Searching for dark matter and exotic physics with atomic clocks and GPS

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Nature Comm. 8, 1195 (2017), arXiv:1704.06844
Phys. Review D (2018), arXiv:1803.10264
arXiv:1803.00617

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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
- Initial search: domain walls
  - limits: orders of magnitude improvement for certain models
- Looking forward: Bayesian search technique + broader models
- Noise asymmetry & annual modulation signatures

Dark Matter: What is it?

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

- We don't know what it is – but we have narrowed it down to a small 90 orders-of-magnitude window

Rough mass-range for various models:

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

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

- Even asserting that DM is a fundamental particle (i.e. ignore MACHOs) $\implies$ 36 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)

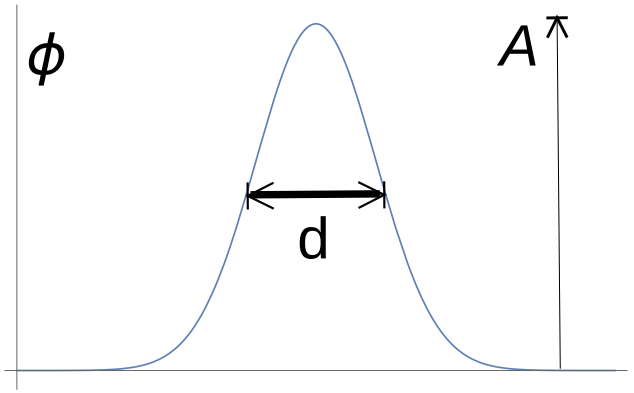
- Masses $\sim 10^{-24} - 1\,\mathrm{eV}$
- Oscillating field: $\phi = a\cos(m_a t)$ [*T. Kalaydzhyan: next talk*]
- Stable topological defects: monopoles, strings, walls
  - Also: Q-balls, solitons, "clumps"

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

Topological Defect DM

Topological Defects

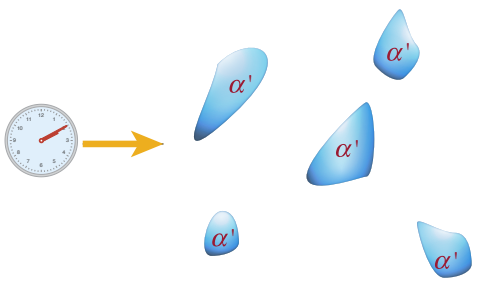
- monopoles, strings, walls,
- Defect width: $d \sim 1/m_\phi$
- Earth-scale object $\sim 10^{-14}$ eV



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, $\mathcal{T}_{\rm b/w\ collisions} \implies \rho_{\rm DM}$



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

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

Shift in atomic clock frequencies

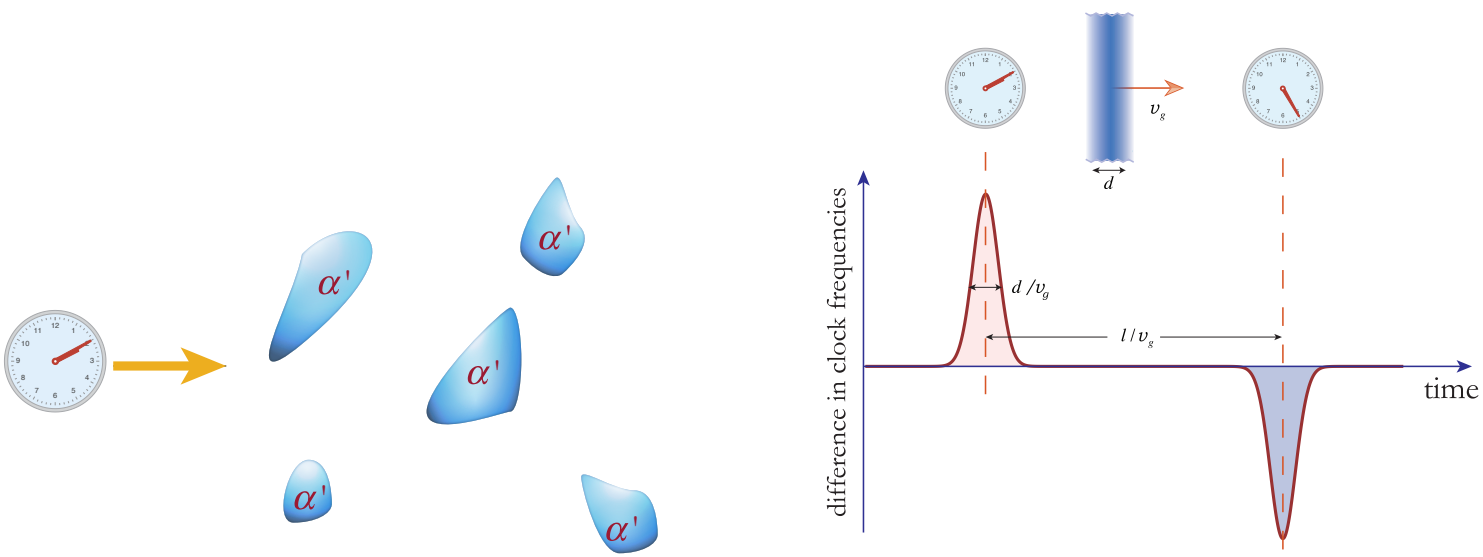
- DM may interact with: Photons, fermions

