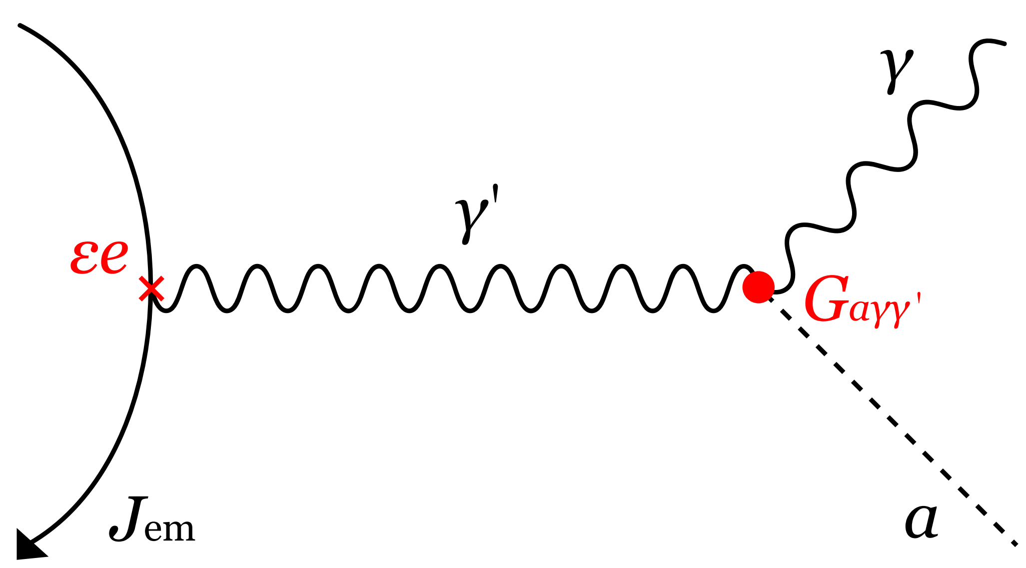
Subfrequency light signals of the dark sector



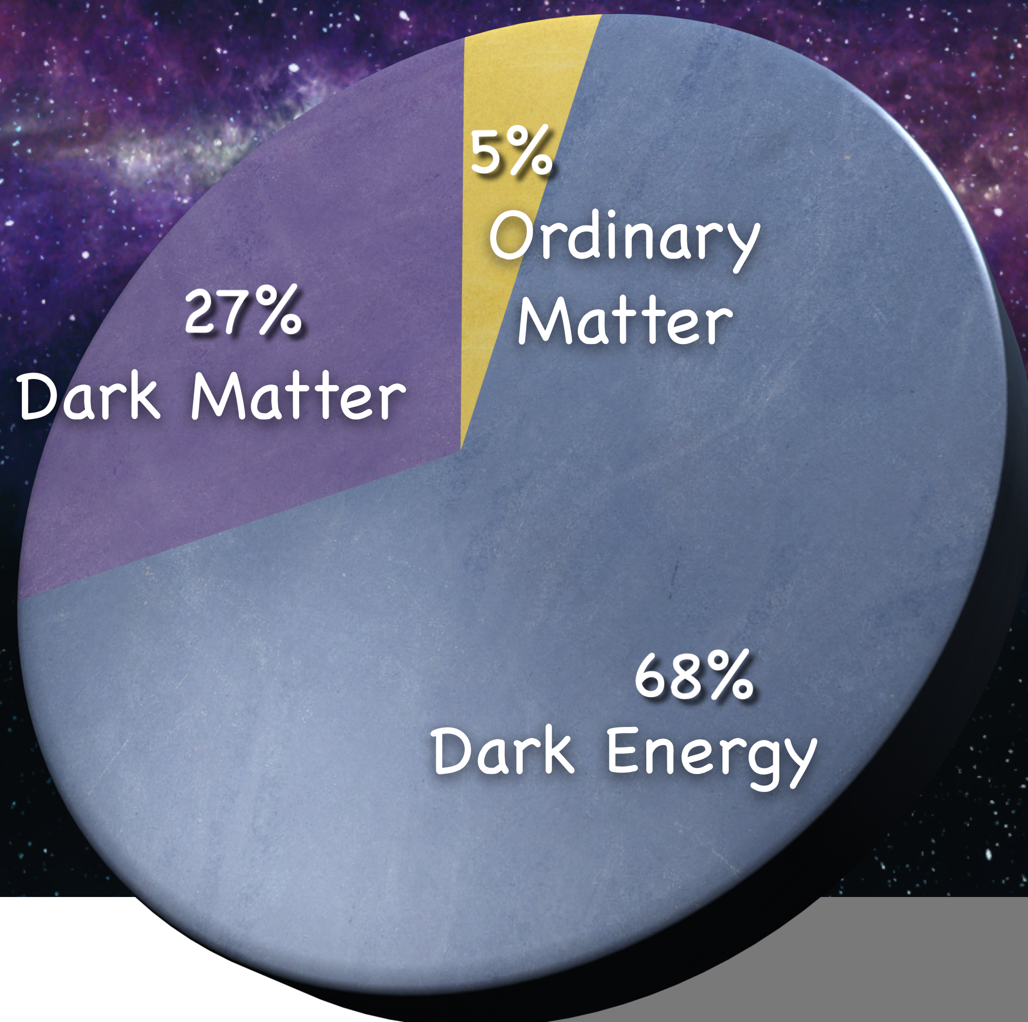
Hye-Sung Lee
Korea Advanced Institute of Science and Technology

2nd Asian-European-Institute Workshop for BSM
November 14 - 18, 2022 / Jeju Island

2201.11906
2011.03276
1904.13061
1806.09972
1806.00757
1704.07542
1611.01466

We live in a Dark World

Total Universe Energy

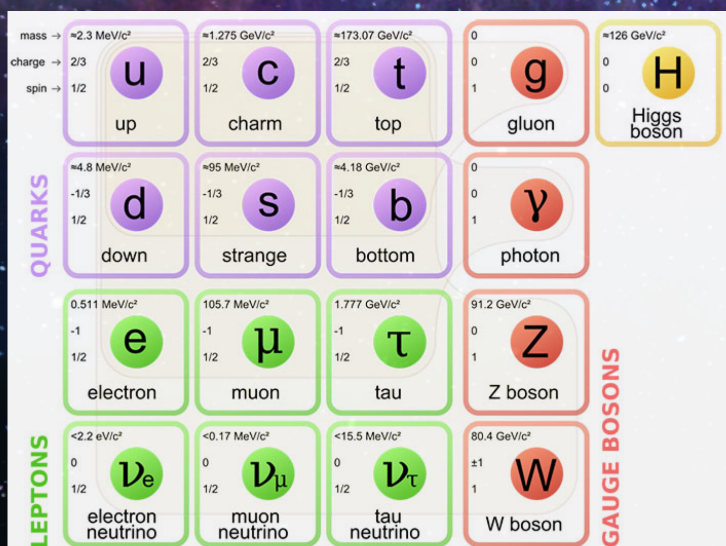


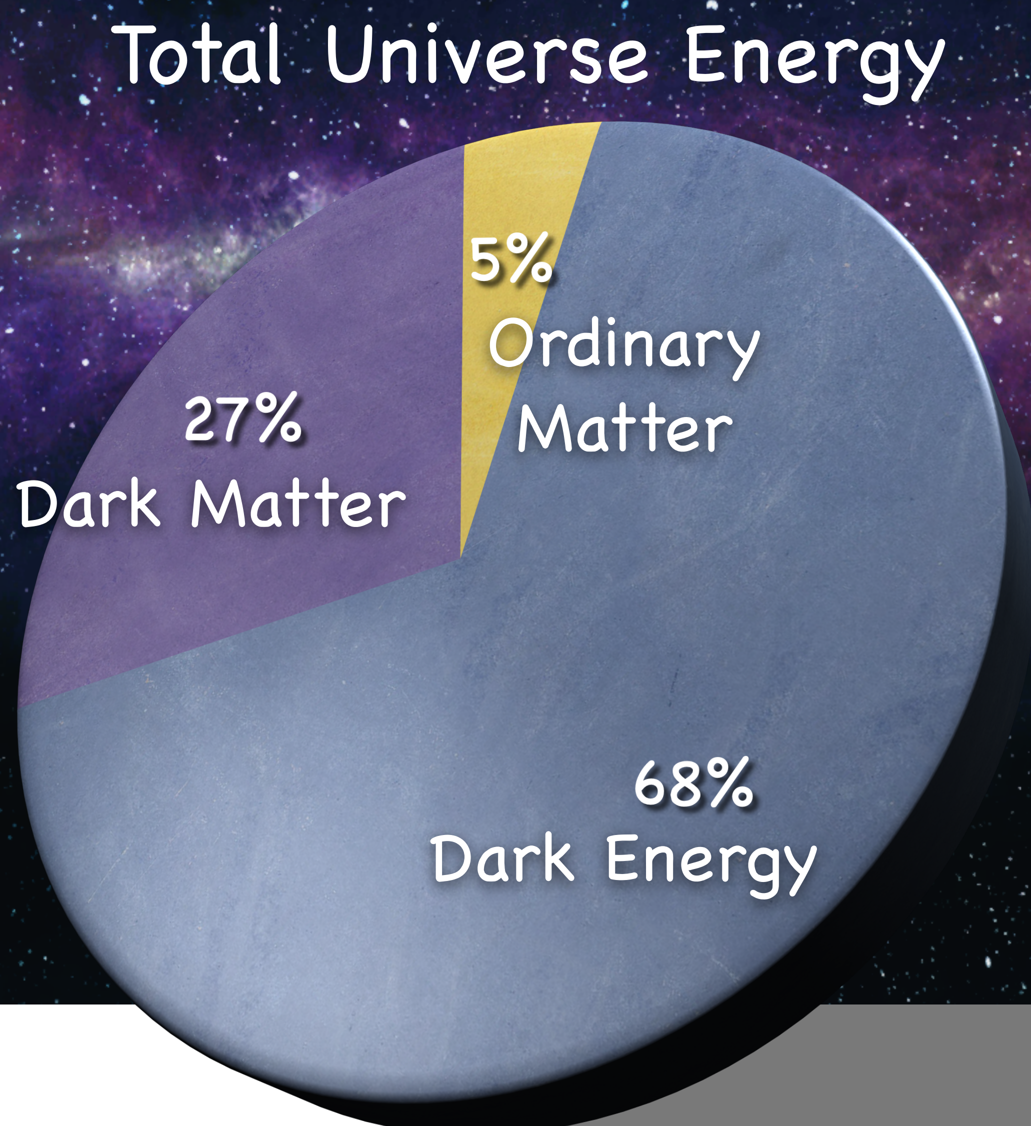
$$
\begin{aligned}
\nabla \cdot \vec{E} &= \rho \\
\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\
\nabla \cdot \vec{B} &= 0 \\
\nabla \times \vec{B} &= \vec{J} + \frac{\partial \vec{E}}{\partial t}
\end{aligned}
$$

Bright sector

Dark sector

We live in a Dark World





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

Bright sector

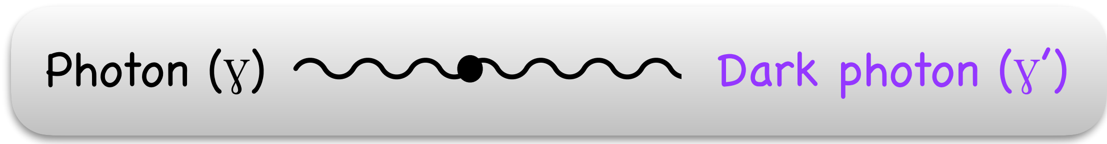
Dark sector

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

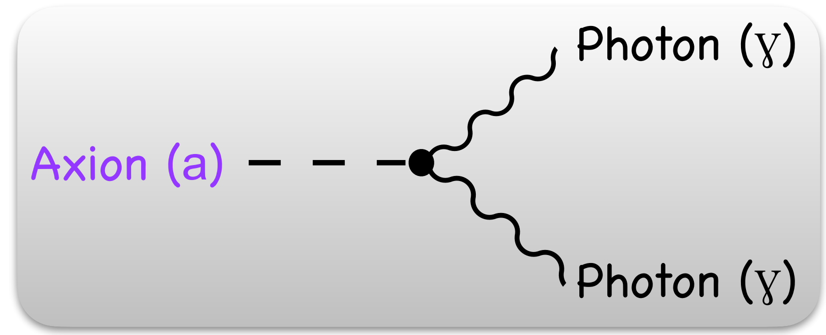
F, ɣ : photon
Z′, ɣ′ : dark photon
a : axion

Portals

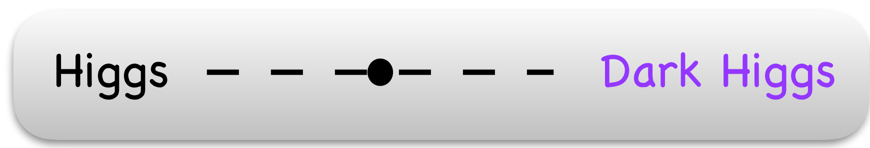
(i) Vector Portal $\frac{\varepsilon}{2} F_{\mu\nu} Z'^{\mu\nu}$



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



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

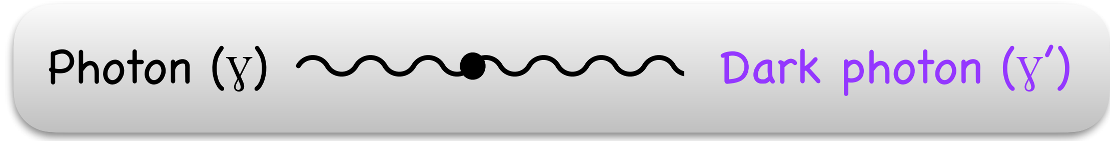


(iv) Neutrino Portal $y\, L H N$

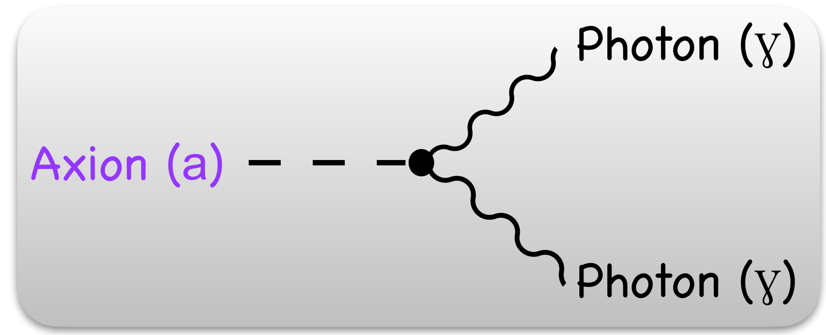
F, ɣ : photon
Z′, ɣ′ : dark photon
a : axion

Portals

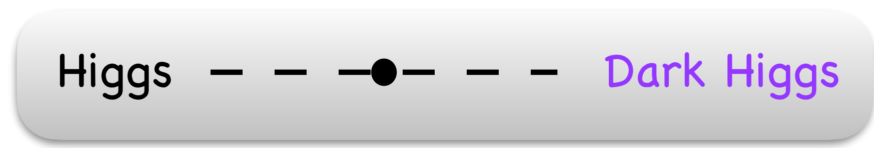
(i) Vector Portal $\frac{\varepsilon}{2} F_{\mu\nu} Z'^{\mu\nu}$



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



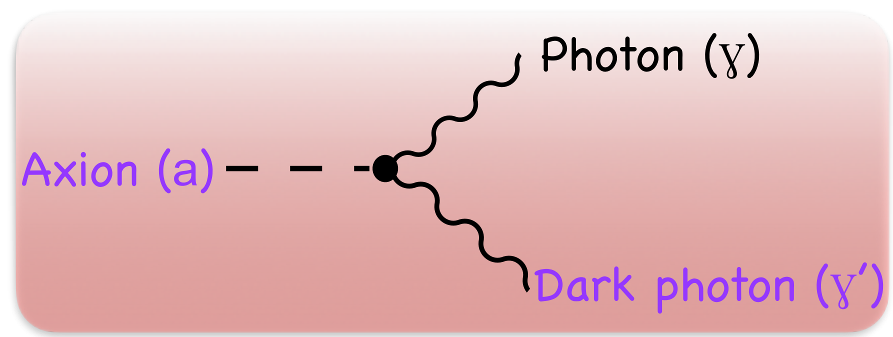
(iii) Higgs Portal $\kappa\, |S|^2 |H|^2 + \mu\, S |H|^2$



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

(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 not a simple product 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.

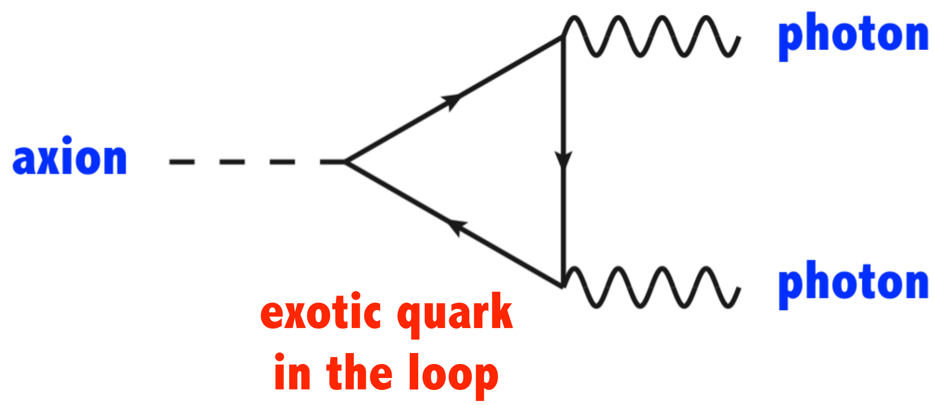
$$m_{\gamma'}^2 = e'^2 D_\Phi^2 v_D^2$$

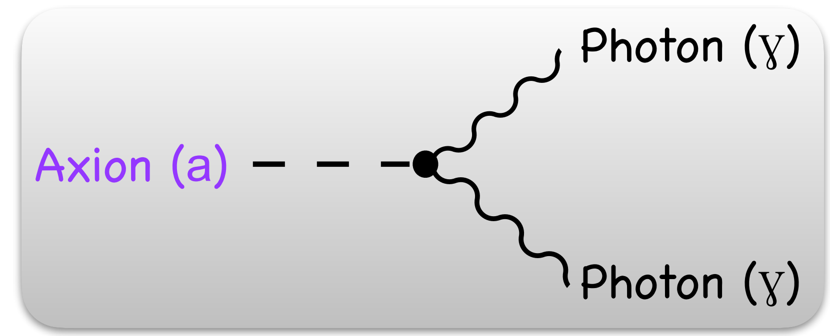
Exotic vector like quarks may decay into other particles through, e.g. $\Phi_D^\dagger \psi \bar{d}_R + h.c.$
for $PQ_\psi = 0$, $Q_\psi = -1/3$, $D_\psi = D_\Phi$.

