Neutrino masse and mixed dark matter from doublet and singlet scalars

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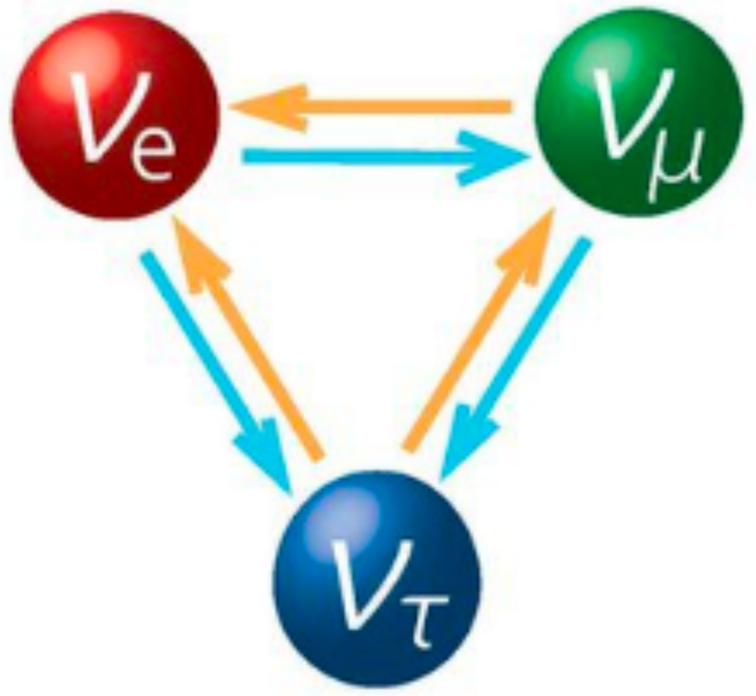
Scalars 2025: Higgs bosons and cosmology
22-25 Sep 2025

