Fermionic Strongly Interacting Massive Particles

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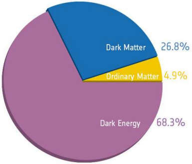
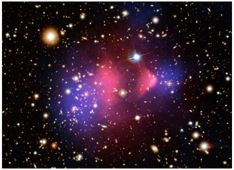
Based on the work in collaboration with
Johannes Herms and Alejandro Ibarra

Introduction

There is much experimental evidence of DM.

- Rotation curves of spiral galaxy
- CMB observations
- Gravitational lensing
- Large scale structure of the universe



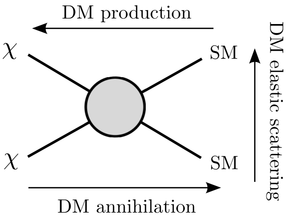


Existence of DM is crucial.

- Well-motivated DM candidate: WIMP
- Basic strategies to detect WIMP

  · Indirect detection
  · Direct detection
  · Collider search

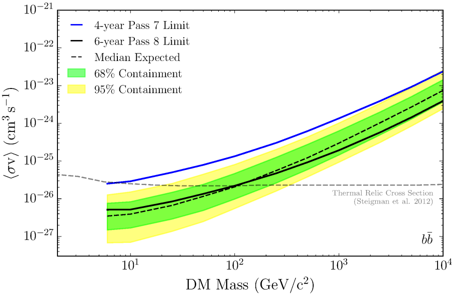
  $\rightarrow$ These are strongly correlated.



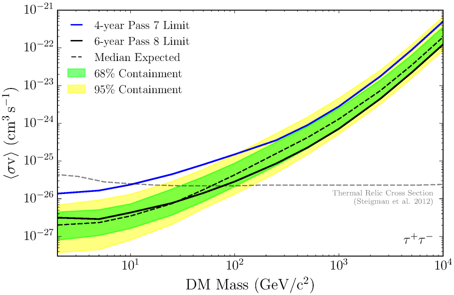
Experimental Situation for WIMP Searches

Indirect search (gamma-rays from dSphs)

$\chi\chi \to b\bar{b}$



$\chi\chi \to \tau^+\tau^-$

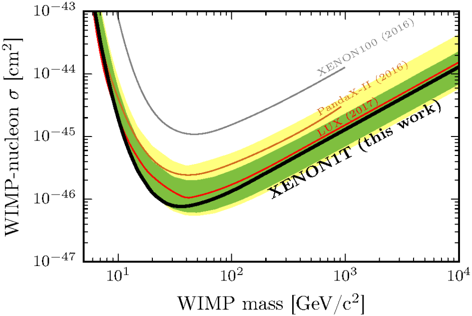


Fermi-LAT, PRL (2015) arxiv:1503.02641

- $m_{\rm DM} \lesssim 100$ GeV is constrained.

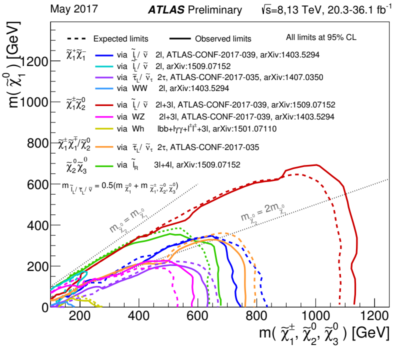
Experimental Situation for WIMP Searches

Direct search



XENON1T, PRL (2017) arxiv:1705.06655

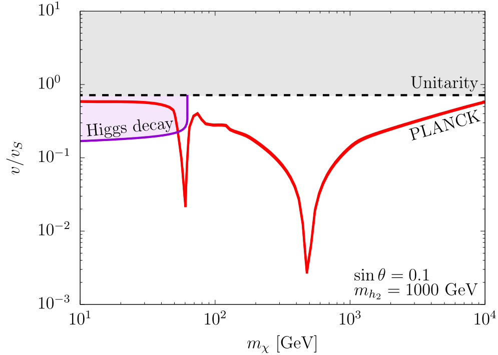
Collider search

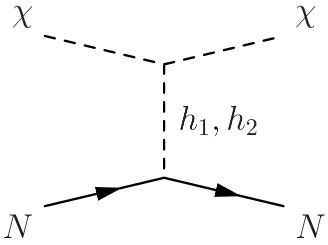


Summary plot from ATLAS

- Experimental constraints become stronger and stronger.
- Interactions between DM and SM may be weak enough.

