Impact of Higgsplosion on Relic Density of Dark Matter

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S. Enomoto, N. Hiroshima, K. Murase, MY, arXiv:2310.XXXXX

Discovery of the Higgs boson

Higgs properties

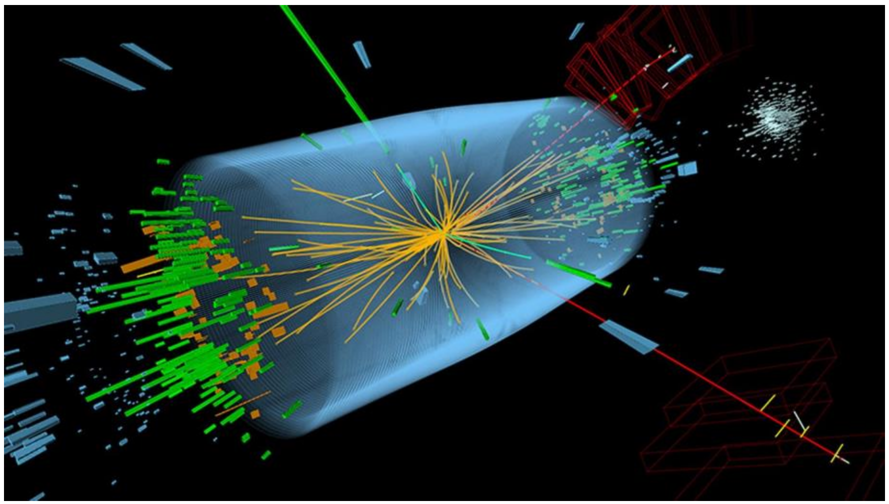
-- origin of particle masses

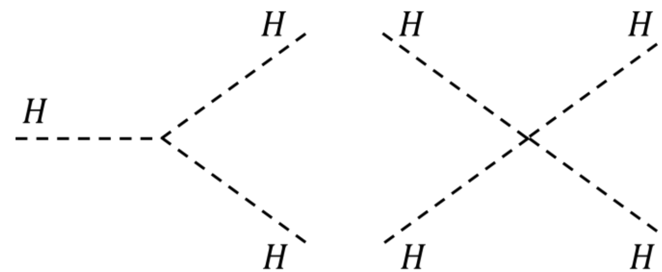
-- mass 125.11 GeV

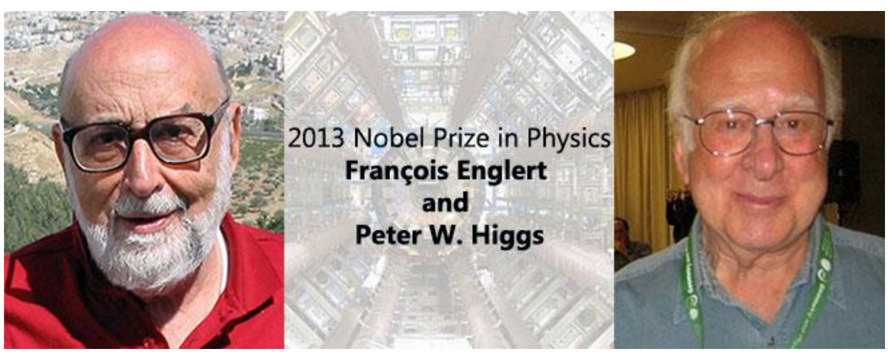
-- electrically neutral

-- spin 0 (fundamental scalar particle)

