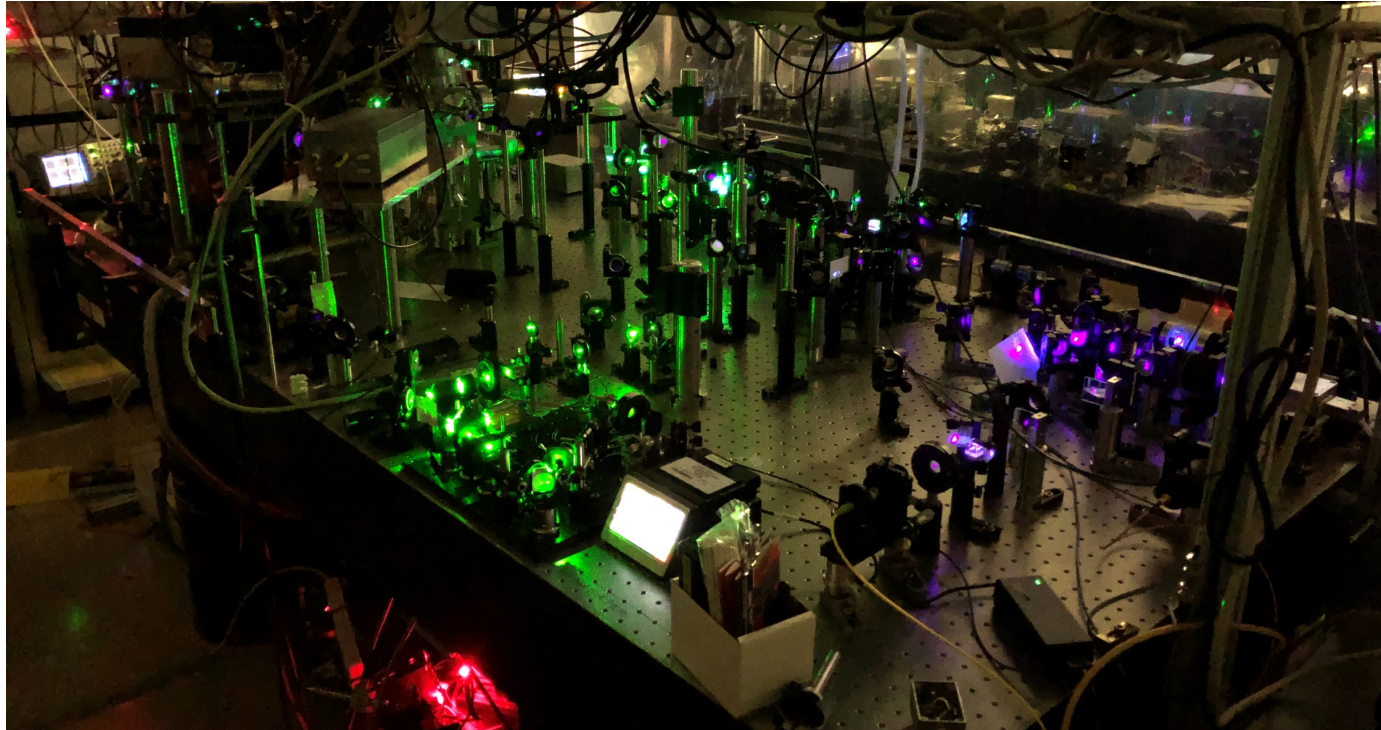


C01: Physics of Cosmogenesis Investigated with Atomic Clocks



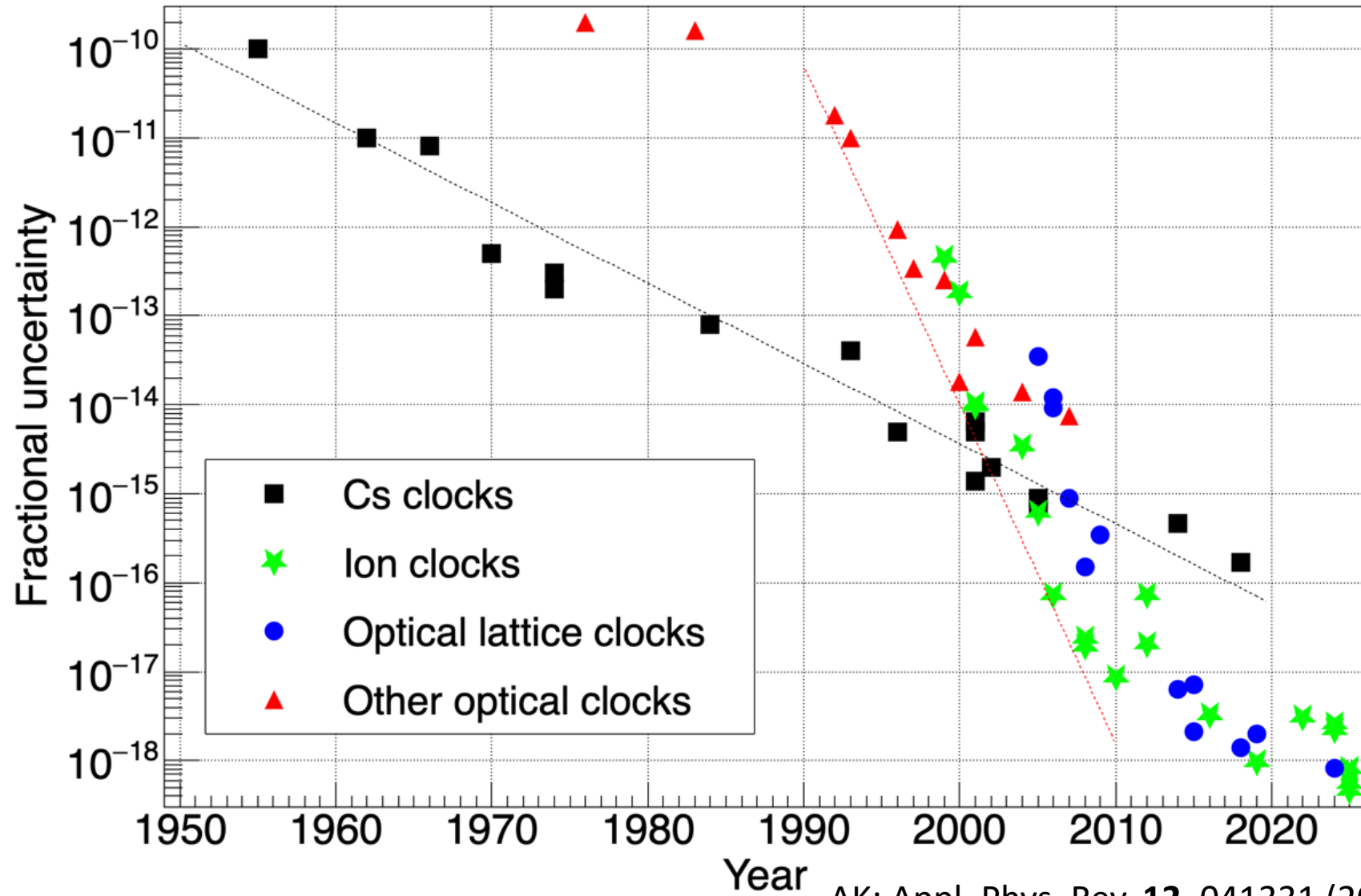
Akio Kawasaki

National Metrology Institute of Japan

National Institute of Advanced Industrial Science and Technology

Introduction to Fundamental Physics Searches Using Precision Spectroscopy

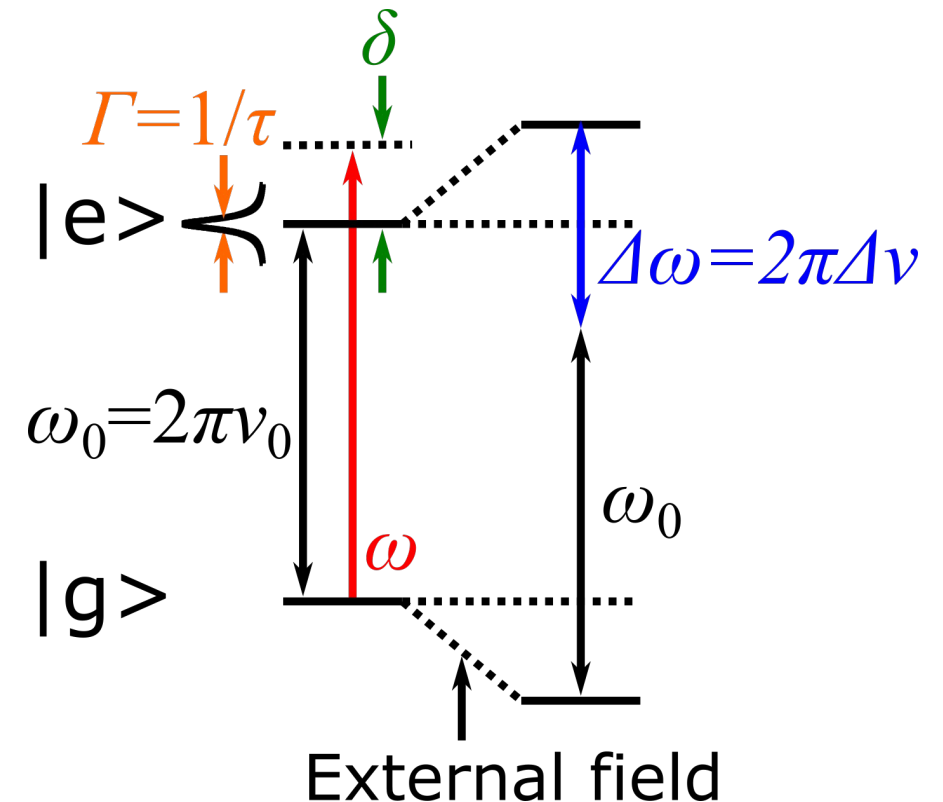
Accuracy of Atomic Clocks



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 $\Rightarrow$ 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.



