Tales from the Dark Sector: Searches for Dark Photons

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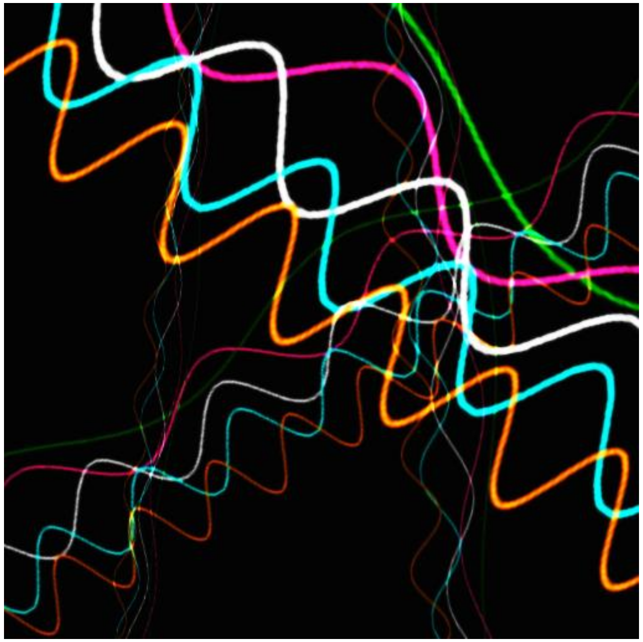
November 2, 2016

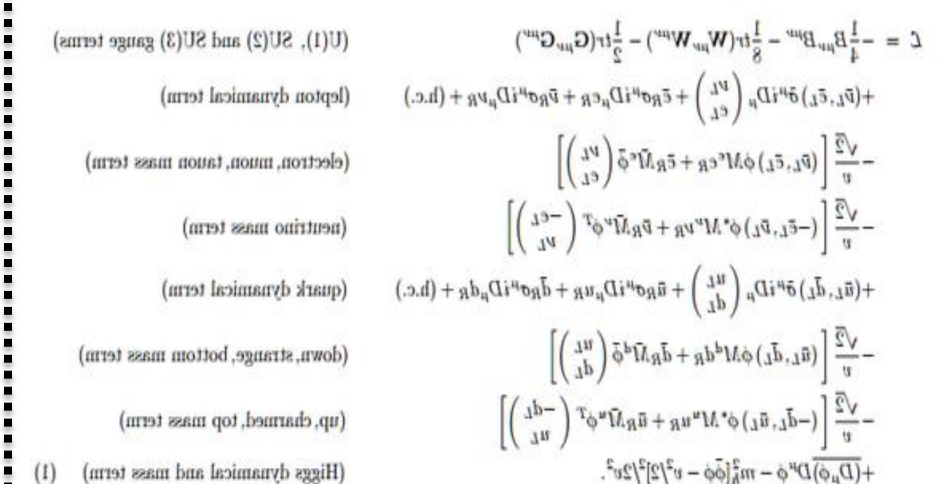
Part I:
What are Dark Photons?



The Dark Sector

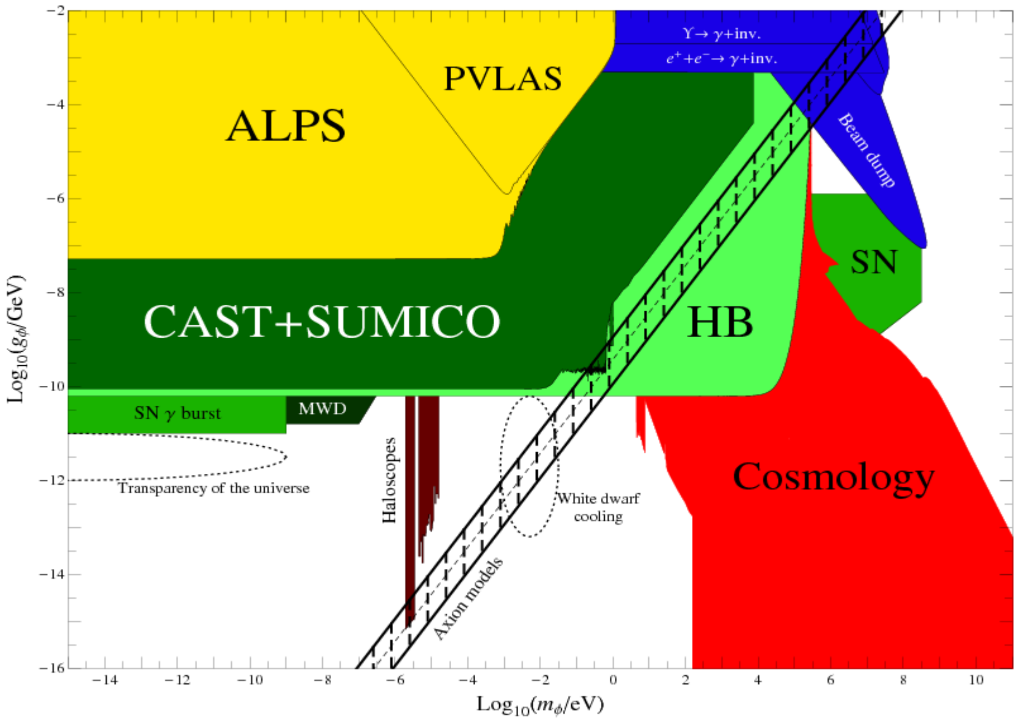
- Dark matter interacts with regular matter gravitationally
  - Gravity doesn't tell us anything very specific about what dark matter IS though
- Perhaps there is a whole "hidden sector" of matter governed by it's own interactions

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)} \\
& +(\bar{\nu}_L, \bar{e}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + \text{(h.c.)} && \text{(lepton dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] && \text{(electron, muon, tauon mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right] && \text{(neutrino mass term)} \\
& +(\bar{u}_L, \bar{d}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + \text{(h.c.)} && \text{(quark dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] && \text{(down, strange, bottom mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right] && \text{(up, charmed, top mass term)} \\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)} \quad (1)
\end{aligned}
$$



Dark Matter and the Standard Model

- What other ways could dark matter interact with standard model particles?
  - Axions
  - [Sterile] Neutrinos
  - Higgs Coupling
  - Dark Photons



arXiv:1210.3196 [hep-ph] MPP-2012-140

What are Dark Photons?

