

DARK PHOTON PHYSICS: A COMPREHENSIVE REVIEW OF THEORETICAL MODELS, DARK MATTER CONNECTIONS, EXPERIMENTAL SEARCHES, AND FUTURE PROSPECTS

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Abstract

The nature of dark matter remains one of the most significant unresolved problems in modern particle physics and cosmology. Astronomical observations indicate that only about 5% of the Universe consists of ordinary matter. Approximately 27% is composed of dark matter, while nearly 68% is dark energy. Among the many theoretical candidates proposed to explain dark matter, the dark photon has emerged as one of the most promising and experimentally accessible possibilities. The dark photon is a hypothetical gauge boson associated with an additional hidden $U(1)_D$ gauge symmetry. Unlike the ordinary photon, the dark photon can possess a small non-zero mass and interact weakly with visible matter through a mechanism known as kinetic mixing. This interaction provides a natural portal between the visible sector and a hidden dark sector, enabling potential experimental detection while remaining consistent with current observational constraints. This article presents a comprehensive overview of the different aspects of dark photons, including their theoretical motivation, mathematical formulation, production mechanisms, decay channels, cosmological implications, astrophysical significance, and experimental searches. The theoretical framework is developed by introducing an extended gauge symmetry with kinetic mixing between the electromagnetic field and the hidden gauge field. The dependence of dark photon phenomenology on its mass and kinetic mixing parameter. Various production mechanisms, including thermal production, freeze-in processes, meson decays, bremsstrahlung, and collider production, are examined. The possible decay modes into Standard Model particles and hidden-sector particles are also analyzed. The cosmological consequences of dark photons are explored in the context of the early Universe, Big Bang nucleosynthesis, the cosmic microwave background, and structure formation. Their possible role as mediators of dark matter interactions and their influence on galaxy dynamics are also discussed. Furthermore, current and future experimental efforts, including collider experiments, beam-dump facilities, fixed-target experiments, precision atomic measurements, and direct detection searches, are reviewed. Constraints on the dark photon parameter space obtained from laboratory experiments and astrophysical observations are summarized. The study highlights how dark photons provide a compelling framework that connects particle physics, cosmology, and astrophysics while offering experimentally testable predictions. Continued theoretical developments and next-generation experiments are expected to significantly improve sensitivity to dark photon signatures, potentially revealing new fundamental interactions beyond the Standard Model. The dark photon therefore remains a leading candidate in the search for new physics and may

play a crucial role in understanding the composition and evolution of the Universe.

1. Introduction

The Standard Model (SM) of particle physics has established itself as one of the most successful scientific theories, providing an accurate description of the fundamental particles and three of the four fundamental interactions: the electromagnetic, weak, and strong forces. The experimental confirmation of the Higgs boson at the Large Hadron Collider (LHC) in 2012 marked the completion of the particle spectrum predicted by the Standard Model and further strengthened its predictive power. Despite these remarkable achievements, the Standard Model is widely recognized as an incomplete theory because it cannot explain several important observations related to the Universe. In particular, it does not provide a viable candidate for dark matter, cannot account for the tiny but nonzero masses of neutrinos, fails to explain the observed matter-antimatter asymmetry, and does not address the origin of dark energy. These shortcomings strongly suggest the existence of new physics beyond the Standard Model [1,3].

One of the most compelling pieces of evidence for physics beyond the Standard Model is the existence of dark matter. Astronomical observations from galaxy rotation curves, gravitational lensing, galaxy cluster dynamics, the Cosmic Microwave Background (CMB), and large-scale structure formation consistently indicate that nearly 27% of the total energy density of the Universe consists of non-luminous matter that interacts gravitationally but has not yet been directly detected through electromagnetic interactions [2,3]. Although numerous theoretical models have been proposed to explain dark matter, its fundamental nature remains one of the greatest unsolved problems in modern physics. This mystery has motivated the development of hidden-sector theories in which dark matter belongs to a separate sector of particles and interactions that are only weakly connected to the Standard Model. Among the simplest and most elegant hidden-sector models is the dark photon framework. In this approach, an additional Abelian gauge symmetry, denoted by $U(1)_D$ is introduced alongside the Standard

Model gauge group. The gauge boson associated with this new symmetry is called the dark photon (A') [4]. Unlike the ordinary photon, which mediates electromagnetic interactions among electrically charged particles, the dark photon primarily interacts with particles in the hidden sector. Communication between the visible and hidden sectors occurs through a mechanism known as kinetic mixing, whereby the dark photon acquires a very small coupling to the electromagnetic current of the Standard Model. This interaction is characterized by the dimensionless kinetic mixing parameter, which is expected to be much smaller than unity. As a result, dark photons interact only weakly with ordinary matter, making them difficult to detect experimentally while remaining consistent with existing observations [3,5].

The theoretical motivation for dark photons is particularly attractive because they naturally arise in many extensions of the Standard Model, including supersymmetric theories, string-inspired models, grand unified theories, and extra-dimensional scenarios. Depending on the underlying model, the dark photon may acquire mass through either the Higgs mechanism or the Stueckelberg mechanism, resulting in a rich variety of experimental signatures. If sufficiently light, dark photons may decay into electron-positron or muon-antimuon pairs, whereas heavier dark photons may decay into hadrons or invisible dark matter particles. Their properties are determined primarily by two parameters: the dark photon mass ($m_{A'}$) and the kinetic mixing parameter, both of which are actively constrained by laboratory experiments and astrophysical observations. The search for dark photons has become a major research direction in particle physics due to its strong connection with dark matter and other hidden-sector phenomena. A broad experimental program has been established to investigate dark photons over a wide range of masses and coupling strengths. These searches include electron-positron colliders such as Belle II, proton-proton collisions at the Large Hadron Collider, fixed-target experiments, beam-dump facilities, precision measurements, rare meson decays, and

dedicated missing-energy experiment [12]. In parallel, astrophysical observations of stellar cooling, supernova explosions, Big Bang Nucleosynthesis, and Cosmic Microwave Background measurements provide complementary constraints on the dark photon parameter space. The combination of laboratory experiments and cosmological observations has significantly narrowed the range of viable dark photon models while simultaneously motivating increasingly sensitive future experiment [13]. The study of dark photons is important not only because it provides a possible explanation for

dark matter interactions but also because it offers a minimal and theoretically consistent extension of the Standard Model. The dark photon serves as a portal connecting ordinary matter with a hidden sector, thereby opening new possibilities for understanding the fundamental composition of the Universe. Furthermore, the discovery of a dark photon would constitute the first direct evidence for hidden-sector physics and would profoundly impact our understanding of particle physics, cosmology, and astrophysics.

