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

Date: Jul 22, 2017 09:00 AM

URL: http://pirsa.org/17070027

Abstract:

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

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

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
  - $\sim$ 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 $\sim 10^{-24} - 1\,\mathrm{eV}$
- 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,...

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)

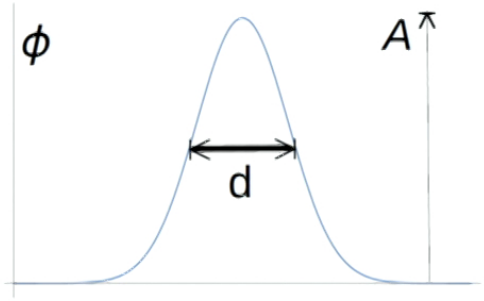
- Masses $\sim 10^{-24} - 1\,\mathrm{eV}$
- Classical oscillating field: $\phi = a\cos(m_a t)$
- Stable topological defects: monopoles, strings, walls
  - Also: Q-balls, solitons, "clumps"

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

Dark matter: Gas of defects

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

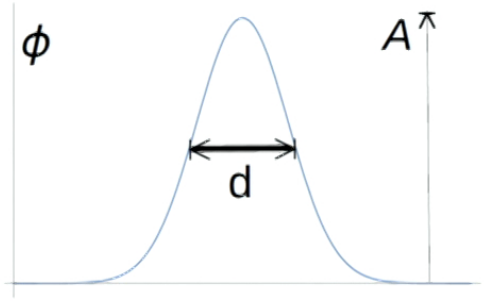
$$A^2 = \rho_{\rm DM}\, v_g\, d\, \mathcal{T}.$$

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

Topological Defect DM

Topological Defects

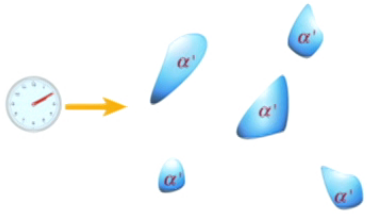
- monopoles, strings, walls,
- Defect width: $d \sim 1/m_\phi$
- Earth-scale object $\sim 10^{-14}$ eV



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, ...

Possible DM–SM interactions

Pseudoscalar (axionic) portal:

- e.g., $\mathcal{L}^{\mathrm{PS}} = \partial_\mu a\, \bar{\psi}\gamma^\mu\gamma^5\psi$
- 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: $\Longrightarrow$ 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)...

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: $\Longrightarrow$ 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

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

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

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

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

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

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

Variation of fundamental constants

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

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

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

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

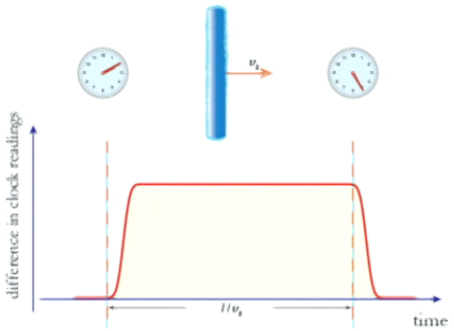
$$\frac{\delta\omega(r,t)}{\omega_0} = \phi^2(r,t)\sum_X \frac{K_X}{\Lambda_X} \qquad K_\alpha \text{ : Sensitivity of } \omega \text{ to } \delta\alpha$$

