Interferometer as a Probe of Dark Relics

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Outline

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Introduction

Interferometer Sensitivity

Application to Probe Dark Relics

Summary and Conclusion

Two Waves Interference

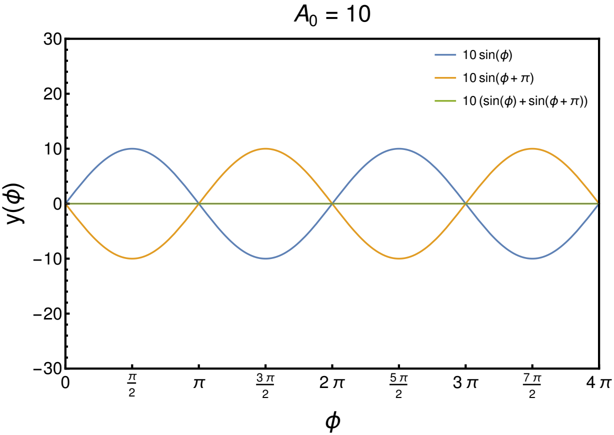


Figure: $y(x,t) = A_0 \sin \phi(x,t) = A_0 \sin(kx - \omega t)$. The phase difference between two waves is $1/2\,\lambda$ or half wavelength.

Two Waves Interference

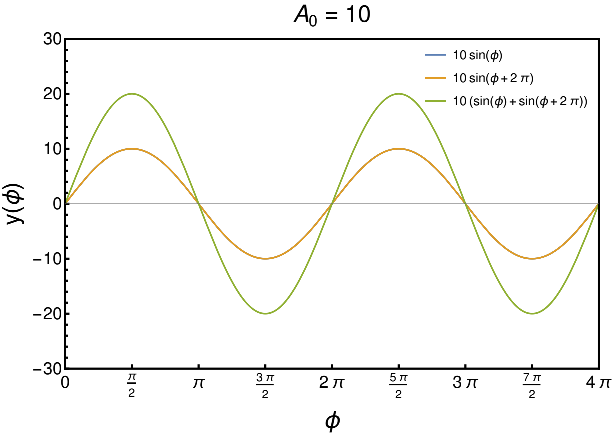


Figure: $y(x,t) = A_0 \sin \phi(x,t) = A_0 \sin(kx - \omega t)$. The phase difference between two waves is $1\,\lambda$ or one wavelength

Interferometer

- Interference can be studied using interferometer

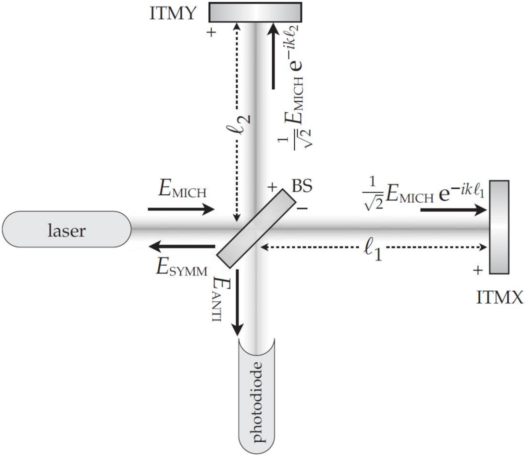


Figure: [Creighton et al. 2011]

The Phase Change

- Constructive interference: $\ell_1 - \ell_2 = n\,\lambda$ (n is integer)
- Destructive interference: $\ell_1 - \ell_2 = \frac{n}{2}\,\lambda$
- The change of interference pattern: $\Delta\ell = \Delta\ell_1 - \Delta\ell_2$
- The phase change is sensitive to the movement of the mirror as well as the interaction between light and its surrounding

The Absence of Ether

- It was believed that ether is required for light propagation

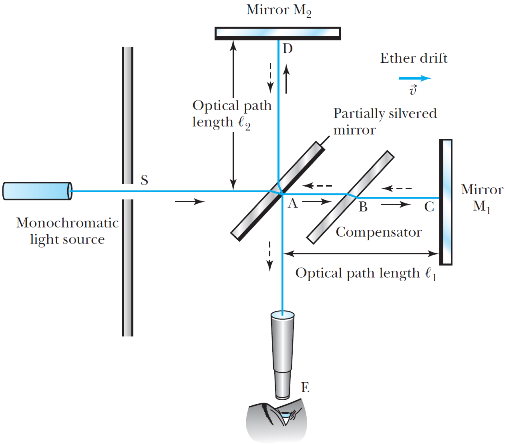


Figure: Round trip time for ℓ_1 is $t_1 = \frac{\ell_1}{c+v} + \frac{\ell_1}{c-v}$ and for ℓ_2 is $t_2 = \frac{2\ell_2}{\sqrt{c^2-v^2}}$. [Thornton et al. 2023]

