ヒッグス爆発終状態を含めた暗黒物質残存量計算

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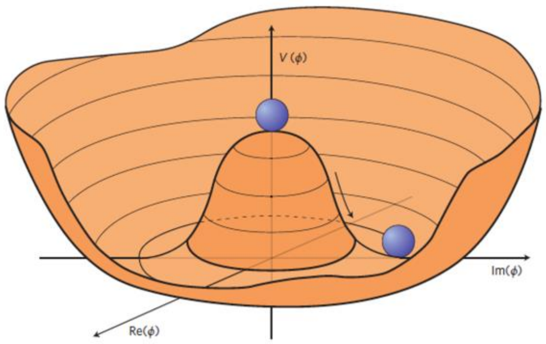
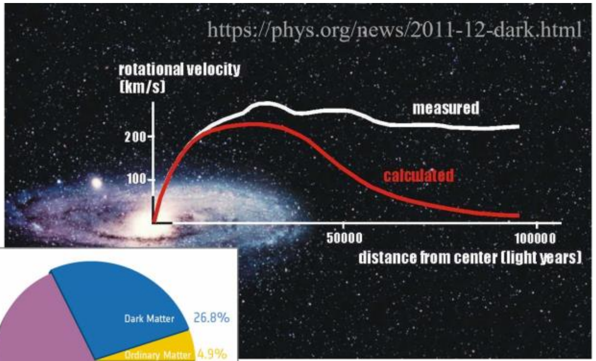
概要

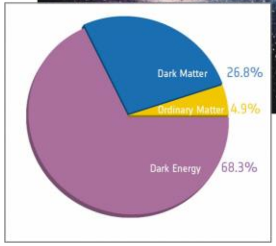
- 高エネルギーヒッグスは多体ヒッグスへ崩壊（$\mathcal{O}(100)$体終状態）
- ヒッグスポータル暗黒物質の対消滅過程は多体ヒッグス終状態が優勢
- ヒッグス共鳴を拾わずに$\mathcal{O}(\mathrm{TeV})$ヒッグスポータル暗黒物質が残存量OK

Higgs discovery complete the particle physics?



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





Planck Collaboration

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

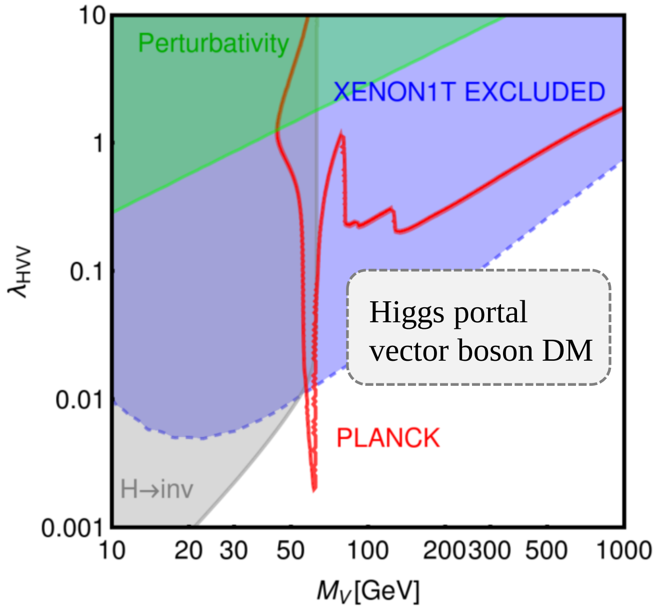
What is dark matter (DM)?
How was it generated?