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

Shift in atomic clock frequencies

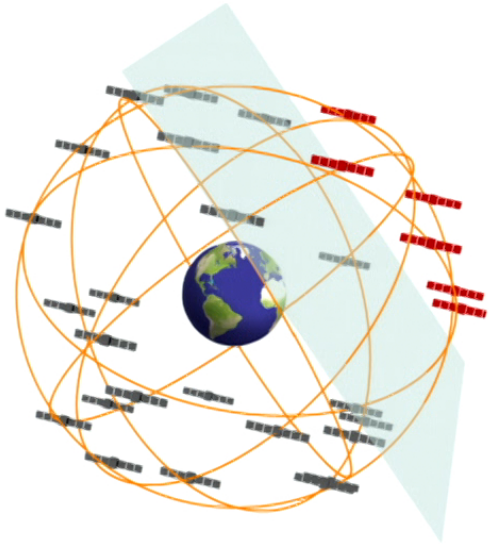
Monitor Atomic Clocks

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



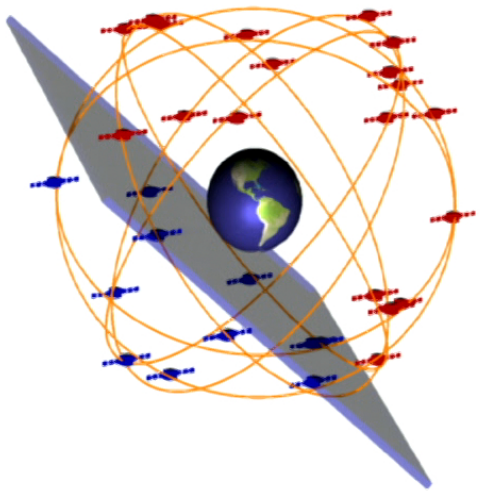
GPS: 50,000 km DM observatory

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



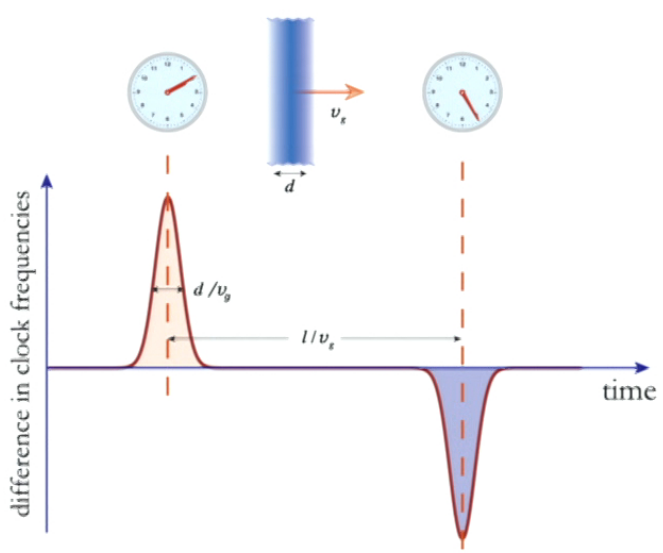
GPS: 50,000 km DM observatory

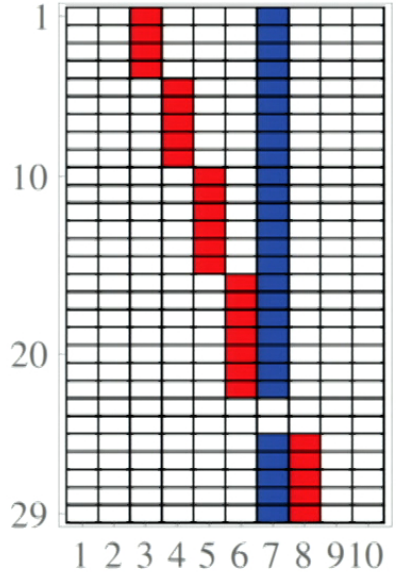
- 32 satellite clocks (Rb/Cs), $\sim$ 16 years of high-quality data
- Also several H-maser ground-based clocks.
- Data from JPL: (sideshow.jpl.nasa.gov/pub/jpligsac/)
  - 30s sampled data; 0.01–0.1 ns precision
- Correlated, directional signal, with $v_g \sim 300\,\mathrm{km/s}$



