EFFECTIVE THEORIES FOR DARK MATTER INTERACTIONS

and the neutrino portal paradigm

May 22, 2015
arXiv:1505.XXXX
Mitchell Workshop on Collider and Dark Matter Physics 2015

Vannia Gonzalez, José Wudka

University of California, Riverside
UC-MEXUS

OUTLINE

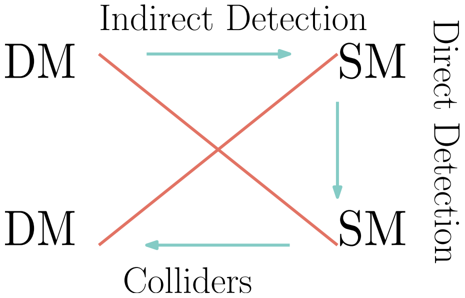
1. Effective DM-SM interactions
2. Scalar & Fermion mediators
3. Fermion DM with fermion mediators
4. Simple model realization
5. Conclusions

DARK MATTER PARTICLE PARADIGM

We are certain (from large scales) that Dark Matter explains:

- Movement of stars orbiting galaxies (rotational curves)
- Gravitational lensing observations
- Average velocities of groups of galaxies

Huge effort at looking for a DM particle and non-gravitational interaction:



DM PARTICLE PHENOMENLOGY?

- Many beyond the SM models include a DM candidate (SUSY, IDM, RNM, etc..)
- Or phenomenological approach: DM candidate (or reduced number of DM candidates) that satisfy a given symmetry to ensure stability

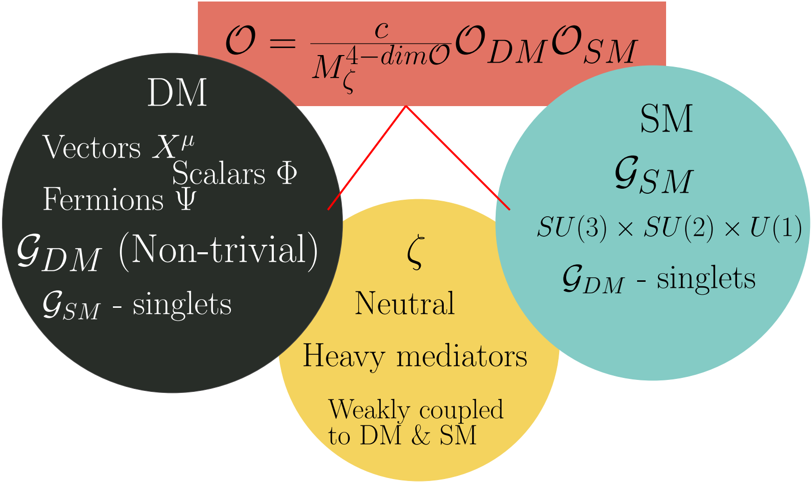
$$\mathcal{L} \sim \mathcal{O}_{DM}\mathcal{O}_{SM}$$

Adopted framework

Effective approach: Multi-component DM spectra with non-trivial symmetries. Can include vector, fermions and scalar particles, interacting with SM through heavy weakly coupled mediators.

EFFECTIVE DM-SM INTERACTIONS

GENERAL PICTURE. CLASSES OF THEORIES



EFFECTIVE OPERATORS

dim.	category	$\mathcal{O}_{\rm SM}\mathcal{O}_{\rm DM}$
4	I	$\lvert\phi\rvert^2(\Phi^\dagger\Phi)$
5	II	$\lvert\phi\rvert^2\bar\Psi\Psi \qquad \lvert\phi\rvert^2\Phi^3$
	III	$(\bar\Psi\Phi)(\phi^T\epsilon\ell)$
	IV	$B_{\mu\nu}X^{\mu\nu}\Phi \qquad B_{\mu\nu}\bar\Psi\sigma^{\mu\nu}\Psi$
6	V	$\lvert\phi\rvert^2\mathcal{O}^{(4)}_{\rm dark} \qquad \Phi^2\mathcal{O}^{(4)}_{\rm SM}$
	VI	$(\bar\Psi\Phi^2)(\phi^T\epsilon\ell) \qquad (\bar\Psi\Phi)\ \not\partial(\phi^T\epsilon\ell)$
	VII	$J_{\rm SM}\cdot J_{\rm dark}$
	VIII	$B_{\mu\nu}\mathcal{O}^{(4)\,\mu\nu}_{\rm dark}$

