Searching for dark matter signatures in 20 years of GPS atomic clock data

Archival data for fundamental and exotic physics

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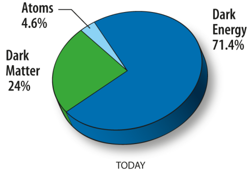
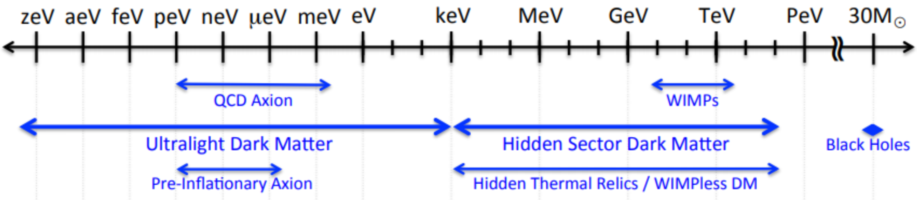
Dark Matter: What is it?

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



[image: wmap.gsfc.nasa.gov]

- Possible mass range: $\sim$90 orders-of-magnitude:



[• US Cosmic Visions report, arXiv:1707.04591]

$\Longrightarrow$ Wide range of possibilities: requires large range of experiments

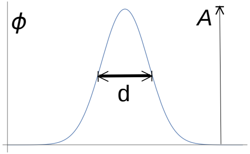
- And the best kind of experiment is one that's already done

Dark Matter Clumps: (Topological Defects)

• Ultralight ($m_\phi \ll eV$) $\implies$ high occupation number
Many possibilities: Here: TDs

Topological Defects

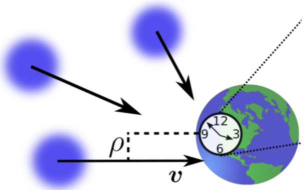
- monopoles, strings, walls,
- Defect width: $d \sim 1/m_\phi$
- Earth-scale object: $m_\phi \sim 10^{-14}$ eV



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

Dark matter: Gas of defects

- DM: galactic speeds: $v_g \sim 10^{-3}c$
- Collisions offer chance for lab detection



• Vilekin '85, Coleman '85, Lee '89, Kibble '80, ...
• Derevianko, Pospelov, Nature Phys. 10, **933** (2014).

Variation of fundamental constants

- Here: (quadratic) scalar: $\mathcal{L}_{\rm int} \sim \phi^2(a\bar{\psi}\psi + bF^2_{\mu\nu} + \ldots)$
- Parameterised in with Λ "energy scale" ($\sim$ inverse coupling strength)

$\implies$ transient additions to *effective values* of 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

$$\frac{\delta\omega(r,t)}{\omega_0} = K_\alpha\frac{\delta\alpha(r,t)}{\alpha} = \phi^2(r,t)\frac{K_\alpha}{\Lambda_\alpha^2}$$

Monitor Atomic Clocks

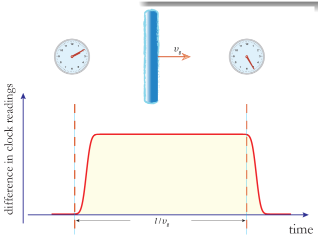
- Clocks: lock frequency to atomic transition $\implies$ Monitor atomic frequencies using atomic clocks
- Shift $\delta\omega$ occurs only when ϕ non-zero (inside DM object)

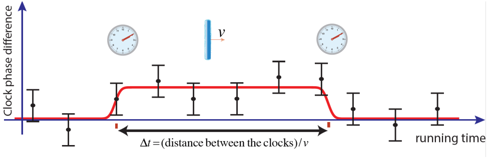
- Olive, Pospelov, Phys. Rev. D **65**, 085044 (2002); Derevianko, Pospelov, Nat. Phys. **10**, 933 (2014).
- Flambaum, Tedesco, PRC, **73**, 55501 (06); Flambaum, Dzuba, Can. J. Phys., **87**, 25 (09).

