Revisit the relic density of Higgs-portal dark matter

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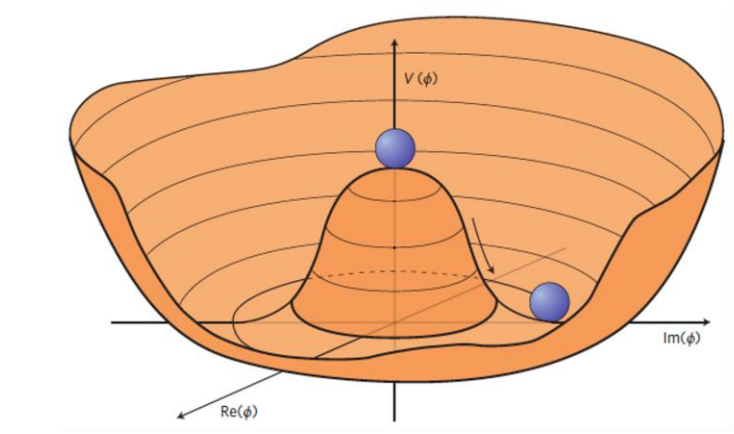
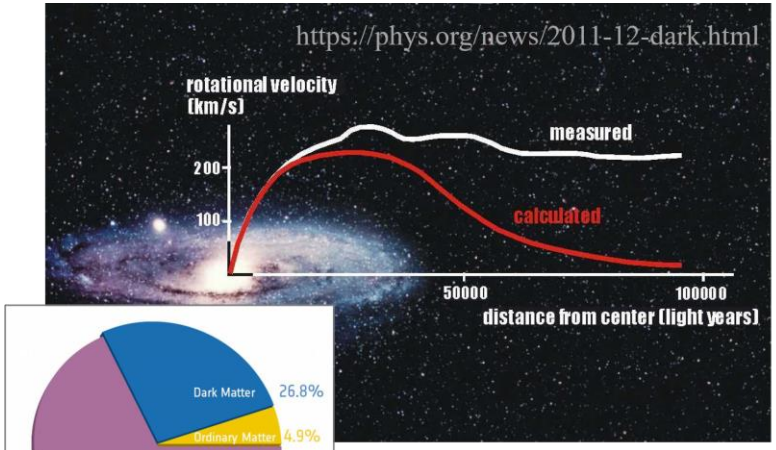
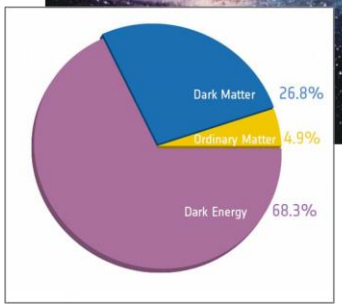
Mysteries after the Higgs discovery



J. Ellis, M. Gaillard, D. Nanopoulos, arXiv:1504.07217

What is the origin of symmetry breaking?
How many Higgs fields?





Planck Collaboration

What is dark matter (DM)?
How was it generated?

Find the fundamental model describing the Higgs and DM in a unified picture!

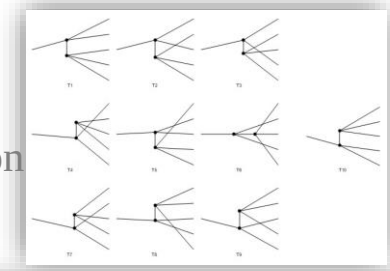
So many literatures suggest that the Higgs is a bridge between the DM and our world

Important and necessary to carefully investigate the connection between the Higgs and DM

