Sunday 5th June 2016, Warsaw Workshop on Non-Standard DM

Semi-Annihilating Dark Matter

Andrew Spray
Yi Cai

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Dark Matter = Ghosts?

Blinky Inky Pinky

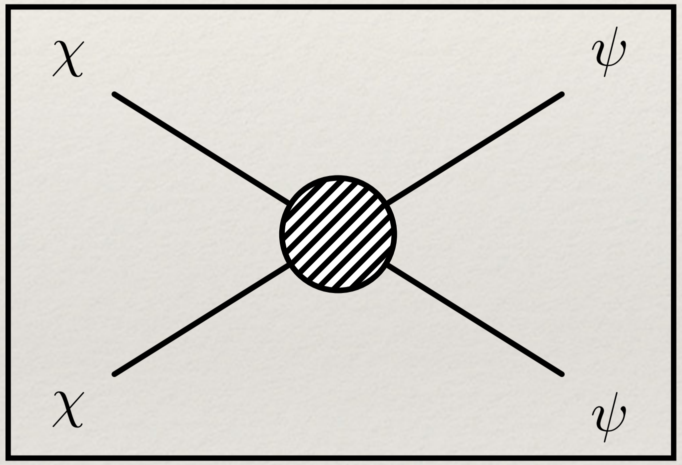
Outline

- Semi-Annihilating Dark Matter
- Sommerfeld Enhancement and Semi-Annihilation
- A Systematic Effective Operator Analysis
- Conclusions

Semi-Annihilating Dark Matter

Symmetries

- Traditional: stabilise Dark Matter with Z_2 Symmetry
  - Supersymmetry: R-Parity
  - Extra Dimensions: KK Parity
  - Little Higgs: T-Parity
  - Inert Doublet Model
- Standard DM processes only



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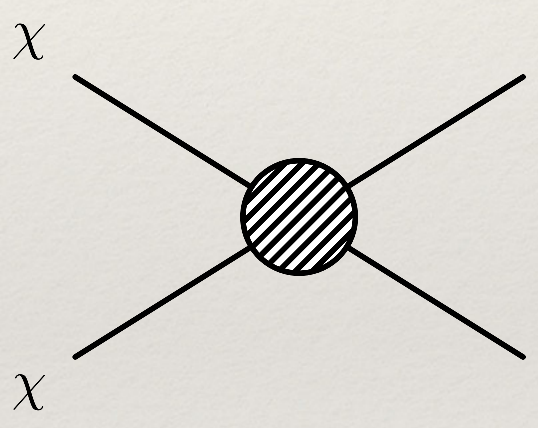
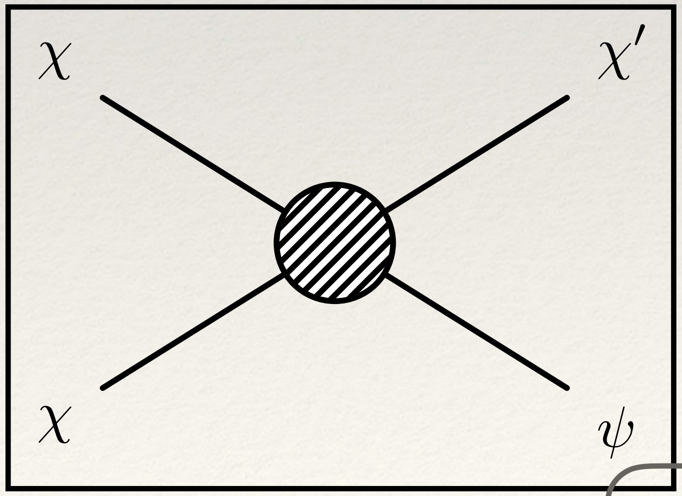


- Standard DM processes only

- Completely non-generic!
  Almost any other symmetry allows
  - Semi-Annihilation (D'Eramo & Thaler, `1003.5912`)

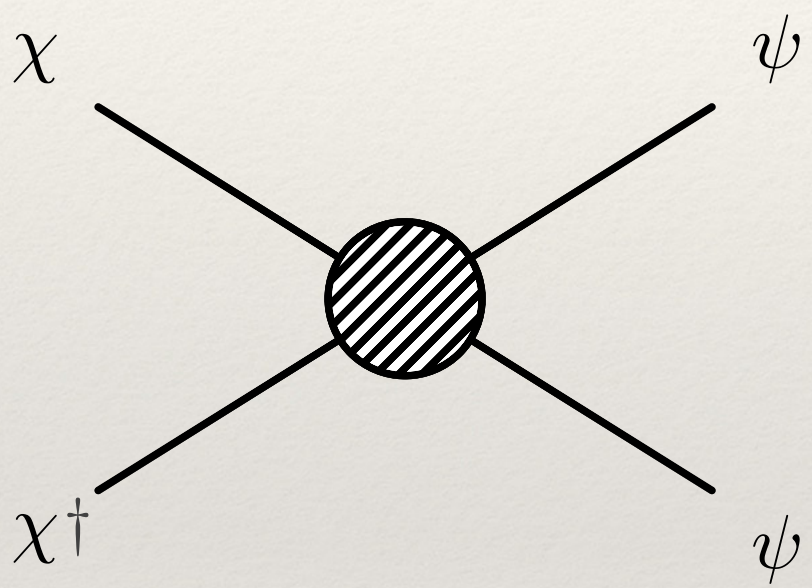


Top-Down

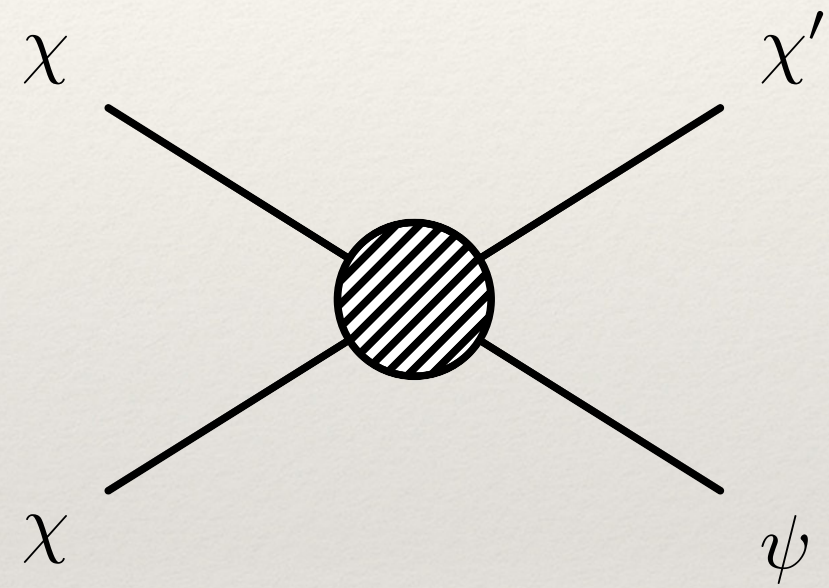
- Composite Theories
  - Flavour and baryon symmetries
    D'Eramo & Thaler, `1003.5912`
- Multi-Higgs Sectors
  - Subgroups of Higgs exchange symmetries
    Ivanov & Kreus, `1203.3426`; Karam & Tamvakis, `1508.03031`
- Supersymmetry
  - Hidden sectors: Feldman *et al* `1004.0649`
  - Right-handed neutrinos: Gherhetta *et al*, `1502.07173`

Semi-Annihilation

- Always have annihilation-like diagram



vs



- Relevant for colliders & direct detection
- Contributes to relic density & indirect signals

- Directly affects relic density & indirect signals
- Indirectly affects direct detection searches

Relic Density

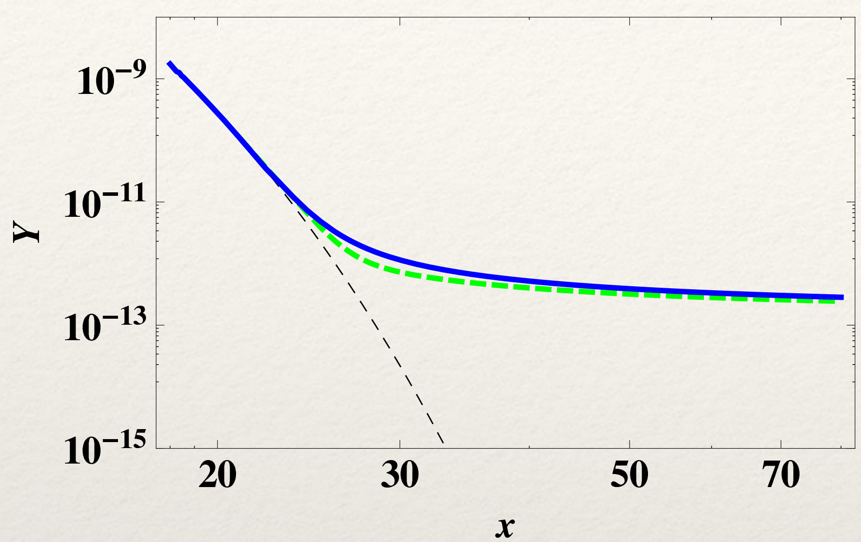
- Semi-annihilation is extra term in Boltzmann equation

$$\frac{dY_\chi}{dx} = \frac{sZ}{Hx}\left[\left(Y_\chi^2 - (Y_\chi^{eq})^2\right)\langle\sigma v\rangle(\chi\chi \to SM) + \left(Y_\chi^2 - Y_{\chi'}\frac{(Y_\chi^{eq})^2}{Y_{\chi'}^{eq}}\right)\langle\sigma v\rangle(\chi\chi \to \chi' SM) + \ldots\right.$$

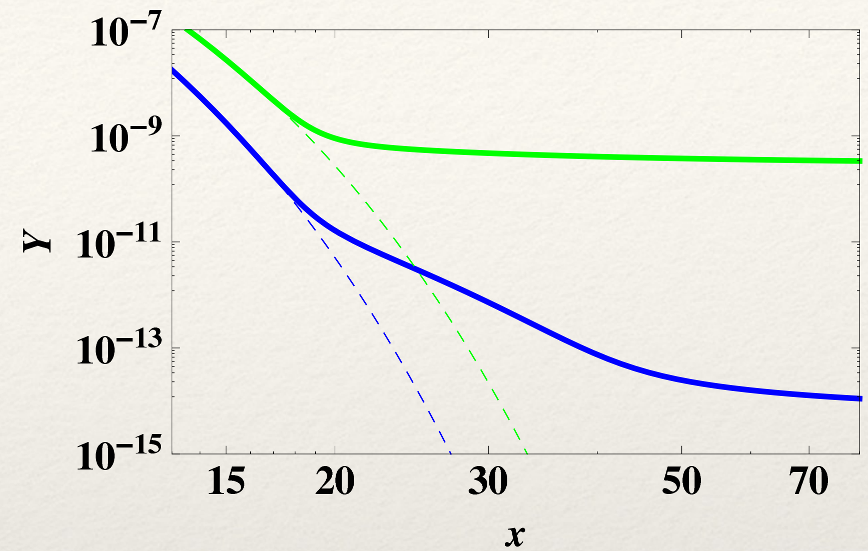
Annihilation Semi-annihilation

- SA lowers relic density in single component models
- Multi-component dark sectors more complex
- Standard calculation at this point:
  micrOMEGAs 4.0 handles arbitrary one/two-DM models

