Charting the light DM landscape with matter-wave interferometers

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Based on 2606.00237 and upcoming work, with Kathryn M. Zurek

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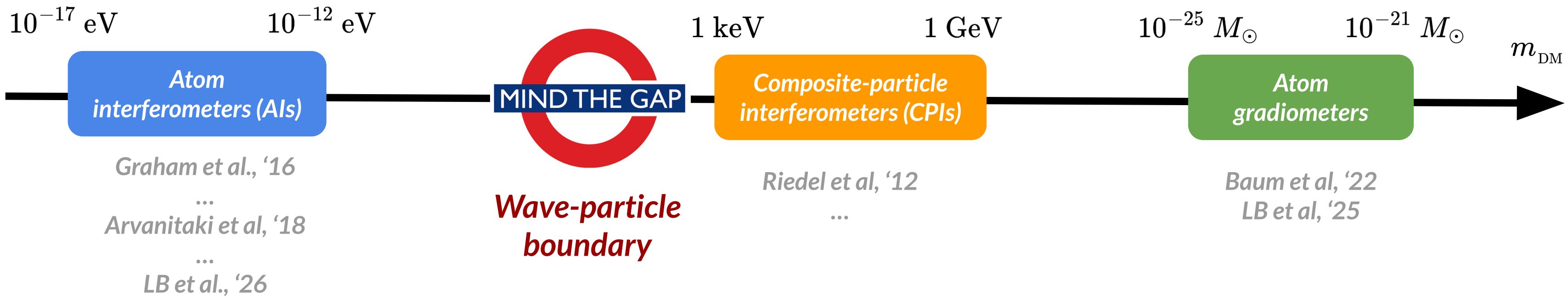
Motivation

Matter-wave interferometers provide a promising route to probing disparate regions of the DM landscape



Pheno question:

*Could we explore **novel** regimes, e.g., the underexplored wave-particle boundary?*

Theory questions:

*How do we **systematically** compute DM signatures?*

*In what precise sense are these detectors **different** from classical sensors?*

Matter-wave interferometers as open quantum systems

System (MWI)

Environment (DM, possible DM-SM mediator)

*Combined evolution of the system and environment is **unitary**.*
*Evolution of the (reduced) system is **not unitary.***

Most generic field theoretic approach to open quantum systems:

Schwinger-Keldsyh formalism
[Schwinger '61, Keldysh '65]

- *Allows one to define **observables at finite time** (no asymptotic in/out states)*
- *Can deal with **large occupation number of environmental particles** (i.e., DM)*
- *Makes the dependence on the **properties of the environment**, e.g., DM quantum state, spin statistics and coherence time, manifest*

Schwinger-Keldysh formalism: a speedy review

Real time formalism on a closed-time path

i.e., find the path integral form of $\langle\psi|\hat{\rho}_s(t)|\psi'\rangle = \langle\psi|\mathrm{Tr}_e[\hat{U}(t,t_0)\hat{\rho}(t_0)\hat{U}^\dagger(t,t_0)]|\psi'\rangle$

Recipe:

1. *Take a (closed) theory, with action*

$$S[\psi,\Xi] = S_s[\psi] + S_e[\Xi] + S_{\rm int}[\psi,\Xi]$$

2. *Double the fields (forward (+) and backward (-) time branch) and define the in-in action*

$$S[\{\psi\},\{\Xi\}] = S[\psi_+,\Xi_+] - S[\psi_-,\Xi_-]$$

3. *Specify initial density matrix of system + environment*
4. *Trace out the environment to obtain the effective action:*

$$S_{\rm eff}[\psi_+,\psi_-] = S_s[\psi_+,\psi_-] + S_{\rm IF}[\psi_+,\psi_-] \qquad \mathrm{Im}[S_{\rm IF}] \geq 0$$

Influence action depends on the system-environment interactions, the field content of the environment sector and initial state of the environment