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

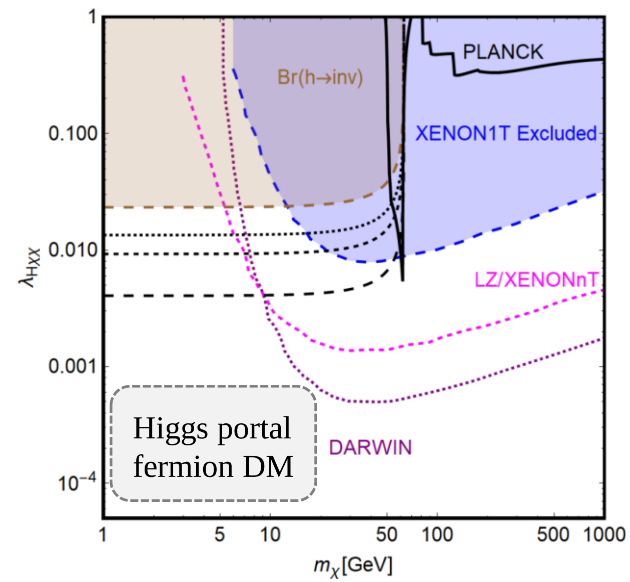
So many literatures suggest that the Higgs is a bridge between the DM and our world

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

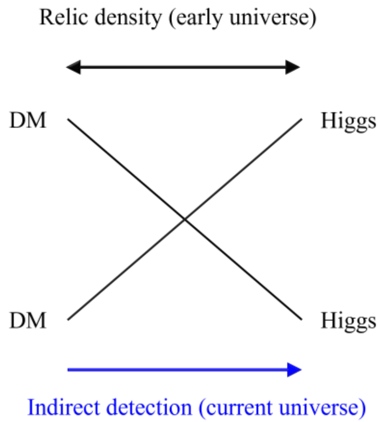
Higgs portal dark matter (literatures)



G. Arcadi, A. Djouadi, M. Kado, PLB (2020)



G. Arcadi, A. Djouadi, M. Raidal, Phys. Rept. (2020)



<u>Previous works</u>

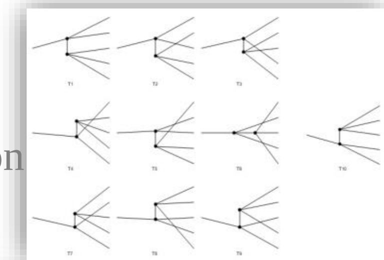
DM + DM $\leftrightarrow$ $H + H$ (in general, two SM particles) only for the calculation of relic density

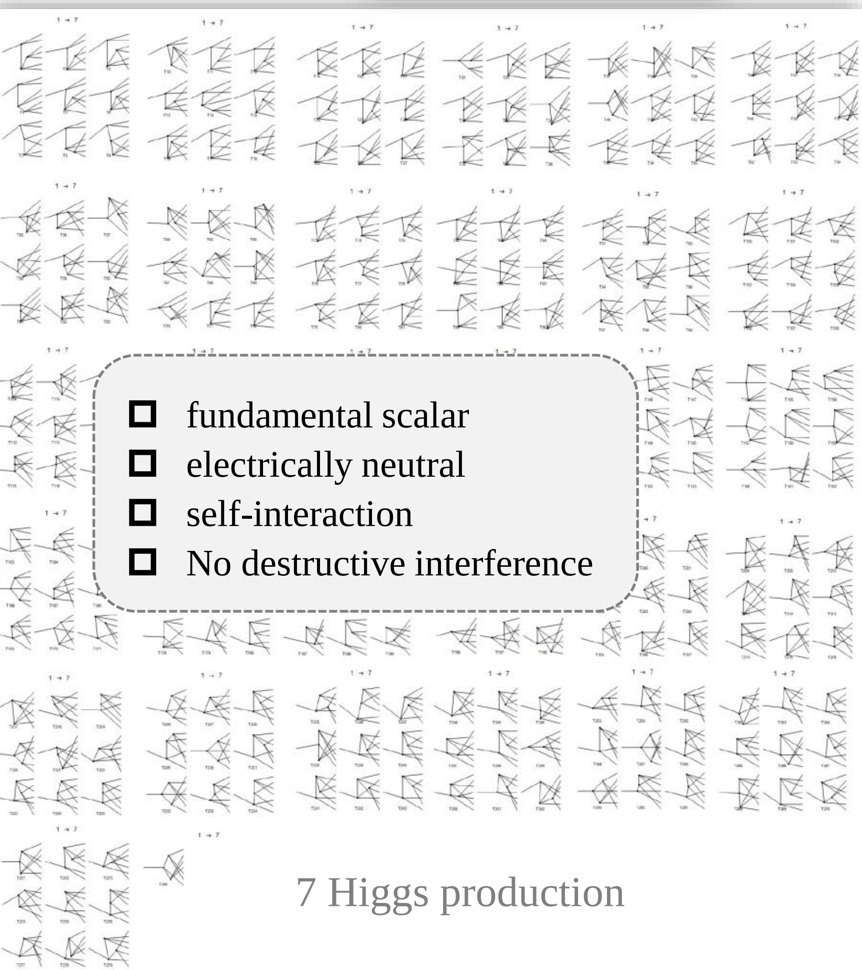
$\langle \sigma v(\text{DMDM} \to HH) \rangle$ (early universe) ⟷ (almost) one-to-one correspondence ⟷ $\sigma v(\text{DMDM} \to HH)$ (current universe)