- Standard model: $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Imagine that dark sector matter is charged under a $U(1)_X$ gauge symmetry
- Its gauge boson is the Dark Photon, A' (but it could have some Z-like properties)
- Unified theory:

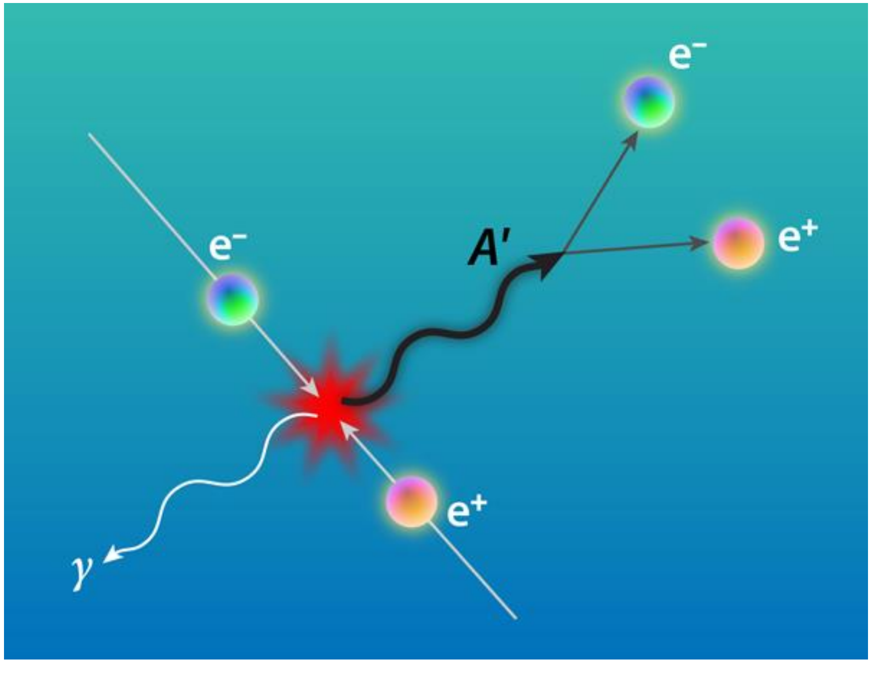
$$\mathcal{L}_{U(1)} = -\frac{1}{4}F^1{}_{\mu\nu}F^{1\mu\nu} - \frac{1}{4}F^2{}_{\mu\nu}F^{2\mu\nu} - \epsilon F^1{}_{\mu\nu}F^{2\mu\nu}$$

- Notice the mixing term!

Kinetic Mixing

- In general, dark photons can be massive
- There can be kinetic mixing between dark and regular photons (or in some models the Z too)
- This leads to an effective interaction:

$$\epsilon e A'_{\mu} J^{\mu}{}_{EM}$$



http://physics.aps.org/articles/v7/115

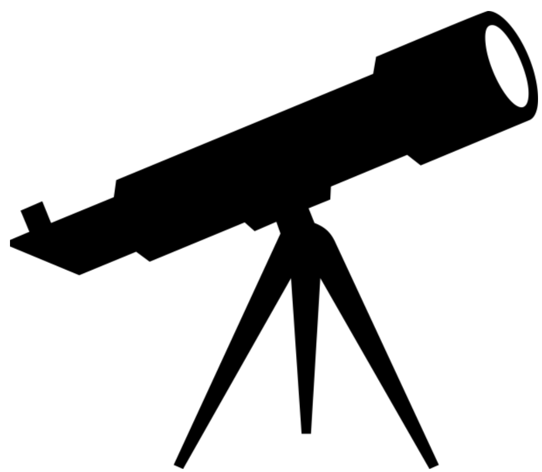
Phenomenology of A’ and EM

- Two mass ranges are considered:
- $m_{A'} > 2m_e$
  - A’ can decay into charged particles (e.g. e^+e^-, $\mu^+\mu^-$)
  - A’ could decay to light hidden sector matter that would in turn decay to ordinary matter
- $m_{A'} < 2m_e$
  - A’ cannot decay to charged particles
  - Only a decay to three γ’s would be allowed
  - At low enough mass, one should see $A' \to \gamma$ oscillations

Is this well motivated?

- There is an excess in cosmic ray e^+ compared to e^-
  - DM annihilation to dark photons could help explain this
- Dark photons could serve as a mediator in DM-nucleon scattering in direct detection experiments
- Dark photons could provide a means of DM long-range self interaction, which could explain observed DM structure formation in galaxies
- A' itself could be the DM of the universe! (If $m_{A'} \sim 100$ keV)

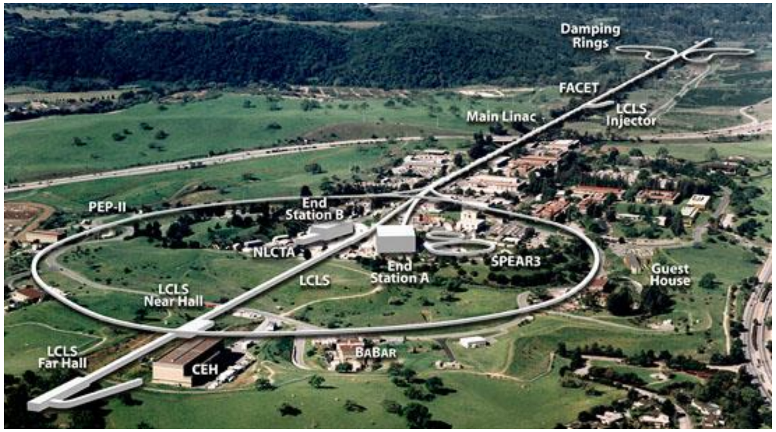
Part II:
Searches for Dark Photons

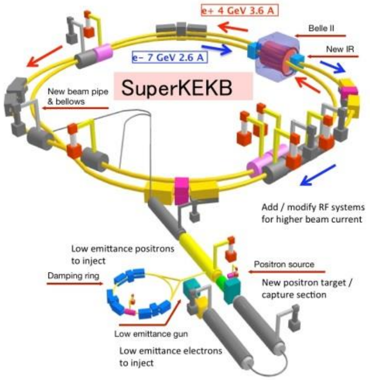


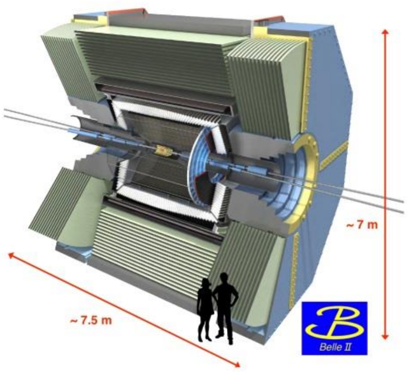
Electron Beam Dump

- A high intensity electron beam is dumped onto a fixed target
- As the electrons scatter through the target, they can produce dark photons (similar to bremsstrahlung)
- A detector is placed directly behind the target and shielding (used to block SM backgrounds)
- This is well suited for exploring $m_{A'}$ in the range ~1-100 MeV and small ϵ
  - ϵ must be small enough that A' doesn't decay in the shield and large enough that a significant number of A' are produced

