Atomic clocks sensitive to variation of the fine structure constant

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Motivation

- Manifestation of new physics (**NP**) at low energy is expected to be small => high accuracy is needed.

- The highest accuracy of the measurements is in optical clocks, e.g. for the $^1S_0 - {}^3P^o_0$ transition in **Yb**, $\delta\omega/\omega \sim 10^{-18}$!

- Optical frequencies depend on the fine structure constant α. **NP** may manifest itself via apparent variation of α.

For any atomic frequency

$$\omega = \omega_0 + q\left[\left(\alpha / \alpha_0\right)^2 - 1\right]$$

where $\omega_0 = \omega(\alpha = \alpha_0)$ and q is a sensitivity coefficient found from atomic calculations as a numerical derivative

$$q = \frac{\omega(x=\delta) - \omega(x=-\delta)}{2\delta}$$

where

$$x = \left[\left(\alpha / \alpha_0\right)^2 - 1\right]$$

Searching for time evolution of **alpha** can be done by monitoring time evolution of dimensionless ratio of two atomic frequencies:

$$\frac{\partial}{\partial t}\ln\frac{\omega_1}{\omega_2} = \left(\frac{2q_1}{\omega_1} - \frac{2q_2}{\omega_2}\right)\frac{1}{\alpha}\frac{\partial\alpha}{\partial t}$$

$K=2q/\omega$ is an enhancement factor.

We need two transitions with large and different K.

Two ways to get large $K=2q/\omega$:

1. Large q.
2. Small ω.

Looking for large K due to small ω is <u>wrong</u> because accuracy of the measurements ($\delta\omega$) is equally important.

Figure of merit: $$\frac{2q}{\omega} / \frac{\delta\omega}{\omega} = \frac{2q}{\delta\omega}$$ does not depend on ω.

Example: **Dy** atom.

1. $4f^{10}5d6s\ {}^3[10]_{10}$ E=19797.06 cm^{-1}, q=6008 cm^{-1}.
2. $4f^{9}5d^{2}6s\ {}^3[10]^0_{10}$ E=19797.06 cm^{-1}, q=-23708 cm^{-1}.

***K* ~ 10^8**

$$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t}=(-5.8\pm6.9)\times10^{-17}\,\mathrm{yr}^{-1}$$

Leefer *et al,* PRL **111**, 060801 (2013) (**Dy**/**Cs**)

$$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t}=(-1.6\pm2.3)\times10^{-17}\,\mathrm{yr}^{-1}$$

Rosenband *et al,* Science **319**, 1808 (2008) (**Al^+**/**Hg^+**)

$$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t}=(-0.7\pm2.1)\times10^{-17}\,\mathrm{yr}^{-1}$$

Godun *et al,* PRL **113**, 210801 (2014) (**Yb^+**/**Yb^+**)

$$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t}=1.0(1.1)\times10^{-18}\ \mathrm{yr}^{-1}$$

Lange *et al,* PRL **126**, 011102 (2021) (**Yb^+**/**Yb^+**)

I.e. **Dy** is good due to large *q*, not small ω .

How to get large q?

Relativistic energy shift:

