Semi-Annihilation and Dark Matter Indirect Detection

A Systematic Analysis

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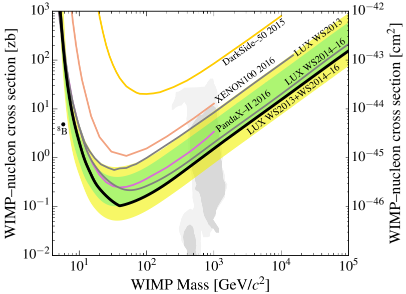
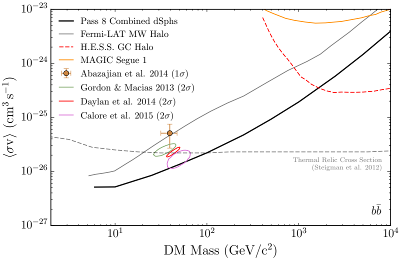
Introduction

Where are we heading?

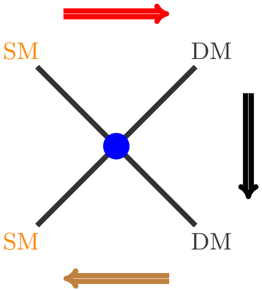
- Strong limits, null signals
  - Direct detection: embracing the neutrino background
  - Indirect detection
  - Collider test
- Take a break and check the assumptions?

  Z_2 well motivated, yet not generic



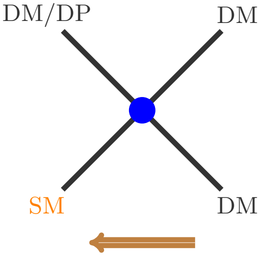


Semi-Annihilation



With Z_2

- Direct detection
- Indirect detection
- Collider test



Beyond Z_2

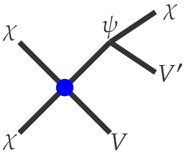
- Semi-annihilation(D'Eramo & Thaler, 2010)
- Odd number of external dark sector particles
- No σ_{DD} or $\sigma_{collider}$
- Modify relic density and ID

A summary of potential differences brought by SA

- (un)fortunately exempt from direct searches
- affect indirect searches
  - asymmetric kinematics for $\chi\chi \to \psi V$

$$E_V = \frac{4m_\chi^2 + m_V^2 - m_\psi^2}{4m_\chi}$$

  - dark partner decays



- SA study so far more model-dependent:

Belanger et al, 1202.2962; D'Eramo et al, 2120.7817; Ko & Tang, 1402.6449; Aoki & Toma, 1405.5870; Cai & Spray 1509.08481; $\cdots$

Model-independent Method: EFT

- integrate out heavy mediators → EFT operators

$$\mathscr{L} \sim \frac{1}{\Lambda^d} \chi^3 \mathcal{O}_{\rm SM}$$

- once dimension d and $\mathcal{O}_{\rm SM}$ fixed, easy to exhaust the theory space with the guidance of symmetries
- EFT especially convenient for semi-annihilation
  - mediator(if any) charged under dark symmetry and necessarily heavier than dark matter
  - only relic density and ID relevant, both non-relativistic
  - valid EFT description

Aims

Construct SA operators under assumptions

- DM is a stable gauge singlet, complex scalar or fermion, charged under exact global symmetry beyond Z_2
- consider $2 \to 2$ process with 3 dark sector particles
- up to dimension 6 and some leading at dimension 7

Derive constraints on operators

- limit on UV scale Λ (expect $d = 4$)
- assume relic density saturated
- other constraints if relevant

Operators

Dark Matter Only

- dark matter is a singlet of the SM gauge group
- $\mathcal{O}_{\rm SM}$: $H^\dagger H$ and $L^\dagger \tilde{H}$ with possible variation of derivatives

Sca. DM Op.	Definition
$\mathcal{O}_{5U}^{H}$	$s^{ijk}\phi_i\phi_j\phi_k\, H^\dagger H$
$\mathcal{O}_{7U}^{Z}$	$(x^{ikj}+y^{ijk})\,\phi_i\phi_j(\partial^\mu\phi_k)\big(iH^\dagger \overleftrightarrow{D}_\mu H\big)$
$\mathcal{O}_{7U}^{H}$	$(x^{ikj}+y^{ijk})\,(\partial_\mu\phi_i)(\partial^\mu\phi_j)\phi_k\, H^\dagger H$