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

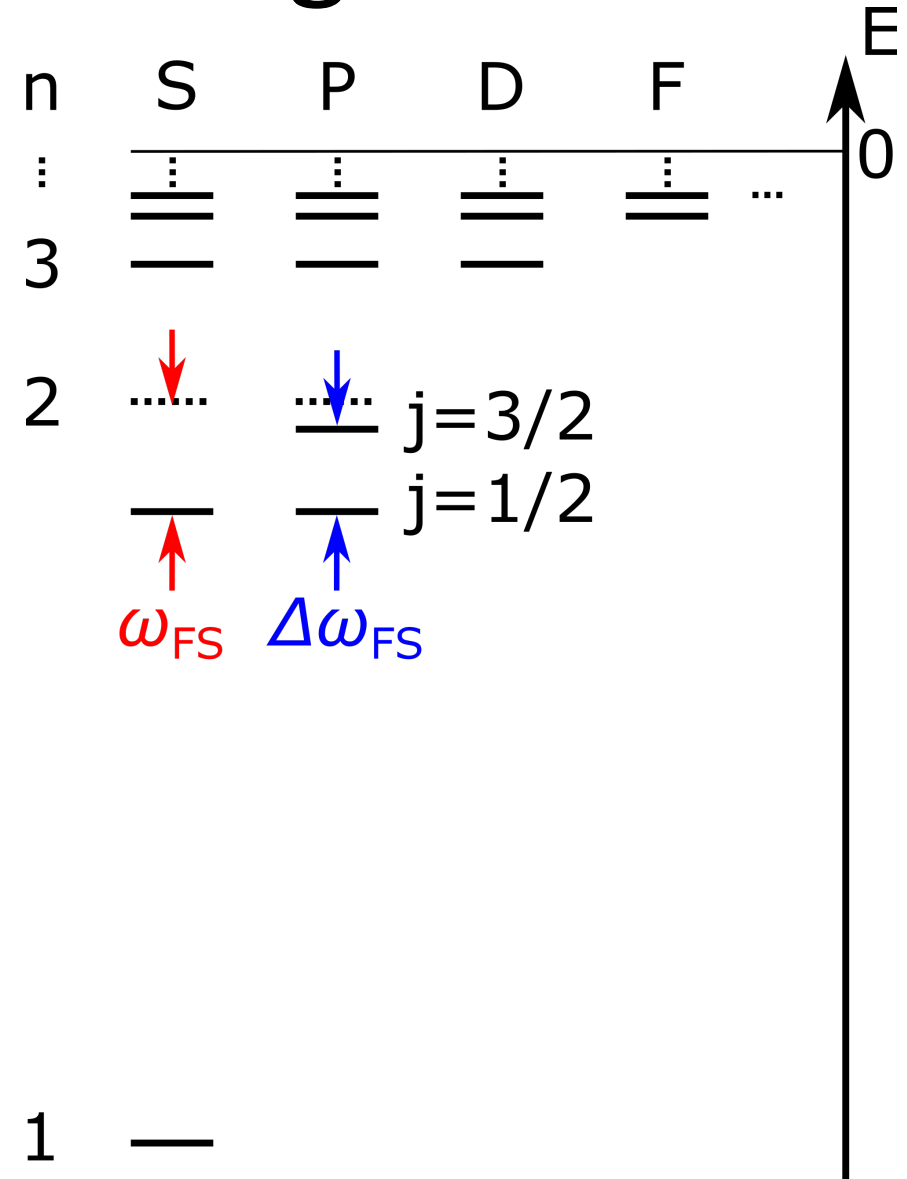
- By Dirac equation (relativistic):

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

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

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

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



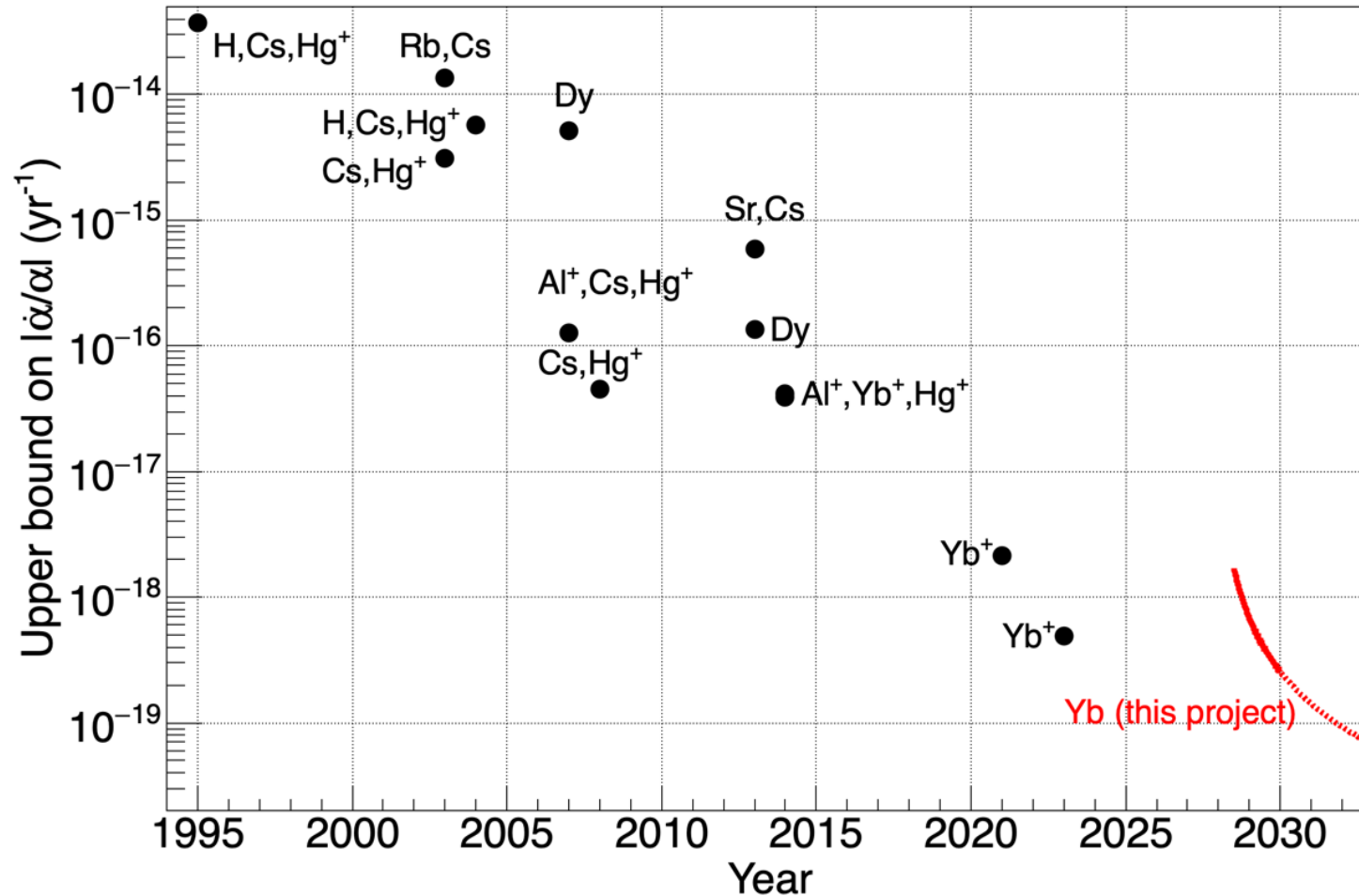
Sensitivity to Variation of α

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	Dzuba, <i>et al.</i> : Phys. Rev. A 98 , 022501 (2018) Safronova, <i>et al.</i> : Rev. Mod. Phys. 90 , 025008 (2018)
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	: New result from our project!
Ac^+	$7s^2\ ^1S_0 - 6d7s\ ^3D_1$	142	9.73	