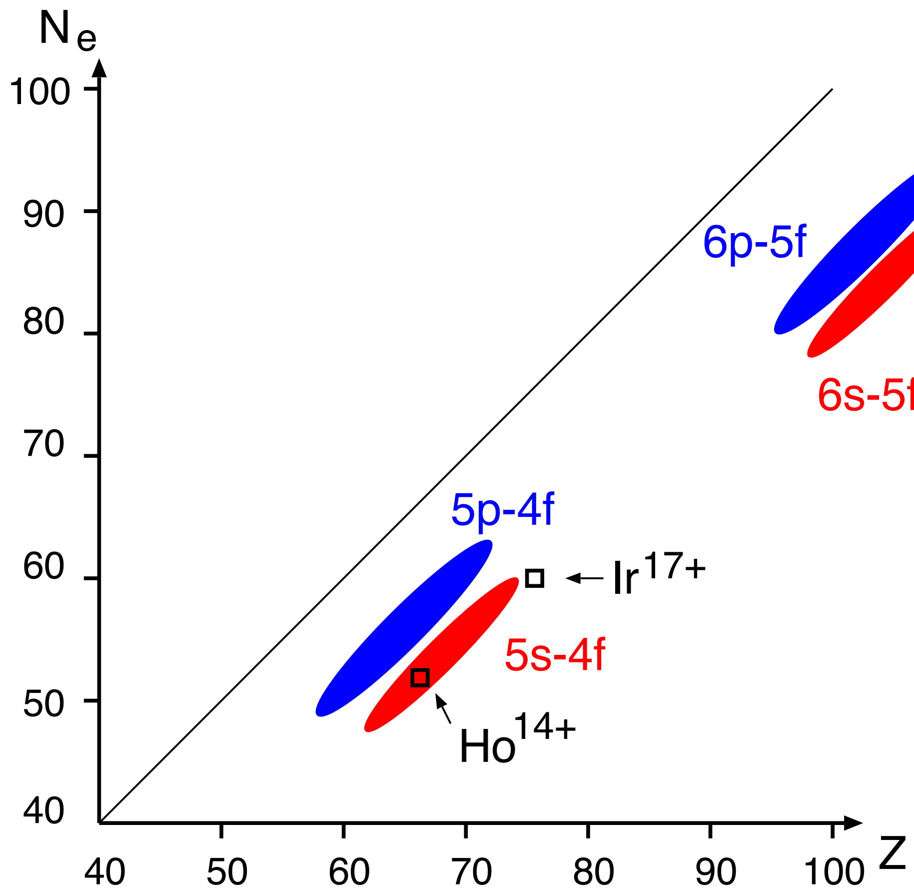
$$\Delta E = -\sqrt{\frac{|E|^3}{2}}(\alpha Z)^2\left[\frac{1}{j+1/2} - C(Z,j,l)\right]$$

Ways to get large q ($q = \Delta E_a - \Delta E_b$):

1. Large |E| (highly charged ions).
2. Large Z.
3. Large Δj (i.e. $s_{1/2}$- $f_{7/2}$, $p_{1/2}$-$f_{7/2}$, etc. transitions).

Can we have all three?
HCI with p-f or s-f level crossing

J. C. Berengut, V. A. Dzuba, V. V. Flambaum, A. Ong, PRA **86**, 022517 (2012).



Experiments in progress:

Ho^{14+}:

$$4f^6 5s\ {}^8F_{1/2} - 4f^5 5s^2\ {}^6H^o_{5/2}$$

RIKEN, Japan;

Ir^{17+}:

$$4f^{13} 5s\ {}^3F^o_4 - 4f^{12} 5s^2\ {}^3H_6$$

MPI, Germany.

Progress for HCI is slow

Experimental problems

- Almost no data − need to start from scratch.
- No strong optical E1 transitions.
- Poor support from theory.

Theoretical problems

- Low accuracy of the calculations,

$$h\omega = E_a+\delta_a - E_a-\delta_a; \qquad \delta_a-\delta_b \sim h\omega .$$

- No experimental data to test the methods.

HCI are still promising but more efforts are needed.

We focus on optical transitions in neutral or nealy neutral systems with large *Z* and large Δj.

The transitions must have features of optical clock transitions

The features are (H. Katori)

