Interplay of Axions and Dark Photons

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

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Outline

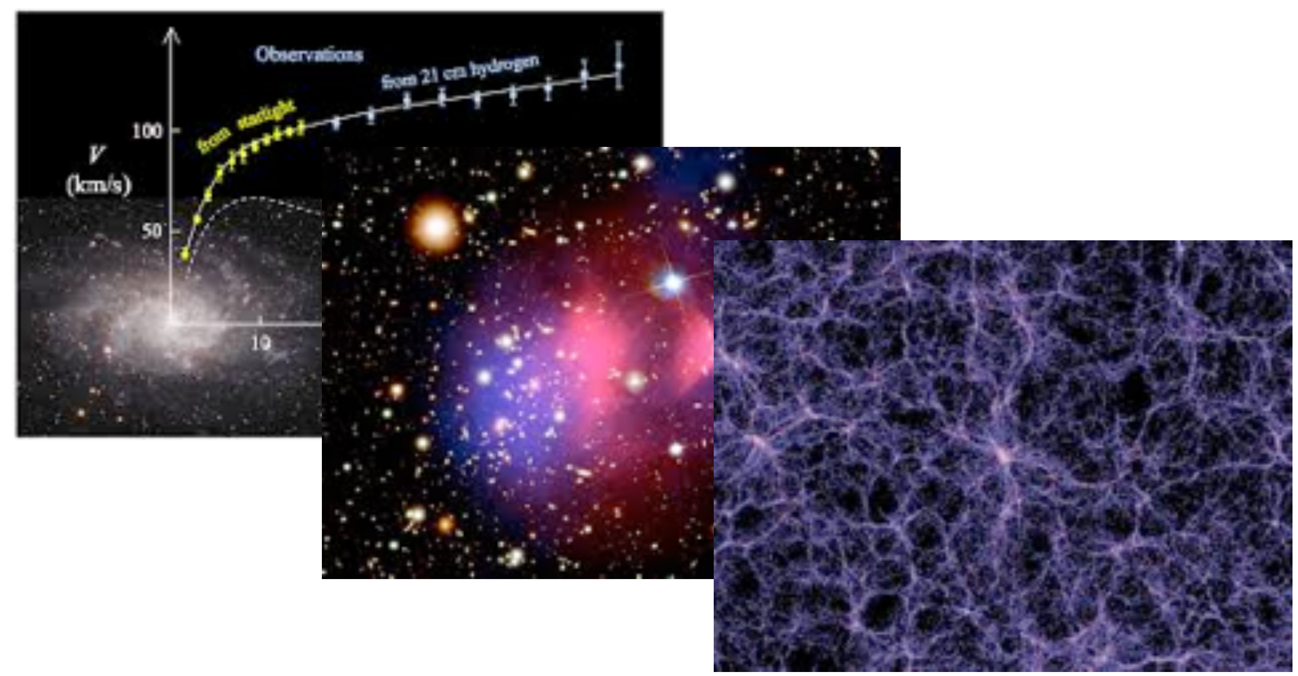
1. Introduction
2. Dark axion portal and the model
3. Implications
4. Summary

1. Introduction

Dark matter

We empirically know the existence of dark matter:

- ➢ it is hard to explain the rotation curve of the galaxy without dark matter
- ➢ gravitational lens effect of galaxy clusters indicates dark matter
- ➢ observation of the bullet cluster
- ➢ large scaler structure formation
- ➢ WMAP, Planck



Properties of dark matter

- ➢ Neutral under $SU(3)_C$ x $U(1)_{EM}$
- ➢ Stable/long-lived
- ➢ Weakly/Feebly interacting

Dark matter is not a part of the standard model

To identify the dark matter is one of the most important tasks in modern particle physics

LSP, LKP, sterile neutrino, axion, dark photon, …

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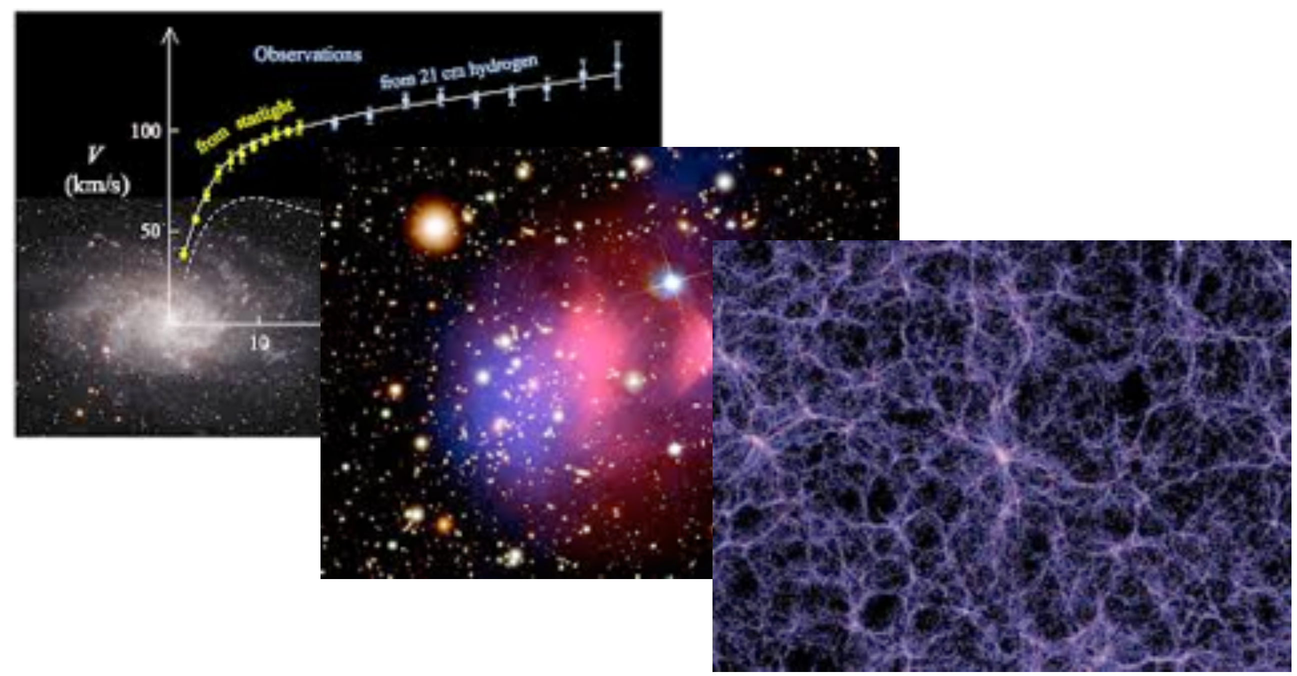

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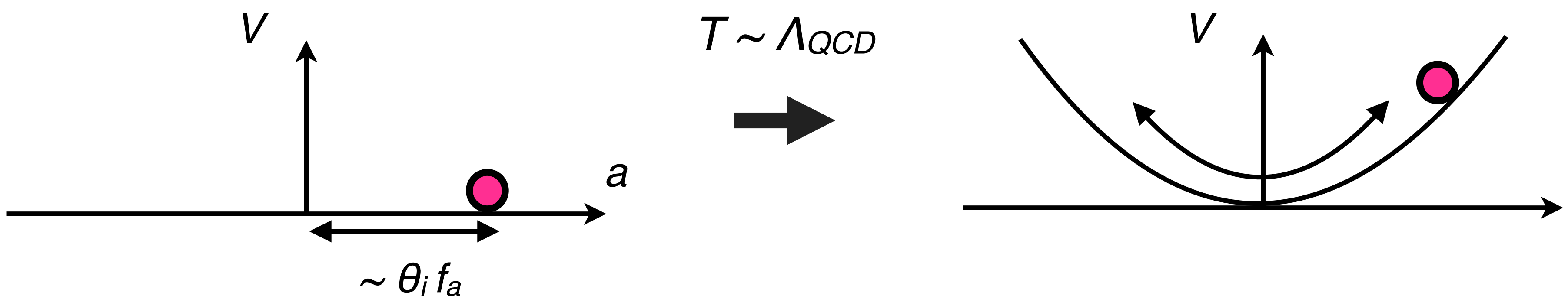
Axion dark matter

- Axion is not only a solution for the strong CP problem, but also a good candidate of dark matter; the coherent oscillation of the axion field
- Right after the PQ symmetry breaking, axion is massless, and the energy density of the axion oscillation depends on the misalignment angle at the QCD phase transition, θ_i



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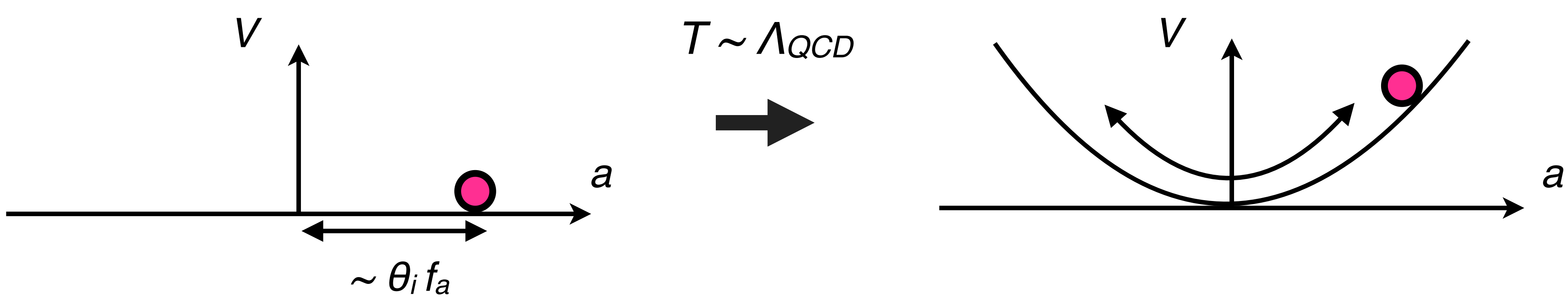


- If the PQ symmetry breaking occurs after the end of inflation, the misalignment angle is given by the spatial average of $\theta_i = [-\pi/2, \pi/2]$

[Turner, '86] [Bae, Huh & Kim, '08] [Visinelli & Gondolo, '09]

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

- Axionic string can form after the symmetry breaking, and may decay into axion dark matter [Harai & Sikivie, '87, Battye & Shelard, '94, Yamaguchi, Kawasaki & Yokoyama, '99]

