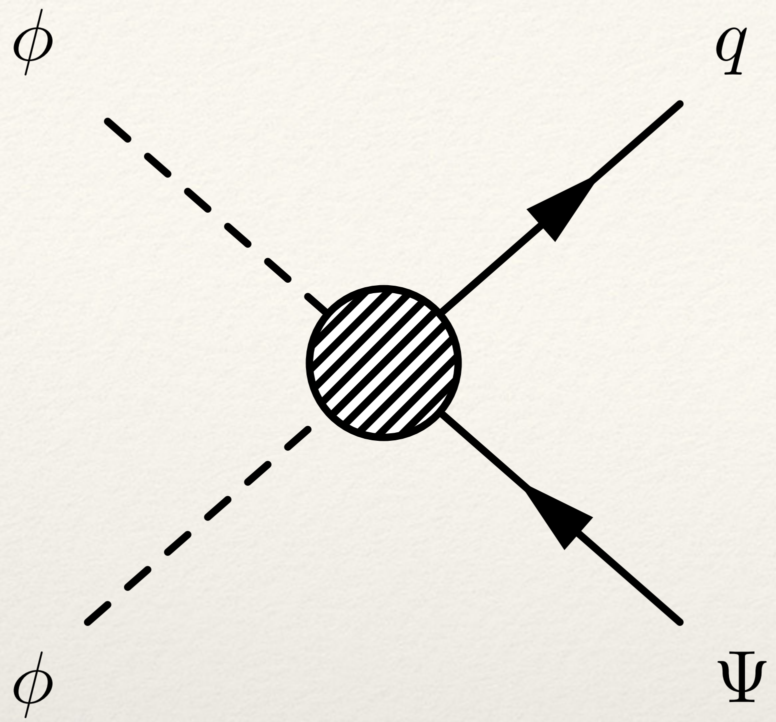

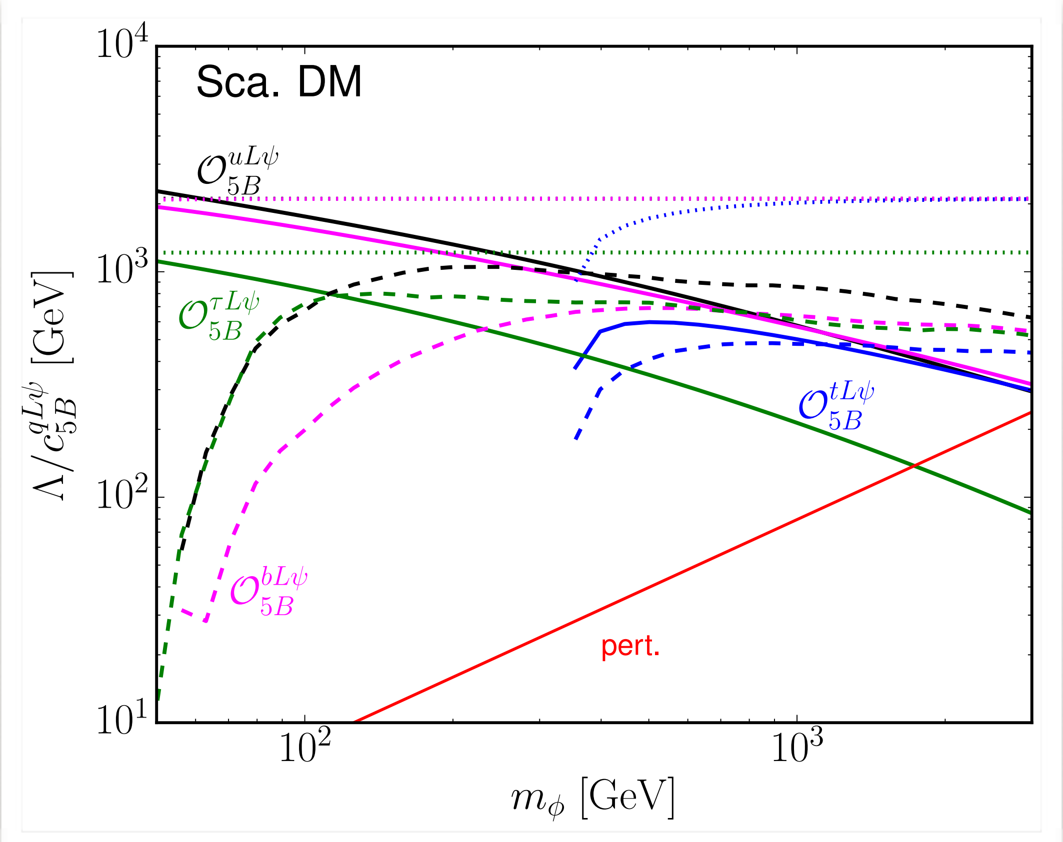

기초과학연구원
Institute for Basic Science

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A Systematic Analysis of Semi-Annihilation