-- interaction with itself



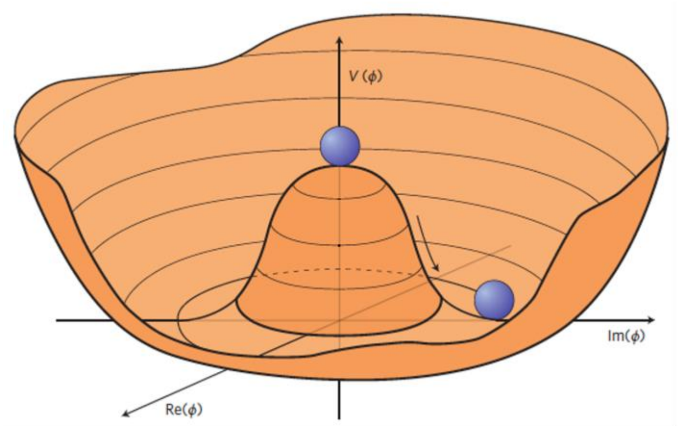




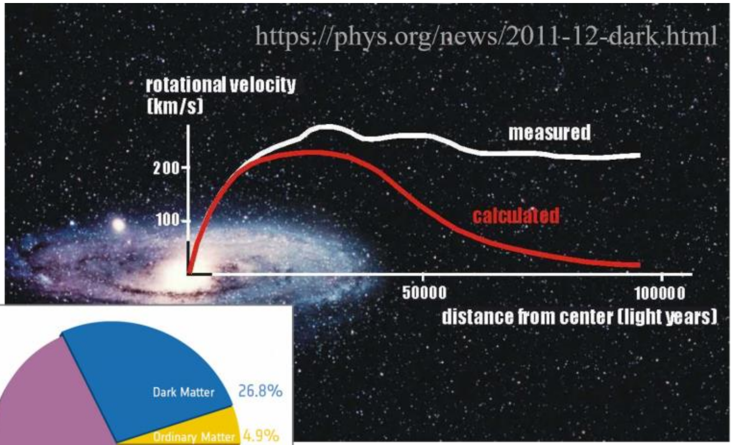
Did the discovery complete the particle physics?

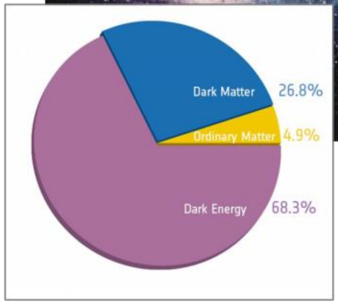
Have we found all the laws of nature?

Mysteries to be unraveled



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





Planck Collaboration

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

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

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

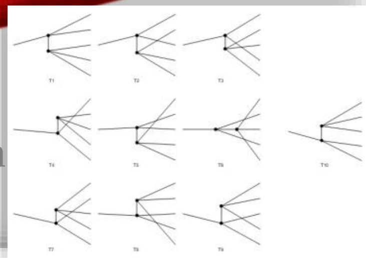
So many literatures suggest that the Higgs is a bridge between the DM and our world

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

High-multiplicity scalar production

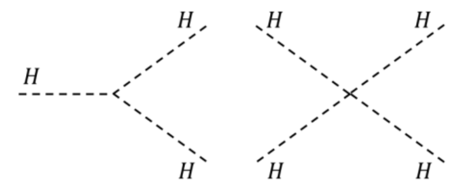
J. M. Cornwall, PLB243 (1990)
H. Goldberg, PLB 246 (1990)

5 Higgs production



7 Higgs production

Higgs property
- -- origin of particle masses
- -- mass 125.25 GeV
- -- electrically neutral
- -- spin 0 (fundamental scalar particle)
- -- interaction with itself



Exponential growth of the “decay rate” of energetic particle with final state multiplicity

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

Contribution of large number of diagrams to the amplitude (no destructive interference)

