Cosmology and accelerator tests of strongly interacting dark matter

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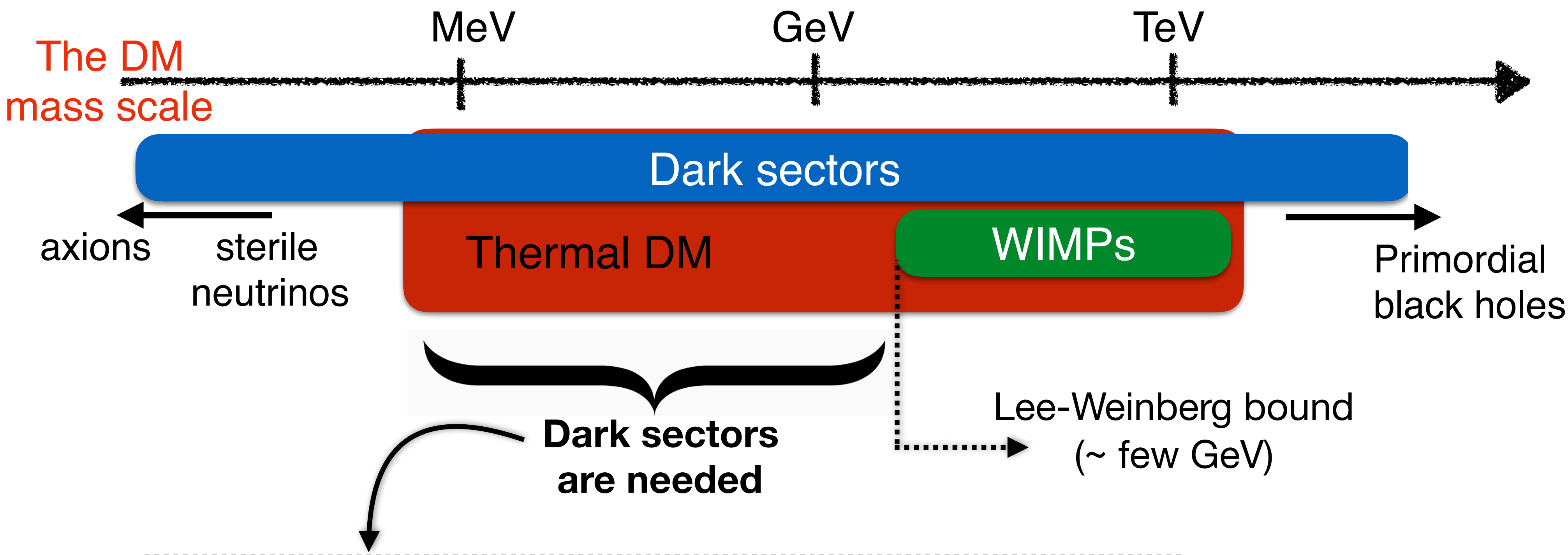
UC Santa Cruz

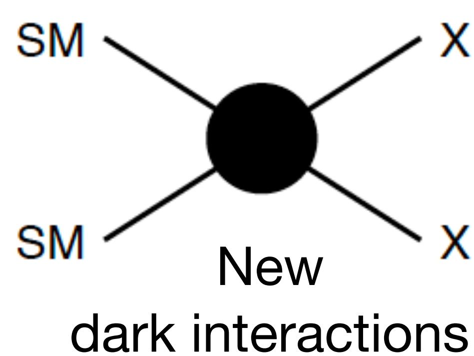
20th Lomonosov conference on elementary particle physics

August 24, 2021

The Dark Matter energy scale



Need for new particles in addition to DM (the “mediator(s)”)



The “WIMP” paradigm

Weakly Interacting Massive Particles (WIMP) models:
One of the dominant models for more than 3 decades

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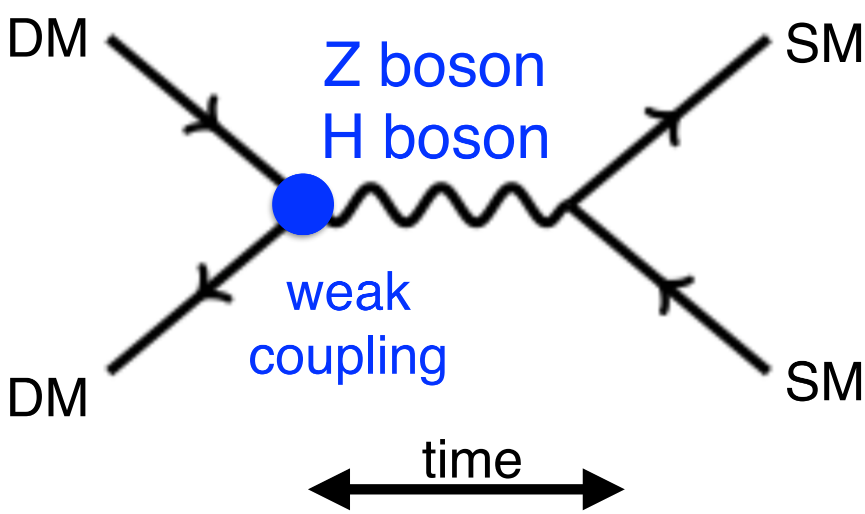
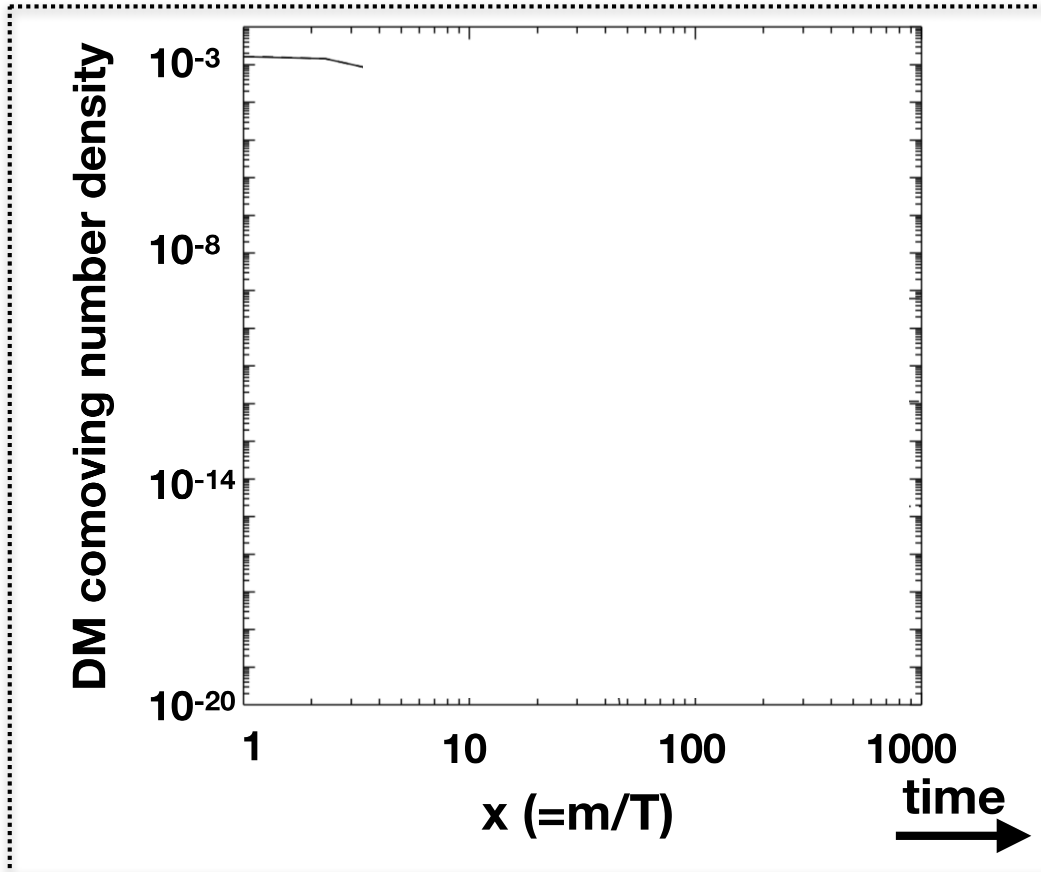
Thermal Dark Matter

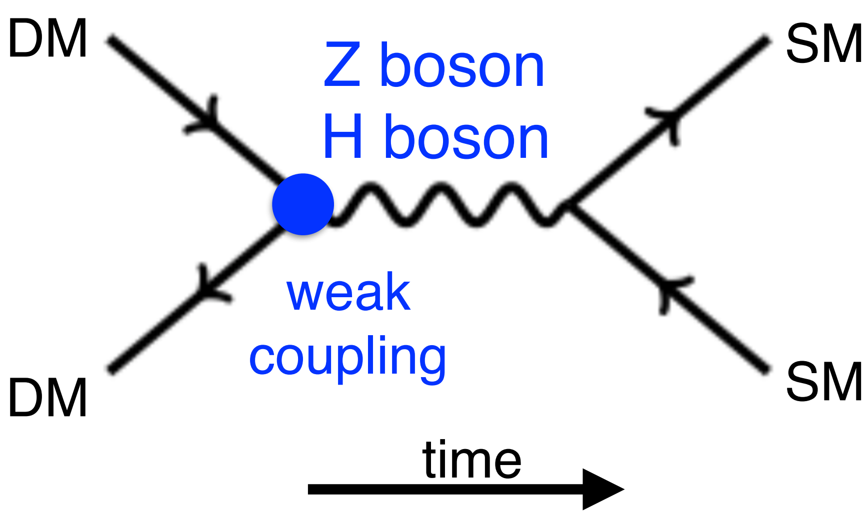


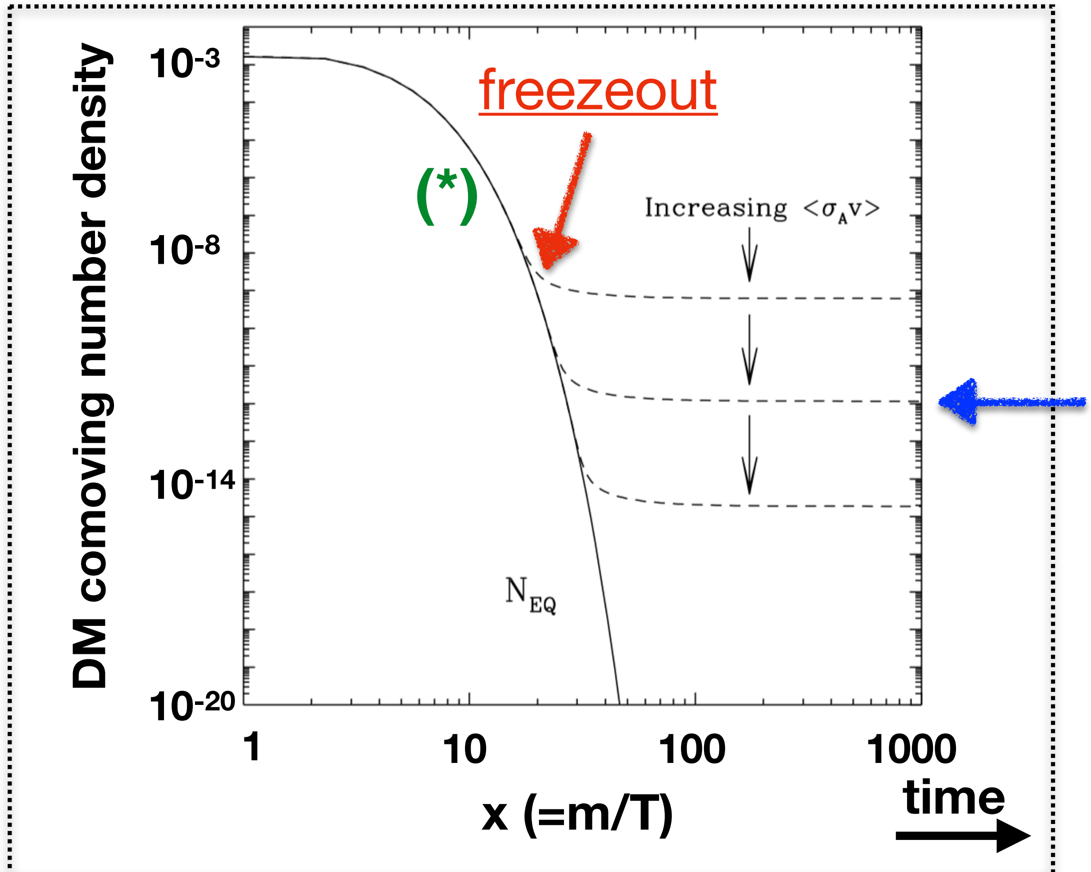


The "WIMP" paradigm

Weakly Interacting Massive Particles (WIMP) models:
One of the dominant models for more than 3 decades

