Indirect Detection of Light dark matter

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based on arxiv: 1808.02579 , Jason Kumar
arxiv: 1903.10632, Dillon Berger, Jason Kumar, AR

Introduction

One of the standard ways of looking for dark matter is indirect detection.

For example, if the dark matter couples to b-quarks through an interaction

$$L = \bar{\chi} \chi \, \bar{b} b$$

then two dark matter particles could annihilate to two b-quarks. These decay products would then shower and hadronized, typically producing a large number of particles.

In particular, such decays often produce photons which can be seen e.g. in searches for gamma-rays.

Introduction

However, direct detection searches constrain a lot of parameter space, suggesting that dark matter may be light.

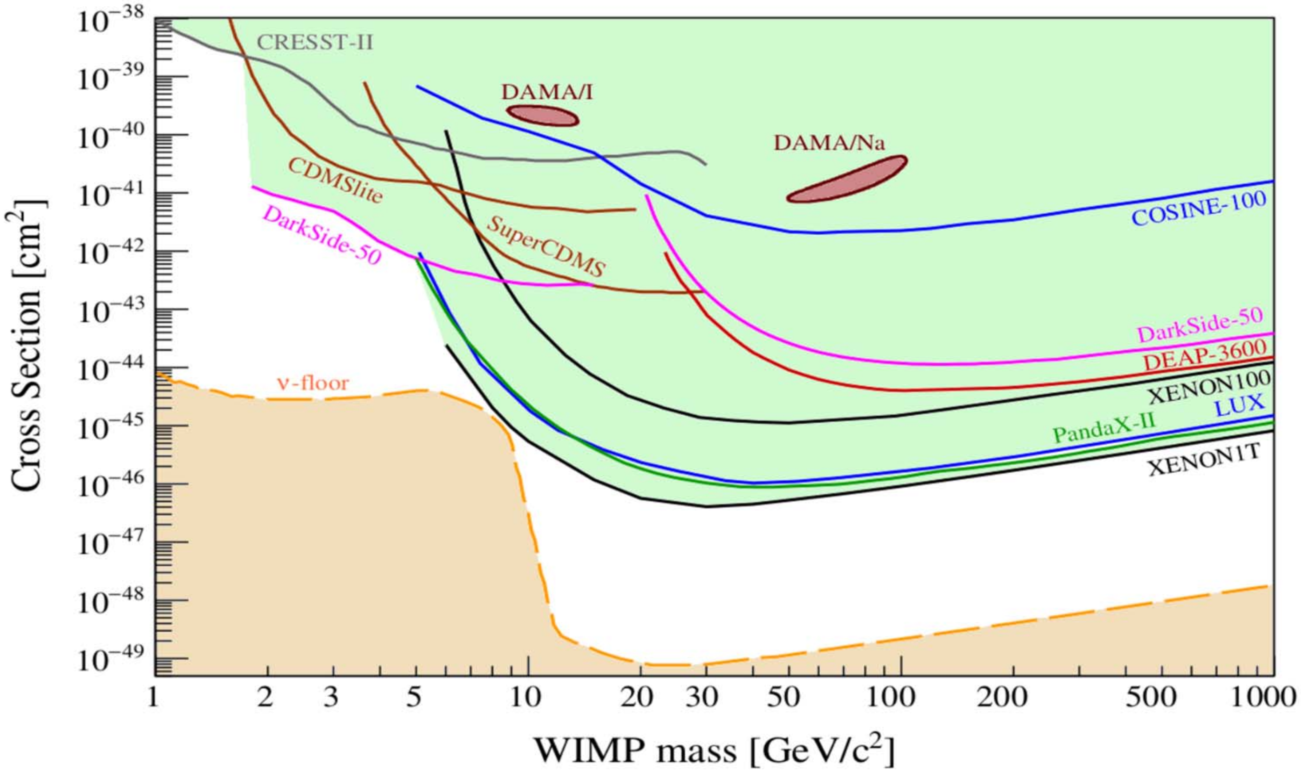


figure taken from Schumann, arxiv: 1903.03026

Introduction

But if dark matter is light, then indirect detection signals change.

