Ultra-light Dark Matter Searches with AION

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DMUK 2021 Meeting
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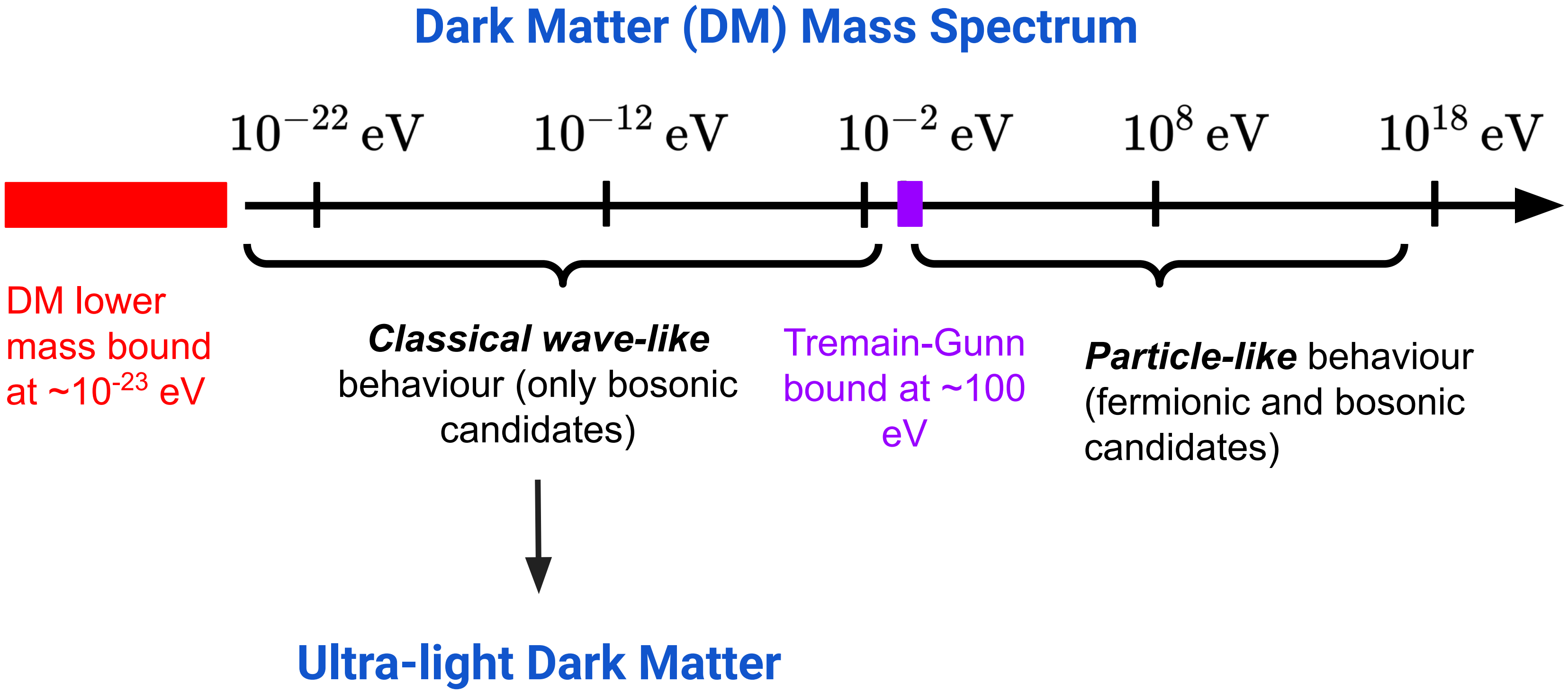
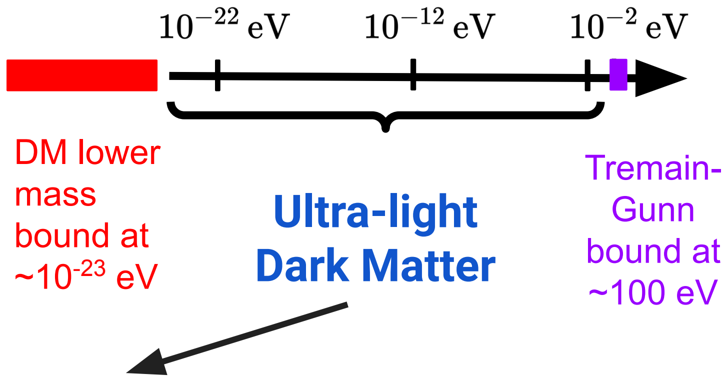
LB, D. Blas, C. McCabe, arXiv:2109.10965.

Dark Matter Landscape



Ultra-light Dark Matter

Dark Matter (DM) Mass Spectrum



Candidates

- **Vectors** (e.g. dark photons)
- **Pseudo-scalars** (e.g. QCD axion, ALPs, relaxions)
- **Scalars** (e.g. dilaton/moduli, Higgs-portal DM)

Universal Properties

- **Frequency**

$$f_\phi = 2.4 \left[\frac{m_\phi}{10^{-14}\,\mathrm{eV}}\right] \mathrm{Hz}$$

- **Temporal** and **spatial coherence** depend on the DM average speed

$$\lambda_c = \frac{\hbar}{m_\phi v_{\mathrm{vir}}} \approx 2.0 \times 10^3 \left(\frac{10^{-10}\mathrm{eV}}{m_\phi}\right) \mathrm{km}$$

$$\tau_c = \frac{\hbar}{m_\phi v_{\mathrm{vir}}^2} \approx 6.6 \left(\frac{10^{-10}\mathrm{eV}}{m_\phi}\right) \mathrm{s}$$