$\Longrightarrow$ shifts in energy levels $\Longrightarrow$ 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).

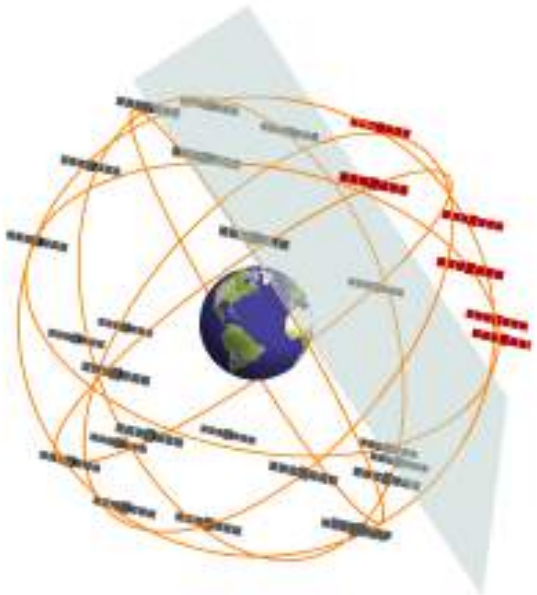
Monitor Atomic Clocks



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

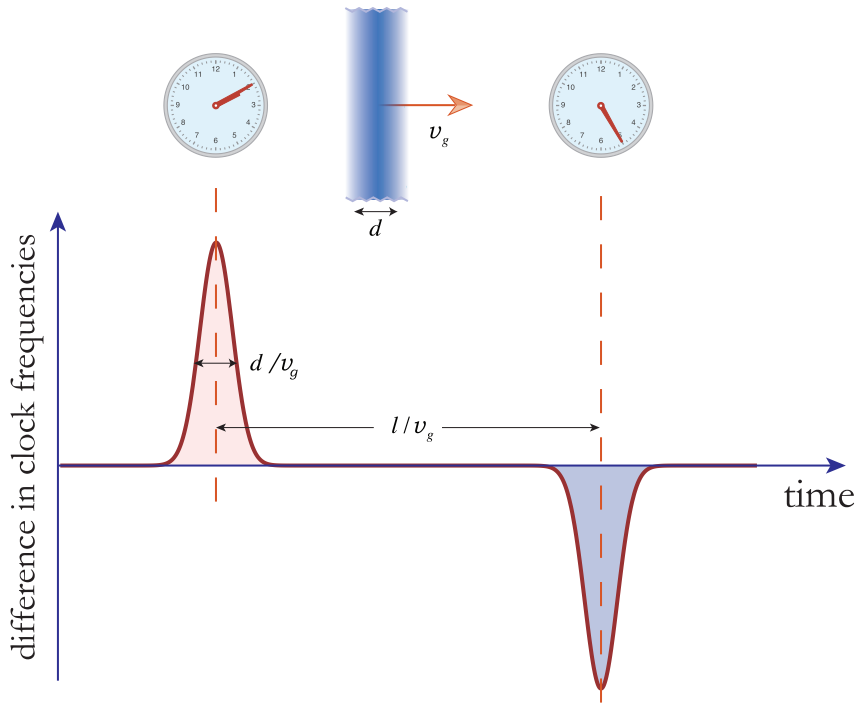


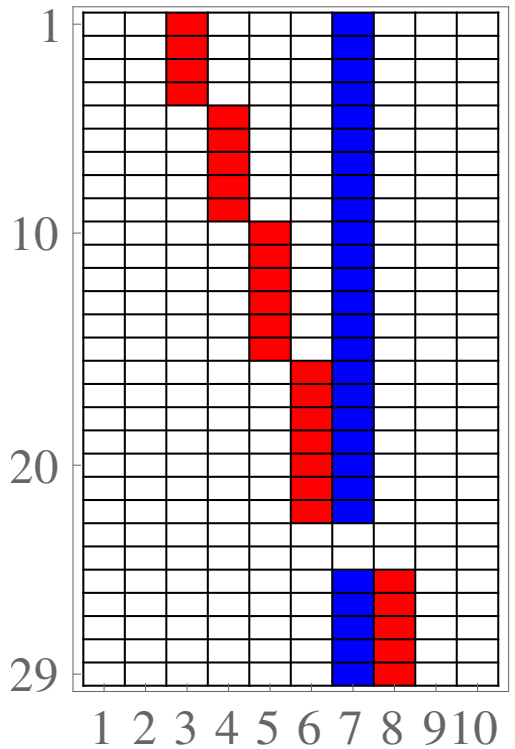
• Derevianko, Pospelov, Nat. Phys. 10, 933 (2014).

