

Atomic clocks and spectroscopy experiments

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6 January 2020



QUANTUM
FLAGSHIP

EMPIR

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La seconde

est la durée de 9 192 631 770 périodes de la radiation correspondant à la transition entre les deux niveaux hyperfins de l'état fondamental de l'atome de césium 133.

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.

Time standards

Atomic fountains

Optical clocks

Gravitational potential

Lorentz invariance

Dark matter

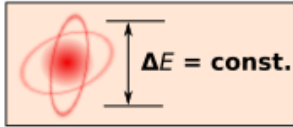
Coupling to SM

Ultralight Scalar DM
detection

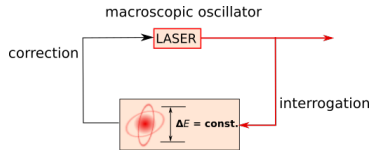
Topological defects
detection

Higgs force in atoms

Atomic clock

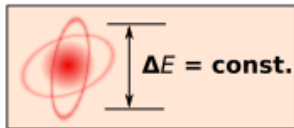


Atomic clock diagram

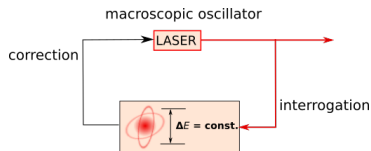


- ▶ Ideal clock: a signal with stable and universal frequency.
- ▶ Energy levels of unperturbed atoms are stable and universal.

Atomic clock



Atomic clock diagram



$$\omega(t) = \omega_{ef} * (1 + \varepsilon + y(t))$$

ε -fractional offset of frequency
 $y(t)$ - fractional fluctuations of frequency

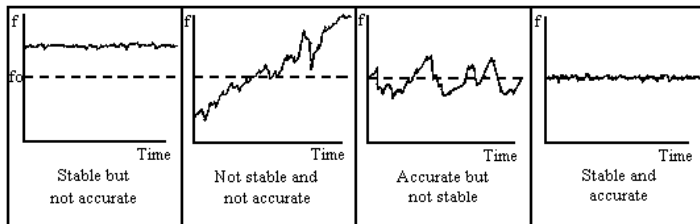
Accuracy

- uncertainty of ε

Stability

- statistical properties of $y(t)$,
characterized by the Allan
deviation $\sigma_y(\tau)$

Accuracy and stability



source: nist.gov

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experiments

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Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

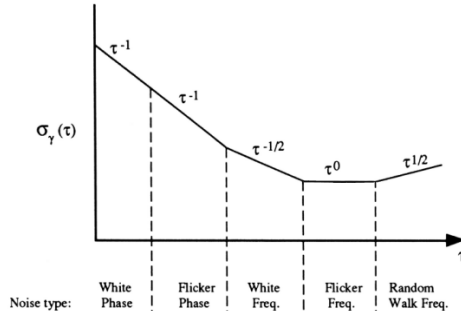
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Ultralight Scalar DM
detection
Topological defects
detection

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atoms

Allan deviation Details - Session II

$$\sigma_f(\tau) = \sqrt{\frac{1}{2} \sum_n \frac{(f_{n+1,\tau} - f_{n,\tau})^2}{n}}$$



source: nist.gov

f_n is a set of frequency offset measurements that consists of individual measurements, f_1, f_2, f_3 , and so on and the data are equally spaced in segments τ seconds long.

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experiments

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Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

Time standards

Atomic clocks and
spectroscopy
experiments

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University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

1. Atomic fountains, **accuracy** of $\sim 10^{-16}$
2. Commercial caesium clocks, with good long term **stability** $\sim 10^{-15}$ over few months and **accuracy** of $\sim 10^{-13}$
3. Hydrogen masers: 1.4 GHz hyperfine structure transition in atomic hydrogen. Much better short-time **stability** than any commercial caesium clock: $\sim 10^{-15}$ over few hours

Caesium clocks and hydrogen masers



HP5071A caesium clock and VCH-1005 hydrogen maser in the Central Office of Measures in Poland



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spectroscopy
experiments

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Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

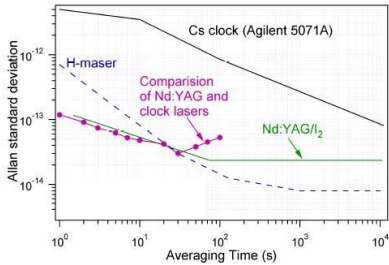
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detection
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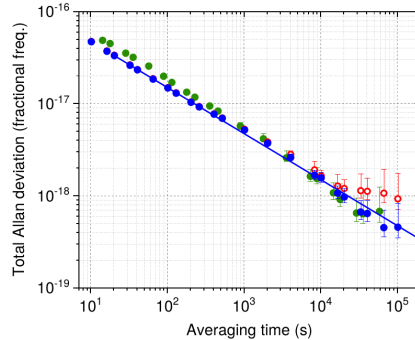
Caesium clocks and hydrogen masers vs optical clock

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spectroscopy
experiments

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Feng-Lei Hong et al. *Opt. Express* 13, 5253-5262 (2005)



W.F. McGrew et al. *Nature* 564, 87-90 (2018)

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Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

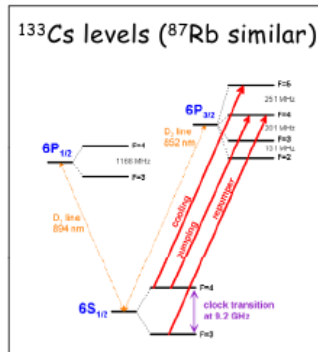
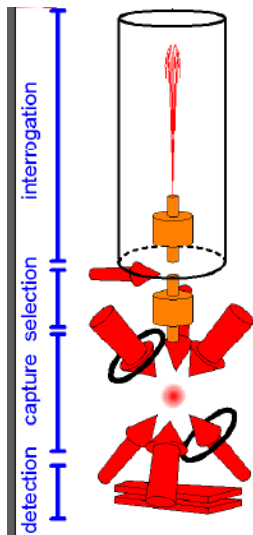
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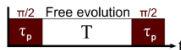
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detection
Topological defects
detection

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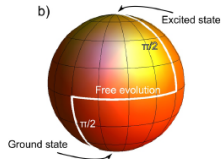
Atomic fountains



a)



b)



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Time standards

Atomic fountains
Optical clocks

Gravitational potential

Lorentz invariance

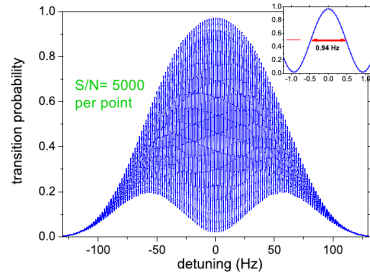
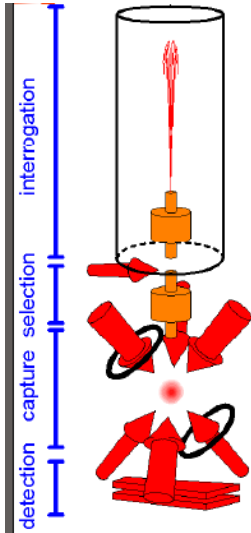
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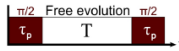
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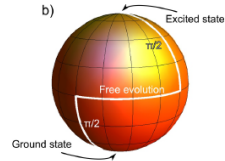
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a)



b)



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experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

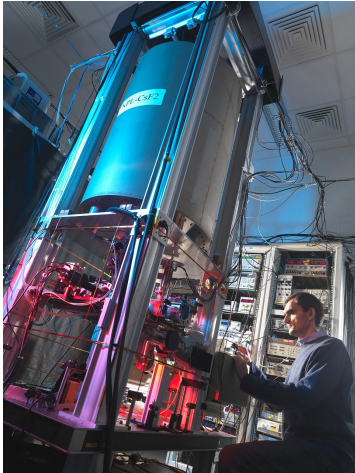
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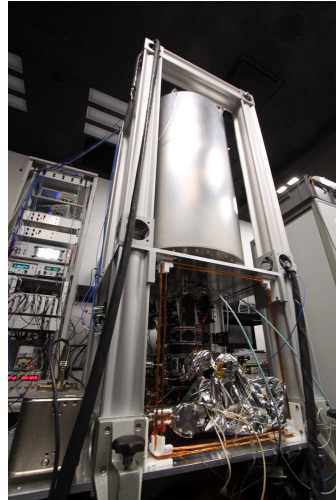
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spectroscopy
experiments

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Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

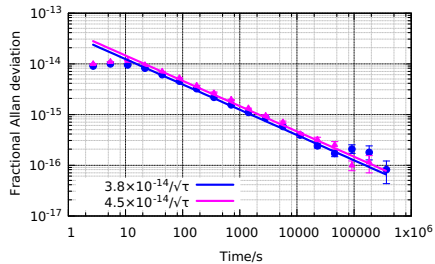
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Coupling to SM

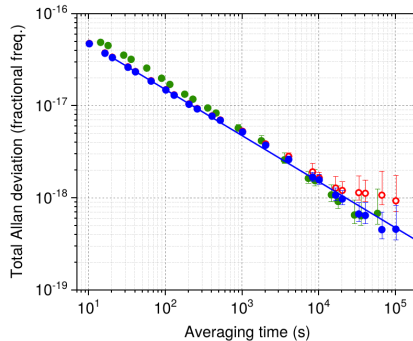
Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

Atomic fountains vs optical clock



J. Lodewyck et al. Metrologia 53, 1123 (2016)



W.F. McGrew et al. Nature 564, 87-90 (2018)

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experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

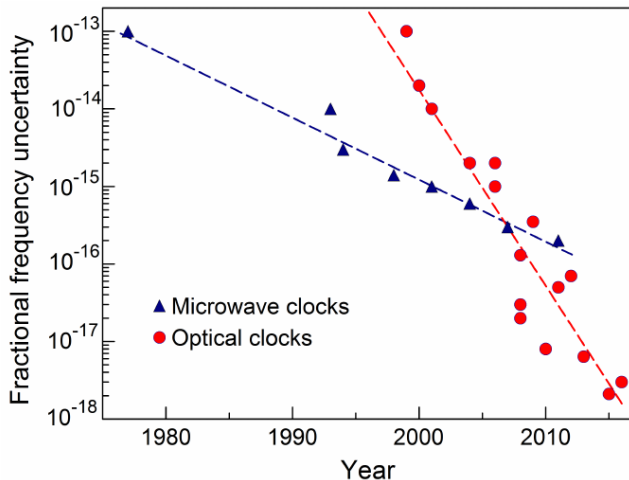
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Microwave clocks vs optical clocks



MS Safronova et al., Rev. Mod. Phys. 90, 025008 (2018)

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experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

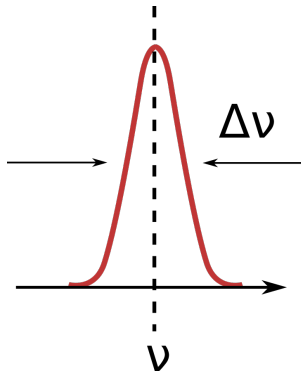
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

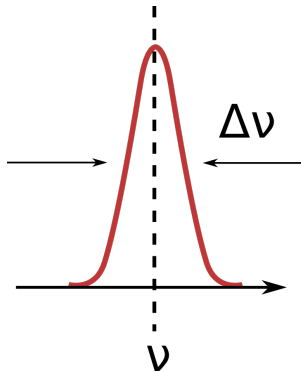
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Microwave clocks vs optical clocks



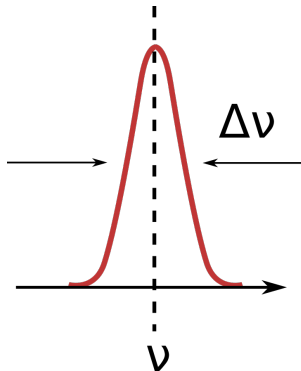
Quality of the clock: $Q = \frac{\nu}{\Delta\nu} \times \frac{s}{N}$

Microwave clocks vs optical clocks



Quality of the clock: $Q = \frac{\nu}{\Delta\nu} \times \frac{S}{N} \sim \nu T \times \frac{S}{N}$

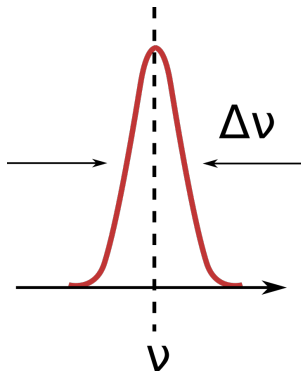
Microwave clocks vs optical clocks



Quality of the clock: $Q = \frac{\nu}{\Delta\nu} \times \frac{S}{N} \sim \nu T \times \frac{S}{N}$

Stability of an atomic clock: $\sigma_y(\tau) \sim \frac{\sigma_{\text{spect}}}{Q} \sqrt{\frac{T_c}{\tau}}$

Microwave clocks vs optical clocks



Quality of the clock: $Q = \frac{\nu}{\Delta\nu} \times \frac{S}{N} \sim \nu T \times \frac{S}{N}$

Stability of an atomic clock: $\sigma_y(\tau) \sim \frac{\sigma_{\text{spect}}}{Q} \sqrt{\frac{T_c}{\tau}}$

Quantum Shot Noise limitation: $\sigma_y(\tau) = \frac{1}{\pi Q} \times \frac{1}{N_{\text{at}}} \times \sqrt{\frac{T_c}{\tau}}$

Optical clocks: trapped ions and neutral atoms

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Ion traps: Ions trapped in the Paul trap by the RF field

- ▶ Trap is perturbed only slightly

⇒ **excellent accuracy**

$$9.4 \times 10^{-18}$$

- ▶ Good stability
($1.2 \times 10^{-15} / \sqrt{\tau}$), but

restricted by

Quantum Shot Noise

- only 1 ion

S. M. Brewer et al. 123, 033201 (2019)

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

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Neutral atoms: Optical lattice

- ▶ A trap with a high-intensity light \Rightarrow high perturbation, though **well under control**.
 $2 * 10^{-18}$

- High number of atoms (10^4) \Rightarrow **high stability possible.**
 $1.5 \times 10^{-16} / \sqrt{\tau}$ down to
 3.2×10^{-19}

Higgs force in atoms

A transition good for optical clock

Natural linewidth of an electric dipole (E1) transition is typically bigger than 1 MHz \Rightarrow
Q below 10^8

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spectroscopy
experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

A transition good for optical clock

Atomic clocks and
spectroscopy
experiments

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Natural linewidth of an electric dipole (E1) transition is typically bigger than 1 MHz \Rightarrow
Q below 10^8

Clock transition should be:

- ▶ Narrow (forbidden)
- ▶ Mostly insensitive to external fields.

