Does one-operator EFT approach miss important DM physics?

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Plan

Answer: sometimes it does not reflect the whole complexity of DM physics…

1. Introduction. Focus on WIMPs. Complementarity of different detection mechanisms.
2. It is all about kinematics: 2←→2 vs 2←→4(many). *Snapshot of "secluded" WIMPs ideas that led to the hunt for "dark forces"*.
3. Limitations/oversimplifications of the collider vs direct detection comparison with one 2←→2 operator in mind: lightness of mediator, multi-stage compositeness of the SM operator, absence of UV completion often introduces too lax limits etc.
4. DM with SM mediators: Photon, EW and Higgs mediation. *Significance of [possible] Higgs discovery for "light" WIMPs*.
5. Producing and detecting Dark Matter: DM "beams" at the intensity frontier facilities.

Simple classification of particle DM models

At some early cosmological epoch of hot Universe, with temperature T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

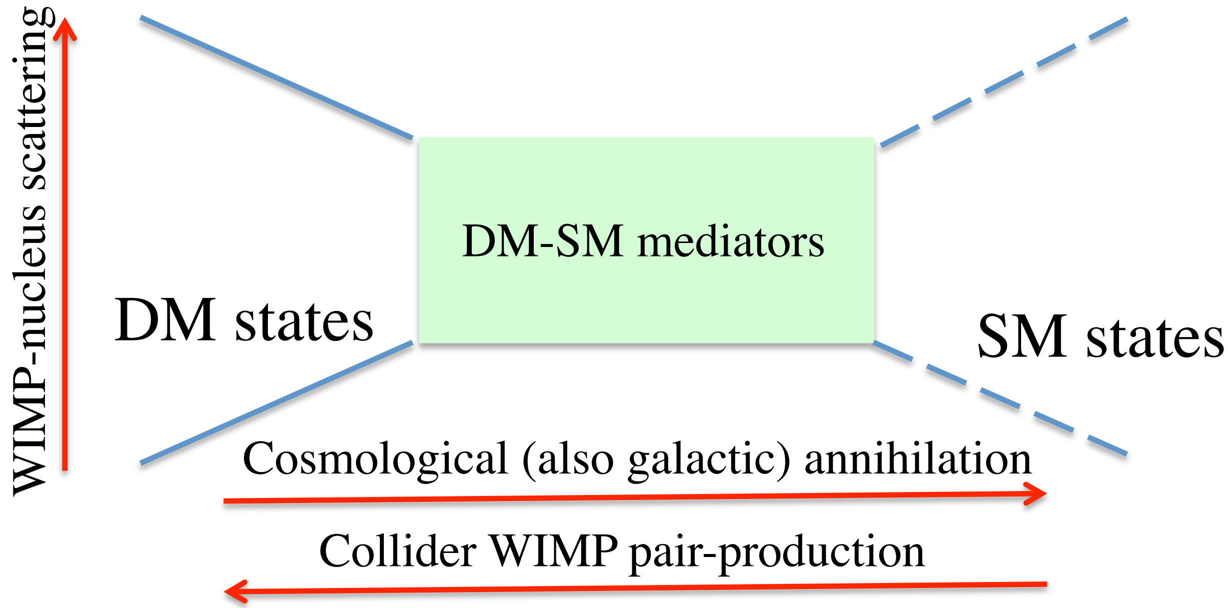
Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_\gamma = 1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM -> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**.

Very small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other "feeble" creatures – call them **super-WIMPs**]

Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_\gamma \sim 10^{10}$. "Super-cool DM". Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

Signatures can be completely different. WIMPs are most realistic for discovery

WIMP paradigm



$$\langle \sigma_{ann} v \rangle \approx 1 \text{pbn} \times c$$

1. What is inside this green box? I.e. what forces mediate WIMP-SM interaction?

2. Do sizable annihilation cross section always imply sizable scattering rate and collider DM production? Not really…

Secluded WIMPs and Dark Forces

MP, Ritz, Voloshin; Finkbeiner and Weiner, 2007. Original model: Holdom 86

$$\mathcal{L}_{\rm WIMP+mediator} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}B_{\mu\nu} - |D_\mu\phi|^2 - U(\phi\phi^*) + \bar{\psi}(iD_\mu\gamma_\mu - m_\psi)\psi.$$

This Lagrangian describes an extra U(1)' group (**dark force**), and some matter charged under it. Mixing angle κ controls the coupling to the SM.

