BBN Constraints on Gravitationally Produced Dark Photons

Moinul Hossain Rahat

Phenomenology 2022 Symposium
May 9, 2022

arXiv:**2205.xxxxx** [hep-ph],
with C.S. Fong, S. Saad

UF Institute for Fundamental Theory
UNIVERSITY *of* FLORIDA

Gravitational vs. Freeze-in Production of Vector Bosons

- Extend SM with a $U(1)$ symmetry, vector boson coupling to the SM

$$\mathcal{L} \supset -g_V \bar{f}\gamma^\mu(Q_L P_L + Q_R P_R) f V_\mu + \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

- Freeze-in production occurs via inverse decay of Standard Model (SM) particles when $g_V \ll 1$ and/or $\epsilon \ll 1$
- Gravitational production occurs via quantum fluctuations in a rapidly expanding universe when fields are not invariant under conformal transformation E. Kolb, A. Long 2009.03828, A. Ahmed et al. 2005.01766
- Vector bosons decaying into SM particles inject energy into cosmological plasma, impacting light element abundances produced via BBN J. Coffey et al., JHEP **07** (2020) 179, J. Berger et al. JCAP **11** (2016) 032
- Observed bounds on light element abundances can be projected back to calculate allowed regions in vector boson parameter space

Example: Dark Photon with Kinetic Mixing

- Five SM decay channels for sub-GeV vector bosons
- all eventually decay into e^+/e^- or photons, $\pi^- \to \bar{\nu_\mu}\mu^-$, $\mu^- \to e^-\bar{\nu}_e\nu_\mu$, $\pi^0 \to \gamma\gamma$
- Consider dark photon with kinetic mixing as an example, can be applied to any other $U(1)$ vector boson model

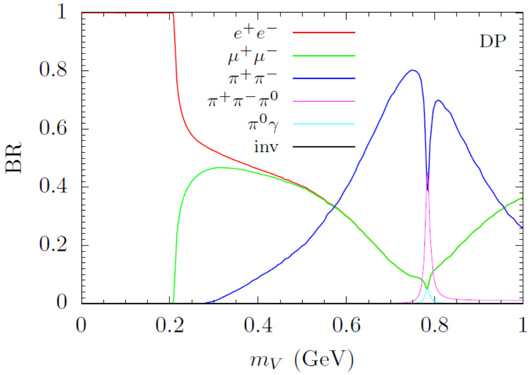


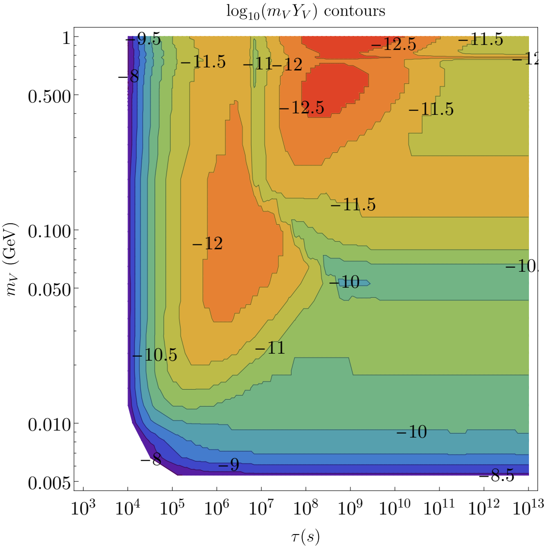
Figure: Dark photon branching ratios

J. Coffey et al., JHEP **07** (2020) 179

BBN Photodisintegration Constraints

- Calculate primary energy spectra of e^+/e^- and photons for all channels in the rest frame of the vector boson
- Electromagnetic cascade: high energy photons scatter off background photons and produce e^+e^- pair, which produce high energy photons via inverse Compton scattering
- Calculate photon cascade spectrum, and use it to solve coupled Boltzmann equations to estimate light element abundances
- Observed light element (^{2}H, ^{3}He, ^{4}He) abundances constrain pre-decay abundance of dark photon and put bounds on the parameter space (m_V, ϵ)
- Computationally expensive calculation done in a cluster computer; code package modified from `ACROPOLIS`, to be made publicly available soon

BBN Bounds on Dark Photon



C.S. Fong, **MHR**, S. Saad, arXiv:2205.xxxxx

Cosmological Constraints

- If the vector boson's lifetime is greater than the age of the universe, it can be a dark matter candidate, cannot exceed the dark matter energy density