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

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Clock transition should be:

- ▶ Narrow (forbidden)
- ▶ Mostly insensitive to external fields.

Possible candidates:

- ▶ two-photon transitions and higher order electric transitions (quadrupole, octupole ...)
- ▶ a low energy nuclear transition (still sought at ^{229}Th)
- ▶ an intercombination transition

Alkaline-earth and alkaline-earth like atoms/ions

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

PERIODIC TABLE

Atomic Properties of the Elements

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

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA	IIA	IIIB	IVB	VB	VIB	VII	VIII	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	H Hydrogen 1.008 1.00794																	He Helium 4.002602 4.002602
2	Li Lithium 6.941 6.941	Be Beryllium 9.0121831 9.0121831																Ne Neon 19.99244 19.99244
3	Na Sodium 22.98976928 22.98976928	Mg Magnesium 24.304 24.304																Ar Argon 39.948 39.948
4	K Potassium 39.0983 39.0983	Ca Calcium 40.078 40.078	Sc Scandium 44.955912 44.955912	Ti Titanium 47.88 47.88	V Vanadium 50.9415 50.9415	Cr Chromium 51.9961 51.9961	Mn Manganese 54.938044 54.938044	Fe Iron 55.845 55.845	Co Cobalt 58.933194 58.933194	Ni Nickel 58.6934 58.6934	Cu Copper 63.546 63.546	Zn Zinc 65.38 65.38	Ga Gallium 69.723 69.723	Ge Germanium 72.630 72.630	As Arsenic 74.921595 74.921595	Se Selenium 78.96 78.96	Br Bromine 79.904 79.904	Kr Krypton 83.798 83.798
5	Rb Rubidium 85.4678 85.4678	Sr Strontium 87.62 87.62	Y Yttrium 88.90584 88.90584	Zr Zirconium 91.224 91.224	Nb Niobium 92.90638 92.90638	Mo Molybdenum 95.94 95.94	Tc Technetium (98) 98	Ru Ruthenium 101.07 101.07	Rh Rhodium 102.9055 102.9055	Pd Palladium 106.42 106.42	Ag Silver 107.8682 107.8682	Cd Cadmium 112.414 112.414	In Indium 114.818 114.818	Sn Tin 118.710 118.710	Sb Antimony 121.757 121.757	Te Tellurium 127.60 127.60	I Iodine 126.90447 126.90447	Xe Xenon 131.29 131.29
6	Cs Cesium 132.905451963 132.905451963	Ba Barium 137.327 137.327		Hf Hafnium 178.49 178.49	Ta Tantalum 180.94788 180.94788	W Tungsten 183.84 183.84	Re Rhenium 186.207 186.207	Os Osmium 190.23 190.23	Ir Iridium 192.222 192.222	Pt Platinum 195.084 195.084	Au Gold 196.966569 196.966569	Hg Mercury 200.59 200.59	Tl Thallium 204.383 204.383	Pb Lead 207.2 207.2	Bi Bismuth 208.9804 208.9804	Po Polonium 209 209	At Astatine 210 210	Rn Radon 222 222
7	Fr Francium (223) 223	Ra Radium (226) 226		Rf Rutherfordium (261) 261	Db Dubnium (262) 262	Sg Seaborgium (266) 266	Bh Bohrium (264) 264	Hs Hassium (277) 277	Mt Meitnerium (268) 268	Ds Darmstadtium (271) 271	Rg Roentgenium (272) 272	Cn Copernicium (285) 285	Nh Nihonium (284) 284	Fl Flerovium (289) 289	Uup Ununpentium (288) 288	Lv Livermorium (293) 293	Uus Ununseptium (294) 294	Uuo Ununoctium (294) 294
			La Lanthanum 138.9047 138.9047	Ce Cerium 140.116 140.116	Pr Praseodymium 140.90766 140.90766	Nd Neodymium 144.242 144.242	Pm Promethium (145) 145	Sm Samarium 150.36 150.36	Eu Europium 151.964 151.964	Gd Gadolinium 157.25 157.25	Tb Terbium 158.92535 158.92535	Dy Dysprosium 162.50 162.50	Ho Holmium 164.93033 164.93033	Er Erbium 167.257 167.257	Tm Thulium 168.93403 168.93403	Yb Ytterbium 173.045 173.045	Lu Lutetium 174.967 174.967	
			Ac Actinium 227 227	Th Thorium 232.0377 232.0377	Pa Protactinium 231.03688 231.03688	U Uranium 238.02891 238.02891	Np Neptunium (237) 237	Pu Plutonium (244) 244	Am Americium (243) 243	Cm Curium (247) 247	Bk Berkelium (247) 247	Cf Californium (251) 251	Es Einsteinium (252) 252	Fm Fermium (257) 257	Md Mendelevium (258) 258	No Nobelium (259) 259	Lr Lawrencium (262) 262	

Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs
 c 299 792 458 m s $^{-1}$ (exact)
 h 6.626 070 15 $\times 10^{-34}$ J s (exact)
 k 1.380 650 5 $\times 10^{-23}$ J K $^{-1}$
 e 1.602 177 6 $\times 10^{-19}$ C
 m_e 9.109 38 3 $\times 10^{-31}$ kg
 m_p 1.672 621 9 $\times 10^{-27}$ kg
 m_n 1.674 927 2 $\times 10^{-27}$ kg
 R_∞ 10 973 731 569 m $^{-1}$
 R_H 1.097 373 157 $\times 10^7$ m $^{-1}$
 α 7.297 352 569 $\times 10^{-3}$
 μ_B 9.274 009 4 $\times 10^{-24}$ J T $^{-1}$
 μ_N 5.050 783 7 $\times 10^{-27}$ J T $^{-1}$
Bohrmann constant
 \hbar 1.054 571 8 $\times 10^{-34}$ J s

☐ Solids
☐ Liquids
☐ Gases
☐ Artificially Prepared

Physical Measurement Laboratory
www.nist.gov/pml
Standard Reference Data
www.nist.gov/srd

[†]Based upon ^{12}C . 0 indicates the mass number of the longest-lived isotope.

[†]IUPAC conventional atomic weights; standard atomic weights for these elements are expressed in intervals; see iupac.org for an explanation and values.

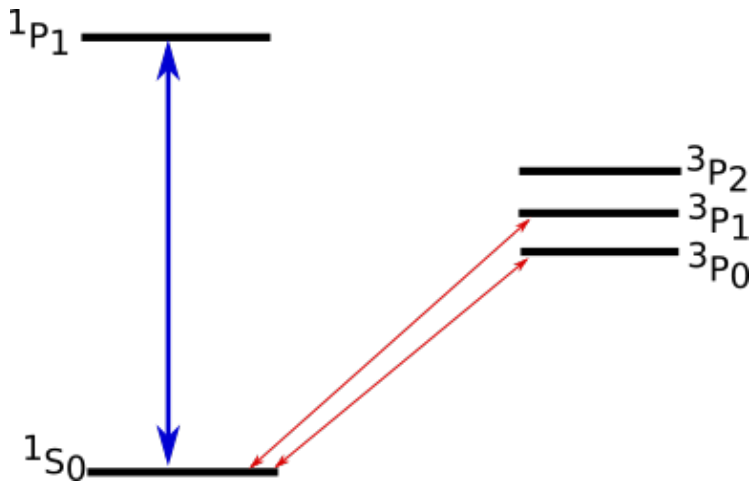
For a description of the data, visit physics.nist.gov/data
NIST SP 966 (September 2014)

¹Based upon ¹²C. () indicates the mass number of the longest-lived isotope.

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spectroscopy
experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Alkaline-earth and alkaline-earth like atoms/ions

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Time standards

Atomic fountains

Optical clocks

Gravitational potential

Lorentz invariance

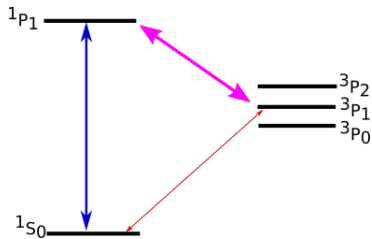
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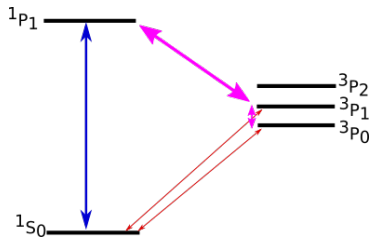
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- ▶ Forbidden $^1S_0 - ^3P_1$ transition:
 - ▶ Fine structure interaction



- ▶ Forbidden $^1S_0 - ^3P_1$ transition:
 - ▶ Fine structure interaction
- ▶ Double forbidden $^1S_0 - ^3P_0$ transition:
 - ▶ Fermions: hyperfine interaction
 - ▶ Bosons: quenching by a static B field

Time standards

Atomic fountains

Optical clocks

Gravitational potential

Lorentz invariance

Dark matter

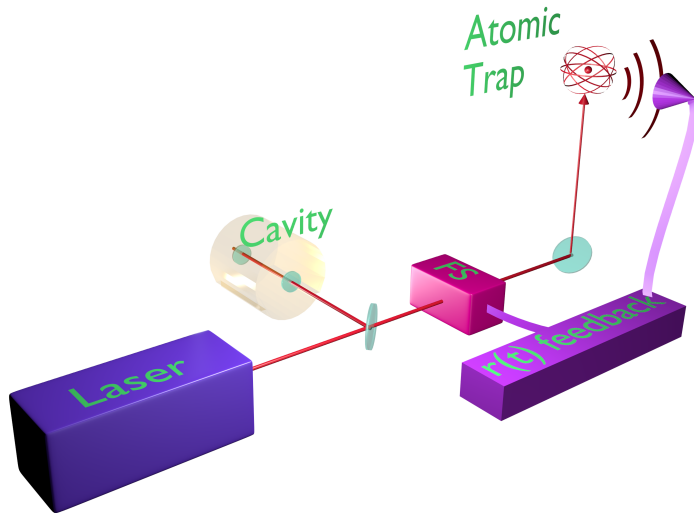
Coupling to SM

Ultralight Scalar DM detection

Topological defects detection

Higgs force in atoms

Optical atomic clocks



Atomic clocks and
spectroscopy
experiments

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University

Time standards

Atomic fountains

Optical clocks

Gravitational
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Lorentz invariance

Dark matter

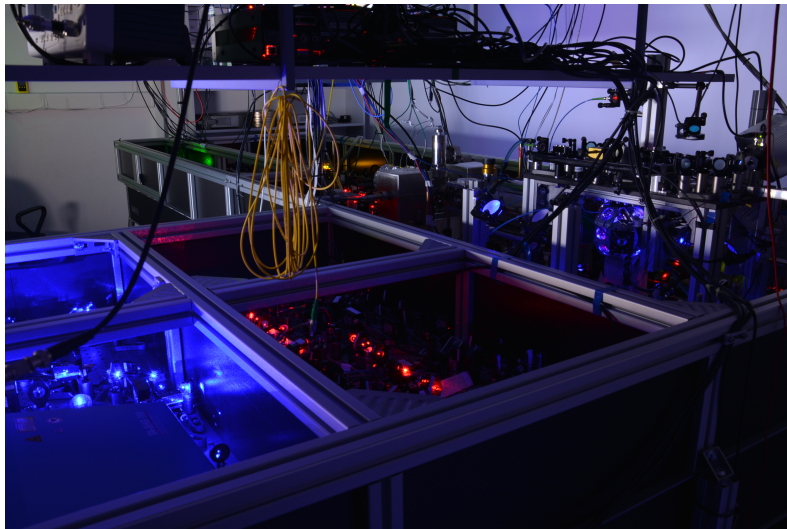
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Optical atomic clocks



Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

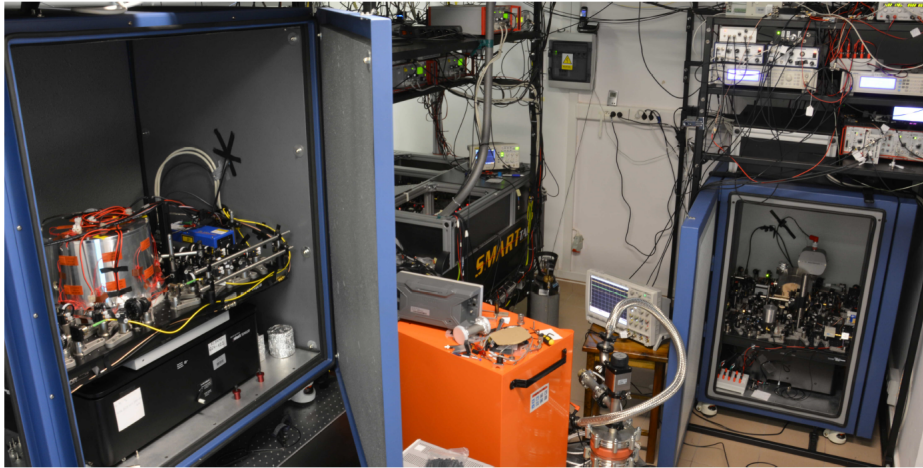
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Optical atomic clocks