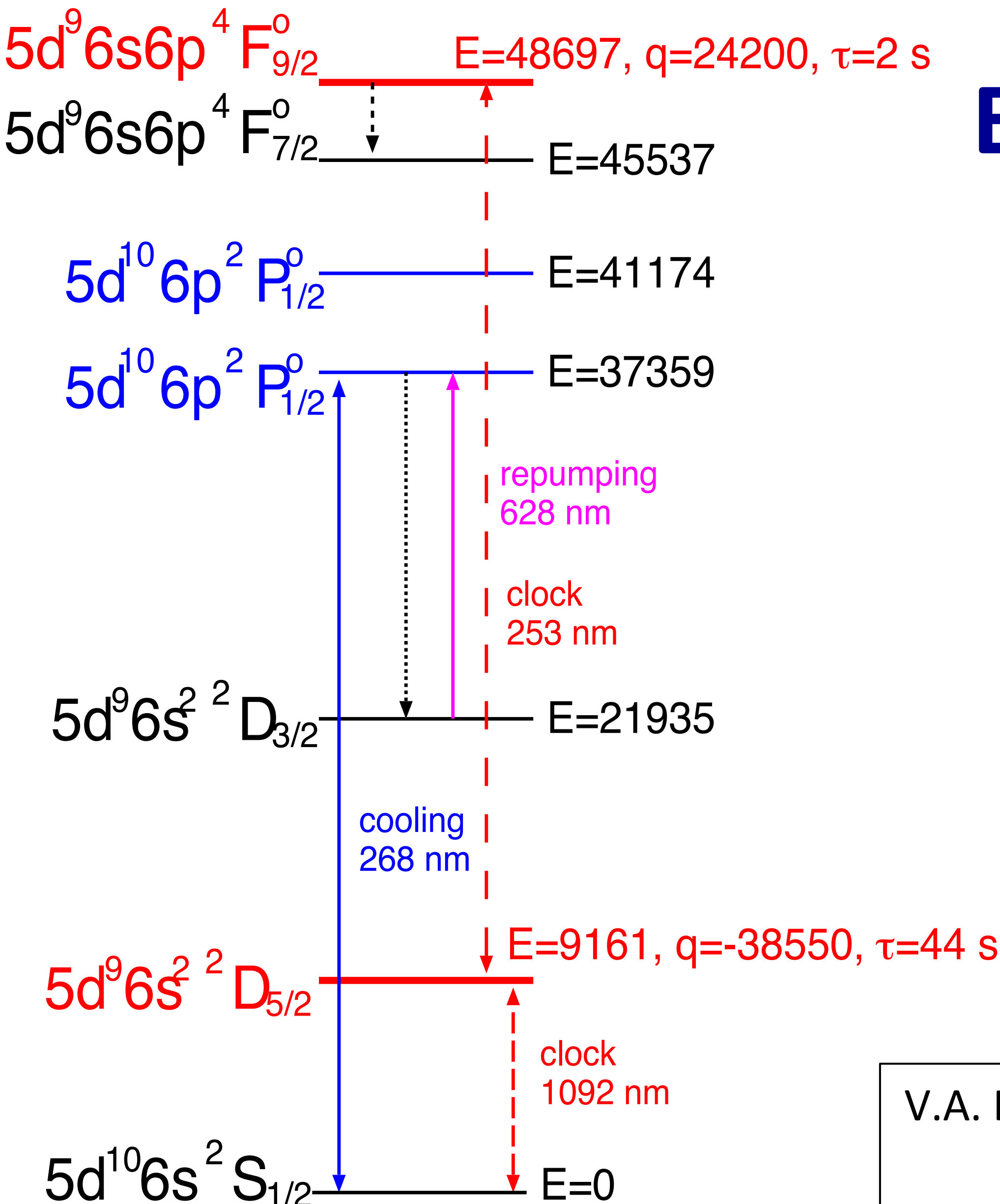
- Optical transition: 5000 cm^{-1} < $h\omega$ <43000 cm^{-1}.
- From ground to a metastable state: 100 s < τ < 10000 s.
- The transition is not sensitive to perturbations (BBR, Zeeman, Stark, etc.).
- There are other transitions with rates > 10^3 s^{-1}.

Clock states with large *q* in neutral or nearly neutral systems.

