

Search for dark matter and transient variations in α using fibre-linked optical atomic clocks

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Dark Matter: What is it?

- $\sim 25\%$ of Universe energy budget (cf $\sim 5\%$ for “normal” matter)
- ~ 90 orders-of-magnitude window:

Rough mass-range for various models:

- MACHOs: $10^{58} - 10^{68}$ eV
- WIMPs: $10^6 - 10^{12}$ eV
- I-WIMPS: $1 - 10^6$ eV
- Axions: $10^{-10} - 10^{-4}$ eV
- Ultralight Q fields: $10^{-24} - 1$ eV

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

- Even asserting that DM is a fundamental particle: $10^{-24} < m/\text{eV} < 10^{19}$
 \implies 40 orders of magnitude range
- Also: All current evidence comes from \sim galactic length scales

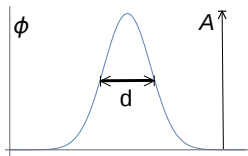
\implies Wide range of possibilities: requires large range of searches

Topological Defect DM

- Ultralight ($m_\phi \ll eV$) \implies high occupation number
- Many possibilities: see also previous talks. Here: TDs

Topological Defects

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

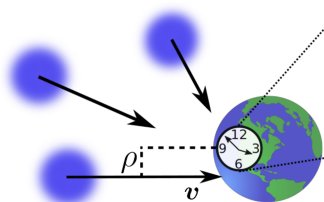


Inside: $\phi^2 \rightarrow A^2$,

Outside: $\phi^2 \rightarrow 0$

Dark matter: Gas of defects

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

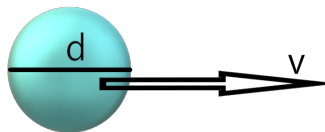


- Vilekin '85, Coleman '85, Lee '89, Kibble '80, ...
- Derevianko, Pospelov, Nature Phys. 10, 933 (2014).

Transients: 3D(+) parameter space

Two time-scales

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



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

And (hopefully) some non-gravitational coupling

- Various possibilities (see previous talks)
- Here: (quadratic) scalar: $\mathcal{L}_{\text{int}} \sim \phi^2 (a\bar{\psi}\psi + bF_{\mu\nu}^2 + \dots)$

See, e.g.: Olive, Pospelov, Phys. Rev. D **65**, 085044 (2002).
 Derevianko, Pospelov, Nature Phys. **10**, **933** (2014).
 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

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

⇒ transient additions to *effective values* of fundamental constants

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

⇒ shifts in energy levels ⇒ shifts in clock frequencies

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

K_α : Sensitivity of ω to $\delta\alpha$ (also other constants, $m_{e/p}$, m_q etc.)⁽¹⁾

Parameterise in terms of Λ effective energy scale

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

Shift in atomic clock frequencies

- DM may interact with: Photons, fermions
 \implies shifts in energy levels \implies shifts in clock frequencies

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

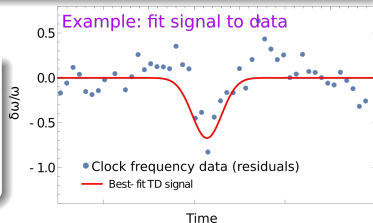
K_X sensitivity: e.g., Flambaum, Dzuba, Can. J. Phys. 87, 25 ('09).

Monitor Atomic Clocks

- Clocks: lock frequency to atomic transition
- Monitor atomic frequencies using atomic clocks

Signal v. noise?

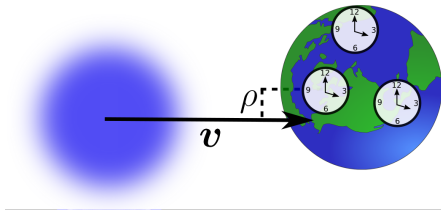
- Transient signal:
looks essentially like any outlier
- i.e. what is the specific DM signature?



Global network of precision devices

Network of separated atomic clocks

- DM expected to move at \sim galactic speeds
- Correlated signal propagation through network, $v \sim 300$ km/s
- \vec{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)

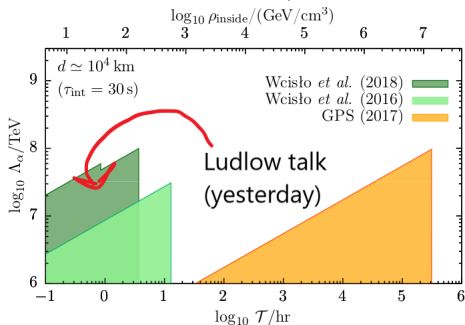


- Clocks: Derevianko, Pospelov, Nature Phys. 10, **933** (2014).
- Magnetometer: Pospelov, Pustelny, Ledbetter, Kimball, Gawlik, Budker, Phys.Rev.Lett. **110**, 021803 (13).

