Atomic and nuclear clocks for ultralight dark matter detection

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thorium nuclear clock

https://thoriumclock.eu/

Q-SEnSE
An NSF Quantum Leap Challenge Institute

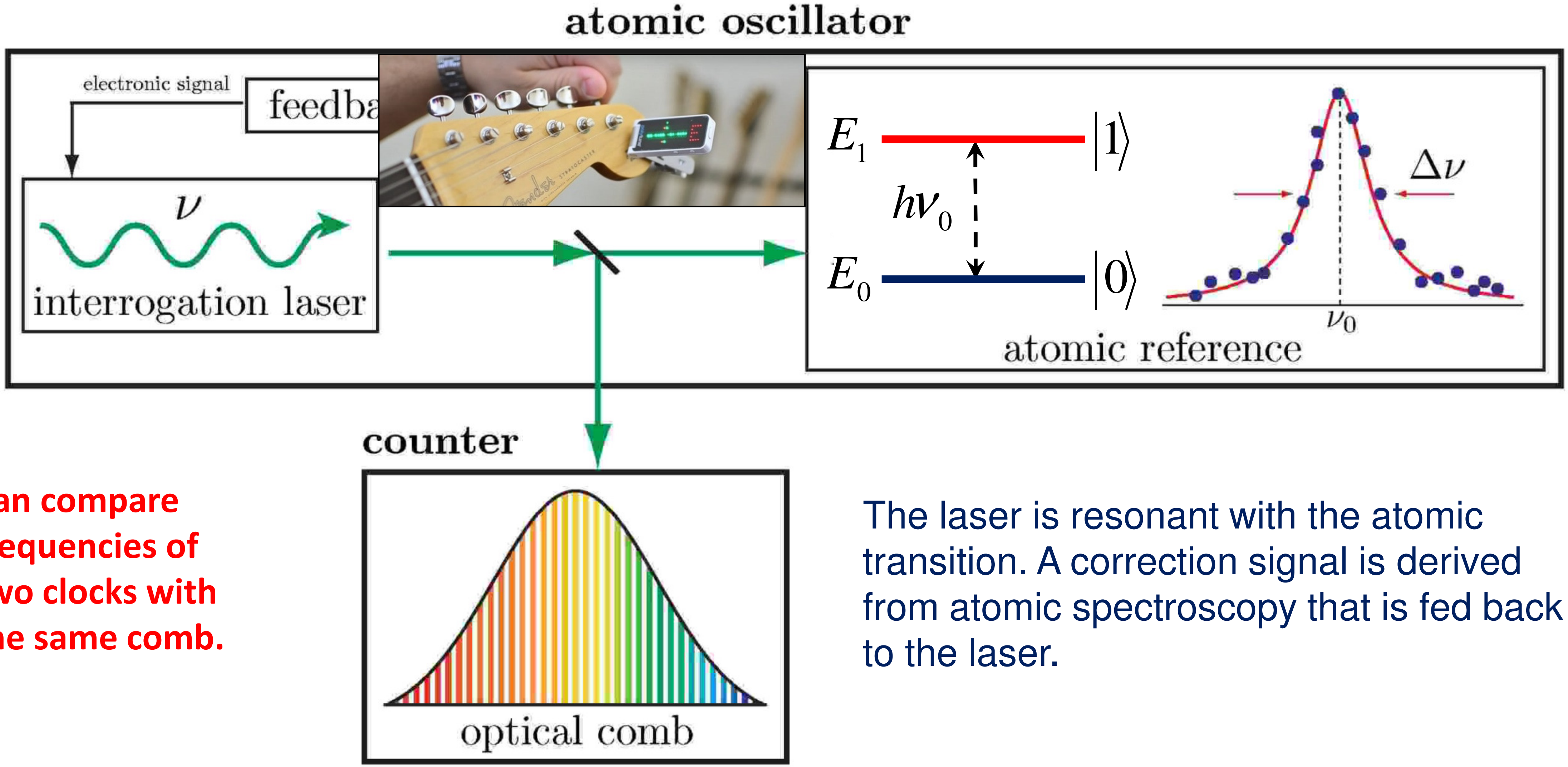
https://www.colorado.edu/research/qsense/

NSF

Office of Naval Research Science & Technology

erc
European Research Council

How optical atomic clock works



Can compare frequencies of two clocks with the same comb.