• & GNOME: Pospelov, Pustelny, Ledbetter, Kimball, Gawlik, Budker, PRL110, 21803 ('13).

DM Walls: Initial search/limits

- Thin wall [easiest case]: brief ($< 30\,\mathrm{s}$) frequency excursion

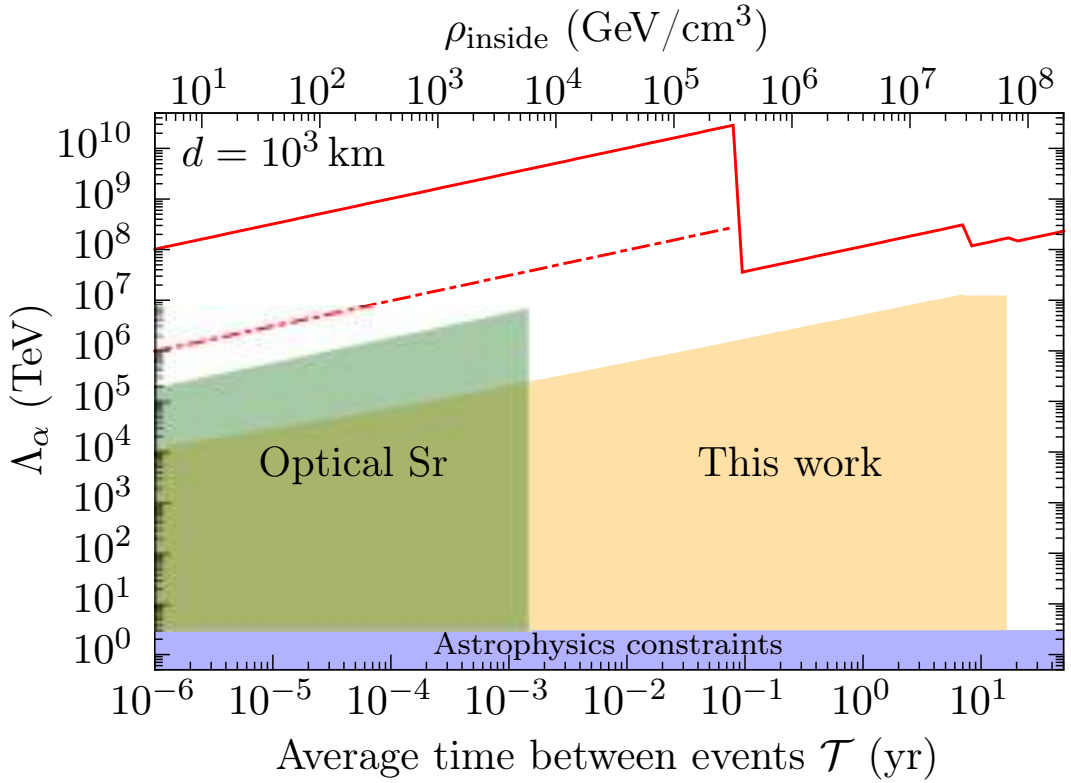




- $\vec{\mathbf{v}}$ encoded in time-delay and signal ordering: $\Delta t \sim$ minutes

