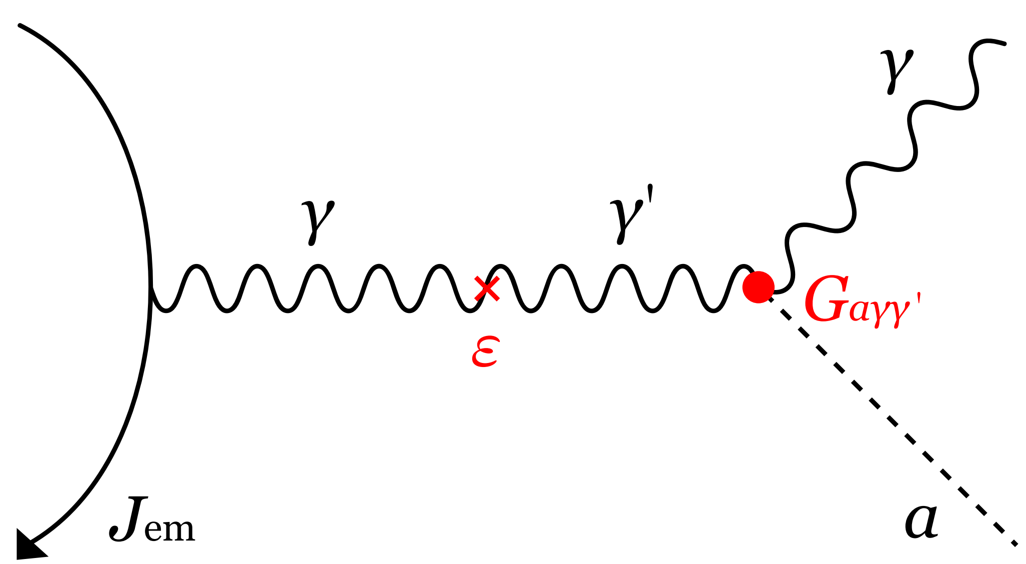
Subfrequency Portal

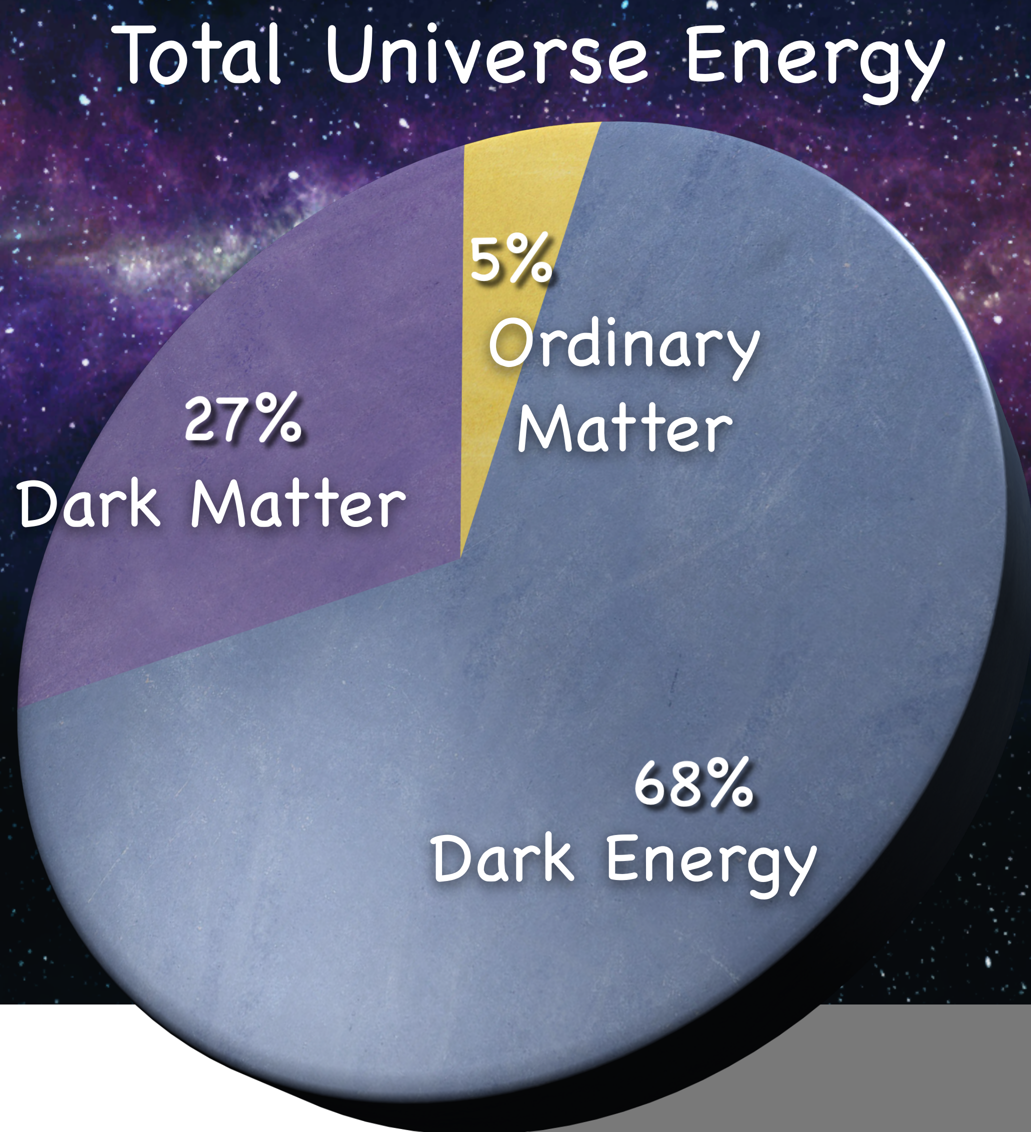


Hye-Sung Lee
Korea Advanced Institute of Science and Technology

Axion 2022
November 22 - 24, 2022

2201.11906
2011.03276
1904.13061
1806.09972
1806.00757
1704.07542
1611.01466

We live in a Dark World

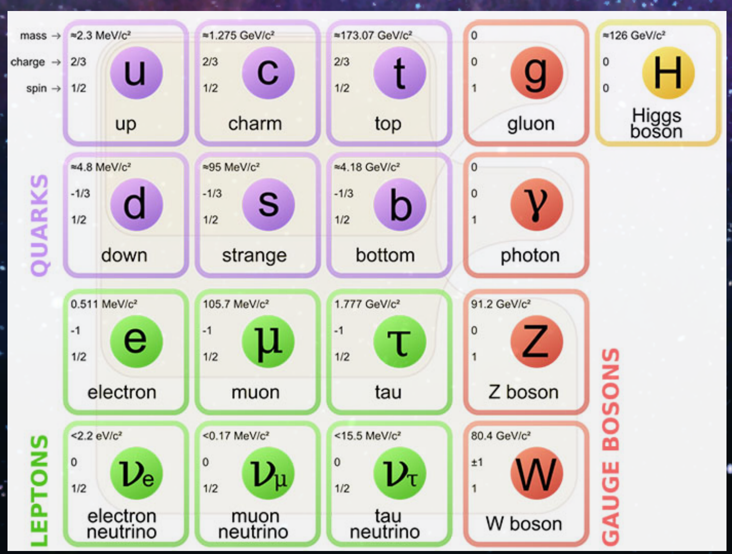


$$
\begin{aligned}
\nabla \cdot \vec{E} &= \rho \\
\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\
\nabla \cdot \vec{B} &= 0 \\
\nabla \times \vec{B} &= \vec{J} + \frac{\partial \vec{E}}{\partial t}
\end{aligned}
$$

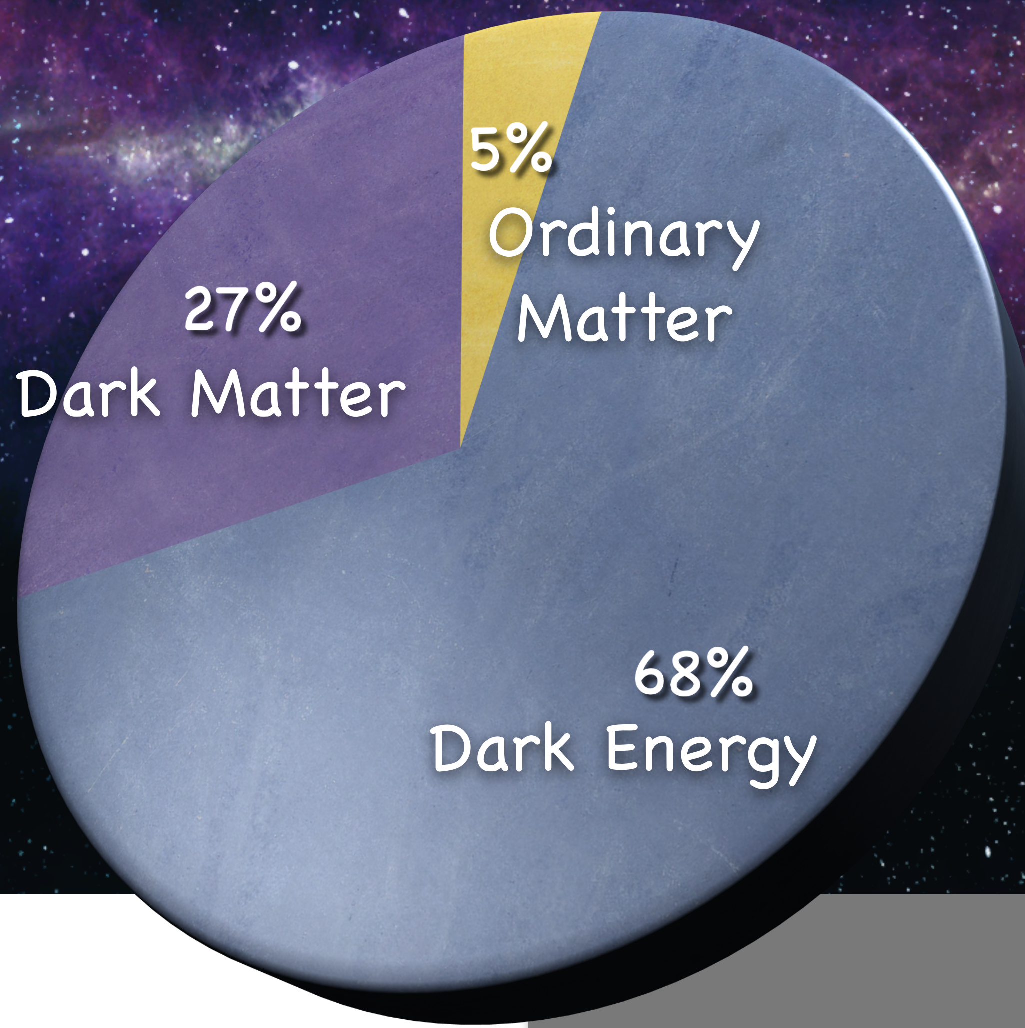
Bright sector

Dark sector

We live in a Dark World



Total Universe Energy



$$
\begin{aligned}
\nabla \cdot \vec{E} &= \rho \\
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\nabla \cdot \vec{B} &= 0 \\
\nabla \times \vec{B} &= \vec{J} + \frac{\partial \vec{E}}{\partial t}
\end{aligned}
$$

Bright sector

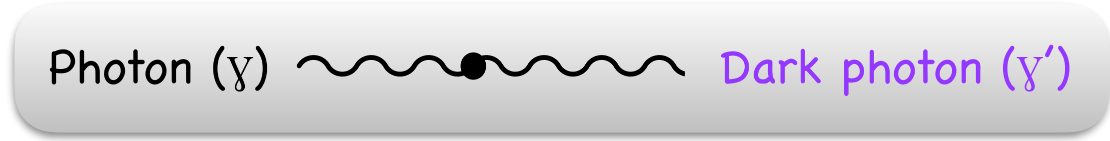
Dark sector

The dark sector particles can be light.
(Light Dark World)

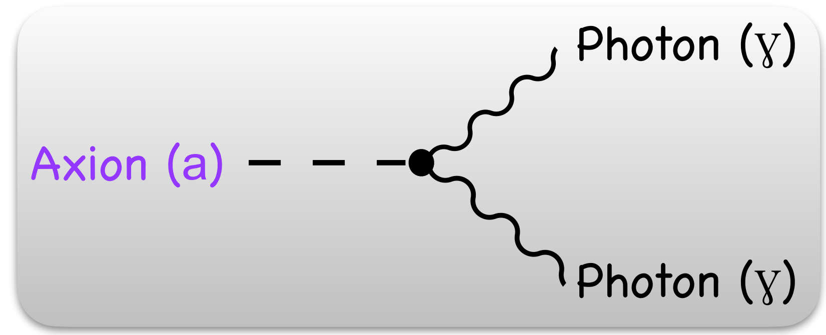
F, ɣ : photon
Z′, ɣ′ : dark photon
a : axion

Portals

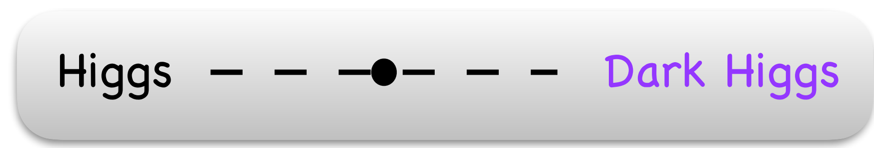
(i) Vector Portal $\frac{\varepsilon}{2} F_{\mu\nu} Z'^{\mu\nu}$



(ii) Axion Portal $\frac{G_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$



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

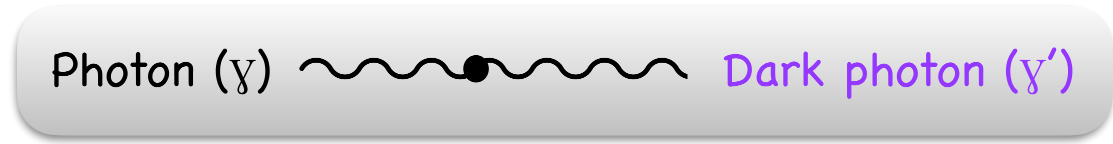


(iv) Neutrino Portal $y\, LHN$

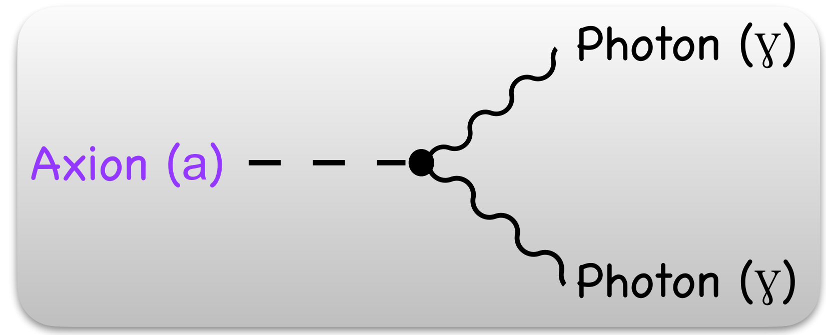
F, ɣ : photon
Z′, ɣ′ : dark photon
a : axion

Portals

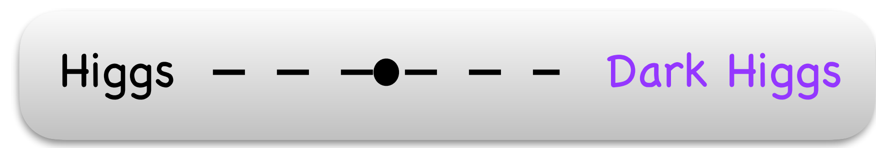
(i) Vector Portal $\frac{\varepsilon}{2} F_{\mu\nu} Z'^{\mu\nu}$



(ii) Axion Portal $\frac{G_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$



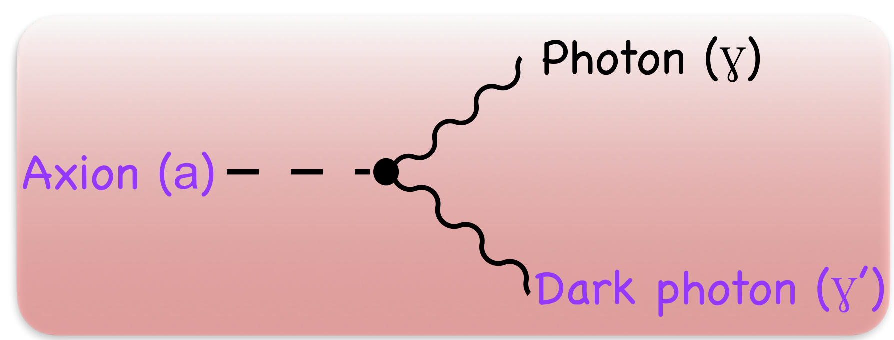
(iii) Higgs Portal $\kappa\,|S|^2|H|^2 + \mu\, S|H|^2$



(iv) Neutrino Portal $y\, LHN$

(v) Dark Axion Portal $\frac{G_{a\gamma\gamma'}}{4} a F_{\mu\nu} \tilde{Z}'^{\mu\nu}$

[Kaneta, LEE, Yun (PRL 2017)]



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

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

Dark Axion Portal

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

"A hidden connection is stronger than an obvious one."