ψ – Dirac type **WIMP**; V_μ – **mediator** particle.

Two kinematic regimes can be readily identified:

- $m_{mediator} > m_{WIMP}$

  ψ + anti-ψ → virtual V^* → SM states

κ has to be sizable to satisfy the constraint on cross section

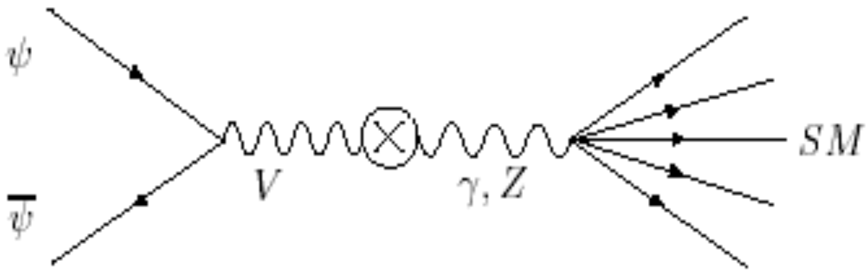
2. $m_{mediator} < m_{WIMP}$

   ψ + anti-ψ → on-shell V + V, followed by V → SM states

There is almost no constraint on κ other than it has to decay before BBN. $\kappa^2 \sim 10^{-20}$ can do the job.

Two types of WIMPs

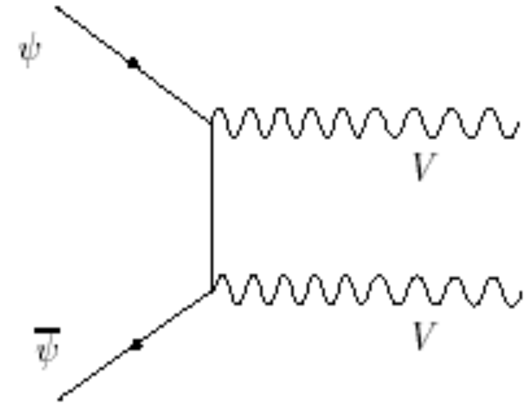
Un-secluded



Ultimately discoverable

Size of mixing*coupling is set by annihilation. Cannot be too small.