The Absence of Ether

- The time difference between t_1 and t_2

$$\Delta t = t_2 - t_1 = \frac{2}{c}\left(\frac{\ell_2}{\sqrt{1 - v^2/c^2}} - \frac{\ell_1}{1 - v^2/c^2}\right)$$

- Rotating the mirror by 90° such that ether parralel to ℓ_2, the time difference $\Delta t^{'}$

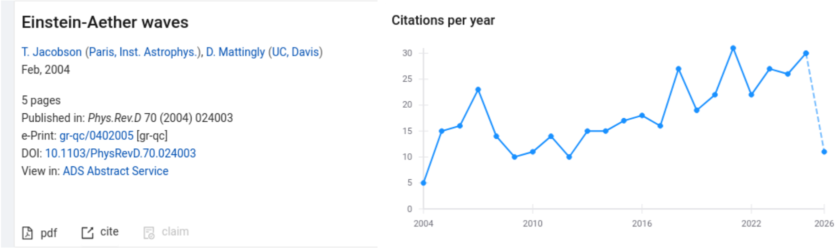
$$\Delta t^{'} = t_2^{'} - t_1^{'} = \frac{2}{c}\left(\frac{\ell_2}{1 - v^2/c^2} - \frac{\ell_1}{\sqrt{1 - v^2/c^2}}\right)$$

- The time modulation which induce the phase change is (for $c >> v$)

$$\Delta t^{'} - \Delta t \approx \frac{v^2\left(\ell_1 + \ell_2\right)}{c^3}$$

The Absence of Ether

- No phase shift was observed proves the absence of Ether and light needs no medium to travel
- Ether theory made a return in 2004 and still an active research field apparently



Einstein-Aether waves

T. Jacobson (Paris, Inst. Astrophys.), D. Mattingly (UC, Davis)
Feb, 2004

5 pages
Published in: *Phys.Rev.D* 70 (2004) 024003
e-Print: gr-qc/0402005 [gr-qc]
DOI: 10.1103/PhysRevD.70.024003
View in: ADS Abstract Service

Figure: [https://inspirehep.net]

Gravitational Wave Detection

- Gravitational wave (GW) propagates along z direction will displace the test mass in x and y direction

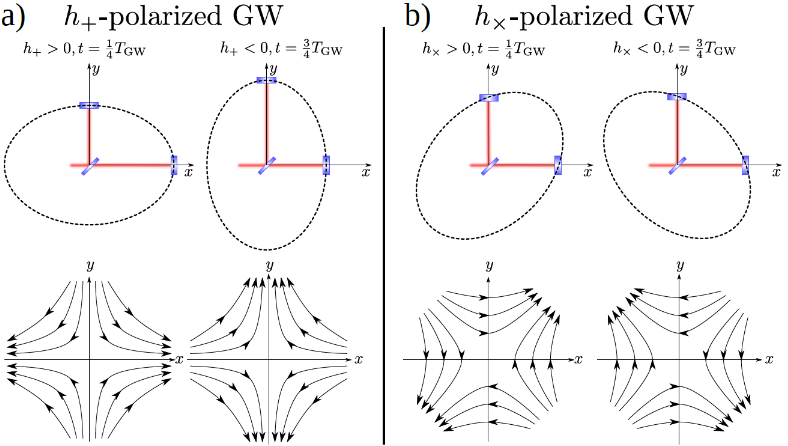


Figure: [Danilishin et al. 2012]

Gravitational Wave Detection

- The change of interference pattern $\Delta\ell = \Delta\ell_1 - \ell_2$ due to GW is related to GW amplitude

$$h_{GW} \propto \frac{\Delta\ell}{L} \leq 10^{-20}$$

[Caltech/MIT/LIGO Lab/Virgo/EGO/ICRR-KAGRA]

Figure: The first GW was observed at LIGO in 2015

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Sensitivity

- Quantum mechanics puts the limit on the phase measurement

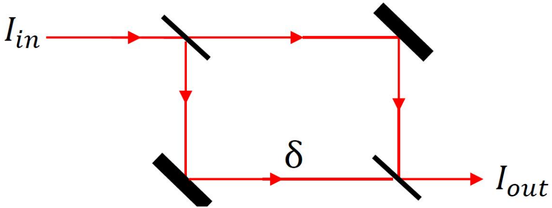

Figure: A simple Mach-Zehnder interferometer

- Consider MZ interferometer adjusted in such a way that it gives destructive interference in the absence of phase shift