From the microscopic theory to the influence action

E.g., monopole-monopole interactions

$$\mathcal{L}_{\rm int} = \frac{g}{\Lambda^D} O_s[\psi] O_e[\Xi]$$

At second order in g, the influence functional is given by

$$S_{\rm IF} = -\tfrac{1}{2}\left(\tfrac{g}{\Lambda^D}\right)^2 \int_{t_0}^{t} \mathrm{d}^4x' \int_{t_0}^{t} \mathrm{d}^4x''\, \vec{O}_s^{\mathsf{T}}(x') \mathsf{K}(x',x'') \vec{O}_s(x'') + \mathcal{O}(g^3)\,,$$

*with **system currents** (Keldysh basis)*

$$\vec{O}_s^{\mathsf{T}}(x') = \begin{bmatrix} O_s^{\rm cl}(x') & O_s^{\rm q}(x') \end{bmatrix} \qquad O^{\rm cl} = \tfrac{1}{2}[O_+ + O_-] \quad O^{\rm q} = O_+ - O_-$$

*and **environment matrix kernel***

$$\mathsf{K}(x',x'') = \begin{bmatrix} 0 & K_{\rm a}(x',x'') \\ K_{\rm r}(x',x'') & K_{\rm k}(x',x'') \end{bmatrix}$$

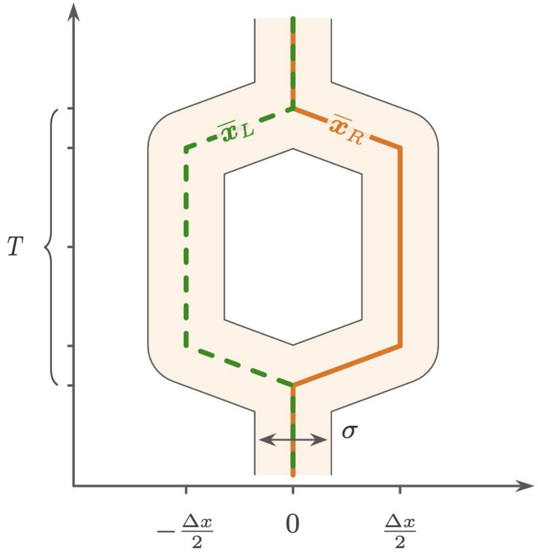
Environment fluctuations

$$K_{\rm k}(x',x'') = -\tfrac{\mathrm{i}}{2}\langle\!\langle \{\hat{O}_e(x'), \hat{O}_e(x'')\}\rangle\!\rangle_c\,,$$

Causal influence/response

$$K_{\rm r}(x',x'') = -\mathrm{i}\,\theta(t'-t'')\langle\!\langle [\hat{O}_e(x'), \hat{O}_e(x'')]\rangle\!\rangle_c\,,$$

Open EFT for matter-wave interferometers



- ➔ *Start from the <u>in-in effective action</u>*
- ➔ ***NR limit:*** *no atoms created or destroyed* $\Rightarrow$ ***path integral over system worldlines.***
- ➔ *Restrict to* ***elastic interactions*** *(for simplicity)*
- ➔ *Introduce* ***external currents*** *defining the* ***left*** *and* ***right arm.***
- ➔ *Choose the* ***initial state of the system****: preparation (product vs bound), number of atoms, wave-packet size.*
- ➔ *Path integral over worldlines in the heavy-probe limit:*

$$\hat{\rho}_s = \frac{1}{2}\begin{pmatrix} e^{\mathrm{i}S_{\mathrm{IF}}[\overline{\boldsymbol{x}}_L,\overline{\boldsymbol{x}}_L]} & e^{\mathrm{i}S_{\mathrm{IF}}[\overline{\boldsymbol{x}}_L,\overline{\boldsymbol{x}}_R]} \\ e^{\mathrm{i}S_{\mathrm{IF}}[\overline{\boldsymbol{x}}_R,\overline{\boldsymbol{x}}_L]} & e^{\mathrm{i}S_{\mathrm{IF}}[\overline{\boldsymbol{x}}_R,\overline{\boldsymbol{x}}_R]} \end{pmatrix} \equiv \frac{1}{2}\begin{pmatrix} 1 & e^{-\mathbb{D}+\mathrm{i}\mathbb{P}} \\ e^{-\mathbb{D}-\mathrm{i}\mathbb{P}} & 1 \end{pmatrix} + \mathcal{O}(1/M)$$