One possibility to evade DD constraint





C. Gross, O. Lebedev, TT, PRL [arXiv:1708.02253]

- SM + a complex scalar with global U(1).
- Pseudo-scalar is DM $[S = (v_s + s + i\chi)/\sqrt{2}]$.
- Cancellation between h_1 and h_2 diagrams always happens.

SIMP (Strongly Interacting Massive Particle)

Y. Hochberg et al. PRL (2014) [arxiv:1402.5143]

- DM abundance is determined by $3 \to 2$ or $4 \to 2$ processes in dark sector itself, but not $2 \to 2$ annihilating processes (WIMP).
- Typical scale of thermal SIMP mass:
  $m_\chi \sim \mathcal{O}(10)$ MeV for $3 \to 2$ process
  $m_\chi \sim \mathcal{O}(100)$ keV for $4 \to 2$ process
  $\to$ Letter one is strongly constrainted by BBN, ΔN_{eff} etc.
- Large coupling is required for $\Omega h^2 \sim 0.12$.
  $\to$ Large self-interaction of DM can solve small scale structure problems.
- Many models (Most of models focus on bosonic SIMP)

  Dark QCD: Hochberg et al., arXiv:1411.3727, 1512.07917,

  Perturbative models: Bernal et al., arXiv:1501.01973, Choi and Lee, arXiv:1505.00960,

  Model with ν mass generation: Ho, Tsumura, TT, arXiv:1705.00592 etc

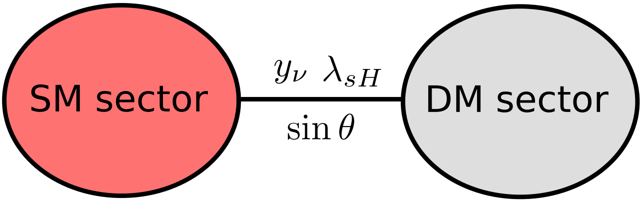
Fermionic SIMP

Simple Model with Fermionic SIMP

- Add a singlet Majorana fermion χ (DM) and a scalar mediator s.

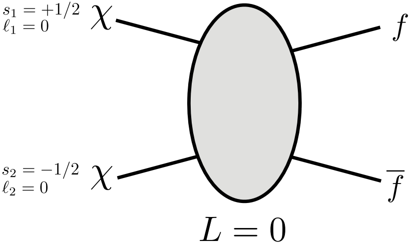
$$\mathcal{L} = -\frac{y_s}{2} s \overline{\chi^c} \chi - y_\nu H \overline{L} P_R \chi - \frac{\lambda_{sH}}{2} s^2 |H|^2$$

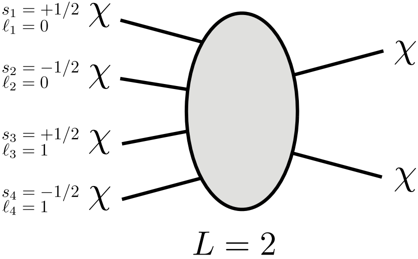
- Dark sector (χ, s) is very weakly coupled with SM sector via y_ν, $\lambda_{sH} \ll 1$ and small mixing $\sin\theta$.
- But Yukawa coupling y_s is large enough. $\rightarrow$ SIMP
- χ may be identified as sterile neutrino.