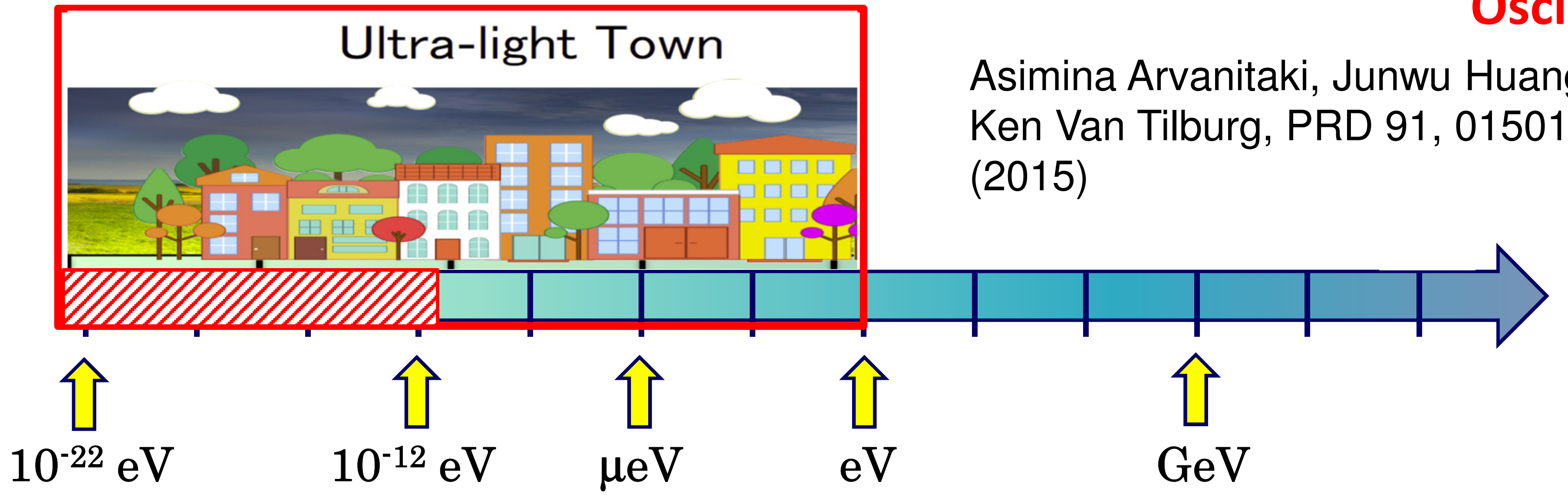
The laser is resonant with the atomic transition. A correction signal is derived from atomic spectroscopy that is fed back to the laser.

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 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"

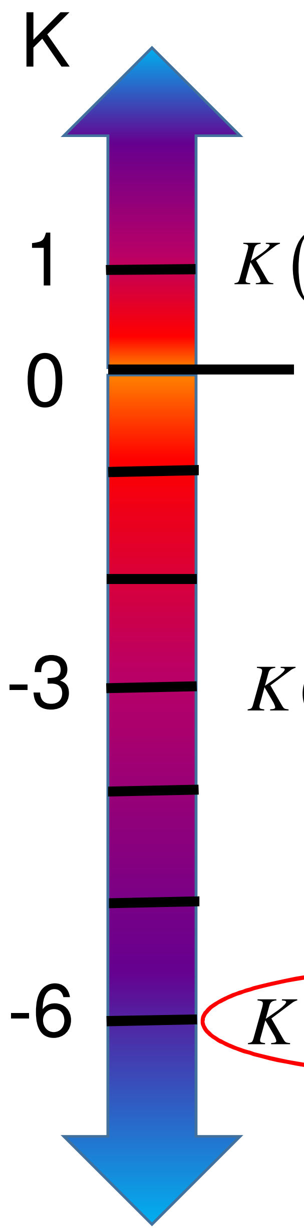
It will make fundamental coupling constants and mass ratios oscillate

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) – effects are much stronger for some clocks

Sensitivity factors for current clocks

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



$K(Sr^+) = 0.4$

$K(Yb) = 0.3$

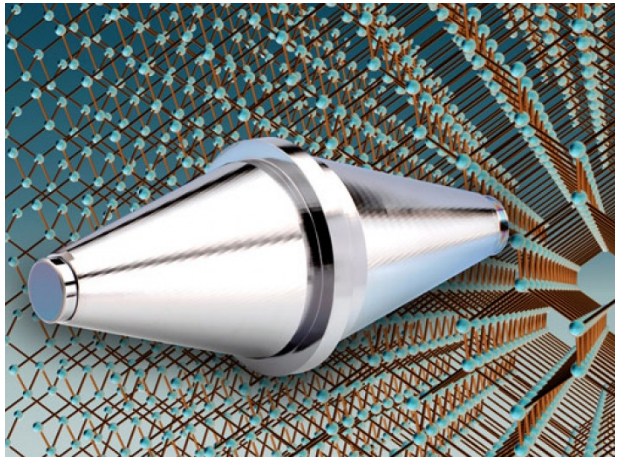
$K(Hg) = 0.8, \quad K(Yb^+ E2) = 1$

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

$K(Hg^+) = -2.9$

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

Cavity: part of the clock laser systems Effective



$$\frac{\partial}{\partial t} \ln \frac{\nu_2}{\nu_1} = (K_2 - K_1) \frac{1}{\alpha} \frac{\partial \alpha}{\partial t}$$

Accuracy of the clock-comparison (i.e. frequency ratio)

