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Millicharged dark matter detection with Mach-Zehnder interferometer

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ABSTRACT

If the dark sector exists and communicates with Standard Model through the $U(1)$ mixing, it is possible that electromagnetism would have influence on matter fields in dark sector, so-called millicharged particles (mCPs). Furthermore, the lightest mCPs could be dark matter particles. Recently, it has been shown that the mCPs would be slowed down and captured by the earth. As a result, the number density of accumulated mCPs underground is enhanced by several orders of magnitude as compared to that of dark matter in our solar system. In this study, we propose to use the Mach-Zehnder (MZ) laser interferometer to detect earth bound mCPs through the detection of phase shifts of photons. We show that, for mass of mCPs larger than 1 GeV, the sensitivity of probing the mixing parameter ϵ could reach as low as 10^{-11} if number density is larger than 1 cm^{-3}.

1. Introduction

One of the undisputed departures from the standard model (SM) of particle physics is the existence of enigmatic matter alias dark matter (DM). Based on several observations, ranging from galactic rotation curve to gravitational lensing, one infers that it gravitationally interacts with ordinary matter. Thus, it is widely believed that DM should be electromagnetically neutral or chargeless. On the theoretical side, however, the unobserved magnetic monopole allows the violation of charge quantization pointing toward new particles with non-quantized charges. Moreover, there exist several studies which assert that these millicharged particles (mCPs) are viable DM candidates that account for some or all of the observed DM abundance despite of their minuscule charge [1–5].

There have been a number of attempts to explore the existence of mCPs. In laboratory frontier, the SLAC millicharge experiment [6], neutrino experiment [7], BEBC beam-dump experiment [8], milliQan pathfinder experiment at the LHC [9] as well as the ArgoNeuT experiment [10] have placed stringent constraints on mCPs mass in MeV to TeV regime. On the other hand, the null results from anomalous emission in stellar environments put strong limits on mCPs mass in less than MeV range [11,12]. In addition, there are several novel strategies to probe mCPs [13–19]. Furthermore, mCPs also escape the conventional direct detection experiments such as XENON1T [20].

Due to its electromagnetic (EM) interaction with ordinary matter, the mCPs could have a large transfer cross section leading to the loss of its virial kinetic energy, and further, be thermalized with the environment. As a result, when mCPs arrive at the detector of direct search experiment, they deposit insufficient energy to the detector. Since these mCPs have lost their energy, they will be trapped thanks to the earth's gravity. This mechanism leads to the terrestrial mCPs accumulation taking place during the earth's existence. Furthermore, for mCPs with masses larger than 1 GeV, they are sunk to the earth's core leading to significant mCPs number density underground [21,22].

Since mCPs interact with the photon, laser interferometer experiments offer a suitable venue for terrestrial mCPs search. When mCPs interact with the laser in one arm of the interferometer, it would induce a phase shift on the laser to be detected at the output port. However, the existing DM search proposals utilizing the laser interferometer employed at Gravitational Wave (GW) experiments [23–40] are not suitable for mCPs search. In the typical interferometer at GW experiment, both of the interferometer arms are located at the same depth underground. Consequently, there is the same amount of mCPs in both arms leading to zero phase shift in the photon path. We propose a phase measurement scheme based on the optical laser experiment using Mach-Zehnder (MZ) interferometer to explore these mCPs. One arm of the MZ interferometer is located underground while keeping another arm on the earth surface. We demonstrate that our proposal is more sensitive

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than the current constraints on heavy mCPs mass regime given by collider experiments and the recent ion trap proposal [41].

The paper is organized as follows: In section 2, we give a brief discussion of terrestrial mCPs accumulation. We proceed to examine how mCPs interact with photons in Section 3. We introduce a phase measurement based on MZ interferometer in Section 4 and further present the projected sensitivities of our proposal in section 5. Our summary is presented in Section 6.

