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

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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

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)

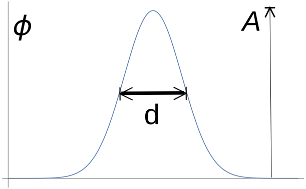
- Masses $\sim 10^{-24} - 1\,\text{eV}$
- Classical oscillating field: $\phi = a\cos(m_a t)$
- Stable topological defects: monopoles, strings, walls
  - Also: Q-balls, solitons, "clumps"

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

Topological Defect DM

Topological Defects

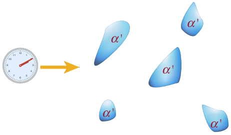
- monopoles, strings, walls,
- Defect width: $d \sim 1/m_\phi$
- Earth-scale object $\sim 10^{-14}$ eV



$$\text{Inside:} \quad \phi^2 \to A^2\,, \qquad \text{Outside:} \quad \phi^2 \to 0$$

Dark matter: Gas of defects

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



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

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

Possible DM–SM interactions

Pseudoscalar (axionic) portal:

- e.g., $\mathcal{L}^{\rm PS} = \partial_\mu a \, \bar{\psi}\gamma^\mu\gamma^5\psi$
- 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: $\implies$ Global network of atomic clocks (2)

1. Pospelov, Pustelny, Ledbetter, Kimball, Gawlik, Budker, PRL **110**, 21803 (2013).
2. Derevianko, Pospelov, Nat. Phys. **10**, 933 (2014).

• Also: Interferometry etc.: Arvanitaki, Graham, Hogan, Rajendran, Van Tilburg (2016); Stadnik, Flambaum (2016)...

Variation of fundamental constants

$$-\mathcal{L}^{\mathrm{S}^2} = \phi^2(r,t)\left(\frac{m_f\bar{\psi}_f\psi_f}{\Lambda_f^2} + \frac{1}{4\Lambda_\alpha^2}F_{\mu\nu}^2 + \dots\right),$$

c.f. $\mathcal{L}^{\mathrm{SM}} \implies$ transient additions to fundamental constants

$$\alpha^{\mathrm{eff}}(r,t) = \alpha\left(1 + \frac{\phi^2(r,t)}{\Lambda_\alpha^2}\right), \qquad {m_f}^{\mathrm{eff}}(r,t) = m_f\left(1 + \frac{\phi^2(r,t)}{\Lambda_f^2}\right),$$

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

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

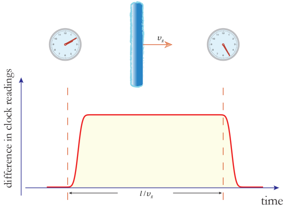
K_α : Sensitivity of ω to $\delta\alpha$

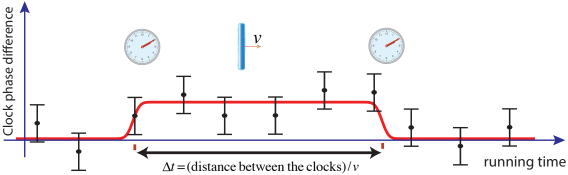
Flambaum, Tedesco, PRC, **73**, 55501 ('06); Flambaum, Dzuba, Can. J. Phys., **87**, 25 ('09).

Shift in atomic clock frequencies

Monitor Atomic Clocks

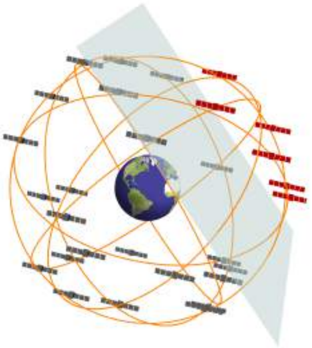
- Temporary frequency shift → bias (phase) build-up
- Initially synchronised clocks become desynchronised





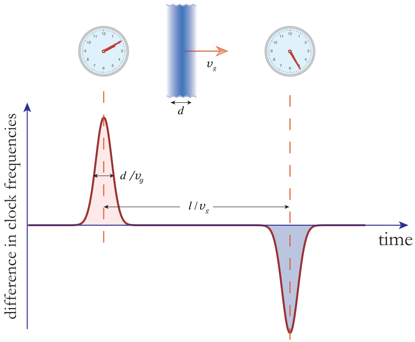
GPS: 50,000 km DM observatory

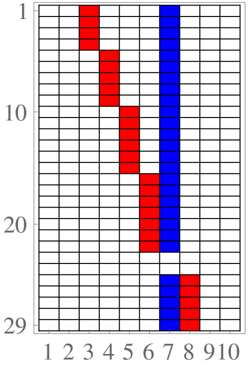
- 32 satellite clocks (Rb/Cs), $\sim$ 16 years of high-quality data
- Also several H-maser ground-based clocks.
- Data from JPL: (sideshow.jpl.nasa.gov/pub/jpligsac/)
  - 30s sampled data; 0.01–0.1 ns precision
- Correlated, directional signal, with $v_g \sim 300$ km/s



