A Search for Dark Sectors Using Lasers

Missing-photon and low-mass reconstruction with an extended photon veto.

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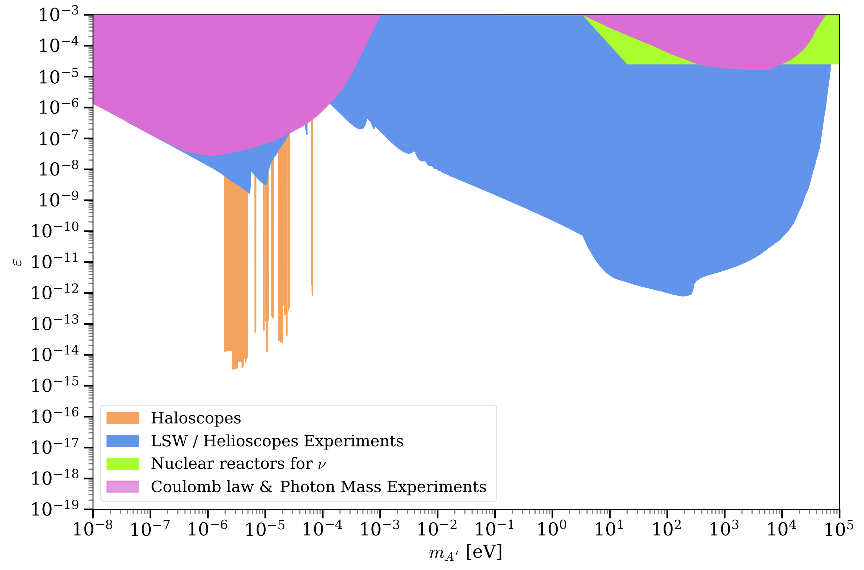
Motivation: why light dark photons?

- Dark photons A' with kinetic mixing ε are a minimal, well-motivated hidden-sector portal.
- The sub-MeV mass range remains experimentally challenging (limited production rates / backgrounds / thresholds).
- Inverse Compton scattering (ICS) provides:
  - clean initial state (laser photon + ultra-relativistic electron),
  - high statistics, precision kinematics,
  - well-controlled systematics via laser on/off modulation.

Goal: exploit ICS to search for $e\gamma \to eA'$ using *missing-photon* and *mass reconstruction* strategies.

Current Dark Photon Limits



The SIRIUS Accelerator

Signal process and dominant SM background

Signal (dark photon production)

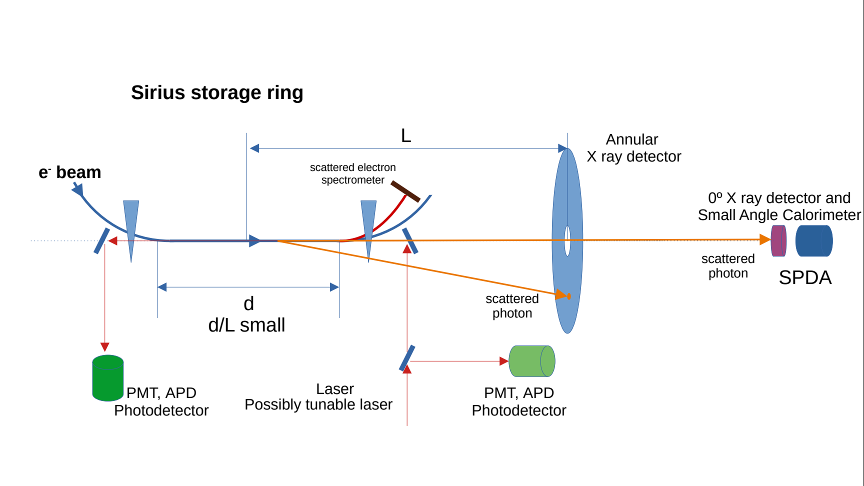
$$e^- + \gamma_{\text{laser}} \to e^- + A' \qquad (A' \text{ escapes invisibly})$$

SM background (ordinary ICS)

$$e^- + \gamma_{\text{laser}} \to e^- + \gamma \qquad \text{with the photon missed by the veto}$$

- **Experimental signature:** scattered electron in acceptance + *no detected photon* in veto.
- The key challenge is controlling the "Compton+missed-photon" background with inefficiency p_{veto}.

