Strongly Interacting Dark Matter at Fixed-Target Experiments

ASHER BERLIN

TeVPA, Ohio State University
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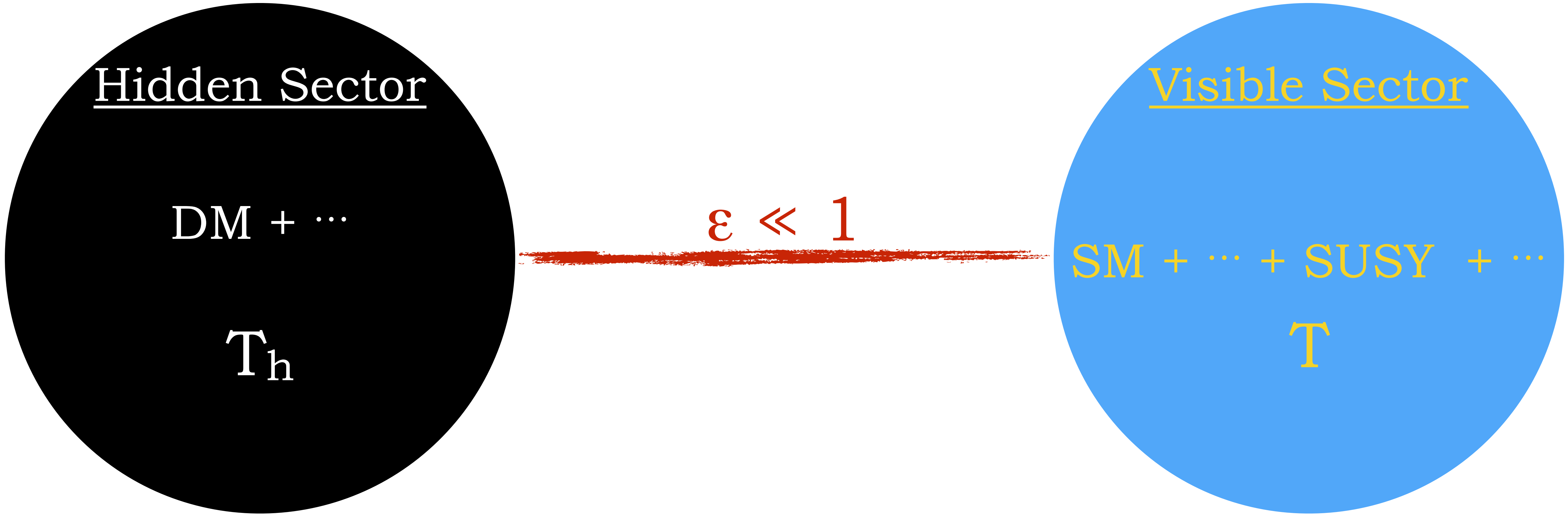
SLAC NATIONAL ACCELERATOR LABORATORY

Collaboration with Nikita Blinov, Stefania Gori, Philip Schuster, & Natalia Toro

Hidden Sector



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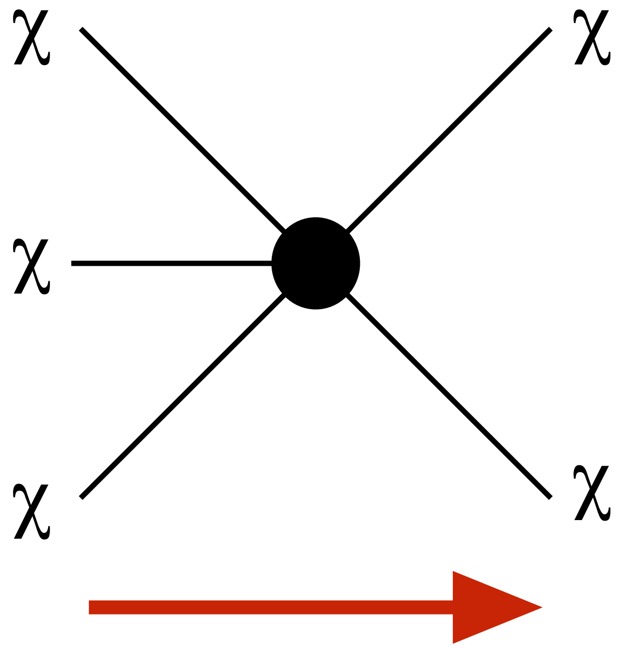

Carlson, Machacek, and Hall (1992)

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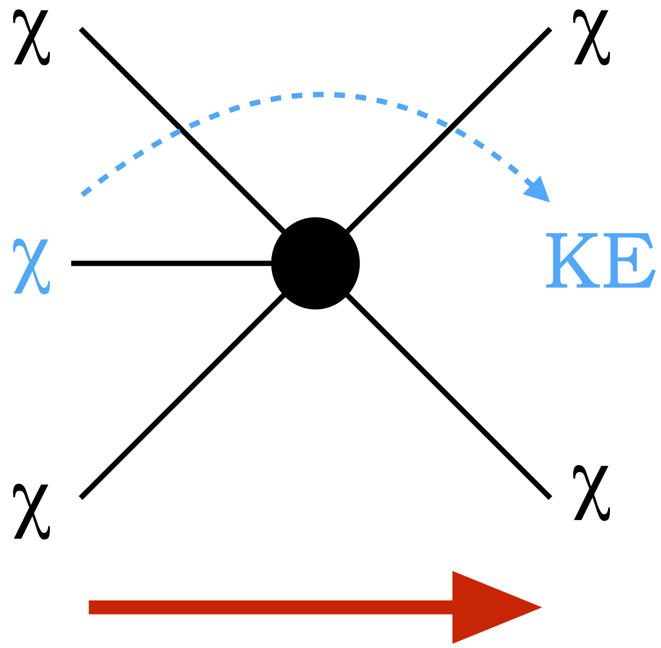

(Need to expel heat)

Carlson, Machacek, and Hall (1992)

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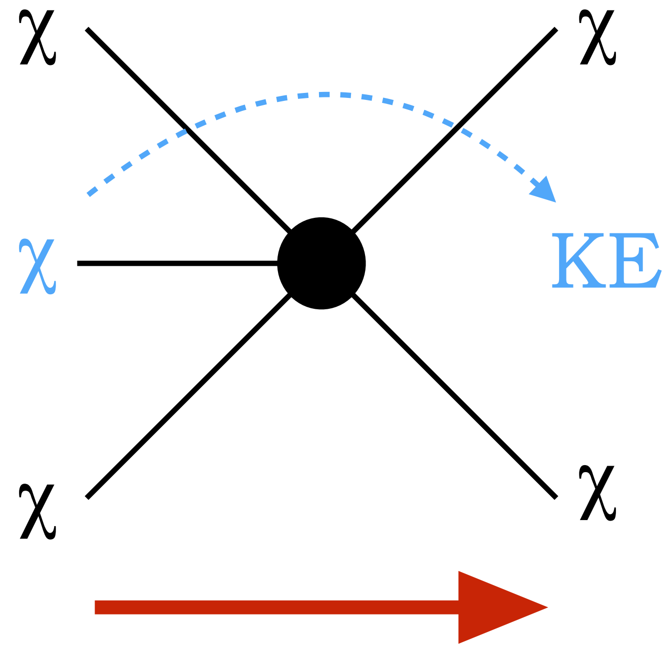


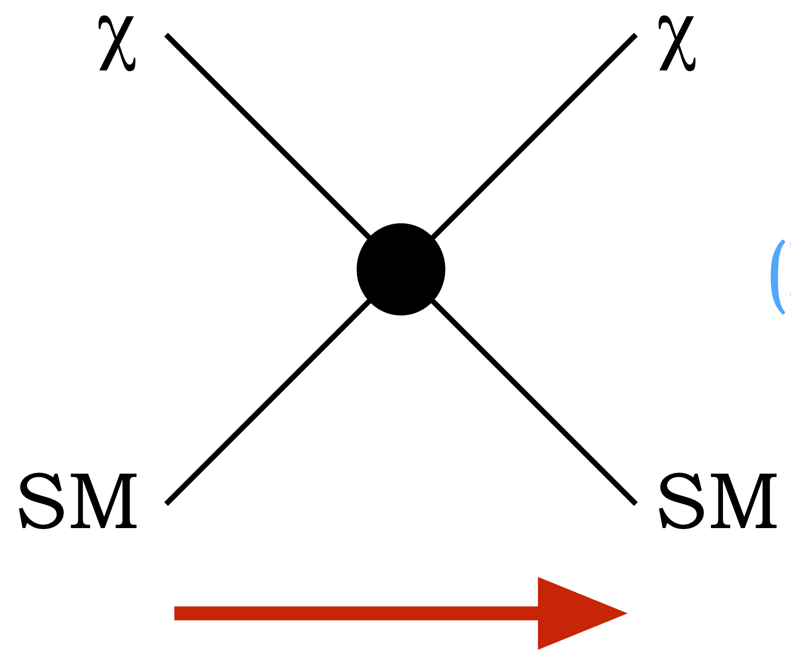
(Need to expel heat)

$$T_h \sim \frac{m_\chi}{\log a} \gg \frac{m_\chi}{a}$$

$\Rightarrow m_\chi \ll \text{keV}$

Carlson, Machacek, and Hall (1992)

