Portal Connecting Axions and Dark Photons

Kunio Kaneta (IBS CTPU)

Based on the work with Hye-Sung Lee and Seokhoon Yun

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arXiv: 1704.07542 (PRD, 95, 115032)

Dark Side of the Universe, July 10, 2017

Outline

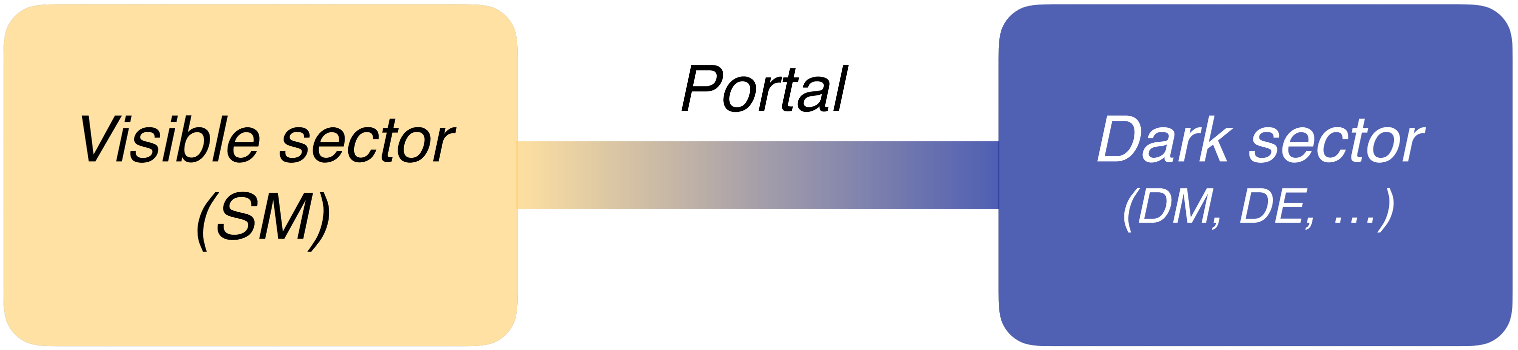
1. Portals toward a dark sector
2. Dark axion portal and the model
3. Implications
4. Summary

1. Portals toward a dark sector

Dark sector

- We know there is a ***dark side of the Universe***.
  (including, e.g., dark matter & dark energy)

- But, we know very few things about the dark (hidden) sector.
- Portal couplings play a central role in probing the dark sector.



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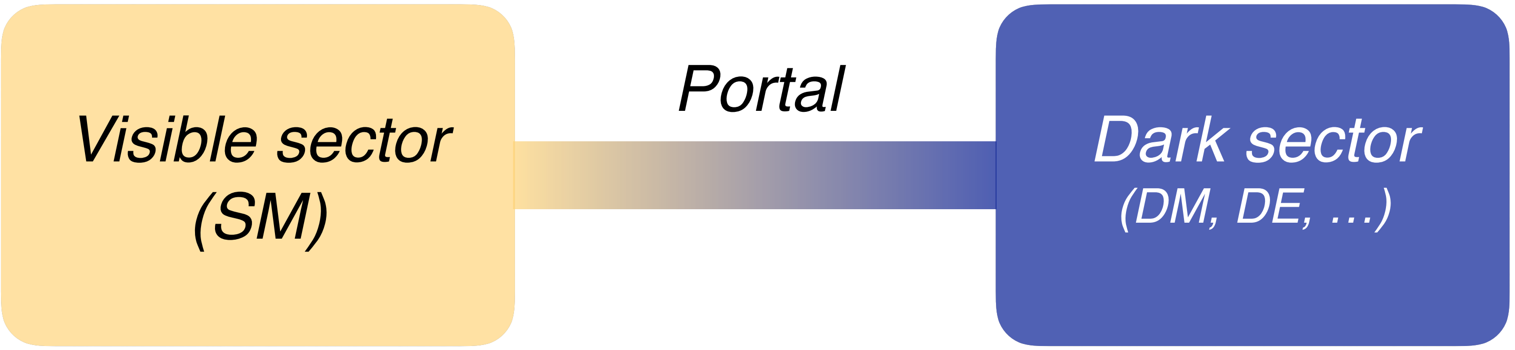

Quest for portals toward the dark sector *(especially, dark matter)*

- Higgs portal: $|S|^2|H|^2$, $S|H|^2$
- Neutrino portal: $LH\nu_R$
- Vector portal (e.g. kinetic mixing)
- Axion portal (via anomaly terms)

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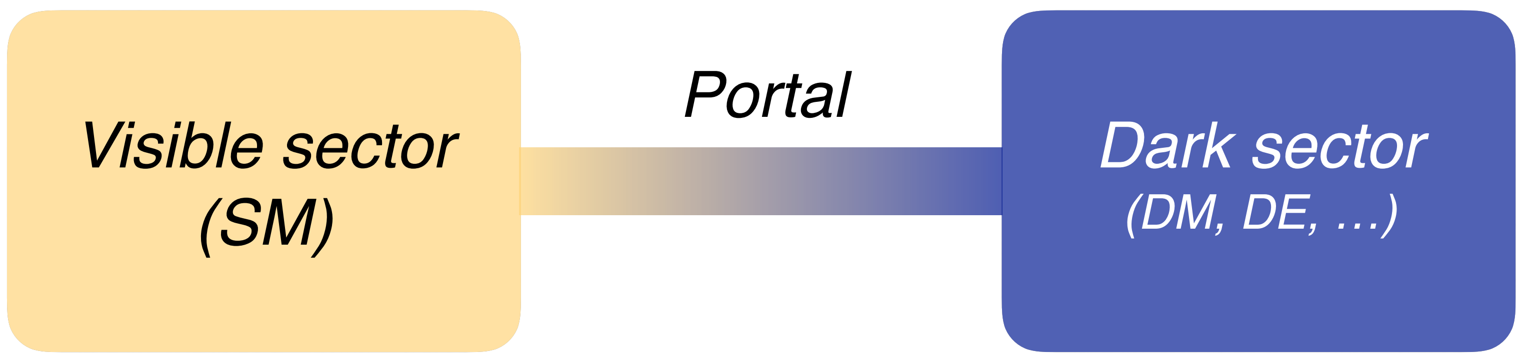

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Dark axion portal (connecting axions and dark photons)

What is the current status of the dark photon and axion as a dark matter candidate?

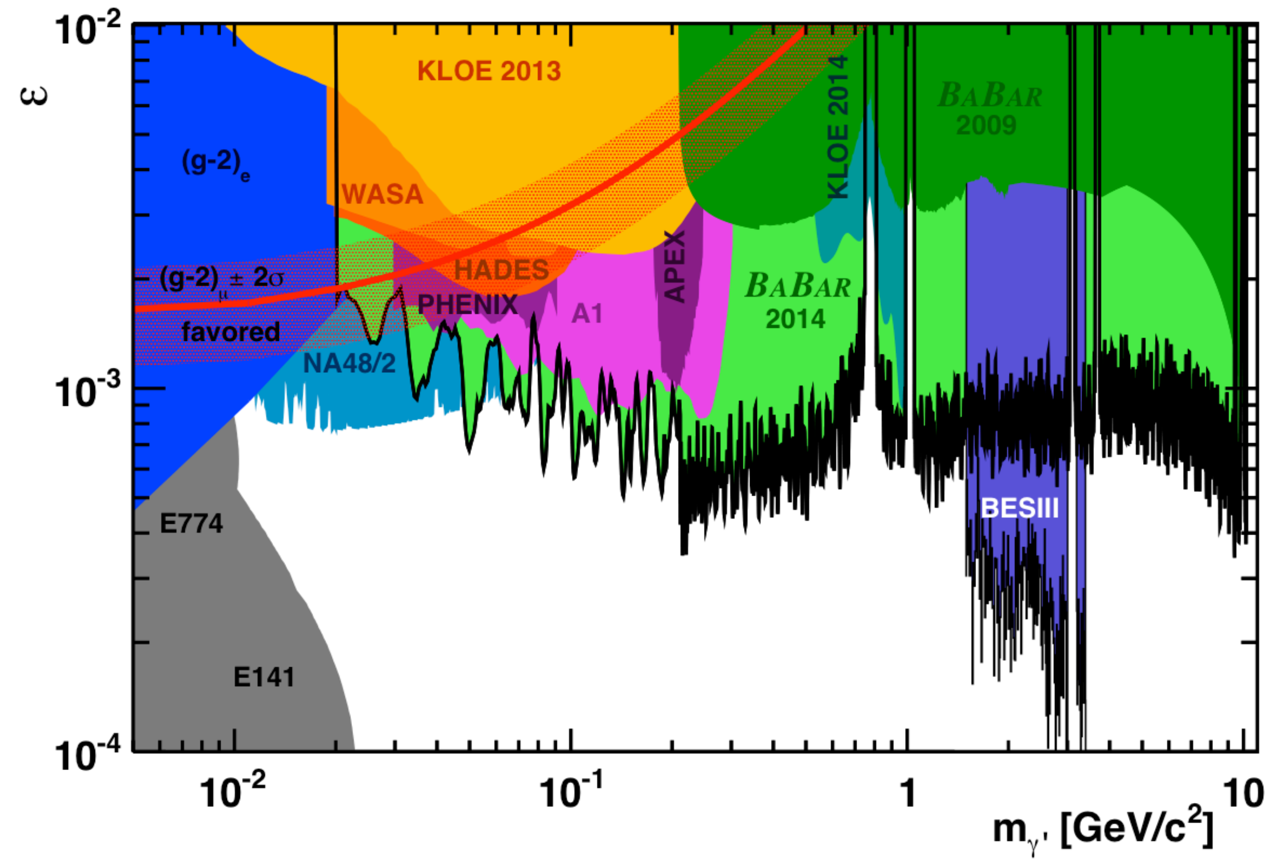
Dark photon as a dark matter

- Dark photon is produced through the kinetic mixing (vector portal)

