Dark Photons Review

Vijay Narayan

290e Dark Matter Seminar

Basic Assumptions

Suppose there is an additional $U(1)'$ in nature

$$\mathcal{L}_{U(1)'} = -\frac{1}{4}X^{\mu\nu}X_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_{\mu}A'^{\mu}$$

- Mass can come from Higgs or Stuckelberg mechanism
- Assume SM particles not charged under new gauge group
- However there would necessarily be kinetic mixing between $X^{\mu\nu}$ and $F^{\mu\nu}$ (satisfies gauge invariance) [Holdom '86]

$$\mathcal{L} \supset \frac{-1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_{\mu}A'^{\mu} - \frac{\epsilon}{2}F^{\mu\nu}X_{\mu\nu} + J_{\mu}A^{\mu}$$

- This is renormalizable, dimension 4 operator $\Rightarrow$ relevant at all energies

Kinetic Mixing

Can remove kinetic mixing term by diagonalizing, changes the mass eigenstates and interactions of the SM vector bosons.

- In mass basis $(A^\mu \mapsto A^\mu - \epsilon X^\mu)$, A' couples directly to EM charged particles:

$$\mathcal{L} \supset \frac{-1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} X^{\mu\nu} X_{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu + J^\mu (A_\mu - \epsilon A'_\mu)$$

- In interaction basis $(X^\mu \mapsto X^\mu - \epsilon A^\mu)$ there is $A' \leftrightarrow \gamma$ oscillation due to small mass-mixing:

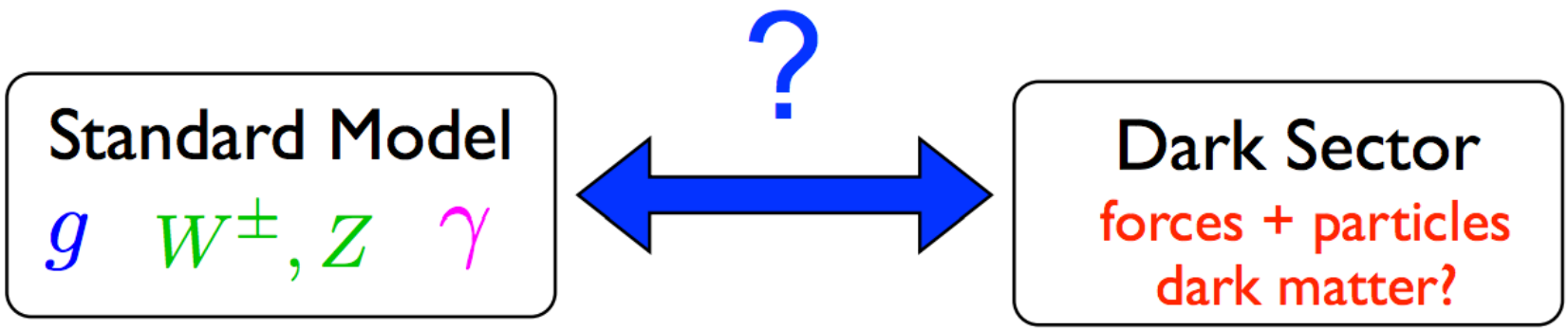
$$\mathcal{L} \supset \frac{-1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} X^{\mu\nu} X_{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu + J^\mu A_\mu - \epsilon m_{A'}^2 A_\mu A'^\mu$$

- Two unknown parameters $\{m_{A'}, \epsilon\}$

Dark Sector

Dark sector consists of particles that do not couple to known SM forces

- Can arise naturally from high energy physics including string theory constructions, low-scale supersymmetry models
- Dark sector need not lie at the weak-scale, and may harbor dark matter! (Although not motivated by just DM)



Portals to the Dark Sector

Dark sector could have rich structure, so what non-gravitational portals exist between dark sector and SM? Only a few possibilities

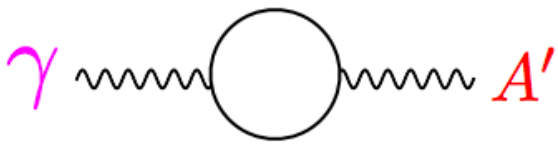
- Axion: $\frac{a}{f_a} F^{\mu\nu} \tilde{F_{\mu\nu}} \Rightarrow$ axion-like particles (ALPs)
- Vector: $\frac{\epsilon}{2} F^{\mu\nu} X_{\mu\nu} \Rightarrow$ dark photon A'
- Higgs: $\epsilon_h |h|^2 |\phi|^2 \Rightarrow$ dark scalar (exotic Higgs decays)
- Neutrino: $\epsilon_\nu (hL)\psi \Rightarrow$ sterile neutrino

A' could be messenger to the dark sector, could even constitute dark matter $\Rightarrow$ strong theoretical arguments for searching entire $\{m_{A'}, \epsilon\}$ parameter space.

