Semi-Annihilating Wino-Like Dark Matter

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THE UNIVERSITY OF MELBOURNE

CoEPP
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About Me

- B.S. in Physics and Mathematics
  Peking University, 2004

- Ph.D. in Physics
  University of California at Davis, 2010
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- 1st Postdoc
  Shanghai Jiao Tong University, 2010-2012

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  The University of Melbourne, 2012-present

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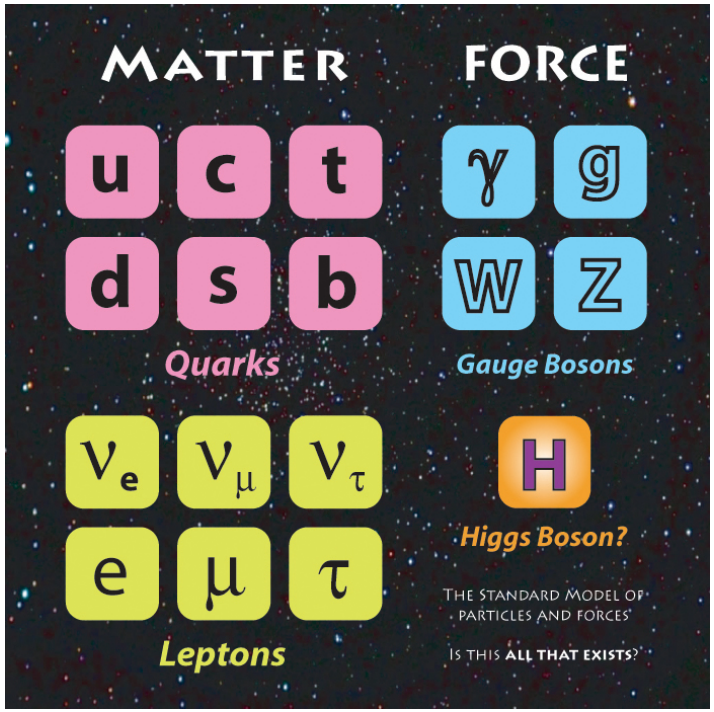
Summary

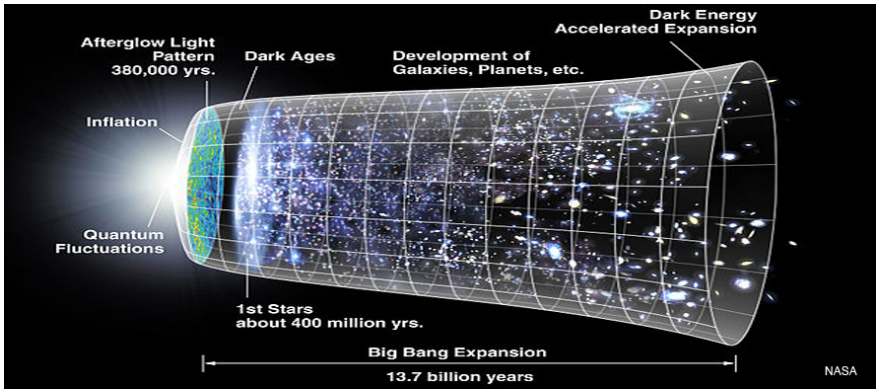
The Two Standard Models

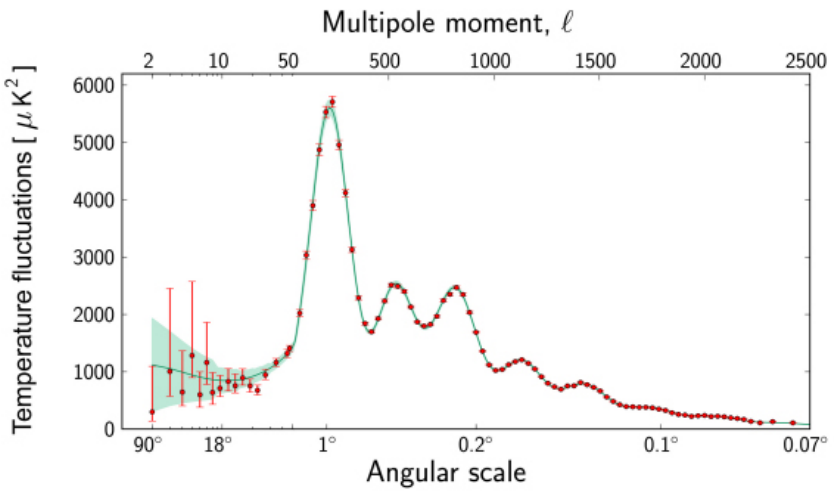
- **Particle Physics**



Higgs found in 2012

- **Cosmology**





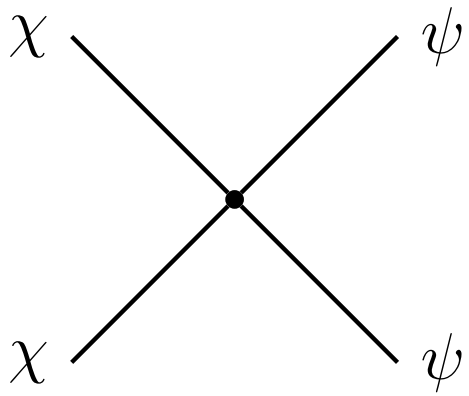
Ordinary Matter

Dark Matter

Dark Energy

Z_2

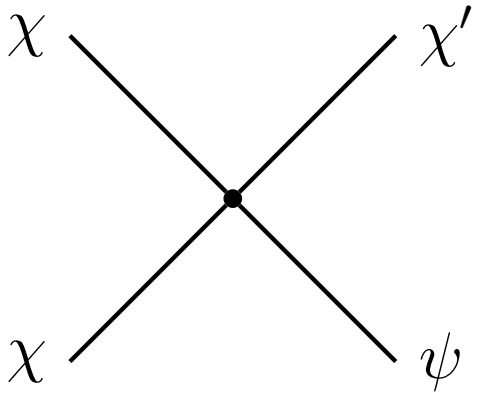
- Traditional: stabilize dark matter with Z_2 symmetry
  - Supersymmetry: R-Parity
  - Littele Higgs: T-Parity
  - Extra dimensions: KK parity
  - Inert doublet model
- DM candidate: the lightest of Z_2 odd, single component
- The generic picture



