ASPEN CENTER FOR PHYSICS

A RAINBOW OF DARK SECTORS

Dark matter searches with quantum sensors

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NSF

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

Office of Naval Research
USN
ONR
Science & Technology

erc
European Research Council

Extraordinary progress in the control of atoms and ions

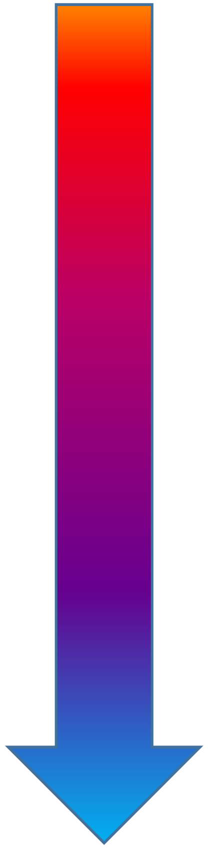
1997 Nobel Prize
Laser cooling and trapping

2001 Nobel Prize
Bose-Einstein Condensation

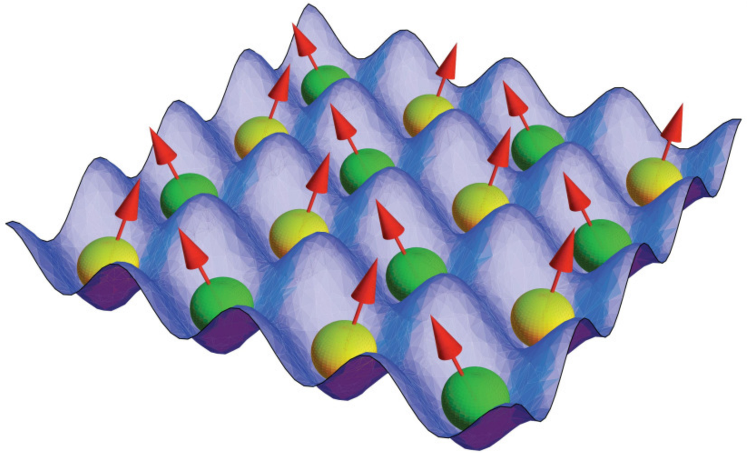
2005 Nobel Prize
Frequency combs

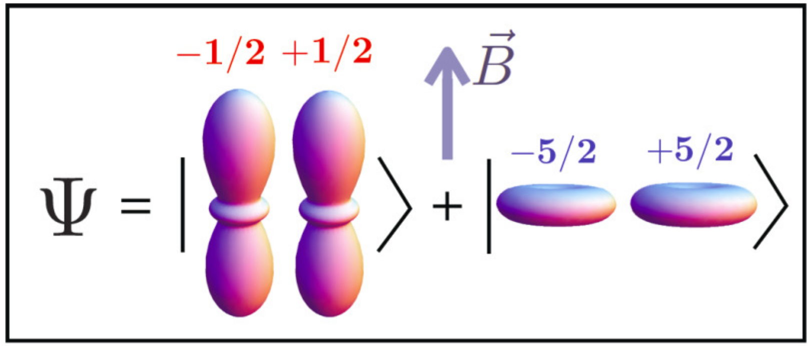
2012 Nobel prize
Quantum control

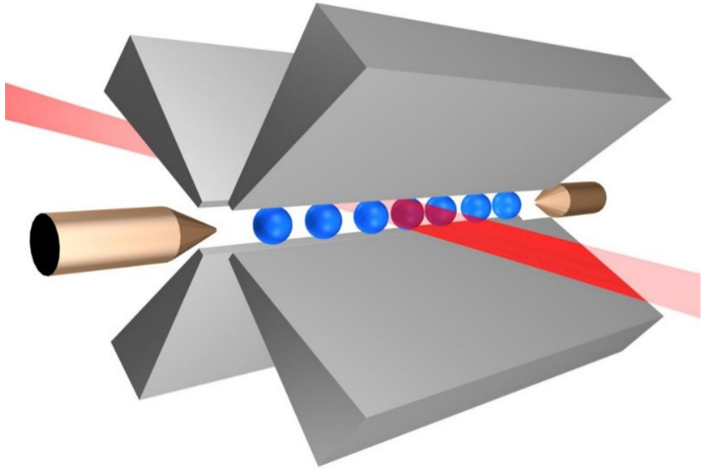
300K

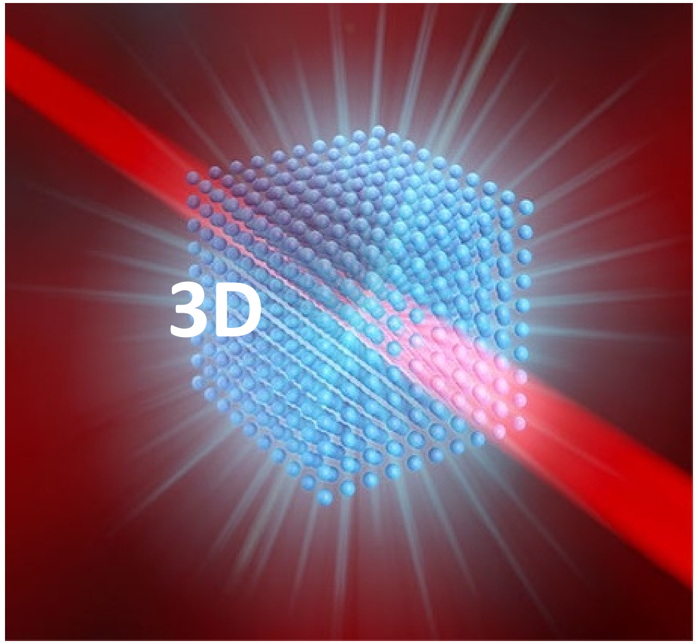


pK









Atoms are now: **Ultracold** **Trapped** **Precisely controlled**

REVIEWS OF MODERN PHYSICS, VOLUME 90, APRIL–JUNE 2018

Search for New Physics with Atoms and Molecules

M.S. Safronova[1,2], D. Budker[3,4,5], D. DeMille[6], Derek F. Jackson Kimball[7], A. Derevianko[8] and C. W. Clark[2]

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[2]Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, College Park, Maryland, USA,
[3]Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany,
[4]University of California, Berkeley, California, USA,
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[8]University of Nevada, Reno, Nevada, USA

This article reviews recent developments in tests of fundamental physics using atoms and molecules, including the subjects of parity violation, searches for permanent electric dipole moments, tests of the CPT theorem and Lorentz symmetry, searches for spatiotemporal variation of fundamental constants, tests of quantum electrodynamics, tests of general relativity and the equivalence principle, searches for dark matter, dark energy and extra forces, and tests of the spin-statistics theorem. Key results are presented in the context of potential new physics and in the broader context of similar investigations in other fields. Ongoing and future experiments of the next decade are discussed.

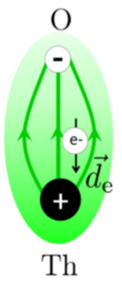
RMP 90, 025008 (2018)

Searches for BSM physics with Atomic, Molecular, and Optical (AMO) Physics

Fundamental symmetries with quantum science techniques

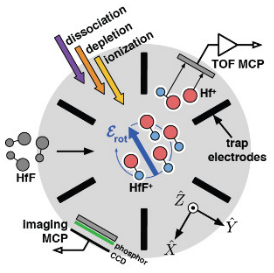
Searches for electron electric-dipole moment (eEDM)

Advanced ACME



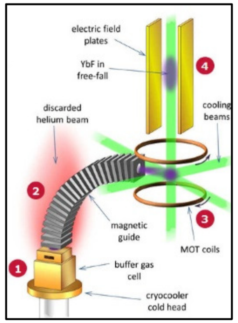
ThO

JILA eEDM



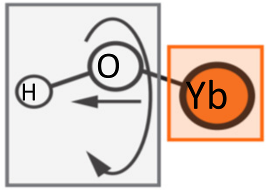
HfF^+, ThF^+

Imperial College



YbF

PolyEDM

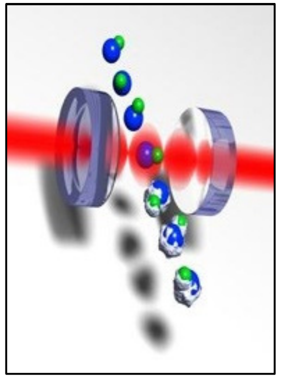


Also NMQM search

YbOH, …

Searches for hadronic EDMs

CeNTREX

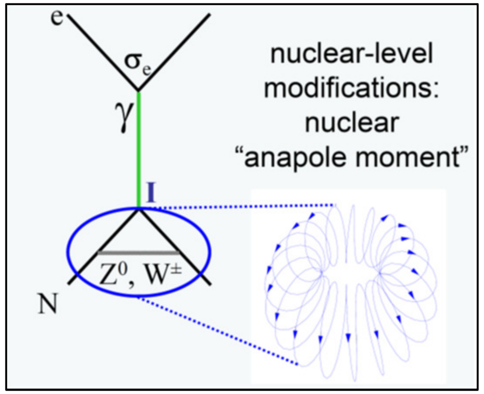


Hg
Xe
Ra
EDMs

TlF (proton EDM)

