QUANTUM SCIENCE SEMINAR 2020

thorium nuclear clock

https://thoriumclock.eu/

Q-SEnSE

An NSF Quantum Leap Challenge Institute

https://www.colorado.edu/research/qsense/

Dark Matter Searches with Atomic and Nuclear Clocks

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NSF

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

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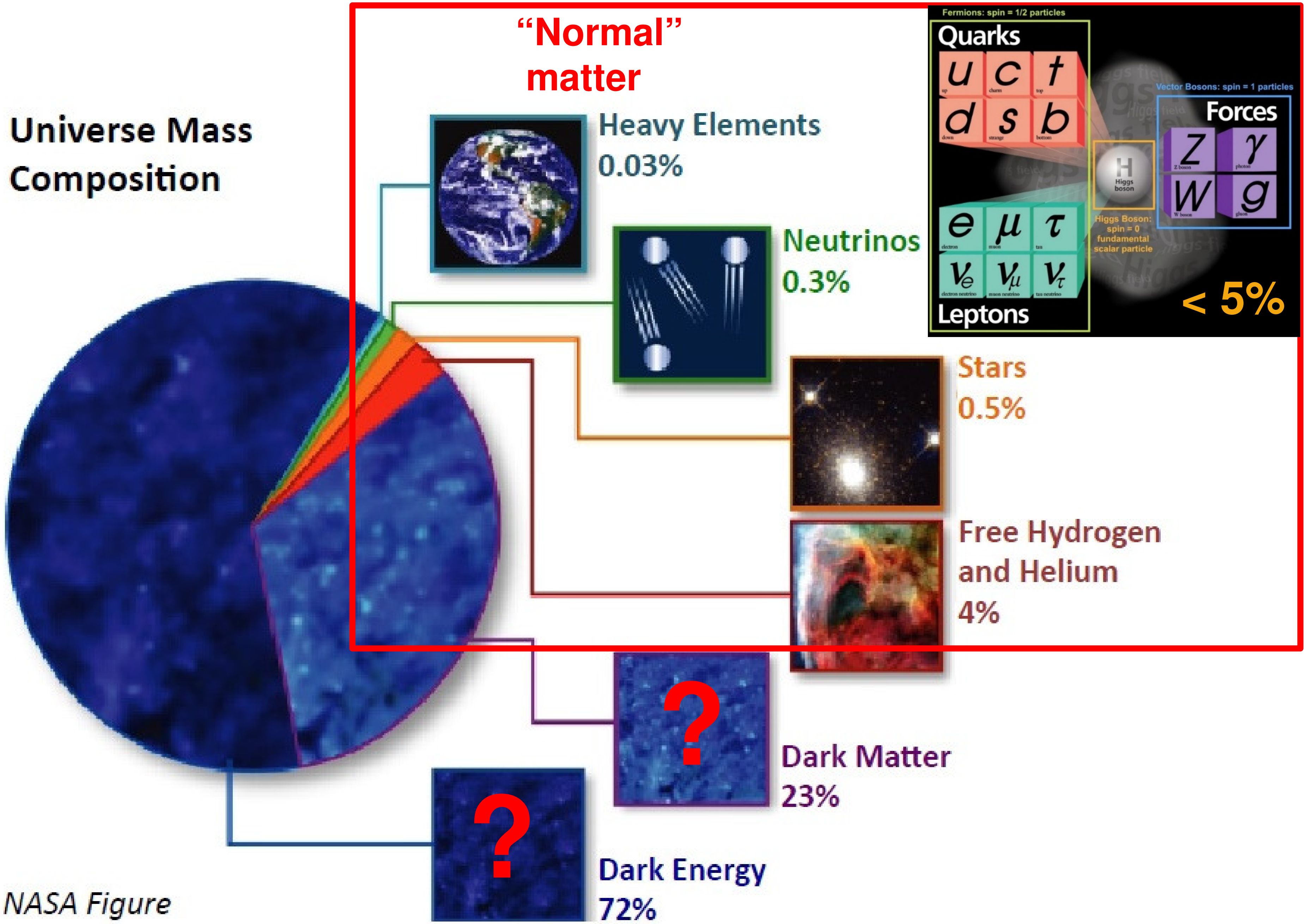
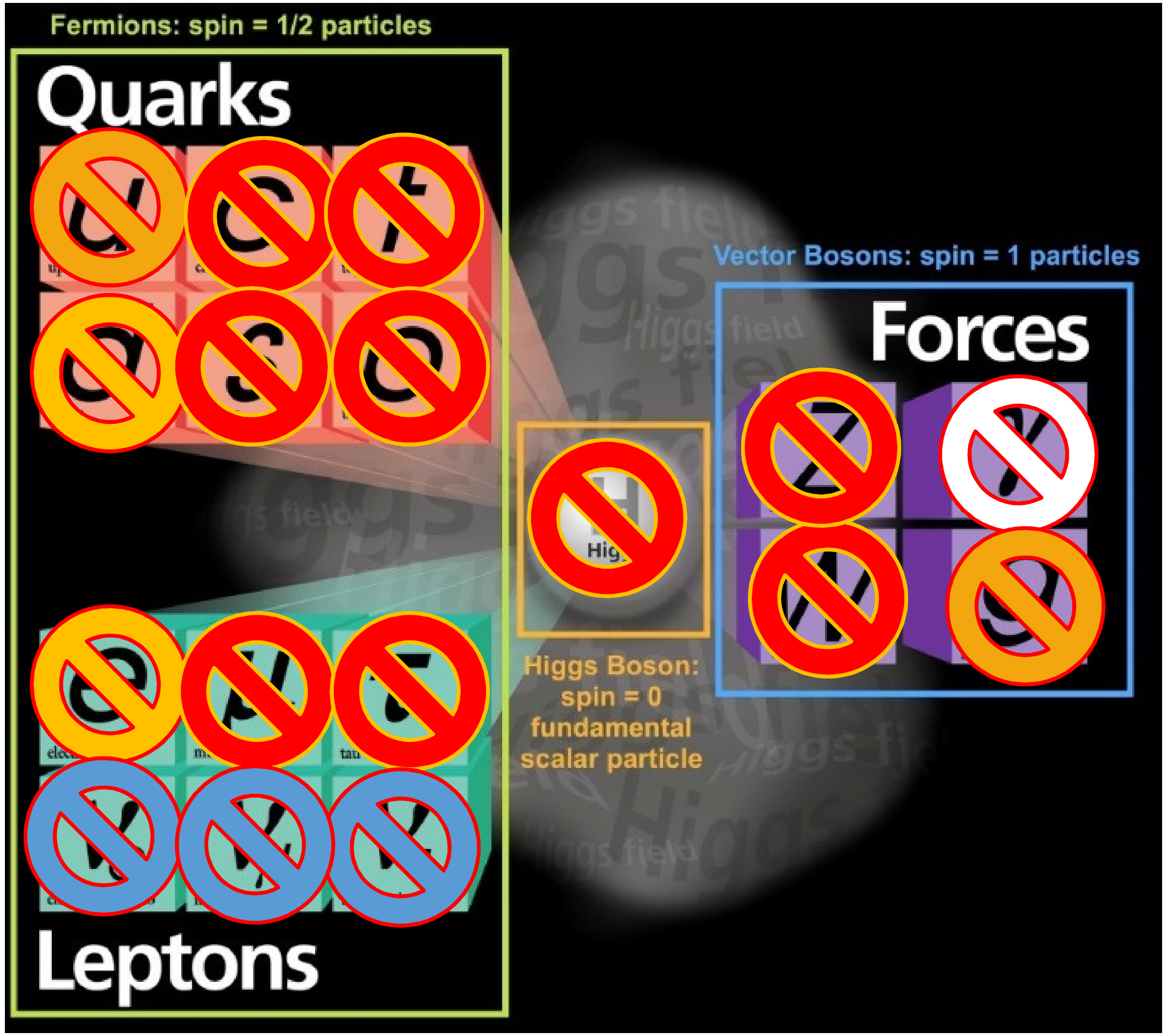
We don't know what most (95%) of the Universe is!



Could elementary particles be cold dark matter?



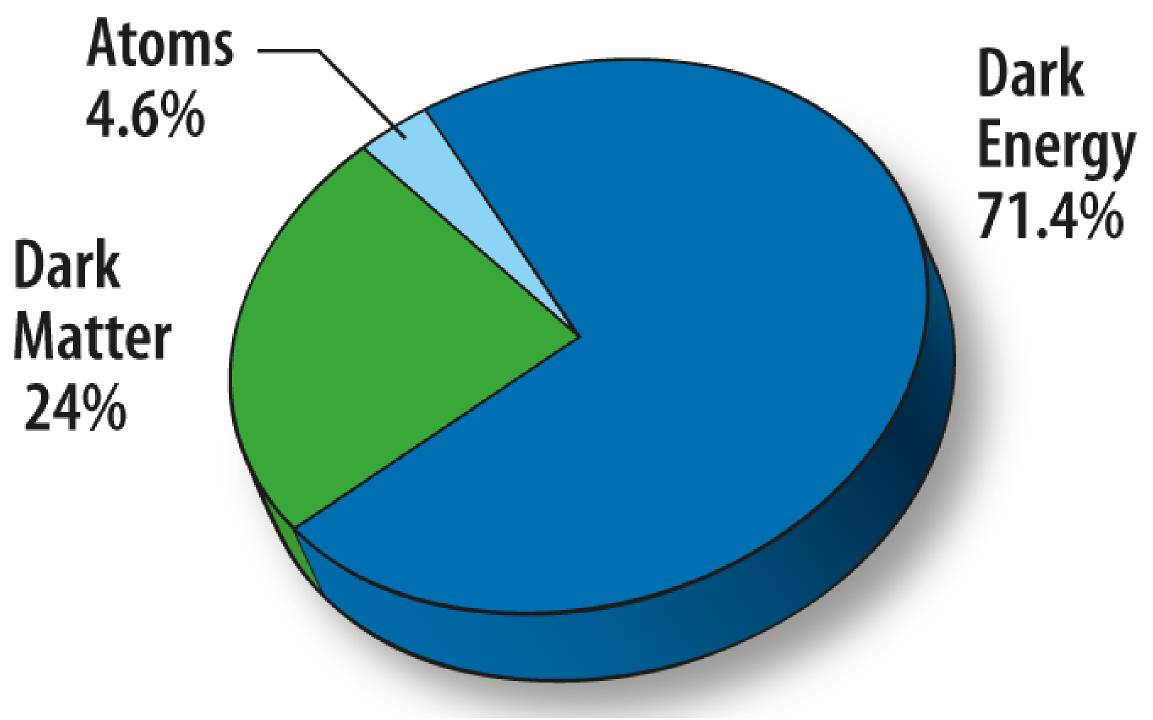
- Particle of light
- Couple to plasma
- Decay quickly
- Hot dark matter

No known particle can be cold dark matter – Need to search for new particles.

Beyond the standard matter (BSM) searches and dark matter/dark sector

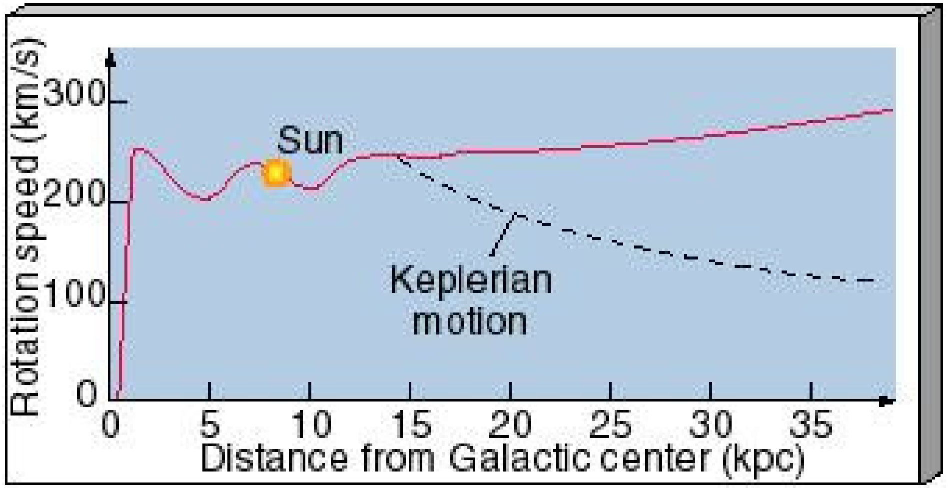
- Many theories beyond the standard model predict new particles or interactions.
- Proposed solutions of fundamental physics problems (matter-antimatter asymmetry, hierarchy problem, strong-CP problem, ..) involve new particles.
- Violations of fundamental symmetries and variations of fundamental constants are sourced by new particles/fields.
- These new particles may contribute significantly to dark matter or they may not.
- Existence of dark matter is confirmed by numerous observations and is definitive “new physics” to find. We know how much dark matter there have to be in our Galaxy.
- Therefore, most of BSM searches are related to dark matter/dark sector searches.

Atomic and Nuclear Clocks as Dark Matter Detectors



How do we know that dark matter exists?

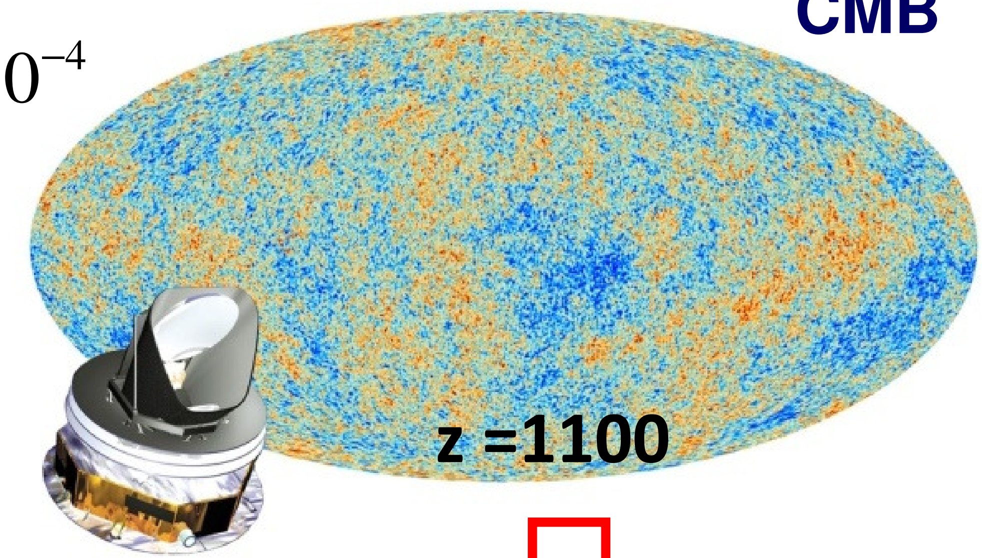
What is the experimental evidence for dark matter?



