

Sensitivity to the Variation of α

α : fine structure constant

Atom	Transition	K
^{87}Rb	Ground state hyperfine	0.34
^{133}Cs	Ground state hyperfine	0.83
Al^+	$3s^1 \ ^1S_0 - 3s3p \ ^3P_0$	0.008
Ca^+	$4s \ ^2S_{1/2} - 3d \ ^2D_{5/2}$	0.15
Sr	$5s^2 \ ^1S_0 - 5s5p \ ^3P_0$	0.06
Sr^+	$5s \ ^2S_{1/2} - 4d \ ^2D_{5/2}$	0.43
Yb	$6s^2 \ ^1S_0 - 6s6p \ ^3P_0$	0.31
Yb	$6s^2 \ ^1S_0 - 4f^{13}5d6s \ (J=2)$	-3.82
Yb^+	$4f^{14}6s \ ^2S_{1/2} - 4f^{14}5d \ ^2D_{5/2}$	1.03
Yb^+	$4f^{14}6s \ ^2S_{1/2} - 4f^{13}6s^2 \ ^2F_{7/2}$	-5.95
Hg^+	$6s \ ^2S_{1/2} - 5d \ ^2D_{5/2}$	-2.94

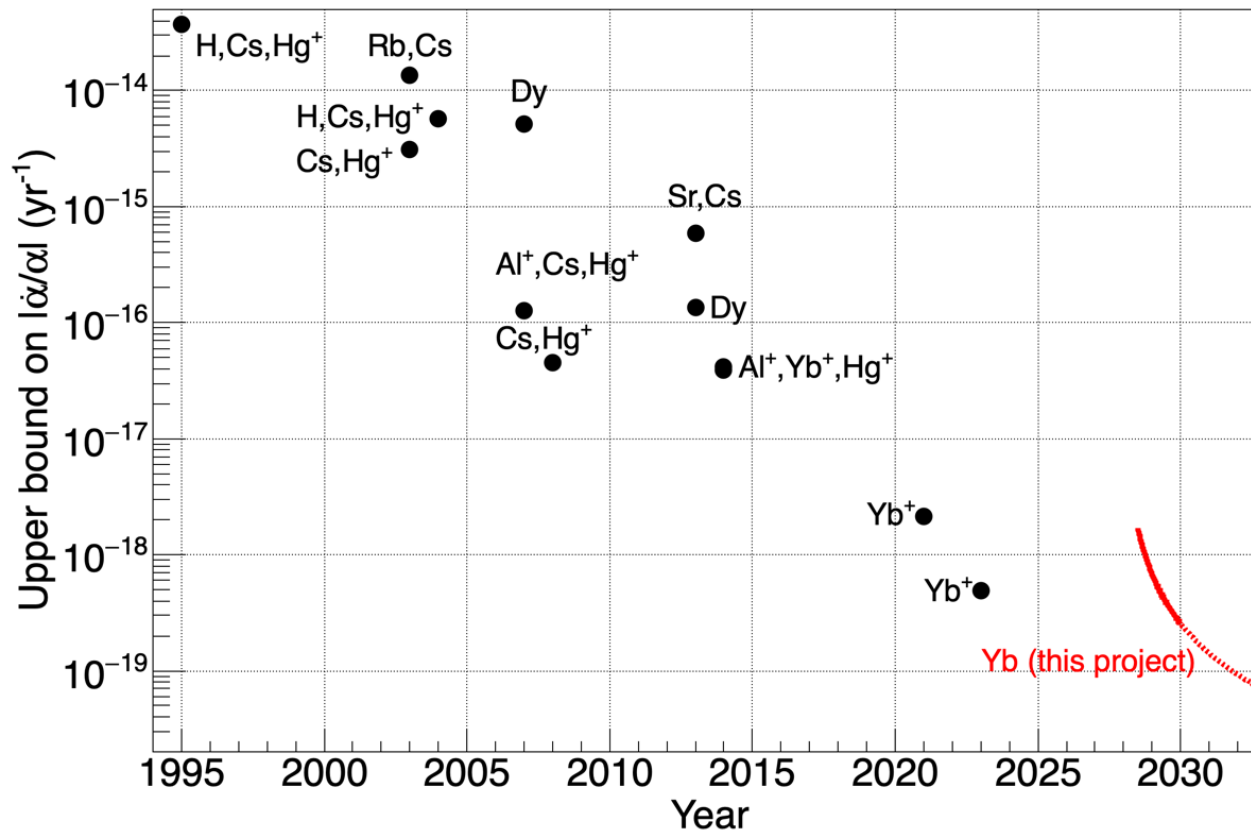
$$\frac{\delta\nu}{\nu} = \frac{2q}{\hbar\omega_0} \frac{\delta\alpha}{\alpha} = K \frac{\delta\alpha}{\alpha}$$