Secluded



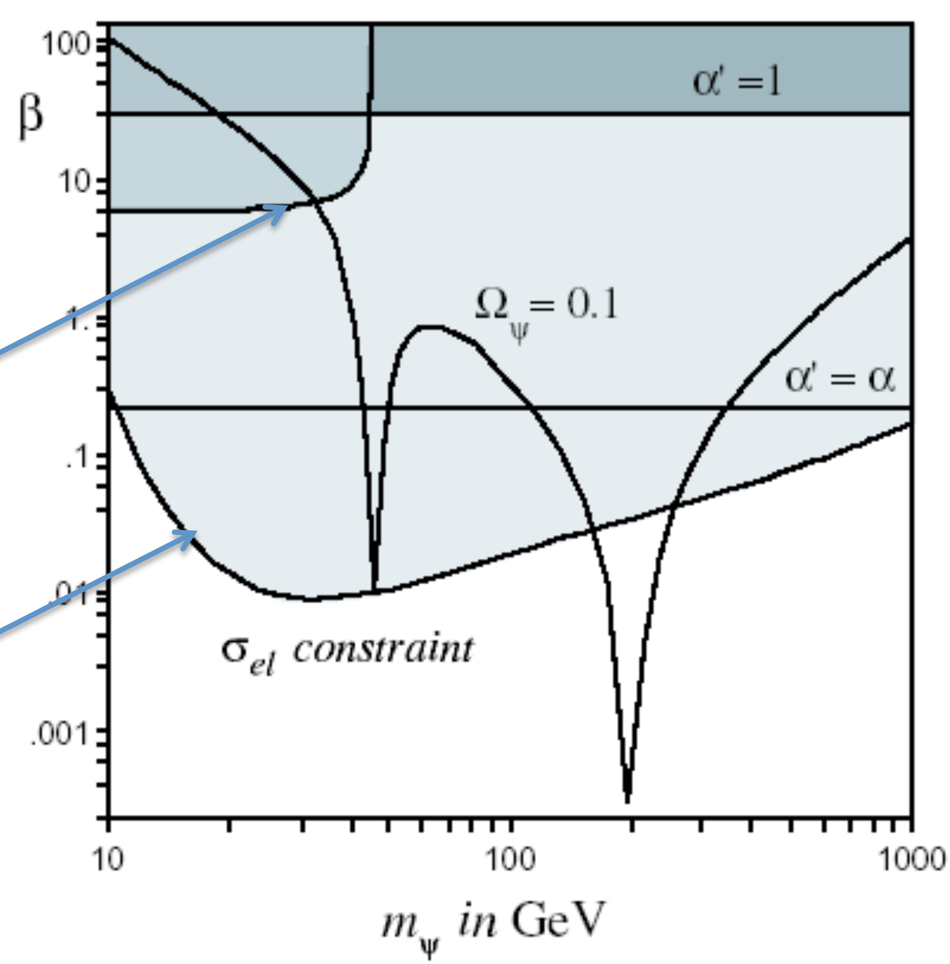
Potentially well-hidden

Mixing angle can be 10^{-10} or so. It is not fixed by DM annihilation

You think gravitino DM is depressing, but so can be WIMPs

Un-secluded regime (for m_V =400 GeV)

$$\beta \equiv \left(\frac{\kappa e'}{e\cos\theta_W}\right)^2,$$



LEP limits

CDMS constraints
(MP, Ritz, Voloshin, 07)

Direct detection all but excludes this model for one kinematic regime, and barely constraints it for the other…

Indirect signatures of secluded WIMPs

Annihilation into a pair of V-bosons, followed by decay create boosted decay products.

If m_V is under $m_{DM} v_{DM}$ ~ GeV, the following consequences are generic

(Arkani-Hamed, Finkbeiner, Slatyer, Weiner; MP and Ritz, 2008)

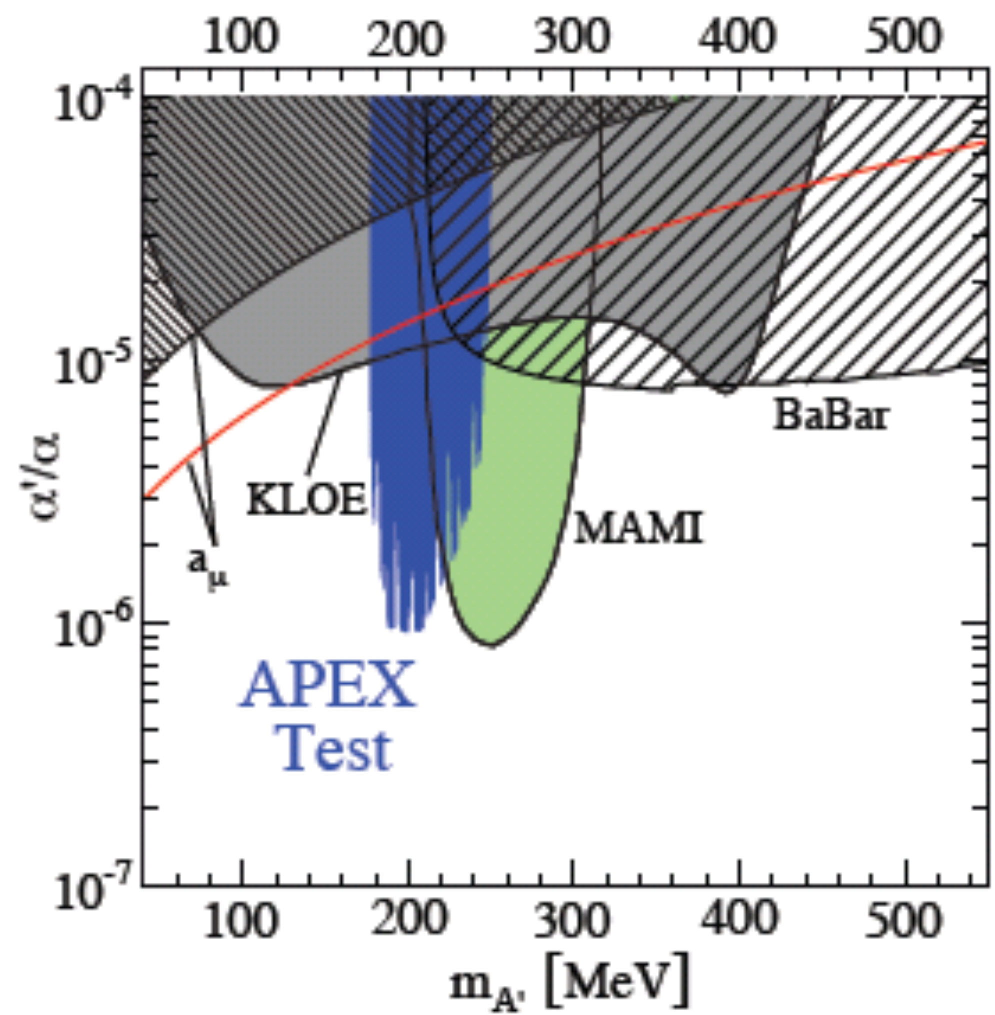
1. Annihilation products are dominated by electrons and positrons
2. Antiprotons are absent and monochromatic photon fraction is suppressed
3. The rate of annihilation in the galaxy, $<\sigma_{ann} v>$, is enhanced relative to the cosmological $<\sigma_{ann} v>$ because of the long-range *attractive* V-mediated force in the DM sector. (Sommerfeld and resonant enhancement)

