Cosmology and Signals of Strongly Interacting Dark Sectors

Nikita Blinov

SLAC National Accelerator Laboratory, California

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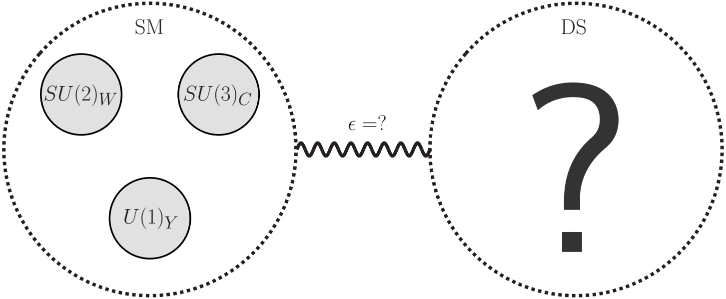
1703.xxxxx with Asher Berlin, Philip Schuster and Natalia Toro

Outline

1. Dark Sectors, Dark Matter and All That
2. Strongly Interacting Dark Sectors and Cosmology
3. Experimental Signals

Dark Sectors

Is $SU(3) \times SU(2) \times U(1)$ all there is?

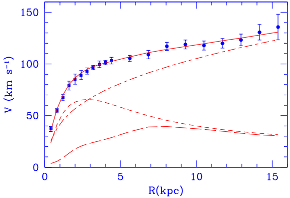


Is there a "dark sector"? Does it couple to the the SM?

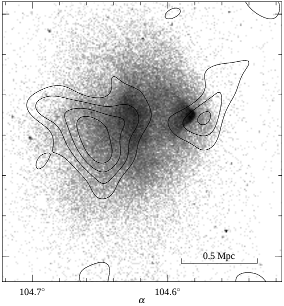
Dark Matter

- Major ingredient of the standard cosmology $\Omega_{\rm cdm} = \rho_{\rm cdm}/\rho_{\rm tot} = 0.27$
- Evidence from *gravitational* effects across **many** length scales

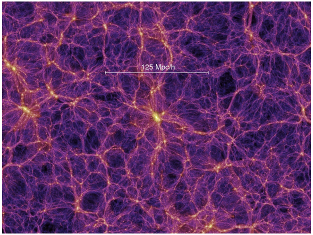
There *is* a dark sector



rotation curves
$\mathcal{O}(10\,\mathrm{kpc})$



Bullet cluster (lensing)
$\mathcal{O}(1\,\mathrm{Mpc})$



large scale structure
$\mathcal{O}(1\,\mathrm{Gpc})$

Nature of Dark Matter

Minimal

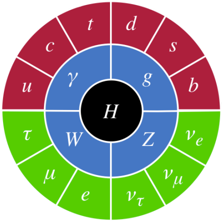
No new gauge forces, DM is

- Electroweak multiplets
- Axion or another ultra-light field
- primordial black holes

⋮

Non-Minimal

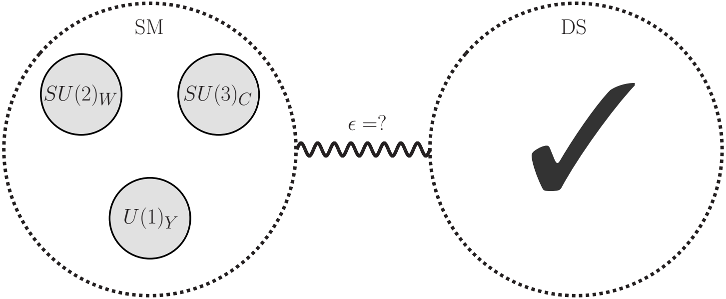
Why should DS be simple when



PC: Kyle Kranmer/Particle Fever

Dark Sectors

Is $SU(3) \times SU(2) \times U(1)$ all there is?

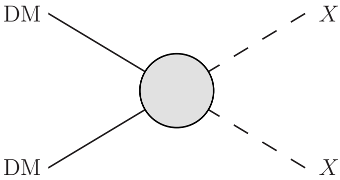


Does it couple to the the SM?

