Searching for dark matter and exotic physics with atomic clocks in space and on the ground

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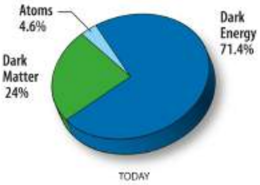
& the Optical clock, link, comb, & cavity teams of NPL, PTB, & SYRTE

Scientific and Fundamental Aspects of GNSS
7th International Colloquium, European Space Agency (ESA)
ETH Zürich, Switzerland

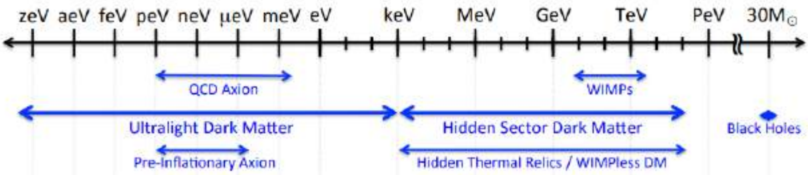
4–6 September 2019

Dark Matter: What is it?



[image: wmap.gsfc.nasa.gov]

- $\sim$ 25% of Universe energy budget (cf $\sim$ 5% for "normal" matter)
- Possible mass range: $\sim$90 orders-of-magnitude:



[• US Cosmic Visions report, arXiv:1707.04591]

(context: $m_{\rm Earth} \sim 10^{60}$ eV $m_{\rm electron} \sim 10^{6}$ eV)

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

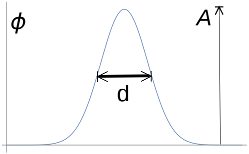
Dark Matter Clumps: (Topological Defects)

- Ultralight ($m_\phi \ll eV$) $\implies$ high occupation number

Many possibilities: Here: TDs

Topological Defects

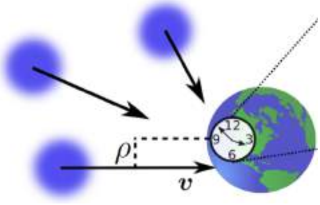
- monopoles, strings, walls,
- Defect width: $d \sim 1/m_\phi$
- Earth-scale object: $m_\phi \sim 10^{-14}$ eV



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

Dark matter: Gas of defects

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

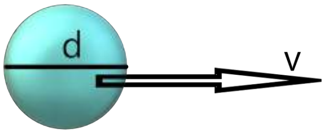


- Vilekin '85, Coleman '85, Lee '89, Kibble '80, ...
- Derevianko, Pospelov, Nature Phys. 10, **933** (2014).

Transients: 3D(+) parameter space

Two time-scales

- $\mathcal{T}$ – time between events
  - Given by number density
- $\tau_{\rm int} = v/d$ – interaction duration
  - For TDs: $d \sim 1/m_\phi$ (free in general)
- For transients: must have $\tau_{\rm int} \ll \mathcal{T}$



$$\phi_0^2 = \boxed{\rho_{\rm DM}}\, v_g\, d\, \mathcal{T},$$

$\rho_{\rm DM} \simeq 0.4\, GeV/cm^3$: local DM density

And (hopefully) some non-gravitational coupling

- Various possibilities. Here: (quadratic) scalar:
- $\mathcal{L}_{\rm int} \sim \phi^2(a\bar\psi\psi + bF_{\mu\nu}^2 + \ldots)$

See, e.g.,: Olive, Pospelov, Phys. Rev. D **65**, 085044 (2002); Derevianko, Pospelov, Nature Phys. 10, **933** (2014); Pustelny, Kimball, Pankow, Ledbetter, Wlodarczyk, Wcislo, Pospelov, Smith, Read, Gawlik, Budker, Ann.Phys. **525**, 659 (2013)
Stadnik, Flambaum, PRL **114**, 161301 (2013).
Hees, Guena, Abgrall, Bize, Wolf, Phys. Rev. Lett. **117**, 061301 (2016).
Arvanitaki, Graham, Hogan, Rajendran, Van Tilburg (2016); Stadnik, Flambaum (2016), ...