Fer. DM Op.	Definition
$\mathcal{O}_{7U}^{LL}$	$\big(s^{ijk}+y^{ijk}+x^{ikj}\big)\,(\eta_i\eta_j)\,\big((L^\dagger\tilde{H})\bar{\xi}_k^\dagger\big)$
$\mathcal{O}_{7U}^{LR}$	$\big(y^{ijk}+x^{ikj}\big)\,(\bar{\xi}_i^\dagger\bar{\xi}_j^\dagger)\,\big((L^\dagger\tilde{H})\bar{\xi}_k^\dagger\big)$

Mixed DM Operator	Definition
$\mathcal{O}_{6U}^{LH^\dagger}$	$s^{ij}\,\phi_i\phi_j\,\big((L^\dagger\tilde{H})\bar{\xi}^\dagger\big)$
$\mathcal{O}_{7U}^{L}$	$a^{ij}\phi_i(\partial_\mu\phi_j)\,\big((L^\dagger\tilde{H})\bar{\sigma}^\mu\eta\big)$
$\mathcal{O}_{6U}^{HS}$	$s^{ij}\,\bar{\chi}_i^c\chi_j\,\phi\, H^\dagger H$
$\mathcal{O}_{6U}^{HP}$	$s^{ij}\,\bar{\chi}_i^c\gamma^5\chi_j\,\phi\, H^\dagger H$
$\breve{\mathcal{O}}_{6U}^{B}$	$a^{ij}\,\bar{\chi}_i^c\sigma^{\mu\nu}\chi_j\,\phi\,\breve{B}_{\mu\nu}$
$\mathcal{O}_{7U}^{ZV}$	$a^{ij}\,\bar{\chi}_i^c\gamma^\mu\chi_j\,\phi\,\big(iH^\dagger\overleftrightarrow{D}_\mu H\big)$
$\mathcal{O}_{7U}^{ZA}$	$s^{ij}\,\bar{\chi}_i^c\gamma^\mu\gamma^5\chi_j\,\phi\,\big(iH^\dagger\overleftrightarrow{D}_\mu H\big)$
$\mathcal{O}_{7U}^{HV}$	$a^{ij}\,\bar{\chi}_i^c\gamma^\mu\chi_j\,\big(\phi\overleftrightarrow{\partial}_\mu(H^\dagger H)\big)$
$\mathcal{O}_{7U}^{HA}$	$s^{ij}\,\bar{\chi}_i^c\gamma^\mu\gamma^5\chi_j\,\big(\phi\overleftrightarrow{\partial}_\mu(H^\dagger H)\big)$

- scalar DM ϕ_i
  fermion DM $\chi_i = (\eta_i, \xi_i^\dagger)^T$
- only two ops. for unique DM
- contain only neutral SM particles: h, Z, γ, ν
- mostly lead to $2 \to 3$ SA processes
- (relatively) simple model space

Higgs portal

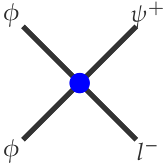
- besides SA ops, Higgs portal ops allowed

$$\mathcal{O}_{\phi H} = \lambda_{\phi H} \phi^\dagger \phi H^\dagger H \qquad \mathcal{O}_{\chi H} = \frac{c_{\chi H}}{\Lambda^5} \bar{\chi} \gamma^5 \chi H^\dagger H$$

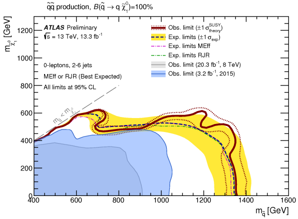
- sometimes even desirable if extra operators need to annihilate dark matter away
- For SA to dominate, constraints on $\lambda_{\phi H}$ and $c_{\chi H}$
  - SA generated at tree-level, Higgs portal at one-loop level
  - UV scale $\Lambda \lesssim 5 - 10$ TeV

Models with Dark Partner

- dark partners: relatively light unstable states
  - allow SA to charged/colored particles
  - allow lower-dimensional operators