It depends on the couplings of the Fermions in the triangle

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

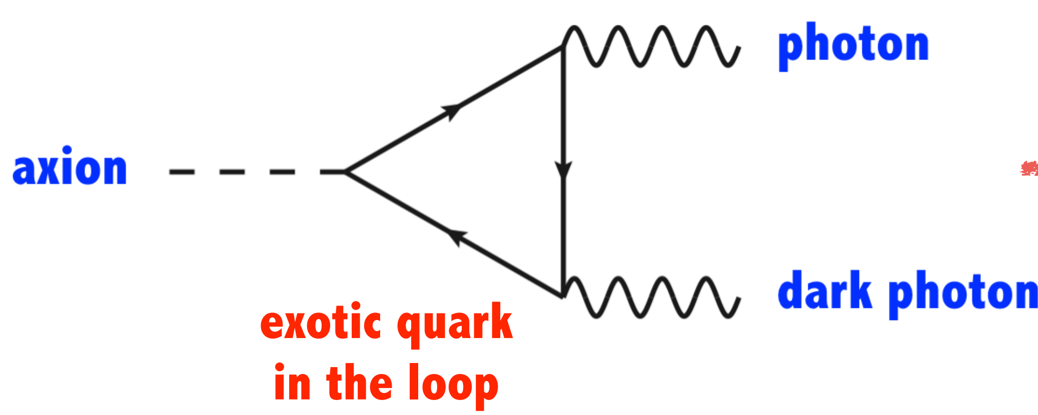
(i) Original KSVZ axion model: Exotic quarks have EM charges

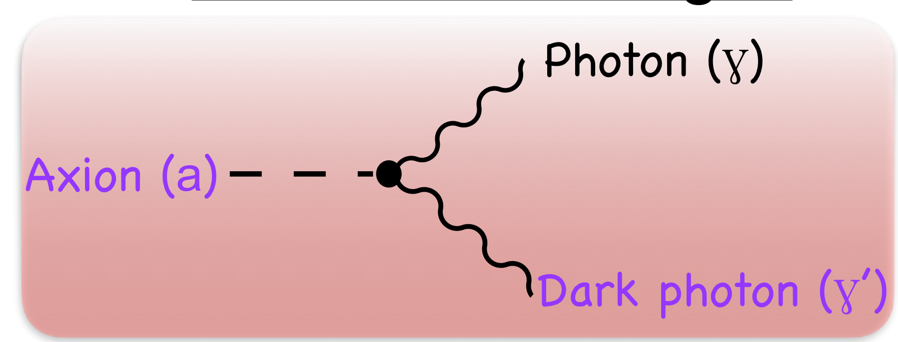




axion portal ($G_{a\gamma\gamma}$)

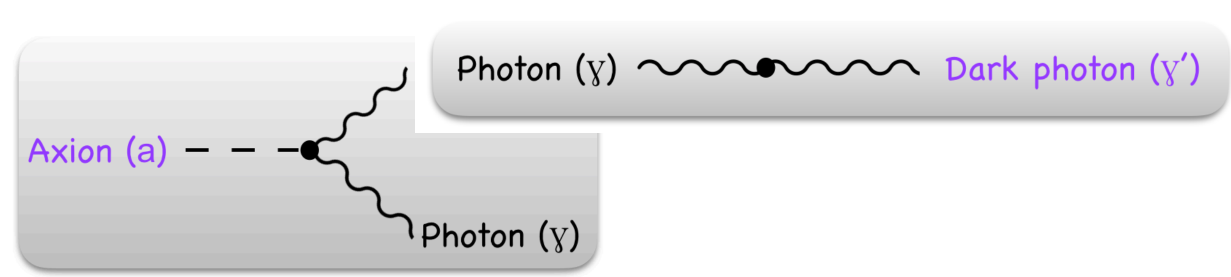
(ii) Dark KSVZ axion model: Exotic quarks have EM & Dark charges





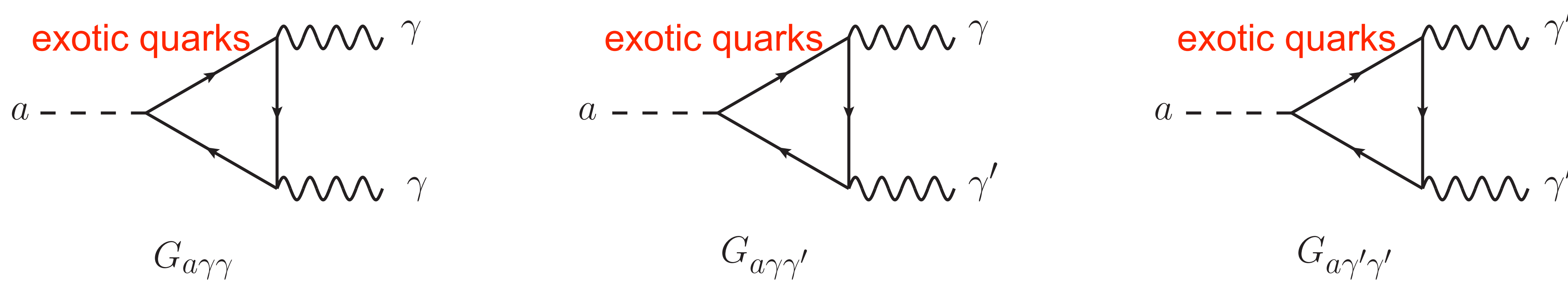
dark axion portal ($G_{a\gamma\gamma'}$)

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



)

Dark Axion Portal (in Dark KSVZ axion model)



Axion Portal

Dark Axion Portal

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).

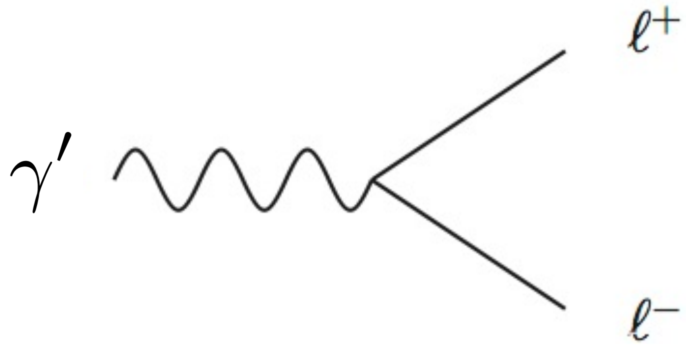
Implications of the dark axion portal

(axion = axion or axion-like particle)

Visible/Invisible decay of Dark photon

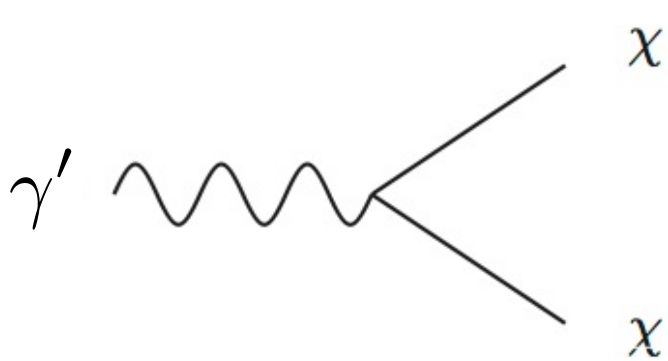
Categories of Dark force search (in terms of the dominant decay modes) :

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



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

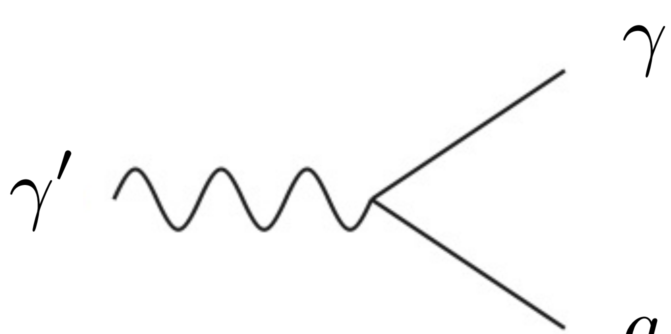
(ii) "Missing Energy" search (invisible dark photon scenario)



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)



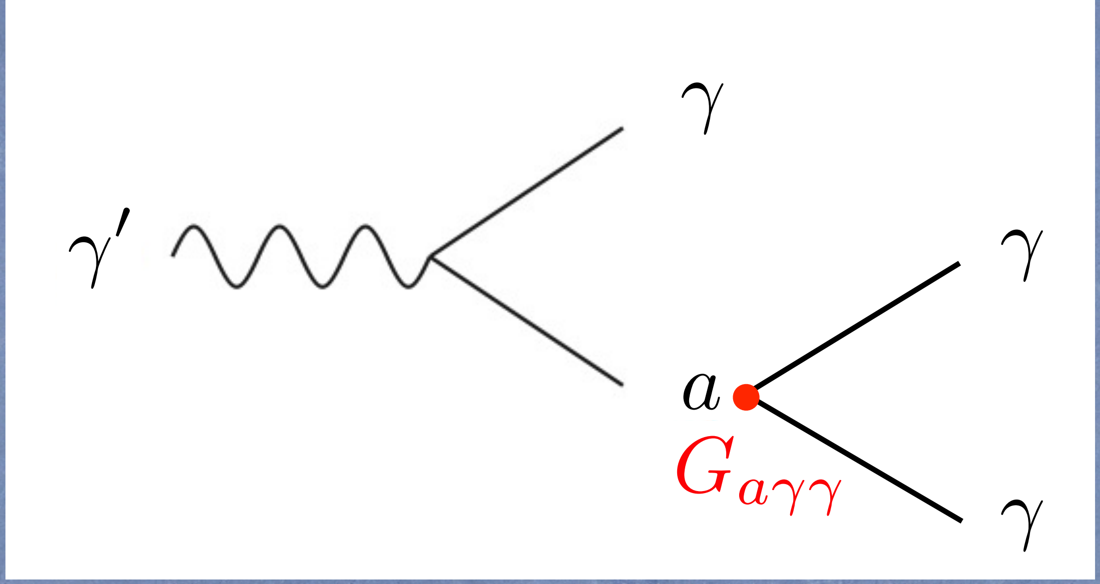
$$\Gamma(\gamma' \to \gamma a) = \frac{G_{a\gamma\gamma'}^2}{96\pi} m_{\gamma'}^3 \left(1 - \frac{m_a^2}{m_{\gamma'}^2}\right)^3$$

(axion or axion-like particle)

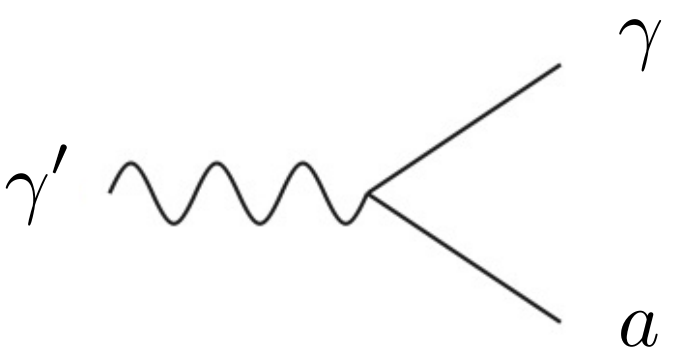
Visible/Invisible decay of Dark photon

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 ($G_{a\gamma\gamma'}$ & $G_{a\gamma\gamma}$)



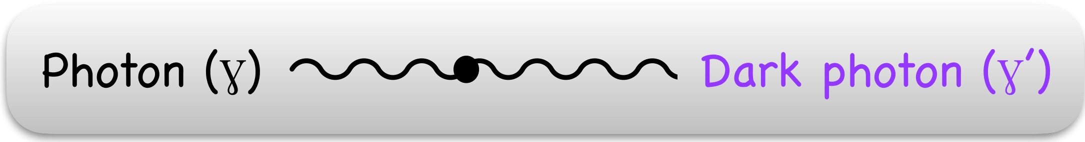
(iii) "Photon" search ("another" visible dark photon scenario)



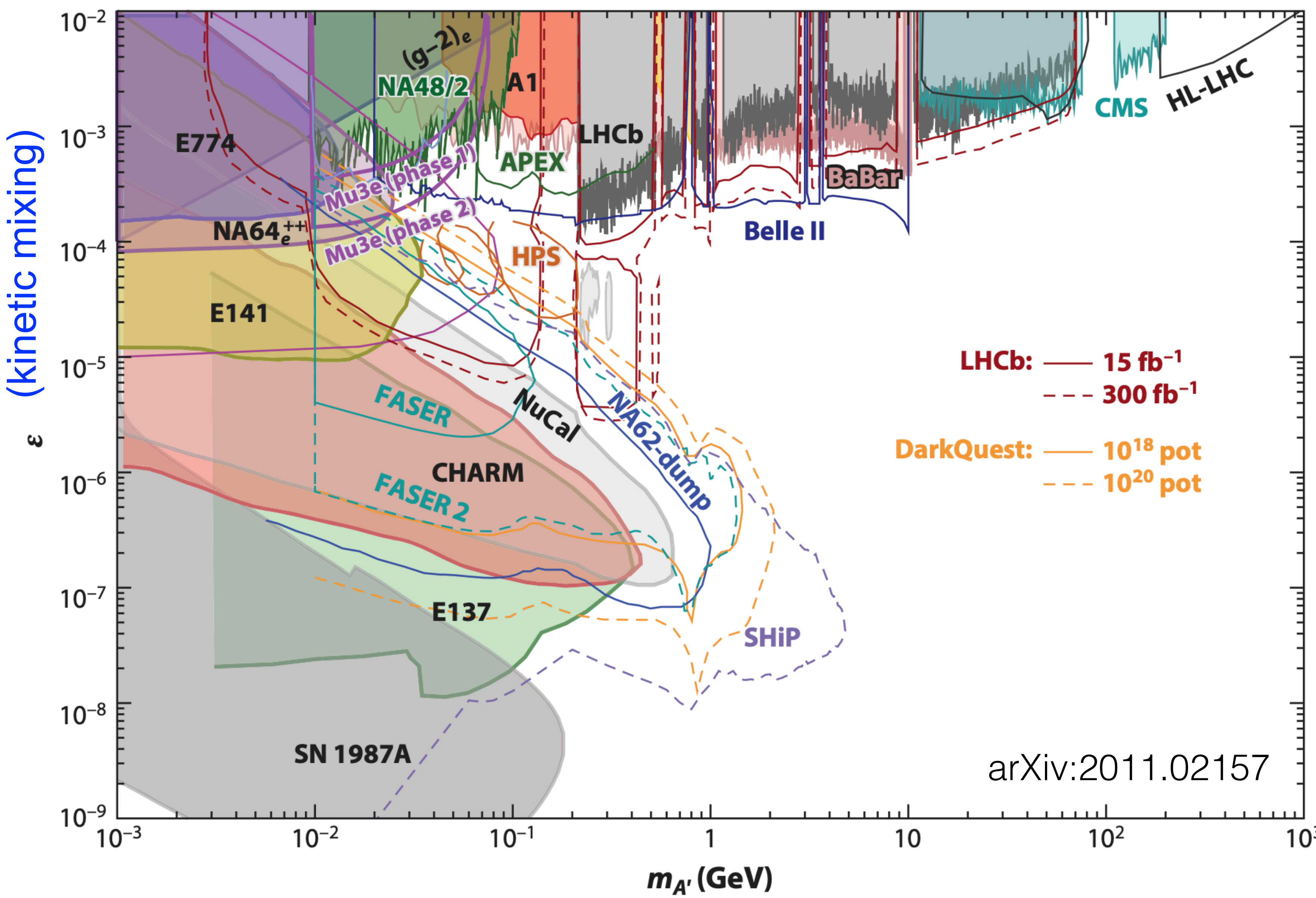
$$\Gamma(\gamma' \to \gamma a) = \frac{G_{a\gamma\gamma'}^2}{96\pi} m_{\gamma'}^3 \left(1 - \frac{m_a^2}{m_{\gamma'}^2}\right)^3$$

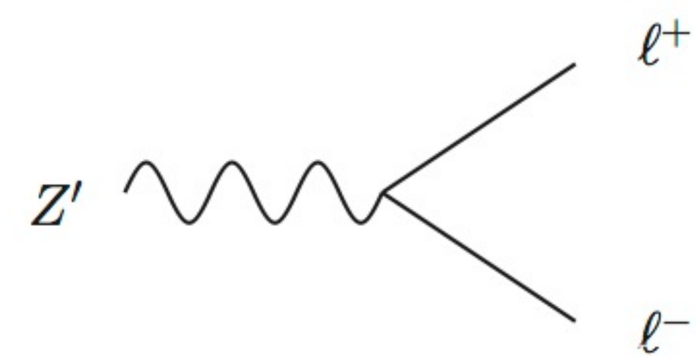
a (axion or axion-like particle)

Dilepton searches for (Visible dark photon)



γ-γ′ kinetic mixing
(vector portal)



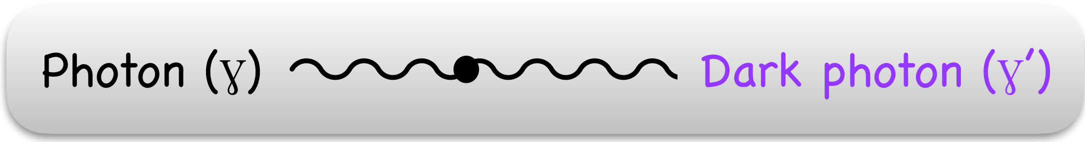


Mostly from the Z' → dilepton searches (e^+e^- or $\mu^+\mu^-$)

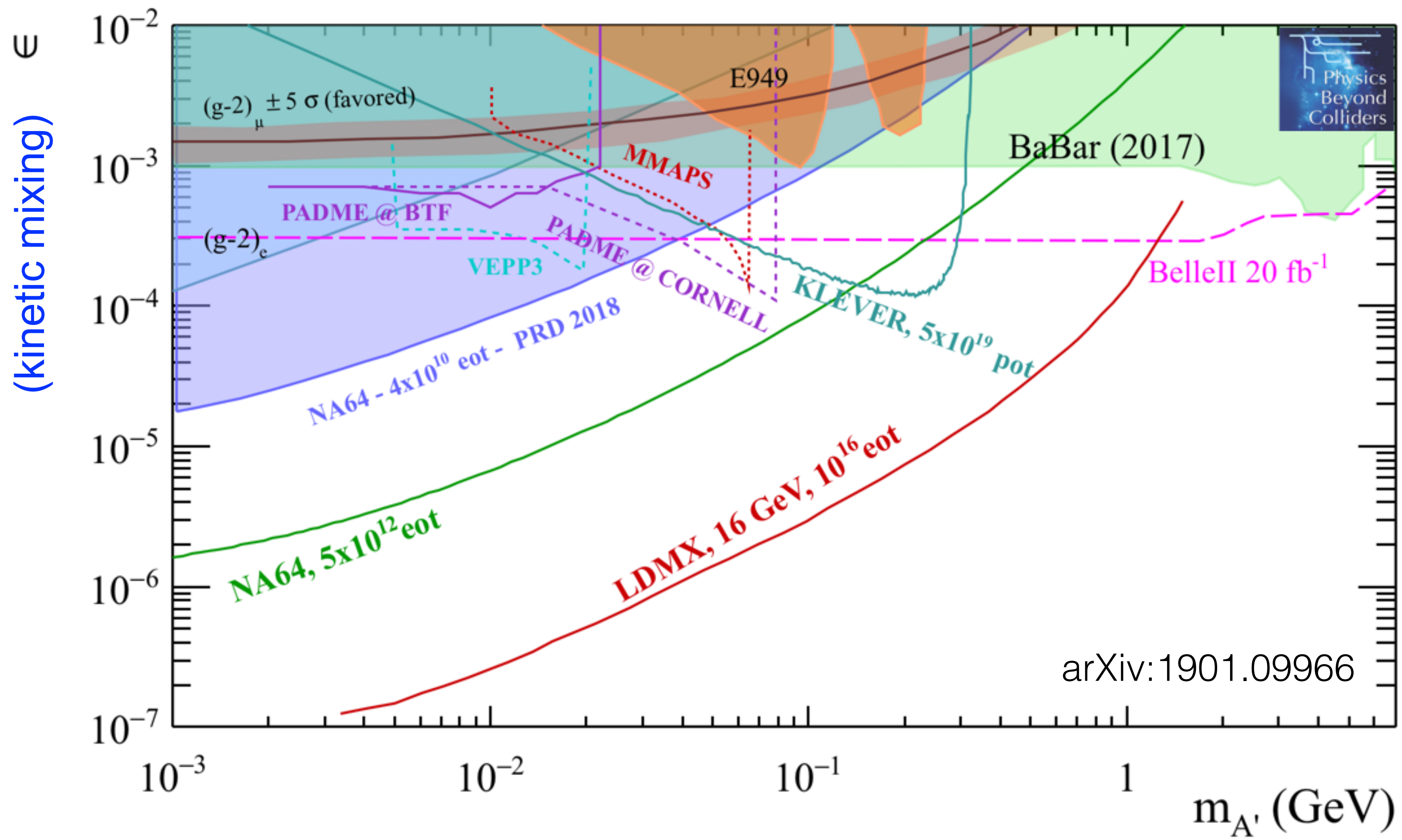
(i) Beam-dumps
(ii) Meson (quarkonium) decays
(iii) e+e- collision (photon+Z')
(iv) Fixed target experiments
…

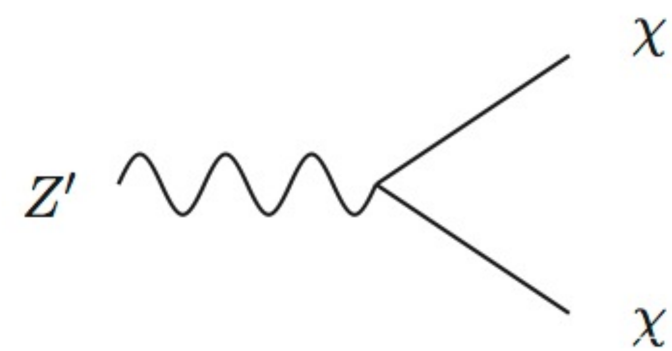
The dark gauge boson is actively searched for in many experiments.
The vector portal is constrained to be small ($\varepsilon \ll 1$) .