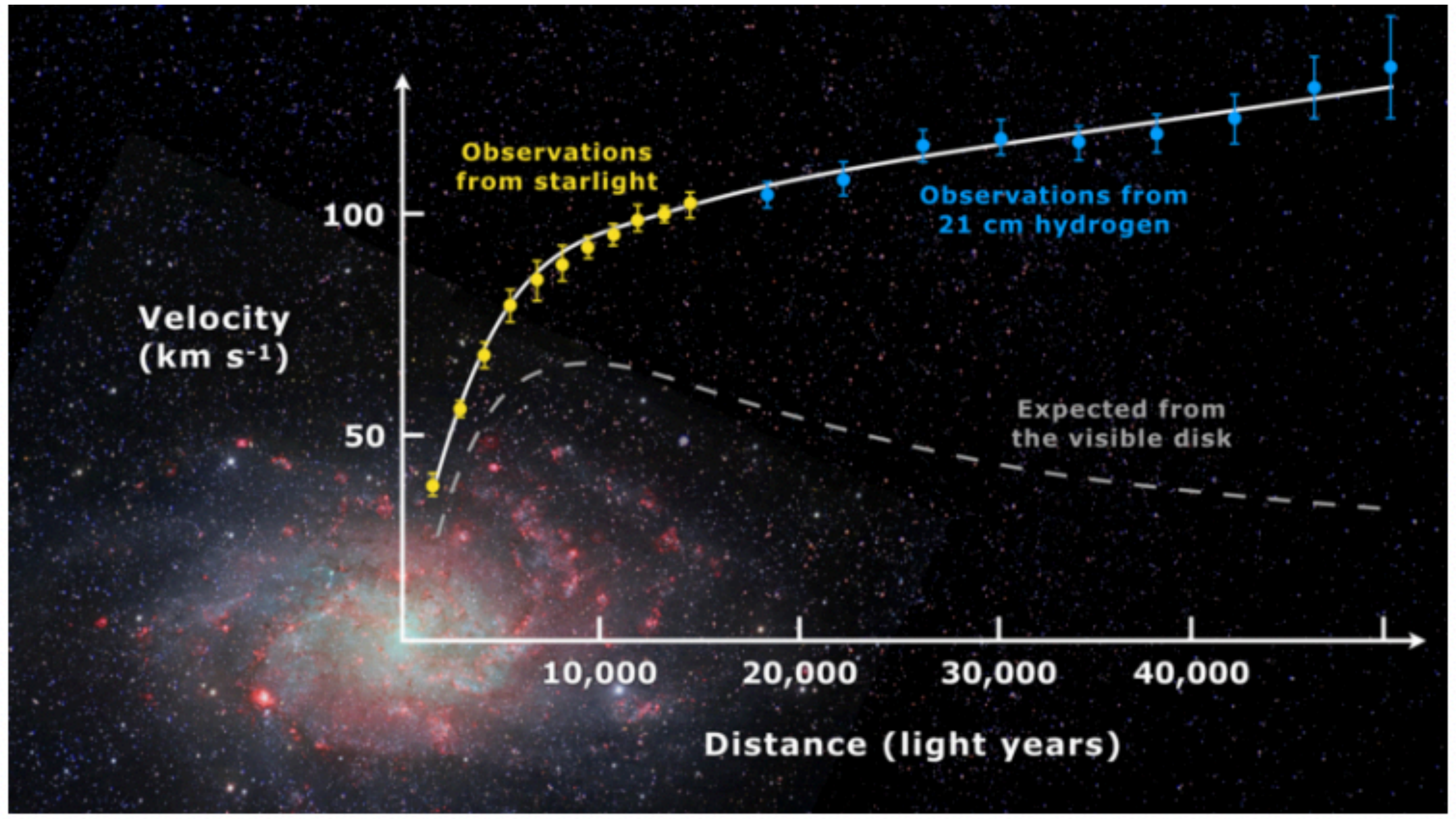
OUT LINE

Motivation



- ❖ eV scale light neutrino mass
- ❖ Measured Dark matter relic density
  $\Omega h^2 = 0.1199 \pm 0.0012$
- ❖ Baryon Asymmetry of universe:

  $\eta_B \simeq 6.1 \times 10^{-10}$



In a common framework…

Model

- BSM Model with SM gauge group + Z_4 symmetry

	S	φ	H_1	H_2	N_R
Z_4	i	-1	$+1$	i	i
Z_2	-1	$+1$	$+1$	-1	-1

$$H_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_H + h \end{pmatrix}$$ **SM Higgs**

EW symmetry breaking

$$\varphi = v_\varphi + \rho$$ **Real Singlet scalar**

$Z_4 \to Z_2$ *breaking*

$$S = \frac{1}{\sqrt{2}}(s + ia)$$ **Complex Singlet scalar**

$$H_2 = \begin{pmatrix} H^+ \\ (H_0 + iA_0)/\sqrt{2} \end{pmatrix}$$ **Inert Doublet**

Lightest Z_2 odd scalar is DM candidate

$N_R \to$ **neutrino mass and leptogenesis**

Heavier than the Z_2 odd scalars

Interaction

- Scalar potential

$$V_1 = \sum_{i=1,2} (m_i^2 |H_i|^2 + \lambda_i |H_i|^4) + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right)$$

$$V_2 = m_S^2 |S|^2 + \lambda_S |S|^4 + m_\varphi^2 \varphi^2 + \lambda_\varphi \varphi^4 + \underline{\lambda_{S\varphi} |S|^2 \varphi^2}$$

$$+ \sum_{i=1,2} \left[\underline{\lambda_{H_iS}\left(H_i^\dagger H_i\right)|S|^2} + \underline{\lambda_{H_i\varphi}\left(H_i^\dagger H_i\right)\varphi^2}\right] \longrightarrow \varphi - H_1 \text{ mass mixing}$$

$$V_3 = -\underline{\sqrt{2}\kappa S^\dagger H_1^\dagger H_2 - \sqrt{2}\lambda'_{S\varphi}\varphi S H_1^\dagger H_2} + \mu\,\varphi S^2 + \mathrm{h.c.}$$

$$\lambda_5 \left(\cancel{\left(H_1^\dagger H_2\right)^2 + h.c.} \right)$$

Absent unlike IDM

$$m_{H_0} = m_{A_0}$$

CP odd and even components of H_2 are degenerate

$$\mathscr{L}_{\mathrm{Yuk}} = -y_N \bar{l}\widetilde{H}_2 N_R - \lambda_N \varphi \overline{N_R^c} N_R + \mathrm{h.c.} \longrightarrow Z_4 \text{ forbids bare mass of } N_R$$

