Dark Axion Portal

(connecting Axion physics and Dark gauge boson physics)

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Based on the work with Kunio Kaneta, Seokhoon Yun

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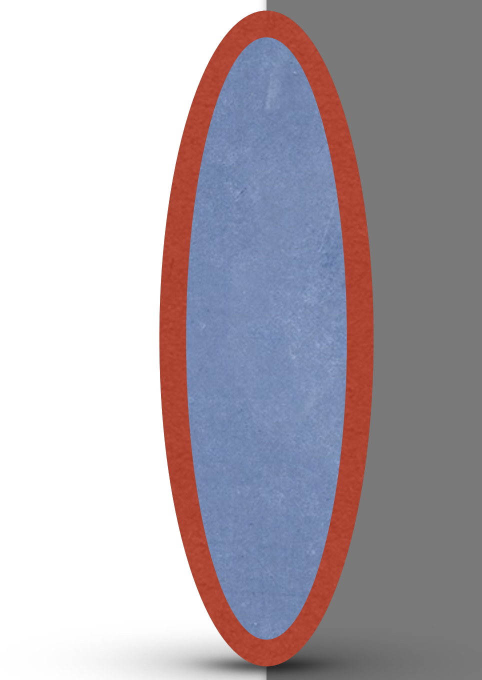
Portal

Standard Model



Hidden sector

Dark matter
Dark gauge boson
Higgs singlet
RH neutrino
Axion
...

Through the portal, two separate sectors can communicate with each other.

Portal

(i) Vector Portal $\frac{\varepsilon}{2} F_{\mu\nu} Z'^{\mu\nu}$ Dark gauge boson physics

(ii) Axion Portal $\frac{G_{agg}}{4} aG_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{G_{a\gamma\gamma}}{4} aF_{\mu\nu}\tilde{F}^{\mu\nu}$ "non-renormalizable" portal

(iii) Higgs Portal $\kappa\, |S|^2 |H|^2 + \mu\, S |H|^2$

(iv) Neutrino Portal $y\, LHN$

Portal

(i) Vector Portal $\frac{\varepsilon}{2} F_{\mu\nu} Z'^{\mu\nu}$ Dark gauge boson physics

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(iii) Higgs Portal $\kappa \, |S|^2 |H|^2 + \mu \, S |H|^2$

(iv) Neutrino Portal $y \, L H N$

(v) Dark Axion Portal $\frac{G_{a\gamma\gamma'}}{4} a F_{\mu\nu} \tilde{Z}'^{\mu\nu} + \frac{G_{a\gamma'\gamma'}}{4} a Z'_{\mu\nu} \tilde{Z}'^{\mu\nu}$ Dark gauge boson physics "non-renormalizable" portal

We introduce a new portal that connects Dark photon (Vector portal) and Axion (Axion portal) to our sector at the same time.

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

Outline

1. Axion Portal (brief overview)

2. Vector Portal (brief overview)

3. Dark Axion Portal (Dark KSVZ model as a concrete realization)

4. Implications of Dark Axion Portal

Axion Portal

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

Axion at a glance

Axion: Pseudo Nambu-Goldstone boson associated with Peccei-Quinn symmetry, a global U(1), introduced to address the strong CP problem
[Pseudo: the $U(1)_{PQ}$ is not exact, and gives a small mass to the axion]

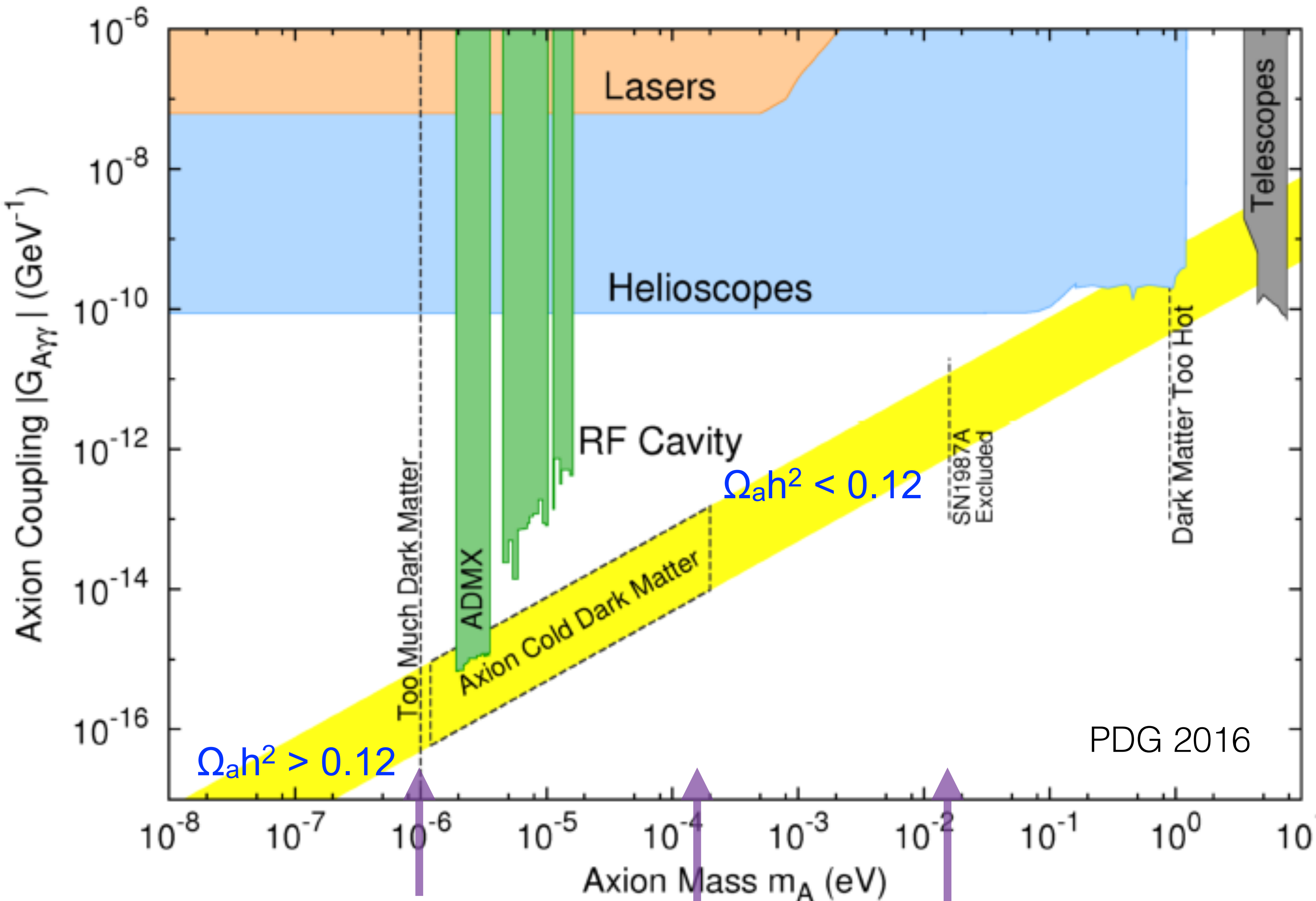
f_a (axion decay constant) = $U(1)_{PQ}$ symmetry breaking scale

$$m_a \approx 0.5 \frac{f_\pi m_\pi}{f_a} , \quad G_{agg} \approx \frac{1}{2} \frac{\alpha_{\rm S}}{f_a} , \quad G_{a\gamma\gamma} \approx \frac{1}{2} \frac{\alpha_{\rm EM}}{f_a} \mathcal{O}(1)$$

Axion coupling is almost determined once its mass is given. $\frac{G_{a\gamma\gamma}}{m_a} \sim \frac{10^{-9}\ {\rm GeV}^{-1}}{\rm eV}$

Axon-Like Particle (ALP): a generalized version of the axion (at the cost of original motivation from the strong CP problem). No direct relation between $G_{a\gamma\gamma}$ and m_a.

Current constraints on Axion, ALP



(Relic density deficit for $f_a < 10^{11}$ GeV)

in a popular scenario where the PQ phase transition occurs before the inflation

Axion relation (Yellow band) $\frac{G_{a\gamma\gamma}}{m_a} \sim \frac{10^{-9}\ \mathrm{GeV}^{-1}}{\mathrm{eV}}$

[See the next talks for more about axion and ALP.]

Vector Portal

$$\frac{\varepsilon}{2} F_{\mu\nu} Z'^{\mu\nu}$$

Dark Photon at a glance

Vector portal has been widely used for the dark photon interaction.
There are various motivations for a dark photon from the DM physics (e.g. positron excess, self-interaction) as well as the non-DM physics (e.g. muon g-2 deviation).
[See S. Tulin's talk]
Pospelov (2008)

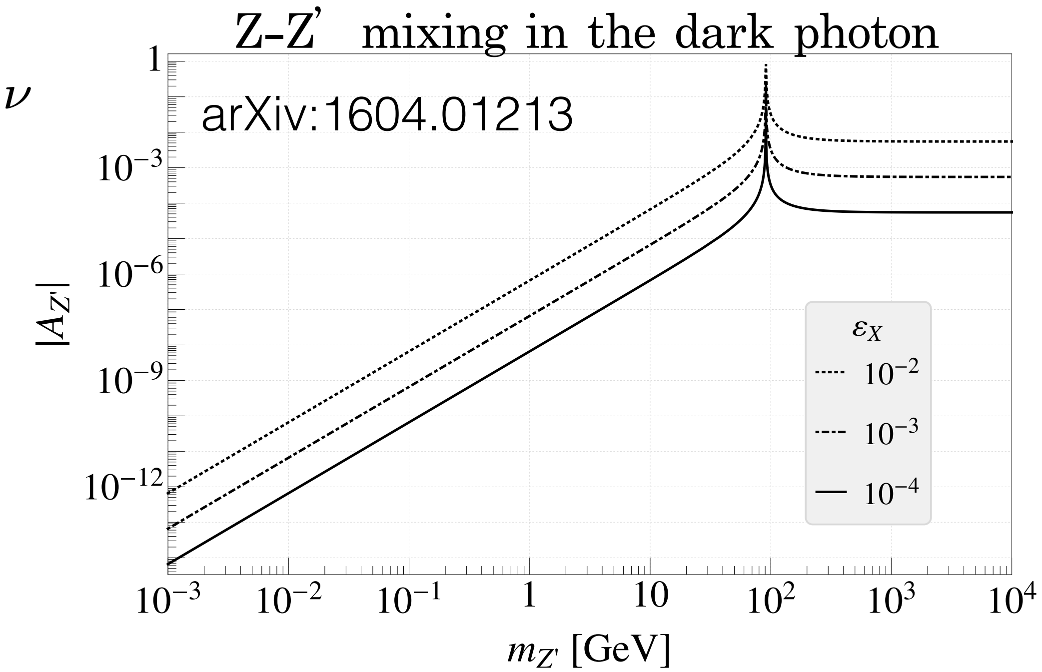
$$\mathcal{L}_{\rm kin} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z'^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu}$$