- Heraclitus of Ephesus -

Dark KSVZ axion model (New axion model realizing the new portal)

[Kaneta, LEE, Yun (2017)]

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

(KSVZ axion model: invisible axion model using exotic quarks) Kim (1979); Shifman, Vainshtein, Zakharov (1980)

	Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{\text{Dark}}$	$U(1)_{PQ}$
SM particles	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
Exotic heavy quarks	ψ	3	1	Q_ψ	D_ψ	PQ_ψ
	ψ^c	$\bar{3}$	1	$-Q_\psi$	$-D_\psi$	PQ_{ψ^c}
Extra scalars (to break PQ & Dark)	Φ_{PQ}	1	1	0	0	PQ_Φ
	Φ_D	1	1	0	D_Φ	0

KSVZ model particles

Additional scalar for γ' mass

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

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

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

Φ_{PQ} is a pure gauge-singlet.

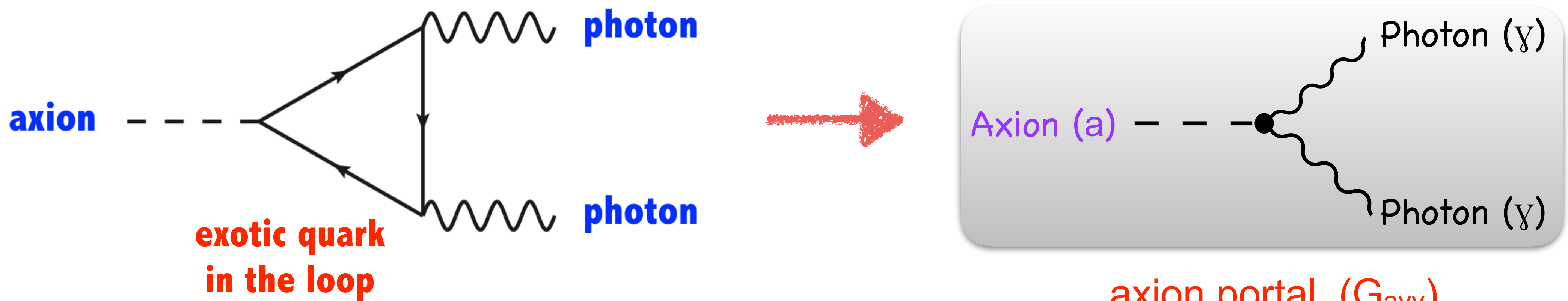
$$m_{\gamma'}^2 = e'^2 D_\Phi^2 v_D^2$$

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

It depends on the couplings of the Fermions in the triangle

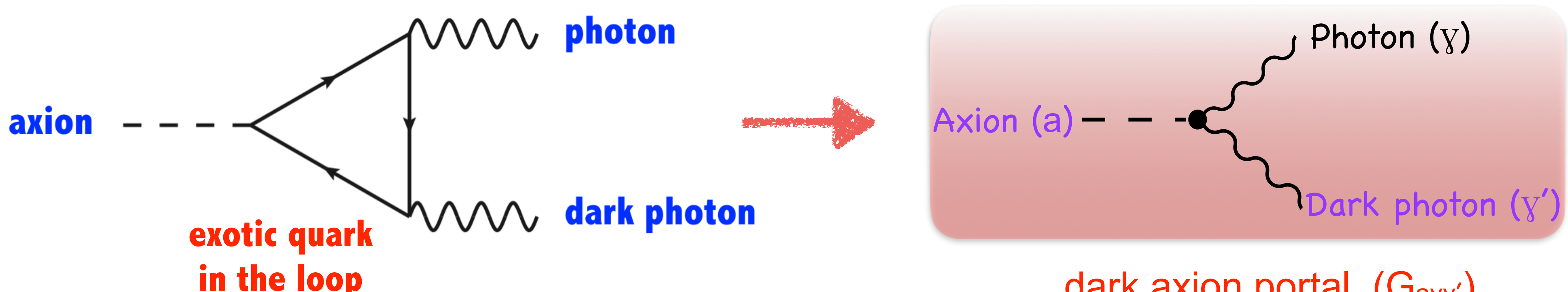
In the KSVZ axion model, there are <u>vector-like quarks</u> forming an anomaly triangle.

(i) Original KSVZ axion model: Exotic quarks have <u>EM charges</u>



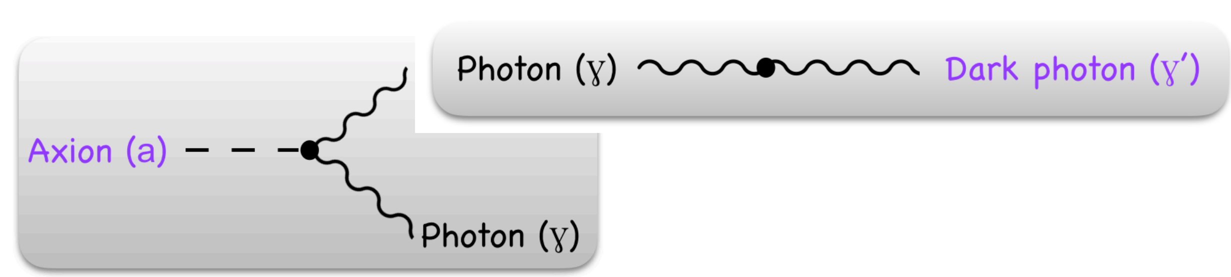
axion portal ($G_{a\gamma\gamma}$)

(ii) Dark KSVZ axion model: Exotic quarks have <u>EM & Dark charges</u>



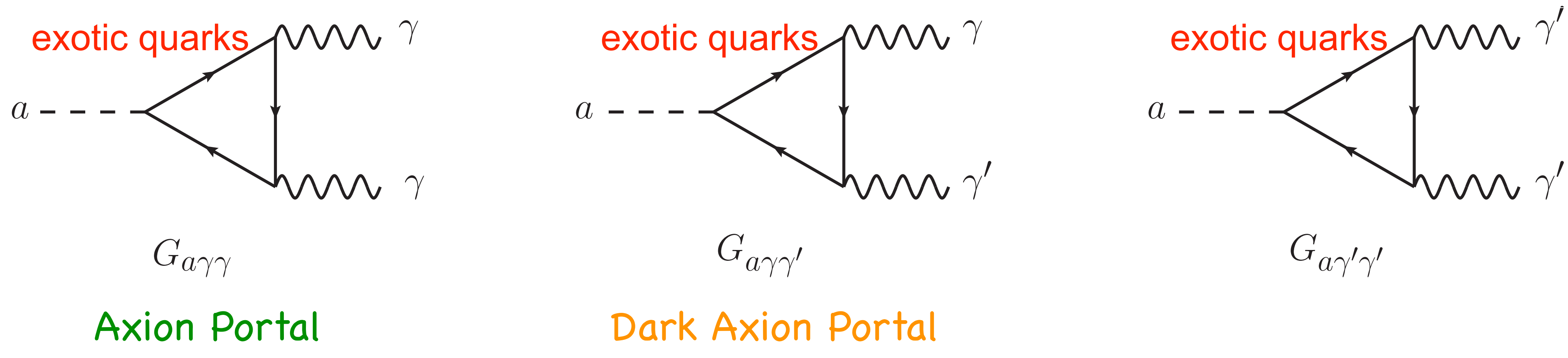
dark axion portal ($G_{a\gamma\gamma'}$)

(The new portal was not made just by combining two old portals [obvious connection].



)

Dark Axion Portal (in Dark KSVZ axion model)



The portal interaction terms in Dark KSVZ axion model

Above the QCD scale (~ 200 MeV)

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

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

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

Q: electric charge
D: dark charge

e: EM coupling constant
e': Dark coupling constant

N_C=3 (color factor)

Vector portal (ε) × Axion portal ($G_{a\gamma\gamma}$) part [obvious connection] should be small because ε << 1.

Dark Axion portal provides a New way to search for Dark gauge boson [using the hidden gauge coupling] even when Vector portal is closed (ε = 0).

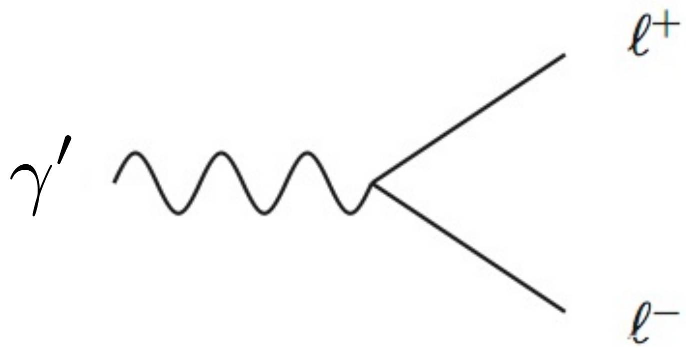
Implications of the dark axion portal

(axion = axion or axion-like particle)

Visible/Invisible decay of Dark photon

Categories of Dark force search (in terms of the dominant decay modes) :

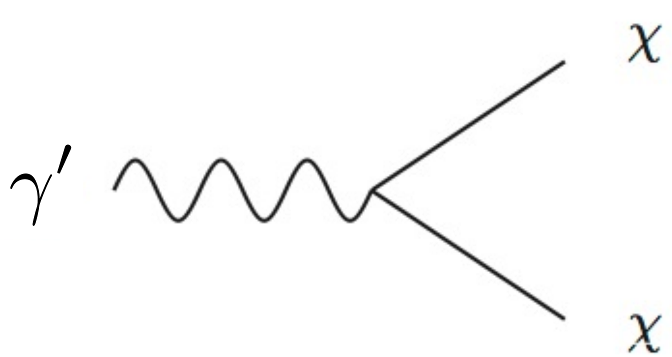
(i) "Dilepton Resonance" search (visible dark photon scenario)



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

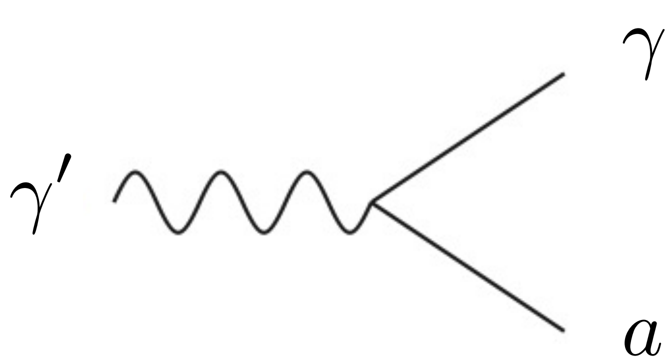
(ii) "Missing Energy" search (invisible dark photon scenario)

if χ (very light dark sector particle) exists.



$$\Gamma(\gamma' \to \chi\bar{\chi}) = \frac{e'^2 D_\chi^2}{12\pi} m_{\gamma'} \left(1 - \frac{4m_\chi^2}{m_{\gamma'}^2}\right)^{1/2}$$

(iii) "Photon" search ("another" visible dark photon scenario)



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

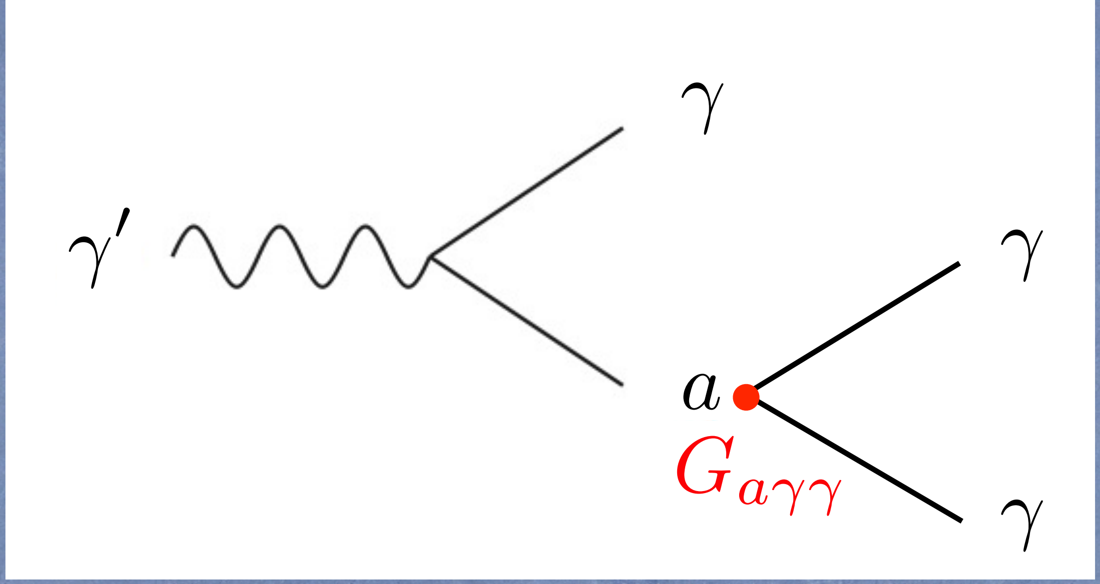
(axion or axion-like particle)

[Possibly dominant decay channel. Sub-MeV dark photons may decay.]

