Singlet Scalar Dark Matter

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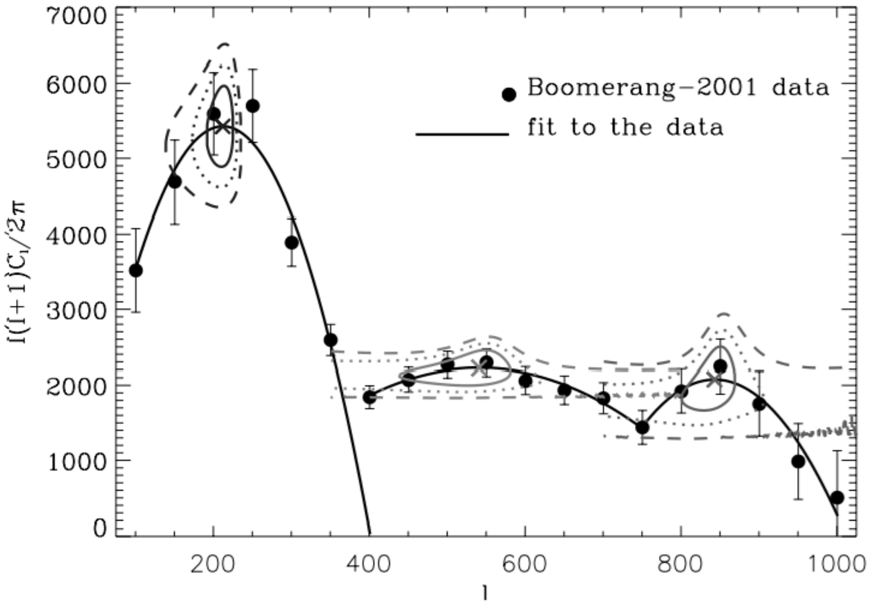
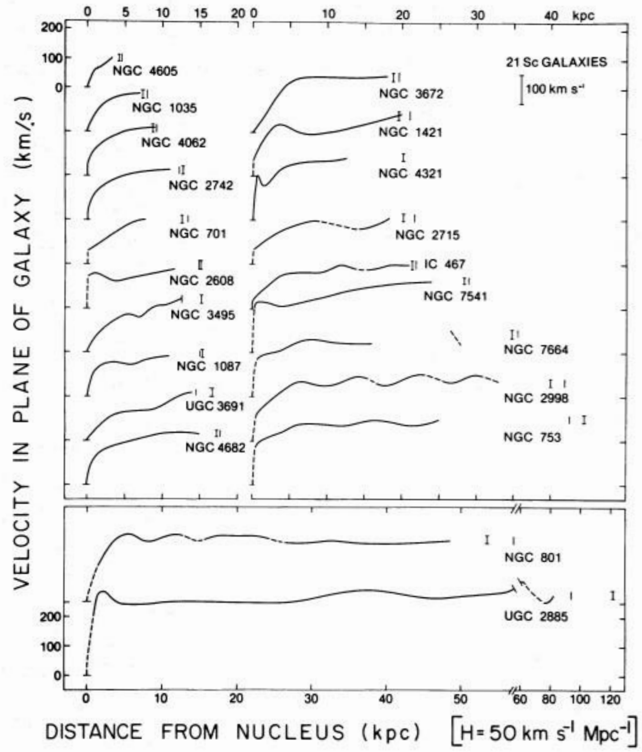
Motivation | S.R.S.M | Origin | Parameter Space | Bounds | Unstable DM

Evidences



R. Durrer , B. Novosyadlyj2 and S. Apunevych ,

ACOUSTIC PEAKS AND DIPS IN THE CMB



Ref: M. Cirelli, A. Strumia, and J. Zupan, “Dark matter,” 2024.

