BBN Photodisintegration Constraints on Gravitationally Produced Vector Bosons

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22 August, 2022
Rio de Janeiro, Brazil

Based on arXiv:2206.02802 with Moinul Hossain Rahat, Shaikh Saad

https://github.com/shengfong/lightvectorboson

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Outline

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BBN: Big Bang Nucleosynthesis

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1 Gravitationally Produced

2 Vector Bosons — *Long-lived, light*

BBN: Big Bang Nucleosynthesis

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2 *Long-lived, light*

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2 *Long-lived, light*

Dark photon

4

BBN: Big Bang Nucleosynthesis

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Hubble scale at the end of inflation

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★ Basic idea

$$a_{\mathbf{k}}^{\rm late} = \alpha_{\mathbf{k}}^* a_{\mathbf{k}}^{\rm early} - \beta_{\mathbf{k}} a_{\mathbf{k}}^{\dagger\rm early} \qquad a_{\mathbf{k}}^{\rm early}|0^{\rm early}\rangle = 0$$

$$\langle \hat{N}^{\rm late}\rangle = \int \frac{d^3k}{(2\pi)^3}\langle 0^{\rm early}|a_{\mathbf{k}}^{\dagger\rm late} a_{\mathbf{k}}^{\rm late}|0^{\rm early}\rangle = V\int \frac{d^3k}{(2\pi)^3}|\beta_{\mathbf{k}}|^2$$

Gravitational production of light vector boson

For a (light) massive vector boson $m_V \ll H_I$ [Graham, Mardon, Rajendran, 1504.02102]

$$\partial_\eta^2 A_{\mathbf{k}}^{T,L} + \omega_{T,L}^2 A_{\mathbf{k}}^{T,L} = 0$$

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One longitudinal mode: like minimally coupled scalar $m_V \to 0$

$$\omega_L^2 = k^2 + a^2 m_V^2 + \frac{1}{6}\frac{k^2 a^2}{k^2 + a^2 m_V^2} R + 3\frac{k^2 a^4 m_V^2 H^2}{(k^2 + a^2 m_V^2)^2}$$

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★ Longitudinal mode can be copiously produced ★ Can be dark matter

Gravitational production of light vector boson

The abundance of a light vector boson

$$Y_V = \frac{na^3}{sa^3} = \frac{T_{\rm RH} H_I}{4M_{\rm Pl}^2} \int \frac{d^3k}{(2\pi)^3} |\beta_{\mathbf{k}}|^2$$

During inflation (de-Sitter), during reheating (matter-dominated), after reheating (radiation-dominated) [Kolb, Long, 2009.03828]

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

$\kappa \sim 1 - 10$ model dependency

$$r_T \equiv \frac{T_{\rm max}}{T_{\rm RH}}$$

Gravitational production of light vector boson

The light vector boson is a dark matter if $\tau > 4.4 \times 10^{17}\,\mathrm{s}$

Dark matter constraint $m_V Y_V \leq 4.36 \times 10^{-10}\,\mathrm{GeV}$

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If V were to be metastable dark matter

$$1.8 \times 10^{10}\,\mathrm{GeV} \leq H_I \kappa^{1/2} \leq 9.9 \times 10^{10}\,\mathrm{GeV}, \quad \text{for } r_T = 1,$$

$$H_I \kappa^{2/5} \leq 1.9 \times 10^{13}\,\mathrm{GeV}, \quad \text{for } r_T = 10^6.$$

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We also impose such that entropy injection between BBN and recombination (CMB) is less than 1%