Higgsplosion

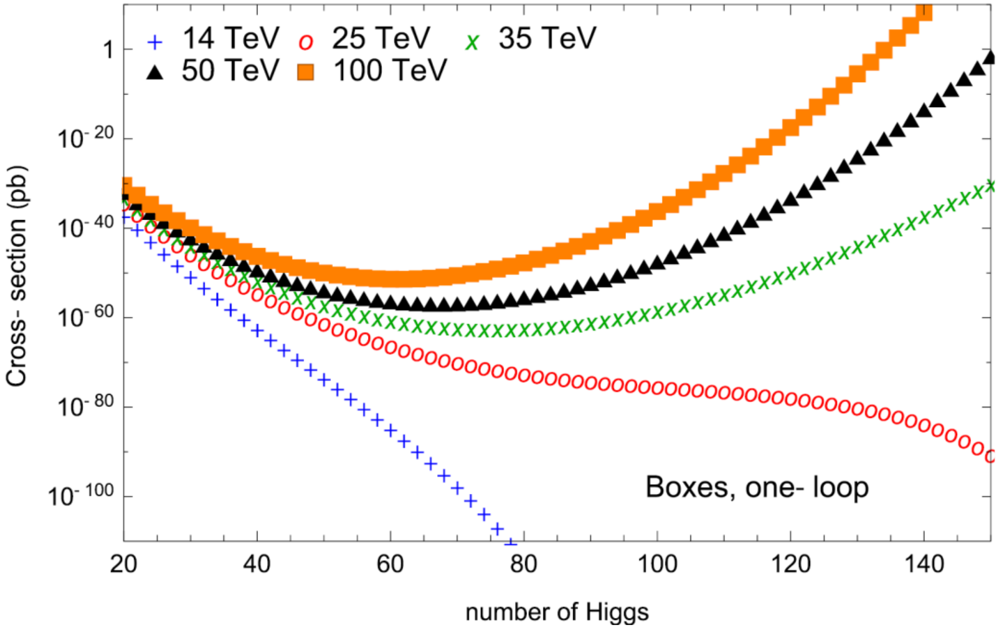
V. Khoze, M. Spannowski, NPB 926 (2018)

"Cross section" for 1 energetic Higgs to n-Higgs

$$\mathcal{R}_n(s) \equiv \frac{1}{2m_\phi^2}\frac{1}{n!}\int \frac{d^3p_1}{(2\pi)^3}\cdots\frac{d^3p_n}{(2\pi)^3}\frac{1}{2E_1\ldots 2E_n}(2\pi)^4\delta^{(4)}\left(q_\phi - p_1\ldots - p_n\right)|\mathcal{M}(\phi^*\to n\phi)|$$

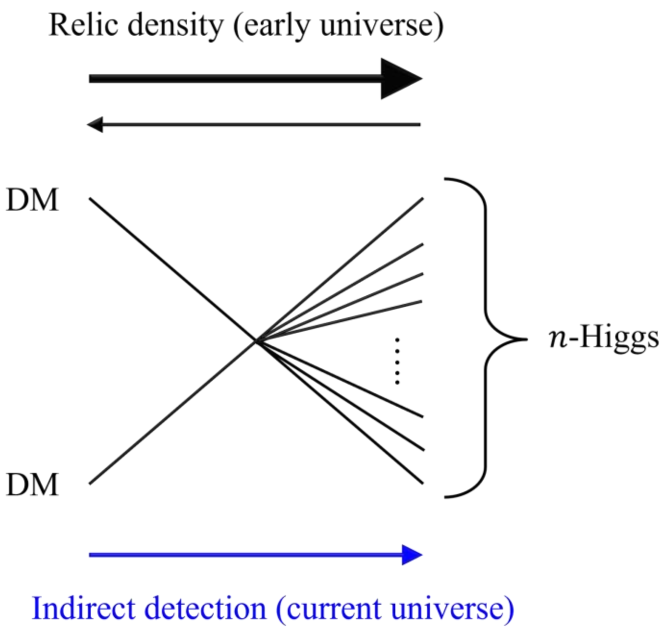
$$= \exp\left[n\left(\ln\frac{\lambda n}{4} + \frac{2}{\sqrt{3}}\frac{\Gamma(5/4)}{\Gamma(3/4)}\sqrt{\lambda n} - 1 + \frac{3}{2}\left(\ln\frac{\epsilon}{3\pi}\right) - \frac{25}{12}\epsilon\right)\right]$$