90% Hidden

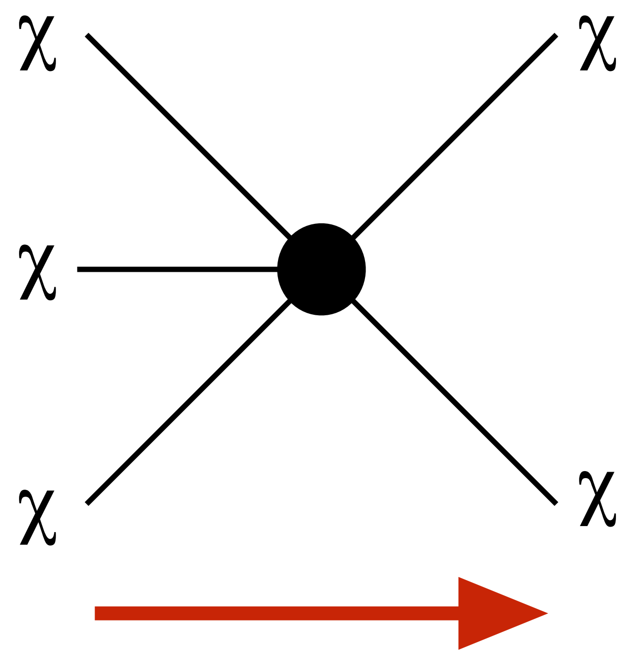


(heat dumped into SM)

$$T_h = T$$

Carlson, Machacek, and Hall (1992)

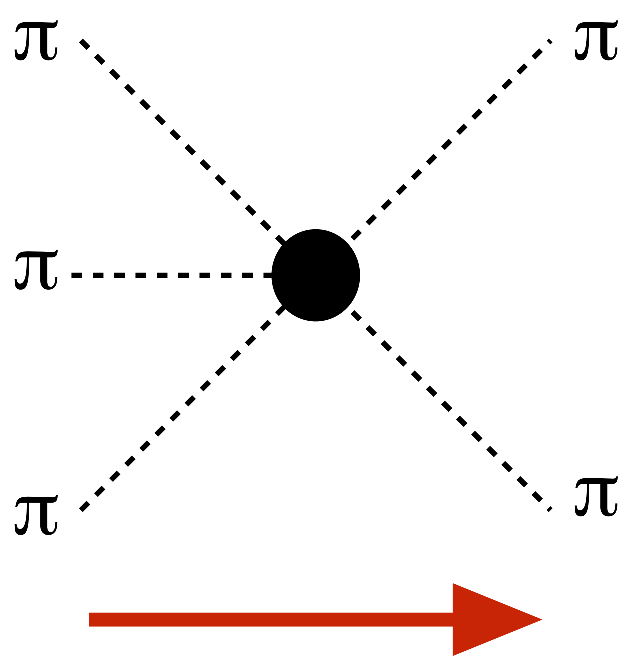
The SIMP Miracle



$$m_\chi \sim \alpha_\chi \left(T_{\rm eq}^2 m_{\rm pl}\right)^{1/3} \sim \alpha_\chi \times 1 \text{ GeV}$$

Hochberg, Kuflik, Volansky, Wacker
arXiv:1402.5143

The SIMP Miracle



$$m_\pi \sim \alpha_\chi \; \left(T_{\rm eq}^2 m_{\rm pl}\right)^{1/3} \sim \alpha_\chi \times 1 \text{ GeV}$$

Hochberg, Kuflik, Volansky, Wacker
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A Theory of Pions

$$SU(N_c) \text{ confines at } \Lambda \implies SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_{L+R} \implies N_f^2 - 1 \text{ pions, } \pi^a T^a$$

$$\frac{2\,N_c}{15\pi^2\,f_\pi^5}\;\epsilon^{\mu\nu\rho\sigma}\;\mathrm{Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right]$$

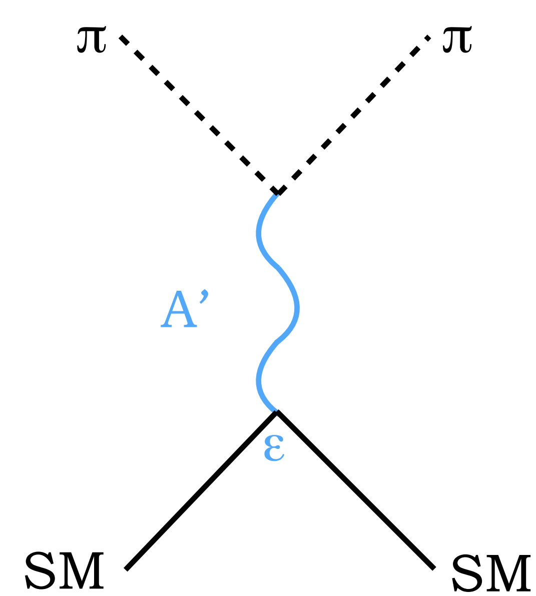
(Wess-Zumino-Witten)

$$\Gamma(3\to 2) = n_\pi^2\,\langle\sigma v^2\rangle\;,\;\;\langle\sigma v^2\rangle \sim \left(\frac{m_\pi}{f_\pi}\right)^{10}\;\frac{1}{m_\pi^5}$$

$$SU(N_1)\times SU(N_2)\times U(1)_D \subset SU(N_f)_{L+R}$$

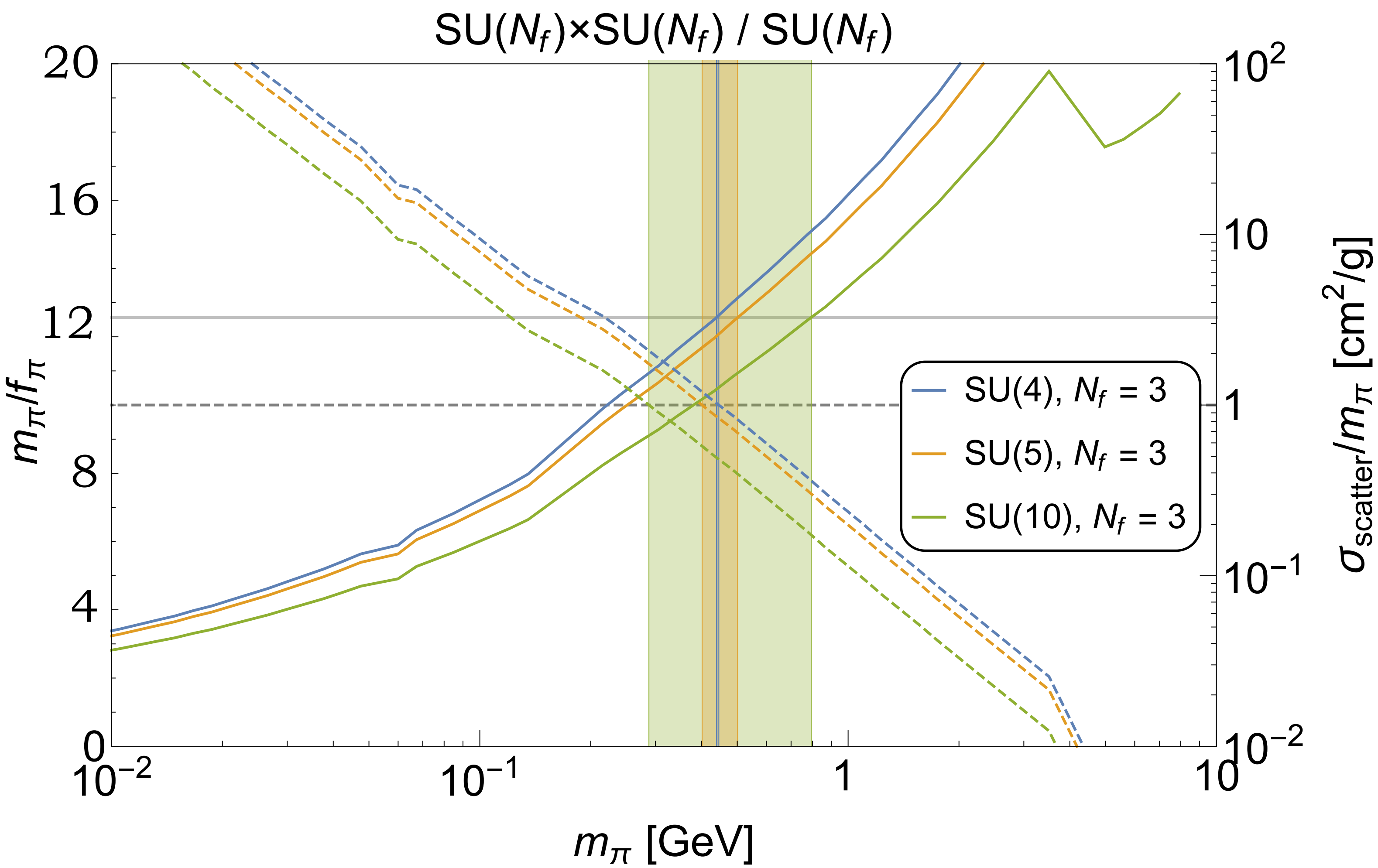
$$\frac{\epsilon}{2\,\cos\theta_W}\;A'_{\mu\nu}\,B^{\mu\nu}$$

