Dark Photon Searches

290E Talk - 10/3/2018

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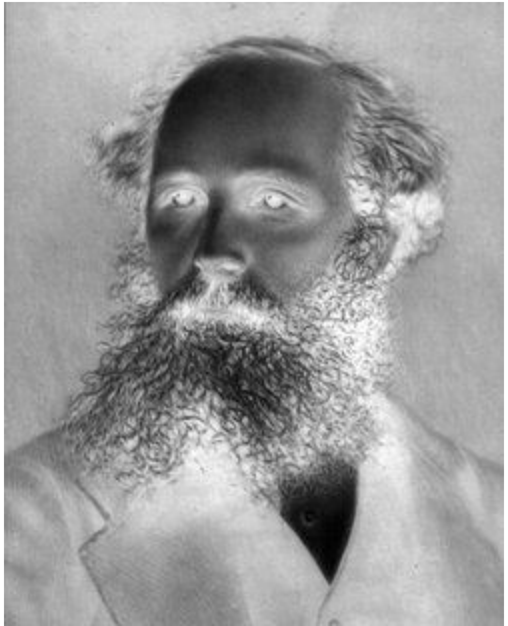
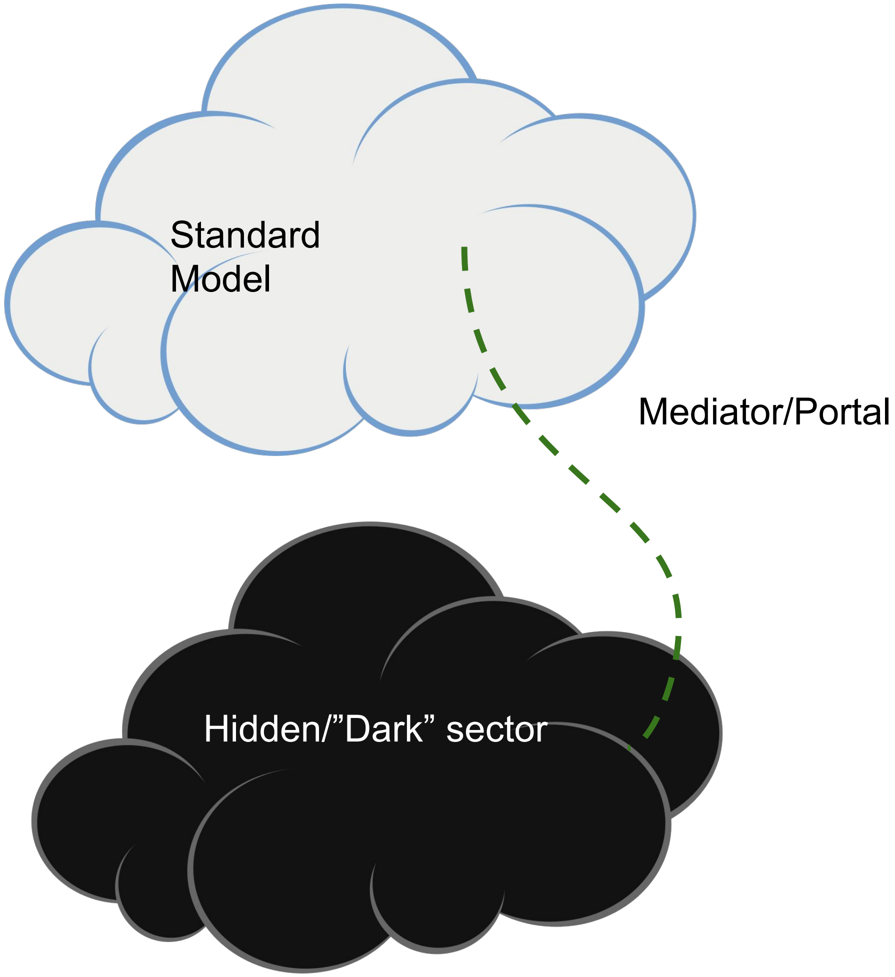


Outline

1. Theory
2. Motivations
    a. DAMPE/PAMELA
    b. EDGES/21cm Line
    c. Muon g-2
    d. Muonic hydrogen
3. Searches
    a. LXe searches
    b. Accelerator searches
    c. Stellar signals

“Hidden Sector”

