

Two-Component Dark Matter

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Matter to the Deepest,
Ustroń, September 2013

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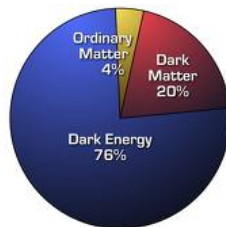
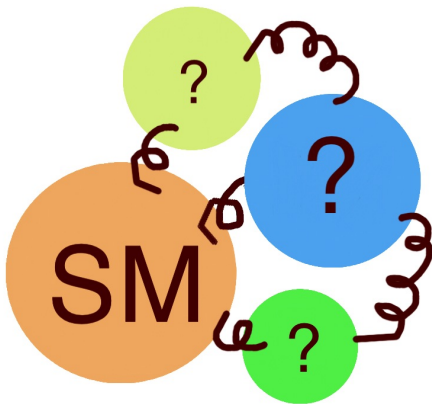


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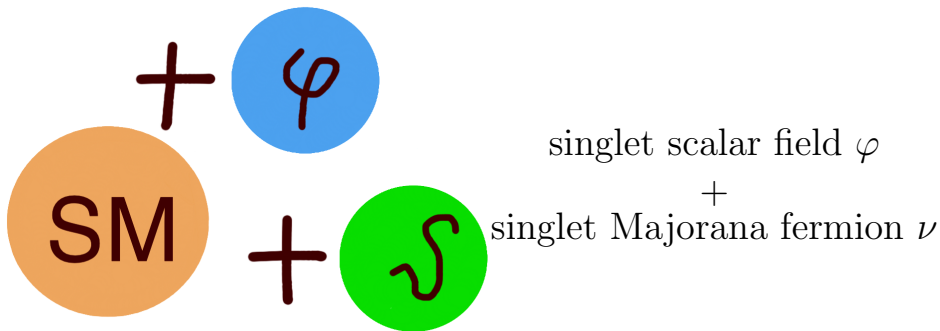


Outline:

- Two-component DM: scalar + fermion
 - relic abundance in two-component DM scenario (the Boltzmann equation)
 - WMAP constraints
 - direct detection constraints
-
- A. Drozd, B. Grządkowski, J. Wudka,
Multi-Scalar-Singlet Extension of the Standard Model, arXiv:1112.2582 [hep-ph]
 - S. Bhattacharya, A. Drozd, B. Grządkowski, J. Wudka,
Two-component Dark Matter Scenarios, arxiv:1309.2986 [hep-ph]



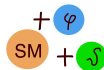
Scalar + Fermionic Dark Matter



Scalar + Fermionic Dark Matter - Lagrangian

SYMMETRY: $\mathbb{Z}_2 \times \mathbb{Z}'_2$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}}$$



$$\begin{aligned} \mathcal{L}_{\text{DM}} = & \partial_\mu \varphi \partial^\mu \varphi + \bar{\nu} i \not{\partial} \nu + \bar{\nu}_h i \not{\partial} \nu_h \\ & - \frac{1}{2} \mu_\varphi^2 \varphi^2 - \frac{\lambda_\varphi}{4!} \varphi^4 - \lambda_x \varphi^2 H^\dagger H \\ & + \frac{1}{2} m_\nu \nu^T C \nu + \frac{1}{2} M_{\text{h}\nu} \nu_h^T C \nu_h \\ & + g_\nu \bar{\nu} \nu_h \varphi \end{aligned}$$

