Implications of Dark Photon Dark Matter for Gravitational Waves

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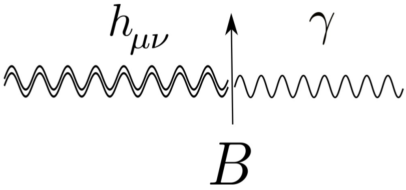
The Gertsenshtein effect: Graviton-Photon Conversion

In a background magnetic field, an incident graviton has a non-zero probability of conversion into a photon.

Derive through the coupling to the energy-momentum tensor $h_{\mu\nu} T^{\mu\nu}$.

Dependent on the magnetic field strength and the length of propagation.



Sufficiently large B and distances $\rightarrow$ graviton-photon oscillations.

Modified from 2006.01161

Conversion in Cosmological Magnetic Fields

Large scale magnetic fields allow for large propagation lengths.

Possible route for detecting high frequency gravitational waves.

- Upper bound on size of intergalactic magnetic fields: $B_0 < 10^{-9}$ G.
- Effective photon mass induced by plasma effects, suppresses the conversion probability.
- Strongly suppressed in the early universe despite stronger B.

Dark Magnetic Fields

Consider instead a dark $U(1)$, that will undergo graviton-dark photon conversion

- Weakened constraints on dark magnetic fields today, by 3 orders of magnitude: $B_0 < 10^{-6}$ G from N_{eff}.
- There may be no dark matter plasma to suppress the conversion probability, or the coupling and density can be small.
- Possibly generated by inflation or first order phase transition, providing information about the early universe.
- Dark matter candidate with imprints of the gravitational wave spectrum.

Dark Photon Dark Matter

The dark matter energy density of the universe today,

$$\rho_{\rm DM} \simeq 9.6 \cdot 10^{-48}\ {\rm GeV}^4\ .$$

- No convincing experimental evidence for proposed dark matter candidates.
- Go beyond the usual WIMP paradigm.
- Novel production methods, such as couplings to the inflaton.
- Differentiable observational and experimental signatures.
- Kinetic mixing to photon.

Initial Set-up

Assume that,

- Stochastic Dark Magnetic field with energy density $\rho_{DM} \simeq \frac{B^2}{2}$ and characteristic momenta k_*, with $\Omega^r_{DM} < 0.01$.
- Gravitational waves with momenta ω propagate in this background with $\Omega^r_{GW} < 0.01$ during the radiation dominated epoch.
- The dark magnetic field is slowly varying relative to the GW, $k_* \ll \omega$.
- The dark photon becomes non-relativistic before matter-radiation equality, $k_*(T_m) < m_{DM}$.
- Stuekelberg mass or from spontaneous symmetry breaking.

Conversion Probability

Solve EOMs of photon and gravitational wave in the dark magnetic field.

In flat spacetime, with propagation distance L and small m_{DM}, the probability is approximately,

$$P_{g\to\gamma} \simeq \sin^2\left(\sqrt{\frac{B_T}{\sqrt{3}M_p}}L\right)$$

In FRW spacetime, must include the dilution with scale factor:

$$i\frac{d}{da}\begin{pmatrix} h_\lambda(a) \\ A_\lambda(a) \end{pmatrix} = \frac{1}{aH}\begin{pmatrix} 0 & \Delta_{GD}(a) \\ \Delta_{GD}(a) & \Delta_D(a) \end{pmatrix}\begin{pmatrix} h_\lambda(a) \\ A_\lambda(a) \end{pmatrix},$$

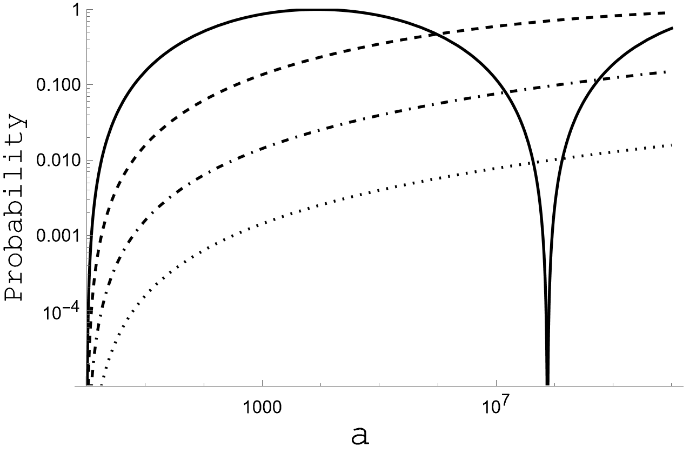
where $\Delta_{GD}(a) = \frac{B_T^0}{\sqrt{3}M_p a^2}$ and $\Delta_D(a) = -\frac{m_{DM}^2}{2\omega}$