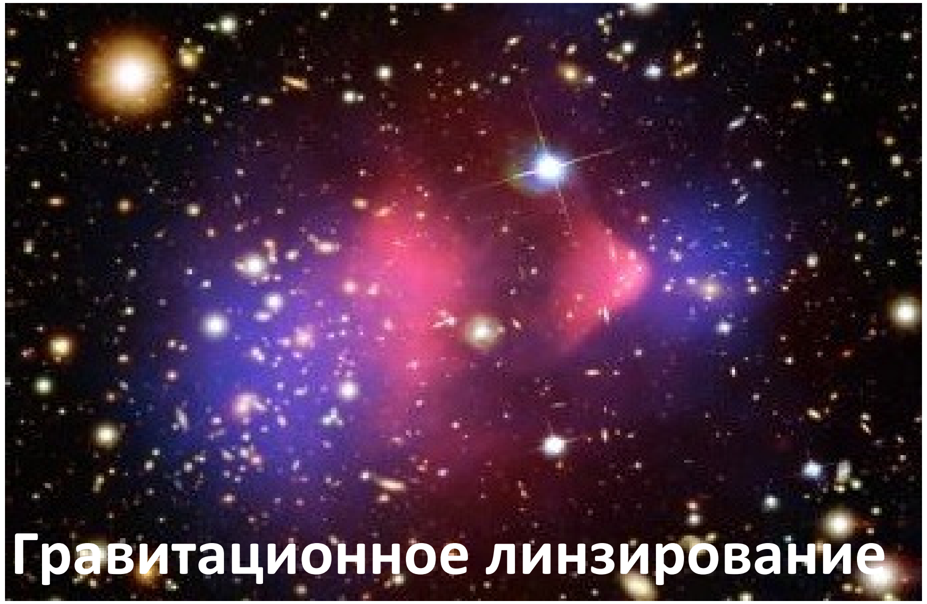
Кривые вращения галактик

$$\frac{\delta\rho}{\rho} \approx 10^{-4}$$

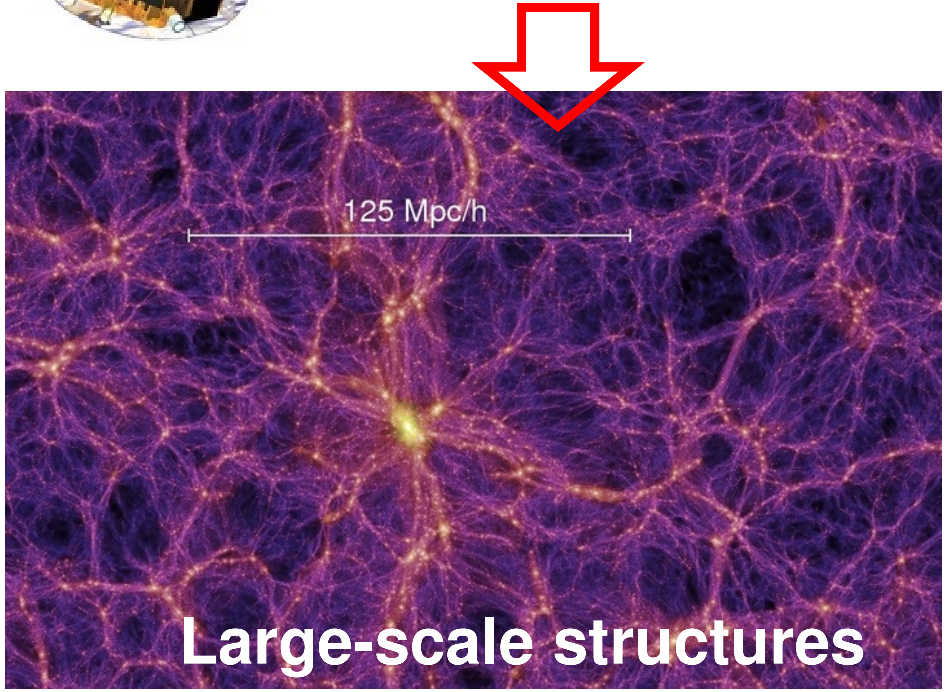
CMB



z =1100



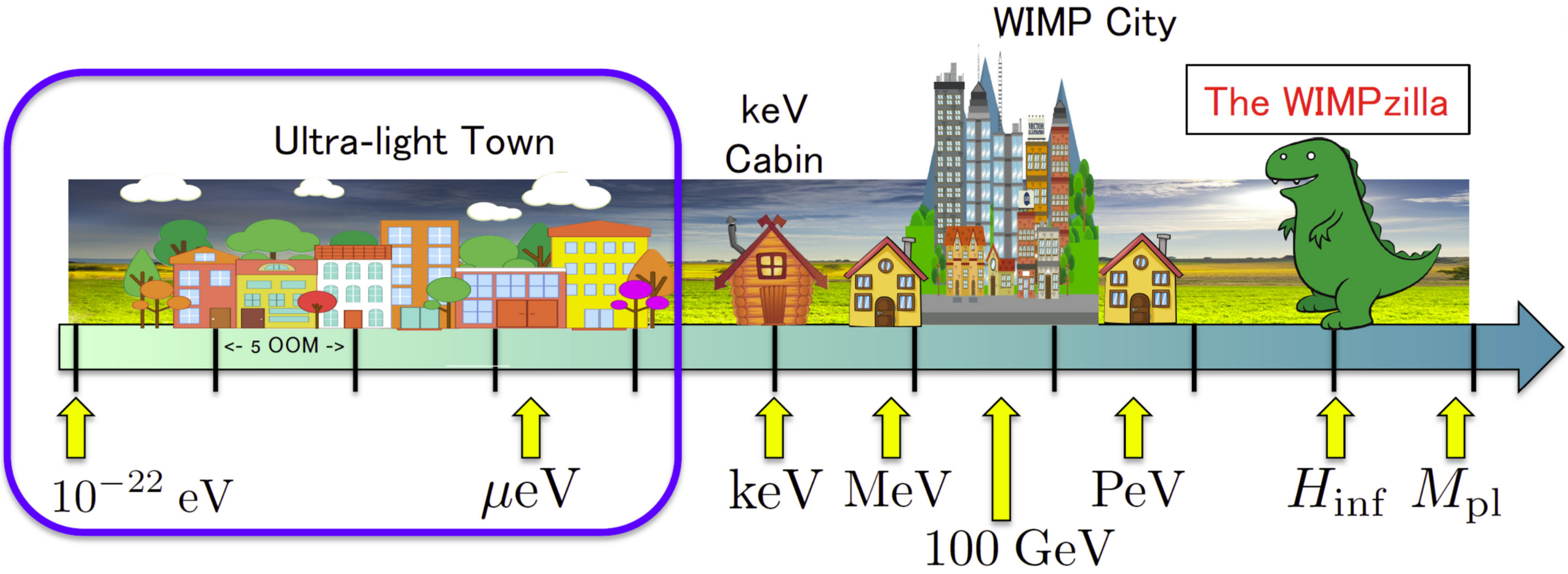
Гравитационное линзирование

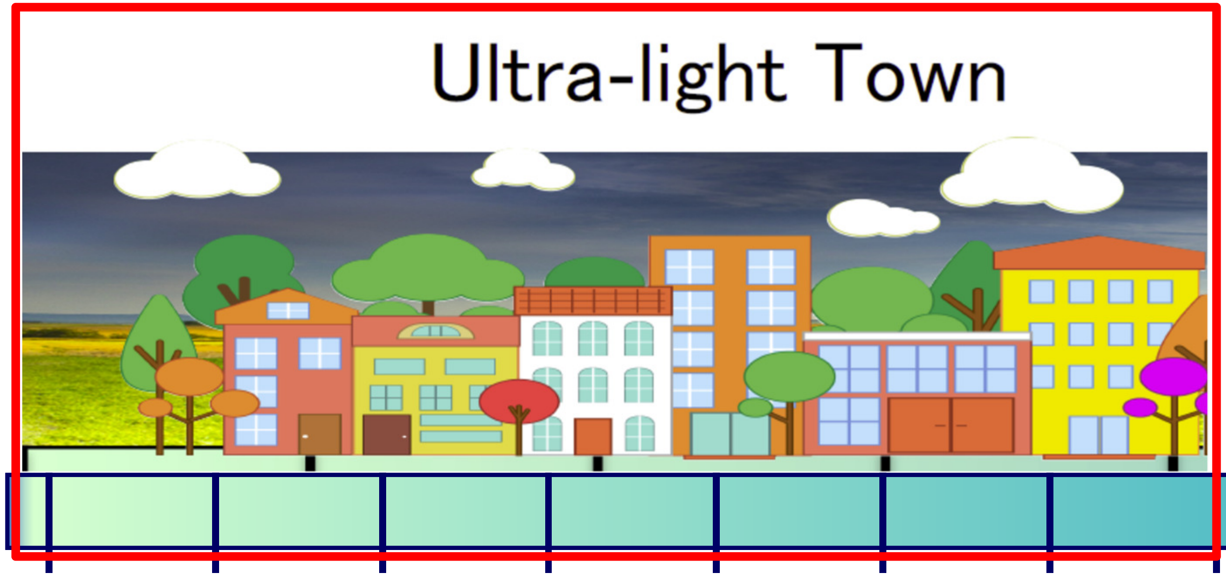


Large-scale structures

Slide from Andrew Long's 2018 LDW talk

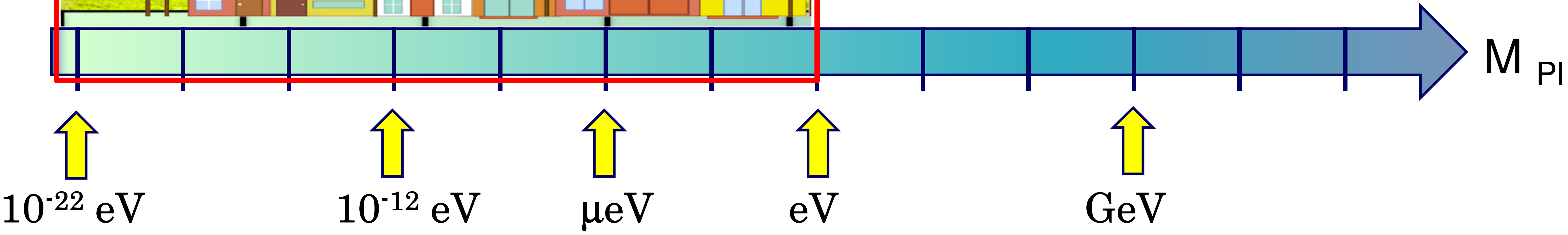
The landscape of dark matter masses





We do not know what dark matter particle mass is.

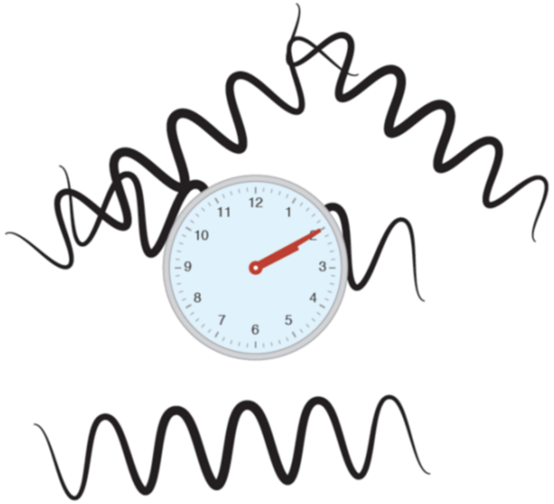
Ultralight dark matter has to be bosonic – Fermi velocity for DM with mass >10 eV is higher than our Galaxy escape velocity.



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

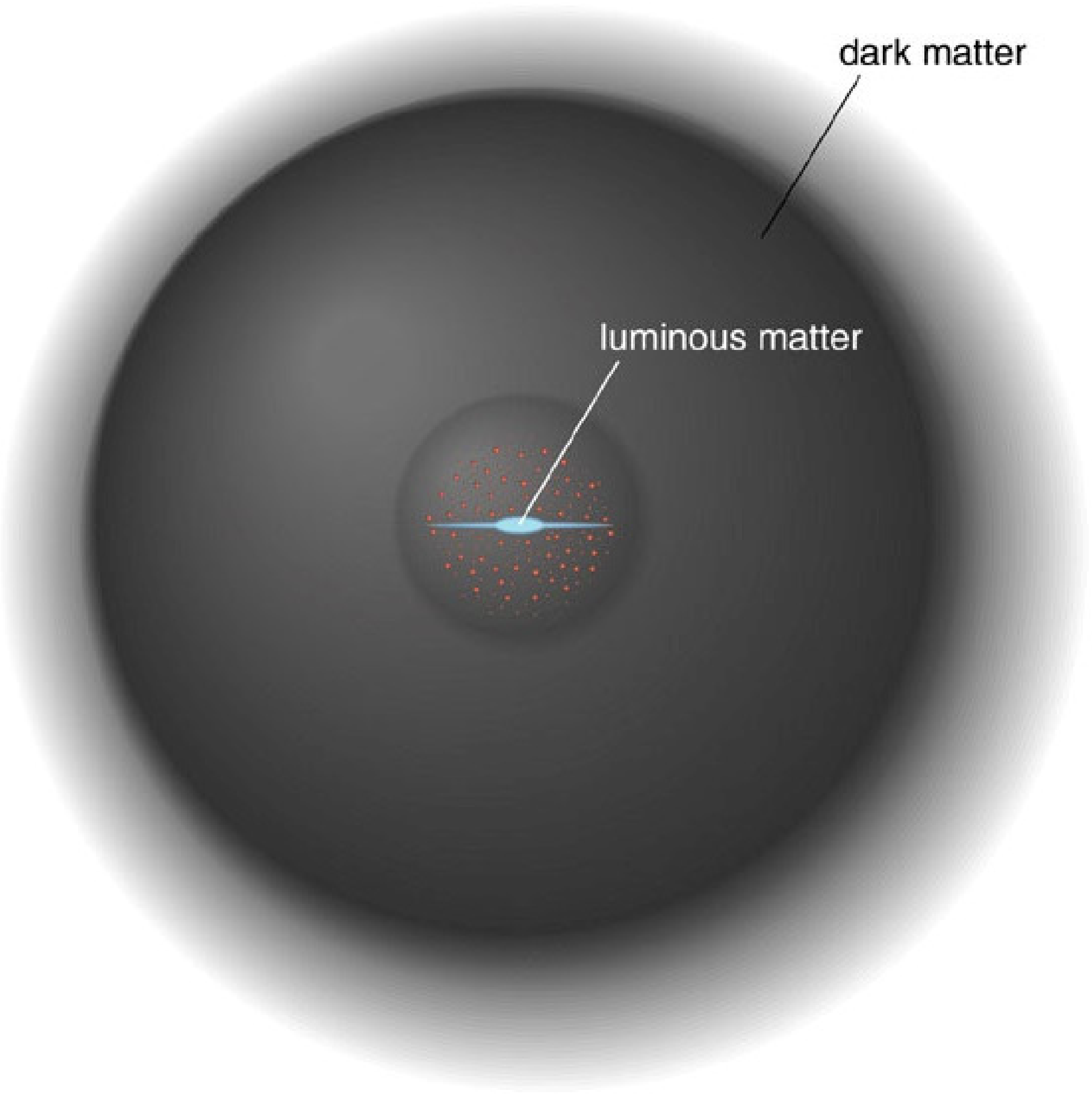
λ_{dB} is the de Broglie wavelength of the particle.

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

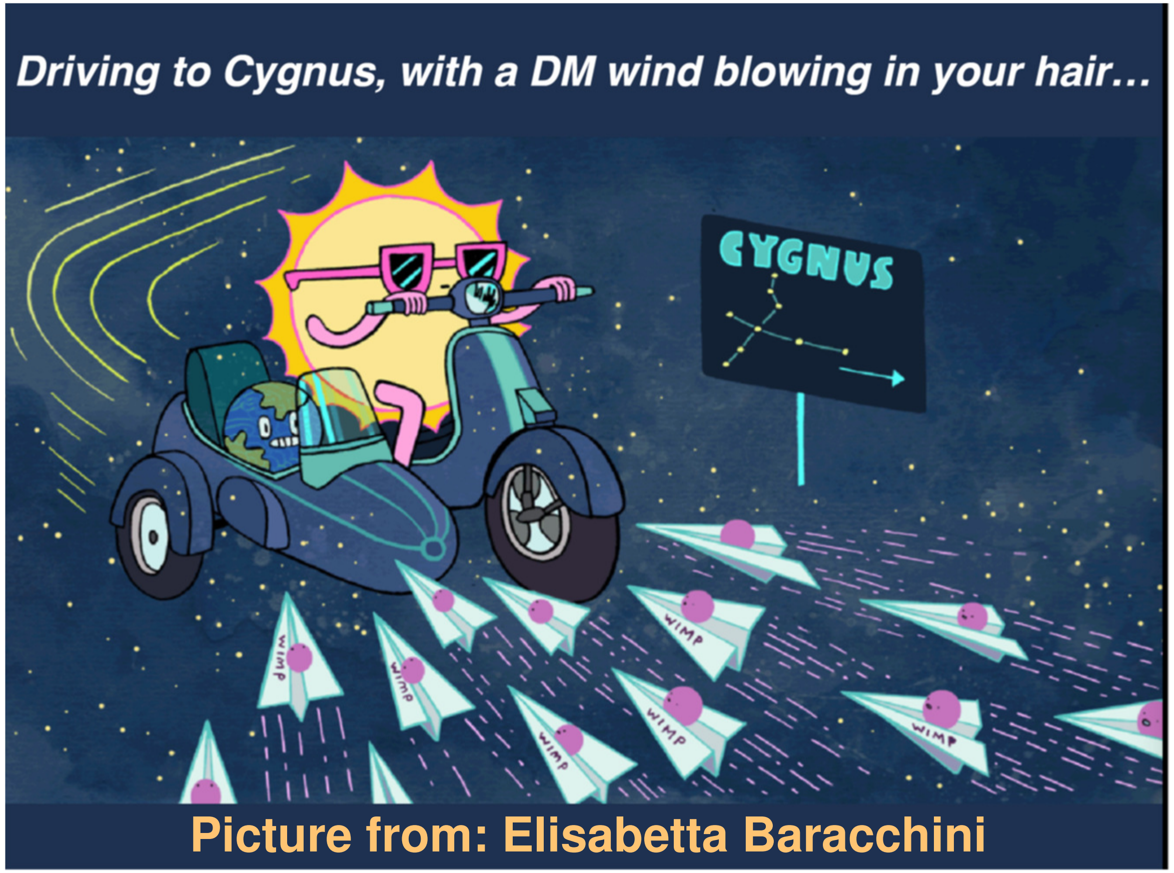


A. Arvanitaki et al., PRD 91, 015015 (2015)

Conf. Ser. **723** (2016) 012043

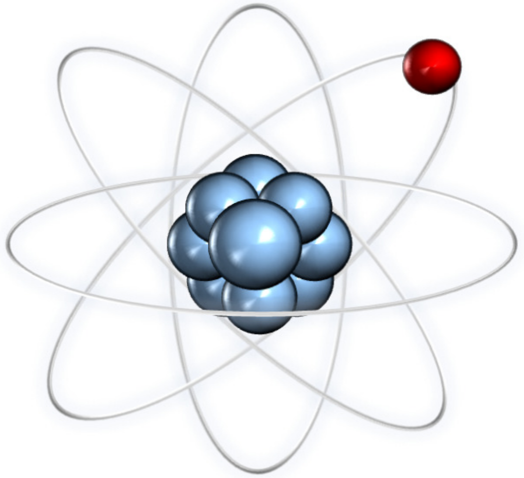


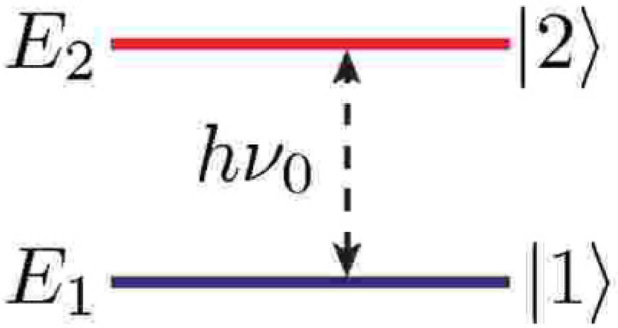
Our visible galaxy is inside of a very large dark matter halo.



http://www.sjsu.edu/people/monika.kress/courses/sci255/

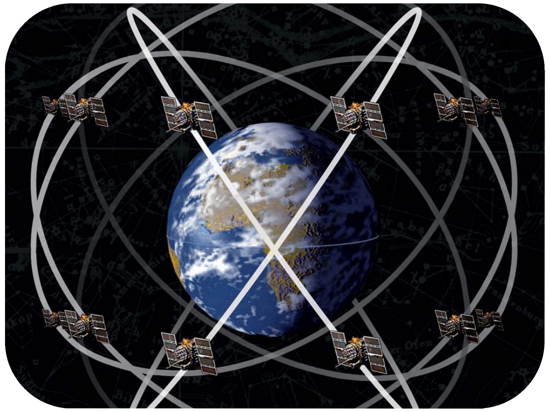
Dark matter can affects atomic energy levels





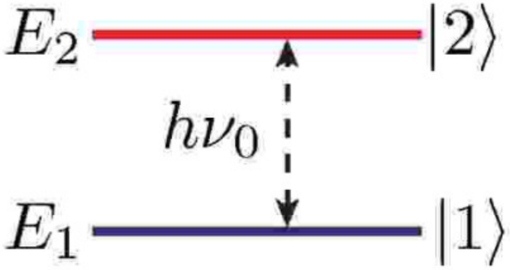
ν_0 is a clock frequency

What dark matter can you detect if you can measure changes in atomic/nuclear frequencies to 19 digits?