2. A brief review of Earth bound millicharged dark matter

The introduction of mCPs can be naturally realized in various ways. One possibility is through the mixing between a $U(1)'$ Abelian gauge field in dark sector and the SM hypercharge field. As the matter fields in dark sector are charged under the $U(1)'$ [42], these particles would have interactions with the photons with a coupling strength proportional to the mixing parameter and their charges under $U(1)'$. Phenomenologically, one can parametrize the electromagnetic coupling of mCPs to be ϵe, where e is the electric charge of electron. As a charged particle passes through the earth, it will be slowed down due to the scattering with ordinary matters through its EM interaction, and even be stopped inside the earth. Recently, Ref. [22] shows that if it constitutes a partial or the total amount of dark matter, then the number density of mCPs could be several orders of magnitude higher than that of the dark matter around our solar system. We summarize the relevant conclusions to our study in this section, and refer readers to [22] for more details and other cases.

For the mass of mCPs we are interested in, namely $m_Q \gtrsim 1$ GeV, the average number density of mCPs on the earth is given as

$$< n_Q > \simeq < n_Q^{cap} > \approx f_Q \left(\frac{t_\oplus}{10^{10}\,\text{year}}\right)\left(\frac{\text{GeV}}{m_Q}\right)\left(\frac{3\times 10^{15}}{\text{cm}^3}\right), \tag{2.1}$$

where f_Q is the fraction of mCPs in total local DM density and $t_\oplus$ is the age of earth, since the evaporation can be neglected. For number density underground, one needs to estimate the transfer cross section σ_T between mCPs and terrestrial medium. Moreover, due to the gravitational pull, mCPs would reach the terminal velocity which has been estimated as

$$v_{\text{term}} = \frac{3 m_Q\, g T}{m_{\text{rock}}^2 n_{\text{rock}} < \sigma_T v_{\text{th}}^3 >} \quad \text{for } m_Q > m_{\text{rock}} \tag{2.2}$$

$$= \frac{m_Q\, g}{3 n_{\text{rock}} T}\left\langle \frac{v_{\text{th}}}{\sigma_T}\right\rangle \quad \text{for } m_Q < m_{\text{rock}}, \tag{2.3}$$

where m_{rock} and n_{rock} are the mass and number density of terrestrial medium atom, respectively, and v_{th} is the thermal velocity of mCPs after their thermalization in the atmosphere. Since the terminal velocity is slower than v_{vir} that is the average velocity of galactic mCPs, a so-called traffic jam effect causes an enhanced number density n_{tj} given by

$$n_{\text{tj}} = \frac{v_{\text{vir}}}{v_{\text{term}}} n_{vir} \tag{2.4}$$

where n_{vir} is the number density of galactic mCPs. Finally, the number density of mCPs underground can be estimated as

$$n_{\text{loc}} = \text{Max}\left(n_{\text{Jeans}}, \text{Min}(n_{\text{tj}}, \langle n_Q \rangle)\right), \tag{2.5}$$

where n_{Jeans} refers to the number density governed by the Jean's equation for a static, steady-state distribution of mCPs [21].

Following [41], we assume that all mCPs considered here are free of binding and spreading everywhere. We focus on the case of heavy mCPs ($m_Q \gtrsim 1$ GeV) and take benchmark values for accumulated number density $n_{\text{loc}} = 1$ cm^{-3}, 10^3 cm^{-3}, and 10^6 cm^{-3} in our numerical study.

3. mCPs and photon interaction

To probe the millicharged dark matter in a laser experiment, we start with the Hamiltonian describing the interaction between non-relativistic charged particles and the photon

$$H = H_P + H_R + H_I\,. \tag{3.1}$$

Here H_P, H_R, and H_I denote the free charged particles, the free radiation field, and the interaction between charged particles and the radiation, respectively. They are given by [43]

$$H_P = \sum_s \frac{\vec{p}_s^{\,2}}{2 m_s} + V_{\text{Coulomb}} \tag{3.2}$$

$$H_R = \sum_i \hbar\omega_i \left(\hat{a}_i^\dagger \hat{a}_i + \frac{1}{2}\right) \tag{3.3}$$