• BMR, Blewitt, Dailey, Pospelov, Rollings, Sherman, Williams, Derevianko, Nature Comm. **8**, 1195 (2017). [1704.06844]

Results: Limits - Λ_α (photon)



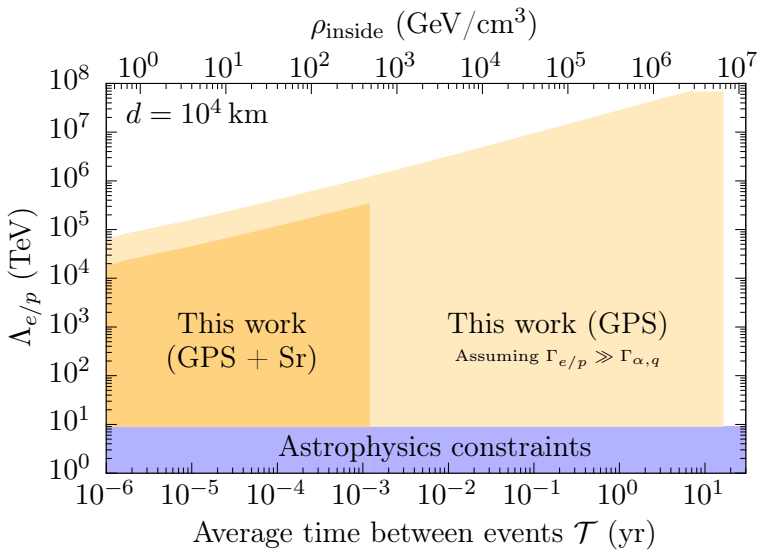
Sr: Wcislo, Morzynski, Bober, Cygan, Lisak, Ciurylo, Zawada, Nat. Astron. 1, 9 (2016).
Astro: Olive, Pospelov, Phys. Rev. D. 77, 43524 (2008).

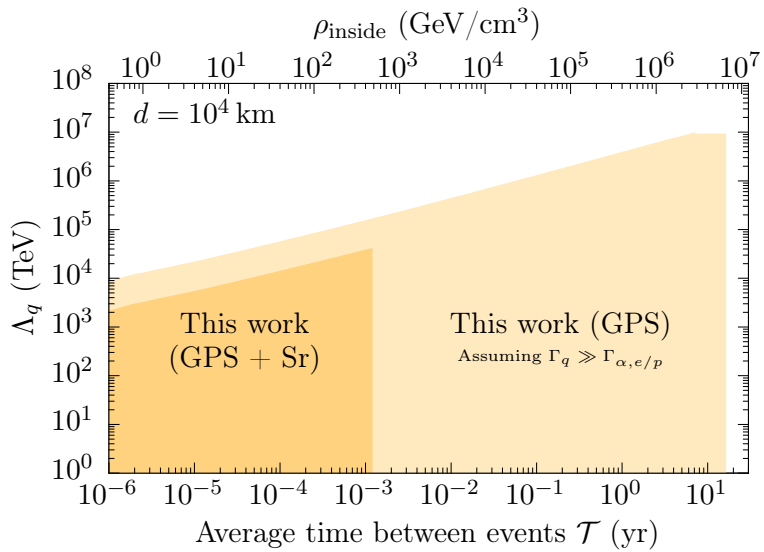
- BMR, Blewitt, Dailey, Pospelov, Rollings, Sherman, Williams, Derevianko, Nature Comm. **8**, 1195 (2017). [1704.06844]

Results: Limits - fermion masses

Combine Rb, Cs, and Sr (optical)