(Kinetic mixing)



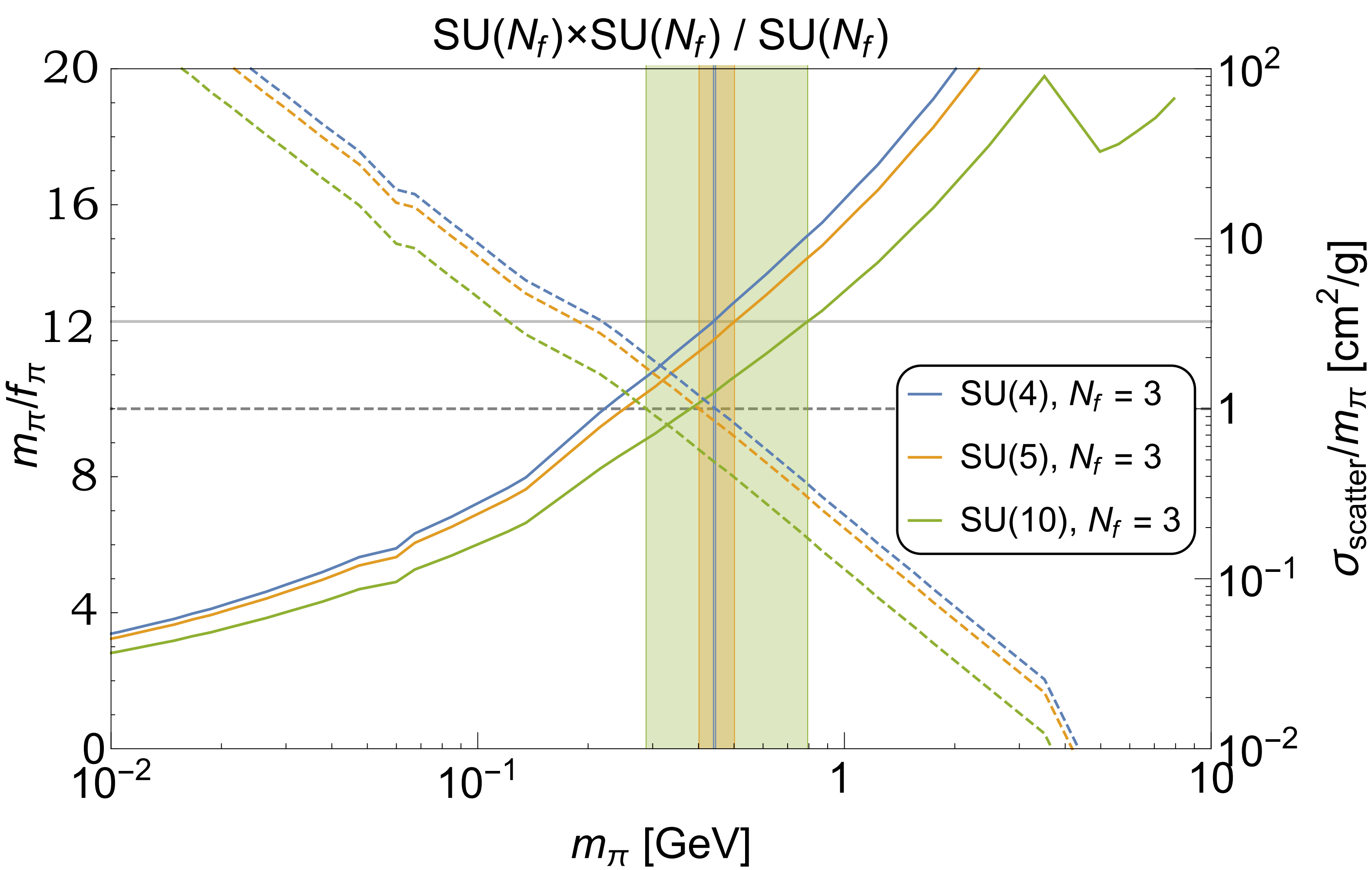
$T_h = T$

The SIMP Miracle



Hochberg, Kuflik, Murayama, Volansky, Wacker
arXiv: 1411.3727

The SIMP Miracle

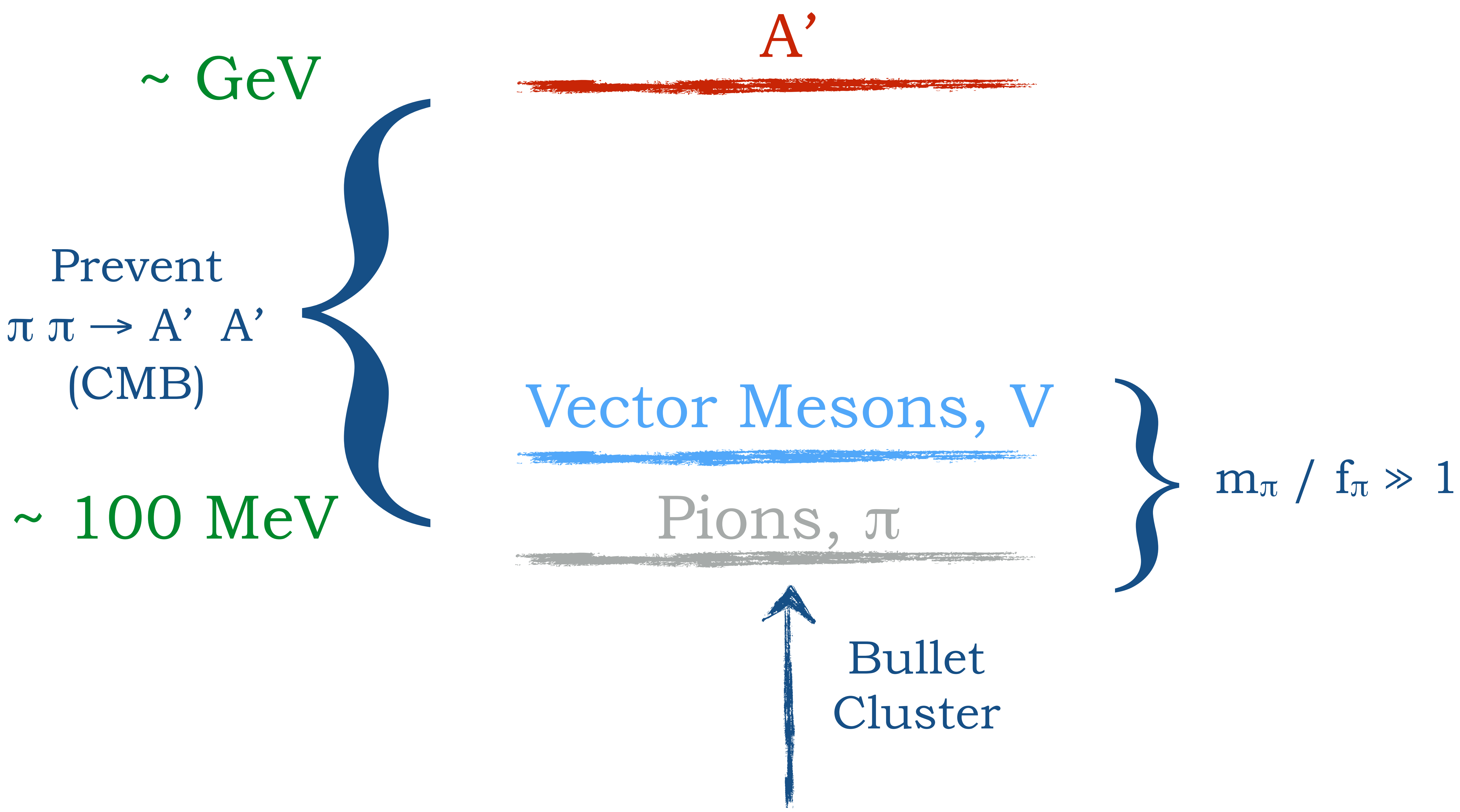


$m_\pi/f_\pi \gg 1 \Rightarrow$ vector mesons nearby in mass

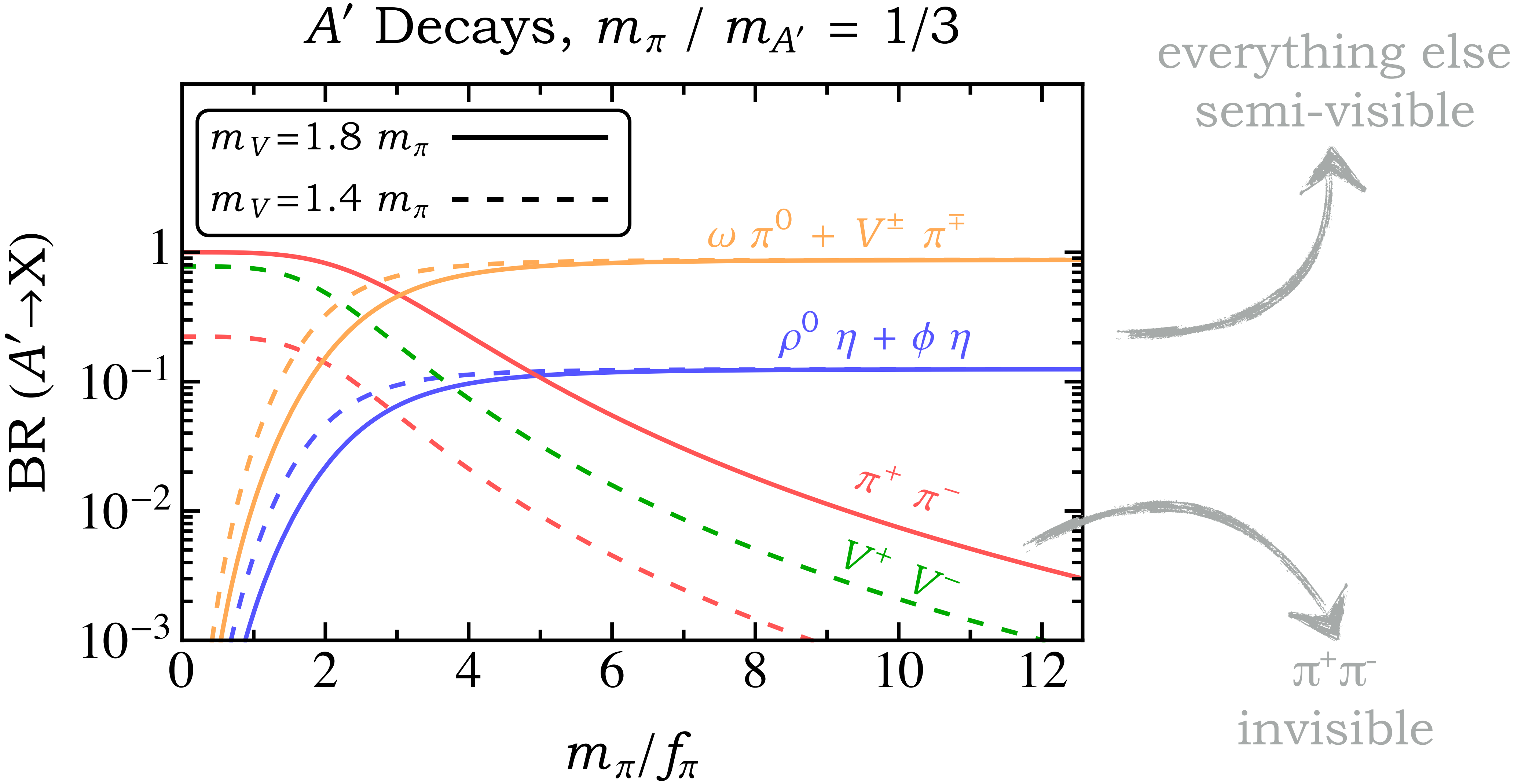
$m_V \sim 4\pi f_\pi / N_c^{1/2}$

Hochberg, Kuflik, Murayama, Volansky, Wacker
arXiv: 1411.3727

Mass Spectrum



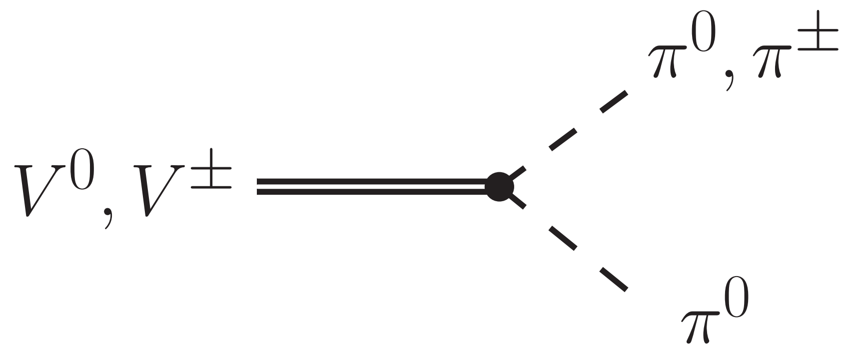