Dark Matter Symmetries

Beyond-Z_2

- Almost any other symmetries
- Semi-Annihilation (D'Eramo and Thaler, 1003.5912)
- Multi-component dark matter
- More generic picture



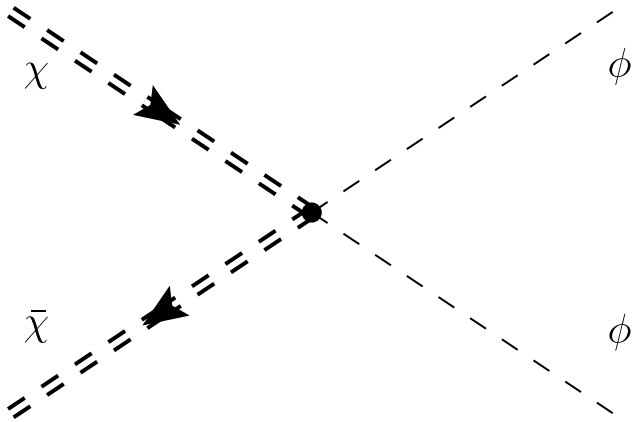
Semi-Annihilation

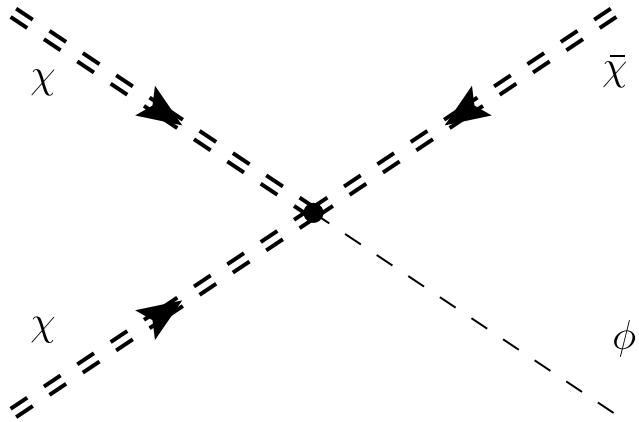
1003.5912

- A Z_3 toy model with pure scalar DM

$$\mathcal{L}_{Z_3} = m_\chi^2\,\chi^\dagger\chi + a_1\,\chi^\dagger\chi\phi + a_2\,\chi^\dagger\chi\phi^2 + a_3\,\chi\chi\chi\phi - V(\phi)$$

- χ: complex scalar with Z^3 charge 1
- ϕ: real scalar with Z^3 charge 0
- Two annihilation diagrams:

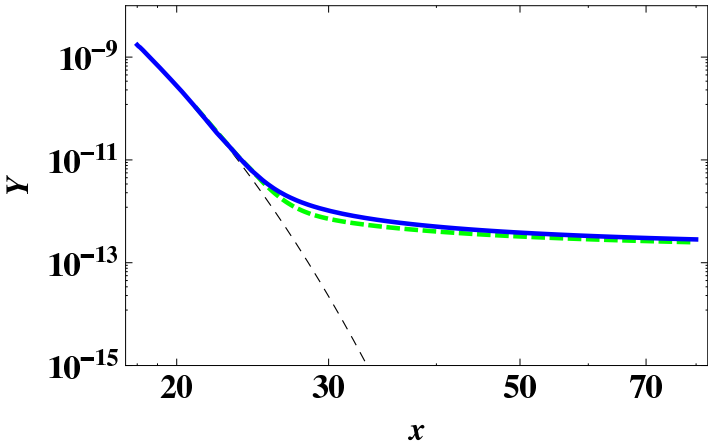




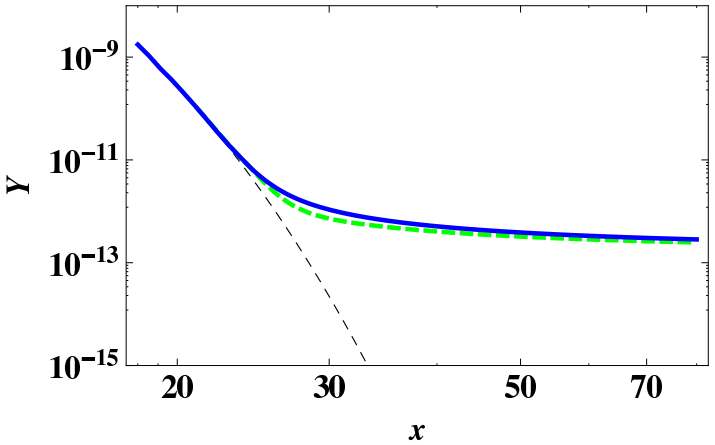
Semi-Annihilation

The relic density

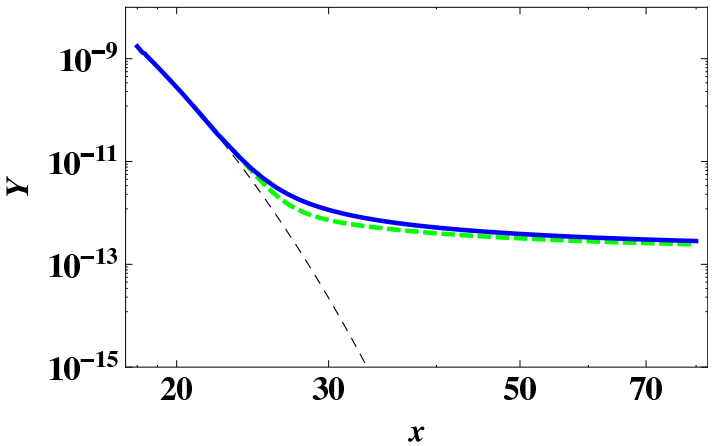
η_a=0.61, η_s=0, $\Omega h^2 \simeq 0.1$