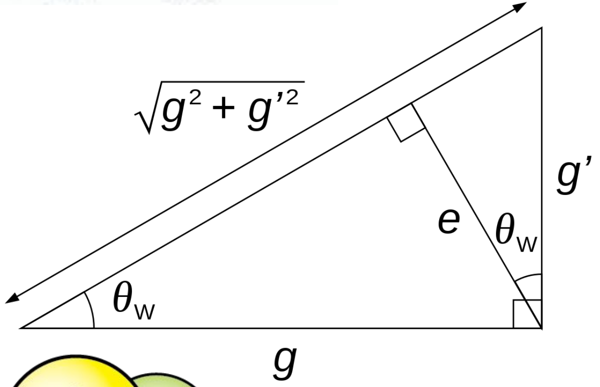
- Standard Model particles and interactions have the normal couplings
- Hidden Sector has its own couplings and particles that are in principle unconstrained.
- Some field, the mediator, provides (we hope) a weak coupling that can be detected.

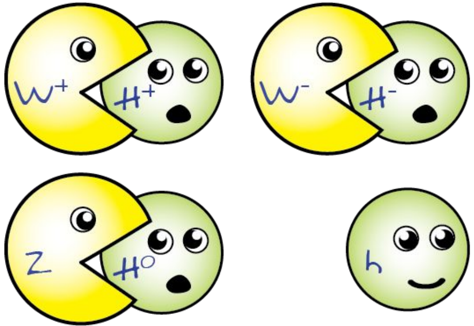


Electroweak symmetry breaking in a nutshell

- Symmetries -> Interactions.
- Gauge Symmetries: $SU(3)_C \times SU(2)_L \times U(1)_Y$
- (1,2, ½) Higgs Φ generates interactions between W^i & B bosons.
- Φ acquires a vacuum expectation value, spontaneously breaking $SU(2)_L \times U(1)_Y \rightarrow U(1)_A$.
  - The interactions between B and W^3 become kinetic mixing, with γ and Z boson being the new mass eigenstates.
  - The goldstone modes of Φ are “eaten” by the W^i bosons, becoming the longitudinal modes necessary for them to have mass.
  - A particle’s charge Q tells you not only about its coupling to EM, but also to Z bosons.

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$
$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. \quad + \quad \ldots$$



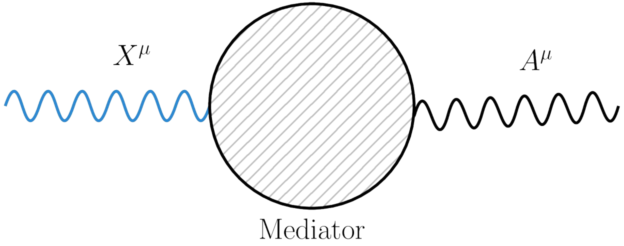


Source:
Quantumdiaries.org

Dark Photons

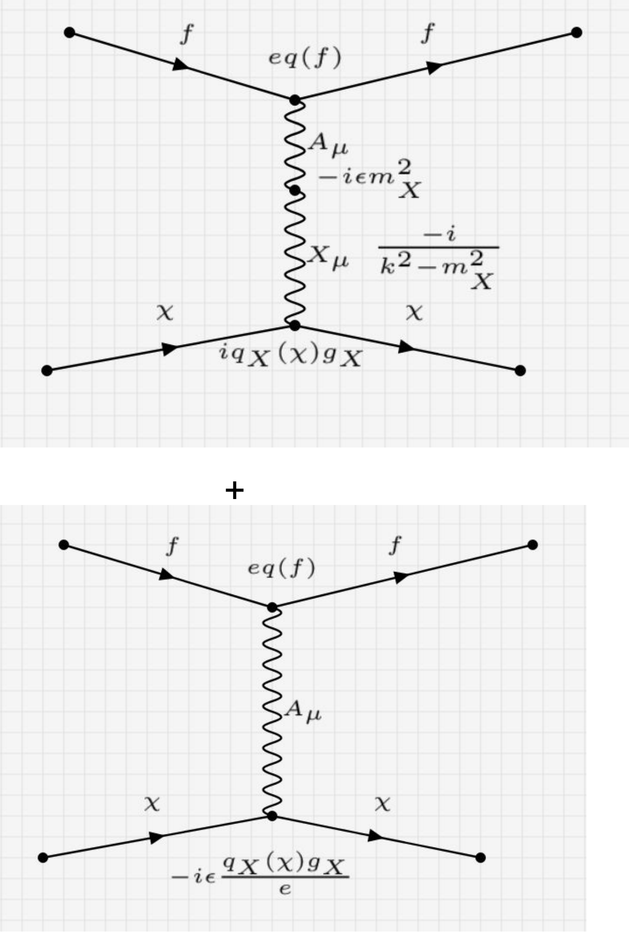
- Let's just tack on a symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{A'}$
  - (And particles charged under this symmetry).
- This implies the existence of a new gauge boson, the dark photon X.
  - Also known as U Boson, V Boson, A' Boson, etc.
- Basic model:
  - Dark Higgs scalar ξ couples to X.
  - Dark Matter fermion χ couples to X.
  - The B & X fields *kinetically mix* their field tensors with mixing parameter ε. This is allowed because they are both Abelian.
- ξ acquires a vev, X gets a mass.
- The mixing comes not from the interaction terms with the Higgs, but from the allowed kinetic mixing (this was not the case in the EW case).
- The mass eigenstates of the X, B, and W fields are shifted.