U(1)$_Y$ U(1)$_{\rm Dark}$

physical

$$\mathcal{L}_{\rm int} = -\varepsilon\, e J^\mu_{\rm EM} Z'_\mu - \varepsilon \tan\theta_W \frac{m_{Z'}^2}{m_Z^2} g_Z J^\mu_{\rm NC} Z'_\mu$$

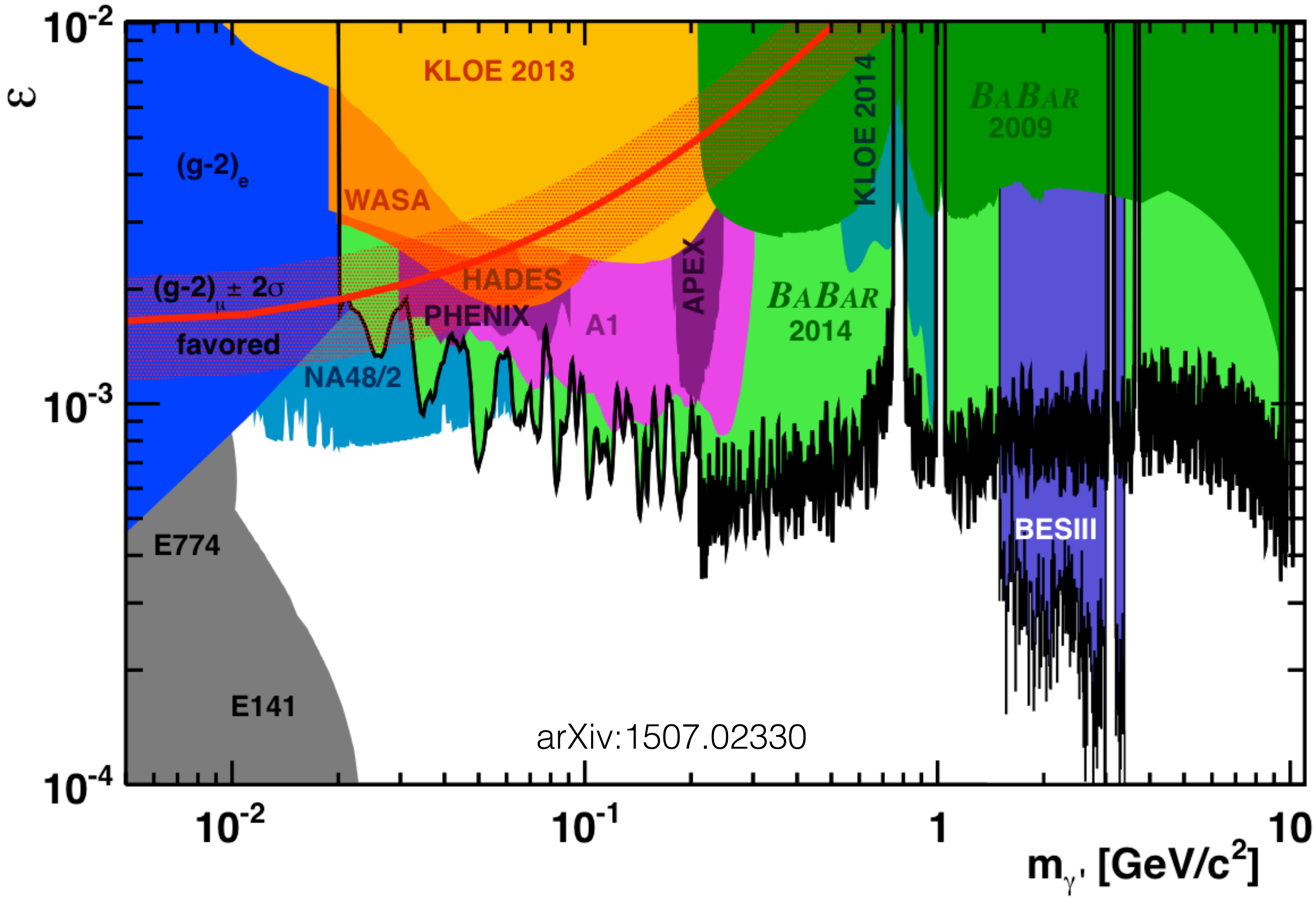
(negligible for $m_{Z'} << m_Z$)



Hypercharge $B_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu$ has both photon and Z boson components.
For a very light Z', the coupling to NC can be neglected ("Dark Photon model") when a simple Higgs structure is assumed for Z' mass (e.g. Higgs singlet).

(With a different Higgs sector (e.g. 2HDM+singlet), the coupling to NC can be larger even for a light Z' because of an additional Z-Z' mass mixing ("Dark Z model"). Davoudiasl, LEE, Marciano (2012))

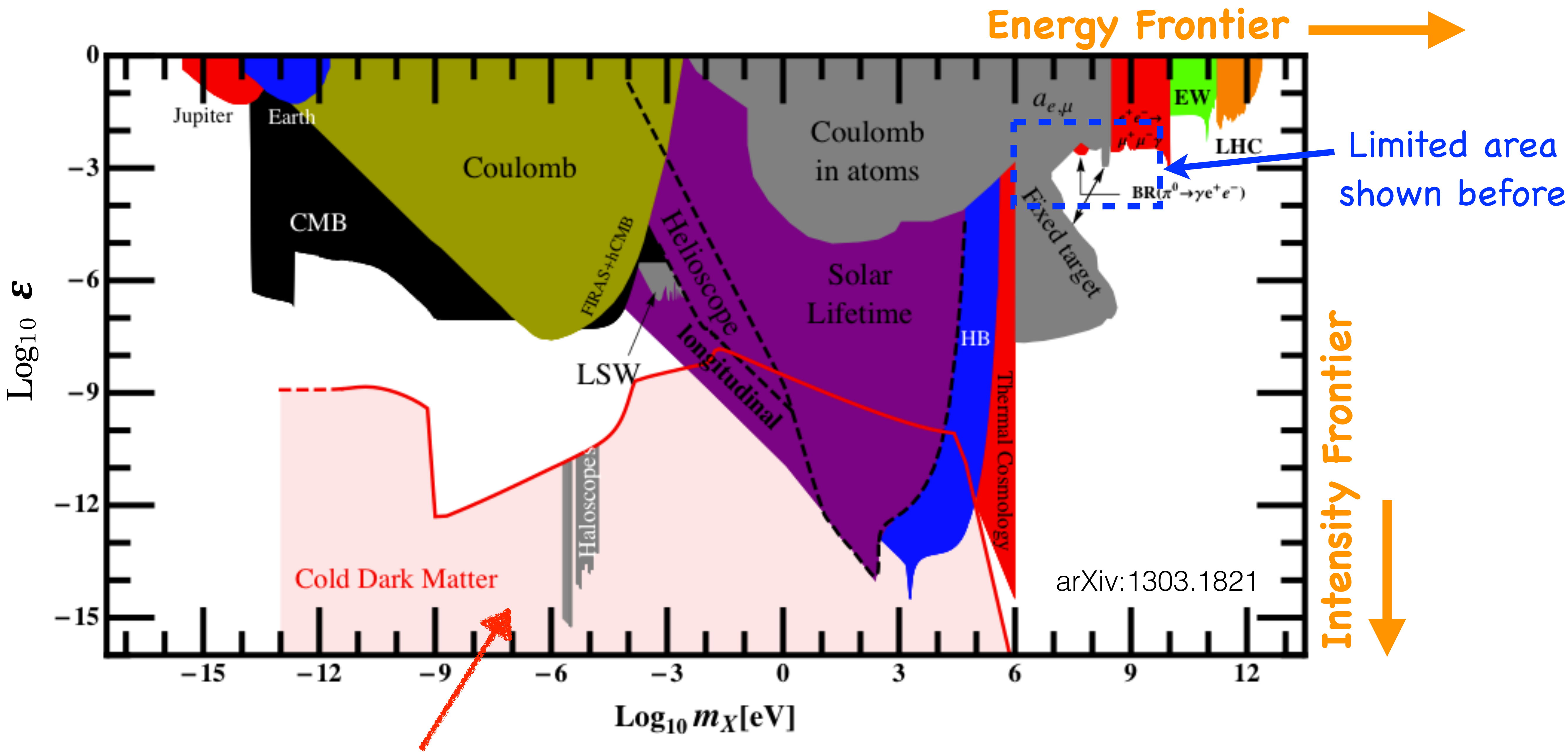
Constraints on Dark Photon (visible one)



(mostly Z'→l+l− searches)

Dark photon is actively searched for in many labs around the world.
The kinetic mixing parameter is constrained to be small $|\varepsilon|^2 << 1$.

Extended range of parameters of the Dark Photon



Region for the Dark photon DM   Arias et al (2008)

Dark photon can be long-lived (> Universe age, 14 billion years) enough to be a DM candidate.

Pospelov, Ritz, Voloshin (2008)

$$\Gamma(\gamma' \to 3\gamma) \approx (5 \times 10^{-8})\varepsilon^2 \left(\frac{e^2}{4\pi^2}\right)^4 \left(\frac{m_{\gamma'}^9}{m_e^8}\right)$$

for sub-MeV dark photon   [See M Pospelov's talk]

Dark Axion Portal

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

A hidden connection is stronger than an obvious one.

- Heraclitus of Ephesus -

Dark KSVZ model

To realize Dark Axion Portal, we construct Dark KSVZ model, which is a simple extension of the KSVZ axion model with the $U(1)_{Dark}$.