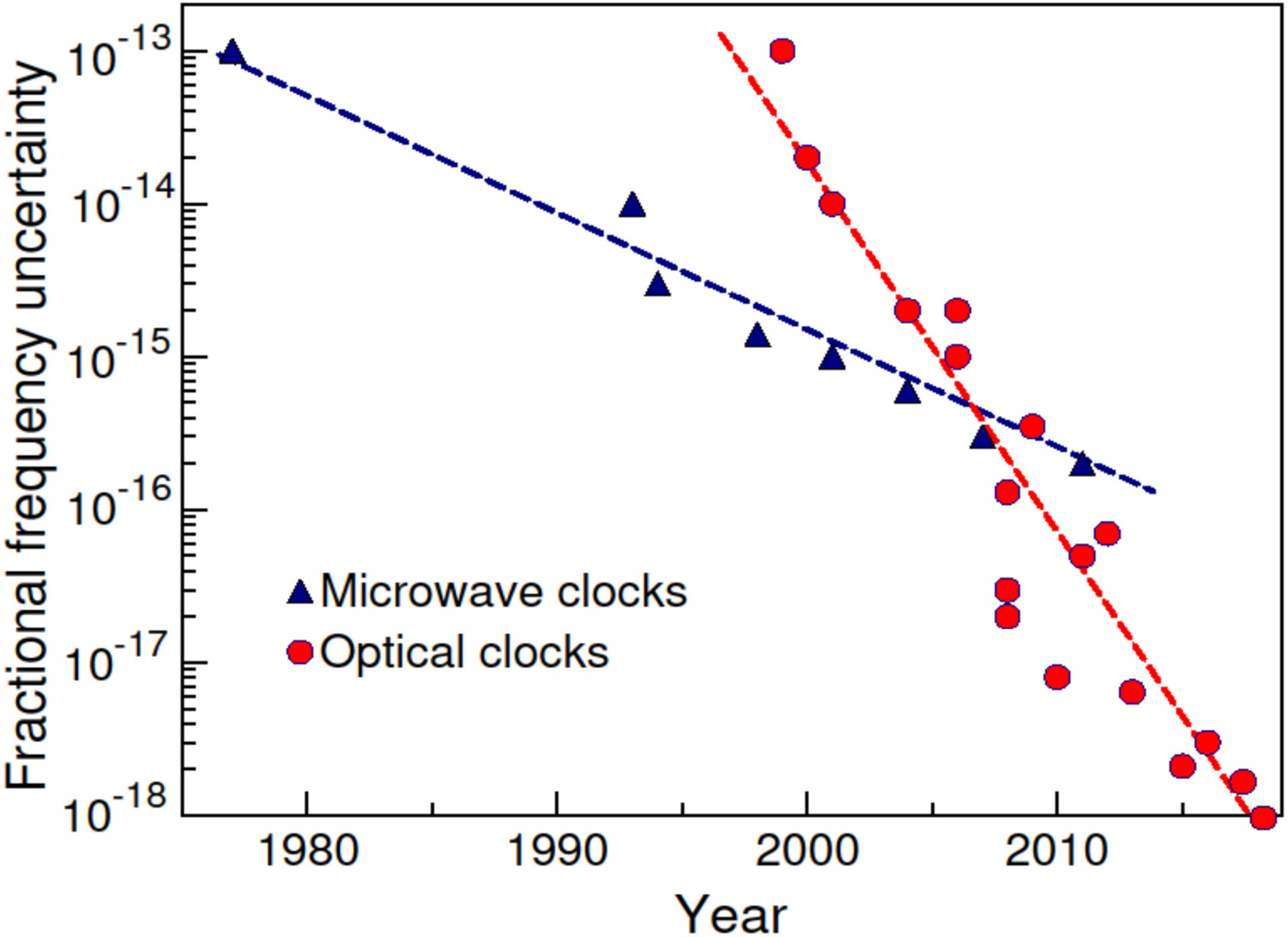


airandspace.si.edu

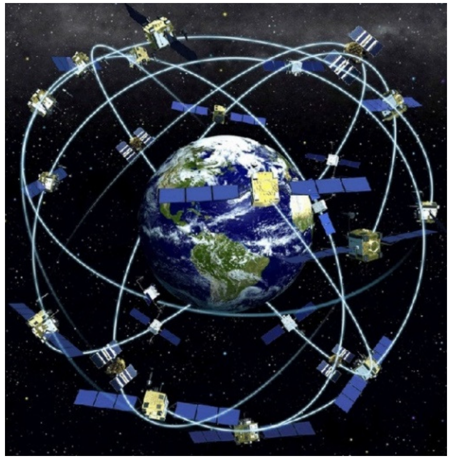
GPS satellites: microwave atomic clocks



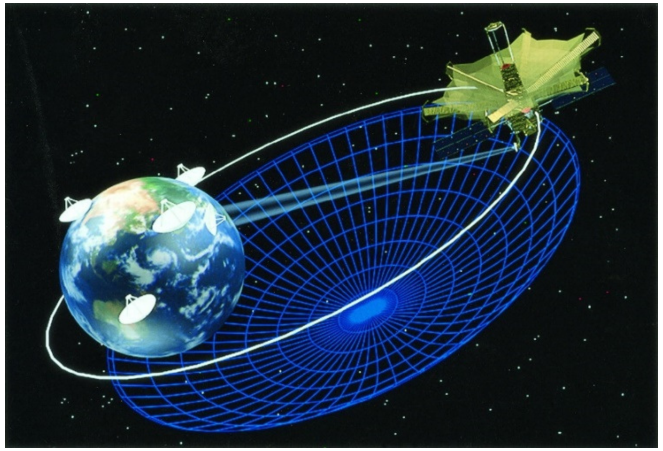
Optical atomic clocks will not lose one second in **30 billion years**



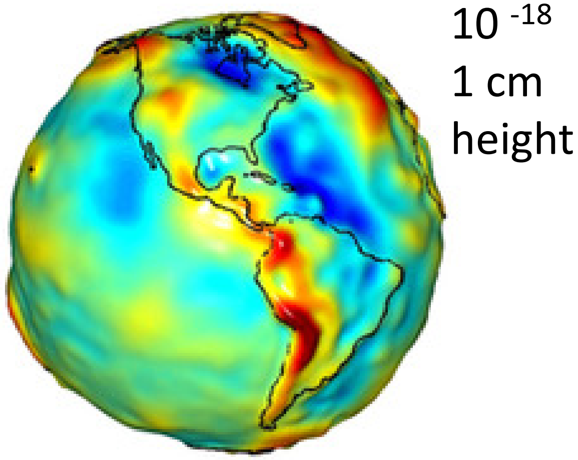
Applications of atomic clocks



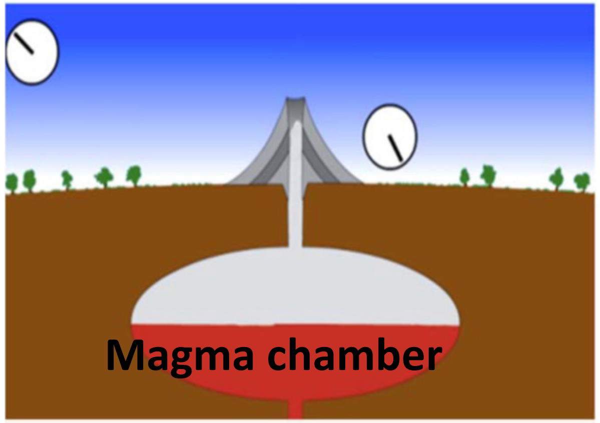
GPS, deep space probes



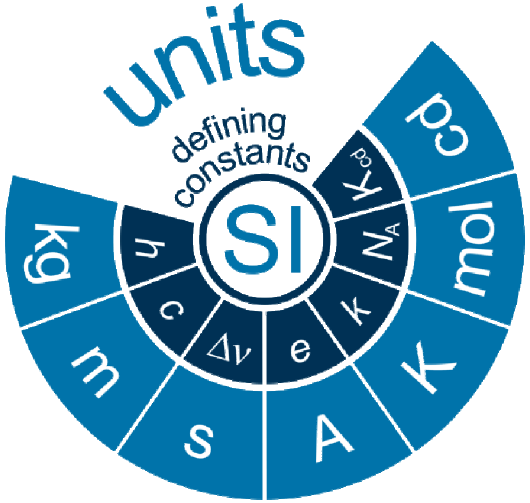
Very Long Baseline Interferometry



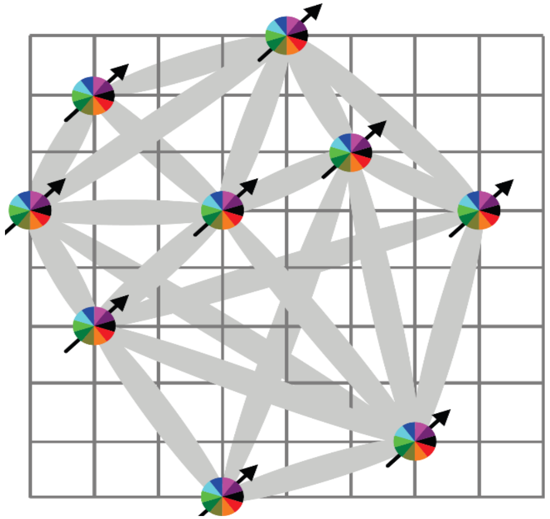
Relativistic geodesy



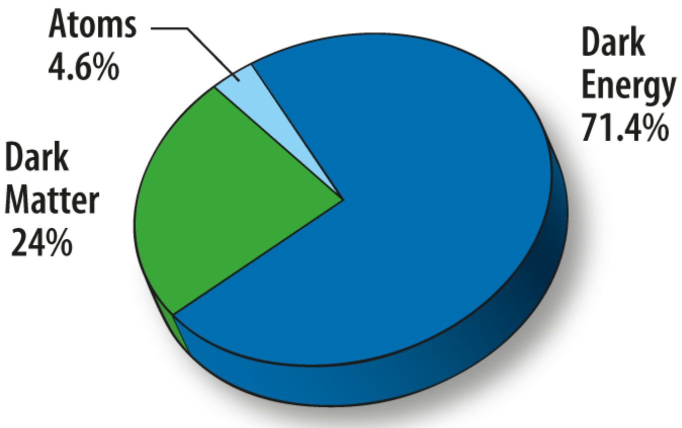
Gravity Sensor

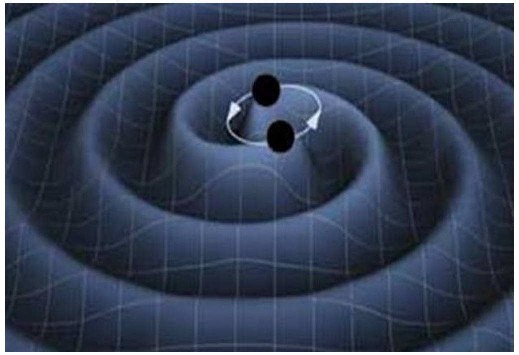


Definition of the second



Quantum simulation

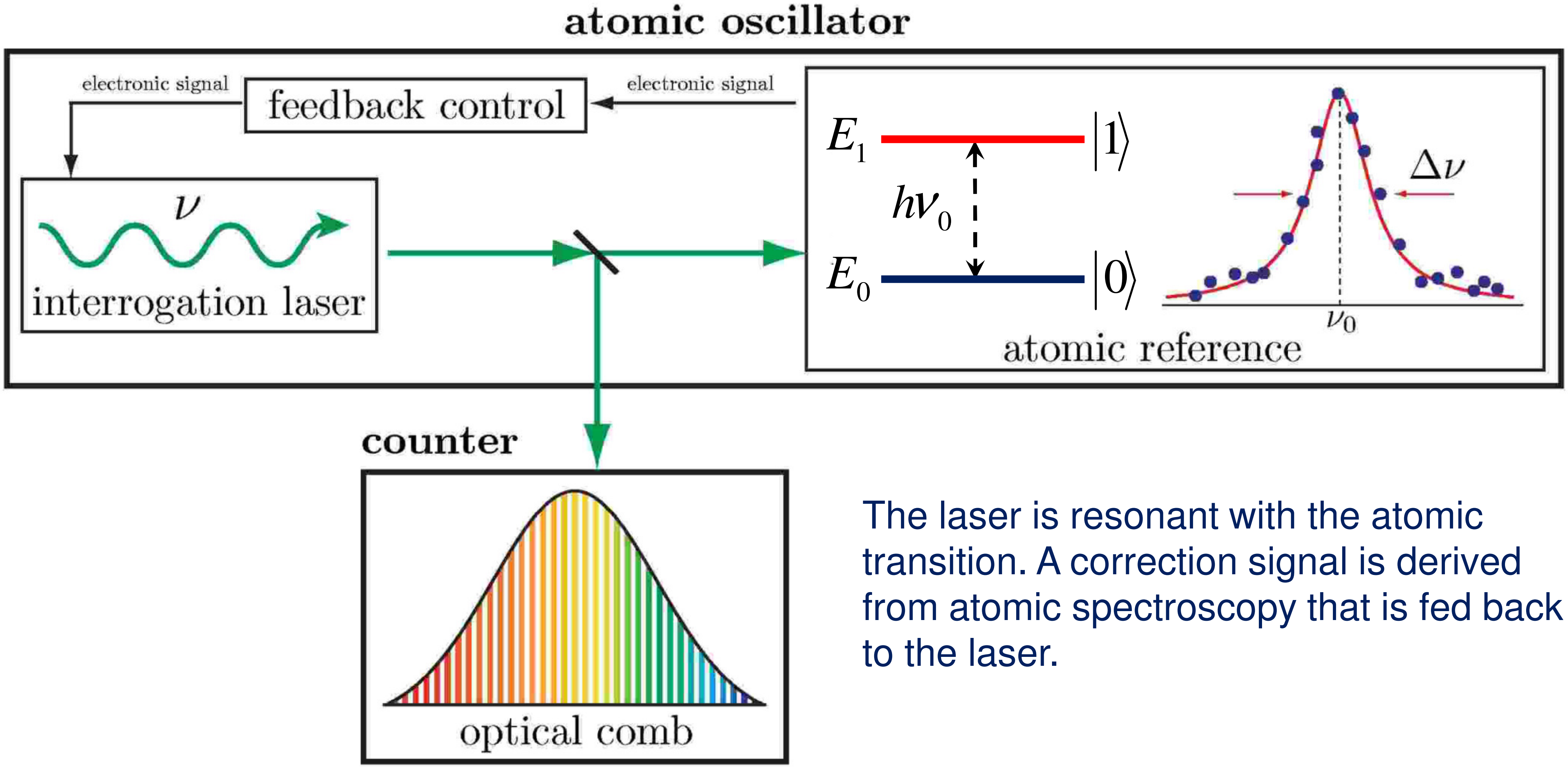




Searches for physics beyond the Standard Model

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

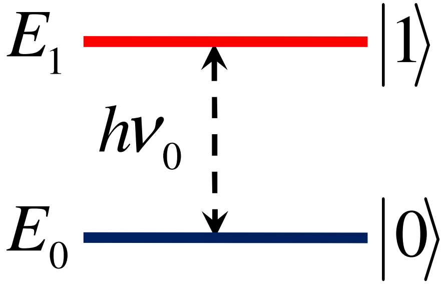
How optical atomic clock works



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

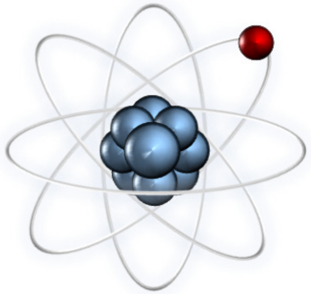
An optical frequency synthesizer (optical frequency comb) is used to divide the optical frequency down to countable microwave or radio frequency signals.

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



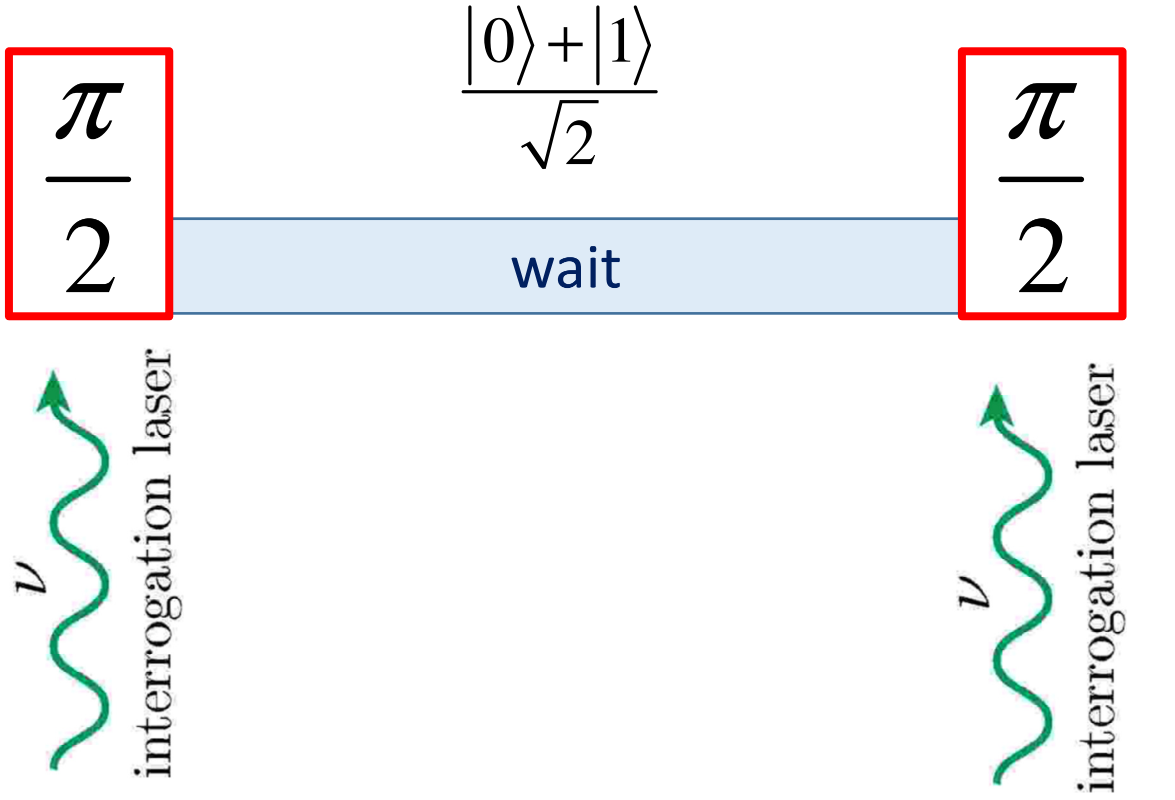
How optical atomic clock works
Ramsey scheme

Measure: $|0\rangle$ or $|1\rangle$?