$$\mathcal{L} = \mathcal{L}_{other} - \frac{1}{4}B^{\mu\nu}B^{\mu\nu} - \frac{1}{4}X^{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}B^{\mu\nu}X_{\mu\nu}$$
$$-g'q(f)\bar{f}\gamma^\mu f B_\mu - g_X g_X \bar{f}\gamma^\mu f X_\mu$$
$$+((\partial_\mu - i g_X q_X(\xi) X_\mu)\xi)^2$$



Interactions

- g_X, ε, M_X, are the parameters.
- There two ways to diagonalize the kinetic matrix: the **mass** basis and the **interaction** basis [1].
- Interaction basis leaves photon unchanged and gives dark matter a mini/milli charge.
- Mass basis diagonalizes the mass matrix, gives normal matter a mini dark charge and dark matter no visible photon charge.
- In the interaction basis, SM photons & dark photons oscillate between each other.
    - At high momentum transfer /**low M_X**, the U(1) symmetry is restored and the dark matter gets a charge under the visible photon.
- Experiments may be looking for a flux of dark photons, dark photon mediated interactions, or millicharged dark matter.

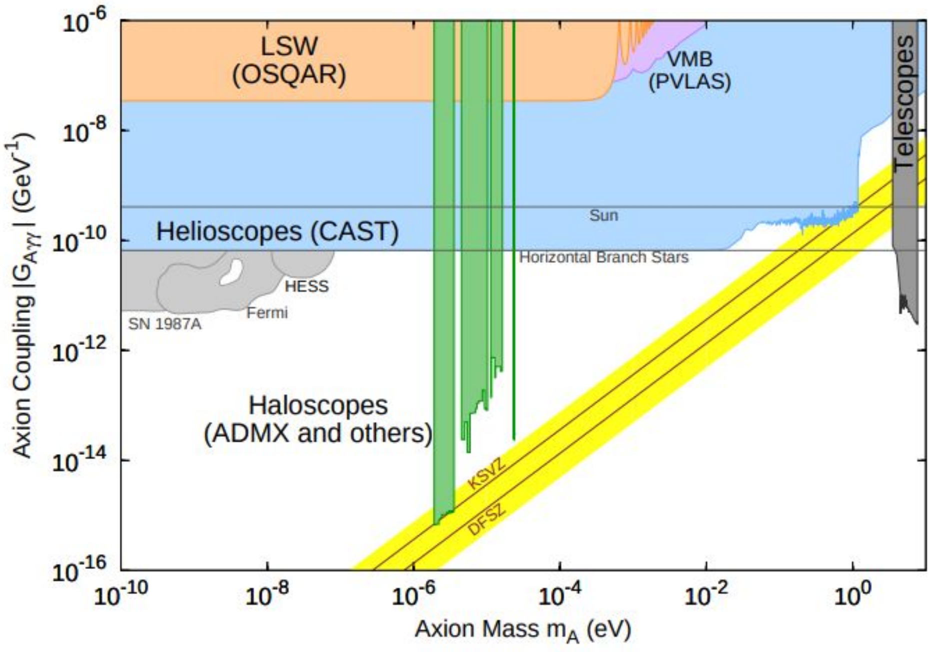


These interaction basis diagrams destructively interfere at low k.

Similarity to Axions

- Axions are a solution to the Strong CP Problem.
- CP-violating parameter θ is promoted to a field.
- Spontaneously broken U(1) symmetry leads to goldstone bosons (axions) and the relaxation of θ to the small values we see in nature.
- Axions may acquire small mass and would exist in enormous occupation numbers -> dark matter candidate.
- They may be detected via the axioelectric effect.
- Detection techniques for axions and dark photons are very similar.

