N_{eff} constraints on the Dark Axion Portal

[H. Hong, U. Min, M. Son, and T. You, 2310.19544]
JHEP 03 (2024) 155

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When we have both **axion** and **dark photon** as BSM particles, we can consider their interaction.

Dark axion portal

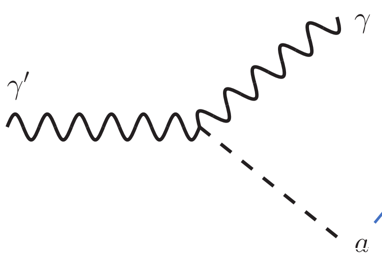
[K. Kaneta, H. Lee, and S. Yun, 1611.01466]

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}F'^2_{\mu\nu} + \frac{1}{2}m_{\gamma'}^2 A'^2_\mu + \boxed{\frac{1}{2f_a} a F_{\mu\nu}\tilde{F}'^{\mu\nu}}$$

interaction term

We suppress other terms by imposing dark charge conjugation symmetry, C_{dark}.

i) Massive dark photon and massless axion



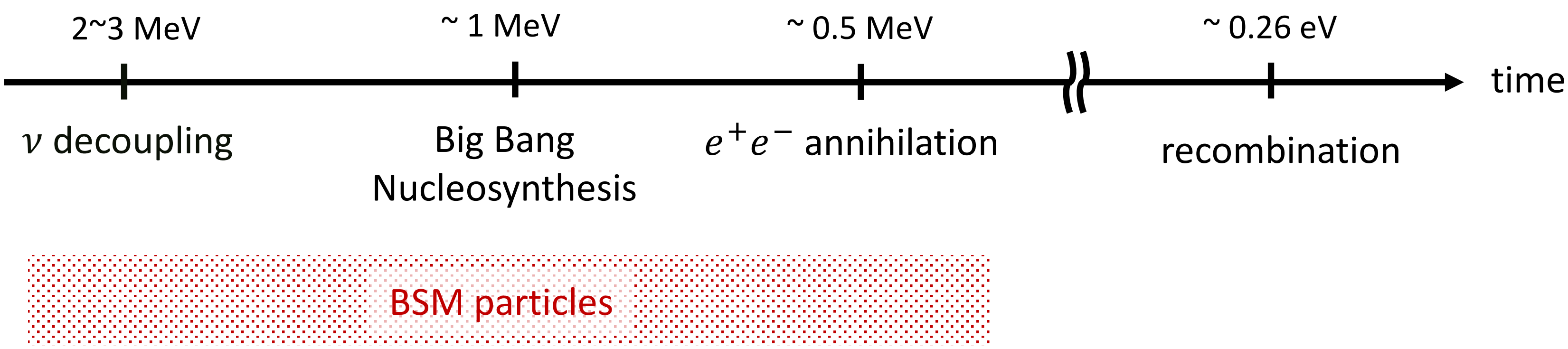
stable

$\Rightarrow$ by the dark matter abundance, $m_a \lesssim \ \mu eV$

ii) Massive axion and massless dark photon

We want to give some constraints on the **coupling** $\boldsymbol{\frac{1}{f_a}}$ and mass $\boldsymbol{m_{\gamma'}}$.

What aspects can be altered?



↳ In this model, γ' and a

1. Change the **effective number of neutrinos**

$$N_{eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{rad} - \rho_\gamma}{\rho_\gamma}$$

2. Change the **light element abundance** at **BBN**

3. Change the cosmological bound on the **neutrino mass sum**

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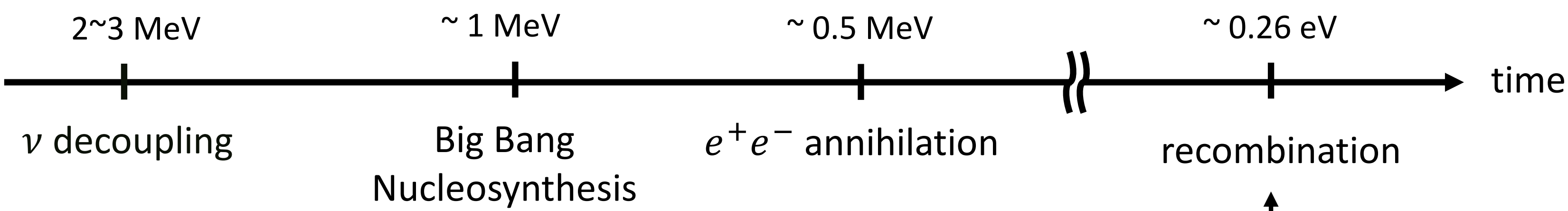

BSM particles

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1. Change the **effective number of neutrinos**

$$N_{eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{rad} - \rho_\gamma}{\rho_\gamma}$$

$N_{eff} = 2.99^{+0.34}_{-0.33}$ (PLANCK 2018)

[Planck Collaboration, 1807.06209]

use this to provide constraints

2. Change the **light element abundance** at **BBN**

3. Change the cosmological bound on the **neutrino mass sum**

Modifications of N_{eff}

$$N_{eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{rad} - \rho_\gamma}{\rho_\gamma}$$

$$\rho_{rad} = \rho_\nu + \rho_\gamma + \rho_{additional}$$

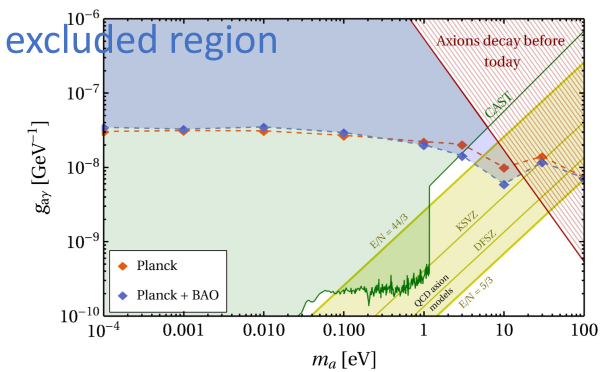
When additional particles interact with photon, ρ_γ can be affected.

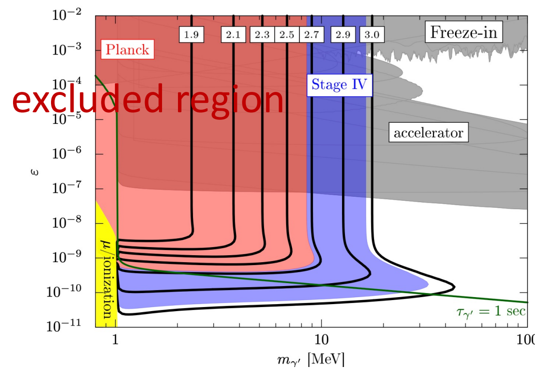
One typical way is increasing ρ_γ by injecting energy into the photon sector.

In most cases, modification happens in one of two ways.

$\longrightarrow$ Divide the parameter space into two regions : excluded or not.