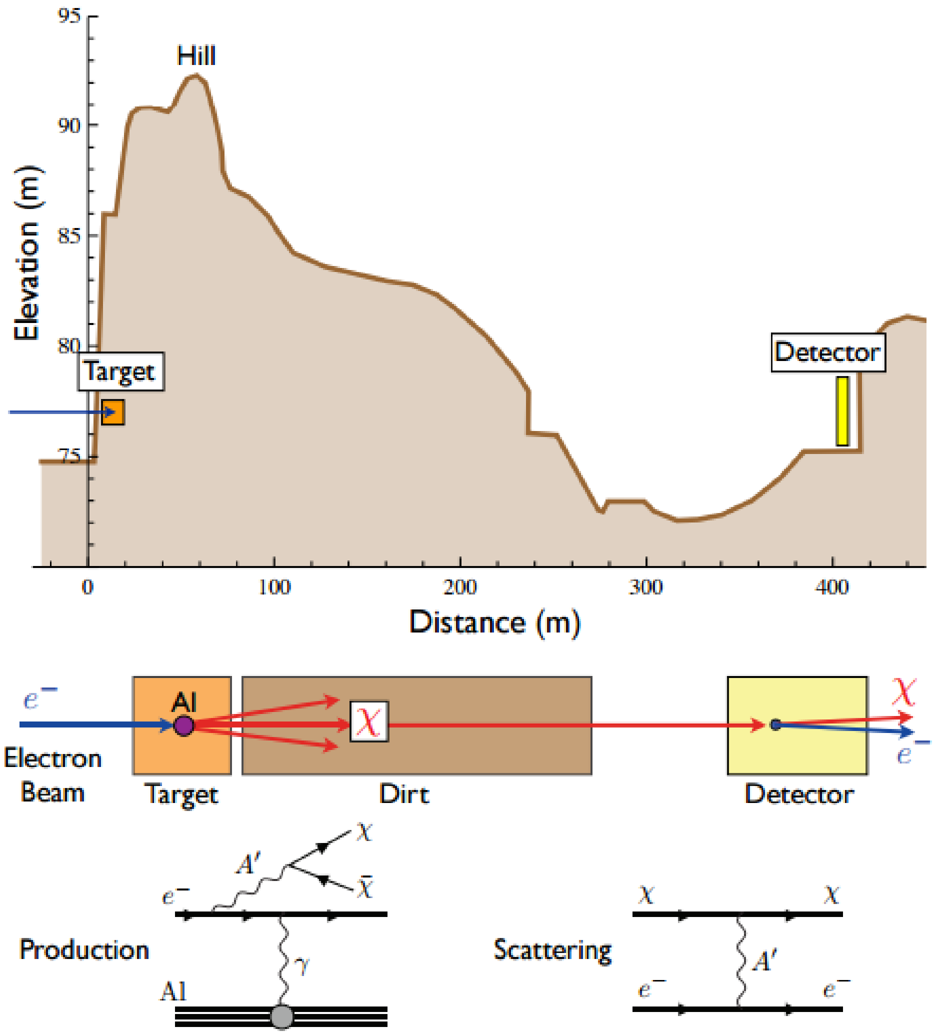
- Searches have been performed at
  - SLAC
  - Fermilab
  - KEK
  - Orsay
- Future searches planned at Cornell







CORNELL UNIVERSITY LEPP
LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS



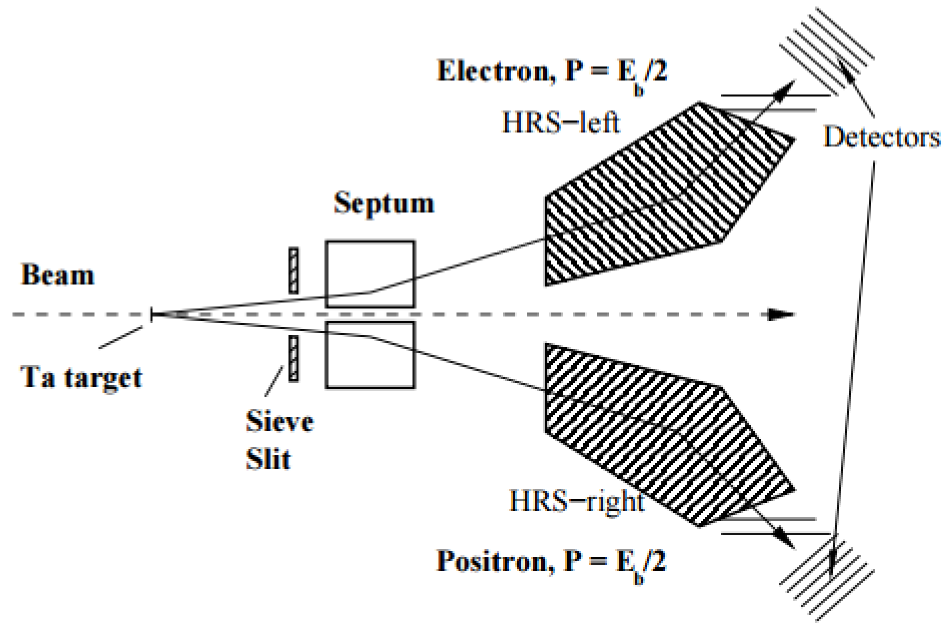
A sample experimental setup from SLAC. The target here was aluminum.
arXiv:1406.2698 [hep-ph]