Fermion SIMP

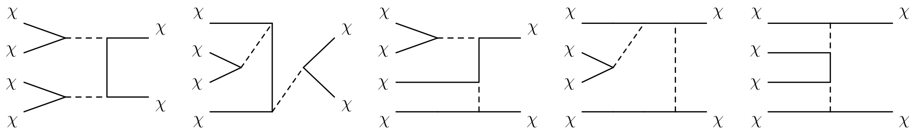
- 4-to-2 cross section for spin $1/2$ Majorana fermion is suppressed by d-wave due to the Pauli exclusion principle.





	2-body	3-body	4-body
1/2 Majorana	s-wave	p-wave	d-wave
1/2 Dirac	s-wave	s-wave	s-wave

4-to-2 Annihilation Cross Section



- Totally ~ 100 diagrams exist.
- Very complicated. Not possible to do by hand.
- Computed with FeynCalc (non-relativistic limit).
- 1st diagram $\sim \overline{v}(p_4)u(p_3)\overline{v}(p_2)u(p_1) \sim v^2 \to \overline{|\mathcal{M}|^2} \sim v^4$
- Naturally, 2nd to 4th diagrams $\to \overline{|\mathcal{M}|^2} \propto v^2$,
  5th diagram $\to \overline{|\mathcal{M}|^2} \propto 1$
- But after including all the diagrams obtained by exchanging initial state particles, the amplitude-squared is eventually proportional to v^4 (d-wave).

Thermal Averaged Cross Section

Final result

$$\langle \sigma v^3 \rangle = \frac{27\sqrt{3} y_s^8 \sum_{n=0}^{8} a_n \xi^n}{20480 \pi m_\chi^8 (16-\xi)^2 (4-\xi)^4 (2+\xi)^6 x'^2}$$

where $\xi = m_s^2/m_\chi^2 \geq 4$

$$a_0 = 2467430400, \quad a_1 = -1648072704, \quad a_2 = 491804416,$$
$$a_3 = -25463616, \quad a_4 = 4824144, \quad a_5 = -1528916,$$
$$a_6 = 473664, \quad a_7 = -35259, \quad a_8 = 1201.$$

If $\xi \gg 1$, $\langle \sigma v^3 \rangle \approx \frac{32427\sqrt{3} y_s^8}{20480 \pi m_s^8 x'^2}$ (effective case)

- There are two resonances at $m_s = 2m_\chi, 4m_\chi$ for the toy model.
- Computing the cross section at resonances is difficult. Multi-dimensional integration has to be done.

Boltzmann Equations

Assumptions:

- Quantum statistics effect is neglected.
  $\to$ Boltzmann statistics is assumed for all the particles and all temperature.
- Initial condition $n_\chi = 0$, $\rho_\chi = 0$.
- Each sector is initially in kinetic equilibrium ($T \neq T'$).

Temperature evolution of dark sector is followed by solving the Boltzmann equations.

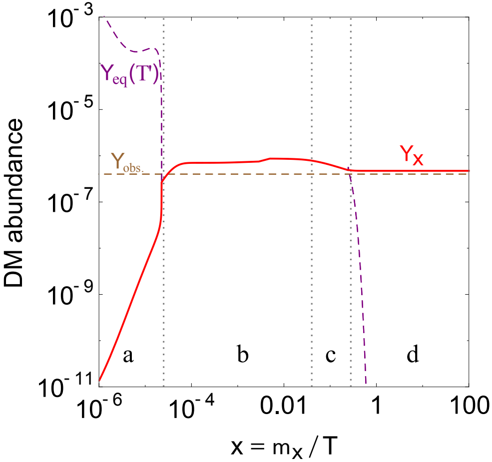
$$\frac{dn_\chi}{dt} + 3Hn_\chi = 2\Gamma_{h\to\chi\chi}\frac{g_h m_h^2 m_\chi}{2\pi^2 x}K_2\left(\frac{m_h}{m_\chi}x\right) - \langle\sigma v^3\rangle\left(n_\chi^4 - n_\chi^2 n_\chi^{\mathrm{eq}\,2}\right)$$

$$\frac{d\rho_\chi}{dt} + CH\rho_\chi = m_h\Gamma_{h\to\chi\chi}n_h^{\mathrm{eq}}$$

where $3 \leq C \leq 4$.

