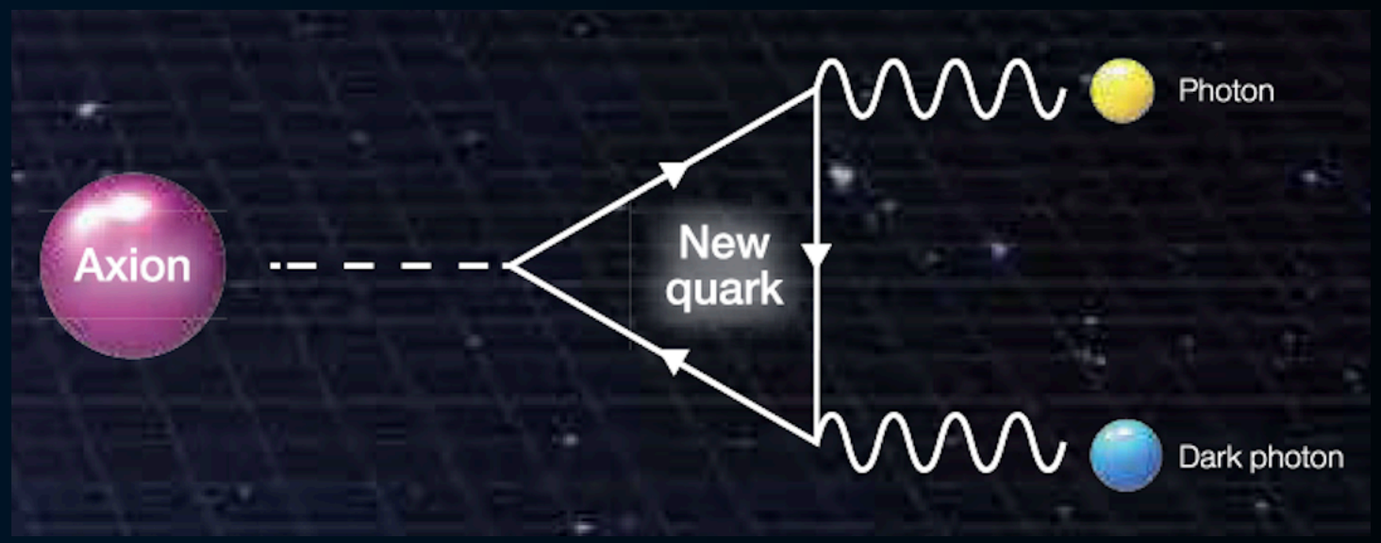
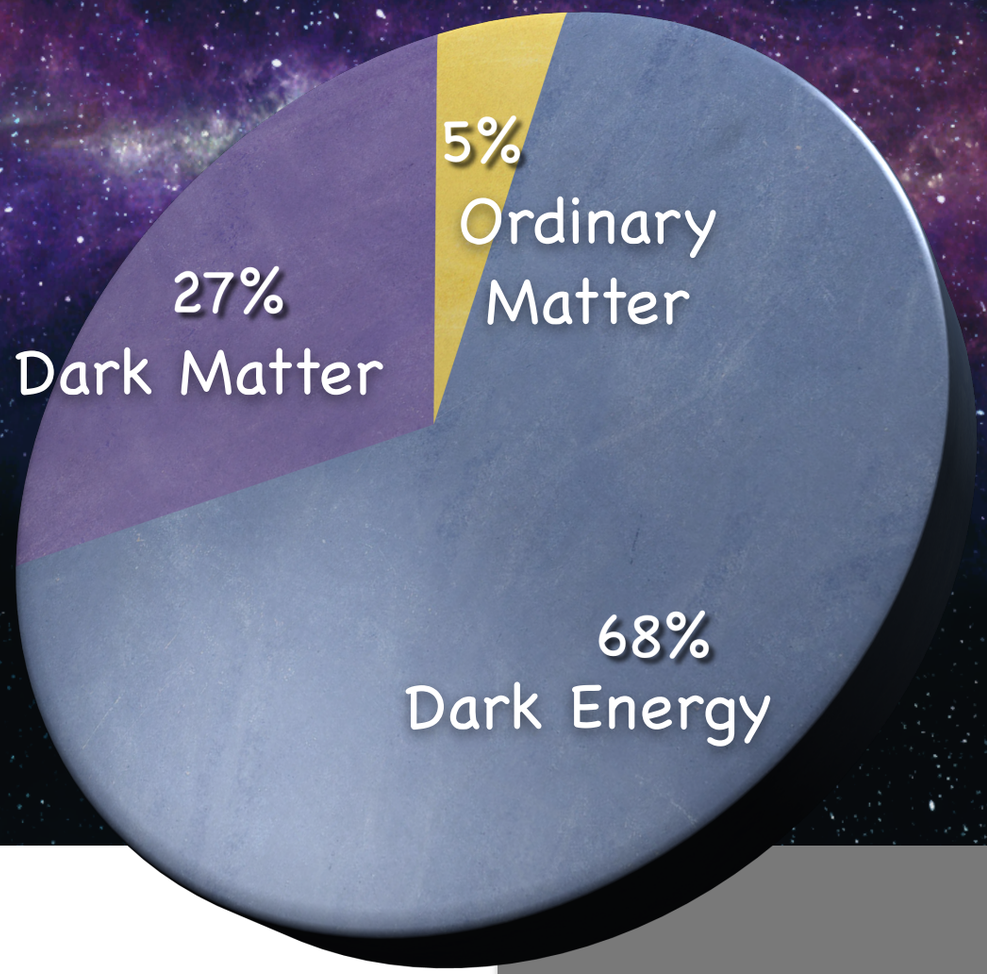
Dark Axion Portal



Hye-Sung Lee
KAIST

International Workshop on New Physics at the Low Energy Scales
KIAS / September 23, 2019

We live in a Dark World

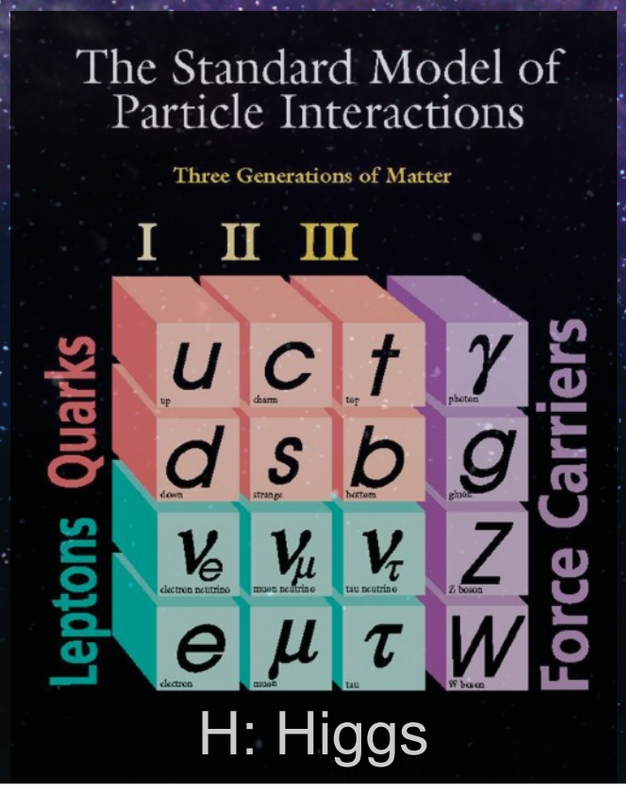


$$\nabla \cdot \vec{E} = \rho$$
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{B} = \vec{J} + \frac{\partial \vec{E}}{\partial t}$$

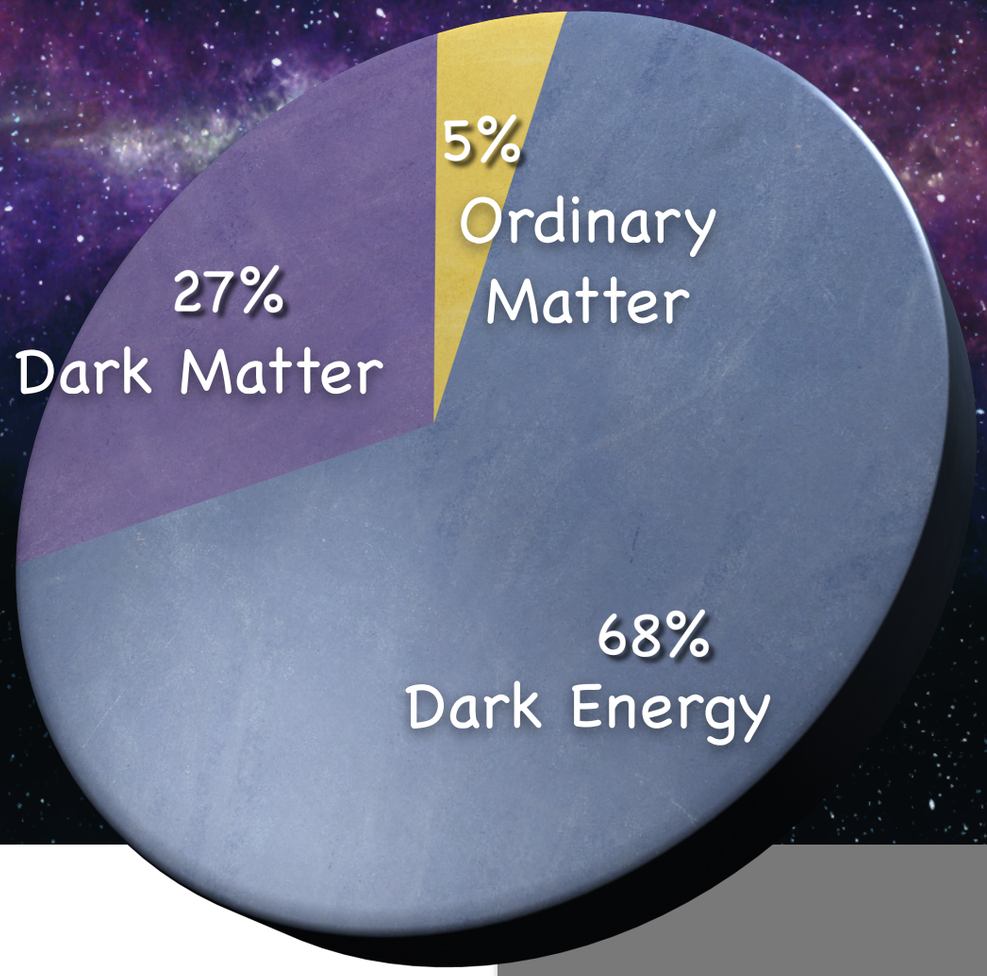
Bright sector

Dark sector

We live in a Dark World



H: Higgs



Dark Sector

Dark matter
Dark Higgs
Dark gauge boson
...

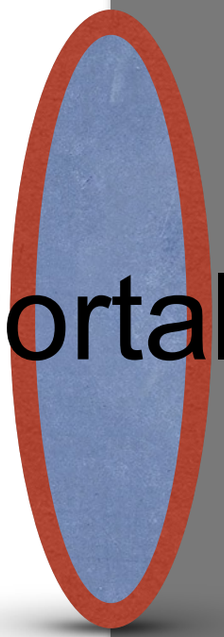
$$\nabla \cdot \vec{E} = \rho$$
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{B} = \vec{J} + \frac{\partial \vec{E}}{\partial t}$$

Bright sector

Dark sector

The dark sector particles can be light.

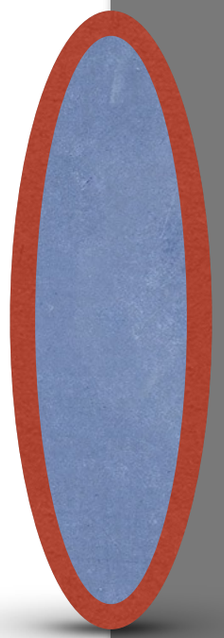
Portals



Standard Model

Dark Sector

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

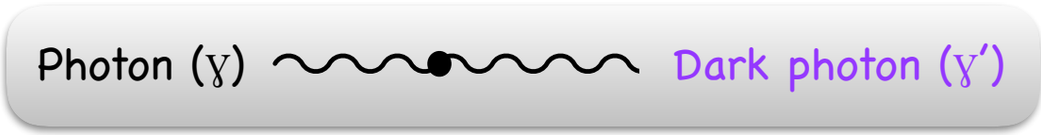


Through the portal, two separate sectors can communicate with each other.

