

ヒッグス多体生成過程がもたらす暗黒物質シナリオ

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Based on 2504.17127 [hep-ph]

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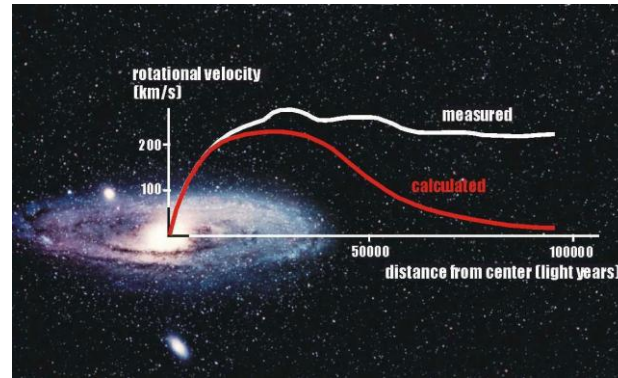
Outlook

1. Introduction
2. Higgspllosion + DM 残存量シナリオ
3. まとめ

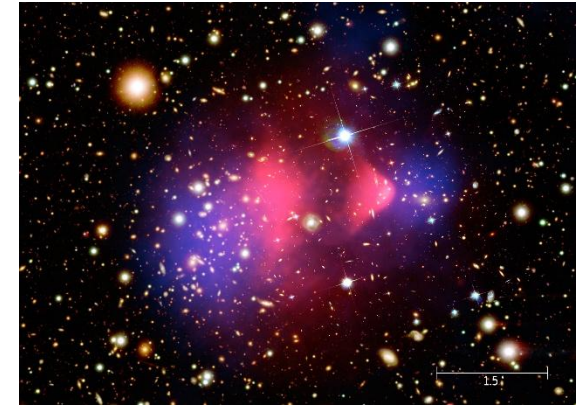
1. Introduction

■ ダークマターはいる

- 銀河の回転曲線
- 衝突銀河
- 宇宙マイクロ波背景放射

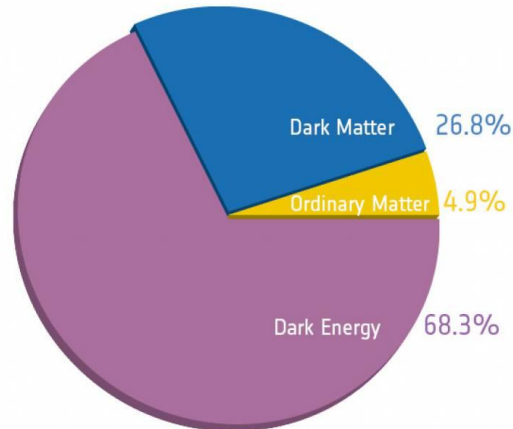
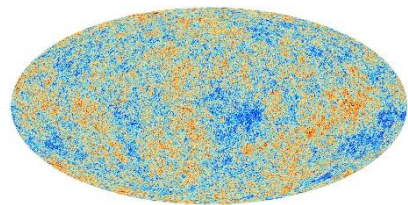


回転曲線の予測と観測が合わない



衝突銀河のX線からと重力レンズからは分布が合わない

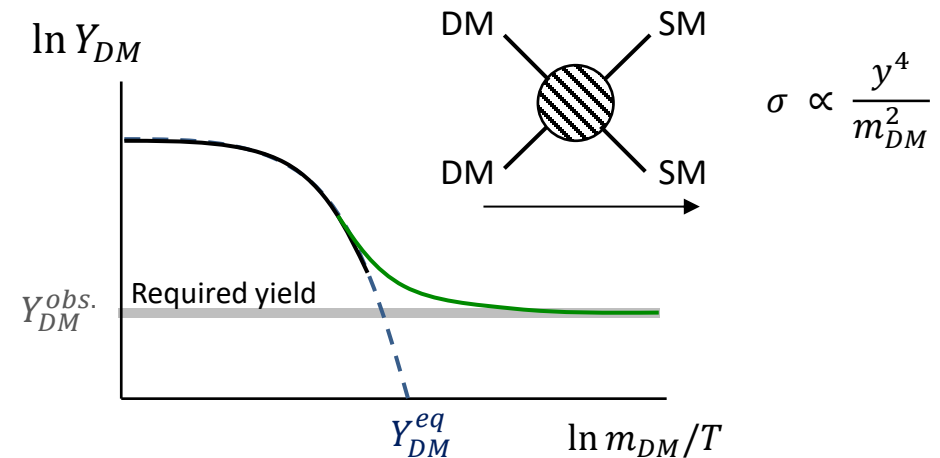
CMB observation [Planck Collab. 2018 Results]



$$\Omega_{CDM} = 0.268$$

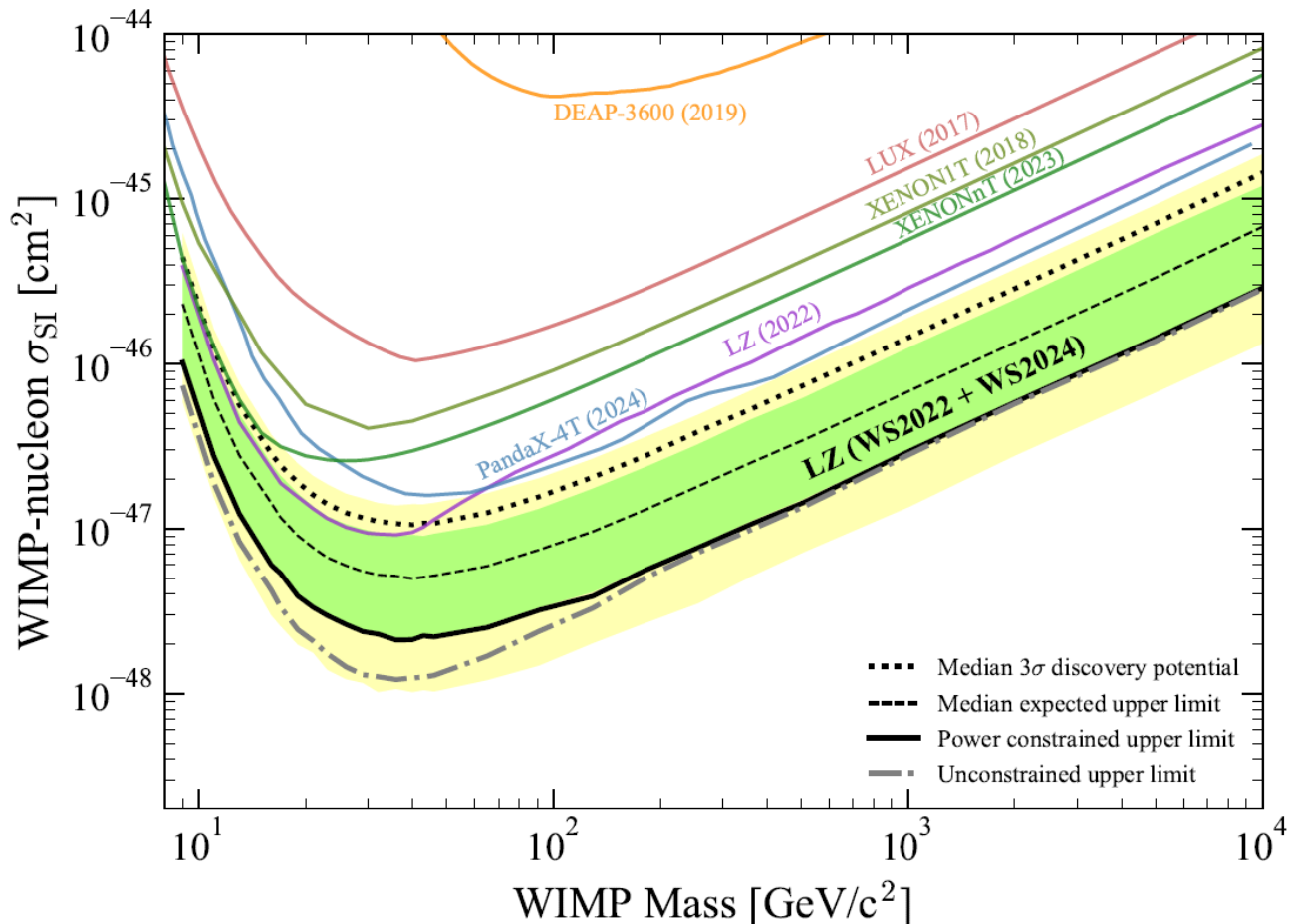
$$\Rightarrow Y_{DM} \equiv \frac{n_{DM}}{s} = 4.36 \times 10^{-12} \cdot \frac{100 \text{ GeV}}{m_{DM}}$$

Thermal relic by freeze-out



■ 現在の DM への制限

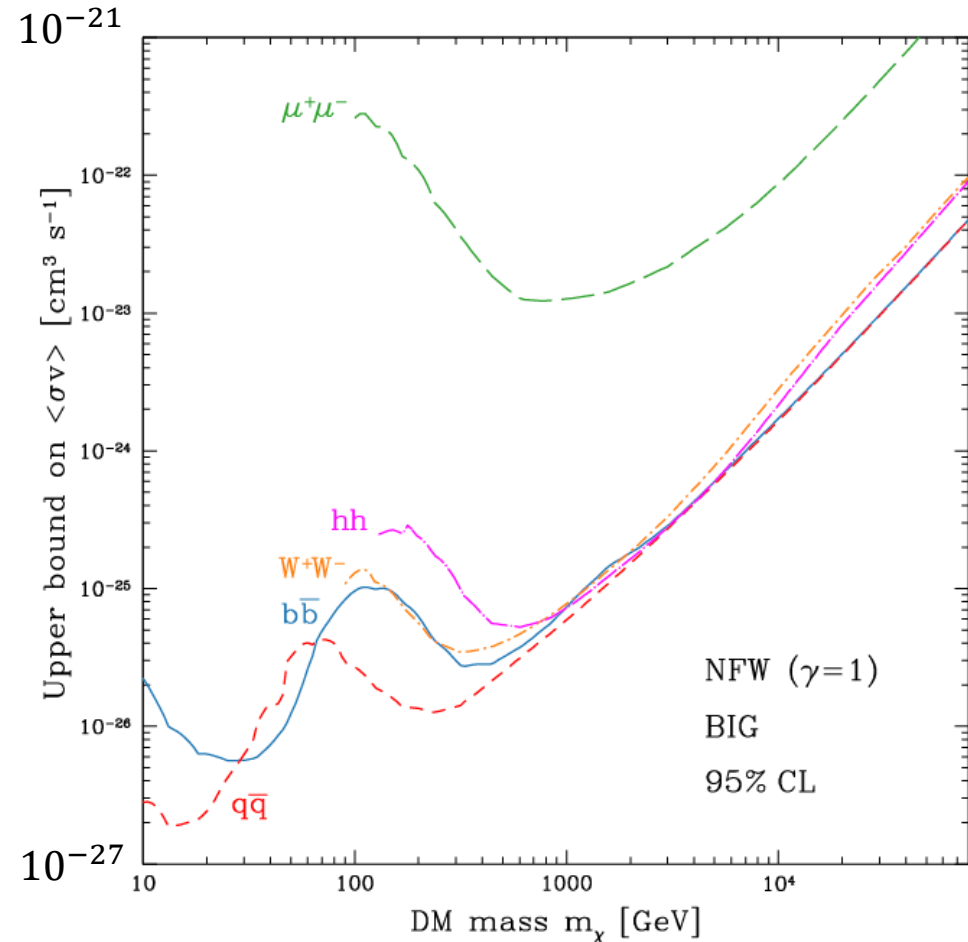
■ Direct search [LZ collablation, 2410.17036 [hep-ex]]