Fits the PAMELA signature. [which can of course be explained by a variety of pure astrophysical mechanisms]

Thinking about secluded WIMPs and dark forces have resulted in the brand new research program at the intensity frontier: searches of light (~ few GeV and lighter) mediators using colliders and fixed target experiments.

Recently, exclusion limits have become more stringent thanks to Mainz and Jlab experiments.

Such searches are motivated in their own right, independently from the DM theme and will be continued in the future.



Message # 1

A lot of things in the "DM research" may depend on very simple kinematic relations (e.g. mass_{DM} vs $\text{mass}_{\text{mediator}}$) that could lead to the profound departure from "naïve 2←→2 logic", where annihilation ~ scattering ~ production cross sections.

In particular, secluded DM with sequential annihilation "2 → 4 or more", can have parametrically different annihilation vs production or scattering cross sections. *One does not imply the other in a model-independent way*.

DM via EFT approach

One has to be careful in taking 2←→2 operator,

$$L_{eff} = \frac{1}{\Lambda^2}\bar{\chi}\Gamma\chi O_{SM}, \quad \text{where} \quad O_{SM} = \bar{q}\Gamma q; \quad G_{\mu\nu}G_{\mu\nu}; etc$$

and interpreting direct detection and collider constraints on (Λ, m_χ) plane because “the effectiveness” of operator can be violated in the collider processes. Relevant for recent theory papers primarily by Irvine and Fermilab groups (Fox, Harnik, Kopp, Radjaraman, Tait, Tsai, Yu among *claimed* participants) and experimental analysis at LEP, Tevatron and LHC.

For direct detection, the [reduced] sensitivity comes from inconvenient choices of Γ, ($\gamma_\mu\gamma_5$, γ_5) and from χ being split into two components, χ_1 and χ_2, so that scattering does not go in the first approximation if $\Delta m > 500$ keV. (Inelastic DM of Tucker-Smith, Weiner)

DM via EFT approach

Collider bounds on

$$L_{eff} = \frac{1}{\Lambda^2}\bar{\chi}\Gamma\chi O_{SM}, \quad \text{where} \;\; O_{SM} = \bar{q}\Gamma q; \;\; G_{\mu\nu}G_{\mu\nu}; etc$$

are far less sensitive to details of Γ or split-unsplit status of χ and can "take a razor" to these models. However, one should be careful:

1. $1/\Lambda^2$ = (small coupling)^2/(small mediator mass)^2 situation (Fayet) because it can quickly invalidate the growth with energy.
2. Compositeness of O_{SM}, like $G_{\mu\nu}^2$ resulting from $m_b bb$ operator (large tanβ SUSY as an important example). Without taking this into account one can "over-push" limits by (m_b/Energy)^4.
3. Analysis of UV complete models can often improve constraints on both Λ and m_χ. E.g. in specific Z' models, or in specific SUSY models, or in Higgs-mediated models.

