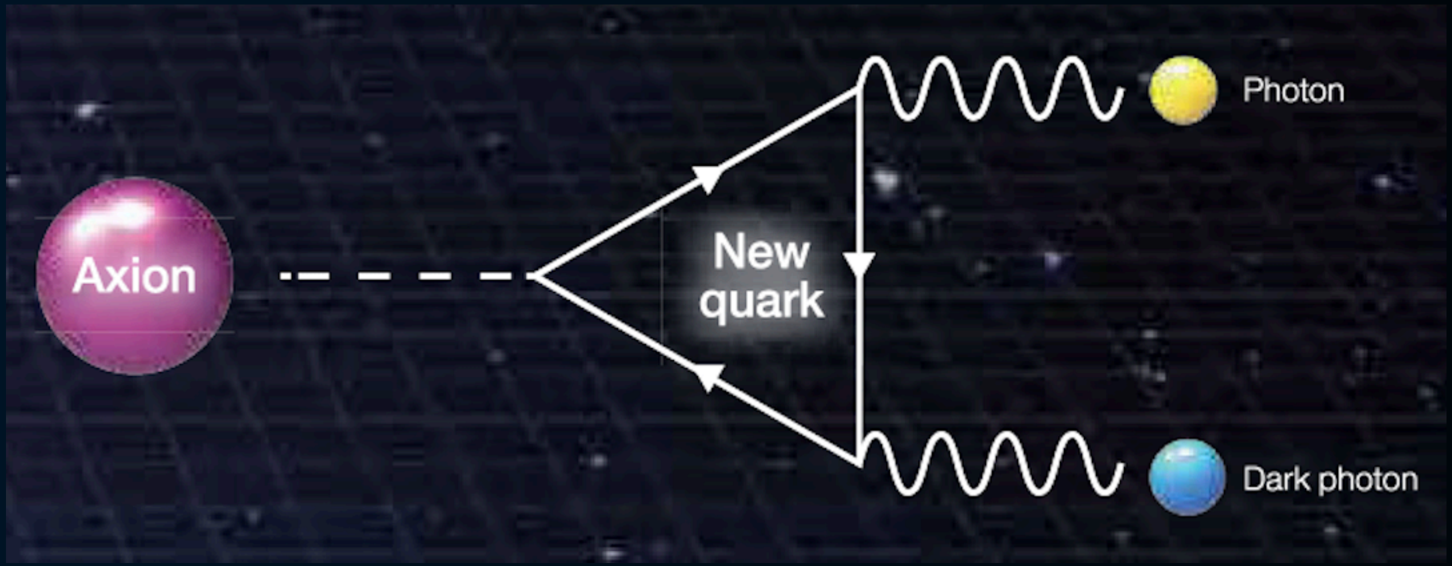
Dark Axion Portal

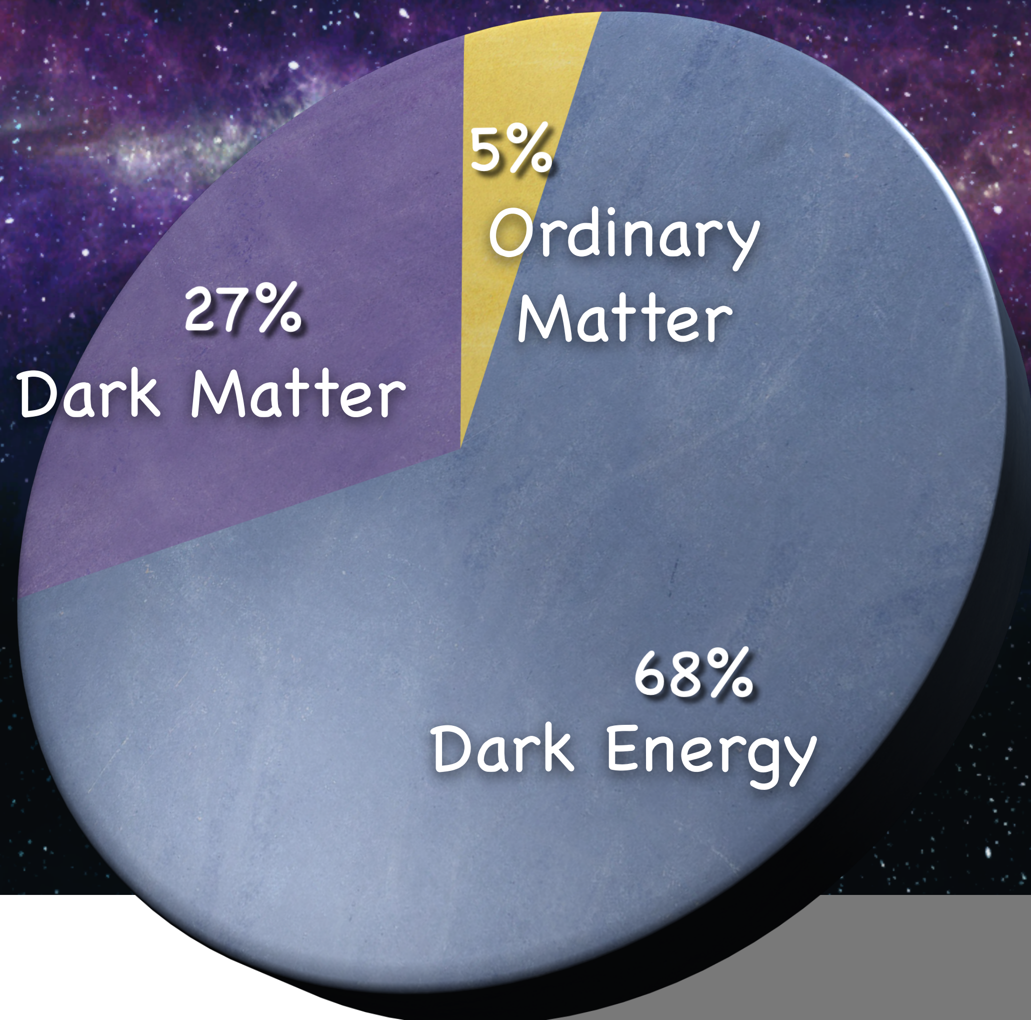


Hye-Sung Lee
KAIST

Chung-Ang University BSM Workshop
February 1, 2021

We live in a Dark World

Total Universe Energy

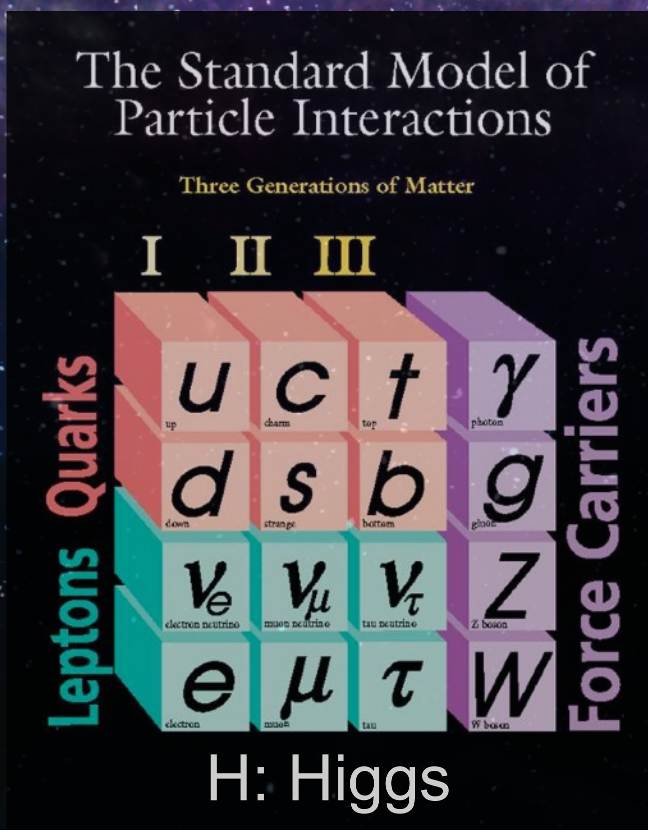


$$
\begin{aligned}
\nabla \cdot \vec{E} &= \rho \\
\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\
\nabla \cdot \vec{B} &= 0 \\
\nabla \times \vec{B} &= \vec{J} + \frac{\partial \vec{E}}{\partial t}
\end{aligned}
$$

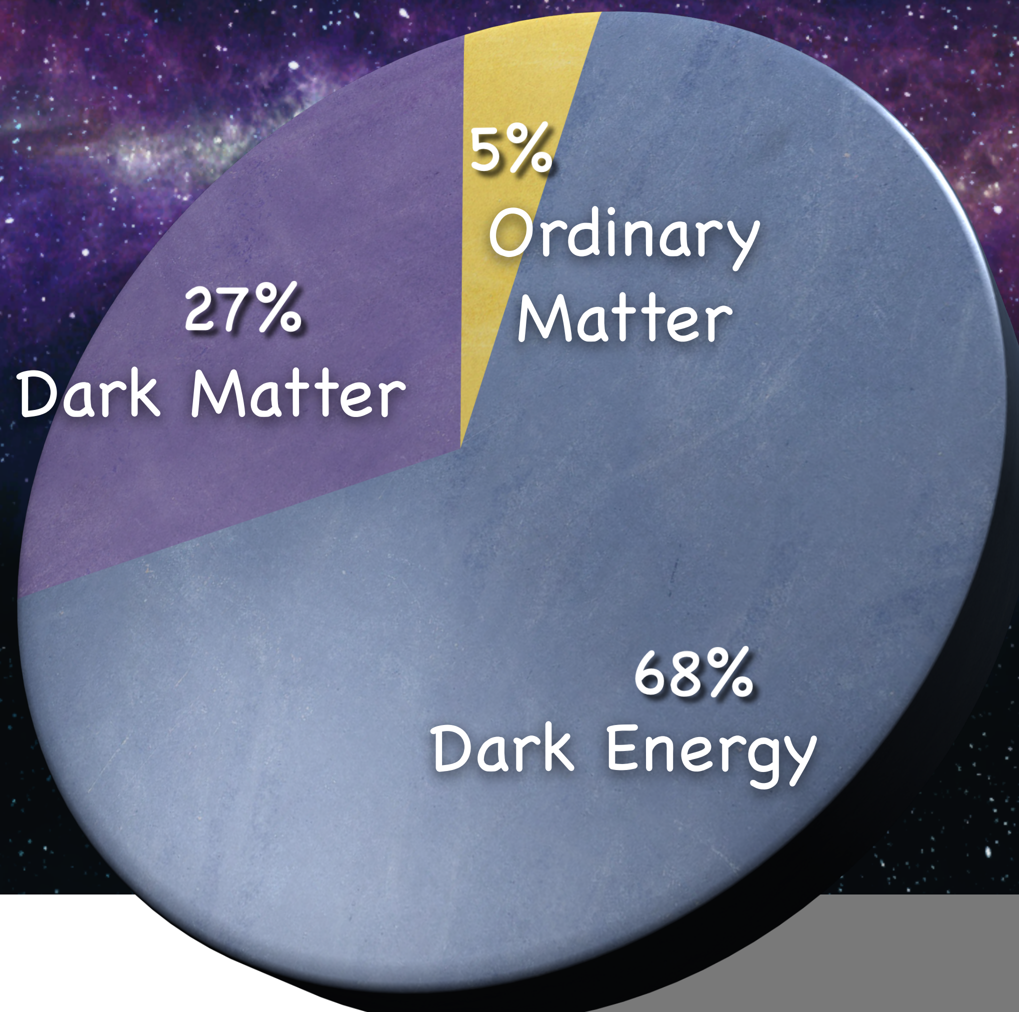
Bright sector

Dark sector

We live in a Dark World



Total Universe Energy



Dark Sector

Dark matter
Dark Higgs
Dark gauge boson
•••

$$\nabla \cdot \vec{E} = \rho$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

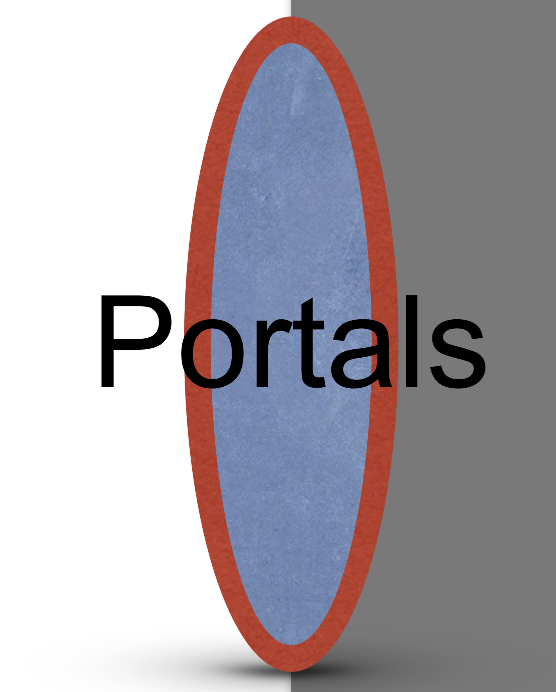
$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{B} = \vec{J} + \frac{\partial \vec{E}}{\partial t}$$

Bright sector

Dark sector

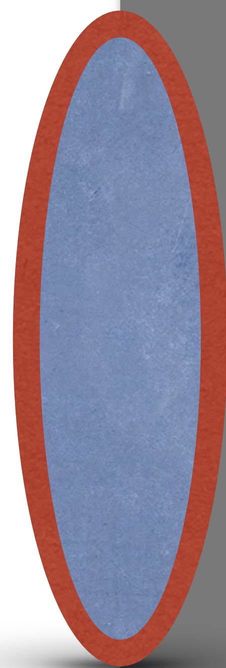
The dark sector particles can be light.



Portals

Standard Model

Dark Sector



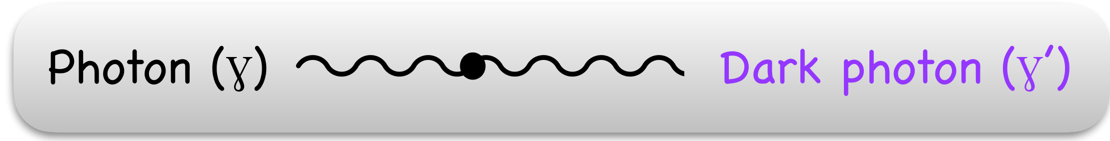
Dark matter
Dark gauge boson
Dark Higgs
RH neutrino
Axion
...

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

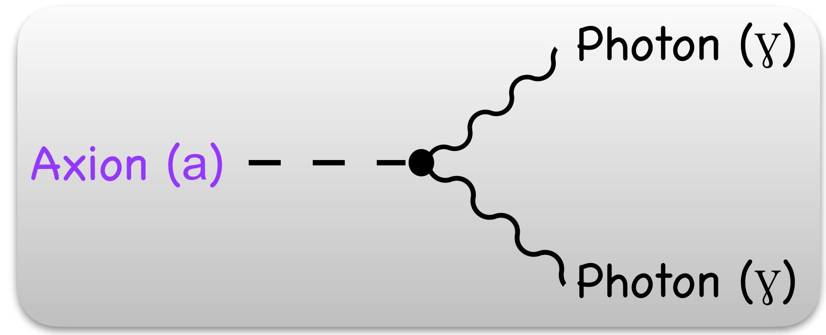
F, ɣ : photon
Z′, ɣ′ : dark photon
a : axion

Portals

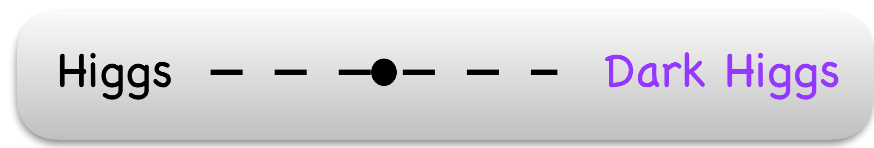
(i) Vector Portal $\frac{\varepsilon}{2} F_{\mu\nu} Z'^{\mu\nu}$



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



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

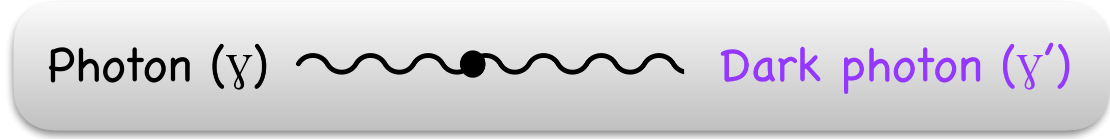


(iv) Neutrino Portal $y\,LHN$

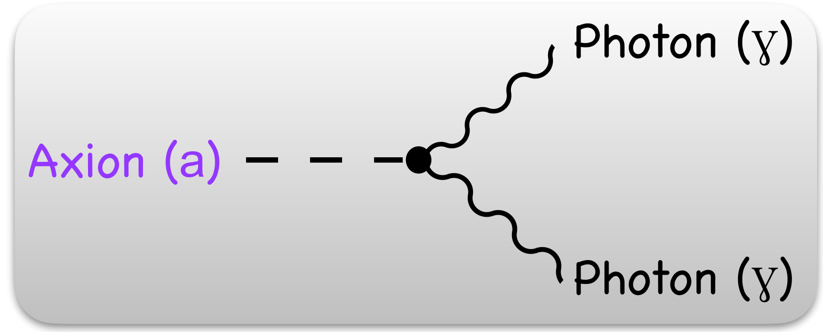
F, γ : photon
Z′, γ′ : dark photon
a : axion

Portals

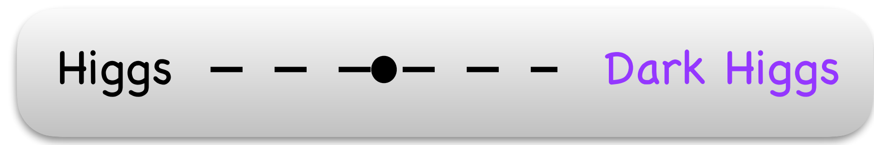
(i) Vector Portal $\frac{\varepsilon}{2} F_{\mu\nu} Z'^{\mu\nu}$



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



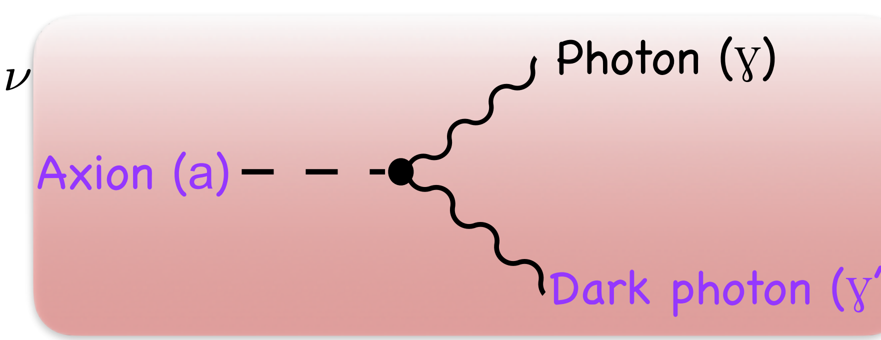
(iii) Higgs Portal $\kappa\, |S|^2 |H|^2 + \mu\, S |H|^2$



(iv) Neutrino Portal $y\, LHN$

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

[Kaneta, LEE, Yun (PRL 2017)]



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 not a simple product of Vector & Axion portals. (e.g. $G_{a\gamma\gamma'} \neq \varepsilon\, G_{a\gamma\gamma}$)

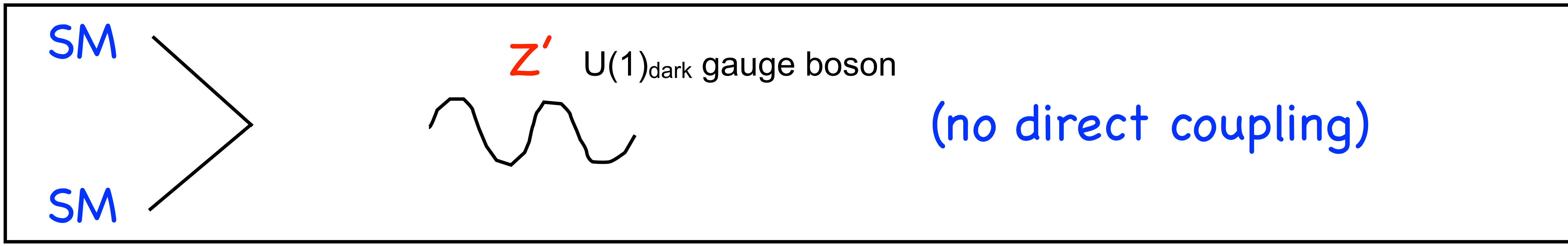
Vector Portal

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

Standard Model + Dark Force

Gauge symmetry = $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{dark}$

It may interact with DM, but
SM particles have zero charges

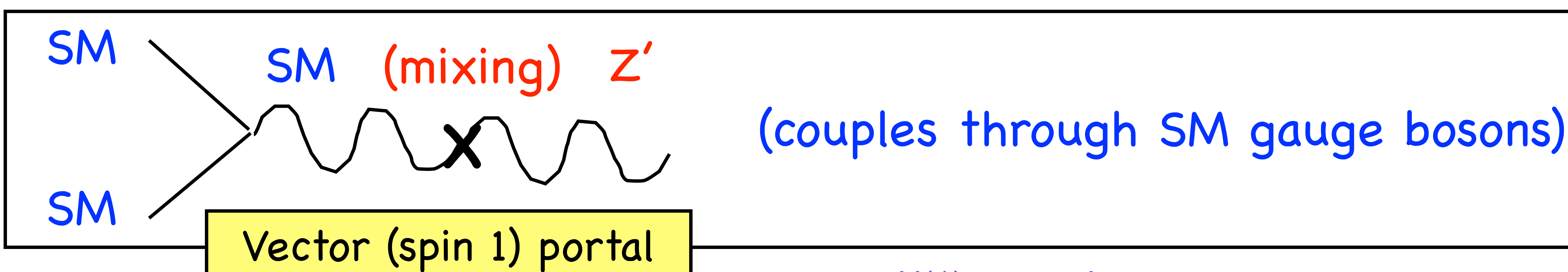


Z' can couple to SM particles through kinetic mixing of $U(1)_Y$ & $U(1)_{dark}$.