$Z_4 \to Z_2$

- v_φ spontaneously breaks $Z_4 \to Z_2$

RHN mass generated

$$\mathscr{L} \supset \sqrt{2}\kappa S^\dagger H_1^\dagger H_2 + \sqrt{2}\kappa' S H_1^\dagger H_2 + \frac{1}{2}\hat{m}_S^2 S^2 - \frac{1}{2}\lambda_N(\varphi + v_\varphi)\overline{N_R^c}N_R$$

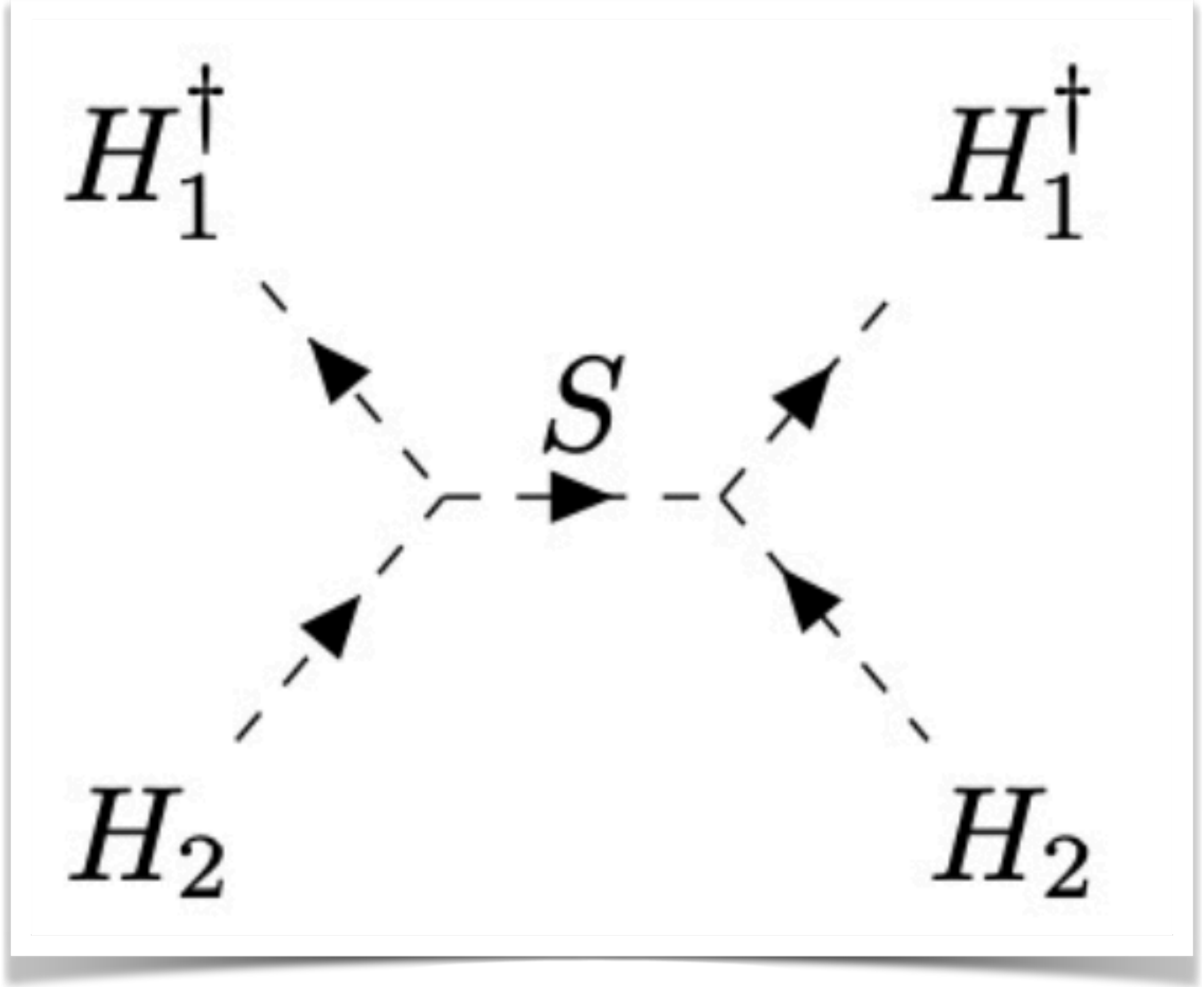
$$\kappa' = \lambda'_{S\varphi} v_\varphi \qquad \hat{m}_S^2 = 2\mu v_\varphi$$

