Searching for transient dark matter signatures with atomic clocks

Benjamin M. Roberts[1],

G. Blewitt[2], C. Dailey[2], A. Derevianko[2] (GPS.DM Collaboration)

A. Hees[1], P. Delva[1], P. Wolf[1]

[1]SYRTE, CNRS, l'Observatoire de Paris, Paris;
[2]University of Nevada, Reno.

ACES Workshop 2018,
TUM, Munich,
22–23 October 2018

23 October 2018

Outline:

- Ultra light dark matter; "clumps", e.g. Topological defects
- Transient signals: Global networks of precision devices
- GPS: 50,000km aperture sensor array
  - ~ 30 satellite clocks, > 15 years of archived data
- GPS + other existing
  - limits: orders of magnitude improvement for certain models
- Extending discovery reach: Optical clock networks
- Noise asymmetry & annual modulation signatures

Dark Matter: What is it?

- $\sim$ 25% of Universe energy budget (cf $\sim$ 5% for "normal" matter)

- Narrowed down to $\sim$90 orders-of-magnitude window:

Rough mass-range for various models:

- MACHOs: $10^{58} - 10^{68}$ eV
- WIMPs: $10^{6} - 10^{12}$ eV
- l-WIMPS: $1 - 10^{6}$ eV
- Axions: $10^{-10} - 10^{-4}$ eV
- Ultralight Q fields: $10^{-24} - 1$ eV

(context: $m_{\rm Earth} \sim 10^{60}\,$eV $\quad m_{\rm electron} \sim 10^{6}\,$eV)

- Even asserting that DM is a fundamental particle:
$10^{-24} < m/eV < 10^{19}$ $\quad\Longrightarrow$ 40 orders of magnitude range

Ultralight Dark Matter:

WIMPs

- long-time "favourite" DM candidate
- Masses $\sim 10 - 1000$ GeV
- Many null WIMP results
- Increased interest in other forms of DM

Ultralight fields (e.g., axions)

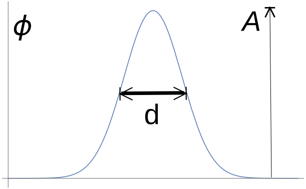
- Masses $\sim 10^{-24} - 1\,\mathrm{eV}$
- Oscillating field: $\phi = a\cos(m_a t)$
- Stable topological defects: monopoles, strings, walls
  - Also: Q-balls, solitons, "clumps"

- Peccei & Quinn '77, Weinberg '78, Dine & Fischler '82,...

Topological Defect DM

Topological Defects

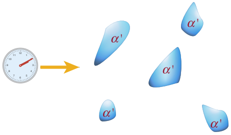
- monopoles, strings, walls,
- Defect width: $d \sim 1/m_\phi$
- Earth-scale object $\sim 10^{-14}$ eV



Inside: $\phi^2 \to A^2$, Outside: $\phi^2 \to 0$

Dark matter: Gas of defects

- DM: galactic speeds: $v_g \sim 10^{-3}c$
- A^2, d, $\mathcal{T}_{\mathrm{b/w\ collisions}} \implies \rho_{\mathrm{DM}}$



$$A^2 = \rho_{\mathrm{DM}}\, v_g\, d\, \mathcal{T},$$

- Sikivie '82, Preskil '83, Vilekin '85, Coleman '85, Lee '89, ...

Shift in atomic clock frequencies

- DM may interact with: Photons, fermions

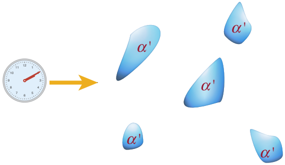
$\implies$ shifts in energy levels $\implies$ shifts in clock frequencies

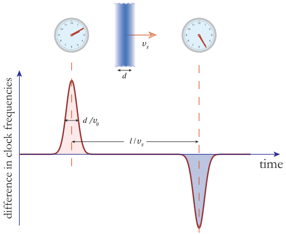
$$\frac{\delta\omega(r,t)}{\omega_0} = \phi^2(r,t)\sum_X K_X \Gamma_X$$

K_X sensitivity: Flambaum, Dzuba, Can. J. Phys. 87, 25 (‘09).