High-multiplicity scalar production

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

5 Higgs production



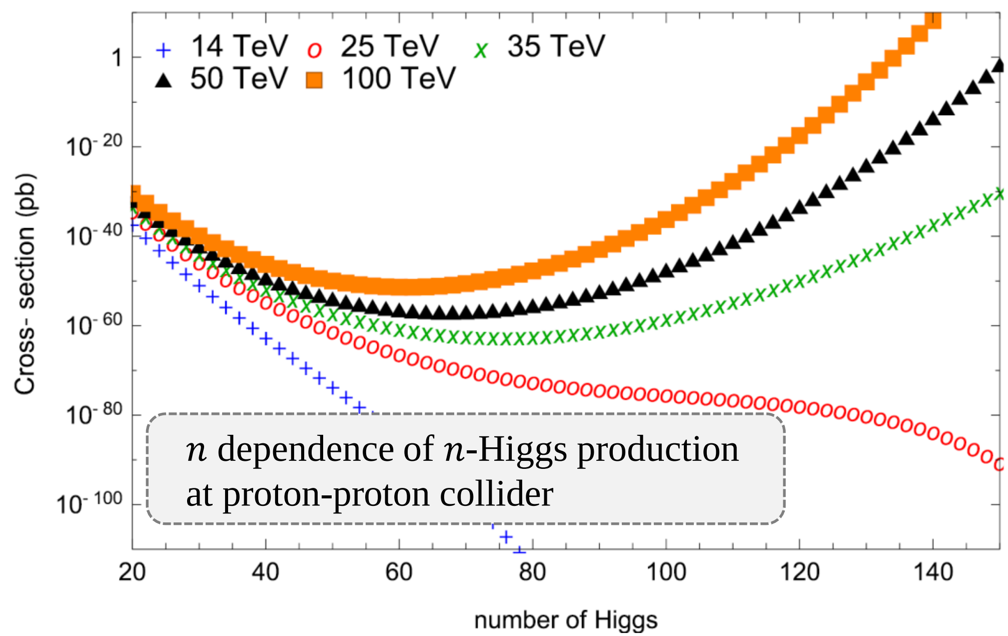


- ☐ fundamental scalar
- ☐ electrically neutral
- ☐ self-interaction
- ☐ No destructive interference

