

Semi-annihilation of Dark Matter

FDE and Jesse Thaler, JHEP 1006:109,2010 (arXiv:1003.5912 [hep-ph])

Francesco D'Eramo

Massachusetts Institute of Technology

Identification of Dark Matter, 26-30 July 2010
University of Montpellier 2, Montpellier, France



Semi-annihilation of dark matter

Evidence for dark matter is overwhelming, $\Omega_{\text{DM}} h^2 = 0.1099 \pm 0.0062$

(WMAP Collaboration, J. Dunkley et al., *Astrophys. J. Suppl.* 180 (2009) 306 - 329, [arXiv:0803.0586])

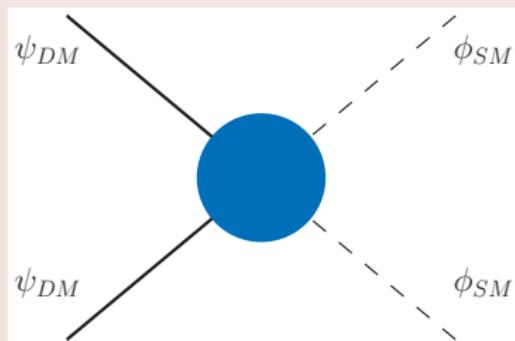
WIMP paradigm one of the best explanations.

(Lee, Weinberg, *Phys.Rev.Lett.*39:165-168,1977)

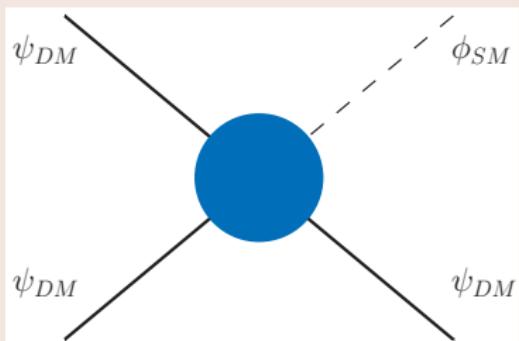
Correct thermal relic density computation important.

(Griest, Seckel, *Phys.Rev.D*43:3191-3203,1991)

Annihilation: $\psi_{\text{DM}} \psi_{\text{DM}} \rightarrow \phi_{\text{SM}} \phi_{\text{SM}}$



Semi-annihilation: $\psi_{\text{DM}} \psi_{\text{DM}} \rightarrow \psi_{\text{DM}} \phi_{\text{SM}}$



Semi-annihilation affects **relic density** and **indirect detection spectra**.

Outline

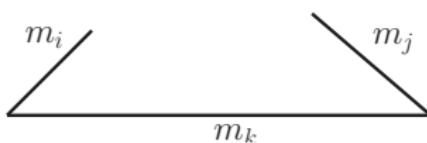
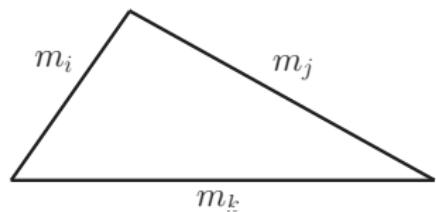
- 1 Introducing semi-annihilation
- 2 Implications for relic density
- 3 Implications for indirect detection
- 4 Conclusions

Semi-annihilation reactions in the early universe

$$\psi_i \psi_j \rightarrow \psi_k \phi$$

Relevant to relic abundance.

Can dominate over ordinary annihilation and control the thermal production.



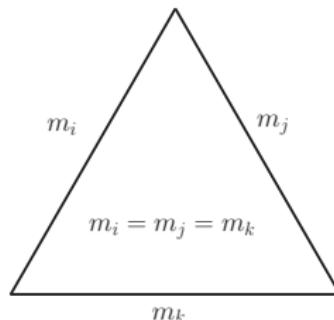
ψ_i , ψ_j and ψ_k are mutually stable as long as $m_k < m_i + m_j$ (and crossed)

Simple models with semi-annihilation

Equilateral triangle

Simplest case when

$$m_k = m_i = m_j$$



Z_3 symmetry

Complex scalar χ stabilized by a Z_3 , $\chi\chi \rightarrow \bar{\chi}\phi$ allowed.

Agashe, Servant, PRL93(2004) and JCAP02(2005); Ma, PLB662(2008); Batell, arXiv:1007.0045.

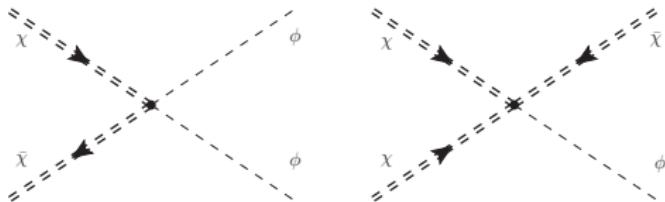
Hidden vector dark matter

Massive gauge bosons. For non-Abelian gauge symmetry $A_i A_j \rightarrow A_k \phi$ allowed.