(KSVZ model: invisible axion model using exotic quarks)

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{\text{Dark}}$	$U(1)_{PQ}$
Q	3	2	$1/6$	0	0
u_R	3	1	$2/3$	0	0
d_R	3	1	$-1/3$	0	0
L	1	2	$-1/2$	0	0
e_R	1	1	-1	0	0
H	1	2	$-1/2$	0	0
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

KSVZ axion model (rows Q through ψ^c)

Exotic colored fermions (ψ, ψ^c)

Additional scalar for γ' mass (Φ_D)

$$\mathcal{L} = y_\psi \Phi_{PQ} \psi \psi^c + h.c. \quad \longrightarrow \quad PQ_\Phi = -(PQ_\psi + PQ_{\psi^c})$$

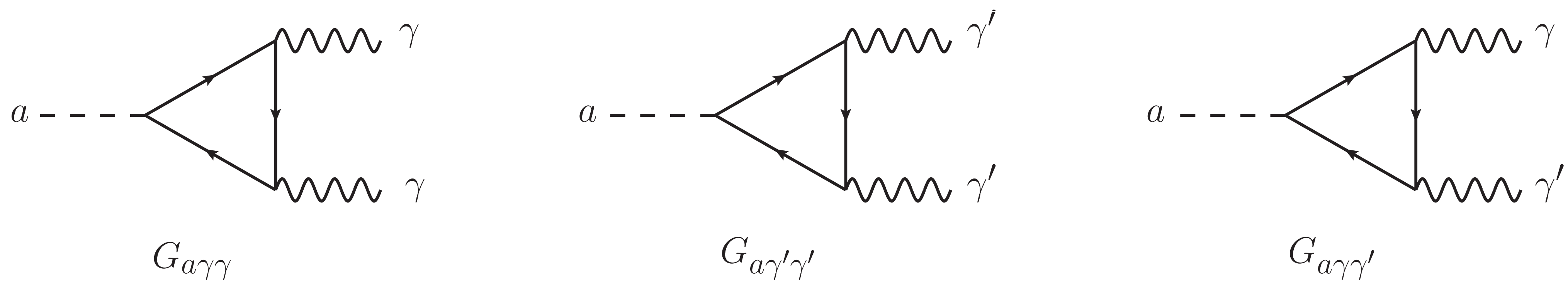
$$f_a^2 = PQ_\Phi^2 \, v_{PQ}^2 \ , \qquad m_a \simeq \frac{\sqrt{z}}{1+z} \frac{f_\pi m_\pi}{f_a} \qquad (\text{with } z \equiv m_u/m_d \simeq 0.56)$$

$$G_{agg} = \frac{g_S^2}{8\pi^2} \frac{PQ_\Phi}{f_a}$$

$$m_{\gamma'}^2 = e'^2 D_\Phi^2 v_D^2$$

Exotic colored fermions may decay into other particles through, e.g. $\Phi_D^\dagger \psi \bar{d}_R + h.c.$ for $PQ_\psi = 0$, $Q_\psi = -1/3$, $D_\psi = D_\Phi$.

Dark Axion Portal (in Dark KSVZ model)



Below the QCD scale, the portal interaction terms are given by

$$G_{a\gamma\gamma} = \frac{e^2}{8\pi^2}\frac{PQ_\Phi}{f_a}\left[2N_C Q_\psi^2 - \frac{2}{3}\frac{4+z}{1+z}\right]$$

$$G_{a\gamma\gamma'} \simeq \frac{ee'}{8\pi^2}\frac{PQ_\Phi}{f_a}\left[2N_C D_\psi Q_\psi\right] + \varepsilon G_{a\gamma\gamma}$$

$$G_{a\gamma'\gamma'} \simeq \frac{e'^2}{8\pi^2}\frac{PQ_\Phi}{f_a}\left[2N_C D_\psi^2\right] + 2\varepsilon G_{a\gamma\gamma'}$$

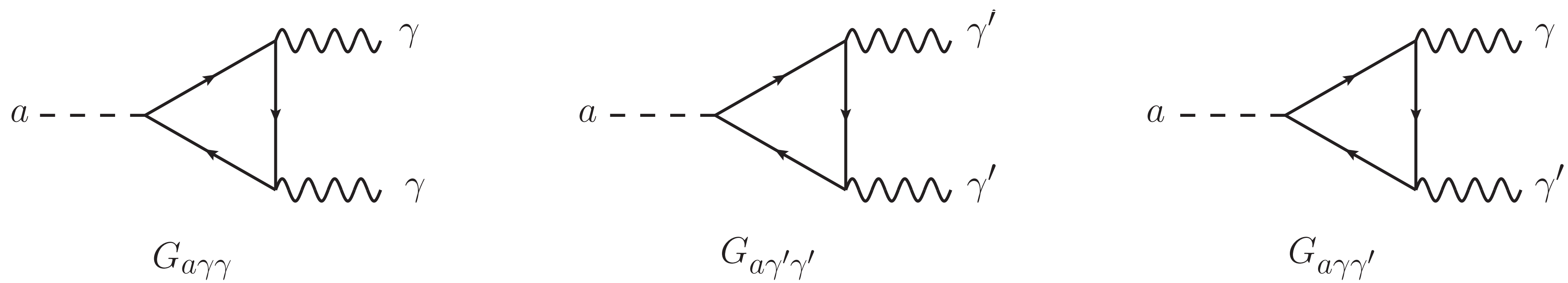
Q: electric charge
D: dark charge

The simple (vector portal. ε) × (axion portal. $G_{a\gamma\gamma}$) part should be much smaller than (axion portal. $G_{a\gamma\gamma}$) because $|\varepsilon|^2$ << 1.

They contain genuinely new couplings coming from the exotic colored fermions in the triangle charged under a dark gauge symmetry.

$G_{a\gamma\gamma} \sim G_{a\gamma\gamma'} \sim G_{a\gamma'\gamma'}$ if $e' \sim e$, $D_\psi \sim Q_\psi$

Decays



Dark photon decay

$$\Gamma(\gamma' \to e^+e^-) = \frac{\varepsilon^2 e^2}{12\pi} m_{\gamma'} \left[1 - \frac{4m_e^2}{m_{\gamma'}^2}\right]^{1/2}$$

$$\Gamma(\gamma' \to \gamma a) = \frac{G_{a\gamma\gamma'}^2}{96\pi} m_{\gamma'}^3 \left[1 - \frac{m_a^2}{m_{\gamma'}^2}\right]^3$$

Axion decay

$$\Gamma(a \to \gamma\gamma) = \frac{G_{a\gamma\gamma}^2}{64\pi} m_a^3$$

$$\Gamma(a \to \gamma\gamma') = \frac{G_{a\gamma\gamma'}^2}{32\pi} m_a^3 \left[1 - \frac{m_{\gamma'}^2}{m_a^2}\right]^3$$

$$\Gamma(a \to \gamma'\gamma') = \frac{G_{a\gamma'\gamma'}^2}{64\pi} m_a^3 \left[1 - \frac{4m_{\gamma'}^2}{m_a^2}\right]^{3/2}$$

Dark DFSZ model

Preliminary

What about the DFSZ model? We can construct a Dark DFSZ model in a similar way we did for the KSVZ model with the $U(1)_{\rm Dark}$.

(DFSZ model: invisible axion model with nonzero PQ charges for the SM fermions. No exotic quarks)

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{\rm Dark}$	$U(1)_{PQ}$
Q	3	2	1/6	0	PQ_Q
u_R	3	1	2/3	0	$PQ_Q + PQ_{H_u}$
d_R	3	1	−1/3	0	$PQ_Q + PQ_{H_d}$
L	1	2	−1/2	0	PQ_L
e_R	1	1	−1	0	$PQ_L + PQ_{H_d}$
H_u	1	2	1/2	0	PQ_{H_u}
H_d	1	2	−1/2	0	PQ_{H_d}
Φ_{PQ}	1	1	0	0	PQ_Φ
Φ_D	1	1	0	D_Φ	0

Type-II 2HDM (H_u, H_d)

DFSZ axion model (Q through Φ_{PQ})

Additional scalar for γ' mass (Φ_D)

Scalar parts are model-dependent.
We take Type-II 2HDM, and assume the $\Phi_{PQ}^2 H_u \cdot H_d$ term.

$$\mathcal{L} = \lambda\, \Phi_{PQ}^2 H_u \cdot H_d \quad \longrightarrow \quad 2PQ_\Phi = -(PQ_{H_u} + PQ_{H_d})$$

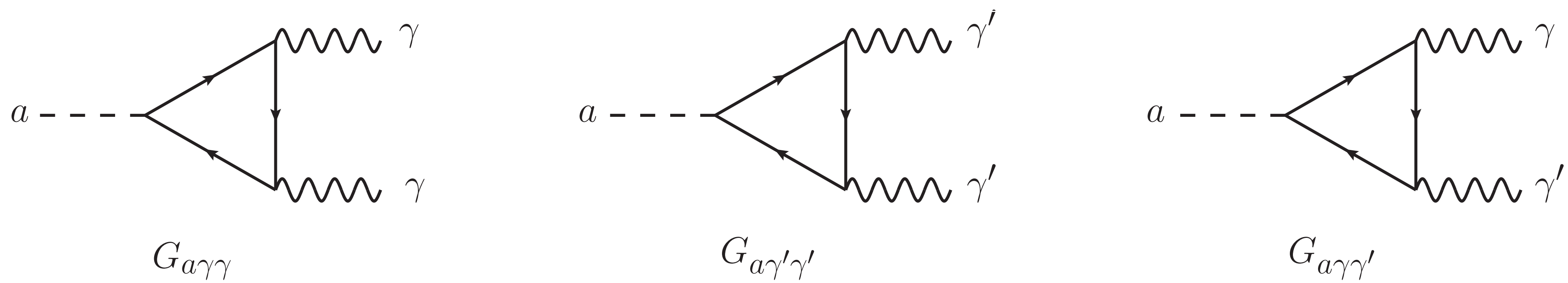
$$PQ_{H_u} = -2PQ_\Phi \cos^2\beta\ , \qquad PQ_{H_d} = -2PQ_\Phi \sin^2\beta \qquad (\text{with}\ \tan\beta \equiv v_u/v_d)$$

$$f_a^2 = PQ_\Phi^2\, v_{PQ}^2 + PQ_{H_u}^2 v_u^2 + PQ_{H_d}^2 v_d^2\ , \qquad m_a \simeq \frac{\sqrt{z}}{1+z}\frac{f_\pi m_\pi}{f_a} \qquad (\text{with}\ z \equiv m_u/m_d \simeq 0.56)$$

$$G_{agg} = \frac{g_S^2}{8\pi^2}\frac{-6PQ_\Phi}{f_a}$$

Dark Axion Portal (in Dark DFSZ model)