	Transition	$h\omega$	q	K
Ag I	$4d^{10}5s\ ^2S_{1/2}$ - $4d^95s^2\ ^2D_{5/2}$	30242	-11300	-0.75
Yb I	$4f^{14}6s^2\ ^1S_0$ - $4f^{14}6s6p\ ^3P^o_0$	17288	2714	0.31
Yb I	$4f^{14}6s^2\ ^1S_0$ - $4f^{13}5d6s^2$ J=2	23188	-44290	-3.82
Yb II	$4f^{14}6s\ ^2S_{1/2}$ - $4f^{13}6s^2\ ^3F^o_{7/2}$	21418	-56737	-5.30
Yb II	$4f^{14}6s\ ^2S_{1/2}$ - $4f^{14}5d\ ^2D_{5/2}$	24333	12582	1.03
Yb III	$4f^{14}\ ^1S_0$ - $4f^{13}5d$ J=2	33385	-38150	-2.29
Yb III	$4f^{14}\ ^1S_0$ - $4f^{13}5d$ J=0	45277	-32800	-1.45
Au I	$5d^{10}6s\ ^2S_{1/2}$ - $5d^96s^2\ ^2D_{5/2}$	9161	-38550	-8.4
Au I	$5d^96s^2\ ^2D_{5/2}$ - $5d^96s6p\ ^4F^o_{9/2}$	39536	24200	1.2
Hg II	$5d^{10}6s\ ^2S_{1/2}$ - $5d^96s^2\ ^2D_{5/2}$	35514	-52200	-2.94

Green − working clocks; black − old proposals, red − new proposals;
Flambaum and Dzuba, CJP **87**, 25 (2009);
Dzuba, Flambaum, Schiller, PRA **98**, 022501 (2018);
Dzuba, Allehabi, Flambaum, Li, Schiller, PRA **103**, 022822 (2021).

Energy levels of Au



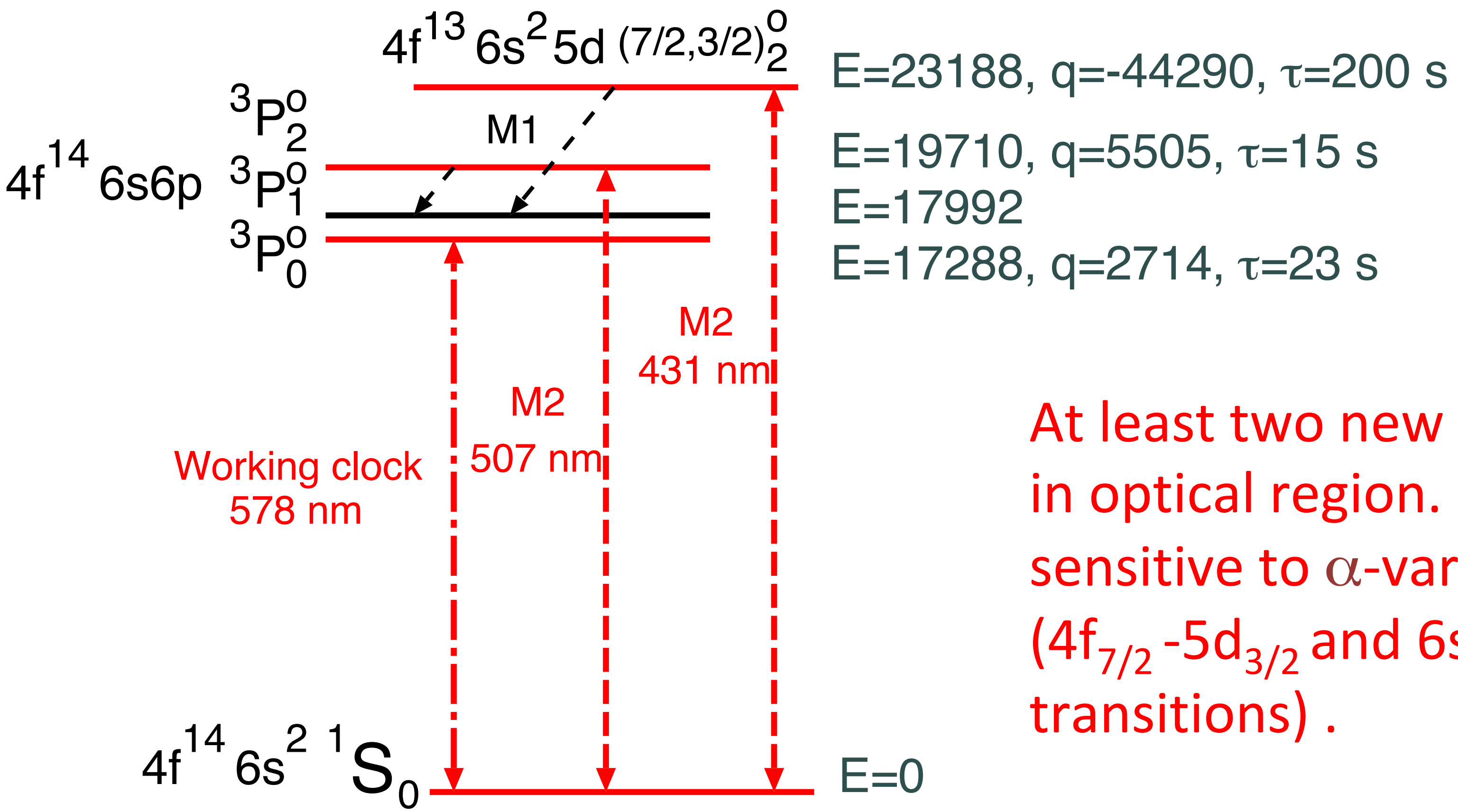
At least two clock states in optical region. Both are sensitive to α-variation ($6s_{1/2}$-$5d_{5/2}$ and $6s_{1/2}$-$6p_{3/2}$ transitions).

