Two-Component Dark Matter

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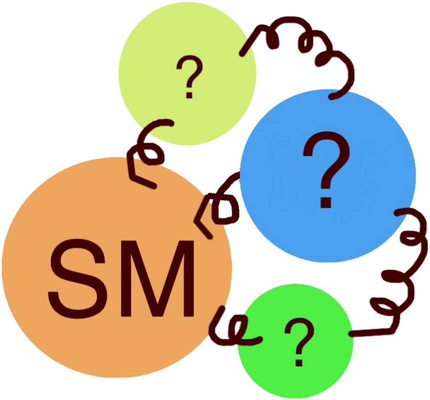
Matter to the Deepest,
Ustroń, September 2013

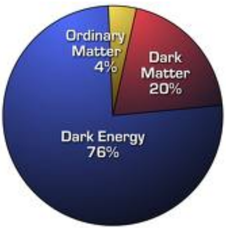
The project "International PhD Studies" at the University of Warsaw is realized within the MPD programme of Foundation for Polish Science, cofinanced from European Union, Regional Development Fund

Outline:

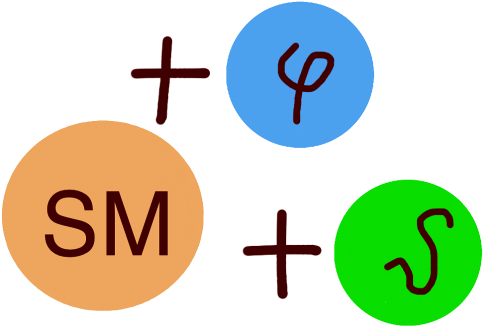
- Two-component DM: scalar + fermion
  - relic abundance in two-component DM scenario (the Boltzmann equation)
  - WMAP constraints
  - direct detection constraints

- A. Drozd, B. Grządkowski, J. Wudka, JHEP 1204:006,2012, Multi-Scalar-Singlet Extension of the Standard Model
- S. Bhattacharya, A. Drozd, B. Grządkowski, J. Wudka, Two-component Dark Matter Scenarios, in preparation


?
?
SM
?


Ordinary Matter 4%
Dark Matter 20%
Dark Energy 76%

Scalar + Fermionic Dark Matter

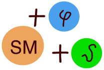


singlet scalar field φ

$+$

singlet Majorana fermion ν

Scalar + Fermionic Dark Matter - Lagrangian



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

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

$$\begin{aligned}\mathcal{L}_{\rm DM} \quad &= \quad \partial_\mu\varphi\partial^\mu\varphi + \bar{\nu}\mathrm{i}\partial\!\!\!/\nu + \bar{\nu}_{\rm h}\mathrm{i}\partial\!\!\!/\nu_{\rm h} \\ &-\frac{1}{2}\mu_\varphi^2\varphi^2 - \frac{\lambda_\varphi}{4!}\varphi^4 - \lambda_{\rm x}\varphi^2\mathrm{H}^\dagger\mathrm{H} \\ &+\frac{1}{2}\mathrm{m}_\nu\nu^{\rm T}\mathrm{C}\nu + \frac{1}{2}\mathrm{M}_{\rm hv}\nu_{\rm h}^{\rm T}\mathrm{C}\nu_{\rm h} \\ &+\mathrm{g}_\nu\,\bar{\nu}\nu_{\rm h}\,\varphi\end{aligned}$$