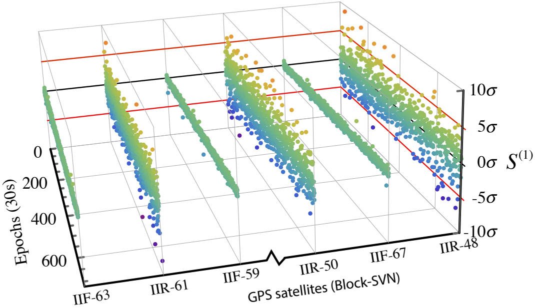
DM Walls: Initial search/limits

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

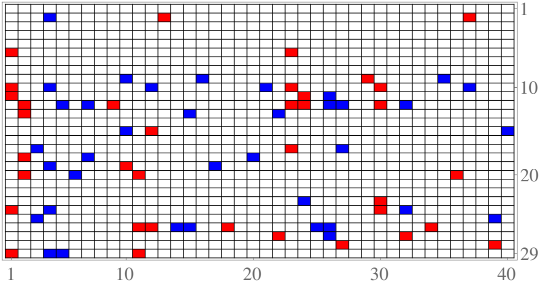




- $\vec{\mathbf{v}}$ encoded in time-delay and signal ordering: $\Delta t \sim$ minutes



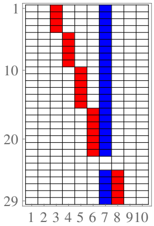
Apply $S_{\rm cut}$ $\Longrightarrow$

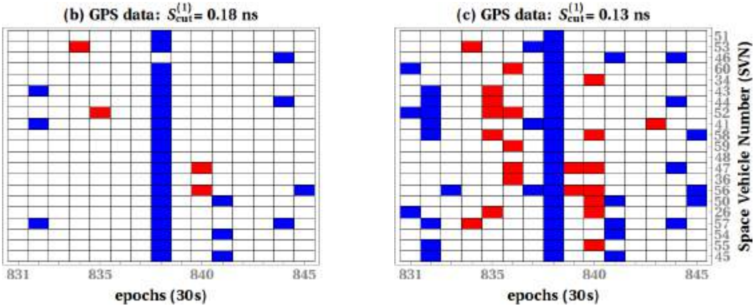


Scan the data

Simple pattern search

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





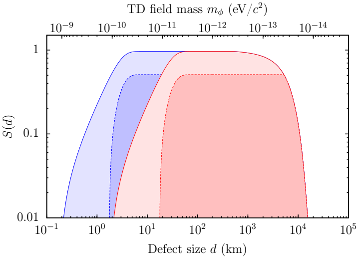
Sensitivity

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

$$S = \hbar c \sqrt{\pi}\, \rho_{\rm DM} \frac{K_X\, d^2\, \mathcal{T}}{\Lambda_X^2} \qquad \rho_{\rm inside} = \frac{\rho_{\rm DM}\, v_g}{d}\, \mathcal{T}$$

Not equally sensitive to each width, d

- Assumes standard halo model
- "Servo time": $\tau = d/v_\perp > \tau_{\rm servo} \approx 0.01 - 0.1\,{\rm s}$
- Wall must be "thin" enough: $\tau = d/v_\perp < 30\,{\rm s}$



- Fraction of events we could "see"
- 90% C.L. (assuming SHM)

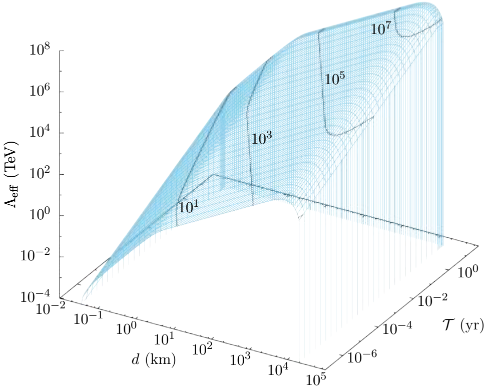
Setting Limits

What we see in the data:

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

$$\frac{\Lambda_{\rm eff}/{\rm TeV}}{d/{\rm km}} > 2\times10^3\sqrt{\frac{T_{\rm obs}s(d)/{\rm yr}}{\lambda\,S_{\rm lim}^{(1)}/{\rm ns}}}.$$