States are not sensitive to perturbations.

Laser cooling is possible.

V.A. Dzuba, Saleh O. Allehabi, V.V. Flambaum, Jiguang Li, S. Schiller,
PRA **103**, 022822 (2021).

Energy levels of Yb



V.A. Dzuba, V.V. Flambaum, S. Schiller, PRA **98**, 022501 (2018).

At least two new clock states in optical region. One is sensitive to α-variation ($4f_{7/2}$-$5d_{3/2}$ and $6s_{1/2}$-$6p_{3/2}$ transitions) .

States are not sensitive to perturbations.

New clock states have large *J*

(due to large Δj), is this a problem?

- **Yb** (for isotopes with *I*=0, *F=J, J=2*) electric quadrupole shift

$$\Delta E_Q = \frac{3J_z^2 - J(J+1)}{J(2J-1)} Q \frac{\partial \epsilon_z}{\partial z}$$

  Averaging over states with J_z=0 and J_z=±2 suppresses both quadrupole and liner Zeeman shifts.

- **Au** (*I*=3/2, J=5/2, *F*=1,2,3,4; *J*=9/2, *F*=3,4,5,6)

$$\Delta E_Q = \frac{3F_z^2 - F(F+1)}{F(2F-1)} Q \frac{\partial \epsilon_z}{\partial z}$$

  ΔE_Q=0 for *F*=3, F_z=±2;
  Linear Zeeman shift can be suppressed by averaging between F_z=+2 and F_z=-2.

Search for NP using King plot.

Isotope shift for two transitions can be linked as

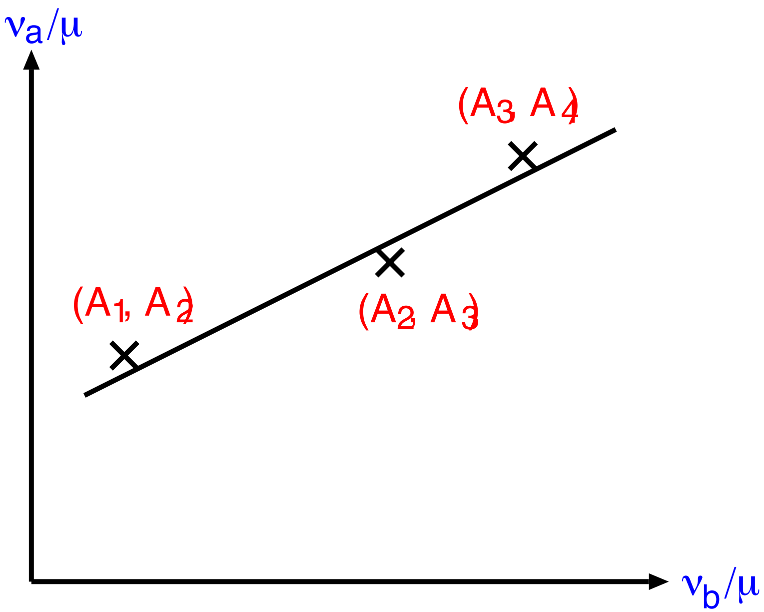
$$\frac{\nu_{bij}}{\mu_{ij}} = \frac{F_b}{F_a}\frac{\nu_{aij}}{\mu_{ij}} + \left(K_b - \frac{F_b}{F_a}K_a\right) + \frac{\alpha_{\rm NP}}{\alpha}\left(D_b - \frac{F_b}{F_a}D_a\right)\frac{\Delta N}{\mu_{ij}}.$$

