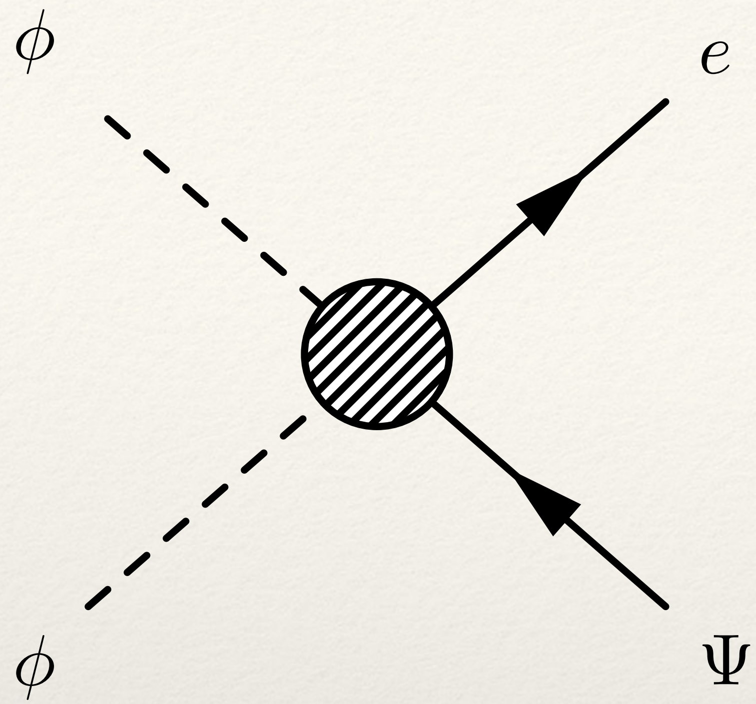
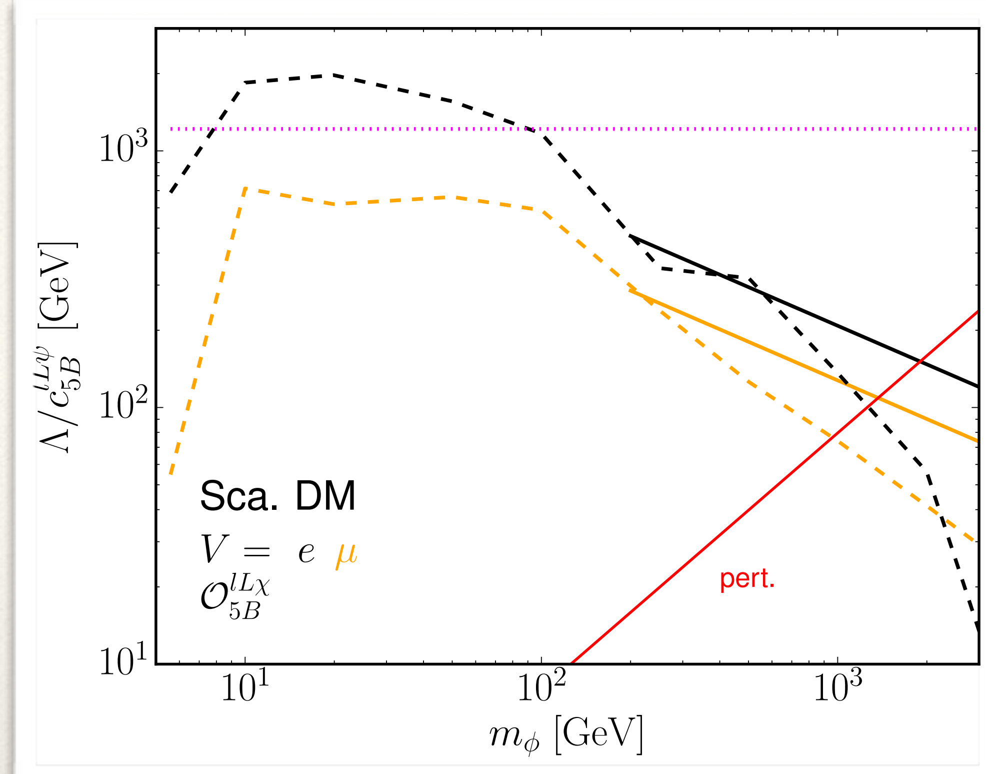