Enhanced parity violation

ZOMBIES



Also Yb (Mainz), Fr (FRIUMF & Japan)

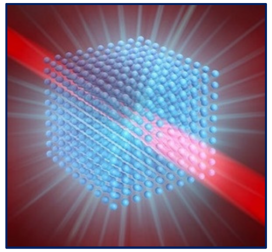
Rapid advances in ultracold molecule cooling and trapping; polyatomic molecules; future: molecules with Ra & "spin squeezed" entangled states

Atomic and Nuclear Clocks & Cavities

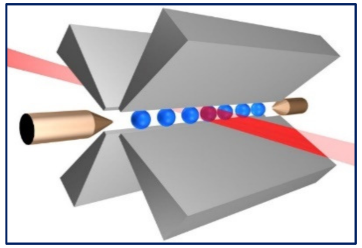
Major clock & cavities R&D efforts below, also molecular clocks, portable clocks and optical links

BSM searches with clocks

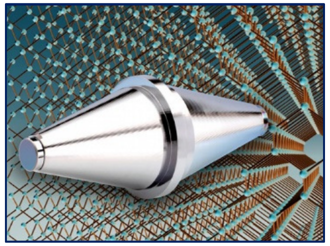
- Searches for variations of fundamental constants
- Ultralight scalar dark matter & relaxion searches
- Tests of general relativity
- Searches for violation of the equivalence principle
- Searches for the Lorentz violation



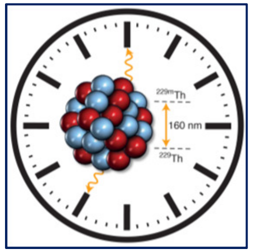
3D lattice clocks



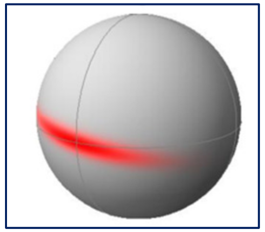
Multi-ion & entangled clocks



Ultrastable optical cavities



Nuclear & highly charge ion clocks



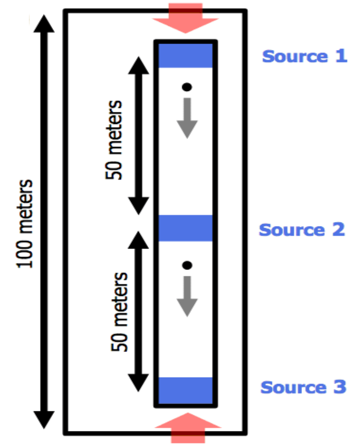
Measurements beyond the quantum limit

Atom interferometry

BSM searches:
Variation of fundamental constants
Ultralight scalar DM & relaxion searches
Violation of the equivalence principle

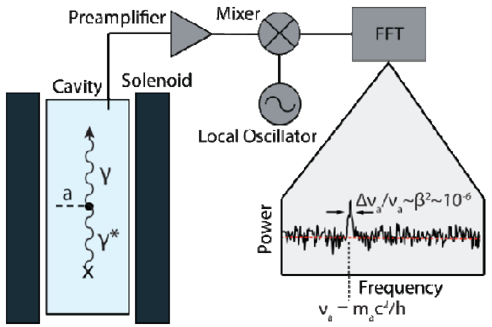
Prototype gravitational wave detectors

MAGIS-100 Fermilab



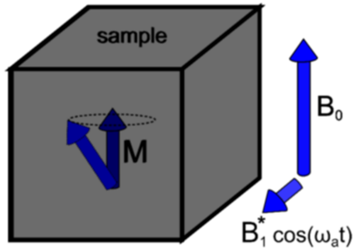
MIGA (France), 150 meters under construction
AION

Axion and ALPs searches



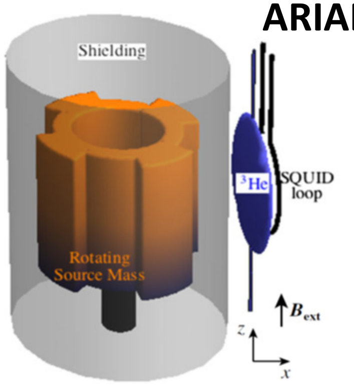
Microwave cavities: HAYSTAC
AMO: measurements beyond quantum limits

CASPEr-electric, solids
(coupling to gluons)



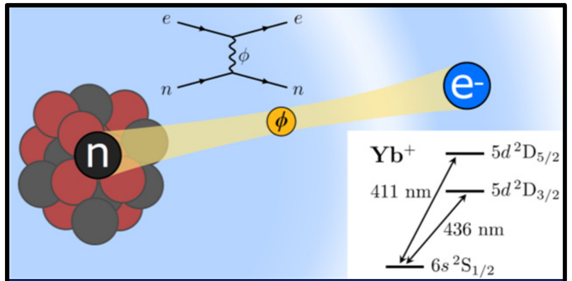
CASPEr-wind, Xe
(coupling to fermions)

ARIADNE



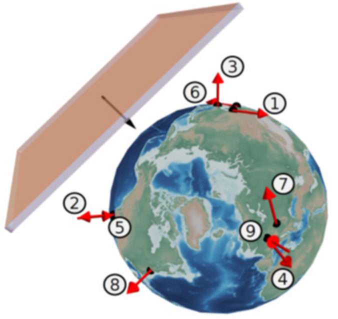
Resonantly detecting axion-mediated forces with NMR

Other dark matter & new force searches



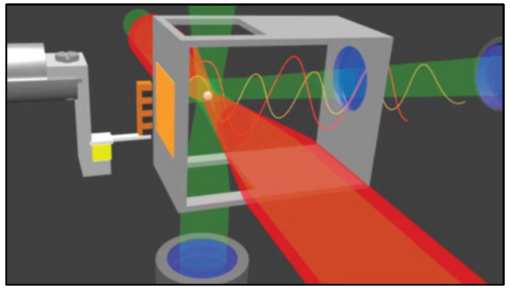
Fifth force searches with precision spectroscopy with atoms and ions

WReSL: Cs spectroscopy



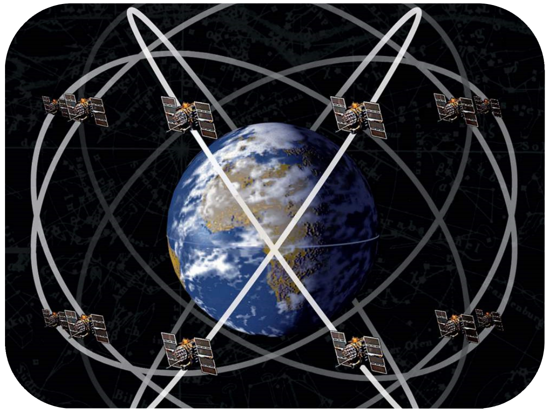
GNOME: network of optical magnetometers for exotic physics

Levitated optomechanics



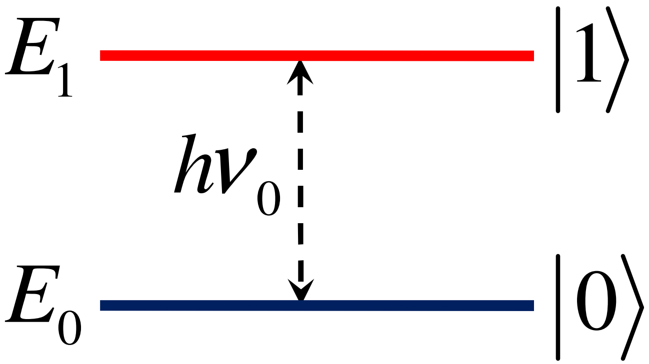
Also: gravitational wave detection and testing the Newtonian inverse square law

Many other current & future experiments: HUNTER (AMO sterile neutrino search), SHAFT, ORGAN & UPLOAD (axions), solid-state directional detection with NV centers (WIMPs), doped cryocrystals for EDMs, Rydberg atoms, tests of the gravity-quantum interface, tests of QED, …
See Rev. Mod. Phys. 90, 025008 (2018) for a recent review.