n dependence of n-Higgs production at proton-proton collider



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

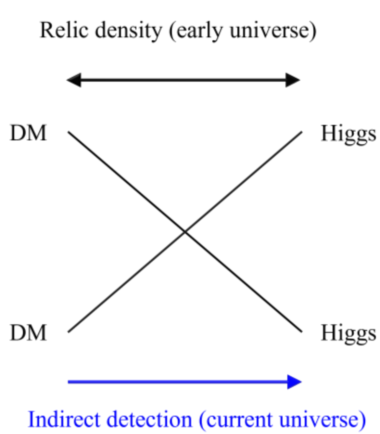
Aim



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



Previous works

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

$\langle \sigma v(\mathrm{DMDM} \to HH) \rangle$ (early universe) ⟷ $\sigma v(\mathrm{DMDM} \to HH)$ (current universe)

(almost) one-to-one correspondence

Talk plan

1. Introduction
2. Setup and formulation
3. Numerical result
4. Summary and discussion

Setup and formulation

Model

ϕ: Higgs (φ after symmetry)

Note: Applicable to other models of a general scalar

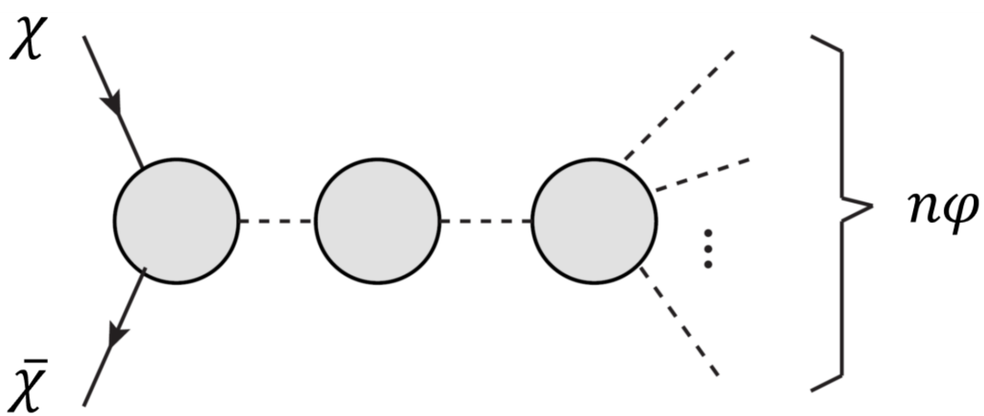
Standard Model + dark matter χ

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

Symmetry breaking

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

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



DM annihilation with Higgsplosion

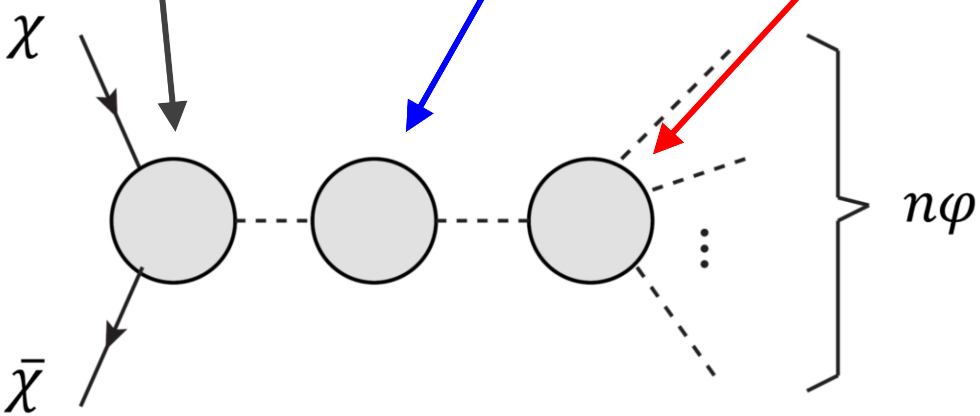
Transition amplitude

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



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DM annihilation to intermediate Higgs
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Dressed propagator
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Boltzmann equation **(evolution equation of DM density)**