Shift in atomic clock frequencies

Monitor Atomic Clocks

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





Signal v. noise?

- Transient signal: looks essentially like any outlier
- So how to distinguish from noise? i.e. what is the specific DM signature?

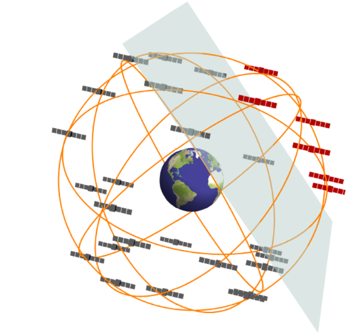
- Derevianko, Pospelov, Nat. Phys. 10, 933 (2014).

Global network of precision devices

- DM expected to move at $\sim$ galactic speeds
- Correlated, directional signal: propagation through network, $v \sim 300\,\text{km/s}$
- $\vec{\mathbf{v}}$ encoded in time-delay, ordering: $\Delta t \sim$ seconds – minutes
- Also: multiple clock-types in network, each has different K_α (prediction of theory)

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

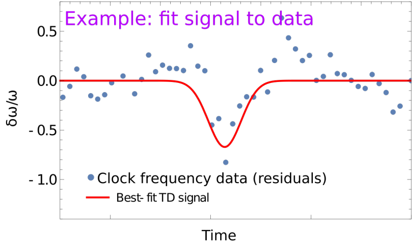


- Clocks: Derevianko, Pospelov, Nature Phys. 10, **933** (2014).
- Magnetometer: Pospelov, Pustelny, Ledbetter, Kimball, Gawlik, Budker, Phys.Rev.Lett. **110**, 021803 (13).

Search method

Fibre network

- Max-likelihood fit method[1]
- Coherent $\delta\omega$ variations (with K_α)
- Signal template $s = s(t_0, d, \boldsymbol{v})$

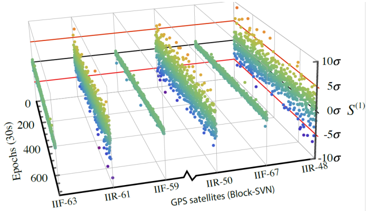


$$p(D_t|\delta\alpha,\theta) = C\,p(\theta)\exp\left(\tfrac{-1}{2}[d-\delta\alpha s]^T H[d-\delta\alpha s]\right),$$

d: data stream; $s = s(\theta)$ signal template, $\delta\alpha$: magnitude; $H = E^{-1}$ covariance

a) Signal-to-noise $R >$ threshold? $\Longrightarrow$ event detection
b) Largest $\delta\alpha$ that cannot be ruled out? $\Longrightarrow$ set limits

$$\delta\alpha^{\rm bf} = dHs/sHs. \qquad \Longrightarrow \qquad \delta\alpha < dHs/sHs + n(sHs)^{-1/2}.$$

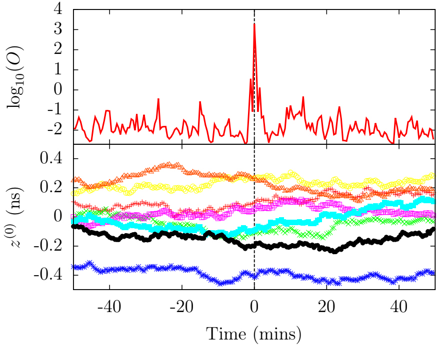


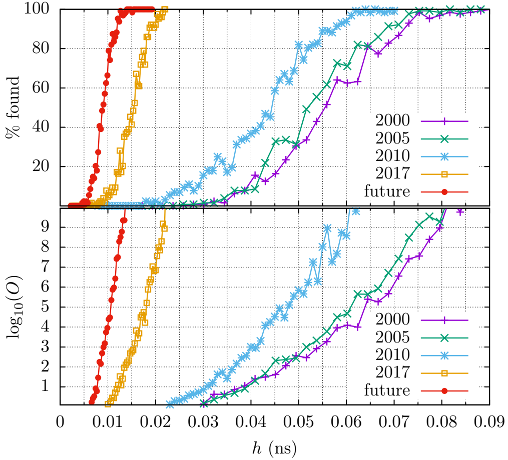
(1) BMR, G. Blewitt, C. Dailey, and A. Derevianko, Phys. Rev. D **97**, 083009 (2018); G. Panelli, BMR, and A. Derevianko, arXiv:1908.03320.

