60TH MEETING OF THE CIVIL GPS SERVICE INTERFACE COMMITTEE

Atomic Clocks for Fundamental Physics: Time for Discovery

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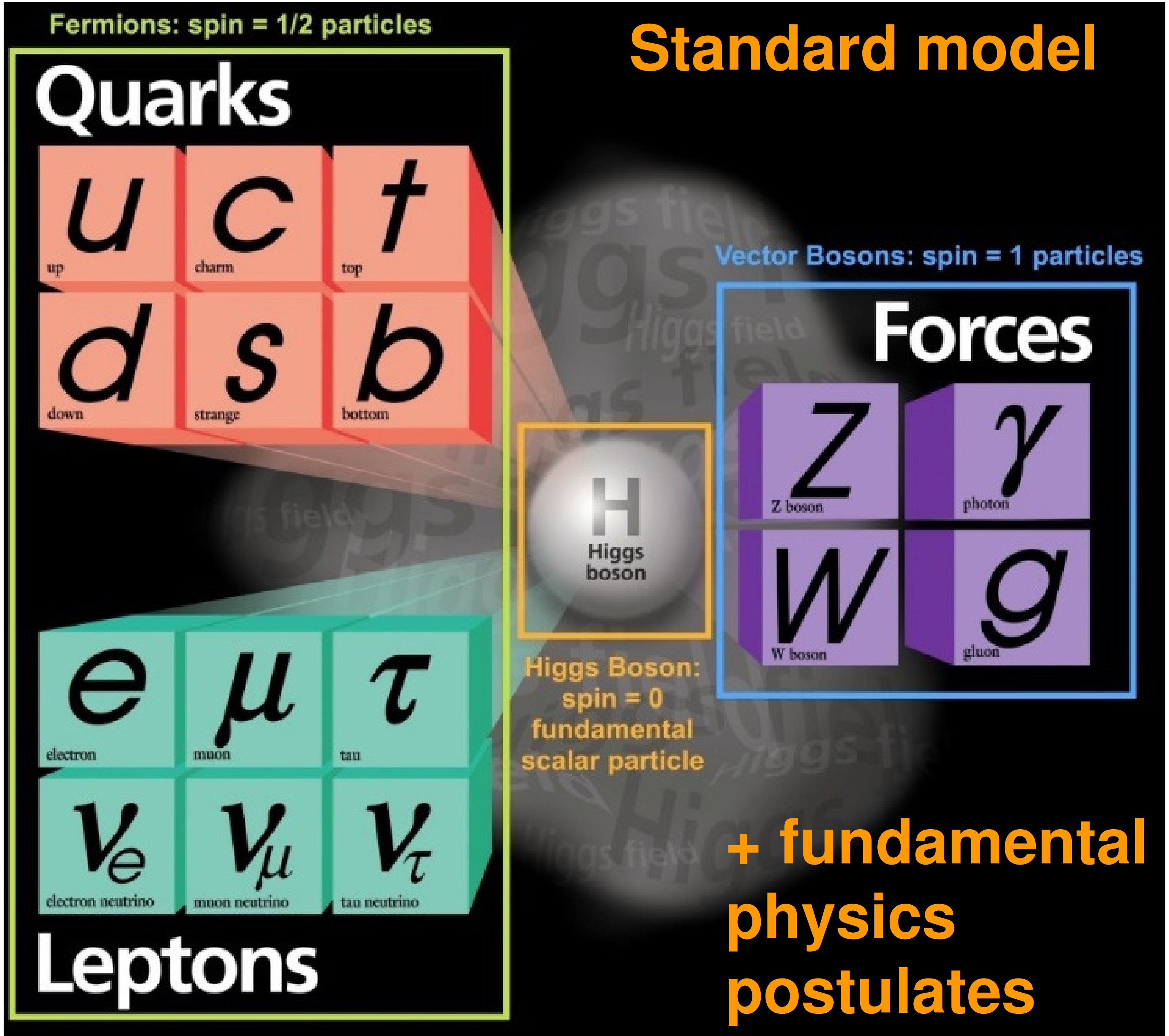
NSF

NIST National Institute of Standards and Technology U.S. Department of Commerce

Office of Naval Research Science & Technology ONR USN

erc European Research Council

Standard model



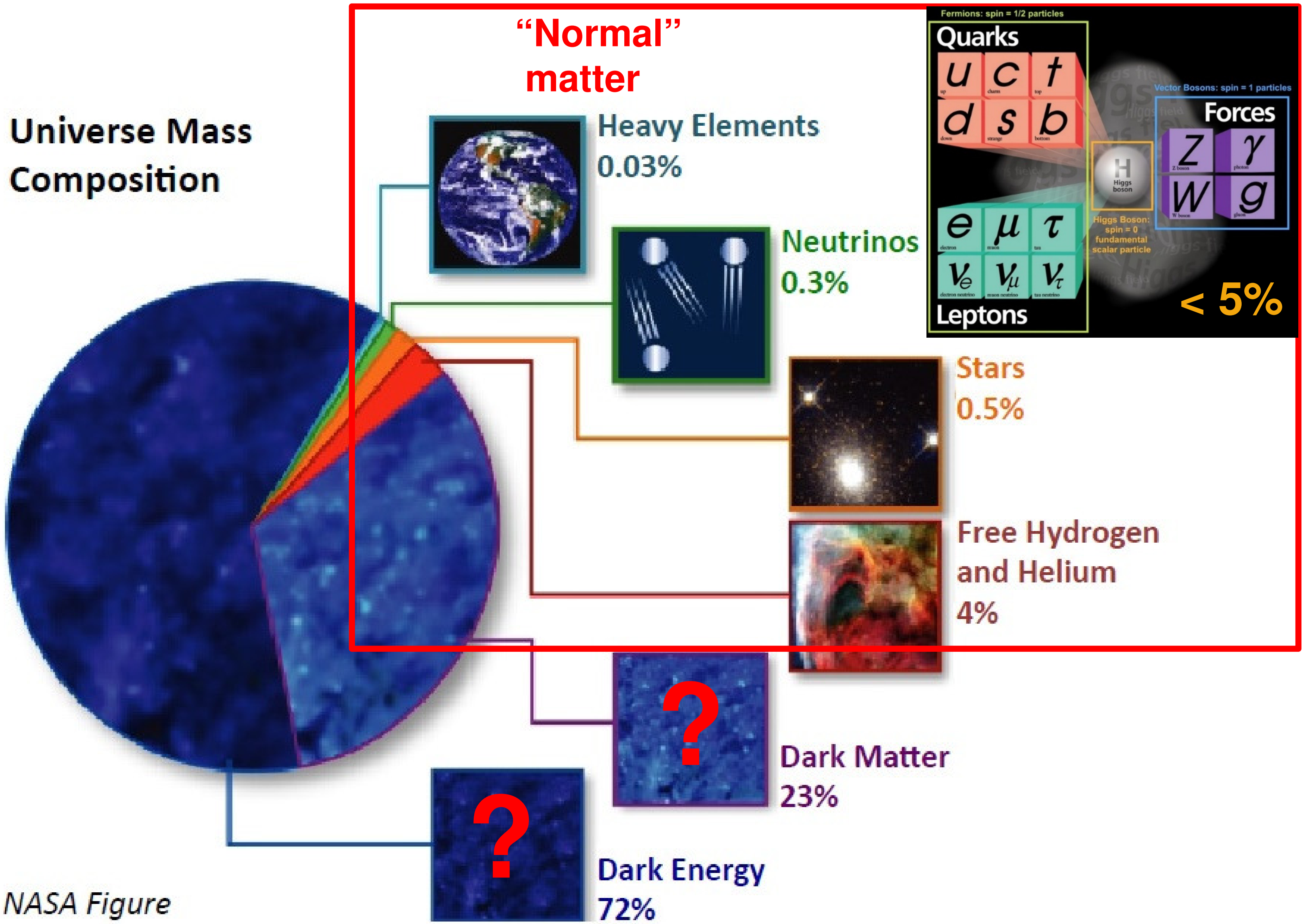
+ fundamental physics postulates

According to the Standard Model

scienceabc.com

Our Universe can not exist !

We don’t know what most (95%) of the Universe is!