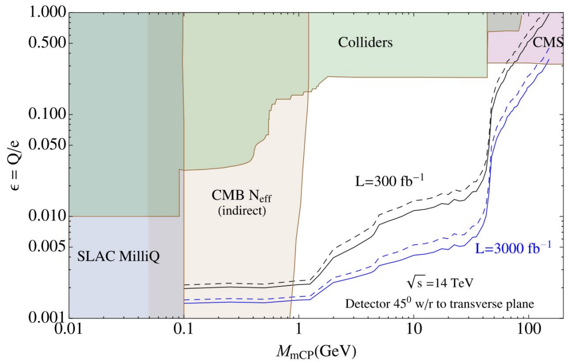
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{n_f g^2 \theta}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$$



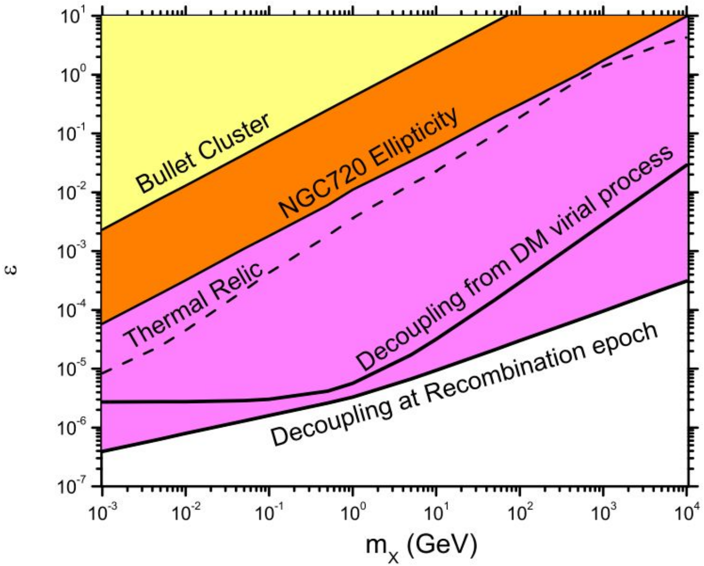
From PDG [2].

Millicharge bounds

- Several experiments have looked at millicharged DM.
- Astrophysically, millicharged DM is constrained by many sources [8].
  - Bullet Cluster needs to remain DM's "smoking gun."
  - CMB anisotropy peaks can't be washed out, so it needs to decouple before recombination.
  - If Q_{SM} is too large, the DM won't virialize: the SM gas will transfer too much energy to DM and fling it out of the galaxy.
  - Large Q_{SM} will also lead to DM annihilating too fast and it is no longer a thermal relic.
  - Some halos are elliptic, which is hard to achieve with large DM self-interactions and heat transfer.



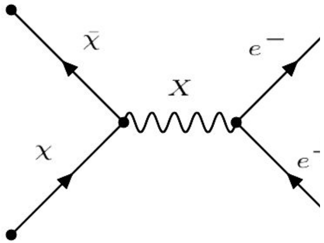
From [3]

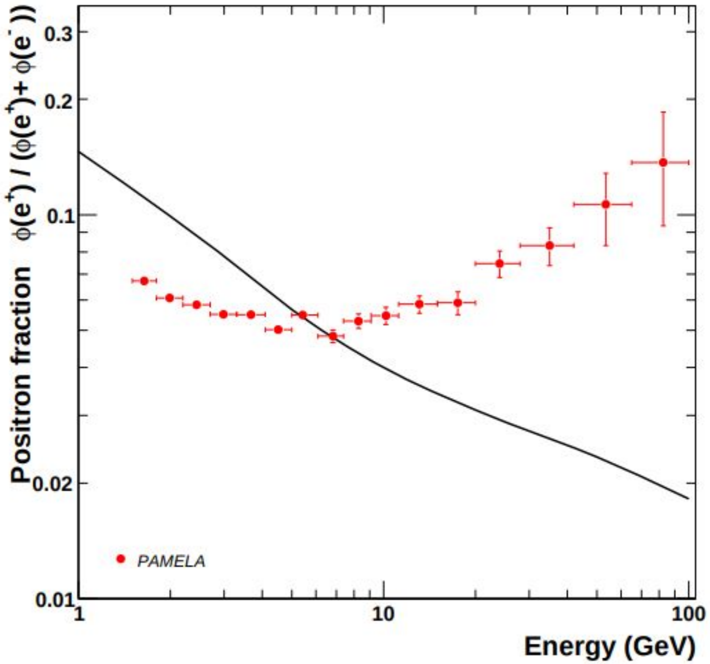


From [8], but ε is the effective charge.