Preliminary



Below the QCD scale, the portal interaction terms are given by

$$G_{a\gamma\gamma} = \frac{e^2}{8\pi^2}\frac{-6PQ_\Phi}{f_a}\left[\frac{8}{3} - \frac{2}{3}\frac{4+z}{1+z}\right]$$

$$G_{a\gamma\gamma'} \simeq 0 + \varepsilon G_{a\gamma\gamma}$$

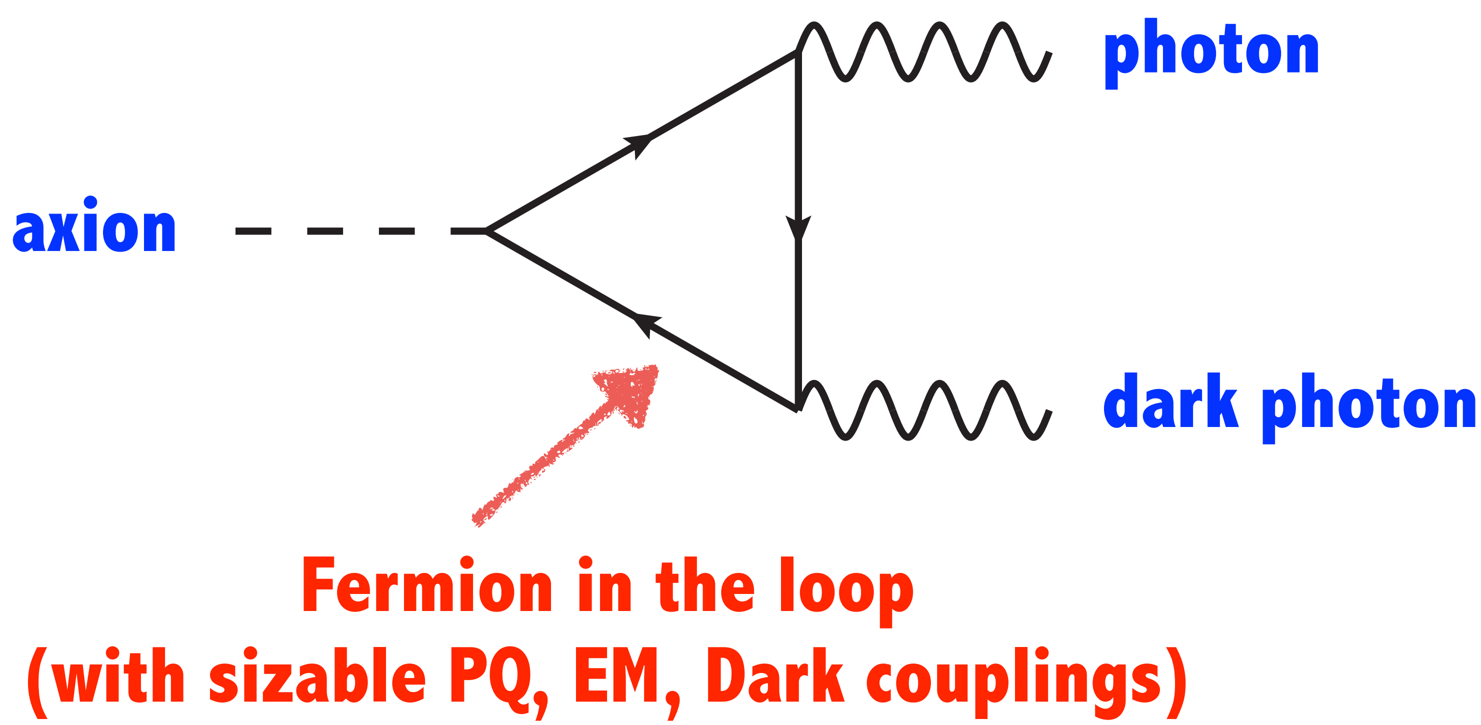
$$G_{a\gamma'\gamma'} \simeq 0 + 2\varepsilon G_{a\gamma\gamma'}$$

There are only simple (vector portal. ε) × (axion portal. $G_{a\gamma\gamma}$) parts since there are no fermions in the triangle charged under the dark gauge symmetry.
Dark Axion Portal couplings are much smaller than the Axion Portal coupling.

$G_{a\gamma\gamma} >> G_{a\gamma\gamma'}$, $G_{a\gamma'\gamma'}$

It depends on the Fermions in the triangle

In order to have a sizable Dark Axion Portal coupling $G_{a\gamma\gamma'}$, we need a fermion in the triangle-loop that have sizable couplings of $U(1)_{PQ}$, $U(1)_{EM}$, $U(1)_{Dark}$ symmetries.



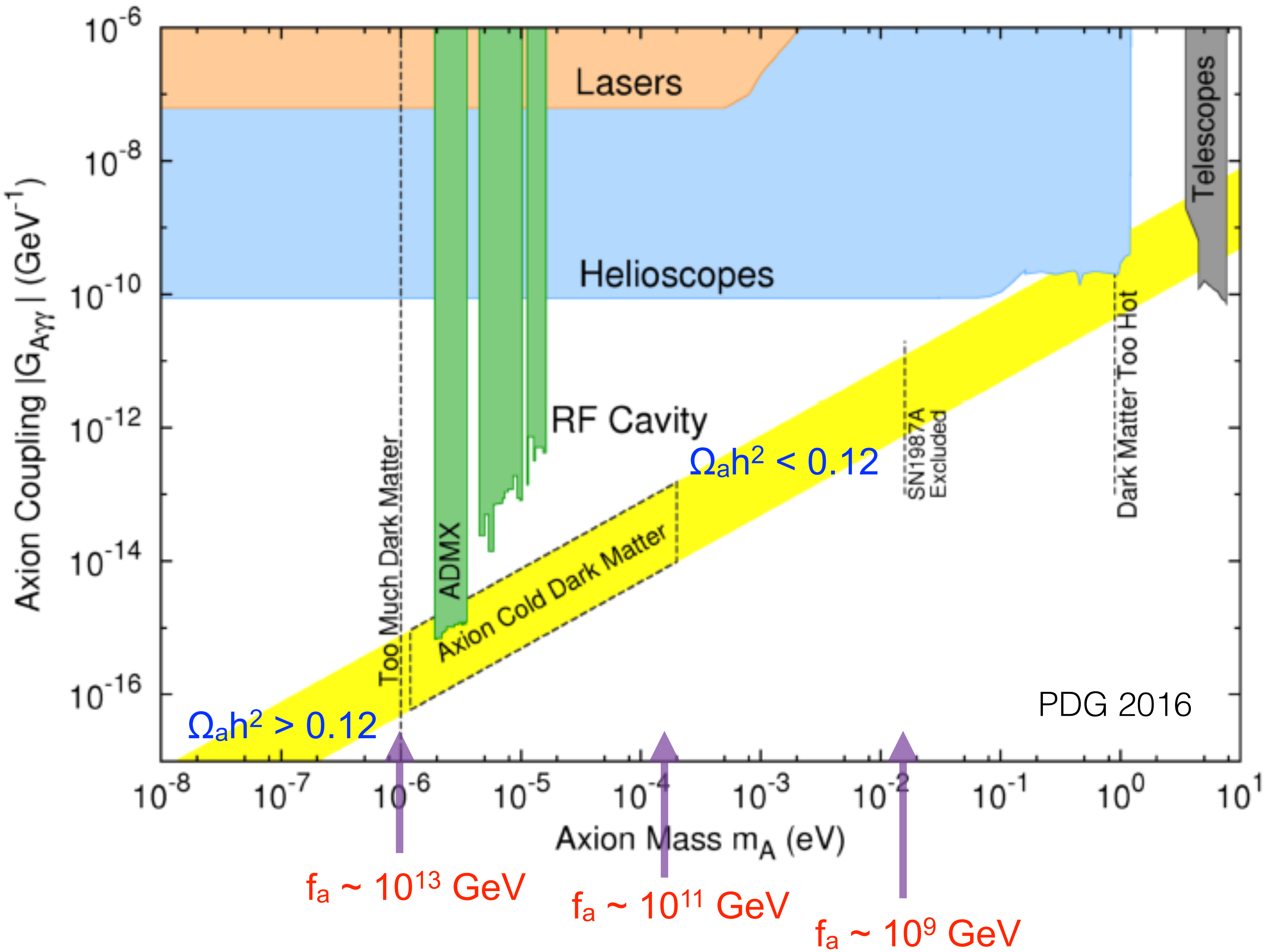
Cf. Note a similarity with the protophobic gauge boson (Z' — π — γ), suggested to explain the 17 MeV ^{8}Be anomaly. Feng et al (PRL 2016)

[See J Feng's talk]

Implication of Dark KSVZ

(Dark photon production in the early universe)

Current constraints on Axion, ALP



(Relic density deficit for $f_a < 10^{11}$ GeV)

We address issue of the relic density deficit of the axion DM, by compensating it with the <u>keV-MeV scale dark photon DM</u>.

Axion + Dark Photon dark matters

For definiteness, we assume ε ≃ 0 in order to avoid additional ɣ' production channels (f fbar → ɣ ɣ' , etc) and constraints with the kinetic mixing.
(We also assume no Higgs portal mixing, and ψ is too heavy ($m_\psi \approx f_a$) to avoid other dark photon production channel.)

Depending on the ψ charge, the leading production channel is determined.