ナイーブな WIMP では $\sigma_{SI} \sim 10^{-40} \text{ cm}^2$: 死んでいる

■ Indirect search (AMS-02)

[F. Calore et al., SciPost Phys. 12 (2022) 5, 163]



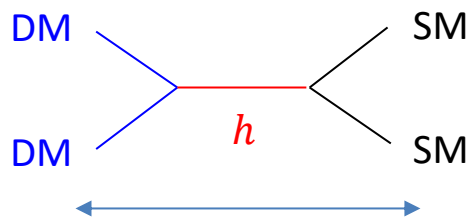
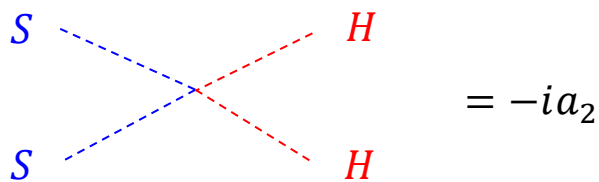
■ ヒッグスポータル DM シナリオ + 共鳴効果 は(ギリギリ)生きてそう (2025年)

[Y. Yu, T. Tang, L. Feng, Nucl.Phys.B 1015 (2025) 116910]

■ ヒッグスポータル

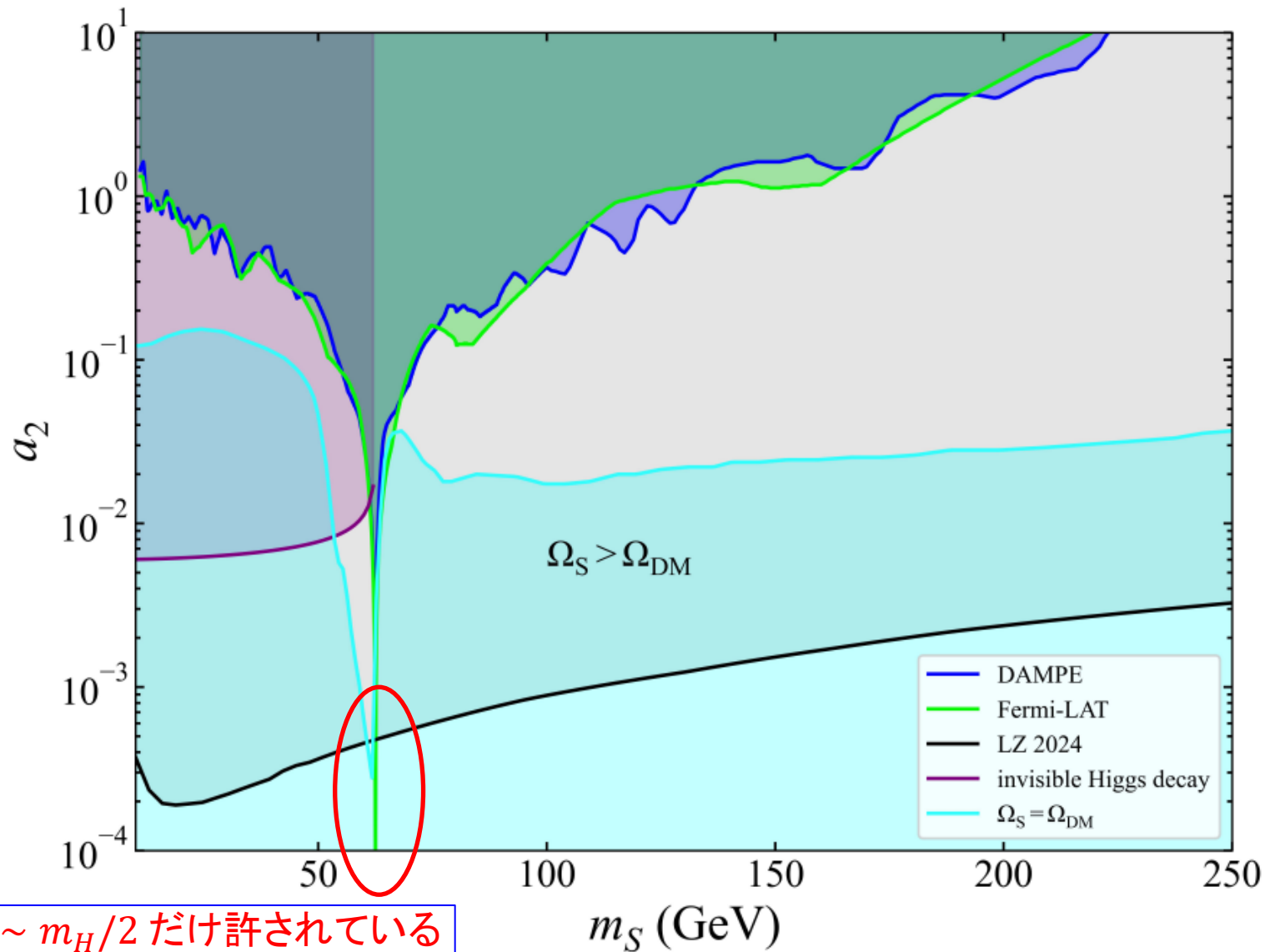
■ ヒッグスが DM と他の SM 粒子とを繋いでいる

- Scalar DM model



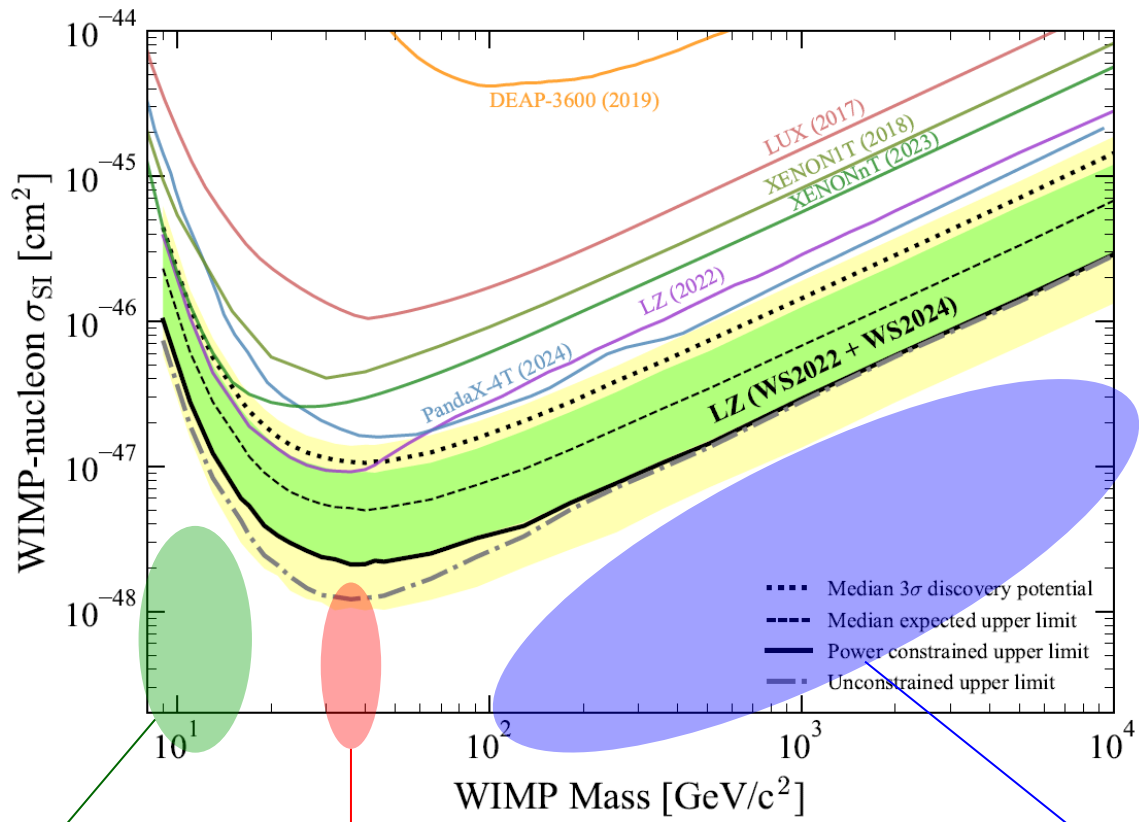
共鳴で DM 対消滅断面積が enhance

→ 小さい coupling でも OK



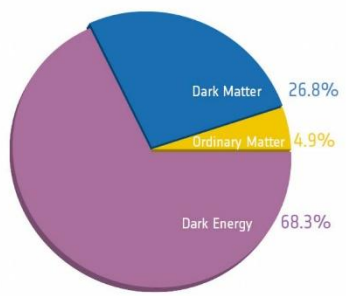
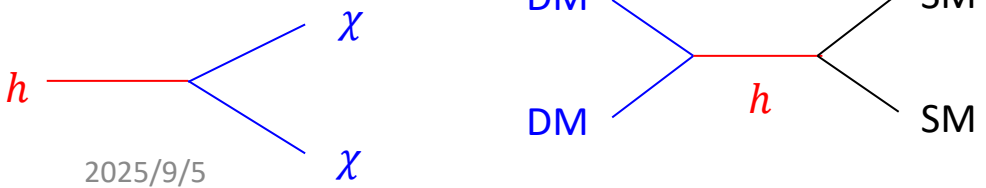
$m_{DM} \sim m_H/2$ だけ許されている

■ (ヒッグスポータルで) 他の質量領域はどうか?