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_{obs}

Sensitivity: Λ_α ($\delta\alpha$)

- Need: small σ_y , large K_X

Size: d (duration τ_{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: Wcislo, Morzynski, Bober, Cygan, Lisak, Ciurylo, Zawada, **Nat. Astro.** **1**,0009 (2016).

2018: Wcislo, Ablewski, Belay, 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).

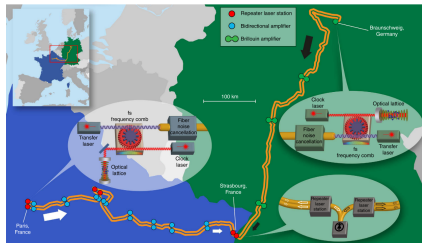
European fibre-linked optical clock network



Fibre network

- High-accuracy long-distance clock comparisons
- Different clocks: Hg/Sr/Yb⁺

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

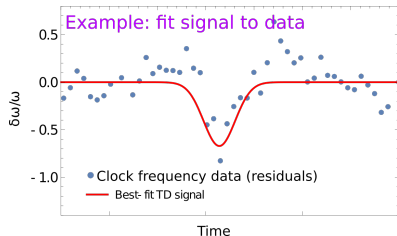


- Lisdat *et al.* (PTB, LNE-SYRTE), *Nature Commun.* **7**, 12443 (2016).
- Delva *et al.* (PTB, SYRTE, NPL, ..), *Phys. Rev. Lett.* **118**, 221102 (2017).

Search method

Fibre network

- Max-likelihood fit method¹
- Coherent α variations
- $N_{\text{pairs}} \geq 2$ - 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) Any regions with R (signal-to-noise) above detection threshold?

⇒ event detection

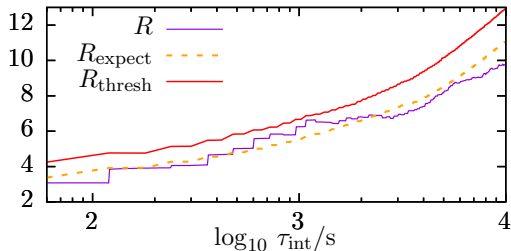
b) Largest $\delta\alpha$ that cannot be ruled out (for given τ)?

⇒ set limits

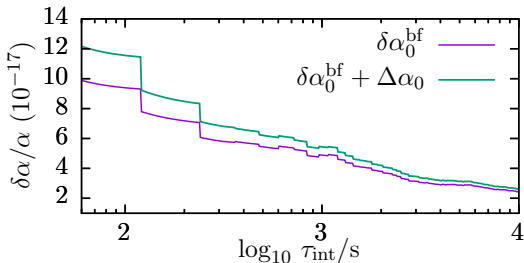
$$\delta\alpha^{\text{bf}} = dHs/sHs. \quad \Rightarrow \quad \delta\alpha < dHs/sHs + n(sHs)^{-1/2}.$$

Preliminary Results

Preliminary:



- With >50 hours of total usable network data (no gaps, $N \geq 4$) taken over \sim month in 2017:

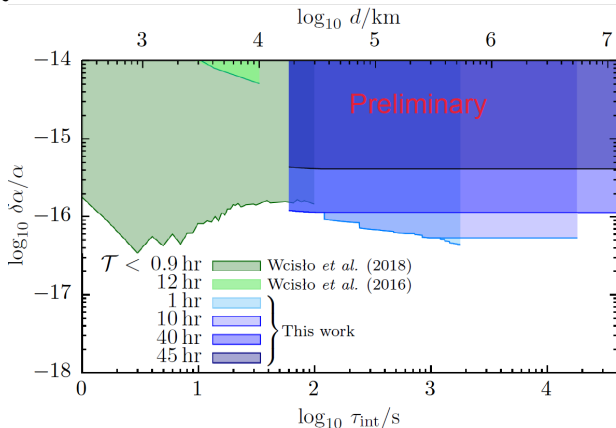


- No significant events found:
place constraints

Transient variation of fine-structure constant

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

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



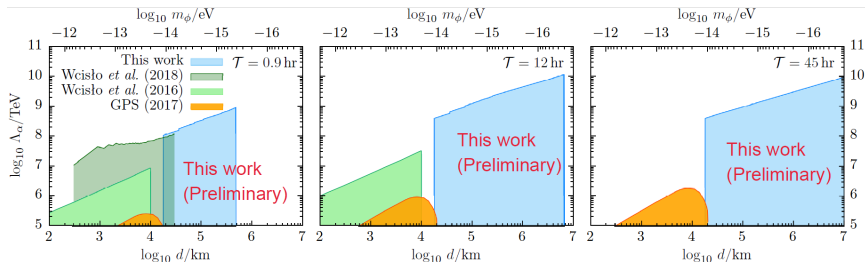
2016: Wcisło, Morzynski, Bober, Cygan, Lisak, Ciurylo, Zawada, *Nat. Astro.* **1**,0009 (2016).