Variation of fundamental constants

- Here: (quadratic) scalar: $\mathcal{L}_{\rm int} \sim \phi^2(a\bar{\psi}\psi + bF_{\mu\nu}^2 + \ldots)$

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

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

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

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

Monitor Atomic Clocks

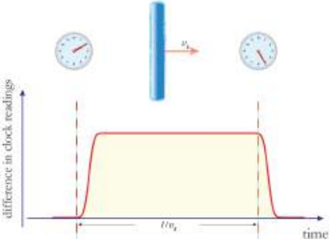
- Clocks: lock frequency to atomic transition
- Shift $\delta\omega$ occurs only when ϕ non-zero (inside DM object)
- Monitor atomic frequencies using atomic clocks
- Parameterised in with Λ "energy scale" ($\sim$ inverse coupling strength)

- 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

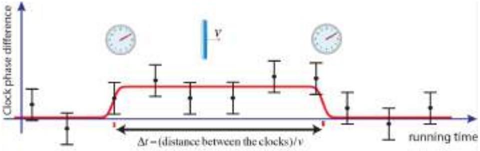
Monitor Atomic Clocks

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



Signal v. noise?

- Transient signal:
  looks essentially like any outlier
- i.e. what is the specific DM signature?

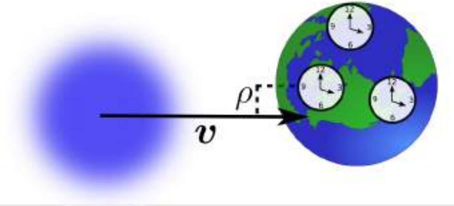


- Derevianko, Pospelov, Nat. Phys. 10, 933 (2014).

Global network of precision devices

Network of separated atomic clocks

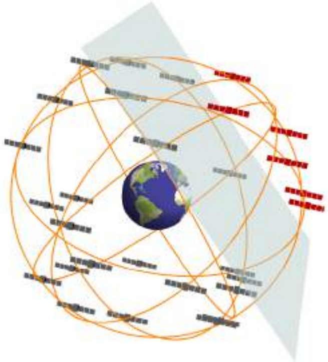
- DM expected to move at $\sim$ galactic speeds
- Correlated signal propagation through network, $v \sim 300\,\text{km/s}$
- $\vec{\mathbf{v}}$ encoded in time-delay, ordering: $\Delta t \sim$ seconds – minutes
- Also: multiple clock-types in network, each has different K_α (relative sensitivities prediction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



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

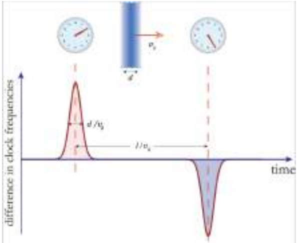
GPS: 50,000 km DM observatory

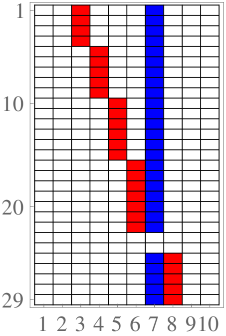
- 32 satellite clocks (Rb/Cs), $\sim$ 16 years of high-quality data
- Also several H-maser ground-based clocks.
- Data from JPL: (sideshow.jpl.nasa.gov/pub/jpligsac/)
  - 30s sampled data; 0.01–0.1 ns precision
- Correlated, directional signal, with $v_g \sim 300\,\mathrm{km/s}$



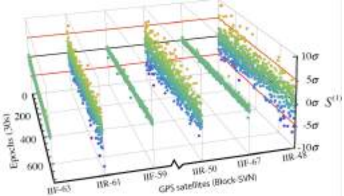
DM Walls: Initial GPS search/limits

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

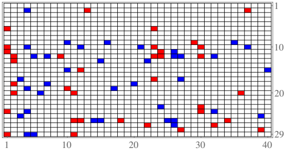




- $\vec{\mathbf{v}}$ encoded in time-delay and signal ordering: $\Delta t \sim$ minutes

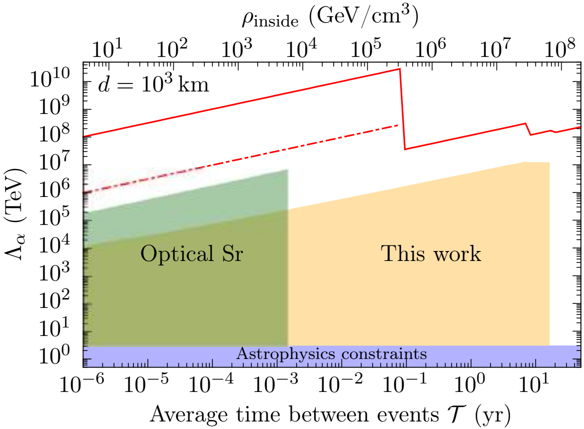


Apply S_{cut} $\Longrightarrow$



Results: Limits - Λ_α (photon)