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

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

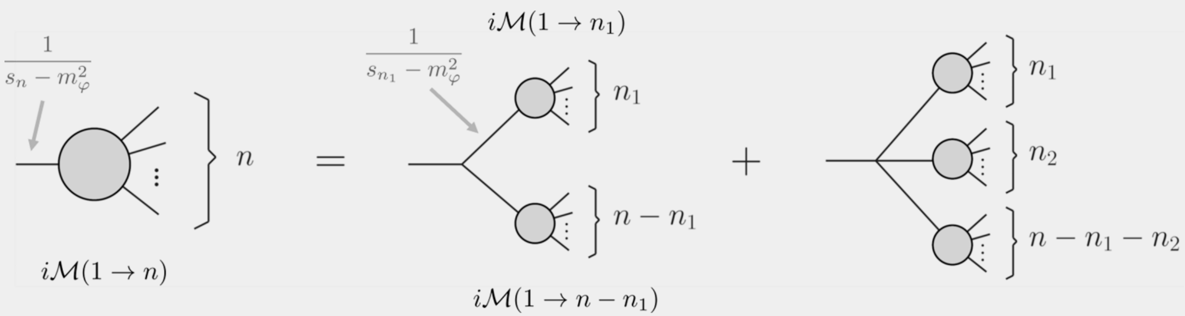
$$\times \frac{1}{n!} \int \frac{d^3p_1}{(2\pi)^3 2E_1} \cdots \frac{d^3p_n}{(2\pi)^3 2E_n} (2\pi)^4 \delta^{(4)}\left(k_\chi + k_{\bar{\chi}} - p_1 - \cdots - p_n\right)$$

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

DM annihilation with Higgsplosion

Dimensionless reaction rate V. Khoze, M. Spannowski, NPB 926 (2018)

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



Recurrence equation of dimensionless amplitude Shown in backup slides

$$c_n = \frac{m_\varphi^2}{s_n - m_\varphi^2}\left(3\sum_{n_1}^{n-1} c_{n_1}c_{n-n_1} + 2\sum_{n_1}^{n-2}\sum_{n_2}^{n-n_1-1} c_{n_1}c_{n_2}c_{n-n_1-n_2}\right)$$

Dimensionless amplitude $$c_n = \frac{(-1)^{1-n}}{n!}\left(\frac{\lambda}{2m_\varphi^2}\right)^{\frac{1-n}{2}}\frac{1}{s_n - m_\varphi^2}\cdot\mathcal{M}(1 \to n)$$

Ref: e.g., M. V. Libanov, V. A. Rubakov, D. T. Son, S. V. Troitsky, PRD50 (1994)

DM annihilation with Higgsplosion

Dimensionless reaction rate V. Khoze, M. Spannowski, NPB 926 (2018)

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

From phase-space volume of n-Higgs final state

Higher-order contribution V. Khoze, JHEP 06 (2017)

$$L_n = \frac{2}{\sqrt{3}}\frac{\Gamma(5/4)}{\Gamma(3/4)}\sqrt{\lambda n} \simeq 0.854\sqrt{\lambda n}$$

Important: argument of the exponential = positive-valued

⟶ $\boldsymbol{R_n(s)}$ **grows with the multiplicity** $\boldsymbol{n}$

DM annihilation with Higgsplosion

Boltzmann equation (evolution equation of DM density)