A’ Decays



A' Decays, m_π / $m_{A'}$ = 1/3
m_V=1.8 m_π
m_V=1.4 m_π
$\omega\ \pi^0 + V^\pm\ \pi^\mp$
$\rho^0\ \eta + \phi\ \eta$
$\pi^+\ \pi^-$
$V^+\ V^-$
BR (A'→X)
1
10^{-1}
10^{-2}
10^{-3}
0
2
4
6
8
10
12
m_π/f_π
everything else
semi-visible
π⁺π⁻
invisible

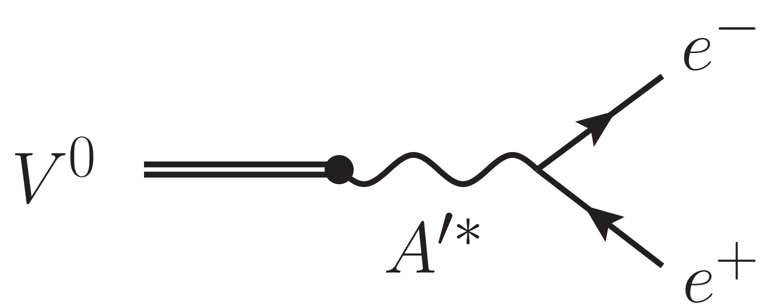
V Decays

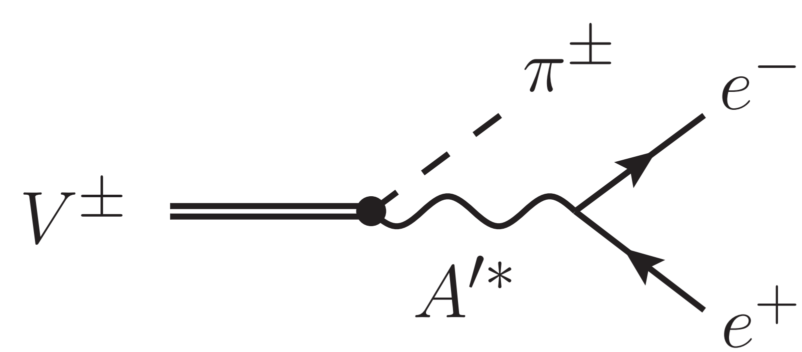
($m_V > 2\ m_\pi$)



(Model requires $m_V \sim m_\pi$)

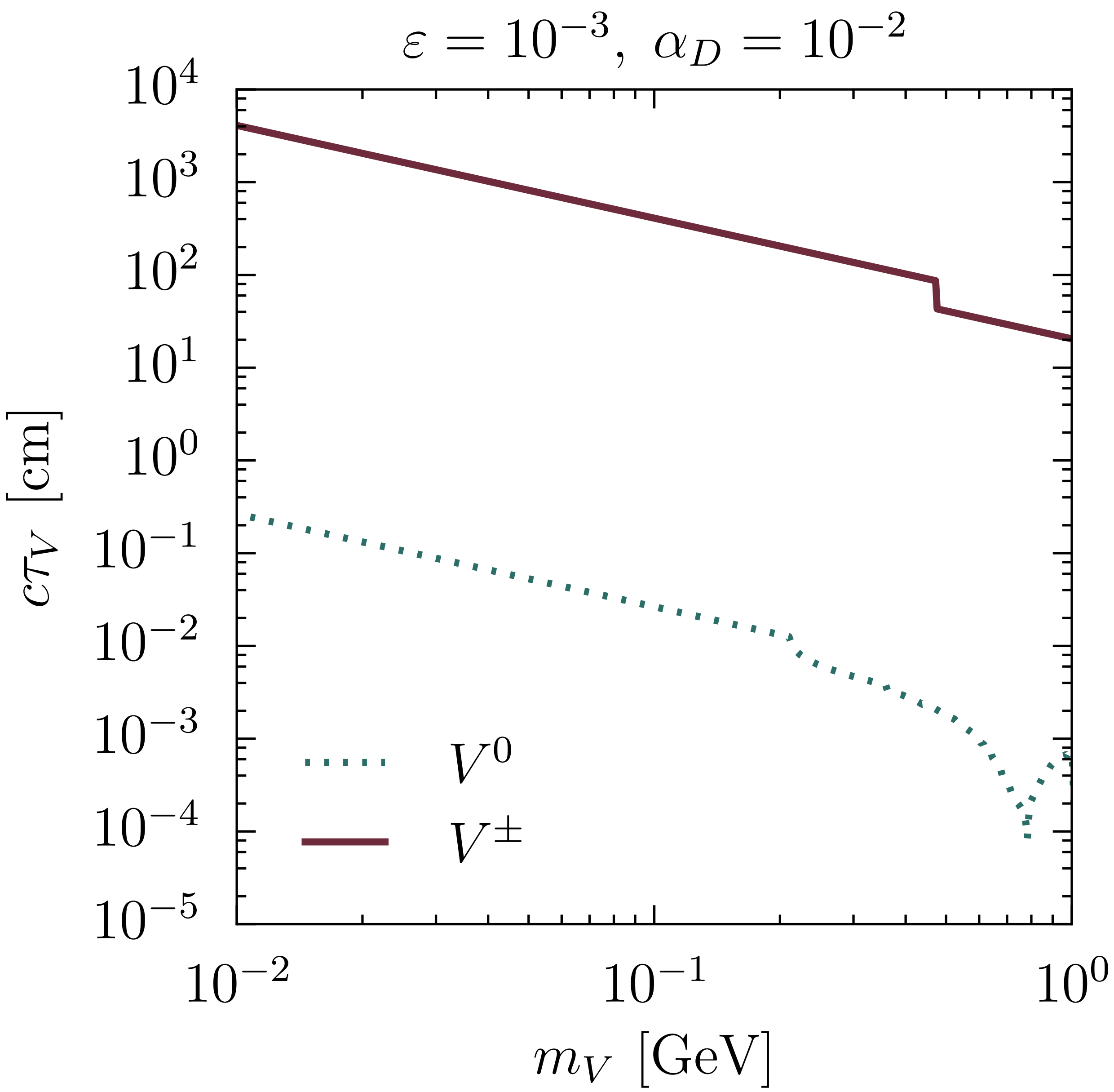
($m_V < 2\ m_\pi$)