Generating $\epsilon, m_{A'}$

Consider loop diagrams of heavy fields charged under both photon and A'.
Simple naturalness arguments $\Rightarrow \epsilon \sim \frac{e g_D}{6\pi^2} \log(\frac{m}{\Lambda}) \sim 10^{-8} - 10^{-2}$

[Essig, Schuster, Toro '09]



However, non-perturbative and large-volume effects in string theory constructions generate much smaller ϵ. No clear minimum, but generally $\epsilon \sim 10^{-12} - 10^{-2}$ is predicted [Goodsell, Jaeckel, Redondo, Ringwald '09]

$m_{A'}$ has a much larger parameter space to be explored,
$m_{A'} \sim 2m_e \sim \mathrm{MeV}$ is a natural dividing line

$m_{A'} \sim$ MeV $-$ GeV

Very well-motivated portion of $m_{A'}$ parameter space with interesting phenomenology and experimental avenues.

- Can decay to quarks, charged leptons ($e^+e^-, \mu^+\mu^-, \pi^+\pi^-$) either directly or indirectly (light dark sector states?)
- Generated by Higgs mechanism in context of supersymmetry, various models for communicating weak-scale SUSY-breaking to dark sector give rise to $m_{A'} \sim \sqrt{\epsilon} m_W$

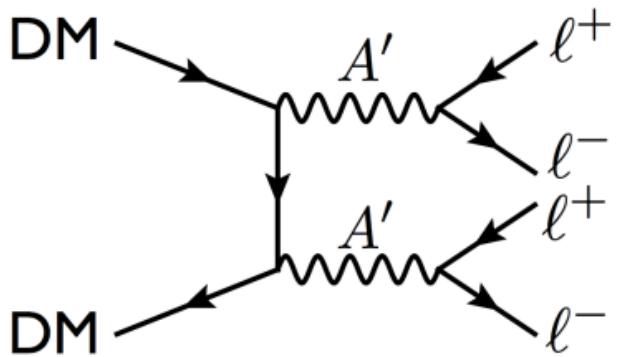
  [Arkani-Hamed, Weiner '08; Cheung, Ruderman, Wang, Yavin '09; Morrissey, Poland, Zurek '09]

$m_{A'} \sim \mathrm{MeV} - \mathrm{GeV}$

- May explain $(g-2)_\mu$ anomaly $\sim 3\sigma, 10^{-9}$ deviation from SM

$$(g-2)_\mu^{A'} \sim \frac{\alpha}{2\pi} \times \epsilon^2, \quad m_{A'} < m_\mu$$

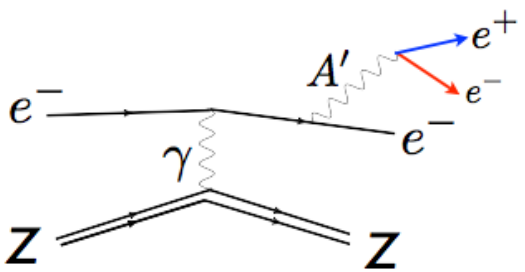
- If DM ($\sim \mathrm{TeV}$) coupled to A' in this range, would produce $\sim \mathrm{GeV}$ cosmic-ray electrons, positrons. Implications for AMS, PAMELA, Fermi?



Some Experimental Probes

Array of fixed-target experiments underway (APEX, HPS, DarkLight, ...)

- Intense beam of charged particles (e^-, p) shot onto a block or a foil
- A' produced forward and carries most of E_{beam}, $\sigma \sim \frac{\epsilon^2 Z^2}{m_{A'}^2}$
- Invariant mass distribution of e^+, e^- pairs has clear peak at $m_{A'}$
- Small ϵ, long-lived $A' \Rightarrow$ displaced vertices