- **Amplitude** scales as $\sqrt{2\rho_{\mathrm{DM}}}/m_\phi$

Phenomenology of ULDM in Laboratory Experiments

Static vs Time-dependent ULDM-induced Signals

e.g. Static fifth/EP-violating force mediated by the DM field

e.g. time-varying fifth/EP-violating force mediated by the DM field, **oscillation of fundamental constants**

Benchmark Model: Linearly-coupled Scalar DM

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \sqrt{4\pi G_N}\phi\left[d_{m_e}m_e\bar{e}e - \frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}\right]$$

Free Scalar Field

Electron Coupling

Photon Coupling

Dark Matter Scalar Field

$$\phi(t,\mathbf{x}) \approx \phi_0 \cos[m_\phi(t - \mathbf{v}\cdot\mathbf{x}) + \theta]$$

Assuming that this saturates the local dark matter density,

$$\phi_0 = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_\phi}$$

Modified Electron Mass

$$m_e(t,\mathbf{x}) = m_e\left[1 + d_{m_e}\sqrt{4\pi G_N}\phi(t,\mathbf{x})\right],$$

Modified Fine Structure Constant

$$\alpha(t,\mathbf{x}) = \alpha\left[1 + d_e\sqrt{4\pi G_N}\phi(t,\mathbf{x})\right]$$

Benchmark model: Effects in Atomic Physics

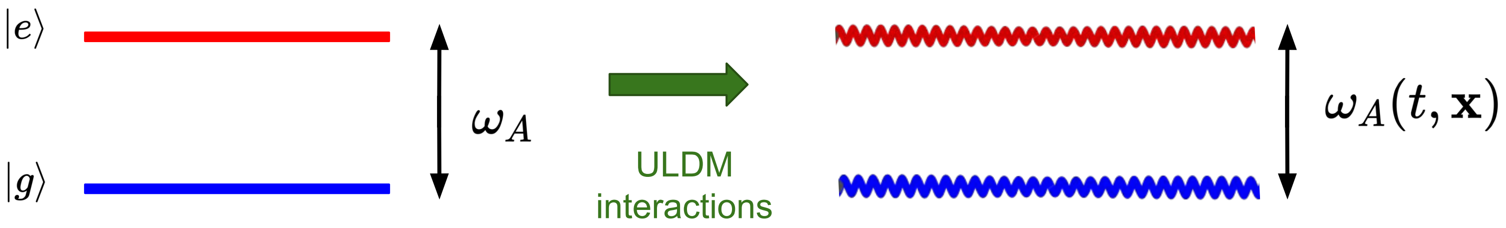
Atomic physics largely depends on the **electron mass** and **fine-structure constant**.

Scalar DM induces oscillations in electronic transition energies (frequencies). For optical transitions,

$$\omega_A \propto m_e \alpha^{\xi_A}$$

$$\omega_A(t, \mathbf{x}) \simeq \omega_A + \Delta\omega_A(t, \mathbf{x})$$

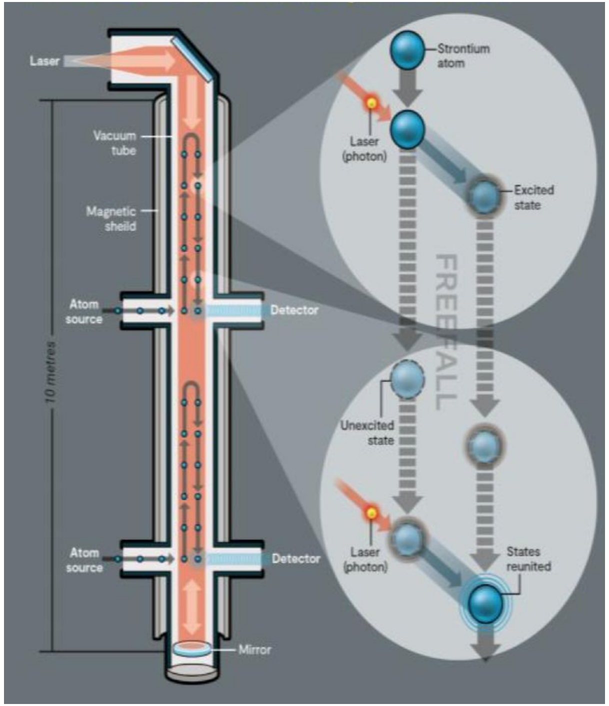
$$\Delta\omega_A(t, \mathbf{x}) = \omega_A \sqrt{4\pi G_N}[d_{m_e} + \xi_A d_e]\phi(t, \mathbf{x})$$



These effects can be searched for in ***atom interferometers/gradiometers***.

AION Project

A UK Atom Interferometer Observatory and Network to explore ultra-light dark matter and mid-frequency gravitational waves.

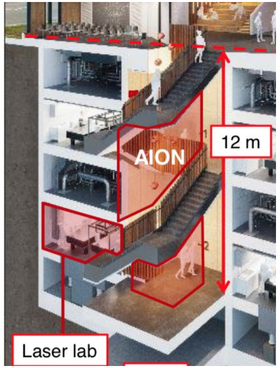


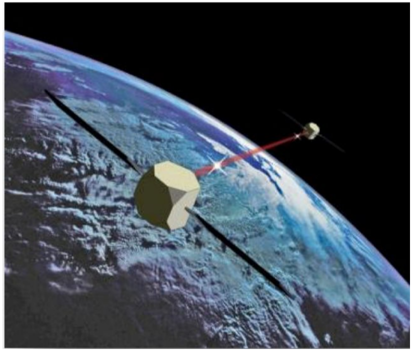
AION-10 (~2023): 10m detector in Oxford

AION-100 (~2030): 100m detector in Boulby/CERN/ Daresbury?