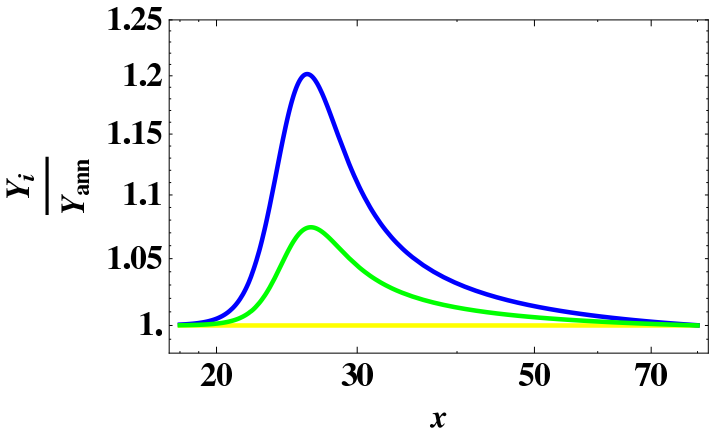
η_a=η_s=0.47, $\Omega h^2 \simeq 0.1$



η_a=0, η_s=0.72, $\Omega h^2 \simeq 0.1$

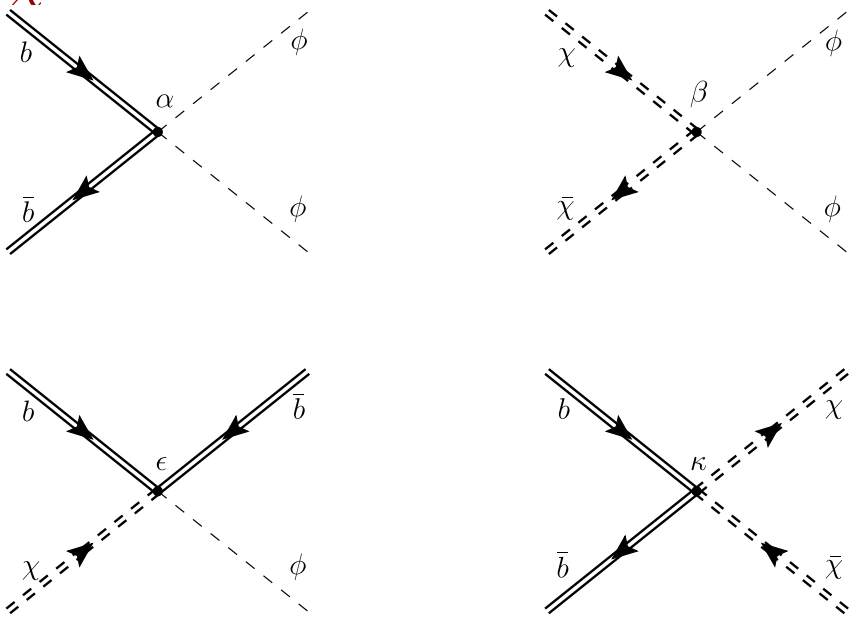


Y_i/Y_{ann} vs x



Multi-component model

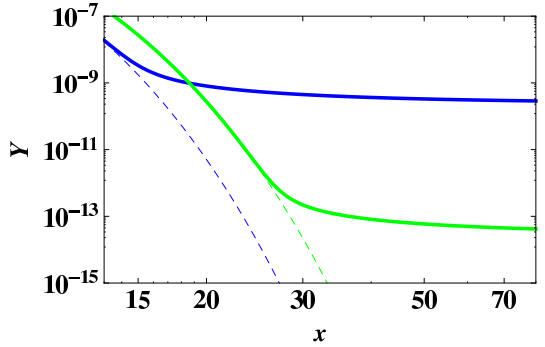
$bb\chi$ model



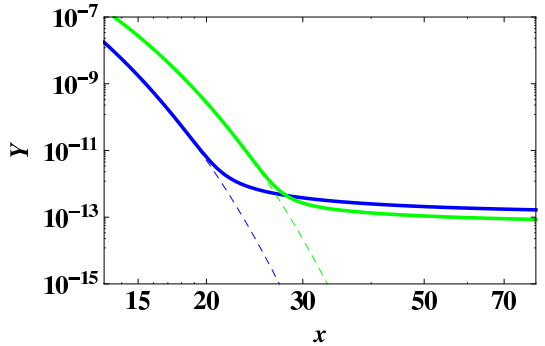
- b, $\bar{b}$ vector-like ,$U(1)$, ± 1
- χ, ϕ, complex/real scalar, -2/0
- α, β, self-annihilation
- ϵ, semi-annihilation
- κ, dark matter conversion
- example, $\alpha = 0.03$, $\beta = 1.5$

$m_\chi = 0.8$ TeV, $m_b = 1$ TeV

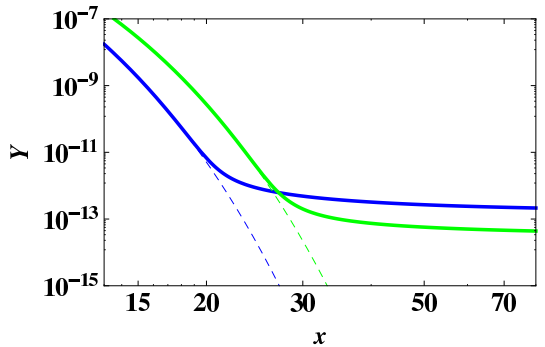
$\kappa = 0,\ \epsilon = 0,\ \Omega h^2 \simeq 100$