Message # 2

EFT approach to collider constraints on WIMP DM is great, and should be continued. However, one should be aware of the fact that the strength of the constraints often results from the "locality" of operator and its high-dimensionality (6,7 etc), resulting in rapid growth of $\sigma_{SM \rightarrow DM}$ with energy. Can be violated by compositeness of operator – either by lightness of mediator, or by additional SM thresholds (e.g. b quark) - that soften growth with E.

UV completion often helps to strengthen constraints.

More minimal DM models

Let us get rid of the "dark force" or "extra mediators" concept or may be make them very very heavy.

Then we are down to the SM mediators:

1. Photons: millicharged WIMPs (Hall et al, 1980s)
   neutral WIMPs with Magnetic Dipole, EDM, charge radius and other EM form factors (MP, ter Veldhuis, 2000).

2. EW boson mediators: Original WIMP heavy ν's (Weinberg, Lee; Russkie); [Yet another] minimal WIMP model with Z,W mediation (Cirelli, Fornengo, Strumia, 2005); inert Higgs models etc…

3. SM Higgs-mediated DM (Silveira, Zee; McDonald; Burgess, MP, ter Veldhuis).

EW mediation: Z bosons

First model of WIMPs constructed: heavy neutrino N annihilating to SM states via virtual Z. NN → Z* → SM for small m_N and NN→ ZZ, WW for m_N above di-boson threshold. (Lee; Weinberg; Zeldovich, Dolgov and Vysotsky, mid 70s).

Collider physics and direct detection provide complementary sensitivity to the model (Direct scattering is very sensitive to small Δm_N, while LEP I provides a very powerful constraint on $Z \to N_1 N_2$ from Z→ invisible. In particular, models with $g_N > 0.3\, g_W$ are all gone after LEP irrespective of Δm_N.

LEP I was a big "reckoning day" for light Z-mediated Dark Matter.

Simplest models of Higgs mediation

Silveira, Zee (1985); McDonald (1993); Burgess, MP, ter Veldhuis(2000)

DM through the Higgs portal – *minimal model of DM*

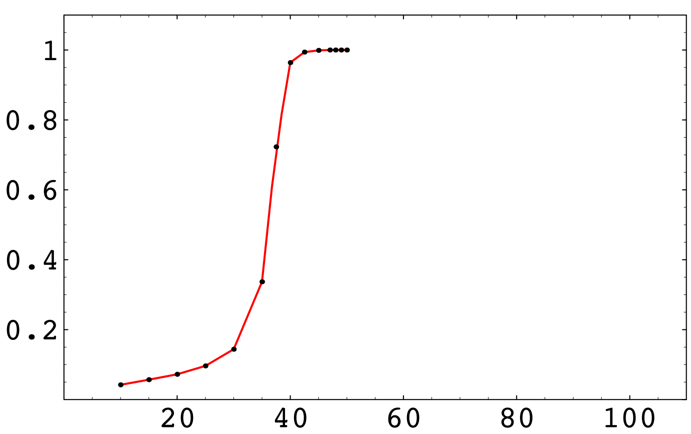
$$-\mathcal{L}_S = \frac{\lambda_S}{4} S^4 + \frac{m_0^2}{2} S^2 + \lambda S^2 H^\dagger H$$

