Cosmological Signatures of Dark Photons

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Dark Sectors

Sectors are mostly separate with their own interactions...

Standard Model Sector
\( e, u, d \ldots \)

Dark Sector
DM...
Dark Sector

... with a mediator possessing some small mixing with the SM.
Dark Photons

Vector mediator of the dark sector. **Mixing** with SM photon generated by UV physics.

\[ \mathcal{L} \supset -\frac{e}{2} F^\mu_\nu F^{\prime \mu}_\nu + \frac{1}{2} m_{A^\prime}^2 (A^\prime_\mu)^2 \]
Dark Photons

Standard Model Sector

$\mathcal{L} \supset -\frac{\epsilon}{2}F_{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2(A'_{\mu})^2$

Dark Sector

Simple, renormalizable interaction between two sectors.

Two parameters: mixing $\epsilon$ and mass $m_{A'}$. 

Scenario I: Dark Photon Existence

The existence of the dark photon, with no further assumptions, already leads to cosmological signatures.
Scenario II: Dark Photon Dark Matter

Light dark photons may even be all of dark matter itself: additional and distinct cosmological signatures.
Why Cosmology?
Dark Photon Oscillations

Standard Model Sector \quad \gamma \quad A' \quad \epsilon \quad \text{Dark Sector}

SM charged under \textbf{interaction eigenstate} of the photon, which is \textbf{not a propagation eigenstate}.
Mixing in Neutrinos

Neutrinos are produced in flavor or interaction eigenstates...
Neutrino Oscillations

\[ \nu_e \sim \nu_\mu \]

... that are not propagation eigenstates.
Photons can likewise oscillate into dark photons \textit{in vacuum}.
DarkSRF

![Image of DarkSRF equipment]

**Plot Description**

- **Y-axis (\(\epsilon\)):** The vertical axis represents the energy density \(\epsilon\) ranging from \(10^{-9}\) to \(10^{-7}\) eV.
- **X-axis (\(m_{\gamma'}\)):** The horizontal axis represents the mass of the mediator \(m_{\gamma'}\) ranging from \(10^{-7}\) to \(10^{-5}\) eV.
- **Frequency (Hz):** The frequency is shown on a log-log scale ranging from \(10^{7}\) to \(10^{9}\) Hz.

**Graph Legend**

- **CMB** represents the cosmic microwave background.
- **Coulomb** represents the Coulomb interaction.
- **CROWS (old cavity)** represents the CROWS experiment with the old cavity configuration.

**Graph Notes**

- The graph illustrates the sensitivity of the DarkSRF experiment to different mediator masses and frequencies, highlighting regions where the mediator mass and frequency are constrained by the observed data.
There is a characteristic oscillation length of maximum conversion.
Lighter Dark Photons

\[ \gamma \sim 10^6 \text{m} \left( \frac{10^{-9} \text{eV}}{m_{A'}} \right)^2 \left( \frac{\nu}{\text{GHz}} \right) \]

\[ P_{\gamma \rightarrow A'} = 4\epsilon^2 \sin^2 \left( \frac{m_{A'}^2 L}{4\omega} \right) \]

Reason #1 for Cosmology: Difficult with terrestrial probes.
Reason #2 for Cosmology: Propagation medium effects can help.
Dark Photon Oscillations
Nonresonant Oscillations

\[ m_\gamma = 0 \]

Photons are massless in vacuum. Energy gap between \( \gamma \) and \( A' \) lead to nonresonant oscillations (like neutrinos).
But photons pick up an effective mass in a plasma.

\[ m_\gamma \approx 2 \times 10^{-14} \text{eV} \left( \frac{n_e}{2.5 \times 10^{-7} \text{cm}^{-3}} \right)^{1/2} \]
Under the assumption of homogeneity, $10^{-14} \text{ eV} \lesssim \overline{m}_\gamma \lesssim 10^{-9} \text{ eV}$ after recombination.

$$\overline{m}_\gamma \simeq 2 \times 10^{-14} \text{ eV} \left( \frac{n_e,0 x_e}{n_e,0} \right)^{1/2} (1 + z)^{3/2}$$
Under the assumption of homogeneity, $10^{-14} \, \text{eV} \lesssim \bar{m}_\gamma \lesssim 10^{-9} \, \text{eV}$ after recombination.