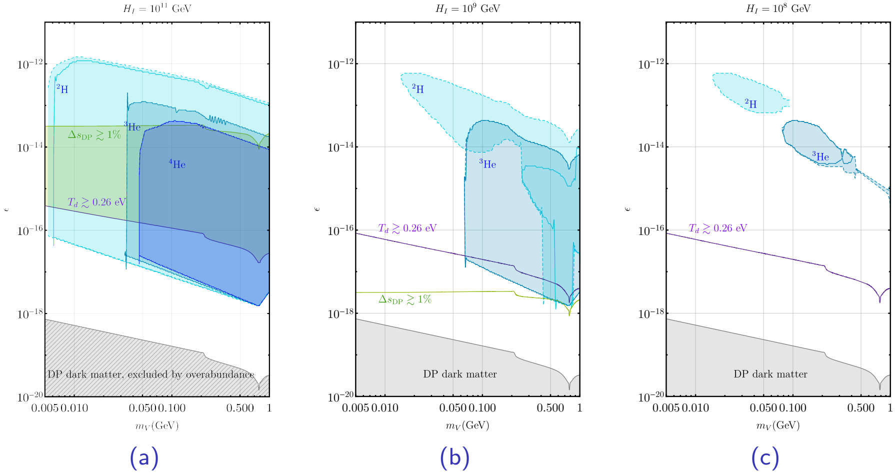
$$m_V Y_V \lesssim 4.36 \times 10^{-10} \text{ GeV}$$

- If the vector boson decays between BBN and CMB, it must not change the Hubble rate throughout BBN. Using `AlterBBN`, this implies

$$m_V Y_V \lesssim 0.9 \times 10^{-6} \text{ GeV}$$

- Entropy dilution of the baryon energy density between the epoch of BBN and CMB is not more than 1%, if the decay happens before the recombination or the formation of the CMB.

Limits on Gravitationally Produced Dark Photons



C.S. Fong, **MHR**, S. Saad, arXiv:2205.xxxxx

Summary and Outlook

- Sub-GeV dark photon decaying into SM particles injects energy into EM plasma, created photon spectrum induces photodisintegration of light elements
- BBN constraints on photodisintegration rules out a large portion of the parameter space when gravitational production is dominant
- Modification of the code package `ACROPOLIS` to include all SM decay channels below GeV; calculation of electron/position and photon spectra applicable to any vector boson models (dark photon, $B - L$ vector boson, $L_\alpha - L_\beta$ vector boson etc.)
- Future directions: extend mass range (more decay channels), extend life time (to include CMB)

Backup Slides

Gravitational Production

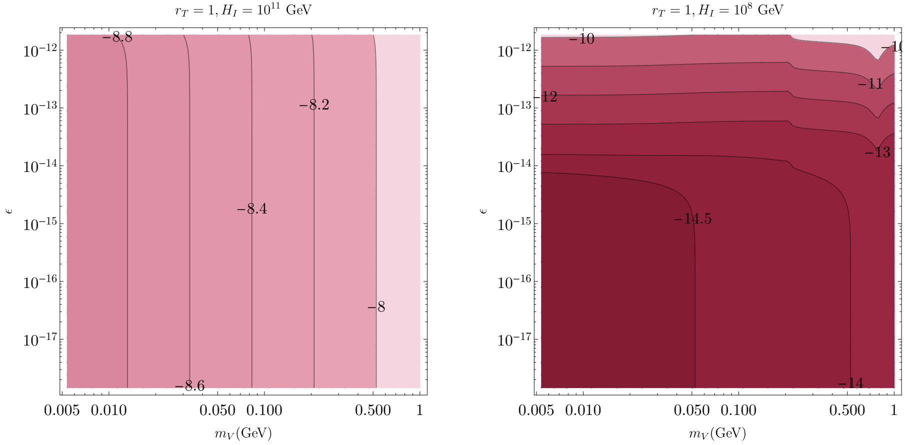
$$Y_V = \frac{\kappa H_I^2}{16\pi^2 M_{\rm Pl}^2} \begin{cases} \frac{b}{\sqrt{m_V}} \left(\frac{3}{2} - \frac{2}{3} \frac{b\sqrt{m_V}}{T_{\rm RH}} - \frac{1}{3} \frac{T_{\rm RH}\sqrt{m_V}}{bH_I} \right) & T_{\rm RH} > b\sqrt{m_V} \\ \frac{T_{\rm RH}}{m_V} \frac{5}{6} \left(1 - \frac{2}{5} \frac{m_V}{H_I} \right) & T_{\rm RH} < b\sqrt{m_V} \end{cases}$$

$b \equiv \left(\frac{\pi^2}{90 M_{\rm Pl}^2} g_{\star {\rm RH}} \right)^{-1/4}$ and $\kappa \sim 1 - 10$

$$m_V Y_V \simeq \kappa \begin{cases} 1.4 \times 10^{-7}\,{\rm GeV} \left(\frac{H_I}{10^{12}\,{\rm GeV}} \right)^2 \left(\frac{m_V}{10\,{\rm MeV}} \right)^{1/2}, & r_T = 1 \\ 2.8 \times 10^{-8}\,{\rm GeV} \left(\frac{H_I}{10^{14}\,{\rm GeV}} \right)^{5/2}, & r_T = 10^6 \end{cases},$$

