Day 2

Search for variation of fundamental constants and dark matter with atomic clocks

Andrei Derevianko
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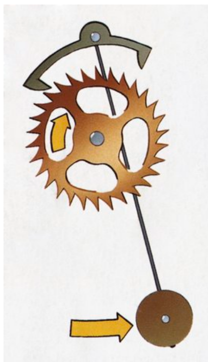
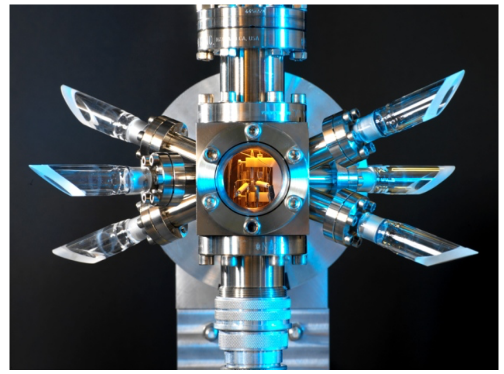
What will we cover today?

- Physics beyond the Standard Model
- Search for variation of fundamental constants and novel regimes of variations
- Ultralight dark matter searches

Review of Day 1



$\Rightarrow$



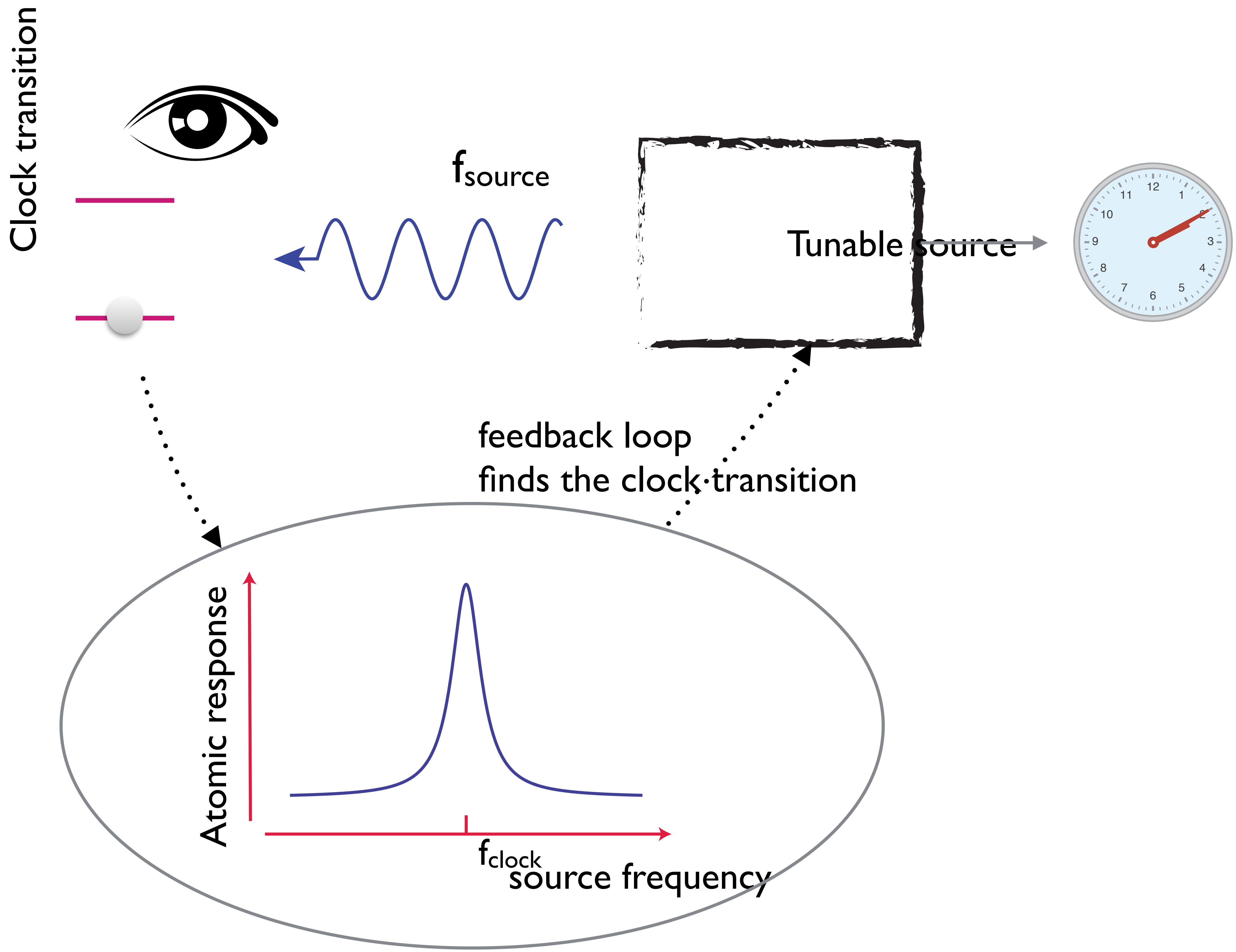
$$|0\rangle + |1\rangle \overset{?}{\Rightarrow} |0\cdots 0\rangle + |1\cdots 1\rangle$$

- ❑ Arguably the most precise quantum sensors ever built
- ❑ A wealth of techniques form a toolbox of quantum information science
- ❑ Natural long-coherence qubits, state preparation, coherent state manipulation
- ❑ Ion clocks - first demonstration of high-fidelity entangling gates
- ❑ Quantum oscillator (qubit) is well protected and characterized $\Longrightarrow$

  novel applications in fundamental physics

Review: How does it work?

Time = (number of oscillations) x (1/f_{clock})



Atomic clocks as quantum sensors

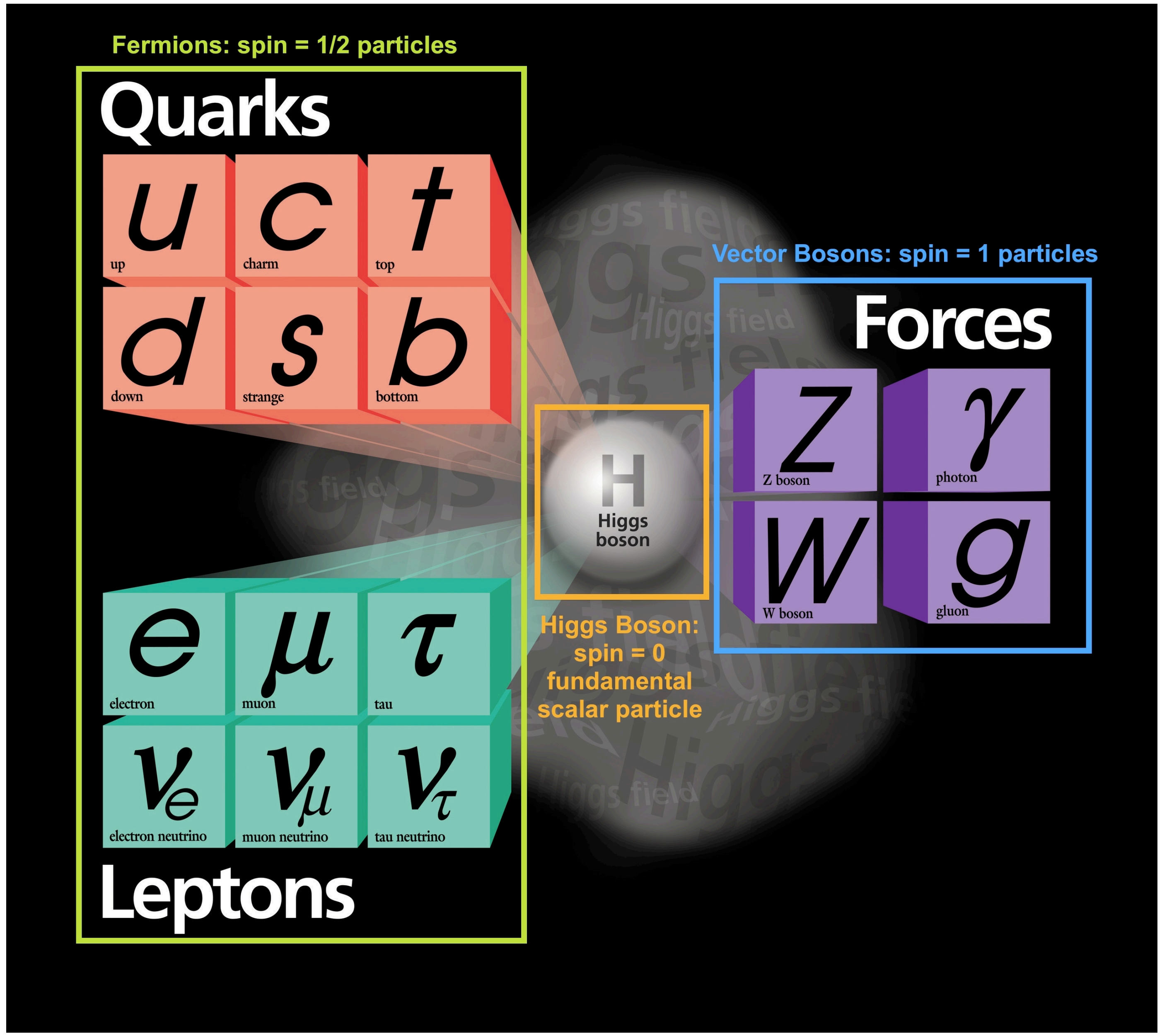
- Quantum oscillator (qubit) is well protected from the traditional physics environmental perturbations

- Residual traditional physics perturbations are well characterized $\Longrightarrow$ low-level background

- Exotic physics can leave uncharacterized perturbations in atomic and cavity frequencies