$L_{mix} \sim \varepsilon \, F_{\mu\nu} \, Z'^{\mu\nu}$

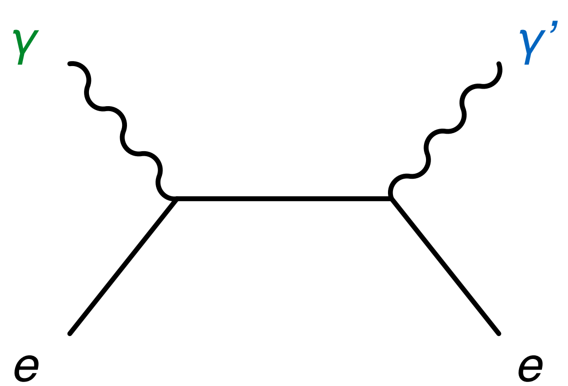
photon dark photon

[Soffer, '15]

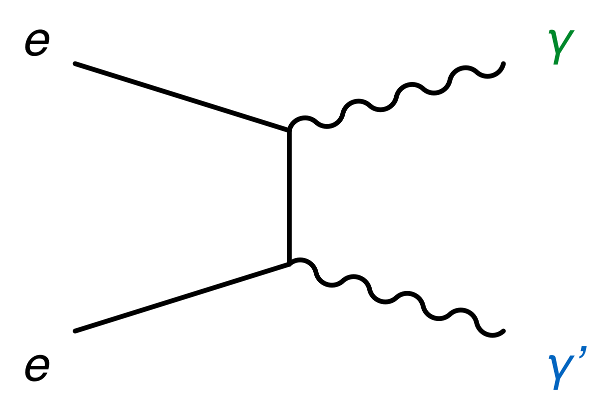


- ε is strongly constrained by lots of experiments.
- For $\varepsilon \ll 1$, dark photon never thermalizes, and the freeze-in mechanism can work.

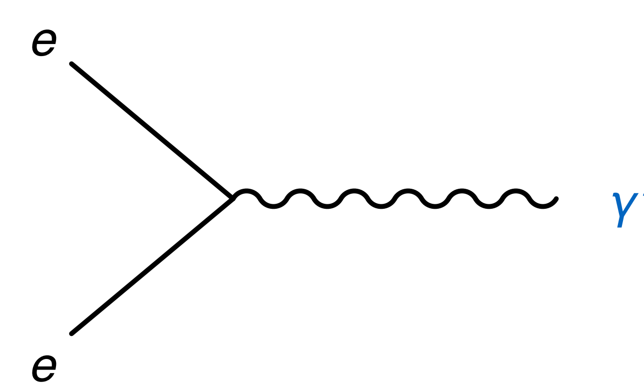
- Main production channels: $e\gamma \to e\gamma'$, $e^+e^- \to \gamma\gamma'$, $e^+e^- \to \gamma'$



(Compton-like production)



(pair annihilation)



(pair coalescence)

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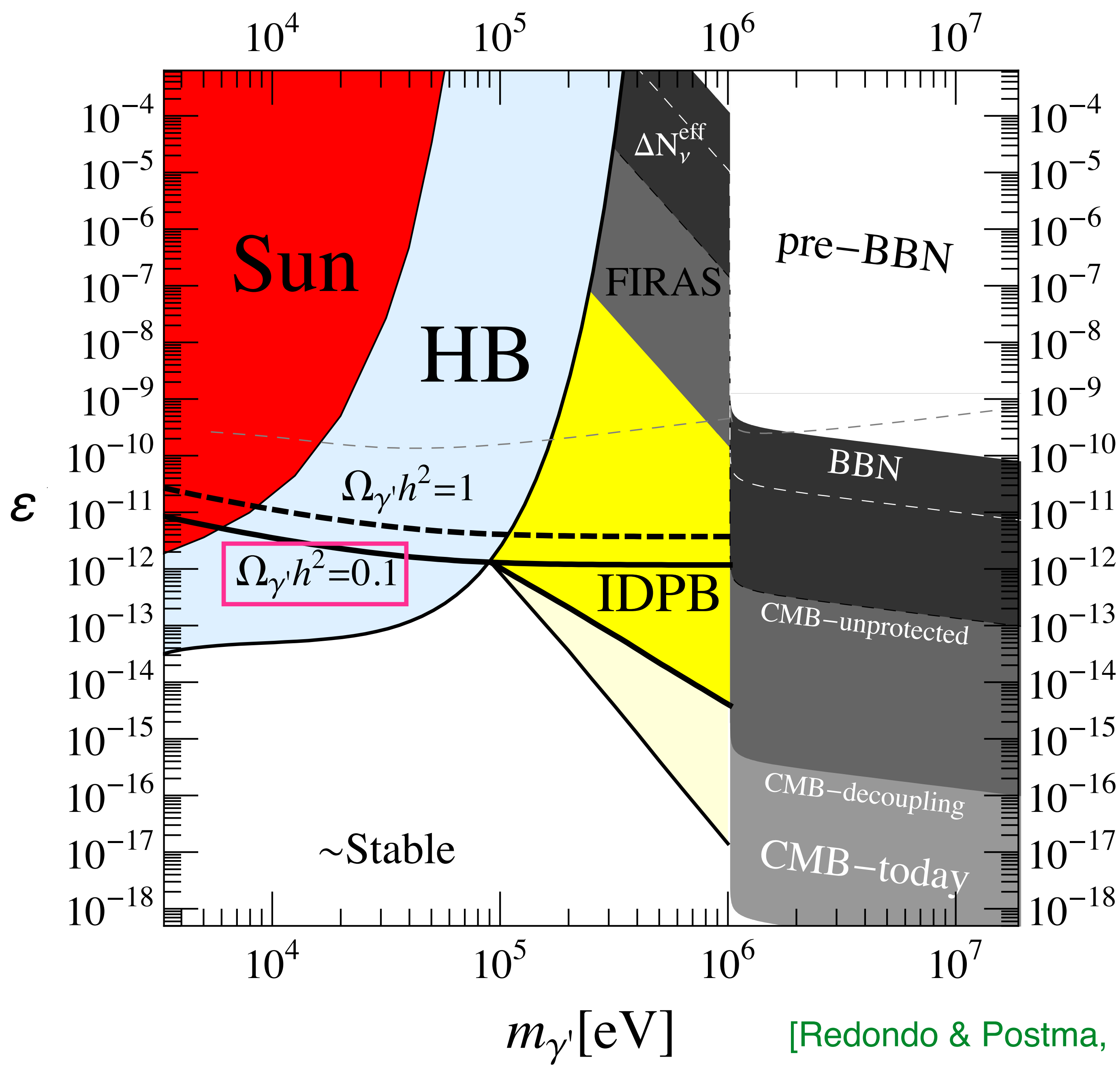
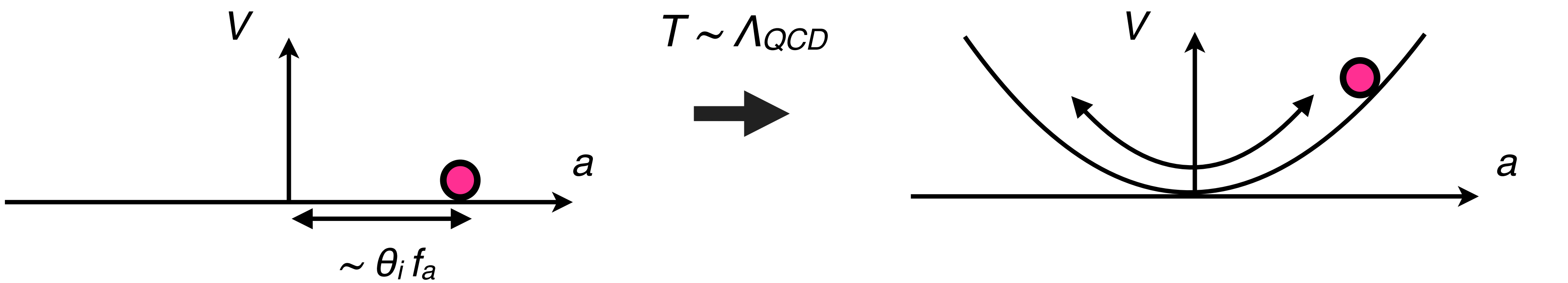


[Redondo & Postma, '08]

- Several observations (horizontal branch stars, intergalactic diffuse photon background,…) give stringent bounds on the $\Omega_{\gamma'} h^2 \sim 0.1$ region.
- *Dark photon alone can not explain the whole amount of dark matter* (if it is produced only through the kinetic mixing).