[Holdom (1986)]

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

U(1) kinetic term (photon part)
⟶ **Maxwell's equations**



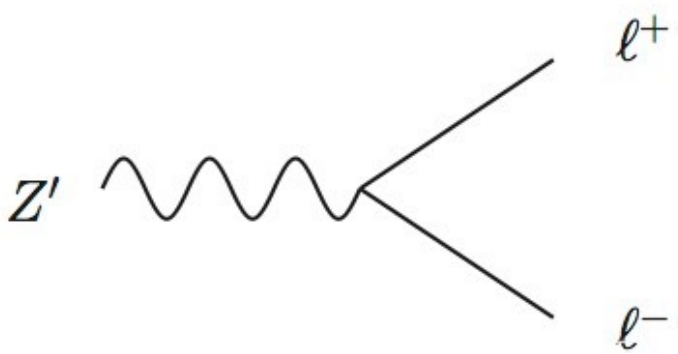
$U(1)_Y$ gauge boson: $B_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu$

(θ_W : Weinberg angle)

Visible/Invisible decay of Dark photon

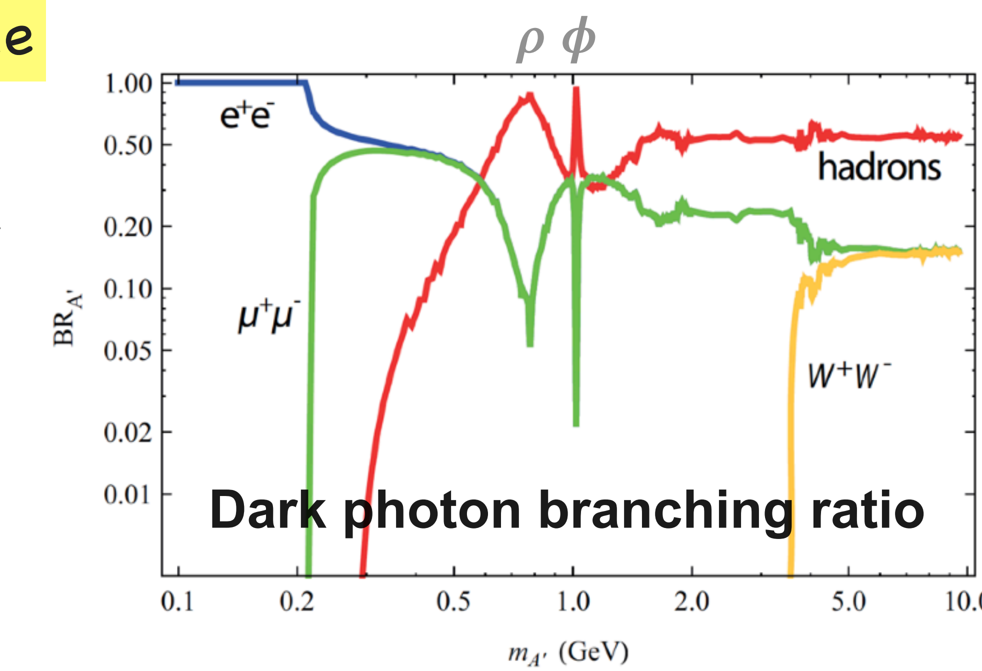
2 main categories of Dark force search (in terms of the dominant decay modes) :

(i) "Dilepton Resonance" search   Visible dark photon mode



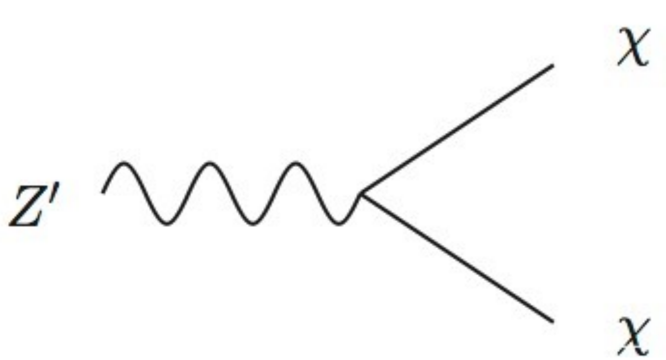
Z' $\to \ell^+\ell^-$ is the major decay mode in an ordinary scenario.

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



[Batell, Pospelov, Ritz (2009)]
[Raggi, Kozhuharov (2015)]

(ii) "Missing Energy" search   Invisible dark photon mode

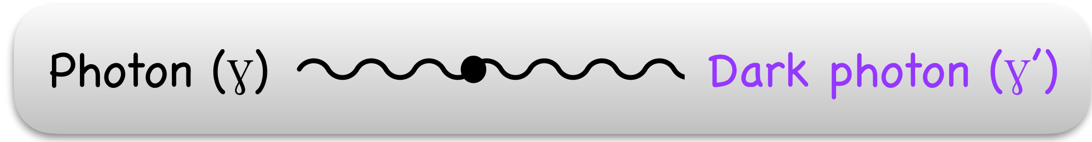


Z' $\to \chi\chi$ is the major decay mode,
if χ **(very light dark sector particle)** exists.

BR(Z' → missing energy) ≈ 1 is taken.

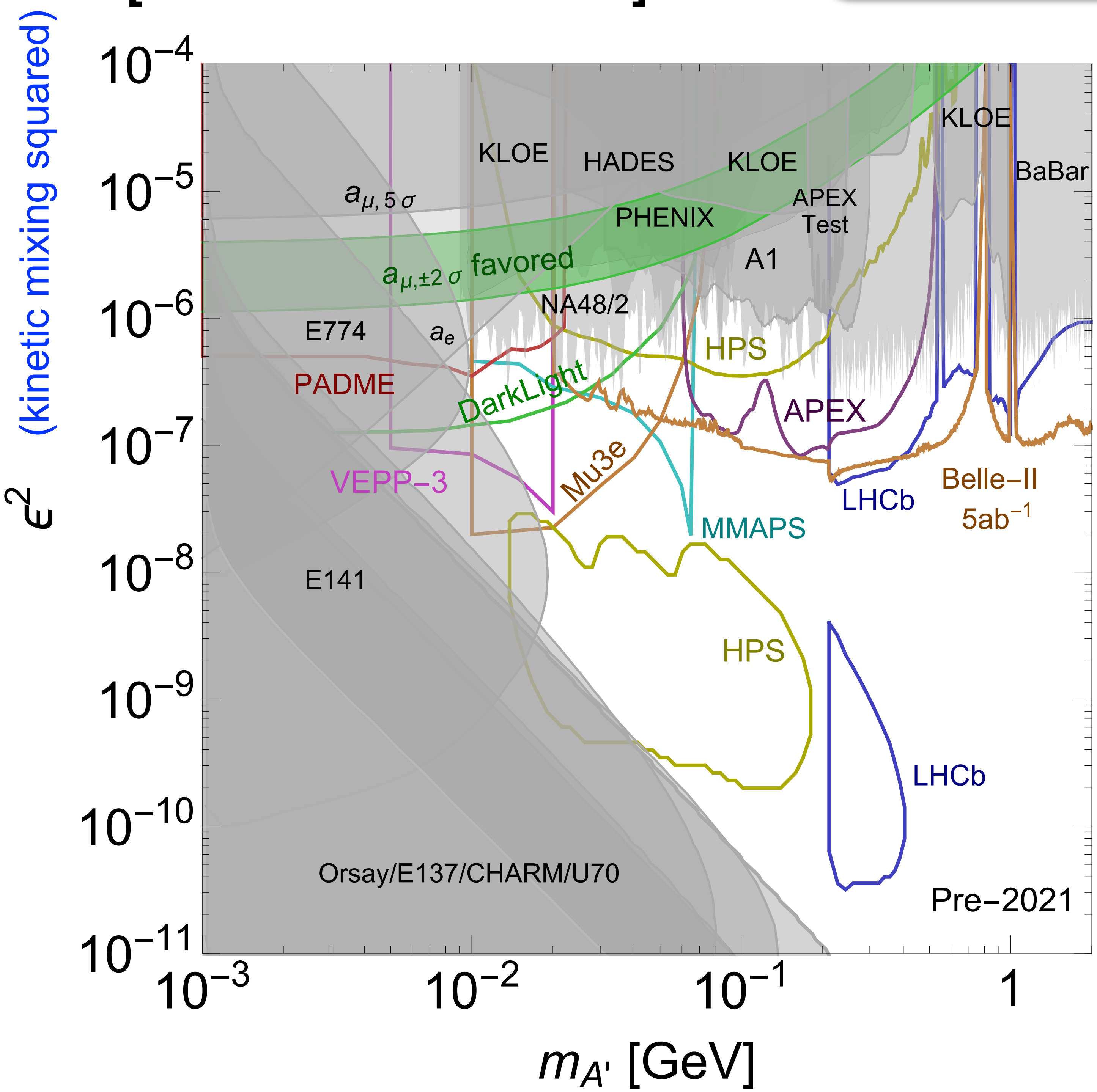
$$\Gamma(\gamma' \to \chi\bar{\chi}) = \frac{e'^2 D_\chi^2}{12\pi} m_{\gamma'} \left(1 - \frac{4m_\chi^2}{m_{\gamma'}^2}\right)^{1/2}$$

Dilepton searches for dark photon (Visible dark photon)

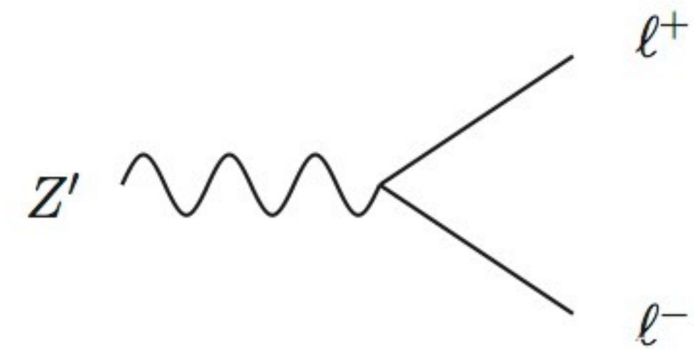


γ-γ′ kinetic mixing (vector portal)

[Current constraints]



From Dark Sector 2016 Workshop (arXiv:1608.08632)



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

(i) Electron, Muon g-2
(ii) Beam-dumps
(iii) Meson (quarkonium) decays
(iv) e+e- collision (photon+Z')
(v) Fixed target experiments

The dark gauge boson is actively searched for in many experiments.

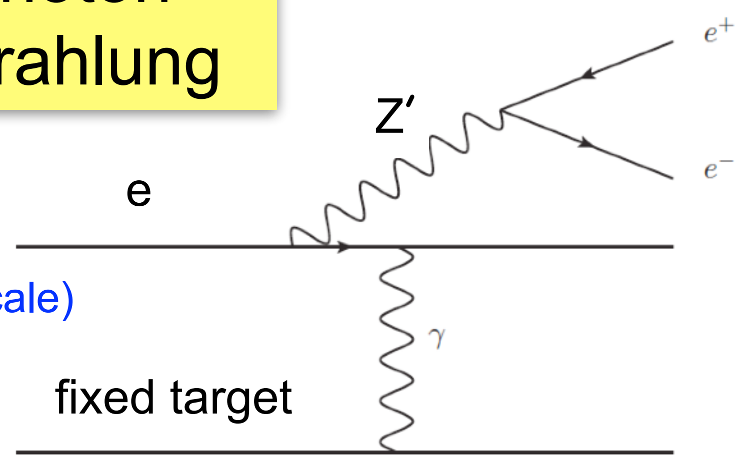
The vector portal is constrained to be small ($\varepsilon \ll 1$) .

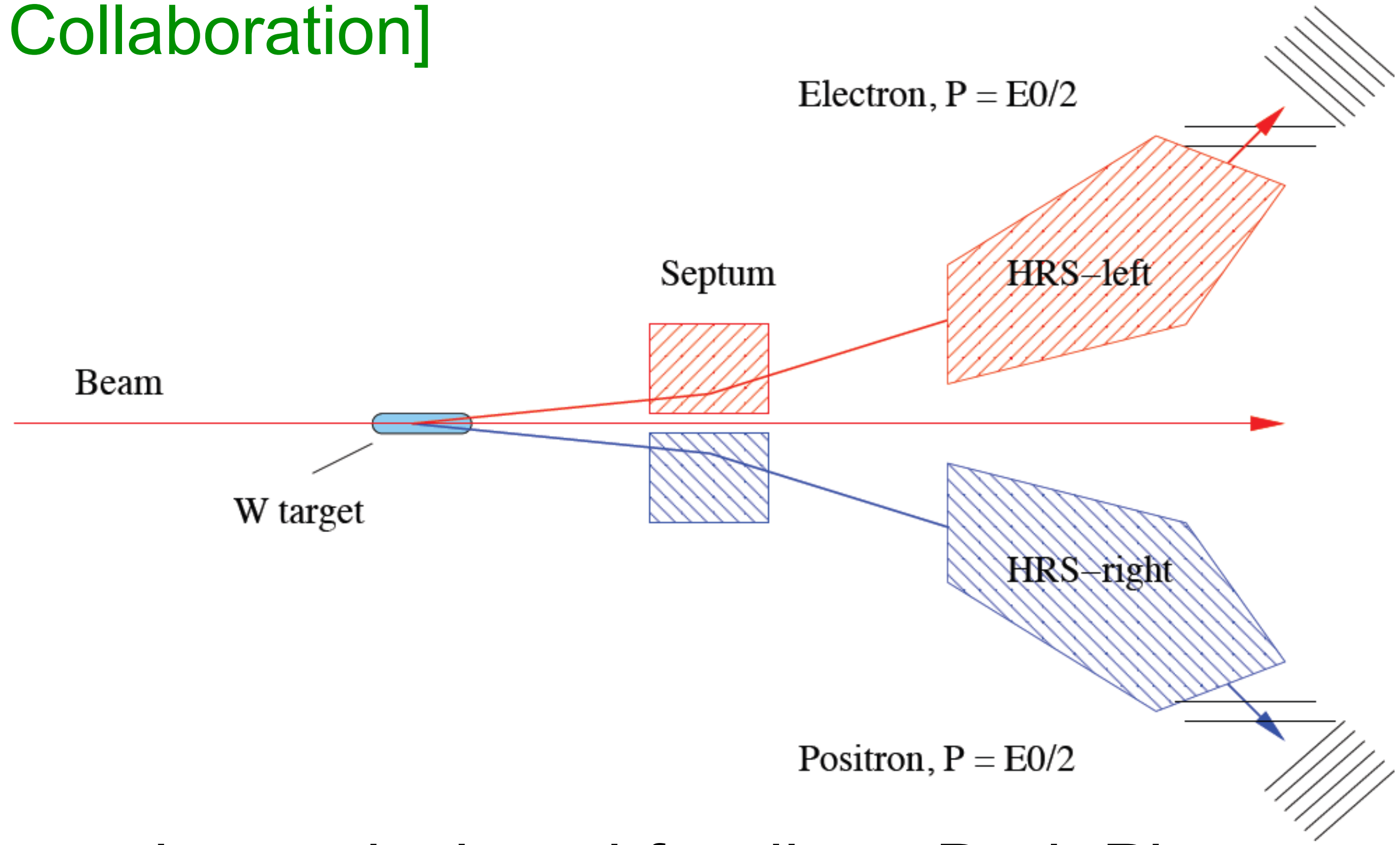
Example: A' Experiment (APEX) at JLab - Hall A

[APEX Collaboration]

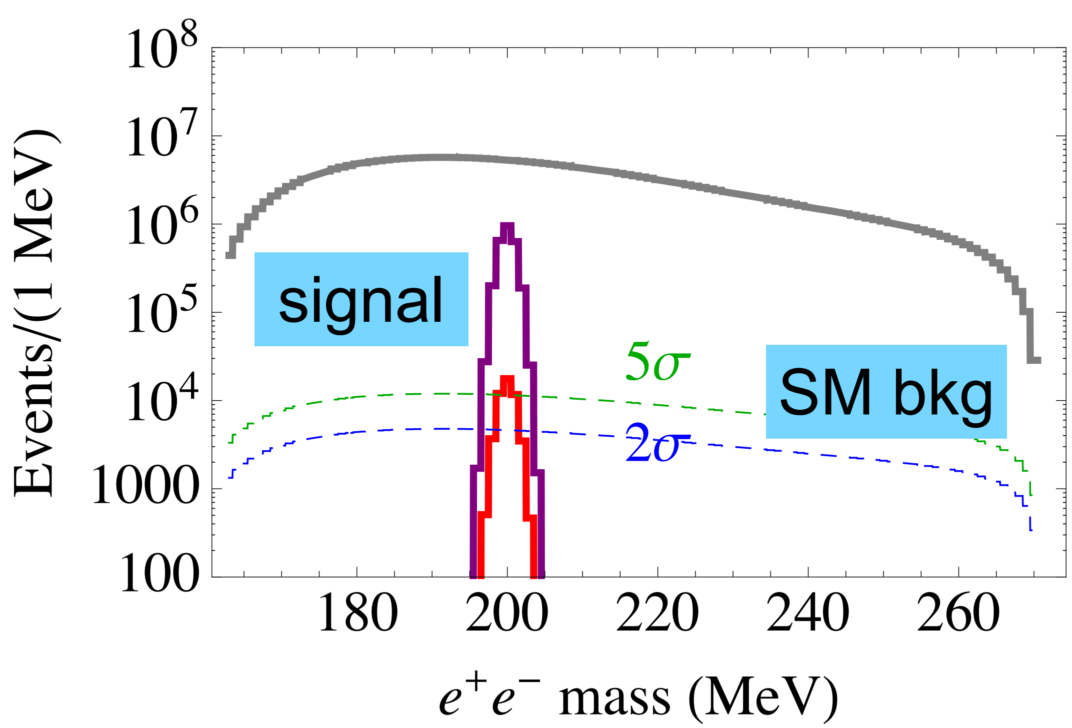
Dark Photon Bremsstrahlung

e-beam (GeV scale)





New Fixed target (Tantalium Z=73) experiment designed for direct Dark Photon production/detection.



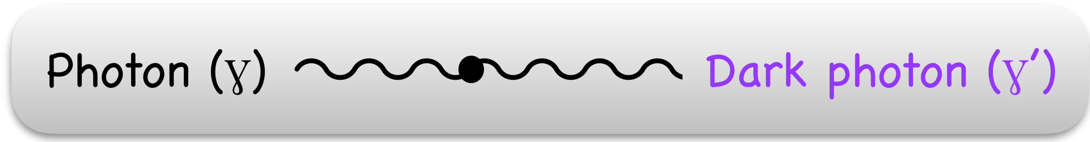
Z' → e^+e^- narrow resonance at Z' mass

(Direct bump search at Low-energy facility)

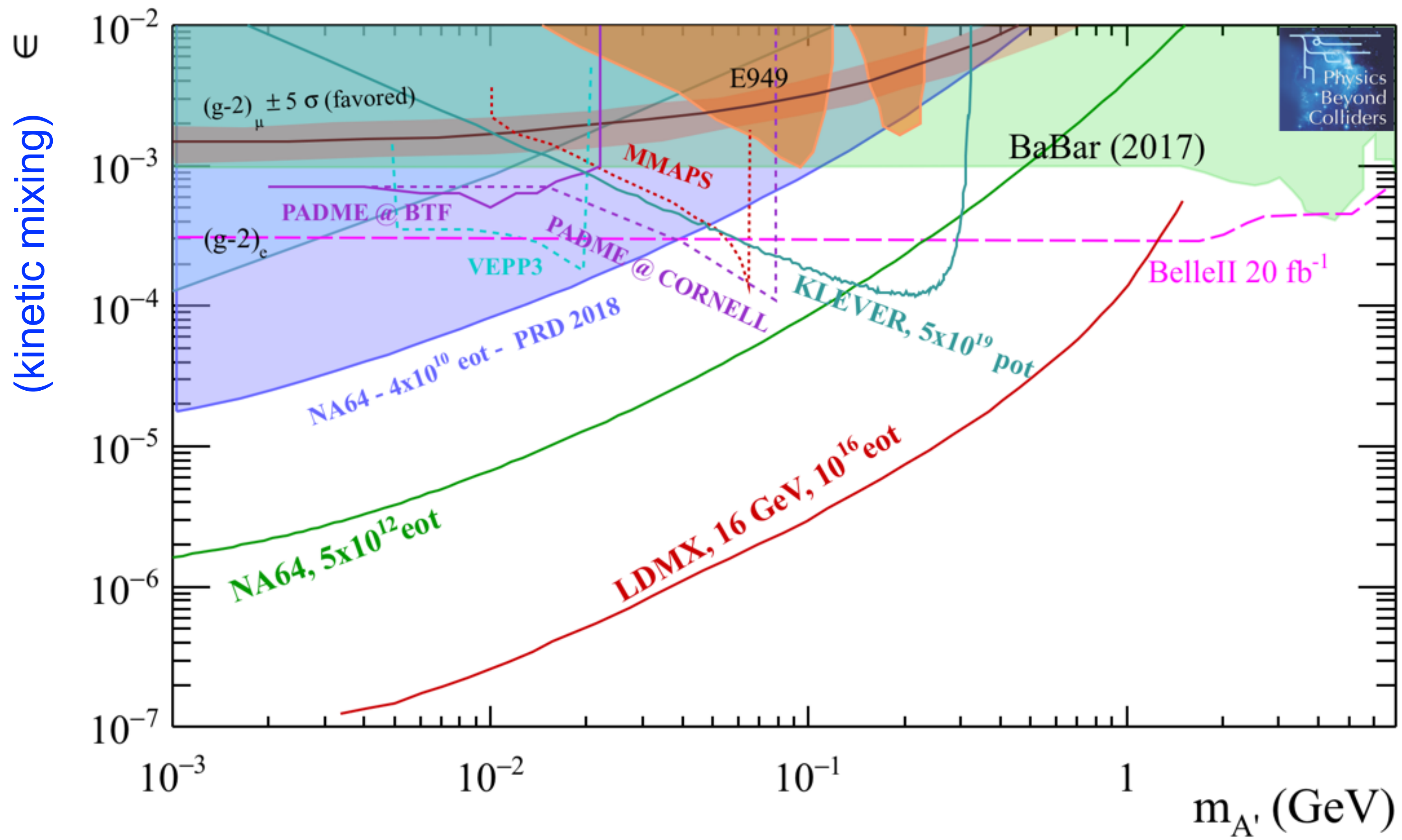
The *High Resolution Spectrometers (HRS)* at Hall A are used.