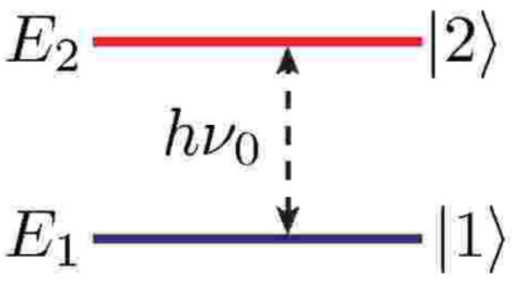


NASA Figure

Optical atomic clocks will not lose one second in

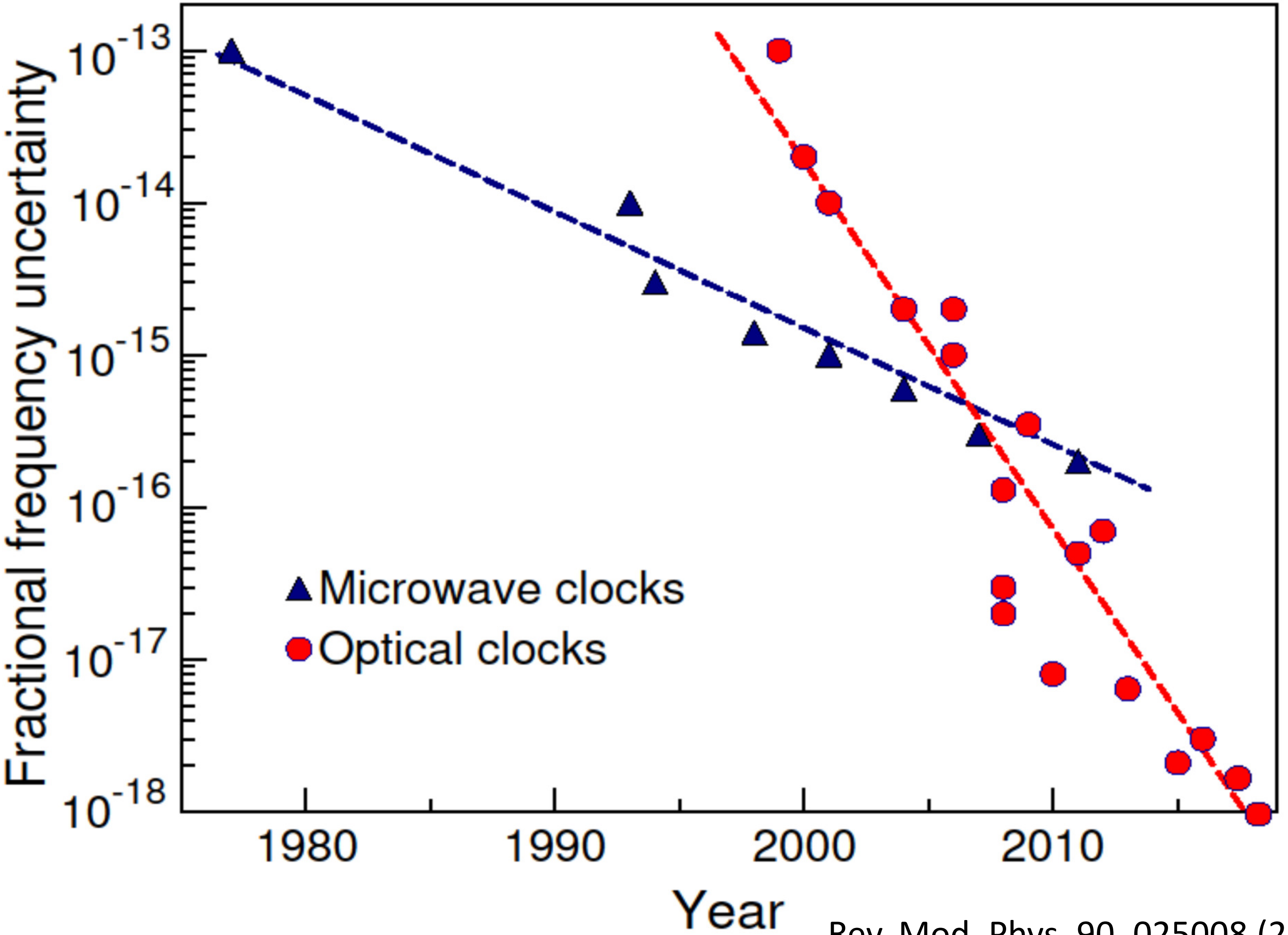
30 billion years

GPS satellites:
microwave
atomic clocks



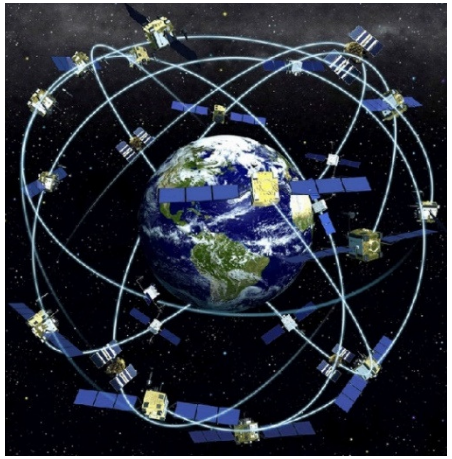
$$\sigma_y(\tau) \approx \frac{1}{2\pi\nu_0}\frac{1}{\sqrt{NT\tau}}$$

Clock transition frequency

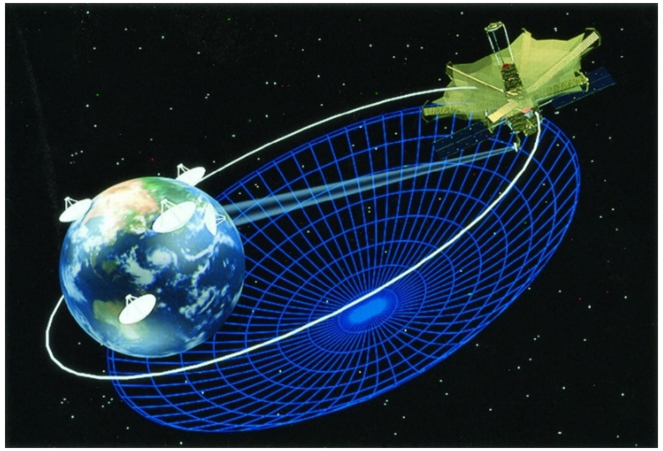


Rev. Mod. Phys. 90, 025008 (2018)

