Two-Component Dark Matter

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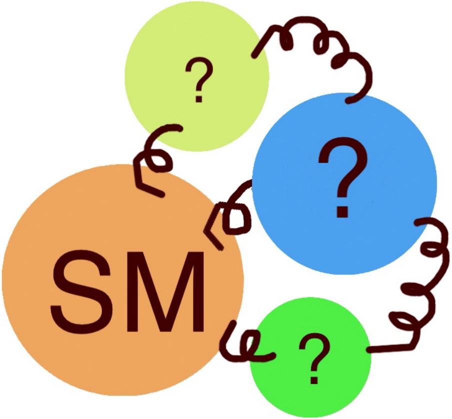
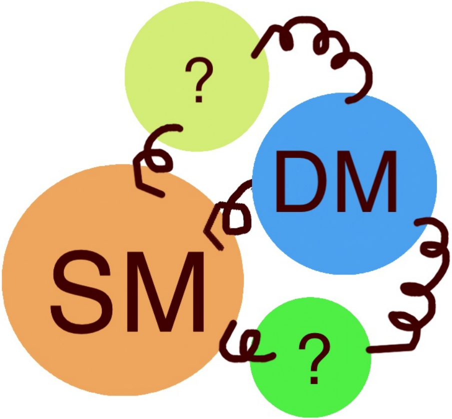
Outline:

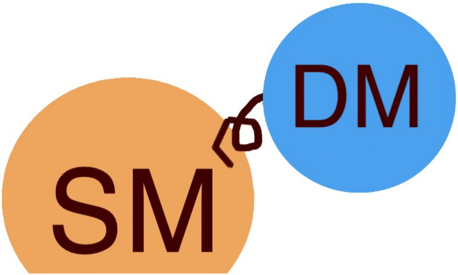
- Two-component DM: scalar + fermion
  - relic abundance in two-component DM scenario (the Boltzmann equation)
    - numerical solutions
    - approximate analytical solutions
  - theoretical constraints
  - WMAP constraints
  - direct detection constraints

- 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]


?
?
SM
?

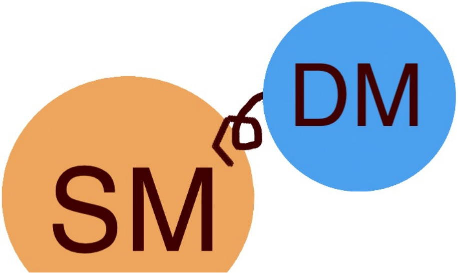

?
DM
SM
?

a Dark Matter candidate?

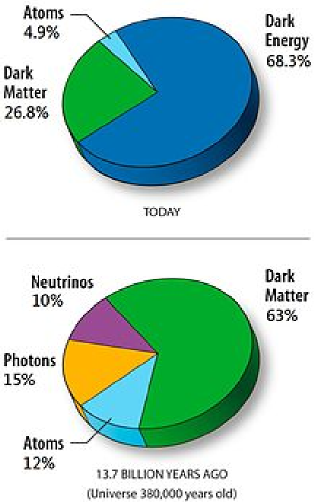


DM: stable, neutral, weakly interacting, massive arxiv:1012.4587

stability: global symmetry ($\mathbb{Z}_2, \ldots$)