$$\mathcal{O}^{(4)}_{\rm SM}\!:\{\lvert\phi\rvert^4,\ \Box\lvert\phi\rvert^2,\ \lvert\Phi\rvert^4,\ \Box\lvert\Phi\rvert^2,\ \bar\psi\varphi\psi',\ B^2_{\mu\nu},\ (W^I_{\mu\nu})^2,\ (G^A_{\mu\nu})^2\}$$

$$\mathcal{O}^{(4)}_{\rm DM}\!:\{\lvert\Phi\rvert^4,\ \Box\lvert\Phi\rvert^2,\ \bar\Psi\Phi\Psi',\ X^2_{\mu\nu}\}$$

$$J^{(\psi)\,\mu}_{\rm SM}=\bar\psi\gamma^\mu\psi,\ i\phi^\dagger\overleftrightarrow{D}^\mu\phi, \qquad J^{(L,R)\,\mu}_{\rm dark}=\bar\Psi\gamma^\mu P_{L,R}\Psi,\ i\Phi^\dagger\overleftrightarrow{\mathcal{D}}^\mu\Phi$$

TREE-LEVEL / LOOP-LEVEL GENERATED OPERATORS

Tree Level $\mathcal{O}$: Neutral mediators ζ

- **Scalars $\mathcal{S}$**
  - $|\phi|^2\bar{\Psi}\Psi, \quad |\phi|^2\Phi^3$
  - $|\phi|^2\Phi^4, \quad \Phi^2|\phi|^4$
- **Fermions $\mathcal{F}$**
  - $(\bar{\Psi}\Phi)(\phi^T\epsilon l)$
  - $(\bar{\Psi}\Phi^2)(\phi^T\epsilon l)$
  - $(\bar{\Psi}\Phi)\ \partial\!\!\!/(\phi^T\epsilon l)$
- **Vectors $\mathcal{V}$**
  - $J_{SM}.J_{DM}$
- **Tensors $\mathcal{T}$**
  - $B_{\mu\nu}X^{\mu\nu}\Phi$
  - $B_{\mu\nu}\mathcal{O}^{(4)\,\mu\nu}_{DM}$
  - $B_{\mu\nu}\bar{\Psi}\sigma^{\mu\nu}\Psi$

Consider case: Fermions and scalars. Vector or antisymmetric tensor mediators require details on local DM symmetries.

THE EFFECTIVE LAGRANGIAN

- Below the mediator mass scale: Effective theory resulting from integrating out all modes with energy above this scale.
- Modes: Mediators and Standard Model and Dark Fields with higher momenta "high-momentum modes" (HMM)
- For neutral mediator integrated modes: operators of dimension ≤ 6 are either generated at tree-level or are not generated at any order in the loop expansion
- From HMM integrated modes: operators are loop generated and suppressed by $\sim 1/(4\pi)^{2L}$, where L is the number of loops.

General form of effective Lagrangian

$$\mathcal{L}_{\text{eff}}^{(\zeta)} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{dark}} + c_{\text{I}}|\phi|^2|\Phi|^2 + \mathcal{L}^{(\zeta-\text{tree})} + \mathcal{L}^{(\zeta-\text{loop})} \quad (1)$$

SCALAR & FERMION MEDIATORS

SCALAR MEDIATORS

The resulting effective Lagrangian is

$$\mathcal{L}^{(\mathcal{S}-\text{treee})} = \frac{c_{\text{II}}}{\Lambda}|\phi|^2\bar{\Psi}\Psi + \cdots$$

$$\mathcal{L}^{(\mathcal{S}-\text{loop})} = \frac{1}{(4\pi\Lambda)^2}\left(\sum_i c_{\text{V}}^i|\phi|^2\mathcal{O}'^{(4)}_{\text{dark},\,i} + \sum_a c_{\text{V}}^a|\Phi|^2\mathcal{O}'^{(4)}_{\text{SM}\,,a}\right)\cdots$$

$\mathcal{O}^{(4)}_{\text{SM}}$:$\{|\phi|^4,\ \Box|\phi|^2,\ |\Phi|^4,\ \Box|\Phi|^2,\ \bar{\psi}\varphi\psi',\ B^2_{\mu\nu},\ (W^I_{\mu\nu})^2,\ (G^A_{\mu\nu})^2\}$
$\mathcal{O}^{(4)}_{\text{DM}}$:$\{|\Phi|^4,\ \Box|\Phi|^2,\ \bar{\Psi}\Phi\Psi',\ X^2_{\mu\nu}\}$