$\kappa = 2,\ \epsilon = 0,\ \Omega h^2 \simeq 0.1$



$\kappa = 0,\ \epsilon = 1.5,\ \Omega h^2 \simeq 0.1$



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Semi-Annihilating Fermions

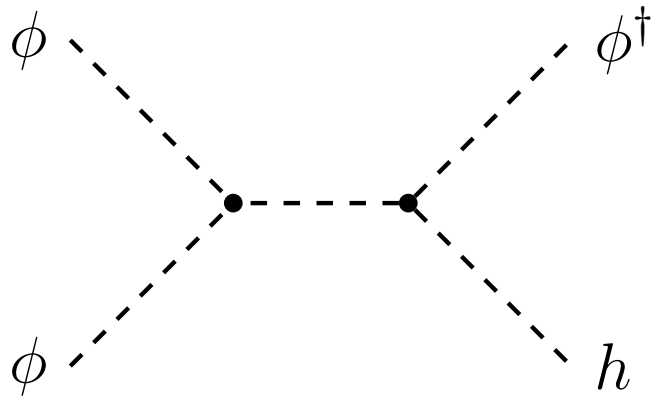
Relic Density

Other Constraints

Summary

Previous Models

- Scalar(or vector) dark matter
  - Batell et al 1007.0045, 1103.3053; D'Eramo et al, 1210.7817;
  - Belanger et al 1112.4491, 1211.1014, 1403.4960; Ivanov and Keus, 1203.3426;
  - Exception: Aoki and Toma, 1405.5870.
- Reason: simplest symmetries Z_3 and Z_4 to have χ^3 and χ^4
  - Bosonic cubic and quartic terms are renormalizable.
  - Scalar semi-annihilating models are simpler.



With Fermions

A Minimal Model

- Minimal flavor-neutral case
  - Z_4 symmetry, Dirac fermion Ψ and real scalar ϕ
    $\Psi \sim (1,1)_0 \quad G_{Z_4}(\Psi) = 1 \qquad \phi \sim (1,1)_0 \quad G_{Z_4}(\phi) = 2$
  - Ψ only couples to ϕ, not SM and thus completely invisible
  - Phenomenology reduces to scalar singlet model.
    Notable exception: galactic center excess
- Minimal interesting case
  - Z_4 symmetry, Dirac fermion Ψ and real scalar ϕ
    $\Psi \sim (1,3)_0 \quad G_{Z_4}(\Psi) = 1 \qquad \phi \sim (1,1)_0 \quad G_{Z_4}(\phi) = 2$
  - Fermion: Dirac "wino"
  - Scalar: Higgs-portal singlet
  - Relevant couplings:

$$\mathcal{L} \sim \tfrac{1}{2}\lambda\phi^2 H^\dagger H + y(\phi\bar{\Psi}^c\Psi + h.c.)$$

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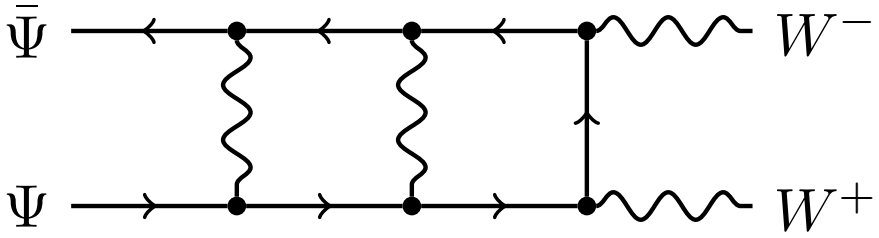
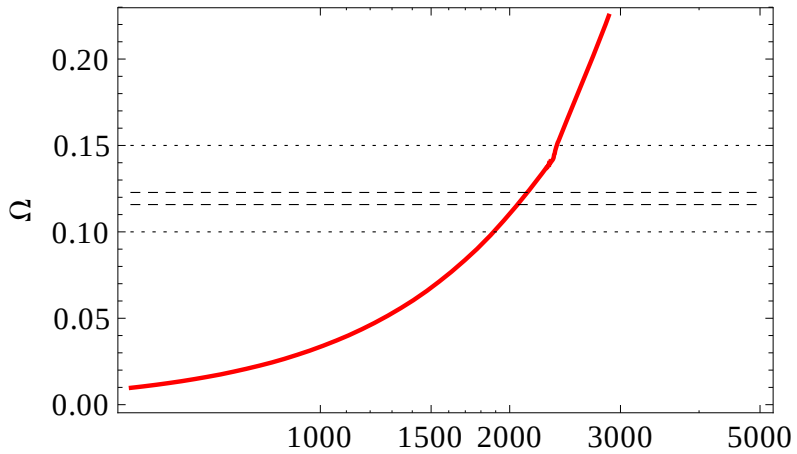
Fermion Relic Density

Sommerfeld Enhancement

- Fermion annihilates via gauge couplings
  - Sommerfeld effect: non-perturbative
    Hisano et al, hep-ph/0412403, hep-ph/0610249
    Cirelli et al, 0706.4071; Feng et al, 1005.4678



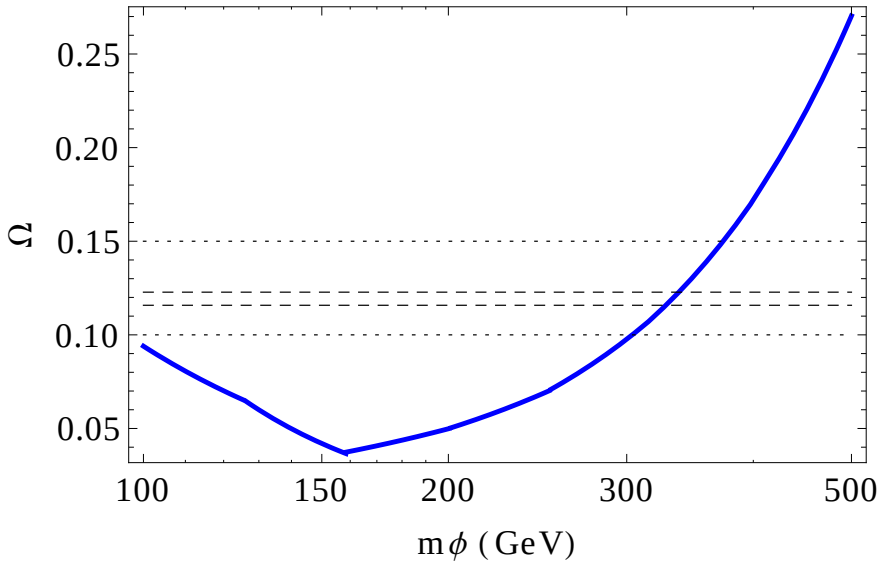
  - Resonance at 2.4 TeV
  - Relic density for $m_\Psi \sim 2\ \mathrm{TeV}$, lower than Wino



