Searching for Dark Photons at Jefferson Lab

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On behalf of the HPS, APEX, DarkLight, and BDX

2017 JLab User's Group Meeting

20 June 2017

OLD DOMINION UNIVERSITY

Overview:

APrime EXperiment

- Motivation
- Dark photon searches:
  - APEX (Hall A)
  - HPS (Hall B)
  - DarkLight (LERF)
  - BDX
- Summary

DARKLIGHT

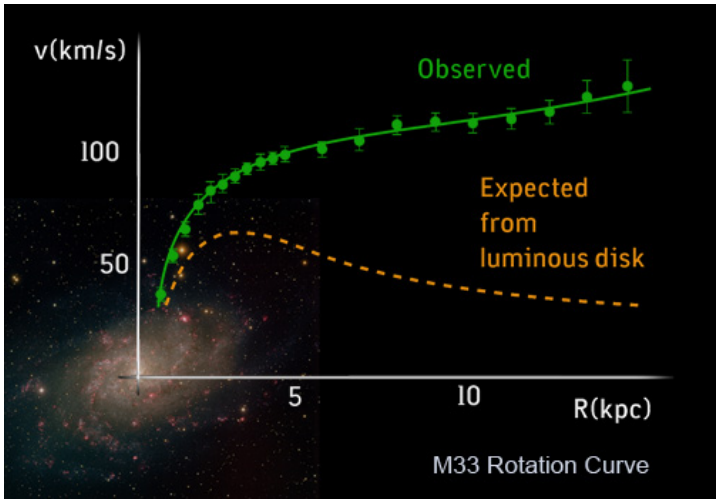
Detecting A Resonance Kinematically with
eLectrons Incident on a Gaseous Hydrogen Target

Beam Dump eXperiment

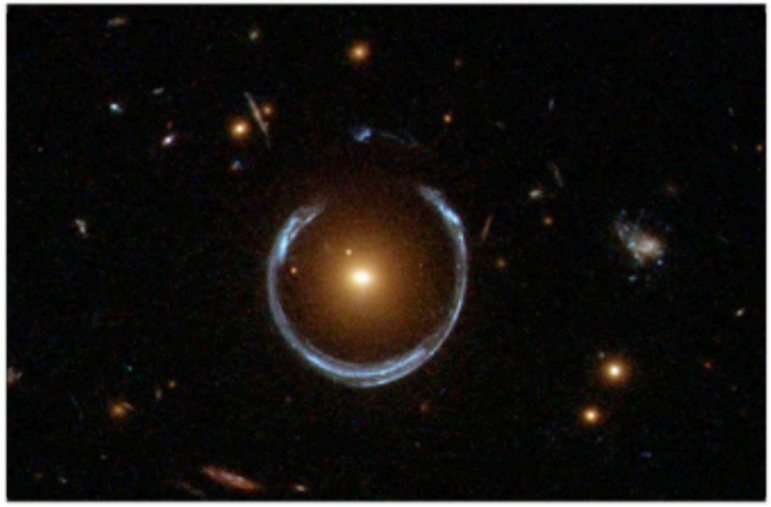
Nature is described well by Standard Model, but we are missing something…

Strong evidence for dark matter!

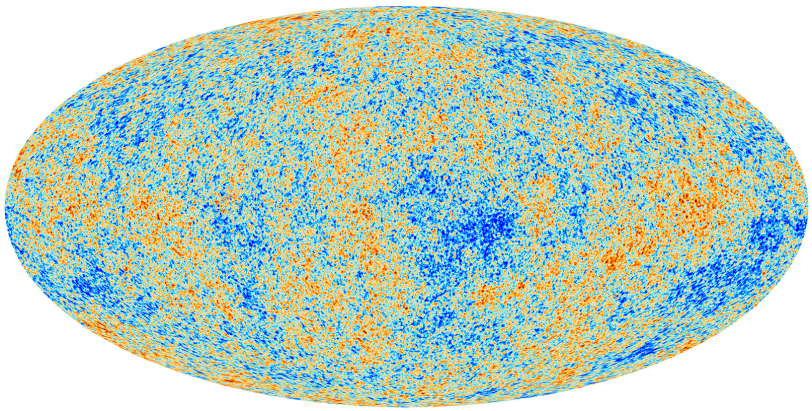
Galaxy rotational velocities

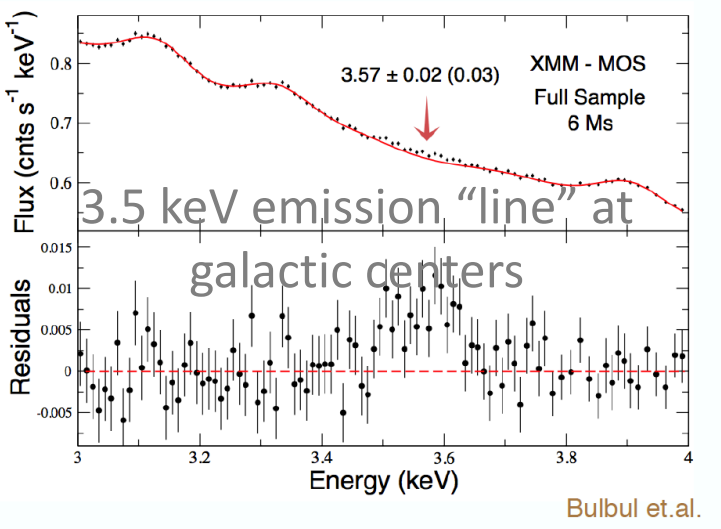


Gravitational Lensing



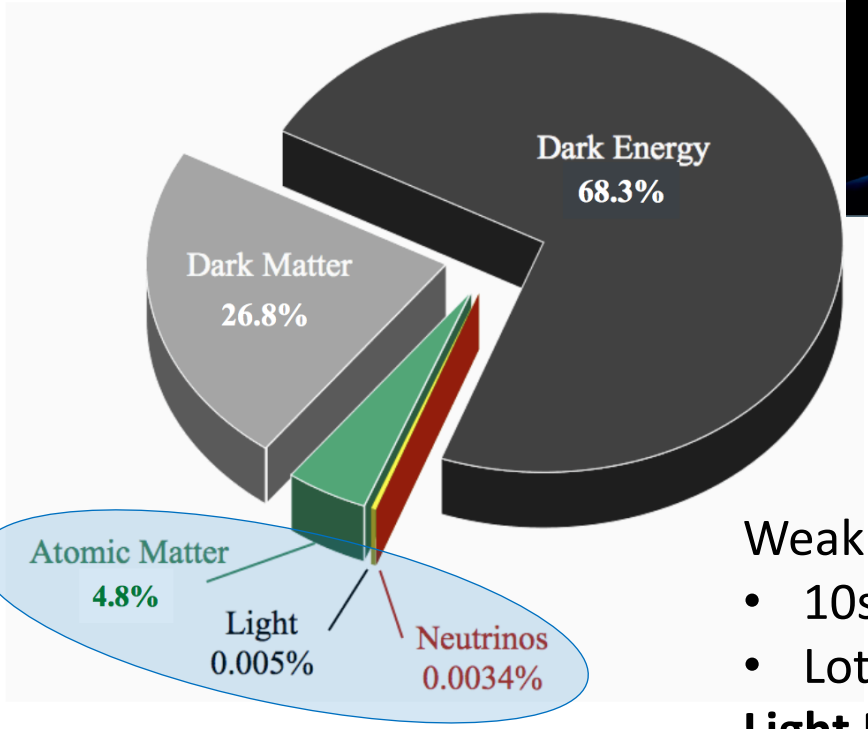
Cosmic Microwave Background structure





Bulbul et.al.

Exploring the Dark Sector



Standard Model:

$U(1)_Y \times SU(2)_W \times SU(3)_S$

EM Weak Strong

Dark Sector:

$U(1)_D \times \ldots$

Dark Forces?

Neutral under SM forces

Dark Matter theories

Weakly Interacting Massive Particle (WIMP)s:

- 10s-100s GeV mass range
- Lots of searches, not detected so far

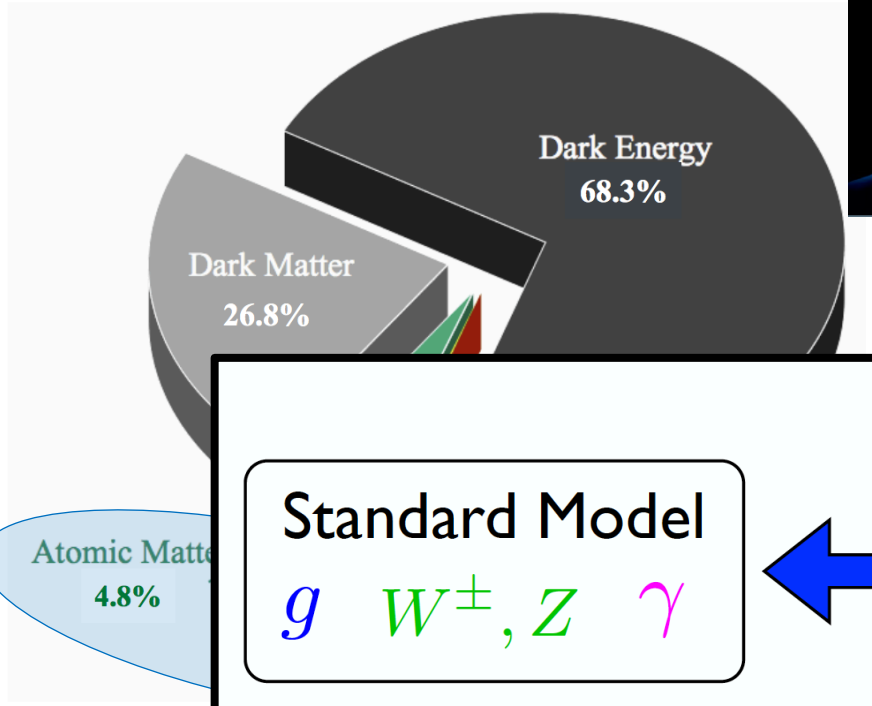
Light Dark Matter:

- MeV-GeV mass range
- Requires new force for correct relic abundance

Strongly Interacting Massive Particles (SIMPs):

- MeV-GeV mass range
- Strongly interacts with itself

Exploring the Dark Sector

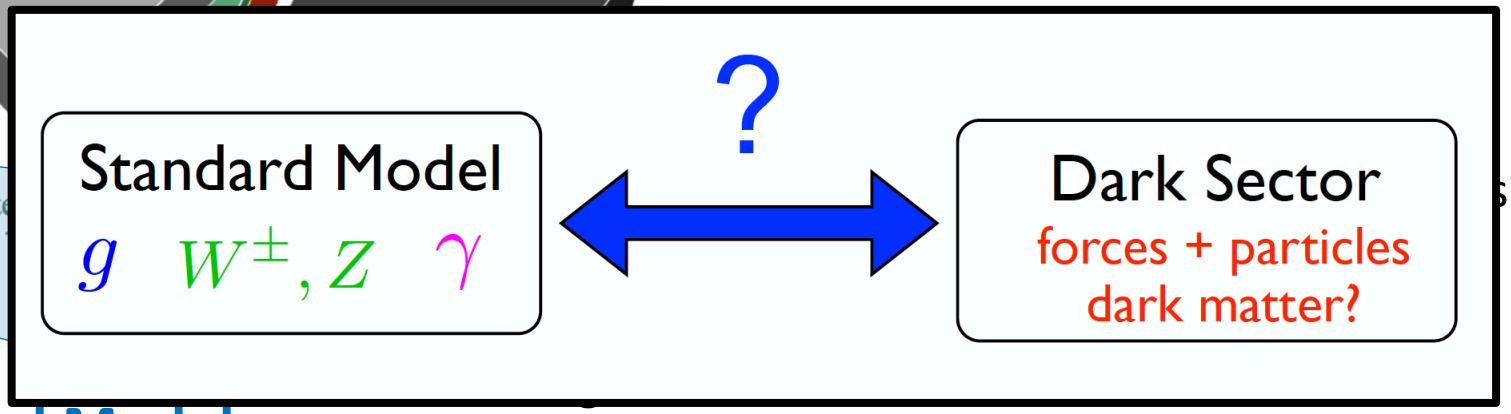


Dark Sector:

$U(1)_D$ x …

Dark Forces?

Neutral under SM forces



Standard Model:

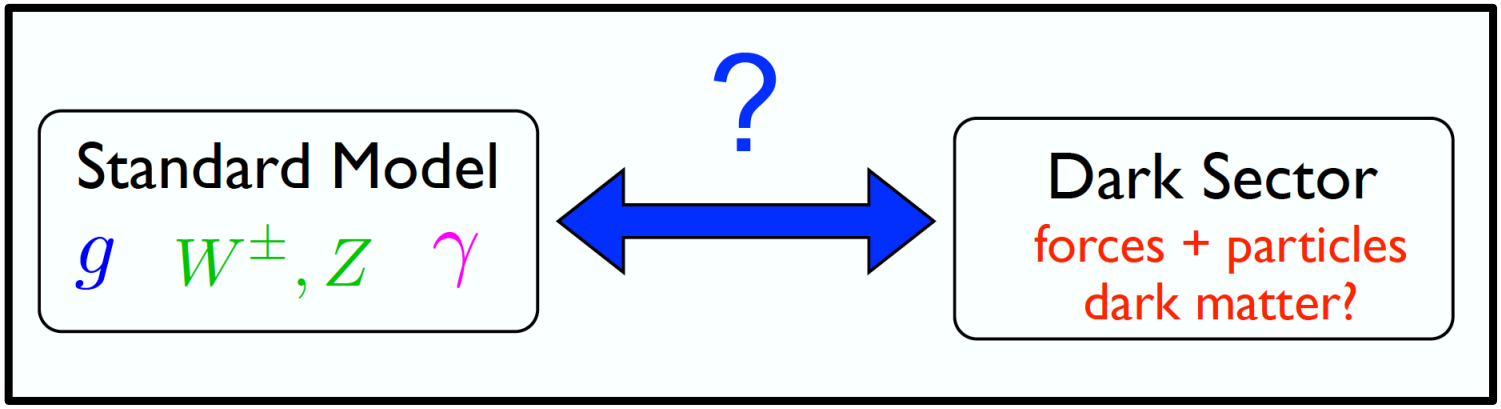
$U(1)_Y$ x $SU(2)_W$ x $SU(3)_S$

EM Weak Strong

- MeV-GeV mass range
- Requires new force for correct relic abundance

Strongly Interacting Massive Particles (SIMPs):

- MeV-GeV mass range
- Strongly interacts with itself

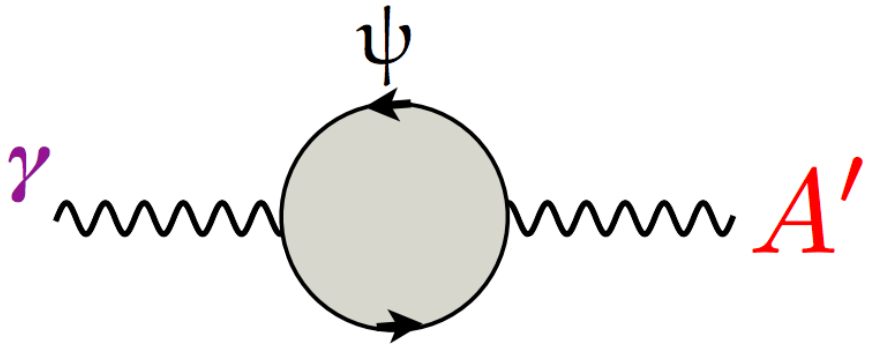

Standard Model
g $W^{\pm}, Z$ γ
?
Dark Sector
forces + particles
dark matter?

Extra Abelian U(1) gauge symmetry → new gauge boson!

Holdom, Phys Lett. B166, 1986

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$

Heavy Photon
(aka: dark photon, A',
U-boson…)



Kinetic mixing induces a small coupling ϵe to electric charge

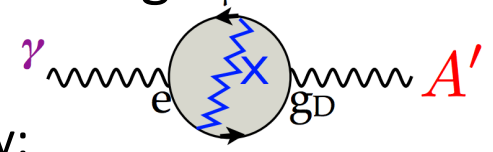
$$A_\mu \rightarrow A_\mu + \epsilon A'_\mu$$

Simplest case:

loop-level interaction

$$\epsilon \sim \frac{g_Y g_D}{16\pi^2} \ln\left(\frac{m_\Phi}{m_{\Phi'}}\right) \sim 10^{-3} - 10^{-1}$$

Grand Unified Theory:



two-loop interactions and higher

$$\epsilon \sim 10^{-6} - 10^{-3}$$

Mass of heavy photon is less constrained

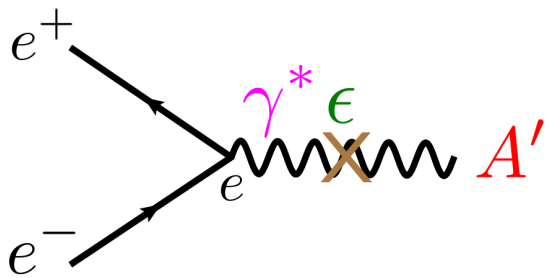
Methods of heavy photon production

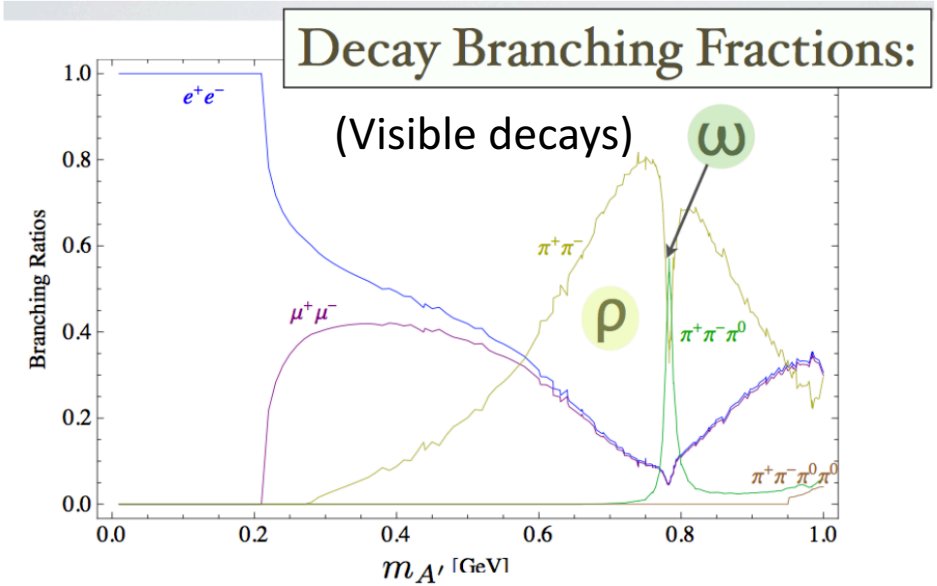
"Wherever there are photons (and sufficient phase space), there are dark photons."
–Philip Schuster

(Z here is atomic number of nucleus)