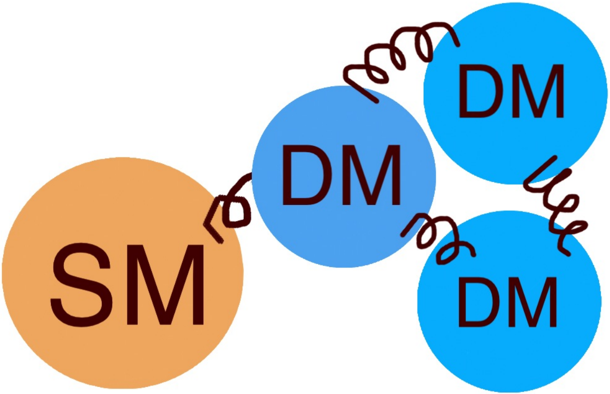


DM: stable, neutral, weakly interacting, massive

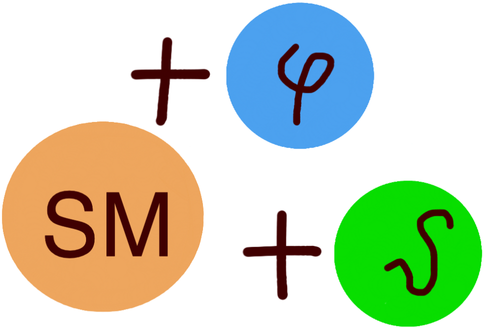


Profumo S. et al. (arXiv:0907.4374),
Gelmini G. (hep-ph/0310022),
Zurek K. (arXiv:0811.4429),
Ma et al.. (arXiv:1308.4177),
Semenov V.A. (arXiv:1306.3210),
Khlopov M. et al., Heikinheimo M et al.,
Duerr M. et al. (arXiv:1207.3318) and others

SYMMETRY > $\mathbb{Z}_2$



Scalar + Fermionic Dark Matter

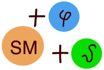


singlet scalar field φ

$+$

singlet Majorana fermion ν

Scalar + Fermionic Dark Matter - Lagrangian



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

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

$m_\varphi^2 > \lambda_x v^2$

$$\begin{aligned}\mathcal{L}_{DM} = & \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi + \frac{1}{2}\bar{\nu}i\partial\!\!\!/\nu + \frac{1}{2}\bar{\nu}_h i\partial\!\!\!/\nu_h \\ & -\frac{1}{2}\mu_\varphi^2\varphi^2 - \frac{\lambda_\varphi}{4!}\varphi^4 - \lambda_x\varphi^2 H^\dagger H \\ & +\frac{1}{2}m_\nu\nu^T C\nu + \frac{1}{2}M_{hv}\nu_h^T C\nu_h \\ & +g_\nu\,\bar{\nu}\nu_h\,\varphi\end{aligned}$$

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 ν_h

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

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

Theoretical constraints

Z_2-consistency requirement

$$m_\varphi^2 > \lambda_x v^2$$

Tree-level unitarity (scalar-scalar scatterings)

$$|\lambda_\varphi| < 8\pi$$
$$|\lambda_x| < 4\pi$$

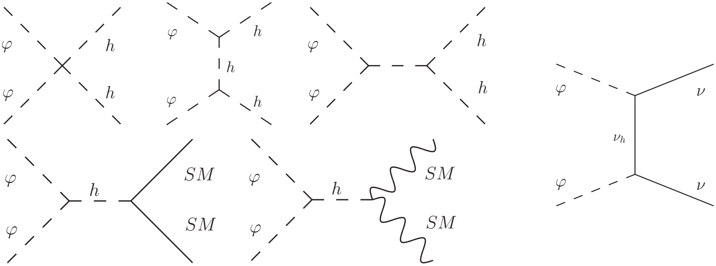
Perturbativity

$$|\lambda_\varphi| < 4\pi$$
$$|\lambda_x| < 4\pi$$
$$|g_\nu| < 4\pi$$

Tree-level vacuum stability

$$\lambda_\varphi > 0$$
$$\lambda_x > -\sqrt{\frac{\lambda_\varphi \lambda_H}{6}}$$

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



+ *crossed*

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, ...