Beyond the Standard Model

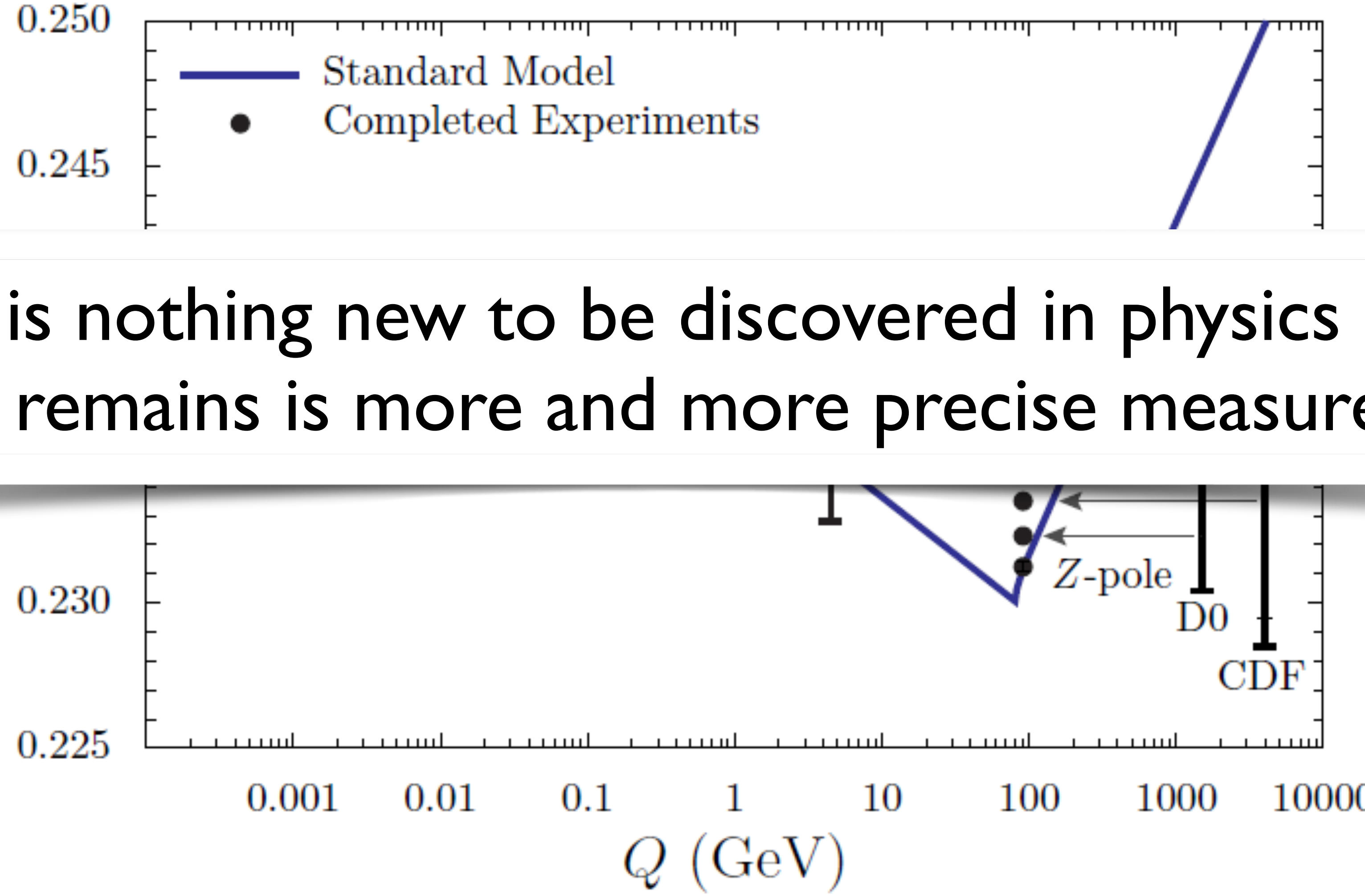
Standard Model



$$\underbrace{U(1)}_{\text{EM}} \otimes \underbrace{SU(2)_L}_{\text{Weak}} \otimes \underbrace{SU(3)}_{\text{Strong}}$$

Is physics dead?

Overwhelming success of the Standard Model
LHC: the Higgs is confirmed :) - no new physics found :(



"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

S. G. Porsev, K. Beloy and A. Derevianko, PRL 102,181601 (2009)

Physics is dead

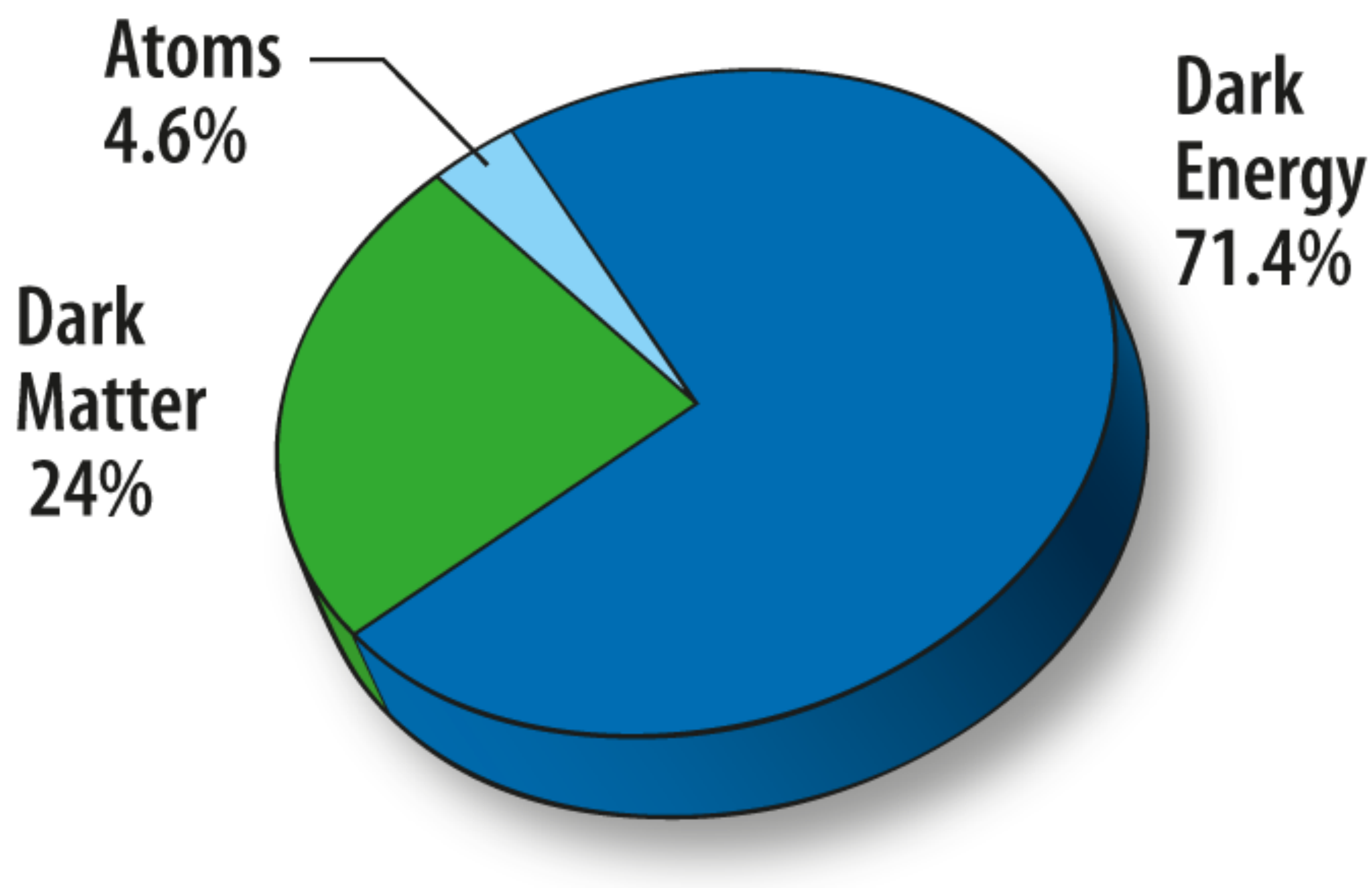
> "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."
>
> ~ William Thomson (Lord Kelvin), 1900

Lord Kelvin: "cloud" hanging over 19th-century physics:
blackbody radiation and the ultraviolet catastrophe

Max Planck (1901) : blackbody spectrum - quantization paradigm - Planck constant *h*- quantum revolution

Cloud over 21st-century physics

Problem of dark matter/dark energy



Excellent textbook: S. Weinberg "Cosmology"

Open problems in SM

- Matter-antimatter asymmetry
- Nature of dark energy
- Nature of dark matter
- Strong CP
- Hierarchy
- Quantum gravity
- Values of fundamental constants
- …

State of confusion?

Tantalizing discovery potential

REVIEWS OF MODERN PHYSICS

Search for new physics with atoms and molecules

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

Rev. Mod. Phys. **90**, 025008 – Published 29 June 2018

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.

Mini tutorial:
How to translate PRD papers

Gained in translation

Units

Natural units: $c = \hbar \equiv 1$

Atomic units: $|e| = \hbar = m_e \equiv 1$

$c_{\text{atomic}} = 1/\alpha \approx 137 \neq c_{\text{natural}} = 1$ (!)

Rationalized Heaviside-Lorentz vs Gaussian

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

Gained in translation

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

Extra term in Dirac Hamiltonian

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

$$H = c\alpha \cdot \mathbf{p} + \underbrace{m_e c^2 \left(1 + \Gamma \phi(\mathbf{r}, t)\right)}\beta$$

Variation in the electron mass

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

$$V \approx -\Gamma \phi \frac{p^2}{2m_e} + \Gamma \phi m_e c^2$$

Today's tutorial

Atomic clocks and fundamental physics

- Variation of fundamental constants
- Dark matter searches
- Gravitational wave detectors
- Tests of general relativity
- Multi-messenger astronomy
- Lorentz invariance
- ?

Variation of fundamental constants

$$\mathscr{L}_{\text{int}} = -\Gamma\phi m_e \bar{e}e \implies H = c\alpha\cdot\mathbf{p} + \underbrace{m_e c^2\left(1+\Gamma\phi(\mathbf{r},t)\right)}\beta$$

Variation in the electron mass

$$\mathscr{L}_{\text{int}} = -\Gamma_\alpha\phi\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \implies$$

Variation in $\alpha = \dfrac{e^2}{\hbar c}$

Fundamental constants

Fundamental constant is any parameter **not** determined by the theory in which it appears

- Standard model: 28 parameters (masses, α, $\hbar$, c, …)
- Cosmology: +12 parameters (e.g., Hubble)

SM: constants are constant
BSM: constants become dynamical variables (fields)
can vary in space and time

Reviews:

J.-P. Uzan, Living Rev. Relativ. 14, (2011)
J.-P. Uzan, Comptes Rendus Phys. 16, 576 (2015)

Variations of fundamental constants

Slow drifts

Transients

Oscillations

Stochastic background

Topological dark matter
Microstructure

Dilaton dark matter

Virialized dark matter

AD & Pospelov (2014)

Arvanitaki et al (2015)

AD (2016)

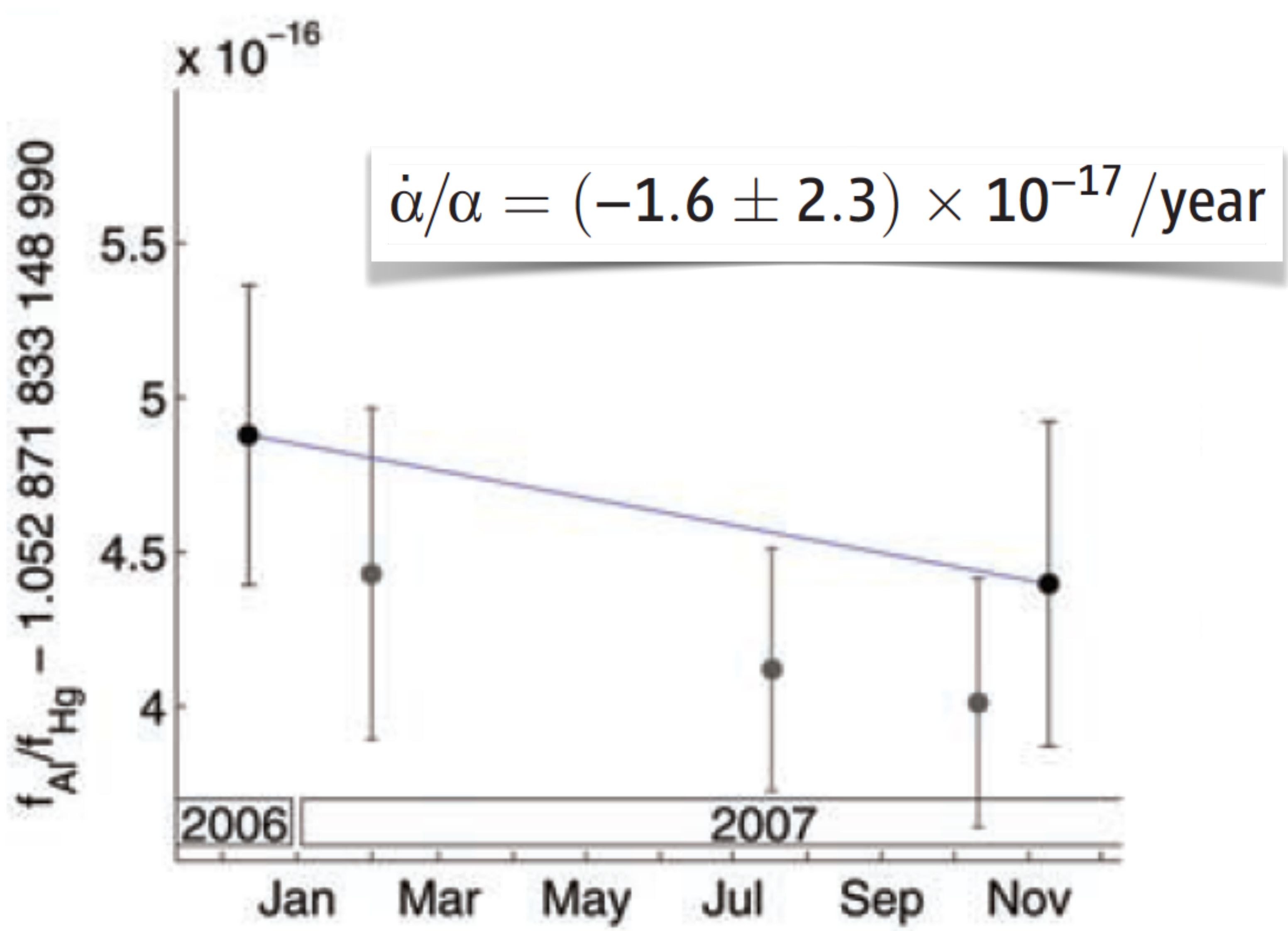
Ultralight dark matter

Slow drifts 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)