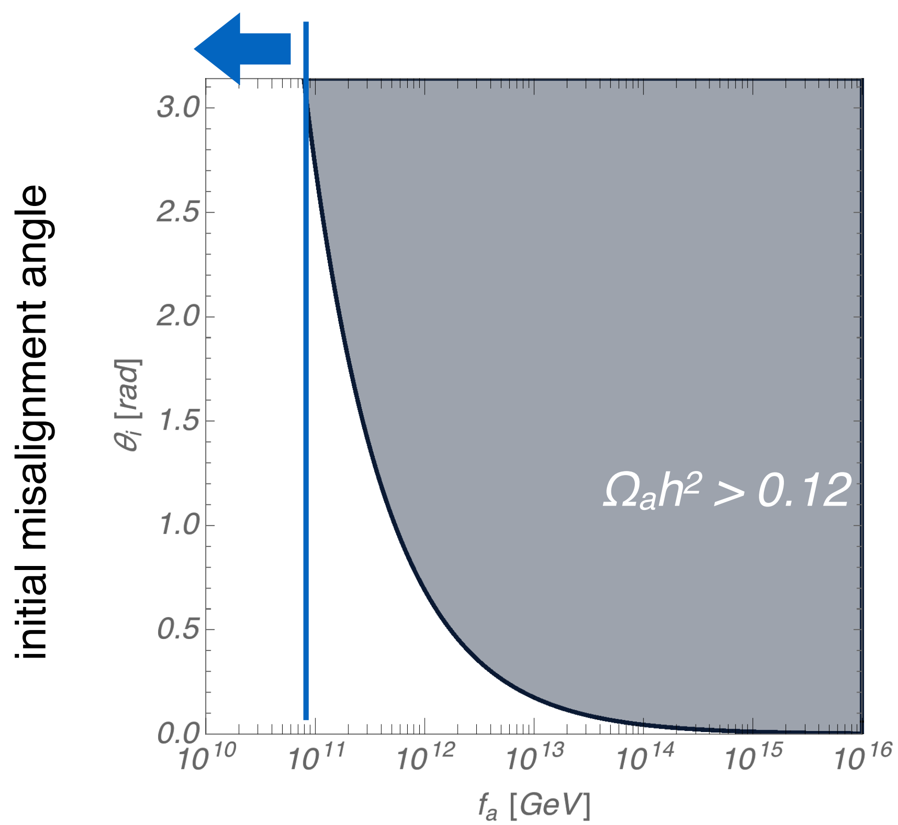
$$\Omega_a^{str} h^2 \simeq 0.11 \times \Delta \left(\frac{f_a}{2 \times 10^{11} GeV} \right)^{1.18} \qquad \Delta \sim O(1)$$

Axion dark matter

- If PQ symmetry breaks before/during inflation and is never restored, the misalignment angle θi takes a certain single value, and thus the axion number density is given by [Turner, ’86] [Bae, Huh & Kim, ’08] [Visinelli & Gondolo, ’09]

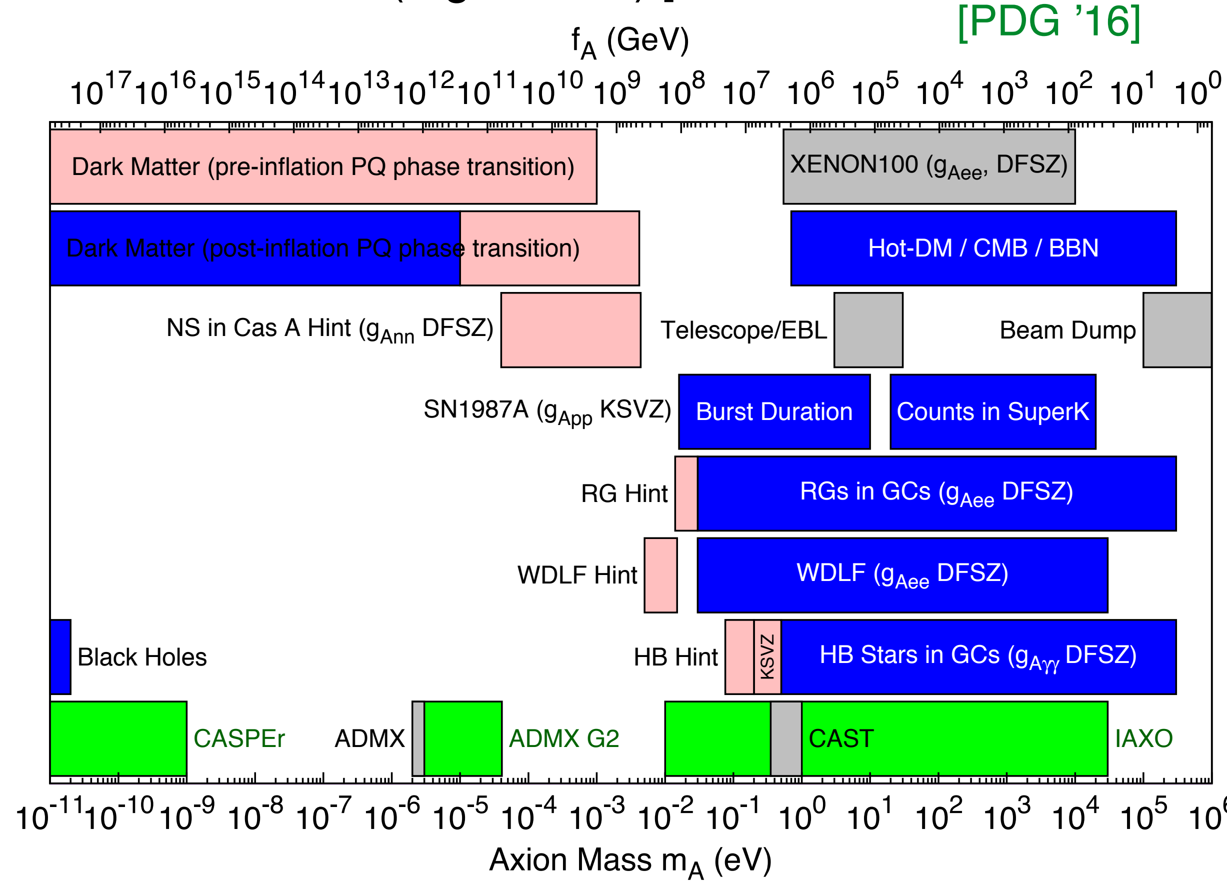
$$\Omega_a h^2 \simeq 0.11 \times \theta_i^2 \left(\frac{f_a}{5\times 10^{11} GeV} \right)^{1.19}$$

- 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).]



axion decay constant (~ PQ symmetry breaking scale)

[PDG ’16]



- *We will see that even for $f_a < 10^{11}$ GeV, dark photon may compensate the deficit through a new portal coupling between axion and dark photon, which appears in a very simple setup.*

Dark photon

- Additional U(1) gauge symmetries do not serve as a solution for any issues of the SM, such as the strong CP problem, but they are ubiquitous if the SM gauge group is embedded into higher rank symmetry.
- For instance, in SO(10) GUT, $U(1)_{B-L}$ can appear at some scale

$$SO(10)$$

$$\Big\downarrow \; \langle 45 \rangle, \langle 54 \rangle$$

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\Big\downarrow \; \langle 126 \rangle, \langle \overline{126} \rangle$$

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

- In the bottom-up approach perspective, probing the existence of additional U(1) gauge boson (dark photon) may not only reveal more fundamental symmetry, but also implies the extended Higgs sector

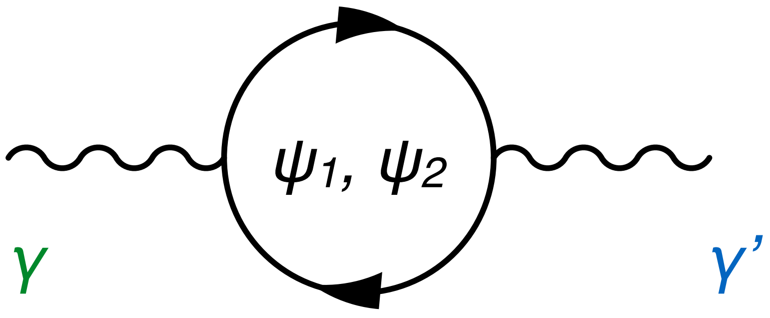
Kinetic mixing (vector portal coupling)

- In the following, we do not consider possible UV completions of additional U(1) gauge symmetry
- Instead, let us suppose just $SU(3)_C \times U(1)_{em} \times U(1)_D$
- By constructing gauge invariant Lagrangian, we generically get a gauge kinetic mixing term

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

photon dark photon

- ε is a free parameter at the tree level, and may change by loop contributions if there is $U(1)_D$ charged particles
- For instance, when fermions ψ_1 and ψ_2 have $U(1)_{em}$ and $U(1)_D$ charges (+1,+1) and (+1,-1), respectively, ε can be induced at 1-loop level



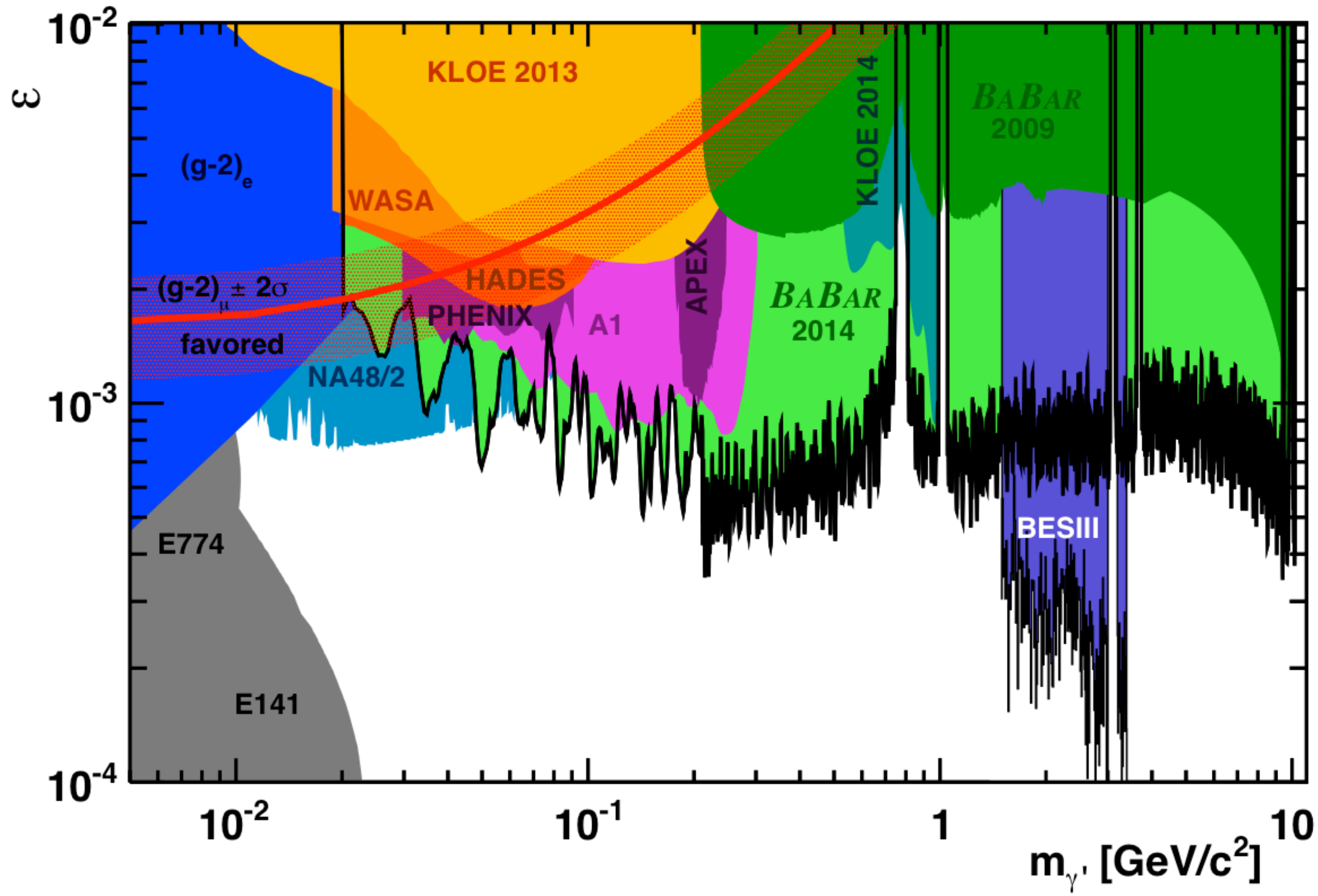
$$\varepsilon \simeq \frac{ee'}{6\pi^2} \log \frac{m_2}{m_1} \quad \sim O(10^{-3}) \qquad (e = e' \sim 0.3)$$

