



Revisit the relic density of Higgs-portal dark matter

Masato Yamanaka (Hosei Univ., Japan)

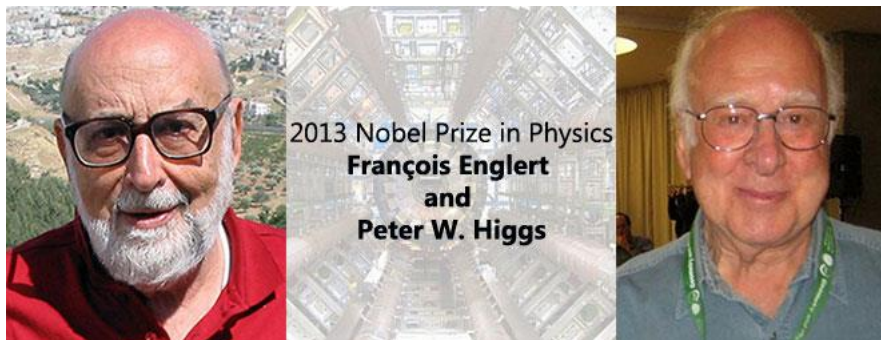
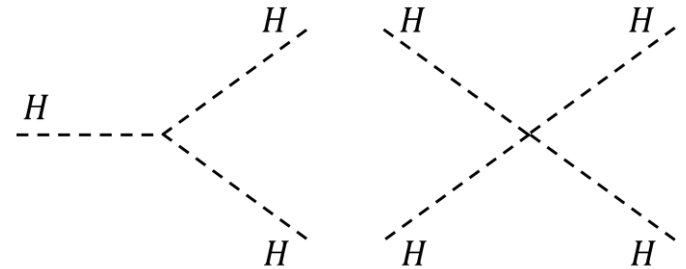
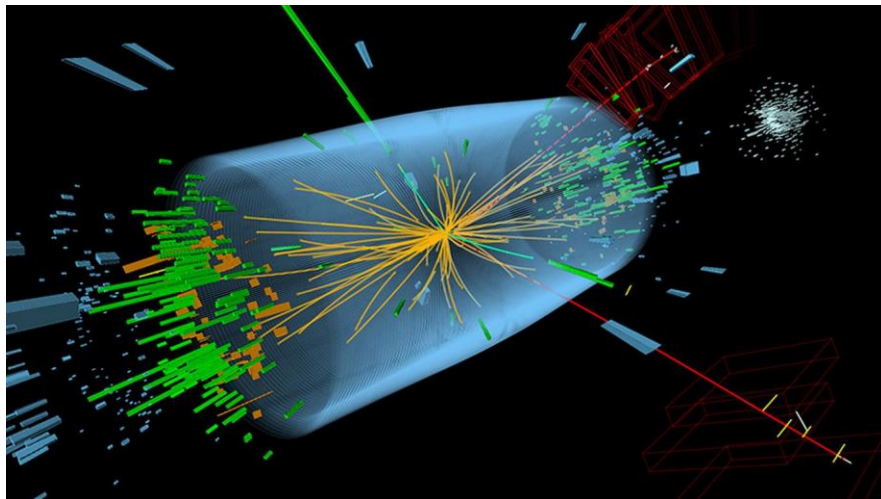
S. Enomoto, N. Hiroshima, K. Murase, MY, arXiv:2311.XXXXX

