DARK PHOTON-PHOTON RESONANCE CONVERSION OF GRB221009A THROUGH EXTRA DIMENSION

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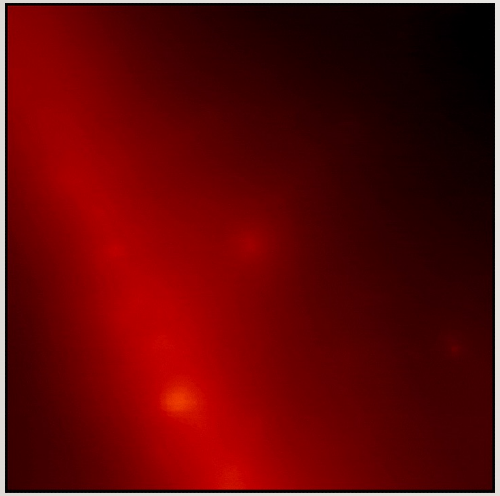
GRB221009A



https://svs.gsfc.nasa.gov/14227/

is an extraordinarily bright and very energetic Gamma Ray Burst (GRB) which detected on October 9, 2022 at redshift z = 0.1505 or approximately 636 Mpc.

Problem:
cannot explained by the SM

Solution:

- the light scalar particle (arXiv:2301.02258)
- the photon to axion-like particle (ALP) conversion (arXiv:2408.0735, arXiv:2210.13120, …)
- high energy photon induced by heavy neutral lepton decay (arXiv:2212.03477, arXiv:2210.14178, …)
- Lorentz invariance by cosmic high energy photon (arXiv:2210.06338, arXiv:2210.05563, …)

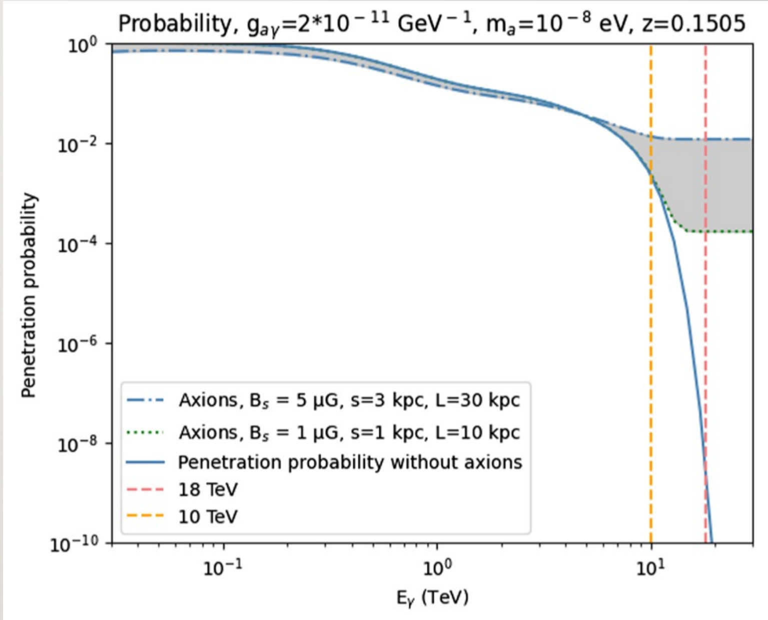
ALTERNATIVE
PHOTON DARK PHOTON OSCILATION IN EXTRA DIMENSION

Why dark photon?

- Because the SM fails to explain
- it does not need to specify the plasma density as well as the magnetic field alignment of the source galaxy as required by the ALP models

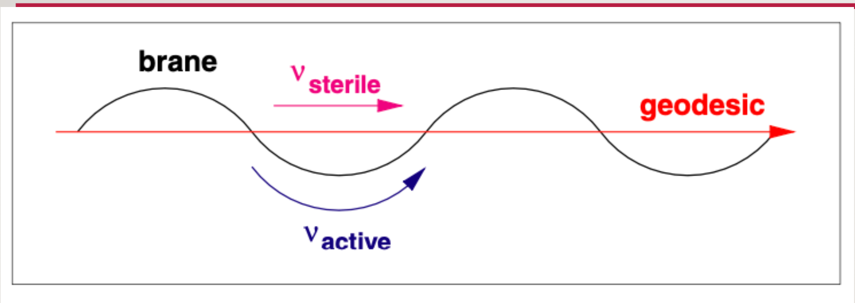
Why we need extra dimension?