Atomic clocks and
spectroscopy
experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

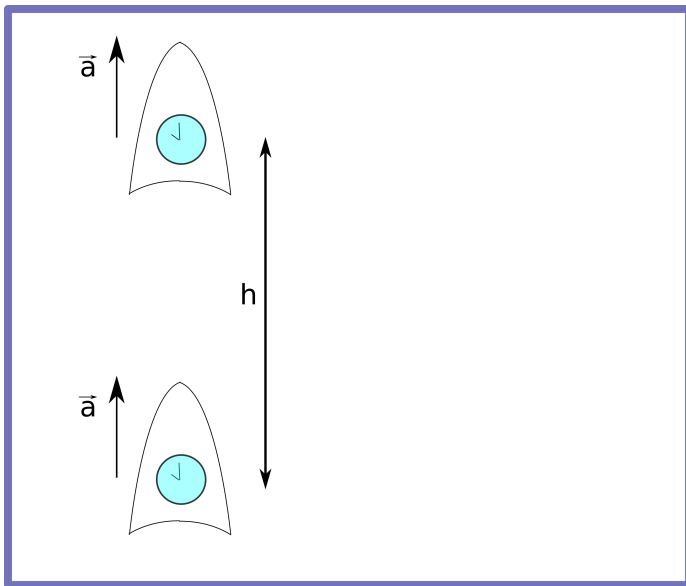
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Optical atomic clocks - gravitational potential sensors



Atomic clocks and
spectroscopy
experiments

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University

Time standards

Atomic fountains

Optical clocks

**Gravitational
potential**

Lorentz invariance

Dark matter

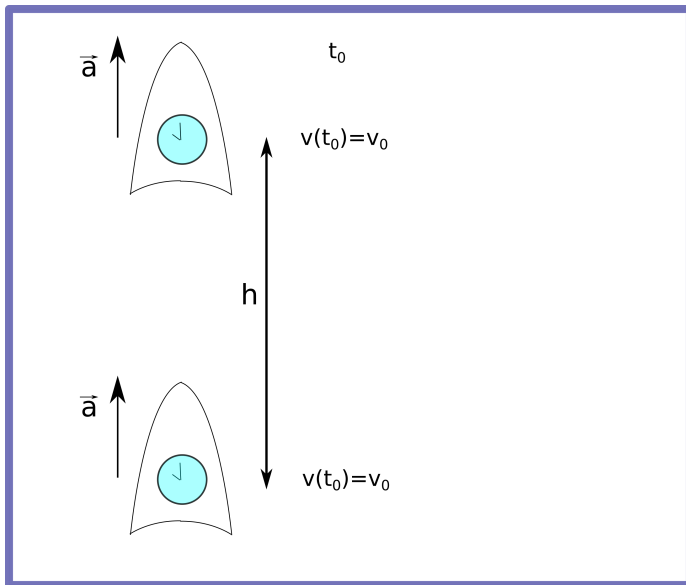
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Optical atomic clocks - gravitational potential sensors



Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

**Gravitational
potential**

Lorentz invariance

Dark matter

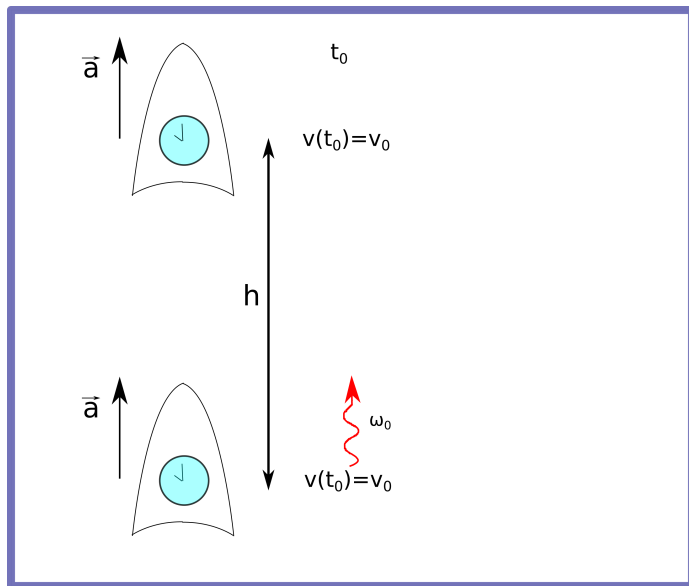
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Optical atomic clocks - gravitational potential sensors



Atomic clocks and
spectroscopy
experiments

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Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

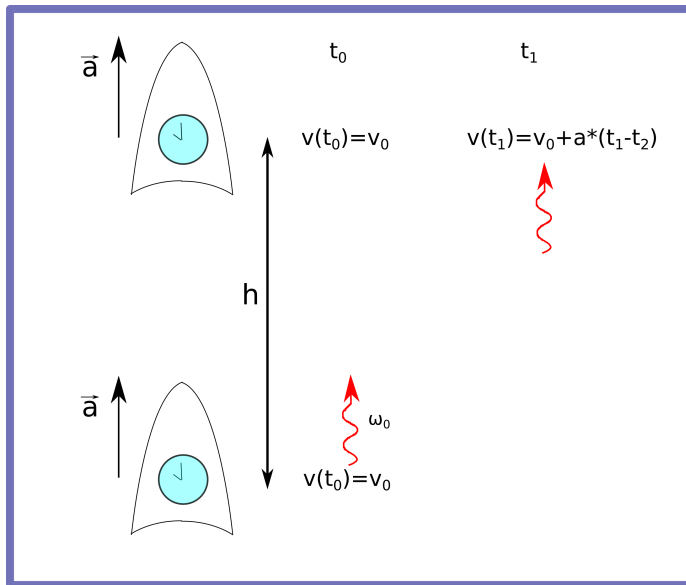
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Optical atomic clocks - gravitational potential sensors



Atomic clocks and
spectroscopy
experiments

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KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

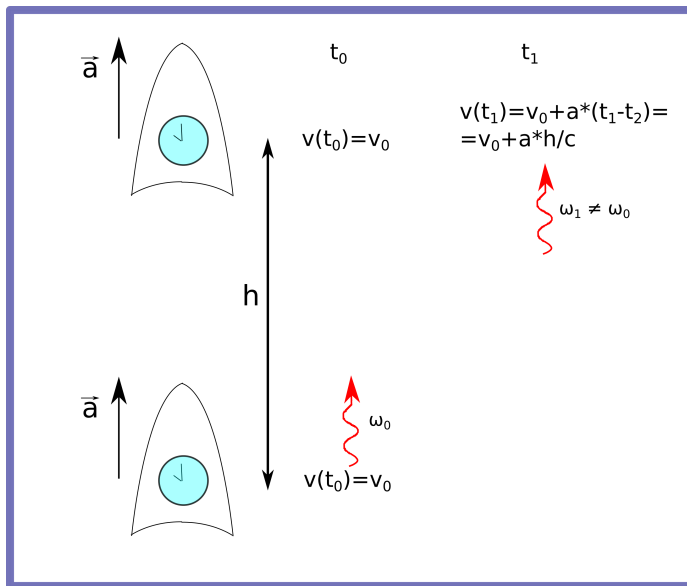
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Optical atomic clocks - gravitational potential sensors



Atomic clocks and
spectroscopy
experiments

Michał Zawada
KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

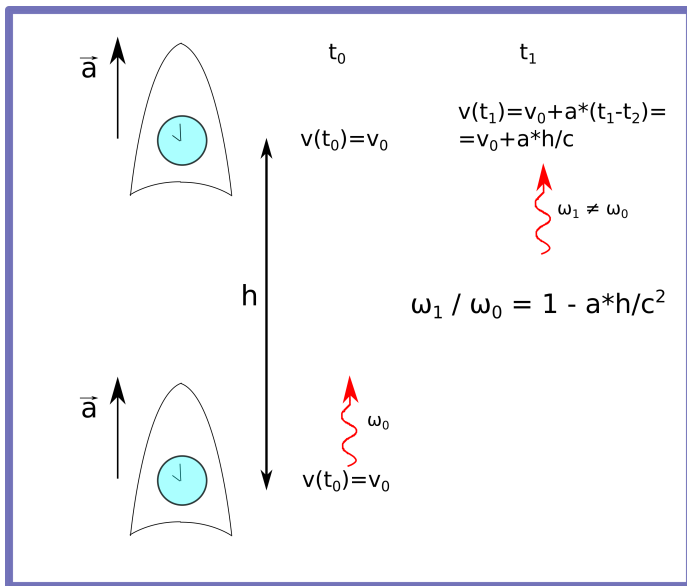
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Optical atomic clocks - gravitational potential sensors



Atomic clocks and
spectroscopy
experiments

Michał Zawada
KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

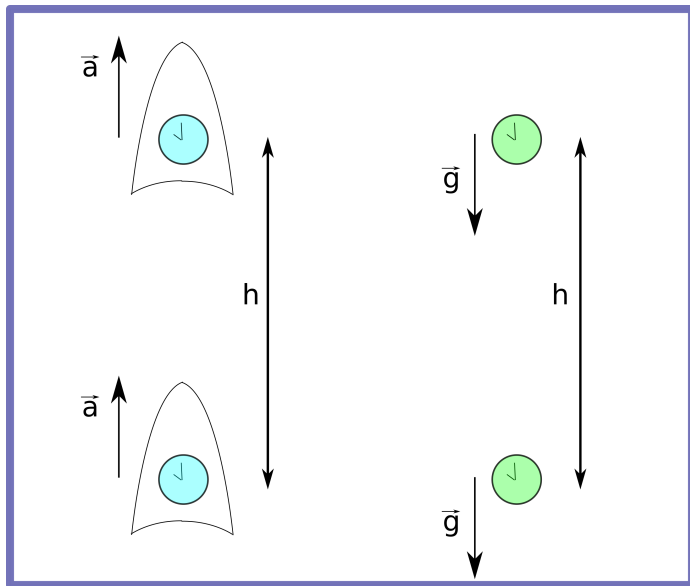
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Optical atomic clocks - gravitational potential sensors



Atomic clocks and
spectroscopy
experiments

Michał Zawada
KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

**Gravitational
potential**

Lorentz invariance

Dark matter

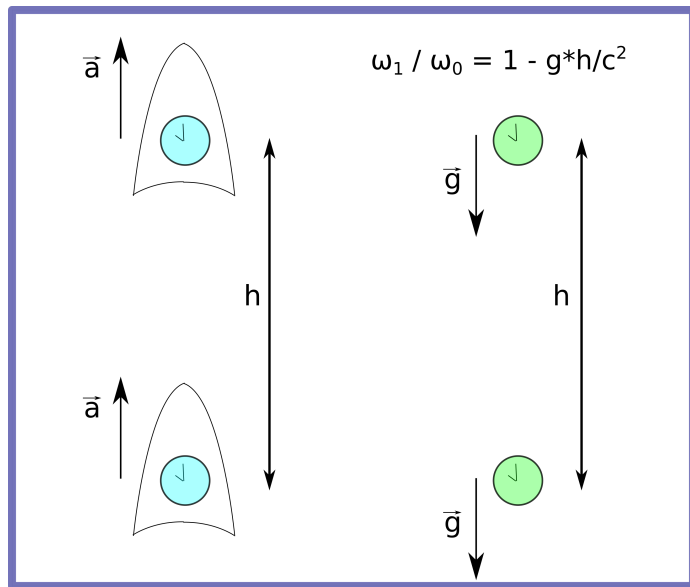
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Optical atomic clocks - gravitational potential sensors



Atomic clocks and
spectroscopy
experiments

Michał Zawada
KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

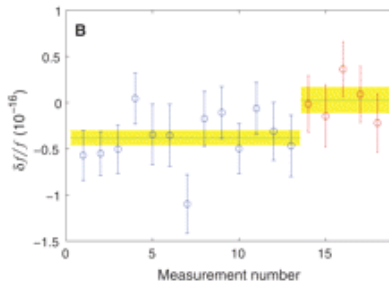
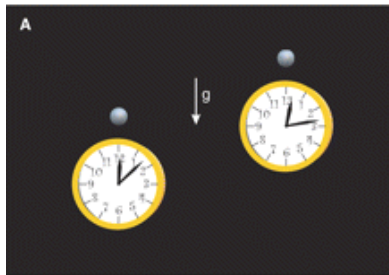
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Gravitational redshift



Clock raised by 33 cm - CW Chou, *et. al.*, Science, **329** 1630 (2010)

Atomic clocks and
spectroscopy
experiments

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Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

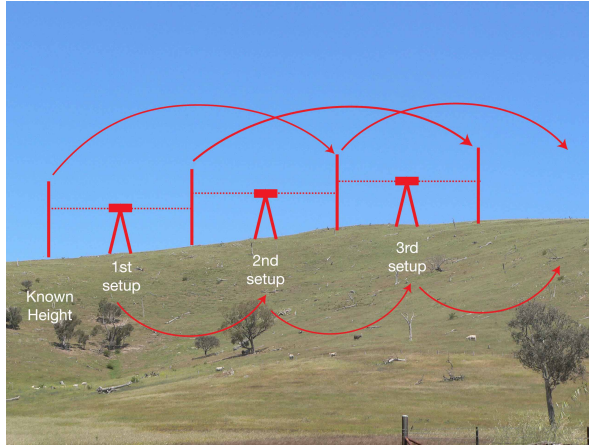
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Gravitational redshift - land surveying



