Search for new physics with atoms and molecules: CLOCKS

Andrei Derevianko

University of Nevada, Reno

Search for New Physics with Atoms and Molecules

M.S. Safronova, D. Budker, D. DeMille, Derek F. Jackson Kimball, A. Derevianko, C. W. Clark

(Submitted on 5 Oct 2017)

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

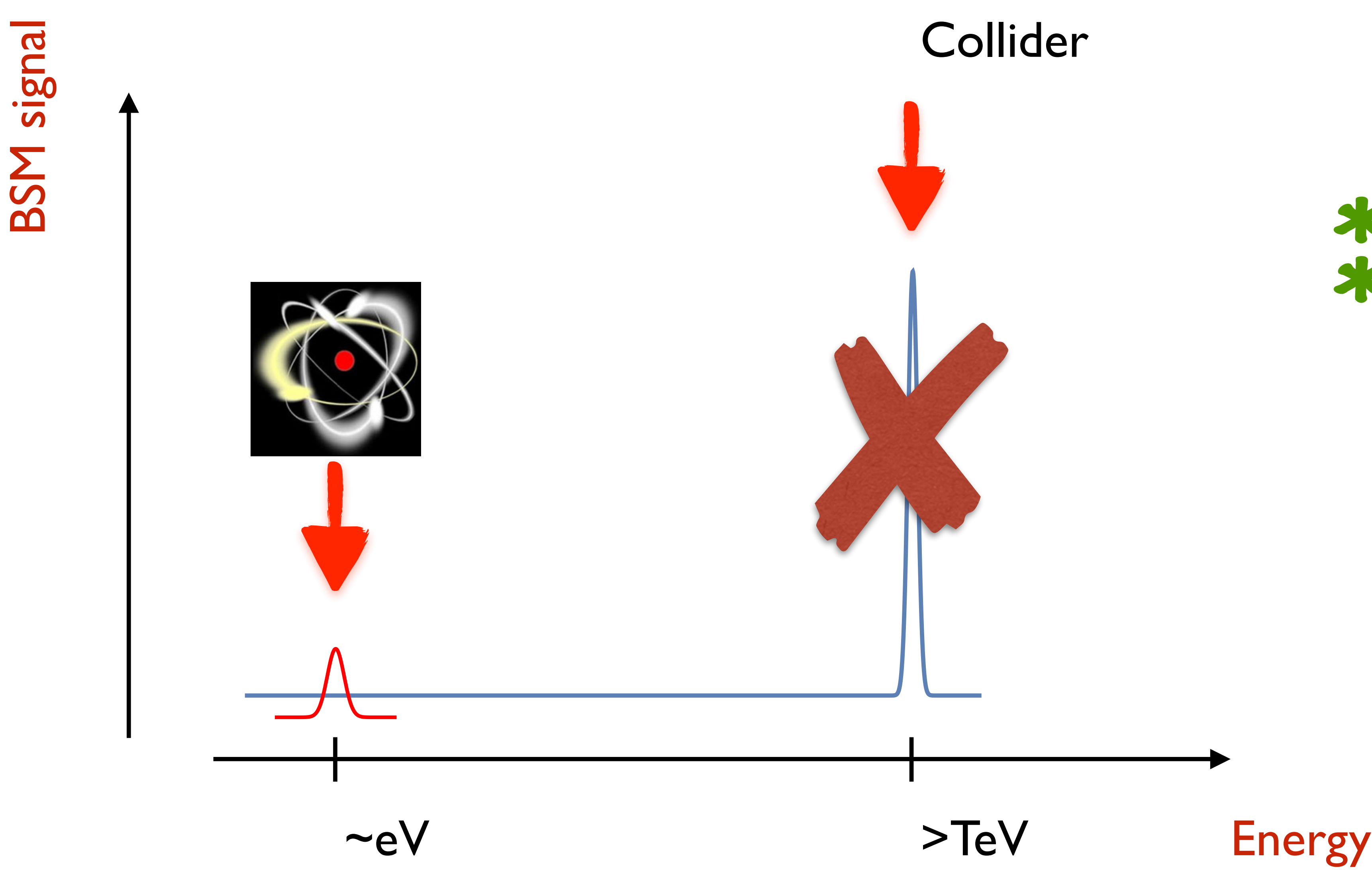
Comments: 112 pages, 24 figures
Subjects: **Atomic Physics (physics.atom-ph)**; High Energy Physics - Phenomenology (hep-ph)
Cite as: **arXiv:1710.01833 [physics.atom-ph]**
(or **arXiv:1710.01833v1 [physics.atom-ph]** for this version)

Rev. Mod. Physics in press

Listening to an atom

- Precision/understanding of traditional physics
- Statistics [1 kg of Cs atoms in atomic parity violation experiments]

=> Extreme listening capabilities



- Wings of resonances
- Weak low-energy resonances

Outline

- How to talk to an AMO friend
- Atomic clocks
- Ultralight dark matter signatures
- First results from the GPS.DM observatory

Mini tutorial:
Interfacing AMO and particle physics

Gained in translation

Units

Natural units: c=1 & hbar=1

Atomic units: |e|=1 & hbar=1 & m_e=1

$c_{atomic} = 1/\alpha \approx 137$

Rationalized Heaviside-Lorentz vs Gaussian

$$\alpha = \left(\frac{e^2}{\hbar c}\right)_{\text{CGS}} = \left(\frac{e^2}{4\pi}\right)_{\text{Natural}} = \left(\frac{1}{c}\right)_{\text{atomic}}$$

Please restore all your hbar's and c's for AMO-centric talks and papers!

Gained in translation

Model builder: $\mathcal{L}_{\rm int} = -\frac{\phi}{\Lambda} m_e \bar{e} e \equiv -\frac{\phi}{\Lambda} m_e c^2 \, \bar{\psi}_e \psi_e$

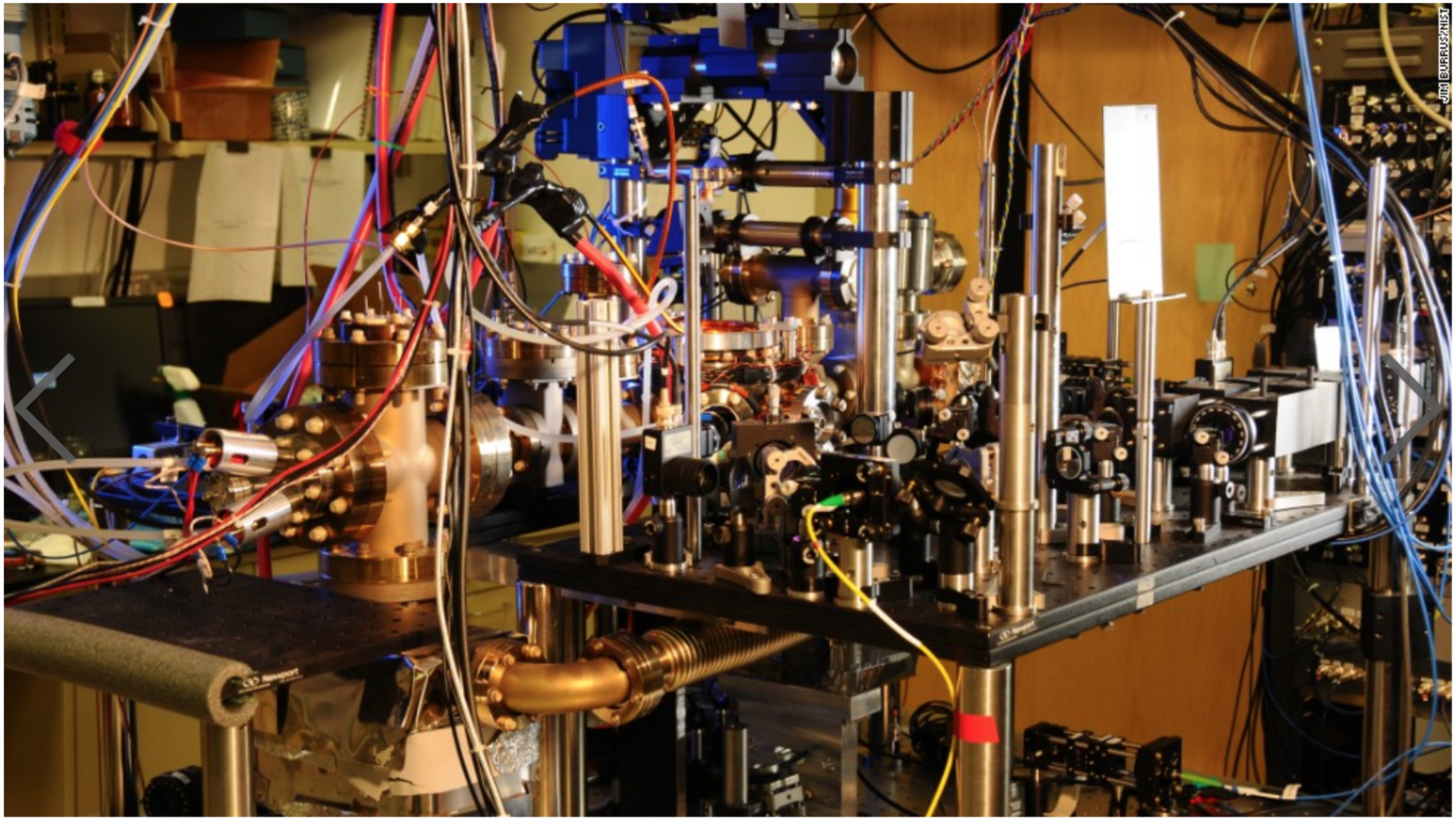
Extra term in Dirac Hamiltonian

$$V_{\rm int}\psi_e = -\gamma^0 \left[\frac{\partial \mathcal{L}_{\rm int}}{\partial \bar{\psi}_e} - \partial_\mu \left(\frac{\partial \mathcal{L}_{\rm int}}{\partial \left(\partial_\mu \bar{\psi}_e \right)} \right) \right] = \frac{\phi}{\Lambda} m_e c^2 \beta \psi_e$$

$$H = c\alpha \cdot \mathbf{p} + \underbrace{m_e c^2 \left(1 + \frac{\phi(\mathbf{r},t)}{\Lambda} \right)}_{\text{Variation in the electron mass}} \beta$$

\+ Non-relativistic reduction (Pauli approx/Foldy–Wouthuysen)

Health » The most accurate clock in the world is redefining the second



Photos: Keeping time

Researchers have created this atomic clock using the atoms of the element ytterbium at the National Institute of Standards and Technology in Boulder, Colorado. They say it could be the most precise method of measuring time in the world. Click through to explore other clocks that are important in other ways.

Recent reviews:

Ludlow, Boyd, Ye, Peik, and Schmidt, Rev. Mod. Phys. **87**, 637 (2015)

Derevianko and Katori, Rev. Mod. Phys. 83, 331 (2011)

What does an AMO theorist do? UNR group & clocks

Fountains: *PRL 97, 040801 (2006); PRA 79, 013404 (2009); PRA 93, 012503 (2016)*

Micromagic clocks: *PRL 106, 063002 (2011); PRA 81, 051606(R) (2010); PRL 102, 120801 (2009); PRA 79, 013404 (2009); PRL 101, 220801 (2008)*

Optical lattice clocks: *RMP 83, 331 (2011); PRA 81, 030302 (2010); JPB 43 074011 (2010); PRL 103, 133201 (2009); PRA 74, 020502 (2006); PRA 69, 042506 (2004); PRA 69, 021403 (2004)*

Yb lattice clock

Nuclear clocks: *PRL 108, 120802 (2012)*

Highly-charged ions: *PRL 107, 093003 (2011); PRL 109, 180801 (2012); PRA 86, 054502 (2012); PRA 86, 054501 (2012); PRL 113, 233003 (2014)*

What is time?

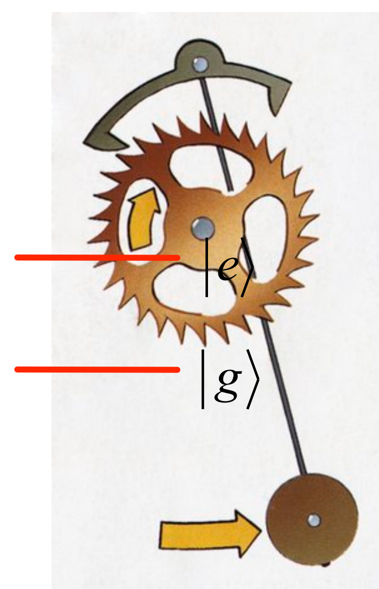
TIME (according to Merriam-Webster)

a : the measured or measurable period during which an action, process, or condition exists or continues

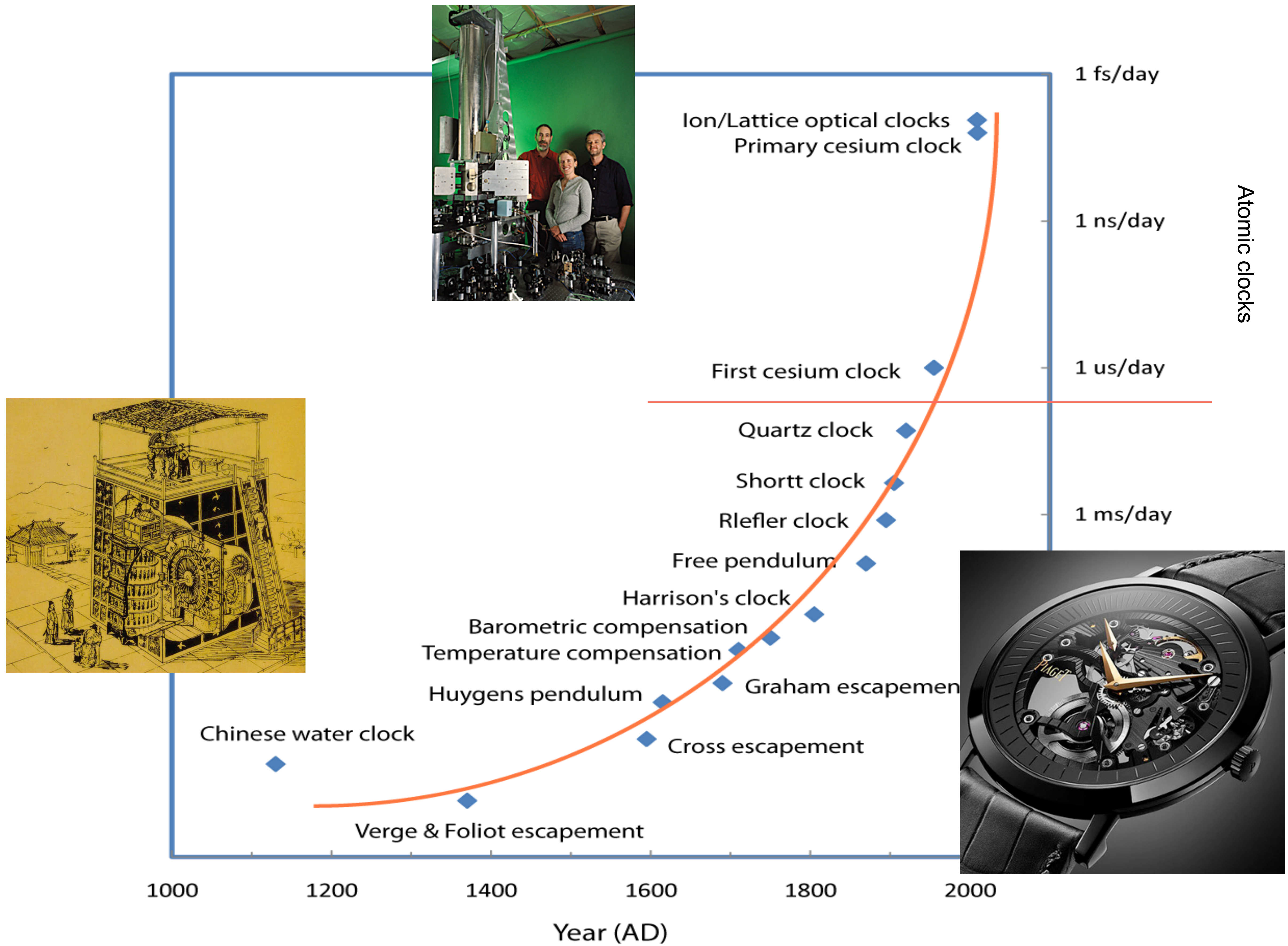
b : a nonspatial continuum that is measured in terms of events which succeed one another from past through present to future