AK: arXiv:2606.29676 (2026)

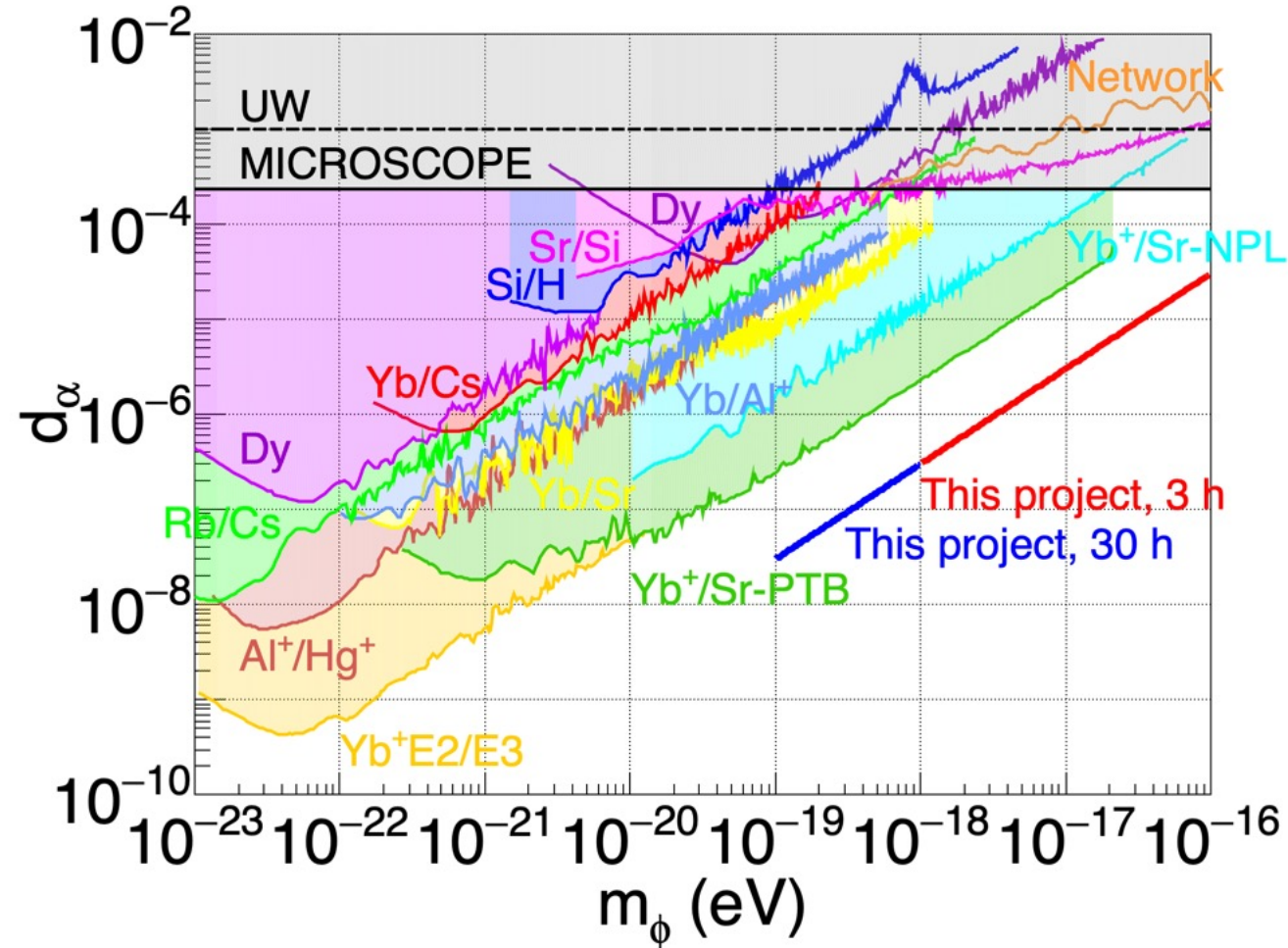
Expected Sensitivity in this Project

- 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)
- $[\text{Xe}] 4f^{14} 6s^2$

1 H Hydrogen Nonmetal		PubCchem																2 He Helium Noble Gas	
3 Li Lithium Alkali Metal		4 Be Beryllium Alkaline Earth Metal																	10 Ne Neon Noble Gas
11 Na Sodium Alkali Metal		12 Mg Magnesium Alkaline Earth Metal																	18 Ar Argon Noble Gas
19 K Potassium Alkali Metal	20 Ca Calcium Alkaline Earth Metal	21 Sc Scandium Transition Metal	22 Ti Titanium Transition Metal	23 V Vanadium Transition Metal	24 Cr Chromium Transition Metal	25 Mn Manganese Transition Metal	26 Fe Iron Transition Metal	27 Co Cobalt Transition Metal	28 Ni Nickel Transition Metal	29 Cu Copper Transition Metal	30 Zn Zinc Transition Metal	31 Ga Gallium Post-Transition Metal	32 Ge Germanium Metalloid	33 As Arsenic Metalloid	34 Se Selenium Nonmetal	35 Br Bromine Halogen	36 Kr Krypton Noble Gas		
37 Rb Rubidium Alkali Metal	38 Sr Strontium Alkaline Earth Metal	39 Y Yttrium Transition Metal	40 Zr Zirconium Transition Metal	41 Nb Niobium Transition Metal	42 Mo Molybdenum Transition Metal	43 Tc Technetium Transition Metal	44 Ru Ruthenium Transition Metal	45 Rh Rhodium Transition Metal	46 Pd Palladium Transition Metal	47 Ag Silver Transition Metal	48 Cd Cadmium Transition Metal	49 In Indium Post-Transition Metal	50 Sn Tin Post-Transition Metal	51 Sb Antimony Metalloid	52 Te Tellurium Metalloid	53 I Iodine Halogen	54 Xe Xenon Noble Gas		
55 Cs Cesium Alkali Metal	56 Ba Barium Alkaline Earth Metal	*	72 Hf Hafnium Transition Metal	73 Ta Tantalum Transition Metal	74 W Tungsten Transition Metal	75 Re Rhenium Transition Metal	76 Os Osmium Transition Metal	77 Ir Iridium Transition Metal	78 Pt Platinum Transition Metal	79 Au Gold Transition Metal	80 Hg Mercury Transition Metal	81 Tl Thallium Post-Transition Metal	82 Pb Lead Post-Transition Metal	83 Bi Bismuth Post-Transition Metal	84 Po Polonium Metalloid	85 At Astatine Halogen	86 Rn Radon Noble Gas		
87 Fr Francium Alkali Metal	88 Ra Radium Alkaline Earth Metal	**	104 Rf Rutherfordium Transition Metal	105 Db Dubnium Transition Metal	106 Sg Seaborgium Transition Metal	107 Bh Bohrium Transition Metal	108 Hs Hassium Transition Metal	109 Mt Meitnerium Transition Metal	110 Ds Darmstadtium Transition Metal	111 Rg Roentgenium Transition Metal	112 Cn Copernicium Transition Metal	113 Nh Nihonium Post-Transition Metal	114 Fl Flerovium Post-Transition Metal	115 Mc Moscovium Post-Transition Metal	116 Lv Livermorium Post-Transition Metal	117 Ts Tennessine Halogen	118 Og Oganesson Noble Gas		
		*	57 La Lanthanum Lanthanide	58 Ce Cerium Lanthanide	59 Pr Praseodymium Lanthanide	60 Nd Neodymium Lanthanide	61 Pm Promethium Lanthanide	62 Sm Samarium Lanthanide	63 Eu Europium Lanthanide	64 Gd Gadolinium Lanthanide	65 Tb Terbium Lanthanide	66 Dy Dysprosium Lanthanide	67 Ho Holmium Lanthanide	68 Er Erbium Lanthanide	69 Tm Thulium Lanthanide	70 Yb Ytterbium Lanthanide	71 Lu Lutetium Lanthanide		
		**	89 Ac Actinium Actinide	90 Th Thorium Actinide	91 Pa Protactinium Actinide	92 U Uranium Actinide	93 Np Neptunium Actinide	94 Pu Plutonium Actinide	95 Am Americium Actinide	96 Cm Curium Actinide	97 Bk Berkelium Actinide	98 Cf Californium Actinide	99 Es Einsteinium Actinide	100 Fm Fermium Actinide	101 Md Mendelevium Actinide	102 No Nobelium Actinide	103 Lr Lawrencium Actinide		

