Cosmology of multi-scalar-singlet extensions of the Standard Model

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Multi-scalar-singlet extension of Standard Model

- Model
- Theoretical Constraints
- Cosmological Constraints

In collaboration with B. Grządkowski and J. Wudka

Model

Standard Model + N-component singlet scalar $\vec{\varphi}$
Z_2 symmetry: $\vec{\varphi} \to -\vec{\varphi}$ and O(N) symmetry

$$L_{\rm scalar} = D_\mu H^\dagger D^\mu H + \frac{1}{2}\partial_\mu \vec{\varphi}\, \partial^\mu \vec{\varphi} - V(\varphi)$$

Scalar Potential $V(\varphi)$

$$-\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \frac{1}{2}\mu_\varphi^2 \vec{\varphi}^2 + \frac{1}{4!}\lambda_\varphi \left(\vec{\varphi}^2\right)^2 + \lambda_x H^\dagger H \vec{\varphi}^2$$

H - Higgs doublet, $\langle H \rangle = (0, v/\sqrt{2})$, $v = 246$ GeV, $\langle \vec{\varphi} \rangle = 0$

after symmetry breaking:
$m_h^2 = -\mu_H^2 + 3\lambda_H v^2 = 2\mu_H^2, \qquad m_\varphi^2 = \mu_\varphi^2 + \lambda_x v^2$

Theoretical constraints

Unitarity

- $m_H^2 < \frac{8\pi}{3} v^2$
- $|\lambda_\varphi| < 8\pi$
- $|\lambda_x| < 4\pi$

Tree Level Vacuum Stability

- quartic couplings are all positive $(\lambda_H, \lambda_\varphi, \lambda_x > 0)$

or

- λ_x is negative and $\lambda_x^2 < \lambda_H \lambda_\varphi / 6$

Triviality

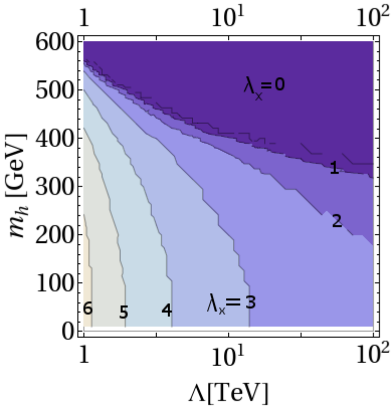


Figure 1: Maximum λ_x contour lines for $N = 1$, $\lambda_\varphi(M_W) = 0.1$.

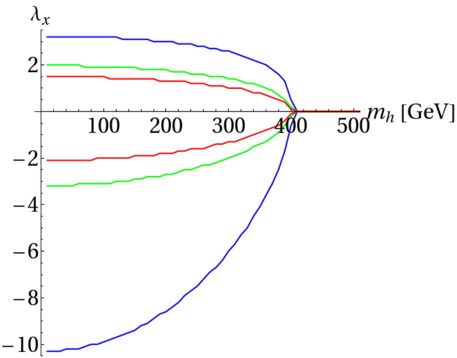


Figure 2: Maximum and minimum λ_x for $\Lambda = 10$ TeV, $\lambda_\varphi(M_W) = 0.1$ for $N = 1, 6, 12$.

$$\lambda_{xMAX}(m_h \sim 130\,\mathrm{GeV}) = \begin{cases} 2 & \Lambda \sim 100\,\mathrm{TeV} \\ 6 & \Lambda \sim 1\,\mathrm{TeV} \end{cases}$$

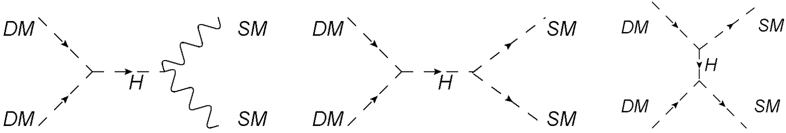
Dark Matter Candidate

Thermal Production of Scalars

The Boltzmann equation ($f_i = n_i/T^3$):

$$\frac{df_i}{dT} = \frac{\langle \sigma v \rangle_i}{K}\left(f_i^2 - f_{EQ}^2\right), \quad K = \sqrt{\frac{4\pi^3 g_i(T)}{45 m_{Pl}^2}}$$