Discovery of the Higgs boson



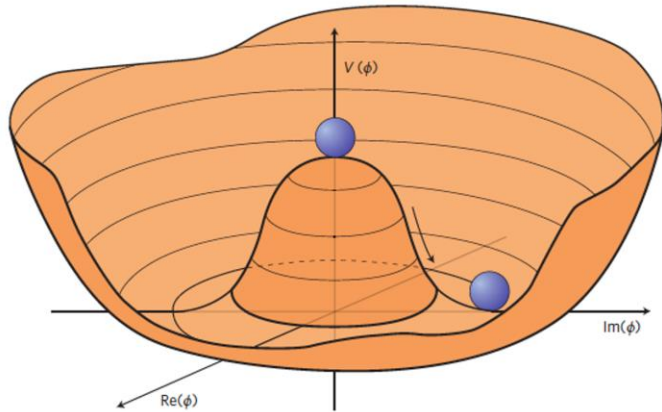
Higgs properties

- 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?**

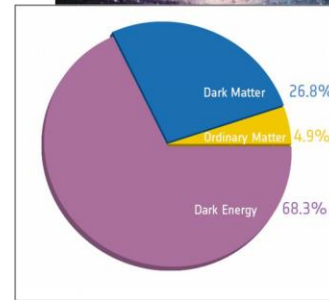
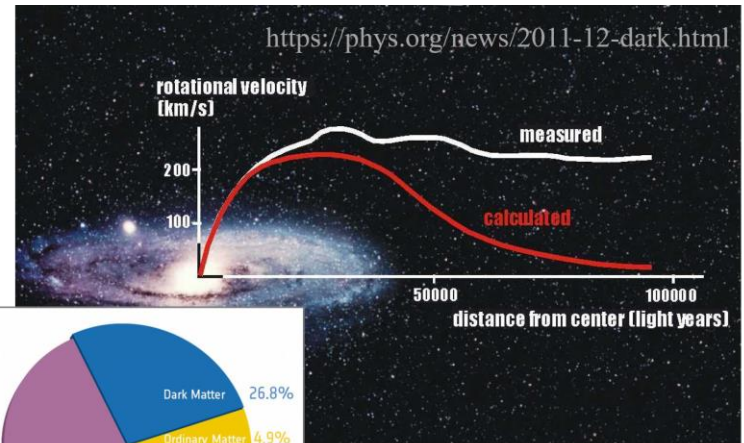
Mysteries to be unraveled



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

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

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



Planck Collaboration

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

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

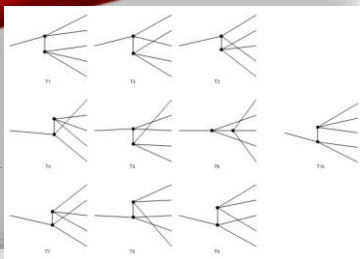
Important and necessary to carefully investigate the connection between the Higgs and DM

High-multiplicity scalar production

J. M. Cornwall, PLB243 (1990)

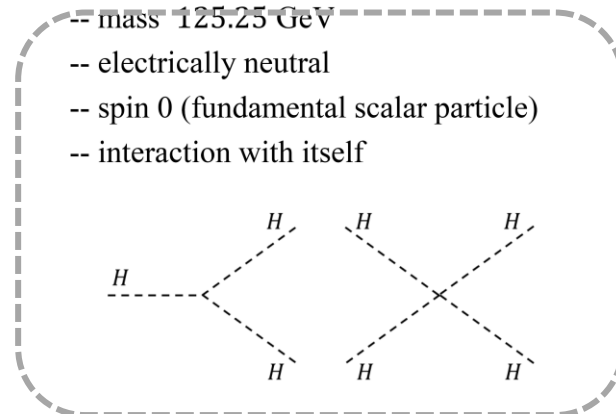
H. Goldberg, PLB 246 (1990)

5 Higgs production



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)