$|\Phi|^2(\bar{\Psi}\Psi)$: $\sim$ Single-component model (lightest dark particle)

Higgs-portal coupling $\rightarrow$ studied extensively

FERMION MEDIATORS

$$
\begin{aligned}
\mathcal{L}^{(\mathcal{F}-\text{tree})} &= \frac{c_{\text{III}}}{\Lambda}(\bar{\Psi}\Phi)(\tilde{\phi}^{\dagger}\ell) + \cdots \\
\mathcal{L}^{(\mathcal{F}-\text{loop})} &= \frac{c_{\text{II}}}{16\pi^2\Lambda}|\phi|^2\bar{\Psi}\Psi + \sum_{a=\ell\,\phi;\; i=L,R} \frac{c_{\text{VII}}^{(a|i)}}{(4\pi\Lambda)^2}\left(J_{\text{SM}}^{(a)} \cdot J_{\text{dark}}^{(i)}\right) \\
&\quad + \frac{1}{(4\pi\Lambda)^2}\left(\sum_i c_{\text{V}}^{i}|\phi|^2\mathcal{O}'^{(4)}_{\text{dark},\,i} + \sum_a c_{\text{V}}^{a}|\Phi|^2\mathcal{O}'^{(4)}_{\text{SM}\,,a}\right)\ldots
\end{aligned}
$$

Note: category II operator $|\phi|^2\bar{\Psi}\Psi$ has a loop-suppressed coefficient for these models, which was not the case for the $\mathcal{S}$-mediated case.

In the unitary gauge:

$$\nu\Phi^\dagger\Psi \in (\bar{\Psi}\Phi)(\tilde{\phi}^\dagger l)$$

Heavier DM decays promptly into Light DM and ν

Single-component DM Relic

$m_\Psi > m_\Phi$

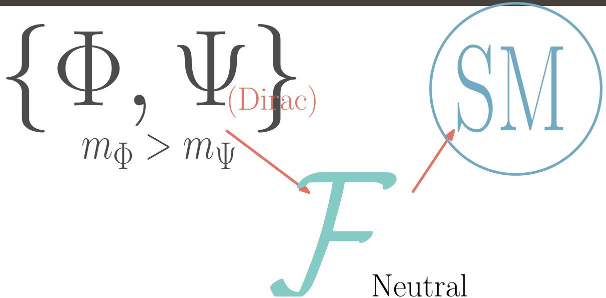
Higgs Portal

$m_\Phi > m_\Psi$

Neutrino Portal

FERMION DM WITH FERMION MEDIATORS

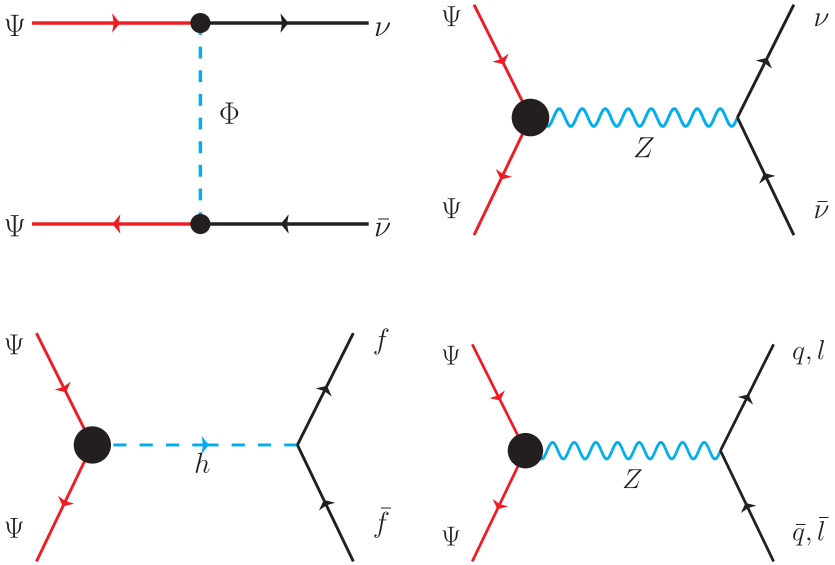
GENERAL SCENARIO



Leading interactions

$$
\begin{aligned}
(\bar{\Psi}\Phi)(\tilde{\phi}^\dagger \ell) &= \frac{v}{\sqrt{2}}(\bar{\Psi}\nu\Phi) + \cdots \\
\bar{\Psi}\Psi|\phi|^2 &= vH(\bar{\Psi}\Psi) + \cdots \\
J_{\text{SM}}^{(\phi)} \cdot J_{\text{dark}}^{(L,R)} &= -v m_Z \bar{\Psi} \not{Z} P_{L,R} \Psi \cdots
\end{aligned} \tag{2}
$$