Yi Cai & Andrew Spray,
1611.xxxxx

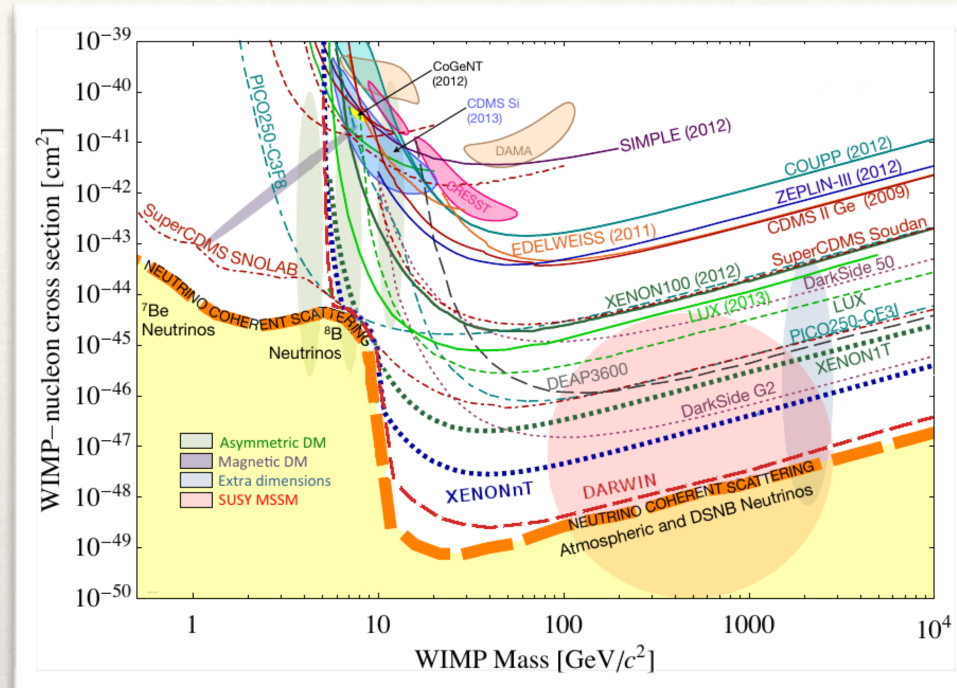
Outline

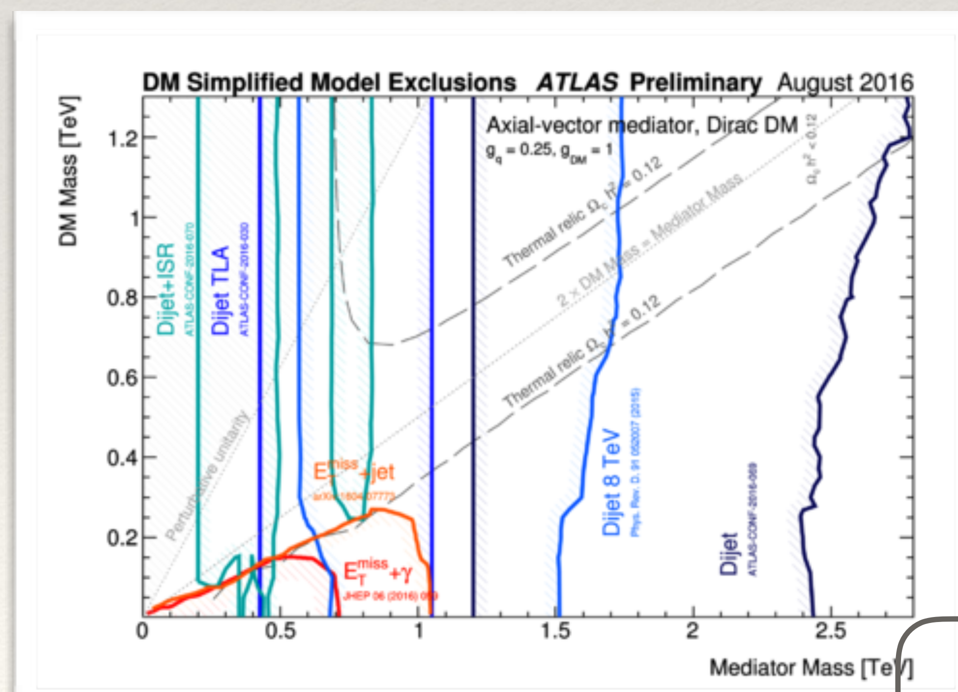
1. Introduction
    (a) Semi-Annihilation
    (b) Effective Operators
2. Effective Operators
    (a) Dark Matter Only
    (b) Dark Partner Models
3. Constraints
4. Conclusions

Introduction

Constraints

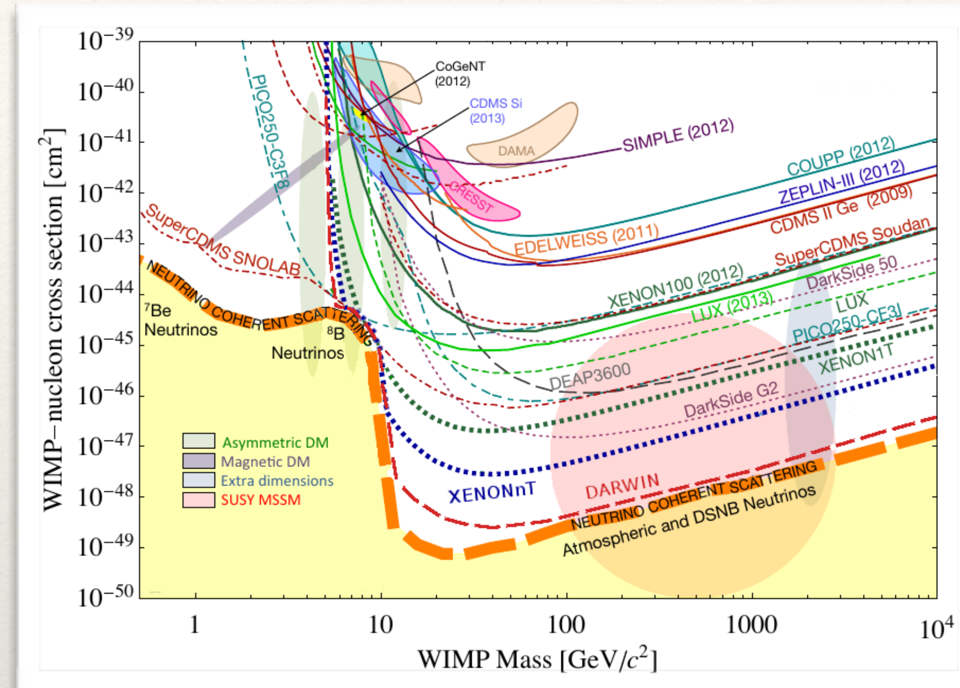
- Bounds on thermal DM starting to get quite strong
- Successful test of this idea!
- But we should be diligent in checking for loopholes
- What are our assumptions? What if we relax them?