scalar φ

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

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

neutrino ν

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

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

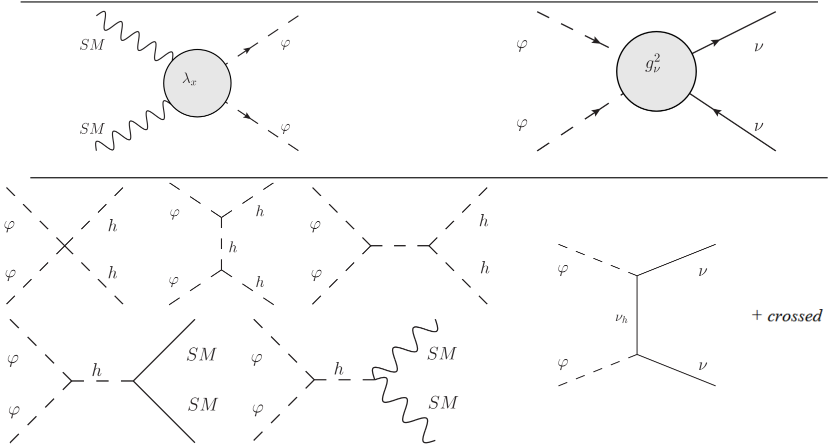
neutrino $\nu_{\rm h}$

$\mathbb{Z}_2$: $\nu_{\rm h} \to -\nu_{\rm h}$

$\mathbb{Z}_2'$: $\nu_{\rm h} \to +\nu_{\rm h}$

Scalar + Fermionic Dark Matter - Interaction with SM

$$\mathcal{L}_{\mathrm{int}} = -\lambda_{\mathrm{x}}\varphi^2 \mathrm{H}^\dagger \mathrm{H} + \mathrm{g}_\nu \, \overline{\nu}\nu_{\mathrm{h}} \, \varphi$$



Evaluating DM Relic Abundance

Expansion of the Universe

isotropic and homogenous Universe (FLRW metric)
$\tilde{f}(E, t)$ - phase space density

the Boltzmann Equation

$$\hat{L}[\tilde{f}] = \hat{C}[\tilde{f}]$$

$\hat{L}[\tilde{f}]$ - Liouville operator, gravitational effects,
$\hat{C}[\tilde{f}]$ - Collision operator, includes creation-annihilation, decay, ...

Creation and Annihilation

Thermally averaged cross section

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

$$< \sigma_{X\bar{X}\rightarrow Y\bar{Y}} \, v > \; = \; \frac{(2\pi)^4}{n_X^{EQ\,2}} \int d\Pi_X d\Pi_{\bar{X}} d\Pi_Y d\Pi_{\bar{Y}} \times$$

$$|M|^2 \delta^4(p_X + p_{\bar{X}} - p_Y - p_{\bar{Y}}) e^{-(E_X + E_{\bar{X}})/T}$$

the Boltzmann Equation

$$\hat{L}[\tilde{f}] = \hat{C}[\tilde{f}]$$

$\hat{L}[\tilde{f}]$ - Liouville operator, gravitational effects,
$\hat{C}[\tilde{f}]$ - Collision operator, includes creation-annihilation, decay, . . .

Scalar + Fermionic Dark Matter

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

the Boltzmann equations

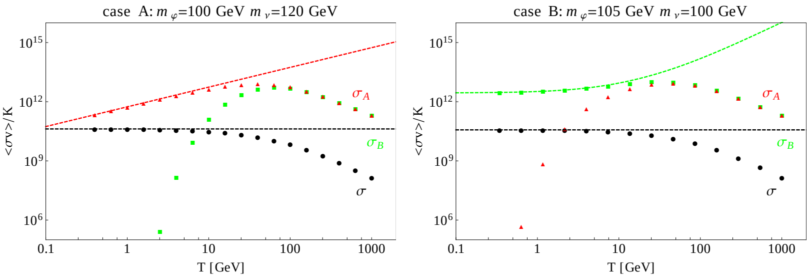
$$f'_\varphi = \frac{\langle \sigma_{\varphi\varphi\to SM\,SM} v\rangle}{K}\left(f_\varphi^2 - f_\varphi^{EQ2}\right) + \frac{\langle \sigma_{\varphi\varphi\to\nu\nu} v\rangle}{K} f_\varphi^2 - \frac{\langle \sigma_{\nu\nu\to\varphi\varphi} v\rangle}{K} f_\nu^2$$

