Dark Photon Coupling to Charged Leptons
- A Theorist's View -

BSM Workshop, Puerto Rico, May 22, 2018

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Outline

Motivations

Searches for visibly decaying dark photon

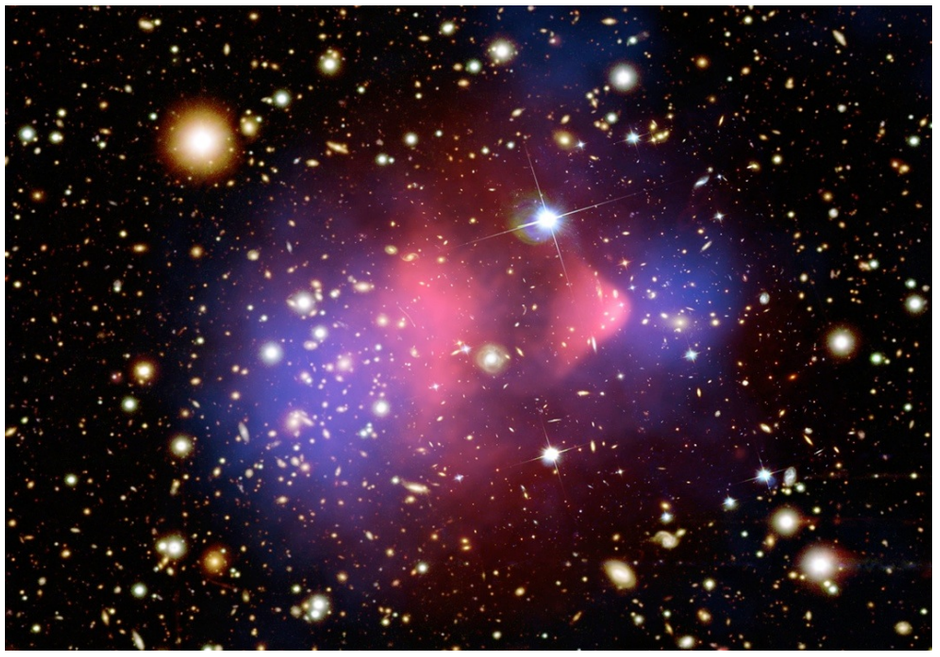
Dark matter connection

Muon g-2 connection

Dark Matter Exists In Nature

Overwhelming evidence from cosmological data.

- Galactic rotational curves
- Bullet cluster
- Large scale structure
- CMB



Curious questions:

Is dark matter a particle? Can it be detected in labs?

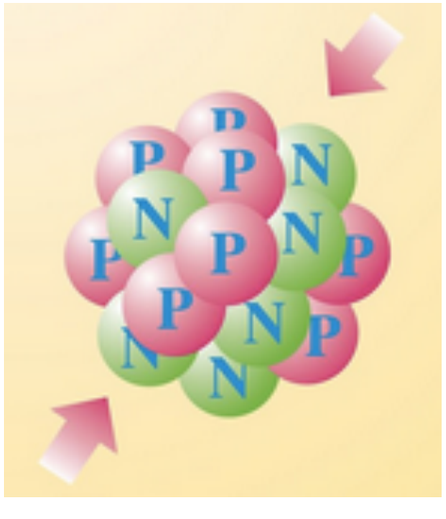
How does it interact?

The Elusive Dark Matter

Gravity

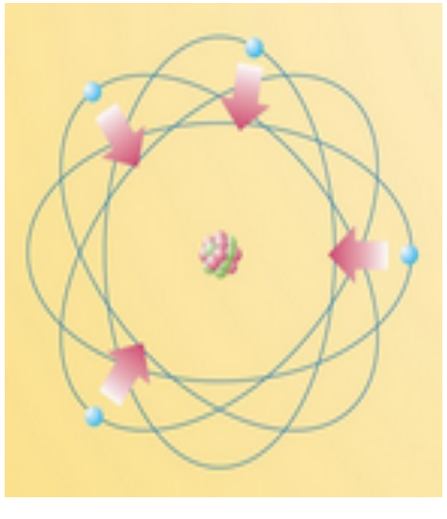
Yes, this is how we knew it exists.

Strong



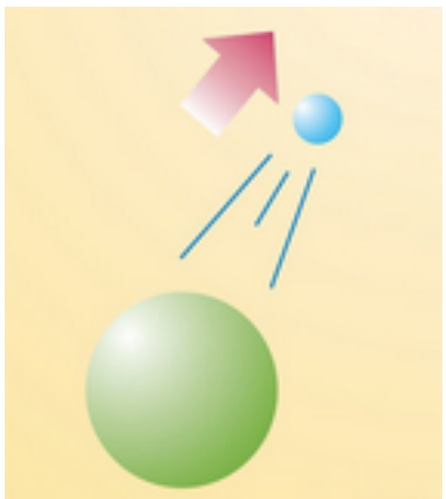
No

E&M



no

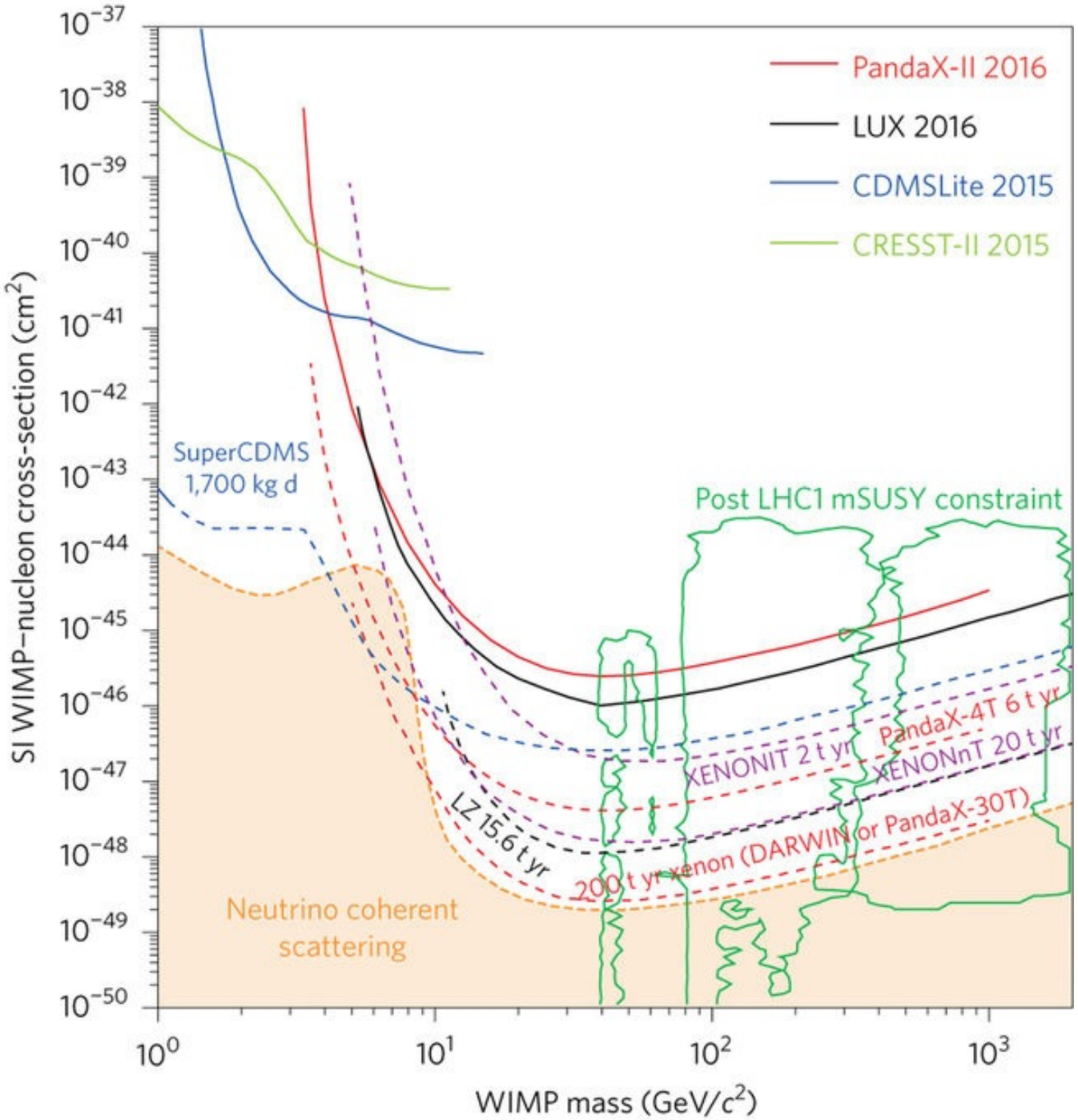
Weak



Maybe.

WIMP dark matter has been widely explored in the past decade.

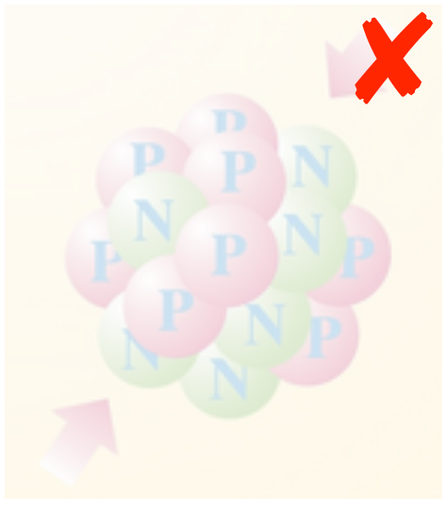
A Drought of Discovery



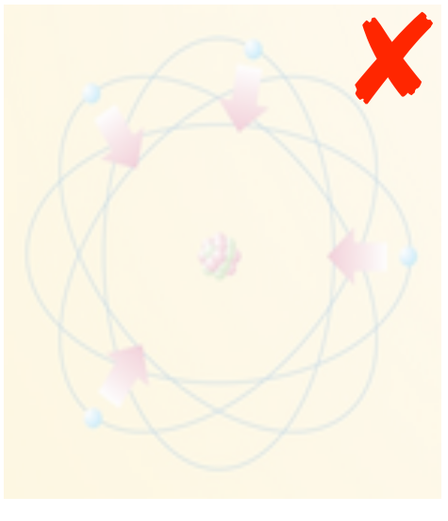
New Force in the Dark

Gravity

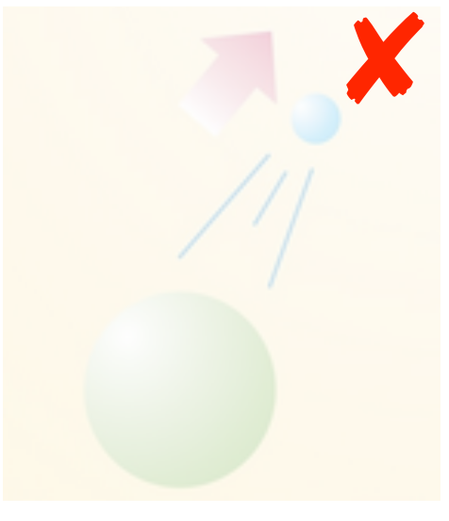
Strong



E&M



Weak

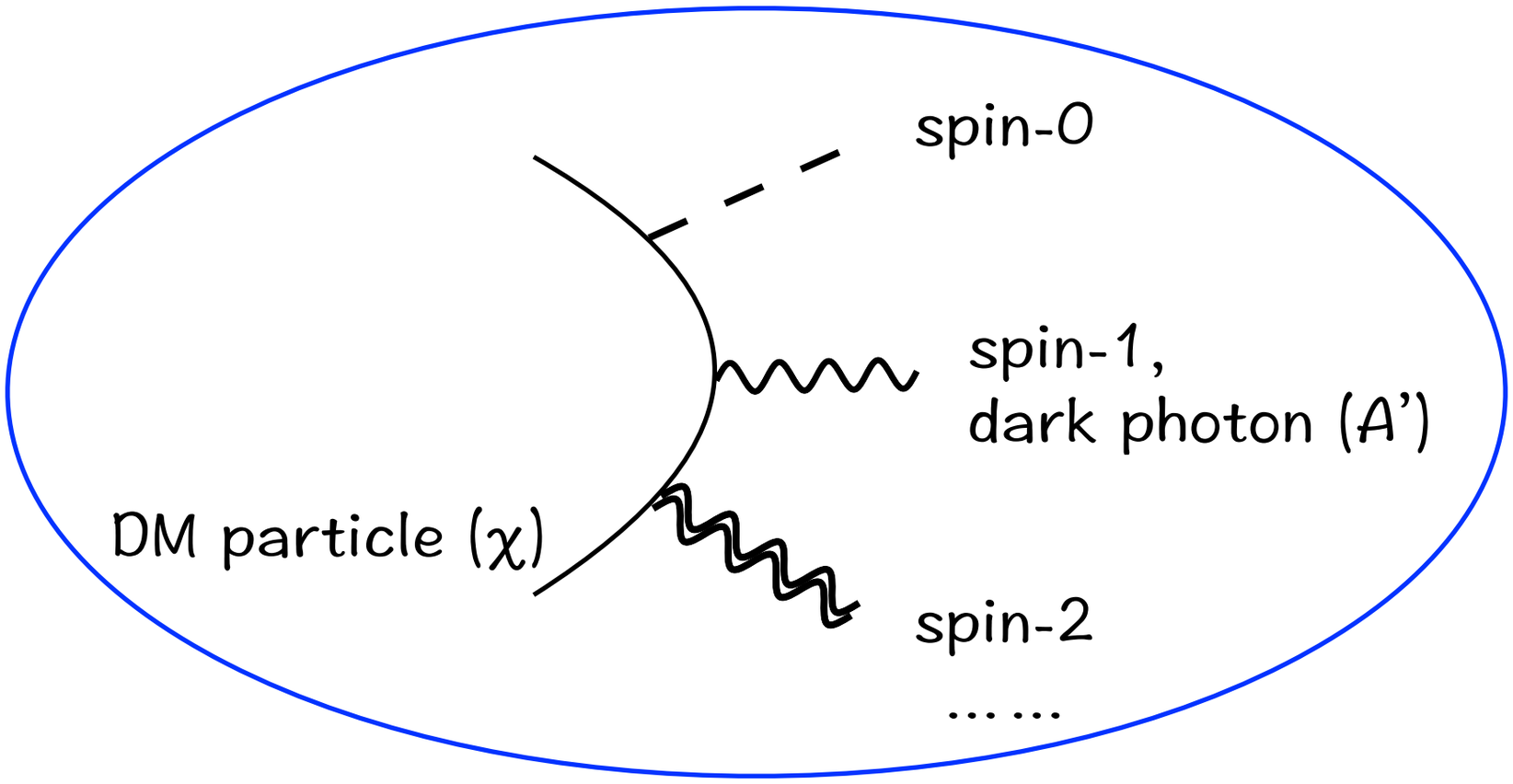


dark forces

Dark matter + dark force = Dark Sector

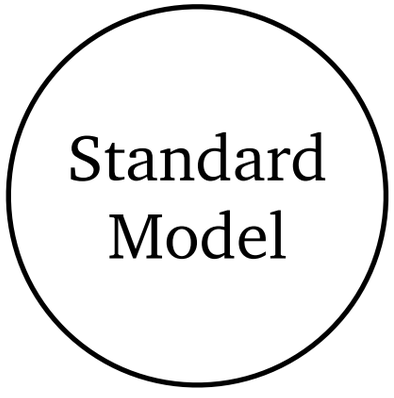
Plausible, think of how rich the physics in SM sector is, and $\Omega_{DM} \sim 5\Omega_{baryon}$

