

Title: Cosmology and Signals of Strongly Interacting Dark Sectors

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Abstract: 

Standard Model particles account for a small fraction of the matter content of the universe. If the remaining dark matter (DM) was ever in thermal equilibrium with itself or with the Standard Model (SM) sector, there must exist interactions that allowed its number density to be depleted to its present value. An interesting possibility for achieving this arises in scenarios where the DM is composed of "pions" of a QCD-like dark sector. The leading number changing process in these theories is the annihilation of three pions into two pions, which heats the pion bath relative to the SM. Consistency with observations of large and small scale structure in the universe requires a non-zero coupling with SM states, suggesting a multitude of experimental probes. I will review the cosmological production of DM in these strongly interacting dark sectors and discuss the prospects for discovering them at fixed target experiments.

# Cosmology and Signals of Strongly Interacting Dark Sectors

Nikita Blinov

SLAC National Accelerator Laboratory, California

Perimeter Institute, November 21, 2017



1711.xxxxx with Asher Berlin, Stefania Gori, Philip Schuster and Natalia  
Toro

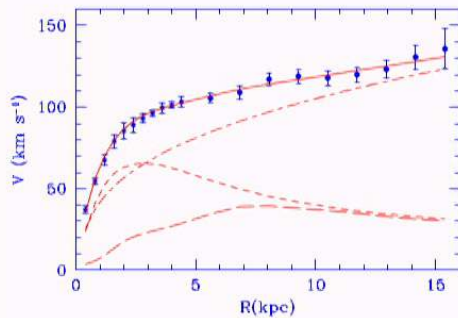
# Outline

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

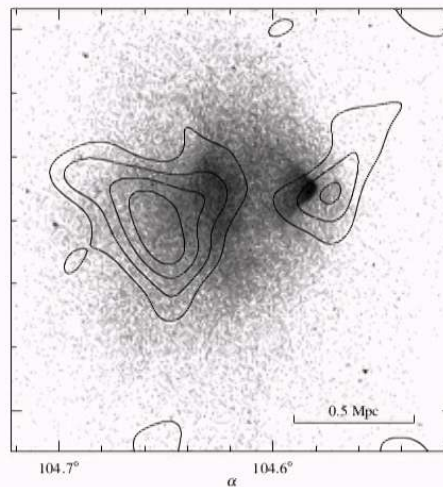
# Dark Matter

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

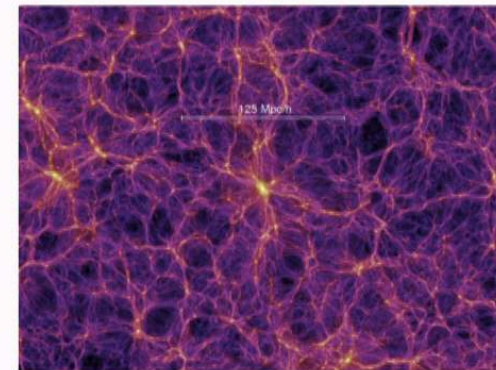
There *is* a dark sector



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



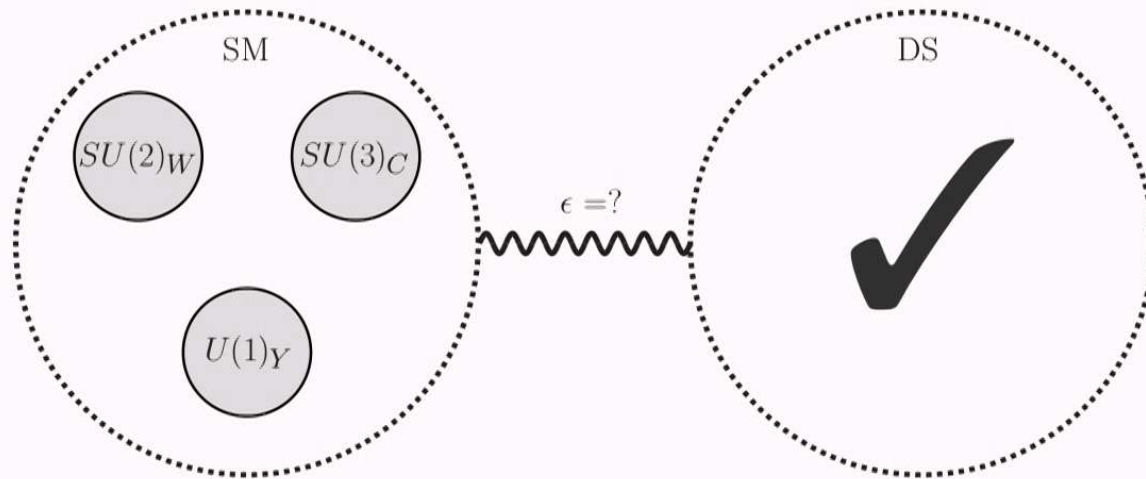
Bullet cluster (lensing)  
 $\mathcal{O}(1 \text{ Mpc})$



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

# Dark Sectors

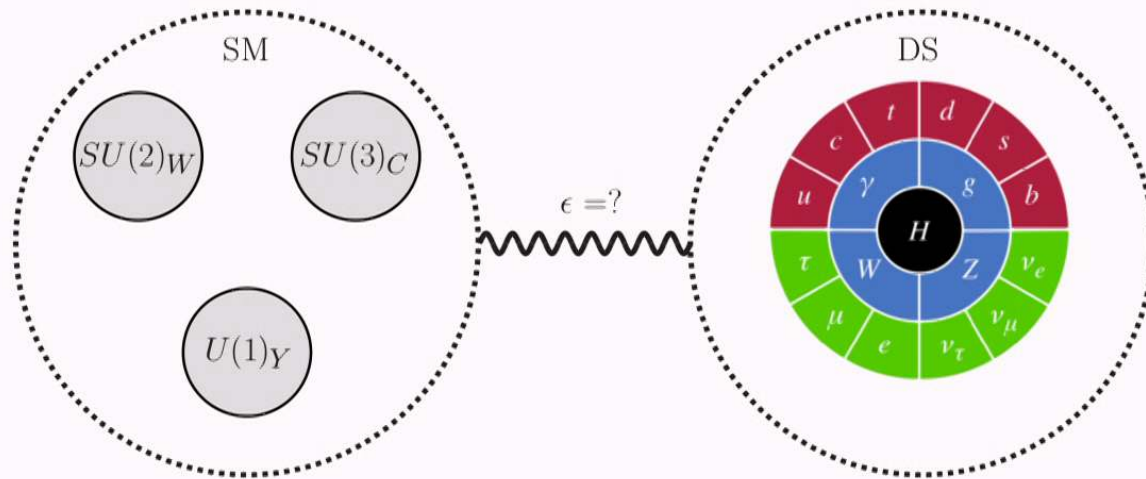
We know there is a Dark Sector



Does it couple to the the SM?

# Dark Sectors

We know there is a Dark Sector



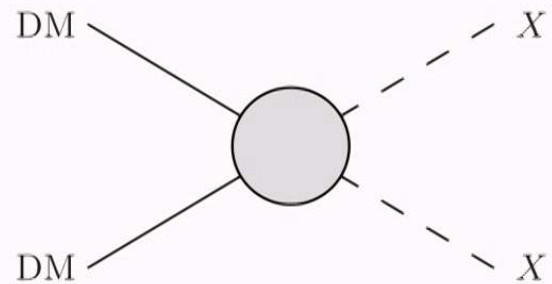
Does it couple to the the SM?

PC: Kyle Cranmer/Particle Fever

# Dark Matter Depletion

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

Annihilation (  $2 \rightarrow 0$  )

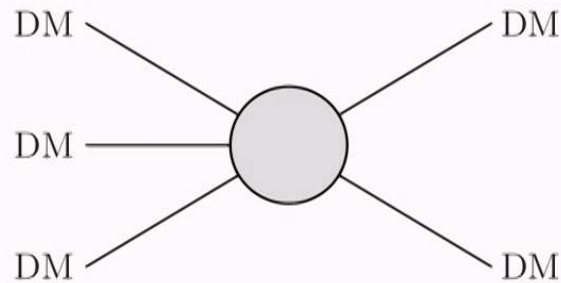


$X \in \text{SM}$  or  $X$  talks to SM, otherwise new light d.o.f.

