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Detecting Quadratically Coupled Ultra-Light Dark Matter with Stimulated Annihilation

Yuanlin Gong[A,1], Xin Liu[B,1], Lei Wu[C,1], Qiaoli Yang[D,2], Bin Zhu[E,3]
[1]Nanjing Normal University, [2]Jinan University, [3]Yantai University

Quadratic Interaction

$$\mathcal{L} = \frac{d_e^{(2)}}{4}\frac{2\pi}{M_{Pl}^2}\phi^2 F_{\mu\nu}F^{\mu\nu} \quad (1)$$

In the background of f_γ radio wave photons

Effective Amplitude

$$M = \mathcal{M}_0^2(f_\phi^2 + 2f_\gamma f_\phi^2 - 2f_\phi f_\gamma^2 - f_\gamma^2) \quad (2)$$

Spontaneous ann. — Stimulated ann. — Inverse spontaneous ann. — Inverse stimulated ann.

Boltzmann Equation

Flux Density

$$\dot{n}_\gamma = 4\beta n_\phi^2 \sigma_0 (1 + 2f_\gamma) \quad (3)$$

Integrate over the time, the solid angle along the direction of the outgoing emission beam, the frequency, and the area

Signal Power

$$P = \frac{1}{8}\frac{g'^2}{m}\frac{P_0}{\Delta\nu}\int_0^{t_{\rm off}} \rho_\phi^2\, dt \quad (4)$$

$$P_n = 2kT_{\rm sys}\sqrt{\frac{\Delta}{t_{\rm off}}}$$

- $d_e^{(2)}$ coupling
- $g' = d_e^{(2)}\frac{2\pi}{M_{Pl}^2}$
- M_{Pl}^2 Plank mass
- $\mathcal{M}_0$ Spontaneous annihilation amplitude.
- f_ϕ, f_γ Phase space function
- n_ϕ, n_γ Number density of ULDM, photon
- β Velocity of the ULDM
- $\Delta\nu$ Bandwidth of ULDM
- $t_{\rm off}$ Effective work time of the emitter
- ρ_ϕ Energy density of ULDM
- Δ Frequency resolution
- P_n Noise power

Motivation

- Ultra-Light Dark Matter (ULDM) is one of the most promising DM candidates. The wavelike nature of ULDM can not only preserve the merits of cold dark matter, but also may provide a solution to the small-scale structure problem.
- The quadratic interactions of the ULDM dominating over the linear ones in recent years have drawn particular interest, such as in theories with Z_2 symmetry [1,2].
- Because of the Bose enhancement [3,4], we find the annihilation rate of ULDM in the presence of background photon radiation can be greatly enhanced and produce a distinctive reflected electromagnetic wave with an angular frequency equal to the ULDM mass.
- We find the production rate of the photons depends on the ULDM density as $\rho_{\rm DM}^2$, rather than $\rho_{\rm DM}$ in the linear interaction.
- We thus propose to utilize such stimulated annihilation to probe the ULDM with electromagnetic quadratic coupling by emitting a radio beam into space.

Methods

- The quadratic interaction (in Eq. (1)) of the ULDM field ϕ with the electromagnetic fields A_μ allows the spontaneous annihilation of two ULDMs into two back-to-back photons $\phi\phi \to \gamma\gamma$. Unfortunately, the corresponding cross section
$$\sigma_0 = \frac{1}{32\pi}\frac{1}{\beta}g'^2 m_\phi^2,$$
is suppressed by the tiny mass of the LUDM.
- In the present of the background of f_γ photons, however, due to the Bose enhancement, the effective amplitude can be enhanced by a factor $2f_\gamma$, which can manifest in Eq. (2) and Eq. (3).
- The signal power received by the telescope can be integrated out as Eq. (4).
- Finally, basing on the performance and related parameters of the array telescope, we get the limits on the coupling $d_e^{(2)}$ for different kinds of local halo modes at the benchmark of $P_0 = 50$ MW.
- Last but not the least, we have verified explicitly that, the process $n\phi \to \gamma\gamma$ (n>3) is subdominant to the $\phi\phi \to \gamma\gamma$ despite the potential enhancement $\dot{n} \propto f_\phi^n$. This is because $\dot{n}$ is actually proportional to a dimensionless factor $\left(\frac{\rho_\phi}{2M_{Pl}^2 m_\phi^2}\right)^n \frac{n^4}{n!}$, which decreases in power with n in our model.