- based on the typical magnitude of the magnetic field of the source galaxy in ALP models, only less than 1 percent of initial photon flux could pass through the intergalactic medium. (arXiv:2304.01819, arXiv:2412.19320, arXiv:2502.03453)
- Using extra dimension we can enhance penetration probability



arXiv:2304.01819

THE MAIN SCENARIO



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Lagrangian interaction of dark photon

$$\mathcal{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F^{'\mu\nu}F^{'}_{\mu\nu} + \frac{\epsilon}{2}F^{\mu\nu}F^{'}_{\mu\nu} + \frac{1}{2}m_{\gamma'}A^{'\mu}A^{'}_{\mu}\,.$$

In dealing with photon-dark photon oscillation, it is more convenient to write the Lagrangian in active-sterile basis

$$\mathbf{A}^{\mu} \equiv \begin{pmatrix} A_a^{\mu} \\ A_s^{\mu} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\epsilon & 1 \end{pmatrix} \begin{pmatrix} A^{\mu} \\ A^{'\mu} \end{pmatrix} + \mathcal{O}(\epsilon^2)\,,$$

In this new basis, the Lagrangian in can be written as

$$\mathcal{L} = -\frac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu} - \frac{1}{4}F_s^{\mu\nu}F^s_{\mu\nu} + \frac{1}{2}\mathbf{A}_{\mu}^T\mathcal{M}^2\mathbf{A}^{\mu} + \mathcal{O}(\epsilon^2)\,.$$

where

$$\mathcal{M}^2 \approx \begin{pmatrix} m_{\text{eff}}^2 & \epsilon\, m_{\gamma'}^2 \\ \epsilon\, m_{\gamma'}^2 & m_{\gamma'}^2 \end{pmatrix},$$

To compute the conversion probability of photon to dark photon or vice versa, one needs to solve the Klein-Gordon (KG) equation which in the frequency domain reads

$$(\omega^2 - k^2 - \mathcal{M}^2)\,\tilde{\mathbf{A}}^\mu(\omega, k) \;=\; 0\,,$$

In relativistic limit $\omega \approx k \gg m_{\gamma'}\,, m_{\rm eff}$

$$i\partial_z \mathbf{A}^\mu = H_0 \mathbf{A}^\mu\,,$$

where

$$H_0 = \begin{pmatrix} \omega + \Delta_{\rm pl} & \epsilon\,\Delta_{A'} \\ \epsilon\,\Delta_{A'} & \omega + \Delta_{A'} \end{pmatrix}\,.$$

$$\Delta_{\rm pl} \;=\; -\frac{m_{\rm eff}^2}{2\,E} \;\text{ and }\; \Delta_{A'} \;=\; -\frac{m_{\gamma'}^2}{2\,E}\,,$$

EXTRA DIMENSION CONTRIBUTION

Difference path between brane and bulk:

$$\delta = \frac{z_{\rm bulk} - z_{\rm brane}}{z_{\rm bulk}} \,,$$

This effect gives an additional term in the Hamiltonian

$$H_\delta = \begin{pmatrix} \Delta_\delta & 0 \\ 0 & -\Delta_\delta \end{pmatrix} \text{ with } \Delta_\delta = -\frac{E\,\delta}{2} \,.$$

Taking into account this additional term, the linearized Schrodinger-like equation becomes

$$i\partial_z \mathbf{A}^\mu = (H_0 + H_\delta)\, \mathbf{A}^\mu \equiv H\, \mathbf{A}^\mu \,,$$

where

$$H = \begin{pmatrix} E + \Delta_{\rm pl} + \Delta_\delta & \epsilon\, \Delta_{A'} \\ \epsilon\, \Delta_{A'} & E + \Delta_{A'} - \Delta_\delta \end{pmatrix}$$