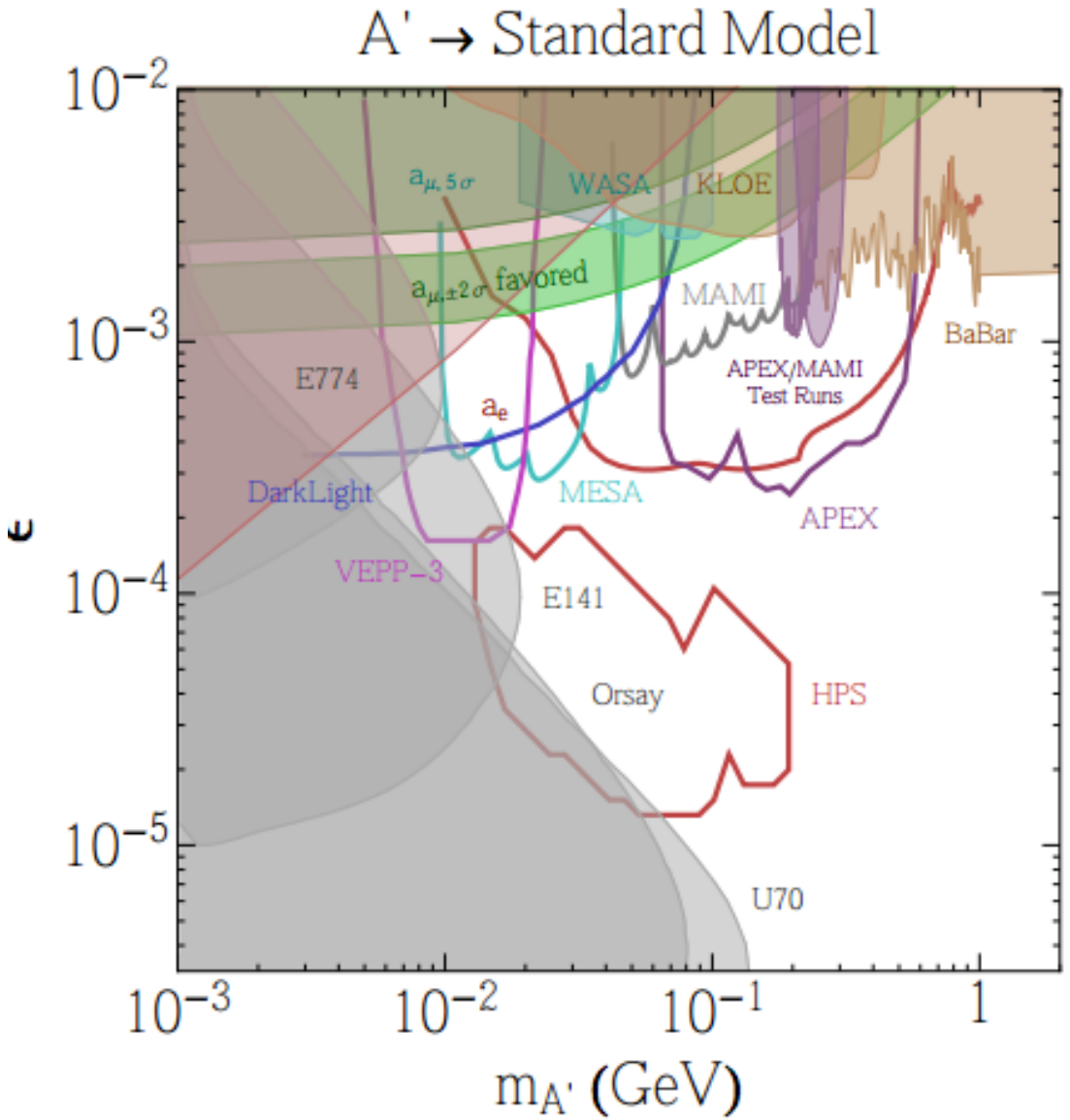


[Bjorken, Essig, Schuster, Toro '09]

Can also use existing e^+e^- collider experiments (BaBar, BELLE,...)

- Need high intensity, low-energy $(\sim 1 - 10\,\mathrm{GeV})$

Current Reach



[Essig, et al. '13]

$m_{A'} <$ MeV

Equally interesting parameter space, dark photons are a valid DM candidate! (Recall very light DM need to be produced non-thermally)

- Possibilities for generating correct relic density: Misalignment mechanism (works well for axions), inflationary fluctuations

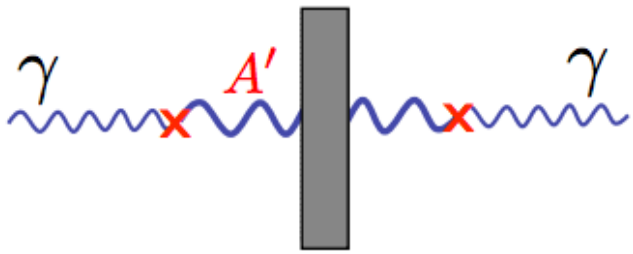
  [Nelson, Scholtz; Graham, Mardon, Rajendran]

$$\Omega \sim 0.3 \sqrt{\frac{m_{A'}}{\mathrm{keV}}} \left(\frac{H_i}{10^{12}\,\mathrm{GeV}} \right)$$