共鳴効果で可能 (ほぼ $m_{DM} = m_h/2$)
 → 小さい coupling でも OK

コライダーで制限
 ($h \rightarrow 2DM$ が開くため)

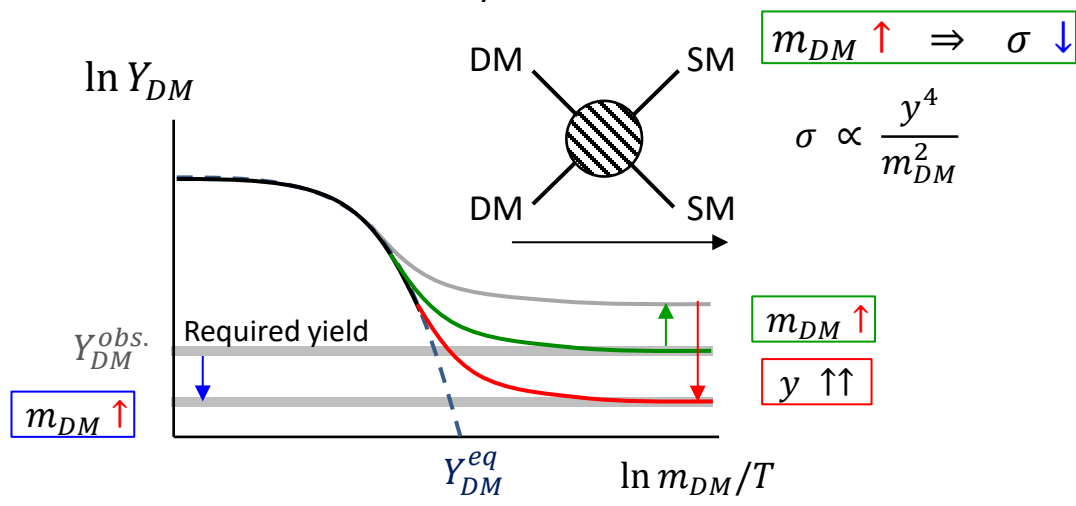


$$\Omega_{CDM} = 0.268$$

$$\Rightarrow Y_{DM} \equiv \frac{n_{DM}}{s} = 4.36 \times 10^{-12} \cdot \frac{100 \text{ GeV}}{m_{DM}}$$

$$m_{DM} \uparrow \Rightarrow Y_{DM} \downarrow$$

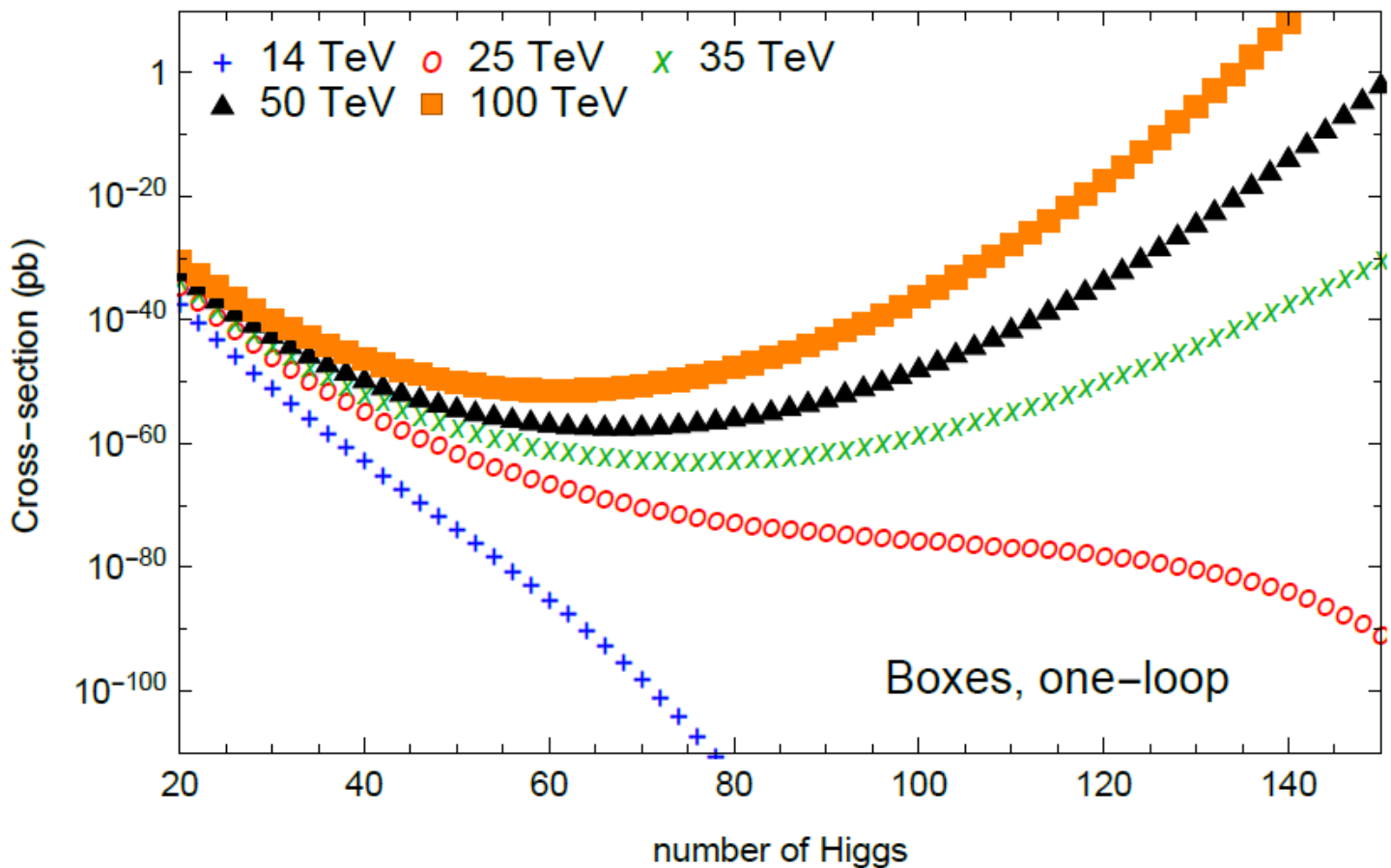
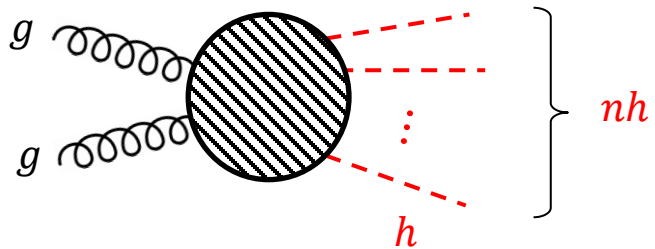
Thermal relic by freeze-out



- 大きすぎる coupling はユニタリティを壊す
- 重い DM はムリ ...?

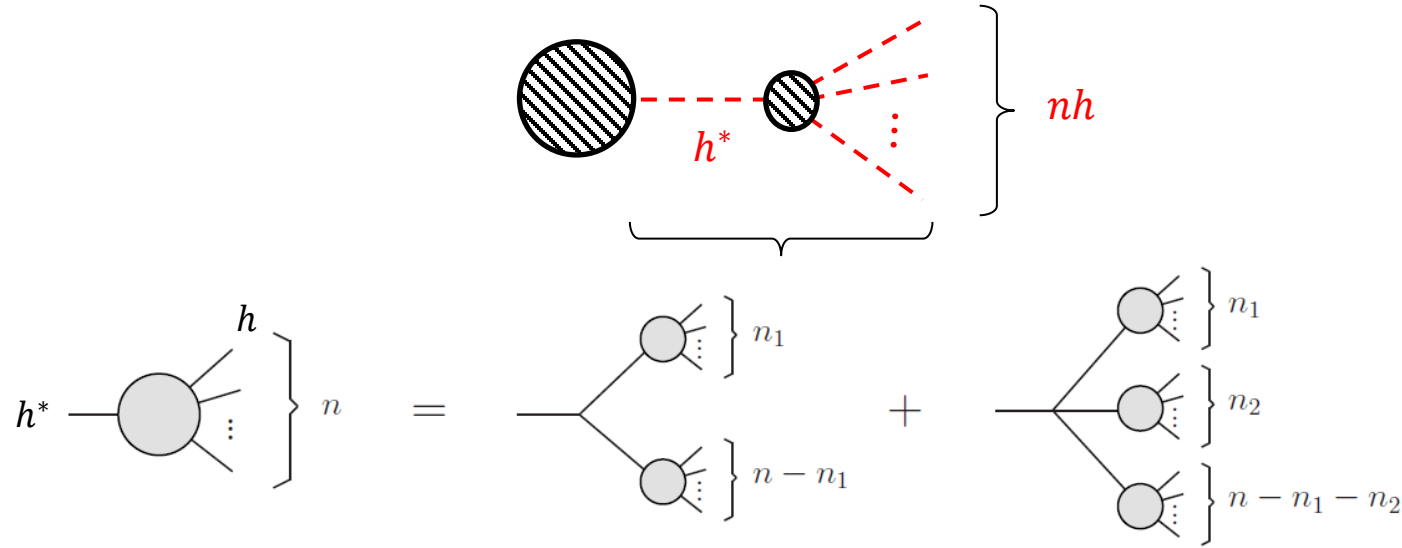
→ “Higgspllosion” と共に考えてみましょう!

■ ある入射エネルギー以上のスケールで多体終状態 (O(100)) のヒッグスが生成される



- Blow up around $\sigma(gg \rightarrow 60h)$
- $\sigma(gg \rightarrow h) \sim \sigma(gg \rightarrow 135h)$

■ Amplitude of $h^*(\text{virtual}) \rightarrow n \times h$ [M. B. Voloshin, NPB383, 233 (1992)]



$$h \text{---} \begin{array}{l} \diagup h \\ \diagdown h \end{array} = -i \sqrt{\frac{9}{2}} \lambda m_h^2$$

$$\begin{array}{l} h \text{---} \diagup h \\ \diagdown h \end{array} = -i\lambda$$

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

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

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

$\sqrt{s} \sim nm_\phi$ のとき: $\mathcal{M}(h^* \rightarrow nh) \sim \lambda^{n/2} n! \cdot f_n(s)$

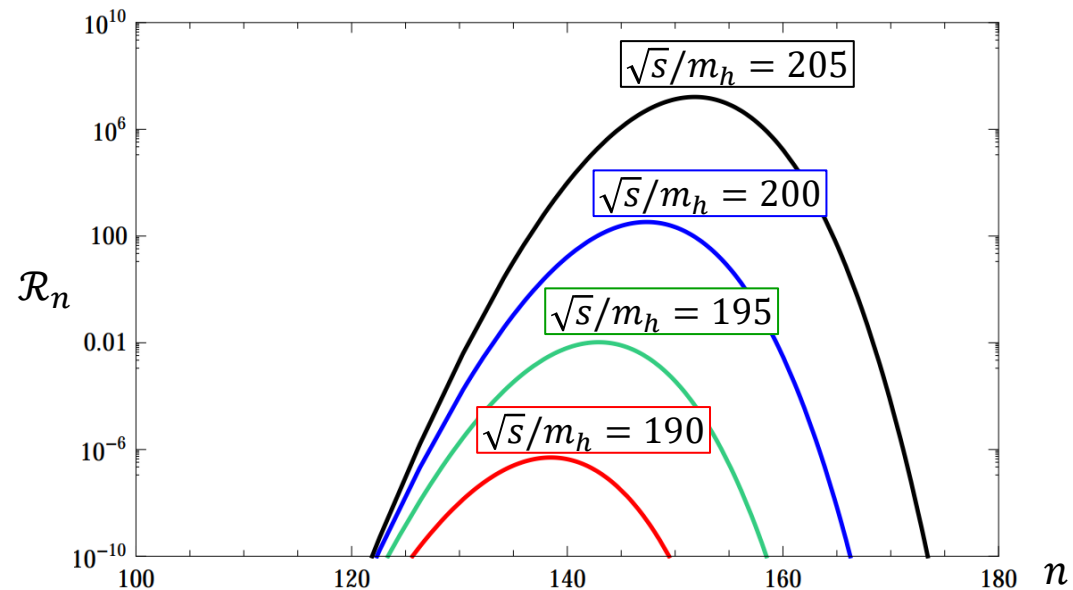
■ $h^* \rightarrow nh$ プロセスの“崩壊幅” ($\sqrt{s} \sim nm_h$ 付近)

$$\mathcal{M}(h^* \rightarrow nh) \sim \underline{\lambda^{n/2} n!} \cdot f_n(s)$$