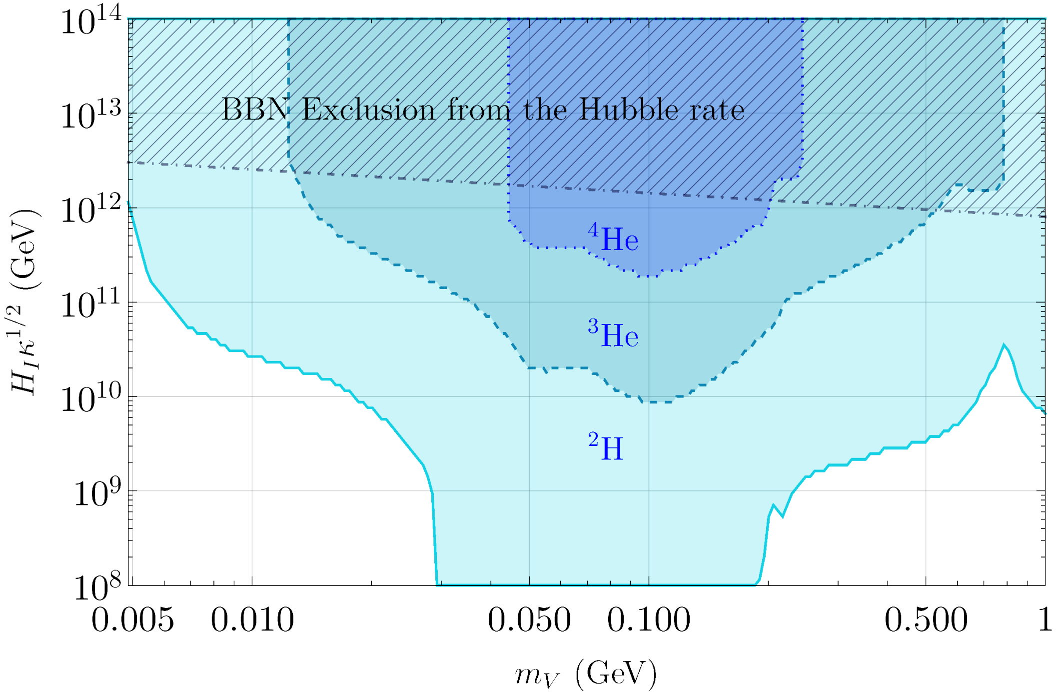
Summary

Kinetic mixing

If the light vector boson were MeV-GeV scale *dark photon*

$$\epsilon = 5 \times 10^{-14}$$

$$-\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} V^{\mu\nu}$$



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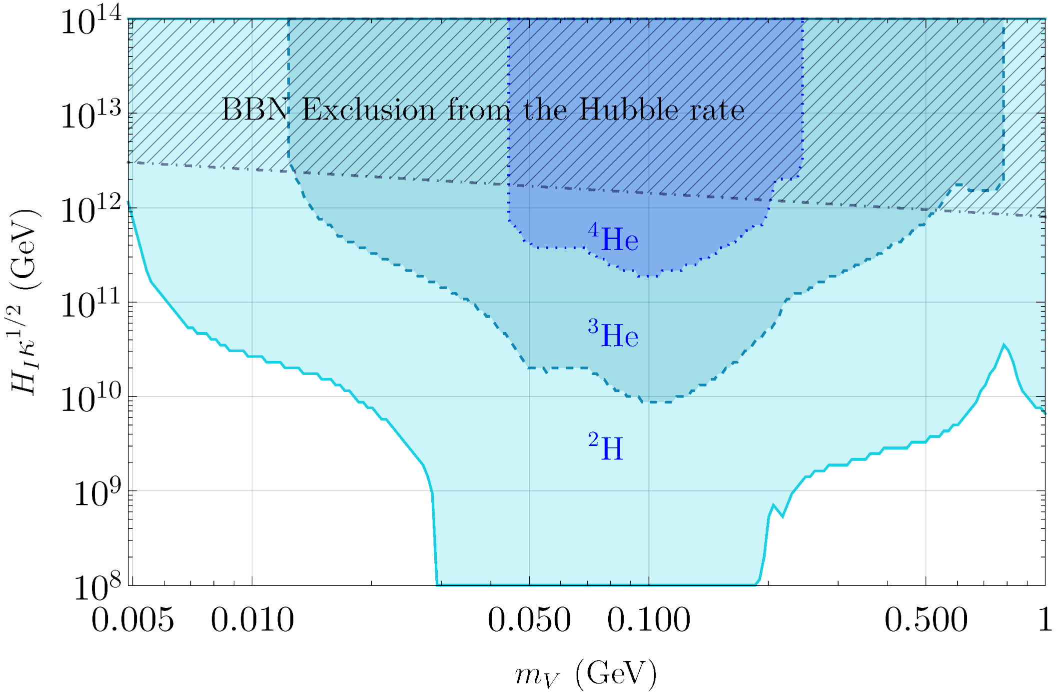