- Bremsstrahlung
  $e^- Z \rightarrow e^- Z A'$
- e+e- annihilation
  $e^- e^+ \rightarrow \gamma A'$
- pZ → X + meson
  $\pi^0 \rightarrow \gamma A'$
  $\eta \rightarrow \gamma A'$
  $\phi \rightarrow \gamma A'$
- Drell-Yan
  $q\bar{q} \rightarrow \gamma A'$

$A' \rightarrow e^+ e^-$
$\rightarrow \mu^+ \mu^-$
$\rightarrow \pi^+ \pi^-$
$\rightarrow \chi \chi$



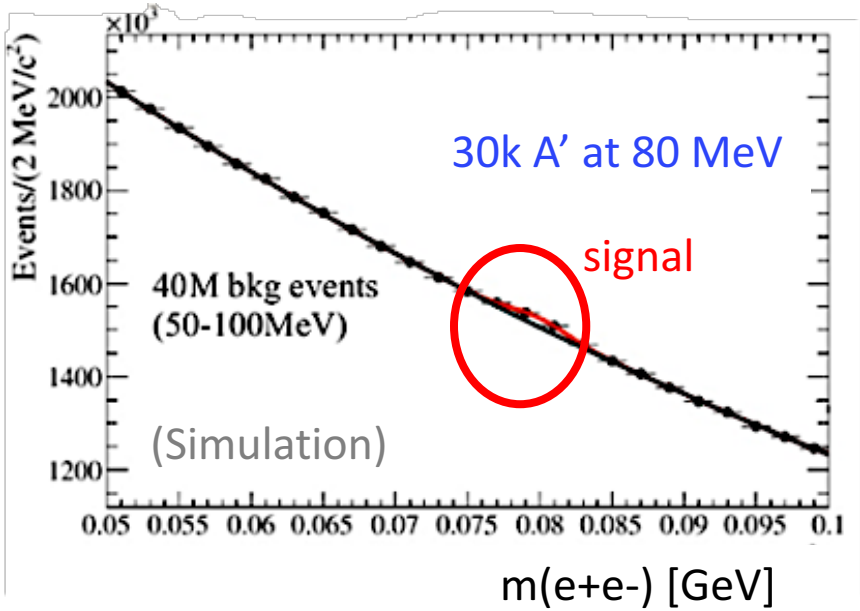


Methods of heavy photon detection

Visible decays:

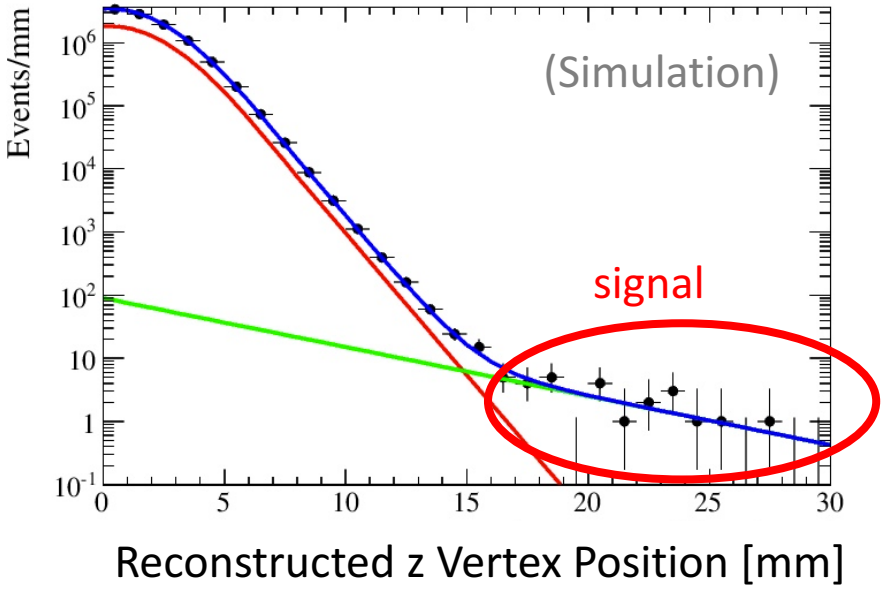
Invariant mass bump hunt:

- Large coupling, prompt decays, lots of background



Displaced vertex:

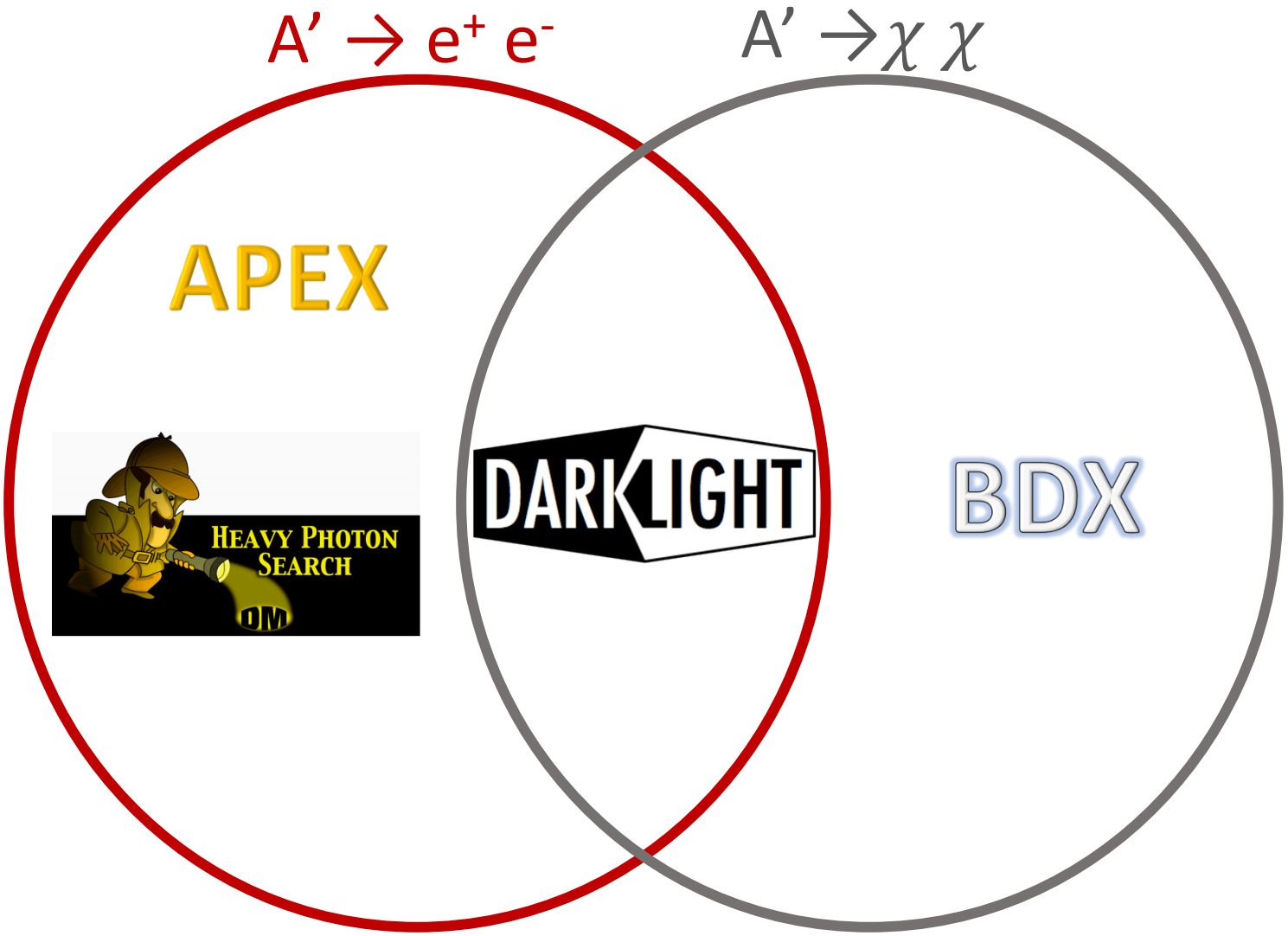
- Small coupling, long-lived decays, little/no background



