Massive Hidden Photons as Lukewarm Dark Matter

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U(1) symmetries in Hidden sectors arise frequently in extensions of SM, specially those based in String Theory. Usually very massive but small masses are also possible, (usually related with large volume scenarios). Very simple models to study
Hidden sector photons, kinetic mixing & flavor oscillations

Visible sector

\[-\frac{1}{4} A_{\mu \nu} A^{\mu \nu} + ej_\mu A^\mu\]

Hidden sector

\[-\frac{1}{4} B_{\mu \nu} B^{\mu \nu} + \frac{1}{2} m_{\gamma'}^2 B_\mu B^\mu\]

Window

\[-\frac{\sin \chi}{2} A_{\mu \nu} B^{\mu \nu}\]
Hidden sector photons, kinetic mixing & flavor oscillations

\[ \mathcal{L}_H = -\frac{\sin \chi}{2} A_{\mu\nu} B^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{2} m_{\gamma'} B_\mu B^\mu \]

- In principle can have any value between 0 and 1...
- If B belongs to a broken non abelian group, \(\sin \chi = 0\) at high \(E\), but it can develop a nonzero value below the SSB scale

\[ A^\mu \quad \sum \psi_{AB} \quad B^\mu \quad = \frac{e g_B}{6\pi^2} \sum Q_A Q_B \log \frac{m_{\psi_{AB}}}{\mu} \]

SUSY, String theory ...

\(\sin \chi = 10^{-4}, -16\)

K. R. Dienes, C. F. Kolda, and J. March-Russell. Nucl. Phys., B492:104–118, 1997.
Hidden sector photons: The Parameter space

Contribution to Cosmic Radiation Density

New experiments @ meV valley:
- ALPS @ DESY (regeneration)
- SuperConducting Box
- SuperK and Improved CAST

Decaying lukewarm Dark Matter?
photon “Flavor” oscillations & kinetic mixing

\[ \begin{align*}
- \frac{1}{4} A_{\mu \nu} A^{\mu \nu} & \quad - \frac{\sin \chi}{2} A_{\mu \nu} B^{\mu \nu} & \quad - \frac{1}{4} B_{\mu \nu} B^{\mu \nu} + \frac{1}{2} m_{\gamma'}^2 B_{\mu \mu} B^{\mu}
\end{align*} \]

\[ A^\mu \rightarrow \tilde{A}^\mu - \sin \chi B^\mu \sim \tilde{A}^\mu - \chi B^\mu \]

\[ - \frac{1}{4} \tilde{A}_{\mu \nu} \tilde{A}^{\mu \nu} \]

\[ \text{“Flavor” eigenstate} \quad \text{“mass” eigenstates} \]

photon–sterile oscillation prob.

\[ P_{A-S} = \sin^2 2\chi \times \sin^2 \frac{m_{\gamma'}^2 L}{4\omega} \]
Hidden sector photons: flavor oscillations in a plasma

\[-\frac{1}{4} A_{\mu\nu} A^{\mu\nu} + j_\mu A^\mu\]

\[-\frac{\chi}{2} A_{\mu\nu} B^{\mu\nu}\]

\[-\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{2} m_{\gamma'}^2 B_\mu B^\mu\]

\[\Pi^{\mu\nu} = \text{Re}\{\Pi^{\mu\nu}\} + \text{Im}\{\Pi^{\mu\nu}\}\]

\[-\frac{1}{4} A_{\mu\nu} A^{\mu\nu} + A_\nu \Pi^{\mu\nu} A^\mu\]

\[-\frac{\chi}{2} A_{\mu\nu} B^{\mu\nu}\]

\[-\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{2} m_{\gamma'}^2 B_\mu B^\mu\]

\[A^\mu \rightarrow \tilde{A}^\mu - \chi_{\text{eff}} \tilde{S}^\mu\] (if small mixing)
Real Part

T-plasmons behave as massive particles

\[ \text{Re} \{ \pi_T \} \simeq \omega_P^2 \]

\[ \omega_T^2 \simeq \omega_P^2 - k^2 \]

\[ \omega_P^2 \simeq \frac{4\pi\alpha}{9} T^2 \quad \text{(Relativistic electrons)} \]

\[ \omega_P^2 \simeq \frac{4\pi\alpha}{m_e} n_e \quad \text{(non-Relativistic electrons)} \]
Imaginary Part

due to absorption and emission...

\[ \text{Im } \pi \equiv -\omega \Gamma = -\omega (\Gamma^A - \Gamma^P) = -\omega (1 - e^{-\frac{\omega}{T}}) \Gamma^A \]

\[ \Gamma^P = \Gamma^A e^{-\frac{\omega}{T}} \]