- Note that the resultant ε can be freely suppressed at the cost of fine-tuning, e.g. $\varepsilon_{\rm tree} + \varepsilon_{\rm induced} \sim 0$ or $\varepsilon_{\rm tree} \sim 0$ & $m_1 \sim m_2$

Kinetic mixing (vector portal coupling)

- The mixing parameter ε is strongly constrained by lots of experiments

[Soffer, '15]



- For such light dark photon case, ε should be somehow suppressed anyway

Dark photon as a dark matter

- On the other hand, in the case of (extremely) small ε, dark photon can be a dark matter candidate

1. $m_{\gamma'} > 2m_e$

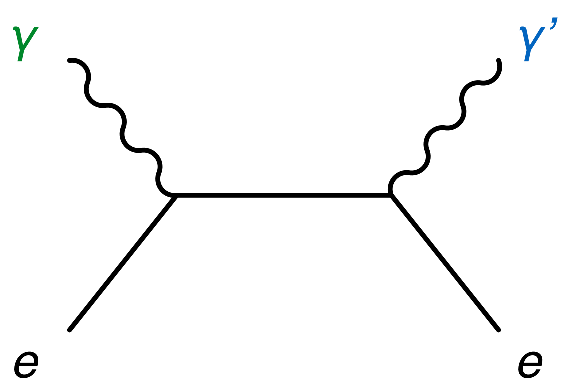
$$\Gamma_{\gamma'\to e^+e^-} \simeq \frac{1}{2}\alpha\varepsilon^2 m_{\gamma'} \longrightarrow \tau_{\gamma'} / \tau_U \sim \left(\frac{10^{-20}}{\varepsilon}\right)^2 \left(\frac{\mathrm{GeV}}{m_{\gamma'}}\right)$$

($\tau_U \sim 10^{17}$ sec: the age of the universe)

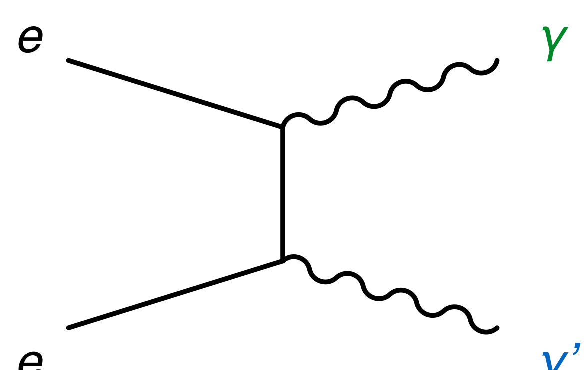
2. $m_{\gamma'} << m_e$

$$\Gamma_{\gamma'\to\gamma\gamma\gamma} \simeq \frac{17\alpha^4\varepsilon^2}{11664000\pi^3}\frac{m_{\gamma'}^9}{m_e^8} \longrightarrow \tau_{\gamma'} / \tau_U \sim \left(\frac{10^{-8}}{\varepsilon}\right)^2 \left(\frac{0.1\mathrm{MeV}}{m_{\gamma'}}\right)^9$$

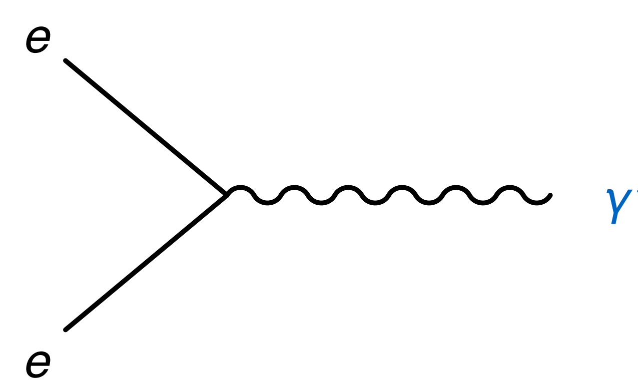
- For $\varepsilon << 1$, dark photon never thermalizes, and can be produced by the freeze-in mechanism
- Main production channels: $e\gamma \to e\gamma'$, $e^+e^- \to \gamma\gamma'$, $e^+e^- \to \gamma'$



(Compton-like production)



(pair annihilation)



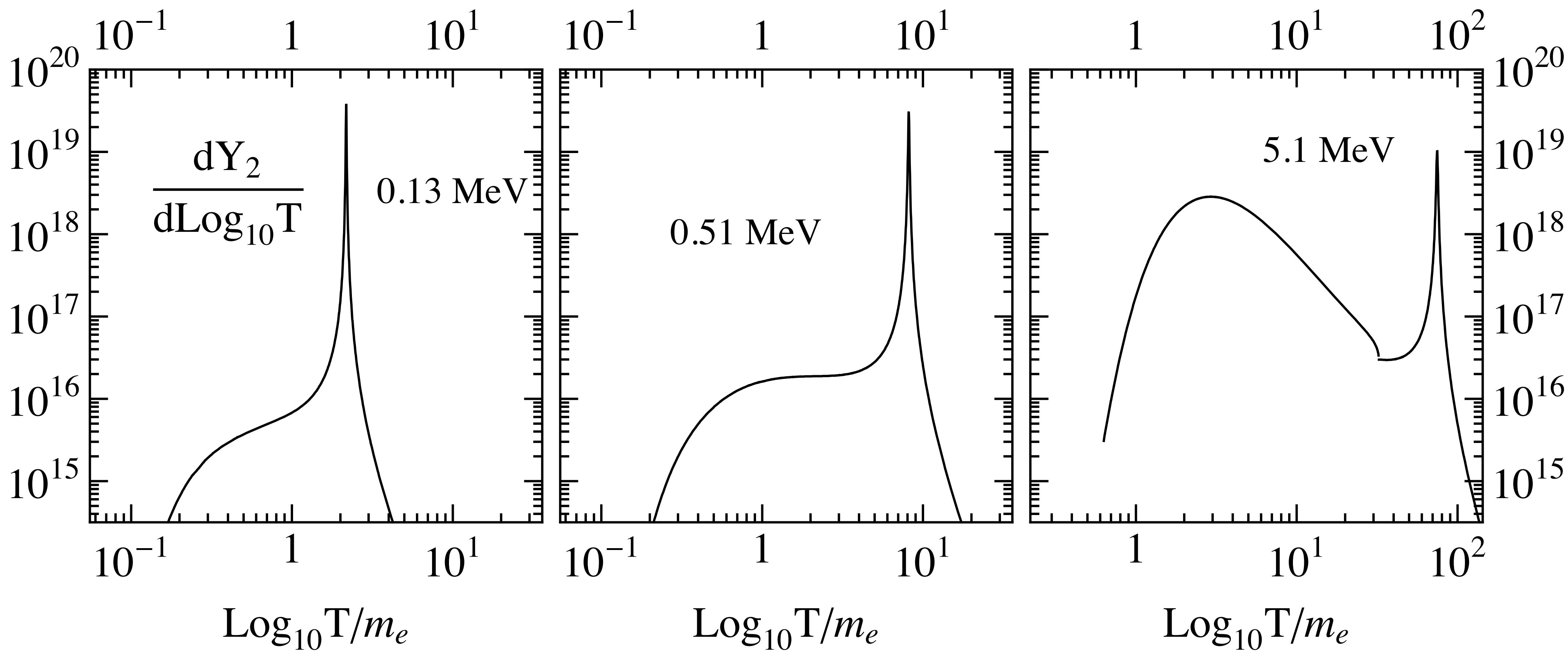
(inverse decay)

Dark photon as a dark matter

- ε has actually the temperature dependence, since photon gets the thermal mass $m_\gamma \sim eT$

$$\varepsilon(T) \sim \frac{m_{\gamma'}}{m_{\gamma'} - m_\gamma(T)} \varepsilon_0$$

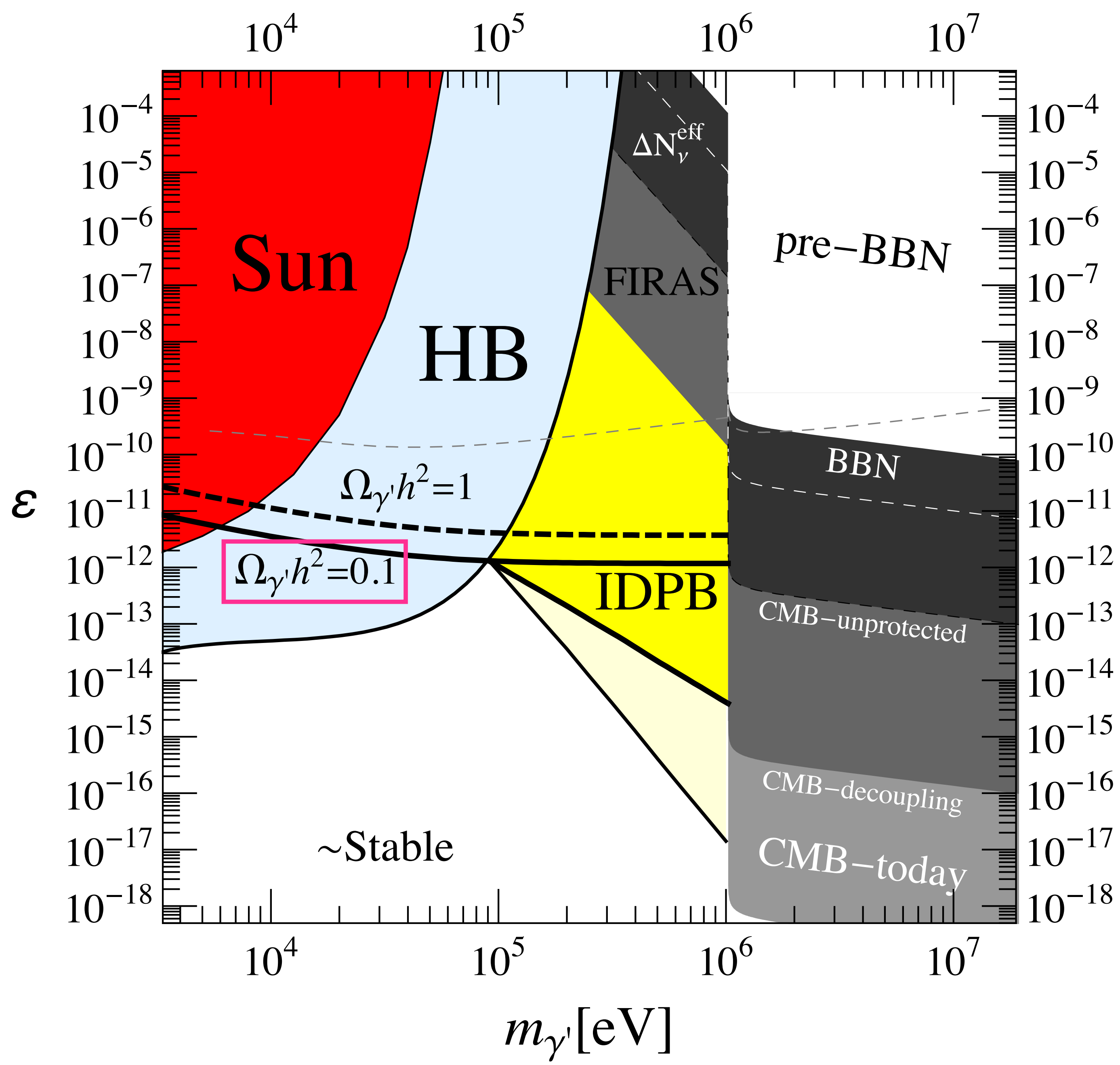
[Redondo & Postma, '08]



- For $m_{\gamma'} < 2m_e$, γ' is dominantly produced at the resonant region
- For $m_{\gamma'} > 2m_e$, γ' is dominantly produced via $e^+e^- \to \gamma'$

Dark photon as a dark matter

[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).