Axion as a dark matter

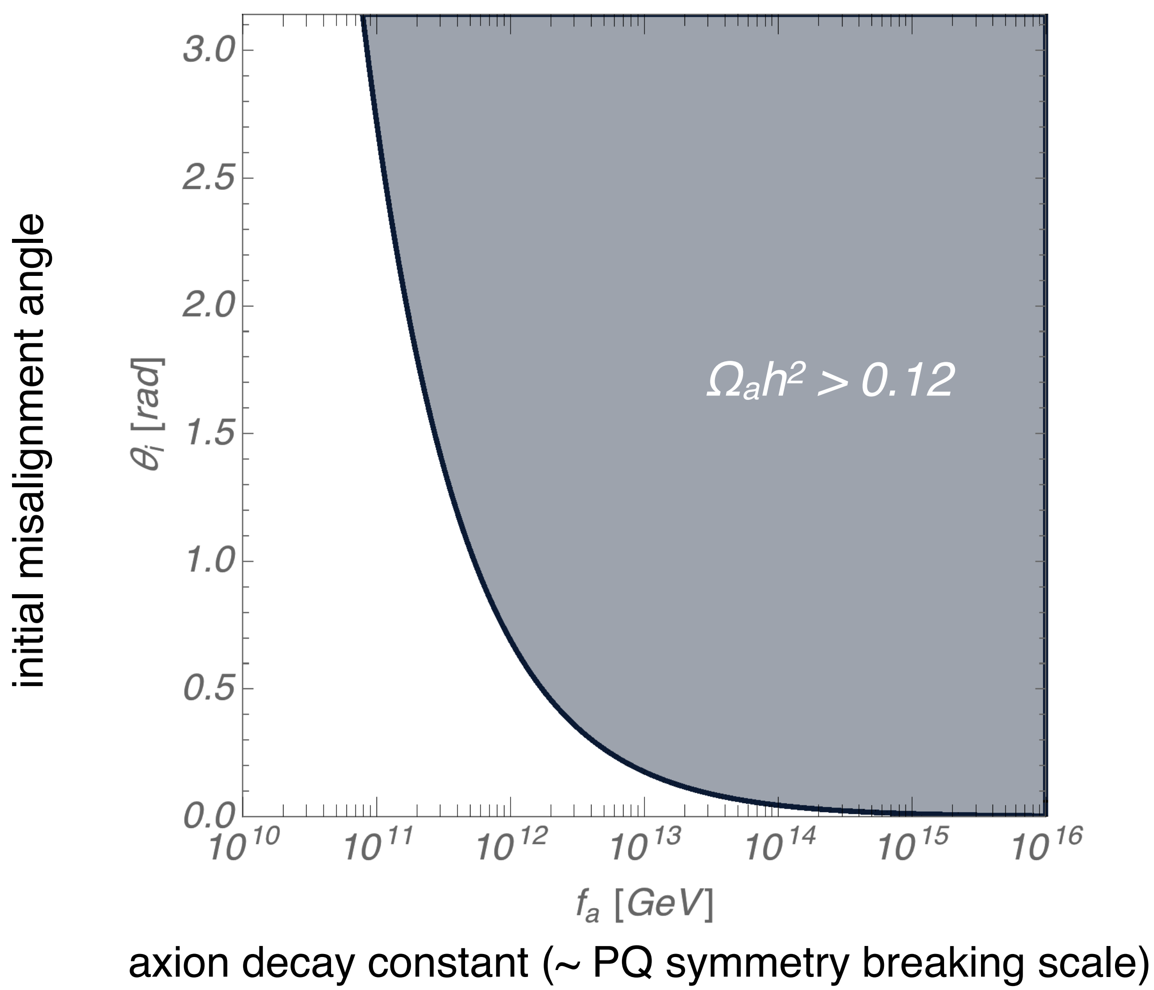
- Coherent oscillation of the axion field can constitute the whole dark matter.



- The relic abundance of the axion dark matter depends on the initial misalignment angle θ_i.

$$\Omega_a h^2 \simeq 0.11 \times \theta_i^2 \left(\frac{f_a}{5 \times 10^{11}\ \mathrm{GeV}} \right)^{1.19}$$

[Bae, Huh & Kim, '08]



Axion as a dark matter

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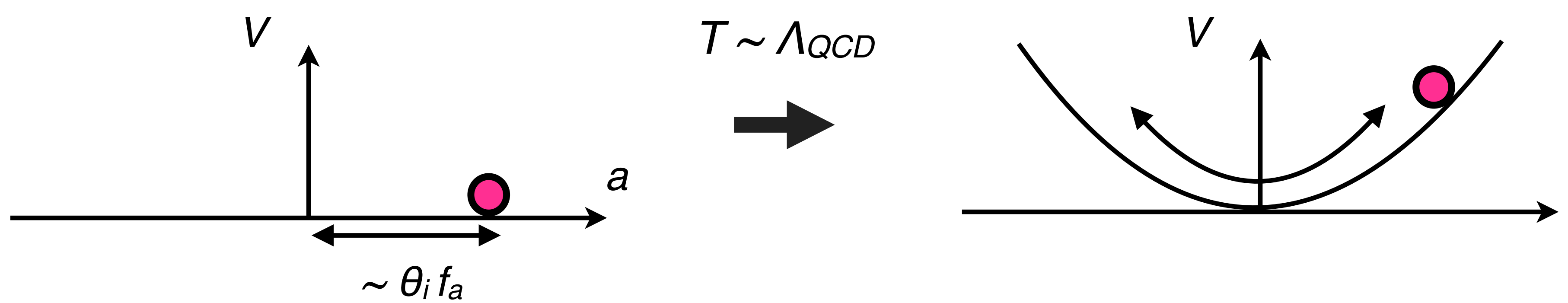

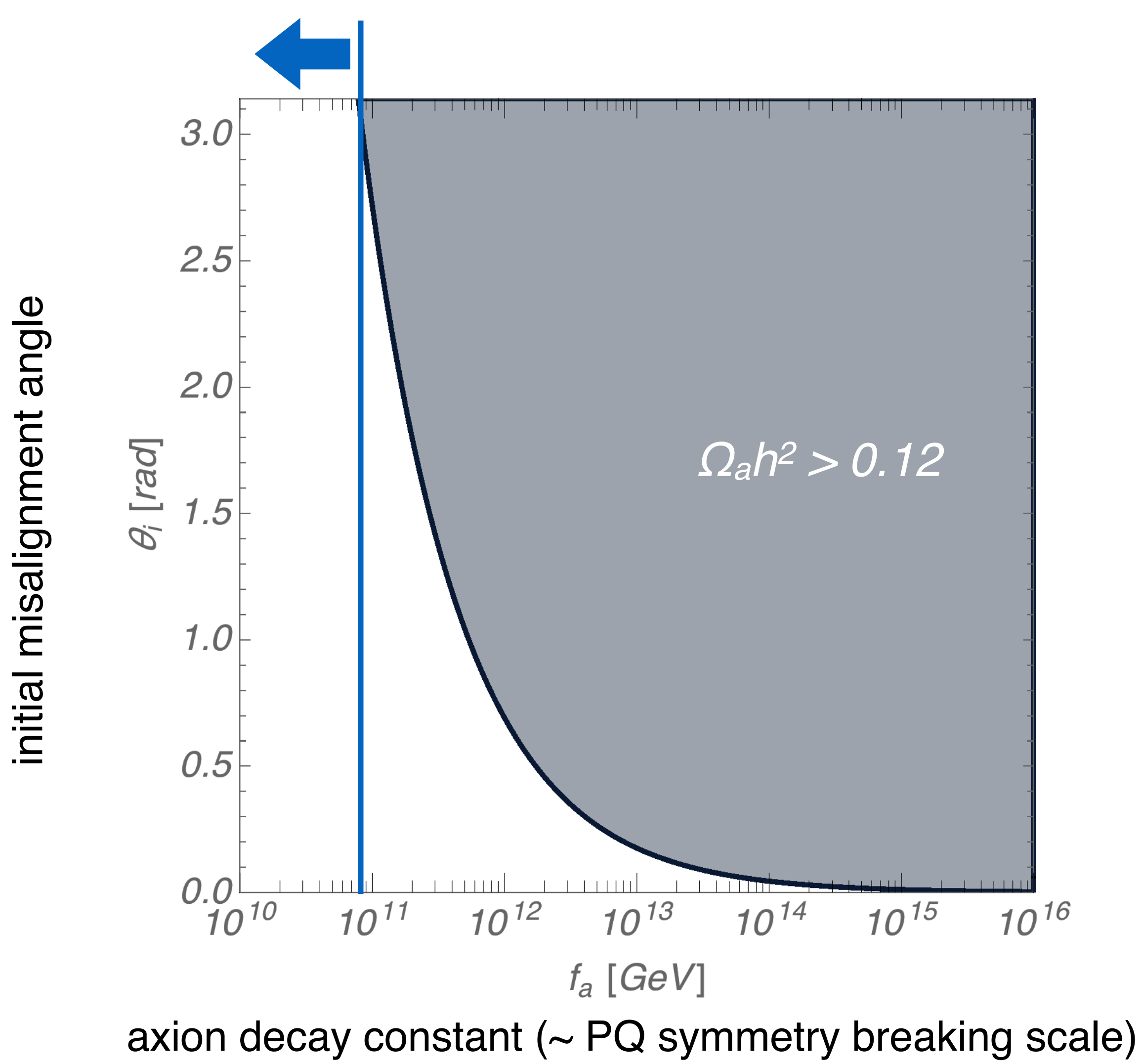

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- For $f_a < 10^{11}$ GeV, axion alone can not compose the whole amount of dark matter.

[Smaller f_a will be tested in next decades (e.g. ADMX).]

