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Impacts of ALP on dark photon searches

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Where is the Physics Beyond the SM?

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$\int \mathcal{L}\, dt$ = (3.6 – 139) fb^{-1} $\sqrt{s}$ = 13 TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Limit	Reference
Extra dimen.	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1 – 4 j	Yes	139	M_D 11.2 TeV, $n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV, $n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	139	M_{th} 9.4 TeV, $n = 6$	1910.08447
	ADD BH multijet	–	≥3 j	–	3.6	M_{th} 9.55 TeV, $n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	139	G_{KK} mass 4.5 TeV, $k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV, $k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV, $\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥2 b, ≥3 j	Yes	36.1	KK mass 1.8 TeV, Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV	1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV	1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV	1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥1 b, ≥2 J	Yes	139	Z' mass 4.1 TeV, $\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV	1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	139	W' mass 5.0 TeV	ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass 4.4 TeV	ATLAS-CONF-2021-043
	HVT $W' \to WZ$ model B	0-2 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV, $g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\,\ell'\ell'$ model C	3 e, μ	2 j (VBF)	Yes	139	W' mass 340 GeV, $g_V c_H = 1$, $g_f = 0$	2207.03925
	HVT $Z' \to WW$ model B	1 e, μ	2 j / 1 J	Yes	139	Z' mass 3.9 TeV, $g_V = 3$	2004.14636
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV, $m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV η_{LL}^-	2006.12946
	CI $eebs$	2 e	1 b	–	139	Λ 1.8 TeV, g_* = 1	2105.13847
	CI $\mu\mu bs$	2 μ	1 b	–	139	Λ 2.0 TeV, g_* = 1	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV, $\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	–	2 j	–	139	m_{med} 3.8 TeV, g_q=0.25, g_χ=1, $m(\chi)$=10 TeV	ATL-PHYS-PUB-2022-036
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med} 376 GeV, g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	$m_{Z'}$ 3.0 TeV, $\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_a 800 GeV, $\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	2 e	≥2 j	Yes	139	LQ mass 1.8 TeV, $\beta = 1$	2006.05872
	Scalar LQ 2nd gen	2 μ	≥2 j	Yes	139	LQ mass 1.7 TeV, $\beta = 1$	2006.05872
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^u mass 1.49 TeV, $\mathcal{B}(LQ_3^u \to b\tau) = 1$	2303.01294
	Scalar LQ 3rd gen	0 e, μ	≥2 j, ≥2 b	Yes	139	LQ_3^d mass 1.24 TeV, $\mathcal{B}(LQ_3^d \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass 1.43 TeV, $\mathcal{B}(LQ_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	0 e, μ, ≥1 τ	0 – 2 j, 2 b	Yes	139	LQ_3^d mass 1.26 TeV, $\mathcal{B}(LQ_3^d \to b\nu) = 1$	2101.12527
	Vector LQ mix gen	multi-channel	≥1 j, ≥1 b	Yes	139	$LQ_3^{\tilde{V}}$ mass 2.0 TeV, $\mathcal{B}(\tilde{U}_1 \to t\mu) = 1$, Y-M coupl.	ATLAS-CONF-2022-052
	Vector LQ 3rd gen	2 e, μ, τ	≥1 b	Yes	139	$LQ_3^{\tilde{V}}$ mass 1.96 TeV, $\mathcal{B}(LQ_3^{\tilde{V}} \to b\tau) = 1$, Y-M coupl.	2303.01294
Vector-like fermions	VLQ $TT \to Zt + X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	T mass 1.46 TeV, SU(2) doublet	2210.15413
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV, SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV, $\mathcal{B}(T_{5/3} \to Wt) = 1$, $c(T_{5/3}Wt) = 1$	1807.11883
	VLQ $T \to Ht/Zt$	1 e, μ	≥1 b, ≥3 j	Yes	139	T mass 1.8 TeV, SU(2) singlet, $\kappa_T = 0.5$	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	1 e, μ	≥1 b, ≥1 j	Yes	36.1	Y mass 1.85 TeV, $\mathcal{B}(Y \to Wb) = 1$, $c_R(Wb) = 1$	1812.07343
	VLQ $B \to Hb$	0 e,μ	≥2b, ≥1j, ≥1J	–	139	B mass 2.0 TeV, SU(2) doublet, $\kappa_B = 0.3$	ATLAS-CONF-2021-018
	VLL $\tau' \to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass 898 GeV, SU(2) doublet	2303.05441
Exctd ferm.	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV, only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV, only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	139	b^* mass 3.2 TeV	1910.08447
	Excited lepton τ^*	2 τ	≥2 j	–	139	τ^* mass 4.6 TeV, $\Lambda = 4.6$ TeV	2303.09444
Other	Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139	N^0 mass 910 GeV	2202.02039
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV, $m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV, DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	139	$H^{\pm\pm}$ mass 1.08 TeV, DY production	2211.07505
	Multi-charged particles					multi-charged particle mass 1.59 TeV, DY production, $\lvert q\rvert = 5e$	ATLAS-CONF-2022-034
	M...						...10130

*Only a

†Small-

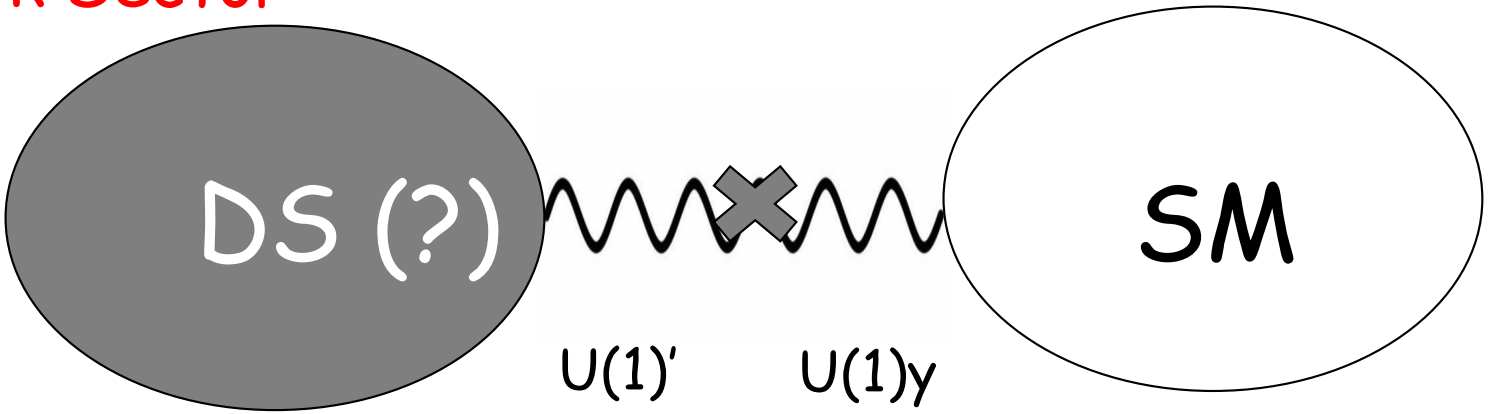
new particles are too heavy?

too light? OR/AND couplings are too small?

Tiny interactions? portals ?

Light particles? dark photon ? axion (axion-like) ?

Dark Sector



Fabbrichesi, Gabrielli, Lanfranchi, 2005.01515

messenger: vector-boson → "dark photon portal"

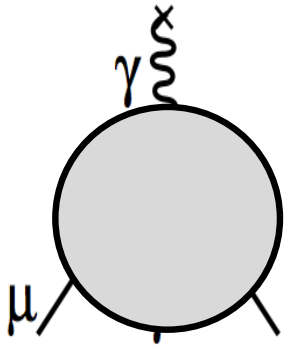
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DS} + \frac{\epsilon}{2c_W} B'_{\mu\nu} B^{\mu\nu}$$

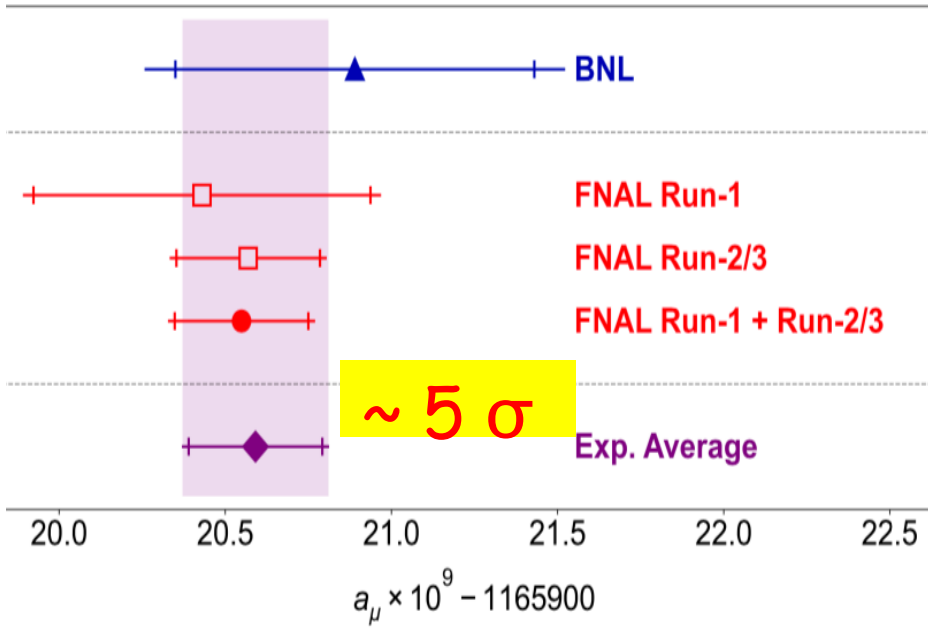
$$B_\mu \to B_\mu - \epsilon / c_W B'_\mu$$

$$B'_\mu \to B'_\mu$$

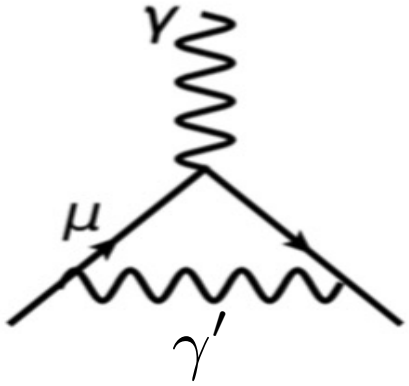
$$\mathcal{L} \supset -\varepsilon e J^\mu_{\rm EM} A'_\mu - \varepsilon \tan\theta_W \frac{m^2_{\gamma'}}{m^2_Z} g_Z J^\mu_{\rm NC} A'_\mu$$