- Exclusion plot (assume coupling to photon dominates)



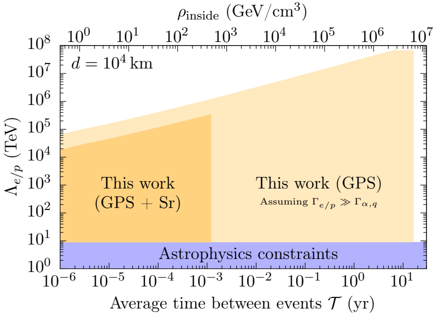
- BMR, Blewitt, Dailey, Murphy, Pospelov, Rollings, Sherman, Williams, Derevianko, Nature Comm. **8**, 1195 (2017).

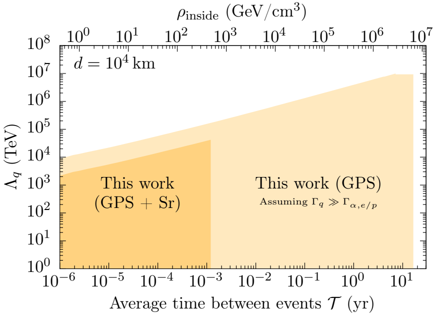
Sr: Wcislo, Morzynski, Bober, Cygan, Lisak, Ciurylo, Zawada, Nat. Astron. 1, 9 (2016).
Astro: Olive, Pospelov, Phys. Rev. D. 77, 43524 (2008).

Results: Limits - fermion masses

Combine Rb, Cs, and Sr (optical)

- Three different combo's of three couplings





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

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

Search for domain wall dark matter with atomic clocks on board global positioning system satellites

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Search for transient ultralight dark matter signatures with networks of precision measurement devices using a Bayesian statistics method

B. M. Roberts, G. Blewitt, C. Dailey, and A. Derevianko
Department of Physics, University of Nevada, Reno 89557, USA

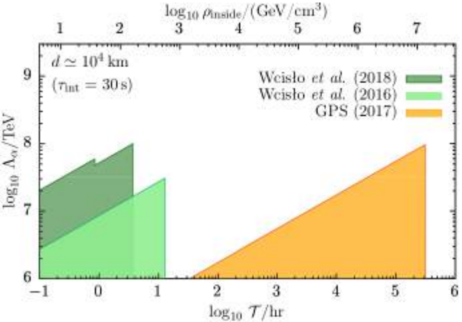
Applying matched-filter technique to the search for dark matter transients with networks of quantum sensors

G. Panelli, B. M. Roberts,* and A. Derevianko

Existing constraints & Discovery frontiers

3D Parameter space:

• $\mathcal{T}$ • Λ_X • d



$$\frac{\delta\omega}{\omega} = K_\alpha \frac{\delta\alpha}{\alpha} = \frac{K_\alpha}{\Lambda_\alpha^2}\phi_0^2$$

• Shown is *full* $\mathcal{T}$ parameter space (fixed d)

Number density/wait time

- large $\mathcal{T}$: need long $T_{\rm obs}$

Sensitivity: Λ_α $(\delta\alpha)$

- Need: small σ_y, large K_X

Size: d (duration $\tau_{\rm int}$)

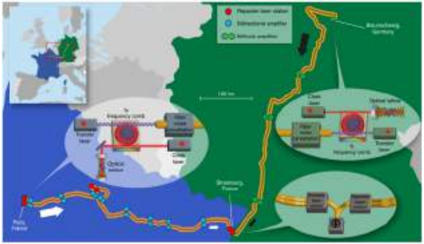
- Existing: only $\lesssim 10^4$ km
- Need: long-term stability

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, Ablewski, Beloy, Bilicki, Bober, Brown, Fasano, Ciurylo, Hachisu, Ido, Lodewyck, Ludlow, McGrew, Morzynski, Nicolodi, Schioppo, Sekido, Le Targat, Wolf, Zhang, Zjawin, Zawada, **Sci. Adv. 4**, 4869 (2018).
Also: Astro: Olive, Pospelov, **Phys.Rev.D 77, 043524** (2008).