7 Higgs production

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

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

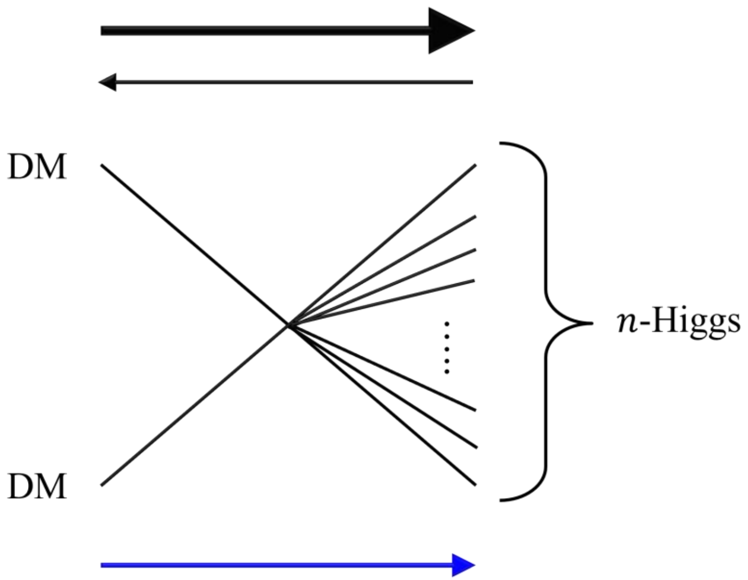


n dependence of n-Higgs production at proton-proton collider

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

Aim and Talk plan

Relic density (early universe)



Indirect detection (current universe)

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

Talk plan

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

Setup

ϕ: Higgs (φ after ~~symmetry~~)

Note: Applicable to other models of a general scalar

Standard Model + dark matter χ

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

Symmetry breaking $\longrightarrow$

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

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

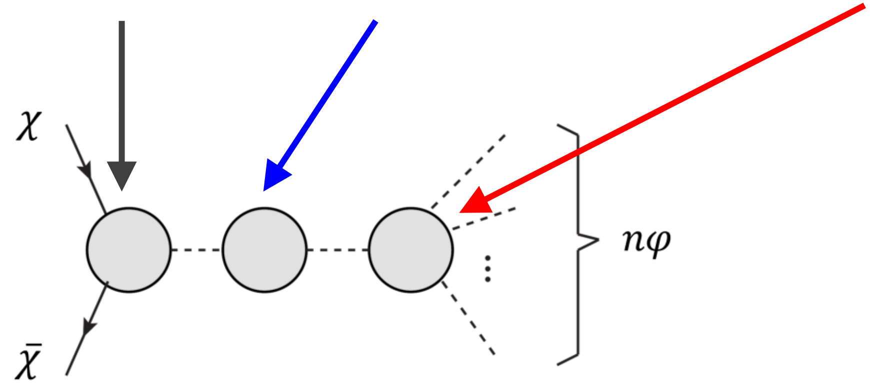
Transition amplitude

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

DM annihilation to intermediate Higgs (straightforwardly calculated)

Dressed propagator
$\supset$ Higgspersion effect

Higgs "decay" into n-body Higgs
$\supset$ Higgsprosion effect



Boltzmann equation (evolution equation of DM density)

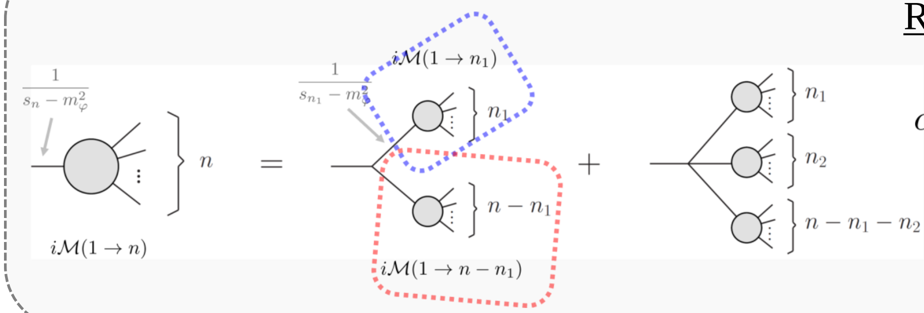
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\sum_n \int \frac{d^3k_\chi}{(2\pi)^3 2E_\chi} \frac{d^3k_{\bar\chi}}{(2\pi)^3 2E_{\bar\chi}}$$
$$\times \frac{1}{n!} \int \frac{d^3p_1}{(2\pi)^3 2E_1} \cdots \frac{d^3p_n}{(2\pi)^3 2E_n} (2\pi)^4 \delta^{(4)}\left(k_\chi + k_{\bar\chi} - p_1 - \cdots - p_n\right)$$
$$\times \sum_{\text{spins}} \left| \mathcal{M}(\chi\bar\chi \to \varphi^*) \frac{1}{s - m_\varphi(s)^2 - i m_\varphi(s)\Gamma_\varphi(s)} \mathcal{M}(\varphi^* \to n\varphi) \right|^2 \left[f_\chi f_{\bar\chi} - f_{\varphi_1} \cdots f_{\varphi_n} \right]$$