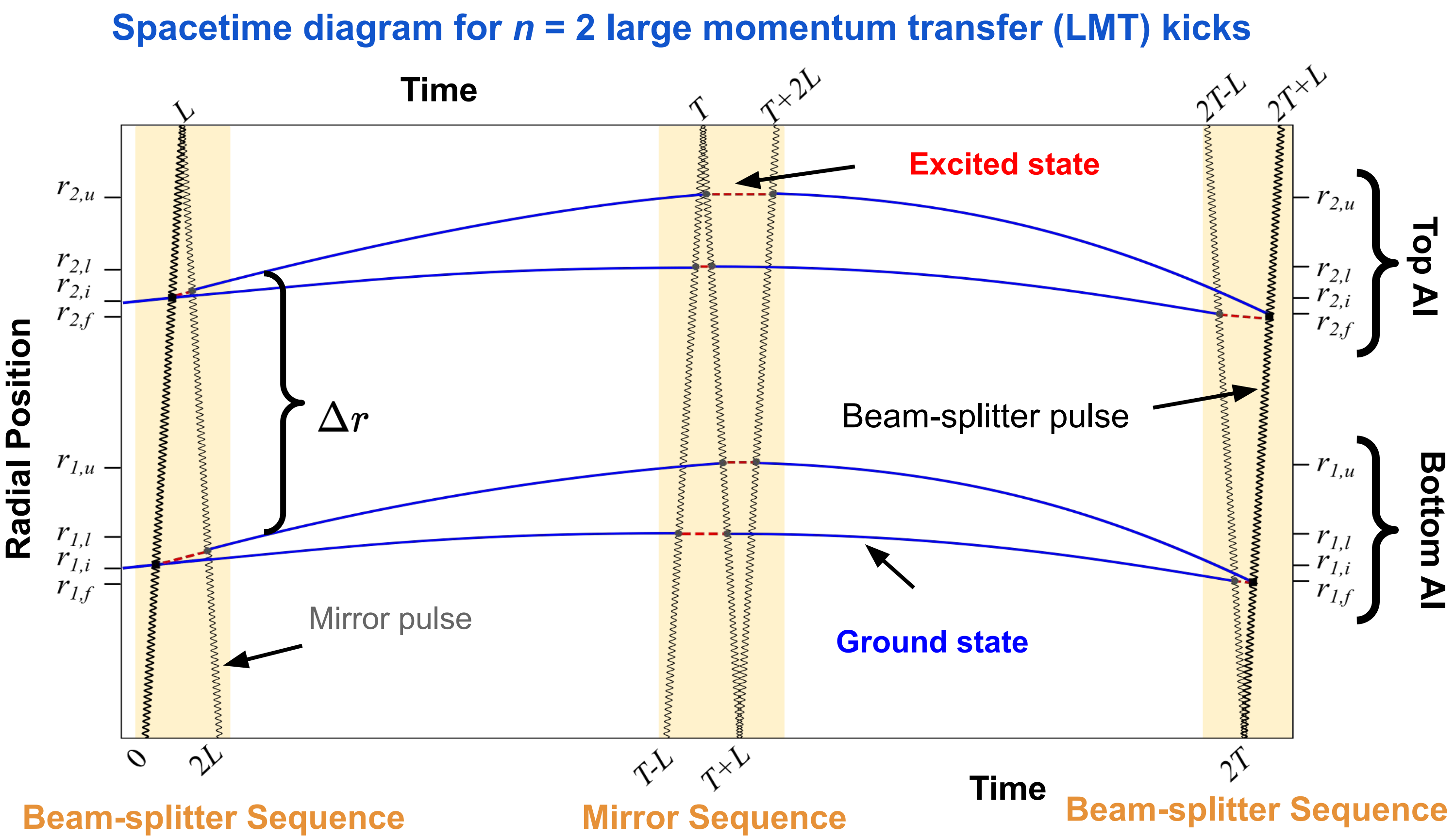
AION-km (late 2030s): 1km detector in ???

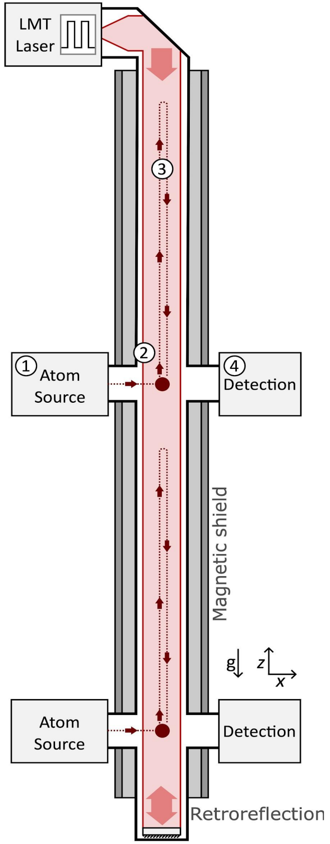
AEDGE (late 2040s): *two* detectors in space!