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Atomic clocks and
spectroscopy
experiments

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University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

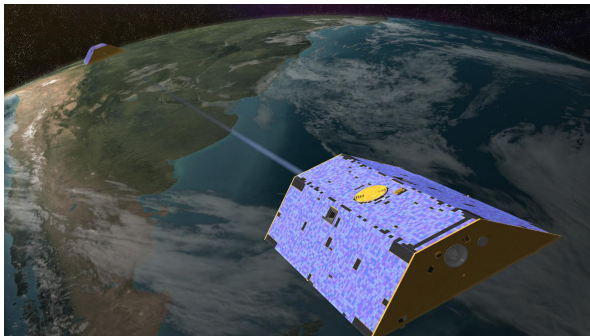
Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

Gravitational redshift - land surveying - GRACE



Source: NASA

Atomic clocks and
spectroscopy
experiments

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KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

**Gravitational
potential**

Lorentz invariance

Dark matter

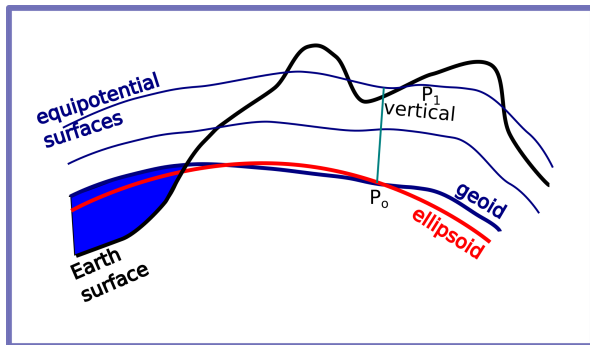
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Gravitational redshift - relativistic geodesy



A. Bjerhammar, Bulletin Geodesique, **59** 207 (1985)

Atomic clocks and
spectroscopy
experiments

Michał Zawada
KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

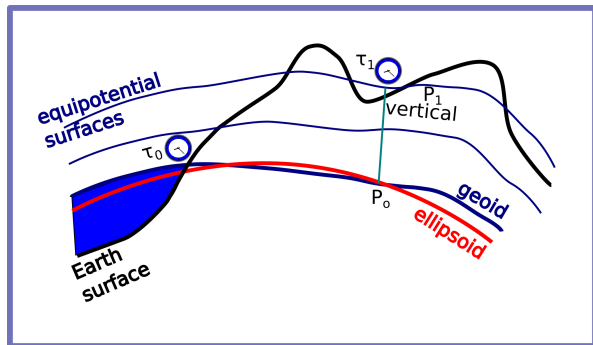
Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

Gravitational redshift - relativistic geodesy



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Atomic clocks and
spectroscopy
experiments

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KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

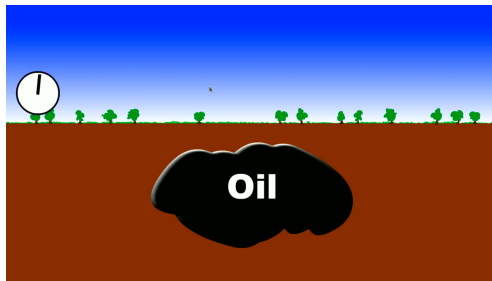
Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

Gravitational redshift - fossils fuel hunt



Courtesy of R. Bondarescu, M. Bondarescu and Media Team University of Zurich

Atomic clocks and
spectroscopy
experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

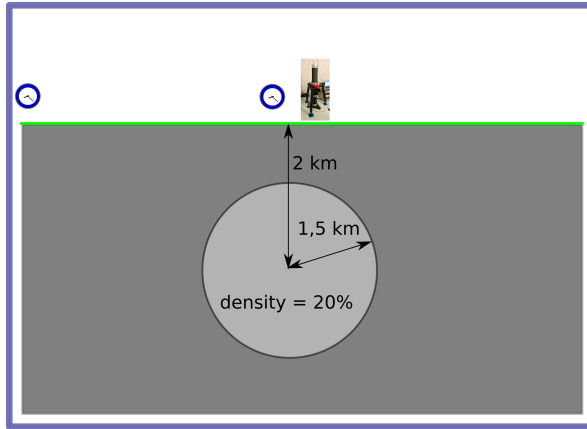
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Gravitational redshift - relativistic geodesy



R. Bondarescu *et. al.* Geophys. J. Int. **191**(1) 78 (2012)

Atomic clocks and
spectroscopy
experiments

Michał Zawada
KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

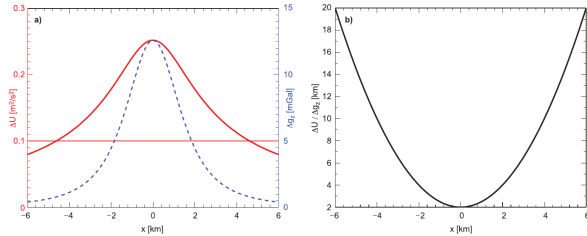
Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

Gravitational redshift - relativistic geodesy

Atomic clocks and
spectroscopy
experiments

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KL FAMO,
Nicolaus
Copernicus
University



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Time standards

Atomic fountains

Optical clocks

**Gravitational
potential**

Lorentz invariance

Dark matter

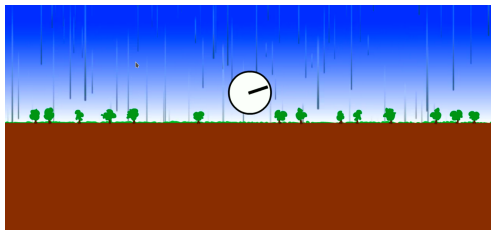
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Gravitational redshift - groundwater level



Atomic clocks and
spectroscopy
experiments

Michał Zawada
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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

**Gravitational
potential**

Lorentz invariance

Dark matter

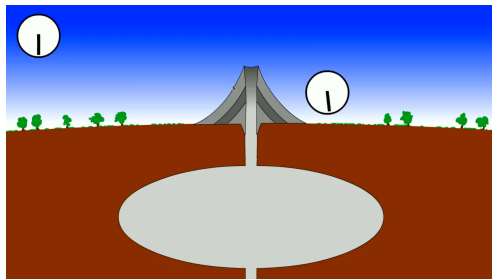
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Gravitational redshift - volcano eruption



Atomic clocks and
spectroscopy
experiments

Michał Zawada
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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

**Gravitational
potential**

Lorentz invariance

Dark matter

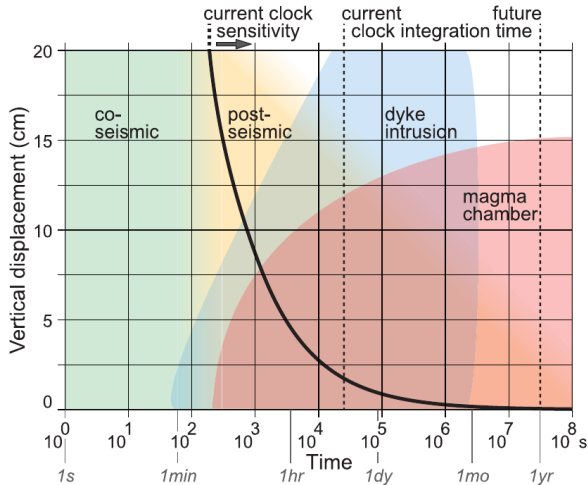
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Gravitational redshift - volcano eruption



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Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

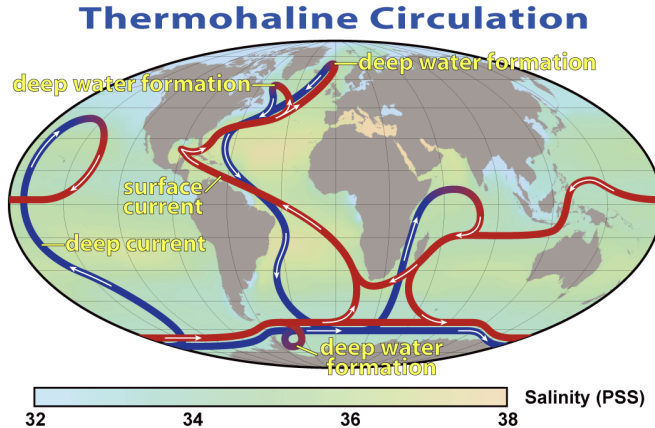
Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

Gravitational redshift - THC



NASA Earth Observatory

Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

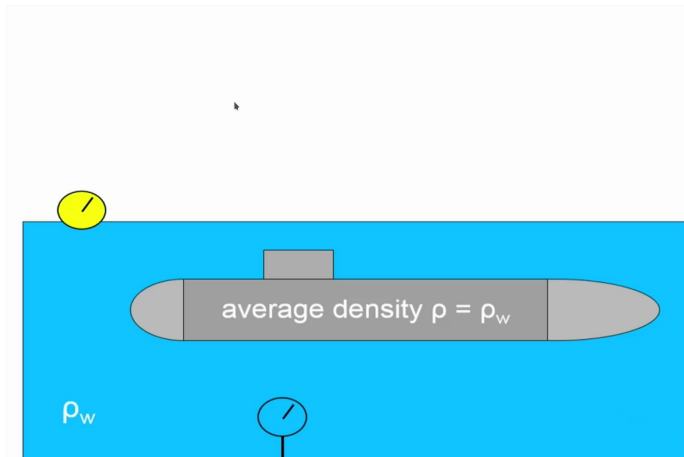
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Gravitational redshift - gravitational anomalies detection



M. Bober and M. Zawada, Proc. SPIE 10438, <https://doi.org/10.1117/12.2277402> (2017)

Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

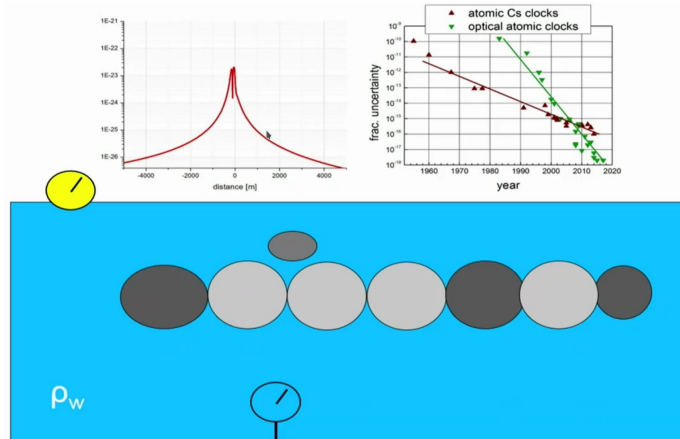
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Gravitational redshift - gravitational anomalies detection



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Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

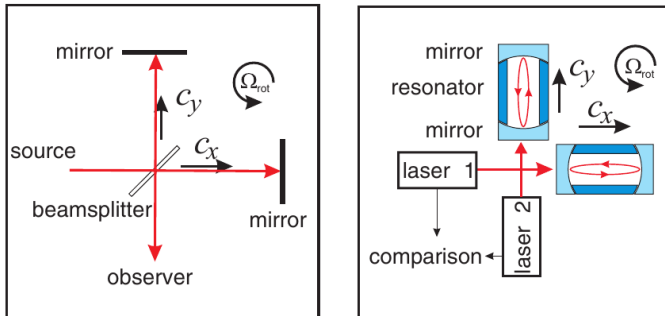
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Lorentz invariance



S. Herrmann *et al.*, Special Relativity. Lecture Notes in Physics, vol 702. Springer, Berlin, Heidelberg (2006)

Atomic clocks and
spectroscopy
experiments

Michał Zawada
KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

Clocks on GPS constellation

PHYSICAL REVIEW A

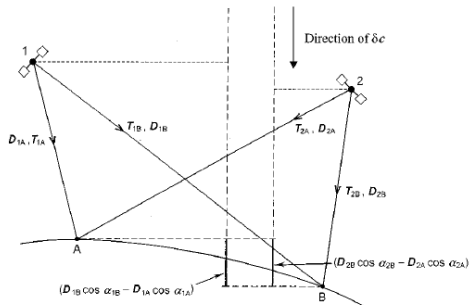
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Satellite test of special relativity using the global positioning system

Peter Wolf^{1,2} and Gérard Petit¹



Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

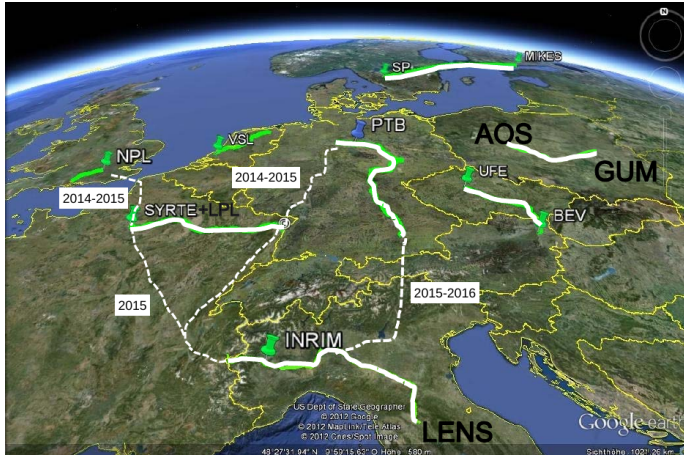
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

