Cosmological Signatures of Dark Photons

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Dark Photons

Standard Model Sector

Vector mediator of the dark sector.

Mixing with SM photon generated by UV physics.

Dark Sector

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

**Dark Photons**

Simple, renormalizable interaction between two sectors.

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

\[ \mathcal{L} \supset -\frac{\epsilon}{2} F_{\mu \nu} F'_{\mu \nu} + \frac{1}{2} m_{A'}^2 (A'_{\mu})^2 \]
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?
SM charged under **interaction eigenstate** of the photon, which is **not a propagation eigenstate**.
Mixing in Neutrinos

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

... that are not propagation eigenstates.
Light-Shining-Through-Wall

Photons can likewise oscillate into dark photons in vacuum.
DarkSRF
Light-Shining-Through-Wall

There is a characteristic oscillation length of maximum conversion.

\[ L \sim \frac{\omega}{m_{A'}^2} \sim 0.8 \text{ m} \left( \frac{10^{-6} \text{ eV}}{m_{A'}} \right)^2 \left( \frac{\nu}{\text{GHz}} \right) \]

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

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

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

Reason #1 for Cosmology: Difficult with terrestrial probes.
Lighter Dark Photons

Reason #2 for Cosmology: *Propagation medium effects* can help.
Photons are massless in vacuum. **Energy gap** between $\gamma$ and $A'$ lead to **nonresonant oscillations** (like neutrinos).
Photons pick up an effective mass in a plasma.

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

mean electron number density today

But photons pick up an **effective mass** in a plasma.
Homogeneous Plasma Mass

Under the assumption of homogeneity, 
$10^{-14}$ eV $\lesssim \bar{m}_\gamma \lesssim 10^{-9}$ eV after recombination.

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

Mirizzi+ 0901.0014, Caputo, HL, Mishra-Sharma & Ruderman 2004.06733
Under the assumption of homogeneity, $10^{-14}$ eV \(\lesssim \overline{m}_\gamma \lesssim 10^{-9}$ eV after recombination.

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

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

later time, decreasing redshift

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

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

\( \gamma \)
Resonant Oscillations

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

- later time, decreasing redshift
- decreasing $\bar{n}_e$ and $\bar{m}_\gamma$

Energy

$\gamma$ $A'$
Resonant Oscillations

later time, decreasing redshift

decreasing $\bar{n}_e$ and $\bar{m}_\gamma$

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

$m_\gamma \ll m_{A'}$
Resonant Oscillations

- later time, decreasing redshift
- decreasing $\bar{n}_e$ and $\bar{m}_\gamma$

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

$$m_{\gamma} = m_{A'}$$

Kuo & Pantaleone '89, Mirizzi+ 0901.0014, Caputo, HL, Mishra-Sharma & Ruderman 2004.06733
Resonant Oscillations

Later time, decreasing redshift

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

Decreasing \( n_e \) and \( m_\gamma \)

Mixing

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

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

(\( \gamma \rightarrow A' \) vacuum oscillation length\(^{-1}\))

Resonance timescale

\( \sim H^{-1} \)
Takeaways

1. Cosmological scales good for long oscillation length.

2. There are nonresonant (vacuum) vs. resonant oscillations.
Resonant Oscillations in the Real Universe
The CMB is very close to a perfect blackbody.

Spectral distortions due to disappearing photons are highly constrained.

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

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

Resonant oscillations when

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

Conversions after recombination covers

\[ 10^{-14} \, \text{eV} \lesssim m_{A'} \lesssim 10^{-9} \, \text{eV}. \]
Inhomogeneities

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

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

\[ P_{\gamma \rightarrow A'} = \sum_i \frac{\pi \varepsilon^2 m_{A'}^2}{\omega} \left| \frac{d \ln m_\gamma^2}{dt} \right|^{-1} \bigg|_{t_i = t_{\text{res}}} = \int dt \frac{\pi \varepsilon^2 m_{A'}^2}{\omega(t)} \delta_D(m_\gamma^2 - m_{A'}^2) \frac{m_\gamma^2}{m_\gamma} \]

Change of integration measure
Analytic Formalism

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

Average over distribution of \( m_{\gamma}^2 \)

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

(time-dependent) probability density function of \( m_{\gamma}^2 \)
Analytic Formalism

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

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

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

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

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

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

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

\[ m_\gamma^2 \text{ fluctuations directly related to baryon density fluctuations, a well-defined cosmological parameter.} \]
Linear Regime

\[ \delta_b = \frac{\rho_b - \overline{\rho}_b}{\overline{\rho}_b} \]

When \( z \gg 20 \), fluctuations are \textbf{small} and \textbf{Gaussian}, characterized fully by the \textbf{variance}, \( \sigma_b^2 \).

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

Gaussian simulation

Simulation vs. analytic probability

$k_{\text{max}} = 20 \ h \text{Mpc}^{-1}$

$r_{\text{filt}} = 2.5 \text{Mpc} \ h^{-1}$
PDF in the Nonlinear Regime

**Phenomenological**: variance from baryonic simulations.

**Theoretically motivated, but DM only.**

Ivanov, Kaurov & Sibiryakov 1811.07913

**From simulations of voids**: useful for underdensities

Adermann, Elahi, Lewis & Power 1703.04885, 1807.02938

**Good agreement between fiducial for**

\[ 10^{-2} \leq 1 + \delta_b \leq 10^2. \]
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.

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

- Homogeneous
- Log-normal PDF
- Analytic PDF

**Limits:**
- Jupiter: \( 10^{-2} < 1 + \delta < 10^2 \)
- PIXIE (projection)
- Dark SRF (projection)

**References:**
- Caputo, HL, Mishra-Sharma & Ruderman, 2002.05165, also García+ 2003.10465
Before Recombination

Density fluctuations not important: universe is smooth.

Existing literature inconsistent and likely incorrect, but small difference.
Two-Point Statistics?

Simple estimate:

\[ \langle \delta T^2_{\gamma \rightarrow A'} \rangle \sim (10^{-5} T_0)^2 \]

But what about angular dependence?

Two-point correlations with other observables?
Dark photons can be probed by cosmology.

Easy to include inhomogeneities!
Oscillation into Photons

Oscillations convert $A'$ dark matter to low frequency photons which are rapidly absorbed.

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

Nonresonant oscillations convert $A'$ dark matter to low frequency photons which are rapidly absorbed.

Compare heating rate with cooling rate in interstellar medium/dwarf galaxy gas.
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 $T_{\text{IGM}} \lesssim 10^4$ 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 Ly$\alpha$ Discrepancy

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

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

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

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

\[ u \propto \Delta^{1/2} \] 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!