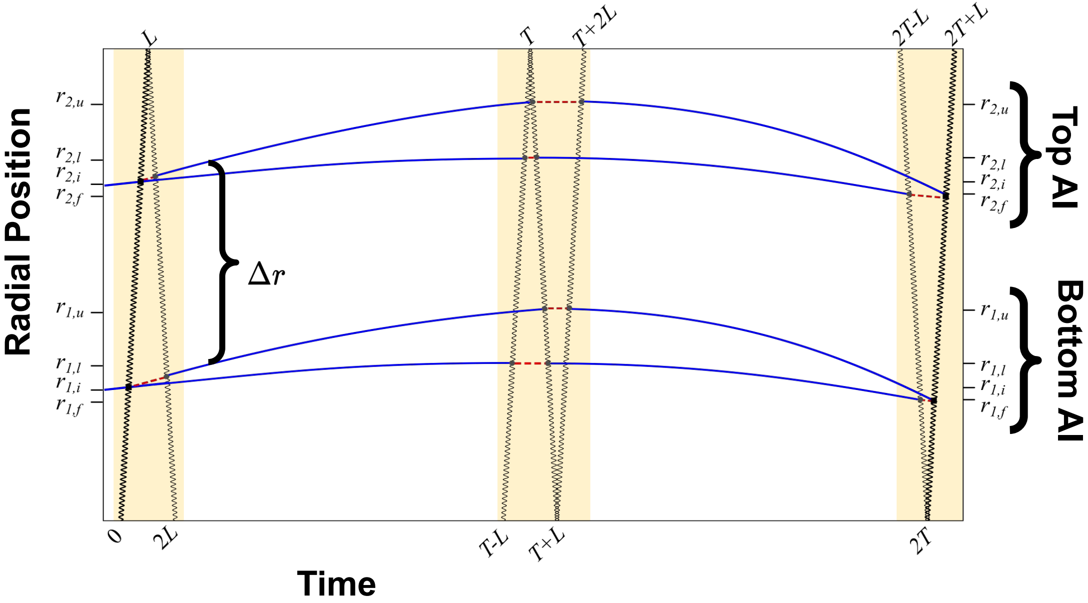
Atom Gradiometer





Refined Signal Calculation for Atom Gradiometers

- We do not fix the initial launch positions at the ends of the baseline
- We do not fix the final position of the atoms
- We consider recoil effects



Refined Signal Amplitude

Correction Factor

$$\bar{\Phi}_s = 8\frac{\Delta\omega_A}{m_\phi}\frac{\Delta r}{L}\left|\sin\left[\frac{m_\phi n L}{2}\right]\sin\left[\frac{m_\phi(T-(n-1)L)}{2}\right]\sin\left[\frac{m_\phi T}{2}\right]\right|$$

Scalar DM Broadband Search

ULDM Signal Amplitude

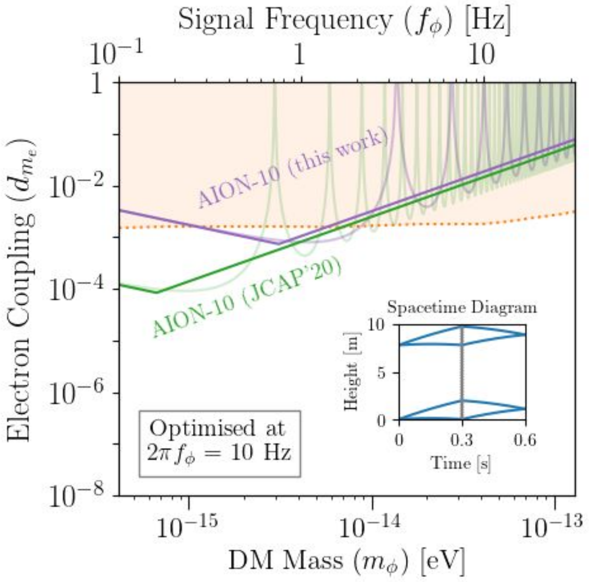
$$\overline{\Phi}_{\text{brodband}} = 8\frac{\overline{\Delta\omega_A}}{m_\phi}\frac{\Delta r}{L}\left|\sin\left[\frac{m_\phi n L}{2}\right]\sin\left[\frac{m_\phi T}{2}\right]\sin\left[\frac{m_\phi (T-(n-1)L)}{2}\right]\right|$$

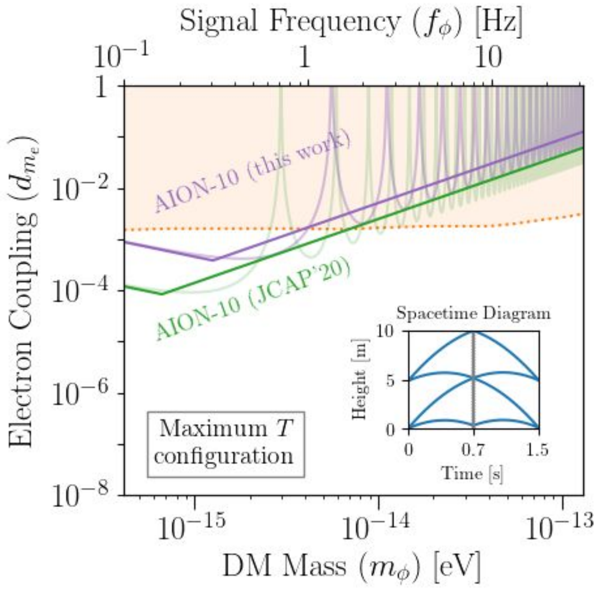
A.Arvanitaki et al., *Phys.Rev.D* 97 (2018) 7, 075020; LB, D. Blas, C. McCabe, arXiv:2109.10965.

The sensitivity is peaked signal at $\sim \pi/T$ with bandwidth $\sim \pi/T$.

No loss in sensitivity at different frequencies.

Different configurations can be used to increase the sensitivity in unconstrained regions of parameter space.





