GPS.DM: The GPS network as a dark matter observatory

Benjamin M. Roberts[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

CosPA 2016
University of Sydney, Australia
28 November 2016

Outline:

- Topological defect dark matter
- GPS: 50,000km aperture sensor array
  - ~ 30 clocks, 15 years of archived data
- Initial limits: orders of magnitude improvement for certain models
- Looking forward: Bayesian search technique

Ultralight Dark Matter:

WIMPs

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

Ultralight spin-0 fields (e.g., axions)

- Masses $\sim 10^{-24} - 1\,\mathrm{eV}$
- May form classical coherent oscillating field: $\phi = a\cos(m_a t)$
- May form stable so-called topological defects: monopoles, strings, walls

Ultralight Dark Matter:

WIMPs

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

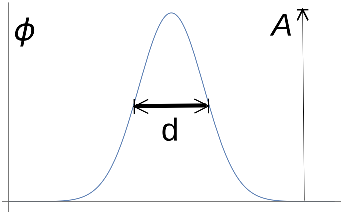
Ultralight spin-0 fields (e.g., axions)

- Masses $\sim 10^{-24} - 1\,\text{eV}$
- May form classical coherent oscillating field: $\phi = a\cos(m_a t)$
- May form stable so-called topological defects: monopoles, strings, walls

Topological Defect DM

Topological Defects

- Self-interacting quantum fields
- may form monopoles, strings, walls,
- Defect width: $d \sim 1/m_\phi$
- Earth-sized object, $m_\phi \sim 10^{-14}\,\mathrm{eV}$



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

TD dark matter: Gas of defects

- Could be dominant or sub-dominant DM/DE contribution
- DM: Travel in galaxy with $\sim$ galactic speeds: $v_g \sim 10^{-3}c$
- A^2, d, $T_{\mathrm{b/w\,collisions}} \implies \rho_{\mathrm{DM}}$

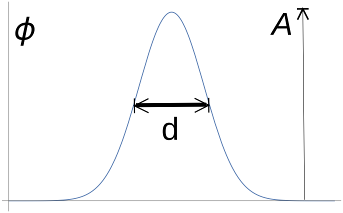
$$A^2 = \rho_{\mathrm{DM}} d^2 \frac{T_{\mathrm{avg}}}{\tau_{\mathrm{avg}}},$$

- Sikivie '82, Preskil '83, Vilekin '85, ...

Topological Defect DM

Topological Defects

- Self-interacting quantum fields
- may form monopoles, strings, walls,
- Defect width: $d \sim 1/m_\phi$
- Earth-sized object, $m_\phi \sim 10^{-14}\,\mathrm{eV}$



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

TD dark matter: Gas of defects

- Could be dominant or sub-dominant DM/DE contribution
- DM: Travel in galaxy with ~ galactic speeds: $v_g \sim 10^{-3}c$
- $A^2,\ d,\ T_{\mathrm{b/w\ collisions}} \implies \rho_{\mathrm{DM}}$

$$A^2 = \rho_{\mathrm{DM}} d^2 \frac{T_{\mathrm{avg}}}{\tau_{\mathrm{avg}}},$$

- Sikivie '82, Preskil '83, Vilekin '85, ...

Possible DM–SM interactions

$$\mathcal{L}_{\rm int} = \mathcal{L}^{\rm PS} + \mathcal{L}^{{\rm S}^1} + \mathcal{L}^{{\rm S}^2} + \ \dots \ ,$$

• Peccei, Quinn '77; Sikivie '82; Dine, Fischler '82, ...

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: $>$Global network of atomic clocks (2)

• Also: LIGO + Laser interfereometry (3)

1. Pospelov, Pustelny, Ledbetter, Kimball, Gawlik, Budker, PRL **110**, 21803 (2013).
2. Derevianko, Pospelov, Nat. Phys. **10**, 933 (2014).
3. Stadnik, Flmbaum, PRL **114**, 161301 (2013).

Possible DM–SM interactions

$$\mathcal{L}_{\rm int} = \mathcal{L}^{\rm PS} + \mathcal{L}^{\rm S^1} + \mathcal{L}^{\rm S^2} + \ \dots\ ,$$

• Peccei, Quinn '77; Sikivie '82; Dine, Fischler '82, ...

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: $>$Global network of atomic clocks (2)

• Also: LIGO + Laser interfereometry (3)

1. Pospelov, Pustelny, Ledbetter, Kimball, Gawlik, Budker, PRL **110**, 21803 (2013).
2. Derevianko, Pospelov, Nat. Phys. **10**, 933 (2014).
3. Stadnik, Flmbaum, PRL **114**, 161301 (2013).