# Dark Matter Depletion

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

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



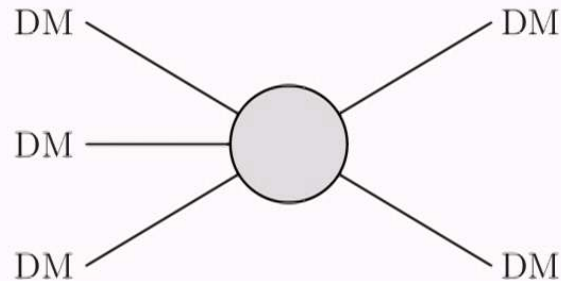
Carlson, Machacek and Hall (1992)

**Kinetic equilibrium with SM required for viable cosmology**

See Hochberg, Kuflik, Volansky and Wacker (2014)

# Characteristic Scales

The reaction



freezes out when

$$n_{\text{dm}}^2 \langle \sigma v^2 \rangle = H$$

Solving for  $m_{\text{dm}}$ , we find for  $\mathcal{O}(1)$  couplings

$$m_{\text{dm}} \sim 0.1 \text{ GeV}$$

WIMP:

$$\langle \sigma v \rangle = \frac{\alpha}{m^2} \Rightarrow$$

$$n \langle \sigma v \rangle = H \Rightarrow m \sim 100 \text{ GeV.}$$

for  $\alpha = 10^{-2}$ .

SIMP

$$\langle \sigma v^2 \rangle = \frac{\alpha^3}{m^5} \Rightarrow$$

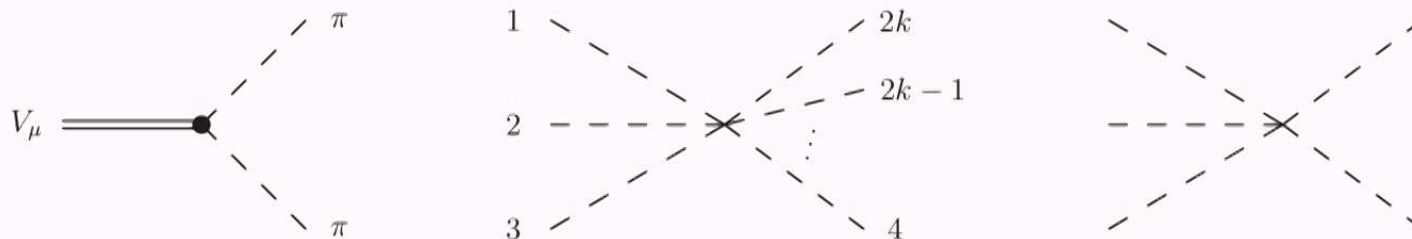
# QCD-like Theories

Previous considerations realized in confining gauge theories.

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

Below confinement, this is a theory of mesons:

Pseudo-Nambu-Goldstones  $\pi$  **and** vector mesons  $V$



Stable  $\pi$  make up the dark matter

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

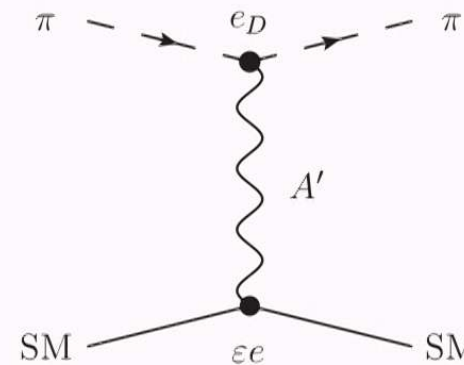
# Kinetic Equilibrium

K.E. requires interactions active at low  $T \Rightarrow A'$  a natural candidate

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

$U(1)_D$  Dark photon  $A'$  couples to  $\epsilon e$  Kinetic equilibrium maintained by

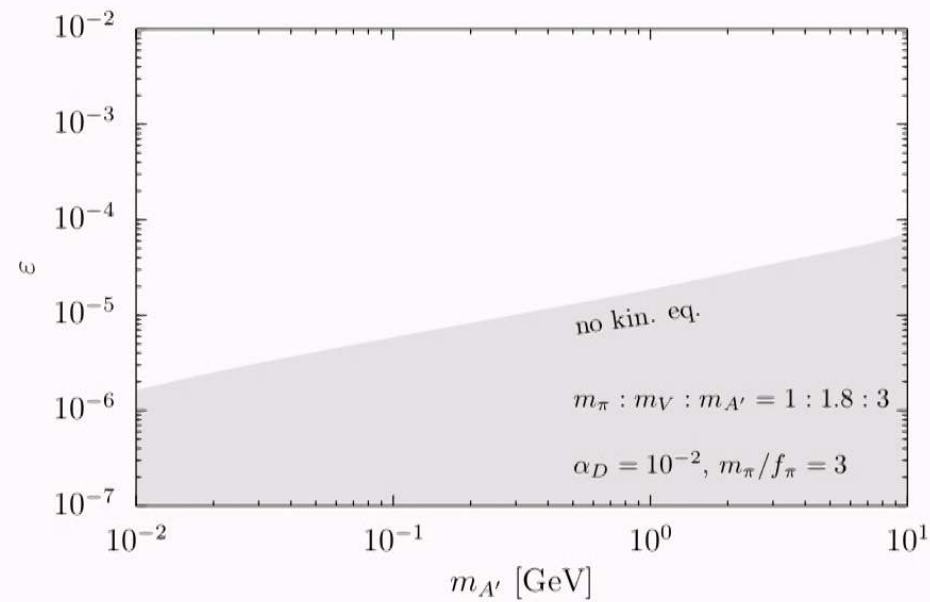
- EM charges with strength  $\epsilon e$
- $U(1)_D$  charges with strength  $e_D$
- Neutral vector mesons via



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

# Kinetic Equilibrium

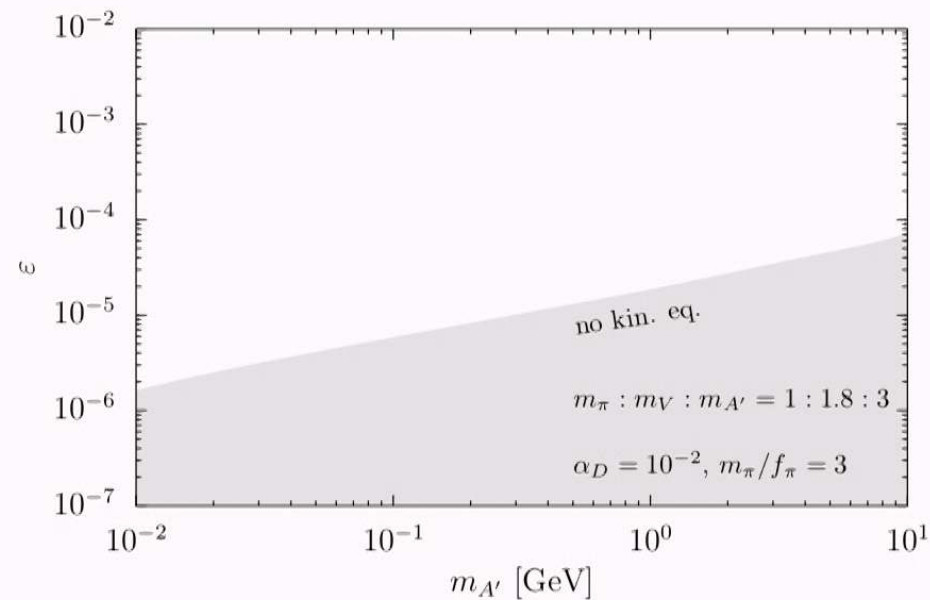
K.E. maintained during  $3 \leftrightarrow 2$  freeze-out iff  $\varepsilon$  large enough