[Asztalos et al., '03]

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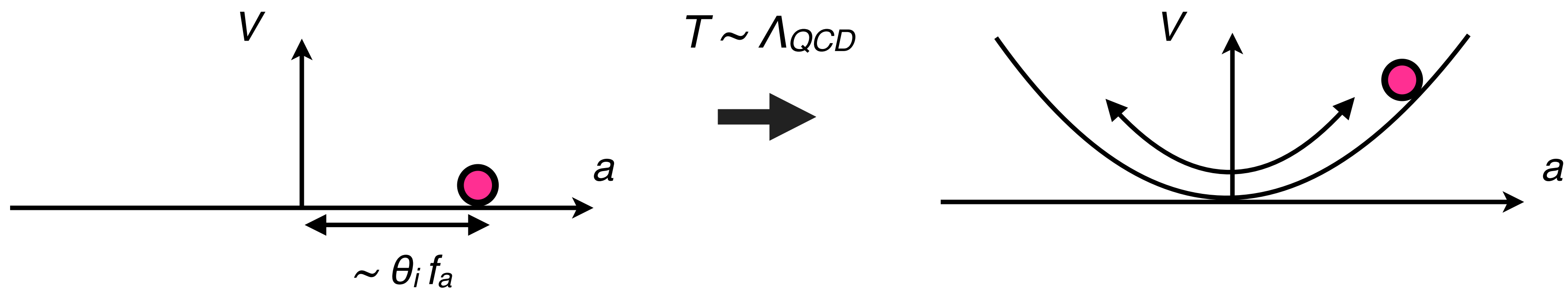

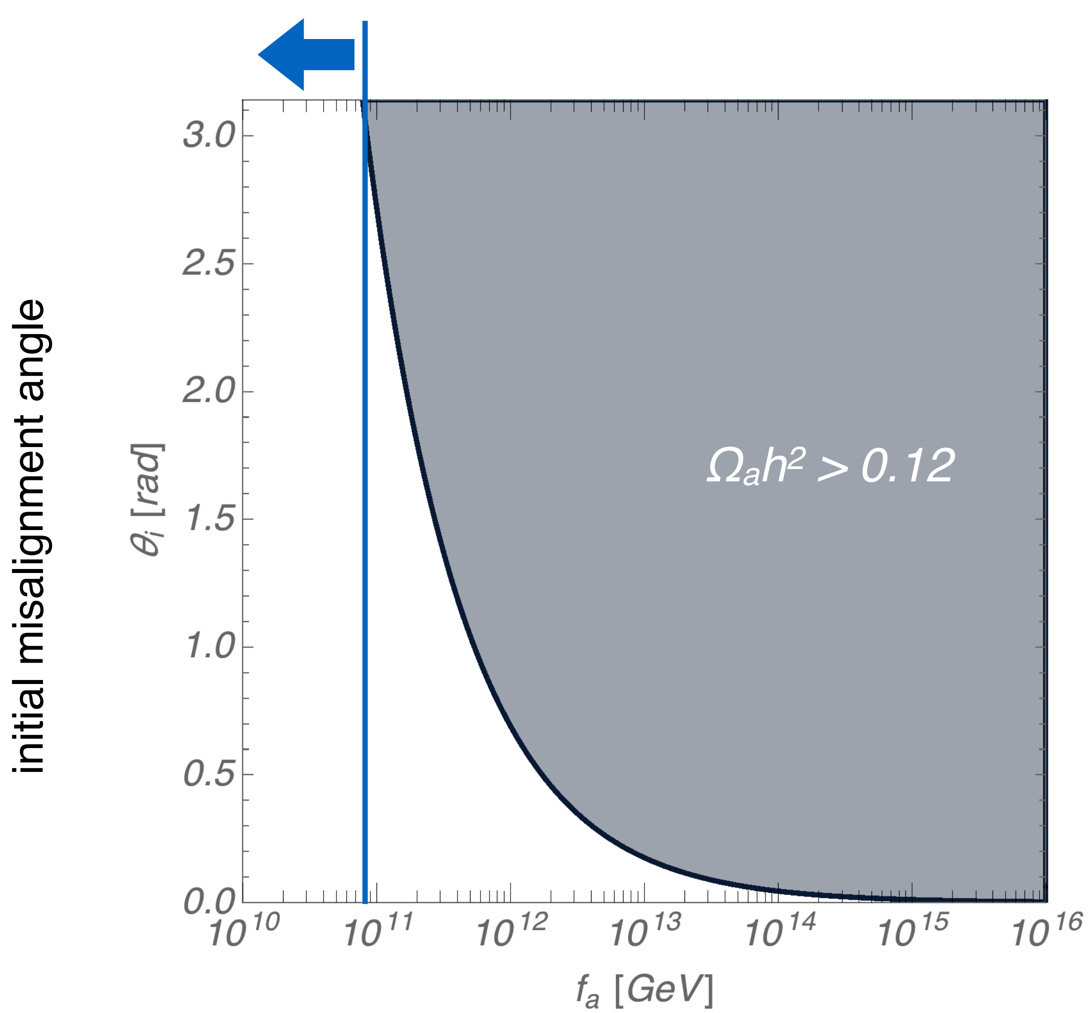

axion decay constant (~ PQ symmetry breaking scale)

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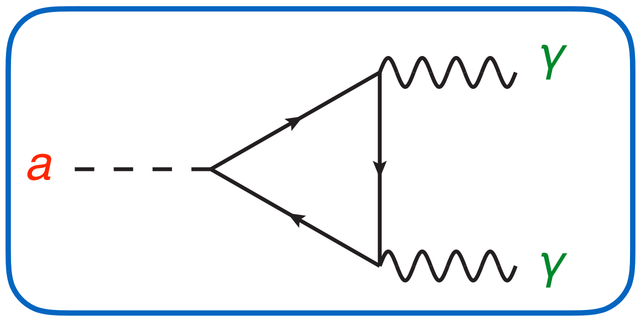
- *We will see that even in $f_a < 10^{11}$ GeV, the dark axion portal can provide an appropriate dark matter candidate (dark photon) in a simple setup.*

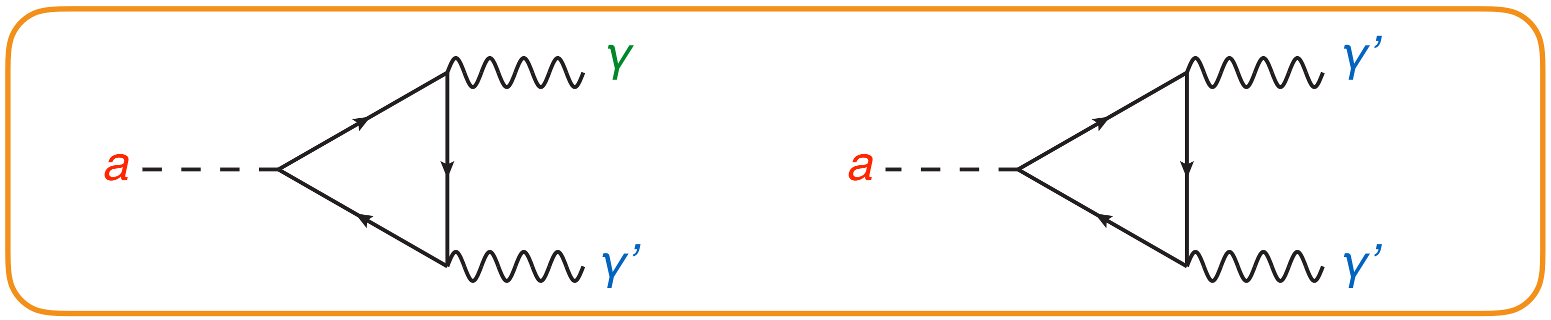
2. Dark axion portal and the model

Dark axion portal

- Let us suppose that *U(1)*$_{PQ}$ is anomalous under *U(1)*$_{Y}$ and *U(1)*$_{Dark}$ gauge symmetries.
- We have couplings among axion, photon and dark photon:



Axion portal



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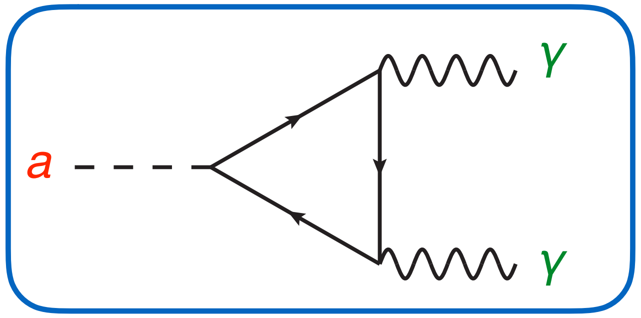

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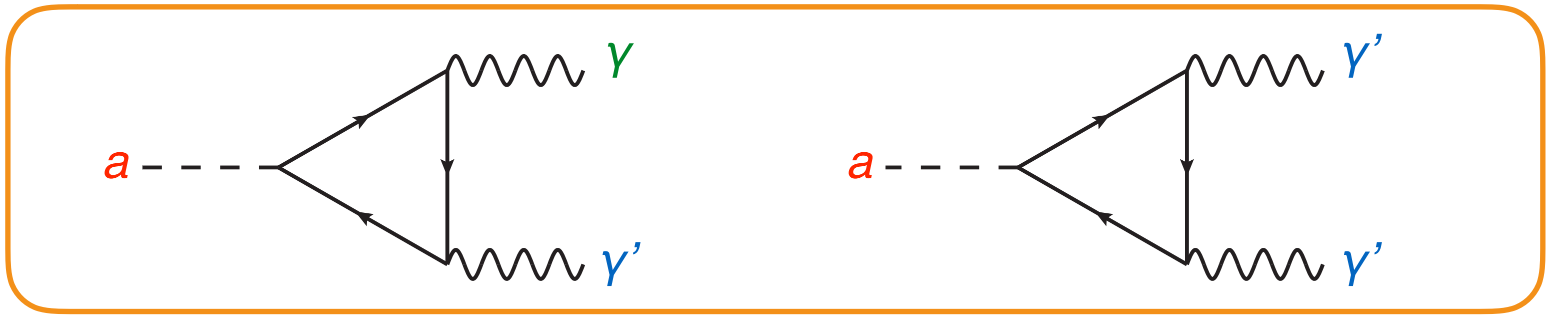

Dark axion portal

Dark KSVZ model (KSVZ axion with *U(1)*$_{Dark}$)

- A simple realization of the dark axion portal based on the KSVZ-type axion model.
  [Kim, '79] [Shifman, Vainshtein & Zakharov, '80]

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{\rm Dark}$	$U(1)_{\rm PQ}$
ψ	3	1	Q_ψ	D_ψ	PQ_ψ
ψ^c	$\bar{3}$	1	$-Q_\psi$	$-D_\psi$	PQ_{ψ^c}
Φ_{PQ}	1	1	0	0	PQ_Φ
Φ_D	1	1	0	D_Φ	0

(Axion is the phase direction of Φ_{PQ}.)