DM annihilation to SM (*):

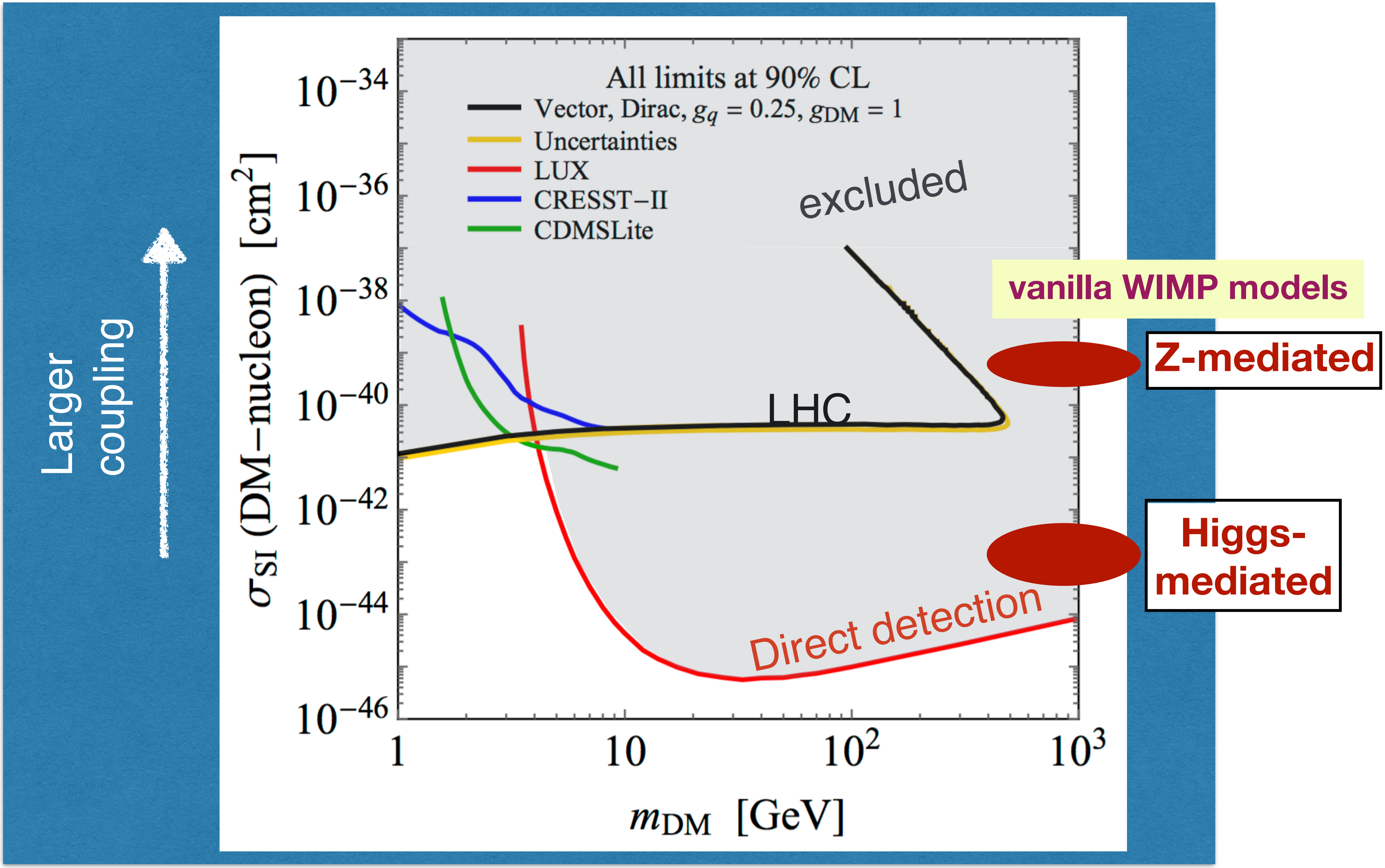




Thanks to these interactions, DM with a mass O(100 GeV) can "freeze out" and obtain the measured relic abundance

WIMP "miracle"? … or "coincidence"

We have learned a lot about WIMPs!



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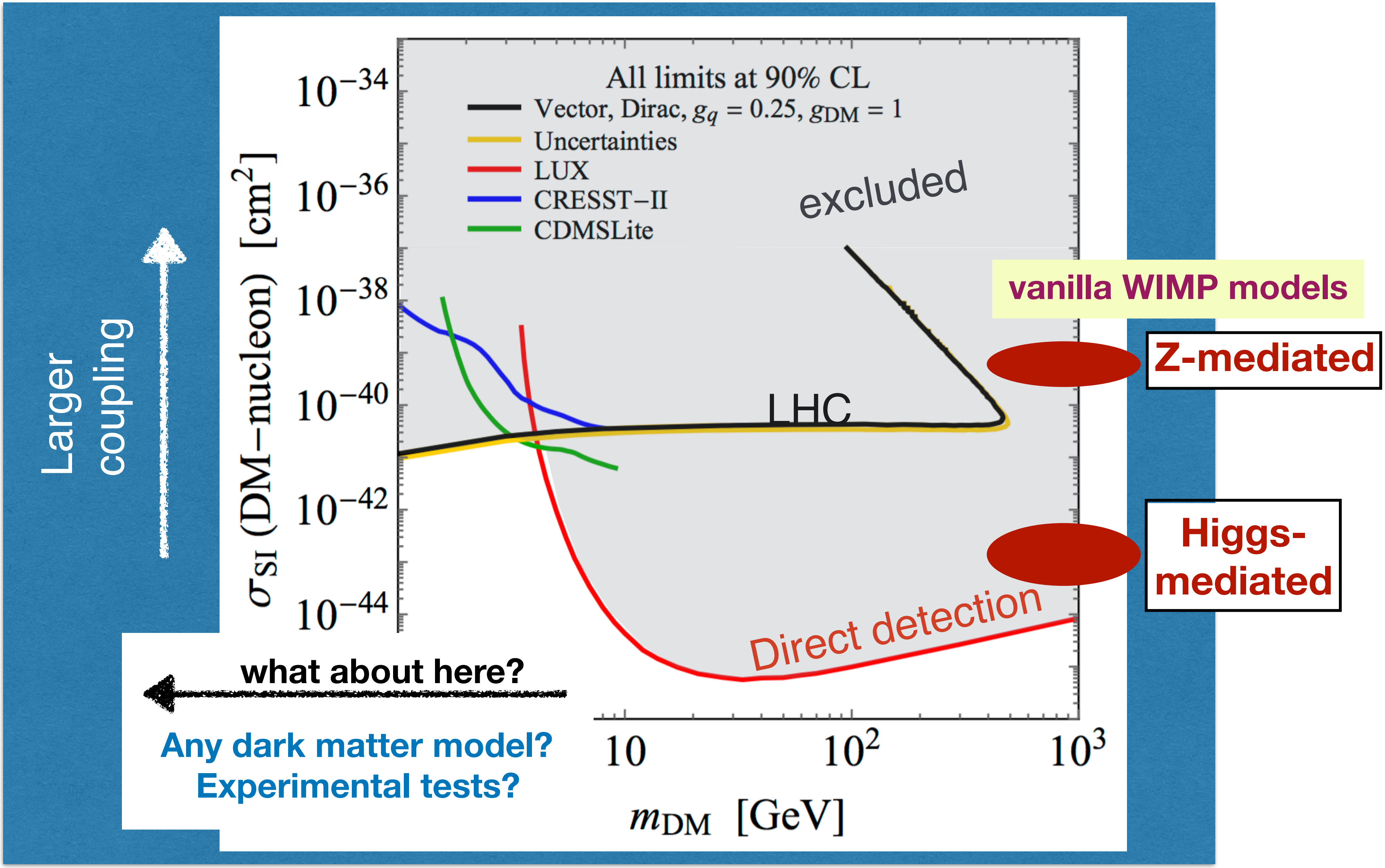
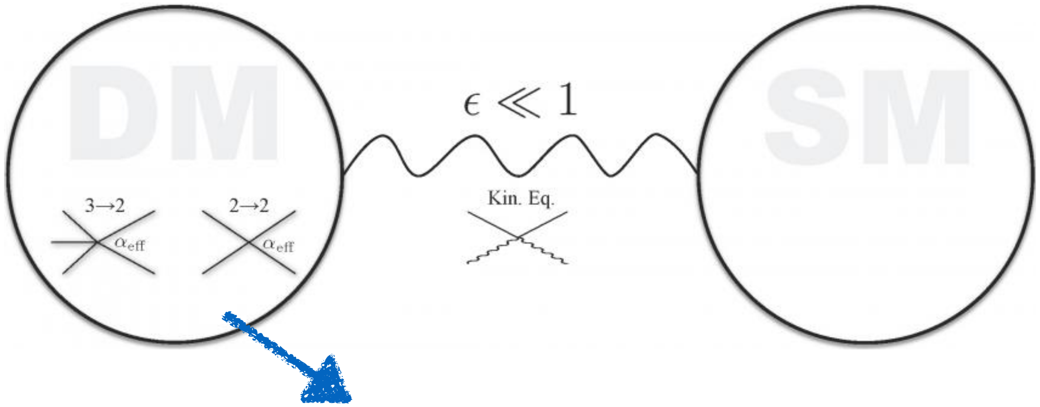


Strongly interacting massive particles (SIMP) in a nutshell



Hochberg, Kuflik, Volansky, Wacker, 1402.5143,

Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727

A new scale for DM?