Eq.(1)

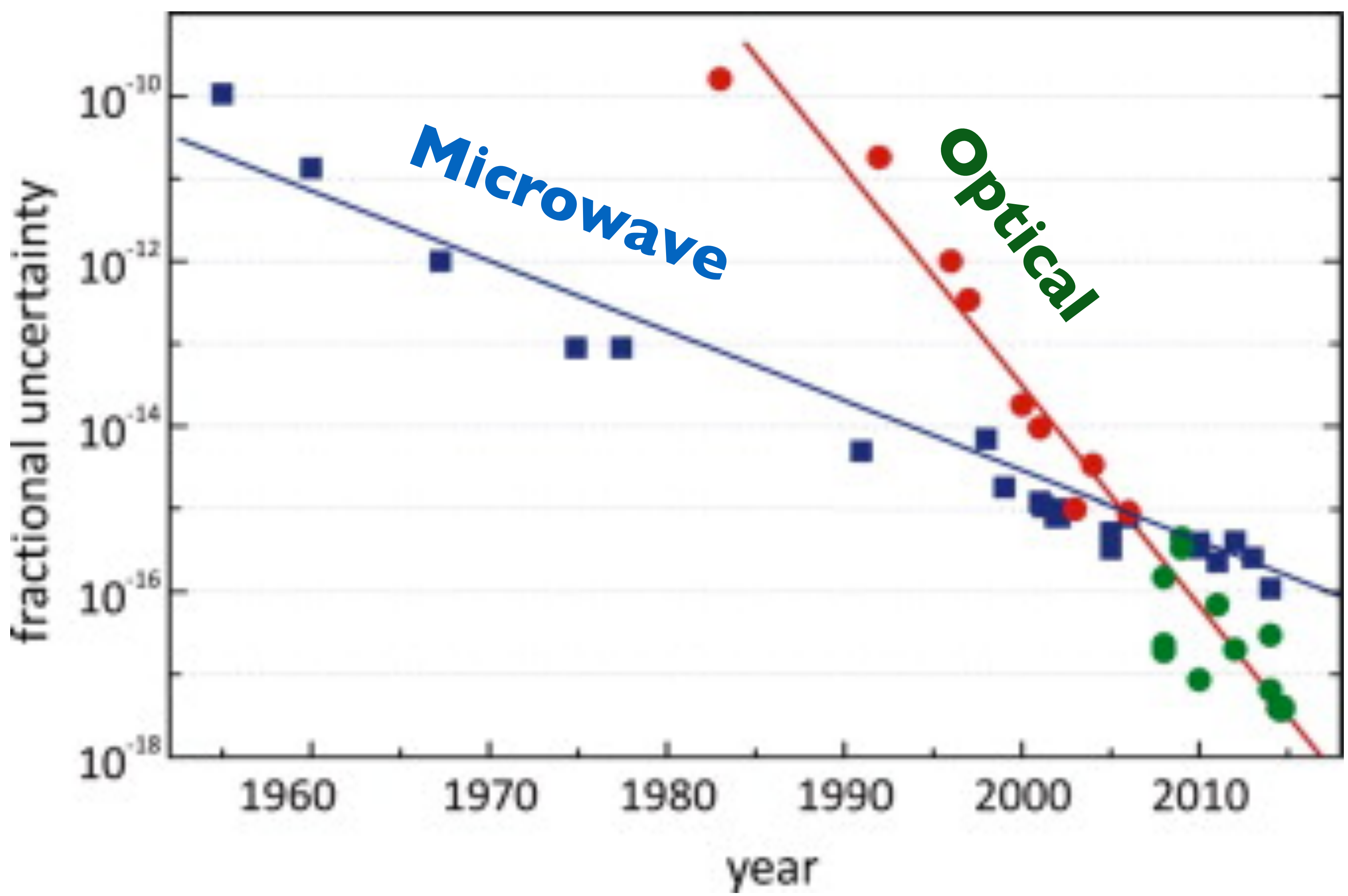
Time = (number of oscillations) x (fixed & known period)



$$\nu_{\text{clock}} = \frac{E_e - E_g}{h}$$


1 fs/day
1 ns/day
1 us/day
1 ms/day
Atomic clocks
Ion/Lattice optical clocks
Primary cesium clock
First cesium clock
Quartz clock
Shortt clock
Rlefler clock
Free pendulum
Harrison's clock
Barometric compensation
Temperature compensation
Graham escapemen
Huygens pendulum
Chinese water clock
Cross escapement
Verge & Foliot escapement
1000
1200
1400
1600
1800
2000
Year (AD)

Recent progress



F. Riehle, Towards a redefinition of the second based on optical atomic clocks. Comptes Rendus Phys. 16, 506–515 (2015).

Atomic clocks

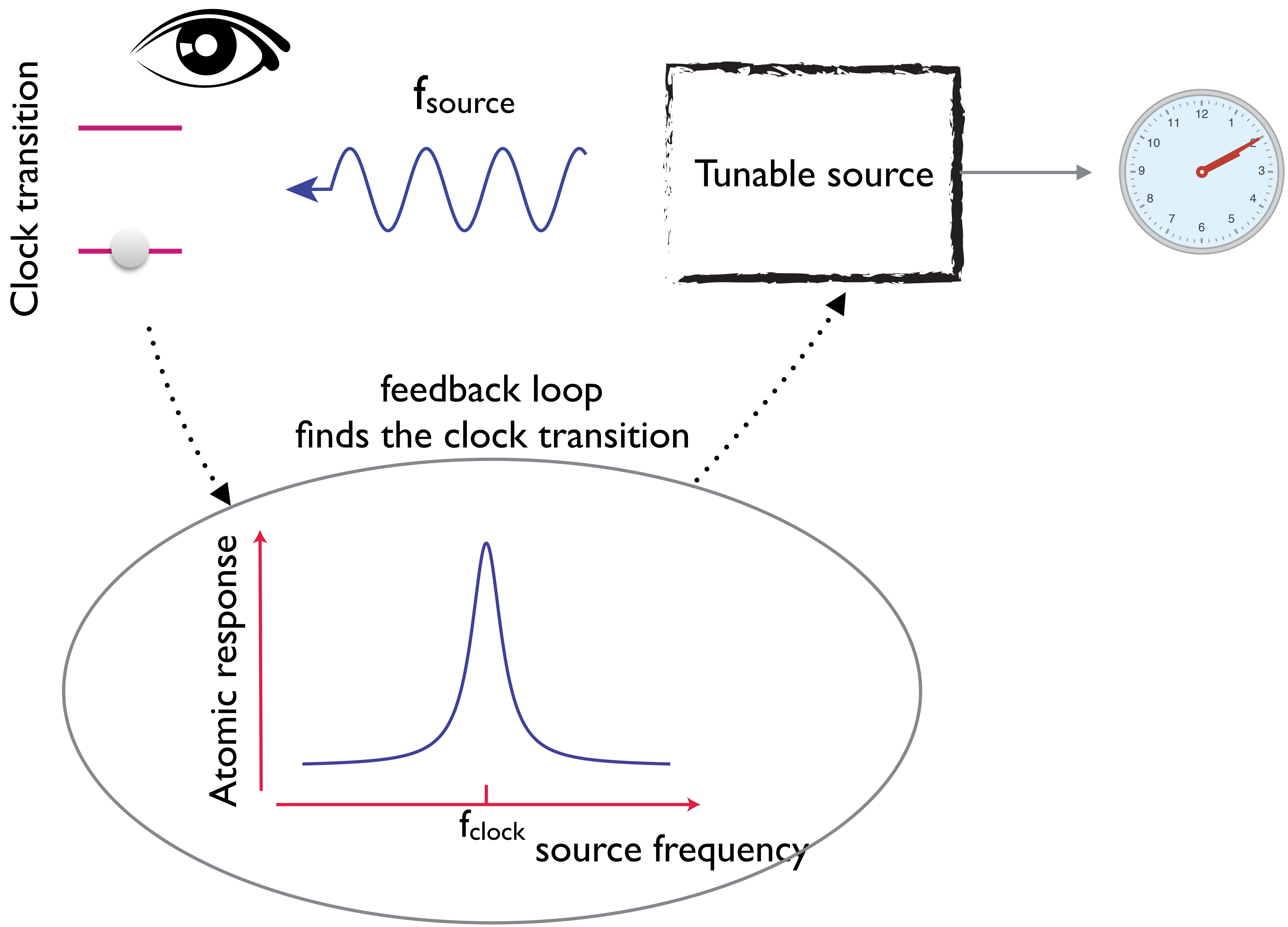
- Most precise instruments ever built
- Modern nuclear/atomic clocks aim at 19 significant figures of precision
- Best limits on modern-epoch drift of fundamental constants

$$\Delta t = \left(\frac{\Delta\omega}{\omega_{\text{clock}}}\right) \times t = 1\,\text{s}$$

fractional inaccuracy 10^{-18}

Age of the universe 10^{18} s

Operation of atomic clock



Atomic clock taxonomy

Clock frequency

Microwave

Hyperfine transitions

- Cs fountains[10^{-16}]
- Rb beam/cell
- Hg+ ion clock
- Hydrogen maser
- ….

Optical

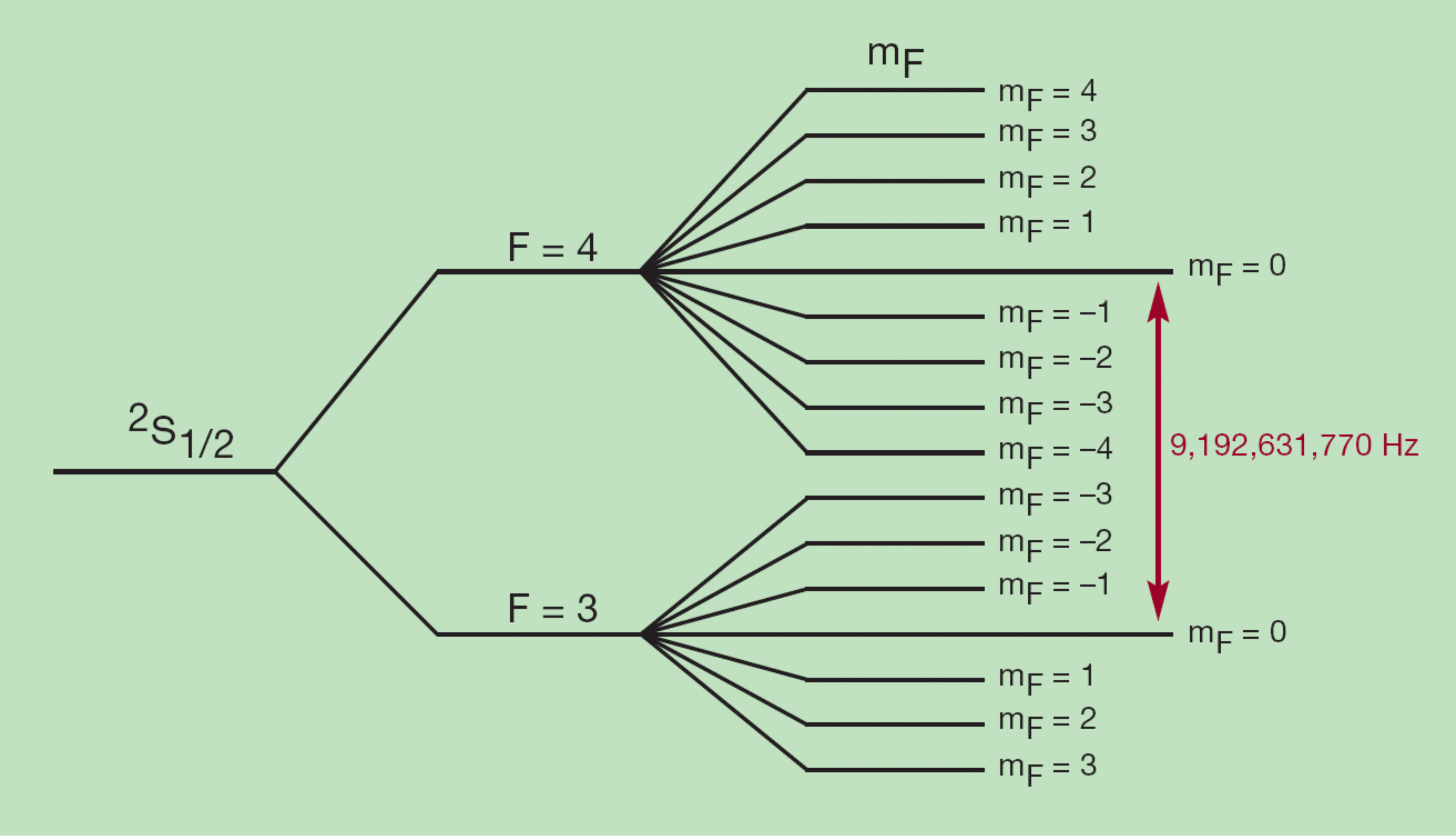
- Al+,Yb+,… ion [10^{-18}]
- Sr,Yb,.. optical lattice [10^{-18}]
- Th nuclear [$<10^{-19}$]
- Highly-charged ions [$<10^{-19}$]
- ….

XUV

Highly-charged ions

SI definition of the second

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 cesium 133 atom. This definition refers to a cesium atom at rest at a temperature of 0 K.



Example of evaluating accuracy

Single-Ion Nuclear Clock for Metrology at the 19th Decimal Place

C. J. Campbell, A. G. Radnaev, A. Kuzmich, V. A. Dzuba, V. V. Flambaum, and A. Derevianko

Phys. Rev. Lett. 108, 120802 (2012)

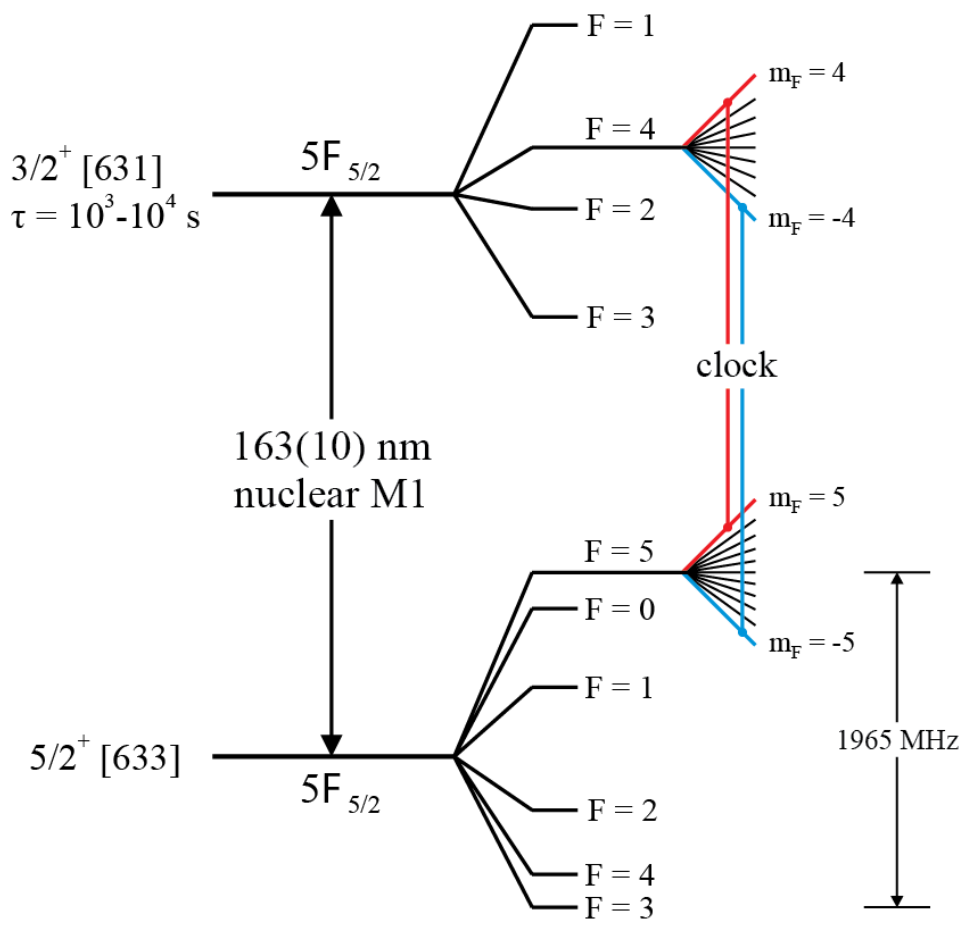


TABLE I. Estimated systematic error budget for a $^{229}Th^{3+}$ clock using realized single-ion clock technologies. Shifts and uncertainties are in fractional frequency units ($\Delta\nu/\nu_{clk}$) where $\nu_{clk} = 1.8$ PHz. See text for discussion.