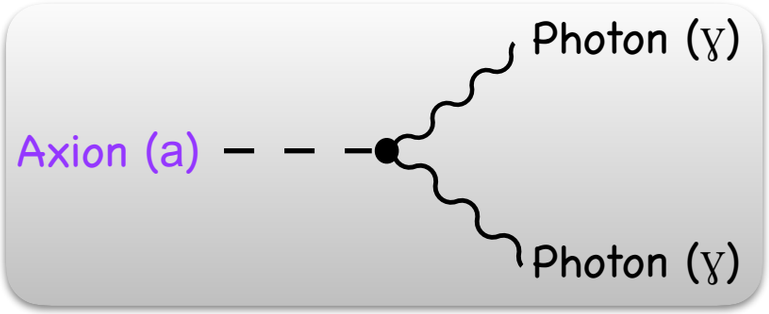
F, γ : photon
Z′, γ′ : dark photon
a : axion

Portals

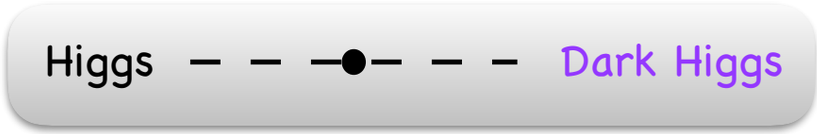
(i) Vector Portal $\frac{\varepsilon}{2} F_{\mu\nu} Z'^{\mu\nu}$



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



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

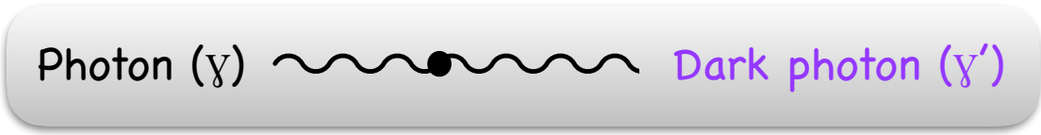


(iv) Neutrino Portal $y\, L H N$

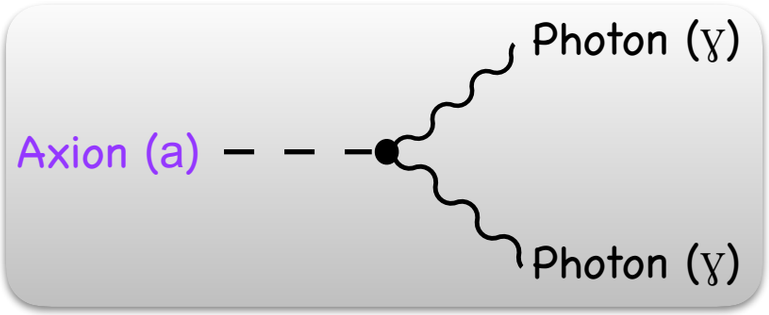
F, γ : photon
Z′, γ′ : dark photon
a : axion

Portals

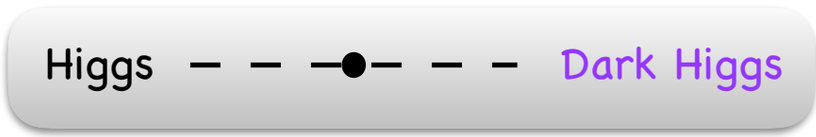
(i) Vector Portal $\frac{\varepsilon}{2} F_{\mu\nu} Z'^{\mu\nu}$



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



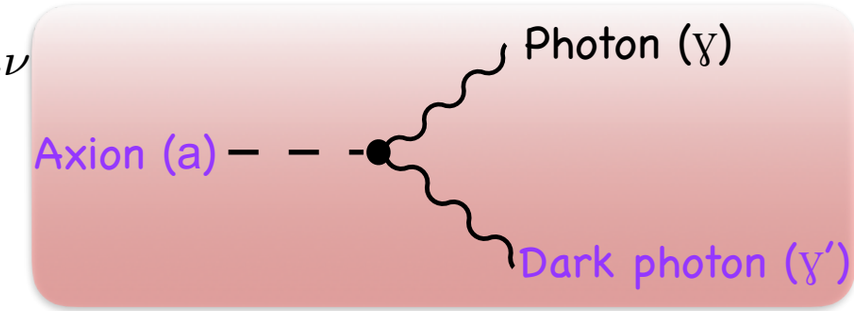
(iii) Higgs Portal $\kappa |S|^2 |H|^2 + \mu\, S |H|^2$



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

(v) Dark Axion Portal [Kaneta, LEE, Yun (PRL 2017)]

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



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. $G_{a\gamma\gamma'} \neq \varepsilon\, G_{a\gamma\gamma}$)

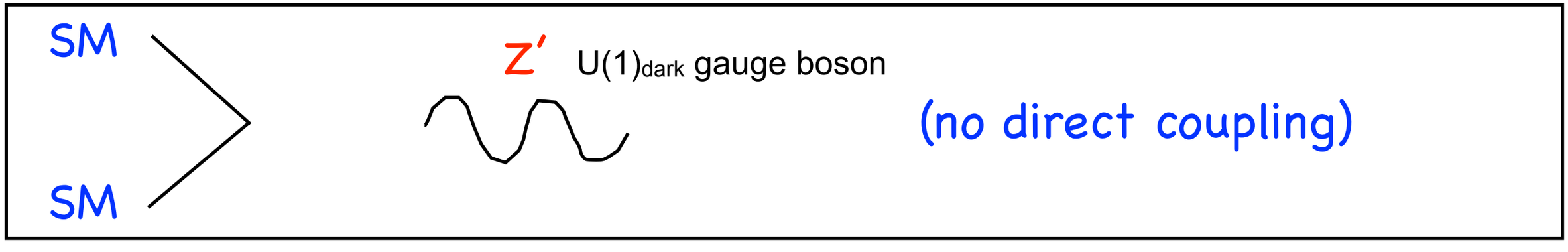
Vector Portal

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

Standard Model + Dark Force

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

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

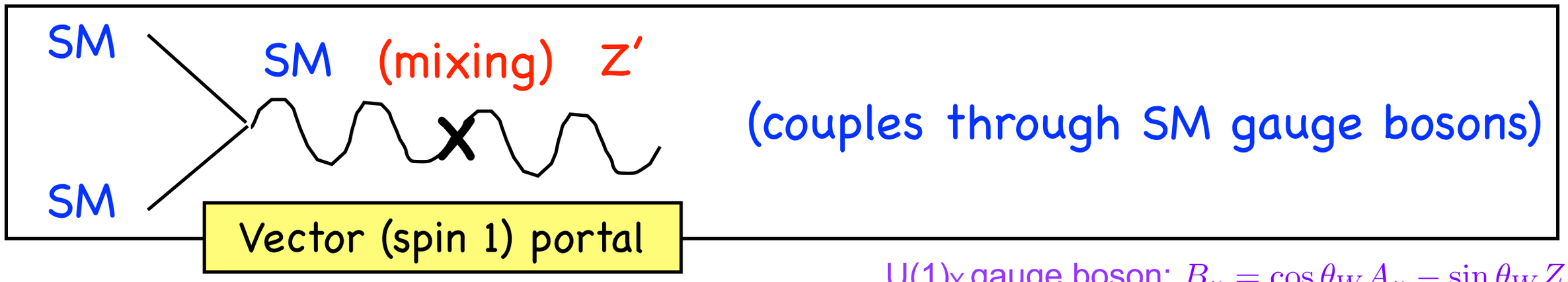


Z' can couple to SM particles through kinetic mixing of $U(1)_Y$ & $U(1)_{dark}$.

[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**



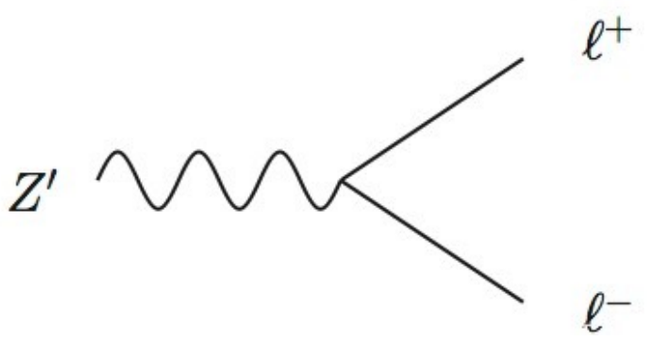
$U(1)_Y$ gauge boson: $B_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu$

(θ_W : Weinberg angle)

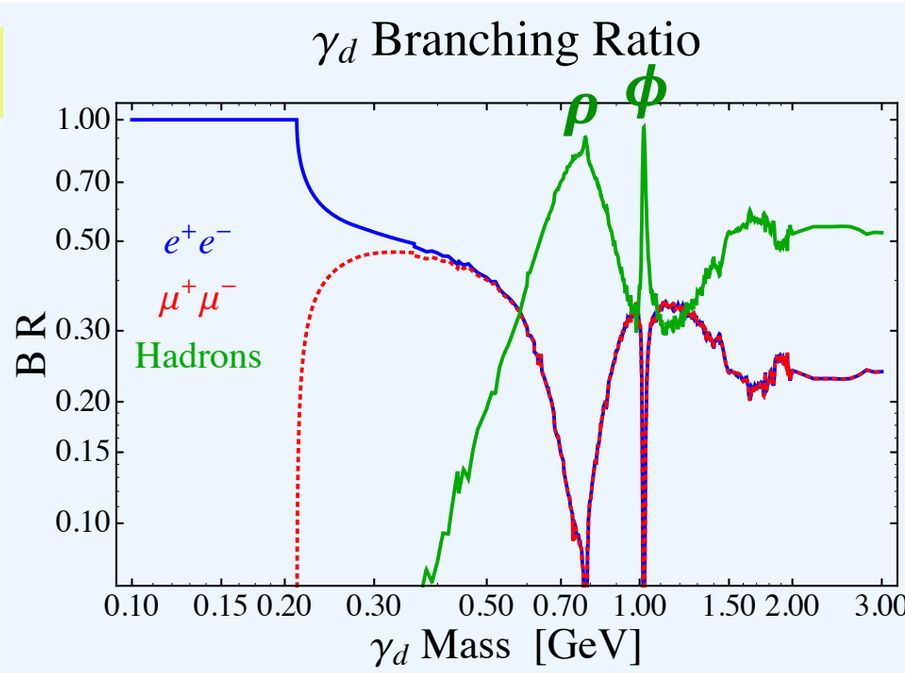
Visible/Invisible decay of Dark photon

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

(i) “Dilepton Resonance” search Visible dark photon mode

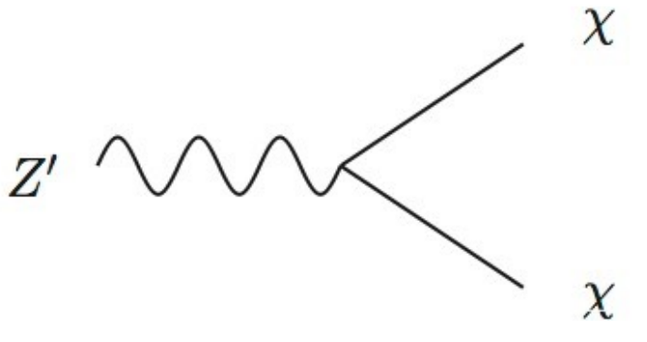


Z’ → $\ell^+\ell^-$ is the major decay mode in an ordinary scenario.



[Batell, Pospelov, Ritz (2009)]
[Falkowski *et al* (2010)]

(ii) “Missing Energy” search Invisible dark photon mode



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

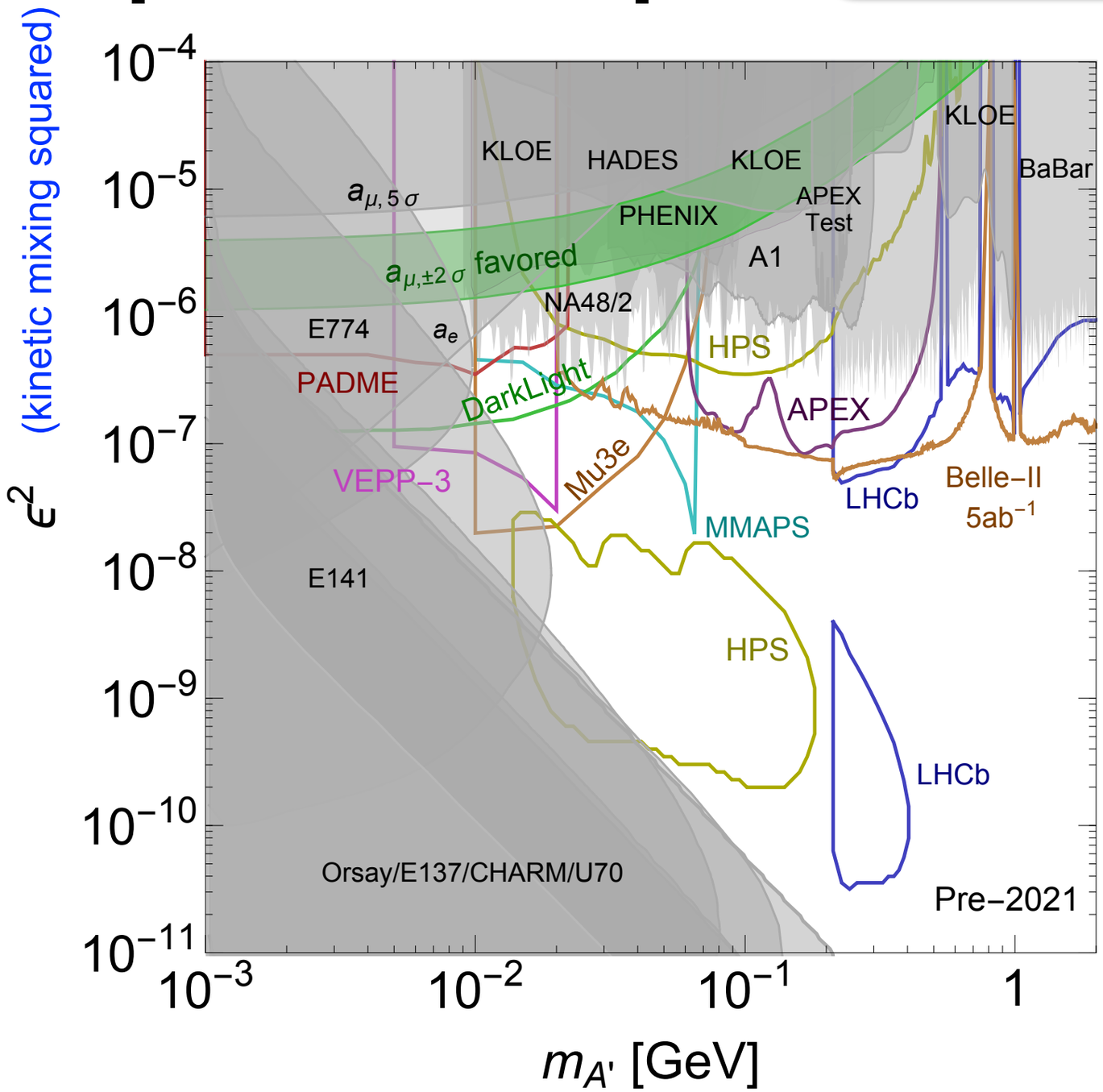
BR(Z’ → missing energy) ≈ 1 is taken.