Scalar Relic Density

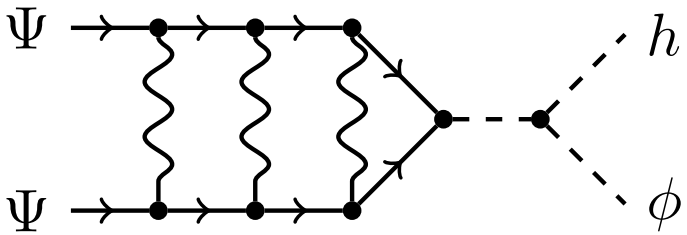
Cline et al, 1306.4710

- Dominant: s-channel Higgs portal into SM particles
- Sub-dominant: anni. into hh
- High mass: relic density for $m_\phi \sim (3\ \mathrm{TeV}) \times \lambda$
- Low mass: more complex(WW^*, ZZ^* decays)

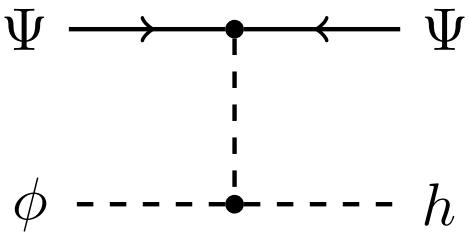


Semi-Annihilation

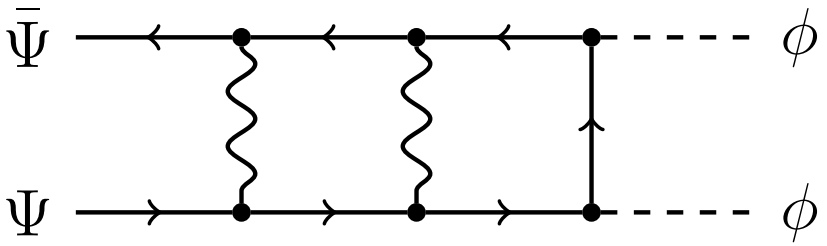
- Two semi-annihilation channels
  - $\Psi\Psi \to \phi h$: Sommerfeld enhanced