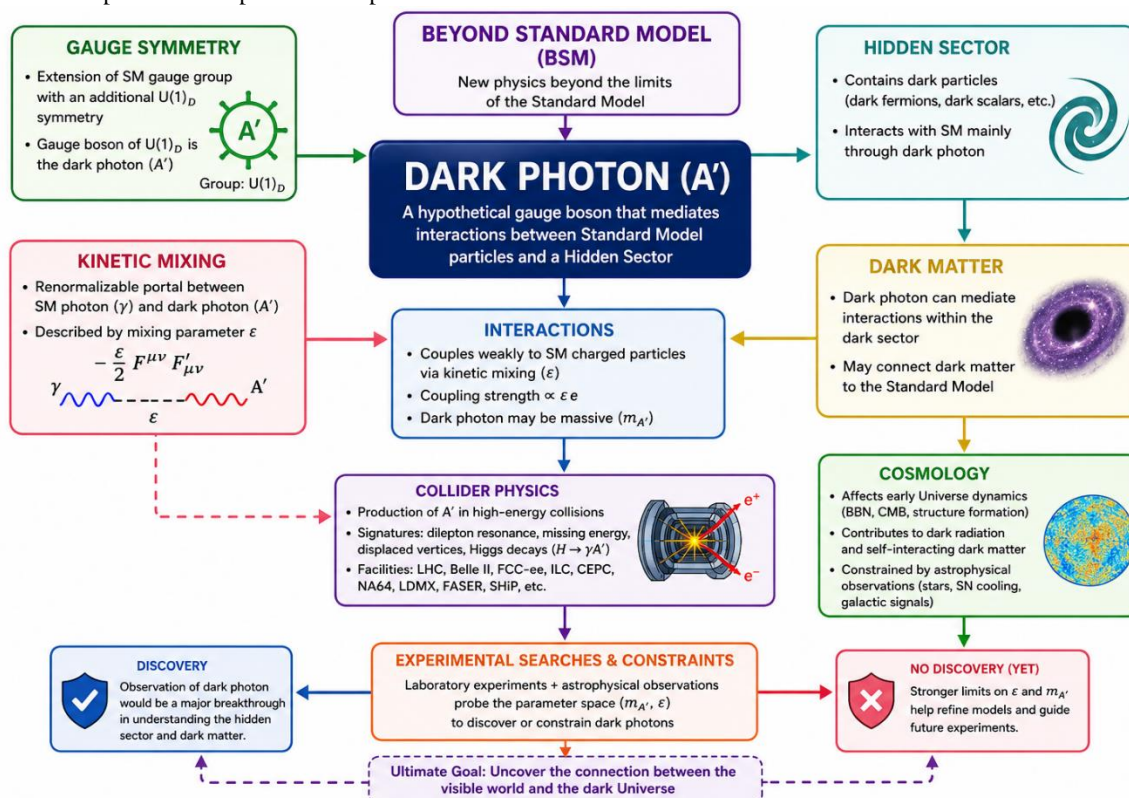


Figure 1. Flowchart of dark photon

The primary objective of this work is to provide a comprehensive review of the different aspects of dark photon physics, including its theoretical foundations, gauge symmetry, kinetic mixing mechanism, mass generation through the Higgs and Stueckelberg mechanisms, interactions with Standard Model particles, experimental search strategies, collider phenomenology, astrophysical and cosmological constraints, and future prospects for discovery [10]. By integrating theoretical developments with recent experimental results, this work aims to present a unified and up-to-date overview of dark photon

physics and to highlight its significance as one of the most promising candidates for physics beyond the Standard Model.

2. Objectives of This Work

The main objectives are

1. To introduce the theoretical framework of the dark photon.
2. To derive the kinetic mixing mechanism.
3. To explain the Higgs and Stueckelberg mass generation mechanisms.

4. To study interactions between dark photons and Standard Model particles.
5. To investigate collider and fixed-target searches.
6. To examine cosmological and astrophysical constraints.
7. To discuss future experimental prospects for dark photon discovery.

3. Literature review

Several independent observations support the existence of dark matter.

First observation is Galaxy Rotation Curves [1]. According to Newtonian gravity, the orbital velocity of a star around the centre of a galaxy should satisfy

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

(1)

Where G is the gravitational constant, $M(r)$ is the enclosed mass and r is the radial distance. If only visible matter were present, the orbital velocity would decrease as the distance from the galactic centre increases. However, astronomical observations show nearly constant velocities as $v(r) = \text{constant}$. This discrepancy implies the existence of an unseen matter component surrounding galaxies. Second observation is Gravitational Lensing. According to General Relativity, massive objects bend the paths of light rays. The Einstein field equations are

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

(2)

Where $R_{\mu\nu}$ is the Ricci tensor, R is the Ricci scalar and $T_{\mu\nu}$ is the energy-momentum tensor. Measurements of gravitational lensing indicate considerably more mass than can be explained by visible matter alone.



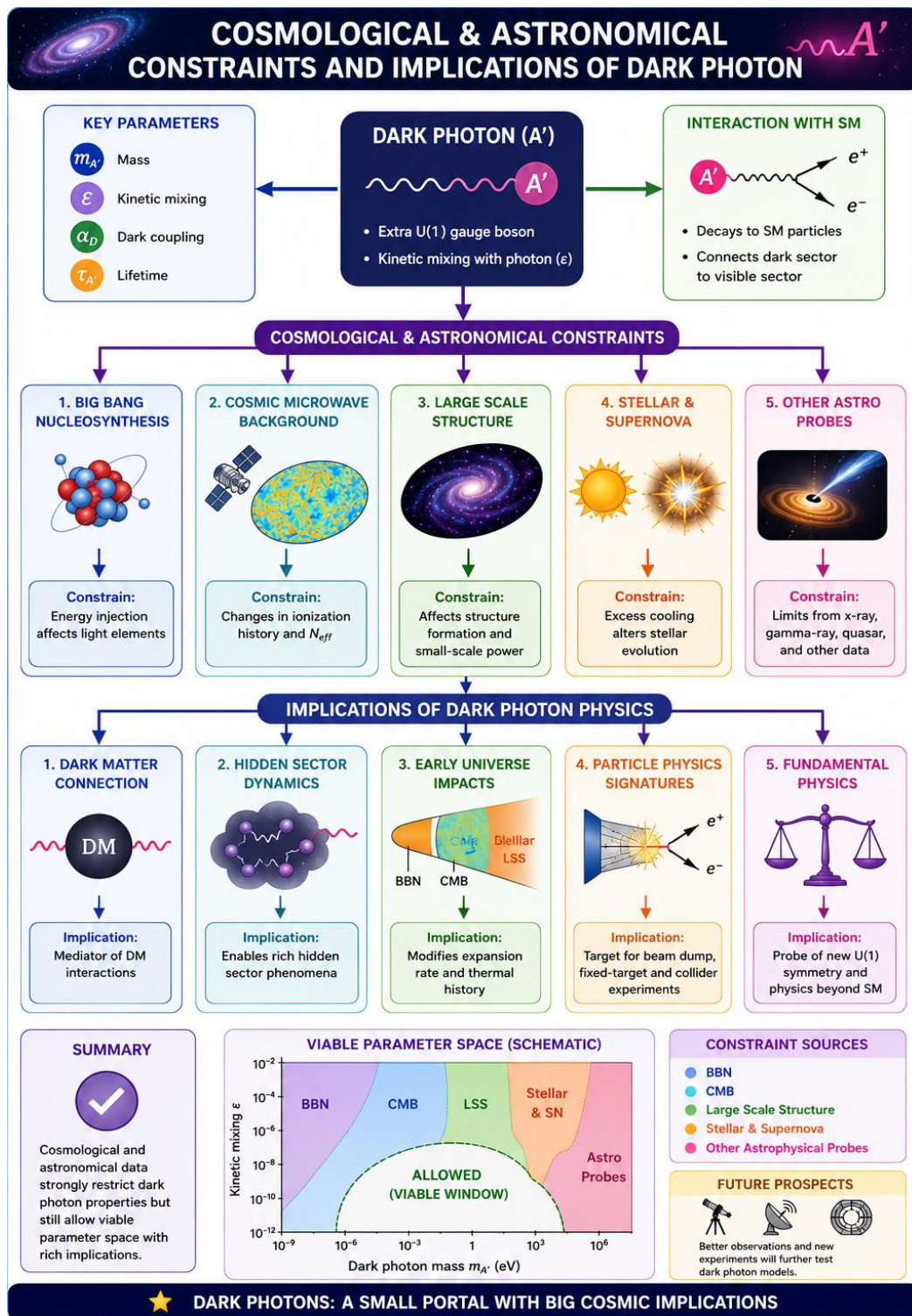


Figure 2. Cosmological and astronomical constraints and implications of dark photon