Planck 2017

A Systematic Analysis of Semi-Annihilation

Yi Cai & Andrew Spray,
1611.09360

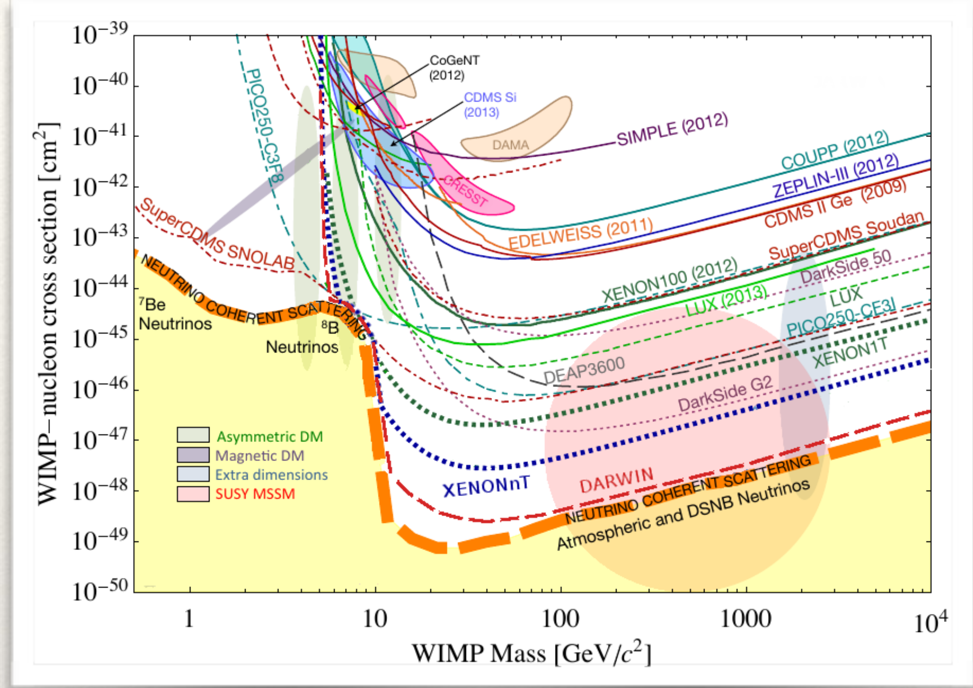
Outline

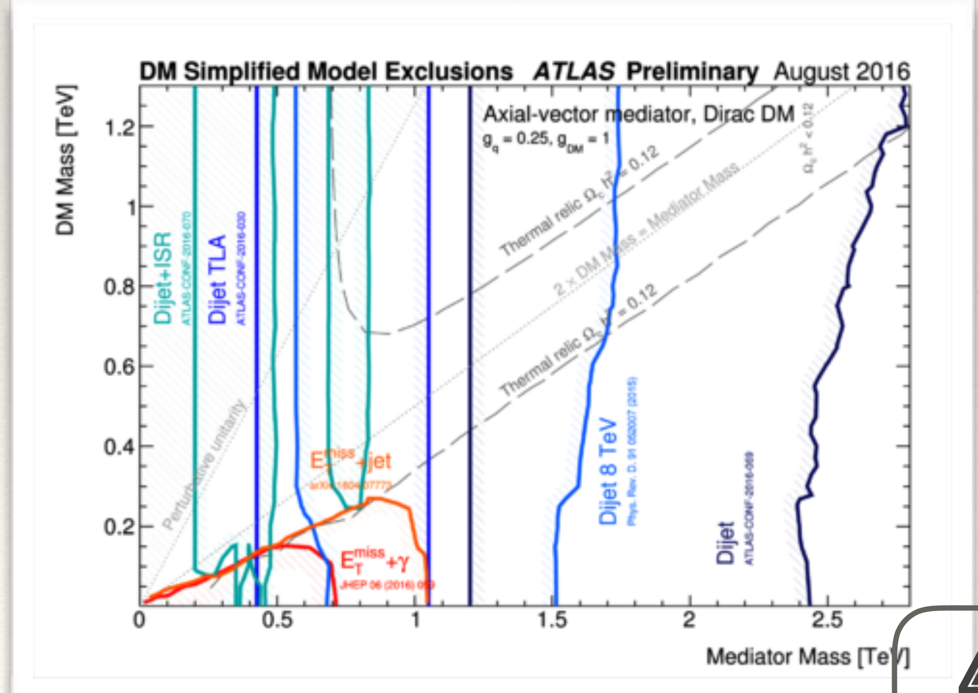
1. Semi-Annihilation
2. Effective Operators
3. Phenomenology & Constraints
4. Conclusions

Semi-Annihilation

Thermal Dark Matter

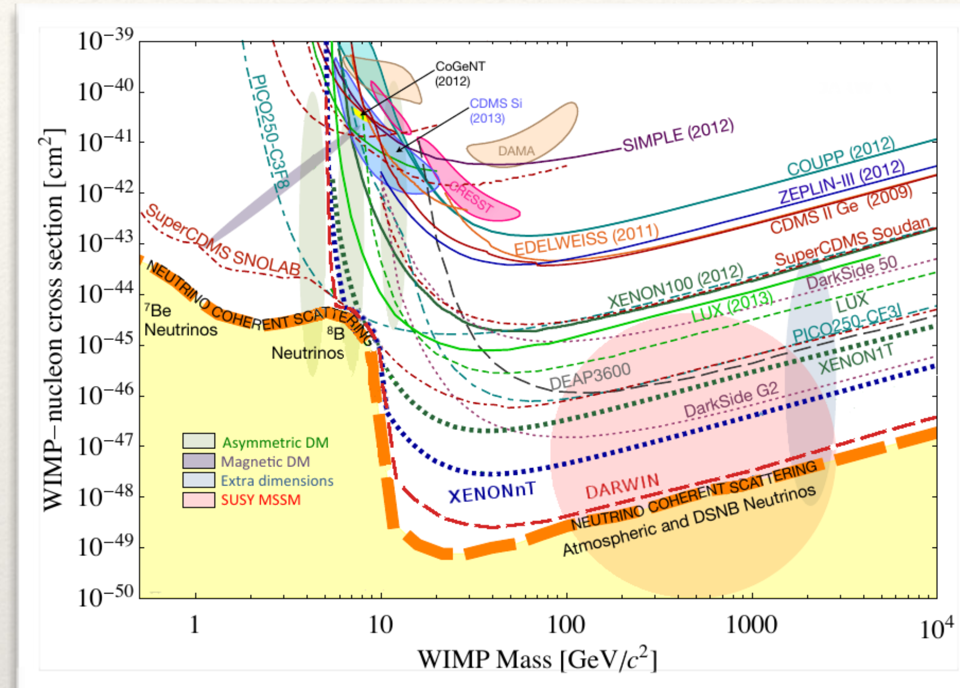
- Bounds on thermal DM starting to get quite strong
- Successful test of this idea!
- But we should be diligent in checking for loopholes
- What are our assumptions? What if we relax them?