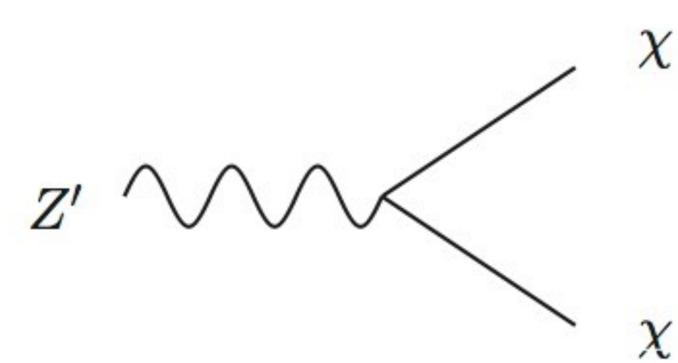
Missing energy searches for dark photon (Invisible dark photon)

[Current constraints]



γ-γ' kinetic mixing
(vector portal)





From Physics Beyond Colliders at CERN (arXiv:1901.09966)

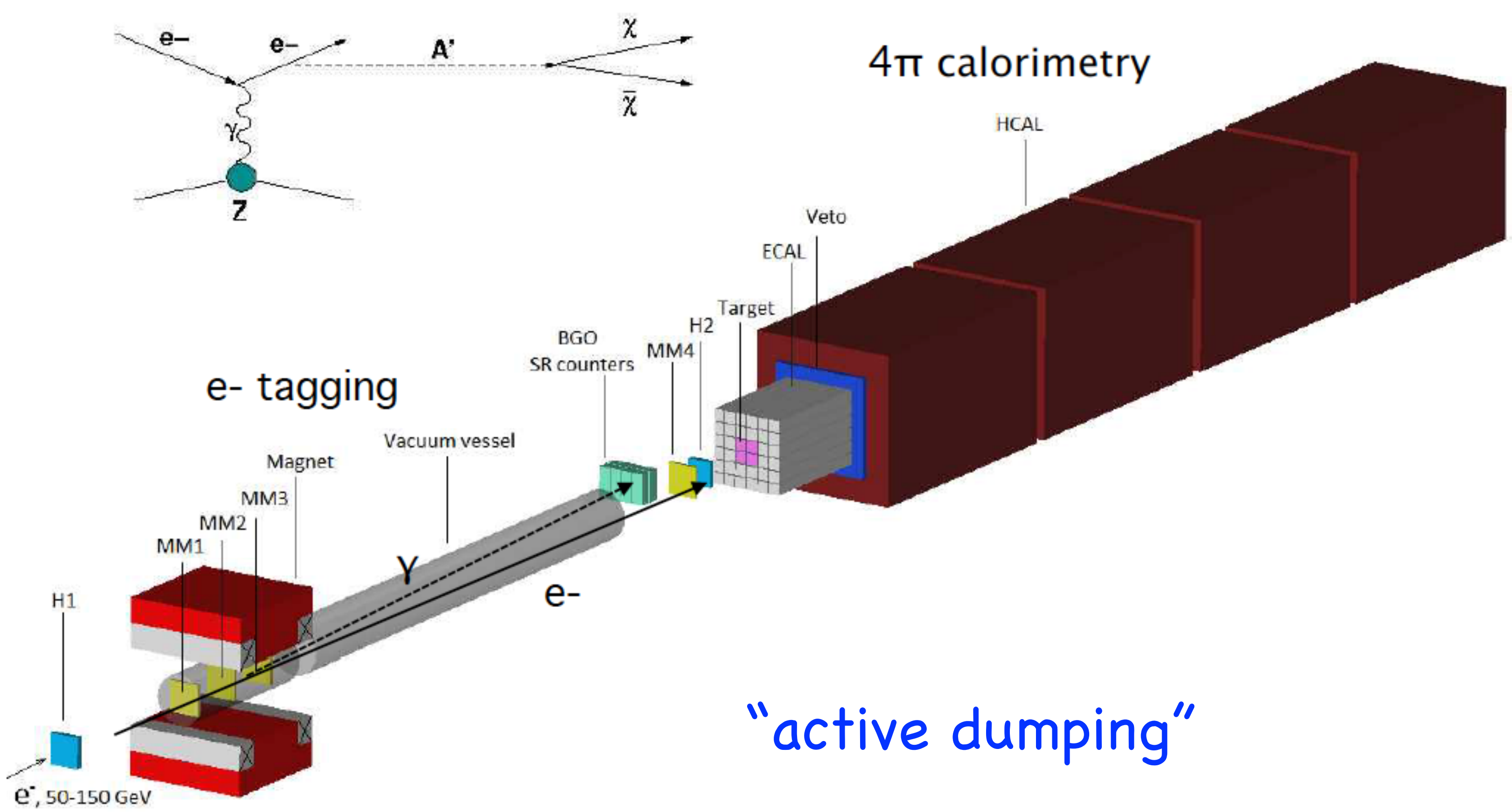
The invisible dark photon is also actively searched for in many experiments.

The vector portal is constrained to be small ($\varepsilon \ll 1$) in this scenario too.

Example: NA64 (beam-dump for dark photon) at CERN SPS

[NA64 Collaboration]

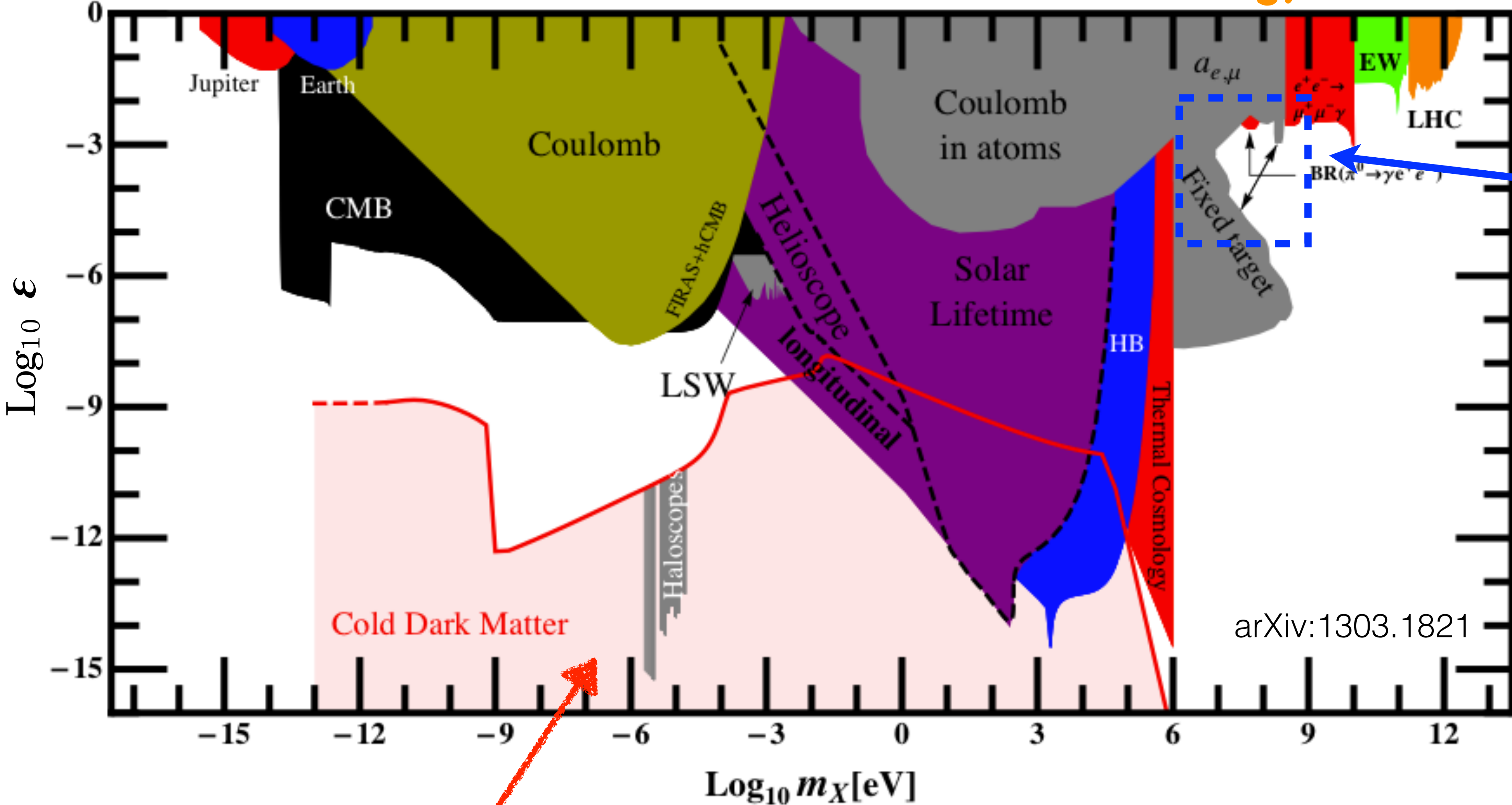
CERN experiment
to test invisibly decaying Z'

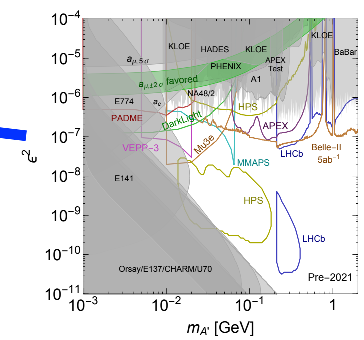


(i) Primarily e-beam (~100 GeV). Ultimately EOT ~ 10^{12}.
(ii) Detector is hermetic (catching all SM particles except for neutrinos) and measures total energy deposit.
(iii) Test "energy loss" (Missing E) by invisibly decaying Z'. (Essentially BKG free.)
(iv) Does not depend on unknown α_D (DM coupling).

Extended range of parameters of the Dark Photon

Energy Frontier →





Limited area shown before

Intensity Frontier ↓

Dark photon is long-lived (compared to the Universe age, 14B years) and can be even a DM candidate. Pospelov, Ritz, Voloshin (2008)

Extremely large parameter space emerges once we accept the idea of a very small coupling.

Axion Portal

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

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]

[strong CP problem: Charge Parity symmetry breaking in the strong interaction sector is too small]

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

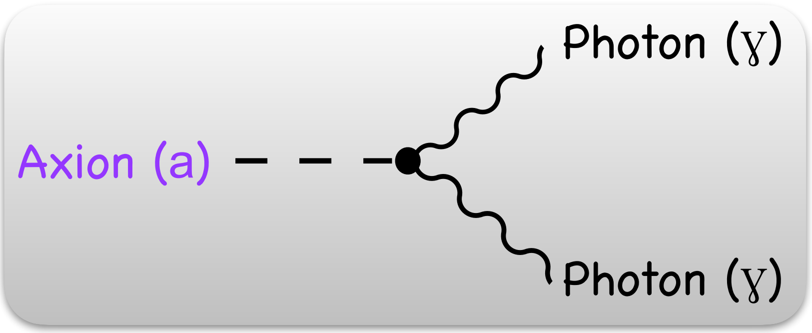
$$m_a \approx \frac{\Lambda^2_{\rm QCD}}{f_a} \approx \frac{10^{-2}\ {\rm GeV}^2}{f_a} \quad , \quad G_{a\gamma\gamma} \approx \frac{\alpha_{\rm EM}}{f_a}\,\mathcal{O}(1) \sim \frac{10^{-2}}{f_a}$$

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

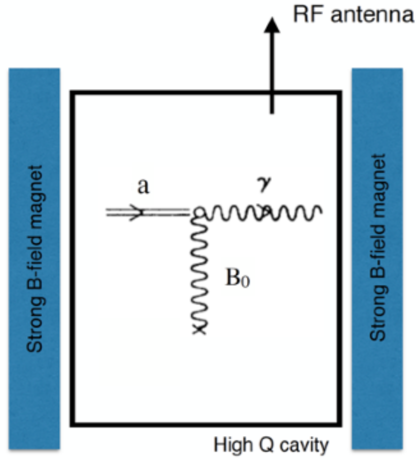
Axion-Like Particle (ALP): a generalized version of the axion (at the cost of original motivation from the strong CP problem). No direct relation between $G_{a\gamma\gamma}$ and mass.

Axion: practically, a very light scalar boson (with CP odd)

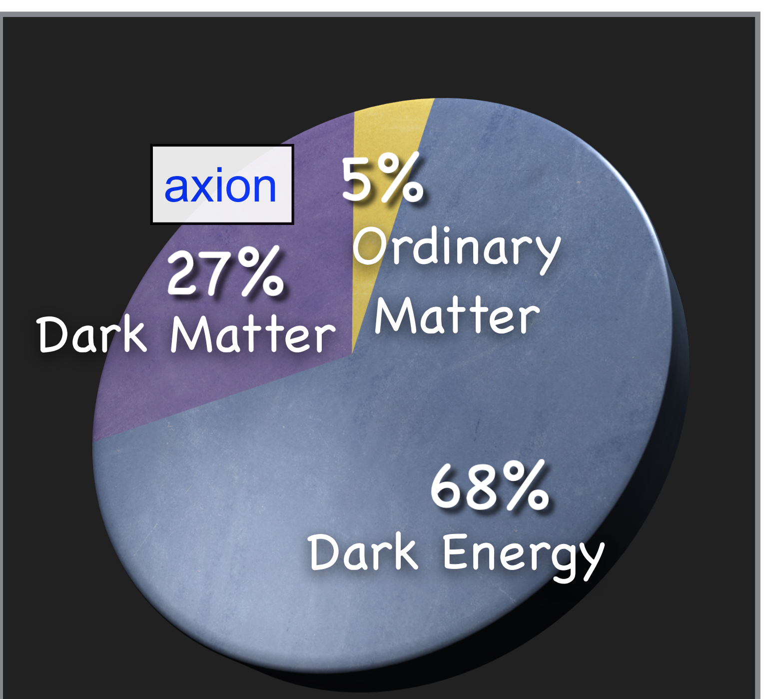
Current constraints on Axion and Axion-Like Particle (ALP)

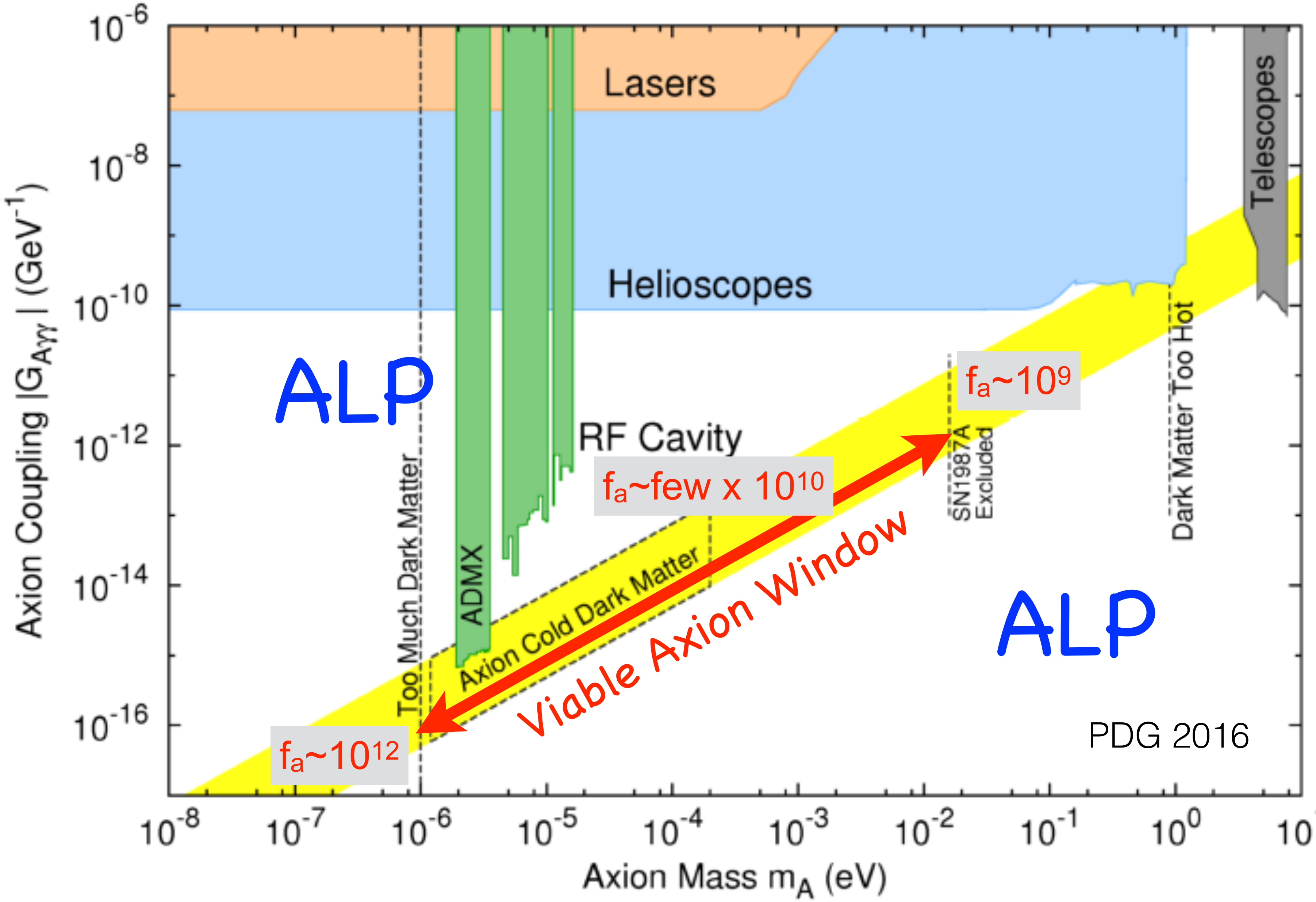


axion portal $(G_{a\gamma\gamma})$



Total Universe energy





Axion suffers the relic density deficit problem for f_a < few x 10^{10} GeV

: too small relic density to explain the data (Ω_{DM} = 27%)

Axion Case
(Yellow band)

$$m_a \approx \frac{10^{-2}\ \mathrm{GeV}^2}{f_a} \quad , \quad G_{a\gamma\gamma} \sim \frac{10^{-2}}{f_a}$$

f_a : $U(1)_{PQ}$ symmetry breaking scale

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 axion model (New axion model realizing the new portal)

[Kaneta, LEE, Yun (PRL 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	KSVZ axion model
	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	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.

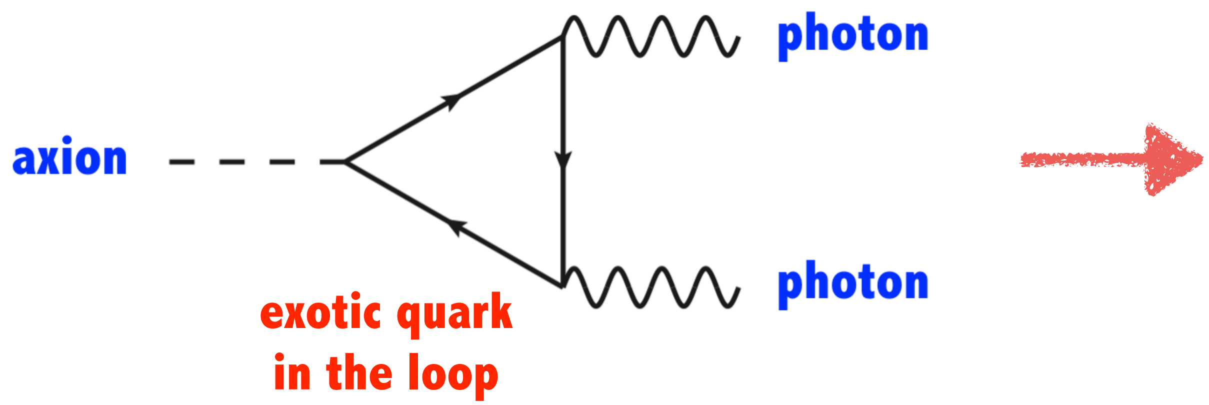
$$m_{\gamma'}^2 = e'^2 D_\Phi^2 v_D^2$$

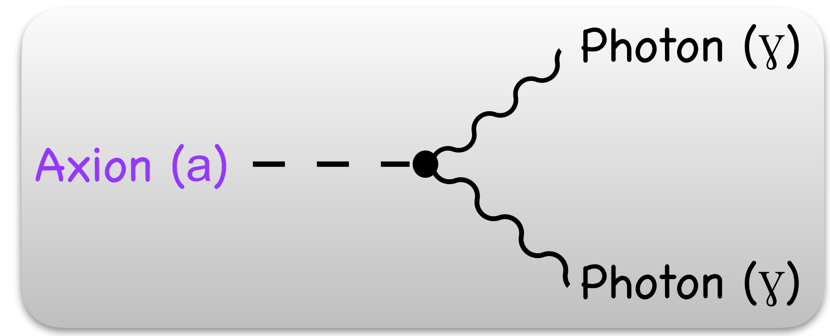
Exotic colored fermions may decay into other particles through, e.g. $\Phi_D^\dagger \psi \bar{d}_R + h.c.$ for $PQ_\psi = 0$, $Q_\psi = -1/3$, $D_\psi = D_\Phi$.