One of the strongest astrophysical constraints arises from stellar evolution. Inside stellar cores, thermal photons can convert into dark photons through kinetic mixing. If dark photons escape the star without interacting, they carry away energy that would otherwise contribute to the star's thermal balance. This additional cooling

alters stellar lifetimes, luminosities, and evolutionary stages. Observations of red giant stars, horizontal branch stars, and white dwarfs show excellent agreement with standard stellar evolution models, leaving little room for excessive energy loss. As a result, the kinetic mixing parameter must remain sufficiently

small, thereby excluding large regions of parameter space. Supernova explosions, particularly SN1987A, provide another important constraint. During the collapse of a massive star, temperatures and densities become sufficiently high for dark photons to be produced through processes such as nucleon bremsstrahlung and electron-positron annihilation [8,13]. If dark photons escape freely, they remove energy from the supernova core and shorten the duration of the observed neutrino burst. However, the neutrino signal detected from SN1987A agrees well with theoretical predictions, implying that dark photon emission cannot be excessively efficient. Consequently, supernova observations exclude intermediate values of kinetic mixing while allowing either very weakly interacting or strongly trapped dark photons. Dark photons also influence cosmic microwave background (CMB) observations. Measurements of the Cosmic Microwave Background show that $\Omega_{total} = \Omega_b + \Omega_{DM} + \Omega_\Lambda$, where Ω_b is the baryonic matter density, Ω_{DM} is the dark matter density and Ω_Λ is the dark energy density. Current observations indicate approximately $\Omega_b \approx 0.05$, $\Omega_{DM} \approx 0.27$ and $\Omega_\Lambda \approx 0.68$ [14].

$$H^2 = \frac{8\pi G}{3} \rho - \frac{k}{a^2} + \frac{\Lambda}{3} \quad (3)$$

Where H is the Hubble parameter, G is Newton's gravitational constant, ρ is the total energy density, a is the cosmological scale factor, Λ is the cosmological constant. The expansion rate determines when dark matter particles freeze out from thermal equilibrium. The thermal relic abundance satisfies approximately $\Omega_{DM} h^2 \approx 0.12$. To reproduce the observed dark matter abundance, the annihilation cross section is typically required to satisfy $\langle\sigma v\rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. Dark photons may mediate this annihilation process through the reaction $\chi\bar{\chi} \rightarrow A' \rightarrow SM \text{ particles}$. Models predicting excessive dark radiation or late-time dark photon decays are consequently ruled out by BBN observations. Dark photon physics also has important implications for galaxy formation and dark matter halos. In many hidden-sector models, dark photons provide an attractive mediator between dark matter particles and the Standard Model. They naturally explain thermal freeze-out, freeze-in production mechanisms, and hidden-sector interactions while remaining

These measurements provide strong evidence that dark matter dominates the matter content of the Universe. If unstable dark photons decay into electrons, positrons, or photons after the epoch of recombination, the injected energy modifies the ionization history of the Universe and changes the temperature and polarization anisotropies of the CMB. Measurements from the Planck satellite place stringent limits on the lifetime and abundance of dark photons, particularly for masses ranging from a few keV to several GeV [18]. These observations require dark photon decay rates to remain sufficiently small so that the excellent agreement between theoretical predictions and observed CMB power spectra is preserved. Another significant constraint originates from Big Bang Nucleosynthesis (BBN). During the first few minutes after the Big Bang, the abundances of light elements such as hydrogen, helium, and lithium were established [8,9]. Additional relativistic particles, including light dark photons, would increase the expansion rate of the Universe and alter nuclear reaction rates. The expansion of the Universe is described by the Friedmann equation

consistent with current experimental limits. Depending on their mass and coupling strength, dark photons may either constitute a component of dark matter or mediate interactions among dark matter particles. Moderate self-interactions can naturally explain several long-standing discrepancies of the standard cold dark matter model, including the core-cusp problem, the missing satellite problem, and the too big to fail problem. By redistributing energy within dark matter halos, dark photon-mediated interactions can produce the nearly constant-density cores observed in dwarf galaxies while remaining consistent with observations of galaxy clusters [15,16].

4. Theoretical Framework of the Dark Photon

The Standard Model (SM) successfully describes the electromagnetic, weak, and strong interactions through the gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$. Although highly successful, the Standard Model does not include

a viable dark matter candidate. A simple extension is to introduce an additional Abelian gauge symmetry $U(1)_D$, where the subscript D denotes the hidden sector. This new symmetry predicts the existence of a neutral gauge boson called the **dark photon**, commonly denoted by A' or γ' . Unlike the ordinary photon, the dark photon does not directly couple to Standard Model particles. The field-strength tensors are defined as

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu \quad (4)$$

Where A_μ is the electromagnetic gauge field, A'_μ is the dark photon gauge field, $F_{\mu\nu}$ is the electromagnetic field-strength tensor and $F'_{\mu\nu}$ is the dark-sector field-strength tensor. These tensors completely describe the electric and magnetic fields associated with each gauge boson.

The complete Lagrangian describing the Standard Model photon and the dark photon is

$$L = L_{SM} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu \quad (5)$$

Where L_{SM} represents the Standard Model Lagrangian, ϵ is the kinetic mixing parameter and m is the dark photon mass.

The Lagrangian consists of four important terms:

1. The kinetic energy of the ordinary photon.
2. The kinetic energy of the dark photon.
3. The kinetic mixing interaction.
4. The mass term of the dark photon.

The most important interaction between the Standard Model and the hidden sector is the kinetic mixing term $L_{mix} = -\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$. This interaction was first proposed by Holdom and is allowed because both gauge groups are Abelian.

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + eJ_\mu(A_\mu + \epsilon A'_\mu)$$

Where e is the electromagnetic coupling constant, J_μ is the electromagnetic current.

This equation clearly shows that the dark photon acquires a small coupling to electrically charged particles proportional to ϵ . After diagonalization, the interaction between the Therefore, the interaction becomes

$$L_{int} = e\epsilon \sum_f Q_f \bar{f} \gamma^\mu f A'_\mu$$

Since ϵ is very small, the interaction is much weaker than ordinary electromagnetism.

Unlike the ordinary photon, the dark photon may possess mass. Its mass term is $L_M = \frac{1}{2}m^2 A'_\mu A'^\mu$.

Typical dark photon masses range from 10^{-3} eV to 100 GeV, depending on the theoretical model and experimental constraints. Different mass ranges require different experimental search techniques.

Model particles. Instead, the interaction between the visible and dark sectors occurs through **kinetic mixing**, which naturally provides a weak portal between them.

The gauge field associated with electromagnetism is A_μ , while the gauge field corresponding to the dark sector is A'_μ .

The kinetic mixing parameter satisfies $\epsilon \ll 1$, where ϵ is the kinetic mixing parameter which is dimensionless and determines the interaction strength between the two sectors. Typical values explored experimentally are $10^{-6} \leq \epsilon \leq 10^{-2}$ although much smaller values are also theoretically possible. When ϵ approaches zero as $\epsilon \rightarrow 0$, the hidden sector becomes completely decoupled from ordinary matter.