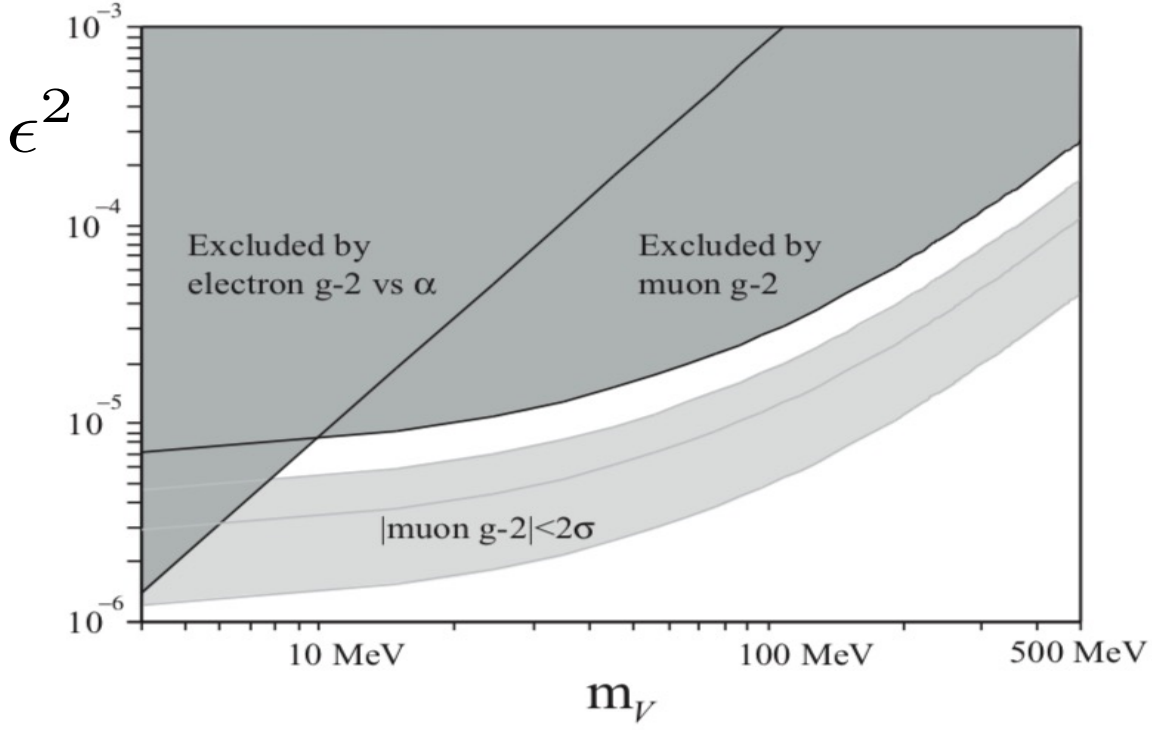
Anomalous muon g-2





$$\epsilon e J_\mu A'^\mu$$





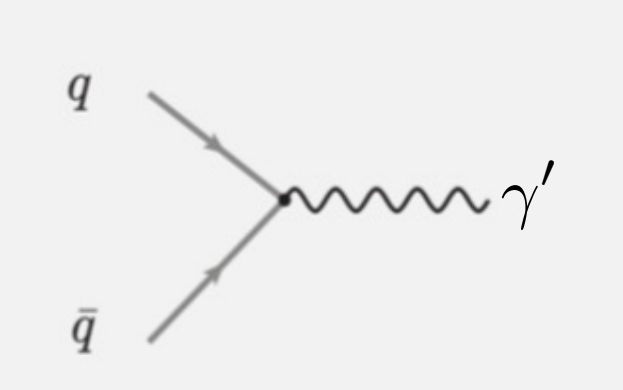
M. Pospelov, PRD 80 (2009) 095002

Dark photon search

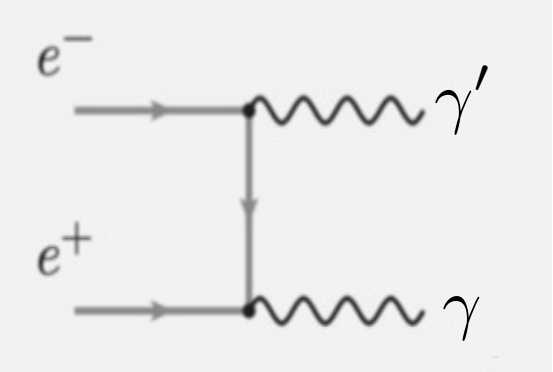
productions: $\epsilon e J_\mu A'^\mu$

Fabbrichesi, Gabrielli, Lanfranchi, 2005.01515

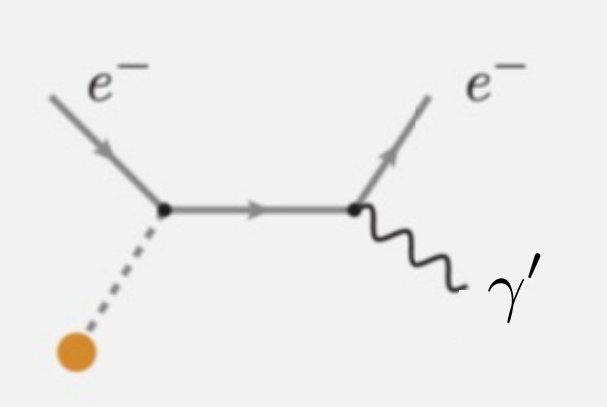
$$q\bar{q}(\text{or } e^+e^-) \to \gamma'$$