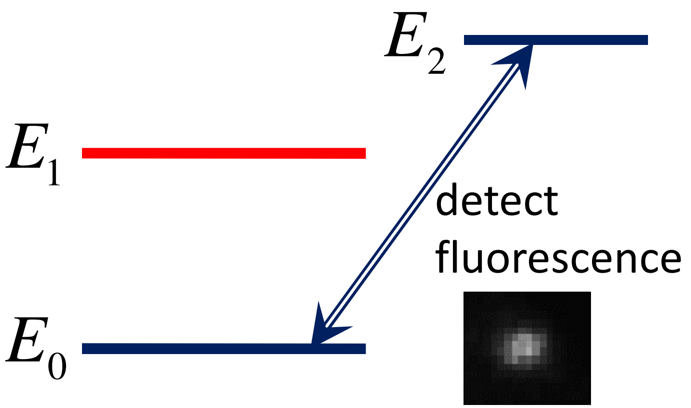
$|0\rangle$

Initialize



$\frac{\pi}{2} = \theta = 2\Omega\tau_L$

Atom should be exactly in $\frac{|0\rangle+|1\rangle}{\sqrt{2}}$ if on resonance



Quantum projection noise: can only get

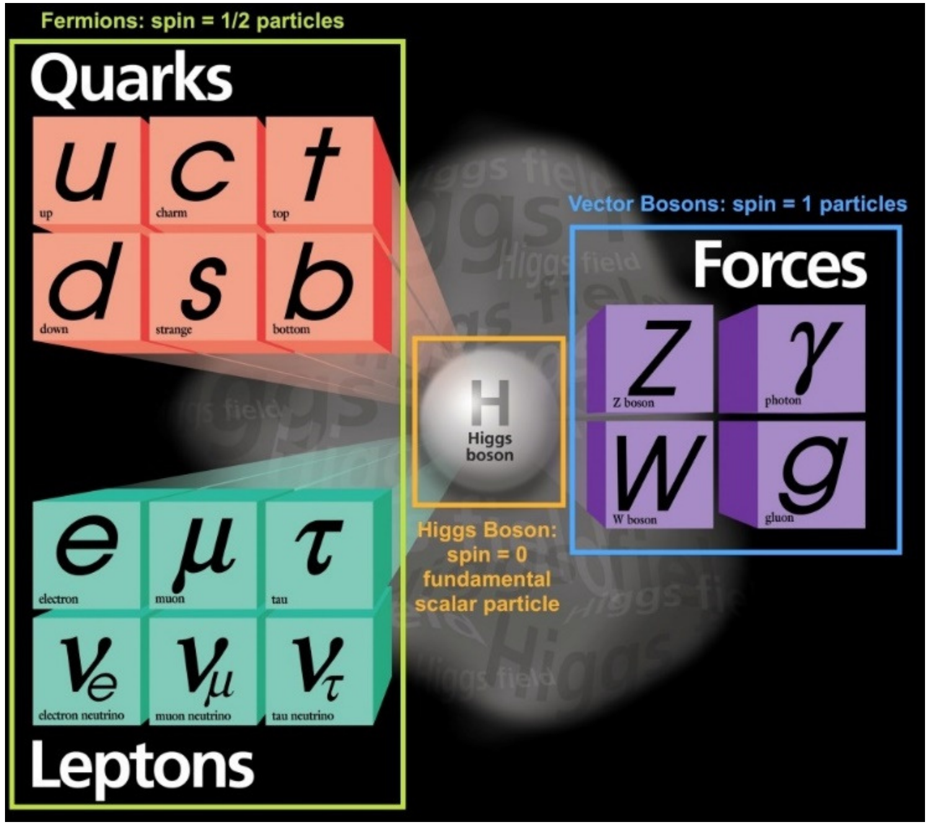
$|0\rangle$ or $|1\rangle$

Repeat many times to get probability of excitation, scan different frequencies to maximize

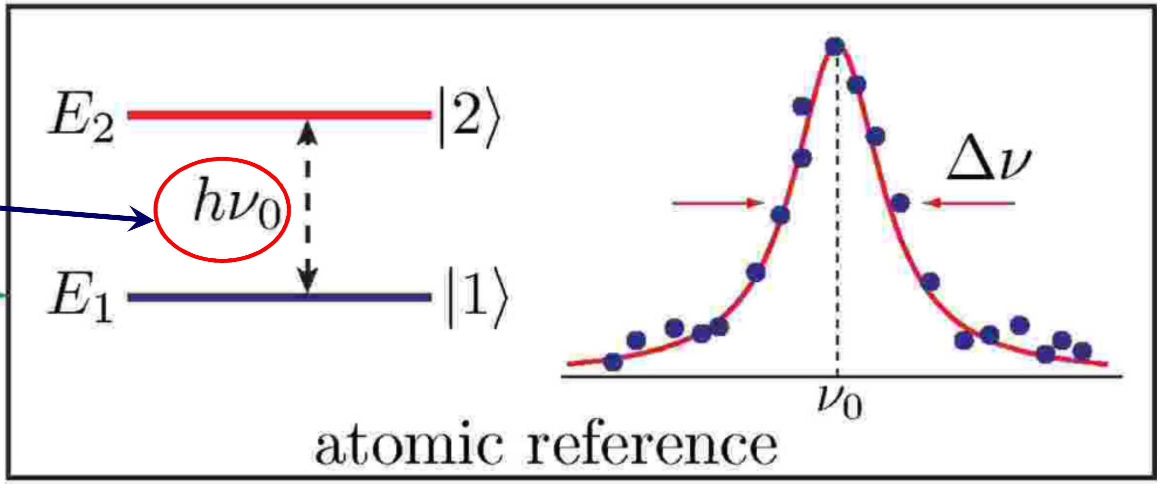
Search for physics beyond the standard model with atomic clocks

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.

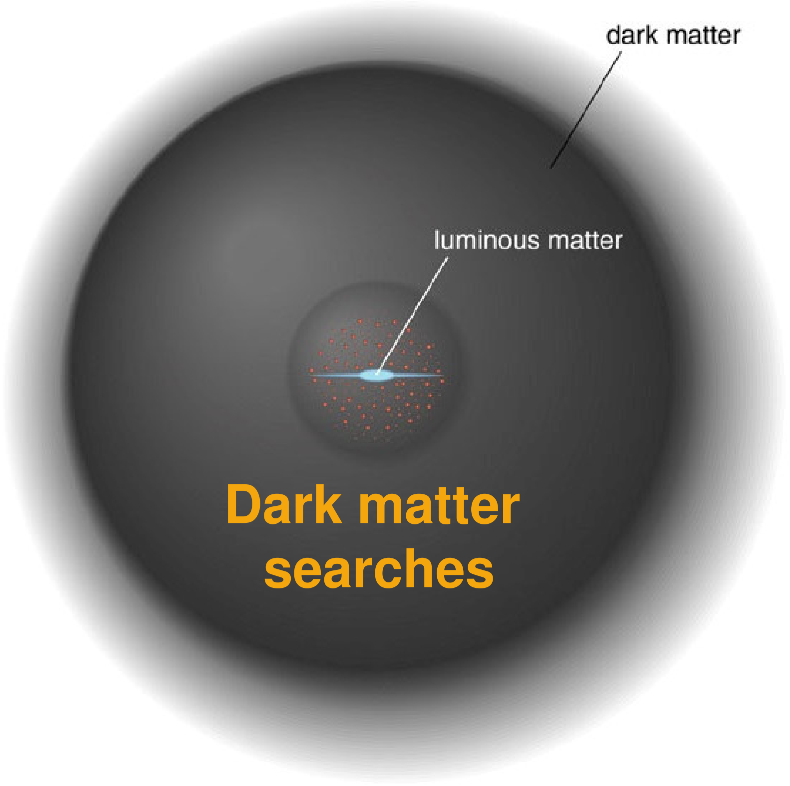


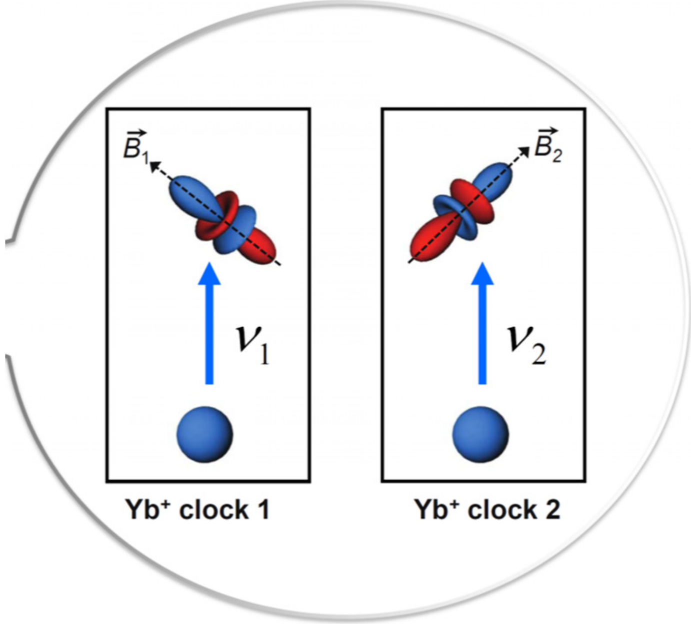
Frequency will change



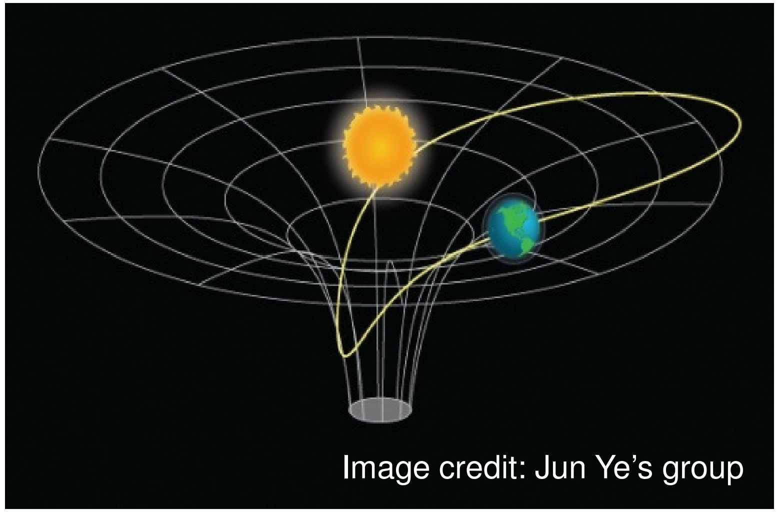
BEYOND THE STANDARD MODEL?

Search for physics beyond the Standard Model with atomic clocks





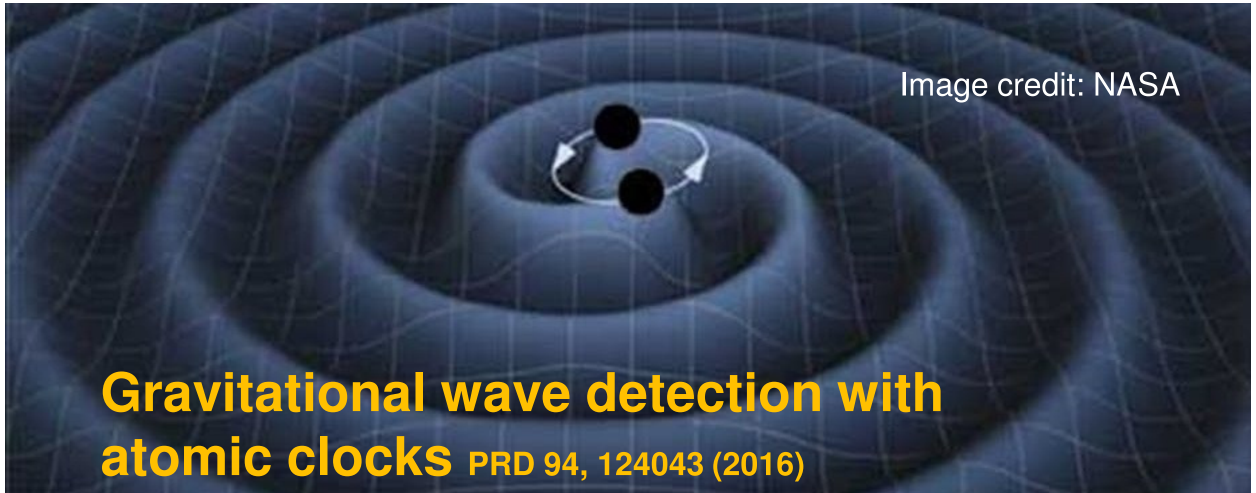
Search for the violation of Lorentz invariance



Tests of the equivalence principle

Are fundamental constants constant?

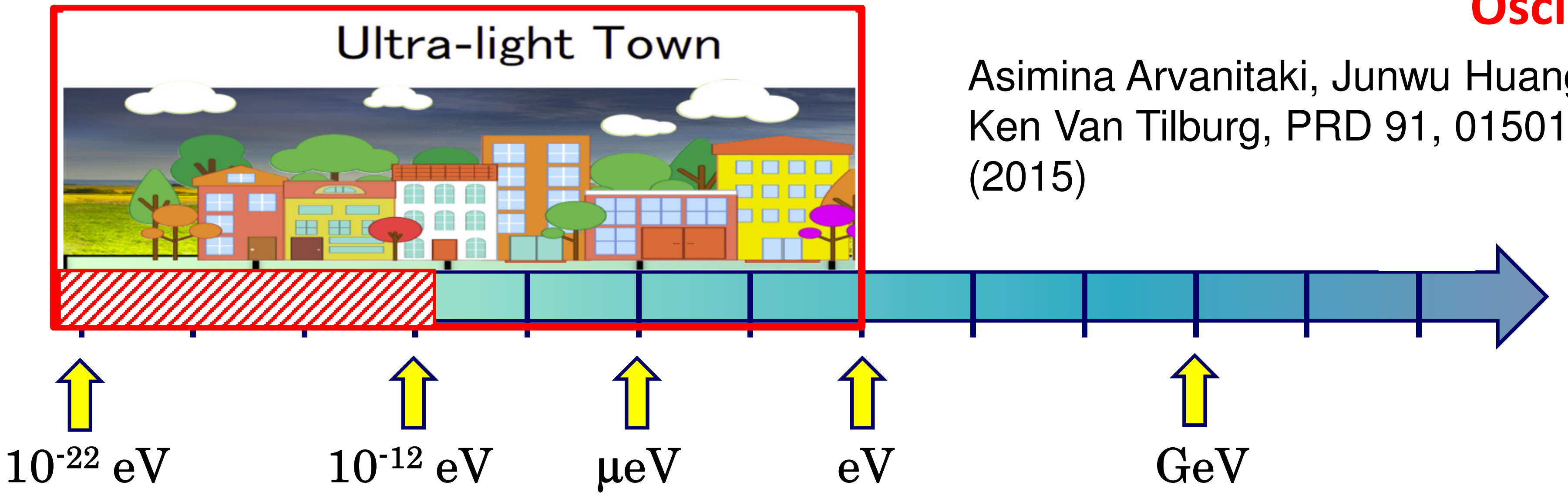
α



How to detect ultralight dark matter with clocks?

Oscillatory effects

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 & nuclear 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

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

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

Ultralight dark matter

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

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

Measure clock frequency ratios: $\frac{\delta(\nu_2/\nu_1)}{(\nu_2/\nu_1)} \simeq d_e(K_2 - K_1)\kappa\phi(t)$

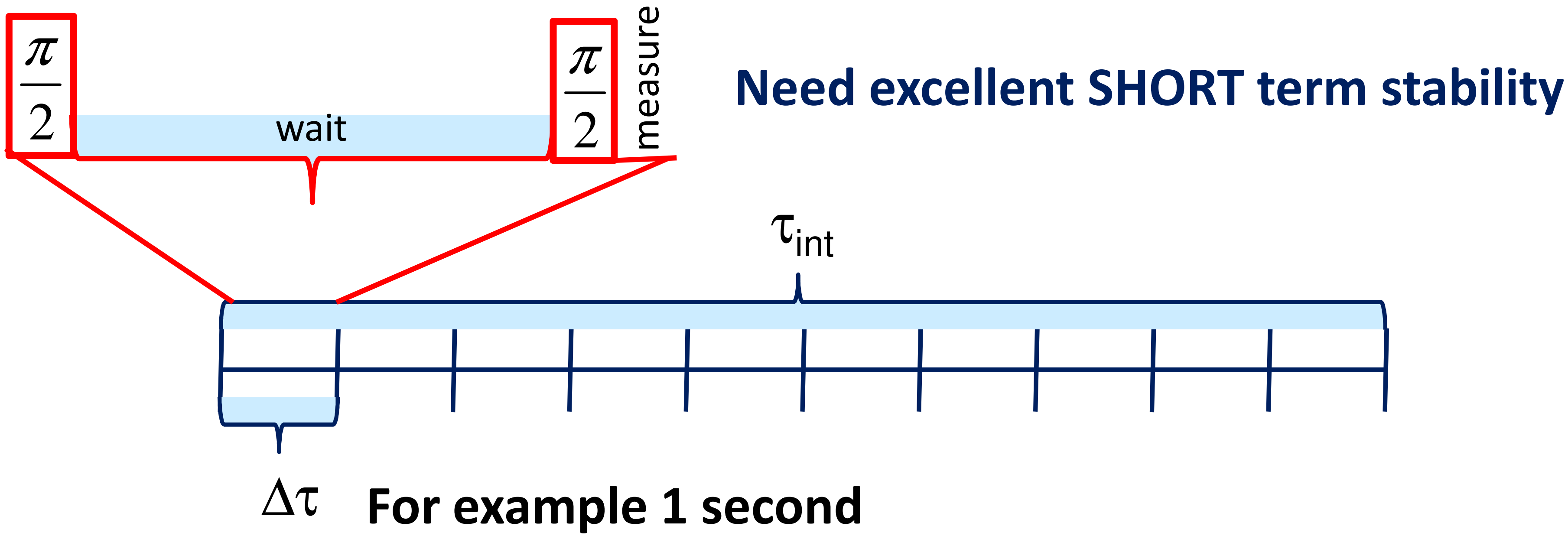
Sensitivity factors to α-variation

Result: plot couplings d_e vs. DM mass m_f

Clock measurement protocols for the dark matter detection

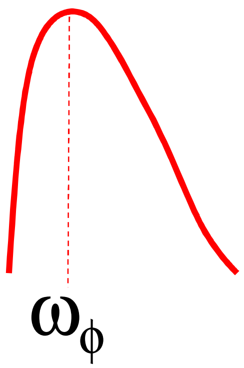
Make a clock ratio measurement over time $\Delta\tau$

Make N such measurements, preferably regularly spaced



Need excellent SHORT term stability

For example 1 second



Detection signal:

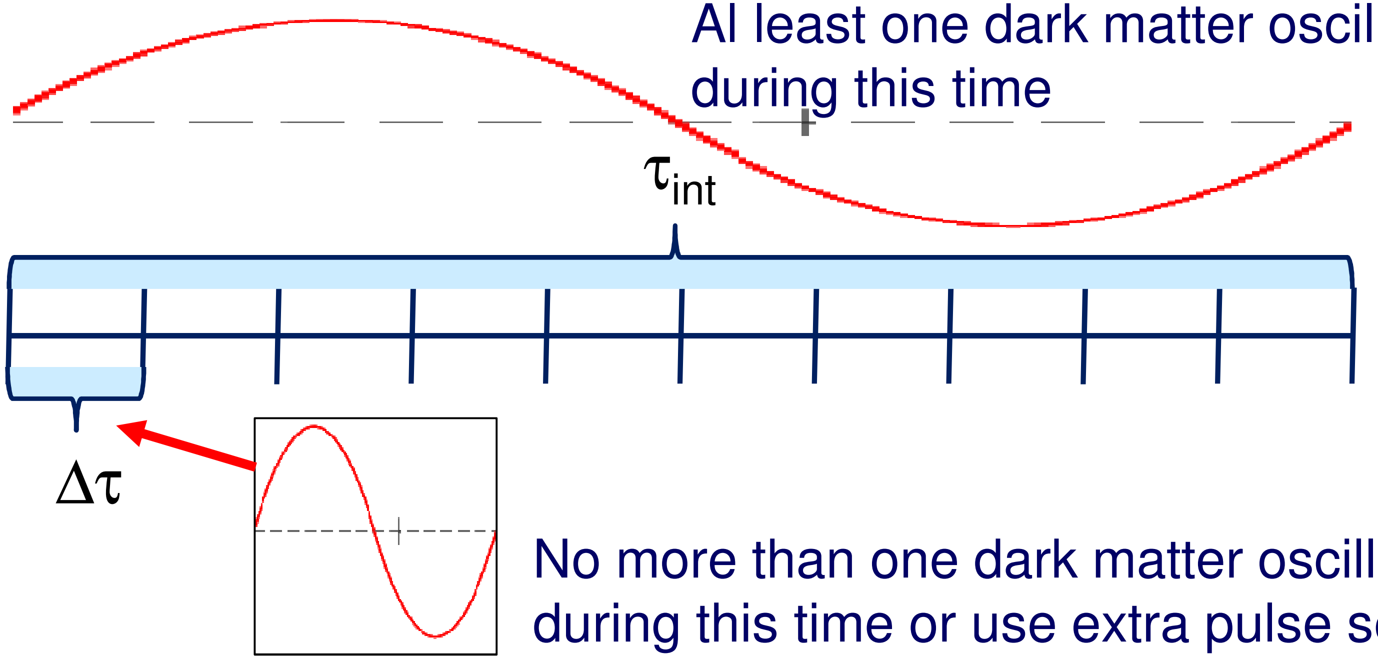
A peak with monochromatic frequency $f = 2\pi/m_\phi$ in the discrete Fourier transform of this time series.