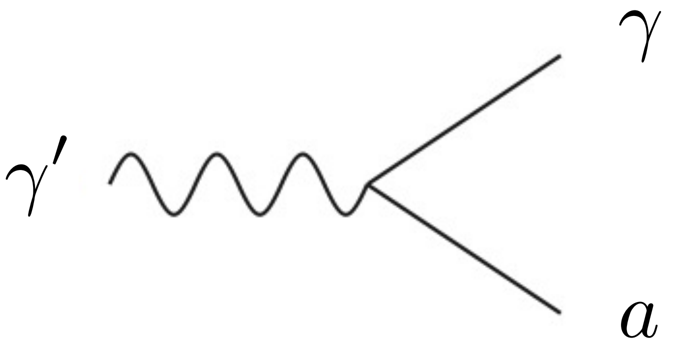
Visible/Invisible decay of Dark photon

For the convenience of the analysis, we will treat the axion as missing energy.
However, the missing energy is not a signal of the dark axion portal;
it is a signal of the dark axion portal in the absence of the axion portal.

(ex) 3-photon resonance signal of the dark photon ($G_{a\gamma\gamma'}$ & $G_{a\gamma\gamma}$)



(iii) "Photon" search ("another" visible dark photon scenario)

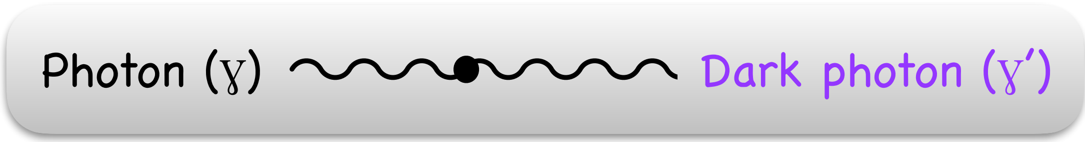


$$\Gamma(\gamma' \to \gamma a) = \frac{G_{a\gamma\gamma'}^2}{96\pi} m_{\gamma'}^3 \left(1 - \frac{m_a^2}{m_{\gamma'}^2}\right)^3$$

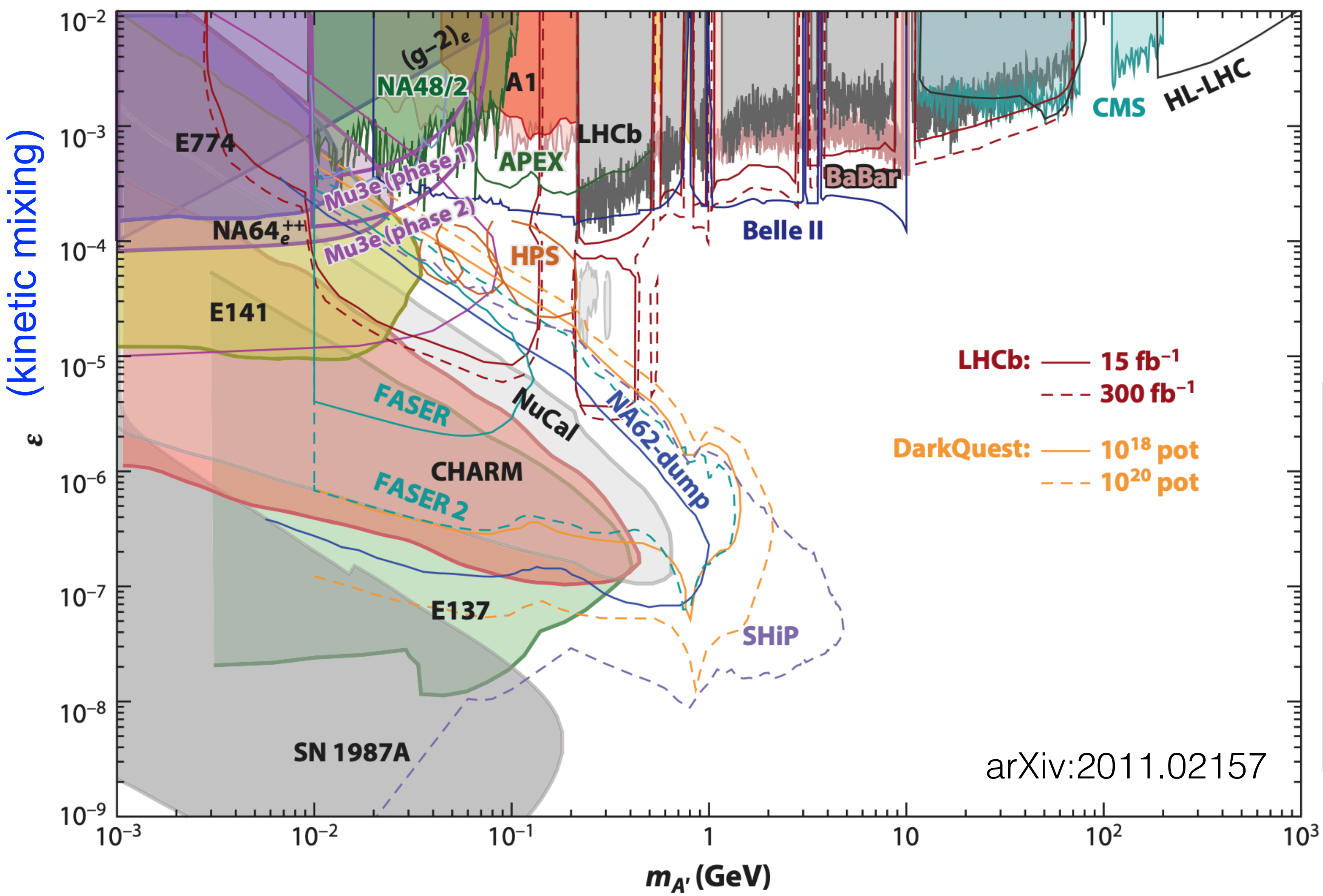
a (axion or axion-like particle)

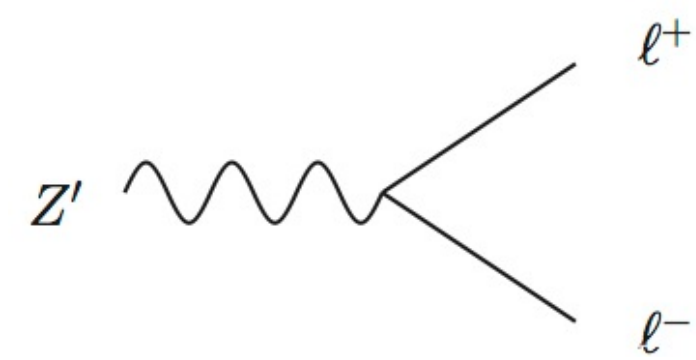
[Possible to be the dominant decay channel. Sub-MeV dark photons may decay.]

Dilepton searches for (Visible dark photon)



γ-γ′ kinetic mixing
(vector portal)



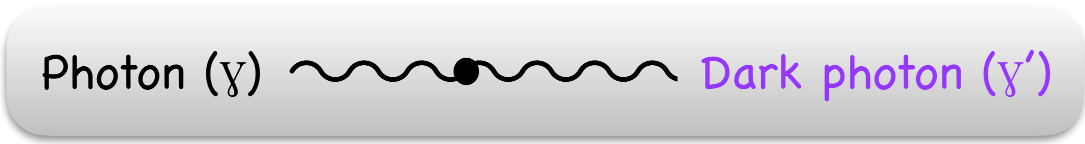


Mostly from the Z' → dilepton searches (e^+e^- or $\mu^+\mu^-$)

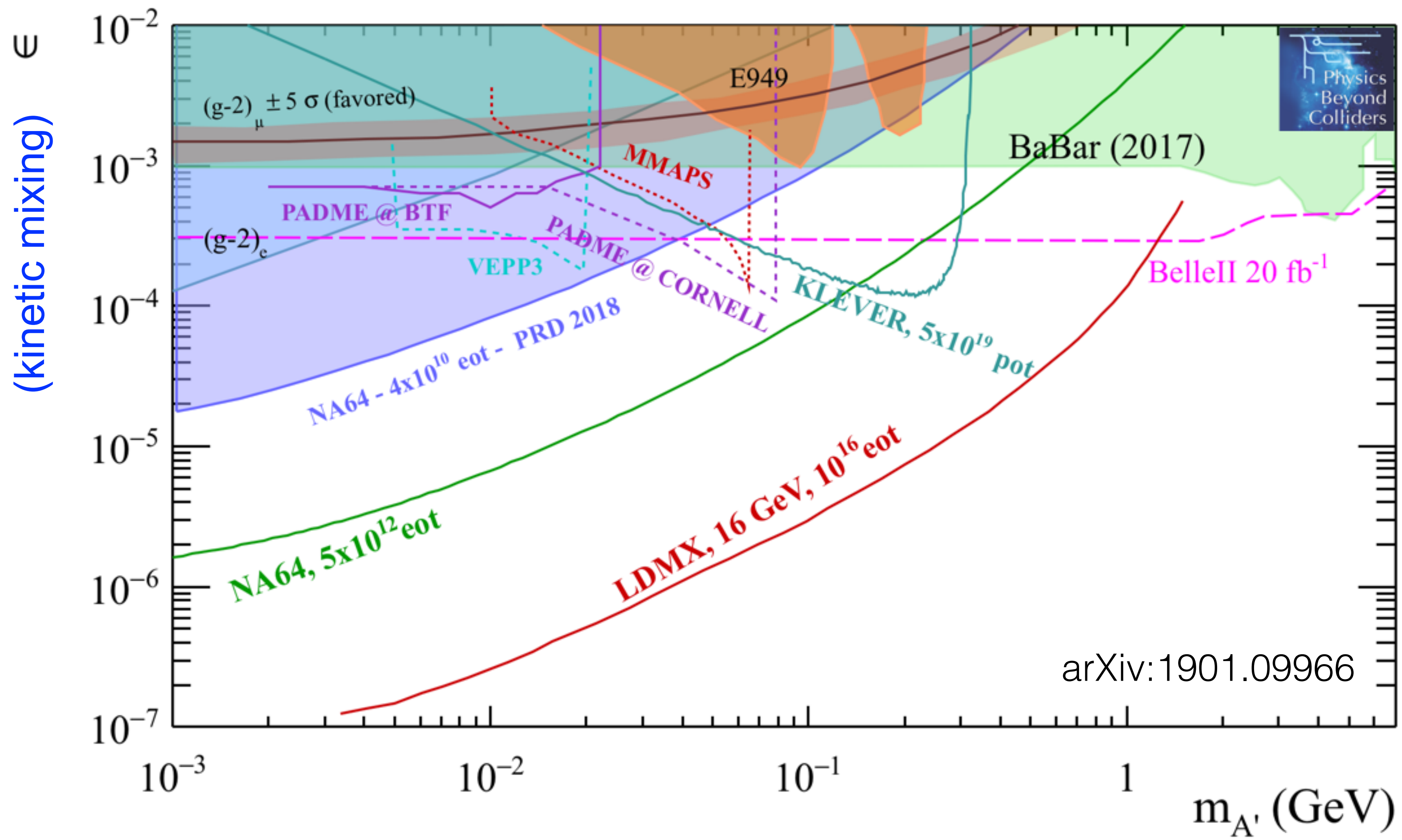
(i) Beam-dumps
(ii) Meson (quarkonium) decays
(iii) e+e- collision (photon+Z')
(iv) Fixed target experiments
…

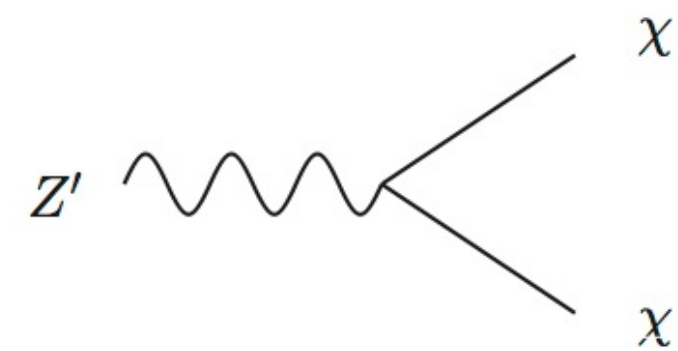
The dark gauge boson is actively searched for in many experiments.
The vector portal is constrained to be small ($\varepsilon \ll 1$) .

Missing energy searches (Invisible dark photon)



γ-γ′ kinetic mixing
(vector portal)





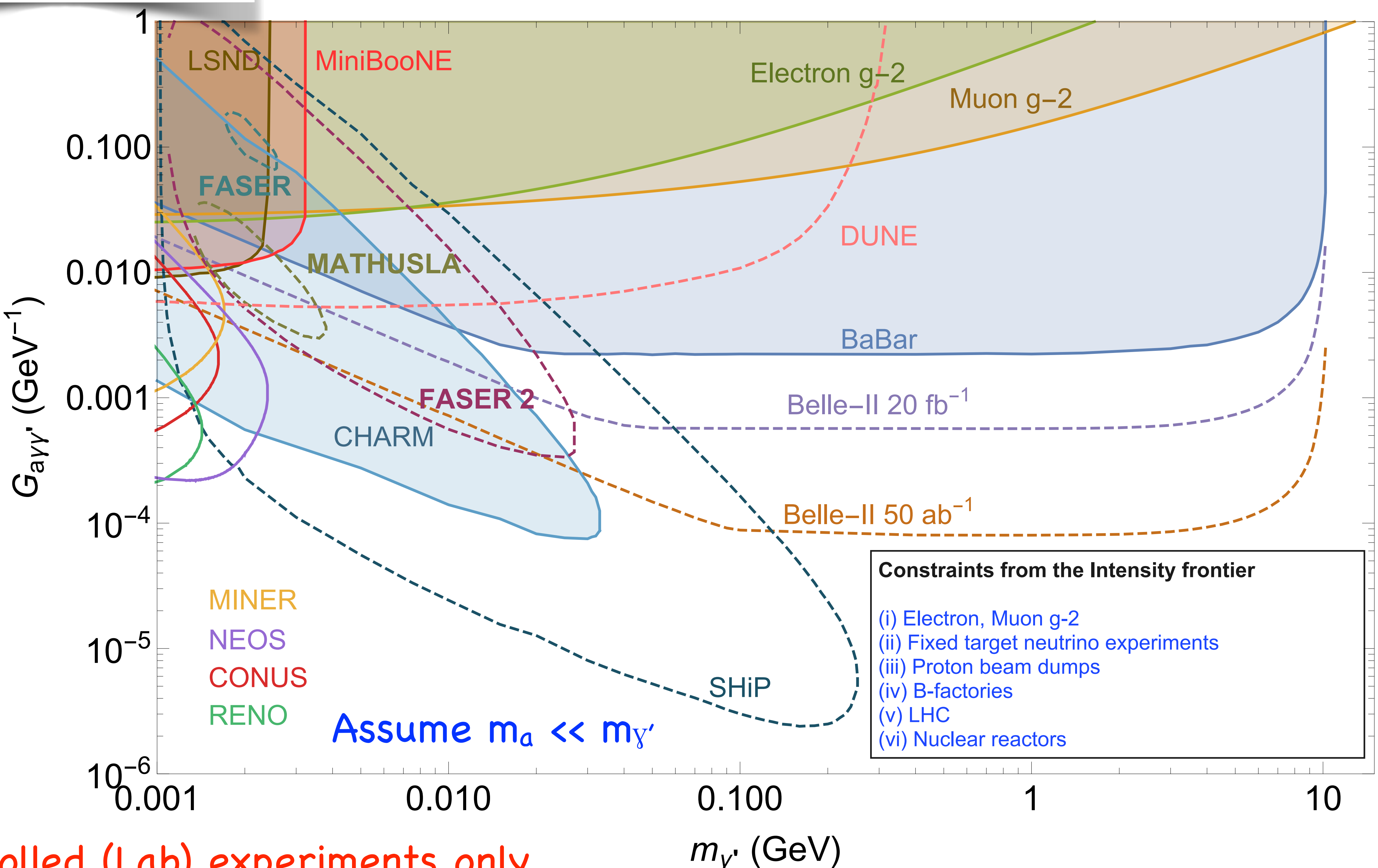
The invisible dark photon is also actively searched for in many experiments.
The vector portal is constrained to be small ($\epsilon \ll 1$) in this scenario too.