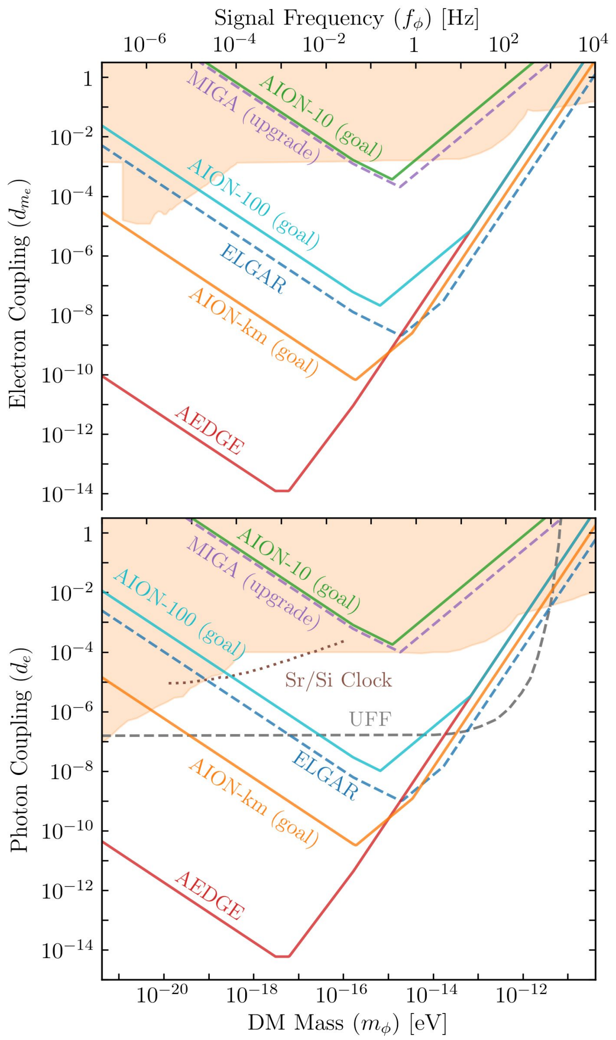
Conclusions & Outlook

We refined the sensitivity projections for AION-10 and determined optimal experimental parameters to maximise the experiment's sensitivity reach.

Early/compact versions of AION can probe unconstrained regions of DM parameter space.

Later stages of the AION project will explore even larger areas of parameter space, thus significantly increasing the potential for a discovery!

Work in progress: finding optimal configurations with multiple gradiometers to boost a ULDM signal and mitigate low-frequency gravity gradient noise.



Thank you for listening!

Backup Slides

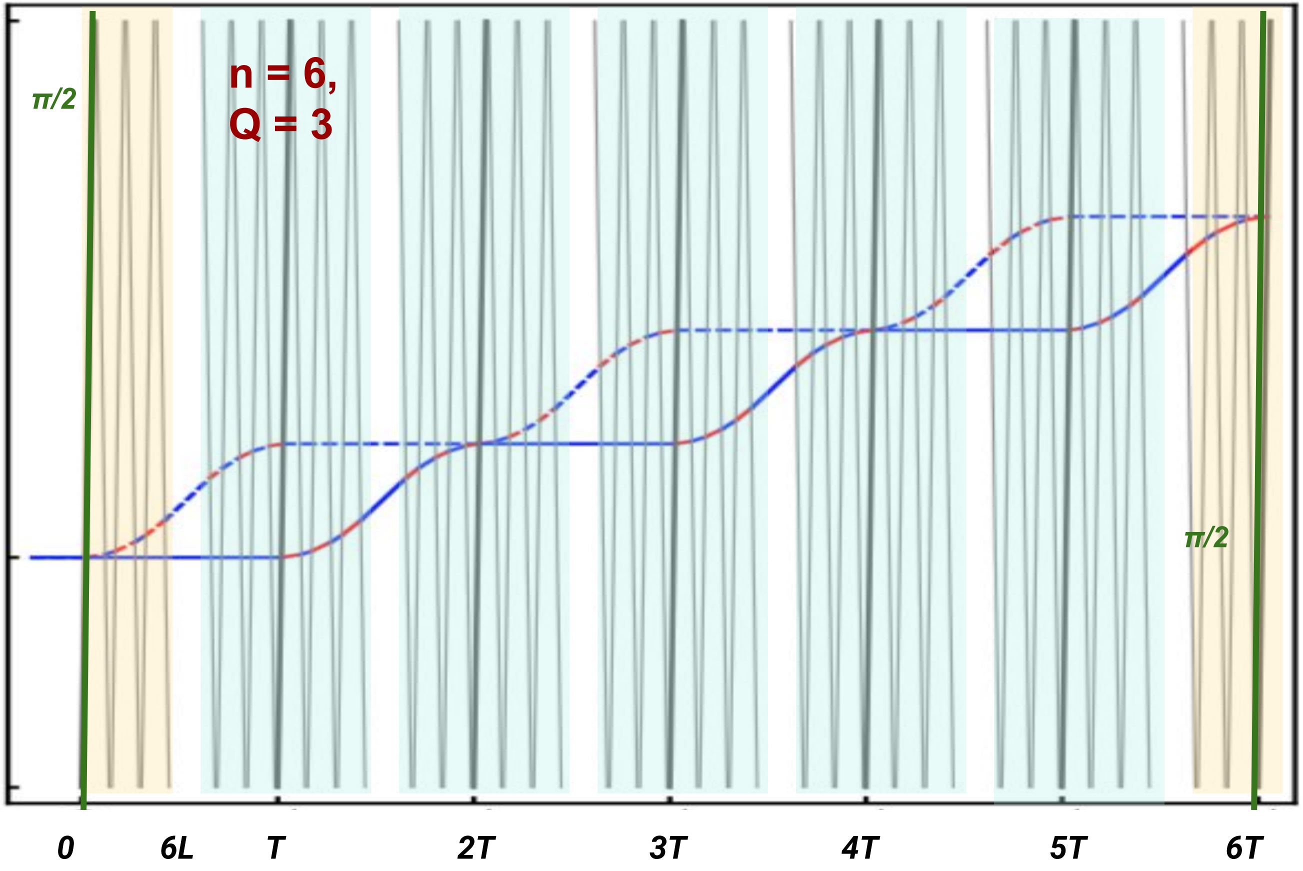
Multi-diamond Atom Gradiometry

Q diamonds of time duration $2T$

Total number of laser pulses is
$n_{\rm tot} = 2Q(2n-1)+1$
of which two are beamsplitter pulses that start and end the sequence.