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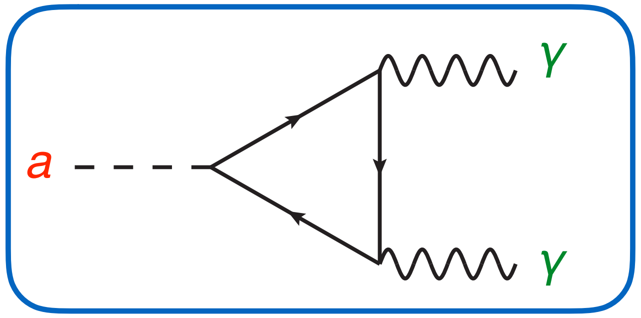

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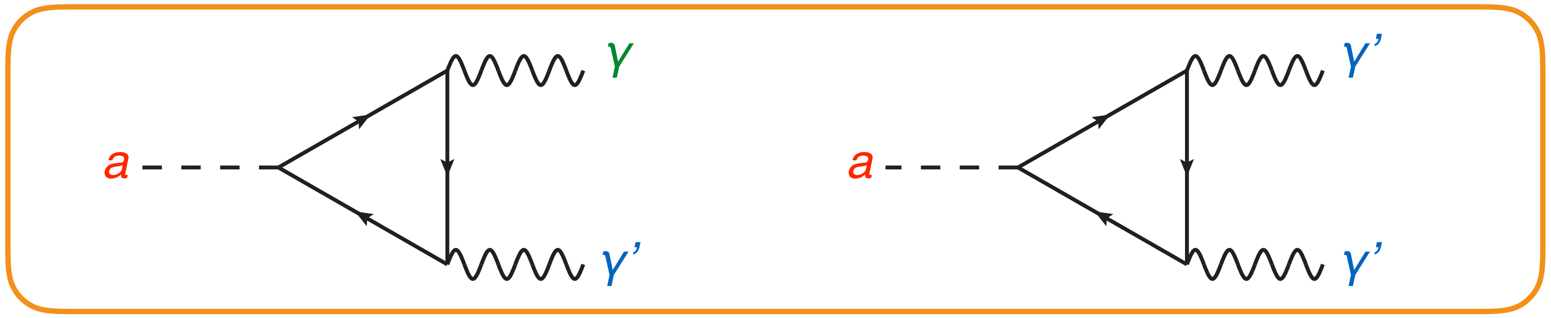

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- ψ is a color-triplet exotic quark that has charges of $U(1)_Y$, $U(1)_{Dark}$ and $U(1)_{PQ}$.

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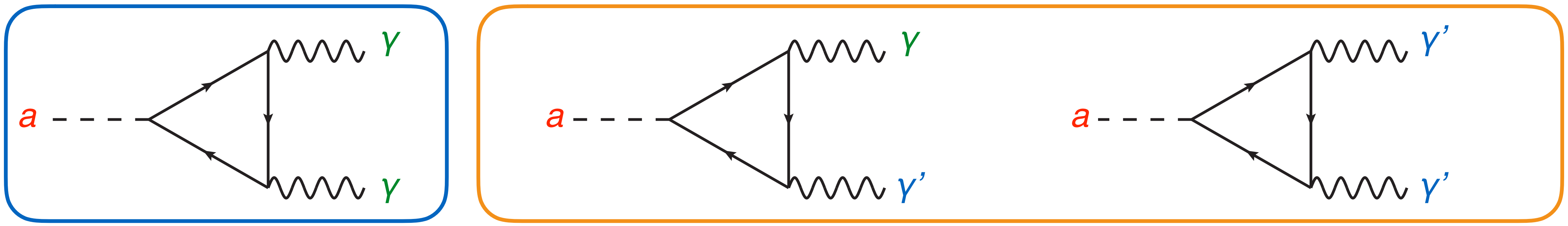

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- ψ is a color-triplet exotic quark that has charges of $U(1)_Y$, $U(1)_{Dark}$ and $U(1)_{PQ}$.

- Complex scalars, Φ_{PQ} and Φ_D, break $U(1)_{PQ}$ and $U(1)_{Dark}$, respectively.

$m_\psi \sim y_\psi \langle\Phi_{PQ}\rangle \sim f_a,$ $\quad m_{\gamma'} \sim e' D_\Phi \langle\Phi_D\rangle$ (we will consider O(keV - GeV) scale dark photon)

More on the dark KSVZ model

- Let us focus on the pre-inflation PQ phase transition scenario: $U(1)_{PQ}$ is spontaneously broken before (during) inflation, and never restored thereafter.
- The relevant part of the Lagrangian:

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \frac{\varepsilon}{2\cos\theta_W}F_{\mu\nu}Z'^{\mu\nu}$$

Vector portal

$$+ \frac{G_{agg}}{4}aG_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{G_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \cdots$$

Axion portal

$$+ \frac{G_{a\gamma'\gamma'}}{4}aZ'_{\mu\nu}\tilde{Z}'^{\mu\nu} + \frac{G_{a\gamma\gamma'}}{4}aF_{\mu\nu}\tilde{Z}'^{\mu\nu}$$

Dark axion portal

- Dark axion portal couplings:

$$G_{a\gamma\gamma} = \frac{e^2}{4\pi^2}\frac{PQ_\Phi}{f_a}N_C\left[Q_\psi^2\right]$$

$$G_{a\gamma\gamma'} = \frac{ee'}{4\pi^2}\frac{PQ_\Phi}{f_a}N_C\left[D_\psi Q_\psi\right] + \varepsilon G_{a\gamma\gamma}$$

$$G_{a\gamma'\gamma'} = \frac{e'^2}{4\pi^2}\frac{PQ_\Phi}{f_a}N_C\left[D_\psi^2\right] + 2\varepsilon G_{a\gamma\gamma'}$$

PQ_Φ: PQ charge of Φ_{PQ}

Q_ψ: EM charge of ψ
D_ψ: dark charge of ψ

e: EM coupling constant
e': Dark coupling constant

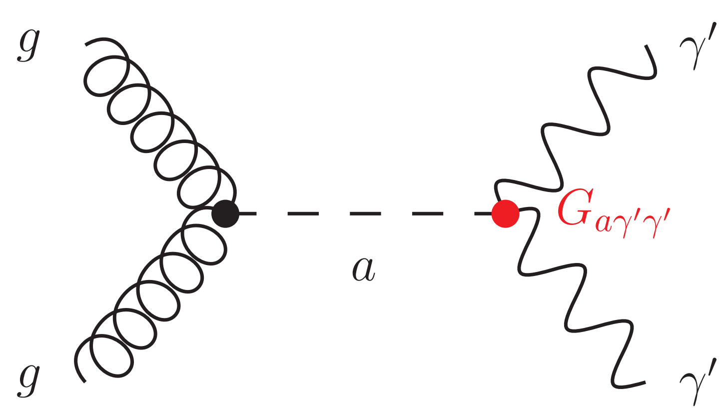
N_C=3 (color factor)

Dark axion portal is <u>not a simple product</u> of Vector and Axion portals. (e.g. $G_{a\gamma\gamma'} \neq \varepsilon\, G_{a\gamma\gamma}$)

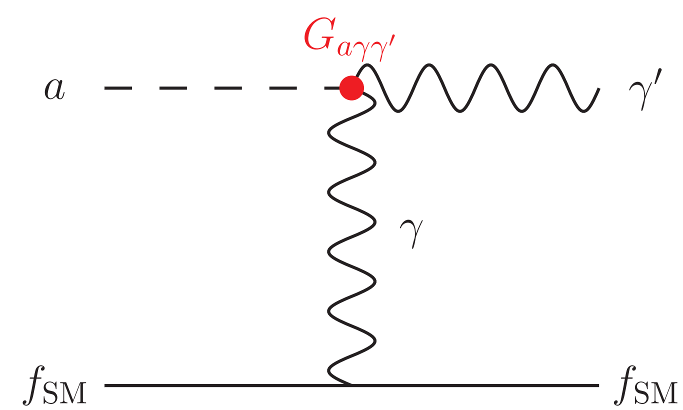
3. Implications

New scenario for dark matter production

- Dark photon can also be a good candidate of dark matter.
- Dark photon can be produced through Dark axion portal.
- In the following discussion, we take $\varepsilon = 0$ just for the simplicity.
- *Since the Dark axion portal is suppressed by large f_a, dark photon never reaches the thermal equilibrium.*
- Main production channels:



axion-mediation process



dark Primakoff effect

Case (i): $Q_\psi = 0$ and $D_\psi \neq 0$ ($G_{a\gamma'\gamma'} \neq 0$ and $G_{a\gamma\gamma'} = 0$) → The dark Primakoff effect is turned off, and γ' is produced by the axion-mediation process.

Case (ii): $Q_\psi \neq 0$ and $D_\psi \neq 0$ ($G_{a\gamma'\gamma'} \neq 0$ and $G_{a\gamma\gamma'} \neq 0$) → The dark Primakoff effect is turned on, and becomes dominant in generating γ'.