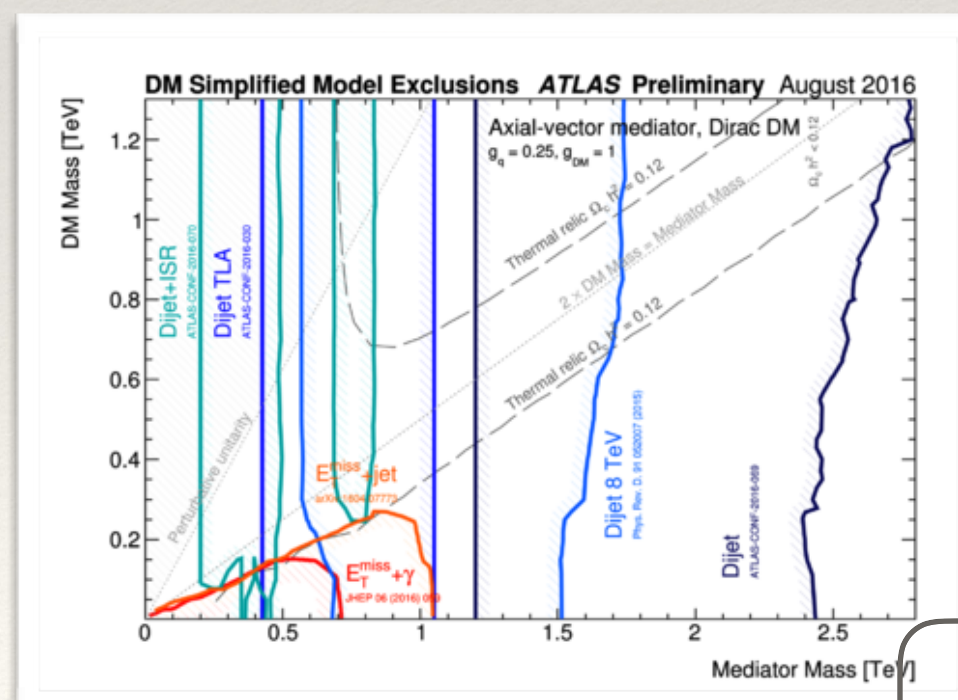




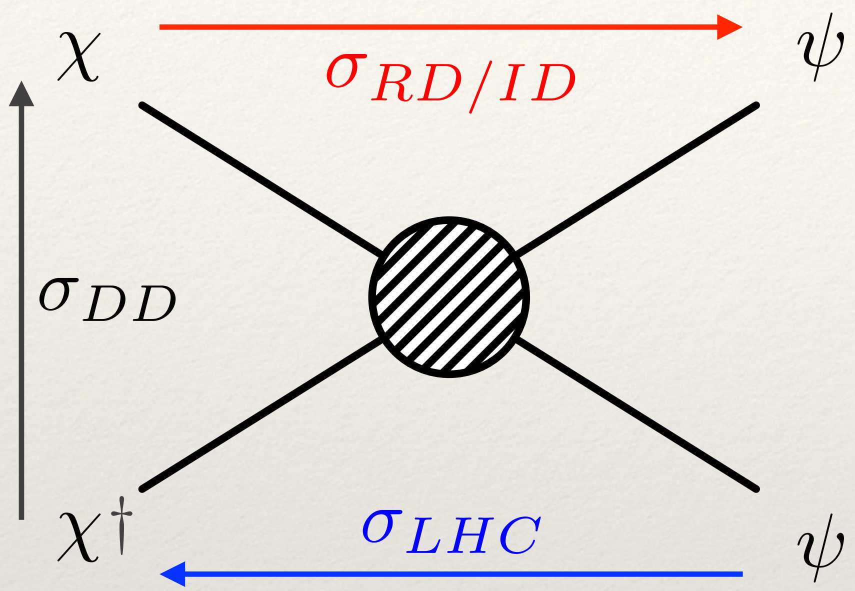
Constraints

- Bounds on thermal DM starting to get quite strong
- Successful test of this idea!
- But we should be diligent in checking for loopholes
- What are our assumptions? What if we relax them?
- Very basic assumption: DM stabilised by Z_2 symmetry





Semi-Annihilation



- Implies this familiar diagram
- Detection rates related to relic density calculation
- Leads to these strong bounds

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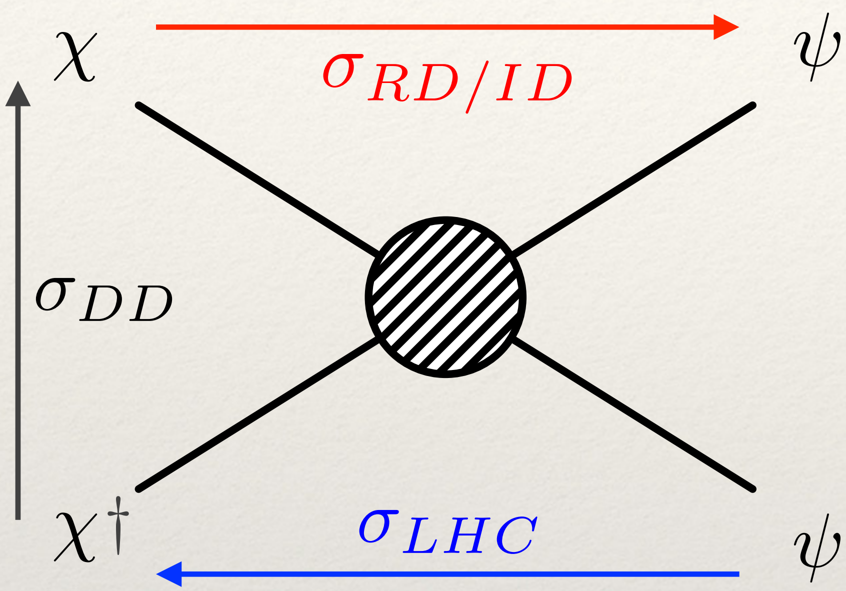
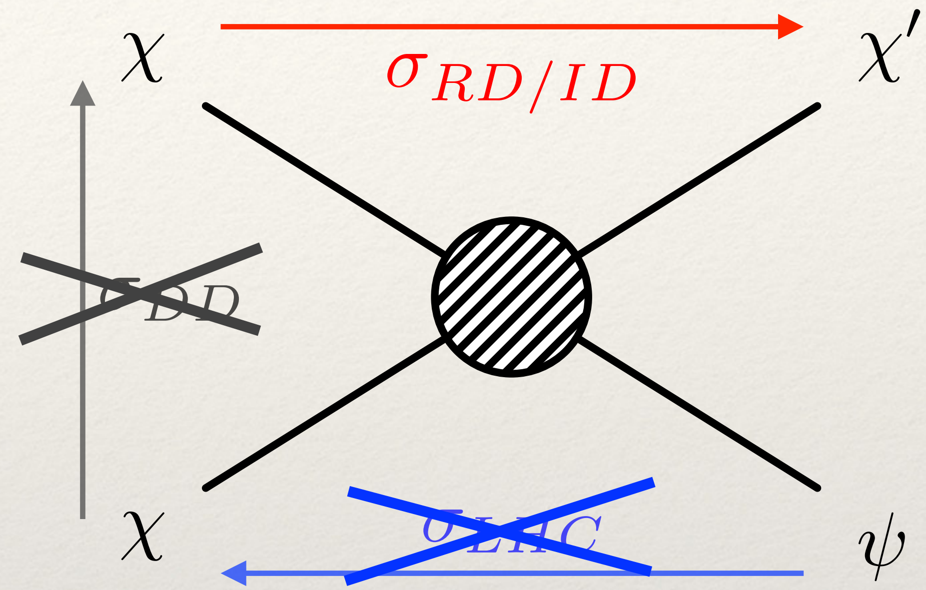