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

where

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

Scalar + Fermionic Dark Matter



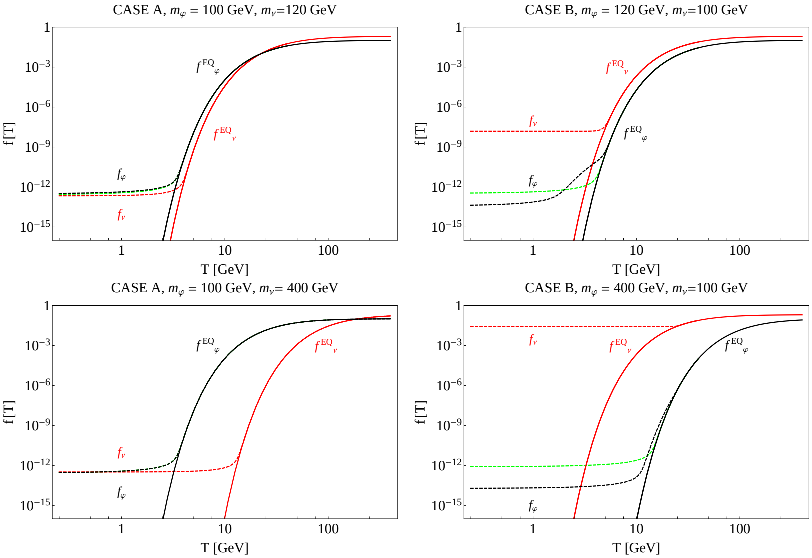
BLACK: $\langle \sigma_{\varphi\varphi\to \mathrm{SM\,SM}} \mathrm{v} \rangle / \mathrm{K}$, GREEN: $\langle \sigma_{\varphi\varphi\to \nu\nu} \mathrm{v} \rangle / \mathrm{K}$,
RED: $\langle \sigma_{\nu\nu\to \varphi\varphi} \mathrm{v} \rangle / \mathrm{K}$

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

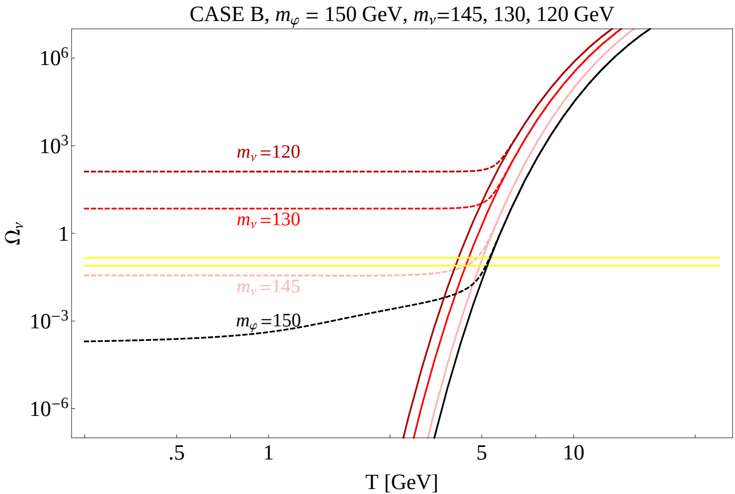
$$\mathrm{CASE\,A} : \sigma_\mathrm{A}(\mathrm{T}) = \langle \sigma_{\nu\nu\to \varphi\varphi} \mathrm{v} \rangle / \mathrm{K} = \alpha \mathrm{T} + \mathcal{O}(\mathrm{T}^2)$$

$$\mathrm{CASE\,B} : \sigma_\mathrm{B}(\mathrm{T}) = \langle \sigma_{\varphi\varphi\to \nu\nu} \mathrm{v} \rangle / \mathrm{K} = \mathrm{a} + \mathrm{bT} + \mathrm{bT}^2 + \mathcal{O}(\mathrm{T}^3)$$

Scalar + Fermionic Dark Matter - solving BEQ



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.

Parameters: m_φ, m_ν, λ_x, g_ν, ~~M_{hv}~~

$M_{hv} = m_\varphi + m_\nu + 10\text{GeV}$

4 independent parameters!

