At the 60th Meeting of the Civil GPS Service Interface Committee, Marianna Safronova presents on "Atomic Clocks for Fundamental Physics: Time for Discovery." She is affiliated with the Department of Physics and Astronomy, University of Delaware, Delaware, and the Joint Quantum Institute, NIST, and the University of Maryland, College Park, Maryland.
Standard model

Quarks
- $u$ (up)
- $c$ (charm)
- $t$ (top)
- $d$ (down)
- $s$ (strange)
- $b$ (bottom)

Fermions: spin = 1/2 particles

Leptons
- $e$ (electron)
- $\mu$ (muon)
- $\tau$ (tau)
- $\nu_e$ (electron neutrino)
- $\nu_\mu$ (muon neutrino)
- $\nu_\tau$ (tau neutrino)

Fermions: spin = 0 fundamental scalar particle

Higgs Boson

Vector Bosons: spin = 1 particles
- Z boson
- W boson
- Gluon

Forces

+ fundamental physics postulates
According to the Standard Model, our Universe cannot exist!
We don’t know what most (95%) of the Universe is!
GPS satellites: microwave atomic clocks

Optical atomic clocks will not lose one second in 30 billion years

\[ \sigma_y(\tau) \approx \frac{1}{2\pi \nu_0} \frac{1}{\sqrt{NT\tau}} \]

Clock transition frequency

Rev. Mod. Phys. 90, 025008 (2018)
Applications of atomic clocks

GPS, deep space probes

Very Long Baseline Interferometry

Relativistic geodesy

Gravity Sensor

Definition of the second

Quantum simulation

Searches for physics beyond the Standard Model

Atomic clocks can measure and compare frequencies to exceptional precisions!

If fundamental constants change (now) due to for various “new physics” effects, atomic clock may be able to detect it.

**BEYOND THE STANDARD MODEL?**
Search for physics beyond the Standard Model with atomic clocks

- Dark matter searches
- Search for the violation of Lorentz invariance
- Tests of the equivalence principle
- Are fundamental constants constant?

Gravitational wave detection with atomic clocks

Image credit: NASA

Image credit: Jun Ye's group

Nature 567, 204 (2019)

PRD 94, 124043 (2016)
Variation of fundamental constants

Theories with varying dimensionless fundamental constants

- String theories
- Other theories with extra dimensions
- Loop quantum gravity
- Dark energy theories: chameleons and quintessence models
- …many others


Frequency of optical transitions $\nu \simeq c R_\infty A F(\alpha)$

depends on the fine-structure constant $\alpha$.

Some clocks are more sensitive to this effect than others

Measure the ratio of two optical clock frequencies to search for the variation of $\alpha$. Keep doing this for a while.
Variation of fundamental constants

Theories with varying dimensionless fundamental constants

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Frequency of optical transitions \( \nu \simeq c R_\infty A F(\alpha) \) depends on the fine-structure constant \( \alpha \).

Measure the ratio of two optical clock frequencies to search for the variation of \( \alpha \).

Dark matter can also cause variation of fundamental constants!

Dark matter can affect atomic energy levels

What dark matter can you detect if you can measure changes in atomic/nuclear frequencies to 20 digits?

\[ \nu_0 \] is a clock frequency

\[
\begin{align*}
E_2 & \quad |2\rangle \\
\hbar \nu_0 & \quad \downarrow \\
E_1 & \quad |1\rangle
\end{align*}
\]
Dark matter density in our Galaxy > $\lambda_{dB}^{-3}$

$\lambda_{dB}$ is the de Broglie wavelength of the particle.

Then, the scalar dark matter exhibits coherence and behaves like a wave

$$\phi(t) = \phi_0 \cos \left( m_\phi t + \vec{k}_\psi \times \vec{x} + \ldots \right)$$

A. Arvanitaki et al., PRD 91, 015015 (2015)
How to detect **ultralight** dark matter with clocks?

Dark matter field \[ \phi(t) = \phi_0 \cos \left( m_\phi t + \vec{k}_\phi \times \vec{x} + \ldots \right) \]
couples to electromagnetic interaction and "normal matter"

It will make fundamental coupling constants and mass ratios oscillate

Atomic energy levels will oscillate so **clock frequencies will oscillate**

Can be detected with monitoring ratios of clock frequencies over time (or clock/cavity).

Present scalar DM limits
Hunting for topological dark matter with atomic clocks

A. Derevianko and M. Pospelov

Dark matter clumps: point-like monopoles, one-dimensional strings or two-dimensional sheets (domain walls).

If they are large (size of the Earth) and frequent enough they may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System.

GPM.DM collaboration: Roberts et al., Nature Communications 8, 1195 (2017)
Topological dark matter may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System, as the Earth passes through the domain wall.

Rana Adhikari, Paul Hamiton & Holger Müller, Nature Physics 10, 906 (2014)
New bounds on dark matter coupling from a global network of optical atomic clocks

Global sensor network. The participating Sr and Yb optical lattice atomic clocks reside at NIST, Boulder, CO, USA, at LNE-SYRTE, Paris, France, at KL FAMO, Torun, Poland, and at NICT, Tokyo, Japan

How to improve laboratory searches for the variation of fundamental constants & dark matter?

Improve atomic clocks: better stability and uncertainty

- Ion chains
- Large ion crystals
- 3D optical lattice clocks

Measurements beyond the quantum limit

Entangled clocks

Image credits: NIST, Innsbruck group, MIT Vuletic group, Ye JILA group
Clocks based on new systems

Clocks with ultracold highly charged ions

Nuclear clock

First demonstration of quantum logic spectroscopy at PTB, Germany
Nature 578 (7793), 60 (2020)

Science 347, 1233 (2015)
Atomic clocks & networks of clocks:
Great potential for discovery of new physics

Many new developments coming in the next 10 years!