Strong exclusion from BBN photodisintegration due to gravitational production ★

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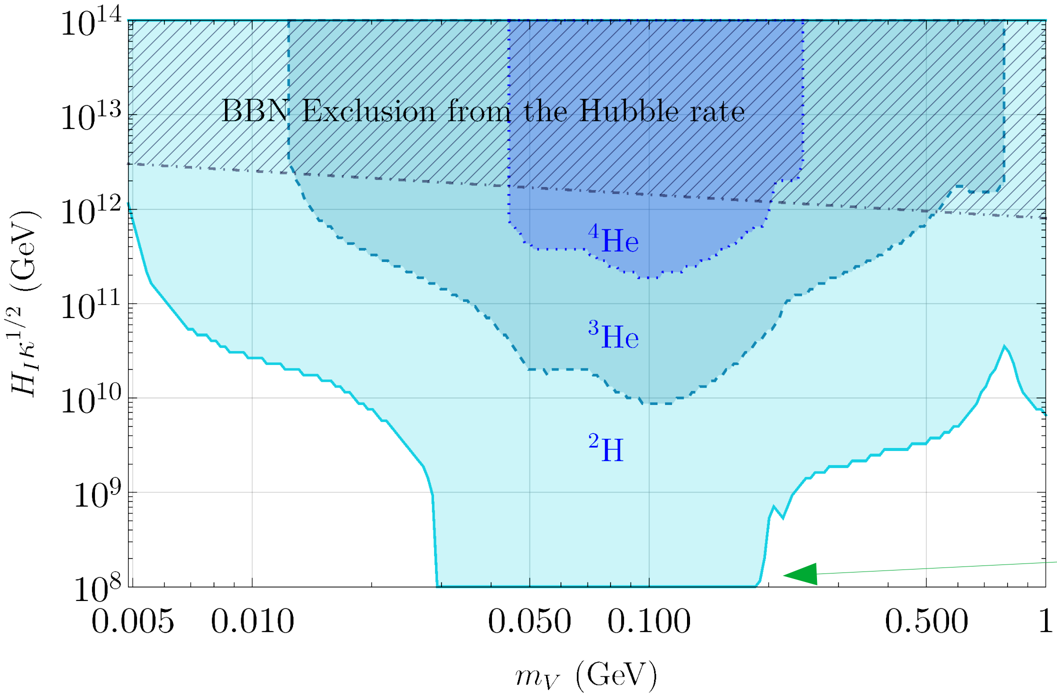

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Recover the exclusion from freeze-in production

[Fong, Rahat, Saad, 2206.02802]

Light vector boson model

The interactions of a general light vector boson with us (SM)

$$-\mathcal{L} \supset \overline{f}\gamma^{\mu}\left(g_V Q_{X,f} + e\epsilon Q_{\mathrm{em},f}\right) P_X \; f \; V_{\mu}$$

$$m_V \ll H_I$$

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Stückelberg mass or by Higgs mechanism at higher scale

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New gauge U(1)

$$L_e - L_{\mu}, L_e - L_{\tau}, L_{\mu} - L_{\tau}$$ anomaly-free

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$B - L, B, L$ new d.o.f needed, assumed all of them heavy

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For MeV-GeV vector boson, all possible decay channels allowed by kinematic

$$V \to e^+e^- \quad V \to \mu^+\mu^- \quad V \to \pi^0\gamma \quad V \to \pi^+\pi^- \quad V \to \pi^+\pi^-\pi^0$$

Cascade to electromagnetic spectra: electrons, positrons and photons

$$\left.\frac{dN}{dE_\alpha}\right|_V = \sum_a \mathrm{BR}(V \to a) \left.\frac{dN^{(a)}}{dE_\alpha}\right|_V, \quad \alpha = e, \gamma, \quad a = e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \pi^0\gamma, \pi^0\pi^+\pi^-$$

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Future direction: extend to heavier V

BBN photodisintegration constraints

Double photon pair creation

$$\gamma\gamma_{BG} \to e^+e^-$$

$$E_{\rm th}^{e^+e^-} \approx \frac{m_e^2}{22T} \approx 2\,\mathrm{MeV}\frac{6\,\mathrm{keV}}{T}$$

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To disintegrate light elements

D-disintegration $E_{\rm th}^{\rm D} = 2.22\,{\rm MeV}$

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To have sufficient photons to photodisintegrate $T \lesssim 10\,{\rm keV}$ $\tau \lesssim 10^4\,{\rm s}$

after BBN completed

BBN photodisintegration constraints

Implementation in `ACROPOLIS` [Depta, Hufnagel, Schmidt-Hoberg, 2011.06518]

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

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Primary EM spectra
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- Initial conditions after BBN from `AlterBBN` [Arbey, Auffinger, Hickerson, Jenssen, 1806.11095]
- Photodisintegrations of light elements are described by