Accuracy of α-variation test

Observable: ratio of two clock frequencies

Measure a ratio of Al^{+} clock frequency to Hg^{+} clock frequency

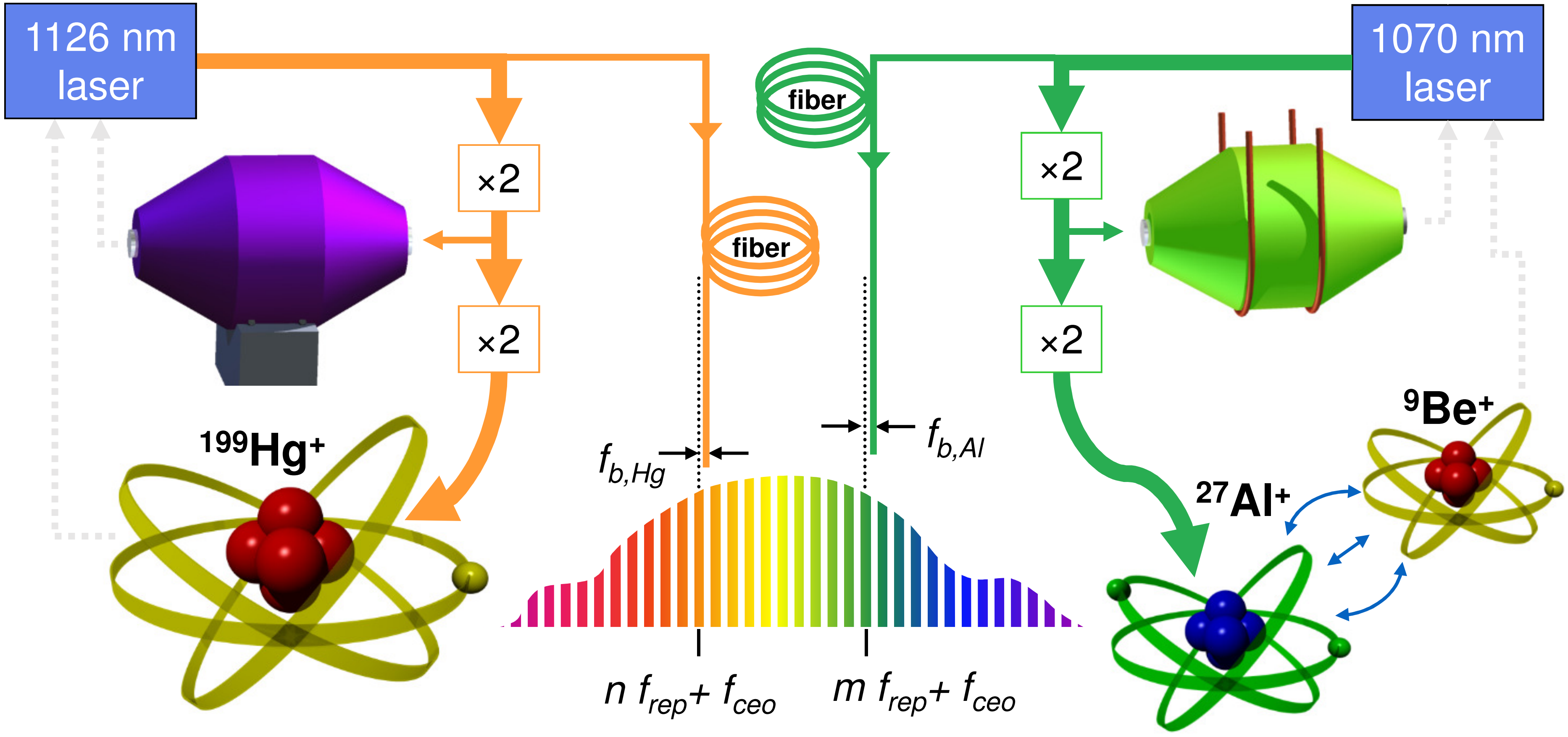
$$\frac{\nu\left(Hg^{+}\right)}{\nu\left(\mathrm{Al}^{+}\right)}$$