Examples of Density Evolution

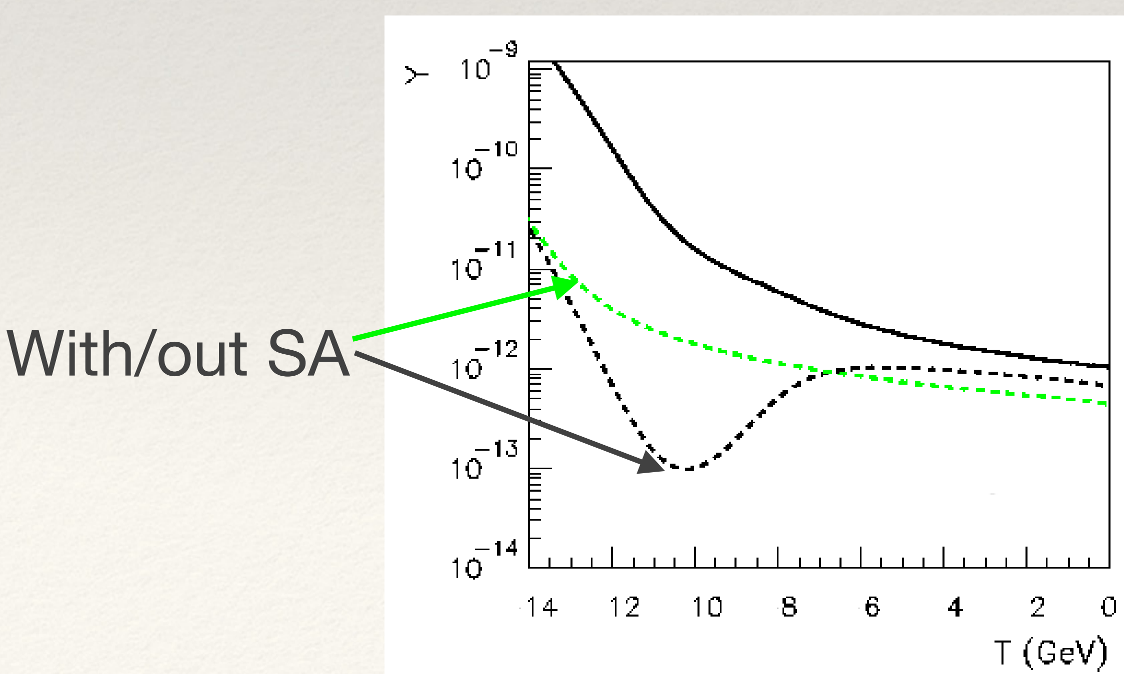


D’Eramo & Thaler, `1003.5912`



- Single particle, pure SA: looks like annihilation

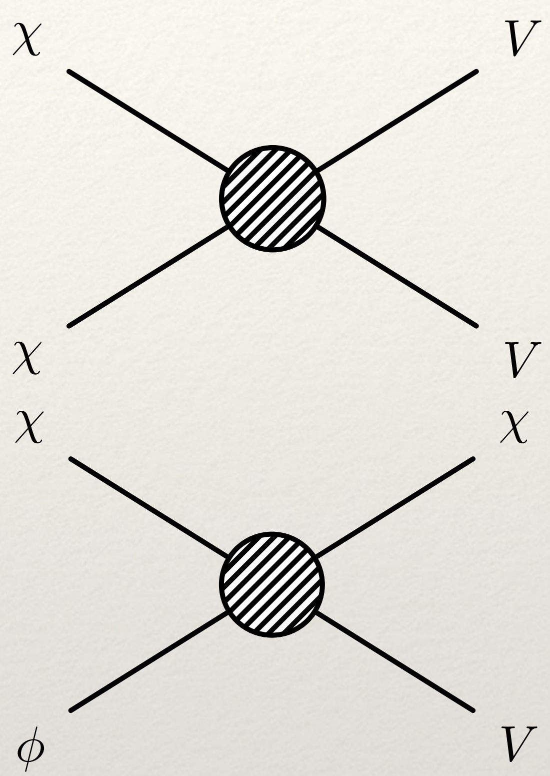
- Two-particle: SA lowers DM relic density



Bélanger *et al*, `1202.2962`

- Two particle: SA raises (one) DM relic density

Indirect Detection



- Other channel where SA plays a role
- Different kinematics
  - Annihilation: $E_V = m_\chi$
  - Semi-annihilation: $E_V = \dfrac{m_\phi^2 + 2m_\chi m_\phi + m_V^2}{2(m_\chi + m_\phi)}$
- Possible uses:
  - Photon/neutrino lines, *e.g.* D'Eramo *et al*, 1210.7817, Aoki *et al*, 1408.1853
  - Boosted signals in direct detection experiments, Agashe *et al*, `1405.7370`; Berger *et al*, 1410.2246; Kong *et al*, `1411.6632`
  - Different spectrum of decay products

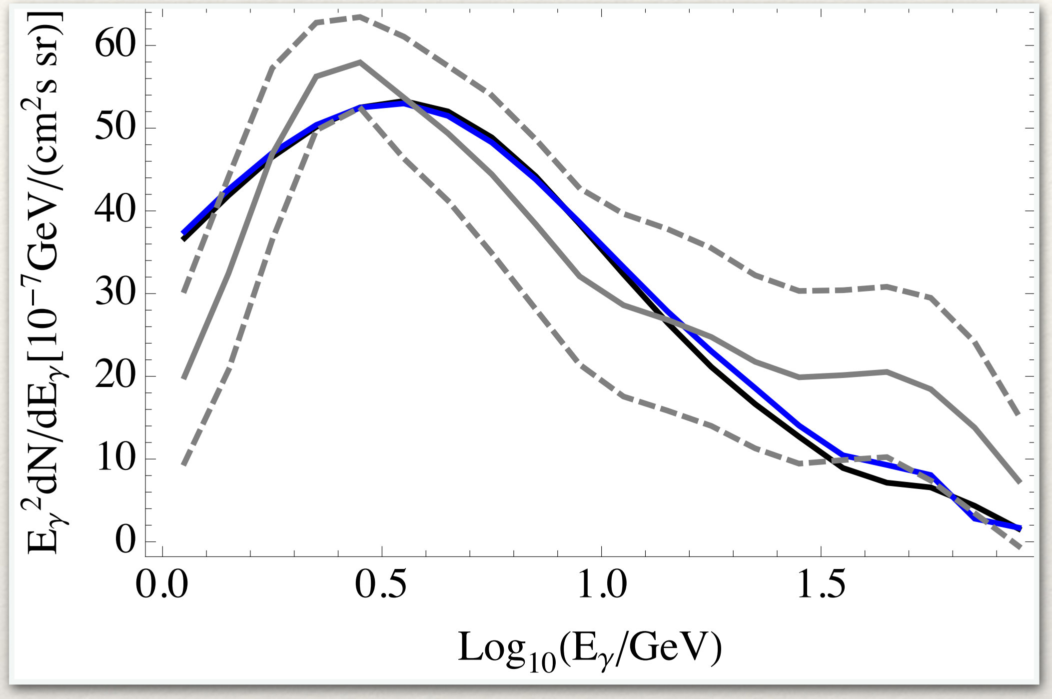
Fitting the GCE

- Minimal fermion SADM model

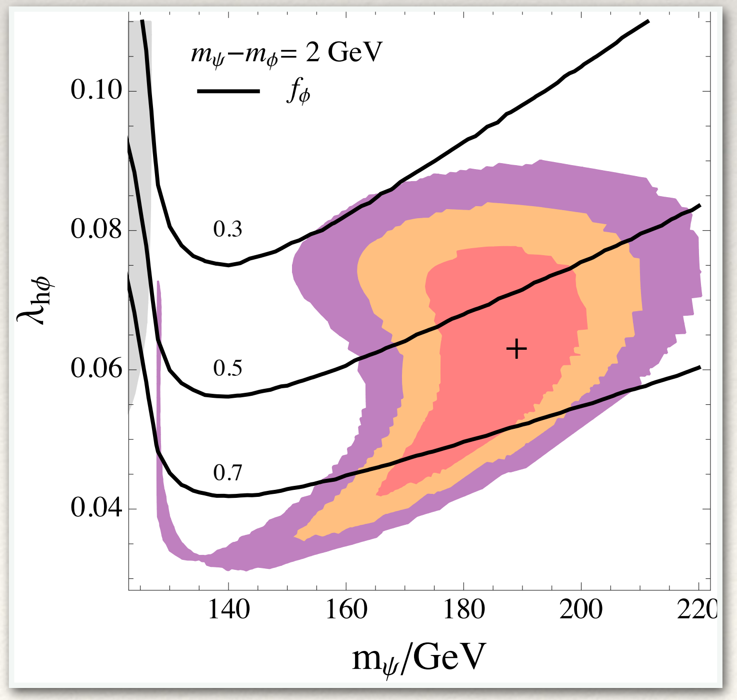
	$\mathcal{G}_{SM}$	$\mathbb{Z}_4$
Ψ	$(1,1)_0$	1
φ	$(1,1)_0$	2

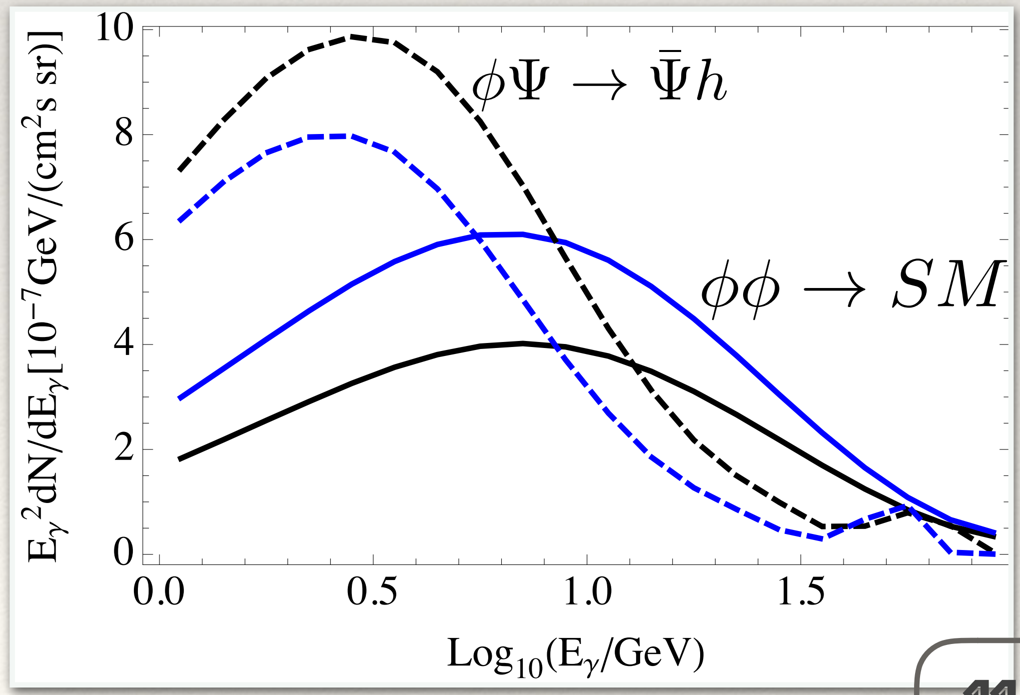
$$\mathcal{L} \supset \frac{1}{2}\lambda_{H\phi} H^\dagger H\,\phi^2 + y\,\phi\bar{\Psi}^c\Psi$$

- Fix mass difference small



Best-fit region fixing y with relic density





Cai & Spray, `1510.02179`

Sommerfeld Enhancement and Semi-Annihilation

A Next-to-Minimal Model

- Minimal gauged fermion flavour-neutral case:
  - Z_4 Symmetry, Dirac Fermion Ψ + Real Scalar φ

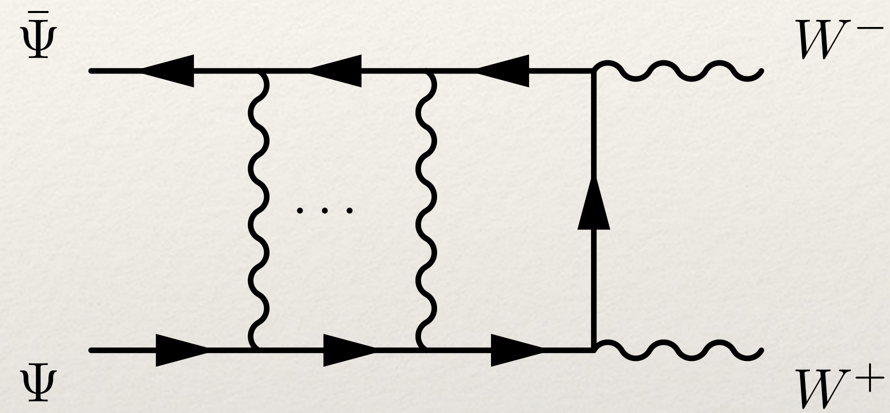
	$\mathcal{G}_{SM}$	$\mathbb{Z}_4$
Ψ	$(1,3)_0$	1
φ	$(1,1)_0$	2

- Dirac "Wino" plus Higgs-portal Singlet
  - Fermion now directly couples to SM
- Same 4 new parameters: m_Ψ, m_φ, $\lambda_{H\varphi}$, y