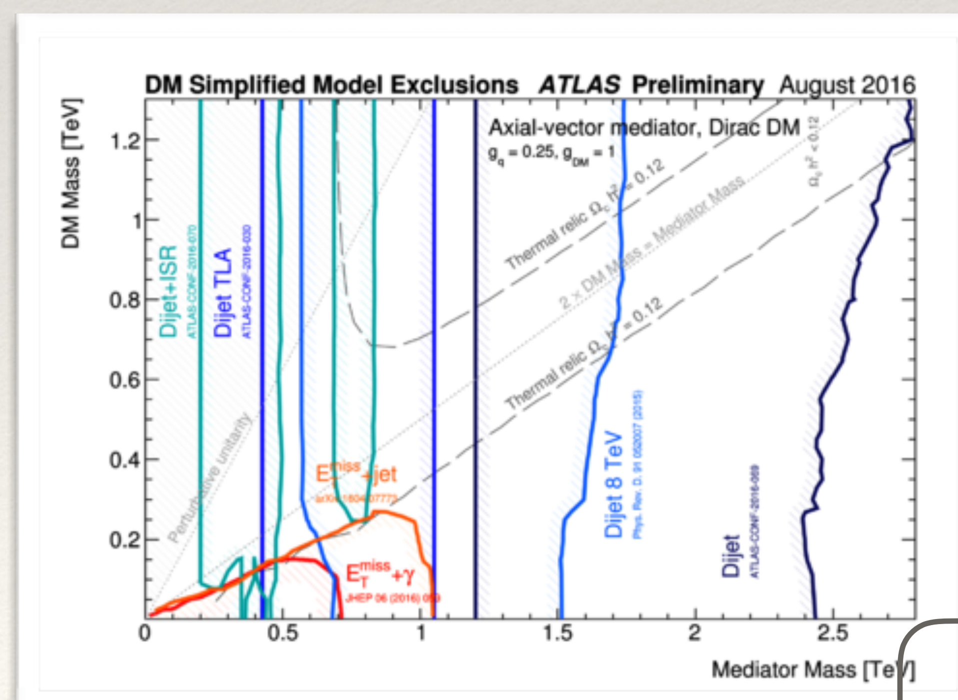




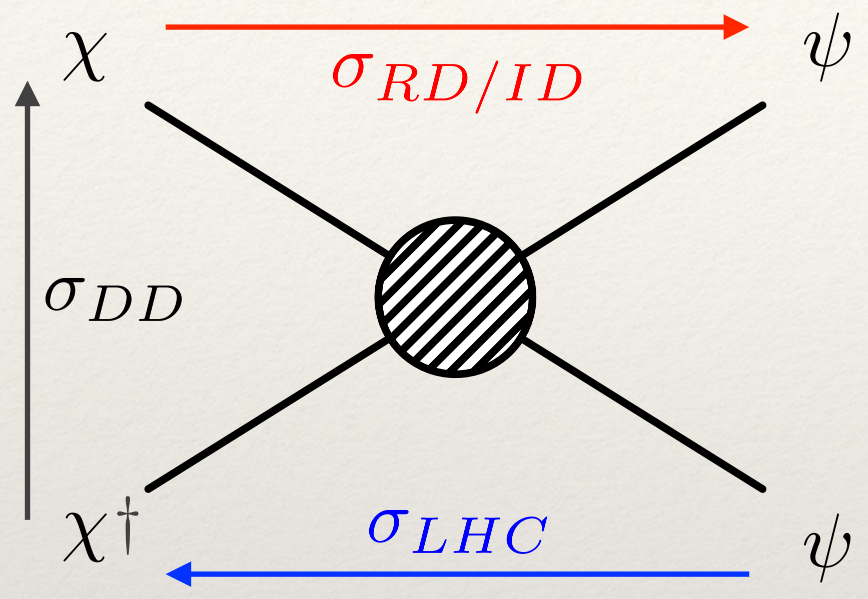
Thermal Dark Matter

- 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



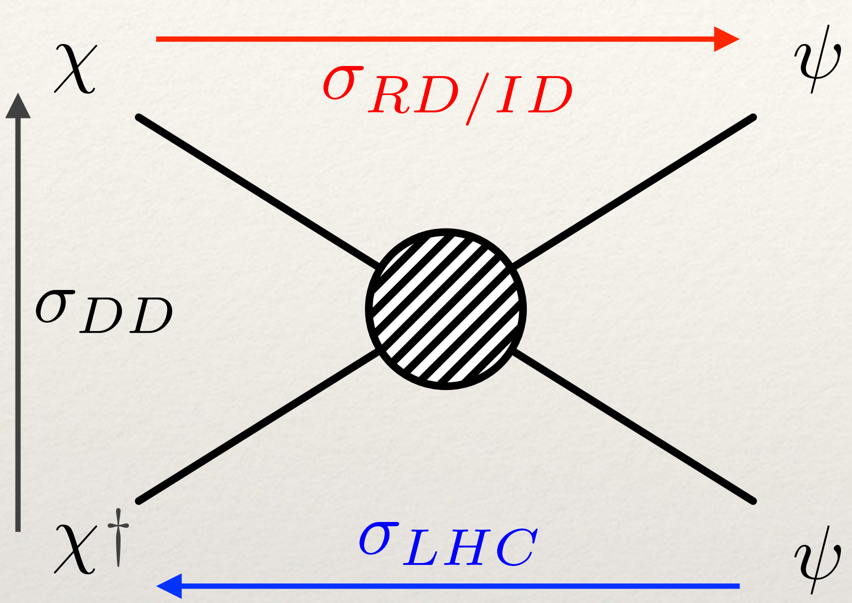


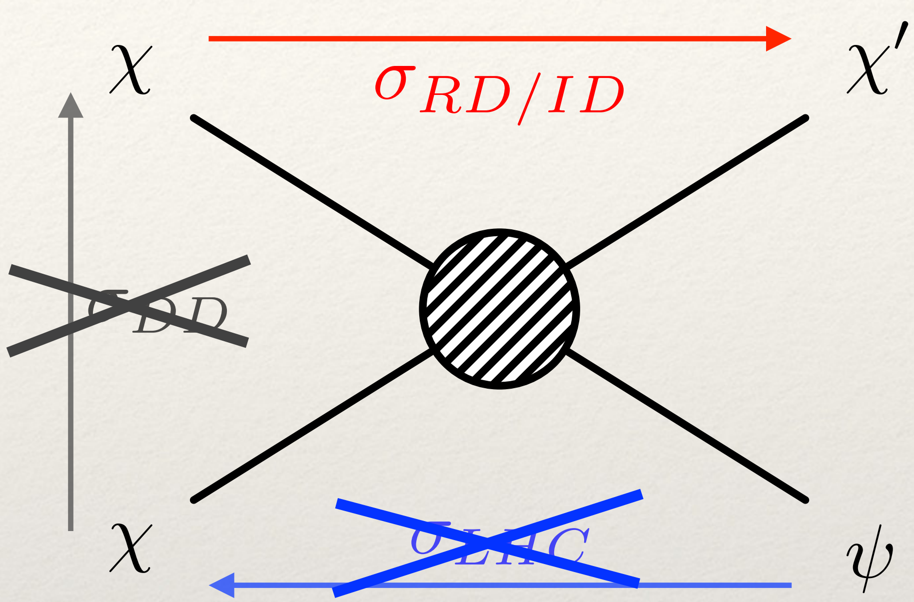
Semi-Annihilation



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

Semi-Annihilation

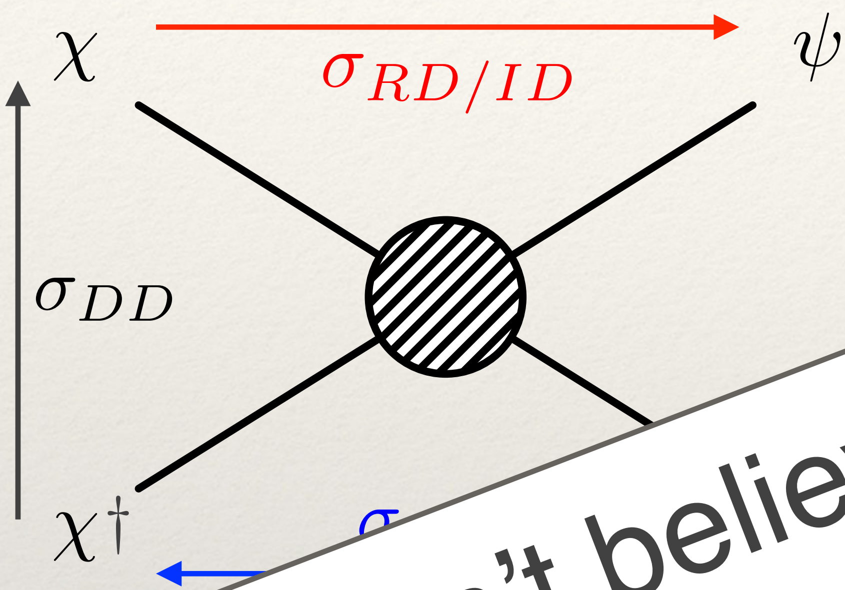


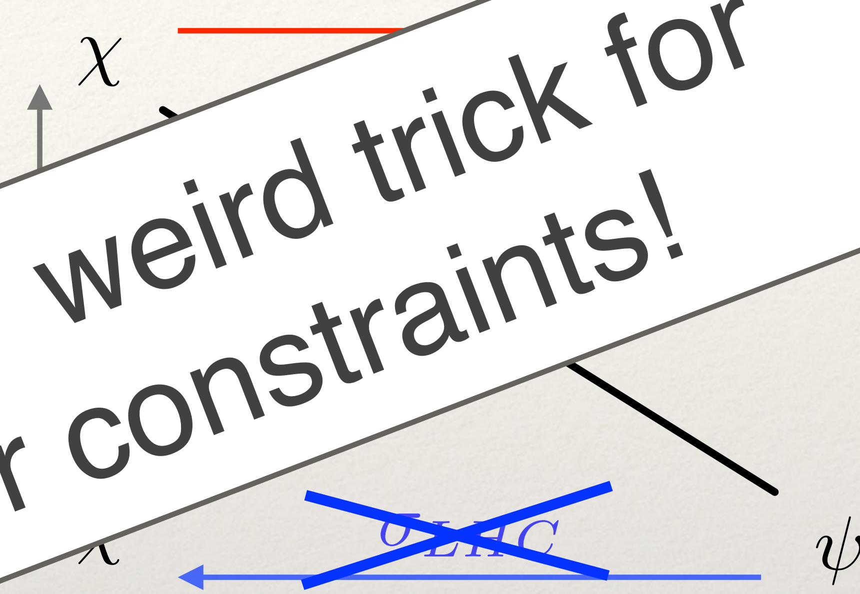


- Implies this familiar diagram
- Detection rates related to relic density calculation
- Leads to these strong bounds

- 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

Semi-Annihilation



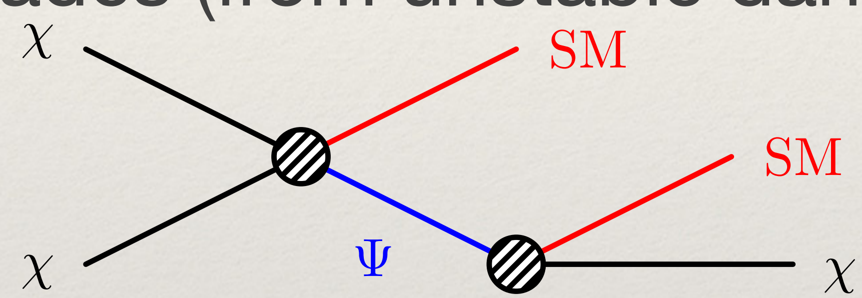