High-multiplicity scalar production

J. M. Cornwall, PLB243 (1990), H. Goldberg, PLB 246 (1990)

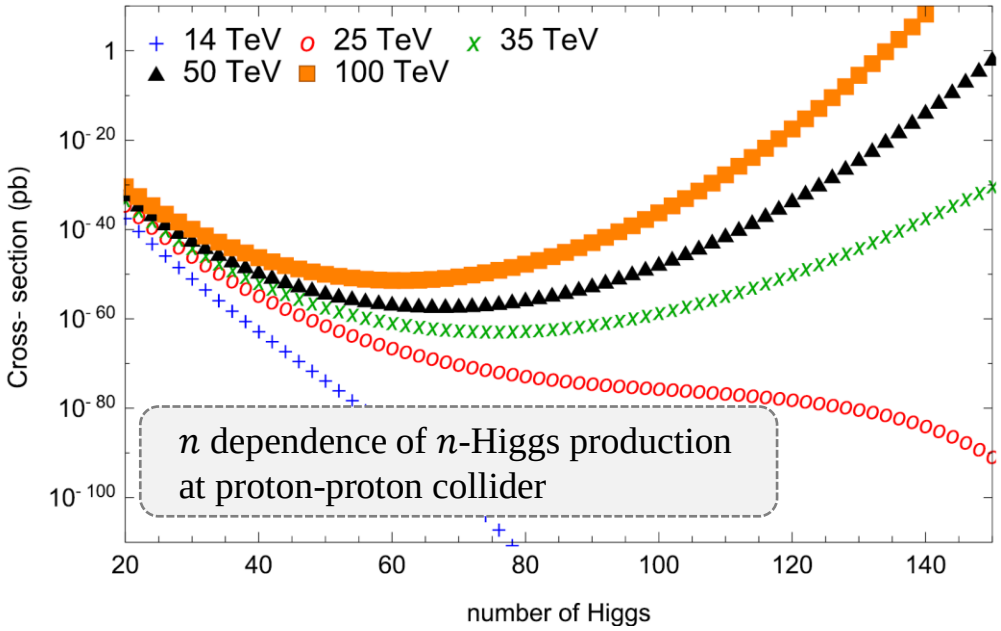
5 Higgs production



7 Higgs production

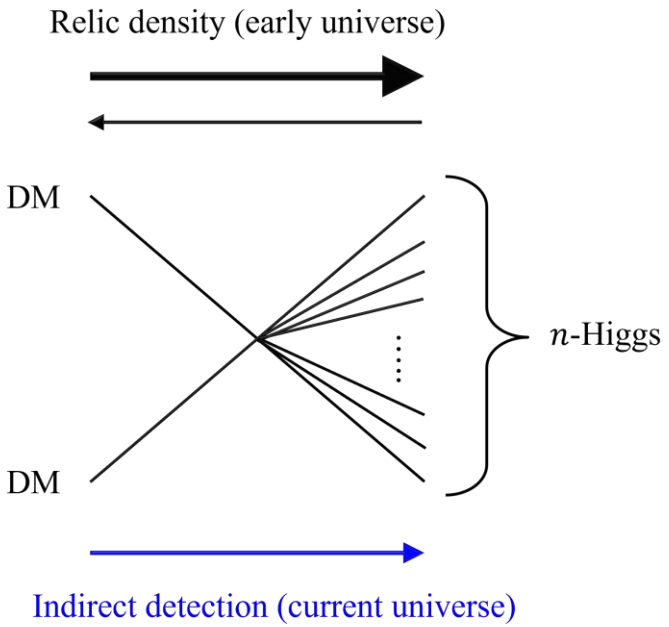
Exponential growth of the "decay rate" of energetic scalar with final state multiplicity

$$\Gamma_n \sim \lambda^n n! \times f_n(E)$$



V. Khoze, M. Spannowski, NPB 926 (2018)

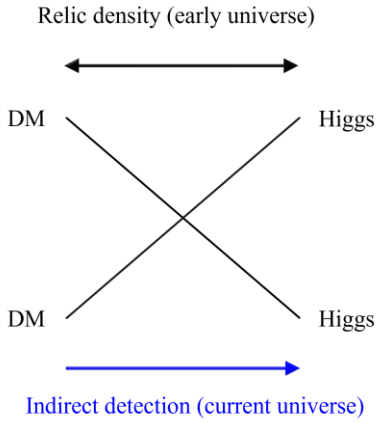
Aim



Revisit the Higgs portal DM with taking into account high-multiplicity final state

-- precisely calculate the relic density to make use of a probe for DM-Higgs interaction

-- analyze the indirect signals of DM annihilation to reconstruct the nature of DM from cosmic rays



<u>Previous literatures</u>

$\mathrm{DM} + \mathrm{DM} \leftrightarrow H + H$ only for the calculation of relic density

$\langle \sigma v(\mathrm{DMDM} \to HH) \rangle$ (early universe) $\longleftrightarrow$ (almost) one-to-one correspondence $\sigma v(\mathrm{DMDM} \to HH)$ (current universe)

Model and Transition amplitude

Standard Model + dark matter χ

ϕ: Higgs (φ after ~~symmetry~~)

Note: Applicable to other models of a general scalar

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{4}\lambda(\phi^2 - v^2)^2 + \bar{\chi}(i\partial - m_\chi)\chi - (y_\chi \phi \overline{\chi_R}\chi_L + \text{h.c.})$$