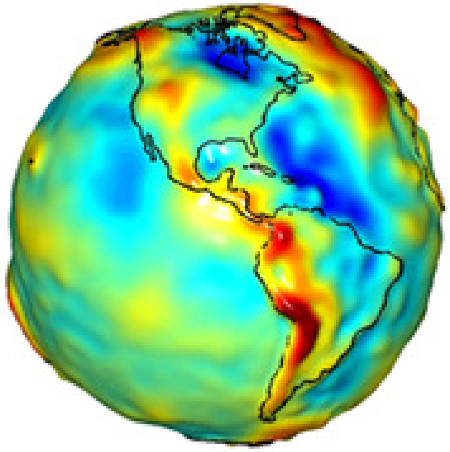
Applications of atomic clocks



GPS, deep space probes

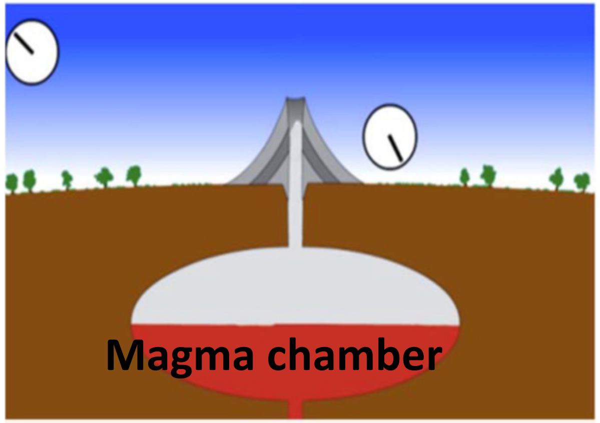


Very Long Baseline Interferometry

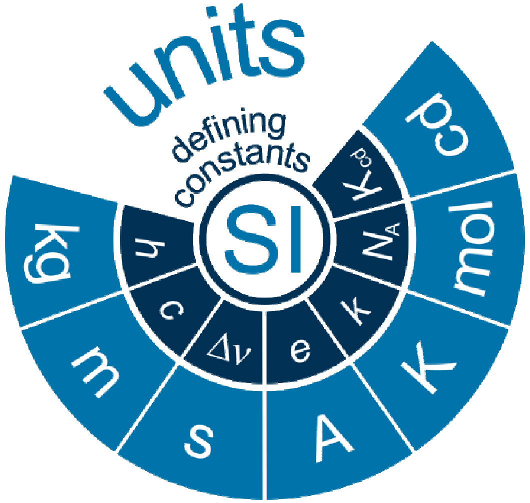


10 $^{-18}$
1 cm
height

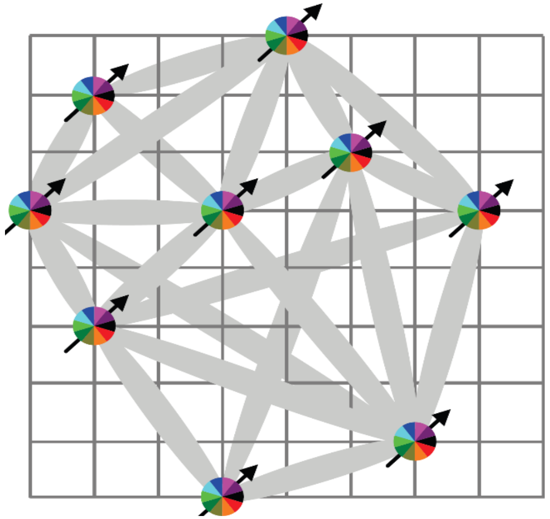
Relativistic geodesy



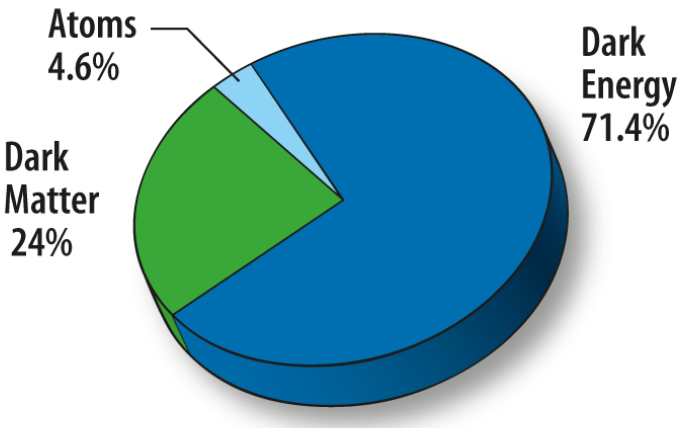
Gravity Sensor

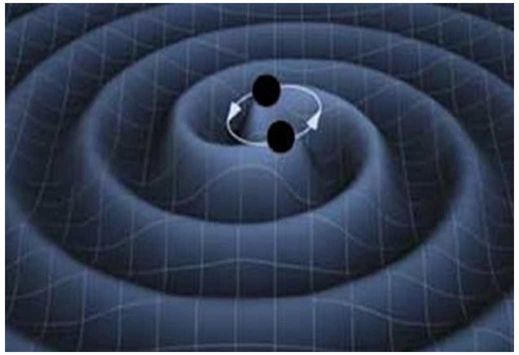


Definition of the second



Quantum simulation





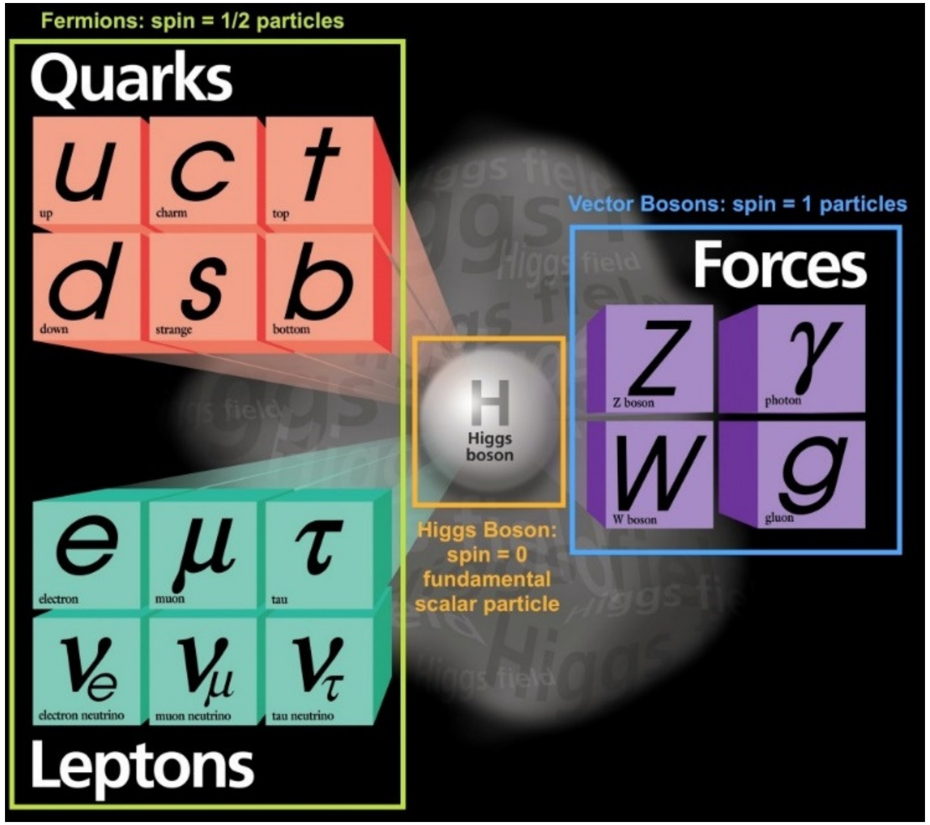
Searches for physics beyond the Standard Model

Image Credits: NOAA, Science 281,1825; 346, 1467, University of Hannover, PTB, PRD 94, 124043, Eur. Phys. J. Web Conf. 95 04009

Search for physics beyond the standard model with atomic clocks

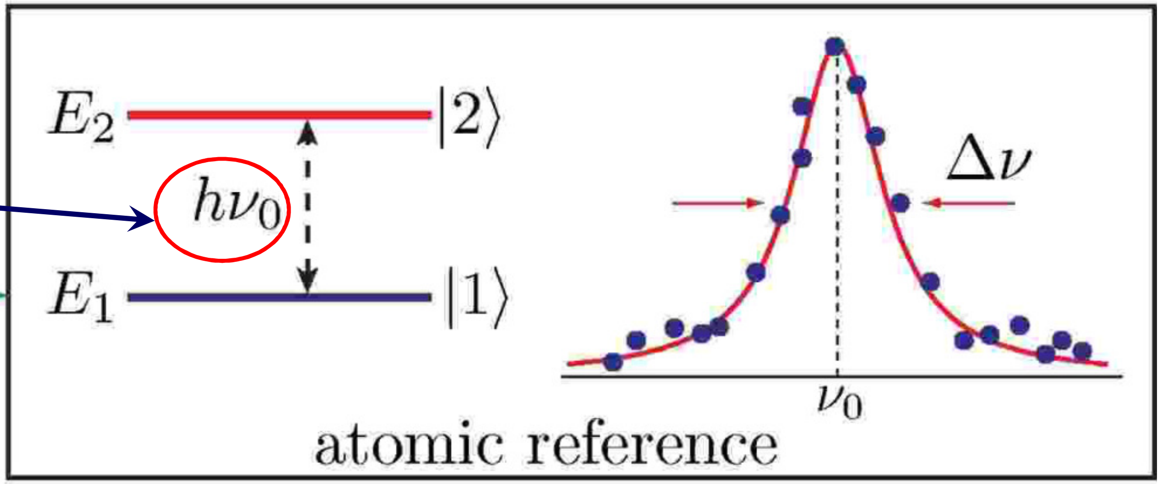
Atomic clocks can measure and compare frequencies to exceptional precisions!