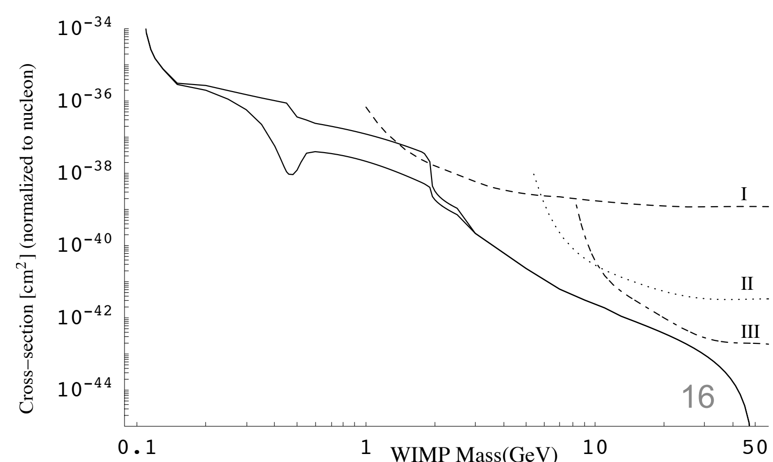
$$= \frac{\lambda_S}{4} S^4 + \frac{1}{2}(m_0^2 + \lambda v_{EW}^2) S^2 + \lambda v_{EW} S^2 h + \frac{\lambda}{2} S^2 h^2.$$

125 GeV Higgs is "very fragile" because its with is ~ y_b^2 – very small

R = $\Gamma_{\text{SM modes}}/(\Gamma_{\text{SM modes}}+\Gamma_{\text{DM modes}})$. Light DM can kill Higgs boson easily

(missing Higgs Γ: van der Bij et al., 1990s, Eboli, Zeppenfeld,2000)





There are many Higgs-mediated models that are invisible for DD yet lead to missing Higgs decay

Example: S – mediator, mixes with h; N – DM particles

$$\mathcal{L} = (H^\dagger H)(AS + \lambda S^2) + \beta S \bar{N} i\gamma_5 N$$

Combination $A\beta$ breaks CP, but in the dark sector. Annihilation cross section

$$\langle \sigma v \rangle_{\bar{N}N \to SM} \simeq \frac{3\lambda_h^2}{4\pi} \left(\frac{m_b}{m_h}\right)^2 \frac{m_N^2}{m_h^4} \sim 1 \text{ pb}$$

requires $\lambda_h^2 \sim 10 \times \left(\frac{20 \text{ GeV}}{m_N}\right)^2$

Suppression of Higgs visible widths, $R < 0.001$. Elastic cross sections are *hopeless*, suppressed by

$$\sigma_p^{\rm eq} \simeq \frac{1}{2\pi}(v/c)^2 \times \frac{g_{hpp}^2 \lambda_h^2 m_p^2}{m_h^4} \times \left(\frac{Am_p}{Am_p + m_N}\right)^2 \lesssim 10^{-48} \text{ cm}^2 \times \lambda_h^2. \quad (8$$

Latest LHC results are of great importance for the Higgs- mediated Dark Matter models

- A discovery of the SM(-like) Higgs with mass of ~ 125 GeV will wipe out many DM models with $m_{DM} < 50$ GeV that use Higgs particle for regulating its abundance in a fairly model-independent way. (this point was made repeatedly in recent literature Mambrini; Raidal, Strumia; X.-G. He, Tandean; Fox, Harnik, Kopp, Tsai; MP, Ritz; Lebedev; others…)

- Any theorist model-builder who wants to play with sub-50 GeV WIMPs may "run out of SM mediators" and will be then bound to introduce new mediation mechanisms, such as new [scalar] partners of SM fermions, new Higgses and/or new Z'.

Message # 3

The most significant LHC result for the DM (in my opinion), is not the monojet search, but the tentative Higgs signal.

If the Higgs signal is confirmed to be the Higgs, many UV complete models of DM with $m_{DM} < m_h/2$ will be eliminated outright.

If the SM Higgs is excluded in the whole light range (meaning current signal is an upward background fluctuation), it might be first sign of the Higgs-mediated light DM.