[M. Ibe, S. Kobayashi, Y. Nakayama, and S. Shirai, 1807.06209]



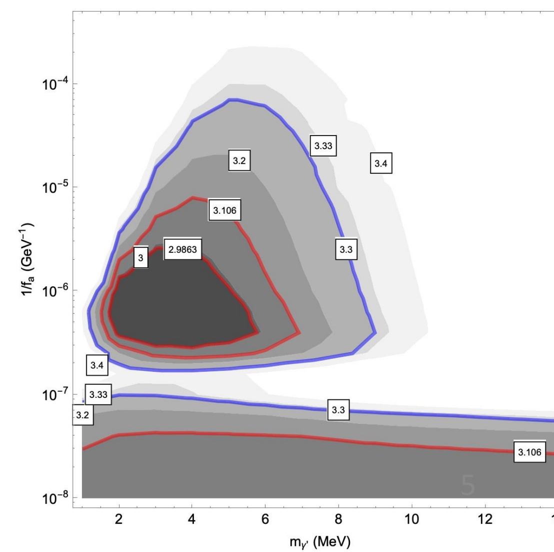


[L. Caloni, M. Gerbino, M.Lattanzi and L. Visinelli, 2205.01637]

If there exists a channel that can have **both modifications**,

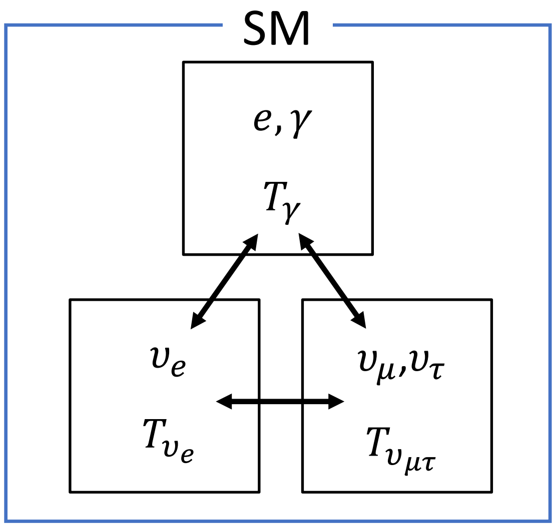
$\longrightarrow$ competition between the two effects can happen,

resulting in a **non-trivial bound**.



Boltzmann equation

$$\frac{d\rho_i}{dt} + 3H(\rho_i + p_i) = -\sum_a C_a^i \quad \text{where} \quad C_a^i = C_a \otimes E_i \ \text{: collision term}$$



Start simulation at a few hundred MeV
($\because$ target $m_{\gamma'} \sim$ a few MeV)
$\longrightarrow$ Muons and heavier particles have already decoupled.

$$e, \gamma : \frac{\partial \rho_{e\gamma}}{\partial t} + 3H(\rho_{e\gamma} + p_{e\gamma}) = -C_{e\leftrightarrow\nu_e} - 2C_{e\leftrightarrow\nu_\mu}$$

$$\nu_e : \frac{\partial \rho_{\nu_e}}{\partial t} + 4H\rho_{\nu_e} = C_{e\leftrightarrow\nu_e} - 2C_{\nu_e\leftrightarrow\nu_\mu}$$

$$\nu_\mu, \nu_\tau : \frac{\partial \rho_{\nu_{\mu\tau}}}{\partial t} + 4H\rho_{\nu_{\mu\tau}} = 2C_{\nu_e\leftrightarrow\nu_\mu} + 2C_{e\leftrightarrow\nu_\mu}$$

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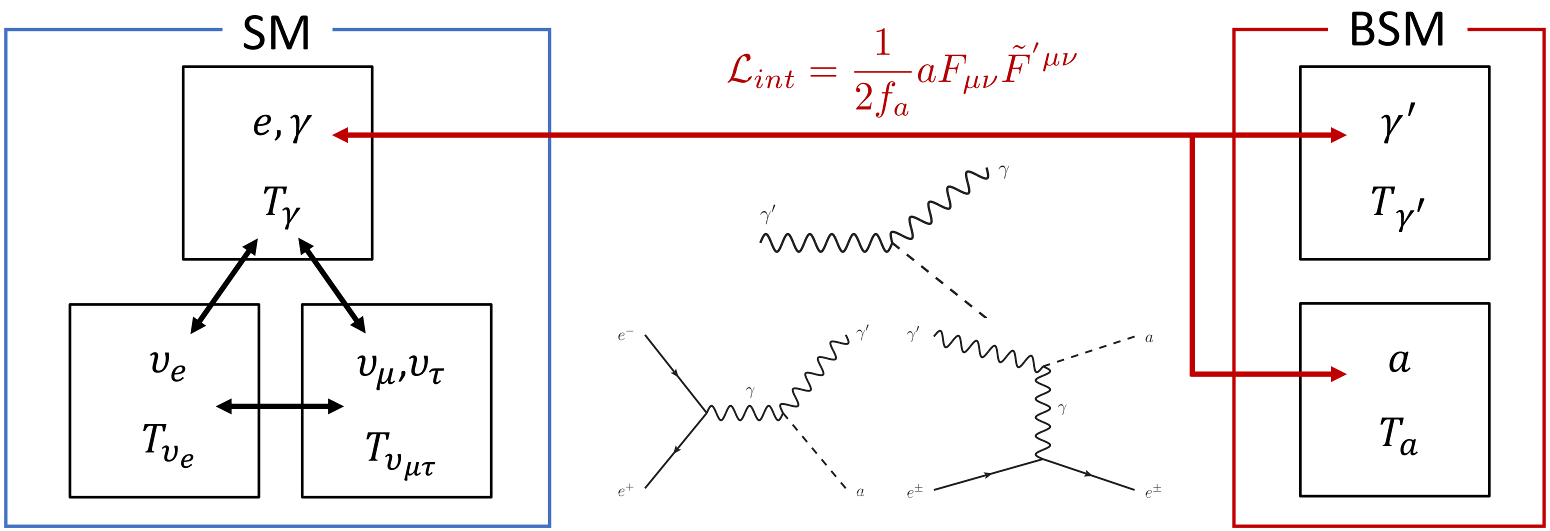

$$e,\gamma : \frac{\partial \rho_{e\gamma}}{\partial t} + 3H(\rho_{e\gamma} + p_{e\gamma}) = -C_{e\leftrightarrow\nu_e} - 2C_{e\leftrightarrow\nu_\mu} + C^{\gamma}_{\gamma'\leftrightarrow\gamma a} + C^{e}_{\gamma' a\leftrightarrow e^+e^-} - 2C^{e}_{e^\pm\gamma'\leftrightarrow e^\pm a}$$

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$$\gamma' : \frac{\partial \rho_{\gamma'}}{\partial t} + 3H(\rho_{\gamma'} + p_{\gamma'}) = -C^{\gamma'}_{\gamma'\leftrightarrow\gamma a} - C^{\gamma'}_{\gamma' a\leftrightarrow e^+e^-} - 2C^{\gamma'}_{e^\pm\gamma'\leftrightarrow e^\pm a}$$

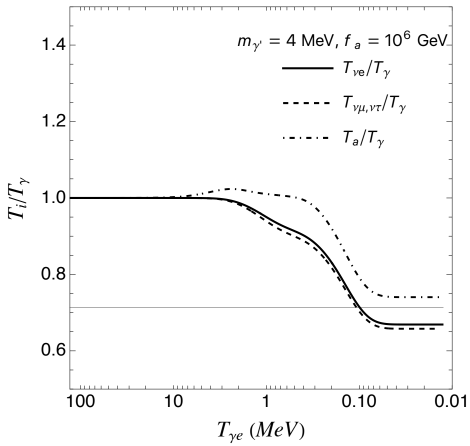
$$a : \frac{\partial \rho_{a}}{\partial t} + 3H(\rho_{a} + p_{a}) = -C^{a}_{\gamma'\leftrightarrow\gamma a} - C^{a}_{\gamma' a\leftrightarrow e^+e^-} - 2C^{a}_{e^\pm\gamma'\leftrightarrow e^\pm a}$$

At first, $\rho_{\gamma'} = \rho_a = 0$.
By 4-point interactions, they are produces.