Dark Matter Depletion

Large initial density $n_{\mathrm{DM}} \sim T_{\mathrm{RH}}^3$ must be depleted

Annihilation ($2 \to 0$)

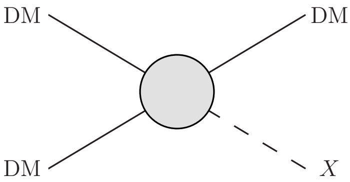


$X \in \mathrm{SM}$ or X talks to SM, otherwise new light d.o.f.

Dark Matter Depletion

Large initial density $n_{\mathrm{DM}} \sim T_{\mathrm{RH}}^3$ must be depleted

Semi-annihilation ($2 \to 1$)



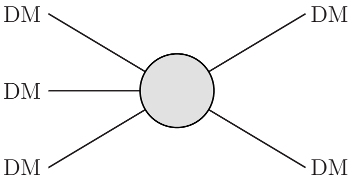
$X \in \mathrm{SM}$ or X talks to SM, otherwise new light d.o.f.

D'Eramo and Thaler (2010)

Dark Matter Depletion

Large initial density $n_{\mathrm{DM}} \sim T_{\mathrm{RH}}^3$ must be depleted

Cannibalization ($3 \to 2$, $n \to n-k$)



No need for any coupling to SM?

Carlson, Machachek and Hall (1992)

Cannibalization (I)

If DS completely decoupled, $T \neq T'$ and

- Dark sector entropy *independently* conserved:

$$\frac{d(s'a^3)}{dt} = 0 \;\Rightarrow\; s' \propto a^{-3}$$

- DM is the lightest state and $3 \to 2$ in equilibrium:

$$n \sim (mT')^{3/2} e^{-m/T'}, \; s' \approx \frac{mn}{T'}$$

- Solving for $T'(a)$:

$$T' \sim 1/\ln a^3$$

  compare with $T' \sim 1/a$ when $s' \sim (T')^3$.

Carlson, Machacek and Hall (1992)

Cannibalization (II)

- While $3 \to 2$ active, energy density also drops slowly

$$\rho' = T' s' \sim \frac{1}{a^3 \ln a}$$

compare with species in equilibrium with radiation: $\rho \propto \exp(-m/T)$.

- After freeze-out of $3 \to 2$ number density is conserved and

$$mn = T'_{\rm fo} s'_{\rm fo} \;\Rightarrow\; \Omega_{\rm dm} = \frac{T'_{\rm fo} s_0}{(s_{\rm fo}/s'_{\rm fo})\rho_c}$$

- Correct relic density then implies

$$T'_{\rm fo}\left(\frac{s'_{\rm fo}}{s_{\rm fo}}\right) \sim 10^{-10}\ \mathrm{GeV}$$

Carlson, Machacek and Hall (1992)

Not So Fast

$$T'_{\rm fo}\left(\frac{s'_{\rm fo}}{s_{\rm fo}}\right) \sim 10^{-10}\ {\rm GeV}$$

$T' \sim T \Rightarrow m \sim 1{\rm eV}$ $\qquad\qquad$ $T' \ll T$

Carlson, Machacek and Hall (1992)

Entropy conservation in DS ⇒ DM is too light, does not have time to redshift

DM free-streaming length too long, small scale structure washed out

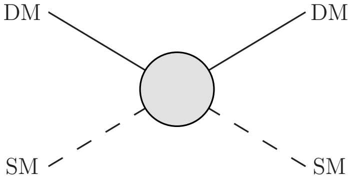
De Laix, Scherrer and Schaefer (1995)

A Workaround

Idea: dump DS entropy into the SM plasma

Hochberg, Kuflik, Volansky and Wacker (2014)

Need kinetic equilibrium between DS and SM

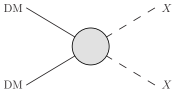


As a result $T = T'$, only total entropy $s + s'$ is conserved

Characteristic Scales

$\rho_R = \rho_{\rm dm}$ at $T_{\rm eq} \approx 1$ eV $\Rightarrow n_{\rm dm} \sim T_{\rm eq} s/m$

Annihilation



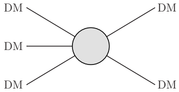
$$\langle \sigma v \rangle = \frac{\alpha_{\rm eff}^2}{m^2}$$

$$n\langle \sigma v \rangle = H \sim \frac{T_{\rm fo}^2}{M_{\rm Pl}}$$

For $\alpha_{\rm eff} \sim 10^{-1} - 10^{-2}$

$$m \sim \alpha_{\rm eff} \left(T_{\rm eq} M_{\rm Pl}\right)^{1/2} \lesssim \text{TeV}$$