[V. V. Khoze and M. Spannowsky; NPB 926 (2018)]

$$\begin{aligned} \mathcal{R}_n &\equiv \frac{\Gamma_{h^* \rightarrow nh}(s)}{m_n} = \frac{1}{2m_h^2} \cdot \frac{1}{n!} \int d\Pi_n |\mathcal{M}(h^* \rightarrow nh)|^2 \\ &= \exp \left[n \left(\ln \frac{\lambda n}{4e} + L_n + P_n \right) \right] \end{aligned}$$

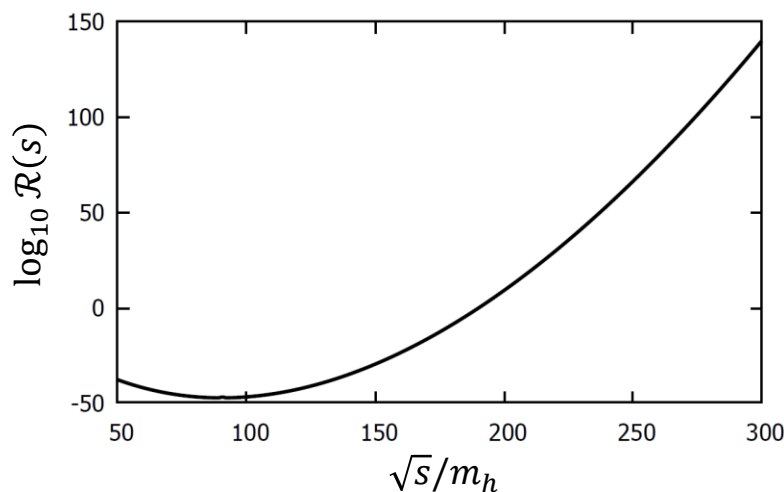
$$\left(\begin{aligned} L_n &\equiv \frac{2}{\sqrt{3}} \frac{\Gamma(5/4)}{\Gamma(3/4)} \sqrt{\lambda n} = 0.854 \sqrt{\lambda n} && \text{全ループ効果} \\ P_n &= \frac{3}{2} \ln \frac{e\epsilon}{3\pi} - \frac{25}{12} \epsilon, \quad \epsilon \equiv \frac{\sqrt{s} - nm_h}{nm_h} \ll 1 \\ &\text{運動量空間体積に関係} \end{aligned} \right)$$



■ “全崩壊幅”

$$\mathcal{R}(s) \equiv \sum_n \mathcal{R}_n \cdot \theta(\sqrt{s} > nm_h)$$

Exp growing for high s



DM 残存量シナリオにこの Higgspllosion 効果を取り入れてみる

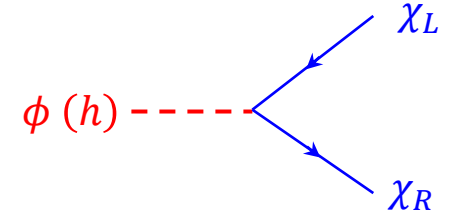
2. Higgspllosion + DM 残存量シナリオ

■ Toy model (ヒッグスポータル DM)

こんな模型ありえるの？(チャージどうなってるの?)
 → 後ほど例を紹介します

■ Lagrangian (ϕ : ヒッグス, χ_L, χ_R : DM)

$$\mathcal{L} \supset \underbrace{-\frac{1}{4}\lambda(\phi^2 - v^2)^2}_{\text{ヒッグスポテンシャル}} - \underbrace{m_\chi(\bar{\chi}_R\chi_L + (h.c.))}_{\text{DM デイラック質量}} - \underbrace{(y_\chi\phi \cdot \bar{\chi}_R\chi_L + (h.c.))}_{\text{ヒッグス-DM 相互作用}} \quad (y_\chi: \text{複素湯川結合定数})$$

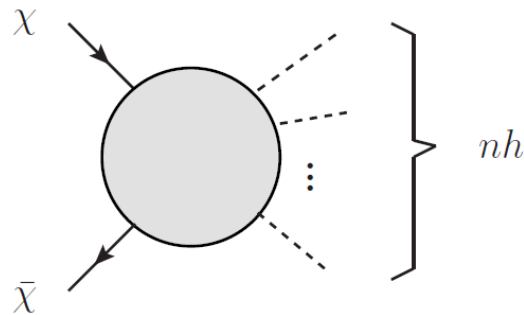


↓ (SSB: $\phi = v + h$)

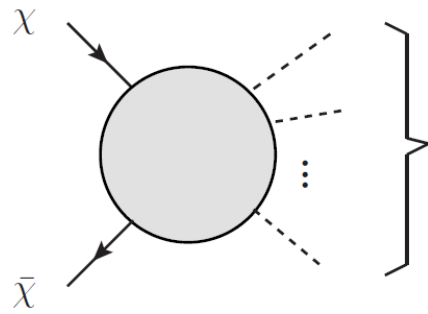
$$= -\frac{1}{2}m_h^2h^2 - \lambda vh^3 - \frac{1}{4}\lambda h^4 - (M_\chi\bar{\chi}_R\chi_L + (h.c.)) - h(y_\chi \cdot \bar{\chi}_R\chi_L + (h.c.)) \quad (M_\chi \equiv m_\chi + y_\chi v: \text{複素})$$

↓ (Re-phasing: $\chi_L e^{i \arg M_\chi} \rightarrow \chi_L$)

$$= -\frac{1}{2}m_h^2h^2 - \lambda vh^3 - \frac{1}{4}\lambda h^4 - |M_\chi|(\bar{\chi}_R\chi_L + (h.c.)) - h(\tilde{y}_\chi \cdot \bar{\chi}_R\chi_L + (h.c.)) \quad (\tilde{y}_\chi \equiv y_\chi e^{-i \arg M_\chi}: \text{複素})$$

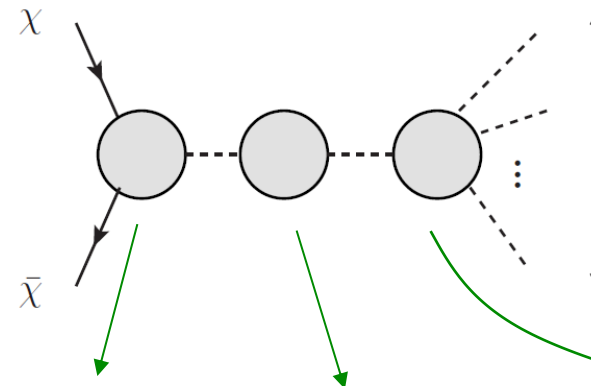


Scattering amplitude



nh

\sim



nh

$$\left[\begin{array}{l} \mathcal{L} \supset -\tilde{y}_\chi h \bar{\chi}_R \chi_L \\ \theta_{\tilde{y}} \equiv \arg \tilde{y}_\chi \end{array} \right]$$

$$\sum_{\text{spins}} |\mathcal{M}(\chi\bar{\chi} \rightarrow nh)|^2 \sim \sum_{\text{spins}} \left| \frac{\mathcal{M}(\chi\bar{\chi} \rightarrow h)}{s - M_h(s)^2 - iM_h(s)\Gamma_h(s)} \mathcal{M}(h \rightarrow nh) \right|^2$$

$$\sim 2|\tilde{y}_\chi|^2 (s - 4|M_\chi|^2 \cos^2 \theta_{\tilde{y}}) \frac{1}{s^2 + m_h^2 \Gamma_h(s)^2} |\mathcal{M}(h \rightarrow nh)|^2,$$

$$\begin{array}{l} M_h(s) \sim m_h \\ \sqrt{s} \gg m_h \end{array}$$

$$\left[\begin{array}{l} \theta_{\tilde{y}} = 0 : p\text{-wave} \\ \theta_{\tilde{y}} = \pm\pi/2 : s\text{-wave} \end{array} \right]$$

断面積を最大化するため
以後、この状況を仮定する

$$\sum_n \int d\Pi_n \times \dots \sim \Gamma_h(s)$$

“Window” になる

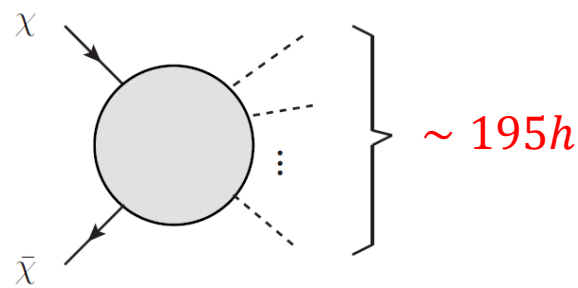
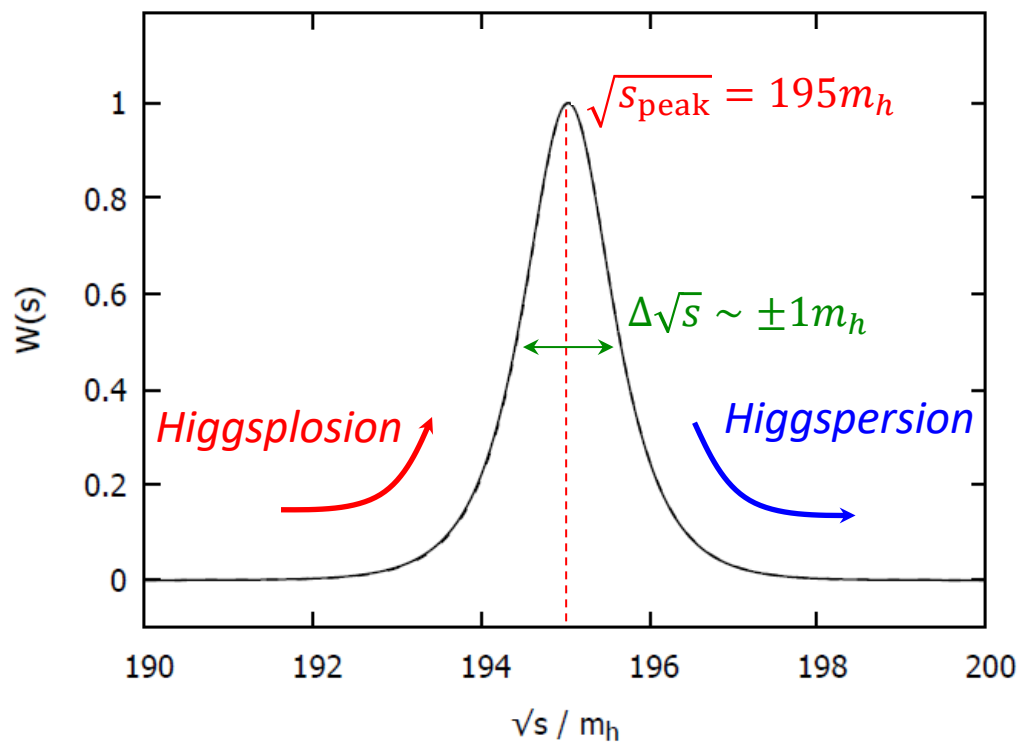
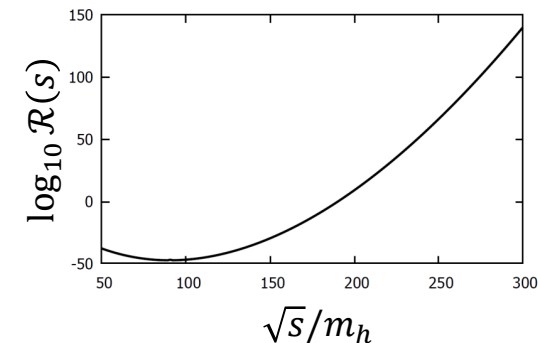
Cross section