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



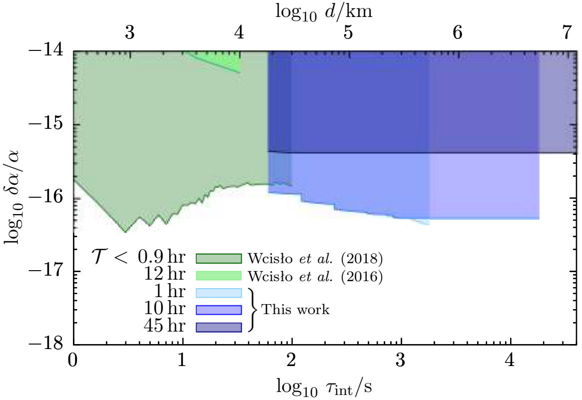
- Sensitivity: $\checkmark$ $(\delta\alpha, \Lambda)$ limited only by clocks: Sr-Sr: $\delta\omega/\omega \sim 3 \times 10^{-17}$ at 1000s
- Long observation time: $\checkmark$ $(\mathcal{T})$
- Long-term stability: $\checkmark$ (d)

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

Transient variation of fine-structure constant

Orders-of-magnitude improvement: especially for large objects (τ)

- $\delta\alpha(\tau)/\alpha \lesssim 5\times10^{-17}$ @ $\tau = 10^3$ s, & $\mathcal{T} = 1$ hr
- $\delta\alpha(\tau)/\alpha \lesssim 4\times10^{-15}$ @ $\tau = 10^4$ s, & $\mathcal{T} = 45$ hr



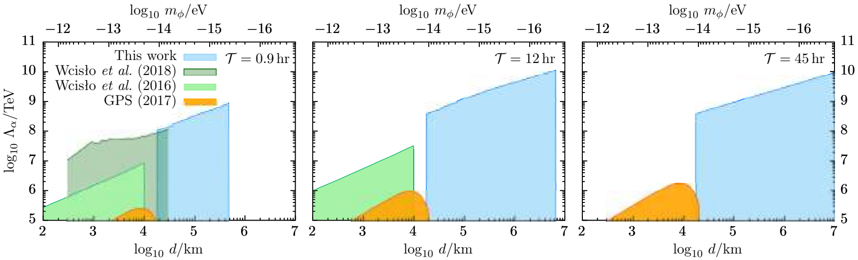
- arXiv:1907.02661

2016: Wcisło, Morzynski, Bober, Cygan, Lisak, Ciurylo, Zawada, **Nat. Astro. 1**,0009 (2016).
2018: Wcislo, Ablewski, Beloy, Bilicki, Bober, Brown, Fasano, Ciurylo, Hachisu, Ido, Lodewyck, Ludlow, McGrew, Morzynski, Nicolodi, Schioppo, Sekido, Le Targat, Wolf, Zhang, Zjawin, Zawada, **Sci. Adv. 4, 4869 (2018)**.

Topological defect dark matter

Assume DM is made from Topological Defects:

$$\phi_0^2 = \hbar c\, \rho_{\rm DM} v_g \mathcal{T} d \ , \qquad \mathcal{T} = \frac{\rho_{\rm inside}}{\rho_{\rm DM}} \frac{d}{v_g}$$



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

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

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, Ablewski, Beloy, Bilicki, Bober, Brown, Fasano, Ciurylo, Hachisu, Ido, Lodewyck, Ludlow, McGrew, Morzynski, Nicolodi, Schioppo, Sekido, Le Targat, Wolf, Zhang, Zjawin, Zawada, **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

B. M. Roberts,[1,*] P. Delva,[1] A. Al-Masoudi,[2] A. Amy-Klein,[3] C. Bærentsen,[1] C. F. A. Baynham,[4] E. Benkler,[2] S. Bilicki,[1] S. Bize,[1] W. Bowden,[4] J. Calvert,[1] V. Cambier,[1] E. Cantin,[1,3] E. A. Curtis,[4] S. Dörscher,[2] M. Favier,[1] F. Frank,[1] P. Gill,[4] R. M. Godun,[4] G. Grosche,[2] C. Guo,[1] A. Hees,[1] I. R. Hill,[4] R. Hobson,[4] N. Huntemann,[2] J. Kronjäger,[4] S. Koke,[2] A. Kuhl,[2] R. Lange,[2] T. Legero,[2] B. Lipphardt,[2] C. Lisdat,[2] J. Lodewyck,[1] O. Lopez,[3] H. S. Margolis,[4] H. Álvarez-Martínez,[1,5] F. Meynadier,[1,6] F. Ozimek,[4] E. Peik,[2] P.-E. Pottie,[1] N. Quintin,[7] C. Sanner,[2,†] L. De Sarlo,[1] M. Schioppo,[4] R. Schwarz,[2] A. Silva,[4] U. Sterr,[2] Chr. Tamm,[2] R. Le Targat,[1] P. Tuckey,[1] G. Vallet,[1] T. Waterholter,[2] D. Xu,[1] and P. Wolf[1,‡]