Dark axion portal parameter space

[deNiverville, LEE, Seo (2018); deNiverville, LEE (2019); deNiverville, LEE, Lee (2020)]

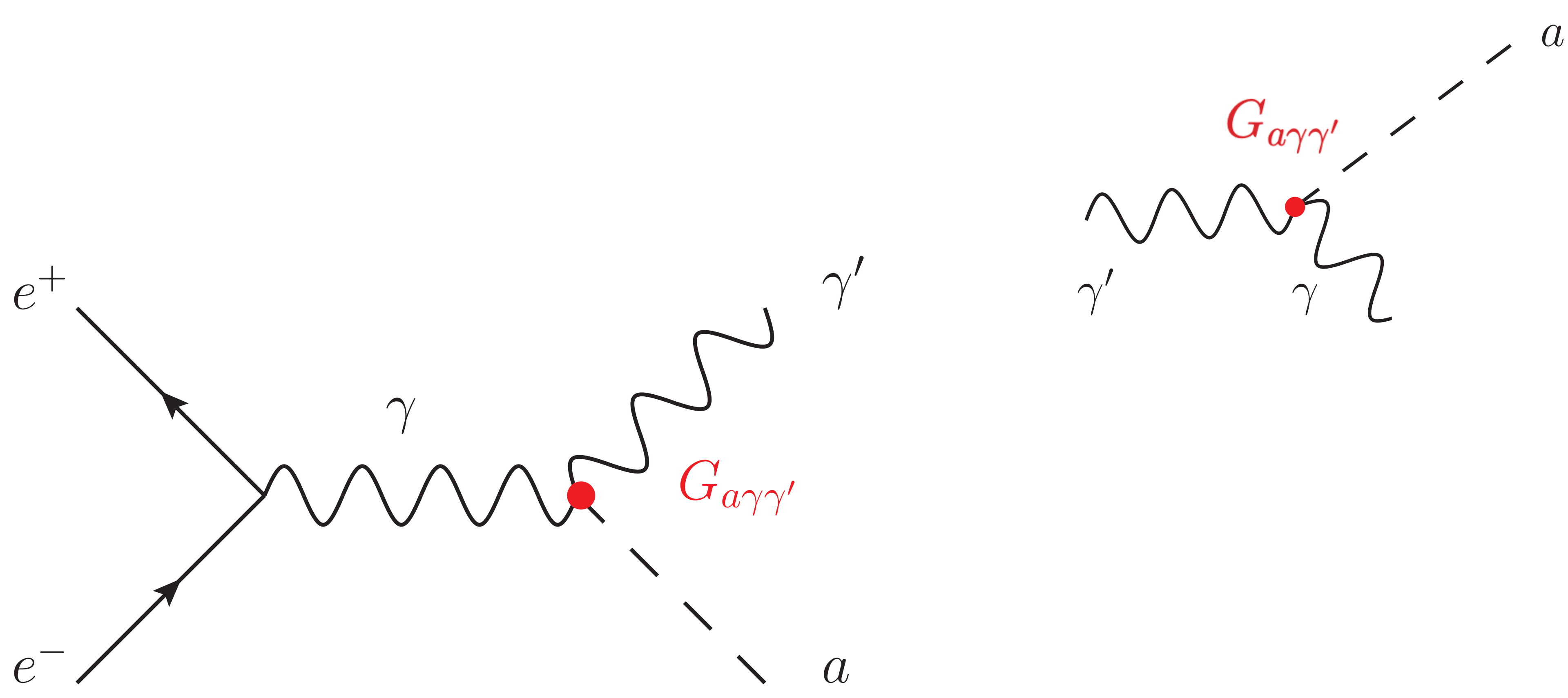
Production & detection through dark axion portal

$G_{a\gamma\gamma'}$ only (model-independent way): We take axion as a very light particle carrying a missing energy, and neglect the possible effect of $G_{a\gamma\gamma}$ vertex.



Controlled (Lab) experiments only

B-factories (BaBar, Belle II)

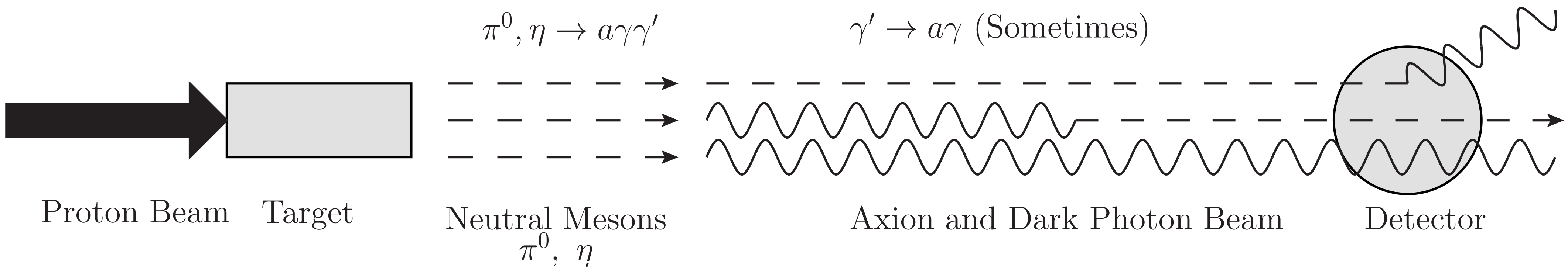


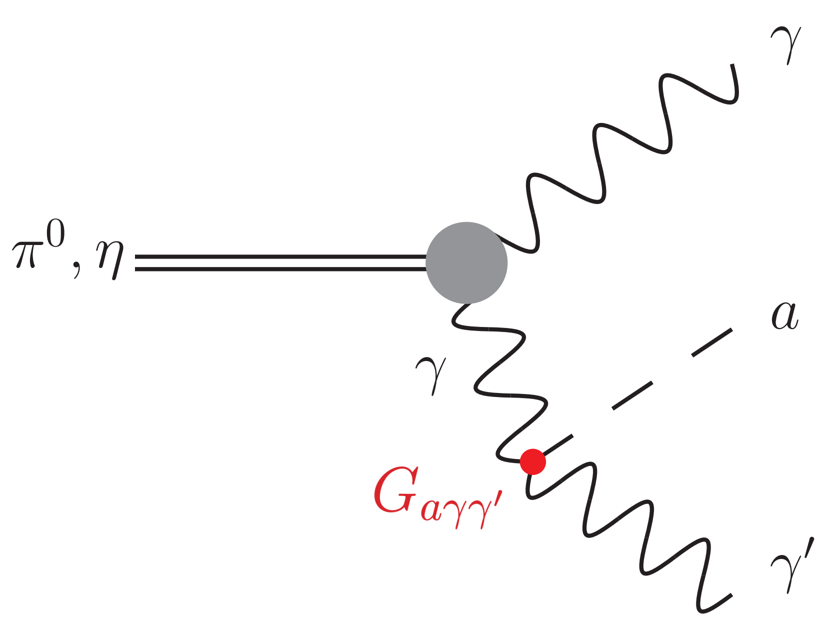
B-factories are asymmetric e+e- colliders of $E_{CM} \approx 10$ GeV.
e+e- can annihilate into a dark photon + axion, and the dark photon can decay into a photon + axion (e+e- → ɣ' a → ɣ a a). It is a mono-photon search.

Fixed Target Neutrino Experiments (LSND, MiniBooNE, DUNE)

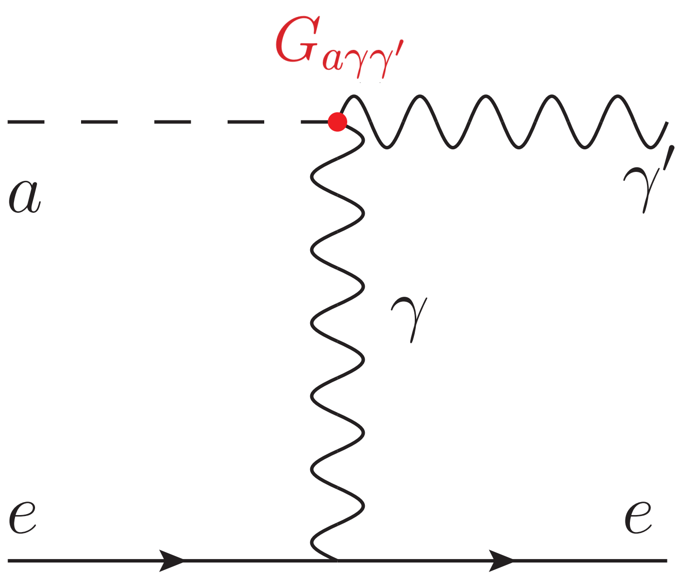
(originally for $\pi^{\pm}, K^{\pm} \to \nu_\mu \mu^{\pm}$)

5 years, on-axis
(10^{21} POT/year)





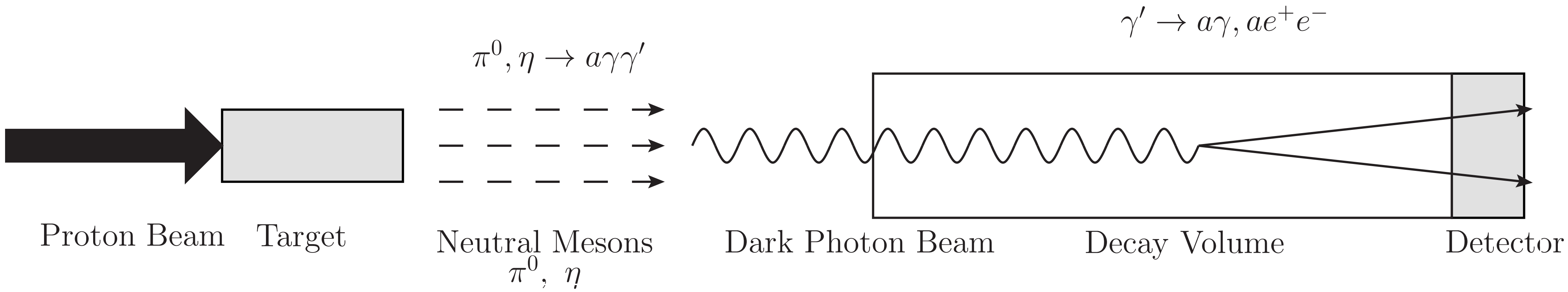
Production

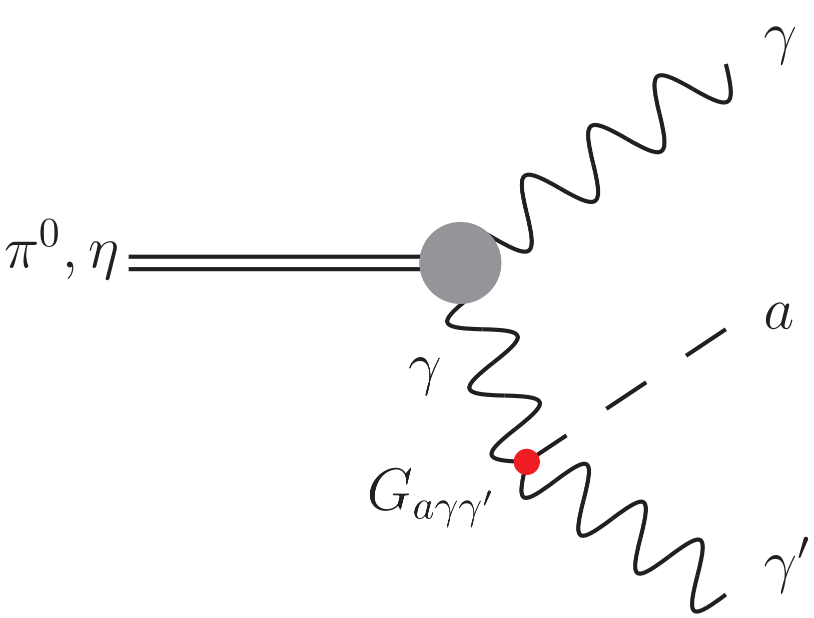


Detection of scattering

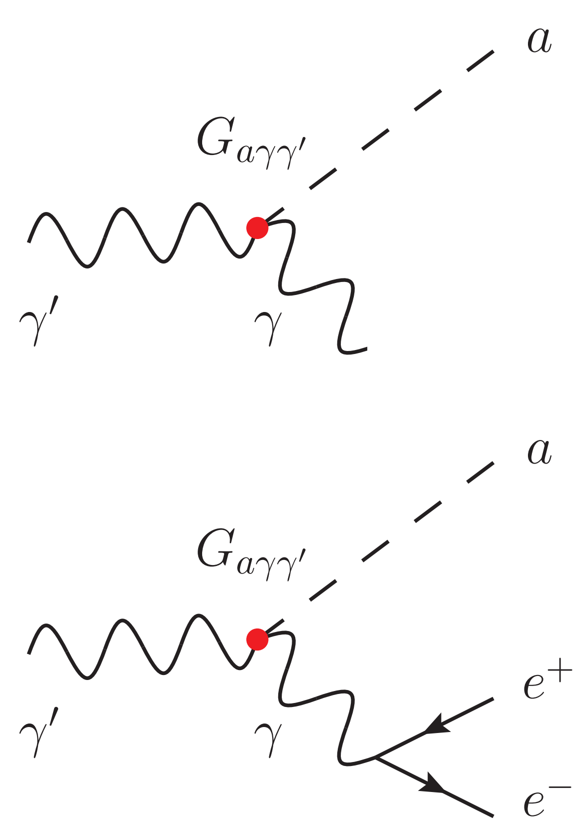
π (η) mesons decay into a photon + axion + dark photon.
Axion can scatter with the electrons in the detector (mineral oil, etc).
Signals are similar to the neutral current elastic (NCE) scattering of the neutrinos.