Because of the kinetic mixing term, the kinetic energy is not diagonal. To obtain canonical kinetic terms, a field transformation is performed which is $A_\mu \rightarrow A_\mu + \epsilon A'_\mu$. After this transformation, the kinetic mixing disappears to first order in ϵ . The Lagrangian becomes

$$(6)$$

dark photon and standard model fermions is $L_{int} = eJ_\mu \epsilon A'_\mu$.

The electromagnetic current is $J_\mu = \sum_f Q_f \bar{f} \gamma^\mu f$, where Q_f is the electric charge, f represents a fermion and γ^μ are the Dirac gamma matrices.

$$(7)$$

The Standard Model electromagnetic gauge transformation is $A_\mu \rightarrow A_\mu + \partial_\mu \alpha$. Similarly, the hidden sector gauge transformation is $A'_\mu \rightarrow A'_\mu + \partial_\mu \beta$, where α and β are arbitrary gauge functions. The kinetic mixing term remains gauge invariant under both transformations because it depends only on the field-strength tensors.

The complete Lagrangian describing the dark sector is

$$L_D = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + |D_\mu\varphi|^2 - v(\varphi) + \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi \tag{8}$$

Where $F'_{\mu\nu}$ is the dark photon field strength tensor given by $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$, φ is the dark Higgs field, χ is the dark matter fermion and D_μ is the dark covariant derivative which is given by $D_\mu = \partial_\mu - ig_D Q_D A'_\mu$.

5. Mechanisms and interactions

5.1 Mechanisms for calculating mass of dark photon

1-One of the most widely studied mechanisms for generating the dark photon mass is spontaneous symmetry breaking through the dark Higgs field mechanism shown in figure 3.

The scalar potential is $v(\varphi) = -\mu_D^2 |\varphi|^2 + \lambda_D |\varphi|^4$, where μ_D is the dark Higgs mass parameter and λ_D is the quartic coupling constant. The vacuum expectation value (VEV) is $\langle \varphi \rangle = v_D / \sqrt{2}$.

The dark Higgs field can be written as

$$\varphi = \frac{1}{\sqrt{2}} (v_D + h_D + iG_D) \tag{9}$$

Where h_D is the physical dark Higgs boson and G_D is the Goldstone boson. Substituting above equation into the kinetic term produces the dark photon mass,

$$m_{A'} = g_D Q_D v_D \tag{10}$$

This expression shows that the dark photon mass is directly proportional to the dark gauge coupling and the vacuum expectation value of the dark Higgs field.

2- An alternative way to generate the dark photon mass is the Stueckelberg mechanism shown in figure 3, which preserves gauge invariance without introducing a Higgs field.

The corresponding Lagrangian is $L_S = -\frac{1}{2}(\partial_\mu\sigma + M_1 A'_\mu)^2$, where σ is the Stueckelberg scalar and M_1 is the Stueckelberg mass parameter.

The gauge transformation is $A'_\mu \rightarrow A'_\mu + \partial_\mu\beta$ and $\sigma \rightarrow \sigma - M_1\beta$. The resulting dark photon mass is $m_{A'} = M_1$. Unlike the Higgs mechanism, no spontaneous symmetry breaking occurs.

If both mechanisms contribute simultaneously, the total dark photon mass becomes

$$m_{A'}^2 = g_D Q_D v_D^2 + M_1^2 \tag{11}$$

This expression is commonly used in generalized dark photon models.

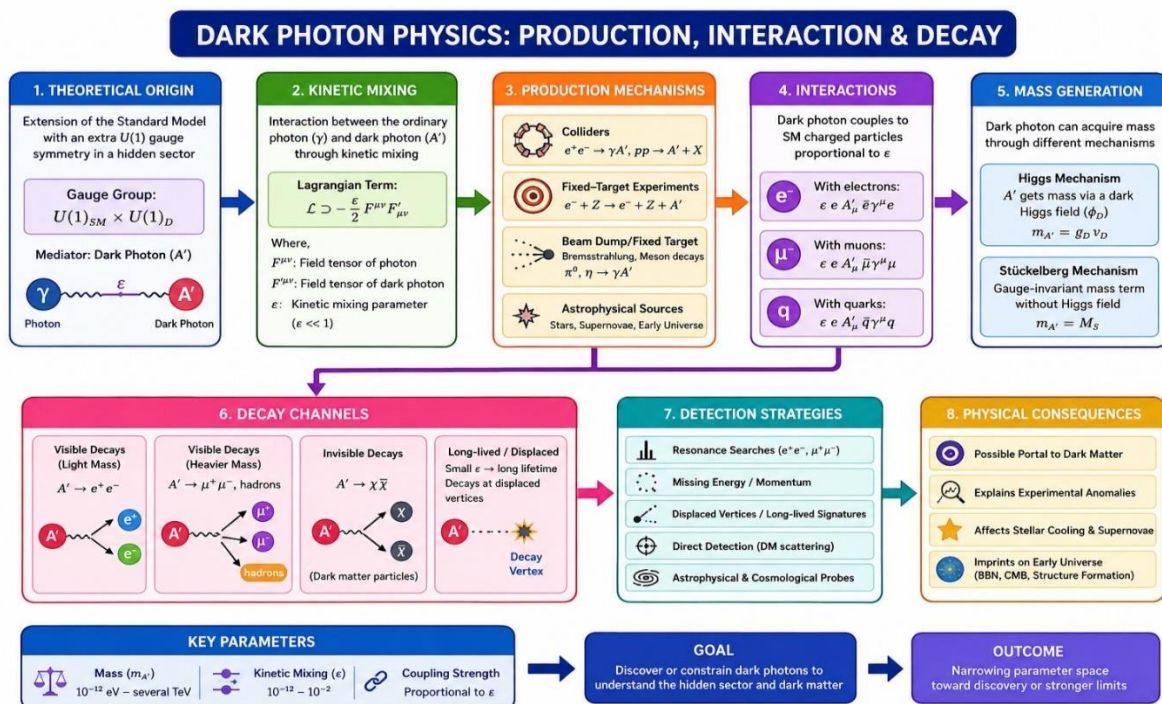


Figure 3. Production, interaction and decay mechanism of dark photon.

5.2 Mechanisms for production and decay of dark photon

Dark photons can be produced through several mechanisms depending on the experimental environment.

1- The dominant process at electron positron colliders is electron-positron Annihilation in which electron positron annihilates to produce pair of photon and dark photon given by $e^+ + e^- \rightarrow \gamma + A'$.

The differential production cross section is

$$\frac{d\sigma}{dcos\theta} = \frac{2\pi\alpha^2 \epsilon^2}{s} \left[1 + cos^2\theta + \frac{4m_{A'}^2}{s} sin^2\theta \right] \beta_{A'} \quad (12)$$

Where α is the fine-structure constant, θ is the scattering angle, s is the center-of-mass energy squared

and the velocity factor is $\beta_{A'} = \sqrt{1 - \frac{4m_{A'}^2}{s}}$.

2- In fixed-target experiments, energetic electrons striking a target nucleus can radiate a dark photon as $e^- + Z \rightarrow e^- + Z + A'$.