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

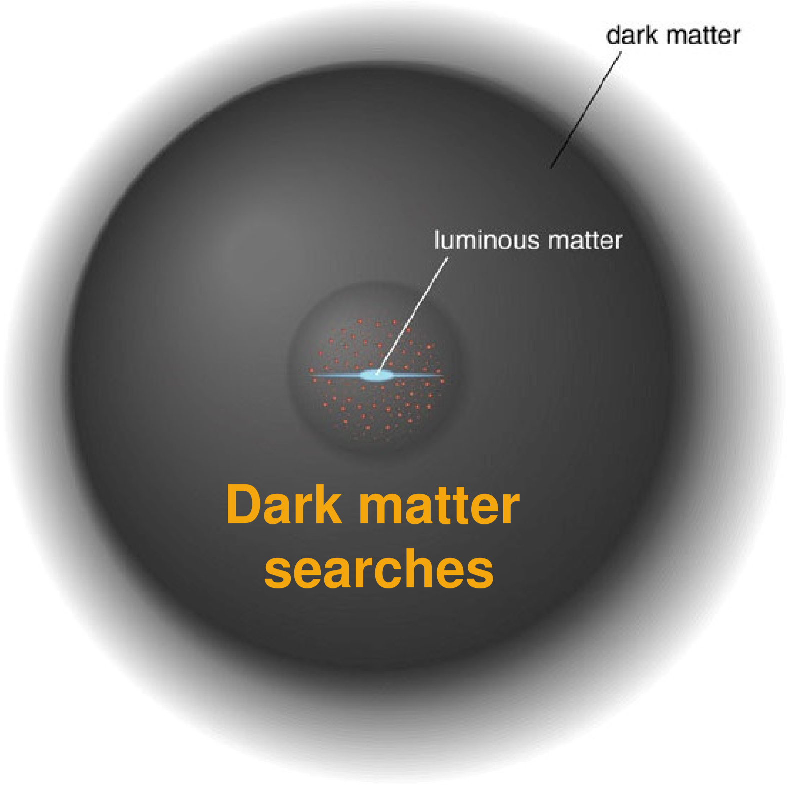


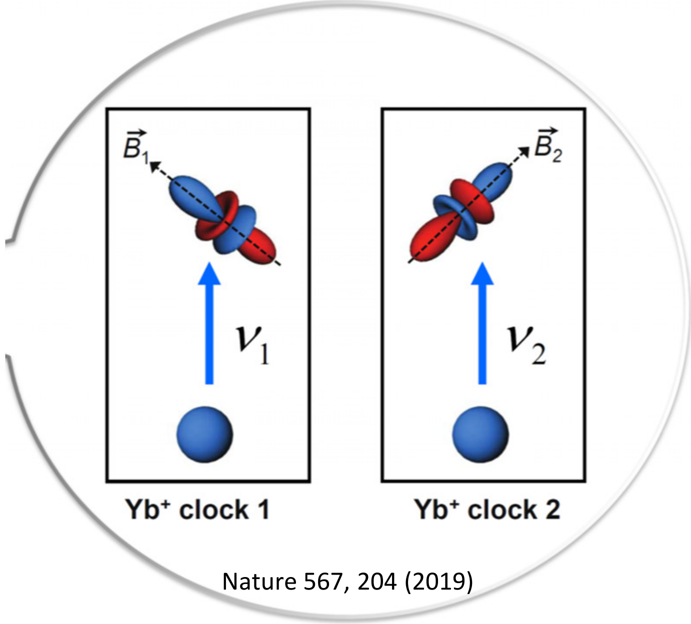
BEYOND THE STANDARD MODEL?

Frequency will change

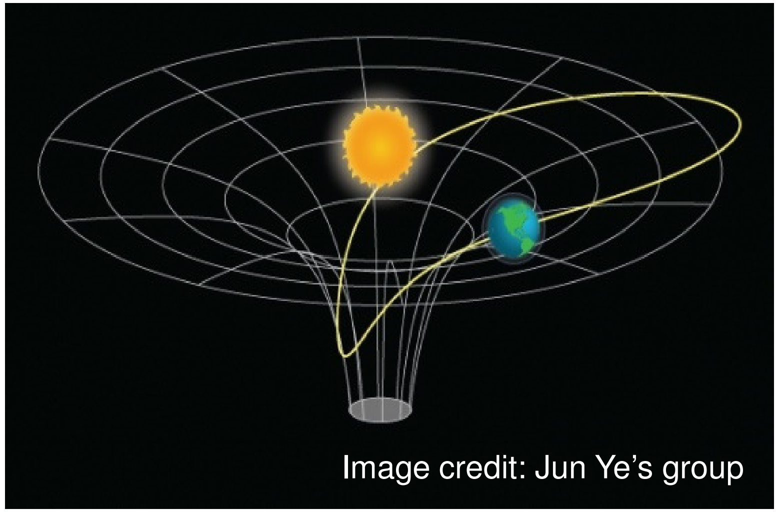


Search for physics beyond the Standard Model with atomic clocks





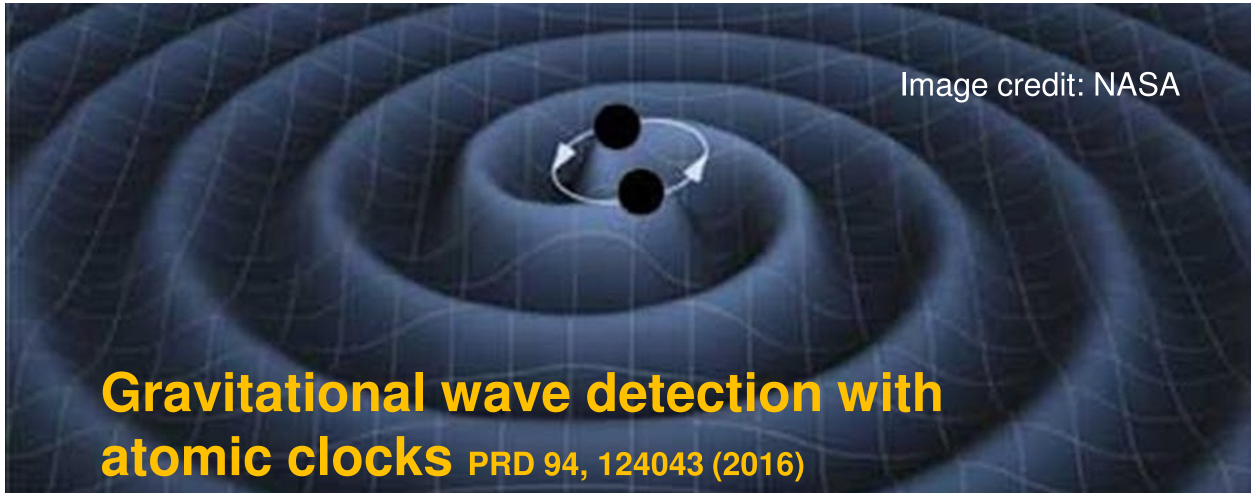
Search for the violation of Lorentz invariance



Tests of the equivalence principle

Are fundamental constants constant?

α



Variation of fundamental constants

Theories with varying dimensionless fundamental constants

J.-P. Uzan, Living Rev. Relativity 14, 2 (2011)

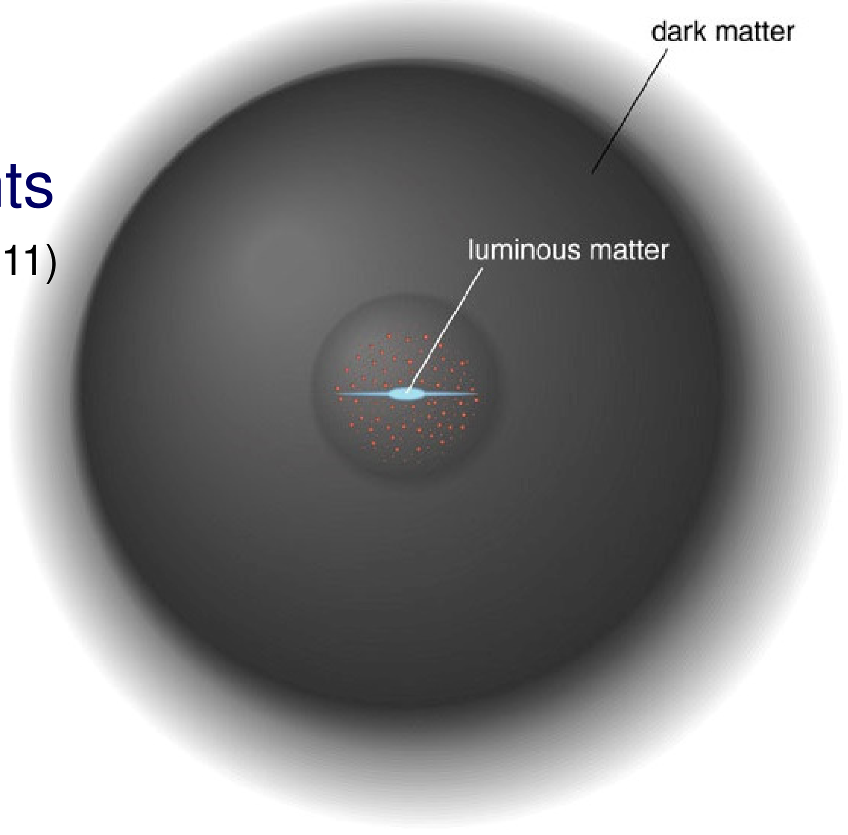
- String theories
- Other theories with extra dimensions
- Loop quantum gravity
- Dark energy theories: chameleon and quintessence models
- …many others

Frequency of optical transitions $\nu \simeq cR_{\infty}AF(\alpha)$ **depends on the fine-structure constant** α.