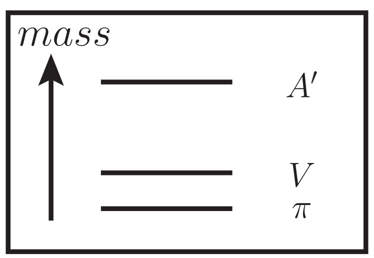
(longer lived)

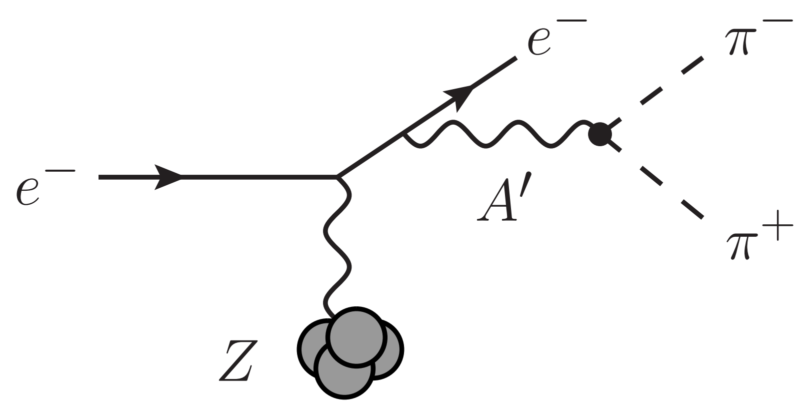
V Decays



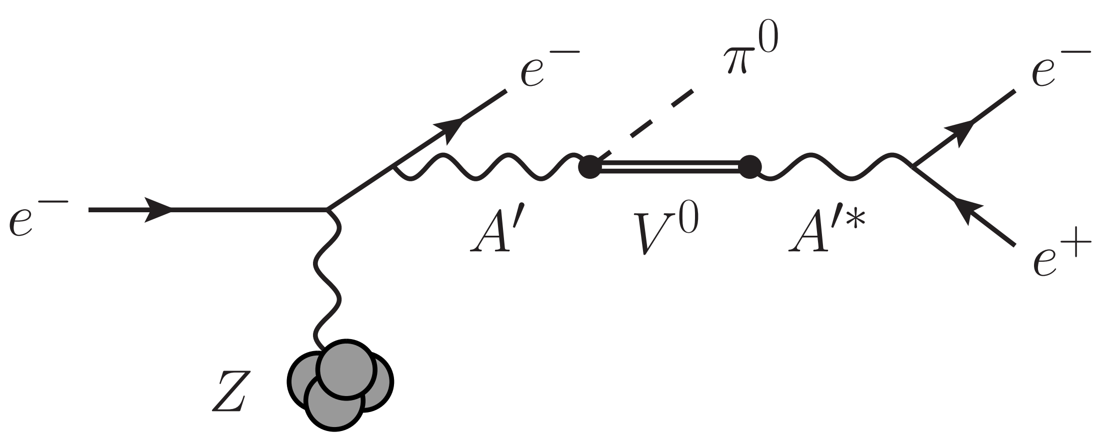
$\varepsilon = 10^{-3},\ \alpha_D = 10^{-2}$
$c\tau_V$ [cm]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-2}
10^{-1}
10^0
m_V [GeV]
V^0
$V^\pm$