$$K(Hg^{+}) = -2.9$$

$$K\left(Al^{+}\right) = 0.01$$

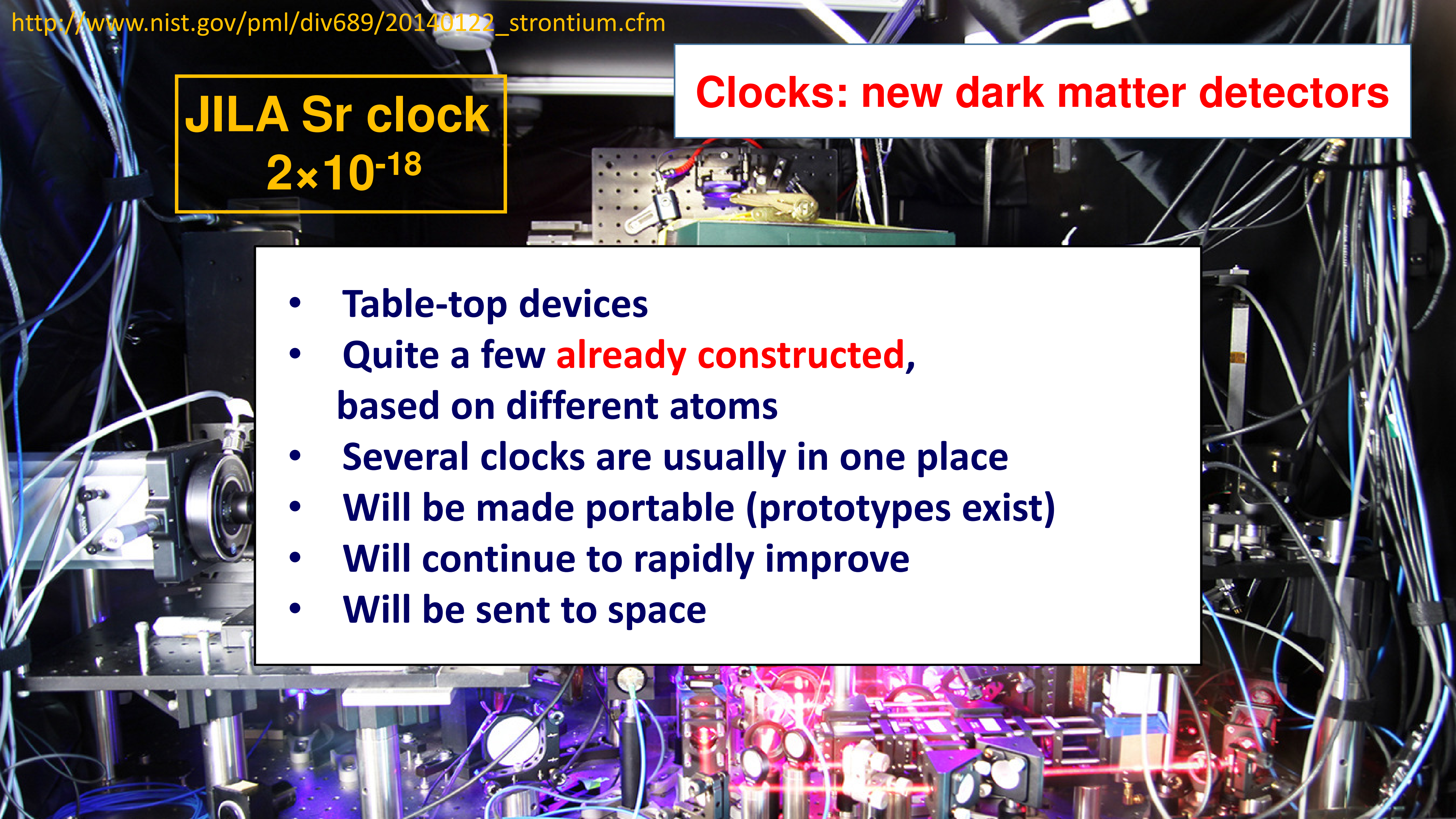
Sensitivity factors

Not sensitive to α-variation, used as reference



Picture credit: Jim Bergquist

Science 319, 1808 (2008)