Decoherence (non-unitary)

$$\mathbb{D} = \mathrm{Im}\{S_{\mathrm{IF}}[\overline{\boldsymbol{x}}_L, \overline{\boldsymbol{x}}_R]\}$$

Phase (unitary)

$$\mathbb{P} = \mathrm{Re}\{S_{\mathrm{IF}}[\overline{\boldsymbol{x}}_L, \overline{\boldsymbol{x}}_R]\}$$

From the influence functional to interferometer observables

Finite-time energy res. (Markovianity or otherwise)

Detector geometry

Environment kernel

$$\mathbb{D} = -T^2\left(\frac{g}{\Lambda^D}\right)^2 \int \frac{\mathrm{d}^4 q}{(2\pi)^4}\, \mathrm{sinc}^2\left(\frac{q_0 T}{2}\right) |F_{\mathbb{D}}(\mathbf{q})|^2 \left(1 - \cos(\mathbf{q}\cdot\boldsymbol{\Delta x})\right) \mathrm{Im}\left[\widetilde{\Pi}_{\mathrm{k}}(q)\right]$$

$$\mathbb{P} \approx 4T\left(\frac{g}{\Lambda^D}\right)^2 \int \frac{\mathrm{d}^4 q}{(2\pi)^4}\, \sin\left(\frac{\mathbf{q}\cdot\boldsymbol{\Delta x}}{2}\right) |F_{\mathbb{P}}(\mathbf{q})|^2 \left[\pi\delta(q_0) - T\,\mathrm{sinc}^2\left(\frac{q_0 T}{2}\right) \sin^2\left(\frac{\mathbf{q}\cdot\boldsymbol{\Delta x}}{4}\right)\right] \mathrm{Im}\left[\widetilde{\Pi}_{\mathrm{r}}(q)\right]$$

System form factors (initial system-state dependent)

Experiment	Decoherence form factor	Phase form factor
Single atom	$\lvert F_A(\mathbf{q})\rvert^2$	$\lvert F_A(\mathbf{q})\rvert^2$
AI, one-body readout	$\lvert F_A(\mathbf{q})\rvert^2$	$\lvert F_A(\mathbf{q})\rvert^2 \left[1 + (N_{\mathrm{at}} - 1)\lvert F_{\mathrm{cloud}}(\mathbf{q})\rvert^2\right]$
CPI	$\lvert F_A(\mathbf{q})\rvert^2 e^{-2W(\mathbf{q})} \left[N_{\mathrm{at}} + N_{\mathrm{at}}^2 \lvert F_{\mathrm{geo}}(\mathbf{q})\rvert^2\right]$	$\lvert F_A(\mathbf{q})\rvert^2 e^{-2W(\mathbf{q})} \left[N_{\mathrm{at}} + N_{\mathrm{at}}^2 \lvert F_{\mathrm{geo}}(\mathbf{q})\rvert^2\right]$

LB, Murgui & Plestid ‘24 + Murgui & Plestid ‘25

Riedel ‘12

N dependence only in the phase (AI-asymmetry)

Applications: contact interactions

Example: ***quadratically-coupled DM to nucleons***

$$\mathcal{L}_{\rm int} \supset -\frac{g}{\Lambda^2}\,\overline{N}N\,O_\chi\,, \quad O_\chi = \begin{cases} m_\chi \chi^2 \\ \overline{\chi}\chi \end{cases}$$

Markovian approximation *(T>> DM coherence time) +* ***Gaussian DM state*** *(Cheong et al. '25)*

(Spin-summed) occupation number per mode

$$\mathbb{P} = 2\pi T\Big(\frac{g}{\Lambda^2}\Big)^2 \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \int \frac{\mathrm{d}^3 q}{(2\pi)^3}\, n_\chi(\mathbf{p}) |F_{\mathbb{P}}(\mathbf{q})|^2 \sin(\mathbf{q}\cdot\boldsymbol{\Delta x})\, \delta(E_{\mathbf{p}} - E_{\mathbf{p}-\mathbf{q}})$$

$$\mathbb{D} = 2\pi T\Big(\frac{g}{\Lambda^2}\Big)^2 \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \int \frac{\mathrm{d}^3 q}{(2\pi)^3}\, n_\chi(\mathbf{p}) S_\chi(\mathbf{p},\mathbf{q}) |F_{\mathbb{D}}(\mathbf{q})|^2 [1 - \cos(\mathbf{q}\cdot\boldsymbol{\Delta x})]\, \delta(E_{\mathbf{p}} - E_{\mathbf{p}-\mathbf{q}})$$