Hambye, JHEP01(2009); Hambye, Tytgat, PLB683(2010); Arina et al., JCAP03(2010).

Semi-annihilation with a Z_3 symmetry

	spin	Z_3
χ	complex scalar	$(-1)^{1/3}$
ϕ	real scalar	0



Relic density controlled by $\chi\bar{\chi} \rightarrow \phi\phi$ and $\chi\chi \rightarrow \bar{\chi}\phi$ (ϕ “portal” field)

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_{\chi\bar{\chi} \rightarrow \phi\phi} [n_\chi^2 - n_\chi^{\text{eq}}]^2 - \langle\sigma v\rangle_{\chi\chi \rightarrow \bar{\chi}\phi} [n_\chi^2 - n_\chi n_\chi^{\text{eq}}]$$

Semi-analytical solution

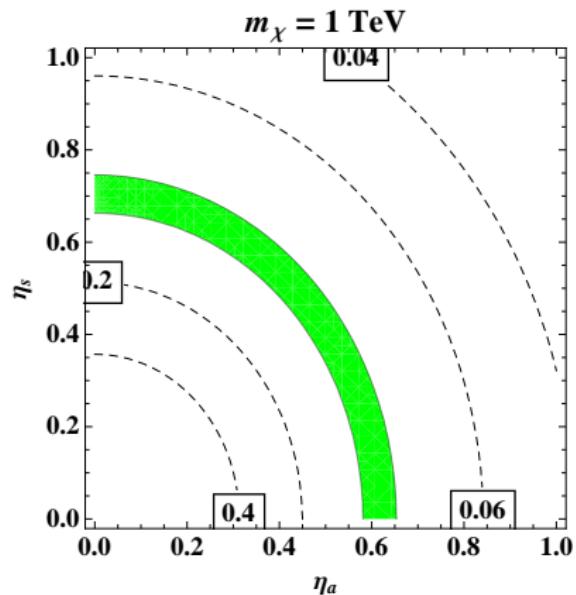
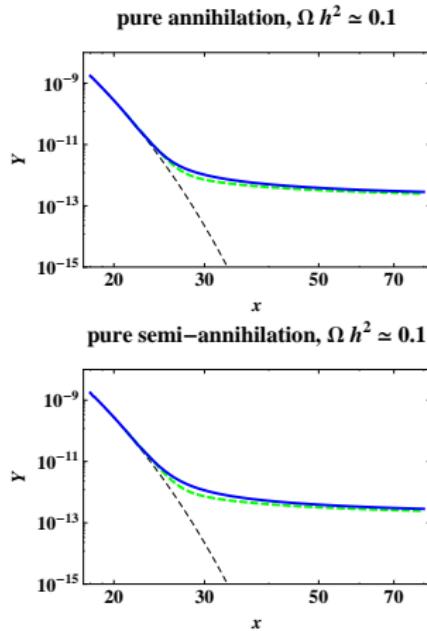
Early and late times, matching at freeze-out ($x_f = m_\chi / T_f$)

$$\text{Shift of freeze-out: } \delta x_f \simeq \log \left[1 + \frac{\langle\sigma v\rangle_{\chi\chi \rightarrow \bar{\chi}\phi}}{\langle\sigma v\rangle_{\chi\bar{\chi} \rightarrow \phi\phi}} \right]$$

$$\text{Relic density: } \Omega_\chi h^2 \propto [\langle\sigma v\rangle_{\chi\bar{\chi} \rightarrow \phi\phi} + \langle\sigma v\rangle_{\chi\chi \rightarrow \bar{\chi}\phi}]^{-1}$$

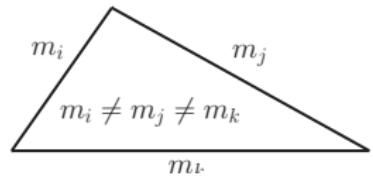
Semi-annihilation with a Z_3 symmetry: results

Wider allowed region of parameter space,
thermal production can be completely controlled by semi-annihilations.