Singlet Scalar Dark Matter

One simple model to describe DM is real scalar That is singlet under SM gauge group.

$$\mathcal{L} = \mathcal{L}_{S\mathcal{M}} + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}(m_s)^2 S^2 - \lambda_{SH} S^2 |H|^2 - \frac{\lambda_S}{4} S^4$$

Symmetry imposed: $\mathbb{Z}_2$

Ref: M. Cirelli, A. Strumia, and J. Zupan, "Dark matter," 2024.

DM Freeze out

Particles start decoupling from other components at equilibrium if:

$$\Gamma = n\langle\sigma v\rangle \sim H$$

$$\langle\sigma v\rangle = \frac{\int d^3p_1 d^3p_2 \sigma v f_1 f_2}{\int d^3p_1 d^3p_2 f_1 f_2}$$

$$= \frac{T}{16T^2m^4(K_2(\frac{m}{T}))^2}\int ds\sqrt{s}K_1(\frac{\sqrt{s}}{T})\sqrt{1-4\frac{m^2}{s}}(4\sigma v E_1 E_2)$$

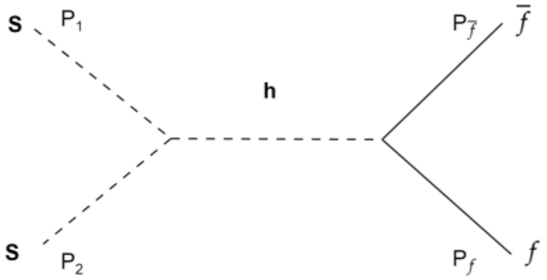
$\hat{\sigma}$

n: **Number density**

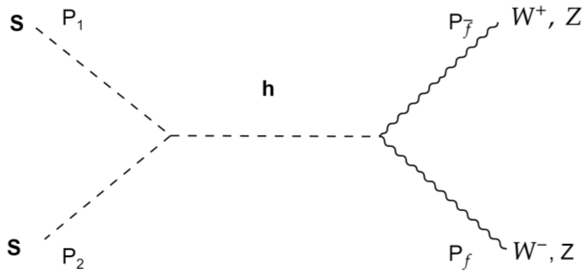
H: **Hubble**

$f_i = e^{\frac{-E_i}{T}}$

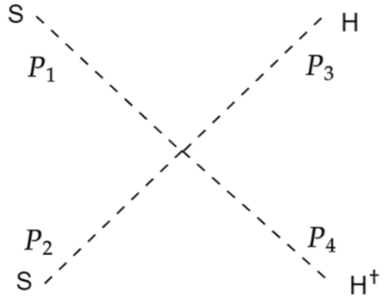
Ref. Gondolo and G. Gelmini, "Cosmic abundances of stable particles: improved analysis,"