Dilepton searches for dark photon (Visible dark photon)

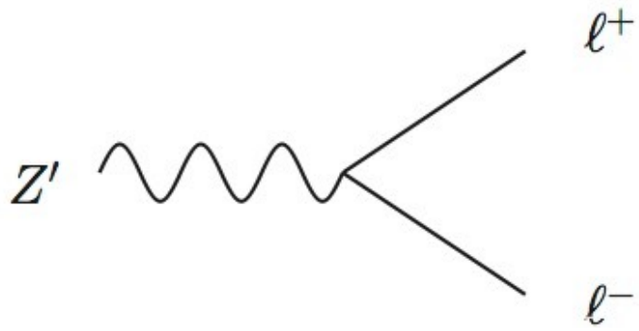
Photon (γ) ~~●~~ Dark photon (γ′)

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

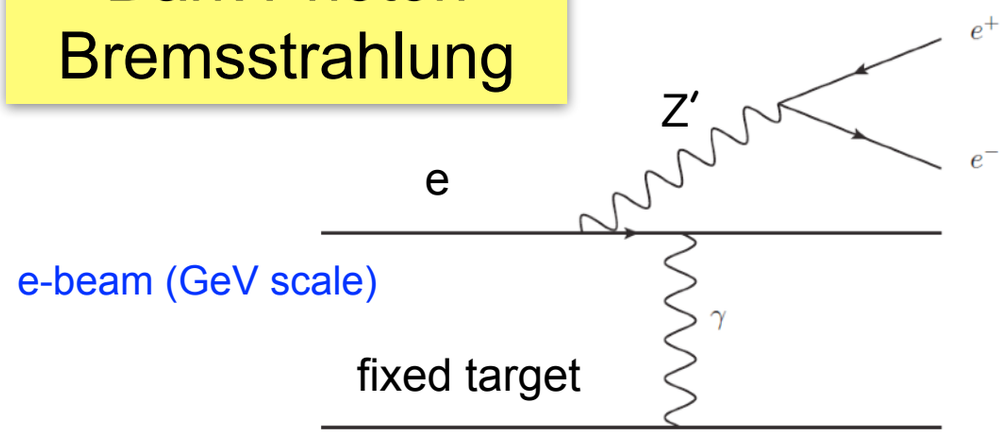
The dark gauge boson is actively searched for in many experiments.

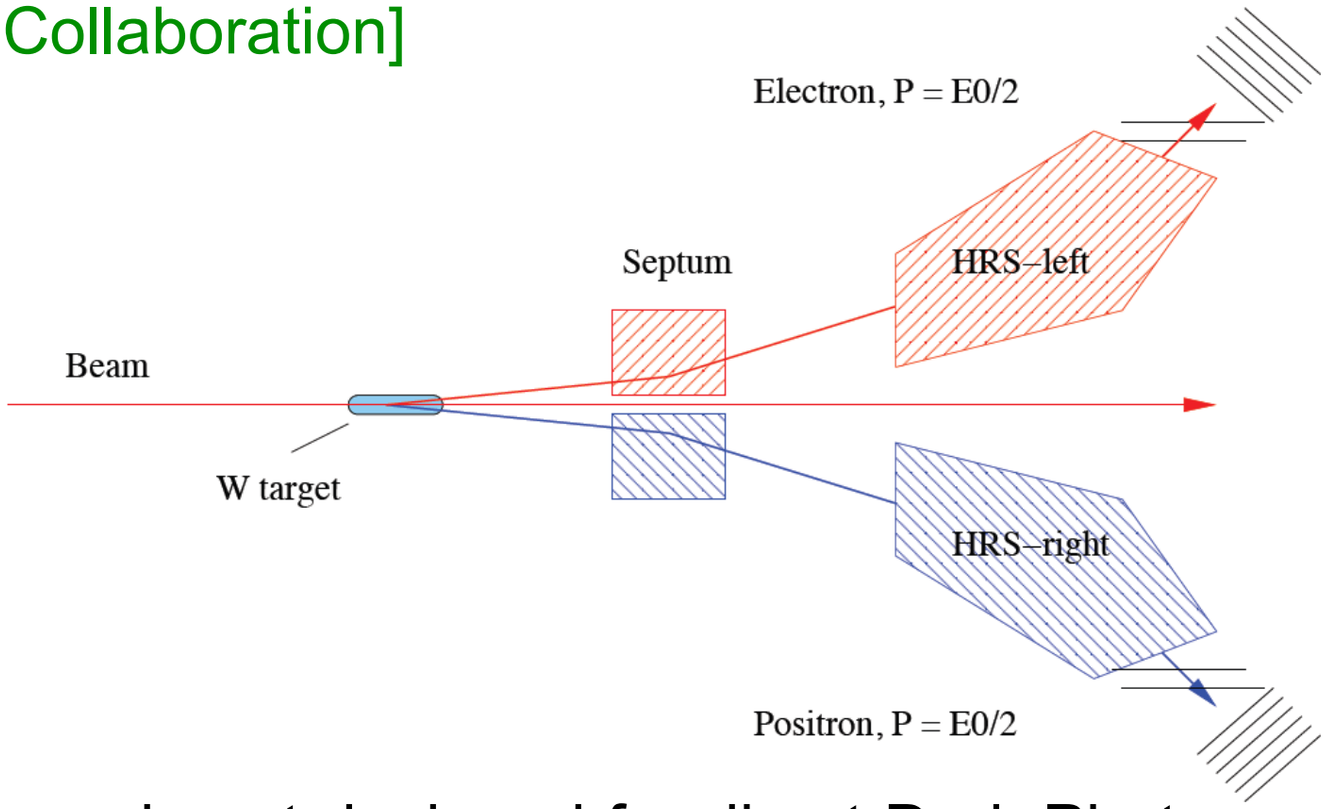
The vector portal is constrained to be small ($\varepsilon << 1$) .

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

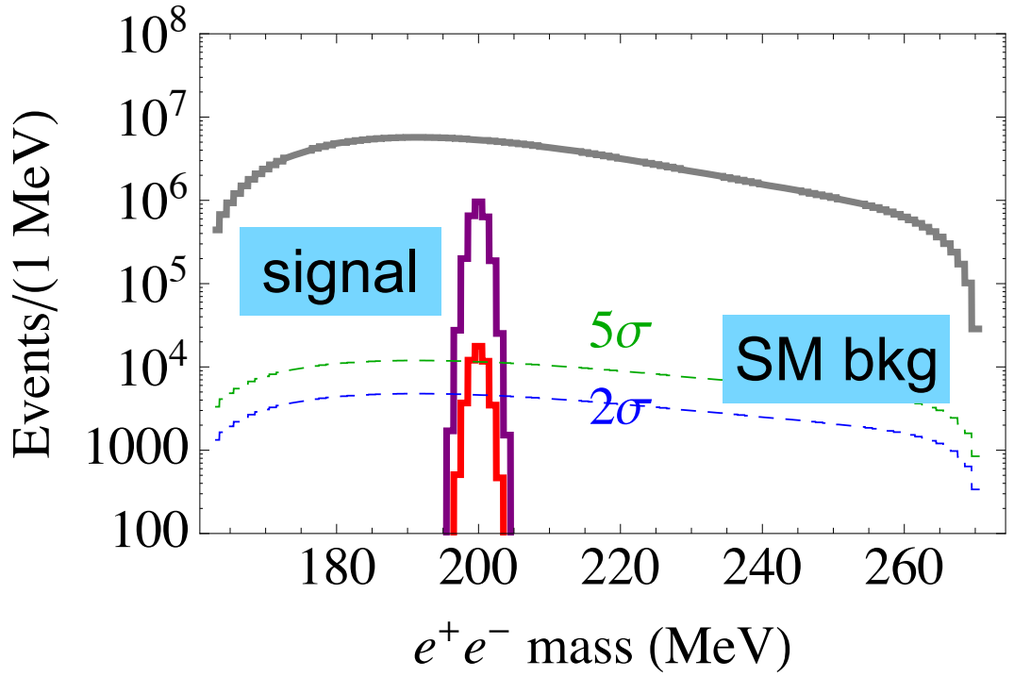
[APEX Collaboration]

Dark Photon Bremsstrahlung





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



$Z' \rightarrow e^+e^-$ narrow resonance at Z' mass
(Direct bump search at Low-energy facility)

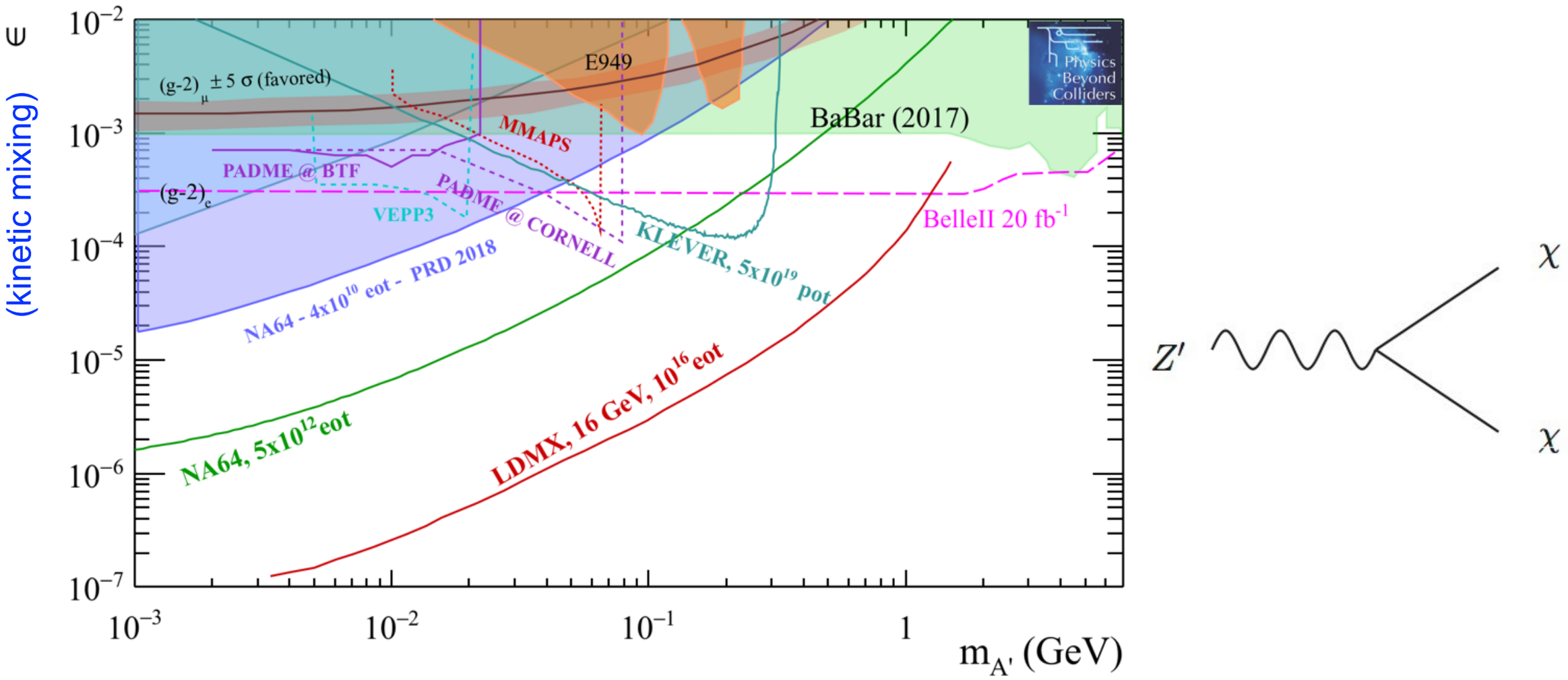
The *High Resolution Spectrometers (HRS)* at Hall A are used.