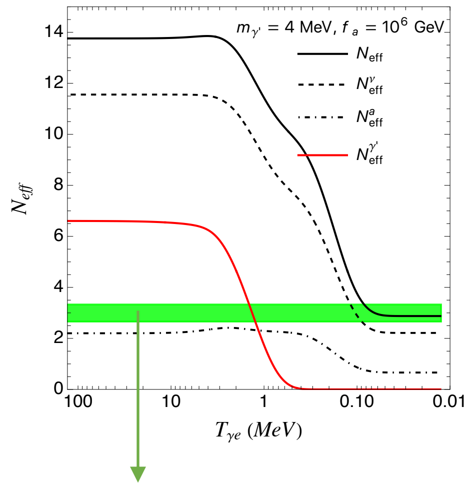
For each parameter point,

by solving **Boltzmann equations**, we obtain such as

Temperature change



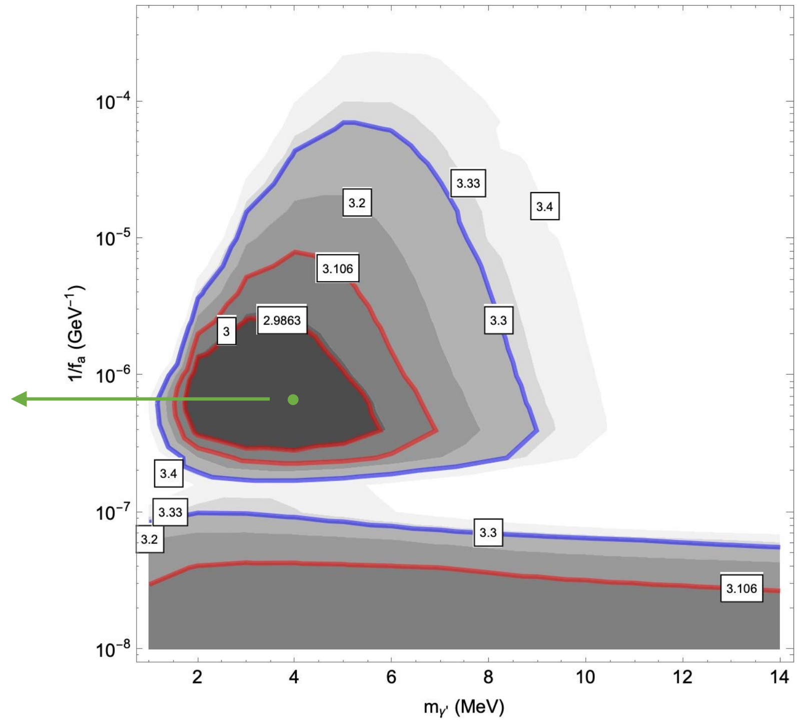
N_{eff} change



$$N_{eff} = 2.99^{+0.34}_{-0.33}$$ (PLANCK 2018)

$\Rightarrow$ **excluded or not!**

Result



Current (blue) : $N_{eff} = 2.99^{+0.34}_{-0.33}$

Future expectation (red) : $N_{eff} = 3.046 \pm 0.06$

(CMB STAGE-IV)

How do a and γ' affect N_{eff}?

In terms of energy density,

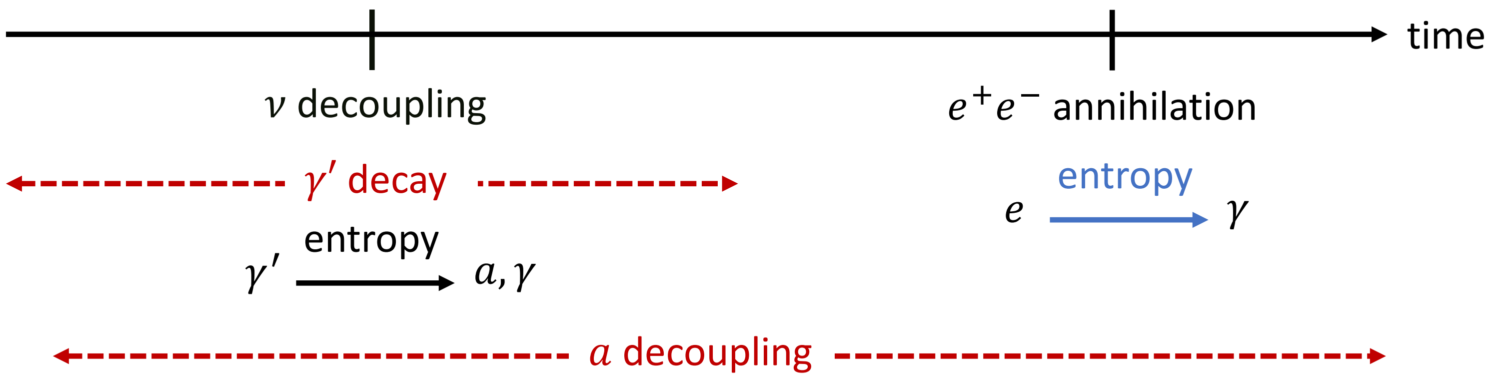
$$N_{eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{rad} - \rho_\gamma}{\rho_\gamma}$$

$$= \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_\nu + \rho_a}{\rho_\gamma}$$

In terms of temperature,

$$\rho_\nu = \frac{\pi^2}{30}\frac{7}{8} g_\nu T_\nu^4 \;,\; \rho_a = \frac{\pi^2}{30} g_a T_a^4$$

$$N_{eff} \approx \left(\frac{11}{4}\right)^{\frac{4}{3}} \left[3\left(\frac{T_\nu}{T_\gamma}\right)^4 + \frac{8}{7}\frac{g_a}{g_\gamma}\left(\frac{T_a}{T_\gamma}\right)^4\right]$$