A clock network in Europe



Atomic clocks and
spectroscopy
experiments

Michał Zawada
KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

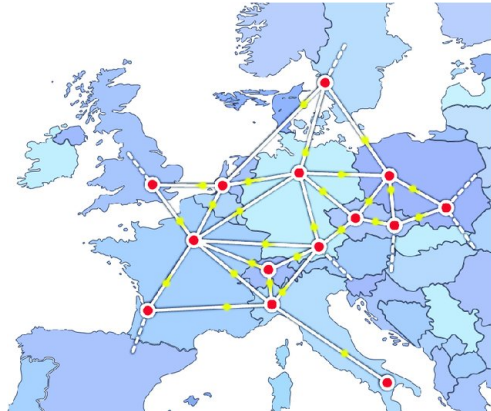
A clock network in Europe

19th International Congress of Metrology, 15001 (2019)

<https://doi.org/10.1051/metrology/201915001>

The TiFOON Project – Time and Frequency Over Optical Networks

Jochen Kronjaeger, TiFOON Project Coordinator,
Time and Frequency Department,
National Physical Laboratory, Teddington, Middlesex TW11 0LW, UK



Atomic clocks and
spectroscopy
experiments

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KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

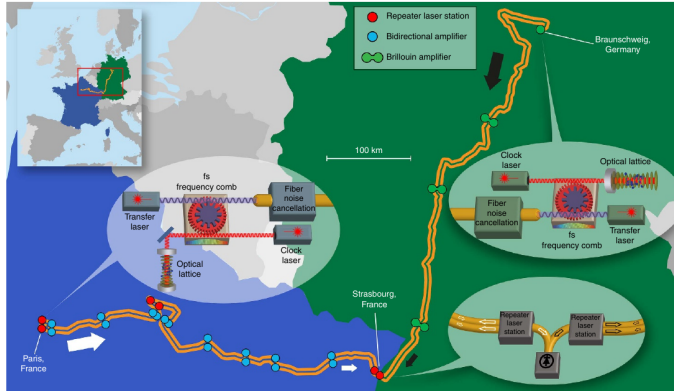
Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

A clock network in Europe - LI



C. Lisdat, *et al.* Nat. Comm. **7** 12443 (2016)
P. Delva, *et al.* Phys. Rev. Lett. **118** 221102 (2017)

Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

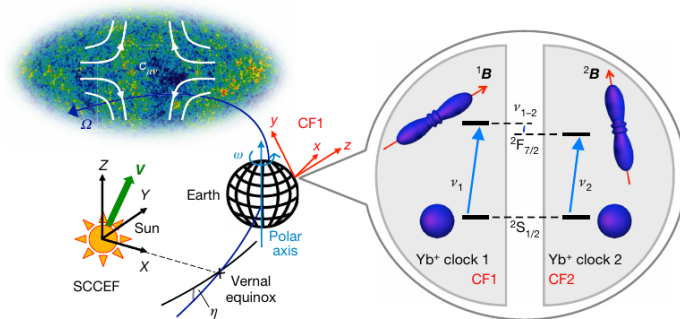
Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

A clock on moving Earth - LI



C. Sanner, *et al.* Nature **567** 204 (2019)

Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

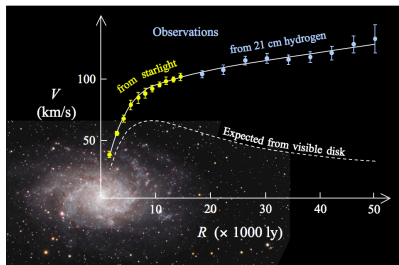
Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

The problem with dark matter



Picture from wikipedia by S. Deluca.

Data for the image are from Corbelli, E., and Salucci, P. (2000). *The extended rotation curve and the dark matter halo of M33*, MNRAS. 311 (2)

- Dark matter is non radiating, mostly non-barionic matter, which interacts very weakly with Standard Model matter.

Atomic clocks and spectroscopy experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains
Optical clocks

Gravitational potential

Lorentz invariance

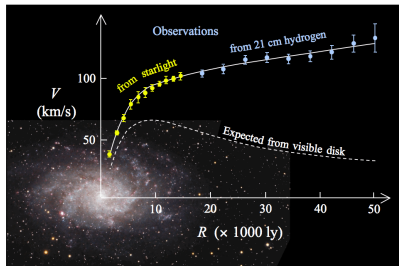
Dark matter

Coupling to SM

Ultralight Scalar DM detection
Topological defects detection

Higgs force in atoms

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- ▶ Dark matter is non radiating, mostly non-barionic matter, which interacts very weakly with Standard Model matter.
- ▶ Density of dark matter (DM) in our galactic neighbourhood (**observations of velocities of visible stars**):

$$\rho_{cDM}^{local} \approx 0.4 \text{ GeV}/\text{cm}^3$$

- ▶ Global dark matter density (**WAMP**):

$$\rho_{DM} = 1.3 \times 10^{-6} \text{ GeV}/\text{cm}^3$$

- ▶ Inside the Solar System (**planetary ephemerides-EPM2011**):

$$\rho_{DM}^{Solar} < 10^5 \text{ GeV}/\text{cm}^3$$

Atomic clocks and spectroscopy experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains
Optical clocks

Gravitational potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM detection
Topological defects detection

Higgs force in atoms

The problem with dark matter - range of masses

Atomic clocks and
spectroscopy
experiments

Michał Zawada
KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Working assumption - dark matter consists of particles

$$\rho_{DM} = m_{DM} * n_{DM}$$

The problem with dark matter - range of masses

Atomic clocks and
spectroscopy
experiments

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Working assumption - dark matter consists of particles

$$\rho_{DM} = m_{DM} * n_{DM}$$

The inverse halo size of smallest galaxies:

$$10^{-22} \text{eV} < m_{DM}$$

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

The problem with dark matter - range of masses

Atomic clocks and
spectroscopy
experiments

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Working assumption - dark matter consists of particles

$$\rho_{DM} = m_{DM} * n_{DM}$$

The inverse halo size of smallest galaxies:

$$10^{-22} \text{ eV} < m_{DM}$$

The particles will not form black holes:

$$m_{DM} < 10^{28} \text{ eV}$$

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

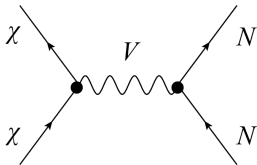
Higgs force in
atoms

The problem with dark matter – WIMP

The most widely accepted hypothesis:

WIMP = Weakly interacting massive particles

Direct detection - collisions with nuclei.



$$\mathcal{L}_{WIMP,eff} = \frac{e'_\chi e'_N}{4\pi} \frac{1}{M_V^2} (\bar{\chi} \gamma^\mu \chi) (\bar{N} \gamma_\mu N)$$

where $\bar{\chi} = \chi^\dagger \gamma^0$, and $\sigma_{scat} = (e'_\chi e'_N / M_V^2)^2$

Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

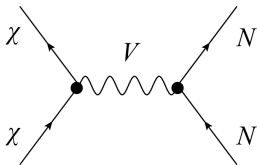
Higgs force in
atoms

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WIMP = Weakly interacting massive particles

Direct detection - collisions with nuclei.



$$\mathcal{L}_{WIMP,eff} = \frac{e'_\chi e'_N}{4\pi} \frac{1}{M_V^2} (\bar{\chi} \gamma^\mu \chi) (\bar{N} \gamma_\mu N)$$

where $\bar{\chi} = \chi^\dagger \gamma^0$, and $\sigma_{scat} = (e'_\chi e'_N / M_V^2)^2$

experimentally (LUX): $\sigma_{scat} < 10^{-45} \text{ cm}^2$!!!

Atomic clocks and
spectroscopy
experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

The problem with dark matter - broadening the scope of DM searches

Atomic clocks and spectroscopy experiments

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Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM detection

Topological defects detection

Higgs force in atoms

$$ToE \rightarrow \dots \rightarrow GUT \rightarrow \dots \rightarrow SU(3) \times SU(2) \times U(1)_Y \rightarrow SU(3) \times U(1)_{em}.$$

A scalar field

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experiments

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The most general form of self-interaction potential of a scalar field ϕ

$$V(\phi) = 2\frac{c^2}{\hbar^2} m_\phi^2 \phi^2 + \lambda \phi^4$$

- ▶ odd powers of ϕ field are ruled out because of symmetry $\phi \rightarrow -\phi$
- ▶ powers of ϕ^6 and higher are ruled out because of renormalisation condition

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

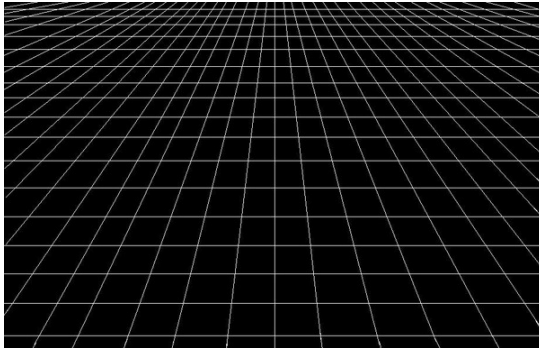
Topological defects
detection

Higgs force in
atoms

A massive scalar field

$$V(\phi) = 2\frac{c^2}{\hbar^2} m_\phi^2 \phi^2 + \lambda \phi^4$$

A coherently oscillating classical field $\phi \sim \phi_0 \cos(\omega t + \delta)$
with Compton frequency $\omega = \frac{m_\phi c^2}{\hbar} \rightarrow$ a valid DM candidate



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spectroscopy
experiments

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University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

A scalar field

$$V(\phi) = 2\frac{c^2}{\hbar^2}m_\phi^2\phi^2 + \lambda\phi^4$$

If $m_\phi^2 < 0$ then the second term yields a spontaneous symmetry breaking and creation of topological solitons, otherwise called topological defects.

PHYSICS REPORTS (Review Section of Physics Letters) 121, No. 5 (1985) 263–315.

COSMIC STRINGS AND DOMAIN WALLS

Alexander VILENKIN

Atomic clocks and
spectroscopy
experiments

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University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

Phase transitions in Space - a spontaneous symmetry breaking

Atomic clocks and
spectroscopy
experiments

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Example

Assume a field theory with a $G = U(1)$ group and a ϕ Higgs field with self-interaction potential $V(\phi)$:

$$V(\phi) = \frac{1}{2}\lambda(\phi^\dagger\phi - \eta^2)^2 = -\lambda\eta^2\phi^2 + \frac{1}{2}\lambda\phi^4 + \text{const},$$

where $\lambda > 1$ and ϕ field is complex.

$U(1)$ means a symmetry with respect of phase changes, $\phi \rightarrow e^{i\alpha}\phi$

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

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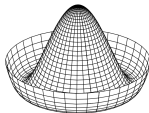
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$U(1)$ means a symmetry with respect of phase changes, $\phi \rightarrow e^{i\alpha}\phi$

The equation of motion of Lagrangian obey the symmetry.

Potential minima $V(\phi)$ (ground state of ϕ) are in non-zero values of ϕ , thus these solutions do not obey the symmetry, i.e.



the symmetry is spontaneously broken.

Atomic clocks and
spectroscopy
experiments

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University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

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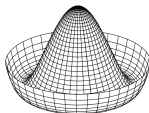
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the symmetry is spontaneously broken.

ϕ has non-zero expectation value $\langle\phi\rangle = \eta e^{i\theta}$, where only η is set by the model.

We have a manifold, M , of degenerate vacuum states corresponding to different choices of θ .

Atomic clocks and
spectroscopy
experiments

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University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

Phase transitions in Space - a spontaneous symmetry breaking

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where $\lambda > 1$ and ϕ field is complex.

$U(1)$ means a symmetry with respect of phase changes, $\phi \rightarrow e^{i\alpha}\phi$

Non-zero temperature adds additional terms to the potential:

$$V_T(\phi) = AT^2\phi^\dagger\phi + V(\phi).$$

The effective mass of the field ϕ in temperature T

$$m^2(T) = AT^2 - \lambda\eta^2$$

is equal to zero in the critical temperature $T_c = \eta\sqrt{\lambda/A}$.

Example

Assume a field theory with a $G = U(1)$ group and a ϕ Higgs field with self-interaction potential $V(\phi)$:

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is equal to zero in the critical temperature $T_c = \eta\sqrt{\lambda/A}$.

If $T > T_c$ then $m^2(T)$ is positive and the minimum of $V_T(\phi)$ is in $\phi = 0$.

The expectation value of ϕ vanishes and the symmetry is restored.

Time standards

Atomic fountains

Optical clocks

Gravitational potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects detection

Higgs force in atoms

Cosmic phase transitions

Atomic clocks and
spectroscopy
experiments

Michał Zawada
KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

What is happening as the universe cools through T_c ?

The field ϕ will tend to develop an expectation value $\langle\phi\rangle$ corresponding to some point in the manifold M .

Since all points in M are equivalent, the choice will depend on random fluctuations and will be different in different regions of space.

Cosmic phase transitions

Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

For the sake of simplicity let's take a real field ϕ and

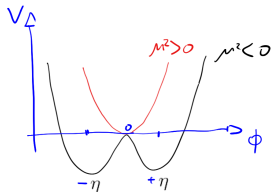
$$\mathcal{L} = \frac{1}{2} (\partial_\mu \phi)^2 - \frac{1}{2} \mu^2 \phi^2 - \frac{1}{4} \lambda \phi^4.$$

Cosmic phase transitions

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$$\mathcal{L} = \frac{1}{2} (\partial_\mu \phi)^2 - \frac{1}{2} \mu^2 \phi^2 - \frac{1}{4} \lambda \phi^4.$$

The symmetry is $Z_2 : \phi \rightarrow -\phi$, the minima of $V(\phi)$ are in $\phi = \pm \sqrt{\frac{-\mu^2}{\lambda}} \equiv \pm \eta$, and so manifold M consists of only two points.