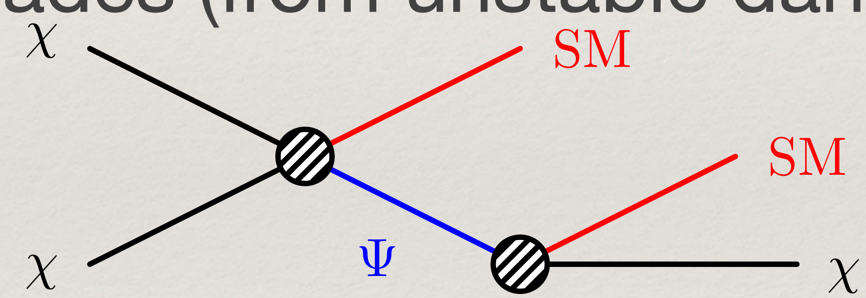


- Implies this familiar diagram
- Detection rates related to relic density calculation
- Leads to these strong bounds

- Not Generic! (D'Eramo & Thaler, 2010)
- Non-Z_2 syms ➻ Semi-Annihilation:
  - Non-decay processes
  - Odd number of external dark states
- Irrelevant for colliders & DD

SA Phenomenology

- Relax bounds from terrestrial searches
- SA affects indirect (cosmic ray) searches
  - Different kinematics $E = \dfrac{(m_{i_1}+m_{i_2})^2 + m_V^2 - m_f^2}{2(m_{i_1}+m_{i_2})}$
  - Dark sector cascades (from unstable dark states)



- A number of studies so far
  Bélanger *et al*, `1202.2962`; D'Eramo *et al*, `1210.7817`; Ko & Tang, `1402.6449`; Aoki & Toma, `1405.5870`; Berger *et al*, `1401.2246`; Fonseca *et al*, `1507.08295`; Cai & Spray, `1509.08481`
- But based on particular models; no general study so far

Exploring Model Space: EFTs

$$\mathcal{L} \supset \frac{1}{\Lambda^d}\,\chi^3 \mathcal{O}_{SM}$$

- Standard tool for model-independent studies
  - Two sectors: dark and visible
  - Integrate out mediators to generate EFT
- Easy to exhaust possibilities
- Direct connection to initial & final states
- Very applicable for Semi-annihilation:
  - Mediators must be more massive than DM
  - Freeze out & indirect detection non-relativistic so EFT valid

Goals

1. Construct “all” SA effective operators
   - DM is stable gauge singlet, complex scalar or fermion, charged under exact global symmetry $\mathrm{D} \neq \mathrm{Z}_2$
   - Consider $2 \to 2$ processes with 3 dark sector fields
   - List all operators up to $\mathrm{d} = 6$ & some leading at $\mathrm{d} = 7$
2. Derive constraints on UV scale Λ
   - Indirect searches assuming saturates relic density
   - Other constraints as relevant; on UV completion if possible

Effective Operators

Dark Matter Only

- Write down all operators consistent with assumptions
  - Scalar

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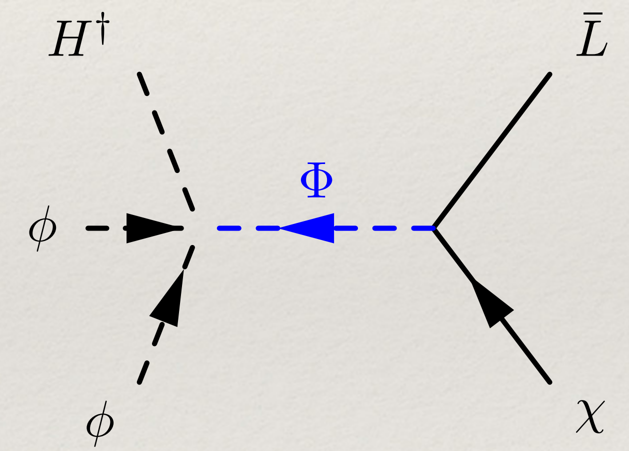
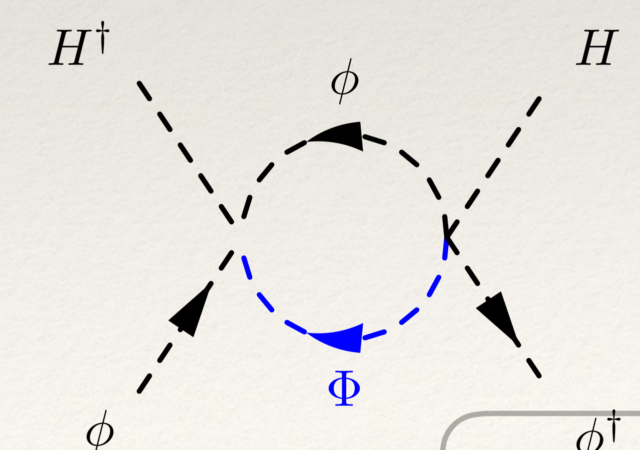
Higgs Portals

- We have found one operator at $\mathrm{d}=5$, four at $\mathrm{d}=6$
- Compare this to the always-allowed Higgs portals:

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

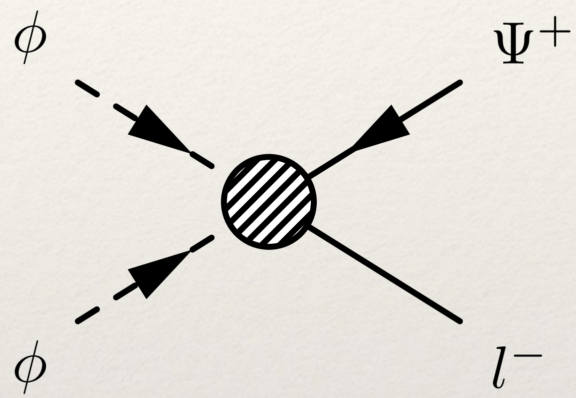
- If SA is to dominate, these must be suppressed
  - SA (Portal) generated at tree-level (one loop)
  - UV scale ≲ 5—10 TeV
- Constrains UV particle content:
  - No gauge- and D-singlet scalars
  - No EW doublets in conjugate D-rep, same spin as DM

