Dark SRF Experiment for Dark Photon Search

Yue Wang

Outline

- Evidences for Beyond Standard Model
- Dark sector theory
  - Motivations for a dark sector theory
  - Dark photon
- Light-shining-through-wall experiments: dark matter searches using SM-dark photon oscillation
- Dark SRF experiment: a light-shining-through-wall experiment
- Dark photon search limits from other experiments

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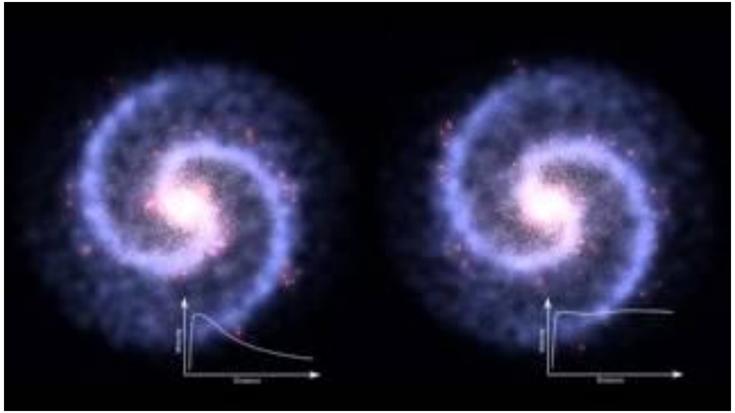
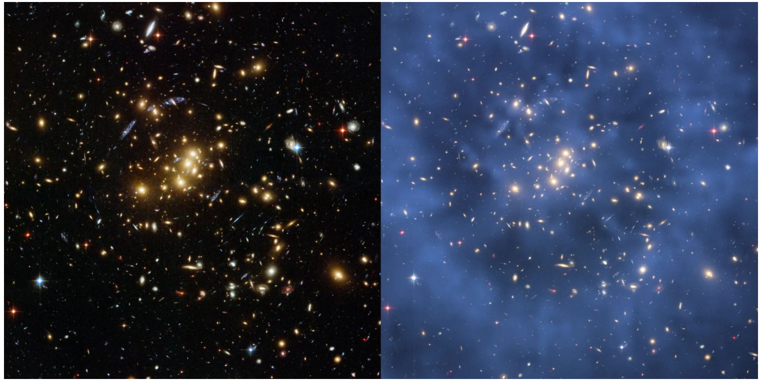
Astronomical evidences of dark matter

Galaxy rotation



Left: galaxy rotation without dark matter; Right: galaxy rotation with dark matter (agrees with astronomical observation)
Ingo Berg

Gravitational lensing



Left: Massive galaxy cluster Cl 0024+17 and distant galaxies (in the blue ring). The ring structure is a characteristic of gravitational lensing; Right: dark matter illustration (in blue) on top of the picture on the left.
NASA, ESA, M.J. Jee, and H. Ford (Johns Hopkins University)