$$\propto \frac{\lambda_{HS}^2 m_f^2}{(s-m_h^2)^2+m_h^2\Gamma^2}\, s$$



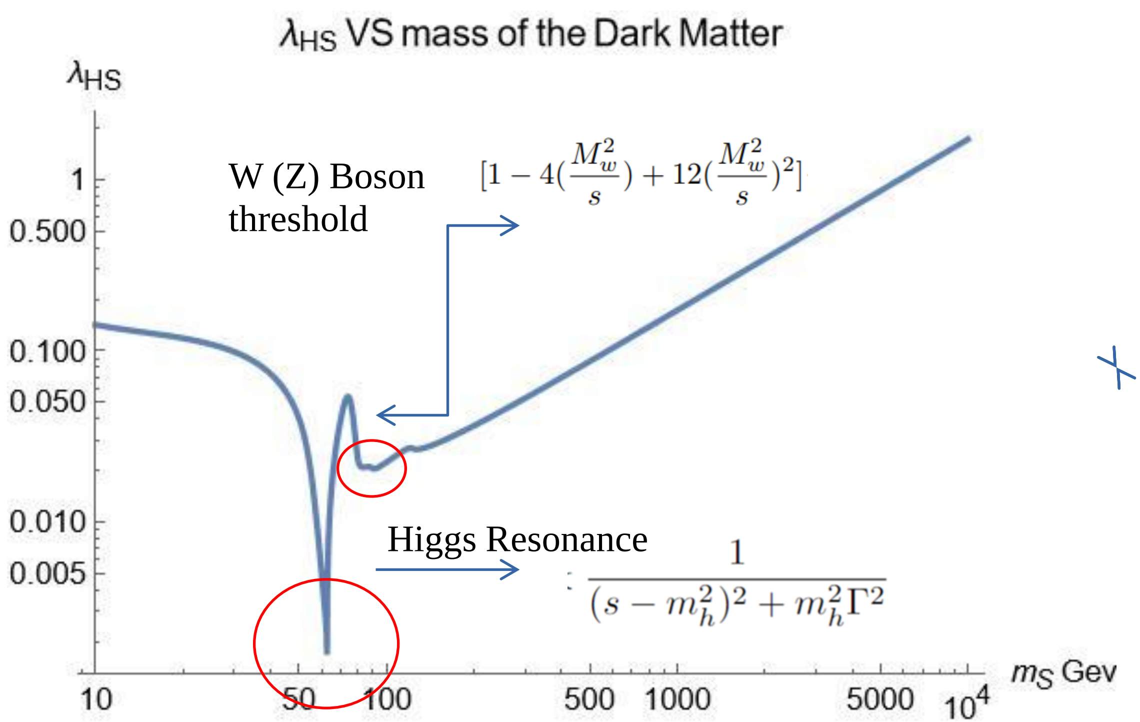
$$\propto \lambda_{HS}^2 \frac{s^2}{(s-m_h^2)^2+m_h^2\Gamma^2}\left[1-4\left(\frac{M_w^2}{s}\right)+12\left(\frac{M_w^2}{s}\right)^2\right]$$



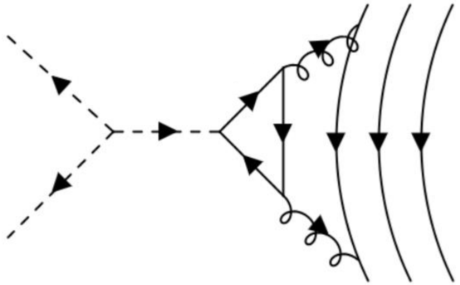
$$\propto \lambda_{HS}^2 \sqrt{1-4\frac{m_h^2}{s}}$$

Ref.D. V. S. Michael E. Peskin, An Introduction To Quantum Field Theory. Frontiers in Physics, Westview Press, 1995.

$$\langle \sigma v \rangle \approx 3 \times 10^{-9}$$



Direct Detection



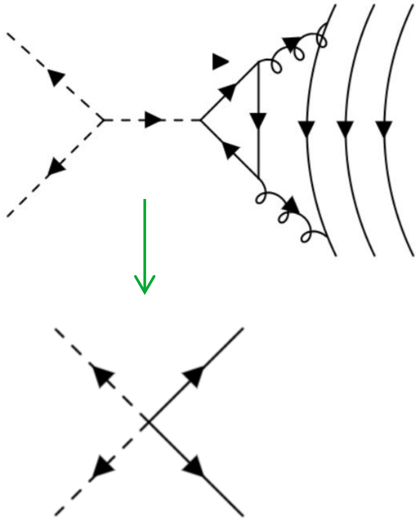
$$\mathcal{L}_{eff} = \frac{H\alpha_s}{12\pi v} G^{a\mu\nu} G_{a\mu\nu}$$

$$T^{\mu}_{\mu} = \Sigma_q m_q \bar{q} q + \frac{\beta(\alpha_s)}{4\alpha_s} G^{a\mu\nu} G_{a\mu\nu}$$

$$i\mathcal{M} = \frac{2\lambda_{HS} M_N}{q^2 - m_h^2} (\frac{7}{9} \frac{< N'|\Sigma_l m_l \bar{l} l|N >}{M_N} + \frac{4}{9} M_N)$$

Ref: E. Del Nobile, The Theory of Direct Dark Matter Detection: A Guide to Computations. Springer International Publishing, 2022.