Atomic clocks and
spectroscopy
experiments

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Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Atomic clocks and spectroscopy experiments

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Nicolaus
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University

Time standards

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Atomic fountains

Optical clocks

Gravitational potential

Lorentz invariance

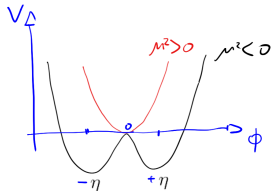
Dark matter

Coupling to SM

Ultralight Scalar DM detection

Topological defects detection

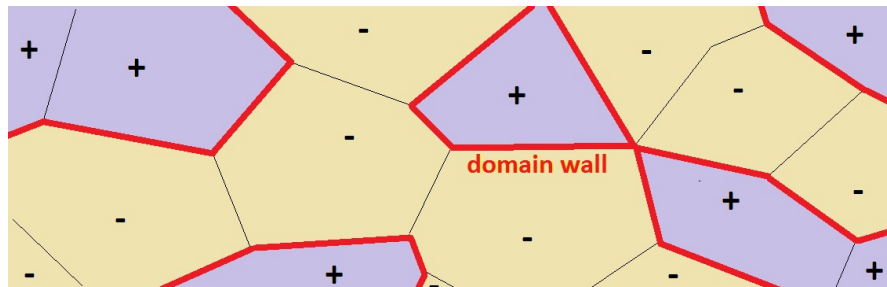
Higgs force in atoms



As we go from a region with $\langle\phi\rangle = +\eta$ to a region with $\langle\phi\rangle = -\eta$, we must pass through $\langle\phi\rangle = 0$, therefore these two regions are separated by a **domain wall** of false vacuum.

Cosmic phase transitions

After the phase transition $\langle \phi \rangle$ will be different in different regions of space.



Picture from MIT by Trung Van Phan

Size of domains is determined by the correlation length $\xi \sim T_C^{-1}$
and restricted by an event horizon - the Kibble-Zurek mechanism with speed c

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spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

Topological defects

Plethora of topological defects:

- ▶ Domain walls
- ▶ Strings
- ▶ Monopoles
- ▶ Monopoles connected by strings
- ▶ Walls bounded by strings
- ▶ ...

Topological defects **carry energy** and are comparable in size to the Compton wavelength $d \sim m^{-1}$ of vector and Higgs bosons of a given field → **another valid DM candidate**

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spectroscopy
experiments

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University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

A scalar field ϕ

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spectroscopy
experiments

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$$V(\phi) = 2\frac{c^2}{\hbar^2} m_\phi^2 \phi^2 + \lambda \phi^4$$

can couple to SM by different "portals", for instance:

$$\mathcal{L}_{scalar}^{lin} = \frac{\phi}{\Lambda_\gamma} \frac{\mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}}{4} - \sum_f \frac{\phi}{\Lambda_f} m_f \bar{f} f + \sum_V \frac{\phi}{\Lambda_V} \frac{M_V^2}{2} V_\nu V^\nu$$

$$\mathcal{L}_{scalar}^{quad} = \frac{\phi^2}{(\Lambda'_\gamma)^2} \frac{\mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}}{4} - \sum_f \frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f + \sum_V \frac{\phi^2}{(\Lambda'_V)^2} \frac{M_V^2}{2} V_\nu V^\nu$$

Λ_γ (Λ'_γ) and Λ_f (Λ'_f) are the energy scales of the respective linear (quadratic) couplings.

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Coupling to QED

$$\mathcal{L}_{QED} = i\hbar c \overline{\psi}_e \gamma^\mu D_\mu \psi_e - m_e c^2 \overline{\psi}_e \psi_e + \frac{1}{4\mu_0} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}$$

where m_e i ψ_e are mass and field of electron, respectively, $\alpha = \frac{\mu_0}{4\pi} \frac{e^2 c}{\hbar}$

Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Coupling to QED

Atomic clocks and
spectroscopy
experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

$$\mathcal{L}_{scalar,int}^{lin} = \frac{\phi}{\Lambda_\gamma} \frac{\mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}}{4} - \sum_f \frac{\phi}{\Lambda_f} m_f \bar{f} f \rightarrow \frac{\phi}{\Lambda_\gamma} \frac{\mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}}{4\mu_0} - \frac{\phi}{\Lambda_e} m_e c^2 \bar{\psi}_e \psi_e$$

$$\mathcal{L}_{scalar,int}^{quad} = \frac{\phi^2}{(\Lambda'_\gamma)^2} \frac{\mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}}{4} - \sum_f \frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f \rightarrow \frac{\phi^2}{(\Lambda'_\gamma)^2} \frac{\mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}}{4\mu_0} - \frac{\phi^2}{(\Lambda'_e)^2} m_e c^2 \bar{\psi}_e \psi_e$$

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where m_e i ψ_e are mass and field of electron, respectively, $\alpha = \frac{\mu_0}{4\pi} \frac{e^2 c}{\hbar}$

$$\alpha \rightarrow \frac{\alpha}{1 - \phi/\Lambda_\gamma} \simeq \alpha \left(1 + \frac{\phi}{\Lambda_\gamma} \right), \quad \frac{\delta m_e}{m_e} = \frac{\phi}{\Lambda_e}$$

$$\alpha \rightarrow \frac{\alpha}{1 - \phi^2/(\Lambda'_\gamma)^2} \simeq \alpha \left(1 + \frac{\phi^2}{(\Lambda'_\gamma)^2} \right), \quad \frac{\delta m_e}{m_e} = \frac{\phi^2}{(\Lambda'_e)^2}$$

Observed values of α and m_e will change because of coupling to ϕ

Effective α and m_e variations due to dark matter scalar fields

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spectroscopy
experiments

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Different forms of scalar fields ϕ yield different α and m_e variations:

- ▶ basic excitations of ϕ - oscillating field - α and m_e oscillate with field's Compton frequency,
- ▶ basic excitations of ϕ - oscillating field - slow drift of α and m_e (time average of $\langle\phi\rangle \sim \phi_0/2$),
- ▶ topological defects created in phase transitions in early Universe - transient-in-time variation of α and m_e .

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

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Atomic clocks and
spectroscopy
experiments

Michał Zawada
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Copernicus
University

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Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms

Effective α oscillations due to dark matter scalar fields

Two frequency references

- ▶ different locations

Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

**Ultralight Scalar DM
detection**

Topological defects
detection

Higgs force in
atoms

Effective α oscillations due to dark matter scalar fields

Two frequency references

- ▶ different locations
- ▶ different sensitivities

Atomic clocks and
spectroscopy
experiments

Michał Zawada
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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

**Ultralight Scalar DM
detection**

Topological defects
detection

Higgs force in
atoms

Effective α oscillations due to dark matter scalar fields

Two frequency references

- ▶ different locations
- ▶ different sensitivities

The electronic part of the Schrödinger equation within the Born-Oppenheimer approximation, in SI units, in dimensionless form, for n electrons and m nuclei:

$$\left(-\frac{1}{2} \sum_{i=1}^n \nabla_{x_i}^2 - \sum_{i,j=1}^{n,m} \frac{Z_j}{x_{ji}} + \frac{1}{2} \sum_{\substack{i,k=1 \\ i \neq k}}^{n,n} \frac{1}{x_{ik}} \right) \psi = \epsilon \psi,$$

where $\epsilon = E/E_h$ and $x_i = r_i/a_0$, with $E_h = \alpha^2 m_e c^2$ and $a_0 = \hbar/(m_e \alpha c)$.

Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

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where $\epsilon = E/E_h$ and $x_i = r_i/a_0$, with $E_h = \alpha^2 m_e c^2$ and $a_0 = \hbar/(m_e \alpha c)$.

$$E \propto \alpha^2 \qquad L \propto \alpha^{-1}$$

Magnetometry - two isotopes with different sign of sensitivity

PRL **115**, 011802 (2015)

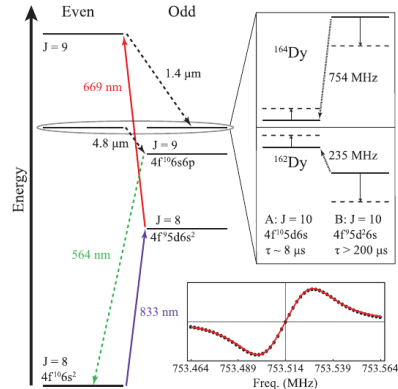
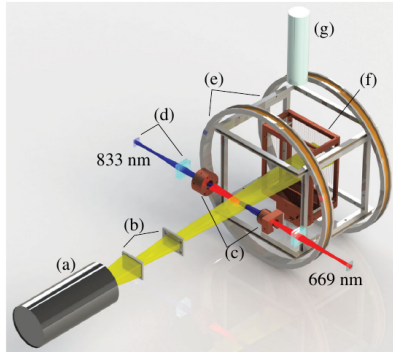
PHYSICAL REVIEW LETTERS

week ending
3 JULY 2015



Search for Ultralight Scalar Dark Matter with Atomic Spectroscopy

Ken Van Tilburg,^{1,*} Nathan Leefer,^{2,†} Lykourgos Bougas,^{2,‡} and Dmitry Budker^{2-4,§}



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spectroscopy
experiments

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KL FAMO,
Nicolaus
Copernicus
University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

**Ultralight Scalar DM
detection**

Topological defects
detection

Higgs force in
atoms

Magnetometry - two isotopes with different sign of sensitivity

PRL 115, 011802 (2015)

PHYSICAL REVIEW LETTERS

week ending
3 JULY 2015



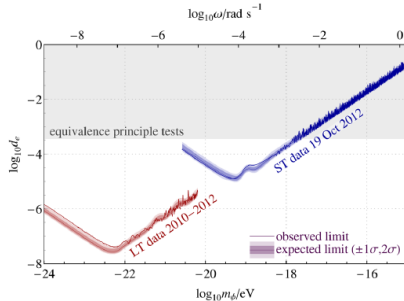
Search for Ultralight Scalar Dark Matter with Atomic Spectroscopy

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The strength of the linear coupling d_e is the inverse of the energy scale Λ_γ .

$$d_e = \frac{M_P c^2}{\sqrt{4\pi} \Lambda_{\gamma,1}}$$

where $M_P c^2 = 1.2 \times 10^{19}$ GeV is the Planck mass energy equivalent.



Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Atomic fountain - two species with different clock frequency

PRL 117, 061301 (2016)

PHYSICAL REVIEW LETTERS

week ending
5 AUGUST 2016

Searching for an Oscillating Massive Scalar Field as a Dark Matter Candidate Using Atomic Hyperfine Frequency Comparisons

A. Hees,^{1,2,*} J. Guéna,^{1,†} M. Abgrall,^{1,‡} S. Bize,^{1,§} and P. Wolf^{1,||}

Atomic clocks and
spectroscopy
experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

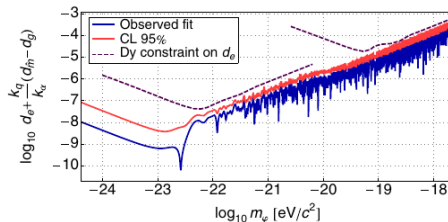
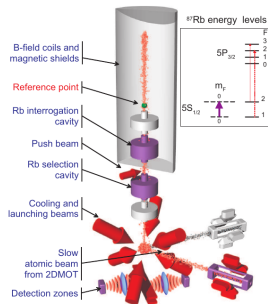
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

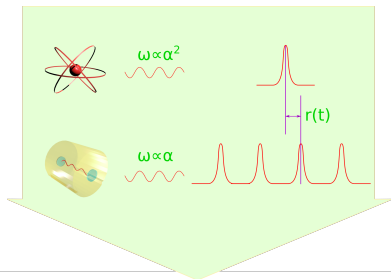
Higgs force in
atoms

II. THE FO2-RB ATOMIC FOUNTAIN

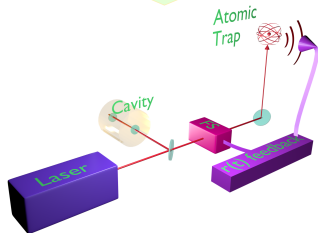


$$d_{\hat{m}} = \frac{d_{m_u} m_u + d_{m_d} m_d}{m_u + m_d}$$

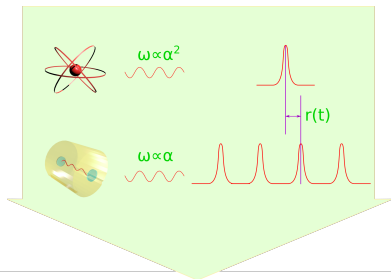
Optical atomic clock - two components with different sensitivity



- ▶ $E \propto \alpha^2 \Rightarrow \omega_0^{at} \propto \alpha^2$
with relativistic effects
 $E \propto \alpha^2 \Rightarrow \omega_0^{at} \propto \alpha^{(2+k_\alpha^{at})}$
- ▶ $L \propto \alpha^{-1}$
 $\Rightarrow \omega_0^{cav} = N_{cav}c/(2L) \propto \alpha^1$