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

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Consider exclusion at 95% for each element individually

$$Y_p = 0.245 \pm 0.003, \quad \frac{n_\mathrm{D}}{n_\mathrm{H}} = (2.547 \pm 0.025) \times 10^{-5}, \quad \frac{n_{^3\mathrm{He}}}{n_\mathrm{H}} = (1.1 \pm 0.2) \times 10^{-5}$$

BBN photodisintegration constraints

★ The light vector boson model for `ACROPOLIS`

https://github.com/shengfong/lightvectorboson [Fong, Rahat, Saad, 2206.02802]

$$m_V \ [\mathrm{MeV}] \quad \tau \ [\mathrm{s}] \quad T_0 \ [\mathrm{MeV}] \quad \left.\frac{n_V}{n_\gamma}\right|_{T_0} \quad \mathrm{BR}_{ee} \quad \mathrm{BR}_{\mu\mu} \quad \mathrm{BR}_{\pi\pi} \quad \mathrm{BR}_{\pi\gamma} \quad \mathrm{BR}_{3\pi}$$

BBN photodisintegration constraints

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```
./decayvector 700 1e8 1 1e-6 0.1 0.1 0.7 0.01 0.09
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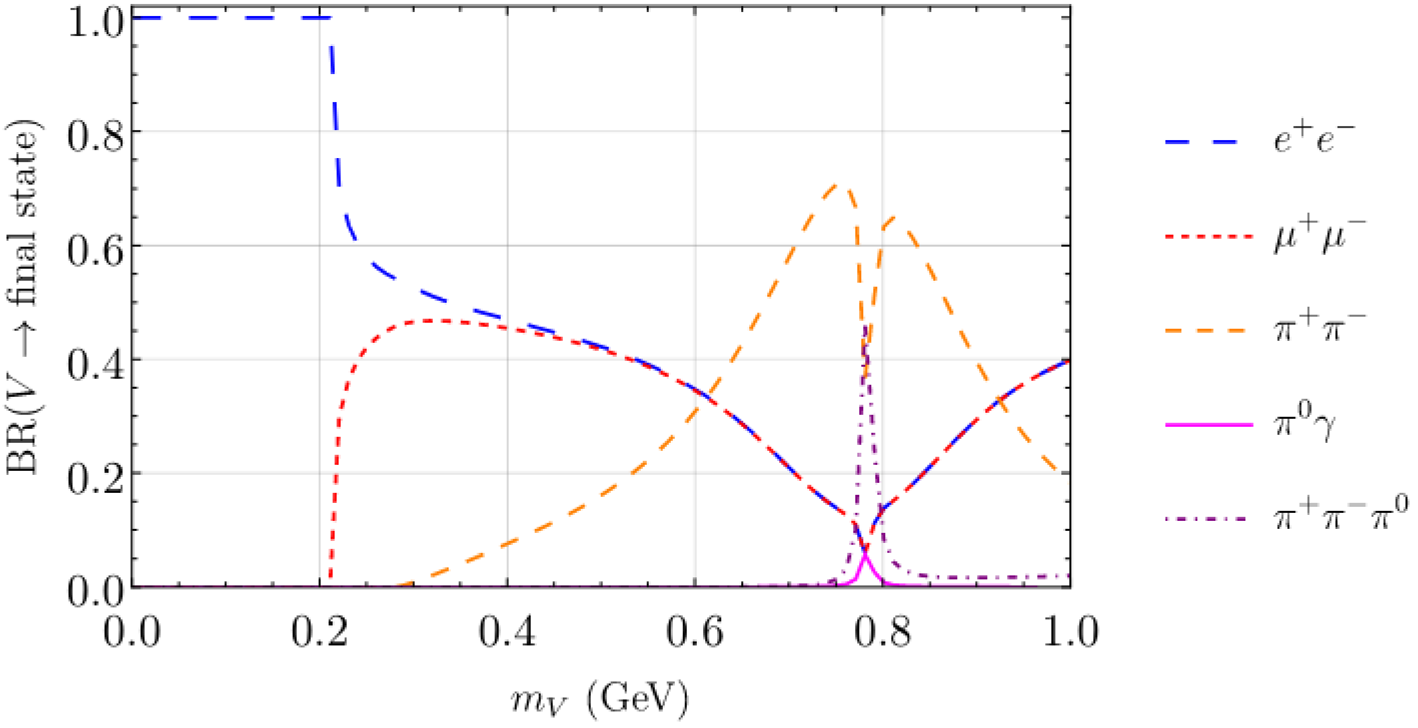
```
./decayvector 700 1e8 1 1e-6 0.1 0.1 0.7 0.01 0.09
```

```
Results:    Yp = 0.224415, H2/p = 0.000395, He3/p = 0.006490
Excluded by the BBN measurements at 2 sigma
(default: He3/p not considered).
Runtime --- 56.018600 mins ---
```