Testing: simulated GPS

Odds ratios: Marginalise all parameters

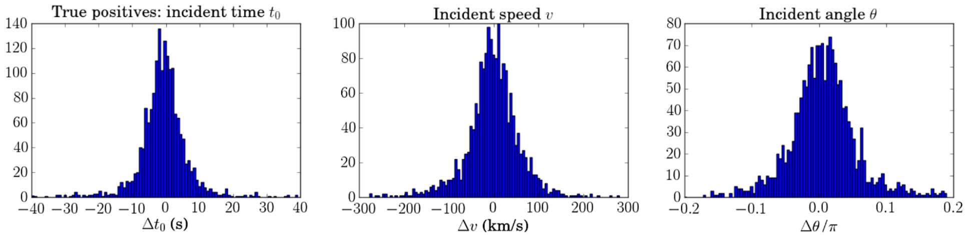
- Simulated GPS data (known power spectrum)
- Threshold: set by false positives
- True positives: inject fake events

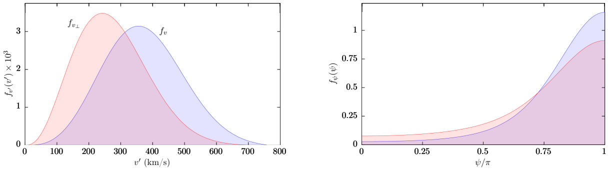




(1) BMR, G. Blewitt, C. Dailey, and A. Derevianko, Phys. Rev. D **97**, 083009 (2018); G. Panelli, BMR, and A. Derevianko 1908.03320

Resolve speed + direction (simulation)





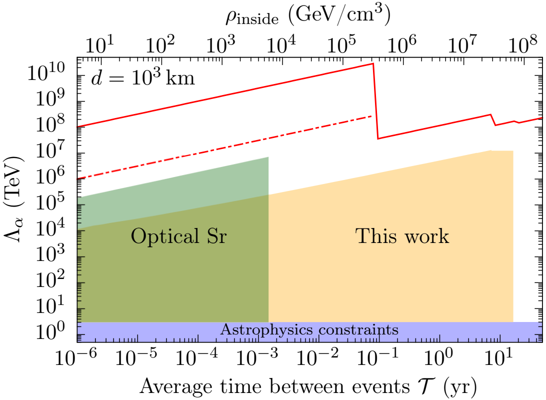
Resolution: simulation using GPS

- Resolve v – DM vel. distro is "known" – reject false positives!
- Many clocks + High sampling frequency and/or **Large distances**

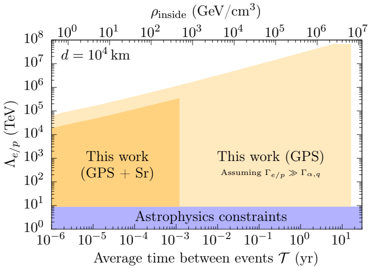
• BMR, Blewitt, Dailey, Derevianko, Phys. Rev. D **97**, 083009 (2018). • Panelli, BMR, Derevianko, arXiv:1908.03320

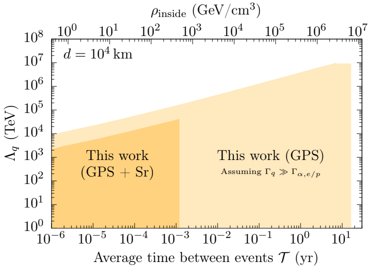
Results: Limits

- Inital search: simplified method (extra large events)
- Exclusion plot (assume coupling to photon dominates)