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

Clock measurement protocols for the dark matter detection

Single clock ratio measurement: averaging over time τ_1

Make N such measurements, preferably regularly spaced

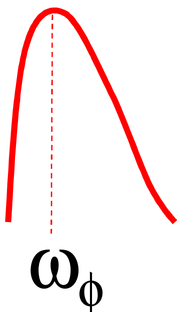


Al least one dark matter oscillation during this time

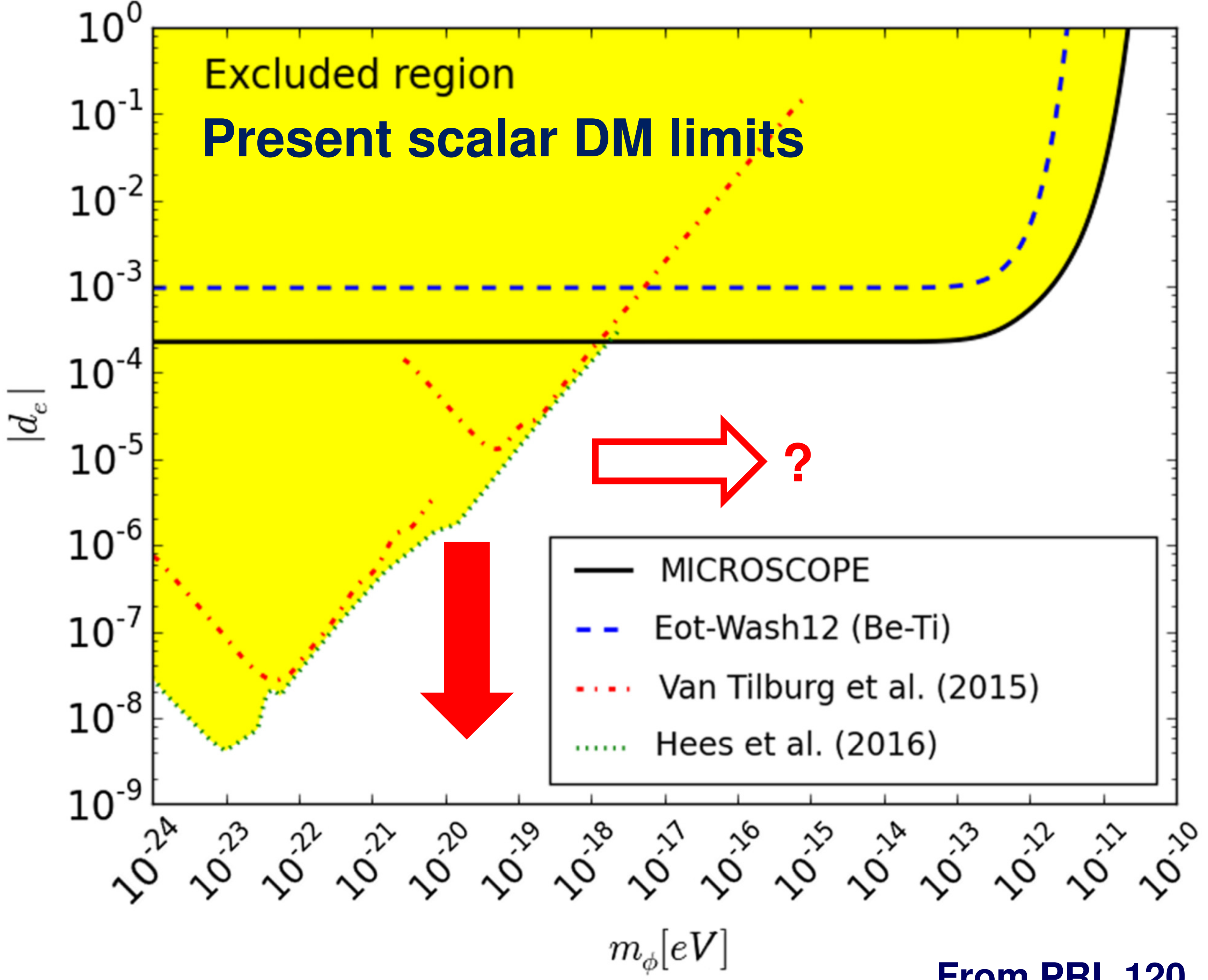
No more than one dark matter oscillation during this time or use extra pulse sequence

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)



From PRL 120, 141101 (2018)

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

Transient variations

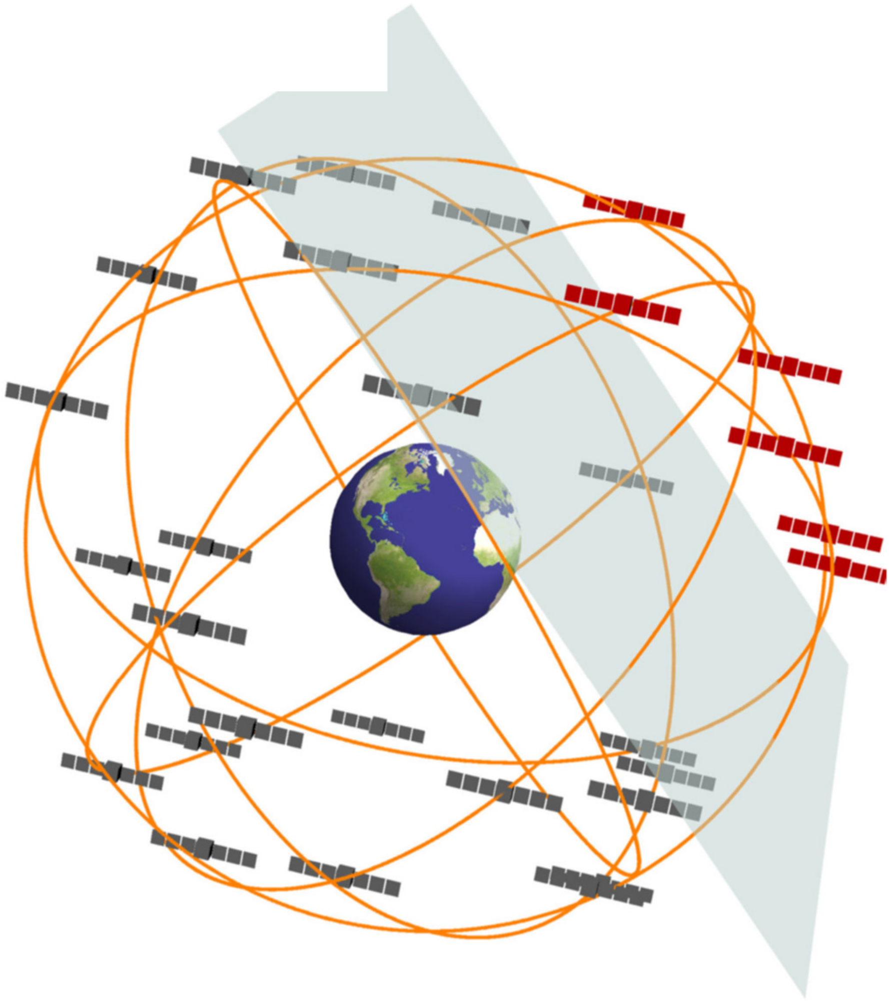
Hunting for topological dark matter with atomic clocks

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

Transient effects

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

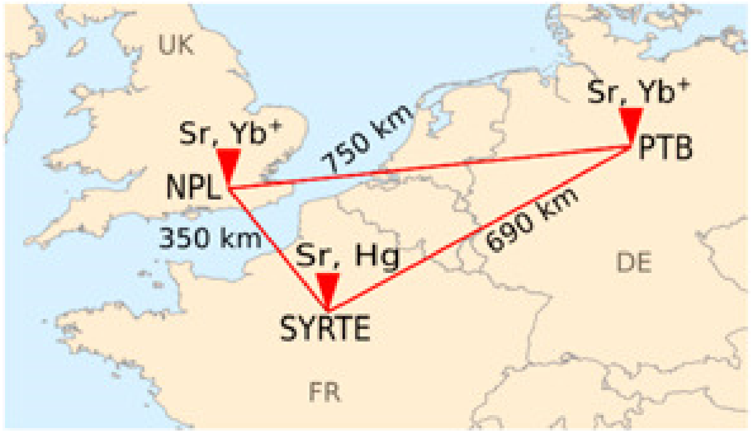
If they are large (size of the Earth) and frequent enough they may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System.

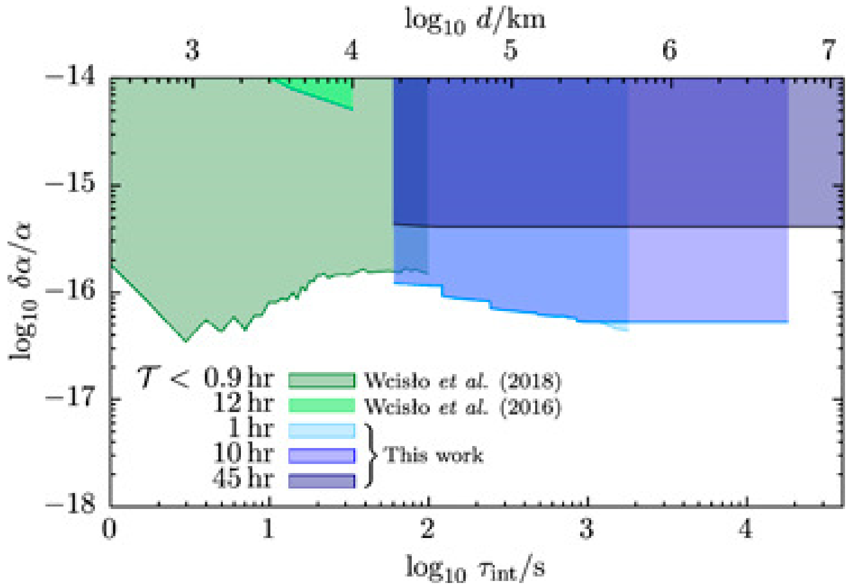


GPM.DM collaboration: Roberts at el., Nature Communications 8, 1195 (2017)

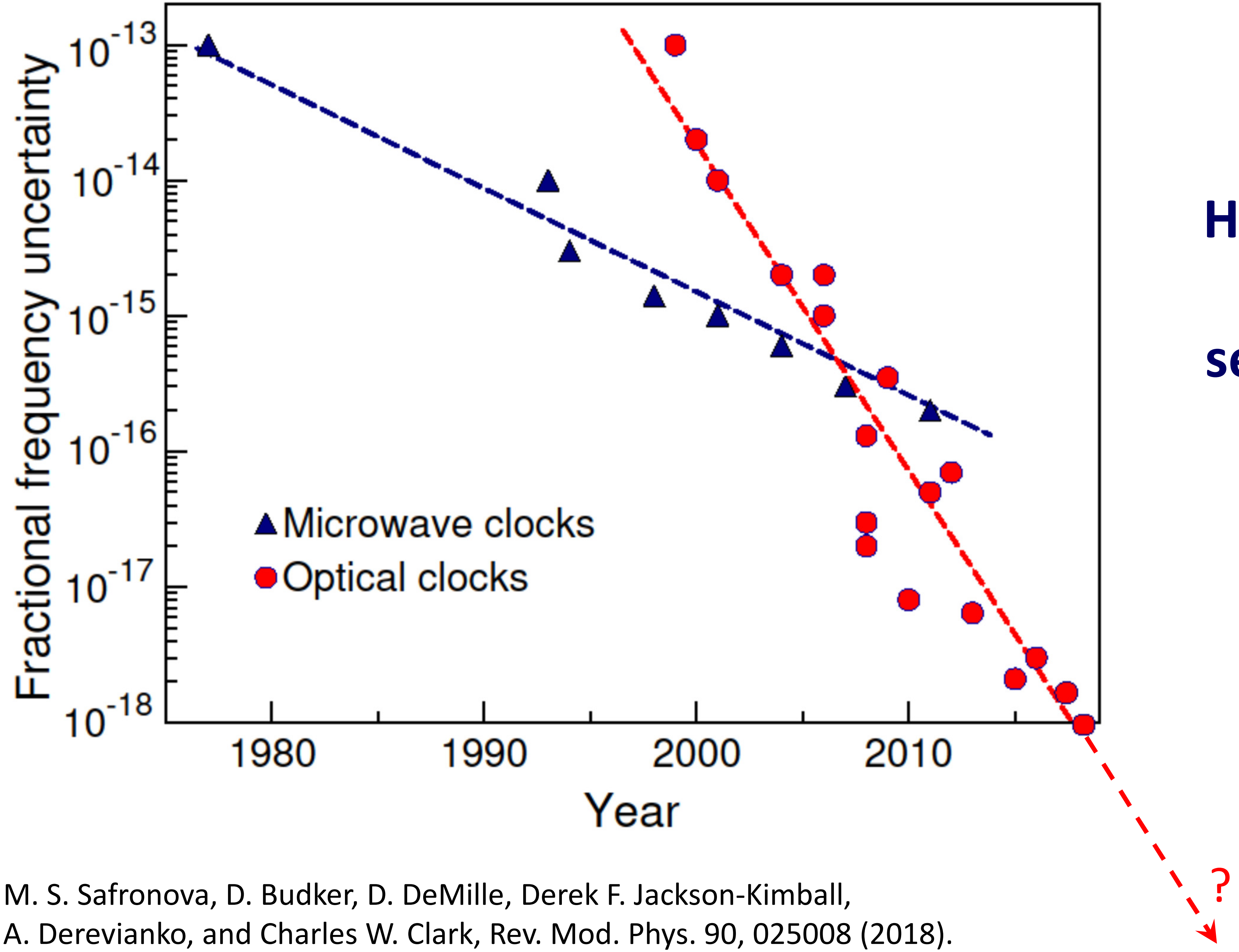
Global sensor network. The participating Sr and Yb optical lattice atomic clocks reside at NIST, Boulder, CO, USA, at LNE-SYRTE, Paris, France, at KL FAMO, Torun, Poland, and at NICT, Tokyo, Japan
Wcisło et al., Sci. Adv. 4: eaau4869 (2018)

European fiber-linked optical clock network. Search for transient variations of the fine structure constant and dark matter using fiber-linked optical atomic clocks; B M Roberts et al. New Journal of Physics, Volume 22, September 2020 (figures below).





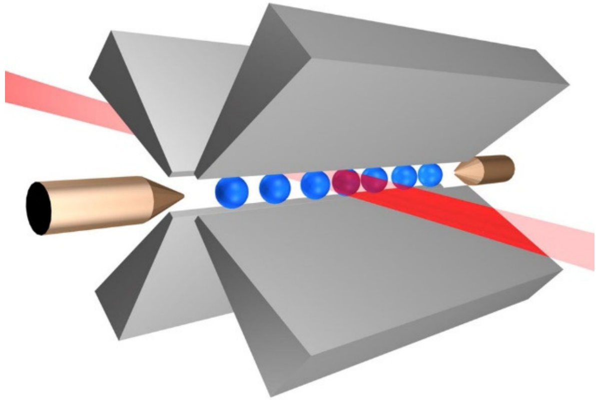
Constraints on the transient variation of the fine-structure constant α as a function of the transient duration, τ_{int}. The secondary horizontal axis shows the corresponding length scale, $d = v_g \tau_{int}$.



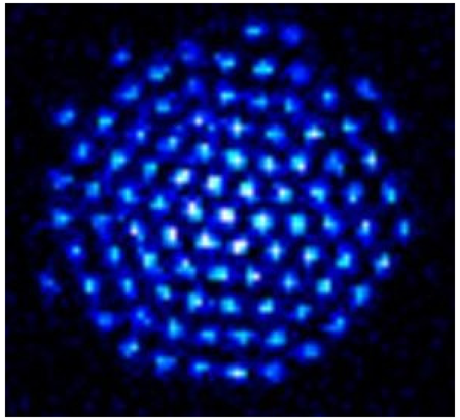
How to improve laboratory searches for the variation of fundamental constants & dark matter?

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

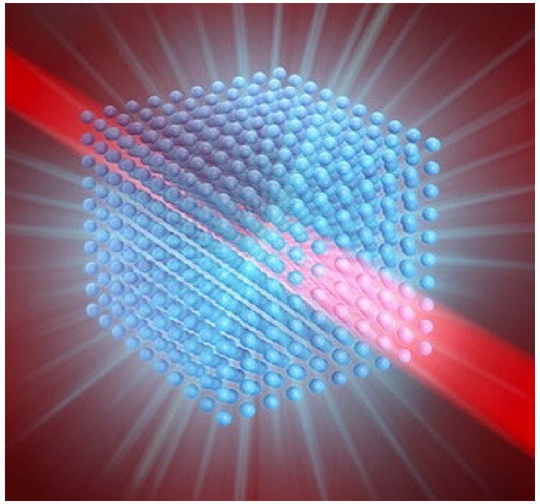
Improve atomic clocks: better stability and uncertainty