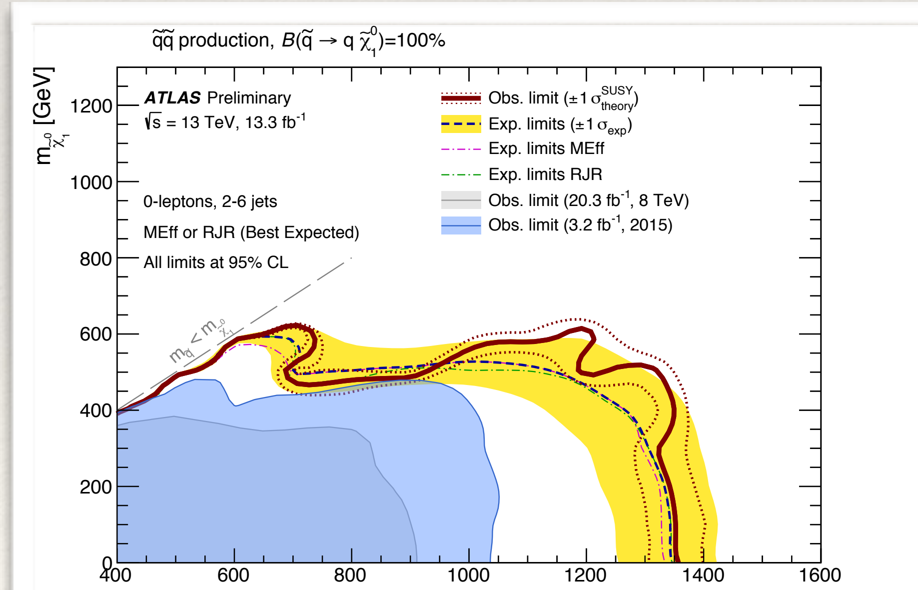




Dark Partners

- Dark Partners: relatively light unstable states
  - Allows SA to charged/coloured objects
  - Allows lower-dimensional operators
- Dark Partners must decay without breaking DM symmetry
- Important for colliders
  - $m_{DP} \gtrsim$ 1—2 TeV (coloured) or 200—500 GeV (charged)
  - Implied bounds on DM, $m_{DM} > \frac{1}{2}\, m_{DP}$





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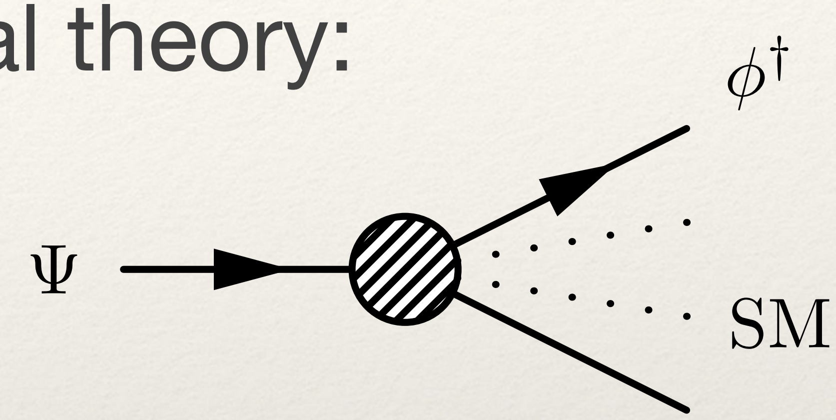
Decay Operators

- Dark partner cannot decay in minimal theory:
  - $\Psi \to \varphi\varphi + \mathrm{SM}$ kinematically forbidden
  - Need new coupling $\Psi \to \varphi^\dagger + \mathrm{SM}$

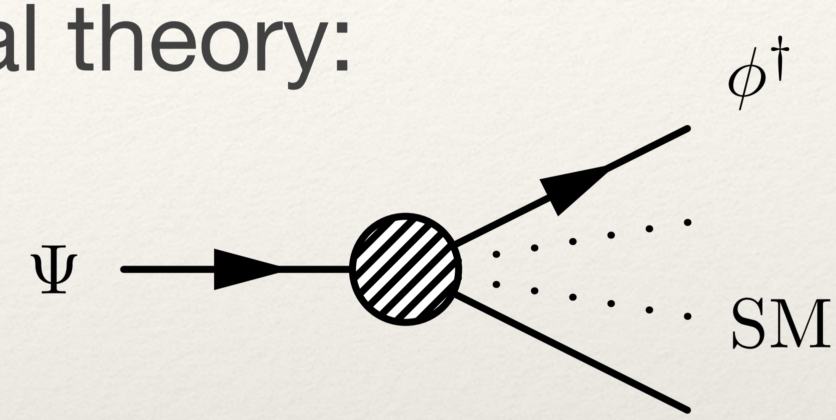


- Additional model dependence
  - Minimal allowed by symmetries? Or similar to SA operator?
  - Fermion DM particularly problematic: 2-body decays forbidden
- Lower bound on decay rate from BBN

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

Decay Operators

- Dark partner cannot decay in minimal theory:
  - $\Psi \to \varphi\varphi + \mathrm{SM}$ kinematically forbidden
  - Need new coupling $\Psi \to \varphi^\dagger + \mathrm{SM}$



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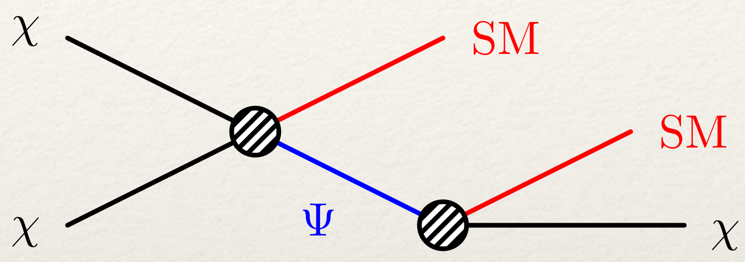
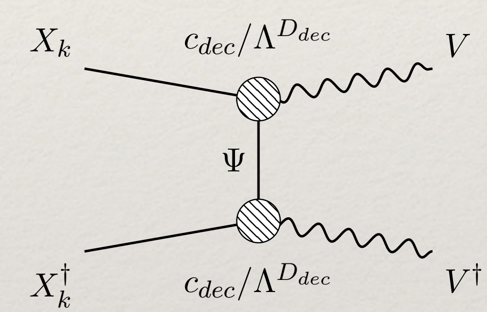
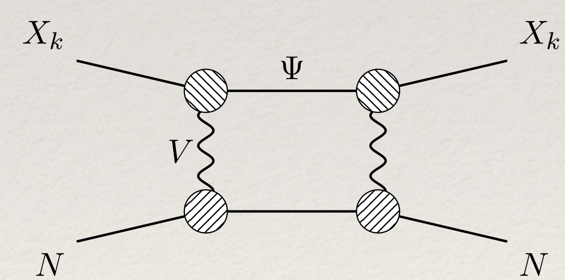
New Phenomenology

- Prompt decays contribute to cosmic ray signals
  - Function of dark partner mass
  - Depends on decay mode



- Lead to upper bounds on Wilson coefficient:
  - DM annihilation through t-channel Dark partner
  - DM-Dark partner coannihilation
  - Enhanced contributions to direct detection
  - Possible DM-Dark partner mixing