$$q\bar{q}(\text{or } e^+e^-) \to \gamma'\gamma$$

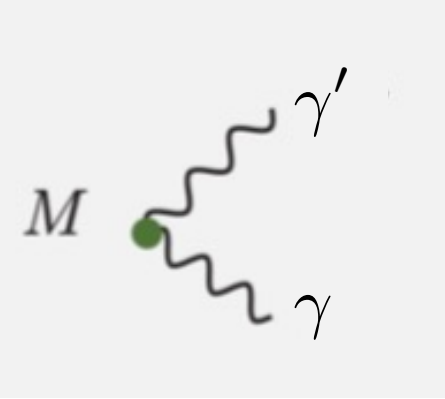


$$e^- Z \to e^- Z\gamma'$$



meson decay

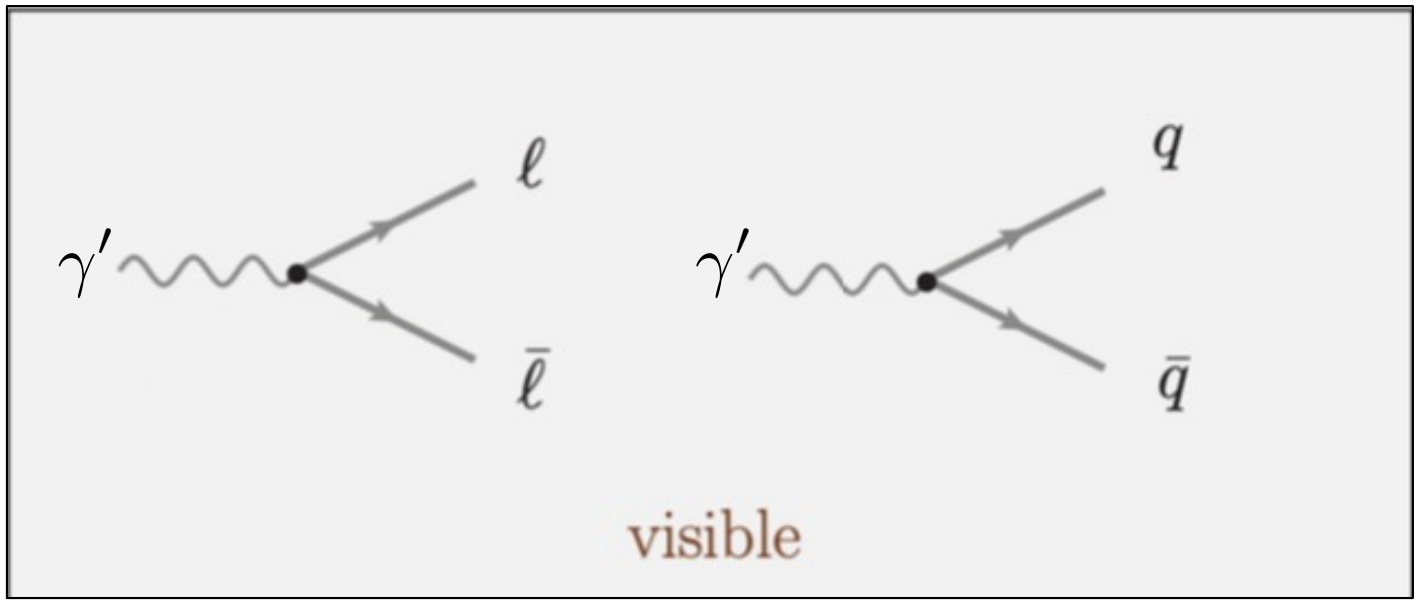
$$M \to \gamma'\gamma$$



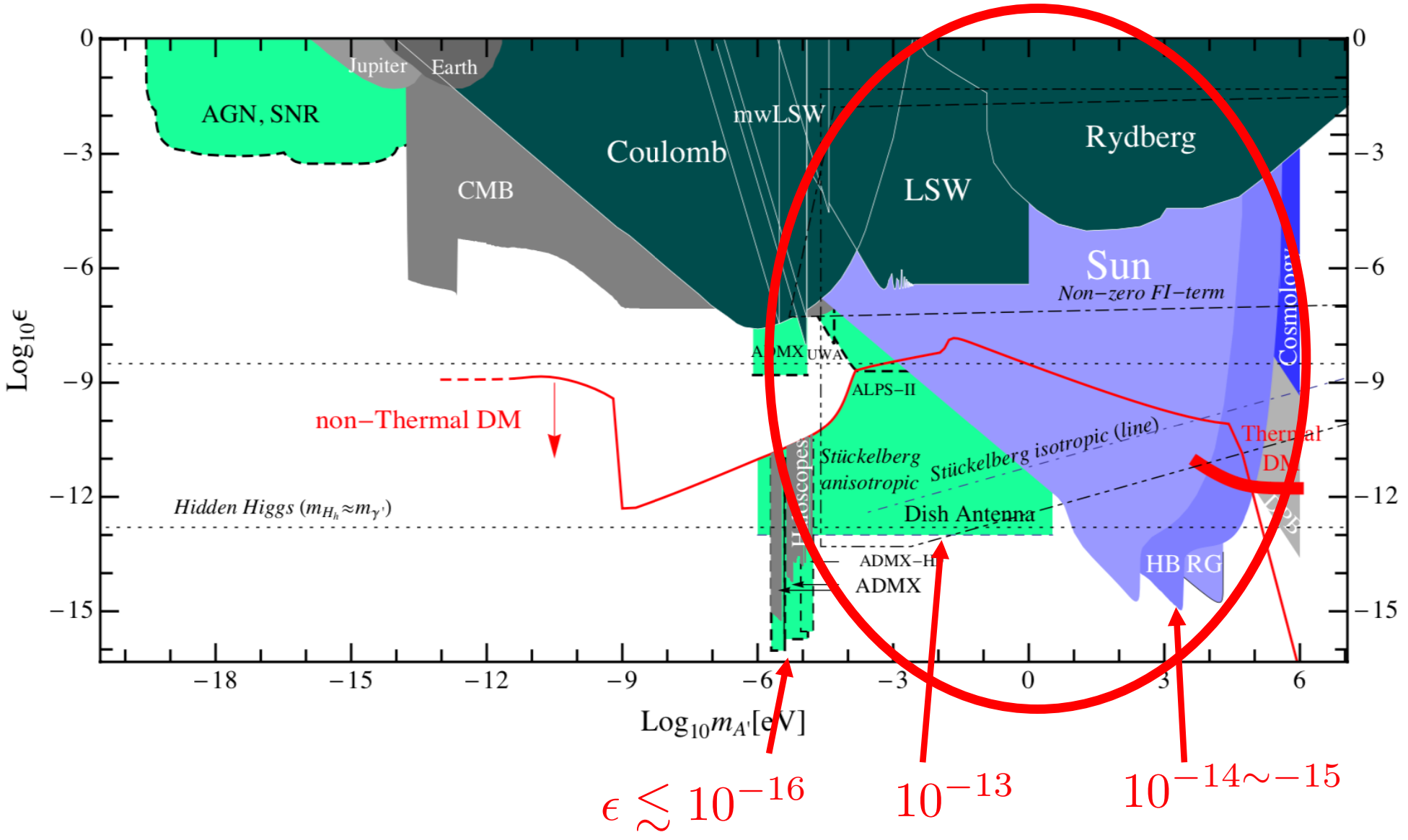
Dark photon search

Visible decays: $\epsilon e J_\mu A'^\mu$

Fabbrichesi, Gabrielli, Lanfranchi, 2005.01515



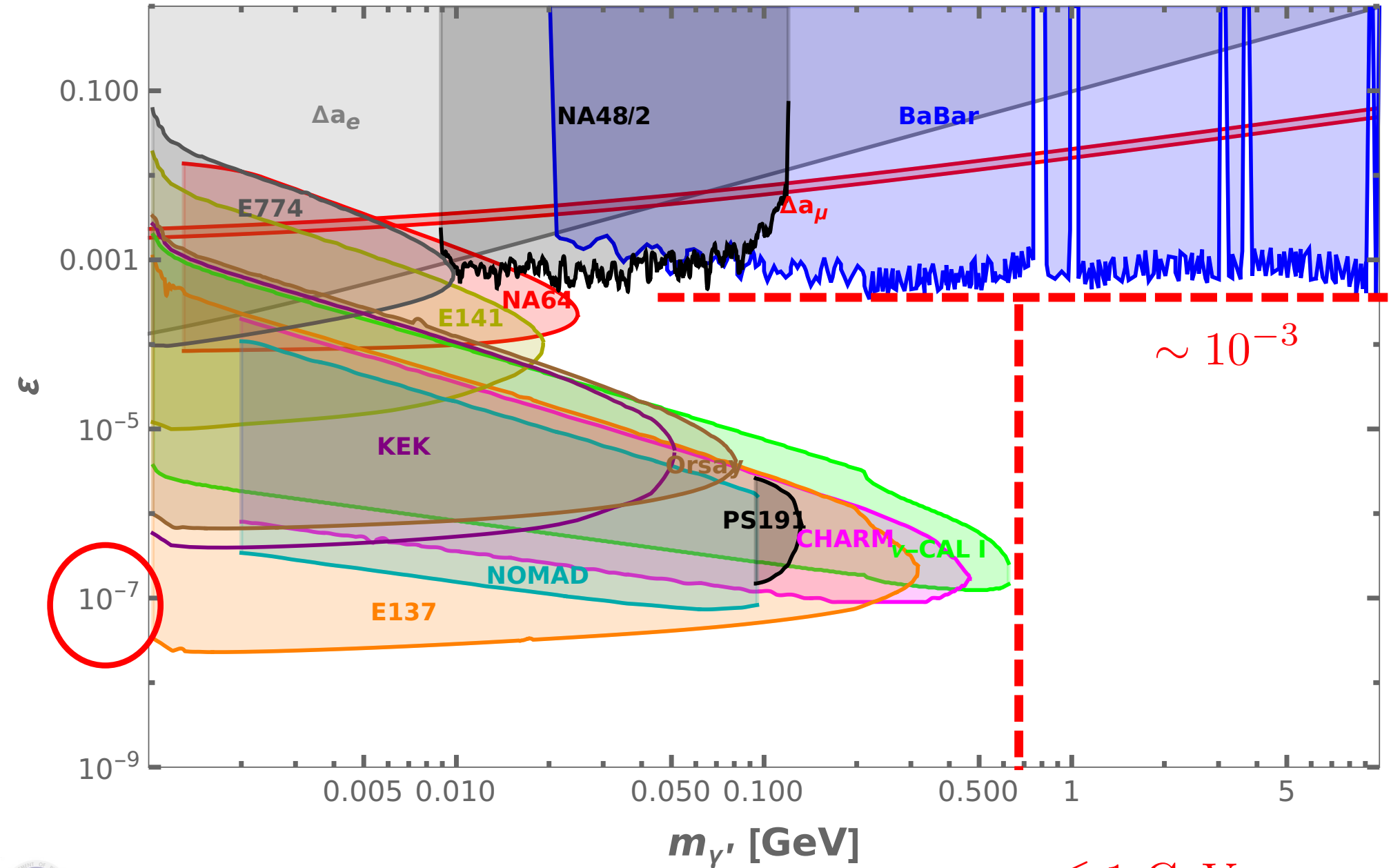
Dark photon constraints



Stringent constraints for light dark photon with mass lighter than 1 MeV

Dark photon constraints

experiment Ilten, Soreq, Williams, Xue, 1801.04847

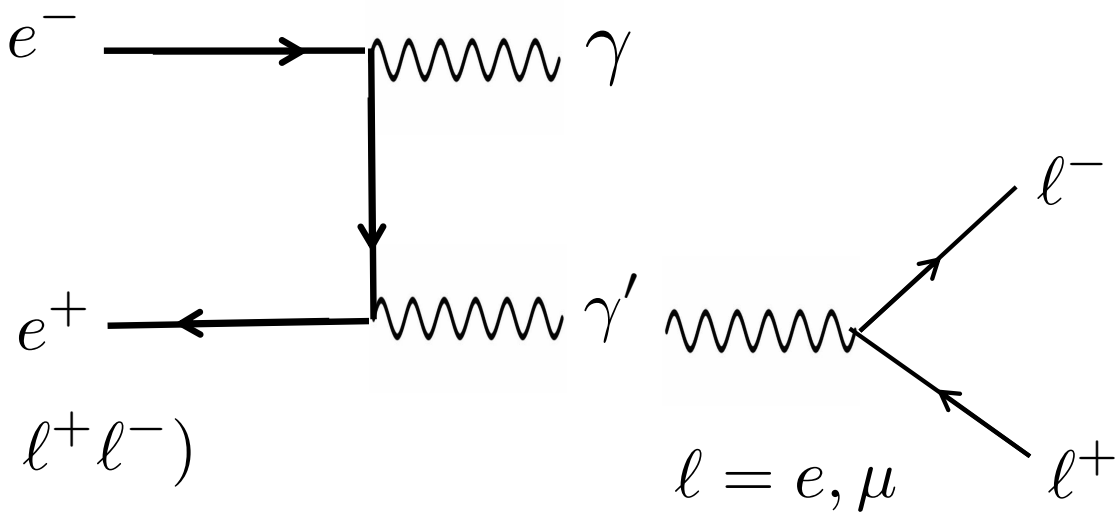


"heavy" dark photon: Stringent constraints for $m_{\gamma'} \lesssim 1$ GeV

Dark photon search

BaBar 514 fb^{-1}

m:0.02 GeV ~ 10.2 GeV

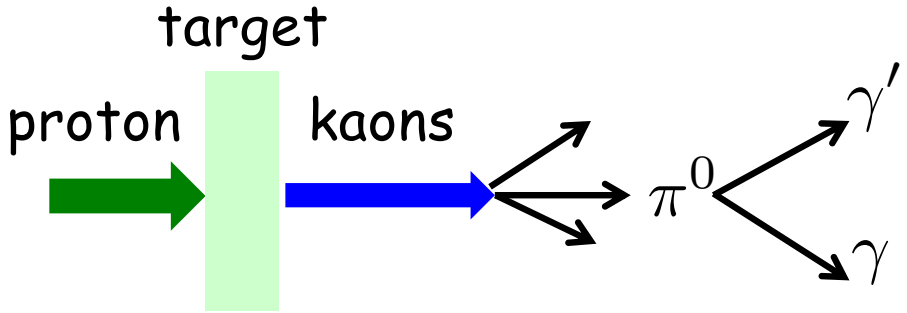


$$\sigma(e^+e^- \to \gamma\gamma') \times \mathrm{Br}(\gamma' \to \ell^+\ell^-)$$

NA48/2

$\sim 1.69 \times 10^7\ \pi^0$

m: 9 MeV ~ 70 MeV



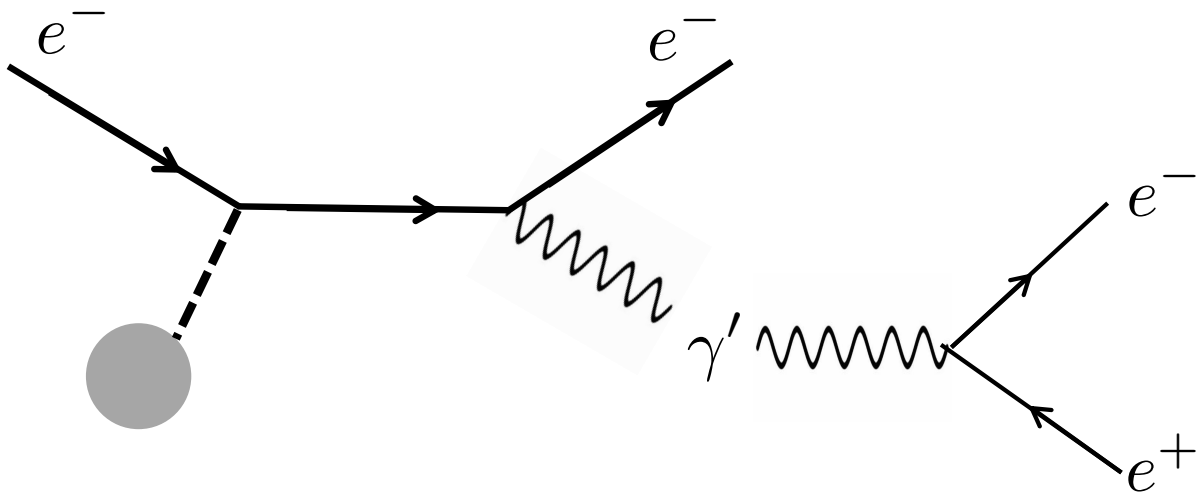
$$\mathcal{B}(\pi^0 \to \gamma A') = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathcal{B}(\pi^0 \to \gamma\gamma)$$

$$c\tau_{A'} = \hbar c/\Gamma_{A'} \approx 0.8\ \mu\mathrm{m} \times \left(\frac{10^{-6}}{\varepsilon^2}\right) \times \left(\frac{100\ \mathrm{MeV}/c^2}{m_{A'}}\right)$$

Dark photon search

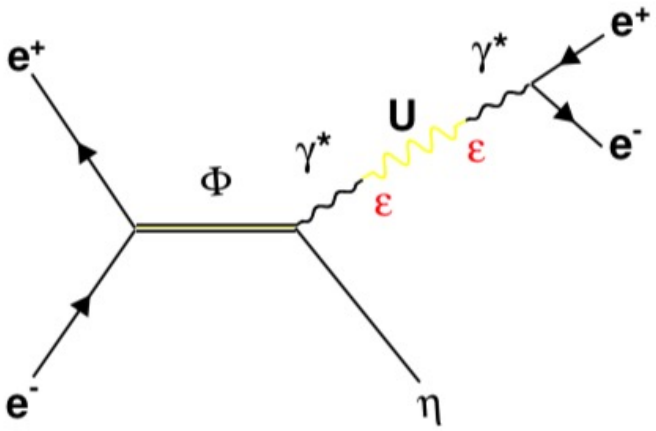
A1

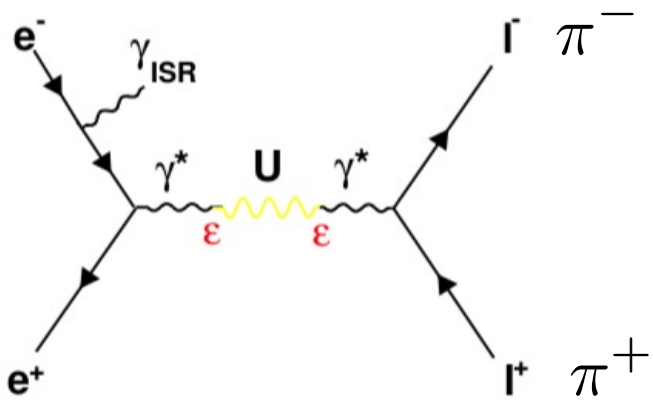
40 MeV ~ 300 MeV



KLOE

5 MeV~987 MeV

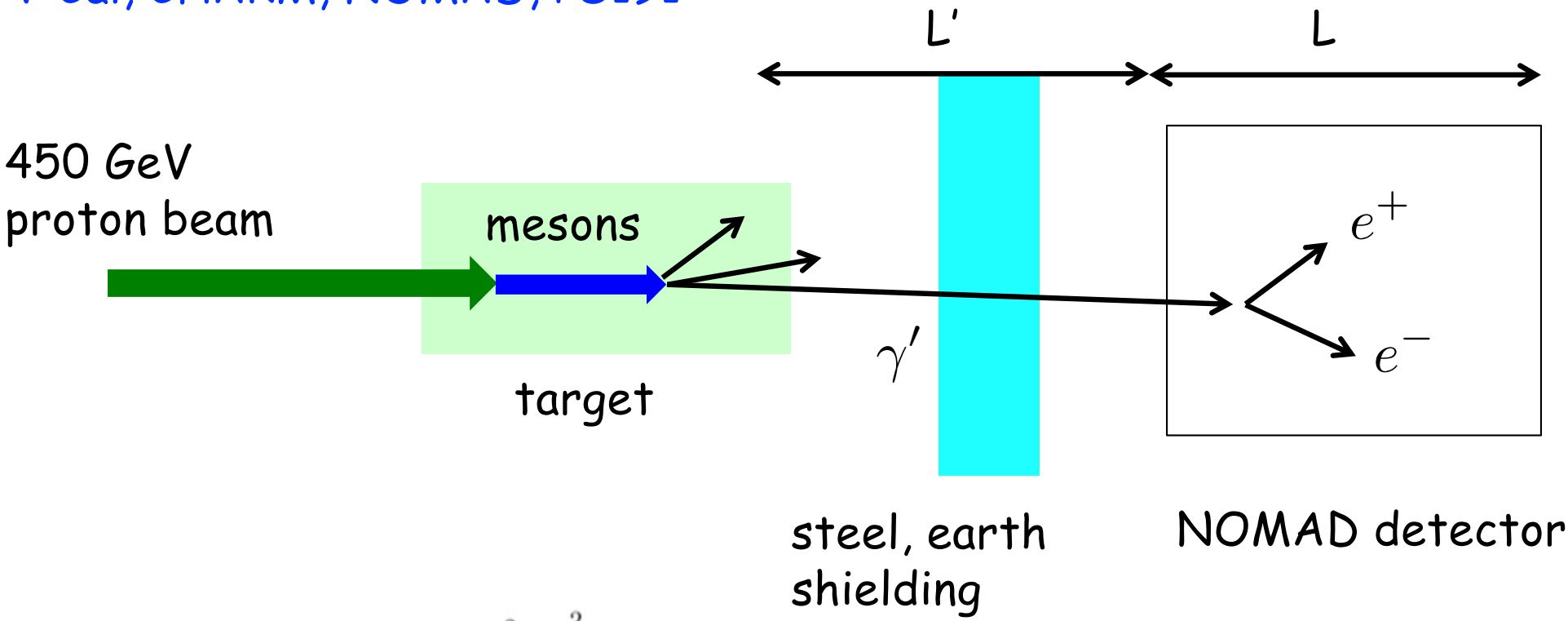




$$\sigma(\phi \to \eta U) = \epsilon^2 \, |F_{\phi\eta}(m_U^2)|^2 \, \frac{\lambda^{3/2}(m_\phi^2, m_\eta^2, m_U^2)}{\lambda^{3/2}(m_\phi^2, m_\eta^2, 0)} \, \sigma(\phi \to \eta\gamma)$$