RELIC ABUNDANCE: $\Psi\Psi \to SM, SM$



The cross section for $\Psi\Psi$ annihilation has a dominant contribution from Φ exchange and two resonant contributions from the Higgs and the Z boson

$$\begin{aligned} \langle \sigma v \rangle_{\Psi\Psi\to ff} &\simeq \frac{N_f m_f^2}{4\pi m_\Psi} \left(\frac{c_{\rm II}}{16\pi^2 \Lambda} \right)^2 \frac{(m_\Psi^2 - m_f^2)^{3/2}}{(m_H^2 - 4m_\Psi^2)^2 + m_H^2 \Gamma_H^2} \\ \langle \sigma v \rangle_{\Psi\Psi\to\nu\nu} &\simeq \frac{(v/\Lambda_{\rm eff})^4}{256\pi m_\Psi^2} \left[\left| \frac{1}{2} + B_L + B_R \right|^2 + \frac{3}{4} \right] \end{aligned} \tag{3}$$

where

$$\begin{aligned} B_{L,R} &= \left(1 + \frac{m_\Phi^2}{m_\Psi^2}\right) \left(\frac{g}{4\pi c_{\rm w}} \right)^2 \frac{c_{\rm VII}^{(\phi|L,R)}}{c_{\rm III}^2} \frac{m_\Psi^2}{m_Z^2 - 4m_\Psi^2 + i m_Z \Gamma_Z} \\ \Lambda_{\rm eff} &= \sqrt{1 + \frac{m_\Phi^2}{m_\Psi^2}} \frac{\Lambda}{c_{\rm III}} \end{aligned} \tag{4}$$

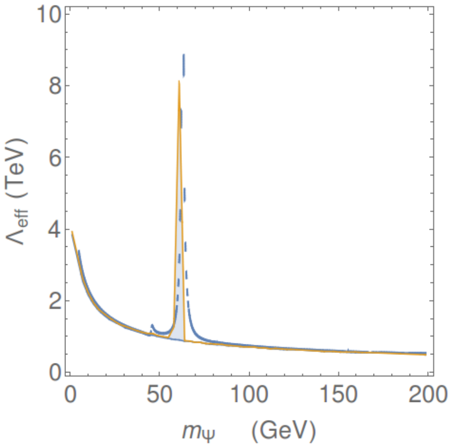
NUMERICAL CONSTRAINTS

Using Planck results (2014) $\Omega_{\rm Planck} h^2 = 0.1198 \pm 0.0026 \quad (3\,\sigma)$.

Parameter space.

Using MicrOmegas code: systematic selection of 2×10^7 points in the 7-dim. parameter space $\{c_{\rm II},\ c_{\rm III},\ c_{\rm VII}^{(\phi|L,R)},\ \Lambda, m_\Psi,\ m_\Phi\}$ within the ranges

$$1\,\text{GeV} \leq m_\Psi \leq 199\,\text{GeV}\,, \quad 1\,\text{TeV} \leq \Lambda \leq 5\,\text{TeV}\,,$$
$$11\,\text{GeV} \leq m_\Phi \leq 836\,\text{GeV}, \qquad 0 \leq c_{\rm III} \leq 4\,,$$
$$|c_{\rm II}| \leq 10\,, \qquad -8 \leq c_{\rm VII}^{(\phi|L)} \leq 0\,, \qquad -10 \leq c_{\rm VII}^{(\phi|R)} \leq 0\,. \tag{5}$$



In analytic expression (blue line):
$c_{\rm II} = 0.08,\ c_{\rm III} = 1.5,\ c_{\rm VII}^{(\phi|R)} = -10,\ c_{\rm VII}^{(\phi|L)} = 0$. The graph clearly exhibits the two resonant peaks at $m_\Psi = m_Z/2$ and $m_\Psi = m_H/2$