Non-zero κ' and $\hat{m}_S^2$ crucial for mass splitting b/w neutral components of H_2

- S is decoupled, $m_S^2 \gg m_{H_0}^2, \hat{m}_S^2$

$$\mathscr{L}_{\rm eff} = -\frac{1}{2}\lambda_{5,\rm eff}(H_1^\dagger H_2)^2 + \mathrm{h.c.}$$

$$\lambda_{5,\rm eff} = \frac{2\hat{m}_S^2(\kappa^2 + \kappa'^2)}{m_S^4} - \frac{4\kappa\kappa'}{m_S^2}$$



Scalar Mixing

- SM Higgs mixing with the singlet Higgs,

$$\tan 2\alpha = \frac{2v_H v_\varphi \lambda_{H_1\varphi}}{m_h^2 - m_\varphi^2}$$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ \rho \end{pmatrix}$$

Assume $s_\alpha = 0$

- CP-even Dark Scalar mixing

$$\tan 2\theta_s = \frac{2(\kappa + \kappa')v_H}{m_{H_0}^2 - m_s^2}$$

$$\begin{pmatrix} H_0 \\ s \end{pmatrix} = \begin{pmatrix} \cos\theta_s & -\sin\theta_s \\ \sin\theta_s & \cos\theta_s \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

Notation: $H_{1,2}$ is mass eigen state not Higgs doublet

- CP-odd Dark Scalar mixing

$$tan2\theta_a = \frac{2(\kappa - \kappa')v_H}{m_{H_0}^2 - m_a^2}$$

$$\begin{pmatrix} A_0 \\ a \end{pmatrix} = \begin{pmatrix} \cos\theta_a & -\sin\theta_a \\ \sin\theta_a & \cos\theta_a \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \end{pmatrix},$$

Scalar Mass Spectrum

- SM Higgs and BSM Singlet Higgs

$$m^2_{h_1,h_2} = \frac{1}{2}\left[m_h^2 + m_\varphi^2 \pm (m_h^2 - m_\varphi^2)\sqrt{1 + \frac{4v_H^2 v_\varphi^2 \lambda_{H_1\varphi}^2}{(m_h^2 - m_\varphi^2)^2}}\right]$$