Evaluating DM Relic Abundance

Creation and Annihilation

Thermally averaged cross section

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

$$
< \sigma_{X\bar{X}\to Y\bar{Y}}\, v > \;=\; \frac{(2\pi)^4}{n_X^{EQ2}} \int d\Pi_X d\Pi_{\bar{X}} d\Pi_Y d\Pi_{\bar{Y}} \times
$$

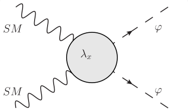
$$
|M|^2 \delta^4(p_X + p_{\bar{X}} - p_Y - p_{\bar{Y}}) e^{-(E_X + E_{\bar{X}})/T}
$$

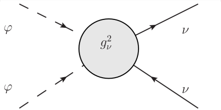
the Boltzmann Equation

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

$\hat{L}[\tilde{f}]$ - 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

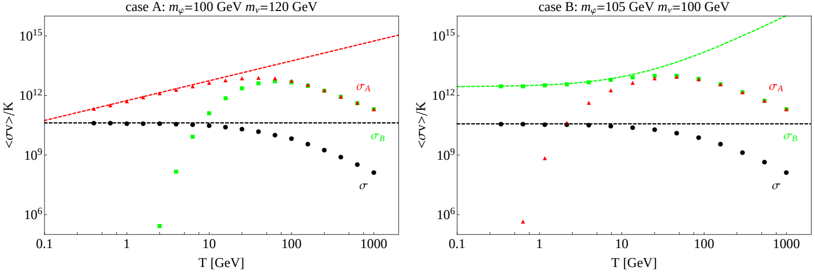
$$f'_\varphi = \frac{\langle \sigma_{\varphi\varphi\to SM\,SM} v\rangle}{K}\left(f_\varphi^2 - f_\varphi^{EQ2}\right) + \frac{\langle \sigma_{\varphi\varphi\to\nu\nu} v\rangle}{K} f_\varphi^2 - \frac{\langle \sigma_{\nu\nu\to\varphi\varphi} v\rangle}{K} f_\nu^2$$

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

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: $\langle\sigma_{\nu\nu\to\varphi\varphi}\mathrm{v}\rangle/\mathrm{K}$

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

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

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

Scalar + Fermionic Dark Matter

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

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

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

errors

$$\mathrm{m}_\varphi < \mathrm{m}_\nu : \delta^{\mathrm{A}}_\varphi \simeq 2.3\% \quad \delta^{\mathrm{A}}_\nu \simeq 1.4\%$$

$$\mathrm{m}_\varphi > \mathrm{m}_\nu : \delta^{\mathrm{B}}_\varphi \simeq 6.3\% \quad \delta^{\mathrm{B}}_\nu \simeq 2.6\%$$

$$f'_\varphi = \sigma(T)\left(f_\varphi^2 - f_\varphi^{EQ\,2}\right) + \sigma_A(T)\left[\left(\frac{f_\nu^{EQ}}{f_\varphi^{EQ}}\right)^2 f_\varphi^2 - f_\nu^2\right]$$

$$f'_\nu = \sigma_A(T)\left[f_\nu^2 - \left(\frac{f_\nu^{EQ}}{f_\varphi^{EQ}}\right)^2 f_\varphi^2\right]$$

$$\sigma(T) = \langle \sigma_{\varphi\varphi\to SM\,SM} v\rangle / K$$

$$\sigma_A(T) = \langle \sigma_{\nu\nu\to\varphi\varphi} v\rangle / K$$

$$\sigma_B(T) = \langle \sigma_{\varphi\varphi\to\nu\nu} v\rangle / K$$

case A : $m_\varphi < m_\nu$

case B : $m_\varphi > m_\nu$

$$f'_\varphi = \sigma(T)\left(f_\varphi^2 - f_\varphi^{EQ\,2}\right) + \sigma_B(T)\left[f_\varphi^2 - \left(\frac{f_\varphi^{EQ}}{f_\nu^{EQ}}\right)^2 f_\nu^2\right]$$

$$f'_\nu = \sigma_B(T)\left[\left(\frac{f_\varphi^{EQ}}{f_\nu^{EQ}}\right)^2 f_\nu^2 - f_\varphi^2\right]$$

$$f_\nu(T_{CMB}) \sim \frac{2}{\sigma_A(T_f^\nu)T_f^\nu}$$

$$f_\varphi(T_{CMB}) \sim \frac{r_f}{\sigma(T_{CMB})T_f^\varphi}\frac{u+\tanh(r_f)}{1+u\tanh(r_f)}$$