Missing energy searches (Invisible dark photon)



γ-γ′ kinetic mixing
(vector portal)





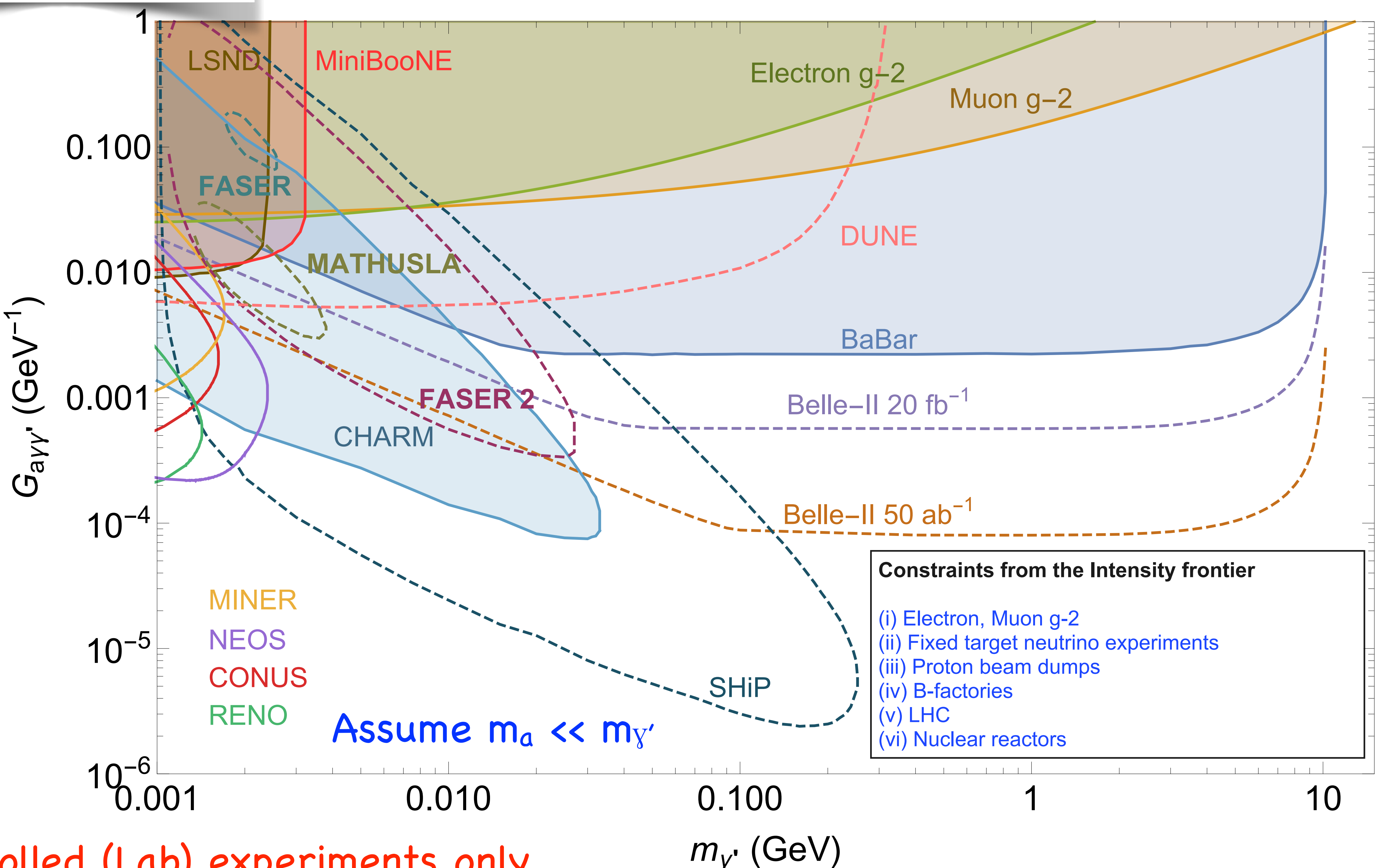
The invisible dark photon is also actively searched for in many experiments.
The vector portal is constrained to be small ($\varepsilon \ll 1$) in this scenario too.

Dark axion portal parameter space

Production & detection through dark axion portal

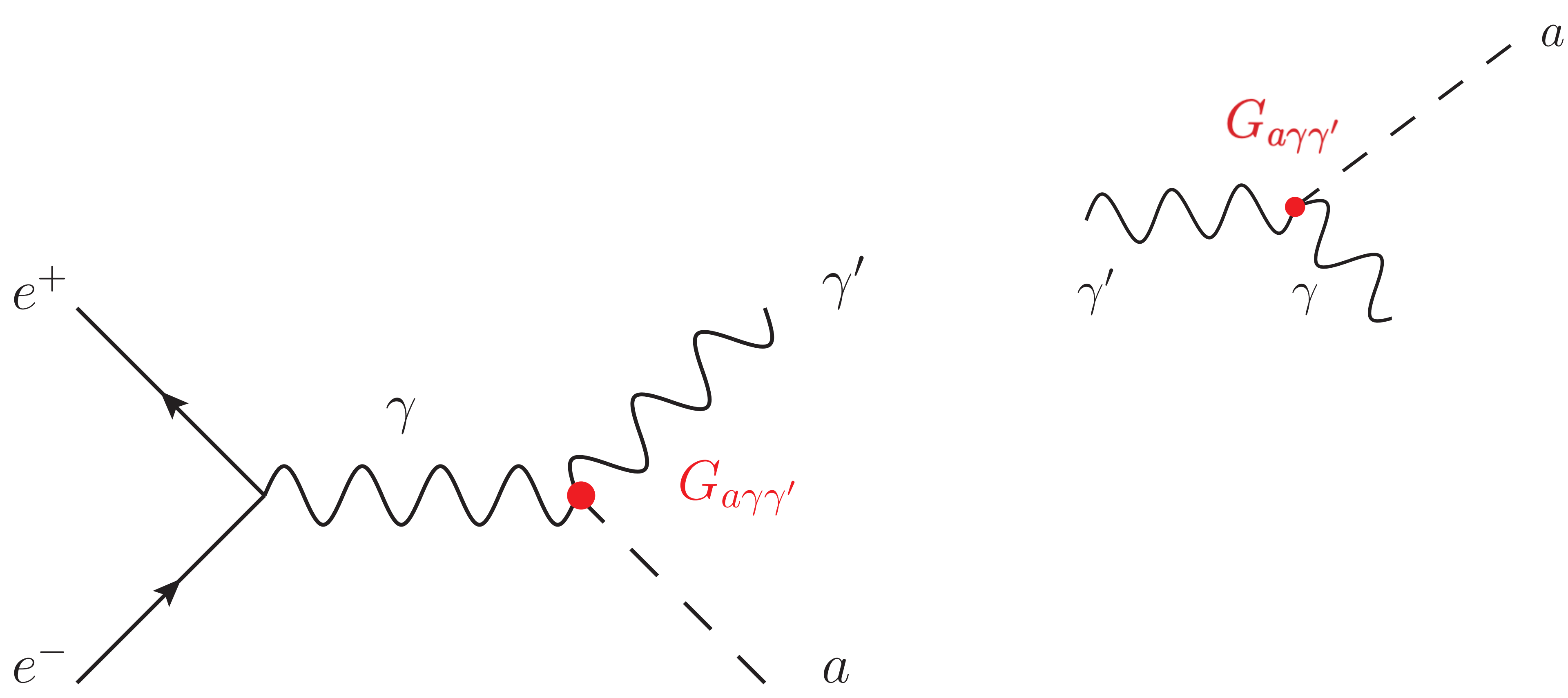
[deNiverville, LEE, Seo (2018); deNiverville, LEE (2019); deNiverville, LEE, Lee (2020)]

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

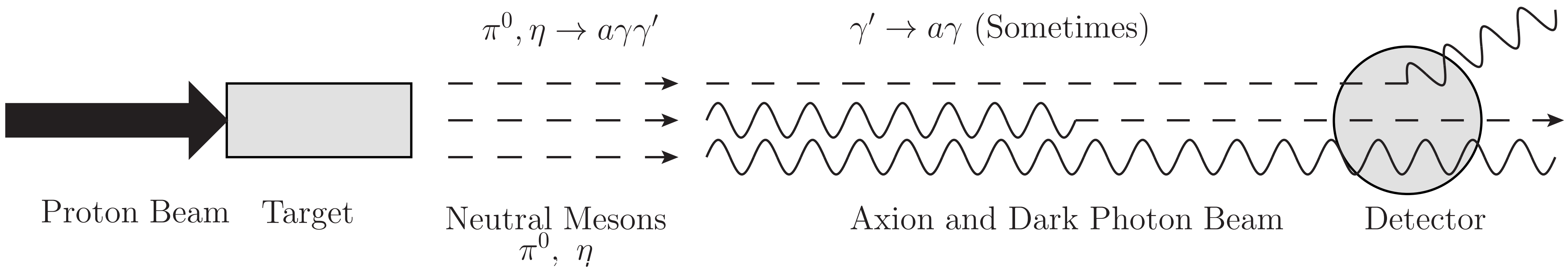


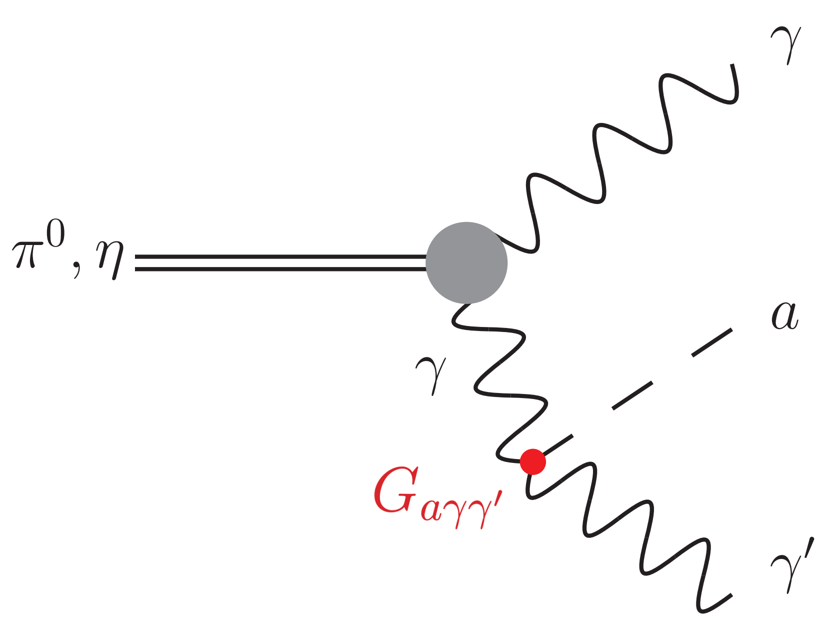
B-factories are asymmetric e+e- colliders of $E_{CM} \approx 10$ GeV.
e+e- can annihilate into a dark photon + axion, and the dark photon can decay into a photon + axion (e+e- → ɣ' a → ɣ a a). It is a mono-photon search.

Fixed Target Neutrino Experiments (LSND, MiniBooNE, DUNE)

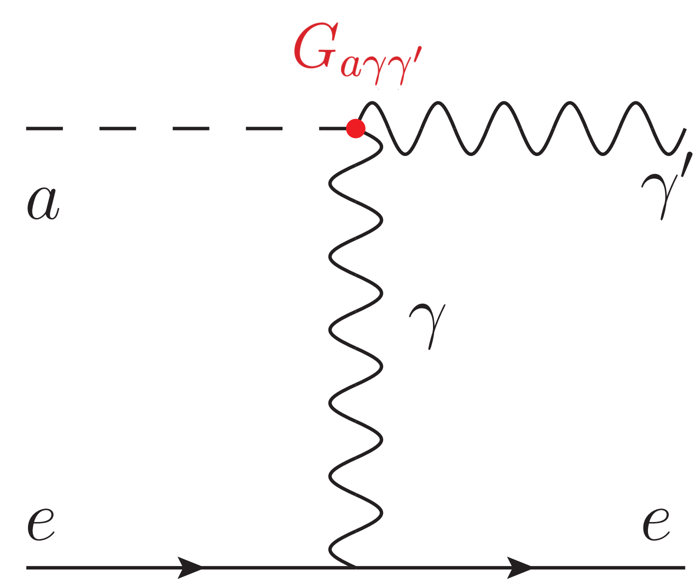
(originally for $\pi^{\pm}, K^{\pm} \to \nu_\mu \mu^{\pm}$)

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





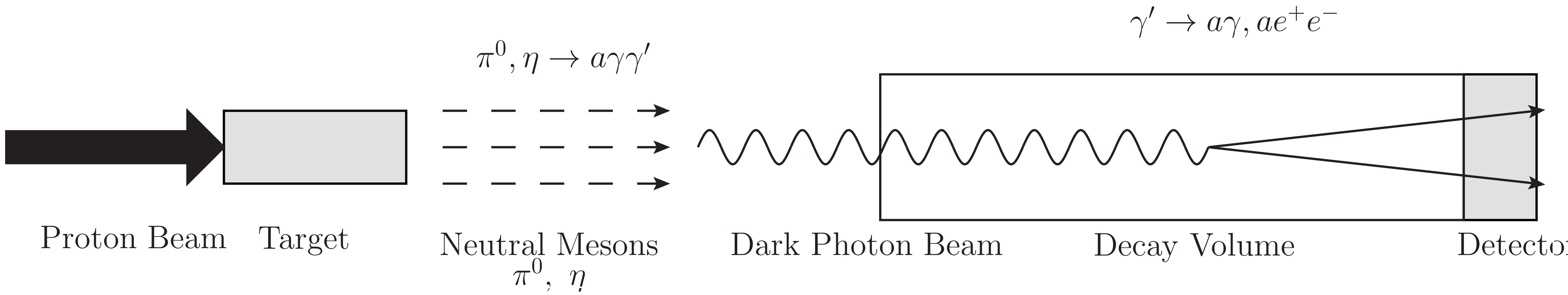
Production

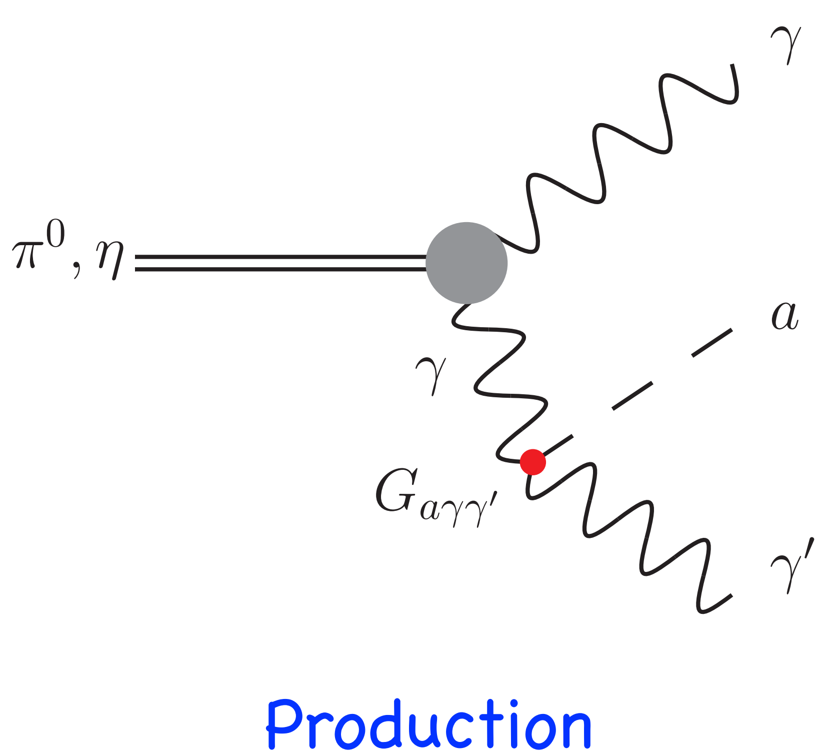


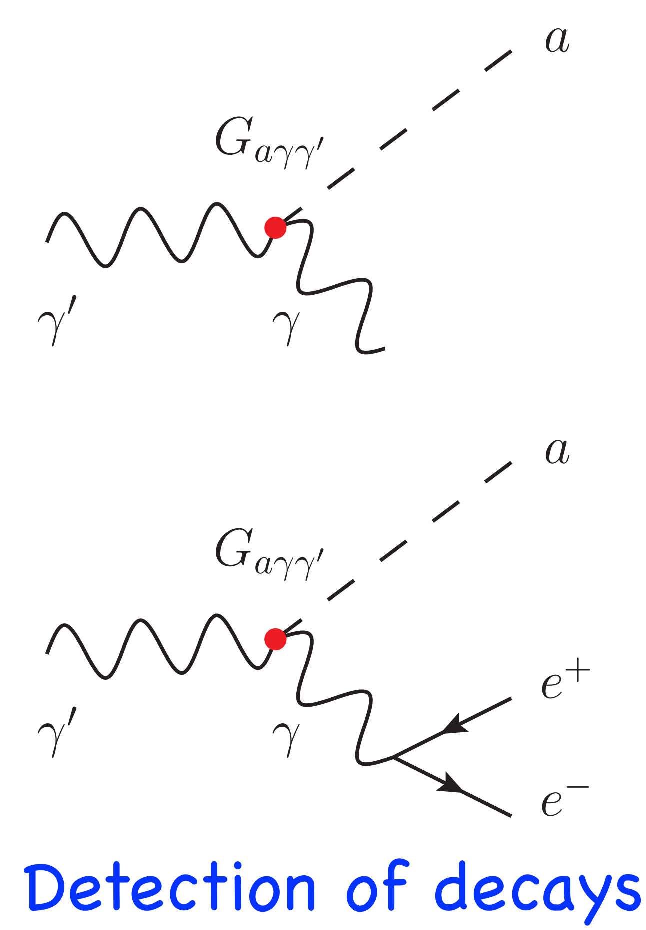
Detection of scattering

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)



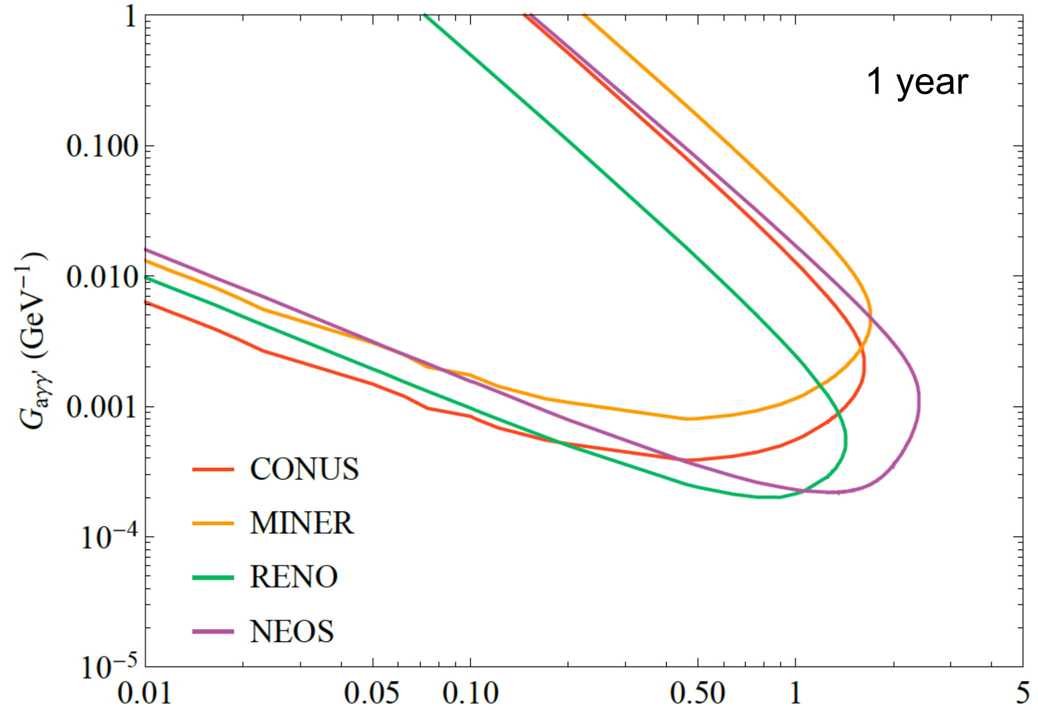


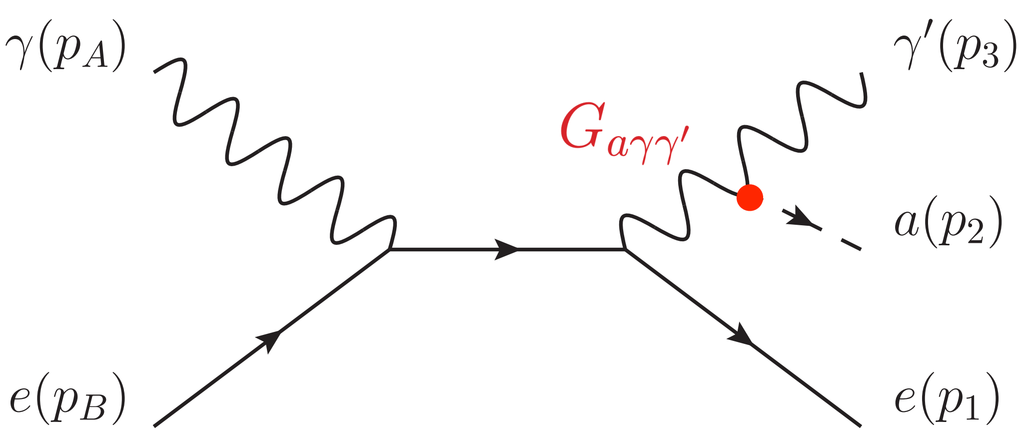


π (η) mesons decay into a photon + axion + dark photon.
Dark photons can decay into the mono-photon + axion (CHARM) or
2 charged tracks + axion (SHiP).