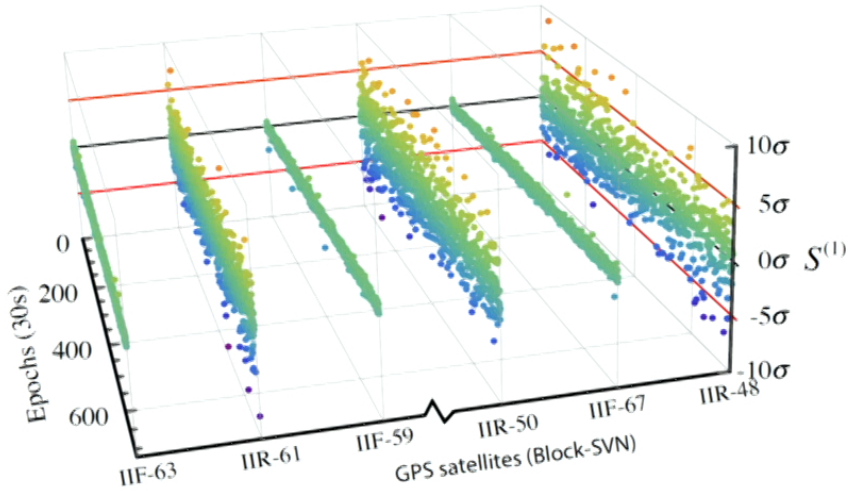
DM Walls: Initial search/limits

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

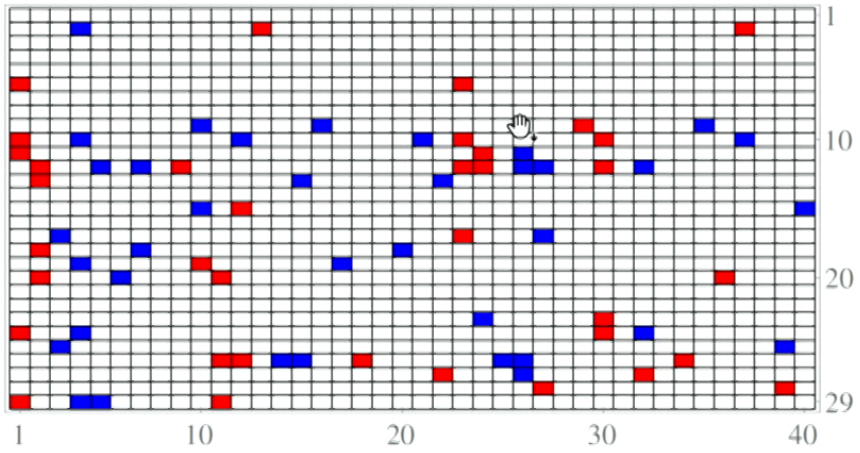




- $\vec{\mathbf{v}}$ encoded in time-delay and signal ordering: $\Delta t \sim$ minutes



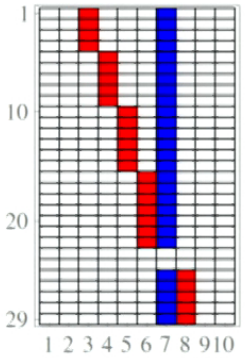
Apply $S_{\mathrm{cut}} \Longrightarrow$

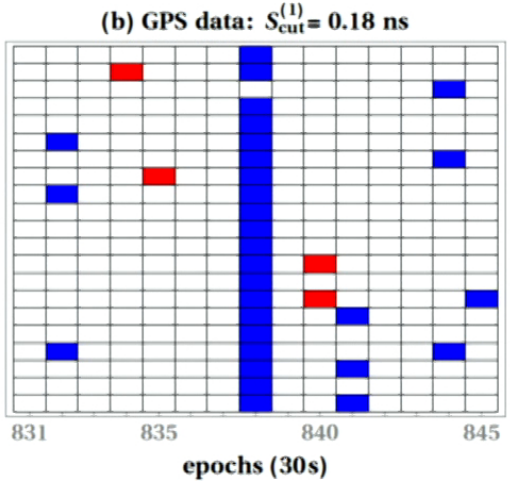


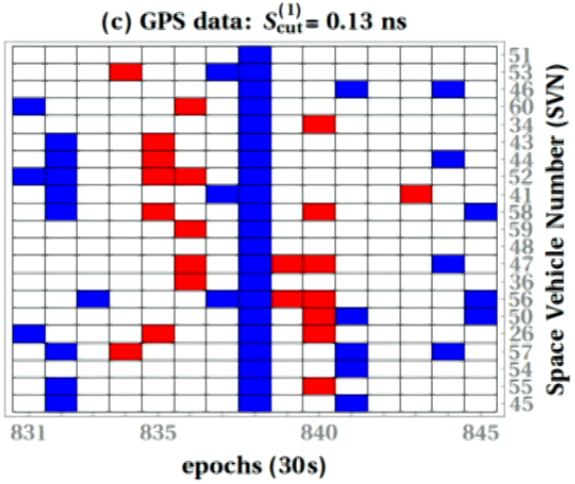
Scan the data

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 (Λ_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)