You won't believe this 1 weird trick for avoiding dark matter constraints!

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

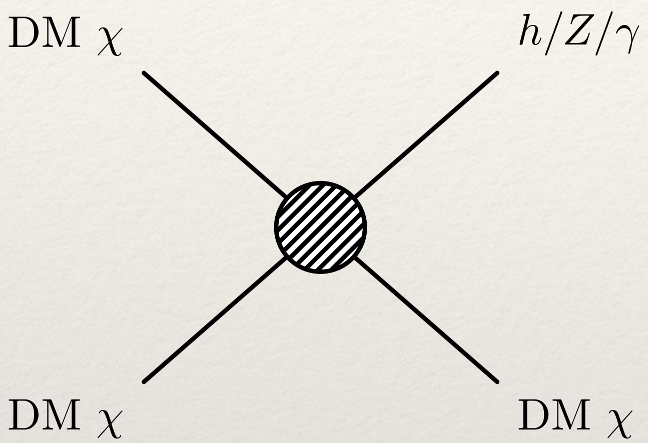


- A number of studies so far

  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

- Two classes of 2 → 2 SA, depending on SM final state

Gauge singlet



- Minimal theories: dark sectors (can be) all DM

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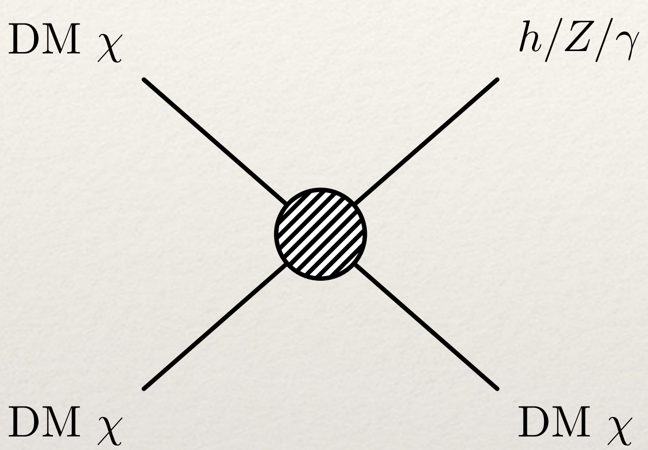
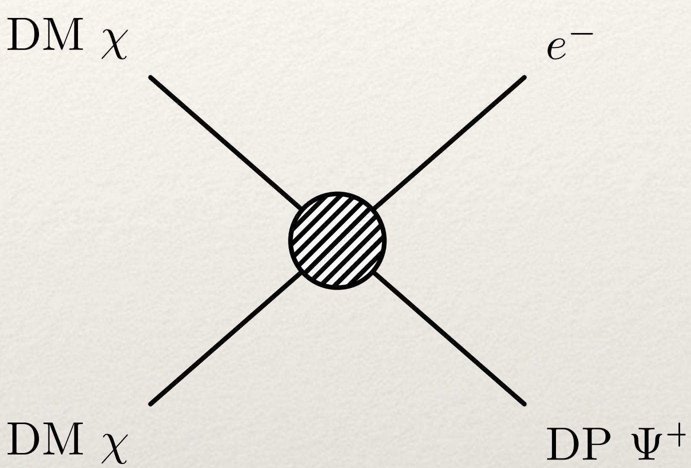


Gauge charged



- Minimal theories: dark sectors (can be) all DM
- Must be light charged unstable dark states