MeV dark matter in collisions

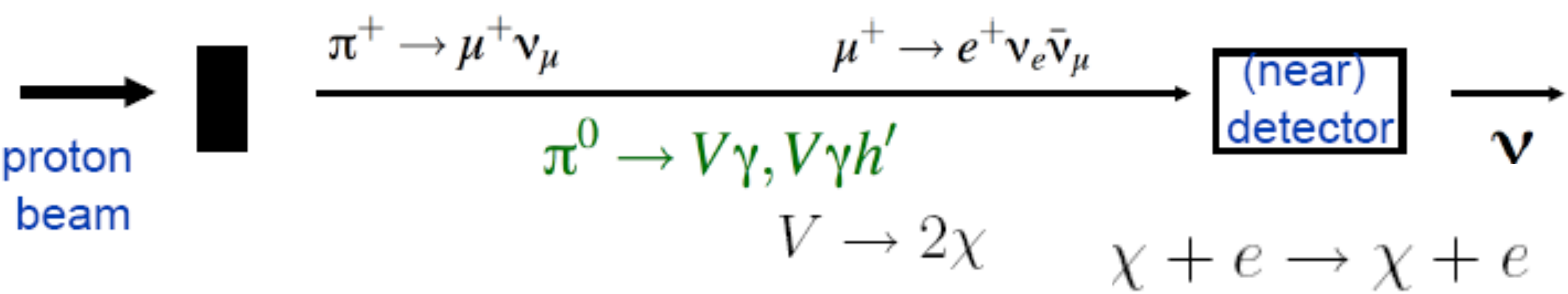
1. Unlike many 10-GeV-and-up WIMP models that can be studied via direct detection, O(MeV) scale DM models are difficult for direct detection as they carry no appreciable energy to deposit.

2. Solution: *make energetic DM particles* in the collisions of protons with a target and subsequent decay of mesons to DM, and *detect produced DM particles* via the (quasi)elastic NC scattering signature.

3. Realistic goal for many short-base line neutrino experiments like LSND, MiniBoone etc. Neutrino beam can be accompanied by the MeV DM beam. (Batell, MP, Ritz; DeNiverville, MP, Ritz).

4. Strong constraints can be obtained that way, owing to the huge number of produced hadrons ($N_{\text{LSND pions}} \sim 10^{21}$).

accompanied by a beam of *other* light neutral states. "Dark matter beam"



Probability of prompt decay of mediator-V into new dark states χ can be sizable.

Scattering within the detector can look like neutral current events, but being mediated by light vectors could be *larger* than weak scattering rates. E.g. LSND provides best constraints on MeV WIMPs

Beam of MeV-dark matter

LSND provides by far the most precise test of the MeV dark matter idea of Boehm and Fayet; MP, Ritz and Voloshin. This model kills SM modes of V decay – escapes most tests.

1. $p + p \to X + \pi^0$
2. $\pi^0 \to \gamma V$
3. $V \to 2\chi$
4. $\chi + e \to \chi + e$

$$\frac{\alpha' \kappa^2}{\alpha} \times \left(\frac{10\ \mathrm{MeV}}{m_V}\right)^4 \times \left(\frac{m_\chi}{\mathrm{MeV}}\right)^2 \sim 10^{-6}.$$

For a "sweet spot" in parameter space (correct abundance of MeV dark matter, enough positrons for 511 keV line), the total count in the LSND detector **should exceed million events**. These type of searches can be repeated at SNS where the huge beam power at 1GeV is being used.