Monitor Atomic Clocks

- Correlated signal propagation through network, $v \sim 300\,\text{km/s}$

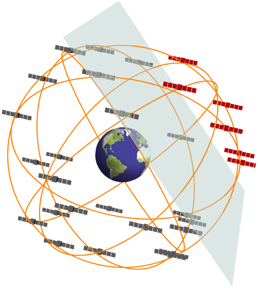




- Derevianko, Pospelov, Nat. Phys. 10, 933 (2014).

GPS: 50,000 km DM observatory

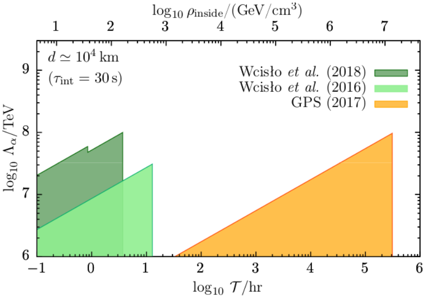
- 32 satellite clocks (Rb/Cs), $\sim$ 16 years of high-quality data
- Also several H-maser ground-based clocks.
- Data from JPL: (sideshow.jpl.nasa.gov/pub/jpligsac/)
  - 30s sampled data; 0.01–0.1 ns precision
- Correlated, directional signal, with $v_g \sim 300\,\mathrm{km/s}$



- Derevianko, Pospelov, Nat. Phys. 10, 933 (2014).
- & GNOME: Pospelov, Pustelny, Ledbetter, Kimball, Gawlik, Budker, PRL110, 21803 ('13).

Discovery frontiers

- $\mathcal{T}$
- Λ_X
- d



Number density

- Low number density, few interactions
- Need longer $T_{\rm obs}$

Sensitivity

- More precise clocks
- High sensitivity K_X

$$\frac{\delta\omega}{\omega} = K_\alpha \frac{\delta\alpha}{\alpha} = \frac{K_\alpha}{\Lambda_\alpha^2}\phi_0^2$$

GPS: BMR, Blewitt, Dailey, Murphy, Pospelov, Rollings, Sherman, Williams, Derevianko, Nature.Comm.**8**,1195 (2017).
2016: Wcisło, Morzynski, Bober, Cygan, Lisak, Ciurylo, Zawada, Nature.Astro.**1**,0009 (2016).
2018: Wcislo, Ablewski, Beloy, Bilicki, Bober, Brown, Fasano, Ciurylo, Hachisu, Ido, Lodewyck, Ludlow, McGrew, Morzynski, Nicolodi, Schioppo, Sekido, Le Targat, Wolf, Zhang, Zjawin, Zawada, arXiv:1806.04762 (2018).
Astro: Olive, Pospelov, Phys.Rev.D **77**,043524 (2008).

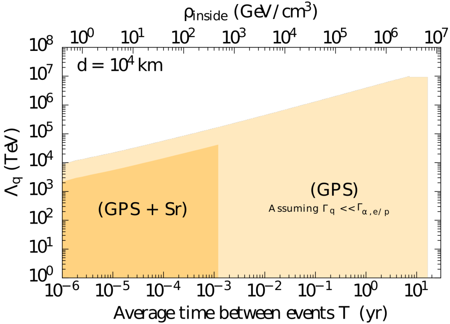
Sensitivity

Optical clocks

- Superior precision; but only have sensitivity to $\delta\alpha$

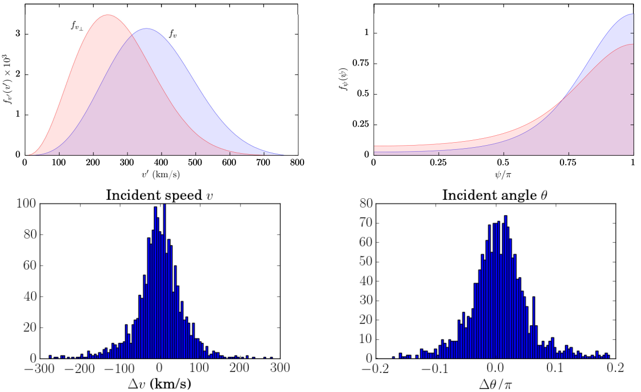
Microwave (hyperfine)

- Sensitivity to: $\delta\alpha$, $\delta(m_q/\Lambda\mathrm{QCD})$, $\delta(m_e/m_p)$



GPS: BMR, Blewitt, Dailey, Murphy, Pospelov, Rollings, Sherman, Williams, Derevianko, Nature.Comm.**8**,1195 (2017).
Optical Sr: Wcisło, Morzynski, Bober, Cygan, Lisak, Ciurylo, Zawada, Nature.Astro.**1**,0009 (2016).