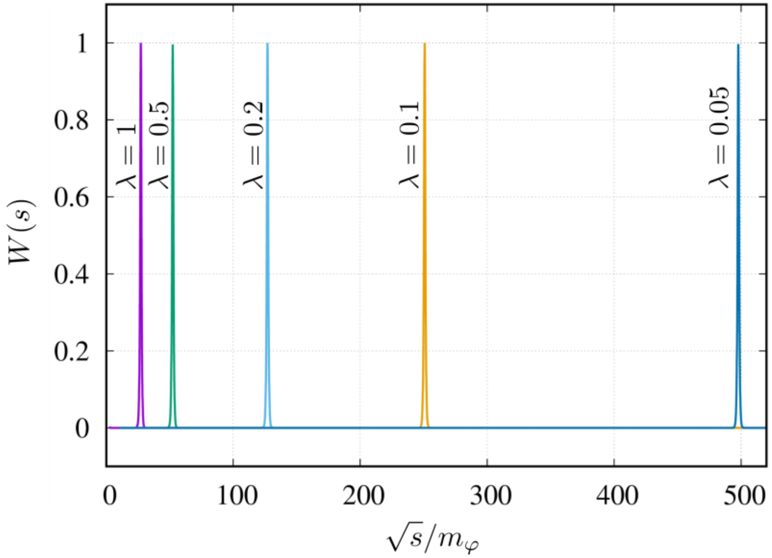
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\int \frac{d^3k_\chi}{(2\pi)^3 2E_\chi}\frac{d^3k_{\bar\chi}}{(2\pi)^3 2E_{\bar\chi}}\left[f_\chi f_{\bar\chi} - f_{\varphi_1}\cdots f_{\varphi_n}\right]$$
$$\times \left|\tilde{y}_\chi\right|^2 (s - 4|M_\chi|^2 \cos\theta_{\tilde{y}_\chi}) \frac{1}{s^2 + m_\varphi^4 \mathcal{R}(s)^2} m_\varphi^2 \mathcal{R}_n(s)$$

With Maxwell-Boltzmann distribution and energy conservation

$$f_\chi f_{\bar\chi} - f_{\varphi_1}\cdots f_{\varphi_n} = \frac{1}{(n_\chi^{eq})^2}\left[(n_\chi)^2 - (n_\chi^{eq})^2\right]$$

$$= -\left[(n_\chi)^2 - (n_\chi^{eq})^2\right] \frac{1}{(n_\chi^{eq})^2} \frac{2\left|\tilde{y}_\chi\right|^2 T^4}{(4\pi)^4}$$
$$\times \int \frac{ds}{s}\frac{1}{T^3}\sqrt{s - 4M_\chi^2}\,(s - 4|M_\chi|^2\cos\theta_{\tilde{y}_\chi})\,K_1(\sqrt{s}/T)\,\frac{2m_\varphi^2 s\mathcal{R}(s)}{s^2 + m_\varphi^4\mathcal{R}(s)^2}$$
$$= -\langle\sigma v\rangle\left[(n_\chi)^2 - (n_\chi^{eq})^2\right]$$

Window function $W(s)$

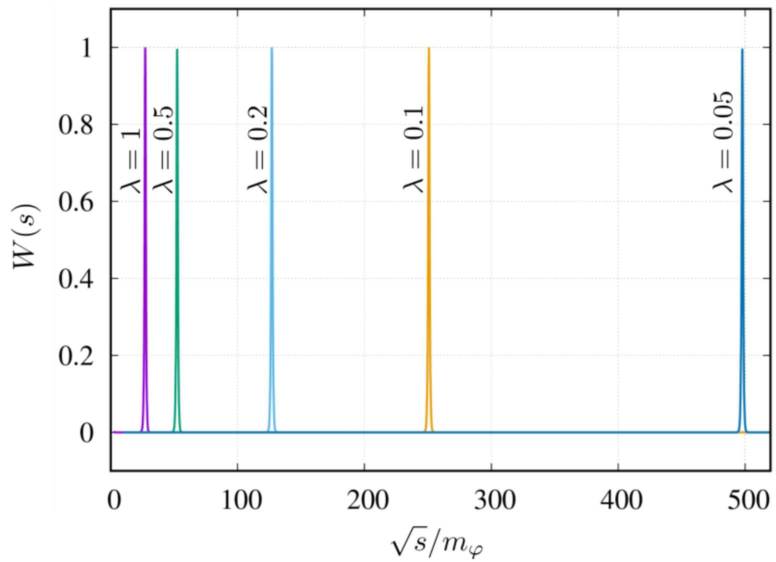


DM annihilation with Higgsplosion

Boltzmann equation **(evolution equation of DM density)**

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\int \frac{d^3k_\chi}{(2\pi)^3 2E_\chi} \frac{d^3k_{\bar\chi}}{(2\pi)^3 2E_{\bar\chi}} \left[f_\chi f_{\bar\chi} - f_{\varphi_1} \cdots f_{\varphi_n} \right]$$