- What could happen if $U(1)_{Dark}$ and $U(1)_{PQ}$ coexist?
- Interestingly, we will see that in such a setup, *new portal coupling emerges, which is not just a combination of the two.*

2. Dark axion portal and the model

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

[Kim, '79] [Shifman, Vainshtein & Zakharov, '80]

- A simple realization of the dark axion portal based on the KSVZ-type axion model

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{\text{Dark}}$	$U(1)_{\text{PQ}}$	
ψ	3	1	Q_ψ	D_ψ	PQ_ψ	heavy PQ (vector-like) quarks
ψ^c	$\bar{3}$	1	$-Q_\psi$	$-D_\psi$	PQ_{ψ^c}	
Φ_{PQ}	1	1	0	0	PQ_Φ	complex PQ scalar
Φ_D	1	1	0	D_Φ	0	complex dark Higgs

- Axion resides in the phase of Φ_{PQ}

$$\Phi_{PQ} = \frac{1}{\sqrt{2}}(v_{PQ} + \rho)e^{iPQ_\Phi(a/f_a)} \qquad f_a \equiv PQ_\Phi v_{PQ}$$

- PQ quark sector: $L \supset y\Phi_{PQ}\psi^c\psi + h.c. \longrightarrow m_\psi = \frac{y}{\sqrt{2}}v_{PQ} \quad \sim O(f_a)$

$$[PQ_\Phi = -(PQ_\psi + PQ_{\psi^c})]$$

- Dark photon acquires a mass via VEV of the dark Higgs:

$$m_{\gamma'} = e' D_{\Phi_D} v_D \qquad \langle \Phi_D \rangle = v_D / \sqrt{2}$$

(we will consider O(keV - GeV) scale dark photon)

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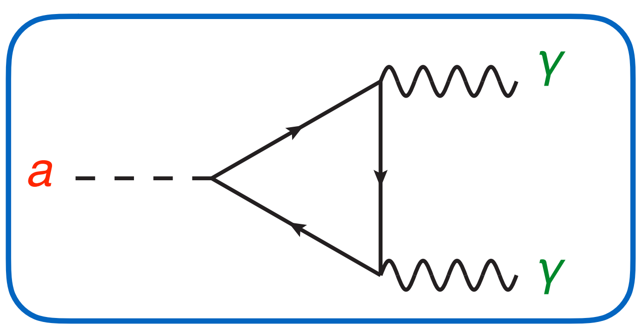
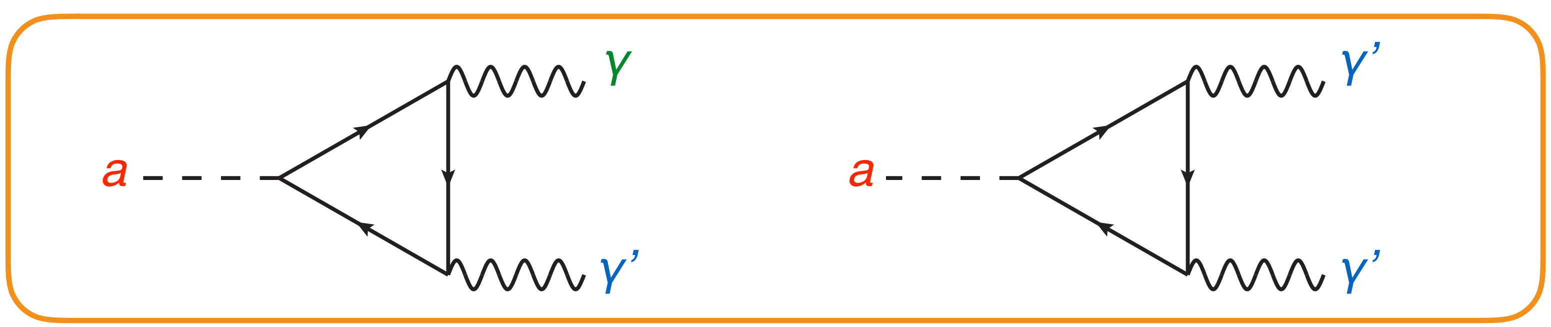
- $U(1)_{PQ}$ is anomalous for the combinations of

$U(1)_{PQ}\,[U(1)_Y]^2$ $\qquad U(1)_{PQ}\,U(1)_Y\,U(1)_{\text{Dark}}$ $\qquad U(1)_{PQ}\,[U(1)_{\text{Dark}}]^2$



Axion portal



Dark axion portal

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

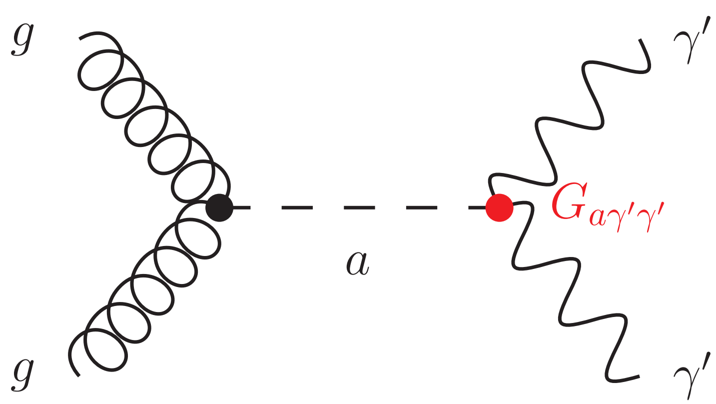
N_C=3 (color factor)

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

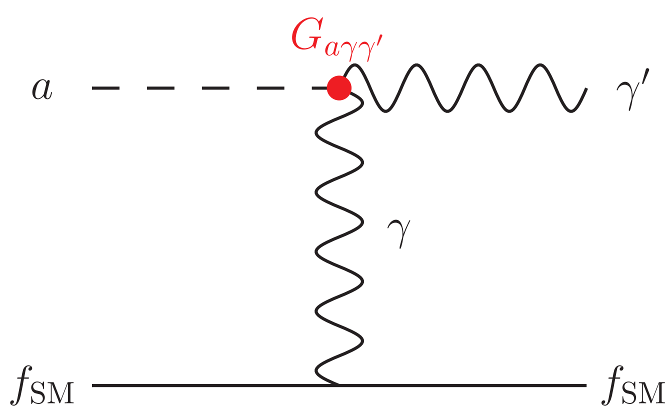
3. Implications

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



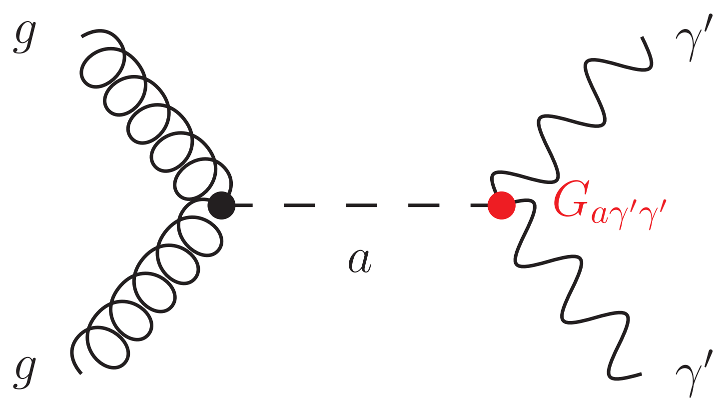
dark Primakoff effect

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'.

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

- $G_{a\gamma'\gamma'} \neq 0$ and $G_{a\gamma\gamma'} = 0$
- Dark photon is stable enough
- 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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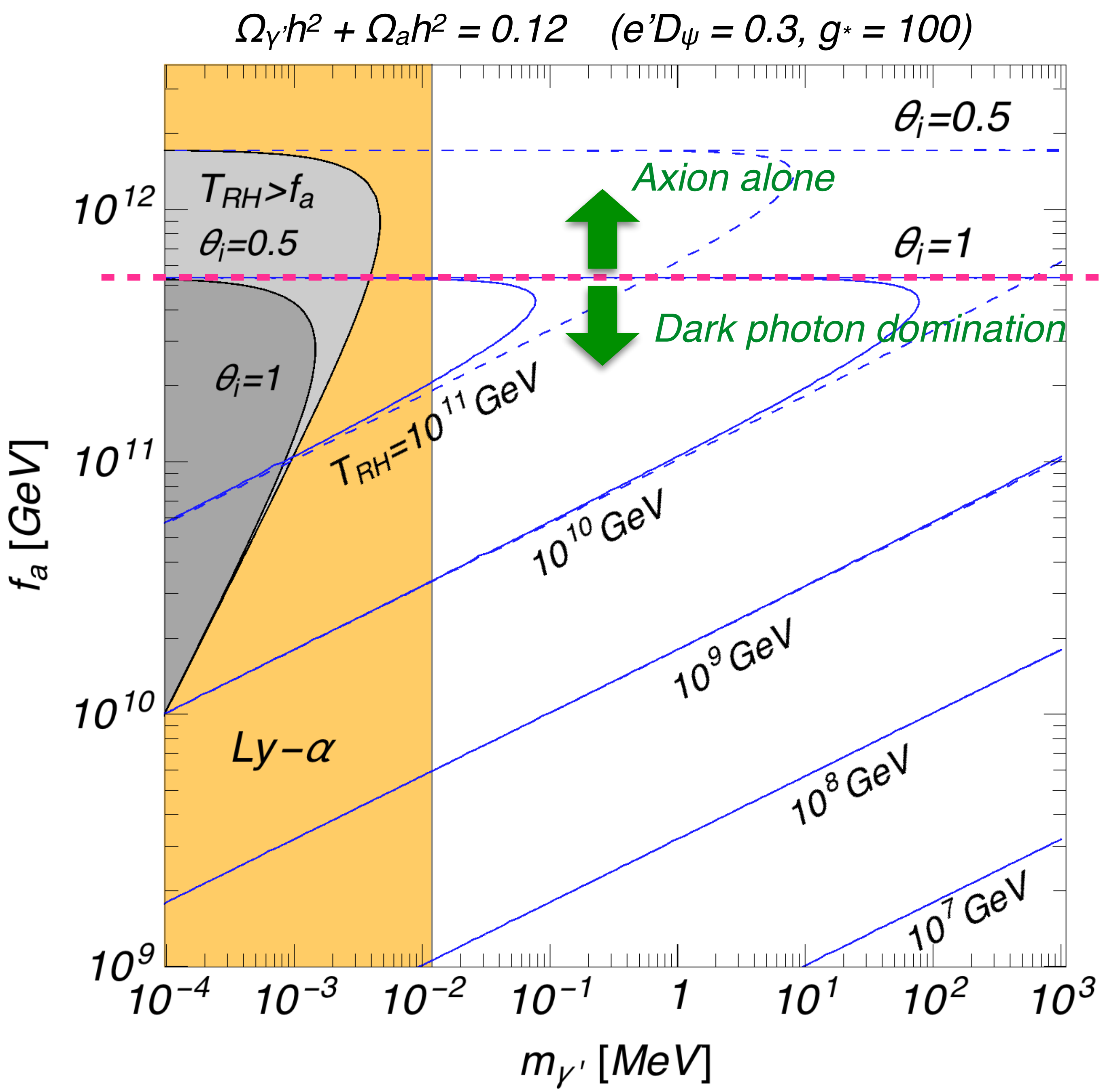
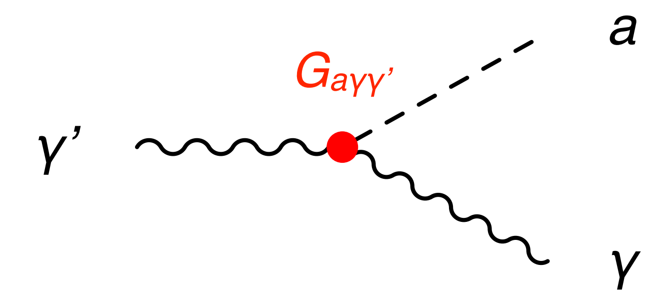