Missing energy searches for dark photon (Invisible dark photon)

[Current constraints]

Photon (γ) ~~~●~~~ Dark photon (γ′)

γ-γ′ kinetic mixing (vector portal)



From Physics Beyond Colliders at CERN (arXiv:1901.09966)

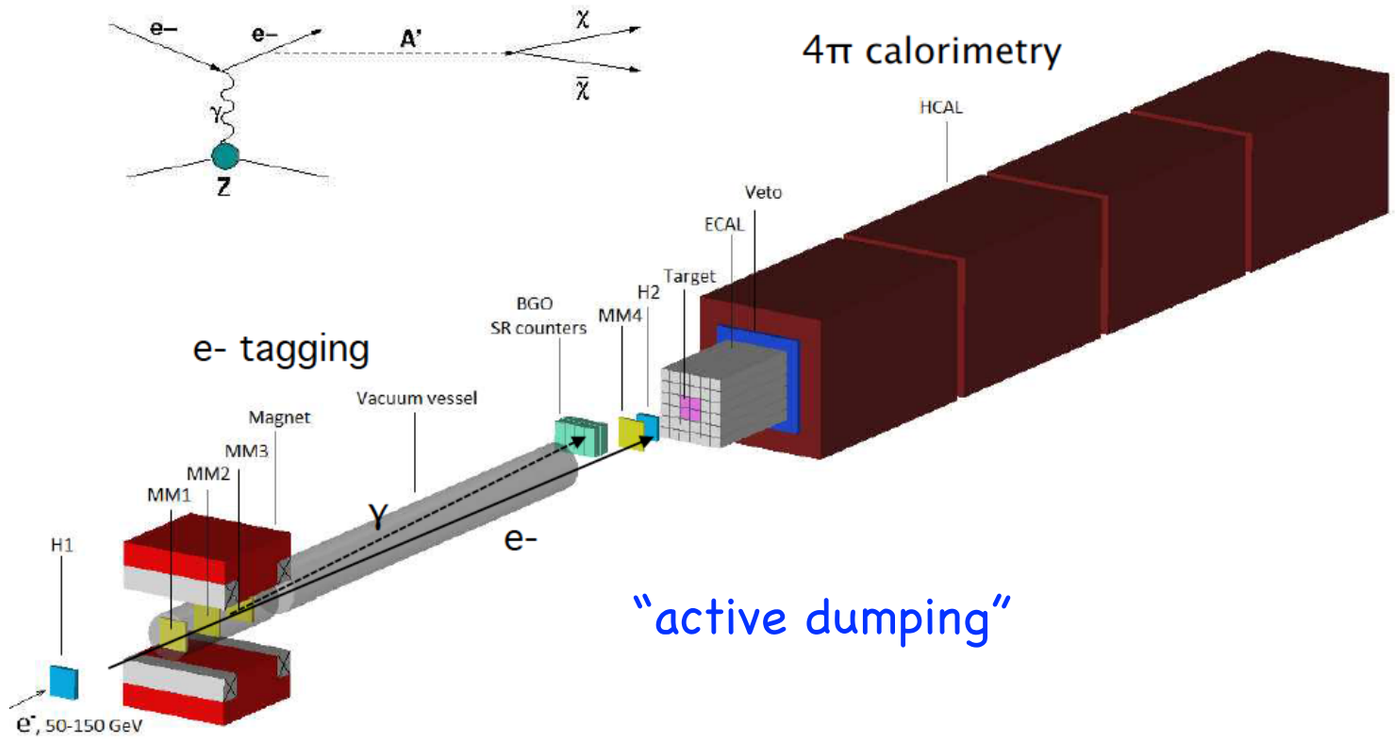
The invisible dark photon is also actively searched for in many experiments.

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

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

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

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{\rm Dark}$	$U(1)_{PQ}$
Q	3	2	$1/6$	0	0
u_R	3	1	$2/3$	0	0
d_R	3	1	$-1/3$	0	0
L	1	2	$-1/2$	0	0
e_R	1	1	-1	0	0
H	1	2	$-1/2$	0	0
ψ	3	1	Q_ψ	D_ψ	PQ_ψ
ψ^c	$\bar{3}$	1	$-Q_\psi$	$-D_\psi$	PQ_{ψ^c}
Φ_{PQ}	1	1	0	0	PQ_Φ
Φ_D	1	1	0	D_Φ	0

SM particles

Exotic heavy quarks

Extra scalars (to break PQ & Dark)

KSVZ axion model

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.

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

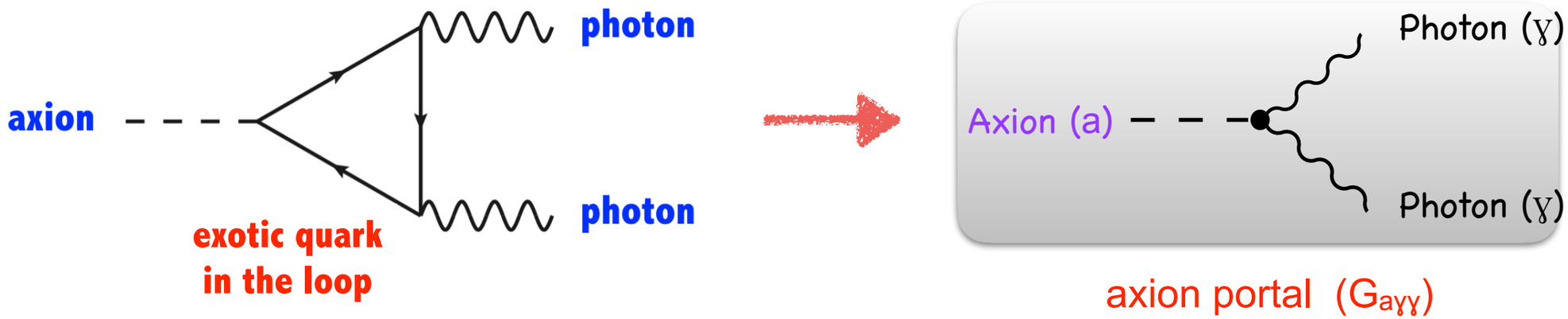
Exotic colored fermions may decay into other particles through, e.g. $\Phi_D^\dagger \psi \bar{d}_R + h.c.$

for $PQ_\psi = 0$, $Q_\psi = -1/3$, $D_\psi = D_\Phi$.

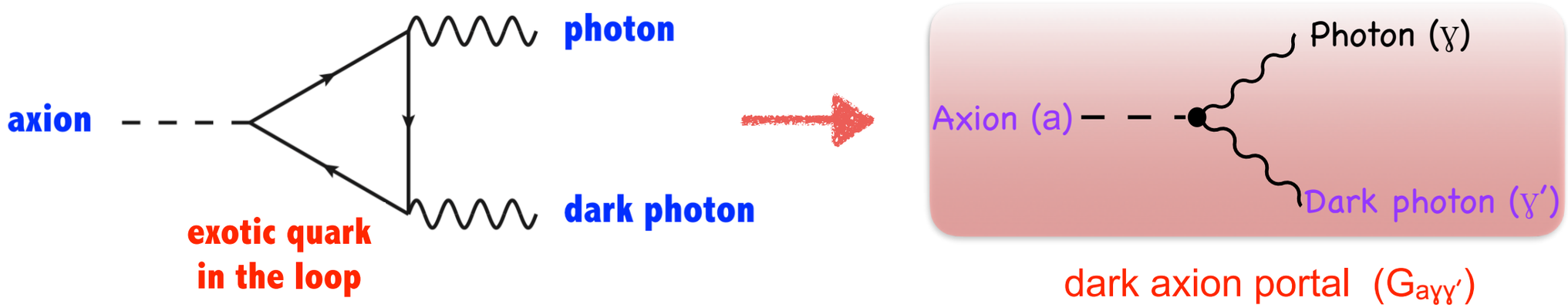
It depends on the couplings of the Fermions in the triangle

In the KSVZ axion model, there are exotic quarks.

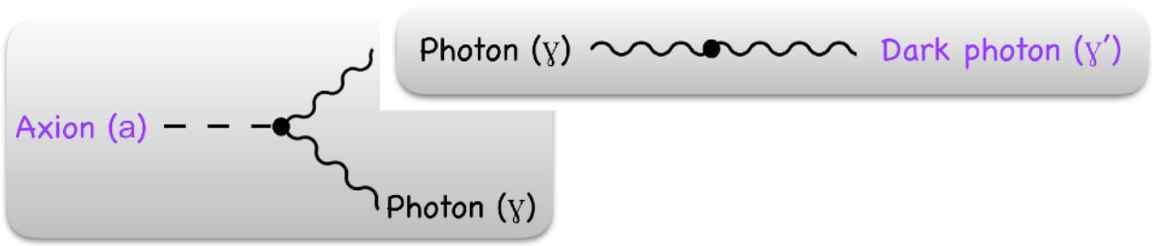
(i) Original KSVZ axion model: Exotic quarks have EM charges



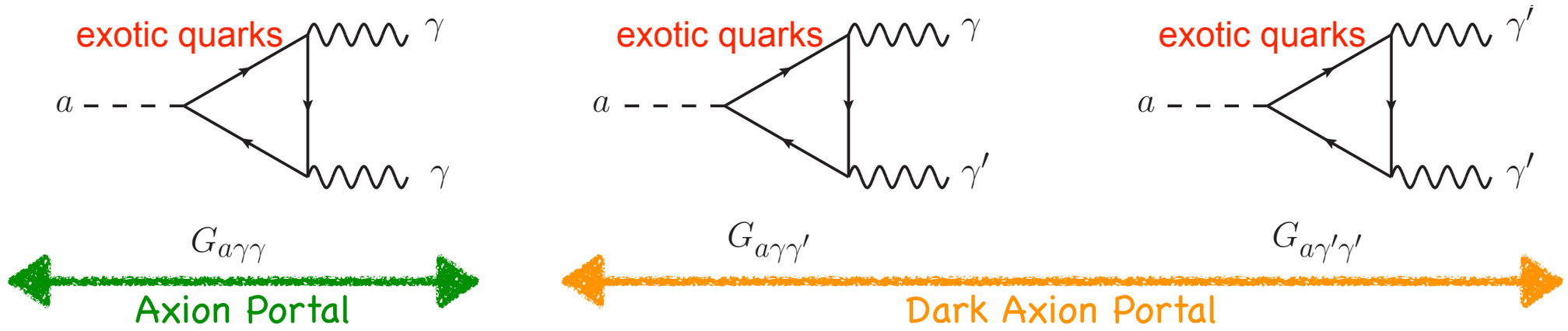
(ii) Dark KSVZ axion model: Exotic quarks have EM & Dark charges



(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

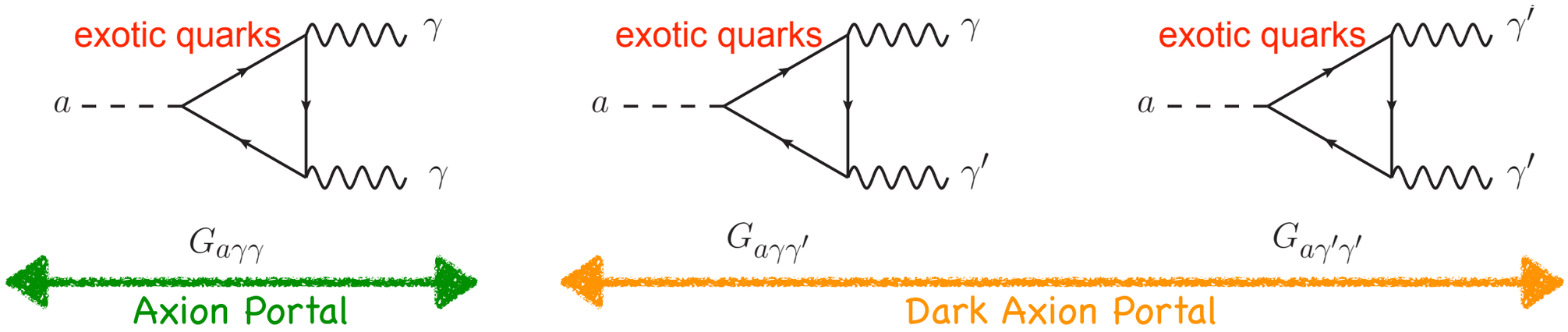
e: EM coupling constant
e': Dark coupling constant

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.