Dzuba, *et al.*: Phys. Rev. A **98**, 022501 (2018)

Safronova, *et al.*: Rev. Mod. Phys. **90**, 025008 (2018)

Search for a linear drift of α

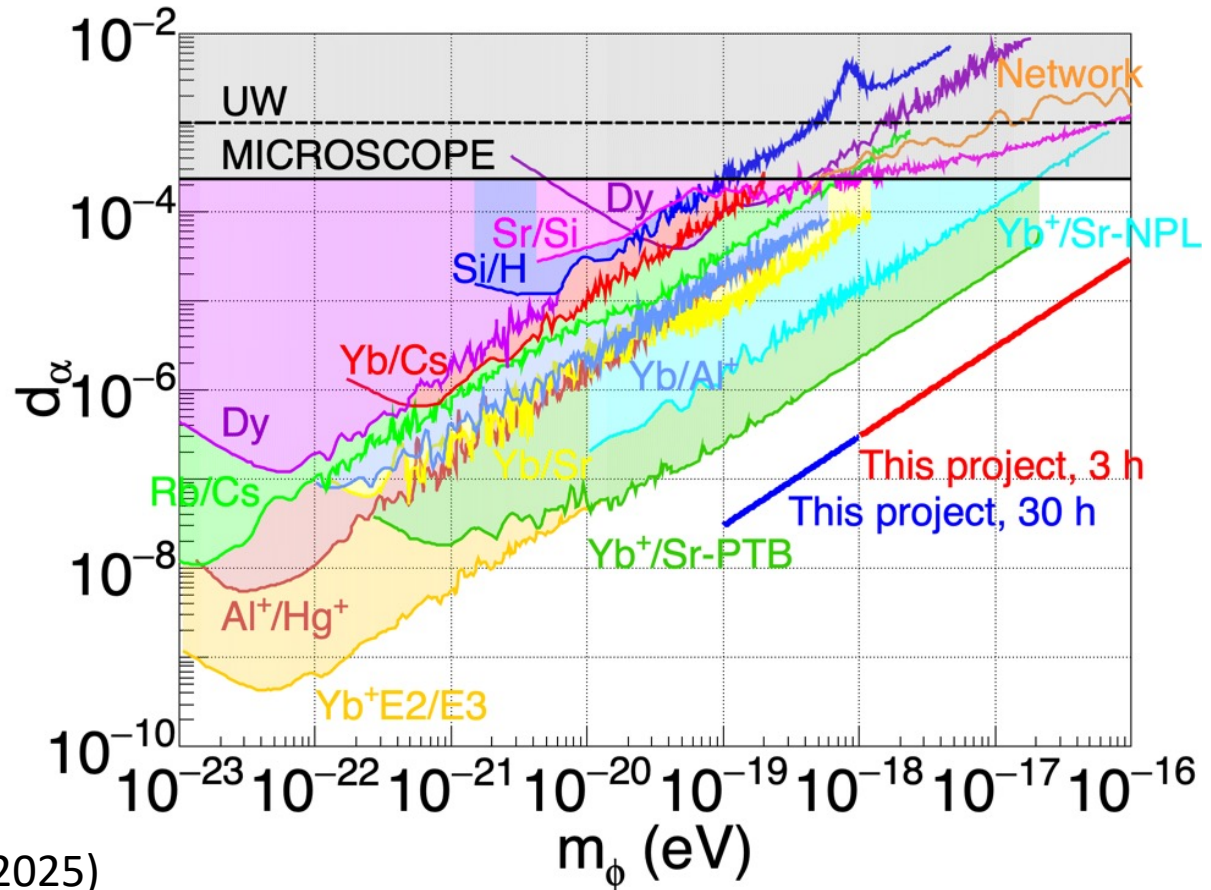
- Assuming stability of $10^{-16}/\sqrt{\tau}$ and 3h operation of the comparison between the 578 nm and 431 nm transition frequencies, we can expect the best constraint in a few years.