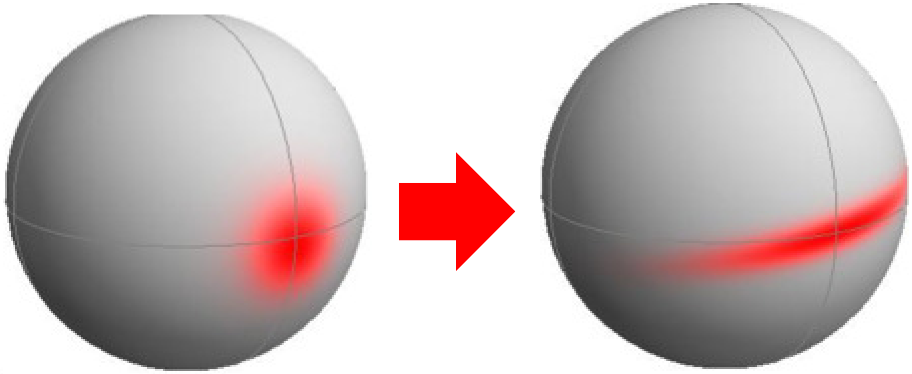
Ion chains



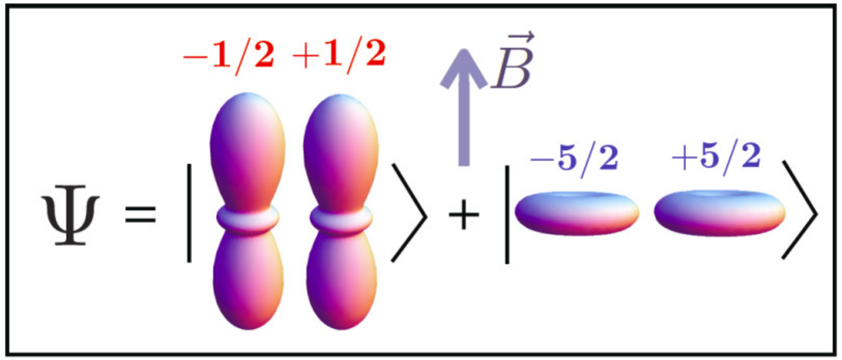
Large ion crystals



3D optical lattice clocks



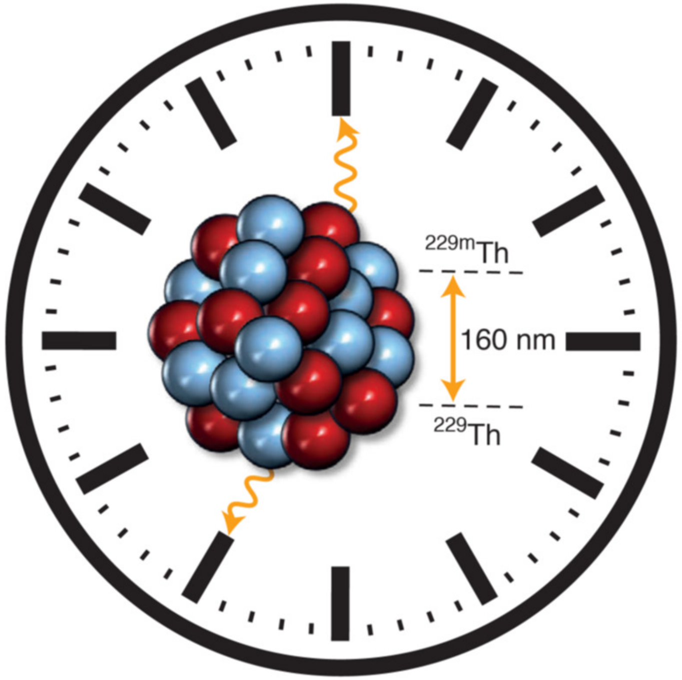
Measurements beyond the quantum limit



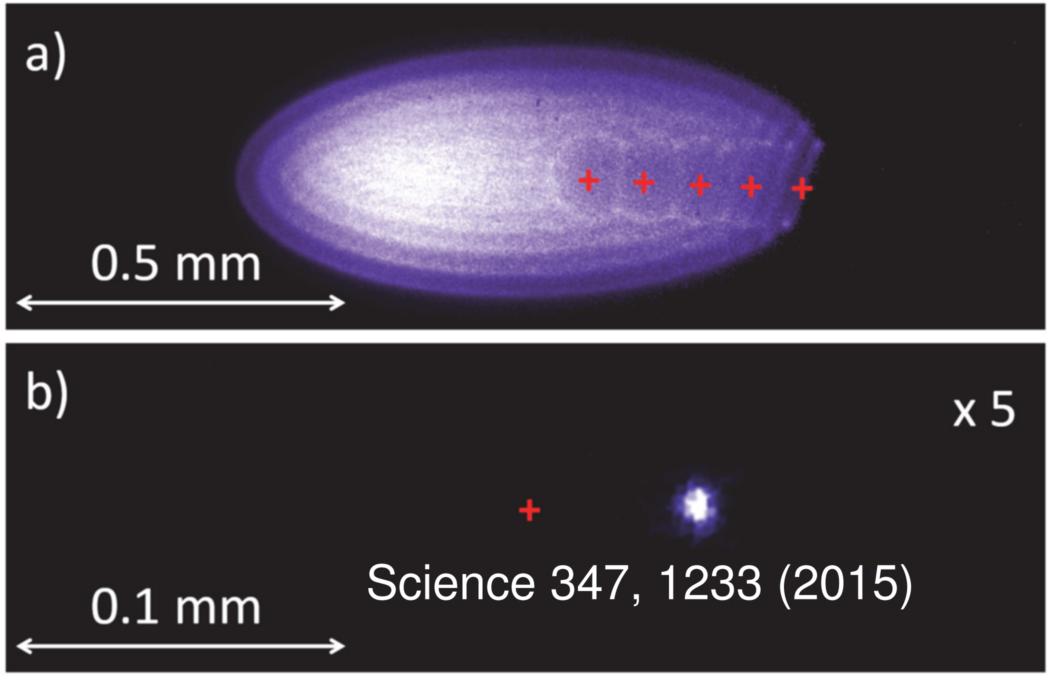
Entangled clocks

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

Clocks based on new systems



Nuclear clock



Clocks with ultracold highly charged ions: much higher sensitivity

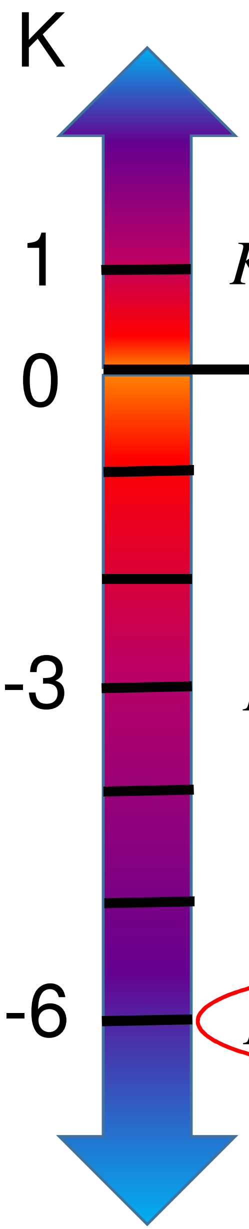
Piet Schmidt, Quantum science seminar #18

First demonstration of quantum logic spectroscopy at PTB, Germany

Nature 578 (7793), 60 (2020)

Enhancement factors for current clocks

$$K = \frac{2q}{E_0}$$



$K(Sr^+) = 0.4$

$K(Yb) = 0.3$

$K(Hg) = 0.8, \quad K(Yb^+E2) = 1$

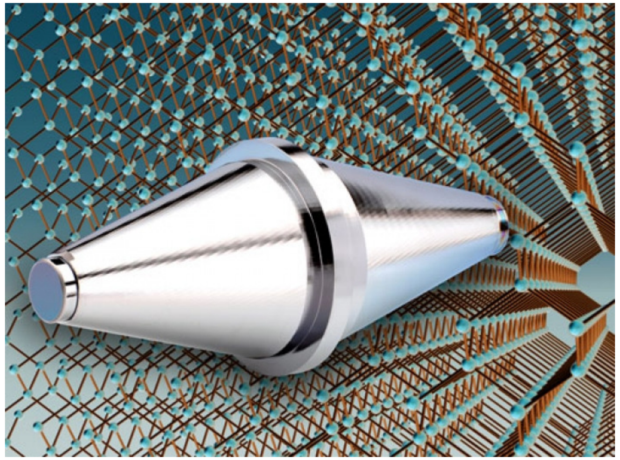
$K(Al^+) = 0.01, \quad K(Sr) = 0.06, \quad K(Ca^+) = 0.1$

$K(Hg^+) = -2.9$

$K(Yb^+E3) = -6$

Cavity: part of the clock laser systems

Effective K=1



$$\frac{\partial}{\partial t}\ln\frac{v_2}{v_1} = (K_2 - K_1)\frac{1}{\alpha}\frac{\partial \alpha}{\partial t}$$

Thorium nuclear clocks for fundamental tests of physics

https://thoriumclock.eu/

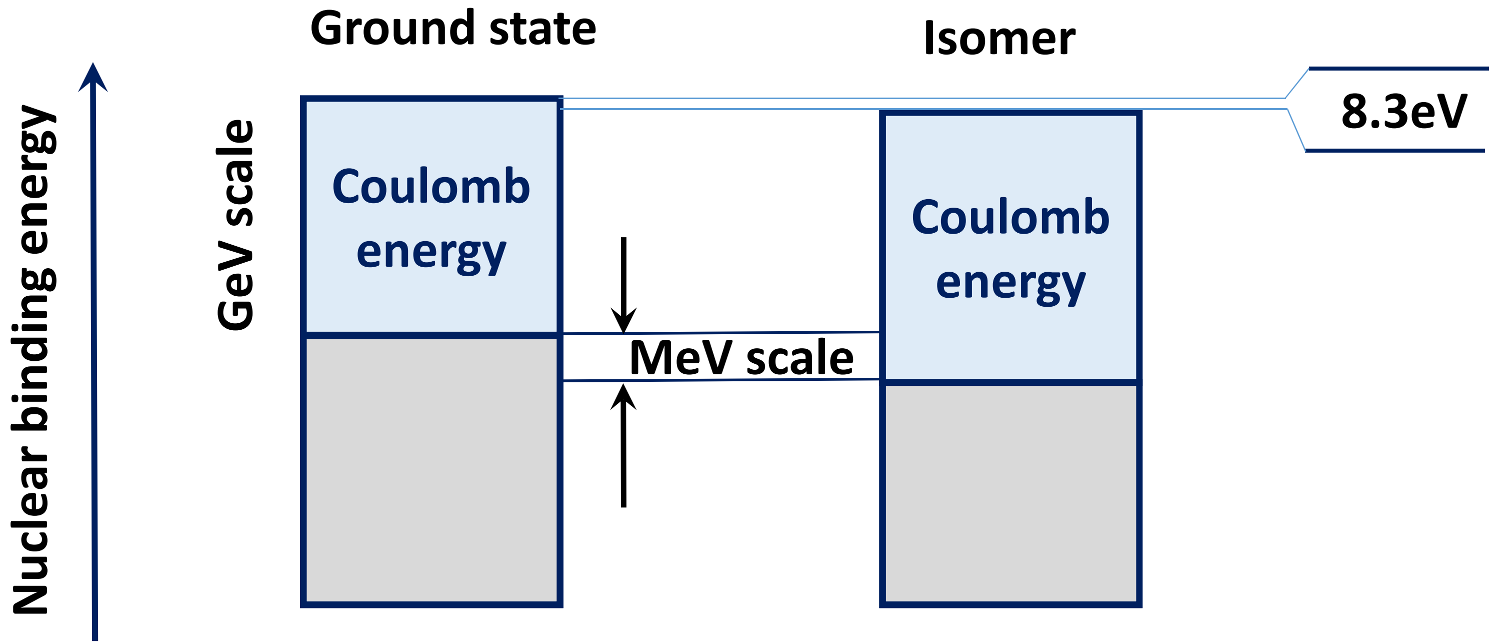
Thorsten Schumm, TU Wein
Ekkehard Peik, PTB
Peter Thirolf, LMU
Marianna Safronova, UDel

What is different for the nuclear clock?

(1) Much higher sensitivity

(2) Nuclear clock is sensitive to coupling of dark matter to the nuclear sector of the standard model

Th nuclear clock: Exceptional sensitivity to new physics



$$\frac{8.3\ \text{eV}}{\text{MeV}} \sim 10^5$$

Possible 4-5 orders of magnitude enhancement to the variation of α and $\frac{m_q}{\Lambda_{QCD}}$ but orders of magnitude uncertainty in the enhancement factors.

It is crucial to establish actual enhancement!

Ultralight dark matter

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

Dark matter coupling to the Standard Model

$$\mathcal{L}_\phi = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu} - d_{m_e}m_e\bar{e}e - \sum_{i=u,d}(d_{m_i} + \gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$

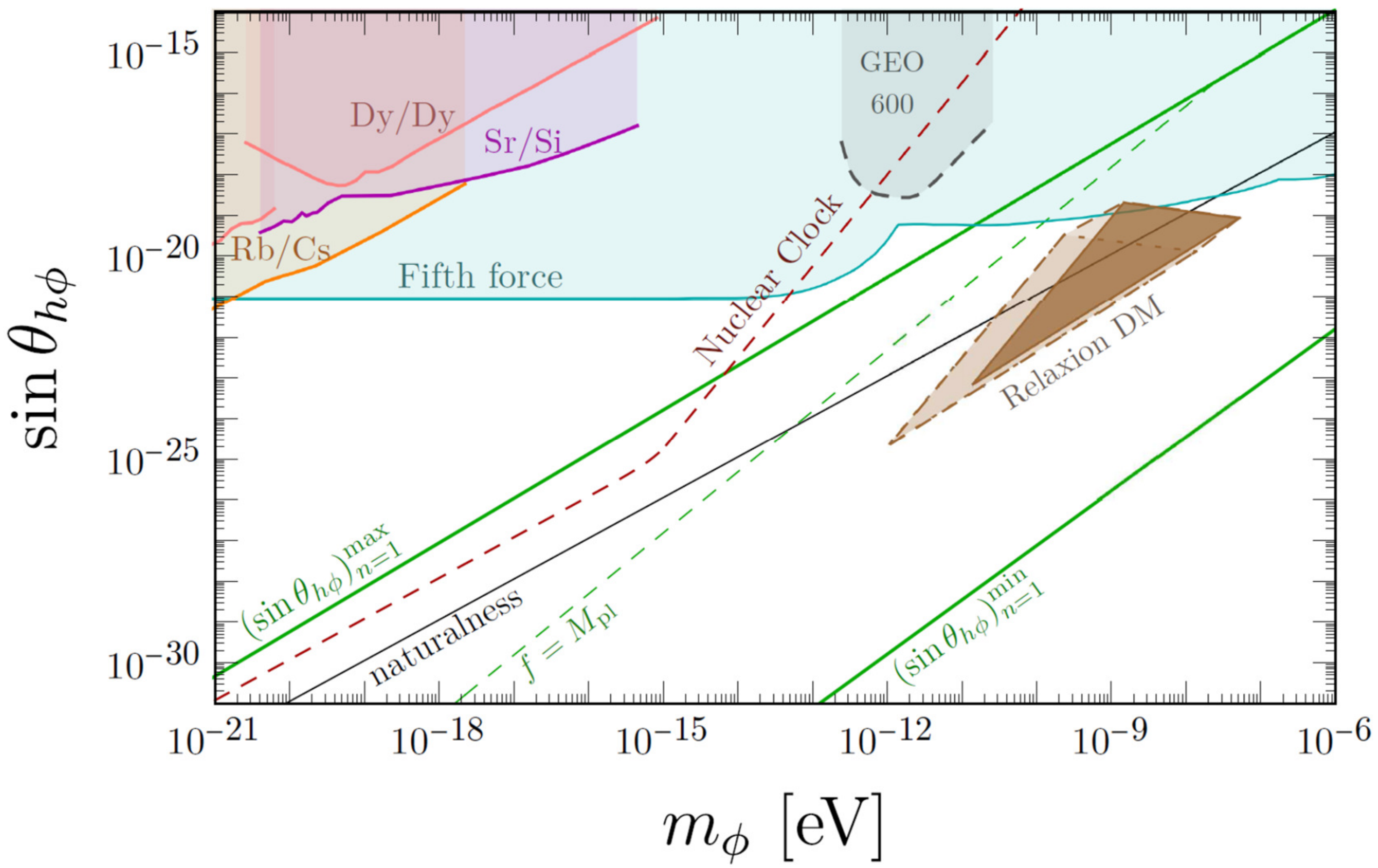
Dark matter (ϕ) · photons (d_e) · gluons (d_g) · electrons (d_{m_e}) · quarks (d_{m_i}, d_g)

Nuclear clock:
additional couplings of dark matter to standard model via d_g and d_m (quark)

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

Probing the Relaxed Relaxion at the Luminosity and Precision Frontiers

Abhishek Banerjee, Hyungjin Kim, Oleksii Matsedonskyi, Gilad Perez, Marianna S. Safronova,
J. High Energ. Phys. 2020, 153 (2020).



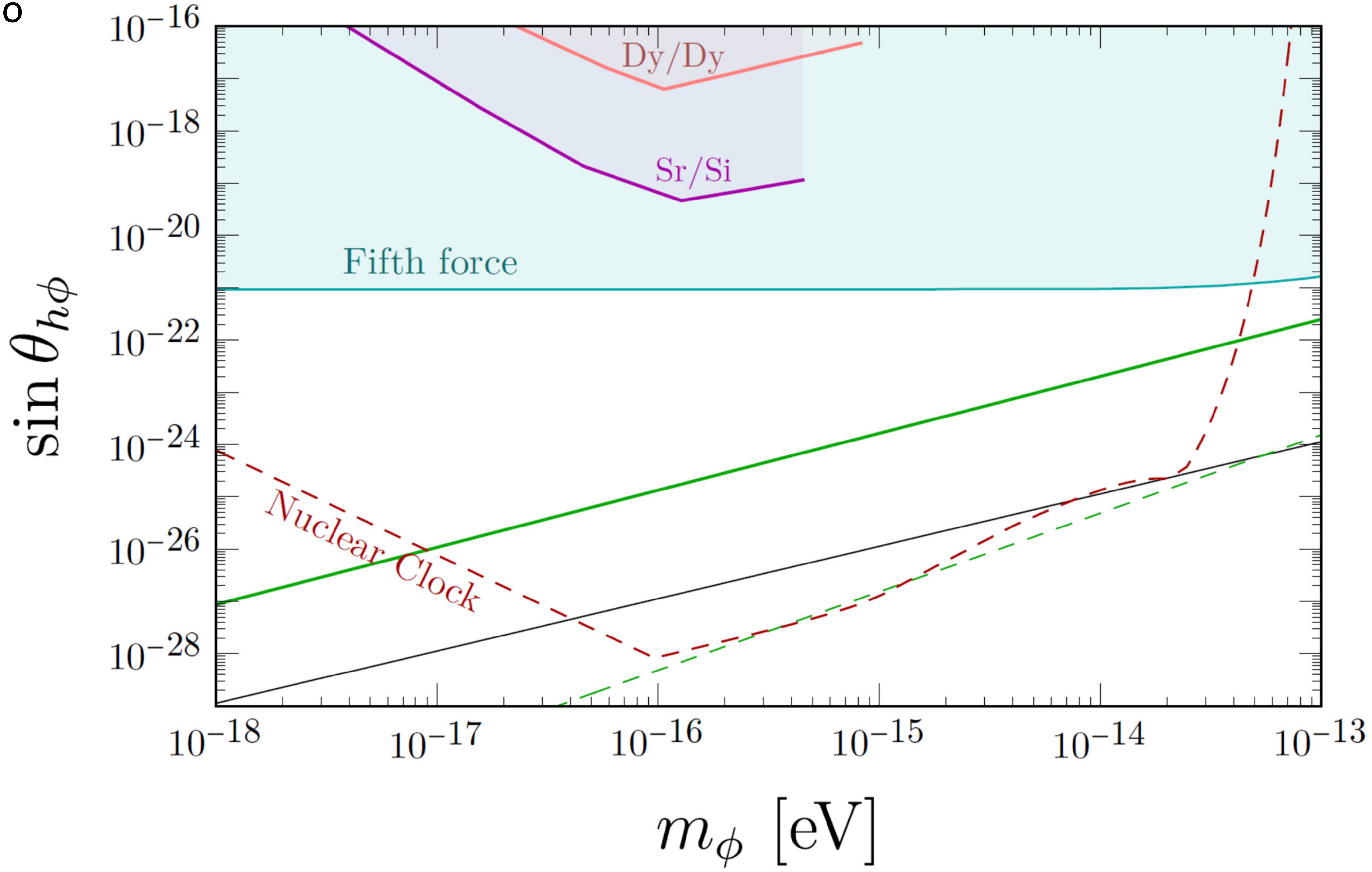
Cosmological relaxation of the electroweak scale is an attractive scenario addressing the gauge hierarchy problem.

Its main actor, the relaxion, is a light spin-zero field which dynamically relaxes the Higgs mass with respect to its natural large value.