$$H_I = H_{I1} + H_{I2} \tag{3.4}$$

$$H_{I1} = -\sum_s \frac{\mathrm{q}_s}{m_s}\, \vec{p}_s \cdot \vec{A}(\vec{r}_s) \tag{3.5}$$

$$H_{I2} = \sum_s \frac{\mathrm{q}_s^2}{2 m_s}\left[\vec{A}(\vec{r}_s)\right]^2, \tag{3.6}$$

where $\vec{p}_s$, m_s, and q_s stand for the momentum, the mass, and the electric charge of the s-th charged particle, respectively. The operator $\hat{a}_i$ ($\hat{a}_i^\dagger$) describes the annihilation (creation) operator of the photon field for the i-th mode that satisfies the commutation relation $[\hat{a}_i, \hat{a}_j^\dagger] = \delta_{ij}$. We use the following photon field expression [43]

$$\vec{A}(\vec{r}) = \sum_i \left[\frac{\hbar}{2\,\epsilon_0\,\omega_i L^3}\right]^{1/2} \left[\hat{a}_i\, \vec{\varepsilon}_i\, e^{\mathrm{i}\vec{k}_i\cdot\vec{r}} + \hat{a}_i^\dagger\, \vec{\varepsilon}_i\, e^{-\mathrm{i}\vec{k}_i\cdot\vec{r}}\right]. \tag{3.7}$$

We quantize the photon field $\vec{A}(\vec{r})$ in a box of volume L^3 with a normalization condition $\vec{k}\cdot\vec{L} = 2\pi$. Note that the wave number and the angular frequency of the photon are related via $\omega = |\vec{k}|\,c$.

When the photon passes through the millicharged particles, it experiences the phase shift δ. This depends on how strong the probe photon interacts with the millicharged particles. In other words, the relevant part of the Hamiltonian responsible for the phase shift is $H_I = H_{I1} + H_{I2}$. The first term H_{I1} is suppressed by the millicharge velocity. Moreover, it is proportional to $(\hat{a} + \hat{a}^\dagger)$ which induces the energy transition in a bound system. However, for a free particle system, there is no such transition otherwise the energy conservation would be violated. Thus, we can neglect this term for free mCPs system under consideration.

The second term H_{I2} is proportional to $(\hat{a}\hat{a} + \hat{a}\hat{a}^\dagger + \hat{a}^\dagger\hat{a} + \hat{a}^\dagger\hat{a}^\dagger)$ which induces two photons transition. Both of the first and the last term violate photon number and energy conservation for free particle system. Therefore, only the second and the third term remain and we have

$$H_I \equiv \hat{H}_{\text{int}} = \sum_s \frac{q_s^2}{2 m_s}\left[\frac{\hbar}{2\,\epsilon_0\,\omega_i L^3}\right] 2\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right)$$

$$= \frac{\epsilon^2 e^2}{m_Q}\left[\frac{\hbar\,\omega^2}{16\pi^3\,\epsilon_0\, c^3}\right]\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) N_Q\,, \tag{3.8}$$

where we have assumed all mCPs have the same charge $q_s = \epsilon\, e$ and the same mass $m_s = m_Q$ such that the sum over mCPs is proportional to the total number of mCPs N_Q. We only consider a single photon mode which is well approximated by laser relevant for our proposal. We would like to detect the phase shift

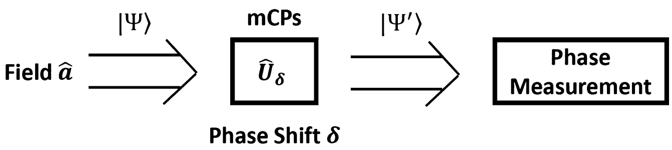

Fig. 1. The phase shift δ on the optical field $\hat{a}$ changes the photon state from $|\Psi\rangle$ to $|\Psi'\rangle$ due to photon-mCPs interaction.