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

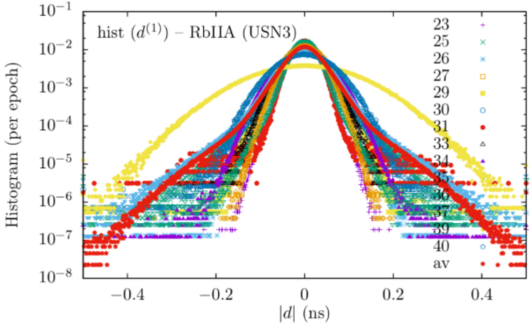




- BMR, Blewitt, Dailey, Murphy, Pospelov, Rollings, Sherman, Williams, Derevianko, Nature Comm. **8**, 1195 (2017).

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.

Aside: challenges of re-purposed data

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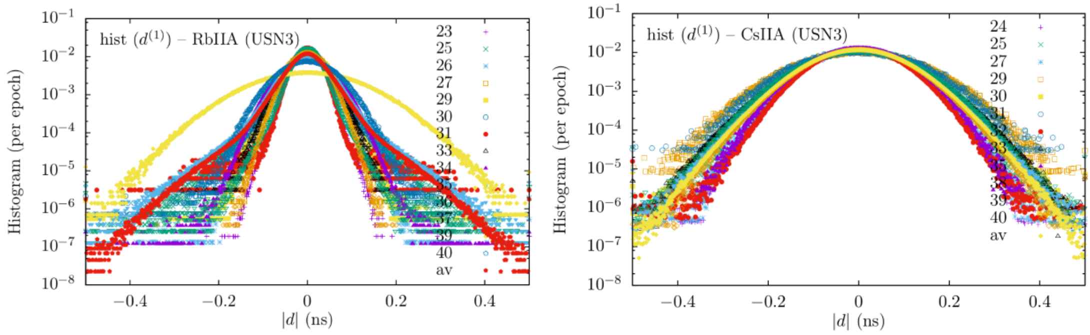

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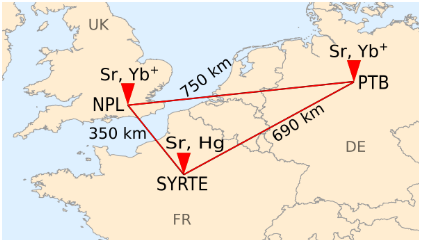
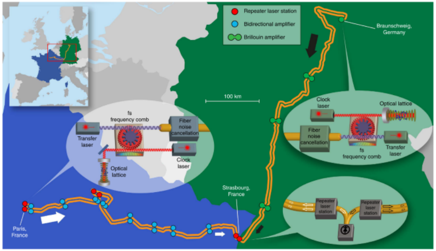
European fibre-linked optical clock network



Fibre network

- High-accuracy long-distance clock-clock (atom-atom) comparisons
- Different clocks: $Hg/Sr/Yb^+$
- $\sim$ Days – weeks synchronous running

- Sensitivity: ✓ $(\delta\alpha,\, \Lambda)$
  limited only by clocks:
  Sr-Sr: $\delta\omega/\omega \sim 3 \times 10^{-17}$ at 1000s
- Long observation time: ✓ $(\mathcal{T})$
- Long-term stability: ✓ (d)