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

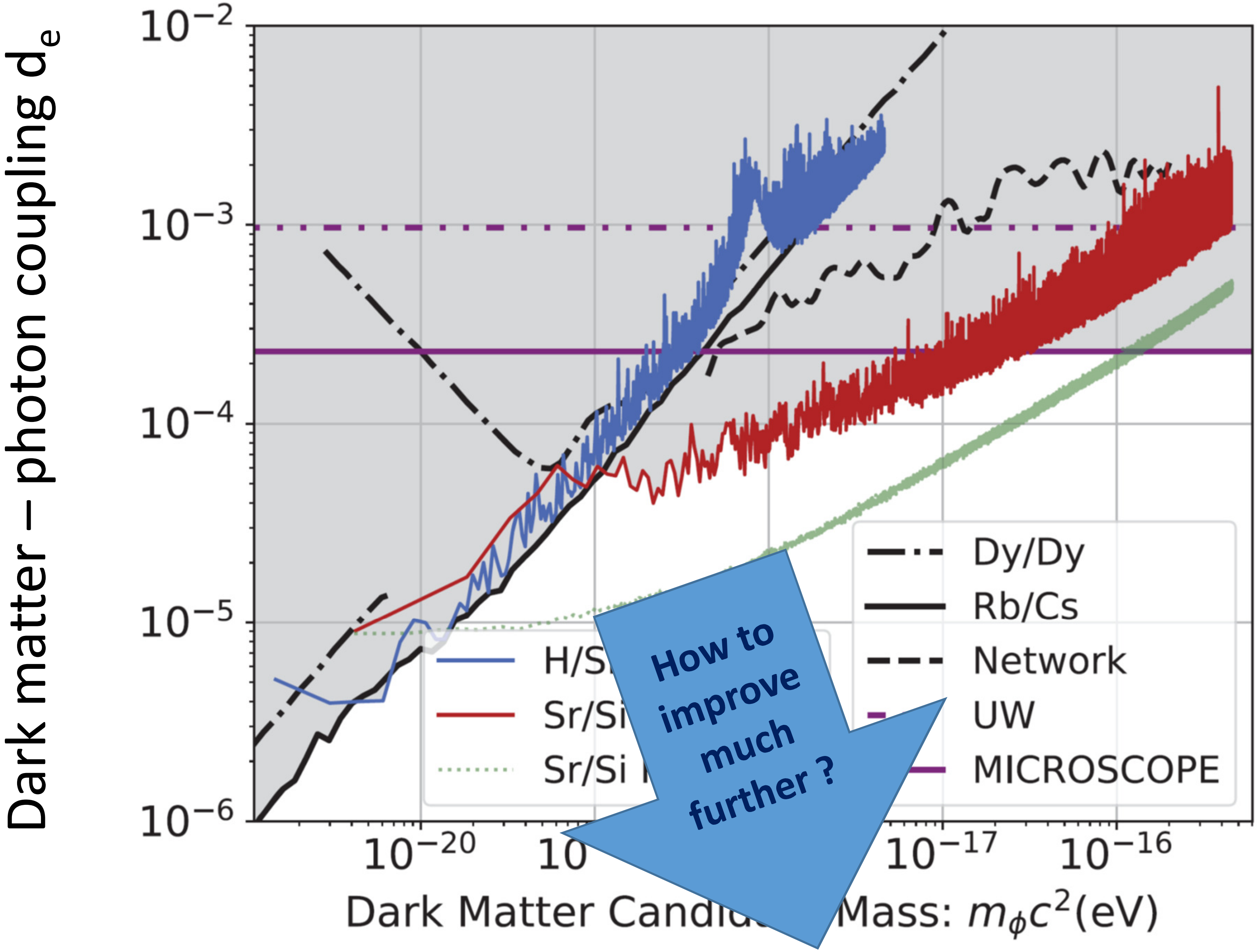
Clocks: new dark matter detectors

JILA Sr clock
2×10^{-18}

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

The most recent limit: JILA Sr clock-cavity comparison C. Kennedy et al., PRL 125, 201302 (2020).

Oscillating dark matter bounds

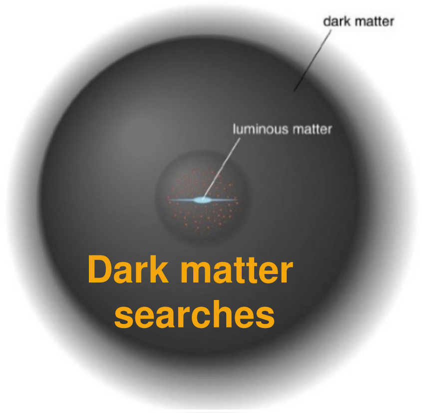


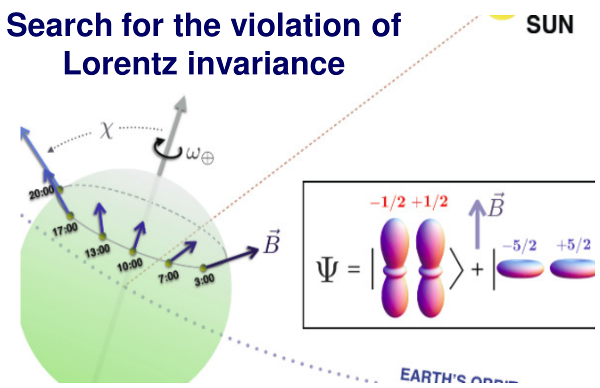
Highly charged ions (HCIs) for ultra-precise clocks

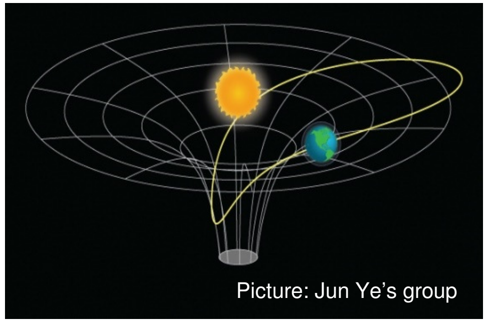
HCIs: **much larger** sensitivity to variation of α and dark matter searches then current clocks

- Enhancement factor K>100, most of present clocks K<1, Yb^+ E3 K=6
- Hyperfine HCI clocks sensitive to m_e/m_p ratio and m_q/Λ_{QCD} ratio variation
- Additional enhancement to Lorentz violation searches

HCI review: Rev. Mod. Phys. 90, 45005 (2018)