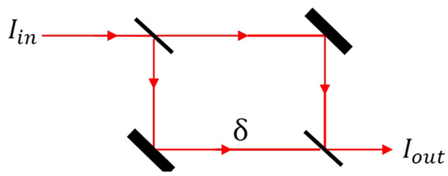

Fig. 2. Mach-Zehnder interferometer with a phase shift δ in one of its arm. [45].

induced by the mCPs-photon interaction using the phase measurement scheme illustrated in Fig. 1. The change of the photon state from $|\Psi\rangle$ to $|\Psi'\rangle$ occurs via the unitary operator $\hat{U}_\delta$ [44,45]

$$|\Psi'\rangle = \hat{U}_\delta\,|\Psi\rangle = e^{-\mathrm{i}\,\hat{H}_{\mathrm{int}}\mathrm{t}/\hbar}\,|\Psi\rangle = e^{-\mathrm{i}\,\hat{n}\delta}\,|\Psi\rangle \tag{3.9}$$

where $\hat{n} \equiv \hat{a}^\dagger \hat{a}$ is the photon number operator which has the average value $n \equiv \langle \hat{a}^\dagger \hat{a}\rangle \gg 1$.

However, due to the quantum nature of the light, there is a limitation that prevents us to probe the phase shift as accurate as possible. To demonstrate this, consider a simple interferometer shown in Fig. 2. The interferometer is adjusted in such a way that if there is no phase shift the output intensity would be zero [45]

$$I_{\mathrm{out}} = I_{\mathrm{in}}\,(1 - \cos\delta)/2\,. \tag{3.10}$$

For a well defined input intensity I_{in}, the change in the output intensity ΔI_{out} comes solely from the phase change $\Delta\delta$

$$\Delta I_{\mathrm{out}} = \frac{I_{\mathrm{in}}}{2}\,\Delta\delta\,\sin\delta\,. \tag{3.11}$$

The sensitivity to detect this change is maximized when $\delta = \pi/2$. Since the intensity can be written in term of the photon number, one has

$$\Delta N^{\mathrm{max}}_{\mathrm{out}} = \frac{N_{\mathrm{in}}}{2}\,\Delta\delta\,, \tag{3.12}$$

where N_{in} is the total photon number in the input and ΔN_{out} stands for the change in output photon number. In quantum mechanics, the lowest possible ΔN_{out} is one. Thus, the minimum detectable phase is given by the Heisenberg limit [46,47]

$$\Delta\delta \geq \frac{1}{N}\,, \tag{3.13}$$

where $N = N_{\mathrm{in}}/2$ is the total number of photon in one of the interferometer arms that encounters the phase shift. Typically, the number of photon in laser interferometer is of the order of 10^{20} or larger allowing us to detect a very tiny phase shift in the laboratory experiment.

4. Phase measurement scheme

In practice, there are several interferometers that achieve the Heisenberg limit [48–50]. One of them is the Mach-Zehnder interferometer shown in Fig. 3. We propose to use this interferometer to measure the change of the photon phase due to its interaction with mCPs.

The Mach-Zehnder (MZ) interferometer under consideration has two input ports. One of the ports is injected by a squeezed vacuum state $|-r\rangle$ while another port is fed by using a squeezed coherent state $|-r, -i\alpha\rangle$ [48], see Fig. 3. Here, the squeezed vacuum state is defined by

$$|r\rangle = e^{r(\hat{a}^{\dagger 2} - \hat{a}^2)/2}|0\rangle \equiv \hat{S}(r)|0\rangle\,, \tag{4.1}$$

where $\hat{S}(r)$ is the squeezing operator with a real positive value of squeezing parameter r [45]. In the photon number basis $|n\rangle$, the coherent state $|\alpha\rangle$ can be written as

$$|\alpha\rangle = e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}\,|n\rangle \equiv \hat{D}(\alpha)|0\rangle\,, \tag{4.2}$$