7 Higgs production



Higgspllosion

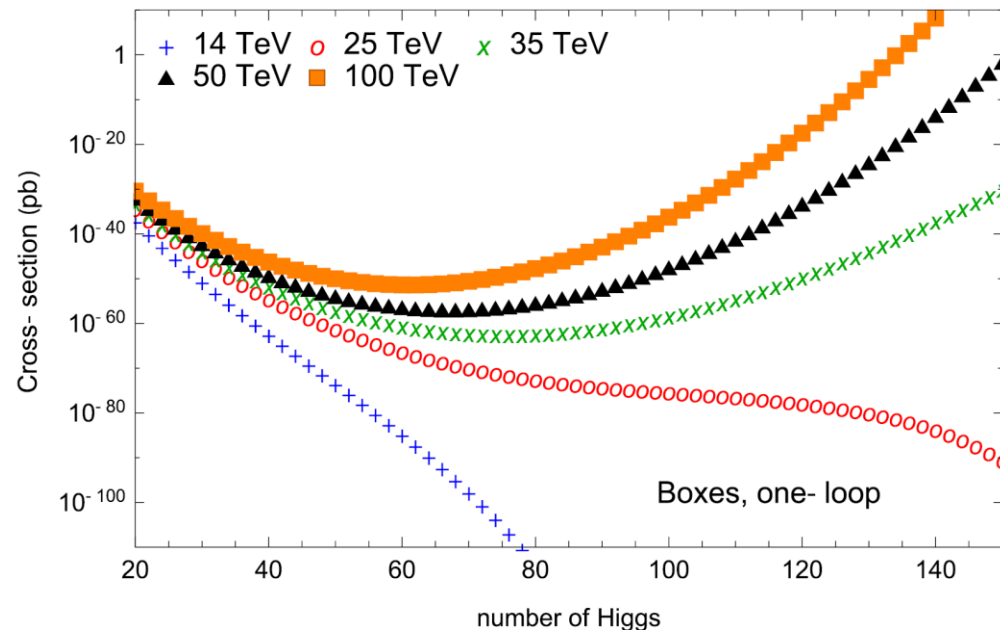
V. Khoze, M. Spannowski, NPB 926 (2018)

“Cross section” for 1 energetic Higgs to n -Higgs

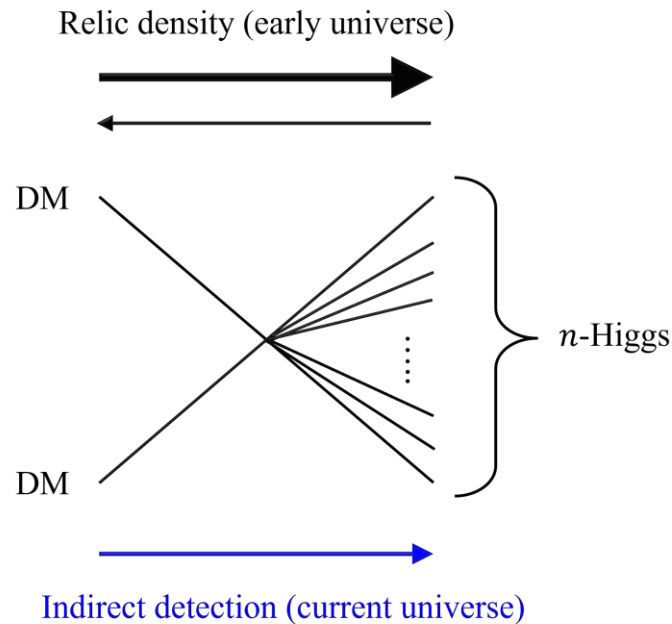
$$\mathcal{R}_n(s) \equiv \frac{1}{2m_\phi^2} \frac{1}{n!} \int \frac{d^3p_1}{(2\pi)^3} \cdots \frac{d^3p_n}{(2\pi)^3} \frac{1}{2E_1 \cdots 2E_n} (2\pi)^4 \delta^{(4)}(q_\phi - p_1 \cdots - p_n) |\mathcal{M}(\phi^* \rightarrow n\phi)|$$

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

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

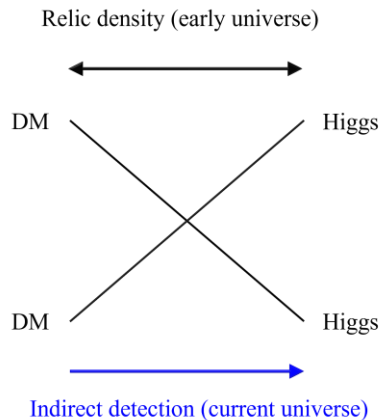


V. Khoze, M. Spannowski, NPB 926 (2018)



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

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

$\langle \sigma v(DMDM \rightarrow HH) \rangle$ (early universe)
 \longleftrightarrow
 $\sigma v(DMDM \rightarrow HH)$ (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

ϕ : Higgs (φ after ~~symmetry~~)