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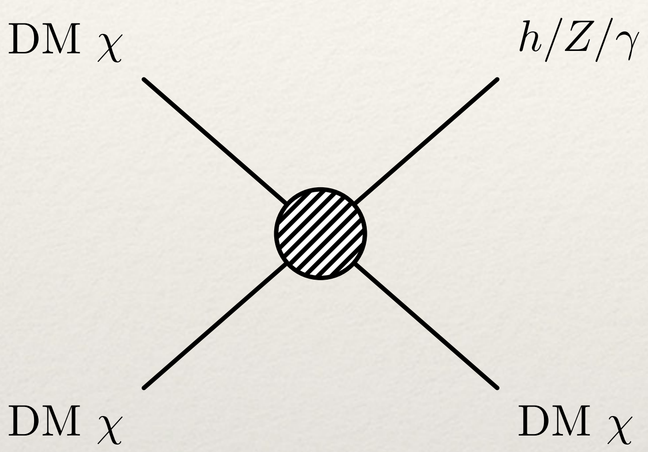

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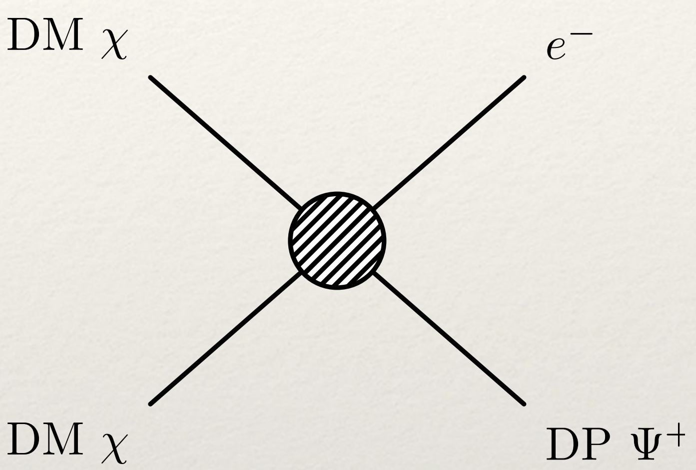

- Minimal theories: dark sectors (can be) all DM
- Must be light charged unstable dark states

- Call states with dark & SM symmetries Dark Partners
- DM-DM initial states: dark partners conjugate to SM

Effective Operators

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

Assumptions

1. DM is gauge singlet complex scalar or fermion, charged under exact global symmetry $\mathrm{D} \neq \mathrm{Z}_2$
2. Consider $2 \to 2$ processes with 3 dark sector fields
   i.e. operators with 4 fields after EWSB
3. Allow dark partners, at most 1 per operator
4. Allow multi-component dark matter
5. Consider all possible terms to dimension 6
   & leading terms at dimension 7

General Results

- See paper/back-up slides for operator lists
- Small number of operators; e.g. for unique DM,

	DM-only	Scalar DP	Fermion DP
Scalar DM	1	9	6
Fermion DM	1 x gens.	19 x gens.	28 x gens.

- DM-only operators involve 5 fields before EWSB
- No operators leading to γ-ray line signatures for < 3 DM
- Lowest-dimension operators involve dark partners

General Results

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	DM-only	
Scalar DM	1	$\phi^3 H^\dagger H$
Fermion DM	1 x gens.	$\bar{\chi}^c P_L \chi (L^\dagger \tilde{H}) \chi$

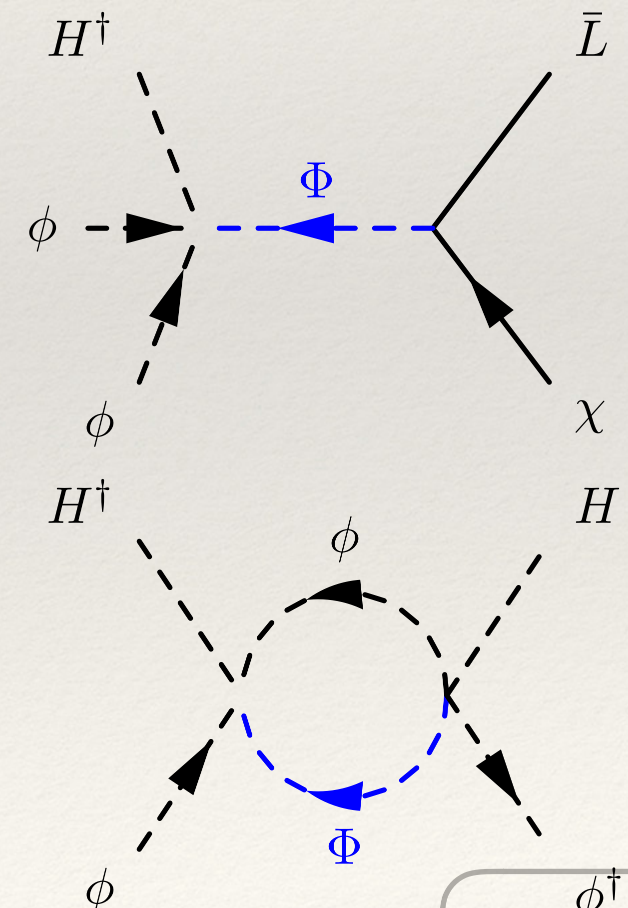
- DM-only operators involve 5 fields before EWSB
- Lowest-dimension operators involve dark partners
- No operators leading to γ-ray line signatures for < 3 DM

Higgs Portals

- Operators for scalar/fermion DM at dimension 5+/6+
- Compare this to the always-allowed Higgs portals:

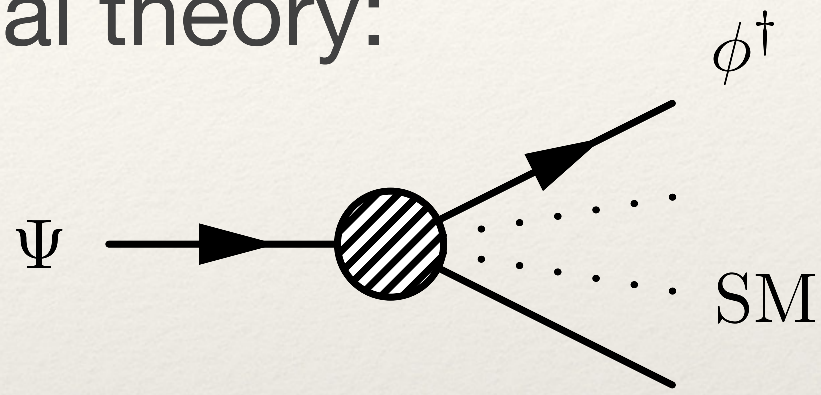
$$\mathcal{O}_{\phi H} = \lambda_{\phi H}\, \phi^\dagger \phi\, H^\dagger H\,, \qquad \mathcal{O}_{\chi H} = \frac{c_{\chi H}}{\Lambda}\, \bar{\chi}\gamma^5\chi\, H^\dagger H$$