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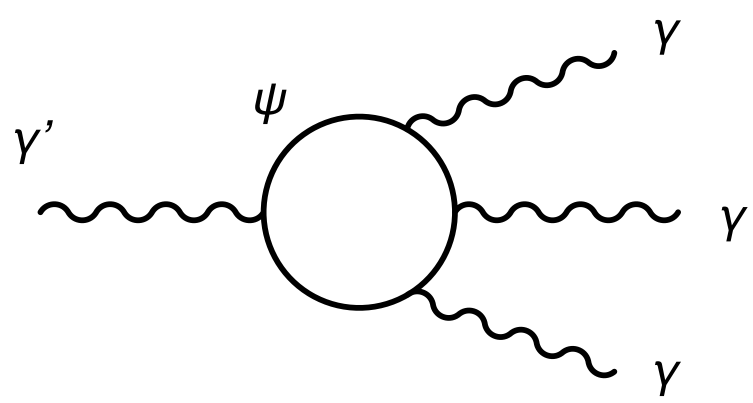
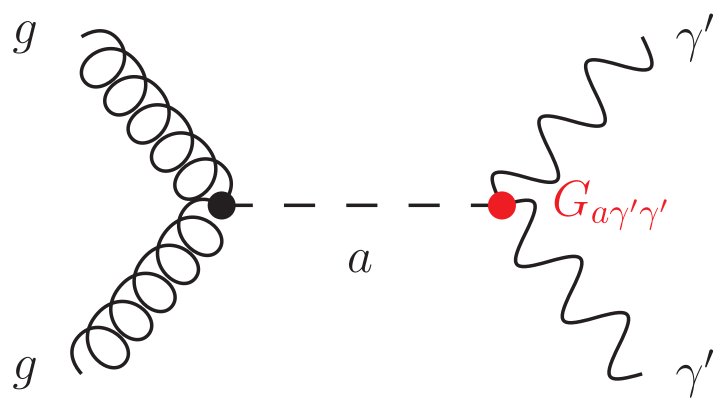


- $G_{a\gamma'\gamma'} \neq 0$ and $G_{a\gamma\gamma'} = 0$
- Dark photon is stable enough when $m_\psi >> m_{\gamma'}$
- Only the axion-mediation process can produce γ'



$$\propto G_{agg} G_{a\gamma'\gamma'} \sim \frac{1}{f_a^2}$$

reaction rate:

$$\Gamma_{gg\to\gamma'\gamma'} \sim G_{agg}^2 G_{a\gamma'\gamma'}^2 T^5$$

- Since the process involves dimension five operators, the production is most efficient at the reheating temperature T_{RH}
- Then, we obtain

$$\Omega_{\gamma'} h^2 \simeq 0.12 \times \left(\frac{e' D_\psi}{0.3}\right)^4 \left(\frac{100}{g_*}\right)^{3/2} \left(\frac{m_{\gamma'}}{10\ \mathrm{keV}}\right) \left(\frac{5}{f_a/T_{\mathrm{RH}}}\right)^3 \left(\frac{10^{10}\ \mathrm{GeV}}{f_a}\right)$$

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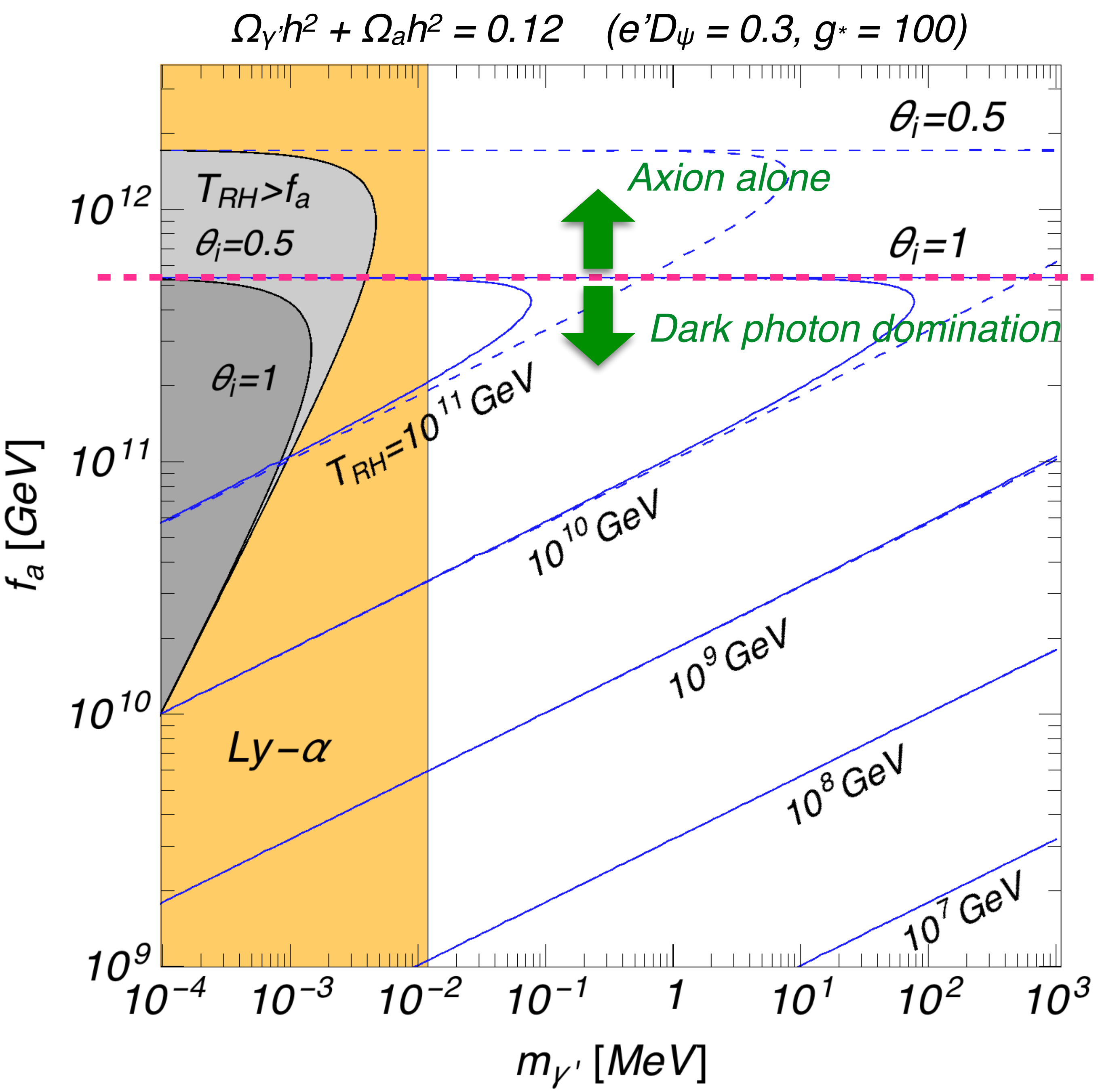
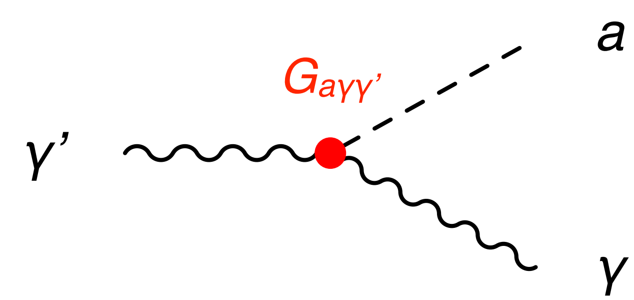


- For large f_a, axion can easily explain the whole dark matter
- For small f_a, dark photon is efficiently produced, and becomes dominant component of dark matter
- Note that in most parameter spaces $T_{RH} < f_a$ is satisfied, so the PQ symmetry is never restored
- Ly-α puts a constraint on the warm dark matter: $m_{\gamma'} \gtrsim 12$ keV [Baur, et al, '15]

The deficit of the axion dark matter in small f_a region is compensated by the dark photon dark matter.

Case (ii): $Q_\psi \neq 0$ and $D_\psi \neq 0$

- $G_{a\gamma'\gamma'} \neq 0$ and $G_{a\gamma\gamma'} \neq 0$
- Decay channel $\gamma' \to a\,\gamma$ opens: $\Gamma_{\gamma' \to a\gamma} \sim G^2_{a\gamma\gamma'} m^3_{\gamma'}$



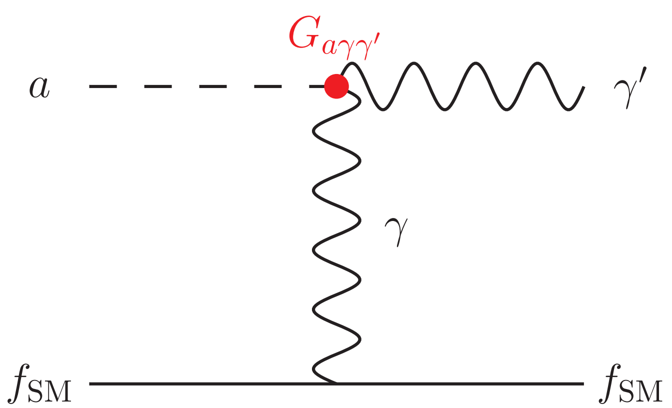
- Then, for γ' to be dark matter, dark photon should satisfy

$$\left(\frac{G_{a\gamma\gamma'}}{5\times10^{-16}\ \mathrm{GeV}^{-1}}\right)^2 \left(\frac{m_{\gamma'}}{\mathrm{MeV}}\right)^3 \lesssim 1 \qquad G_{a\gamma\gamma'} \sim 5\times10^{-16}\ \mathrm{GeV}^{-1} \times Q_\psi \left(\frac{e' D_\psi}{0.01}\right)\left(\frac{5\times10^{11}\ \mathrm{GeV}}{f_a}\right)$$

(by imposing the life time of γ' should larger than the age of the Universe)

- For the dark photon production, the dark Primakoff effect becomes dominant.