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

# Kinetic Equilibrium

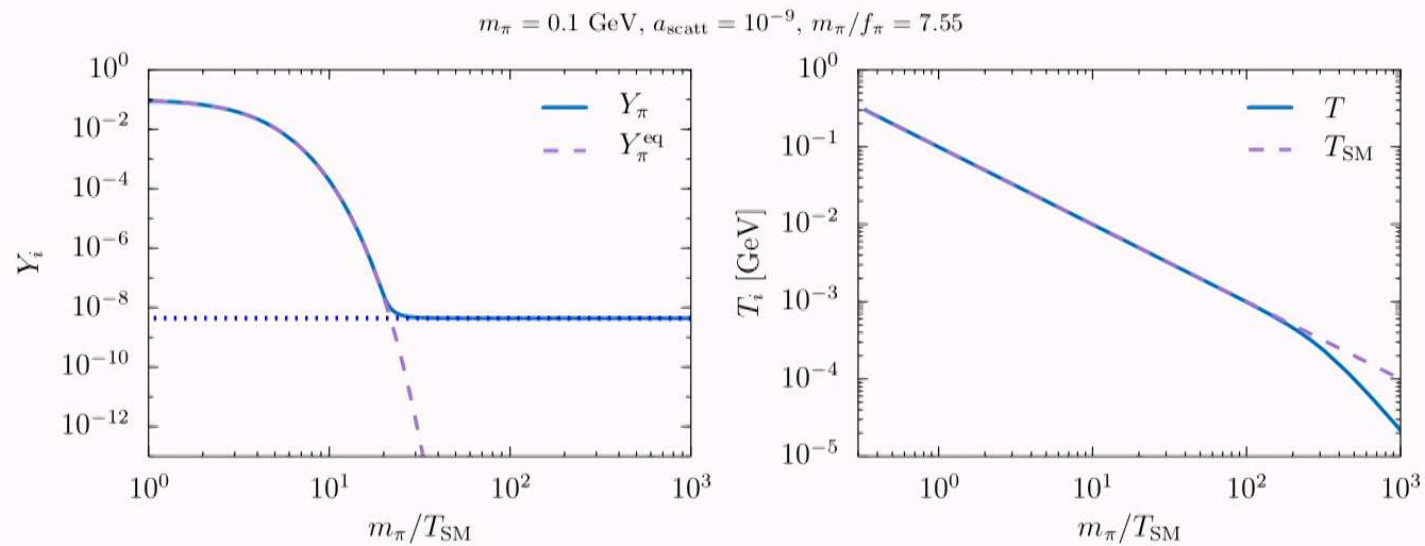
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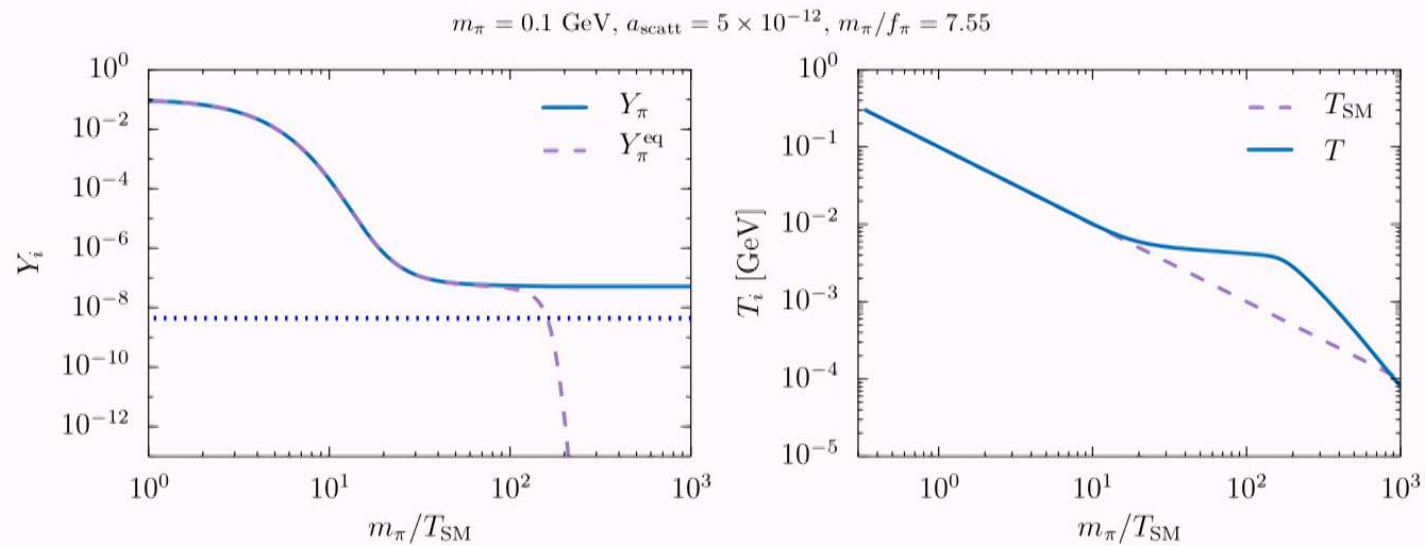
# Why is there a lower limit on $\varepsilon$ ?

DS-SM Energy transfer efficient: kinetic decoupling after chemical



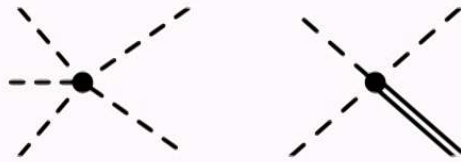
# Why is there a lower limit on $\varepsilon$ ?

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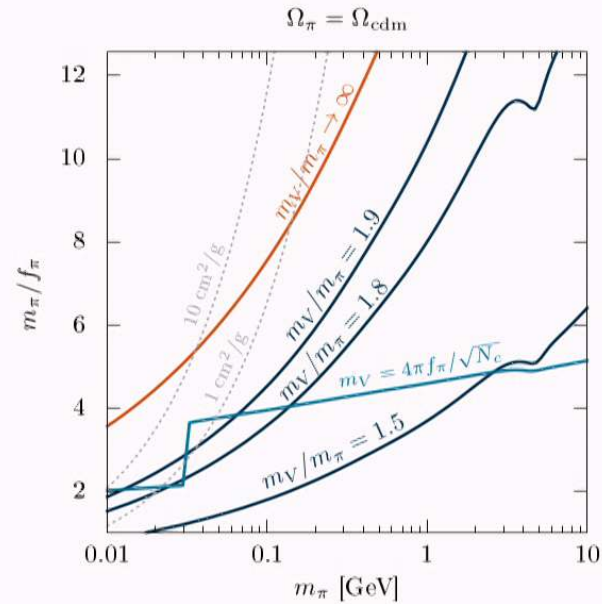
# Dark Matter Production

Two processes determine abundance:



Rates depend on

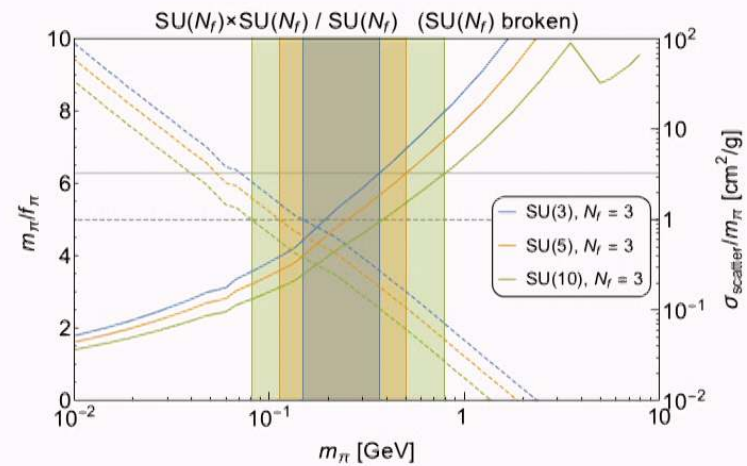
1.  $m_\pi/f_\pi$
2.  $m_V/m_\pi$



Correct relic abundance requires  $m_\pi/f_\pi \gtrsim \text{few}$

# The New SIMP Window

Parameters constrained by DM self-interaction bounds and relic abundance



Hochberg, Kuflik, Volansky and Wacker (2014)

Semi-annihilation extends viable models to  $m_\pi \lesssim 100$  TeV

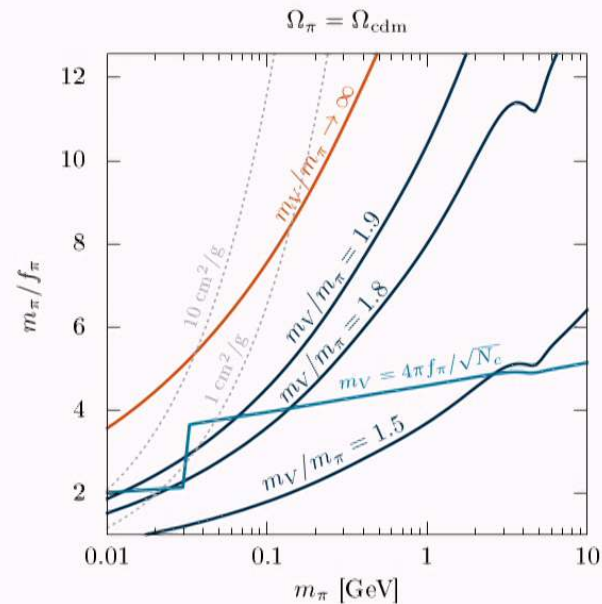
# Dark Matter Production

Two processes determine abundance:



Rates depend on

1.  $m_\pi/f_\pi$
2.  $m_V/m_\pi$



Correct relic abundance requires  $m_\pi/f_\pi \gtrsim \text{few}$

# 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

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

\*  $m_\pi$  is determined by quark masses  $m_q$

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

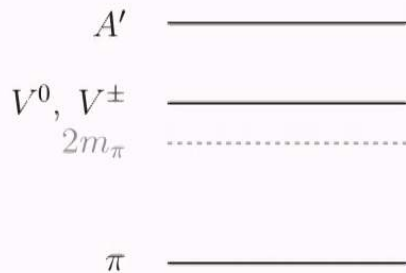
# Mass Spectrum

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

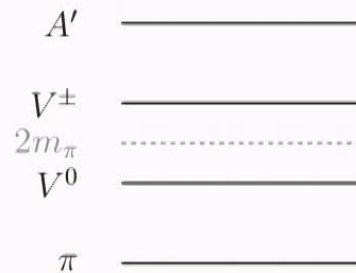
This can be modified by quantum  $U(1)_D$  corrections  $\Rightarrow m_{V^\pm} > m_{V^0}$

If  $m_V \lesssim 2m_\pi$ ,  $V$  decays to SM:  $V^0 \rightarrow \bar{f}f$ ,  $V^\pm \rightarrow \pi^\pm \bar{f}f$

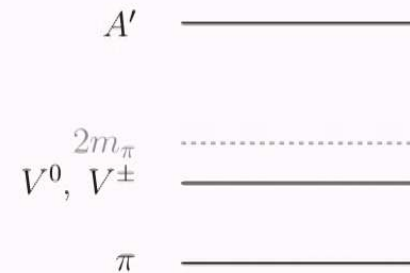
**$V$  decay invisibly**



**$V^0$  vis.,  $V^\pm$  inv.**



**$V$  decay visibly**



# Decay Modes and Lifetimes

$$\alpha_D = 10^{-2}, m_{A'}/m_\pi = 3$$

$$\varepsilon = 10^{-3}, \alpha_D = 10^{-2}$$

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

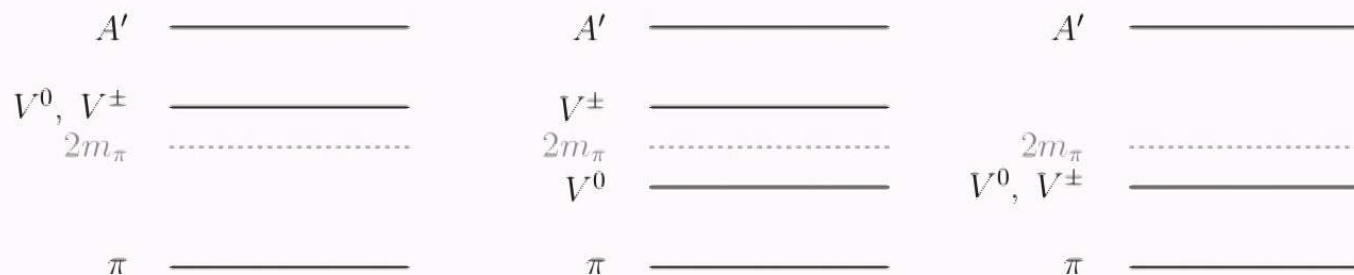
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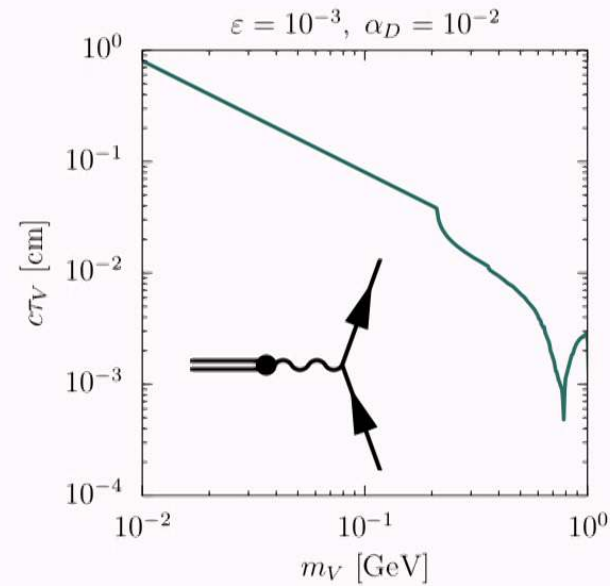
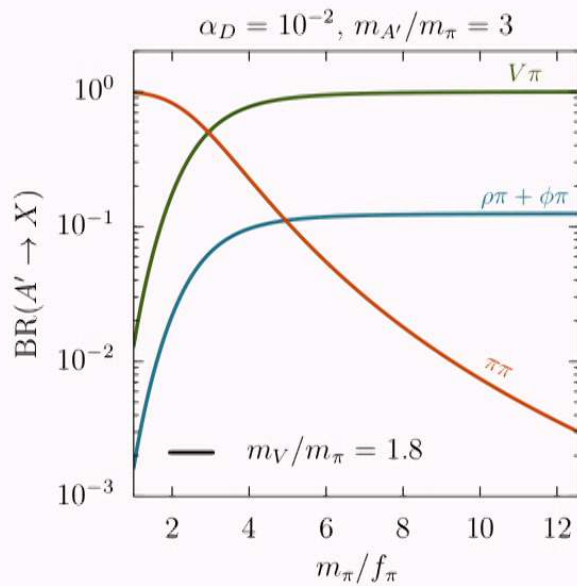
**$V$  decay invisibly**

**$V^0$  vis.,  $V^\pm$  inv.**

**$V$  decay visibly**



# Decay Modes and Lifetimes



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

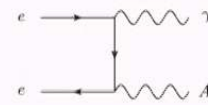
**Vector mesons naturally long-lived**

# Looking for Strongly Interacting DS

DS states produced through  $A'$ . Many production modes:

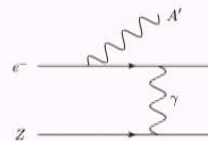
## 1. $e^+e^-$ collisions

Borodatchenkova et al (2005), Fayet (2007), Batell, Pospelov & Ritz (2009), Essig, Schuster & Toro (2009)



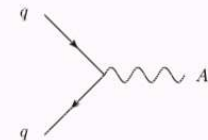
## 2. Bremsstrahlung

Bjorken et al (2009), Reece & Wang (2009), Freytsis, Ovanesyan, & Thaler (2009)



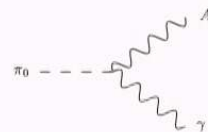
## 3. Drell-Yan

Batell, Pospelov & Ritz (2009)



## 4. Meson Decays

Fayet (2007), Batell, Pospelov & Ritz (2009), Reece & Wang (2009)



WIMP:

$$\langle \sigma v \rangle = \frac{a}{m^2} \Rightarrow$$

$$n \langle \sigma v \rangle = H \Rightarrow m \sim 100 \text{ GeV.} \\ \text{for } \alpha = 10^{-2}$$



SIMP

$$\langle \sigma v^2 \rangle = \frac{a^3}{m^5} \Rightarrow$$



# Why Fixed Target?

Fixed targets are ideal for studying kinetic mixing portal:

1. Coherent  $Z^2$  enhancement of  $A'$  brem

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

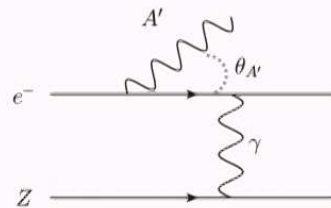
2. Forward kinematics and boosted final states

crucial for background rejection

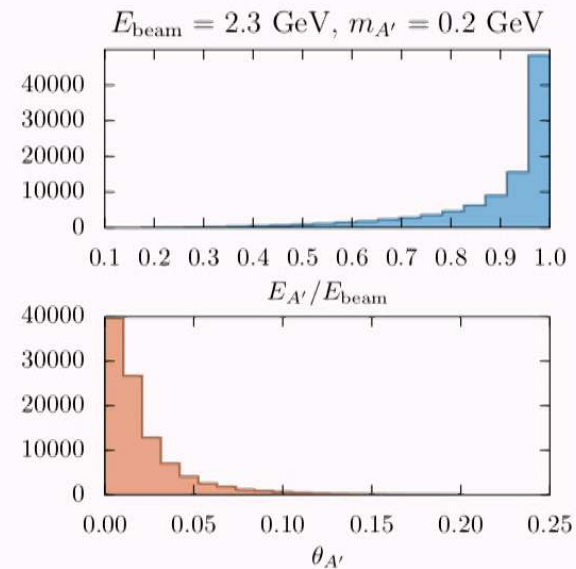
3. Potential for larger luminosities (compared to colliders)

sensitivity to tiny couplings

# $A'$ Production in a $e^-$ -Fixed Target Collision



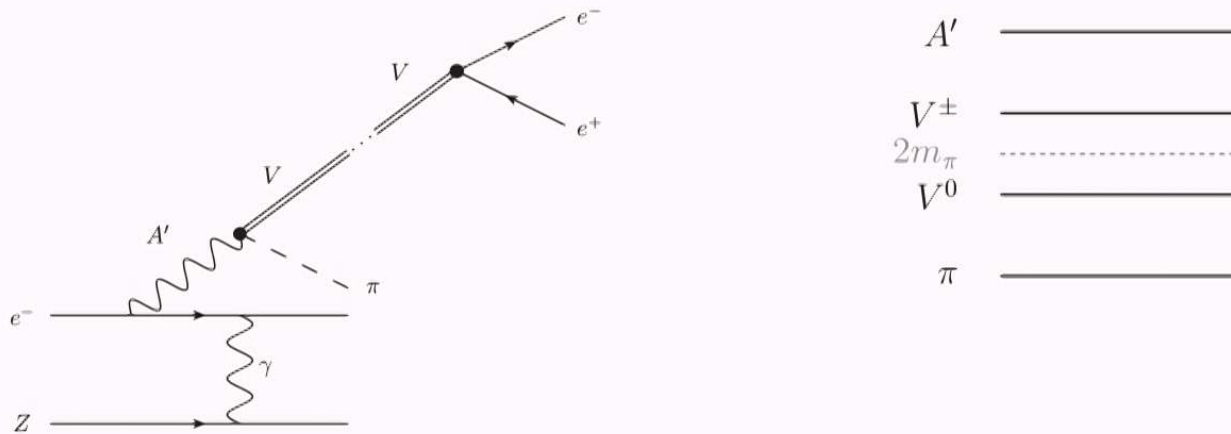
- $\sigma_{A'}$  largest for  $m_{A'} \ll E_{\text{beam}}$
- $A'$  carries away  $\sim E_{\text{beam}}$
- Decay products boosted  
 $\sim E_{\text{beam}}/m_{A'}$
- Emitted forward with  $\theta_{A'} \ll 1$



Bjorken, Essig, Schuster & Toro, Reece & Wang, Freytsis, Ovanesyan, & Thaler (2009)

# Signals at Fixed Target Experiments

**Resonant  $e^+ e^-$**

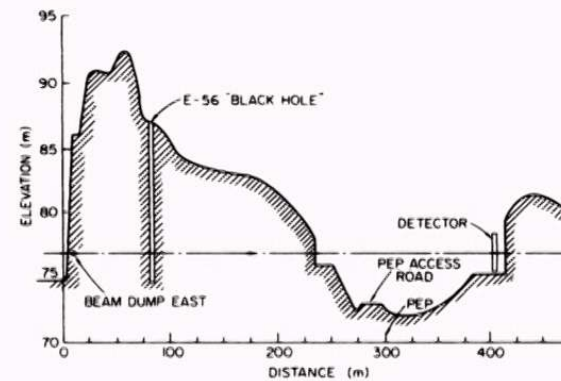
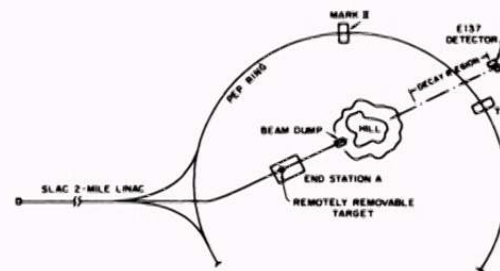


$A'$  decays promptly,  $V$  gives displaced vertex

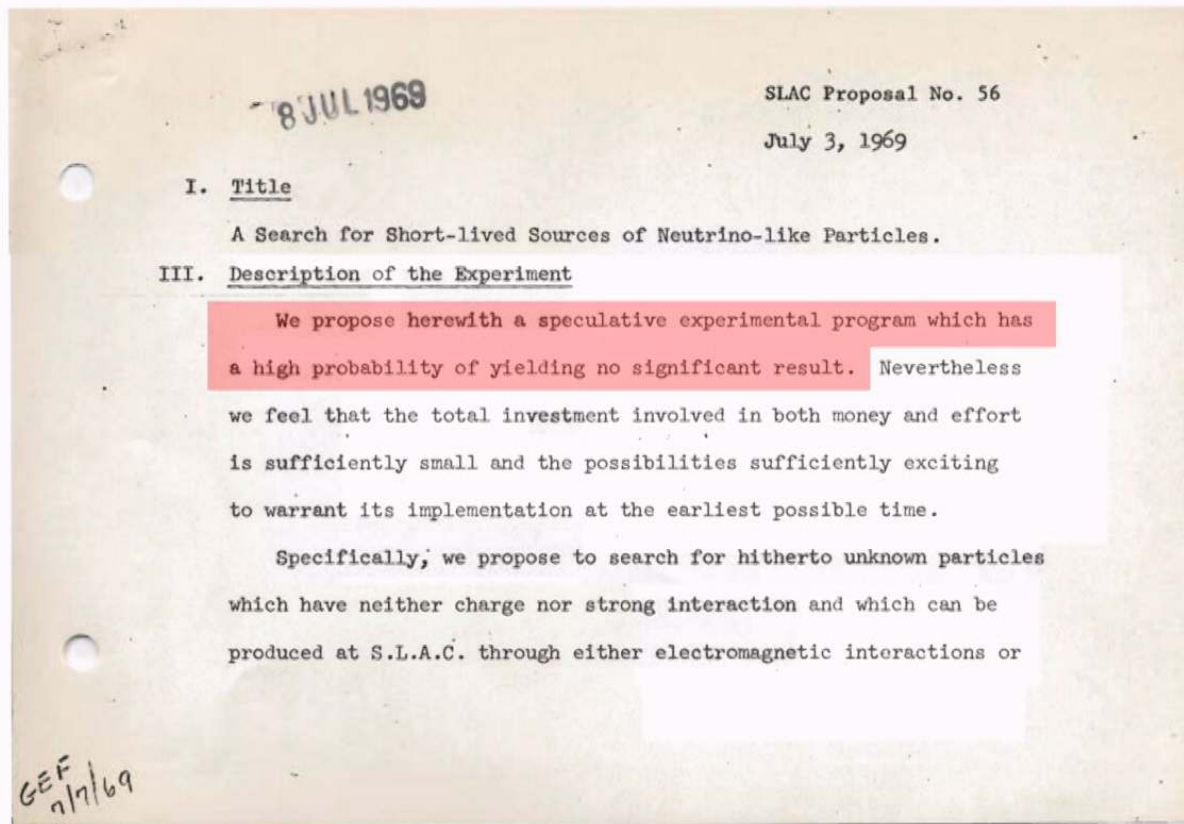
**Can have DVs and large production rate**

# SLAC E137

- 20 GeV  $e^-$  beam on Al target w/ downstream ECAL
- 30 C (!) dumped  $\Rightarrow \sim 10^{20}$  EOT
- $\sim 200$  m absorber,  $\sim 200$  m decay region



Bjorken et al (1988)



# Schematic Experimental Reach

Factors that determine signal yield:

1. Number of  $A'$  produced

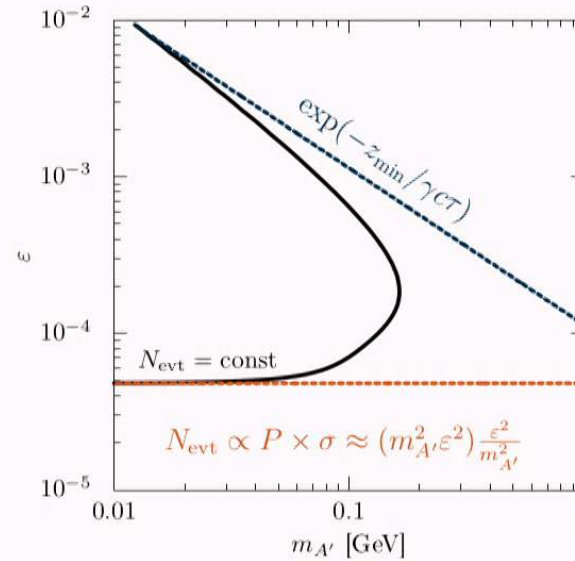
$$\sigma_{A'} \sim \frac{\epsilon^2 \alpha^3}{m_{A'}^2}$$

2.  $A'$  decays in detector volume

$$P = e^{-z_{\min}/\gamma c\tau} - e^{-z_{\max}/\gamma c\tau},$$

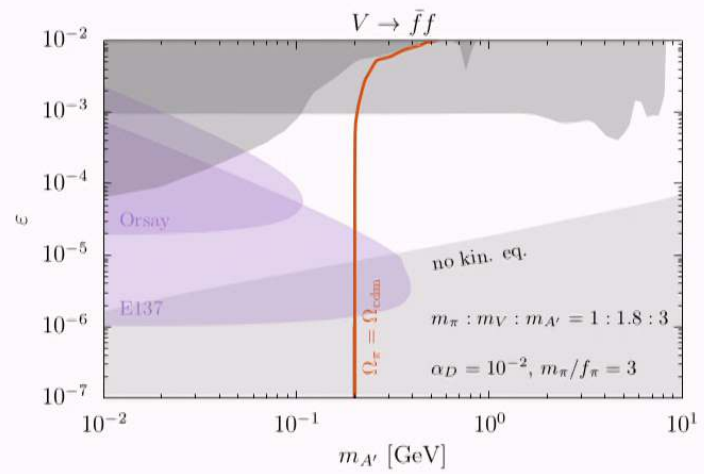
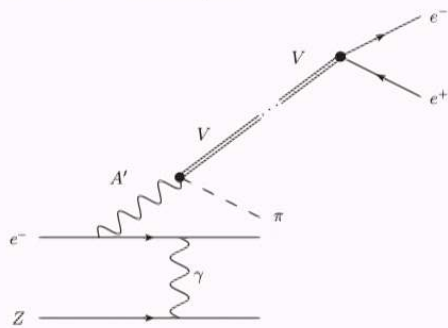
with decay length

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



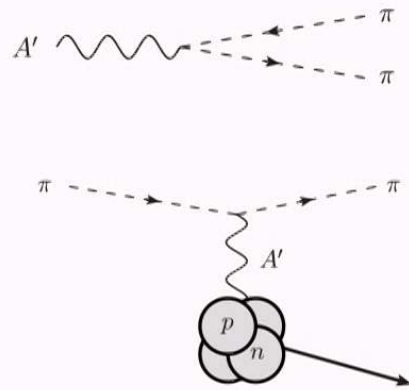
# Present Status

## ■ Beam dumps

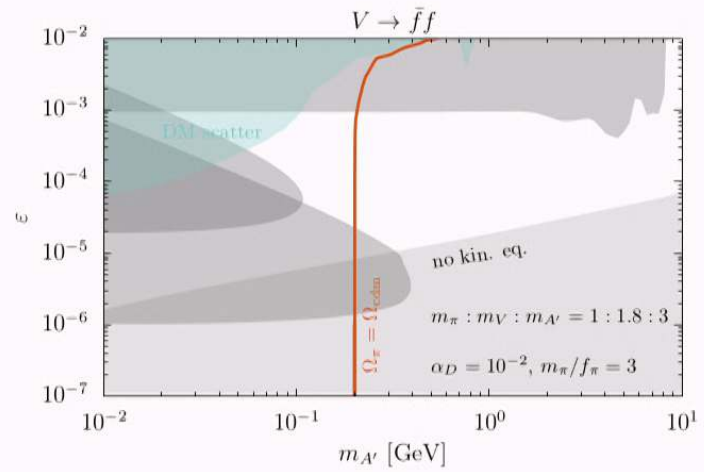


# Present Status

- Beam dumps
- LSND, MiniBooNE, E137

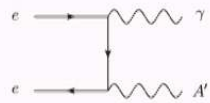


Batell, Pospelov & Ritz (2009),  
deNiverville, Pospelov & Ritz (2011) +

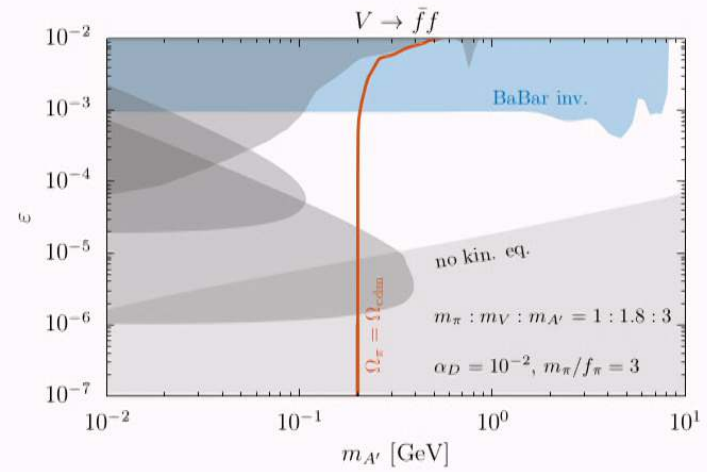


# Present Status

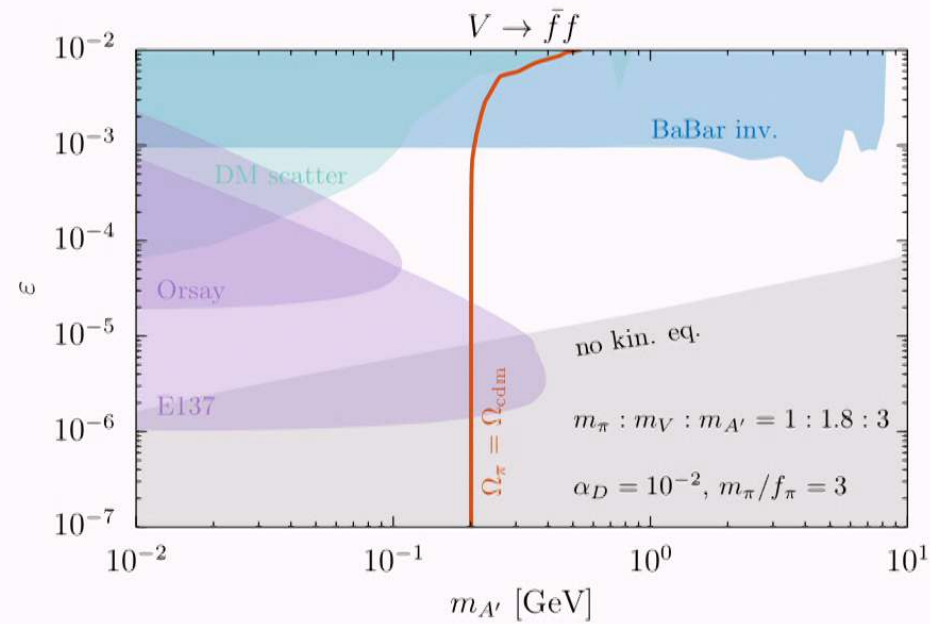
- Beam dumps
- LSND, MiniBooNE, E137
- BaBar:  $e^+e^- \rightarrow \gamma A'$ ,  $A' \rightarrow \text{inv.}$