where $\hat{D}(\alpha) = e^{\alpha\hat{a}^\dagger - \alpha^*\hat{a}}$ is the displacement operator. Both of the squeezing operator as well as the displacement operator have the following effects when acting on the annihilation operator $\hat{a}$ and the creation operator $\hat{a}^\dagger$

$$\hat{S}^\dagger(r)\,\hat{a}\,\hat{S}(r) = \hat{a}\cosh r + \hat{a}^\dagger\sinh r\,, \tag{4.3}$$

$$\hat{S}^\dagger(r)\,\hat{a}^\dagger\,\hat{S}(r) = \hat{a}^\dagger\cosh r + \hat{a}\sinh r\,, \tag{4.4}$$

$$\hat{D}^\dagger(\alpha)\,\hat{a}\,\hat{D}(\alpha) = \hat{a} + \alpha\,, \tag{4.5}$$

$$\hat{D}^\dagger(\alpha)\,\hat{a}^\dagger\,\hat{D}(\alpha) = \hat{a}^\dagger + \alpha^*\,. \tag{4.6}$$

Using these operators, one can construct the squeezed coherent state $|r, \alpha\rangle$

$$|r, \alpha\rangle = \hat{S}(r)\,\hat{D}(\alpha)\,|0\rangle\,. \tag{4.7}$$

In MZ interferometer, two input fields enter the first 50:50 beam splitter which divides the photon path associated with two field operators $\hat{A}$ and $\hat{B}$. Next, the operator $\hat{A}$ transforms into $\hat{A}'$ due to its interaction with mCPs while another operator $\hat{B}$ becomes $\hat{B}'$ because of the interferometer adjustment. The later is set such that in the absence of mCPs-photon interaction, the dark fringe output located at $\hat{a}_{out}$ would read the squeezed coherent state input $|-r, -i\alpha\rangle$. The input annihilation operator $\hat{a}_{in}$ acts on the state $|-r\rangle$ while $\hat{b}_{in}$ operates on $|-r, -i\alpha\rangle$. Furthermore, the operators $\hat{A}$, $\hat{B}$, $\hat{A}'$, $\hat{B}'$, $\hat{a}_{out}$, and $\hat{b}_{out}$ appearing in Fig. 3 are

$$\hat{A} = \frac{(\hat{a}_{in} + \hat{b}_{in})}{\sqrt{2}}, \quad \hat{B} = \frac{(-\hat{a}_{in} + \hat{b}_{in})}{\sqrt{2}}\,, \tag{4.8}$$

$$\hat{A}' = \hat{A}\,e^{\mathrm{i}\delta}, \quad \hat{B}' = \hat{B}\,e^{\mathrm{i}\theta}\,, \tag{4.9}$$

$$\hat{a}_{out} = \frac{(\hat{A}' - \hat{B}')}{\sqrt{2}}, \quad \hat{b}_{out} = \frac{(\hat{A}' + \hat{B}')}{\sqrt{2}}\,. \tag{4.10}$$

We set $\theta = \pi$ such that the dark fringe output becomes

$$\hat{a}_{out} = \mathrm{i}\,e^{\mathrm{i}\delta/2}\left(\hat{a}_{in}\sin\frac{\delta}{2} - \mathrm{i}\,\hat{b}_{in}\cos\frac{\delta}{2}\right)\,. \tag{4.11}$$

We measure the quadrature amplitude $\hat{X}_a = \hat{a}_{out} + \hat{a}^\dagger_{out}$ at the output by homodyne detection (HD) and have

$$\hat{X}_a = -\sin\frac{\delta}{2}\,\hat{Y}_{a_{in}}(-\delta/2) + \cos\frac{\delta}{2}\,\hat{X}_{b_{in}}(-\delta/2)\,. \tag{4.12}$$