  - $\Psi\phi \to \bar{\Psi} h$: only changes the scalar number

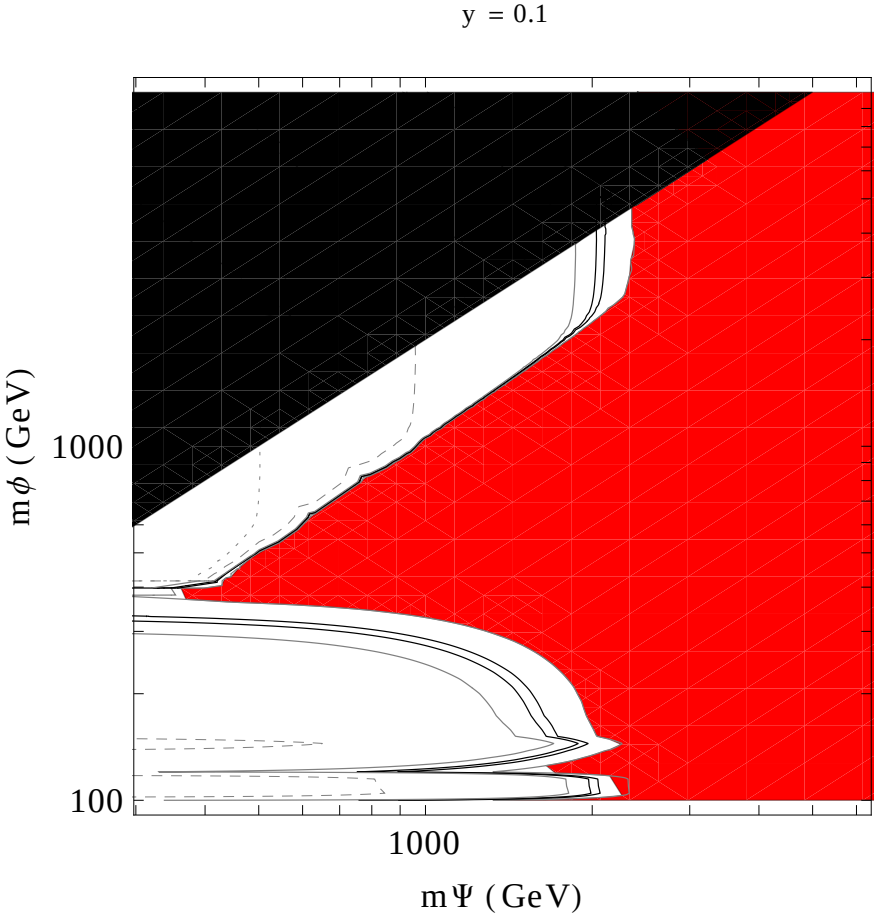


- DM exchange $\Psi\Psi \leftrightarrow \phi\phi$: Sommerfeld enhanced

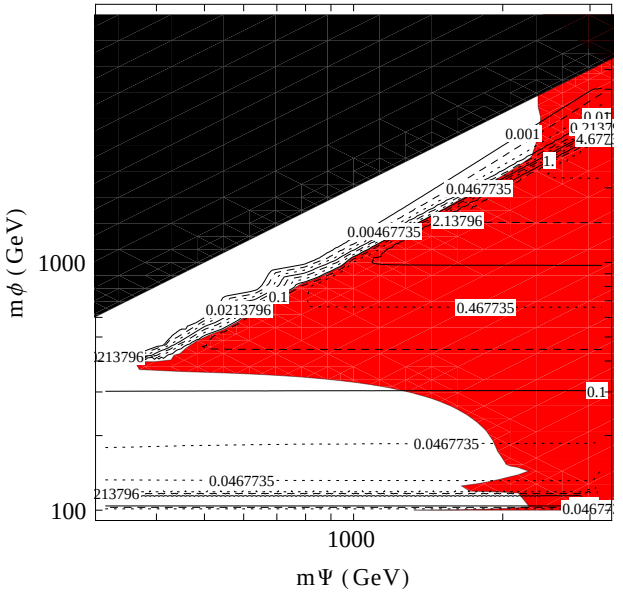


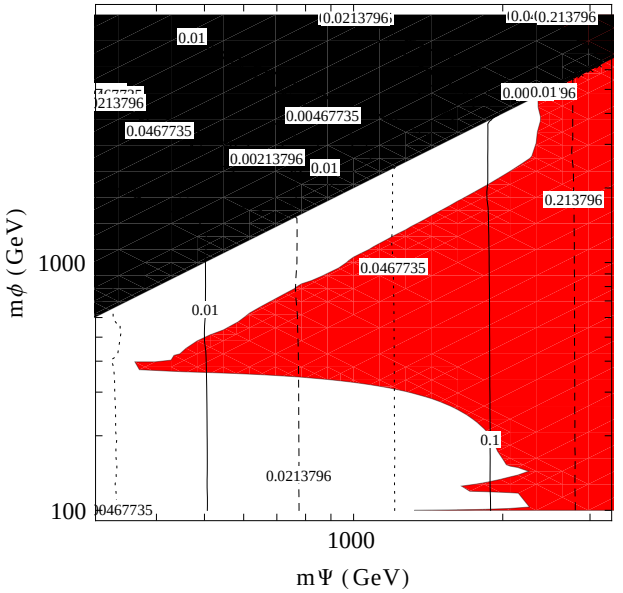
Benchmark Scenarios

- $y = 0.1, \lambda = 0.1$
- Red: $\Omega h^2 > 0.15$
- Black: scalar unstable



scalar and fermion density





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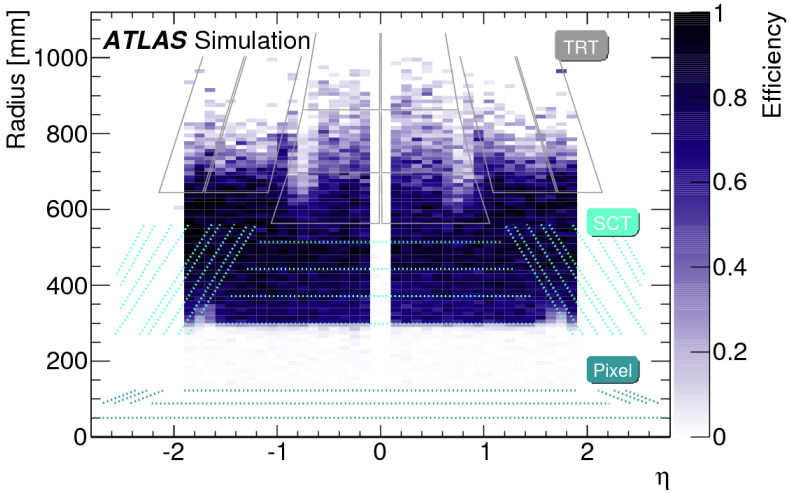
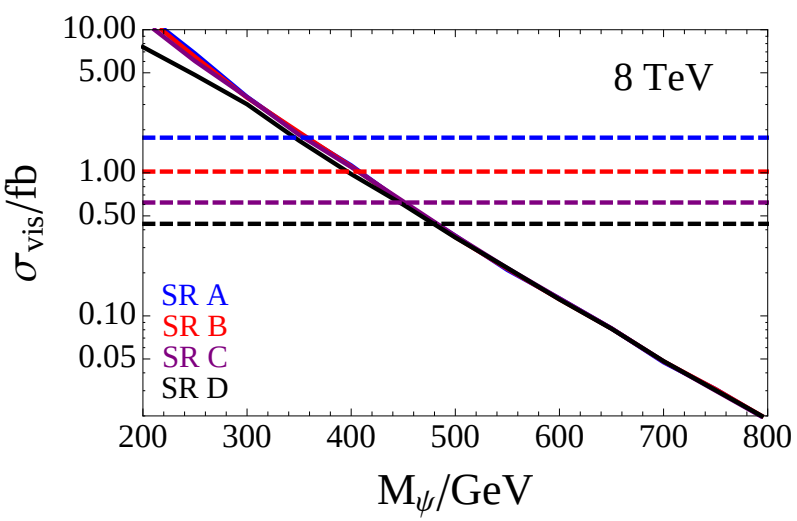
Collider Search

- Mono-jet puts constraints on m_ϕ, but very weak
- Disappearing tracks $pp \to W \to \Psi^\pm \Psi^0$, $\Psi^\pm \to \pi^\pm \Psi^0$
  - $p_T > 90$ GeV, $E_T^{miss} > 90$ GeV, $\Delta\phi_{min}^{jet-E_T^{miss}} > 1.5$
  - lepton veto
  - disappearing-track: $\Psi^\pm$ decays after SCT and before TRT
  - four signal regions with $p_T > 75, 100, 150, 200$ GeV