Sensitivity

- In this case, one can write the output intensity

$$I_{out} = \frac{I_{in}}{2}(1 - \cos\delta)$$

- For a well defined input the change in the output comes from the phase change

$$\Delta I_{out} = \frac{I_{in}}{2}\Delta\delta \sin\delta$$

- The maximum value occurs for $\delta = \pi/2$. In terms of photon number

$$\Delta N_{out}^{max} = \frac{N_{in}}{2}\Delta\delta$$

Sensitivity

- In quantum mechanics, the minimum photon number change is one

$$\Delta\delta \geq \frac{1}{N} \quad \text{(Heisenberg Limit)}$$

- Here $N = N_{in}/2$ total number of photon in one arm that experiences the phase shift

Sensitivity

- Several limits on phase measurements in quantum optics achieved in the lab:
- Standard Quantum Limit (SQL)

$$\Delta\delta \geq \frac{1}{\sqrt{N}}$$

- Heisenberg Limit (see, for example Daryanoosh et al. 2018)

$$\Delta\delta \geq \frac{1}{N}$$

- Super-Heisenberg Limit (Napolitano et. al 2011)

$$\Delta\delta \geq \frac{1}{N^{3/2}}$$

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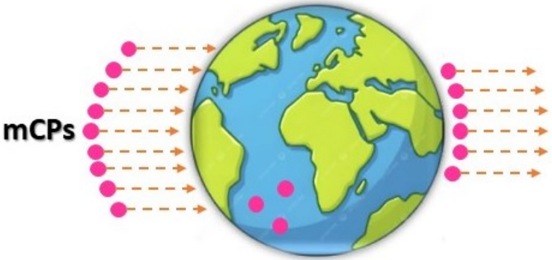
Earth-bound Millicharged Particles (mCPs)

- It has been shown that the Earth accumulates mCPs during its existence

$$\langle n_Q^{cap} \rangle = \frac{\pi R_\oplus^2 v_{vir} t_\oplus}{4/3\pi R_\oplus^3} f_Q \frac{\rho_{DM}}{m_Q} \approx \frac{3\times 10^{15}}{\mathrm{cm}^3} \frac{t_\oplus}{10^{10}\,\mathrm{year}} \frac{\mathrm{GeV}}{m_Q}$$

- The density on the Earth can be written as

$$\langle n_Q \rangle = \langle n_Q^{cap} \rangle \frac{1 - exp(-\Gamma_{loss} t_\oplus)}{\Gamma_{loss} t_\oplus}$$



Earth-bound Millicharged Particles (mCPs)

- Due to Earth's gravity vs scattering with terrestrial medium, mCPs are accumulated underground

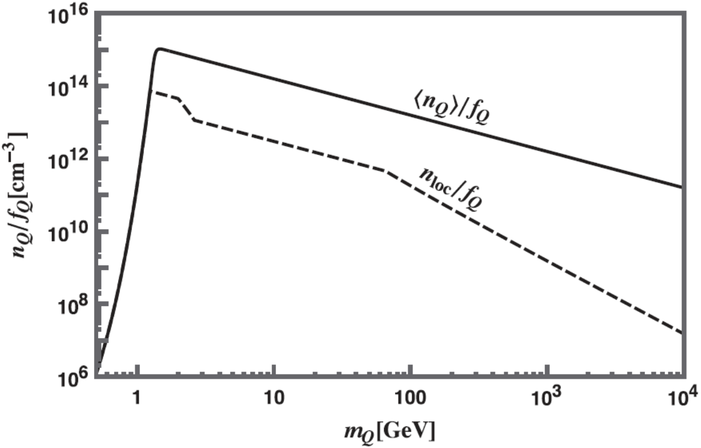


Figure: [Pospelov et al. '21 (arXiv:2012.03957)]

Earth-bound Millicharged Particles (mCPs)

- To detect mCPs using interferometer, we need to know how it interacts with photon

$$H_{int} = -\sum_s \frac{q_s}{m_s}\,\vec{p}_s.\vec{A}(\vec{r}_s) + \sum_s \frac{q_s^2}{m_s}\,[\vec{A}(\vec{r}_s)]^2$$