Experimental Setup



Geometry: head-on collision at $\sim 180^\circ$

- Electron beam defines $+z$; laser photons propagate along $-z$ (head-on).
- Outgoing ICS photon is emitted *forward* along the electron direction in the lab.
- Characteristic cone:

$$\theta_\gamma \sim \frac{1}{\gamma}, \qquad \gamma = \frac{E_e}{m_e} \sim \mathcal{O}(10^3\text{–}10^4).$$

Key point

Even though the incoming laser photon is opposite to the electron beam, the scattered photon follows the electron direction in the lab.

ICS kinematics: energy–angle correlation (lab)

For head-on ICS in the ultra-relativistic limit:

$$E_\gamma(\theta) \simeq \frac{E_{\gamma,\mathrm{max}}}{1+\gamma^2\theta^2}, \qquad E_{\gamma,\mathrm{max}} \simeq 4\gamma^2 E_{\mathrm{laser}}.$$

- Hard photons $\Rightarrow$ very small angles $\theta \lesssim 1/\gamma$.
- Softer photons populate larger angles, but with rapidly falling rate.

Example numbers (benchmark)

$E_e \simeq 3\ \mathrm{GeV}$, $E_{\mathrm{laser}} \sim 1\ \mathrm{eV} \Rightarrow E_{\gamma,\mathrm{max}} \sim \mathcal{O}(100\ \mathrm{MeV})$.

ICS photon spectrum (lab): broad, soft-dominated

- The lab-frame photon spectrum is strongly weighted to low energies.
- A useful approximation (in the Thomson/small-recoil regime) is

$$\frac{dN}{dE_\gamma} \propto \frac{1}{E_\gamma^2}, \qquad E_\gamma \in (E_{\mathrm{laser}},\ E_{\gamma,\mathsf{max}}).$$

- This implies an enormous population of eV–keV photons and a small fraction of MeV–100 MeV photons.

Implication

Background rejection is primarily set by veto performance in the photon phase space that overlaps the signal selection.

Baseline veto concept: bend electrons, catch forward photons

- After the interaction point:
  - electrons are deflected by dipole magnets,
  - photons travel straight along the tangent of the incoming electron direction.
- Place a forward calorimeter on the straight line to veto the small-angle hard-photon cone.

Veto-limited regime

If the background is dominated by Compton events with a missed photon:

$$N_b \simeq p_{\mathrm{veto}} N_{\mathrm{C}}^{\mathrm{tot}}, \qquad \varepsilon_{\mathsf{min}} \propto \left(\frac{p_{\mathrm{veto}}}{L}\right)^{1/4}.$$

Which photons actually mimic the signal?

- A SM event mimics $e\gamma \to eA'$ only if:
  1. the electron is detected (in signal selection),
  2. the corresponding SM photon would fall inside an instrumented veto region,
  3. that photon is missed (inefficiency).
- With **forward-only** veto coverage:
  - primarily small-angle **hard** photons are "dangerous",
  - very soft wide-angle photons are mostly irrelevant because they never enter the veto acceptance.

Takeaway

The background is defined by the *overlap* of (ICS photon phase space) with (veto acceptance).

Extended veto: add wide-angle cryogenic photon detection

- Add additional veto systems covering larger polar angles, e.g. up to 45°:
  - forward MeV calorimeter for small angles,
  - wide-angle cryogenic detectors with sub-eV threshold for soft photons.
- This increases the photon vetoed phase space toward near-4π coverage.

Physics benefit

Access to additional kinematic configurations where the SM partner photon is soft and wide-angle, enabling tighter control of backgrounds and more usable electron acceptance.

Two complementary search regimes

(1) Missing-photon search (ultra-light A')

- Best for $m_{A'}$ in the eV–keV regime.
- No resolvable mass peak: signal looks like missing photon.
- Sensitivity limited by total missed-photon probability in the relevant phase space.