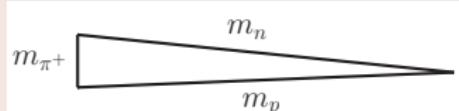
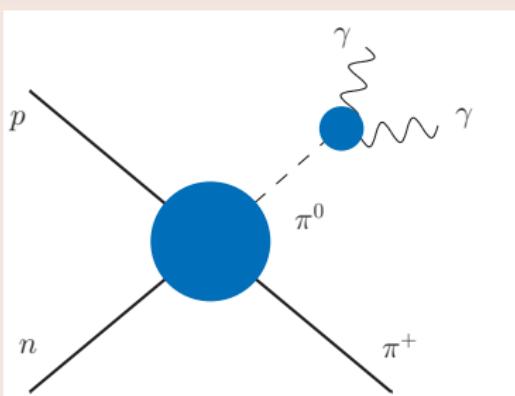


Semi-annihilation with multiple species

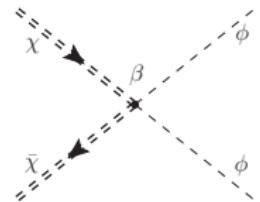
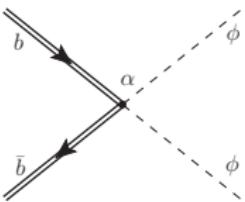
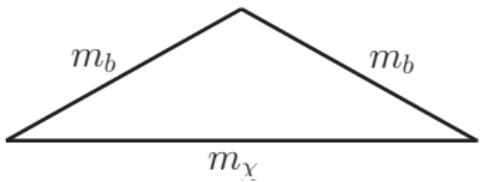
Such reactions are generically present when dark matter is composed of more than one species with “flavor” and/or “baryon” symmetries.



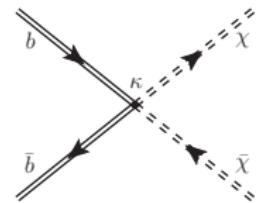
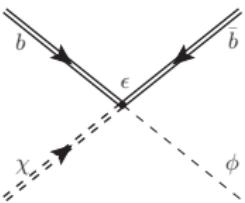
QCD without weak interactions



The $b\bar{b}\chi$ model



Fields	Spin	$U(1)$ charge
b	Weyl left	+1
b^c	Weyl left	-1
χ	complex scalar	-2
ϕ	real scalar	0



s-wave matrix elements

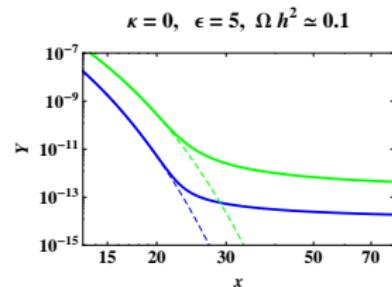
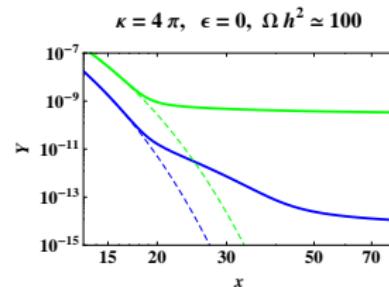
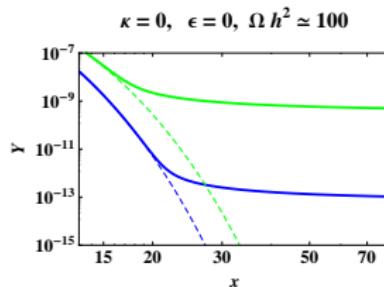
$$\mathcal{M}_{b\bar{b} \rightarrow \phi\phi} = \alpha, \quad \mathcal{M}_{\chi\bar{\chi} \rightarrow \phi\phi} = \beta, \quad \mathcal{M}_{b\bar{b} \rightarrow \chi\bar{\chi}} = \kappa, \quad \mathcal{M}_{\chi b \rightarrow \phi\bar{b}} = \epsilon.$$

How does ϵ (semi-annihilations) affect the relic abundance?

The $bb\chi$ model: numerical results

$m_\chi = 0.8 \text{ TeV}$, $m_b = 1 \text{ TeV}$. (b blue and χ green)

Semi-annihilations are a truly unique species changing interactions.



$\alpha = 2$ and $\beta = 0.01$

Start with very few b and overabundance of χ (opposite case).

species conversion

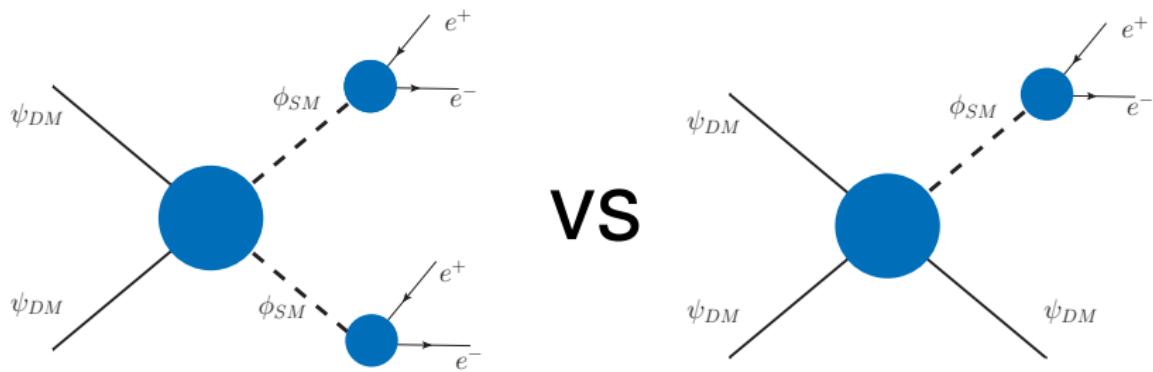
This reaction is powerless, because of the phase space suppression.

semi-annihilation

This reaction is never phase space suppressed, $\chi b \rightarrow \bar{b}\phi$ still able to get rid of χ 's and $\Omega_{DM} h^2 \simeq 0.1$.