Direct Detection



$$\mathcal{L}'_{eff} \supset -CS^2\bar{N}N$$

Effective theory at energy scale below Higgs mass

$$C = \frac{2\lambda_{HS} M_N}{m_h^2}\left(\frac{7}{9}\frac{< N'|\Sigma_l m_l \bar{l} l|N >}{M_N} + \frac{4}{9}M_N\right)$$

$$\sigma_{CM} = \frac{|\mathcal{M}|^2}{64\pi^2 s}\frac{|\vec{p}_f|}{|\vec{p}_i|}4\pi$$
$$= \frac{\lambda_{HS}^2 M_N^2 f}{\pi m_h^4 m_s^2}$$

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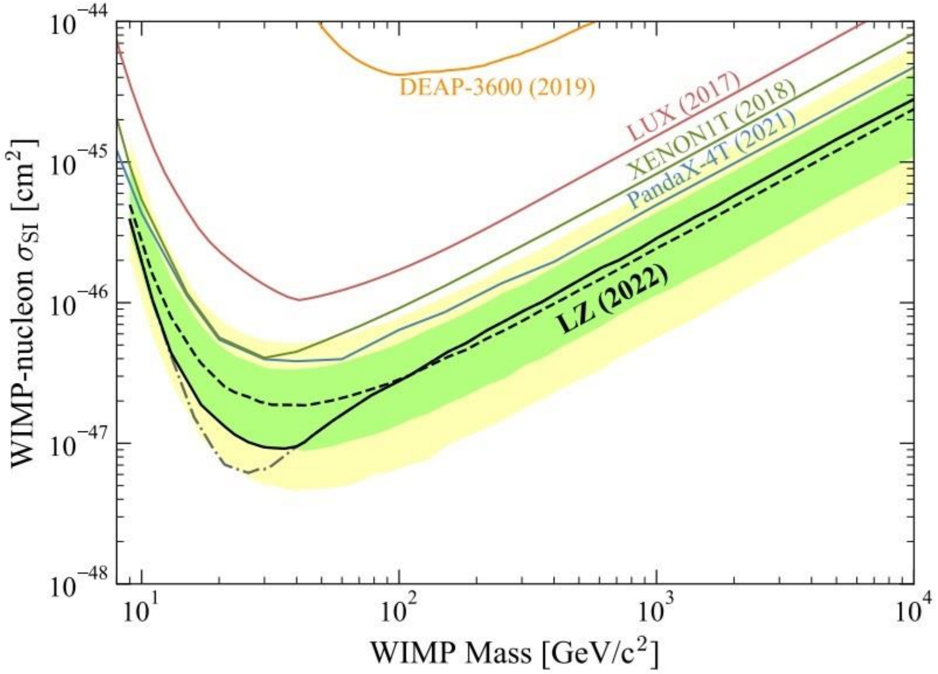
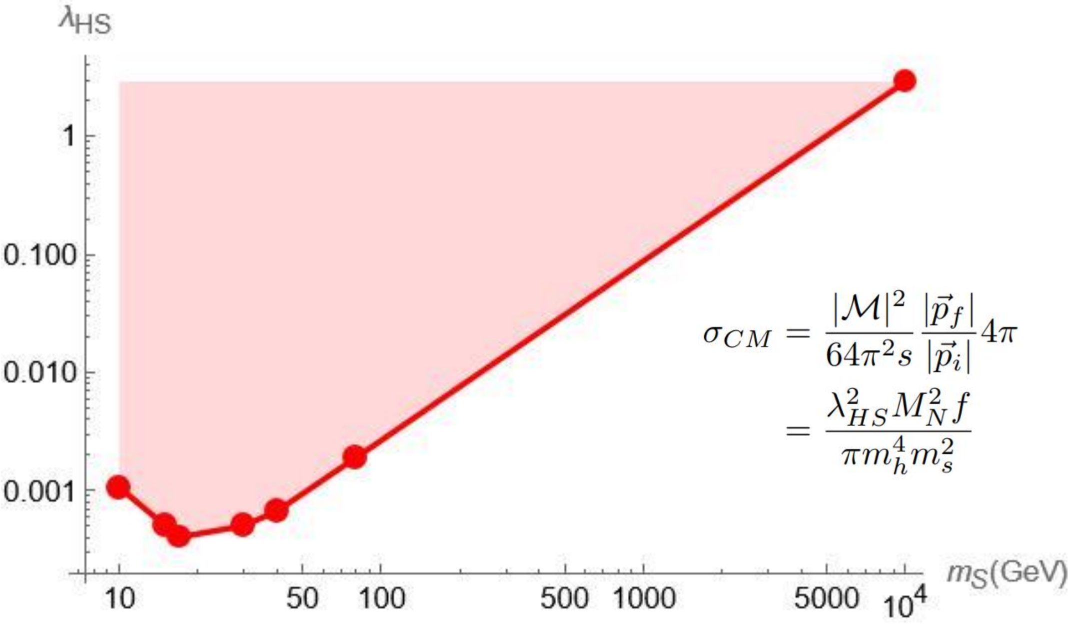
Direct Detection