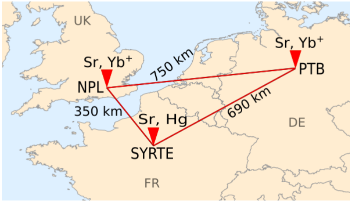
Resolve speed + direction



Resolution: simulation using GPS

- Resolve $\vec{v}$ – DM vel. distro is "known" – reject false positives!
- Many clocks
- High sampling frequency and/or **Large distances**
    - BMR, Blewitt, Dailey, Derevianko, Phys. Rev. D **97**, 083009 (2018).

Optical fibre network



Fibre network

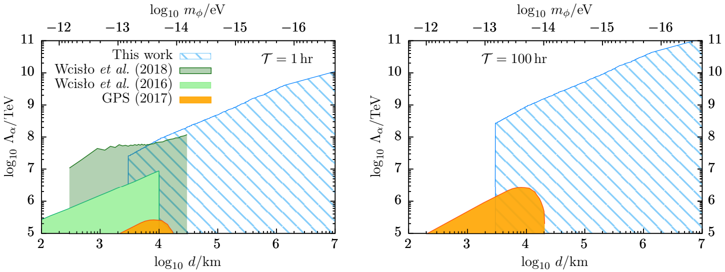
- High-accuracy long-distance clock comparisons
- Different clocks: Hg/Sr/Yb
- $\sim$ Days – weeks synchronous running

- High sensitivity: limited only by clocks themselves
- Sr-Sr: $\delta\omega/\omega \sim 3 \times 10^{-17}$ at 1000s
- "Long" observation time + Good for large objects

• Lisdat *et al.* (PTB, LNE-SYRTE), Nature Commun. **7**, 12443 (2016).
• Delva *et al.* (PTB, SYRTE, NPL, ..), Phys. Rev. Lett. **118**, 221102 (2017).

Size (field-mass)

- Lines: Sr/Hg/Yb optical network *simulation*
- Simulated 1 month of data (randomly generated noise noise)



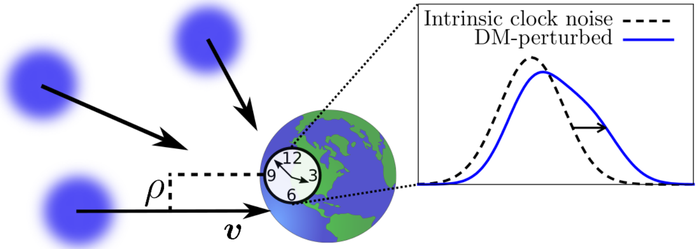
Large size (low mass)

- Require tracking signal over time (>minutes)
- Homogeneous network: Clocks far apart
- Or, networks of clocks with different K_X

Asymmetry

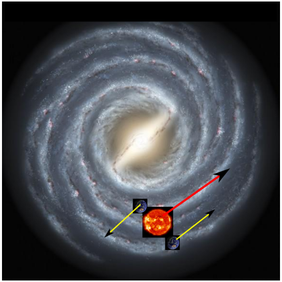
Small objects: no correlated signal

- small size $\sim\!\rightarrow$ large rate
- Shift in mean: unobservable (DM always present)
- Induce non-Gaussian features (such as an asymmetry)

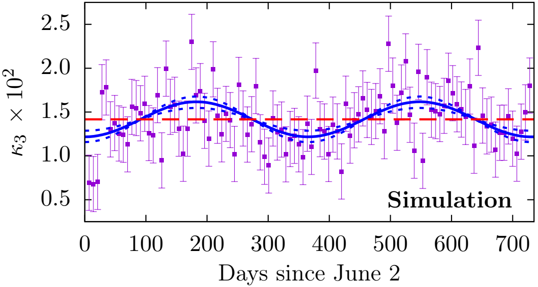


$$\mathcal{R} = \frac{1}{\mathcal{T}} = \frac{3\rho_{\rm DM} v_g}{4\rho_{\rm inside} R}, \qquad \kappa_3 \approx \frac{2\mathcal{R}\tau_0\chi_0^3}{5\sigma^3}.$$