Here, we have defined $\hat{Y}_{a_{in}}(-\delta/2)$ and $\hat{X}_{b_{in}}(-\delta/2)$ as

$$\hat{Y}_{a_{in}}(-\delta/2) = -\mathrm{i}\left(\hat{a}_{in}\,e^{\mathrm{i}\,\delta/2} - \hat{a}^\dagger_{in}\,e^{-\mathrm{i}\,\delta/2}\right)\,, \tag{4.13}$$

$$\hat{X}_{b_{in}}(-\delta/2) = \left(\hat{b}_{in}\,e^{\mathrm{i}\,\delta/2} + \hat{b}^\dagger_{in}\,e^{-\mathrm{i}\,\delta/2}\right)\,. \tag{4.14}$$

To determine the signal to noise ratio (SNR) of our phase measurement, one needs the expectation value of the quadrature amplitude $\hat{X}_a$ as well as its fluctuation $\Delta^2\hat{X}_a$

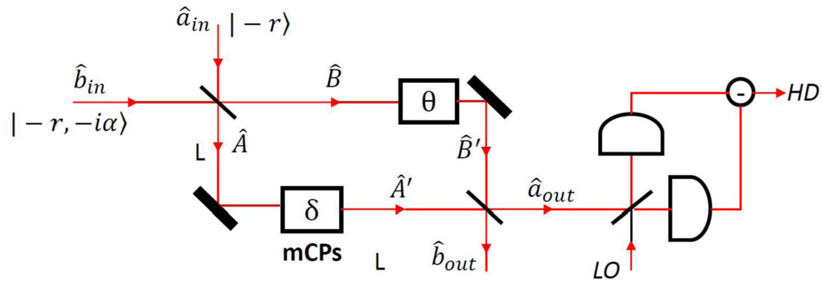

Fig. 3. Mach-Zehnder interferometer used in [48] with squeezed coherent state and squeezed vacuum in its input. The phase shift δ induced by mCPs-photon interaction is measured at the output port by homodyne detection (HD) via local oscillator (LO).

$$\left\langle \hat{X}_a \right\rangle = \alpha\,(\mu+\nu)\sin\delta \tag{4.15}$$

$$\left\langle \Delta^2 \hat{X}_a \right\rangle = (\mu-\nu)^2\,, \tag{4.16}$$

with $\mu = \cosh r$ and $\nu = \sinh r$. The signal to noise ratio (SNR) for the observable $\hat{X}_a$ reads [45]

$$\mathrm{SNR} \equiv \frac{\left\langle \hat{X}_a \right\rangle^2}{\left\langle \Delta^2 \hat{X}_a \right\rangle} = \frac{\alpha^2\,(\mu+\nu)^2 \sin^2\delta}{(\mu-\nu)^2}\,. \tag{4.17}$$

The phase sensing photon number is defined as $N_{ps} \equiv \left\langle \hat{A}^\dagger \hat{A} \right\rangle = \nu^2 + \alpha^2(\mu+\nu)^2/2$. We keep N_{ps} constant and take $\nu \gg 1$ such that $\mu - \nu = 1/(\mu+\nu) \approx 1/2\nu$. Thus, the SNR becomes

$$\mathrm{SNR} = 8\,(N_{ps} - \nu^2)\,\nu^2 \sin^2\delta \le 2\,N_{ps}^2 \sin^2\delta\,, \tag{4.18}$$

reaching the maximum value when $\nu^2 = N_{ps}/2$. In the limit $\delta \ll 1$ and SNR ~ 1, the minimum detectable phase shift is $\delta_{min} \sim 1/N_{ps}$ or the Heisenberg limit. From here on, we take the maximum SNR value in Eq. (4.18).