Welcome to the Dark Sector

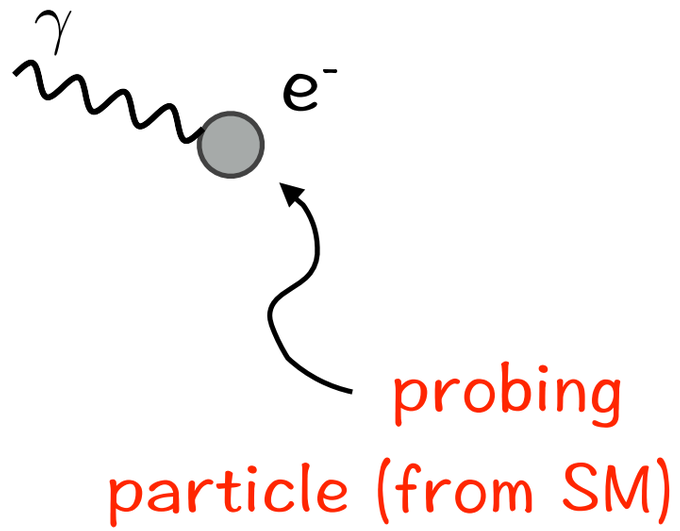


Two sectors:

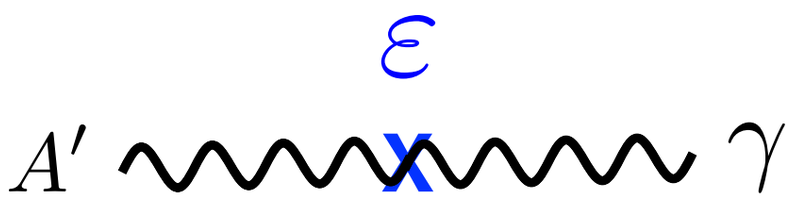
Gauge singlets with respect to each other.



Dark Photon as a Hair of Dark Sector



Gauge kinetic mixing $\varepsilon F'_{\mu\nu} F^{\mu\nu}$

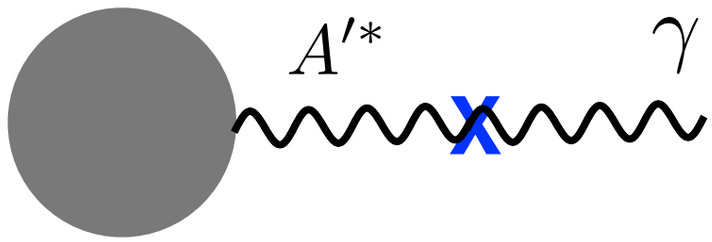


Features of Kinetic Mixing

I will assume *A'* to be massive in most of the talk.

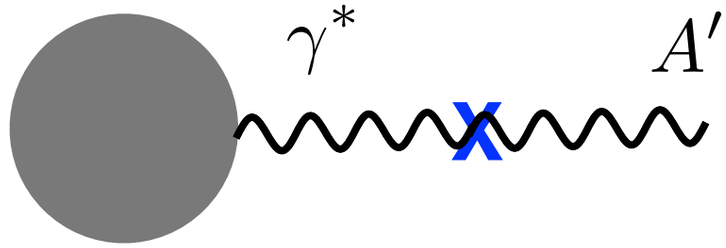
The SM photon created from this mixing cannot be on-shell, could only turn into charged pairs.

$$F_{\mu\nu}F'^{\mu\nu} \to q^2\epsilon\cdot\epsilon' - (q\cdot\epsilon)(q\cdot\epsilon')$$



$$\mathcal{M} \propto \frac{1}{q^2 - m_{A'}^2}\varepsilon q^2 \to 0$$

(On-shell photon $q^2=0$)



$$\mathcal{M} \propto \frac{1}{q^2}\varepsilon q^2 \neq 0$$

(On-shell dark photon $q^2=m_{A'}^2$)

Subtlety In $m_{A'}^2 \to 0$ Limit

A' production in high energy experiments

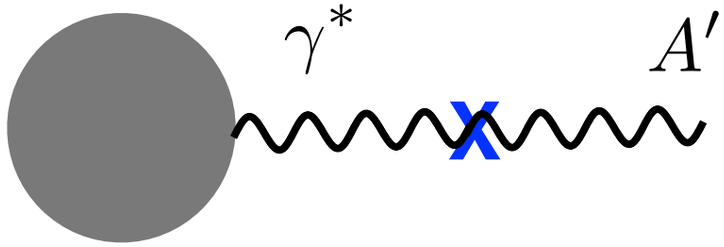
Low energy tests of Coulomb $1/r$

$$\sigma \sim \alpha(1 + \varepsilon^2 + \cdots) \qquad\qquad \mathcal{M} \propto \alpha(1 + \varepsilon^2 + \cdots)$$

Thus if $m_{A'}$ is small enough to fool all our experiments, can redefine α so that A' decouples.

No decoupling if dark electrons are around, milli-charged particles.

Features of Kinetic Mixing



$$\mathcal{M} \propto \frac{1}{q^2} \varepsilon q^2 \neq 0$$ (Valid for generic q^2)

For massive *A*', it effectively couples to SM particles as

$$\varepsilon e A'_\mu J^\mu_{\mathrm{EM}}$$

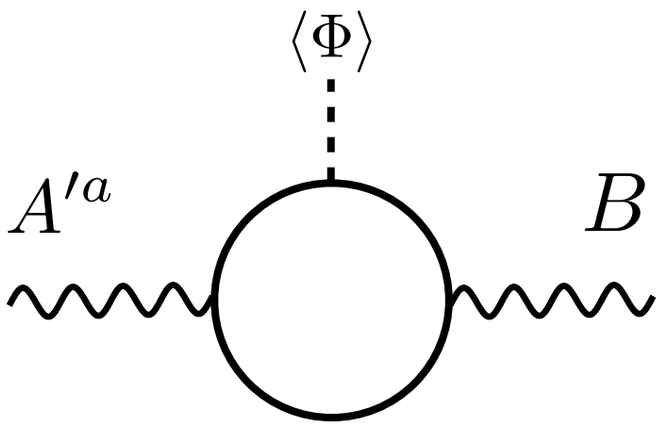
Simple BSM model, one new particle and two parameters:

$$\varepsilon \qquad\qquad m_{A'}$$

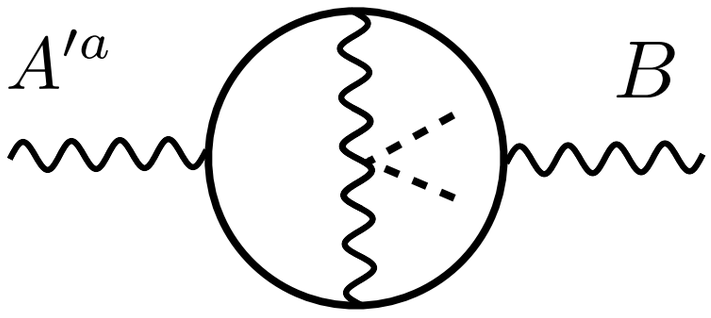
Origin of the Kinetic Mixing

If the dark $U(1)_D$ symmetry is fundamental, then the kinetic mixing with SM $U(1)_Y$ is gauge invariant, ε exists in UV.

If $U(1)_D$ from $SU(N)_D$ breaking at higher scales, no ε in the UV. Generated by particle loops charged under $SU(N)_D$ and $U(1)_Y$.



$\mathrm{Tr}(T^a\Phi)F'^a_{\mu\nu}B_{\mu\nu}$

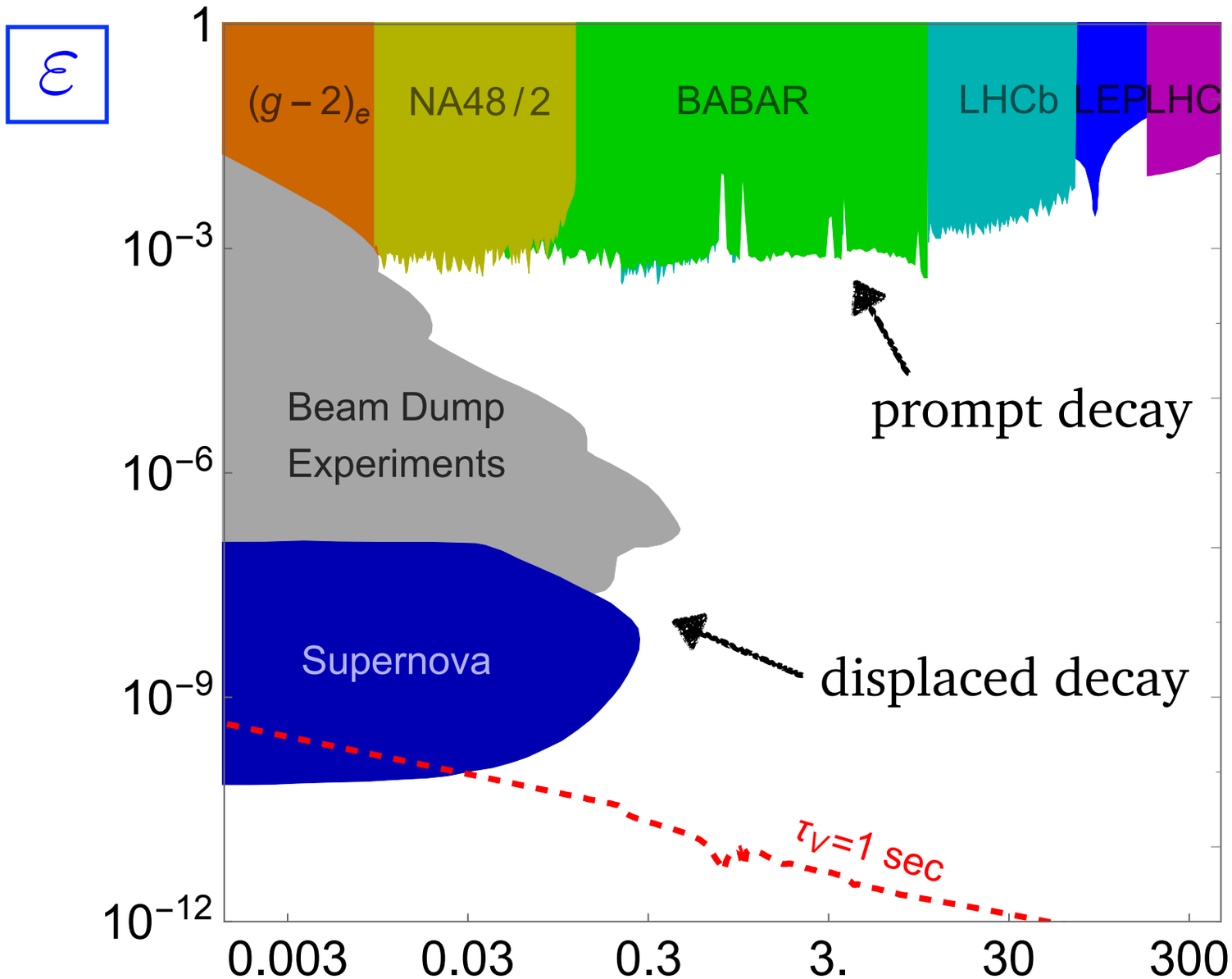


$\mathrm{Tr}(T^aT^bT^c)F'^a_{\mu\nu}B^{\mu\nu}F\left(m^2_{a,b}(\Phi^2)\right) \propto \Phi^2 d_{bc8}$

$$\varepsilon \sim (16\pi^2)^{-1} e g_D, \quad \text{or} \quad (16\pi^2)^{-2} e g_D^3$$

Status of Dark Photon Search

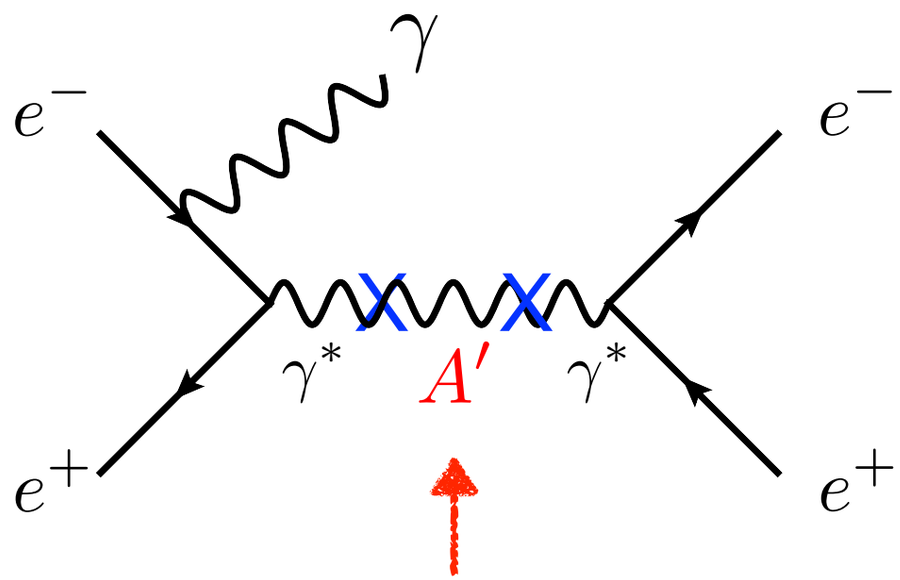
Existing constraints (colored regions excluded)



- Assume *A'* decays back to SM particles.
- Heavier than 100GeV, usual Z' search
- Lighter than MeV, cosmologically long lived dark photon

Prompt Dark Photon

BaBar: production via radiative return, prompt decay



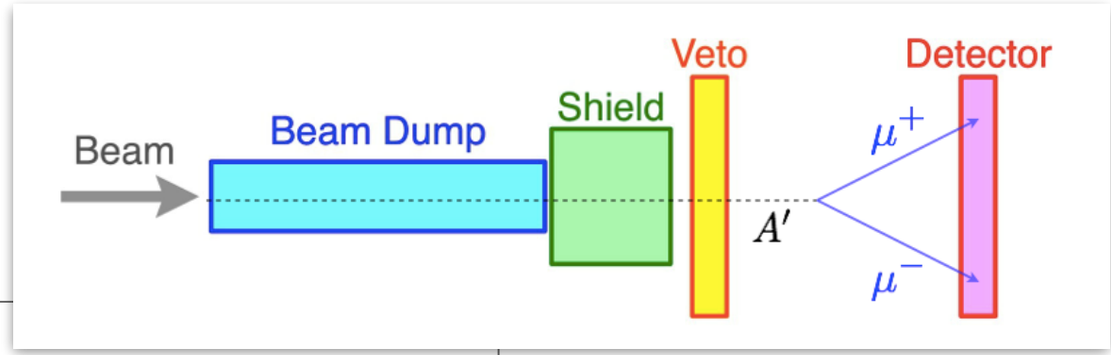
Search for resonance in dilepton invariant mass (bump hunt).