Some clocks are more sensitive to this effect than others

Measure the ratio of two optical clock frequencies to search for the variation of α. **Keep doing this for a while.**

Variation of fundamental constants



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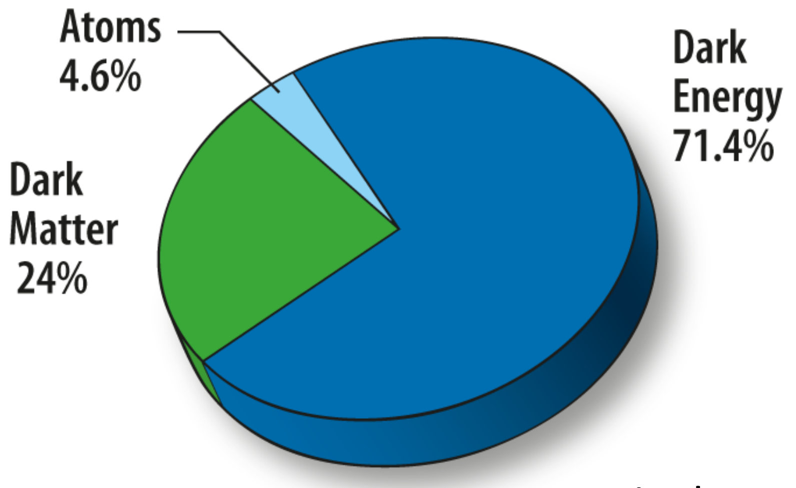
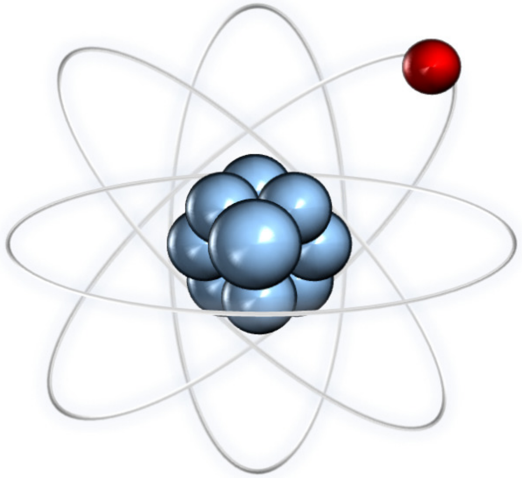


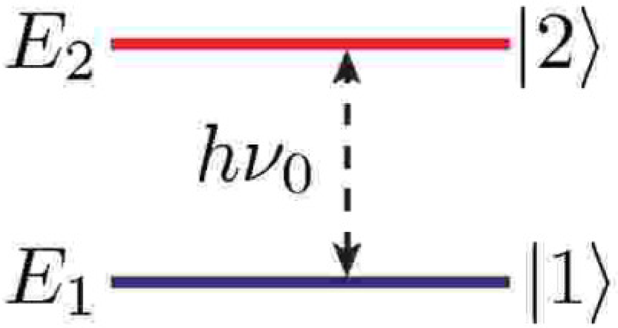
Measure the ratio of two optical clock frequencies to search for the variation of α**.**

Dark matter can also cause variation of fundamental constants!

A. Derevianko and M. Pospelov, Nature Phys. 10, 933 (2014), A. Arvanitaki et al., PRD 91, 015015 (2015)

Dark matter can affects atomic energy levels





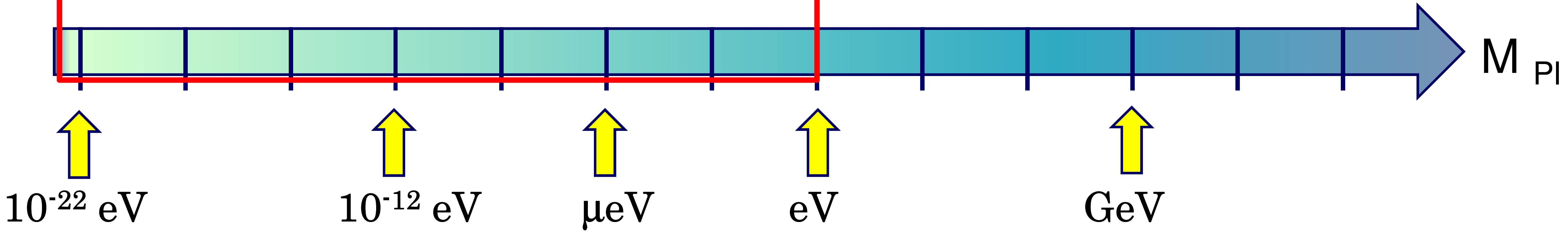
ν_0 is a clock frequency

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

We do not know what dark matter particle mass is.

Ultralight dark matter:
mass less than 1eV

Ultralight dark matter has to be bosonic – Fermi velocity for DM with mass >10 eV is higher than our Galaxy escape velocity.



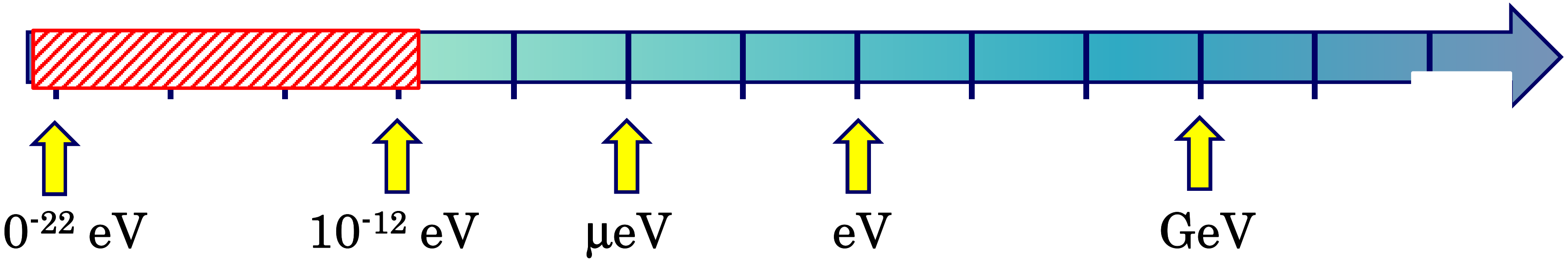
Dark matter density in our Galaxy > λ_{dB}^{-3}

λ_{dB} is the de Broglie wavelength of the particle.

Then, the scalar dark matter exhibits coherence and behaves like a wave $\phi(t) = \phi_0 \cos\left(m_\phi t + \bar{k}_\psi \times \bar{x} + \ldots\right)$

A. Arvanitaki et al., PRD 91, 015015 (2015)

How to detect **ultralight** dark matter with clocks?



Dark matter field $\phi(t) = \phi_0 \cos\left(m_\phi t + \bar{k}_\phi \times \bar{x} + \ldots\right)$

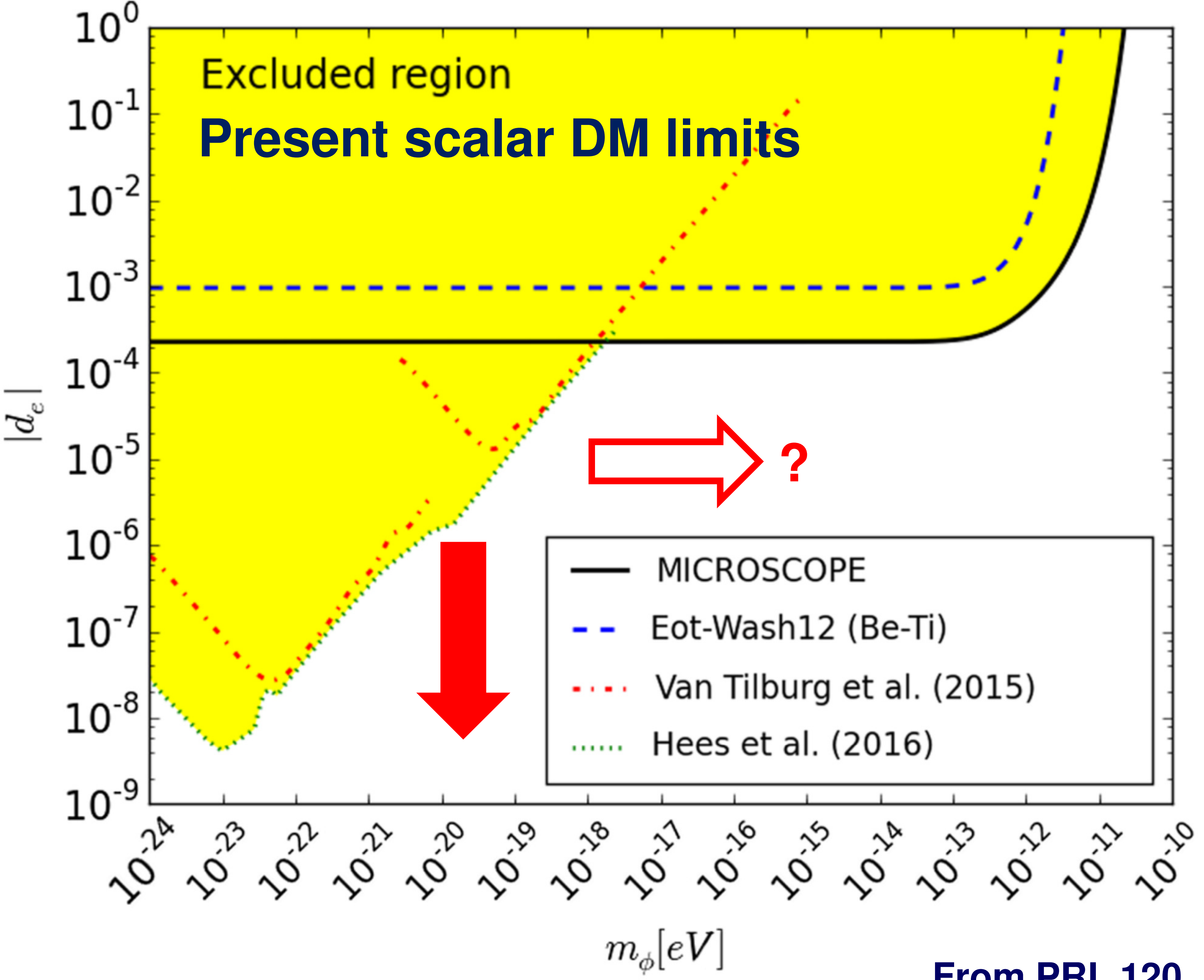
couples to electromagnetic interaction and “normal matter”