(Note that the axion is in the thermal bath for $T_{\mathrm{RH}} \gtrsim T \gtrsim 10^5\ \mathrm{GeV} \times (f_a/10^{10}\ \mathrm{GeV})^2$)



reaction rate:

$$\Gamma_{fa \to f\gamma'} \sim \alpha G^2_{a\gamma\gamma'} T^3 \left(\log\frac{T^2}{m^2_\gamma} + O(1)\right) \qquad (m_\gamma \sim eT)$$

- Then, we obtain

$$\Omega_{\gamma'} h^2 \simeq 0.12 \times \left(\frac{e' D_\psi}{0.01}\right)^2 \left(\frac{Q_\psi}{1/3}\right)^2 \left(\frac{100}{g_*}\right)^{3/2} \left(\frac{m_{\gamma'}}{\mathrm{MeV}}\right)\left(\frac{100}{f_a/T_{\mathrm{RH}}}\right)\left(\frac{10^{10}\ \mathrm{GeV}}{f_a}\right)$$

Case (ii): $Q_\psi \neq 0$ and $D_\psi \neq 0$

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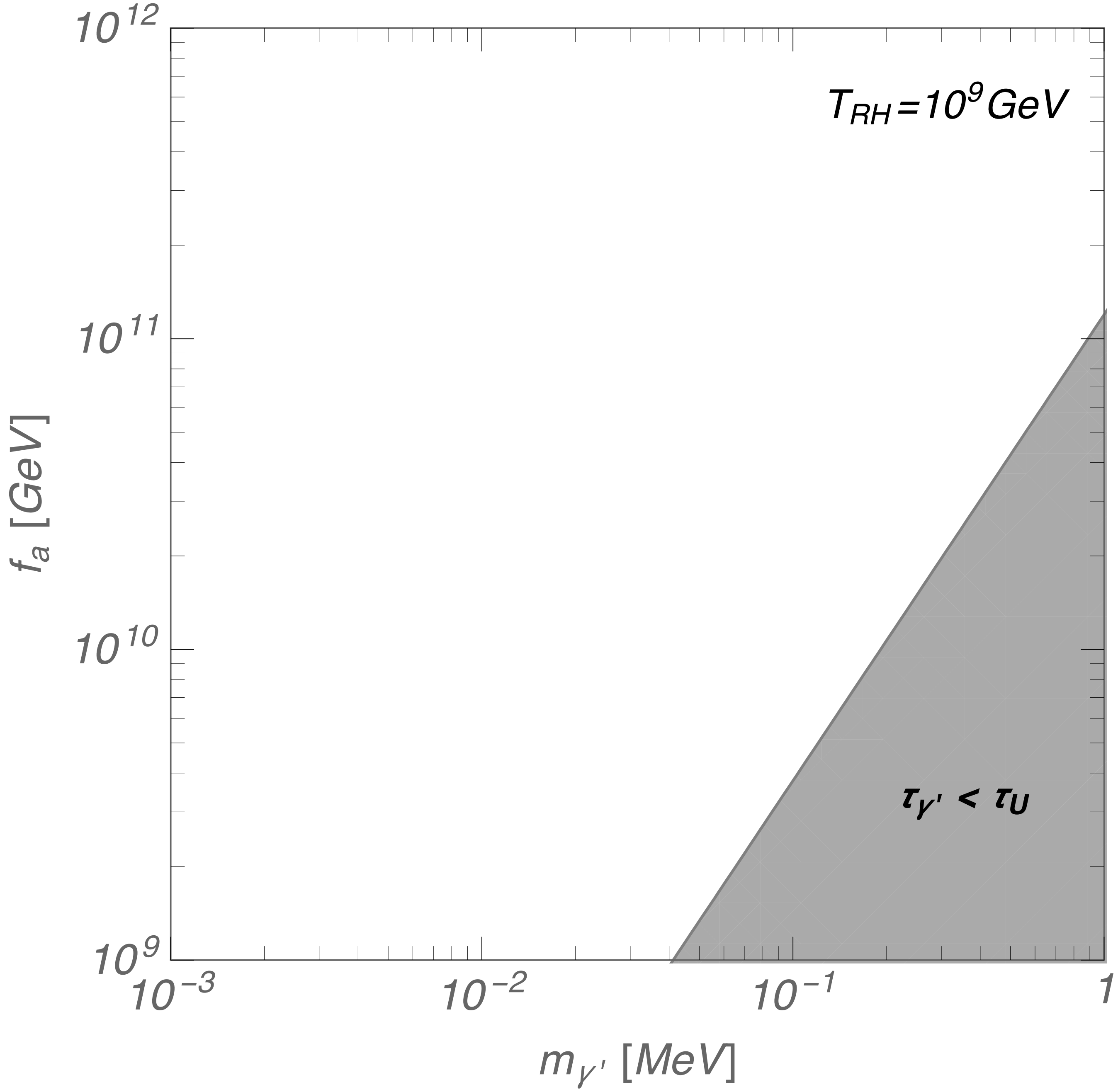

- In the gray region, the dark photon decays too fast.

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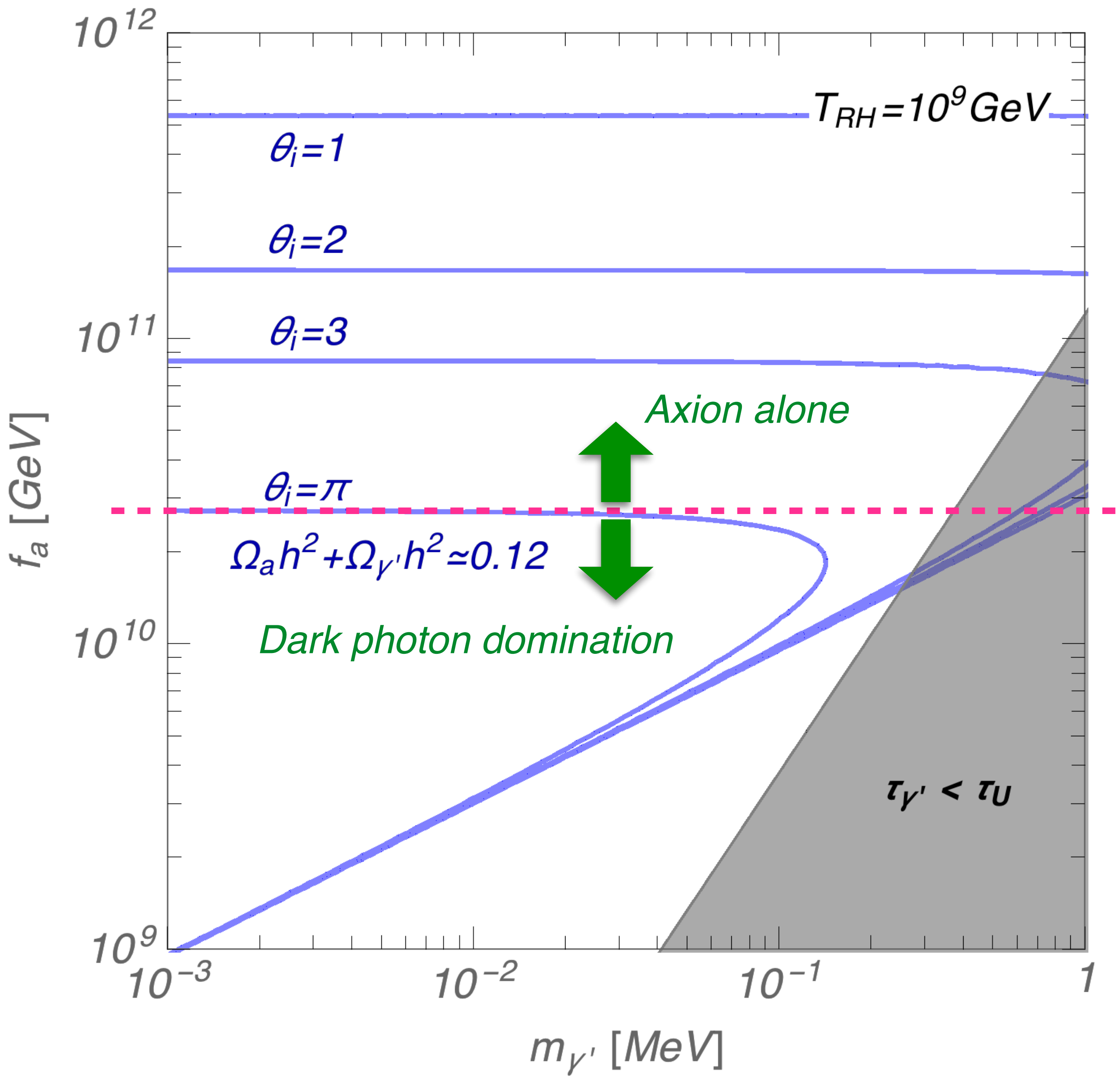

- In the gray region, the dark photon decays too fast.
- For $f_a > 3\times10^{10}$ GeV, axion alone can explain the whole relic dark matter.
- For $f_a < 10^{10}$ GeV, dark photon becomes dominant component.