H. A. Weldon. Phys. Rev., D28:2007, 1983.

Thomson scattering as an example:

\[ \Gamma \simeq 16\pi \alpha^2 T \]  
  \( \text{(Relativistic electrons)} \)

\[ \Gamma \simeq \frac{8\pi \alpha^2}{3m_e^2} n_e \]  
  \( \text{(non-Relativistic electrons)} \)

other absorption processes are relevant for relativistic electrons!
Hidden sector photons: flavor oscillations in a plasma

\[-\frac{1}{4} A_{\mu\nu} A^{\mu\nu} + A_\nu \Pi^{\mu\nu} A_\mu\]

\[-\frac{\chi}{2} A_{\mu\nu} B^{\mu\nu}\]

\[-\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{2} m_{\gamma'} B_\mu B^\mu\]

\[A^\mu \to \tilde{A}^\mu - \chi_{\text{eff}} \tilde{S}^\mu\]

\[-\frac{1}{4} \tilde{A}_{\mu\nu} \tilde{A}^{\mu\nu} + \frac{1}{2} \pi \tilde{A}_\mu \tilde{A}^\mu\]

\[j_\mu (\tilde{A}^\mu - \chi_{\text{eff}} \tilde{S}^\mu)\]

\[-\frac{1}{4} \tilde{S}_{\mu\nu} \tilde{S}^{\mu\nu} + \frac{1}{2} m_{\gamma'} \tilde{S}_\mu \tilde{S}^\mu\]

The mixing angle depends on \(\pi(\omega_P)\)

(usefull small mixing approximation)

\[\chi_{\text{eff}} = \chi \frac{m_{\gamma'}^2}{\pi - m_{\gamma'}^2}\]

\[\chi \frac{m_{\gamma'}^2}{\omega_P^2 - m_{\gamma'}^2 - i\omega \Gamma_T}\]

\[\chi \frac{m_{\gamma'}^2}{\omega_P^2 - k^2 - m_{\gamma'}^2 - i\omega \Gamma_L}\]
Hidden sector photons: “flavor” oscillations in a plasma: regimes

\[ \chi_{\text{eff}} (m_{\gamma'} \ll \omega_P, \Gamma) \ll \chi \]
Suppression

\[ \chi_{\text{eff}} (m_{\gamma'} \simeq \Re \{ \pi \}) > \chi \]
Resonance

\[ \chi_{\text{eff}} (m_{\gamma'} \gg \omega_P, \Gamma) \simeq \chi \]
Vacuum

High temperatures production is inhibited

\[ \chi_{\text{eff}} = \chi \frac{m_{\gamma'}^2}{\pi - m_{\gamma'}^2} \]
photon oscillations ... in a plasma?

\[ A(t, z) \simeq e^{i\omega t - ik_A z} e^{-\Gamma_A z} \tilde{A} - \chi_{\text{eff}} e^{i\omega t - ik_S z} e^{-\Gamma_S z} \tilde{S} \]

Usually, (in the range of interest) the masses will comparable with the temperature so oscillations are very fast, decohere very fast.

Consider \( \tilde{A}, \tilde{S} \) as different final states

well, in the resonance the mass difference is minimal but still the imaginary part is usually enough to “decohere” the beam

After \( z \sim \Gamma_A^{-1} \) \[ A(z) \simeq \chi_{\text{eff}} e^{-\Gamma_S z} \tilde{S} \]

\[ P_{A \rightarrow \tilde{S}} = |\chi_{\text{eff}}|^2 = \chi^2 \frac{m_\gamma^4}{(m_\gamma^2 - m_{\gamma'}^2)^2 + (\omega \Gamma)^2} \]
Impact in cosmology ...

\( m_{\gamma'} > \text{keV} \)

\[ \Gamma = \frac{17 \alpha^4 \chi^2 m_{\gamma'}^9}{11664000 \pi^3 m_e^8} \]

\[ \gamma' \rightarrow e^+e^- \]

no trace pre–BBN

destruction of light elements

\( \Gamma = \frac{\alpha \chi^2 m_{\gamma'}}{2} \)

too much background radiation

\( \gamma' \rightarrow \gamma \gamma \gamma \)

\( \gamma' \rightarrow e^- e^- \)

\( \gamma' \rightarrow \gamma \gamma \gamma \)

\( \gamma' \rightarrow e^- e^- \)

\( \gamma' \rightarrow \gamma \gamma \gamma \)