Schematic Picture

Evolution of DM number density as a function of T



- Energy is transferred from visible sector by $h \to \chi\chi$.
- $\chi\chi \to \chi\chi\chi\chi$ enters to thermal eq.

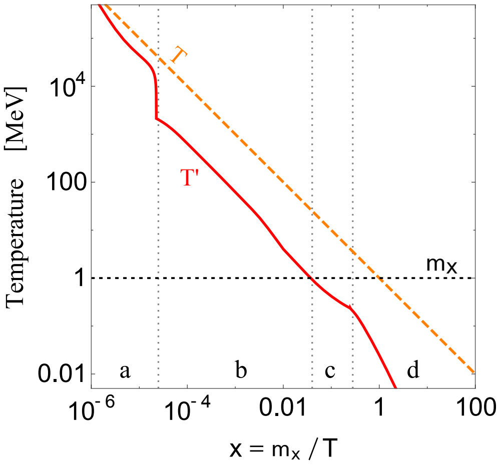
$\to n_\chi$ increases rapidly, and T' decreases.

- Dark thermalization $\to n_\chi = n_\chi^{eq}$.
- Freeze-out in dark sector occurs when DM becomes non-relativistic as same as WIMP.

N. Bernal, X. Chu, arXiv:1510.08527

Schematic Picture

Temperature in dark sector T'



- Energy is transferred from visible sector by $h \to \chi\chi$.
- $\chi\chi \to \chi\chi\chi\chi$ enters to thermal eq.

$\to$ n_χ increases rapidly, and T' decreases.

- Dark thermalization $\to n_\chi = n_\chi^{\rm eq}$.
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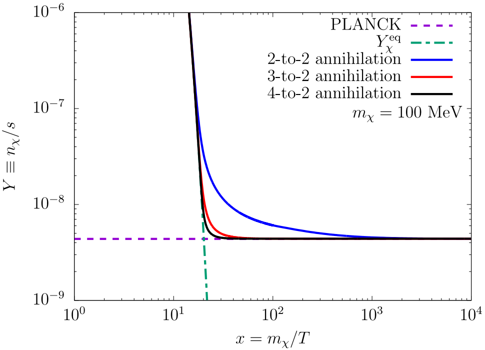
Instantaneous Freeze-out Approximation



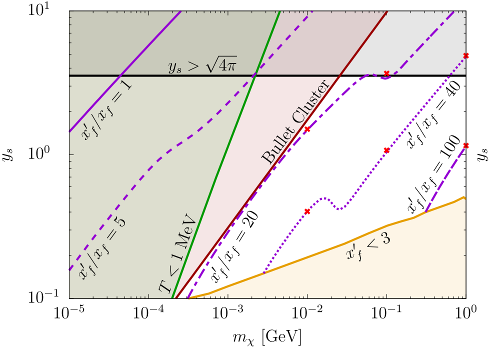
- Generally coupled Boltzmann equations have to be solved.
- Instantaneous freeze-out approximation

$$\Gamma_{4\to2}(x_f') = H(x_f),$$
$$Y_\chi(\infty) = Y_\chi(x_f')$$

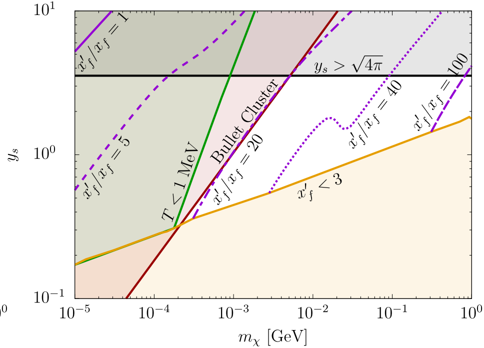
- Instantaneous freeze-out approximation is very accurate.
  $\Gamma_{4\to2} \equiv \langle \sigma v^3 \rangle n_\chi^{\rm eq3} \propto e^{-3x'}$ for non-relativistic DM
  $\to$ Reaction rate rapidly decreases with temperature.
  cf: $\Gamma_{2\to2} \equiv \langle \sigma v \rangle n_\chi^{\rm eq} \propto e^{-x'}$