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).

Asimina Arvanitaki, Junwu Huang, and Ken Van Tilburg, PRD 91, 015015 (2015)



From PRL 120, 141101 (2018)

Transient variations

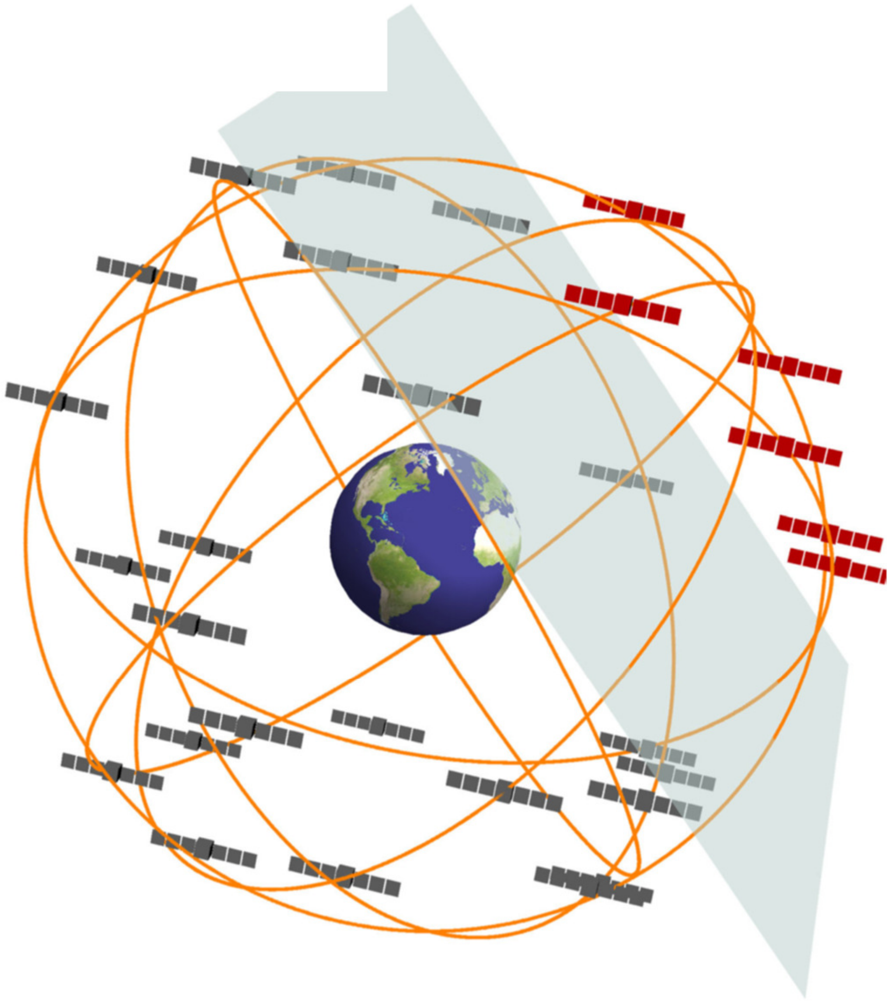
nature physics
LETTERS
PUBLISHED ONLINE: 17 NOVEMBER 2014 | DOI: 10.1038/NPHYS3137

Hunting for topological dark matter with atomic clocks

A. Derevianko[1*] and M. Pospelov[2,3]

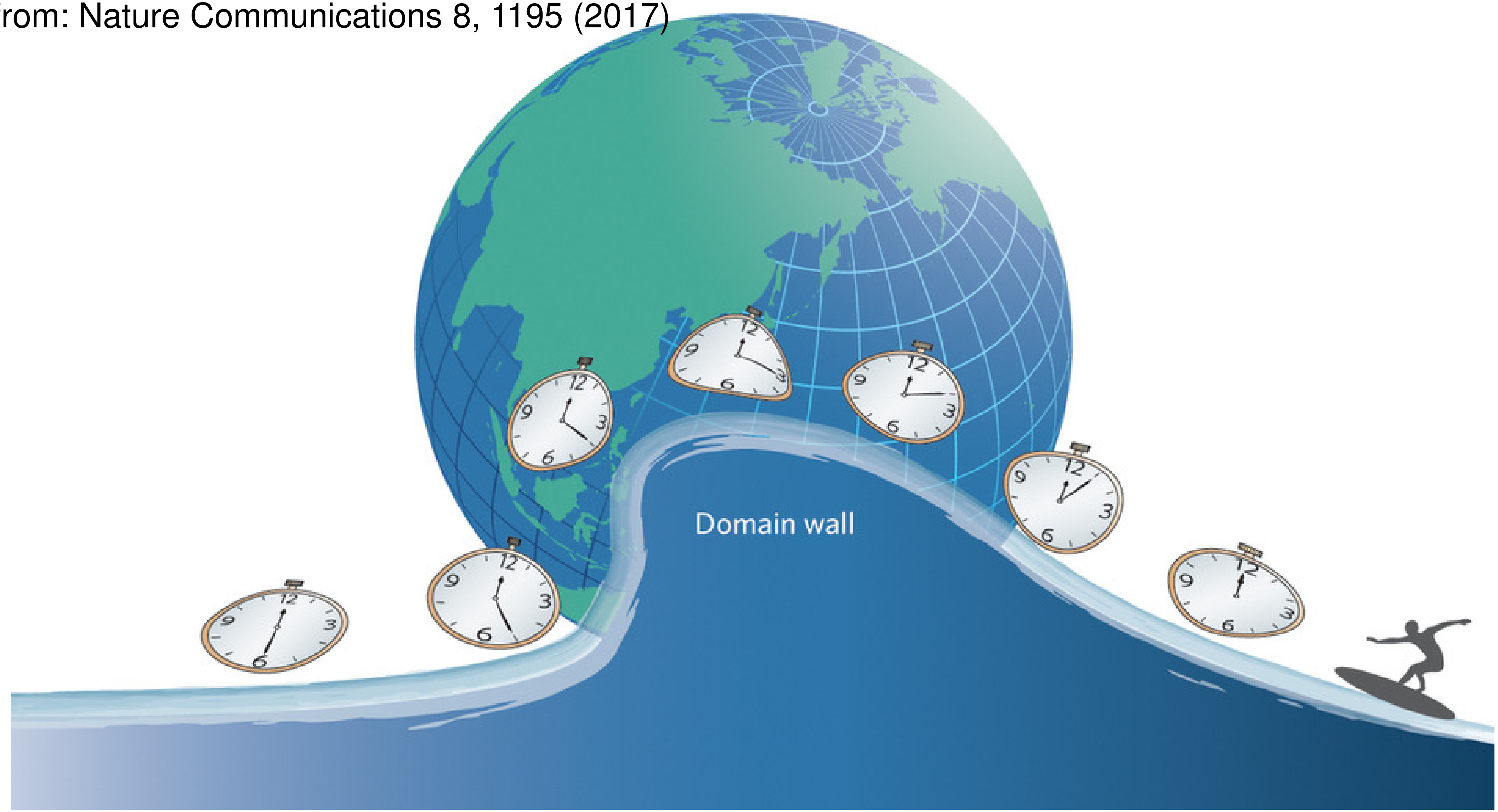
Dark matter clumps: point-like monopoles, one-dimensional strings or two-dimensional sheets (domain walls).