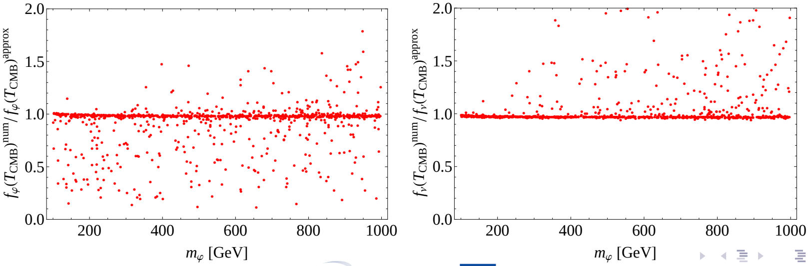
where

$$r_f = 2\frac{T_f^\varphi}{T_f^\nu}\sqrt{\frac{\sigma(T_{CMB})}{\sigma_A(T_f^\varphi)}}, u = \frac{c_\varphi m_\varphi}{r_f T_f^\varphi}$$

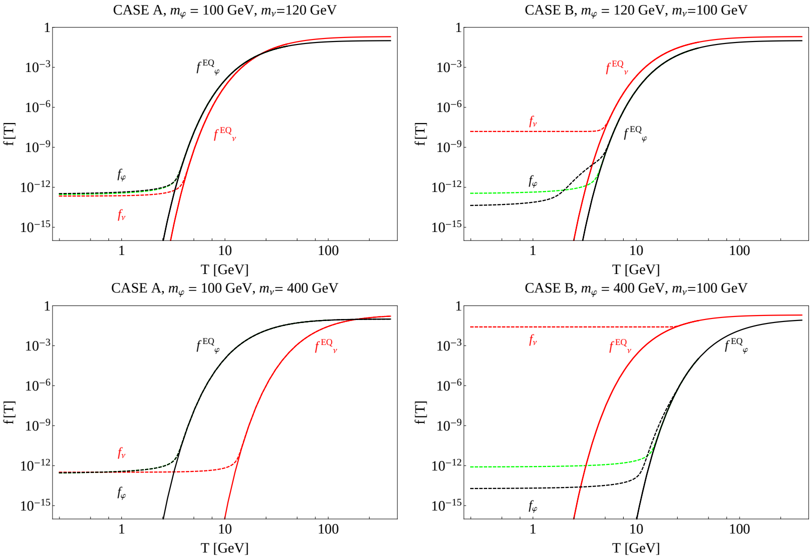
$$\sigma(T) = \langle\sigma_{\varphi\varphi\to SM\,SM} v\rangle/K$$

$$\sigma_A(T) = \langle\sigma_{\nu\nu\to\varphi\varphi} v\rangle/K$$

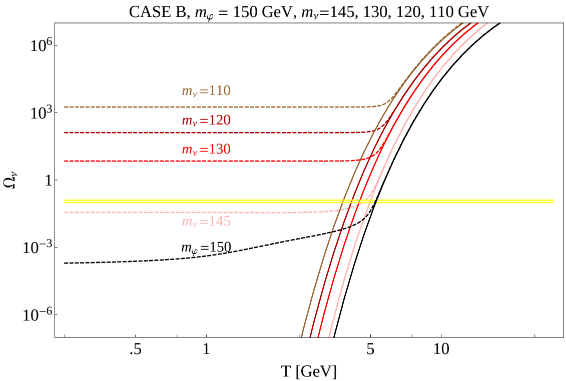
case A : $m_\varphi < m_\nu$



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!