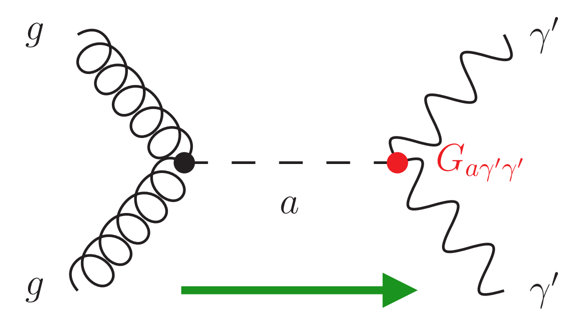
case (i) e' = 0.1 , D_ψ = 3 , Q_ψ = 0 (electrically neutral)

$$G_{a\gamma\gamma} = 0$$

$$G_{a\gamma\gamma'} = 0$$

$$G_{a\gamma'\gamma'} \simeq 10^{-1}/f_a$$

Dominant channel = Axion-mediation



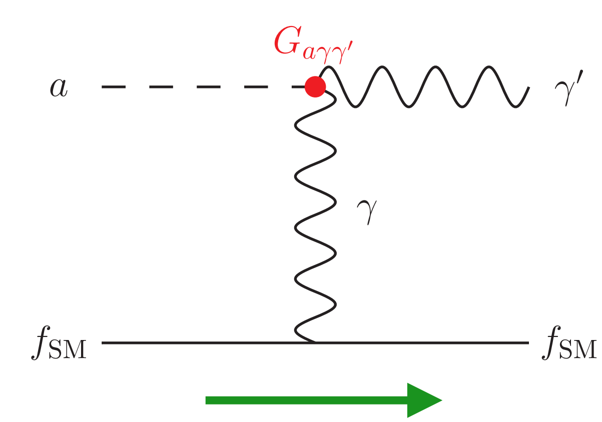
case (ii) e' = 0.1 , D_ψ = 3 , Q_ψ = -1/3 (electrically charged)

$$G_{a\gamma\gamma} \simeq 10^{-2}/f_a$$

$$G_{a\gamma\gamma'} \simeq -10^{-2}/f_a$$

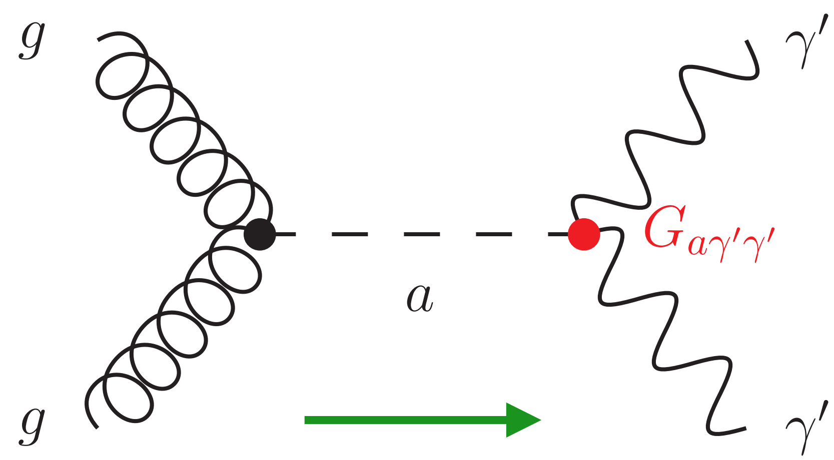
$$G_{a\gamma'\gamma'} \simeq 10^{-1}/f_a$$

Dominant channel = Dark Primakoff effect



We will give an illustration for each case.

Case (i) Axion-mediated production ($G_{a\gamma'\gamma'}$) for $Q_\psi = 0$



The keV-MeV scale dark photon is produced through the axion in the Dark KSVZ.
(non-thermal production through feeble interaction)

$$\frac{dn_{\gamma'}}{dt} + 3Hn_{\gamma'} = C[n_{\gamma'}]$$

Boltzmann equation for the γ' DM

$$C[n_{\gamma'}] \simeq \frac{48}{\pi^4} G_{agg}^2 G_{a\gamma'\gamma'}^2 T^8$$

non-renormalizable couplings

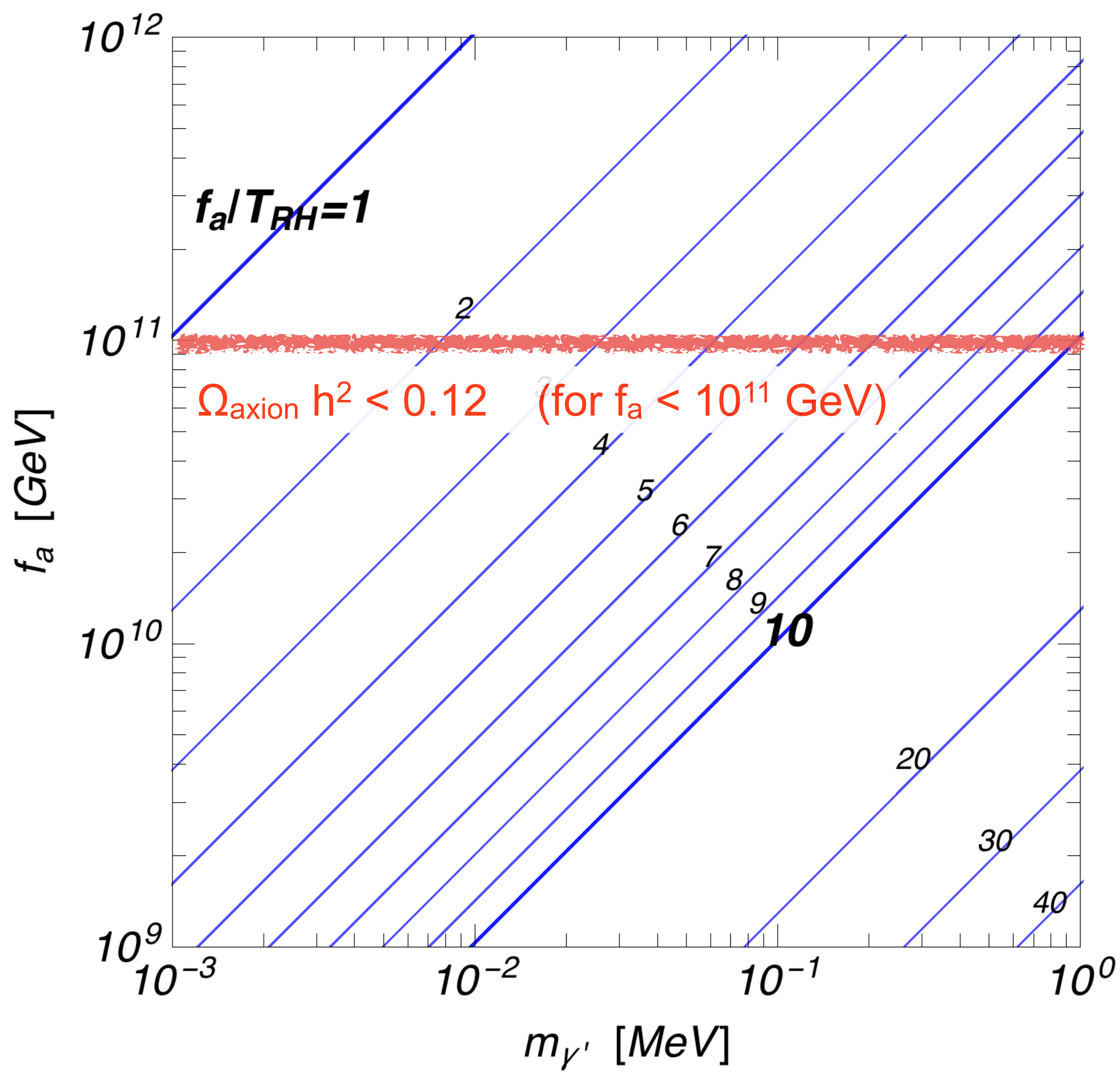
$$Y_{\gamma'}(T=0) = \int_{T_{\rm RH}}^{0} dT \frac{dY_{\gamma'}}{dT} \qquad \text{with} \quad Y_{\gamma'} \equiv n_{\gamma'}/S$$

$$\Omega_{\gamma'} h^2 = \frac{S_0 Y_{\gamma'}^0}{\rho_c} m_{\gamma'} h^2 \simeq 0.12 \times \left[\frac{e' D_\psi}{0.3}\right]^4 \left[\frac{10^2}{g_*}\right]^{\frac{3}{2}} \left[\frac{m_{\gamma'}}{10\,\text{keV}}\right] \left[\frac{5\,T_{\rm RH}}{f_a}\right]^3 \left[\frac{10^{10}\,\text{GeV}}{f_a}\right]$$

(Dark photon relic density)

with $T_{\rm RH} < (10^{10}\,\text{GeV}) \times \left[\frac{e' D_\psi}{0.3}\right]^{-\frac{4}{3}} \left[\frac{g_*}{10^2}\right]^{\frac{1}{6}} \left[\frac{f_a}{10^{10}\,\text{GeV}}\right]^{\frac{4}{3}}$ from the condition $\Gamma_{\gamma'} < H$ at $T_{\rm RH}$ with $\Gamma_{\gamma'} \equiv C[n_{\gamma'}]/n_{\gamma'}^{\rm eq}$

Case (i) Axion-mediated production ($G_{a\gamma'\gamma'}$) for $Q_\psi = 0$



Blue curves:

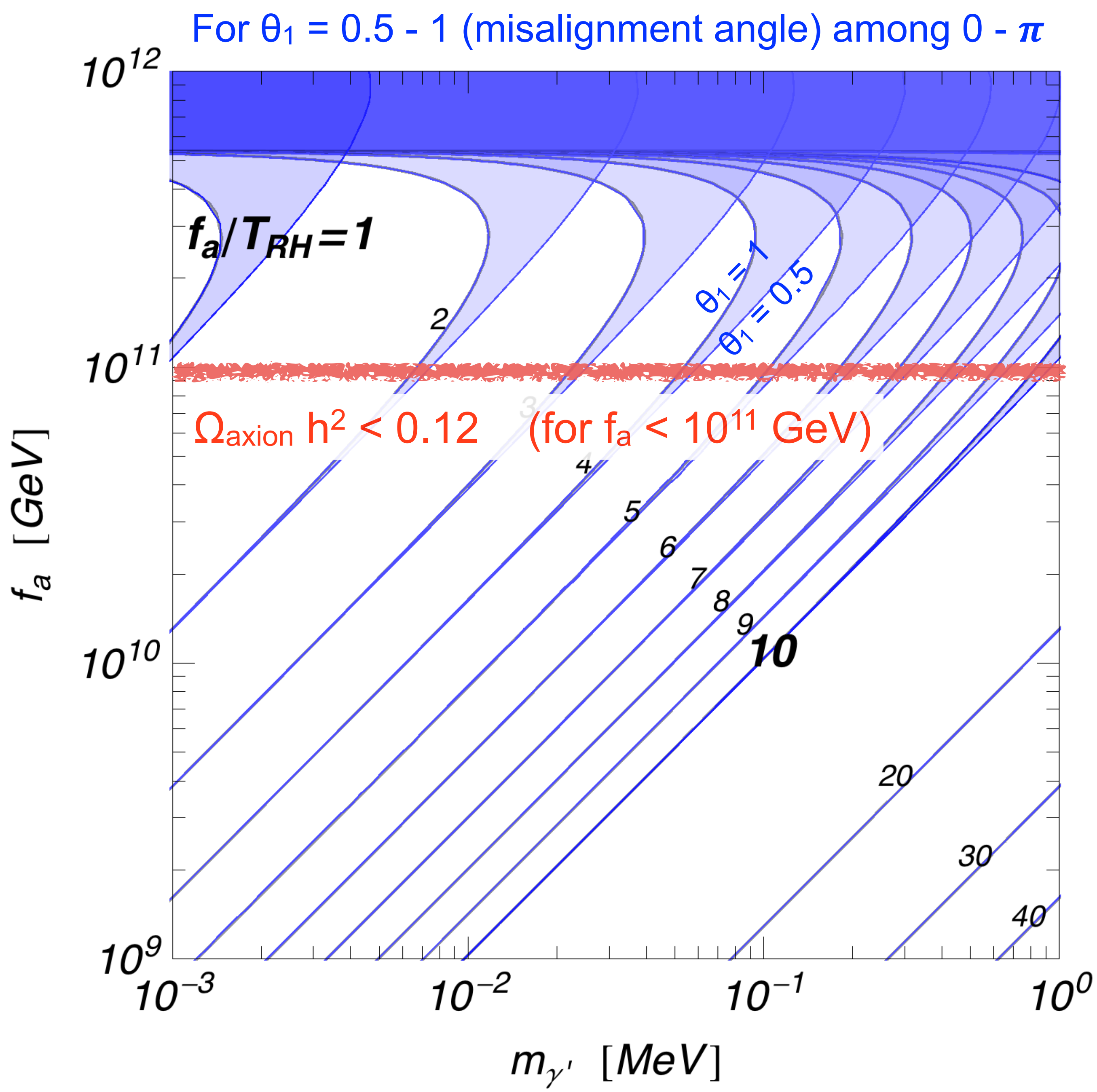
$\Omega_{\text{dark photon}}\, h^2 = 0.12$

for e' = 0.1, $D_\psi = 3$, $Q_\psi = 0$ in Dark KSVZ model
(taking ε = 0, g* = 100)

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

Axion alone is hard to explain the DM relic density for $f_a < 10^{11}$ GeV.
Dark KSVZ model naturally provides Axion + Dark photon DMs that can explain it.

Case (i) Axion-mediated production ($G_{a\gamma'\gamma'}$) for $Q_\psi = 0$



Blue curves:

$(\Omega_{\text{dark photon}} + \Omega_{\text{axion}})\, h^2 = 0.12$

for e' = 0.1, $D_\psi = 3$, $Q_\psi = 0$ in Dark KSVZ model (taking ε = 0, g* = 100)

$$\Omega_a = 0.3796ABC\left(\frac{\theta_1^2 F(\theta_1)}{\gamma}\right)\left(\frac{0.701}{h}\right)^2,$$

where $A=(m_u m_d m_s/3\times 6\times 103\ \text{MeV}^3)^{-0.092}$, $B=(F_a/10^{12}\ \text{GeV})^{1.184-0.010x}$ with $x=(\Lambda_{\text{QCD}}/380\ \text{MeV})-1$, and $C=(\Lambda_{\text{QCD}}/380\ \text{MeV})^{-0.733}$.

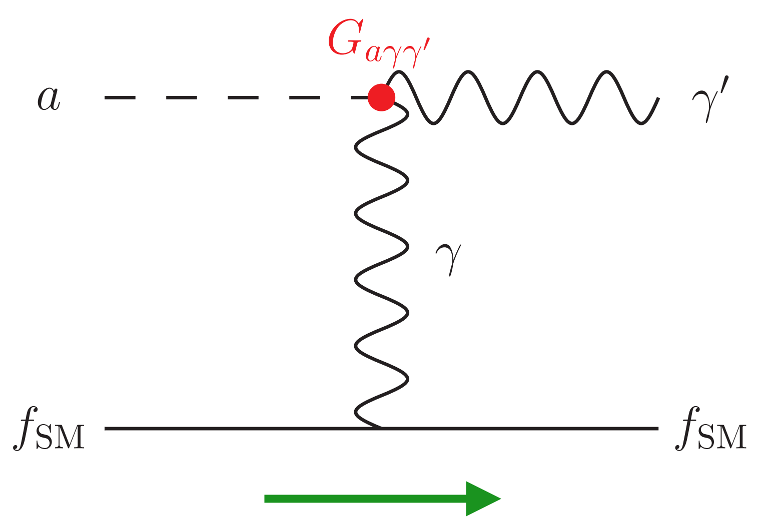
Bae, Huh, Kim (2008)

$$\Omega_{\gamma'} h^2 \simeq 0.12 \times \left[\frac{e' D_\psi}{0.3}\right]^4 \left[\frac{10^2}{g_*}\right]^{\frac{3}{2}} \left[\frac{m_{\gamma'}}{10\,\text{keV}}\right] \left[\frac{5\,T_{\text{RH}}}{f_a}\right]^3 \left[\frac{10^{10}\,\text{GeV}}{f_a}\right]$$

Axion alone is hard to explain the DM relic density for $f_a < 10^{11}$ GeV.
Dark KSVZ model naturally provides Axion + Dark photon DMs that can explain it.

Case (ii) Dark Primakoff effect ($G_{a\gamma\gamma'}$) for $Q_\psi \neq 0$

Preliminary



The keV-MeV scale dark photon is produced using the axion in thermal bath (gg ⟷ ga, etc).

(non-thermal production through feeble interaction)

$$T_d(\text{axion}) \approx 10^5\ \text{GeV}\left(\frac{f_a}{10^{10}\ \text{GeV}}\right)^2$$

Salvio, Strumia, Xue (2014)

$$\frac{dn_{\gamma'}}{dt} + 3Hn_{\gamma'} = C[n_{\gamma'}]$$

Boltzmann equation for the γ' DM

$$C[n_{\gamma'}] \simeq \Big(\sum_f g_f Q_f^2\Big)\frac{e^2 G^2_{a\gamma\gamma'}}{8\pi^5}T^6\left(\log\frac{T^2}{m_\gamma^2} + O(1)\right)$$

non-renormalizable couplings

taking plasma mass $m_\gamma \sim eT$

$$Y_{\gamma'}(T=0) = \int_{T_{\rm RH}}^{0} dT\,\frac{dY_{\gamma'}}{dT} \qquad \text{with}\quad Y_{\gamma'} \equiv n_{\gamma'}/S$$

$$\Omega_{\gamma'}h^2 \simeq 0.12\times\left[\frac{\sum_f g_f Q_f^2}{32}\right]\left[\frac{e' D_\psi}{0.3}\right]^2\left[\frac{Q_\psi}{-1/3}\right]^2\left[\frac{10^2}{g_*}\right]^{\frac{3}{2}}\left[\frac{m_{\gamma'}}{10\,\text{keV}}\right]\left[\frac{10^{10}\ \text{GeV}}{f_a}\right]\left[\frac{10^3}{f_a/T_{\rm RH}}\right]$$

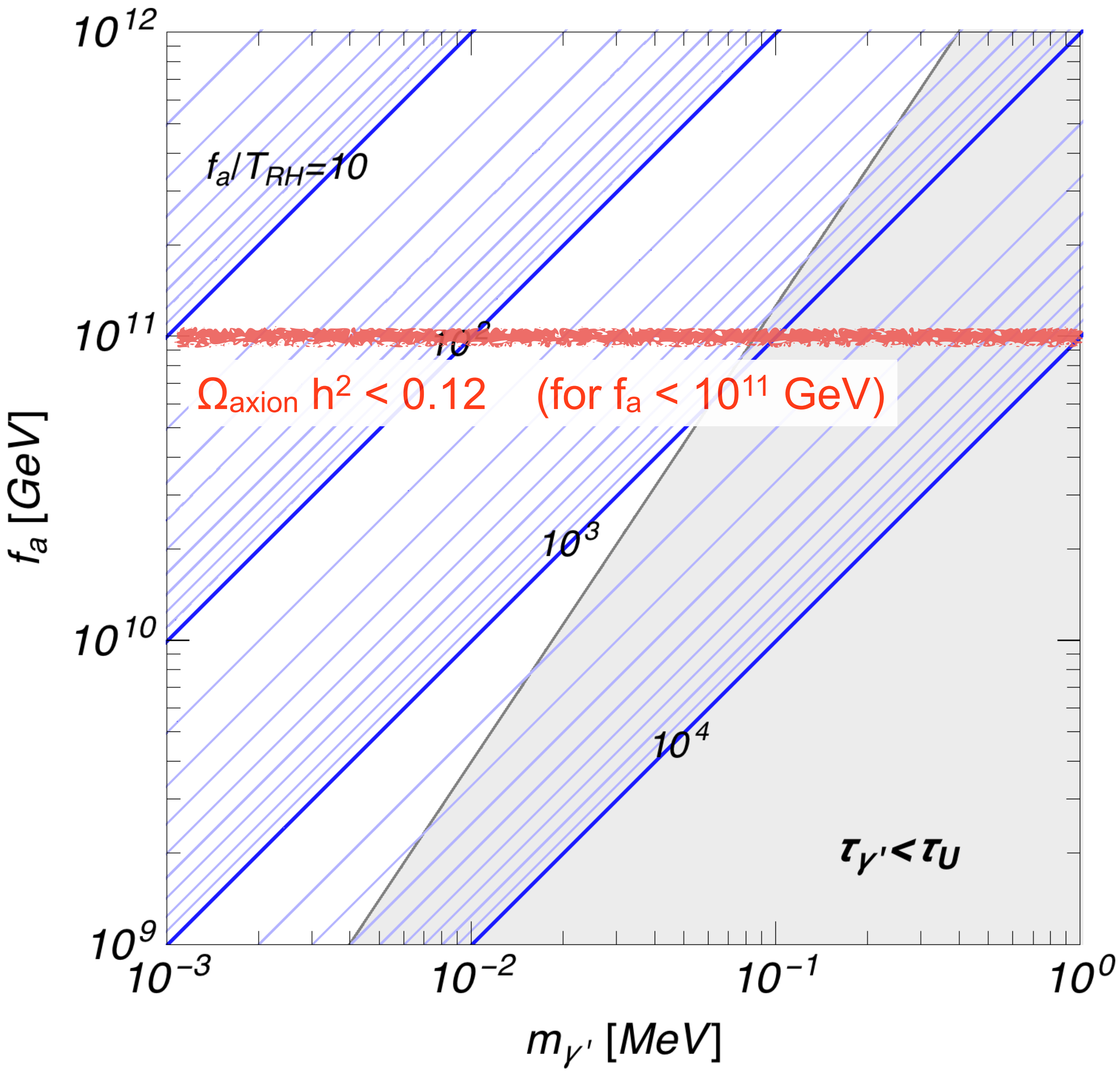
(Dark photon relic density)