$$\sigma = \sum_n \sigma_{\chi\chi \rightarrow nh} = \frac{1}{\sqrt{s(s - 4|M_\chi|^2)}} \cdot \frac{|\tilde{y}_\chi|^2}{4} \left(1 - \frac{4|M_\chi|^2 \cos^2 \theta_{\tilde{y}}}{s} \right) \underline{\underline{W(s)}}$$

$2\chi \rightarrow 2h$ だと λ^2 くらいだが
“window”に置き換わっている

“Window” function

$$W(s) = \frac{2sm_h^2 \mathcal{R}(s)}{s^2 + m_h^4 \mathcal{R}(s)^2}, \quad 0 \leq W(s) \leq 1 \quad \left(\mathcal{R}(s) \equiv \Gamma_h(s)/m_h \right)$$



$$\sqrt{s} \sim 2M_\chi \sim 195m_h$$

$$\therefore M_\chi \sim 100 m_h$$

こうだと断面積が最大化

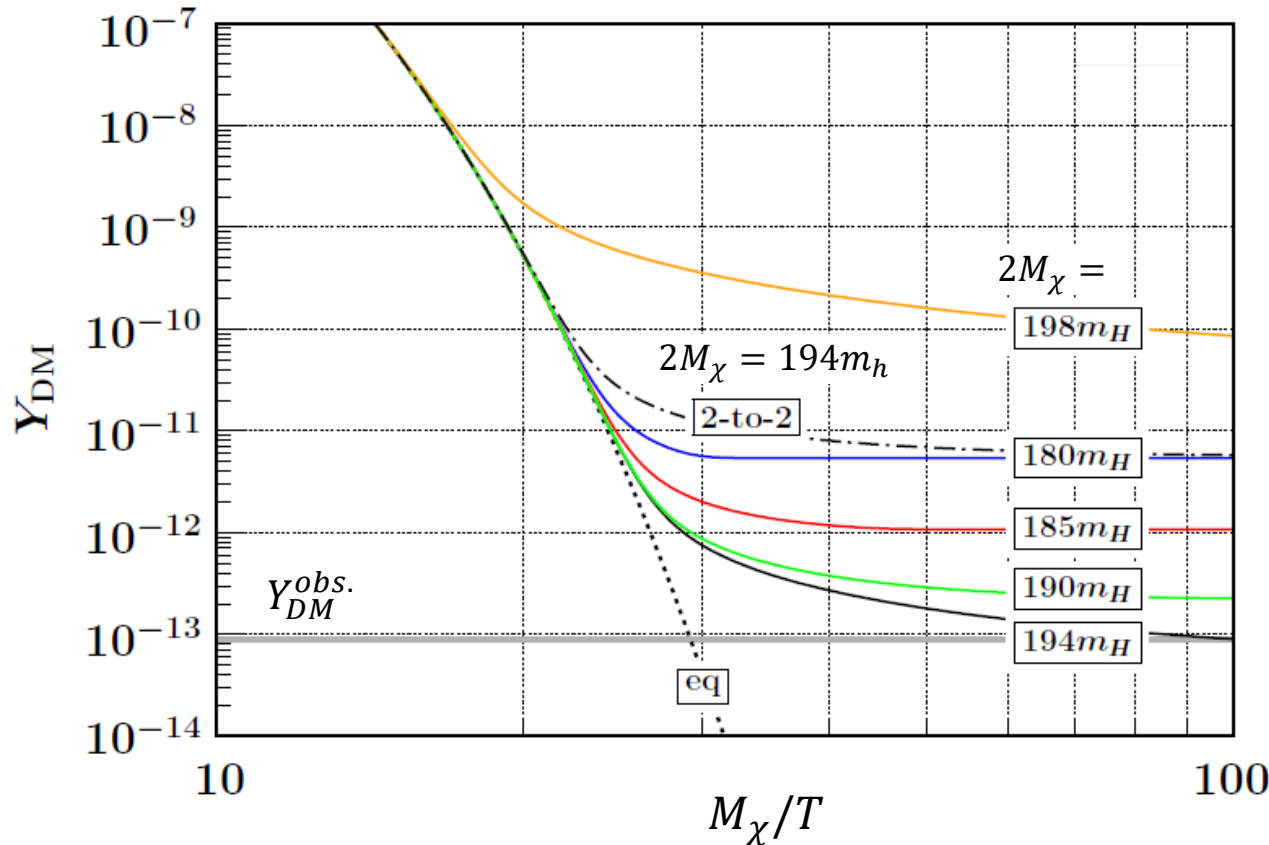
DM (thermal) relic abundance

$$\left(\mathcal{L} \supset -\tilde{y}_\chi h \overline{\chi}_R \chi_L \right)$$

■ ボルツマン方程式: $\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle (n_\chi^2 - (n_\chi^{eq})^2)$

■ 数値結果

Evolution of DM abundance ($\tilde{y}_\chi = 1.3i$)



■ Freeze-out のスケール

$$T \sim M_\chi / 25$$

$$\sim 4m_h \quad \leftarrow M_\chi \sim 100m_h$$

$$\sim 500 \text{ GeV} \quad (m_h = 125 \text{ GeV})$$

Failed (:: before SSB)

$$T \sim 200 \text{ GeV} \quad (m_h = 50 \text{ GeV})$$

OK (during SSB)

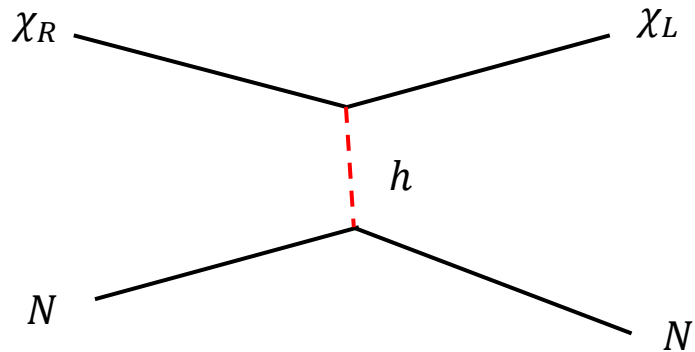
$$\Rightarrow M_\chi \sim 100m_h \sim \underline{5 \text{ TeV}}$$

■ どうやって toy model のラグランジアンをだすか？

■ ディラック質量の部分がちょい不自然

$$\mathcal{L} \supset -m_\chi (\bar{\chi}_R \chi_L + (h.c.)) - \left(\underset{\substack{\uparrow \\ ?}}{y_\chi} H \cdot \underset{\substack{\uparrow \\ SU(2)}}{\bar{\chi}_R} \underset{\substack{\uparrow \\ SU(2)}}{\chi_L} + (h.c.) \right) \quad (H: \text{Higgs}, \quad \chi_L, \chi_R: \text{DMs})$$

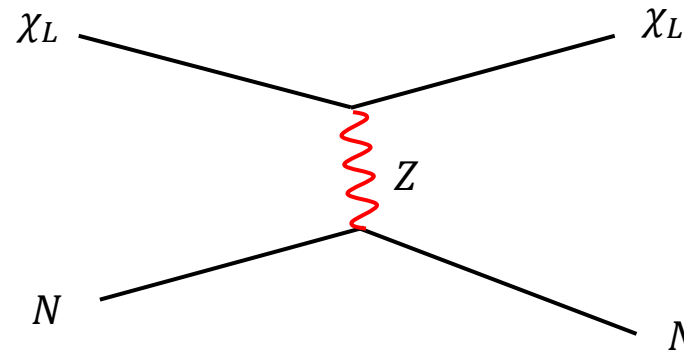
■ DM 直接探索にひっかかる？



湯川が純虚数だと制限弱い

$$y_\chi H \cdot \bar{\chi}_R \chi_L + (h.c.) = i \text{Im}(y_\chi) \cdot h \bar{\chi} \chi$$

$$\rightarrow \sigma \sim 10^{-56} \text{ cm}^2$$



こちらはヤバい

Singlet-doublet DM model (+ 複素パラメータ)

[T. Cohen, J. Kearney, A. Pierce, and D. Tucker-Smith; PRD85 (2012)]

$$\mathcal{L} \supset -\frac{1}{2}m_\psi\psi\psi - m_D f_R^c f_L - y_L \psi f_L \cdot H - y_R \psi f_R^c \cdot H^\dagger + (h.c.)$$

SSB ($H = (0, v + h)^T / \sqrt{2}$) (m_ψ : complex, others: real)

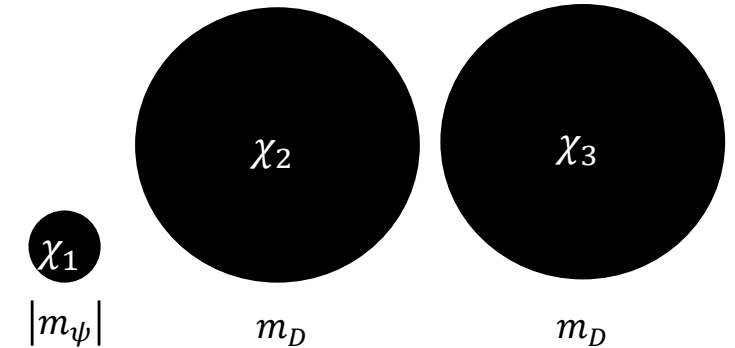
$$\supset -\frac{1}{2}(\psi \ f^0 \ f'^0) \mathbf{M} \begin{pmatrix} \psi \\ f^0 \\ f'^0 \end{pmatrix} \quad \left[\mathbf{M} = \begin{pmatrix} m_\psi & m_L & m_R \\ m_L & 0 & m_D \\ m_R & m_D & 0 \end{pmatrix}, \quad m_{L(R)} = \frac{1}{\sqrt{2}} y_{L(R)} v \right]$$

$$= -\frac{1}{2}(\chi_1 \ \chi_2 \ \chi_3) \begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{pmatrix} \begin{pmatrix} \chi_1 \\ \chi_2 \\ \chi_3 \end{pmatrix} \quad \left[m_1 \leq m_2 \leq m_3 \right]$$