DM statistical factor (novel)

$$S_\chi(\mathbf{p},\mathbf{q}) = \begin{cases} 1 + n_\chi(\mathbf{p}-\mathbf{q}) & \text{for bosonic DM,} \\ 1 - \frac{1}{2} n_\chi(\mathbf{p}-\mathbf{q}) & \text{for fermionic DM.} \end{cases}$$

Bose enhancement
Pauli blocking

Environment-dependent asymmetry

Fermions: $n_\chi \to 2 : \mathbb{D} \to 0, \mathbb{P}$ *finite: the open system behaves like a closed-system!*
Bosons: $n_\chi \gg 1 : \mathbb{P} \propto m_\chi^{-4}$ *and* $\mathbb{D} \propto m_\chi^{-8}$ *; decoherence channel is parametrically enhanced*

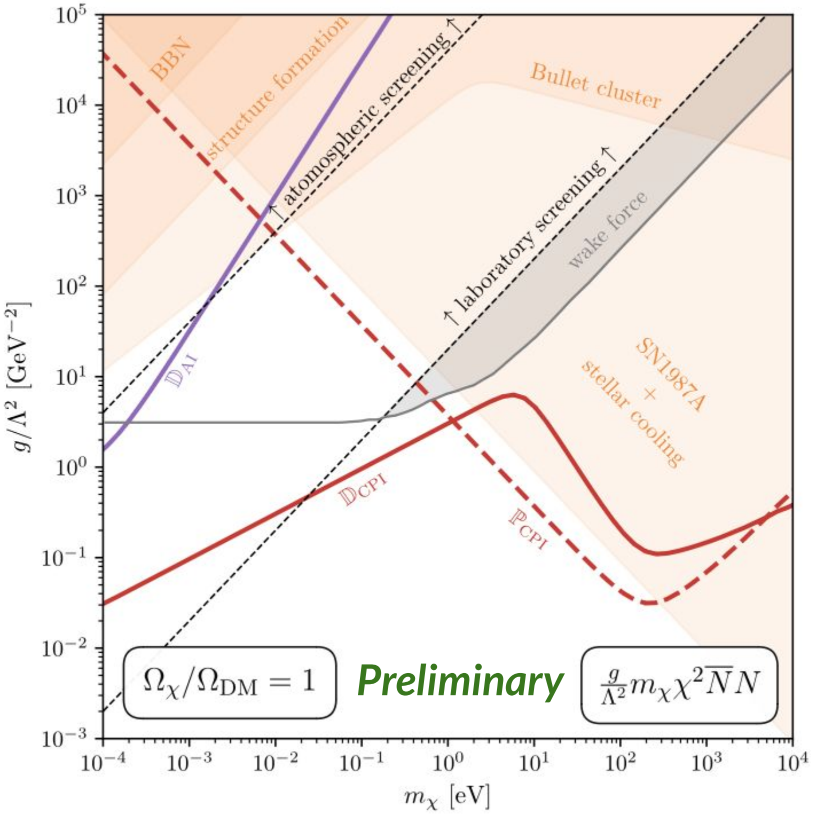
Contact interactions: projected reach

Parameter	AI	CPI
Atomic species	Rb-87	Nb-93
Mass number, A	87	93
Number of atoms, N_{at}	10^8	2.3×10^{11}
Number of nucleons, AN_{at}	8.7×10^9	2.1×10^{13}
Superposition size, Δx	5 m	100 nm
Interrogation time, T	1 s	0.5 s
Total integration time, T_{int}	3 yr	3 yr

For the AI, decoherence provides the best sensitivity due to Bose enhancement

*For the CPI, **peak sensitivity at 1/q ~ Δx** above the wave-particle boundary.*