- For large f_a, axion can easily explain the whole dark matter
- For small f_a, dark photon is efficiently produced, and becomes dominant component of dark matter
- Note that in most parameter spaces $T_{RH} < f_a$ is satisfied, so the PQ symmetry is never restored
- Ly-α puts a constraint on the warm 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: $\Gamma_{\gamma' \to a\gamma} \sim G^2_{a\gamma\gamma'} m^3_{\gamma'}$

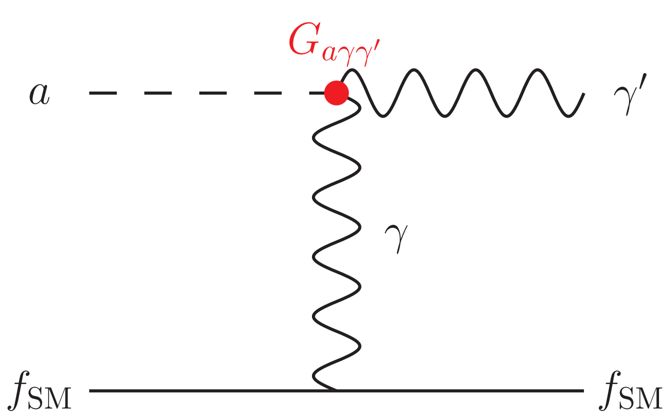
- Then, for γ' to be dark matter, dark photon should satisfy

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

(by imposing the lifetime of γ' should be longer 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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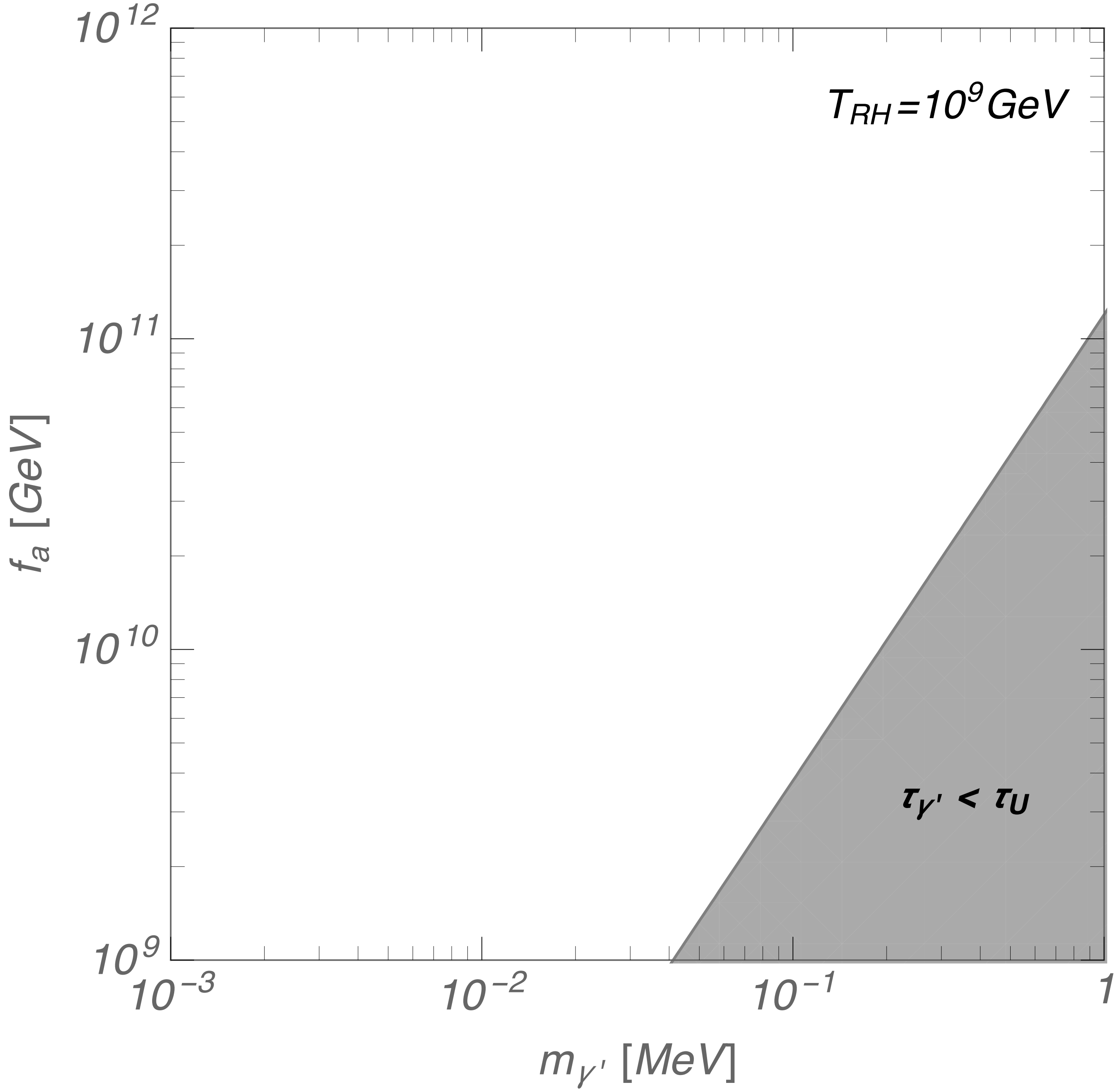
($e'D_\psi = 0.01$, $|Q_\psi| = 1/3$, $g_* = 100$)



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

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

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

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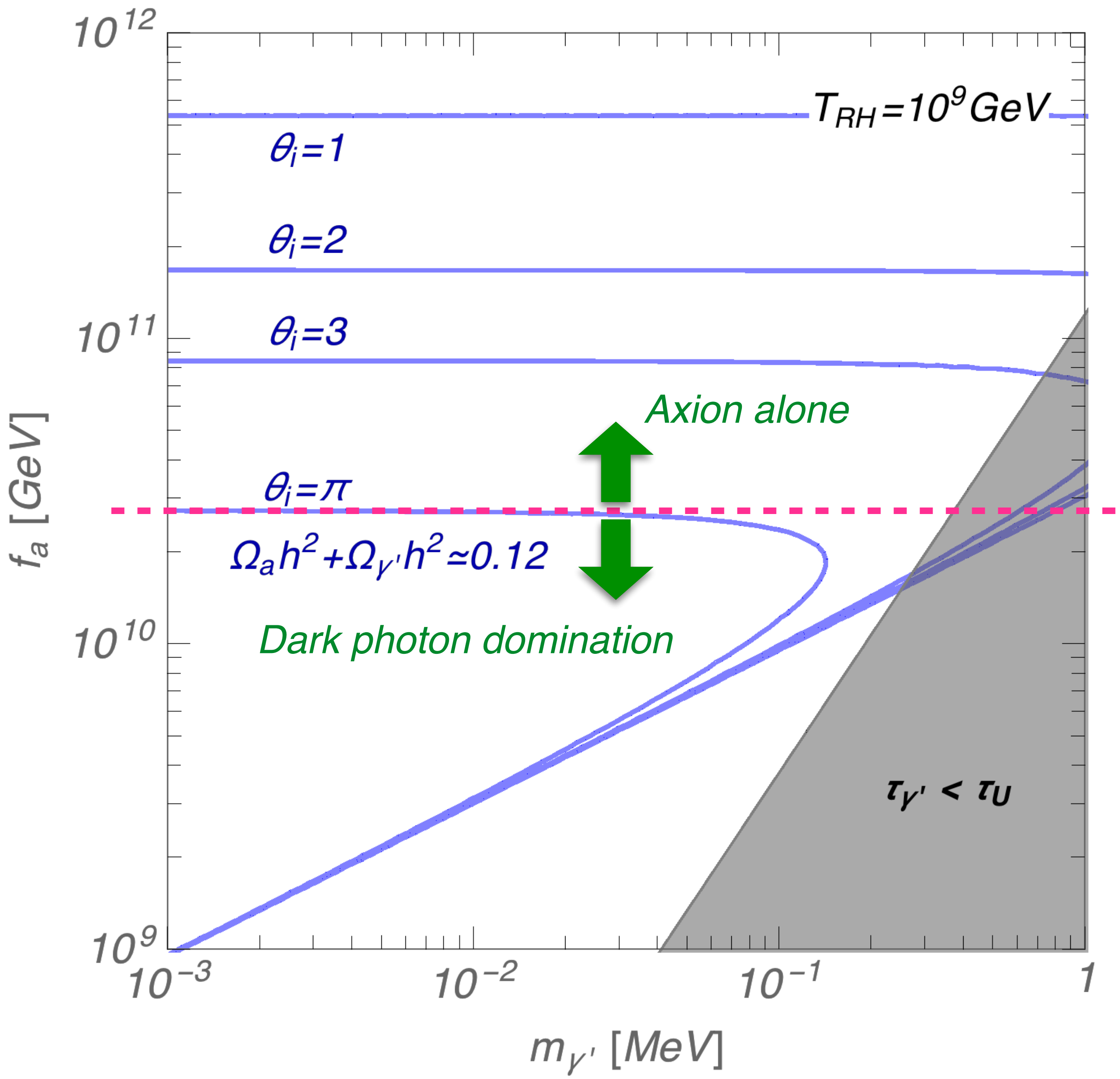
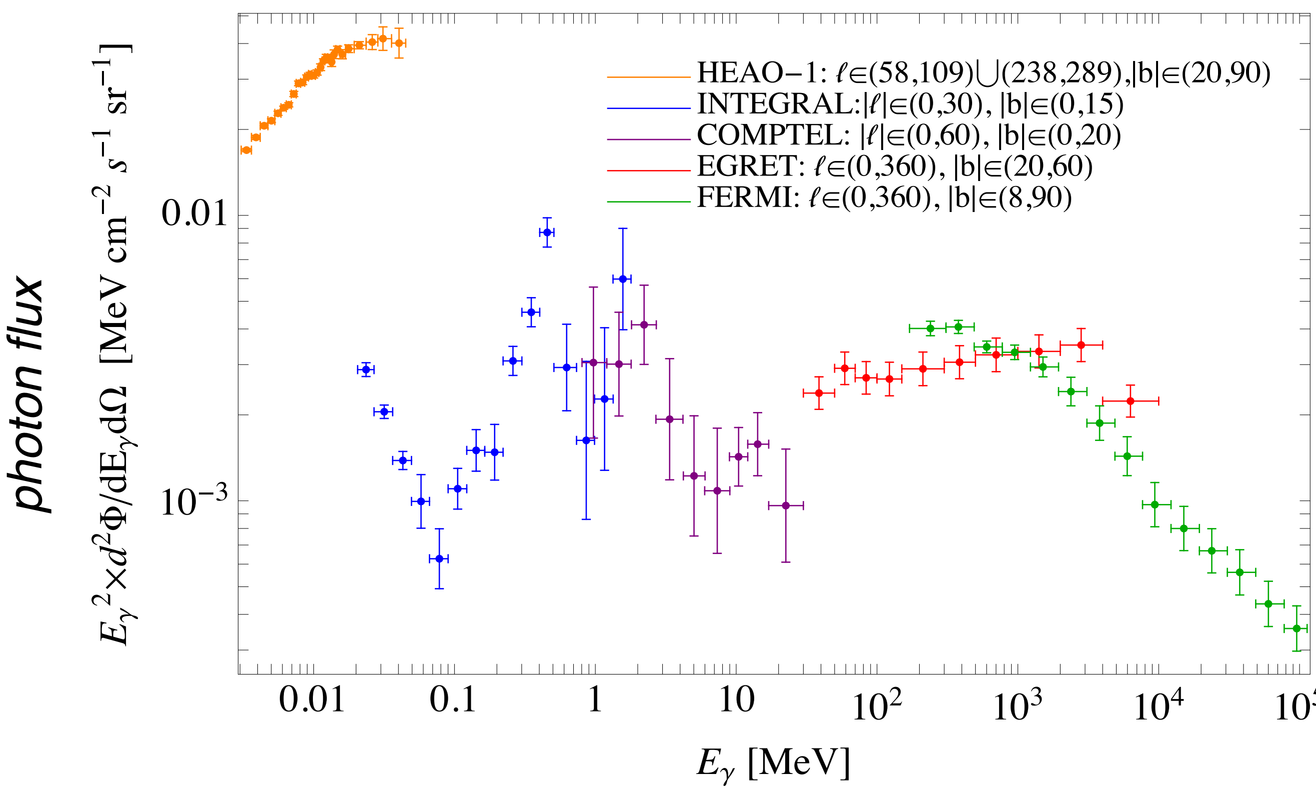