It depends on the couplings of the Fermions in the triangle

In the KSVZ axion model, there are exotic quarks forming an anomaly triangle.

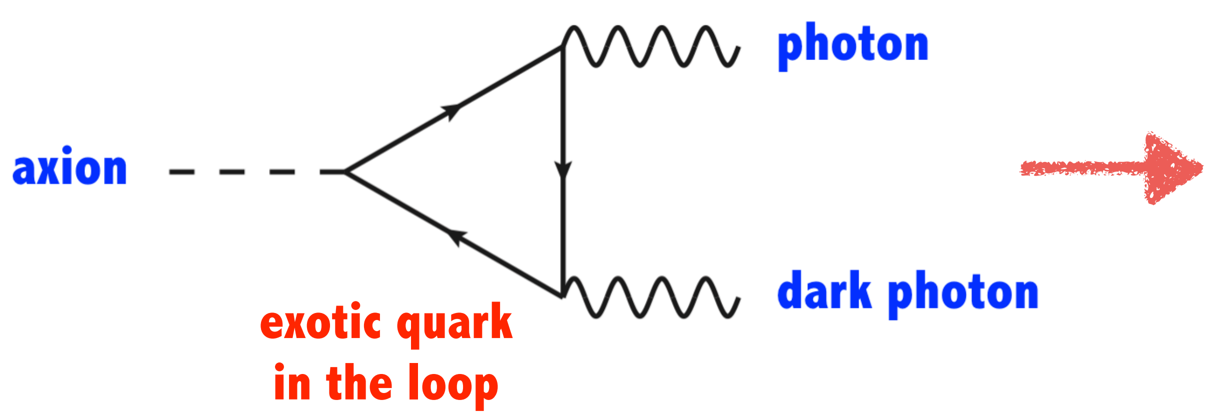
(i) Original KSVZ axion model: Exotic quarks have EM charges

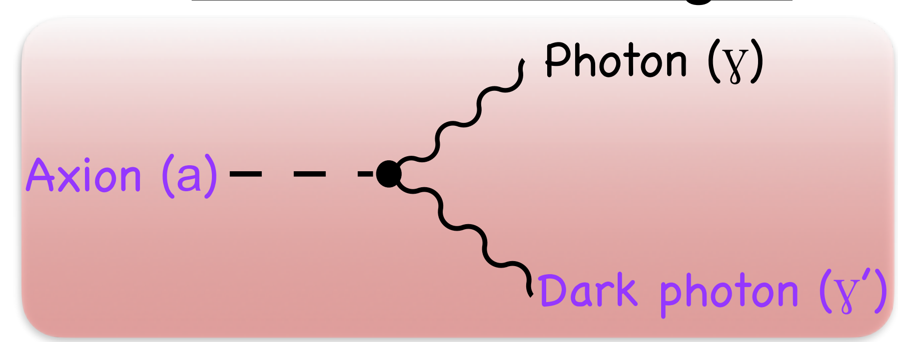




axion portal ($G_{a\gamma\gamma}$)

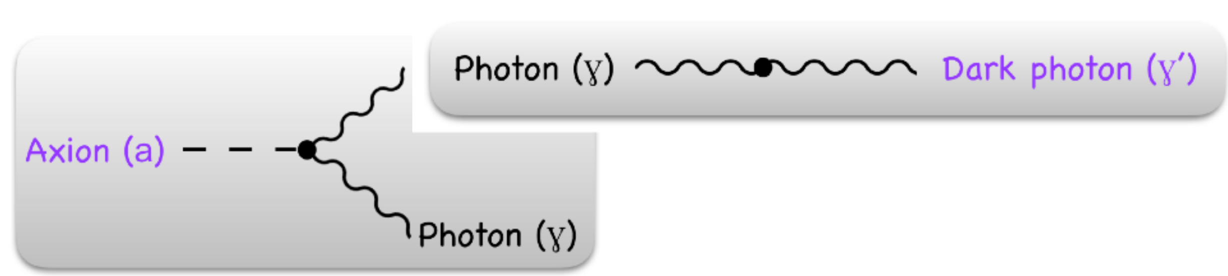
(ii) Dark KSVZ axion model: Exotic quarks have EM & Dark charges



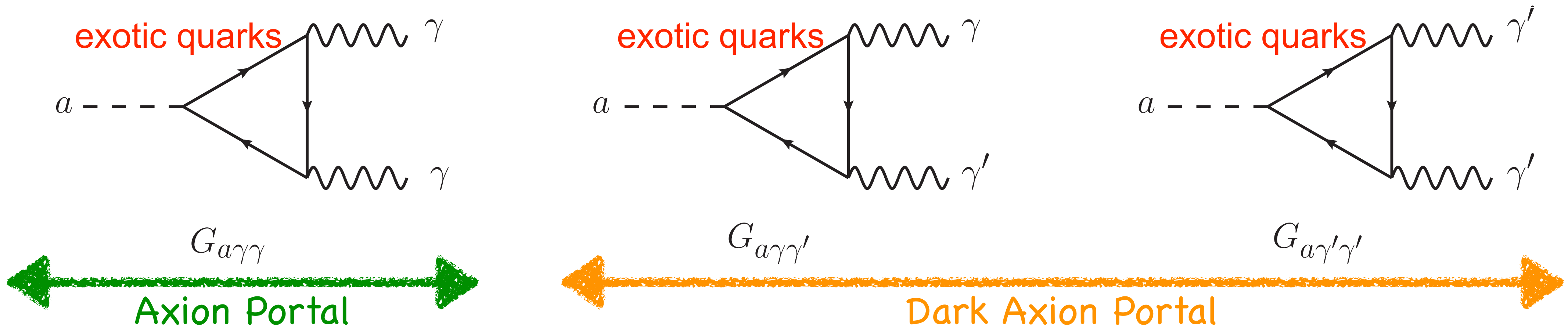


dark axion portal ($G_{a\gamma\gamma'}$)

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



Dark Axion Portal (in Dark KSVZ axion model)



The portal interaction terms are given by

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

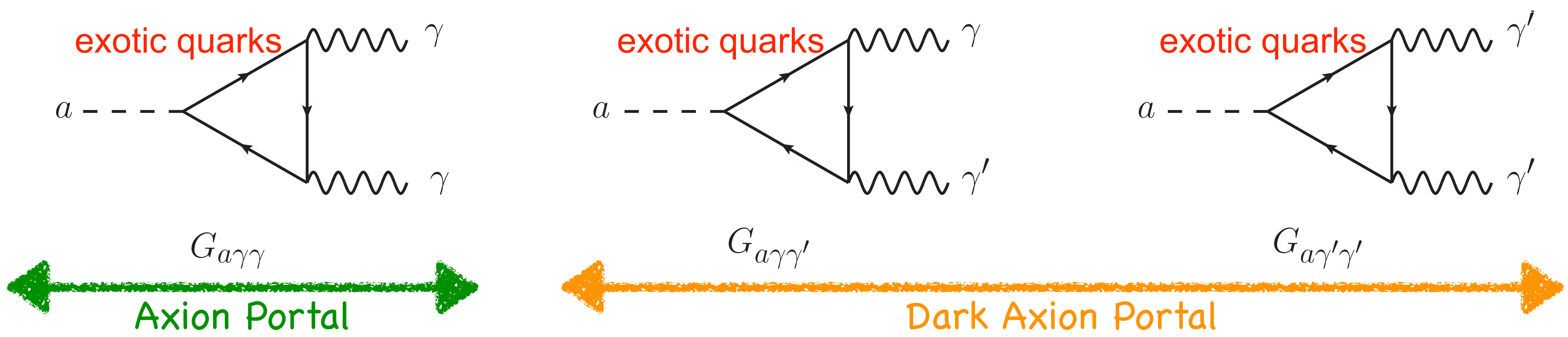
e: EM coupling constant
e': Dark coupling constant

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).

Decay modes



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

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

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

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

While typical dark photon search looks for dileptons, its dominant decay could be into a photon + axion.

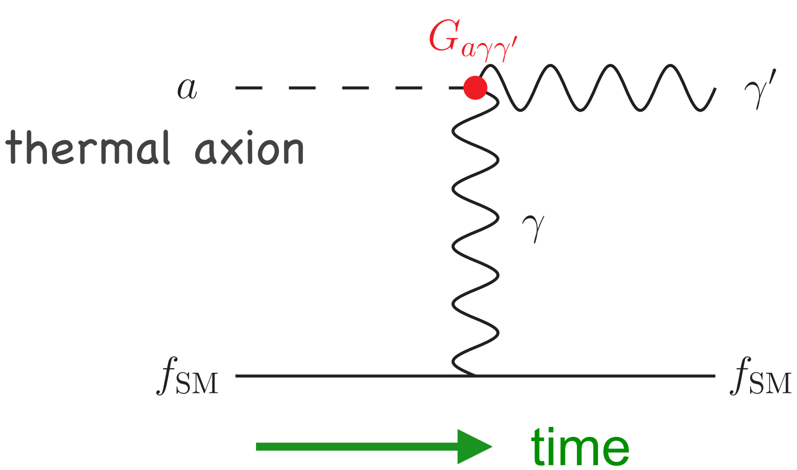
(Γ = partial decay width)

Implications of the Dark Axion Portal
(Cosmic Frontier)

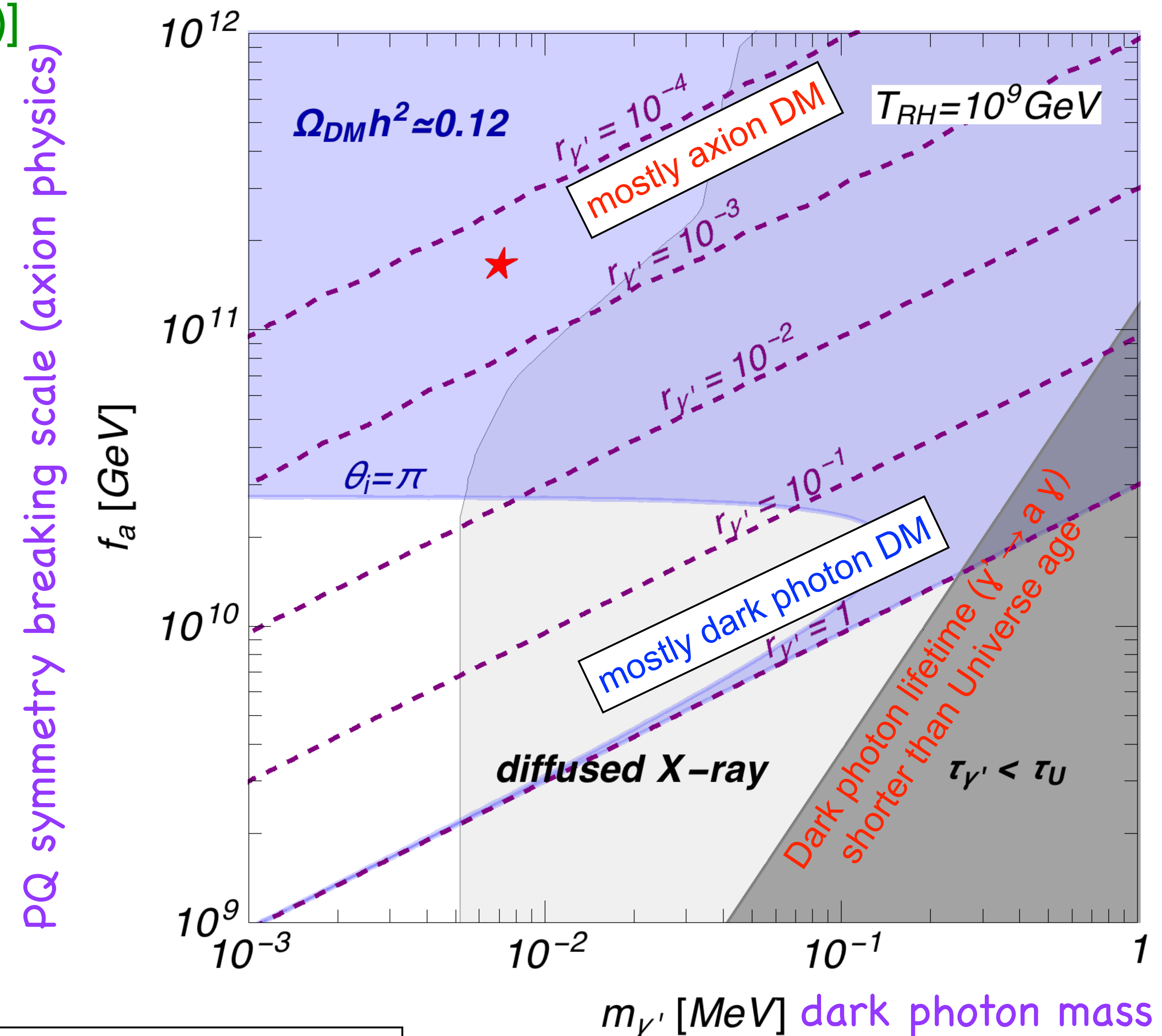
(i) New dark photon production mechanism

[Kaneta, LEE, Yun (2017)]

Very light dark photon
: DM candidate



(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

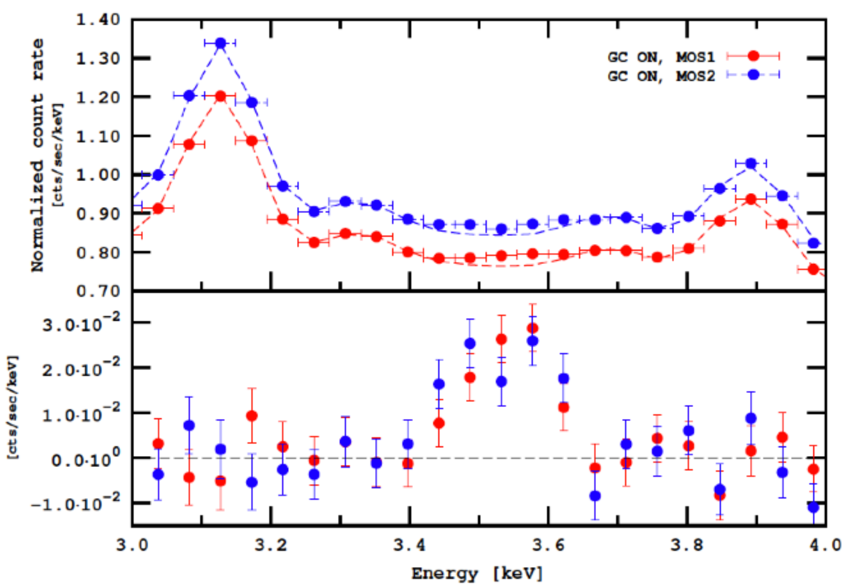
[Kaneta, LEE, Yun (2017)]

axion mass ≈ 10^{-4} eV

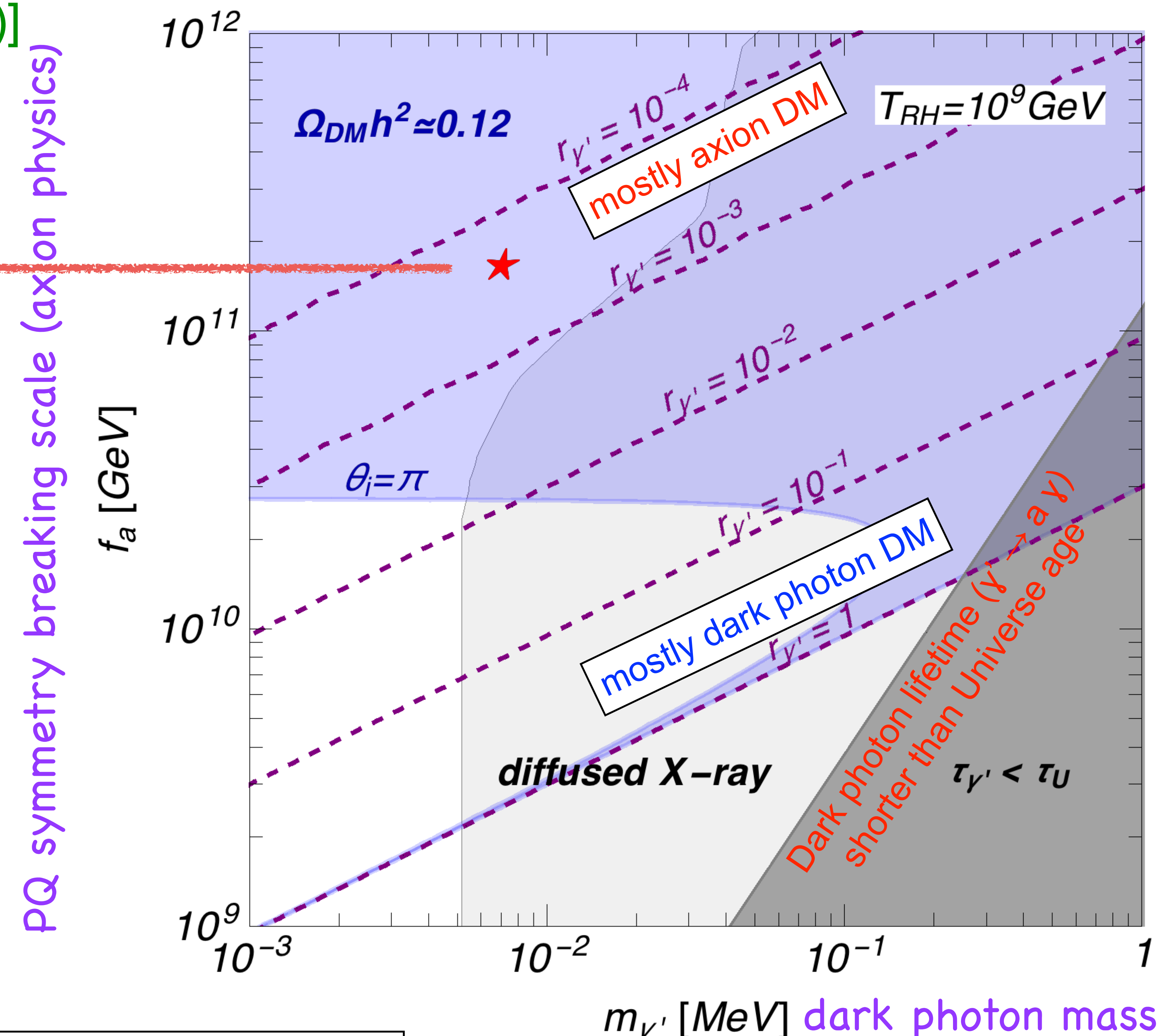
γ' mass = 7 keV

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

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 3.5 keV X-ray excess from the galaxies (roughly 3~4σ C.L.). Currently, under scrutiny by many studies.