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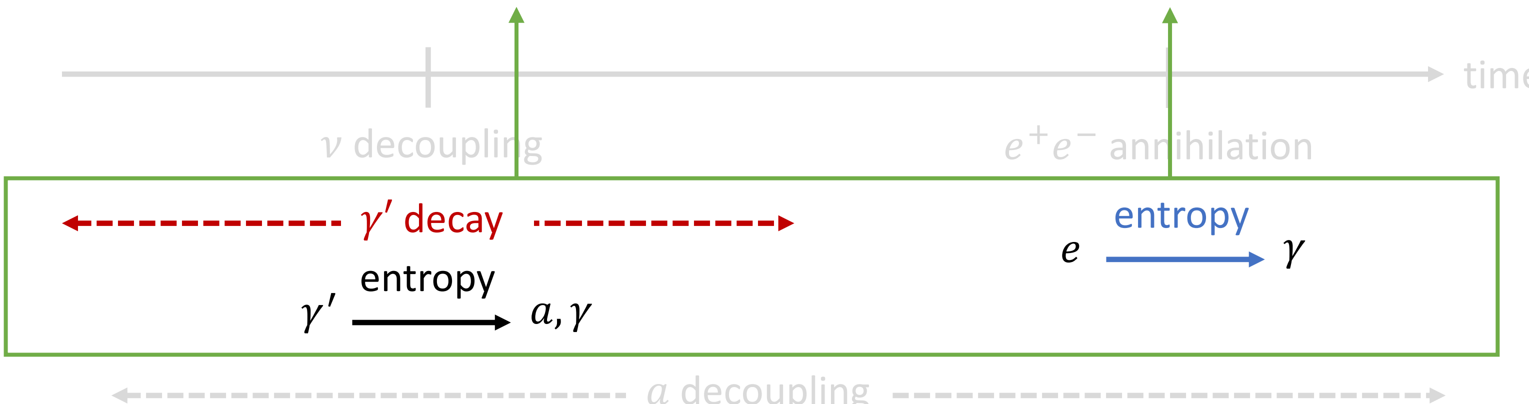

Increase ρ_γ $\Longleftrightarrow$ $\frac{T_\nu}{T_\gamma}$ becomes even smaller

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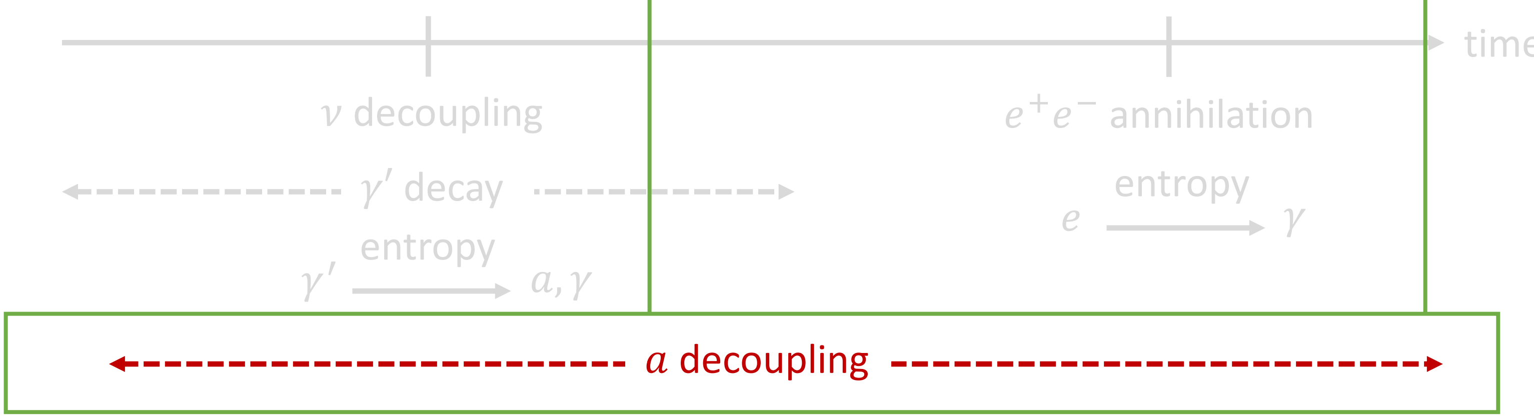

additional ρ_a $\Longleftrightarrow$ additional $\frac{T_a}{T_\gamma}$ term

How do a and γ' affect N_{eff}?

In terms of energy density,

$$N_{eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{rad} - \rho_\gamma}{\rho_\gamma}$$

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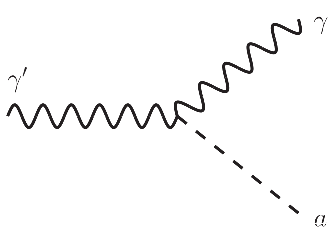


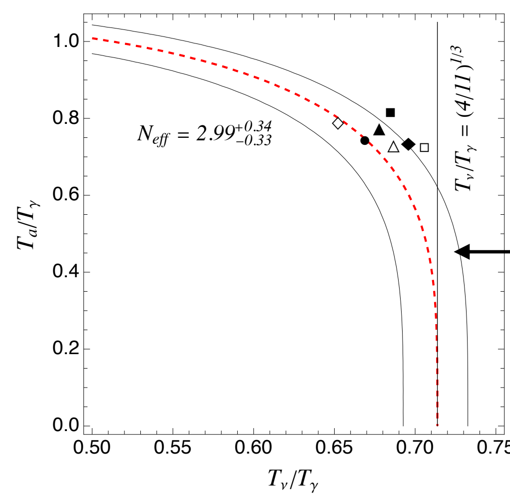
$\longrightarrow$ Increase ρ_γ

$\longrightarrow$ Additional ρ_a

smaller $\frac{T_\nu}{T_\gamma}$

additional $\frac{T_a}{T_\gamma}$ term

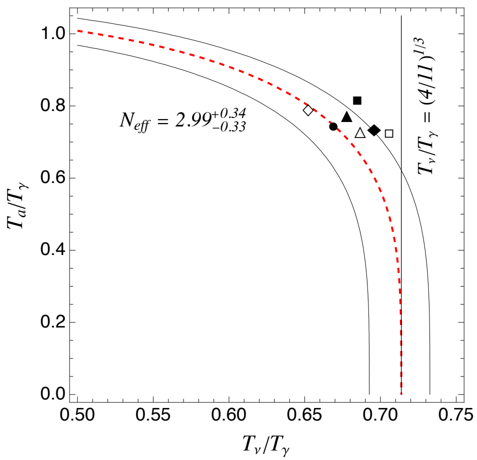
compete

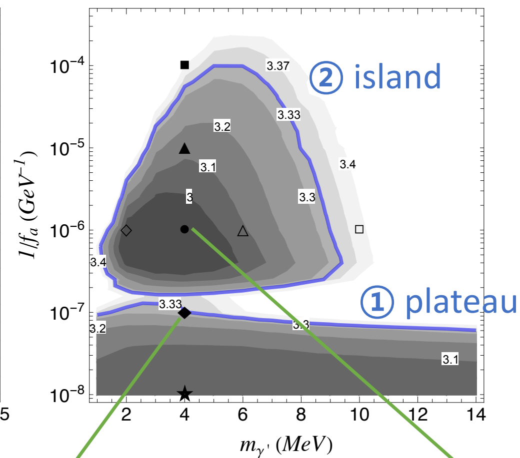


Allowed band

∴ Due to the **dark axion portal**,

we have multiple modifications to N_{eff}.