- Expressing the photon field in terms of annihilation and creation operator, one has

$$\hat{H}_{int} = \frac{\epsilon^2 e^2}{m_Q}\left[\frac{\hbar\omega^2}{16\pi^3\epsilon_0 c^3}\right]\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) N_Q$$

Earth-bound Millicharged Particles (mCPs)

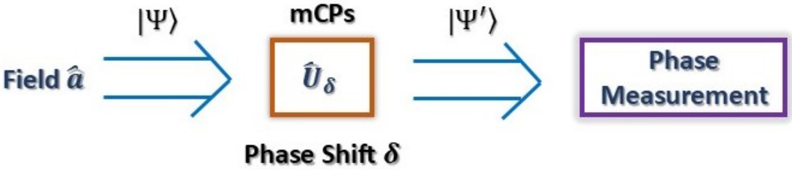


Figure: $|\Psi^{'}\rangle = \hat{U}_\delta |\Psi\rangle = e^{-\mathrm{i}\,\hat{H}_{\mathrm{int}}\mathrm{t}/\hbar} |\Psi\rangle = e^{-\mathrm{i}\,\hat{N}\delta} |\Psi\rangle$ [Ou '17]

- The induced phase shift due to mCPs-photon interaction

$$\delta = \frac{\epsilon^2 e^2}{m_Q} \left[\frac{\omega^2}{16\pi^3 \epsilon_0 c^3}\right] N_Q \frac{L}{c}$$

Earth-bound Millicharged Particles (mCPs)

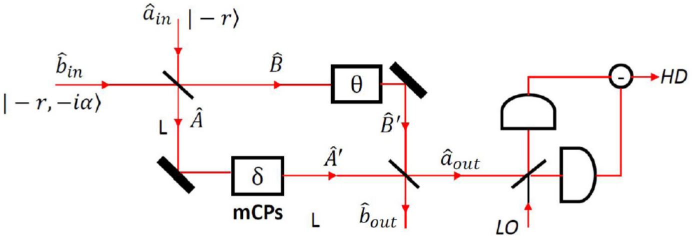


Figure: [Chen, Nhung, CSN '23 (arXiv:2212.13017)]

- The output is written in terms of quadrature

$$\hat{X}_a = a_{out} + a_{out}^{\dagger}$$

- The signal-to-noise ratio (SNR) in this case

$$\mathrm{SNR} = \frac{\left\langle \hat{X}_a \right\rangle^2}{\left\langle \Delta^2 \hat{X}_a \right\rangle} = N^2 \sin^2 \delta$$

Earth-bound Millicharged Particles (mCPs)

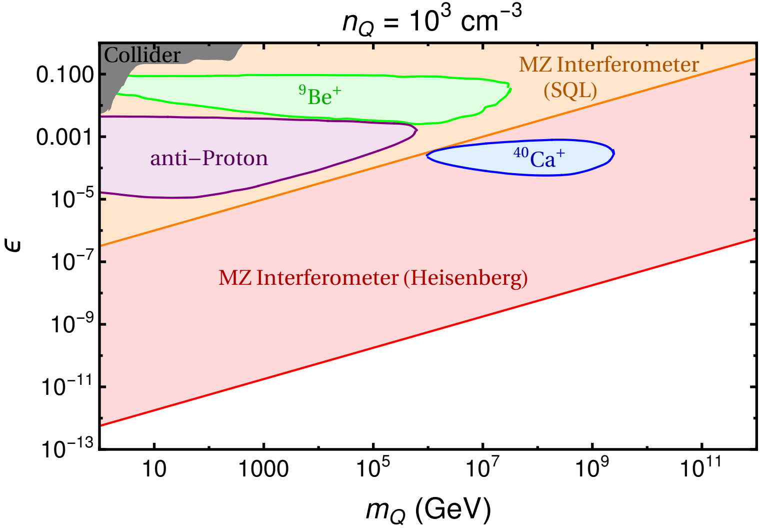


Figure: [Chen, Nhung, CSN ’23 (arXiv:2212.13017)]

Terrestrial CNB Accumulation

- Due to neutrino in-matter potential U, ν and $\bar{\nu}$ experience different interaction

$$
\begin{aligned}
U &= \frac{G_F}{2\sqrt{2}}\,\rho_{matter}\,(-)\,(3Z - A) \text{ for } \nu_e(\bar{\nu}_e) \\
&= \frac{G_F}{2\sqrt{2}}\,\rho_{matter}\,(-)\,(Z - A) \text{ for } \nu_{\mu,\tau}(\bar{\nu}_{\mu,\tau})
\end{aligned}
$$