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

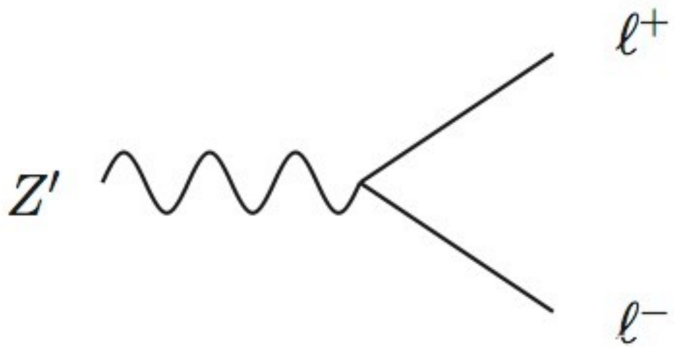
Implications of the Dark Axion Portal
(Intensity Frontier)

Visible/Invisible decay of Dark photon

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

(i) "Dilepton Resonance" search

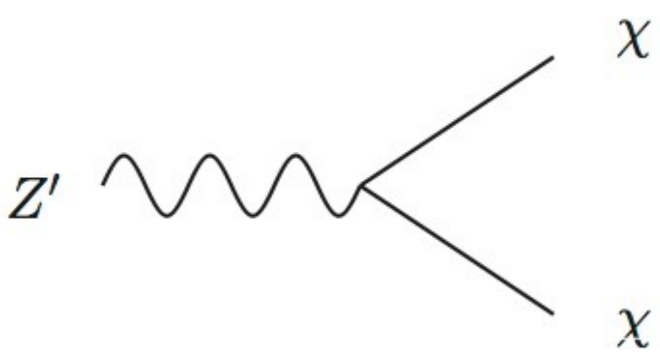
Visible dark photon mode



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

(ii) "Missing Energy" search

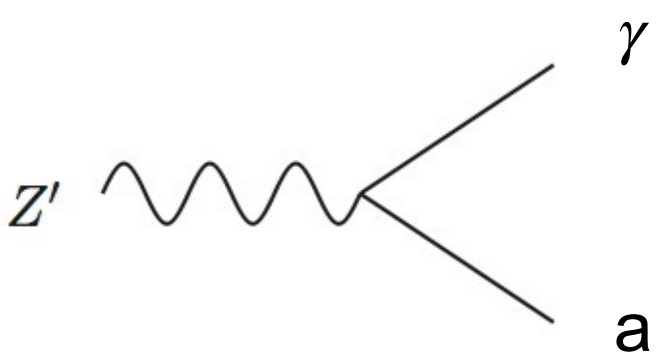
Invisible dark photon mode



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

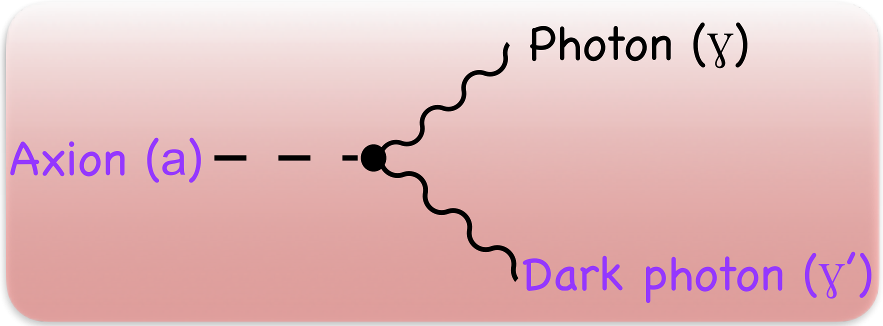
(iii) "Photon" search

"New" visible dark photon mode



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

(From now on, axion includes axion-like particle)

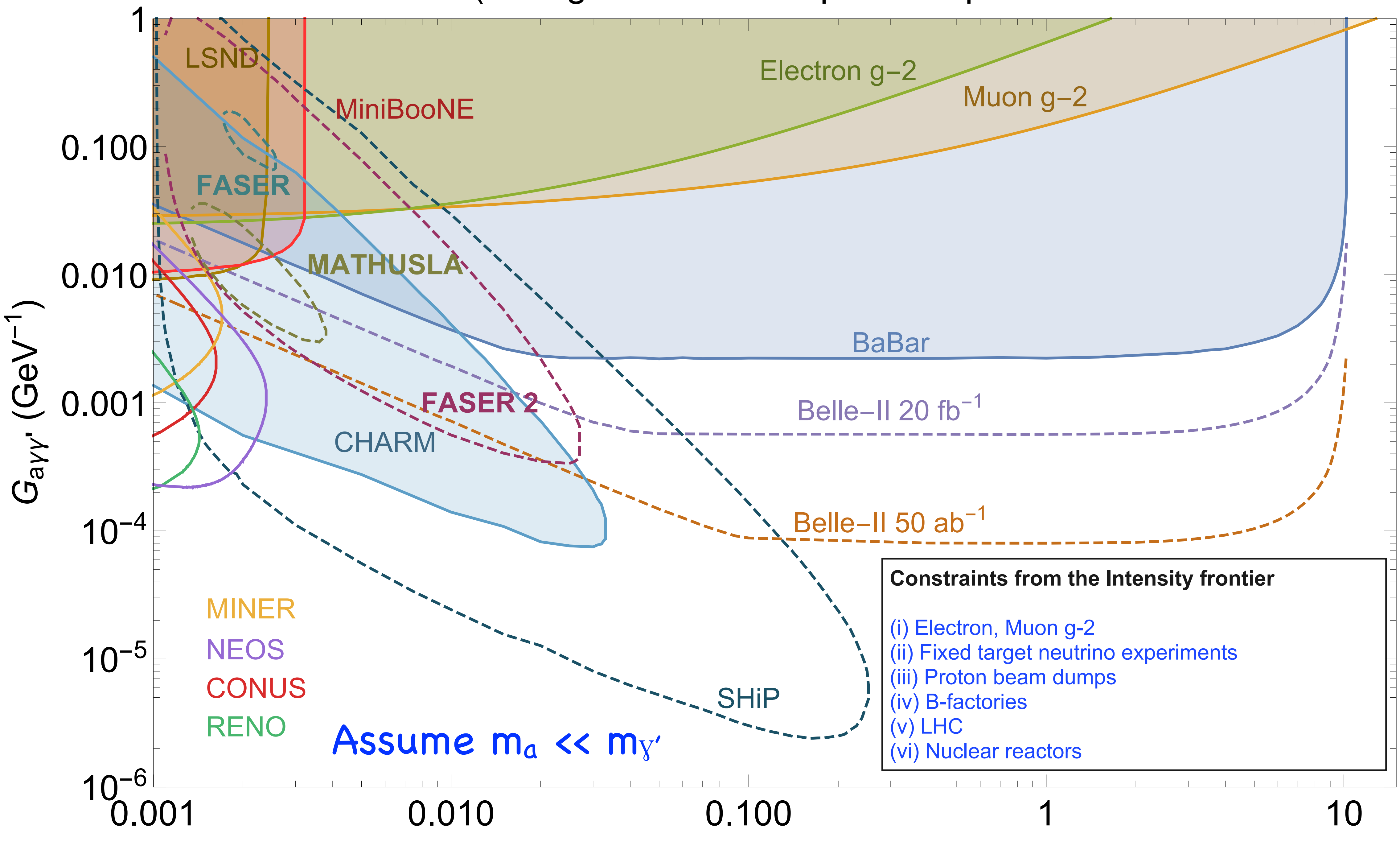


dark axion portal ($G_{a\gamma\gamma'}$)

Photon searches for dark photon

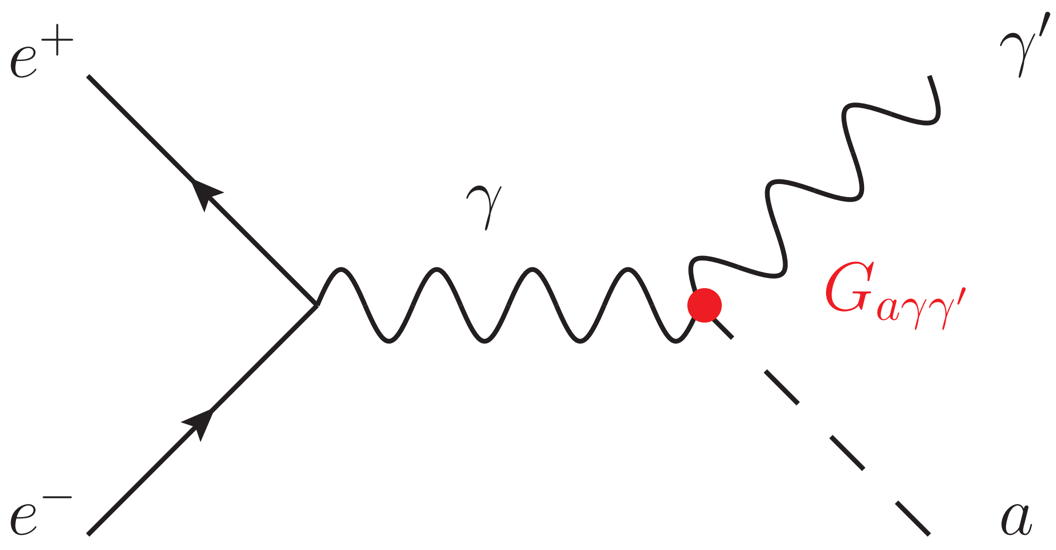
[deNiverville, LEE, Seo (2018); deNiverville, LEE (2019); deNiverville, LEE, Lee (2020)]

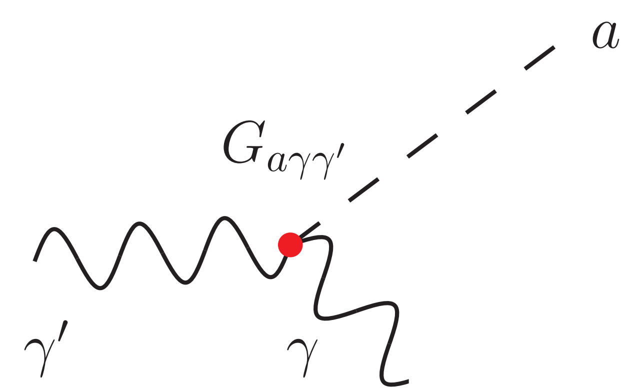
$G_{a\gamma\gamma'}$ only (model-independent way): We take axion as a very light particle carrying a missing energy, and neglect the effect of $G_{a\gamma\gamma}$ vertex. (No signals of exotic quarks impose additional constraints.)



Controlled (Lab) experiments only

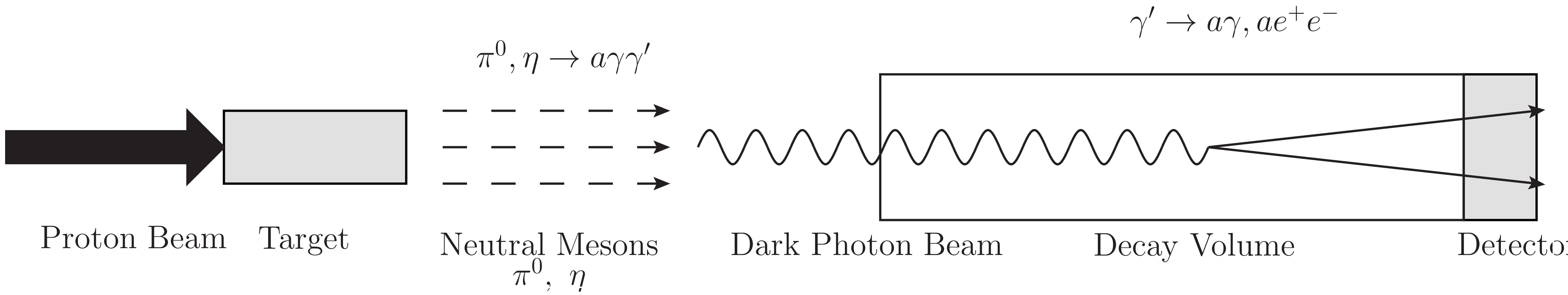
B-factories (BaBar, Belle II)

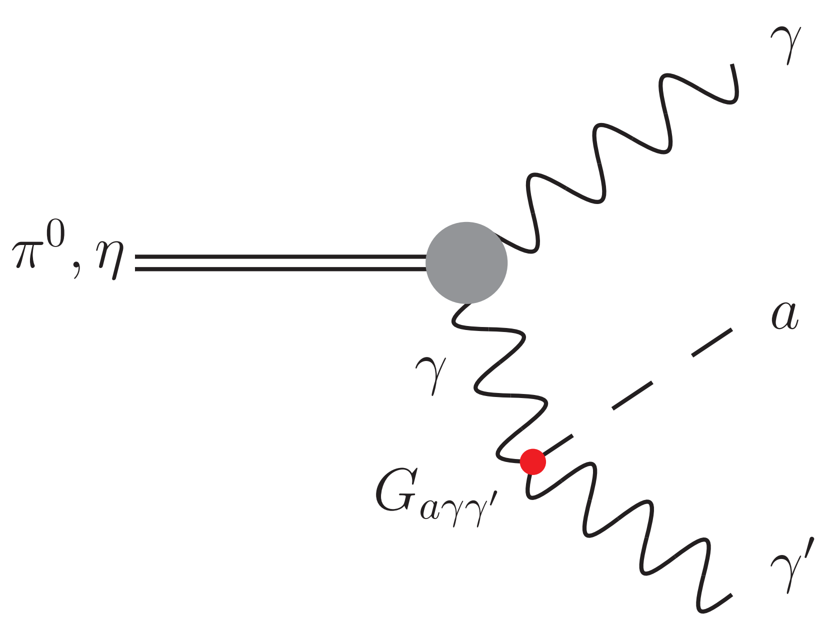




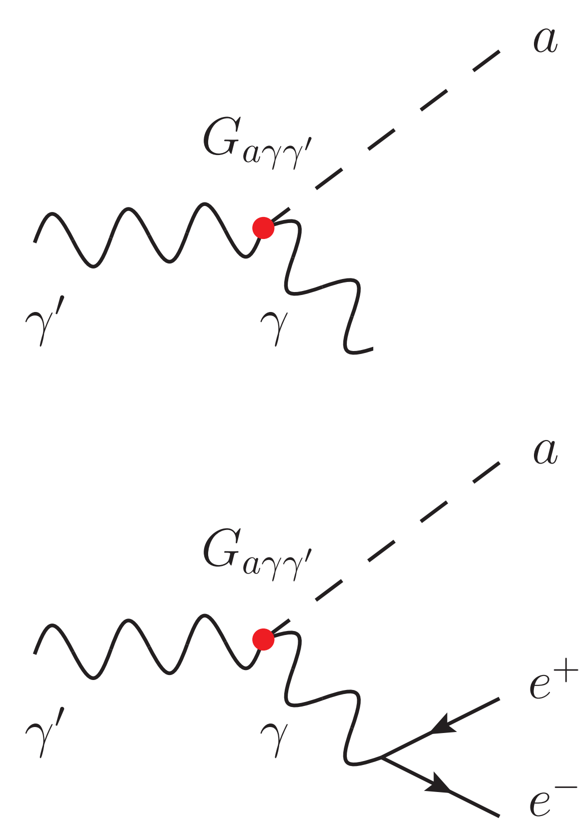
B-factories are asymmetric e+e- colliders of $E_{CM} \approx 10$ GeV.
e+e- can annihilate into a dark photon + axion, and the dark photon can decay into a photon + axion (e+e- → ɣ' a → ɣ a a). It is a mono-photon search.

Proton beam dumps (CHARM, SHiP future)





Production

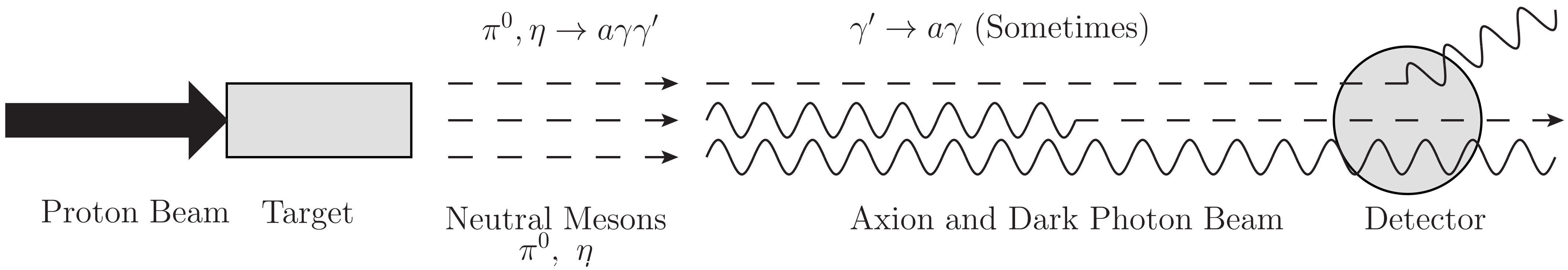


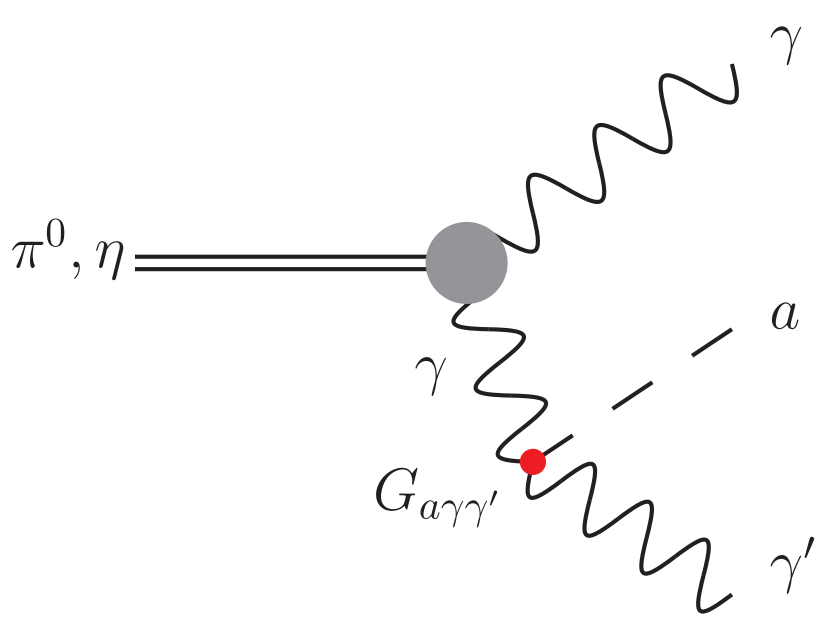
Detection of decays

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).

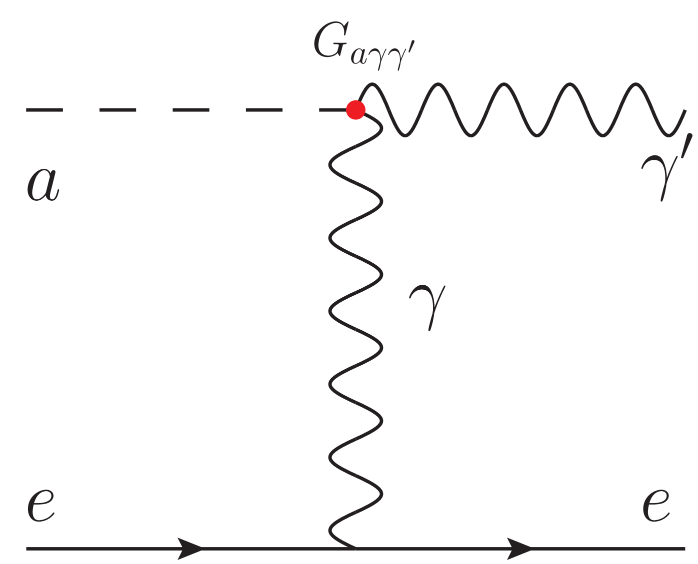
Neutrino fixed target experiments (LSND, MiniBooNE)