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

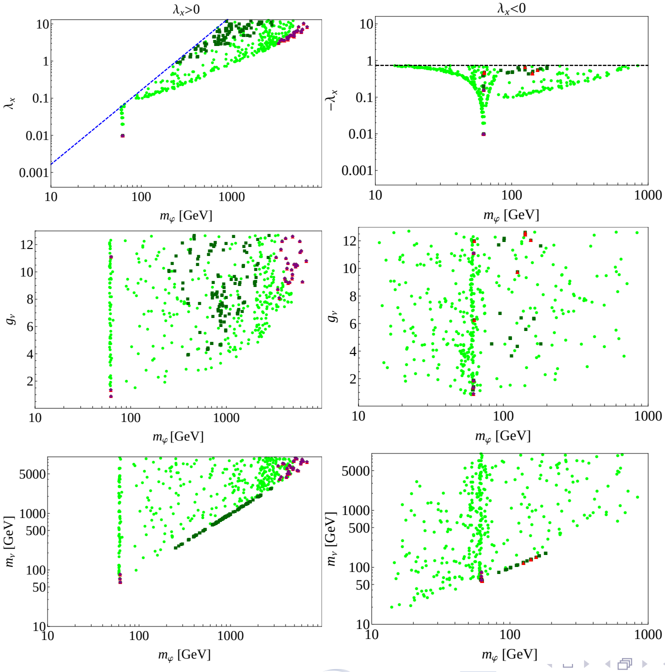
Scanned parameter space:

m_φ, m_ν= 10 GeV - 10 TeV

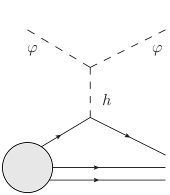
$\lambda_x = 10^{-3}$ - 10;

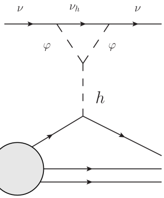
$g_\nu = 0.1$ - 10;

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

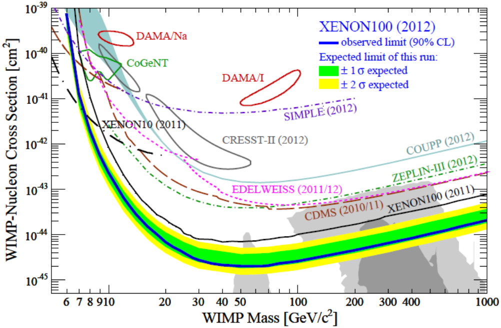

$\lambda_x>0$
$\lambda_x<0$
λ_x
$-\lambda_x$
g_ν
m_ν [GeV]
m_φ [GeV]

Direct Detection - DM scattering

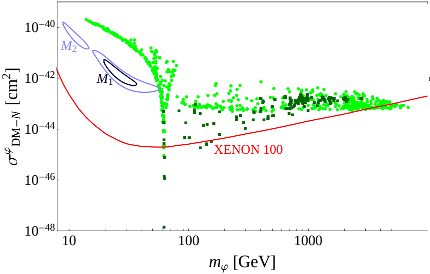


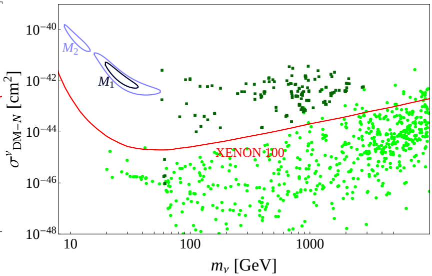


$$\sigma^{\varphi}_{\mathrm{DM-N}} = \frac{\mathrm{n}_\varphi}{\mathrm{n}_\varphi + \mathrm{n}_\nu} \sigma_{\varphi \mathrm{N}} \qquad \sigma^{\nu}_{\mathrm{DM-N}} = \frac{\mathrm{n}_\nu}{\mathrm{n}_\varphi + \mathrm{n}_\nu} \sigma_{\nu \mathrm{N}}$$