Instead of annihilating to quarks, which subsequently produce a large number of hadronic particles and photons, there will be only a few particles in the final state.

For example, if the dark matter mass is about 280 MeV, then the only allowed hadronic decays are to two pions (either two neutral or two charged pions). The pions subsequently decay to leptons and/or photons.

Such a process is not captured in perturbative QCD.

We use the Chiral Lagrangian to calculate this decay.

The Chiral Lagrangian

The Chiral Lagrangian is a low energy effective theory for QCD.

The QCD Lagrangian with three light quark flavors (u, d,s)

$$L = q\,(i\ \gamma^{\mu} D_{\mu}\ - m)\, q\ -\ \frac{1}{2}\, G^{\mu\nu}\ G_{\mu\nu}$$

has a SU(3) x SU(3) symmetry.

This symmetry is spontaneously broken to SU(3)_V by the quark condensate

$$< q\ q> \ \neq 0$$

We therefore get 8 light bosons. These are the pions , kaons and eta. They acquire small masses because the quark masses are nonzero.

The Chiral Lagrangian

The low energy Lagrangian of the Goldstone modes is strongly constrained by this symmetry.

To exhibit this, we introduce a field

$$U \sim \langle qq \rangle$$

U therefore transforms under the SU(3) x SU(3) symmetry as

$$U \rightarrow L\, U\, R^{\dagger}$$

Once the quark condensate forms, we should expand around a nonzero value of U. This then yields the Goldstone modes

$$U = F \exp\left(\frac{i t^a \, \grave{\pi}_a}{F}\right)$$

The Lagrangian should then be written in terms of U, and expanded to find the Goldstone mode interactions.

The Chiral Lagrangian

Breaking of the symmetry is handled by introducing spurion fields. For example, a quark mass can be added by noting that the mass matrix couples to qq.

The Lagrangian for the pions is then of the form

$$L = \partial U \partial U^{\dagger} - B \,\mathrm{Tr}\, (MU^{\dagger} + U M^{\dagger}) + ..$$

where B is a constant that can be related to the quark condensate, and where the ellipses indicate higher order terms with more factors of U.

The Chiral Lagrangian

We now add a dark matter coupling to quarks. Specifically, we will use the vector coupling

$$L = \lambda \chi \gamma^{\mu} \chi \quad q \gamma_{\mu} q$$

This can be incorporated into the chiral Lagrangian by noting that if we gauge the U(1), we get a similar coupling

$$q \gamma_{\mu} q A_{\mu}$$

we can therefore identify

$$v_{\mu} \sim \lambda \quad \chi \gamma_{\mu} \chi$$

We find the couplings of the dark matter to pions by gauging the Chiral Lagrangian to find

$$L = \frac{F^2}{4} \mathrm{Tr} [(\partial_{\mu} U - i v_{\mu} U + i U v_{\mu}) (\partial^{\mu} U^{\dagger} + i U^{\dagger} v^{\mu} - i v^{\mu} U^{\dagger})]$$

The Chiral Lagrangian

This can be used to calculate the annihilation rate of light dark matter to two pions.

We find that the primary decay mode is to two charged pions (the neutral pion decay is in fact forbidden by symmetry).

Unfortunately, charged pions do not produce a significant number of pions; this therefore does not lead to a significant indirect detection signal.

We will therefore consider slightly higher masses, where the dark matter can annihilate to heavier mesons, in particular etas and kaons. This will require the dark matter to be somewhat heavier than the kaon mass (~500 MeV).