- 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 $\mathbb{D}$-singlet scalars
  - No EW doublets in conjugate $\mathbb{D}$-rep, same spin as DM



Dark Partner Decay

- Dark partners 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

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

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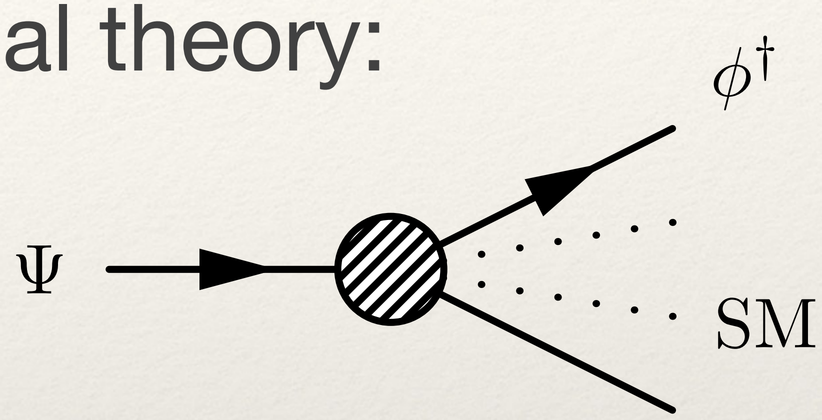

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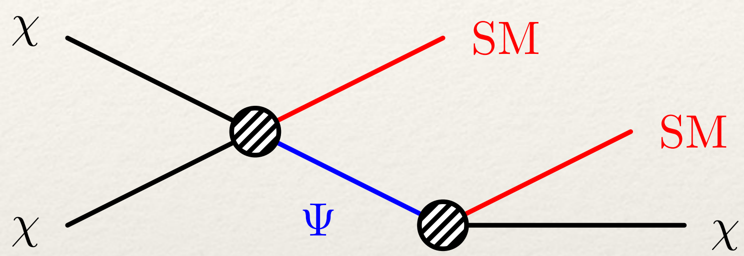
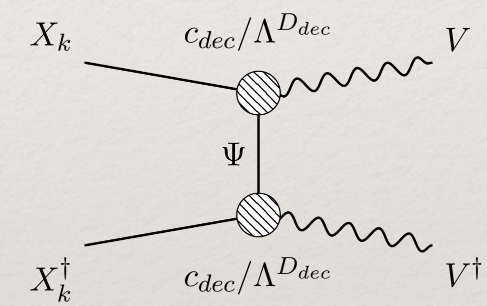
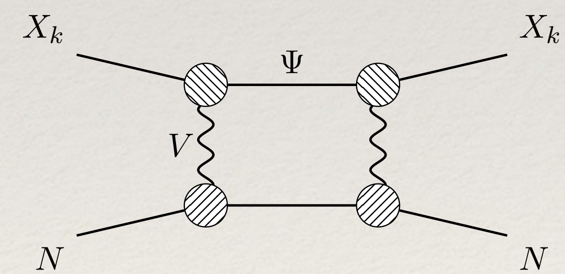
Impact of Decay Operators

- 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





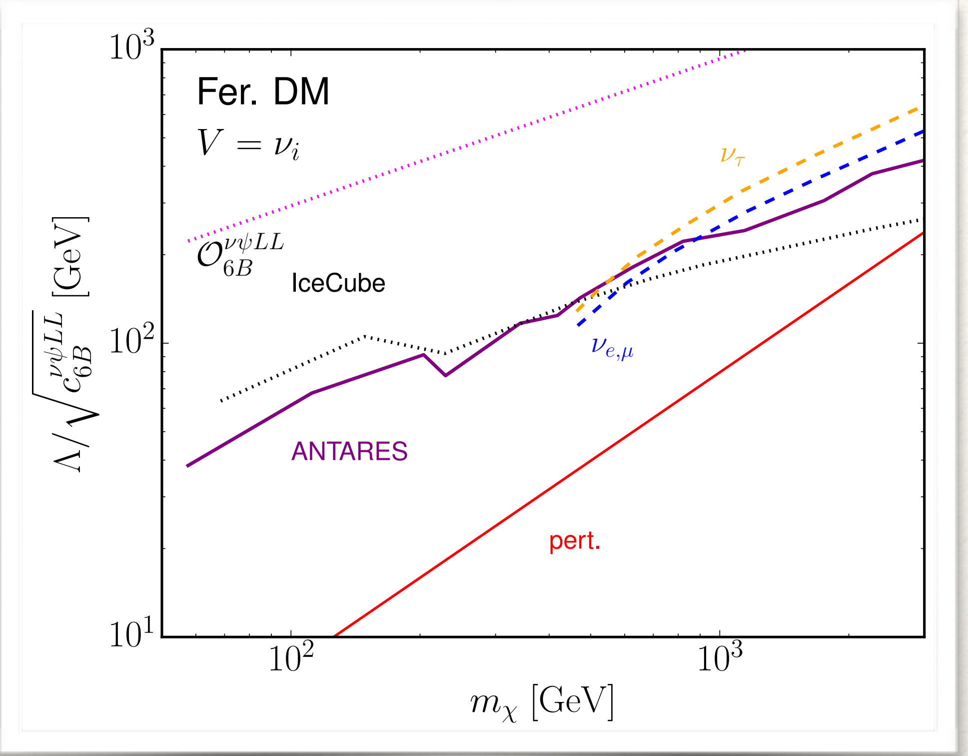
- General bound $c_{dec} \lesssim 0.1$—0.01