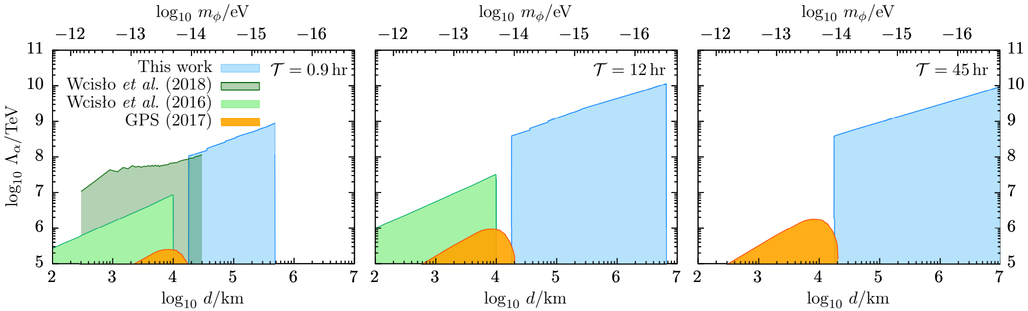


• Lisdat *et al.* (PTB, LNE-SYRTE), Nature Commun. **7**, 12443 (2016).
• Delva *et al.* (PTB, SYRTE, NPL, ..), Phys. Rev. Lett. **118**, 221102 (2017).

Topological defect dark matter

Very sensitive to different models, different range of parameters

$$\phi_0^2 = \hbar c\, \rho_{\rm DM} v_g \mathcal{T} d\,, \qquad \mathcal{T} = \frac{\rho_{\rm inside}}{\rho_{\rm DM}} \frac{d}{v_g} \qquad \Longrightarrow \qquad \Lambda_\alpha^2(\mathcal{T}, d) > \frac{\hbar c \alpha \rho_{\rm DM} v_g \mathcal{T} d}{|\delta\alpha_0(\mathcal{T}, \tau_{\rm int})|}.$$



- nb: GPS reults (orange): go up to $\mathcal{T} \sim 10\,\mathrm{yrs} \sim 10^5$ hrs

GPS: BMR, Blewitt, Dailey, Murphy, Pospelov, Rollings, Sherman, Williams, Derevianko, **Nature Comm. 8**, 1195 (2017).
2016: Wcisło, Morzynski, Bober, Cygan, Lisak, Ciurylo, Zawada, **Nat. Astro. 1**,0009 (2016).
2018: Wcislo et al., **Sci. Adv. 4, 4869 (2018)**.

arXiv:1907.02661

Search for transient variations of the fine structure constant and dark matter using fiber-linked optical atomic clocks

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l'Observatoire de Paris — SYRTE — Systèmes de Référence Temps-Espace

NPL National Physical Laboratory

PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

Conclusion

Fundamental physics with archival data

- Beyond standard model physics + dark matter
- Wide variety of possible models $\implies$ wide range of experiments
- Archived time-stamped data from precision measurement devices

GPS: 50,000 km DM observatory

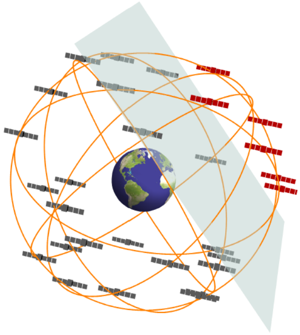
- Initial limits: orders of magnitude improvement
- Nature Comms. **8**, 1195 (2017)

Optical clock networks

- Also: European fibre-linked clocks [arXiv:1907.02661]

Other networks

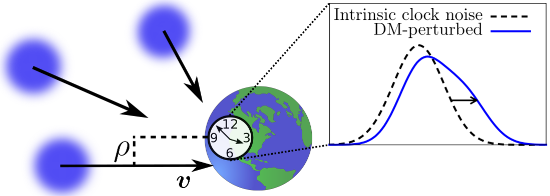
- Magnetometers, gravimeters, EDM searches
- complementary: sensitive to different models



Extra: Asymmetry

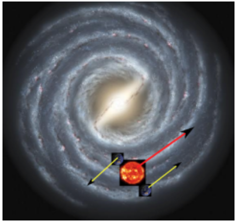
Small objects: no correlated signal

- small size $\rightsquigarrow$ large rate
- Shift in mean: unobservable (DM always present)
- Induce non-Gaussian features (such as an asymmetry)