straight line on the ν_a/μ, ν_b/μ plane

- **NP** term breaks linearity

$$D = e^2\langle \exp(-Mcr/\hbar)/r\rangle$$

M – mass of new boson.



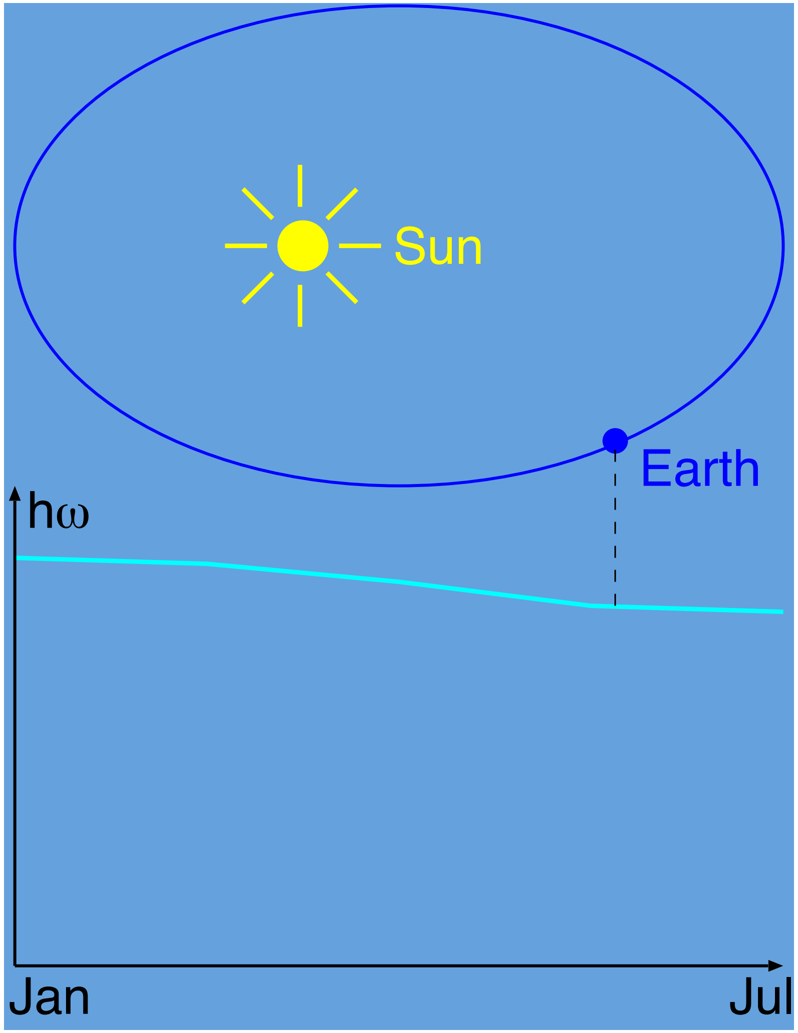
Minimum data:

2 transitions; **4** isotopes.

Yb has **7** stable isotopes (**5** with *I*=0)

Work is in progress for **Yb/Yb+** (see Dionysios Antypas' talk yesterday).