To solve previous equation, we need to diagonalize by introducing:

$$VHV^\dagger = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix},$$

where

$$V = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \quad \text{with} \quad \tan 2\theta = \frac{2\epsilon\Delta_{A'}}{\Delta_{A'} - \Delta_{\mathrm{pl}} - 2\Delta_\delta}.$$

$$\Longrightarrow \quad \lambda_{1,2} = \frac{1}{2}\left\{(2\,E + \Delta_{\mathrm{pl}} + \Delta_{A'}) \pm \sqrt{4\epsilon^2\Delta_{A'}^2 + (\Delta_{\mathrm{pl}} - \Delta_{A'} + 2\Delta_\delta)^2}\right\}.$$

In this diagonal basis $\tilde{\mathbf{A}}^{\mu} = V\mathbf{A}^{\mu}$

The propagation from initial point z_0 to z: $\tilde{A}^{\mu}_{j}(z) = e^{-i\,(z-z_0)\,\lambda_j}\,\tilde{A}^{\mu}_{j}(z_0)\,.$

Assuming that we have a photon (active field) in the initial state at $z_0 = 0$, the probability of detecting dark photon (sterile field) after traversing a distance z is:

$$P_{\gamma\to\gamma'} = |\langle A_s(z)|A_a(z_0)\rangle|^2\;, \Longrightarrow P_{\gamma\to\gamma'} = \frac{4\epsilon^2\Delta^2_{A'}\sin^2\left(\frac{z}{2}\sqrt{4\epsilon^2\Delta^2_{A'} + (\Delta_{\rm pl} - \Delta_{A'} + 2\Delta_\delta)^2}\right)}{4\epsilon^2\Delta^2_{A'} + (\Delta_{\rm pl} - \Delta_{A'} + 2\Delta_\delta)^2}\,.$$