Electron Fixed-Target

- Once again, a high-current electron beam is shot onto a fixed target, and the A’ is radiated of electrons that scatter off the target nuclei
- Similar to electron beam-dump, but generally lower energy electrons (.1-1 Gev vs 10-100 GeV)
  - Useful for investigating shorter A’ lifetimes
- Looking for $e^{+}e^{-}$ mass resonances and displaced vertices

Example: A' Experiment (APEX)

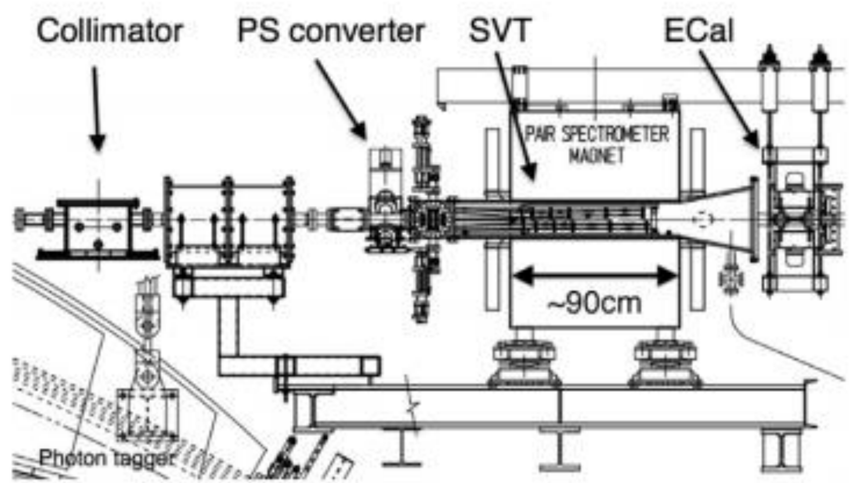
- JLab Hall A
- Uses double-arm spectrometer
- Looks for a bump in the e^+e^- invariant mass distribution
- Beam energy and spectrometer angle actively varies to explore regions of invariant mass



Setup of the APEX experiment
arXiv:1108.2750 [hep-ex]

Example: Heavy Photon Search (HPS)

- JLab Hall B
- Si-Strip vertex tracker in magnet
- Measures invariant mass and decay points of e^+e^- pairs
- Better signal-background discrimination

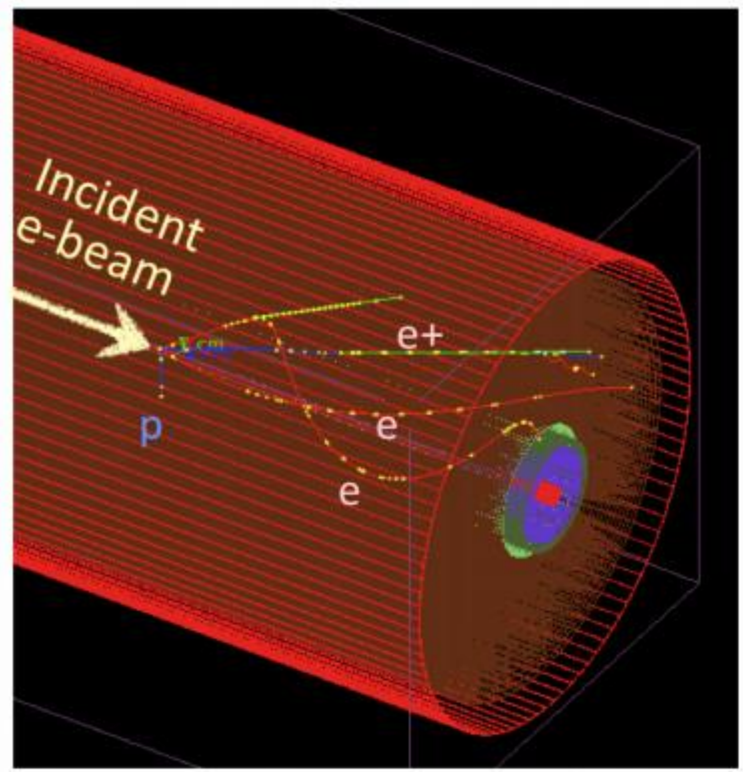


HPS experimental layout

http://www.sciencedirect.com/science/article/pii/S0168900214014582

Example: DarkLight

- Jlab FEL
- Beam incident on hydrogen gas target in solenoidal magnet
- Compact, magnetic spectrometer
  - Silicon detectors (recoil protons)
  - Low mass tracker (leptons)
  - Shower counters (photons)
- Full kinematic reconstruction

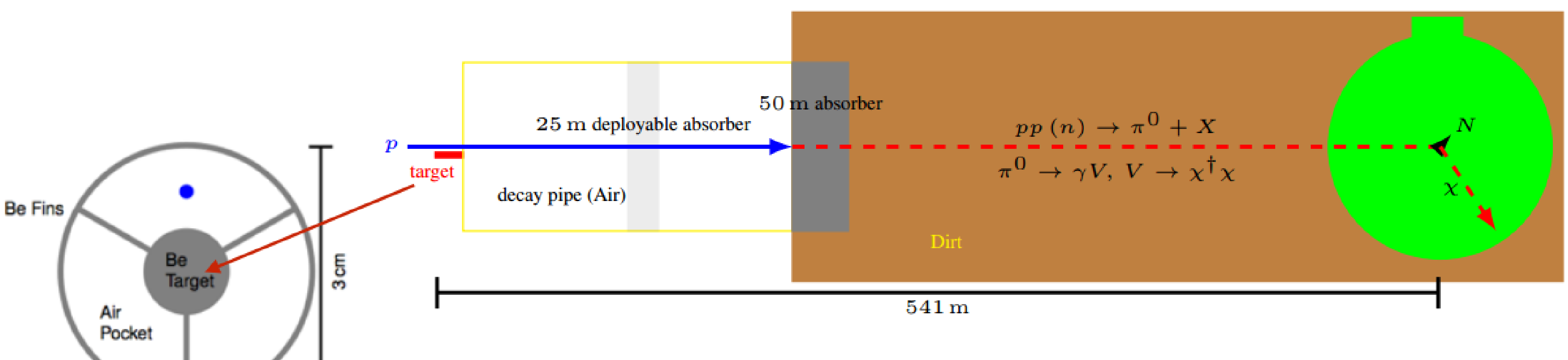


Sample DarkLight event

https://www.cfa.harvard.edu/events/2014/sackler/index/talks/Harvard2014_Epstein.pdf