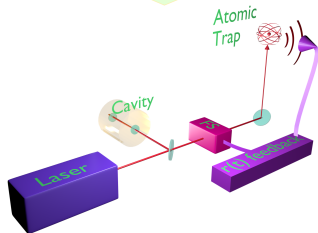


Optical atomic clock - two components with different sensitivity

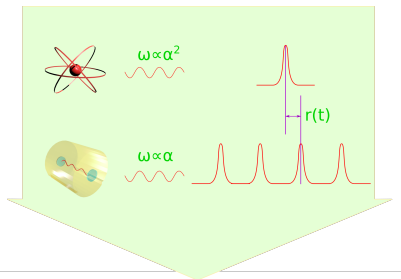


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$$\begin{aligned} d\omega_0 &= \omega_0(2 + k_\alpha^{at} - 1) \frac{d\alpha}{\alpha} \\ &= \omega_0(1 + k_\alpha^{at}) \frac{d\alpha}{\alpha} \\ &\equiv \omega_0 K_\alpha \frac{d\alpha}{\alpha} \end{aligned}$$

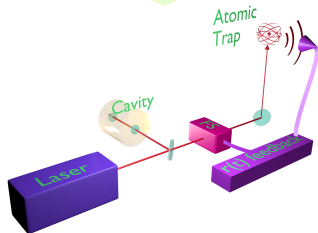


Optical atomic clock - two components with different sensitivity



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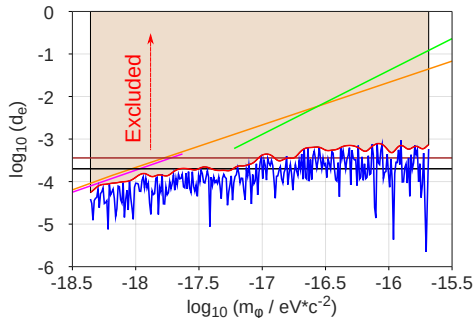
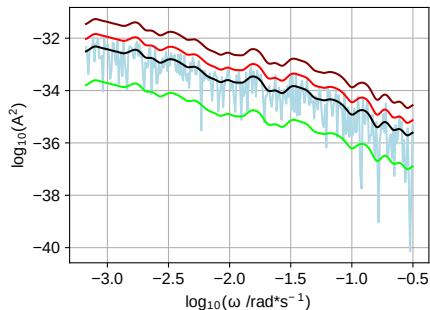
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The variations of α can be seen in the feedback signal $r(t)$

Optical atomic clock - two components with different sensitivity

For each frequency of the oscillation ω , i.e. for each mass m_ϕ , the $R(t) = B + A(\omega)\cos(\omega t + \delta)$ function is fitted to the normalised signals.



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

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experiments

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Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Transient-in-time variation of effective α

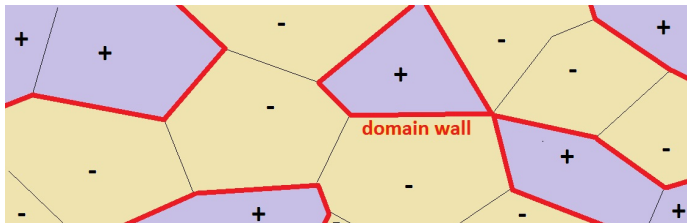
PHYSICS REPORTS (Review Section of Physics Letters) 121, No. 5 (1985) 263–315.

COSMIC STRINGS AND DOMAIN WALLS

Alexander VILENKIN

$$V(\phi) = 2\frac{c^2}{\hbar^2} m_\phi^2 \phi^2 + \lambda \phi^4$$

where $m_\phi^2 < 0$



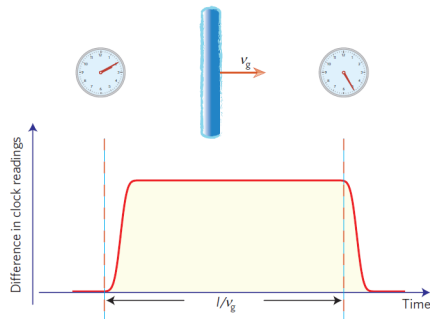
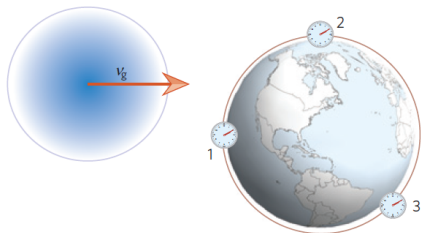
Transient-in-time variation of effective α

Nature Physics **10**, 933–936 (2014)

Hunting for topological dark matter with atomic clocks

A. Derevianko and M. Pospelov

$$\frac{d\omega_0}{\omega_0} = k_\alpha \frac{d\alpha}{\alpha}$$



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experiments

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Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

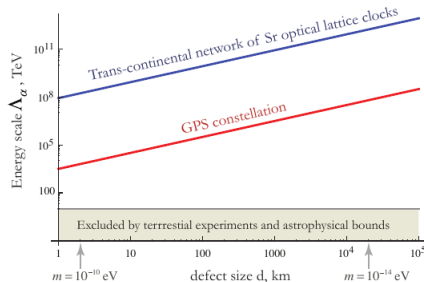
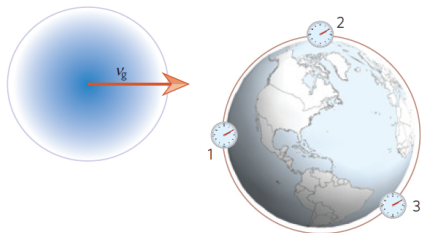
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Atomic fountains

Optical clocks

Gravitational potential

Lorentz invariance

Dark matter

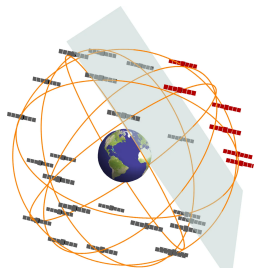
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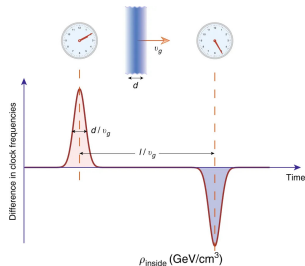
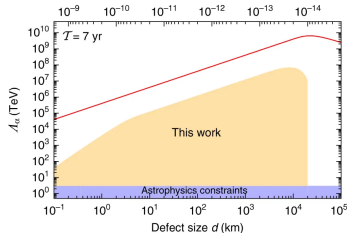
Topological defects
detection

Higgs force in
atoms

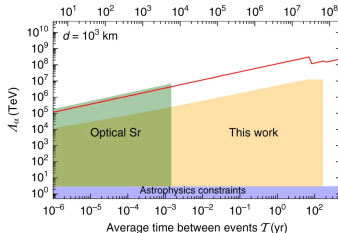
Microwave clocks on GPS constellation



Field mass m_ϕ (eV/c²)



ρ_{inside} (GeV/cm³)



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Time standards

Atomic fountains

Optical clocks

Gravitational potential

Lorentz invariance

Dark matter

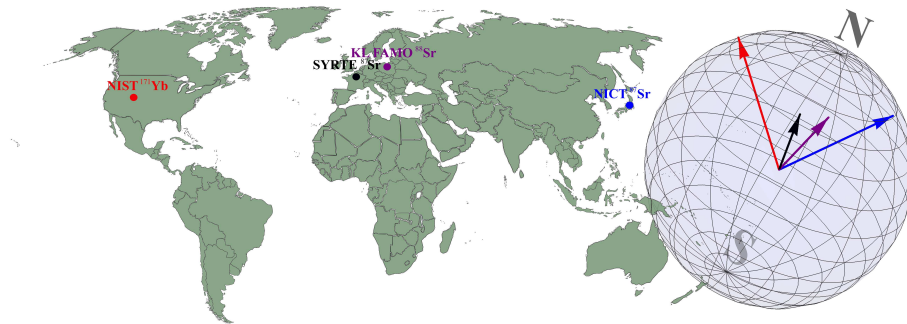
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Ultralight Scalar DM detection

Topological defects detection

Higgs force in atoms

Intercontinental network of optical atomic clocks.



The readouts of the distant clocks do not need to be correlated in real time. Just as in the standard radio-astronomical technique, very-long-baseline interferometry, they can be locally recorded (with time stamps that are accurate to the level of 1 ms) and cross-correlated later.

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experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

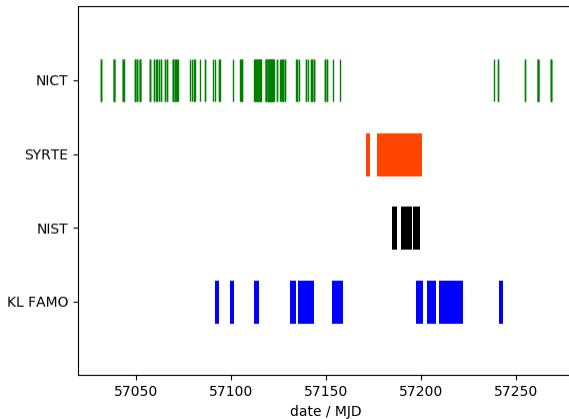
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Observation campaign made from archival data



Observation sessions spanning Jan. 2015 to Dec. 2015.

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experiments

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Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

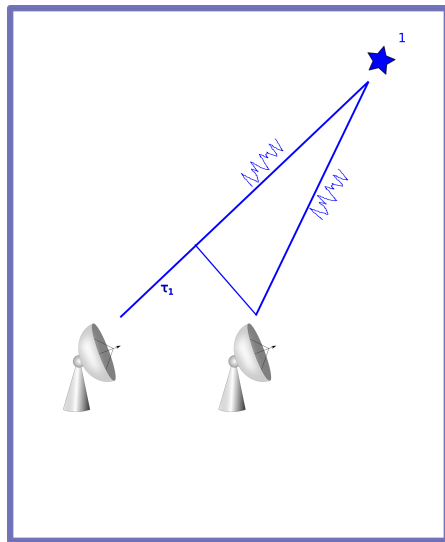
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Supplement - how the correlation in VLBI works?



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spectroscopy
experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

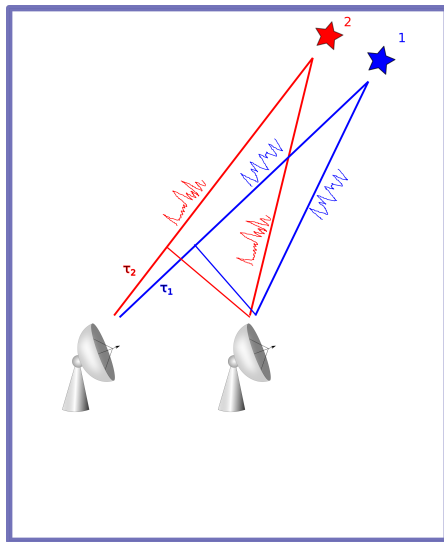
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

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Atomic clocks and
spectroscopy
experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

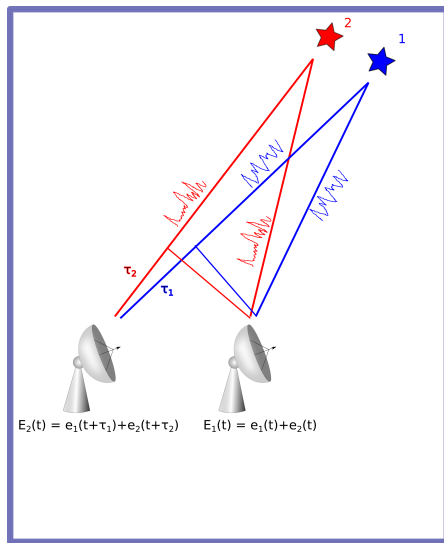
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

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spectroscopy
experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

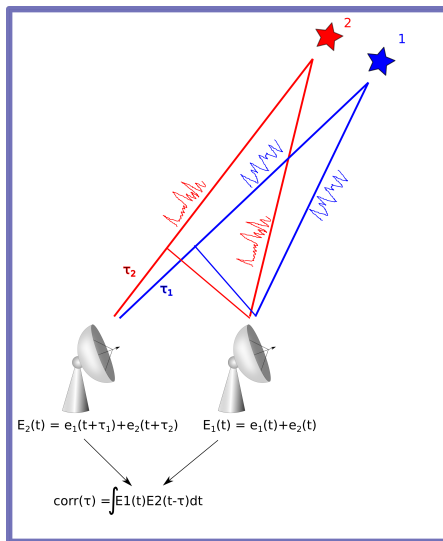
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Supplement - how the correlation in VLBI works?