Atoms vs cavities

Optical transitions: energies scales as $\mathrm{Ry} = \dfrac{m_e e^4}{2\hbar^2}$

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

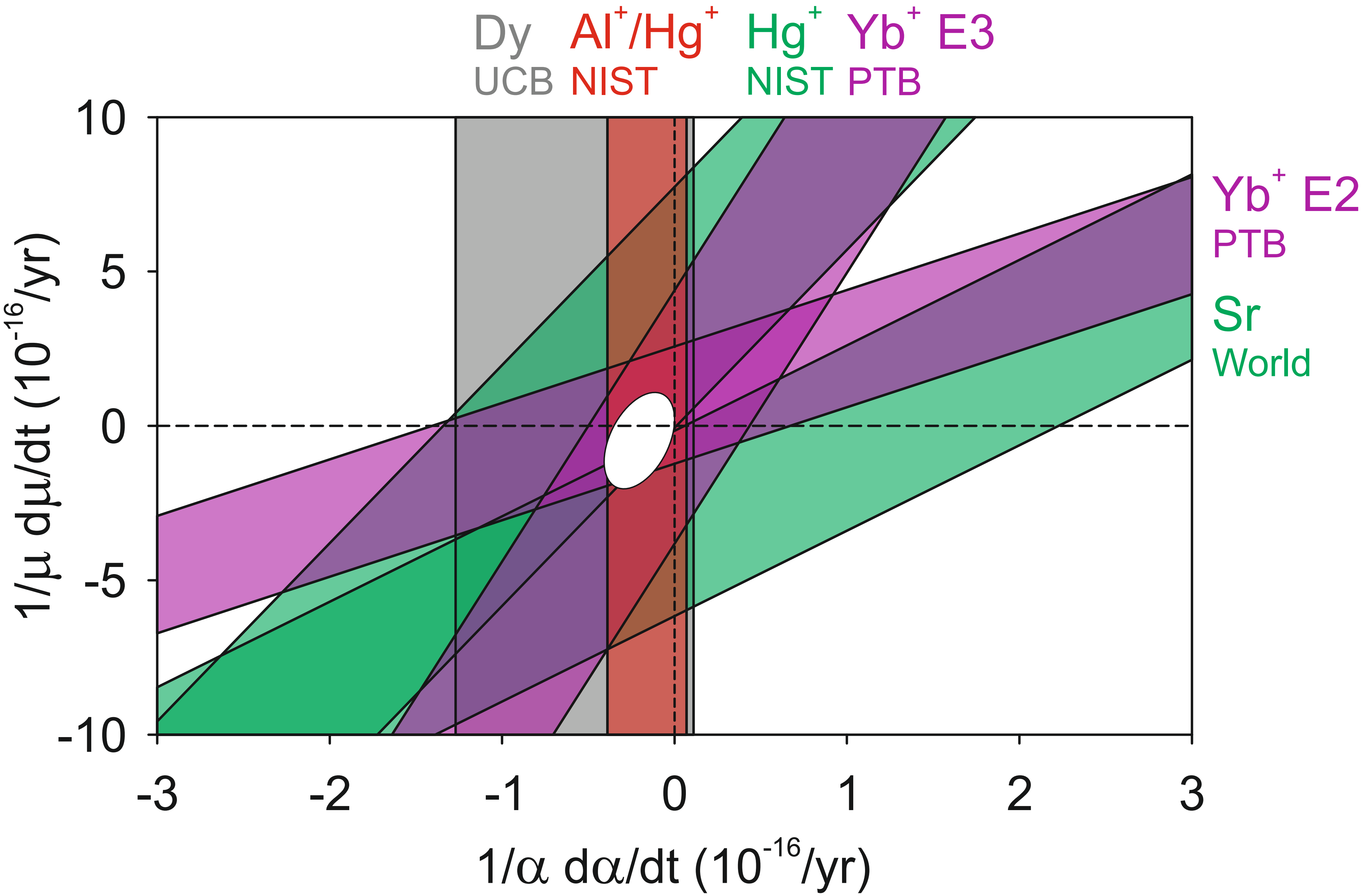
$$f_{\mathrm{cavity}} \propto \frac{1}{\mathrm{length}} \propto \frac{1}{a_{\mathrm{Bohr}}} \propto \alpha^{-1} m_e$$

Today's tutorial

$\Longrightarrow$ effective comparison of atomic and cavity frequencies

Present limits on the slow drifts

$$\mu = \frac{m_e}{m_p}$$



Huntemann et al. Phys. Rev. Lett. 113, 210802 (2014)

Variations of fundamental constants

Slow drifts

Transients

Topological dark matter
Microstructure

AD & Pospelov (2014)

Oscillations

Dilaton dark matter

Arvanitaki et al (2015)

Stochastic background

Virialized dark matter

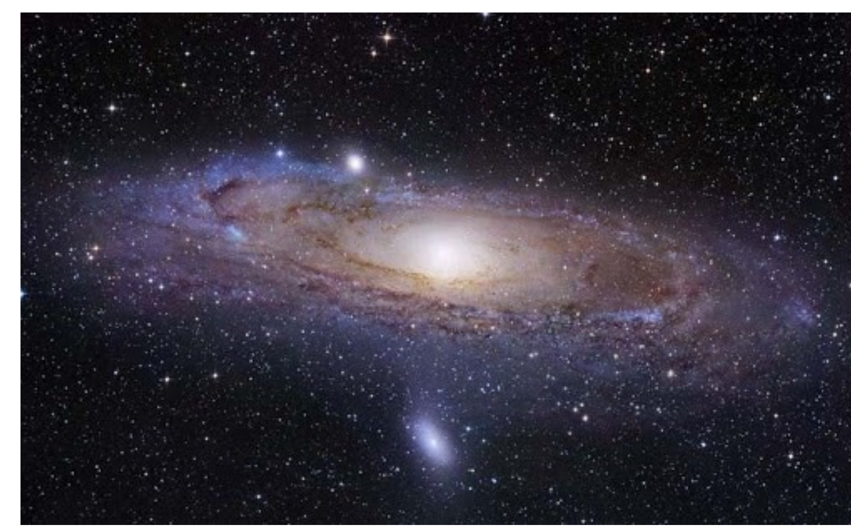
AD (2016)

Ultralight dark matter

Atomic clocks as dark matter detectors

Dark matter puzzle

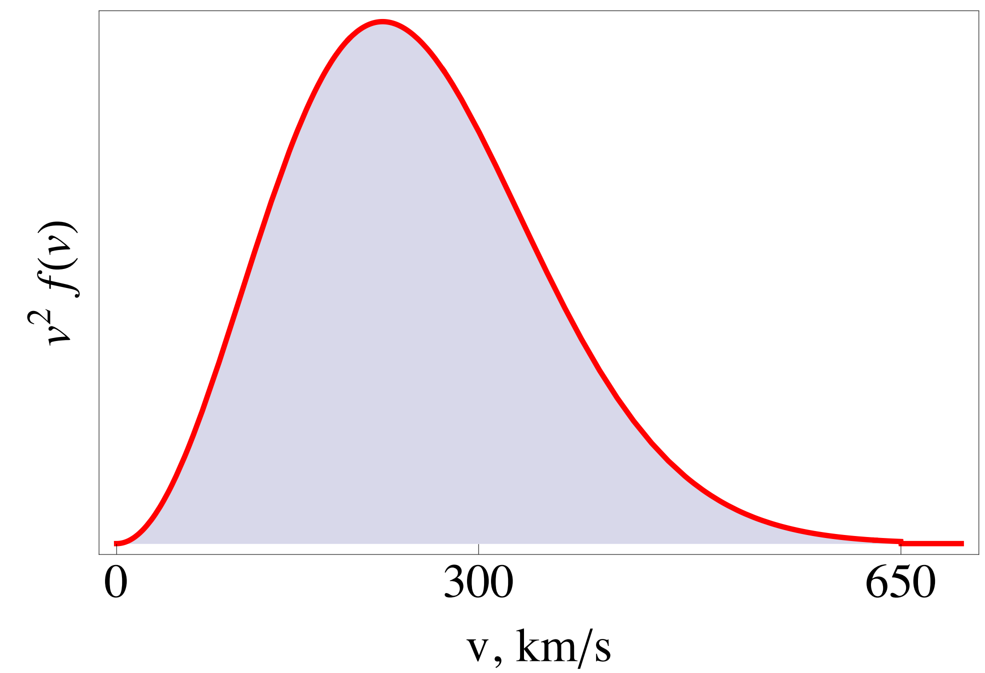
- Five times more abundant than ordinary (baryonic) matter
- Does not emit/absorb radiation: can not be seen with telescopes
- Multiple observational evidences: galactic rotation curves, gravitational lensing, cosmic microwave background,…
- Inferred from **gravitational interactions** with luminous matter on **galactic scales**
- What is it?
  Does it interact with baryonic matter non-gravitationally?



What do we know about DM?