Atomic Number

Symbol

Name

Chemical Group Block

1
H
Hydrogen
Nonmetal

5
B
Boron
Metalloid

6
C
Carbon
Nonmetal

7
N
Nitrogen
Nonmetal

8
O
Oxygen
Nonmetal

9
F
Fluorine
Halogen

13
Al
Aluminum
Post-Transition Metal

14
Si
Silicon
Metalloid

15
P
Phosphorus
Nonmetal

16
S
Sulfur
Nonmetal

17
Cl
Chlorine
Halogen

19
K
Potassium
Alkali Metal

20
Ca
Calcium
Alkaline Earth Metal

21
Sc
Scandium
Transition Metal

22
Ti
Titanium
Transition Metal

23
V
Vanadium
Transition Metal

24
Cr
Chromium
Transition Metal

25
Mn
Manganese
Transition Metal

26
Fe
Iron
Transition Metal

27
Co
Cobalt
Transition Metal

28
Ni
Nickel
Transition Metal

29
Cu
Copper
Transition Metal

30
Zn
Zinc
Transition Metal

31
Ga
Gallium
Post-Transition Metal

32
Ge
Germanium
Metalloid

33
As
Arsenic
Metalloid

34
Se
Selenium
Nonmetal

35
Br
Bromine
Halogen

36
Kr
Krypton
Noble Gas

37
Rb
Rubidium
Alkali Metal

38
Sr
Strontium
Alkaline Earth Metal

39
Y
Yttrium
Transition Metal

40
Zr
Zirconium
Transition Metal

41
Nb
Niobium
Transition Metal

42
Mo
Molybdenum
Transition Metal

43
Tc
Technetium
Transition Metal

44
Ru
Ruthenium
Transition Metal

45
Rh
Rhodium
Transition Metal

46
Pd
Palladium
Transition Metal

47
Ag
Silver
Transition Metal

48
Cd
Cadmium
Transition Metal

49
In
Indium
Post-Transition Metal

50
Sn
Tin
Post-Transition Metal

51
Sb
Antimony
Metalloid

52
Te
Tellurium
Metalloid

53
I
Iodine
Halogen

54
Xe
Xenon
Noble Gas

55
Cs
Cesium
Alkali Metal

56
Ba
Barium
Alkaline Earth Metal

57
La
Lanthanum
Lanthanide

58
Ce
Cerium
Lanthanide

59
Pr
Praseodymium
Lanthanide

60
Nd
Neodymium
Lanthanide

61
Pm
Promethium
Lanthanide

62
Sm
Samarium
Lanthanide

63
Eu
Europium
Lanthanide

64
Gd
Gadolinium
Lanthanide

65
Tb
Terbium
Lanthanide

66
Dy
Dysprosium
Lanthanide

67
Ho
Holmium
Lanthanide

68
Er
Erbium
Lanthanide

69
Tm
Thulium
Lanthanide

70
Yb
Ytterbium
Lanthanide

71
Lu
Lutetium
Lanthanide

72
Hf
Hafnium
Transition Metal

73
Ta
Tantalum
Transition Metal

74
W
Tungsten
Transition Metal

75
Re
Rhenium
Transition Metal

76
Os
Osmium
Transition Metal

77
Ir
Iridium
Transition Metal

78
Pt
Platinum
Transition Metal

79
Au
Gold
Transition Metal

80
Hg
Mercury
Transition Metal

81
Tl
Thallium
Post-Transition Metal

82
Pb
Lead
Post-Transition Metal

83
Bi
Bismuth
Post-Transition Metal

84
Po
Polonium
Metalloid

85
At
Astatine
Halogen

86
Rn
Radon
Noble Gas

87
Fr
Francium
Alkali Metal

88
Ra
Radium
Alkaline Earth Metal

89
Ac
Actinium
Actinide

90
Th
Thorium
Actinide

91
Pa
Protactinium
Actinide

92
U
Uranium
Actinide

93
Np
Neptunium
Actinide

94
Pu
Plutonium
Actinide

95
Am
Americium
Actinide

96
Cm
Curium
Actinide

97
Bk
Berkelium
Actinide

98
Cf
Californium
Actinide

99
Es
Einsteinium
Actinide

100
Fm
Fermium
Actinide

101
Md
Mendelevium
Actinide

102
No
Nobelium
Actinide

103
Lr
Lawrencium
Actinide

104
Rf
Rutherfordium
Transition Metal

105
Db
Dubnium
Transition Metal

106
Sg
Seaborgium
Transition Metal

107
Bh
Bohrium
Transition Metal

108
Hs
Hassium
Transition Metal

109
Mt
Meitnerium
Transition Metal

110
Ds
Darmstadtium
Transition Metal

111
Rg
Roentgenium
Transition Metal

112
Cn
Copernicium
Transition Metal

113
Nh
Nihonium
Post-Transition Metal

114
Fl
Flerovium
Post-Transition Metal

115
Mc
Moscovium
Post-Transition Metal

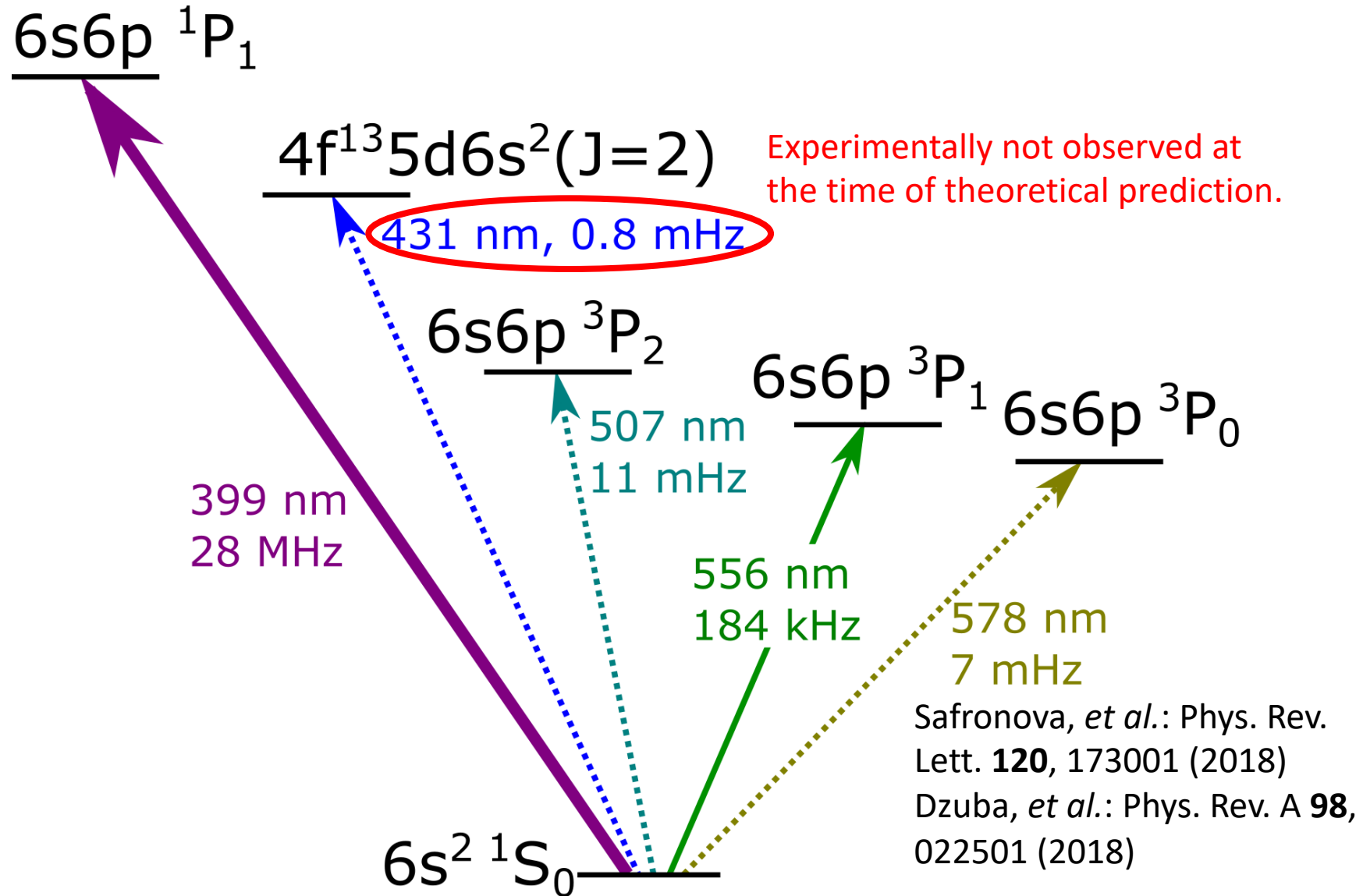
116
Lv
Livermorium
Post-Transition Metal