- Three different combo's of three couplings





Sr: Wcislo, Morzynski, Bober, Cygan, Lisak, Ciurylo, Zawada, Nat. Astron. 1, 9 (2016).
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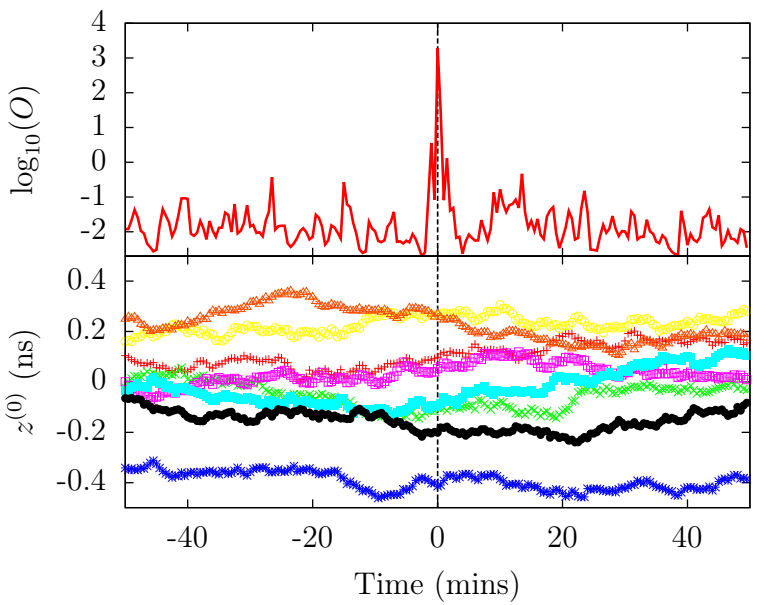
• BMR, Blewitt, Dailey, Pospelov, Rollings, Sherman, Williams, Derevianko, Nature Comm. **8**, 1195 (2017). [1704.06844]

How to improve upon this?

- There may be events "hiding" below the noise.
- Other geometries: monopoles, strings, thicker walls

Bayesian Analysis

- Marginalise (integrate) all parameters (In-built Occam's Razor)
  - Time, velocity, object size, impact parameter
- Form odds ratios

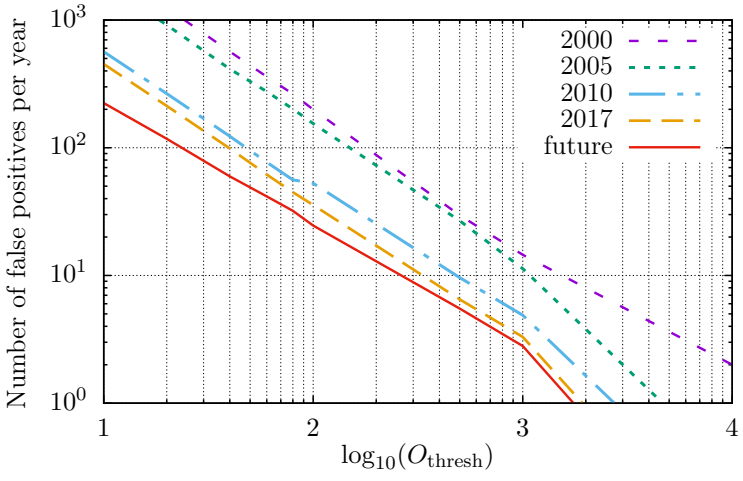


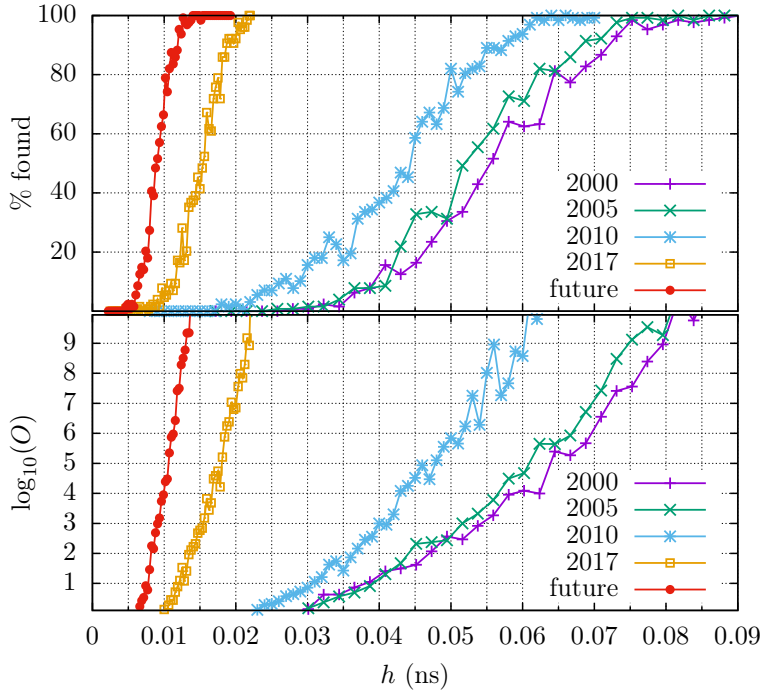
- Events as small as:

$$s \approx \sigma/\sqrt{N} \approx 0.001\,\mathrm{ns}$$

(for the best GPS clocks)