Detection Setup

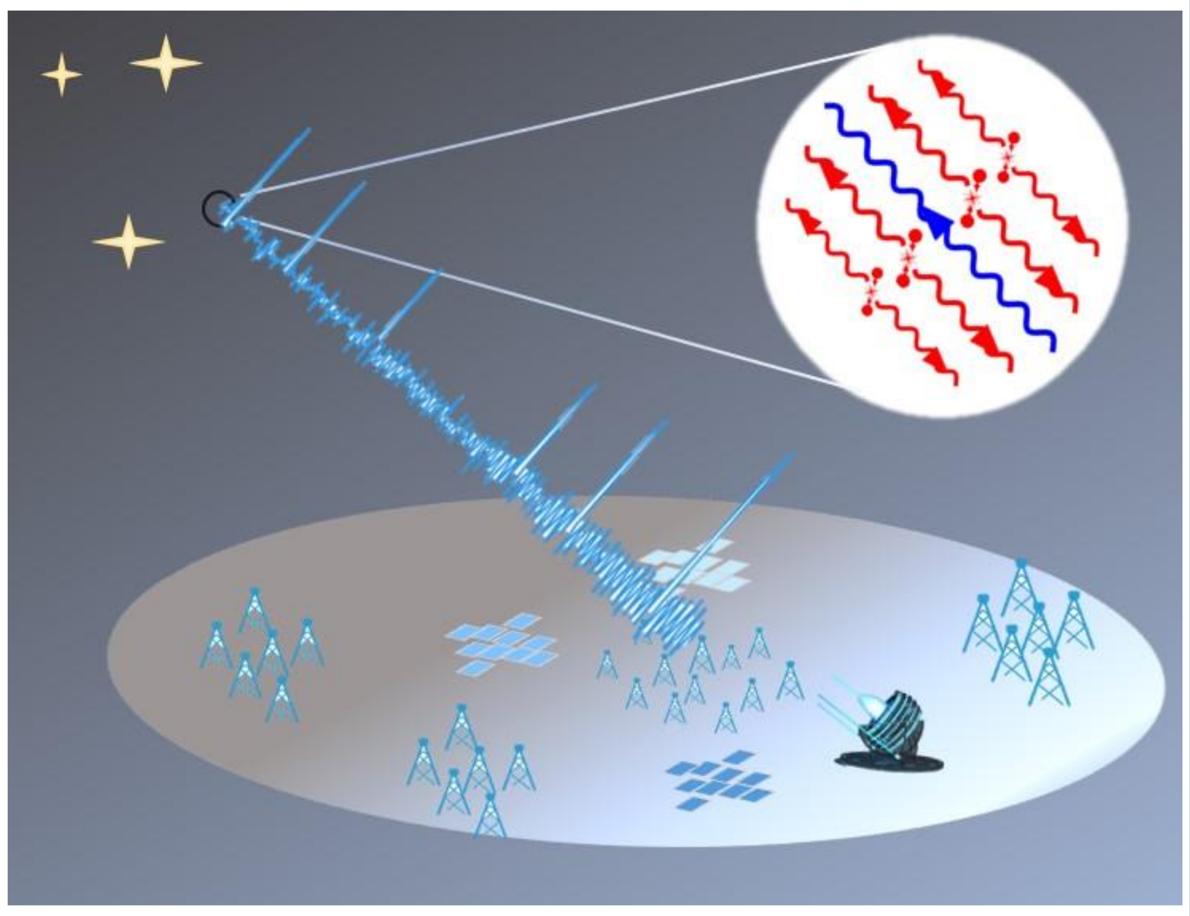

Figure 1. Conceptual design of our proposed experiment. A powerful radio beam (blue wavy line) is sent to space to stimulate the annihilation of the ULDM (red bullet). The reflected radio (red wavy line) will be detected by the array telescope, such as LOFAR, ngLOBO, UTR-2.

Results

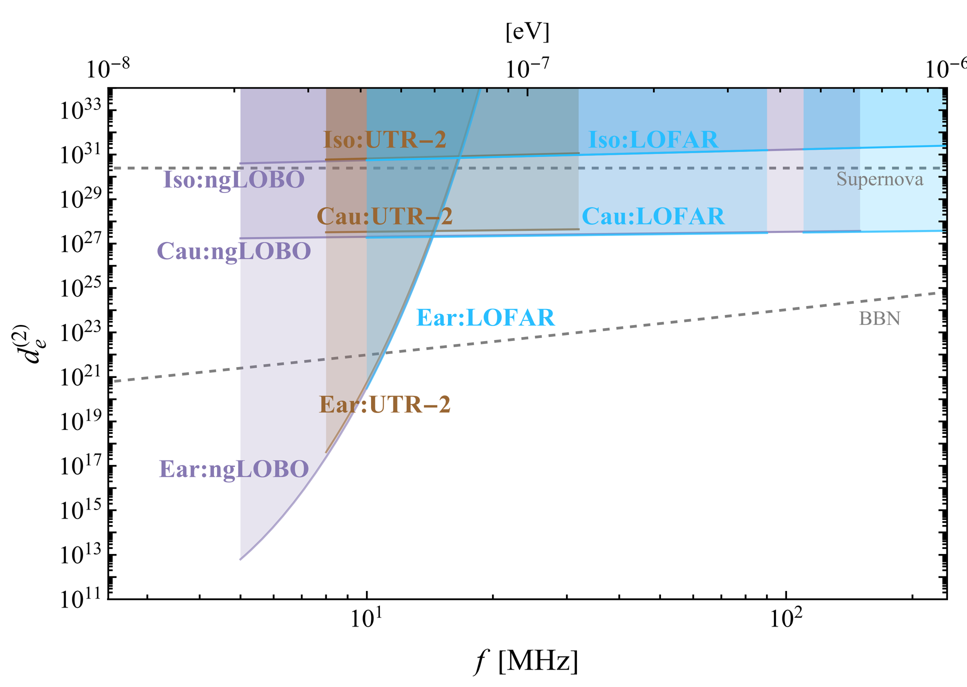

Figure 2. Projected Limits on the $d_e^{(2)}$. In $5 < f < 20$ MHz, for the earth halo, the limits can be at most 8 orders of magnitude stronger than that of the BBN and at most 17 orders of magnitude stronger than that of the Supernova.

Contact

[A]yuanlingong@nnu.edu.cn
[B]liuxin@njnu.edu.cn
[C]leiwu@njnu.edu.cn
[D]qiaoliyang@jnu.edu.cn
[E]zhubin@mail.nankai.edu.cn

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Base on our recent work: Y. Gong *et al*, PhysRevD.109.055026(2024).