Searching for dark matter with GPS and global networks of atomic clocks

Benjamin M. Roberts\textsuperscript{1}, G. Blewitt\textsuperscript{1}, C. Dailey\textsuperscript{1}, M. Pospelov\textsuperscript{2,3}, A. Rollings\textsuperscript{1}, J. Sherman\textsuperscript{4}, W. Williams\textsuperscript{1}, and A. Derevianko\textsuperscript{1}

\textsuperscript{1}University of Nevada, Reno; \textsuperscript{2}Perimeter Institute; \textsuperscript{3}University of Victoria, BC; \textsuperscript{4}NIST Boulder

arXiv:1704.06844

New Directions in Dark Matter and Neutrino Physics, Perimeter Institute, 20–22 July 2017

*Supported by the NSF
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
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 $\sim 10^{-24} - 1$ eV
- Classical 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: $\phi^2 \rightarrow A^2$,      Outside: $\phi^2 \rightarrow 0$

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

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

- Sikivie ‘82, Preskil ‘83, Vilekin ‘85, Coleman ‘85, Lee ‘89, ...
Possible DM–SM interactions

Pseudoscalar (axionic) portal:
- e.g., $\mathcal{L}^{PS} = \partial_\mu a \bar{\psi} \gamma^\mu \gamma^5 \psi$
- Leads to magnetic-like interactions: magnetometry
  - GNOME: Global network of magnetometers (1)

Quadratic scalar portal:
- Effective local shifts in values of fundamental constants
- Leads to shifts in clock frequencies
  - GPS.DM: $\rightarrow$ Global network of atomic clocks (2)


- Also: Interferometry etc.: Arvanitaki, Graham, Hogan, Rajendran, Van Tilburg (2016);
  Stadnik, Flambaum (2016)…
Variation of fundamental constants

\[-L^{SM^2} = \phi^2(r,t) \left( \frac{m_f \bar{\psi}_f \psi_f}{\Lambda_f^2} + \frac{1}{4\Lambda_\alpha^2} F_{\mu\nu}^2 + \ldots \right),\]

c.f. \( L^{SM} \implies \) transient additions to fundamental constants

\[
\alpha^{\text{eff}}(r,t) = \alpha \left( 1 + \frac{\phi^2(r,t)}{\Lambda_\alpha^2} \right), \quad m_f^{\text{eff}}(r,t) = m_f \left( 1 + \frac{\phi^2(r,t)}{\Lambda_f^2} \right),
\]

\implies \text{shifts in energy levels} \implies \text{shifts in clock frequencies}

\[
\frac{\delta \omega(r,t)}{\omega_0} = \phi^2(r,t) \sum_X \frac{K_X}{\Lambda_X}, \quad K_\alpha : \text{Sensitivity of } \omega \text{ to } \delta \alpha
\]

Flambaum, Tedesco, PRC, 73, 55501 (‘06); Flambaum, Dzuba, Can. J. Phys., 87, 25 (‘09).
Shift in atomic clock frequencies

Monitor Atomic Clocks

- Temporary frequency shift $\rightarrow$ bias (phase) build-up
- Initially synchronised clocks become desynchronised

\[
\frac{v}{g} = \frac{\text{time difference in clock readings}}{\text{running time}}
\]

\[
\Delta t = \frac{\text{distance between the clocks}}{v}
\]
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 \(v_g \sim 300\) km/s
DM Walls: Initial search/limits

- Thin wall: brief (<30 s) frequency excursion

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

Ultralight DM + TDs

Variation in clock frequencies

GPS

Initial search/first results

Bayesian search

Testing method

Possible outcomes

Apply $S_{\text{cut}}$
Simple pattern search

- Match data windows against expected signals
- Reduce $S_{\text{cut}}$ until signal can no longer be ruled out
- This case: excluded since ref $>$ rest

Scan the data
Sensitivity

• 3D parameter space \((\Lambda_X, \mathcal{T}, d)\):

\[
S = \hbar c \sqrt{\pi} \rho_{\text{DM}} \frac{K_X d^2 \mathcal{T}}{\Lambda_X^2}
\]

\[
\rho_{\text{inside}} = \frac{\rho_{\text{DM}} v_g}{d} \mathcal{T}
\]

Not equally sensitive to each width, \(d\)