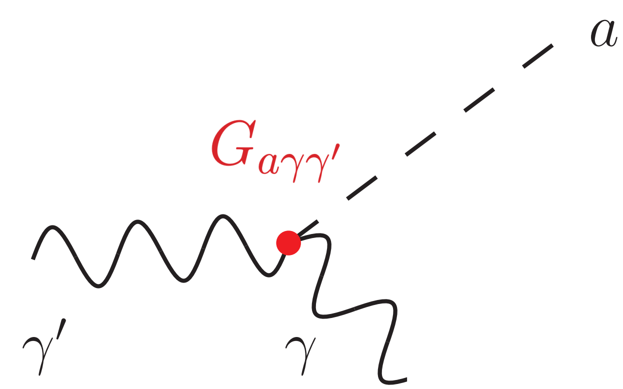
Reactor experiments (MINER/CONUS, RENO/NEOS)

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





Production



Detection of decays

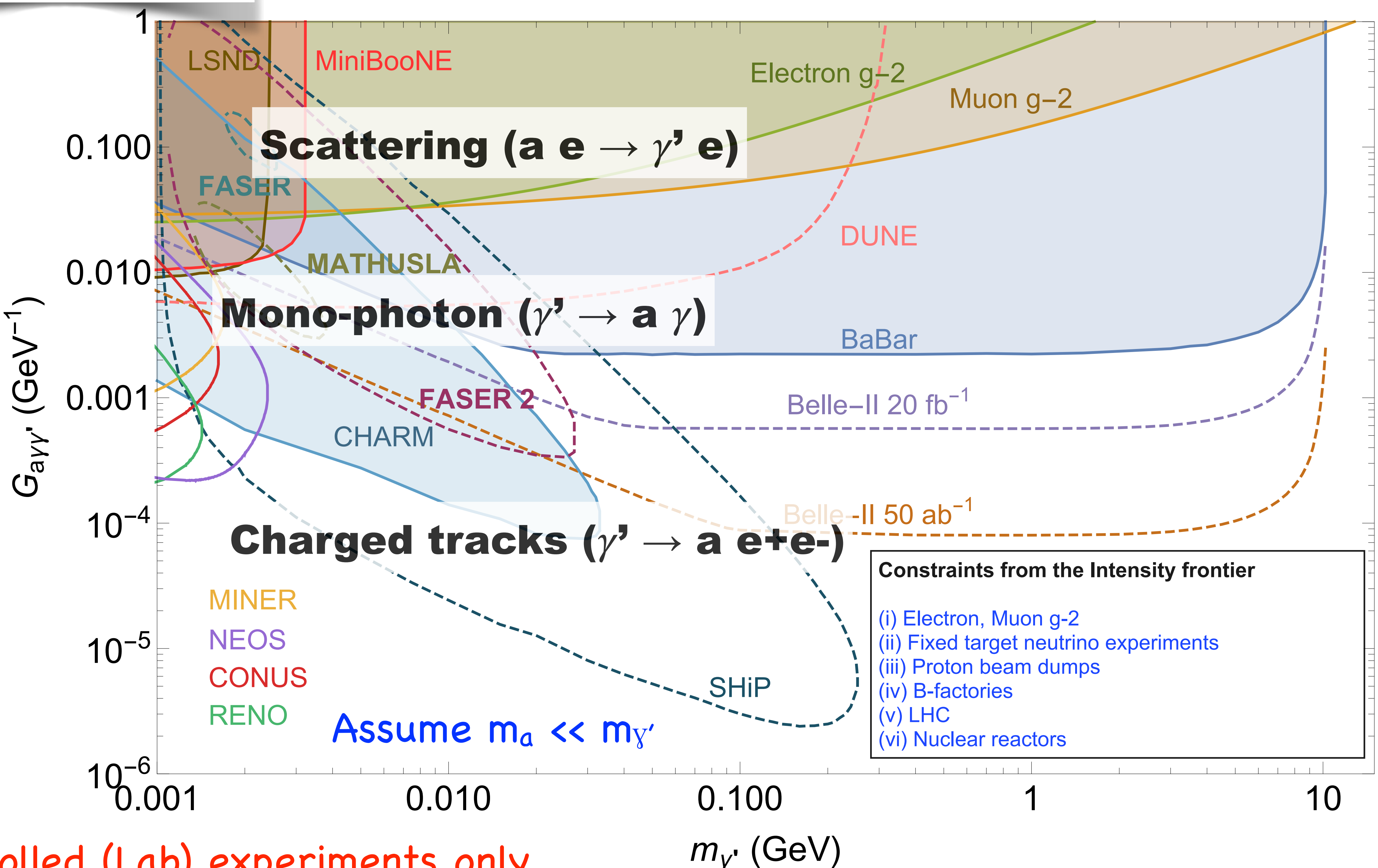
Reactor energy is low, but it produces huge flux of photons.
Good to probe the small mass, small coupling region.
(Because of isotropic production, the closer distance is more sensitive.)

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.



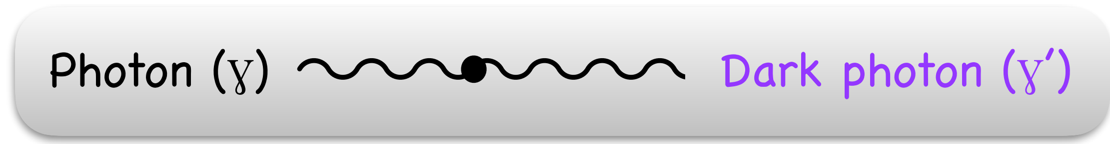
Controlled (Lab) experiments only

Combination of the “dark photon portals”

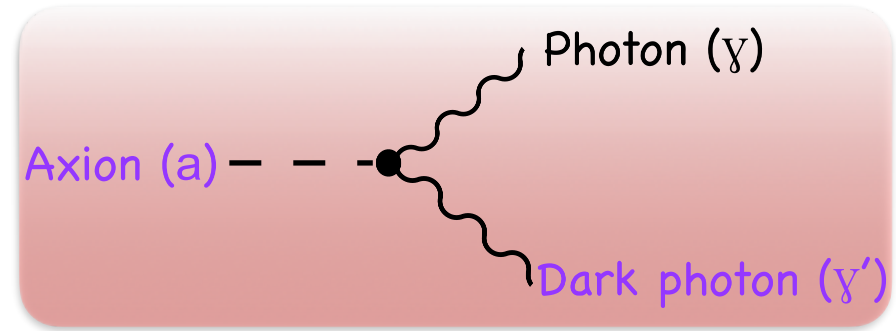
$$(K \equiv \varepsilon G_{a\gamma\gamma'})$$

Portals for the dark photon

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

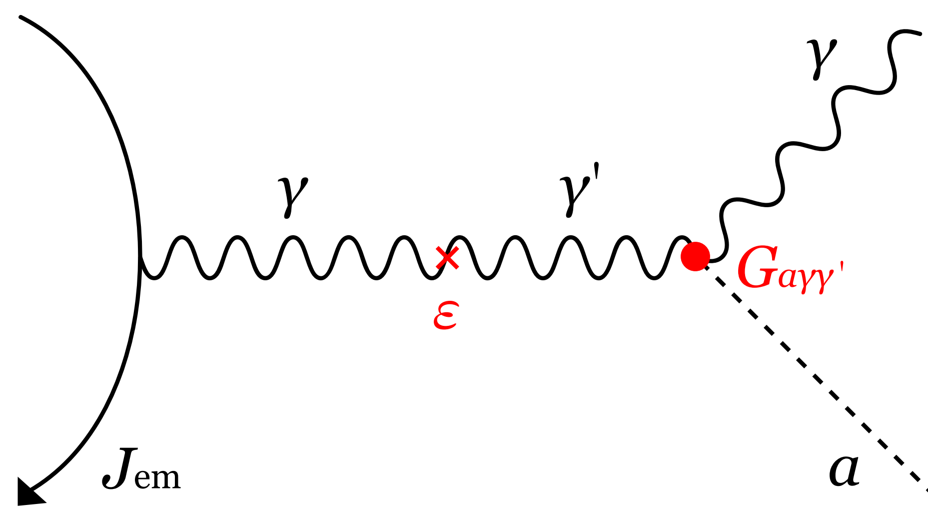


(ii) Dark Axion Portal $\frac{G_{a\gamma\gamma'}}{4} a F_{\mu\nu} \tilde{Z}'^{\mu\nu}$



We consider a combination of two "dark photon portals".

Production with vector portal,
Decay with dark axion portal.

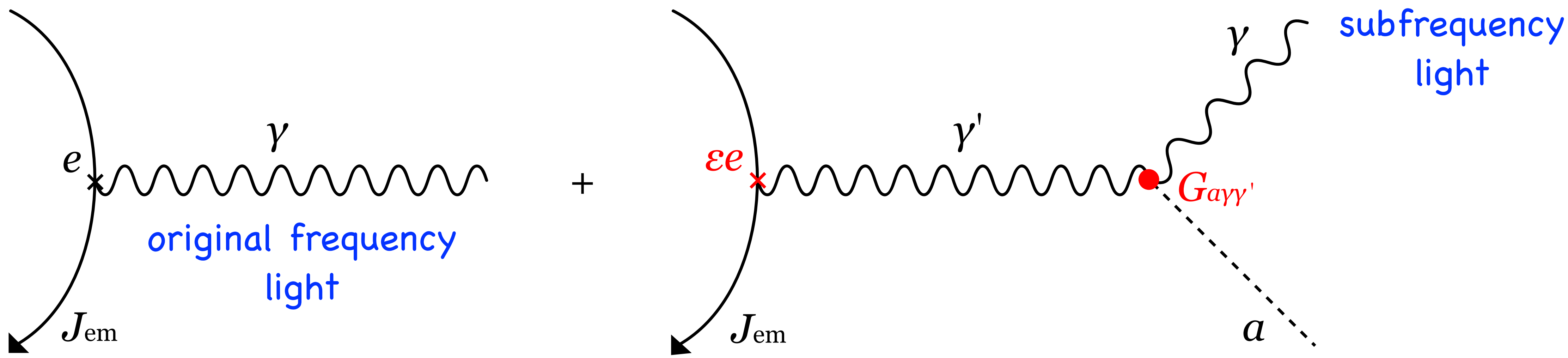


(In the interaction eigenstates)

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.

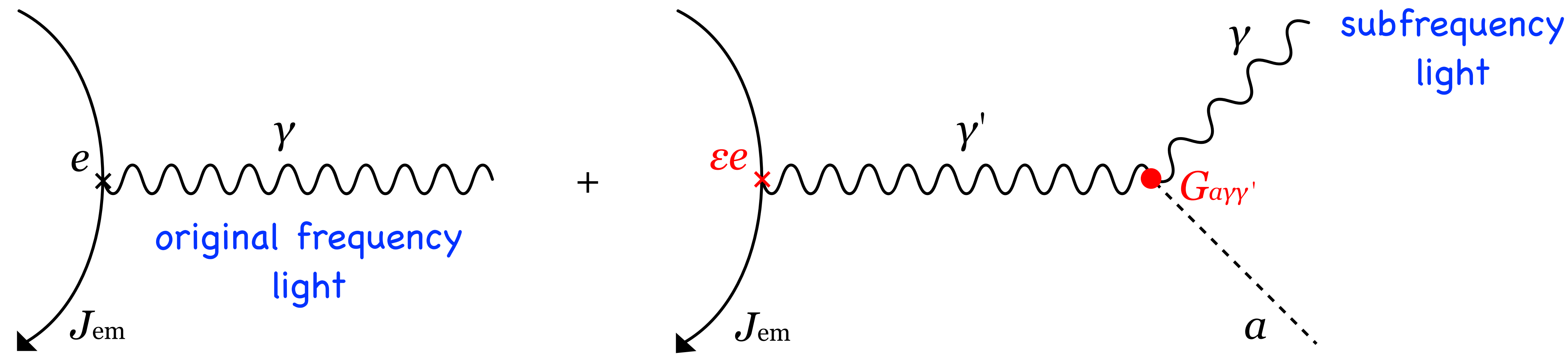
$$\mathcal{L} \sim -(A_\mu + \varepsilon A'_\mu) J^\mu_{\rm em} + \frac{G_{a\gamma\gamma'}}{2} a F_{\mu\nu} \tilde{F}'^{\mu\nu}$$

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

Combined portal

[LEE, Lee, Yi (2022)]

(In the mass eigenstates)



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

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

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

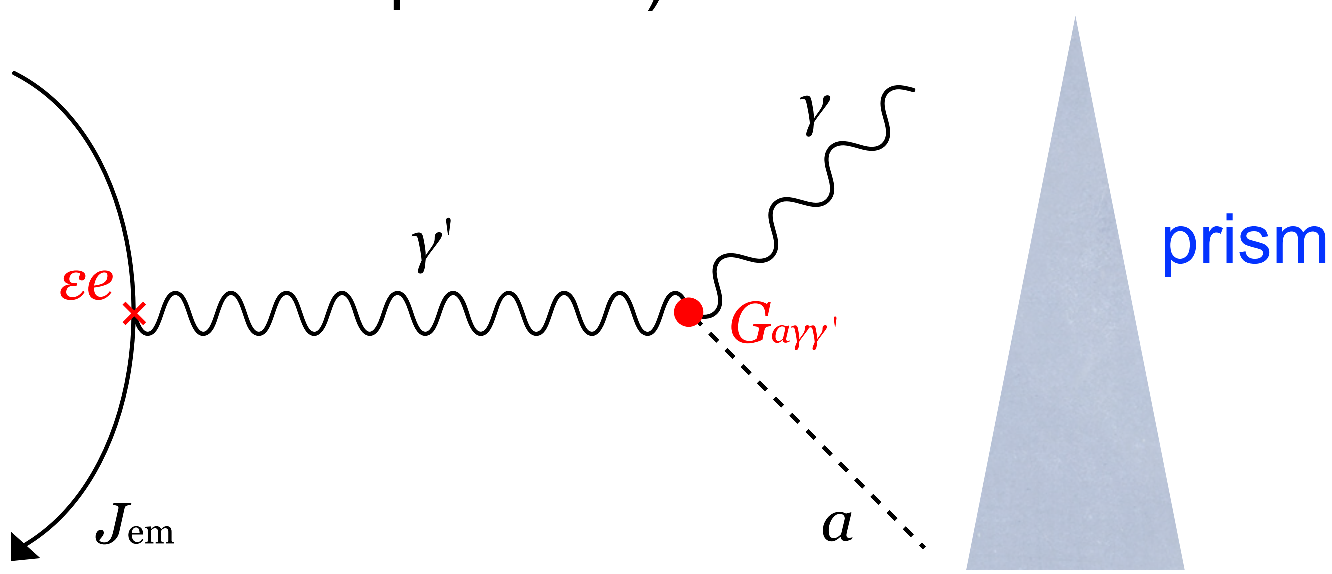
We assume $m_a \ll m_{\gamma'}$.