Dark Matter halo

Velocity distribution



Galactic orbital motion

$$v_g \sim 300\,\mathrm{km/s}$$

Energy density

$$\rho_{DM} \sim 0.3\,\mathrm{GeV/cm^3}$$

Particle DM candidates

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

λ_{dBr}< Galactic size (~10 kpc) $\Rightarrow m_{\mathrm{DM}} \gg 10^{-22}$ eV

λ_C > Schwarzschild radius $\Rightarrow m_{\mathrm{DM}} \ll 10^{+28}$ eV

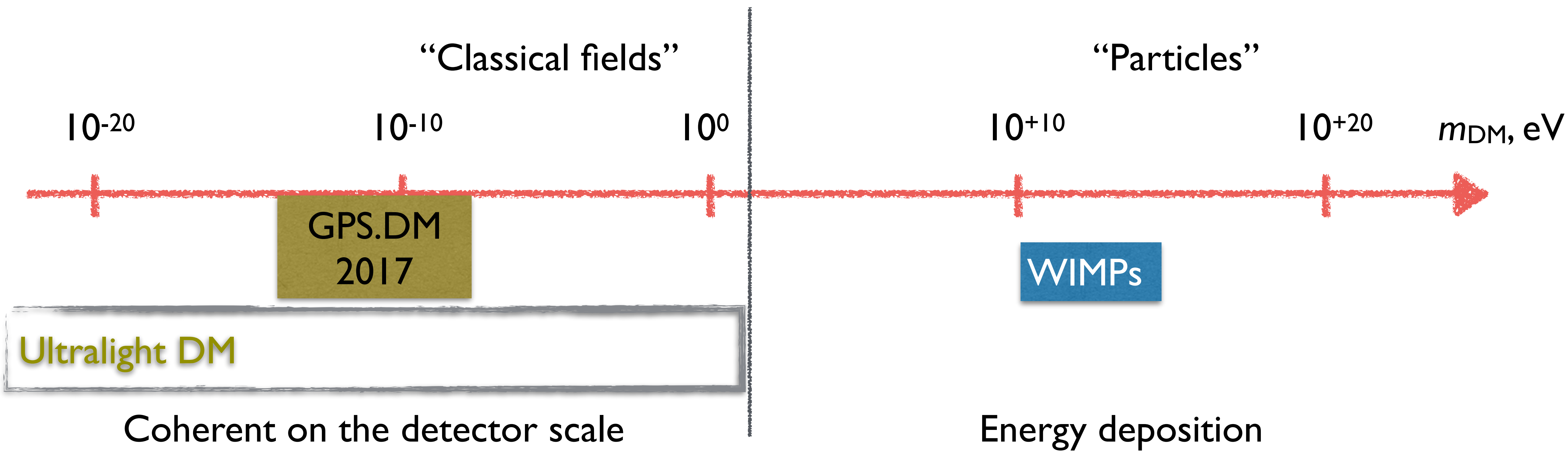


Table-top Cosmology

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

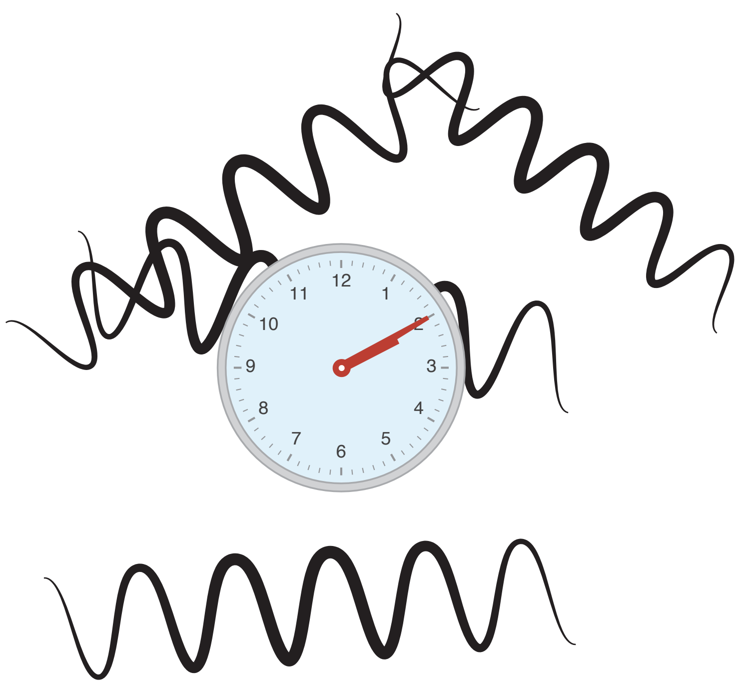
These depend on fundamental constants

$$\Rightarrow$$

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

Ultralight DM and atomic clocks

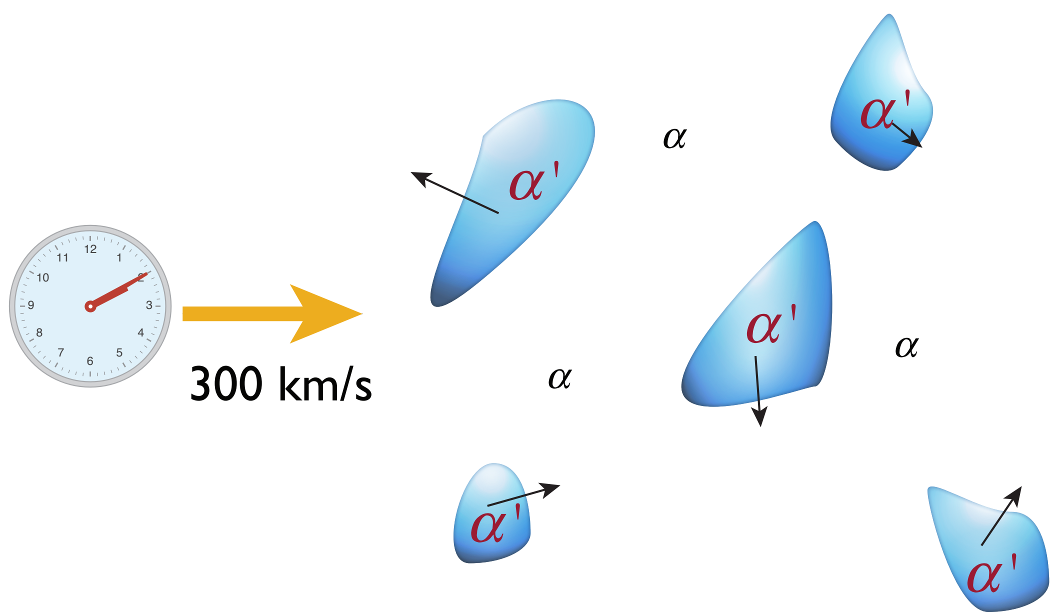
non-self-interacting fields



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)

Non-self-interacting dark matter fields

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

Fields oscillate at Compton frequencies

Plane wave solutions of Klein-Gordon Eq.

$$\phi(t,r) = \phi_0 \cos(\omega_\phi t - \mathbf{k}\cdot\mathbf{r})$$

$$\phi_0 = \frac{\hbar}{m_\phi c}\sqrt{2\rho_{\mathrm{DM}}}$$

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 Compton frequencies

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

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

Basic idea

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

Fundamental constants oscillate $\Longrightarrow$

Modulation of atomic frequencies $\Longrightarrow$

Power spectral density exhibits peak at Compton frequency

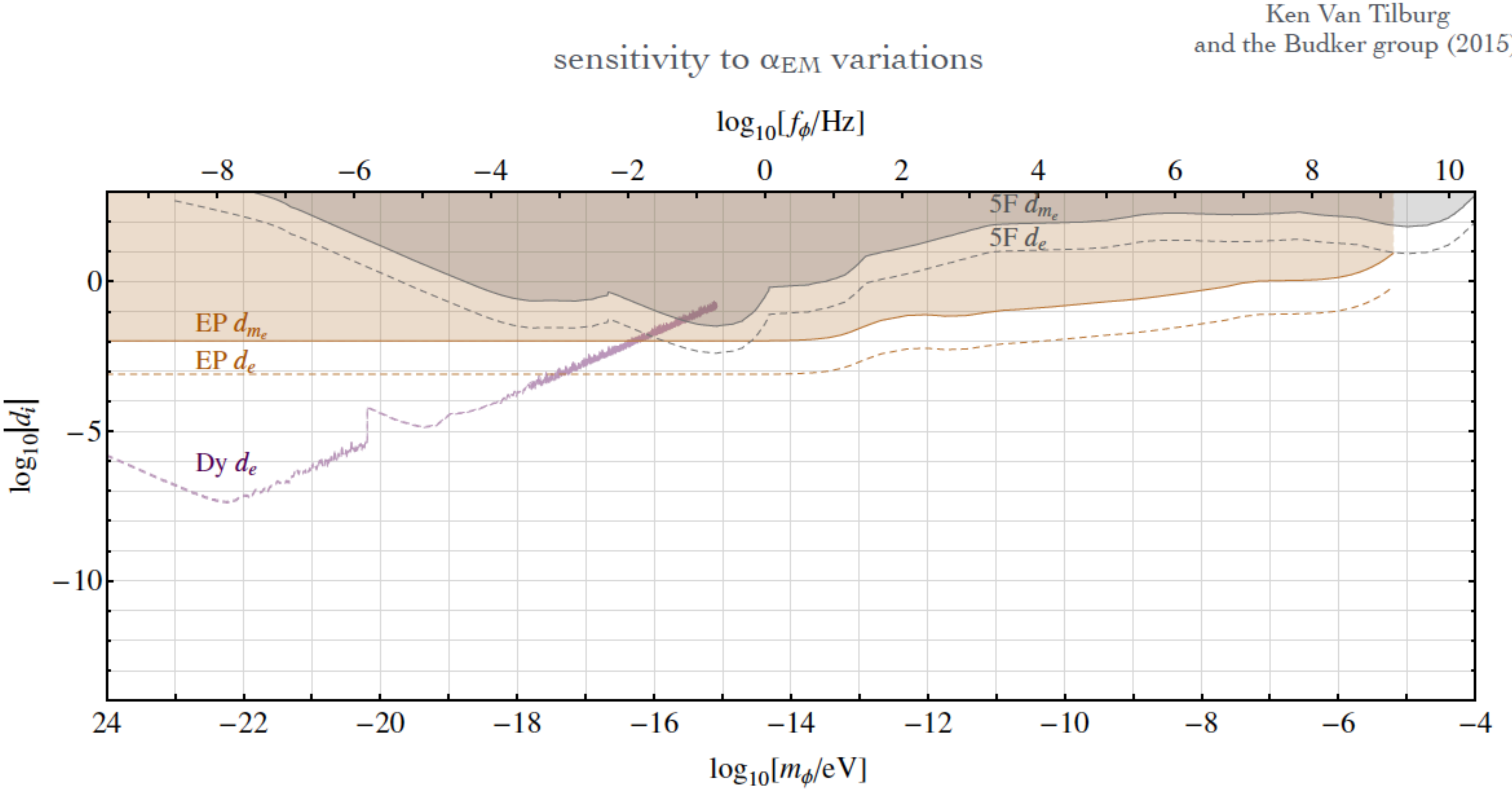
A. Arvanitaki, J. Huang & K Van Tilburg, PRD 91, 15015 (2015)

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

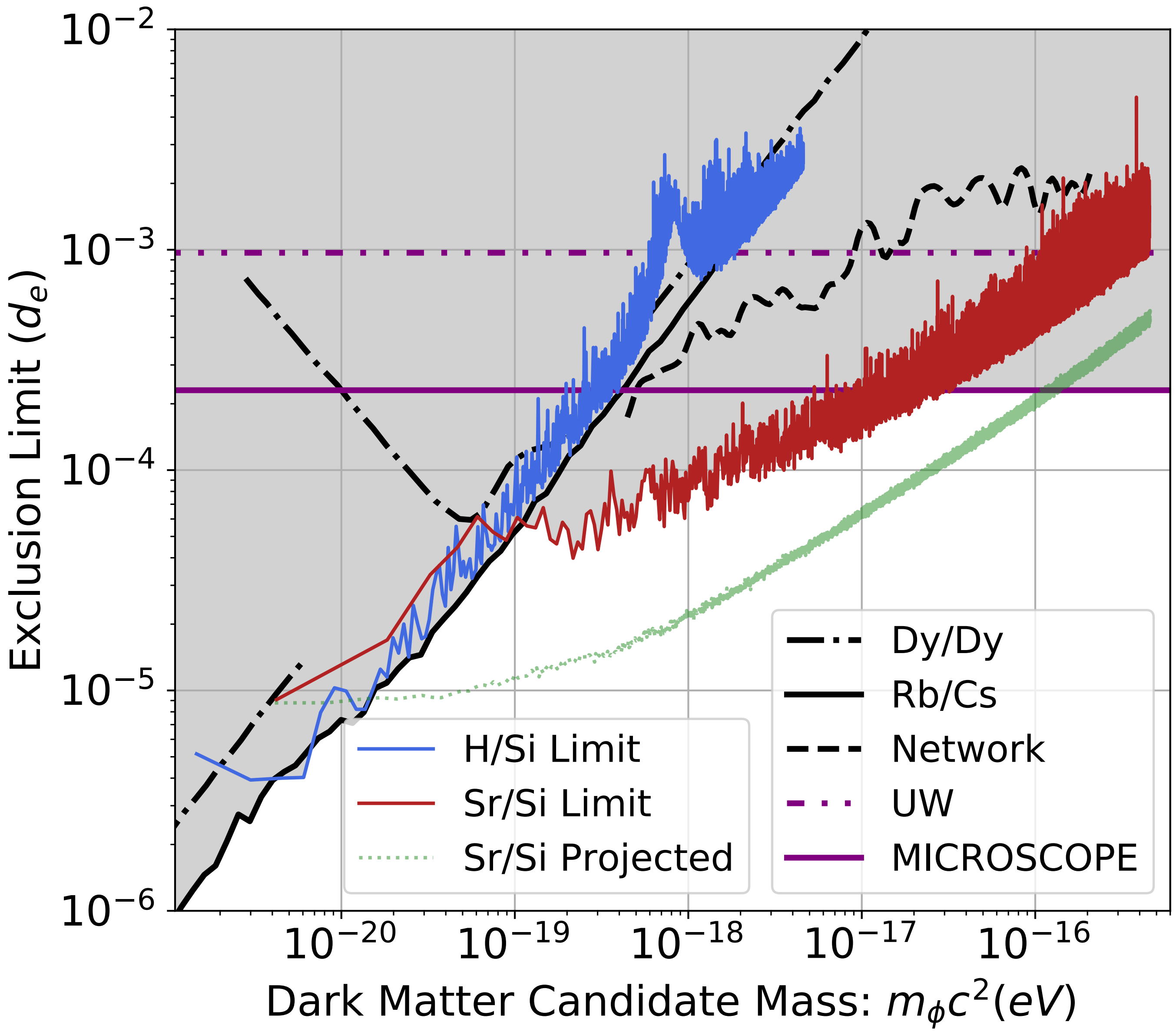
A. Derevianko, Phys. Rev.A ***97****, 042506 (2018)*