5. Results and discussion

To claim a discovery, the required SNR value must be larger than one. We take three benchmark values of millicharged mCPs density n_{Q}: $1\,\mathrm{cm}^{-3}$, $10^3\,\mathrm{cm}^{-3}$, and $10^6\,\mathrm{cm}^{-3}$ to compare with the projected sensitivities set by ion trap proposal [41]. Looking at Eq (3.8) and (3.9), the phase shift is given by

$$\delta = \frac{\epsilon^2 e^2}{m_{\mathrm{Q}}} \left[\frac{\omega^2}{16\,\pi^3\,\epsilon_0\,c^3}\right] N_{\mathrm{Q}}\,t\,. \tag{5.1}$$

Since the probed photon only interacts with mCPs along its path ℓ, the total mCPs number N_{Q} can be obtained by integrating the number of mCPs per unit length with respect to the total length traversed by the photon

$$N_{\mathrm{Q}} = \int_0^{\mathrm{L}} d\ell\,\tilde{n}_{\mathrm{Q}}\,, \tag{5.2}$$

where L is the interferometer arm length and $\tilde{n}_{\mathrm{Q}} = n_{\mathrm{Q}}^{1/3}$ denotes the number of mCPs per unit length in cm^{-1}. In this case, the number of mCPs per unit length for three different mCPs densities considered here are $1\,\mathrm{cm}^{-1}$, $10\,\mathrm{cm}^{-1}$, and $100\,\mathrm{cm}^{-1}$, respectively. The time parameter t in Eq. (5.1) describes the mCPs-photon interaction time which is simply L/c.

The sensitivity of MZ interferometer is shown in Fig. 4. For $n_{\mathrm{Q}} = 1\,\mathrm{cm}^{-3}$ (the upper left panel), the excluded region from collider search is also given by the gray area in the upper-left corner. Moreover, the parameter regime of projected sensitivity from ion trap proposal is shown by the light blue region. The light red region corresponds to the SNR $>$ 1 of our phase measurement scheme. We see that our proposal is several orders of magnitude more sensitive compared to the existing limits. For higher mCPs number density, ion trap results cover several regions of parameter space in case of $n_{\mathrm{Q}} = 10^3\,\mathrm{cm}^{-3}$ depending on the ion employed in the trap (see the upper-right panel of Fig. 4). As the number of mCPs density gets higher, the ion trap proposal covers large area in the parameter space of coupling ϵ and mCPs mass m_{Q}. Still, for these two cases, our proposal is taking a lead on sensitivity as can be seen from the light red area for mCPs density equals to $10^3\,\mathrm{cm}^{-3}$ and $10^6\,\mathrm{cm}^{-3}$ (the upper-right and lower panel), respectively. This shows that the MZ interferometer can be utilized as mCPs detector in higher mCPs mass, especially the earth bound mCPs.

6. Summary

The existence of mCPs can be naturally realized if the dark sector communicates with the SM via a $U(1)$ mixing. It is possible that the mCPs constitute a part of the dark matter and are stopped and accumulated inside the earth. As a result, the number density of mCPs inside the earth can be several orders of magnitude higher than that of the local DM. In this paper, we propose that the mCPs bound in earth can be probed by using the Mach-Zehnder interferometer (MZ interferometer) though a phase shift of laser beam when photons interact with mCPs, and we focus on the case of heavy mCPs of mass $m_Q > 1$ GeV. Notice that, for the mass of mCPs to be larger than 1 GeV, the number density underground will be much higher than that on the surface of the earth due to gravitational pull and traffic jam effects [22]. Hence, one arm of the MZ interferometer should be implemented underground (e.g. the lower horizontal beam with $\hat{A}'$ in Fig. 3) while the other arm on the earth surface (e.g. the upper horizontal beam with $\hat{B}'$ in Fig. 3). The difference of the number densities of mCPs in the locations of two arms of MZ interferometer could be significant.

Given the number density of mCPs underground, we estimate the signal to noise ratio for the phase shift, and found that the $U(1)$ mixing parameter ϵ can be probed as low as the order of 10^{-11} (10^{-13}) if the number density underground is about 1 cm^{-3} (10^6 cm^{-3}) for mass of mCPs around 1 GeV. As compared with the current bound by LHC, where ϵ is of order $10^{-3} \sim 10^{-2}$, the sensitivity of our proposal is about 10^{10} higher for the mass of mCPs m_Q up to 100 GeV. One should also notice that for $m_Q \gtrsim 1$ GeV, astrophysical observations and beam-dump experiments have no sensitivity. Even compared with the novel detection approach using ion trap recently proposed by [41], MZ interferometer can cover larger parameter space.