CMB distortion ...
today

\( \gamma' \rightarrow \gamma \gamma \gamma \)

\( \gamma' \rightarrow e^- e^- \)

\( \gamma' \rightarrow \gamma \gamma \gamma \)

\( \gamma' \rightarrow e^- e^- \)

\( \gamma' \rightarrow \gamma \gamma \gamma \)

\( \gamma' \rightarrow e^- e^- \)

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\( \gamma' \rightarrow e^- e^- \)

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\( \gamma' \rightarrow \gamma \gamma \gamma \)
Boltzmann equation for the Hidden Photon production:

\[
\frac{\partial Y_{\tilde{S}}}{\partial \ln T} = \frac{PR_{\tilde{S}}}{H} \times \frac{d \log s}{d \log T^3} Y_{\tilde{A}}
\]

with Hidden Photon production rate:

\[
PR_{\tilde{S}} = (n_{e^+} + n_{e^-}) \langle \sigma_{e\gamma'} v_{\text{Mol}} \rangle + \frac{n_{e^+} n_{e^-}}{n_\gamma} \langle \sigma_{\gamma' v_{\text{Mol}}} \rangle + \frac{n_{e^+} n_{e^-}}{n_\gamma} \langle \sigma_{\gamma' v_{\text{Mol}}} \rangle + ...
\]

\[
\gamma e^\pm \rightarrow \gamma' e^\pm \quad e^+ e^- \rightarrow \gamma' \quad e^+ e^- \rightarrow \gamma \gamma'
\]

Thermal averaged cross sections:

\[
n_a n_b \langle \sigma_{ab \rightarrow f} v_{\text{Mol}} \rangle = \\
= \int \frac{dp_a^3}{(2\pi)^3} \frac{g_a}{e E_a/T - 1} \int \frac{dp_b^3}{(2\pi)^3} \frac{g_b}{e E_b/T + 1} \sigma_{ab \rightarrow f (s)} \sqrt{|v_a - v_b|^2 - |v_a \times v_b|^2}
\]

\[
= \int dn_e dn_\gamma \sigma v_{\text{Mol}}
\]
Production History depends on the mass

\[ \frac{\partial Y_{\tilde{S}}}{\partial \log_{10} T} \]

Resonance dominates for smaller masses

Coalescence dominates for \( m_{\gamma'} > 2m_e \).

Very good news! for both we have analytical expressions
Production History depends on the mass $m_{\gamma'} > 2m_e$ (Coalescence region $e^+e^- \rightarrow \gamma'$).

$$\sigma(s) = 4\pi\chi^2 \alpha \sqrt{s - 4m_e^4} \left(1 + \frac{2m_e^2}{\mu^2}\right) \delta(s - \mu^2)$$

Trivial thermal average and integration over time

$$Y_{\tilde{S}} \approx 1.2 \times 10^{17} \chi^2 \frac{\text{GeV}}{\mu}$$

$m_{\gamma'} < 2m_e$ (Resonant region)

$$Y_{\tilde{S}} \propto f(T_r) \int d\omega \frac{PR\tilde{S}(T_r, \omega)}{d\omega} \int \chi_{\text{eff}}(T, \omega)^2 dT$$

$$\Gamma^P = \frac{\Gamma}{e^{\omega/T} - 1}$$

$$\chi^2 \frac{m_{\gamma'}^4}{(m_{\gamma}^2 - m_{\gamma'}^2)^2 + (\omega\Gamma)^2} \sim \chi^2 \frac{m_{\gamma'}^4}{(\omega\Gamma)^2}$$

$$\delta T \propto T \frac{\omega\Gamma}{m_{\gamma'}^2}$$

The dependence on the interaction rate cancels out!
Abundance as a function of mass

\[ \Omega_{\gamma'} h^2 = 1 \]

\[ \Omega_{\gamma'} h^2 = 0.1 \]

\[ \sim \text{Stable} \]

\[ \Omega_{\gamma'} h^2 = 0.1 \]

right (today) abundance but decay before CMB...

can they exploit BBN, or CMB spectrum?
Hidden photons that decay into $e^+ e^-$
they might initiate electromagnetic cascades and high energy photons will dissociate Deuterium or He

\[ HE \gamma + D \rightarrow p \; n \]

\[ HE \gamma + He \rightarrow D \]