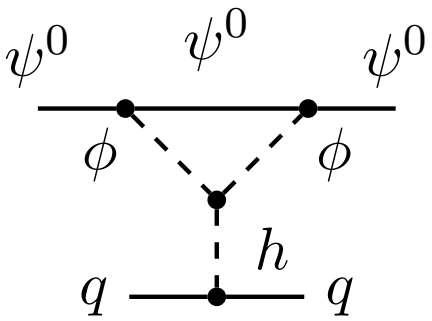


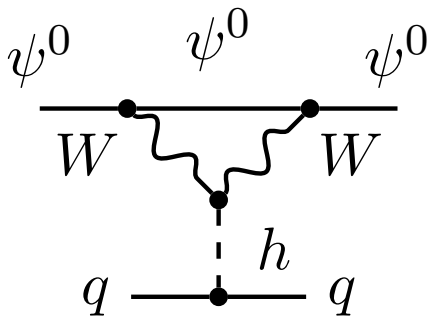


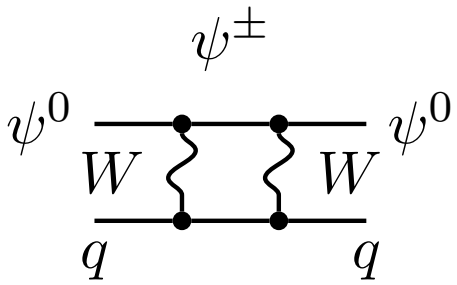
- $m_\Psi > 480$ GeV

Direct Detection and Indirect Detection

- Direct detection
  - Fermion: loop suppressed





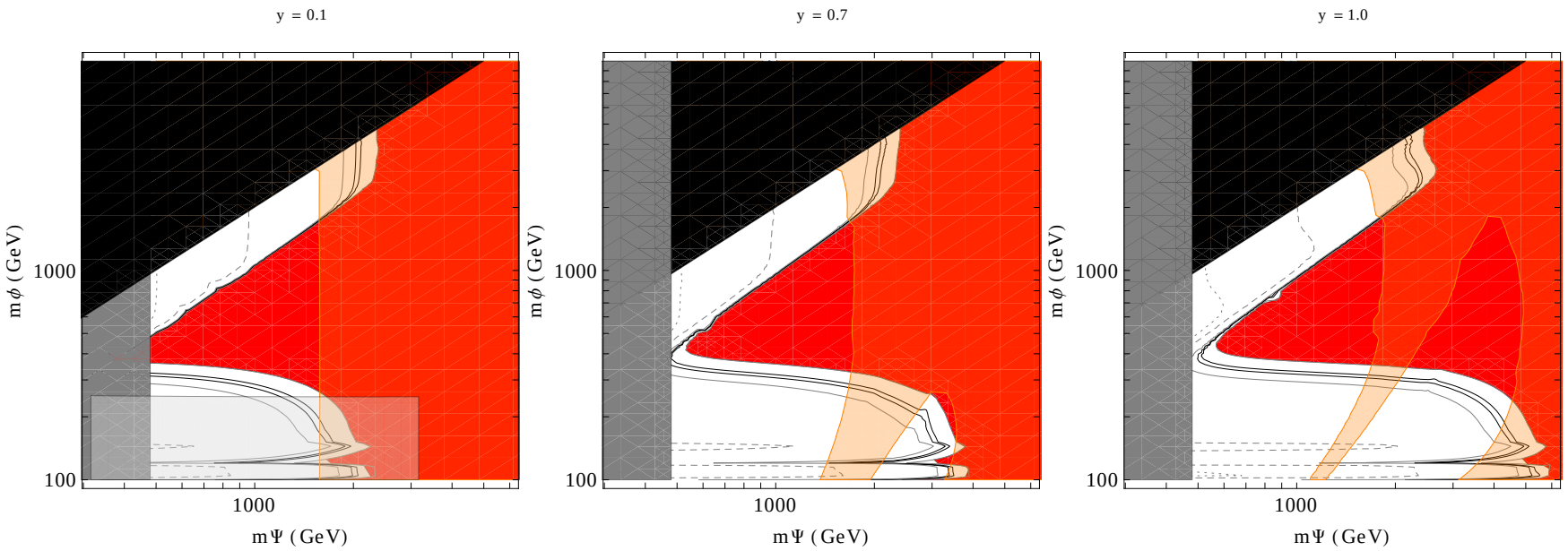


  - Scalar: Higgs portal

$$m_\phi > (300\ \mathrm{GeV}) \times (\lambda/0.1)^2 \times (\Omega_\phi/0.112)$$

- Indirect detection
  - HESS: Gamma ray lines from fermion annihilation at the galactic center
  - Sommerfeld enhanced, assume NFW profile

Constraint Plots



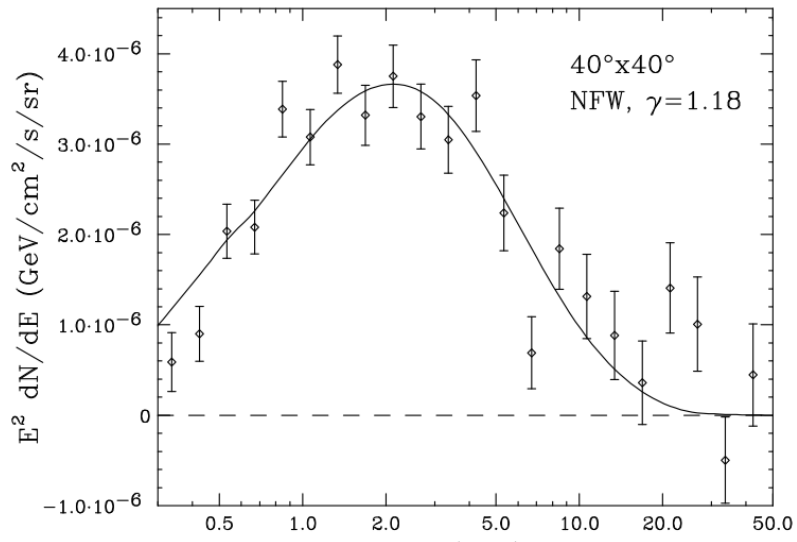
Gray: LHC Orange: HESS Lightgrey: Direct detection

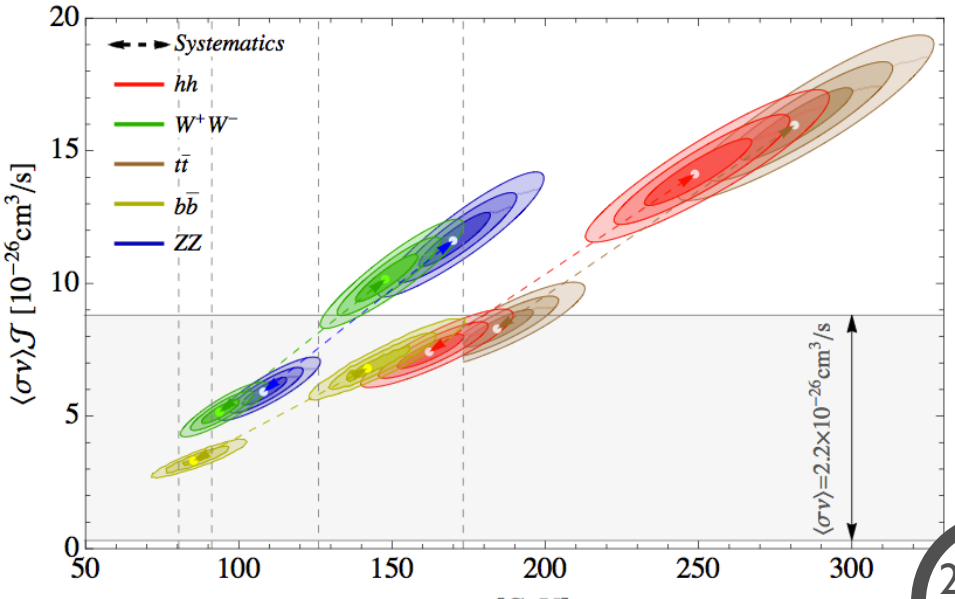
Upper and lower bounds

Semi-annihilation and multi-component region remains.