2018: Wcisło, Ablewski, Beloy, Bilicki, Bober, Brown, Fasano, Ciurylo, Hachisu, Ido, Lodowyck, 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:

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



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

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

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

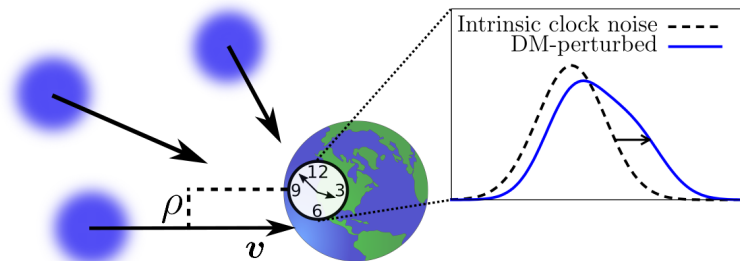
2016: Wcislo, Morzynski, Bober, Cygan, Lisak, Ciurylo, Zawada, *Nat. Astro.* **1**, 0009 (2016).

2018: Wcislo, Ablewski, Beloy, Bilicki, Bober, Brown, Fasano, Ciurylo, Hachisu, Ido, Lodowyck, Ludlow, McGrew, Morzynski, Nicolodi, Schioppo, Sekido, Le Targat, Wolf, Zhang, Zjawin, Zawada, *Sci. Adv.* **4**, 4869 (2018).

Asymmetry

Small objects: no correlated signal

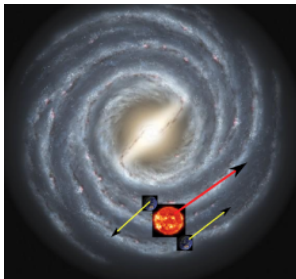
- small size $\sim \rightarrow$ large rate
- Shift in mean: unobservable (DM always present)
- Induce non-Gaussian features (such as an asymmetry)



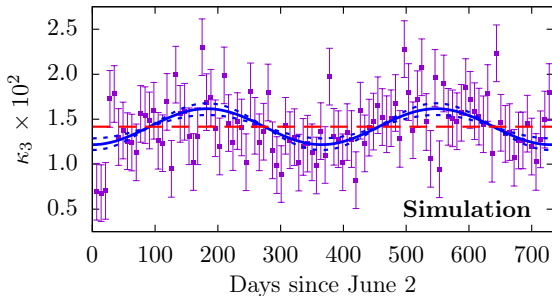
$$\mathcal{R} = \frac{1}{\mathcal{T}} = \frac{3\rho_{\text{DM}} v_g}{4\rho_{\text{inside}} R},$$

$$\kappa_3 \approx \frac{2\mathcal{R}\tau_0\chi_0^3}{5\sigma^3}.$$

Annual modulation

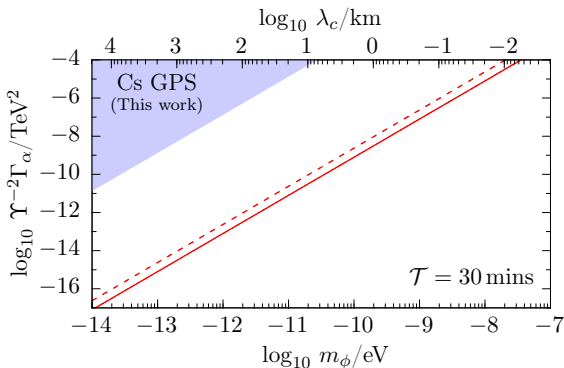


- Yearly change in event rate:
- Sun + Earth velocities add
- $R(t) = R_0 + R_m \cos(\omega t + \phi_{\text{June}2})$
- $\Delta\kappa_3/\kappa_3 = 10\%$



Limits Q-balls: α (photon field)

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



- BMR, Derevianko, arXiv:1803.00617

Red line: sensitivity estimate for 1 year of optical Sr

- Can also place limits on topological defects

Conclusion & Thanks

Optical fibre-network

- Transient variation of α :
- $\delta\alpha(\tau)/\alpha \lesssim 2 \times 10^{-17}$ @ $\tau = 10^4$ s, & $\mathcal{T} = 1$ hr
- Topological defect DM: significant improvement + new parameter space
- Long-term stability of clock-clock: large d
- Statistical signatures; annual modulation

Big thanks to the Optical clock, link, comb, & cavity teams at:
NPL, PTB, & SYRTE

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany; National Physical Laboratory, Teddington, United Kingdom; SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE.



Systèmes de Référence Temps-Espace