Dark matter candidates

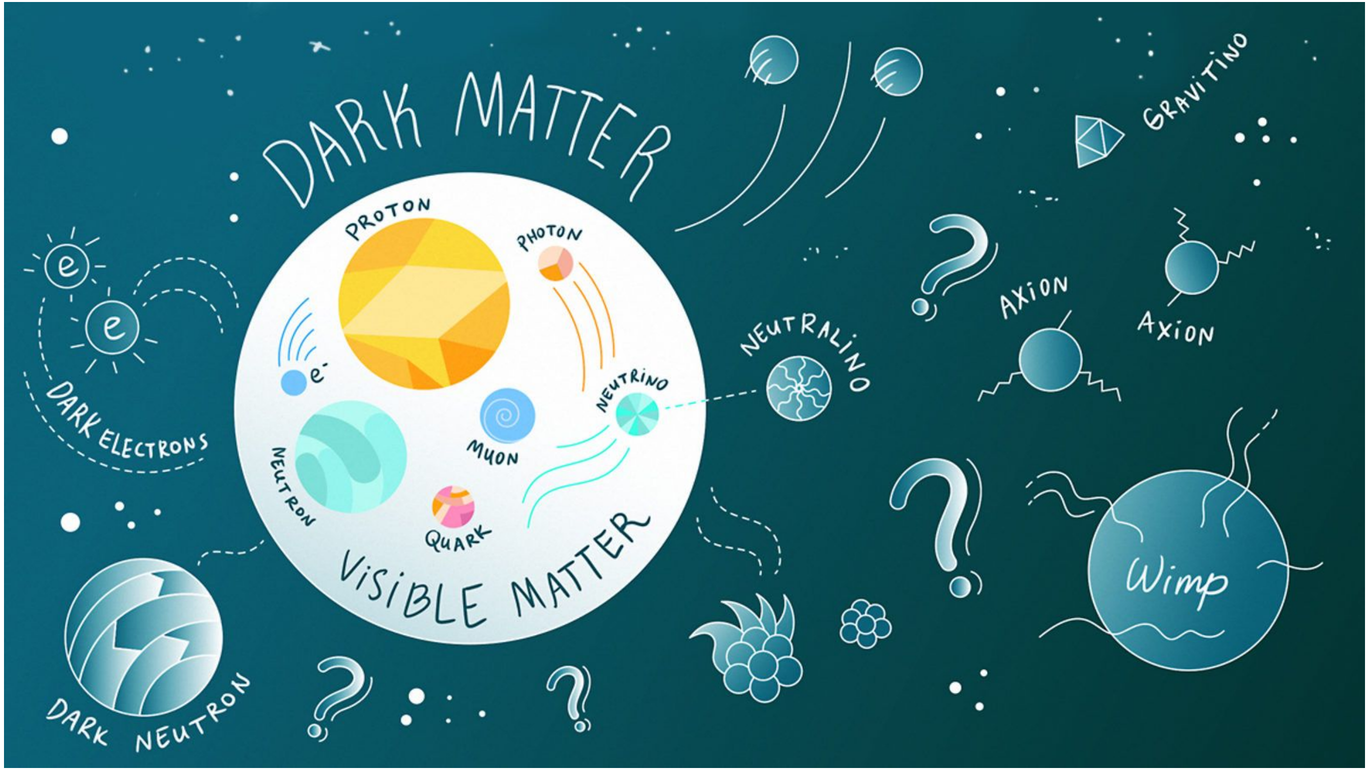
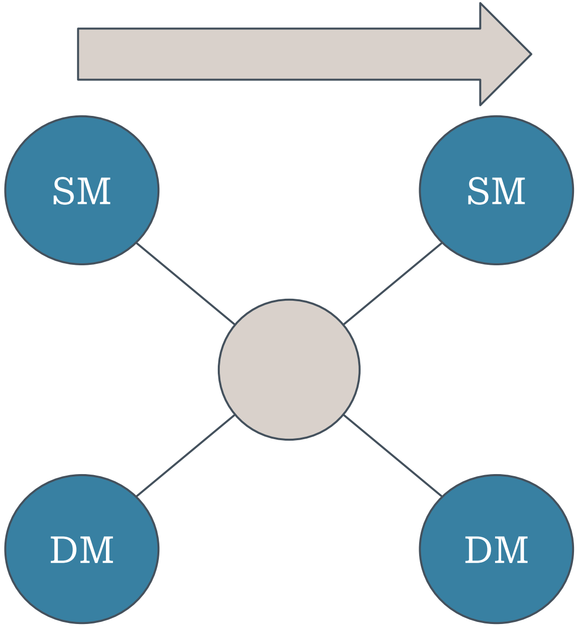
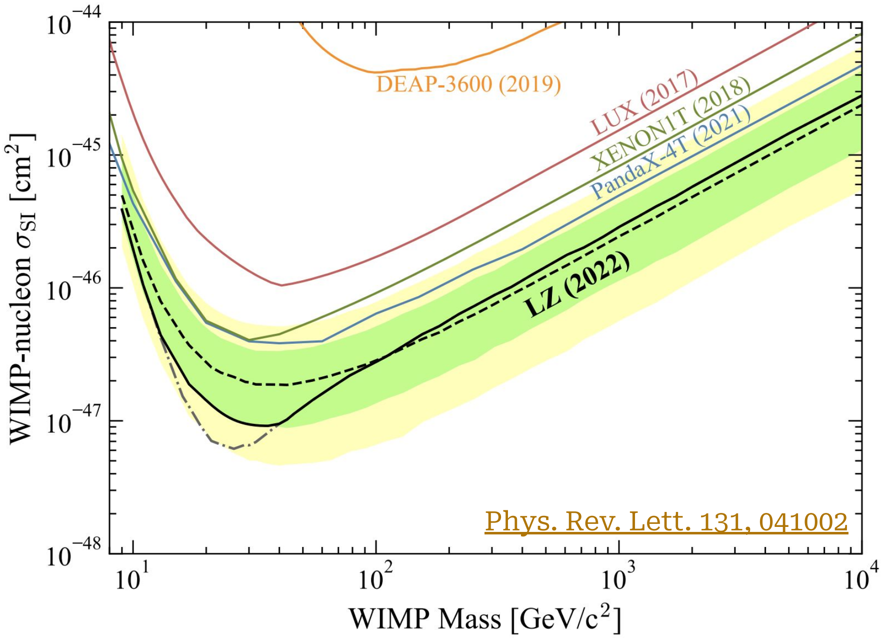


Figure source: Symmetry Magazine.

Lack of direct evidence of dark matter



A pseudo Feynman diagram: dark matter direct detection



The LZ 90% confidence limit (black line) for the spin-independent Weakly Interacting Massive Particle (WIMP) mass and limits reported by other dark matter direct detection experiments.

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The existence of dark matter motivates dark sector

The standard model

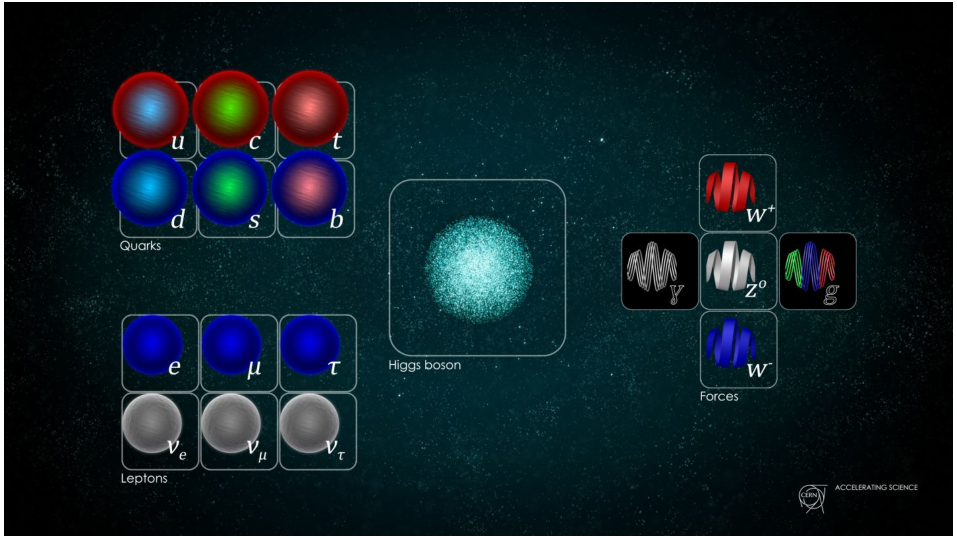
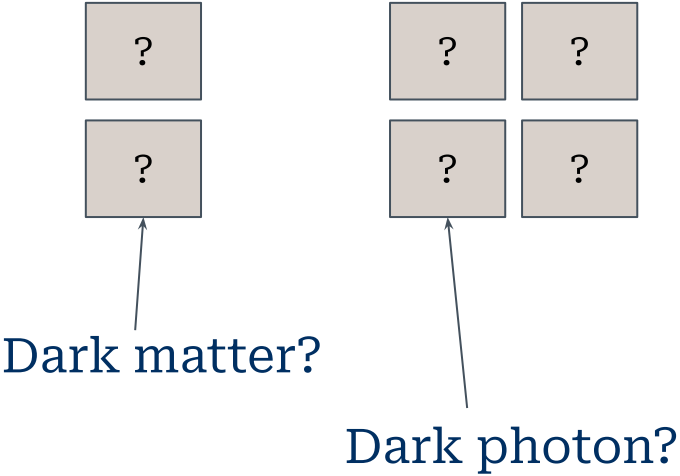