***Below the wave-particle boundary,** the decoherence observable dominates over the phase shift observable,*
providing enhanced sensitivity



Applications: long-range interactions

Example: **hadrophilic light scalar mediator**

$$\mathcal{L} \supset -y_\chi m_\chi \phi \chi^2 - y_N \phi \overline{N} N$$

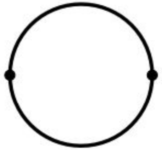
Environment = mediator + DM, with $\hat{\rho}_e(t_0) = |0\rangle\langle 0|_\phi \otimes \hat{\rho}_\chi$

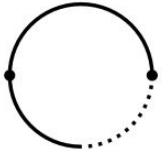
Fifth-force bounds ⇒ $y_N \ll 1$

For a DM subcomponent (Lin et al, '17): $y_\chi \lesssim \mathcal{O}(1)$

Hence, the **environment kernels** are now **dressed mediator propagators** at $\mathcal{O}(y_N^2)$

$$\widetilde{D}_{\mathrm{r}}^{\phi}(0,\mathbf{q}) = -\frac{1}{|\mathbf{q}|^2 + m_\phi^2 + \widetilde{\Pi}_{\mathrm{r}}^{\chi}(0,\mathbf{q})} \qquad \widetilde{D}_{\mathrm{k}}^{\phi}(0,\mathbf{q}) = |\widetilde{D}_{\mathrm{r}}^{\phi}(0,\mathbf{q})|^2 \widetilde{\Pi}_{\mathrm{k}}^{\chi}(0,\mathbf{q})$$

$-\mathrm{i}$  $= -\frac{\mathrm{i}}{2}\left(2m_\chi \frac{g}{\Lambda^2}\right)^2 \int đ^4p\, \widetilde{G}_{\mathrm{k}}^{\chi}(p)\widetilde{G}_{\mathrm{k}}^{\chi}(q-p) \equiv \widetilde{\Pi}_{\mathrm{k}}^{\chi}(q)$

$-\mathrm{i}$  $= -\mathrm{i}\left(2m_\chi \frac{g}{\Lambda^2}\right)^2 \int đ^4p\, \widetilde{G}_{\mathrm{k}}^{\chi}(p)\widetilde{G}_{\mathrm{r}}^{\chi}(q-p) \equiv \widetilde{\Pi}_{\mathrm{r}}^{\chi}(q)$

Long-range interactions: DM-induced screening

$$\mathrm{Im}[\widetilde{D}^{\phi}_{\mathrm{r}}(0,\mathbf{q})] \simeq \frac{\mathrm{Im}[\widetilde{\Pi}^{\chi}_{\mathrm{r}}(0,\mathbf{q})]}{(|\mathbf{q}|^2 + m_{\mathrm{eff}}^2)^2} \qquad \mathrm{Im}[\widetilde{D}^{\phi}_{\mathrm{k}}(0,\mathbf{q})] \simeq \frac{\mathrm{Im}[\widetilde{\Pi}^{\chi}_{\mathrm{k}}(0,\mathbf{q})]}{(|\mathbf{q}|^2 + m_{\mathrm{eff}}^2)^2} \qquad m_{\mathrm{eff}}^2 \simeq m_\phi^2 + y_\chi^2 \frac{f_\chi \rho_{\mathrm{DM}}}{m_\chi^2 v_0^2}$$

$$m_{\mathrm{eff}}^2 \simeq m_\phi^2 + \boxed{y_\chi^2 \frac{f_\chi \rho_{\mathrm{DM}}}{m_\chi^2 v_0^2}}$$