Cosmic rays via the ϕ portal

Possible new primary source of galactic e^\pm (PAMELA, FERMI...).



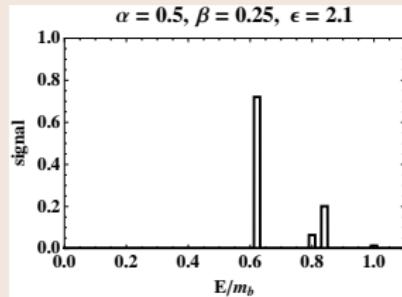
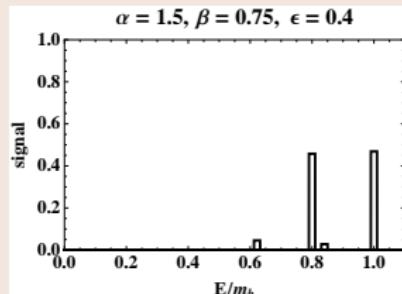
Additional channels to produce light particles, spectra enriched.
 ϕ spectrum: monocromatic lines.

Indirect detection spectra in the $bb\chi$ model

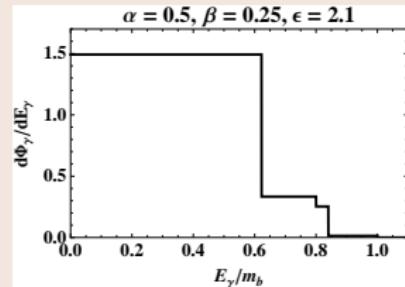
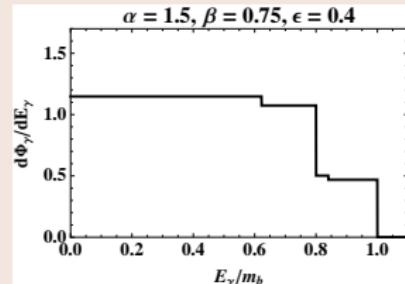
$m_\chi = 0.8 \text{ TeV}$, $m_b = 1 \text{ TeV}$

ϕ lines: $E_{b\bar{b} \rightarrow \phi\phi} = 1 \text{ TeV}$, $E_{\chi\bar{\chi} \rightarrow \phi\phi} = 0.8 \text{ TeV}$, $E_{b\chi \rightarrow \bar{b}\phi} = 0.62 \text{ TeV}$, $E_{bb \rightarrow \phi\bar{\chi}} = 0.84 \text{ TeV}$.

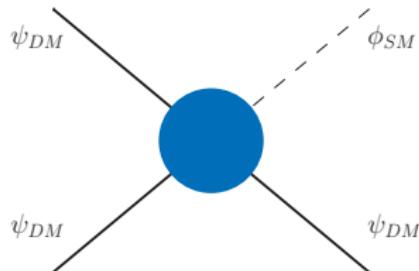
ϕ spectra



$\phi \rightarrow \gamma\gamma$



Conclusions



Semi-annihilation of Dark Matter

$$\psi_{DM} \psi_{DM} \rightarrow \psi_{DM} \phi_{SM}$$

FDE and Jesse Thaler, JHEP 1006:109,2010
(arXiv:1003.5912 [hep-ph])

- stabilization symmetry larger than Z_2 (Z_3 , “baryon” and/or “flavor”...);
- far less trivial dark matter dynamics dynamics in the early universe;
- enriched indirect detection spectra.