(**WIMP**

$2 \rightarrow 2$

$m_{\rm DM} \sim \alpha_{\rm ann}(T_{\rm eq} M_{\rm pl})^{1/2} \sim \text{TeV}$)

SIMP

$3 \rightarrow 2$

$m_{\rm DM} \sim \alpha_{\rm ann}(T_{\rm eq}^2 M_{\rm pl})^{1/3} \sim 100 \text{ MeV}$

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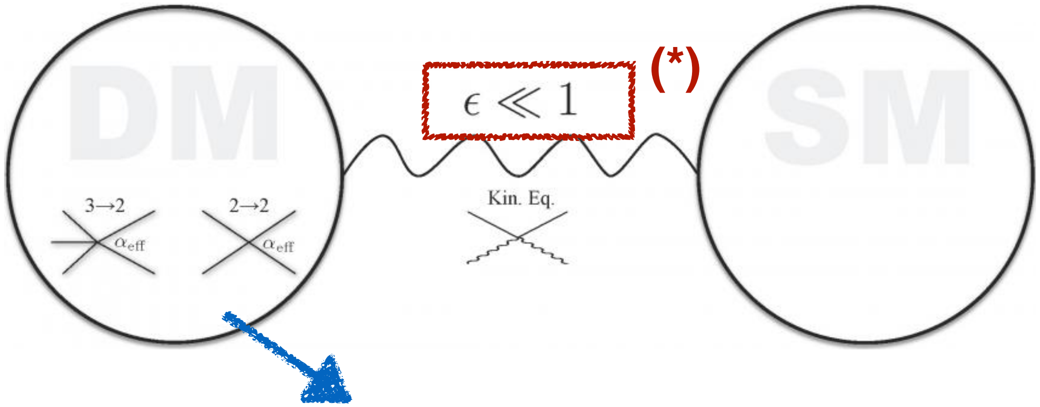


Hochberg, Kuflik, Volansky, Wacker, 1402.5143,

Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727

(*) Needed to maintain thermalization between the two sectors

A new scale for DM?

(**WIMP**

$$2 \rightarrow 2$$

$$m_{\rm DM} \sim \alpha_{\rm ann}(T_{\rm eq} M_{\rm pl})^{1/2} \sim {\rm TeV}$$)

SIMP

$$3 \rightarrow 2$$

$$m_{\rm DM} \sim \alpha_{\rm ann}(T_{\rm eq}^2 M_{\rm pl})^{1/3} \sim 100\ {\rm MeV}$$

Possibly realized in a QCD-like theory SU(N_c) with

$$SU(N_f) \times SU(N_f) \rightarrow SU(N_f)$$

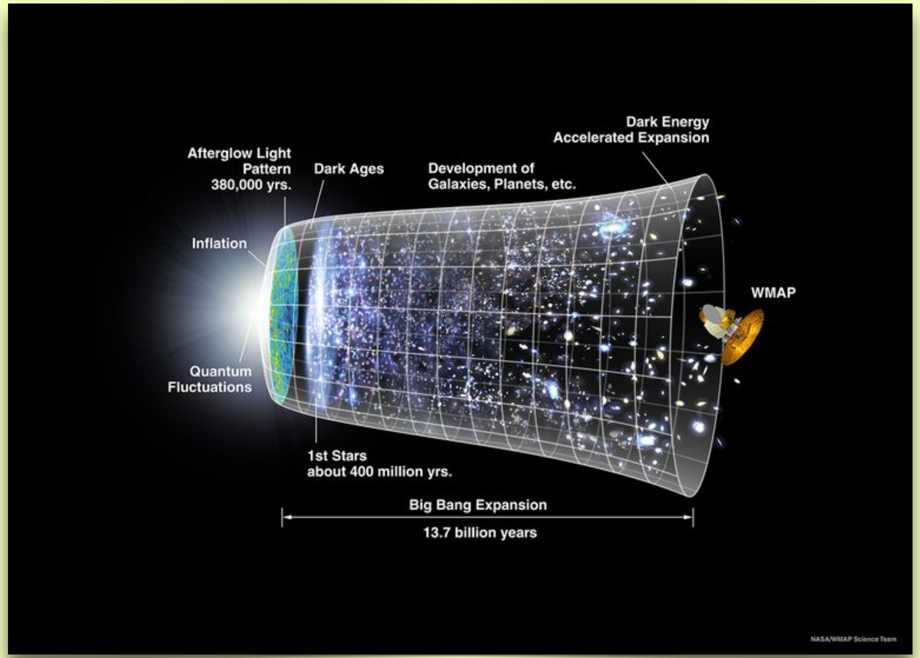
N_f^2-1 pions   Light pions

$$\mathcal{L}_{\rm WZW} = \frac{2N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} {\rm Tr}(\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi)$$

If the portal operator is not too small, the dark pions can be in thermal equilibrium with the SM → **Detection?**

Chapter I

SIMP cosmology



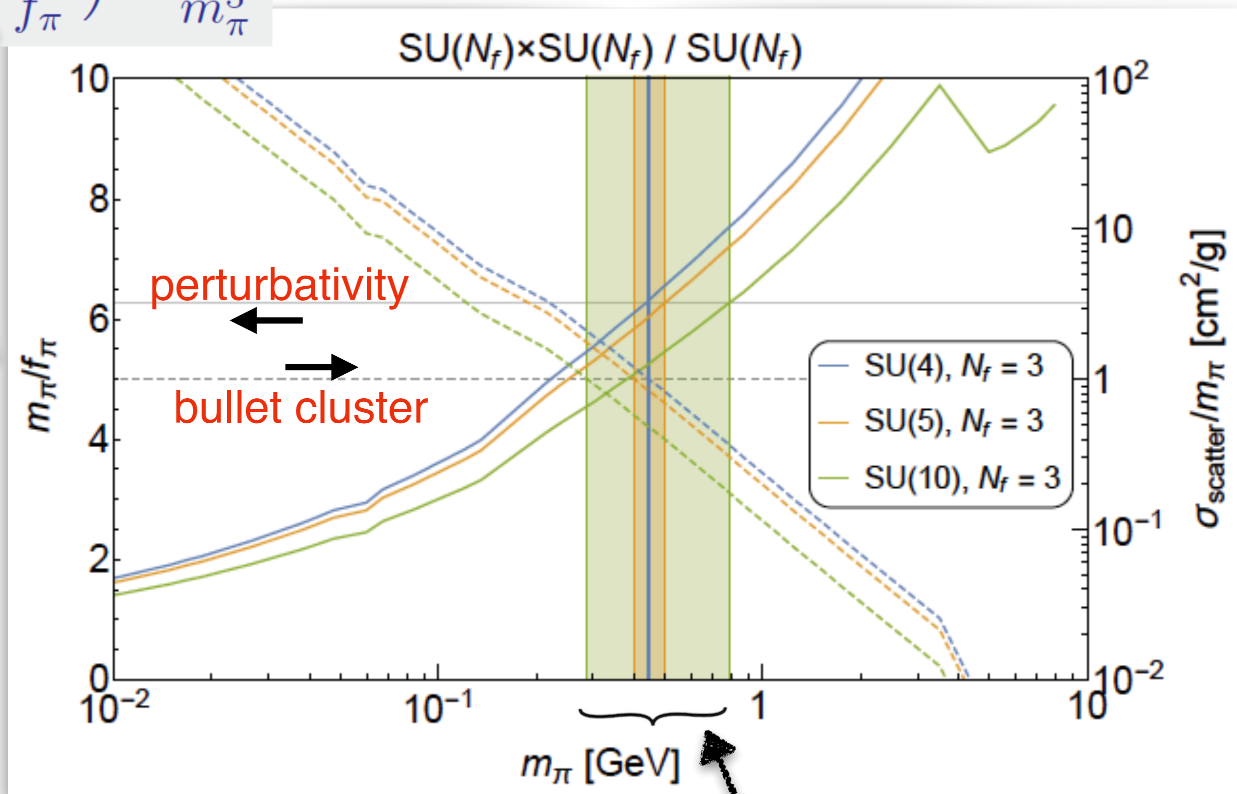
3→2 annihilation

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

Hochberg, Kuflik, Murayama, Volanski, Wacker, 1411.3727

perturbativity
⇩
upper bound on mπ

bullet cluster
⇩
lower bound on mπ



Relatively narrow range of allowed masses

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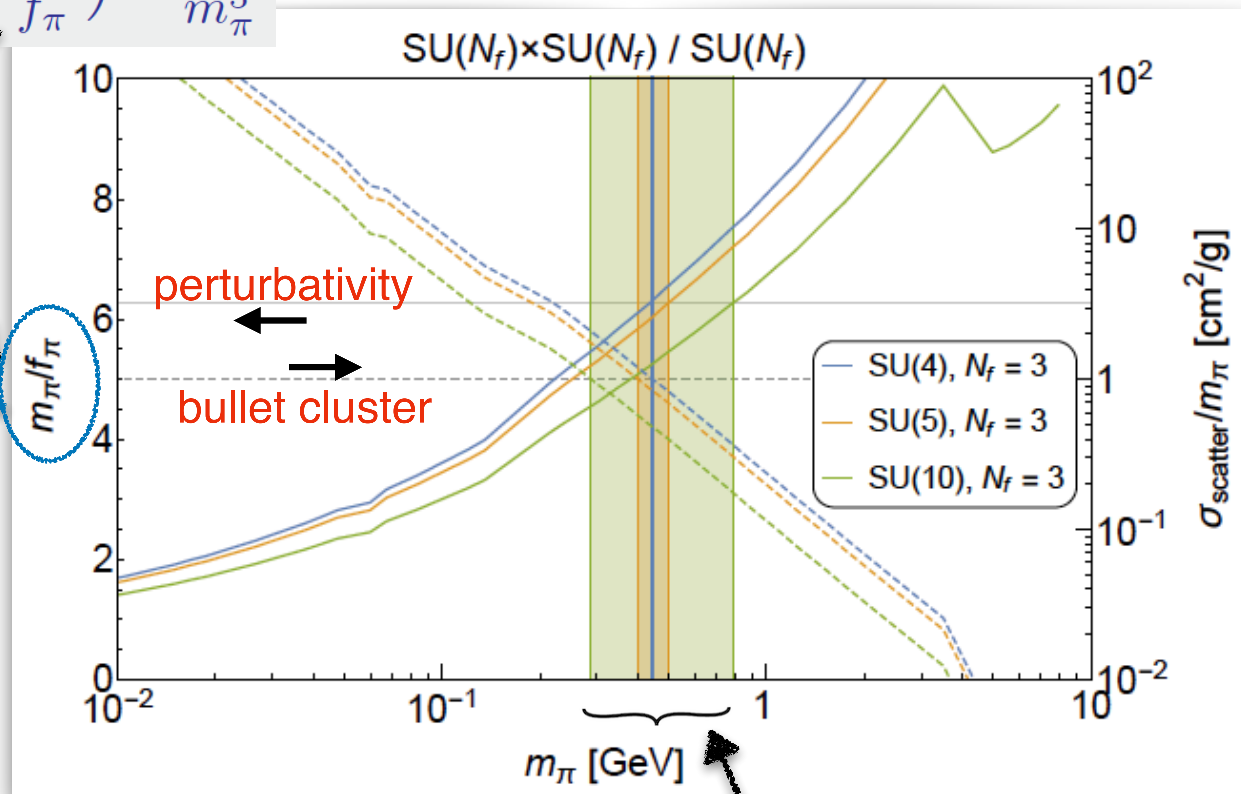