- General bound $c_{\rm dec} \lesssim 0.1$—0.01

Operator List

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

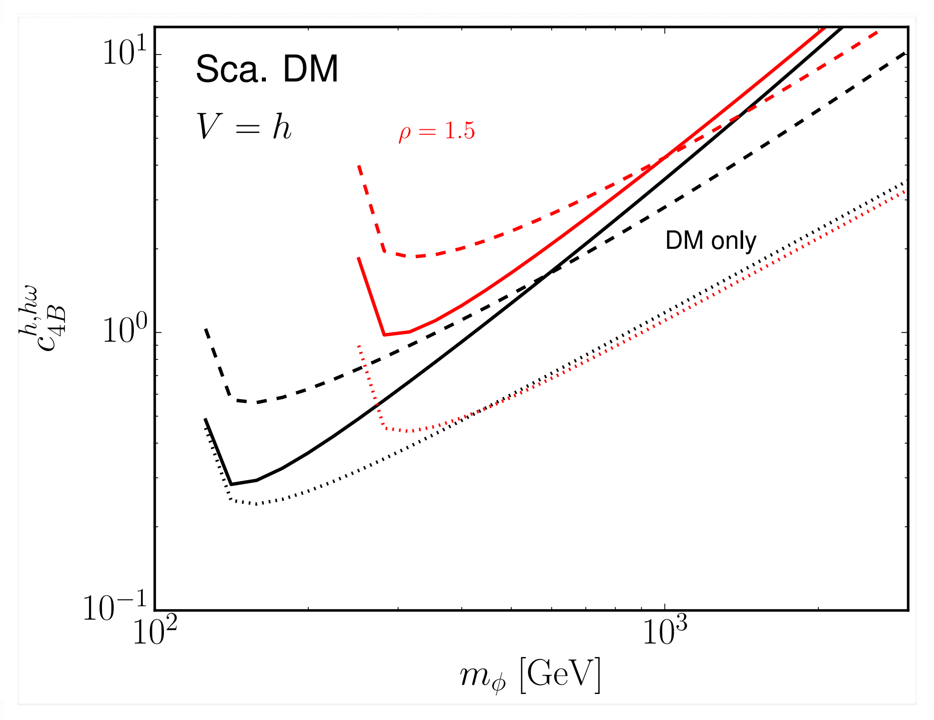
- Possibilities vastly increased
- Scalar DM plus
  - Scalar dark partner (top)
  - Fermion dark partner (bottom)
- One renormalisable operator
- Multiple $d = 5$ operators
- Situation for fermion and scalar-fermion DM similar
- All SM final states possible
  - γ/g require multi-component DM

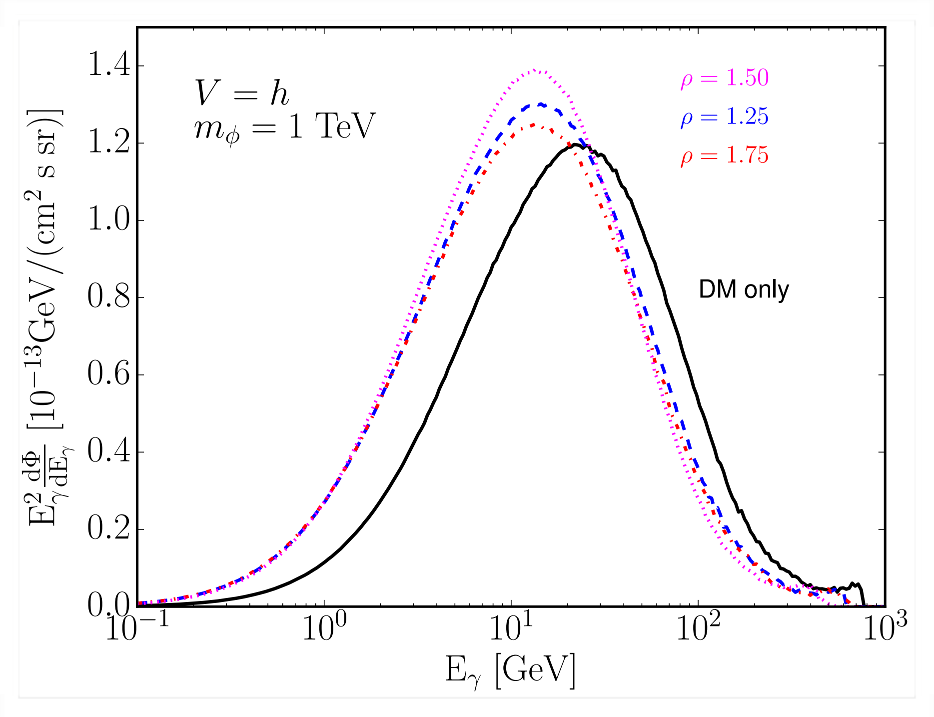
Constraints

Overview

- Derive limits from γ-ray, positron & neutrino telescopes
- Additional assumptions:
  - DM is single component
  - Only one operator is relevant
  - Fix dark partner-DM mass ratio to 1.5
- Set limits on EW broken phase operators
  - Direct connection to amplitudes
  - More easily applicable to general models