We see that outside the resonant values of m_Ψ the Planck constraint restricts $\Lambda_{\rm eff} - m_\Psi$ plane to a narrow region that is well approximated by the relation

$$\Lambda_{\rm eff} \simeq \sqrt{\frac{m_\Omega}{m_\Psi}}\,\text{TeV}; \quad m_\Omega \simeq 74\text{GeV} \quad \text{(non-resonant region)}. \qquad (6)$$

DIRECT DETECTION $\Psi, SM \to \Psi, SM$

Relevant terms contained in:

$$\mathcal{L}^{(\mathcal{F}-\text{loop})} = \frac{v c_{\text{II}}}{16\pi^2 \Lambda} H \bar{\Psi}\Psi - \frac{g}{2 c_{\text{w}}} \frac{v^2}{16\pi^2 \Lambda^2} \bar{\Psi} \not{Z} \left(c_{\text{VII}}^{(\phi|L)} P_L + c_{\text{VII}}^{(\phi|R)} P_R \right) \Psi$$

From this expression we extract

$$\epsilon_H = \frac{v^3}{16\pi^2 \Lambda m_H^2} c_{\text{II}} \, ; \qquad \epsilon_Z = -\frac{v^2}{16\pi^2 \Lambda^2} \frac{c_{\text{VII}}^{((\phi|L))} + c_{\text{VII}}^{((\phi|L))}}{2}$$

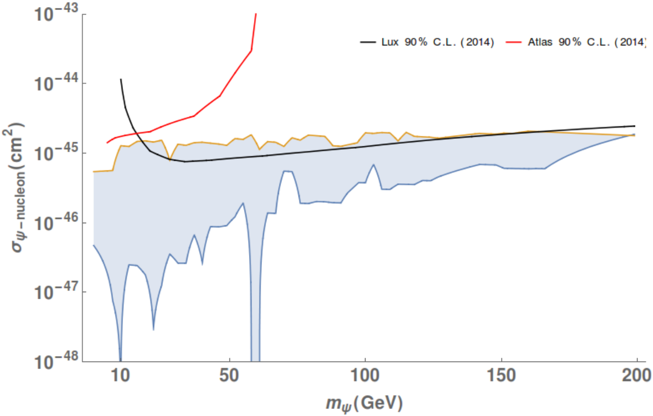
that provide estimates of the strength of the H and Z exchanges to the total direct-detectino cross section

The total cross section is given by

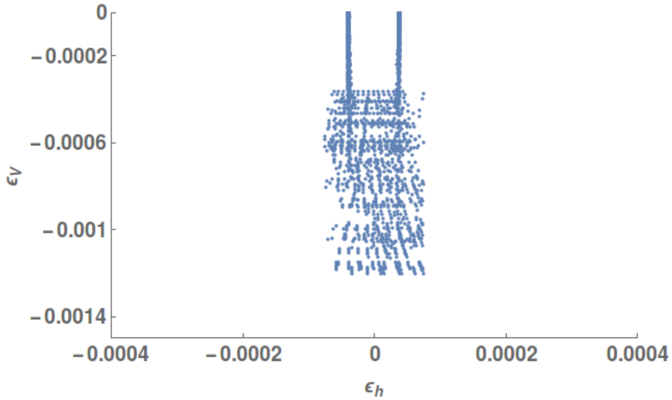
$$\sigma_{\Psi\mathcal{N}\to\Psi\mathcal{N}} = \frac{4}{\pi} \mu_{\text{red}}^2 \left| (Z/A)\mathcal{A}_p + (1 - Z/A)\mathcal{A}_n \right|^2$$

where $\mathcal{A}_{p,n}$ denote, respectively the amplitudes for proton and neutron scattering (in units of $1/\text{mass}^2$), and $A, \ Z$ denote the atomic number and charge and μ_{red} the $\mathcal{N} - \Psi$ reduced mass

LUX & ATLAS RESULTS



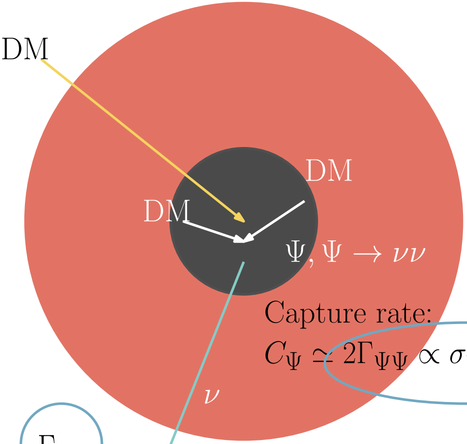
Planck @3σ. 90% C.L. Lux limit (black line). Atlas upper limits (red line) at 90% C.L. on the DM-nucleon cross section from Higgs invisible decay to DM (Majorana) fermions.



