Cosmological Signatures of Dark Photons

Hongwan Liu
NYU & Princeton

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with James Bolton, Andrea Caputo, Siddharth Mishra-Sharma, Joshua Ruderman, and Matteo Viel

Hongwan Liu (NYU/Princeton)
Dark Sectors

Sectors are mostly separate with their own interactions...
Dark Sector

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

Standard Model Sector

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

Dark Sector

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

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.

Graham+ ‘15, Agrawal+, Dror+, Co+ & Bastero-Gil+ ‘18, but East & Huang ‘22
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

\[ \nu_e \quad \nu_e \quad \nu_\mu \]

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

Emitter RF Cavity

\[ \gamma \rightarrow A' \rightarrow \gamma \]

Receiver RF Cavity

Photons can likewise oscillate into dark photons \textit{in vacuum}.
DarkSRF

Frequency (Hz)

$10^{-7}$ $10^{-6}$ $10^{-5}$

$10^{7}$ $10^{8}$ $10^{9}$

CMB
Coulomb
CROWS (old cavity)

$\epsilon$

$10^{-9}$ $10^{-8}$ $10^{-7}$

$m_{\gamma'}$ (eV)

Pathfinder Run
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

\[ \gamma \rightsquigarrow \quad \cdots \quad \cdots \]

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

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

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

Reason #2 for Cosmology: Propagation medium effects can help.
Dark Photon Oscillations
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**.

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

mean electron number density today
Under the assumption of homogeneity, $10^{-14} \text{eV} \lesssim m_\gamma \lesssim 10^{-9} \text{eV}$ after recombination.

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

$\bar{m}_\gamma$ is the mean electron number density today, $n_{e,0}$ is the free electron fraction, $x_e$ is the mean electron number density today, $n_{e,0}x_e$ is the free electron fraction, $n_{e,0}$ is the mean electron number density today, $z$ is the redshift.
Under the assumption of homogeneity, $10^{-14} \text{ eV} \lesssim \bar{m}_\gamma \lesssim 10^{-9} \text{ eV}$ after recombination.

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

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

Later time, decreasing redshift

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

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

Energy

\( \gamma \)

\( A' \)
Resonant Oscillations

Later time, decreasing redshift

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

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

Energy
Resonant Oscillations

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

- later time, decreasing redshift
- decreasing $n_e$ and $m_\gamma$
Resonant Oscillations

Later time, decreasing redshift

Decreasing $n_e$ and $m_\gamma$

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

\[ \gamma \rightarrow A' : \text{vacuum oscillation length}^{-1} \]

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

Later time, decreasing redshift

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

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

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

Mixing

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

1. Cosmological scales good for long oscillation length.

2. Resonant oscillations due to medium effects are important cosmologically.

\[ m_\gamma = m_{A'} \]
Resonant Oscillations in the Real Universe

see also:

Bondarenko+ 2002.08942
A. A. Garcia+ 2003.10465
Witte+ 2003.13698
The CMB is very close to a perfect blackbody.

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

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

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 $m_\gamma \neq \bar{m}_\gamma$. Numerous resonance crossings along each photon path...
Analytic Formalism

Perturbations in the photon plasma mass

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

$\delta \propto m_\gamma$ inhomogeneous plasma mass $m_\gamma$

$\delta \propto m_\infty$ homogeneous plasma mass $m_\infty$

$P_{\gamma\rightarrow h}$: Analytic crossing probability

$P_{\gamma\rightarrow h}$: Crossings in simulation

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

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

Change of integration measure
Analytic Formalism

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

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

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

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

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

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

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

\[ m_\gamma^2 \text{ fluctuations directly related to baryon density fluctuations, a well-defined cosmological parameter.} \]
When $z \gg 20$, fluctuations are \textbf{small} and \textbf{Gaussian}, characterized fully by the \textbf{variance}, $\sigma_b^2$. 

$$\delta_b \equiv \frac{\rho_b - \overline{\rho}_b}{\overline{\rho}_b}$$

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

Gaussian simulation

Simulation vs. analytic probability

\( k_{\text{max}} = 20 \, h \, \text{Mpc}^{-1} \)
\( r_{\text{filt}} = 2.5 \, \text{Mpc} \, h^{-1} \)

Analytic
Gaussian simulation
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.

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

Conversions in underdensities at low redshifts

Weakening as conversion probability pushed into future

Inhomogeneities unimportant

Conversions in overdensities at reionization

$\gamma \rightarrow A'$

$\epsilon$

$m_{A'}$ [eV]

$10^{-16} < 1 + \delta < 10^2$

Homogeneous

Log-normal PDF

Analytic PDF

PIXIE (projection)

Dark SRF (projection)

Jupiter

COBE/FIRAS

Caputo, HL, Mishra-Sharma & Ruderman, 2002.05165, also García+ 2003.10465
Dark photons can be probed by cosmology.

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

Light dark photons may even be all of dark matter itself: additional and distinct cosmological signatures.
Resonant Conversion into Photons

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

$$\nu = 2.5 \text{ Hz} \left( \frac{m_{A'}}{10^{-14} \text{ eV}} \right) \quad \lambda_{\text{mfp}} = \frac{140 \text{ pc}}{(1+z)^6} \Delta_b^{-2} \left( \frac{T}{10^4 \text{ K}} \right)^{3/2} \left( \frac{m_{A'}}{10^{-14} \text{ eV}} \right)^2$$
Low-frequency photons **rapidly absorbed**, leading to strong **heating** of the gas. Can we detect this effect?
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 Ly$\alpha$ Discrepancy

IGM simulations find Ly$\alpha$ 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 on average for $z \lesssim 2$, with density dependence $u \propto \Delta^{0.6}$. Possibly: turbulence, dust.
Dark Photon Dark Matter Heating

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

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

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

\( u \propto \Delta^{1/2} \) due to photon plasma mass evolution.
Dark Photon Dark Matter Heating

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

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