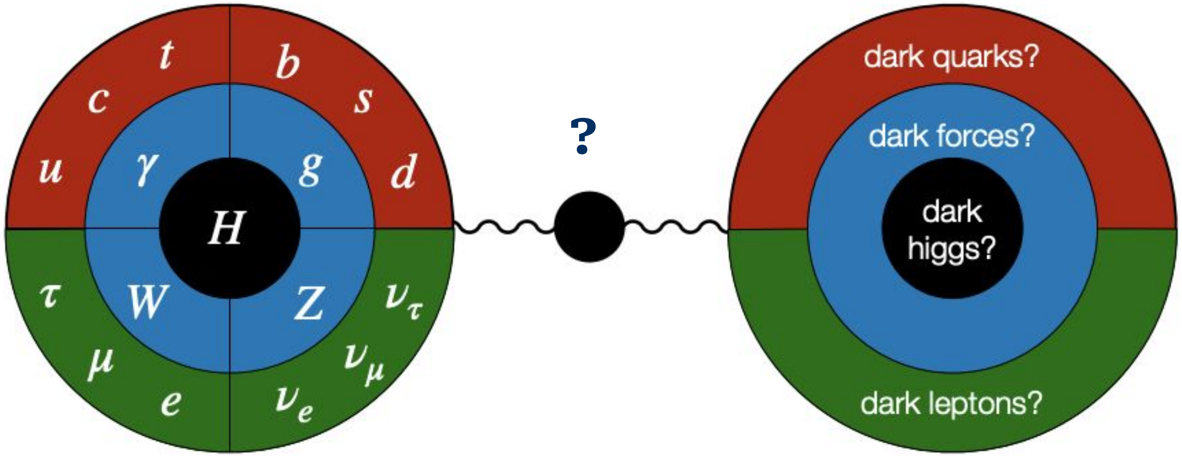
Figure source: CERN

Dark sector?



Dark sector

- Standard Model (SM) particles do not experience dark sector forces.
- Dark matter particles do not experience SM forces.



Standard Model Dark Sector

Figure source: S. Gori, M. Williams, et. al. Dark Sector Physics at High-Intensity Experiments.

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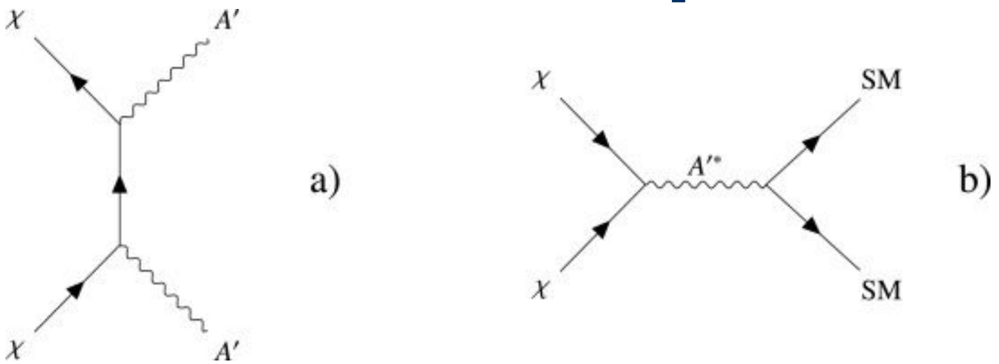
Dark photon models

Spin-one gauge boson (a “dark force” mediator), $U(1)_D$.

- Massive dark photon: couples to SM matter through a current J_μ with arbitrary charge.
- Massless dark photon: does not couple directly to any of the SM currents J_μ and interacts instead with SM matter only through operators of dimension higher than four. [M. Fabbrichesi, et. al., 2020]

Dark photon and dark matter

- Very light massive dark photon as dark matter candidate
  - $m_{\gamma'}$ the mass of dark photon is less than 10 MeV
  - ε SM photon - dark photon kinetic mixing parameter is less than 10^{-7}
  - The constraints above came from cosmic microwave background and the critical density of the universe.
- Possible massive dark photon and dark matter interactions



a) $m_{A'}<2m_\chi$: Dark photon A’ production via annihilation $\chi\chi \rightarrow A'A'$

b) $m_{A'}>2m_\chi$: s-channel resonant production into SM particles $\chi\chi \rightarrow A'^* \rightarrow SM\ SM$

Figure source: A. Filippi and M. De Napoli. Searching in the Dark: the hunt for the dark photon.