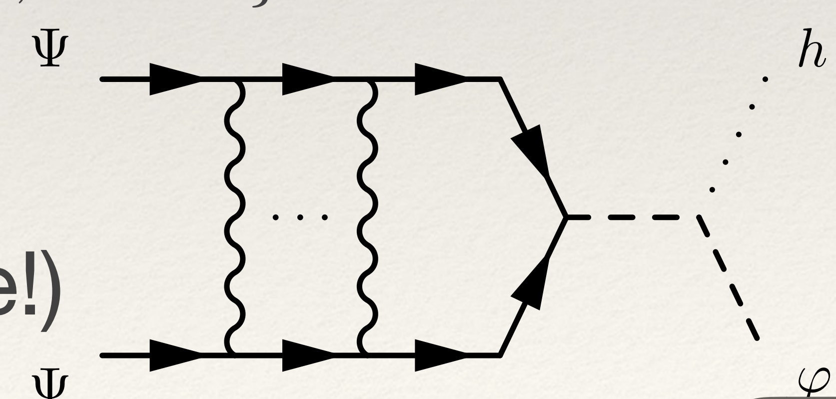
Enhanced (Semi-)Annihilation

- When $m_\Psi \gg m_W$, weak force is long-range
- Sommerfeld Effect:
  - Non-perturbative effect
  - Must be included for fermion triplet

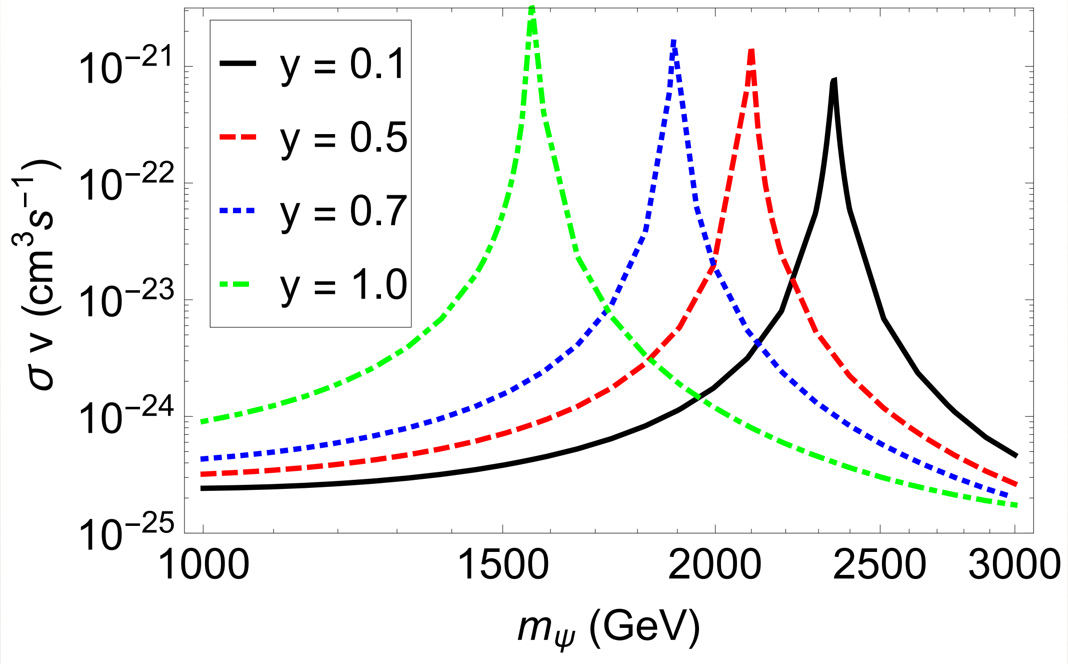
    Hisano *et al*, `hep-ph/0412403` & `hep-ph/0610249`; Cirelli *et al*, `0706.4071`

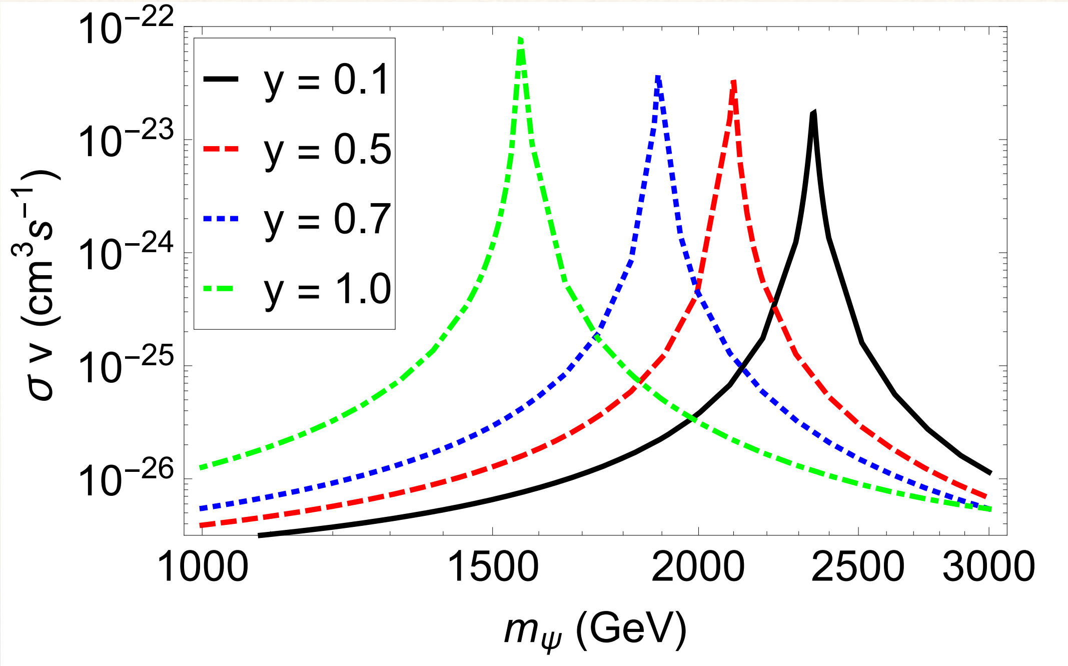


- New Two-Body States
  - Q = 0, S = 1 state: $\{\chi^+\chi^-\}$ vs $\{\Psi^+\overline{\Psi}^-, \Psi^0\Psi^0, \Psi^-\overline{\Psi}^+\}$
  - Semi-annihilating initial states $\Psi\Psi/\overline{\Psi}\overline{\Psi}$
- Required custom code (biggest hurdle!)



Resonances





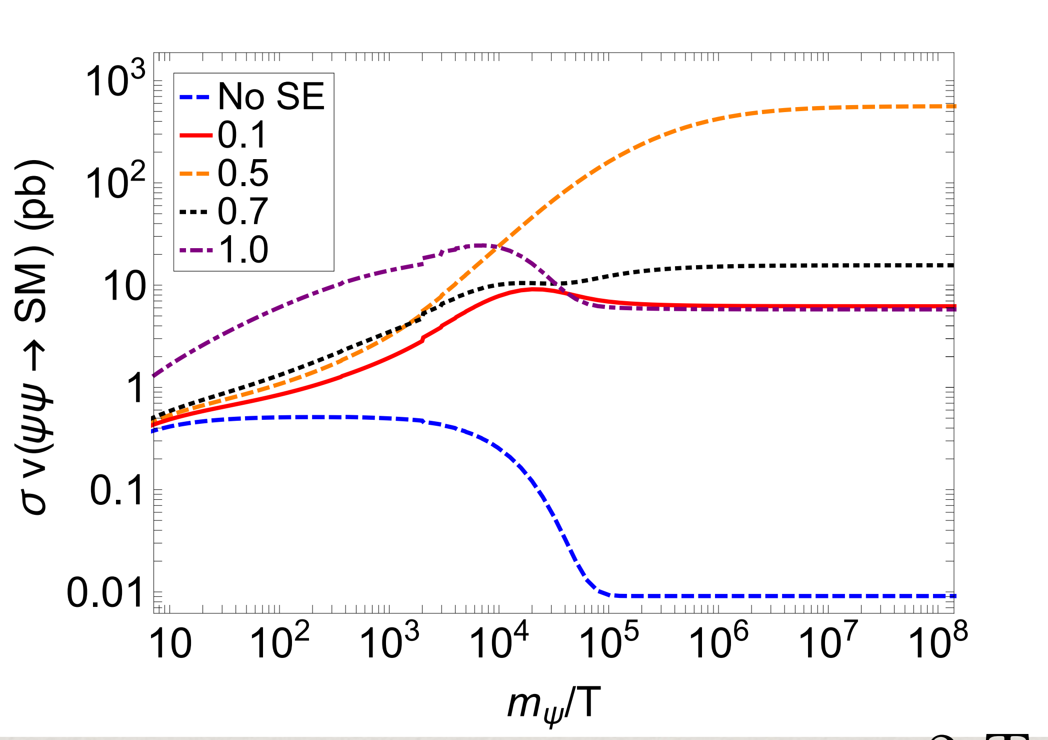
$\mathrm{m}_\varphi = 200\ \mathrm{GeV}$

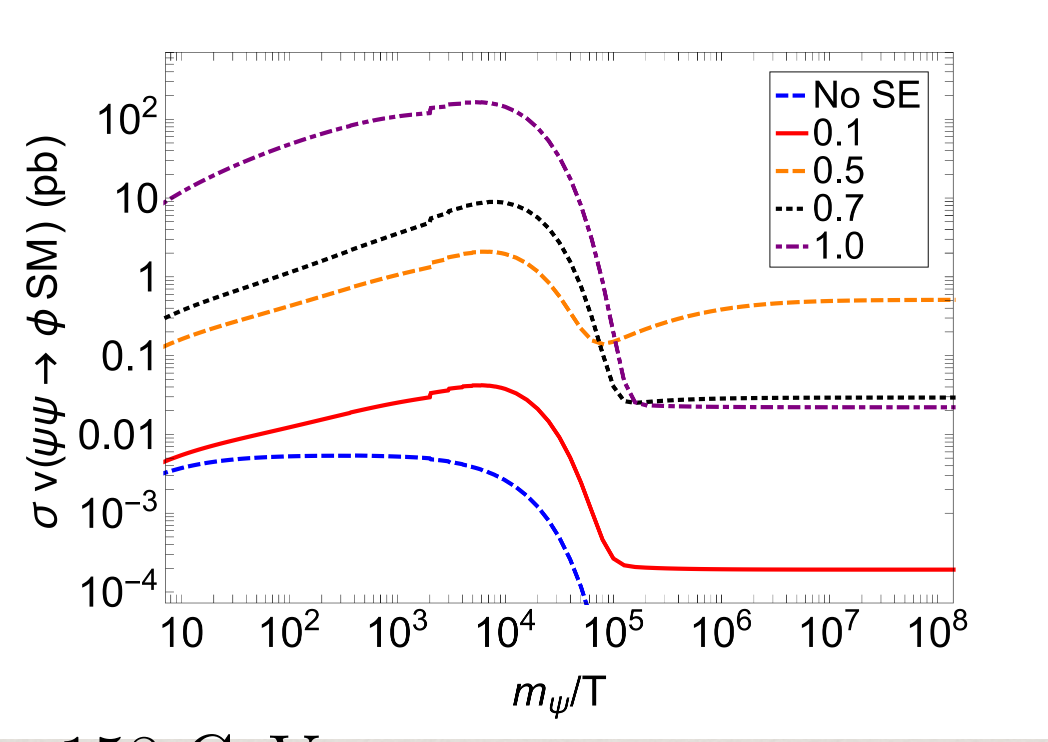
Annihilation

Semi-Annihilation

- Scalar mediates attractive force
- Deeper potential with increasing y
- Resonance moves to lower fermion masses