$$\bar{m}_\gamma \approx 2 \times 10^{-14} \, \text{eV} \left(\frac{n_{e,0} x_e}{n_e^0 x_e^0}\right)^{1/2} (1 + z)^{3/2}$$
Resonant Oscillations

Later time, decreasing redshift

\[ \gamma \]

\[ m_\gamma \gg m_{A'} \]

decreasing \( n_e \) and \( m_\gamma \)

Energy

\[ \gamma \]

\[ A' \]
Resonant Oscillations

later time, decreasing redshift

\[ \hat{H} = \frac{1}{4\omega} \begin{pmatrix} m_\gamma^2 - m_{A'}^2 & 2em_{A'}^2 \\ 2em_{A'}^2 & -m_\gamma^2 + m_{A'}^2 \end{pmatrix} \]

\[ m_\gamma = m_{A'} \]

decreasing \( n_e \) and \( m_\gamma \)

Decreasing energy
Resonant Oscillations

\[ \hat{h} = \frac{1}{4\omega} \left( m_\gamma^2 - m_{A'}^2 \right) \]

\[ \left( \begin{array}{cc}
2em_A^2 & -m_\gamma^2 + m_{A'}^2 \\
2em_A^2 & -m_\gamma^2 + m_{A'}^2
\end{array} \right) \]

\[ m_\gamma \ll m_{A'} \]

Later time, decreasing redshift

decreasing \( \bar{n}_e \) and \( \bar{m}_\gamma \)

Energy
Resonant Oscillations

later time, decreasing redshift

\( \gamma \) \rightarrow A' \quad m_\gamma = m_{A'}

decreasing \( \bar{n}_e \) and \( \bar{m}_\gamma \)

\[
P_{\gamma \rightarrow A'} = \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \left| \frac{d \ln m_{\gamma}^2}{dt} \right|^{-1} \bigg|_{m_\gamma=m_{A'}}
\]
Resonant Oscillations

$\gamma \rightarrow A'\ 
\text{mixing} \ 
\gamma \rightarrow A' \text{vacuum oscillation length}^{-1} \ 
\gamma \rightarrow A' \text{resonance timescale} \sim H^{-1} \ 
\text{later time, decreasing redshift} \ 
\text{decreasing } n_e \text{ and } m_\gamma \ 

\begin{align*}
\gamma \rightarrow A' & \quad P_{\gamma \rightarrow A'} = 2\pi \times \epsilon^2 \times \frac{m^2_{A'}}{2\omega} \times \left| \frac{d \ln m_{\gamma}^2}{dt} \right|^{-1} \\
\text{at later time, decreasing redshift} & \quad m_\gamma = m_{A'} \\
\text{decreasing } n_e \text{ and } m_\gamma & \quad (\gamma \rightarrow A' \text{vacuum oscillation length})^{-1} \\
\text{resonance timescale} & \quad \sim H^{-1} \ 
\end{align*}
Takeaways

1. Cosmological scales good for long oscillation length.

2. Resonant oscillations due to medium effects are important cosmologically.
Resonant Oscillations in the Real Universe

see also:

Bondarenko+ 2002.08942
A. A. Garcia+ 2003.10465
Witte+ 2003.13698
Cosmic Microwave Background

The CMB is very close to a perfect blackbody.

Spectral distortions due to $\gamma \rightarrow A'$ disappearance highly constrained.

$$P_{\gamma \rightarrow A'} = \sum_i \frac{\pi c^2 m_{A'}^2}{\omega} \left| \frac{d \ln m_{\gamma}^2}{dt} \right|^{-1}$$

COBE/FIRAS CMB spectrum

Blackbody $T_{\text{CMB}} = 2.725$ K

COBE/FIRAS data

$m_{A'} = 4 \times 10^{-15}$ eV, $\epsilon = 6 \times 10^{-6}$
Resonant Oscillations

\[ P_{\gamma \rightarrow A'} = \sum_i \frac{\pi e^2 m_A'^2}{\omega} \left| \frac{d \ln m_\gamma^2}{dt} \right|^{-1} \]

Resonant oscillations when \( m_\gamma = m_A' \).