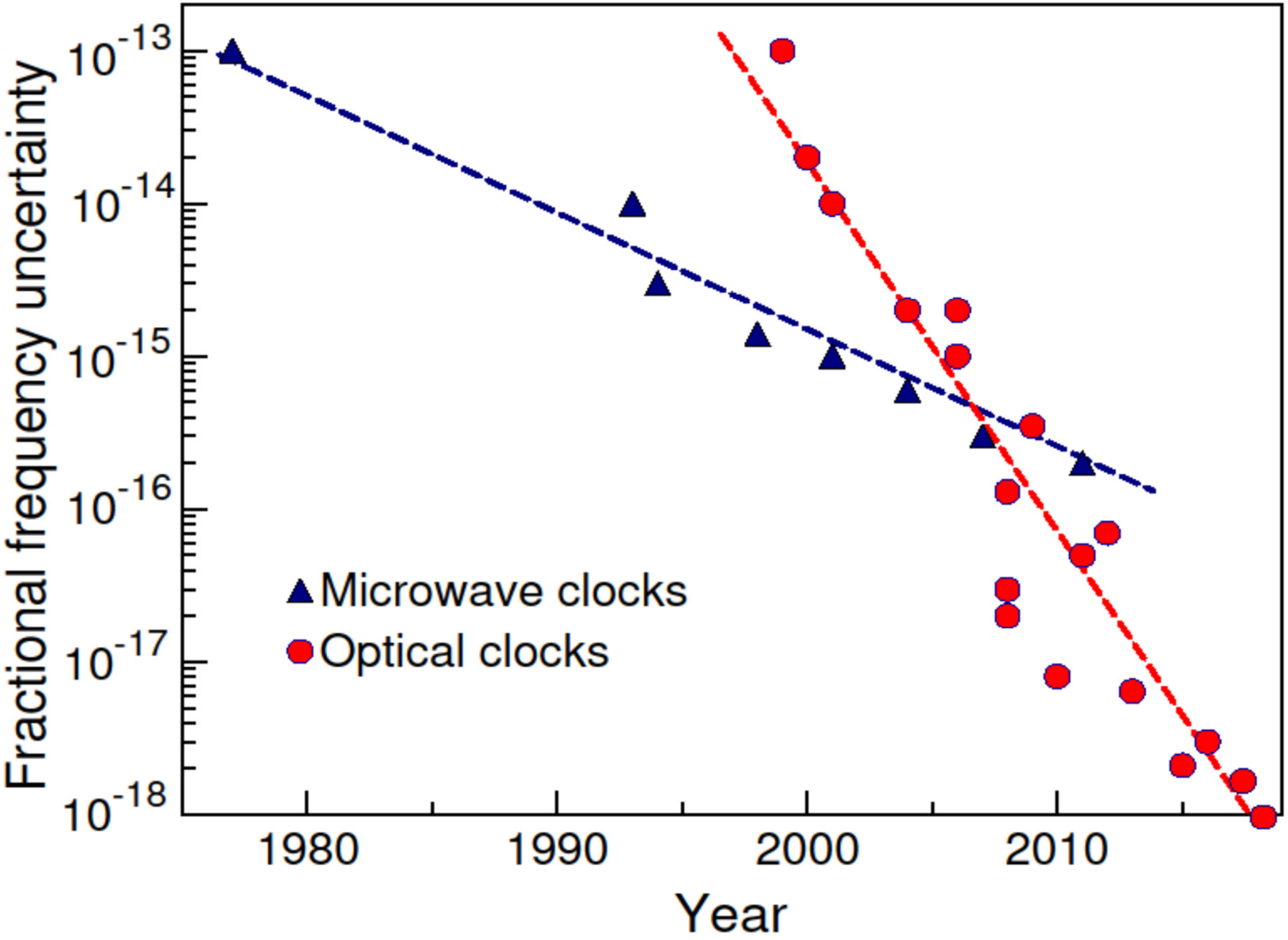


airandspace.si.edu

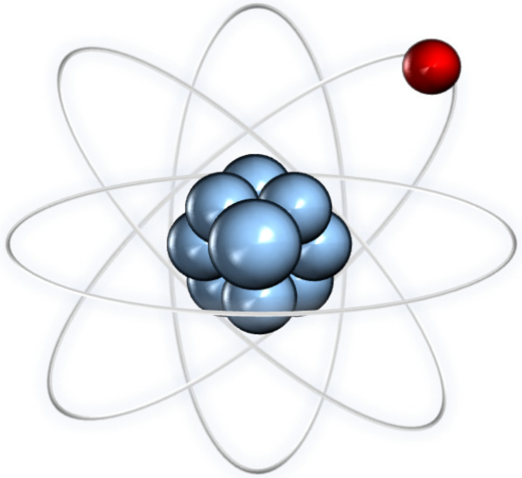
GPS satellites:
microwave
atomic clocks
Accuracy: 0.1 ns

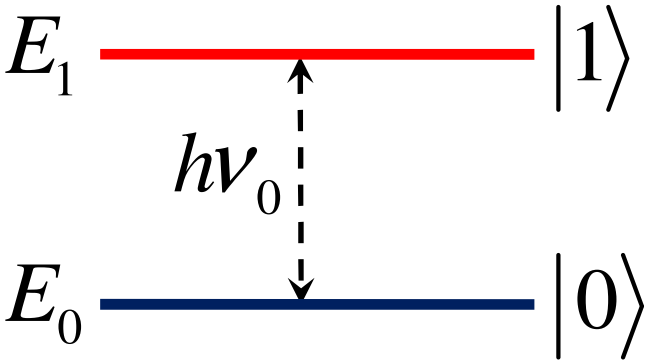


Optical atomic clocks will not lose one second in **30 billion years**



What dark matter 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?

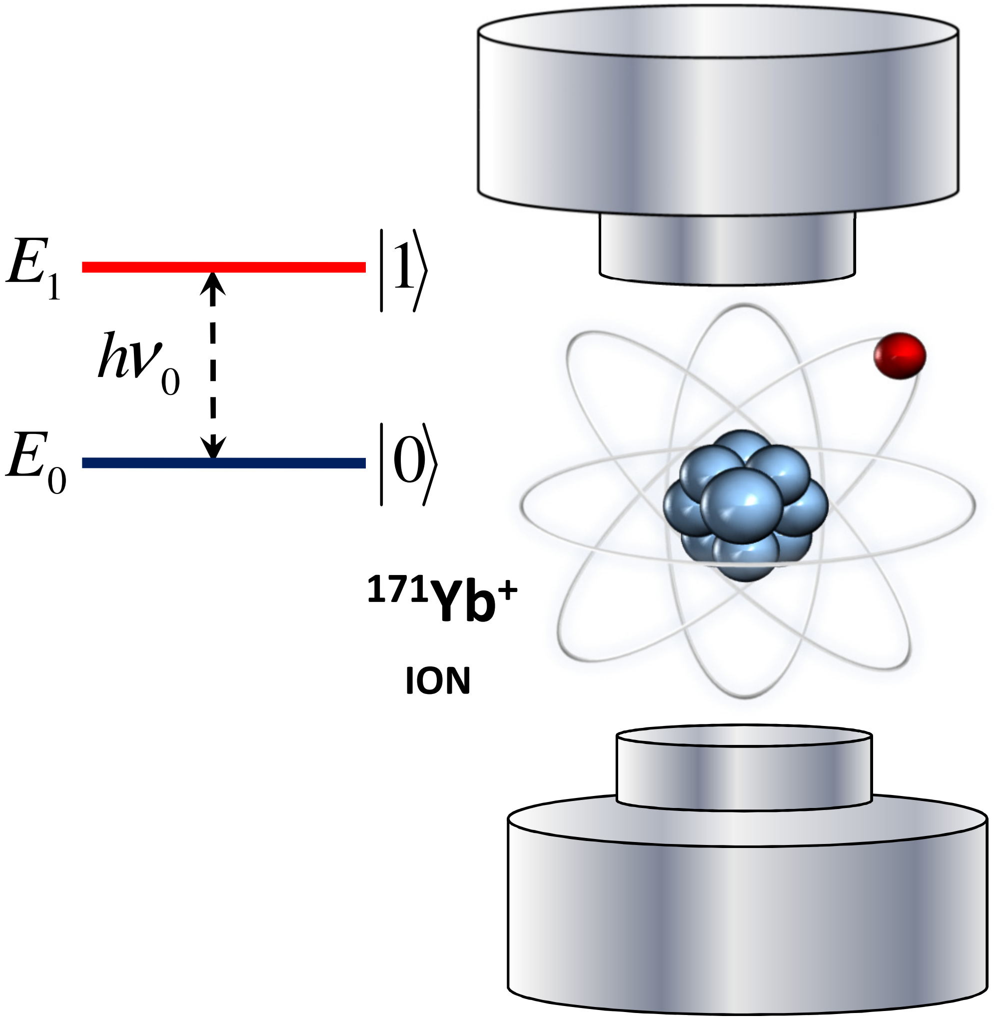
Ingredients for an atomic clock

1. Atoms are all the same and will oscillate at exactly the same frequency (in the same environment):
   You now have a perfect oscillator!