Note: Applicable to other models of a general scalar

Standard Model + dark matter χ

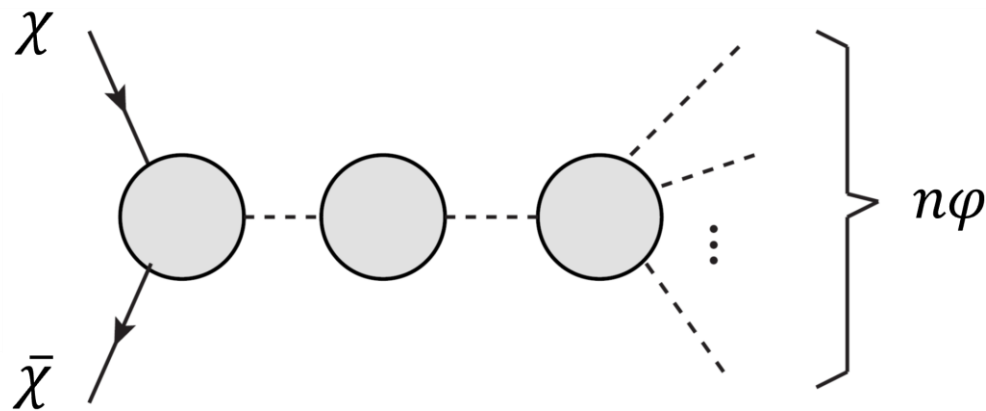
$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{4}\lambda(\phi^2 - v^2)^2 + \bar{\chi}(i\partial - m_\chi)\chi - (y_\chi\phi\bar{\chi}_R\chi_L + \text{h.c.})$$

\longrightarrow
 Symmetry breaking

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

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

$$M_\chi = m_\chi + y_\chi v$$



DM annihilation with Higgsplosion

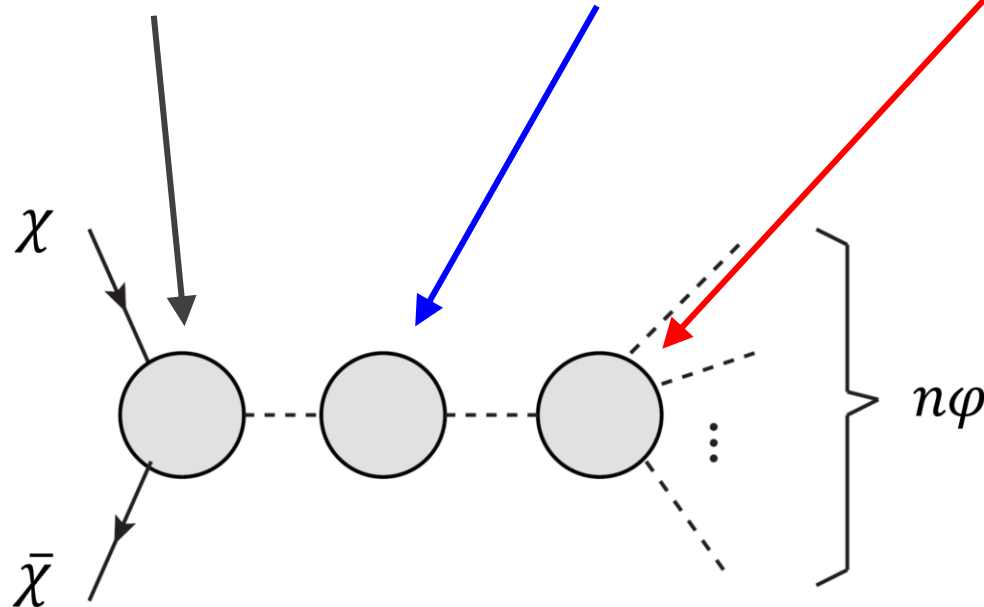
Transition amplitude

Higgs “decay” into n -body Higgs
 \supset Higgsplosion effect

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

DM annihilation to intermediate Higgs
 (straightforwardly calculated)