Transient Variations of fundamental constants

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

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

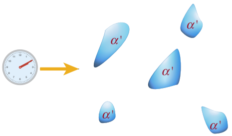
$$\alpha^{\mathrm{eff}} = \frac{\alpha}{1 - \phi^2/\Lambda_\gamma^2}, \qquad \left(\frac{m_e}{m_p}\right)^{\mathrm{eff}} = \frac{m_e}{m_p}\left(1 + \frac{\phi^2}{\Lambda_{mep}^2}\right),$$

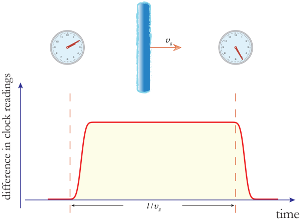
- leads to shifts in transition frequencies used for timing in for atomic clock

$$\frac{\delta\omega(t)}{\omega_0} = \phi^2 \sum_X \frac{\kappa_X}{\Lambda_X} \qquad \kappa_\alpha : \frac{\text{Sensitivity of } \omega \text{ to } \delta\alpha}{\text{Known from atomic calculations (1)}}$$

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

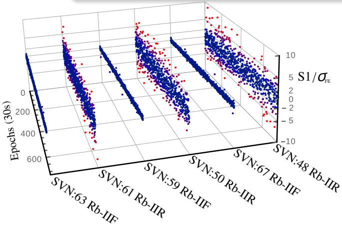
Shift in atomic clock frequencies





Monitor Atomic Clocks

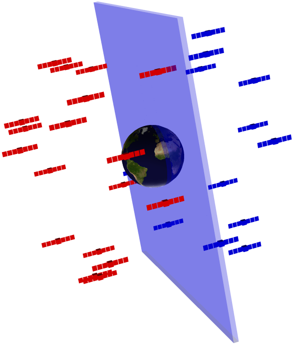
- Temporary frequency shift → bias (phase) build-up
- Initially synchronised clocks become desynchronised



- Actual clocks noisy

Global Positioning System

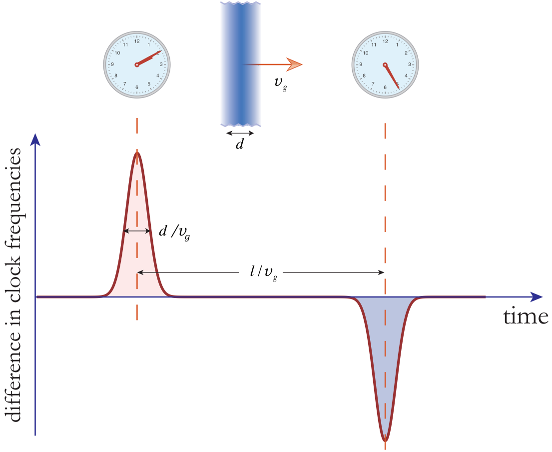
- 32 satellite clocks (Rb/Cs), $\sim$ 10 years of high-quality data
- Also several H-maser ground-based clocks.
- 30s sampled data; 0.01–0.1 ns effective precission
- Correlated, direction signal, propagates with $v_g \sim 300\,\mathrm{km/s}$



[Click to play movie]

Thin walls: Initial search/limits

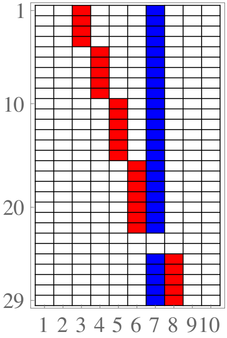
- Thin wall: breif ($< 30\,\mathrm{s}$) frequency excursion

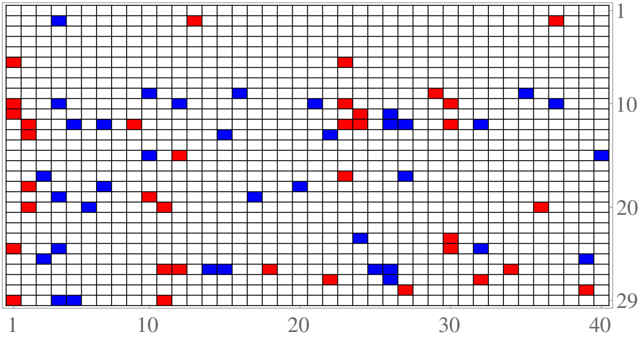


Thin walls: Initial search/limits

Simplest case: Thin walls

- $\tau < 1$ epoch (30s)
- Only consider Rb clocks (all "jumps" of equal size)
- For now: just look for bunches of jumps