- In the gray region, the dark photon decays too fast.
- For $f_a > 3\times10^{10}$ GeV, axion alone can explain the whole relic dark matter.
- For $f_a < 10^{10}$ GeV, dark photon becomes dominant component.

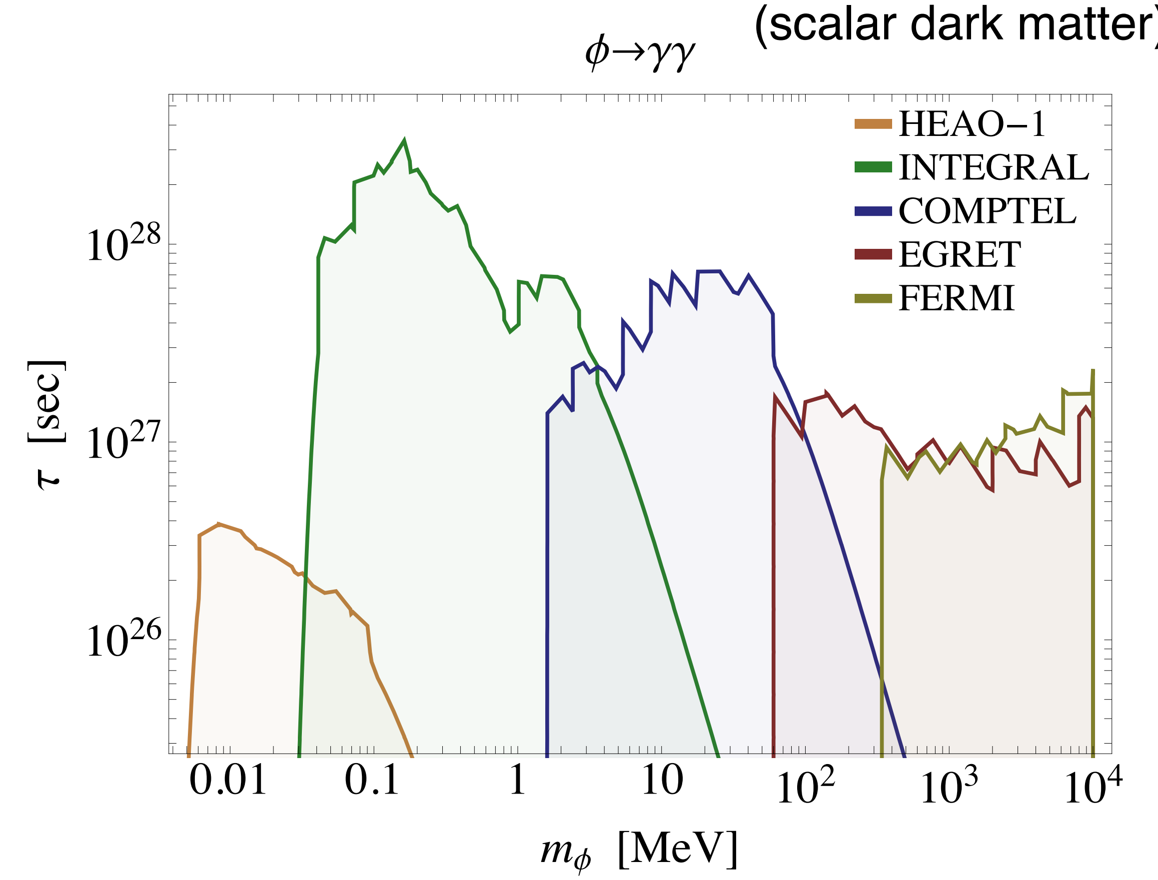
Case (ii): $Q_\psi \neq 0$ and $D_\psi \neq 0$

- Since the dark photon in case (ii) slowly decays into ordinary photon, its lifetime is constrained by the diffuse X-ray observations

[Essig et al., '13]



(scalar dark matter)



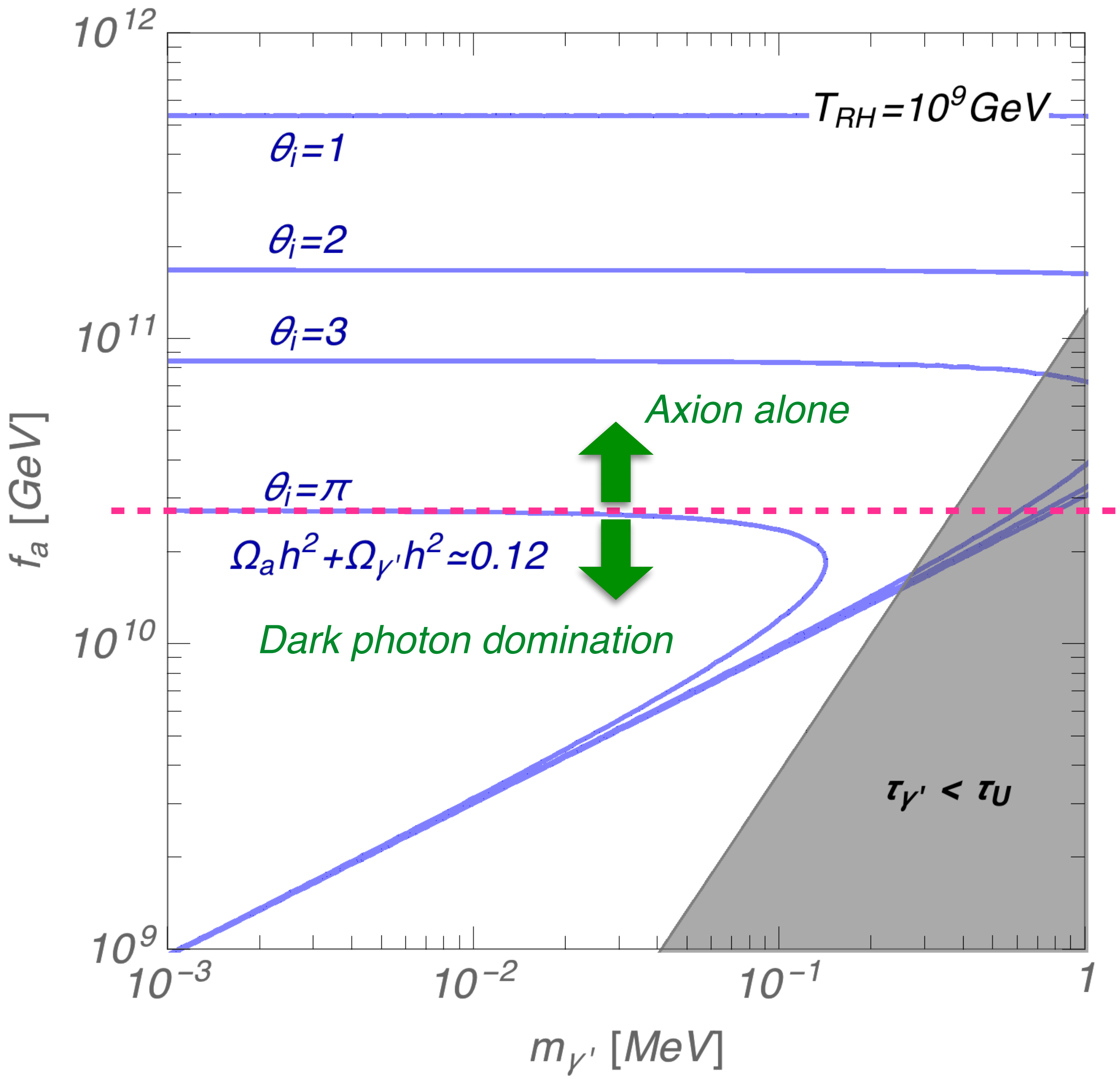
- The lifetime of γ': $\tau_{\gamma'} \simeq 2\times 10^{19}\, sec \times \left(\frac{10^{-16} GeV^{-1}}{G_{a\gamma\gamma'}}\right)^2 \left(\frac{MeV}{m_{\gamma'}}\right)^3$

$$G_{a\gamma\gamma'} \sim 5\times 10^{-16}\ \mathrm{GeV}^{-1} \times Q_\psi \left(\frac{e' D_\psi}{0.01}\right)\left(\frac{5\times 10^{11}\ \mathrm{GeV}}{f_a}\right)$$

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

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

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



- 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.