with $T_{\rm RH} < (3\times 10^8\,\text{GeV})\times\left[\frac{e' D_\psi}{0.3}\right]^{-2}\left[\frac{g_*}{10^2}\right]^{\frac{1}{2}}\left[\frac{f_a}{10^{10}\,\text{GeV}}\right]^2$ from the condition $\Gamma_{\gamma'} < H$ at $T_{\rm RH}$

with $\Gamma_{\gamma'} \equiv C[n_{\gamma'}]/n^{\rm eq}_{\gamma'}$

Case (ii) Dark Primakoff effect ($G_{a\gamma\gamma'}$) for $Q_\psi \neq 0$

Preliminary



Blue curves:

$\Omega_{\text{dark photon}}\, h^2 = 0.12$

for e' = 0.1, D_ψ = 3, Q_ψ = -1/3 in Dark KSVZ model
(taking ε = 0, g* = 100)

γ' decay: γ' → a γ (through $G_{a\gamma\gamma'}$ coupling)

X-ray constraint/implication is not considered yet.

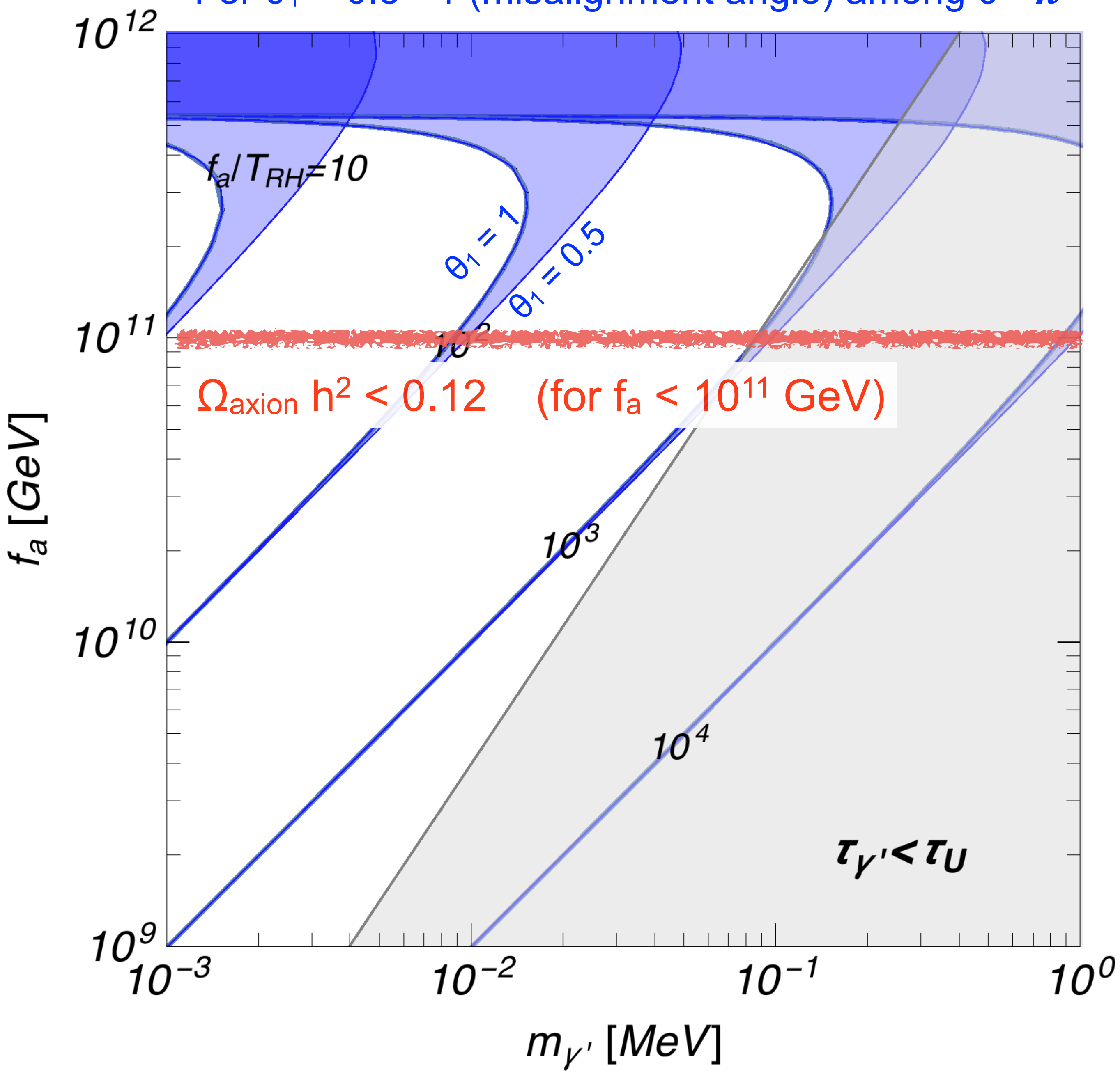
$$\Omega_{\gamma'} h^2 \simeq 0.12 \times \left[\frac{\sum_f g_f Q_f^2}{32}\right]\left[\frac{e' D_\psi}{0.3}\right]^2\left[\frac{Q_\psi}{-1/3}\right]^2\left[\frac{10^2}{g_*}\right]^{\frac{3}{2}}\left[\frac{m_{\gamma'}}{10\,\text{keV}}\right]\left[\frac{10^{10}\,\text{GeV}}{f_a}\right]\left[\frac{10^3}{f_a/T_{\text{RH}}}\right]$$

Axion alone is hard to explain the DM relic density for $f_a < 10^{11}$ GeV.
Dark KSVZ model naturally provides Axion + Dark photon DMs that can explain it.

Case (ii) Dark Primakoff effect ($G_{a\gamma\gamma'}$) for $Q_\psi \neq 0$

Preliminary

For θ_1 = 0.5 - 1 (misalignment angle) among 0 - π



Blue curves:

$(\Omega_{\text{dark photon}} + \Omega_{\text{axion}})\, h^2 = 0.12$

for e' = 0.1, D_ψ = 3, Q_ψ = -1/3 in Dark KSVZ model (taking ε = 0, g* = 100)

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Dark gauge boson for the Relaxion physics

arXiv.org > hep-ph > arXiv:1611.08569

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High Energy Physics – Phenomenology

Dynamics of cosmological relaxation after reheating

Kiwoon Choi, Hyungjin Kim, Toyokazu Sekiguchi

(Submitted on 25 Nov 2016)

We examine if the cosmological relaxation mechanism, which was proposed recently as a new solution to the hierarchy problem, can be compatible with high reheating temperature well above the weak scale. As the barrier potential disappears at high temperature, the relaxion rolls down further after the reheating, which may ruin the successful implementation of the relaxation mechanism. It is noted that if the relaxion is coupled to a dark gauge boson, the new frictional force arising from dark gauge boson production can efficiently slow down the relaxion motion, which allows the relaxion to be stabilized after the electroweak phase transition for a wide range of model parameters, while satisfying the known observational constraints.

Comments: 9 pages, 4 figures
Subjects: **High Energy Physics – Phenomenology (hep-ph)**
Report number: CTPU-16-33
Cite as: **arXiv:1611.08569 [hep-ph]**
(or **arXiv:1611.08569v1 [hep-ph]** for this version)