Signal Examples

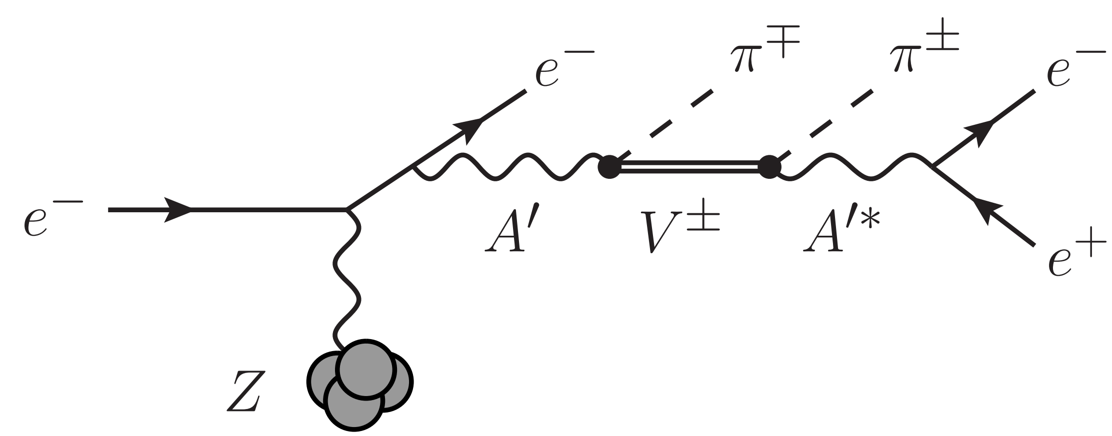




missing energy

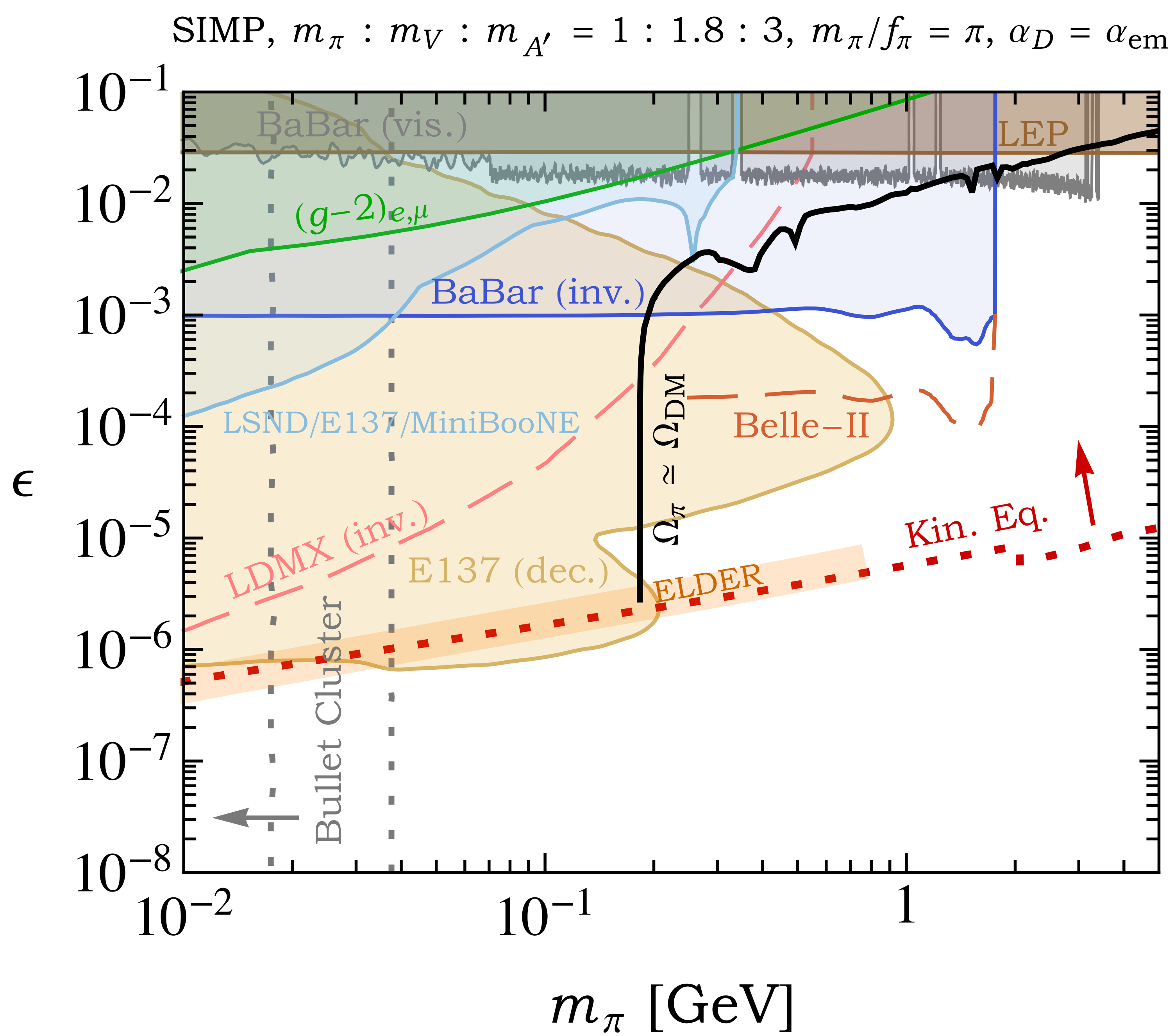


missing energy
+ displaced resonant leptons



missing energy
+ displaced leptons

Parameter Space



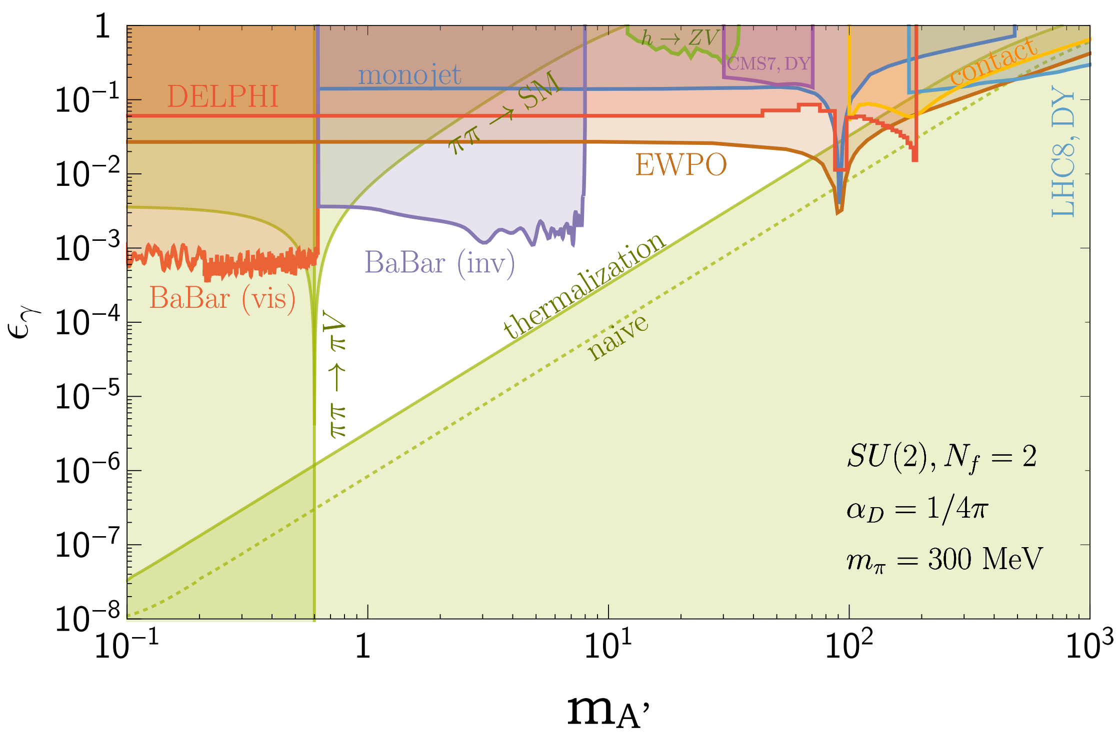
Berlin, Blinov, Gori, Schuster, Toro
arXiv:171X.XXXX

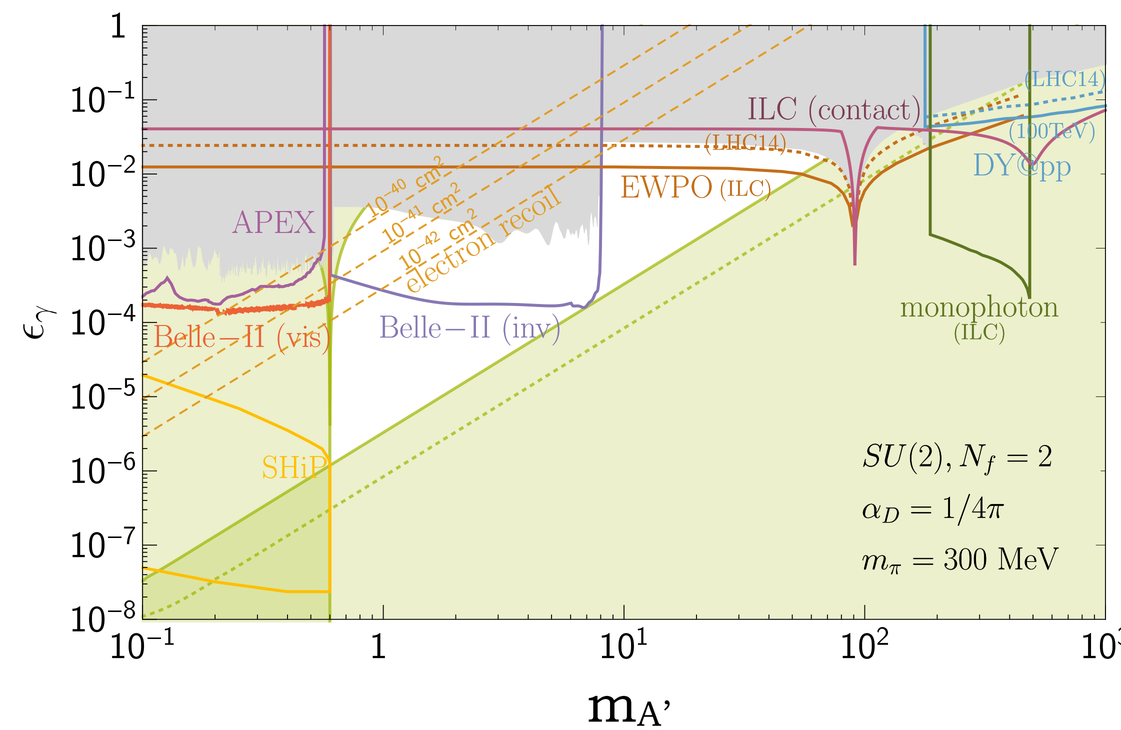
Summary

- SIMP cosmology favors $m_\pi / f_\pi \gg 1$, i.e., $m_\pi \sim m_V$ parametrically true.
- Semi-Visible decays of A' and V can be tested extensively in low-energy accelerators.