117
Ts
Tennessine
Halogen

118
Og
Oganesson
Noble Gas

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

Transitions in Neutral Ytterbium



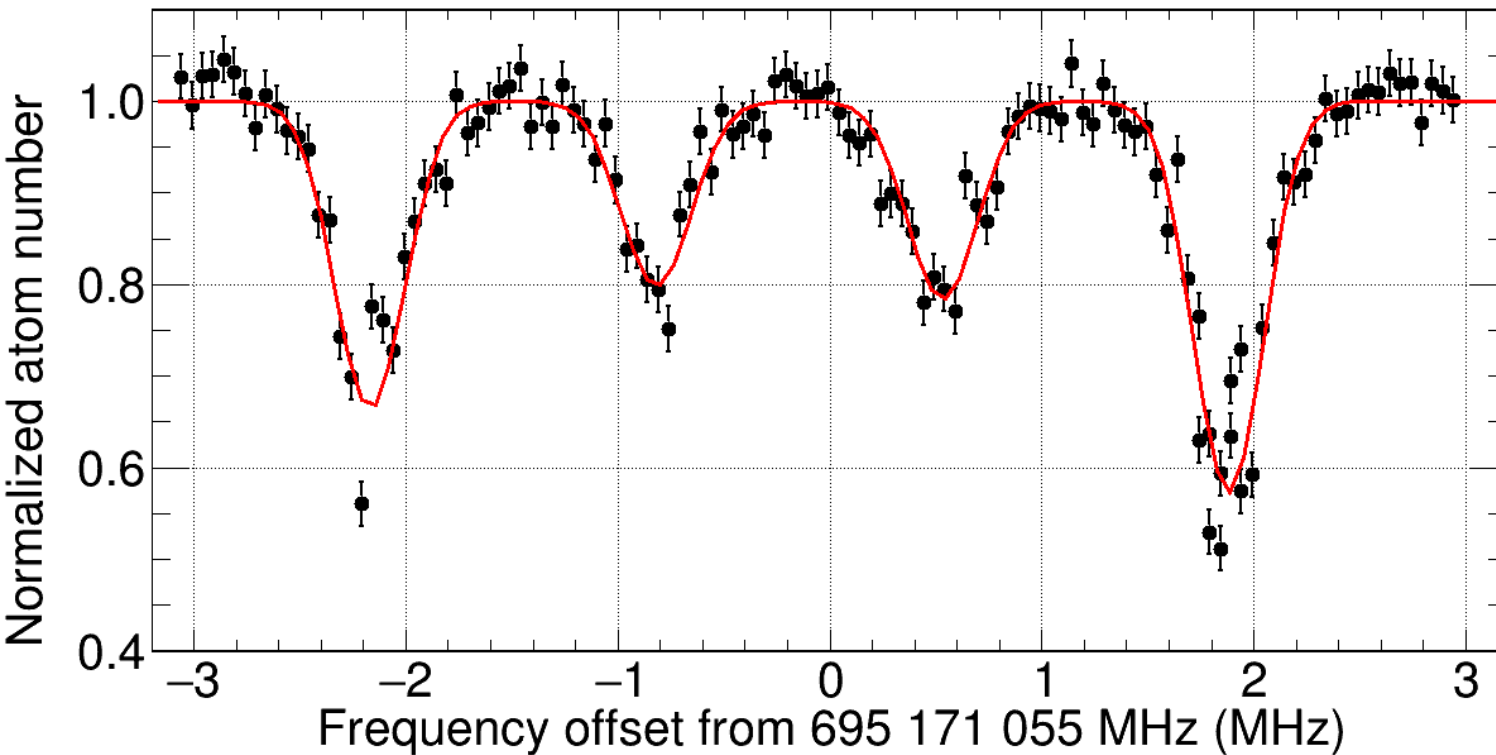
Progress So Far

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

	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]

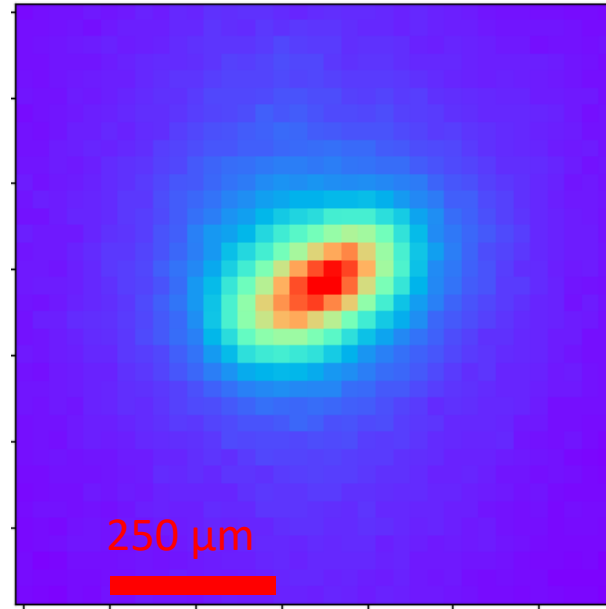
[1] AK, *et al.*: Phys. Rev. A **107**, L060801 (2023)

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

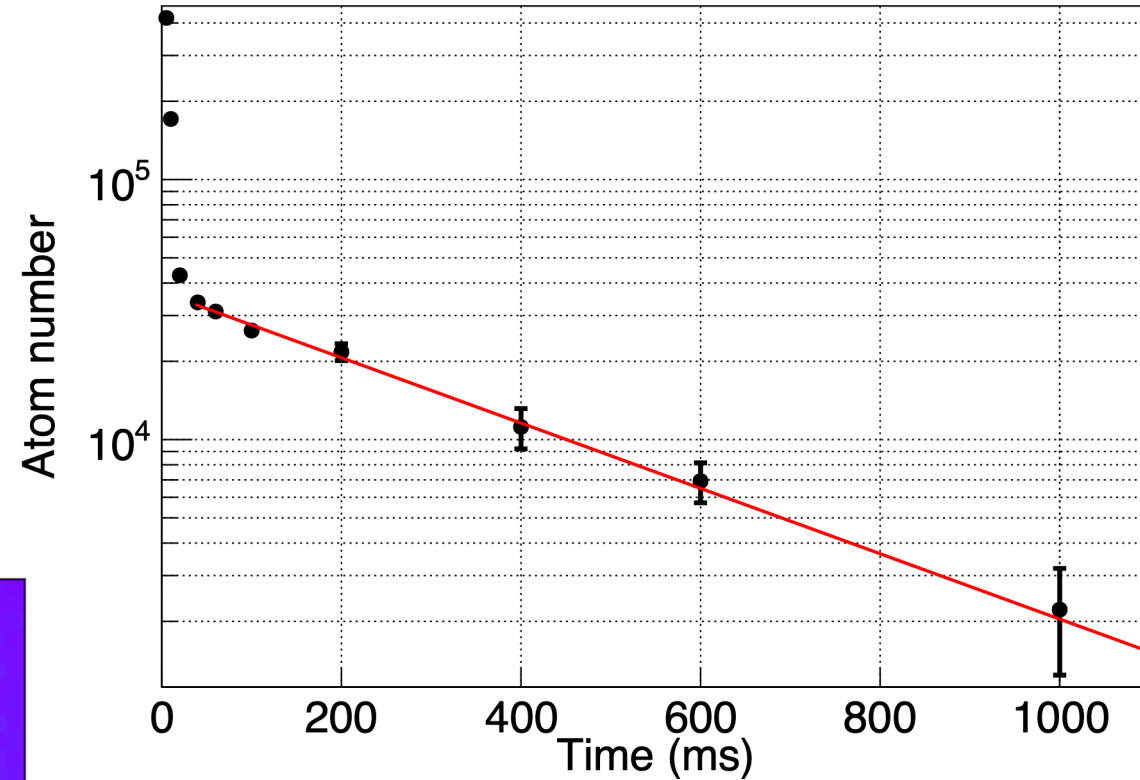
[3] Ishiyama, *et al.*: Phys. Rev. Lett. **130**, 153402 (2023)