Unique Scalar Limits



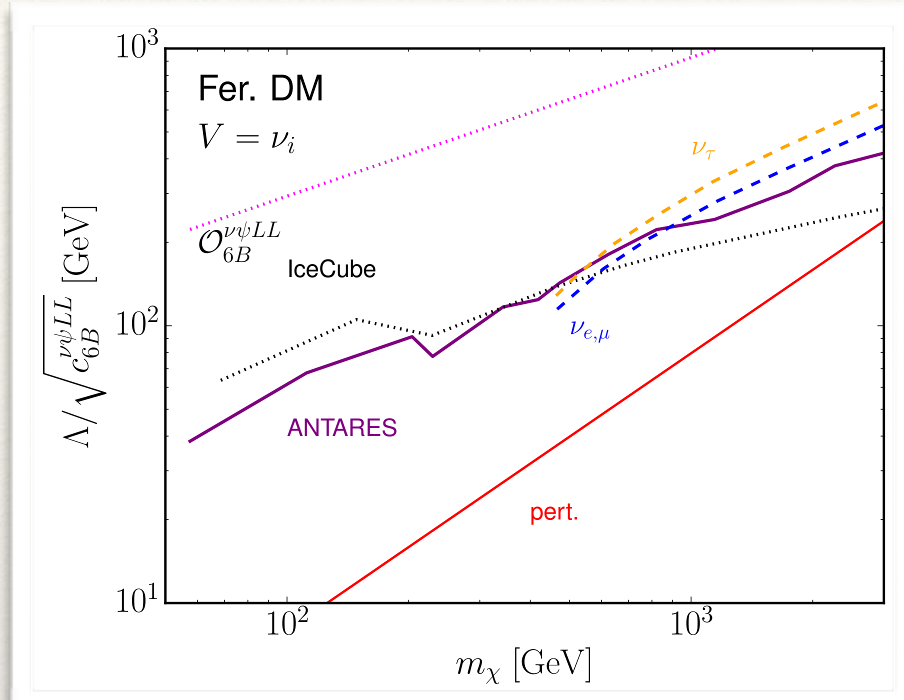


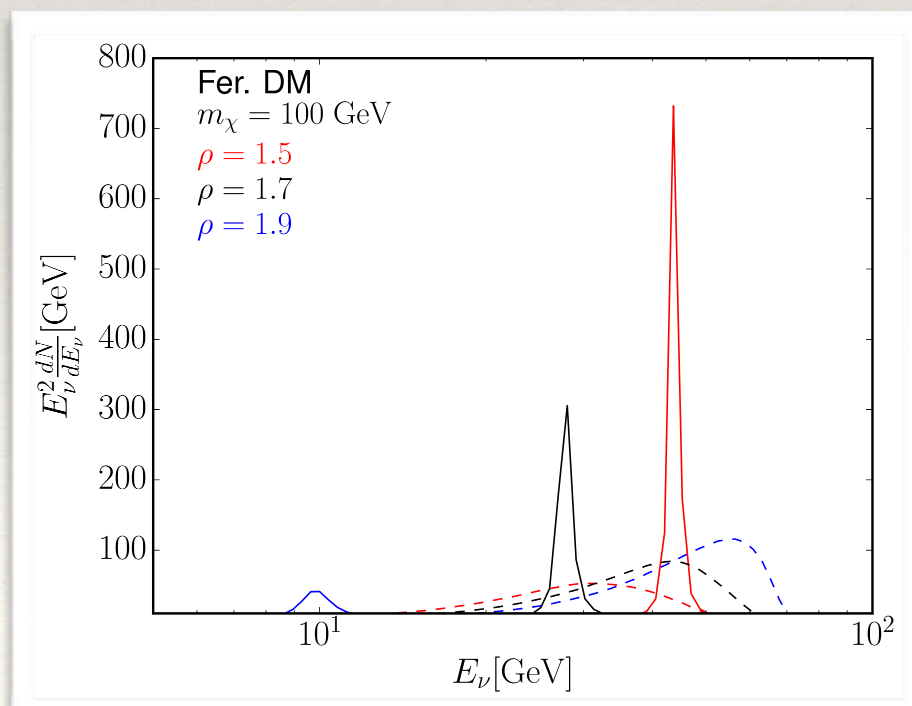
- Bound on dimension-4 ops

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

- Regions above lines excluded:
  - Solid: Fermi (current)
  - Dashed: CTA (projected)
- Dots: relic density just from SA
- Bottom: γ-ray spectra:
  - Solid: DM alone
  - Other: varied dark partner masses

Unique Fermion Limits



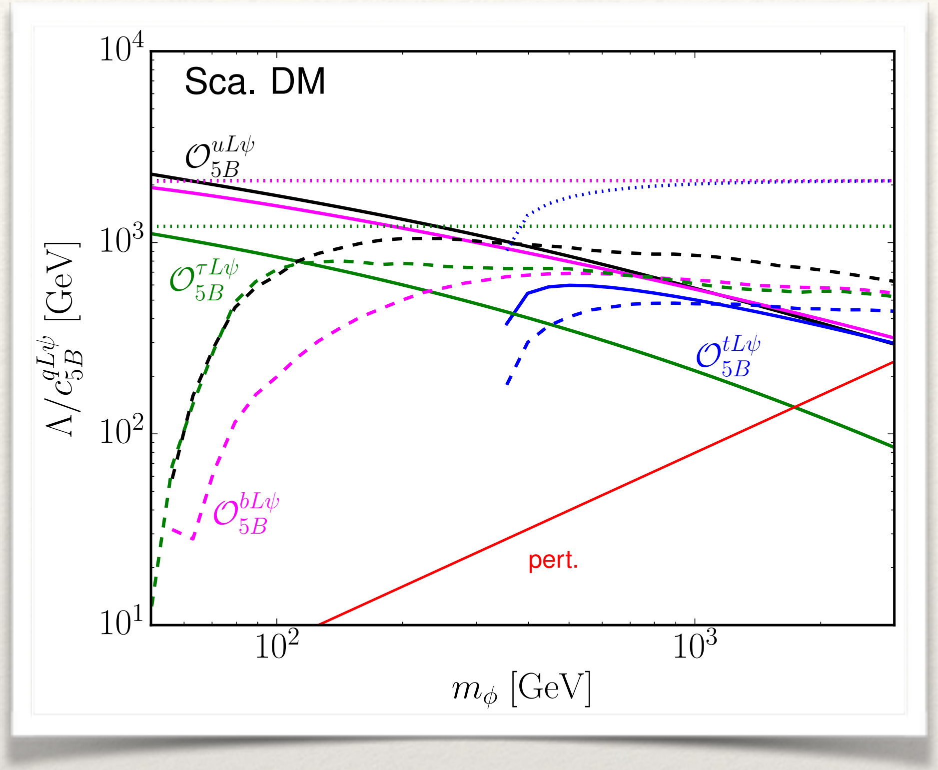


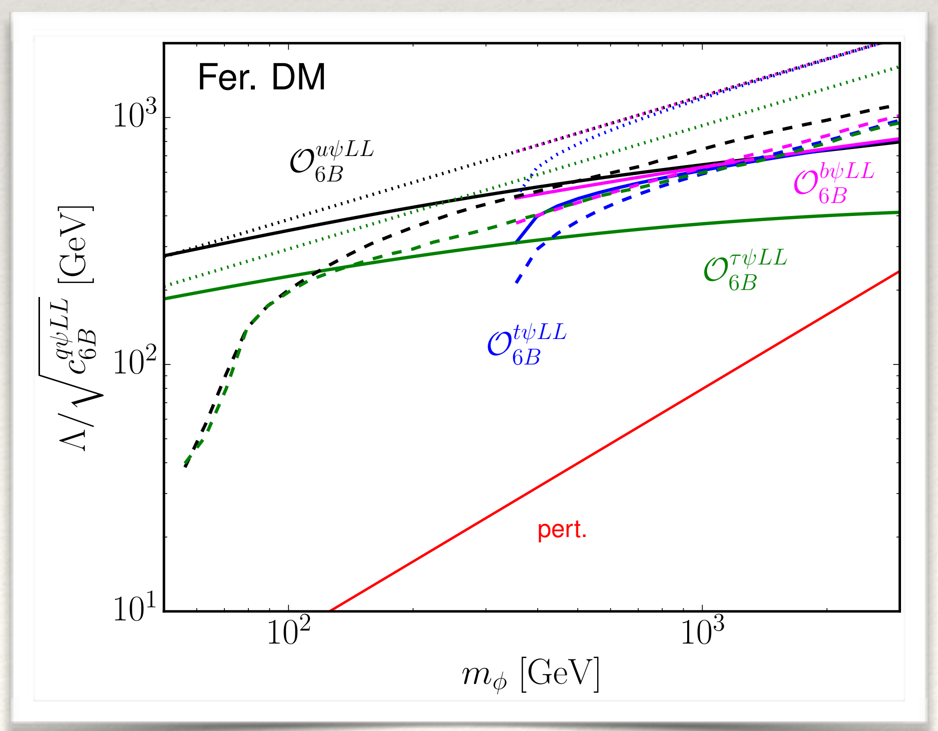
- Bounds on dimension-6 ops

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

- Regions below lines exluded
  - Red: perturbativity (EFT)
  - Solid: as marked (current)
  - Dashed: CTA (projected)
- Dots: relic density from SA alone
- Bottom: ν spectrum
  - Solid: SA neutrinos
  - Dashed: Dark partner decay neutrinos
  - Choose DP mass to suppress latter