Dark photon search

ν-Cal, CHARM, NOMAD, PS191



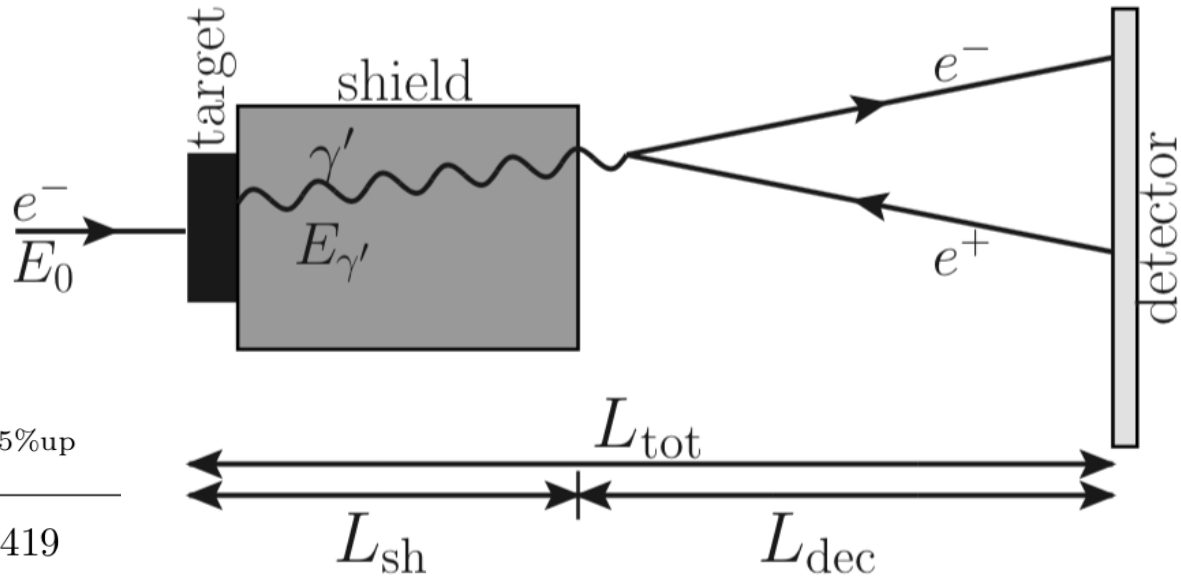
$$\sigma(pp \to \gamma' X) = 2\epsilon^2 \left(1 - \frac{m_{\gamma'}^2}{m_{\pi^0}^2}\right)^3 \mathrm{Br}(\pi^0 \to \gamma\gamma)\sigma(pp \to \pi^0 X)$$

$$N \propto N_{POT} \times \sigma(\gamma' X) \times w$$

$$w = \exp^{-\frac{L' m_{\gamma'}}{\tau_{\gamma'} p_{\gamma'}}} [1 - \exp^{-\frac{L m_{\gamma'}}{\tau_{\gamma'} p_{\gamma'}}}]$$

Dark photon search

E141, E137, E774,
KEK, Orsay

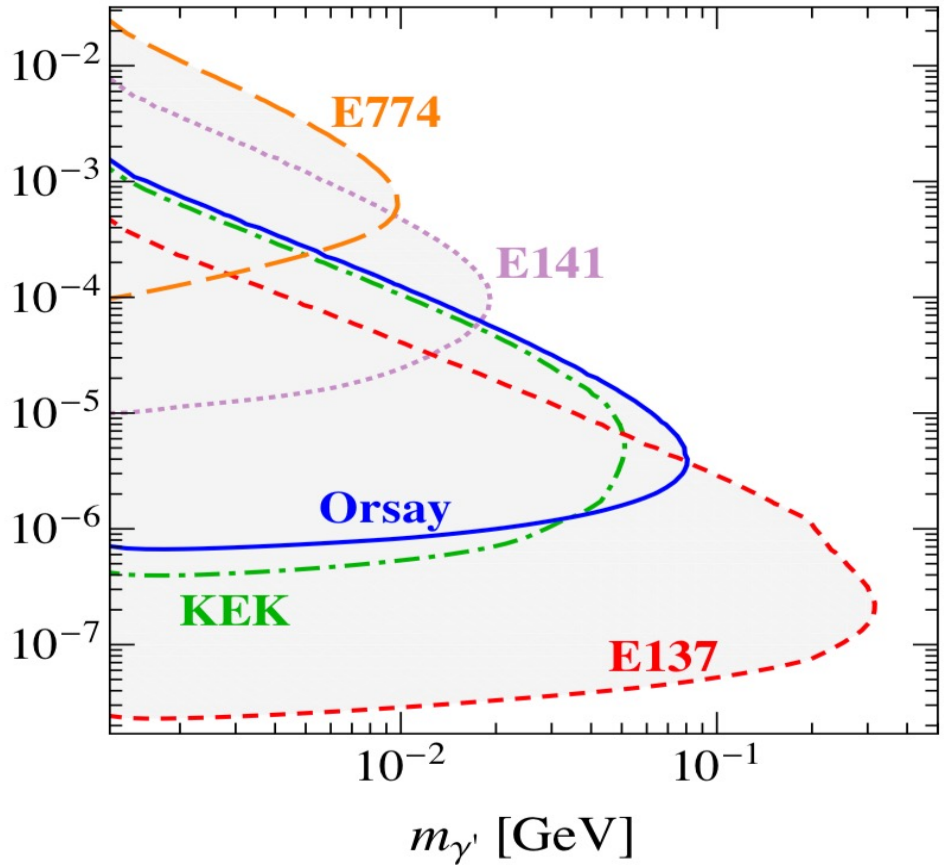


Experiment	$L_{\rm sh}$ [m]	$L_{\rm dec}$ [m]	$N_{\rm obs}$	$N_{95\%\rm up}$
E141 [47]	0.12	35	1126^{+1312}_{-1126}	3419
E137 [48]	179	204	0	3
E774 [49]	0.3	2	0^{+9}_{-0}	18
KEK [39]	2.4	2.2	0	3
Orsay [40]	1	2	0	3

$$N \simeq N_e \frac{N_0 X_0}{A} \int_{m_{\gamma'}}^{E_0 - m_e} dE_{\gamma'} \int_{E_{\gamma'}+m_e}^{E_0} dE_e \int_0^T dt \, \epsilon$$

$$\left[I_e(E_0, E_e, t) \, \frac{1}{E_e} \, \frac{d\sigma}{dx_e}\bigg|_{x_e = \frac{E_{\gamma'}}{E_e}} \right.$$

$$\left. e^{-L_{\rm sh}/l_{\gamma'}} \left(1 - e^{-L_{\rm dec}/l_{\gamma'}}\right) \right] {\rm BR}_{\rm detect} \, .$$



Axion-like Particle

$$\mathcal{L}_{\text{CP-viol.}} = \frac{\alpha_s}{8\pi}\,\theta\, G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \qquad \bar{\theta} \equiv \theta + \arg\,\det\, M$$

$$|d_n| \sim \frac{e}{m_n}\left(\frac{m_q}{m_n}\right)|\bar{\theta}| \sim 10^{-16}\ |\bar{\theta}|\ e\,\text{cm}\ < 2.9\times 10^{-26}\ e\,\text{cm} \Rightarrow |\bar{\theta}| \lesssim 10^{-10}$$

promote $\theta \to a/f_a$

$U(1)_{PQ}$ ⇒ axion $\quad m_a = \dfrac{m_\pi f_\pi}{f_a}\dfrac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 0.6\,\text{meV} \times \left(\dfrac{10^{10}\,\text{GeV}}{f_a}\right)$

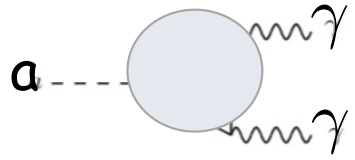
γ

Similar idea → breaking of other global symmetry $U(1)_\phi$
→ PNGB (ALP a)

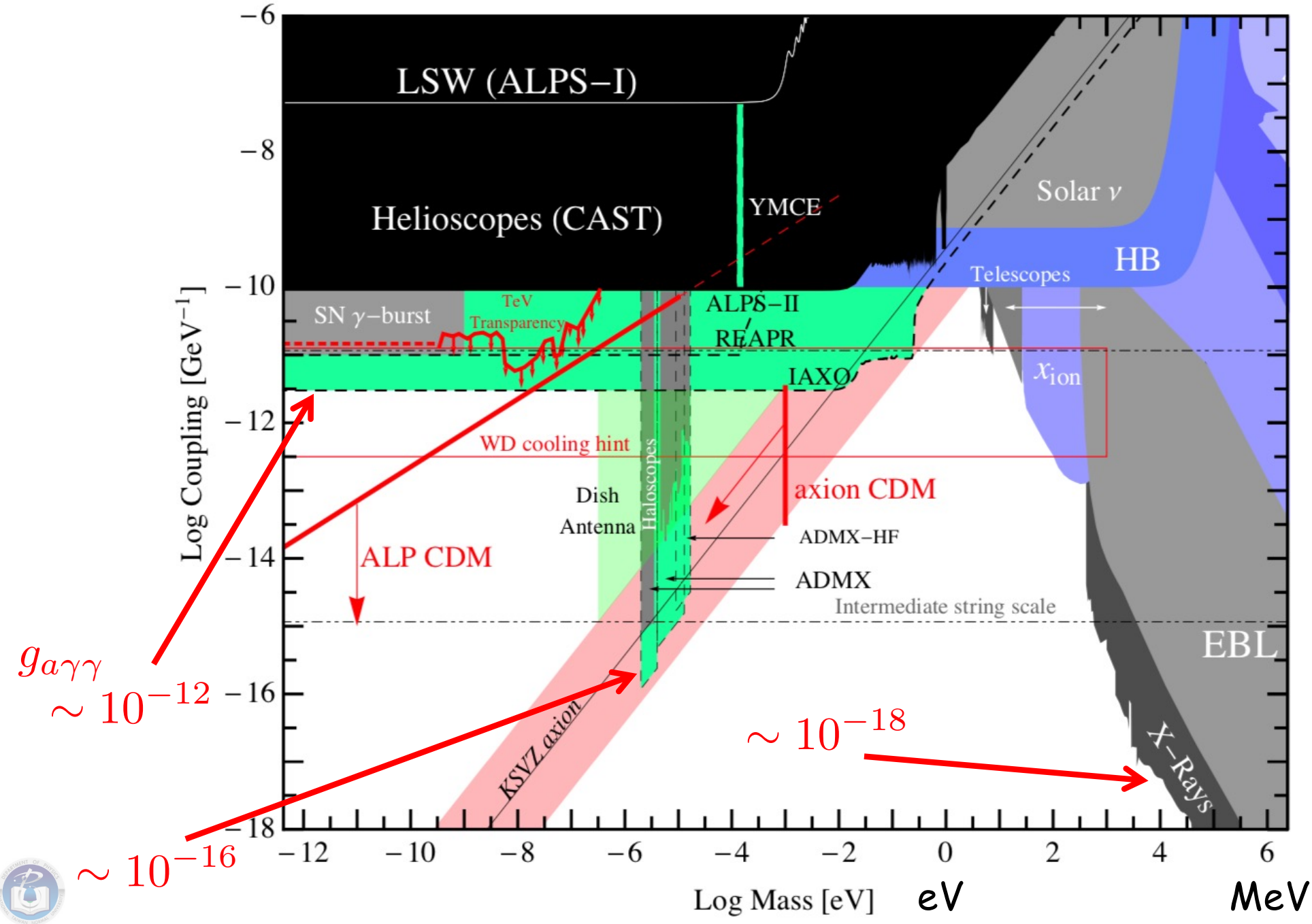
$$\phi = \frac{1}{\sqrt{2}}(v_\phi + s)e^{ia/v_\phi}$$

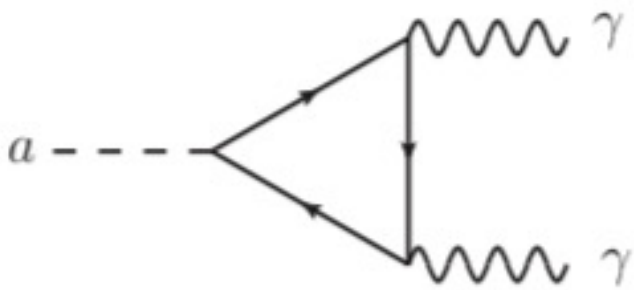
interactions:

$$\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

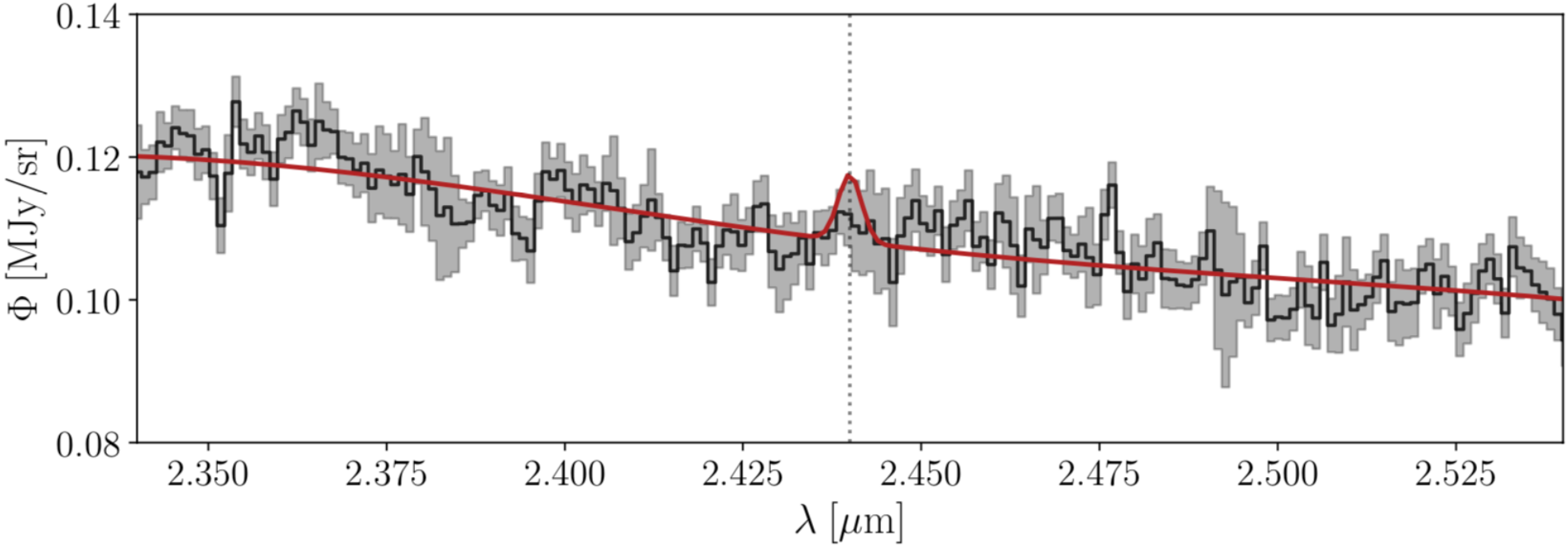


ALP constraints



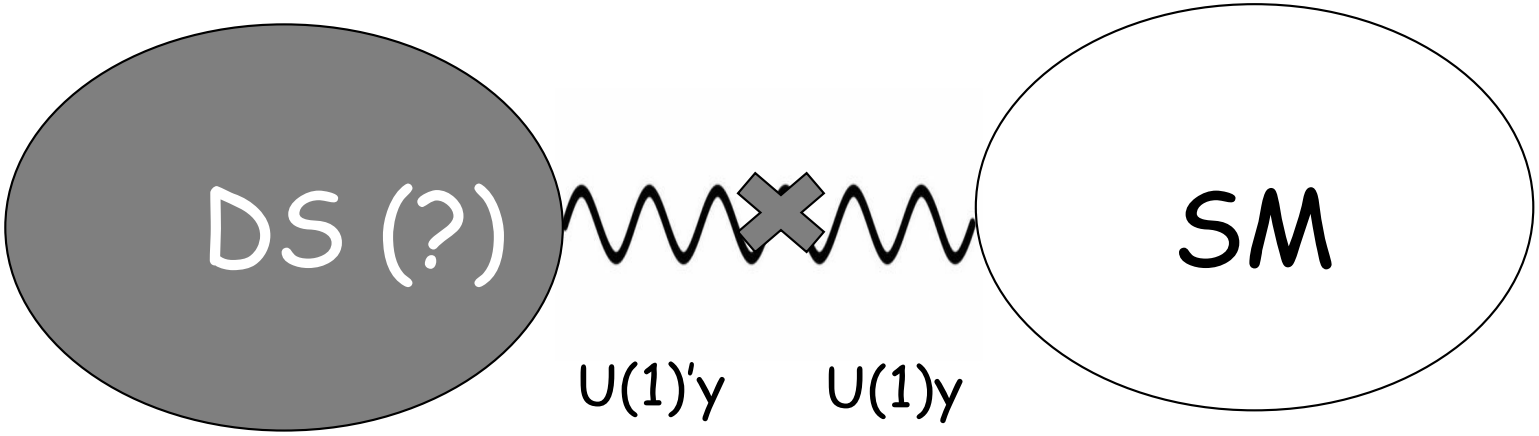


Janish, Pinetti, 2310.15396



JWST spectrum observation

$$g_{a\gamma\gamma} < 2.4 \times 10^{-11}\ \mathrm{GeV}^{-1} \quad \text{for} \quad m_a = 1\ \mathrm{eV}$$



if there exists axion-like particle in DS,

$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma'\gamma'} a F'_{\mu\nu} \tilde{F}'^{\mu\nu} + \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \boxed{\frac{1}{2} g_{a\gamma'\gamma} a F'_{\mu\nu} \tilde{F}^{\mu\nu}}$$

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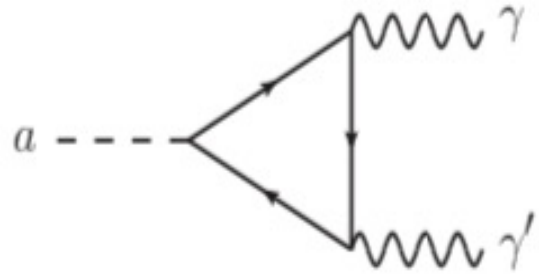

Induce a new decay channel for dark photon

$$\gamma' \to a\gamma$$

photon + missing energy

An Example KSVZ-type

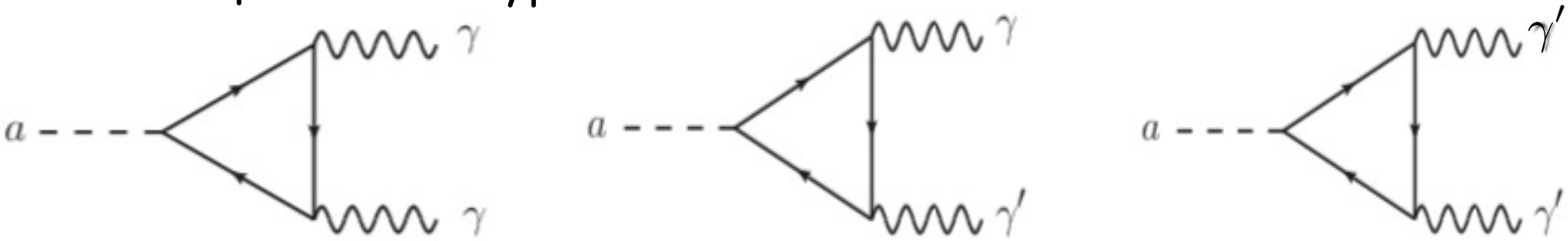

TABLE I. New fields and charge assignments in our model. Q_ψ is the electromagnetic charge of the exotic fermion ψ.

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
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

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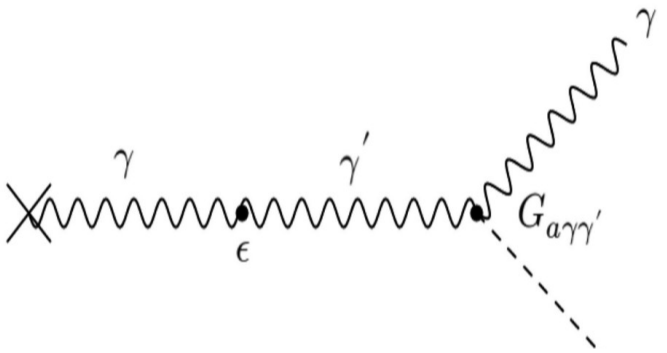
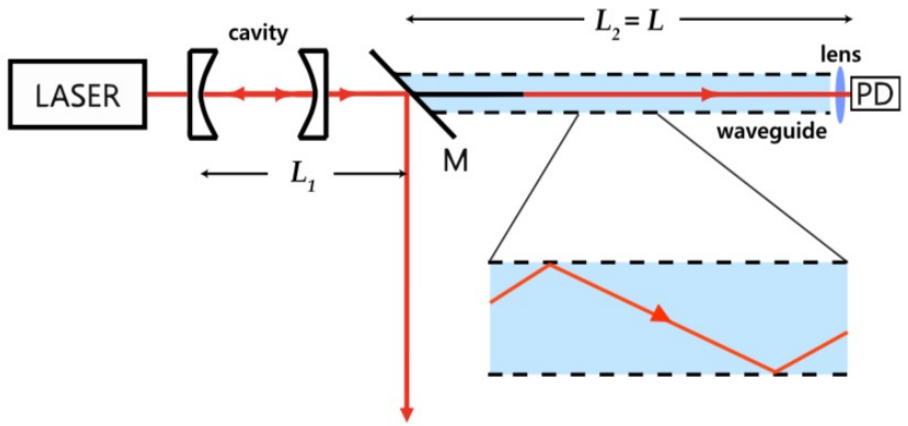
$$g_{a\gamma\gamma} = \frac{e^2}{8\pi^2}\frac{\text{PQ}_\Phi}{f_a}(2N_c Q_\psi^2)$$

$$g_{a\gamma\gamma'} = \frac{ee'}{8\pi^2}\frac{\text{PQ}_\Phi}{f_a}(2N_c Q_\psi D_\psi) + \epsilon g_{a\gamma\gamma}$$

$$g_{a\gamma'\gamma'} = \frac{e'^2}{8\pi^2}\frac{\text{PQ}_\Phi}{f_a}(2N_c D_\psi^2) + 2\epsilon g_{a\gamma\gamma'}$$

Constraints of $g_{a\gamma\gamma'}$





$$N_{\text{sub}} = \mathcal{P}_{A\to X}(L_1)\mathcal{P}_{X\to\text{decay}}(L_2)N_\gamma,$$
$$= \varepsilon^2 N_\gamma \left[1 - e^{-\frac{m_{\gamma'}\Gamma L_2}{p}}\right]$$
$$\times \left[1 + e^{-\frac{m_{\gamma'}\Gamma L_1}{p}} - 2e^{-\frac{m_{\gamma'}\Gamma L_1}{2p}}\cos(L_1\Delta p)\right].$$

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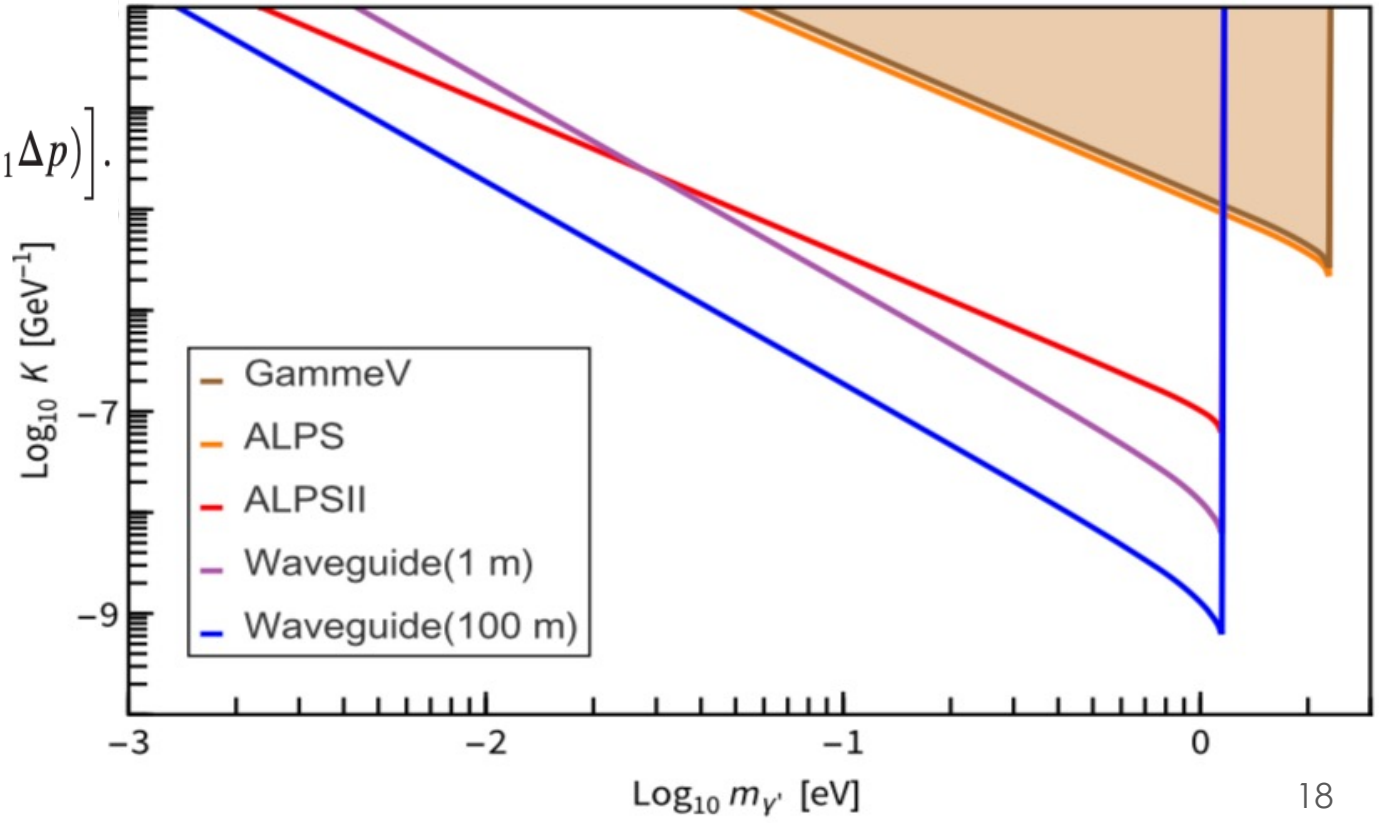
$$K = \epsilon g_{a\gamma\gamma'}$$