- Stability on cosmological scales($A' \to 3\gamma$) and current observations place upper limit on ϵ
- $m_{A'}$ generated by Stuckelberg mechanism (no phase transition), occurs naturally in large volume string compactifications

Some ways to detect low-mass A'

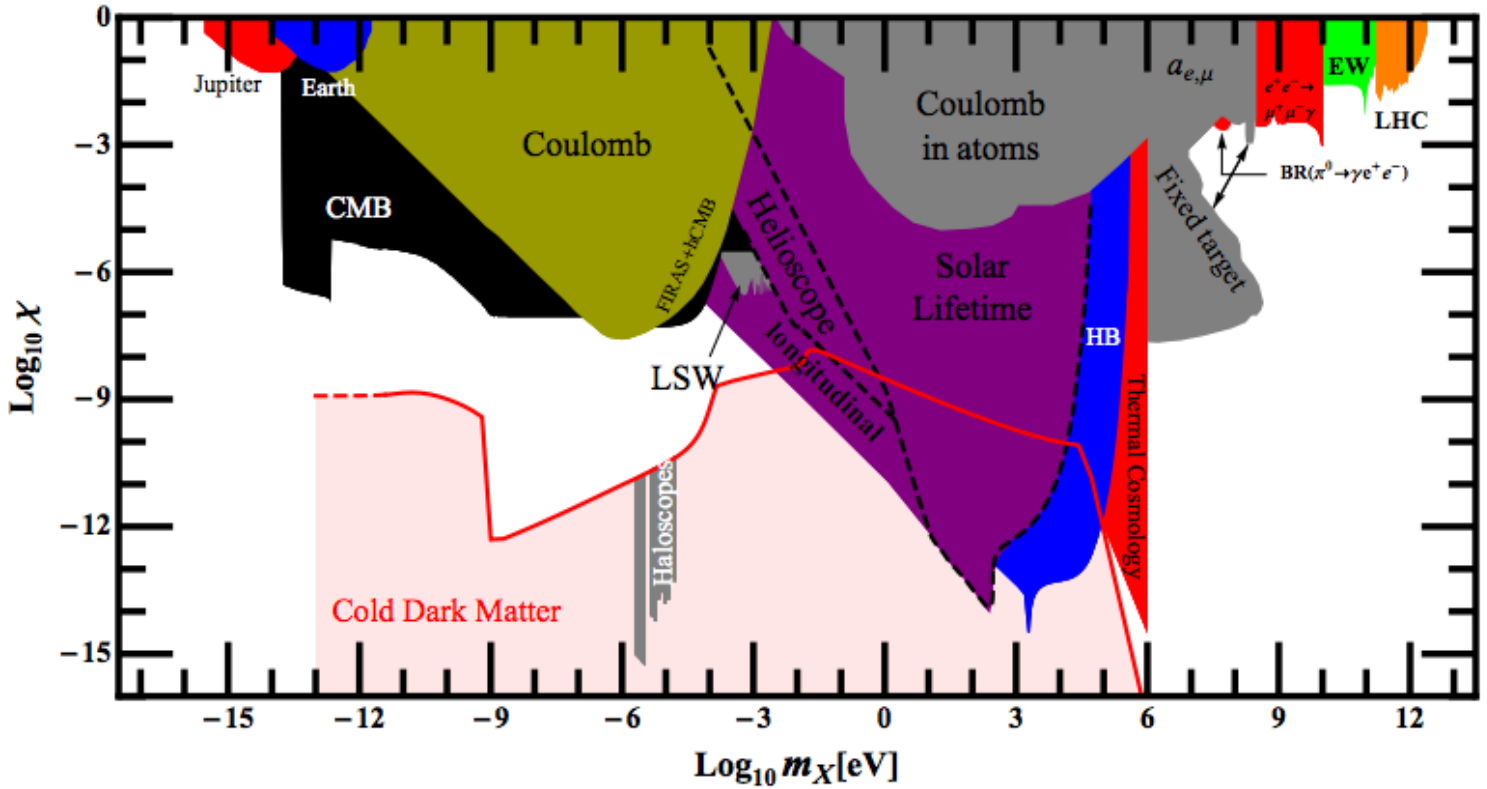
- "Light-Shining-Through-Walls" experiments



- Helioscope: "Staring at the Sun"

Full A' Parameter Space

Evidently a large parameter space needs to be explored!



[Jaeckel '13]

Final Remarks

- DM may be part of a more complicated dark sector
- Dark photons can provide a portal to DM (kinetic mixing), may even be the DM (kinetic mixing)
- Lots of parameter space still out there, and new/existing experiments are continuing the search!