Effect	$\lvert$Shift$\rvert$ (10^{-20})	Uncertainty (10^{-20})
Excess micromotion	10	10
Gravitational	0	10
Cooling laser Stark	0	5
Electric quadrupole	3	3
Secular motion	5	1
Linear Doppler	0	1
Linear Zeeman	0	1
Background collisions	0	1
Blackbody radiation	0.013	0.013
Clock laser Stark	0	$\ll 0.01$
Trapping field Stark	0	$\ll 0.01$
Quadratic Zeeman	0	0
Total	18	15

Summary of basic concepts

- Time = (number of oscillations) x (known period)
- Atomic clocks work by locking sources of EM radiation to atomic transitions.
  Oscillations are counted at the source.
- Quantum oscillator must be well protected from the environmental perturbations (no systematic shifts)
- Clocks are characterized by accuracy (systematics) and stability (statistics, Allan variance)

D. Allan, N. Ashby, and C. Hodge, Hewlett Packard Appl. Note 1289 (1997).

Atomic clocks as DM detectors

Particle DM candidates

Compton wavelength: $\lambda_C \sim \frac{\hbar}{m_{DM} c}$

$$\frac{\#\text{ of particles}}{\text{mode}} \sim \left(\frac{\rho_{DM}}{m_{DM} c^2}\right) \times \left(\lambda_{\text{de Broglie}}\right)^3$$

λ_{vir} < Galactic size (~10 kpc) ⇒ m_{DM} >> 10^{-22} eV

λ_C > Schwarzschild radius ⇒ m_{DM} << 10^{+28} eV

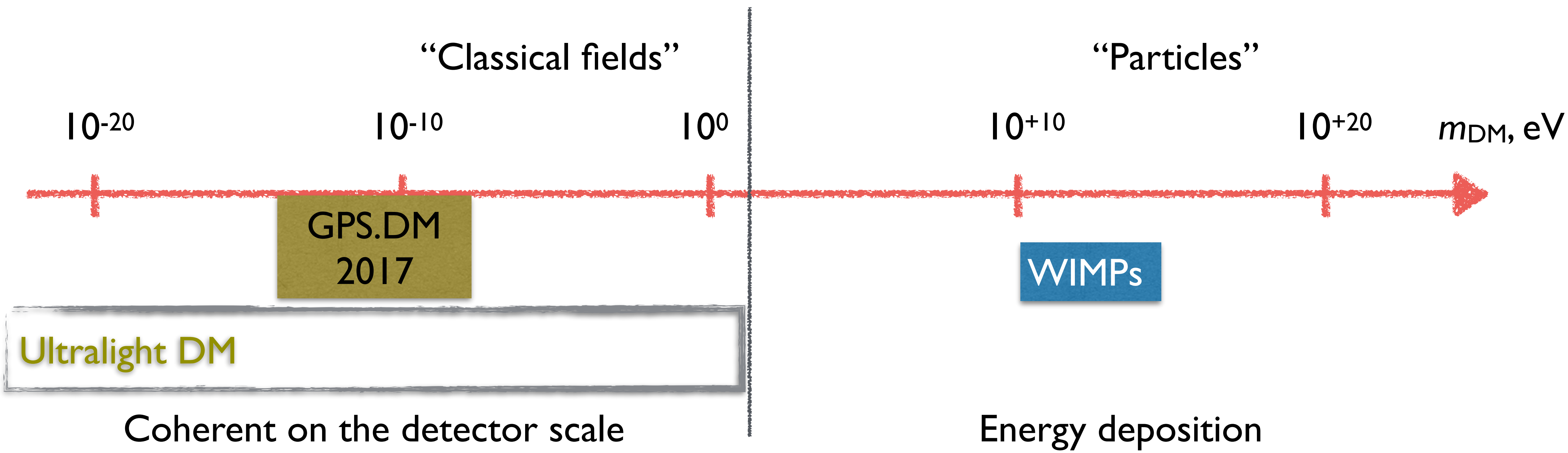


Table-top Cosmology

Ultralight Dark Matter

- atomic clocks
- magnetometers
- accelerometers
- interferometers
- cavities
- resonators
- permanent electric-dipole and parity-violation measurements
- gravitational wave detectors

D. Budker, P.W. Graham, M. Ledbetter, S. Rajendran, and A. O. Sushkov, PRX 4, 21030 (2014)
A. Arvanitaki and A.A. Geraci, PRL 113, 161801 (2014)
A. Derevianko and M. Pospelov, Nature Phys. (2014)
A. Arvanitaki, J. Huang, and K. Van Tilburg, Phys. Rev. D 91, 015015 (2015)
Y.V. Stadnik and V.V. Flambaum, PRL 114, 161301 (2015)
P.W. Graham, D. E. Kaplan, J. Mardon, S. Rajendran, and W.A. Terrano, PRD 93, 075029 (2016)
A.A. Geraci and A. Derevianko, PRL (2016)
A. Arvanitaki, S. Dimopoulos, and K. Van Tilburg, PRL 116, 031102 (2016)
….

DM signatures and atomic clocks

Clocks monitor atomic transition frequencies

These depend on fundamental constants

$$\Rightarrow$$

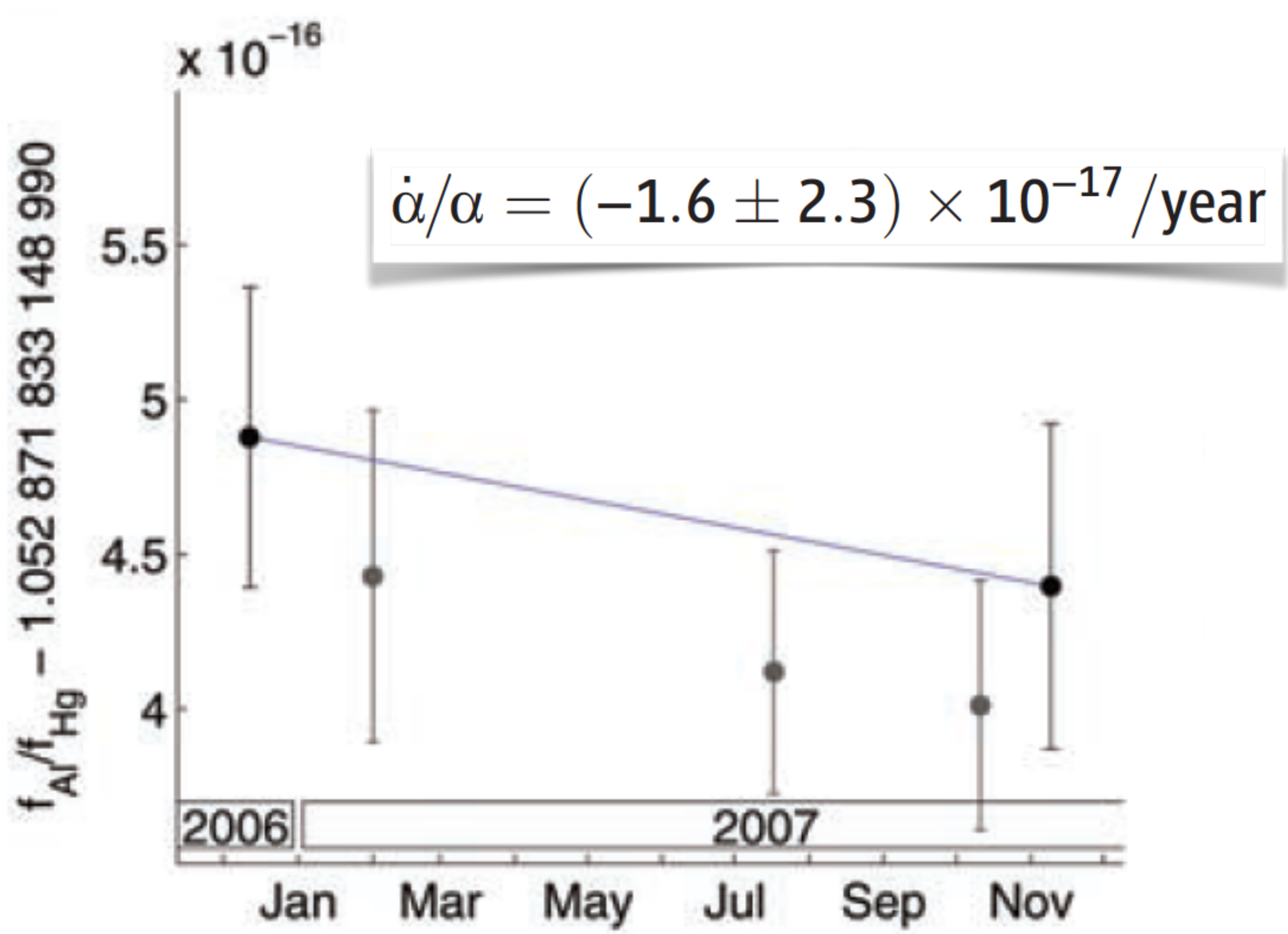
Search for variation of fundamental constants that is consistent with DM models

Variation of fundamental constants

$$\omega_{\text{clock}}\left(\alpha, \frac{m_q}{\Lambda_{\text{QCD}}}, \frac{m_e}{m_p}\right)$$

$$\frac{\delta\omega(t)}{\omega_0} = \sum_{X=\text{fnd consts}} K_X \frac{\delta X(t)}{X} = K_\alpha \frac{\delta\alpha(t)}{\alpha} + \ldots$$

Compare ratio of frequencies of two clocks with different sensitivities



T. Rosenband, et al. Science 319, 1808 (2008)

Sensitivity to variation of fundamental constants

$$\frac{\delta\omega(t)}{\omega_0} = \sum_{X=\text{fnd consts}} K_X \frac{\delta X(t)}{X} = K_\alpha \frac{\delta\alpha(t)}{\alpha} + \ldots \qquad X \equiv \alpha, \frac{m_q}{\Lambda_{\text{QCD}}}, \frac{m_e}{m_p}$$

↑ sensitivity coefficients

Microwave clocks: hyperfine transitions $\quad K_\alpha \neq 0,\ \ K_q \neq 0,\ \ K_{me/p} \neq 0$

$$K_\alpha = 2\left({}^{1}\text{H}\right) \rightarrow 4.28\left({}^{199}\text{Hg}^{+}\right)\ ,\quad K_{me/p} = 1$$

$$K_q = -0.1\left({}^{1}\text{H}\right),\ -0.0016\left({}^{133}\text{Cs}\right),\ -0.169\left({}^{199}\text{Hg}^{+}\right)$$

Optical clocks: electronic transitions $\quad K_\alpha \neq 0,\ \ K_q = 0,\ \ K_{me/p} = 0$

$$K_\alpha(\text{ions}) = 8\times10^{-3}\left(\text{Al}^{+}\right) \rightarrow -3\left(\text{Hg}^{+}\right)$$

$$K_\alpha(\text{neutrals}) = 6\times10^{-2}(\text{Sr}) \rightarrow 0.3(\text{Yb}) \rightarrow 0.8(\text{Hg})$$

Nuclear clock (Th): $\quad K_X \sim 10^5$

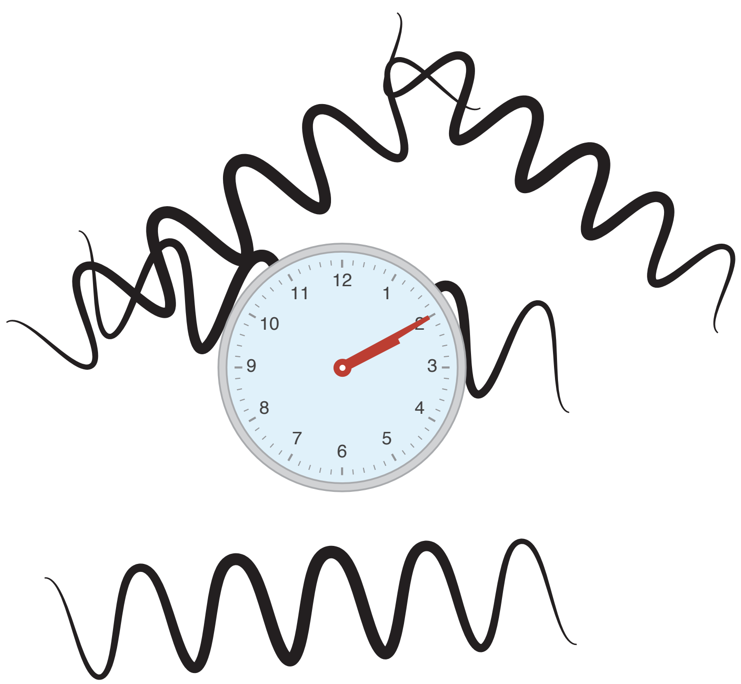
Review: Dzuba & Flambaum, Can J Phys (2009)

Variations of fundamental constants

Slow drifts	Transients	Oscillations	Stochastic background
	Topological DM Microstructure	Dilaton DM Axion-like particles	Virialized DM
	↑	↑	↑
	AD & Pospelov (2014)	Arvanitaki et al (2015)	AD (2016)

Ultralight DM and atomic clocks

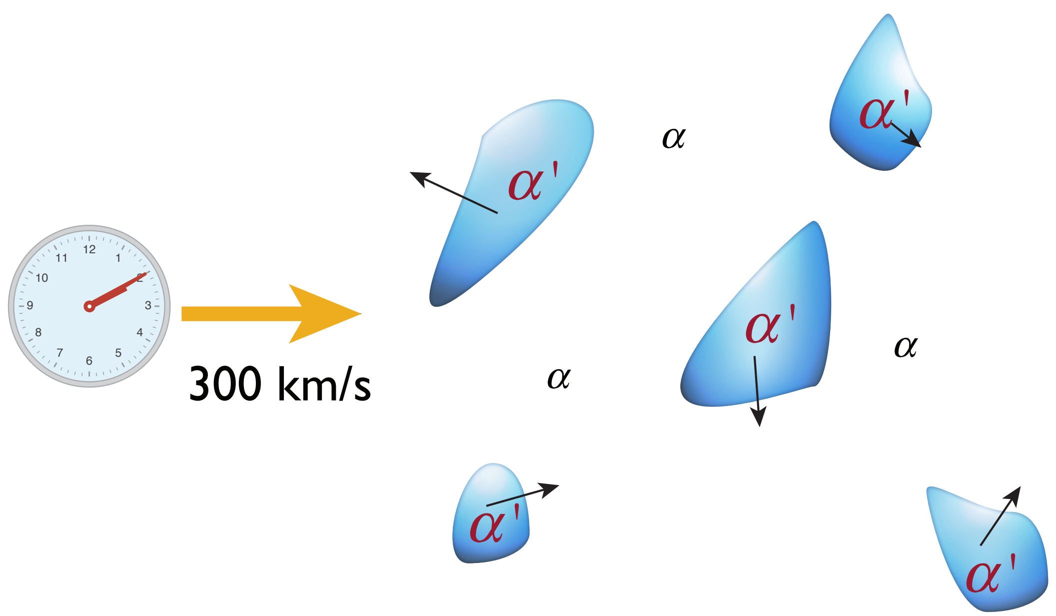
non-interacting fields



Oscillating variations of fund. const

Arvanitaki et al. PRD 91, 15015 (2015)

self-interacting fields



Transient variations of fund. const

Derevianko & Pospelov, Nature Phys. 10, 933 (2014)

Free dark matter fields

- (Pseudo-) scalar (S=0) bosonic fields
- Electrically neutral
- Generic prediction of many extensions to the SM (dilatons)
- Interact gravitationally
- No self-interaction

- Coherent on the scale of individual devices

Fields oscillate at Compton frequencies

Plane wave solutions of Klein-Gordon Eq.

$$\phi(t,r) = \phi_0 \cos(\omega_\phi t - \mathbf{k}\cdot\mathbf{r}) \qquad \phi_0 = \frac{\hbar}{m_\phi c}\sqrt{2\rho_{\mathrm{DM}}}$$

Oscillation frequency

$$\omega_\phi = \frac{1}{\hbar}\sqrt{\left(m_\phi c^2\right)^2 + \left(\frac{kc}{\hbar}\right)^2} \approx \boxed{\frac{m_\phi c^2}{\hbar}} + \frac{m_\phi v^2}{2}$$