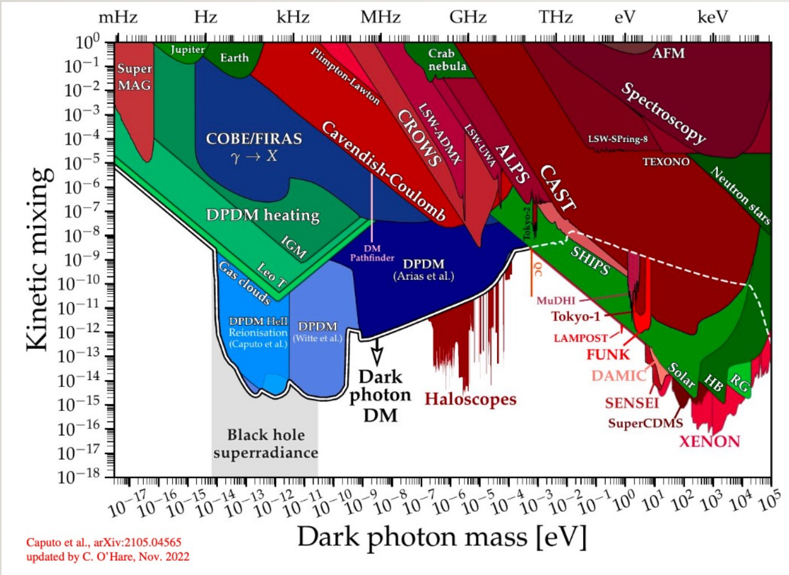
In the resonance condition

$$\Delta_{A'} - \Delta_{\rm pl} = 2\Delta_\delta \,.$$

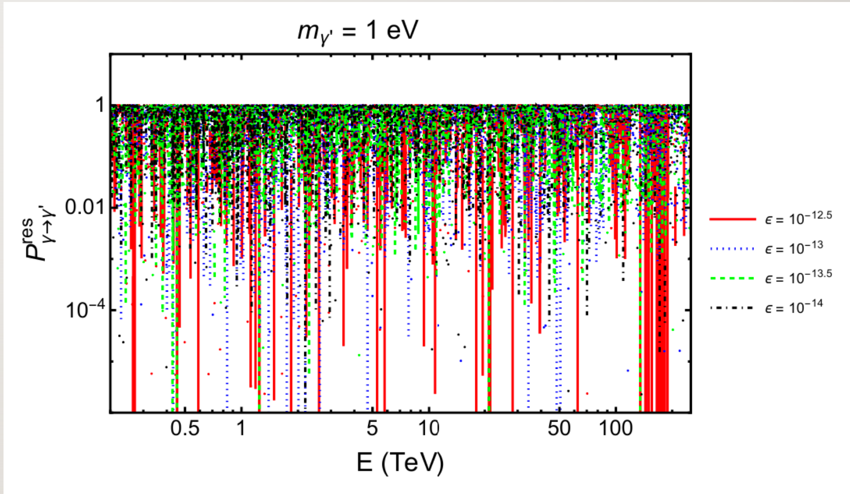
$$\Downarrow$$

$$P^{\rm res}_{\gamma\to\gamma'} = \sin^2\left(z\,\epsilon\,\Delta_{A'}\right)\,. \quad E_{\rm res} \approx \sqrt{\frac{m^2_{\gamma'}}{2\,\delta}}\,,$$

RESULT AND DISCUSSION

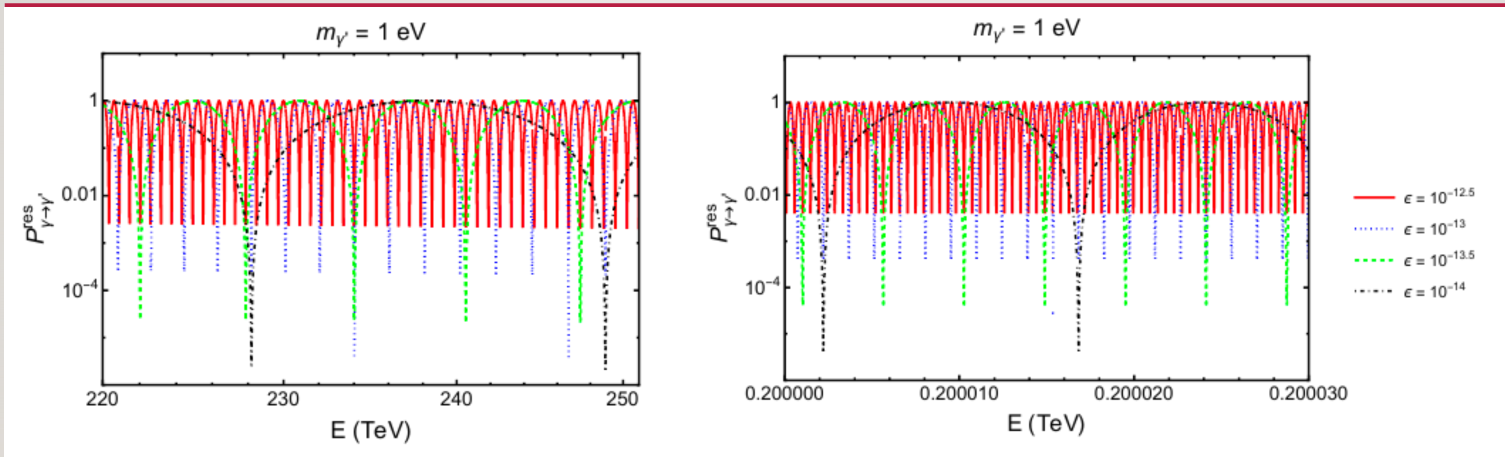


J.M. Cline, arXiv:2405.08534 [hep-ph]