Continued collaboration with Gilad Perez' particle physics theory group.

Relaxion-Higgs mixing angle as a function of the relaxion mass.
A relaxion window and the available parameter space for the light relaxion, current and projected constraints.

Solar halo

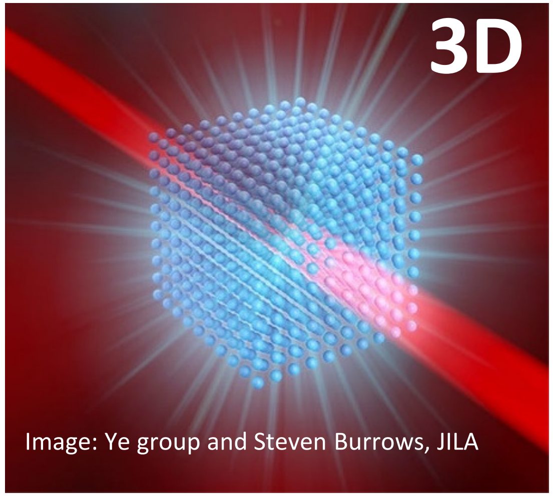


Dy/Dy
Sr/Si
Fifth force
Nuclear Clock
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
$\sin\theta_{h\phi}$
10^{-18}
10^{-17}
10^{-16}
10^{-15}
10^{-14}
10^{-13}
m_ϕ [eV]

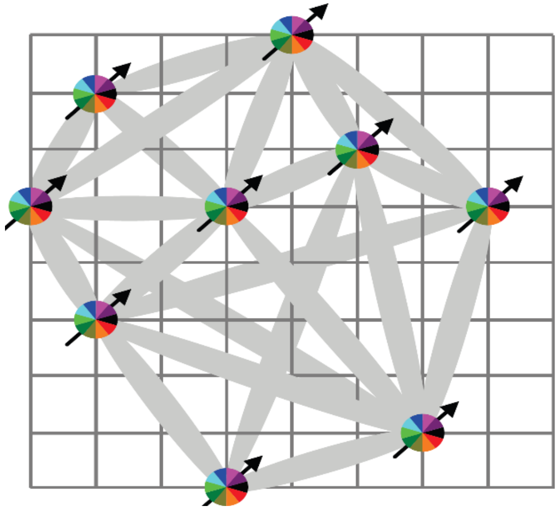
Recent progress in atomic theory

Very recent … past year

Numerous applications that need precise atomic data

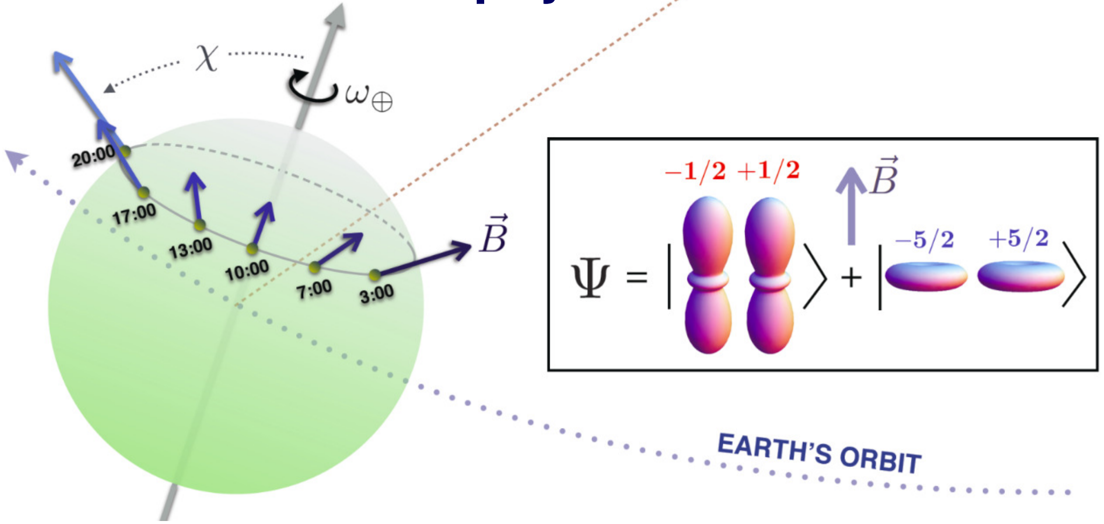


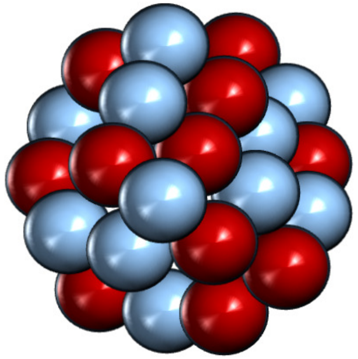
Atomic clocks



Ultracold atoms
Quantum computing and simulation

Particle physics:
Searches for dark matter and other "new" physics





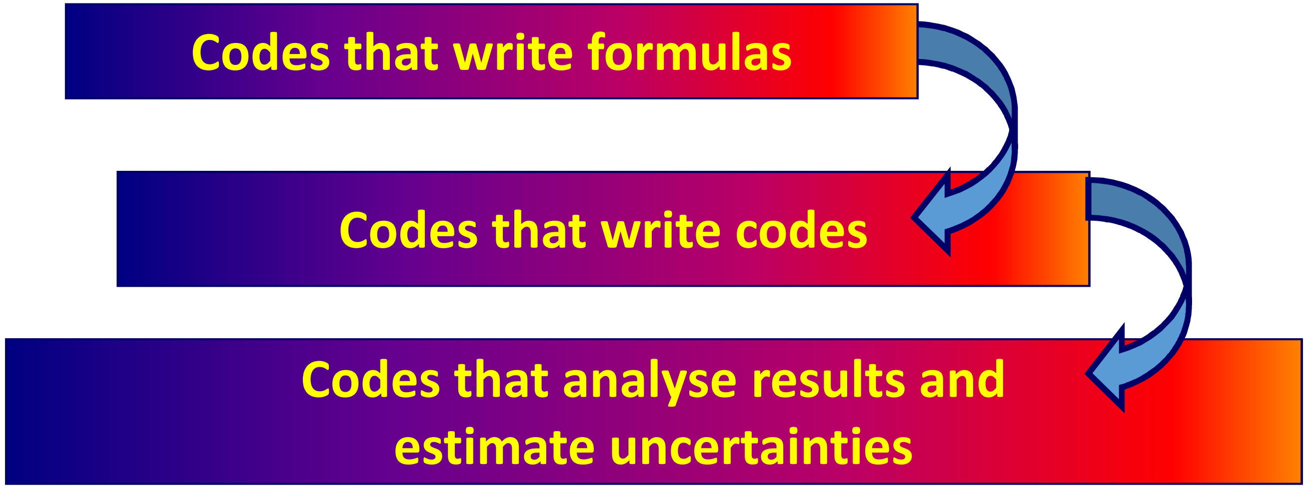
Nuclear and hadronic physics - extracting nuclear properties

Astrophysics

Plasma physics

University of Delaware team & collaborators

- We have been developing high precision atomic codes and applying them to solve completely different problems for over 20 years
- All codes are written by UD team and collaborators (Charles Cheung, Mikhail Kozlov, Sergey Porsev, Marianna Safronova, Ilya Tupitsyn)
- Because we have several *ab initio* codes we can estimate how accurate numbers are – we are the only group to routinely publish reliable uncertainties



Present UD team computer resources: 550 cores, 12.7Tb of memory

We can compute atomic data for any atoms/ions with 1-5(6) valence electron

Recent theory progress in predicting properties of highly-charged ions: New parallel code – we can now run 100x larger problems!

High-resolution Photo-excitation Measurements Exacerbate the Long-standing Fe XVII-Oscillator-Strength Problem

Steffen Kühn, Chintan Shah, José R. Crespo López-Urrutia, Keisuke Fujii, René Steinbrügge, Jakob Stierhof, Moto Togawa, Zoltán Harman, Natalia S. Oreshkina, Charles Cheung, Mikhail G. Kozlov, Sergey G. Porsev, Marianna S. Safronova, Julian C. Berengut, Michael Rosner, Matthias Bissinger, Ralf Ballhausen, Natalie Hell, SungNam Park, Moses Chung, Moritz Hoesch, Jörn Seltmann, Andrey S. Surzhykov, Vladimir A. Yerokhin, Jörn Wilms, F. Scott Porter, Thomas Stöhlker, Christoph H. Keitel, Thomas Pfeifer, Gregory V. Brown, Maurice A. Leutenegger, Sven Bernitt; **Phys. Rev. Lett. 124, 225001 (2020).**

3C $([(2p^5)_{1/2}3d_{3/2}]_{J=1} \rightarrow [2p^6]_{J=0})$

3D $([(2p^5)_{3/2}3d_{5/2}]_{J=1} \rightarrow [2p^6]_{J=0})$

TABLE S5. Contributions to the 3C and 3D line strengths S and the 3C/3D oscillator strength ratios (energy ratio 1.01655 is used). Energies in eV, transition rates A in s^{-1} and natural linewidths Γ in meV are listed in the last three rows of the tables.

	$S(3C)$	$S(3D)$	Ratio
Small basis	0.11217	0.03183	3.582
Medium basis	0.11241	0.03198	3.573
Large basis	0.11240	0.03199	3.572
+ triple excitations	0.11241	0.03198	3.573
$+1s^2$ shell excitations	0.11233	0.03201	3.567
+QED	0.11221	0.03212	3.552
Final	0.1122(2)	0.0321(4)	3.55(5)
Energies (eV)	825.67	812.22	
A (s^{-1})	$2.238(4) \times 10^{13}$	$6.10(7) \times 10^{12}$	
Γ (meV)	14.74(3)	4.02(5)	

Experiment:

$\mathbf{3.09 \pm 0.08_{stat.} \pm 0.06_{sys.}}$

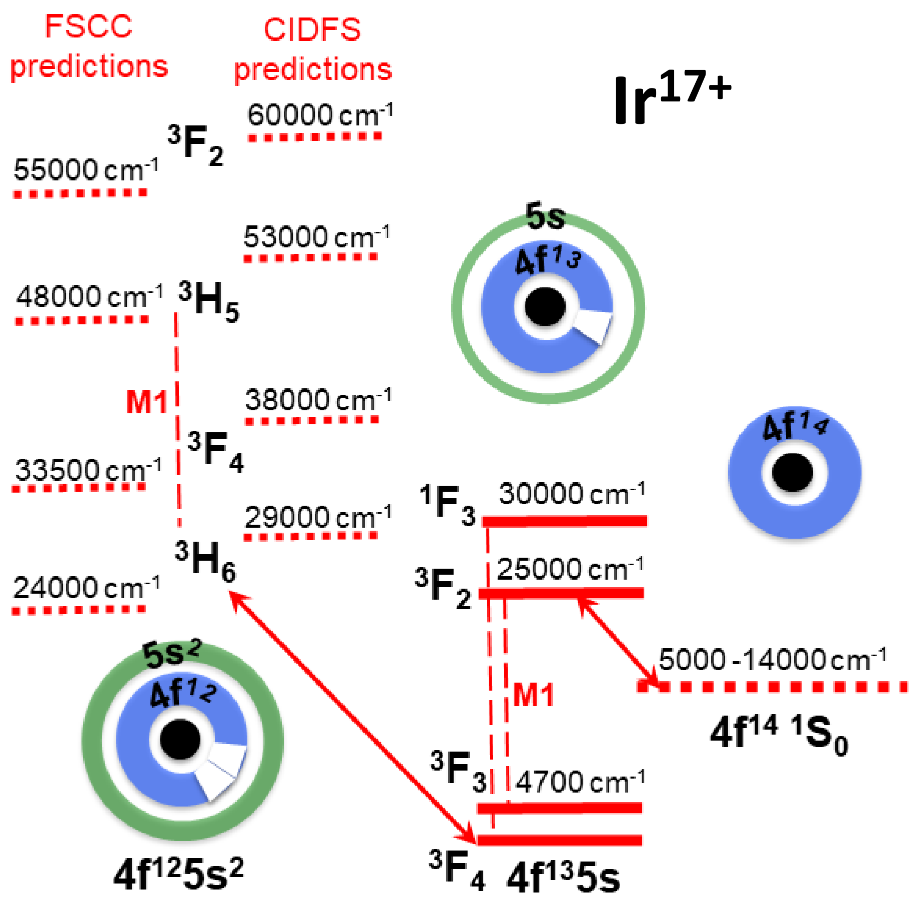
Full correlation of 10 electrons – nothing else to include at this level of accuracy!

Recent theory progress in predicting properties of highly-charged ions

Accurate prediction of clock transitions in a highly charged ion with complex electronic structure

C. Cheung, M. S. Safronova, S. G. Porsev, M. G. Kozlov, I. I. Tupitsyn, A. I. Bondarev, **Phys. Rev. Lett. 124, 163001 (2020)**

First configuration interaction calculation for 60 electrons with all shells open!



Clock transitions???

E1 transitions???

Previous predictions (FAC):

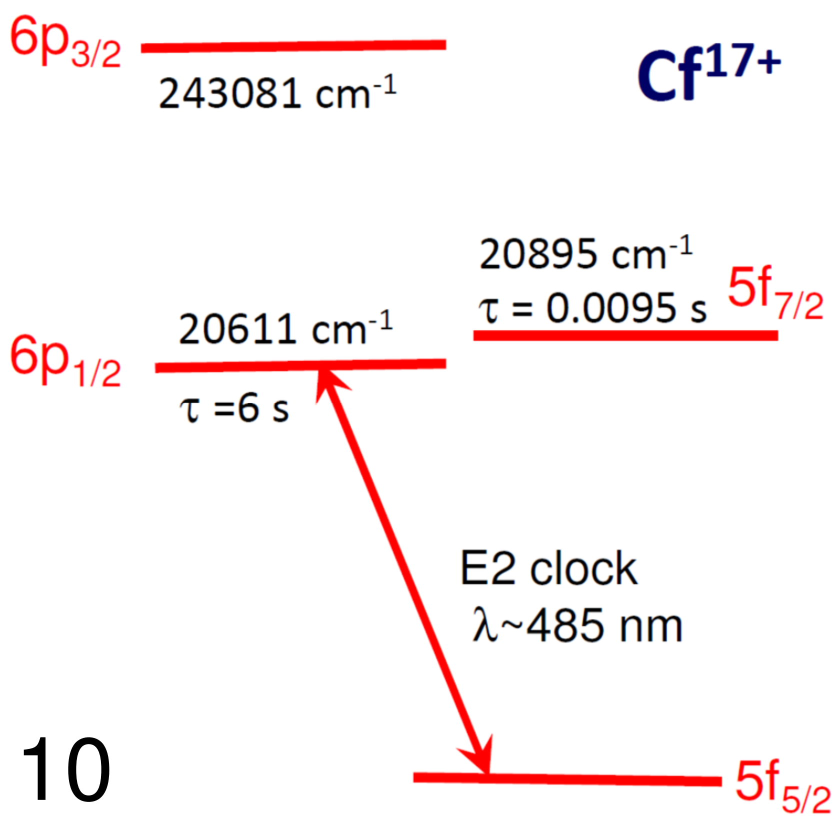
E1 Transition	Rate (s^{-1})
$4f^{12}\,5s^2\,{}^3F_4 - 4f^{13}\,5s\,{}^3F_4^o$	~~71~~ 0.2
$4f^{12}\,5s^2\,{}^3F_4 - 4f^{13}\,5s\,{}^3F_3^o$	~~48~~ 1.2
$4f^{12}\,5s^2\,{}^3F_2 - 4f^{13}\,5s\,{}^1F_3^o$	~~163~~ 3

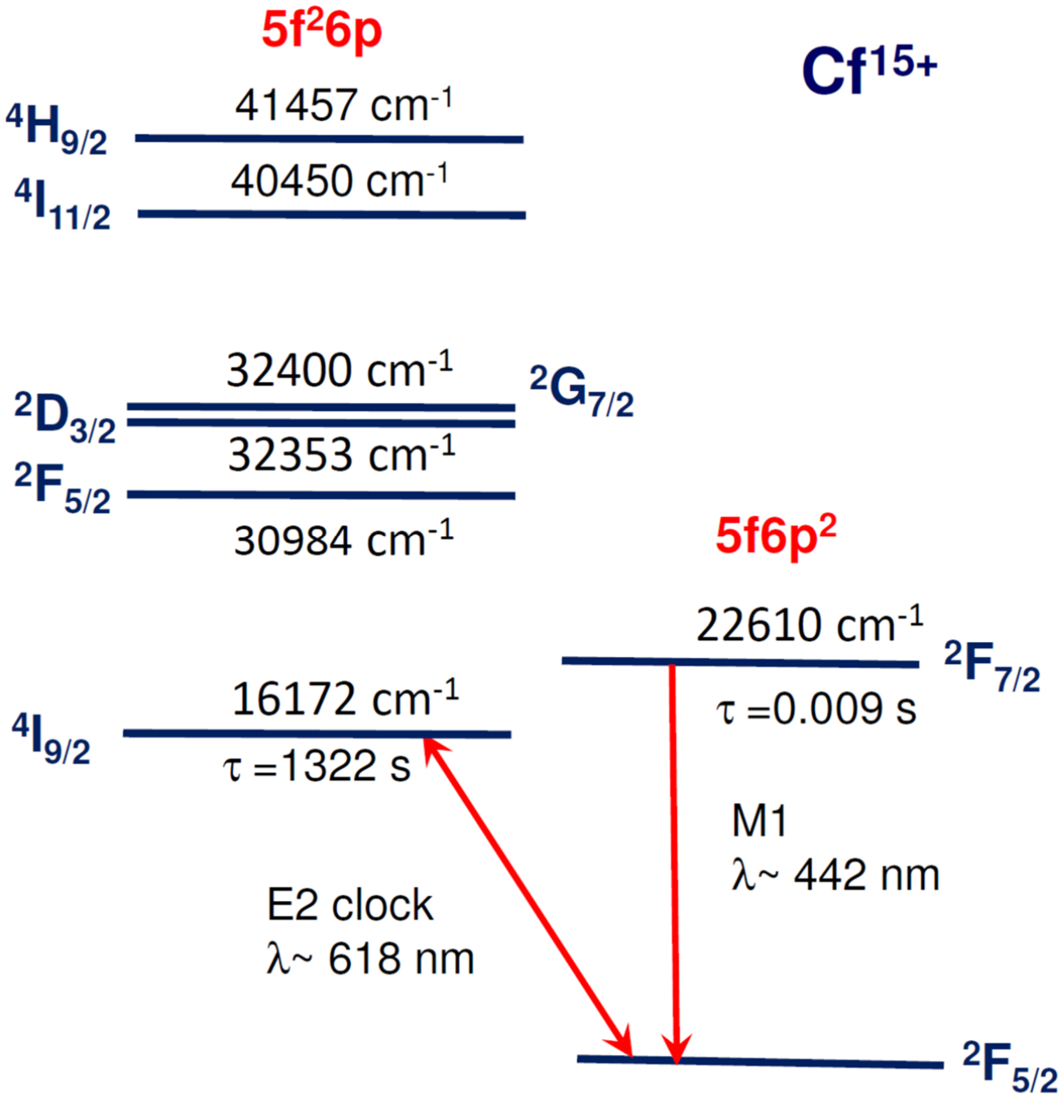
Hendrik Bekker, FAC calculations, private communication vs. new results