**EXCLUDED** (too little D)

**EXCLUDED** (too much D)

Data from Kawasaki, Kohri and Moroi, Phys.Rev.D63:103502,2001.
Hidden photons that decay into e+ e−
they might initiate electromagnetic cascades and
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\[ \text{HE } \gamma + D \rightarrow p \ n \]

\[ \text{EXCLUDED} \]
\[ \text{too little D} \]

\[ \text{HE } \gamma + He \rightarrow D \]

\[ \text{EXCLUDED} \]
\[ \text{too much D} \]

\[ m_{\gamma'} Y_{\tilde{S}} \]

\[ \frac{\text{GeV}}{\text{GeV}} \]

\[ 10^{-4} \]

\[ 10^{-5} \]

\[ 10^{-6} \]

\[ 10^{-7} \]

\[ 10^{-8} \]

\[ 10^{-9} \]

\[ 10^{-10} \]

\[ 10^{-11} \]

\[ 10^{-12} \]

\[ 10^{-13} \]

\[ 10^{-14} \]

\[ 10^{-15} \]

\[ 10^4 \]

\[ 10^5 \]

\[ 10^6 \]

\[ 10^7 \]

\[ 10^8 \]

\[ 10^9 \]

\[ 10^{10} \]

\[ 10^{11} \]

\[ 10^{12} \]

\[ \tau [\text{sec}] \]

But!!
bounds are quoted for masses roughly above 20 MeV!

Data from Kawasaki, Kohri and Moroi, Phys.Rev.D63:103502, 2001.
Bounds on light & decaying Dark Matter

From the presentation of O. Ruchayskiy in the 4th Patras Workshop on Axions, WIMPs and WISPs (June 2008 @DESY)

Limits on the lifetime of a decaying particle producing a single monochromatic photon line

Restrictions on life-time of decaying DM

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Oleg Ruchayskiy

**DARK MATTER BOUNDS**

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http://axion-wimp.desy.de/e30/e218/talk-18-ruchayskiy.pdf
\[
\frac{m_{\gamma'} \tau}{\text{GeV s}} < 10^{27} \left( \frac{\varepsilon}{\text{GeV}} \right)^{1.3}
\]
(Assuming the right abundance)

Include a factor

\[
\Omega_{\gamma'} h^2 \leq 0.1
\]

**Photon energy**

H. Yuksel and M. D. Kistler. Dark Matter Might Decay... Just Not Today! *Phys. Rev.*, D78:023502, 2008.
Bounds from InterGalactic Photon Diffuse Background

\[ \Omega_{\gamma'} h^2 = 1 \]

\[ \Omega_{\gamma'} h^2 = 0.1 \]

Average photon energy is \( m_{\gamma'} / 3 \)

Overclosure

No Bounds!

IDPB

BBN–CMB

CMB–today

\( \sim \) Stable

\[ m_{\gamma'} \text{[eV]} \]
Compton scattering on electrons will produce Hidden Photons, which due to feeble interactions would leave the stellar interior.

In the interesting (surviving) region HB stars are very sensitive to lukewarm DM Hidden Photos. They have a typical core temperature of 8.6 KeV, a density of $10^4$ g cm$^{-3}$, and the composition is mainly He. The corresponding plasma frequency is sim 2 keV

$$\chi_{eff}^2 \simeq \chi^2$$

Hidden Photons are mainly produced at the threshold, so need to compute the full cross section ...

$$\sigma(s) = \frac{2\pi\alpha^2\chi^2}{(s - m_e^2)^3} \left( \frac{\beta}{2s} \left( s^3 + 15s^2m_e^2 - sm_e^4 + m_e^6 + m_{\gamma'}^2 \left( 7s^2 + 2sm_e^2 - m_e^4 \right) \right) + +2 \left( s^2 - 6sm_e^2 - 3m_e^4 - 2m_{\gamma'}^2 (s - m_e^2 - m_{\gamma'}^2) \right) \log \left( \frac{s(1 + \beta) + m_e^2 - m_{\gamma'}^2}{2m_e\sqrt{s}} \right) \right)$$
Bounds from InterGalactic Photon Diffuse Background

In the Sun
\[ \mathcal{L}_{\gamma'} < \mathcal{L}_{\text{Sun}} \]

In a HB core
\[ \epsilon_{\gamma'} < 10 \, \text{erg} \, \text{g}^{-1} \, \text{s}^{-1} \]

Conservative Bounds ...
but need to refine
Massive Hidden Photons of 100 keV mass can account for a fraction of the Dark matter.

It is unlikely that they can be the main part.

But even such small fraction can have observable consequences in HB stars and might be detectable in the IDPB.

And be detectable in direct searches. Check out ... M. Pospelov, A. Ritz, and M. B. Voloshin. 2008.