The plot is modified from AK: Appl. Phys. Rev. **12**, 041331 (2025)

Search for Ultralight Dark Matter

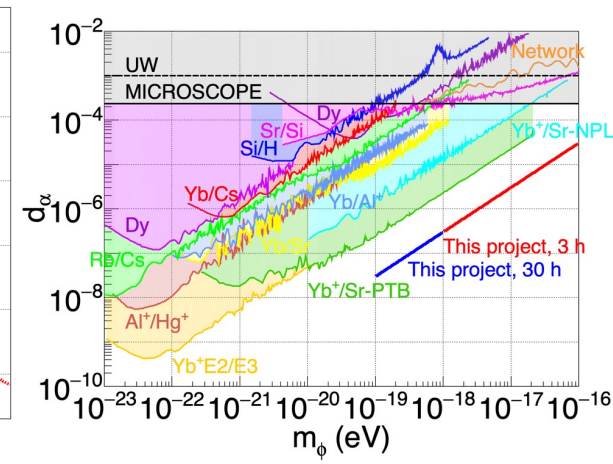
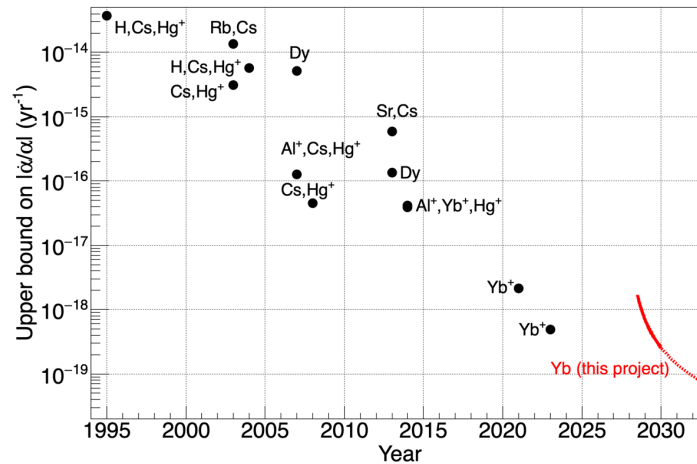
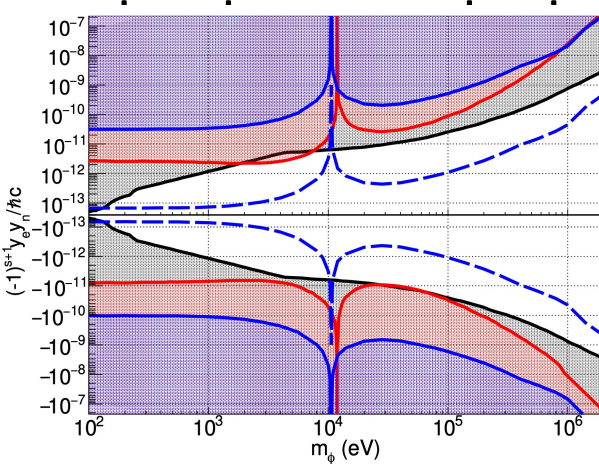
- Dilaton-like scalar dark matter induces an oscillation in α .
- This oscillation can be detected using long-term comparison between two optical lattice clocks.
- Stability of $10^{-16}/\sqrt{\tau}$ is assumed.