We then get the processes

$$\chi\,\chi \rightarrow K^+ K^- ,\, K^0 K^0$$

The Chiral Lagrangian

$$L = \frac{F^2}{4}\,\mathrm{Tr}\left[(\partial_\mu U - i v_\mu U + i U v_\mu)(\partial^\mu U^\dagger + i U^\dagger v^\mu - i v^\mu U^\dagger) \right]$$

with the definitions`

$$U = e^{i\sqrt{2}\Phi/F}$$

$$\Phi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta^8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta^8}{\sqrt{6}} & K^0 \\ K^- & \overline{K}^0 & -2\frac{\eta^8}{\sqrt{6}} \end{pmatrix} \qquad v^\mu = \begin{pmatrix} v_u^\mu & 0 & 0 \\ 0 & v_d^\mu & 0 \\ 0 & 0 & v_s^\mu \end{pmatrix}$$

Expanding this out, we find the couplings

$$L = i\left[(v_d^\mu - v_s^\mu)\,\overline{K}^0 \partial_\mu K^0 + (v_s^\mu - v_u^\mu)\,K^+ \partial_\mu K^- + (v_d^\mu - v_u^\mu)\,\pi^+ \partial_\mu \pi^- - \text{h.c.} \right]$$

The Chiral Lagrangian: Vector mesons

Unfortunately, at this mass scale, further decay channels are accessible.

In particular, we can have on-shell decays to vector mesons accompanied by
a scalar meson

$$\chi\,\chi \rightarrow \rho\,\pi,\ \omega\,\pi$$

We must understand these decays as well.

Fortunately, the extension of the chiral Lagrangian to vector mesons has been done,
and we can use that. These are not Goldstone bosons, so there is more freedom in the Lagrangian.

The Chiral Lagrangian: Vector mesons

The vector couplings are written using a formalism where the fields are in an antisymmetric tensor $\Phi_{\mu\nu}$

$$L = \frac{1}{4}(D^{\mu}\Phi_{\mu\alpha})(D_{\nu}\Phi^{\nu\alpha}) + \frac{1}{8} m_V^2 (\Phi^{\mu\nu}\Phi_{\mu\nu}) + \frac{1}{2} f_V \, Tr[\Phi^{\mu\nu} f_{\mu\nu}] + \frac{i}{2} f_V h_P \, Tr(U_{\mu}\Phi^{\mu\nu}U_{\nu})$$
$$+ \frac{i}{8} h_A \, \varepsilon^{\mu\nu\alpha\beta}\{\Phi_{\mu\nu}, D^{\tau}\Phi_{\tau\alpha}\} U_{\beta} + \frac{i}{8} h_O \, \varepsilon^{\mu\nu\alpha\beta}\{D_{\alpha}\Phi_{\mu\nu}, \Phi_{\tau\beta}\} U^{\tau}$$

$$\Phi_{\mu\nu} = \sqrt{2}\begin{pmatrix} \frac{\rho_{\mu\nu} + \omega_{\mu\nu}}{\sqrt{2}} & \rho^{+}_{\mu\nu} & K^{*+}_{\mu\nu} \\ \rho^{-}_{\mu\nu} & \frac{-\rho_{\mu\nu} + \omega_{\mu\nu}}{\sqrt{2}} & K^{*0}_{\mu\nu} \\ K^{*-}_{\mu\nu} & K^{*0}_{\mu\nu} & \phi_{\mu\nu} \end{pmatrix}$$

arxiv:1204.4125
Terschlusen, Leupold, Lutz

$$f^{+}_{\mu\nu} = e^{i\Phi/\sqrt{2}F}(\partial_{\mu} v_{\nu} - \partial_{\nu} v_{\mu}) e^{-i\Phi/\sqrt{2}F} + e^{-i\Phi/\sqrt{2}F}(\partial_{\mu} v_{\nu} - \partial_{\nu} v_{\mu}) e^{i\Phi/\sqrt{2}F}$$

$$U_{\mu} = \frac{1}{2} e^{-i\Phi/\sqrt{2}F} (\partial_{\mu} e^{i\Phi/\sqrt{2}F}) e^{-i\Phi/\sqrt{2}F} - \frac{i}{2} e^{-i\Phi/\sqrt{2}F} v_{\mu} e^{i\Phi/\sqrt{2}F} + \frac{i}{2} e^{i\Phi/\sqrt{2}F} v_{\mu} e^{-i\Phi/\sqrt{2}F}$$