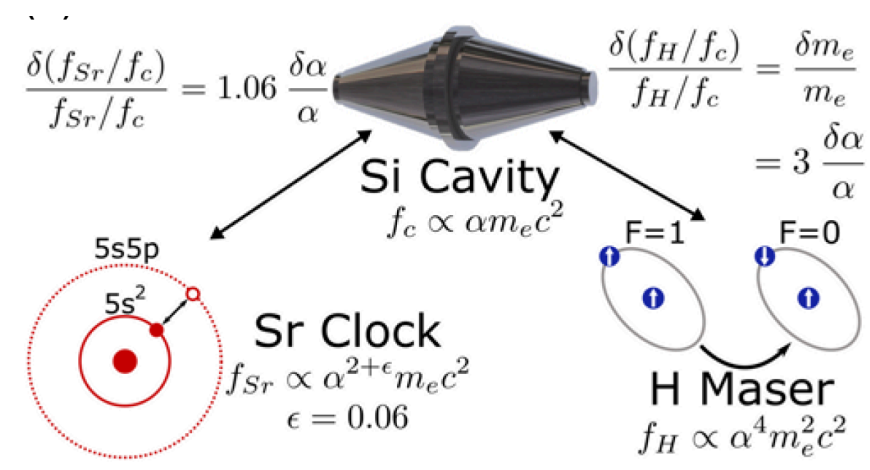
First limits on oscillating α



Credit: Mina Arvanitaki

Best constraints on oscillating DM





Lattice clock ↔ cavity↔ H-maser

C. J. Kennedy, E. Oelker, J. M. Robinson, T. Bothwell, D. Kedar, W. R. Milner, G. E. Marti, A. Derevianko, and J. Ye, Phys. Rev. Lett. 125, 201302 (2020)

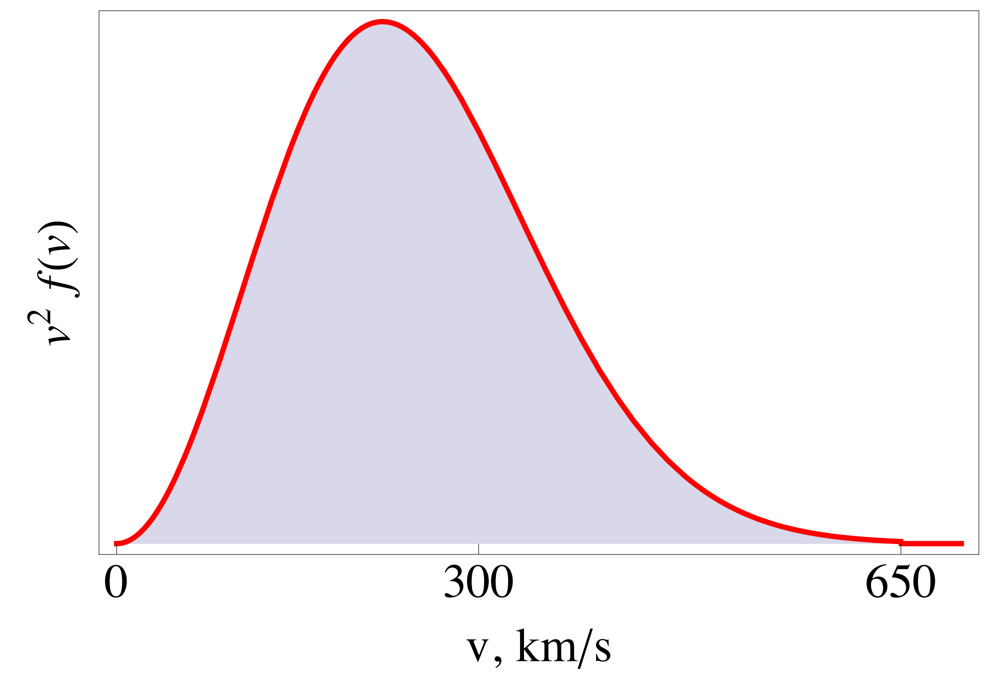
More sophisticated approach: stochastic field, dark matter lineshape, and networks

*A. Derevianko, Phys. Rev. A **97**, 042506 (2018)*

What do we know about DM?

Dark Matter halo

Velocity distribution



Galactic orbital motion

$$v_g \sim 300\,\mathrm{km/s}$$

Energy density

$$\rho_{DM} \sim 0.3\,\mathrm{GeV/cm^3}$$

Many modes ⇒Stochastic field

$$\frac{\#\text{ of particles}}{\text{mode}} \sim \left(\frac{\rho_{\text{DM}}}{mc^2}\right) \times \left(\lambda_{\text{de Broglie}}\right)^3 \gg 1$$

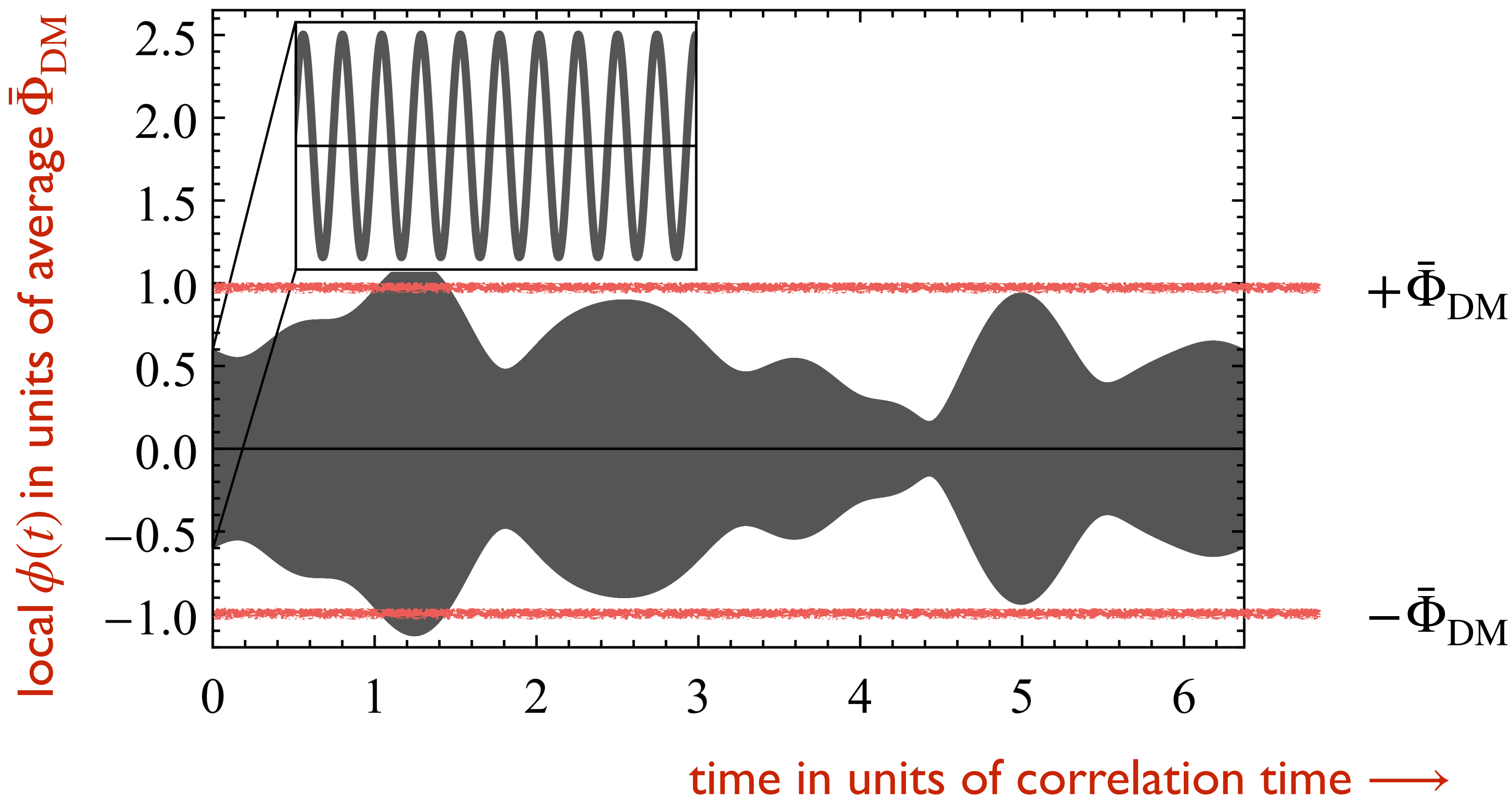
$m \ll 10\,\text{eV}$ ⇒ ultralight DM

$$\phi(t,\mathbf{r}) = \sum_{\text{modes}} \text{many waves with random phases}$$

⇒ Gaussian random fields (radiophysics, CMB, stochastic GW background,…)

- Correlation time and length
- Statistics is fully determined by 2-point correlation function

How does the DM field look like?