Symmetry breaking

$$\mathcal{L}_{\text{int}} = -\lambda v\varphi^3 - \frac{1}{4}\lambda\varphi^4 - \varphi\bar{\chi}\left(\tilde{y}_\chi P_L + \tilde{y}_\chi^* P_R\right)\chi$$

$$\tilde{y}_\chi = y_\chi e^{-i\arg M_\chi}$$
$$M_\chi = m_\chi + y_\chi v$$

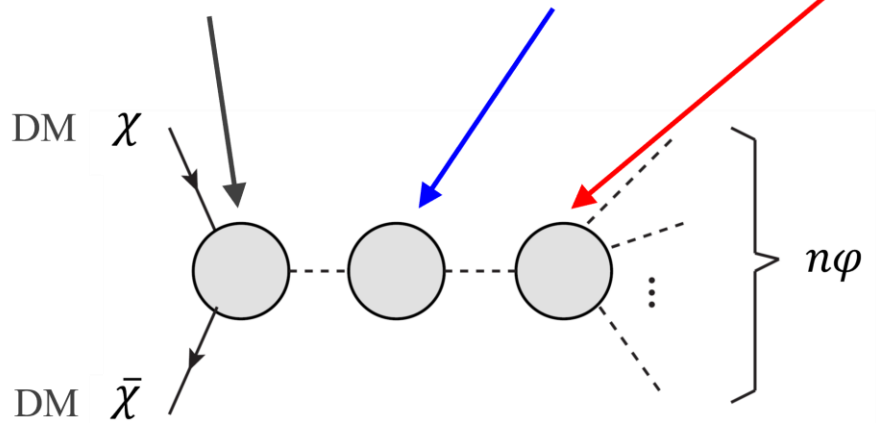
Transition amplitude

Higgs "decay" into n-body Higgs
⊃ Higgsprosion effect

$$\sum_{\text{spins}} |\mathcal{M}(\chi\bar{\chi} \to n\varphi)|^2 = \sum_{\text{spins}} \left| \mathcal{M}(\chi\bar{\chi} \to \varphi^*) \frac{1}{s - m_\varphi(s)^2 - i m_\varphi(s)\Gamma_\varphi(s)} \mathcal{M}(\varphi^* \to n\varphi) \right|^2$$

DM annihilation to intermediate Higgs
(straightforwardly calculated)

Dressed propagator
⊃ Higgspersion effect



DM annihilation with Higgsplosion

Boltzmann equation (evolution equation of DM density)

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\sum_n \int \frac{d^3k_\chi}{(2\pi)^3 2E_\chi} \frac{d^3k_{\bar{\chi}}}{(2\pi)^3 2E_{\bar{\chi}}}$$

$$\times \frac{1}{n!} \int \frac{d^3p_1}{(2\pi)^3 2E_1} \cdots \frac{d^3p_n}{(2\pi)^3 2E_n} (2\pi)^4 \delta^{(4)} \left(k_\chi + k_{\bar{\chi}} - p_1 - \cdots - p_n\right)$$

$$\times \sum_{\text{spins}} \left| \mathcal{M}(\chi\bar{\chi} \to \varphi^*) \frac{1}{s - m_\varphi(s)^2 - i m_\varphi(s)\Gamma_\varphi(s)} \mathcal{M}(\varphi^* \to n\varphi) \right|^2 \left[f_\chi f_{\bar{\chi}} - f_{\varphi_1} \cdots f_{\varphi_n} \right]$$

Dimensionless reaction rate

$$\mathcal{R}_n(s) = \Gamma(\varphi^* \to n\varphi)/m_\varphi$$

Dimensionless reaction rate

M. V. Libanov, V. A. Rubakov, D. T. Son, S. V. Troitsky, PRD50 (1994)
V. Khoze, M. Spannowski, NPB 926 (2018)

$$\mathcal{R}_n(s) \simeq \exp\left[n \left(0.854\sqrt{\lambda n} + \ln\frac{\lambda n}{4e} + \frac{3}{2} \ln\left(\frac{e}{3\pi} \frac{\sqrt{s} - n m_\varphi}{n m_\varphi} \right) - \frac{25}{12} \frac{\sqrt{s} - n m_\varphi}{n m_\varphi} \right) \right]$$