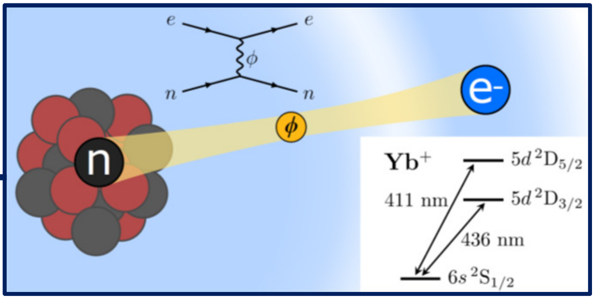






Tests of the equivalence principle

- Searches for the variation of fundamental constants
- Tests of QED: precision spectroscopy
- Fifth force searches: precision measurements of isotope shifts with HCIs to study non-linearity of the King plot



5 years: Optical clocks with selected HCIs will reach 10^{-18} accuracy
10 years: Strongly α-sensitive transitions in HCIs will reach of 10^{-18} uncertainty, multi-ion HCI clocks

Thorium nuclear clocks for fundamental tests of physics

Thorsten Schumm, TU Wein
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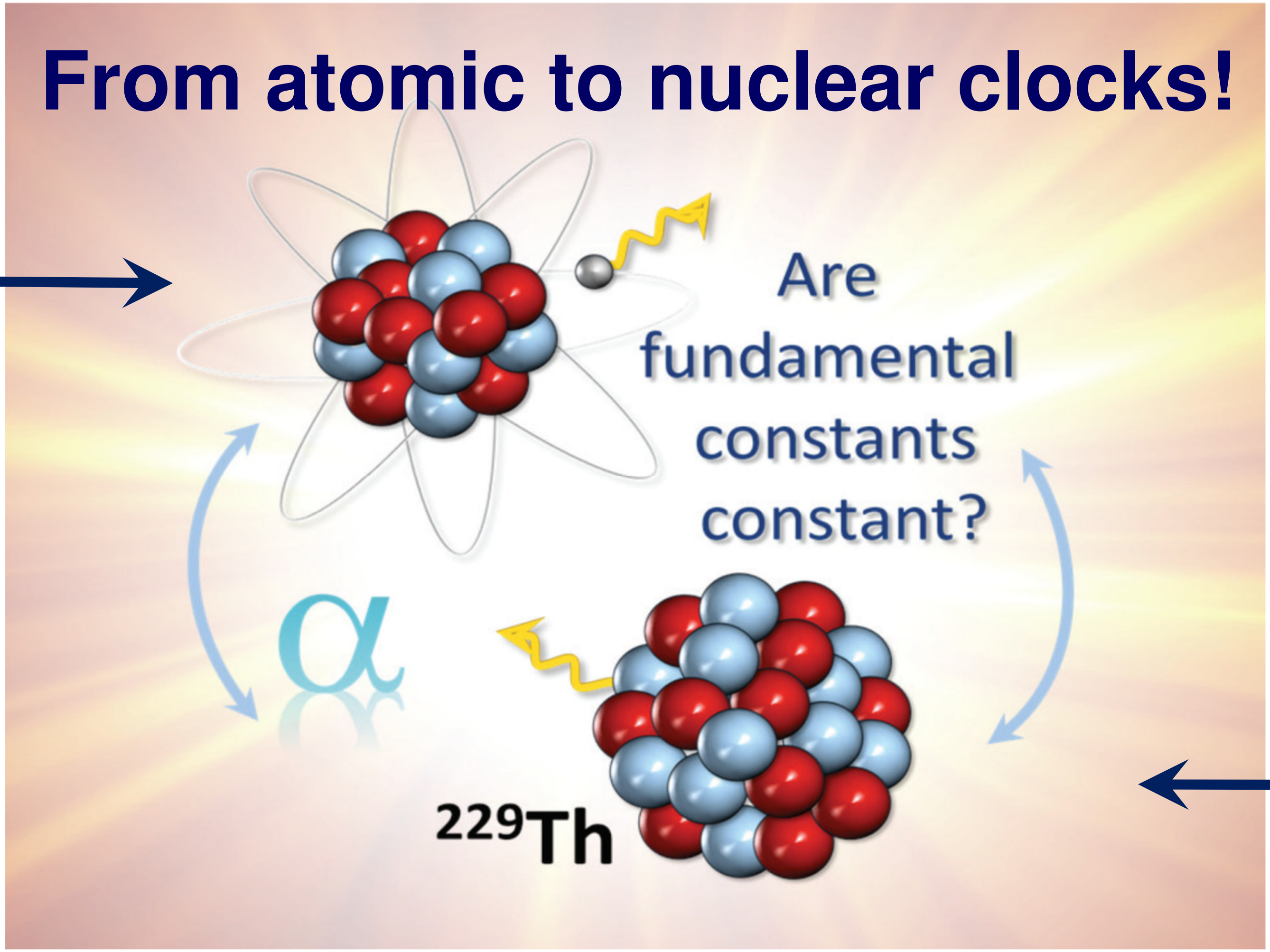
https://thoriumclock.eu/