$$\sigma_{CM} = \frac{|\mathcal{M}|^2}{64\pi^2 s}\frac{|\vec{p}_f|}{|\vec{p}_i|}4\pi = \frac{\lambda_{HS}^2 M_N^2 f}{\pi m_h^4 m_s^2}$$

Ref: "First dark matter search results from the lux-zeplin (lz) experiment," Physical Review Letters, vol. 131, July 2023.

Perturbative limits

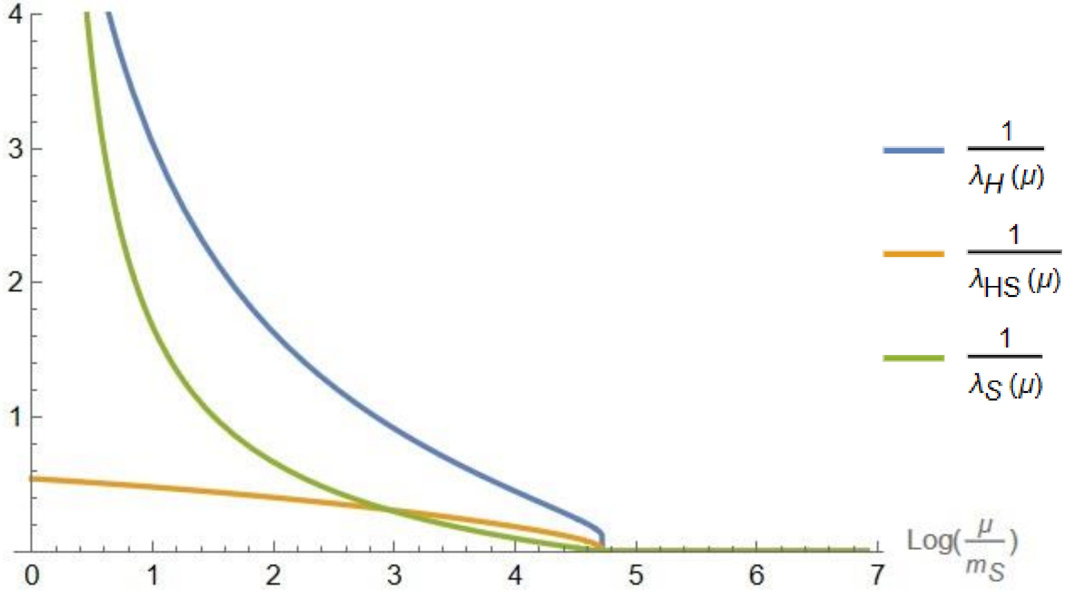
$$\ln(\Lambda) = \ln\left(\frac{\mu}{m_S}\right)$$