• Assumes standard halo model
• “Servo time”: \(\tau = d/v_\perp > \tau_{\text{servo}} \approx 0.01 - 0.1\) s
• Wall must be “thin” enough: \(\tau = d/v_\perp < 30\) s

![Graph showing sensitivity vs defect size and TD field mass](image)

• Fraction of events we could “see”
• 90% C.L. (assuming SHM)
Setting Limits

What we see in the data:

- $S_{\text{lim}}^{(1)}$: largest signal size that can’t be ruled out
- Assume Poisson distribution, and SHM
  - $S_{\text{lim}}^{(1)} \sim 0.5 \text{ ns}$
  - $T_{\text{obs}} = 16 \text{ years}$

\[
\frac{\Lambda_{\text{eff}}/\text{TeV}}{d/\text{km}} > 2 \times 10^3 \sqrt{\frac{T_{\text{obs}}s(d)/\text{yr}}{\lambda S_{\text{lim}}^{(1)}/\text{ns}}}.
\]
Rb sub-network

- $\Lambda_{\text{eff}}$: combination of $\alpha, m_e, m_p, m_q$
- Until recently, existing limits did not exceed 10 TeV
- $T = 1 \text{ yr} \& d = 10^3 \text{ km} \implies \rho_{\text{inside}} \approx 10^6 \text{ GeV/cm}^3$
- c.f. $\rho_{\text{water}} \sim 10^{24} \text{ GeV/cm}^3$
Results: Limits - $\Lambda_\alpha$ (photon)

- (Assume this coupling dominates)

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).

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

\[
p(D_j | m, l) = K \int \cdots \int p(x | m, l) \exp(-\chi_s)\]

\[
\chi_s = \sum_i \sum_{jl} (d_j^i - s_j^i) H_{jl} (d_j^i - s_j^i)
\]

- Should be able to detect events as small as:

\[
s \approx \sigma / \sqrt{N} \approx 0.001 \text{ ns (for the best clocks)}
\]
Test the method:

Statistical properties of data:

- Power-spectrums, Auto-correlation functions, Allan variance, …

- Generate “fake” data: mimics properties of the real data
  - $y$: Input white noise, $S$: PSD, $z$: Simulated data

$$z = FT^{-1}(FT(y)\sqrt{S_{\text{target}}/S_y})$$
Inject fake events: True positive rate
Don’t inject events: False positive rate
Currently running large-scale simulations. Results promising!
Possible outcomes:

a) See (∼ few) very good candidate events
   - Large odds ratio, good fit to model
   - “best” case scenario: Analyse these in great detail
   - Check against other precision experiments

b) we don’t
   - Set limits.
   - Is that all?
   - Case when there is a large number of small events?
Possible outcomes:

- All actual events should* have same sign

Vector velocity resolution:

- > 30 clocks: quite good speed/direction resolution
- Potential to resolve velocity distribution (SHM)

False positives will have different distribution
- But: have to “discount” priors for this analysis)
Possible outcomes:

**Annual variation:**

![Graph showing annual variation](image)

Lower threshold. Lots of false-positives

- Assymetry in event ‘sign’ & resolve SHM predictions, +
- Annual modulation:
  - Event rate
  - Average velocity
  - Most-common incident direction

May extend discovery reach for $T \ll 1\,\text{yr}$ and $d \ll R_{\text{GPS}}$
Some references:

**Axions, ultralight scalar DM:**

**Topological defect DM:**

**non-topological solitons, Q-balls:**

**Other non-gravitational TD searches:**
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 $\sigma_{\text{clock}}$
- General technique: archived, time-stamped data

More: see arXiv:1704.06844, BMR$^1$, G. Blewitt$^1$, C. Dailey$^1$, M. Pospelov$^{2,3}$, A. Rollings$^1$, J. Sherman$^4$, W. Williams$^1$, and A. Derevianko$^1$.

$^1$University of Nevada, Reno; $^2$Perimeter Institute; $^3$University of Victoria, BC; $^4$NIST Boulder
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.
Clock stability: Mixed network

Launched:

- 1989–1997: II + IIA = ~ 17,000 clock-days
- 1997–2009: IIR = ~ 64,000 clock-days
- 2010–2016: IIF = ~ 8,000 clock-days
- Block III: Due in 2016 2017 2018(?)