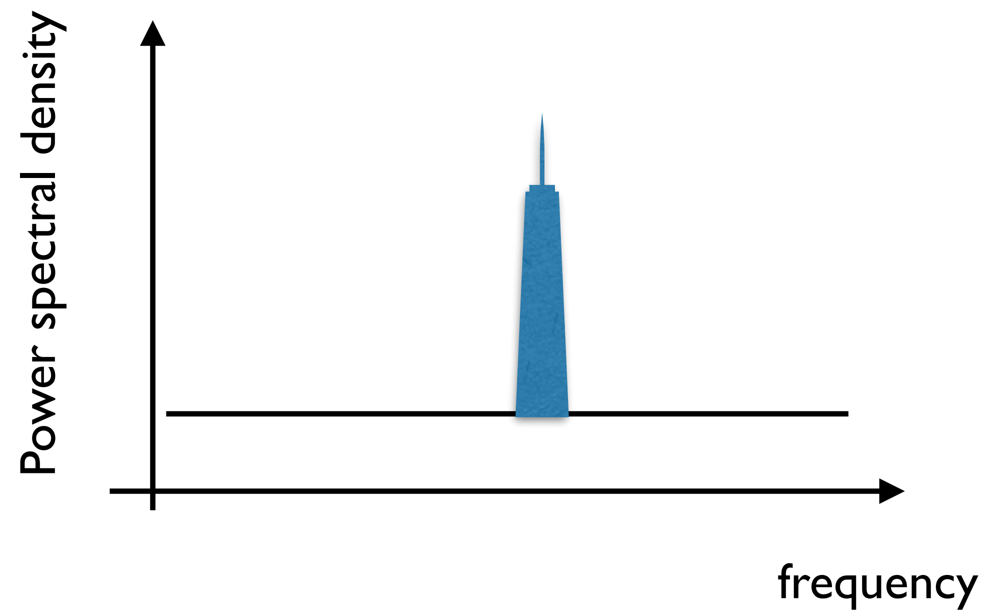


Variation of fundamental constants is stochastic

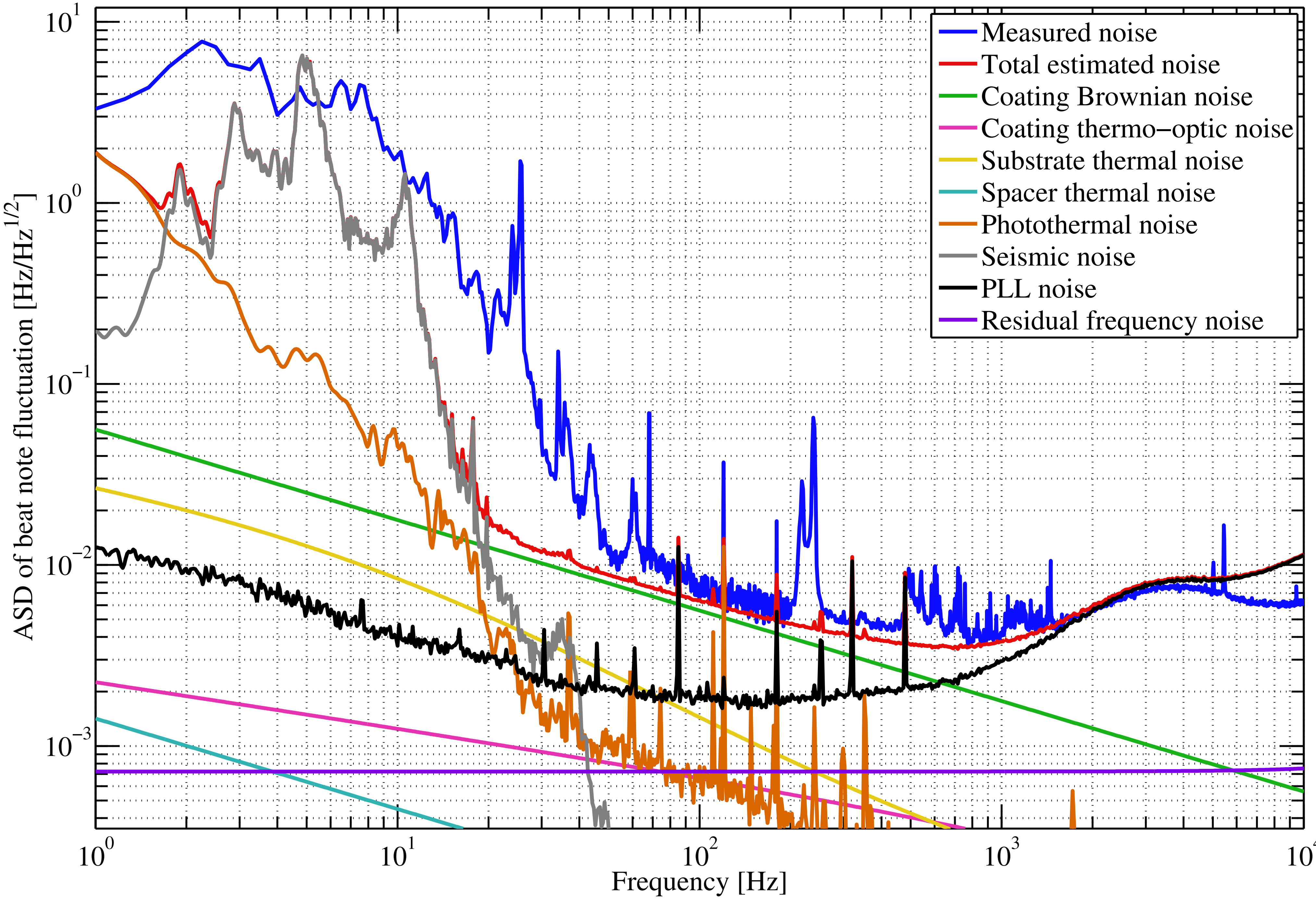
Coherence time is $\sim 10^5$ Compton periods

Has important 3-10 factor implications for experiments. See *arXiv:1905.13650*

We expect a peak at DM Compton frequency

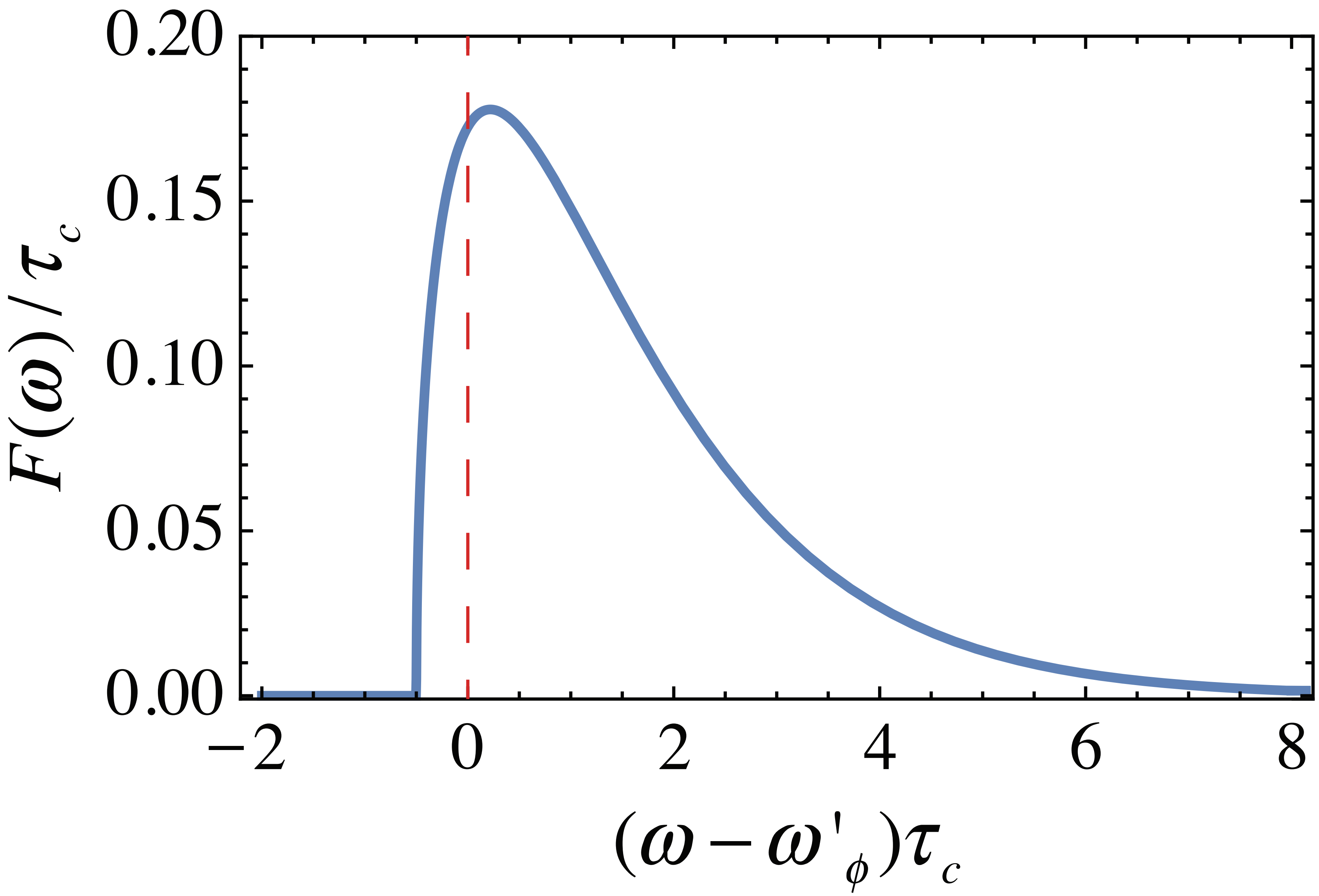


Measured cavity power spectrum, or where is the DM signal?



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

Dark matter line shape



A. Derevianko, *Phys. Rev.A* ***97***, *042506 (2018)*

Profile encodes all DM priors:

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

PHYSICAL REVIEW A **97**, 042506 (2018) **arXiv:1605.09717**

Editors' Suggestion

Detecting dark-matter waves with a network of precision-measurement tools

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Limits on the coupling strengths

All nodes within coherence length

$$\Gamma_X^{(\mathrm{network})} < \Gamma_X^{(1)} / N^{1/2}$$

Incoherent limit

$$\Gamma_X^{(\mathrm{network})} < \Gamma_X^{(1)} / N^{1/4}$$

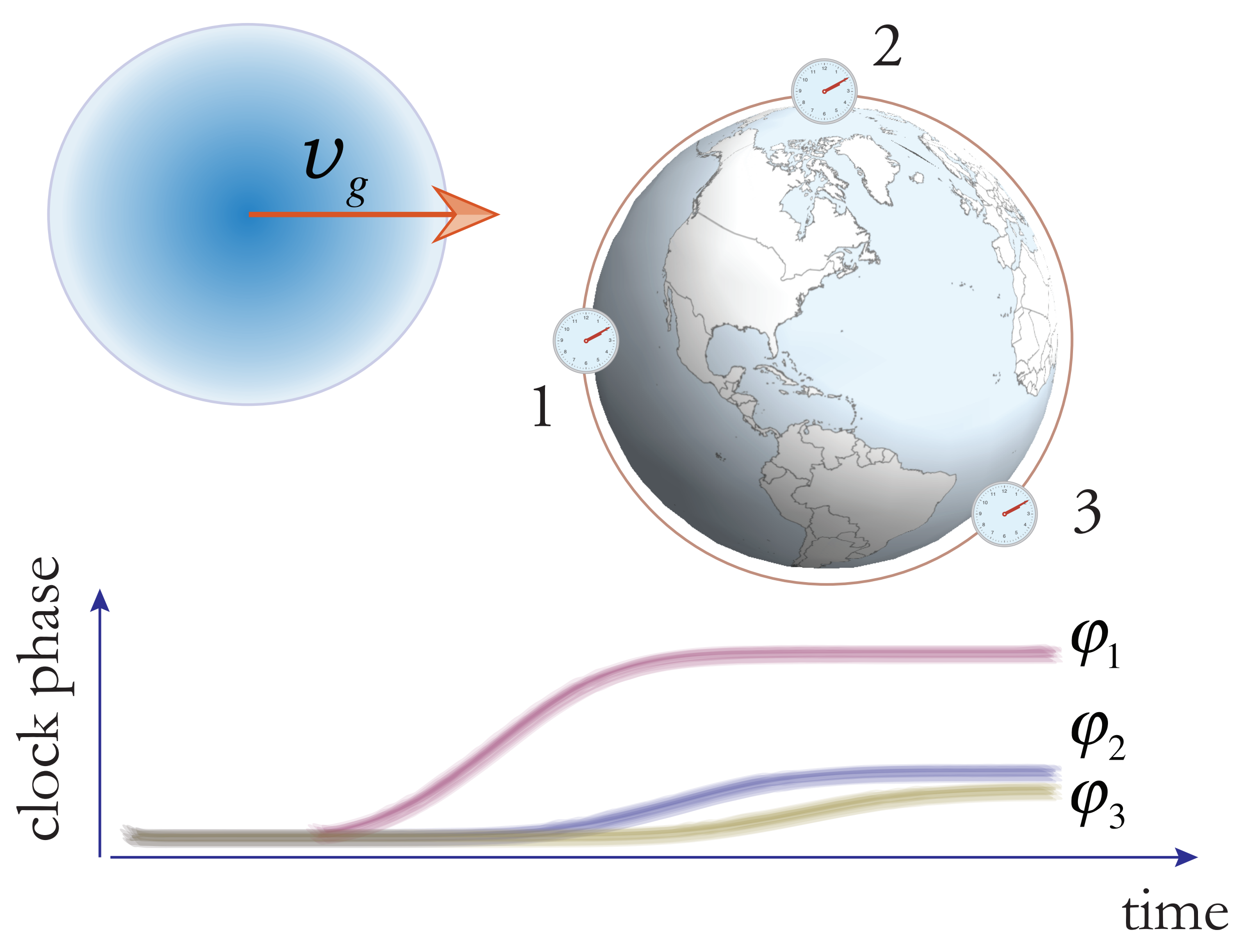
Search for clumpy dark matter

(Transient variation of fundamental constants)