$= 4.6$

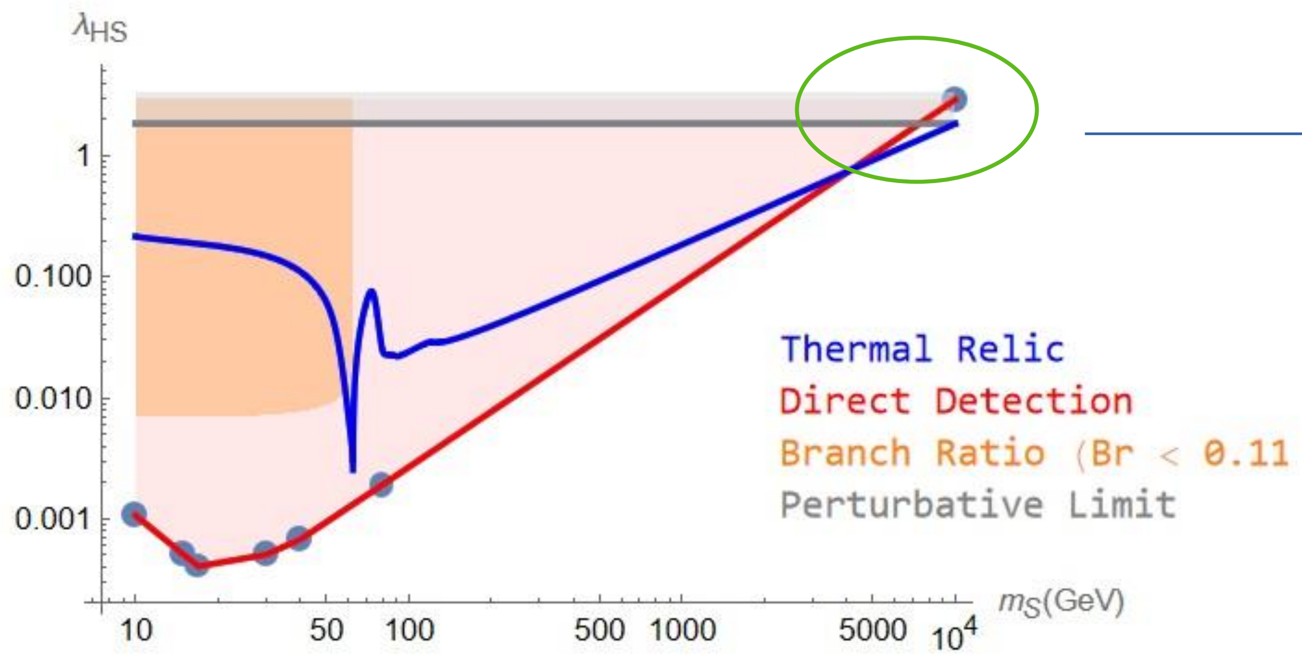
$\downarrow$

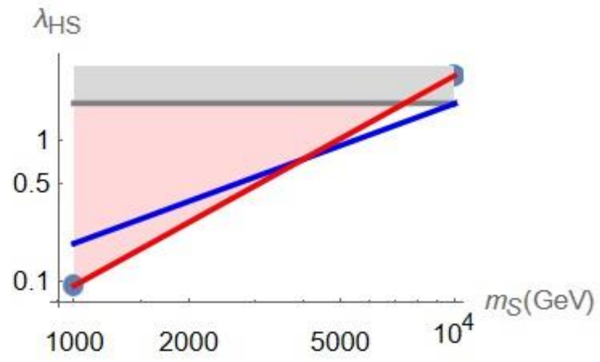
λ_{HS}^{max}
$= 1.85$

$$\mathcal{L}_{\mathcal{I}} \supset -\lambda_{HS} S^2 |H|^2 - \lambda_H |H|^4 - \frac{\lambda_S}{4} S^4$$