Cannibalization



$$\langle \sigma v^2 \rangle = \frac{\alpha_{\rm eff}^3}{m^5}$$

$$n^2\langle \sigma v^2 \rangle = H \sim \frac{T_{\rm fo}^2}{M_{\rm Pl}}$$

For $\alpha_{\rm eff} \sim 1$

$$m \sim \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 0.1 \text{ GeV}$$

Summary: Model Requirements

Viable cosmology where $3 \to 2$ dominates DM production requires

- Strong interactions

  $n \to n - k$ naturally suppressed by couplings, number density

- DM number non-conservation

  No symmetries forbidding $3 \to 2$ (e.g. fermion number)

- Efficient scattering off light SM d.o.f.'s to maintain kinetic equilibrium

  Sizable coupling to SM states during freeze-out

A Strongly Interacting Dark Sector

QCD-like Theories

Previous considerations realized in confining gauge theories.

Consider

$$G = SU(N_c) \times SU(N_f) \times SU(N_f)$$

Below confinement, this is a theory of mesons:

- Pseudo-Nambu-Goldstones $\pi = \pi^a T^a$ of chiral symmetry breaking:

$$\mathscr{L} \supset \mathrm{Tr}\left(\partial_\mu \pi - i\left[e_D Q A'_\mu, \pi\right]\right)^2 + 2ig\,\mathrm{Tr}\left(V^\mu\left[\partial_\mu \pi, \pi\right]\right) + \ldots$$

- **And** vector mesons $V = V^a T^a$

$$\mathscr{L} \supset -\frac{1}{2}\,\mathrm{Tr}\; V_{\mu\nu} V^{\mu\nu}$$

Hochberg, Kuflik, Volansky and Wacker (2014), Hochberg, Kuflik and Murayama (2015)

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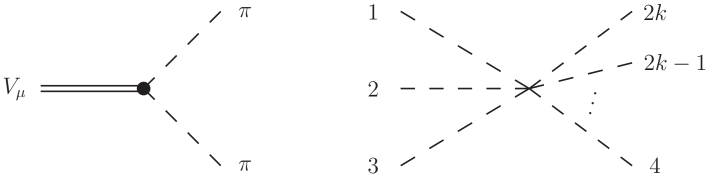


Stable π make up the dark matter

Kinetic Equilibrium

Introduce a kinetically mixed $U(1)_D$, with DS quarks carrying charge Q

$$\mathscr{L} \supset -\frac{1}{2}\varepsilon F^{\mu\nu}F'_{\mu\nu}$$

A' couples to

- EM charges with strength εe
- $U(1)_D$ charges with strength e_D

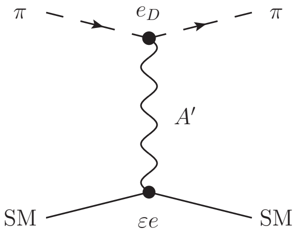
Kinetic Equilibrium

Introduce a kinetically mixed $U(1)_D$, with DS quarks carrying charge Q

$$\mathscr{L} \supset -\frac{1}{2}\varepsilon F^{\mu\nu} F'_{\mu\nu}$$

K.E. maintained during π f.o. if

$$\varepsilon \gtrsim 10^{-6} \left(\frac{m_{A'}}{\text{GeV}}\right)^2 \sqrt{\frac{10^{-2}}{\alpha_D}}$$



Neutral vector mesons mix with A':

V^a  $A' \sim e_D g\, m_V^2 \, \text{Tr}(Q T^a)$

Hochberg, Kuflik, Volansky and Wacker (2014), Hochberg, Kuflik and Murayama (2015)

Anomalies and $3 \to 2$

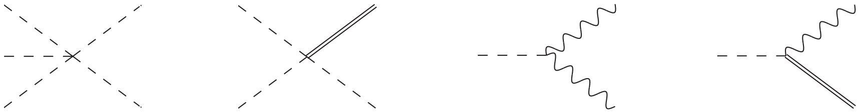
Chiral Lagrangian preserves "Bose" symmetry: $\pi(x) \to -\pi(x)$

Not a symmetry of the underlying theory!