- As a result, there will be an asymmetry between n_ν and $n_{\bar{\nu}}$ when neutrinos interact with terrestrial medium

Terrestrial CNB Accumulation

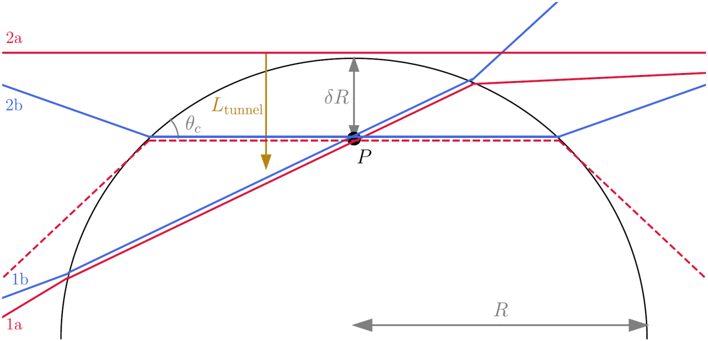


Figure: Scattering between ν ($\bar{\nu}$) and the Earth. Blue (red) rays is neutrino (anti-neutrino) path. [Kalia '24] (arXiv: 2404.11664)

- It is shown that the size of the asymmetry on the Earth's surface is

$$n_\nu^{\text{asy}} = \frac{n_\nu - n_{\bar{\nu}}}{n_{\text{CNB}}} \approx 10^{-8} \text{ (Huang}\,'24, \text{Kalia}\,'24)$$

Terrestrial CNB Accumulation

- Assuming that the CNB are non-relativistic and have non-zero electric charge, we wish to detect them using MZ interferometer

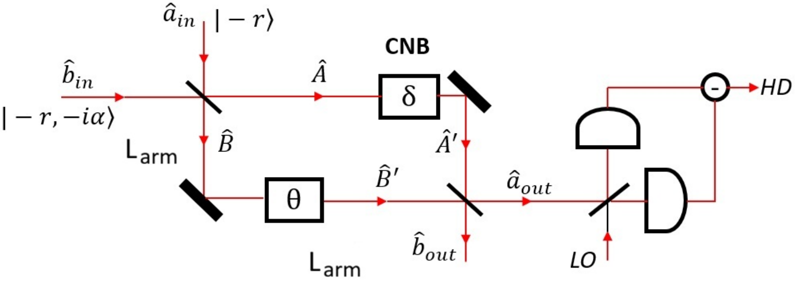


Figure: [Chen, CSN, Otero '25] (arXiv: 2506.04621)

Terrestrial CNB Accumulation

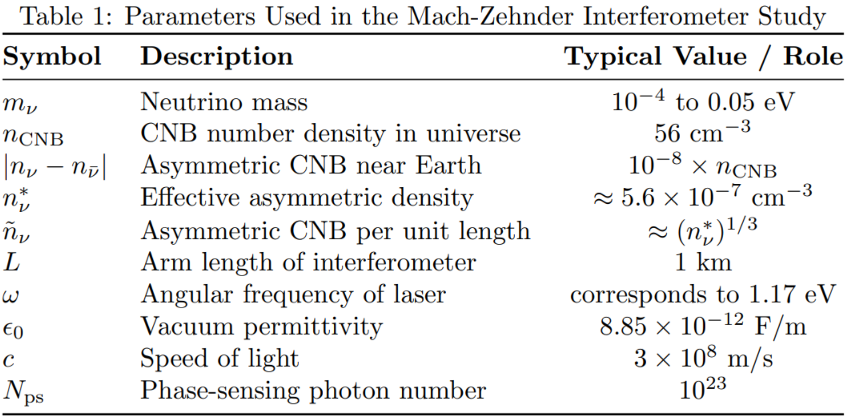


Table 1: Parameters Used in the Mach-Zehnder Interferometer Study

Symbol	**Description**	**Typical Value / Role**
m_ν	Neutrino mass	10^{-4} to 0.05 eV
n_{CNB}	CNB number density in universe	$56\ \text{cm}^{-3}$
$\lvert n_\nu - n_{\bar{\nu}} \rvert$	Asymmetric CNB near Earth	$10^{-8} \times n_{\text{CNB}}$
n_ν^*	Effective asymmetric density	$\approx 5.6 \times 10^{-7}\ \text{cm}^{-3}$
$\tilde{n}_\nu$	Asymmetric CNB per unit length	$\approx (n_\nu^*)^{1/3}$
L	Arm length of interferometer	1 km
ω	Angular frequency of laser	corresponds to 1.17 eV
ϵ_0	Vacuum permittivity	$8.85 \times 10^{-12}\ \text{F/m}$
c	Speed of light	$3 \times 10^8\ \text{m/s}$
N_{ps}	Phase-sensing photon number	10^{23}