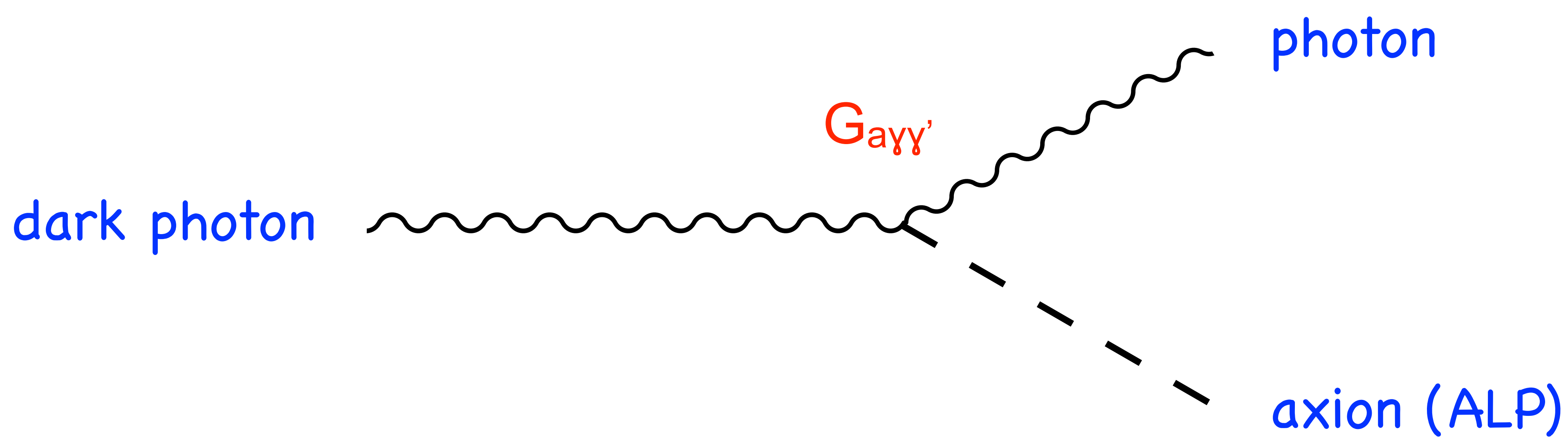
Testing Dark Axion Portal in the labs

Under investigation

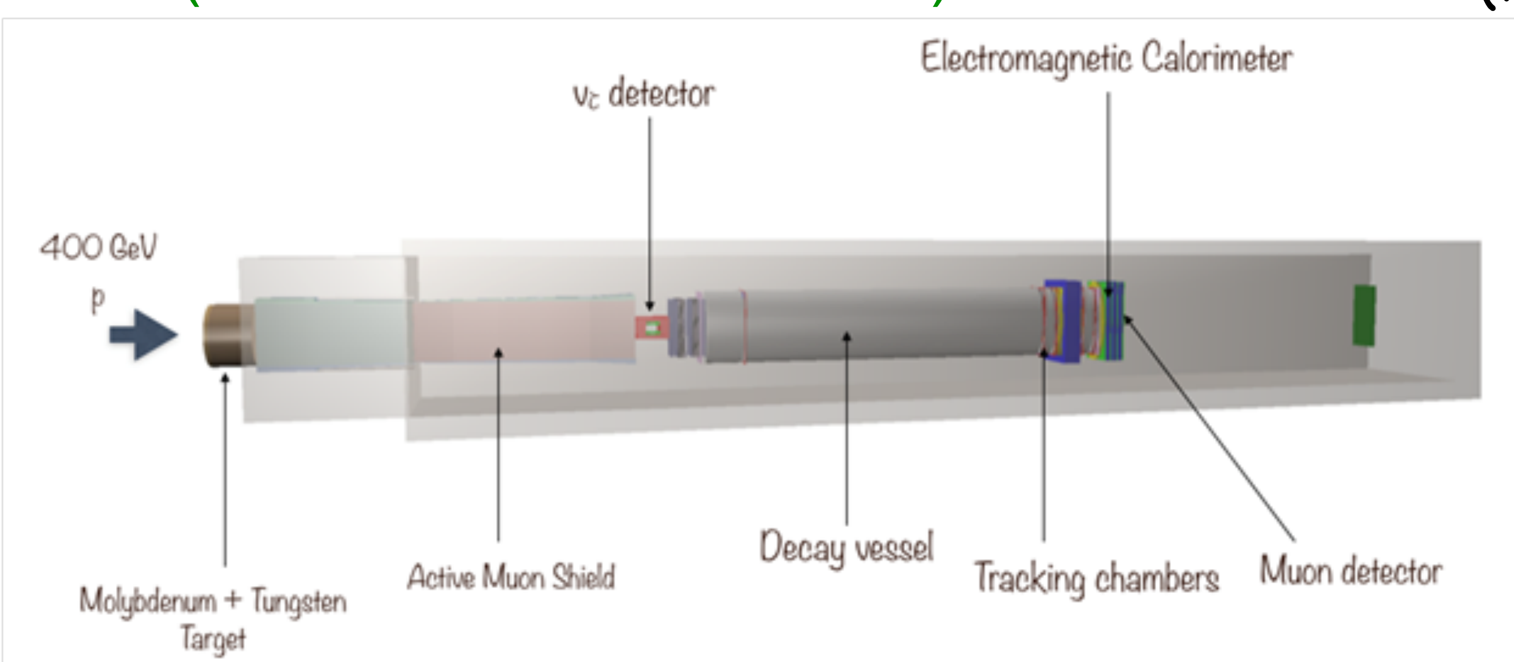
Detection

Under investigation

(i) decay example



SHiP implications of $\gamma' \rightarrow \gamma + ALP$, $ALP \rightarrow \gamma + \gamma'$ are under investigation (with P. deNiverville et al). (for MeV-GeV scale particles)



SHiP: designed to search for long-lived particles

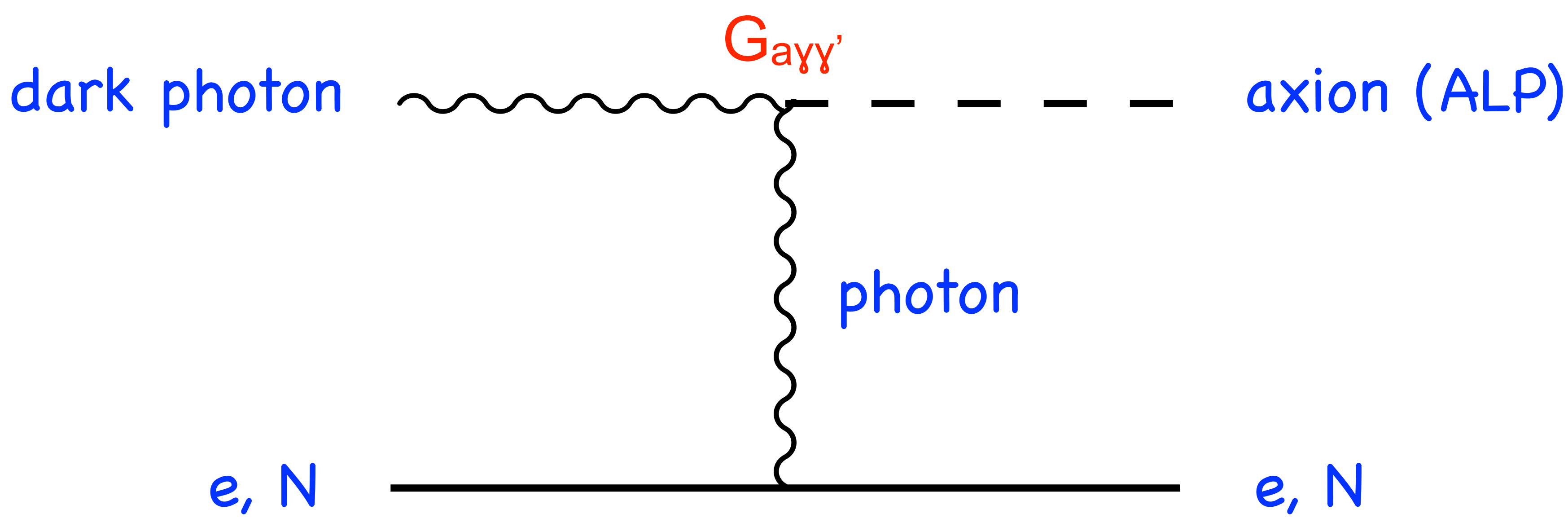
(image from Neutel11)

Detection

Under investigation

(ii) scattering example

(Dark Primakoff effect)



(Ex) Low-Q^2 electron recoil (dark photon DM direct detection experiment)

Summary

Summary

Dark sector can be investigated through portals.

We introduced "Dark Axion Portal" (a-γ-γ' , a-γ'-γ') that can establish a new connection to the dark sector.

They are not from a product of the existing portals (say, $G_{a\gamma\gamma'} \neq \varepsilon G_{a\gamma\gamma}$), but genuinely new couplings from the fermions carrying the $U(1)_{Dark}$ charges, and they can be much larger than naive expectations.

We constructed Dark KSVZ model as a concrete example that realizes the Dark Axion Portal. The new model provides new γ' production mechanisms in the early universe. It can address the axion relic density deficit problem for $f_a < 10^{11}$ GeV.

Works in progress include

(i) to construct more general models with the heavier Z' and ALP

(ii) to constrain $G_{a\gamma\gamma'}$, $G_{a\gamma'\gamma'}$ in a wide parameter space from the existing data

(iii) to develop new ways to test $G_{a\gamma\gamma'}$, $G_{a\gamma'\gamma'}$ (new experiments for a, γ' search)

Concluding Remark

Axion physics (a)

Dark gauge boson physics (γ')

Connecting Two Dots

Axion physics (a)

Dark gauge boson physics (γ')

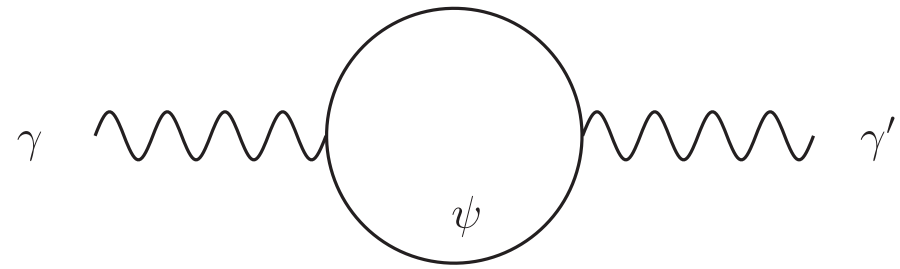
Dark Axion Portal

$G_{a\gamma\gamma'}$ $G_{a\gamma'\gamma'}$

Thank you.

Backup Slides

Loop-induced kinetic mixing



Effect of the exotic colored fermions (ψ) on the kinetic mixing (ε).

$$\varepsilon_{\text{induced}} = \frac{N_C}{6\pi^2}\left(eQ_\psi e' D_\psi\right)\log\left(\frac{\Lambda}{m_\psi}\right)$$

(**Λ** is where $\varepsilon_{\text{induced}} = 0$).

For **Λ** ~ 10^{16} GeV (typical GUT scale) and $m_\psi \sim f_a$, we get $\varepsilon_{\text{induced}} \sim O(10^{-3} - 10^{-2})$ for e' = e, $Q_\psi \sim D_\psi \sim 1$. ➞ On its own, inconsistent with the experimental constraints for keV-MeV scale dark photon DM.

This can be addressed either by

(i) assuming a cancellation between the $\varepsilon_{\text{induced}}$ and and the short-distance (UV) contribution to ε (taking fine-tuning).

(ii) introducing more particle that couple to ɣ and ɣ' to change the loop-induced contribution (increasing model complexity).

$$\varepsilon_{\text{induced}} = \frac{eQ_\psi e' D_\psi}{6\pi^2}\log\left(\frac{m'_{12}}{m_{12}}\right)$$ Holdom (1986)