Witten (1983)

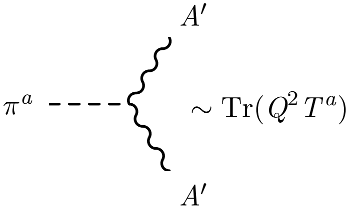
$$\mathscr{L}_{\mathrm{WZW}} \supset \frac{N_c}{240\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} \, \mathrm{Tr}(\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi) + \ldots$$

Wess and Zumino (1971)



Anomalies and DM Stability

For general charge assignments neutral pions are unstable:



Stability during freeze-out $\Rightarrow$ choose $Q^2 \propto \mathbb{1}$

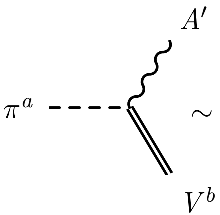
For example, for $N_f = 3$:

$$Q = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

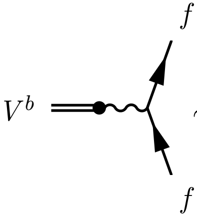
Hochberg, Kuflik and Murayama (2015)

Anomalies and DM Stability

Even with $Q^2 = \mathbb{1}$, still have



$\sim \mathrm{Tr}(QT^a T^b)$



$\sim \mathrm{Tr}(QT^b)$

As a result only one $U(1)_D$ neutral pion stable!

Dark Matter Production

$$\dot{n}_\pi + 3Hn_\pi = -\langle \sigma v^2 \rangle (n_\pi^3 - n_\pi^2 n_\pi^{\rm eq})$$

- Rate from anomaly

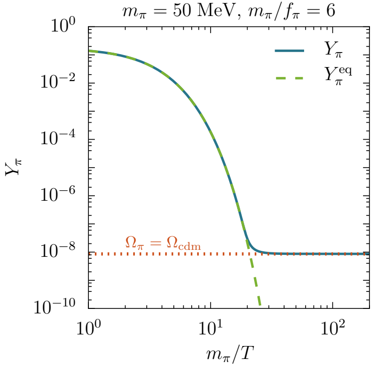
$$\langle \sigma v^2 \rangle = \frac{a(m_\pi/f_\pi)^{10}}{x^2 m_\pi^5},$$

$x = m_\pi/T$ and $a \sim 10^{-4}$

Hochberg et al (2014)

- Large coupling needed to compensate for a, n_π^2 in rate:

$$\Gamma_{3\to 2} = \langle \sigma v^2 \rangle n_\pi^2$$



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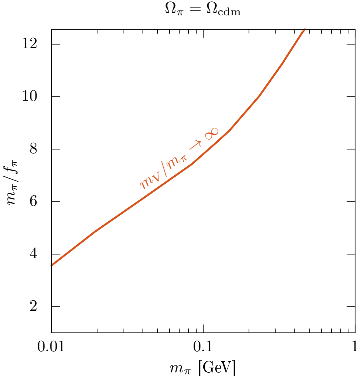


Mass Spectrum

Correct relic abundance $\Rightarrow$ need $m_\pi/f_\pi > 1^*$

Vector mesons have masses close to the cutoff

$$m_V \sim \Lambda \approx \frac{4\pi f_\pi}{\sqrt{N_c}}$$

Harigaya and Nomura (2016), Georgi (1992)

$\therefore\ m_\pi/f_\pi > 1$ implies

$$\frac{m_V}{m_\pi} \approx 1.8\sqrt{\frac{3}{N_c}}\left(\frac{4}{m_\pi/f_\pi}\right)$$

* m_π is determined by quark masses m_q

$$m_\pi \sim \frac{1}{f_\pi^2}|\langle\bar{q}q\rangle|m_q$$

Mass Spectrum

$m_\pi / f_\pi > 1$ **implies a squeezed spectrum with** $m_V \lesssim 2 m_\pi$

Consequences for phenomenology:

1. Additional processes important during freeze-out

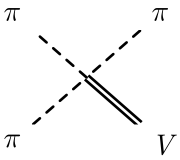
   semi-annihilation: $\pi\pi \to \pi V$