For $\Delta_D \to 0$, the probability is given by

$$P_{g\to\gamma} \simeq \sin^2(\sqrt{\Omega_{\rm DM}}\ln(a))$$

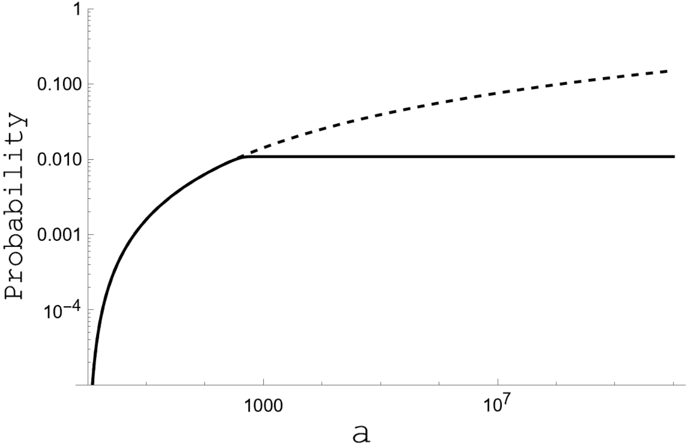
Conversion Probability

For a small mass and approximately constant magnetic field,



for $\Omega_{\mathrm{DM}} = 0.01, 0.001, 0.0001, 0.00001$

Conversion Probability



Once the mass becomes important, the conversion quickly slows.

Dark Photon Dark Matter

If we want the dark photon to also be dark matter:

- ρ_{DM} dilutes as radiation until the characteristic momenta becomes comparable to its mass m_{DM}.
- Then it will become non-relativistic and will instead redshift in a matter-like way.
- The temperature at which this occurs is given by,

$$T_m = m\frac{T_{\rm reh}}{k_*} = m\left(\frac{90}{\pi^2 g_*}\right)^{1/4}\frac{\sqrt{M_p H_{\rm inf}}}{k_*}$$

where we have taken $k_{\rm phys} = k_* \frac{T}{T_{\rm reh}}$ in this case.

Dark Photon Dark Matter

Thus, the required dark photon density at the end of inflation is:

$$\rho_{\mathrm{DM}}^{\mathrm{req}} = 7 \cdot 10^{57}\ \mathrm{GeV}^4 \left(\frac{10^{-10}\ \mathrm{GeV}}{m}\right) \left(\frac{H_{\mathrm{inf}}}{10^{12}\ \mathrm{GeV}}\right)^{5/2}$$

which can be converted to a ratio of the total energy density of the universe ($\rho = 3M_p^2 H_{\mathrm{inf}}^2$),

$$\Omega_{\mathrm{DM}}^{\mathrm{req}} = 0.01 \left(\frac{4 \cdot 10^{-12}\ \mathrm{GeV}}{m}\right) \left(\frac{H_{\mathrm{inf}}}{10^{12}\ \mathrm{GeV}}\right)^{1/2}$$

The maximum contribution to the DM from gravitational waves is $\sim 0.5\%$.

Additional Dark Sector Components

- Effects of possible dark fermions are dependent on size of coupling g_D and mass scales.
- Plasma effects can be strongly suppressed relative to the usual magnetic field case, preserving the efficient conversion.
- The dark $U(1)$ could have Stuekelberg mass or be generated by spontaneous symmetry breaking.
- Imprints of these scales on the gravitational wave spectrum.
- Additional $U(1)$ fields.
- Inclusion of E component - ratio to B important to determining possible chiral effects and enhancement/suppression.

Conclusion

Dark magnetic fields lead to efficient graviton-photon conversion in the early universe.

- Imprints of gravitational wave sources on the dark matter spectrum.
- Correlated imprints in the gravitational wave spectrum.
- Avoids effects that suppress the conversion probability for ordinary magnetic fields.
- Kinetic mixing between dark photon and SM photon provides experimental tests.
- Signatures of other dark sector components also imprinted in gravitational waves.

Thank You! :)