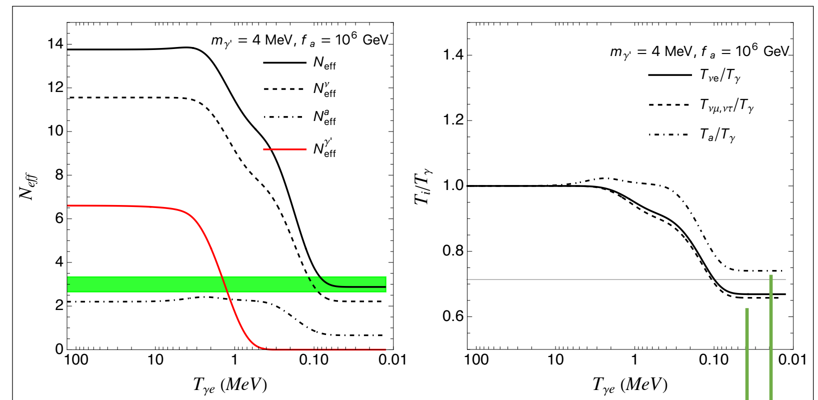


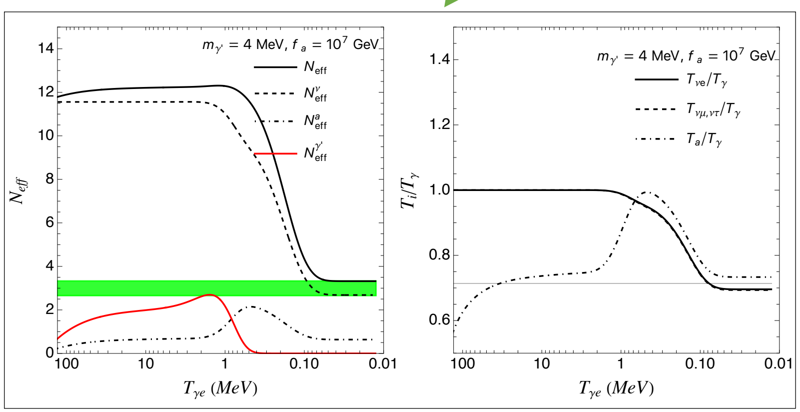
② island

Relatively big coupling constant $\dfrac{1}{fa}$

⇒ **Sufficient production** of axion and dark photon &

High probability to **thermalize with SM** particles





small $\dfrac{T_\nu}{T_\gamma}$ & additional $\dfrac{T_a}{T_\gamma}$

compensate each other

$$N_{eff} = \left(\frac{11}{4}\right)^{\frac{4}{3}} \left[3\left(\frac{T_\nu}{T_\gamma}\right)^4 + \frac{8}{7}\frac{g_a}{g_\gamma}\left(\frac{T_a}{T_\gamma}\right)^4\right]$$

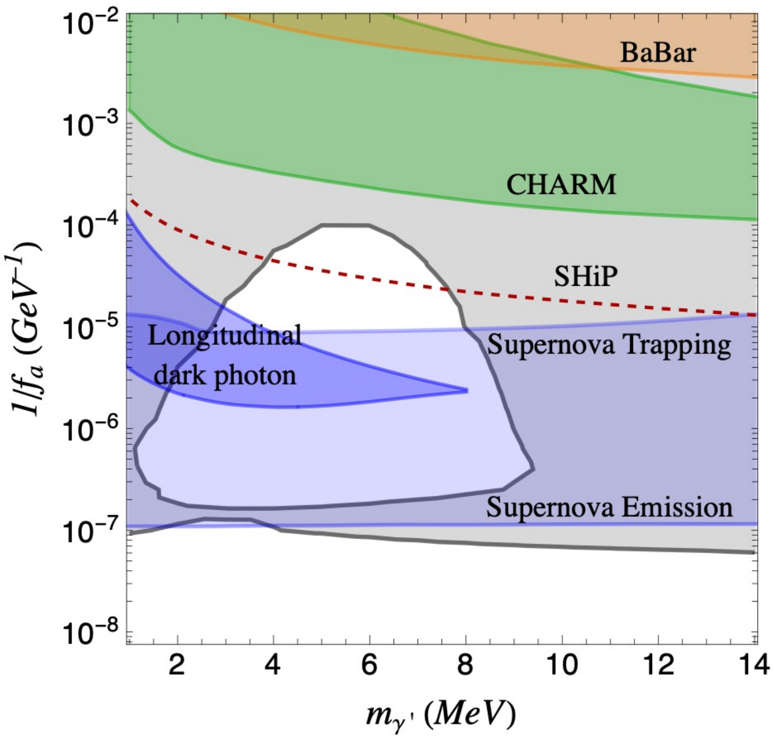
① plateau

Small coupling constant $\dfrac{1}{fa}$

⇒ **Less production** of axion and dark photon &

Hard to thermalize with SM particles

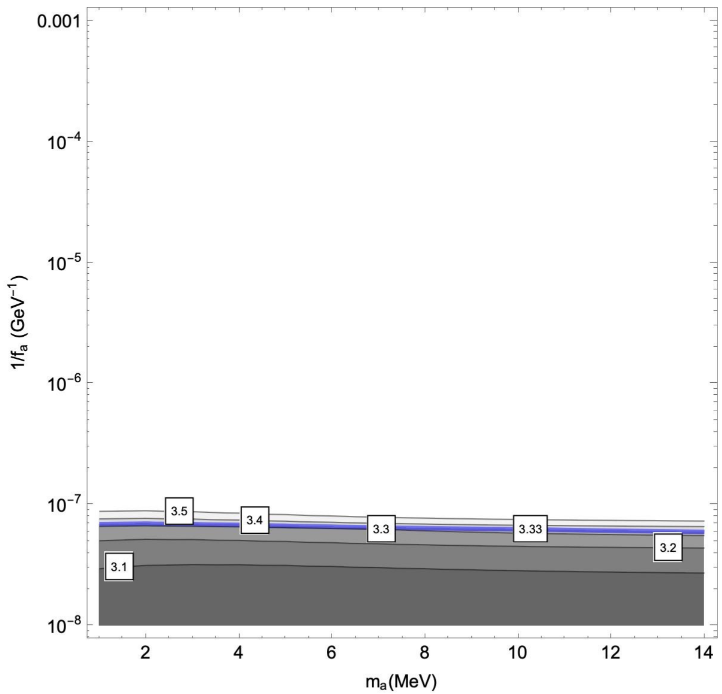
Overlapped with existing searches



- Provide a stronger bound than the constraint than others

- Some portion of the island still survives

Massive axion & massless dark photon case



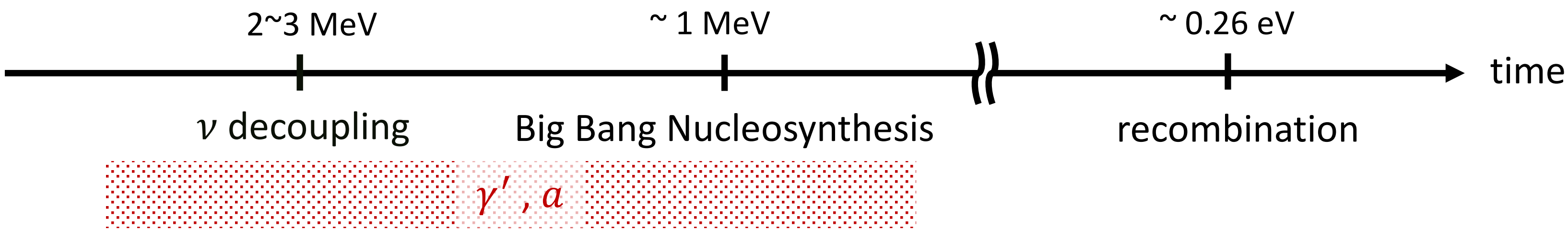
$$N_{eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_\nu + \rho_{\gamma'}}{\rho_\gamma}$$
$$= \left(\frac{11}{4}\right)^{\frac{4}{3}} \left[3\left(\frac{T_\nu}{T_\gamma}\right)^4 + \frac{8}{7}\frac{g_{\gamma'}}{g_\gamma}\left(\frac{T_{\gamma'}}{T_\gamma}\right)^4\right]$$