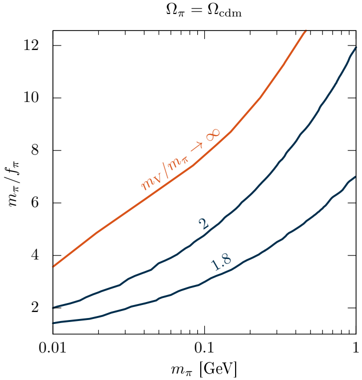
2. $V \to \pi\pi$ kinematically forbidden

   V must decay to SM $\Rightarrow$ new long-lived states

Semi-Annihilation

Semi-annihilation important even if $m_V/m_\pi \sim 2$!





$$\langle \sigma v \rangle \sim \frac{(m_\pi/f_\pi)^8}{x m_\pi^2} e^{-(m_V - m_\pi)/T}$$

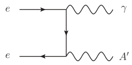
$$\frac{\Gamma_{3\to 2}}{\Gamma_{2\to 1}} \sim \frac{(m_\pi/f_\pi)^2}{x^{5/2}} e^{-(2m_\pi - m_V)/T}$$

Signals of Strongly Interacting Dark Sectors

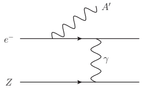
Looking for Strongly Interacting DS

DS states produced through A'. Many production modes:

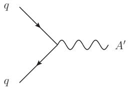
1. e^+e^- collisions



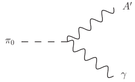
2. Bremsstrahlung



3. Drell-Yan

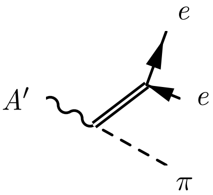


4. Meson Decays



Detection Strategies

Visible

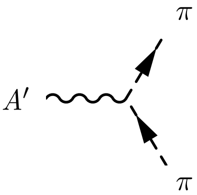


Striking signatures:

- e^+e^- invariant mass peaks
- displaced vertices

BUT: pay ε^2 for production and ε^2 for visible decay

Invisible



No ε^2 for detection:

- missing momentum
- missing mass

BUT: backgrounds, e.g. ν, $\not\gamma$,...

Izaguirre et al (2014)

Why Fixed Target?

Fixed targets are ideal for studying kinetic mixing portal:

1. Coherent Z^2 enhancement of A' brem

$$\sigma_{A'} \sim \frac{\alpha^3 \varepsilon^2 Z^2}{m_{A'}^2}$$

2. Forward kinematics and boosted final states

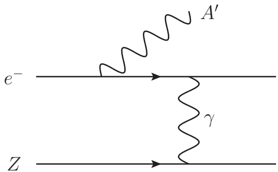
   crucial for background rejection

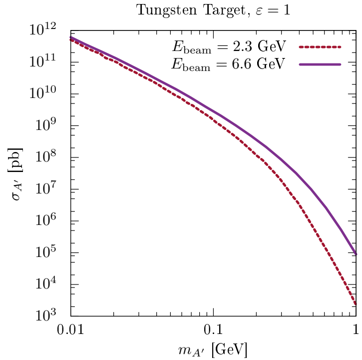
3. Potential for larger luminosities (compared to colliders)