If $\frac{m_\pi}{f_\pi} \gg 1$,

vector mesons nearby in mass

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

Relatively narrow range of allowed masses

Spectrum and portal to the SM

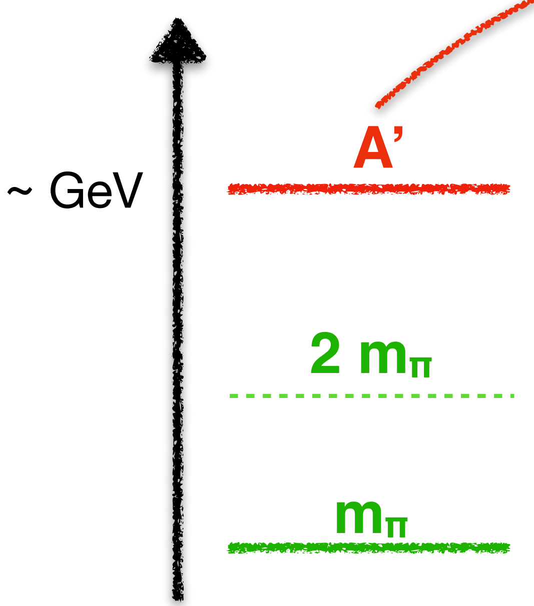
A concrete realization for SIMPs

Berlin, Blinov, SG, Schuster, Toro, 1801.05805

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

DM is kept in thermal equilibrium

SM



prevent

$$\pi\pi \to A'A'$$

(CMB)

N_f^2-1 = 8 dark pions:

$$\frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \overline{K^0} & -\sqrt{\frac{2}{3}}\,\eta \end{pmatrix}$$

$$SU(3)_L \times SU(3)_R \to SU(3)_D \supset U(1)_D$$

$$N_f = 3$$

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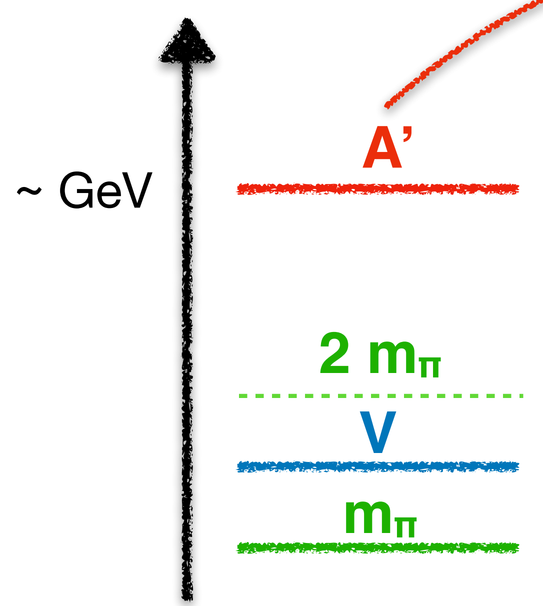

prevent

$\pi\pi \to A'A'$

(CMB)

$$\frac{m_\pi}{f_\pi} \gtrsim 3$$

$$SU(3)_L \times SU(3)_R \to SU(3)_D \supset U(1)_D$$

$$N_f = 3$$

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vector mesons, V:

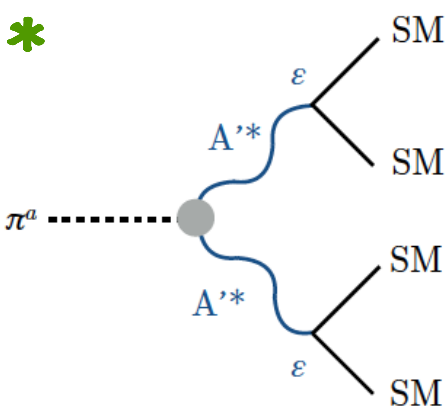
$$\frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+_\mu & K^{*+}_\mu \\ \rho^-_\mu & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0}_\mu \\ K^{*-}_\mu & \overline{K^{*0}_\mu} & \phi \end{pmatrix}$$

The stability of pions

Pions need to be long-lived on timescales compared to freeze-out.

However, the **neutral pions:**

*

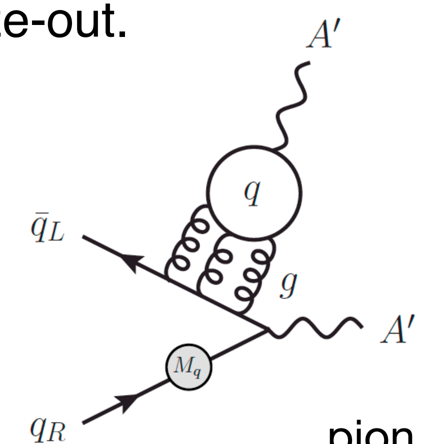


If $Q^2 \propto \mathbf{I}_{3\times 3}$

e.g. $Q = (+1, -1, -1)$

no contribution to the neutral pion decay from the chiral anomaly.

* additional contribution:



pion matrix

$$\frac{\alpha_D}{4\pi f_\pi} i\, \epsilon^{\mu\nu\alpha\beta} A'_{\mu\nu} A'_{\alpha\beta} \, \mathrm{Tr}\, Q \; \mathrm{Tr}\left(Q\, M_q\, U^\dagger\right) + \mathrm{h.c.}$$

$$\Rightarrow \quad \Gamma(\pi \to 4\ell) \sim \frac{\alpha_D^2\, \alpha_{em}^2\, \epsilon^4}{2048\, \pi^5} \frac{m_\pi^{11}}{f_\pi^2\, m_{A'}^8}$$

Lifetime can be comparable to the time of recombination.
OK if $m_{\pi 0} > m_{\pi +}$

U(1)$_D$ charged pions are stable ⇨ **they can be DM**

The dark pion relic abundance

Berlin, Blinov, SG, Schuster, Toro, 1801.05805

Several processes can contribute to the dark pion annihilation:

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

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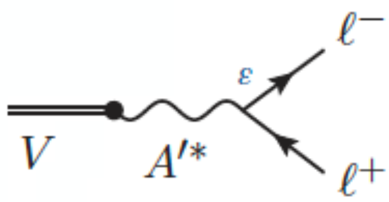
2. $\pi_D \pi_D \to V_D \pi_D$ semi-annihilation



$m_V < 2 m_\pi$

(If the dark vectors (V) have a mass close to the mass of the dark pions)

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

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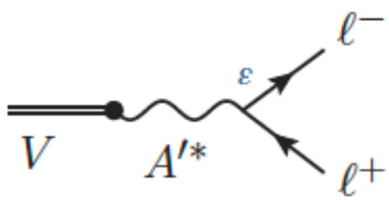

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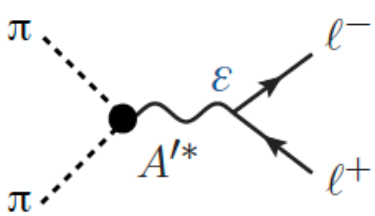

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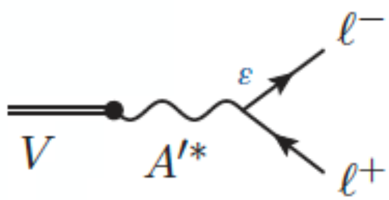

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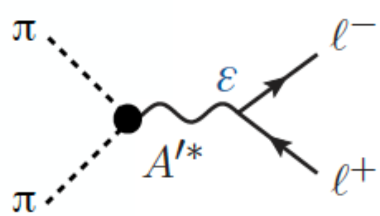

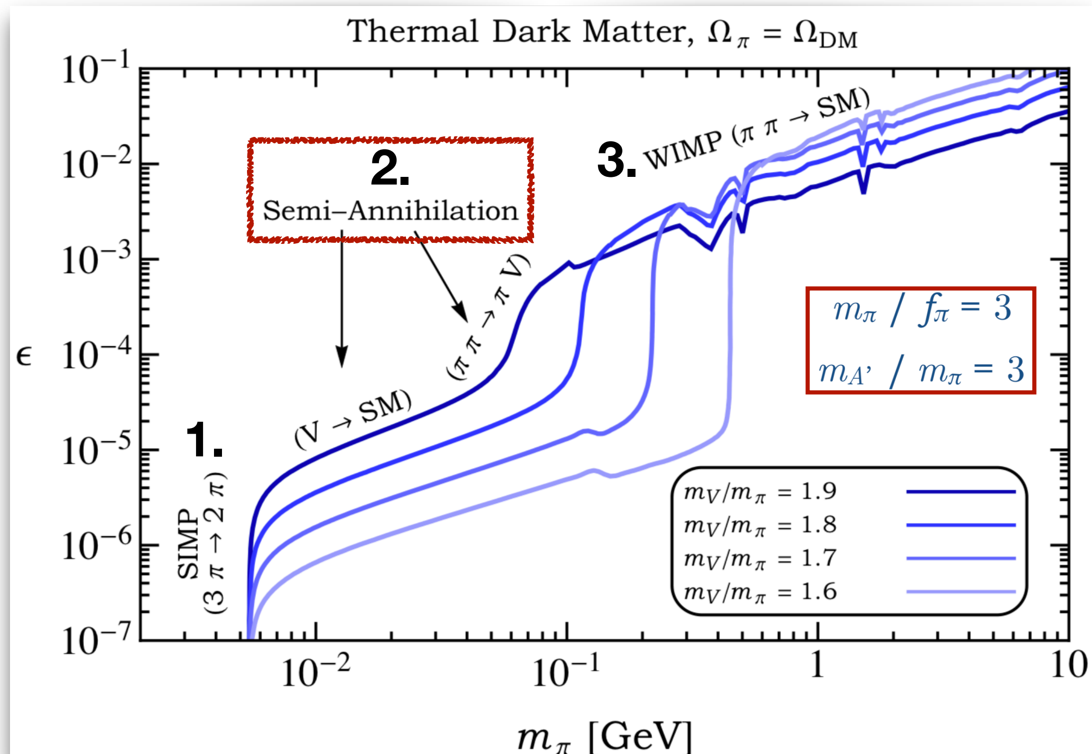

Broader range of values of m_π are possible

Chapter II

SIMP signatures at colliders

Fixed target experiments

Several detection strategies to discover dark sectors.

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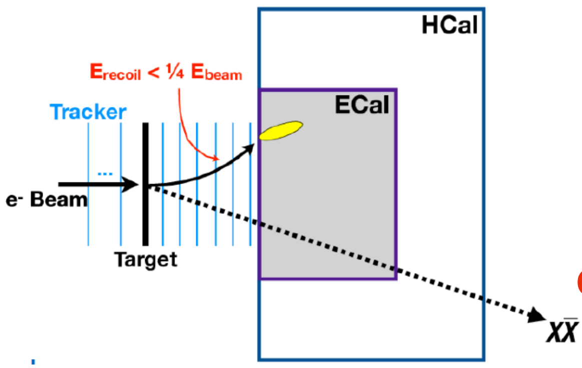
1. Invisible