2. Take a sample of atoms (or just one)

3. Build a laser in resonance with this atomic frequency

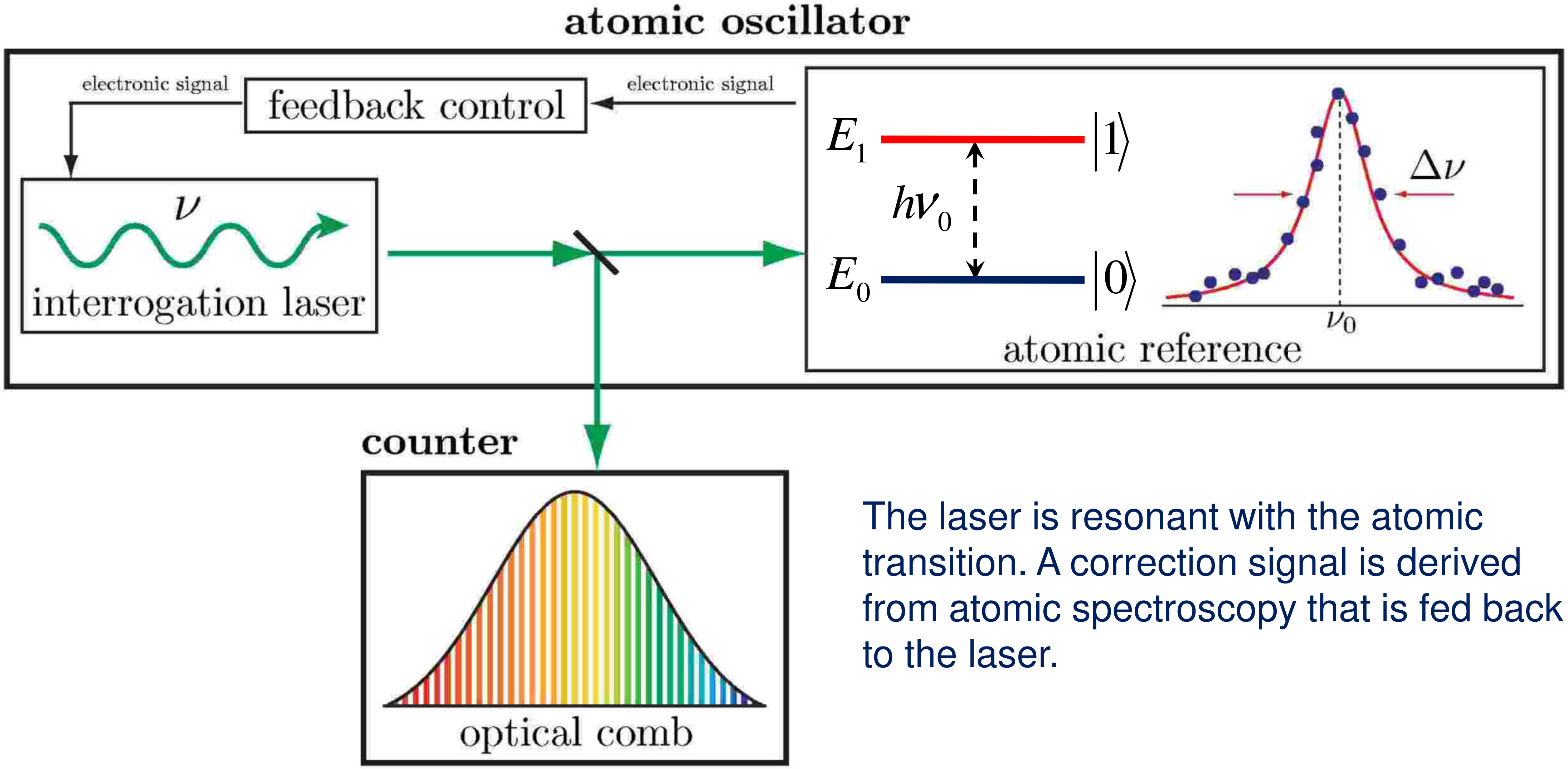
4. Count cycles of this signal



Ludlow et al., RMP 87, 637 (2015)


Fender
STRATOCASTER

How optical atomic clock works



The laser is resonant with the atomic transition. A correction signal is derived from atomic spectroscopy that is fed back to the laser.

An optical frequency synthesizer (optical frequency comb) is used to divide the optical frequency down to countable microwave or radio frequency signals.

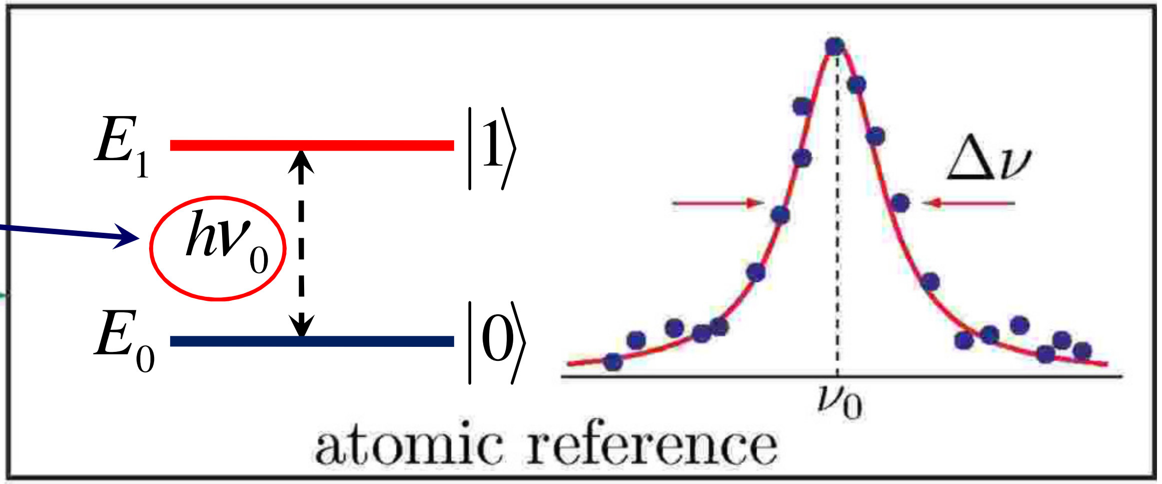
From: Poli et al. "Optical atomic clocks", La rivista del Nuovo Cimento 36, 555 (2018) arXiv:1401.2378v2