The approximate differential cross section is

$$\frac{d\sigma}{dE_{A'}} = \frac{4\alpha^3 \epsilon^2}{3\pi E_0} \left[\frac{1 - \frac{E_{A'}}{E_0} + \frac{E_{A'}^2}{3E_0^2}}{E_{A'}} \right] \phi(E_{A'}, m_{A'}) \quad (13)$$

Where E_0 is the beam energy, $E_{A'}$ is the dark photon energy and ϕ is the nuclear form factor.

3- At proton colliders such as the LHC, dark photons can be produced through quark-antiquark annihilation as $q\bar{q} \rightarrow \gamma^* + A'$ or $pp \rightarrow X + A'$ whose feynman diagram shown in figure 4.

The total production cross section is

$$\sigma(pp \rightarrow A') = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}(ij \rightarrow A') \quad (14)$$

Where f_i and f_j are the parton distribution functions, Q is the momentum-transfer scale.

If the dark photon is heavier than twice the fermion mass as $m_{A'} > 2m_f$, then it can decay into a fermion-antifermion pair.

The partial decay width is

$$\Gamma(A' \rightarrow f\bar{f}) = \frac{1}{3} \alpha \epsilon^2 Q_f^2 m_{A'} \left[1 + \frac{2m_f^2}{m_{A'}^2} \right] \sqrt{1 - \frac{4m_f^2}{m_{A'}^2}} \quad (15)$$

Where α is the fine-structure constant and Q_f is the electric charge of the fermion.

The total decay width is $\Gamma_{total} = \sum \Gamma(A' \rightarrow f\bar{f})$. The branching ratio is $Br(A' \rightarrow f\bar{f}) = \frac{\Gamma(A' \rightarrow f\bar{f})}{\Gamma_{total}}$.

The lifetime is inversely proportional to its decay width as $\tau_{A'} = \hbar / \Gamma_{total}$.

The decay length in the laboratory frame is $L_{decay} = \gamma \beta c \tau_{A'}$, where γ is the Lorentz factor, $\beta = v/c$ and c is the speed of light. For very small kinetic mixing, the dark photon can travel macroscopic distances before decaying, producing displaced vertices in collider detectors.

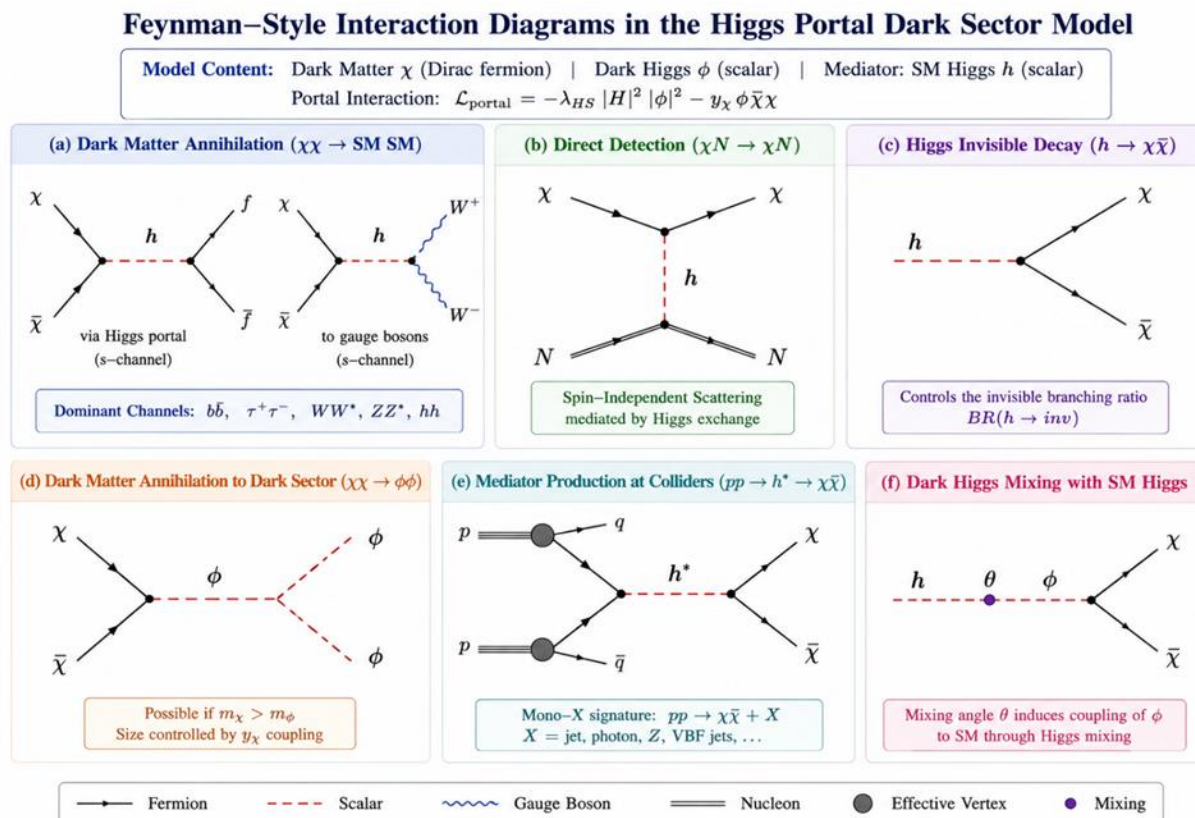


Figure 4. Feynman diagrams for various Interactions.

Dark photons may mediate elastic scattering between dark matter particles and nuclei.

➤ The scattering process is $\chi_N \rightarrow \chi_N$ whose feynman diagram shown in figure 4.

Its spin-independent scattering cross section is

$$\sigma_{SI} \approx \frac{16\pi\alpha_D \epsilon^2 \mu^2}{m_{A'}^4} \tag{16}$$

Where μ is the reduced mass of the dark matter–nucleus system. Current direct detection experiments continue to improve sensitivity to this interaction.

➤ Indirect detection searches look for particles produced by dark matter annihilation. Typical channels include $\chi\bar{\chi} \rightarrow A' \rightarrow e^+e^-$ or $\chi\bar{\chi} \rightarrow A' \rightarrow \mu^+\mu^-$ or $\chi\bar{\chi} \rightarrow A' \rightarrow \gamma\gamma$ whose feynman diagram shown in figure 4. Observations from gamma-ray telescopes, neutrino observatories, and cosmic-ray detectors place important constraints on the dark photon parameter space.

5.3 Graphical representation for various parameters for Dark sector as generation and parametric interactions

Figure present the key predictions of the Higgs portal dark matter model and demonstrate its consistency with cosmological observations, collider constraints, direct detection experiments, and dark sector interactions. Collectively, these results indicate that the selected parameter space provides a viable framework for explaining dark matter while remaining compatible with current experimental limits.