Proton beam dumps (CHARM, SHiP future)





Production

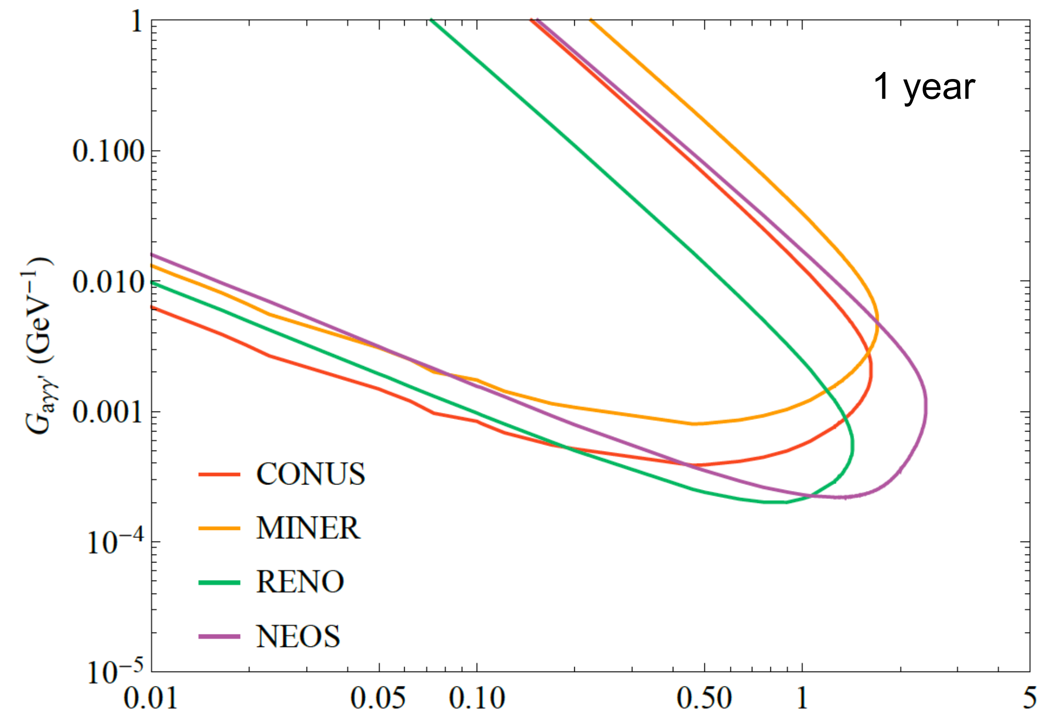


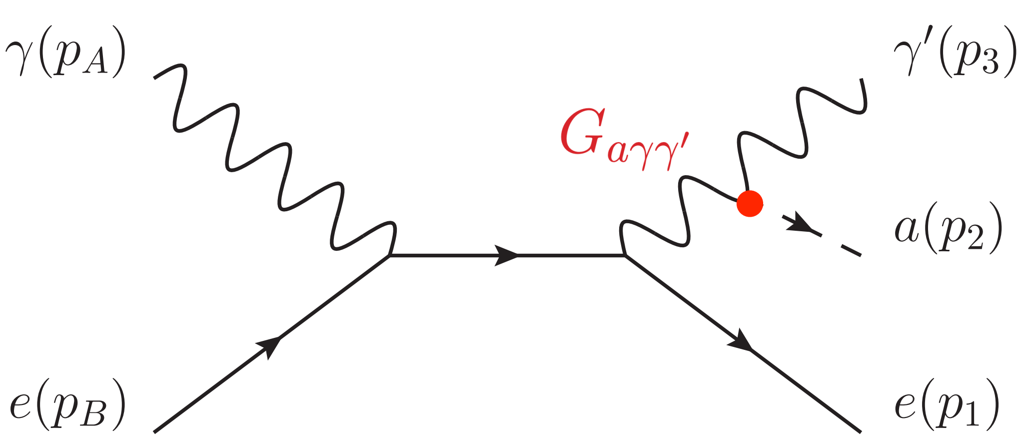
Detection of decays

π (η) mesons decay into a photon + axion + dark photon.
Dark photons can decay into the mono-photon + axion (CHARM) or 2 charged tracks + axion (SHiP).

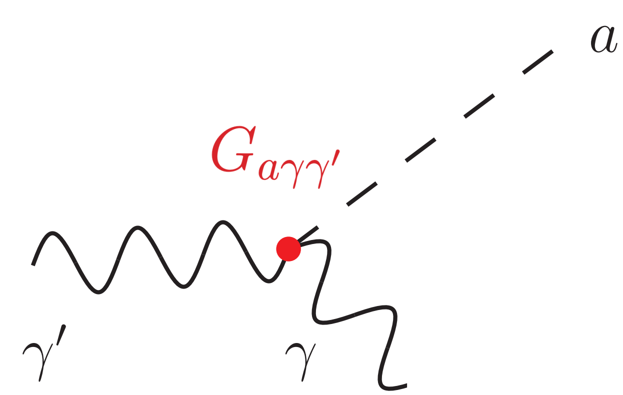
Reactor experiments (MINER/CONUS, RENO/NEOS)

(1GW: 10^{28} photons/year)





Production



Detection of decays

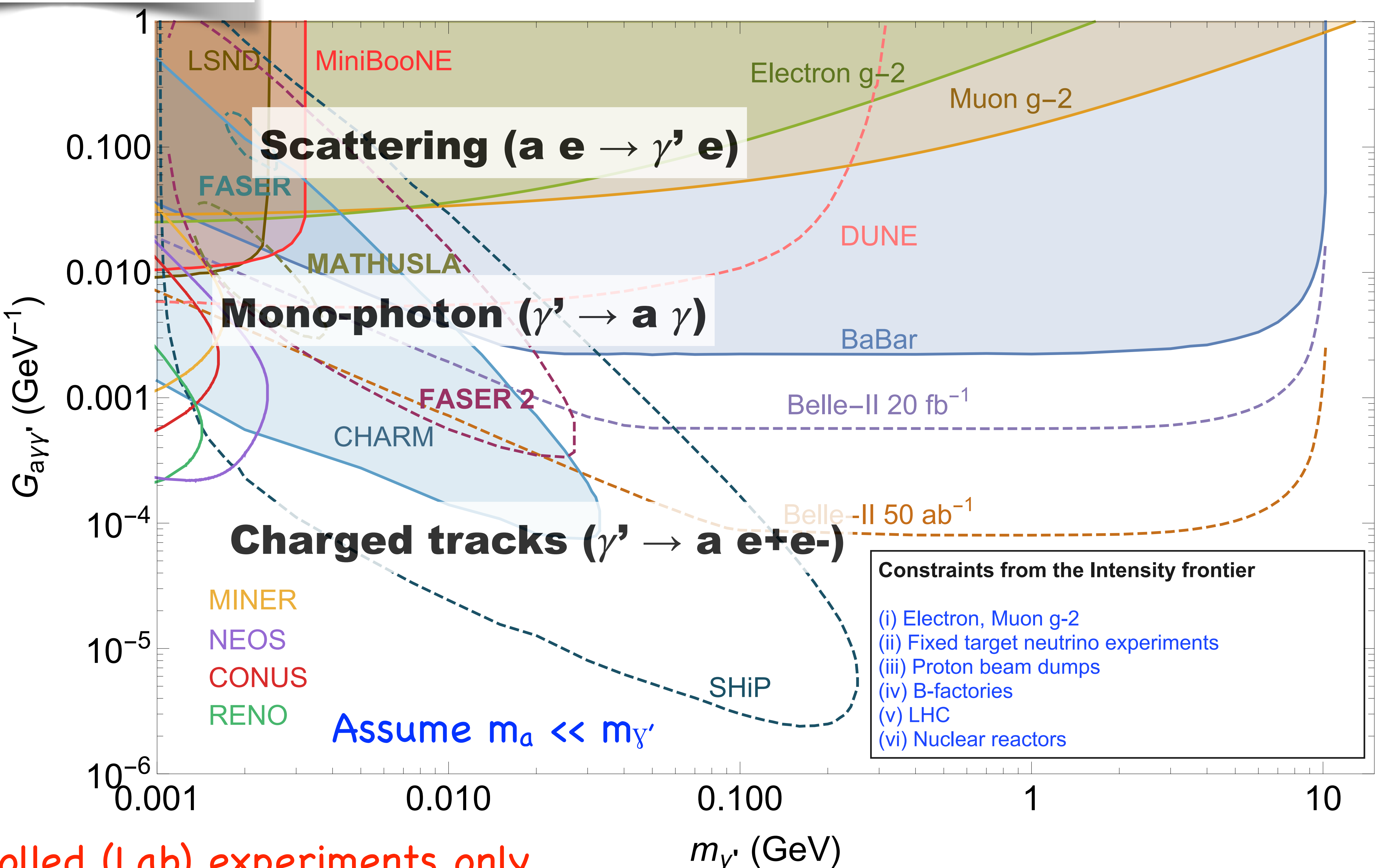
Reactor energy is low, but it produces huge flux of photons.
Good to probe the small mass, small coupling region.
(Because of isotropic production, the closer distance is more sensitive.)

Dark axion portal parameter space

[deNiverville, LEE, Seo (2018); deNiverville, LEE (2019); deNiverville, LEE, Lee (2020)]

Production & detection through dark axion portal

$G_{a\gamma\gamma'}$ only (model-independent way): We take axion as a very light particle carrying a missing energy, and neglect the possible effect of $G_{a\gamma\gamma}$ vertex.



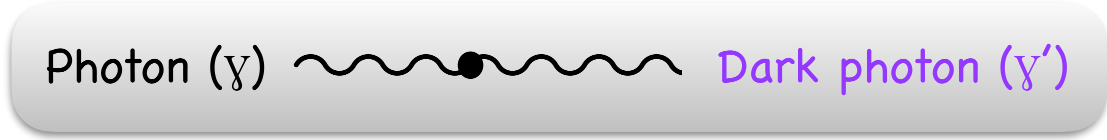
Controlled (Lab) experiments only

Combination of the “dark photon portals”

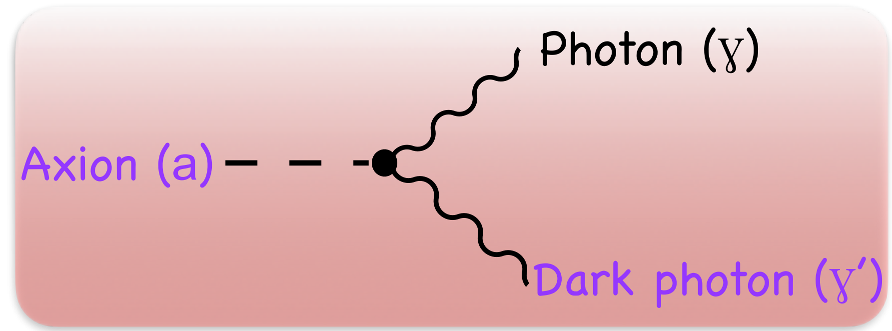
$$(K \equiv \varepsilon G_{a\gamma\gamma'})$$

Portals for the dark photon

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

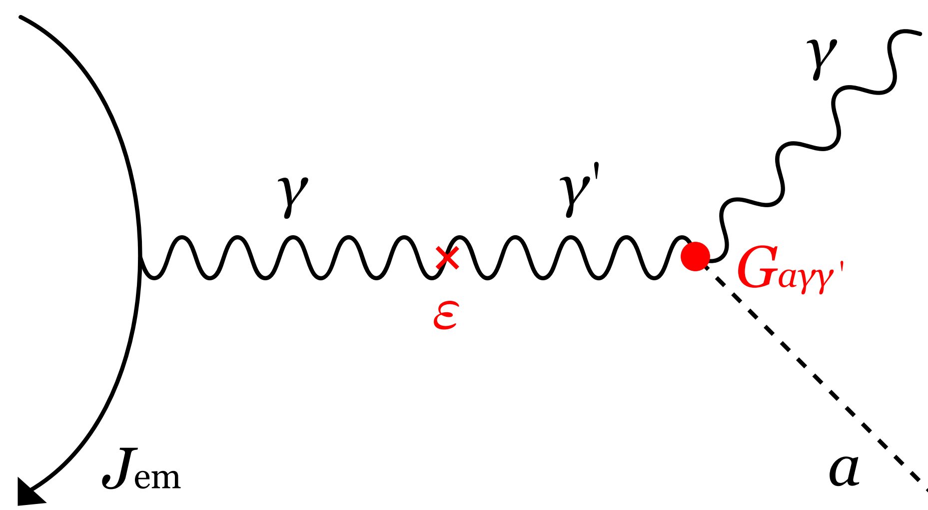


(ii) Dark Axion Portal $\frac{G_{a\gamma\gamma'}}{4} a F_{\mu\nu} \tilde{Z}'^{\mu\nu}$



We consider a combination of two “dark photon portals”.

Production with vector portal,
Decay with dark axion portal.

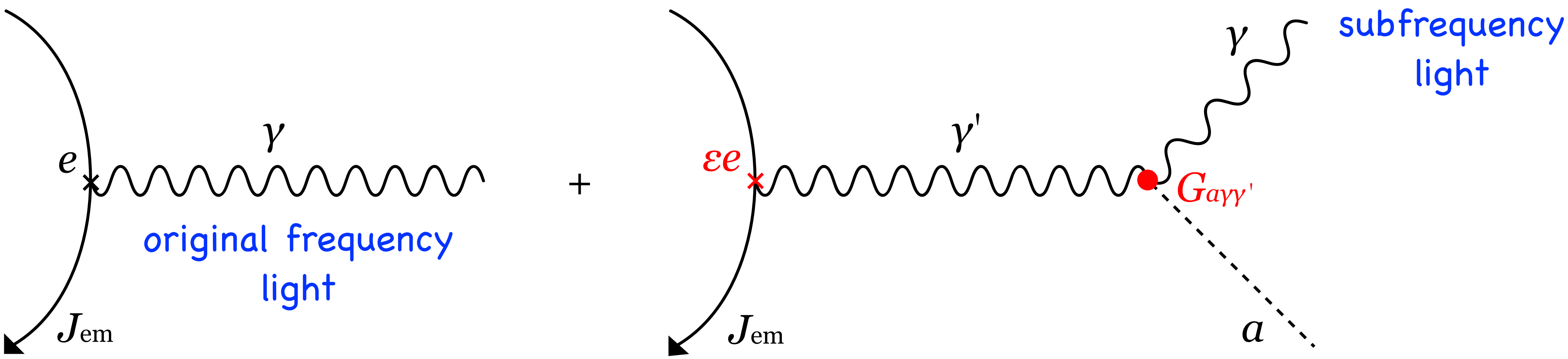


(In the interaction eigenstates)

Subfrequency portal (combined portal)

[LEE, Lee, Yi (2022)]

(In the mass eigenstates)



Subfrequency signal: Any light source can also emit subfrequency light.

