Snowmass2021 - Letter of Interest

Dark Matter Interferometry with Multiple Spatially-Separated Detectors

Thematic Areas: (check all that apply □/■)

■ (CF2) Dark Matter: Wavelike
■ (TF9) Astro-particle Physics and Cosmology

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Abstract: The next generation of wavelike dark matter direct detection experiments will feature multiple detectors operating at various terrestrial locations performing searches of complementary or competitive sensitivity. When experiments are separated at a distance comparable to the dark matter de Broglie wavelength, phase-sensitive data combined at the time-series level will not simply add coherently, but will exhibit interference patterns due to the spatial variation of the dark matter phase. This "dark matter interferometry" allows access to directional information about the dark matter phase space distribution that is completely invisible to a single detector. For example, two detectors are able to observe a daily modulation effect unique to wavelike dark matter, from which one can extract all three components of the local solar velocity vector. This observation strongly motivates multiple spatially-separated detectors located at distances of order the de Broglie wavelength, which can vary from tens of meters for the mass range targeted by HAYSTAC to thousands of kilometers for the mass range targeted by DM-Radio.

Introduction. Wavelike dark matter (DM) experiments take advantage of the spatial and temporal coherence of the DM field. The spatial coherence of the DM waves is of order the de Broglie wavelength $\lambda_{\rm dB} \sim 2\pi/m_{\rm DM}\Delta v$, with Δv the DM velocity dispersion and $m_{\rm DM}$ the DM mass, while the DM coherence time is $\tau \sim 2\pi/m_{\rm DM}(\Delta v)^2$. In the solar neighborhood we expect $\Delta v \sim 10^{-3}$ in natural units for the bulk of the DM, such that the de Broglie wavelength is around 10^3 times the Compton wavelength, and the coherence time is around 10^6 times the oscillation period for the DM wave. While several experimental proposals have noted or exploited sensitivity to the coherence length, see *e.g.* [1–7], in this LOI we specifically focus on combining data from multiple spatially-separated experiments.

It is straightforward to understand why multiple detectors offer unique insights for wavelike DM. The DM field may be written as a sum over plane waves of the form $a(x,t) = a_0 \cos(\omega t - \mathbf{k}\cdot\mathbf{x} + \phi)$, where ω is the energy or oscillation frequency, $\mathbf{k}$ is the momentum vector, ϕ is a random phase, and a_0 is the amplitude. For a single detector, we may always chose coordinates such that $\mathbf{x} = 0$, and therefore a single experiment is only sensitive to the speed through ω and not the direction of the DM velocity.[1] By contrast, two or more experiments separated by distances $\mathbf{x}_{ij} = \mathbf{x}_i - \mathbf{x}_j$ will be sensitive to the phase factors $\mathbf{k}\cdot\mathbf{x}_{ij}$, which directly probe the velocity rather than the speed.

In work by Foster, Kahn, Nguyen, Rodd, and Safdi to appear on the arXiv shortly, we will flesh out the details of this argument and perform in-depth studies of the statistical power of multiple detectors to constrain e.g. the direction of the solar velocity vector once a signal is observed in both experiments. In this LOI, we wish to illustrate through preliminary results that *multiple spatially-separated detectors can access information about the DM velocity distribution that is completely invisible to a single isolated detector.* As a result, the advantages of multiple detectors go beyond the increase in bulk signal amplitude from detectors placed inside a coherence length, as was pointed out in Ref. [8] for ultralight DM.

Modified two-point functions. In [9] it was shown that we may represent a spin-0 DM field with mass m_a as seen by a single detector as

$$a(t) = \frac{\sqrt{\rho_{\rm DM}}}{m_a} \sum_j \alpha_j \sqrt{f(v_j)\Delta v} \cos\left[\omega_j t + \phi_j\right]. \tag{1}$$

Here, $\rho_{\rm DM}$ is the local DM density, $\omega_j = m_a\left(1 + |\mathbf{v}_j|^2/2\right)$, $\phi_j \in [0, 2\pi)$ is a random phase, and $f(v)$ is the DM speed distribution in the laboratory frame. Formally we may let $v_j = j/N_a$, with the sum performed from $j = 0$ to N_a and $\Delta v = 1/N_a$; we then want to take the limit $N_a \to \infty$. The parameters α_j are Rayleigh-distributed random variables, which are drawn from the probability distribution $p[\alpha] = \alpha\, e^{-\alpha^2/2}$. For the case of multiple spatially-separated detectors, we need to generalize (1) to account for spatial dependence. This may naturally be accomplished by splitting the sum over speeds into three independent sums along three Cartesian axes i, j, l,

$$a(\mathbf{x}, t) = \frac{\sqrt{\rho_{\rm DM}}}{m_a} \sum_{ijl} \alpha_{ijl} \sqrt{f(\mathbf{v}_{ijl})\Delta v^3} \times \cos\left[\omega_{ijl} t - \mathbf{k}_{ijl}\cdot\mathbf{x} + \phi_{ijl}\right], \tag{2}$$

where α_{ijl} and ϕ_{ijl} are again Rayleigh- and uniform-distributed random variables.

Suppose a single experiment takes a time-series of N measurements $\{\Phi_n(\mathbf{x}) = \Phi(\mathbf{x}, n\Delta t)\}$ of a quantity Φ which is proportional to the DM field a. The real and imaginary parts R_k and I_k of the discrete Fourier transform $\Phi_k(\mathbf{x}) = \sum_{n=0}^{N-1} \Phi_n(\mathbf{x})\, e^{-i2\pi kn/N}$ are normally distributed and uncorrelated for a single experiment. Now let us suppose that we have $\mathcal{N}$ independent experiments at positions $\mathbf{x}_i$ and that we have

[1] Exceptions would be experiments that make use of ∇a, but such signals are suppressed by $v \sim 10^{-3}$ relative to experiments that are instead sensitive to $\partial a/\partial t$.