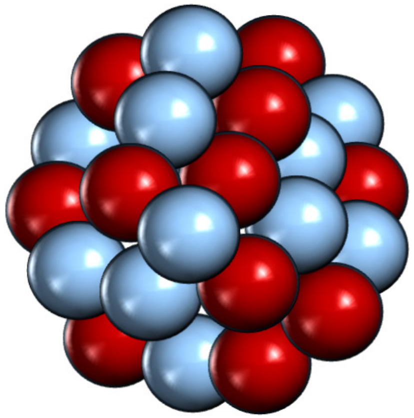
Clock based on transitions in atoms

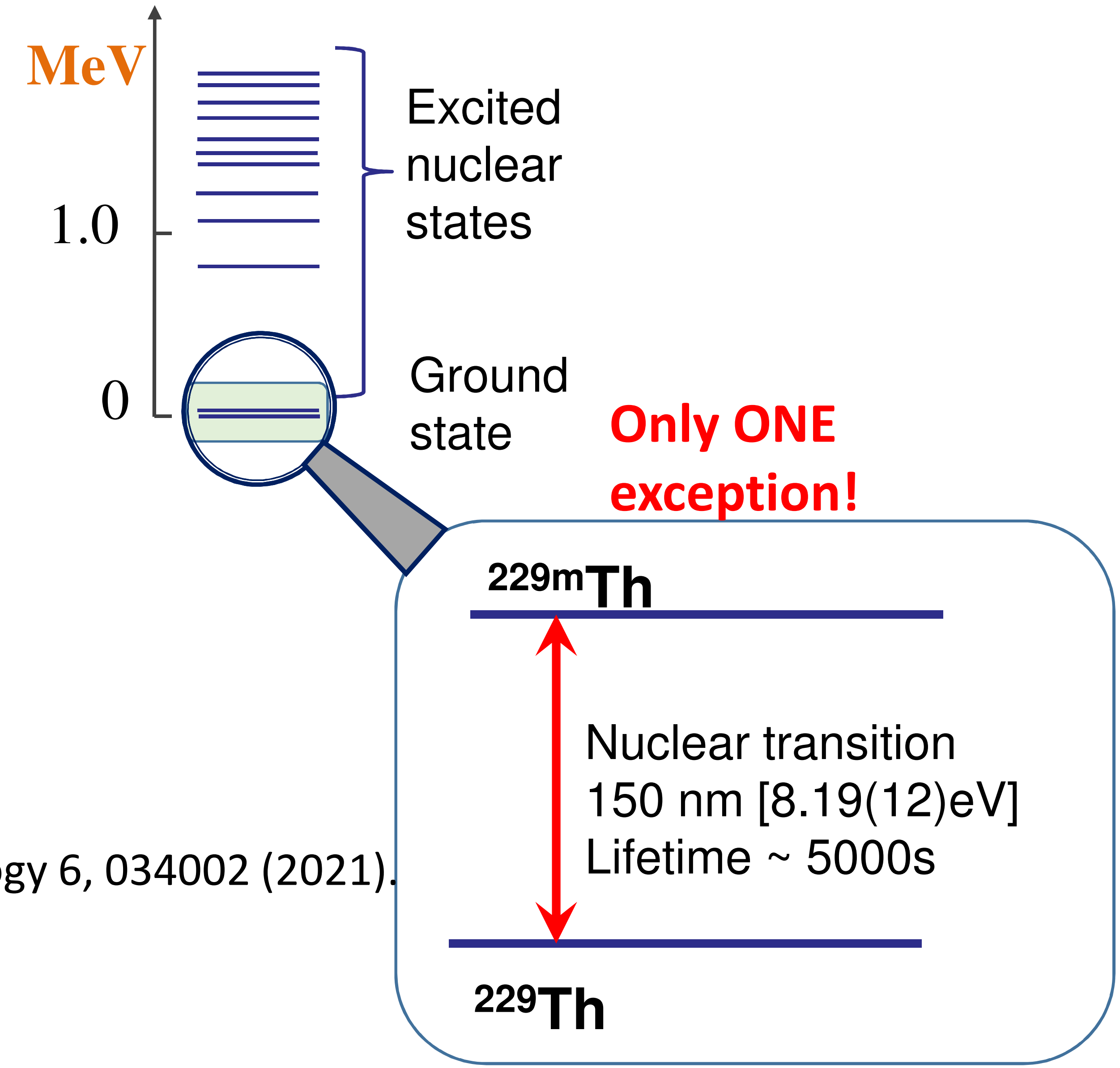


Clock based on transitions in nuclei

Th nuclear clock

Atomic
Nucleus



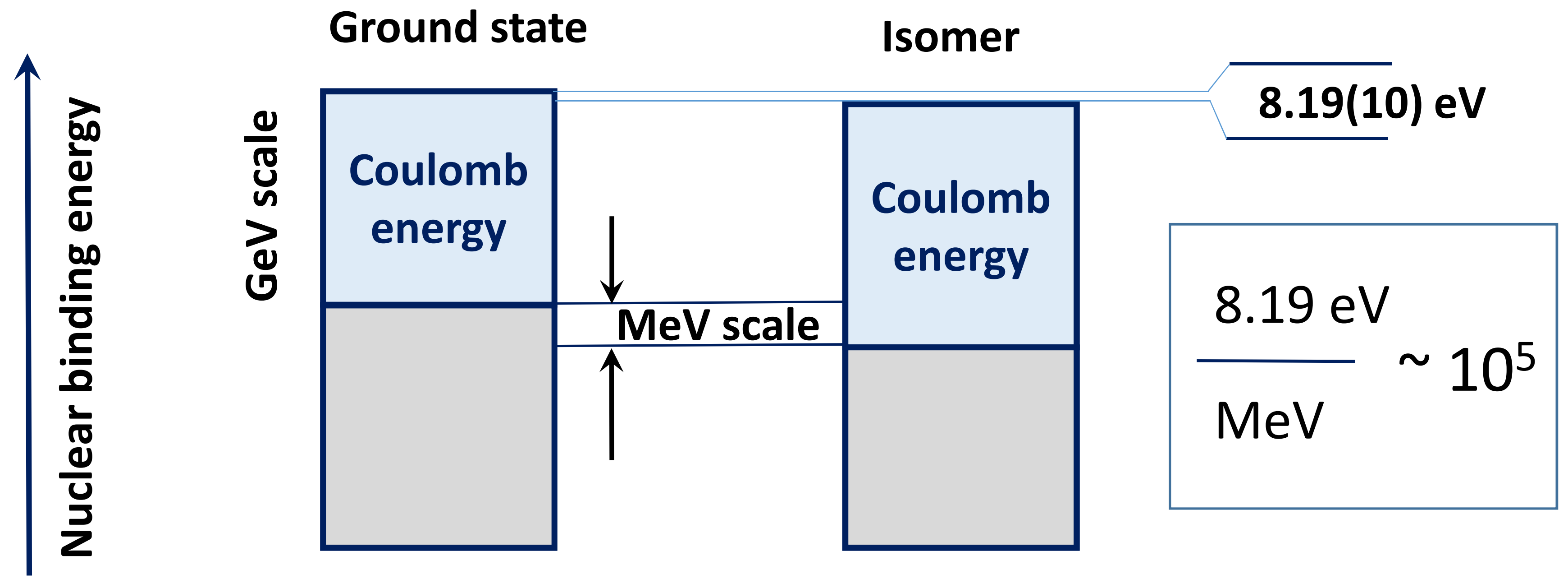


Only ONE exception!

Energy of the ^{229}Th nuclear clock transition:
Seiferle *et al.*, Nature 573, 243 (2019)
T. Sikorsky et al., Phys. Rev. Lett. 125, 142503 (2020).

Review: E. Peik, et al., Quantum Science and Technology 6, 034002 (2021).

Th nuclear clock: Exceptional sensitivity to new physics



Much higher predicted sensitivity (K = 10000-100000) to the variation of α and $\frac{m_q}{\Lambda_{QCD}}$.

Nuclear clock is sensitive to coupling of dark matter to the nuclear sector of the standard model.

5 years: prototype nuclear clocks, based on both solid state and trapped ion technologies
Measure isomer properties to establish of sensitivity to new physics
Variation of fundamental constant and dark matter searches competitive with present clock

10 years: 10^{-18} – 10^{-19} nuclear clock, 5 - 6 orders improvement in current clock dark matter limits

Atomic & nuclear clocks:

Many new developments coming in the next 10 years!

Need particle physics theory support

Questions for theory

- **What new physics can a network of clocks probe that two-clock or clock-cavity system in one place can not? Need more theory on transient objects.**