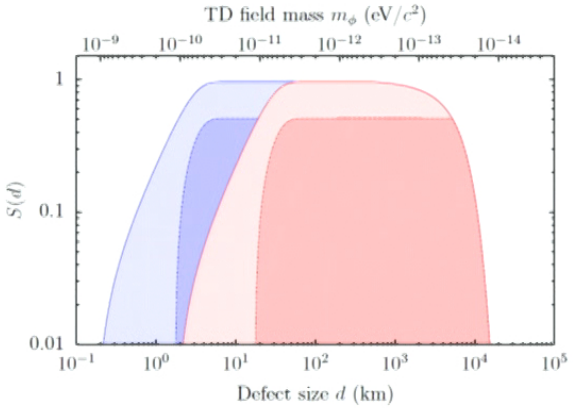
Sensitivity

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

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

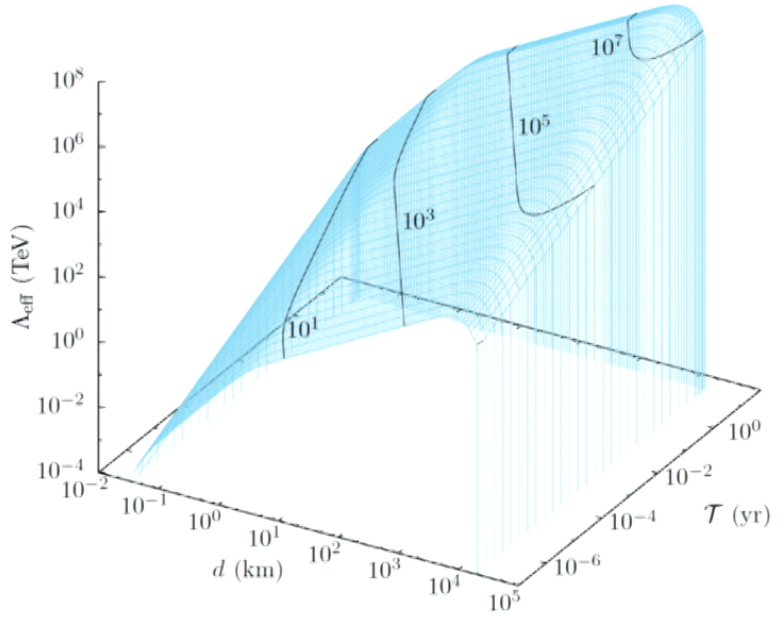
Not equally sensitive to each width, d

- 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)

Results: Limits

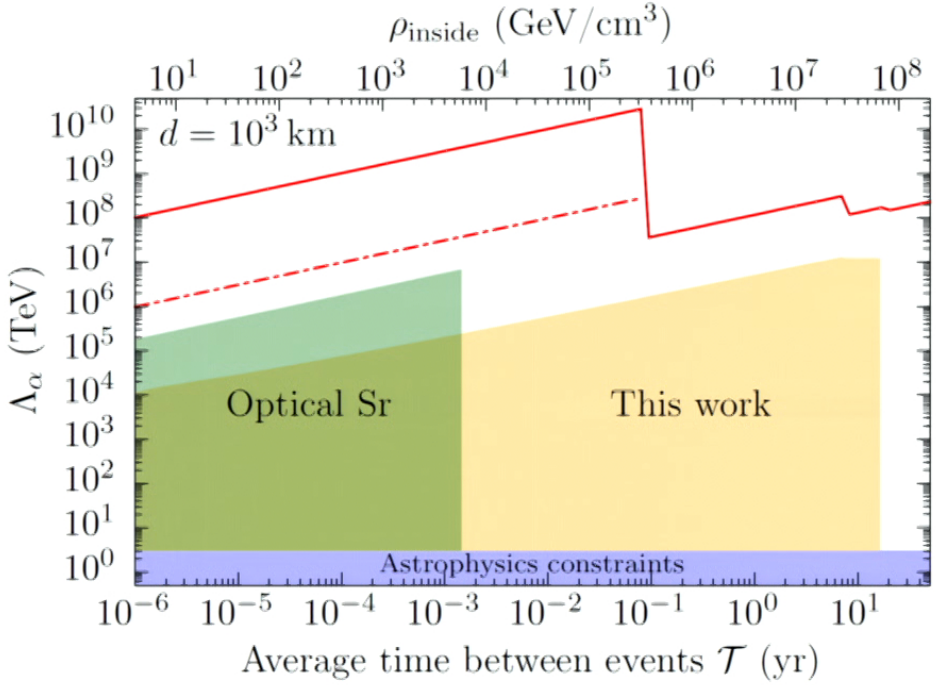


Rb sub-network

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

Results: Limits - Λ_α (photon)

- (Assume this coupling dominates)



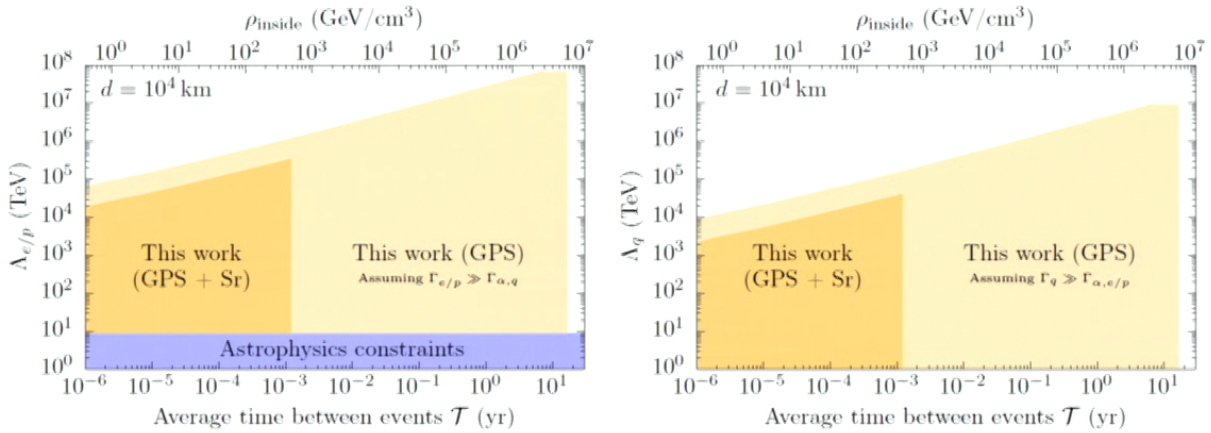
Sr: Wcislo, Morzynski, Bober, Cygan, Lisak, Ciurylo, Zawada, Nat. Astron. 1, 9 (2016).