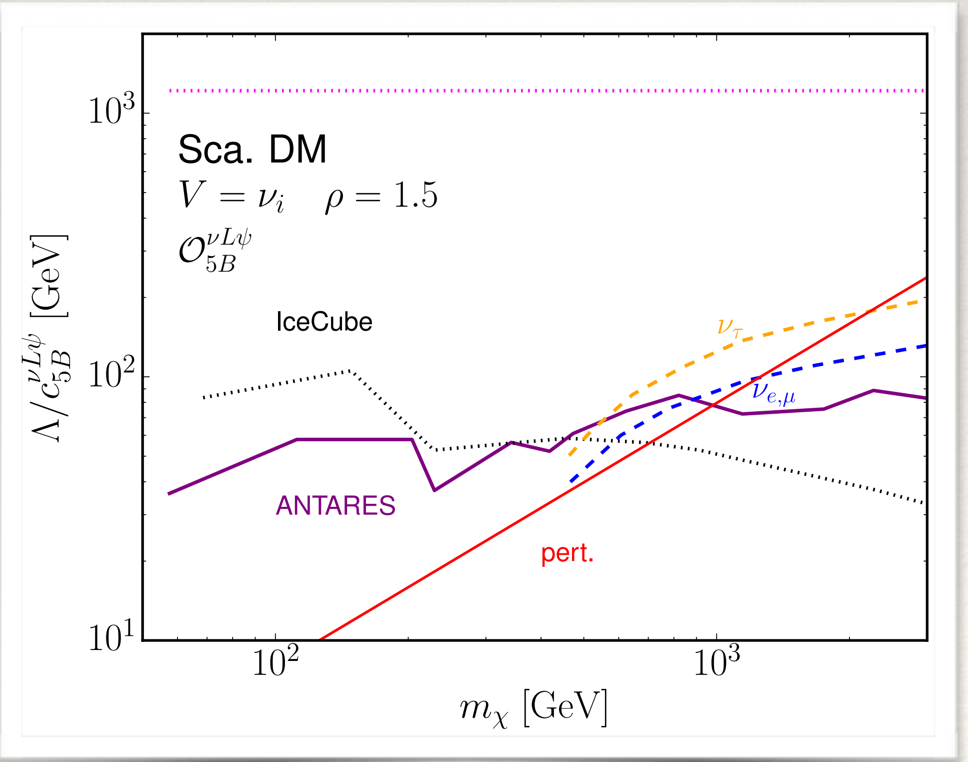
Phenomenology & Constraints

Overview

- Derive limits from γ-ray, positron & neutrino telescopes
- Additional assumptions:
  - DM is single component
  - 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
- Only time & space to show a small selection of results

SA to Neutrinos





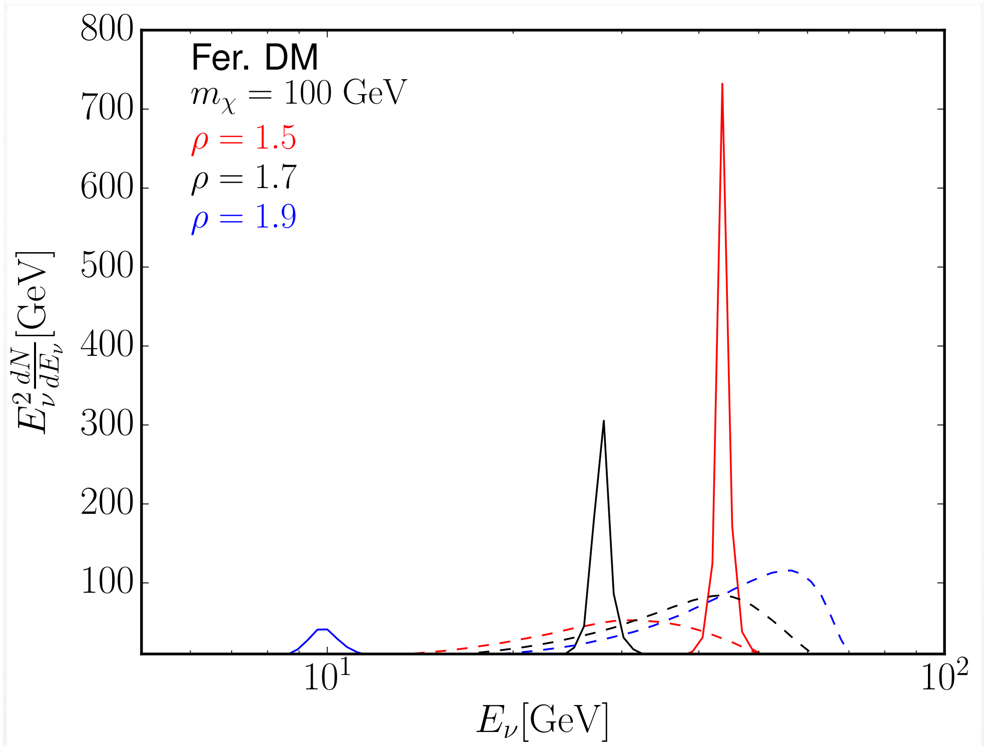
- Top: Bounds on dim-6 ops

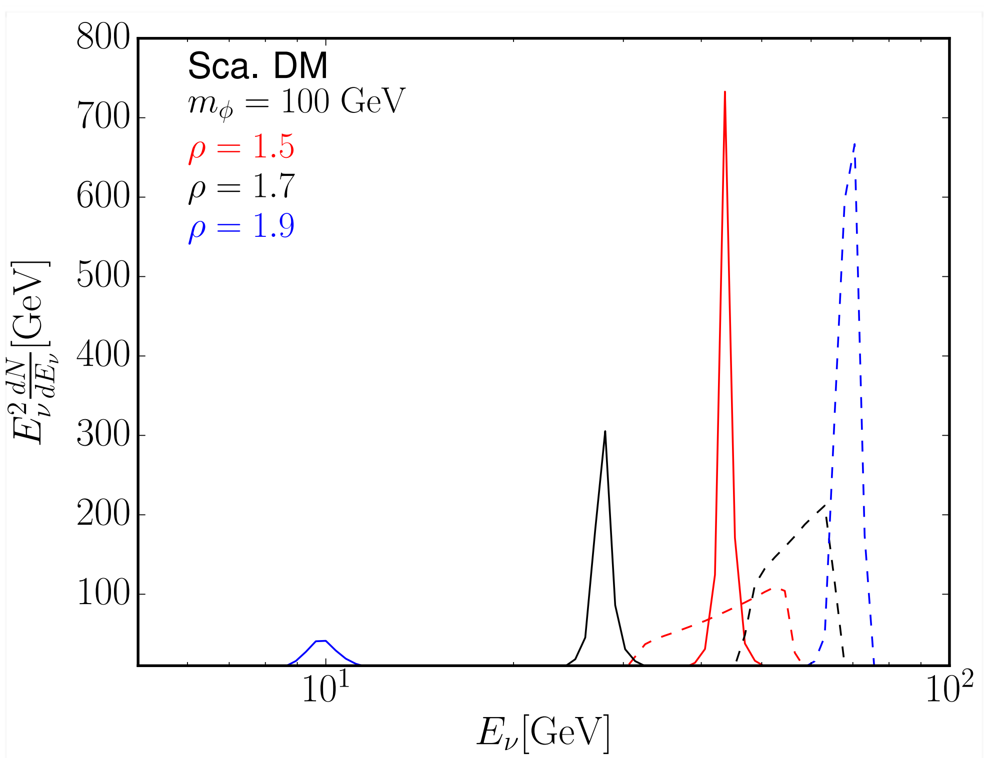
$$\frac{1}{6\Lambda^2}\chi^3\nu \quad \& \quad \frac{1}{2\Lambda^2}(\chi\chi)(\bar{\nu}\psi)$$