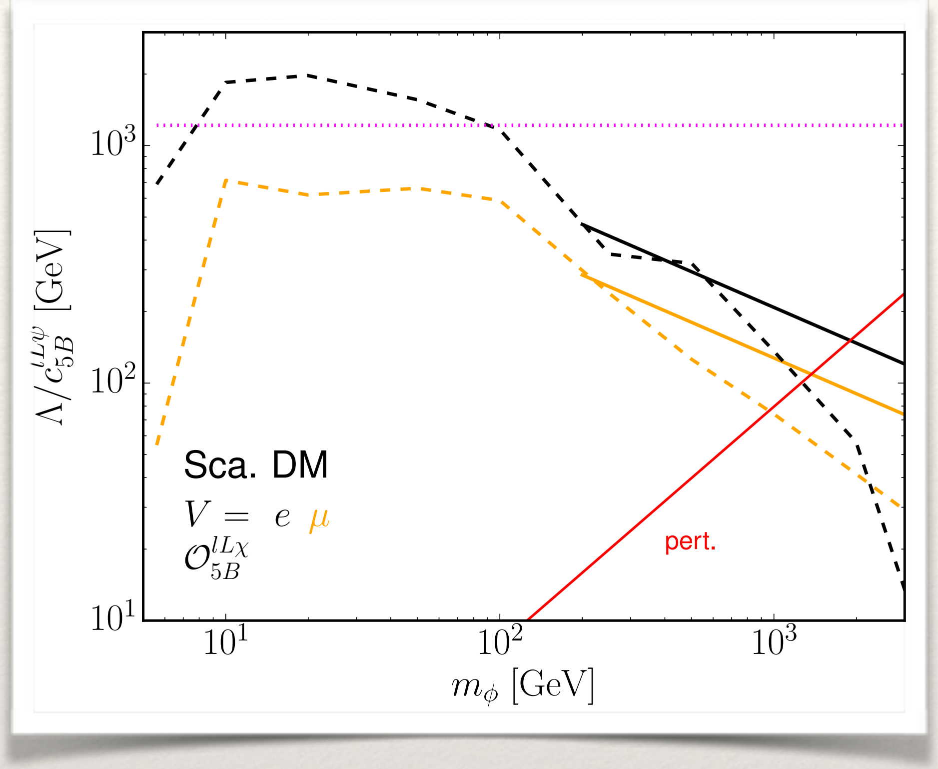
Hadronic Dark Partner Limits

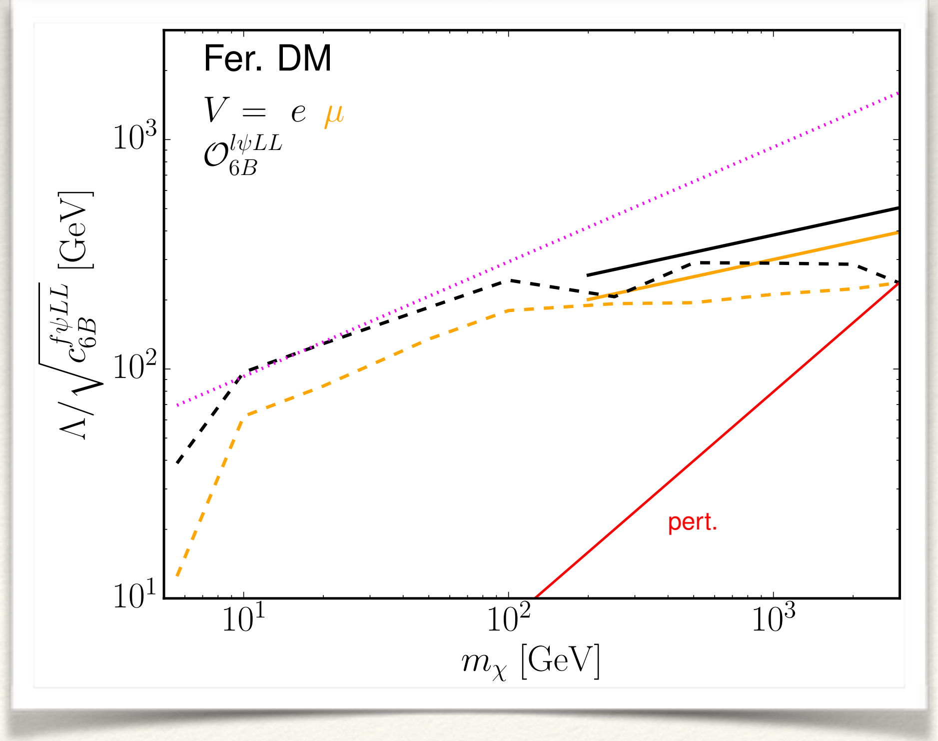




- Top: bounds on d = 5 ops
$$\frac{1}{2\Lambda}\,\phi^2\,\bar{f}\psi$$
- Bottom: bounds on d = 6 ops
$$\frac{1}{2\Lambda^2}\,(\chi\chi)\,\bar{f}\psi$$
- Regions below lines exluded
  - Red: perturbativity (EFT)
  - Solid: Fermi (current)
  - Dashed: CTA (projected)
- Dots: relic density from SA alone
- LHC limits not shown

Leptonic Dark Partner Limits





- Top: bounds on d = 5 ops

$$\frac{1}{2\Lambda}\,\phi^2\,\bar{f}\psi$$

- Bottom: bounds on d = 6 ops

$$\frac{1}{2\Lambda^2}\,(\chi\chi)\,\bar{f}\psi$$

- Regions below lines exluded
  - Red: perturbativity (EFT)
  - Solid: AMS (current)
  - Dashed: CMB (current)
- Dots: relic density from SA alone
- As of 6 hours ago!

Conclusions

Conclusions

- 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 & prospects from cosmic ray searches; close to relic cross section in some fermionic channels
- Many questions remain, e.g. UV completions