Lattice Configuration

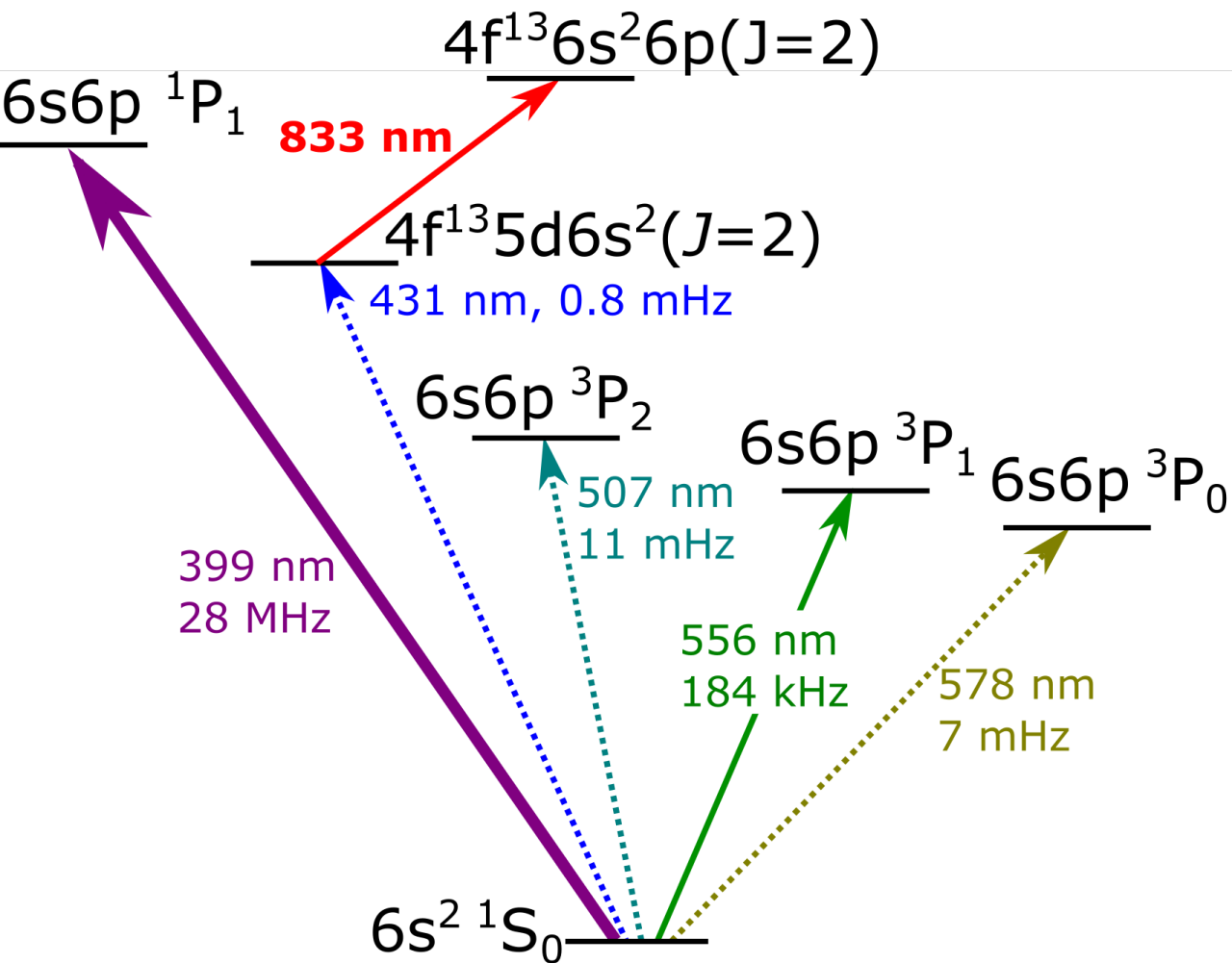
- Horizontal 1D lattice
- laser power: < 0.85 W
- waist size: $w_0 = 26$ μm
- atom number: 2.7×10^4
- atom lifetime: ~ 350 ms
- probe beam size: $w_0 = 120$ μm
- probe beam power: 8 mW



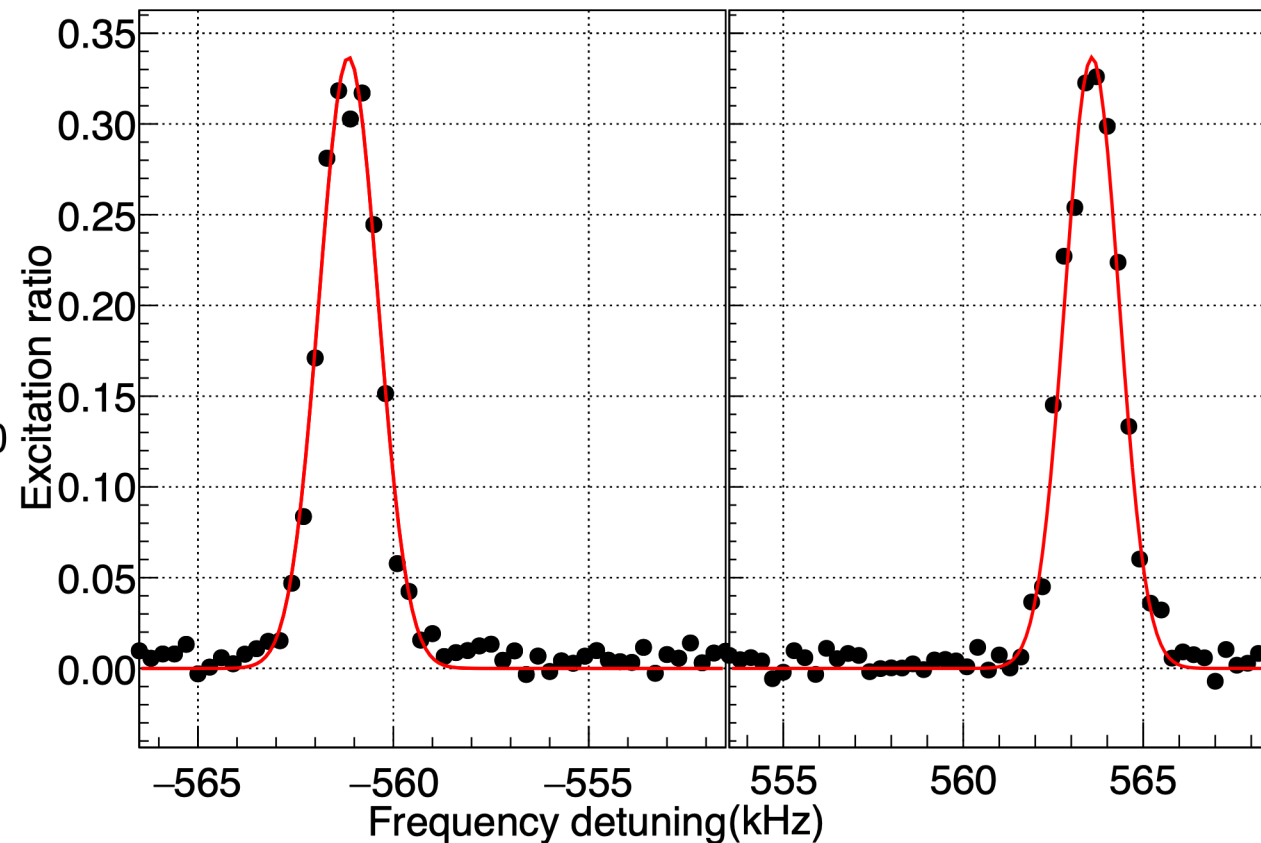
Akio Kawasaki



Measurement of Excited State Population



- Linewidth is ~ 800 Hz.



Magic Frequency

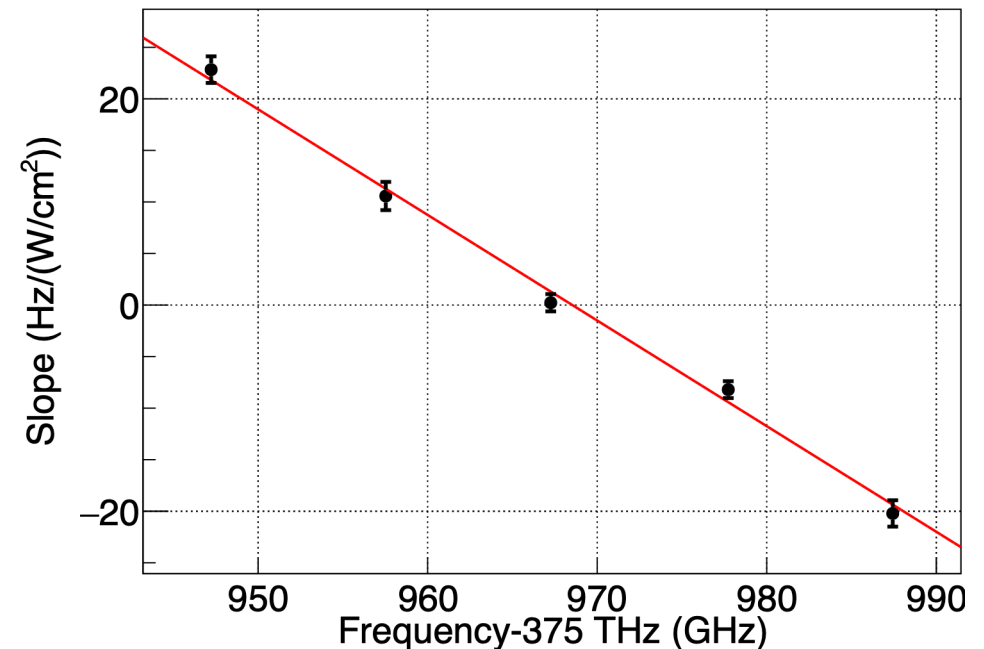
At a magic frequency, energy shifts for the ground and excited states due to the optical lattice is the same.