PAMELA

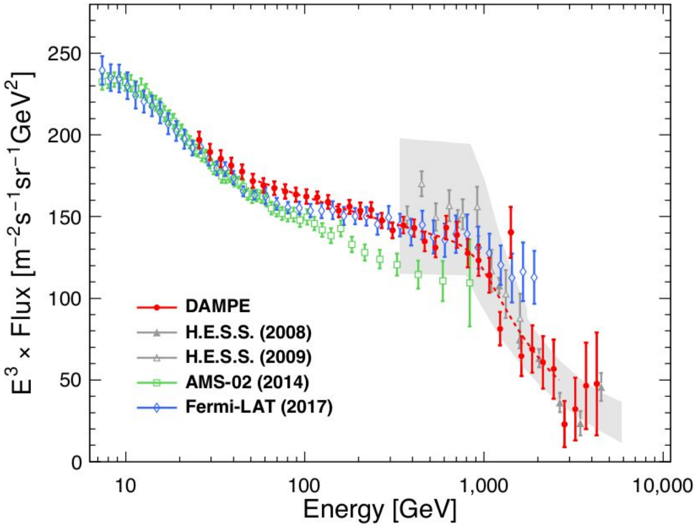
- PAMELA was a satellite-based detector launched in 2006[4].
- It could effectively discriminate electrons and positrons from other
- It saw a large excess of high-energy cosmic rays.
- This excess could be explained by dark matter annihilating into positrons and leptons.
- Combined with AMS-02 and FERMI-LAT results, [5] finds a best fit at MDM = 104 GeV, but isotropic dark matter model excludes much of the parameter space.





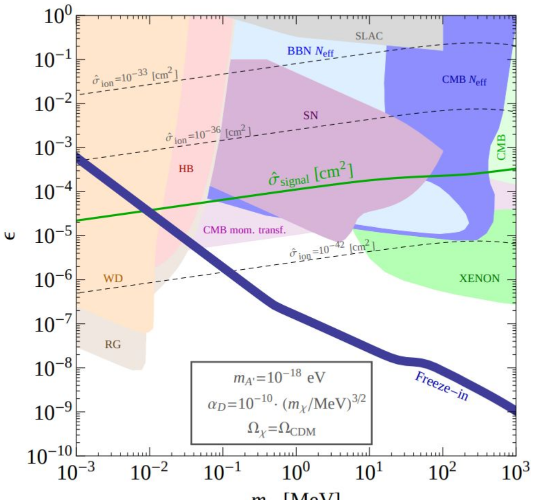
DAMPE

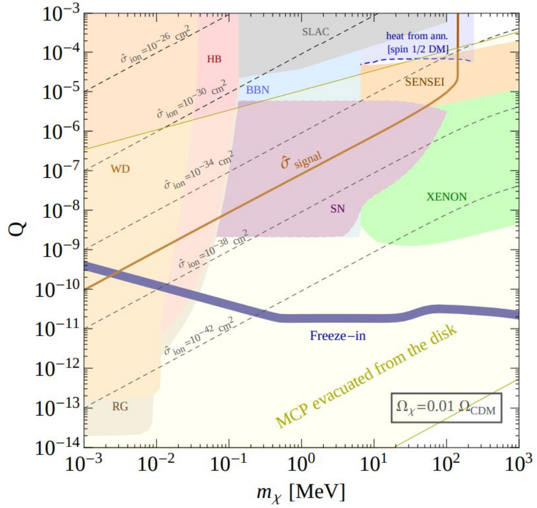
- **DA**rk **M**atter **P**article **E**xplorer is a satellite that measured cosmic ray electrons up to 10 TeV [6].
- Consistent with earlier measurements, but also shows evidence of a resonance at ~1.4 TeV.
- No peak found for antiprotons -> the dark matter must couple to leptons preferentially (leptophillic).
- Dark photon coupling to SM is determined by electric charge, so $\chi\chi \to X \to e^+e^-$ must be subdominant to other mediators.
- In [7], they use Yukawa couplings with a scalar mediator to make the model leptophilic, the $U(1)_X$ symmetry exists to forbid quark couplings.
  - They also find that the X-mediated DM scattering cross section that barely escapes current DD experiments (10^{-46} cm^2).
  - Negligible effect on muon g-2 values.



EDGES 21 cm result.