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)



Recurrence equation of dimensionless amplitude

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

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

From phase-space volume of n-Higgs final state

Higher-order contribution V. Khoze, JHEP (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 Higgsplosion

Boltzmann equation

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

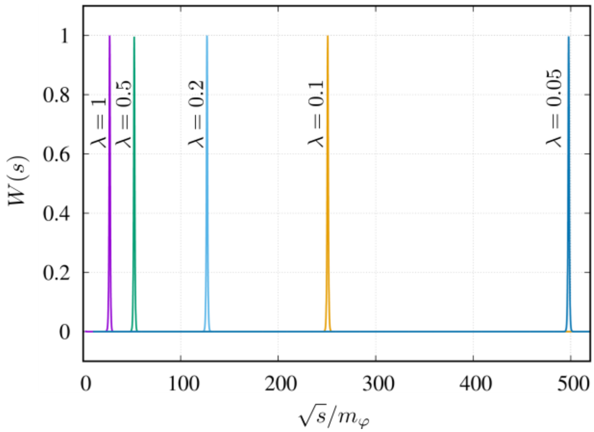
With Maxwell-Boltzmann distribution and energy conservation

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

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

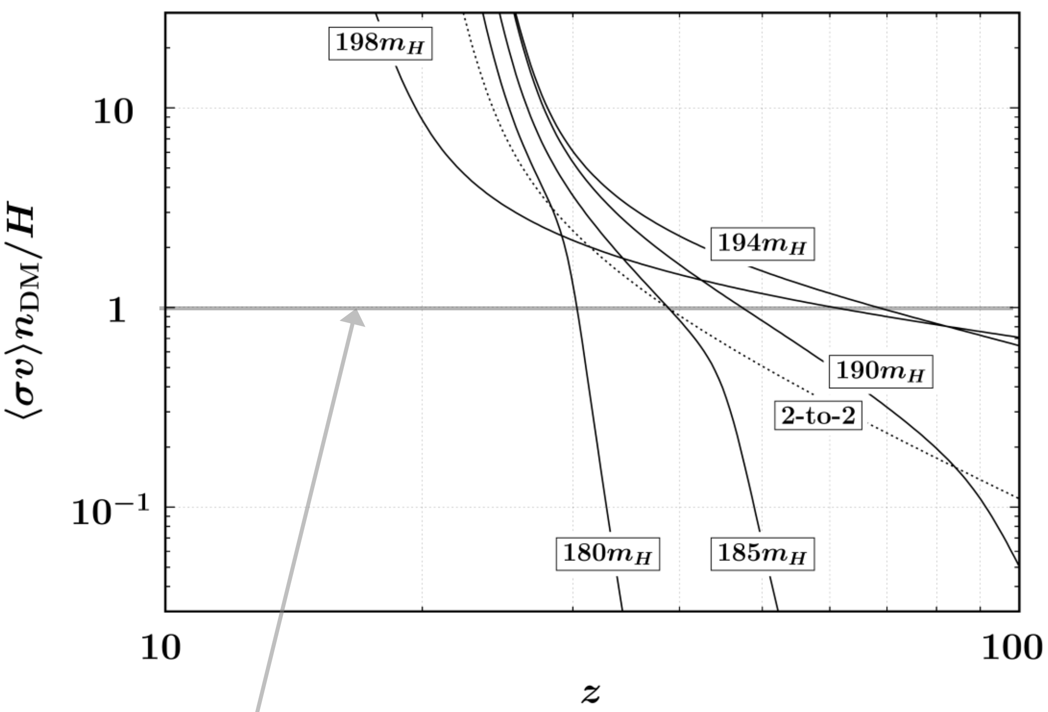
Window function $W(s)$

- 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 $\Delta\sqrt{s} \simeq \pm 1 m_\varphi$