No island

∵ Since $g_{\gamma'} = 2$ here, whereas $g_a = 1$ before,

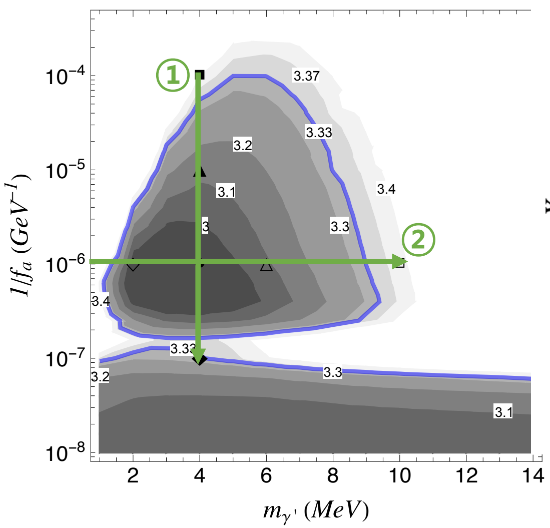
It is much harder to achieve allowed N_{eff}.

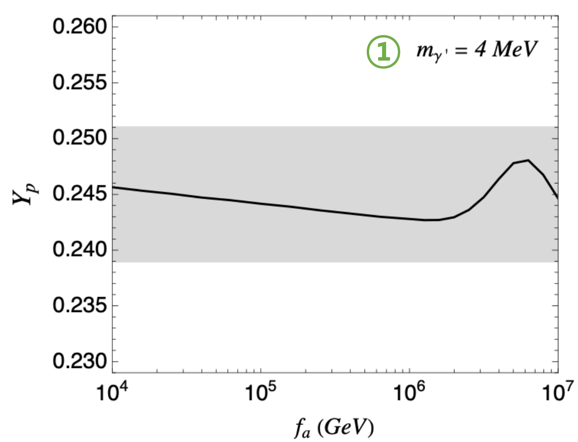
Constraint from BBN

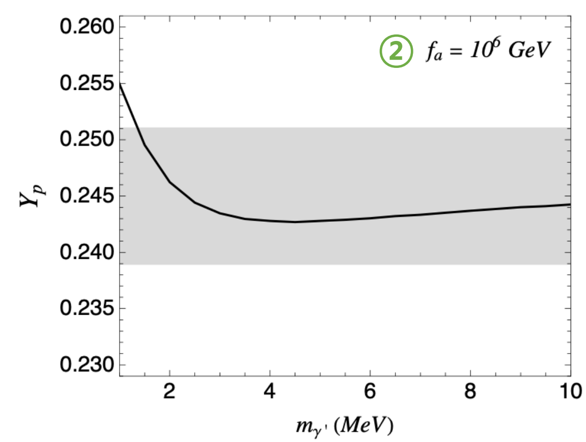


can affect BBN

- Helium abundance : Y_P = 0.245 ± 0.006 [Particle Data Group Collaboration, *Phys.Rev.D* 98 (2018) 3, 030001]







N_{eff} provides a stronger constraint.

- Deuterium abundance : $D/H_P \times 10^5$ = 2.569 ± 0.027

Can mildly change the contour but not much, since the change in N_{eff} and D/H_P is correlated.

Need more simulations using PArthENoPE, PRIMAT, … to get exact results.

Bound on the sum of neutrino masses

Current bounds on neutrino masses

1. Cosmological bound

$$\sum m_\nu < 0.09\ \mathrm{eV}\ (95\%\ \mathrm{CL})$$ [E. Valentino, S. Gariazzo, and O. Mena, 2106.15267]

recently, $\sum m_\nu < 0.07\ \mathrm{eV}\ (95\%\ \mathrm{CL})$ [N. Craig, D.Green, J.Meyers and S. Rajendran, 2405.00836]

2. Neutrino oscillation (with $m_0 = 0$)

$$\sum m_\nu > 0.06\ \mathrm{eV}\ (\mathrm{NO}) \qquad \sum m_\nu > 0.10\ \mathrm{eV}\ (\mathrm{IO})$$

[P. Salas, D. Forero, S. Gariazzo, P. Martínez-Miravé, O. Mena, C. Ternes, M. Tórtola, and J. Valle, 2006.11237]

If the number density of neutrino differs from SM,

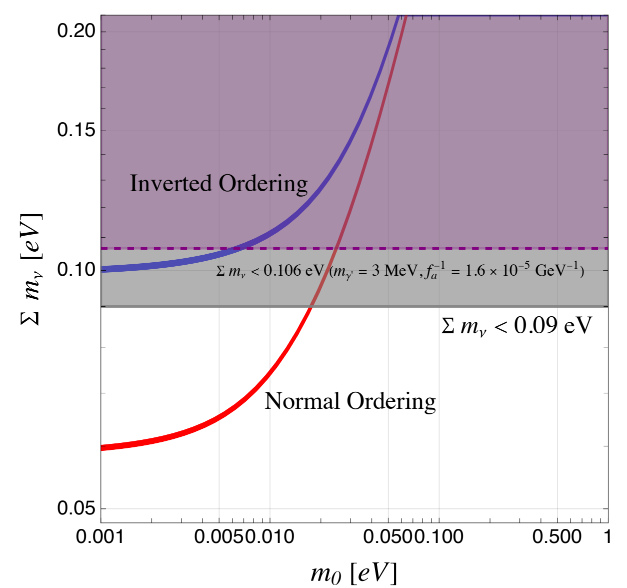
cosmological bound becomes

$$\sum m_\nu < 0.09\ \mathrm{eV}\ \times \frac{n_\nu^{SM}}{n_\nu}\ (95\%\ \mathrm{CL})$$

$$n_\nu \propto (T_\nu / T_\gamma)^3$$

For many points, T_ν/T_γ is smaller than SM value, $\left(\frac{4}{11}\right)^{1/3}$.

⇒ Relax the cosmological bound on neutrino masses



ex) $m_{\gamma'} = 3$ MeV, $f_a = 1.6\times10^{-5}$ GeV,

$$\sum m_\nu < 0.106\ \mathrm{eV}$$

Summary

We made constraints on $\frac{1}{f_a}$ and $m_{\gamma'}$ of dark axion portal using N_{eff}.

- In this model, both effects of increasing and decreasing N_{eff} were observed, resulting in a non-trivial bound.
- Compared to previous studies, we applied stronger bound and found a non-trivial area that still survived.
- CMB stage IV observation ($\delta N_{eff} \simeq 0.06$) will give strong bound.