The Chiral Lagrangian: Vector mesons

The coefficients can be determined by experiment and are

$f_V = (140 \pm 14)$ MeV $\qquad m_V \sim 0.764$ GeV $\qquad h_A = 2.33 \pm 0.03 \qquad h_P \sim 1.75$

Expanding, we find

$$L = -\frac{f_V}{2}\left[(\partial^\mu v_d^\nu - \partial^\nu v_d^\mu)(\rho_{\mu\nu} - \omega_{\mu\nu}) - (\partial^\mu v_u^\nu - \partial^\nu v_u^\mu)(\rho_{\mu\nu} + \omega_{\mu\nu}) - \sqrt{2}\,(\partial^\mu v_s^\nu - \partial^\nu v_s^\mu)\,\phi_{\mu\nu}\right]$$

The Chiral Lagrangian: Trilinear couplings

We must also include processes like

$$\chi\chi \to \omega \to \rho\pi$$

which can have a resonant enhancement.

For these we require trilinear couplings of vector mesons and scalar mesons; these can also be found from the above lagrangian, and are

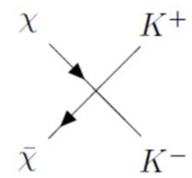
$$L = -\frac{\sqrt{2}\,h_A}{F}\,\varepsilon^{\mu\nu\alpha\beta}\left[\frac{1}{2}\;\partial_\beta\pi\,(\rho_{\mu\nu}\,\partial^\tau\,\omega_{\tau\alpha} + \omega_{\mu\nu}\,\partial^\tau\,\rho_{\tau\alpha}) + \partial_\beta\,\pi^-\,(\rho^+{}_{\mu\nu}\,\partial^\tau\,\omega_{\tau\alpha} + \omega_{\mu\nu}\,\partial^\tau\,\rho^+{}_{\tau\alpha}) + cc\right]$$

$$-\frac{h_O}{\sqrt{2}\,F}\,\varepsilon^{\mu\nu\alpha\beta}\left[(\partial_\alpha\,\rho_{\mu\nu})\,(\partial^\tau\pi)\,\omega_{\tau\beta} + \rho_{\tau\beta}\,(\partial^\tau\pi)\,(\partial_\alpha\,\omega_{\mu\nu}) + (\partial^\tau\,\pi^-)(\omega_{\tau\beta}\,\partial_\alpha\rho^+{}_{\mu\nu} + \rho^+{}_{\tau\beta}\,\partial_\alpha\omega_{\mu\nu}) + cc\right]$$

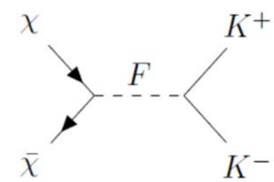
$$+\frac{i8f_V h_P}{F^2}\left[2\,(\partial^\mu\pi^+)(\partial^\nu\pi^-)\,\rho_{\mu\nu} + (\partial^\mu K^0)(\partial^\nu K^0)\,(\rho_{\mu\nu} - \omega_{\mu\nu} - \sqrt{2}\,\phi_{\mu\nu}) - (\partial^\mu K^-)(\partial^\nu K^+)\,(\rho_{\mu\nu} + \omega_{\mu\nu} - \sqrt{2}\,\phi_{\mu\nu})\right]$$

The Chiral Lagrangian: Summary

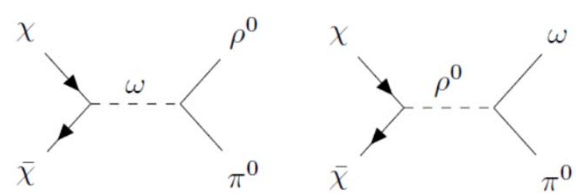
Scalar meson contact production



Scalar meson production through a vector
(F= ρ, ω, π)



Vector + scalar meson production



Meson Decays

The dark matter therefore annihilates to the primary mesons K^+ , K^- , K^0, ρ, ω, π.
These subsequently decay to lighter mesons or to photons. In particular, the neutral pion decays to two photons essentially every time.