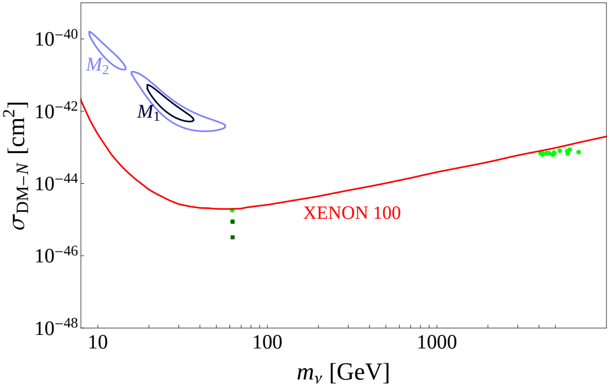
arXiv:1207.5988





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

Scalar + Fermionic DM - all constraints satisfied



Plot of the cross section $\sigma_{\rm DM-N} = \sigma^{\varphi}_{\rm DM-N} + \sigma^{\nu}_{\rm DM-N}$ 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.

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 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

International PhD Projects Programme (MPD) -
Grants for Innovations

Extra slides

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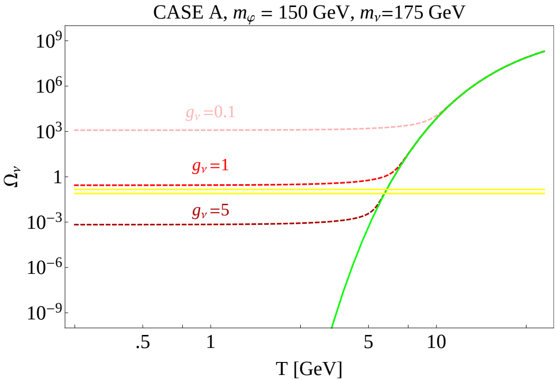
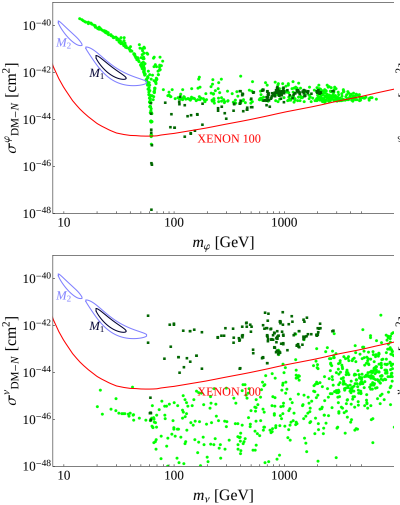
Scalar + Fermionic DM - WMAP constraint



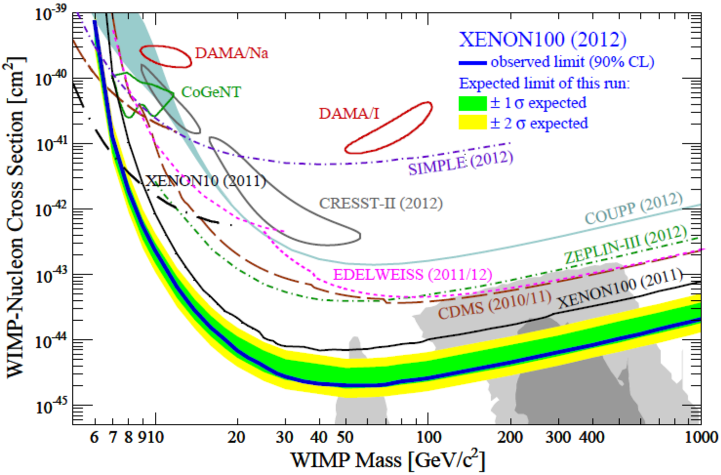
Solutions of the BEQs for $m_\varphi = 150$ GeV, $m_\nu = 175$ GeV (case A), $\lambda_x = 1$. Pink, red, dark red lines: solutions for the neutrino abundance for $g_\nu = 0.1, 1, 5$, respectively. Green: equilibrium distribution for neutrinos at 175 GeV.

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 $\Omega_\varphi < \Omega_\nu$ ($\Omega_\varphi > \Omega_\nu$).

Direct Detection



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