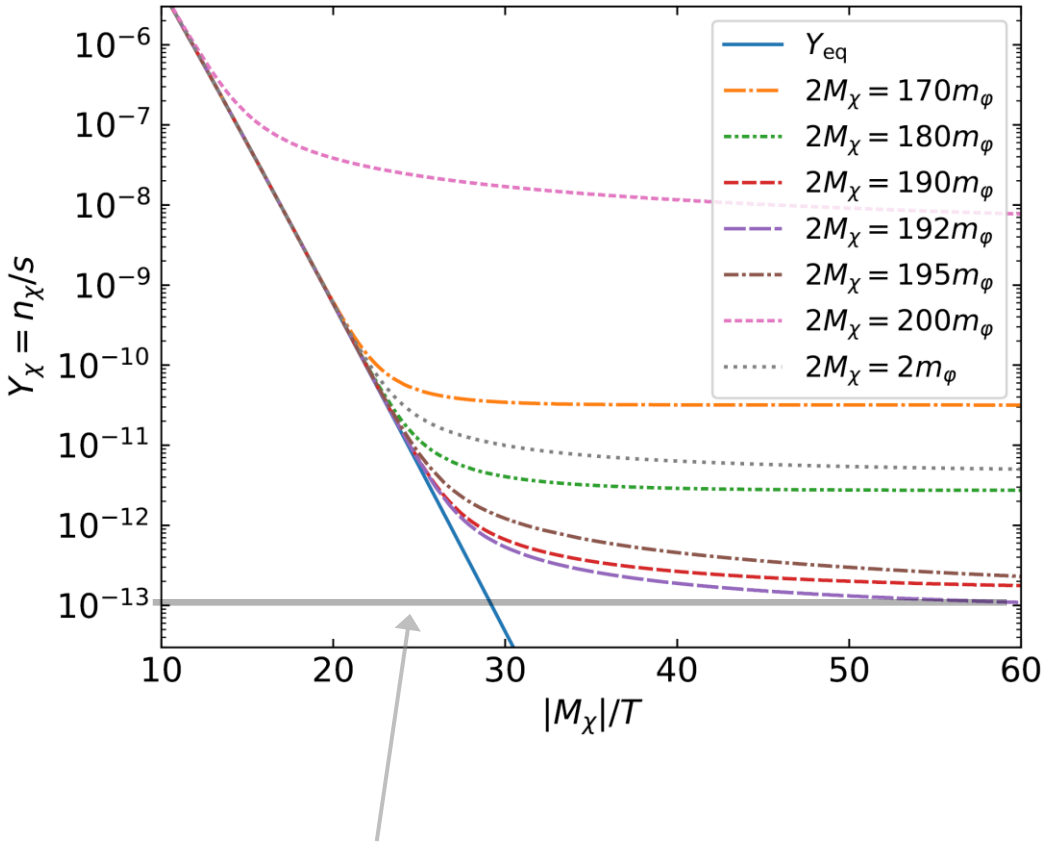
Important

Argument of the exponential = positive-valued

⟶ $R_n(s)$ grows with the multiplicity n

Relic density

$M_\chi = nm_\varphi/2,\ \ \lambda = 0.129,\ \ m_\varphi = 50\ \mathrm{GeV}$



$\Omega_{\mathrm{DM}}h^2 = 0.120 \pm 0.001$

Planck collaboration

- Parameter set ($M_\chi = 4.8$ TeV, $\tilde{y}_\chi = 1.53i$) successfully accounts for relic abundance

  Much heavier than the Higgs portal DM in previous works, $m_{\mathrm{DM}} \simeq 62$ GeV, where relic density is achieved by the Higgs pole

- Quantum statistics for the high-multiplicity state could change the results

  Bose-Einstein distribution should be applied for the thermal averaging of DM annihilation, which may be enhanced by stimulated emission

Summary and discussion

- **Revisit to Higgs portal DM with taking into account Higgsplosion**

  -- energetic Higgs boson decays into n-Higgs boson

  -- long-stay in equilibrium through strong interaction with Higgsplosion

  -- a favored parameter: $M_\chi = 4.8$ TeV and $|\tilde{y}_\chi| = 1.53$

  (much heavy compared with Higgs portal DM in previous works)

  -- simple and applicable to various models

- **Discussion**

  -- quantum statistics effects for high-multiplicity

  Bose-Einstein distribution and stimulated emission could change the shape of window function $W(s)$

  -- test in indirect search of DM

  important and necessary to reanalyze the signal with high-multiplicity state to reconstruct the nature of DM