Back Up Slides

Invisible or Visible Decays



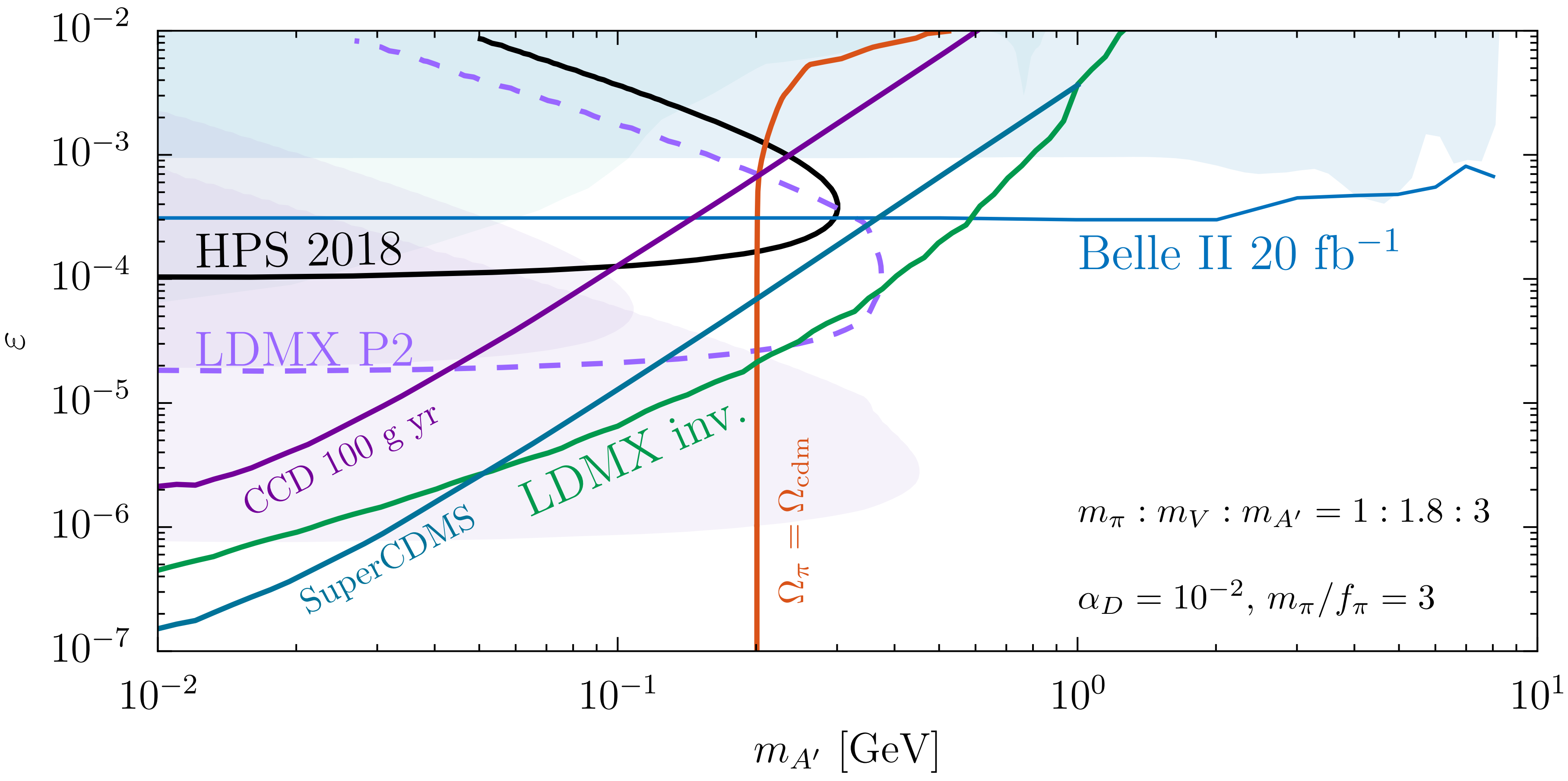


(upper bound on $m_{A'}$ from thermalization)

(lower bound on $m_{A'}$ from CMB)

Hochberg, Kuflik, Murayama
arXiv: 1512.07917

LDMX Reach



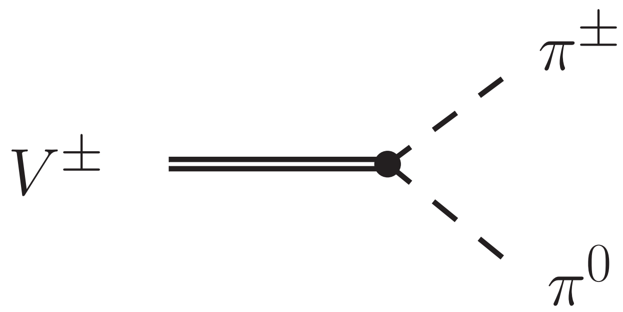
HPS 2018
LDMX P2
Belle II 20 fb^{-1}
CCD 100 g yr
SuperCDMS
LDMX inv.
$\Omega_\pi = \Omega_{\rm cdm}$
$m_\pi : m_V : m_{A'} = 1 : 1.8 : 3$
$\alpha_D = 10^{-2}$, $m_\pi / f_\pi = 3$
ε
$m_{A'}$ [GeV]

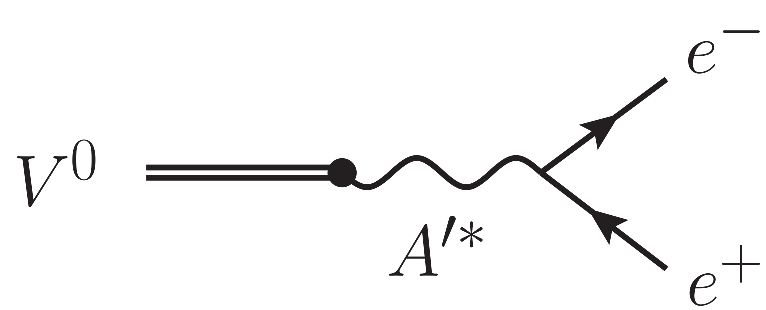
V Decays

$(m_{V^\pm} > 2\ m_\pi)$

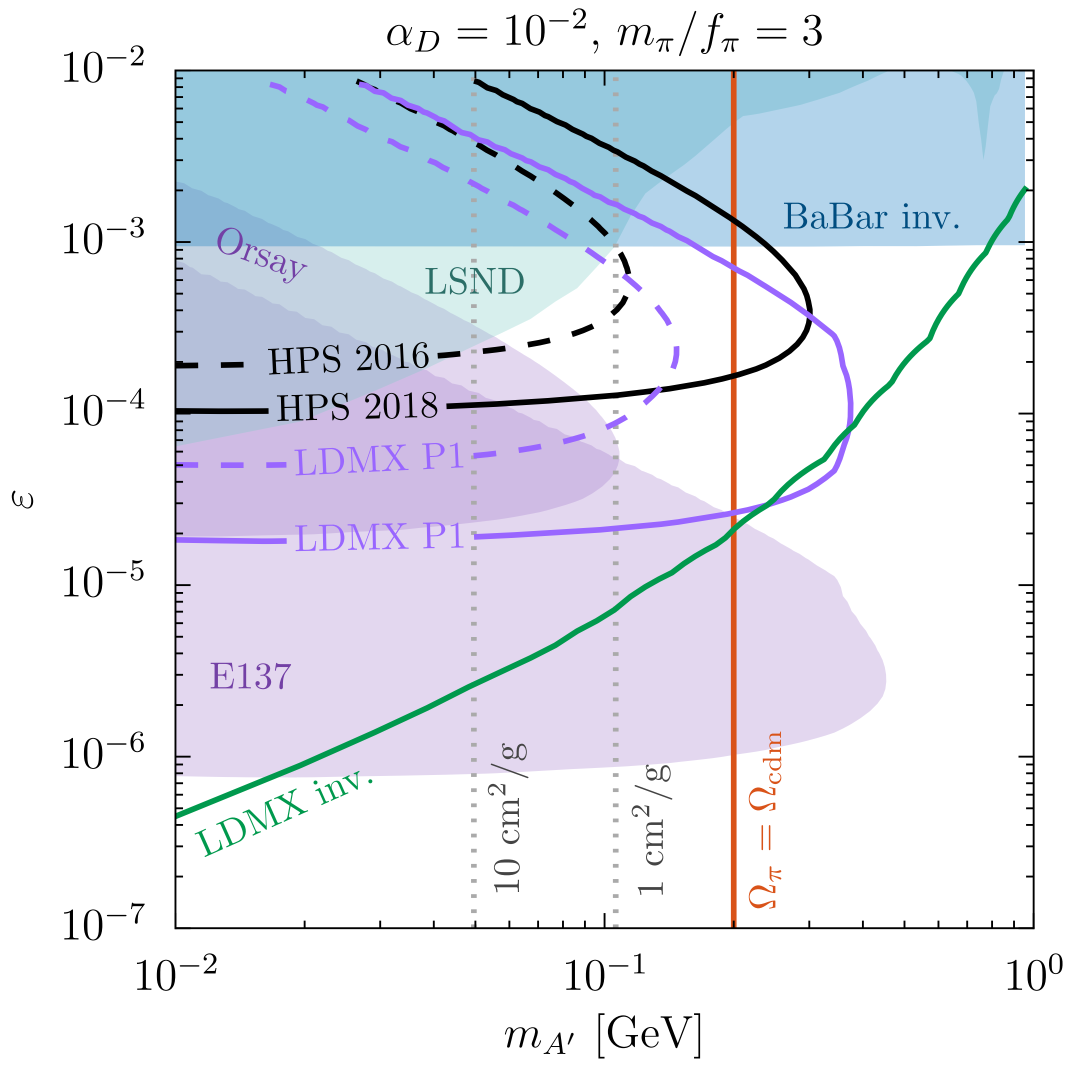
radiative corrections under $U(1)_D$

$(m_{V^0} < 2\ m_\pi)$





LDMX Reach



$\alpha_D = 10^{-2}$, $m_\pi/f_\pi = 3$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
ε
BaBar inv.
Orsay
LSND
HPS 2016
HPS 2018
LDMX P1
LDMX P1
E137
LDMX inv.
10 cm^2/g
1 cm^2/g
$\Omega_\pi = \Omega_{\rm cdm}$
10^{-2}
10^{-1}
10^{0}
$m_{A'}$ [GeV]