Proton Beam Dump

- Often a reanalysis of data from neutrino experiments (e.g. LSND, NOMAD, PS 191, CHARM)
- Pseudoscalar vectors produced by these collisions may decay to $\gamma A'$
- Dedicated beam dump run at MiniBooNe has been proposed



A. Aguilar-Arevalo et al., arXiv:1211.2588 (2012)

Proposed MiniBooNe beam dump mode

Electron-Positron Colliders

- Use large datasets from e.g. KLOE ($DA\Phi NE$), BABAR (PEP-II), Belle (KEK-B), BESIII (BEPC)
- $e^+e^- \rightarrow \gamma A', A' \rightarrow l^+l^-$
- $e^+e^- \rightarrow h'A'$ (where h’ is a new light scalar particle)
- Mesons could also decay to A’

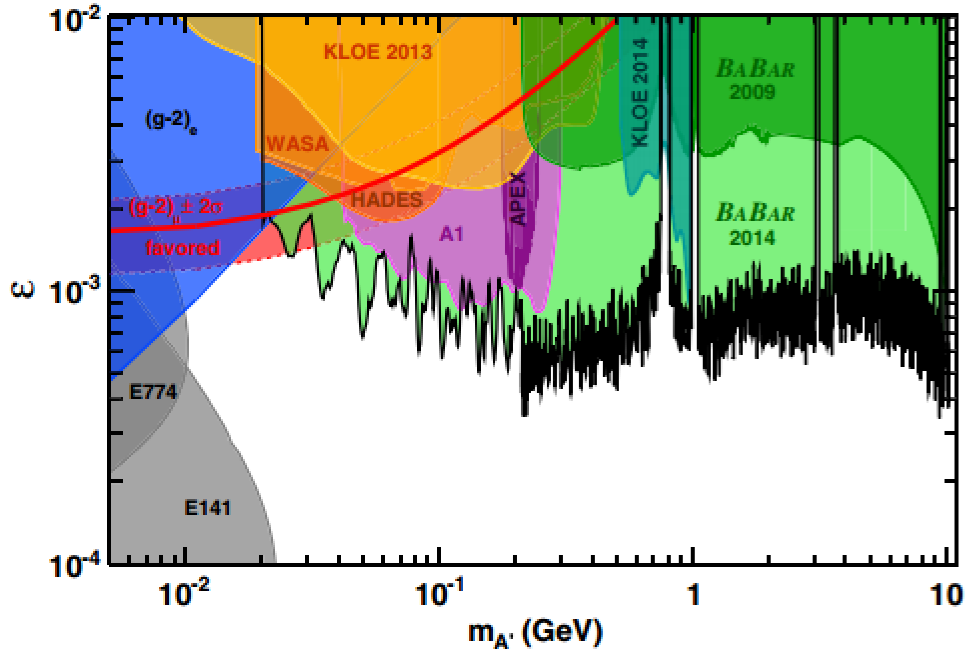
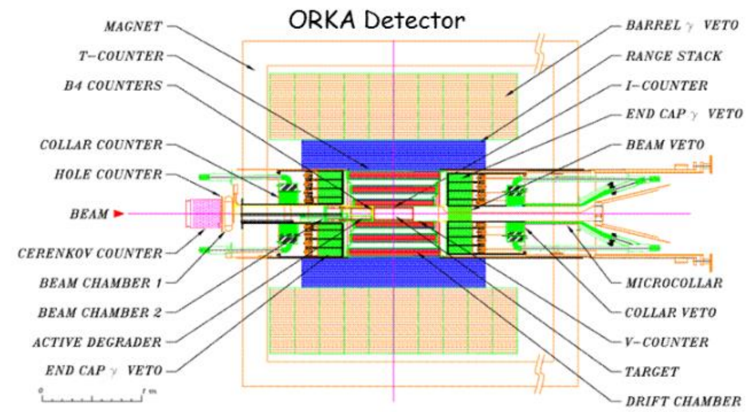


FIG. 4 (color online). Upper limit (90% C.L.) on the mixing strength ϵ as a function of the dark photon mass. The values required to explain the discrepancy between the calculated and measured anomalous magnetic moment of the muon [39] are displayed as a red line.

http://physics.aps.org/featured-article-pdf/10.1103/PhysRevLett.113.201801

Rare Kaon Decays

- Dedicated rare Kaon decay experiments are sensitive to:
  - $K^+ \to \mu^+ \nu A', A' \to e^+ e^-$
  - $K^+ \to \pi^+ A', A' \to e^+ e^-$
- ORKA, NA62, TREK/E36



ORKA detector schematic diagram

CDF COT removal (the ORKA detector fits within the COT)