Bayes: True + false positive rates

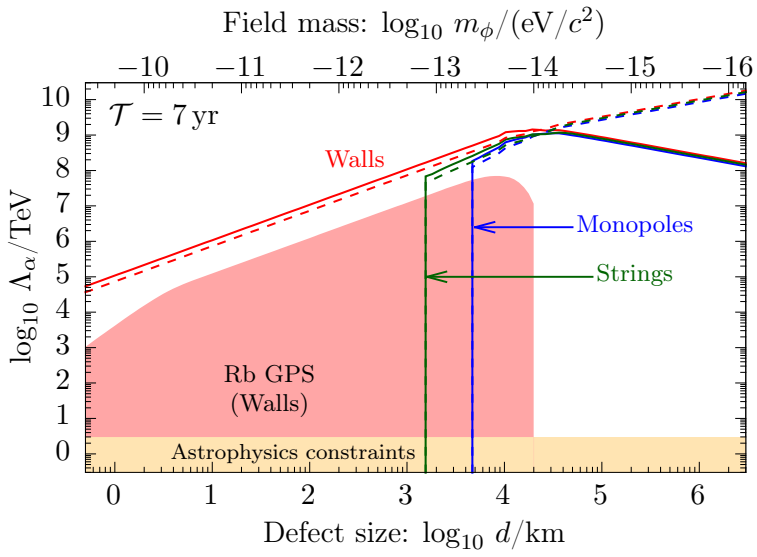


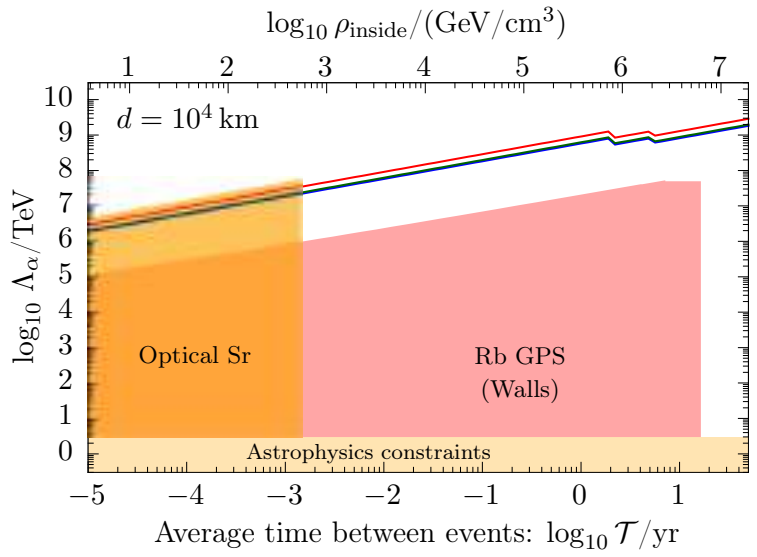


- BMR, Blewitt, Dailey, Derevianko, Phys.Rev.D (2018). [1803.10264]

Bayes: Projected sensitivity

Large time between events (low number density), large objects:

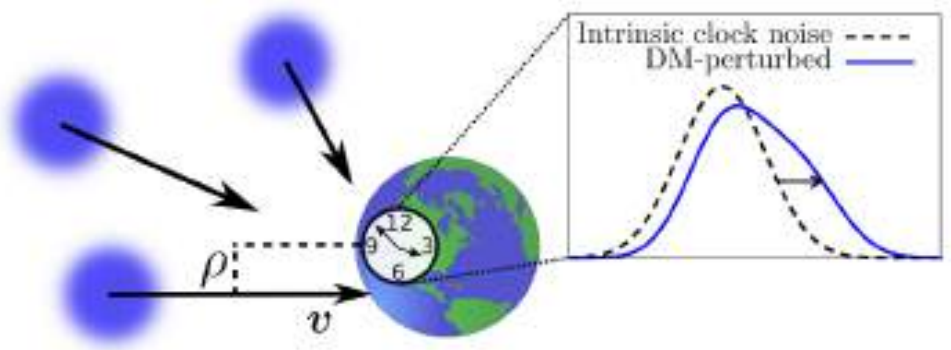


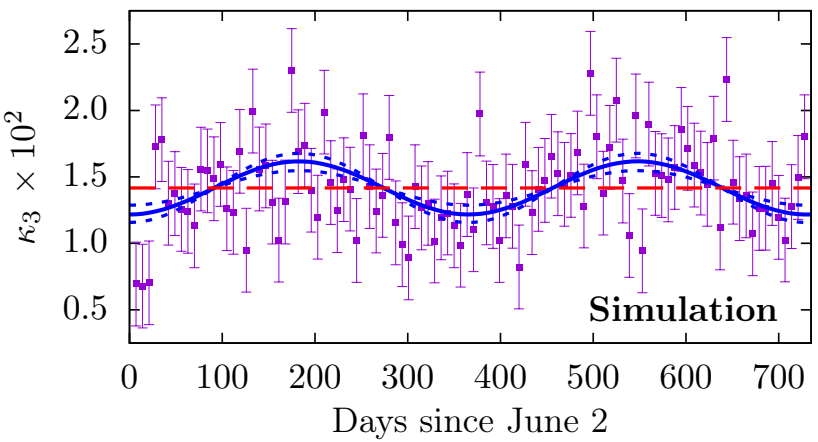


- BMR, Blewitt, Dailey, Derevianko, Phys.Rev.D (2018). [1803.10264]

Asymmetry + an. modulation

Small objects, large event rate: asymmetry in noise distribution

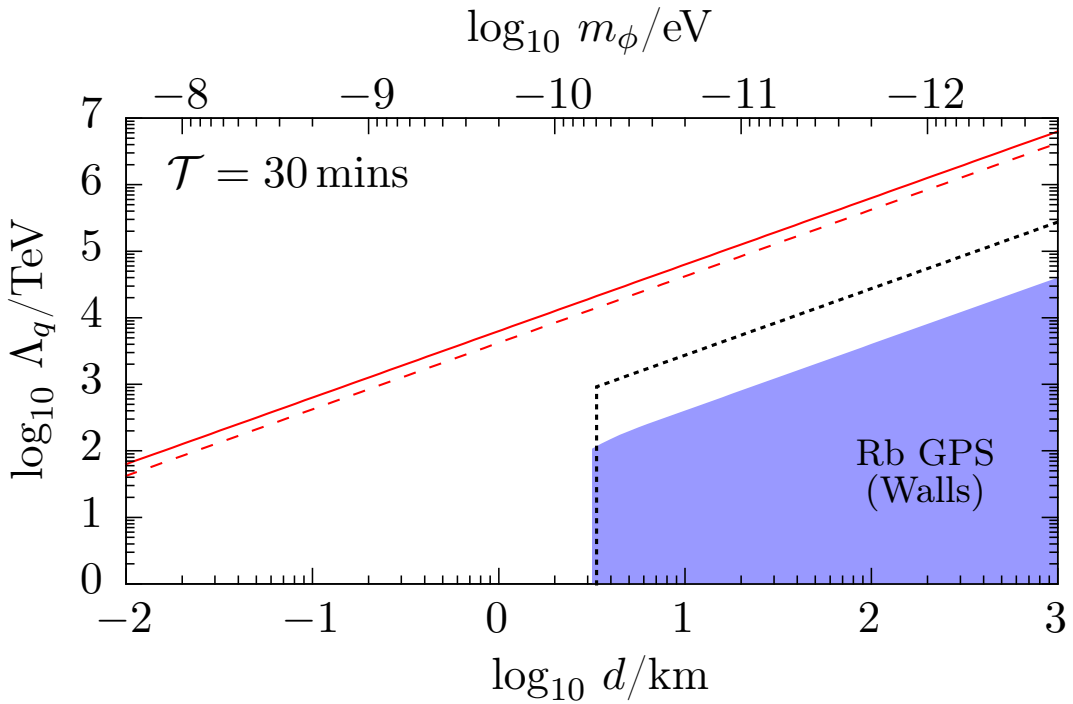




- Yearly change in event rate:
- Sun + Earth velocities add
- $R(t) = R_0 + R_m \cos(\omega t + \phi_{\rm June2})$