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

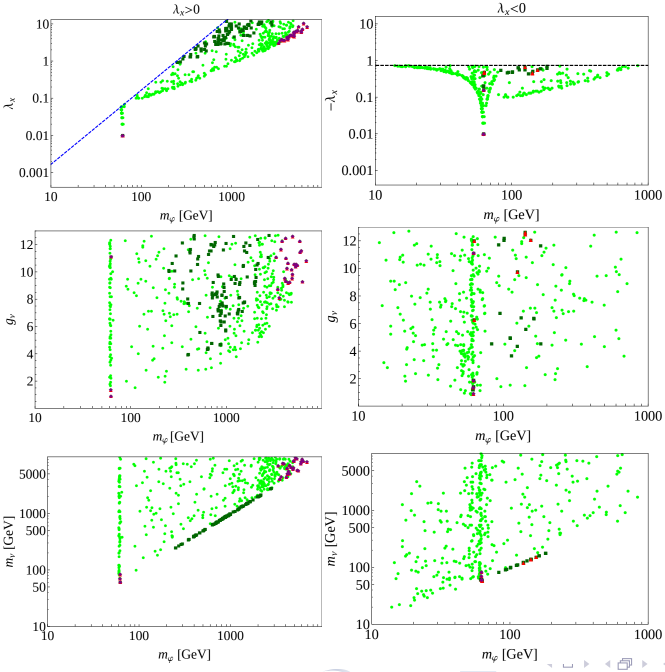
Scanned parameter space:

m_φ, m_ν = 10 GeV - 10 TeV

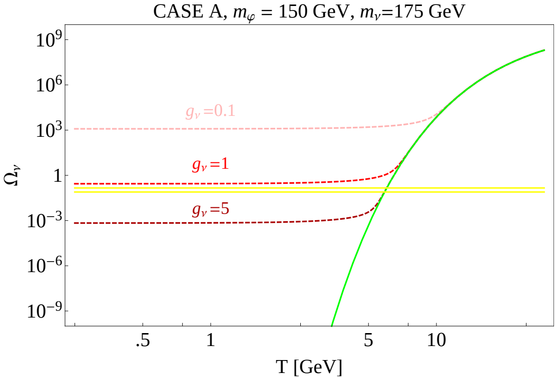
$\lambda_x = 10^{-3}$ - 4π;

$g_\nu = 0.1$ - 4π;

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


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

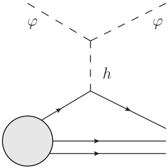
Scalar + Fermionic DM - WMAP constraint

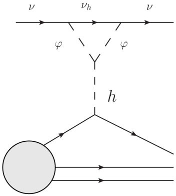


Solutions of the BEQs for $m_\varphi = 150$ GeV, $m_\nu = 175$ GeV (case A), $\lambda_x = 1$. Pink, red, dark red lines: solutions for the neutrino abundance for $g_\nu = 0.1, 1, 5$, respectively. Green: equilibrium distribution for neutrinos at 175 GeV.

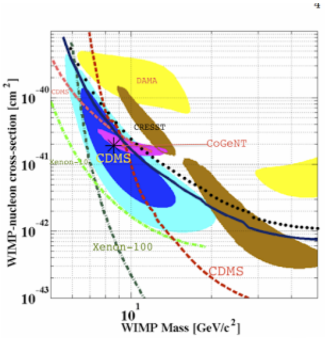
Yellow lines: WMAP 3σ limit on DM abundance.