Dressed propagator
 \supset Higgsplosion effect



DM annihilation with Higgsplosion

Transition amplitude

Higgs “decay” into n -body Higgs
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$$\sum_{\text{spins}} |\mathcal{M}(\chi\bar{\chi} \rightarrow n\varphi)|^2 = \sum_{\text{spins}} \left| \mathcal{M}(\chi\bar{\chi} \rightarrow \varphi^*) \frac{1}{s - m_\varphi(s)^2 - im_\varphi(s)\Gamma_\varphi(s)} \mathcal{M}(\varphi^* \rightarrow n\varphi) \right|^2$$

DM annihilation to intermediate Higgs
 (straightforwardly calculated)

Dressed propagator
 \supset Higgsplosion effect

Boltzmann equation (evolution equation of DM density)

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

Dimensionless reaction rate

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

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

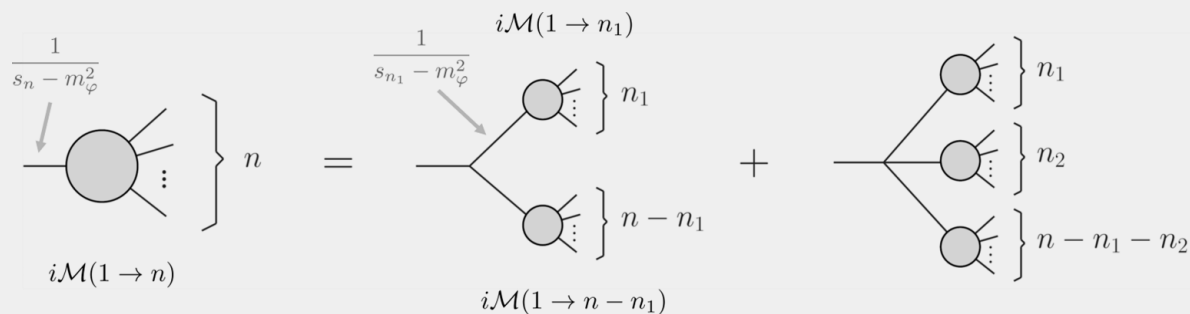
$$\times \sum_{\text{spins}} \left| \mathcal{M}(\chi\bar{\chi} \rightarrow \varphi^*) \frac{1}{s - m_\varphi(s)^2 - im_\varphi(s)\Gamma_\varphi(s)} \mathcal{M}(\varphi^* \rightarrow n\varphi) \right|^2 [f_\chi f_{\bar{\chi}} - f_{\varphi_1} \cdots f_{\varphi_n}]$$

DM annihilation with Higgspllosion

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

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

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

DM annihilation with Higgspllosion

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

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

DM annihilation with Higgspllosion

Boltzmann equation (evolution equation of DM density)

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

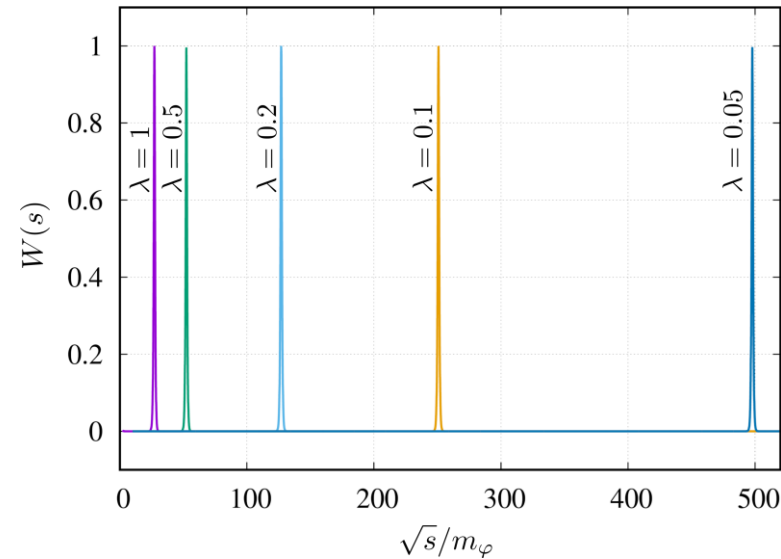
With Maxwell-Boltzmann distribution and energy conservation