$\langle \sigma v \rangle_i$ - thermal cross section for DM + DM $\rightarrow$ SM + SM



$$\Omega_{DM} = \sum_i \Omega_{DM}^i = N\Omega_{DM}^i$$

Dark Matter Abundance - Cold Dark Matter (CDM)

$$\Omega^{i}_{DM}h^2(\lambda_x, m_\varphi, N, m_h, ...) = 1.06 \times 10^9 \frac{x_f}{\sqrt{g_*}\, m_{Pl}\langle\sigma v\rangle} \frac{1}{\mathrm{GeV}} = 0.110 \pm 0.018$$

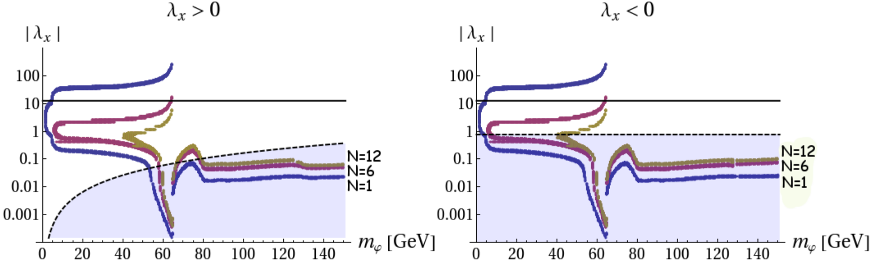


Figure 3: $\lambda_x(m_\varphi)$ for $N = 1, 6, 12$ scalars (blue, violet, yellow respectively) and $m_h = 130$ GeV. Blue regions are allowed. Thick black line: $|\lambda_x| < 4\pi$. Dashed line on the right:$\lambda_x < \lambda_H \lambda_\varphi / 6$ for $\lambda_\varphi = 8\pi$.

Dashed line on the left: $\lambda_x < m_\varphi^2 / v^2$.

Dark Matter Abundance - Feebly Interacting Dark Matter (FIDM)

$$f(T=\infty)=0, \qquad \frac{df}{dT} = -\frac{<\sigma v>}{K} f_{EQ}^2$$

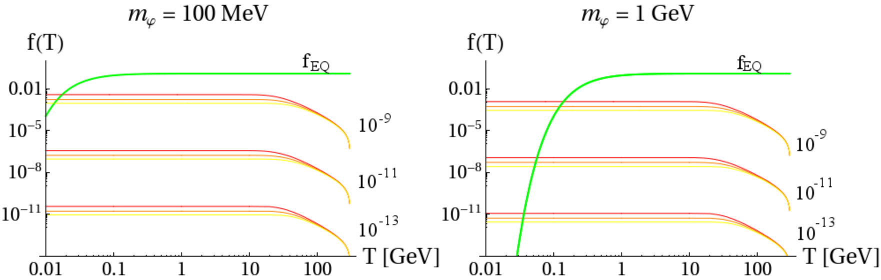


Figure 4: Solutions to Boltzman equation for $\lambda_x = 10^{-13}, 10^{-11}, 10^{-9}$. Splitting comes from $m_h = 100, 130, 160$ GeV (red, orange, yellow). Green curve is the equilibrium density f_{EQ}.