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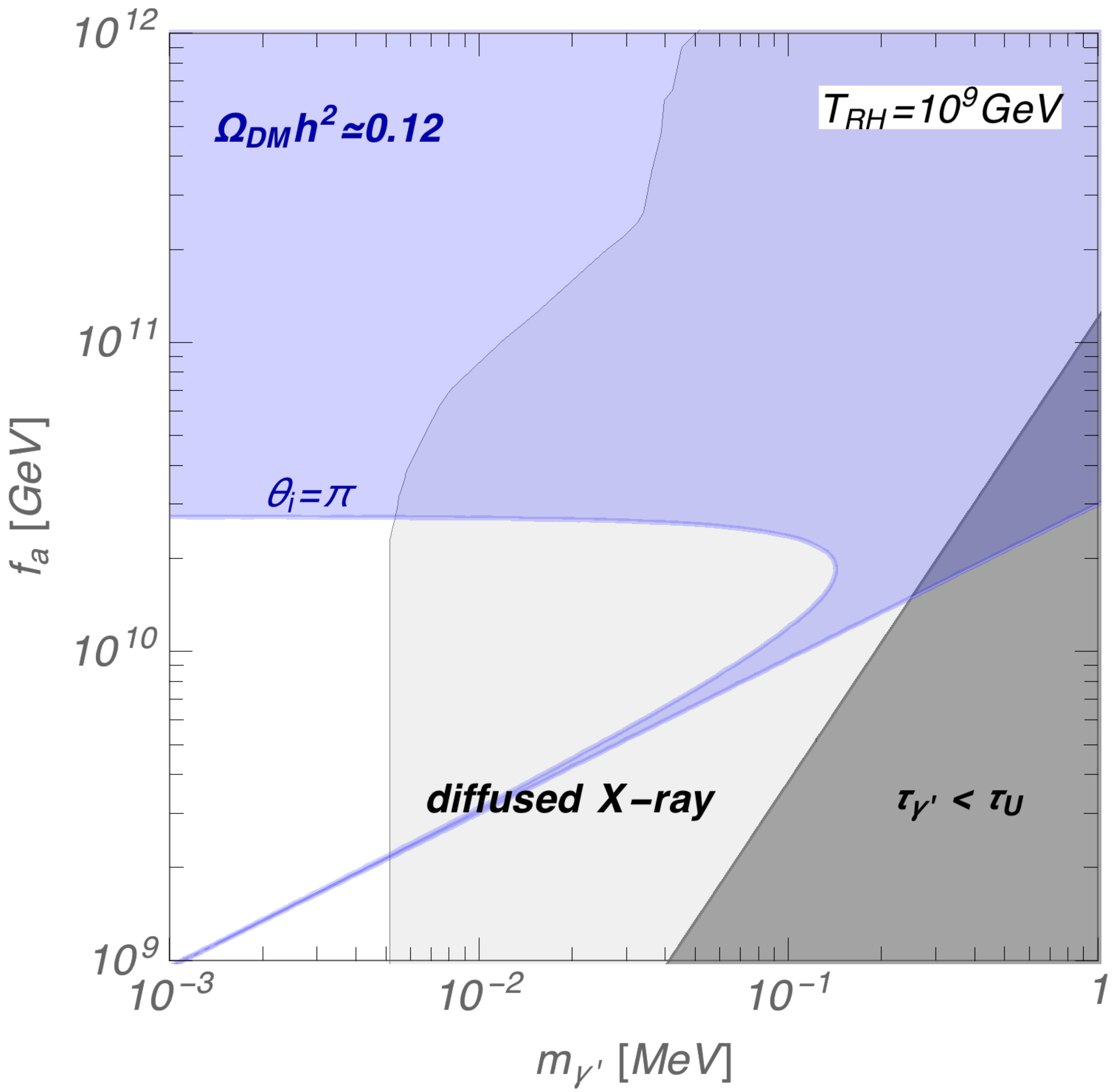
$$\Omega_{\gamma'} h^2 \simeq 0.12 \times \left(\frac{e' D_\psi}{0.01}\right)^2 \left(\frac{Q_\psi}{1/3}\right)^2 \left(\frac{100}{g_*}\right)^{3/2} \left(\frac{m_{\gamma'}}{\mathrm{MeV}}\right) \left(\frac{100}{f_a/T_{\mathrm{RH}}}\right) \left(\frac{10^{10}\ \mathrm{GeV}}{f_a}\right)$$

($e' D_\psi = 0.01$, $|Q_\psi| = 1/3$, $g_* = 100$)

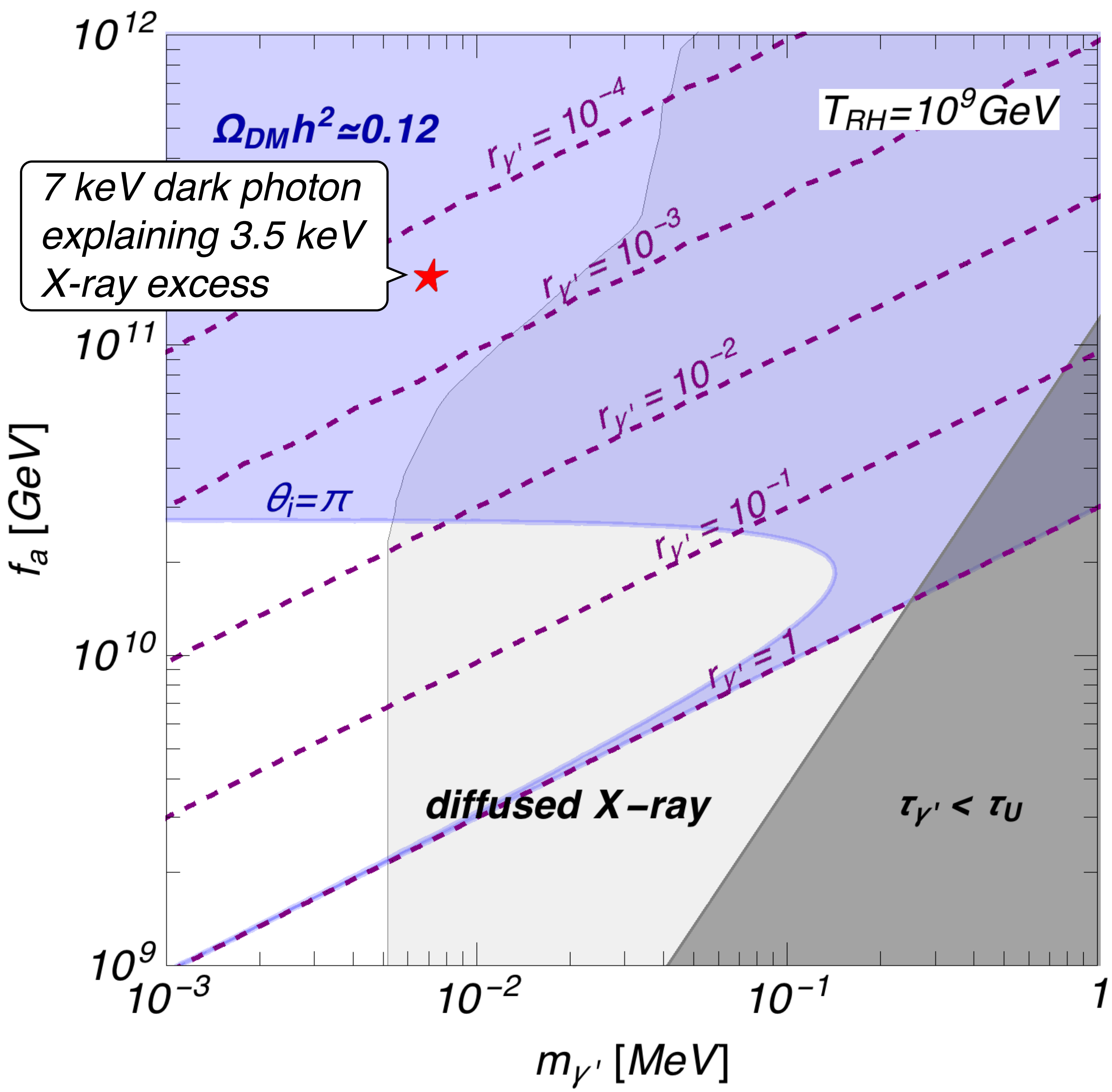


- In the gray region, the dark photon decays too fast.
- For $f_a > 3\times10^{10}$ GeV, axion alone can explain the whole relic dark matter.
- For $f_a < 10^{10}$ GeV, dark photon becomes dominant component.
- In the light gray region, since the dark photon slowly decays, observations of the diffused X-ray give a strong constraint.
- The Ly-α constraint ($m_{\gamma'} \gtrsim 12$ keV) may exclude the dark photon domination scenario.

Case (ii): $Q_\psi \neq 0$ and $D_\psi \neq 0$

$$\Omega_{\gamma'} h^2 \simeq 0.12 \times \left(\frac{e' D_\psi}{0.01}\right)^2 \left(\frac{Q_\psi}{1/3}\right)^2 \left(\frac{100}{g_*}\right)^{3/2} \left(\frac{m_{\gamma'}}{\mathrm{MeV}}\right) \left(\frac{100}{f_a/T_{\mathrm{RH}}}\right) \left(\frac{10^{10}\ \mathrm{GeV}}{f_a}\right)$$

($e'D_\psi = 0.01$, $|Q_\psi| = 1/3$, $g_* = 100$)



$r_{\gamma'} = \Omega_{\gamma'}/\Omega_{DM}$

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- In the light gray region, since the dark photon slowly decays, observations of the diffused X-ray give a strong constraint.
- The Ly-α constraint ($m_{\gamma'} \gtrsim 12$ keV) may exclude the dark photon domination scenario.
- *On the other hand, even if the dark photon fraction is small, dark photon can explain the 3.5 keV X-ray line excess.*

[Bulbul, et al, '14] [Boyarsky, et al, '14]

Summary

- We proposed a new portal: Dark Axion Portal.

- We built a simple model as a realization of the new portal: Dark KSVZ model.

- The new portal opens novel scenarios for the dark matter production.

- The 3.5 keV X-ray line excess can be explained by a new dark photon decay channel ($\gamma' \to a\, \gamma$).