- Final state multiplicity depends only on the self-coupling λ
- If $2M_\chi > \sqrt{s_{peak}}$, the final state does not explode (averaging integral covers the region outside $W(s)$ only)
- For the case of SM ($\lambda \simeq 0.13$): $\sqrt{s_{peak}} \simeq 195 m_\varphi$ with $\Delta\sqrt{s} \simeq \pm 1 m_\varphi$



$$= -\left[(n_\chi)^2 - (n_\chi^{eq})^2 \right] \frac{1}{(n_\chi^{eq})^2} \frac{2|\tilde{y}_\chi|^2 T^4}{(4\pi)^4}$$

$$\times \int \frac{ds}{s} \frac{1}{T^3} \sqrt{s - 4M_\chi^2} \left(s - 4|M_\chi|^2 \cos\theta_{\tilde{y}_\chi}\right) K_1(\sqrt{s}/T) \frac{2m_\varphi^2 s \mathcal{R}(s)}{s^2 + m_\varphi^4 \mathcal{R}(s)^2}$$

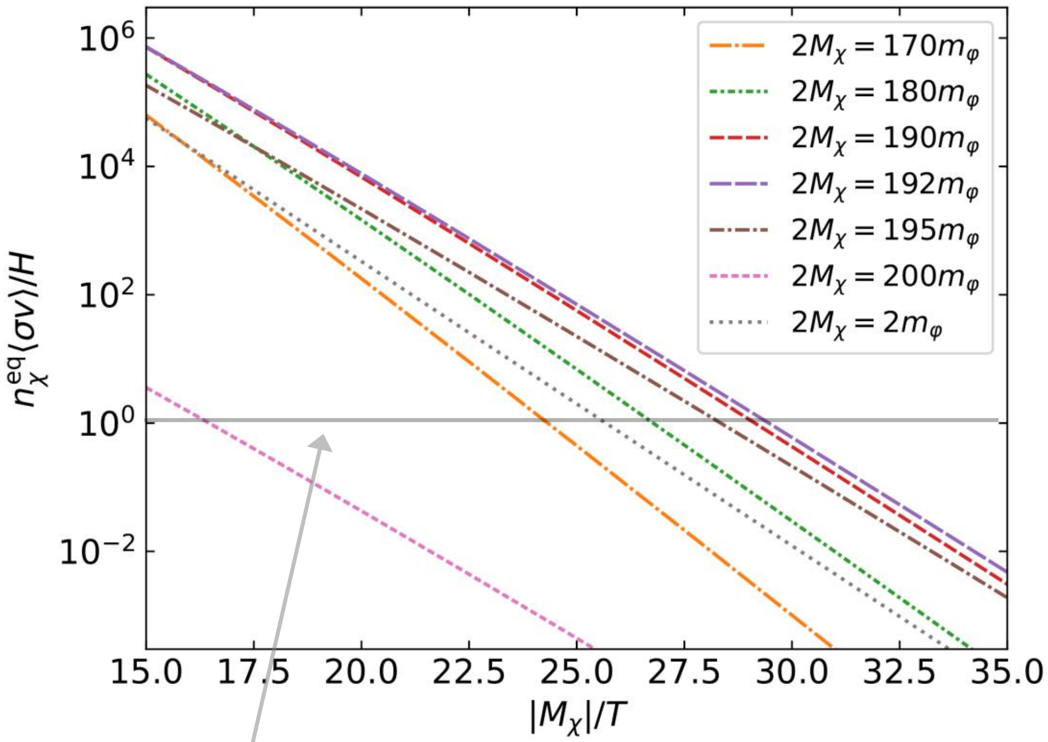
Window function $W(s)$

$$= -\langle \sigma v \rangle \left[(n_\chi)^2 - (n_\chi^{eq})^2 \right]$$

Numerical result

Interaction rate/Hubble rate vs M_χ/T

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



Freeze-out of $\chi\bar{\chi} \leftrightarrow n\varphi$
(rough criterion)