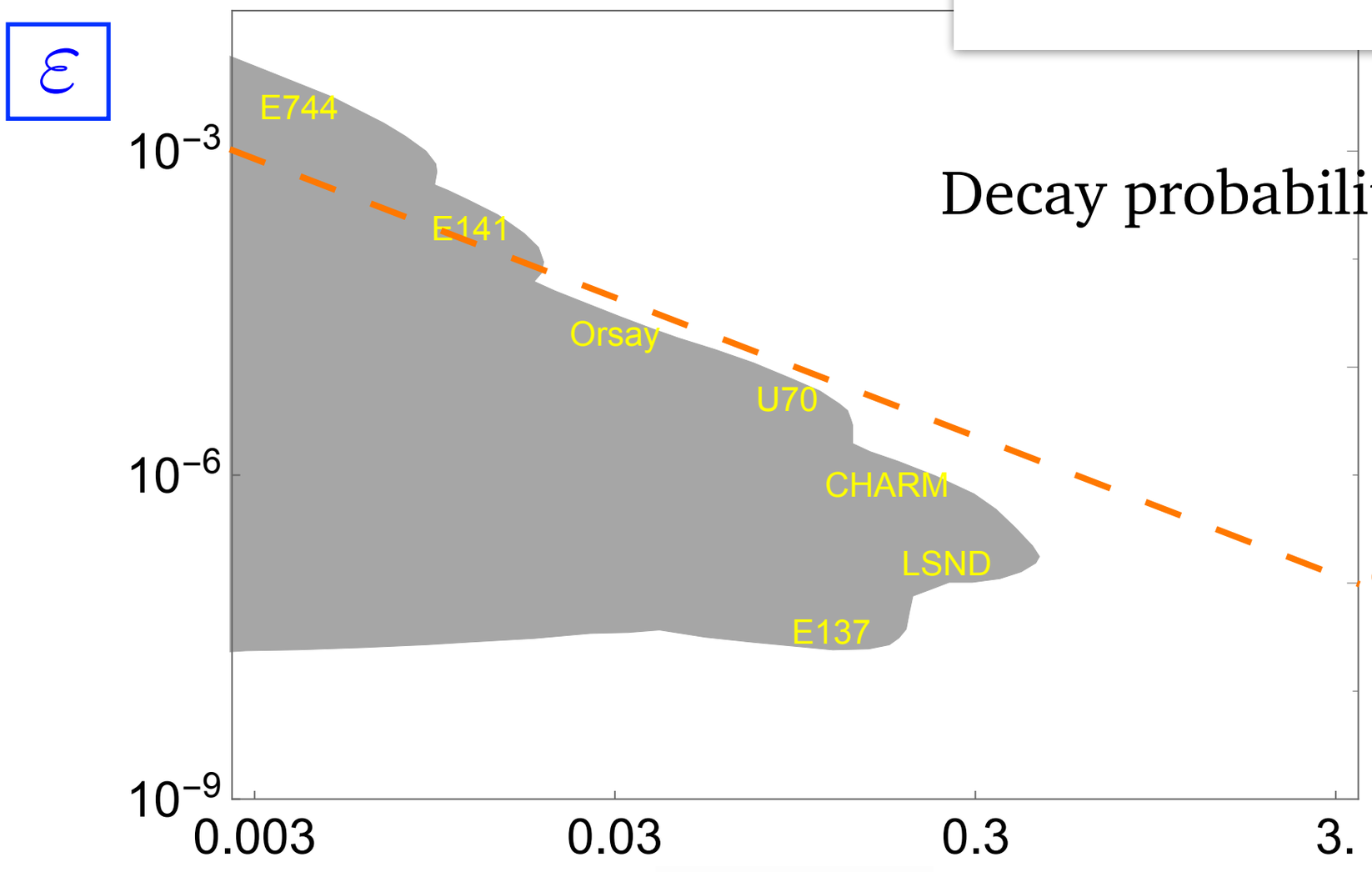
Current limit: $\varepsilon < 10^{-3}$, for $50\,\mathrm{MeV} \lesssim m_{A'} \lesssim 10\,\mathrm{GeV}$

BaBar collaboration (2014)

Displaced Dark Photon

Fixed-target experiments:





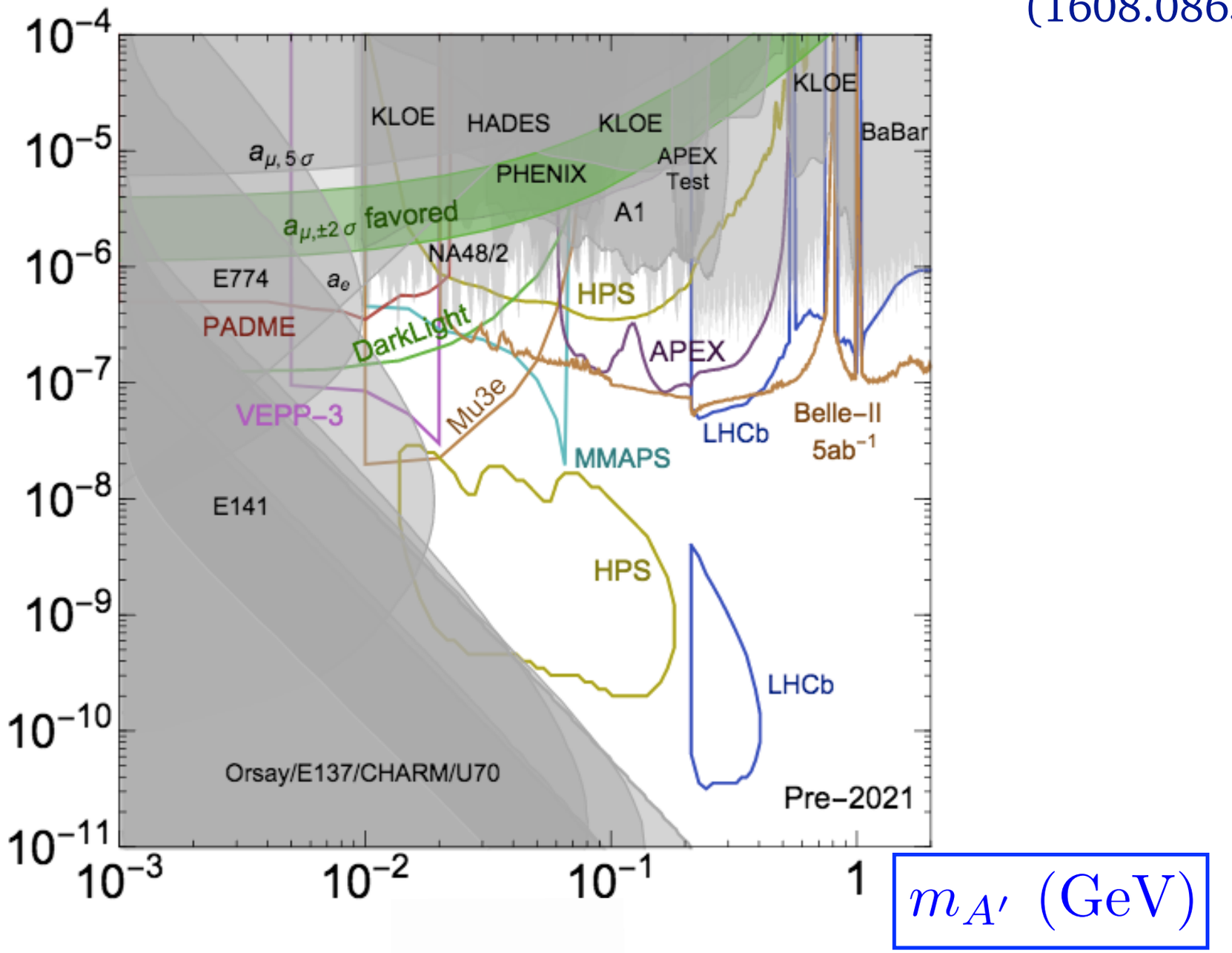
Decay probability: $\sim \frac{L_D}{\gamma c\tau} \propto \varepsilon^2 m_{A'}^2$

decay length = constant

Status of Dark Photon Search

The near future (before 2021)

Dark Sectors Community Report (1608.08632)



How about dark matter?

The main motivation for scrutinizing dark photon physics.

Two possibilities:

- Dark photon mediates interaction between DM and SM particles; And serves as a dark force.
- Dark photon itself could be a DM candidate.

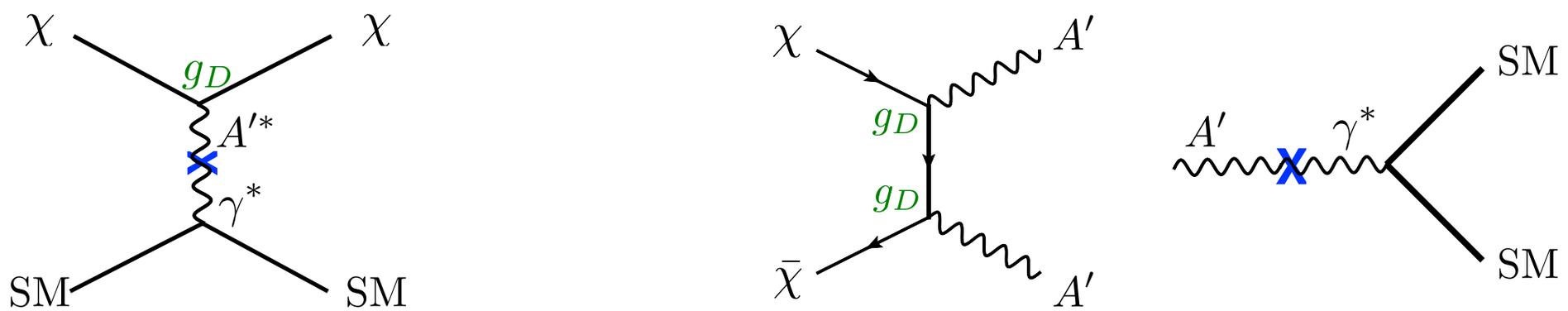
Opportunity to explore both dark matter and dark photon.

Taking dark matter into account can have a strong impact on the dark photon search.

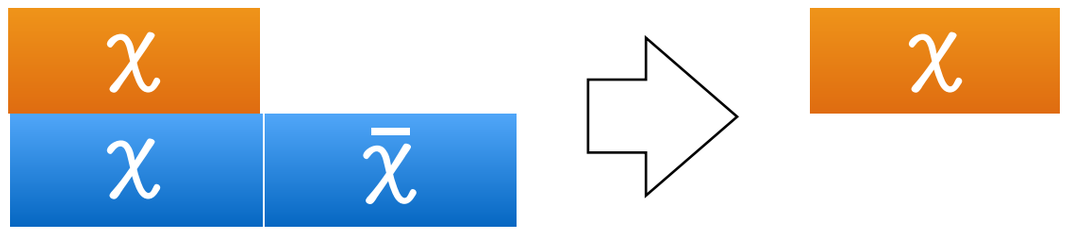
Dark photon couples to dark matter

Dark Photon as a Dark Force

Secluded DM ($m_{A'}<m_{\chi}$): motivated by indirect detection anomalies:
Time scale for each detection process to occur can be quite different.



Asymmetric DM: $\Omega_{DM}\sim 5\Omega_{baryon}$, naturally expect DM mass ~5GeV.
Require a light dark photon to efficiently deplete symmetric relics in early universe.