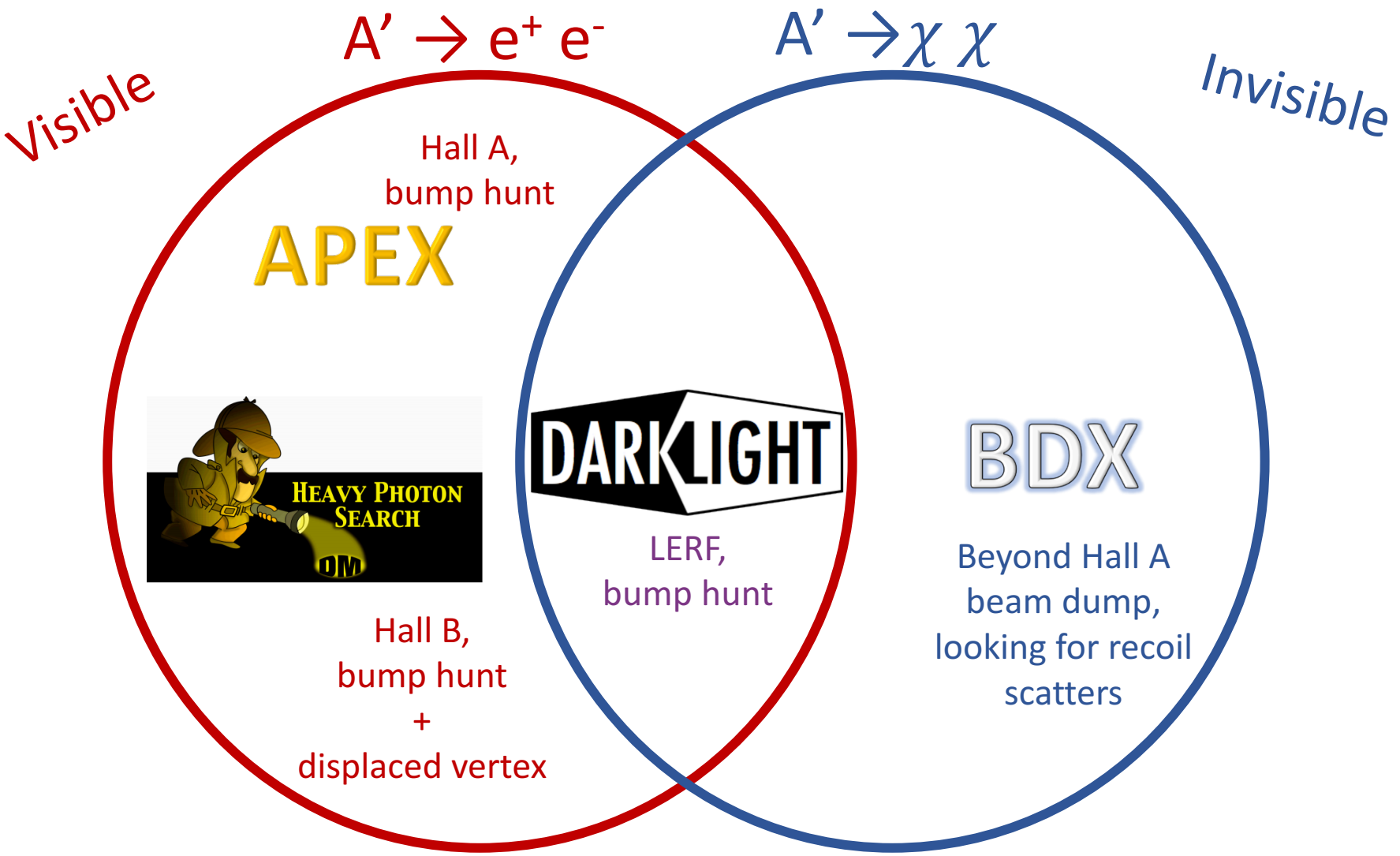
Invisible decays:

Missing mass bump hunt, allows for decay to Dark Sector

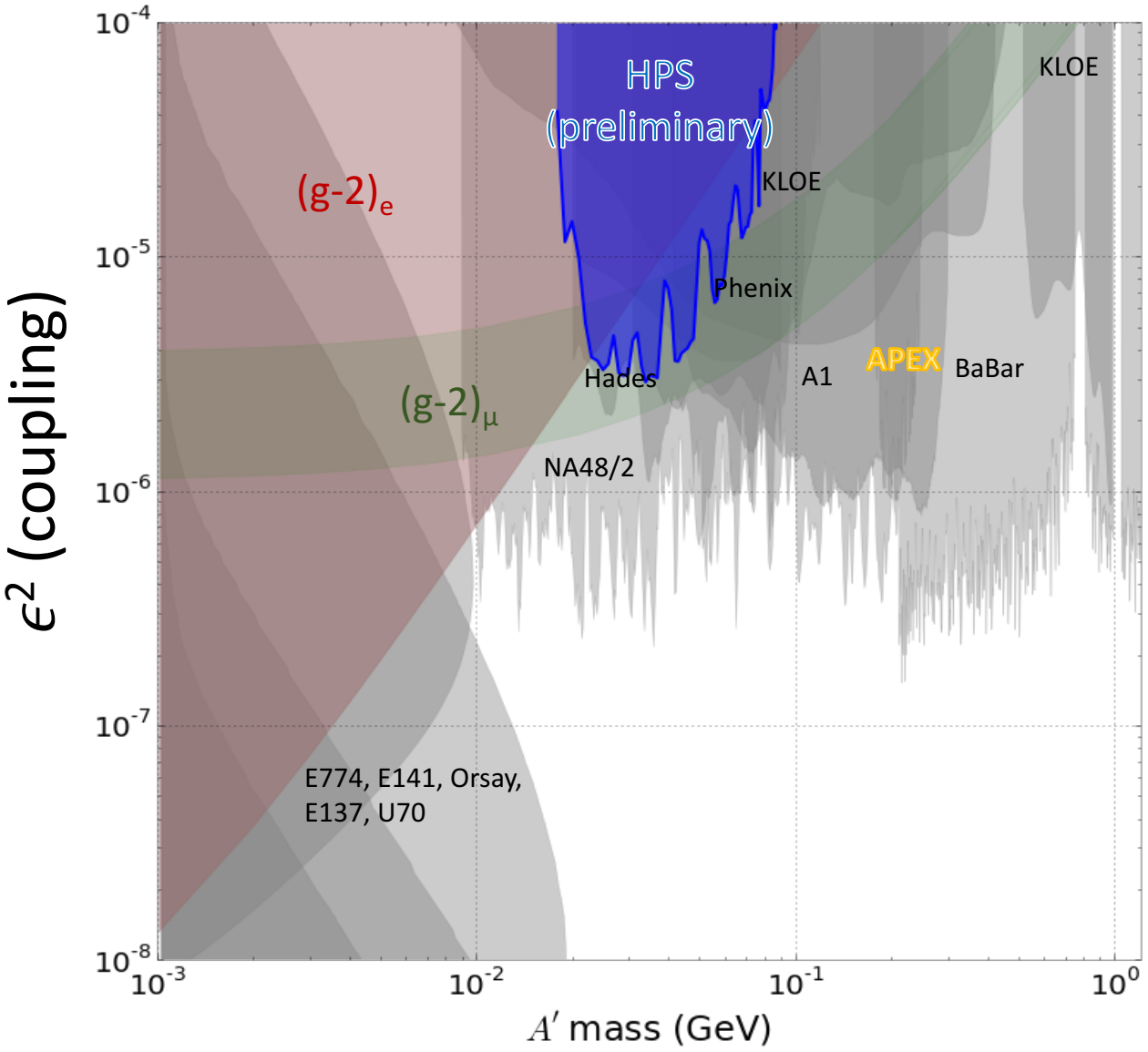
Searches at Jefferson Lab



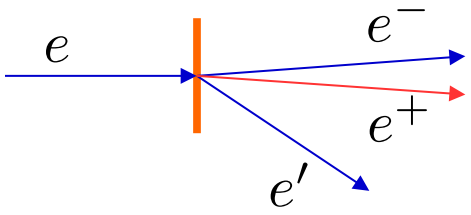
Searches at Jefferson Lab



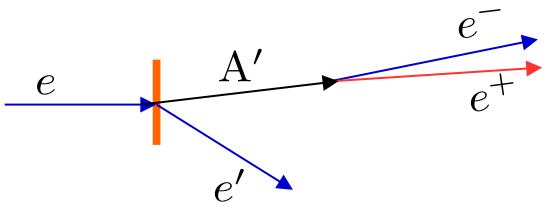
Existing constraints (A' decays visibly)



Large ϵ coupling
→ prompt decay



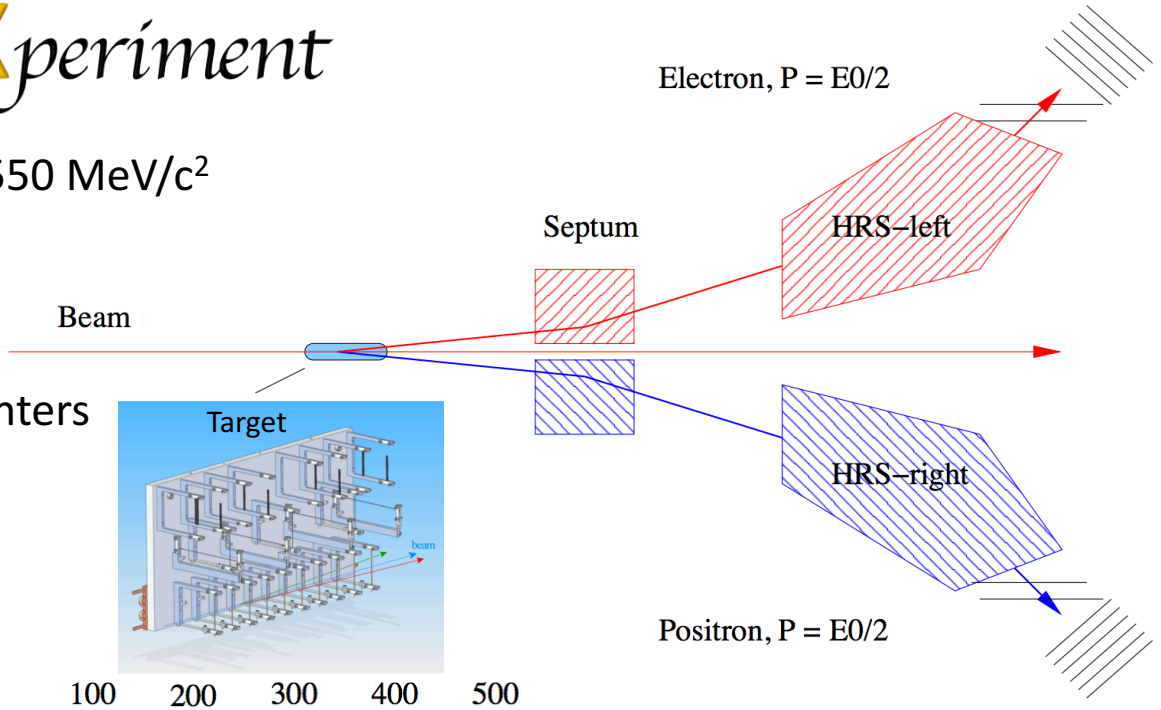
Small ϵ coupling
→ A' long-lived



APrime EXperiment

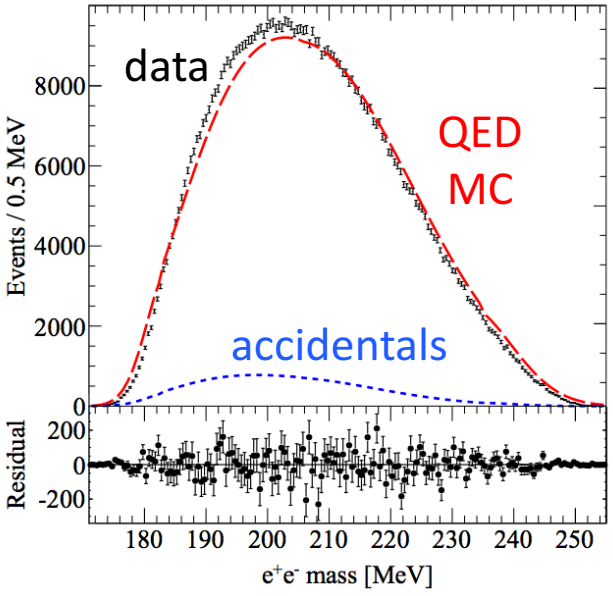
Hall A, bump hunt (e^+e^-), $m_{A'}$: 65-550 MeV/c^2