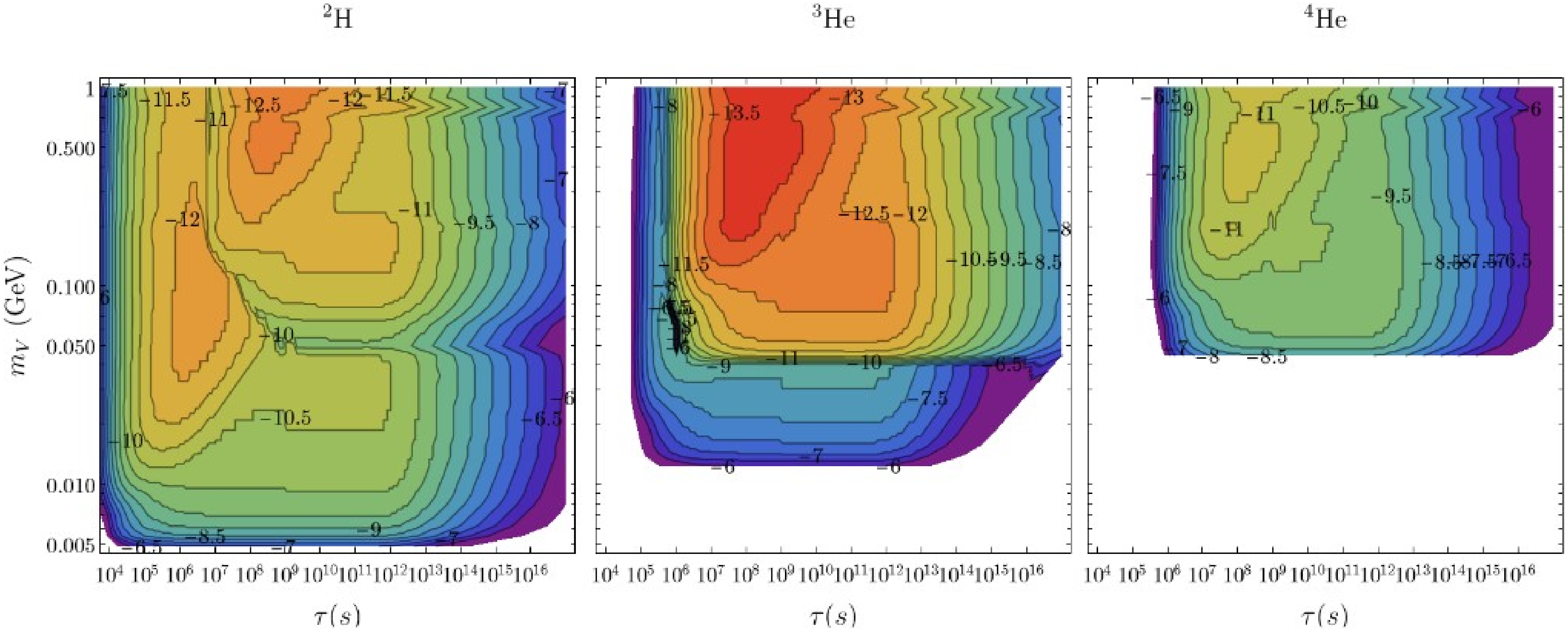
Dark photon model

Application $-\mathcal{L} \supset e\epsilon Q_{\mathrm{em},f}\overline{f}\gamma^{\mu}P_X\ f\ V_{\mu}$