New computations in progress: all strong E1 transitions; Between $4f^{12}5s^2$-$4s^{12}5s5p$ and $4f^{13}5s$-$4f^{13}5p$ configurations

Optical clocks based on the Cf^{15+} and Cf^{17+} ions

^{249}Cf I = 9/2 (351 y)
^{250}Cf I = 0 (13.1 y)
^{251}Cf I = 1/2 (898 y)





$\Delta K \approx 110$

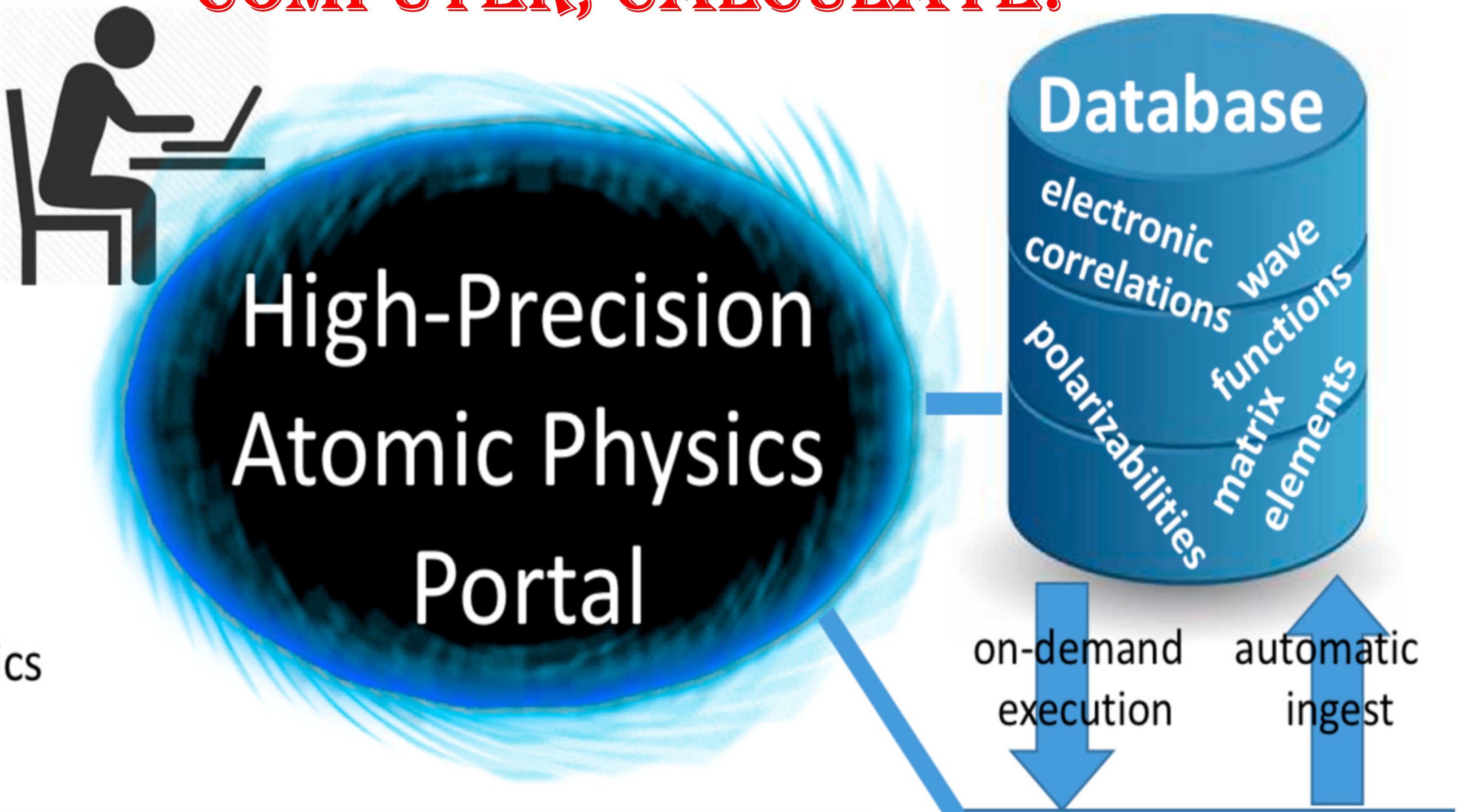
S. G. Porsev, U. I. Safronova, M. S. Safronova, P. O. Schmidt, A. I. Bondarev, M. G. Kozlov, I. I. Tupitsyn, PRA 102, 012802 (2020)

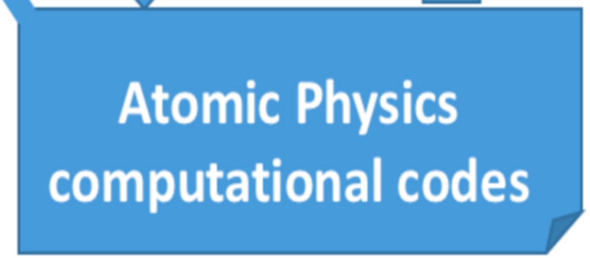
New project at University of Delaware in collaboration with computer science

COMPUTER, CALCULATE!

Applications in science and engineering

- quantum information
- degenerate quantum gases
- atomic clocks
- precision measurements
- plasma physics
- astrophysics
- studies of fundamental physics

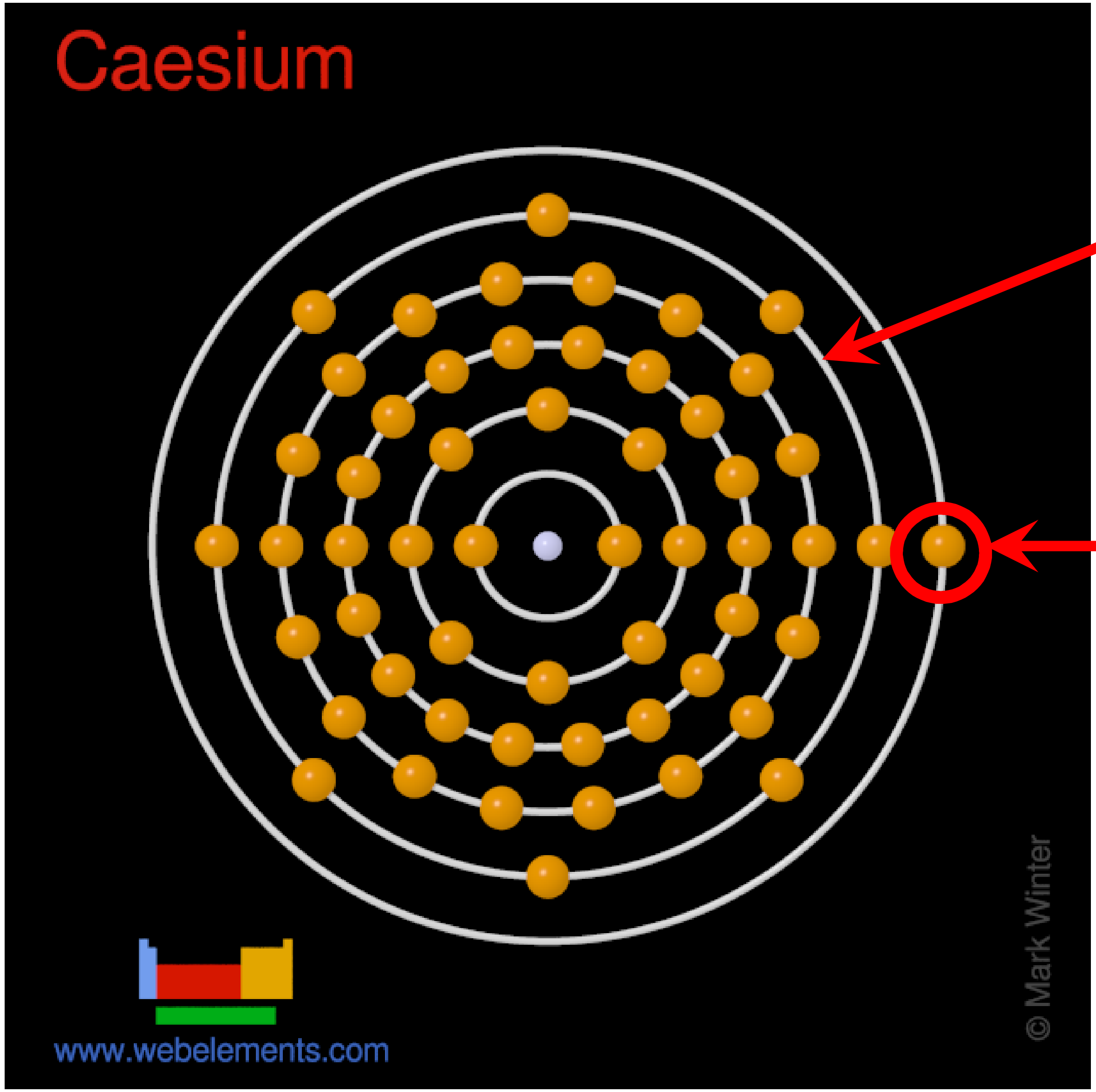




Building on:

- CI+MBPT/CI+all-order program package and expertise
- Portal technology (Science Gateways, Hubzero,…)
- Parallel programming methodology

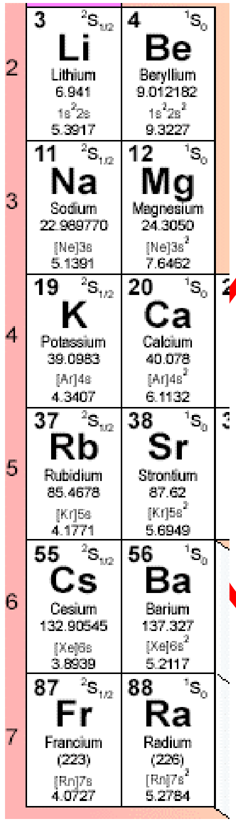
Classify atomic calculations by difficulty level



Closed shells
Can be approximated by a mean field

Single valence electron

Classify atomic calculations by difficulty level



Group 1
Calculations we can do "routinely", with default parameters

1 – 2(3) valence electrons

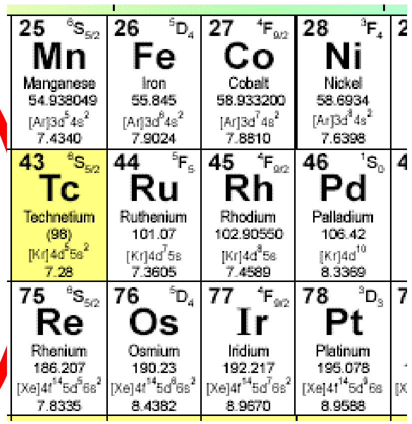
Can automate: already done for 1 valence electron

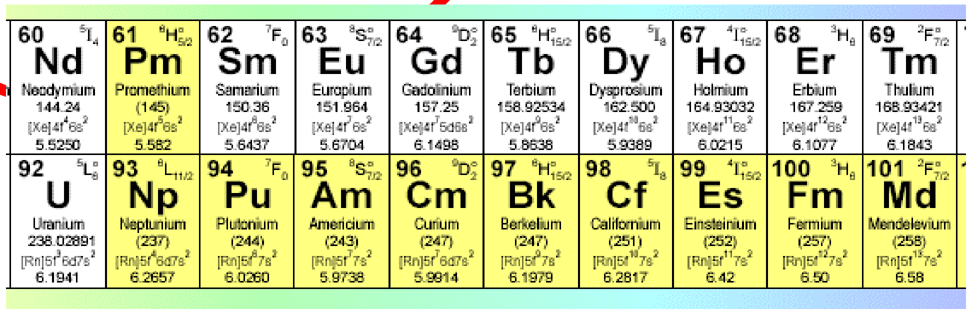
Group 2
Calculations that require expert knowledge

(3)/4-6 valence electrons or special cases with more valence electrons

Only calculations of wave functions requires expert knowledge

Group 3
No precision methods exist: **exponential scaling** with the number of valence electrons





Half-filled shells and holes in shells

Method development in progress, need new ideas – machine learning

Codes for monovalent systems are completely automated
OpenMP version just has been developed

COMPUTER, CALCULATE Th^{3+}!

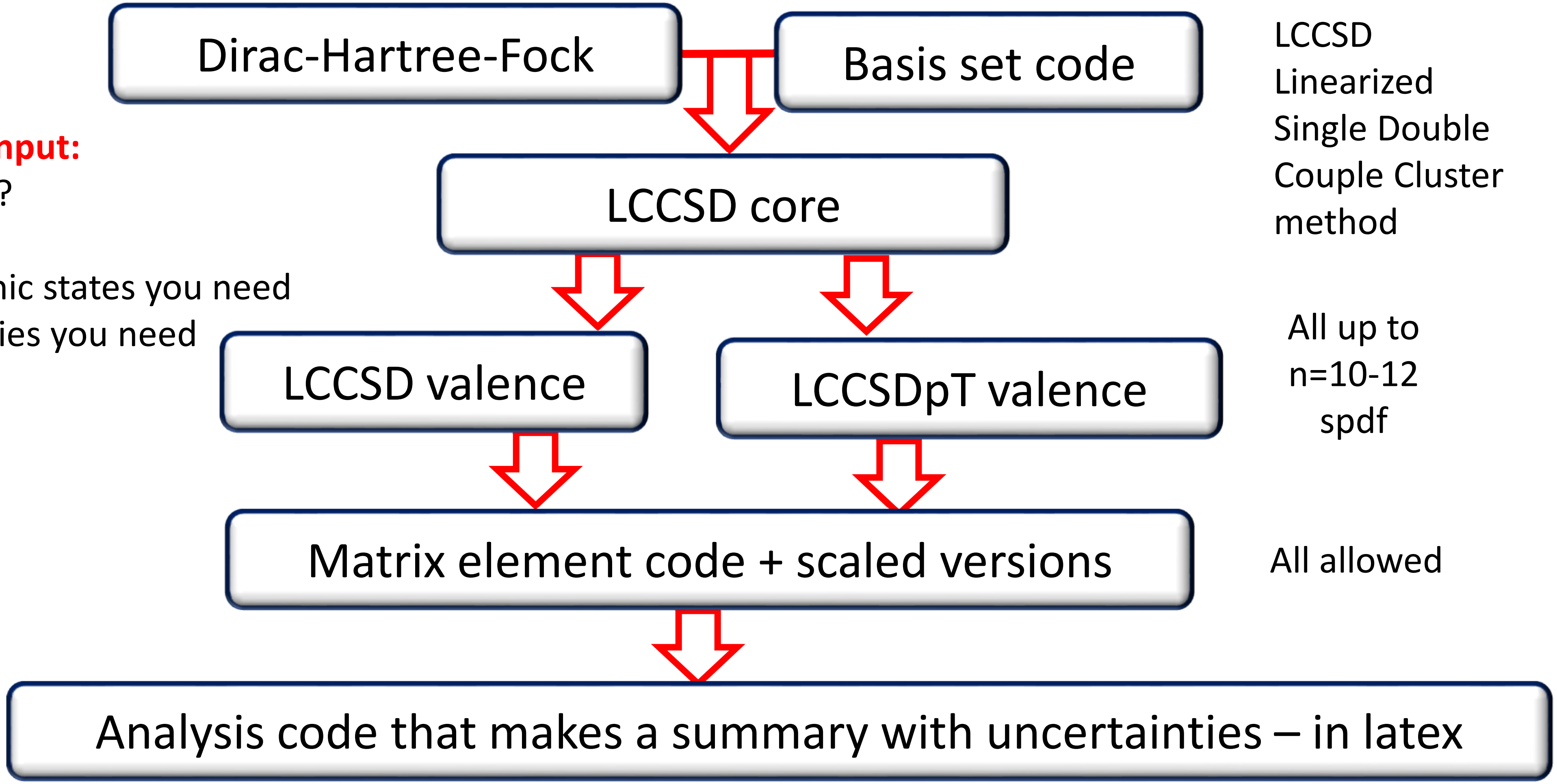
Only need to input:

Which isotope?

Core shells

Which electronic states you need

Which properties you need



LCCSD
Linearized
Single Double
Couple Cluster
method

All up to
n=10-12
spdf

All allowed

Online Portal will provide:

A: Transition matrix elements, transition rates, branching ratios, lifetimes; E1, E2, and M1 matrix elements

B: Dynamic polarizabilities & magic wavelength

C: Many other data (hyperfine constants, etc).
Computations-of –the fly from online requests.

Uncertainty estimates will be provided for all data.

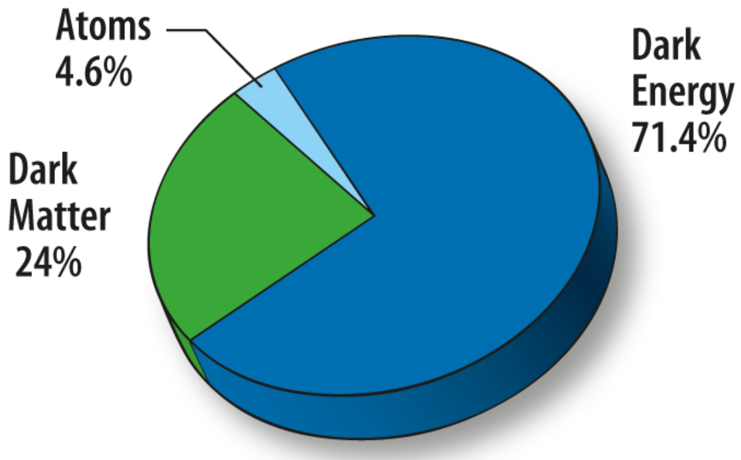
Code release, tutorials, online workshops, guest scientists & future international portal collaborations

Plan to release version 1 of the portal next month, December 2020
Next release: more monovalents, all alkaline-earth metals: Be, Mg, Ca, Sr, Ba, Ra & similar ions: Al+, etc.
Email me which atoms/ions/data would you like to see included into the portal project.

Atomic & nuclear clocks:

Great potential for discovery of new physics

Many new developments coming in the next 10 years!



Need NEW IDEAS how to use quantum technologies for new physics searches

Research scientist:
Sergey Porsev

Graduate students:
Charles Cheng, Aung Naing, Adam Mars, Hani Zaheer

Online portal collaboration, Electrical & Computer Engineering:
Prof. Rudolf Eigenmann, graduate student: Parinaz Barakhshan
Prof. Bindiya Arora, GNDU, India

Senior Research Associate position (with postdoc experience) is available now

Another postdoc position will become available in January

Contact Marianna Safronova (msafrono@udel.edu) for more information

COLLABORATORS:

Mikhail Kozlov, PNPI, Russia
Ilya Tupitsyn, St. Petersburg University, Russia
José Crespo López-Urrutia, MPIK, Heidelberg
Piet Schmidt, PTB, University of Hannover
Gilad Perez, The Weizmann Institute of Science, Israel

Thorium nuclear clocks for fundamental tests of physics

Thorsten Schumm, TU Wein
Ekkehard Peik, PTB
Peter Thirolf, LMU