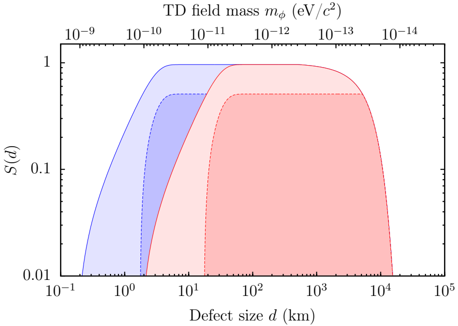




Sensitivity

Not equally sensitive to each width, d

- Assumes walls follow SHM velocity distribution
- Clock "servo time" (best/worst case = blue/red)
- Wall must be "thin" enough $\tau = d/v_\perp < 30\,\mathrm{s}$
- minimum $v_\perp$ we consider (small $v \to$ large T)



- Gives fraction of events we could "see" in the data

Setting Limits

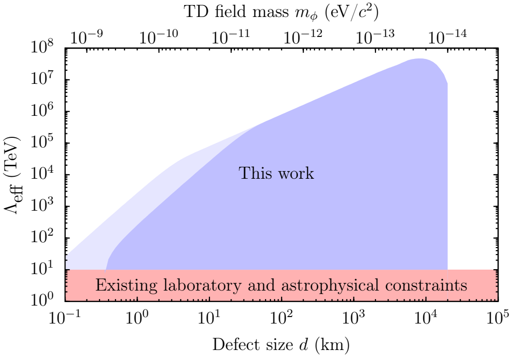
What we see in the data?

- For now: just look for most general signal
- $S^{(1)}_{\rm lim}$: largest signal size that can't be ruled out
- Assume Poisson distribution
  - $S^{(1)}_{\rm lim} = 0.34\,\text{ns}$
  - $T_{\rm obs} = 15$ years

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

Preliminary Results: Limits

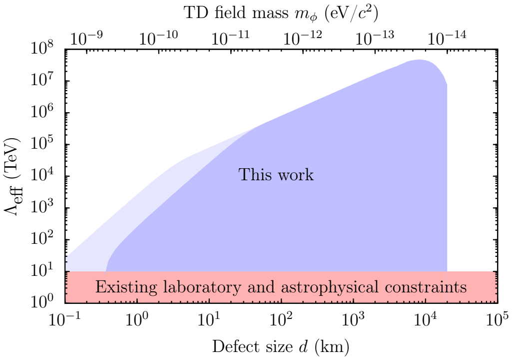
- 90% confidence level
- **Preliminary**: some assumptions still to sort out



- Limits well above noise: $S^{(1)} \sim 4\sigma$
- Can improve by several order of magnitude..

Preliminary Results: Limits

- 90% confidence level
- **Preliminary**: some assumptions still to sort out



- Limits well above noise: $S^{(1)} \sim 4\sigma$
- Can improve by several order of magnitude..

How to we improve upon this?

Bayesian Analysis

- "Marginalise" (integrate) over all parameters of model
  - In-built Occam's Razor
- Odds ratio: positive–to–negative model likelihood

$$p(D_{j_0}|m,I) = K\int d^3v\ p(v|m,I)\int dh\ p(h|m,I)\ \int_{j_{-1}}^{j_0} dt_0\ \exp\left(\frac{-1}{2}\chi_s\right)$$

Simple case:

$$\chi_s = \sum_i^N \sum_j^{J_W} \frac{\left(d_{ij} - s_{ij}^m\right)^2}{\sigma^2}$$

- Should be able to detect events as small as:

$$s \approx \sigma/\sqrt{N} \approx 0.003\,\mathrm{ns}\ \text{(for the best clocks)}$$

$$\implies \delta\omega/\omega \sim 10^{-14}\ \text{(best case)}$$

How to we improve upon this?

Bayesian Analysis

- "Marginalise" (integrate) over all parameters of model
  - In-built Occam's Razor
- Odds ratio: positive–to–negative model likelihood

$$p(D_{j_0}|m,I) = K\int d^3v\ p(v|m,I)\int dh\ p(h|m,I)\ \int_{j_{-1}}^{j_0} dt_0\ \exp\left(\frac{-1}{2}\chi_s\right)$$

Simple case:

$$\chi_s = \sum_i^N \sum_j^{J_W} \frac{\left(d_{ij} - s_{ij}^m\right)^2}{\sigma^2}$$

• Should be able to detect events as small as:

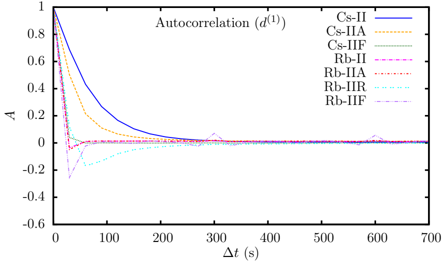
$$s \approx \sigma/\sqrt{N} \approx 0.003\,\mathrm{ns}\ \text{(for the best clocks)}$$

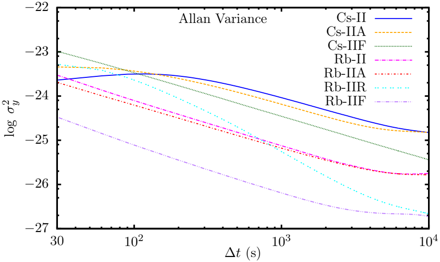
$$\implies \delta\omega/\omega \sim 10^{-14}\ \text{(best case)}$$

Test the method:

Statistical properties of data:

- Standard deviations, Auto-correlation functions, Power-spectrums, Allan variance etc.



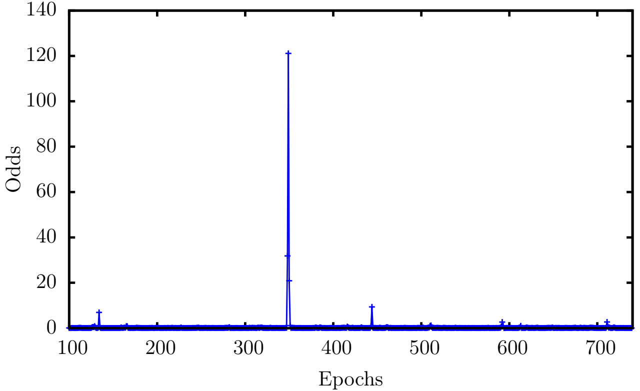


• From this, we can generate "fake" time-series data, that mimics the noise properties of the real data

Test the method:

Inject fake 0.5σ event

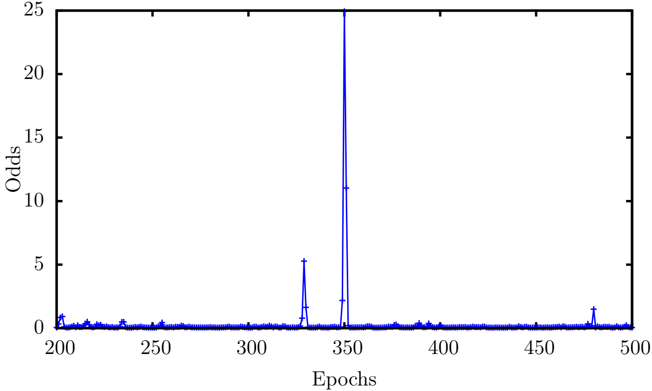
- Inject $v \sim 250\,\mathrm{km/s}$ event, crosses at Epoch=350



Test the method:

Inject fake 0.3σ event

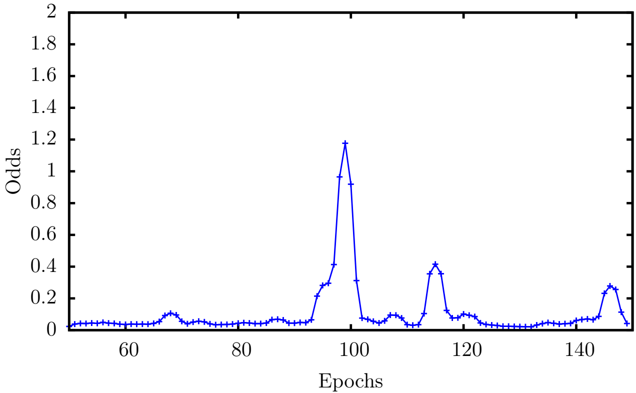
- Inject $v \sim 250\,\mathrm{km/s}$ event, crosses at Epoch=350



Test the method:

Inject fake 0.25σ event

- Inject $v \sim 250\,\mathrm{km/s}$ event, crosses at Epoch=100



Test the method:

Summary:

- If we require $O > 10$, there seems to be very few false-positives
- ..but then only positively detect $\sim 70\%$ of 0.5σ events
- Run time: ~ 3 hours per day of data, using 64 cores
- There are still tweaks needed to improve efficiency and efficacy

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 archived data
- Initial limits: orders of magnitude improvement for certain models
- Looking forward: Bayesian search technique