   sensitivity to tiny couplings

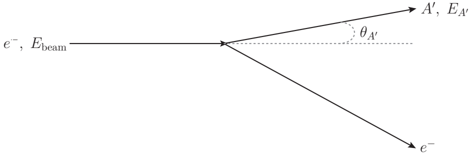
A' Production and Kinematics

Cross-section falls rapidly with $m_{A'} \Rightarrow m_{A'} \ll E_{\text{beam}}$





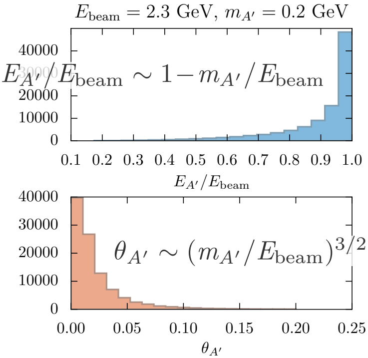
A' Production and Kinematics



- A' carries away $\sim E_{\text{beam}}$

  Its decay products inherit boost $\sim E_{\text{beam}}/m_{A'}$

- Emitted in forward direction

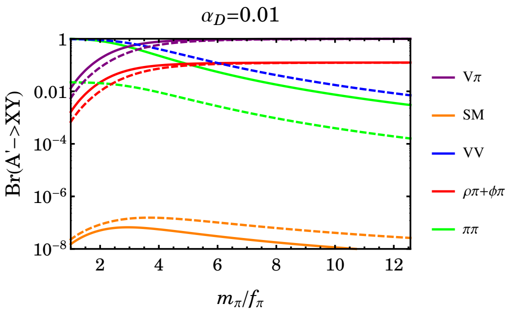


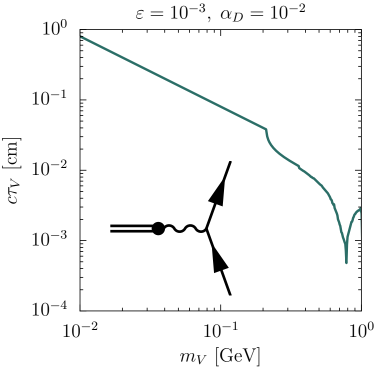
A' Production and Kinematics

This provides 2 handles on background:

1. Visible decay products of A' carry $\mathcal{O}(1) \times E_{\text{beam}}$
2. Boosted final states can lead to macroscopic displaced vertex

Decay Modes and Lifetimes

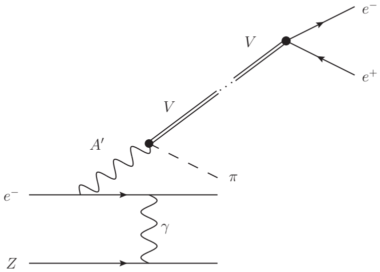




$A' \to V\pi,\ V \to \mathrm{SM}$ with $\mathcal{O}(10\%)$ branching fraction!

Vector mesons naturally long-lived

New Signals at Fixed Target Experiments



1. A' decays promptly
2. V gives displaced vertex (DV)
3. e^+e^- spectrum has invariant mass peak

Can have DVs even for ε not tiny $\Rightarrow$ production rate can be large

Schematic Experimental Reach

Factors that determine signal yield:

1. Number of A' produced

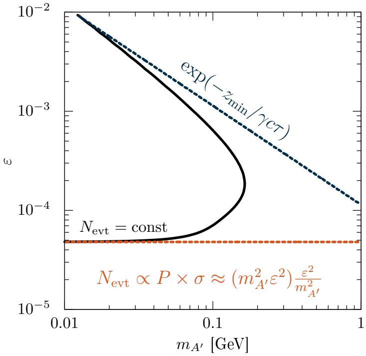
$$\sigma_{A'} \sim \frac{\epsilon^2 \alpha^3}{m_{A'}^2}$$

2. A' decays in detector volume

$$P \sim e^{-z_{\min}/\gamma c\tau}\left(1 - e^{-z_{\max}/\gamma c\tau}\right),$$

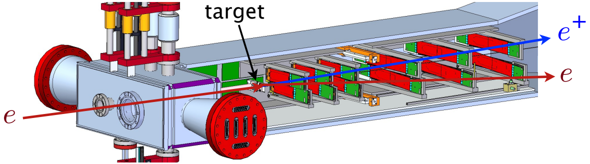
with decay length

$$\gamma c\tau \sim (E_{\text{beam}}/m_{A'})(\epsilon^2 m_{A'})^{-1}$$



Heavy Photon Search

HPS looks for $A' \to e^+e^-$ at JLab



Uemura (2013)

2016 data set:

$$E_{\text{beam}} = 2.3 \text{ GeV, } 4\ \mu\text{m W target, } 10^{17} \text{ EOT} \Rightarrow \mathcal{L} \approx 0.01 \text{ fb}^{-1}$$

possible future run (~ 2018):

$$E_{\text{beam}} = 6.6 \text{ GeV, } 8\ \mu\text{m W target, } 10^{19} \text{ EOT} \Rightarrow \mathcal{L} \approx 0.3 \text{ fb}^{-1}$$

Heavy Photon Search

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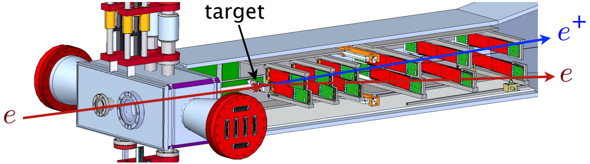
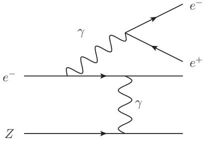