Dark Matter Abundance - FIDM

$$\Omega h^2 = \frac{m_\varphi f_\varphi(T_\gamma) T_\gamma^3}{\rho_{\rm crit}} = 0.11 \pm 0.018$$

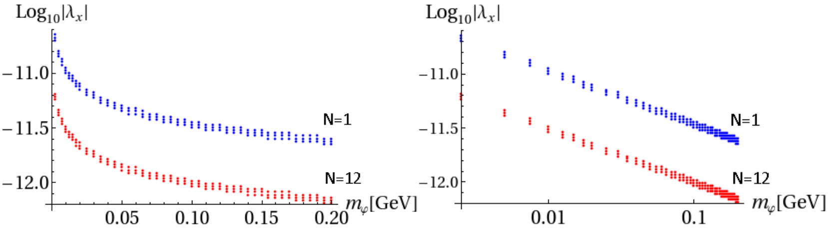
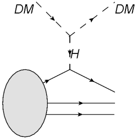


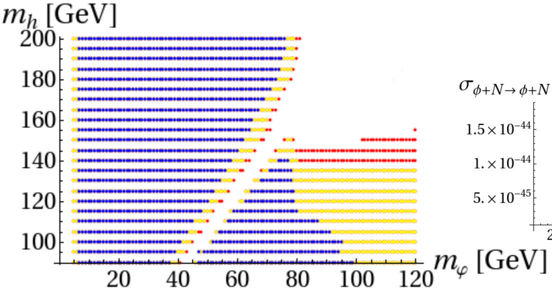
Figure 5: Left panel: Solutions to Boltzman equation: $m_h = 130$ GeV, $N = 1, 12$ (blue, red respectively).

Right panel: Solutions to Boltzman equation: $m_h = 130$ GeV, $N = 1, 12$ (blue).

Direct Detection - XENON 100

$$\mathrm{DM} + \mathrm{N} \rightarrow \mathrm{DM} + \mathrm{N}$$





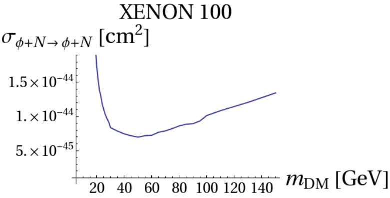


Figure 6: Right panel: XENON 100 results.
Left panel: Forbidden parameters $(\mathrm{m}_\varphi, \mathrm{m}_\mathrm{h})$: $\mathrm{N} = 1, 6, 12$ (blue, yellow, red) for CDM.

Self-Interaction Rate

Steinhardt & Spergel: Phys.Rev.Lett.84:3760-3763, 2000

$$\frac{\sigma_{\varphi\varphi\to\varphi\varphi}}{\mathrm{m}_\varphi} = (2.05\times 10^3 - 2.57\times 10^4)\mathrm{GeV}^{-3}$$

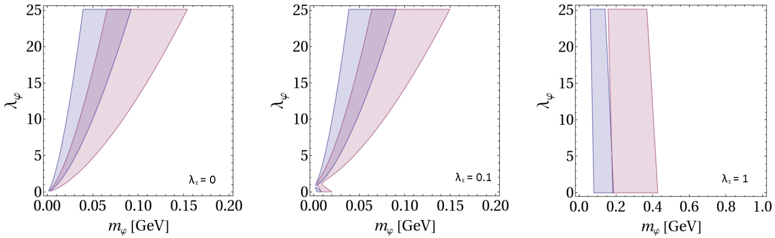


Fig 7: Allowed values of λ_φ: N = 1 (blue) and N = 12 (pink), $\lambda_x = 0$ (left panel), 0.1 (middle), 1 (right).

Conclusions

1. Strongest theoretical constraints on $|\lambda_{\mathrm{x}}|$:
   - vacuum stability $\Rightarrow$ $\lambda_{\mathrm{x}}^2 < \lambda_{\mathrm{H}}\lambda_{\varphi}/6$
   - $\mu_{\varphi}^2 > 0$ $\Rightarrow \lambda_{\mathrm{x}} < \mathrm{m}_{\varphi}^2/\mathrm{v}^2$
2. Direct detection constraints on CDM:
   $\mathrm{m_h} \sim 2\mathrm{m}_{\varphi}$ & $|\lambda_{\mathrm{x}}| < 0.1$ for large number of scalars.
3. Steinhardt and Spergel bound implies very light (below 1 GeV) and feebly coupled singlet scalars.