$$\epsilon_H = \frac{v^3}{16\pi^2 \Lambda m_H^2} c_{\text{II}}\,; \qquad \epsilon_Z = -\frac{v^2}{16\pi^2\Lambda^2}\frac{c_{\text{VII}}^{((\phi|L))} + c_{\text{VII}}^{((\phi|L))}}{2}$$

INDIRECT DETECTION

Neutrino flux induced by DM annihilation in Sun/Earth (Gould 87', Loundberg 04', Cirelli et al. 10')

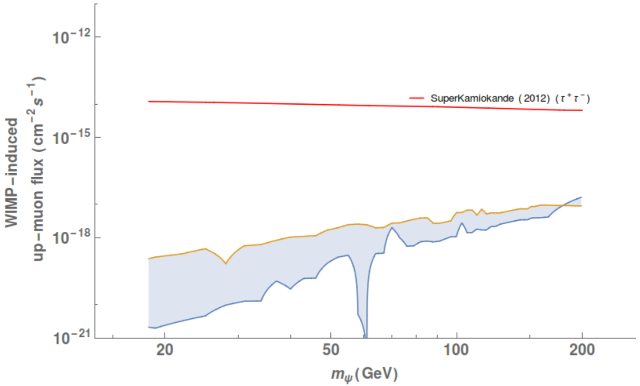


Capture rate:
$$C_\Psi \simeq 2\Gamma_{\Psi\Psi} \propto \sigma_{\Psi N}\rho^{DM}_{\text{local}}$$

$$\frac{dN_\nu}{dE_\nu} \sim \frac{\Gamma_{\Psi\Psi}}{4\pi R^2}\delta(E - m_\Psi)$$

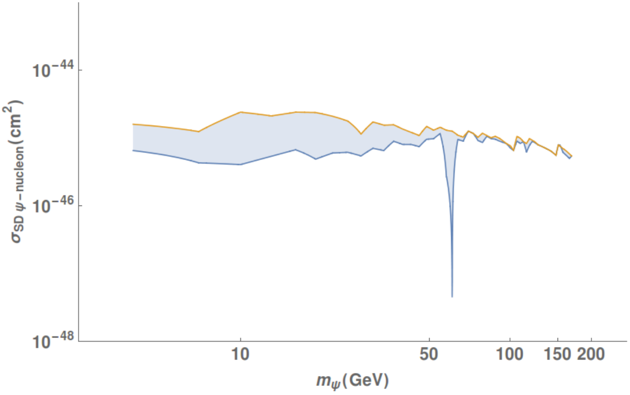
SUPER-K CONSTRAINTS

- In this scenario: $\mathcal{BR}_\nu \simeq 1$ and $\sigma_p \mathcal{BR} \sim \sigma_{\mathcal{SD}} \sim 10^{-10}$ pb (σ_{SD} generated by axial Z couplings), not enough sensitivity for discovery in present experiments.



SD cross sections: generated by the axial Z couplings and are of the same order as the spin-independent ones: several orders of magnitude below the limits of the spin-dependent cross sections (Super-K ,ICECUBE, ANTARES..) (because of the absence of a $\sim A^2$ coherence factor).