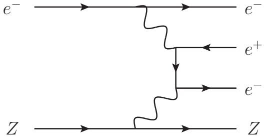
Uemura (2013)

That's 10^4 **and** 10^6 A'**s at** $m_{A'} = 0.1$ GeV **and** $\varepsilon = 10^{-3}$

Triggering and Backgrounds at HPS

Trigger selects time-coincident e^+ e^- hits in Ecal. Still have QED backgrounds:





For the following assume

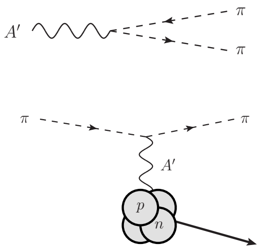
Displaced vertex + invariant mass peak $\Rightarrow$ "background-free"

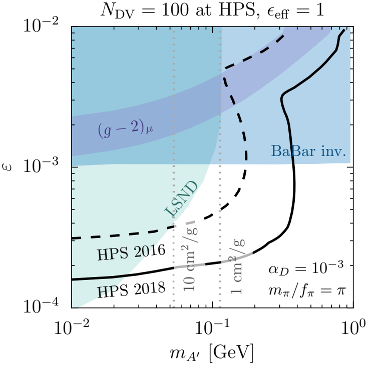
HPS Reach (I)

100 DVs in $1\ \mathrm{cm} < z < 10\ \mathrm{cm}$ from target, assuming 100% efficiency

- LSND: $pN \to \pi_0 + X$, $\pi_0 \to \gamma A'$

$$m_\pi : m_V : m_{A'} = 1 : 1.8 : 3$$

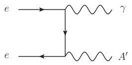




HPS Reach (I)

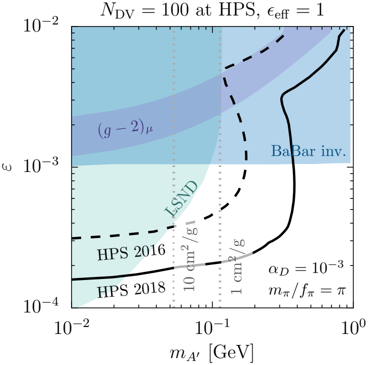
100 DVs in $1\ \mathrm{cm} < z < 10\ \mathrm{cm}$ from target, assuming 100% efficiency

- LSND: $pN \to \pi_0 + X$, $\pi_0 \to \gamma A'$
- BaBar: $e^+ e^- \to \gamma A'$, $A' \to \mathrm{inv.}$



$\mathcal{L} = 53\ \mathrm{fb}^{-1}$ mono-$\gamma \Rightarrow$
sensitivity to $\varepsilon \sim 10^{-3}$

$m_\pi : m_V : m_{A'} = 1 : 1.8 : 3$



HPS Reach (I)

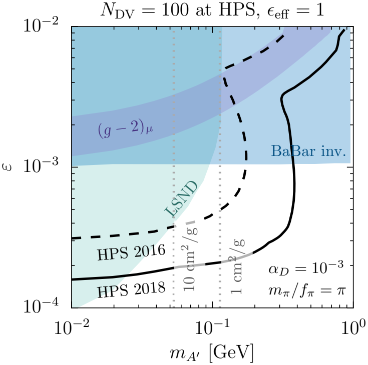
100 DVs in $1\ \mathrm{cm} < z < 10\ \mathrm{cm}$ from target, assuming 100% efficiency

- LSND: $pN \to \pi_0 + X$, $\pi_0 \to \gamma A'$
- BaBar: $e^+e^- \to \gamma A'$, $A' \to \mathrm{inv.}$
- Large self-scattering rates

$$\sigma_{\mathrm{scatt}} = \frac{(m_\pi/f_\pi)^4}{128\pi m_\pi^2}$$

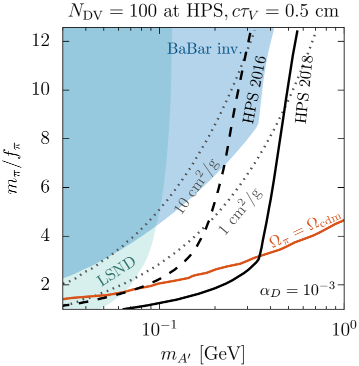
can aid small scale structure anomalies

$m_\pi : m_V : m_{A'} = 1 : 1.8 : 3$



HPS Reach (II)

$m_\pi : m_V : m_{A'} = 1 : 1.8 : 3$, ε fixed by requiring $c\tau_V = 0.5$ cm



Future runs of HPS can probe cosmologically interesting models!