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

$$\underbrace{p(D_{j0}|m,I)}_{Likelihood} = K \overbrace{\int dx_1 \ldots \int dx_n}^{\text{marginalise parameters}} \underbrace{p(x_1 \ldots x_n|m,I)}_{\text{Priors}} \overbrace{\exp\left(-\chi_s\right)}^{\text{Gaussian likelihood}}$$

$$\chi_s = \overbrace{\sum_i \sum_{jl}}^{Clocks\ Data} \left(d_j^i - s_j^i\right) \overbrace{H_{jl}^i}^{\text{co-variance}} \left(d_l^i - s_l^i\right)$$

- Should be able to detect events as small as:

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

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

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

$$\chi_s = \sum_{i}^{Clocks} \sum_{jl}^{Data} \left(d_j^i - s_j^i\right) \overbrace{H_{jl}^i}^{\text{co-variance}} \left(d_l^i - s_l^i\right)$$

- Should be able to detect events as small as:

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

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

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

$$\chi_s = \sum_{i}^{Clocks} \sum_{jl}^{Data} \left(d_j^i - s_j^i\right) \overbrace{H_{jl}^i}^{\text{co-variance}} \left(d_l^i - s_l^i\right)$$

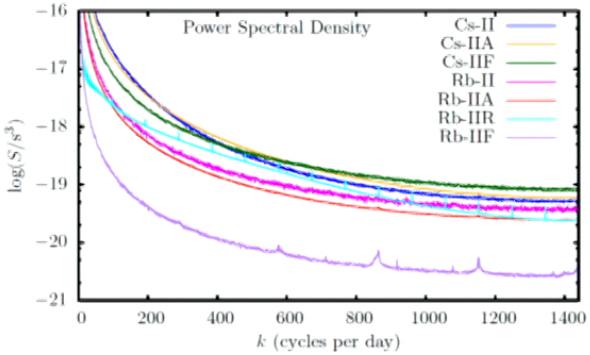
- Should be able to detect events as small as:

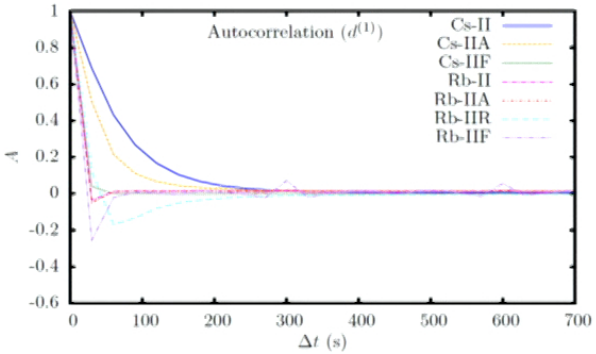
$$s \approx \sigma/\sqrt{N} \approx 0.001\,\text{ns} \text{ (for the best clocks)}$$

Test the method:

Statistical properties of data:

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





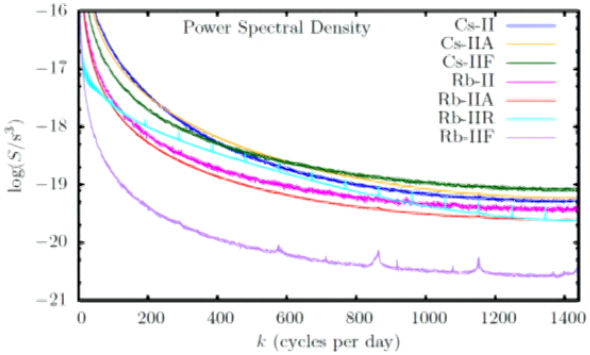
- Generate "fake" data: mimics properties of the real data
  - y: Input white noise, S: PSD, z: Simulated data