- Bottom: dim-5 ops

$$\frac{1}{2\Lambda}\phi^2(\bar{\nu}\psi)$$

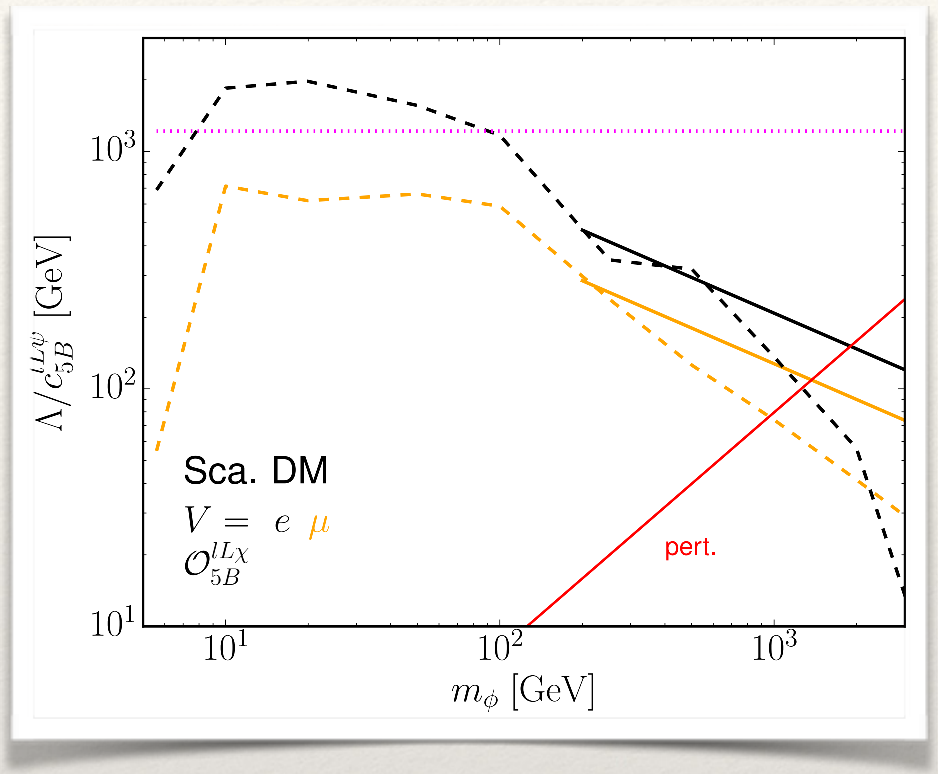
- Regions below lines exluded
  - Red: perturbativity (EFT)
  - Solid: as marked (current)
  - Dashed: CTA (projected)
- Dots: relic density from SA alone

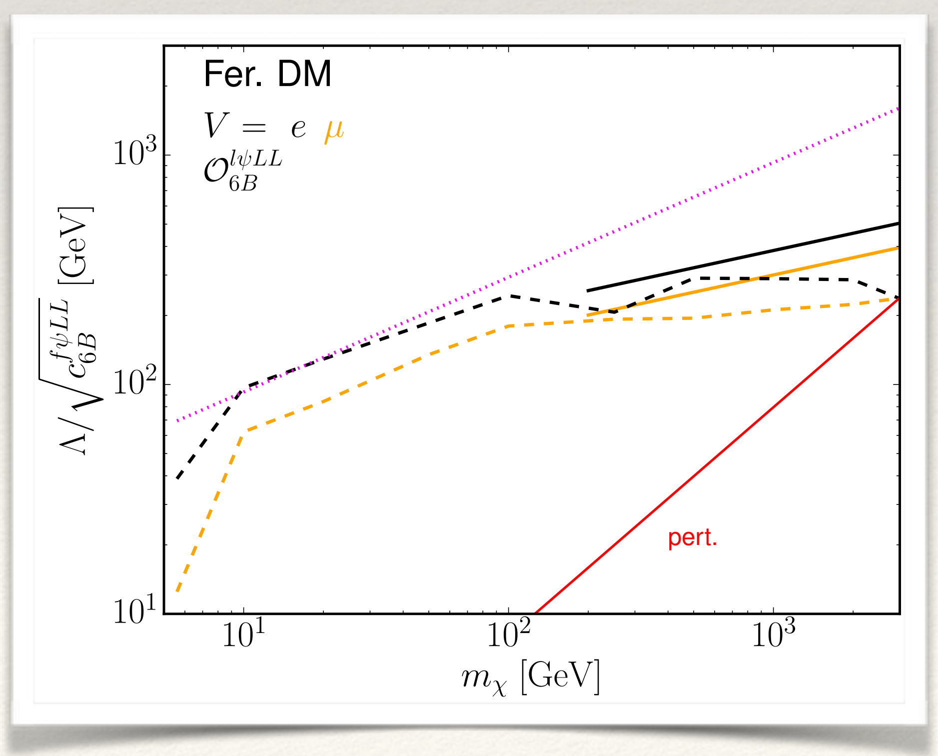




- Neutrino spectra for same operators as on last slide
- Varied DM—DP mass ratio
- Solid lines:
  - SA final state neutrinos
  - Nearly monochromatic
- Dashed lines
  - Dark partner decay neutrinos
  - Broad spectrum; more so for fermion DM due to 3-body decay
  - More important for heavier DPs

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)
- Exclude RD params for electron channel and $10 \lesssim m \lesssim 100$ GeV

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

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- Many questions remain, e.g. UV completions

Thank You!

Back-Up Slides

Dark Matter Only

- Write down all operators consistent with assumptions
  - Scalar

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

  - Fermion

Operator	Definition
$\mathcal{O}^{LL}_{7U}$	$\big(s^{ijk}+y^{ijk}+x^{ikj}\big)\,(\eta_i\eta_j)\,\big((L^\dagger\tilde{H})\xi^\dagger_k\big)$
$\mathcal{O}^{LR}_{7U}$	$\big(y^{ijk}+x^{ikj}\big)\,(\xi^\dagger_i\xi^\dagger_j)\,\big((L^\dagger\tilde{H})\xi^\dagger_k\big)$

  - Both

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

- Small number of operators; Only TWO for unique DM
- Only neutral SM: h, Z, γ, ν
- (Almost) all lead to 2 $\rightarrow$ 3 SA
- Very simple model space

Dark Partner

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 $\mathrm{d} = 5$ operators
- Situation for fermion and scalar-fermion DM similar
- All SM final states possible
  - γ/g require multi-component DM