Annual modulation



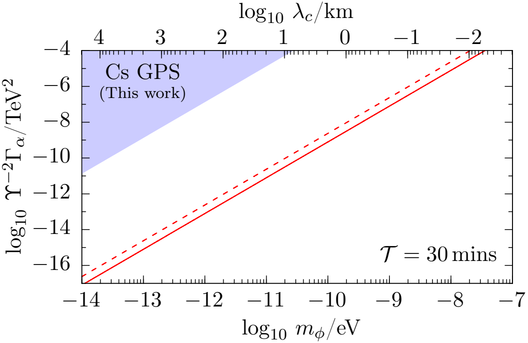
- Yearly change in event rate:
- Sun + Earth velocities add
- $R(t) = R_0 + R_m \cos(\omega t + \phi_{\mathrm{June2}})$
- $\Delta\kappa_3/\kappa_3 = 10\%$



- BMR, Derevianko, arXiv:1803.00617

Limits Q-balls: α (photon field)

$K_\alpha(Cs/H) \simeq 0.8$



- BMR, Derevianko, arXiv:1803.00617

Red line: sensitivity estimate for 1 year of optical Sr

- Can also place limits on topological defects

Take-away:

Global clock networks as a DM observatory

- Large network size: better resolution: better discrimination
- Different clock types: broader range of models/couplings
- Already: Orders of magnitude improvement for certain models
- Substantial improvements expected: especially for large objects

Precision measurement data:

- Don't need continuous data – time-stamps
- Synchronisation is not a leading source of error (DM is "slow")
- Not restricted to clocks: other precision devices also

Some references:

Axions, ultralight scalar DM:

- R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977).
- P. Sikivie, Phys. Rev. Lett. 51, 1415 (1983); Phys. Rev. Lett. 48, 1156 (1982).

Topological defect DM, non-topological solitons, Q-balls:

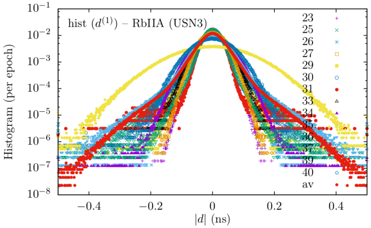
- T. W. B. Kibble, Phys. Rep. 67, 183 (1980).
- A. Vilenkin, Phys. Rep. 121, 263 (1985).
- S. Coleman, Nucl. Phys. B 262, 263 (1985).
- K. Lee, J. A. Stein-Schabes, R. Watkins, and L. M. Widrow, Phys. Rev. D 39, 1665 (1989).
- A. Kusenko and P. J. Steinhardt, Phys. Rev. Lett. 87, 141301 (2001).

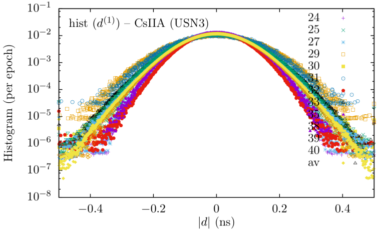
Non-gravitational TD searches + proposals

- Derevianko, Pospelov, Nat. Phys. 10, 933 (2014).
- M. Pospelov, S. Pustelny, M. P. Ledbetter, D. F. J. Kimball, W. Gawlik, and D. Budker, Phys. Rev. Lett. 110, 21803 (2013).
- Y. V. Stadnik, V. V. Flambaum, Phys. Rev. Lett. 113, 151301 (2014); PRL 114, 161301 (2015).
- E. D. Hall, T. Callister, V. V. Frolov, H. Muller, M. Pospelov, and R. X. Adhikari, arXiv:1605.01103.
- P. Wcisło, Morzynski, Bober, Cygan, Lisak, Ciuryło, M. Zawada, Nat. Astron. 1, 9 (2016).
- P. Wcisło, *et al.*, arXiv:1806.04762 (2018).
- BMR, Blewitt, Dailey, Murphy, Pospelov, Rollings, Sherman, Williams, Derevianko, Nature.Commun.**8**, 1195 (2017); BMR, Blewitt, Dailey, Derevianko, Phys.Rev.D 97, 083009 (2018).
- BMR, Derevianko, (2018).

Aside:
challenges of re-purposed data

data from JPL: Histogram





- Possible that some clocks mis-identified
  (Here, one of the “Rb” clocks is probably Cs).
- Same discrepancy in autocorrelation function, Allan variance etc.