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)

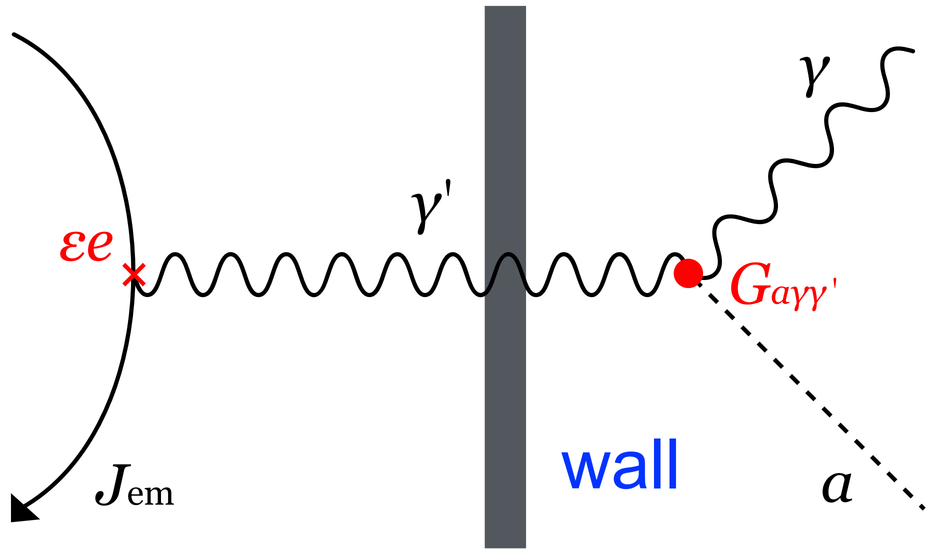
Laser experiment

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

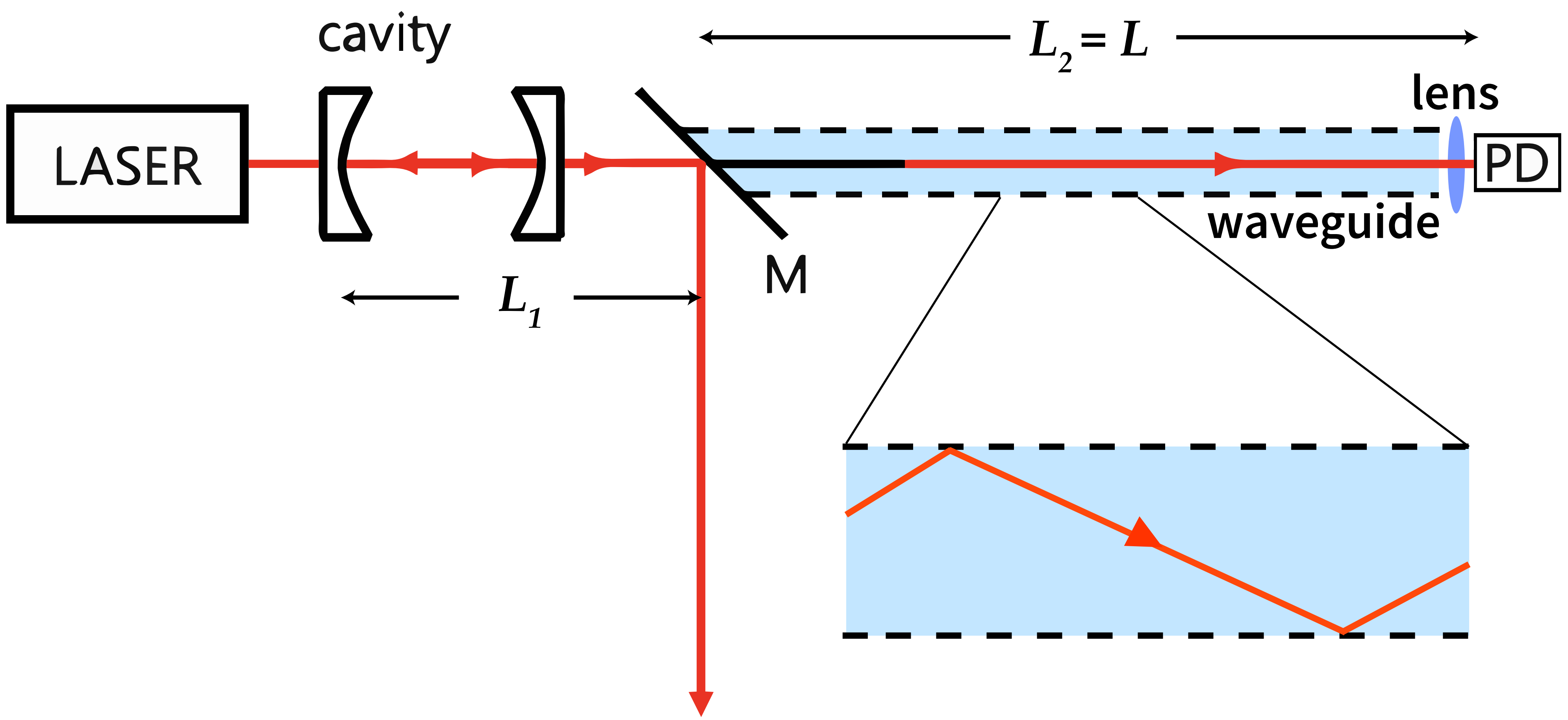
(i) **Prism** (different directions for different frequencies)



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



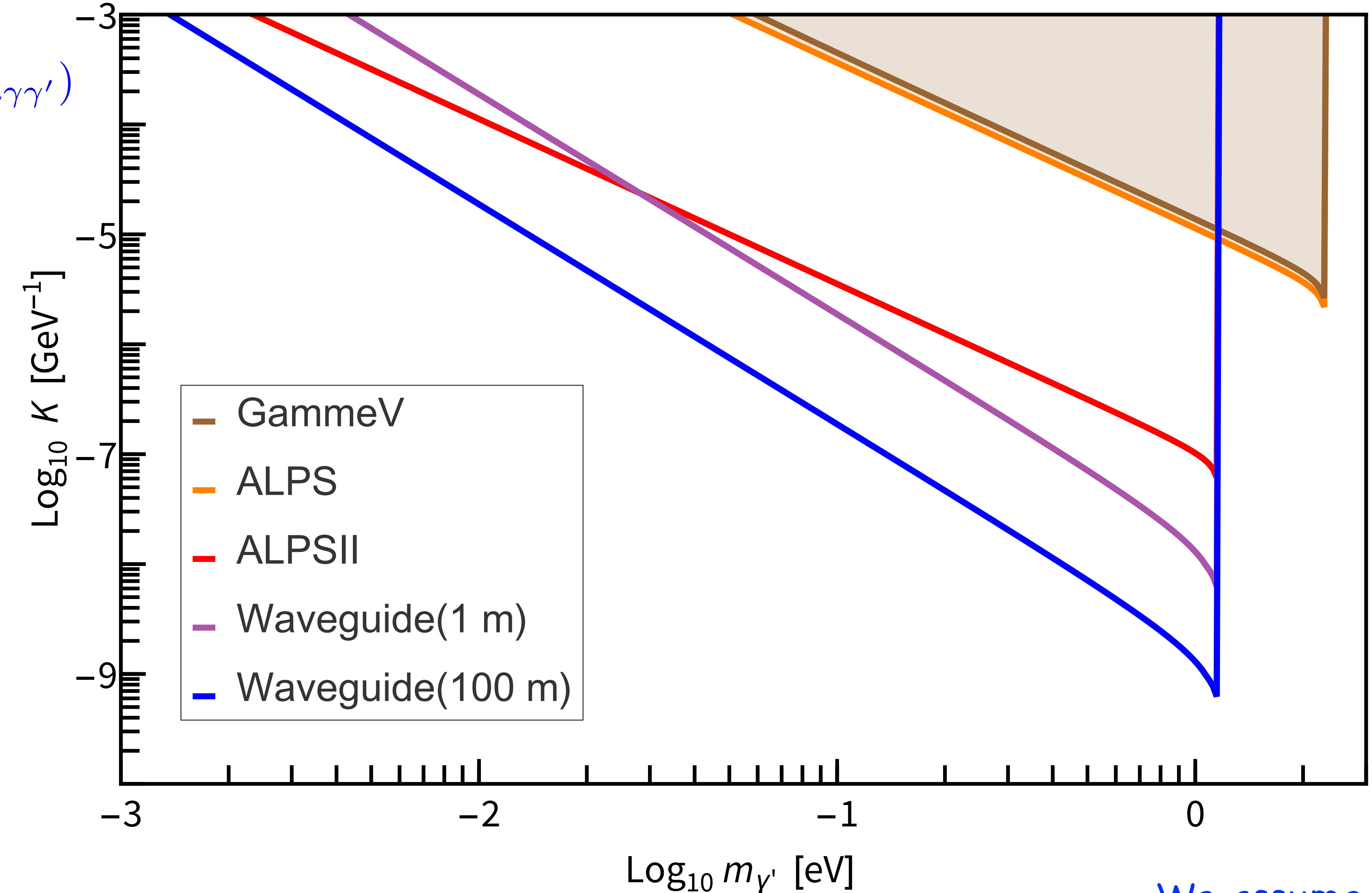
Laser experiment



(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

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

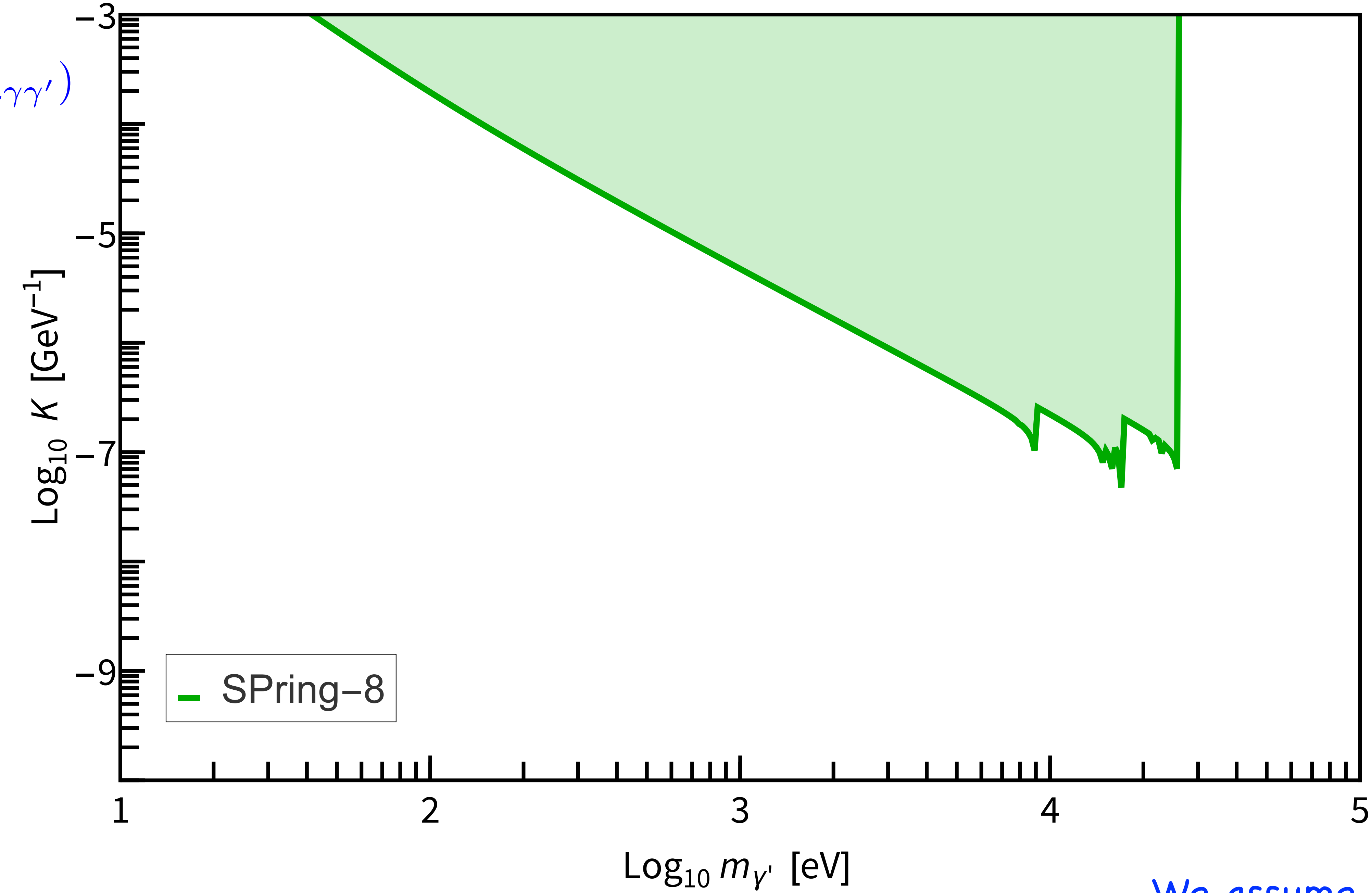


We assume $m_a << m_{\gamma'}$.

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

Subfrequency search with X-ray

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

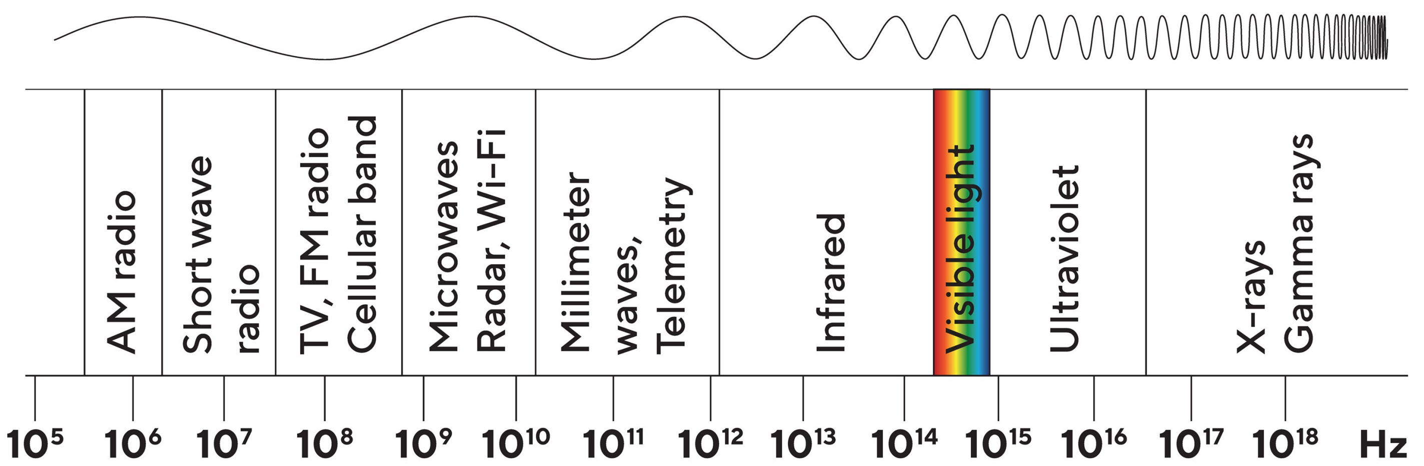


We assume $m_a \ll m_{\gamma'}$.

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

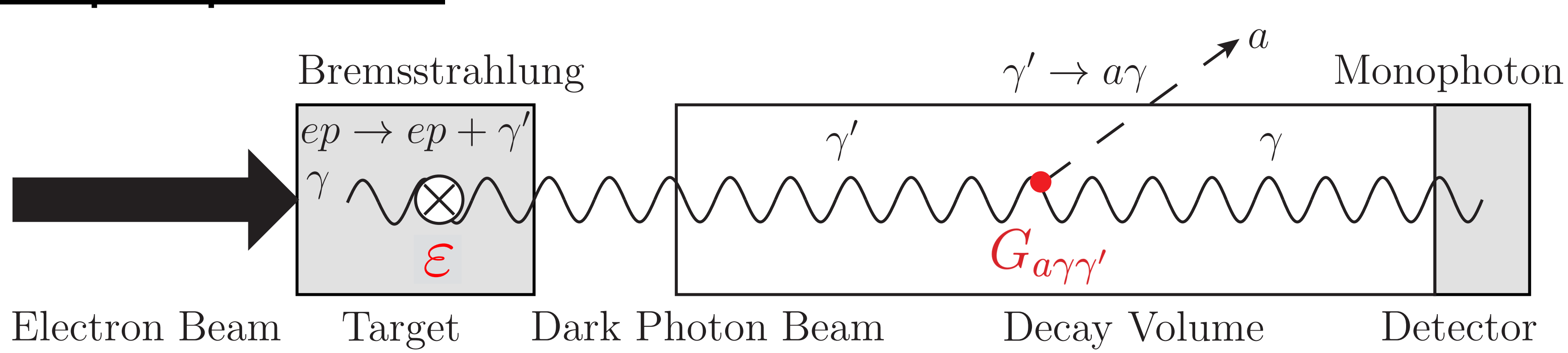
Subfrequency searches at other places

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, ⋯

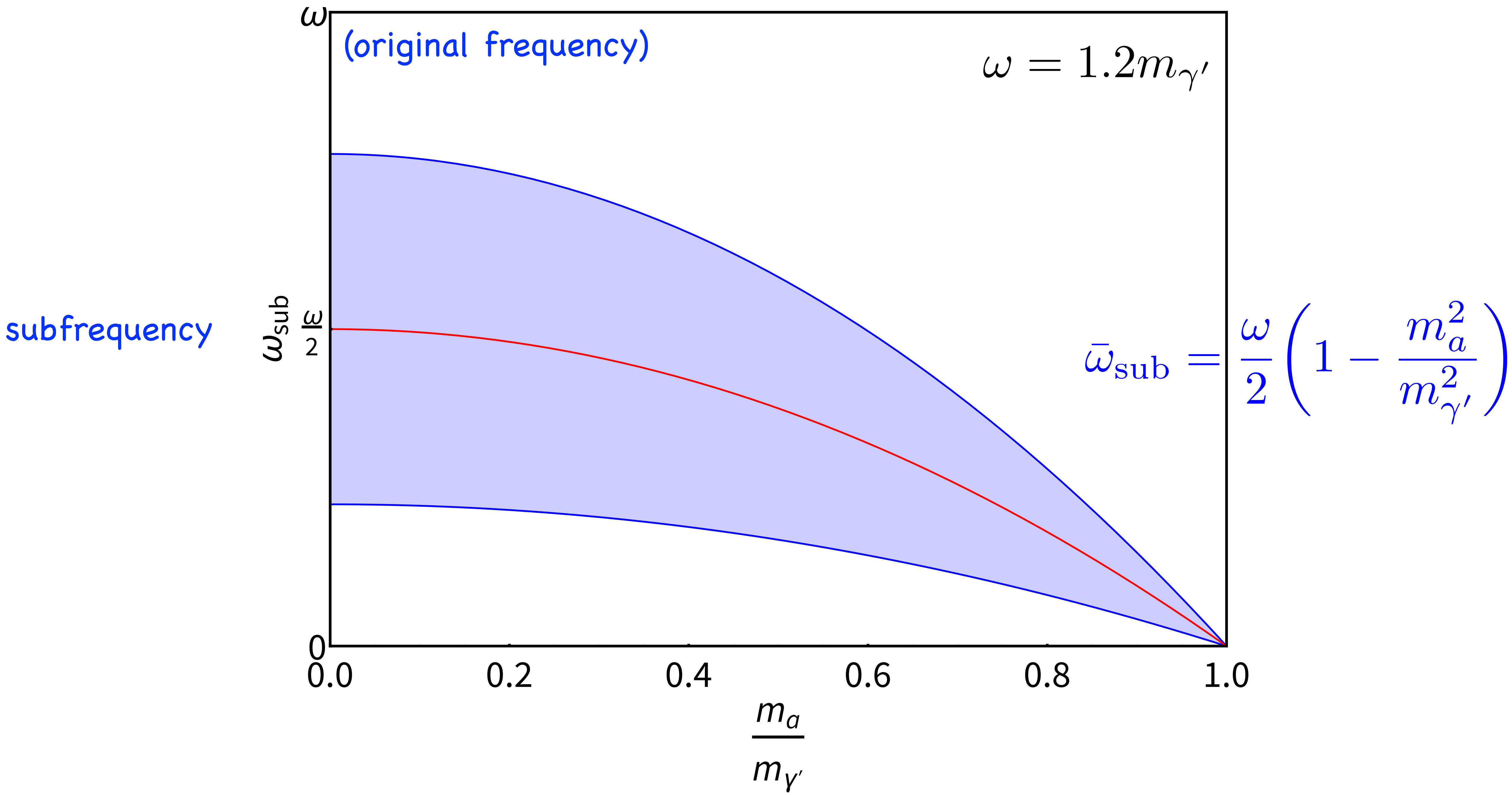
(ex) e-beam dump experiment



Production of a dark photon through vector portal (Bremsstrahlung).
Decay of a dark photon through 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.)