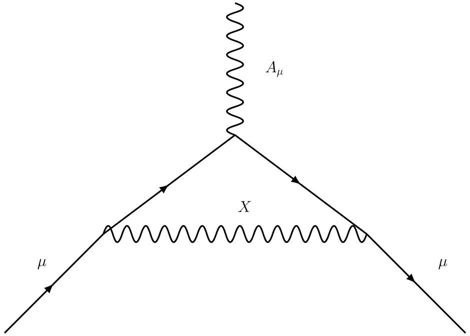
- “Cosmic dawn”: first stars are born, and the cosmic gas is cold.
- Various processes keep the hyperfine spin state temperature higher than the gas temperature at this period of history.
- EDGES found an absorption peak in the CMB during this period, meaning that the gas was much colder than expected.
- This could be due to the gas scattering with DM, transferring heat.
- In [9] they analyze the millicharge and hidden photon cases.
- Due to self-interaction constraints, they all but rule out hidden photons as an explanation.
- Millicharged DM can explain the EDGES result and just barely escape all the other constraints, if only 1% of the DM mass is made up of millicharges.

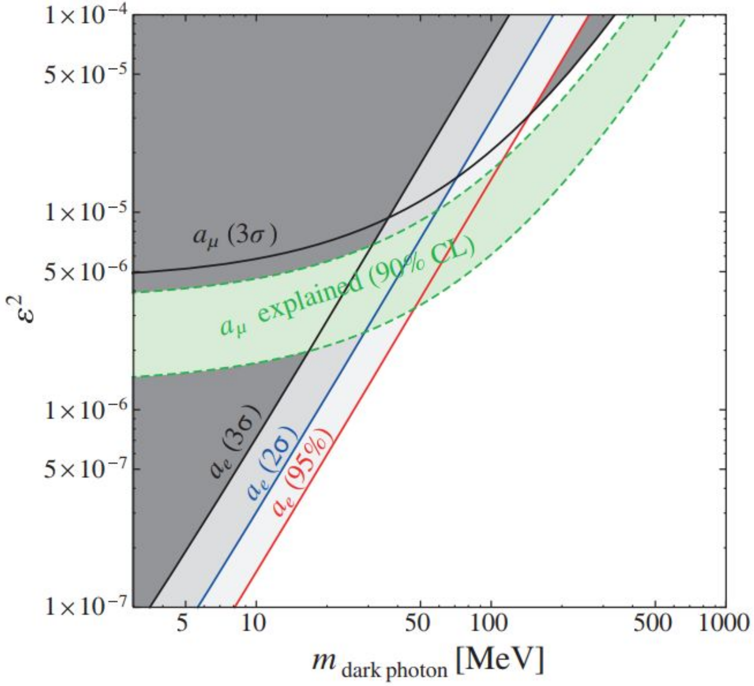




Muon g-2

- As other talks this semester will address, experiments show the muon has a g-2 value that differs from theory.
- The hidden photon could appear in a loop diagram, contributing to the amplitude.





From [10]

Accelerators

- Visible decay: One can look for a decay of the massive dark photon.
  - These completely rule out the g-2 explanation.
- Meson decays: BaBar looked near the Y(2S), Y(3S), Y(4S) resonances for e^+e^- -> γX events and did not see any [11].
  - Other experiments did similar searches and benefit from huge datasets.
- Beam dump: e or p incident on a target produces dark brehmstrahlrung, which travels through a thick shield and decays.
  - Combining results can constrain both leptophobic and leptophillic models.
  - Interestingly, it provides 2-sided exclusion limits.
- Target experiments: use accurate invariant mass reconstruction to look for resonances.

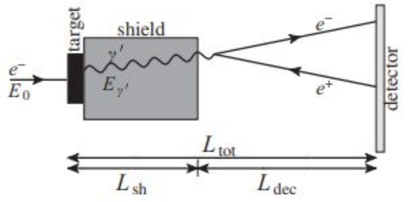


Fig. 9. – Sketch of the setup of an electron beam dump experiment.