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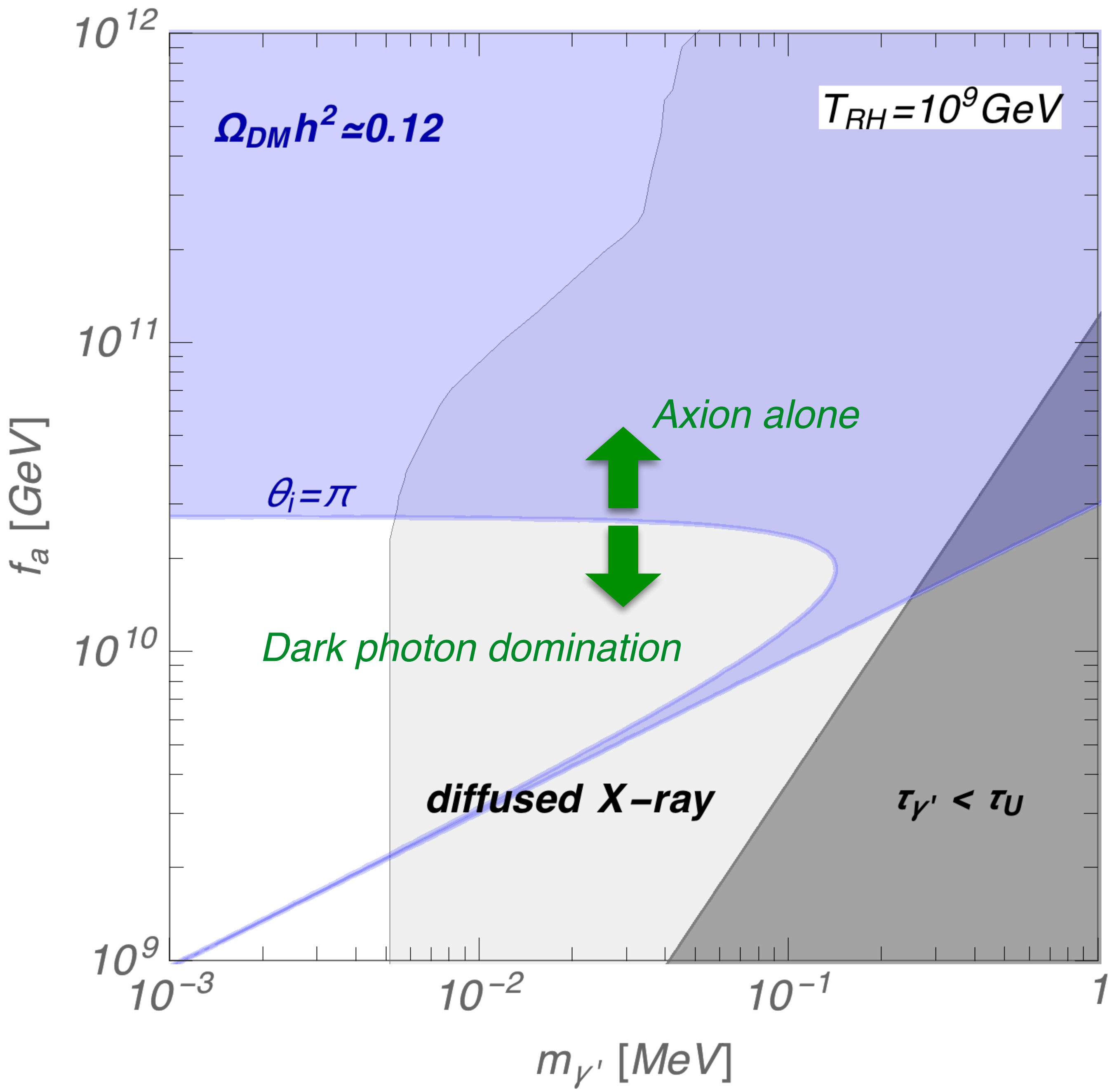
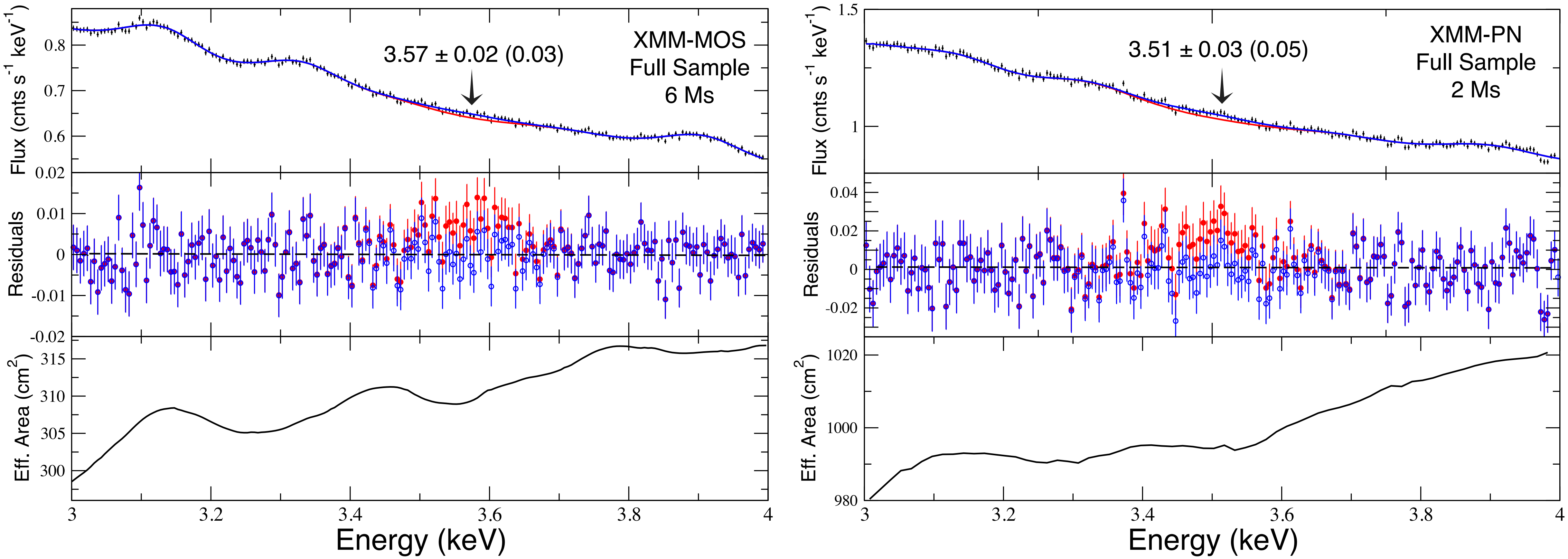


- In the gray region, the dark photon decays too fast.
- For $f_a > 3\times10^{10}$ GeV, axion alone can explain the whole relic dark matter.
- For $f_a < 10^{10}$ GeV, dark photon becomes dominant component.
- In the light gray region, since the dark photon slowly decays, observations of the diffused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

3.5 keV X-ray line excess

- Even though γ' can not make up of full of dark matter number density, it can be a source of the anomalous 3.5 keV excess in the X-ray spectrum of galaxies

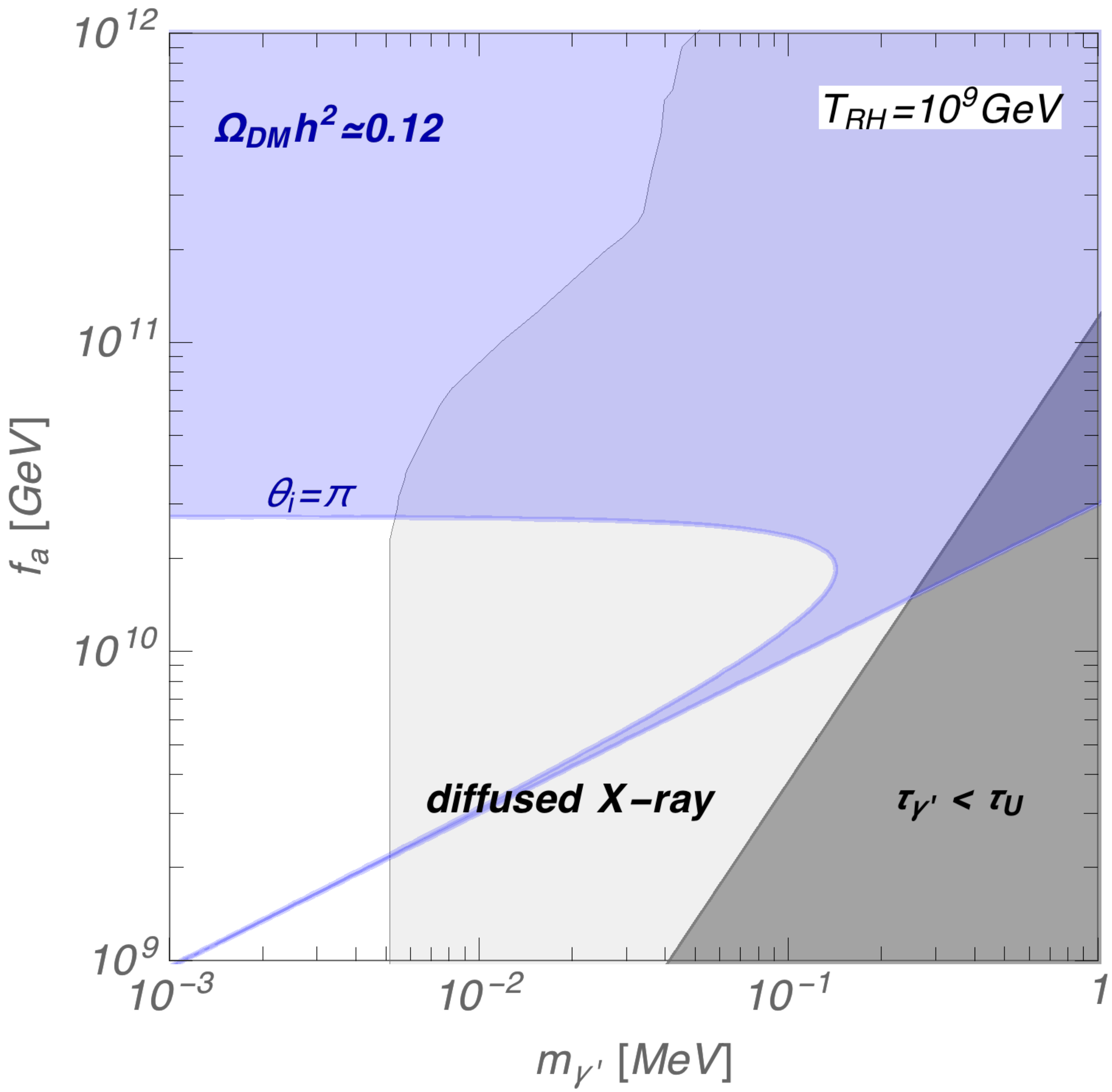
[Bulbul et al., '14]



- It turns out that the excess can be explained if the lifetime of γ' and the fraction of relic density satisfy

$$\tau_{\gamma'} \simeq r_{\gamma'} \times 10^{28}\ sec \qquad r_{\gamma'} = \Omega_{\gamma'}/\Omega_{DM}$$

3.5 keV X-ray line excess



- dark photon abundance

$$\Omega_{\gamma'} h^2 \simeq 0.12 \times \left(\frac{m_{\gamma'}}{\mathrm{MeV}}\right)\left(\frac{100}{f_a / T_{RH}}\right)\left(\frac{10^{10}\,\mathrm{GeV}}{f_a}\right)$$