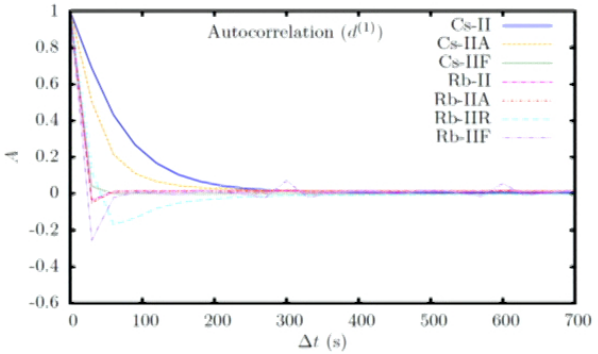
$$z = FT^{-1}\left(FT(y)\sqrt{S^{\text{target}}/S^{y}}\right)$$

Test the method:

Statistical properties of data:

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

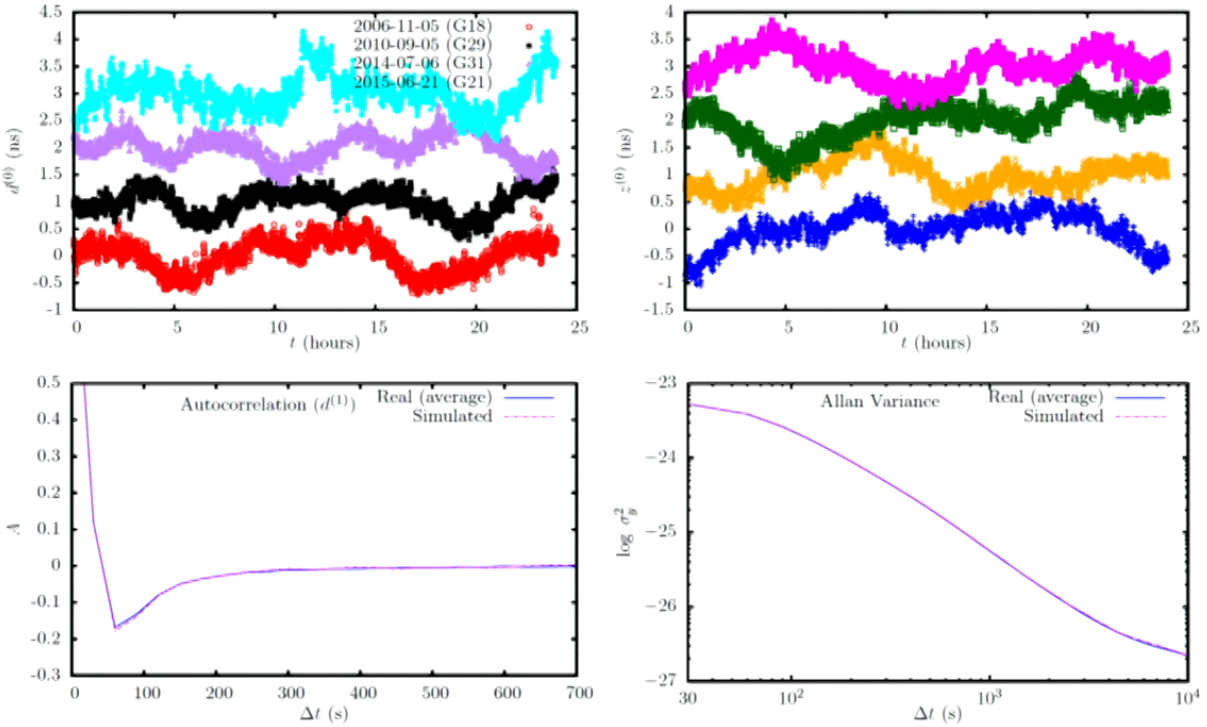




- Generate "fake" data: mimics properties of the real data
  - y: Input white noise, S: PSD, z: Simulated data