Interaction rate/Hubble rate vs M_χ/T

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



Freeze-out of $\chi\bar{\chi} \leftrightarrow n\varphi$

(rough criterion)

- Maximized by $2|M_\chi| \simeq 194 m_\varphi$

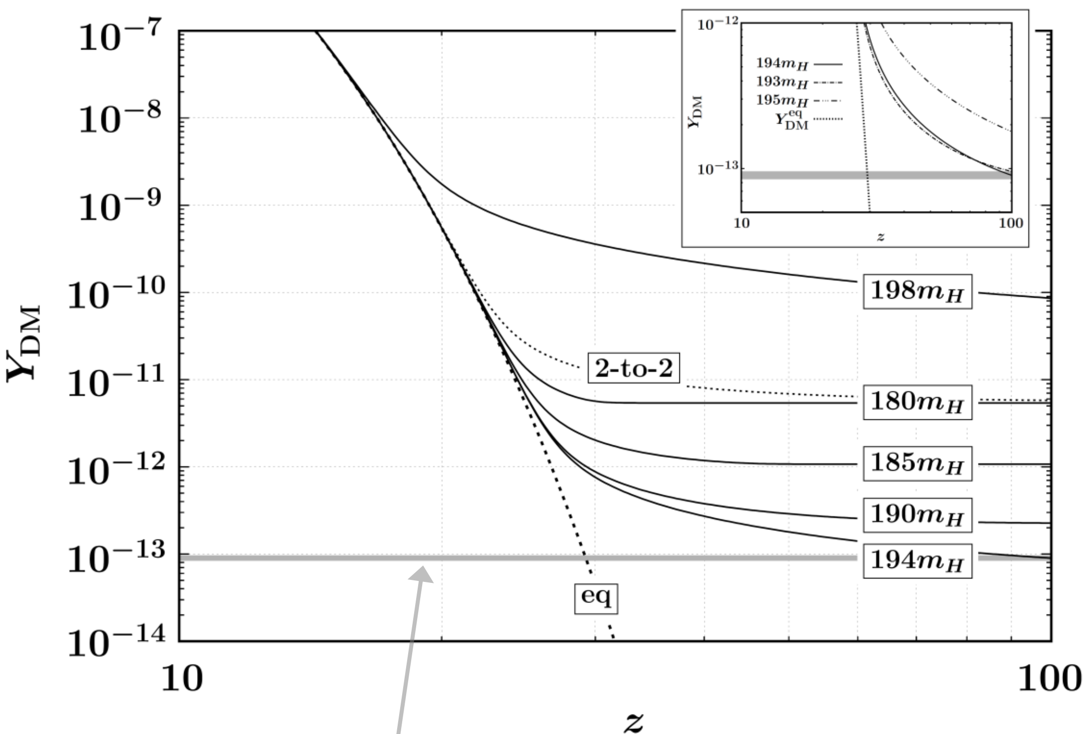
  smaller compared with the expectation from window function, $2|M_\chi| \simeq 195 m_\varphi$, due to thermal kinetics of DM

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

  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

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



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

Planck collaboration

- Parameter set ($M_\chi = 4.9$ TeV, $\tilde{y}_\chi = 1.3i$) 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, which may be enhanced by stimulated emission