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

assuming $\Omega_{DM} \sim \Omega_a >> \Omega_{\gamma'}$

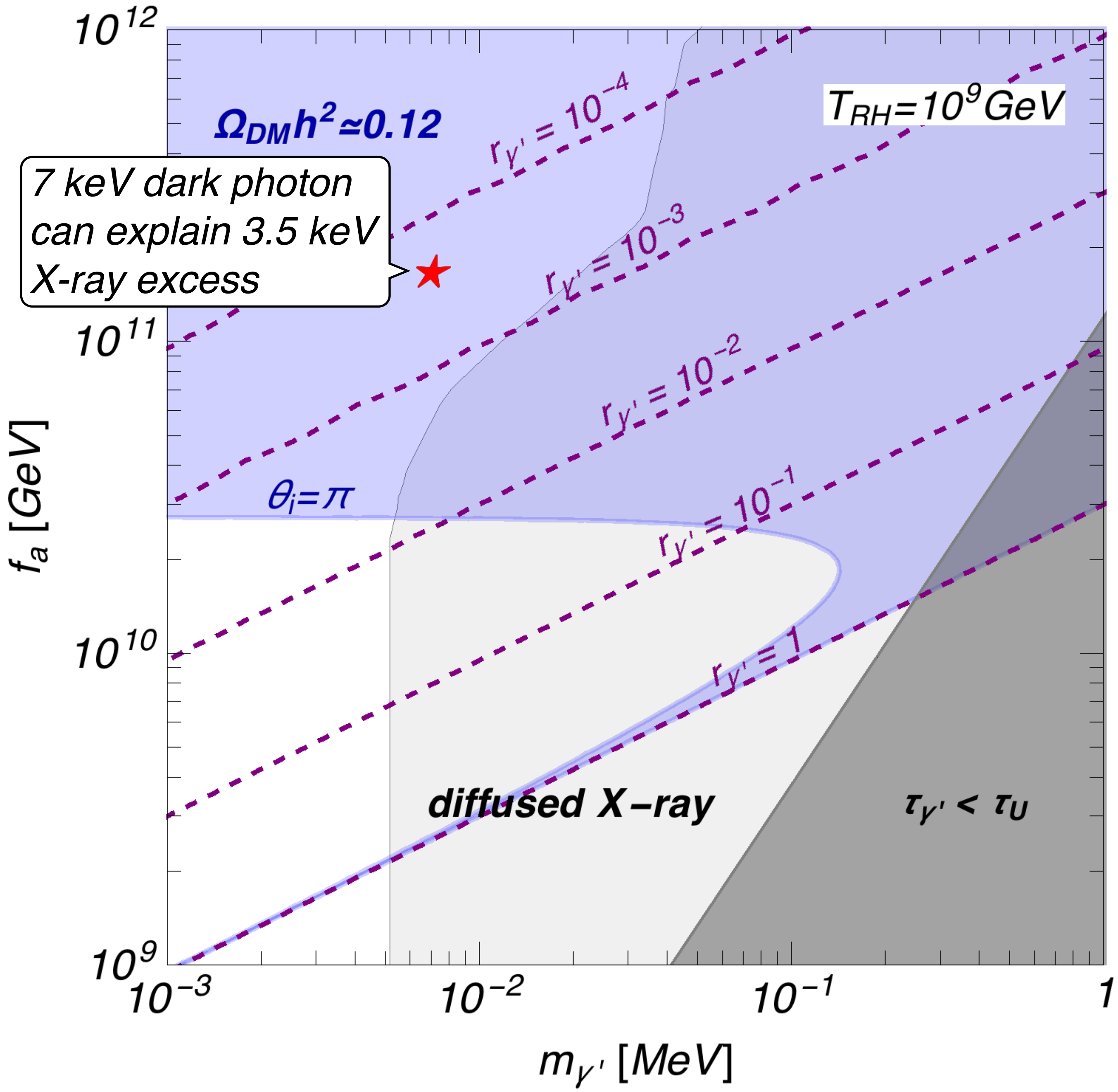
$$r_{\gamma'} \simeq 10^{-3} \times \left(\frac{m_{\gamma'}}{7\,\mathrm{keV}}\right)\left(\frac{T_{RH}}{10^9\,\mathrm{GeV}}\right)\left(\frac{10^{11}\,\mathrm{GeV}}{f_a}\right)^2$$

- dark photon lifetime

$$\tau_{\gamma'} \simeq (3.5 \times 10^{24}\,\mathrm{sec}) \times \left(\frac{m_{\gamma'}}{7\,\mathrm{keV}}\right)^3 \left(\frac{f_a}{10^{11}\,\mathrm{GeV}}\right)$$

$$\tau_{\gamma'} \simeq r_{\gamma'} \times 10^{28}\,\mathrm{sec}$$

3.5 keV X-ray line excess



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3.5 keV X-ray line excess

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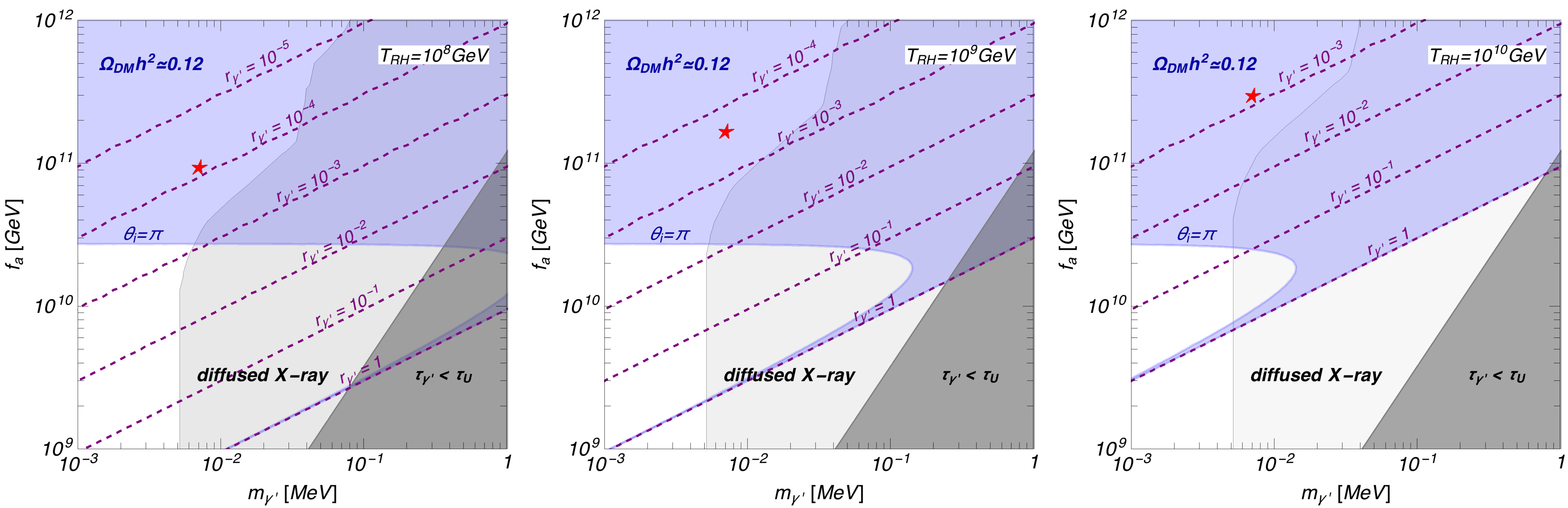


- Higher (lower) T_{RH} increases (decreases) the dark photon fraction
- By demanding γ' is the source of 3.5 keV excess, we can derive a relationship between T_{RH} and f_a (or $G_{a\gamma\gamma'}$)

3.5 keV X-ray line excess

to explain the 3.5 keV excess: $G_{a\gamma\gamma'} \simeq (10^{-16}\ \mathrm{GeV}^{-1}) \left(\frac{10^{11}\ \mathrm{GeV}}{T_{\rm RH}}\right)^{1/4}$

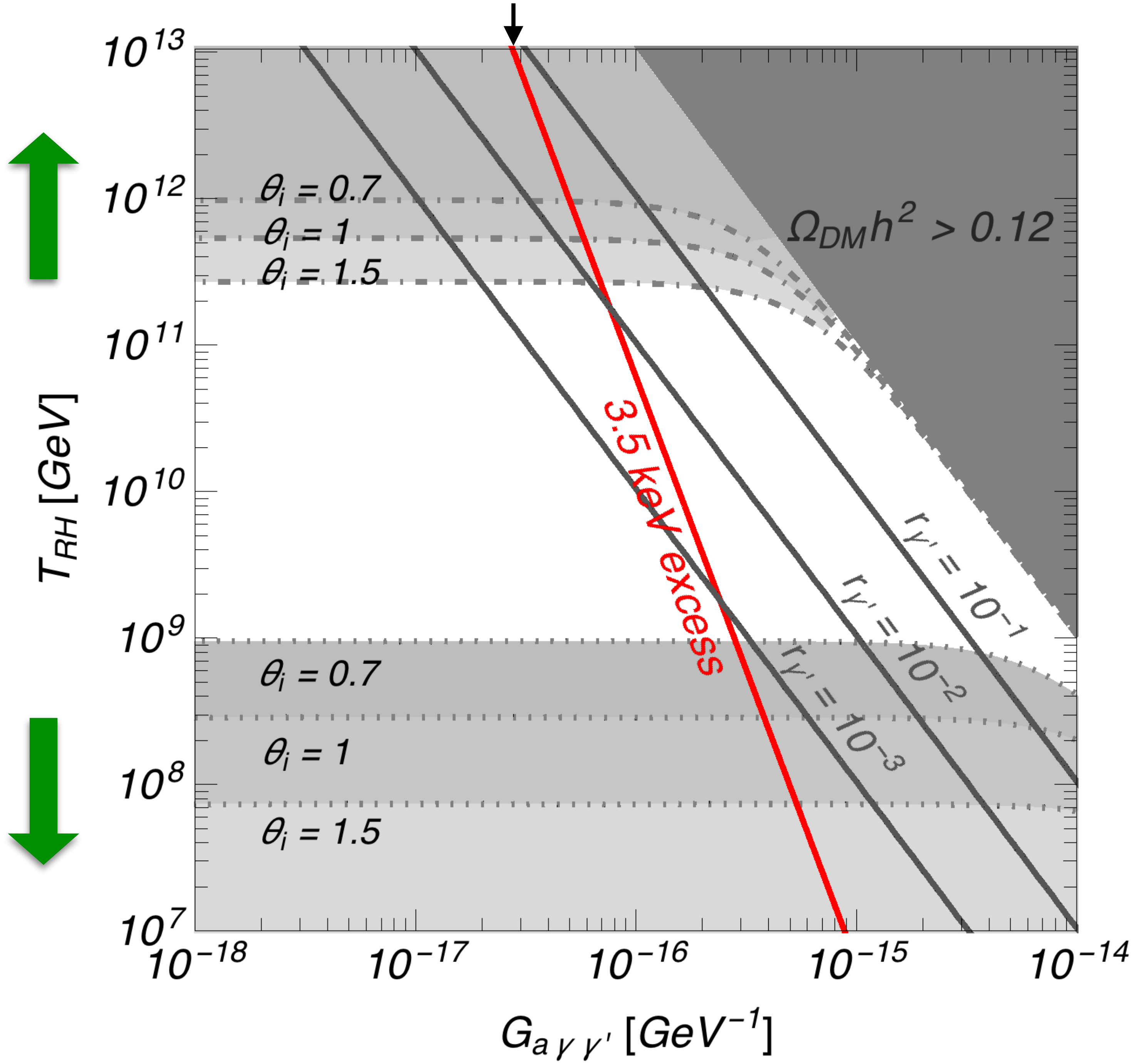
For $T_{RH} > f_a$, PQ symmetry may be restored, where f_a is a function of θ_i by taking

$$\Omega_a h^2 \simeq 0.11 \times \theta_i^2 \left(\frac{f_a}{5\times10^{11}GeV}\right)^{1.19}$$

$$= \Omega_{DM} h^2$$

For $T_{RH} < T_D$, axion never thermalises, where T_D is the axion decoupling temperature given by

$$T_D \simeq (10^5\ \mathrm{GeV}) \left(\frac{f_a}{10^{10}\ \mathrm{GeV}}\right)^2$$



T_{RH} can vary from 10^8 GeV to 10^{12} GeV for the 3.5 keV excess, while $G_{a\gamma\gamma'}$ is almost constant around $G_{a\gamma\gamma'} \sim 10^{-16}$ GeV^{-1}, corresponding to $f_a \sim O(10^{11}$ GeV)

Summary

- We discussed 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 ($\gamma' \rightarrow a\,\gamma$).