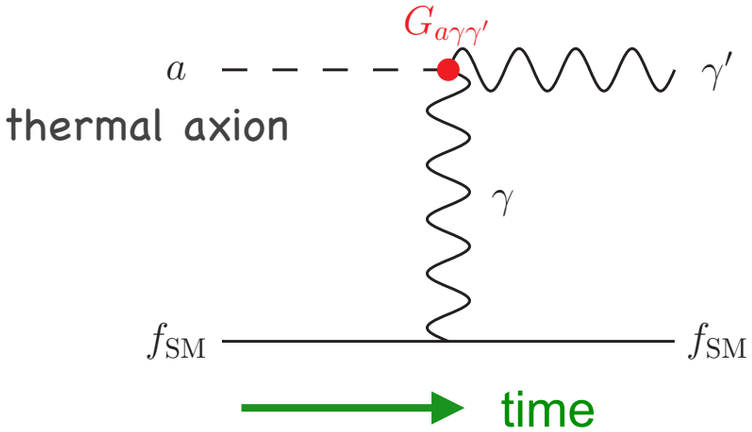
(Γ = partial decay width)

Implications of the Dark Axion Portal (Cosmic Frontier)

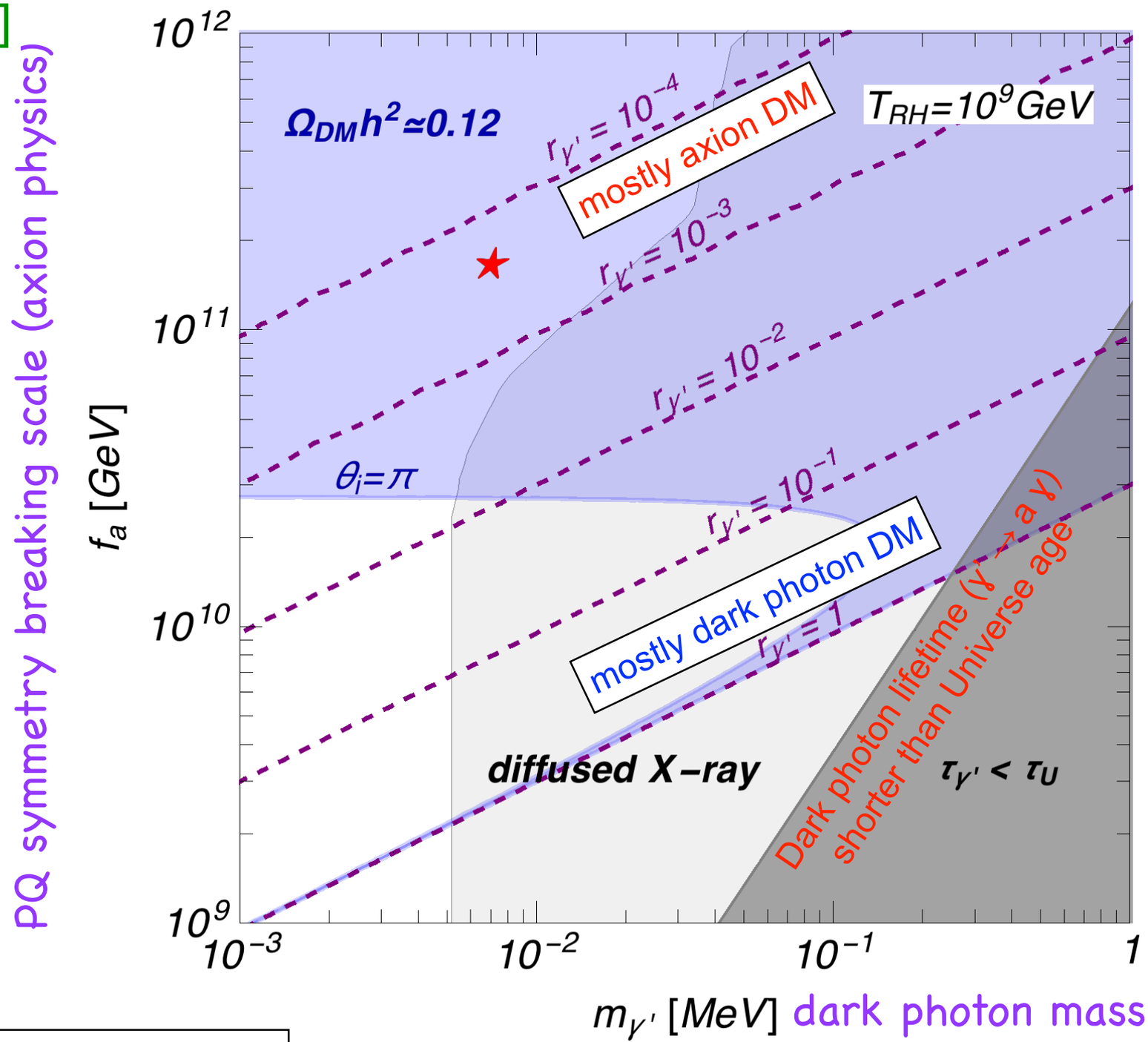
(i) New dark photon production mechanism

[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 the correct total 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

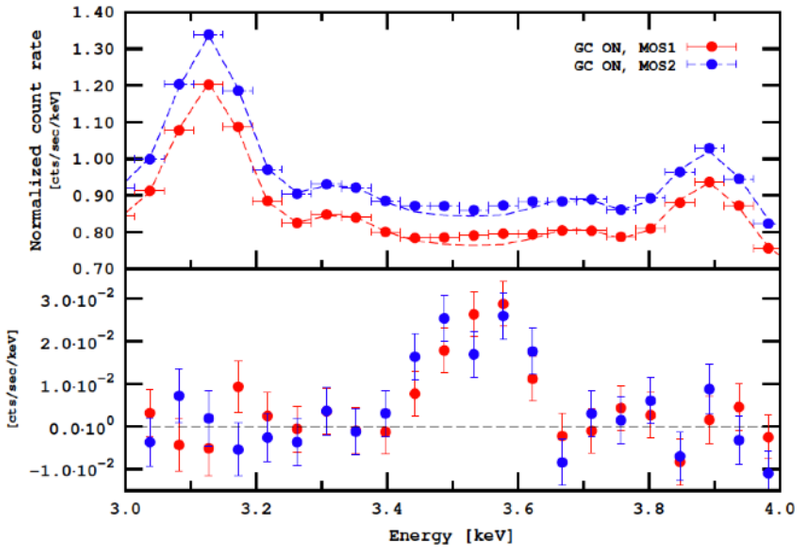
[Kaneta, LEE, Yun (2017)]

axion mass ≈ 10^{-4} eV

γ' mass = 7 keV

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

3.5 keV X-ray excess explained



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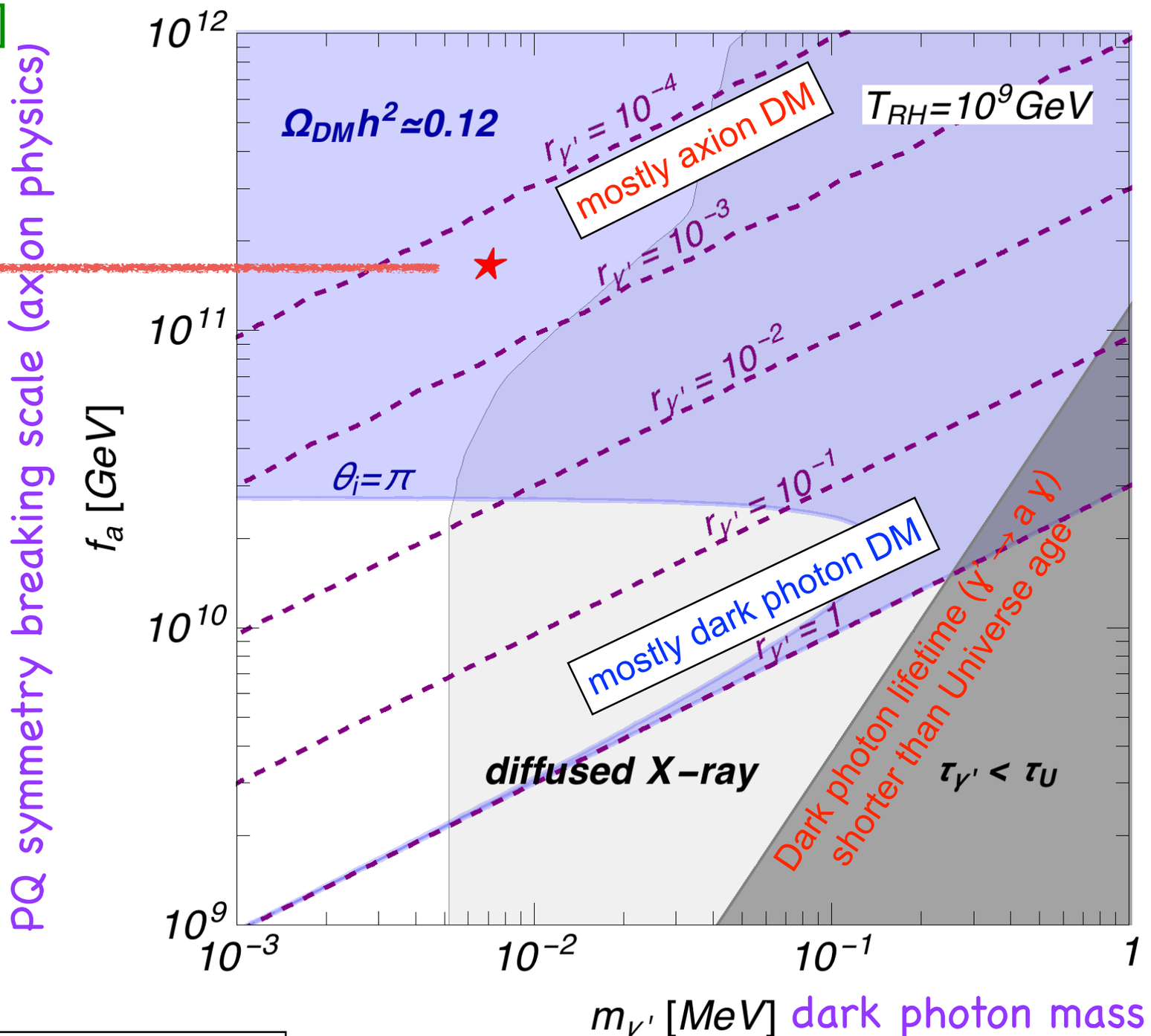


Dark photon decays slowly into axion + photon. ($\gamma' \to a\,\gamma$)

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

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

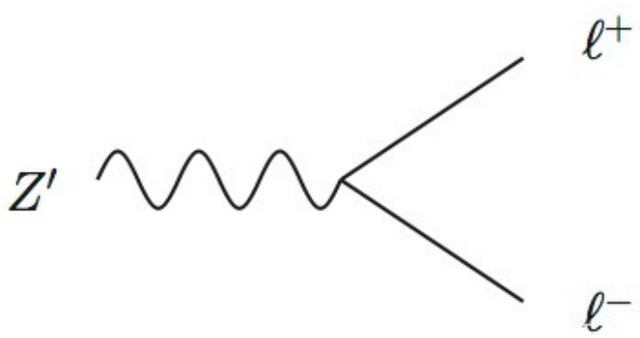
Implications of the Dark Axion Portal (Intensity Frontier)

Visible/Invisible decay of Dark photon

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

(i) “Dilepton Resonance” search

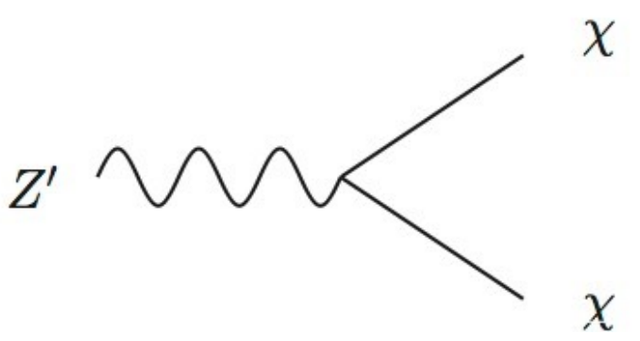
Visible dark photon mode



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

(ii) “Missing Energy” search

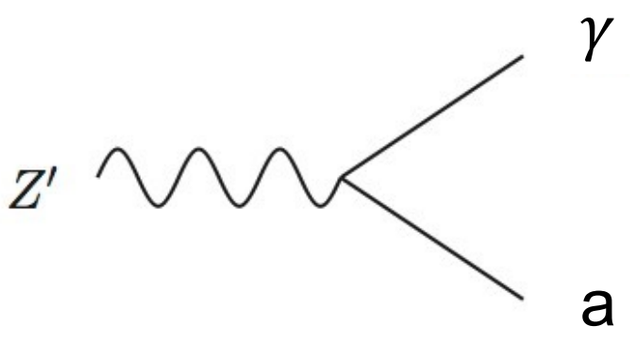
Invisible dark photon mode



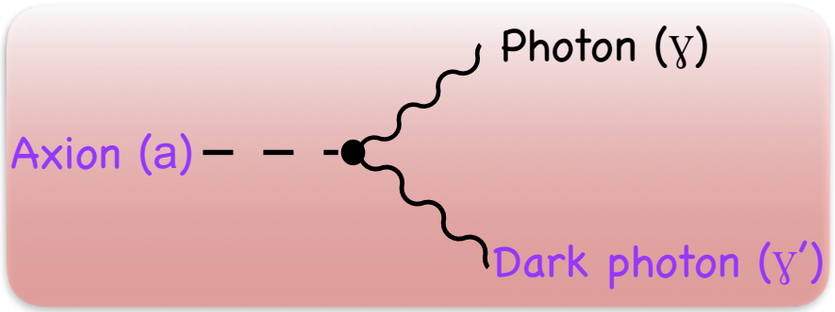
$$\Gamma(\gamma' \to \chi\bar{\chi}) = \frac{e'^2 D_\chi^2}{12\pi} m_{\gamma'} \left(1 - \frac{4m_\chi^2}{m_{\gamma'}^2}\right)^{1/2}$$