BACKUP SLIDES

The “WIMP miracle”

Dark Matter one of the best motivation for beyond the standard model physics.
Evidences at vastly different scales (galactic, clusters, horizon), only inferred through its gravitational effects. Not explained by any Standard Model (SM) degree of freedom: nature, origin and composition unknown.

$$\Omega_{\text{DM}} h^2 = 0.1099 \pm 0.0062$$

$$\Omega_{\text{DM}} \equiv \frac{\rho_{\text{DM}}}{\rho_{\text{cr}}} , \quad \rho_{\text{cr}} = \frac{3H_0^2}{8\pi G},$$

$$H_0 = 100 \text{ } h \text{ km s}^{-1} \text{ Mpc}^{-1}, \quad h = 0.719^{+0.026}_{-0.027}$$

(WMAP Collaboration, J. Dunkley et al., *Astrophys. J. Suppl.* 180 (2009) 306 - 329, [arXiv:0803.0586])

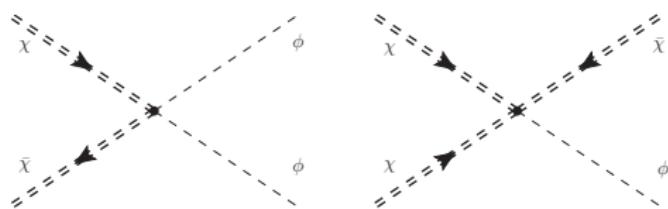
Weakly Interacting Massive Particles (WIMP)

- Well-motivated class of dark matter particles, naturally appearing in various extension of the SM to stabilize the Fermi scale;
- WIMPs thermalize in the early universe through $\psi\bar{\psi} \rightarrow \phi\phi$, until their density freezes out, mass density today $\Omega_{\text{DM}} \propto \langle \sigma v \rangle^{-1}$;
- for coupling g_X and mass scale m_X thermal cross section $\langle \sigma v \rangle \sim g_X^4/m_X^2$, and for weak scale coupling ($g_w \sim 0.65$) and weak scale mass ($m_w \sim 10 \text{ GeV} - 1 \text{ TeV}$) we get $\Omega_{\text{DM}} h^2 \simeq 0.1$ (“WIMP miracle”).

(Lee, Weinberg, Phys.Rev.Lett.39:165-168,1977)

Semi-annihilation with a Z_3 symmetry

	spin	Z_3
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Relic density controlled by $\chi\bar{\chi} \rightarrow \phi\phi$ and $\chi\chi \rightarrow \bar{\chi}\phi$ (ϕ “portal” field)

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_{\chi\bar{\chi} \rightarrow \phi\phi} [n_\chi^2 - n_\chi^{\text{eq}}]^2 - \langle\sigma v\rangle_{\chi\chi \rightarrow \bar{\chi}\phi} [n_\chi^2 - n_\chi n_\chi^{\text{eq}}]$$

Semi-analytical solution

Boltzmann equation solved at early and late times, matching at the freeze-out ($x_f = m_\chi/T_f$)

$$x_f = \log \left[0.038 c(c+2) \langle\sigma v\rangle_{\chi\bar{\chi} \rightarrow \phi\phi} \frac{g_\chi m_\chi M_{\text{Pl}}}{\sqrt{g_*} x_f} \right] + \log \left[1 + \frac{c+1}{c+2} \frac{\langle\sigma v\rangle_{\chi\chi \rightarrow \bar{\chi}\phi}}{\langle\sigma v\rangle_{\chi\bar{\chi} \rightarrow \phi\phi}} \right]$$

Effect of semi-annihilation: shift the freeze-out temperature by a small logarithmic amount

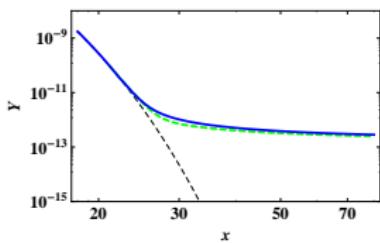
$$\Omega_\chi h^2 = 2 \times \frac{1.07 \times 10^9 \text{ GeV}^{-1}}{\sqrt{g_*} M_{\text{Pl}} J(x_f)}, \quad J(x_f) = \int_{x_f}^{\infty} dx \frac{\langle\sigma v\rangle_{\chi\bar{\chi} \rightarrow \phi\phi} + \langle\sigma v\rangle_{\chi\chi \rightarrow \bar{\chi}\phi}}{x^2}$$

Observed relic density for a wider region of parameter space, thermal production can be completely controlled by semi-annihilations.

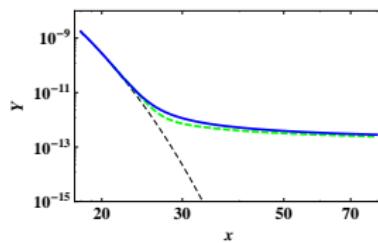
Z_3 symmetry: backup results

Wider allowed region of parameter space,
thermal production can be completely controlled by semi-annihilations.