Constraints of $g_{a\gamma\gamma'}$

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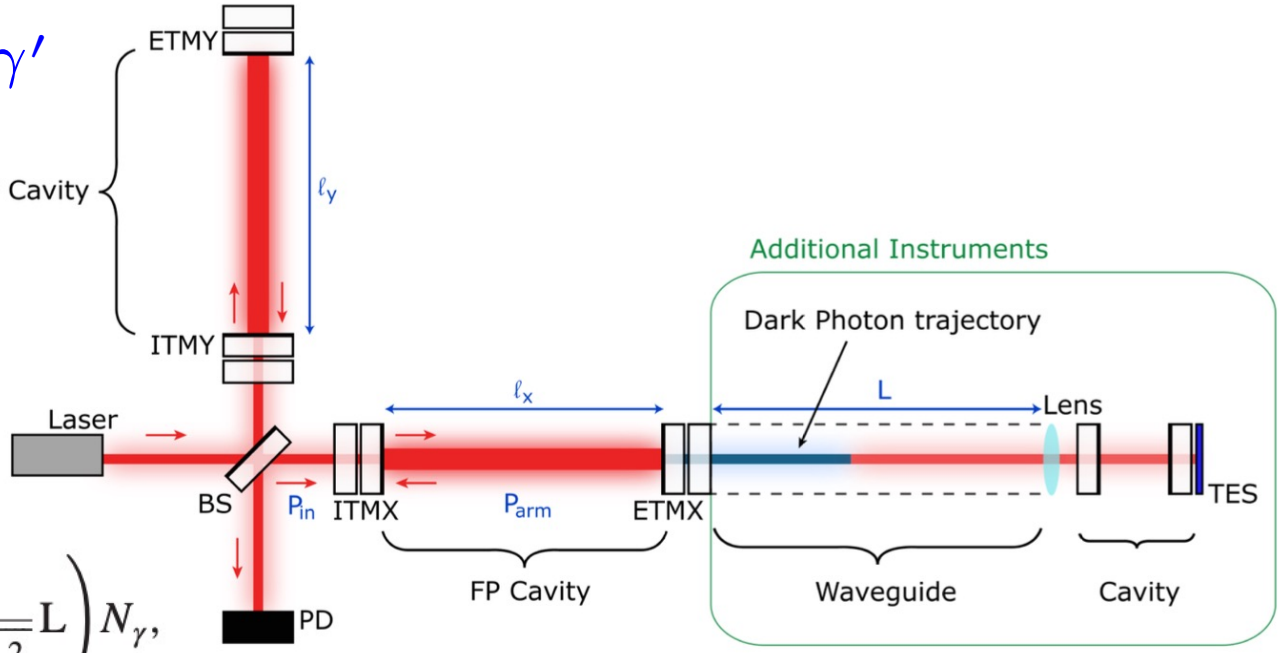
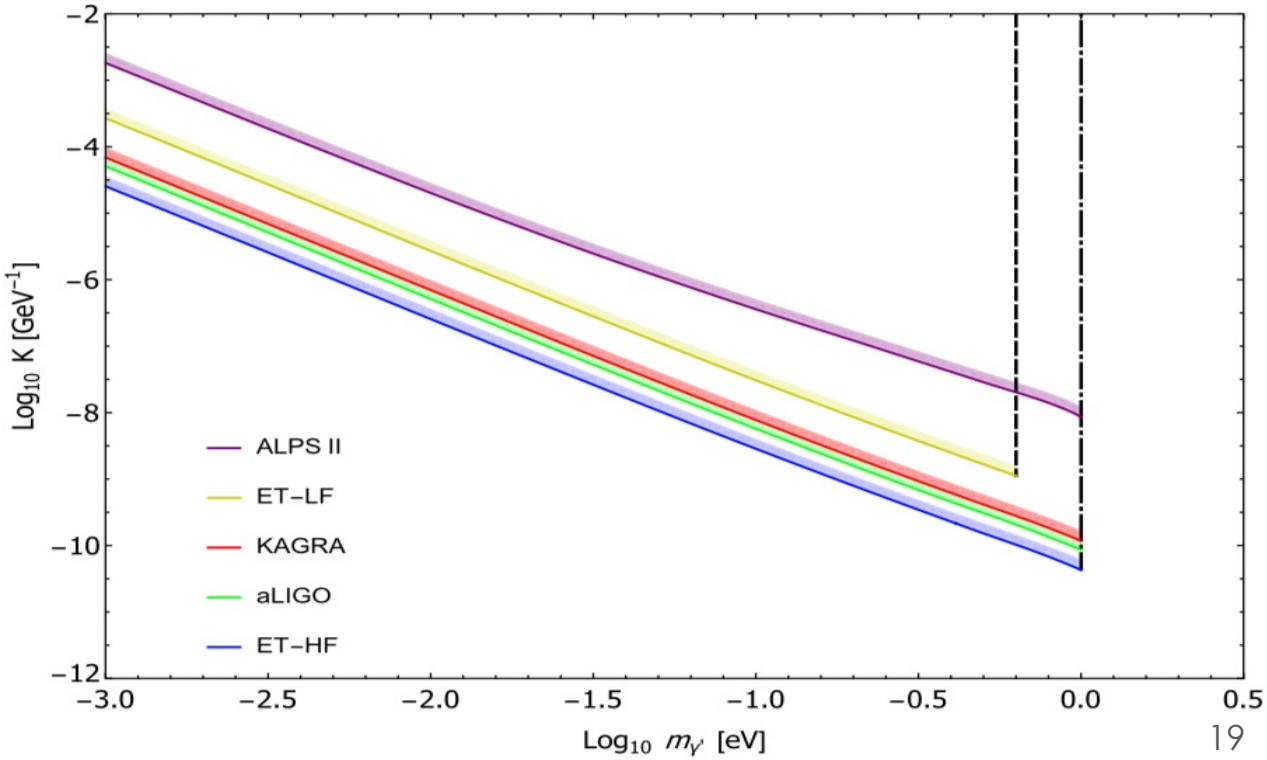
$$\mathrm{SNR} = \frac{N_s\sqrt{t_s}}{\sqrt{N_s + N_d}},$$

$$N_s^{\mathrm{tot}} = \eta_{\mathrm{kin}}\eta_{\mathrm{cav}}\bar{\eta}_{\mathrm{eff}}\eta_{\mathrm{cav}}^{\mathrm{WG}}\left(\frac{K^2}{96\pi}\frac{m_{\gamma'}^4}{\sqrt{\omega^2 - m_{\gamma'}^2}}\mathrm{L}\right)N_\gamma,$$

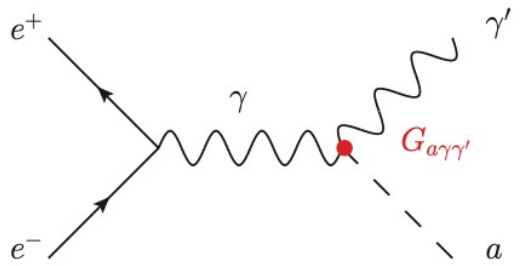


$$K = \epsilon g_{a\gamma\gamma'}$$



Constraints of $g_{a\gamma\gamma'}$

P. deNiverville, H.S. Lee, M.S. Seo, 1806.00757



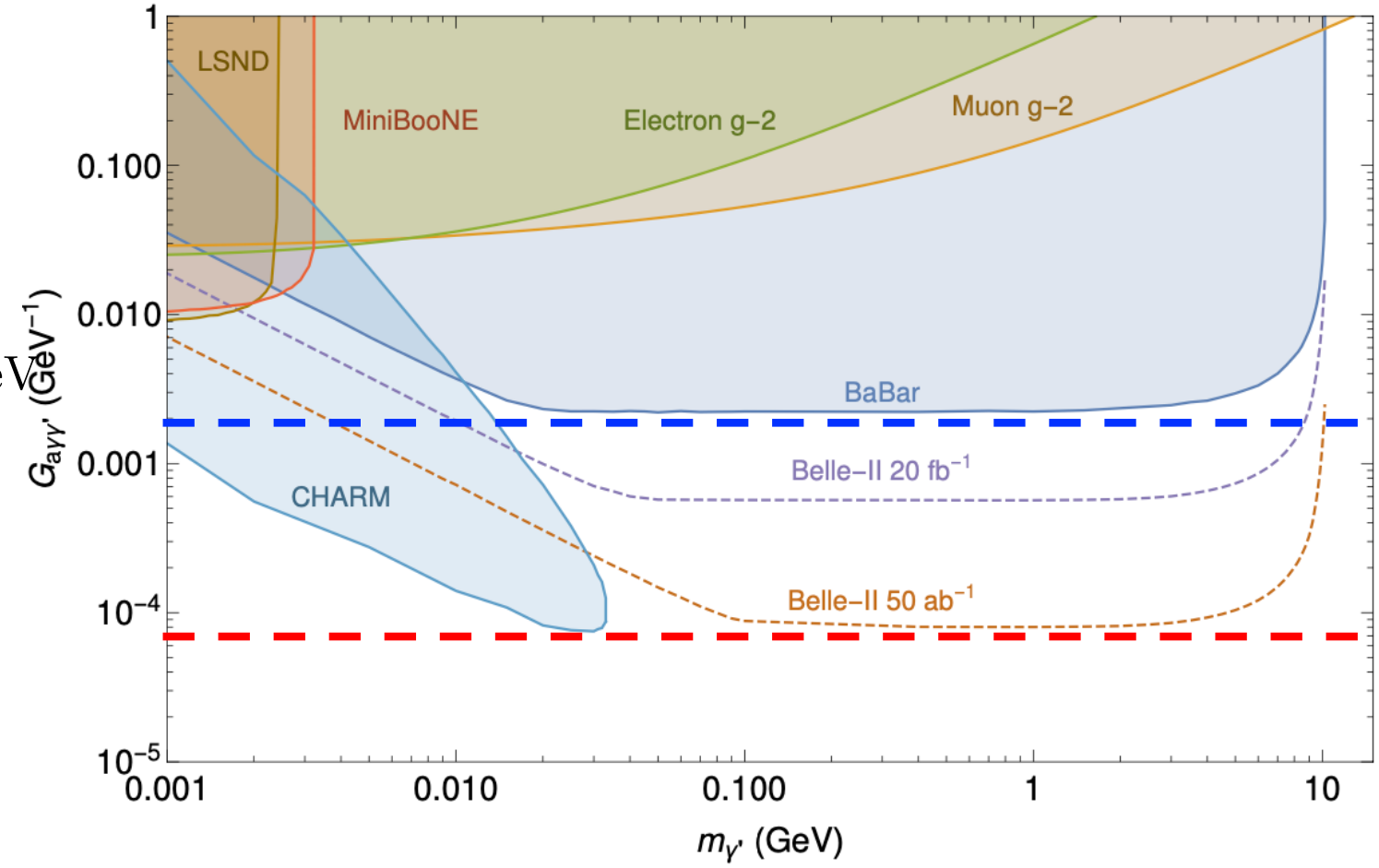
For $m_{\gamma'} \lesssim 50$ MeV

$g_{a\gamma\gamma'} \lesssim 10^{-4}$

For

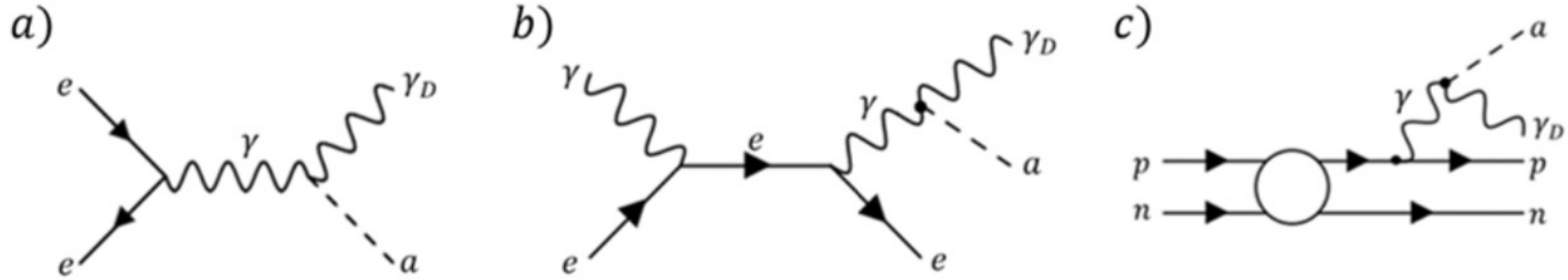
$20\ \text{MeV} \lesssim m_{\gamma'} \lesssim 1\ \text{GeV}$