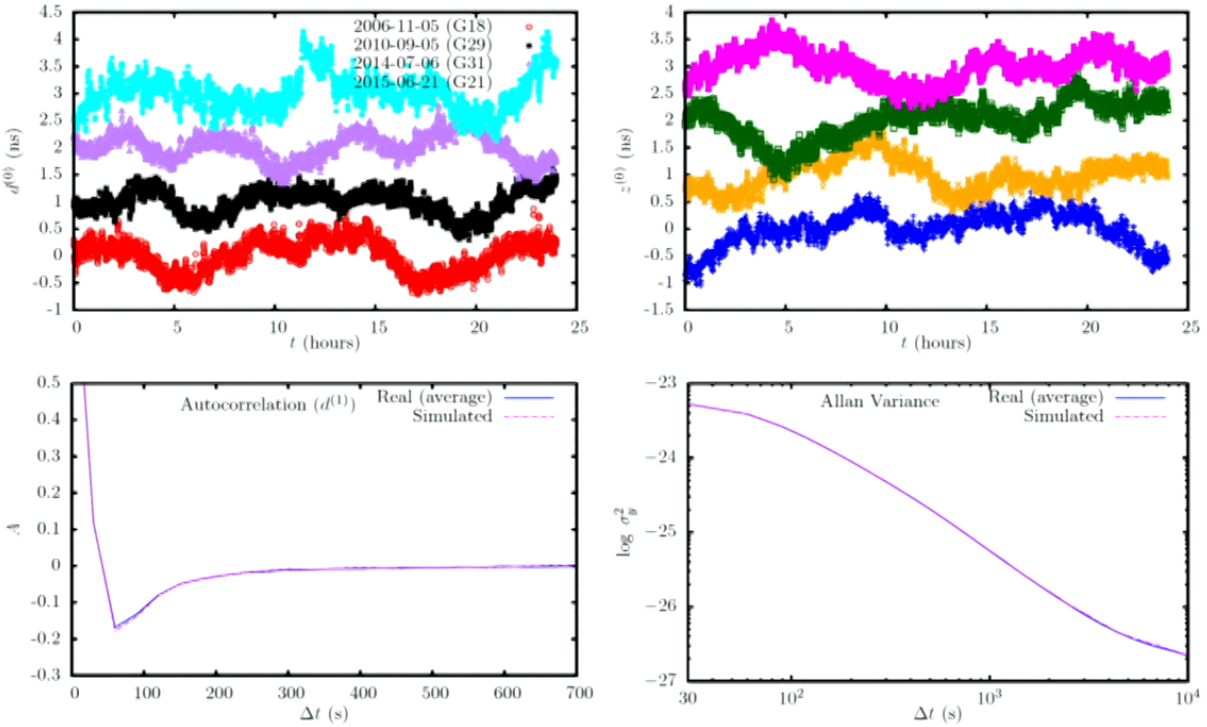
$$z = FT^{-1}\left(FT(y)\sqrt{S^{\text{target}}/S^{y}}\right)$$

Test the method:



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

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:

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)

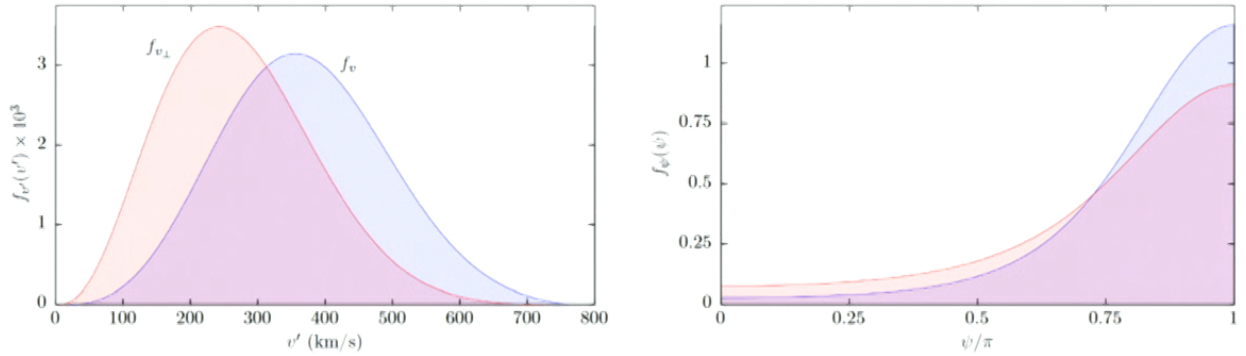
- False positives will have different distribution
- But: have to "discount" priors for this analysis)

Possible outcomes:

- All actual events should* have same sign

Vector velocity resolution:

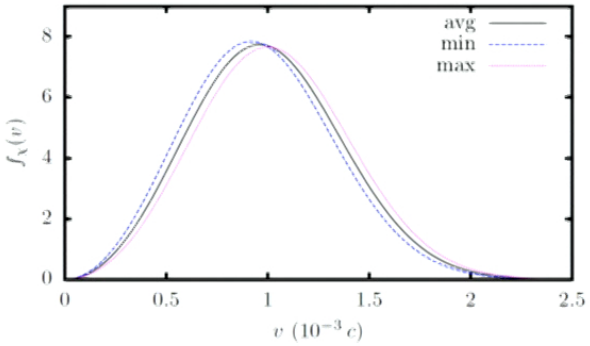
- $>$ 30 clocks: quite good speed/direction resolution
- Potential to resolve velocity distribution (SHM)