Missing momentum or energy

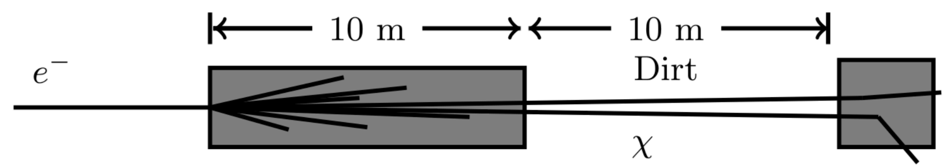
NA64, LDMX, M3



dark matter,
invisible

DM beam dump

BDX, DarkMESA



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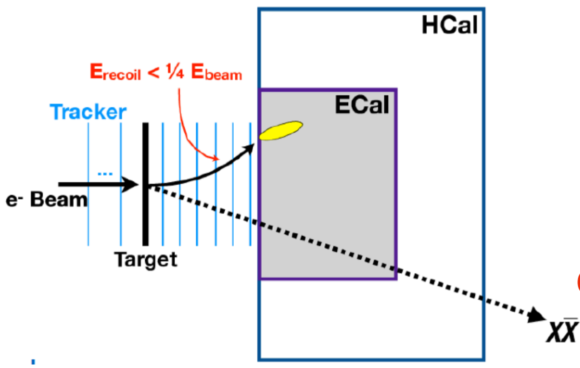
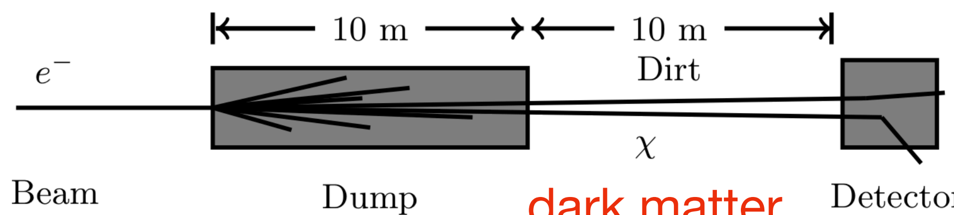


dark matter, invisible

DM beam dump

BDX, DarkMESA



dark matter, invisible

2. Visible

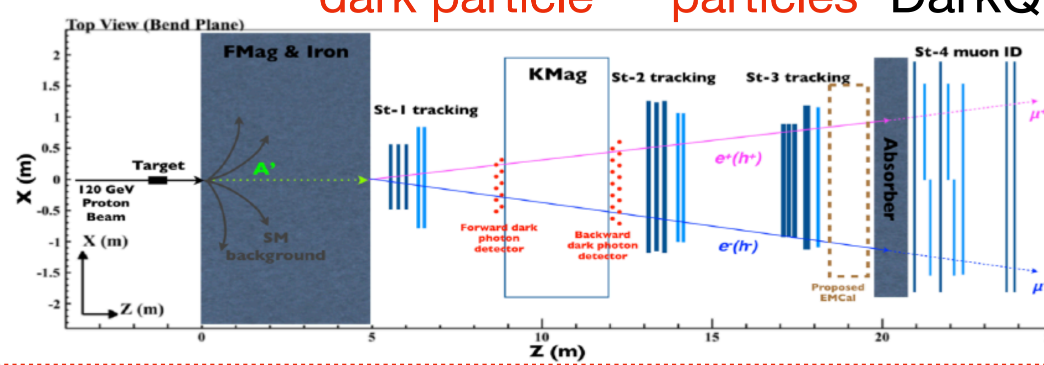
Visible beam dump

DarkQuest, HPS, Magix (E137)

unstable dark particle

SM particles

DarkQuest



SIMP production at fixed targets

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

→ Dark photons can be produced at colliders
(they mix with the SM photons)

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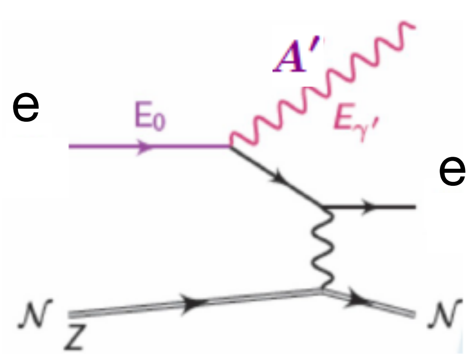
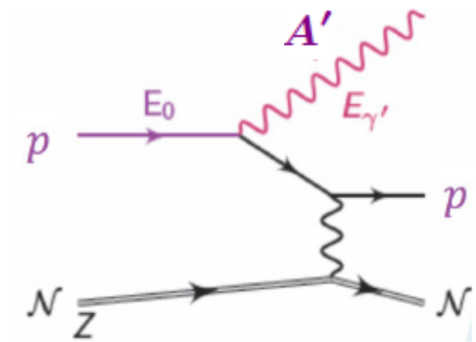
Electron fixed target

* 

brems-strahlung

Proton fixed target

* 

brems-strahlung

* meson decay. Eg.

$$\pi^0_{\rm SM} \to \gamma A', \quad \omega \to \pi^0_{\rm SM} A'$$

* Drell-Yan production: pp→A’

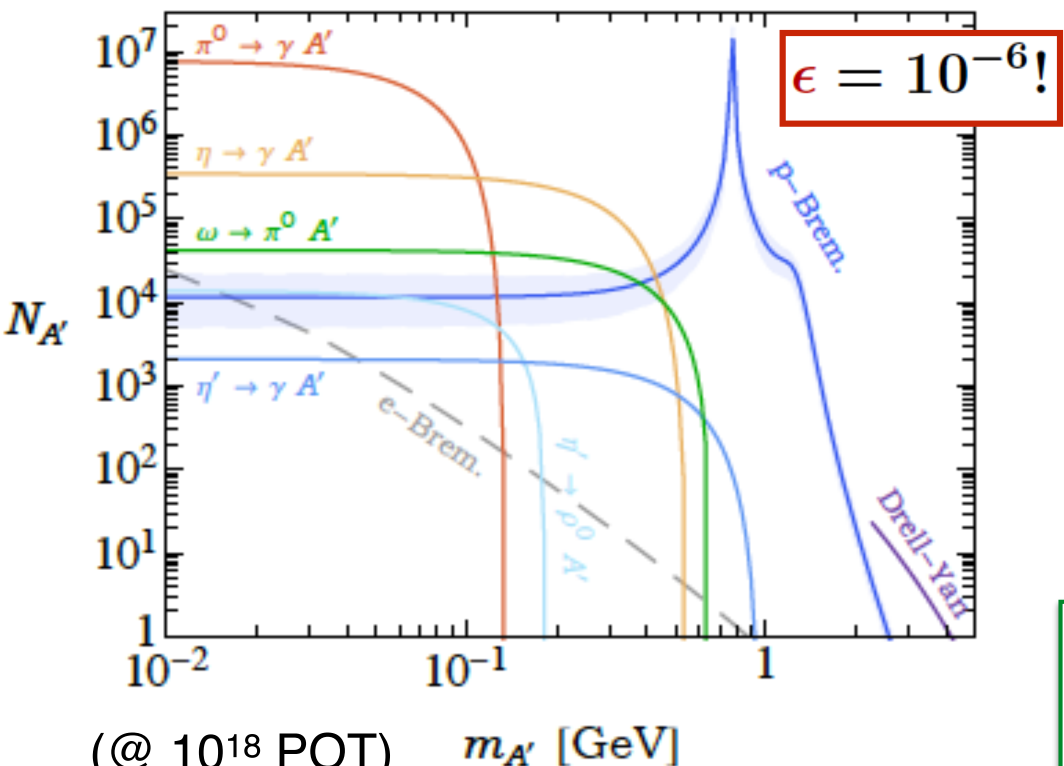
The dark photon will be produced either at the target or in the dump, depending on the experiment

+ Direct production of vector meson through bremsstrahlung (subdominant)

An example: production at 120 GeV proton fixed target

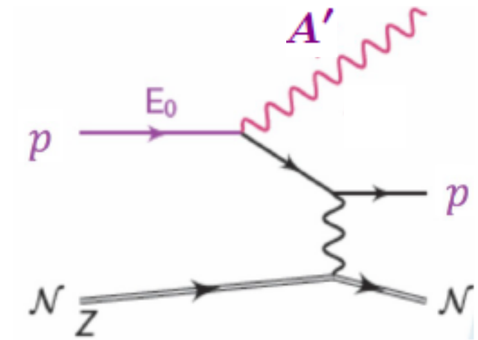
$$\frac{\epsilon}{2\cos\theta_W} A'_{\mu\nu} B^{\mu\nu}$$

Berlin, SG, Schuster, Toro, 1804.00661

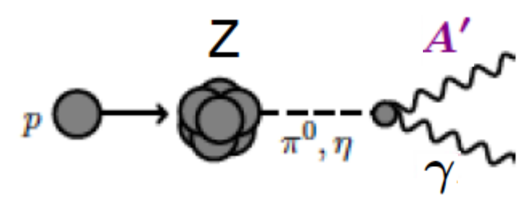


(@ 10^{18} POT)

Huge production!



brems-strahlung



meson decay

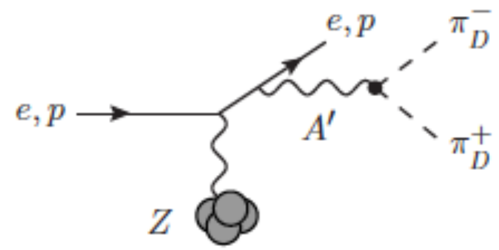
Generically larger rates than at electron fixed target experiments

$$N_{A'}(e\text{ Brem.}) \sim \left(\frac{\epsilon}{10^{-6}}\right)^2 \left(\frac{m_{A'}}{\text{GeV}}\right)^{-2} \left(\frac{\text{EOT}}{10^{18}}\right)$$

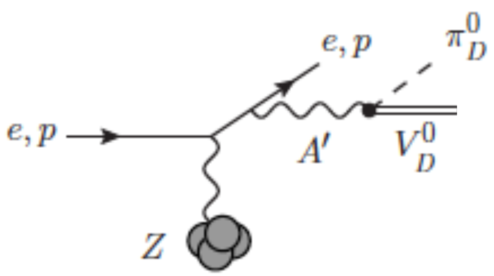
$$N_{A'}(p\text{ Brem.}) \sim 10^4 \times \left(\frac{\epsilon}{10^{-6}}\right)^2 \left(\frac{\text{POT}}{10^{18}}\right)$$

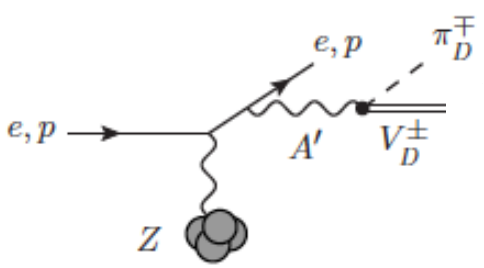
SIMP decays of the dark photon

$$A' \to \pi_D^+ \pi_D^- \quad \text{(DM)}$$



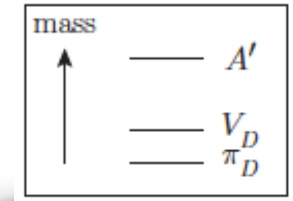
$$\Gamma \propto \alpha_D m_{A'}$$



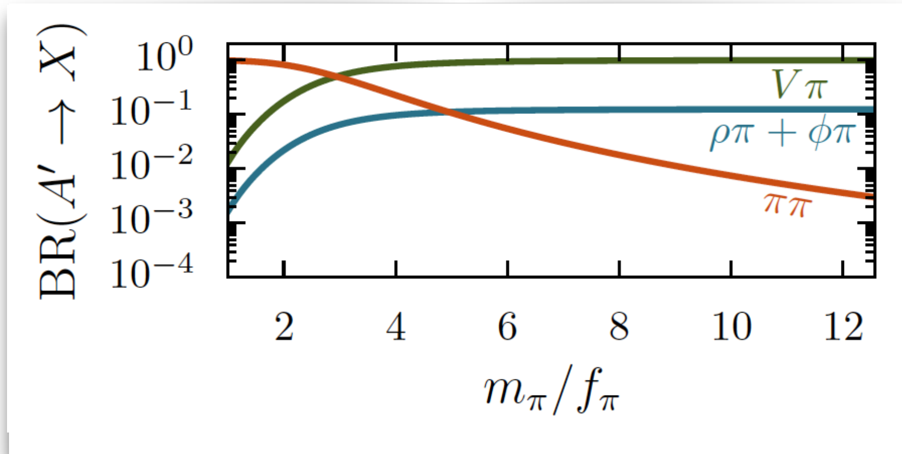


$$\Gamma \propto \alpha_D \frac{m_{A'}^3 m_V^2}{f_\pi^4}$$

$$A' \to \pi_D V_D$$



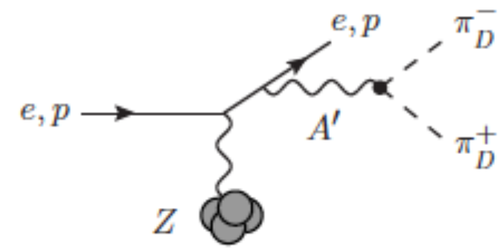
Berlin, Blinov, SG, Schuster, Toro, 1801.05805