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 at el., Nature Communications 8, 1195 (2017)

Picture from: Nature Communications 8, 1195 (2017)

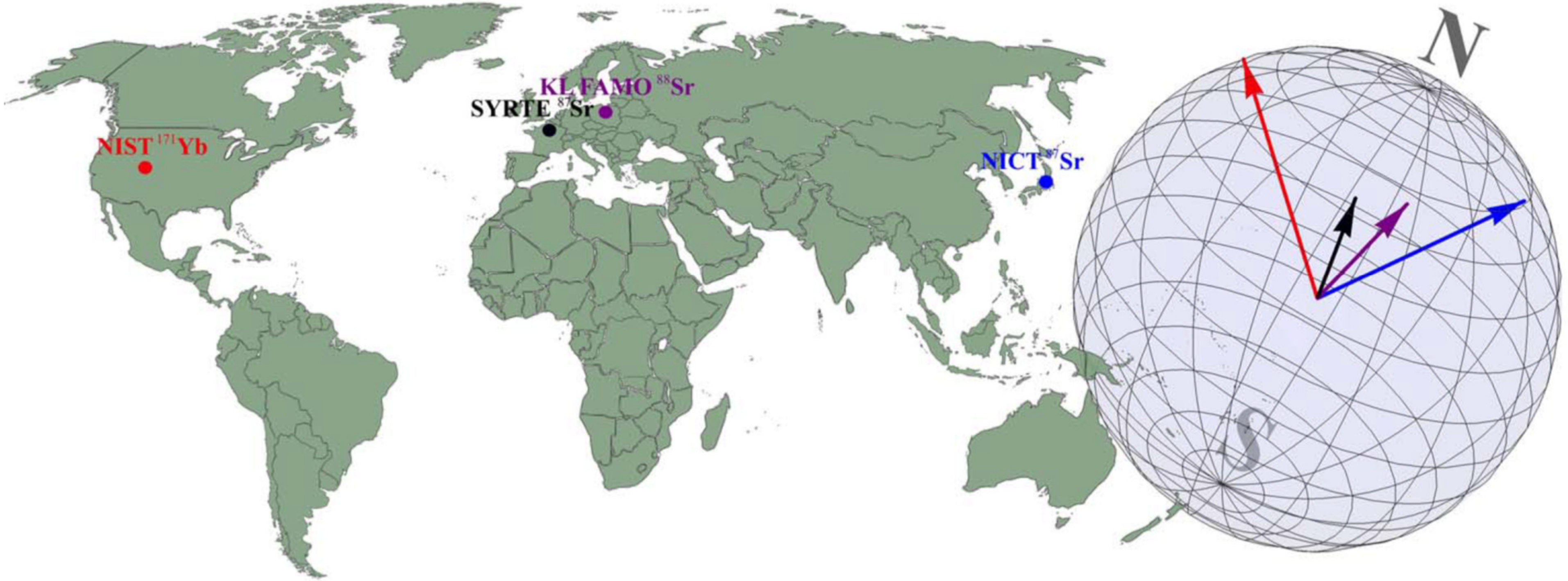


Topological dark matter may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System, as the Earth passes through the domain wall.

Rana Adhikari, Paul Hamiton & Holger Müller, Nature Physics 10, 906 (2014)

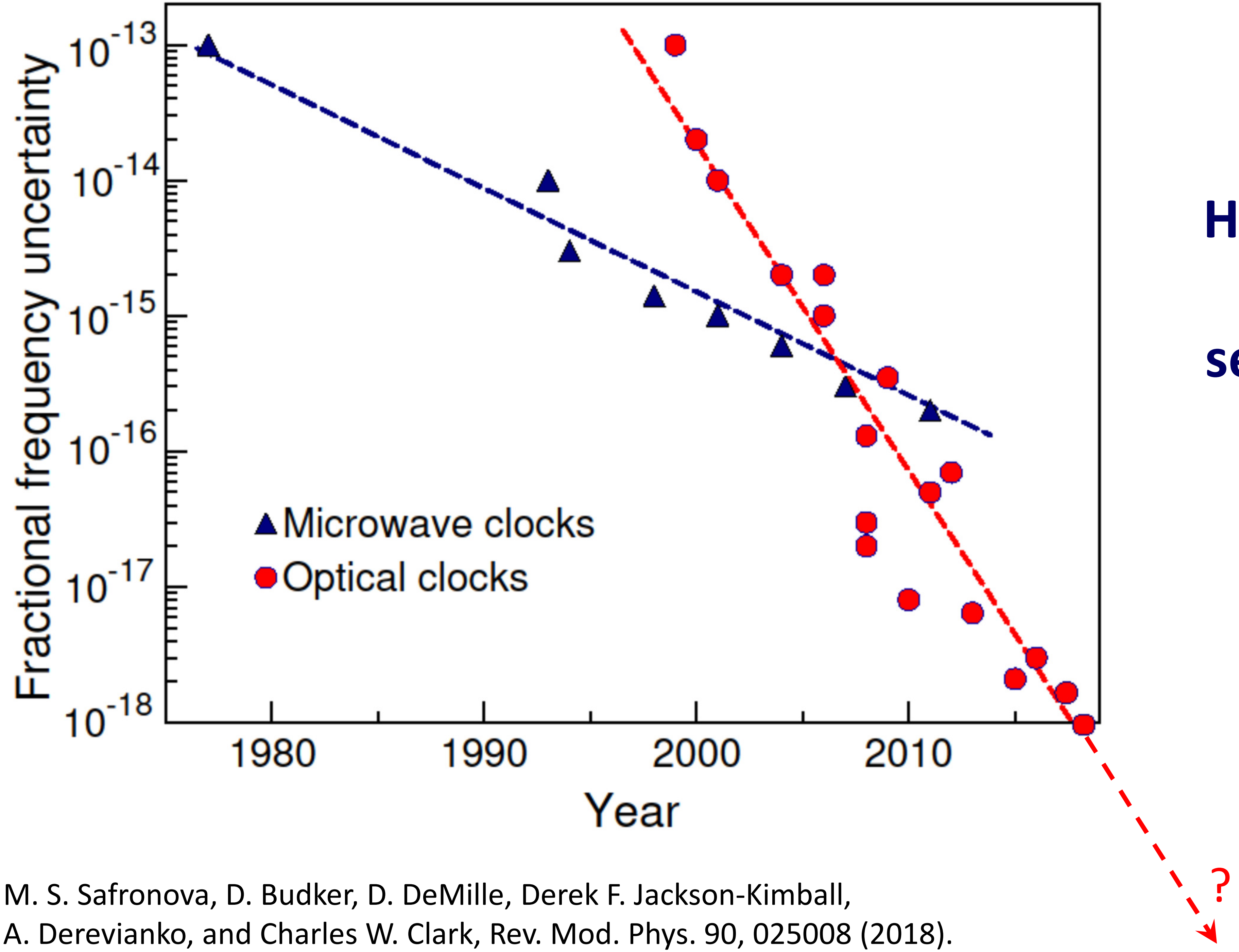
APPLIED PHYSICS

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

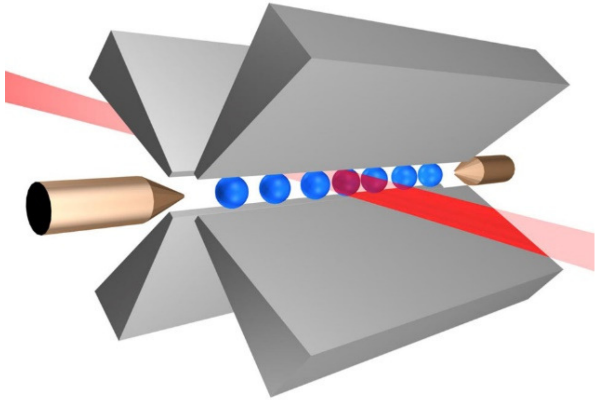
Wcisło et al., Sci. Adv. 4: eaau4869 (2018)



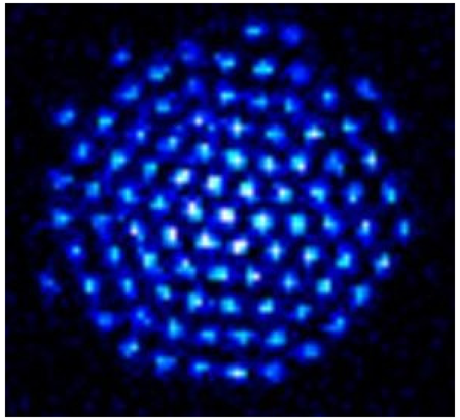
How to improve laboratory searches for the variation of fundamental constants & dark matter?

M. S. Safronova, D. Budker, D. DeMille, Derek F. Jackson-Kimball,
A. Derevianko, and Charles W. Clark, Rev. Mod. Phys. 90, 025008 (2018).