Summary and discussion

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

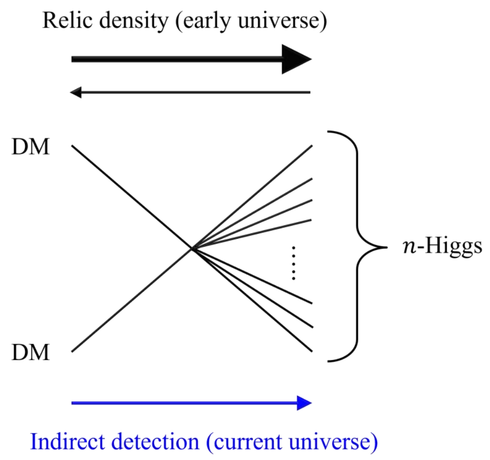
  -- energetic Higgs boson decays into n-Higgs boson

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

  -- a favored parameter: $M_\chi = 4.9$ TeV and $|\tilde{y}_\chi| = 1.3$

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

  -- simple and applicable to various models



- **Discussion**

  -- quantum statistics effects for high-multiplicity

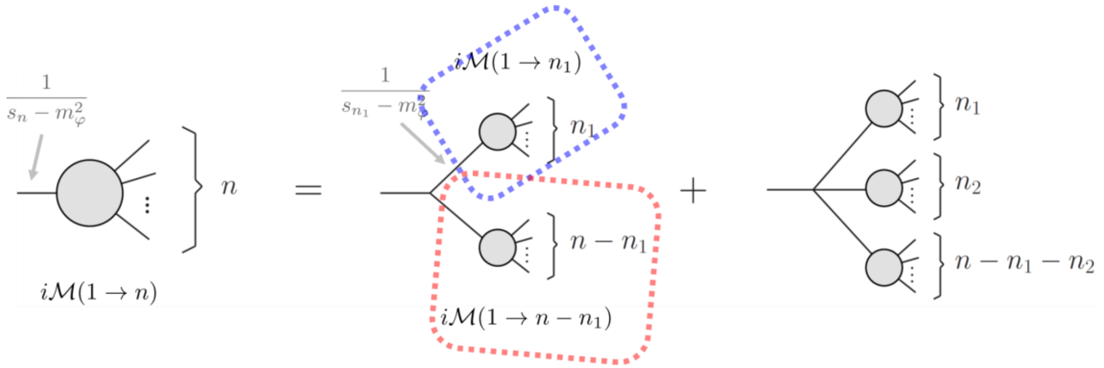
  Bose-Einstein distribution and stimulated emission could change the shape of window function $W(s)$

  -- test in indirect search of DM

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

Recurrence equation of dimensionless amp.

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



$$i\mathcal{M}(1\to n) = \sum_{n_1=1}^{n-1}\left(-i\sqrt{\frac{9}{2}}\lambda m_\varphi^2\right)\frac{n!}{n_1!(n-n_1)!}\cdot\frac{i}{s_{n_1}-m_\varphi^2}\cdot i\mathcal{M}(1\to n_1)\cdot\frac{i}{s_{n-n_1}-m_\varphi^2}\cdot i\mathcal{M}(1\to n-n_1)$$

$$+\sum_{n_1=1}^{n-2}\sum_{n_2=1}^{n-n_1-1}(-i\lambda)\frac{n!}{n_1!n_2!(n-n_1-n_2)!}\cdot\frac{i}{s_{n_1}-m_\varphi^2}\cdot i\mathcal{M}(1\to n_1)$$

$$\times\frac{i}{s_{n_2}-m_\varphi^2}\cdot i\mathcal{M}(1\to n_2)\cdot\frac{i}{s_{n-n_1-n_2}-m_\varphi^2}\cdot i\mathcal{M}(1\to n-n_1-n_2)$$