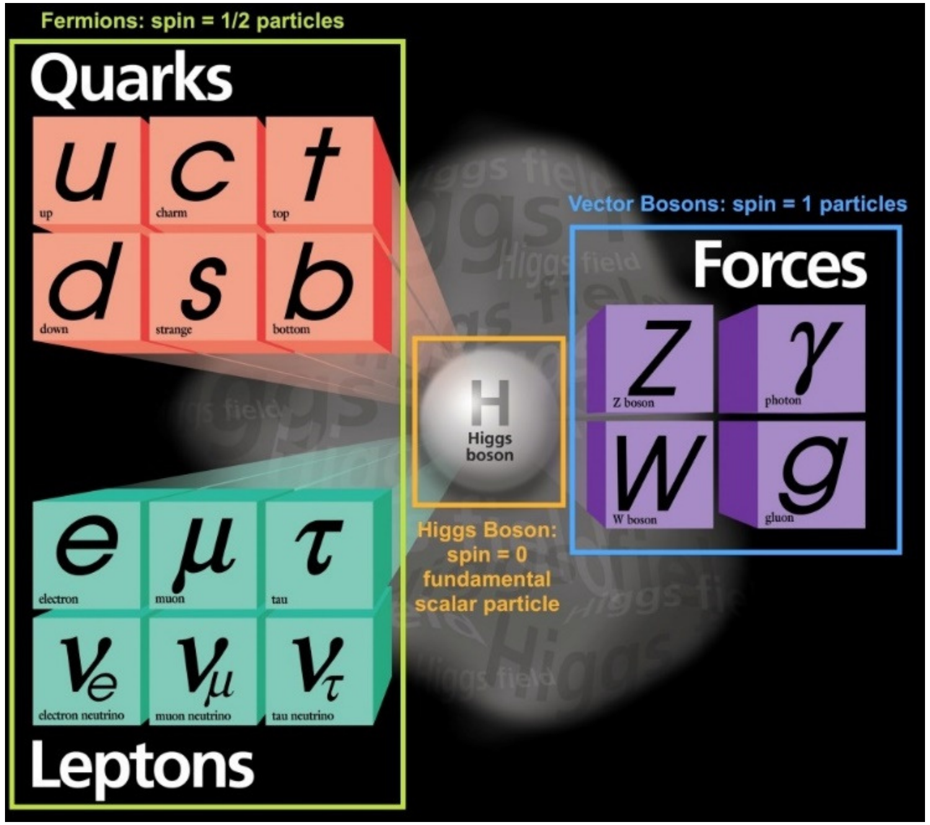
Search for physics beyond the standard model with atomic clocks

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.

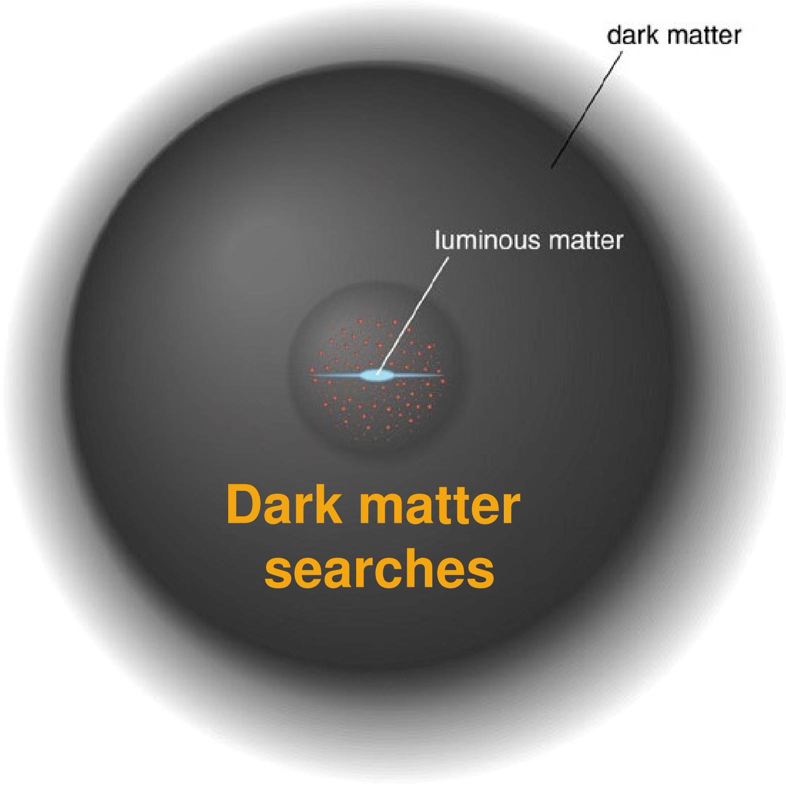
Frequency will change

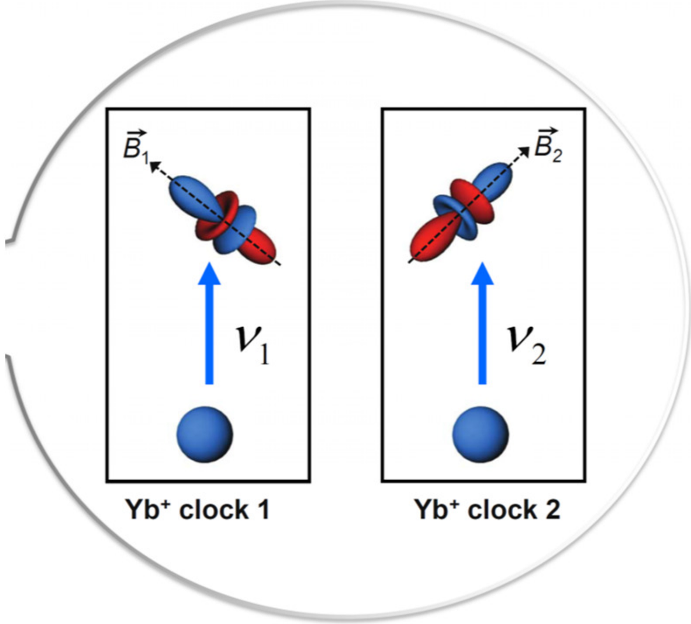




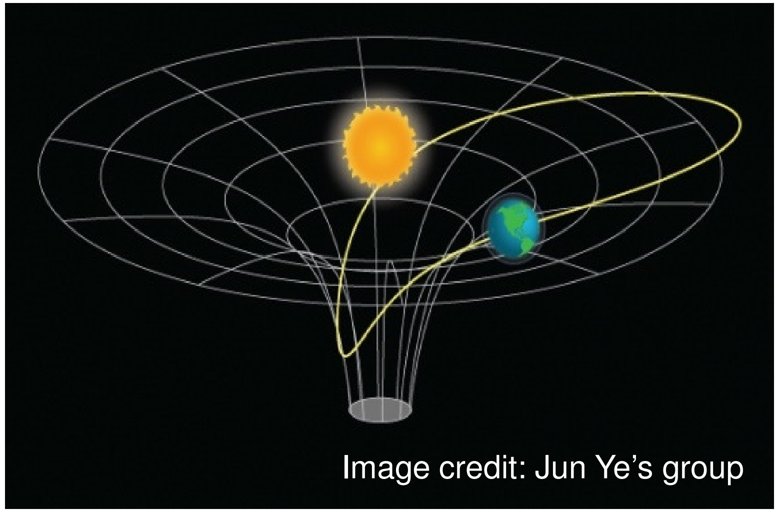
BEYOND THE STANDARD MODEL?

Searches for physics beyond the Standard Model with atomic clocks





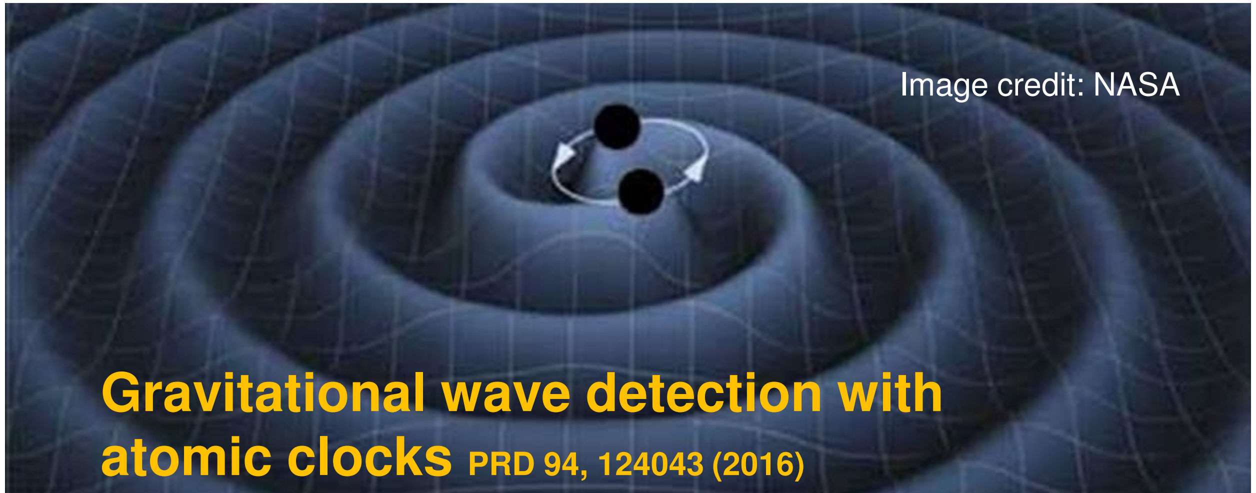
Search for the violation of Lorentz invariance



Tests of the equivalence principle

Are fundamental constants constant?