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[7]*Réseau National de télécommunications pour la Technologie, l'Enseignement et la Recherche, 23-25 Rue Daviel, 75013 Paris, France*

(Dated: July 10, 2019)

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

NPL National Physical Laboratory

PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

Some new directions

Signal propagation

- DM couples to electromagnetism: may affect signal propagation
- Bruno Bertrand, *Royal Observatory Of Belgium* – next talk

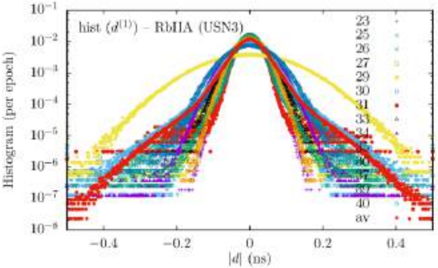
Galileo Satellites

- Hydrogen Masers
- Potentially large improvements from taking advantage of properties of Galileo clocks + satellites
- Francesco Vespe, *Agenzia Spaziale Italiana* – next talk+1

09:20	Bertrand *Royal Observatory Of Belgium*	Fundamental physics tests using the propagation of GNSS signals
09:40	Vespe *Agenzia Spaziale Italiana*	Dark Matter Search by GALILEO

Aside: challenges of re-purposed data

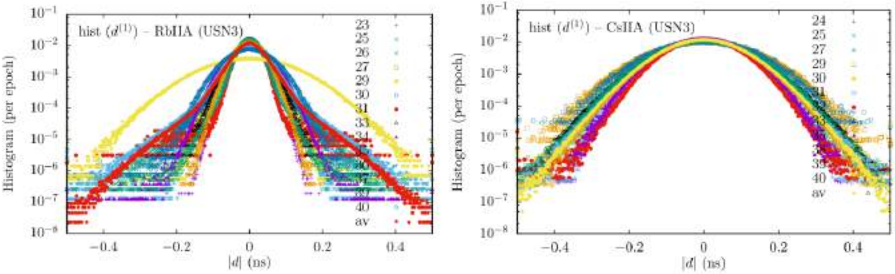
data from JPL: Histogram



- 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

data from JPL: Histogram

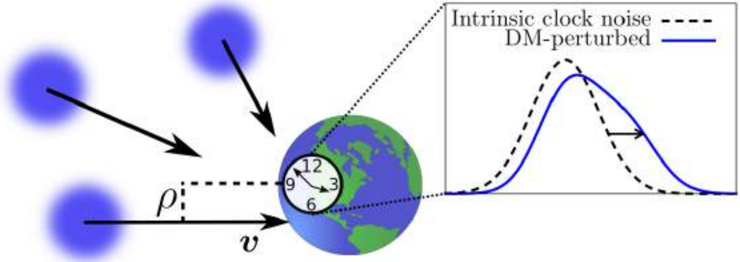


- Possible that some clocks mis-identified
  (Here, one of the “Rb” clocks is probably Cs).
- Same discrepancy in autocorrelation function, Allan variance etc.

Extra: Asymmetry

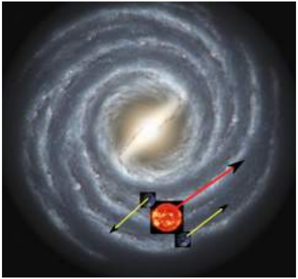
Small objects: no correlated signal

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

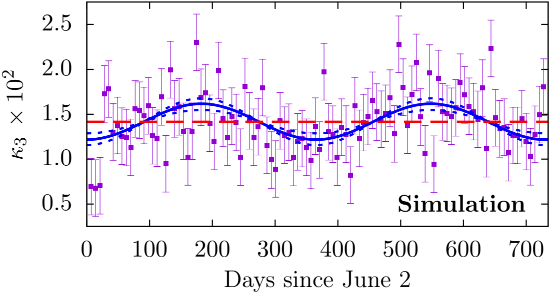


$$\mathcal{R} = \frac{1}{\mathcal{T}} = \frac{3\rho_{\rm DM} v_g}{4\rho_{\rm inside} R}, \qquad \kappa_3 \approx \frac{2\mathcal{R}\tau_0\chi_0^3}{5\sigma^3}.$$