The important decay modes to consider are thus

K^+	$\pi^0 e^+ \nu$	5%
	$\pi^0 \mu^+ \nu$	3.4%
	$\pi^+ \pi^0$	20.7%
	$\pi^+ \pi^0 \pi^0$	1.7%
$\rho^\pm$	$\pi^\pm \pi^0$	100%

K^S	$\pi^0 \pi^0$	30.7%
K^L	$\pi^0 \pi^0 \pi^0$	19.5%
	$\pi^+ \pi^- \pi^0$	12.5%
ω	$\pi^+ \pi^- \pi^0$	89%
	$\pi^0 \gamma$	8%

We therefore get photons from processes like

$$\chi\chi \to K^+ K^- \to \pi^+ \pi^- \pi^0 \pi^0 \to 4\gamma$$

Meson Decays

The decay modes of these mesons are reasonably well quantified. The two-body decays are essentially fixed by kinematics, while the three-body decays are described by Dalitz plots. The existing data is sufficient to obtain the decay energy spectra.

For example, the decay of $K^- \rightarrow \pi^0\, \pi^0\, \pi^-$ is described by

$$|A(s,t;u)|^2 = 1 + g\,\frac{(s_3 - s_0)}{m_\pi^{\,2}} + h\,\frac{(s_3 - s_0)^2}{m_\pi^{\,4}} + k\,\frac{(s_2 - s_1)^2}{m_\pi^{\,4}}$$

where

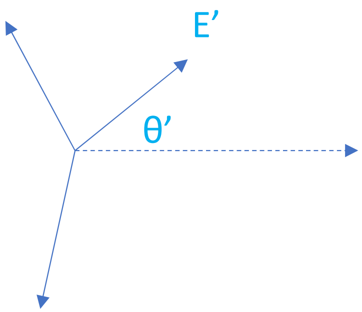
$$s_i = (\,p_K - p_i\,)^2$$

$$s_0 = \frac{s_1 + s_2 + s_3}{3} = \frac{1}{3}\,(m_K^2 + m_1^2 + m_2^2 + m_3^2)$$

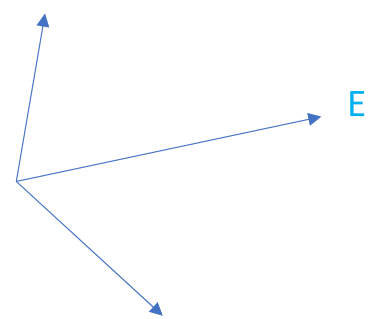
Boosting Spectra

The decay spectra are naturally given for mesons at rest. For a meson moving at some speed, we must boost the spectra. We assume that the decays in the decay chain are uncorrelated with each other.