Forbidden Semi-Annihilation

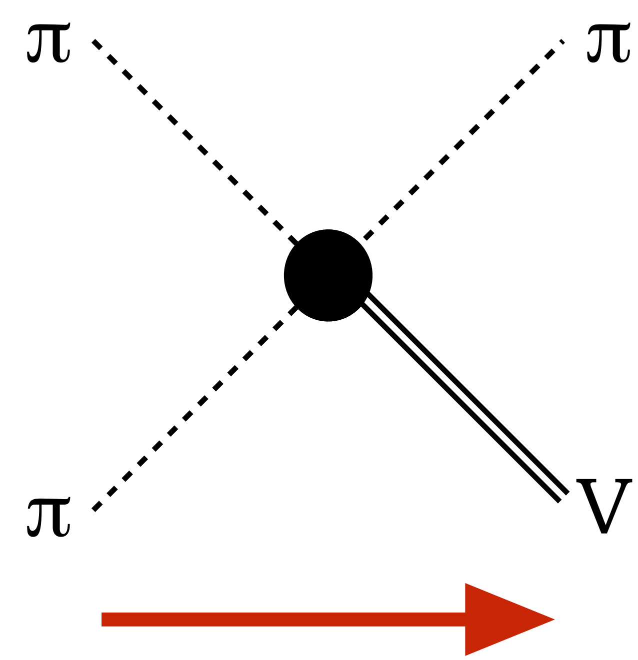
$$\langle \sigma v \rangle \sim \frac{e^{-(m_V - m_\pi)/T}}{m_\pi^2} \sim \frac{e^{-(f_\pi - m_\pi)/T}}{m_\pi^2}$$

$$\Gamma \sim n_\pi \frac{e^{-(f_\pi - m_\pi)/m_\pi}}{m_\pi^2} \sim H \sim \frac{m_\pi^2}{m_{\rm pl}}$$

$$n_\pi \sim \frac{m_\pi^4}{m_{\rm pl}} \; e^{(m_\pi/f_\pi)^{-1}-1}$$

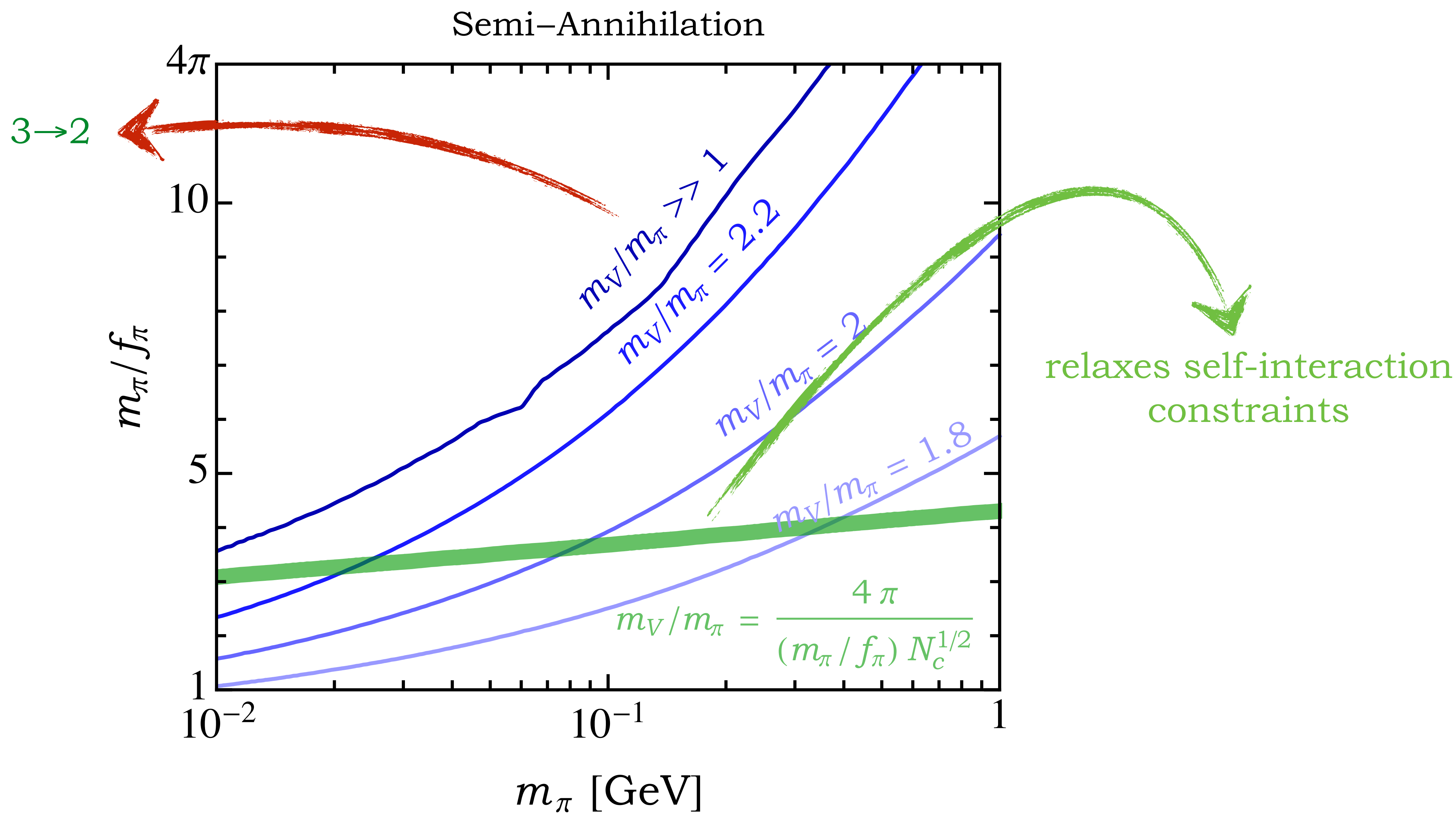
$$\rho_{\rm eq} \sim \frac{m_\pi^4}{m_{\rm pl}} \; e^{(m_\pi/f_\pi)^{-1}-1} \left(\frac{T_{\rm eq}}{m_\pi}\right)^3 \sim T_{\rm eq}^4$$

$$\frac{m_\pi}{f_\pi} \sim \left(1 + \log \frac{(T_{\rm eq}\, m_{\rm pl})^{1/2}}{m_\pi}\right)^{-1}$$



$$\frac{m_\pi}{f_\pi} \sim \frac{2\pi\, x_f}{N_c^{1/2} \;\; [x_f/2 + \log(\sqrt{m_{\rm pl}\, T_{\rm eq}} \,/\, m_\pi)]}$$

Forbidden Semi-Annihilation



Decays

$$\Gamma(A' \to \ell^+\ell^-) = \frac{\alpha_{\rm em}\,\epsilon^2}{3}\,\left(1-4\,r_\ell^2\right)^{1/2}\,\left(1+2\,r_\ell^2\right) m_{A'}$$

$$\Gamma(A' \to \text{hadrons}) = R(\sqrt{s} = m_{A'})\;\Gamma(A' \to \mu^+\mu^-)$$

$$\Gamma(A' \to \pi\pi) = \frac{2\,\alpha_D}{3}\,\frac{(1-4r_\pi^2)^{3/2}}{(1-r_V^{-2})^2}\,m_{A'}$$

$$\Gamma(A' \to \eta^0\;\rho) = \frac{\alpha_D\,r_V^2}{256\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1-2(r_\pi^2+r_V^2)+(r_\pi^2-r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to \eta^0\;\phi) = \frac{\alpha_D\,r_V^2}{128\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1-2(r_\pi^2+r_V^2)+(r_\pi^2-r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to \pi^0\;\omega) = \frac{3\alpha_D\,r_V^2}{256\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1-2(r_\pi^2+r_V^2)+(r_\pi^2-r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to K^0\;\overline{K^{*0}}\;,\;\overline{K^0}\;K^{*0}) = \frac{3\alpha_D\,r_V^2}{128\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1-2(r_\pi^2+r_V^2)+(r_\pi^2-r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to \pi^\pm\;\rho^\mp) = \frac{3\alpha_D\,r_V^2}{128\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1-2(r_\pi^2+r_V^2)+(r_\pi^2-r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to K^\pm\;K^{*\mp}) = \frac{3\alpha_D\,r_V^2}{128\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1-2(r_\pi^2+r_V^2)+(r_\pi^2-r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to VV) = \frac{\alpha_D}{6}\,\frac{(1-4r_V^2)^{1/2}(1+16r_V^2-68r_V^4-48r_V^6)}{(1-r_V^2)^2}\,m_{A'}$$

$$\Gamma(\rho \to \ell^+\ell^-) = \frac{32\pi\,\alpha_{\rm em}\,\alpha_D\,\epsilon^2}{3}\,\left(\frac{r_\pi}{m_\pi/f_\pi}\right)^2\,(r_V^2-4r_\ell^2)^{1/2}\,(r_V^2+2r_\ell^2)\,(1-r_V^2)^{-2}\,m_{A'}$$

$$\Gamma(\phi \to \ell^+\ell^-) = \frac{16\pi\,\alpha_{\rm em}\,\alpha_D\,\epsilon^2}{3}\,\left(\frac{r_\pi}{m_\pi/f_\pi}\right)^2\,(r_V^2-4r_\ell^2)^{1/2}\,(r_V^2+2r_\ell^2)\,(1-r_V^2)^{-2}\,m_{A'}$$

$$\Gamma(\omega \to \ell^+\ell^-) = 0$$