Freeze-in Production

$$Y_V = \frac{3}{2\pi^2} m_V^3 \tilde{\Gamma}_V \int_0^{x_{\rm QCD}} dx \frac{K_1(x)}{x^2 s\ H} + \frac{3}{2\pi^2} m_V^3 \Gamma_V \int_{x_{\rm QCD}}^{\infty} dx \frac{K_1(x)}{x^2 s\ H}$$



Electromagnetic Cascade

Double photon pair creation: $\gamma\gamma_{BG} \to e^- e^+$,

Photon-photon scattering: $\gamma\gamma_{BG} \to \gamma\gamma$,

Bethe-Heitler pair creation: $\gamma N \to e^- e^+ N$, with $N \in ({}^1H, {}^4He)$,

Compton scattering: $\gamma e^-_{BG} \to \gamma e^-$, and

Inverse Compton scattering: $e^\mp \gamma_{BG} \to e^\mp \gamma$

Photodisintegration Thresholds

D-disintegration with $E^{\mathrm{D}_{\mathrm{th}}\approx 2.22\,\mathrm{MeV}}$: $T \lesssim 5.34\,\mathrm{keV}$,

$^{3}\mathrm{H}$-disintegration with $E^{^{3}\mathrm{H}}_{\mathrm{th}\approx 6.26\,\mathrm{MeV}}$: $T \lesssim 1.90\,\mathrm{keV}$,

$^{3}\mathrm{He}$-disintegration with $E^{^{3}\mathrm{He}}_{\mathrm{th}\approx 5.49\,\mathrm{MeV}}$: $T \lesssim 2.16\,\mathrm{keV}$,

$^{4}\mathrm{He}$-disintegration with $E^{^{4}\mathrm{He}}_{\mathrm{th}\approx 19.81\,\mathrm{MeV}}$: $T \lesssim 0.60\,\mathrm{keV}$,

$^{6}\mathrm{Li}$-disintegration with $E^{^{6}\mathrm{Li}}_{\mathrm{th}\approx 3.70\,\mathrm{MeV}}$: $T \lesssim 3.21\,\mathrm{keV}$,

$^{7}\mathrm{Li}$-disintegration with $E^{^{7}\mathrm{Li}}_{\mathrm{th}\approx 2.47\,\mathrm{MeV}}$: $T \lesssim 4.81\,\mathrm{keV}$, and

$^{7}\mathrm{Be}$-disintegration with $E^{^{7}\mathrm{Be}}_{\mathrm{th}\approx 1.59\,\mathrm{MeV}}$: $T \lesssim 7.48\,\mathrm{keV}$.

Photodisintegration Equations

- The electromagnetic cascade spectra of photons and electrons evolve according to the following Boltzmann equations:

$$\frac{d\mathcal{N}_a}{dt}(E) = -\Gamma_a(E)\mathcal{N}_a(E) + \mathcal{S}_a(E); \quad \mathcal{N}_a \equiv \frac{dn_a}{dE}, \ \ a = \gamma, e,$$

- The quasistatic limit, $\frac{d\mathcal{N}_a}{dt} \to 0$ is a good approximation, which leads to

$$\mathcal{N}_a = \frac{\mathcal{S}_a(E)}{\Gamma_a(E)}$$

-

$$\mathcal{S}_a = R\frac{dN_a}{dE} + \sum_b \int_E^{E_X} dE' K_{ab}(E, E')\mathcal{N}_b(E'),$$

BBN Constraints

- The effect of photodisintegration on the abundances of light elements is dictated by the following Boltzmann equations:

$$\frac{dY_A}{dt} = \sum_i Y_i \int_0^\infty dE_\gamma \mathcal{N}_\gamma(E_\gamma)\sigma_{\gamma+i\to A}(E_\gamma) - Y_A \sum_f \int_0^\infty dE_\gamma \mathcal{N}_\gamma(E_\gamma)\sigma_{\gamma+A}$$

- The "theoretical" error in the light element abundances is estimated by conservatively taking

$$\sigma_{Y_A} = \max\left[|Y_A(\mathrm{high}) - Y_A(\mathrm{mean})|, |Y_A(\mathrm{low}) - Y_A(\mathrm{mean})|\right],$$

where $Y_A(\mathrm{mean})$, $Y_A(\mathrm{high})$, and $Y_A(\mathrm{low})$ are respectively the outputs of `ACROPOLIS` using the initial conditions produced by `AlterBBN` with mean, high, and low values of the nuclear reaction rates

- Compare with Helium-4 mass fraction, deuterium and Helium-3 abundances from the PDG

$$Y_p = 0.245 \pm 0.003, \qquad \frac{n_{\mathrm{D}}}{n_{\mathrm{H}}} = (2.547 \pm 0.025) \times 10^{-5},$$

$$\frac{n_{^3\mathrm{He}}}{n_{\mathrm{H}}} = (1.1 \pm 0.2) \times 10^{-5}.$$