Numerical Results

$m_s/m_\chi = 3$



$m_s/m_\chi = 10$

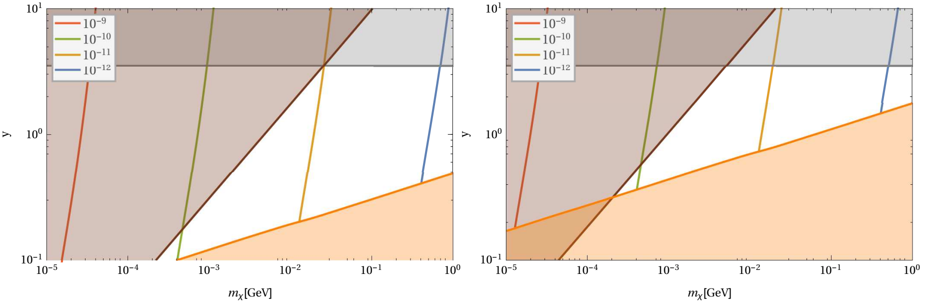


- Perturbative coupling $y_s \leq \sqrt{4\pi} \approx 3.55$.
- Region that freeze-out happens at semi-relativistic $x'_f < 3$ is not valid for our computation.
- Bullet Cluster constraint $\sigma_{\rm self}/m_\chi = y_s^4 m_\chi/(8\pi m_s^4) \leq 1\ {\rm cm}^2/{\rm g}$.

Required magnitude of the portal couplings 1

Contours of λ_{sH} in plane of (m_χ, y_s)

$m_s/m_\chi = 3$ $\qquad$ $m_s/m_\chi = 10$

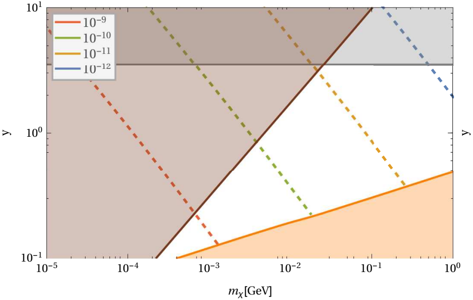


- Temperature ratio T'/T is controlled by the couplings y_ν, λ_{sH} and $\sin\theta$.
- $\lambda_{sH} \lesssim 10^{-10}$ to evade all the constraints.

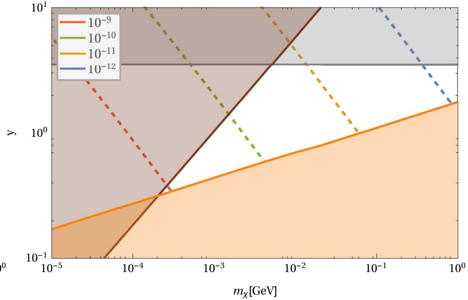
Required magnitude of the portal couplings 2

Contours of $\sin\theta$

$m_s/m_\chi = 3$



$m_s/m_\chi = 10$



- Temperature ratio T'/T is controlled by the couplings y_ν, λ_{sH} and $\sin\theta$.
- $\sin\theta \lesssim 10^{-9}$ to evade all the constraints.

Summary

1. We have considered a simple model for Majorana SIMP DM.
2. 4-to-2 annihilation cross section for Majorana SIMP DM is necessarily suppressed by d-wave due to the Pauli exclusion principle. (Independent on detailed interactions of DM)
3. DM abundance is determined by instantaneous freeze-out approximation with high precision since the reaction rate very rapidly decreases with T' when DM is non-relativistic.
4. This may give a new mechanism to produce sterile neutrino DM.