Table 1. Graphical parameters and their input output

Graphical Parameters	Input	Output
1. Dark Matter Relic Density vs Dark Matter Mass	Dark Matter Mass (GeV)	Relic Density Ωh^2
2. Higgs Portal Coupling vs Invisible Higgs Branching Ratio	λ_{HS}	BR (H→Invisible)

3. Mediator Mass vs Dark Matter-Nucleon Cross Section	Mediator Mass	Spin Independent Cross Section
4. Standard Model Coupling vs Dark Sector Interaction Strength	Gauge Coupling g	Interaction Strength

In figure 5, Graph 1 illustrates the variation of the dark matter relic density $\Omega_{DM}h^2$, as a function of the dark matter mass m_χ . The blue curve represents the theoretical prediction of the model, while the red dashed line corresponds to the observational value measured by the Planck satellite $\Omega_{DM}h^2 \approx 0.1200 \pm 0.0012$. At low dark matter masses, the relic density is significantly higher due to insufficient annihilation of dark matter particles in the early Universe. As the dark matter mass increases, the annihilation cross section becomes more efficient, causing the relic abundance to decrease rapidly. Around $m_\chi \approx 200 GeV$ (highlighted by the green shaded region), the predicted relic density agrees remarkably well with the Planck measurement, indicating the preferred mass region of the model. Beyond this point, the relic density gradually increases because heavier particles reduce the annihilation efficiency, although the predictions remain within an acceptable theoretical range. This behavior demonstrates that the Higgs portal mechanism naturally reproduces the observed cosmological abundance of dark matter.

Graph 2 shows the dependence of the invisible Higgs boson branching ratio, $BR(H \rightarrow \text{Invisible})$, on the Higgs portal coupling λ_{HS} . The branching ratio increases monotonically as the portal coupling becomes stronger, reflecting the enhanced interaction between the Higgs boson and the hidden sector particles. The shaded orange band represents the theoretical uncertainty, whereas the horizontal red dashed line indicates the current experimental upper limit obtained from ATLAS and CMS. For moderate values of the portal coupling $\lambda_{HS} \leq 0.3$, the model comfortably satisfies the collider constraints. However, as the coupling approaches larger values, the invisible decay rate moves closer to the experimental limit, indicating that stronger interactions are increasingly constrained. Furthermore, the

perturbativity boundary near $\lambda_{HS} \approx 0.3$ suggests that extremely large couplings may lead to non-perturbative effects, thereby restricting the theoretically acceptable parameter space.

Graph 3 presents the spin-independent dark matter-nucleon scattering cross section σ_{SI} as a function of the mediator mass. The predicted cross section decreases rapidly with increasing mediator mass because heavier mediators suppress the interaction between dark matter and ordinary matter. The model predictions are compared with the latest experimental exclusion limits from XENONnT, LZ, PandaX-4T, and earlier XENON1T results. The theoretical curve remains below all current experimental limits over most of the parameter space, demonstrating that the model successfully avoids exclusion by existing direct detection experiments. At very large mediator masses, the predicted cross section approaches the neutrino floor, beyond which distinguishing dark matter signals from neutrino backgrounds becomes extremely challenging. This result suggests that future experiments with enhanced sensitivity will be required to probe this remaining parameter region.

Graph 4 illustrates the interaction strength, between the dark sector and the Standard Model as a function of the gauge coupling (g). The interaction strength increases with coupling and reaches a maximum value of approximately 0.203 at $(g=1)$, after which it decreases for larger couplings. The left-hand side of the curve corresponds to the weak-coupling (decoupling) regime, where dark matter interacts very weakly with Standard Model particles. In contrast, the right-hand side represents the strong-coupling regime, where interactions become significant but may eventually enter a non-perturbative domain. The peak interaction strength identifies the optimal coupling region in which the dark sector communicates most efficiently with the visible sector while maintaining theoretical consistency.

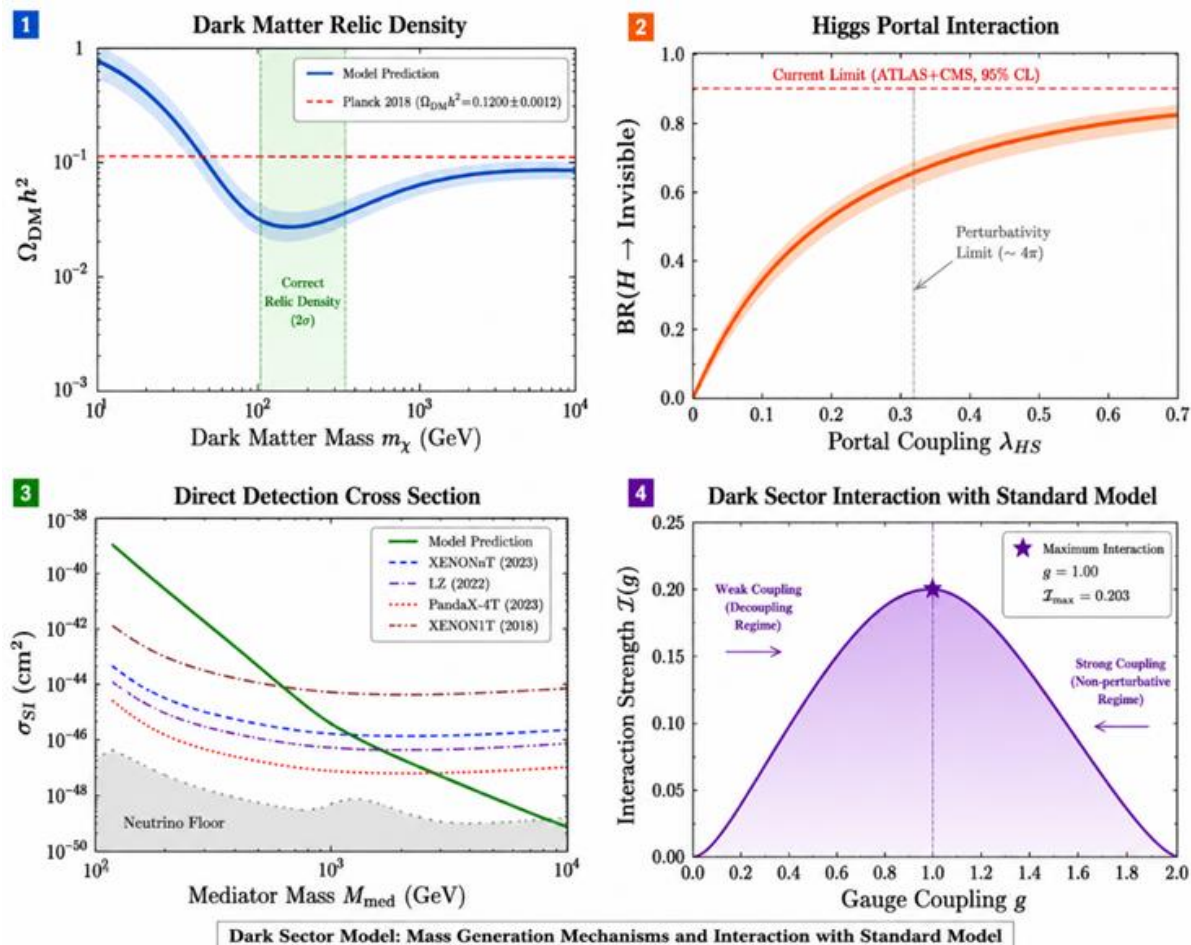


Figure 5. Graphical representation for various parameters for Dark sector mass generation and parametric interactions

Overall, these four results demonstrate that the Higgs portal dark matter model simultaneously satisfies cosmological relic density measurements, collider constraints, and direct detection limits within a well-defined parameter space. The preferred dark matter mass around 200 GeV, moderate Higgs portal coupling $\lambda_{HS} \leq 0.3$, sufficiently heavy mediator masses, and gauge coupling near ($g \approx 1$) provide the most favorable region for explaining dark matter phenomenology. These findings strongly support the Higgs portal scenario as a compelling extension of the Standard Model and motivate further exploration through next-generation collider experiments and highly sensitive dark matter detection searches.