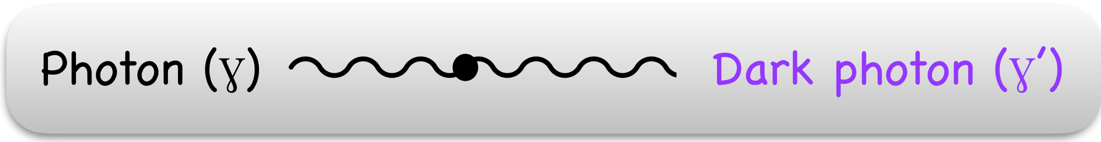
Axion mass dependence of the subfrequency

[LEE, Lee, Yi (Preliminary)]

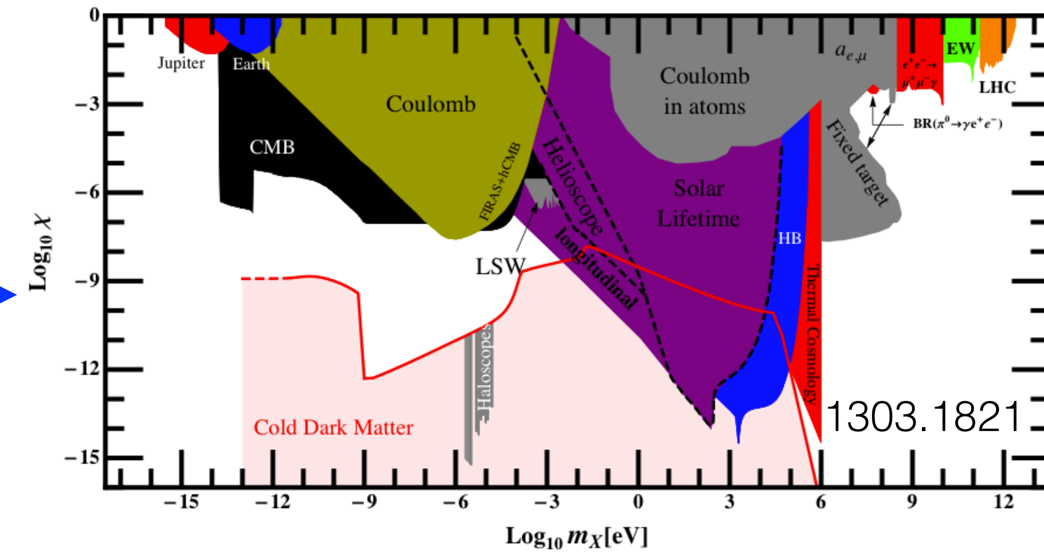


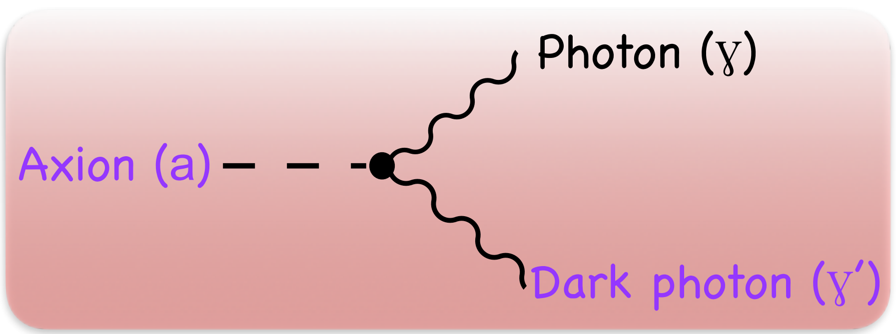
The subfrequency photons come from the boosted decay. The subfrequency could be much smaller than the original frequency for a heavy axion.
(For instance, a gamma-ray source can emit infrared light.)

Concluding Remarks

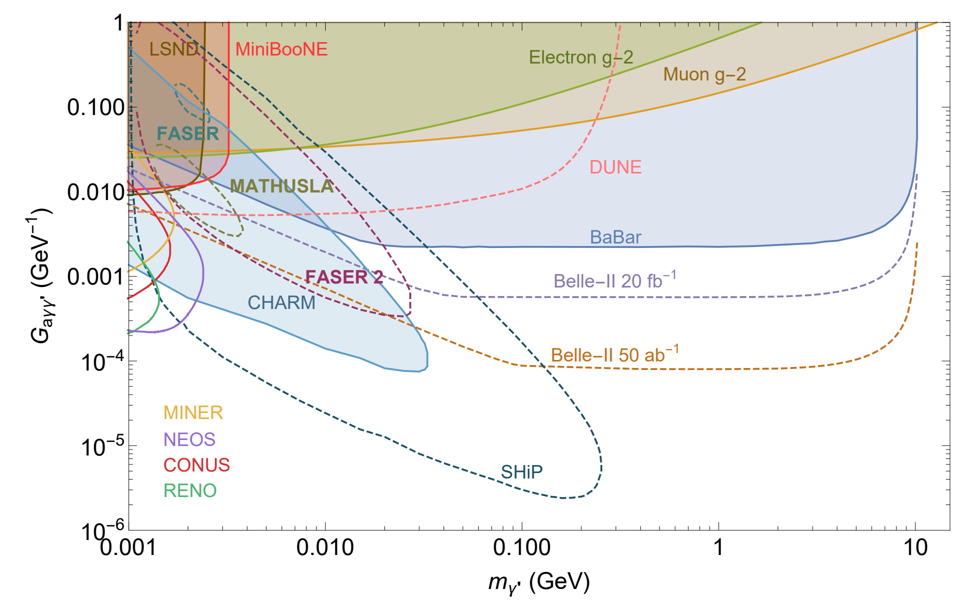


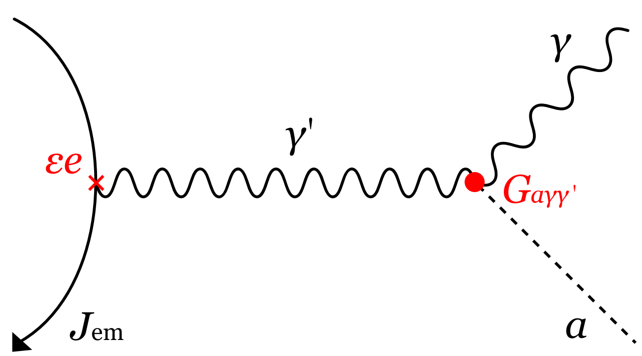
vector portal (ε)



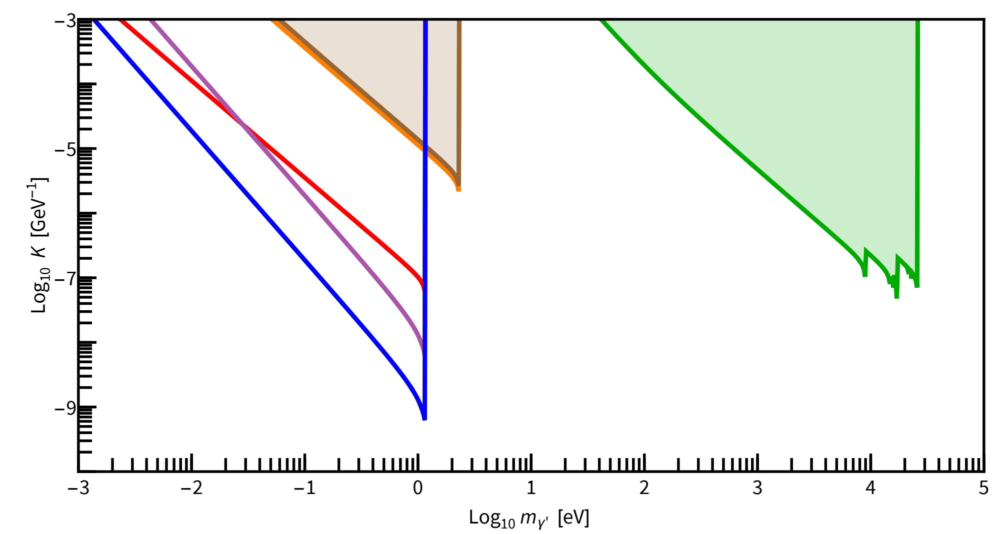


dark axion portal ($G_{a\gamma\gamma'}$)





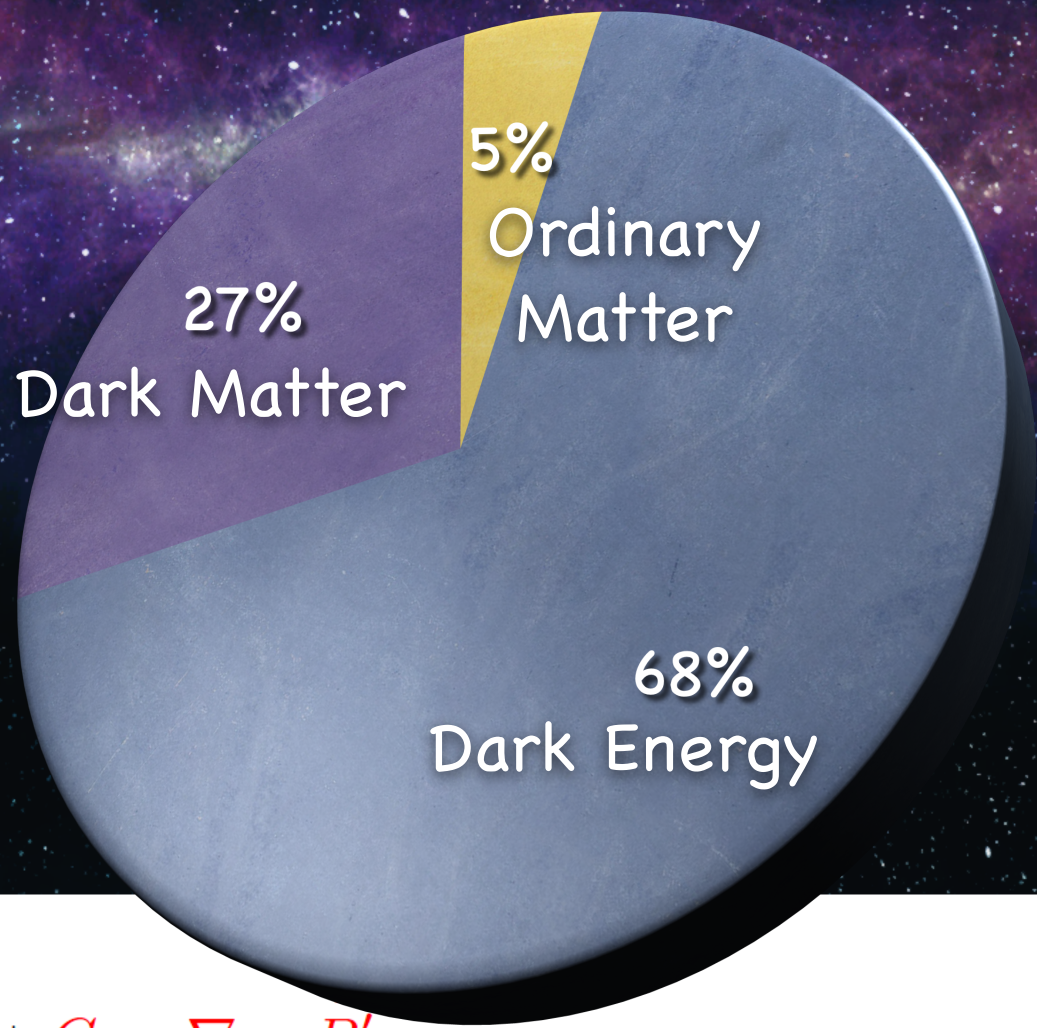
subfrequency ($K = \varepsilon\, G_{a\gamma\gamma'}$)



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

Total Universe Energy



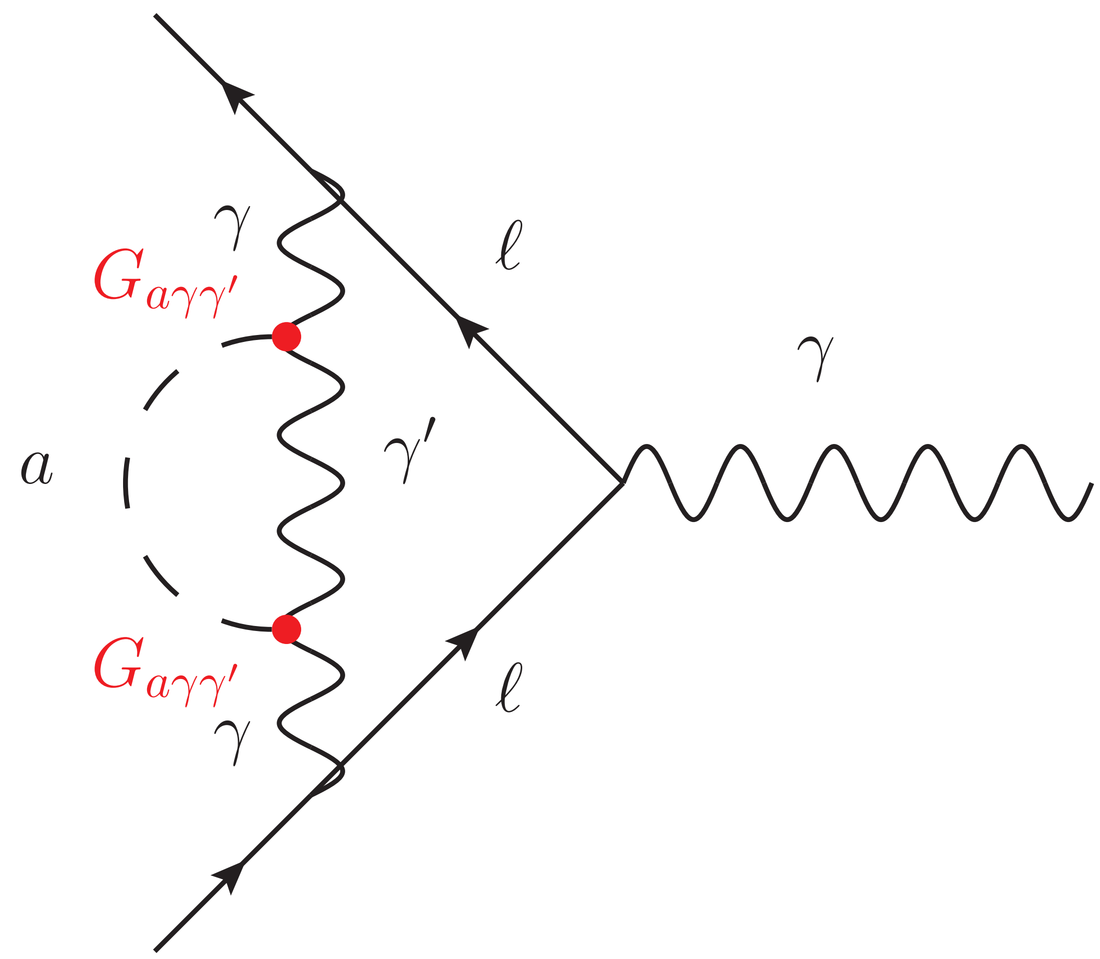
$$
\begin{aligned}
\nabla \cdot \vec{E} &= \rho + G_{a\gamma\gamma} \nabla a \cdot \vec{B} + G_{a\gamma\gamma'} \nabla a \cdot B' \\
\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\
\nabla \cdot \vec{B} &= 0 \\
\nabla \times \vec{B} &= \vec{J} + \frac{\partial \vec{E}}{\partial t} - G_{a\gamma\gamma}\left(\frac{\partial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

The future of the dark sector is bright.

- Thank you -

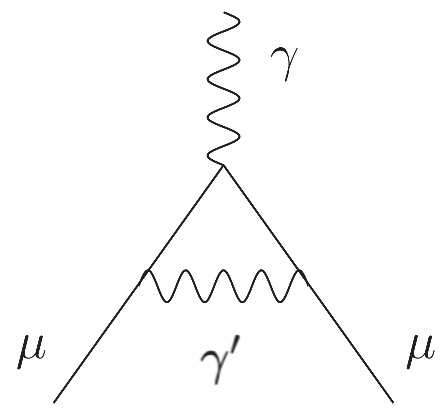
Backup Slides

Electron and Muon g-2



The dark axion portal contribution gives a wrong sign to explain muon g-2 anomaly.
We use the g-2 data to place a limit.

Cf. The dark photon contribution to the muon g-2 (right sign, but excluded now).



Maxwell's equations

[Huang, LEE (2018)]

From the equations of motion

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

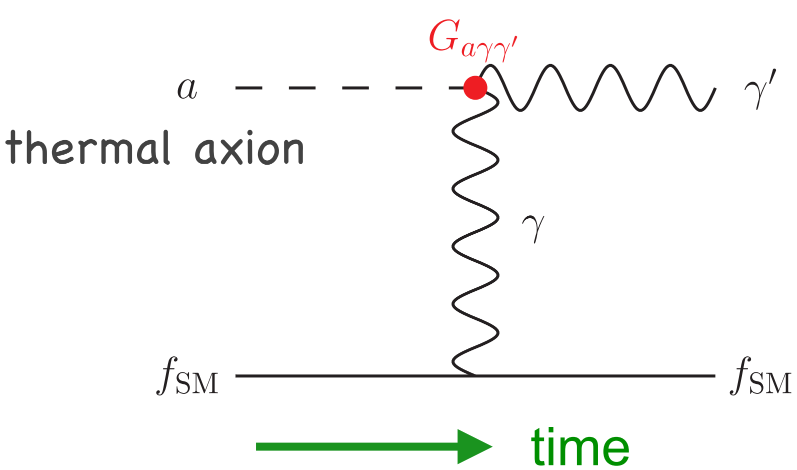
$$
\begin{aligned}
\nabla \cdot \vec{E}' &= (\rho' + \varepsilon \rho) - m_{\gamma'}^2 A'^0 + G_{a\gamma'\gamma'} \nabla a \cdot \vec{B}' + G_{a\gamma\gamma'} \nabla a \cdot \vec{B} \\
\nabla \times \vec{B}' &= (\vec{J}' + \varepsilon \vec{J}) - m_{\gamma'}^2 \vec{A}' + \frac{\partial \vec{E}'}{\partial t} - G_{a\gamma'\gamma'} \left(\frac{\partial a}{\partial t} \vec{B}' + \nabla a \times \vec{E}' \right) - G_{a\gamma\gamma'} \left(\frac{\partial a}{\partial t} \vec{B} + \nabla a \times \vec{E} \right) \\
\nabla \cdot \vec{B}' &= 0 \\
\nabla \times \vec{E}' &= -\frac{\partial \vec{B}'}{\partial t}
\end{aligned}
$$

Dark sector particles (through portals) serve as the extra source of electromagnetic field.