Results: Limits

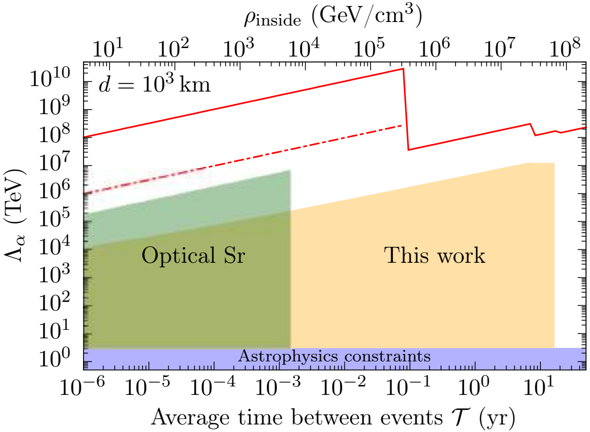


Rb sub-network

- $\Lambda_{\rm eff}$: combination of α, $m_{e,p}$, m_q
- Until recently, existing limits did not exceed 10 TeV
- $\mathcal{T} = 1\,{\rm yr}$ & $d = 10^3$ km $\implies$ $\rho_{\rm inside} \approx 10^6\,{\rm GeV/cm^3}$
  - c.f. $\rho_{\rm water} \sim 10^{24}\,{\rm GeV/cm^3}$

Results: Limits - Λ_α (photon)

- (Assume this coupling dominates)



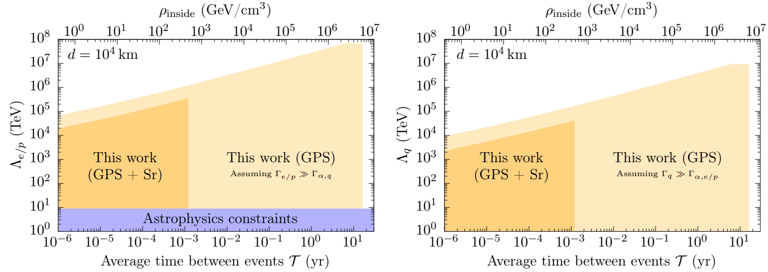
Sr: Wcislo, Morzynski, Bober, Cygan, Lisak, Ciurylo, Zawada, Nat. Astron. 1, 9 (2016).

Astro: Olive, Pospelov, Phys. Rev. D. 77, 43524 (2008).

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).

Astro: Olive, Pospelov, Phys. Rev. D. 77, 43524 (2008).

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

$$\underbrace{p(D_{j_0}|m,I)}_{Likelihood} = K \overbrace{\int dx_1 \ldots \int dx_n}^{\text{marginalise parameters}} \underbrace{p(x_1 \ldots x_n|m,I)}_{\text{Priors}} \overbrace{\exp(-\chi_s)}^{\text{Gaussian likelihood}}$$

$$\chi_s = \sum_i^{Clocks} \sum_{jl}^{Data} \left(d^i_j - s^i_j\right) \overbrace{H^i_{jl}}^{\text{co}-\text{variance}} \left(d^i_l - s^i_l\right)$$

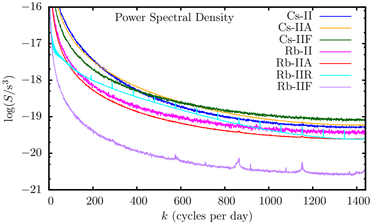
- Should be able to detect events as small as:

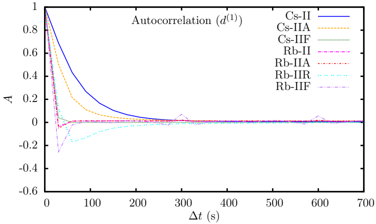
$$s \approx \sigma/\sqrt{N} \approx 0.001\,\mathrm{ns} \text{ (for the best clocks)}$$

Test the method:

Statistical properties of data:

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

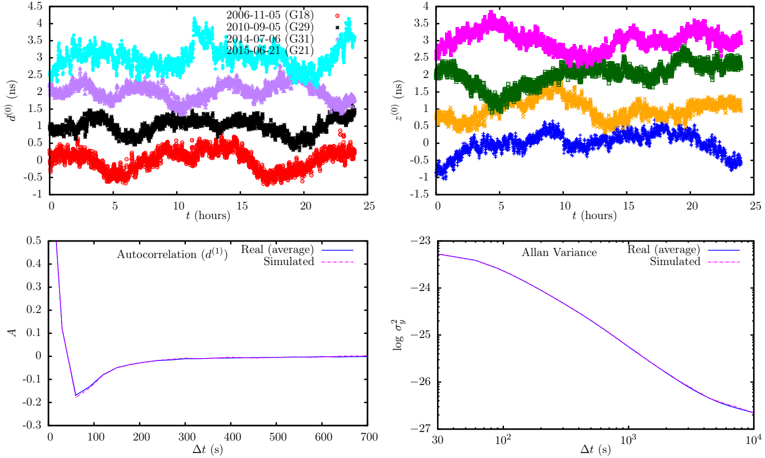




- Generate "fake" data: mimics properties of the real data
  - y: Input white noise, S: PSD, z: Simulated data

$$z = FT^{-1}\left(FT(y)\sqrt{S^{\rm target}/S^{y}}\right)$$

Test the method:



- Inject fake events: True positive rate
- Don't inject events: False positive rate
- Currently running large-scale simulations. Results promising!

Possible outcomes:

a) See ($\sim$ 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

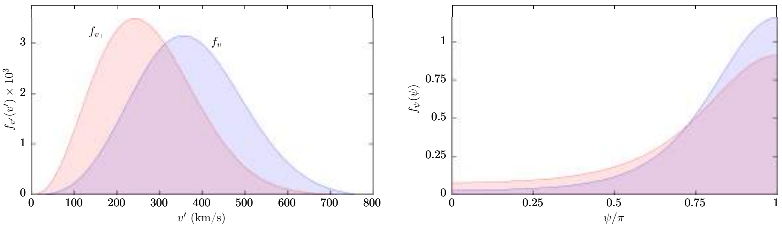
- Set limits.
- Is that all?
- Case when there is a large number of small events?

Possible outcomes:

- All actual events should* have same sign

Vector velocity resolution:

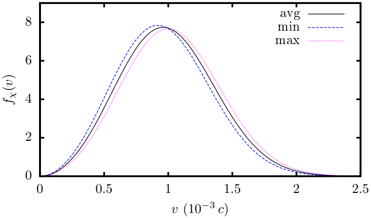
- >30 clocks: quite good speed/direction resolution
- Potential to resolve velocity distribution (SHM)

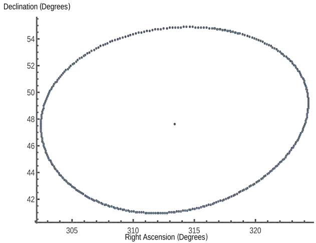


- False positives will have different distribution
- But: have to "discount" priors for this analysis)

Possible outcomes:

Annual variation:





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 $\mathcal{T} \ll 1\,\mathrm{yr}$ and $d \ll R_{\mathrm{GPS}}$

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:

- T. W. B. Kibble, Phys. Rep. 67, 183 (1980).
- A. Vilenkin, Phys. Rep. 121, 263 (1985).

non-topological solitons, Q-balls:

- 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).

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).
- E. D. Hall, T. Callister, V. V. Frolov, H. Mller, M. Pospelov, and R. X. Adhikari, arXiv:1605.01103.
- P. Wcisło, Morzynski, Bober, Cygan, Lisak, Ciuryło, M. Zawada, Nat. Astron. 1, 9 (2016).

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

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].

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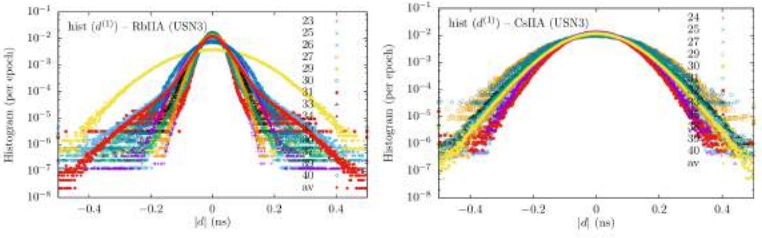
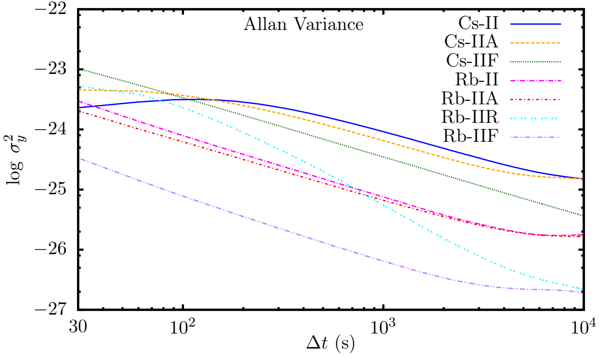
Aside: challenges of re-purposed data

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 $= \sim 17\,000$ clock-days
- 1997–2009: IIR $= \sim 64\,000$ clock-days
- 2010–2016: IIF $= \sim 8\,000$ clock-days
- Block III: Due in ~~2016~~ ~~2017~~ 2018(?)