Hidden gauge mediator candidates

- Dark photon is one of the possible candidates for a “dark force” mediator => even if a dark sector exists, it is not necessarily true that dark photons exist.
- Other possible hidden gauge mediator candidates: dark particles of different spins such as
    - Scalar dark CP-even or -odd Higgs (scalar portal)
    - Pseudoscalar axion (axion portal)
    - Rich dark sectors: a larger number of new dark matter candidates.

Massive dark photon Lagrangian

- $F_{\mu\nu}$: field strength for SM photon. The field strength tensor for the SM electromagnetic gauge field A^{μ}. $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$
- $F'_{\mu\nu}$: field strength for dark photon. The field strength tensor for the hidden sector $U(1)_D$ field A'^{μ}. $F'_{\mu\nu} = \partial_{\mu}A'_{\nu} - \partial_{\nu}A'_{\mu}$
- ε: small kinetic mixing parameter ~ 10^{-3} - 10^{-1}.
- $m_{\gamma'}$: mass of dark photon.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2_{\gamma'}A'_{\mu}A'^{\mu}$$

Kinetic term for SM photon field

Kinetic term for dark photon field

SM and dark electromagnetic fields mixing term: allows dark photon and SM matter interactions

Term accounts for dark photon mass

Deriving the γ-γ' oscillation

Diagonalizing the kinetic terms in the Lagrangian from the previous slide with this shift [J. Jaeckel and A. Ringwald 2007]:

$$A'^{\mu} \to \tilde{A}'^{\mu} - \epsilon A^{\mu}$$

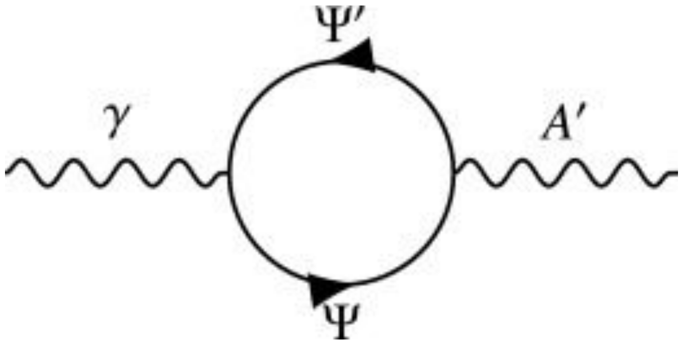
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4}\tilde{F}'^{\mu\nu}\tilde{F}'_{\mu\nu} + \frac{1}{2}m_{\gamma'}^2(\tilde{A}'^{\mu}\tilde{A}'_{\mu} - 2\epsilon\tilde{A}'^{\mu}A_{\mu} + \epsilon^2 A^{\mu}A_{\mu})$$

Diagonalized kinetic terms

The non-diagonal mass term allows a γ-γ' oscillation

A Feynman diagram for γ-γ' oscillation

- Ψ: Any massive DM particle charged under both the SM hypercharge gauge group and the dark symmetry.
- Ψ': anti particle of Ψ.
- γ: SM photon.
- A': dark photon.

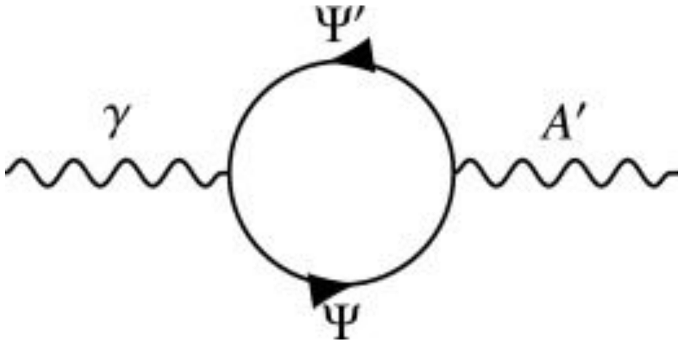


Kinetic mixing of SM photon and dark photon at the one-loop level.

Figure source: A. Filippi and M. De Napoli. Searching in the Dark: the hunt for the dark photon.

Significance of the γ-γ’ oscillation

- The **mixing between dark photon and SM photon** connects the hidden sector and the SM.
- Possible dark photon mixing with the heavy Z boson at the next-to-leading order.