Direct Detection

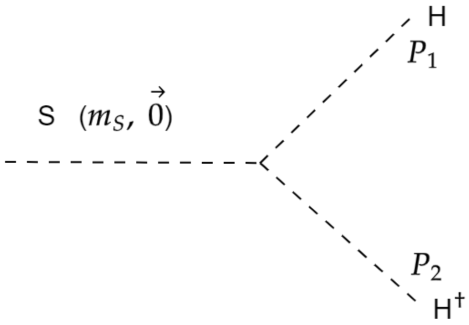


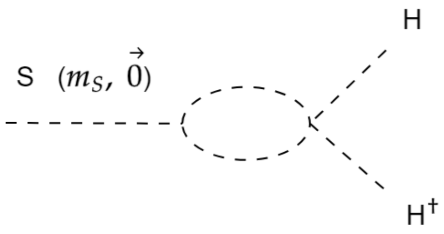


Unstable DM

$$\mathcal{L} \supset -\mu_{HS} S|H|^2 - \mu_S S^3 - \lambda_{HS} S^2 |H|^2 - \lambda_H |H|^4$$

$$\Gamma_{S \to H^\dagger H} < \frac{10^{-42}}{6.6} \mathrm{GeV}$$





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Unstable DM

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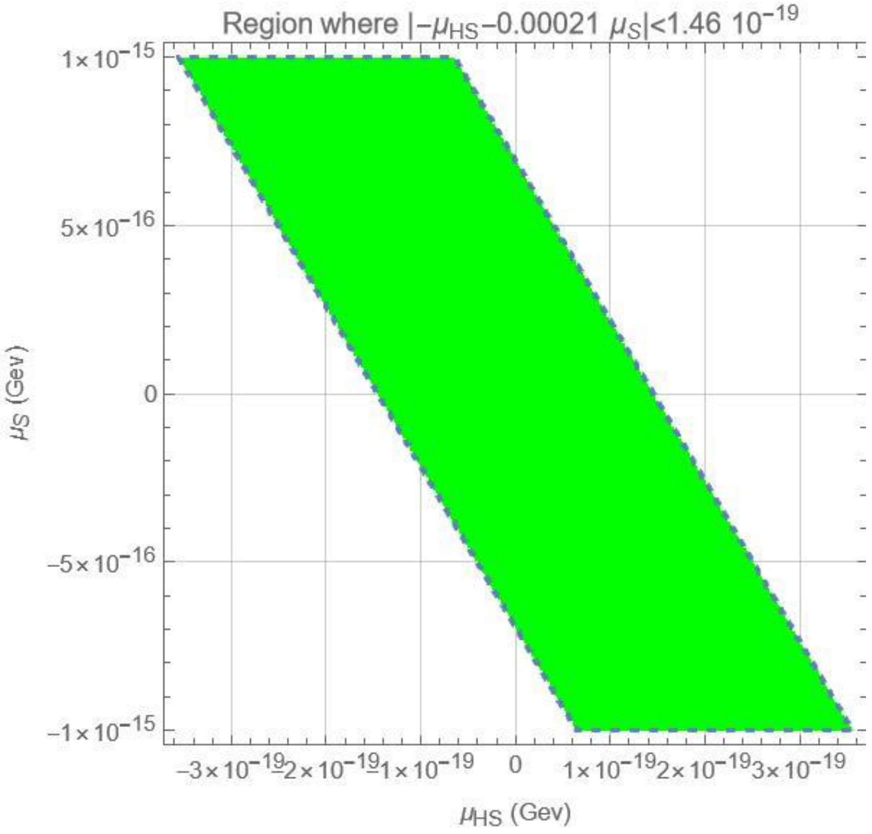

Conclusion

In summary we have...

- ✓ **discussed the evidences.**
- ✓ **defined DM to be Stable Real Scalar.**
- ✓ **found Space of Parameters.**
- ✓ **found the allowed region due to Experimental and Perturbative Limits.**
- ✓ **realized with good approximation DM is stable in this model.**

What next ?!