=> Fundamental constants oscillate at VULF Compton frequencies

$$m_e(t,\mathbf{r}) = m_e \times \left(1 + \sqrt{\hbar c}\,\Gamma_{me}\,\phi(t,\mathbf{r})\right) \qquad \alpha(t,\mathbf{r}) = \alpha \times \left(1 + \sqrt{\hbar c}\,\Gamma_{\alpha}\,\phi(t,\mathbf{r})\right)$$

Basic idea

$$f_{\text{atom}} \propto \underbrace{\alpha^2 m_e}_{\text{from Ry}} F_{\text{relativistic}}(\alpha)$$

Fundamental constants oscillate=>

Modulation of atomic frequencies=>

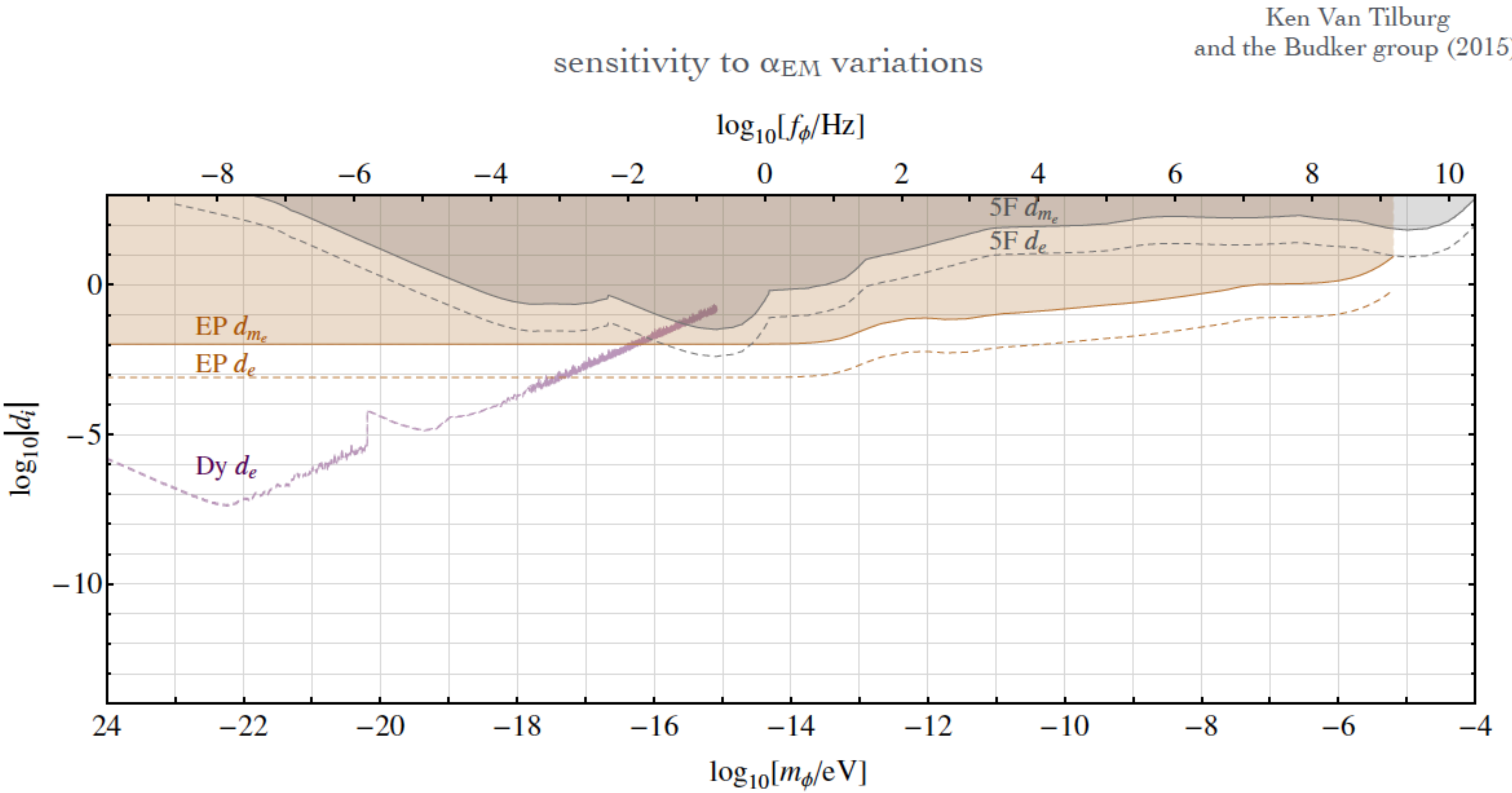
Power spectral density exhibits peak at Compton frequency

A. Arvanitaki, J. Huang & K Van Tilburg, PRD 91, 15015 (2015)

Frequency range

m_ϕ, eV	f_ϕ, Hz	
10^{-24}	2×10^{-10}	
10^{-20}	2×10^{-6}	← One oscillation per year
10^{-15}	2×10^{-1}	
10^{-10}	2×10^{4}	
10^{-5}	2×10^{9}	← Microwave frequencies
1	2×10^{14}	← Optical frequencies

Limits on oscillating alpha



Credit: Mina Arvanitaki

More sophisticated approach: DM lineshape, aliasing & networks

A. Derevianko arxiv:1605.09717

Stochastic approach: two-point correlation function

$$\omega_\phi = \frac{1}{\hbar}\sqrt{\left(m_\phi c^2\right)^2 + \left(\frac{kc}{\hbar}\right)^2} \approx \frac{m_\phi c^2}{\hbar} + \boxed{\frac{m_\phi v^2}{2}}$$

Dephasing

=> coherence time & length

$\phi\left(t', \mathbf{r}'\right)$

$\phi\left(t, \mathbf{r}\right)$

$$g\left(\tau, \mathbf{d}\right) = \left\langle \phi\left(t' = t + \tau, \mathbf{r} = \mathbf{r}' + \mathbf{d}\right)\phi\left(t, \mathbf{r}\right)\right\rangle$$

Two point correlation function

$$g(\tau,\mathbf{d}) = \left(\frac{\hbar}{m_\phi c}\right)^2 \rho_{\mathrm{DM}}\, A(\tau,\mathbf{d}) \cos\left(\omega_\phi' \tau - \mathbf{k}_g \cdot \mathbf{d} + \Phi(\tau,\mathbf{d})\right)$$

$$A(\tau,\mathbf{d}) = \frac{\exp\left(-\frac{|\mathbf{d}-\mathbf{v}_g\tau|^2}{2\lambda_c^2}\frac{1}{1+(\tau/\tau_c)^2}\right)}{\left(1+(\tau/\tau_c)^2\right)^{3/4}}$$

$$\Phi(\tau,\mathbf{d}) = -\frac{|\mathbf{d}-\mathbf{v}_g\tau|^2}{2\lambda_c^2}\frac{\tau/\tau_c}{1+(\tau/\tau_c)^2} + \frac{3}{2}\tan^{-1}(\tau/\tau_c)$$

$$\omega_\phi' = \omega_\phi + m_\phi v_g^2/(2\hbar)$$

Doppler-shifted Compton frequency

$$\tau_c \equiv \frac{1}{\omega_\phi (v_{vir}/c)^2} \approx 10^6/\omega_\phi$$

Coherence time (dephasing)

$$\lambda_c \equiv \frac{\hbar}{m_\phi v_{vir}} \approx 10^3\, \lambda_{\mathrm{Compton}}$$

Coherence length (dispersion)

A. Derevianko arxiv:1605.09717

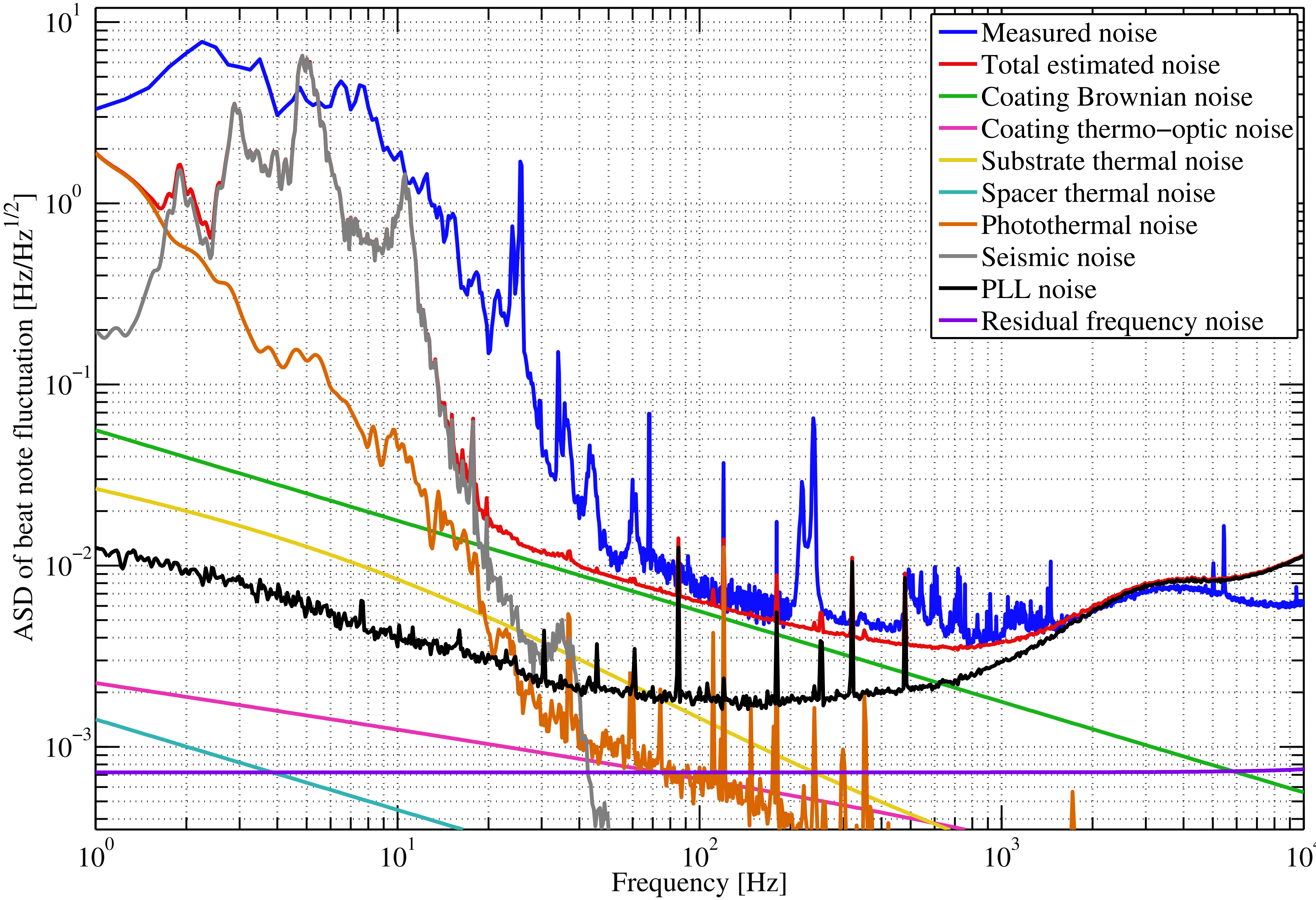
Correlation function encodes all the DM priors!

Experimental relevance

Spatio-temporal variation of fundamental constants

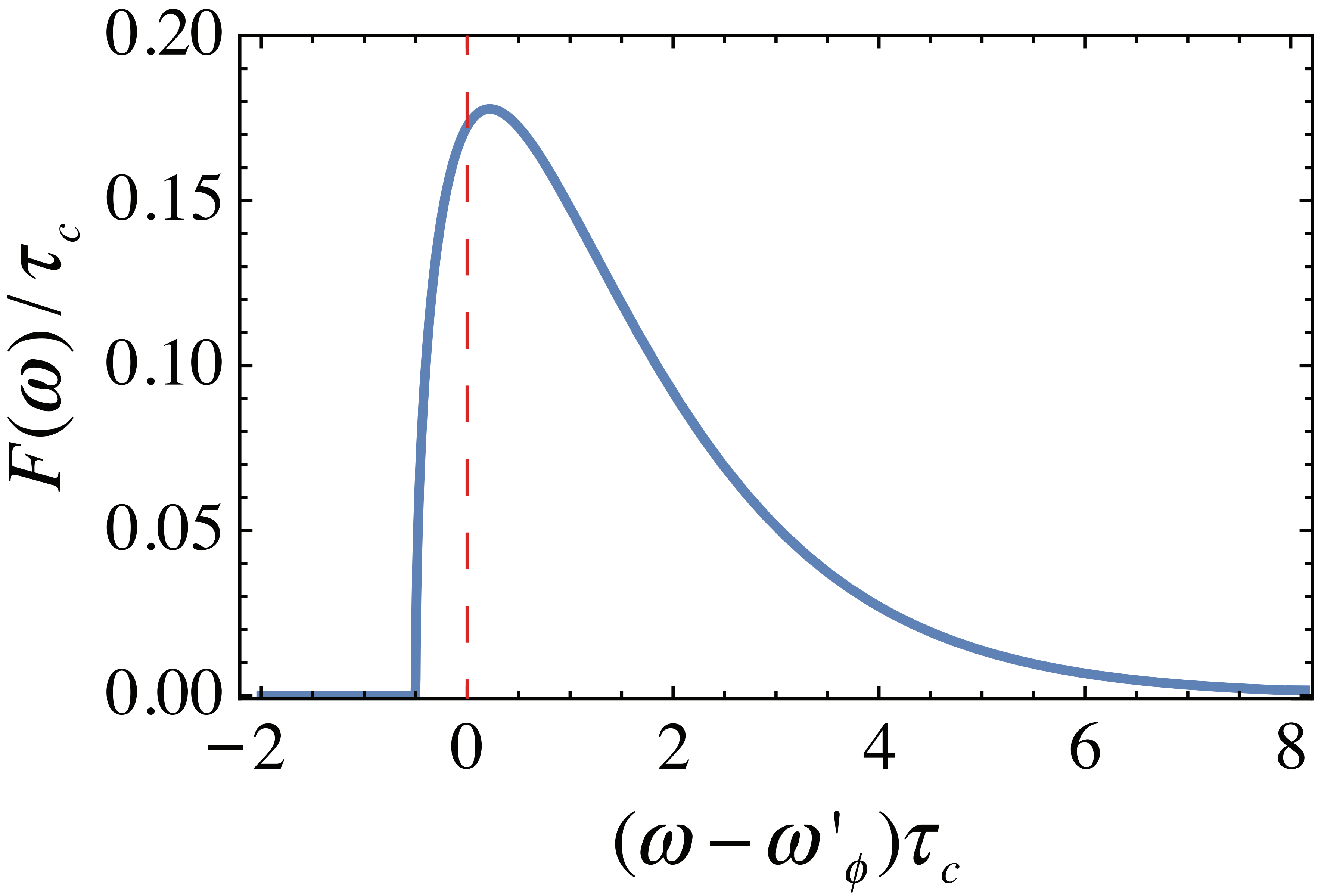
$$\frac{\langle \alpha(t',\mathbf{r}')\alpha(t,\mathbf{r})\rangle}{\alpha^2} = 1 + \hbar c\,\Gamma_\alpha^2\, g(\tau,\mathbf{d})$$

Measured cavity power spectrum, or where is the DM signal?