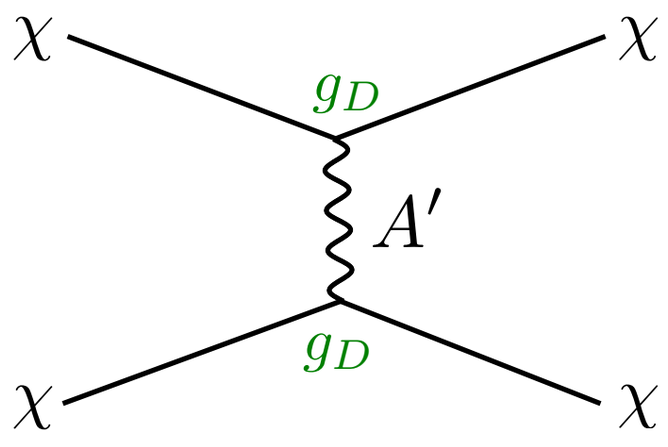


Dark Photon as a Dark Force

Dwarf galaxies: core/cusp problem? Simulations with WIMP gives cusp; Self interaction can yield core. A controversial topic, but viewed as a hint for special dark matter properties.

$$\sigma_{\chi\chi\to\chi\chi} = 1\ barn$$ Spergel, Steinhardt (1999)

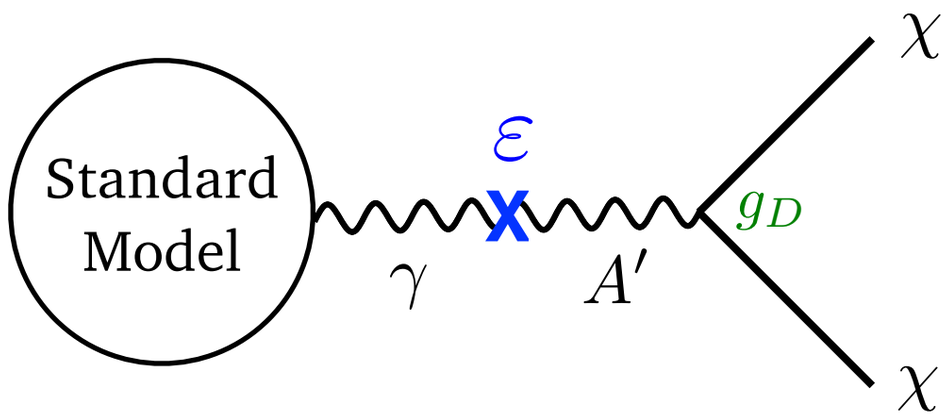
Large cross section at low velocity through light dark photon exchange.



For a recent review, see Tulin, Yu (2017)

Strawman Model

All of these reasons point to a simple dark sector (dark QED)



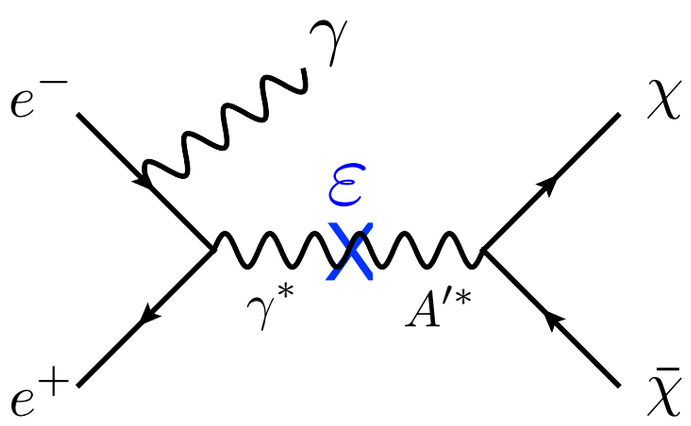
Simple setup: dark photon = mediator = dark force

With a particle spectrum, $m_\chi > m_{A'}$, *A*’ does not decay into χ, so the visible dark photon limits shown earlier still hold.

With dark matter, new signatures become available.

Light Dark Matter at B Factories

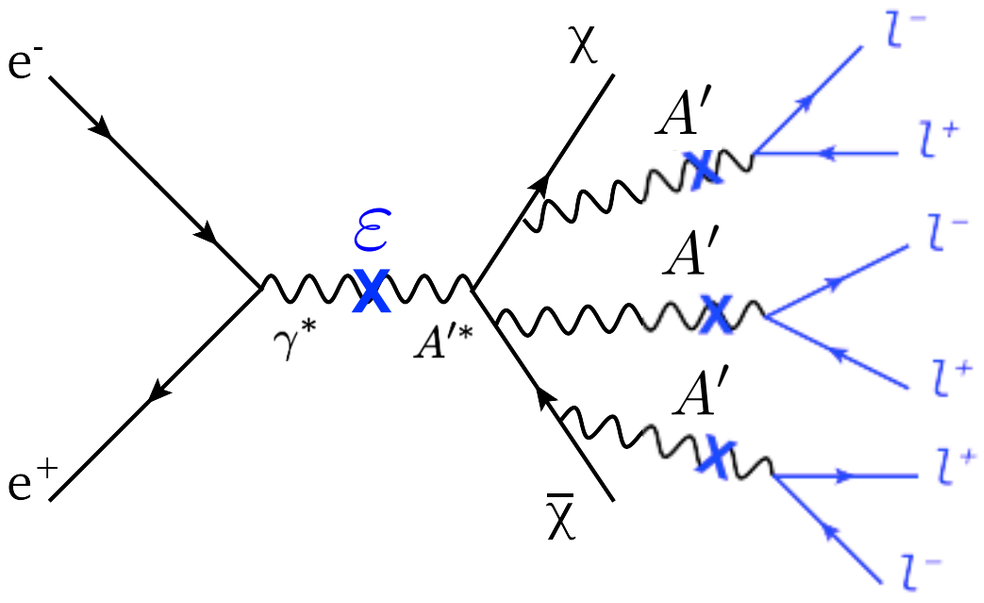
Missing energy signals from dark matter:



Mono-photon from ISR

Limit from BaBar: $\kappa g_D \lesssim 10^{-2} - 10^{-1}$

Essig, Mardon, Papucci, Volansky, Zhong (1309.5084)



Having dark photon FSR can help

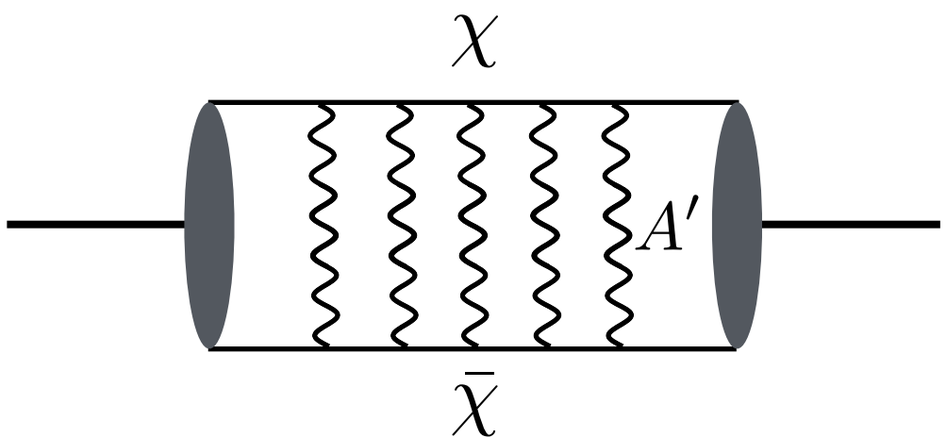
Large α_D makes it more likely,

$$\sigma_{e^+e^- \to \chi\bar{\chi}+nA'} \propto \alpha_D^{n+1}$$

An, Echenard, Pospelov, **YZ** (1510.05020, PRL)

Dark Matter Bound States

A natural consequence: Dark force makes bound states.



Dark Matter Bound State

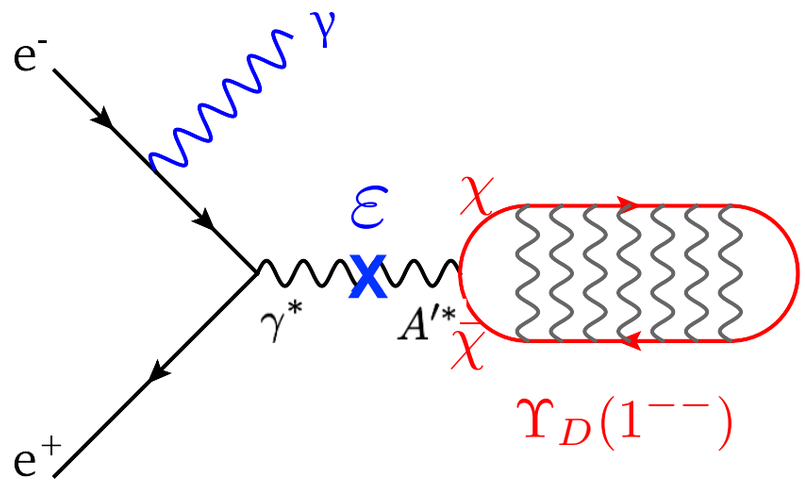
The dark analog of positronium

$(\alpha_D m_\chi)^{-1} \lesssim m_{A'}^{-1}$ (Bohr radius < Size of potential well)

Probing dark force in labs: produce DM pairs, put them together for long enough, let them interact with each other.

Dark Matter Bound States @ BaBar

The dark Upsilon, produced the same way as the SM Upsilon, but decays within dark sector first.



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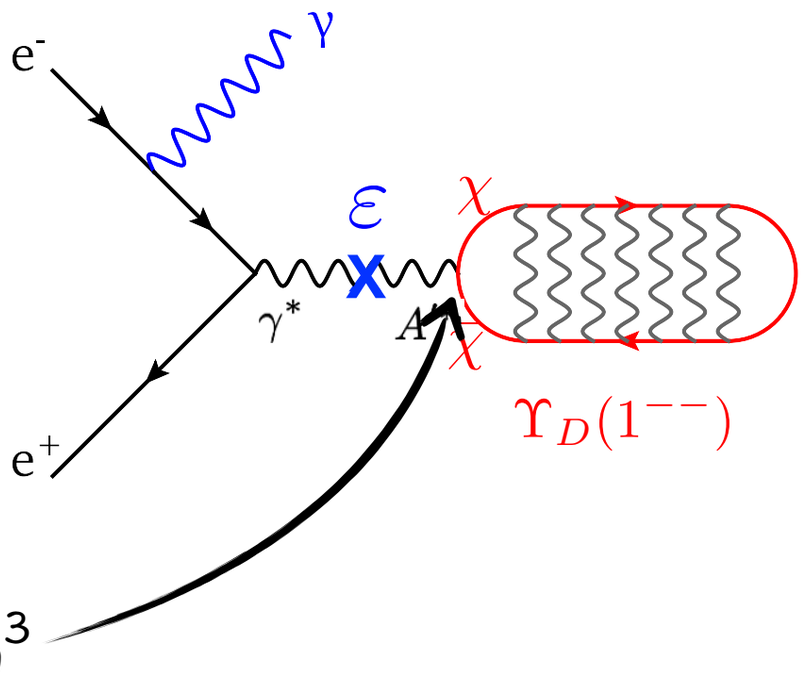

important when α_D is large

An, Echenard, Pospelov, **YZ** (1510.05020, PRL)

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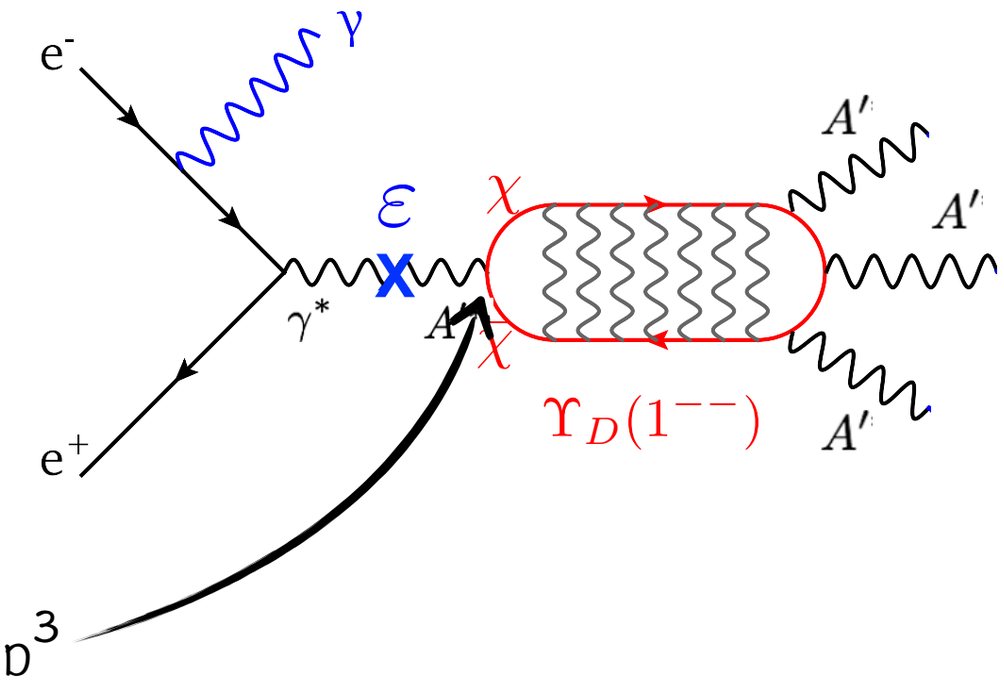

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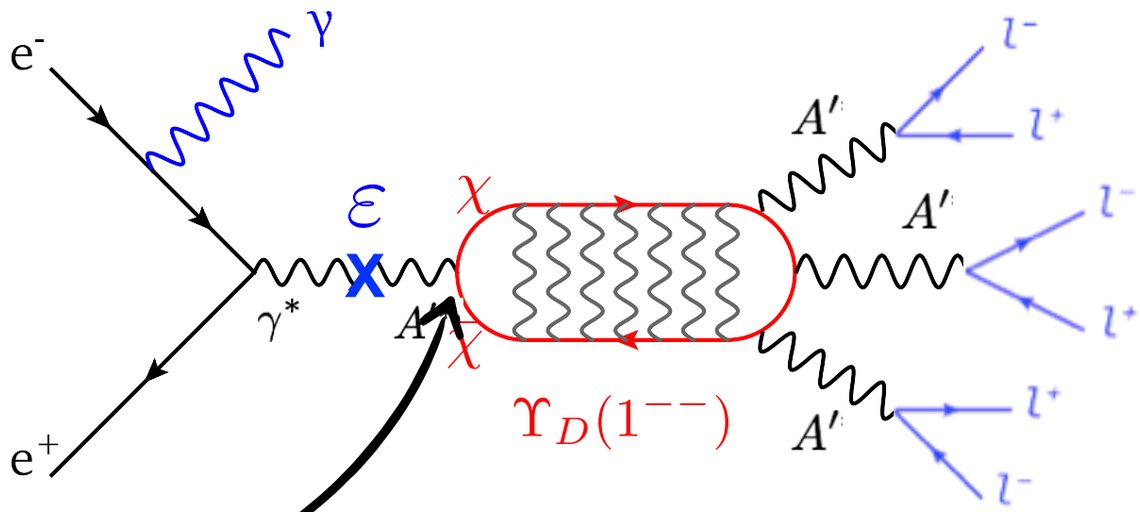