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

Hunting for topological dark matter with atomic clocks

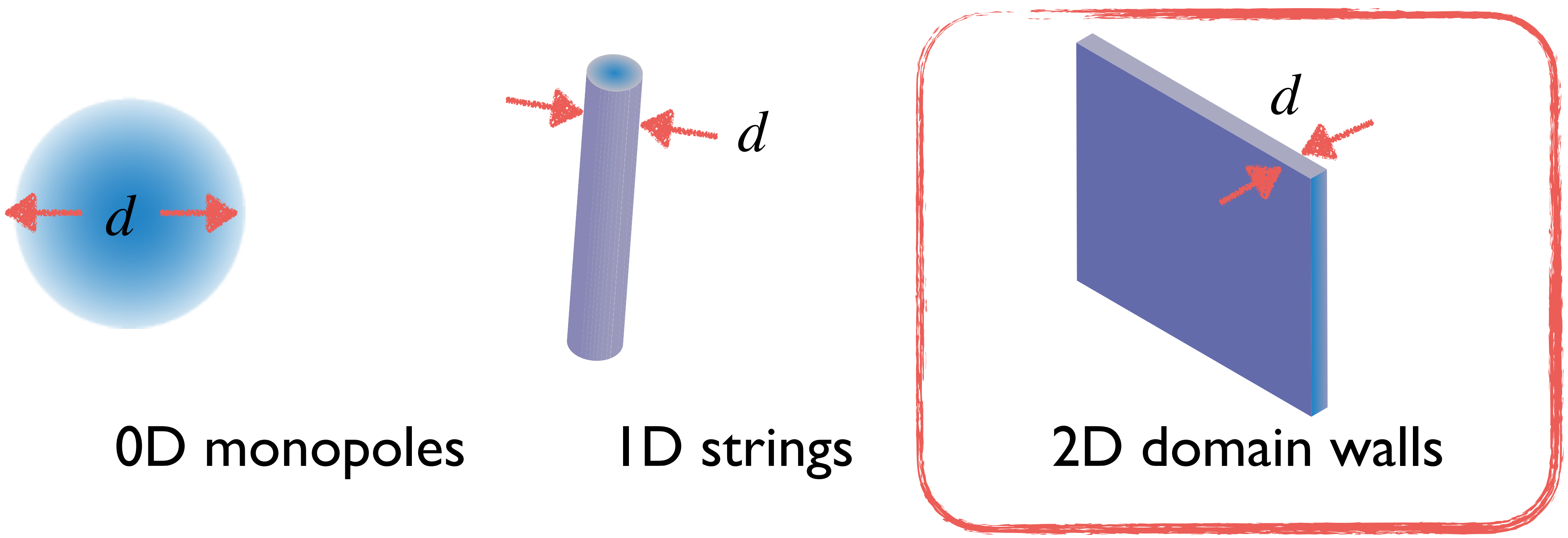
A. Derevianko[1*] and M. Pospelov[2,3]