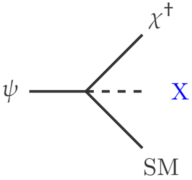


- dark partners decay without breaking DM symmetry
- search dark partners at colliders
  - mass $\gtrsim 1-2$ TeV for colored or $200-500$ GeV for charged particles
  - indirectly set a bound on DM mass, $m_{\rm DM} > \frac{1}{2}m_{\rm DP}$



Decay of Dark Partners

- dark partner can not decay via the same operator
  - $\psi \to \phi\phi + \text{SM}$ kinematically forbidden
  - new coupling needed $\psi \to \phi^\dagger + \text{SM}$
- model dependent decay of dark parnters
  - should be allowed by all symmetries
  - fermion DM can not have two body decays



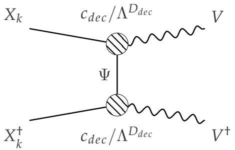
- bounds on lifetime of dark partner from BBN

  $\tau \lesssim 0.05\ s \Rightarrow c_{dec} \gtrsim 10^{-11}(4\pi)^{n-2}\left(\frac{\Lambda}{m_{\text{DP}}}\right)^{D_{\text{dec}}-4}$

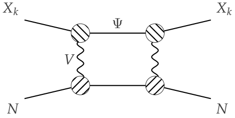
New Pheno from Dark Partner Decay

- obviously dark partner decay contributes to cosmic ray signal
  - depends on the mass of dark partner
  - the details of the decay, quite model dependent
- other complications (see e.g. 1509.08481)
  - dark matter annihilation through t-channel dark partner
  - dark matter coannihilates with dark partner
  - could enhance contributions to direct detection
  - possible dark matter and dark partner mixing
- general bounds $c_{\rm dec} \lesssim 0.1 - 0.01$

annihilation through t-channel



contribution to direct detection



A Review of the Ops.

- possibilities vastly increased
- on the right: scalar DM ops.
- one $d = 4$ op.
- a handful of $d = 5$ ops.
- can couple to all SM particles
  γ/g require multi-component DM