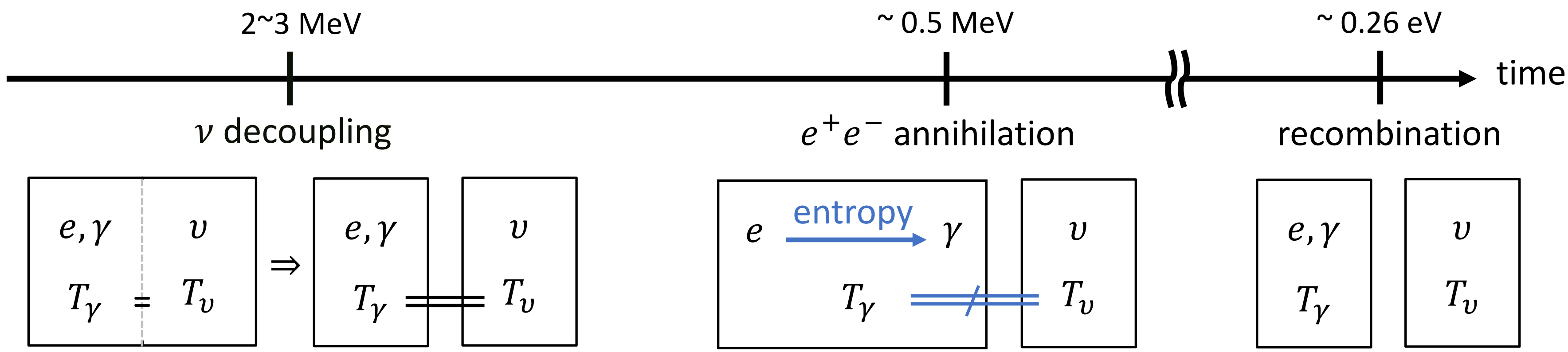
BBN could also provide some constraints on the model,

but we expect that the overall picture will remain the same.

Can relax the neutrino masses constraint from cosmological observation.

Back up

Effective number of neutrinos



$$\because T_\gamma, T_\nu \propto \frac{1}{a}$$

$$\frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{\frac{1}{3}} \xrightarrow[\text{same}]{\text{remain}} \frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{\frac{1}{3}}$$

by entropy conservation

At recombination,

$$\begin{aligned}\rho_{rad} &= \rho_\gamma + \rho_\nu \\ &= \frac{\pi^2}{30} g_\gamma T_\gamma^4 + \frac{7}{8}\frac{\pi^2}{30} g_\nu T_\nu^4 \\ &= \frac{\pi^2}{30} g_\gamma T_\gamma^4 \left\{1 + \frac{7}{8}\frac{g_\nu}{g_\gamma}\left(\frac{T_\nu}{T_\gamma}\right)^4\right\}\end{aligned}$$

where $g_\gamma = 2$, $g_\nu = 3 \times 2$

number of neutrino species

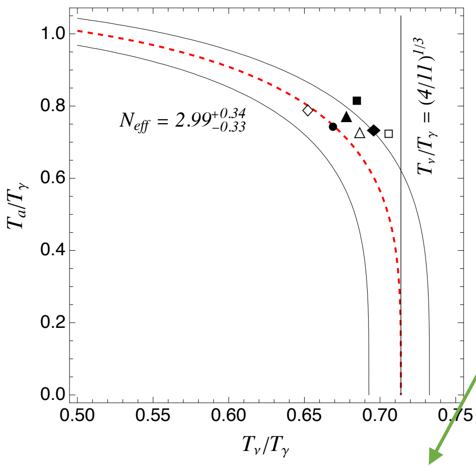
→ **generalize to N_{eff}**

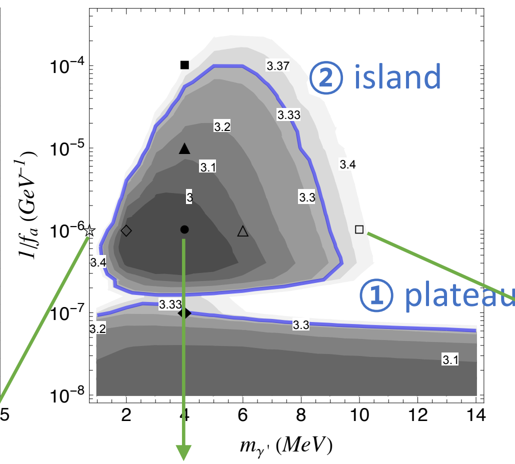
In SM, $N_{eff} = 3.043$

weyl fermion

$$\Rightarrow N_{eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{rad} - \rho_\gamma}{\rho_\gamma}$$

: **Effective number of neutrinos**





$$N_{eff} = \left(\frac{11}{4}\right)^{\frac{4}{3}} \left[3\left(\frac{T_\nu}{T_\gamma}\right)^4 + \frac{8}{7}\frac{g_a}{g_\gamma}\boxed{\left(\frac{T_a}{T_\gamma}\right)}^4\right]$$

② island

Relatively big coupling constant $\frac{1}{f_a}$

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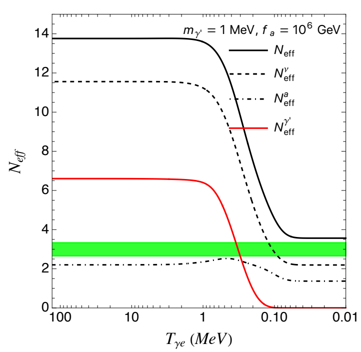
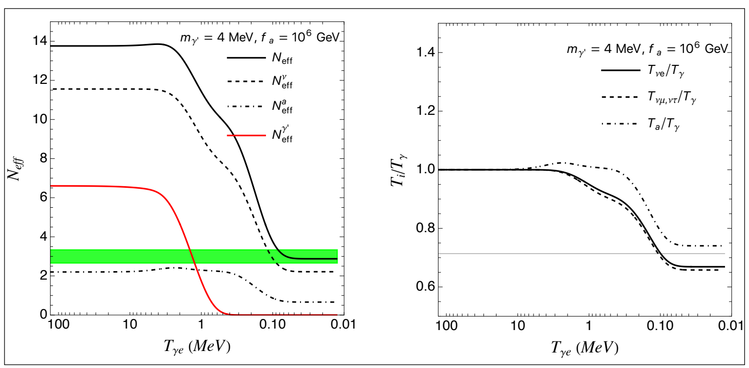
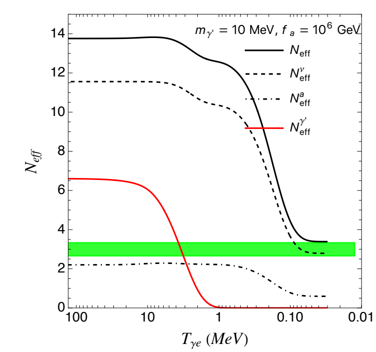
High probability to **thermalize with SM** particles