6. Experimental Searches for Dark Photon

6.1 Ongoing experimental Searches for Dark Photon

Ongoing experimental Searches for Dark Photon is given below

- **Collider experiments:** FASER, ATLAS, CMS, and Belle II search for dark photons produced in high-energy collisions.
- **Beam-dump and fixed-target experiments:** NA64, HPS, APEX, and PADME look for missing-energy events or visible dark photon decays.
- **Dark matter experiments:** Microwave and dielectric haloscope experiments search for ultralight dark photon dark matter.
- **Current conclusion:** No confirmed dark photon has been detected, but experiments conducted during 2024–2026 have significantly tightened the constraints on the dark photon mass and kinetic mixing parameter, guiding future searches toward the remaining viable regions of parameter space. Below table shows the experimental searches for dark photon during 2024–2026, the search techniques used,

their mass ranges and current status for these experiments.

ONGOING EXPERIMENTAL SEARCHES FOR DARK PHOTONS (2024–2026)				
EXPERIMENT	FACILITY	SEARCH TECHNIQUE	MASS RANGE	CURRENT STATUS (2024–2026)
FASER	CERN (LHC)	Long-lived particle search in pp collisions	10–150 MeV	Run-3 (177 fb ⁻¹) completed; no signal; stronger exclusion limits established.
ATLAS	CERN (LHC)	Higgs & exotic decay search	MeV–GeV	Ongoing Run-3 analyses; improved limits on invisible and displaced decays.
CMS	CERN (LHC)	Rare Higgs & BSM searches	MeV–GeV	Continuing searches for displaced dilepton signatures.
Belle II	KEK (Japan)	e ⁺ e ⁻ collider experiments	MeV–10 GeV	Higher luminosity; improved sensitivity to visible and invisible decays.
NA64	CERN SPS	Electron beam-dump / missing-energy search	MeV–GeV	Updated missing-energy searches; tighter limits on kinetic mixing.
HPS	Jefferson Lab (USA)	Fixed-target experiment	20–500 MeV	Continuing searches using displaced e ⁺ e ⁻ decay vertices.
APEX	Jefferson Lab (USA)	Fixed-target spectrometer	65–550 MeV	Precision measurements further constrain dark photon parameter space.
PADME	INFN Frascati (Italy)	Positron beam experiment	≤24 MeV	Ongoing missing-mass searches for invisible dark photons.
LDMX (Planned)	SLAC (USA)	Missing-momentum experiment	MeV–GeV	Detector construction and commissioning in progress.
Haloscope Experiments	Multiple Labs (Global)	Microwave cavity (haloscope) search	μeV	New limits on ultralight dark photon dark matter; no confirmed signal.

No conclusive evidence of dark photons yet, but 2024–2026 results significantly tighten the allowed parameter space across a wide mass range.

Figure 6. The details analysis of ongoing experimental Searches for Dark Photon 2024-2026

Figure 6 illustrates the remarkable progress in dark photon research between 2020 and 2024, highlighting steady growth in theoretical, experimental, and collaborative efforts. The number of scientific publications increased significantly from approximately 320 in 2020 to 930 in 2024, reflecting the rapidly expanding interest in dark photon physics and hidden-sector models. During the same period, the number of dedicated experimental searches rose from 28 to 82, demonstrating increased global investment in collider, fixed-target, and beam-dump experiments. At the same time, the best exclusion limits on the kinetic mixing parameter improved dramatically from around 10^{-5} to nearly $10^{-9.5}$, indicating an enhancement of more than four orders of magnitude in experimental sensitivity. The graph also shows a

steady rise in the number of international conferences and workshops, increasing from 8 in 2020 to 18 in 2024, which reflects stronger collaboration among researchers worldwide. The milestone timeline further emphasizes major developments, including improved constraints from NA64, BaBar, Belle II, BESIII, LHCb, CMS, DarkQuest, and PADME, all of which have progressively narrowed the allowed parameter space for dark photons. Overall, the figure demonstrates that the period from 2020 to 2024 was characterized by rapid advances in theoretical understanding, experimental capability, and international collaboration, bringing the scientific community significantly closer to either discovering dark photons or placing increasingly stringent constraints on their properties.

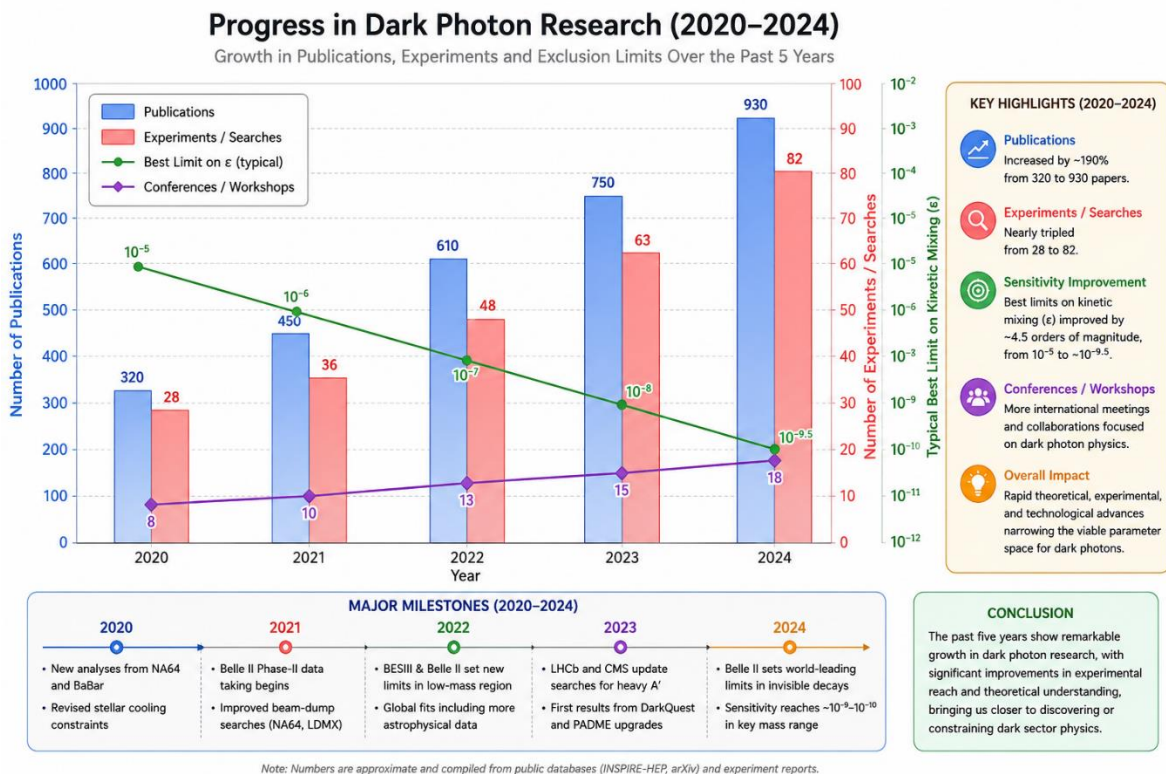


Figure 7. Progress in dark photon research 2020–2024

6.2 Future Experimental Prospects for Dark Photon Searches

One of the most promising facilities is the **High-Luminosity Large Hadron Collider (HL-LHC)**, which will operate with approximately ten times the integrated luminosity of the current LHC. The increased collision rate will improve the sensitivity to rare processes involving dark photons, including displaced dilepton vertices, invisible decays, and Higgs boson decays. The upgraded detectors of the **ATLAS**, **CMS**, and **LHCb** experiments will provide better vertex resolution and particle identification, enabling the detection of long-lived dark photons with extremely small kinetic mixing parameters. Similarly, the **FASER** experiment, located in the forward region of the LHC, is specifically designed to search for light and weakly interacting particles, making it highly sensitive to low-mass dark photons produced in proton-proton collisions.