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

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

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

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



Window function $W(s)$

DM annihilation with Higgspllosion

Boltzmann equation (evolution equation of DM density)

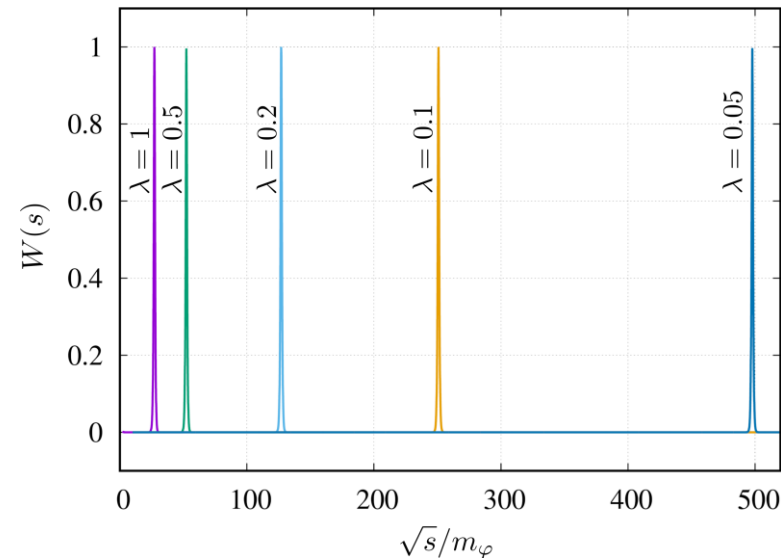
$$\frac{dn_\chi}{dt} + 3Hn_\chi = - \int \frac{d^3k_\chi}{(2\pi)^3 2E_\chi} \frac{d^3k_{\bar{\chi}}}{(2\pi)^3 2E_{\bar{\chi}}} [f_\chi f_{\bar{\chi}} - f_{\varphi_1} \cdots f_{\varphi_n}]$$

- ❑ 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 ($\lambda \simeq 0.13$):
 $\sqrt{s_{peak}} \simeq 195m_\varphi$ with $\Delta\sqrt{s} \simeq \pm 1m_\varphi$