(iii) “Photon” search

“New” visible dark photon mode



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

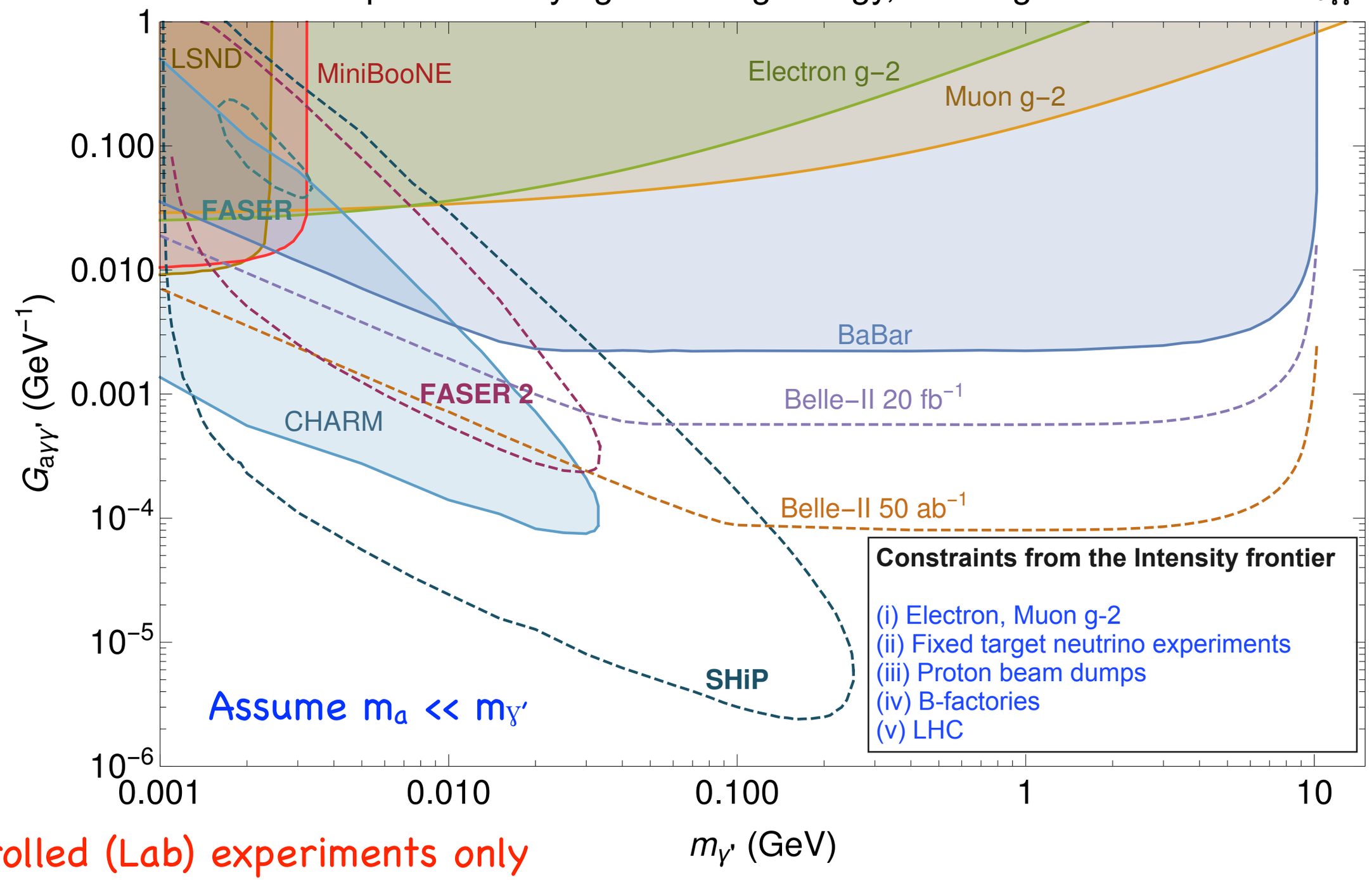


Photon searches for dark photon

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

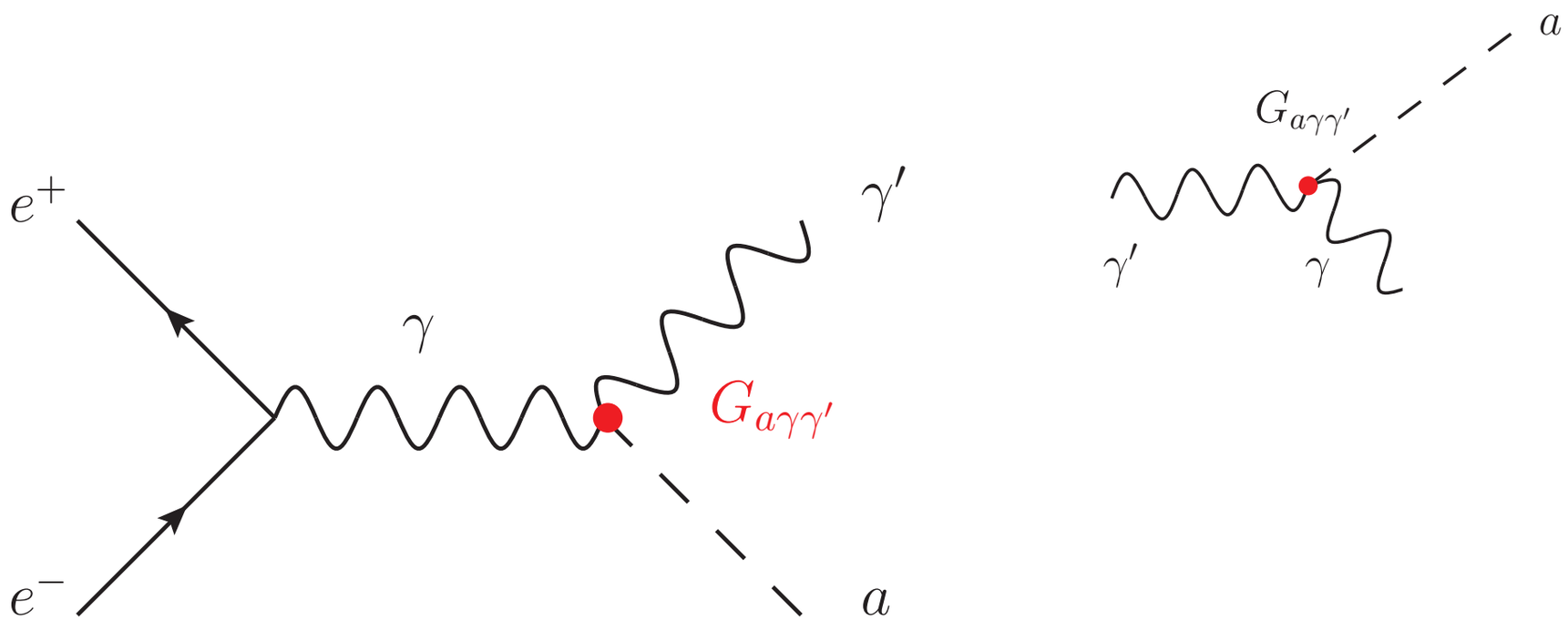
dark axion portal ($G_{a\gamma\gamma'}$)

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



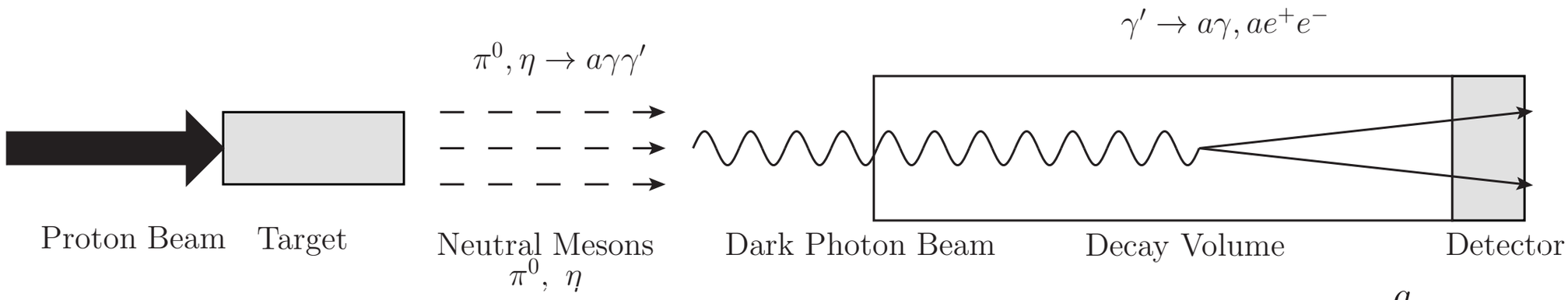
Controlled (Lab) experiments only

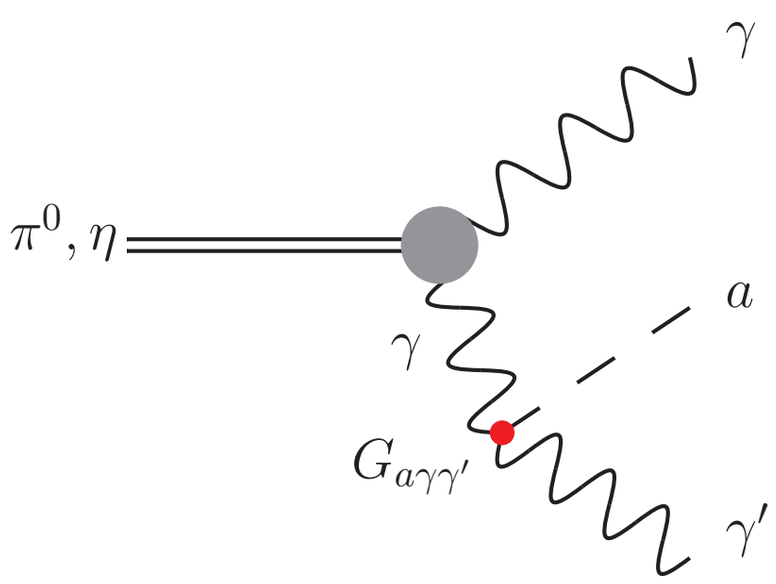
B-factories (BaBar, Belle II)



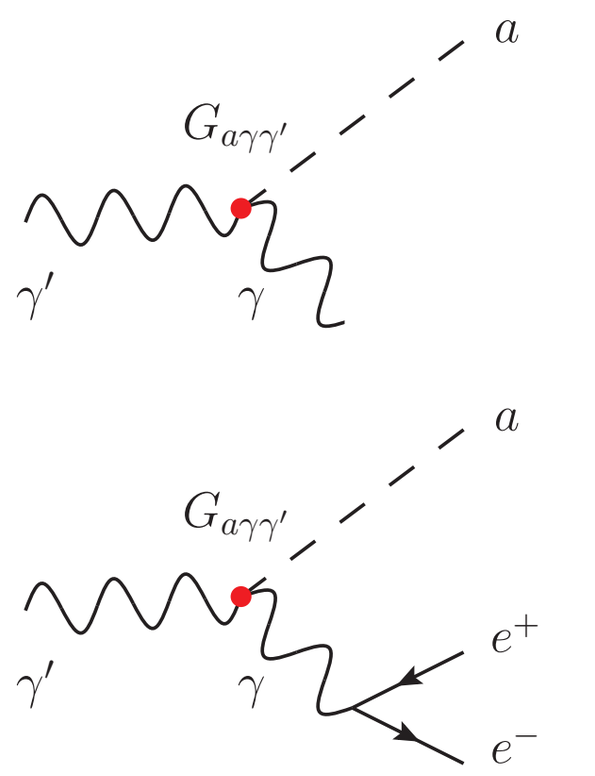
B-factories are asymmetric e+e- colliders of $E_{CM} \approx 10$ GeV.
e+e- can annihilate into a dark photon + axion, and the dark photon can decay into a photon + axion (e+e- → γ' a → γ a a). It is a mono-photon search.