Contents	$SU(2)_L$	$U(1)_Y$	Z_2
Ψ	1	0	odd
$f_L = \begin{pmatrix} f^0 \\ f^- \end{pmatrix}$	2	-1/2	odd
$f_R^c = \begin{pmatrix} f'^+ \\ f'^0 \end{pmatrix}$	2	+1/2	odd

$m_D \gg |m_\psi|, m_L, m_R$ を仮定すると

$m_1 = |m_\psi| \ll m_2 \sim m_3 \sim m_D$: χ_1 が LSP = DM



直接検出実験に関する couplings: $\mathcal{L} \supset c_h \cdot h \bar{\chi}_1 \chi_1 + c_Z \cdot \bar{\chi}_1 Z \gamma^5 \chi_1$

$$c_h \sim \frac{2m_L m_R \operatorname{Re} m_\psi}{m_D v |m_\psi|} = 0, \quad \boxed{\operatorname{Re} m_\psi = 0}$$

$$c_Z \sim \frac{g_2}{4 \cos \theta_W} \frac{|m_L^2 - m_R^2|}{m_D^2} = 0, \quad \boxed{m_L = m_R}$$

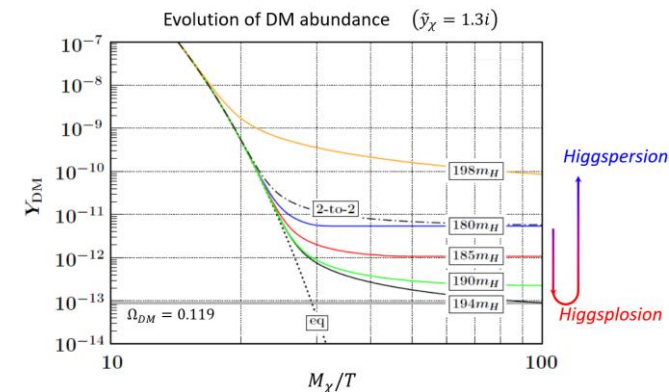
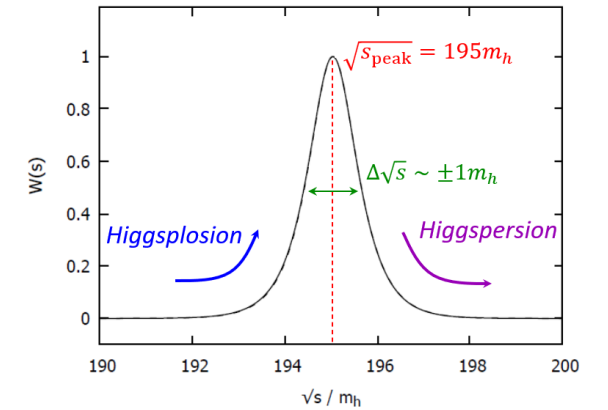
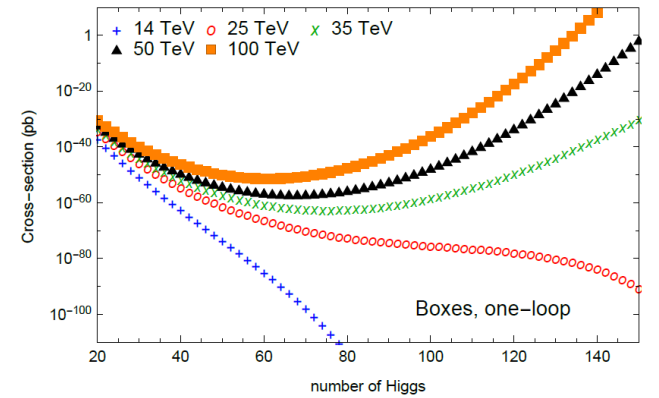
3. まとめ

Higgspllosion:

- $\sqrt{s} \gtrsim O(100) m_h$ でヒッグス多体状態が生成される
 - $\sigma(gg \rightarrow h) \sim \sigma(gg \rightarrow 135h)$ @ 100 TeV p-p collider
 - ホントかどうか
 - 理論側の再精査
 - 摂動論の破綻を見るという意味で将来実験でも確認されるべき

DM 残存量シナリオへの応用

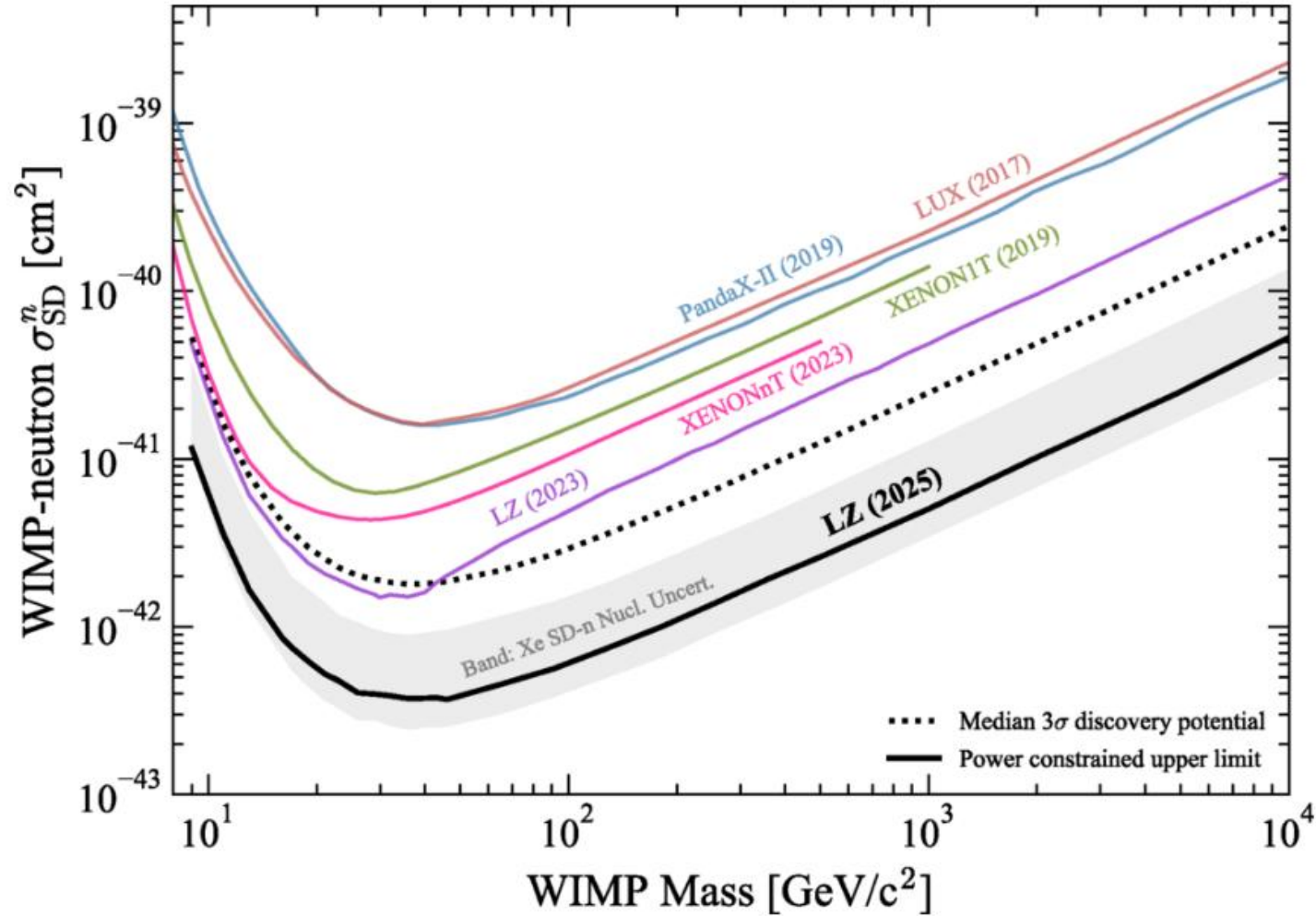
- “崩壊幅” の構造が DM 散乱では “*window*” を形成する
 - $\sqrt{s} = 195m_h$ で最大化
- $M_{DM} \sim 5 \text{ TeV}$ のヒッグスポータル模型が可能に
 - freeze-out 中に $m_h \sim 50 \text{ GeV}$ (SSB 中, $T \sim 200 \text{ GeV}$) であることが必要
- 実験からの制限を考えると模型にひと工夫必要
 - 例: Singlet-doublet model