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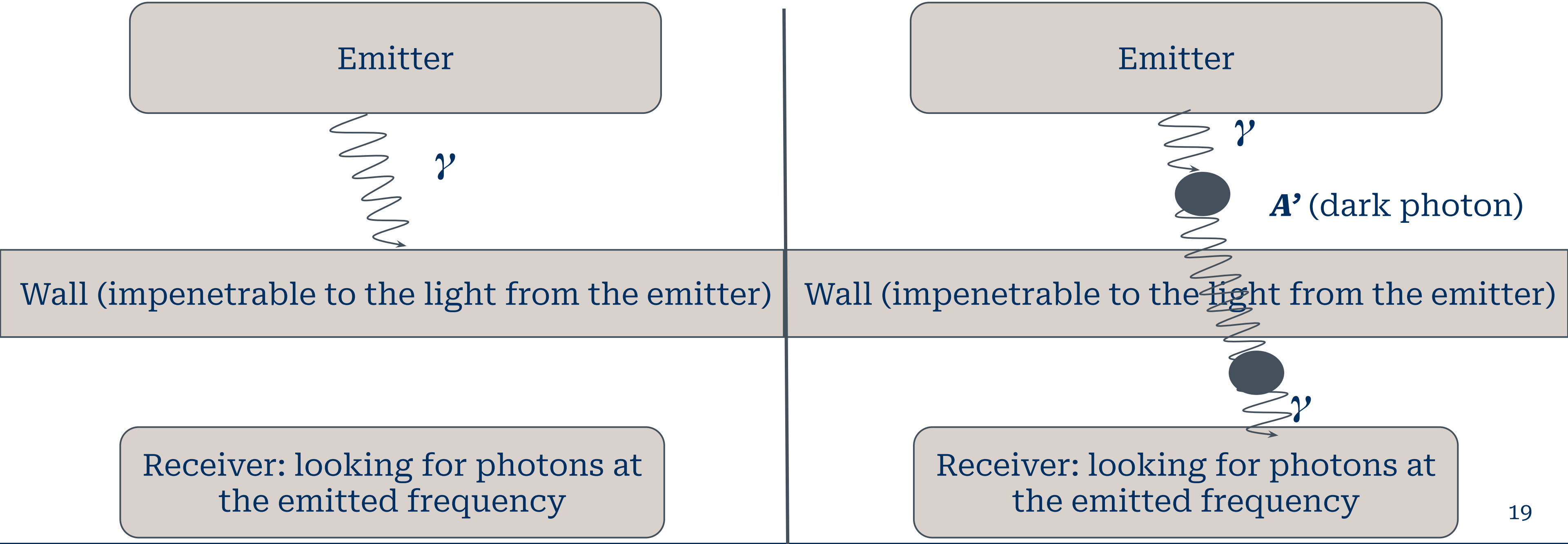
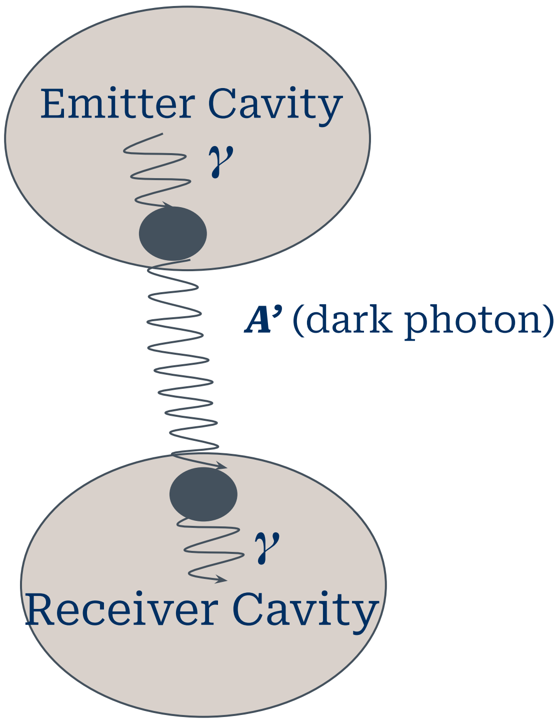
Light-shining-through-wall (LSW)

The classical experimental setup (1980s and 1990s)



Cavity LSW experiments

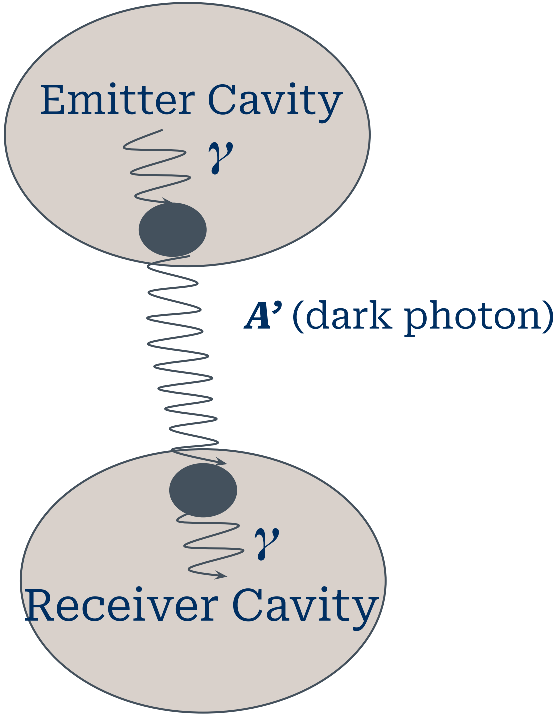
- An **radiofrequency (RF) cavity** is a metallic chamber that contains an electromagnetic field.
- In accelerators, RF cavities are used to accelerate charged particles.
- The cavity LSW experiments use an RF cavity (the emitter cavity) to obtain an electromagnetic field and another RF cavity (the receiver cavity) to measure the signal.



An illustration of the alternative LSW setup

Cavity LSW experiments

- A coherently oscillating SM electromagnetic field in the emitter cavity that produces SM photons, therefore acting as a source of dark photons at the oscillating frequency.
- The coherent dark photon field can resonantly excite a receiver cavity if the dark photon frequency matches the receiver cavity resonance frequency.
- First proposed by J. Jaeckel and A. Ringwald in 2008.
- A high **intrinsic quality factor** (Q_0) of the cavities in this setup => the photons in the emitter cavity and the receiver cavity have little damping => more stored photons in the emitter cavity and a higher dark photon detection sensitivity in the receiver cavity.



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Dark SRF experiment

- Dark SRF (superconducting radio frequency) experiment is an LSW experiment.
- This experiment uses **ultrahigh quality factor SRF cavities** as the emitting and receiving cavities.