Proton beam dumps (CHARM, SHiP future)



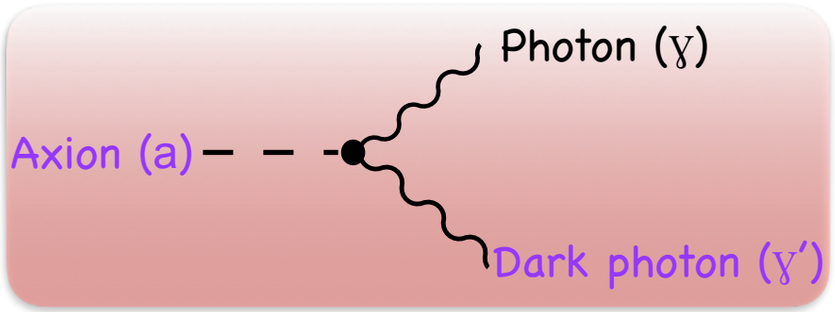


Production



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).



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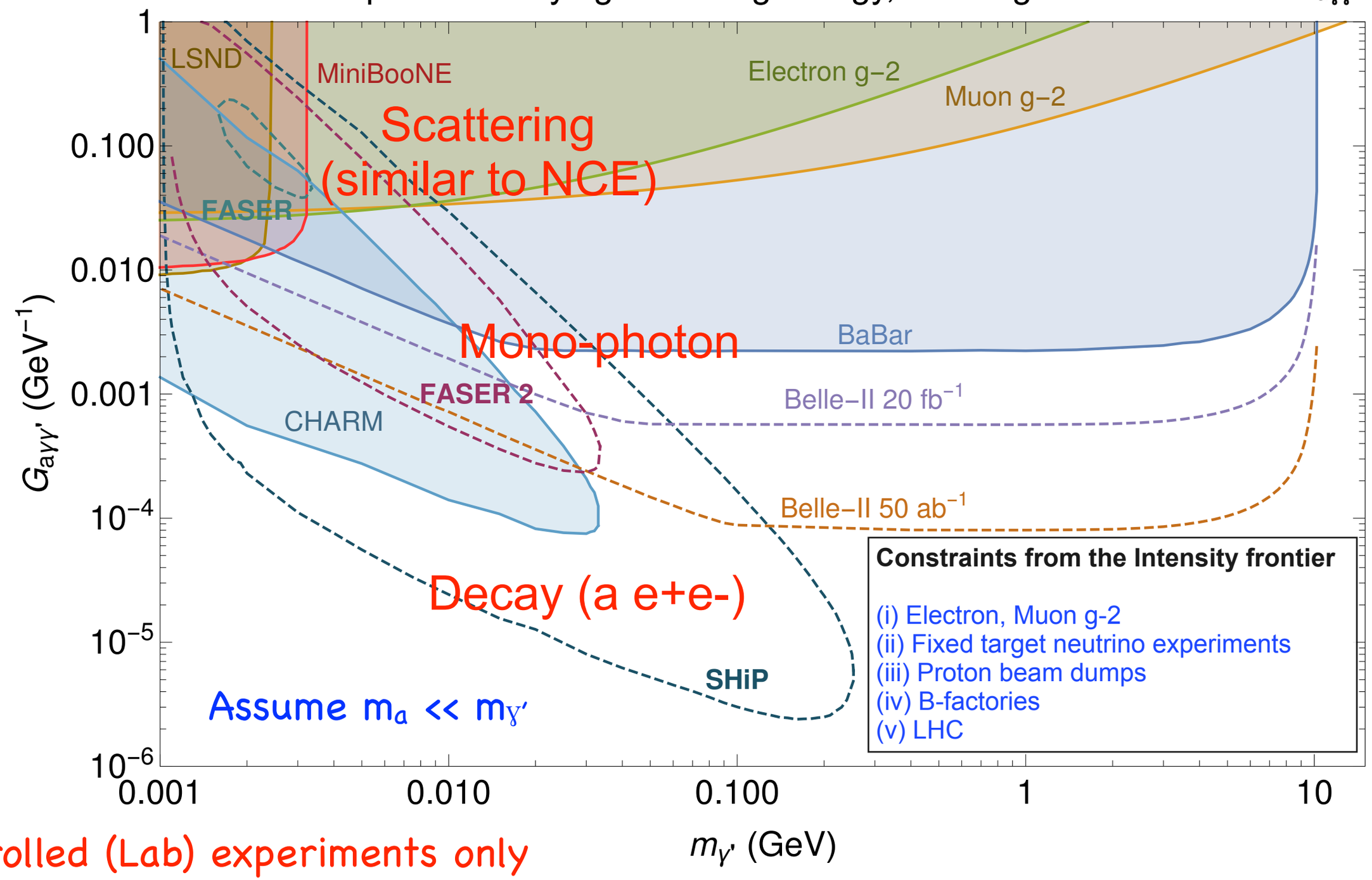
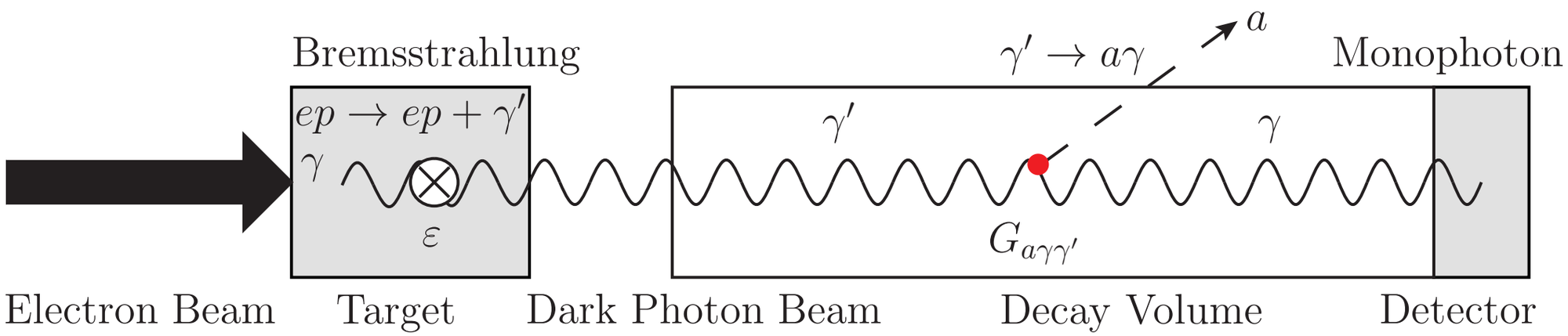


Controlled (Lab) experiments only

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

[deNiverville, LEE (2019)]



Promising direction of the new experiments for a dark photon search:
Production of dark photon through the vector portal (Bremsstrahlung), and decay to the mono-photon through the dark axion portal (γ'$\rightarrow \gamma$+a).

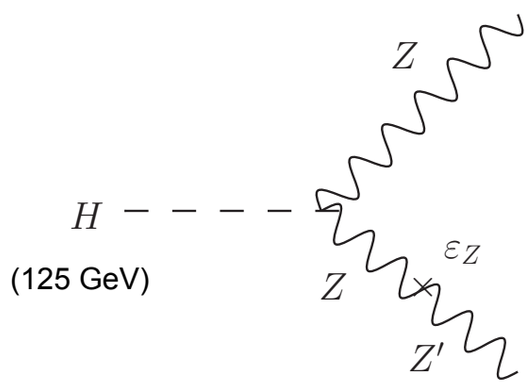
(Design study is called for.)

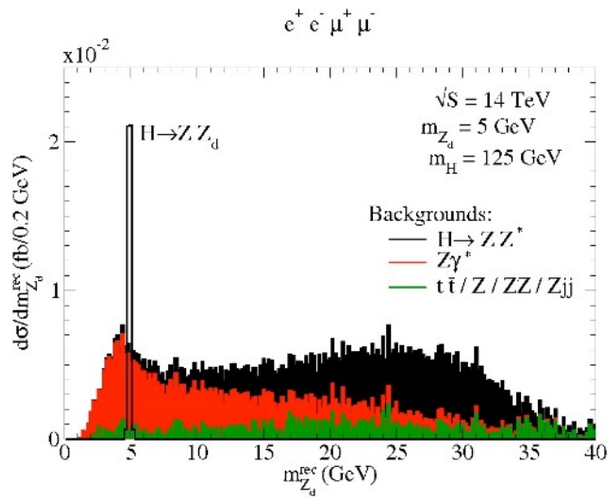
Dark Axion Portal at the LHC (Energy Frontier)?

There are models which have a dark photon (or its variant) in the final states.
Searched for in "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



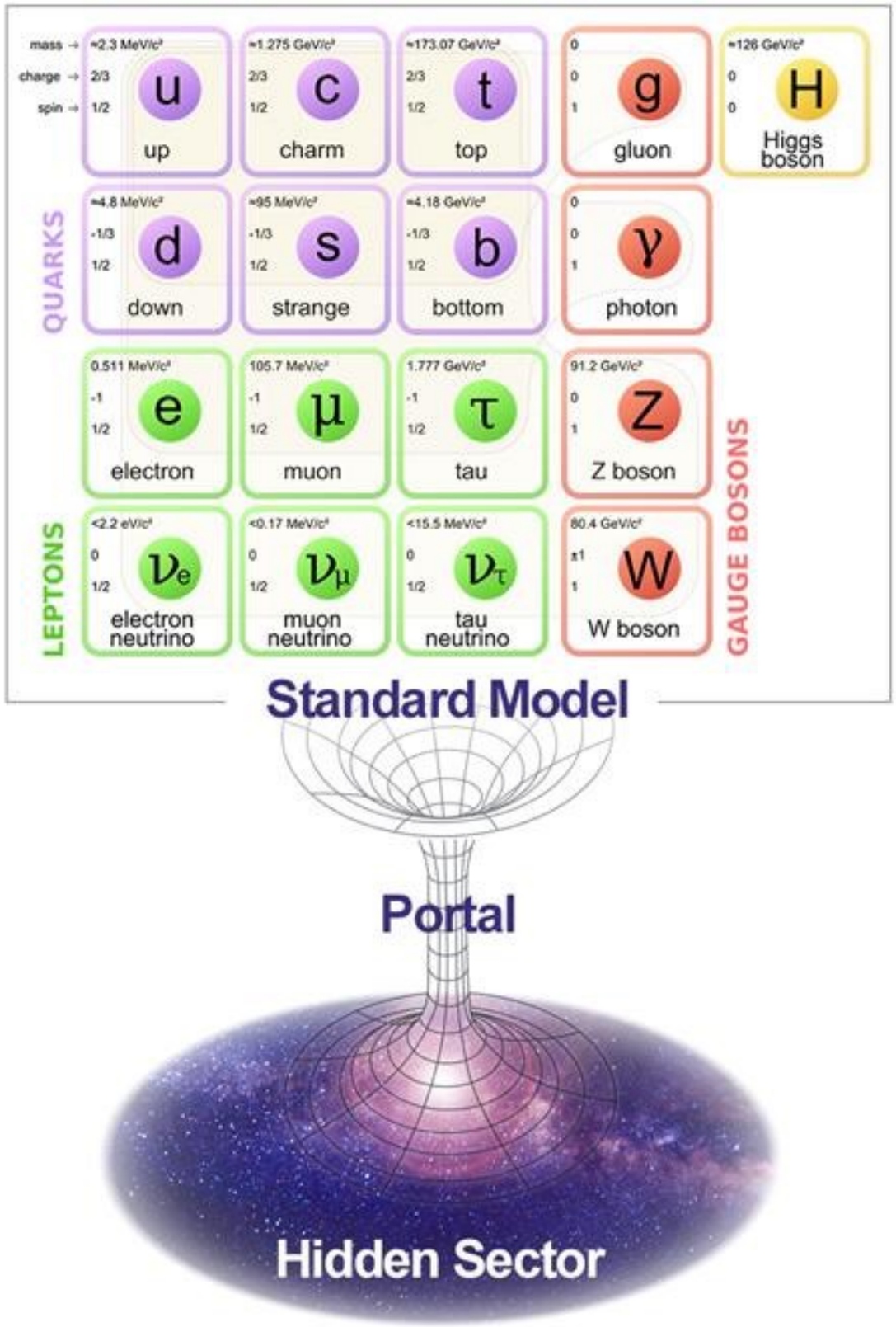


[Davoudiasl, LEE, Lewis, Marciano (2013)]

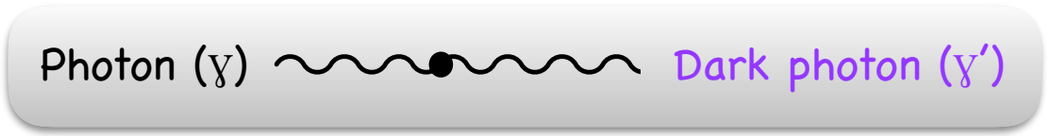
Depending on the model, the decay modes to dark photon can dominate.
(ex) top-partner $\longrightarrow$ top + γ' as the dominant decay mode (followed by $\gamma' \longrightarrow \ell^+\ell^-$).
[JH Kim, Lane, LEE, Lewis, Sullivan (2019)]