T. Chalermsongsak et al., Metrologia 52, 17–30 (2014)

Dark matter line shape

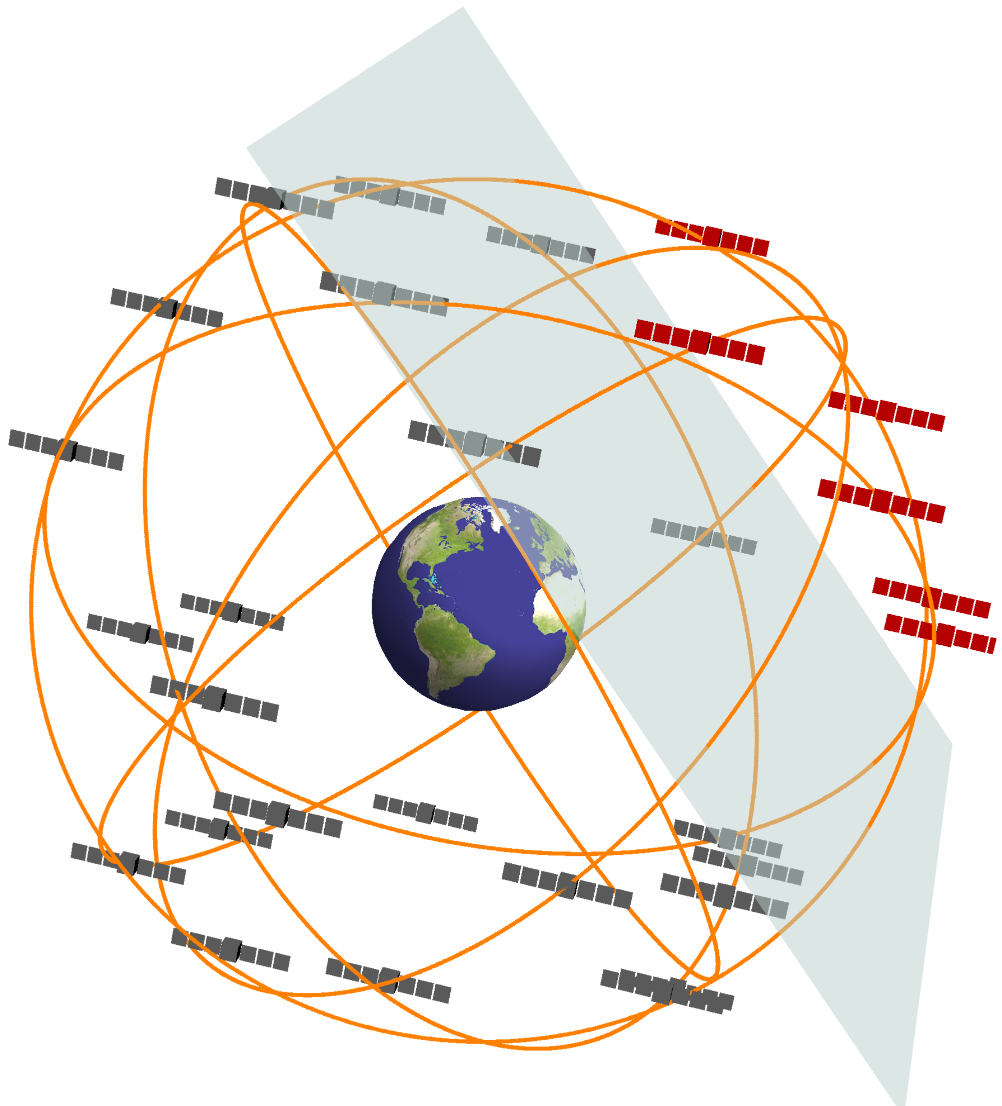


A. Derevianko arxiv:1605.09717

Profile encodes all DM priors:

- Dispersion relation for massive S=0 bosons
- Virial velocity distribution
- Galactic velocity

Search for clumpy DM with GPS



Search for GPS glitches correlated with the Earth's motion through the DM halo

50,000 km-aperture dark matter detector

Derevianko & Pospelov, Nature Phys. 10, 933 (2014)
GPS.DM collaboration, Nature Comm. **8**, 1195 (2017)

GPS.DM dark matter observatory

G. Blewitt (GPS, Nevada-Reno)
A. Derevianko (Theory/data analysis, Nevada-Reno)
M. Pospelov (QFT/Cosmology, Perimeter)
J. Sherman (Clocks, NIST-Boulder)

Postdoc: B. Roberts

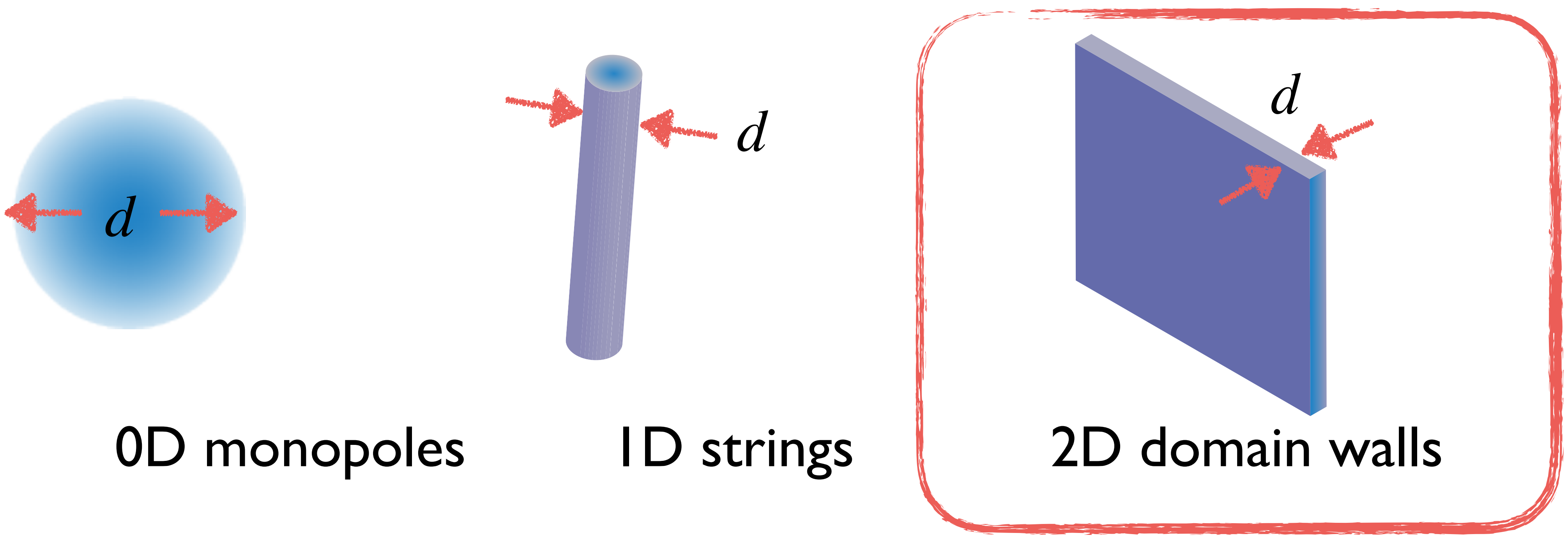
Students (all Nevada-Reno): C.Dailey, K.Lane, A. Rowling

Former members: N. Lundholm, M. Murphy, W. Williams

More information: derevianko group.com

"Clumpy" (topological) Dark Matter

- Self-interacting quantum fields => multiple vacua + phase transition
- Networks of topological defects



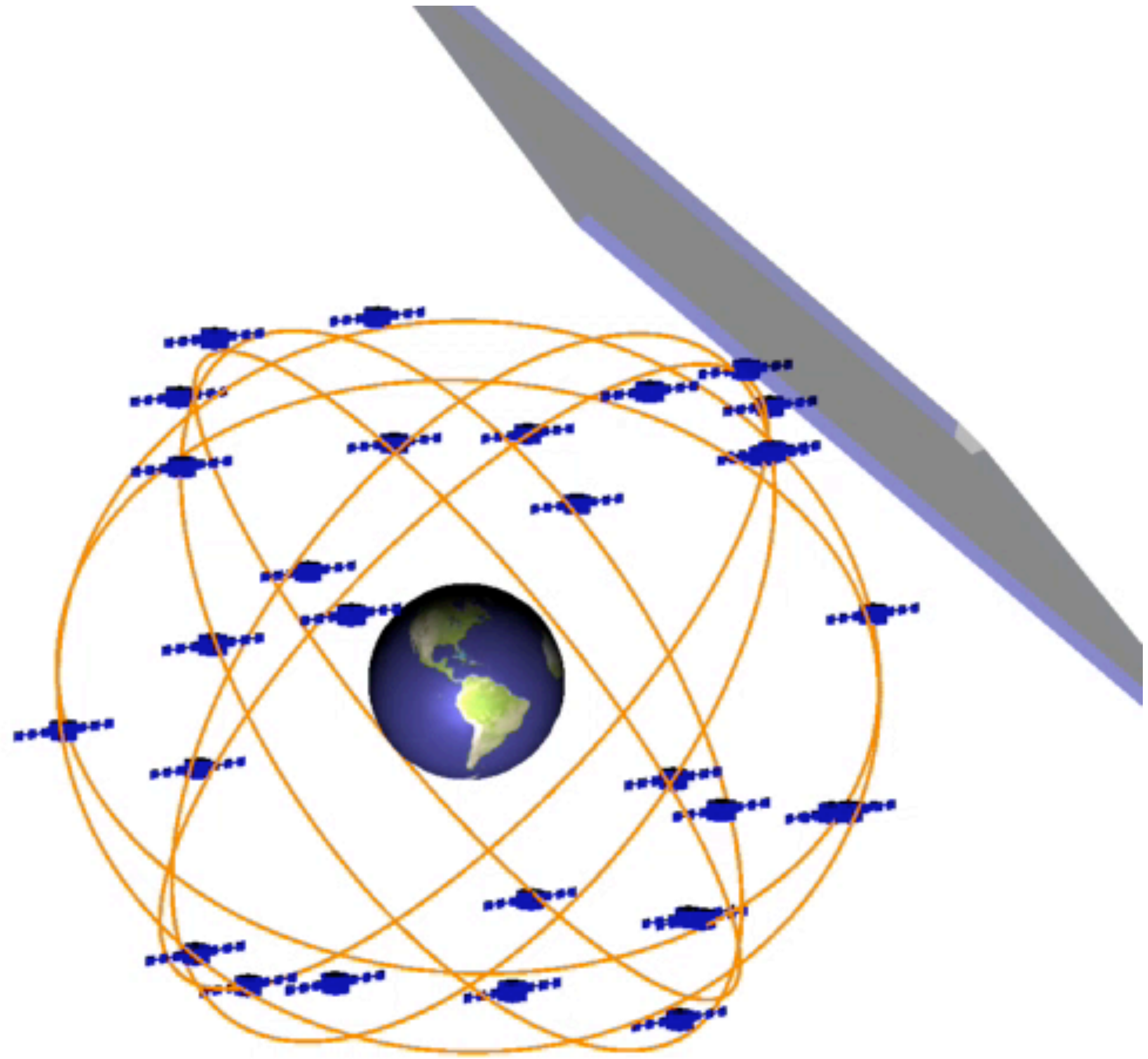
$$d \sim \frac{\hbar}{m_\phi c}$$

$$d \sim 10^4\ \mathrm{km} \Rightarrow m_\varphi \sim 10^{-14}\ \mathrm{eV}$$

Ultralight DM

Review: A. Vilenkin, Phys. Rep. 121, 263 (1985)

Domain wall GPS sweep



Credit: Conner Dailey

Formalizing coupling to DM

$$-\mathcal{L}_{\text{int}} = \varphi^2(\mathbf{r},t)\left(\frac{1}{\Lambda_e^2} m_e c^2 \bar{e}e + \frac{1}{\Lambda_p^2} m_p c^2 \bar{p}p + \frac{1}{\Lambda_\alpha^2}\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \ldots\right)$$

DM field — electrons — protons — EM field

$$-\mathcal{L}_{\text{QED}} = -i\hbar c\bar{e}\not{D}e + m_e c^2 \bar{e}e + \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$m_e \to m_e \times \left(1 + \frac{1}{\Lambda_e^2}\varphi^2(\mathbf{r},t)\right)$$

$$\alpha \to \alpha \times \left(1 + \frac{1}{\Lambda_\alpha^2}\varphi^2(\mathbf{r},t)\right)$$

DM clumps pull on the rest masses of electrons, quarks and EM coupling

Atomic energies and frequencies are modulated as DM clump sweeps through!

DM-induced **transient** variation of fundamental constants

$$\omega_{\text{clock}}\left(\alpha, \frac{m_q}{\Lambda_{\text{QCD}}}, \frac{m_e}{m_p}\right) \Rightarrow \frac{\delta\omega(t)}{\omega_{\text{clock}}} = \sum_{X=\text{fnd consts}} K_X \frac{\delta X(t)}{X} = K_\alpha \frac{\delta\alpha(t)}{\alpha} + \ldots$$

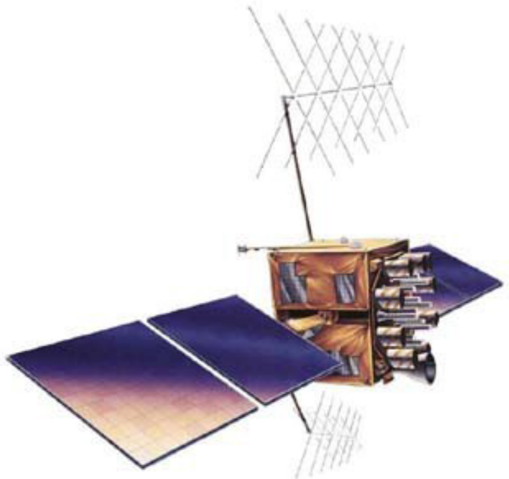
$$\frac{\left|\delta\omega_{\text{DM}}\right|_{\max}}{\omega_{\text{clock}}} \approx (\hbar c)\,\Gamma_{\text{eff}}\,\rho_{\text{DM}}\, v_g\, \mathcal{T}\, d$$

Time b/w encounters ($\mathcal{T}$)

Defect size (d)

$$\Gamma_{\text{eff}} = 4.34\,\Gamma_\alpha - 0.019\,\Gamma_{m_q/\Lambda_{\text{QCD}}} + \Gamma_{m_e/m_p}$$

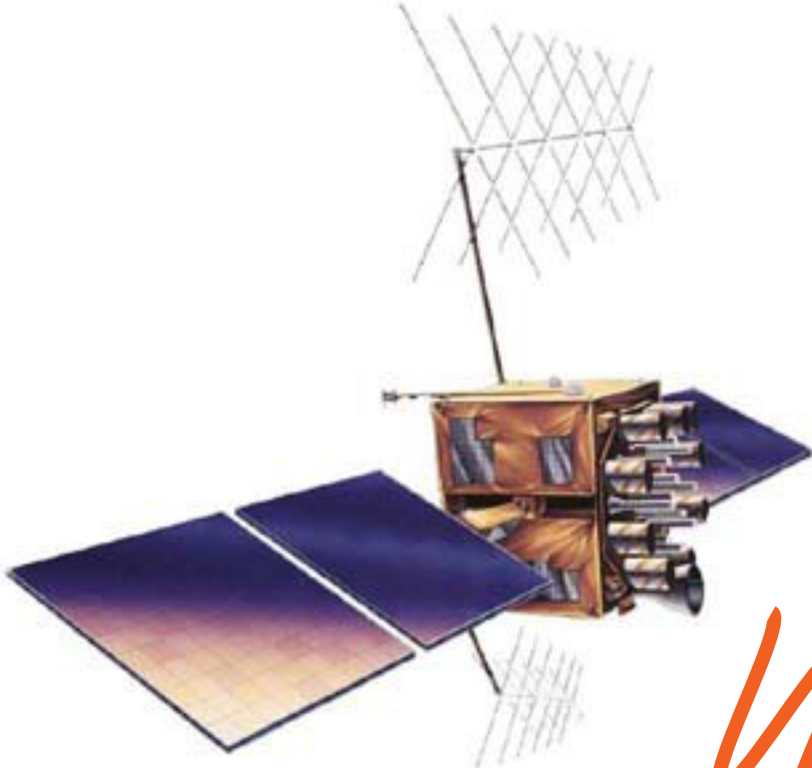
^{87}Rb



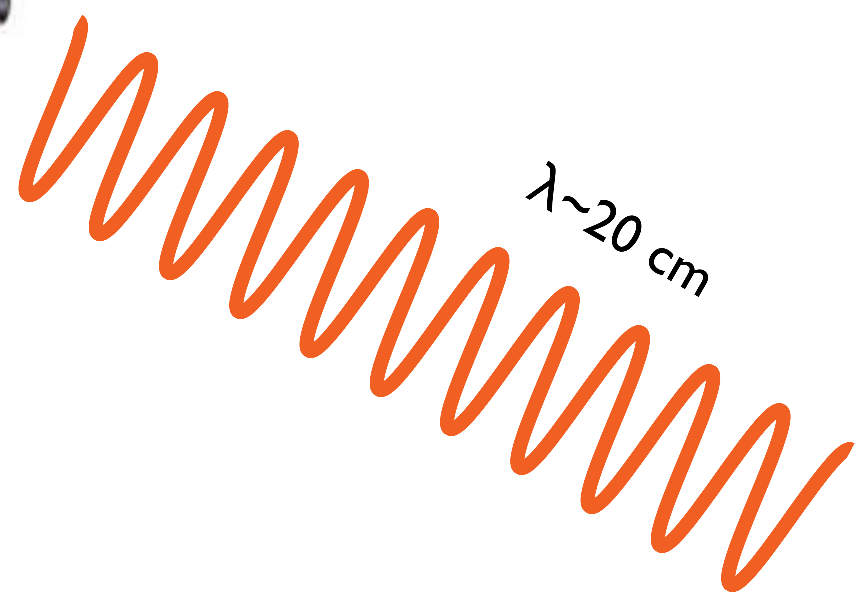
GPS clocks

- Presently a mix of II-generation block sats (IIA,IIR,IIRM,IIF)
- 12 hr orbits
- Each satellite has 4 clocks (depends on individual satellite)
- Only a single clock is operational at a time on a single satellite (misbehaving clocks are swapped, swaps are documented)
- Rb and Cs clocks (20+ Rb, 5 Cs)
- The broadcast microwave signals are tied to the clock output