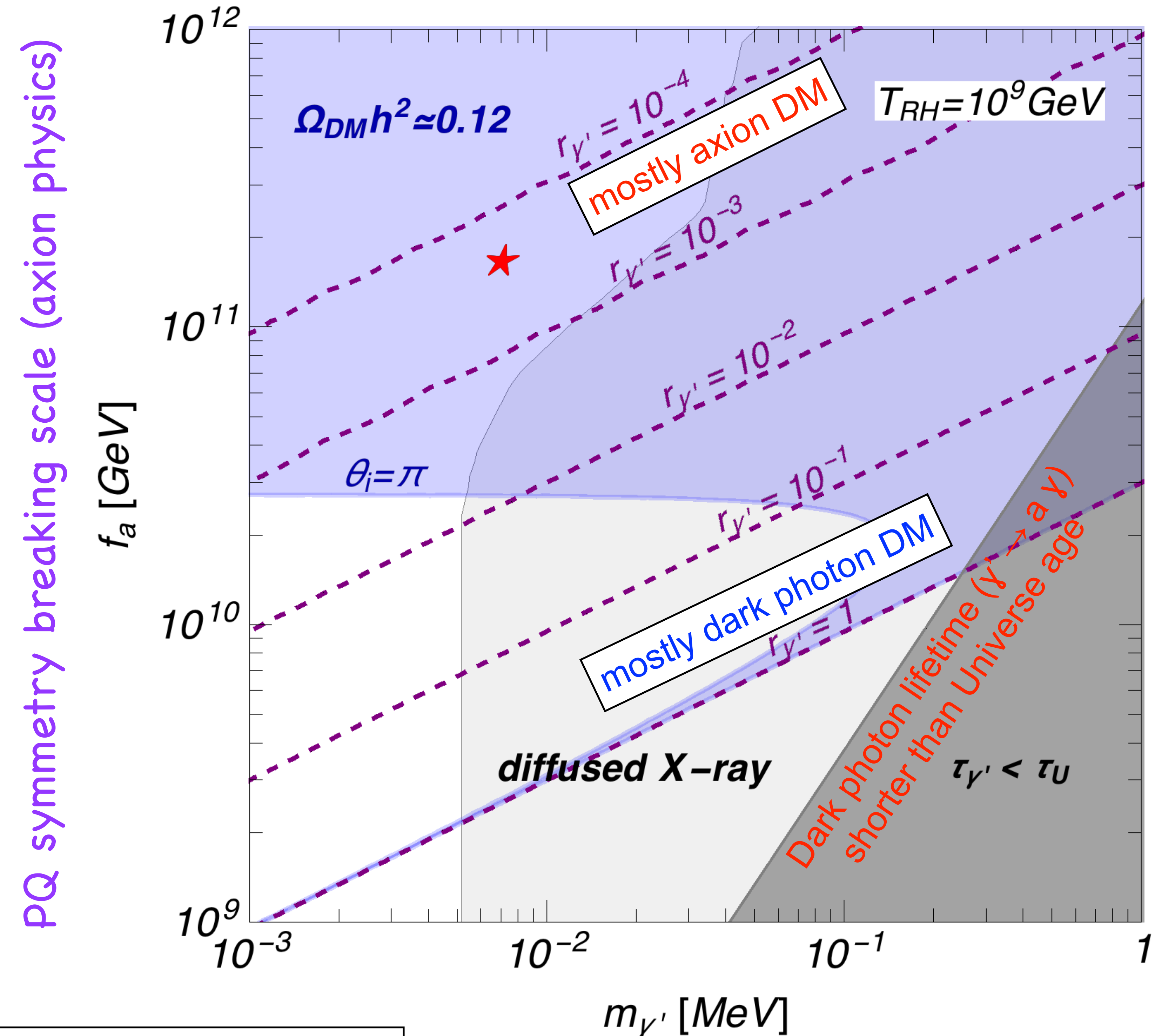
(i) New dark photon production mechanism

[Kaneta, LEE, Yun (2017)]

multiple relic DM:
QCD axion +
very light dark photon



(Dark Primakoff effect)



Dark photon decays slowly into axion + photon. ($\gamma' \to a\ \gamma$)

Purple region gives correct total (axion + dark photon) DM relic density (Ω_{DM} = 27%).
for e' = 0.1, D_ψ = 0.1, Q_ψ = -1/3

$r_{\gamma'}$ = fraction of dark photon (γ') in total DM

(ii) Explanation of the 3.5 keV X-ray puzzle

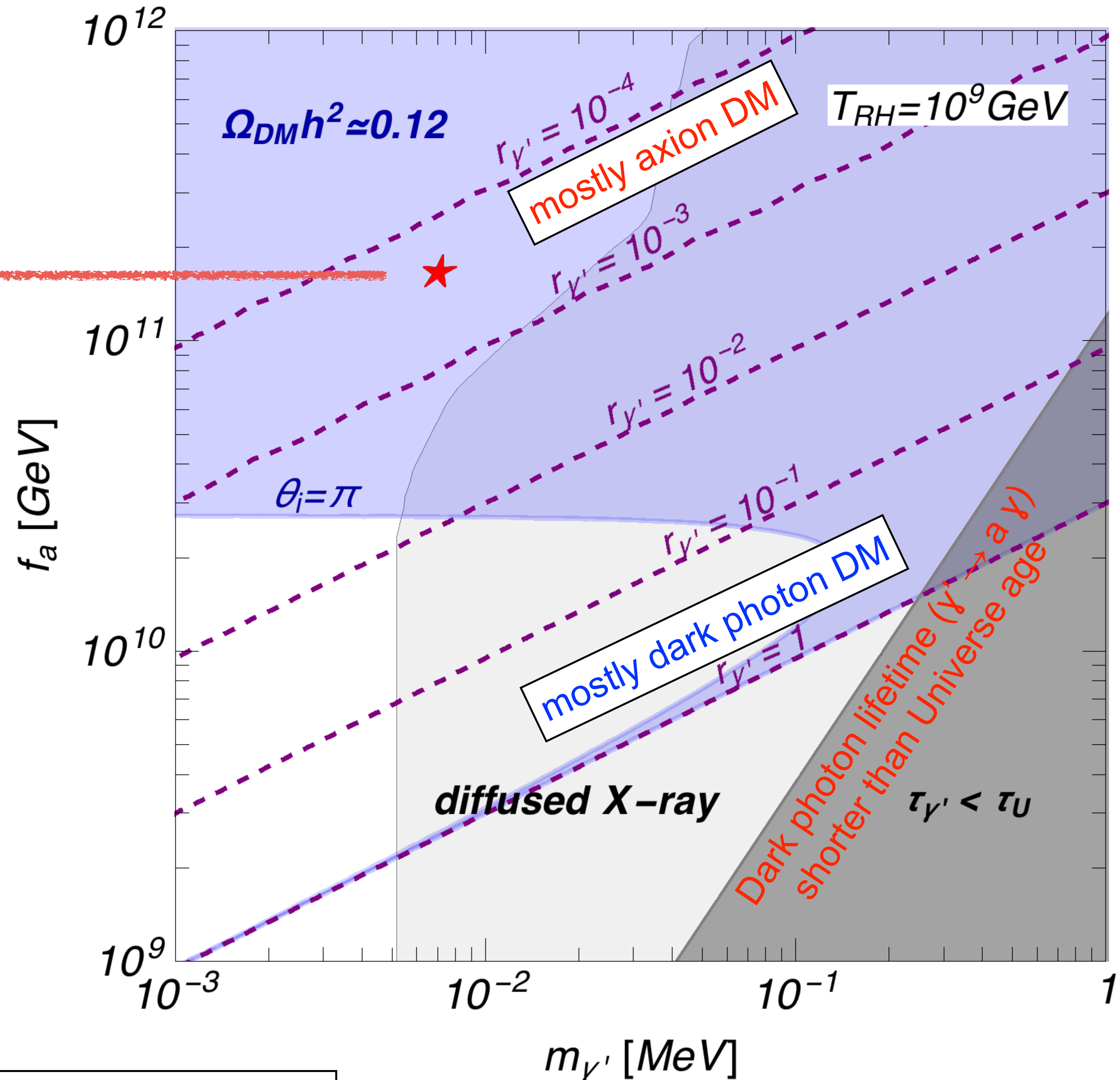
[Kaneta, LEE, Yun (2017)]

axion mass ≈ 10^{-4} eV

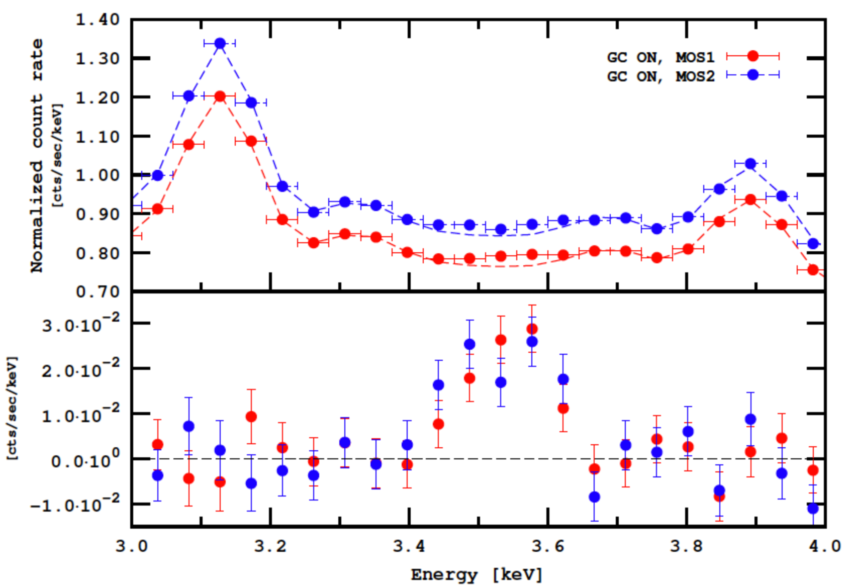
γ' mass = 7 keV

γ' lifetime = $r_{\gamma'}$ x 10^{28} sec

PQ symmetry breaking scale (axion physics)



3.5 keV X-ray excess explained



1408.2503

Dark photon decays slowly into axion + photon. ($\gamma' \to a\ \gamma$)

Interestingly, (from 2014) there is a reported <u>3.5 keV X-ray excess</u> from the galaxies (roughly 3~4σ C.L.). Currently, under scrutiny by many studies.

$r_{\gamma'}$ = fraction of dark photon (γ') in total DM

Reactor experiments (MINER/CONUS, RENO/NEOS)

[deNiverville, LEE, Lee (2020)]

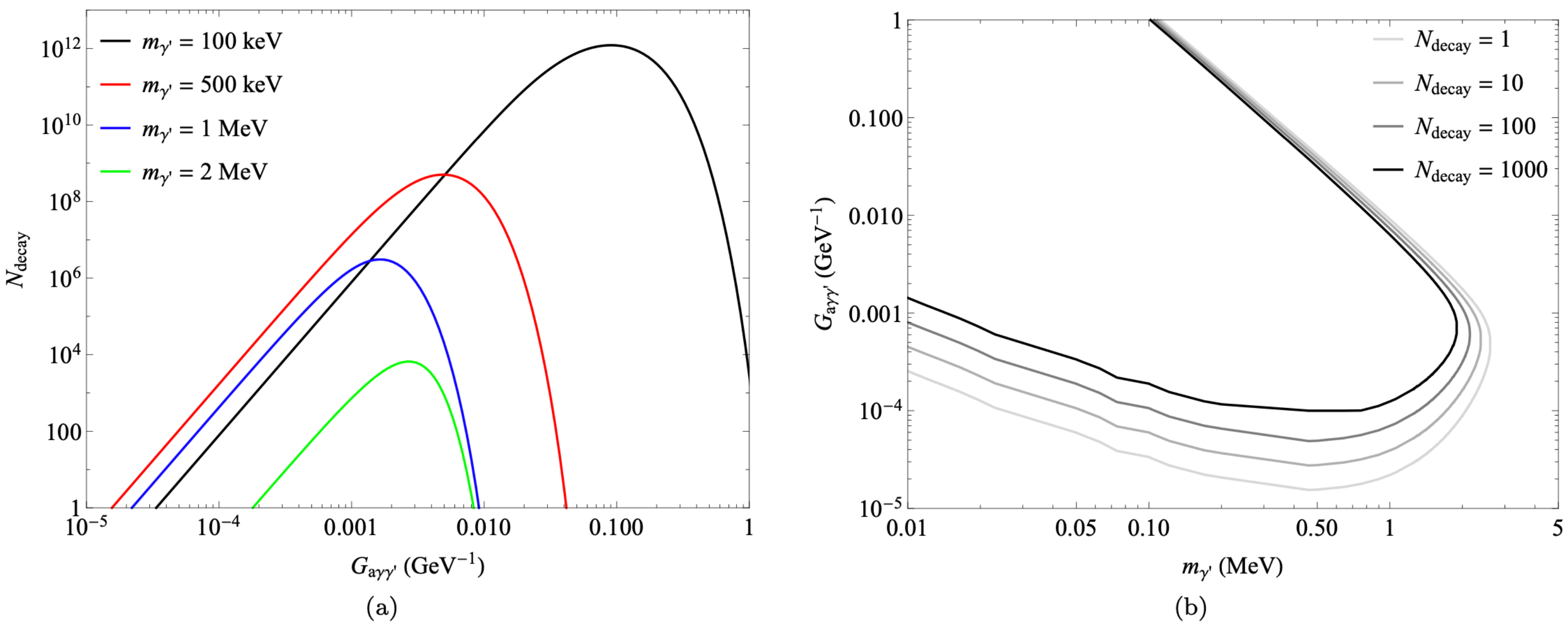


FIG. 3. The expected number of dark photon decay events under the benchmark setup with one detector of 1 m^3 100 m far from the 1 GW single reactor core with 1 year of run time. There are more than enough events to be detected due to the high intensity of the flux from the reactor. The dark photon production becomes minute to be detected if the dark axion portal coupling is too small, while most of them decay before they reach the detector if the coupling is too large. (a) The number of decays as a function of the coupling for various dark photon masses. (b) The number of decays as a contour in the coupling-dark photon mass space.

The reactor photon production distribution was modeled by

$$\frac{dN_\gamma}{dE_\gamma} = \frac{0.58 \times 10^{18}}{\text{sec} \cdot \text{MeV}} \frac{P}{\text{MW}} e^{-E_\gamma/(0.91\text{MeV})}, \qquad (4)$$

Detectors for neutrino oscillation (RENO/NEOS/…) use scintillation to detect gamma's. (MeV scale threshold).
Detectors for coherent elastic neutrino-nucleus scattering (MINER/CONUS/…) use crystals to detect gamma's (negligible threshold).

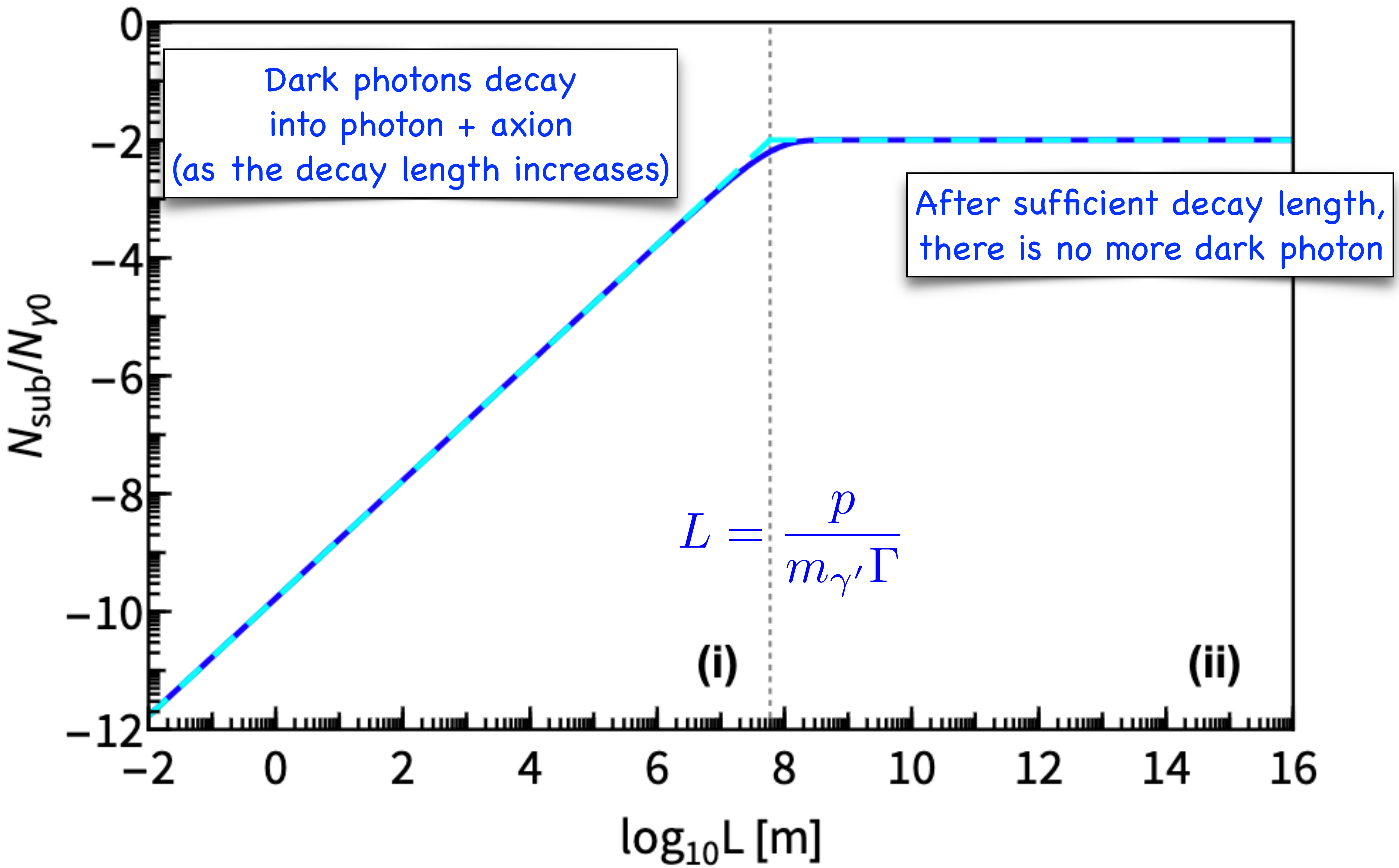
Bkg (single photon): radioactive isotopes in the rocks, PMT glasses, liquid scintillators, etc.
Detailed bkg analysis to reduce the isotope peaks would enhance the sensitivities significantly.

TABLE I. Summary of the experimental setups. The specifications for the experiments are based on Refs. [12, 16, 17, 54, 55], and the background rates are determined based on Refs. [33, 54–56]. The detector volume of CONUS and MINER was estimated from their payload. (*Phase-2 is assumed. **Signal+Background rate.)

Experiment	Detector volume	Reactor power	Reactor-detector distance	Background rate	Energy cutoff
CONUS	751.46 cm^3	3.9 GW	17 m	12 Hz	Negligible
MINER*	3085.2 cm^3	1 MW	2.835 m	6 Hz	Negligible
RENO	18.7 m^3	16.4 GW (total) 2.73 GW (each)	304.8 m (nearest) 739.1 m (farthest)	30 Hz	1 MeV
NEOS	1.008 m^3	2.73 GW	23.7 m	0.16 Hz**	3.5 MeV

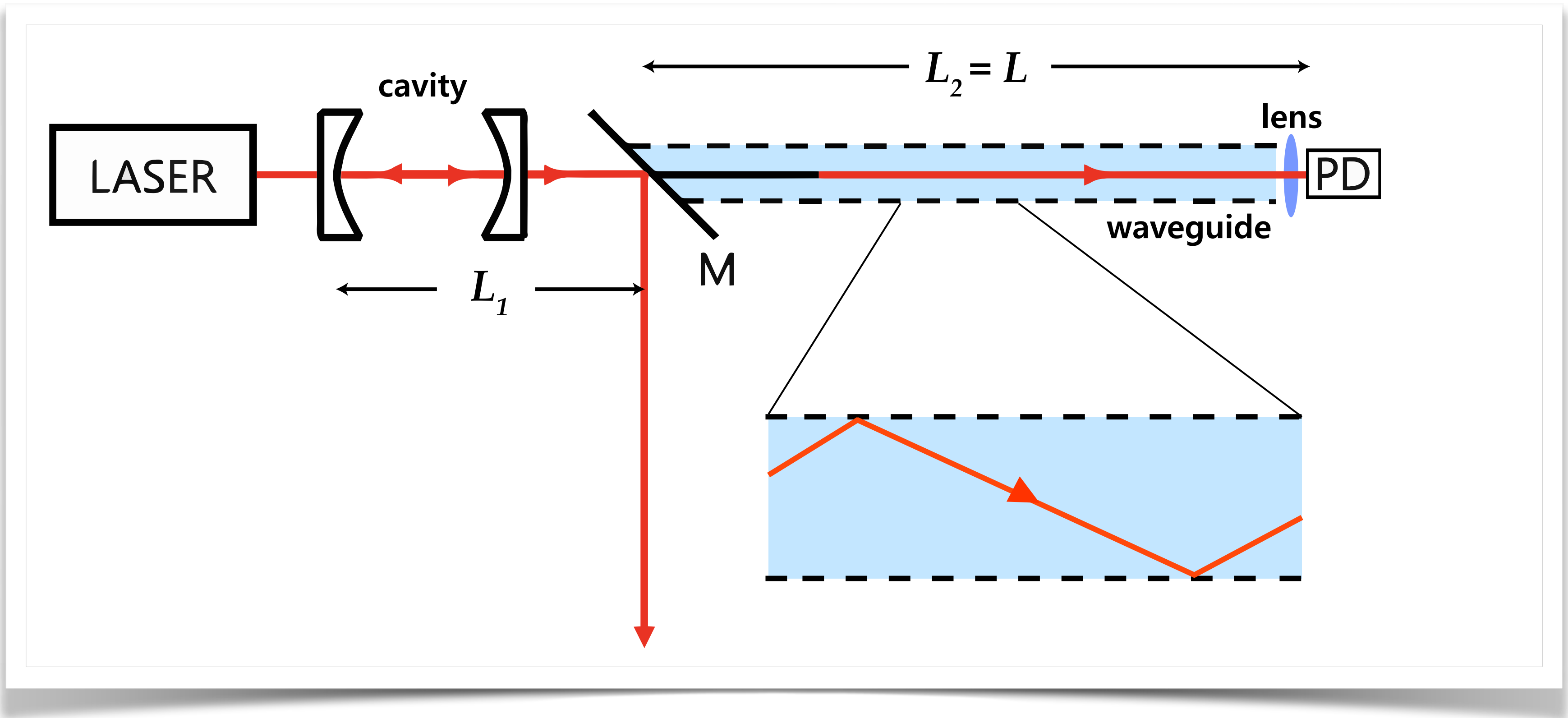
Subfrequency photon number vs. length

[LEE, Lee, Yi (Preliminary)]