Extra: Annual modulation



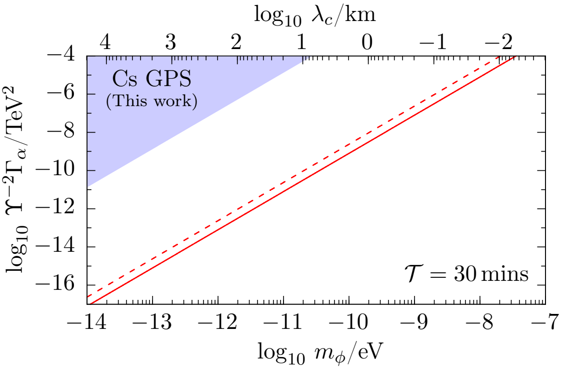
- Yearly change in event rate:
- Sun + Earth velocities add
- $R(t) = R_0 + R_m \cos(\omega t + \phi_{\rm June2})$
- $\Delta\kappa_3/\kappa_3 = 10\%$
- $\Delta\kappa_4/\kappa_4 = 15\%$



• 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

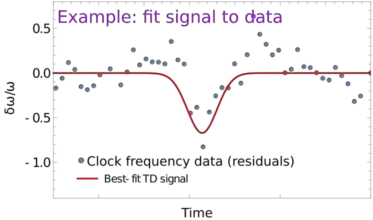
Red line: sensitivity estimate for 1 year of optical Sr

- Can also place limits on topological defects

Extra: Search method

Fibre network

- Max-likelihood fit method[1]
- Coherent α variations
- $N_{\rm pairs} \geq 2$ - to use network

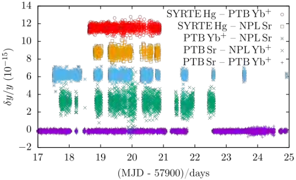


$$p(D_t|\delta\alpha,\theta) = C\, p(\theta) \exp\left(\frac{-1}{2}[d - \delta\alpha s]^T H [d - \delta\alpha s]\right),$$

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

a) Signal-to-noise $R >$ threshold?
$\Longrightarrow$ event detection

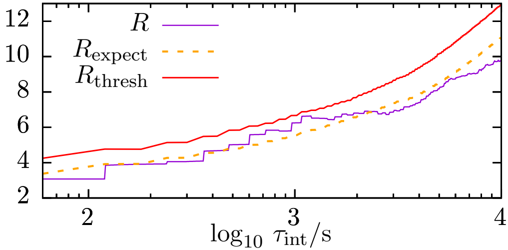
b) Largest $\delta\alpha$ that cannot be ruled out?
$\Longrightarrow$ set limits

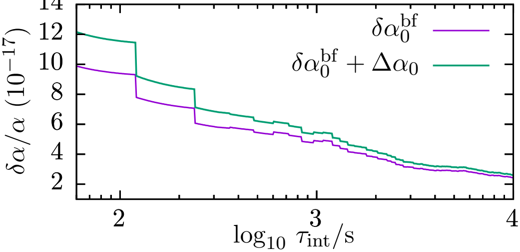


$$\boxed{\delta\alpha^{\rm bf} = dHs/sHs. \qquad \Longrightarrow \qquad \delta\alpha < dHs/sHs + n(sHs)^{-1/2}.}$$

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

Extra: Search results





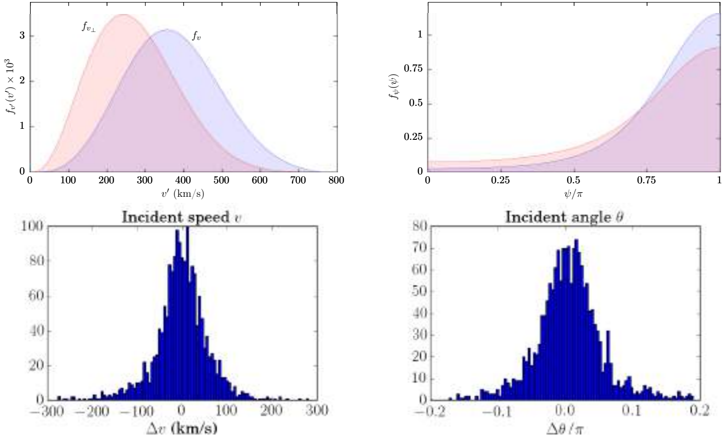
- With >50 hours of total usable network data

  (no gaps, $N \geq 4$) taken over $\sim$ month in 2017:

- No significant events found: place constraints

- arXiv:1907.02661

Extra: Resolve speed + direction



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