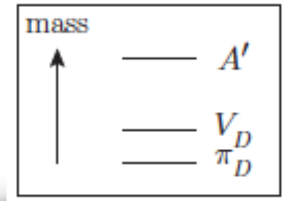
$\alpha_D = 10^{-2}, \quad \epsilon = 10^{-3}$

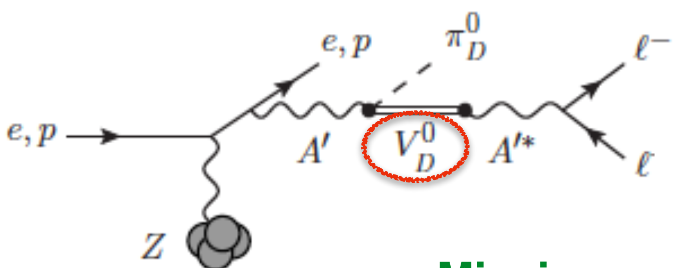
SIMP decays of the dark photon

$A' \rightarrow \pi_D^+ \pi_D^-$ (DM)



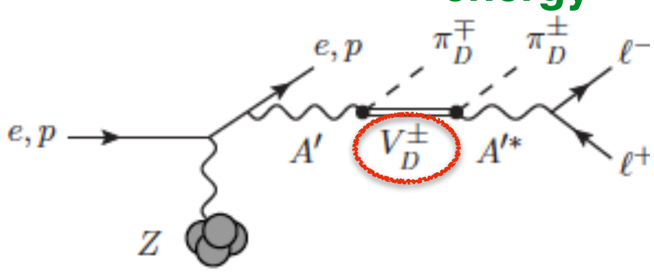
Invisible
A' decay





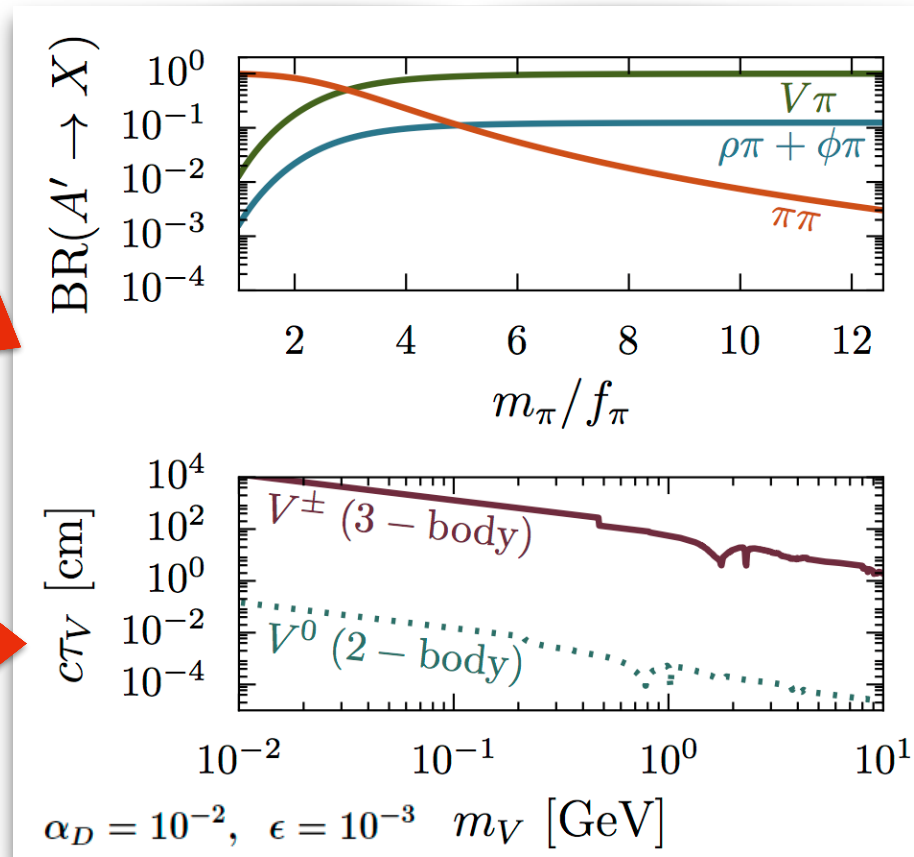
Missing energy

Visible
A' decay



$A' \rightarrow \pi_D V_D$

Berlin, Blinov, SG, Schuster, Toro, 1801.05805



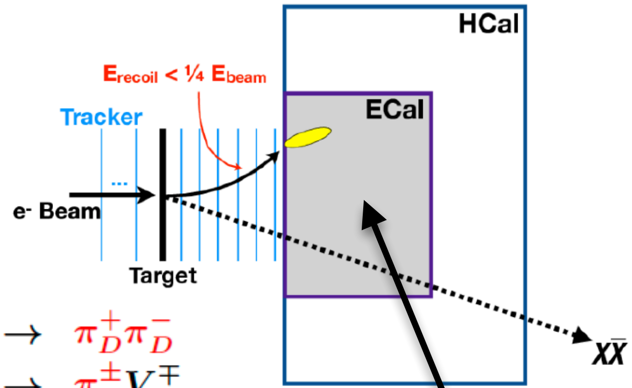
Displaced decays of the dark vector

Good for beam dumps!

DarkQuest and LDMX

Let us focus on two proposed experiments:

1. Invisible



$A' \to \pi_D^+ \pi_D^-$

$A' \to \pi_D^\pm V_D^\mp$

$V_D^\pm \to \pi_D^\pm \ell^+ \ell^-$

can also look for visible decays

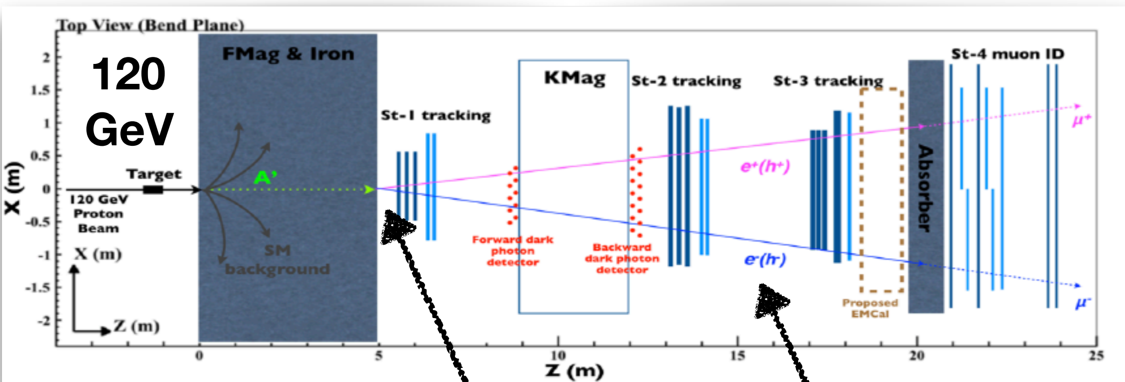
LDMX @ SLAC

4 x 10^{14} electrons on target, 4 GeV beam (phase 1)

10^{16} electrons on target, 8 GeV beam (phase 2)

2. Visible

DarkQuest @ Fermilab



decay of the dark vector

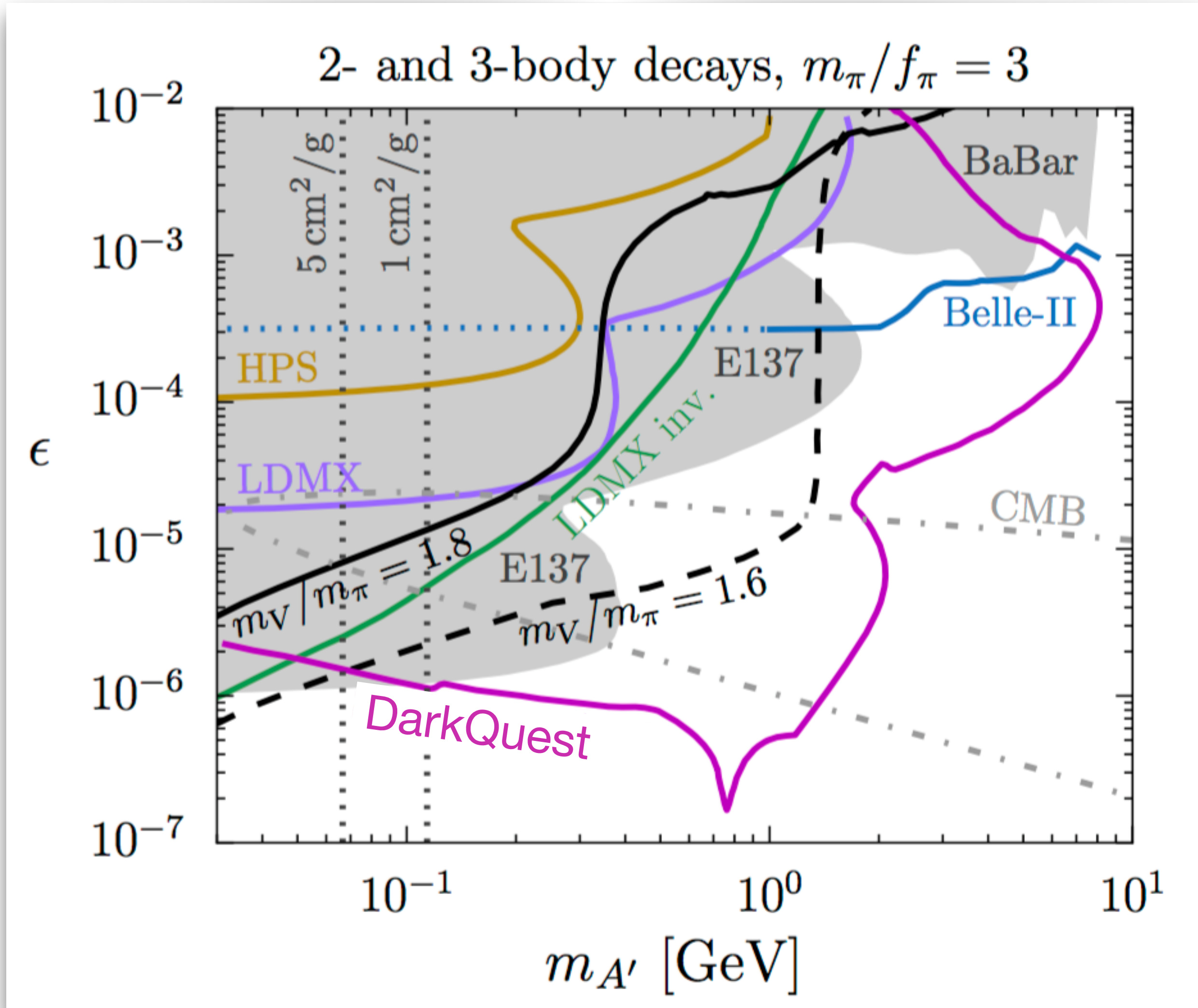
$V_D^\pm \to \pi_D^\pm \ell^+ \ell^-$

$V_D^0 \to \ell^+ \ell^-$

Experiment	Proton energy	POT	Dump	Decay volume
DarkQuest	120GeV	10^{18}	5 m	10 m
CHARM	400GeV	2.4×10^{18}	480 m	35 m
LSND	800MeV	10^{22}	30 m	10 m
NA62	400 GeV	10^{18}	100 m	250 m
SHiP	400 GeV	10^{20}	65 m	125 m