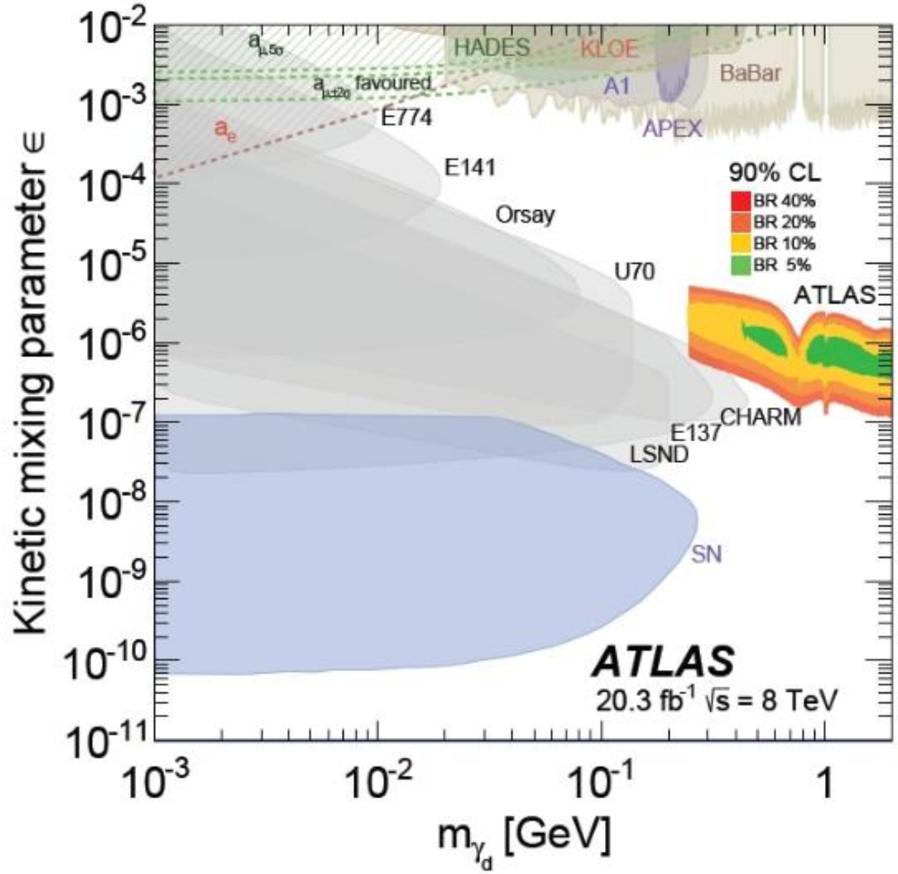
https://orka.bnl.gov/

Proton Colliders

- High COM energy could lead to production of novel heavy particles directly
- New particles could decay to A’ (perhaps a dominant decay chain even)
- GeV-scale A’ could produce highly collimated jets mostly composed of leptons
- Search for events with large missing transverse energy
- Search for events with particular di-lepton mass (which would be the A’ mass)

Within ATLAS

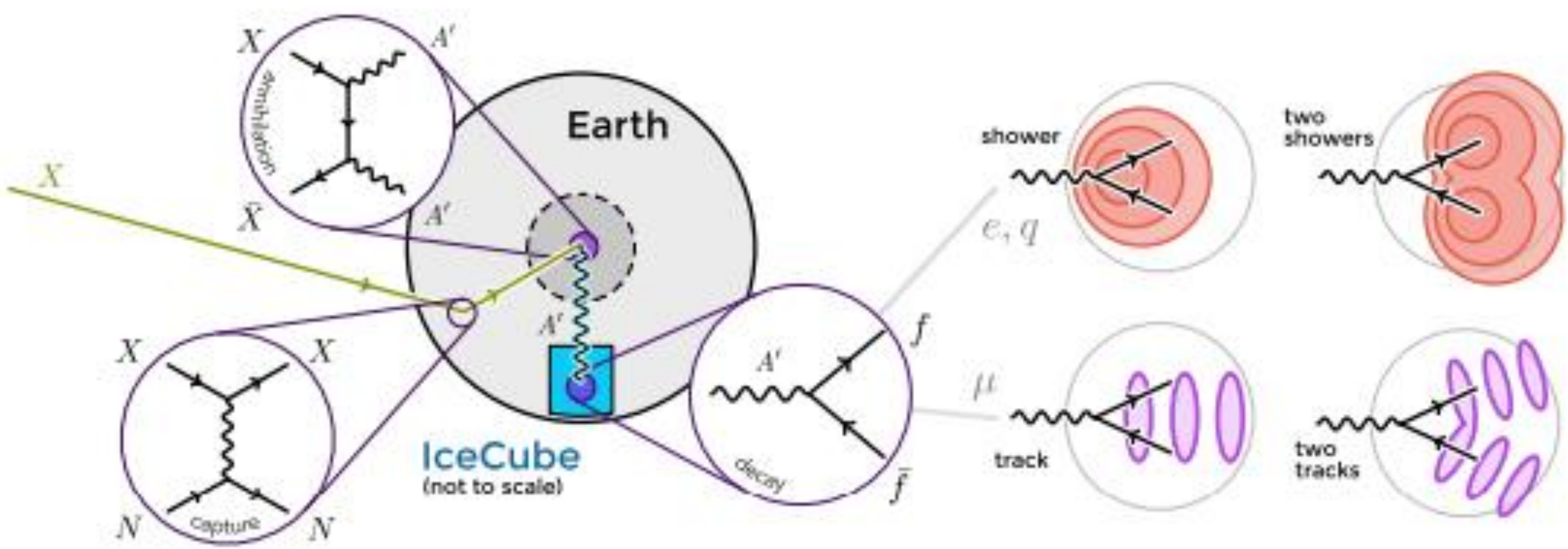
- Mostly focused on A' heavy enough to decay to muons
- Has conducted searches for Higgs to electron lepton-jets and Higgs to long-lived A'



https://arxiv.org/pdf/1409.0746.pdf

Dark Photons from the Earth’s Core

- Dark matter may accumulate in the center of the Earth
- This dark matter could self annihilate $XX \rightarrow A'A'$
- The A’ could then propagate up and decay to SM particles
- These particles could then be detected by underground/ice/water experiments such as
  - SuperK
  - IceCube
  - ANTARES
  - DUNE