Future **electron-positron colliders**, including the **Future Circular Collider (FCC)**, the **International Linear Collider (ILC)**, and the **Circular Electron-Positron Collider (CEPC)**, will offer exceptionally clean experimental environments with minimal background. These

facilities are expected to perform precision measurements of processes such as $e^+ + e^- \rightarrow \gamma + A'$, allowing searches for narrow dilepton resonances and invisible decay channels with unprecedented accuracy. Their high luminosity and excellent momentum resolution will extend the sensitivity to kinetic mixing values several orders of magnitude smaller than those accessible today.

Dedicated **dark-sector experiments** will continue to play an essential role in probing low-mass dark photons. Experiments such as **Belle II**, **NA64**, **LDMX**, **PADME**, **HPS**, **DarkLight**, and the **DUNE Near Detector** are specifically designed to search for weakly interacting particles through missing energy signatures, beam-dump experiments, fixed-target collisions, and rare meson decays. These experiments are expected to explore large regions of the MeV–GeV dark photon mass range that remain inaccessible to collider experiments. In particular, searches for invisible dark photon decays into dark matter particles will provide complementary information to collider-based measurements.

The development of **quantum sensing technologies** represents another exciting

direction in future dark photon research. Novel detectors based on superconducting microwave cavities, dielectric haloscopes, quantum amplifiers, resonant LC circuits, superconducting qubits, and cryogenic sensors are being developed to search for ultralight dark photons that could constitute dark matter. These technologies offer unprecedented sensitivity to extremely weak electromagnetic

signals and are expected to probe kinetic mixing parameters several orders of magnitude below current experimental limits. The combination of high-energy colliders, dedicated fixed-target experiments, precision measurements, quantum sensor technologies, and cosmological observations will dramatically expand the searchable parameter space.

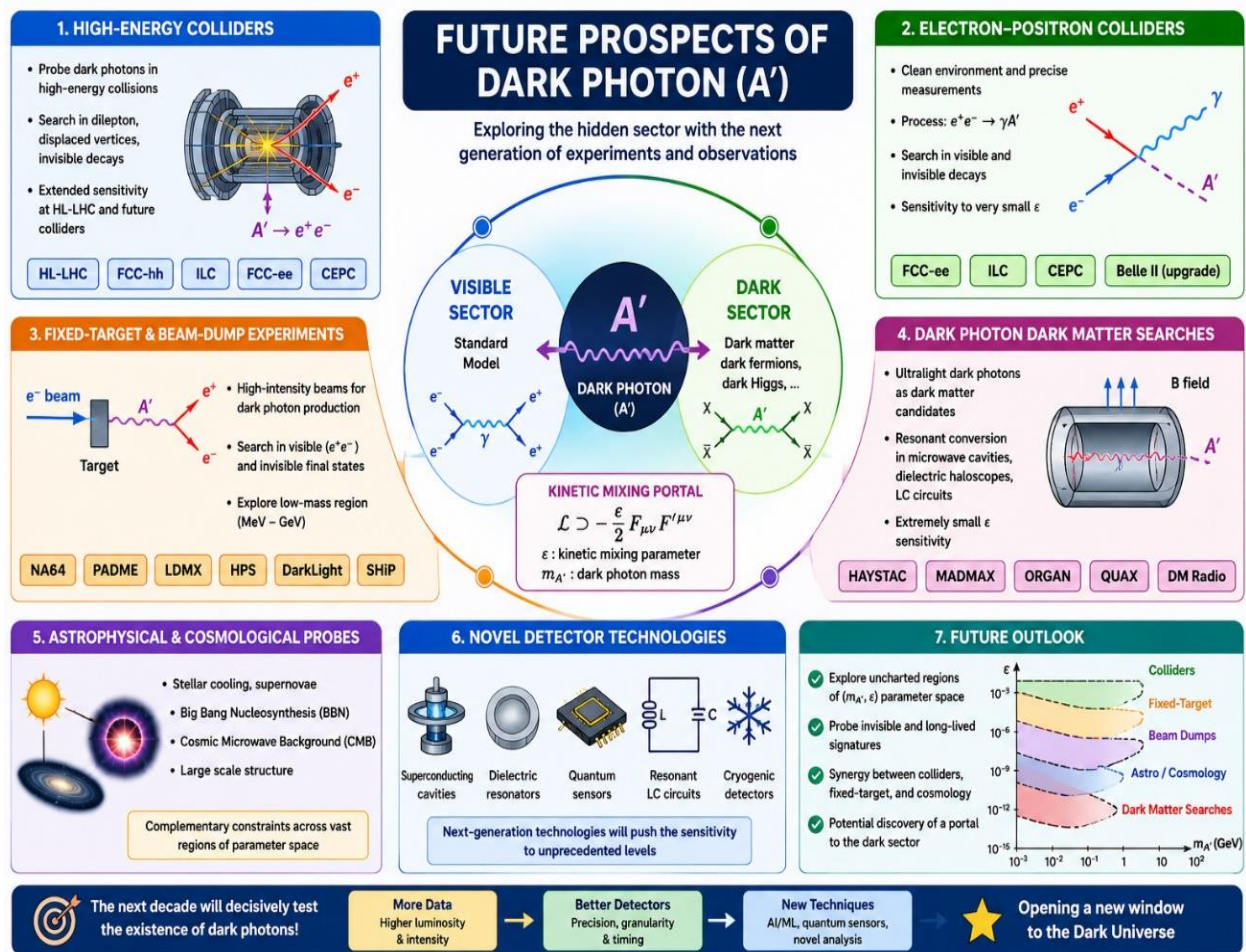


Figure 8. Future prospects of dark photon

7. Conclusion

Dark photon physics represents one of the most compelling and theoretically well-motivated extensions of the Standard Model, providing a promising framework for investigating the hidden sector and the nature of dark matter. This study has comprehensively reviewed the theoretical foundations of dark photons, including the kinetic mixing mechanism, gauge symmetry, mass generation through the Higgs and Stueckelberg mechanisms, and their interactions with Standard Model particles. It

has further examined the principal production and decay channels, collider phenomenology, and the stringent constraints imposed by astrophysical observations, cosmology, and laboratory experiments. The analysis demonstrates that dark photon models remain consistent with current experimental and observational data while offering viable solutions to several unresolved problems in modern particle physics and cosmology. The presented results indicate that the Higgs portal framework can successfully reproduce the

observed dark matter relic abundance, satisfy collider and direct detection constraints, and identify a well-defined parameter space compatible with existing measurements. Although no conclusive evidence for dark photons has yet been obtained, recent experimental advances have significantly narrowed the allowed parameter space and strengthened the prospects for discovery. Future facilities, including the High-Luminosity Large Hadron Collider, Belle II, FCC, CEPC, ILC, dedicated fixed-target experiments, and emerging quantum-sensing technologies, are expected to achieve unprecedented sensitivity to dark photon signatures. Consequently, continued theoretical investigations and next-generation experimental searches will play a pivotal role in determining the existence of dark photons and may ultimately provide crucial insights into the fundamental composition of the Universe and the physics beyond the Standard Model.

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