Dark photon model

BBN photodisintegration constraints: deuterium, helium-3 & helium-4

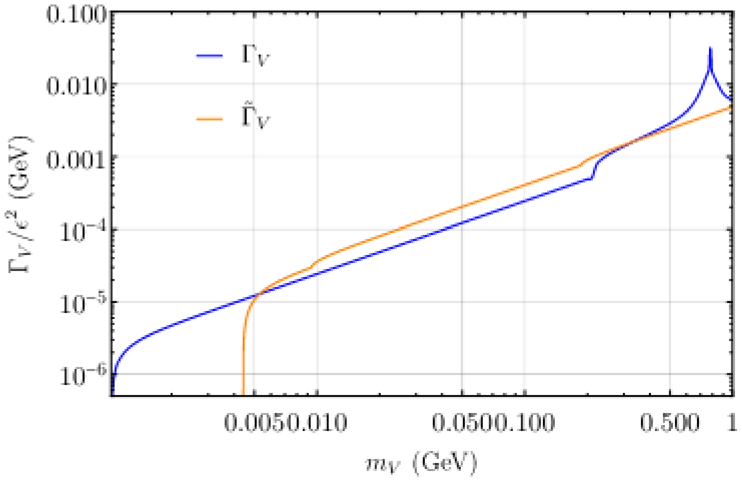


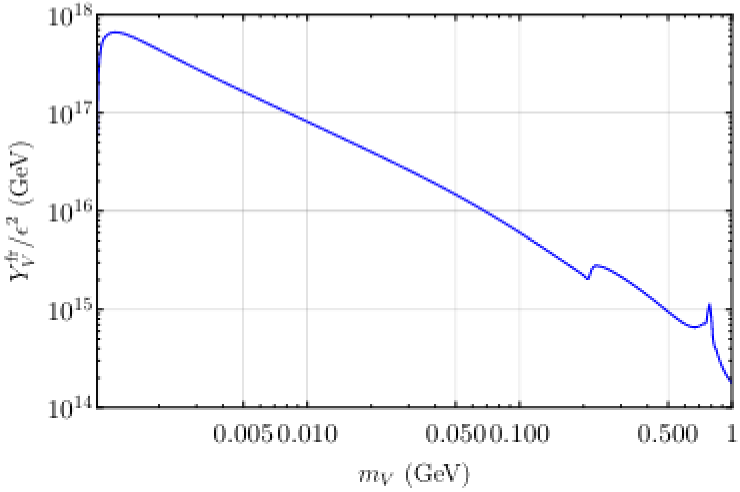
Contours are upper bounds on $m_V Y_V/\mathrm{GeV}$

Dark photon model

Freeze-in production

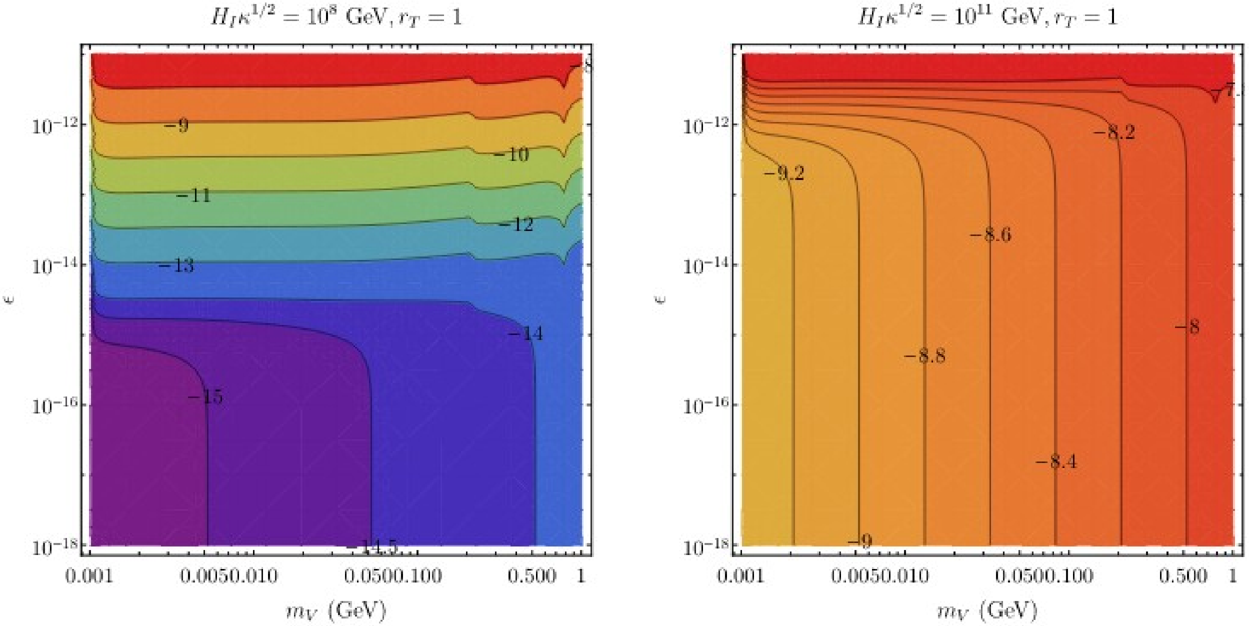
$$Y_V^{\rm fr} = \frac{3}{2\pi^2} m_V^2 \left[\Gamma_V \int_{T_f}^{T_{\rm QCD}} dT \frac{K_1(m_V/T)}{sH} + \tilde{\Gamma}_V \int_{T_{\rm QCD}}^{T_i} dT \frac{K_1(m_V/T)}{sH} \right]$$