The reach for SIMPs (2+3 body decays)

Berlin, Blinov, SG, Schuster, Toro, 1801.05805



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

The reach for SIMPs (2+3 body decays)

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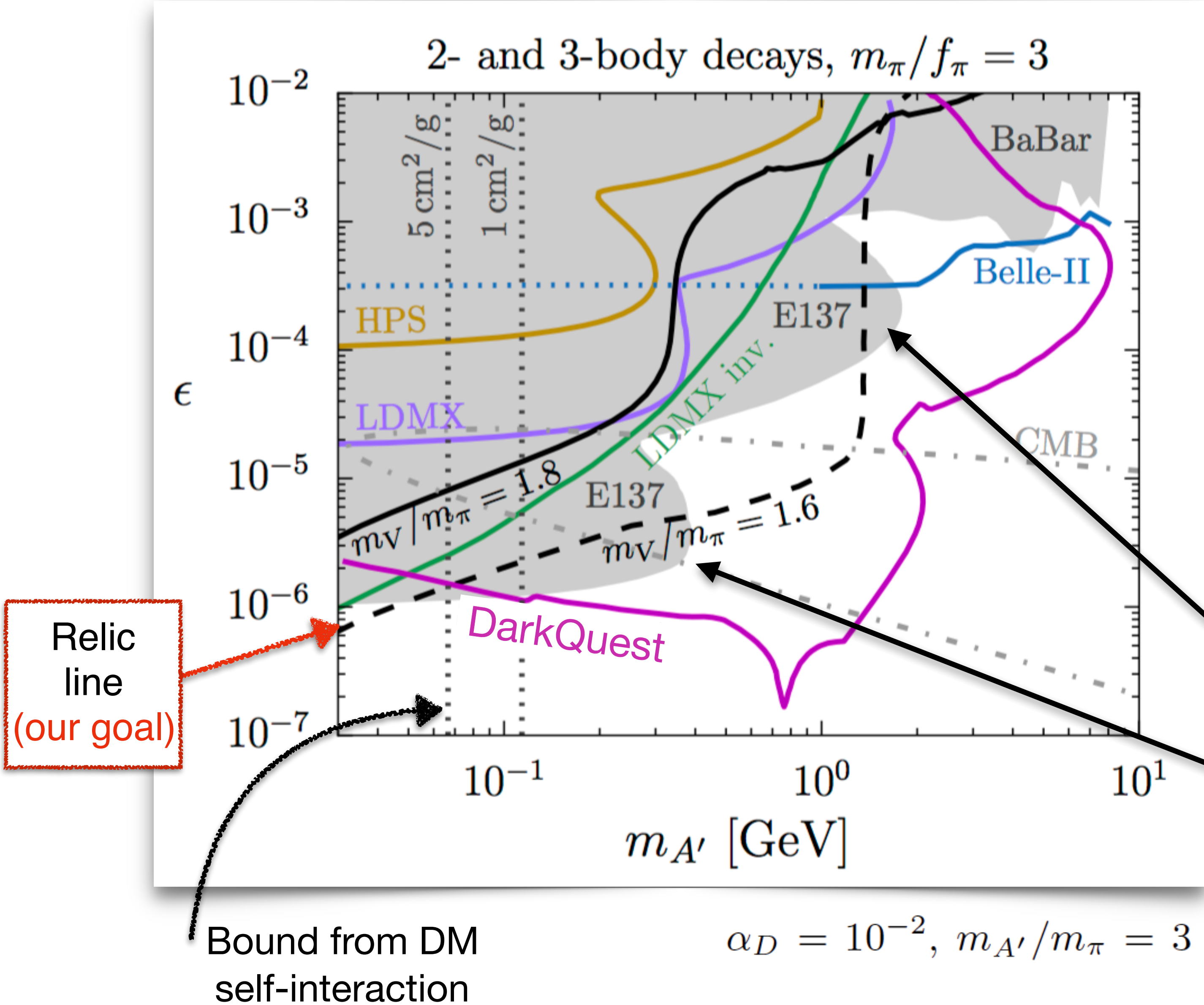

$\alpha_D = 10^{-2}$, $m_{A'}/m_\pi = 3$

Gray:

reach of past experiments:

- Babar:

$e^+e^- \to \gamma A', \quad A' \to \text{inv}$

- E137:

past electron beam dump experiment. Search for visibly decaying A'

$A' \to \pi_D V_D$

$V_D^0 \to \ell^+\ell^-$

$V_D^\pm \to \pi_D^\pm \ell^+\ell^-$

The reach for SIMPs (2+3 body decays)

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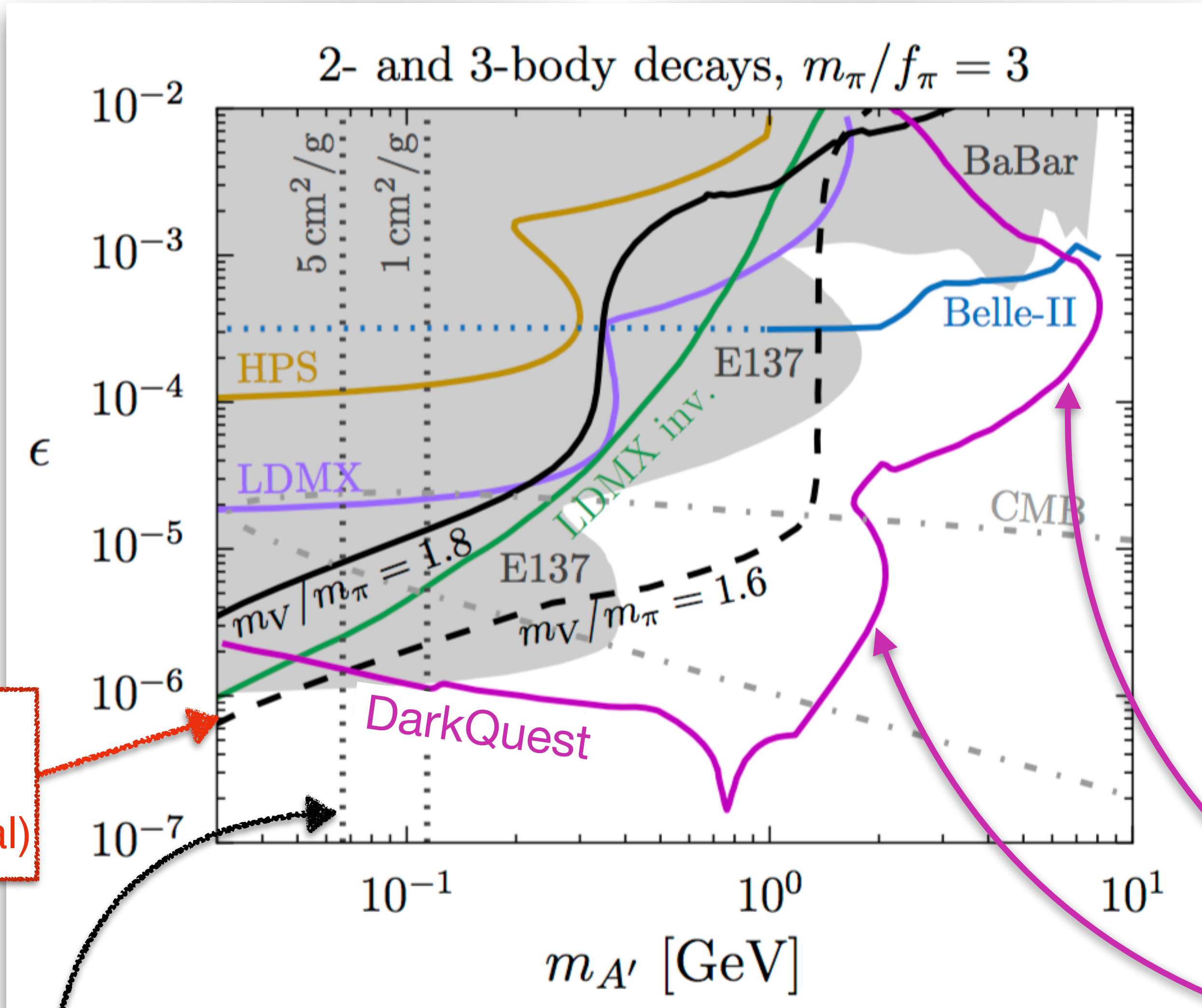


Relic line (our goal)

Bound from DM self-interaction

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

In color:

reach of past experiments:

- Belle II: (same Babar signature)

$e^+e^- \to \gamma A',\quad A' \to \mathrm{inv}$

- LDMX: invisible A'
- LDMX: visible A'
- HPS: electron beam dump experiment. Search for visibly decaying A' **(*)**
- DarkQuest