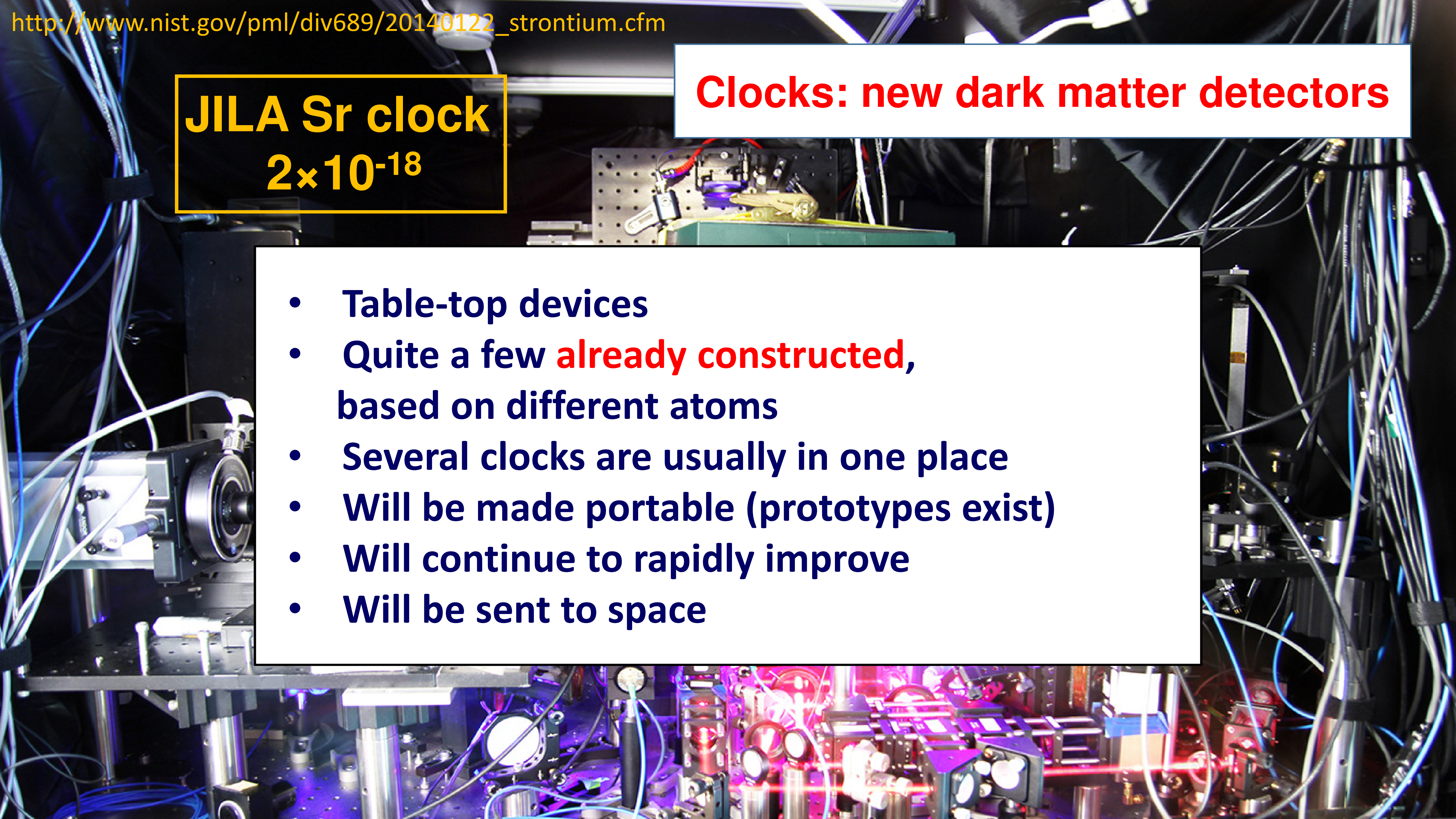
α



http://www.nist.gov/pml/div689/20140122_strontium.cfm

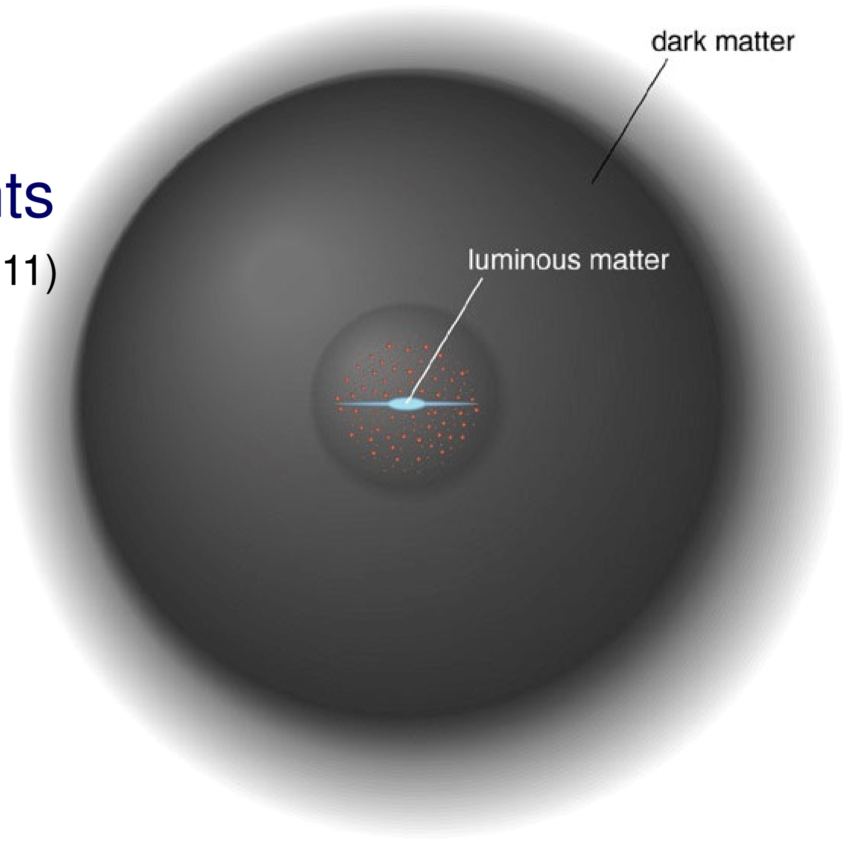
Clocks: new dark matter detectors

JILA Sr clock
2×10^{-18}



- Table-top devices
- Quite a few already constructed, based on different atoms
- Several clocks are usually in one place
- Will be made portable (prototypes exist)
- Will continue to rapidly improve
- Will be sent to space

Variation of fundamental constants



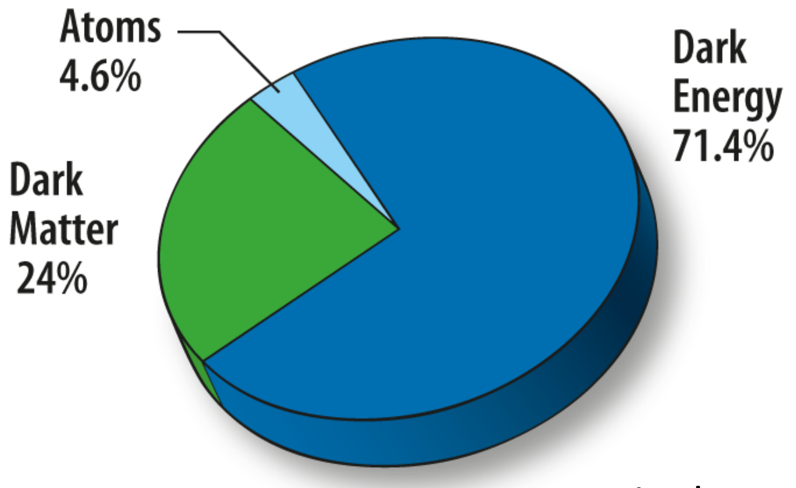
Theories with varying dimensionless fundamental constants

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.