Conversions after recombination covers \( 10^{-14} \text{ eV} \lesssim m_A' \lesssim 10^{-9} \text{ eV} \).
Inhomogeneities

Perturbations in the photon plasma mass

Fluctuations in electron density means $m_\gamma \neq \overline{m_\gamma}$. Numerous resonance crossings along each photon path...
Analytic Formalism

Perturbations in the photon plasma mass

\[ m_A = 2.73 \times 10^{-13} \text{ eV} \]

\[ m_{\gamma} = 2 \times 10^{-13} \text{ eV} \]

\[ \frac{\partial m_{\gamma}}{\partial z} \]

... but we can **average over photon paths** analytically!
Analytic Formalism

\[ P_{\gamma \to A'} = \sum_i \frac{\pi e^2 m_{A'}^2}{\omega} \left| \frac{d \ln m_{\gamma}^2}{dt} \right|^{-1} = \int dt \frac{\pi e^2 m_{A'}^2}{\omega(t)} \delta_D(m_{\gamma}^2 - m_{A'}^2) m_{\gamma}^2 \]

Change of integration measure
Analytic Formalism

\[ P_{\gamma \rightarrow A'} = \int dt \frac{\pi \epsilon^2 m_{A'}^2}{\omega(t)} \delta_D(m_\gamma^2 - m_{A'}^2) \frac{m_\gamma^2}{\omega(t)} \]

\[ \langle P_{\gamma \rightarrow A'} \rangle = \int dt \int dm_\gamma f(m_\gamma^2; t) \frac{\pi \epsilon^2 m_{A'}^2}{\omega(t)} \delta_D(m_\gamma^2 - m_{A'}^2) \frac{m_\gamma^2}{\omega(t)} \]

(time-dependent) probability density function of \( m_\gamma^2 \)

Average over distribution of \( m_\gamma^2 \)
Analytic Formalism

\[ \langle P_{\gamma \rightarrow A'} \rangle = \int dt \int dm_{\gamma}^2 f(m_{\gamma}^2; t) \frac{\pi \epsilon^2 m_{A'}^2}{\omega(t)} \delta_D(m_{\gamma}^2 - m_{A'}^2) m_{\gamma}^2 \]

Integrate over \( m_{\gamma}^2 \)

\[ \langle P_{\gamma \rightarrow A'} \rangle = \int dt f(m_{\gamma}^2 = m_{A'}^2; t) \frac{\pi \epsilon^2 m_{A'}^4}{\omega(t)} \]

Finding the average conversion probability reduces to knowing the PDF of the plasma mass squared.
One-Point PDF

\[ m_\gamma \simeq 2 \times 10^{-14} \text{eV} \left( \frac{n_e}{2.5 \times 10^{-7} \text{cm}^{-3}} \right)^{1/2} \left( \frac{x_e}{1.0} \right)^{1/2} \]

\[ m_\gamma^2 \propto n_e \quad \Rightarrow \quad f(m_\gamma^2; t) \propto \mathcal{P}(\delta_b; t) \]

\[ \delta_b \equiv \frac{\rho_b - \overline{\rho_b}}{\overline{\rho_b}} \]

\( m_\gamma^2 \) fluctuations directly related to baryon density fluctuations, a well-defined cosmological parameter.
Linear Regime

\[ \delta_b \equiv \frac{\rho_b - \bar{\rho}_b}{\bar{\rho}_b} \]

\[ \mathcal{P}(\delta_b; z) = \frac{1}{\sqrt{2\pi\sigma_b^2(z)}} \exp\left( -\frac{\delta_b^2}{2\sigma_b^2(z)} \right) \]

When \( z \gg 20 \), fluctuations are small and Gaussian, characterized fully by the variance, \( \sigma_b^2 \).
Analytic vs. Simulation

Gaussian simulation

Simulation vs. analytic probability

\[ k_{\text{max}} = 20 \, h \, \text{Mpc}^{-1} \]
\[ r_{\text{fill}} = 2.5 \, \text{Mpc} \, h^{-1} \]
PDF in the Nonlinear Regime

Phenomenological: variance from baryonic simulations.