Galactic Center Excess

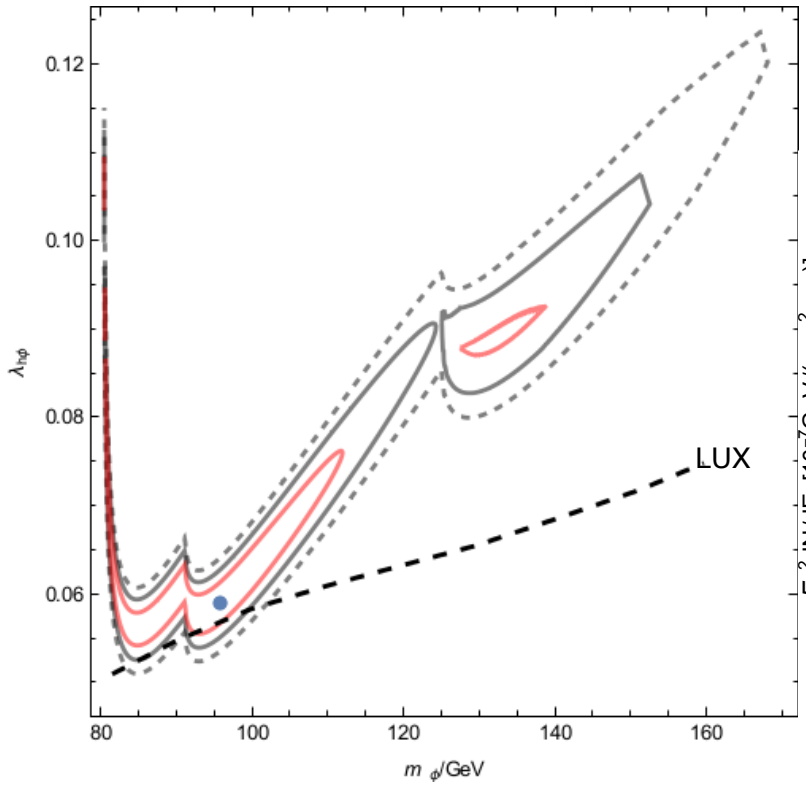
- Broad excess in Fermi γ ray data
  - Hooper et al, 1010.2752, 1110.0006, 1305.0830;
  - Abazajian and Kaplinghat, 1207.6047;
  - Boehm et al, 1401.6458; Daylan eta al, 1402.6703.
- Fermi collaboration: only a talk
- Alternative explanation: pulsars
  Mirabal, 1309.3428; Yuan and Zhang, 1404.2318; · · ·
- Perhaps dark matter annihilation
  Agarawal et al, 1411.2592; Colore et al, 1411.4647

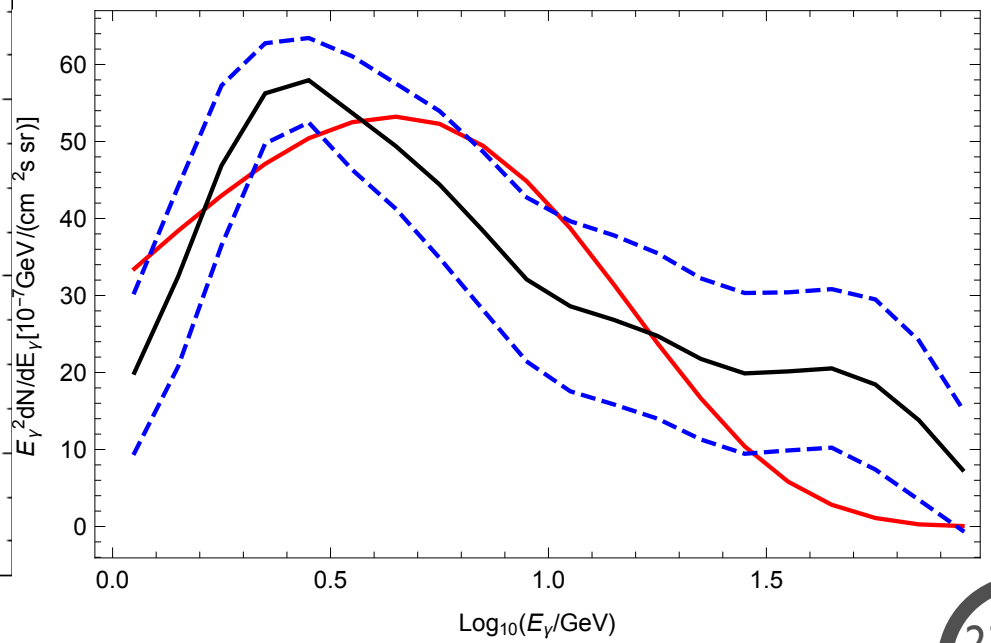




Fit

- The simplest approach: pure scalar annihilation
- Assumption: $\Omega_\phi \approx \Omega_{\rm DM}$
- Fit spectrum for $\phi\phi \to {\rm SM}$
- Need semi-annihilation to get right relic density
- m_Ψ, y





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- Generic feature of dark sectors: semi-annihilation
- Multi-component: necessary for fermion models
- Simple models: wino-like Ψ and Higgs portal
- Limits from relic density and other observations. It can be excluded
- Fermi fit need semi-annihilation