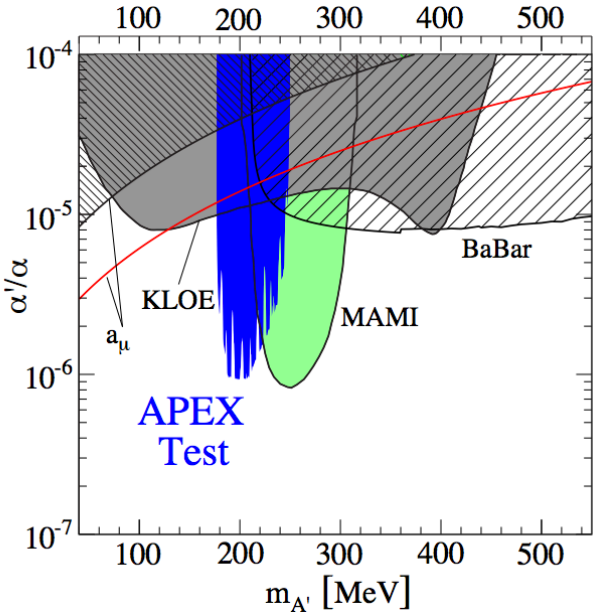
- Momentum reconstruction: drift chambers
- Triggering and PID: Cerenkov and scintillator counters



Test run 2010:

- 2.26 GeV, 150 μA e^- beam on thin Ta target





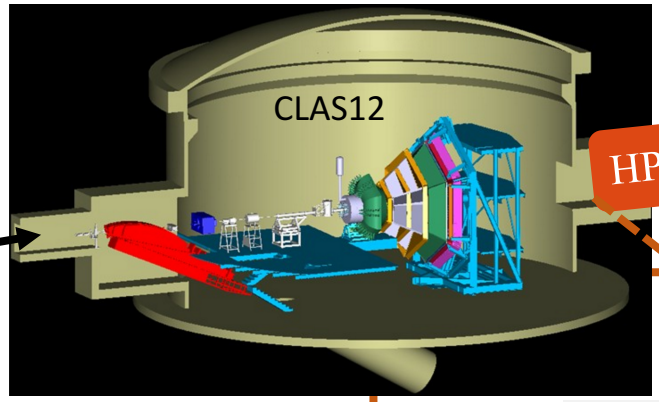
Weekend run achieved world record sensitivity!

Ready for installation this fall

Projected to run after ^{3}H experiments in 2018

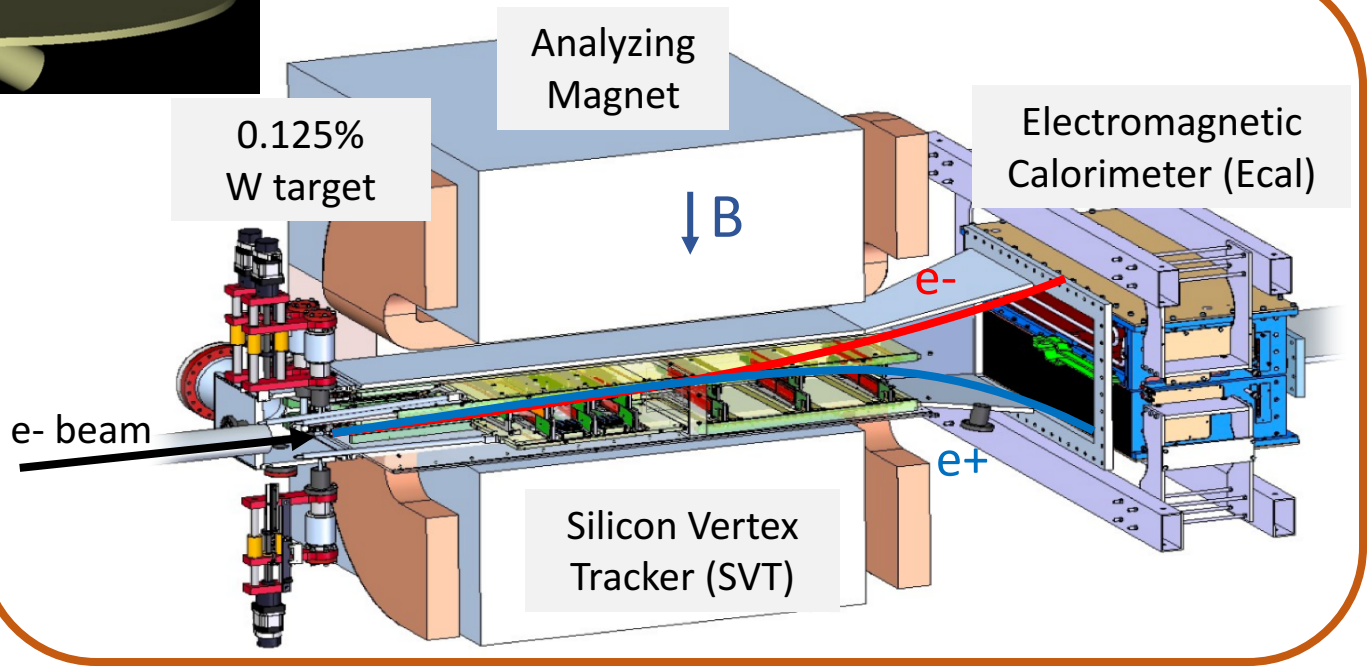
- Searches for A' with **prompt** and **displaced** vertices
- Downstream Hall B alcove
- 2015 Engineering Run, 1 GeV beam at 50 nA
- 2016 Physics Run, 2.3 GeV beam at 200 nA
- Future running planned for 2018 and beyond