CM frame



Lab frame



$$E = \gamma\ (E' + p'\beta\cos\theta')$$

To have a solution for E, we must have

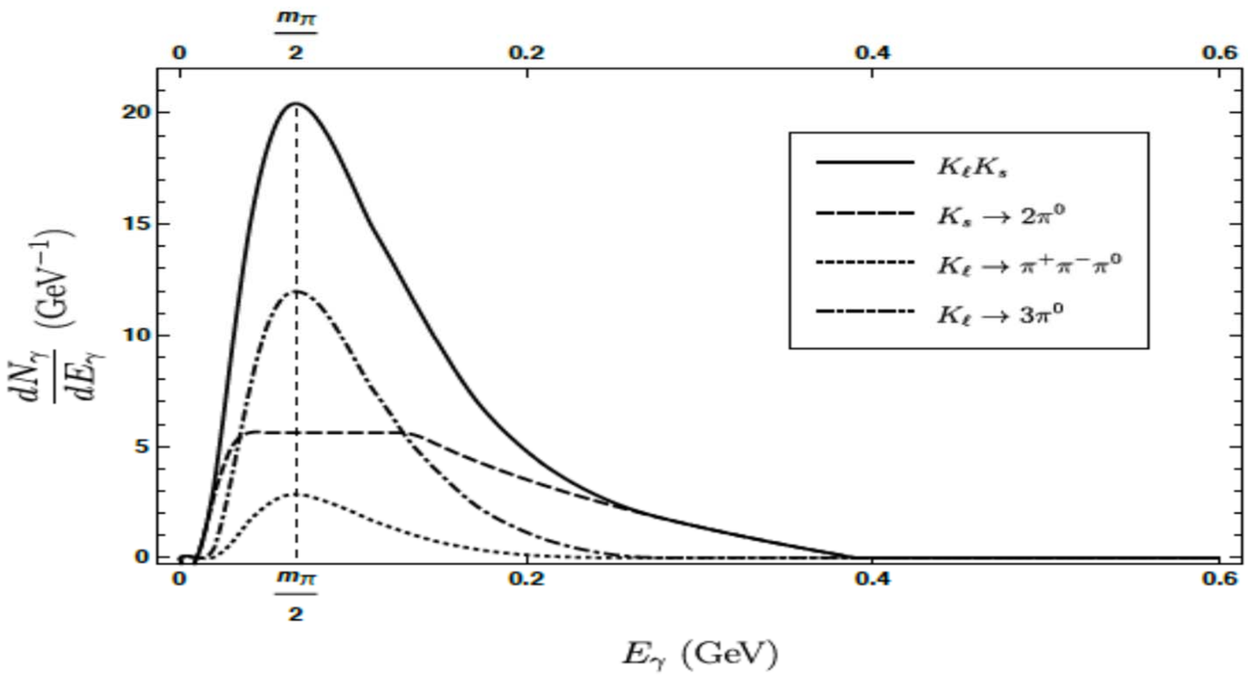
$$\gamma\ (E' - p'\beta) \leq E \leq \gamma\ (E' + p'\beta)$$

and we get

$$\frac{dP(E)}{dE} = \frac{1}{2}\int_{E_1}^{E_2} dE'\ \frac{dP(E')}{dE'}\ \frac{1}{p'\beta\gamma}$$

Boosting Spectra

We can therefore find decay spectra after boosting. For example, this is the photon spectrum for kaons produced at a CM energy of 1.14 GeV.



Experimental Constraints

We can now compare the expected signal with observations to set a bound on the interactions.

We compare to current observations of the diffuse photon emission, and from future observations of photon emission from a dwarf galaxy (Draco). We will take as a benchmark an experiment with a fractional 1σ energy resolution of e = 0.3 and an exposure of 3000 cm^2 yr.