Operator	Definition	ω/ψ
$\mathcal{O}_{4U}^{H}$	$s^{ij}\,\phi_i\phi_j\,(H^\dagger\omega)$	$(1,\,2,\,\frac{1}{2})$
$\mathcal{O}_{5U}^{\lvert H\rvert_1^2}$	$s^{ij}\,\phi_i\phi_j\,\omega\,H^\dagger H$	$(1,\,1,\,0)$
$\mathcal{O}_{5U}^{\lvert H\rvert_3^2}$	$s^{ij}\,\phi_i\phi_j\,\omega^a\,H^\dagger\sigma^a H$	$(1,\,3,\,0)$
$\mathcal{O}_{5U}^{H^2}$	$s^{ij}\,\phi_i\phi_j\,\omega^a\,H^\dagger\sigma^a\tilde{H}$	$(1,\,3,\,1)$
$\mathcal{O}_{6U}^{Hd}$	$s^{ij}\,\phi_i\phi_j\,(H^\dagger\omega)(H^\dagger H)$	$(1,\,2,\,\frac{1}{2})$
$\mathcal{O}_{6U}^{Hq}$	$s^{ij}\,\phi_i\phi_j\,\omega^{IJK}H_I^\dagger H_J^\dagger\tilde{H}_K^\dagger$	$(1,\,4,\,\frac{1}{2})$
$\mathcal{O}_{6U}^{H^3}$	$s^{ij}\,\phi_i\phi_j\,\omega^{IJK}H_I^\dagger H_J^\dagger H_K^\dagger$	$(1,\,4,\,\frac{3}{2})$
$\mathcal{O}_{6U}^{H\partial^2}$	$s^{ij}\,(\partial_\mu\phi_i)(\partial^\mu\phi_j)(H^\dagger\omega)$	$(1,\,2,\,\frac{1}{2})$
$\mathcal{O}_{6U}^{H\partial D}$	$a^{ij}\,\phi_i(\partial_\mu\phi_j)\left(H^\dagger\overleftrightarrow{D}_\mu\omega\right)$	$(1,\,2,\,\frac{1}{2})$
$\mathcal{O}_{6U}^{HD^2}$	$s^{ij}\,\phi_i\phi_j\,(D^\mu H)^\dagger(D_\mu\omega)$	$(1,\,2,\,\frac{1}{2})$
$\mathcal{O}_{5U}^{\bar{f}\psi}$	$s^{ij}\,\phi_i\phi_j\,\bar{f}\zeta$	$(\bar{R}_{\bar{f}},\,1,\,-Y_{\bar{f}})$
$\mathcal{O}_{5U}^{F\psi}$	$s^{ij}\,\phi_i\phi_j\,F^\dagger\bar{v}^\dagger$	$(R_F,\,2,\,Y_F)$
$\mathcal{O}_{6U}^{\bar{f}H\psi}$	$s^{ij}\,\phi_i\phi_j\,\bar{f}(\tilde{H}^\dagger\zeta)$	$(\bar{R}_{\bar{f}},\,2,\,-Y_{\bar{f}}-\frac{1}{2})$
$\mathcal{O}_{6U}^{\bar{f}H^\dagger\psi}$	$s^{ij}\,\phi_i\phi_j\,\bar{f}(H^\dagger\zeta)$	$(\bar{R}_{\bar{f}},\,2,\,-Y_{\bar{f}}+\frac{1}{2})$
$\mathcal{O}_{6U}^{FH\psi_1}$	$s^{ij}\,\phi_i\phi_j\,(F^\dagger H)\bar{v}^\dagger$	$(R_F,\,1,\,Y_F-\frac{1}{2})$
$\mathcal{O}_{6U}^{FH^\dagger\psi_1}$	$s^{ij}\,\phi_i\phi_j\,(F^\dagger\tilde{H})\bar{v}^\dagger$	$(R_F,\,1,\,Y_F+\frac{1}{2})$
$\mathcal{O}_{6U}^{FH\psi_3}$	$s^{ij}\,\phi_i\phi_j\,(F^\dagger\sigma^a H)\bar{v}^{a\dagger}$	$(R_F,\,3,\,Y_F-\frac{1}{2})$
$\mathcal{O}_{6U}^{FH^\dagger\psi_3}$	$s^{ij}\,\phi_i\phi_j\,(F^\dagger\sigma^a\tilde{H})\bar{v}^{a\dagger}$	$(R_F,\,3,\,Y_F+\frac{1}{2})$
$\mathcal{O}_{6U}^{\bar{f}\partial}$	$a^{ij}\phi_i(\partial_\mu\phi_j)\,\bar{f}\sigma^\mu\bar{v}^\dagger$	$(\bar{R}_{\bar{f}},\,1,\,-Y_{\bar{f}})$
$\mathcal{O}_{6U}^{F\partial}$	$a^{ij}\phi_i(\partial_\mu\phi_j)\,F^\dagger\bar{\zeta}^\mu\eta$	$(R_F,\,2,\,Y_F)$

Constraints

Overviews

- limits from cosmic ray and other astrophysical observations

gamma ray, positron, neutrinos

cosmic microwave background

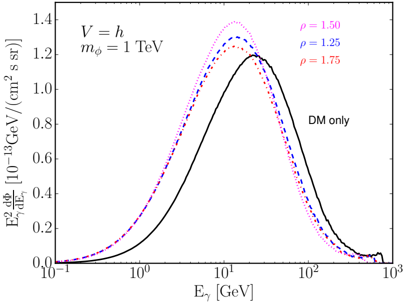
- assumptions:
  - DM is single component
  - one operator at a time
  - fix the mass ratio of dark partner and dark matter
- set limits on the EW broken phase operators
  - direct connection to amplitudes
  - easier to translate to constraints for general models

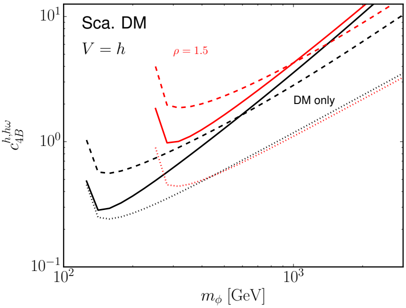
Unique Scalar Limit

- two operators

$$\frac{1}{6} c_{4B}^{h} \phi^3 h \qquad \frac{1}{2} c_{4B}^{h\omega} \phi^2 \omega h$$