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)

Variation of fundamental constants

Theories with varying dimensionless fundamental constants

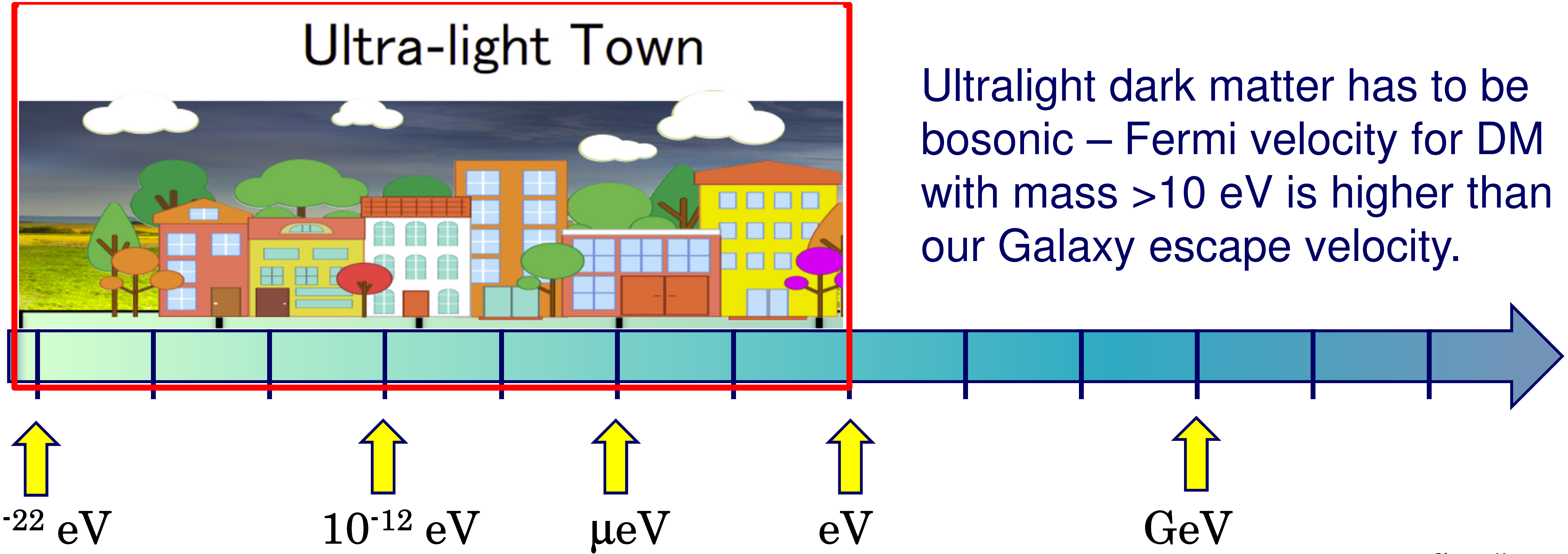
J.-P. Uzan, Living Rev. Relativity 14, 2 (2011)

- 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.

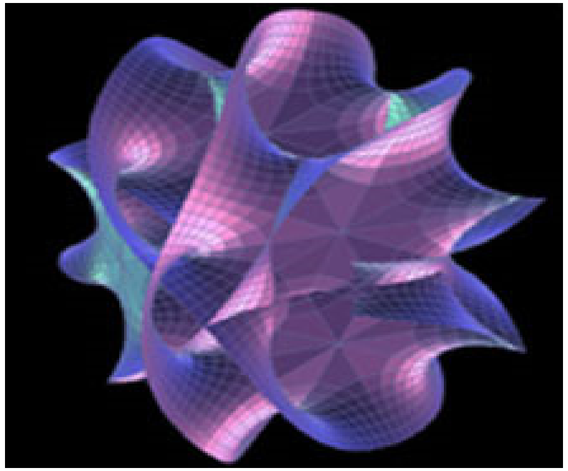
Some clocks are more sensitive to this effect than others

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



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

Simon Knapen, 2018 KITP



Dilatons

$$\frac{\phi}{M^*}\mathcal{O}_{\rm SM}$$

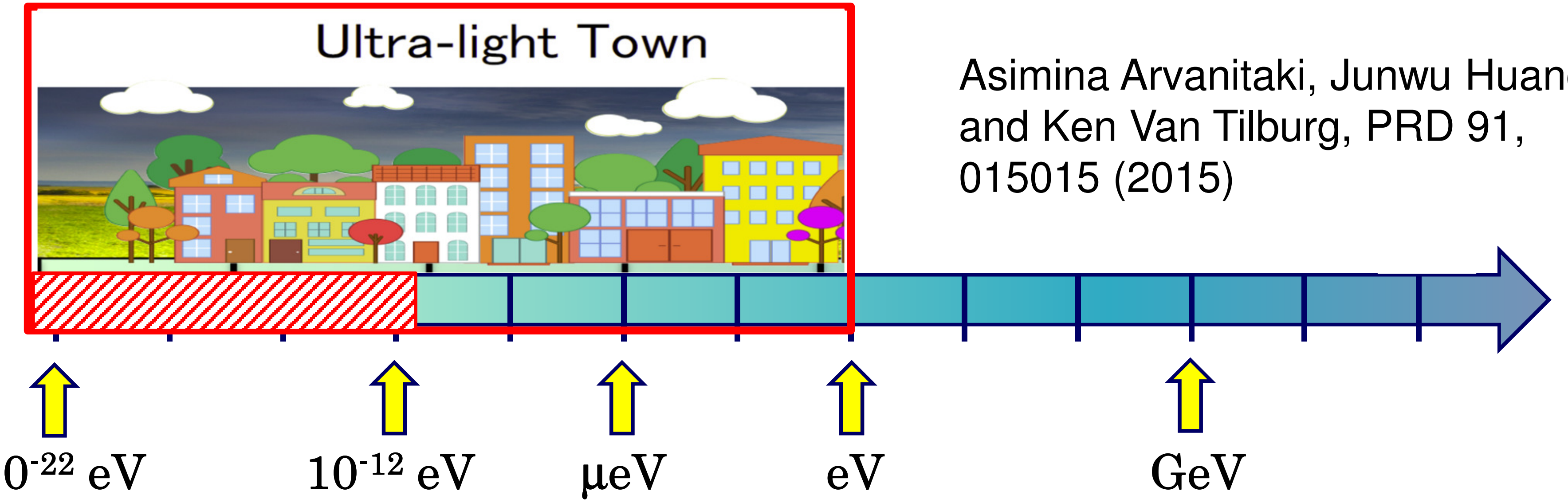
Dark matter density in our Galaxy > λ_{dB}^{-3}

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?



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

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).

Ultralight dark matter

$$\frac{\phi}{M^*}\mathcal{O}_{\text{SM}} \longrightarrow \mathcal{L}_\phi = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} \ldots\right] \qquad \alpha = \alpha^{\text{SM}} + \delta\alpha$$

photons

Dark matter

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

Then, clock frequencies will oscillate!

DM virial velocities ~ 300 km/s

τ [s]	$f = 2\pi/m_\phi$ [Hz]	m_ϕ [eV]
10^{-6}	1 MHz	4×10^{-9}
10^{-3}	1 kHz	4×10^{-12}
1	1	4×10^{-15}
1000	1 mHz	4×10^{-18}
10^{6}	10^{-6}	4×10^{-21}