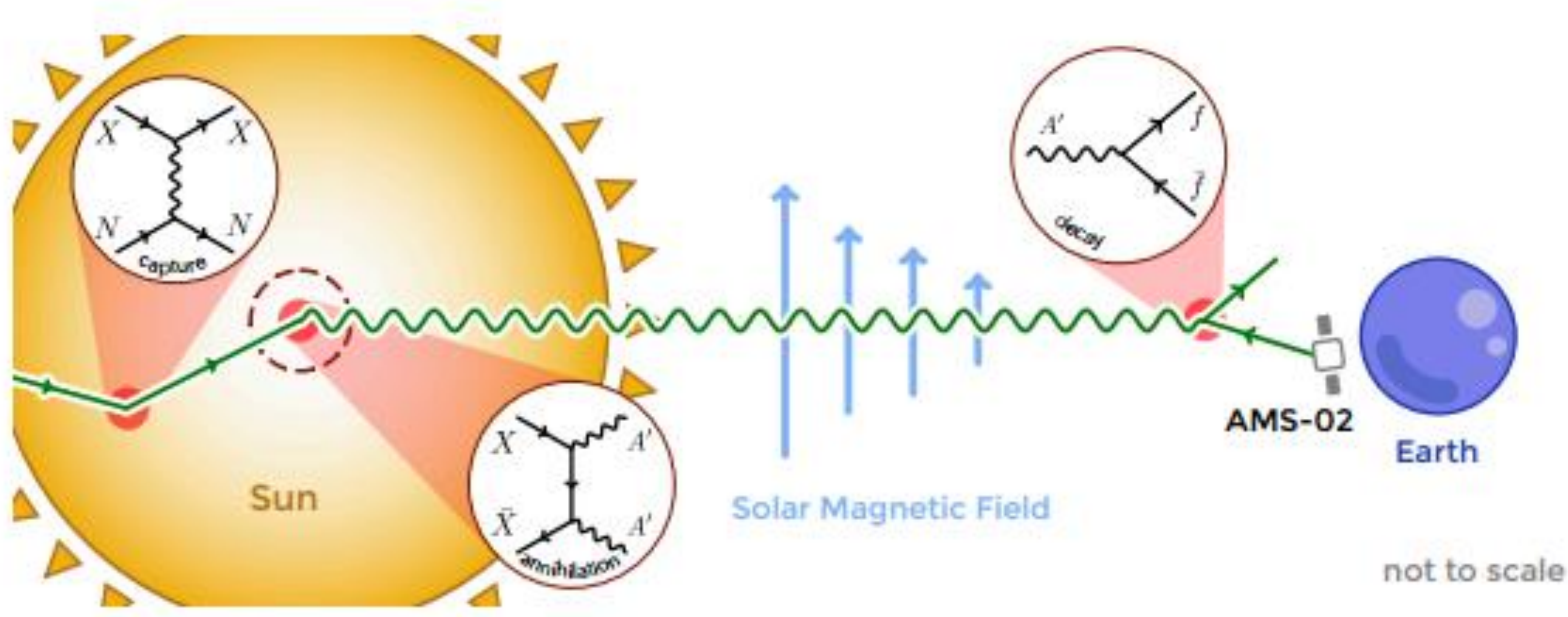


Model for A’ production within the Earth. IceCube used here as example. A signal from within the Earth would be a sign of dark matter.

[arXiv:1509.07525](https://arxiv.org/abs/1509.07525) [hep-ph]

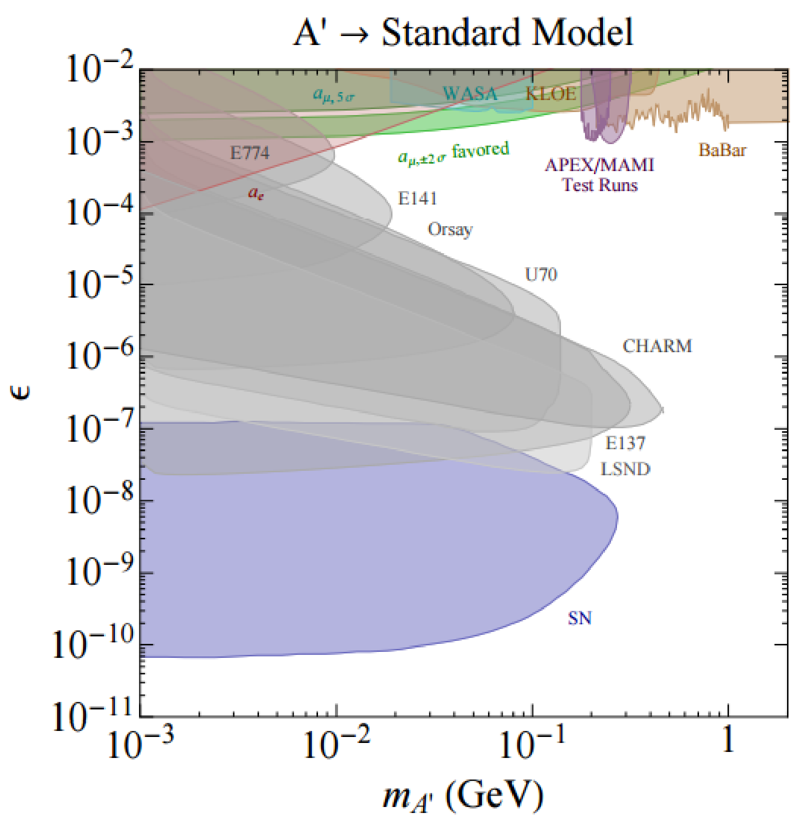
Dark Sunshine

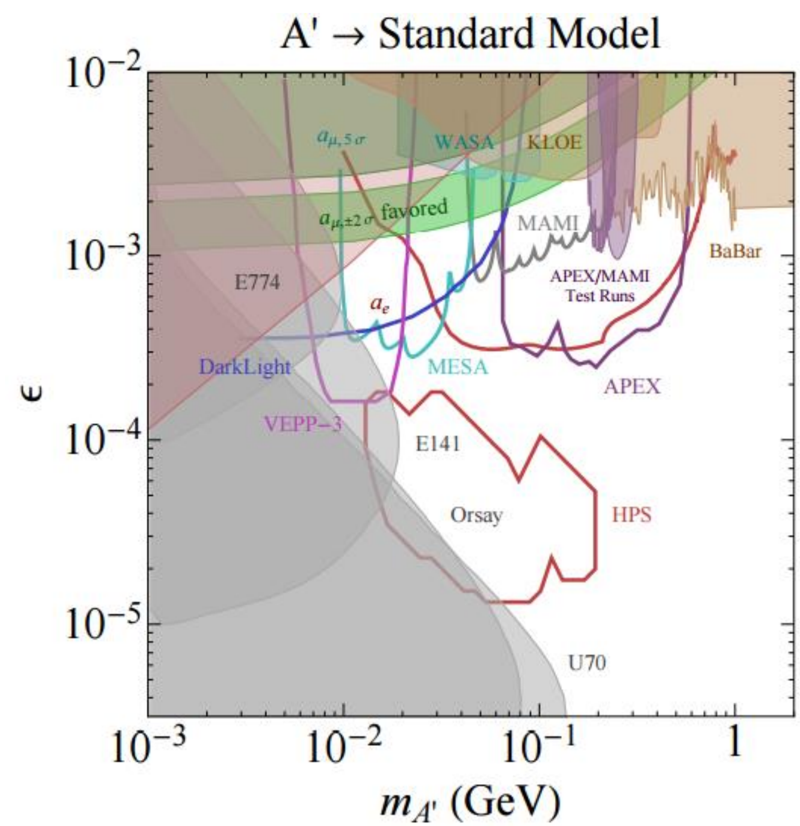
- DM accumulates in Sun and self-annihilates
- Essentially the opposite of deep earth searches
  – But here magnetic forces of Sun and Earth can distort directionality
  – Probes longer lifetimes
- These searches use space based detectors such as Fermi Large Area Telescope or the Alpha Magnetic Spectrometer