In the broadband case, *Q=1*.

P. Graham et al., *Phys.Rev.D* 94 (2016) 10, 063509.



Multi-loop = Resonant Mode ULDM Search

ULDM Signal Amplitude

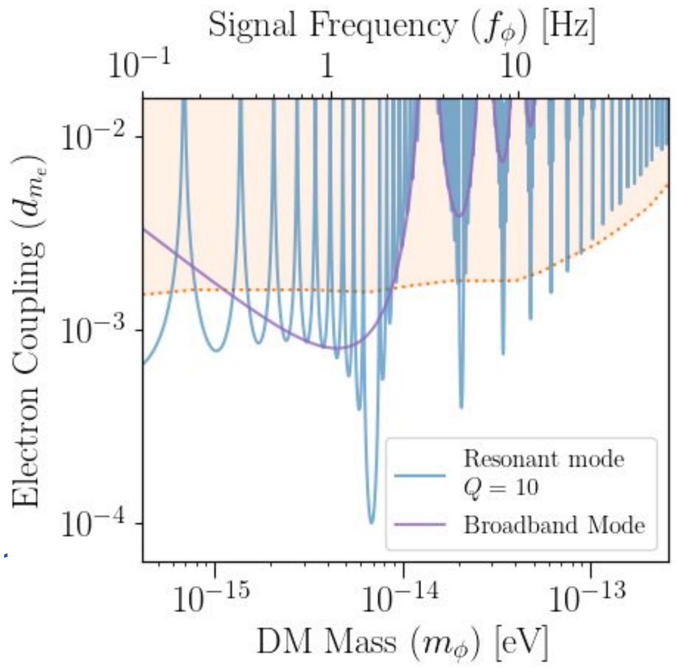
$$\overline{\Phi}_{\text{resonant}} = 8\frac{\overline{\Delta\omega_A}}{m_\phi}\frac{\Delta r}{L}\left|\sin\left[\frac{m_\phi nL}{2}\right]\sin\left[\frac{m_\phi T}{2}\right]\sin\left[\frac{m_\phi(T-(n-1)L)}{2}\right]\boxed{\frac{\sin[Qm_\phi T]}{\sin[m_\phi T]}}\right|$$

Multi-loop contribution

$$\overline{\Phi}_{\text{brodband}} = 8\frac{\overline{\Delta\omega_A}}{m_\phi}\frac{\Delta r}{L}\left|\sin\left[\frac{m_\phi nL}{2}\right]\sin\left[\frac{m_\phi T}{2}\right]\sin\left[\frac{m_\phi(T-(n-1)L)}{2}\right]\right|$$

The sensitivity is peaked signal at masses $\sim \pi/T$ with bandwidth $\sim \pi/TQ$

On resonance, we observe a *Q*-fold signal enhancement relative to broadband searches with ***identical*** experimental parameters

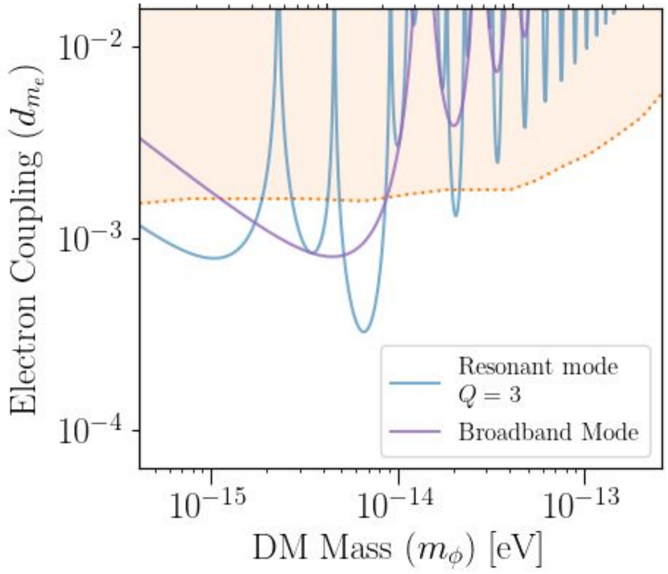


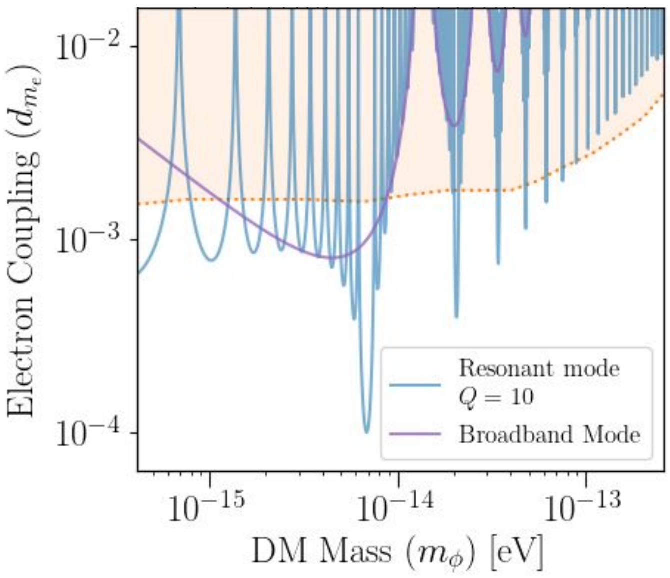
A.Arvanitaki et al., *Phys.Rev.D* 97 (2018) 7, 075020; LB, D. Blas, C. McCabe, arXiv:2109.