Subfrequency photon number

[LEE, Lee, Yi (2022)]



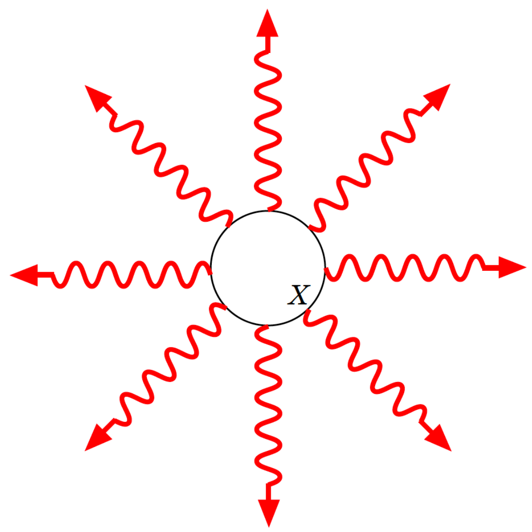
$$N_{\text{sub}} = \mathcal{P}_{A\to X}(L_1)\mathcal{P}_{X\to\text{decay}}(L_2)N_\gamma$$
$$= \varepsilon^2\left[1 + e^{-\frac{m_{\gamma'}\Gamma L_1}{p}} - 2e^{-\frac{m_{\gamma'}\Gamma L_1}{2p}}\cos(L_1\Delta p)\right]\left[1 - e^{-\frac{m_{\gamma'}\Gamma L_2}{p}}\right]N_\gamma$$

Simple setup: (i) $m_a \ll m_{\gamma'} < \omega.$

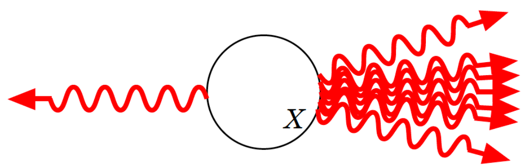
(ii) $\dfrac{m_{\gamma'}\Gamma L_i}{\sqrt{\omega^2 - m_{\gamma'}^2}} \ll 1 \quad (\text{for } i = 1,\ 2).$

(iii) $L_1 \Delta p \gg 2\pi.$

Subfrequency photon

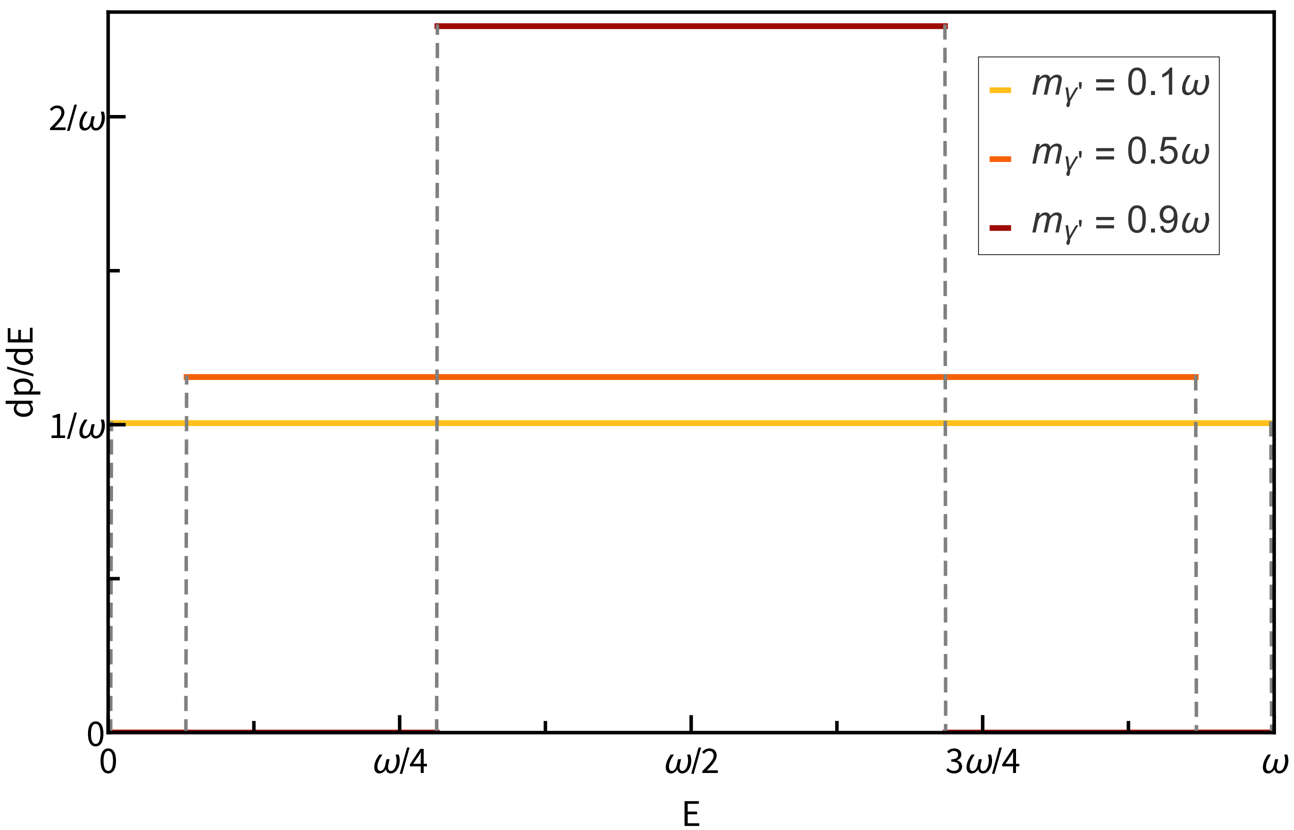


dark photon rest frame

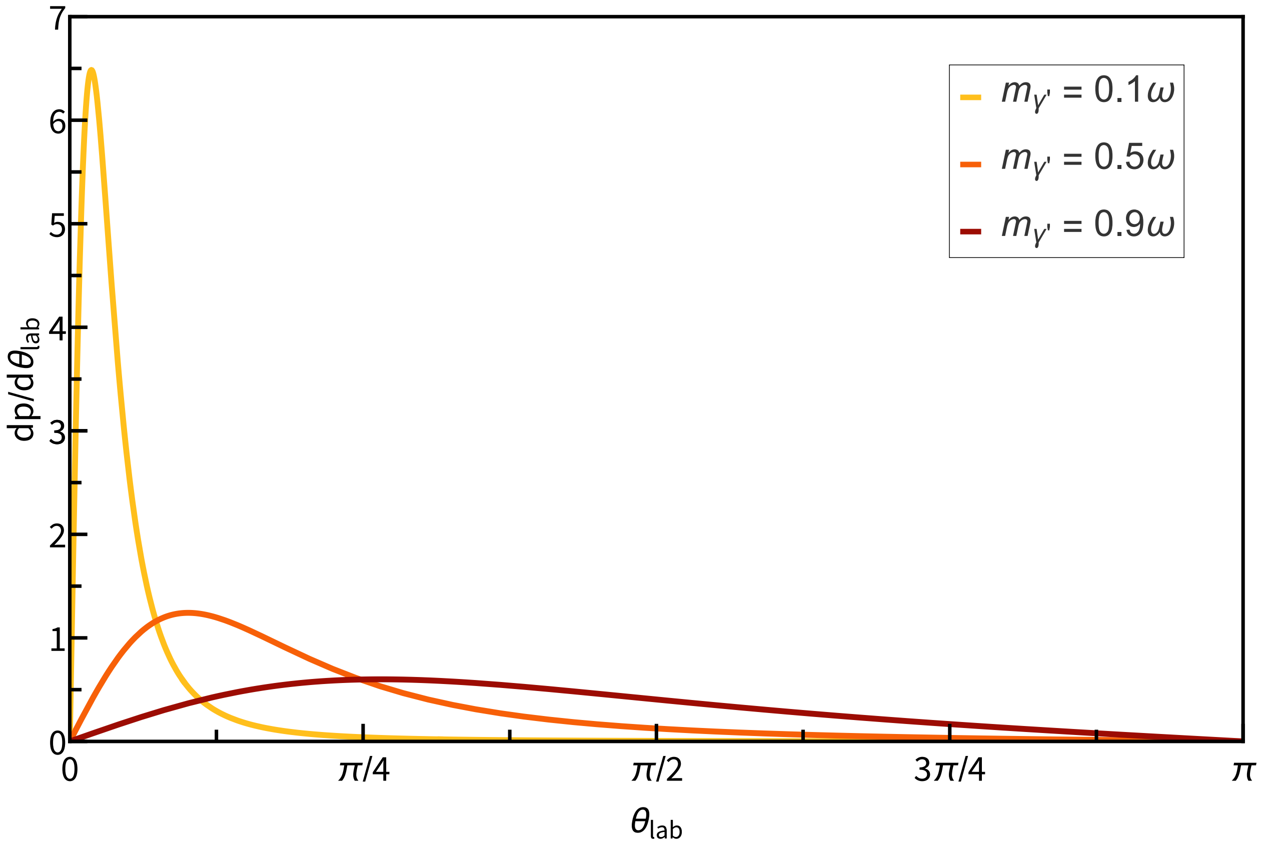


lab frame

(energy dispersion of the subfrequency photon)



(angular dispersion of the subfrequency photon)



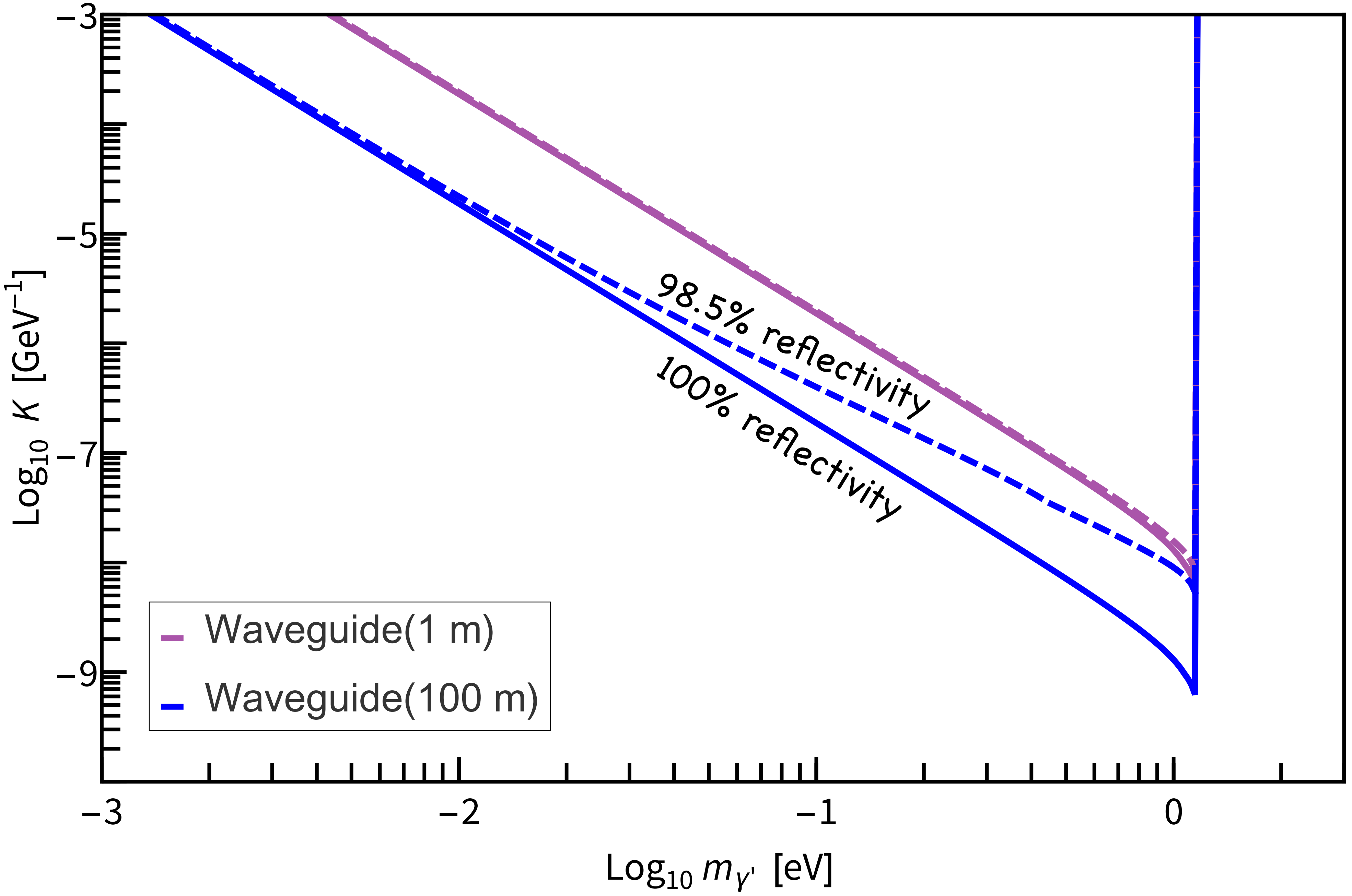
Specifications of laser/X-ray setups

	a (mm)	L (m)	ω (eV)	N_γ (Hz)	N_{pass}	η_{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
SPring-8	6[d]	0.654	$7270 \sim 26000$	$4.3 \times 10^{12} \sim 8.9 \times 10^{13}$	1	$0.23 \sim 0.83$	$0.0019 \sim 0.0142$	$5.28 \sim 8.88$

[a] The ALPS II uses an optic suitable to collect a 17.5 mm diameter beam [30].
[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 [31].
[c] We take the size of the lens in front of the PMT [10].
[d] We take the radius of crystal in Ge detector [32].

TABLE I. Specifications of the experimental setups we use in our analysis. The LSW experiments (GammeV, ALPS, ALPS II) are partly sensitive to the sub-frequency new physics scenario. Our proposed experimental setup (Waveguide) adopts a waveguide. The parameters for the LSW experiments including η_{eff} were taken from Refs. [7, 32–34]. Some of the parameter values may not properly reflect the actual experiments. For instance, the η_{eff} of the LSW experiments would change if the frequency-dependence is properly applied.

Effect of the reflectivity in the waveguide



Waveguides of 100% reflectivity (solid) and 98.5% reflectivity (dashed).
The signal loss is more critical for longer L and larger dark photon mass.

Tungsten Transition Edge Sensor (TES) device

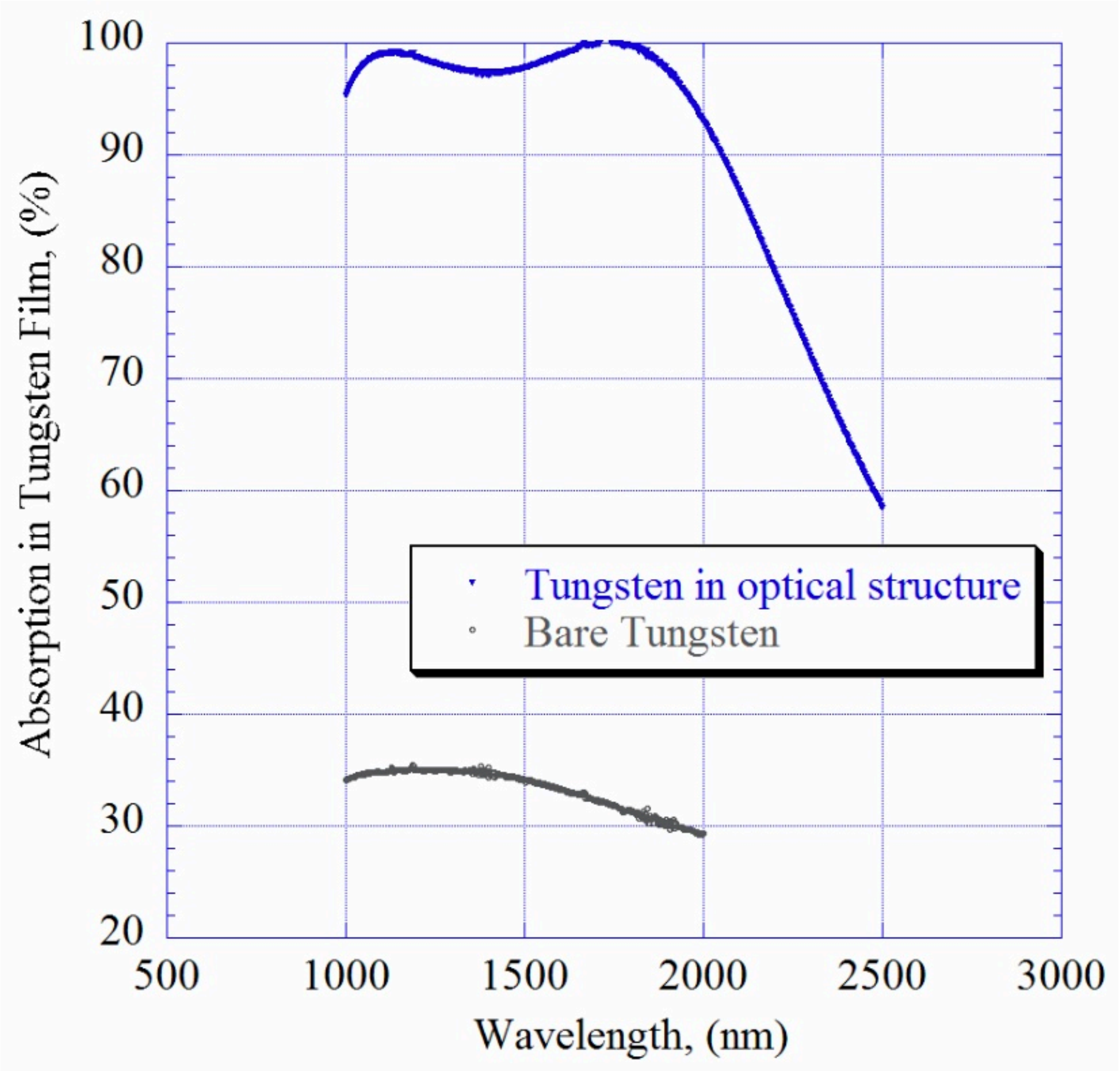
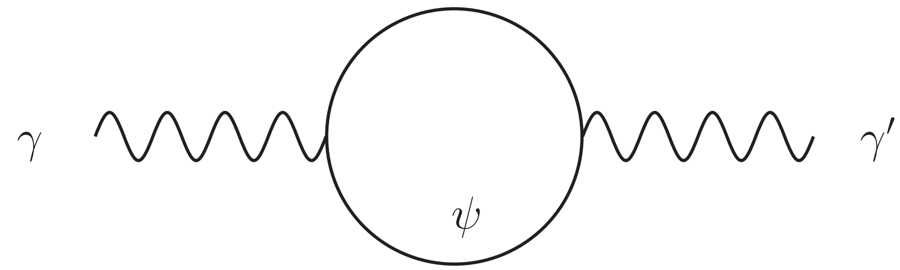


Fig. 1. (Color online) Spectrophotometer data taken at room temperature indicating significant improvement in tungsten absorption at both 1310 and 1550 nm wavelengths when tungsten is embedded between appropriate dielectric layers.

Loop-induced kinetic mixing



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

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

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

<u>For **Λ** ~ 10^{16} GeV (typical GUT scale)</u> and $m_\psi \sim f_a$, (10^9 - 10^{12} GeV), we get <u>$\varepsilon_{\rm induced}$ ~ -O(10^{-2})</u> for e' = 0.1, $Q_\psi D_\psi$ = 1. → On its own, inconsistent with the experimental constraints for keV-MeV scale dark photon.

This can be addressed either by

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

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

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