$|\Psi(0)|^2 \sim \alpha_D^3$

important when α_D is large

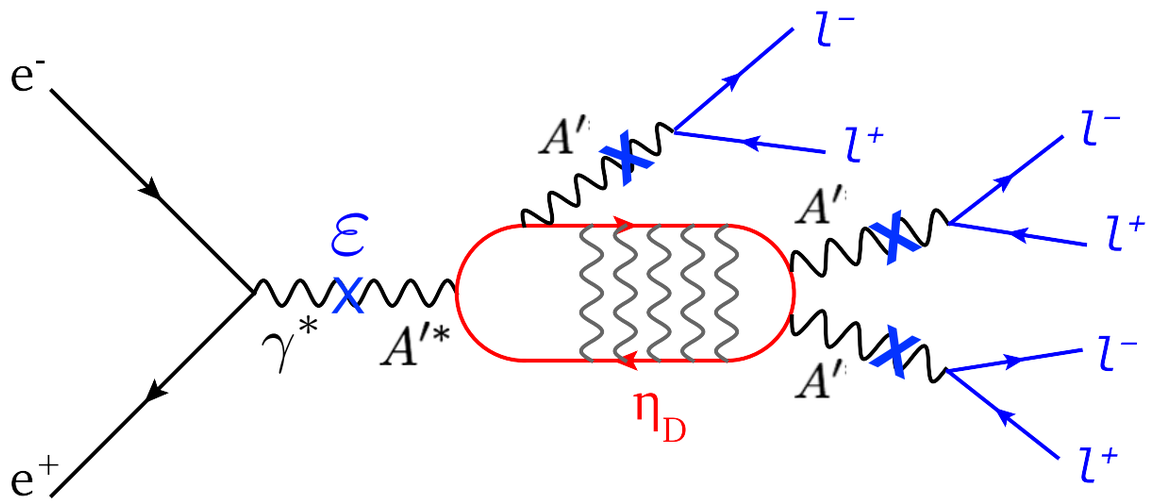
6 charged track: very low SM background

An, Echenard, Pospelov, **YZ** (1510.05020, PRL)

Dark Matter Bound States @ BaBar

For fermionic DM, two nearly-degenerate ground states

$$\Upsilon_D\ (J^{PC} = 1^{--}) \qquad \eta_D\ (J^{PC} = 0^{-+})$$

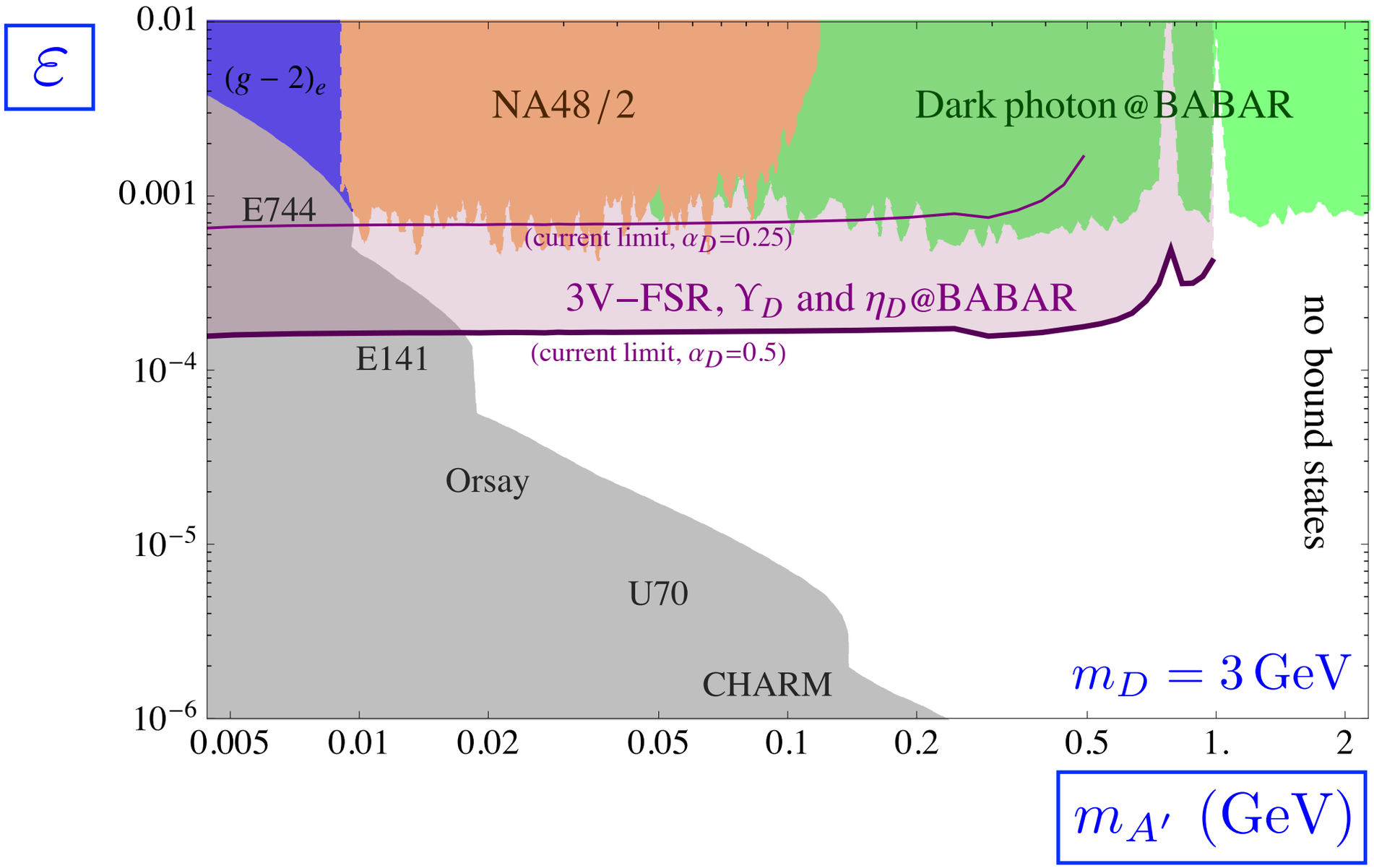


Again, 6-charged track final states. We derive new limits based on existing Babar data by combining the two channels.

An, Echenard, Pospelov, **YZ** (1510.05020, PRL)

New BaBar Limit and Beyond

Stronger limit from Υ_D, η_D channels (6ℓ resonance), if $\alpha_D > 0.25$



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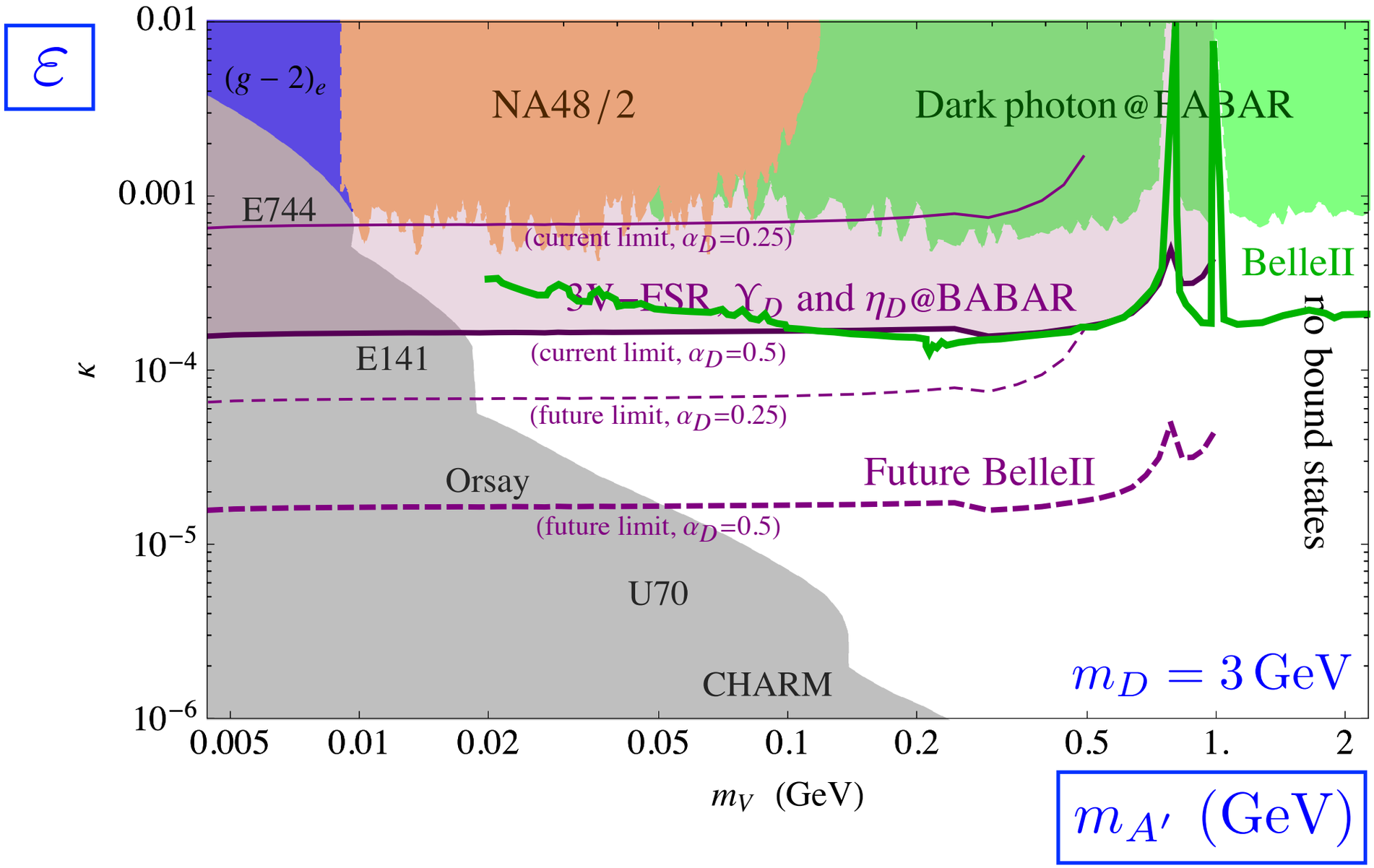
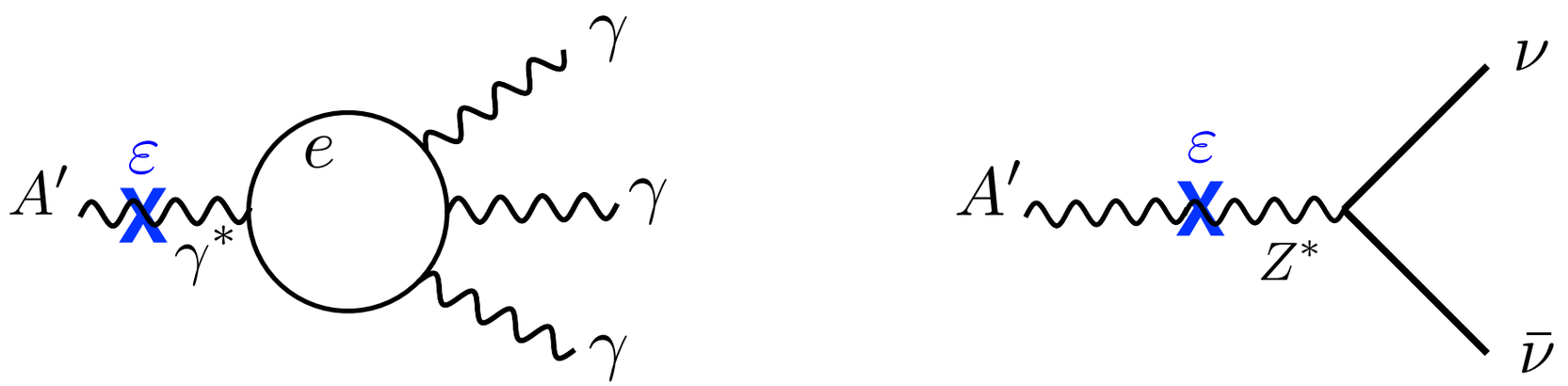


An, Echenard, Pospelov, **YZ** (1510.05020, PRL)