Examples of Resonant Mode Searches

$$\overline{\Phi}_{\text{resonant}} = 8\frac{\overline{\Delta\omega_A}}{m_\phi}\frac{\Delta r}{L}\left|\sin\left[\frac{m_\phi nL}{2}\right]\sin\left[\frac{m_\phi T}{2}\right]\sin\left[\frac{m_\phi(T-(n-1)L)}{2}\right]\frac{\sin[Qm_\phi T]}{\sin[m_\phi T]}\right|$$

Multi-loop contribution





Resonant Mode ULDM Searches with AION-10

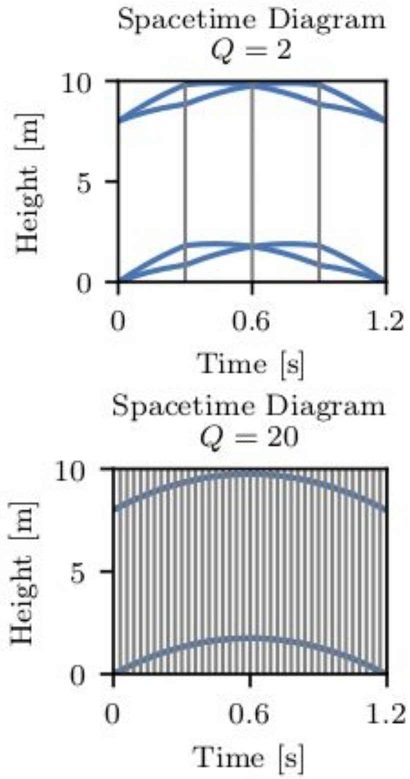
If the maximum number of pulses available is fixed, what search mode (i.e. broadband vs resonant) offers the largest sensitivity?

Maximum number of pulses: $n_{max} = 2Q(2n-1)+1$
(i.e. pulses can be distributed between LMT kicks and diamonds)

In AION-10, we assume $n_{max} \approx 4000$

The number of diamonds Q is limited by the size of the interferometer.

To ensure that the atoms remain within the baseline, increasing *Q* implies reducing *T* (i.e. the maximum sensitivity shifts to higher frequencies).



Q = 2
T = 0.3 s
n = 1000

Q = 20
T = 0.03 s
n = 100

LB, D. Blas, C. McCabe, arXiv:2109.10965.

Resonant Mode ULDM Searches with AION-10

Increasing Q and reducing T shifts the maximum sensitivity to higher masses and larger coupling strengths

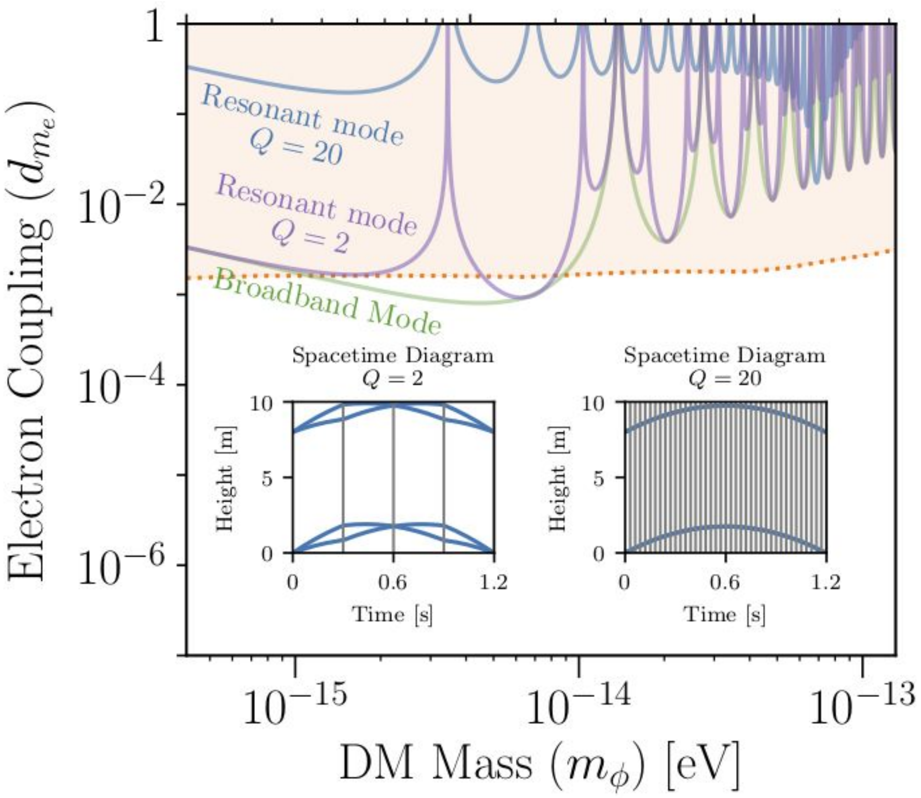
Since $n_{max} = 2Q(2n-1)+1$, at $\sim \pi/T$ an optimal resonant configuration can do as well as a well-chosen broadband configuration.

Resonant mode searches can cover blindspots in the sensitivity curve - will be important for AION-100, etc., but not AION-10 because of constraints from EP tests).