Thermal Cross Sections

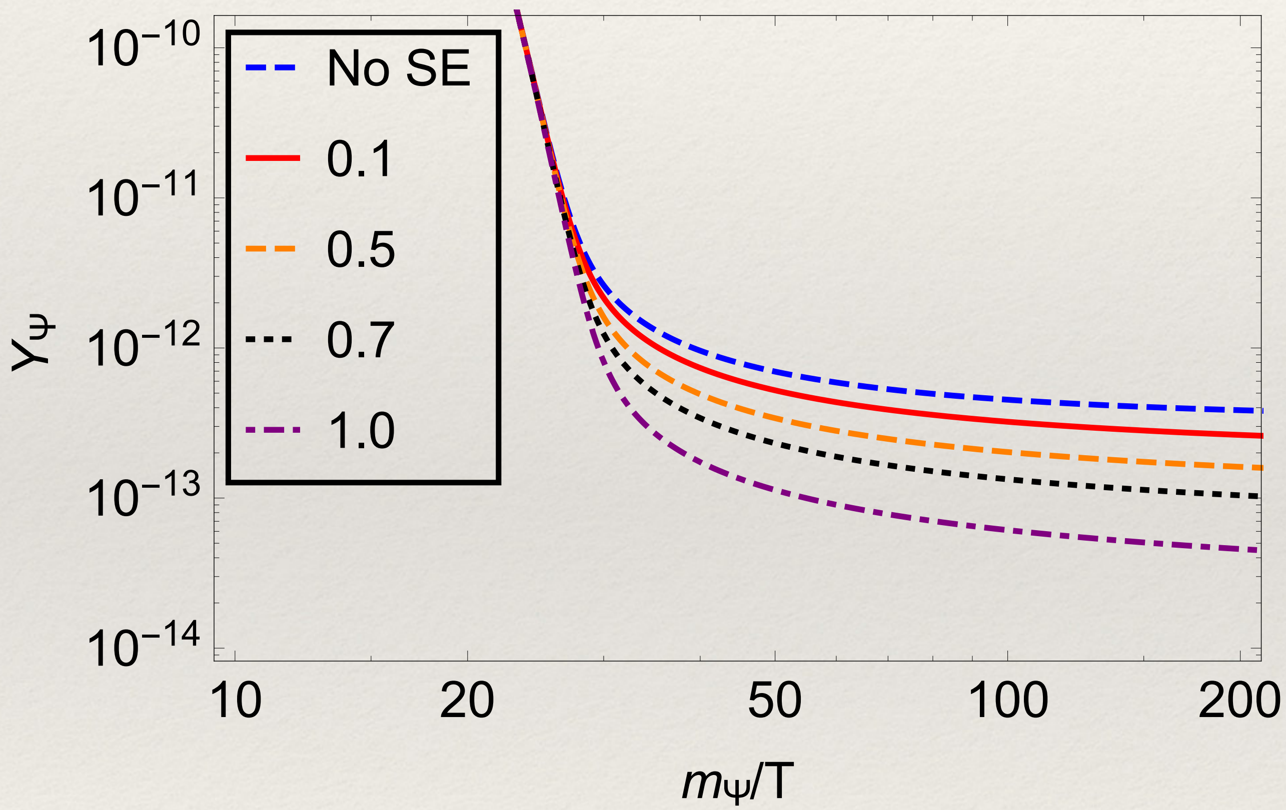




$$m_\Psi = 2\ \text{TeV}, m_\varphi = 158\ \text{GeV}$$

- Sommerfeld effect:
  - Increases cross sections by orders of magnitude
  - Relatively more important for semi-annihilation
  - Annihilation cross sections generally larger

Evaluating the Relic Density

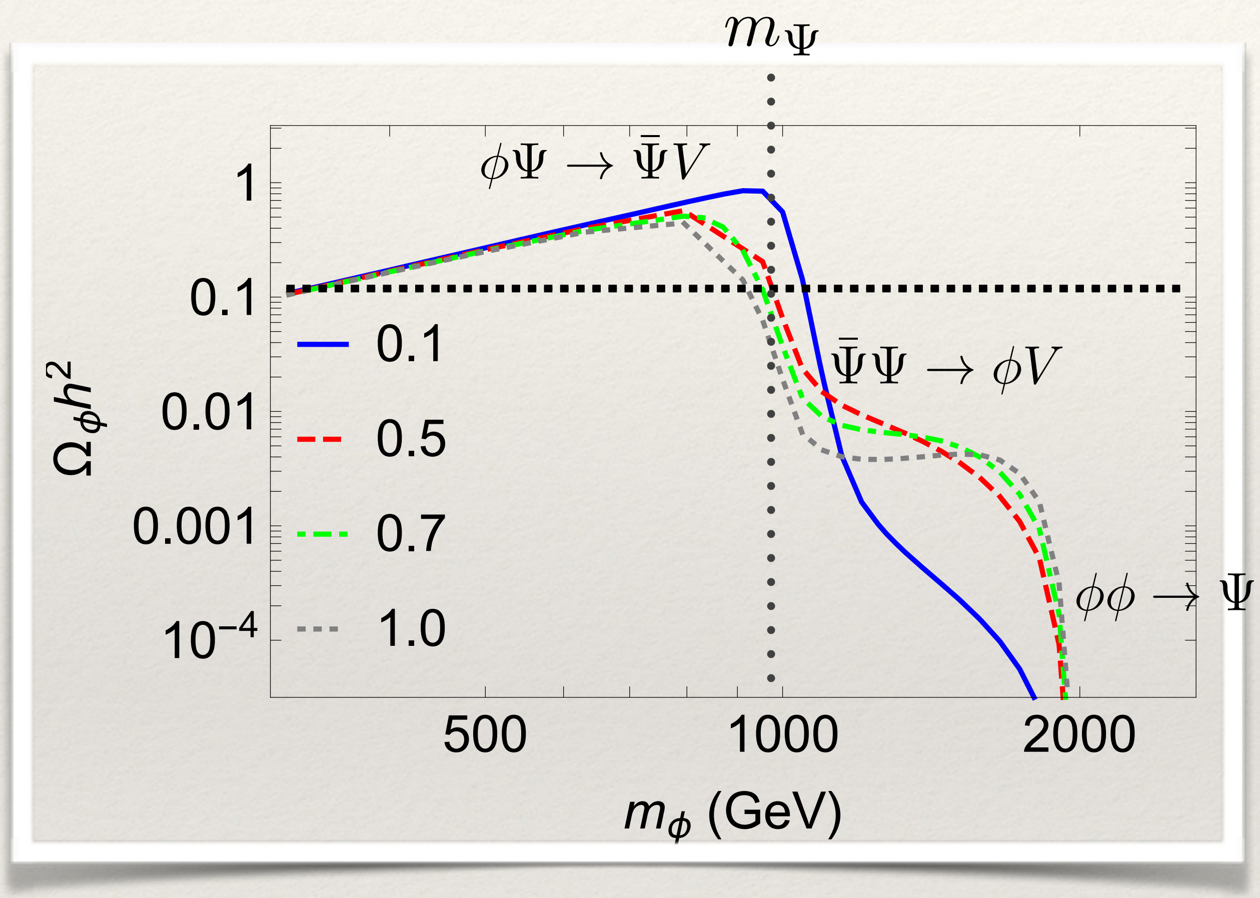


$$m_\Psi = 2\ \text{TeV}, m_\varphi = 158\ \text{GeV}$$

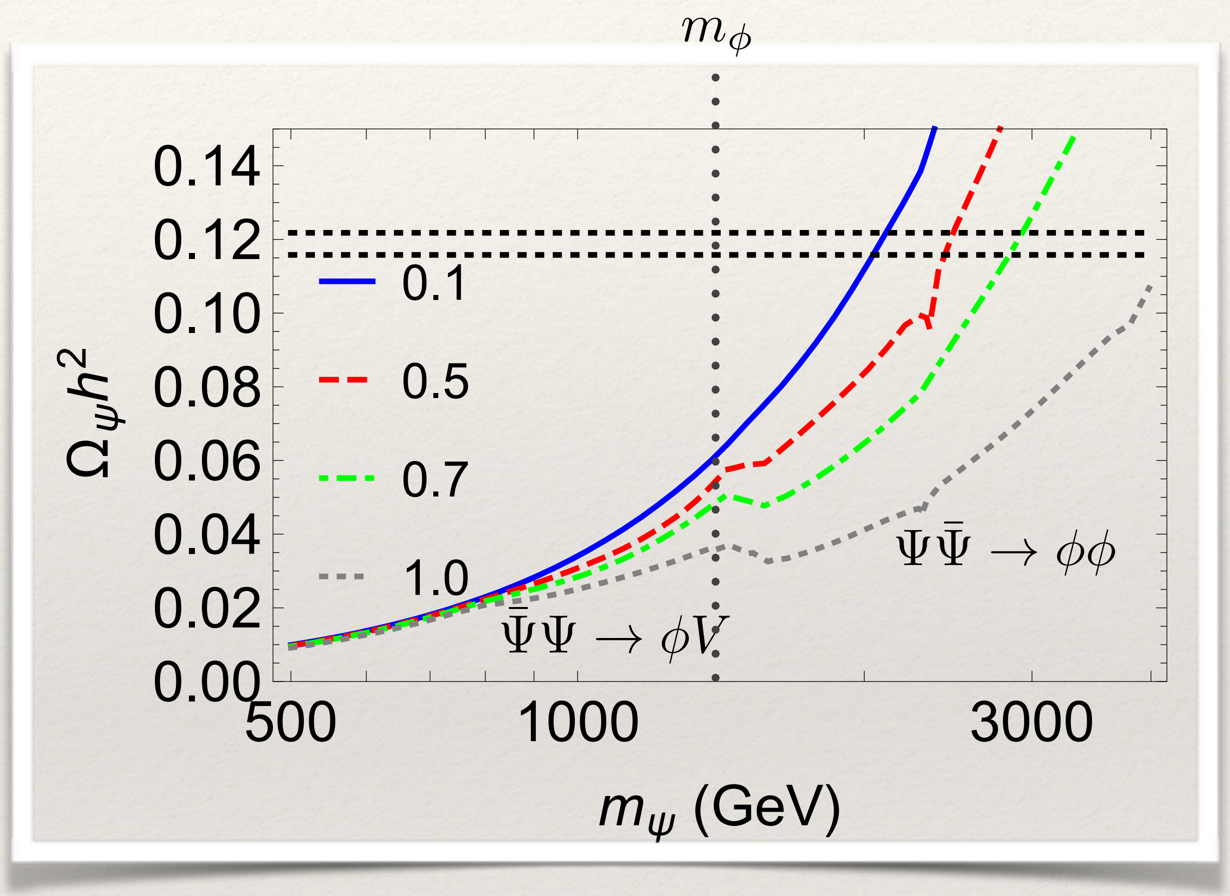
- Sommerfeld Effect:
  - Lowers relic density
  - (Semi-)Annihilations have continued effect at late time
- Semi-annihilations enhanced