- BMR, Derevianko, arXiv:1803.00617

Asymmetry + an. modulation



- BMR, Derevianko, arXiv:1803.00617

Conclusion:

GPS: 50,000km aperture DM observatory

- Topological defect dark matter/transient exotic physics
- GPS: 50,000km aperture sensor array
  - $\sim$ 30 satellite clocks, many earth clocks, $>$ 15 years of clock data
- DM walls: Orders of magnitude improvement for certain models
- Looking forward: Bayesian search technique
  - Monopoles, strings, signals below $\sigma_{\rm clock}$
- General technique: archived, time-stamped data

- Nature Comm. **8**, 1195 (2017). BMR[1], G. Blewitt[1], C. Dailey[1], M. Pospelov[2,3], A. Rollings[1], J. Sherman[4], W. Williams[1], A. Derevianko[1] [1704.06844].
- Phys. Rev. D (2018). BMR, G. Blewitt, C. Dailey, A. Derevianko [1803.10264].
- BMR, A. Derevianko [1803.00617].

[1]University of Nevada, Reno; [2]Perimeter Institute; [3]University of Victoria, BC; [4]NIST Boulder

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Axions, ultralight scalar DM:

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Topological defect DM:

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non-topological solitons, Q-balls:

- S. Coleman, Nucl. Phys. B 262, 263 (1985).
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Other non-gravitational TD searches:

- 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).
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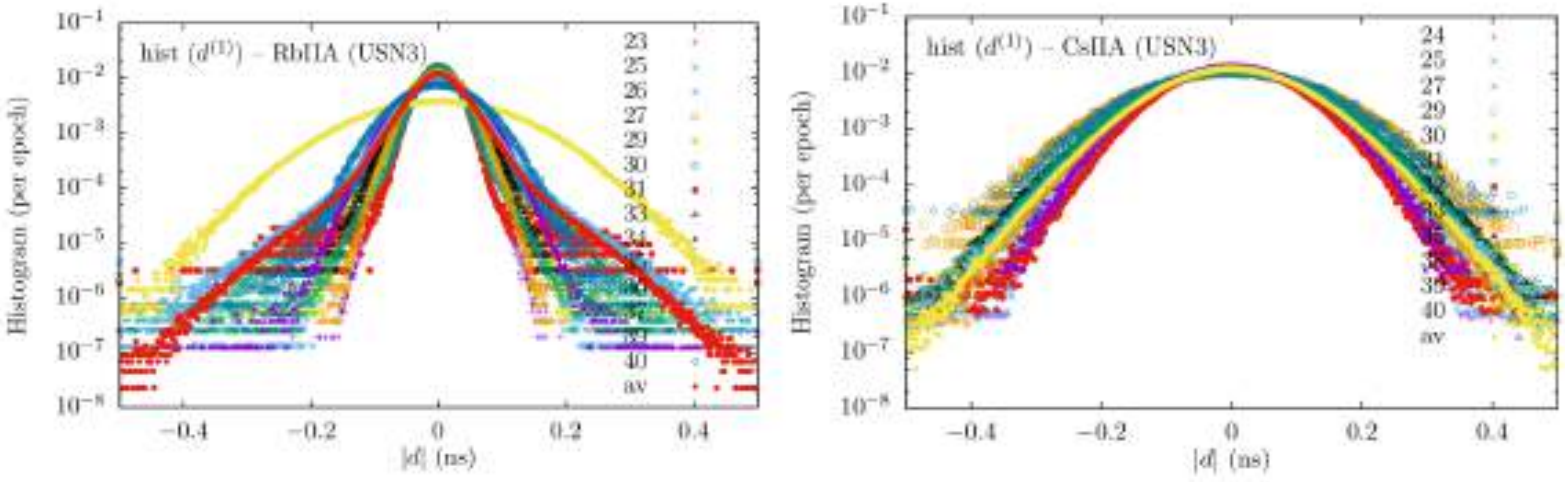
- P. Wcisło, Morzynski, Bober, Cygan, Lisak, Ciuryło, M. Zawada, Nat. Astron. 1, 9 (2016).

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.