For diffuse photon emission, the spectrum is well fit by

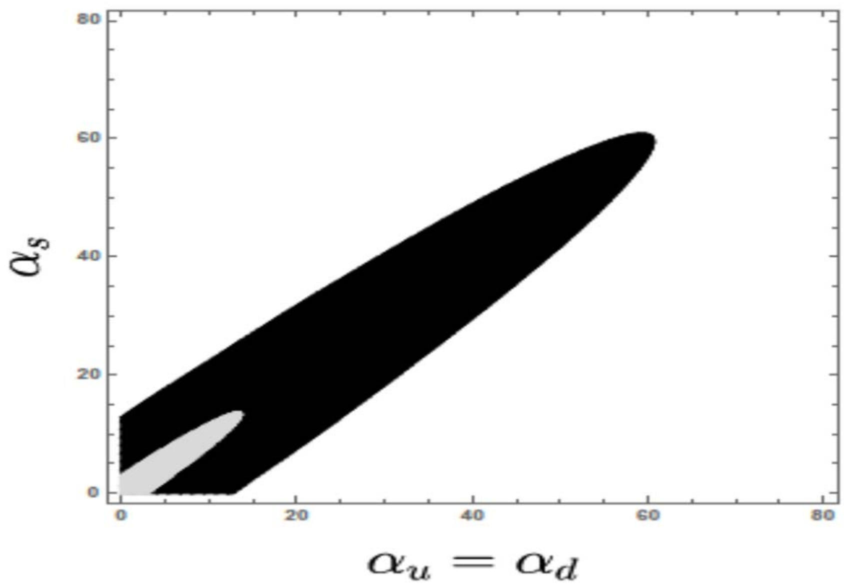
$$\frac{d^2\Phi}{d\Omega\, dE} = 2.74 \times 10^{-3} \left[\frac{E}{\text{MeV}}\right]^{-2.0} \text{cm}^{-2}\, \text{s}^{-1}\, \text{sr}^{-1} \text{MeV}^{-1}$$

Our signal is peaked near half the pion mass. Accordingly, we look at a bin of energy around the pion mass with width e m_π . We impose a very conservative bound that our signal should not exceed the number of observed events.

For a dwarf galaxy, we can estimate the background by using the diffuse spectrum. We then assume that the number of observed events is the same as the expected number of background events, then a model can be ruled out at n − σ confidence level if NS > n NO.

Experimental Constraints: Annihilations

$$L = \sum_q \frac{\alpha_q}{\Lambda^2} \chi \gamma^\mu \chi q \gamma_\mu q$$



Here Λ =100 GeV. The dark region is allowed by diffuse emission, and all but the light region could be ruled out by future Draco observations.

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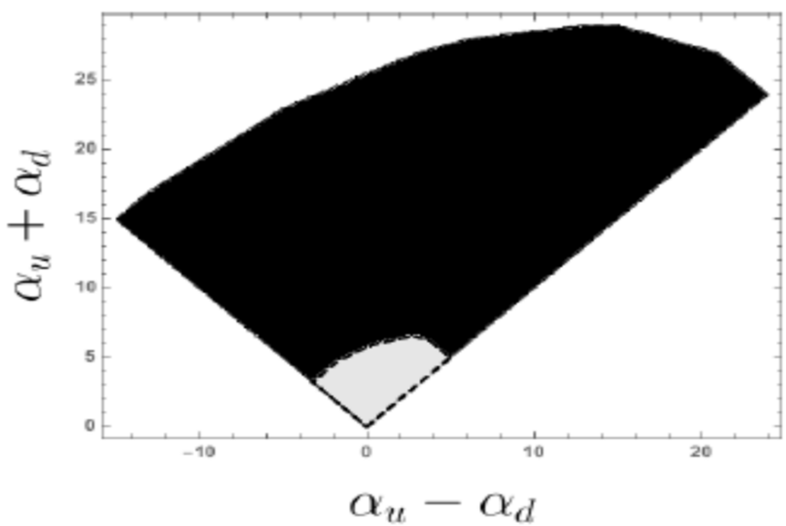

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Experimental Constraints: Decays

So far we have considered only dark matter annihilations.

In principle we can also consider decays of dark matter.

These would occur if the dark matter itself was a vector, coupling as

$$L = g \sum_q \alpha_q \; X^\mu \, q \, \gamma_\mu \, q$$

We must take the coupling small so that the lifetime is comparable to the age of the universe.