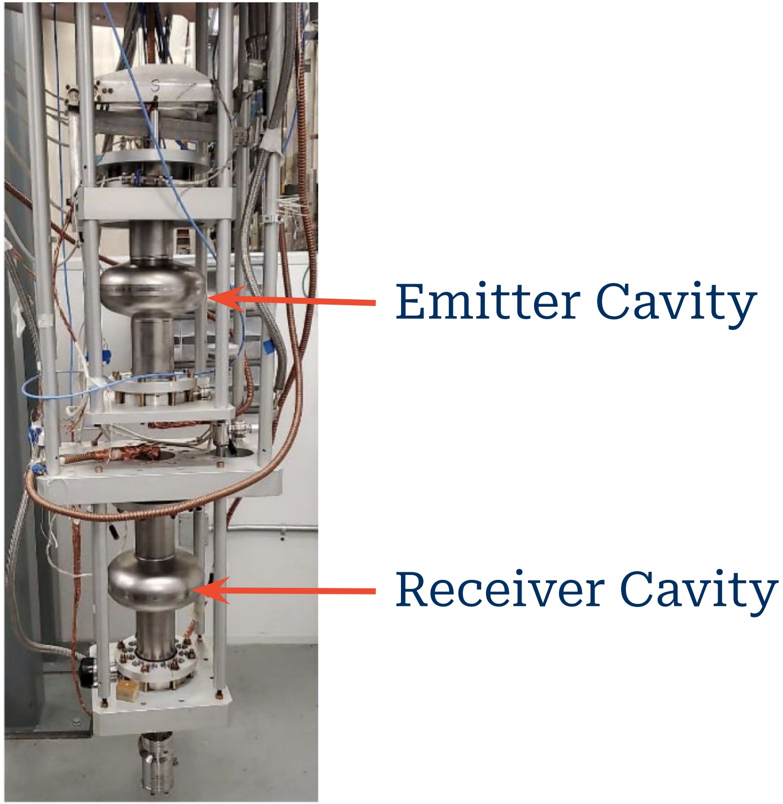


Figure source: A. Romanenko, et. al. Search for Dark Photons with Superconducting Radio Frequency Cavities.

Signal power: prediction

- Radiated dark photon field will deposit power P_{rec} in the receiver cavity.
- For cavities oriented to produce and detect the longitudinal polarization of the dark photon field:

$$P_{\rm rec} = \epsilon^4 \left(\frac{m_{\gamma'}}{\omega}\right)^4 |G|^2 \omega Q_{\rm rec} U_{\rm em}$$

- Q_{rec}: intrinsic quality factor of the emitter cavity.
- U_{em}: energy stored in the emitter cavity.
- G: a fixed known form factor, depending on the spatial mode shape of the receiver cavity.
- $\boldsymbol{\omega}$: dark photon frequency.

Signal-to-noise ratio

Assuming the noise in the receiver is dominant by thermal noise, the signal-to-noise ratio (SNR) is follows the radiometer formula:

$$\mathrm{SNR} = \frac{P_{\mathrm{rec}}}{P_{\mathrm{th}}}\sqrt{\delta\nu t_{\mathrm{int}}} = \frac{P_{\mathrm{rec}}}{k_B T_{\mathrm{eff}}}\sqrt{\frac{t_{\mathrm{int}}}{\delta\nu}}$$

$\boldsymbol{\delta\nu} t_{int}$: number of independent measurements

- $\boldsymbol{\delta\nu}$: bandwidth of the analysis.
- t_{int}: integration time.
- T_{eff}: effective noise. temperature.
- P_{th}: noise power. $P_{th} = k_B T_{eff} \boldsymbol{\delta\nu}$

Experiment setup

- The resonant frequencies of the fundamental TM_{010} modes of the two cavities are close.
- The emitter SM electromagnetic field oscillation frequency is controlled by an accelerator-style frequency tuner: a stepper motor for coarse tuning and a piezoelectric element for fine tuning.
- The emitter and receiver cavities are immersed in helium bath around 2K when taking data.

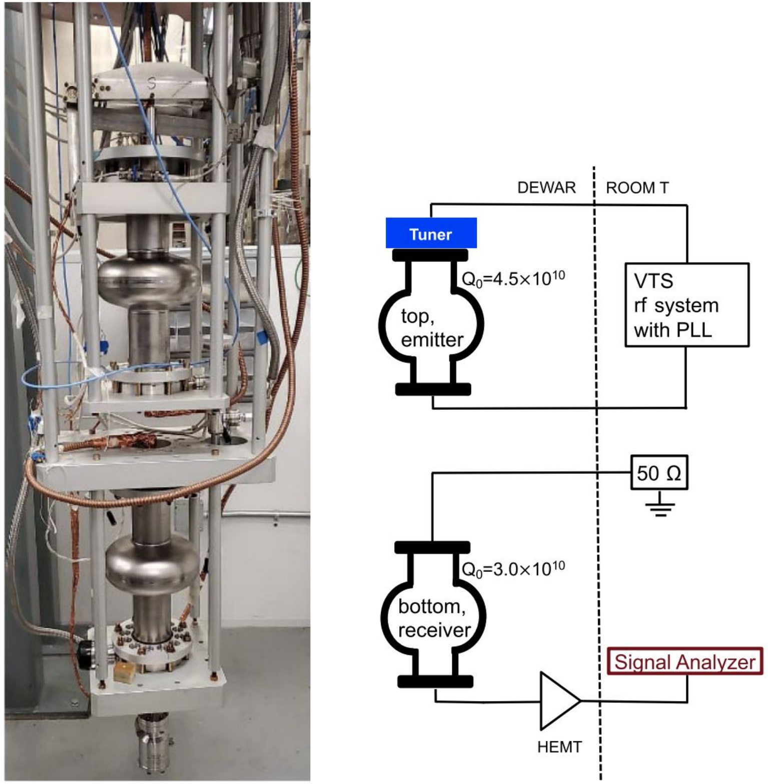


FIG. 1. Left: the experimental setup for the Dark SRF experiment consisting of two 1.3 GHz cavities. Right: a sketch of the Dark SRF electronic system.

Figure source: A. Romanenko, et. al. Search for Dark Photons with Superconducting Radio Frequency Cavities.