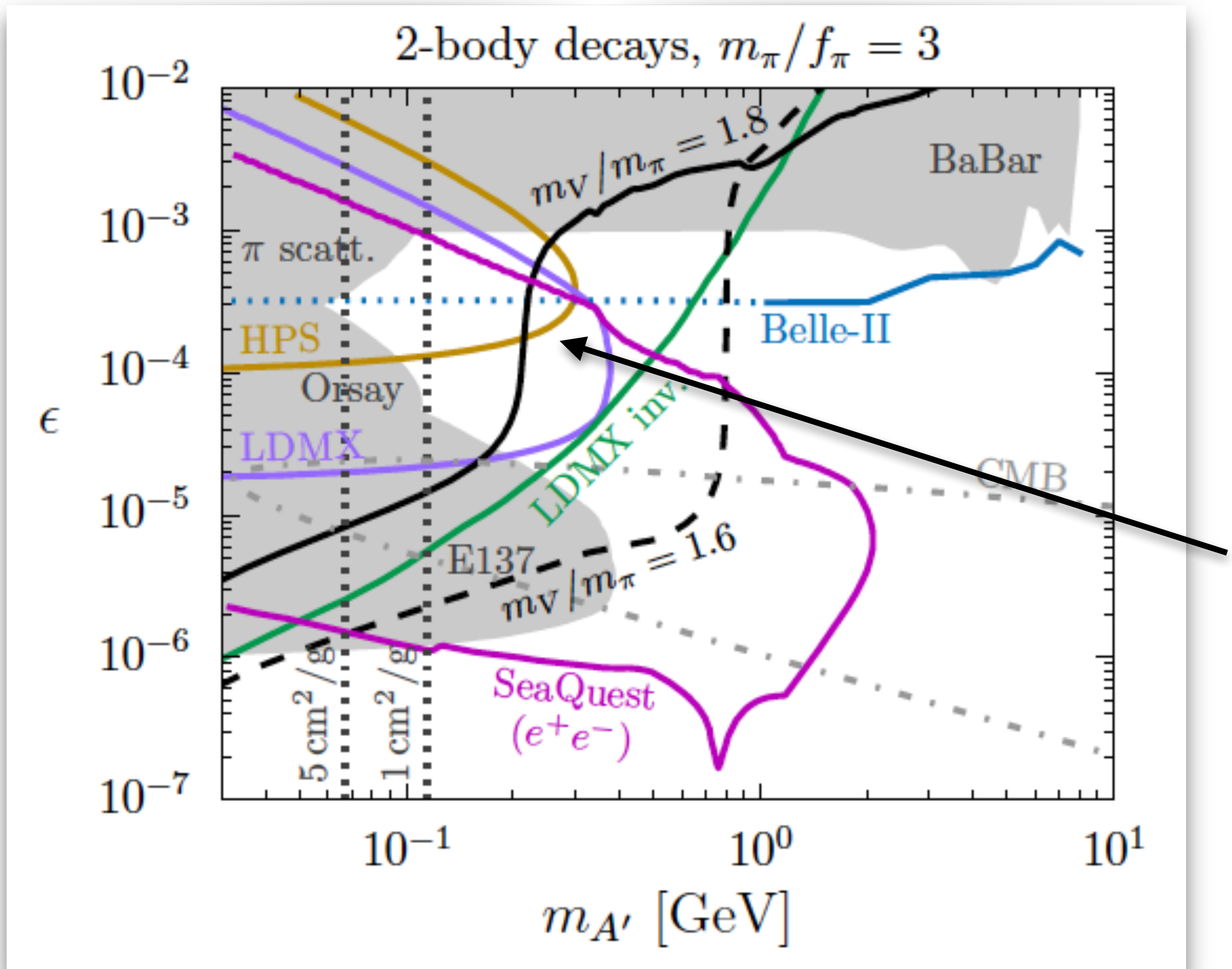
$A' \to \pi_D V_D$

$V_D^0 \to \ell^+\ell^-$

$V_D^\pm \to \pi_D^\pm \ell^+\ell^-$

(*) the collaboration is working on this:
https://indico.jlab.org/event/411/contributions/6724/attachments/5550/6888/SIMP_Analysis_at_HPS_11.20.20.pdf

The reach for SIMPs (2 body decays)



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

If the charged vectors are heavier than $2m_\pi$, then only the neutral vectors will appreciably decay visibly:

$$V_D^0 \rightarrow \ell^+\ell^-$$

E137 (past) bounds are relaxed since the experiment had a long baseline (~400 m).

➡ Larger regions of parameter space are open

Conclusions

Strongly interacting massive particles are an interesting thermal DM candidate:

- natural emergence of O(100MeV) scale (3→2 annihilation)
- (possible explanation of DM self-interaction observations)

* **Wide range of viable DM masses, once we consider all processes depleting DM in the early universe (3→2, semi-annihilation, annihilation)**

* **Reach collider phenomenology to be searched for at several fixed target experiments**

Dark sector decays

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

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

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

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

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

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

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

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

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

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

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

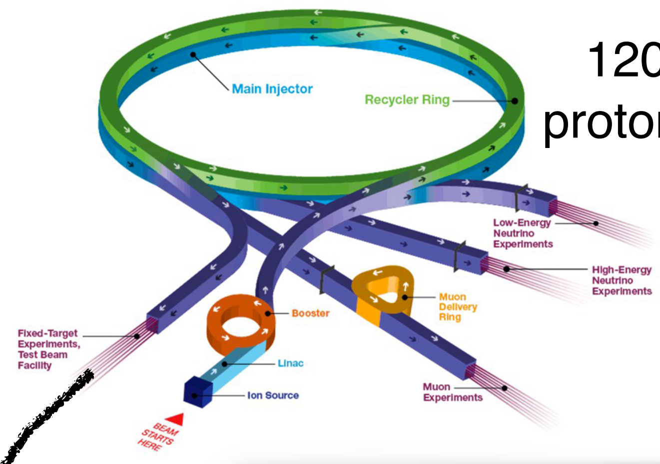
$$\Gamma(\phi \to \ell^+\ell^-) = \frac{16\pi\,\alpha_{\rm em}\,\alpha_D\,\epsilon^2}{3}\left(\frac{r_\pi}{m_\pi/f_\pi}\right)^2 (r_V^2-4r_\ell^2)^{1/2}\,(r_V^2+2r_\ell^2)\,(1-r_V^2)^{-2}\,m_{A'}$$

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

$$r_i \equiv m_i/m_{A'}$$

The SeaQuest experiment

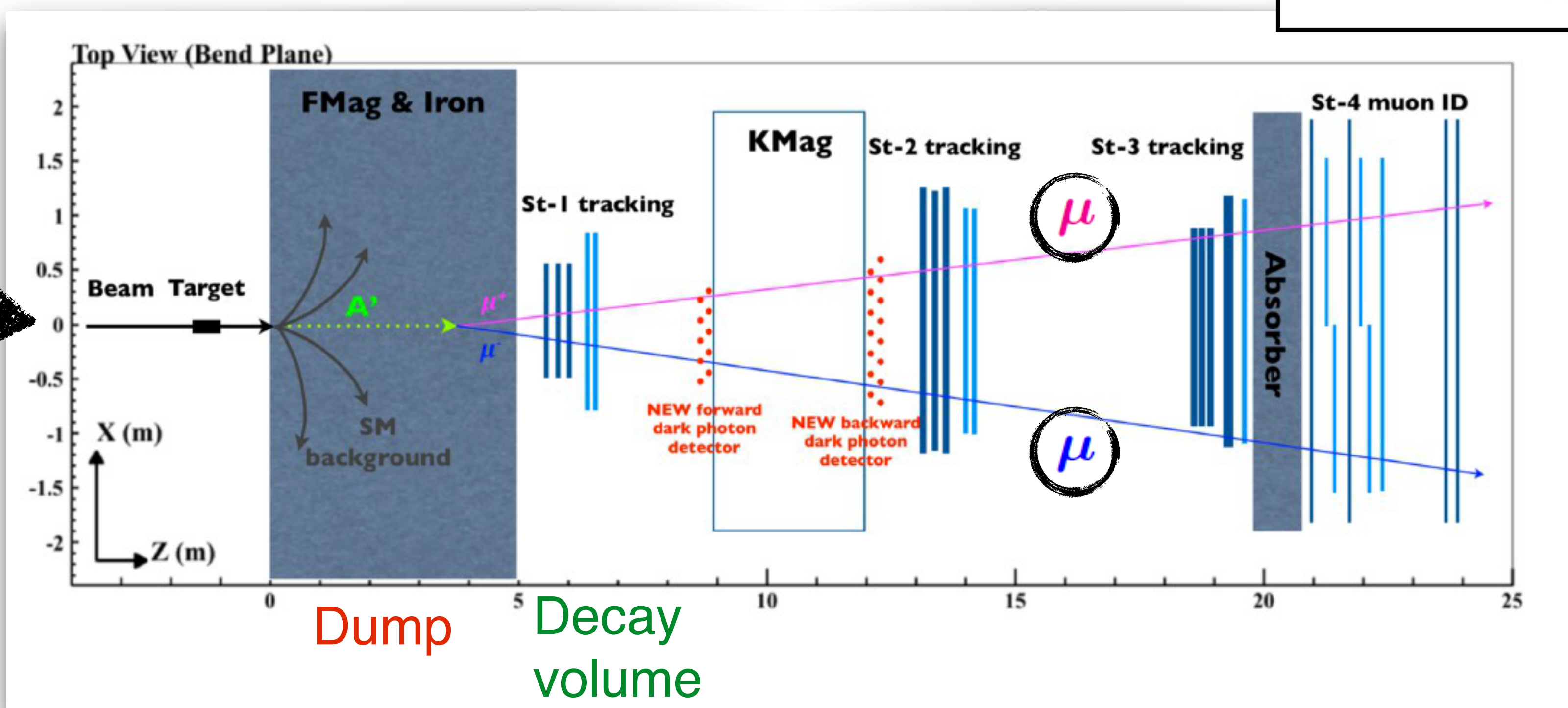
Fermilab Accelerator Complex



120 GeV proton beam

This is a **nuclear physics experiment**, with the goal of measuring the anti-quark content of the proton at large Bjorken-x

5% main injector beam

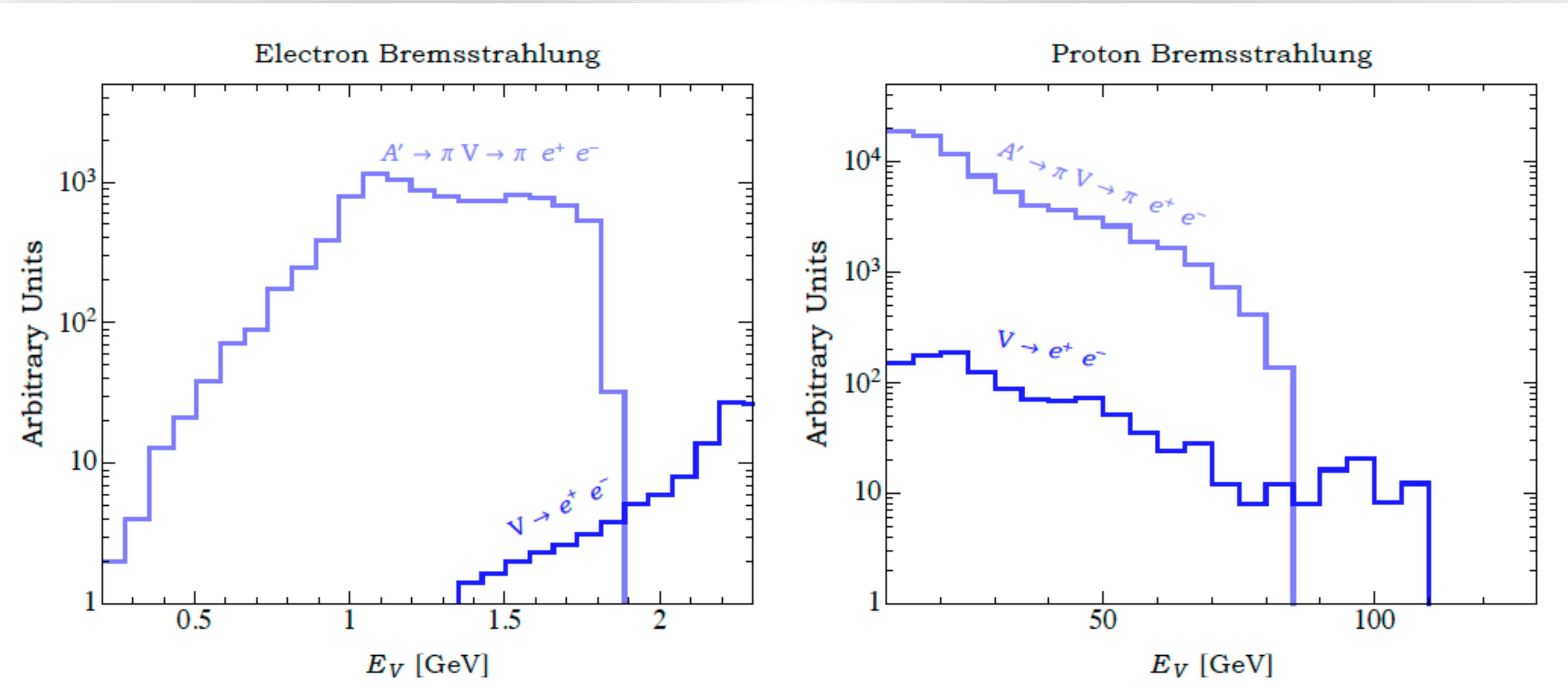


SeaQuest E906

S.Gori

Backup

Kinematics of the decays



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