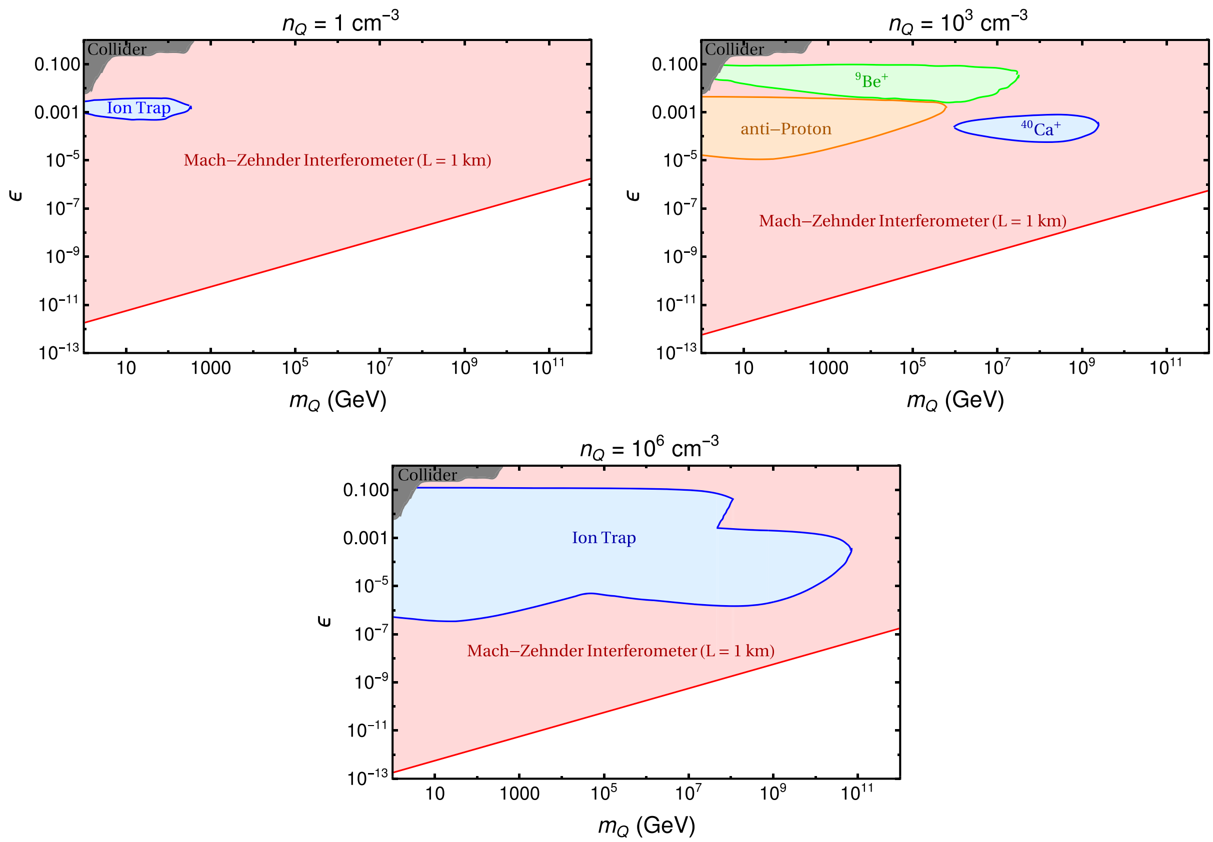

Fig. 4. The projected sensitivity of MZ interferometer with arm length L = 1 km and 1.17 eV laser for different mCPs densities n_Q: 1 cm^{-3} (top-left), 10^3 cm^{-3} (top-right), and 10^6 cm^{-3} (bottom). We take the phase sensing photon number $N_{ps} = 10^{23}$ [51–54].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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