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spectroscopy
experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

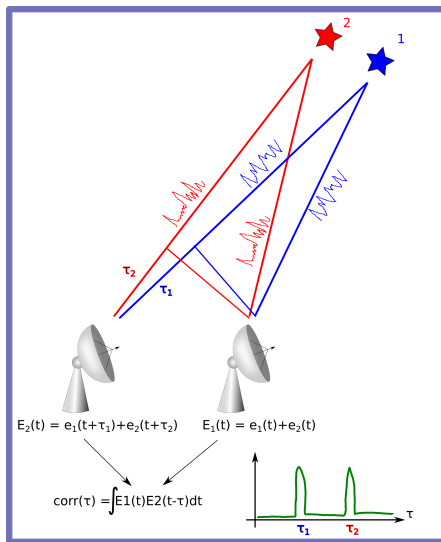
Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

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spectroscopy
experiments

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University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

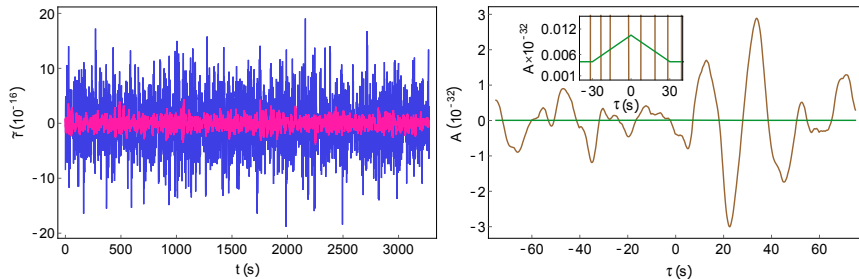
Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

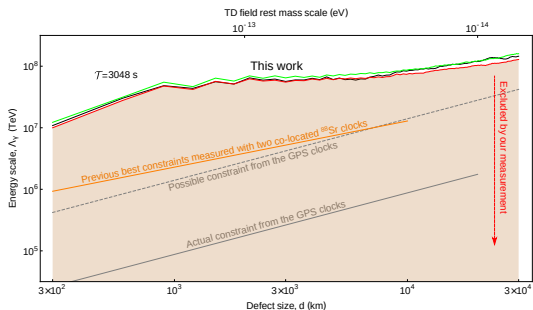
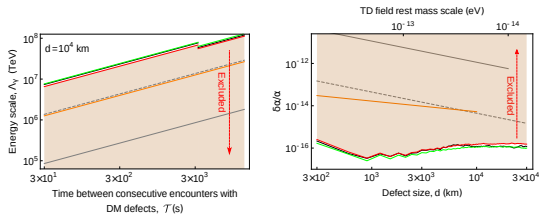
Topological defects

The transient effect can be detected by cross-correlating the pairs of feedbacks $r_i(t)$ recorded in the network of worldwide dispersed clocks.



The expected cross-correlation shape is fitted to cross-correlated data.

Topological defects



The topological defect size comparable to the size of the Earth (10,000 km) \Rightarrow
 $\delta\alpha/\alpha < 1.6 \times 10^{-16}$.

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Time standards

Atomic fountains
 Optical clocks

Gravitational potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM detection

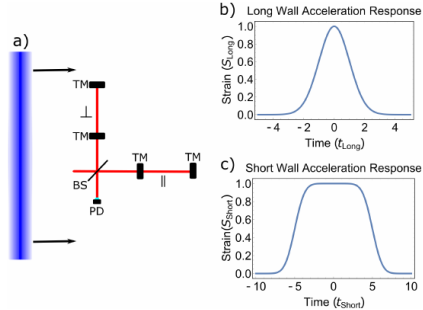
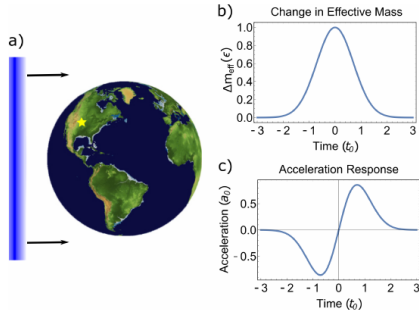
Topological defects detection

Higgs force in atoms

Coupling to SM mass

Constraining domain wall dark matter with a network of superconducting gravimeters and LIGO

Rees L. McNally  and Tanya Zelevinsky



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spectroscopy
experiments

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Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

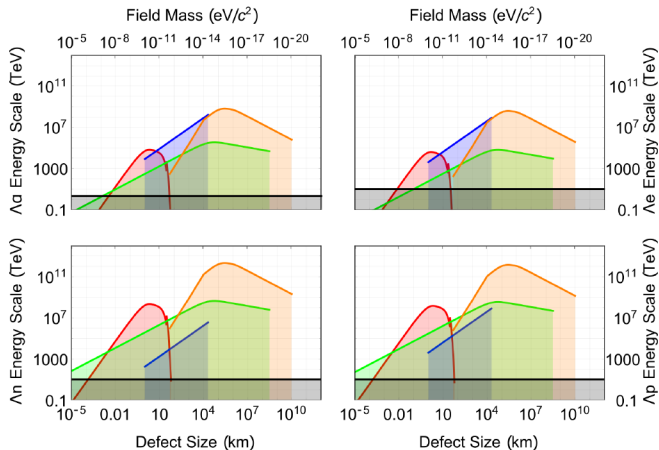
Topological defects
detection

Higgs force in
atoms

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spectroscopy
experiments

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University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Search for New Physics with Atoms and Molecules

M.S. Safronova^{1,2}, D. Budker^{3,4,5}, D. DeMille⁶, Derek F. Jackson Kimball⁷, A. Derevianko⁸ and Charles W. Clark²

Spin	Type	Operator	Interaction	DM effects	Searches
0	scalar	$\varphi h^\dagger h, \phi^n \mathcal{O}_{\text{SM}}$	Higgs portal / dilaton	fund.-constant variation	Atomic clocks, GPS, DM
		$a G^{\mu\nu} \tilde{G}_{\mu\nu}$	axion-QCD	nucleon EDM	CASPER-Electric
	pseudo-scalar	$a F^{\mu\nu} \tilde{F}_{\mu\nu}$	axion-E&M	EMF along B field	ADMX, CULTASK, MADMAX
		$(\partial_\mu a) \bar{\psi} \gamma^\mu \gamma_5 \psi$	axion-fermion	spin torque	CASPER-Wind, GNOME, QUAX
1	vector	$F'_{\mu\nu} F^{\mu\nu}$	vector-photon mixing	EMF in vacuum	DM Radio, ADMX
		$F'_{\mu\nu} \bar{\psi} \sigma^{\mu\nu} \psi$	dipole operator	spin torque	CASPER-Wind
	axial-vector	$A'_\mu \bar{\psi} \gamma^\mu \gamma_5 \psi$	minimally coupled	spin torque	CASPER-Wind

Time standards

Atomic fountains

Optical clocks

Gravitational potential

Lorentz invariance

Dark matter

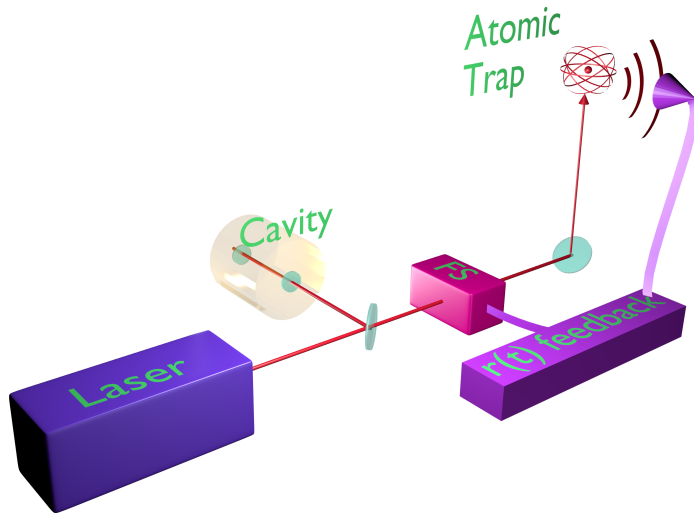
Coupling to SM

Ultralight Scalar DM detection

Topological defects detection

Higgs force in atoms

Passive optical atomic clock



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experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

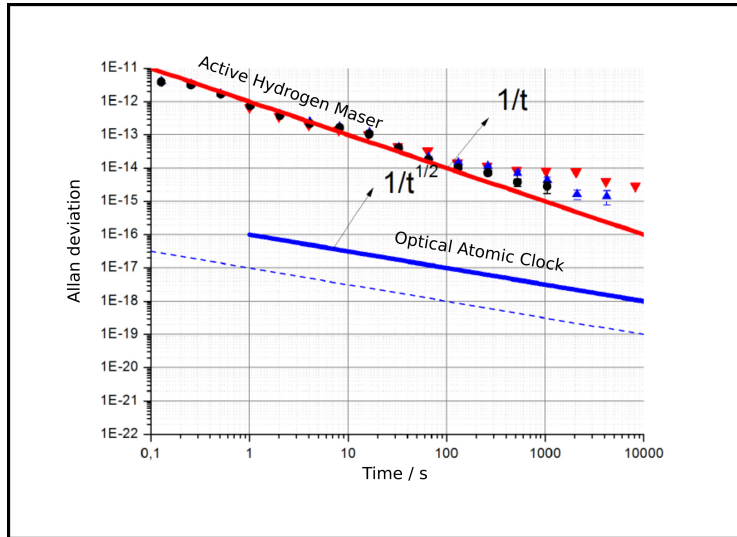
Coupling to SM

Ultralight Scalar DM
detection

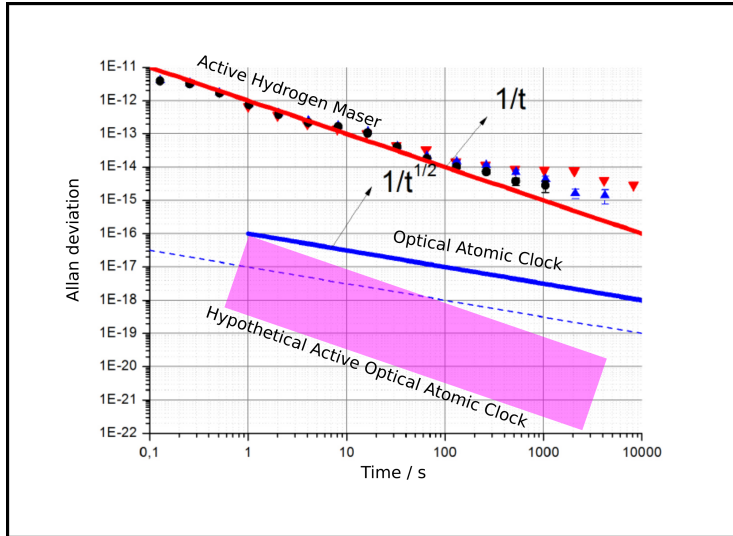
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Higgs force in
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Passive vs active atomic clock



Passive vs active atomic clock



Passive vs active atomic clock



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Time standards

Atomic fountains

Optical clocks

Gravitational potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM detection

Topological defects detection

Higgs force in atoms

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Atomic clocks and
spectroscopy
experiments

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Nicolaus
Copernicus
University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

**Higgs force in
atoms**

What is the origin of electron, and up and down quarks masses?

The Higgs coupling form SM:

$$y_e^{SM}(m_h) \approx 2.0 \times 10^{-6}, y_u^{SM}(m_h) \approx 5.4 \times 10^{-6}, y_d^{SM}(m_h) \approx 1.1 \times 10^{-6},$$

Higgs force in atoms

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spectroscopy
experiments

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Indirect LHC bounds (from Higgs decay, status as of 2015)

$$y_e < 1.3 \times 10^{-3}, y_{u,d} < 1.3 \times 10^{-2}$$

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Higgs-mediated force in atoms

Atomic clocks and
spectroscopy
experiments

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PHYSICAL REVIEW D **96**, 093001 (2017)

Probing atomic Higgs-like forces at the precision frontier

Cédric Delaunay,^{1,*} Roei Ozeri,^{2,†} Gilad Perez,^{3,‡} and Yotam Soreq^{4,§}

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
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Higgs boson exchange between a nucleus of mass number A and one of its bound electrons induces an attractive potential of Yukawa type:

$$V_{Higgs}(r) = -\frac{y_e y_A}{4\pi} \frac{e^{-rm_h}}{r}$$

Higgs force - attractive, the higher l state, the less is affected

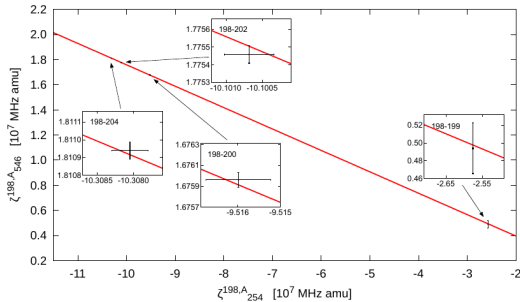
$$\delta E_{nlm}^{Higgs} = \langle nlm | V_{Higgs} | nlm \rangle \approx -\frac{y_e y_A}{4\pi m_h^2} |\phi(0)|^2 \frac{\delta l, 0}{n^3}$$

How to measure the Higgs force? Change the total mass not changing the total charge.

Kings plot

W. H. King, Isotope Shifts in Atomic Spectra (Springer, 1984).

$$\delta\nu_i^{A'A} = \frac{A' - A}{AA} MS_i + \delta\langle r^2 \rangle^{A'A} E_i$$



M. Witkowski et. al. Opt. Express 27 11069 (2019)

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spectroscopy
experiments

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Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

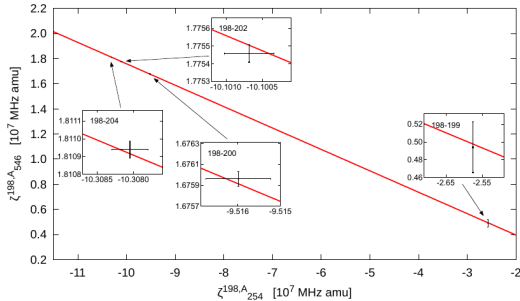
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detection

Higgs force in
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M. Witkowski et. al. Opt. Express 27 11069 (2019) The Higgs give non-linear contributions

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spectroscopy
experiments

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University

Time standards

Atomic fountains

Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection

Topological defects
detection

Higgs force in
atoms

Thank you for your attention!



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spectroscopy
experiments

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Copernicus
University

Time standards

Atomic fountains
Optical clocks

Gravitational
potential

Lorentz invariance

Dark matter

Coupling to SM

Ultralight Scalar DM
detection
Topological defects
detection

Higgs force in
atoms