Focus on SA Regions

- Scalar

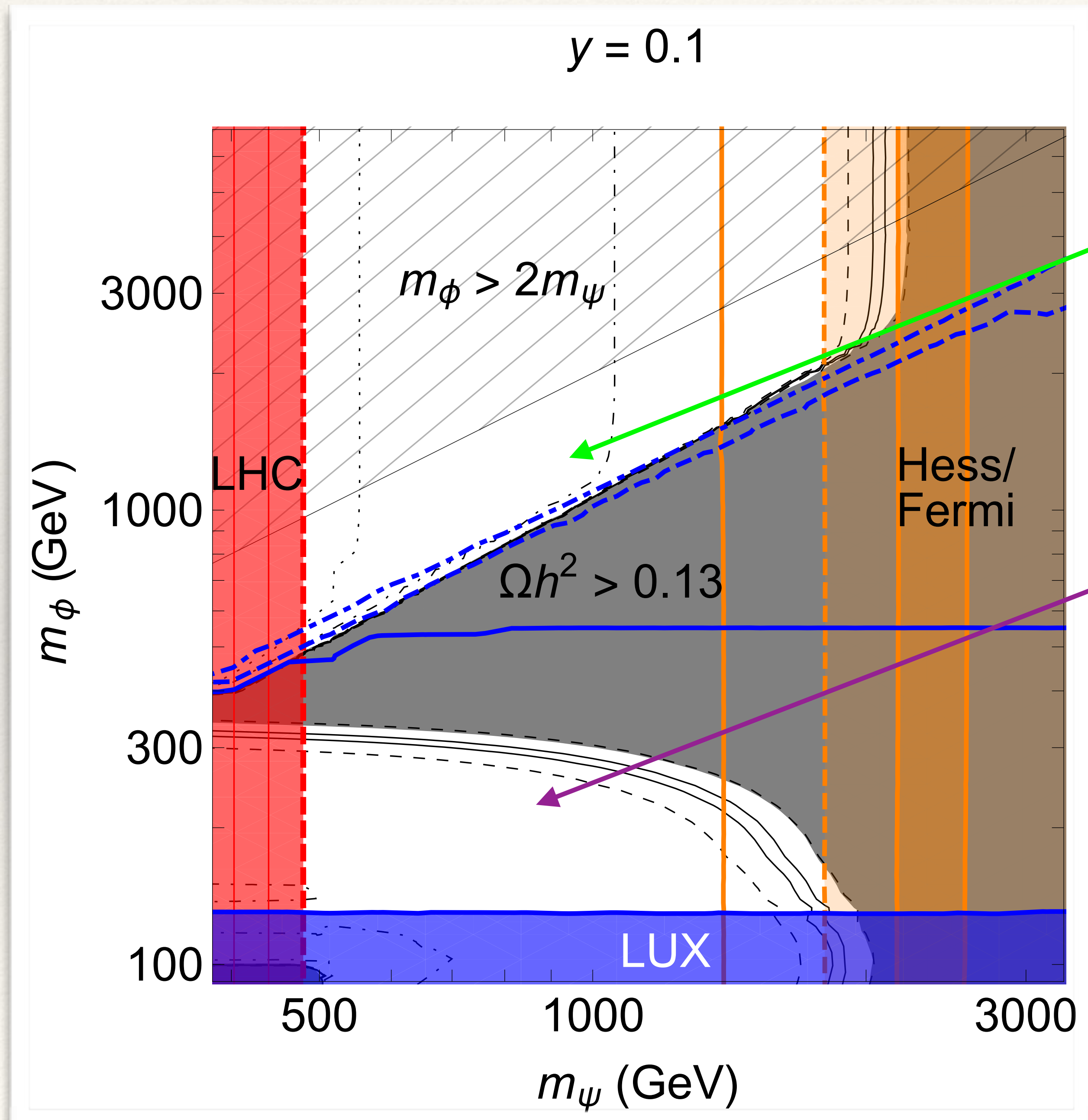


- Fermion



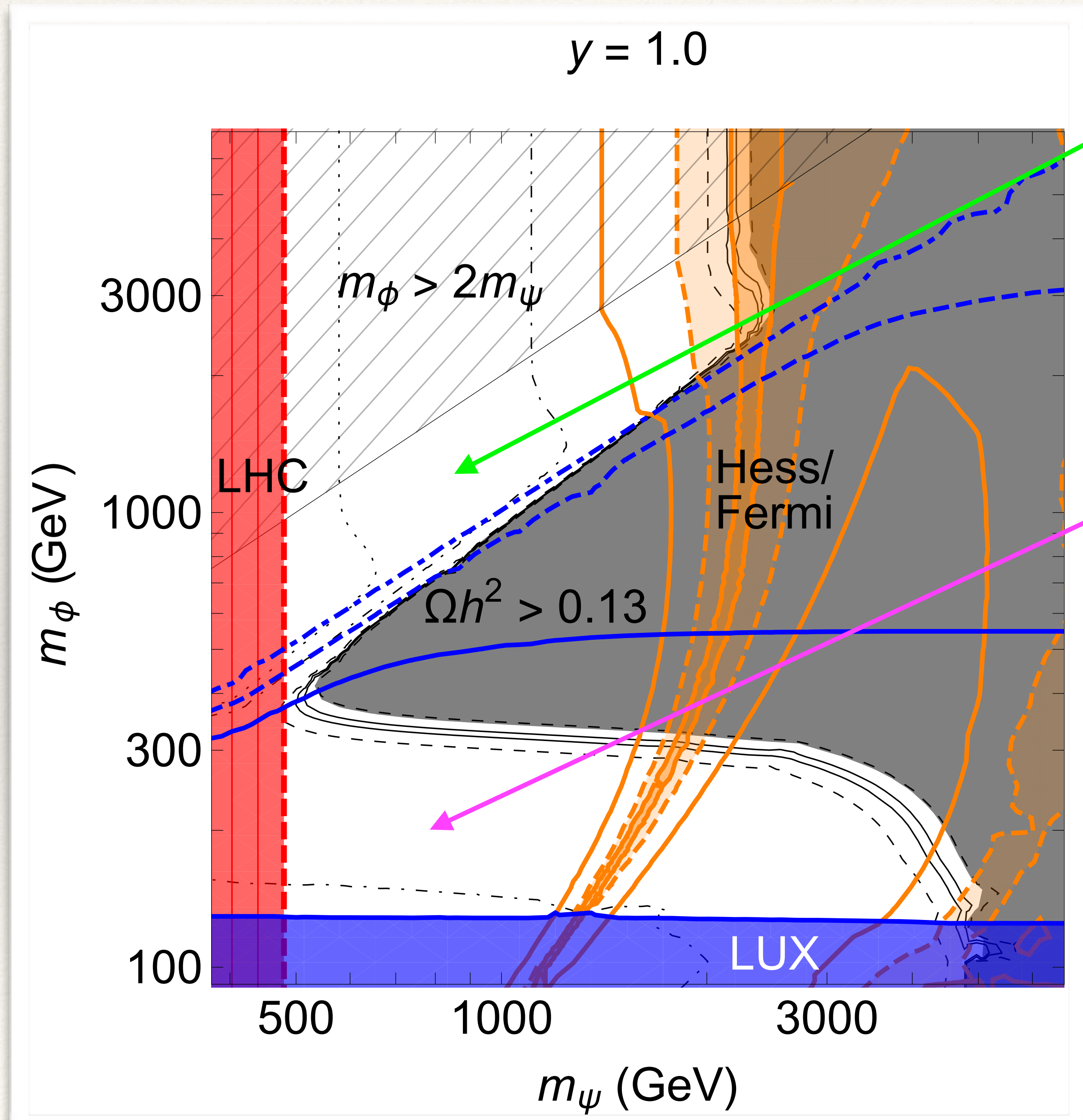
- Fix one DM mass and vary other
- SA most important when $m_\varphi < m_\psi < 2m_\varphi$

Small y Parameter Space



- Ψ/φ freeze out independently
- Upper region
  - $\Psi\Psi \to \mathrm{SM}$ sets fermion relic density
  - $\varphi\varphi \to \mathrm{FF}$ sets scalar relic density
- Lower region:
  - $\Psi\Psi \to \mathrm{SM}$ sets fermion relic density
  - $\varphi\varphi \to \mathrm{SM}$ sets scalar relic density
- Collider/DD/ID bounds
- All regions with correct relic density can be excluded

Including Semi-Annihilation



- Upper region
  - $\Psi\varphi \to \Psi V$ heavily affects scalar density
  - $\Psi\Psi \to \varphi V$ weakly alters fermion density
- Lower region
  - $\Psi\Psi \to \varphi V$ hugely changes fermion relic density, extends to higher masses
  - Scalar abundance largely unchanged
- Indirect constraints much weaker, tightly focused on resonance
- Still can rule out all regions with correct relic density

A Systematic Effective Operator Analysis

Strategy

- Approaches thus far somewhat *ad hoc*
- Can we systematically analyse the model space of Semi-Annihilating Dark Matter?
- Many variables: dark matter particles, couplings, etc

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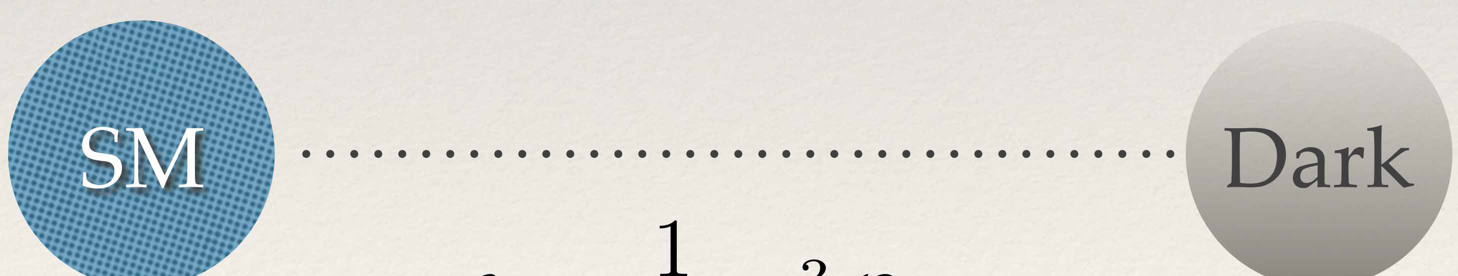
- Approaches thus far somewhat *ad hoc*
- Can we systematically analyse the model space of Semi-Annihilating Dark Matter?
- Many variables: dark matter particles, couplings, etc
- Simplifying Framework: Effective Operators
  Integrate out Heavy Mediators



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

The EFT Language

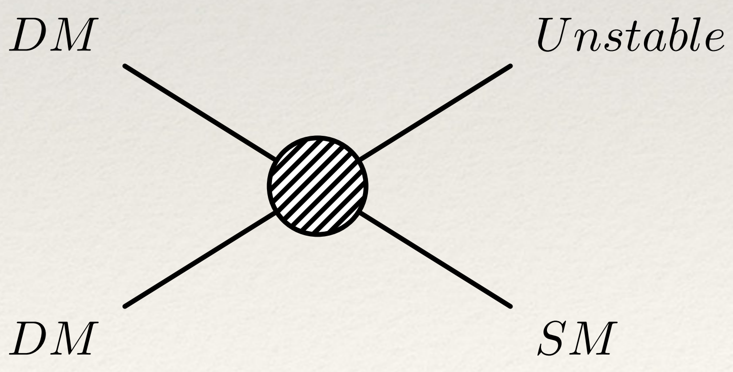
- Strengths:
  - Simple & complete classification of terms
  - Good for non-relativistic processes:
    indirect detection, direct detection (irrelevant), relic density?
- Weaknesses:
  - Not good at colliders, but SA is unimportant there
  - Additional terms for annihilation might be necessary

Assumptions

- DM is neutral and stable
  - Can be scalar or fermion
  - Initially assume total gauge singlet; will generalise
- Focus on 2 → 2 processes
  - All operators to dimension 6
  - Leading terms at dimension 7

$$\mathcal{L} \supset \frac{1}{\Lambda^d} \chi^3 F_{SM}$$

- Dark sector may be multicomponent
  - Possible for multiple stable fields
  - Possible for light (SA-relevant) unstable fields



Step One: Constructing Operators

- Write down all operators consistent with assumptions
  - Scalar

Operator	Definition
$\bar{\mathcal{O}}_5^{H\phi}$	$\frac{1}{6}\, s^{ijk}\phi_i\phi_j\phi_k\, H^\dagger H$
$\bar{\mathcal{O}}_7^{Z\phi}$	$\frac{1}{2}\, x_Z^{ijk}\phi_i\phi_j(\partial_\mu\phi_k)\big(H^\dagger \overleftrightarrow{D}^\mu H\big)$
$\bar{\mathcal{O}}_7^{H\phi}$	$\frac{1}{2}\, x_h^{ijk}(\partial_\mu\phi_i)(\partial^\mu\phi_j)\phi_k\, H^\dagger H$
$\bar{\mathcal{O}}_7^{B\phi}$	$\frac{1}{6}\, a^{ijk}B^{\mu\nu}(\partial_\mu\phi_i)(\partial_\nu\phi_j)\phi_k$
$\bar{\mathcal{O}}_7^{BB\phi}$	$\frac{1}{6}\, s^{ijk}\phi_i\phi_j\phi_k B^{\mu\nu}B_{\mu\nu}$
$\bar{\mathcal{O}}_7^{WW\phi}$	$\frac{1}{6}\, s^{ijk}\phi_i\phi_j\phi_k W^{a\mu\nu}W^a_{\mu\nu}$

  - Fermion

Operator	Definition
$\bar{\mathcal{O}}_7^{\nu\chi L}$	$\frac{1}{2}\, x_L^{ijk}(\bar{\chi}_i^c P_L\chi_j)\,(H^\dagger \bar{L}_L\chi_k)$
$\bar{\mathcal{O}}_7^{\nu\chi R}$	$x_R^{ijk}(\bar{\chi}_i^c P_R\chi_j)\,(H^\dagger \bar{L}_L\chi_k)$
$\bar{\mathcal{O}}_7^{\nu\chi T_S}$	$\frac{1}{6}\, a^{ijk}(\bar{\chi}_i^c\sigma^{\mu\nu}\chi_j)\,(H^\dagger \bar{L}_L\sigma_{\mu\nu}\chi_k)$
$\bar{\mathcal{O}}_7^{\nu\chi T_A}$	$\frac{i}{6}\, a^{ijk}\epsilon_{\mu\nu\rho\sigma}(\bar{\chi}_i^c\sigma^{\mu\nu}\chi_j)\,(H^\dagger \bar{L}_L\sigma^{\rho\sigma}\chi_k)$