Model for A' production within the Sun. AMS used here as example.
[arXiv:1602.01465](https://arxiv.org/abs/1602.01465) **[hep-ph]**

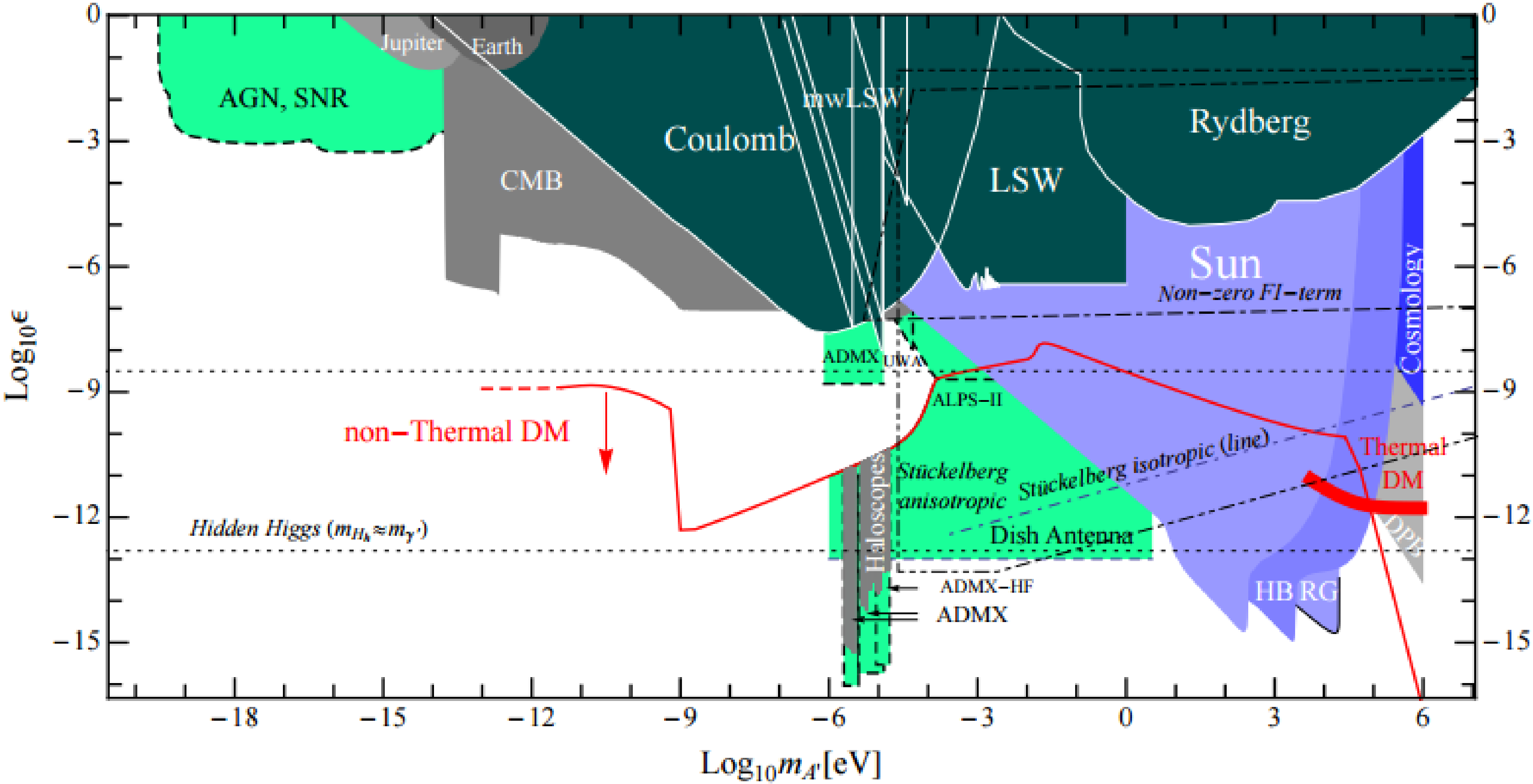
Exclusion Plots





Parameter space for searches for A' with mass greater than $2m_e$. Shaded regions represent 90% CL. Right hand plot is a zoomed in version of the left to detail higher ϵ searches.

arXiv:1311.0029 [hep-ph]



Parameter space for searches for A' with mass less than $2m_e$. Shaded regions represent 90% CL. Regions where A' could account for all Big Bang DM are shown in red.

[arXiv:1311.0029](https://arxiv.org/abs/1311.0029) **[hep-ph]**

Dark matter searches that aren't deep underground?

- Some of these searches do in fact repurpose neutrino or direct dark matter search detectors e.g.:
  - Center of the Earth A'
  - Proton Beam dump
- Most of these searches rely on producing A' in the lab
  - Standard shielding is used in lab
  - Dominant backgrounds are not long-lifetime nuclear decays, but SM particles
  - Directionality of A' decay particles is well understood in the experiment

Sources

- "Dark Sectors and New, Light, Weakly-Coupled Particles", arXiv:1311.0029 [hep-ph]
- "Search for Dark Photon in e+e- Collisions at BaBar", http://physics.aps.org/featured-article-pdf/10.1103/PhysRevLett.113.201801
- "Dark Sunshine: Detecting Dark Matter through Dark Photons from the Sun", arXiv:1602.01465 [hep-ph]
- "Dark Photons from the Center of the Earth: Smoking-Gun Signals of Dark Matter", arXiv:1509.07525 [hep-ph]
- "Dark matter and a new gauge boson through kinetic mixing", arXiv:1011.3300 [hep-ph]
- "Kinetic mixing and symmetry breaking dependent interactions of the dark photon", arXiv:1409.2082 [hep-ph]
- http://hallaweb.jlab.org/experiment/APEX/
- https://confluence.slac.stanford.edu/display/hpsg/Heavy+Photon+Search+Experiment