- Can network of clocks or Earth-space clock network probe the same new physics much better precision (beyond the statistics improvement)?

- What new physics can we probe by sending clocks to space?
  What is the preferred orbit? NASA BPS Decadal Survey

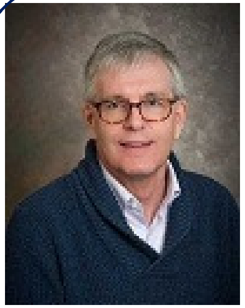
- What specific dark matter candidates can clocks probe?
  Relaxions? Possible dark matter transients besides domain walls?

- Clocks as part of the multi-messenger astronomy? Transient signals correlated with LIGO/VIRGO gravitational wave detection – what are their potential sources and detection strategy.

- Ultralight dark matter clustering (i.e. can we have more dark matter to detect due to Earth/Sun gravitational wells?)

UD team and collaborators

Online portal team



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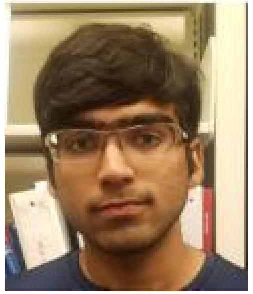

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August 2021

Postdoc position in dark matter searches with quantum technologies will be available
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Dmitry Budker, Mainz and UC Berkeley, Andrew Jayich, UCSB, Murray Barrett, CQT, Singapore, José Crespo López-Urrutia, MPIK, Heidelberg , Piet Schmidt, PTB, University of Hannover, Charles Clark, JQI, and many others!