Conditions to have the subfrequency signal:

(i) Both vector portal (ε) and dark axion portal ($G_{a\gamma\gamma'}$) exist.

(ii) Mass (energy) hierarchy [$m_a < m_{\gamma'} < \omega$] where ω is light source energy.

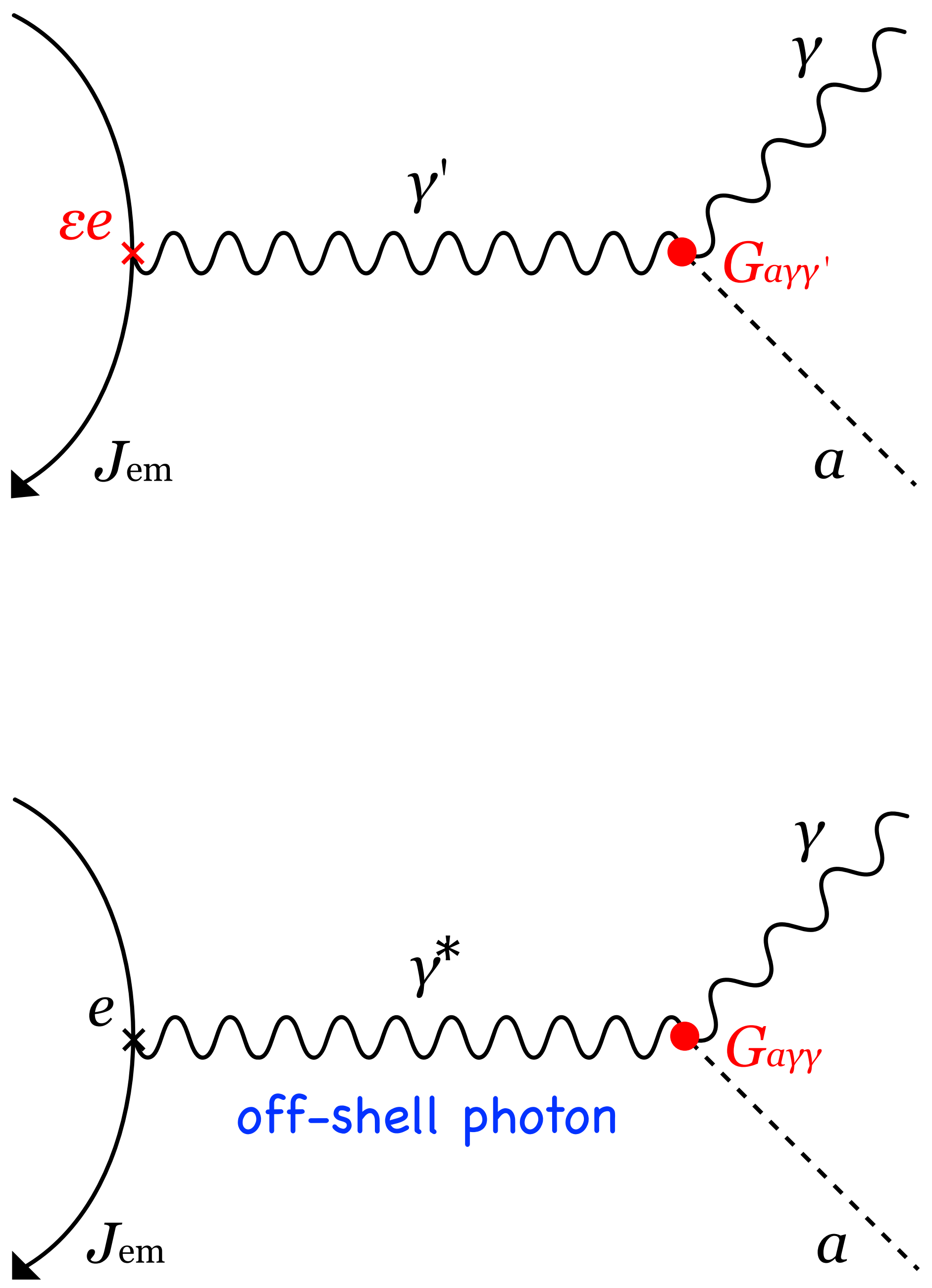
$$\mathcal{L} \sim -\left(A_\mu + \varepsilon A'_\mu\right) J^\mu_{\rm em} + \frac{G_{a\gamma\gamma'}}{2} a F_{\mu\nu} \tilde{F}'^{\mu\nu}$$

$$\Gamma_{\gamma' \to a\gamma} = \frac{G^2_{a\gamma\gamma'}}{96\pi} m^3_{\gamma'} \left(1 - \frac{m_a^2}{m_{\gamma'}^2}\right)^3$$

Subfrequency portal (combined portal)

[LEE, Lee, Yi (2022)]

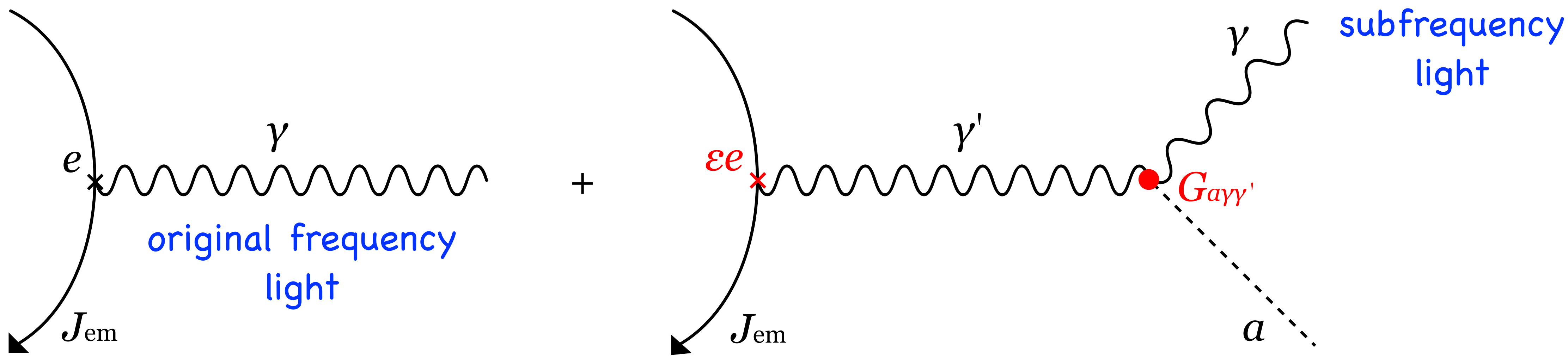
Unlike the off-shell suppressed axion portal, this combined portal may have all on-shell particles.



Subfrequency portal (combined portal)

[LEE, Lee, Yi (2022)]

(In the mass eigenstates)



Subfrequency signal: Any light source can also emit subfrequency light.

$$\frac{N_{\rm sub}}{N_\gamma} = \varepsilon^2 \left(1 - \exp\left[-\frac{m_{\gamma'}\Gamma L}{\sqrt{\omega^2 - m_{\gamma'}^2}}\right]\right)$$

$$\approx \frac{K^2}{48\pi}\frac{m_{\gamma'}^4}{\sqrt{\omega^2 - m_{\gamma'}^2}} L \qquad (K \equiv \varepsilon G_{a\gamma\gamma'})$$

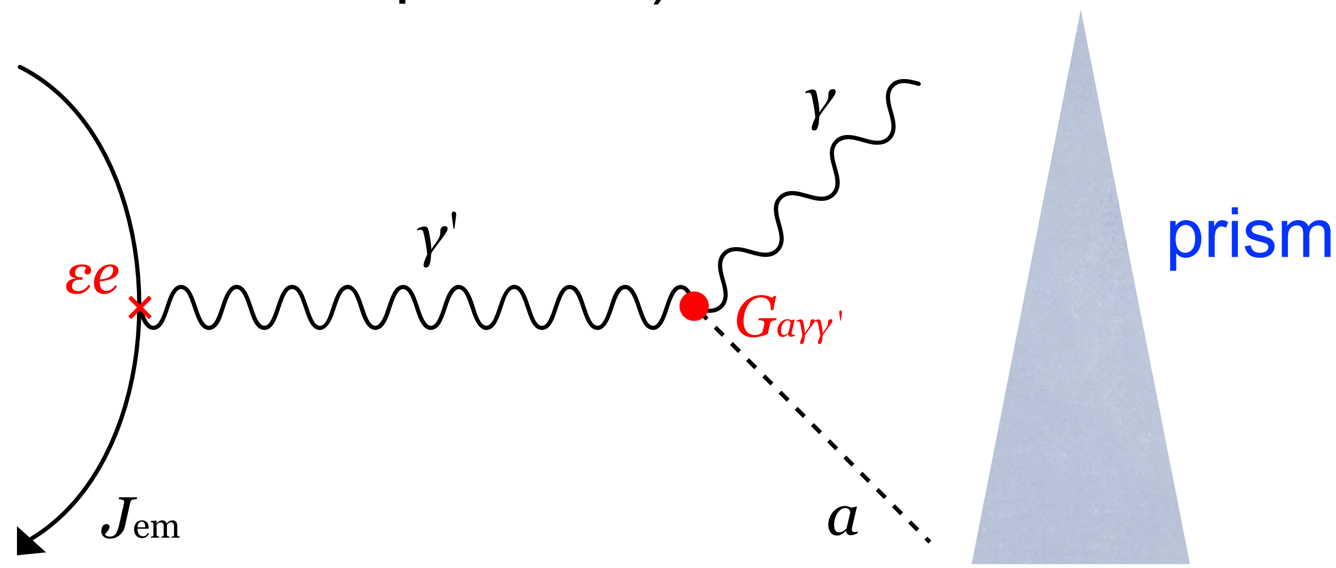
We assume $m_a << m_{\gamma'}$.

Ratio of the subfrequency photon number to the original frequency photon number in the laser experiment. (ω: laser frequency, L: distance from the γ' production)

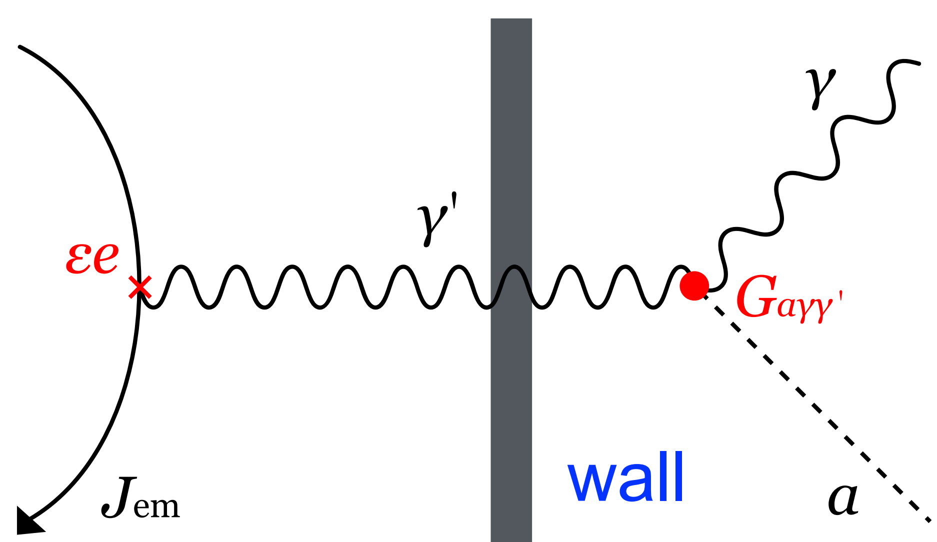
Laser experiment

Q: How can we distinguish the subfrequency signal from the original laser light?

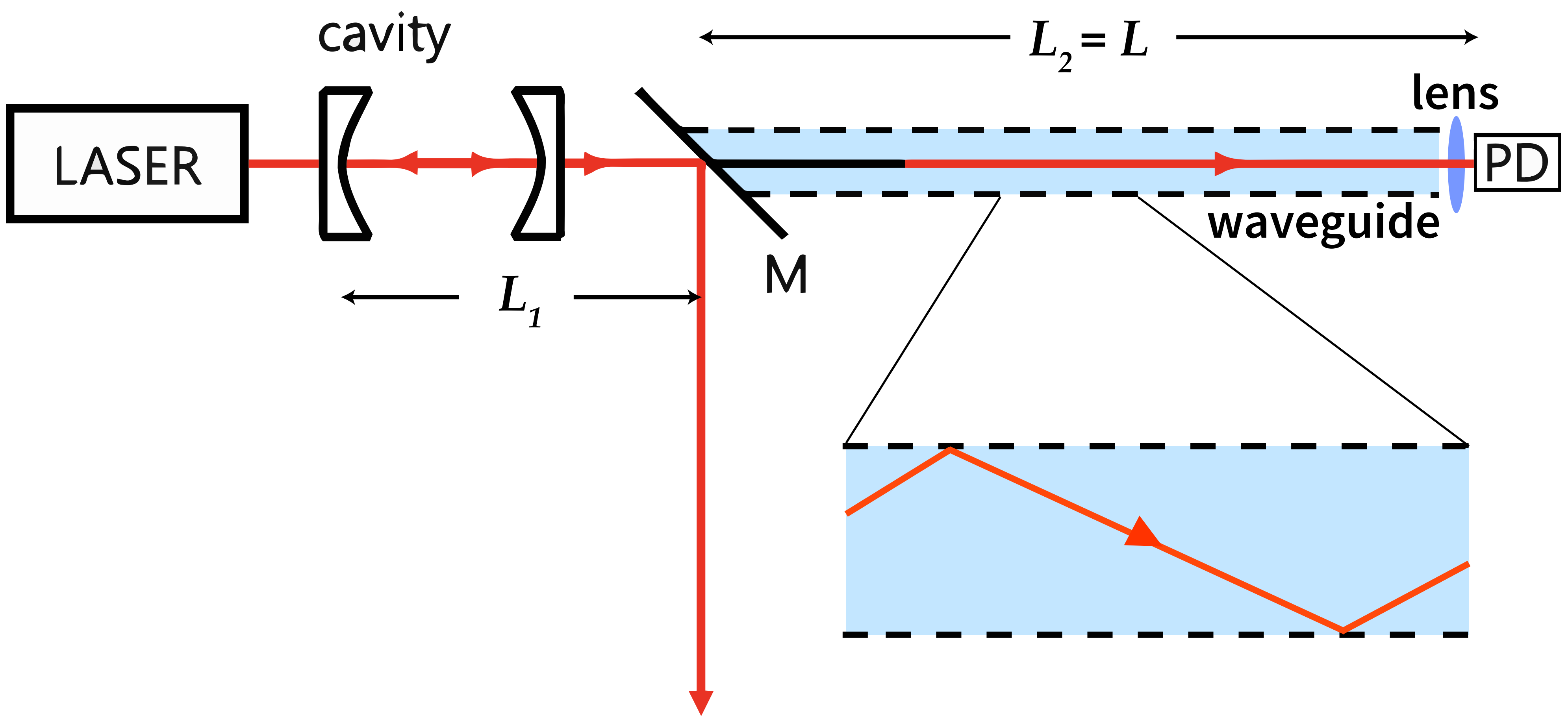
(i) **Prism** (different directions for different frequencies)



(ii) **Wall** (blocking the photon, passing the dark photon) similar to the Light Shining through Wall (LSW) experiments.