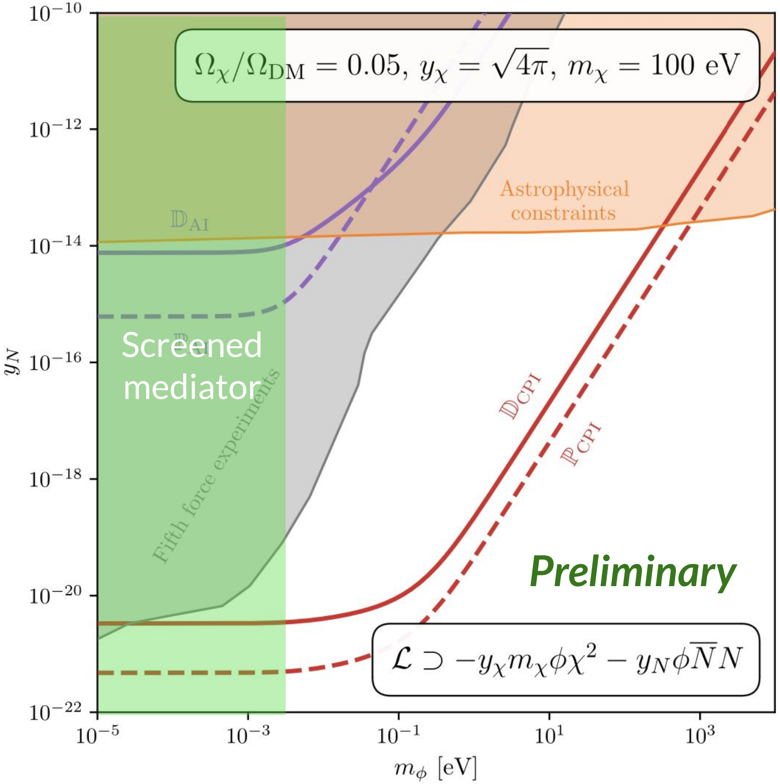
DM-induced mediator mass correction

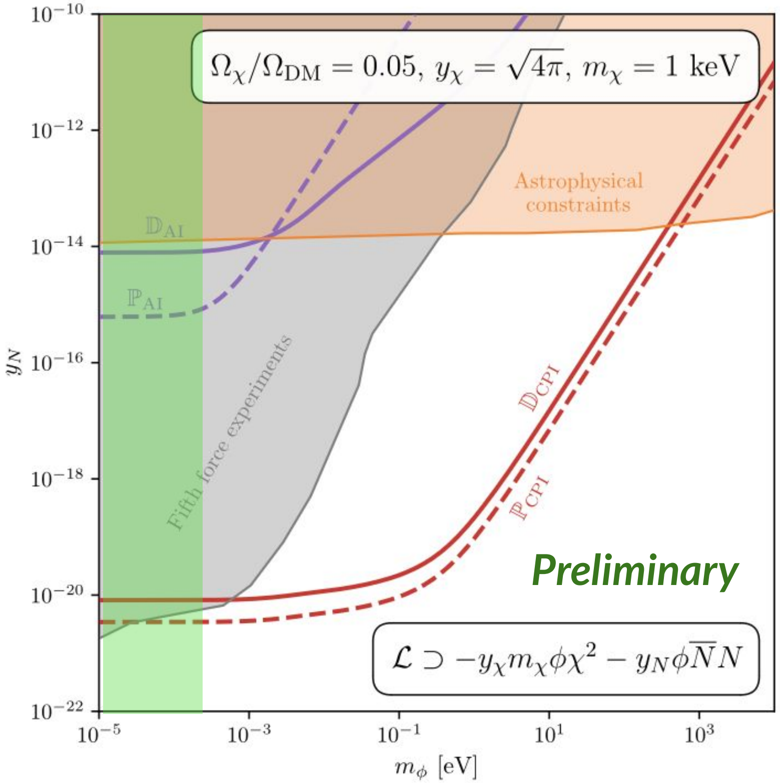
***Physical intuition** — akin to **Debye screening**.*

The polarisable DM background responds to the mediator as a plasma responds to an electric field:

Part of the kernel (in-built in our open EFT).

Long-range interactions: projected constraints





Summary

*We introduced an **open EFT** for computing DM-induced effects in **matter-wave interferometers** using the **Schwinger Keldysh formalism***

*General, and particle-physics friendly, and requires only the **DM model**, the **DM state** and **the interferometer geometry as inputs***

Novel results

***Pauli blocking / Bose enhancement in the decoherence channel but not in the phase** – with direct pheno consequences for which observable to measure.*

***Mediator screening** arises due to an effective **in-medium mass from the finite DM number density**. Reduced sensitivity, but still interesting and unique reach in CPIs.*

Thank you for your attention!