Unconstrained from spin-dependent limits



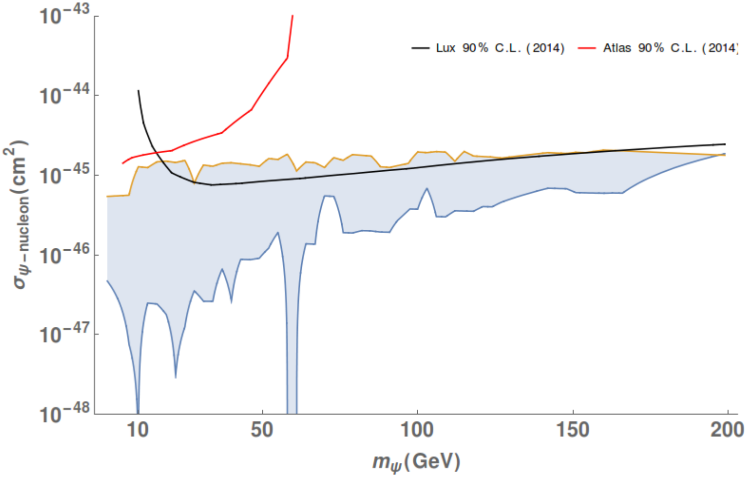
EW CONSTRAINTS

The only significant constraint: Higgs decay

For $m_H > 2m_\Psi$,

$$\mathcal{BR}(Hh \to \Psi\Psi) \simeq 3 \times 10^{-3} \left(\frac{c_{\mathrm{II}}}{\Lambda_{\mathrm{TeV}}}\right)^2 \left(1 - 4\frac{m_\Psi^2}{\mathrm{m}_H^2}\right)^{3/2} \quad (7)$$

- The direct search for Higgs invisible decays in Atlas experiment sets an upper limit of 63% at 90% C.L.
- The limit on $\mathcal{BR}(H \to \mathrm{inv})$ sets an upper limit on the DM-nucleon SI scattering cross section (for the higgs portal operator only, [Kanemura et al., Djouadi et al.]) . No exclusion regions over the effective couplings.


Lux 90% C.L. (2014)
Atlas 90% C.L. (2014)
10^-43
10^-44
10^-45
10^-46
10^-47
10^-48
σ_ψ−nucleon (cm^2)
10
50
100
150
200
m_ψ (GeV)

TRULY NEUTRINO PORTAL

Even if we do not see a DM signal in DD, ID and LHC experiments, $c_{\rm II}, c_{\rm VII}^{\phi,(L,R)} \sim 0$ $c_{\rm III} \neq 0$, we still meet Planck constraints, truly neutrino portal, (only phenom consequences may come from $C\nu B$)

$$\mathcal{L}^{(\mathcal{F})} = \frac{c_{\rm III}}{\Lambda}(\bar{\Psi}\Phi)(\tilde{\phi}^\dagger \ell) + \frac{c_{\rm II}}{16\pi^2\Lambda}|\phi|^2\bar{\Psi}\Psi + \sum_{a=\ell\,\phi;\,i=L,R} \frac{c_{\rm VII}^{(a|i)}}{(4\pi\Lambda)^2}\left(J_{\rm SM}^{(a)} \cdot J_{\rm dark}^{(i)}\right) \tag{8}$$

SIMPLE MODEL REALIZATION

MODEL REALIZATION

Simple model: Heavy Fermion singlet (mediator), DM content: Ψ and Φ

$$\mathcal{L} = \bar{\mathcal{F}}_J(i\not{\partial} - m_o)\mathcal{F}_J - (\bar{\ell}_i\tilde{\phi}\mathcal{F}_J y_{iJ} + \mathrm{H.c}) + \bar{\ell}_i(i\not{\partial})\ell_i + (z_J\bar{\mathcal{F}}_J\Phi^\dagger\Psi + \mathrm{H.c}) \quad (9)$$

where ℓ is the left-handed SM lepton isodoublet, i, j, etc. are family indices $\mathcal{F}_J$ are neutral fermions, ϕ is the SM scalar isodoublet and $\tilde{\phi} = i\sigma_2\phi^*$.

Upon spontaneous symmetry breaking ($\langle\phi\rangle = v/\sqrt{2}$, $\langle\Phi\rangle = 0$),

$$\mathcal{L} = \bar{\mathcal{F}}_J(i\not{\partial} - m_o)\mathcal{F}_J - (\bar{\nu}_i\mathcal{F}_J\mu_{iJ} + \mathrm{H.c}) + \bar{\nu}_i(i\not{\partial})\nu_i + (z_J\bar{\mathcal{F}}_J\Phi^\dagger\Psi + \mathrm{H.c}) \quad (10)$$

where $\mu = vy/\sqrt{2}$.