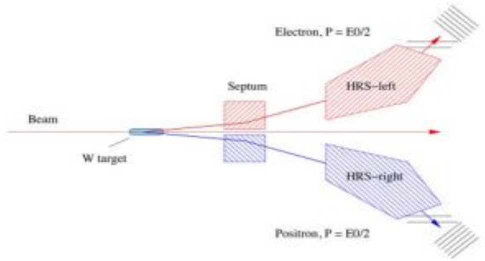
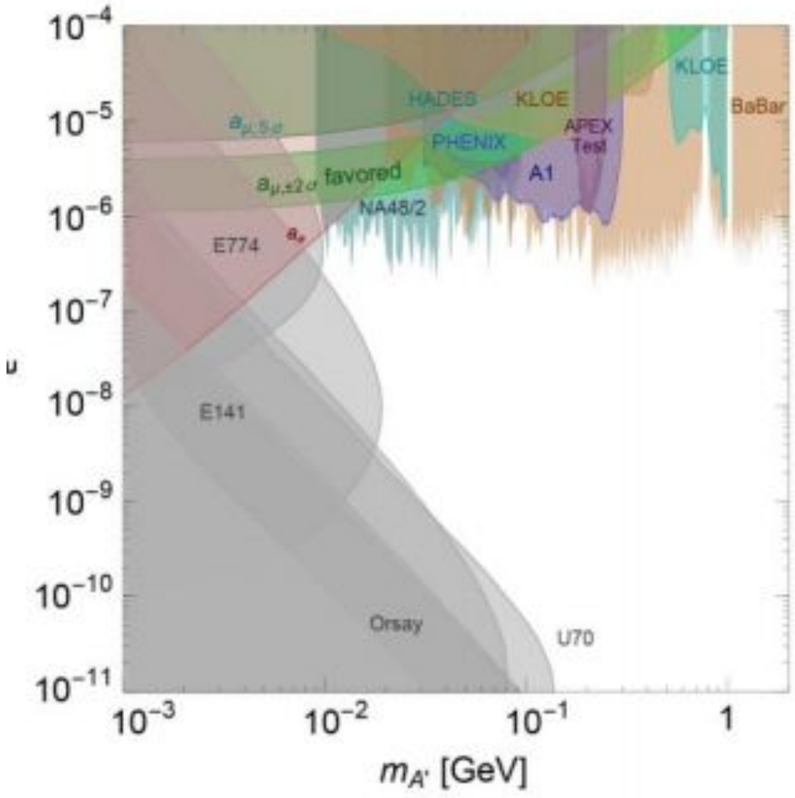


Fig. 19. – Layout of the APEX experiment.

From [12]

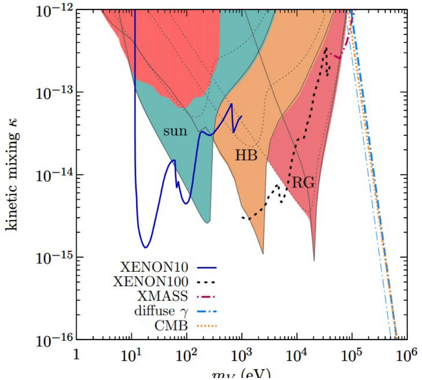
Accelerator limits

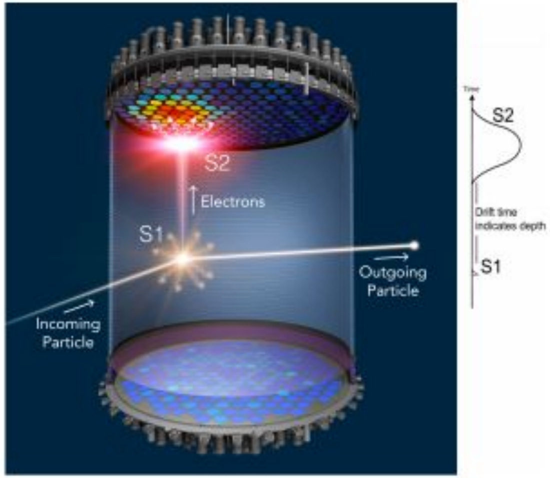
- Invisible decays: look for decays of dark photon to dark matter/hidden sector particles (i.e. dark photon is not the lightest hidden sector state.
- A1 and others looked and placed limits.



Liquid Xenon Experiments

- Liquid Noble element Time projection chambers (TPCs) detect light signals from scintillation and ionization.
- Built to detect WIMPS, they can also detect long-lived vector particles (dark photons).
  - In this model, they are assumed to be the lightest hidden sector state.
  - Mass basis: the LXe couples to the dark photon.
  - Interaction basis: The dark photon oscillates into a real photon, which then recoils off the LXe.
  - 12.1 eV threshold enables low energy probes into this portal.
- In [13] they show that DD experiments can be competitive with astrophysical bounds.





From [14].

Light Shining Through Walls

- Look for oscillations between SM photon and hidden photon.
- Excite EM mode, shield with perfect conductor, and see if mode is excited on the other side in a way inconsistent with Maxwell's equations.
- Produce and detect modes with microwave cavities, like ADMX and CROWS.
- The longitudinal mode doesn't exist for photons, but it does exist for massive hidden photons, so it you try to excite that mode, you get pure hidden photons.
  - Don't pay the price for oscillations, either. The signal is proportional to $(M_X^2 / \omega^2)\, \varepsilon^2$.
- Research ongoing at UC Davis and other places [15].