The plot is modified from
 AK: Appl. Phys. Rev. **12**, 041331 (2025)

Summary

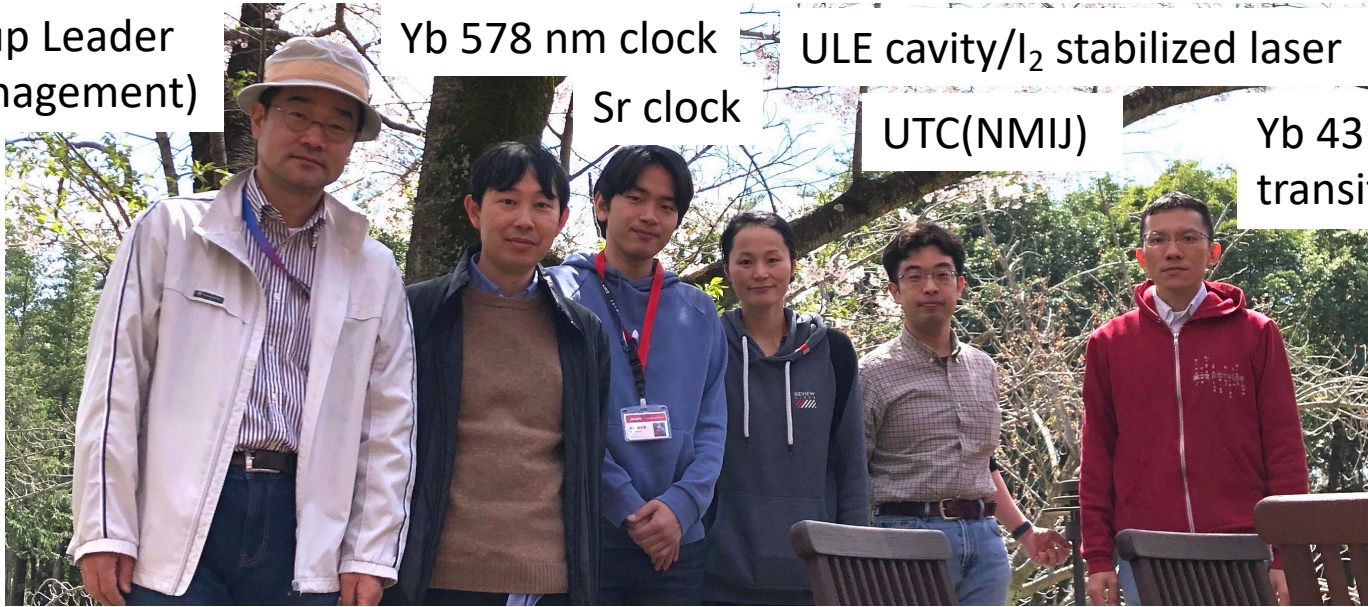
- Precise comparison of two clocks can be utilized for fundamental physics searches.
- I am working on precision spectroscopy of the 431 nm transition in Yb.
- With an initial data, we put constraint on fifth forces between an electron and a neutron.
- The transition is highly sensitive to variation of the fine structure constant and ultralight scalar dark matter coupling to the fine



Acknowledgments

Team: Masami Takumi Shintaro Akiko Takehiko
Yasuda Kobayashi Nagase Nishiyama Tanabe AK

Group Leader
(Management)



A postdoc and a grad student position are available!

Funding:



創発的研究支援事業
Fusion Oriented REsearch for disruptive Science and Technology



Positions are Available!

Postdoc

- Under KAKENHI Transformative Research A grant. See the following job posting, or you can Google my personal webpage and go to Available Positions page.

https://unit.aist.go.jp/deihrd07/keiyaku_koubo/2026-ripm_0002.html#ttl

Graduate student

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



Back up slides

How to Observe 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):

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

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

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