Data taking procedure

1. Frequency matching
   a. Connecting the emitter and the receiver cavities with a cable.
   b. Using a phase lock loop to have the rf generator, **that powers up both the emitter and receiver cavities**, follow the frequency of the emitter frequency
   c. Using the tuner to change emitter frequency until both the emitter and receiver cavities are resonantly excited by the same signal.
2. Dark photon search
   a. Disconnecting the generator from the receiver cavity.
   b. **Measuring the transmitted power from the receiver cavity** using a spectrum analyzer center around the resonance frequency measure from the step above.
3. Frequency recheck
   a. Reconnect the generator and the receiver cavity.
   b. Verify if both the emitter and receiver cavity remained frequency matched.

Background measurements

After the frequency recheck following of each dark photon search run, the team performed crosstalks checks. If there was no crosstalk seen, they measured the thermal background.

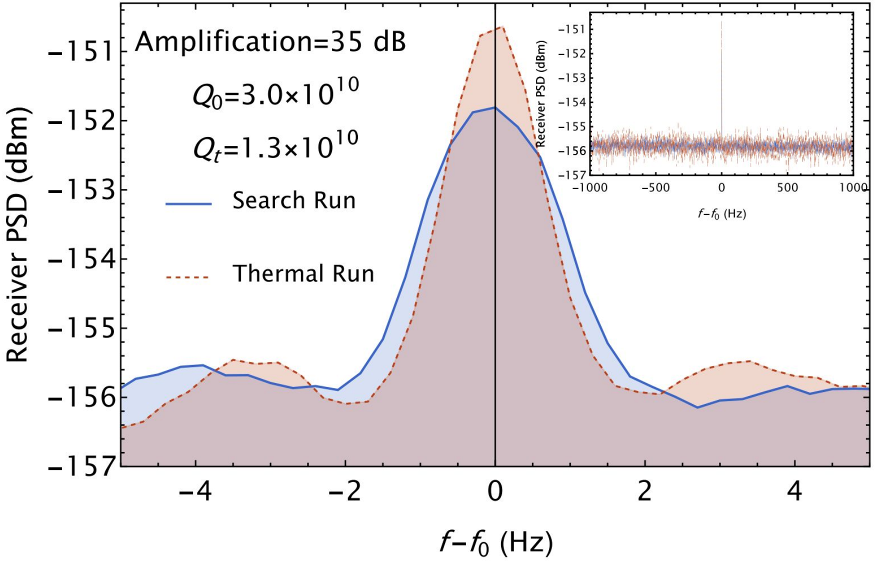
- Crosstalk check:
  - Keeping the connections between the generator and both the emitter and the receiver cavities.
  - Disengaging the phase lock to lose the synchronization between the generator and the emitter cavity and to drop the emitter cavity’s stored power.
  - If a peak of excess power, that follows the frequency of the generator, seen in the receiver cavity, they report a measurement of crosstalk.
- Thermal background measurement, if no crosstalk was seen
  - Measuring the receiver cavity frequency spectra with no excitation in the emitter cavity.

First result

- The power measured between the thermal run and search run is consistent with each other within 1σ => no dark photon discovery.
- The center peak was observed when the emitter power was off => not originated from crosstalk.

Measured Power

Thermal Run	$-151.6^{+0.23}_{-0.25}$ dBm
Search Run	$-151.8^{+0.16}_{-0.17}$ dBm



The measured power spectral density (PSD) of the receiver cavity during a dark photon run and a thermal noise run.

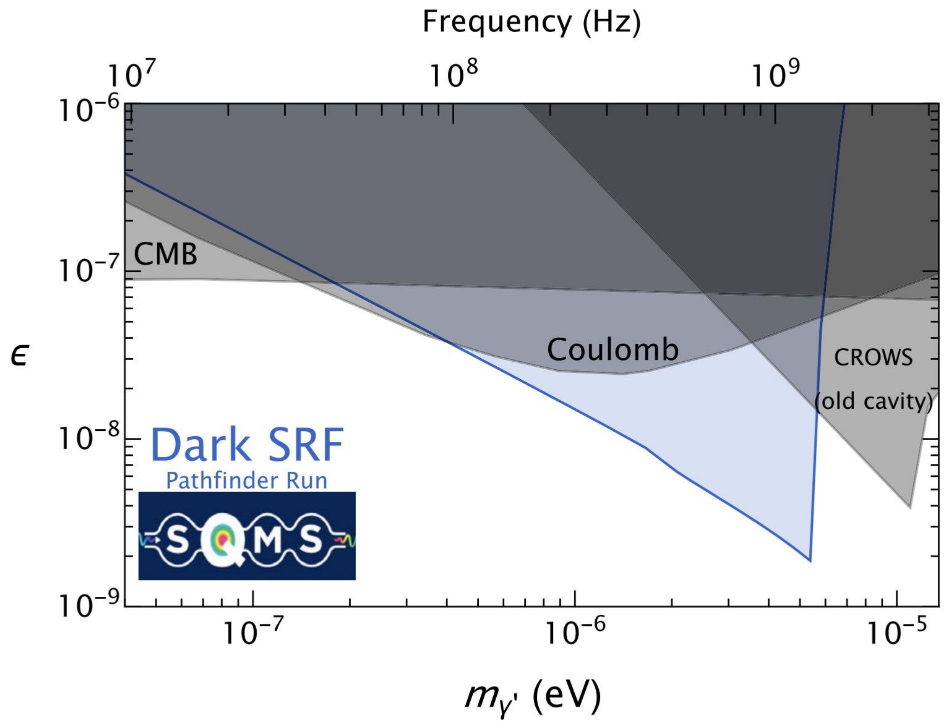
Limit setting

- Fitting the equation below using a modified frequentist confidence level (C.L.) method

free parameters

$$P_{\text{rec}} = \epsilon^4 \left(\frac{m_{\gamma'}}{\omega}\right)^4 |G|^2 \omega Q_{\text{rec}} U_{\text{em}}$$