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

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

(Numbers are preliminary)

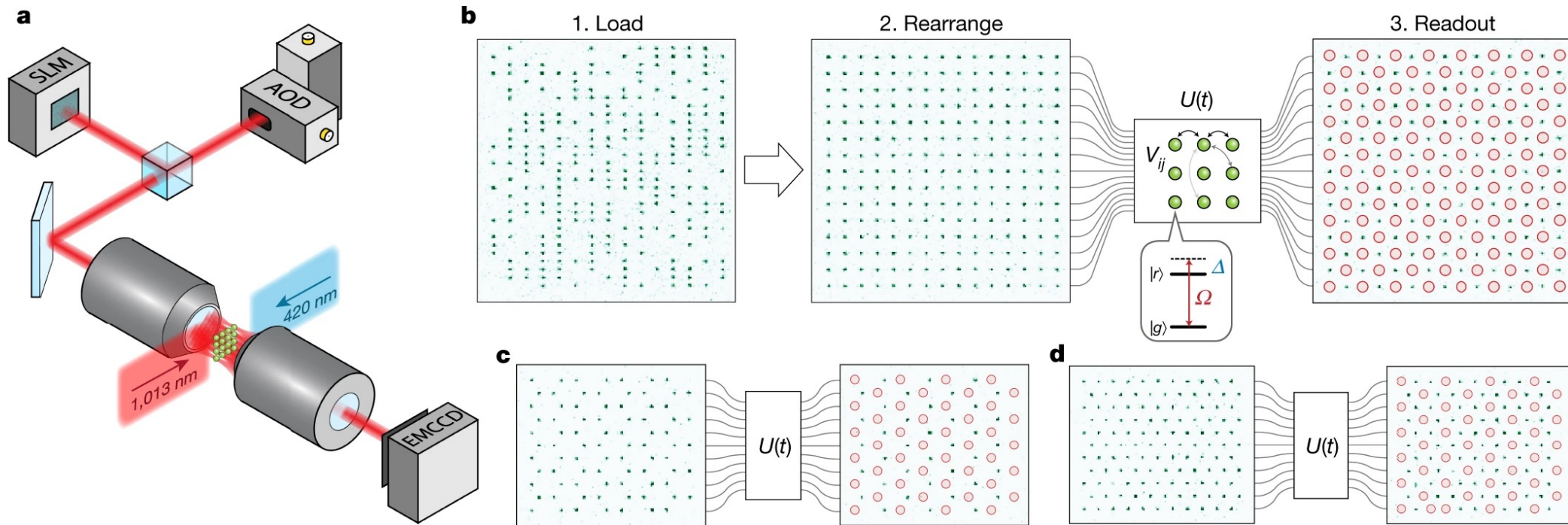
- In reality, using $m_F = \pm 1/2$ for precision spectroscopy makes the most sense, because of narrower linewidths.
- More precise determination for $m_F = \pm 1/2$:
375 968.53(60) GHz.



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 tweezers 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.

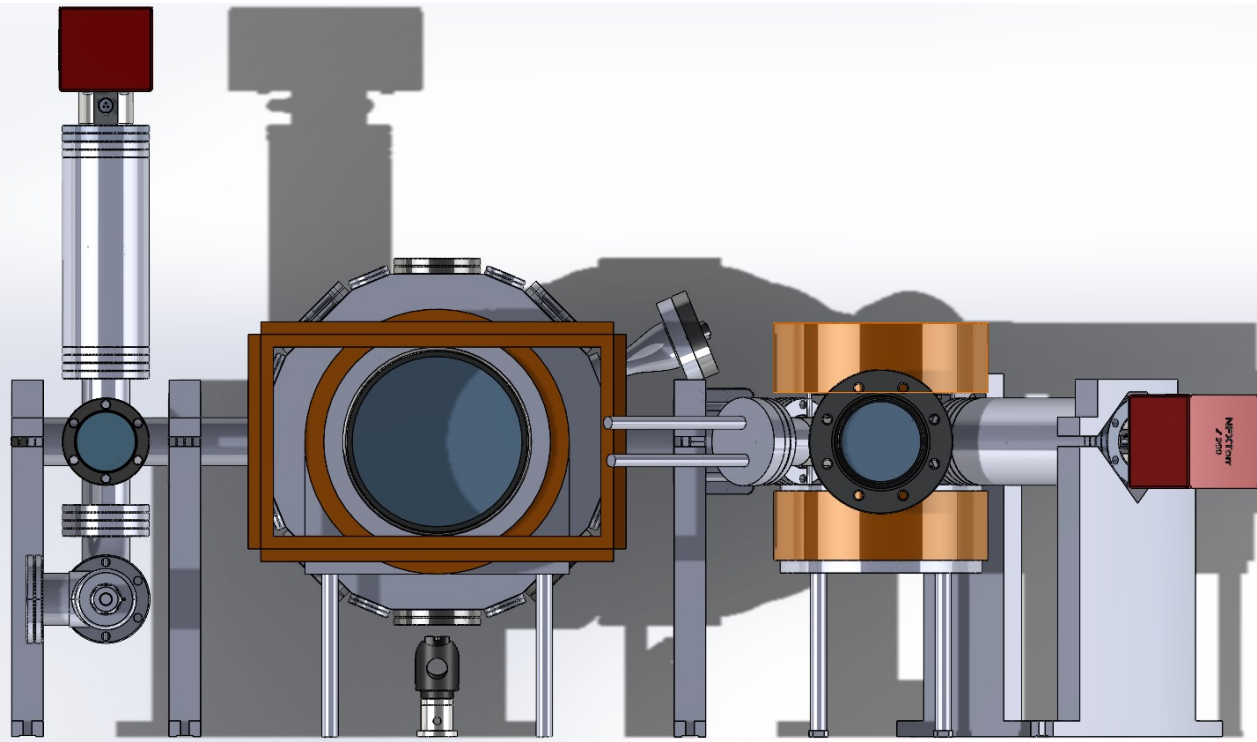


Ebadi, *et al.*: Nature 595, 227 (2021)