scalar φ

$$\mathbb{Z}_2: \varphi \rightarrow -\varphi$$

$$\mathbb{Z}'_2: \varphi \rightarrow -\varphi$$

neutrino ν

$$\mathbb{Z}_2: \nu \rightarrow +\nu$$

$$\mathbb{Z}'_2: \nu \rightarrow -\nu$$

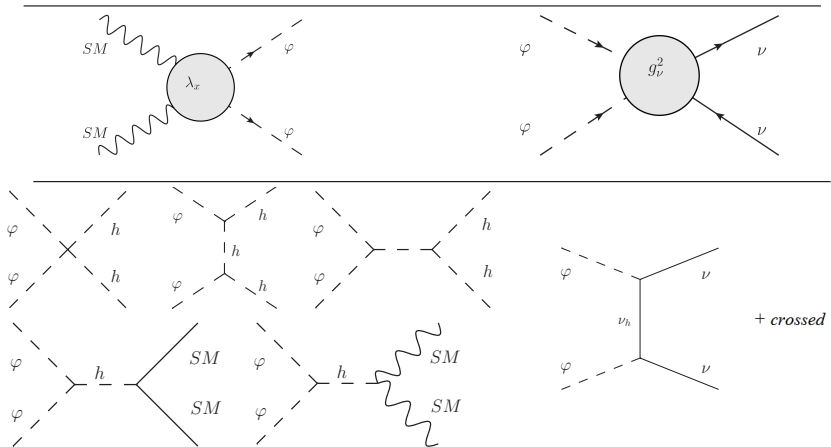
neutrino ν_h

$$\mathbb{Z}_2: \nu_h \rightarrow -\nu_h$$

$$\mathbb{Z}'_2: \nu_h \rightarrow +\nu_h$$

Scalar + Fermionic Dark Matter - Interaction with SM

$$\mathcal{L}_{\text{int}} = -\lambda_x \varphi^2 H^\dagger H + g_\nu \bar{\nu} \nu_h \varphi$$



Expansion of the Universe

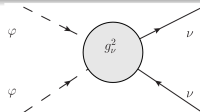
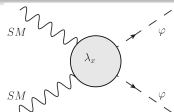
Creation and Annihilation

Thermally averaged cross section

for annihilations $X + \bar{X} \rightarrow Y + \bar{Y}$

$$\langle \sigma_{X\bar{X} \rightarrow Y\bar{Y}} v \rangle = \frac{(2\pi)^4}{n_X^{\text{EQ}2}} \int d\Pi_X d\Pi_{\bar{X}} d\Pi_Y d\Pi_{\bar{Y}} \times \\ |M|^2 \delta^4(p_X + p_{\bar{X}} - p_Y - p_{\bar{Y}}) e^{-(E_X + E_{\bar{X}})/T}$$

Scalar + Fermionic Dark Matter



$$f_\varphi = \frac{n_\varphi}{T^3} \quad f_\nu = \frac{n_\nu}{T^3} \quad K = \sqrt{\frac{4\pi^3 g(T)}{45 m_{Pl}^2}} \quad n_x^{EQ} = \int \frac{g_x}{(2\pi)^3} \frac{d^3 p}{2E} \frac{1}{e^{E/T} \pm 1}$$

the Boltzmann equations

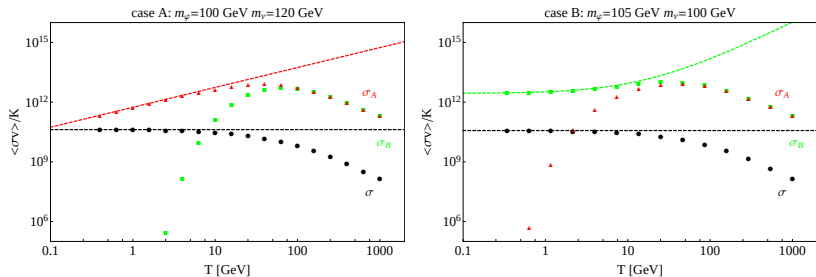
$$f'_\varphi = \frac{\langle \sigma_{\varphi\varphi \rightarrow SM SM \nu} \rangle}{K} (f_\varphi^2 - f_\varphi^{EQ2}) + \frac{\langle \sigma_{\varphi\varphi \rightarrow \nu\nu \nu} \rangle}{K} f_\varphi^2 - \frac{\langle \sigma_{\nu\nu \rightarrow \varphi\varphi \nu} \rangle}{K} f_\nu^2$$

$$f'_\nu = \frac{\langle \sigma_{\nu\nu \rightarrow \varphi\varphi \nu} \rangle}{K} f_\nu^2 - \frac{\langle \sigma_{\varphi\varphi \rightarrow \nu\nu \nu} \rangle}{K} f_\varphi^2$$

where

$$\langle \sigma_{\nu\nu \rightarrow \varphi\varphi \nu} \rangle = \langle \sigma_{\varphi\varphi \rightarrow \nu\nu \nu} \rangle \frac{f_\varphi^{EQ2}}{f_\nu^{EQ2}}$$