Conclusion

- Strongly interacting dark sectors – another paradigm for thermal DM

  novel production mechanisms in early universe

- Unique signals at *current* and future fixed target experiments

  displaced vertex + inv. mass peak

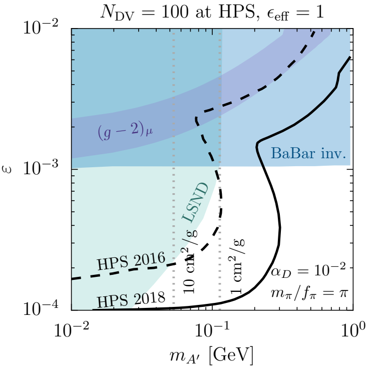
- Kinetic equilibrium implies minimum coupling to SM

  Is there a set of realistic experiments to decisively probe these scenarios?

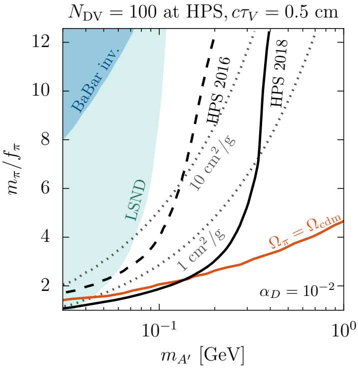
Thank you!

Backup

$\alpha_D = 10^{-2}$

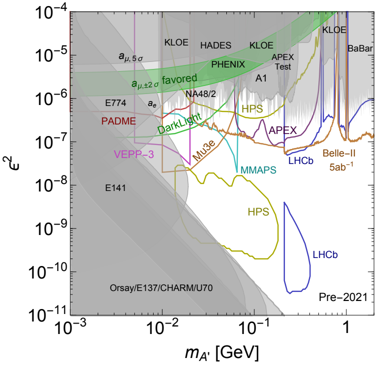


$N_{\rm DV} = 100$ at HPS, $\epsilon_{\rm eff} = 1$
10^{-2}
10^{-3}
10^{-4}
ε
$(g-2)_\mu$
BaBar inv.
LSND
HPS 2016
HPS 2018
10 cm^2/g
1 cm^2/g
$\alpha_D = 10^{-2}$
$m_\pi/f_\pi = \pi$
10^{-2}
10^{-1}
10^0
$m_{A'}$ [GeV]



$N_{\rm DV} = 100$ at HPS, $c\tau_V = 0.5$ cm
12
10
8
6
4
2
m_π/f_π
BaBar inv.
LSND
HPS 2016
HPS 2018
10 cm^2/g
1 cm^2/g
$\Omega_\pi = \Omega_{\rm cdm}$
$\alpha_D = 10^{-2}$
10^{-1}
10^0
$m_{A'}$ [GeV]

Vast array of near future experiments looking for A'

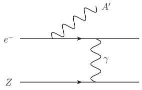


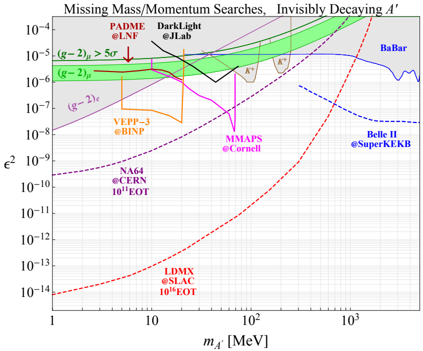
Dark Sectors 2016

Future Experiments

Invisible channels can be extremely powerful

E.g. Light DarkMatter eXperiment:





- Measure p_e^{in} and p_e^{out}
- Signal: scattered e^- and nothing else $\Rightarrow \not{p}$
- No ε^2 penalty for detection