Figure: [Chen, CSN, Otero '25] (arXiv: 2506.04621)

Terrestrial CNB Accumulation

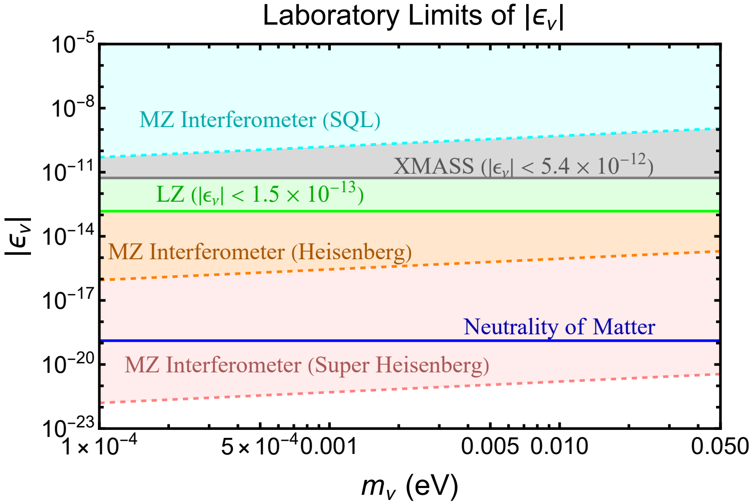


Figure: [Chen, CSN, Otero ’25] (arXiv: 2506.04621)

Terrestrial CNB Accumulation

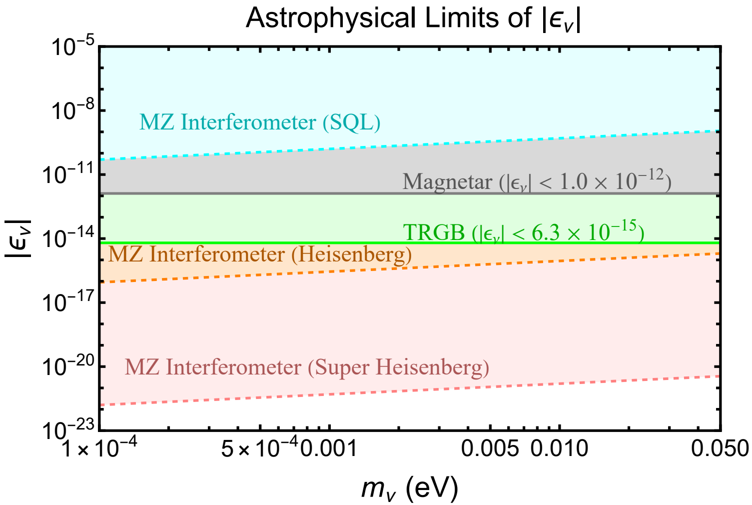
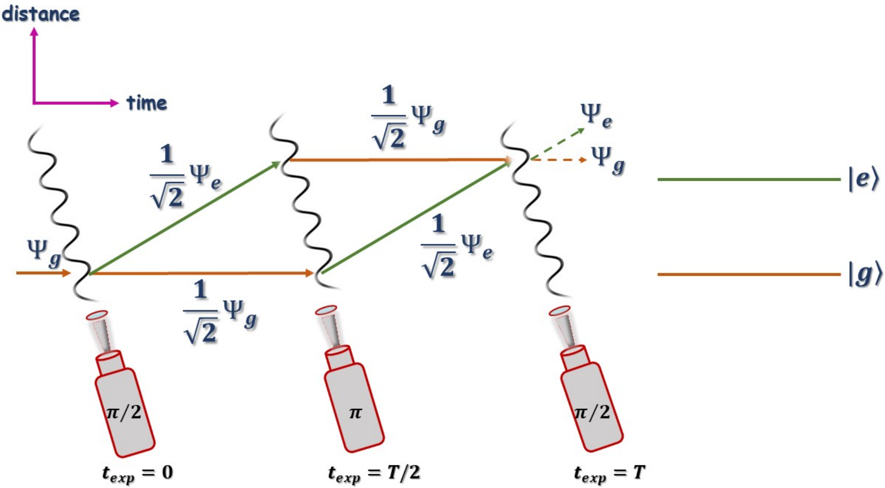