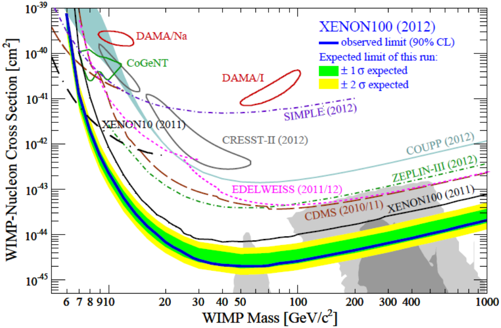
Direct Detection - DM scattering

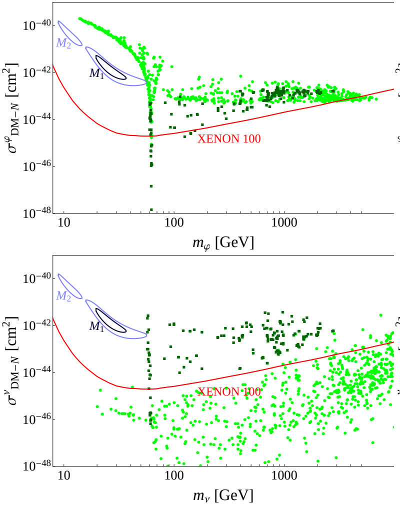




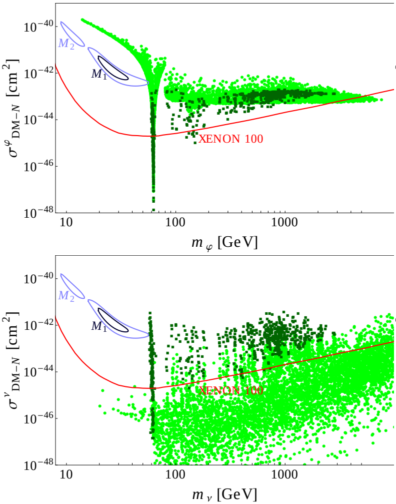
$$\sigma^{\varphi}_{\mathrm{DM-N}} = \frac{\mathrm{n}_\varphi}{\mathrm{n}_\varphi + \mathrm{n}_\nu} \sigma_{\varphi \mathrm{N}} \qquad \sigma^{\nu}_{\mathrm{DM-N}} = \frac{\mathrm{n}_\nu}{\mathrm{n}_\varphi + \mathrm{n}_\nu} \sigma_{\nu \mathrm{N}}$$







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



Points satisfying the WMAP data without a lower bound on Ω; 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 $\Omega_\varphi < \Omega_\nu$ ($\Omega_\varphi > \Omega_\nu$).

What we did:

- discussed the minimal extension of SM that provides two-component Cold Dark Matter with $\mathbb{Z}_2 \times \mathbb{Z}_2'$ symmetry
- discussed the DM density using the B. EQs
- found approximate analytical solutions of the the B. EQs
- constraied the parameter space by theoretical bounds, 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, $m_\varphi > 3\,\mathrm{TeV}$ and $m_\nu > m_\varphi$
  - very small λ_x (resonance region, $m_\varphi \sim m_{\mathrm{Higgs}}/2$)

Thank you for your attention !

International PhD Projects Programme (MPD) -
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INNOVATIVE ECONOMY
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FNP
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DEVELOPMENT FUND

Extra slides

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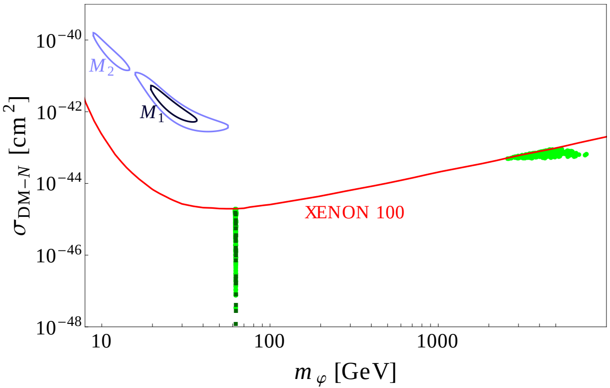
Scalar + Fermionic DM - all constraints satisfied



Plot of the cross section $\sigma_{\mathrm{DM-N}} = \sigma^{\varphi}_{\mathrm{DM-N}} + \sigma^{\nu}_{\mathrm{DM-N}}$ as a function of φ for points satisfying the WMAP data upper bound. 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.