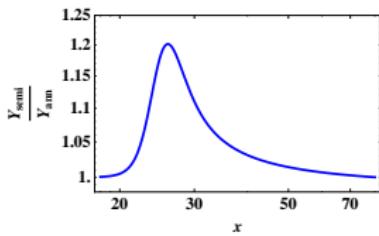
pure annihilation, $\Omega h^2 \simeq 0.1$



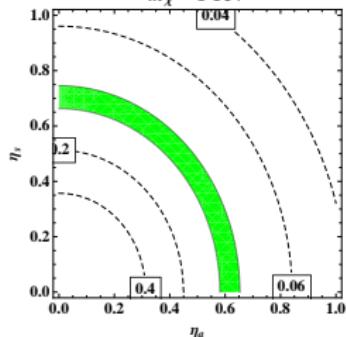
pure semi-annihilation, $\Omega h^2 \simeq 0.1$



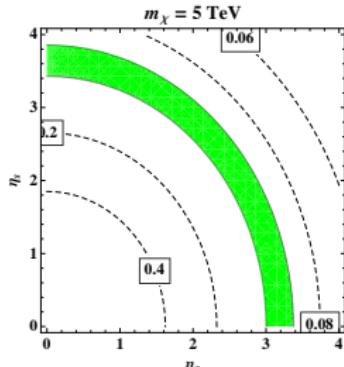
$Y_{\text{semi}}/Y_{\text{ann}}$ vs x



$m_\chi = 1 \text{ TeV}$



$m_\chi = 5 \text{ TeV}$



Semi-annihilation vs other freeze-out scenarios

	$\psi_i \psi_j \rightarrow \phi \phi'$	$\psi_i \phi \rightarrow \psi_j \phi'$	$\psi_i \psi_j \rightarrow \psi_k \phi$	$\psi_i \rightarrow \psi_j \phi$
Lee-Weinberg	✓($i = j$)	✓($i = j$)	✗	✗
Co-annihilation	✓	✓	✗	✓
Multi-component	✓($i = j$)	✓($i = j$)	✗	✗
Semi-annihilation	✓($i = j$)	✓($i = j$)	✓	✗

Semi-annihilation with multiple species

Such reactions are generically present when dark matter is composed of more than one species with “flavor” and/or “baryon” symmetries.

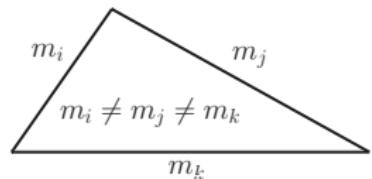
SUSY QCD dark matter

SUSY QCD theory with $N_f > N_c$.

IR degrees of freedom: meson and baryon color singlets.

Semi-annihilation allowed by symmetries, e.g. $B_2 M_{12} \rightarrow B_1 \phi_1$.

Seiberg, PRD49(1994).



Non SUSY “QCD” dark matter

	spin	$U(N_f)$	$U(1)_B$
b^i	Weyl left	$\bar{\square}$	1
b^c_i	Weyl left	\square	-1
χ^j_i	complex scalar	Adj	0

System of N_f dark baryons and N_f^2 dark mesons.

$\phi \equiv \text{Tr}[\chi^j_i]$ not charged \Rightarrow “portal” field to SM.

Semi-annihilations present in this class of models,
e.g. $\chi^1_2 \chi^3_1 \rightarrow \chi^3_2 \phi^1_1$, $b^{c2} \chi^1_2 \rightarrow b_1 \phi^1_1$.

Co-annihilation vs semi-annihilation

Co-annihilation

$$\psi_i \psi_j \rightarrow \phi \phi'$$

Collision operator:

$$\mathcal{C}_{\text{ann}} = - \sum_j \langle \sigma_{ij} v_{\text{rel}} \rangle \left(n_i n_j - n_i^{\text{eq}} n_j^{\text{eq}} \right)$$

$\psi_i \phi \rightarrow \psi_j \phi$ very effective at the freeze-out for $i \neq j$.

$$\frac{n_i}{n_j} = \frac{n_i^{\text{eq}}}{n_j^{\text{eq}}}$$

Equivalent to the Lee-Weinberg scenario, semi-analytical solution.

(Griest, Seckel, Phys.Rev.D43:3191-3203, 1991)

Semi-annihilation

$$\psi_i \psi_j \rightarrow \psi_k \phi$$

Collision operator:

$$\mathcal{C}_{\text{semi}} = - \sum_{j,k} \langle \sigma_{ijk} v_{\text{rel}} \rangle \left(n_i n_j - \frac{n_k n_i^{\text{eq}} n_j^{\text{eq}}}{n_k^{\text{eq}}} \right)$$

$\psi_i \phi \rightarrow \psi_j \phi$ only effective at the freeze-out for $i = j$.