Figure: [Chen, CSN, Otero '25] (arXiv: 2506.04621)

Matter Interferometer



Matter Interferometer

- Matter interferometers had been used to probe:
  - Aharonov-Bohm effect (electron interferometer, Tonomura et al. 1982)
  - Aharonov-Casher effect (neutron interferometer, Cimmino et al. 1989)
  - Gravitational Aharonov-Bohm effect (atom interferometer, Overstreet et al. ’23)
- Atom interferometers are being developed to probe gravitational waves and ultralight dark matter:
  - AION, AICE, MAGIS, ELGAR, MIGA, ZAIGA (see, Buchmueller et al. ’23, arXiv: 2306.17726)

Matter Interferometer

- The phase shift in matter interferometer can be writen as

$$\Delta\Phi = -\frac{1}{\hbar}\oint V(\vec{x})\,\mathrm{d}\,t = \frac{1}{\hbar}(V_2 - V_1)\,T$$

- The sensitivity of matter interferometer can be estimated as

$$\Delta\Phi = \frac{1}{\sqrt{N_c}}$$

- N_c is the number of probe in the cloud with $N_C \approx 10^7$

CNB Detection using Matter Interferometer

- The interaction between CNB and the probe in matter interferometer

$$\mathcal{H}(x) = \frac{G_F}{\sqrt{2}} \sum_{i,j} \bar{\nu}_i \gamma_\mu (1 - \gamma_5) \nu_j \, \bar{\psi}_T \gamma^\mu (V_{ij} - A_{ij} \gamma_5) \psi_T$$

- The index i and j denote the neutrinos in mass basis
- ψ_T is the fermion utilized as a probe in the interferometer
- V_{ij} and A_{ij} are the matrices with vector and axial-vector couplings

CNB Detection using Matter Interferometer

- For Dirac neutrino, the potential energy induced by the CNB

$$V_\nu^D = \frac{G_F}{\sqrt{2}} \sum_{k,s_k} \frac{1}{E_T\, E_k} \Big\{ (n_k - \bar{n}_k) V_{kk} (p_k \cdot p_T) \\ - (n_k + \bar{n}_k) V_{kk} m_k (S_k \cdot p_T) \\ - (n_k - \bar{n}_k) A_{kk} m_T (p_k \cdot S_T) + (n_k + \bar{n}_k) A_{kk} m_k\, m_T (S_k \cdot S_T) \Big\}$$

- In case of Majorana neutrino

$$V_\nu^M = -\frac{G_F}{\sqrt{2}} \sum_{k,s_k} \frac{2\, m_k}{E_T\, E_k} n_k(s_k) \left\{ V_{kk}(S_k \cdot p_T) - m_T\, A_{kk}(S_k \cdot S_T) \right\}$$

CNB Detection using Matter Interferometer

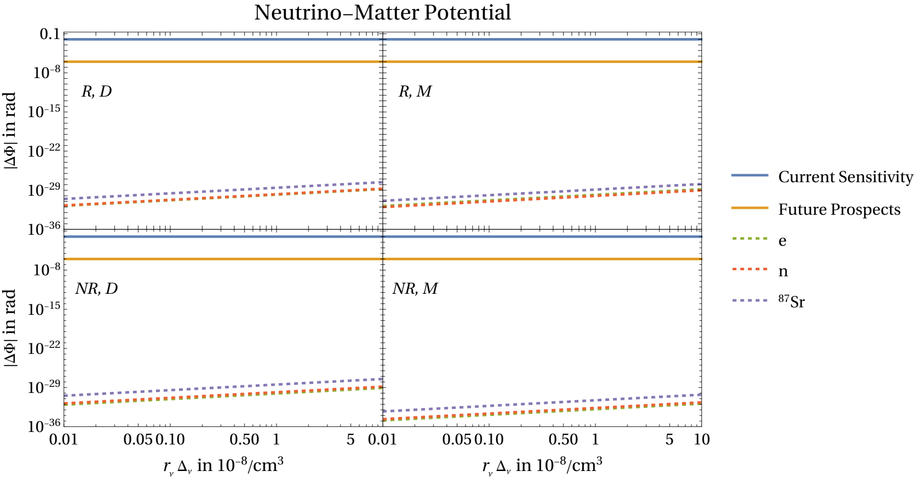


Figure: Neutrino-matter potential (V_{ij} term). Here, we set T = 1 s [CSN, Spinrath '25] (arXiv: 2511.18245).