- Maximized by $2|M_\chi| \simeq 192m_\varphi$

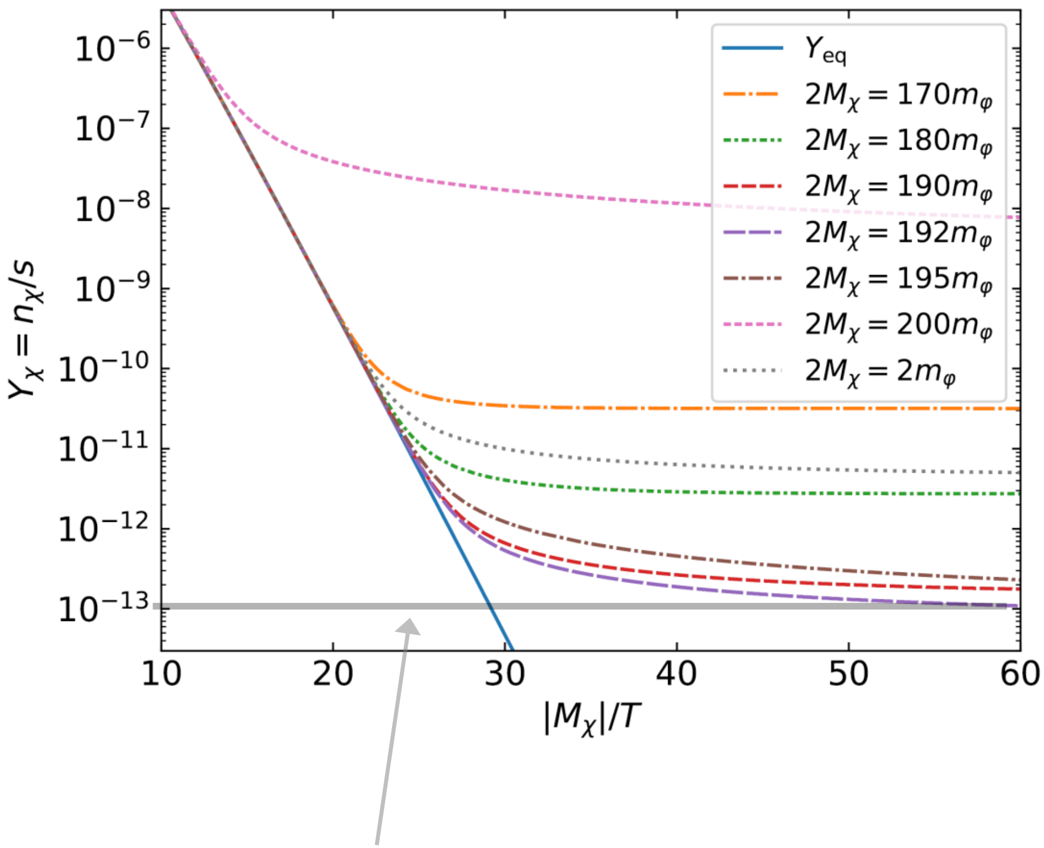
  smaller compared with the expectation from window function, $2|M_\chi| \simeq 195m_\varphi$, due to thermal kinetics of DM

- Small interaction rate for $2|M_\chi| < 190m_\varphi$

  mismatch between the window function and other part in thermal averaging due to $K_1(\sqrt{s}/T) \ll 1$ wherein the window opens

Relic density

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



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

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, $m_{\rm DM} \simeq 62$ 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

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