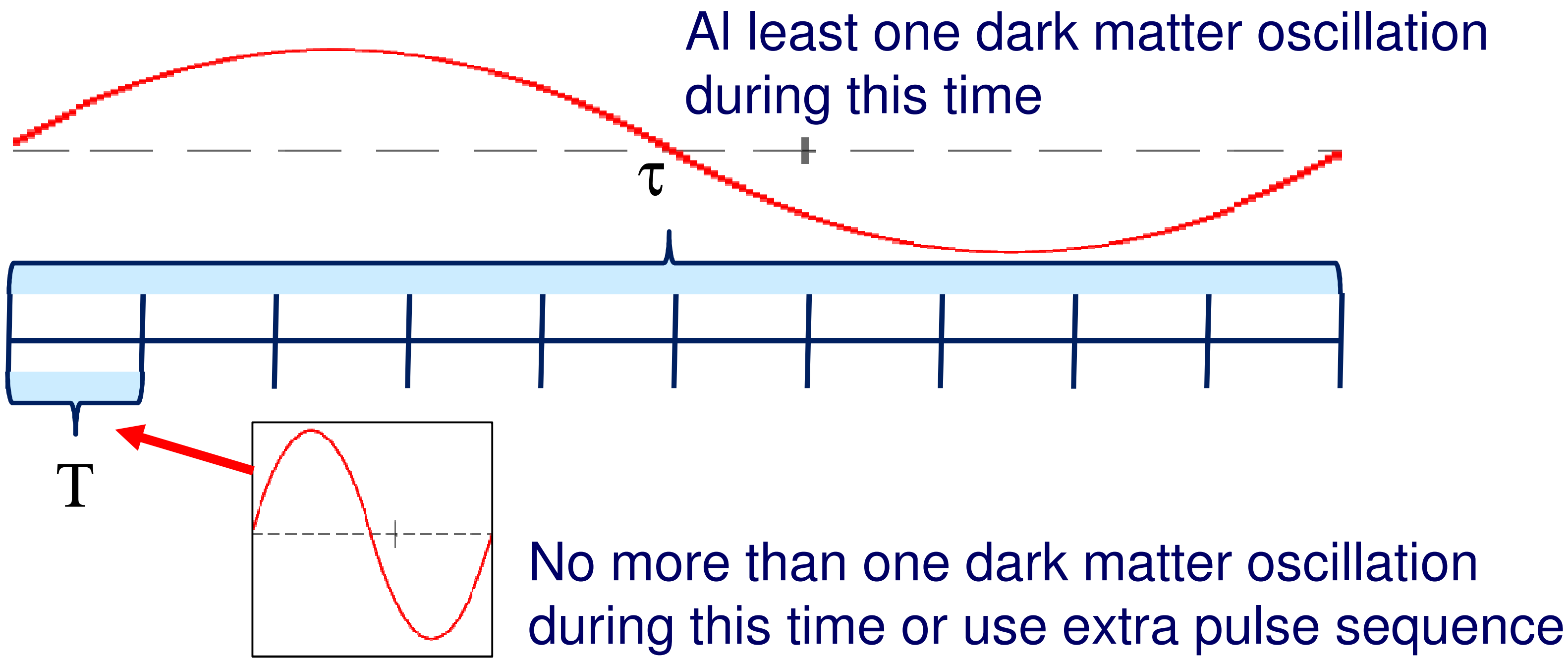
One oscillation per second

One oscillation per 11 days

Clock measurement protocols for the dark matter detection

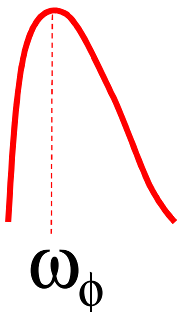
Single clock ratio measurement: averaging over time τ_1

Make N such measurements, preferably regularly spaced



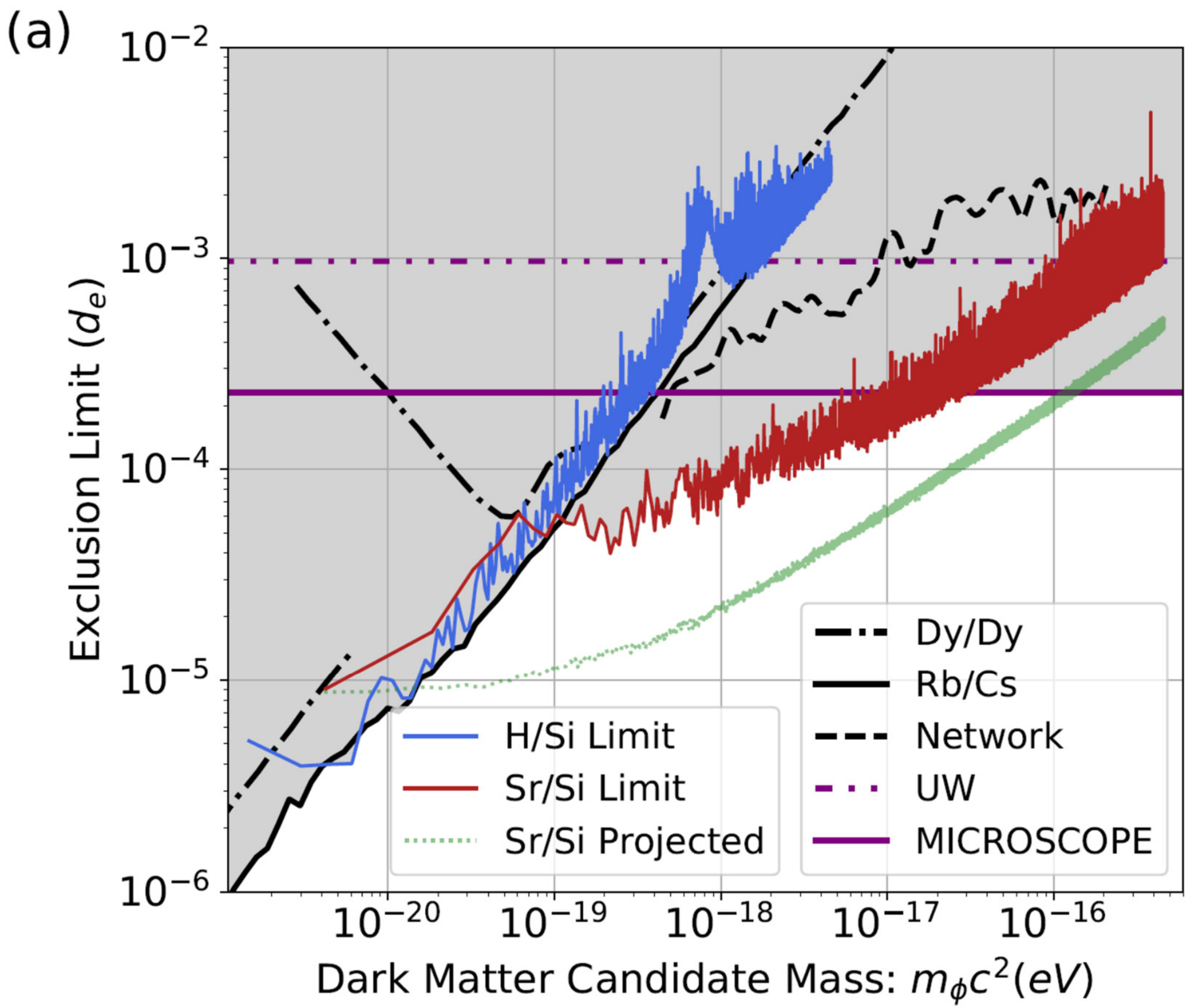
Detection signal:

A peak with monochromatic frequency $f = 2\pi / m_\phi$ in the discrete Fourier transform of this time series.



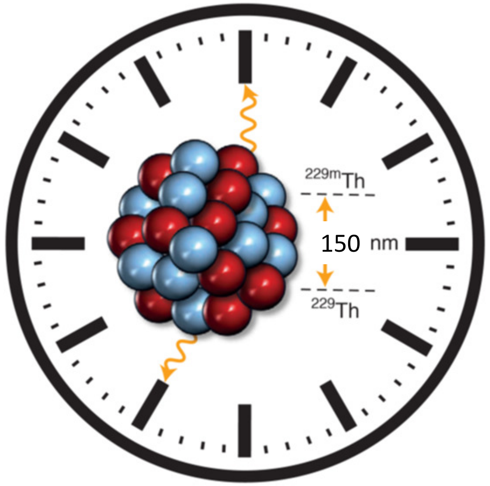
A. Arvanitaki et al., PRD 91, 015015 (2015)

Dark Matter Exclusion (dilatonic coupling) Plot, Kennedy et al., Phys. Rev. Lett. 125, 201302 (2020)



Many improvements and new clocks are coming!

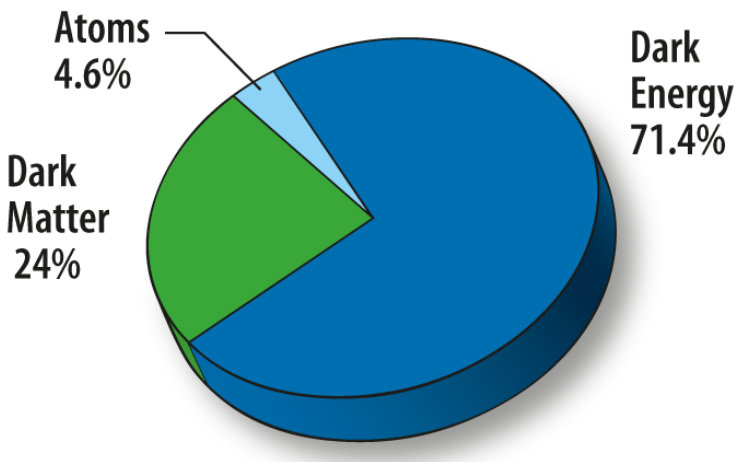
Nuclear clock-
5 orders of magnitude improvement in sensitivity



Atomic clocks:

Great potential for discovery of new physics

Many new developments coming in the next 10 years!



Need NEW IDEAS how to use clocks for new physics searches