Monopole or Q-ball signature

"Clumpy" (topological) Dark Matter

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



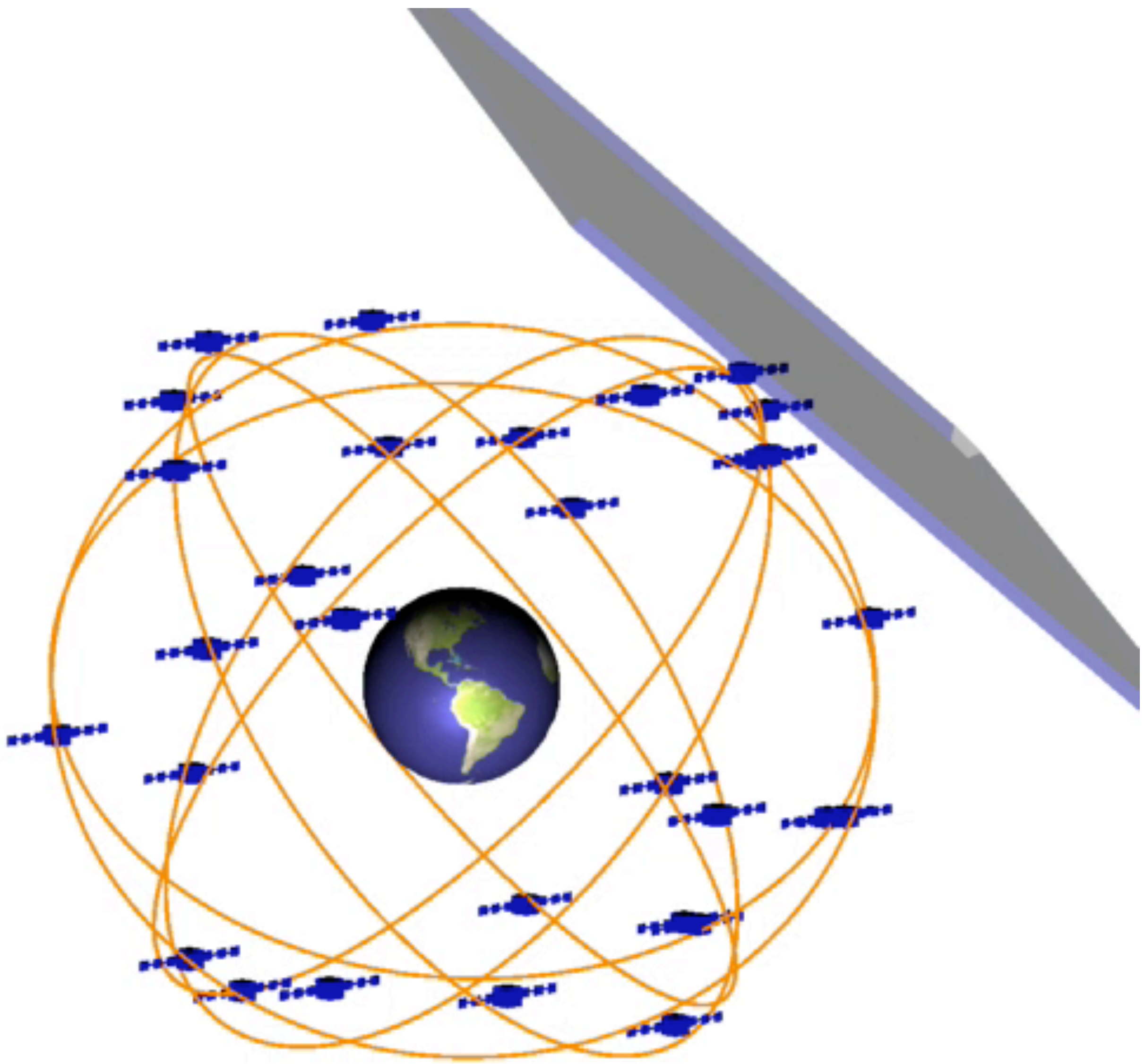
$$d \sim \frac{\hbar}{m_\phi c}$$

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

Ultralight DM

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

Domain wall sweep of GPS constellation



Credit: Conner Dailey

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

Formalizing coupling to DM

Today's tutorial

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

DM field — electrons — protons — EM field

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

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

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

Transient variation of fundamental constants

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

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

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

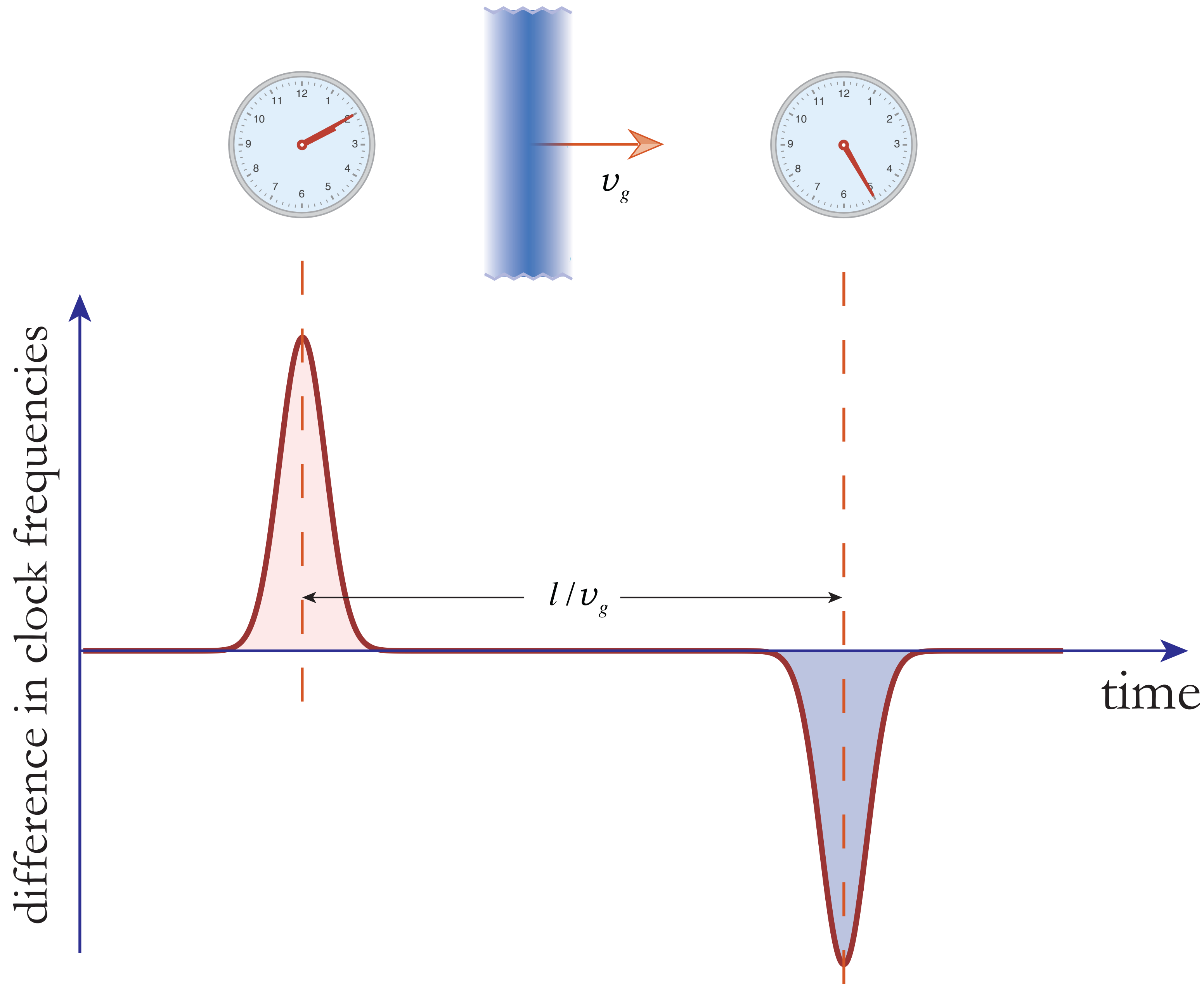
Defect size

Time b/w encounters

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

^{87}Rb

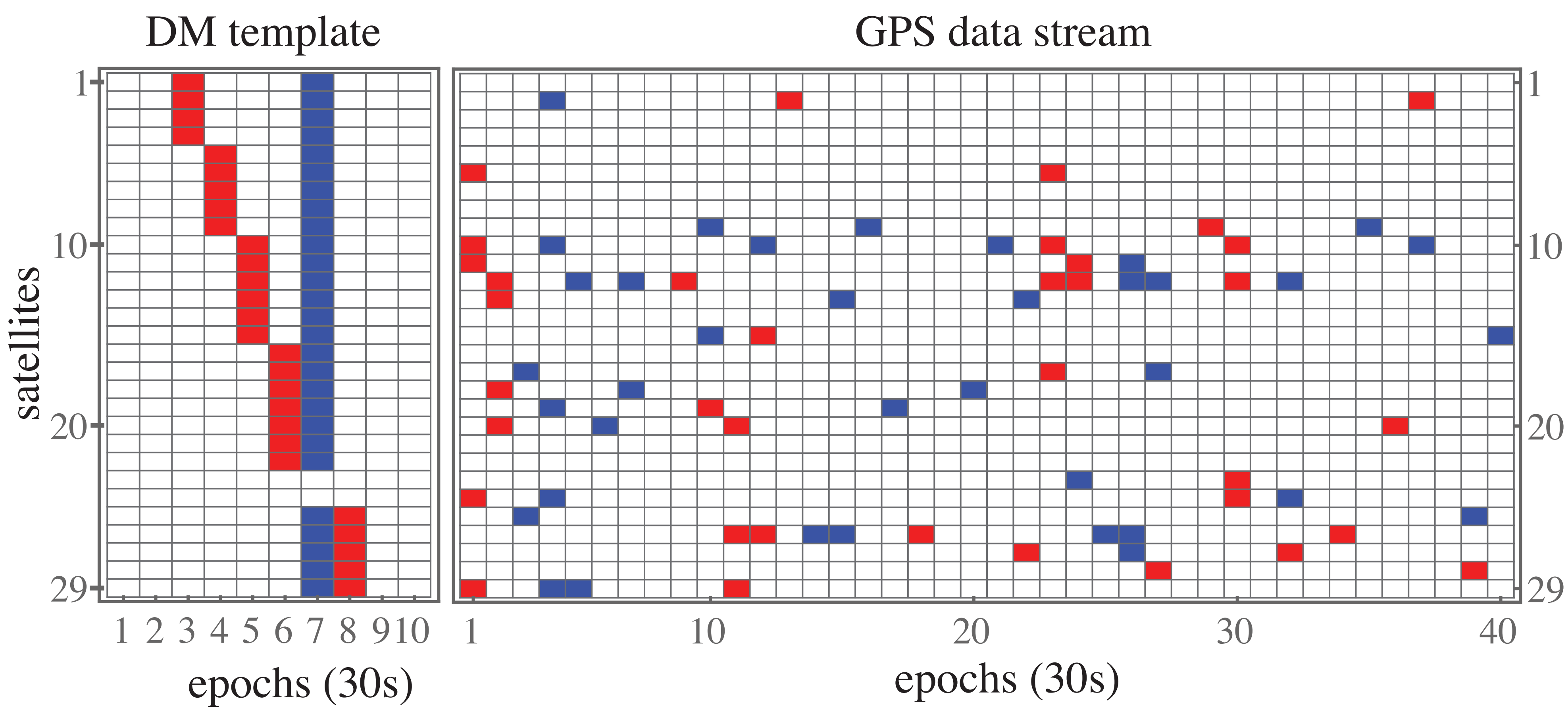
Two-clock signature



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

Andrei Derevianko - U. Nevada-Reno

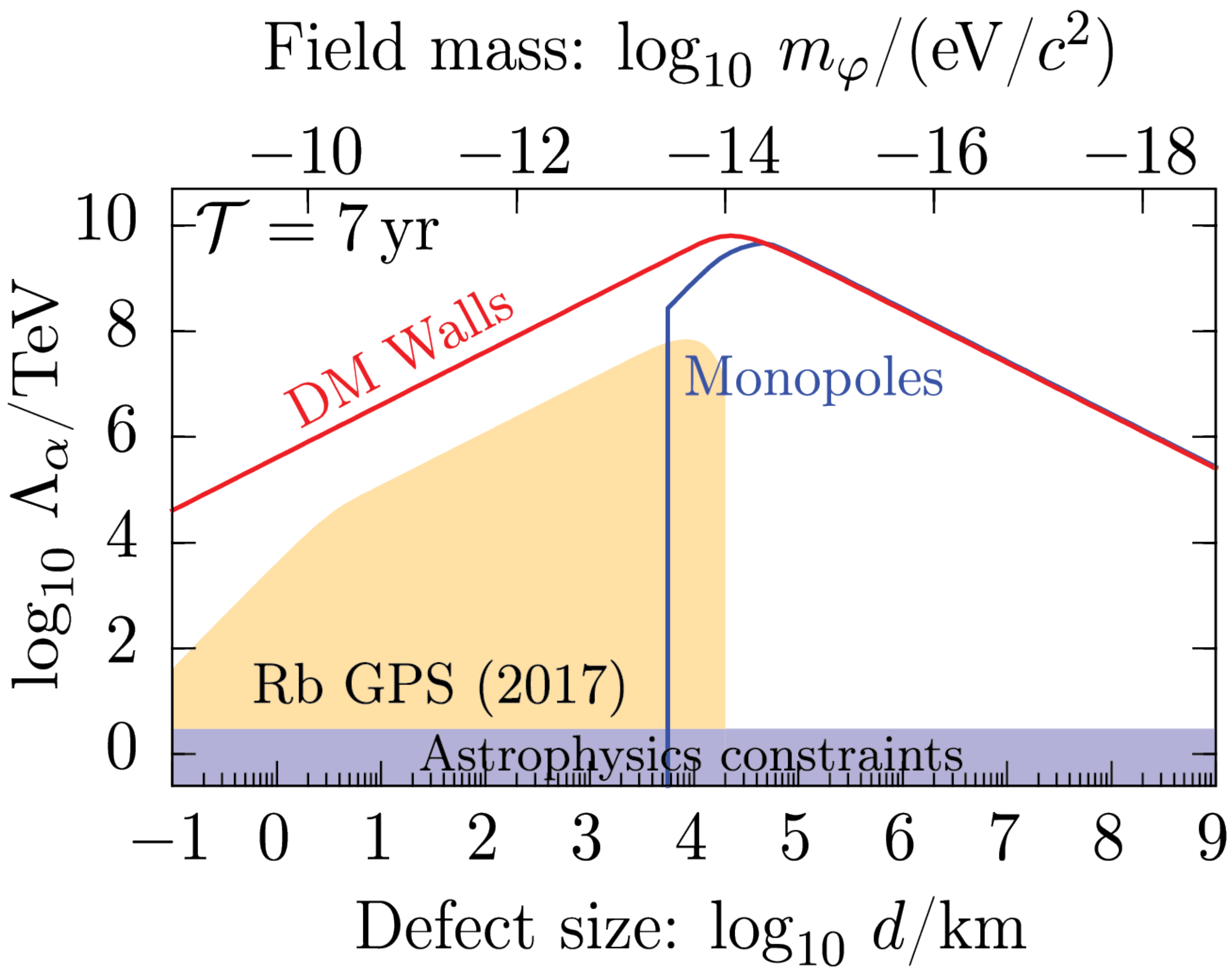
Network tile pattern (thin walls)



- 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 Commun. ***8****, 1195 (2017)*

Constraints on clumpy DM



+ terrestrial networks of clocks Roberts…Wolf, 1907.02661

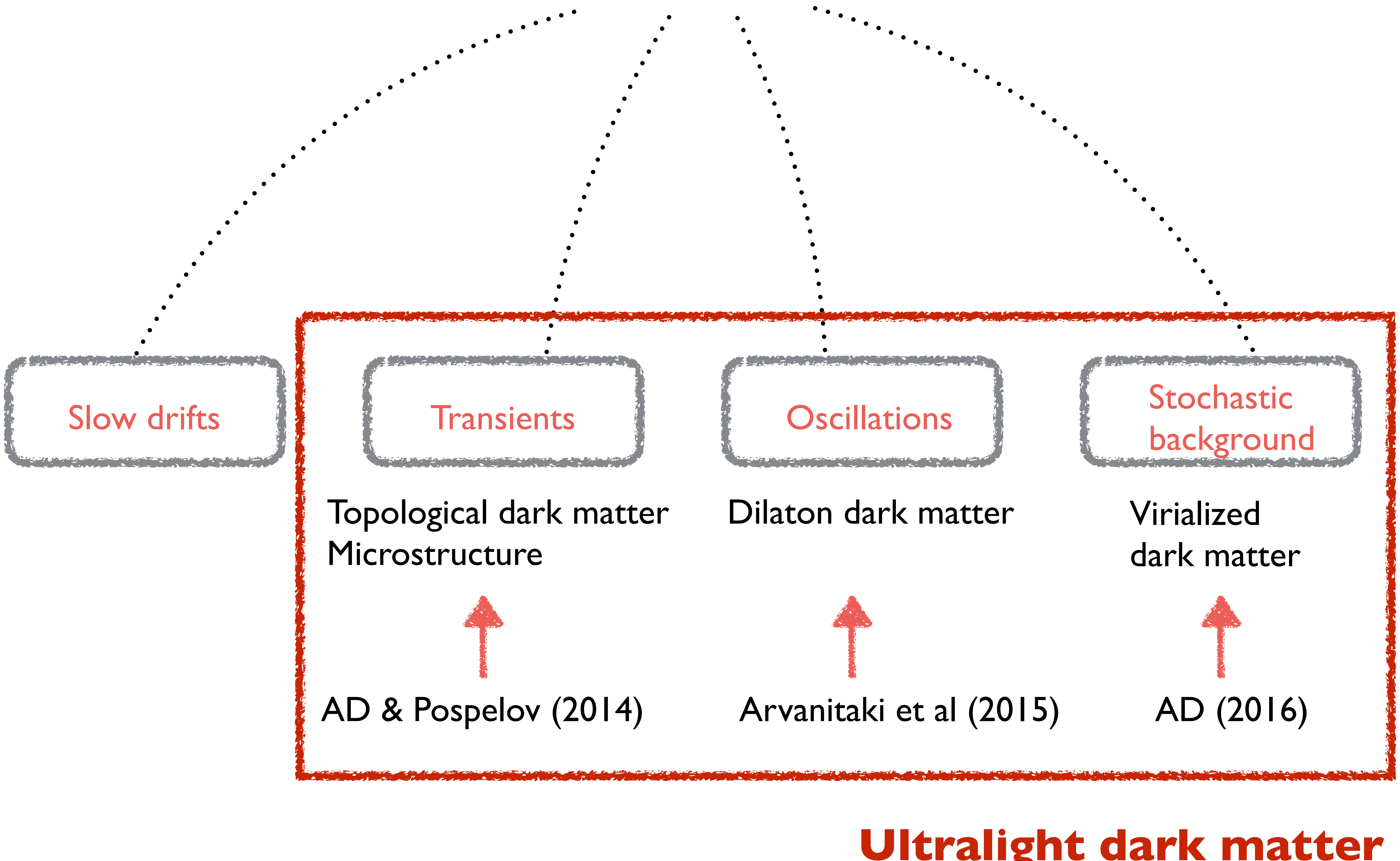
B. M. Roberts, G. Blewitt, C. Dailey, and A. Derevianko, PRD 97, 83009 (2018)

GPS as a dark matter detector

- Largest human-built dark matter detector (~50,000 km)
- Data mining of ~ 20 years of archival data
- Improved limits on certain ordinary-dark matter couplings by six orders of magnitude : $\alpha, m_e/m_p, m_q/\Lambda_{\rm QCD}$
- Next steps: Full search (100x in sensitivity, ongoing)
- Other possibilities:
  networks of magnetometers (GNOME), LIGO, laboratory clocks
- First demonstration of using a network of precision quantum sensors for DM searches

Derevianko & Pospelov, Nature Phys. 10, 933 (2014)
*GPS.DM collaboration, Nature Commun. **8**, 1195 (2017)*
*Roberts, Blewitt, Dailey, and Derevianko, Phys. Rev. D **97**, 83009 (2018)*

Variations of fundamental constants



Summary for day 2

- Standard Model is not complete
- Fundamental constants can vary both in space in time
- Atomic clocks are uniquely sensitive to variations of FCs
- Ultralight dark matter : wavy vs clumpy
- Wavy DM is stochastic in nature - must use the correct framework
- DM searches benefit from networks
- Archiving data makes testing novel theories easier