Data acquisition



Downlink microwave signals:
L1 = 1572.42 MHz
L2 = 1227.6 MHz
L5 = 1176.45 MHz



Measure the carrier phase of the broadcast signal
(much more precise than the navigational message)

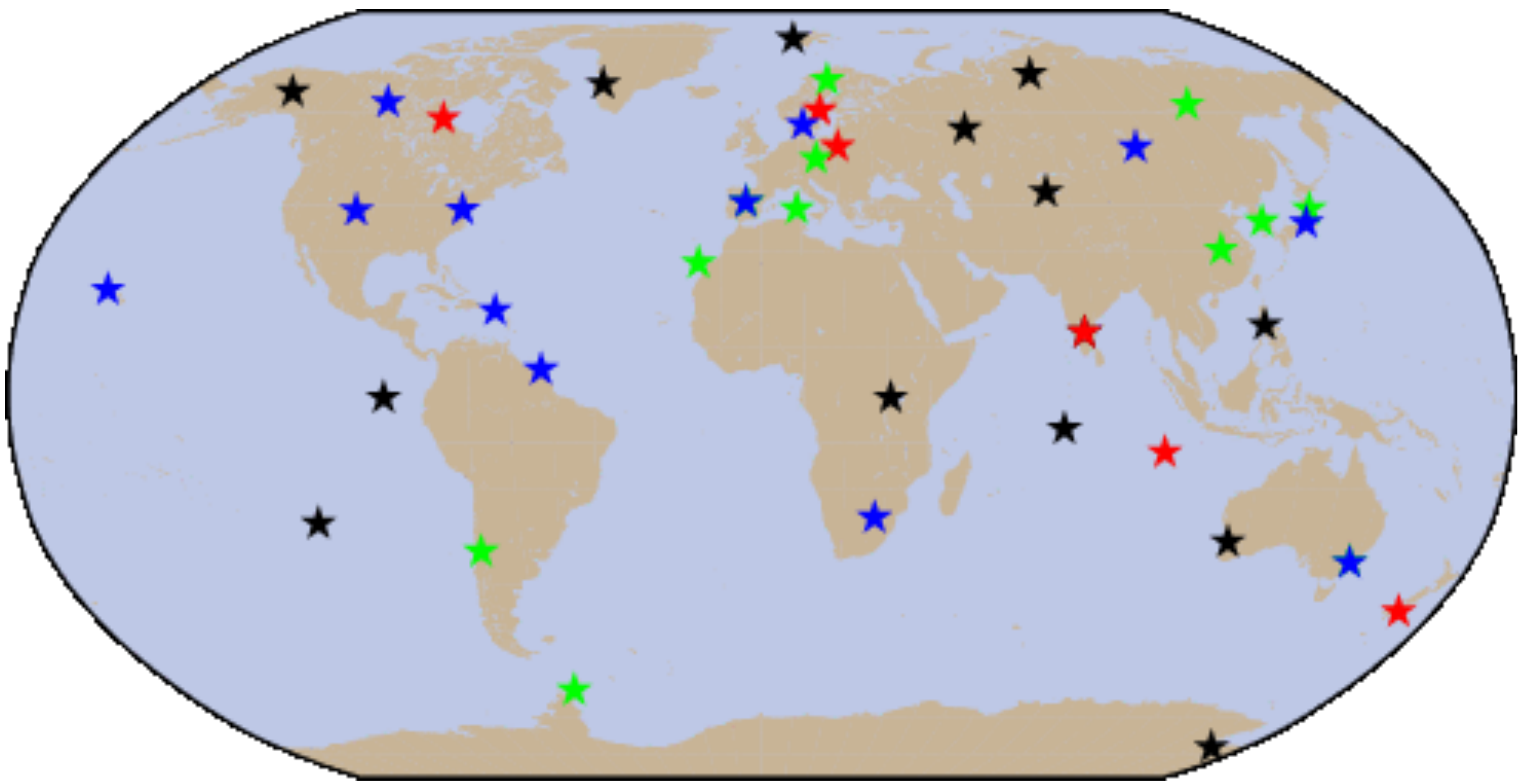
Collect data from many receivers around the world

Phases are combined => clock,orbit, position solutions

Errors: time ~ 0.1ns and positions ~ 1 mm

Figure 1 Permanent IGS station at Slide Mountain, Nevada, USA.

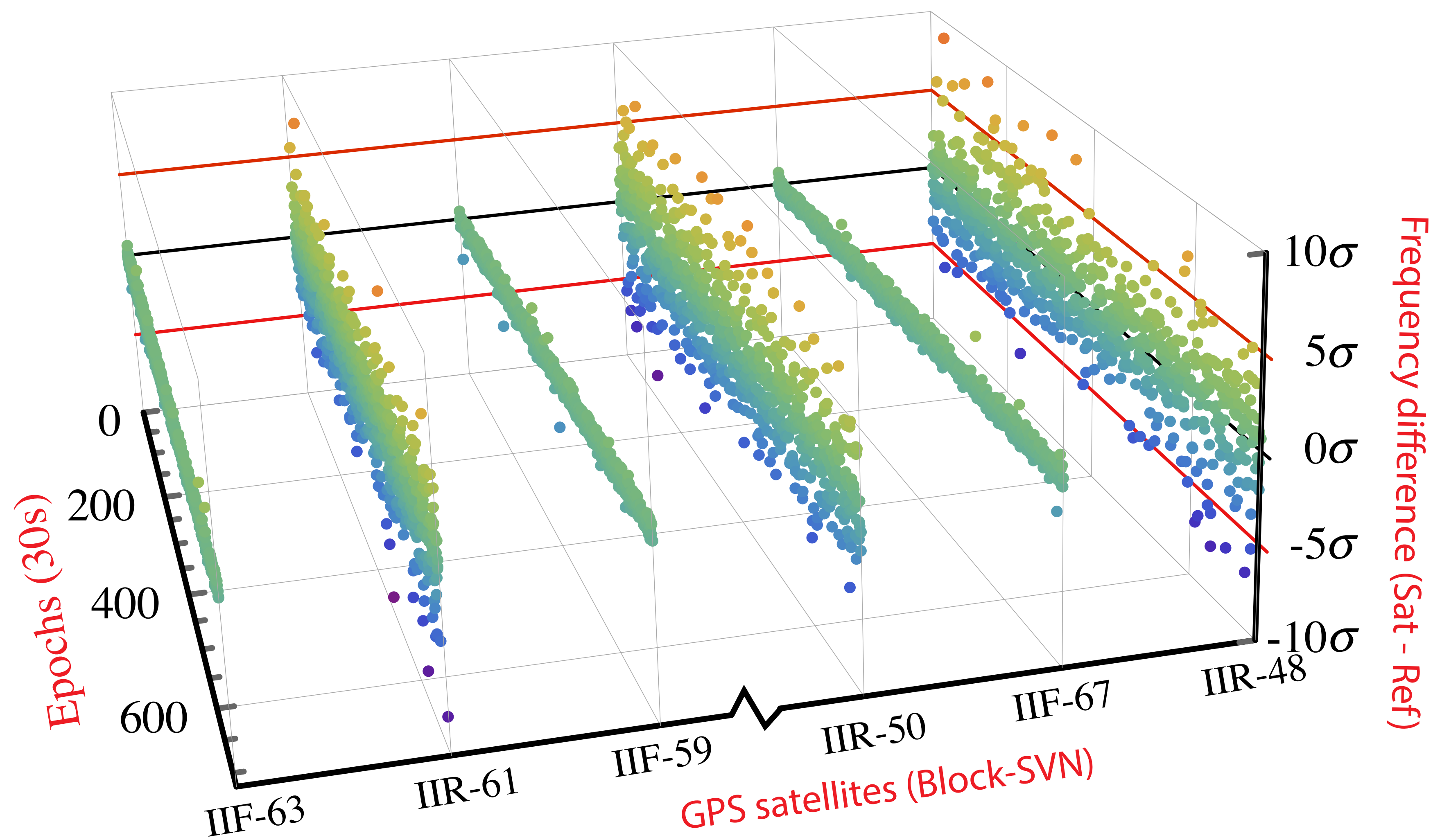
Representative GNSS ground stations
(with 10 years of 1-sec carrier phase data)

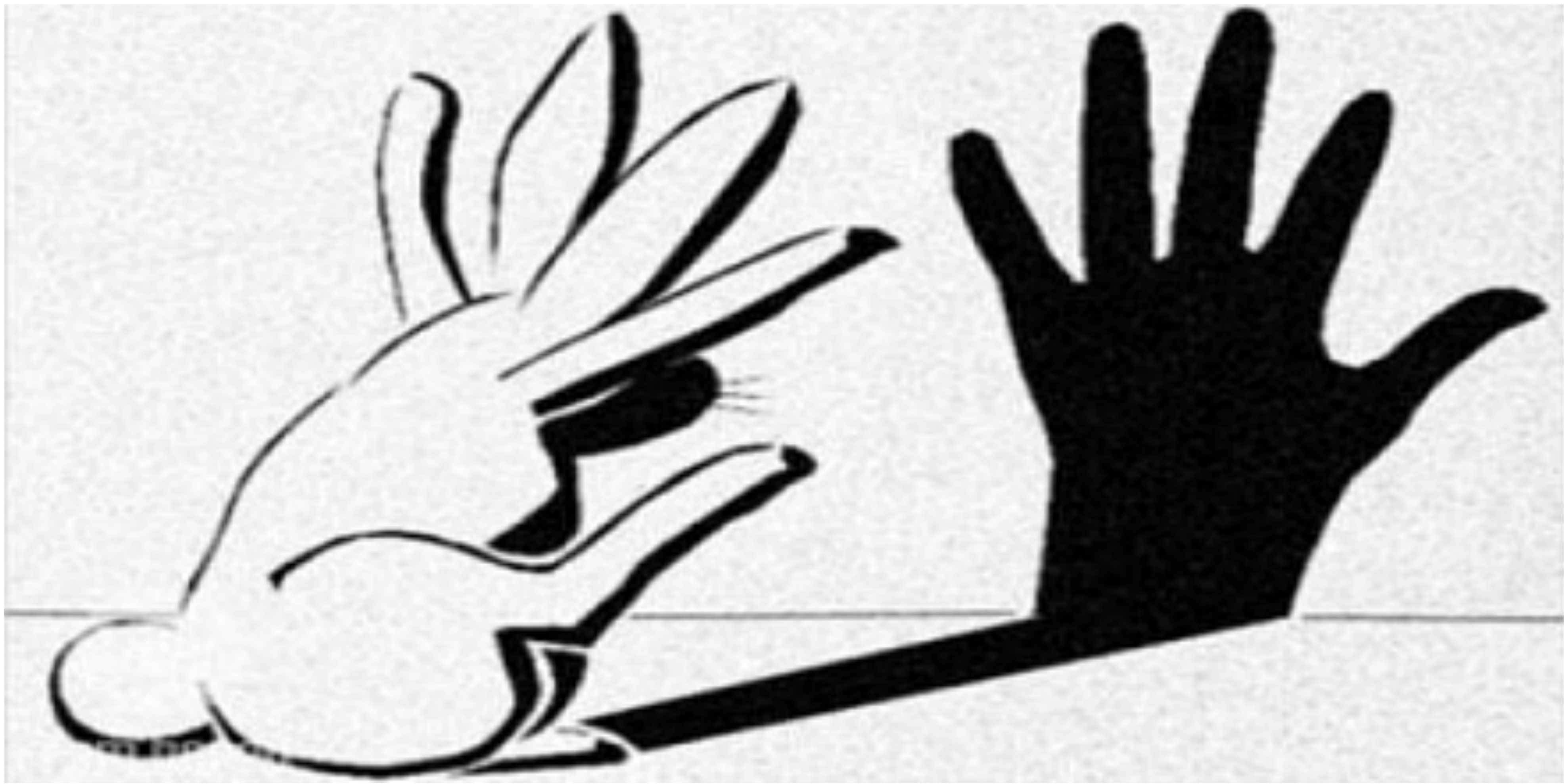


Quartz oscillators (black)
Atomic clocks: Hydrogen Rubidium Cesium

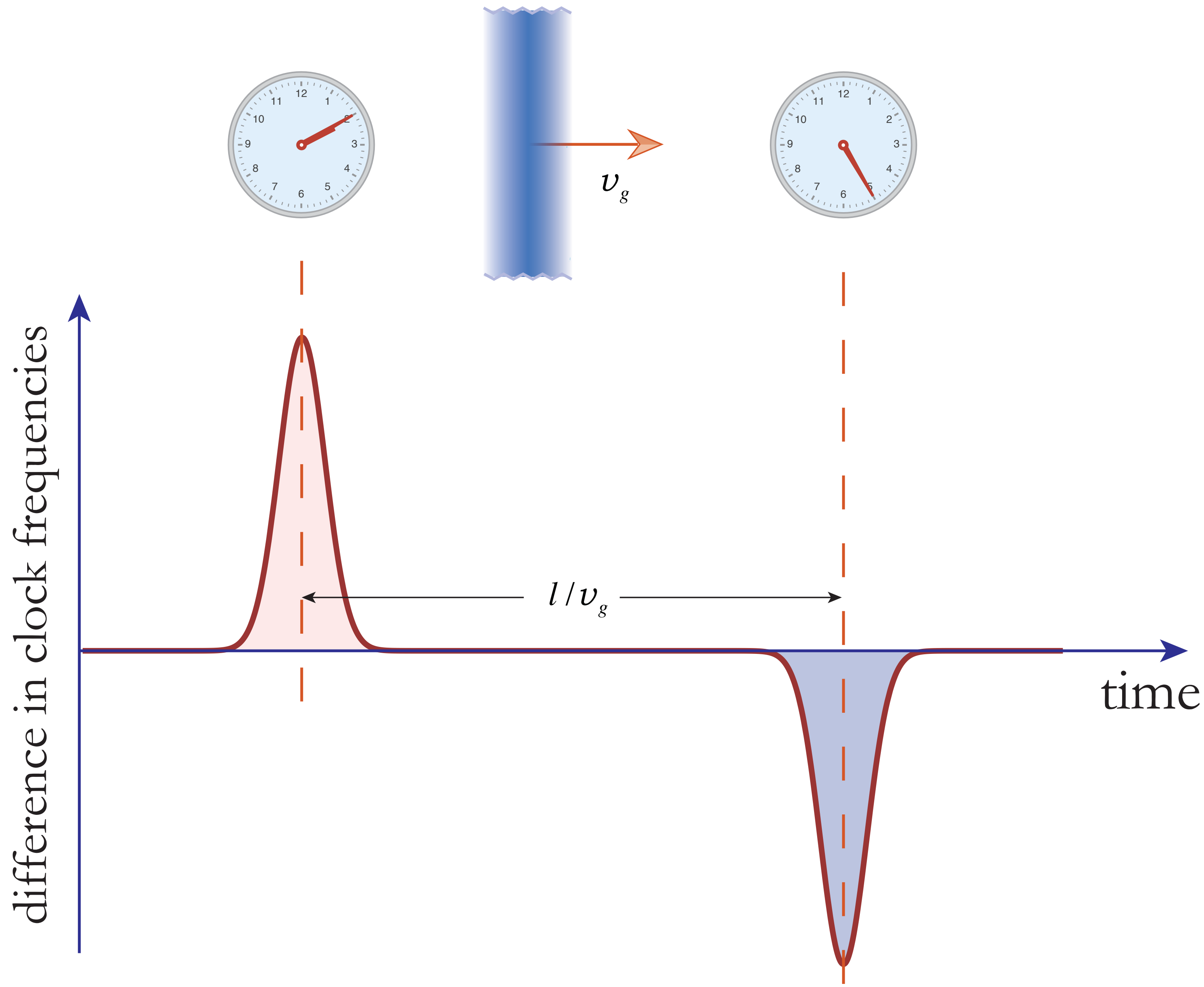
Typical GPS data stream

- 30s sampling
- ~16 years of public domain data from JPL
- 32 sats + ground stations