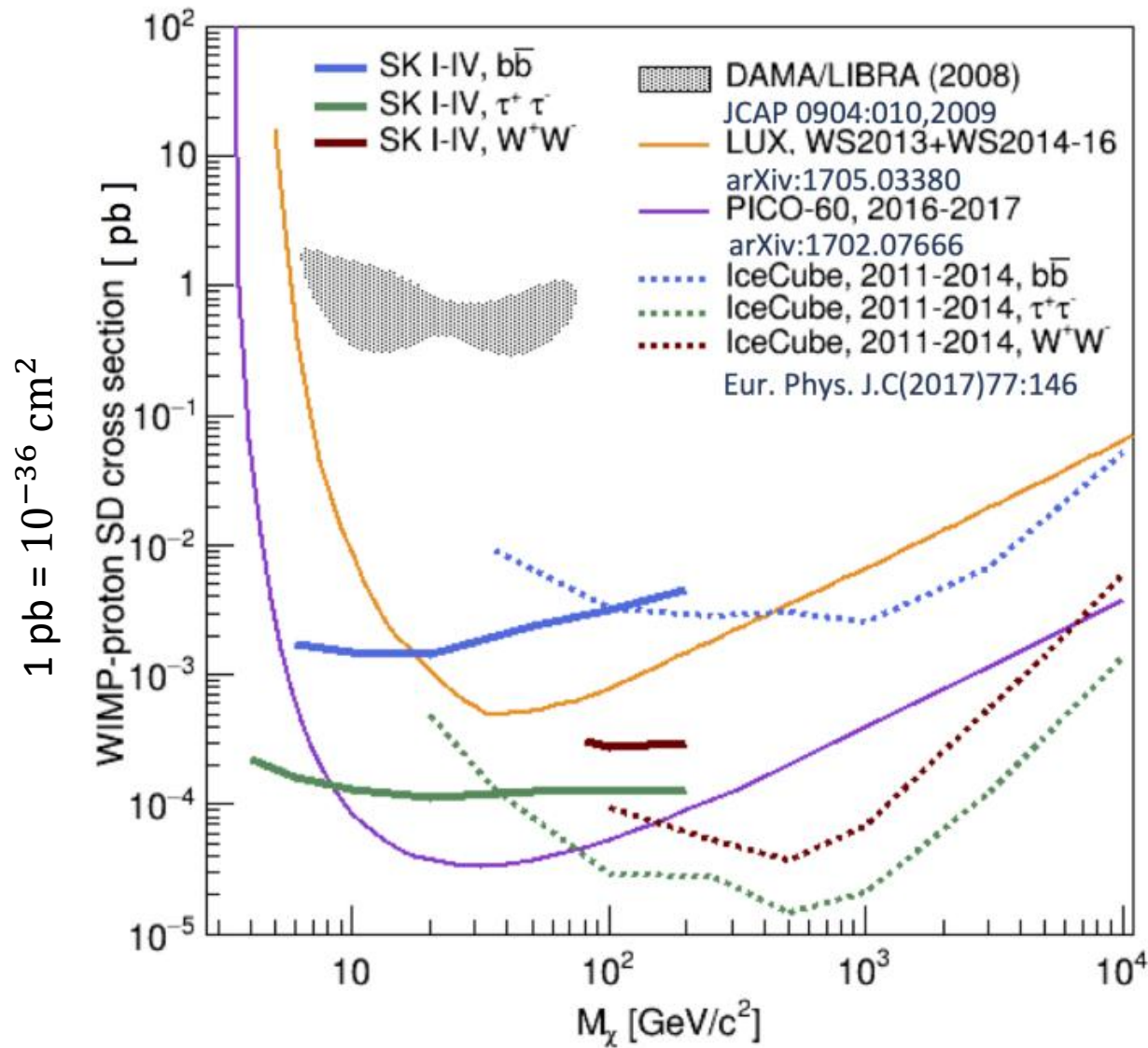
Backup

■ Present bound for DM

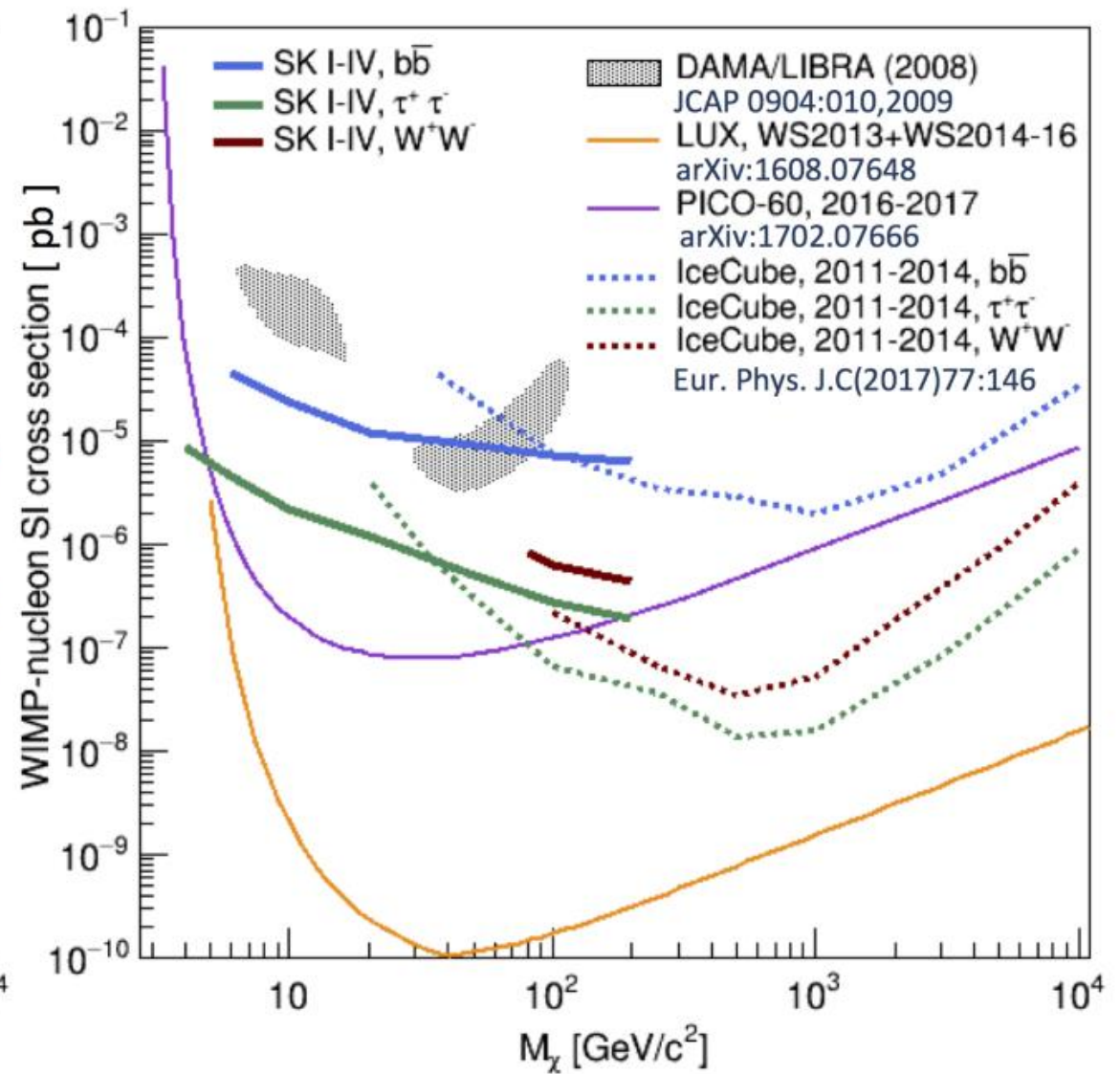
■ Spin-independent cross section [LZ collablation, 2410.17036 [hep-ex]]



(a) spin dependent interactions



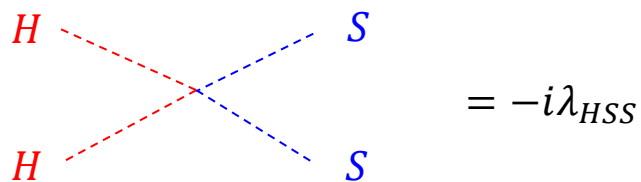
(b) spin independent interactions



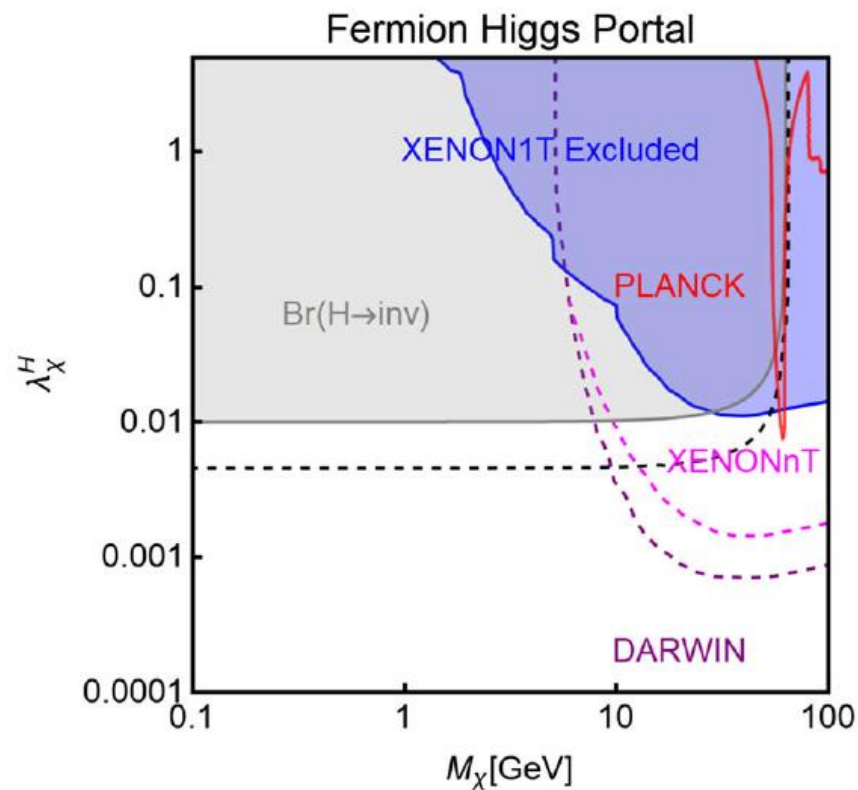
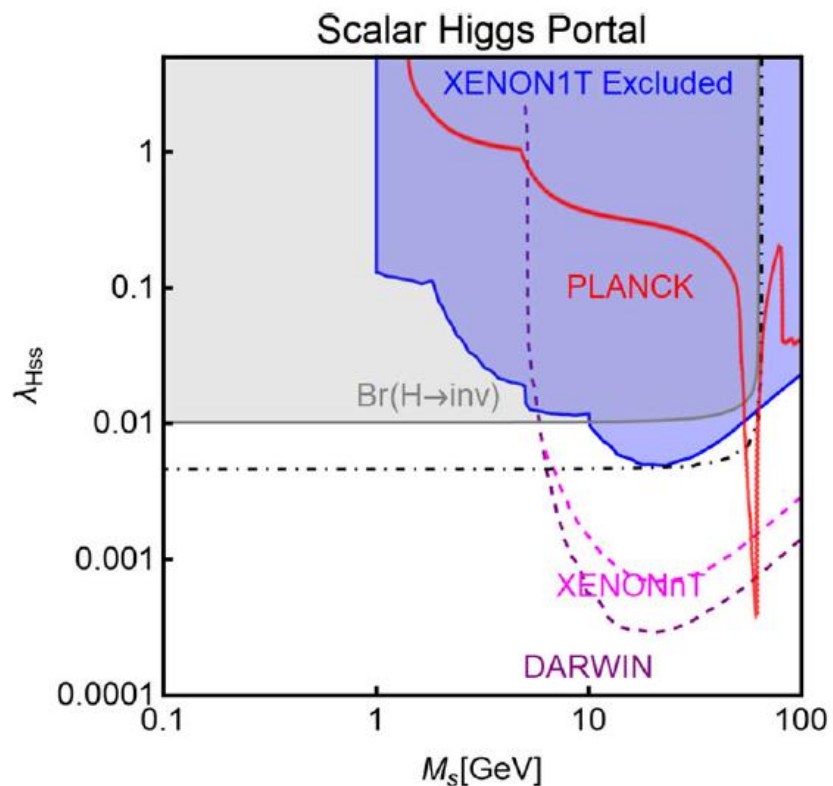
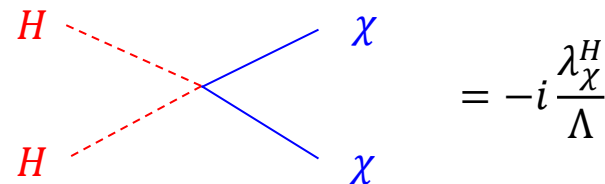
■ ヒッグスポータル DM シナリオ + 共鳴効果 は生きてそう (2021年時)

[G. Arcadi, A. Djouadi, M. Kado, EPJC 81 (2021) 7, 653]

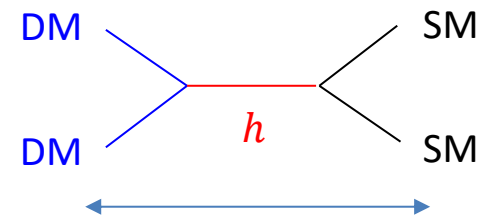
- Scalar DM model



- Fermion DM model



$m_{DM} \sim m_H/2$ is allowed



共鳴で DM 対消滅断面積が enhance

→ 小さい coupling でも OK

■ Cross sections via triangles, boxes, pentagons, ...