- Small number of operators

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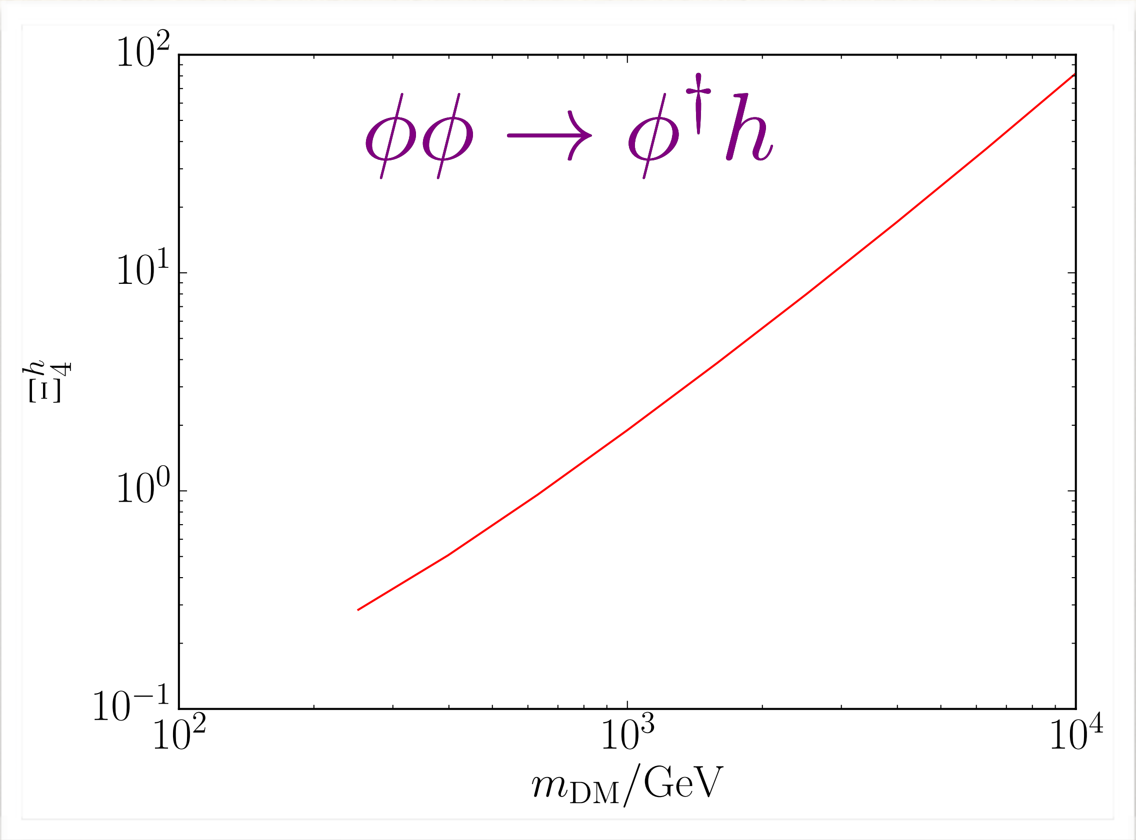
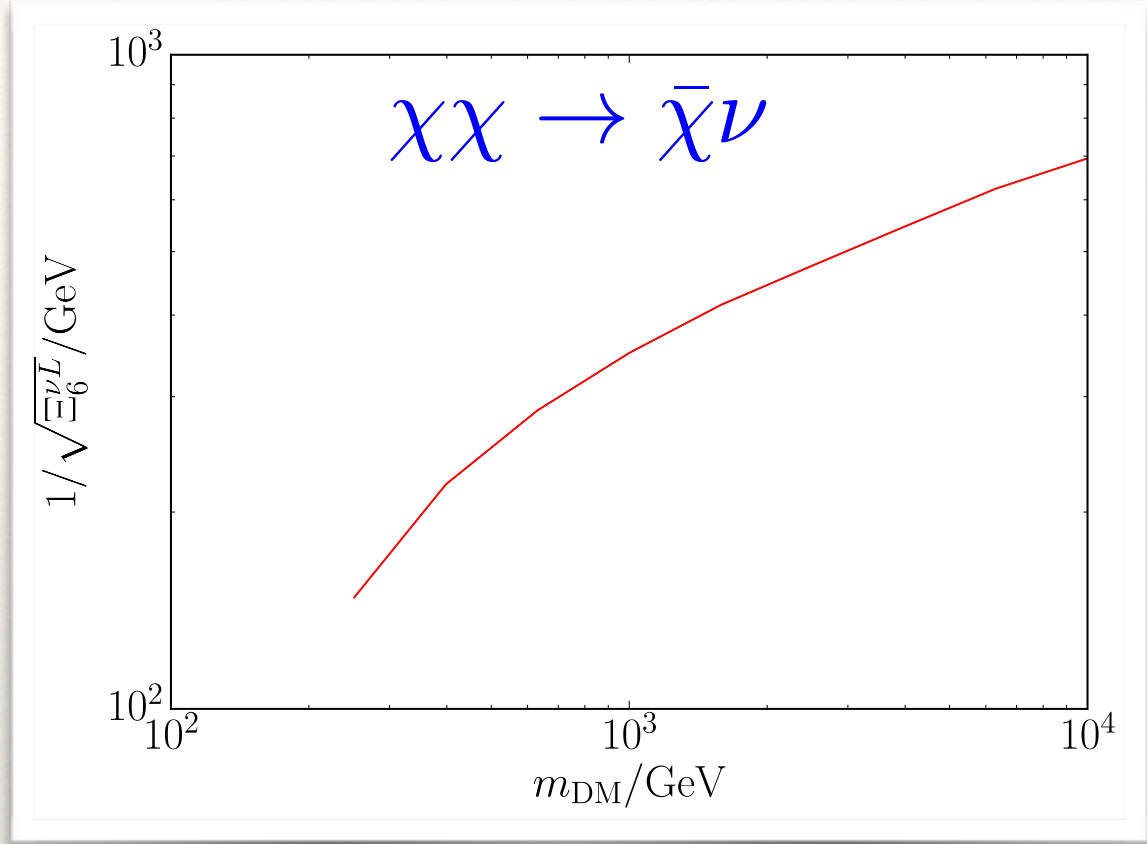
$\bar{\mathcal{O}}_7^{\nu\chi R}$	$x_R^{ijk}(\bar{\chi}_i^c P_R\chi_j)\,(H^\dagger L_L\chi_k)$
$\bar{\mathcal{O}}_7^{\nu\chi T_S}$	$\frac{1}{6}\, a^{ijk}(\bar{\chi}_i^c\sigma^{\mu\nu}\chi_j)\,(H^\dagger \bar{L}_L\sigma_{\mu\nu}\chi_k)$
$\bar{\mathcal{O}}_7^{\nu\chi T_A}$	$\frac{i}{6}\, a^{ijk}\epsilon_{\mu\nu\rho\sigma}(\bar{\chi}_i^c\sigma^{\mu\nu}\chi_j)\,(H^\dagger \bar{L}_L\sigma^{\rho\sigma}\chi_k)$

- Small number of operators
- Even fewer for unique DM

Step Two: Constraints





- Limits from Fermi (left) and IceCube (right)
- Connection to relic density in progress

More Operators

Scalar and
Fermion DM

Operator	Definition
$\bar{\mathcal{O}}_6^{\nu\phi}$	$\frac{1}{2}\, s^{ij}\, \phi_i \phi_j\, (H^\dagger \bar{L}_L \chi)$
$\bar{\mathcal{O}}_6^{H\chi S}$	$\frac{1}{2}\, s^{ij}\, (\bar{\chi}_i^c \chi_j)\, \phi\, H^\dagger H$
$\bar{\mathcal{O}}_6^{H\chi P}$	$\frac{1}{2}\, s^{ij}\, (\bar{\chi}_i^c \gamma^5 \chi_j)\, \phi\, H^\dagger H$
$\bar{\mathcal{O}}_6^{B\chi}$	$\frac{1}{2}\, a^{ij}\, (\bar{\chi}_i^c \sigma^{\mu\nu} \chi_j) \phi\, B_{\mu\nu}$
$\bar{\mathcal{O}}_7^{\nu\phi}$	$\frac{1}{2}\, a^{ij}\, \big(\phi_i \overleftrightarrow{\partial}_\mu \phi_j\big)(H^\dagger \bar{L}_L \gamma^\mu \chi)$
$\bar{\mathcal{O}}_7^{Z\chi V}$	$\frac{1}{2}\, a^{ij}\, (\bar{\chi}_i^c \gamma^\mu \chi_j)\, \phi\, \big(H^\dagger \overleftrightarrow{D}_\mu H\big)$
$\bar{\mathcal{O}}_7^{Z\chi A}$	$\frac{1}{2}\, s^{ij}\, (\bar{\chi}_i^c \gamma^\mu \gamma^5 \chi_j)\, \phi\, \big(H^\dagger \overleftrightarrow{D}_\mu H\big)$
$\bar{\mathcal{O}}_7^{H\chi V}$	$\frac{1}{2}\, a^{ij}\, (\bar{\chi}_i^c \gamma^\mu \chi_j) \big(\phi \overleftrightarrow{\partial}_\mu (H^\dagger H)\big)$
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More Operators

Scalar and Fermion DM

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$\bar{\mathcal{O}}_6^{H\chi S}$	$\frac{1}{2}\, s^{ij}(\bar{\chi}_i^c\chi_j)\,\phi\, H^\dagger H$
$\bar{\mathcal{O}}_6^{H\chi P}$	$\frac{1}{2}\, s^{ij}(\bar{\chi}_i^c\gamma^5\chi_j)\,\phi\, H^\dagger H$
$\bar{\mathcal{O}}_6^{B\chi}$	$\frac{1}{2}\, a^{ij}(\bar{\chi}_i^c\sigma^{\mu\nu}\chi_j)\phi\, B_{\mu\nu}$
$\bar{\mathcal{O}}_7^{\nu\phi}$	$\frac{1}{2}\, a^{ij}\big(\phi_i \overleftrightarrow{\partial_\mu}\phi_j\big)(H^\dagger \bar{L}_L\gamma^\mu\chi)$
$\bar{\mathcal{O}}_7^{Z\chi V}$	$\frac{1}{2}\, a^{ij}(\bar{\chi}_i^c\gamma^\mu\chi_j)\,\phi\,\big(H^\dagger \overleftrightarrow{D_\mu} H\big)$
$\bar{\mathcal{O}}_7^{Z\chi A}$	$\frac{1}{2}\, s^{ij}(\bar{\chi}_i^c\gamma^\mu\gamma^5\chi_j)\,\phi\,\big(H^\dagger \overleftrightarrow{D_\mu} H\big)$
$\bar{\mathcal{O}}_7^{H\chi V}$	$\frac{1}{2}\, a^{ij}(\bar{\chi}_i^c\gamma^\mu\chi_j)\big(\phi\overleftrightarrow{\partial_\mu}(H^\dagger H)\big)$
$\bar{\mathcal{O}}_7^{H\chi A}$	$\frac{1}{2}\, s^{ij}(\bar{\chi}_i^c\gamma^\mu\gamma^5\chi_j)\big(\phi\overleftrightarrow{\partial_\mu}(H^\dagger H)\big)$

Gauge charged Dark Partners

Name	Operator	Hypercharge & Isospin
$\bar{\mathcal{O}}_5^{fR}$	$\frac{1}{2}\,\phi^2\,(\bar{f}_R\psi)$	$Y_\psi = Q_f\,,\; I_\psi = 0$
$\bar{\mathcal{O}}_5^{QL}$	$\frac{1}{2}\,\phi^2\,(\bar{Q}_L\psi)$	$Y_\psi = \frac{1}{6}\,,\; I_\psi = \frac{1}{2}$
$\bar{\mathcal{O}}_5^{LL}$	$\frac{1}{2}\,\phi^2\,(\bar{L}_L\psi)$	$Y_\psi = -\frac{1}{2}\,,\; I_\psi = \frac{1}{2}$
$\bar{\mathcal{O}}_{6H^\dagger}^{fR}$	$\frac{1}{2}\,\phi^2\,\big(\bar{f}_R(H^\dagger\psi)\big)$	$Y_\psi = Q_f + \frac{1}{2}\,,\; I_\psi = \frac{1}{2}$
$\bar{\mathcal{O}}_{6H}^{fR}$	$\frac{1}{2}\,\phi^2\,\big(\bar{f}_R(\tilde{H}^\dagger\psi)\big)$	$Y_\psi = Q_f - \frac{1}{2}\,,\; I_\psi = \frac{1}{2}$
$\bar{\mathcal{O}}_{6S}^{uL}$	$\frac{1}{2}\,\phi^2\,\big((\bar{Q}_L\tilde{H})\psi\big)$	$Y_\psi = \frac{2}{3}\,,\; I_\psi = 0$
$\bar{\mathcal{O}}_{6T}^{uL}$	$\frac{1}{2}\,\phi^2\,\big((\bar{Q}_L\sigma^a\tilde{H})\psi^a\big)$	$Y_\psi = \frac{2}{3}\,,\; I_\psi = 1$
$\bar{\mathcal{O}}_{6S}^{dL}$	$\frac{1}{2}\,\phi^2\,\big((\bar{Q}_L H)\psi\big)$	$Y_\psi = -\frac{1}{3}\,,\; I_\psi = 0$
$\bar{\mathcal{O}}_{6T}^{dL}$	$\frac{1}{2}\,\phi^2\,\big((\bar{Q}_L\sigma^a H)\psi^a\big)$	$Y_\psi = -\frac{1}{3}\,,\; I_\psi = 1$
$\bar{\mathcal{O}}_{6S}^{eL}$	$\frac{1}{2}\,\phi^2\,\big((\bar{L}_L H)\psi\big)$	$Y_\psi = -1\,,\; I_\psi = 0$
$\bar{\mathcal{O}}_{6T}^{eL}$	$\frac{1}{2}\,\phi^2\,\big((\bar{L}_L\sigma^a H)\psi^a\big)$	$Y_\psi = -1\,,\; I_\psi = 1$
$\bar{\mathcal{O}}_{6S}^{\nu}$	$\frac{1}{2}\,\phi^2\,\big((\bar{L}_L\tilde{H})\psi\big)$	$Y_\psi = 0\,,\; I_\psi = 0$
$\bar{\mathcal{O}}_{6T}^{\nu}$	$\frac{1}{2}\,\phi^2\,\big((\bar{L}_L\sigma^a\tilde{H})\psi^a\big)$	$Y_\psi = 0\,,\; I_\psi = 1$