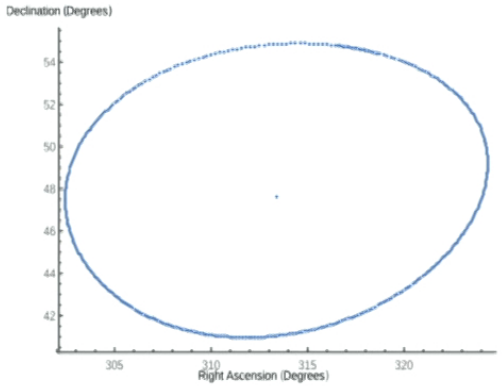


- False positives will have different distribution
- But: have to "discount" priors for this analysis)

Possible outcomes:

Annual variation:





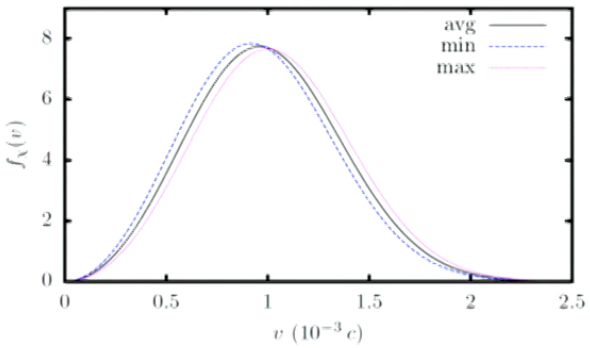
Lower threshold. Lots of false-positives

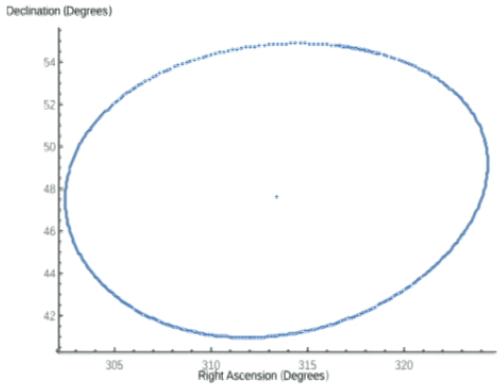
- Assymetry in event 'sign' & resolve SHM predictions, +
- Annual modulation:
  - Event rate
  - Average velocity
  - Most-common incident direction

May extend discovery reach for $T \ll 1\,\mathrm{yr}$ and $d \ll R_{\mathrm{GPS}}$

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 $d \ll R_{\mathrm{GPS}}$

Conclusion:

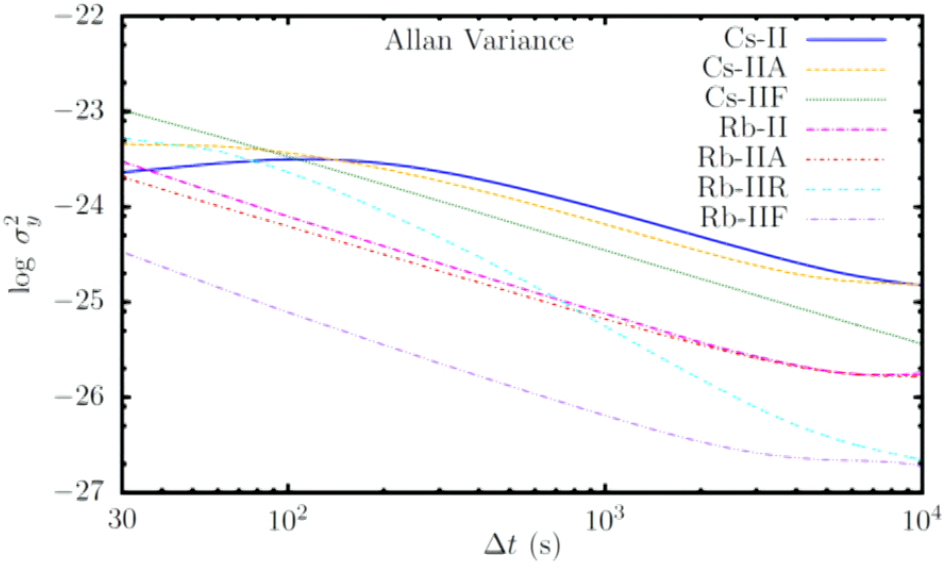
GPS: 50,000km aperture DM observatory

- 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 σ_{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


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(?)