Experimental Constraints: Decays

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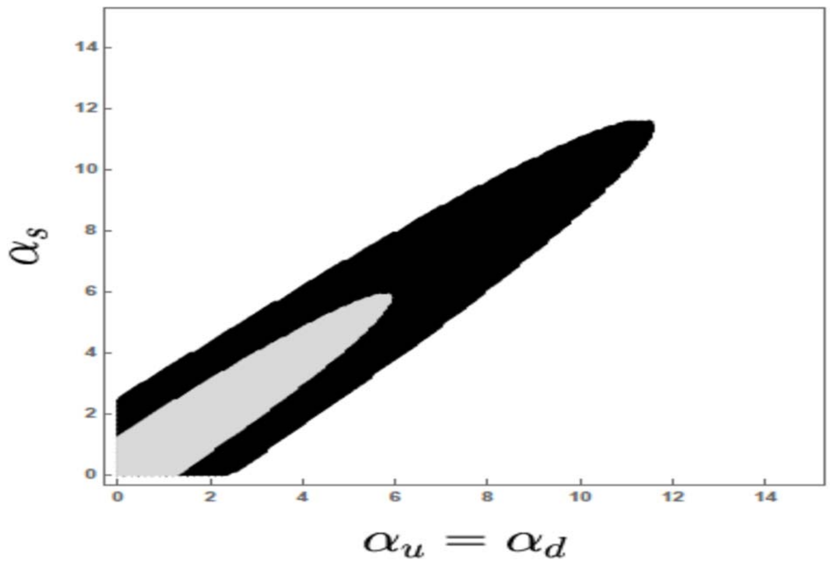

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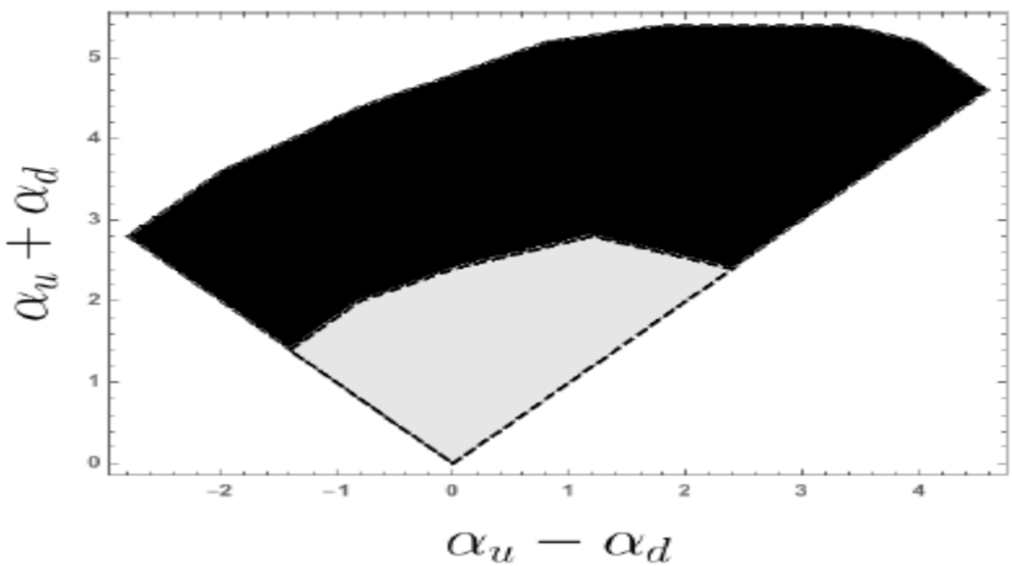

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Summary

Light dark matter (m ~< 1 GeV) can decay to a small number of hadrons.

These decays are not calculable in perturbative QCD; one needs new approaches like the chiral lagrangian.

We have shown that dark matter with vector couplings can have annihilations
into scalar and vector mesons and calculated the photon spectrum for these decays.

Current observations do not put very strong limits, but future observations have the potential
to probe interesting regions of parameter space.

Many interesting directions: include more decay channels, other operators, etc.

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Thank you!