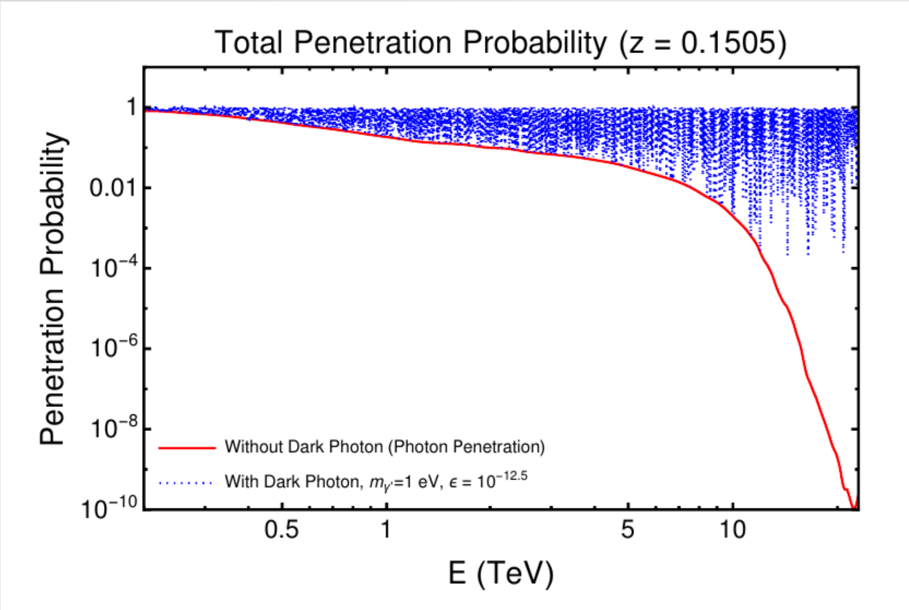
Resonance conversion from photon to dark photon in the intergalactic medium

CONVERSION PHOTON TO DARK PHOTON



High energy regime and low energy regime

PENETRATION PROBABILITY

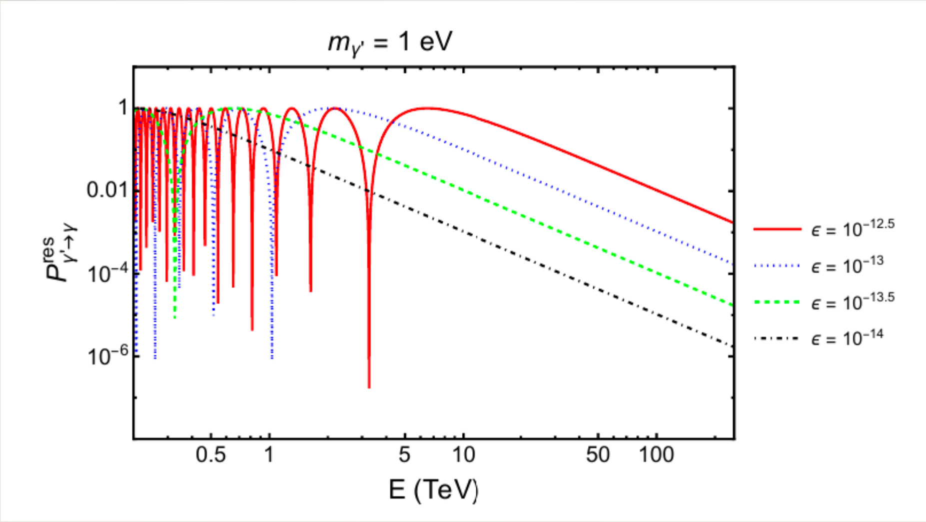


Resonance conversion of photon into dark photon and vice versa in intergalactic medium

Total penetration probability without dark photon (red solid line) and with dark photon (blue dotted line) from $z = 0.1505$. The red solid line indicates the photon penetration probability which is scattered by the EBL.

$$[I_\gamma(E) + I_{\gamma'}(E)] \,/ I_0(E_0) = (1 - P^{\rm res}_{\gamma\to\gamma'})\, e^{-\tau_\gamma(E)} + P^{\rm res}_{\gamma\to\gamma'}$$

RECONVERSION DARK PHOTON TO PHOTON



$$n_e \approx 1.1 \times 10^{-3}\ \mathrm{cm}^{-3}$$
$$m_{\mathrm{eff}}^2 = 4\pi\alpha n_e/m_e \approx 4.1 \times 10^{-12}\ \mathrm{eV}$$
$$z = 23.95\ \mathrm{kpc}$$

CONCLUSION

- By setting dark photon mass to 1 eV as well as taking four benchmark values of the photon-dark photon mixing parameter $\epsilon = 10^{-12.5}, 10^{-13}, 10^{-13.5}, 10^{-14}$, we demonstrate that there is 10^{-6} up to 95% fraction of the initial GRB221009A photon flux would be detectable at the terrestrial gamma ray observatories.