More Operators

Scalar and Fermion DM

Operator	Definition
$\bar{\mathcal{O}}_6^{\nu\phi}$	$\frac{1}{2}\, s^{ij}\, \phi_i\phi_j\, (H^\dagger \bar{L}_L \chi)$
$\bar{\mathcal{O}}_6^{H\chi S}$	$\frac{1}{2}\, s^{ij}\, (\bar{\chi}_i^c \chi_j)\, \phi\, H^\dagger H$
$\bar{\mathcal{O}}_6^{H\chi P}$	$\frac{1}{2}\, s^{ij}\, (\bar{\chi}_i^c \gamma^5 \chi_j)\, \phi\, H^\dagger H$
$\bar{\mathcal{O}}_6^{B\chi}$	$\frac{1}{2}\, a^{ij}\, (\bar{\chi}_i^c \sigma^{\mu\nu} \chi_j) \phi\, B_{\mu\nu}$
$\bar{\mathcal{O}}_7^{\nu\phi}$	$\frac{1}{2}\, a^{ij}\, (\phi_i \overleftrightarrow{\partial}_\mu \phi_j)(H^\dagger \bar{L}_L \gamma^\mu \chi)$
$\bar{\mathcal{O}}_7^{Z\chi V}$	$\frac{1}{2}\, a^{ij}\, (\bar{\chi}_i^c \gamma^\mu \chi_j)\, \phi\, (H^\dagger \overleftrightarrow{D}_\mu H)$
$\bar{\mathcal{O}}_7^{Z\chi A}$	$\frac{1}{2}\, s^{ij}\, (\bar{\chi}_i^c \gamma^\mu \gamma^5 \chi_j)\, \phi\, (H^\dagger \overleftrightarrow{D}_\mu H)$
$\bar{\mathcal{O}}_7^{H\chi V}$	$\frac{1}{2}\, a^{ij}\, (\bar{\chi}_i^c \gamma^\mu \chi_j)(\phi \overleftrightarrow{\partial}_\mu (H^\dagger H))$
$\bar{\mathcal{O}}_7^{H\chi A}$	$\frac{1}{2}\, s^{ij}\, (\bar{\chi}_i^c \gamma^\mu \gamma^5 \chi_j)(\phi \overleftrightarrow{\partial}_\mu (H^\dagger H))$

Gauge charged Dark Partners

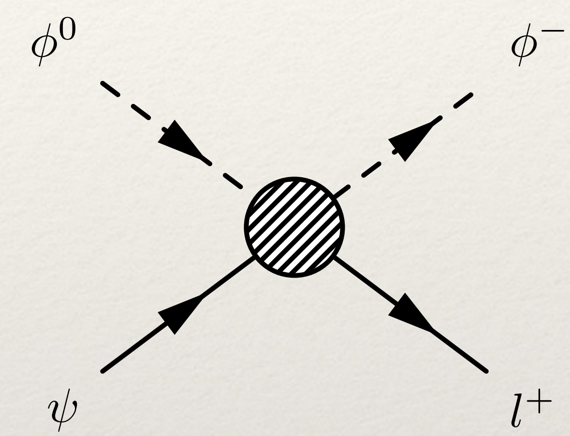
Name	Operator	Hypercharge & Isospin
$\bar{\mathcal{O}}_5^{fR}$	$\frac{1}{2}\, \phi^2\, (\bar{f}_R \psi)$	$Y_\psi = Q_f\,,\ I_\psi = 0$
$\bar{\mathcal{O}}_5^{QL}$	$\frac{1}{2}\, \phi^2\, (\bar{Q}_L \psi)$	$Y_\psi = \frac{1}{6}\,,\ I_\psi = \frac{1}{2}$
$\bar{\mathcal{O}}_5^{LL}$	$\frac{1}{2}\, \phi^2\, (\bar{L}_L \psi)$	$Y_\psi = -\frac{1}{2}\,,\ I_\psi = \frac{1}{2}$
$\bar{\mathcal{O}}_{6H^\dagger}^{fR}$	$\frac{1}{2}\, \phi^2\, (\bar{f}_R (H^\dagger \psi))$	$Y_\psi = Q_f + \frac{1}{2}\,,\ I_\psi = \frac{1}{2}$
$\bar{\mathcal{O}}_{6H}^{fR}$	$\frac{1}{2}\, \phi^2\, (\bar{f}_R (\tilde{H}^\dagger \psi))$	$Y_\psi = Q_f - \frac{1}{2}\,,\ I_\psi = \frac{1}{2}$
$\bar{\mathcal{O}}_{6S}^{uL}$	$\frac{1}{2}\, \phi^2\, ((\bar{Q}_L \tilde{H}) \psi)$	$Y_\psi = \frac{2}{3}\,,\ I_\psi = 0$
$\bar{\mathcal{O}}_{6T}^{uL}$	$\frac{1}{2}\, \phi^2\, ((\bar{Q}_L \sigma^a \tilde{H}) \psi^a)$	$Y_\psi = \frac{2}{3}\,,\ I_\psi = 1$
$\bar{\mathcal{O}}_{6S}^{dL}$	$\frac{1}{2}\, \phi^2\, ((\bar{Q}_L H) \psi)$	$Y_\psi = -\frac{1}{3}\,,\ I_\psi = 0$
$\bar{\mathcal{O}}_{6T}^{dL}$	$\frac{1}{2}\, \phi^2\, ((\bar{Q}_L \sigma^a H) \psi^a)$	$Y_\psi = -\frac{1}{3}\,,\ I_\psi = 1$
$\bar{\mathcal{O}}_{6S}^{eL}$	$\frac{1}{2}\, \phi^2\, ((\bar{L}_L H) \psi)$	$Y_\psi = -1\,,\ I_\psi = 0$
$\bar{\mathcal{O}}_{6T}^{eL}$	$\frac{1}{2}\, \phi^2\, ((\bar{L}_L \sigma^a H) \psi^a)$	$Y_\psi = -1\,,\ I_\psi = 1$
$\bar{\mathcal{O}}_{6S}^{\nu}$	$\frac{1}{2}\, \phi^2\, ((\bar{L}_L \tilde{H}) \psi)$	$Y_\psi = 0\,,\ I_\psi = 0$
$\bar{\mathcal{O}}_{6T}^{\nu}$	$\frac{1}{2}\, \phi^2\, ((\bar{L}_L \sigma^a \tilde{H}) \psi^a)$	$Y_\psi = 0\,,\ I_\psi = 1$

- More possibilities
- Lower dim. operators

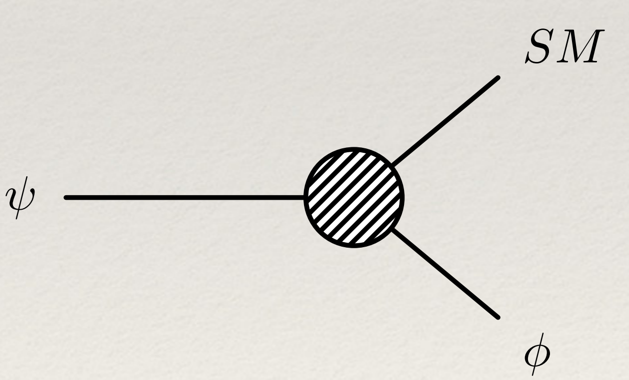
- Most (not all) operators give single 2 to 2 process

Dark Partners and Challenges

- Dark Partners: relatively light unstable states
  - Allows SA to charged/coloured objects
  - Allows lower-dimensional operators



- Dark Partners must decay without breaking DM symmetry
  - Needs additional operator
  - May lead to new signals & constraints



- Important for collider phenomenology

Conclusions

Conclusions

- Semi-annihilation is a generic feature of dark matter
- Renormalisable fermion models multi-component
- Fermion triplet model features Sommerfeld effect; interplay with semi-annihilation new
- Have explored triplet parameter space; can be excluded with future searches
- First steps to a systematic effective operator analysis

Conclusions

- Semi-annihilation is a generic feature of dark matter
- Renormalisable fermion models multi-component
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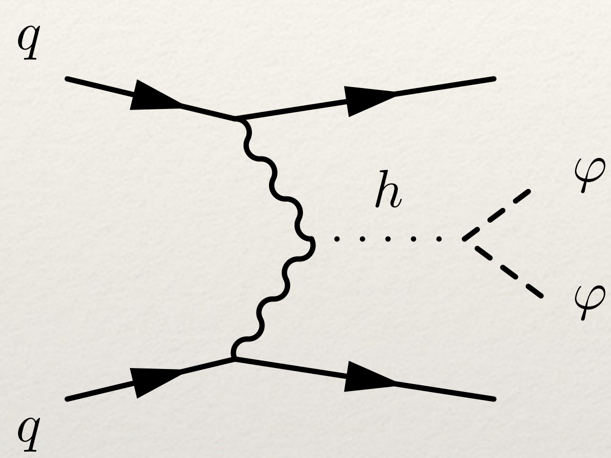
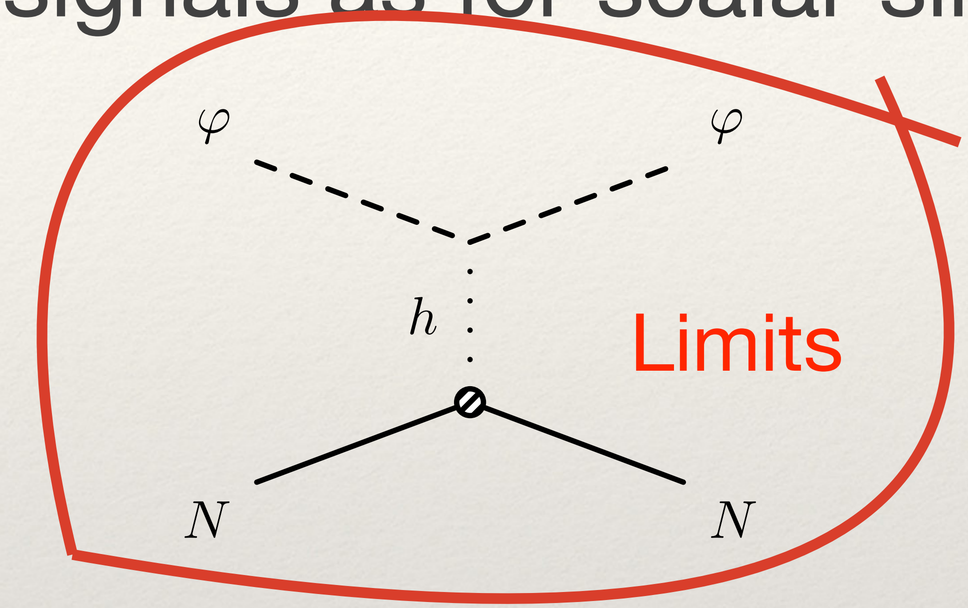
THANK YOU!