- gamma ray spectra vary with ρ with the strongest at $\rho = 1.5$
- constraints and projection
  - solid for Fermi-LAT limit
  - dashed for CTA projection
- relic density shown in dotted lines



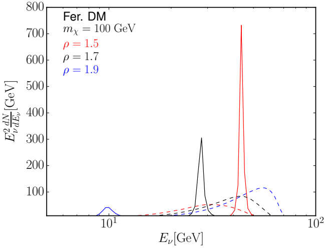


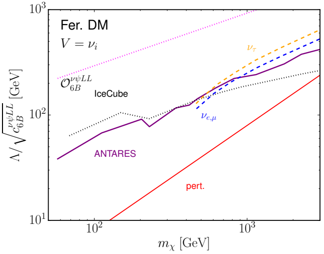
Unique Fermion Limit

- $d = 6$ ops.

$$\frac{1}{6\Lambda^2}\chi^3\nu \qquad \frac{1}{2\Lambda^2}(\chi\chi)(\bar{\nu}\psi)$$

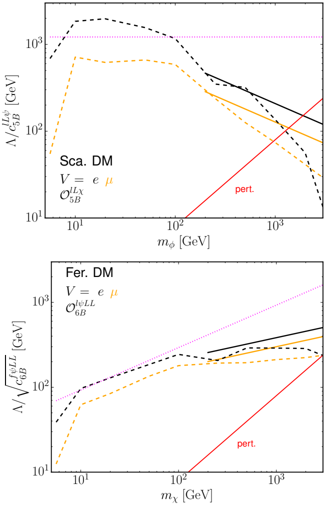
- ρ determines the size of contribution from SA and the decay of DP
- $\rho = 1.5$ sets the former to be absolutely dominant
- regions below excluded
- perturbativity shown in red dotted line
- below the relic curve the universe is not overclosed





Leptonic Dark Partner

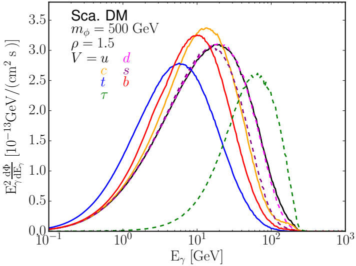
- $d = 5$ and 6 ops
  top: $\frac{1}{2\Lambda}\phi^2\bar{f}\psi$
  bottom: $\frac{1}{2\Lambda^2}(\chi\chi)\bar{f}\psi$
- positron propagated with DRAGON
- AMS limits: dashed lines
- CMB limits: solid lines

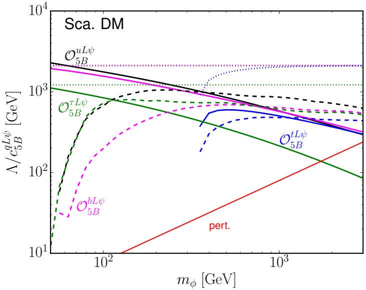


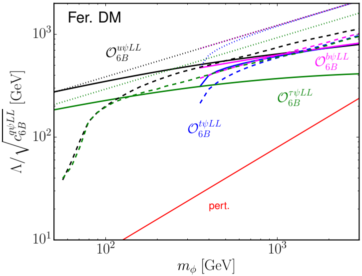
Hadronic Dark Partner: quarks and τ

- $d = 5$ and 6 ops
  $\frac{1}{2\Lambda}\phi^2\bar{f}\psi$ and $\frac{1}{2\Lambda^2}(\chi\chi)\bar{f}\psi$
- Fermi-LAT limits: solid lines
- CTA projection: dashed lines
- four spieces shown

u,b,t and τ







Conclusion

Conclusion

- Semi-Annihilation is a generic feature of dark matter
- Constructed all SA operators up to dimension 6
- Model space for DM-only theories is small
- Dark partners lead to more varied phenomenology at cost of dependence on dark partner decay modes
- Derived limits and prospects from cosmic ray searches; close to relic cross section in some fermionic channels
- Many questions remain, e.g. UV completions