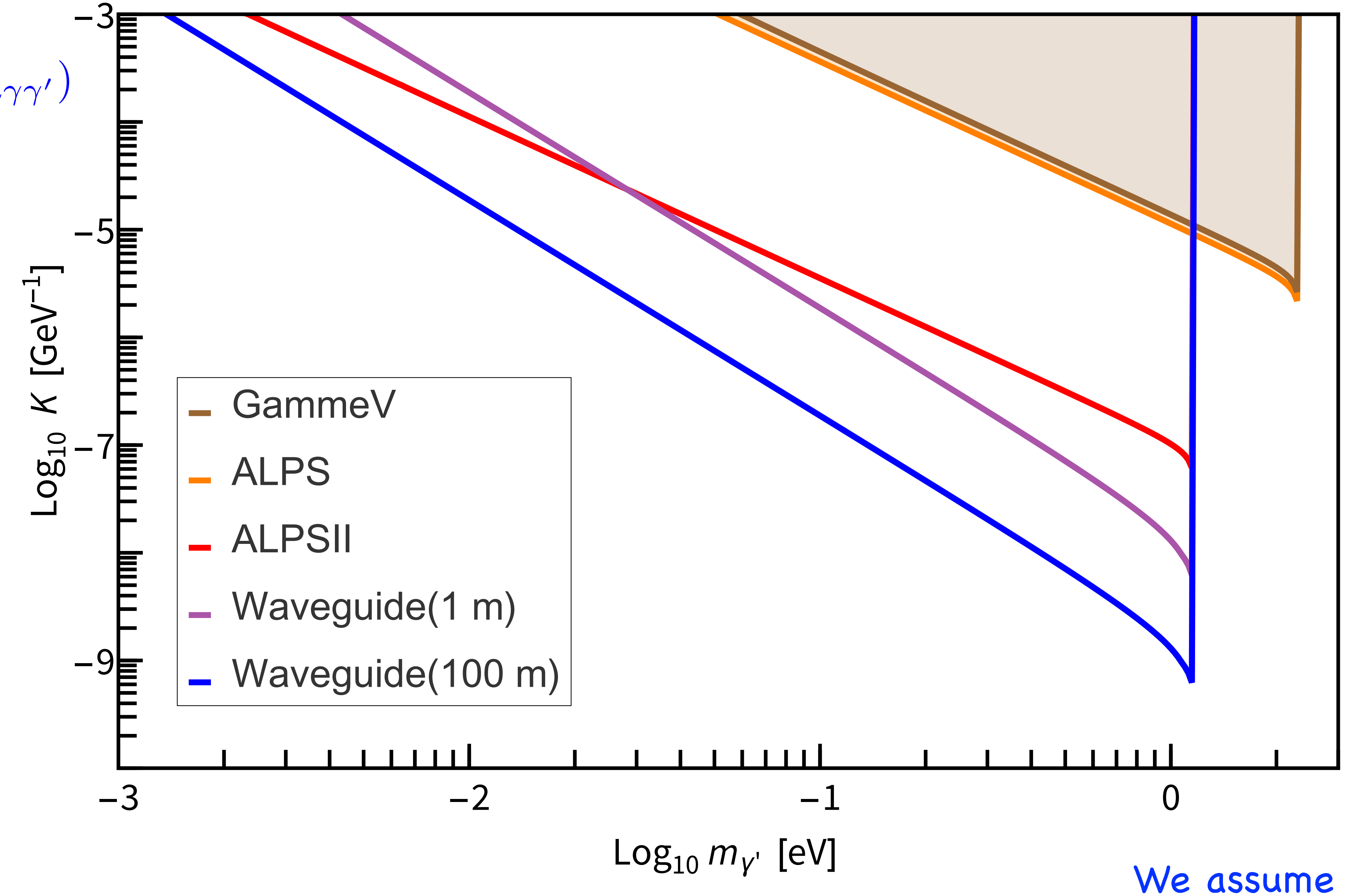
Laser experiment



(i) The mirror M serves as a wall.
(ii) The waveguide (hollow pipe with a highly reflective metal coating inside) helps collecting the signal photons of angular dispersion.
(iii) The photon detector (e.g. tungsten Transition Edge Sensor) covers wide range of frequency.

Subfrequency search with Laser

$(K \equiv \varepsilon G_{a\gamma\gamma'})$

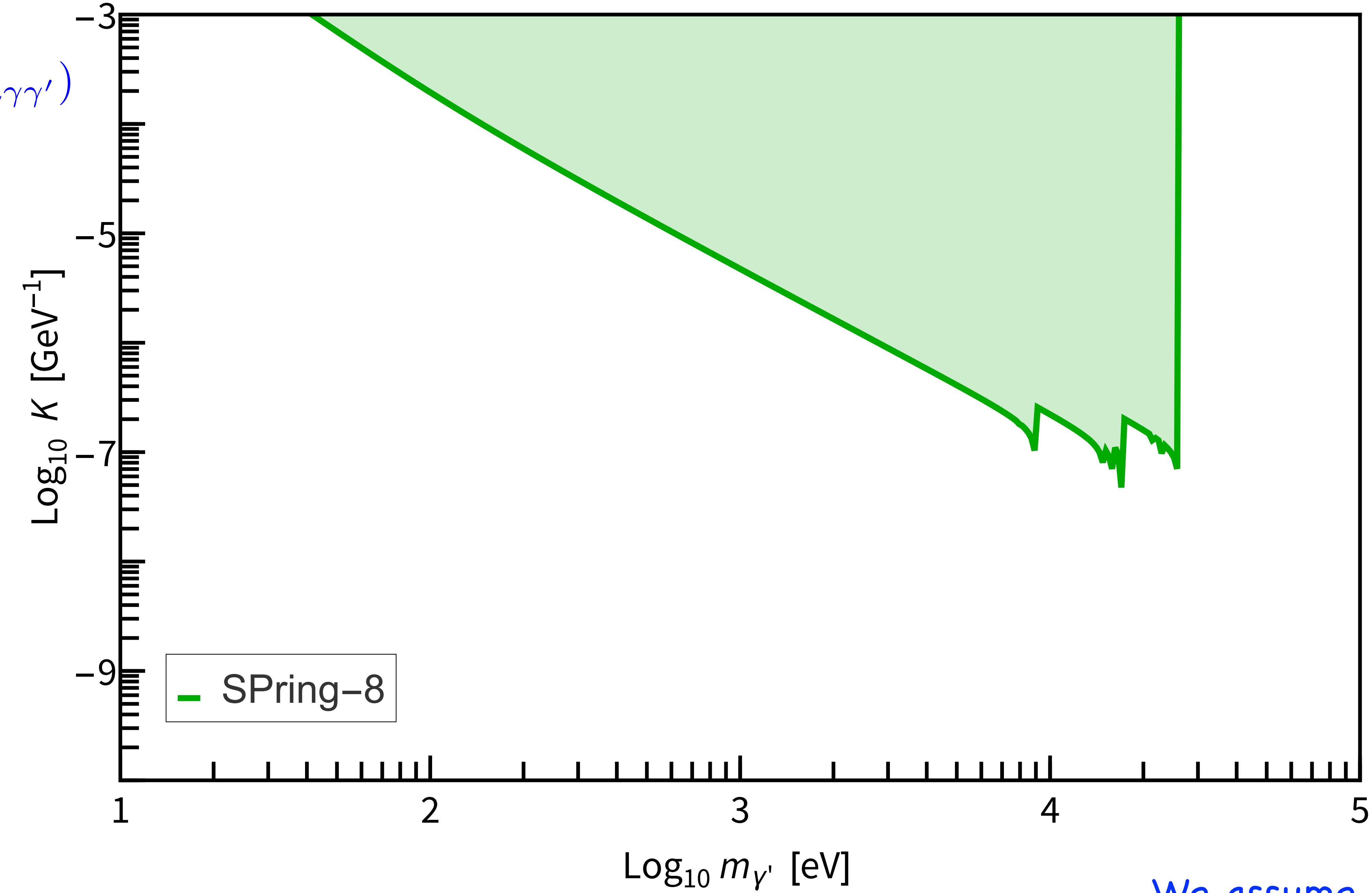


We assume $m_a \ll m_{\gamma'}$.

Lasers can cover the eV-scale dark photon and below.

Subfrequency search with X-ray

$(K \equiv \varepsilon G_{a\gamma\gamma'})$

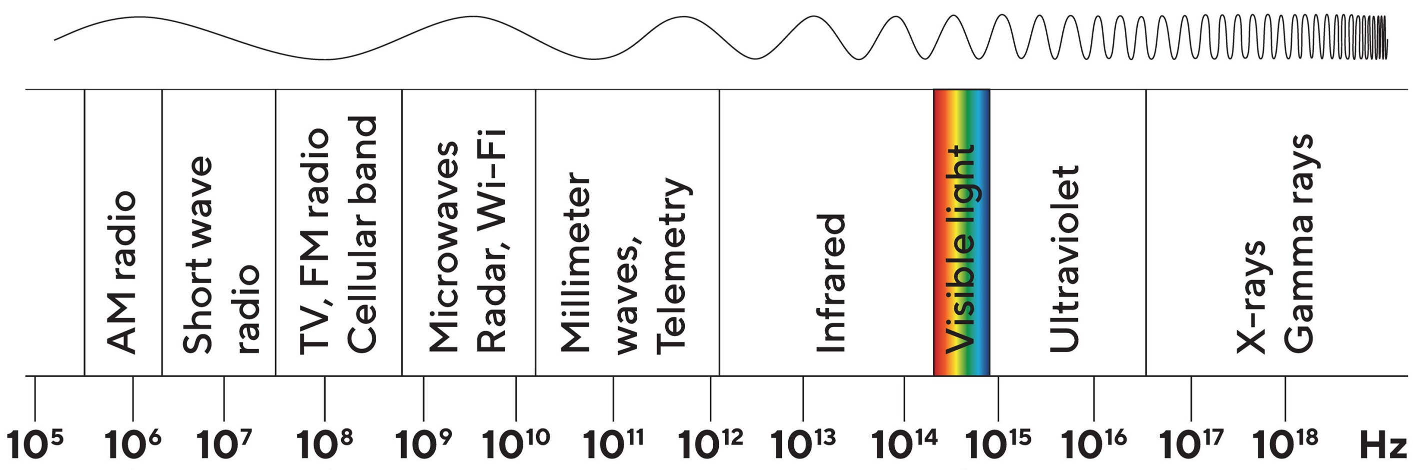


We assume $m_a \ll m_{\gamma'}$.

X-ray light sources can cover heavier (10 keV-scale) dark photons.

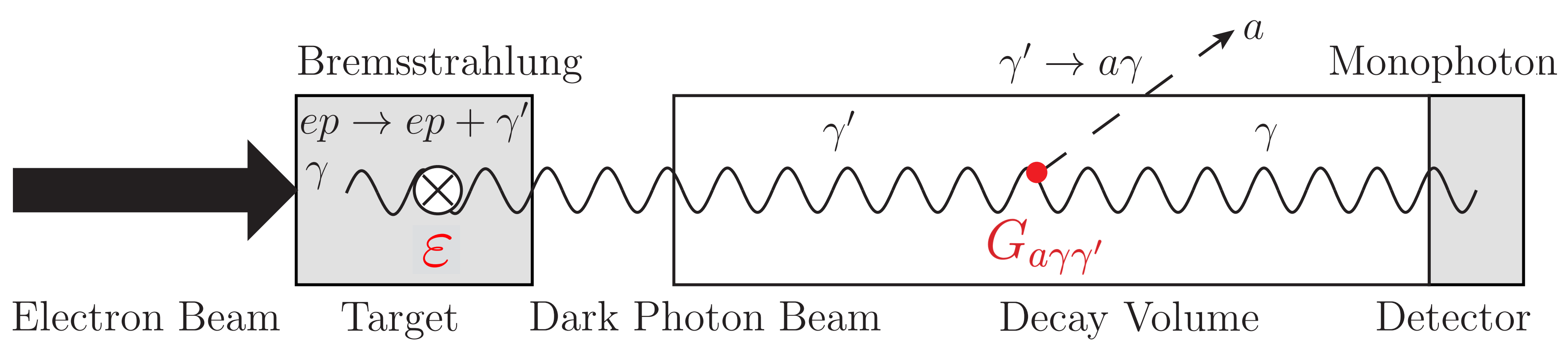
Subfrequency searches at other places

Subfrequency signal: Any light source can also emit a subfrequency light.



Plenty of other possible sources (other than optical laser and X-ray)
: Reactor, Meson decays, Bremsstrahlung, CMB, Stellar, Other astrophysical, ···

(ex) e-beam dump experiment

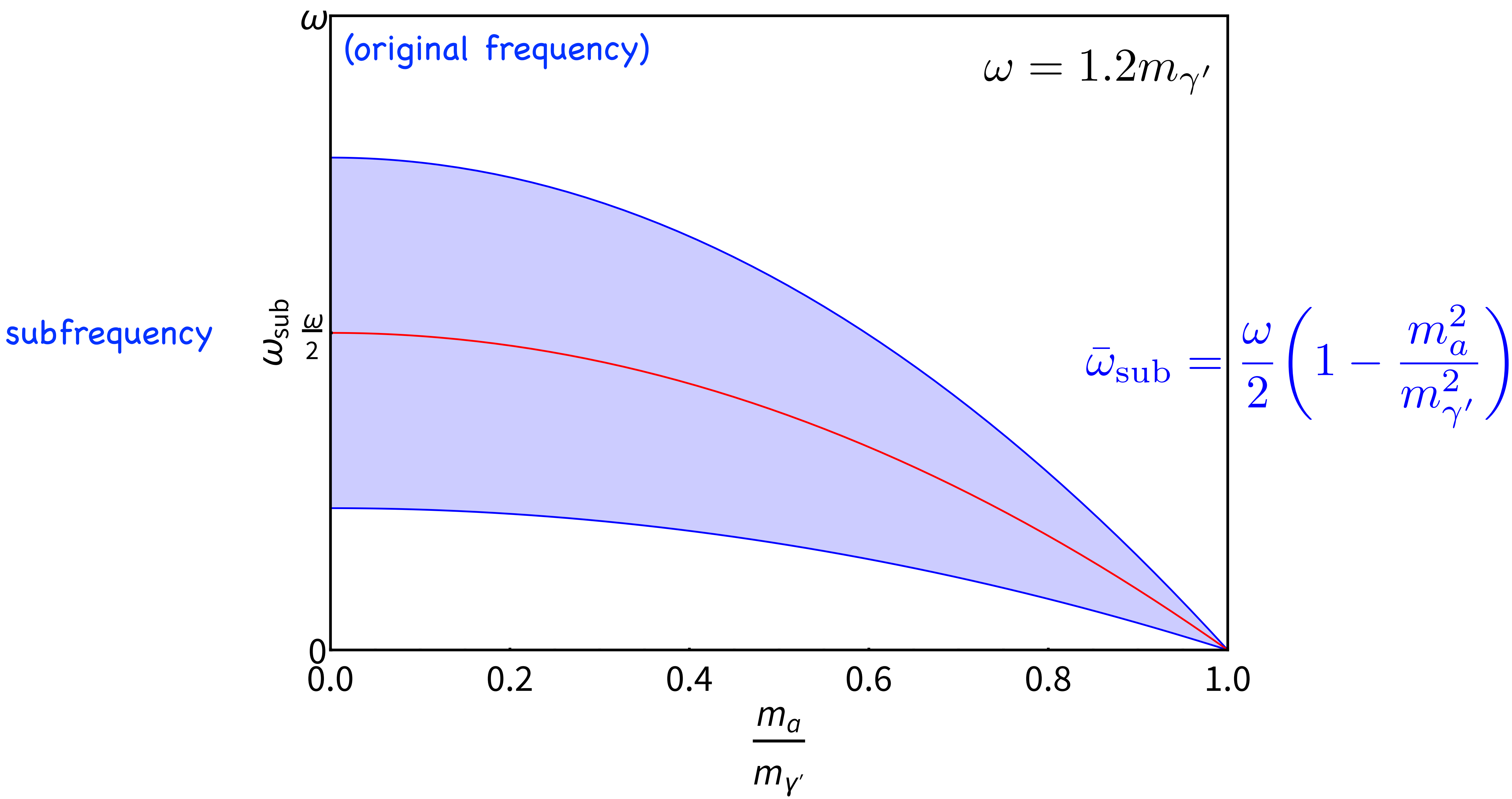


Production via vector portal, decay via dark axion portal (into a subfrequency photon).
: A new low-E dark photon experiment using an affordable e-beam facility.
(Most dark photon searches look for dilepton resonances or missing energy.)