Scalar + Fermionic Dark Matter



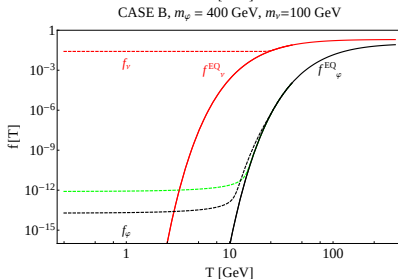
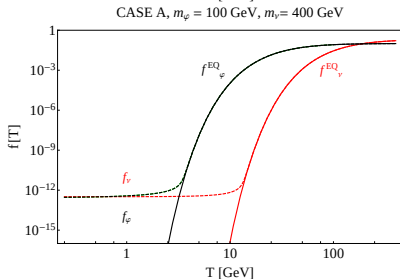
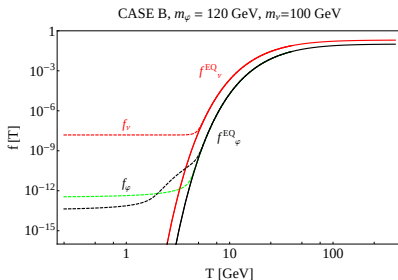
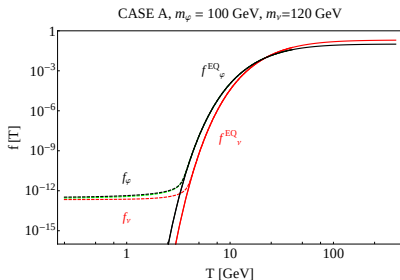
BLACK: $\langle\sigma_{\varphi\varphi\rightarrow\text{SM SM}\nu}\rangle/K$, GREEN: $\langle\sigma_{\varphi\varphi\rightarrow\nu\nu\nu}\rangle/K$,
 RED: $\langle\sigma_{\nu\nu\rightarrow\varphi\varphi\nu}\rangle/K$

CASE A, B : $\sigma(T) = \langle\sigma_{\varphi\varphi\rightarrow\text{SM SM}\nu}\rangle/K = \text{const} + \mathcal{O}(T)$

CASE A : $\sigma_A(T) = \langle\sigma_{\nu\nu\rightarrow\varphi\varphi\nu}\rangle/K = \alpha T + \mathcal{O}(T^2)$

CASE B : $\sigma_B(T) = \langle\sigma_{\varphi\varphi\rightarrow\nu\nu\nu}\rangle/K = a + bT + cT^2 + \mathcal{O}(T^3)$

Scalar + Fermionic Dark Matter - solving BEQ



Constraining the parameter space

Parameters: m_φ , m_ν , λ_x , g_ν , $M_{h\nu}$
 $M_{h\nu} = m_\varphi + m_\nu + 10\text{GeV}$

4 independent parameters!

$$\mathcal{L}_{\text{int}} = -\lambda_x \varphi^2 H^\dagger H + g_\nu \bar{\nu}_\nu \varphi$$

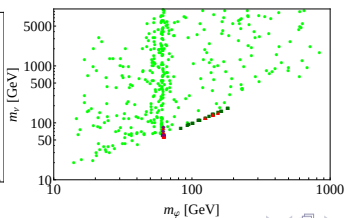
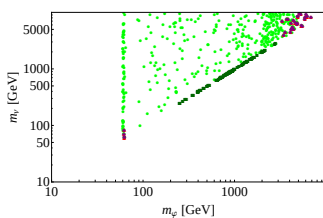
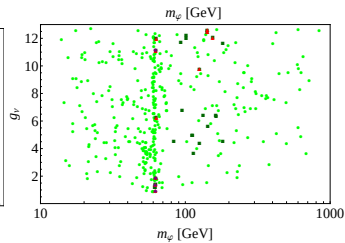
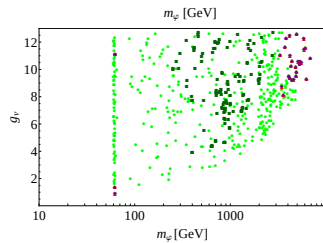
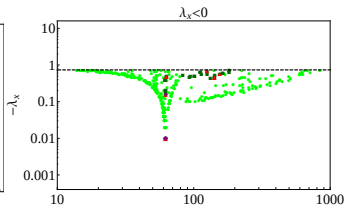
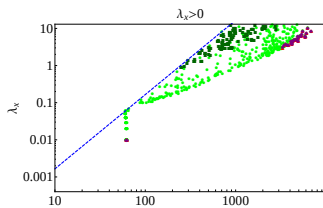
Scanned parameter space:

$$m_\varphi, m_\nu = 10 \text{ GeV} - 10 \text{ TeV}$$

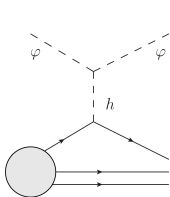
$$\lambda_x = 10^{-3} - 10;$$

$$g_\nu = 0.1 - 10;$$

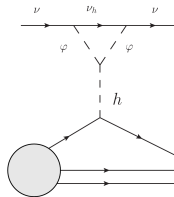
$$\Omega_{\text{total}} = 0.114 \pm 3\sigma;$$



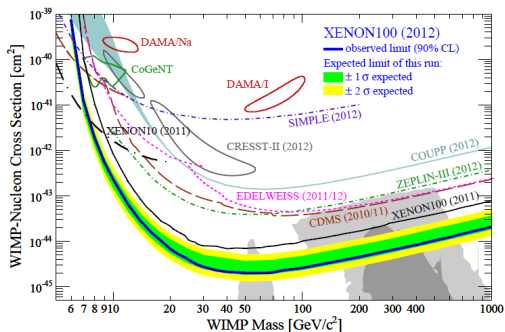
Direct Detection - DM scattering



$$\sigma_{\text{DM-N}}^{\varphi} = \frac{n_{\varphi}}{n_{\varphi} + n_{\nu}} \sigma_{\varphi N}$$

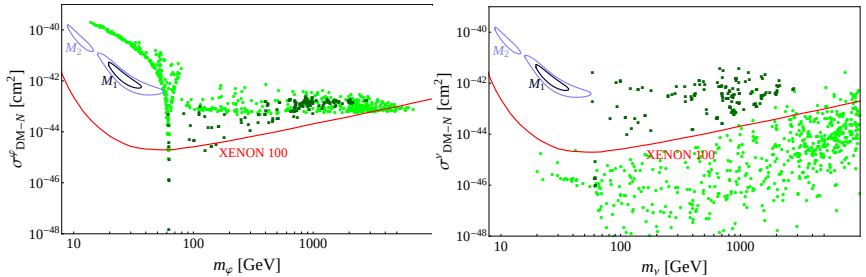


$$\sigma_{\text{DM-N}}^{\nu} = \frac{n_{\nu}}{n_{\varphi} + n_{\nu}} \sigma_{\nu N}$$



arXiv:1207.5988

<http://www.fuw.edu.pl/~mpd/>



Points satisfying the WMAP data within 3σ ; other parameters randomly chosen. Green circles (dark green squares) correspond to case A (case B) solutions.

What we did:

- We discussed the minimal extension of SM that provides two-component Cold Dark Matter with $\mathbb{Z}_2 \times \mathbb{Z}'_2$ symmetry
- We discussed the DM density using the B. EQs
- We found approximate analytical solutions of the the B. EQs
- Parameter space was constrained by theoretical constraints, WMAP and direct detection

Conclusions:

- Scalars cannot be much heavier than neutrinos ($\sim 20\%$)
- We need large values of g_ν ($\gtrsim 1$) to satisfy WMAP
- XENON100 bound favours
 - points with heavy scalars, $m_\varphi > 3 \text{ TeV}$ and $m_\nu > m_\varphi$
 - very small λ_x (resonance region, $m_\varphi \sim m_{\text{Higgs}}/2$)

Thank you for your attention !

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Extra slides

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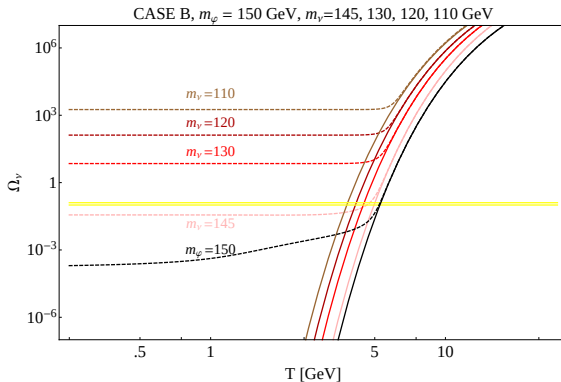