Back Up Slides

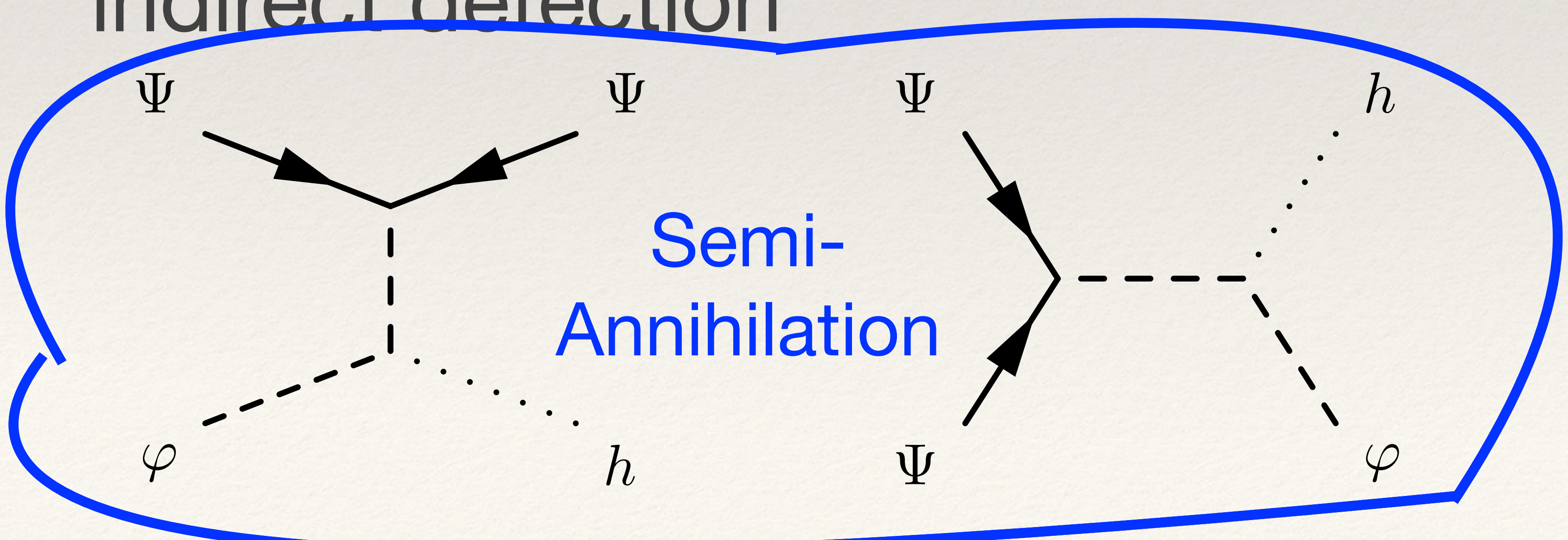
Minimal Model Phenomenology

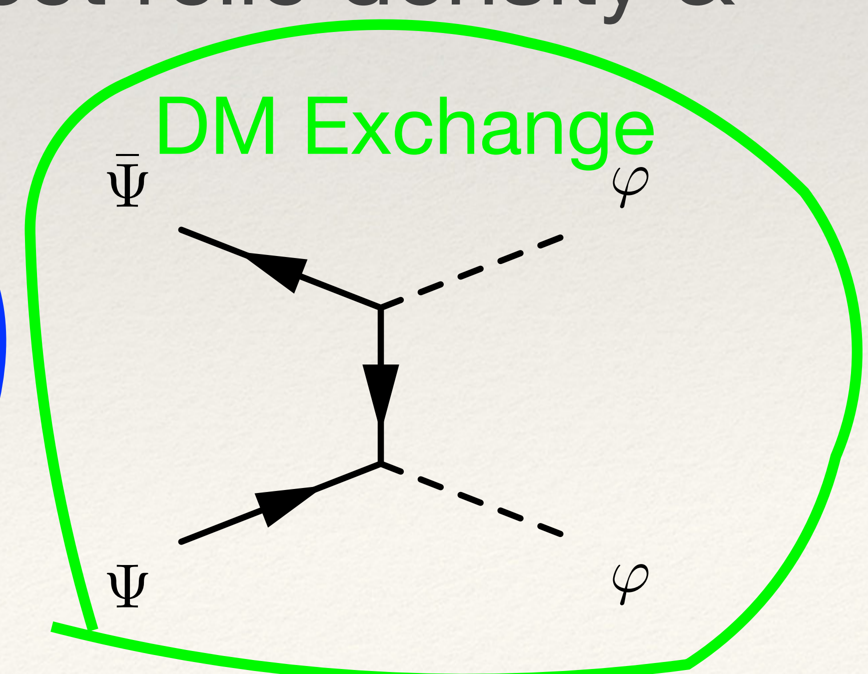
- Collider/Direct Detection signals as for scalar singlet





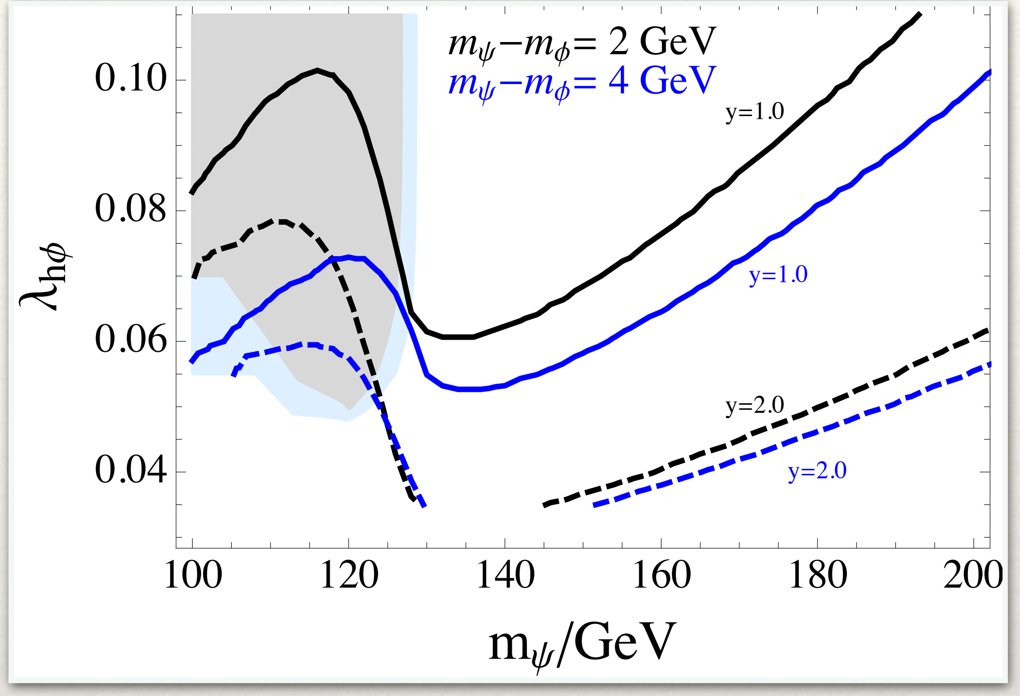
- Fermion & Semi-Annihilation only affect relic density & indirect detection

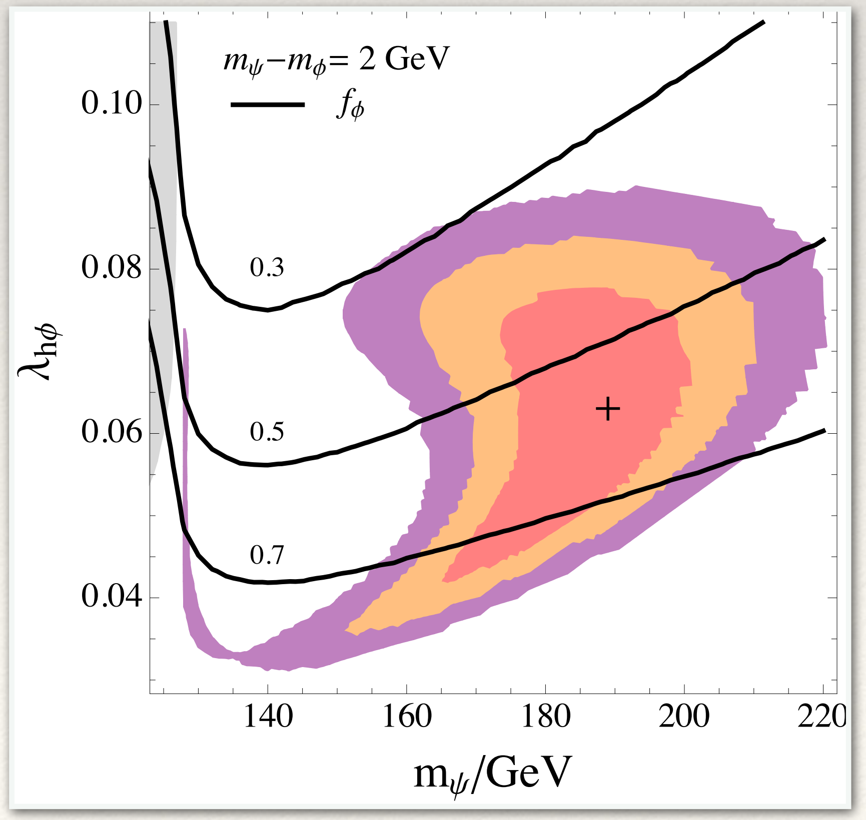




Fitting the GCE

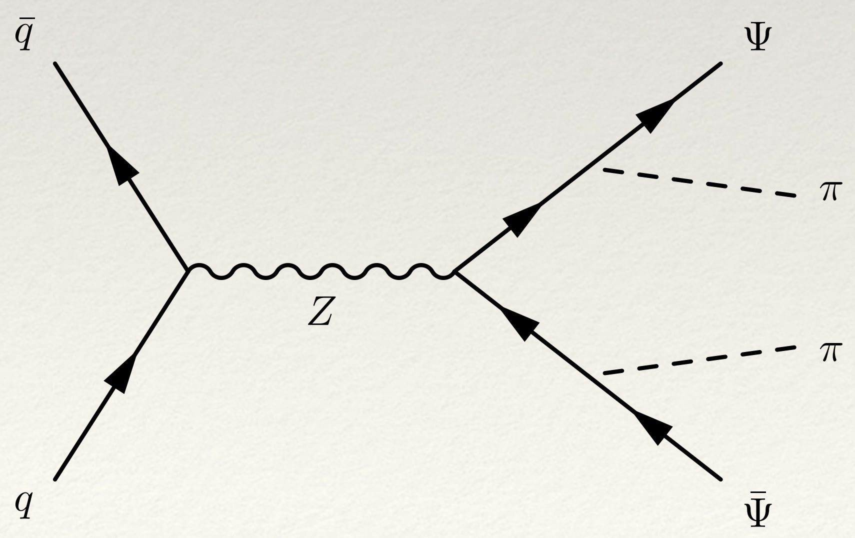
- Expect $\Psi\varphi \to \Psi\mathrm{h}$ to help fit: Higgs decays to bb
- 2D Parameter scan:
  - Fix mass difference 2/4 GeV
  - Fix y to give correct Ω_{DM}
  - Same DM profile as before
- Find Ω_φ, Ω_Ψ comparable: Weakens LUX constraints

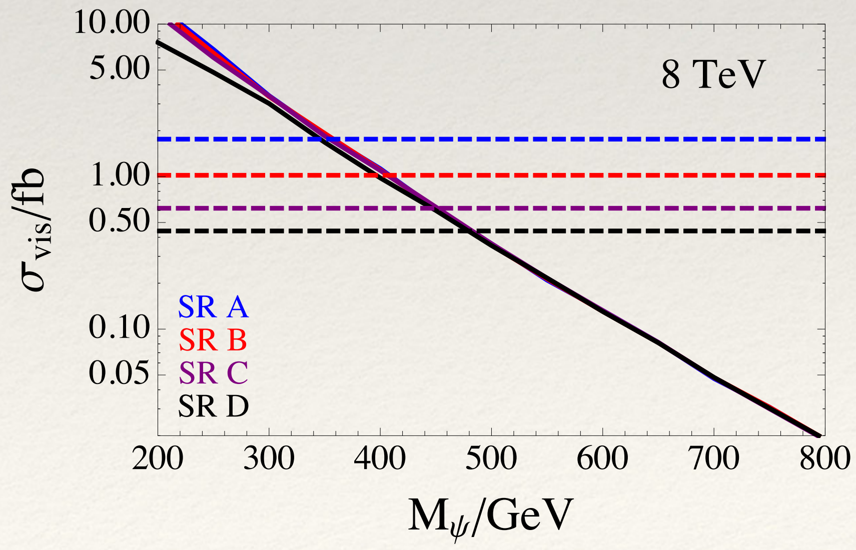




Constraints & Signals

- φ Higgs portal: similar limits from direct detection
- New collider bounds: disappearing tracks
  - Produce charged fermions through *s*-channel $\mathrm{W/Z}$
  - Decay to DM + pion, $\mathrm{c}\tau$ ~ 10 cm
  - Similar to Wino searches, but stronger bound: m_Ψ > 480 GeV





Indirect Detection

- LHC bounds exclude explanation of GCE
- Fermion annihilation to SM gives important bounds
  - Semi-annihilation zero at late times
  - HESS γ-line search dominates

Cirelli *et al*, `1507.0551`; Ibarra *et al*, `1507.0553`