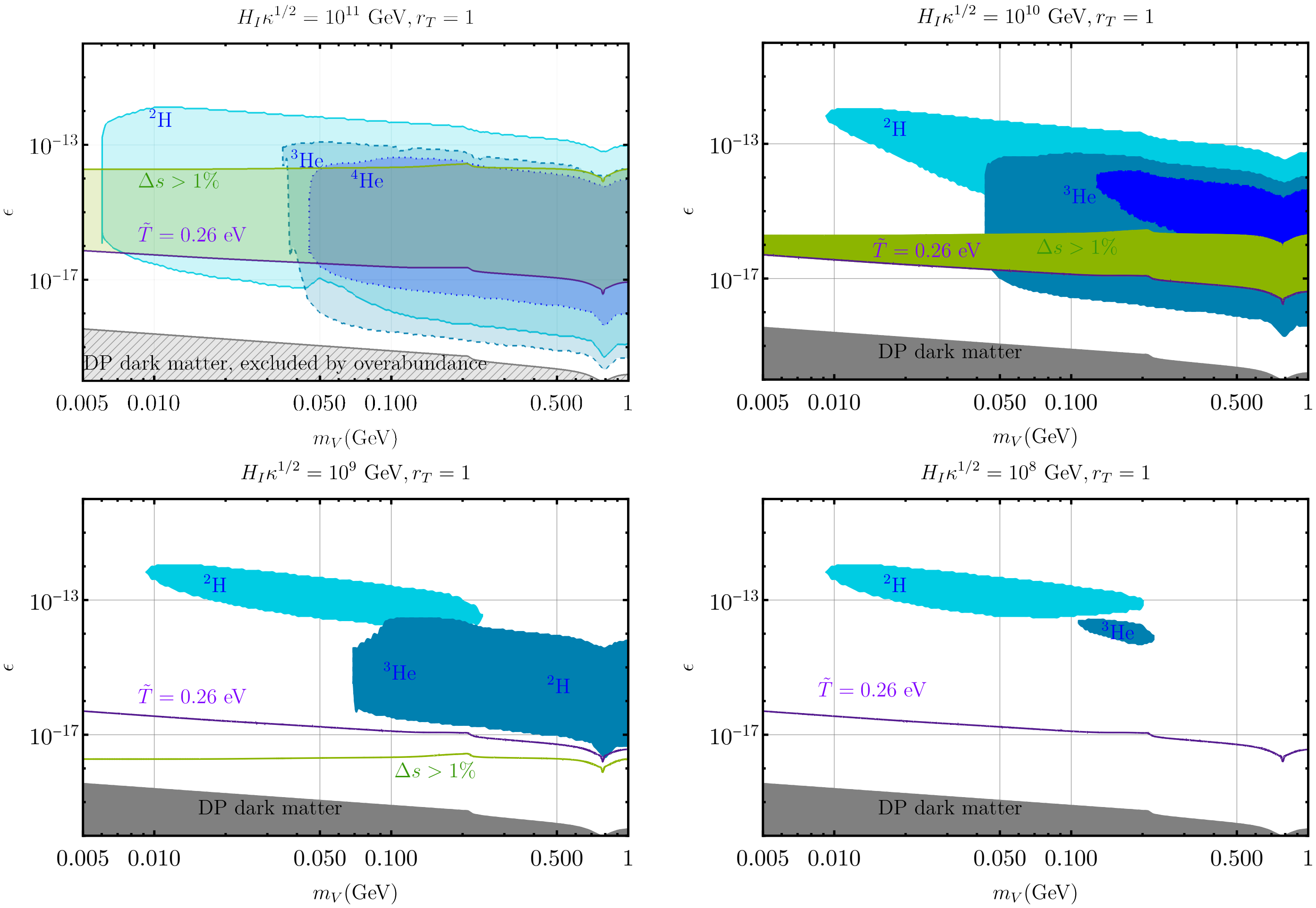
Dark photon model

Gravitational plus freeze-in production



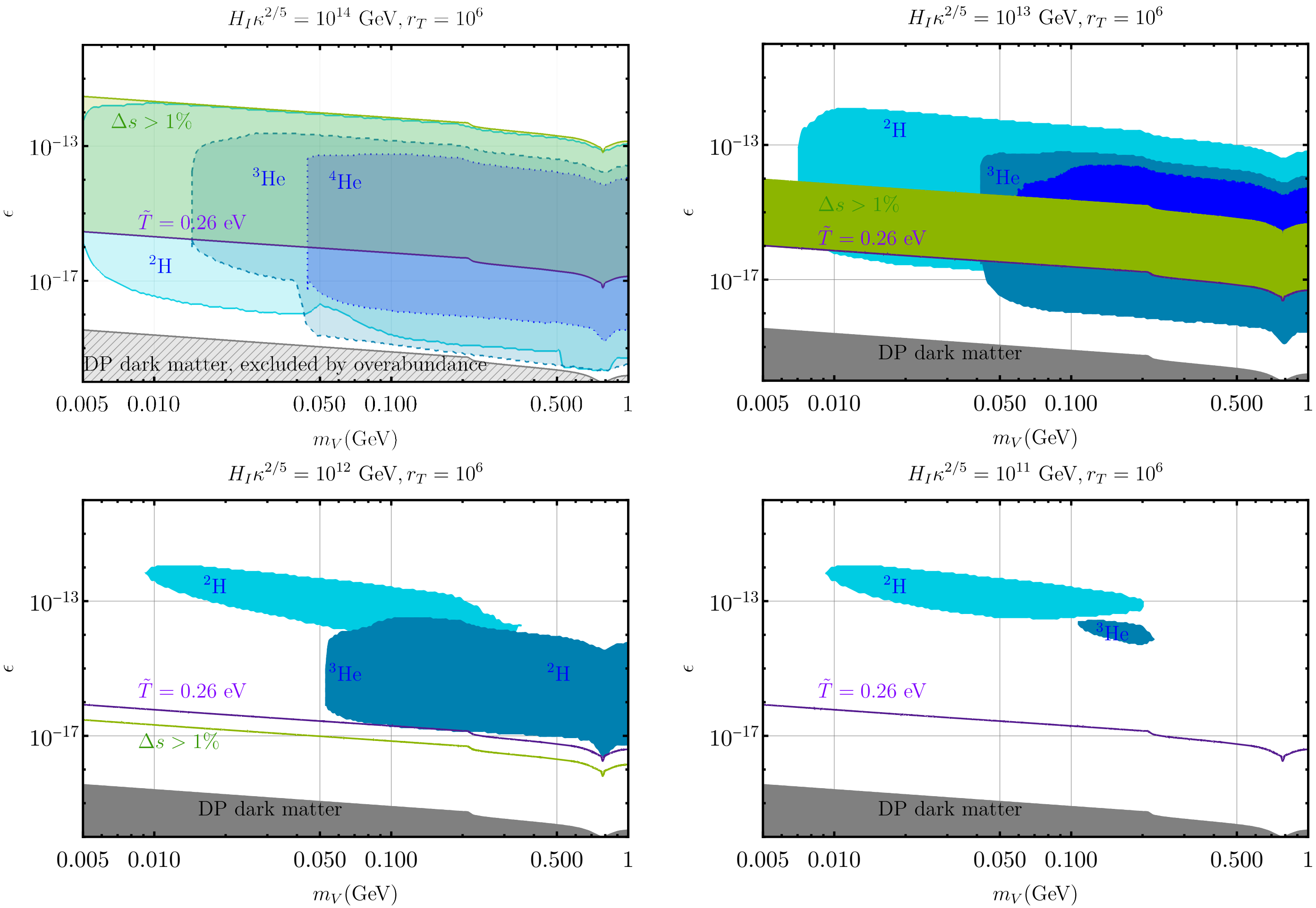
Dark photon model

High reheating cases



Dark photon model

Low reheating cases



Summary and outlook

- Gravitational production is relevant for any massive field when Hubble rate after inflation HI is greater than 10^8 GeV
- For gravitational produced long-lived particles with lifetime 10^4 s, BBN photodisintegration constraints are important
- We consider BBN photodisintegration effects of decaying light gauge boson (spectra and model file for `ACROPOLIS`) https://github.com/shengfong/lightvectorboson
- Example: **large exclusion from BBN photodisintegration** of parameter space of **gravitationally produced dark photon** with HI > 10^8 GeV
- Extend the model to consider heavier vector boson