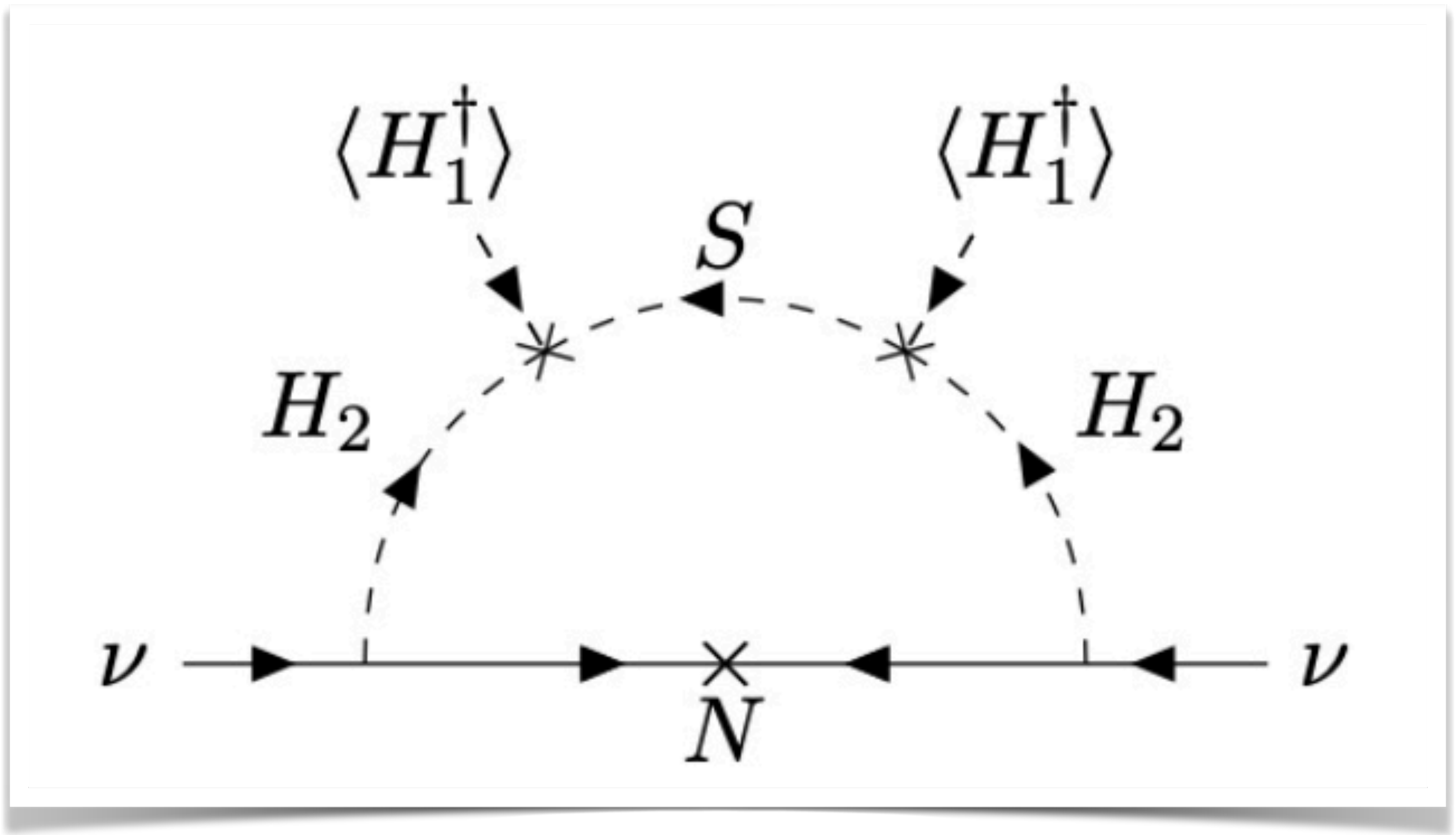
- Z_2 odd Scalars

$$m^2_{H_{1,2}} = \frac{1}{2}\left[m_{H_0}^2 + m_s^2 \pm (m_{H_0}^2 - m_s^2)\sqrt{1 + \frac{4(\kappa + \kappa')^2 v_H^2}{(m_{H_0}^2 - m_s^2)^2}}\right]$$

$$m^2_{A_{1,2}} = \frac{1}{2}\left[m_{H_0}^2 + m_a^2 \pm (m_{H_0}^2 - m_a^2)\sqrt{1 + \frac{4(\kappa - \kappa')^2 v_H^2}{(m_{H_0}^2 - m_a^2)^2}}\right]$$

Neutrino mass @1-loop

$$\mathscr{L} \supset -y_N \bar{l}\widetilde{H}_2 N_R - \frac{1}{2}\lambda_{5,\text{eff}}(H_1^\dagger H_2)^2$$