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





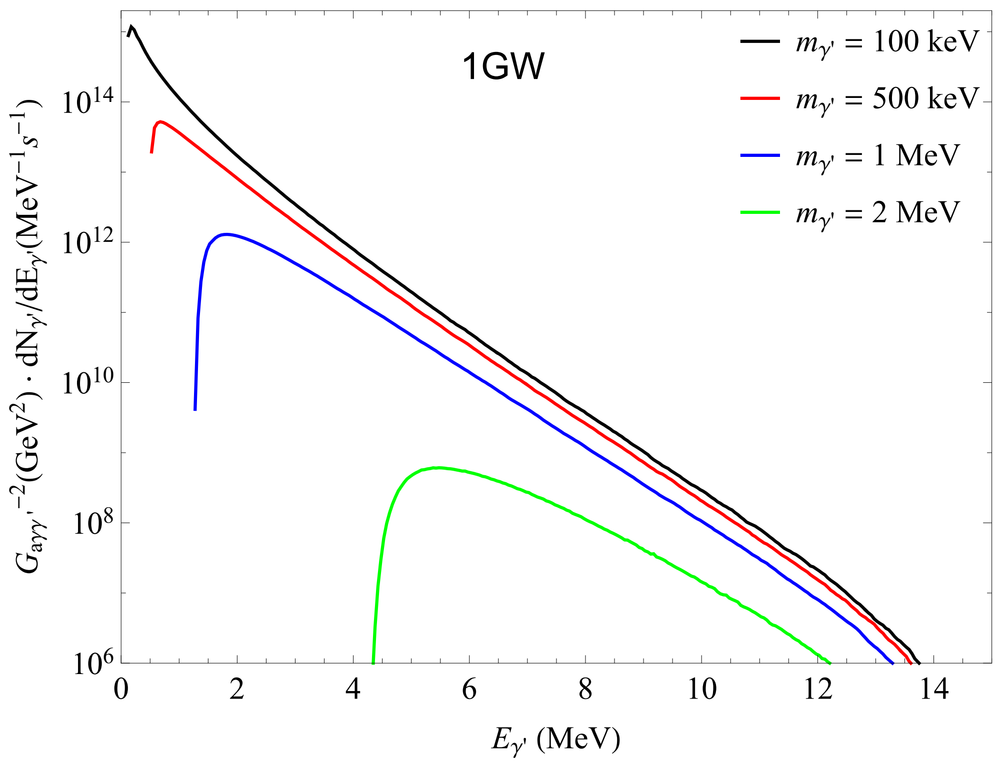
Production

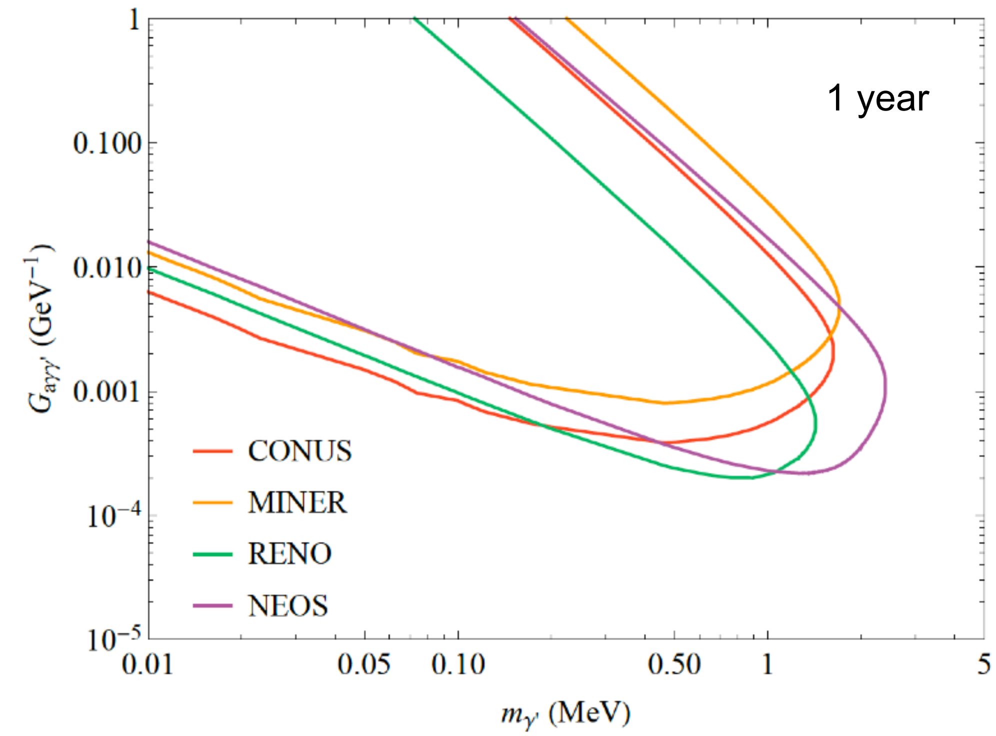


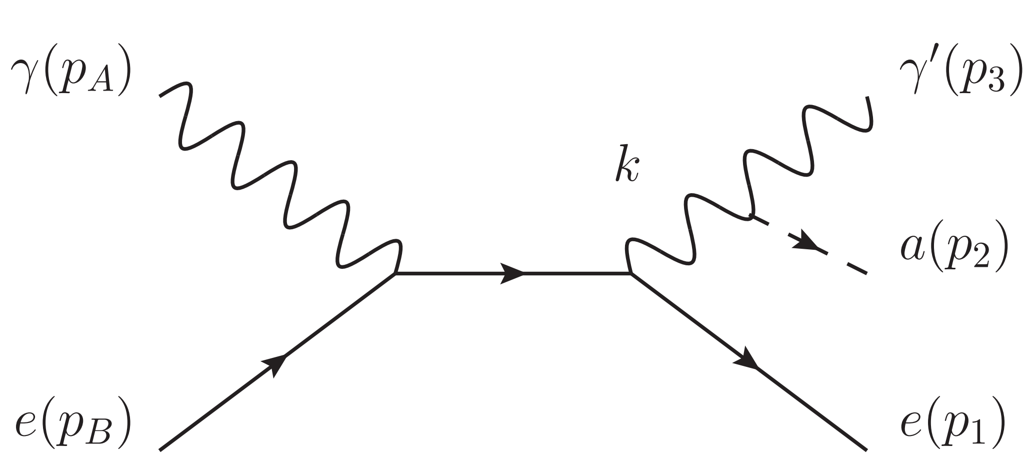
Detection of scattering

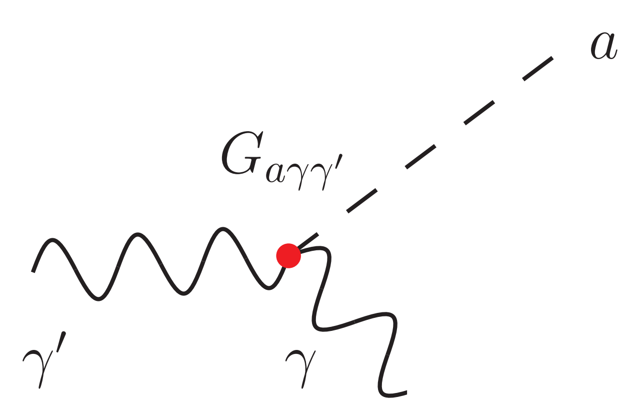
π (η) mesons decay into a photon + axion + dark photon.
Axion can scatter with the electrons in the detector (mineral oil, etc).
Signals are similar to the neutral current elastic (NCE) scattering of the neutrinos.

Reactor experiments (MINER/CONUS, RENO/NEOS)





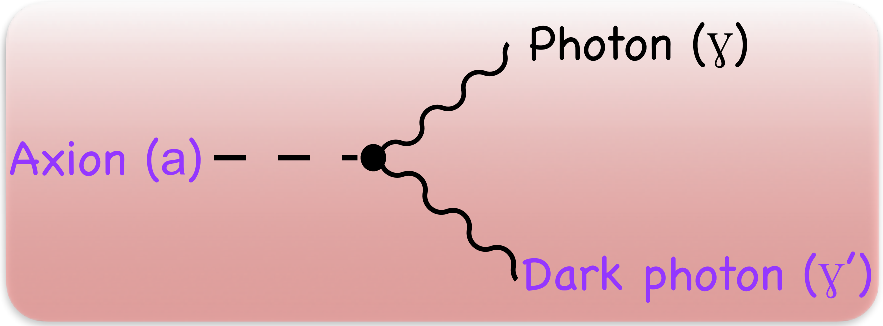




Production

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.)

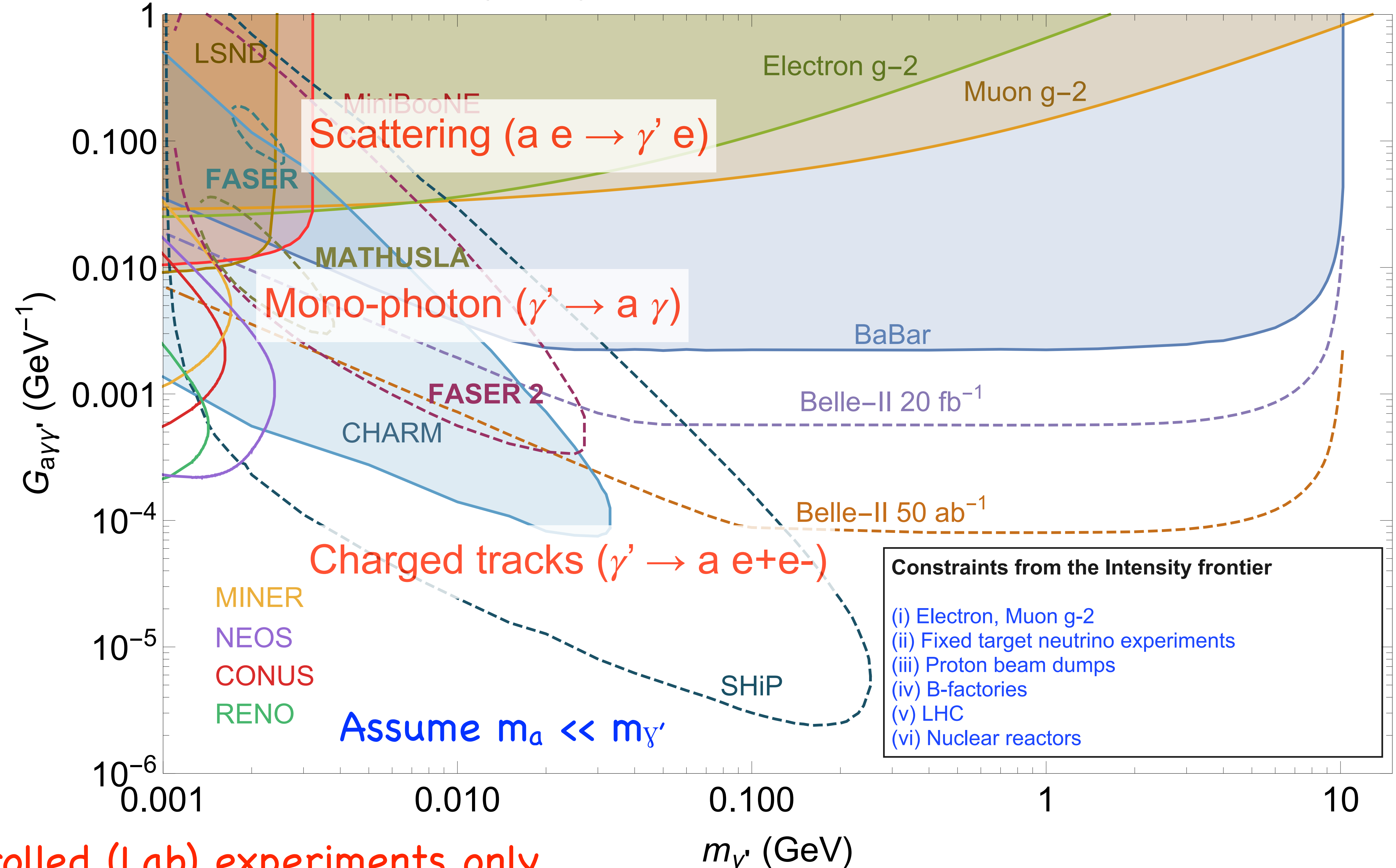


Photon searches for dark photon

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

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

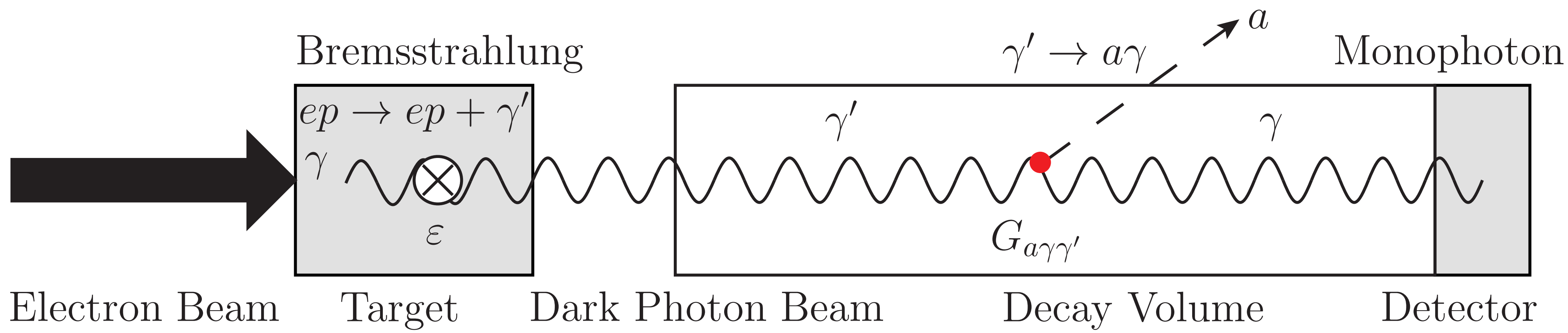
$G_{a\gamma\gamma'}$ only (model-independent way): We take axion as a very light particle carrying a missing energy, and neglect the effect of $G_{a\gamma\gamma}$ vertex. (No signals of exotic quarks impose additional constraints.)



Controlled (Lab) experiments only

New possibility: Low-energy e-beam dump with photon signal

[deNiverville, LEE (2019)]

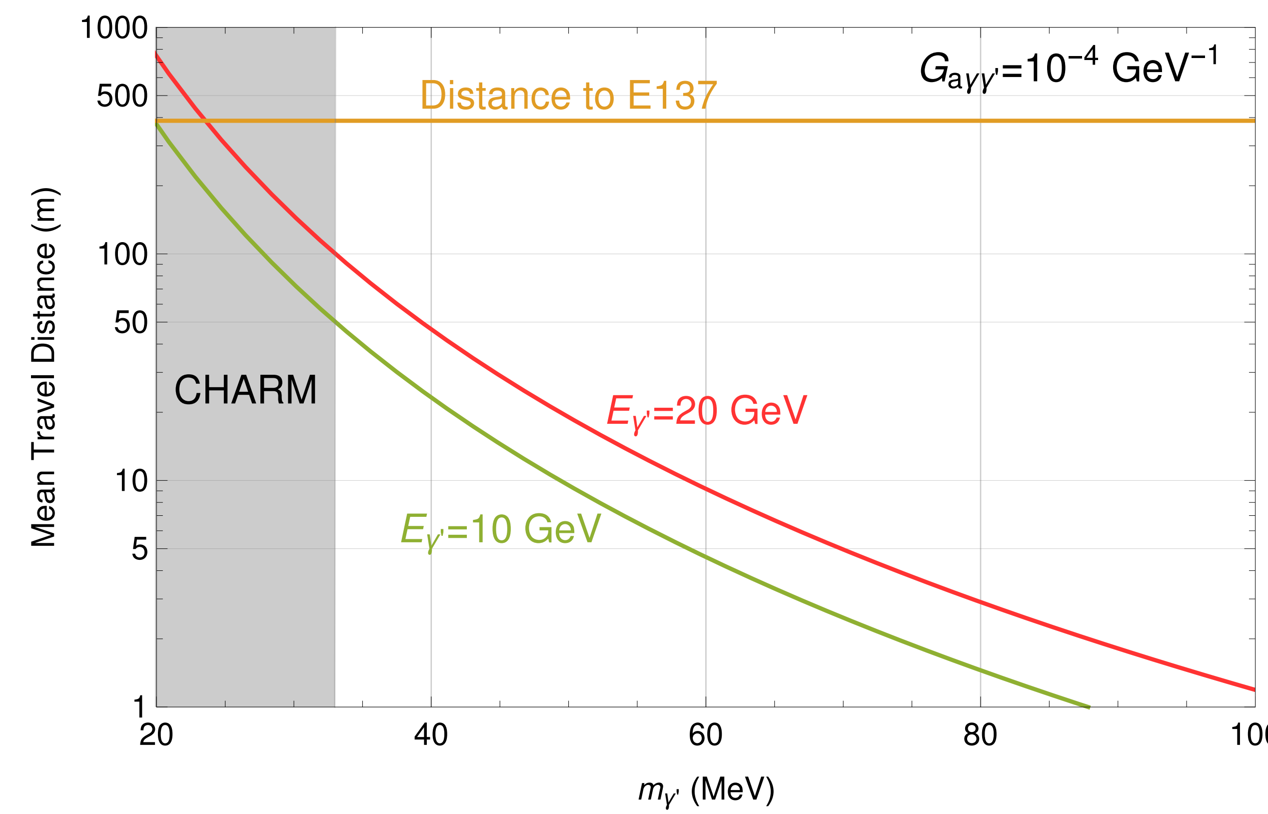


Most viable options of the e-beam dump using the vector portal were taken.

Major production of dark photon through the vector portal (Bremsstrahlung) at the affordable e-beam facilities, and the major decay to the photon through the dark axion portal ($\gamma' \to \gamma + a$).

The dominant $\gamma' \to \gamma + a$ can suppress the severe kinetic mixing (ε) constraints.

(Detailed design study is called for.)

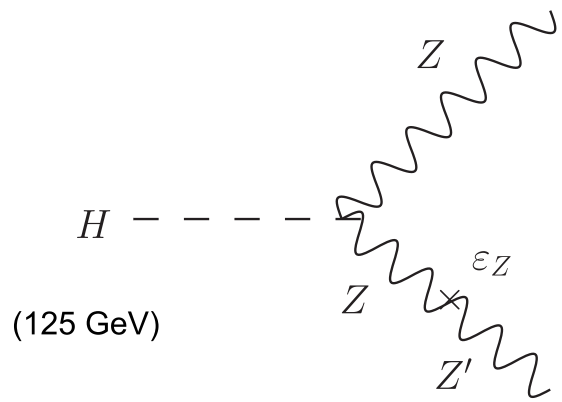


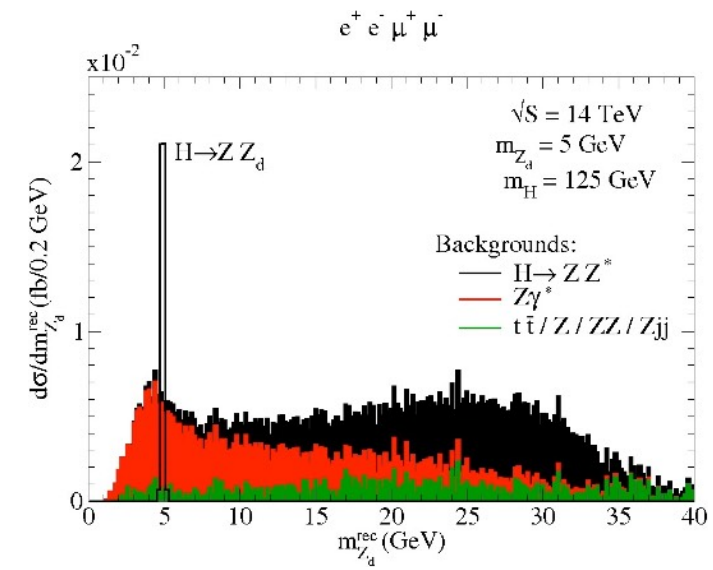
Dark Axion Portal at the LHC (Energy Frontier)?

There are models which have a dark photon (or its variant) in the final states.
Searched for as "Lepton-Jets" (highly collimated leptons. $\gamma' \longrightarrow \ell^+\ell^-$) using vector portal.

(Currently, searching for dark photons at the LHC = searching for lepton-jets.)

(ex) rare Higgs decay



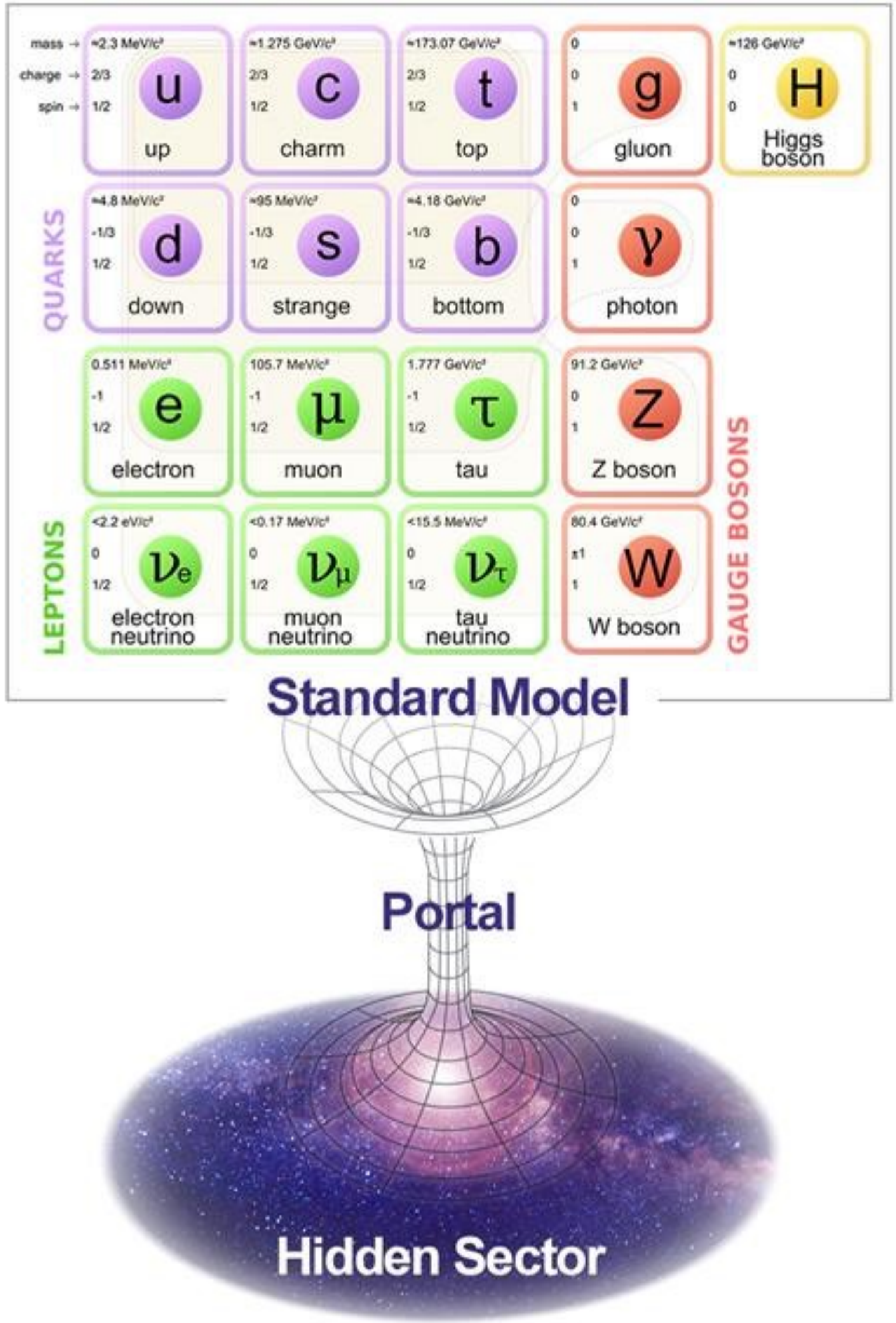


[Davoudiasl, LEE, Lewis, Marciano (2013)]

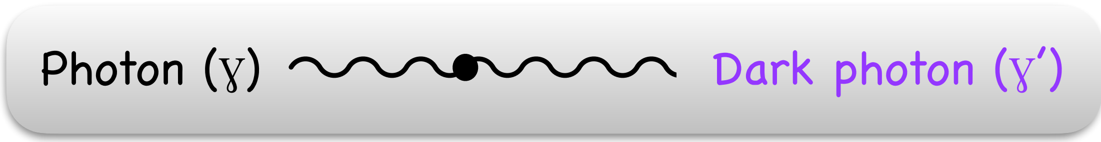
Depending on the model, the decay mode to dark photon can even dominate.
(ex) Top-partner $\longrightarrow$ Top + γ' as the dominant decay mode (followed by $\gamma' \longrightarrow \ell^+\ell^-$). [Kim, Lane, LEE, Lewis, Sullivan (2019)]

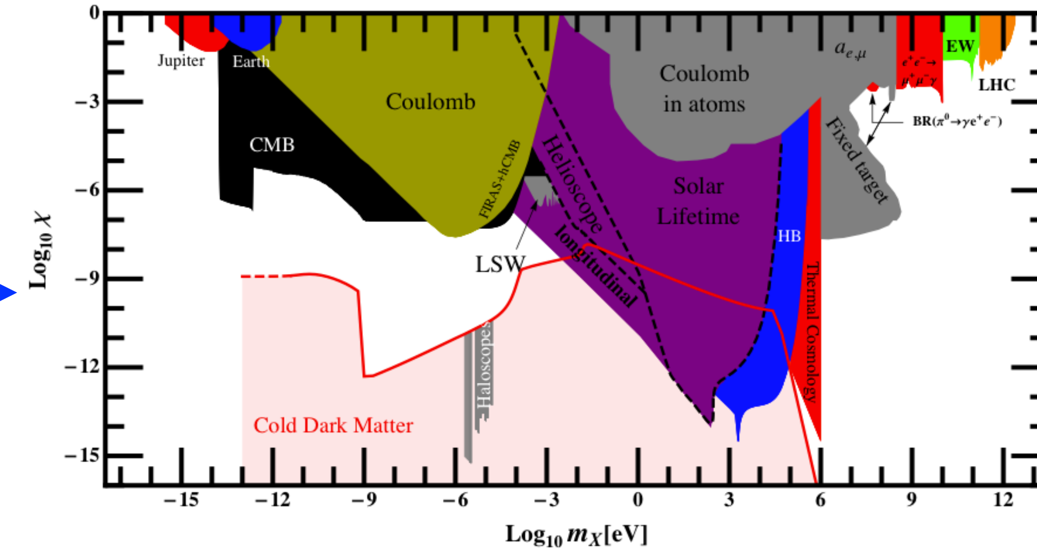
In the presence of the dark axion portal ($G_{a\gamma\gamma'}$), one might need to search for "photons" ($\gamma' \to \gamma$ a), which can dominate the decay BR, at the LHC.