$g_{a\gamma\gamma'} \lesssim 10^{-3}$

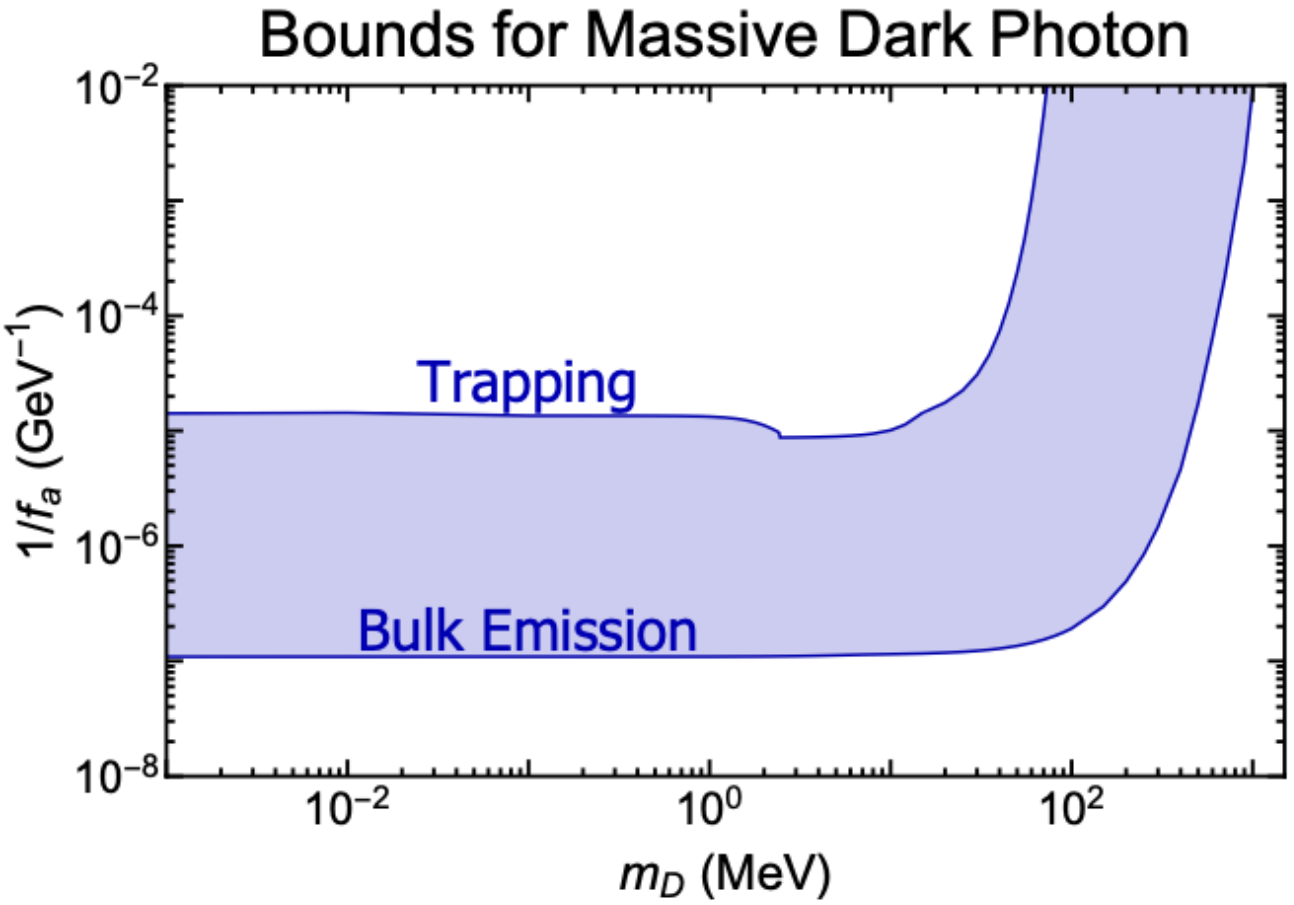


Constraints of $g_{a\gamma\gamma'}$

A. Hook, G. Marques-Tavares, C. Ristow, 2105.06476



$$\mathcal{L} \supset \frac{1}{2}\frac{a}{f_a}F_{\mu\nu}\tilde{F}_D^{\mu\nu}$$



Decays

$$\Gamma(\gamma' \to \text{hadrons}) = \frac{\alpha\epsilon^2}{3} m_{\gamma'} \sqrt{1 - \frac{4m_\mu^2}{m_{\gamma'}^2}} \left(1 + \frac{2m_\mu^2}{m_{\gamma'}^2}\right) R$$

$$\Gamma(\gamma' \to \ell^+\ell^-) = \frac{\alpha\epsilon^2}{3} m_{\gamma'} \sqrt{1 - \frac{4m_\ell^2}{m_{\gamma'}^2}} \left(1 + \frac{2m_\ell^2}{m_{\gamma'}^2}\right)$$

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

$\epsilon = 10^{-4}$

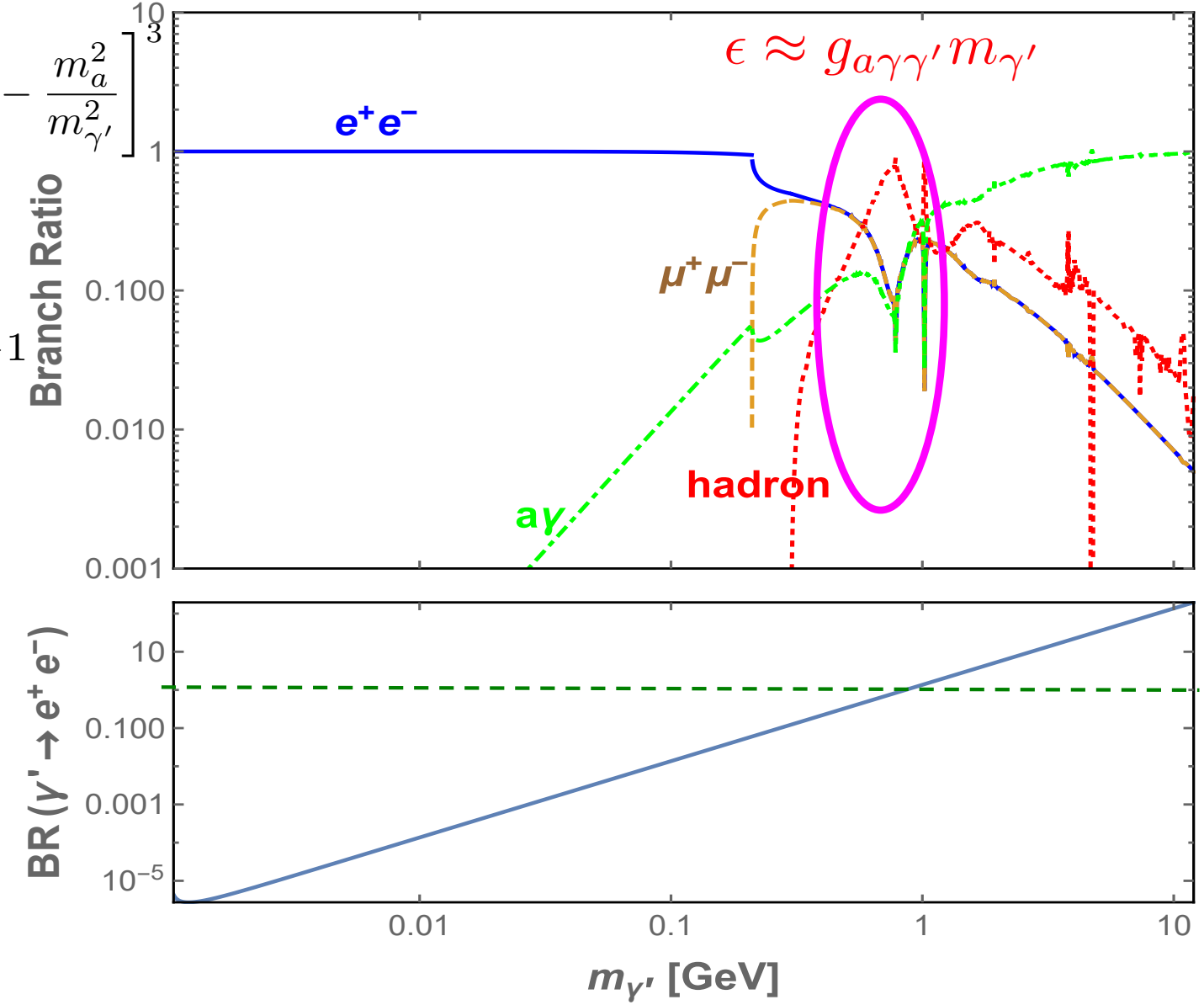
$g_{a\gamma\gamma'} = 10^{-4}\ \text{GeV}^{-1}$