Dark photon itself as dark matter

Dark Photon Itself as Dark Matter

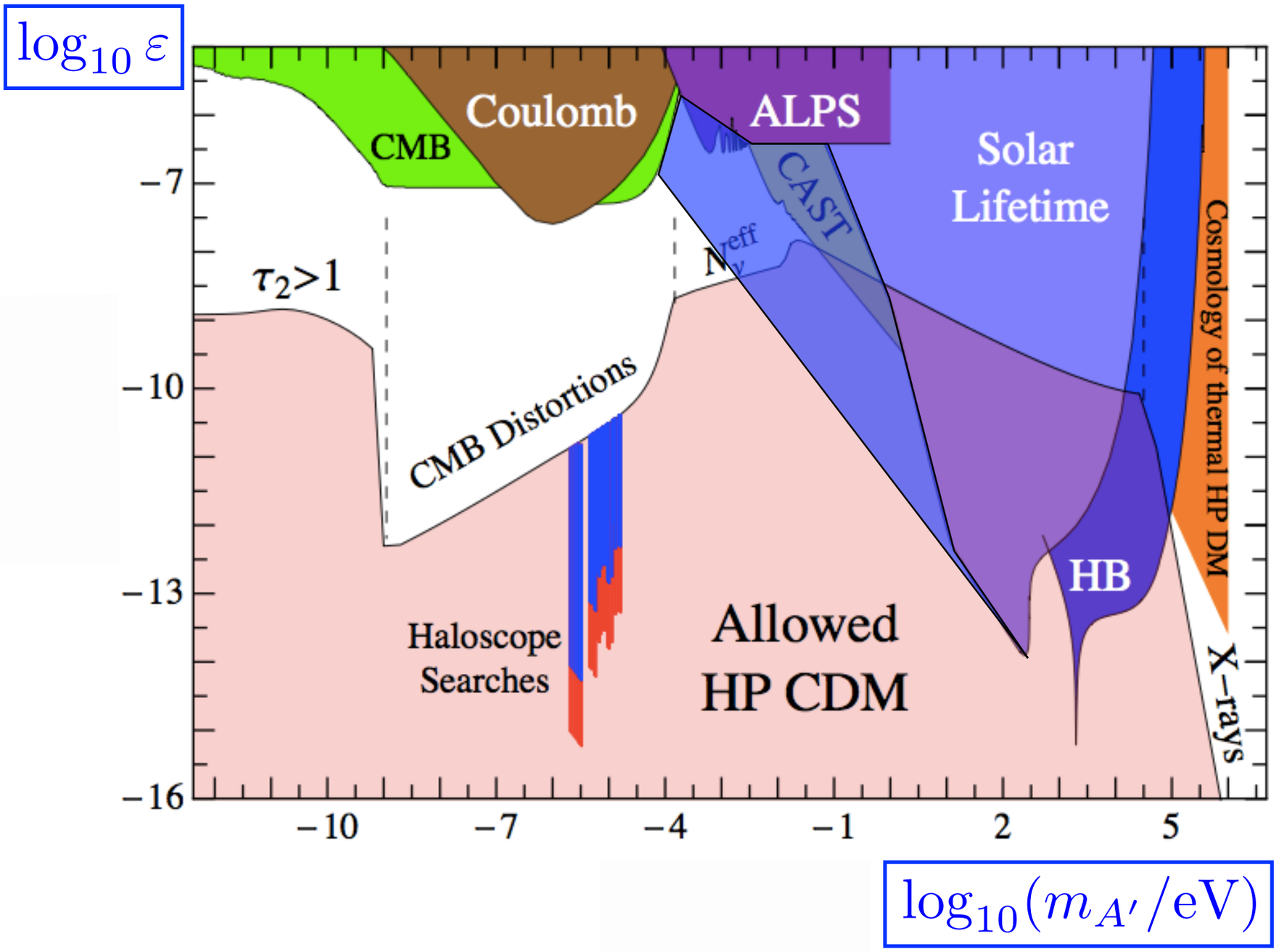
Minimalistic approach: dark photon becomes cosmological stable if much lighter than MeV scale.



$$\tau_{A'\to 3\gamma} \sim \frac{1}{\alpha^4\varepsilon^2}\frac{m_e^8}{m_{A'}^9} \sim 10^{26}\,\mathrm{sec}\left(\frac{10^{-7}}{\varepsilon}\right)^2\left(\frac{1\,\mathrm{keV}}{m_{A'}}\right)^9$$

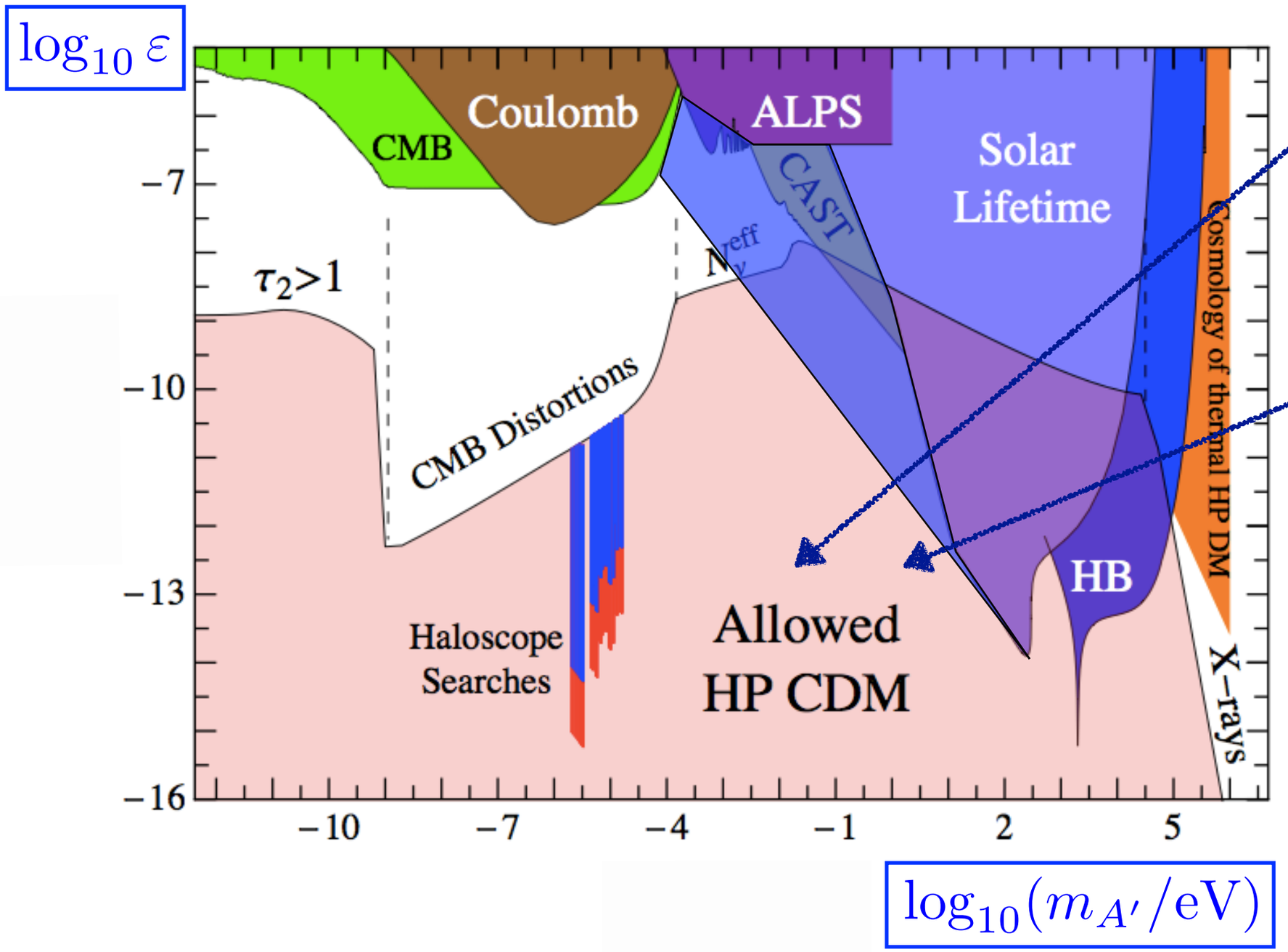
$$\tau_{A'\to \nu\bar{\nu}} \sim \frac{1}{\varepsilon^2}\frac{1}{G_F^2 m_{A'}^5} \sim 10^{28}\,\mathrm{sec}\left(\frac{10^{-7}}{\varepsilon}\right)^2\left(\frac{1\,\mathrm{keV}}{m_{A'}}\right)^5$$

Existing and Proposed Searches



Jaeckel et al, 1201.5902

Existing and Proposed Searches



New materials from CM physics 1708.08929

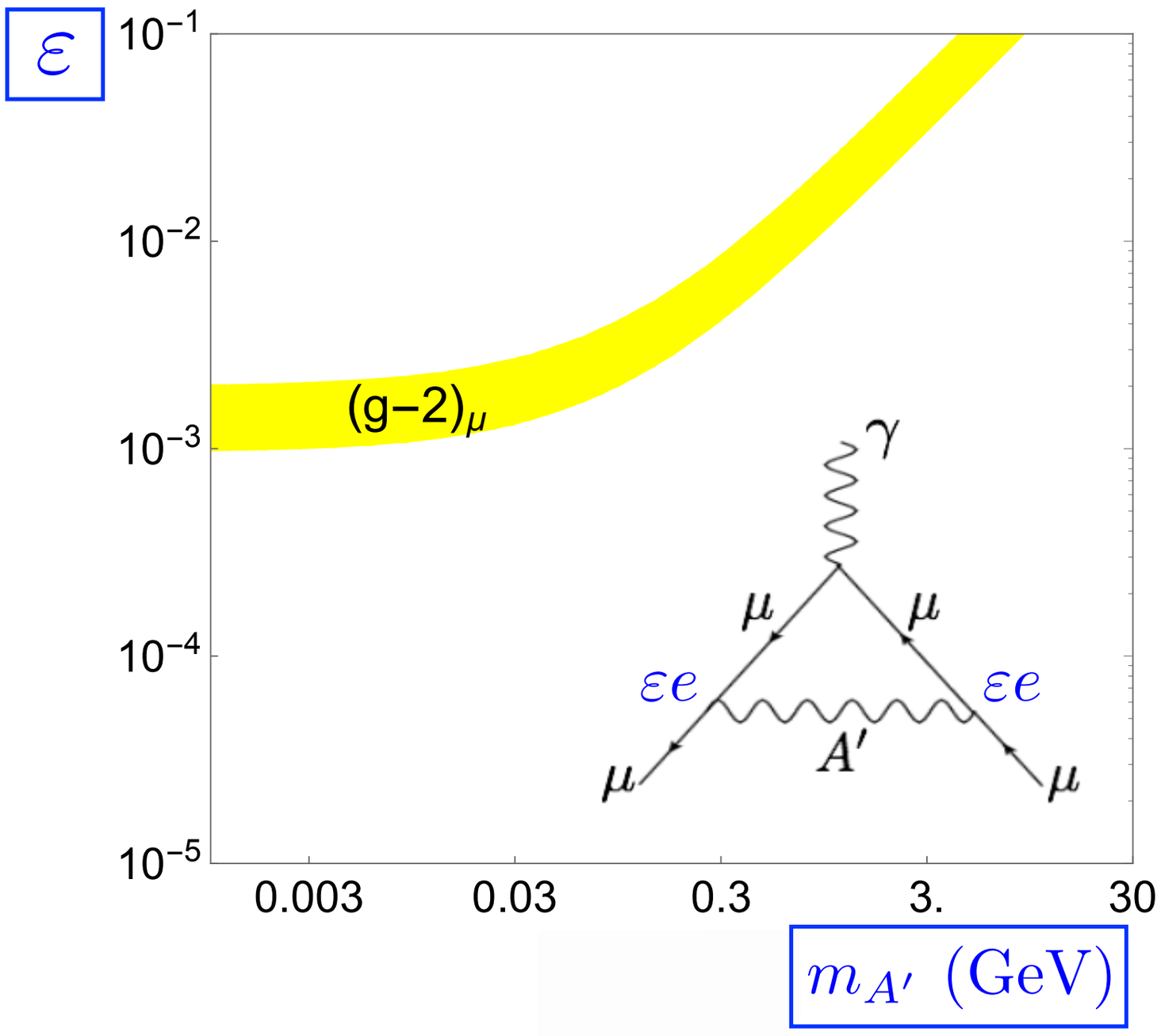
DM detector for solar dark photon 1412.8378

Jaeckel et al, 1201.5902

Muon g-2 connection

Dark Photon and Muon g-2

Very simple explanation using the dark photon.



If $m_{A'} \ll m_\mu$,

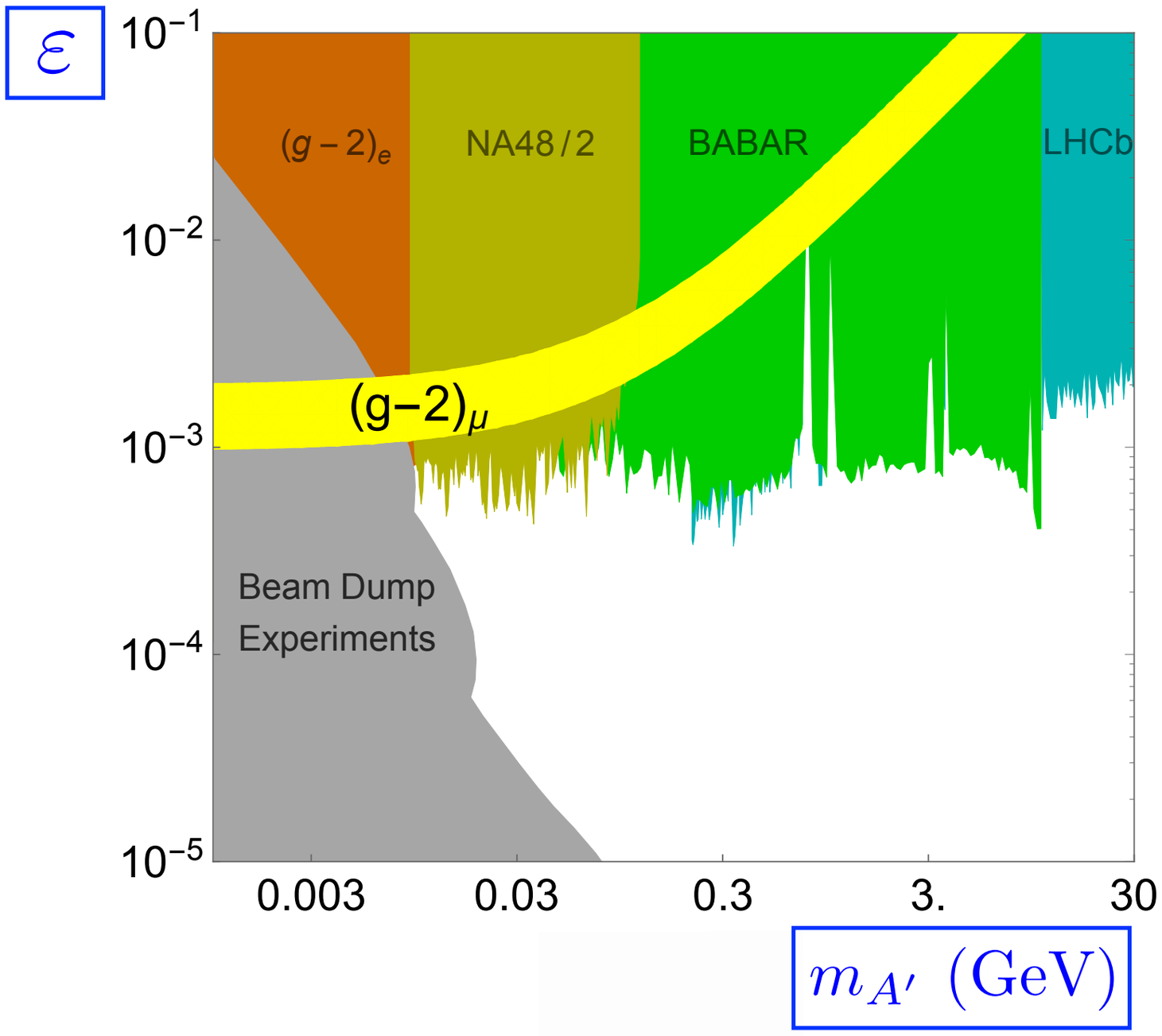
$$\frac{\delta(g_\mu - 2)}{2} = \frac{\varepsilon^2 \alpha}{2\pi}$$

If $m_{A'} \gg m_\mu$,

$$\frac{\delta(g_\mu - 2)}{2} = \frac{\varepsilon^2 \alpha}{3\pi} \frac{m_\mu^2}{m_{A'}^2}$$

Dark Photon and Muon g-2

This very simple explanation has been ruled out.