Hall B

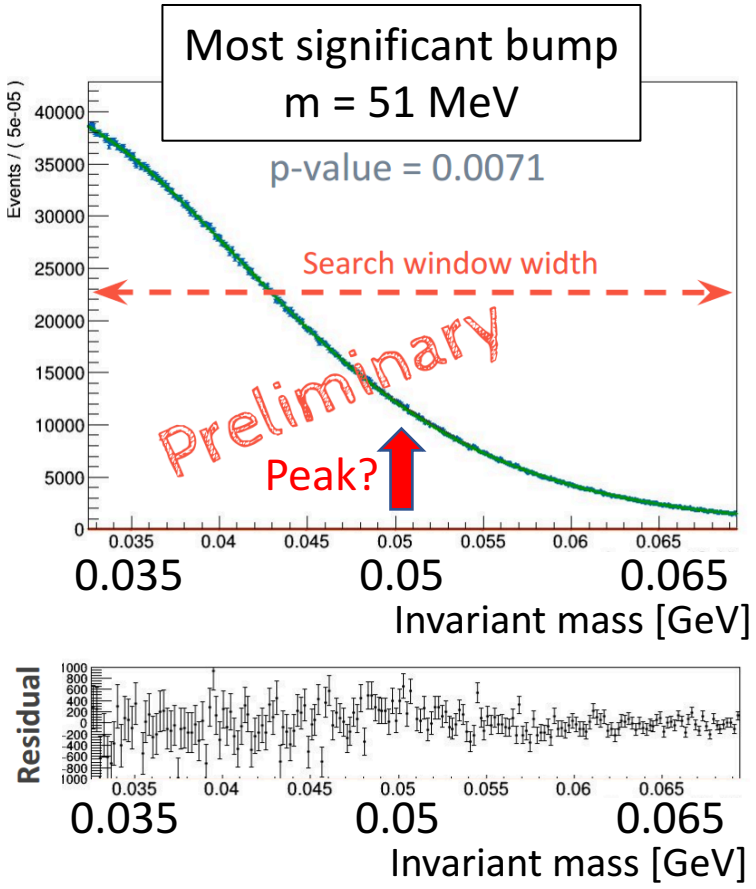


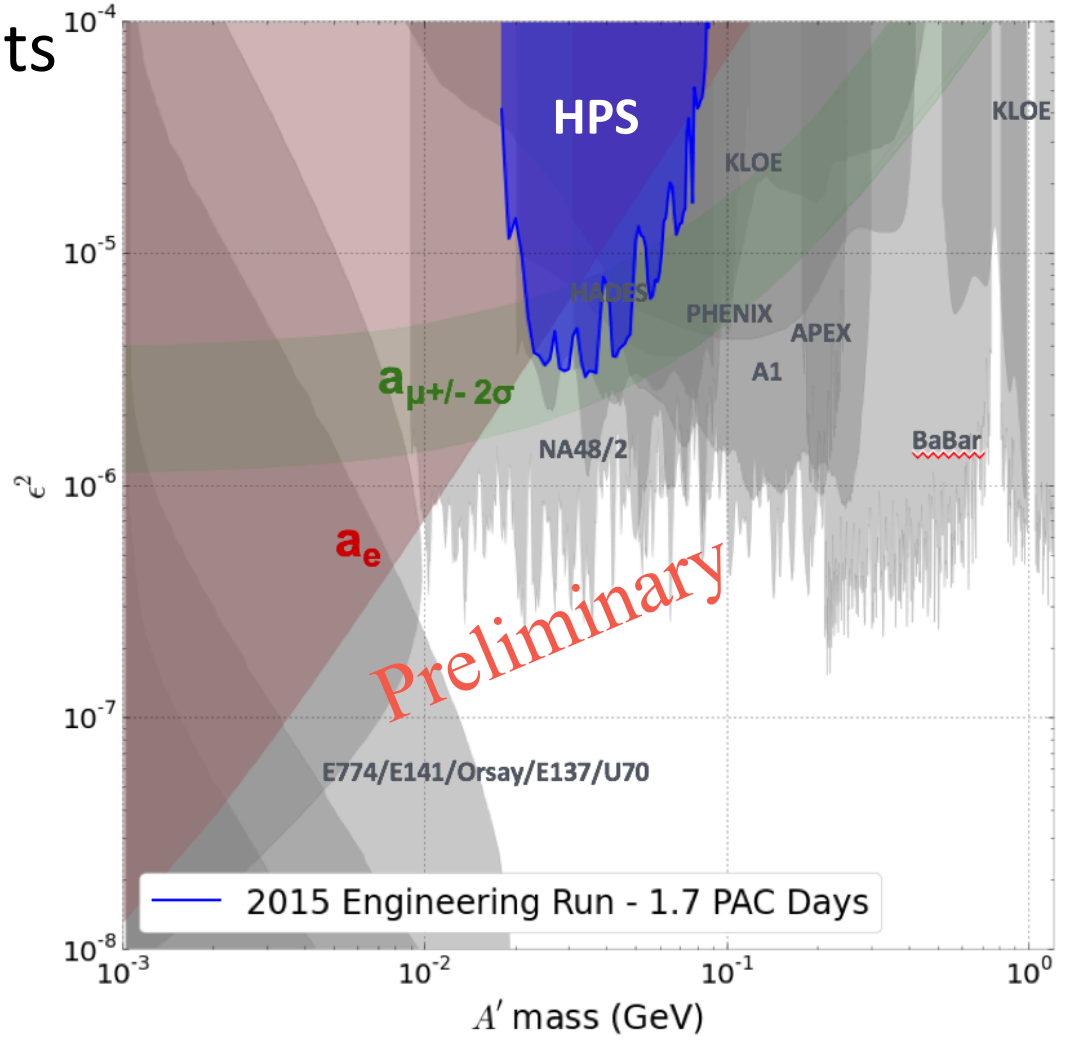
Silicon Vertex Tracker:
- Tracks particles
- Momentum and vertex reconstruction

EM Calorimeter:
- Triggers events
- Energy and timing



2015 Engineering Run results

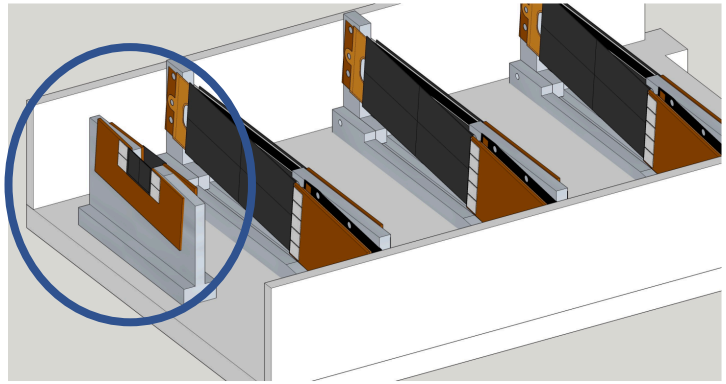


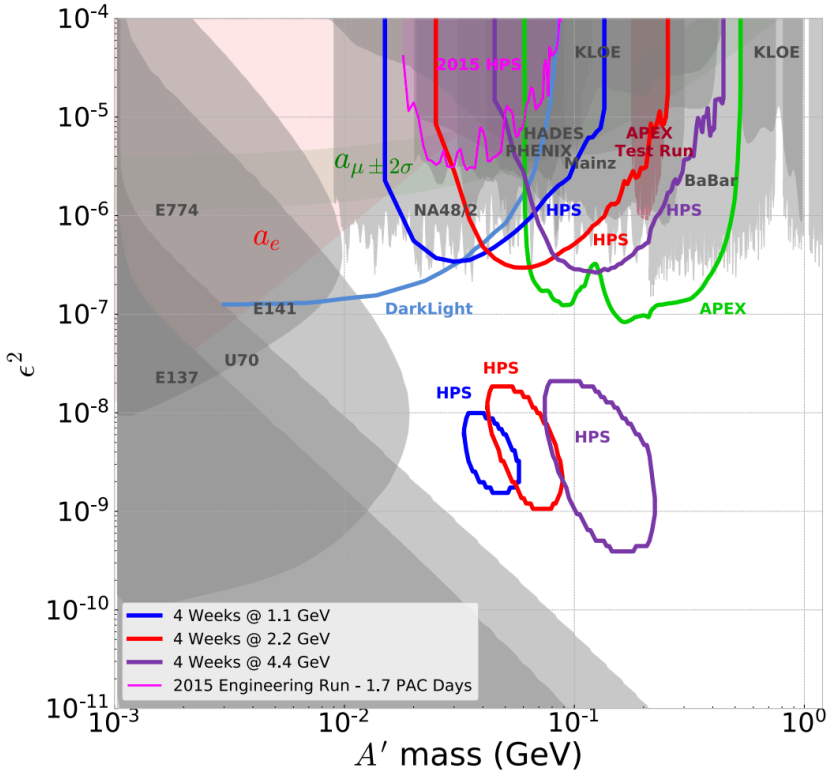


No vertexing reach attained → needed to run much longer!

- Projected reach did not fully account for acceptance and efficiency

HPS Upgrades



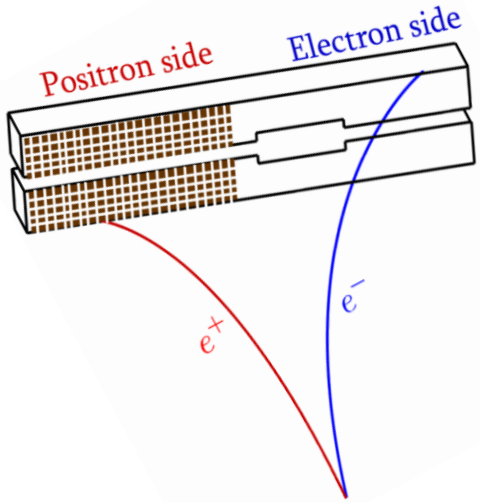


Add SVT layer at 5cm

- Halves vertex resolution
- Move SVT Layers 2 and 3 toward beam to improve acceptance for long-lived A'

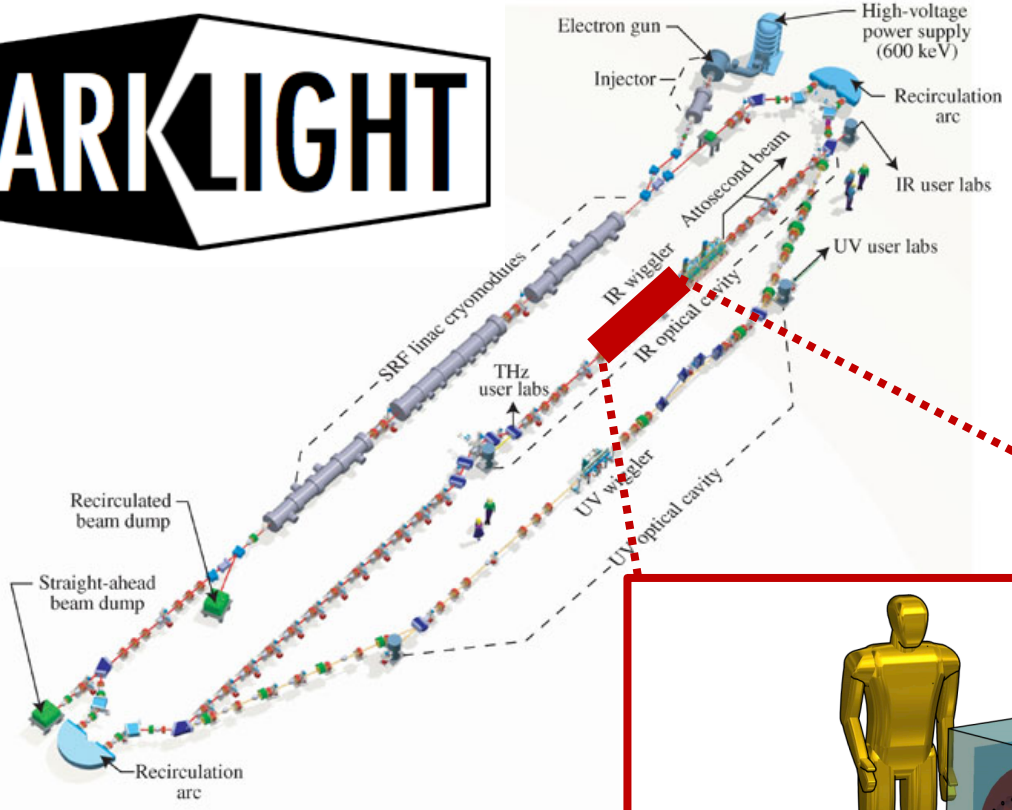
Hodoscope on positron side of ECal:

- Keeps events where e- lost in hole
- Reduce triggers from $e^-\gamma$

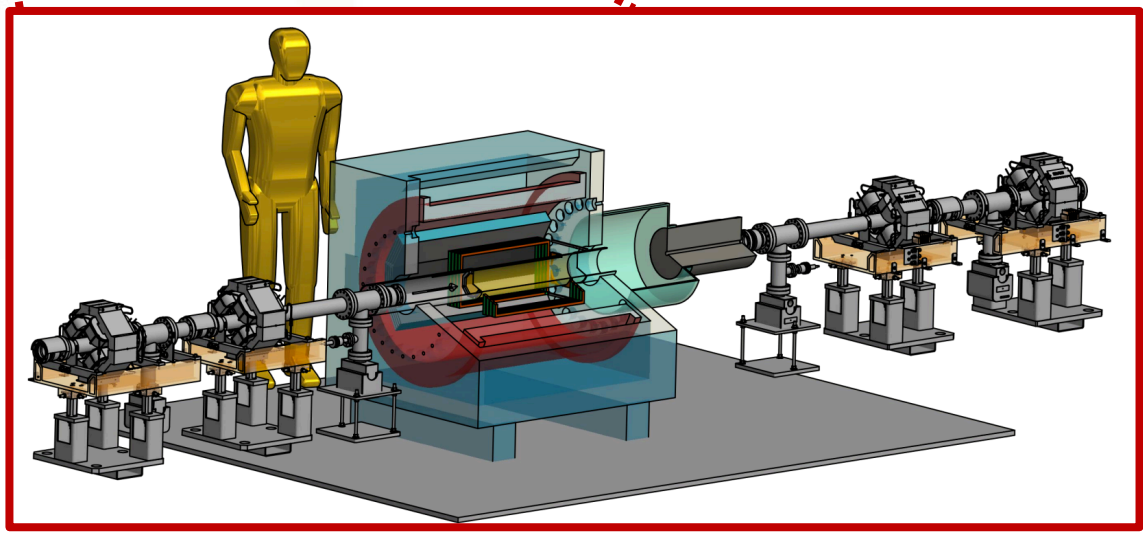


With proposed upgrades, will request **40 days** of beam time at **4.4 GeV** for the next run

DARKLIGHT



- Low Energy Recirculating Facility (LERF)
- High-current (10 mA), 100 MeV e^- beam
- Full final state reconstruction: access to visible and invisible decays, $m_{A'}$: 10-90 MeV/c^2



Cylindrically symmetric target and detector:

- Windowless target cell, gas H 10^{19}cm^2
- Si detector for low-energy recoiling proton
- Scintillating fiber and GEM tracking
- Scintillators as photon vetos

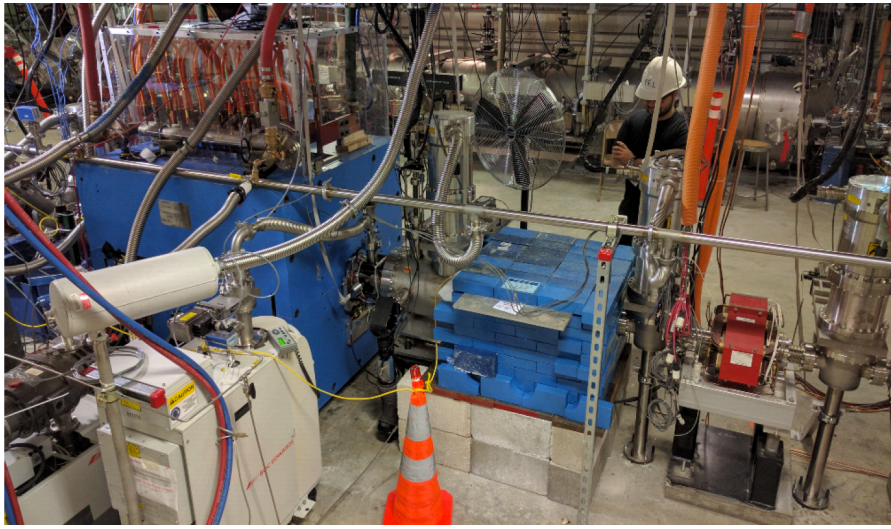
Phase 1:

1a: Accelerator studies, learn to operate LERF with solenoid + target (2016, to redo 2017)

1b: Measure SM physics (Moller, elastic), detector readout test (2017/2018)

1c: Pilot DM search, with partial coverage detector (2017/2018)

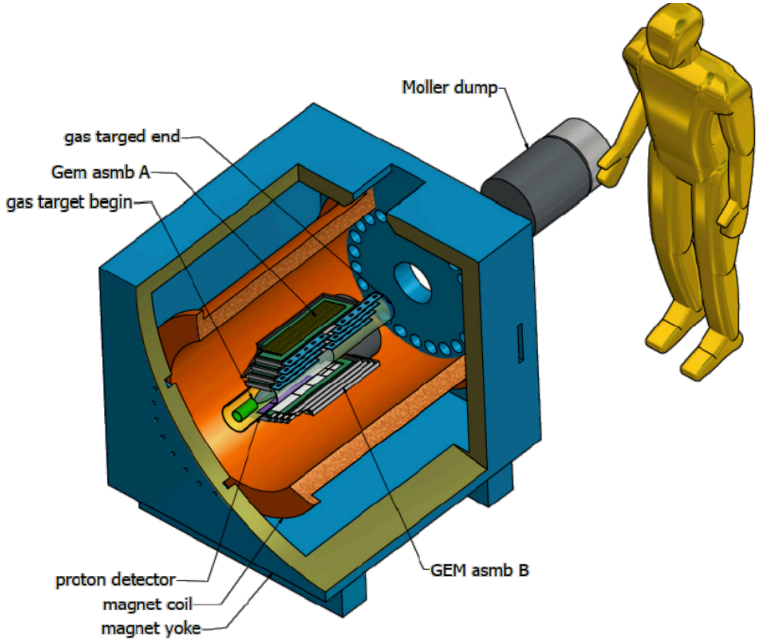
Phase 2: High statistics measurement with full detector



Status:

Successful target commissioning and running!

Identified improvements needed before running



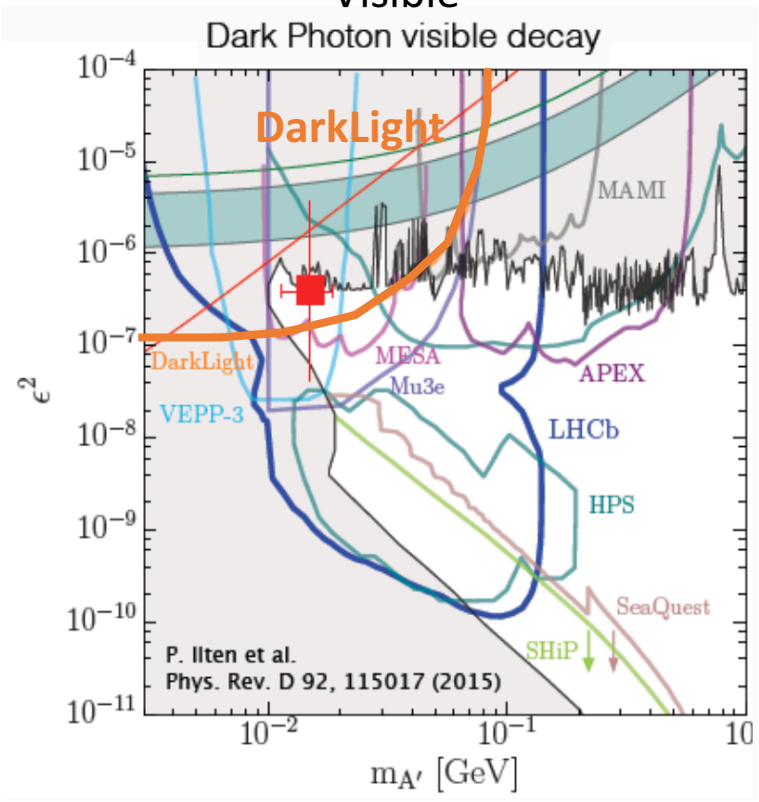
With improvements, follow-up Phase I run:

→look for new physics!

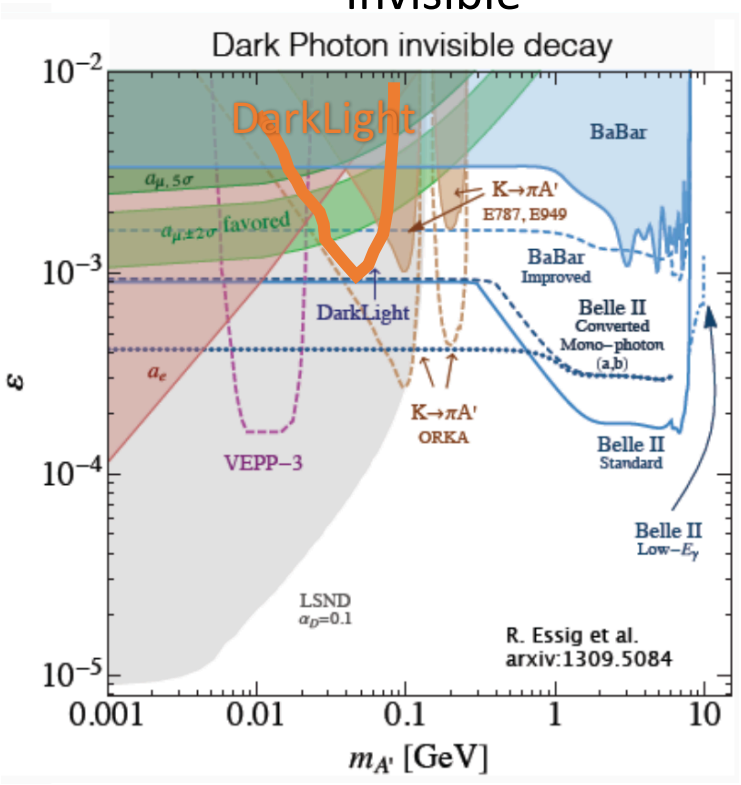
(17 MeV particle from Be-8 experiment)