Also useful in verifying a putative ULDM signal post discovery

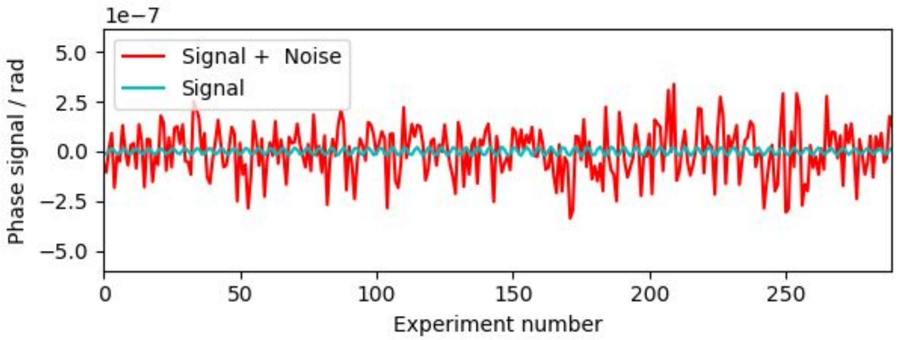
A resonant mode sequence can always be made symmetric (not true for broadband).

LB, D. Blas, C. McCabe, arXiv:2109.10965.



Data Collection Strategies for Extracting a Time-dependent ULDM Signal

- Data is collected as a discrete time series over a period T_{int} (i.e. integration time).
- We assume that successive measurements are temporally separated by Δt, where Δt exceeds the duration of a single interferometric sequence.
- Hence, the ULDM signal is sampled at a frequency of $1/\Delta t$, such that the time series will contain $N = T_{\text{int}}/\Delta t$ data points.
- The signal measured at the m$^{\text{th}}$ experiment $\Phi^{(m)}$ will be a sum of the ULDM-induced phase difference $\Phi_{\text{DM}}^{(m)}$ and noise $\Phi_{\text{n}}^{(m)}$



$$\Phi^{(m)} = \Phi_{\text{DM}}^{(m)} + \Phi_{\text{n}}^{(m)}$$

We assume that atom shot noise is the dominant noise source, which is a Poisson distributed variable with variance $\sigma_n^2 = 1/N_{\text{atom}}$ and mean 0 sampled at each experiment number *m.*

Data Analysis Strategies for Extracting a Time-dependent ULDM Signal

- Analysis via periodogram (i.e. estimator of the power spectral density)

$$S_{\Phi\Phi}^{(k)} = \frac{(\Delta t)^2}{T_{\rm int}} \left|\Phi^{(k)}\right|^2$$

$$\Phi^{(k)} = \sum_{m=0}^{N-1} \Phi^{(m)} \exp\left(\frac{-2\pi i k m}{N}\right) \quad \text{(DFT)}$$

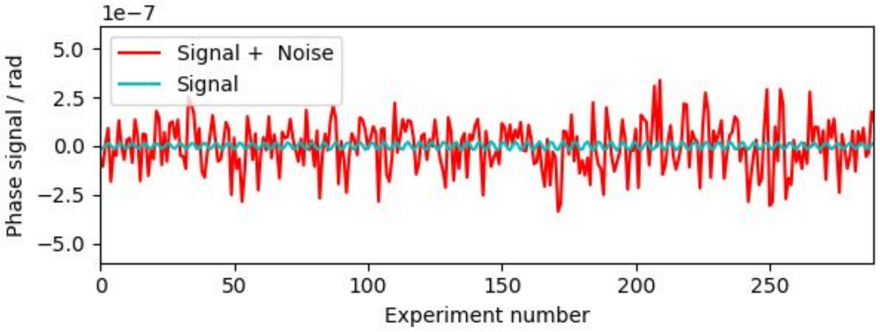
- Signal PSD is the sum of the noise and ULDM PSD.

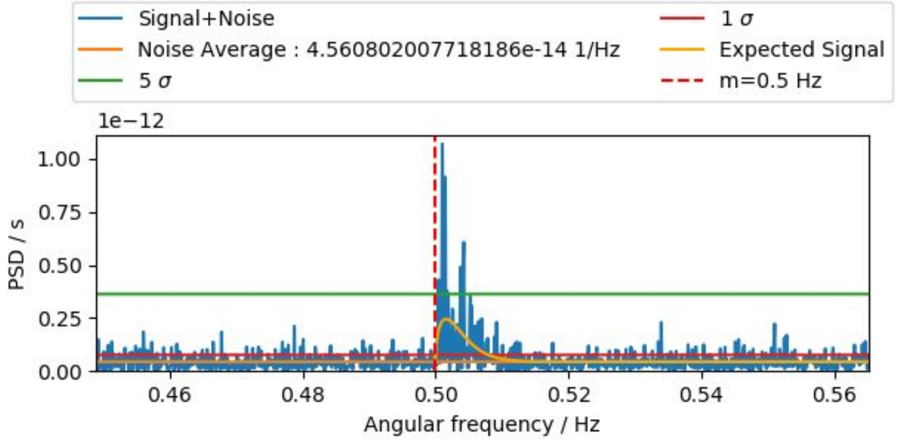
$$S_{\phi\phi}(\omega) = S_{\rm DM}(\omega) + S_{\rm n}(\omega)$$

$$S_{\rm n}(\omega) = \Delta t \sigma_n^2 = \Delta t / N$$

- Signal threshold at a signal-to-noise ratio

$$SNR = \frac{\int S_{\rm DM}(\omega) d\omega}{\int S_{\rm n}(\omega) d\omega}$$





Time-dependent EP-violating effects

Anomaly-free interactions via dark photon coupled to baryon minus lepton number operator or electron charge. For $U(1)_{B-L}$, the low energy interaction Lagrangian can be parametrized as

$$\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}m^2 A'_\mu A'^\mu + g_{B-L}A'_\mu \bar{\psi}_n \gamma^\mu \psi_n$$

Fifth force between isotopes implies an acceleration that scales like

$$a_{net} \simeq \frac{4}{3} \times 10^{11}(g_{B-L}\Delta_{B-L})g$$

$$\Delta_{B-L} = \frac{Z}{A_2} - \frac{Z}{A_1}$$