CNB Detection using Matter Interferometer

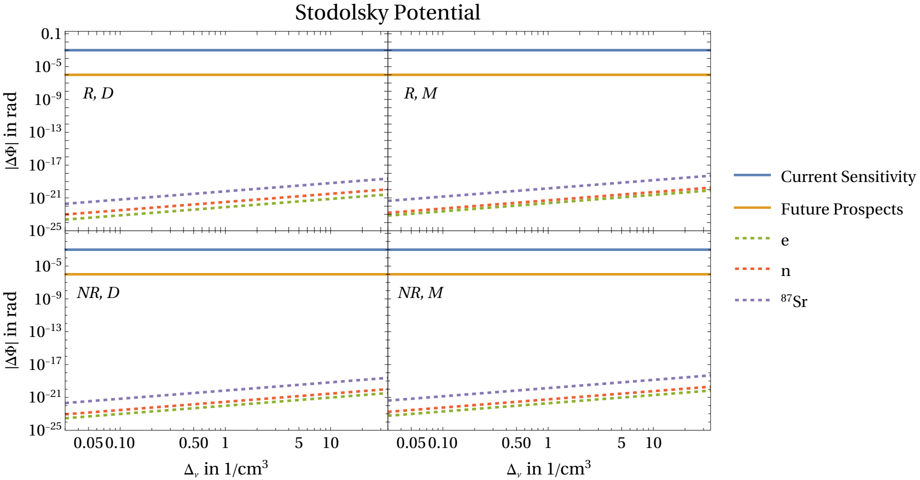


Figure: Stodolsky potential (A_{ij} term). Here, we set T = 1 s [CSN, Spinrath '25] (arXiv: 2511.18245).

Dark Matter Case

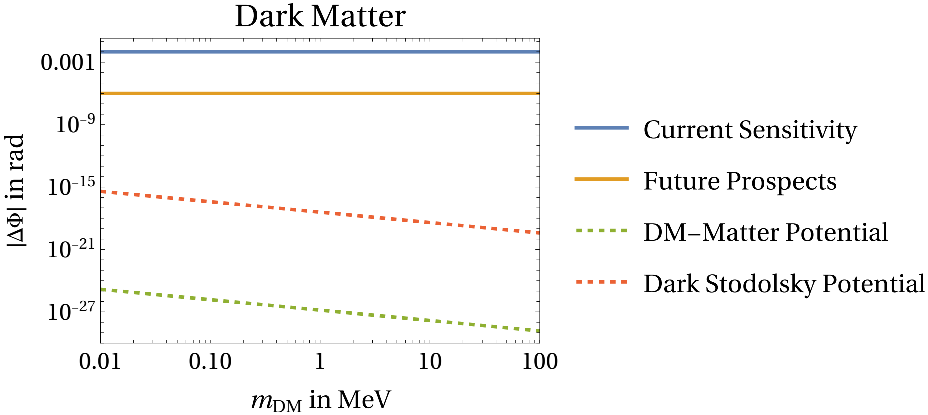


Figure: Dark matter search with $G_{DM} = 10\, G_F$. Here, we set T = 1 s [CSN, Spinrath '25] (arXiv: 2511.18245).

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- Laser interferometry offers a promising venue to probe elusive relics
- The matter interferometry needs more number of probe to get better sensitivity
- More research on quantum sensors and quantum measurements would help to improve the current sensitivity

Backup Slides

- The phase shift in DM case due to DM-matter potential

$$\Delta\Phi_{\rm DMM} \approx 1.48\times 10^{-28}\,\frac{T}{1\ {\rm s}}\,\frac{G_{\rm DM}}{G_F}\,\frac{r_{\rm DM}}{10^{-6}}\,\frac{\rho_{\rm DM}}{0.4\ {\rm GeV/cm^3}}\,\frac{1\ {\rm MeV}}{m_{\rm DM}}$$
$$\times\,\frac{a_{\rm DM}}{0.5}\,\frac{\cos\theta_{\rm DM}}{0.5}\,\frac{F^V_{\rm atom}}{10}$$

- The phase shift due to dark Stodolsky potential

$$\Delta\Phi_{\rm DST} \approx -3.86\times 10^{-19}\,\frac{T}{1\ {\rm s}}\,\frac{G_{\rm DM}}{G_F}\,\frac{\rho_{\rm DM}}{0.4\ {\rm GeV/cm^3}}\,\frac{1\ {\rm MeV}}{m_{\rm DM}}\,\frac{a_{\rm DM}}{0.5}\,\frac{F^A_{\rm atom}}{10}$$