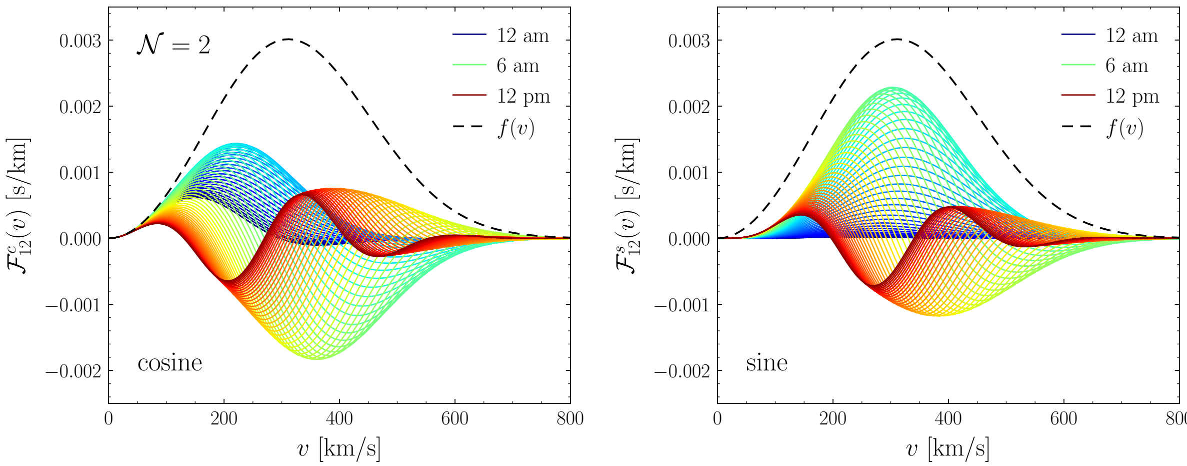

Figure 1: Interference effects characterized by the effective speed distributions $F^c_{12}(v)$ and $F^s_{12}(v)$ over a 24-hour period, for $m_a = 8.3 \times 10^{-11}$ eV and two experiments separated by $|\mathbf{x}_{12}| = 10,000$ km (slightly less than the diameter of the Earth). Since $F^c(v)$ and $F^s(v)$ are functions of $m_a|\mathbf{x}_{12}|$, qualitatively similar effects exist for e.g. $m_a \sim 10^{-9}$ eV and $|\mathbf{x}_{12}| \sim 1000$ km, or $m_a \sim 10^{-5}$ eV and $|\mathbf{x}_{12}| \sim 100$ m.

calculated the ensemble of power spectra $\{R(\mathbf{x}_i, \omega)\}$, $\{I(\mathbf{x}_i, \omega)\}$. The phase factors $\mathbf{k} \cdot \mathbf{x}_{ij}$, give rise to a nontrivial covariance matrix, parameterized by the following modified speed distributions

$$\mathcal{F}^c_{ij}(v) = \int d^3\mathbf{v} f(\mathbf{v}) \cos(m_a \mathbf{v} \cdot \mathbf{x}_{ij}) \delta[|\mathbf{v}| - v_\omega] \,, \qquad \mathcal{F}^s_{ij}(v) = \int d^3\mathbf{v} f(\mathbf{v}) \sin(m_a \mathbf{v} \cdot \mathbf{x}_{ij}) \delta[|\mathbf{v}| - v_\omega] \,, \quad (3)$$

with $v_\omega = \sqrt{2\omega/m_a - 2}$. The functions $\mathcal{F}^{c/s}_{ij}(v)$, shown in Fig 1 for $\mathcal{N} = 2$, are generalized speed distributions which exhibit characteristic interference patterns for $|\mathbf{x}_{ij}| \sim \lambda_{\rm dB}$. In particular, for fixed locations on the surface of the Earth, the separation vector $\mathbf{x}_{ij}$ will rotate in the Galactic frame over the course of a day, giving rise to striking daily modulation signatures visible in the figure. In forthcoming work to appear on the arXiv, we will construct a likelihood function for the multi-detector data and perform parameter estimation on the full three-dimensional Standard Halo Model. In most cases, we can show that the directional parameters can be extracted at comparable statistical significance to the amplitude of the signal itself, meaning that as soon as a signal is seen at one detector, the full velocity distribution can immediately be probed by combining the data from two or more detectors with comparable sensitivity. Note that for a single detector we would have $\mathbf{x} = 0$, and therefore $\mathcal{F}^c(v) = f(v)$ and $\mathcal{F}^s(v) = 0$; the information on angular moments of $f(\mathbf{v})$ captured by $\mathcal{F}^s(v)$ is invisible to a single isolated detector.

Conclusion. Discovering the axion is a primary goal of CF2. The signal template for most existing and planned experiments is the speed distribution $f(v)$, which contains some of the information we know about dark matter, but far from all. Two axion detectors can probe the full $f(\mathbf{v})$ through dark matter interferometry, and can discover much of the velocity distribution at the same significance of the axion signal itself. Further, multiple detectors allow access to a smoking gun daily modulation signature unique to wavelike dark matter. The sensitivity to $g_{a\gamma\gamma}$ for axion experiments which use external magnetic fields is typically $BV^{1/2}$ for resonant cavity experiments and $BV^{5/6}$ for experiments in the quasistatic regime where B is the peak magnetic field strength and V is the magnetic field volume; our analysis here motivates achieving the same figure of merit with two spatially-separated smaller experiments rather than a single large experiment. Not only will this help reject transient backgrounds, but it will open up significant additional physics potential if the axion is found.

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