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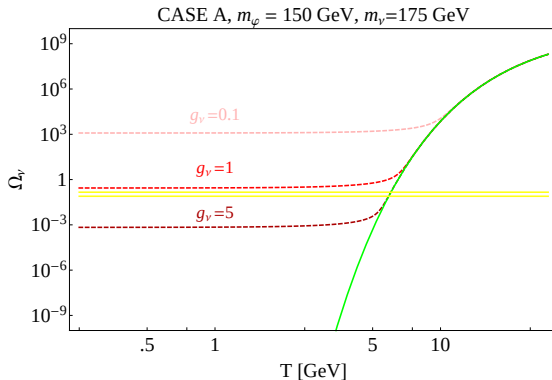
Scalar + Fermionic DM - WMAP constraint



RIGHT: Solutions to the BEQs: f_φ (dashed black line), f_φ^{EQ} (solid black line) and f_ν .

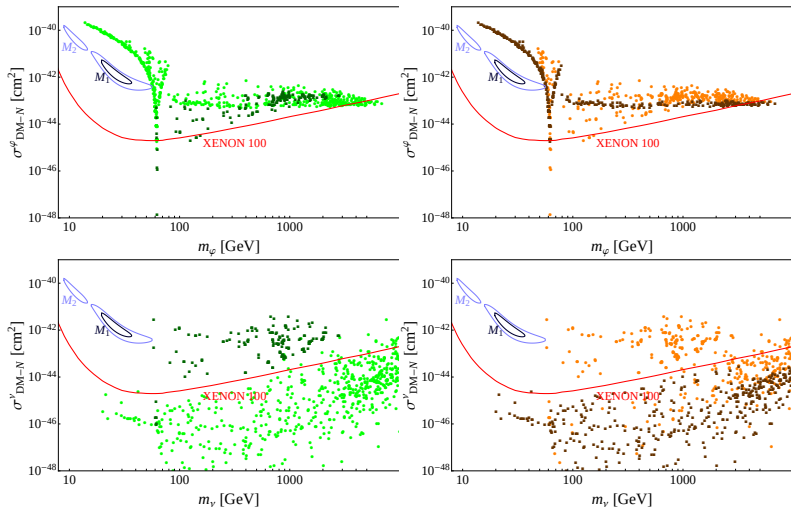
Yellow lines: WMAP 3σ limit on DM abundance.

Scalar + Fermionic DM - WMAP constraint



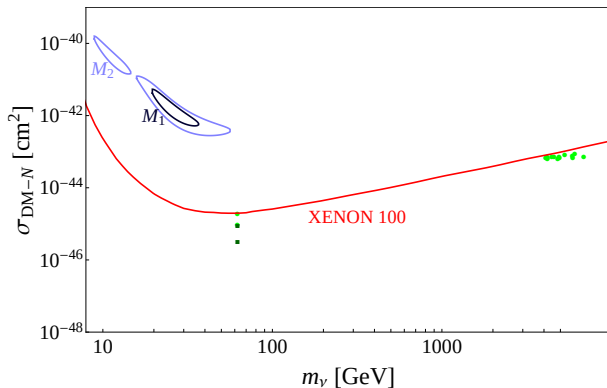
Solutions of the BEQs for $m_\phi = 150$ GeV, $m_\nu = 175$ GeV (case A), $\lambda_x = 1$. Pink, red, dark red lines: solutions for the neutrino abundance for $g_\nu = 0.1, 1, 5$, respectively. Green: equilibrium distribution for neutrinos at 175 GeV.

Yellow lines: WMAP 3σ limit on DM abundance.



Points satisfying the WMAP data within 3σ ; other parameters randomly chosen. Left panel: green circles (dark green squares) correspond to case A (case B) solutions. Right panel: orange circles (dark orange squares) correspond to $\Omega_\varphi < \Omega_\nu$ ($\Omega_\varphi > \Omega_\nu$).

Scalar + Fermionic DM - all constraints satisfied



Plot of the cross section $\sigma_{\text{DM-N}} = \sigma_{\text{DM-N}}^{\varphi} + \sigma_{\text{DM-N}}^{\nu}$ as a function of φ for points satisfying the WMAP data within 3σ . Green circles (dark green squares) correspond to case A (case B) solutions. The red line shows the XENON100 data, and the two islands in blue indicate 1 and 2σ CRESST-II results.