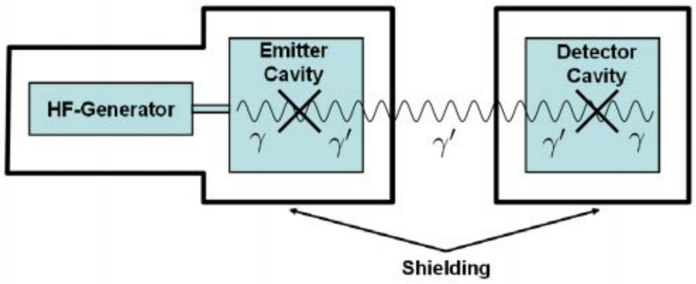
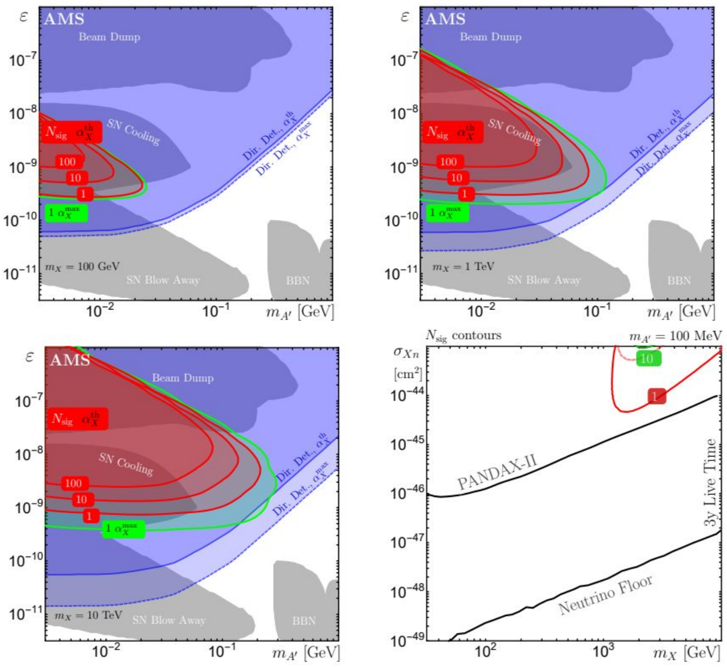


Figure 3: Schematic illustration of a "microwaves permeating through a shielding" experiment for the search for massive hidden sector photons mixing with the photon (a high-frequency (HF) generator drives the emitter cavity).

From [15].

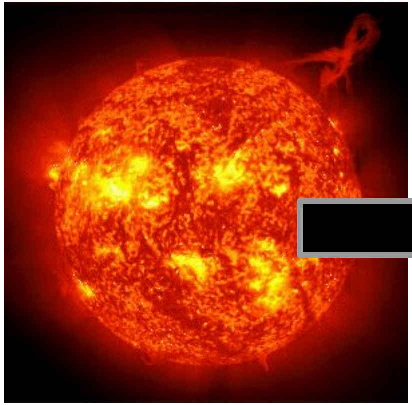
Stellar Dark Matter

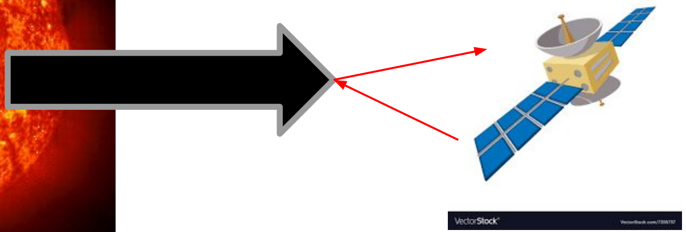
- Dark matter may collide with the sun and become trapped in its potential well.
- It could decay into a dark photon, which in turn could decay into leptons in a leptophillic theory.
- These high-energy leptons would be highly directional, providing a clear signal that could be used to identify dark matter.
- However, the Sun’s B-field smears out the directionality, making it not as competitive as LXe TPC experiments.



From [16].

Source: nasa.gov





Summary

- The dark photon is a hidden sector particle considered as a candidate for some component of a given theory.
- It can serve as a dark matter candidate itself or mediate a force.
- A closely-related theory, millicharged dark matter, is also a possibility.
- Both theories are aggressively constrained from both accelerator experiments, cosmological detection experiments, and cosmological considerations, but they have small allowed regions where they could be hiding.

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