Diagonalization

Assume there are 3 $\mathcal{F}$'s and rotate $\mathcal{F}$ and ν to diagonalize μ

$$\mathcal{L} = \bar{\mathcal{F}}(i\not\partial - m_o)\mathcal{F} - \mu(\bar{\nu}\mathcal{F} + \mathrm{H.c})(1 + h/v) + \bar{\nu}(i\not\partial)\nu + (z\bar{\mathcal{F}}\Phi^\dagger\Psi + \mathrm{H.c}) \tag{11}$$

Let

$$\mathcal{F} = -sn + (cP_L + P_R)N, \quad \nu = cn + sP_L N \tag{12}$$

where n is left handed and

$$s = \frac{\mu}{M} \qquad c = \frac{m_o}{M} \qquad M = \sqrt{\mu^2 + m_o^2} \tag{13}$$

then

$$\begin{aligned} \mathcal{L} \;=\; & \bar{N}(i\not\partial - M)N + \bar{n}(i\not\partial)n + [z(\bar{N}(cP_L + P_R) + s\bar{n})\Phi^\dagger\Psi + \mathrm{H.c}] \\ & -\frac{g}{2c_{\mathrm{w}}}[(c\bar{n} - s\bar{N})\not Z P_L(cn - sN)] \\ & -\frac{\mu}{v}\left[s\bar{N}N + c(\bar{n}N + \bar{N}n)\right]h - \lambda_x(\Phi^\dagger\Phi)h \end{aligned} \tag{14}$$

MATCHING EFFECTIVE INTERACTIONS

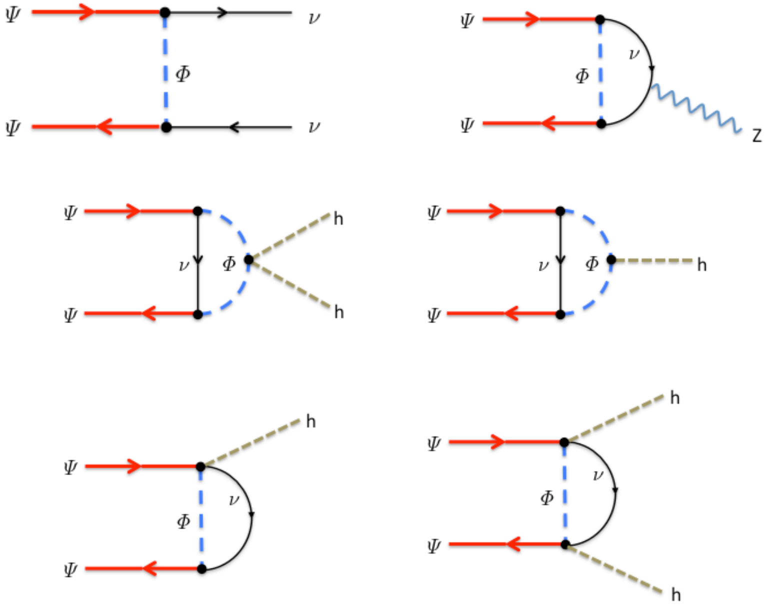
HMM loop induced contributions

There are no tree level interactions within DM and Z or the Higgs, these are induced at one loop.

$$\mathcal{L} = -I\frac{f_{ZL}}{\Lambda^2}\bar{\phi}\ \not{D}\phi\,\bar{\Psi}\gamma^{\mu}.P_L.\Psi - I\frac{f_{ZR}}{\Lambda^2}\bar{\phi}\ \not{D}\phi\,\bar{\Psi}\gamma^{\mu}.P_R.\Psi - \frac{f_h}{\Lambda}\bar{\phi}\phi\,\bar{\Psi}.\Psi$$

Matching with the effective interaction for large M

$$f_h = \frac{C_{II}}{16\pi^2}, \qquad f_{Z,(L,R)} = \frac{C_{VII}^{\phi,(L,R)}}{16\pi^2}$$
$$\mu z = \frac{C_{III}v}{\sqrt{2}}, \qquad \Lambda = \sqrt{m_0^2+\mu^2} \tag{15}$$


Ψ
ν
Φ
Z
h

CONCLUSIONS

CONCLUSIONS

- After categorizing all the possible non-redundant effective operators for non-trivial multi-component Dark Symmetries and SM interactions we see there are a few interesting set:
  - Scalar mediators: Higgs Portal (studied extensively),
  - Fermion mediators. DM content: Scalar and fermions: Heavier scalar $\to$ Neutrino portal ,
  - Vector mediators & Tensor mediators: further work..
- Neutrino Portal: Fermion meditor: satisfy experimental constraints,
  - Resonant (HMM loop induced) contributions from Z andd H
  - At reach for direct detection experiments,
  - DM annihilation in the core of the sun (almost monoenergetic neutrino): Still not sensitive enough, 4 to 5 order of magnitudes below SK limit
- Truly neutrino portal if DD, ID, exclude DM, meets correct relic abundance.