$m_{\gamma'} \lesssim 300\ \text{MeV}$

e^+e^- dominates

$m_{\gamma'} \gtrsim 1\ \text{GeV}$

$a\gamma$ is important



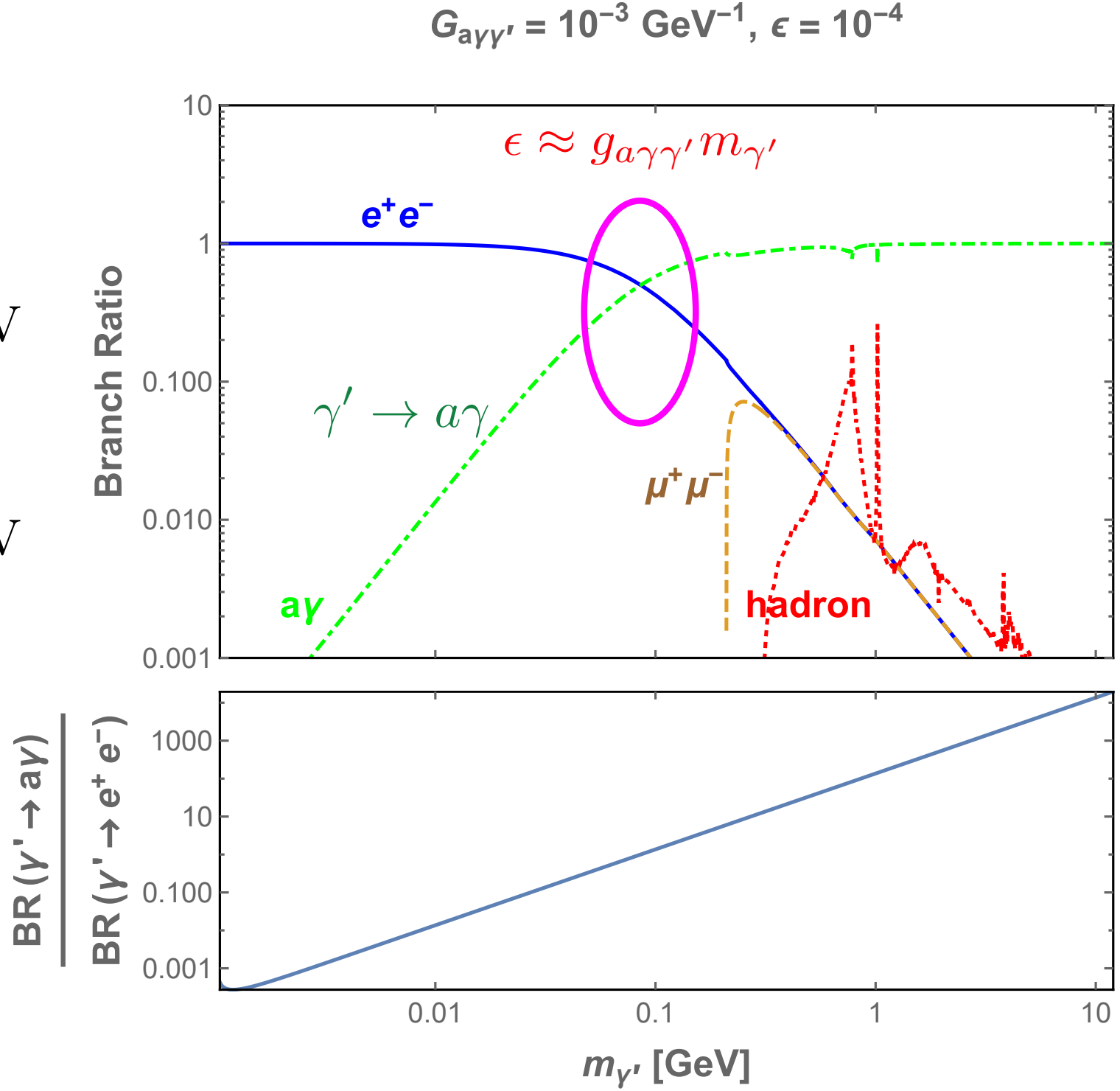
Decays

$m_{\gamma'} \lesssim 100$ MeV

e^+e^- dominates

$m_{\gamma'} \gtrsim 100$ MeV

$a\gamma$ is important



New Constraints

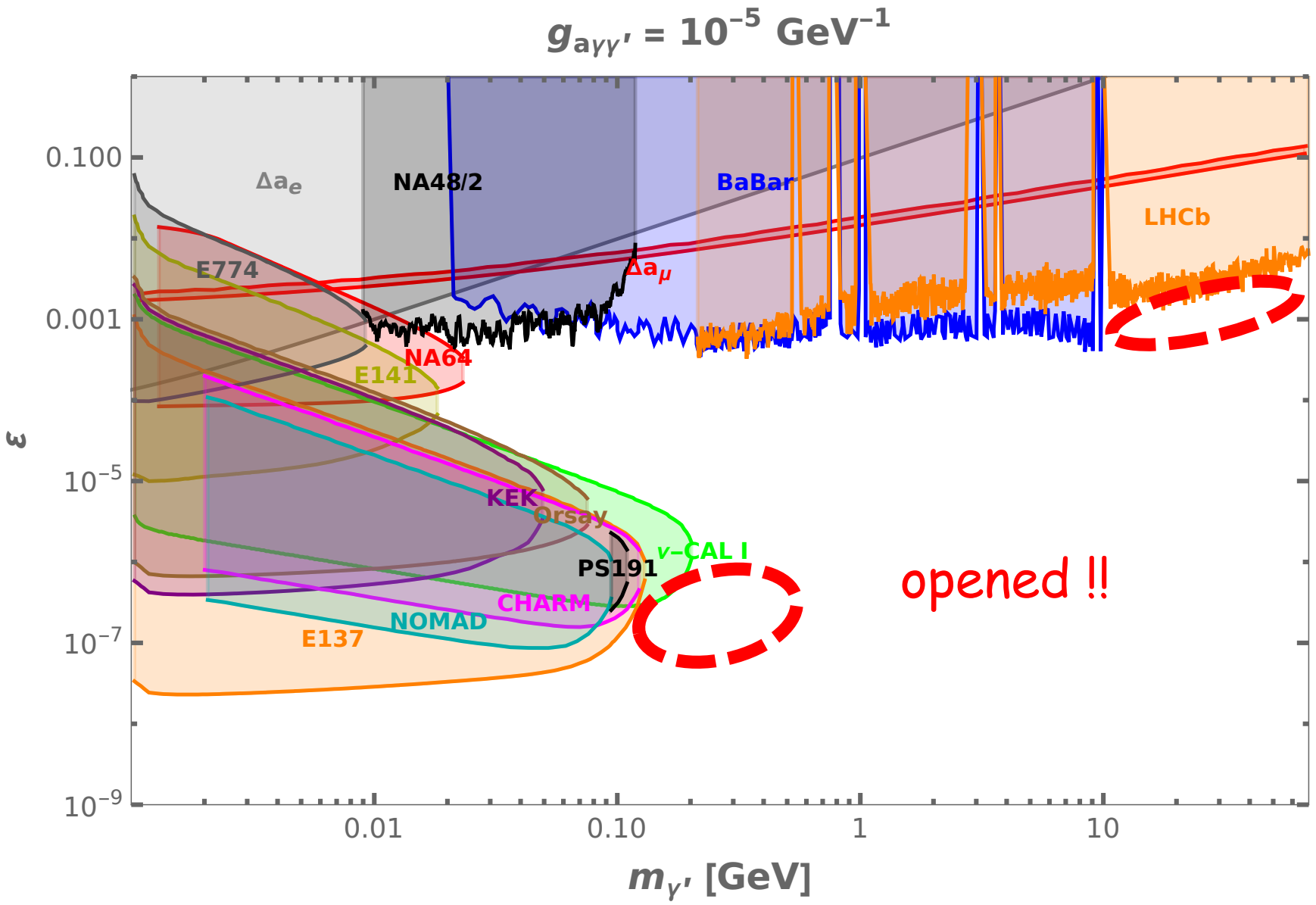
BaBar, KLOE, A1, NA48/2:

$$\ell^+\ell^- \text{ events} = \sigma \times \mathrm{Br}(\gamma' \to \ell^+\ell^-)$$
$$\sim (\mathrm{old}) \times (1 + (\frac{g_{a\gamma\gamma'} m_{\gamma'}}{e\epsilon})^2)^{-1}$$

beam dump

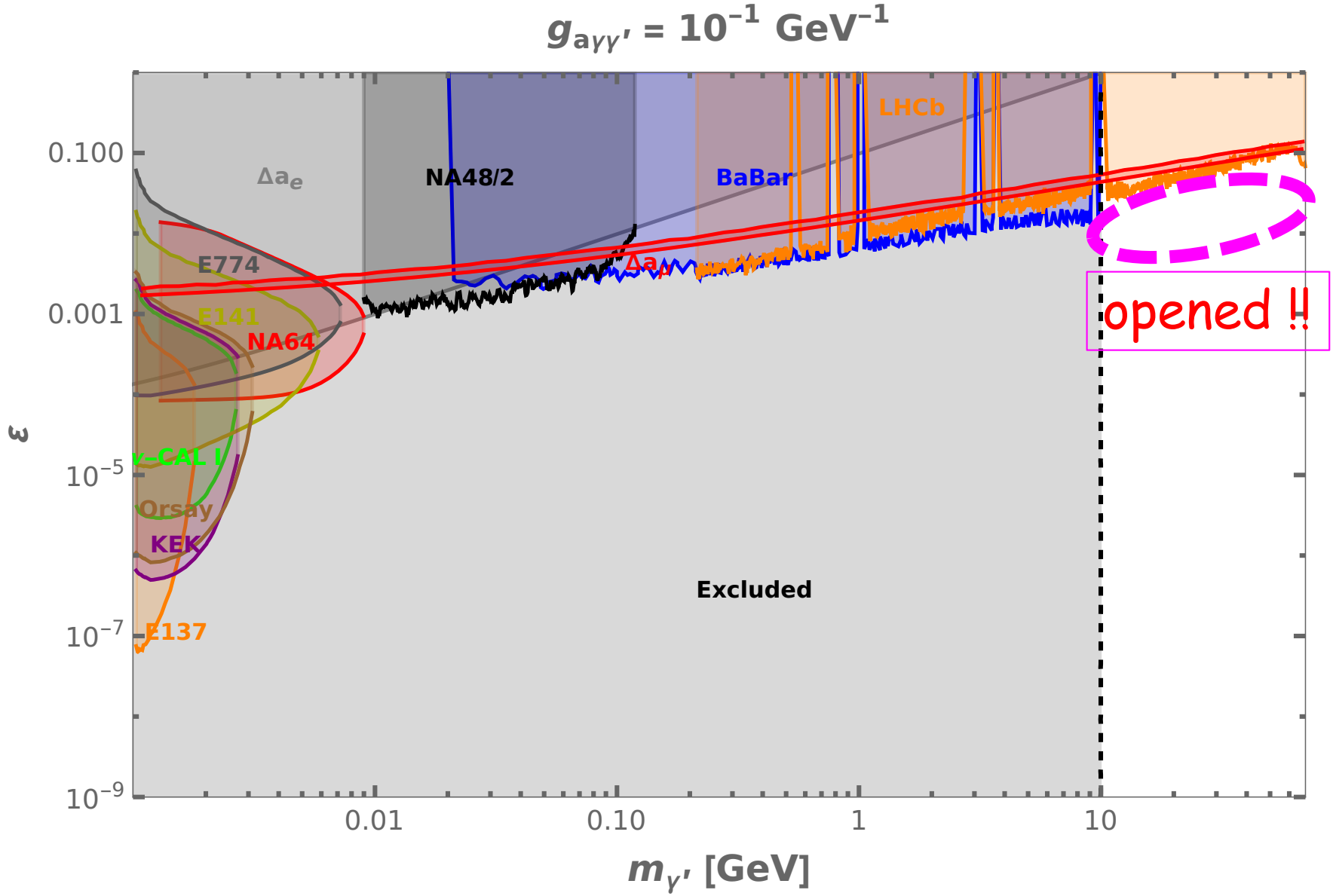
$$e^+e^- \text{ events}$$
$$\sim (old) \times \exp^{-\frac{L' m_{\gamma'}^4}{p_{\gamma'}}} \times (1 + (\frac{g_{a\gamma\gamma'} m_{\gamma'}}{e\epsilon})^2)^{-1}$$

New Constraints

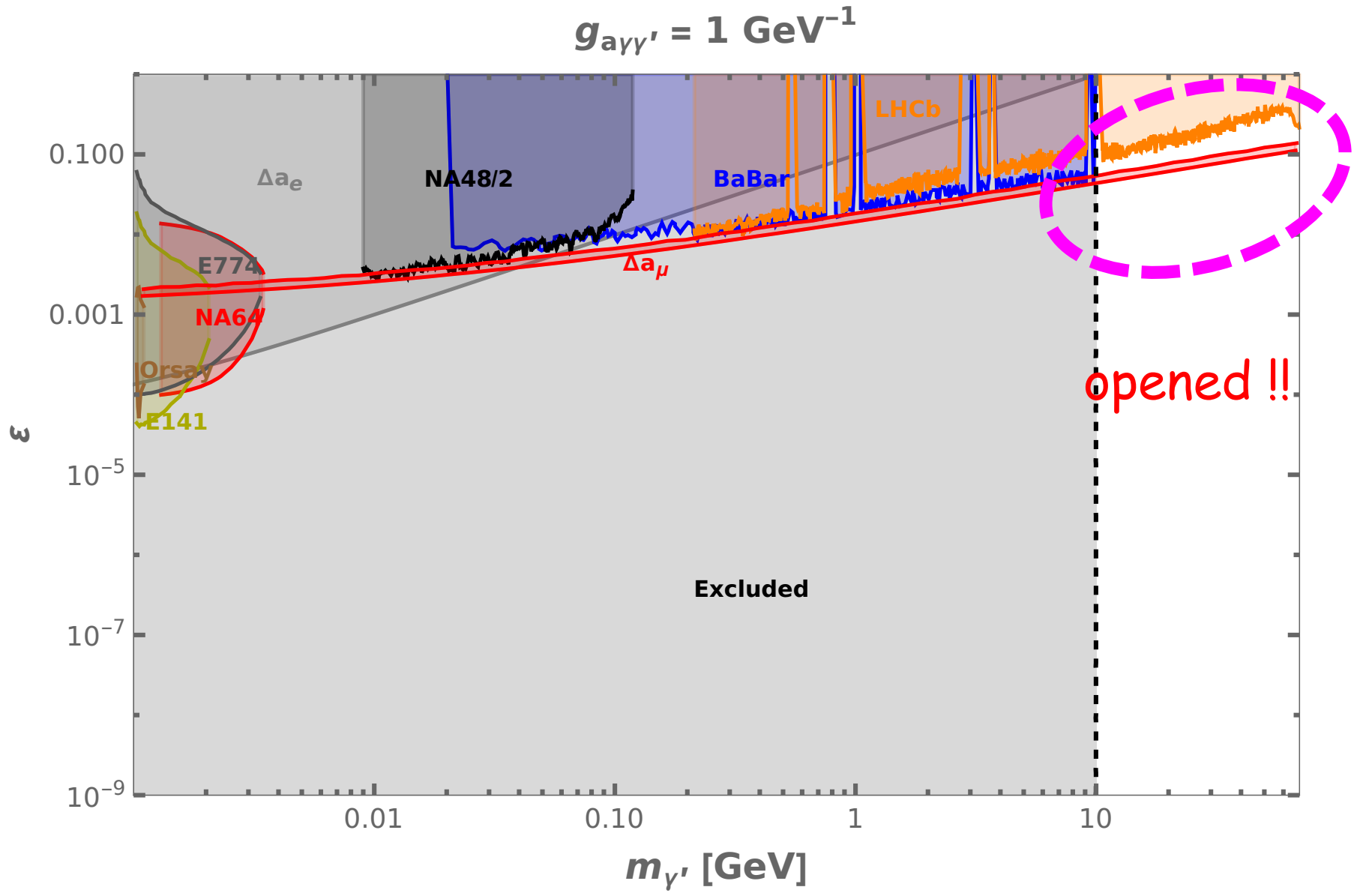


SN constraints are not included!

New Constraints



New Constraints



Summary

IF ALP lives in DS, it could couple to photon and dark photon !!

ALP could significantly change the constraints for dark photon (> 1 MeV)!

- ➡ may open or close parameter space
- ➡ especially for heavier dark photon
- ➡ may reopen the parameter to explanation muon g-2

Search strategy for dark photons should be visited

- ➡ mono-photon with missing ET should be explored

Back UP

H.-S. Lee, J. Lee, J. Yi, PRD 106, 015011 (2022)

TABLE I. Specifications of the experimental setups we use in our analysis. The LSW experiments (GammeV, ALPS, ALPS II) are partly sensitive to the subfrequency new physics scenario. Our proposed experimental setup (waveguide) adopts a waveguide. The parameters for the LSW experiments including $\eta_{\rm eff}$ were taken from Refs. [7,30,31]. Some of the parameter values may not properly reflect the actual experiments. For instance, the $\eta_{\rm eff}$ of the LSW experiments would change if the frequency dependence is properly applied.

	a (mm)	L (m)	ω (eV)	N_γ (Hz)	$N_{\rm pass}$	$\eta_{\rm eff}$	N_d (Hz)	t_s (h)
Waveguide	...	1, 100	1.17	1.6×10^{20}	5000	0.54	10^{-6}	480
ALPS II	8.75[a]	100	1.17	1.6×10^{20}	5000	0.95	10^{-6}	480
ALPS	7[b]	7.6	2.33	2.6×10^{21}	1	0.9	0.0018	27
GammeV	25.5[c]	7.2	2.33	6.6×10^{23}	1	0.25	130	24

[a]The ALPS II uses an optic suitable to collect a 17.5 mm diameter beam [32].
[b]Because we are unaware of the radius of the lens, we take the maximum of the vacuum tube size that can be inserted in the HERA dipole magnet [33].
[c]We take the size of the lens in front of the photomultiplier tube (PMT) [10].

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TABLE I. Parameters of the experiments used in our calculation. The references for the primary FP cavity and laser setup of each experiment are presented in the table. In addition, we adopt the ALPS II cavity finesse to our proposed second cavity for GW experiments.

Parameters	ALPS II [14]	aLIGO [62]	KAGRA [63–65]	ET-HF [59–61]	ET-LF [59–61]
$\mathcal{F}_{\rm Cav}$	7853	450	1550	880	880
$P_{\rm in}$ (W)	30	2600	412	5355	32
ω (eV)	1.165	1.165	1.165	1.165	0.799
L (m)	100	10	10	10	10
N_d (Hz)	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}
$\mathcal{F}^{\rm WG}_{\rm Cav}$	...	7853	7853	7853	7853