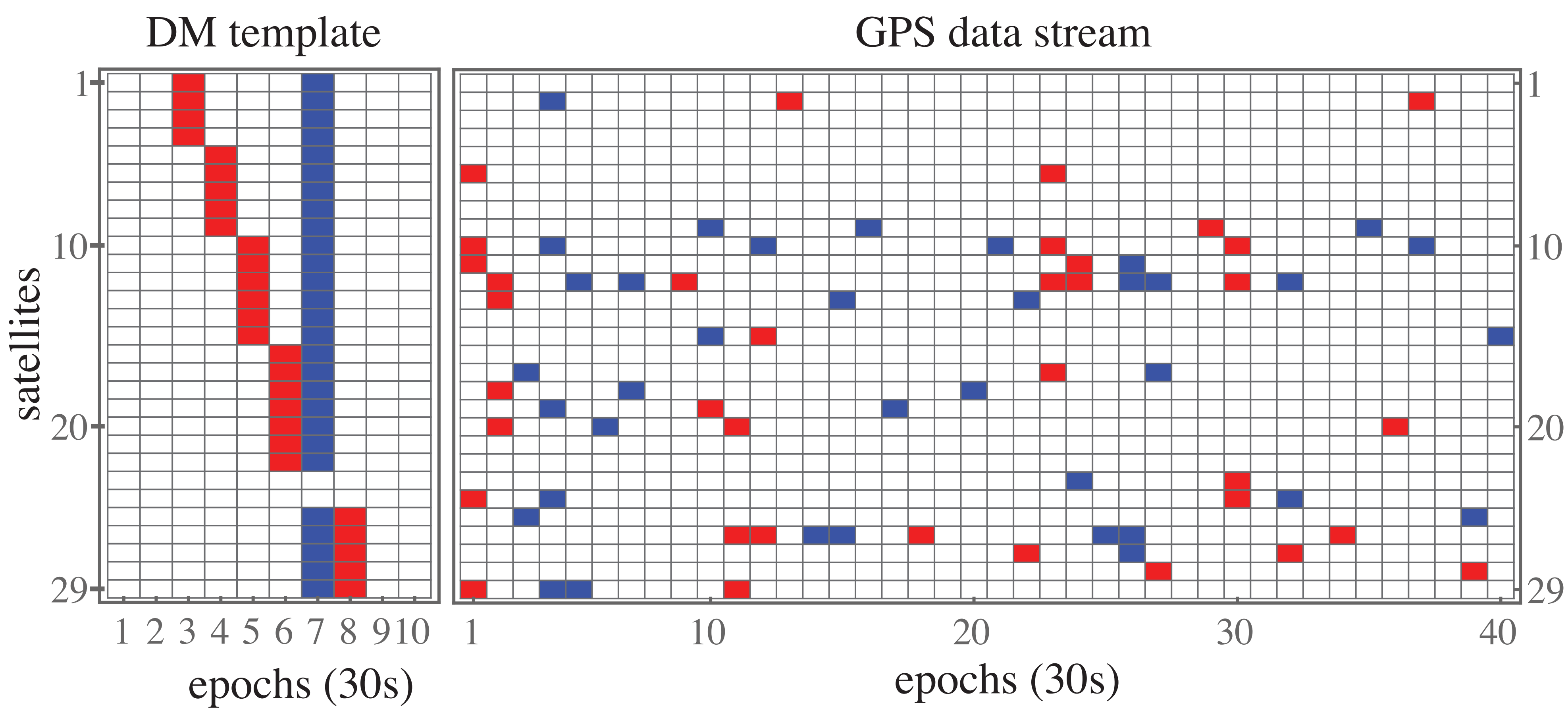


Two-clock pattern (thin wall)



GPS aperture =50,000 km => l/v_g~ 150 sec

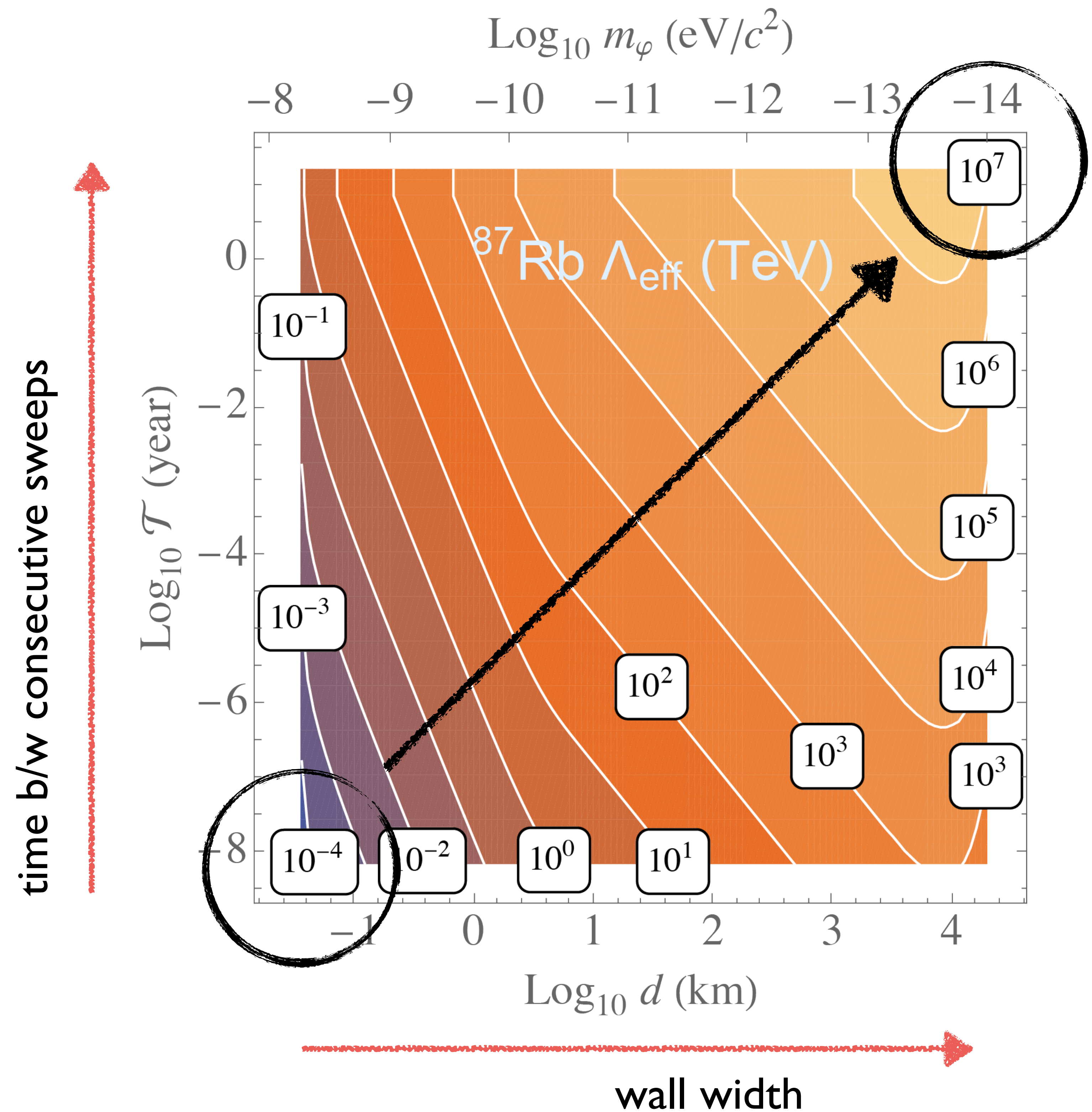
Network tile pattern (thin walls)



- No DM wall signal found at our current sensitivity level
- Excluded clock excursions > 0.48 ns Rb and > 0.56 ns for Cs @ 300 km/s

GPS.DM collaboration, Nature Comm. **8**, 1195 (2017)

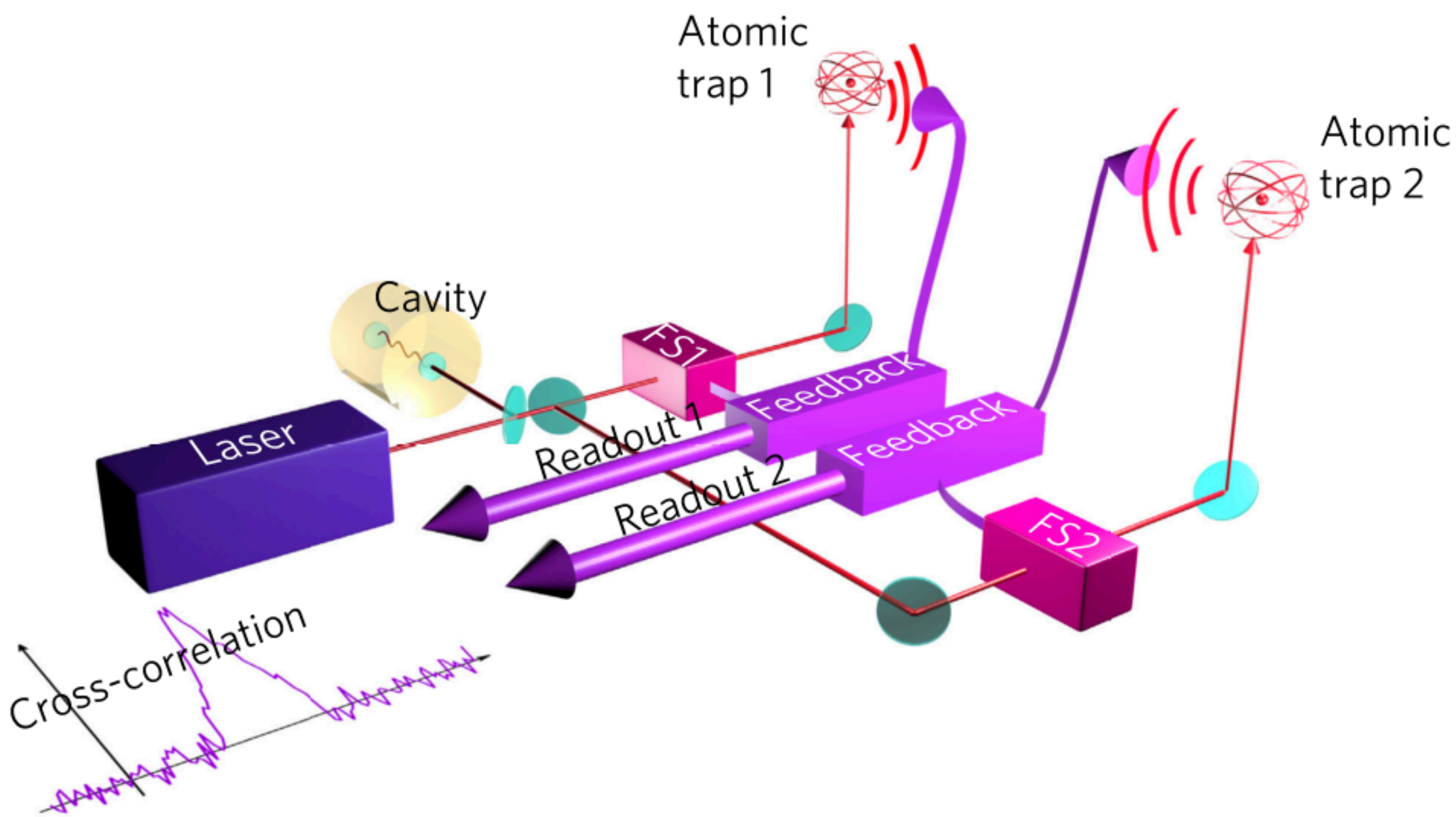
Constraints on Rb Λ_{eff}



nature astronomy
LETTERS
PUBLISHED: 19 DECEMBER 2016 | VOLUME: 1 | ARTICLE NUMBER: 0009

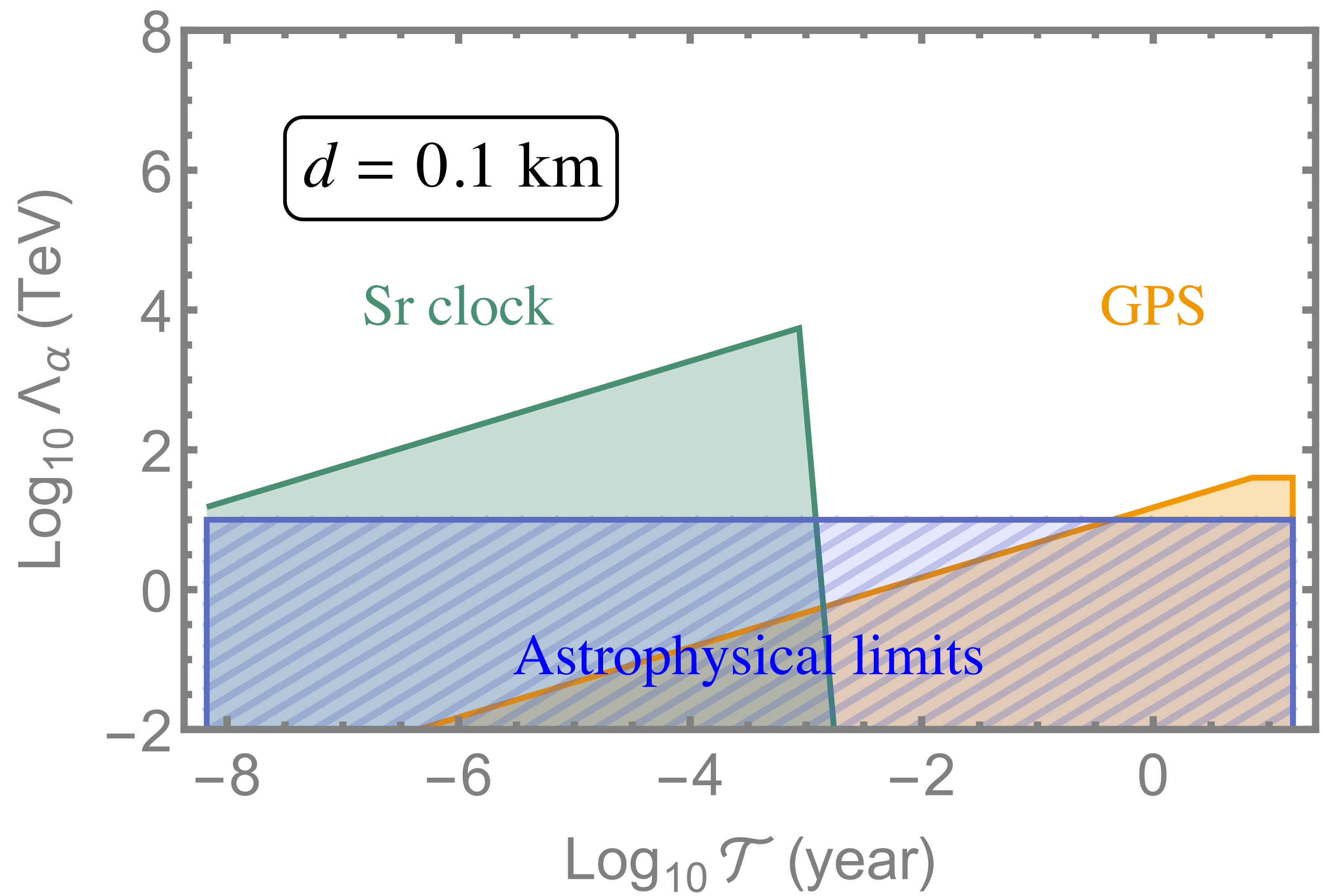
Experimental constraint on dark matter detection with optical atomic clocks

P. Wcisło*, P. Morzyński, M. Bober, A. Cygan, D. Lisak, R. Ciuryło and M. Zawada



If both clocks have frequency excursions simultaneously = could be clumpy DM

Limits on Λ_α (transient variation of α)