Theoretically motivated, but DM only.

From simulations of voids: useful for underdensities.

Good agreement between fiducial for $10^{-2} \leq 1 + \delta_b \leq 10^2$. 

Ivanov, Kaurov & Sibiryakov 1811.07913

Caputo, HL, Mishra-Sharma & Ruderman, 2004.06733
Constraints on Dark Photons Existing
Cosmic Microwave Background

The CMB is very close to a perfect blackbody.

Spectral distortions due to disappearing photons are highly constrained.

\[ P_{\gamma \rightarrow A'} = \sum_i \frac{\pi c^2 m_{A'}^2}{\omega} \left| \frac{d \ln m_{\gamma}^2}{dt} \right|^{-1} \bigg|_{t_i=t_{\text{res}}} \]
Constraints with Inhomogeneities

Conversions in underdensities at low redshifts

Weakening as conversion probability pushed into future

Inhomogeneities unimportant

Conversions in overdensities at reionization

COBE/FIRAS $\gamma \rightarrow A'$

Jupiter

Homogeneous

Log-normal PDF

Analytic PDF
Dark photons can be probed by cosmology.

Easy to include inhomogeneities!
Dark Photon
Dark Matter
Scenario II: Dark Photon Dark Matter

Light dark photons may even be **all of dark matter** itself: additional and distinct cosmological signatures.

Graham+ '15, Agrawal+, Dror+, Co+ & Bastero-Gil+ '18, but East & Huang ‘22
Resonant Conversion into Photons

Oscillations convert \( A' \) dark matter to low frequency photons which are rapidly absorbed.

\[
\nu = 2.5 \text{ Hz} \left( \frac{m_{A'}}{10^{-14} \text{ eV}} \right) \quad \lambda_{\text{mfp}} = \frac{140 \text{ pc}}{(1 + z)^6} \Delta_b^{-2} \left( \frac{T}{10^4 \text{ K}} \right)^{3/2} \left( \frac{m_{A'}}{10^{-14} \text{ eV}} \right)^2
\]
Free-Free Absorption

Low-frequency photons rapidly absorbed, leading to strong heating of the gas. Can we detect this effect?

Before Resonant Conversion

Resonant Conversion

Free-Free Absorption (Inverse Bremsstrahlung)
Dark matter $A' \rightarrow \gamma$ resonant conversions produce low-energy photons that heat the IGM.

Must include inhomogeneities.

Constraints can be roughly set by requiring $T_{\text{IGM}} \lesssim 10^4 \text{K}$ for consistency with $2 \lesssim z \lesssim 5$ Ly$\alpha$ forest.
Low-Redshift Lyα Discrepancy

IGM simulations find Lyα Doppler widths that are too narrow at low redshifts compared to observations.
Low-Redshift Ly$\alpha$ Discrepancy

Cannot be explained by increased feedback, or steeper ionizing radiation spectrum.
Low-Redshift Lyα Discrepancy

Requires $u = 6.9$ eV per baryon on average for $z \lesssim 2$, with density dependence $u \propto \Delta^{0.6}$. Possibly: turbulence, dust.
Dark Photon Dark Matter Heating

\[
P_{A'\rightarrow \gamma} = \pi \epsilon^2 m_{A'} \left| \frac{d \ln m_{\gamma}^2}{dt} \right|^{-1}
\]

Dark matter \( A' \rightarrow \gamma \) conversions can give anomalous heating.

\( m_{A'} \lesssim 8 \times 10^{-14} \) eV to be consistent with Ly\( \alpha \) forest at \( 2 \leq z \leq 5 \).

\( u \propto \Delta^{1/2} \) due to photon plasma mass evolution.
Significantly better agreement with HST/COS Doppler widths.
Future Work

Predicts inverted temperature-density relation at $z \sim 3$, for which we have mild evidence for (Rorai+).

Use these simulations to set robust limits on $A'$ DM, improving on current estimates.

Stay tuned!
\[ \gamma \rightarrow A': \text{CMB is an excellent probe.} \]

\[ A' \text{DM } \rightarrow \gamma: \text{Heating effect potentially detected in Ly-\(\alpha\) forest.} \]