NA48/2 : $\pi^0 \to \gamma A' \to \gamma e^+ e^-$

BaBar : $e^+ e^- \to A' \to e^+ e^-, \mu^+ \mu^-$

Electron $g-2$

Clearly, electron coupling is the killer.

What's the next experimental target?

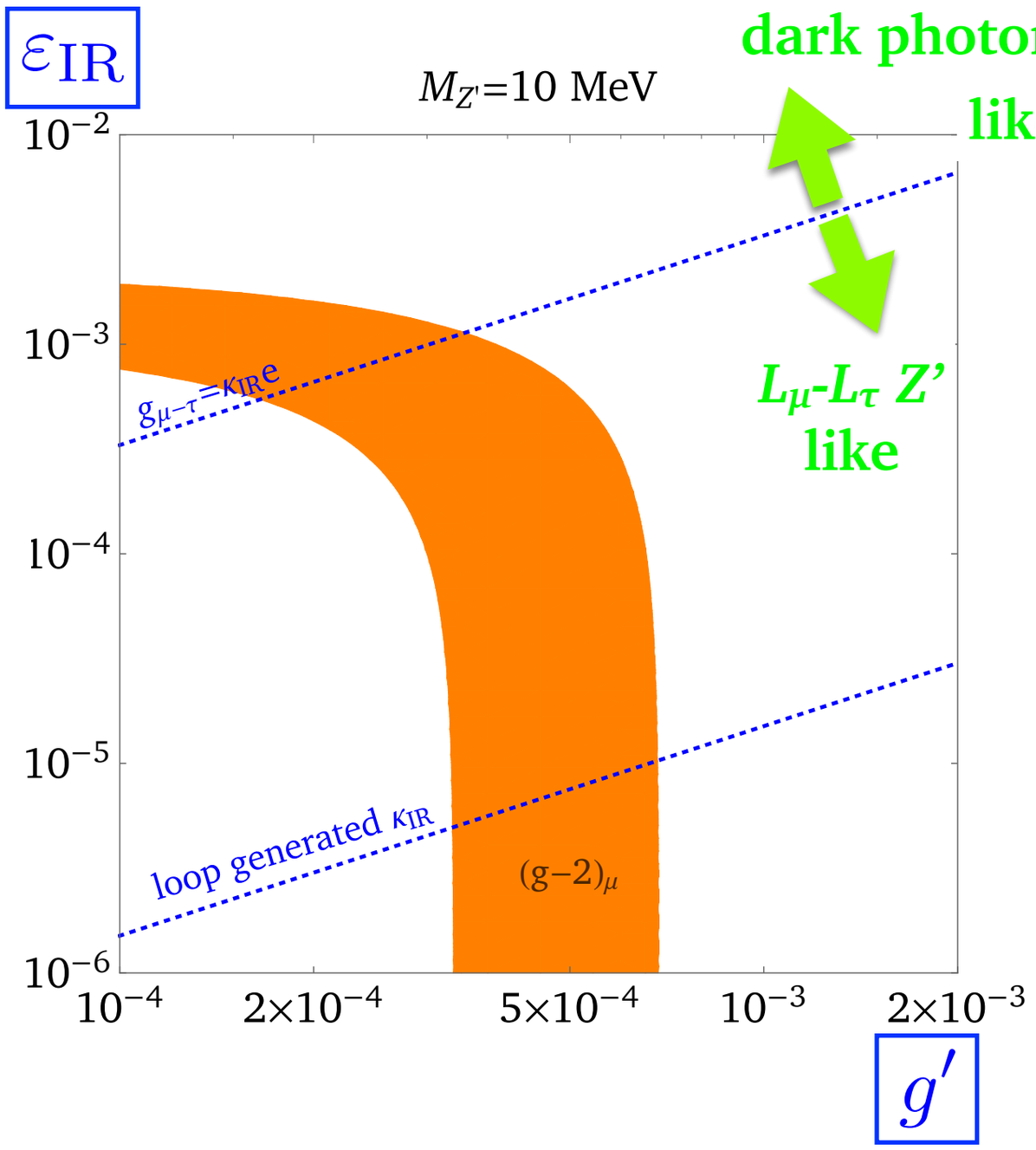
Z' from Gauged L_μ-L_τ Model

Anomaly free model.

kinetic mixing term allowed.

Generalized dark photon:

$$\varepsilon_{\rm IR} = \varepsilon_{\rm UV} + \quad Z' \quad \mu,\tau \quad \gamma$$



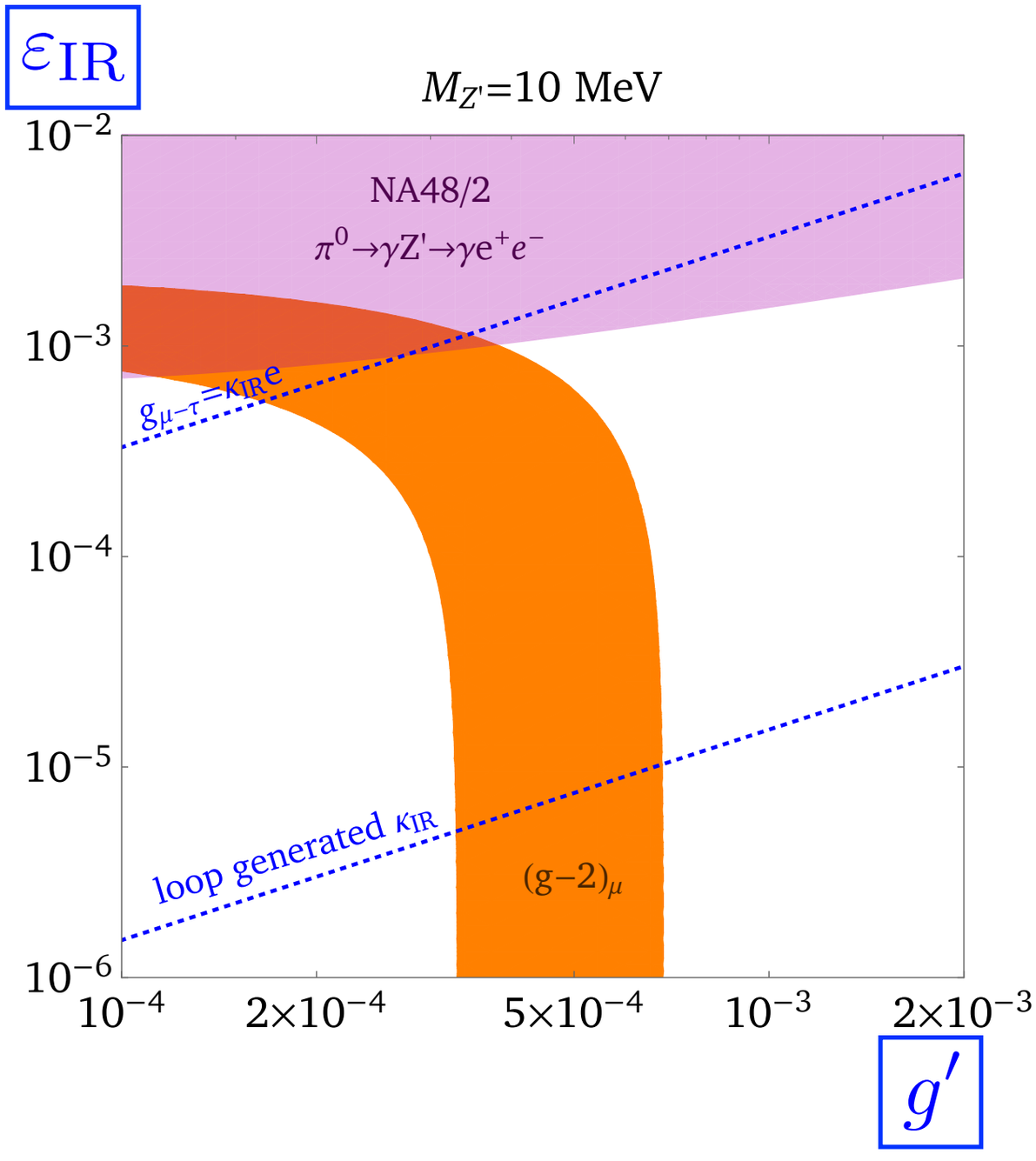
de Gouvea, Machado, **YZ** (in preparation)

Weaker Constraints from Visible decay

If $\varepsilon e \ll g'$, hierarchical couplings of Z' to electron and L_μ & L_τ.

If so, Z' lighter than 210 MeV mainly decays into neutrinos.

— Constraints for the usual dark photon (NA48/2) can be avoided.



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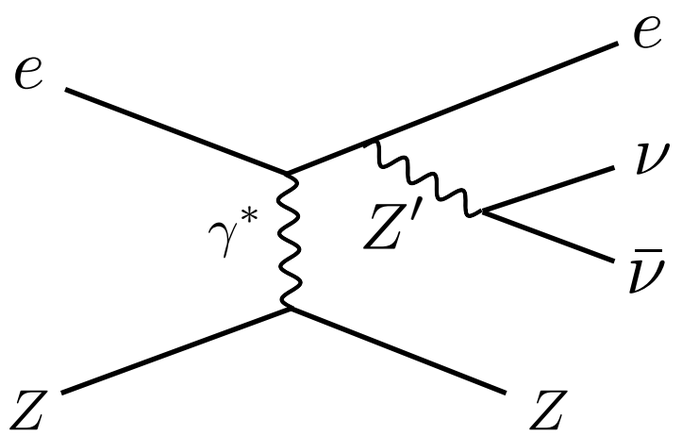
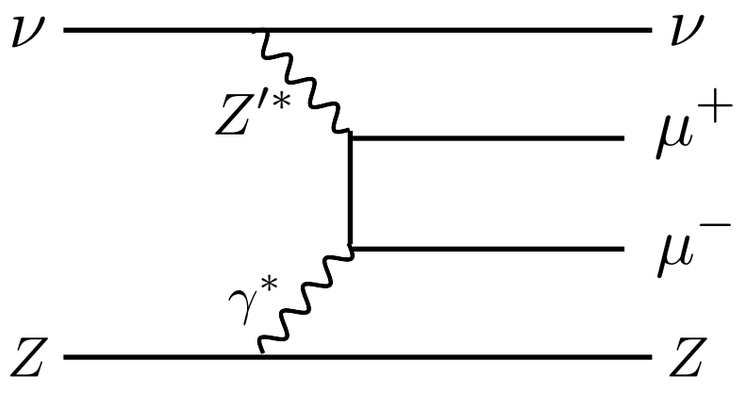
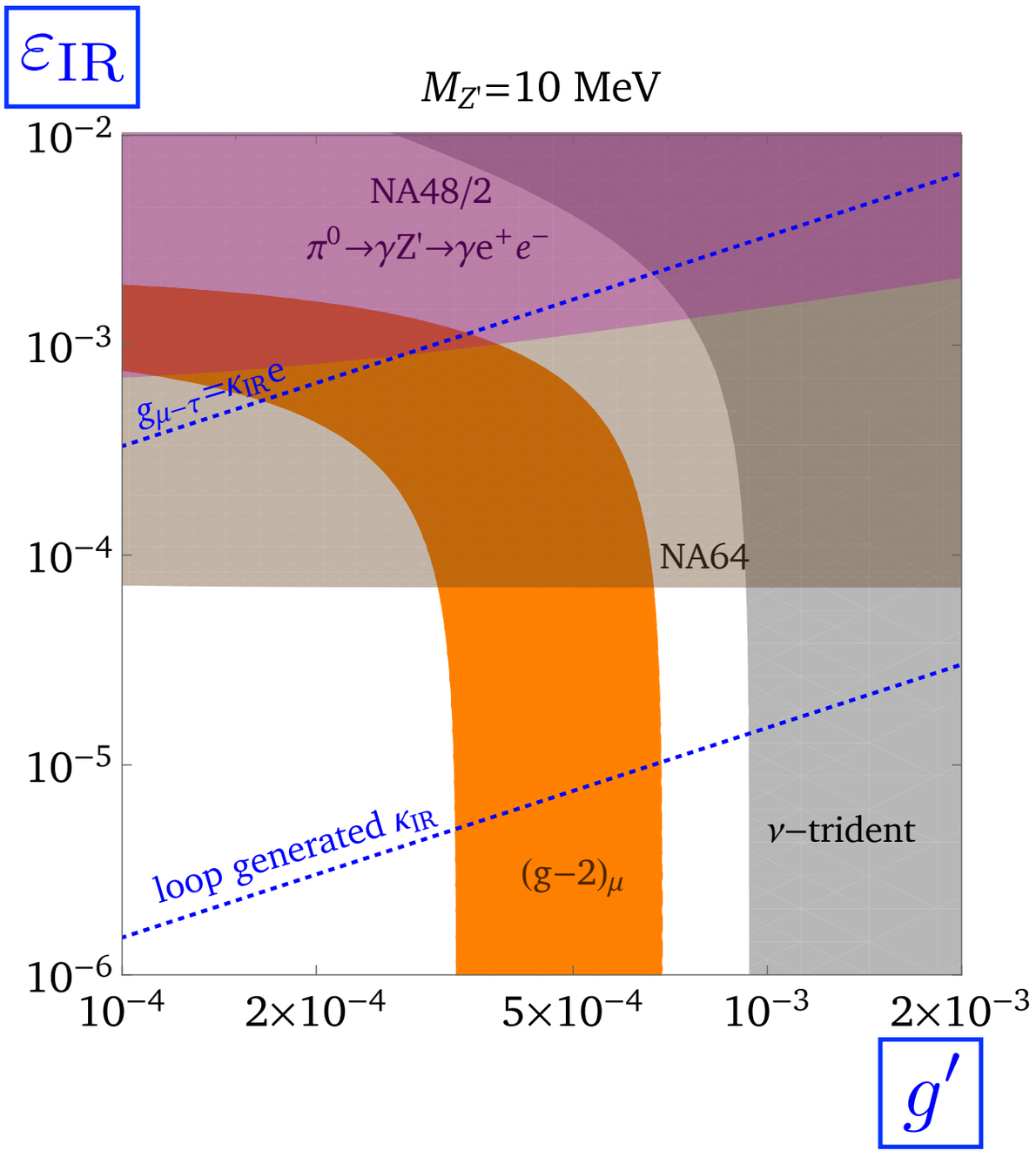
New Constraints from Invisible Decay