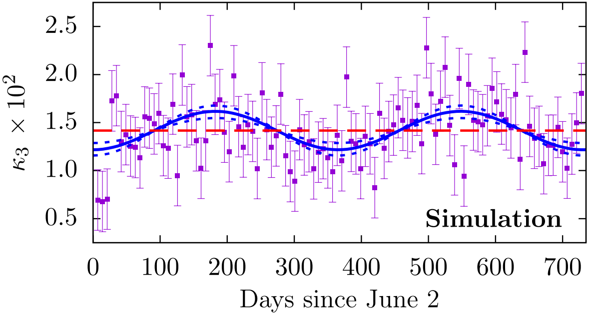


$$\mathcal{R} = \frac{1}{\mathcal{T}} = \frac{3\rho_{\rm DM} v_g}{4\rho_{\rm inside} R}, \qquad \kappa_3 \approx \frac{2\mathcal{R}\tau_0\chi_0^3}{5\sigma^3}.$$

Extra: Annual modulation



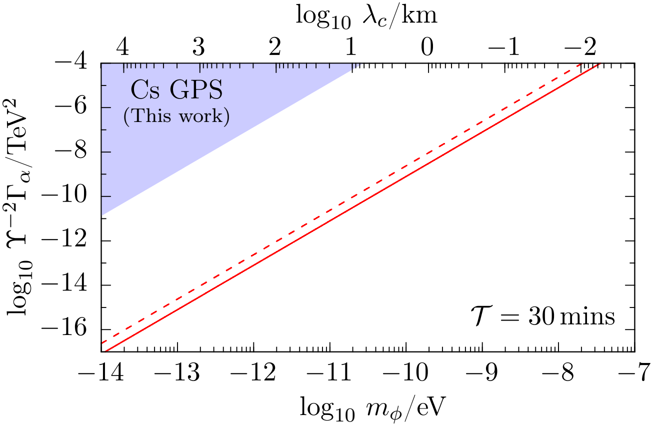
- Yearly change in event rate:
- Sun + Earth velocities add
- $R(t) = R_0 + R_m \cos(\omega t + \phi_{\mathrm{June2}})$
- $\Delta\kappa_3/\kappa_3 = 10\%$
- $\Delta\kappa_4/\kappa_4 = 15\%$



- BMR, Derevianko, arXiv:1803.00617

Extra: Limits Q-balls: α (photon field)

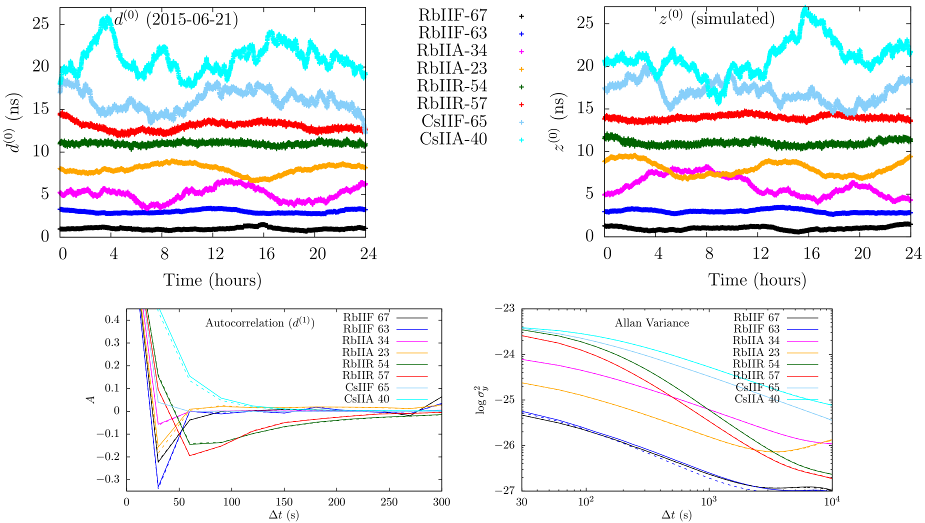
Proof of concept: Limits from GPS Cs/H $\quad K_\alpha(Cs/H) \simeq 0.8$



- BMR, Derevianko, arXiv:1803.00617

Red line: sensitivity estimate for 1 year of optical Sr

Test the method: simulated GPS



- Inject fake events: True positive rate
- Don't inject events: False positive rate