More new physics . . .



A Scalar term in SME

$$\delta H_S = -\left(C_0^{(0)} - \frac{2U}{3c^2} c_{00} \right) \frac{\mathrm{p}^2}{2}$$

Leads to dependence of atomic frequencies on the date in the year **(EEP violation)**

Interpretation for the scalar term

a. Non-relativistic limit

$$\delta H_S = -\left(C_0^{(0)} - \frac{2U}{3c^2}c_{00}\right)\frac{\mathrm{p}^2}{2}$$

Using Virial theorem ($\Delta P^2 = -2h\omega$) we get

$$\frac{\delta\omega}{\omega} = \left(C_0^{(0)} - \frac{2U}{3c^2}c_{00}\right)$$

- The same for all transitions

The effect is unobservable in ratios ω_1/ω_2 (both optical) !

$\delta\omega$ can still be measured using Cs clocks.

b. Relativistic case

$$\frac{\delta\omega}{\omega} = R\left(C_0^{(0)} - \frac{2U}{3c^2}c_{00}\right) \equiv RC(U)$$

R is relativistic factor

For two transitions

$$R = -\frac{\Delta E_2 - \Delta E_1}{2\omega}$$

$$\delta \ln\frac{\omega_1}{\omega_2} = \frac{\delta\omega_1}{\omega_1} - \frac{\delta\omega_2}{\omega_2} = (R_1 - R_2)C(U)$$

Very similar to the case of α-variation!

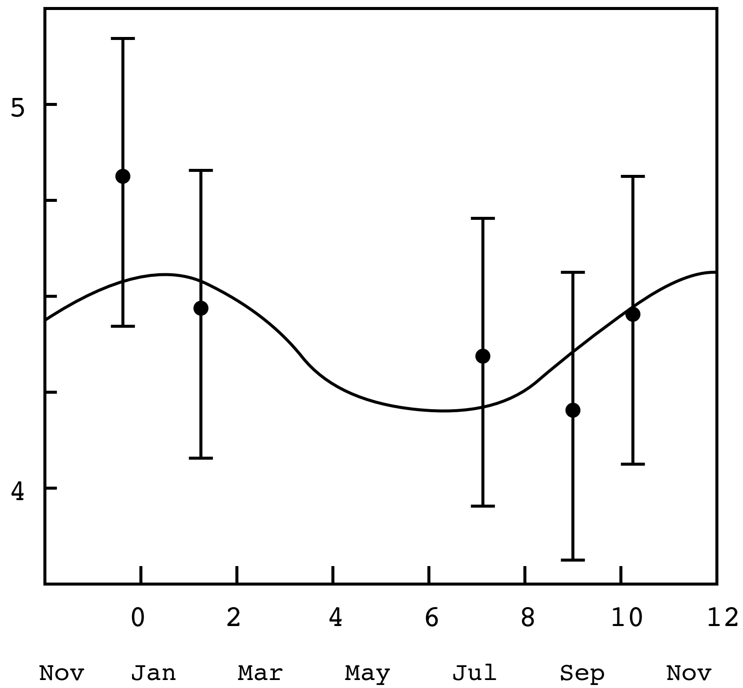
Same transitions can be used.

Measurements are the same, interpretation is different.

Example: Comparing Al^+ and Hg^+ clocks between 11/2006 and 11/2007

(Rosenband et al, Science 319, 1808 (2008))