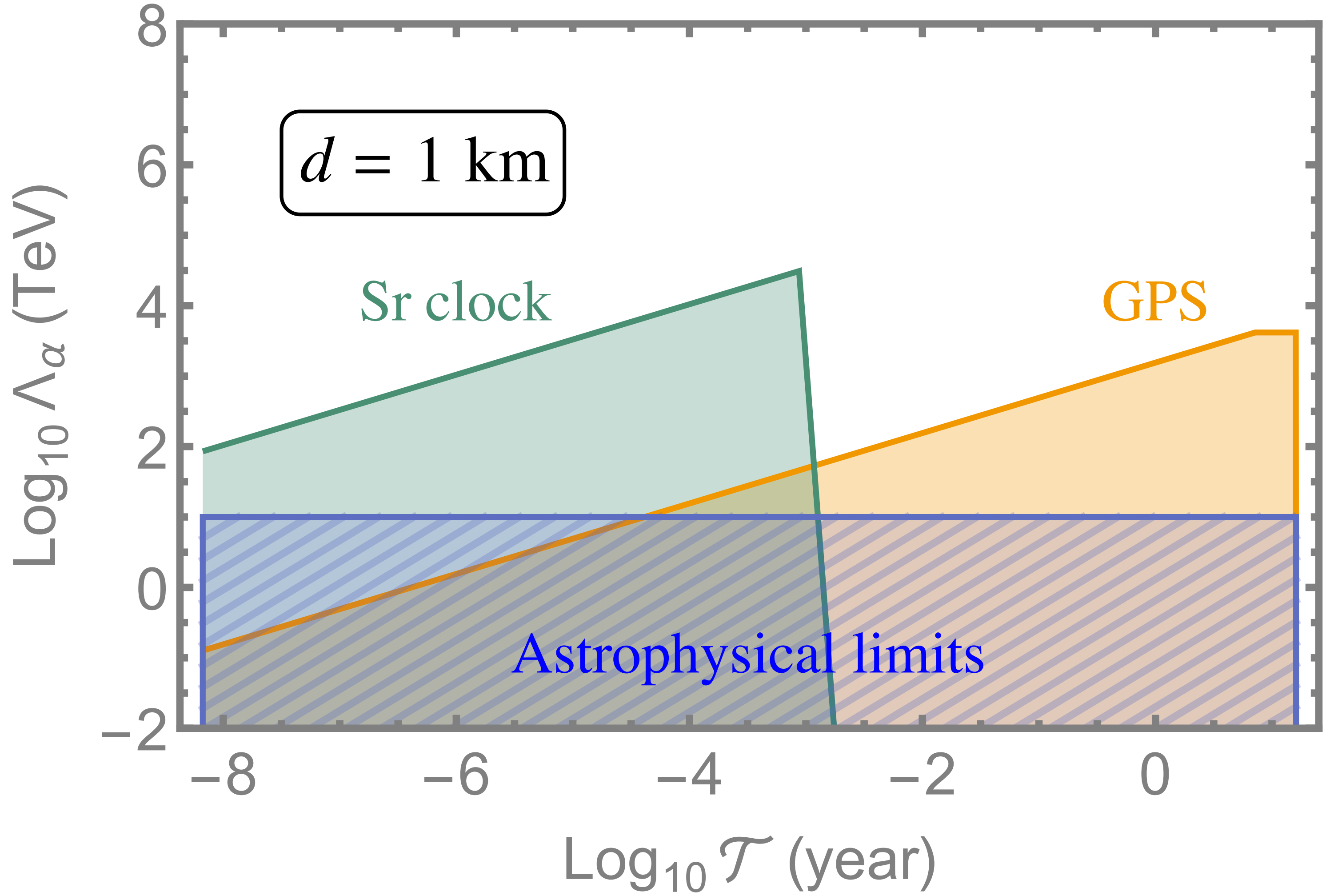
GPS.DM collaboration, Nature Commun. **8**, 1195 (2017)

AstroLimits: Olive & Pospelov, PRD (2008)

Sr limits: P. Wcislo et al, Nat. Astron. (2016)

Limits on Λ_α (transient variation of α)

GPS.DM collaboration, Nature Commun. **8**, 1195 (2017)

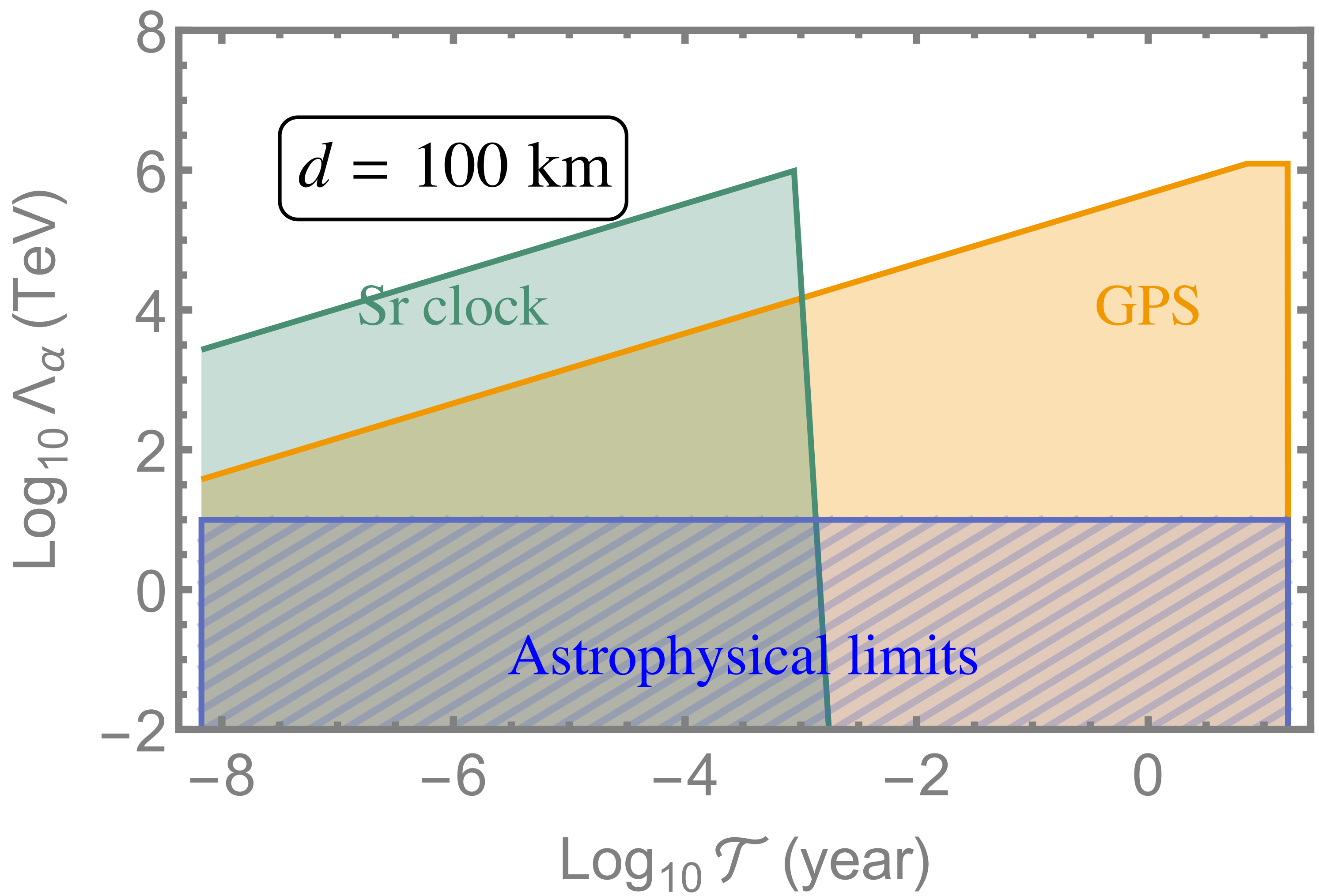


AstroLimits: Olive & Pospelov, PRD (2008)

Sr limits: P. Wcislo et al, Nat. Astron. (2016)

Limits on Λ_α (transient variation of α)

GPS.DM collaboration, Nature Commun. **8**, 1195 (2017)

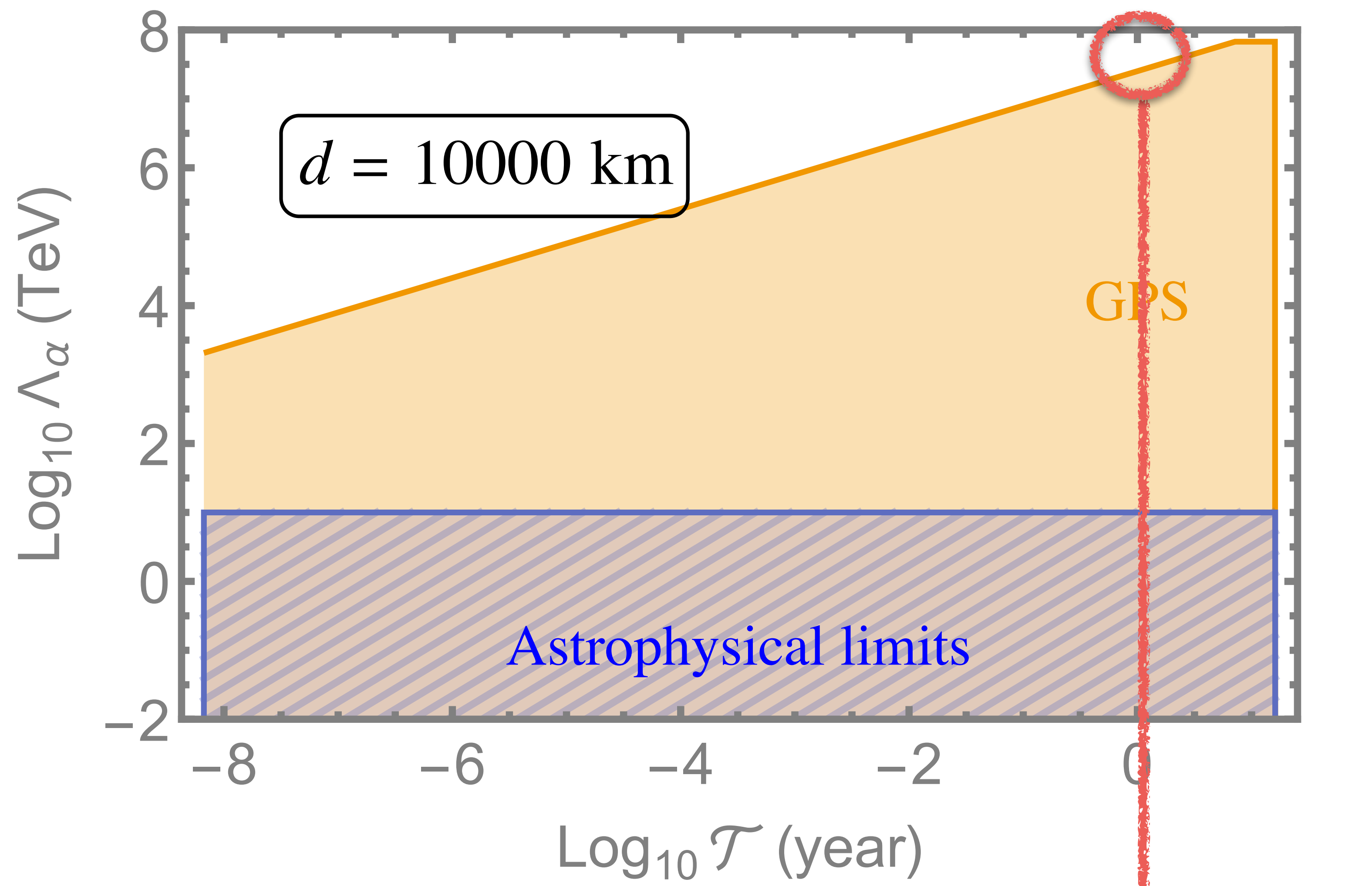


AstroLimits: Olive & Pospelov, PRD (2008)

Sr limits: P. Wcislo et al, Nat. Astron. (2016)

Limits on Λ_α (transient variation of α)

GPS.DM collaboration, Nature Commun. **8**, 1195 (2017)

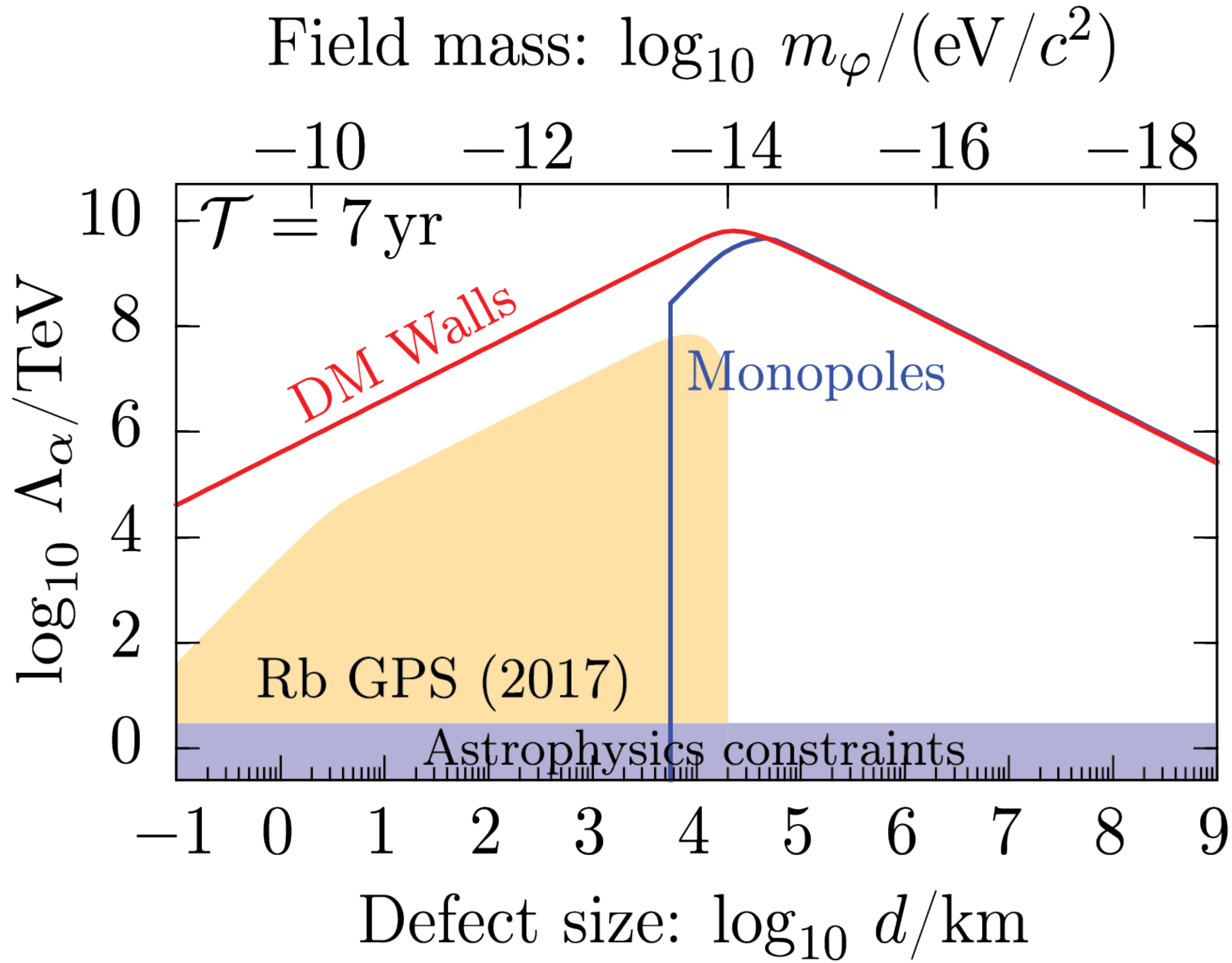


$$\frac{\delta\alpha}{\alpha} \lesssim 2\times 10^{-12}$$

AstroLimits: Olive & Pospelov, PRD (2008)

Sr limits: P. Wcislo et al, Nat. Astron. (2016)

Bayesian future



B. Roberts et al, ArXiv:1803.10264

GPS as a dark matter detector

- Largest human-built dark matter detector (~50,000 km)
- Data mining of ~ 15 years of archival data
- Improved limits on certain ordinary-dark matter couplings by six orders (!) of magnitude : α, m_e/m_p, m_q/Λ_{QCD}
- Next steps: Bayesian statistics (100x) + search for monopoles
- Other possibilities:
  networks of magnetometers (GNOME), LIGO, laboratory clocks
- First demonstration of using a network of precision measurement devices for DM searches

Derevianko & Pospelov, Nature Phys. **10**, 933 (2014)
GPS.DM collaboration, Nature Comm. **8**, 1195 (2017)
B. Roberts et al., arXiv:1803.10264