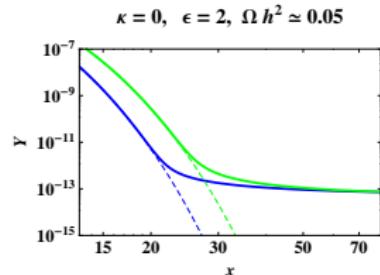
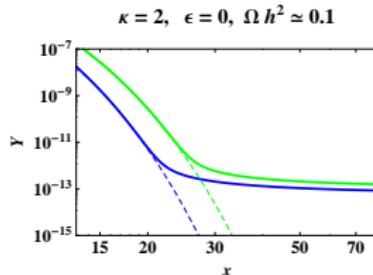
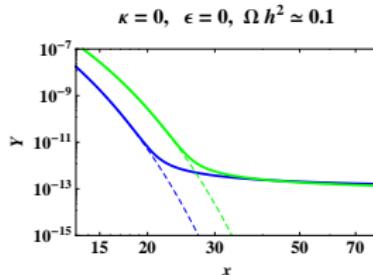
$$\frac{n_i}{n_j} \neq \frac{n_i^{\text{eq}}}{n_j^{\text{eq}}}$$

No simplification in the Boltzmann equations, numerical solutions.

The $bb\chi$ model: numerical results backup I

$m_\chi = 0.8 \text{ TeV}$, $m_b = 1 \text{ TeV}$. (b blue and χ green)

Semi-annihilations do affect the dark matter relic density.



$\alpha = 1.6$ and $\beta = 0.8$

Start with an equal amount of b and χ ($\Omega_{DM} h^2 \simeq 0.1$).

species conversion

With $k \neq 0$, small dilution of b 's.

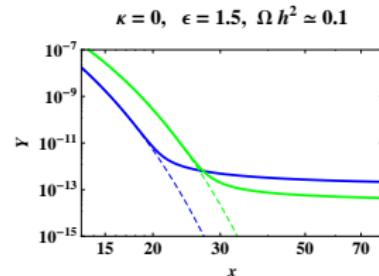
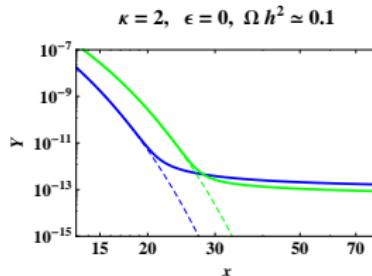
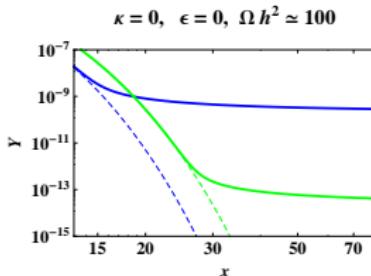
semi-annihilation

When $\epsilon \neq 0$, fewer relics total, because new destruction channel.

The $bb\chi$ model: numerical results backup II

$m_\chi = 0.8 \text{ TeV}$, $m_b = 1 \text{ TeV}$. (b blue and χ green)

Semi-annihilations and species conversion have similar effects?



$\alpha = 0.03$ and $\beta = 1.5$

Start with very few χ and overabundance of b (would be excluded by overclosure).

species conversion

When $k \neq 0$, b 's converted into χ 's, which annihilate very effectively and $\Omega_{DM} h^2 \simeq 0.1$

semi-annihilation

When $\epsilon \neq 0$, same effect by the reaction $bb \rightarrow \bar{\chi}\phi$, and again $\Omega_{DM} h^2 \simeq 0.1$.

SUSY QCD for $N_f = N_c + 1$

UV d.o.f. quark and antiquark Q^i and \bar{Q}_j . Mass term in the superpotential $W_{\text{UV}}^{\text{mass}} = m_i^{\bar{i}} Q^i \bar{Q}_j$.
For $W_{\text{UV}}^{\text{mass}} = 0$ global $U(N_f)_L \times U(N_f)_R$ symmetry \Rightarrow mass matrix $m_i^{\bar{i}} = m_i \delta_i^{\bar{i}}$.

Below QCD dynamical scale appropriate degrees of freedom meson and baryon color singlets

$$W_{\text{IR}} = \frac{1}{16\pi^2} \left[c^3 \bar{B}_j M_{ji} B_i - c^{N_f} \Lambda^{3-N_f} \det(M) + c \Lambda \text{Tr}(mM) \right],$$