	$\sigma_{gg \rightarrow hh}$	$\sigma_{gg \rightarrow hhh}$	$\sigma_{gg \rightarrow hhhh}$
Triangles	$y_t^2 \frac{m_t^2 M_h^2}{s^3} \log^4 \left(\frac{m_t}{\sqrt{s}} \right) \frac{M_h^2}{v^2}$	$y_t^2 \frac{m_t^2}{s^2} \log^4 \left(\frac{m_t}{\sqrt{s}} \right) \frac{M_h^4}{v^4}$	$y_t^2 \frac{m_t^2}{s^2} \log^4 \left(\frac{m_t}{\sqrt{s}} \right) \frac{M_h^6}{v^6}$
Boxes	$y_t^4 \frac{1}{s}$	$y_t^4 \frac{1}{s} \frac{M_h^2}{v^2}$	$y_t^4 \frac{1}{s} \frac{M_h^4}{v^4}$
Pentagons	—	$y_t^6 \frac{m_t^2}{s^2} \log^4 \left(\frac{m_t}{\sqrt{s}} \right)$	$y_t^6 \frac{m_t^2}{s^2} \log^4 \left(\frac{m_t}{\sqrt{s}} \right) \frac{M_h^2}{v^2}$
Hexagons	—	—	$y_t^8 \frac{1}{s}$

■ SSB しないと Higgspllosion ない

[M. B. Voloshin, PRD 47 (1993) R357-R361]

[B. H. Smith, PRD 47 (1993) 3518-3520]

[E. N. Argyres, R. H. P. Kleiss, and C. G. Papadopoulos, PLB 308 (1993) 292-296]

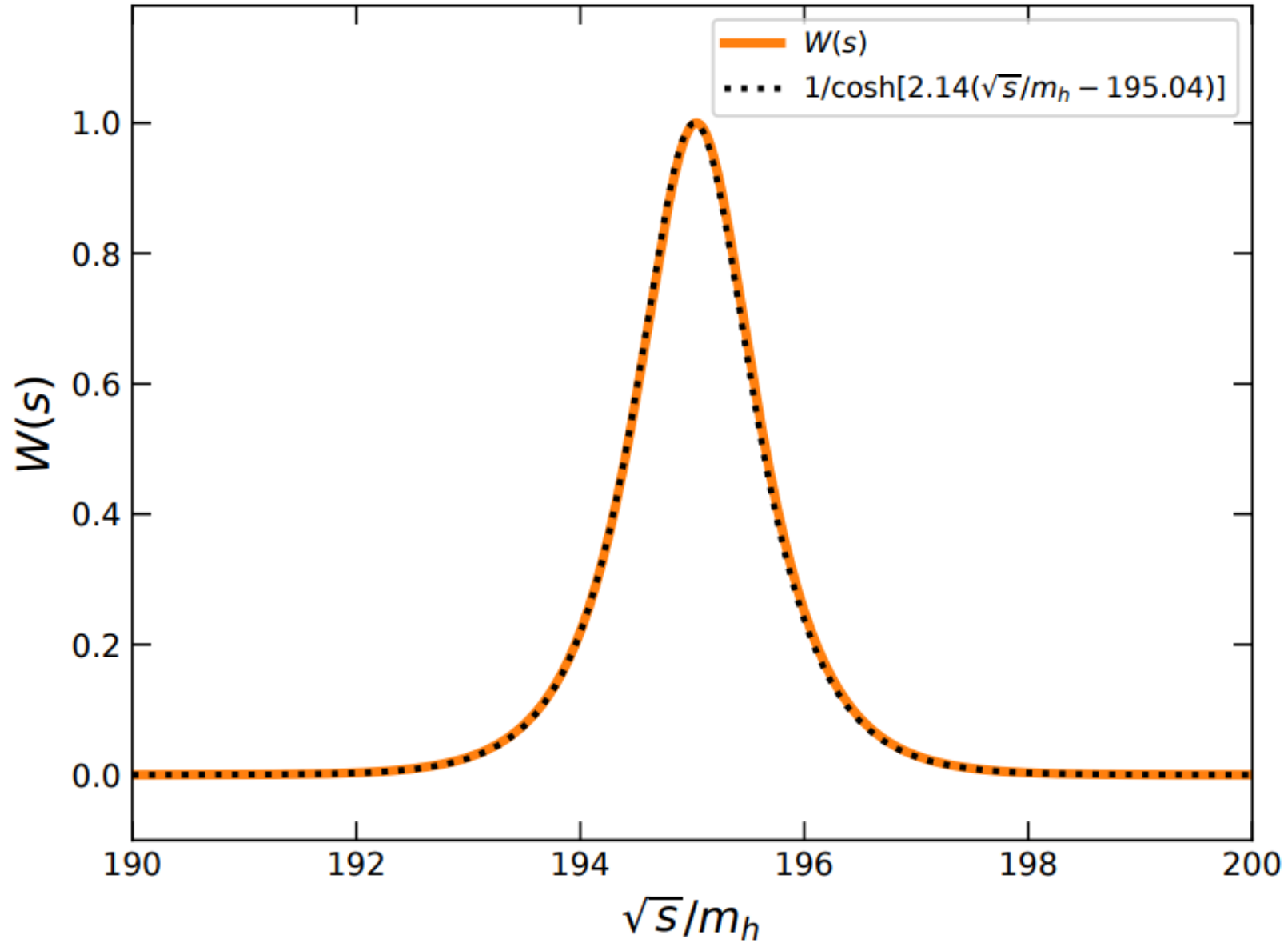
[V. V. Khoze, JHEP 06 (2017) 148]

$$\mathcal{A}(n) = \left[\text{Diagram with a shaded circle and } n \text{ external } h \text{ lines} \right] \sim \mathcal{A}_{tree}(n) \times \exp[Cn^2\lambda]$$

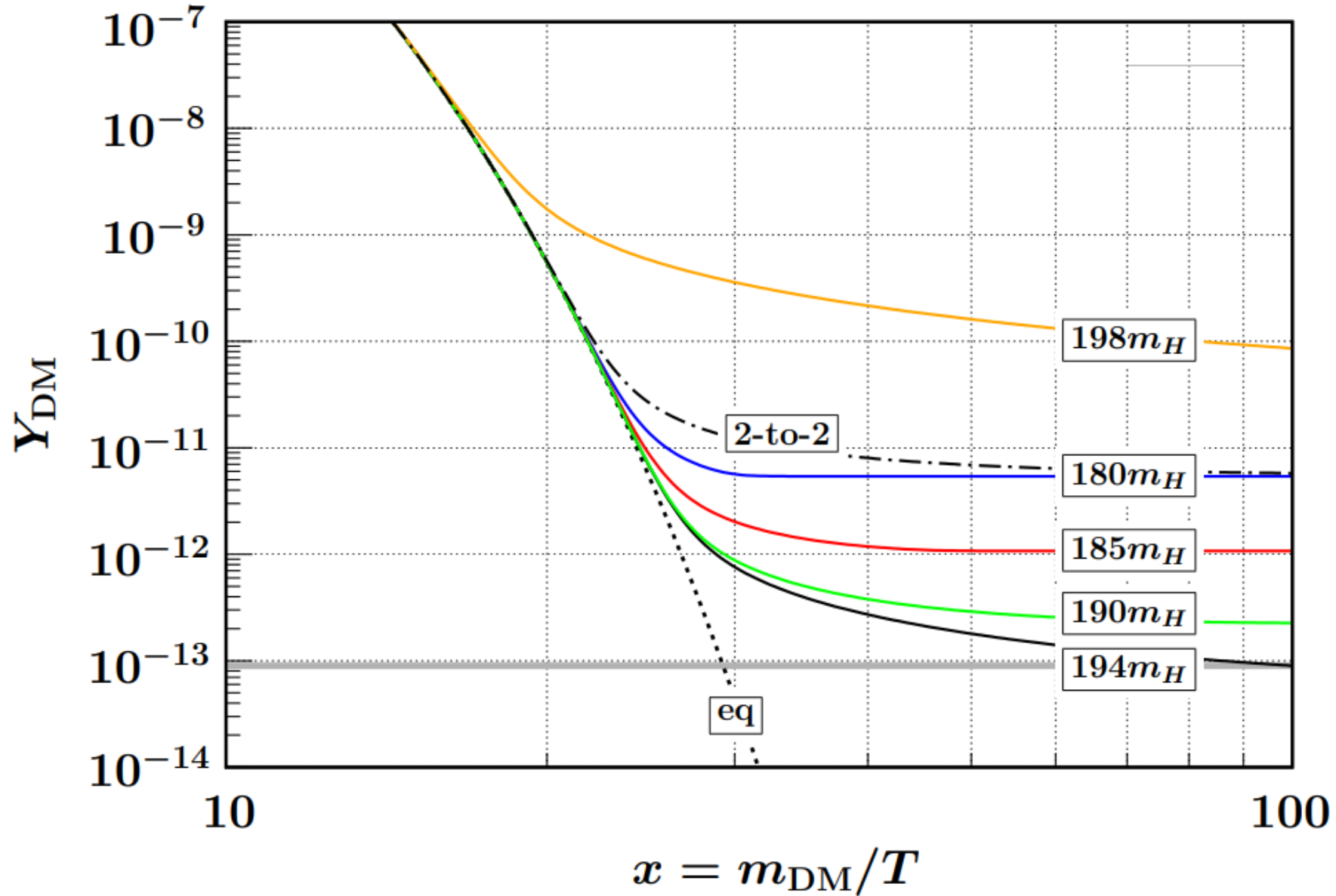
The diagram shows a central shaded circle with diagonal lines. It has several external lines extending outwards, labeled with the letter h . Some lines are solid red, and others are dashed red. There are also some dotted lines. A large curly brace on the right groups the diagram and is labeled nh .

$$C = \begin{cases} \frac{3\sqrt{3}}{64\pi^2} [\ln(7 - 4\sqrt{3}) - i\pi] & \text{(unbroken theory)} \\ \frac{\sqrt{3}}{8\pi} & \text{(broken theory)} \end{cases}$$

Window function



Evolution of relic abundance



■ Reaction rate v.s. Hubble