Concluding Remarks



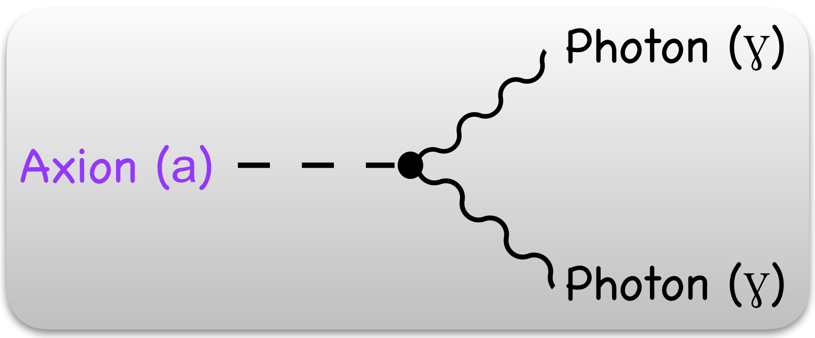
Dark sector could be investigated through portals.

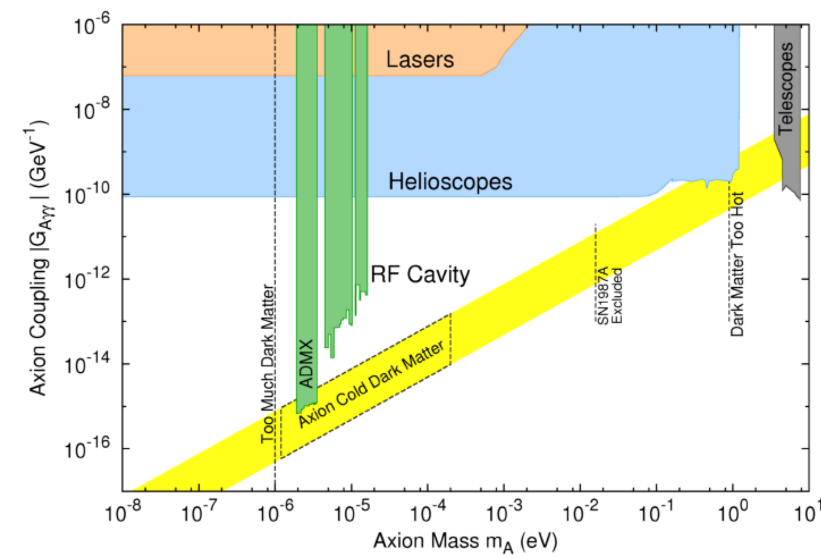




vector portal (ε)

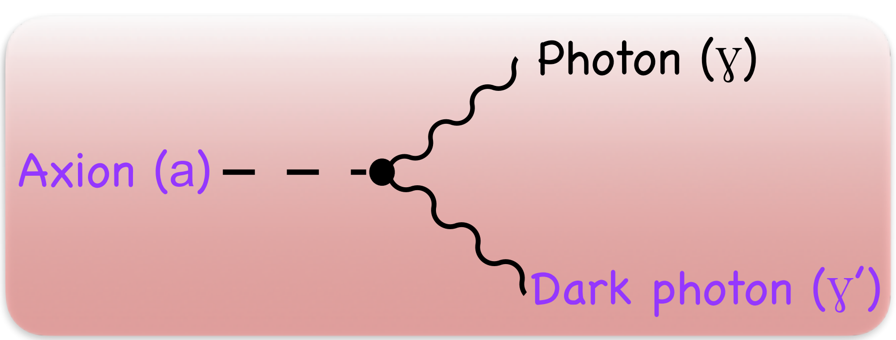
(ex) Holdom (1986): 1100+ citations (used in actual searches)

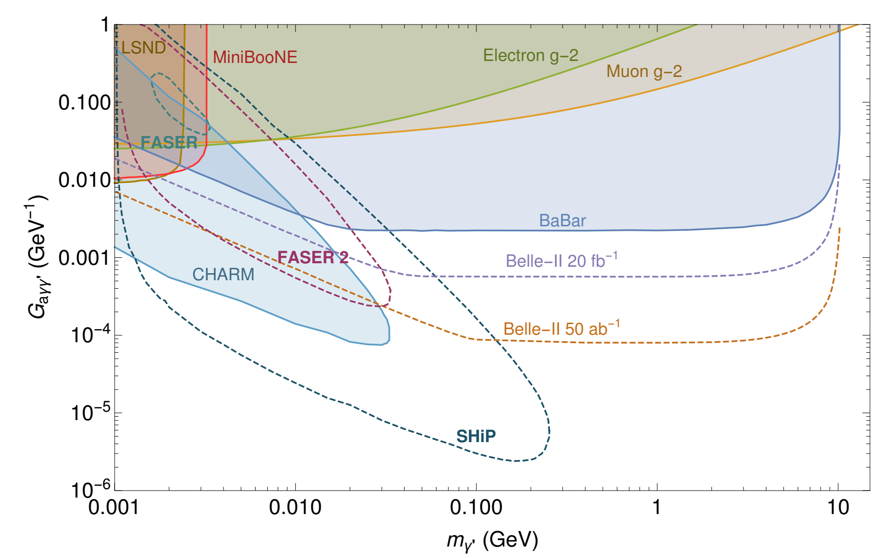




axion portal ($G_{a\gamma\gamma}$)

(ex) Sikivie (1983): 1000+ citations (used in actual searches)





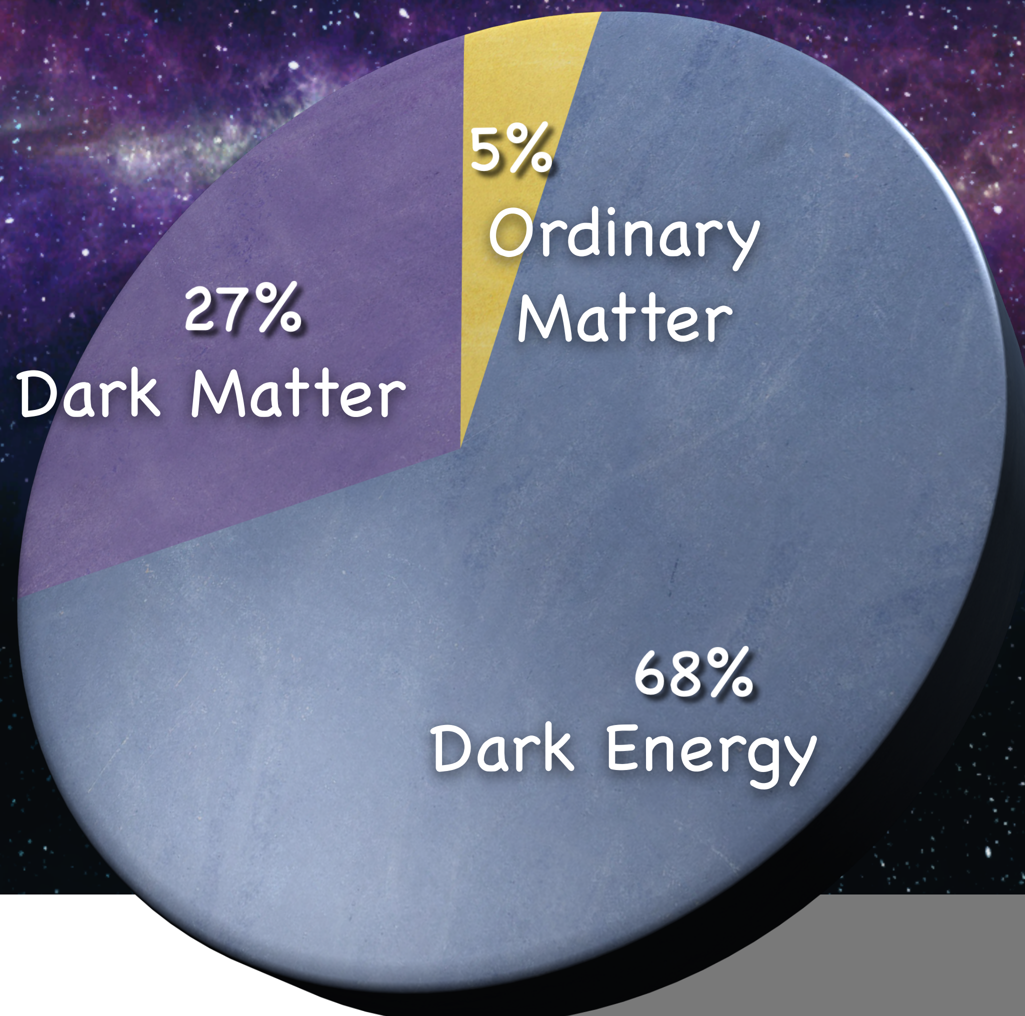
dark axion portal ($G_{a\gamma\gamma'}$)

Kaneta, LEE, Yun (2017)

When a new portal is introduced,
there are a lot of physics we can explore with it

We live in a Dark World

Total Universe Energy

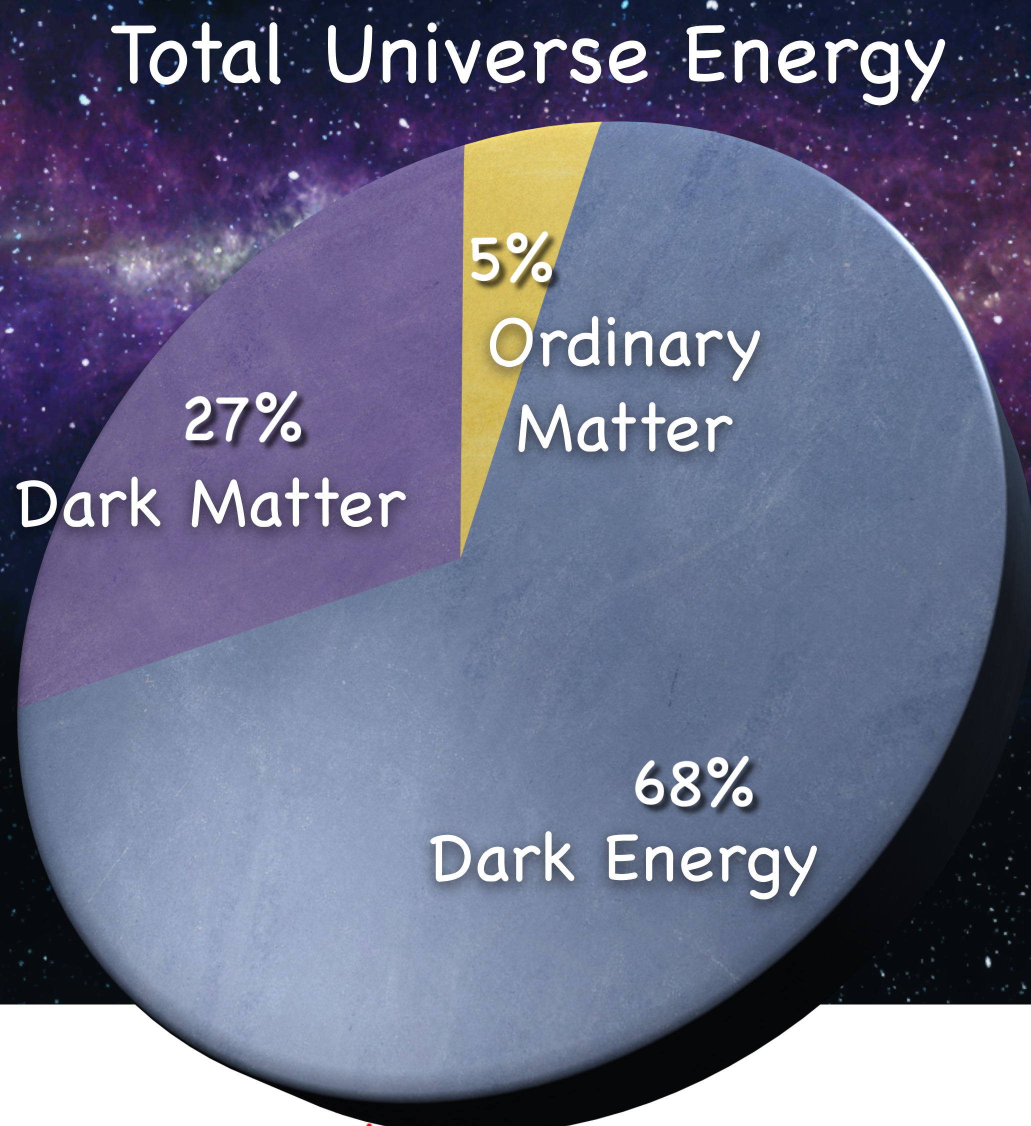


$$\begin{aligned}
\nabla \cdot \vec{E} &= \rho \\
\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\
\nabla \cdot \vec{B} &= 0 \\
\nabla \times \vec{B} &= \vec{J} + \frac{\partial \vec{E}}{\partial t}
\end{aligned}$$

Bright sector

Dark sector

We live in a Dark World



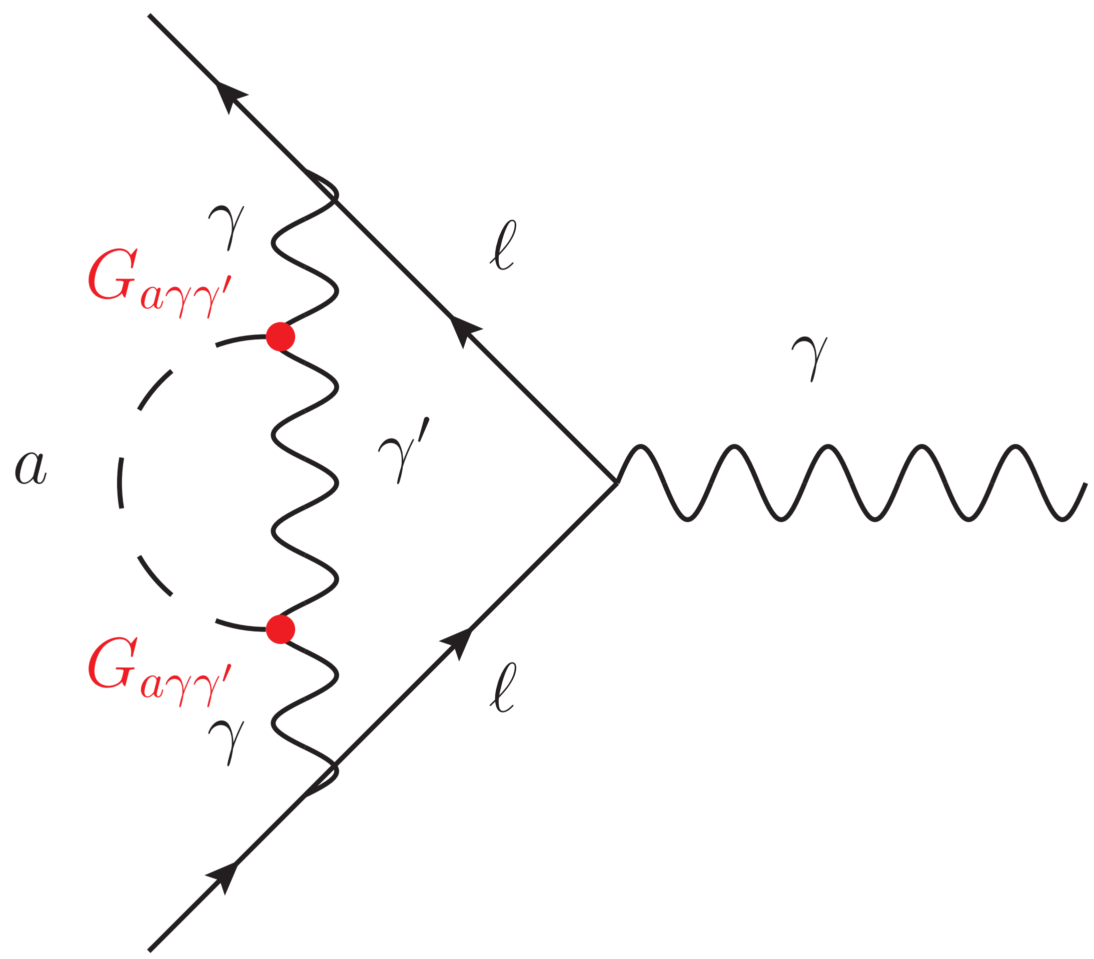
$$
\begin{aligned}
\nabla \cdot \vec{E} &= \rho + G_{a\gamma\gamma} \nabla a \cdot \vec{B} + G_{a\gamma\gamma'} \nabla a \cdot B' \\
\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\
\nabla \cdot \vec{B} &= 0 \\
\nabla \times \vec{B} &= \vec{J} + \frac{\partial \vec{E}}{\partial t} - G_{a\gamma\gamma}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

The future of the dark sector is bright.

- Thank you -

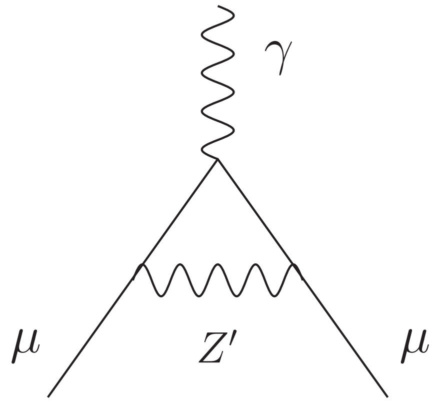
Backup Slides

Electron and Muon g-2

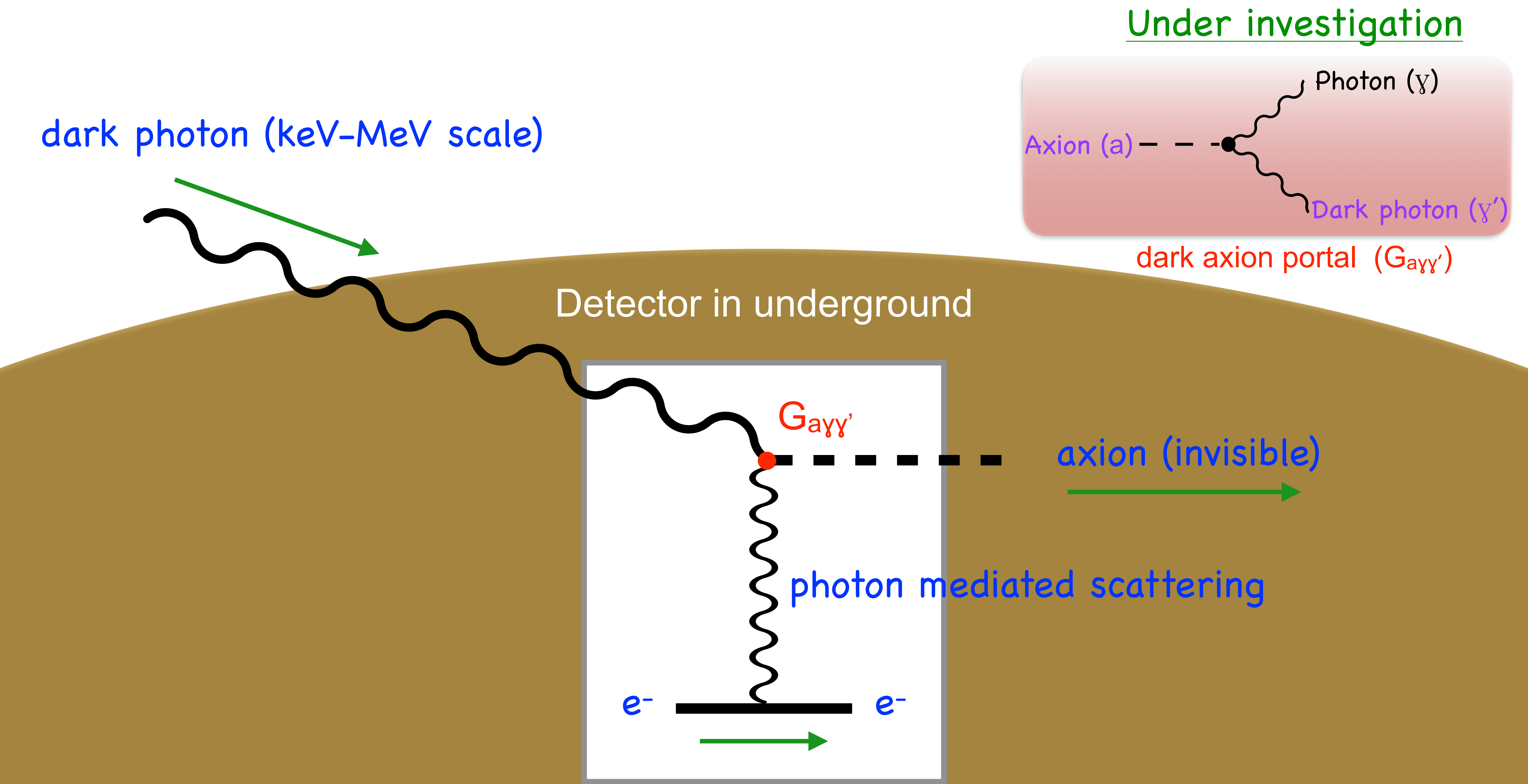


The dark axion portal contribution gives <u>a wrong sign</u> to explain muon g-2 anomaly.
We use the g-2 data to place a limit.