Nothing! Just enjoy the journey and embrace the storm while smiling...

$$\frac{1}{a^3}\frac{d(na^3)}{dt} = \int d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 \, |\mathcal{M}_{12\to 34}|^2 (f_1 f_2 - f_3 f_4)(2\pi)^4 \delta(\Sigma_{i=initial} P_i - \Sigma_{f=final} P_f)$$

$$d\Pi_i \equiv \frac{g}{(2\pi)^3}\frac{d^3 p_i}{2E_i}$$

$$\frac{dY}{dt} = s\langle\sigma v\rangle (Y_{eq}^2 - Y^2)$$

$$x = \frac{m}{T} \to \frac{dx}{dt} = Hx$$

$$\frac{dY}{dx} = \frac{2\pi^2}{45} g_S^* \frac{m^3 \langle\sigma v\rangle}{x^2 H(m)} (Y_{eq}^2 - Y^2)$$

Boltzmann' Eq.

DM Abundance.

$$\begin{aligned}
\Omega &= \frac{\rho_0}{\rho_{cr}} = \frac{m n_0}{3H_0^2 M_p^2} \\
&= \frac{m s_0}{3H_0^2 M_p^2}\frac{n_0}{s_0} \\
&= \frac{m s_0}{3H_0^2 M_p^2}\left(\frac{2\pi^2}{45} g_S^* \frac{m^3\langle\sigma v\rangle}{x_f H(m)}\right)^{-1} \\
&= \frac{\pi}{9}\frac{x_f}{\langle\sigma v\rangle}\sqrt{\frac{g_S^*(m)}{10}}\frac{g_S^*(T_0)}{g_S^*(m)}\frac{T_0^3}{H_0^2 M_p^3}
\end{aligned}$$

$$\begin{aligned}
\Omega h^2 &= 0.4\frac{\pi}{9}\frac{20}{\langle\sigma v\rangle}\sqrt{\frac{1}{10 g_S^*(m)}}\frac{3.91(2.4\times 10^{-4} ev)^3}{(1.4\times 10^{-33} ev)^2 (2\times 10^{27} ev)^3} \\
&= 3.04412\times 10^{-27} ev^{-2}\frac{1}{\langle\sigma v\rangle\sqrt{g_S^*(m)}}
\end{aligned}$$

$$\mathcal{L} \supset \lambda_{HS} S^2 |H|^2 + (D_\mu H)^\dagger (D^\mu H)$$

$$D_\mu = \begin{pmatrix} \partial_\mu - i\frac{g_1}{2} B_\mu - i\frac{g_2}{2} W_\mu^3 & -i\frac{g_2}{2} W_\mu^+ \\ -i\frac{g_2}{2} W_\mu^- & \partial_\mu - i\frac{g_1}{2} B_\mu + i\frac{g_2}{2} W_\mu^3 \end{pmatrix}$$

$$\begin{aligned} \mathcal{M}_{SS\to WW} &= \frac{2g^2 v}{2} \frac{\lambda_{HS} v}{(s - m_h^2) - i m_h \Gamma} \epsilon_\mu^*(q) \epsilon^\mu(p) \\ &= \frac{4M_W^2}{v} \frac{\lambda_{HS} v}{(s - m_h^2) - i m_h \Gamma} \epsilon_\mu^*(q) \epsilon^\mu(p) \\ |\mathcal{M}|^2_{SS\to WW} &= \frac{4\lambda_{HS}^2 v^2}{(s - m_h^2)^2 + m_h^2 \Gamma^2} (\frac{2M_W^2}{v})^2 (4 - 2\frac{(p.q)}{M_w^2} + \frac{(p.q)^2}{M_w^4}) \end{aligned}$$

$$\Gamma_{SM} = \frac{\lambda^2 v^2}{8\pi m_h} \sqrt{1 - 4\frac{m_S^2}{m_h^2}} \Theta(m_S - 2m_h),$$