Invisible decay constraint on dark photon (NA64)



Neutrino trident production





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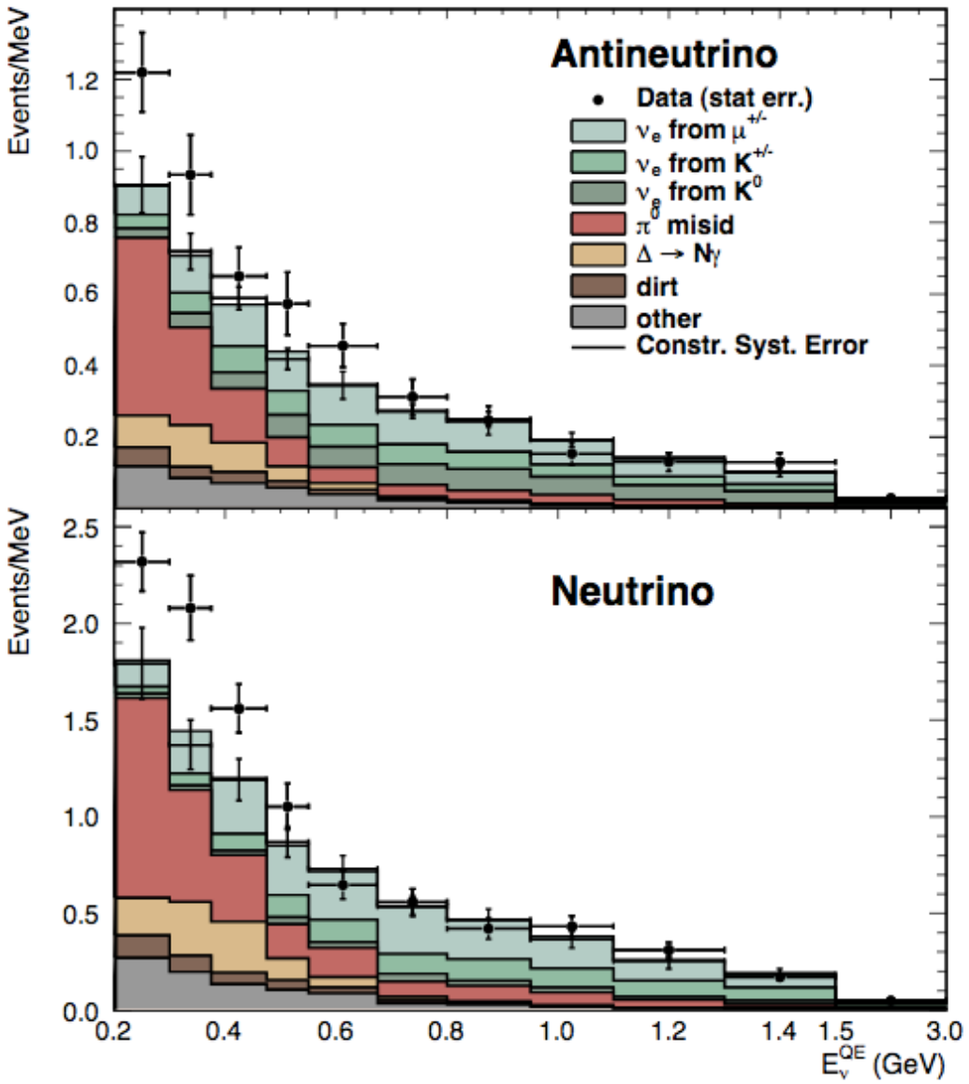
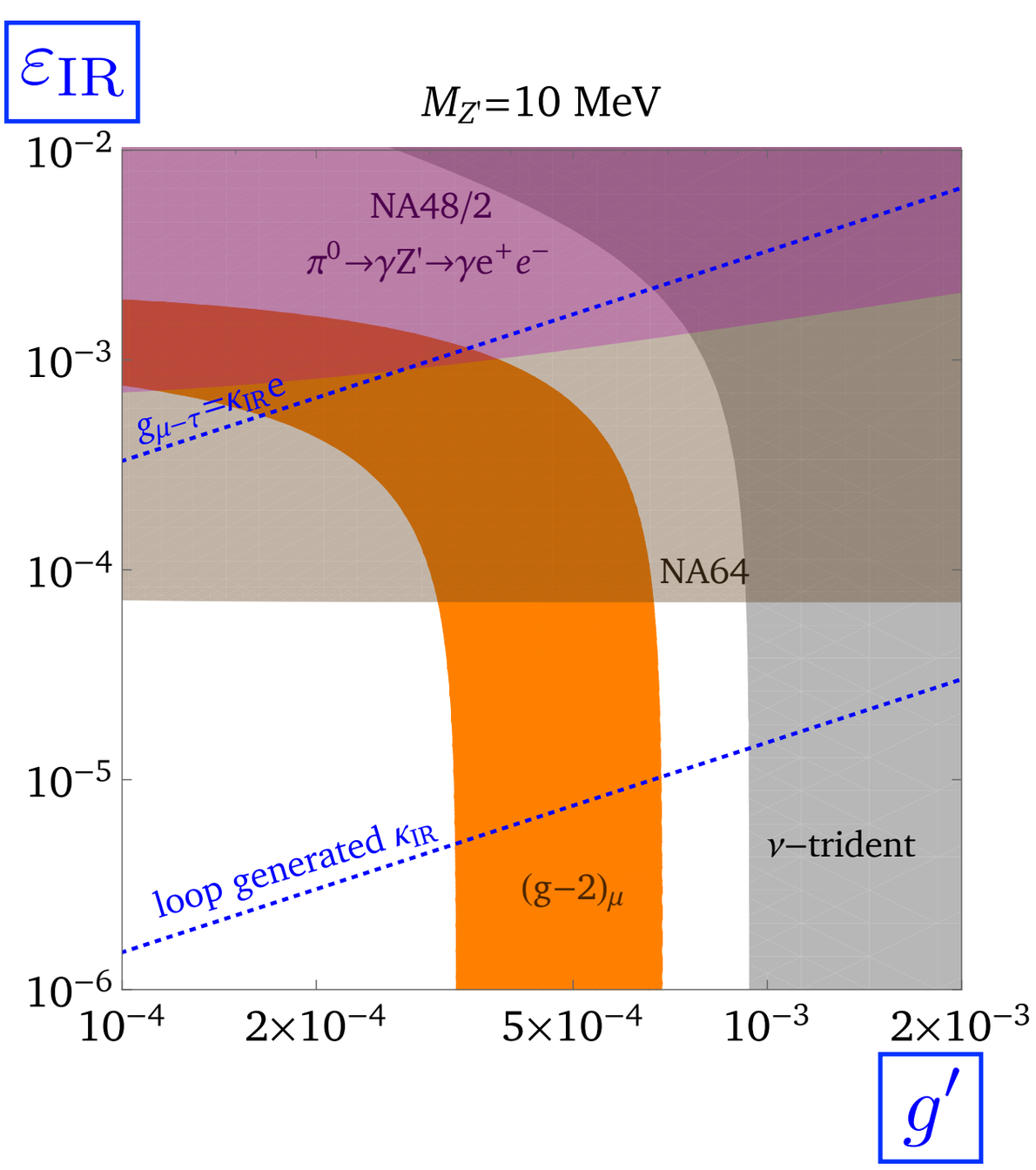
Connection to a ν-Experiment

MiniBooNE low energy excess





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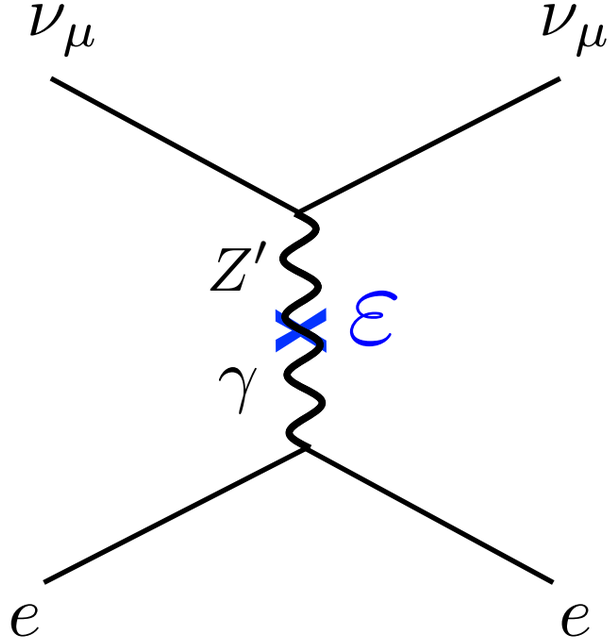
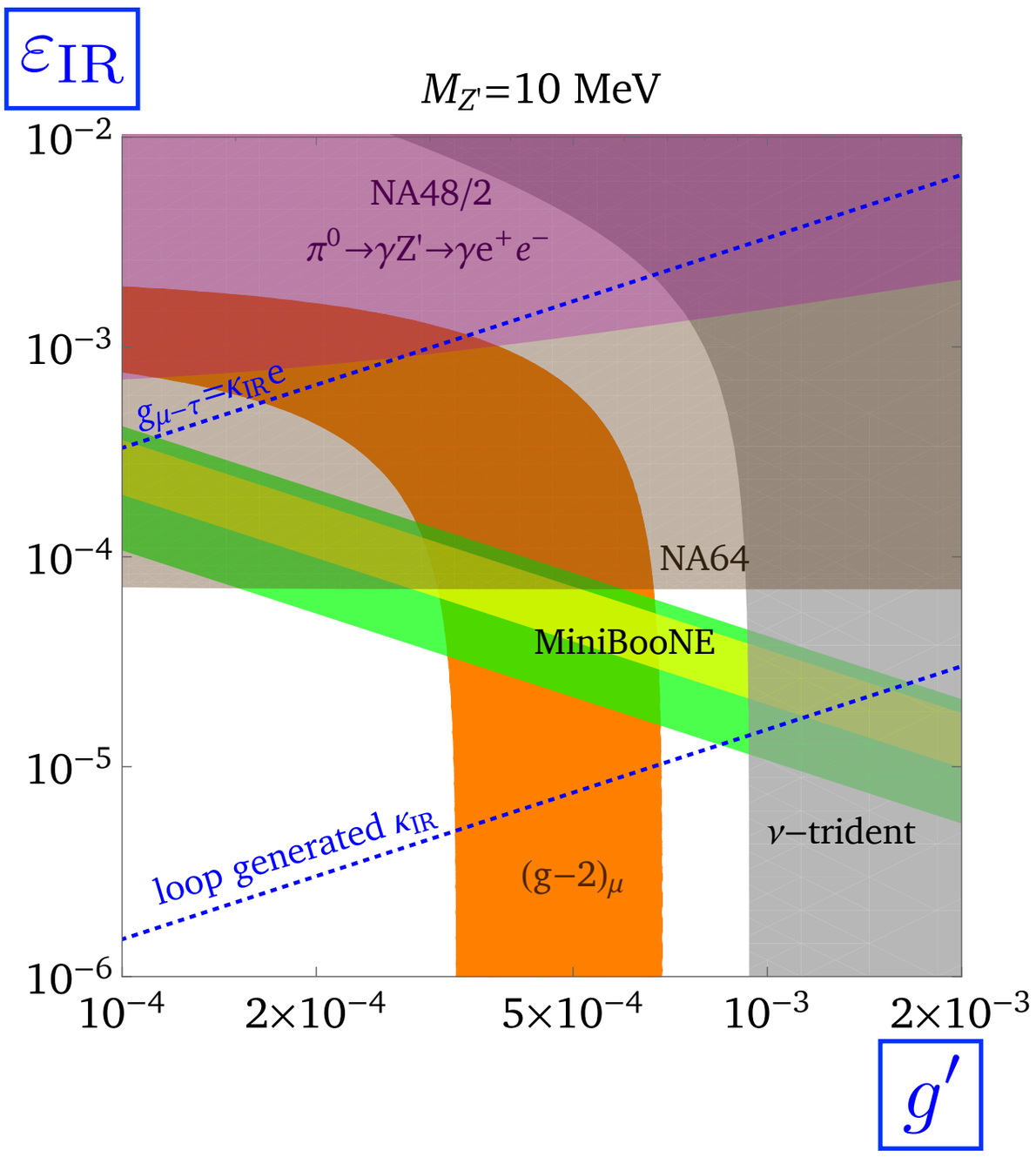
Connection to a ν-Experiment

Neutrino-electron scattering as explanation of MinoBooNE low energy excess.





de Gouvea, Machado, **YZ** (in preparation)

Conclusion

We are not yet able to explore the nature of DM in labs.

Dark Photon is a simple and well motivated candidate of portals to dark sector — a (light) weakly coupled world.

Many ongoing and proposals to look for it.

Interplay between dark photon with dark matter physics could play an important role.

Cast a wide net in both theory and experiments.