deNiverville, MP, Ritz; DM sourced by π^0 and η decays

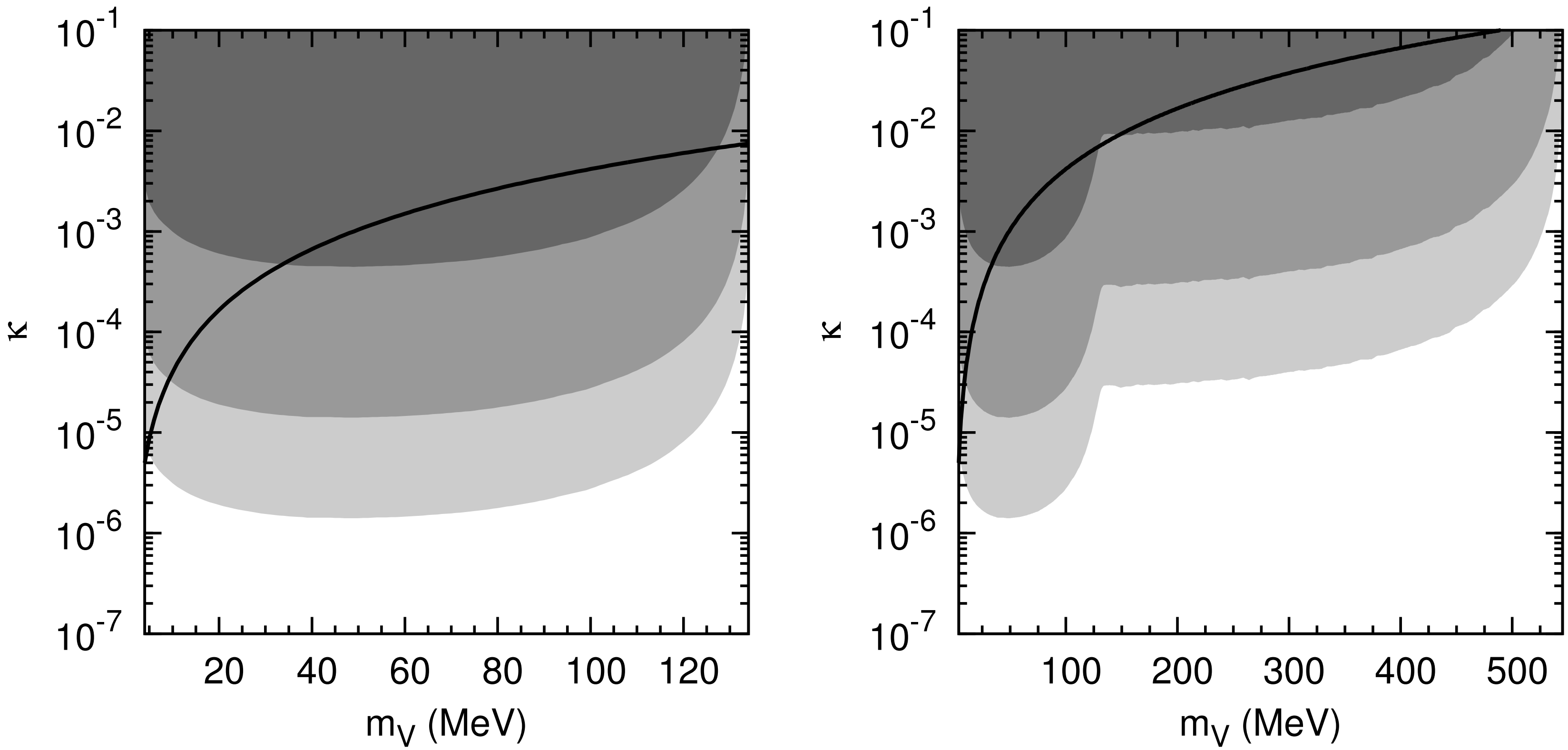


Figure 3: Expected number of neutral current-like dark matter electron scattering events at the MiniBooNE detector for $m_\chi = 1$ MeV. The regions show greater than 10 (light), 1000 (medium) and 10^6 (dark) expected events. The plot on the left shows dark matter resulting from π^0 decays, while the plot on the right combines dark matter from both π^0 and η decays. The area below the black line corresponds to $\alpha' > 4\pi$.

Message # 4

LHC and direct detection efforts are important for limiting "true WIMPs" – few GeV scale and heavier. They are not useful for limiting "light" DM a-la-Fayet and Boehm.

Intensity frontier experiments – e.g. short base line accelerator neutrino exp – can be used. Neutrino beam will be accompanied by the DM beam, and will lead to the scattering events in the near detector. Most constraining for the O(1-100 MeV) range of DM masses.

Conclusions

1. Do not over-push WIMP argument: large annihilation does not imply large scattering or production in the model independent way. Secluded models break this connection but remain interesting because of the connection to indirect signal.

2. EFT always works, but sometimes can be over-pushed by inaccurate use. Beware of light mediators, compositeness of SM operators, (like $G_{\mu\nu}G_{\mu\nu}$ induced by $m_b bb$). Always a good idea to UV complete your model, especially if $E \sim m_{mediator}$. Your limits may get stronger.

3. LHC may deliver decisive blow to light-ish (10 -- 55 GeV) DM coupled to the SM via the Higgs by *observing H*.

4. Should DM be in an uncomfortable for the LHC range of MeV-100MeV, the proton-on-fixed-target high intensity facilities is the best avenue for constraining light DM.