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

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

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



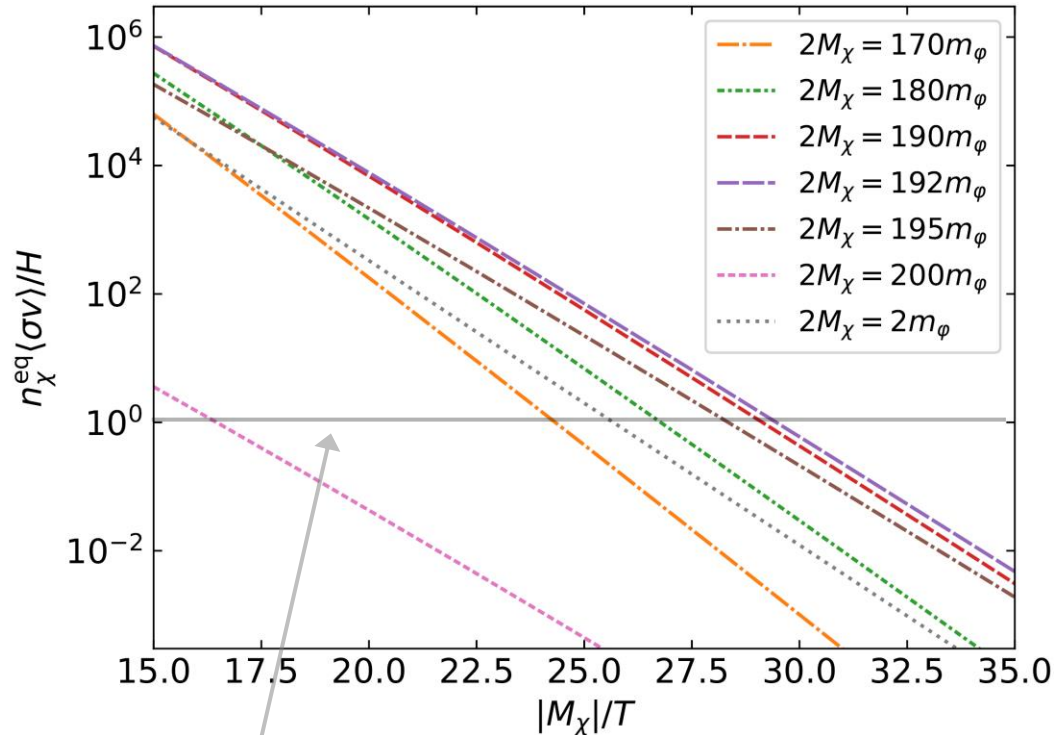
Window function $W(s)$



Numerical result

Interaction rate/Hubble rate vs M_χ/T

$$M_\chi = nm_\phi/2, \quad \lambda = 0.129, \quad m_\phi = 50 \text{ GeV}$$



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

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

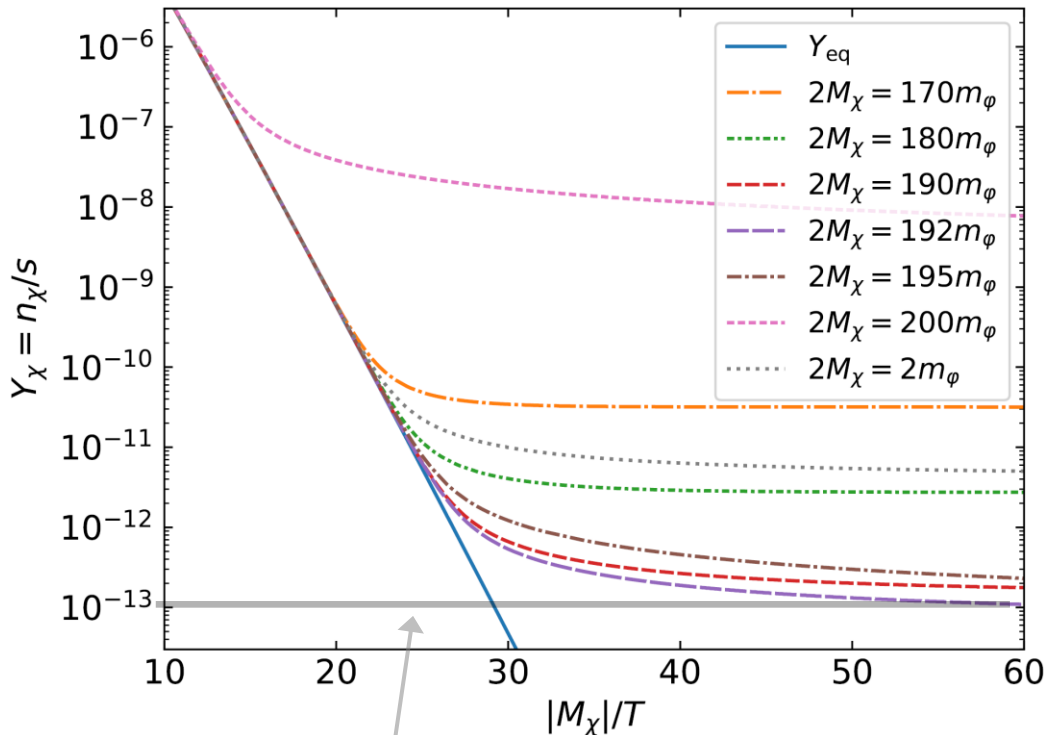
smaller compared with the expectation from window function, $2|M_\chi| \simeq 195m_\phi$, due to thermal kinetics of DM

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

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

$$M_\chi = nm_\phi/2, \quad \lambda = 0.129, \quad m_\phi = 50 \text{ GeV}$$



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

Planck collaboration

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

Much heavier than the Higgs portal DM in previous works, $m_{\text{DM}} \simeq 62 \text{ GeV}$, 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 Higgspllosion

- energetic Higgs boson decays into n -Higgs boson
- long-stay in equilibrium through strong interaction with Higgspllosion
- a favored parameter: $M_\chi = 4.8 \text{ TeV}$ 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