(2) Mass reconstruction ("low" but resolvable masses)

- Use kinematics of the scattered electron (and optionally measured photon) to reconstruct

$$m_{A'}^2 \simeq E_e \, \theta_e^2 \, \Delta E.$$

- Viable when the mass peak is separated from the Compton core: $m_{A'} \gtrsim \text{few} \times \sigma_m$.

Mass reconstruction: what sets the low-mass limit?

- In the small-angle approximation:

$$m_{A'}^2 \simeq E_e \theta_e^2 \Delta E.$$

- Resolution is driven by electron energy and angular resolutions:

$$\sigma_{m^2}^2 \simeq E_e^2 \theta_e^4 \, \sigma_E^2 + 4 E_e^2 \, \Delta E^2 \, \theta_e^2 \, \sigma_\theta^2.$$

- Extended photon veto improves background control, but the minimum resolvable $m_{A'}$ is set by σ_E and σ_θ.

Rule of thumb

Mass reconstruction becomes practical once $m_{A'} \gtrsim \mathcal{O}(10\ \mathrm{keV})$–$\mathcal{O}(100\ \mathrm{keV})$, depending on resolution and chosen kinematics.

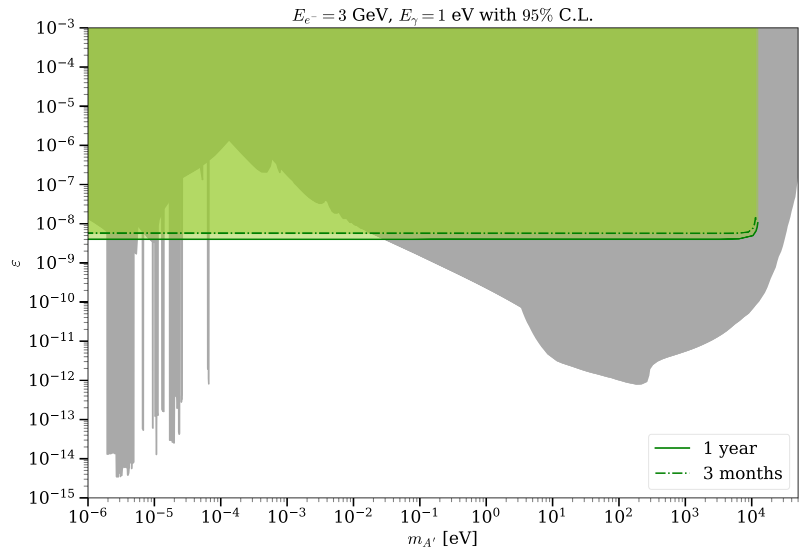
Impact of a wide-angle (to 45°) soft-photon veto

- A cryo veto up to 45° targets photons down to eV/sub-eV energies.
- It reduces missed-photon backgrounds in kinematic regions where the SM partner photon is soft and wide-angle.
- It allows:
  - larger electron deflection acceptance,
  - more robust control samples (laser on/off; sideband photons),
  - cross-checks of the ICS model and veto performance.

Caveat

Cryogenic veto performance will be limited by dark counts, thermal/IR backgrounds, timing coincidence, and geometric hermeticity.

Expected Sensitivity



Outlook: what we need next

- Full end-to-end simulation of:
  - ICS photon phase space $(E_\gamma, \theta_\gamma)$,
  - electron transport through magnets and acceptance,
  - forward calorimeter + wide-angle cryo veto geometry and inefficiencies.
- Quantify the transition from veto-limited to (effectively) background-free regimes:

$$p_{\mathrm{eff}} N_{\mathrm{C}}^{\mathrm{tot}} \lesssim 1 \quad \Rightarrow \quad \varepsilon_{\mathsf{min}} \propto L^{-1/2}.$$

- Define benchmark detector specs: σ_θ, σ_E, timing window, p_{veto} in each subsystem.

Summary

- Head-on ICS at GeV energies produces a forward, high-rate photon beam with strong energy–angle correlations.
- Dark photon signal: scattered electron with no corresponding photon (missing-photon signature).
- Baseline sensitivity at ultra-light masses is veto-limited; mass reconstruction becomes viable at higher (still "low") masses.
- Extending photon veto coverage (forward + wide-angle cryo to 45°) increases controlled phase space and reduces missed-photon backgrounds.

Questions?