[Possibly dominant decay channel. Sub-MeV dark photons may decay.]

Axion mass dependence of the subfrequency

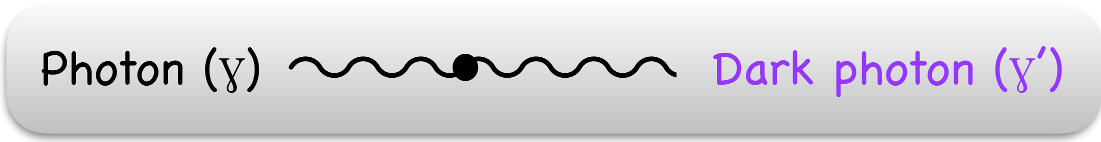
[LEE, Lee, Yi (Preliminary)]



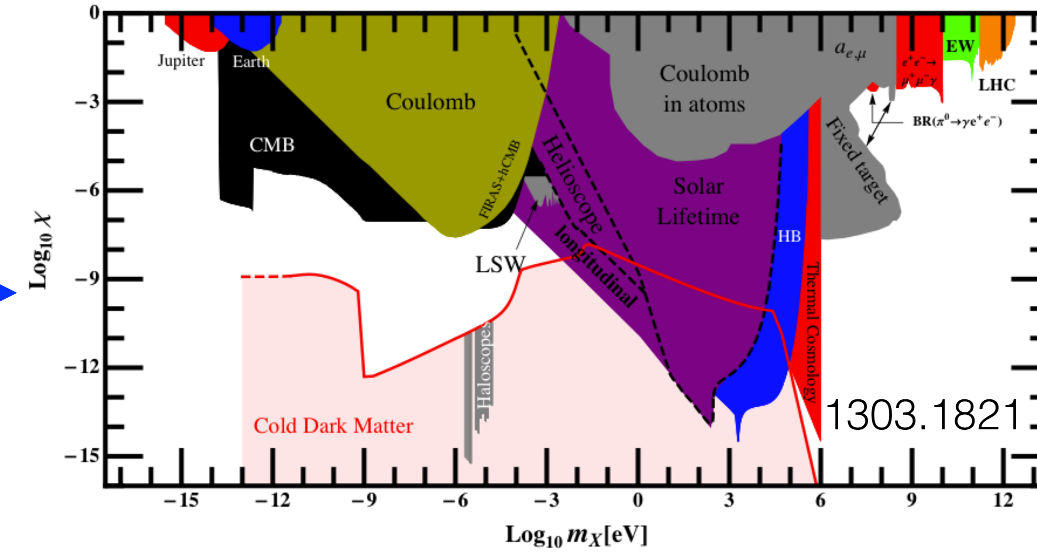
The subfrequency photons come from the boosted decay. The subfrequency could be much smaller than the original frequency for a heavy axion.

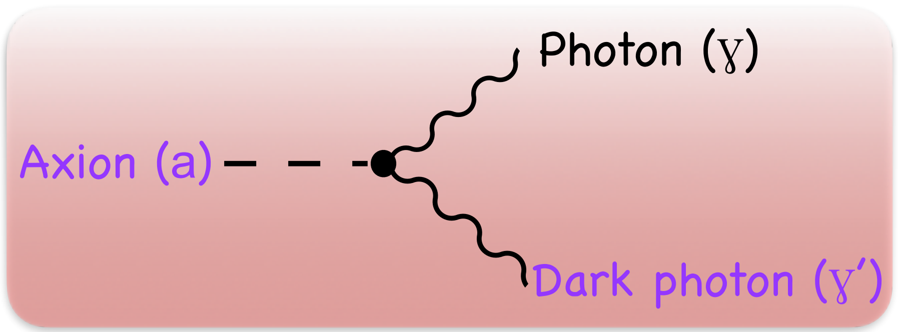
(For instance, a gamma-ray source can emit infrared light.)

Concluding Remarks

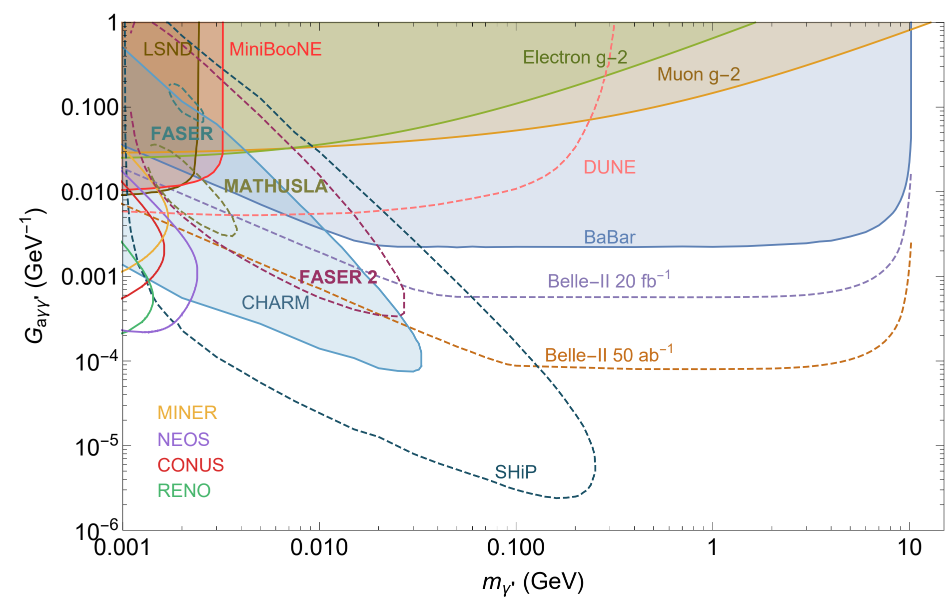


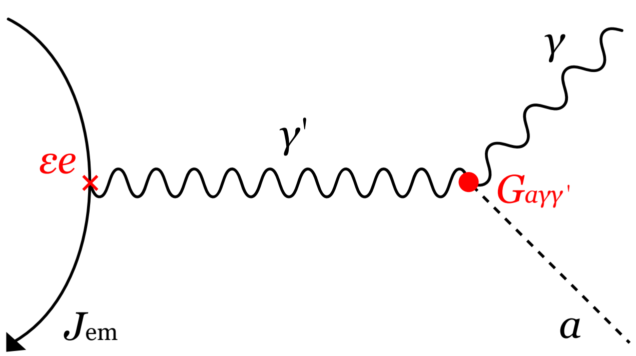
vector portal (ε)



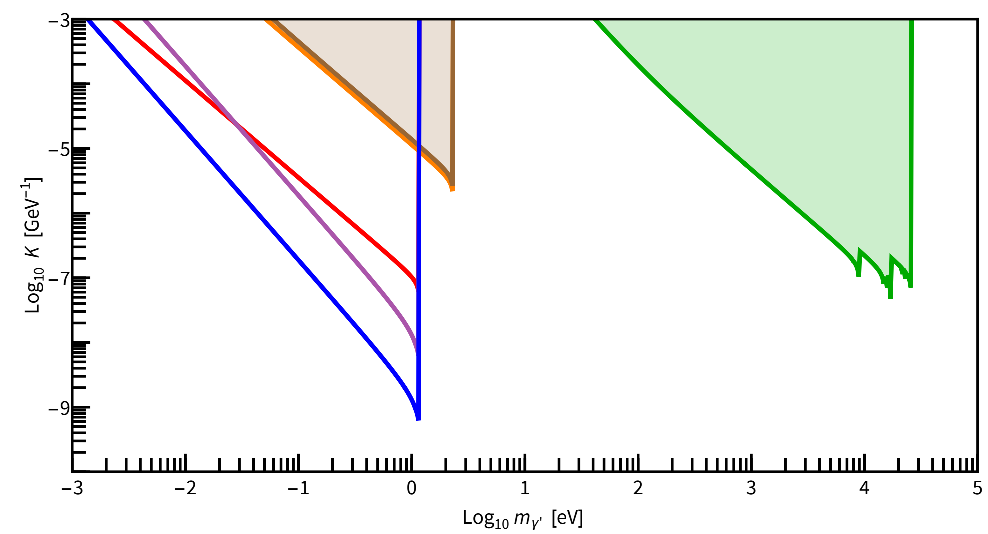


dark axion portal ($G_{a\gamma\gamma'}$)



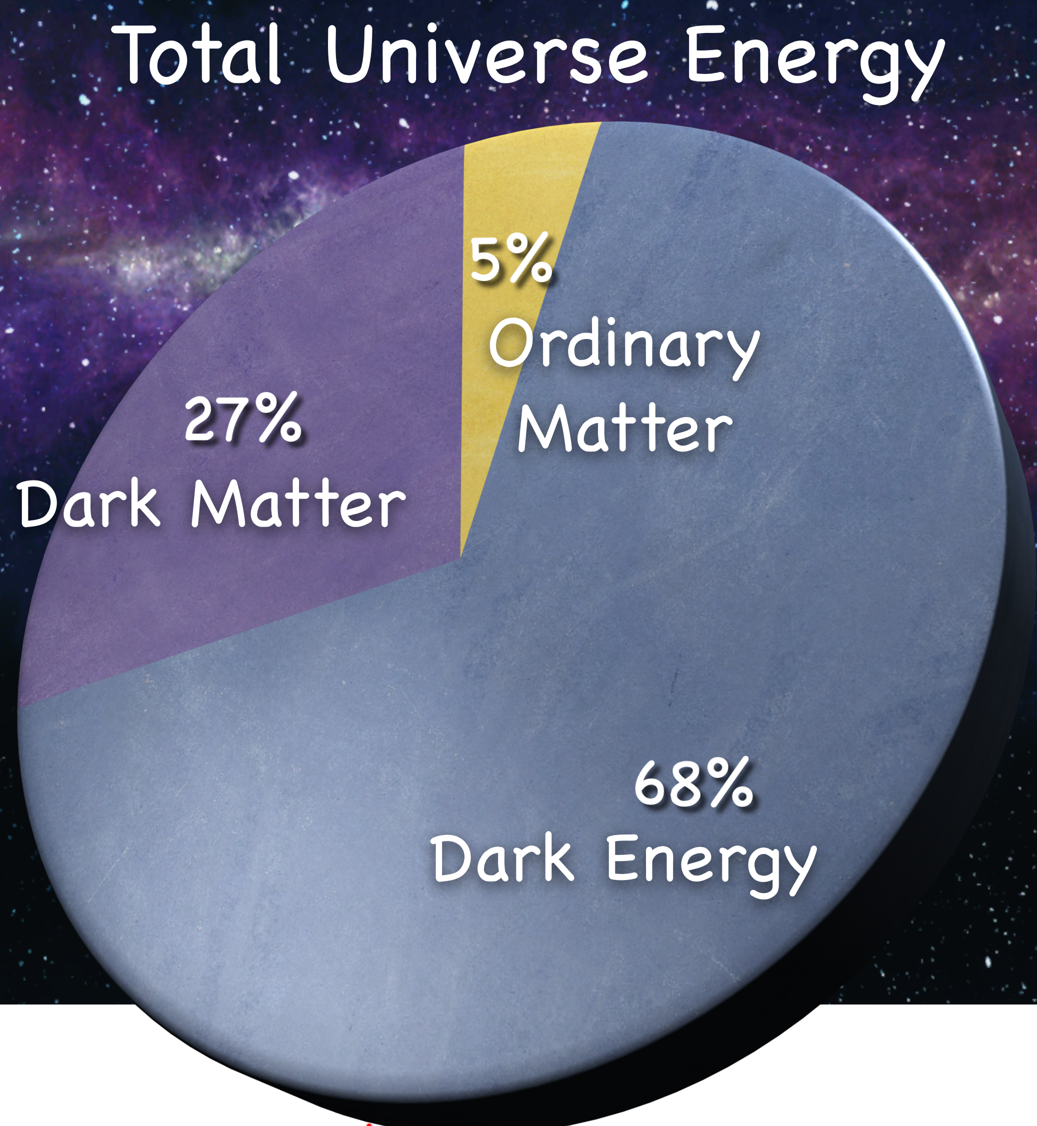


subfrequency ($K = \varepsilon\, G_{a\gamma\gamma'}$)



Even without the vector portal, we can study the dark photon.
With the combined portal, any light source can give subfrequency light.

We live in a Dark World



$$
\begin{aligned}
\nabla\cdot\vec{E} &= \rho + G_{a\gamma\gamma}\nabla a\cdot\vec{B} + G_{a\gamma\gamma'}\nabla a\cdot B' \\
\nabla\times\vec{E} &= -\frac{\partial\vec{B}}{\partial t} \\
\nabla\cdot\vec{B} &= 0 \\
\nabla\times\vec{B} &= \vec{J} + \frac{\partial\vec{E}}{\partial t} - G_{a\gamma\gamma}\left(\frac{\partial a}{\partial t}\vec{B} + \nabla a\times\vec{E}\right) - G_{a\gamma\gamma'}\left(\frac{\partial a}{\partial t}\vec{B}' + \nabla a\times\vec{E}'\right)
\end{aligned}
$$

Light to explore the Dark World!

- Thank you -