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

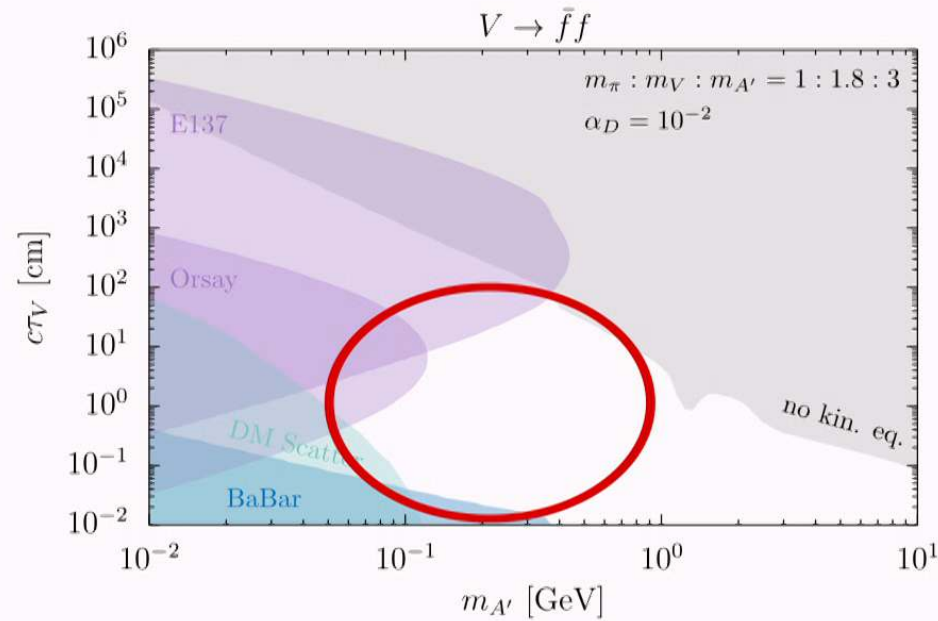


# An Obvious Gap



$$\varepsilon \leftrightarrow c\tau_V \sim \varepsilon^2 m_V$$

# An Obvious Gap

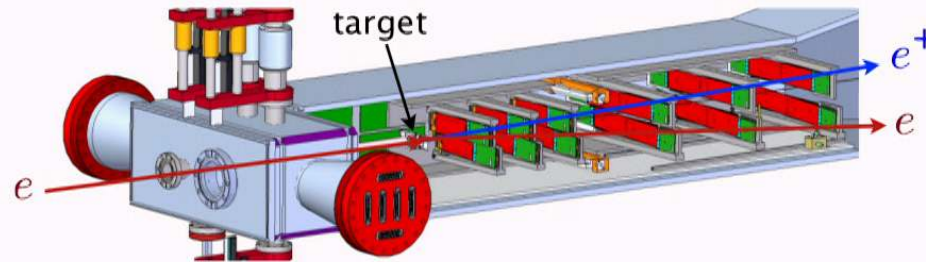


$$\varepsilon \leftrightarrow c\tau_V \sim \varepsilon^2 m_V$$

$\therefore$  need experiments with  $\mathcal{O}(\text{cm})$  baselines

# Enter Heavy Photon Search

HPS looks for  $A' \rightarrow e^+ e^-$  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 ( $\sim 2018$ ):

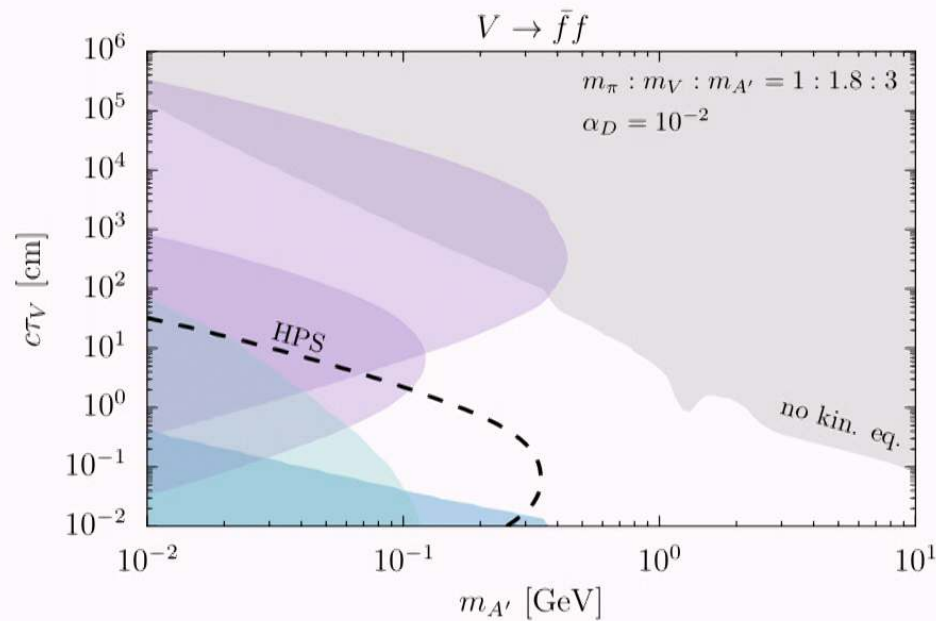
$$E_{\text{beam}} = 6.6 \text{ GeV}, 8 \mu\text{m W target}, 10^{19} \text{ EOT} \Rightarrow \mathcal{L} \approx 0.3 \text{ fb}^{-1}$$

23/34

# HPS Reach

100 DVs in  $1 \text{ cm} < z < 8 \text{ cm}$  from target, assuming 100% efficiency

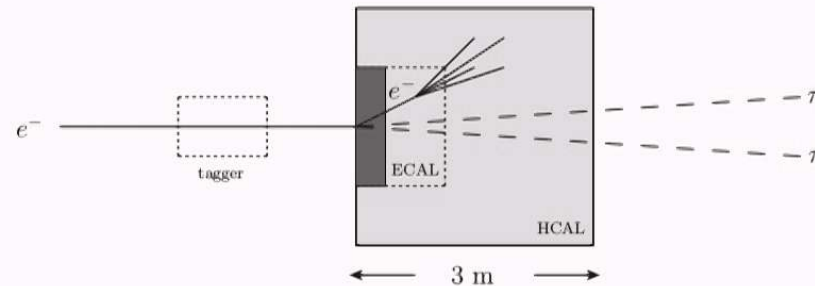
Acceptances are  $\mathcal{O}(5\%)$  - thanks to Takashi Maruyama & Bradley Yale



Note:  $m_{\pi}/f_{\pi}$  determined by requiring correct relic abundance

# Future Experiments: LDMX

Invisible channels can be extremely powerful

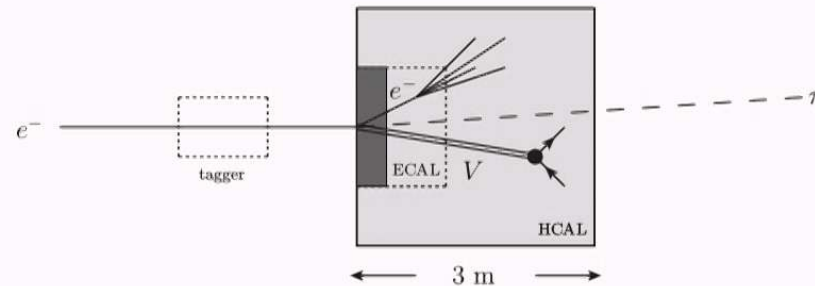


- Measure  $p_e^{\text{in}}$  and  $p_e^{\text{out}}$ ; signal: scattered  $e^-$  and nothing else  $\Rightarrow \cancel{p}$
- Phase 1:  $E = 4 \text{ GeV}$ ,  $4 \times 10^{14} e^-$ , Phase 2:  $E = 8 \text{ GeV}$ ,  $4 \times 10^{16} e^-$
- Timeline:  $> 2020$  (see Dark Sectors 2016 report)