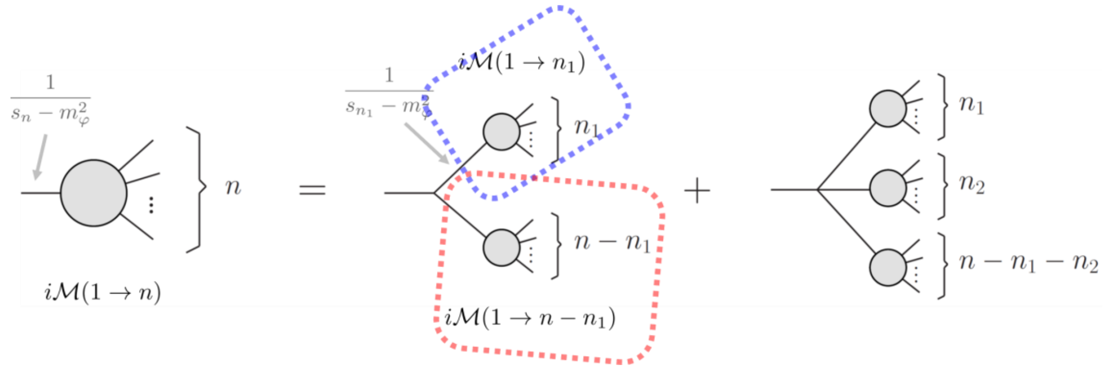
Dimensionless amplitude

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

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

Backup slides 1

Finite momentum amplitude



<u>Zero-momentum limit</u>

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

$$s_n - m_\varphi^2 = (n^2-1)m_\varphi^2 \qquad\qquad \widetilde{c}_n \equiv c_n\left(\boldsymbol{p}_n = \boldsymbol{0}\right)$$

$$\widetilde{c}_n = \frac{1}{n^2-1}\left(3\sum_{n_1}^{n-1} \widetilde{c}_{n_1}\widetilde{c}_{n-n_1} + 2\sum_{n_1}^{n-2}\sum_{n_2}^{n-n_1-1} \widetilde{c}_{n_1}\widetilde{c}_{n_2}\widetilde{c}_{n-n_1-n_2}\right)$$

$$\therefore \quad \widetilde{c}_1 = 1,\ \ \widetilde{c}_2 = 1,\ \ \widetilde{c}_3 = 1,\ \ ....,\ \ \widetilde{c}_n = 1 \ \ (\forall n \geq 1)$$

Backup slides 2

Finite momentum amplitude

With finite momentum

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

$$\begin{aligned} s_n - m_\varphi^2 &= (E_1 + \ldots + E_n)^2 - (\boldsymbol{p}_1 + \ldots + \boldsymbol{p}_n)^2 - m_\varphi^2 \\ &\simeq \left(n m_\varphi + \frac{1}{2m_\varphi}\sum_i \boldsymbol{p}_i\right)^2 - \sum_{i,j} \boldsymbol{p}_i \cdot \boldsymbol{p}_j - m_\varphi^2 \\ &\simeq (n^2-1)\, m_\varphi^2 \left(1 + \frac{1}{n+1} K_n\right) \end{aligned}$$

$$K_n \equiv \sum_i^n \frac{\boldsymbol{p}_i^2}{m_\varphi^2}$$

Amplitude in terms of expansion parameter δ_n

$$c_n \simeq \widetilde{c}_n\,(1 + \delta_n K_n)$$
$$= 1 + \delta_n K_n$$

$$(n^2-1)\left(\frac{n}{n+1} + n\delta_n\right) = 6\sum_{n_1=1}^{n-1}(n-n_1)\, n_1 \delta_{n_1}$$

$$\delta_n \simeq -\frac{7}{12} + \frac{0.858}{n} + \mathcal{O}\left(n^{-2}\right)$$ (in large n limit)

$$c_n = \frac{(-1)^{1-n}}{n!}\left(\frac{\lambda}{2m_\varphi^2}\right)^{\frac{1-n}{2}}\left(1 - \frac{7}{12}\sum_{i=1}^n \frac{\boldsymbol{p}_i^2}{m_\varphi^2} + \mathcal{O}\left(n^{-2}\right)\right) \simeq c\frac{(-1)^{1-n}}{n!}\left(\frac{\lambda}{2m_\varphi^2}\right)^{\frac{1-n}{2}} \exp\left[-\frac{7}{12}\sum_{i=1}^n \frac{\boldsymbol{p}_i^2}{m_\varphi^2}\right]$$