light $m_{\gamma'}$ ⟷ heavy $m_{\gamma'}$

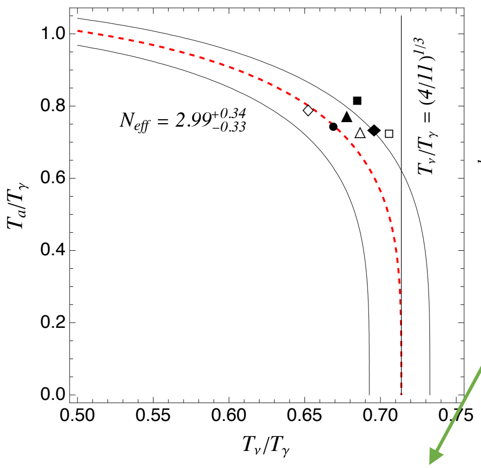
2~3 MeV — ν decoupling

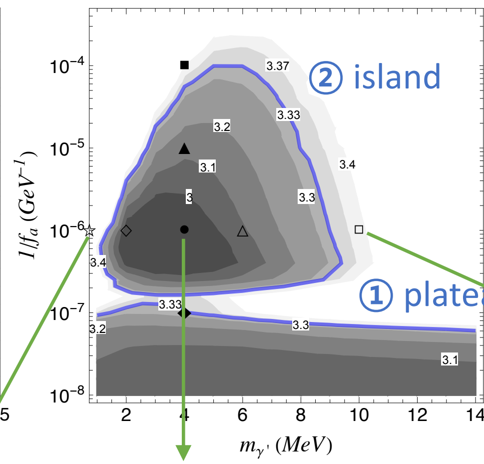
~ 0.5 MeV — e^+e^- annihilation

← γ' decay →

← a decoupling →

light $m_{\gamma'}$ ⟶ late γ' decay ⟶ late a decoupling ⟶ $\frac{T_a}{T'_\gamma} \approx 1$ ⟶ large N_{eff}





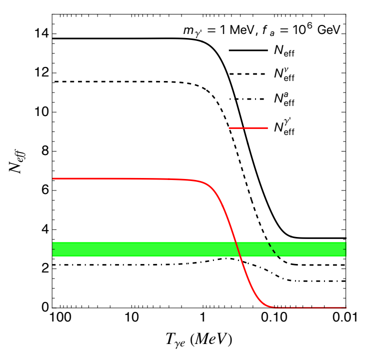
$$N_{eff} = \left(\frac{11}{4}\right)^{\frac{4}{3}} \left[3 \boxed{\left(\frac{T_\nu}{T_\gamma}\right)}^4 + \frac{8}{7}\frac{g_a}{g_\gamma}\left(\frac{T_a}{T_\gamma}\right)^4 \right]$$

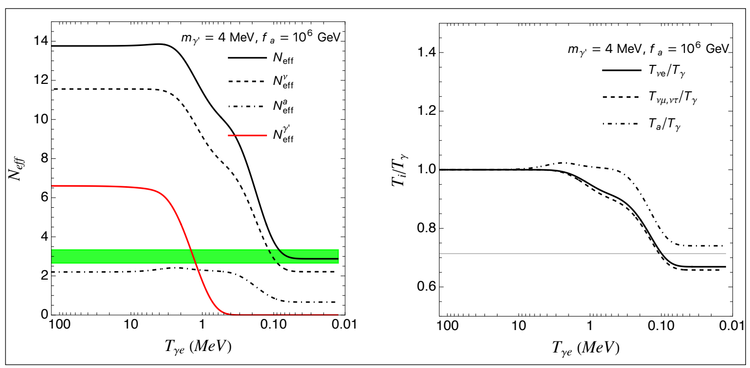
② island

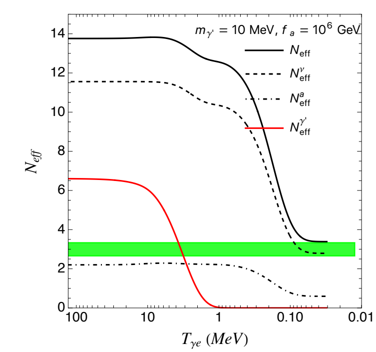
Relatively big coupling constant $\frac{1}{f_a}$

⇒ **Sufficient production** of axion and dark photon &

High probability to **thermalize with SM particles**







light $m_{\gamma'}$ ⟷ $\boxed{\text{heavy } m_{\gamma'}}$

2~3 MeV — ν decoupling

~ 0.5 MeV — e^+e^- annihilation

γ' decay

a decoupling

heavy $m_{\gamma'}$ ⟶ early γ' decay ⟶ early a decoupling ⟶ $\frac{T_\nu}{T_\gamma} \approx \left(\frac{4}{11}\right)^{\frac{1}{3}}$ ⟶ large N_{eff}

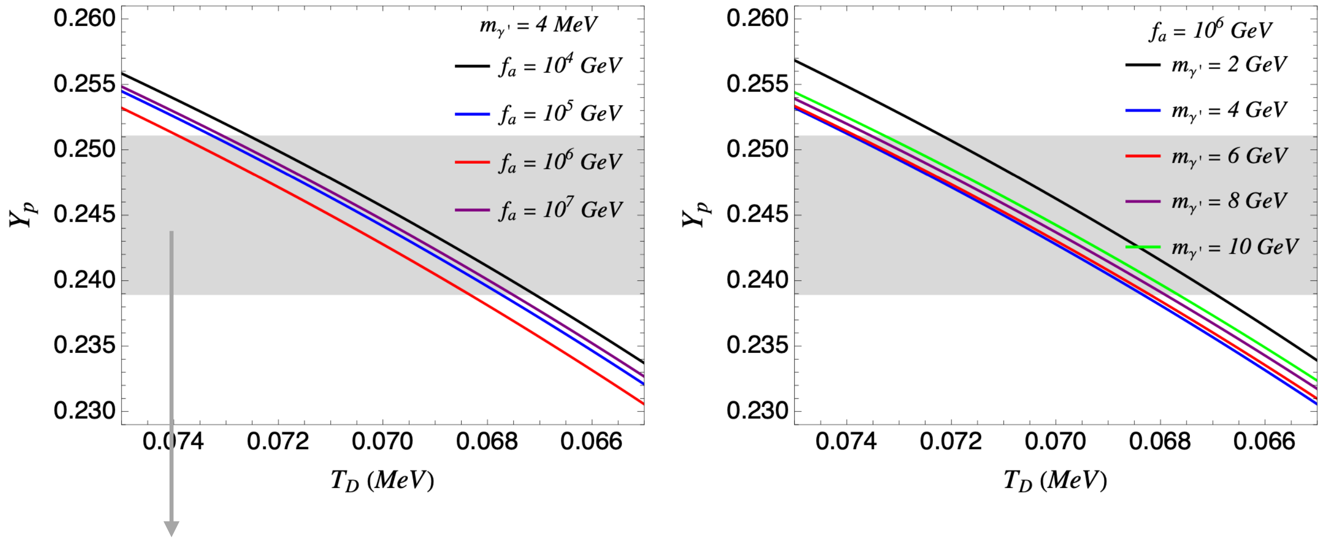
Helium abundance dependence on T_D

$$\frac{dX_n}{dt} = \Gamma_{p\to n}X_p - \Gamma_{n\to p}X_n\ , \quad \frac{dX_p}{dt} = \Gamma_{n\to p}X_n - \Gamma_{p\to n}X_p \quad \text{where} \quad X_i \equiv n_i/n_B$$

$$Y_p \approx 2X_n|_{T_D}$$

We used $T_D = 0.07$ MeV, the temperature at which deuterium is no longer dissociated by photons so that all neutrons at that time are expected to form Helium.

The result can depend on this temperature.



Y_P = 0.245 ± 0.006