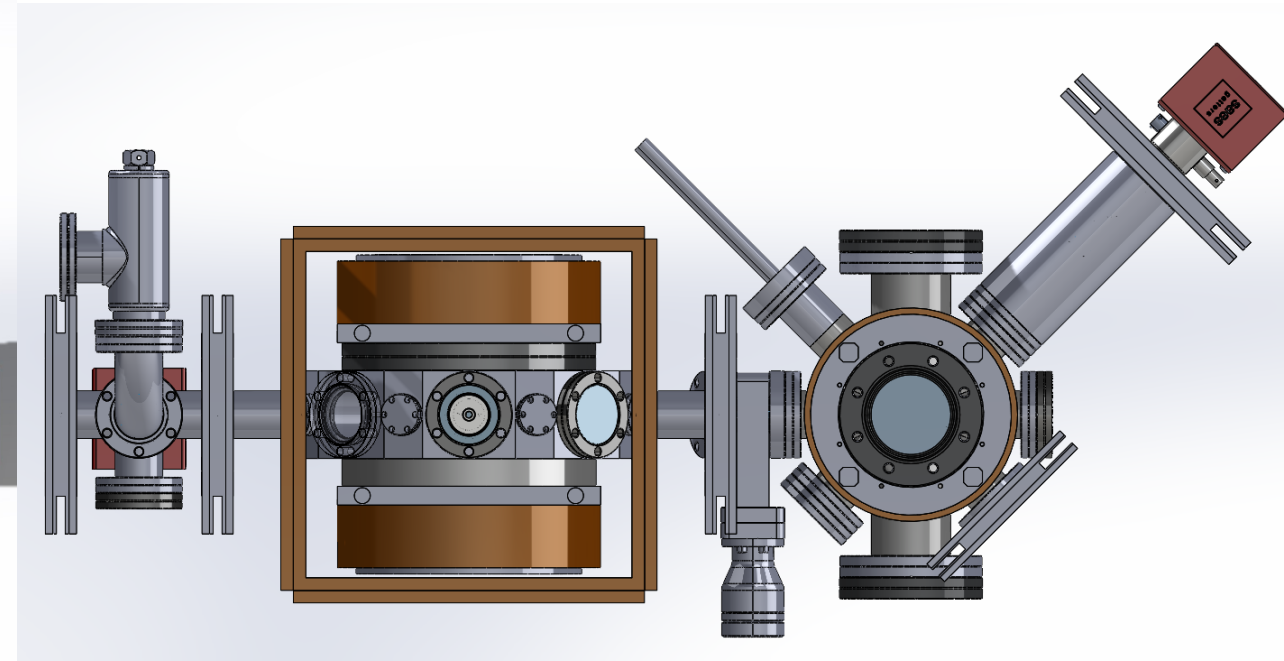
New Vacuum System

- 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

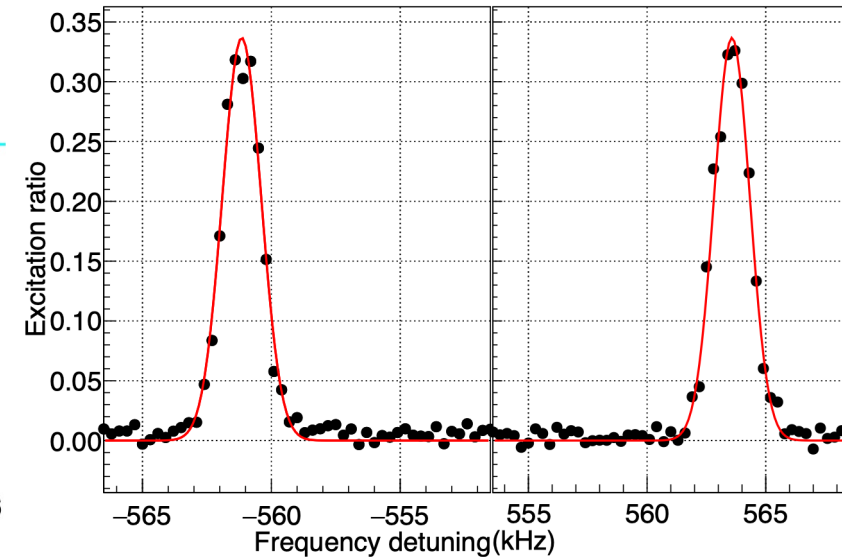
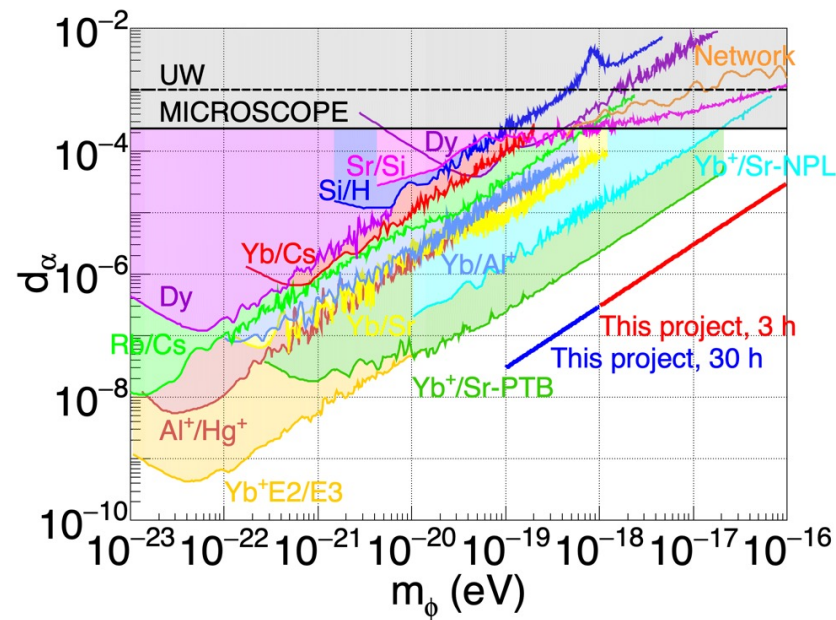
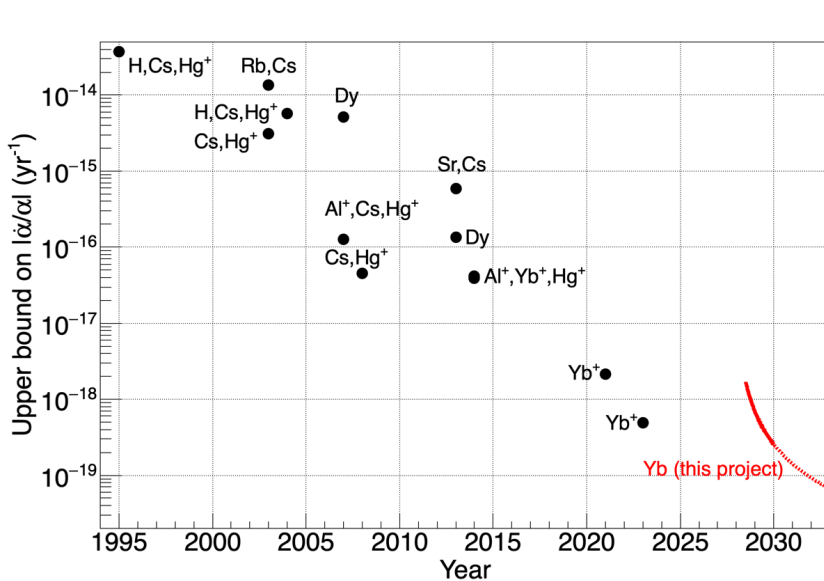


bottom view



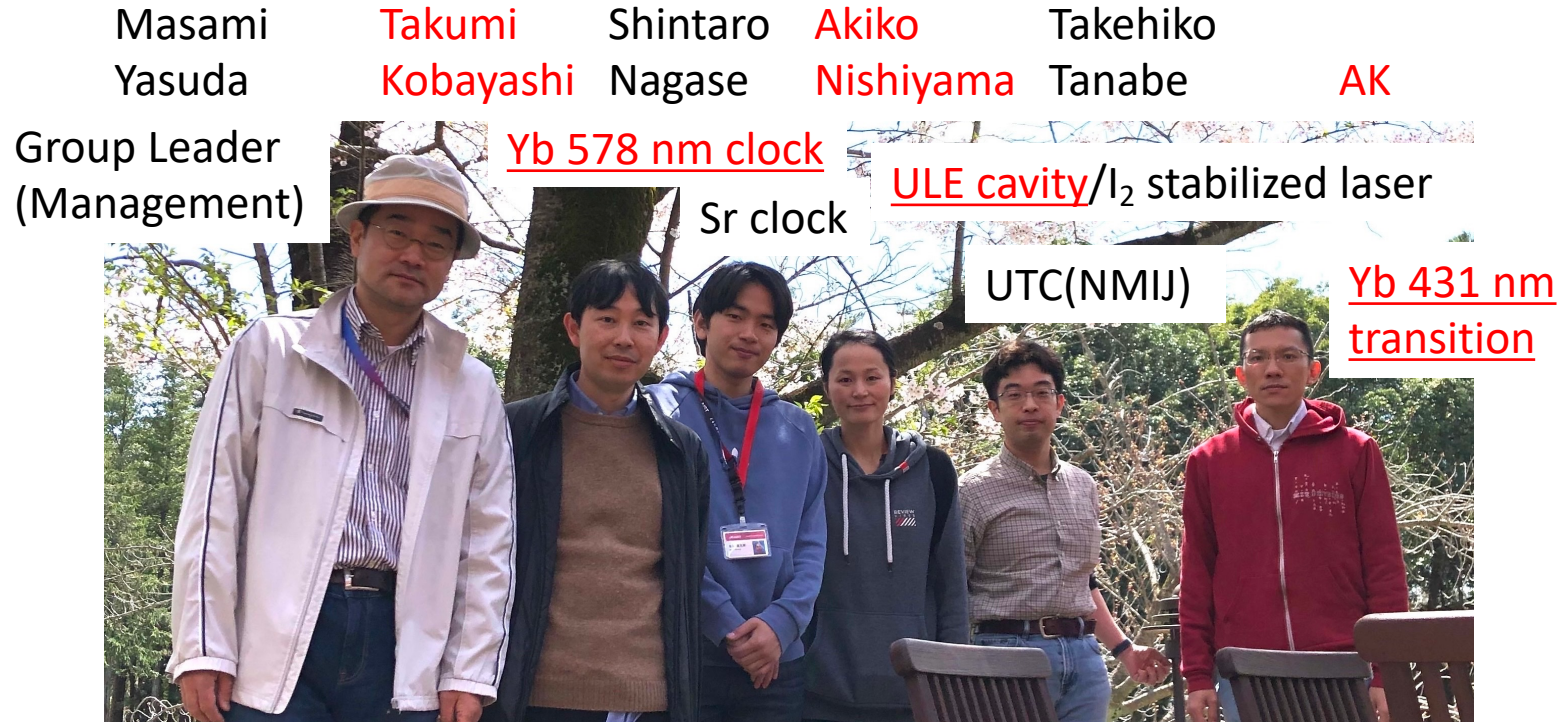
Summary

- 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



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

- 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.