$(f_{Al}/f_{Hg} - 1.05287) \times 10^{-16}$



Fitting the measurements with

$A\cos(\omega t)+B$ we get

c_{00}=(-3.0+/-5.7)x10^{-7}

V. A. Dzuba and V. V. Flambaum PRD **95**, 015019 (2017)

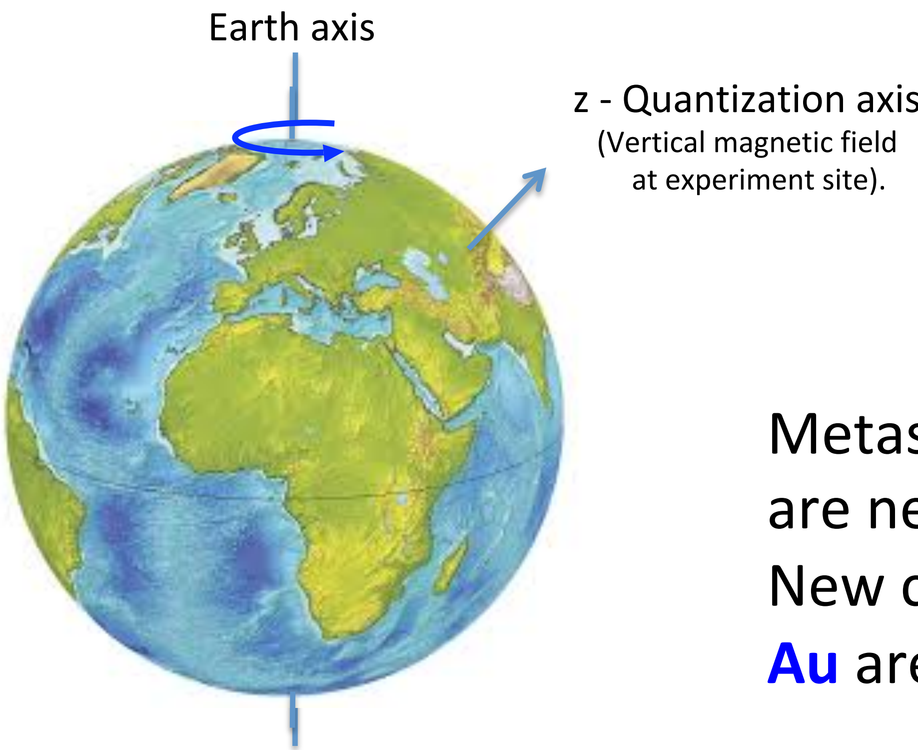
$$\delta H_S = -\left(C_0^{(0)} - \frac{2U}{3c^2} c_{00}\right)\frac{\mathrm{p}^2}{2}$$

See also Sanner *et al*, Nature **567**, 204 (2019),
Lange *et al*, PRL **126**, 011102 (2021),
and a talk by E. Peik on 8.7.2021, 17:30.

LLI violation

A Tensor term in the SME $\delta H_T = -\frac{1}{6} C_0^{(2)} T_0^{(2)} \equiv -\frac{1}{6} C_0^{(2)} \left(\vec{p}^2 - 3p_z^2 \right)$

leads to dependence of atomic frequencies on the <u>orientation</u> of the system.



$$\Delta E \propto 3J_z^2 - J(J+1)$$

Metastable states with $J \geq 1$ are needed.
New clock states of **Yb** and **Au** are good candidates.

Recent progress in experimental study of LLI violation

- **Dy**, Hohensee *et al*, PRL **111**, 050401 (2013).
  State A: $4f^{10}5d6s$, J=10, E=19798 cm^{-1}
  State B: $4f^{9}5d^{2}6s$, J=10, E=19798 cm^{-1}
  Monitoring rf A-B transition limits LLI violation at $\mathbf{10^{-17}}$.

- **Ca^{+}**, Pruttivarasin *et al*, Nature **517**, 592 (2015).
  Monitoring transitions between Zeeman components of the $3d_{5/2,m}$ state limits LLI violation at $\mathbf{10^{-18}}$.

- **Yb^{+}** (proposal) Dzuba *et al*, Nature Physics, (2016).
  Monitoring transitions between Zeeman components of the $4f^{13}6s^{2}\ {}^{2}F^{o}_{7/2,m}$ state may limit LLI violation at $\mathbf{10^{-23}}$.

- **Yb^{+}** Sanner *et al*, Nature **567**, 204 (2019).
  Comparing two Yb^{+} clocks over 6 months limits LLI violation at $\mathbf{10^{-21}}$.

Conclusion

New clock states in **Yb** and **Au** bring new opportunities in search for new physics, such as α-variation, new boson, **EEP** and **LLI** violations, etc.