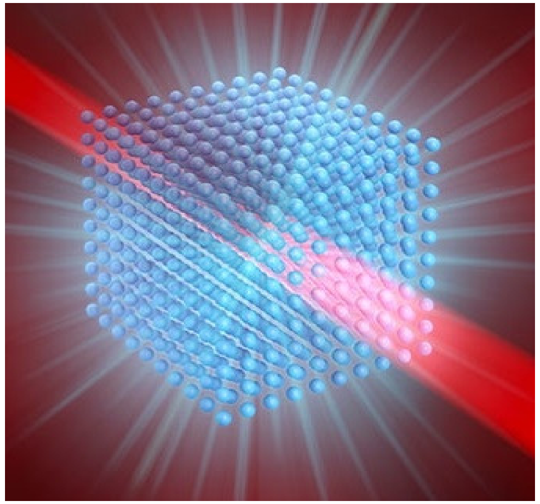
Improve atomic clocks: better stability and uncertainty



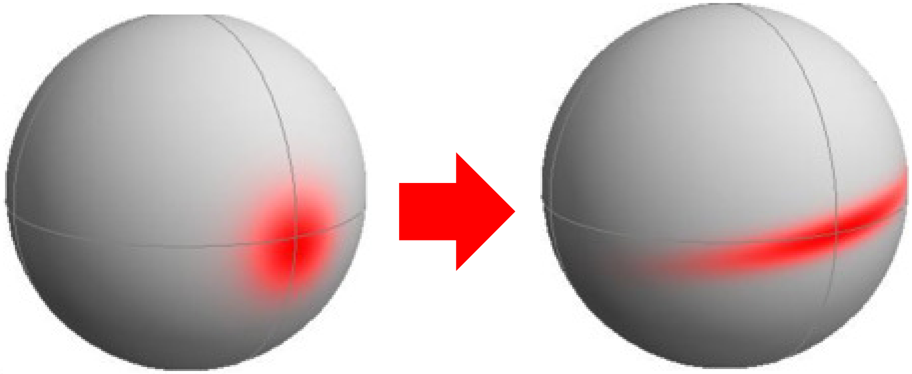
Ion chains



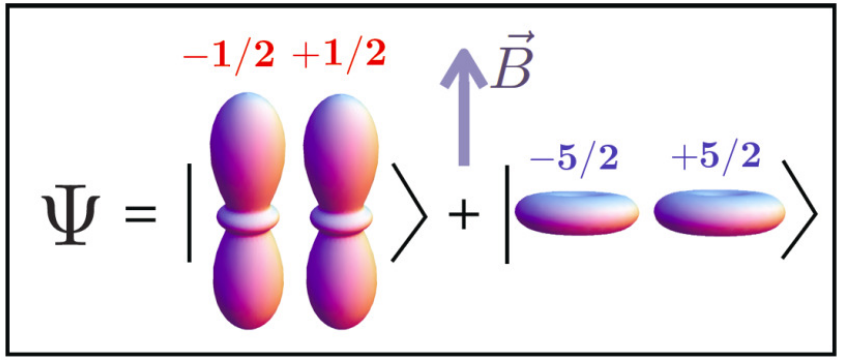
Large ion crystals



3D optical lattice clocks



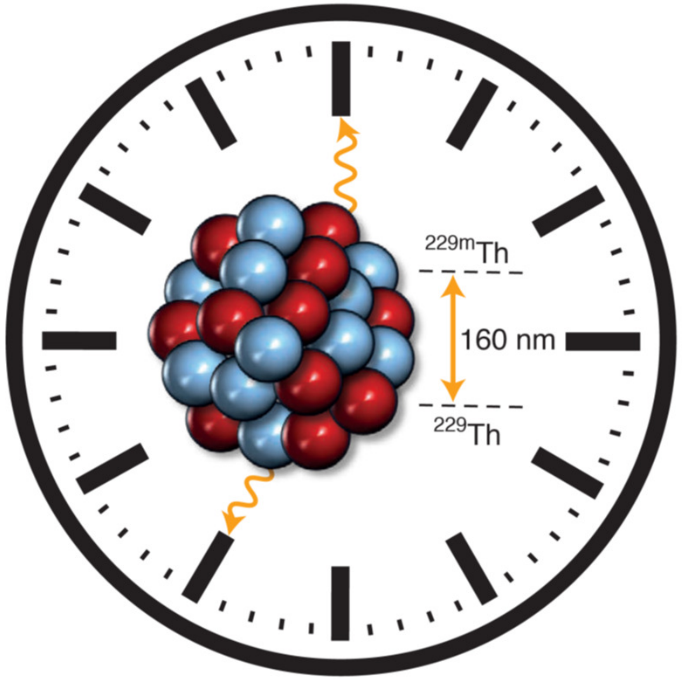
Measurements beyond the quantum limit



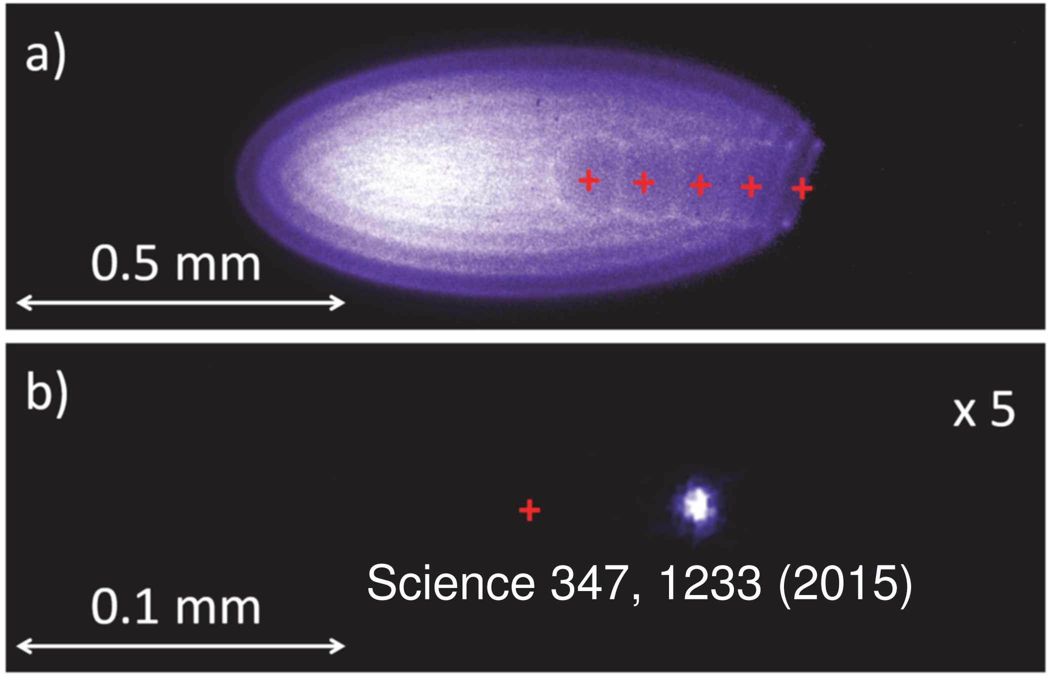
Entangled clocks

Image credits: NIST, Innsbruck group, MIT Vuletic group, Ye JILA group

Clocks based on new systems



Nuclear clock

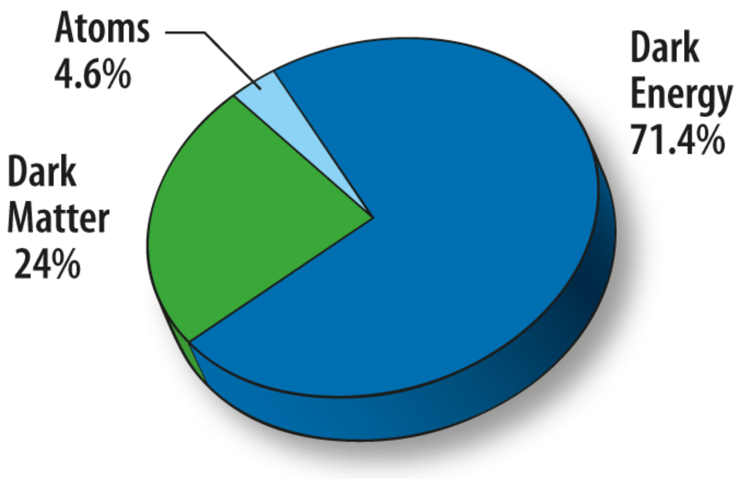


Clocks with ultracold highly charged ions

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

Atomic clocks & networks of clocks:

Great potential for discovery of new physics



Many new developments coming in the next 10 years!