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

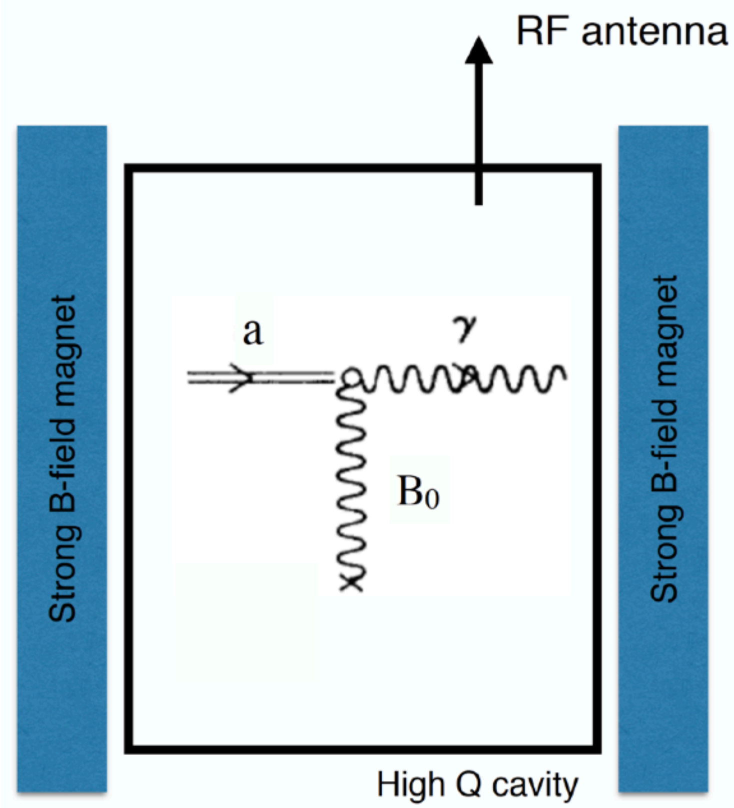


(iii) New dark matter detection scheme



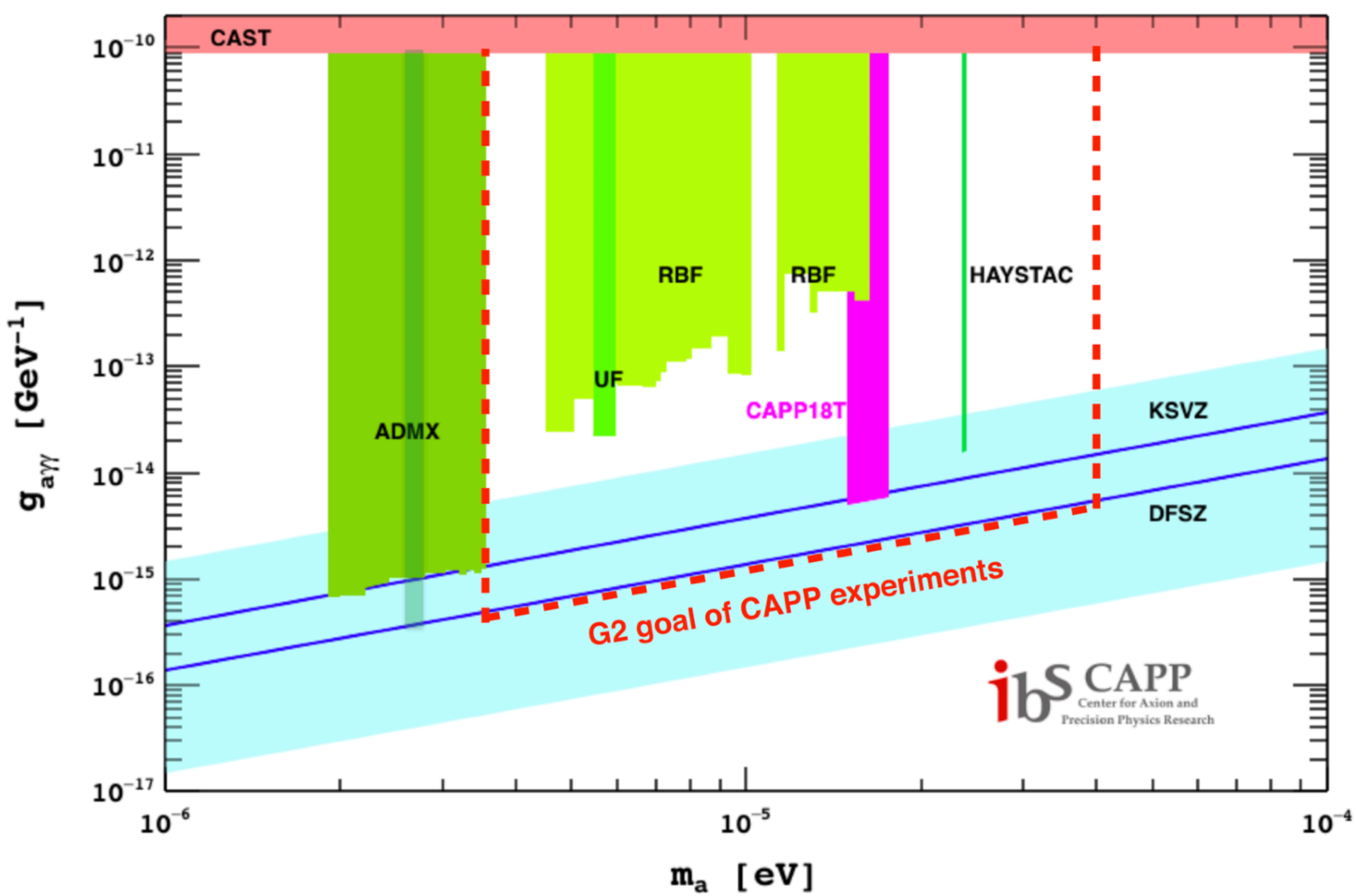
(Ex) Low-Q^2 electron recoil or ionization (dark photon DM direct detection)

Whether a new detector design is necessary or just a new interpretation of the existing dark matter search will be enough should be studied carefully.

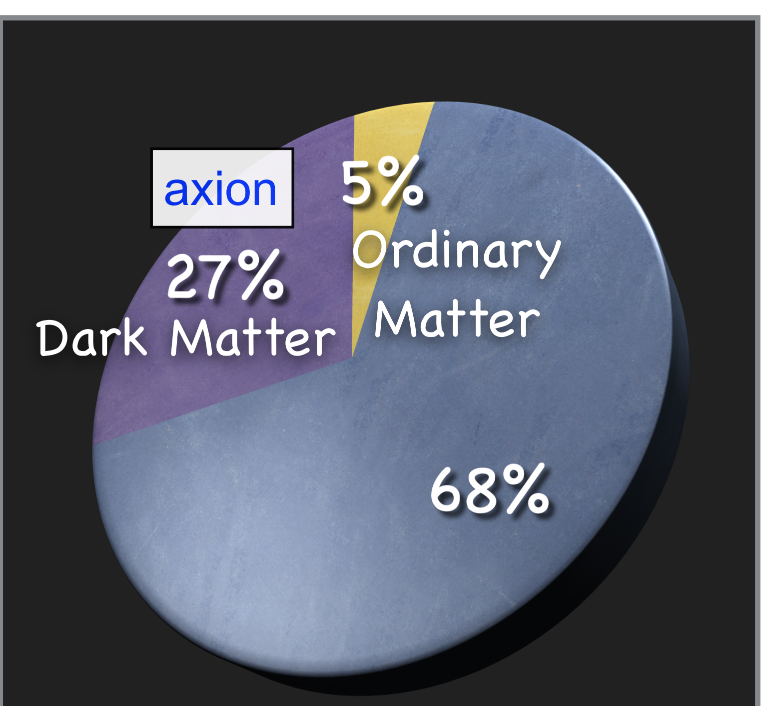


KAIST/IBS-CAPP experiments will test a good portion of the axion dark matter region using the axion portal.

Expected coverage of the KAIST/IBS-CAPP experiments



Total Universe energy



Extension of the electrodynamics (in the presence of the axion and dark photon)

Extended Electrodynamics in the presence of the axion and dark photon

[Huang, LEE (2018)]

(Effective) Lagrangian for "extended" electrodynamics

- $$\mathcal{L} = -\frac{1}{4}FF - \frac{1}{4}F'F' + \frac{1}{2}m_{\gamma'}^2 A'A' + \frac{1}{2}\left(\partial_\mu a\right)^2 - \frac{1}{2}m_a^2 a^2 + \frac{G_{a\gamma\gamma}}{4}aF\tilde{F} + \frac{G_{a\gamma\gamma'}}{2}aF\tilde{F}' + \frac{G_{a\gamma'\gamma'}}{4}aF'\tilde{F}' - \left(A + \varepsilon A'\right)J - A'J'$$

vector portal, axion portal, dark axion portal

after the kinetic mixing (vector portal) is already diagonalized

$$\mathcal{L}_{\text{kin}} = -\frac{1}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} + \frac{\varepsilon}{2}\hat{F}_{\mu\nu}\hat{F}'^{\mu\nu} - \frac{1}{4}\hat{F}'_{\mu\nu}\hat{F}'^{\mu\nu}$$

$$\hat{A} \to A + \varepsilon A' \;, \quad \hat{A}' \to A'$$

Extended Electrodynamics in the presence of the axion and dark photon

[Huang, LEE (2018)]

Euler-Lagrange equations of motion

- $\partial_\nu F^{\nu\mu} - G_{a\gamma\gamma}\partial_\nu a\tilde{F}^{\nu\mu} - G_{a\gamma\gamma'}\partial_\nu a\tilde{F}'^{\nu\mu}$ for photon
$= J^\mu$

- $\partial_\nu F'^{\nu\mu} - G_{a\gamma'\gamma'}\partial_\nu a\tilde{F}'^{\nu\mu} - G_{a\gamma\gamma'}\partial_\nu a\tilde{F}^{\nu\mu}$ for dark photon
$= -m_{\gamma'}^2 A'^\mu + J'^\mu + \varepsilon J^\mu$

- $(\partial^2 + m_a^2)a - \frac{G_{a\gamma\gamma}}{4}F\tilde{F} - \frac{G_{a\gamma\gamma'}}{2}F\tilde{F}' - \frac{G_{a\gamma'\gamma'}}{4}F'\tilde{F}' = 0$ for axion

Maxwell's equations

[Huang, LEE (2018)]

From the equations of motion

$$\nabla \cdot \vec{E} = \rho + G_{a\gamma\gamma} \nabla a \cdot \vec{B} + G_{a\gamma\gamma'} \nabla a \cdot \vec{B}'$$

$$\nabla \times \vec{B} = \vec{J} + \frac{\partial \vec{E}}{\partial t} - G_{a\gamma\gamma}\left(\frac{\partial a}{\partial t}\vec{B} + \nabla a \times \vec{E}\right) - G_{a\gamma\gamma'}\left(\frac{\partial a}{\partial t}\vec{B}' + \nabla a \times \vec{E}'\right)$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \cdot \vec{E}' = (\rho' + \varepsilon\rho) - m_{\gamma'}^2 A'^0 + G_{a\gamma'\gamma'} \nabla a \cdot \vec{B}' + G_{a\gamma\gamma'} \nabla a \cdot \vec{B}$$

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

$$\nabla \cdot \vec{B}' = 0$$

$$\nabla \times \vec{E}' = -\frac{\partial \vec{B}'}{\partial t}$$

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

Wave equations

[Huang, LEE (2018)]

From the equations of motion

$$\partial^2 \vec{E} - G_{a\gamma\gamma} \frac{\partial}{\partial t}\left(\frac{\partial a}{\partial t}\vec{B} + \nabla a \times \vec{E}\right) - G_{a\gamma\gamma'} \frac{\partial}{\partial t}\left(\frac{\partial a}{\partial t}\vec{B}' + \nabla a \times \vec{E}'\right) = 0$$

$$\partial^2 \vec{B} + G_{a\gamma\gamma} \nabla \times \left(\frac{\partial a}{\partial t}\vec{B} + \nabla a \times \vec{E}\right) + G_{a\gamma\gamma'} \nabla \times \left(\frac{\partial a}{\partial t}\vec{B}' + \nabla a \times \vec{E}'\right) = 0$$

$$(\partial^2 + m_{\gamma'}^2)\vec{E}' - G_{a\gamma'\gamma'} \frac{\partial}{\partial t}\left(\frac{\partial a}{\partial t}\vec{B}' + \nabla a \times \vec{E}'\right) - G_{a\gamma\gamma'} \frac{\partial}{\partial t}\left(\frac{\partial a}{\partial t}\vec{B} + \nabla a \times \vec{E}\right) = 0$$

$$(\partial^2 + m_{\gamma'}^2)\vec{B}' + G_{a\gamma'\gamma'} \nabla \times \left(\frac{\partial a}{\partial t}\vec{B}' + \nabla a \times \vec{E}'\right) + G_{a\gamma\gamma'} \nabla \times \left(\frac{\partial a}{\partial t}\vec{B} + \nabla a \times \vec{E}\right) = 0$$

$$(\partial^2 + m_a^2)a + G_{a\gamma\gamma}\vec{E} \cdot \vec{B} + G_{a\gamma\gamma'}(\vec{E} \cdot \vec{B}' + \vec{E}' \cdot \vec{B}) + G_{a\gamma'\gamma'}\vec{E}' \cdot \vec{B}' = 0$$

Reactor experiments (MINER/CONUS, RENO/NEOS)

[deNiverville, LEE, YM Lee (2020)]

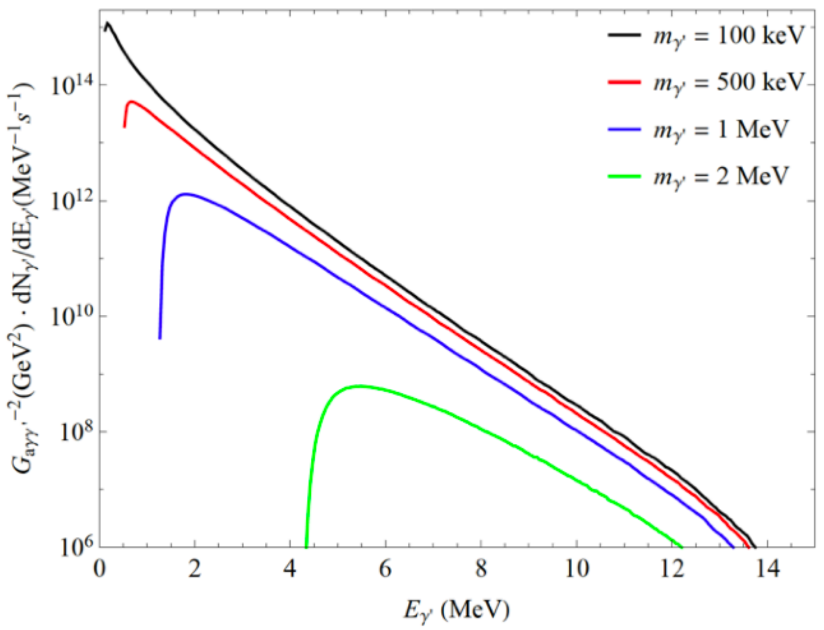


FIG. 2. Production spectrum of dark photons through the dark axion portal ($G_{a\gamma\gamma'}$) in a 1 GW nuclear reactor for four dark photon masses. One can see that there are kinematic cutoffs in the energy spectrum that depend on the dark photon mass.

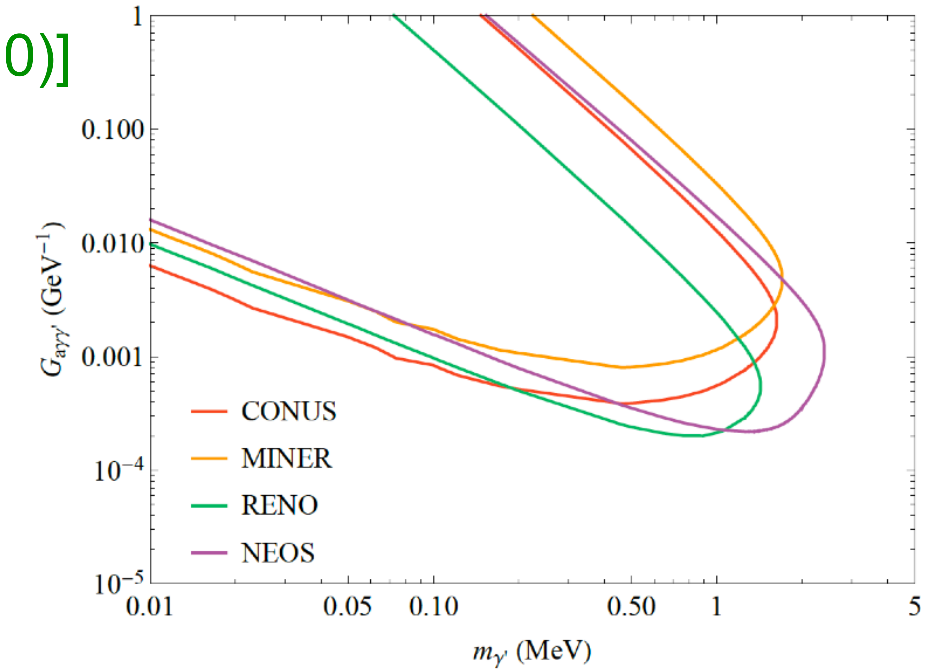


FIG. 4. Expected sensitivities at CONUS, MINER, RENO and NEOS. Presented are 95% C.L. contours for one year of data. The result with 1 MeV-cutoff is shown for RENO, and the result with 3.5 MeV-cutoff is shown for NEOS. MINER and CONUS do not require an energy cutoff. The cutoff reduces the sensitivity at the lower bound of $G_{a\gamma\gamma'}$ since the dark photon signal mostly comes from the low energy region when the coupling is small (see Fig. 2). NEOS has better sensitivity than RENO in larger couplings and masses benefiting from its close location to the reactor core. MINER and CONUS have smaller coverage compared to RENO and NEOS because of their smaller detector volume. An analysis of the background energy spectrum could improve the presented sensitivities.

The reactor photon production distribution was modeled by

$$\frac{dN_\gamma}{dE_\gamma} = \frac{0.58\times10^{18}}{\mathrm{sec}\cdot\mathrm{MeV}}\frac{P}{\mathrm{MW}}e^{-E_\gamma/(0.91\mathrm{MeV})}, \qquad (4)$$

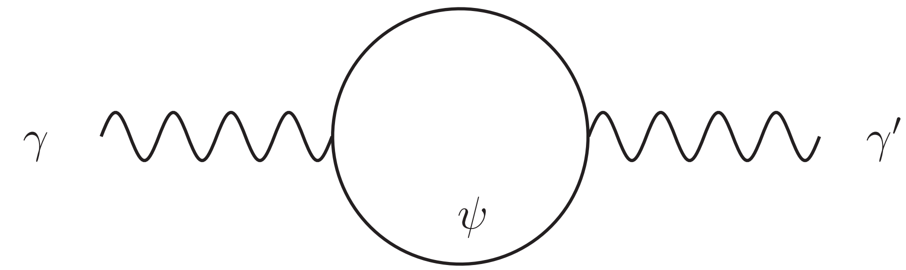
Detectors for neutrino oscillation (RENO/NEOS/…) use scintillation to detect gamma's. (MeV scale threshold).
Detectors for coherent elastic neutrino-nucleus scattering (MINER/CONUS/…) use crystals to detect gamma's (negligible threshold).

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

Loop-induced kinetic mixing



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

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

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

For $\Lambda \sim 10^{16}$ GeV (typical GUT scale) and $m_\psi \sim f_a$, (10^9 - 10^{12} GeV), we get $\varepsilon_{\text{induced}} \sim -O(10^{-2})$ 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 $\varepsilon_{\text{induced}}$ and the short-distance (UV) contribution to ε (taking fine-tuning).

(ii) introducing more particle that couple to γ and γ' 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)