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

Summary

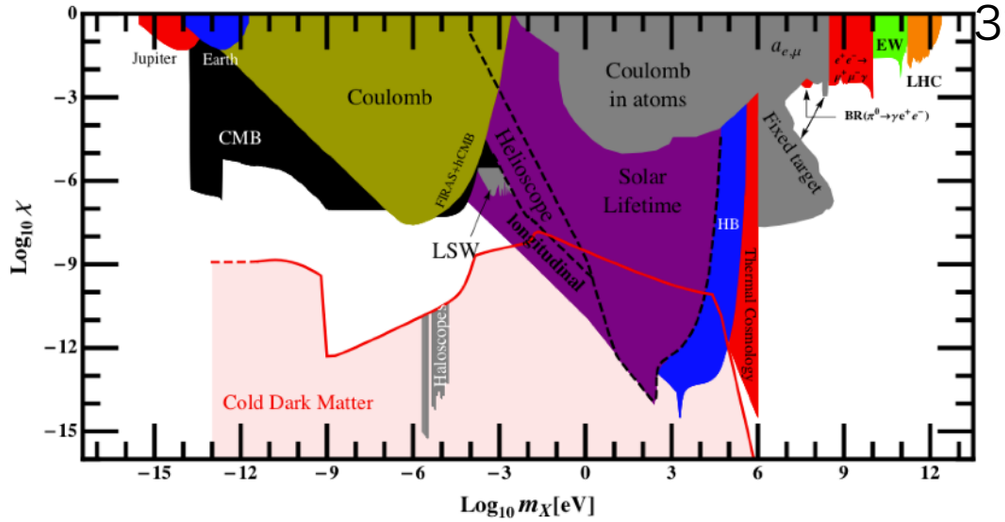


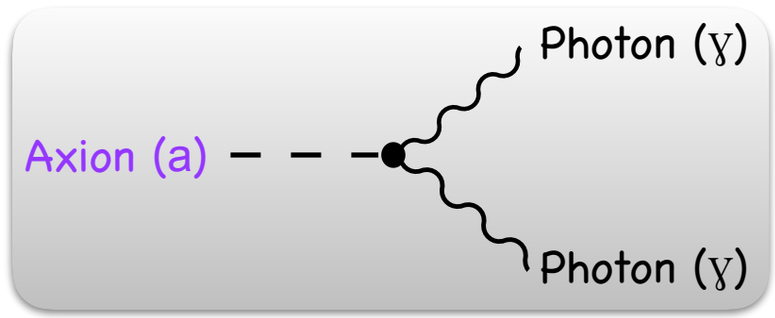
Dark sector could be investigated through portals.



vector portal (ε)

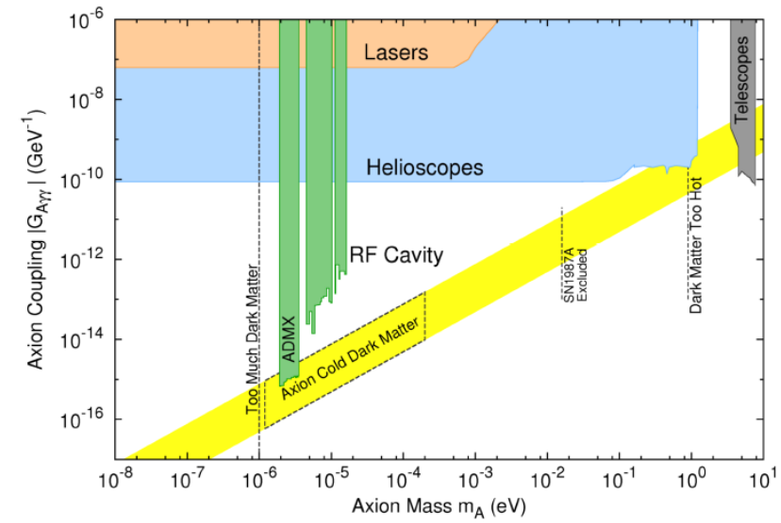
(ex) Holdom (1986): 1100+ citations (used in actual searches)

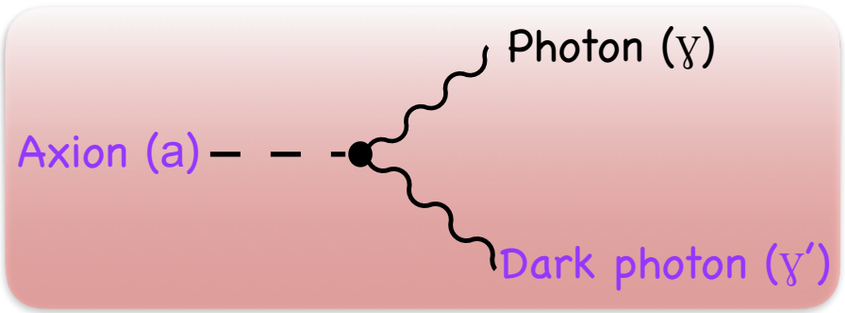




axion portal ($G_{a\gamma\gamma}$)

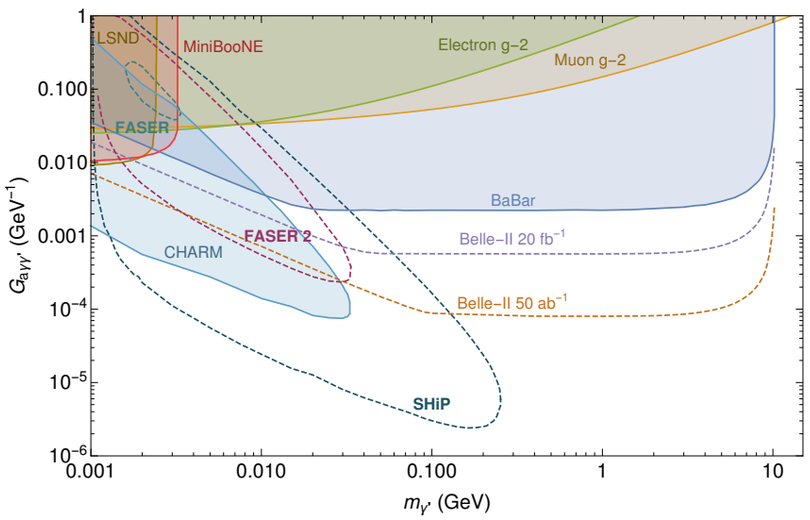
(ex) Sikivie (1983): 1000+ citations (used in actual searches)





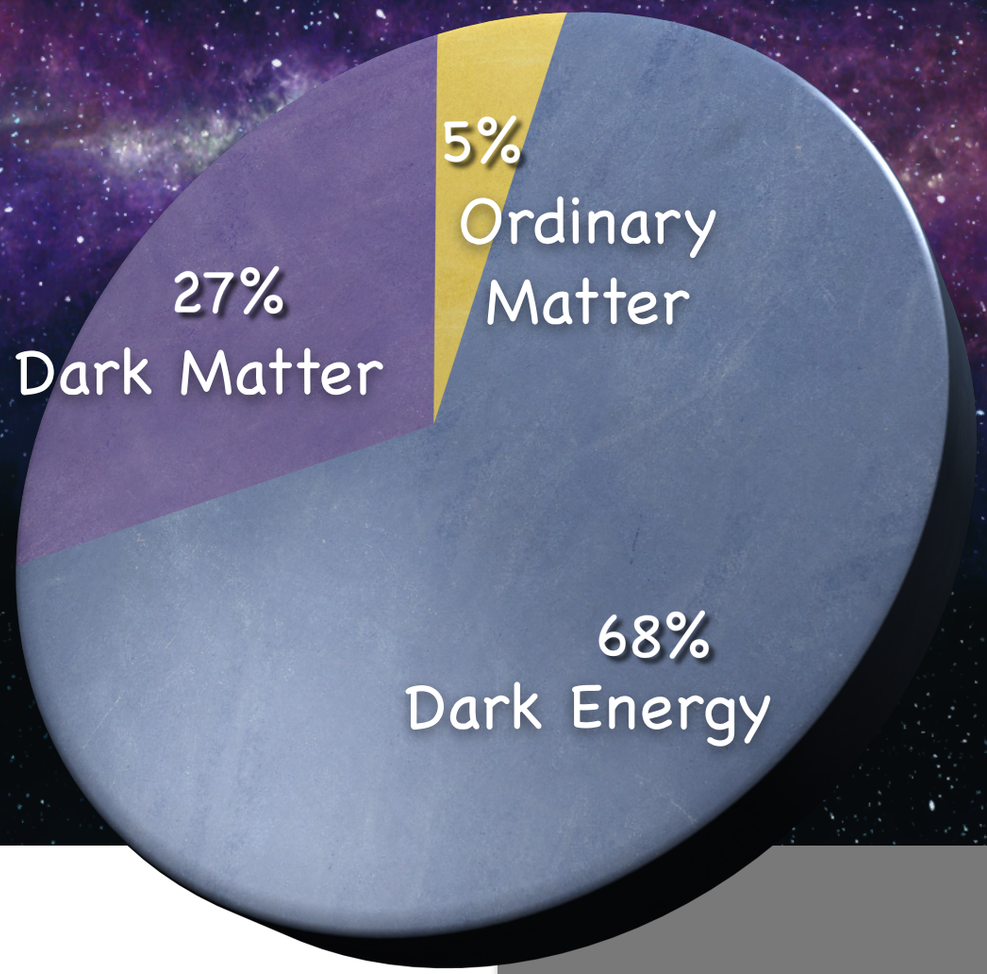
dark axion portal ($G_{a\gamma\gamma'}$)

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

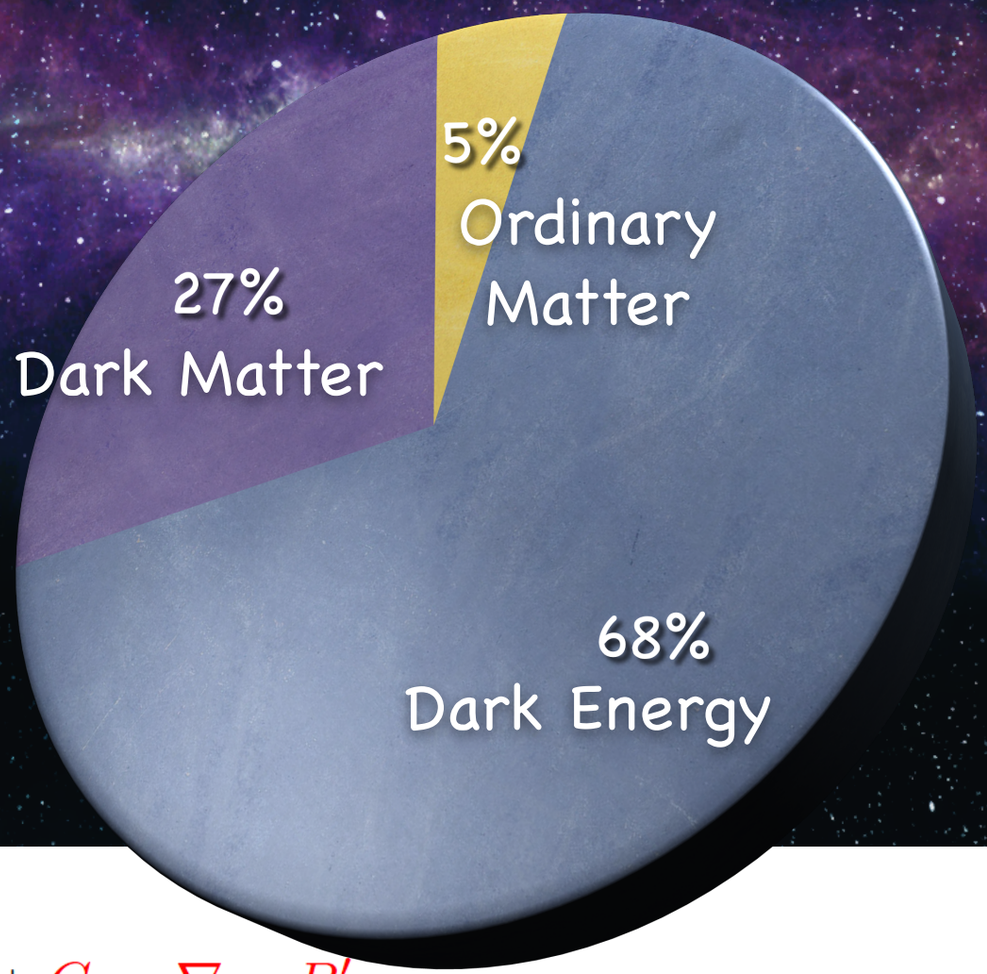


$$\nabla \cdot \vec{E} = \rho$$
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{B} = \vec{J} + \frac{\partial \vec{E}}{\partial t}$$

Bright sector

Dark sector

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 -