Izaguirre et al (2014), Dark Sectors 2016

# Future Experiments: LDMX

Potential sensitivity to visible signal



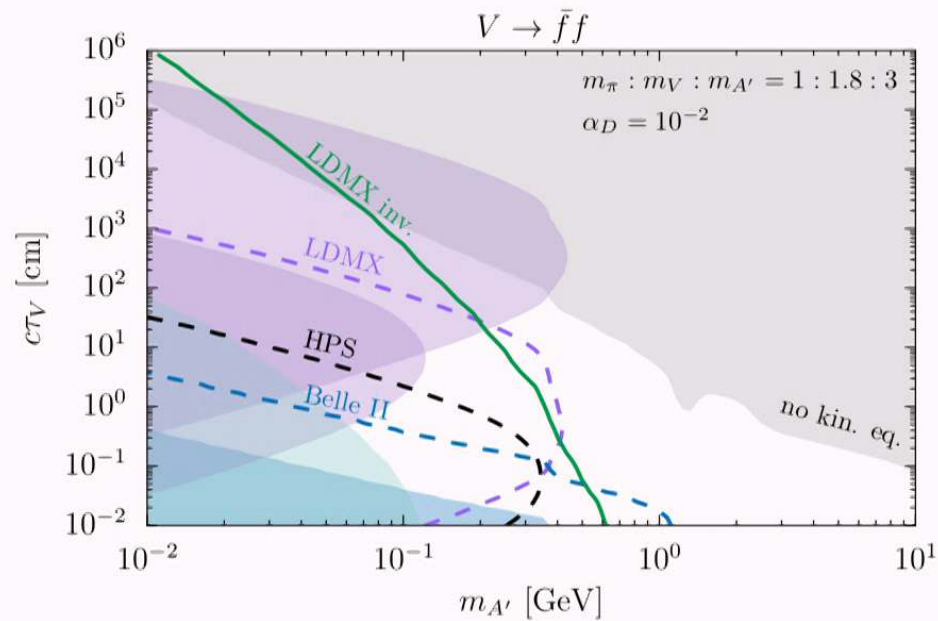
- Significant MET + displaced EM shower

$$E_e^{\text{out}} < 0.3E_{\text{beam}},$$

- Use large detector to range out background EM showers

$$DV > 20X_0 \text{ (7 cm in W) from target}$$

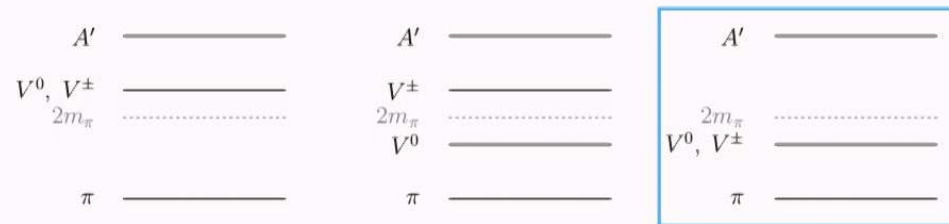
# Visible and Invisible Signals at LDMX



**LDMX will test even more cosmologically interesting models!**

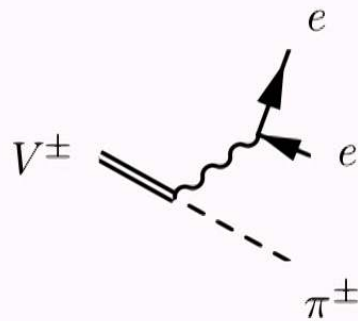
# Possible Spectra

So far: visible signals from  $U(1)_D$ -neutral vector mesons only

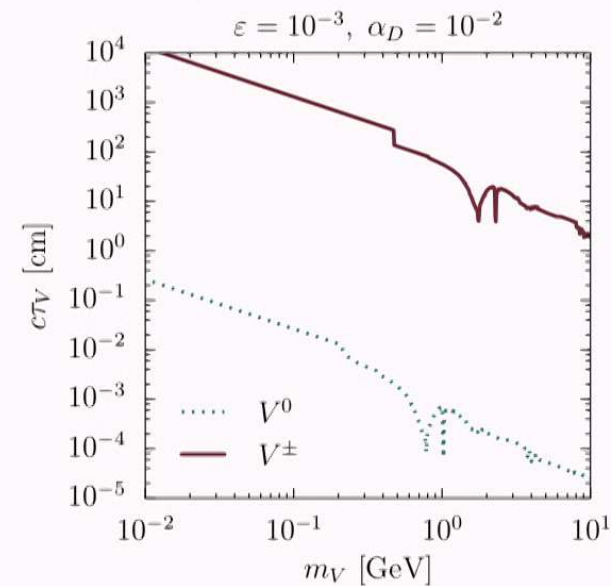


# Charged Vector Mesons

If  $m_{V^\pm} < 2m_\pi$ ,  $V^\pm$  decays introduce a second length scale



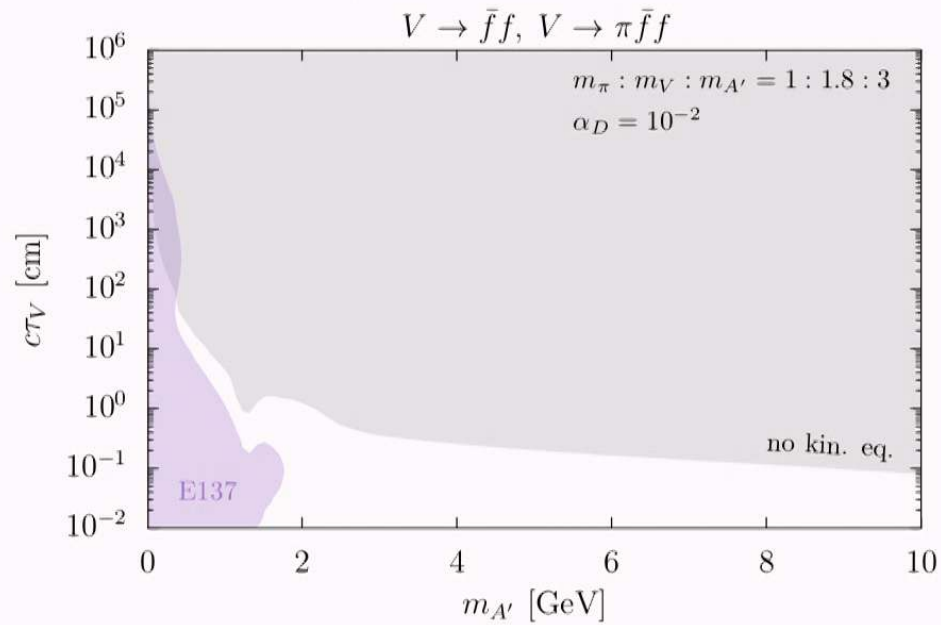
Similar cascades in SUSY hidden sectors  
- see Morrissey and Spray (2014)



$V^\pm$  decay length  $\sim 10^4$  times longer  $\Rightarrow$  long-baseline experiments important

$$m_{V^0}, V^\pm < 2m_\pi$$

For  $\varepsilon \sim 10^{-3} - 10^{-4}$ ,  $c\tau_{V^\pm}$  in perfect range for E137



Lots of room for improvement!

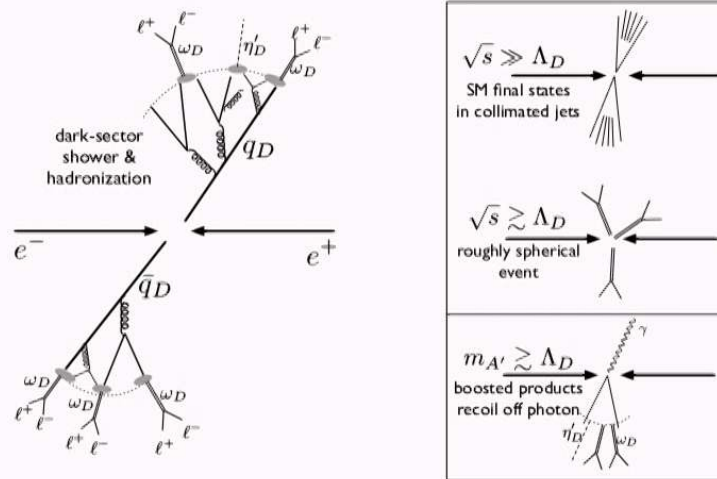
## Conclusion

- Strongly interacting dark sectors – another paradigm for thermal DM  
novel production mechanisms in early universe
- Kinetic equilibrium implies minimum coupling to SM  
opportunity for experimental tests
- Unique signals at *current* and future fixed target experiments  
displaced vertex  $\pm$  inv. mass peak +  $\cancel{p}$

Thank you!

# Characterizing the Dark Sector: Shape & Multiplicity

So far we assumed dark confinement scale  $\Lambda_D \lesssim m_{A'}$   $\Rightarrow$  No DS shower  
 If  $m_{A'}$  or  $\sqrt{s} \gg \Lambda_D$  can have high multiplicity signals



From Essig, Schuster & Toro (2009)

Most recently studied by Cohen et al (2017), Pierce et al (2017)