DarkLight proposed reach:

Visible



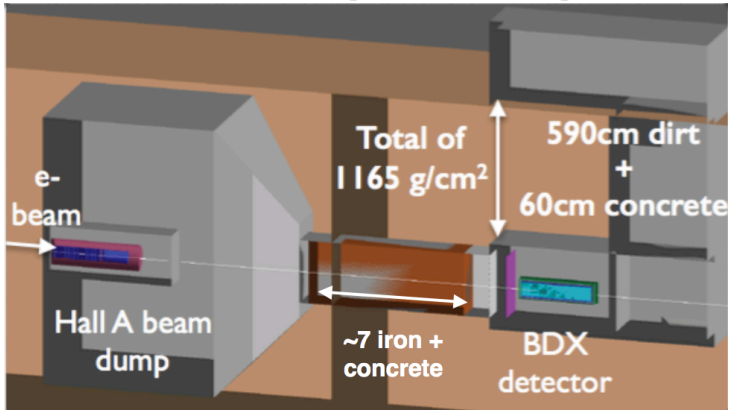
Invisible



- 17 MeV fifth force carrier "found" by Hungarian group in Be8 experiment within reach!

Proposed reach shown for 60 days (1 ab^{-1})

Beam Dump eXperiment

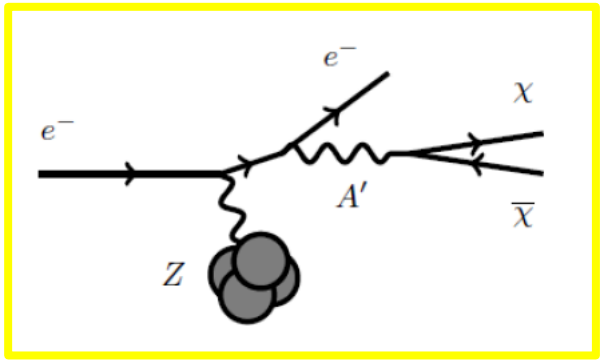


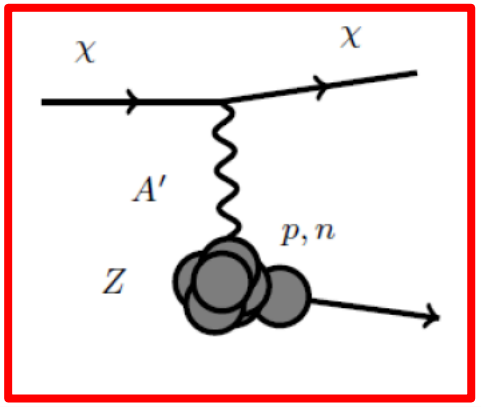
New hall!

- Conditionally approved
- Detector ~20m downstream Hall A beam dump

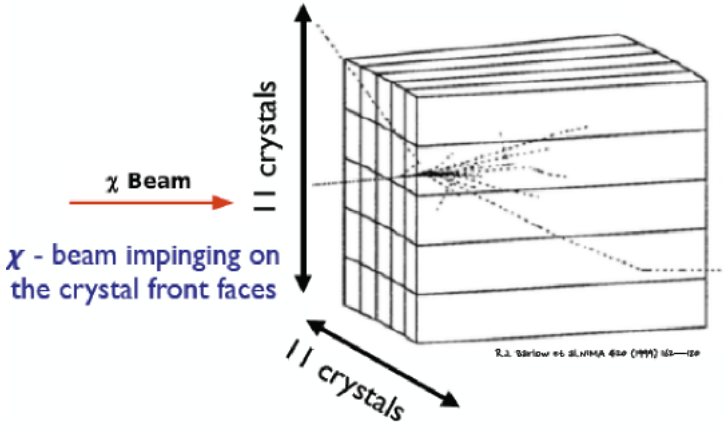
Electron radiates A'→$\chi\chi$

χ scatters on nuclei, nucleon, e-
Scatter produces signal!

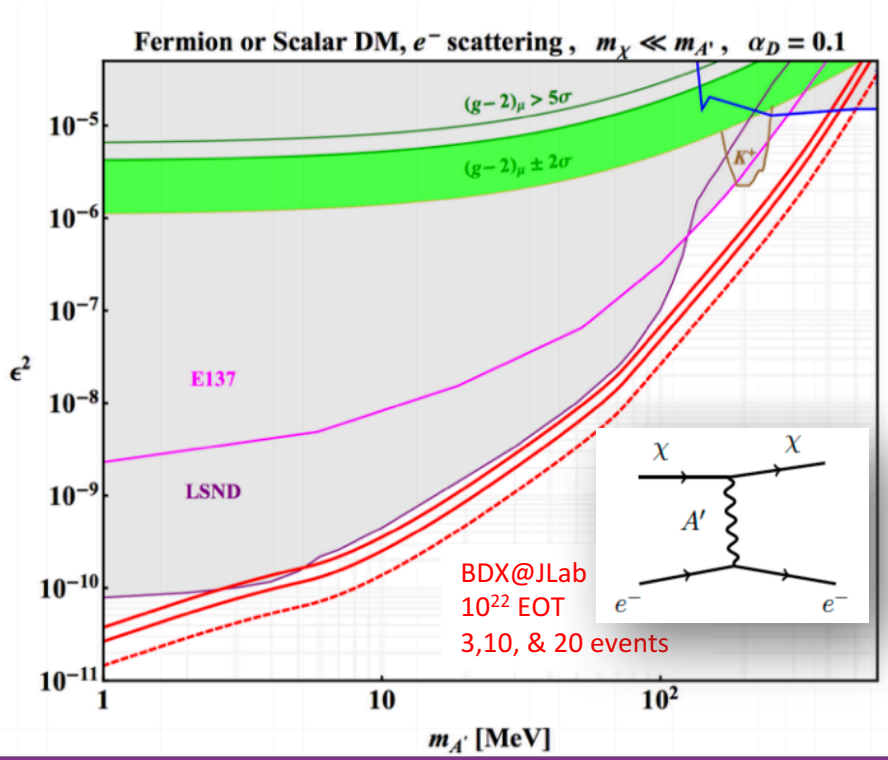


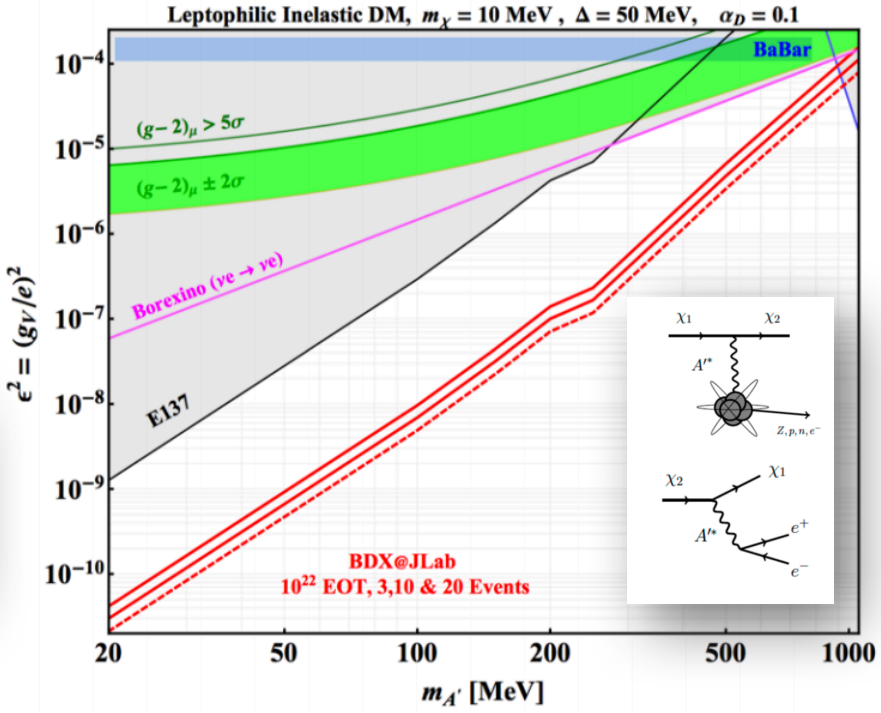


CsI(Tl) crystals with Si PM readout



- Measure backgrounds behind the hall and develop background simulation
- Triggerless DAQ for full waveform readout





Summary

Light Dark Matter largely unexplored, explains the correct DM relic abundance

Lots of exciting dark photon searches at JLab with important ramifications for Light Dark Matter!

- APEX to run again in Hall A
- HPS announced first results from 2015 run, working on upgrades
- DarkLight preparing for follow-up engineering run and look for 17 MeV fifth force carrier
- BDX conditionally approved, further understanding backgrounds

Relevant publications

APEX test run:

Phys. Rev. Lett. 107 (2011) 191804

HPS NIM papers:

Beamline, 2015 run: Nucl. Instrum. Meth. A 859 (2017) 69
ECal, 2015 run: Nucl. Instrum. Meth. A 854 (2017) 89

2012 test run: Nucl. Instrum. Meth. A 777 (2015) 91

DarkLight, 2012 test run precision beam steering:

Phys. Rev. Lett. 111, 165801 (2013)

BDX letter of intent to 2014 PAC:

arXiv:1607.01390