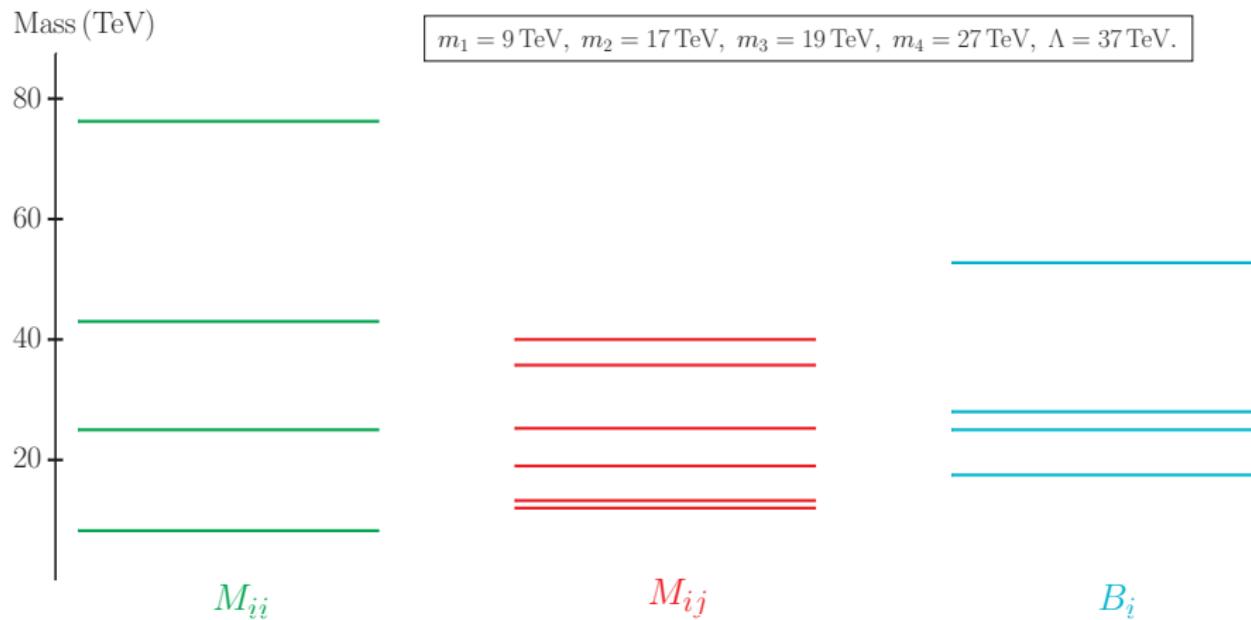
Theory vacuum: $\mathbf{B} = \mathbf{\bar{B}} = 0$

$$\mathbf{M} = \text{diag}(\mathbf{M}_1, \mathbf{M}_2, \dots, \mathbf{M}_F) = c^{-1} \Lambda^{\frac{N_f-2}{N_f-1}} \left(\prod_{i=1}^{N_f} m_i \right)^{\frac{1}{N_f-1}} \text{diag} \left(m_1^{-1}, m_2^{-1}, \dots, m_{N_f}^{-1} \right)$$

Spectrum: $W_{\text{mass}} = \left[\frac{\det(m)}{\Lambda^{N_f}} \right]^{\frac{1}{N_f-1}} \frac{\Lambda^2}{m_i} \bar{B}_i B_i + \left[\frac{\Lambda^{N_f}}{\det(m)} \right]^{\frac{1}{N_f-1}} \sum_{i < j} \frac{m_i m_j}{\Lambda} (M_{ij} M_{ji} - M_{ii} M_{jj})$

Baryon and the off-diagonal mesons mass eigenstates, diagonal mesons have mixing terms.

SUSY QCD spectrum for $N_f = 4$ and $N_c = 3$



Indirect detection formulae

Semi-annihilations: additional channels to produce light particles.

Spectra enriched with respect to the standard multi-component scenarios.

ϕ spectrum monocromatic lines with different intensities:

$$\frac{d\Phi_\phi}{dE_\phi} \propto \sum_{ij} N_{ij}^\phi n_i n_j \langle \sigma v \rangle_{ij} \delta(E_\phi - E_\phi^{ij})$$

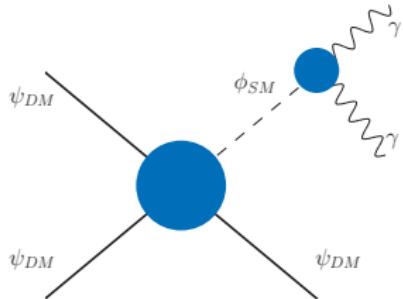
ϕ spectrum four monocromatic lines

$$E_{b\bar{b} \rightarrow \phi\phi} = m_b = 1 \text{ TeV},$$

$$E_{\chi\bar{\chi} \rightarrow \phi\phi} = m_\chi = 0.8 \text{ TeV},$$

$$E_{b\chi \rightarrow b\phi} = \frac{m_\chi}{2} \frac{2m_b + m_\chi}{m_b + m_\chi} = 0.62 \text{ TeV},$$

$$E_{bb \rightarrow \phi\bar{\chi}} = m_b - \frac{m_\chi^2}{4m_b} = 0.84 \text{ TeV},$$



$$\phi \rightarrow \gamma\gamma$$

Decay products are isotropic in the ϕ rest frame, flat energy distribution in the galactic frame.

$$m_{DM} \gg m_\phi: \frac{d\Phi_\gamma}{dE_\gamma} \propto \sum_{ij} N_{ij}^\phi \frac{n_i n_j}{E_\phi^{ij}} \langle \sigma v \rangle_{ij} \theta(E_\phi^{ij} - E_\gamma)$$