- Reporting the world's best constraints on dark photons in the 2.1×10^{-7}-5.7×10^{-6} eV mass range, among the cavity LSW experiments

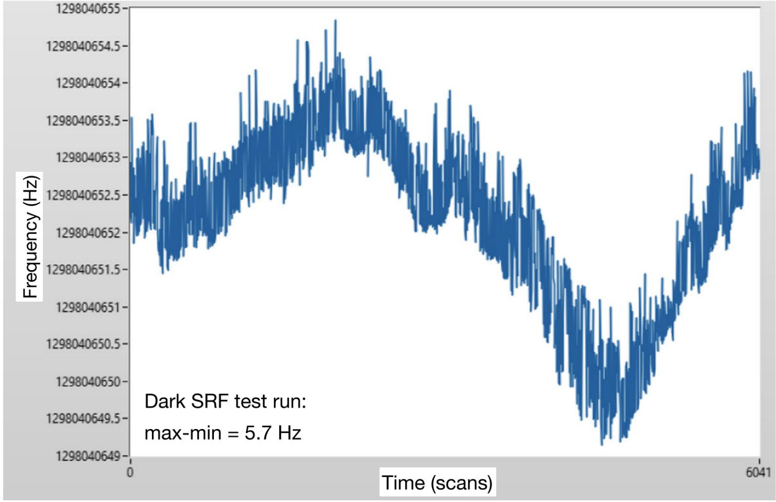


Blue: the 95% C.L. exclusion limit on dark photon parameter space. Gray: existing limits from the CROWs cavity experiment, measurements of the cosmic microwave background (CMB), and tests of Coulomb's law.

Challenge: frequency stability

Frequency stability run:

- Cavities' temperature: 1.4 K
- The frequency stability run was conducted within a day of the dark photon search run from the previous slides.



Emitter frequency stability run measurements. The frequency variation span in this plot is 5.7 Hz.

	Time duration (min)	Frequency variation span [Hz]
Emitter Cavity	100	5.7
Receiver Cavity	40	3

Dark SRF next steps

- Further crosstalk suppression
- Thermal background reduction
  - The center peak in the thermal run receiver cavity PSD was classified as a leak of thermal photons from the receiver input lin used to align the emitter and the receiver cavities.
  - The team suggested placing the receiver cavity at millikelvin temperature in a dilution refrigerator and coupled with a quantum-limited amplifier to reduce the noise level.
- The team suggested switching to phase-sensitive readout to discriminate between signal and noise.
- Frequency stability and control: a order of magnitude reduction in frequency variation will significantly enhance the sensitivity.

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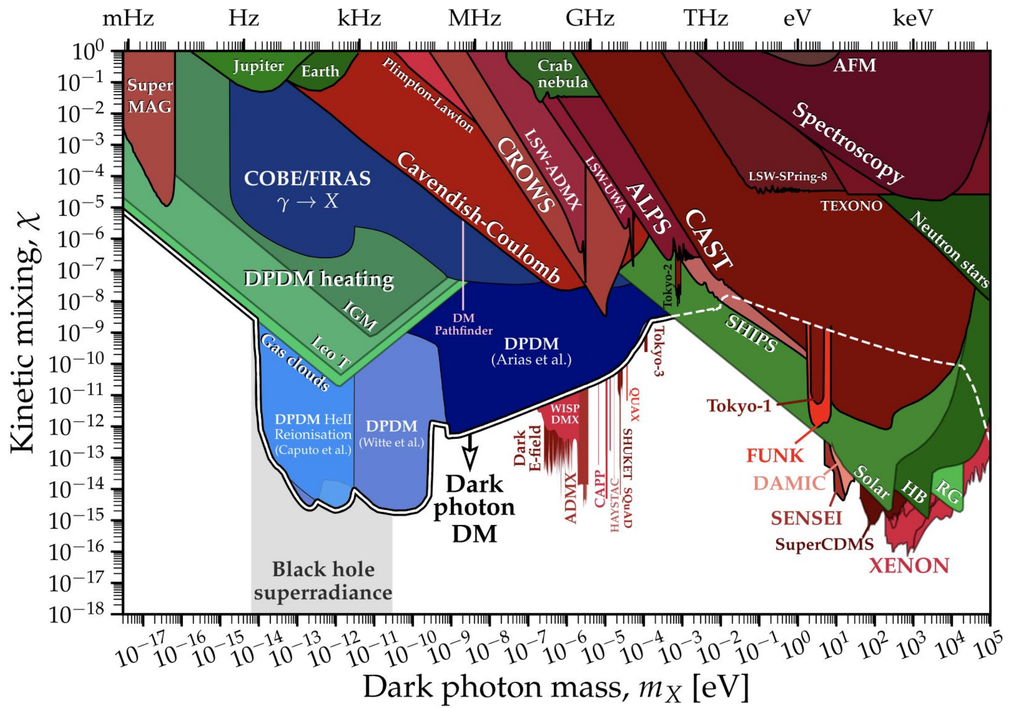
Dark photon limits by 2021



- Dark photon mass limits by 2021. The kinetic mixing factor χ is the ε in this presentation.
- Cosmological bounds in blue, experimental bounds in red, and astrophysical bounds in green.
- The thick white line that divides the parameter space in two is the upper limit for which dark photons are a viable candidate for 100% of the DM.

Figure source: A. Caputo, et. al., Dark photon limits: A handbook.

References

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