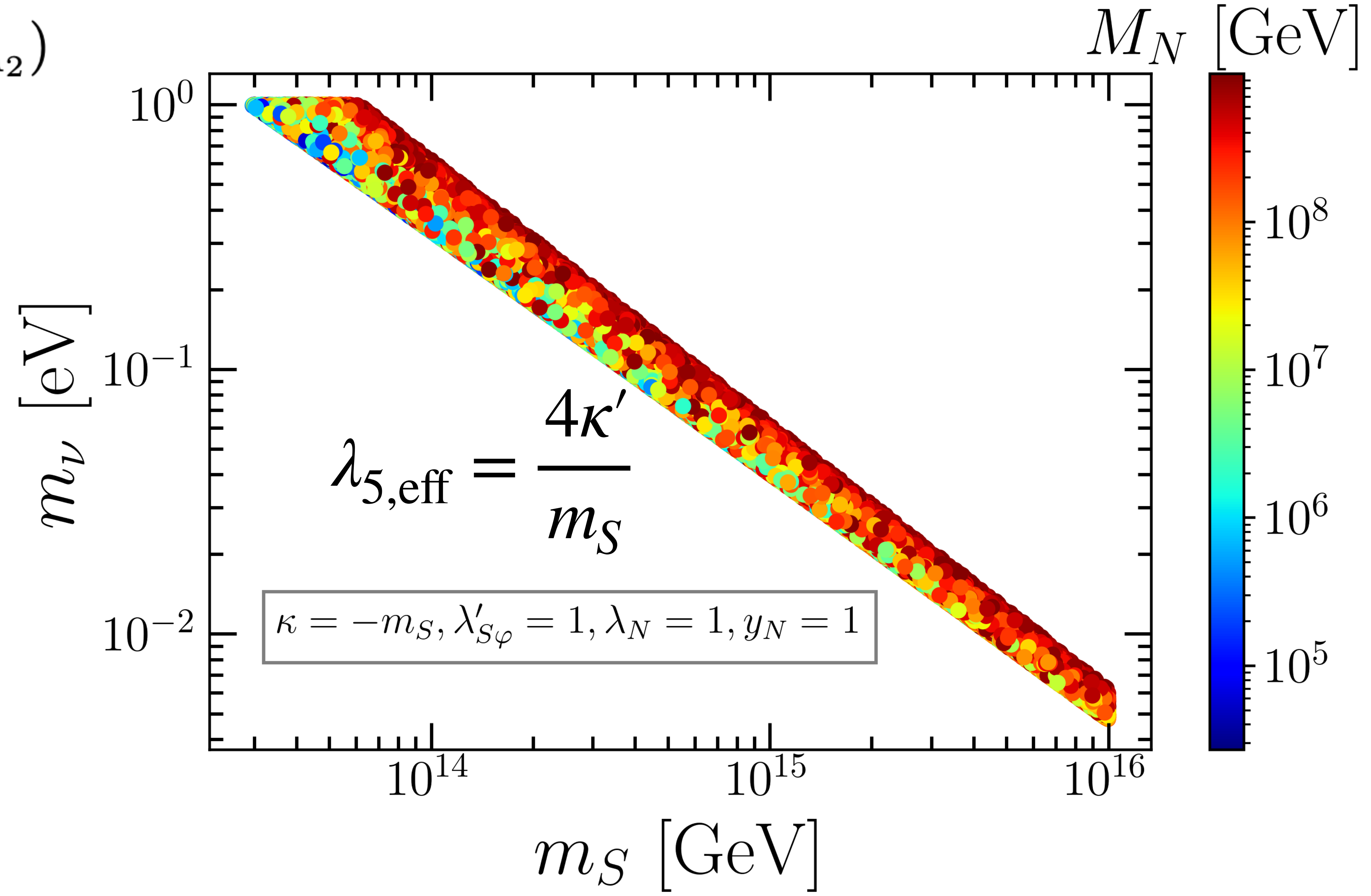
$$(\mathcal{M}_\nu)_{ij} = \frac{1}{16\pi^2}\sum_\alpha \sum_k y_{N,ik} y_{N,jk} M_{N,k} F_\alpha \left[\frac{m_\alpha^2}{m_\alpha^2 - M_{N,k}^2} \ln \frac{m_\alpha^2}{M_{N,k}^2}\right]$$

$F_\alpha \equiv (\cos^2\theta_s, \sin^2\theta_s, -\cos^2\theta_a, -\sin^2\theta_a)$ and $m_\alpha \equiv (m_{H_1}, m_{H_2}, m_{A_1}, m_{A_2})$

- decoupling limit of the singlet scalar S and $M_N \gg m_0$

$$M_\nu \simeq \frac{\lambda_{5,\text{eff}} v_H^2}{16\pi^2}\frac{y_N^2}{M_N}\left[\ln\frac{M_N^2}{m_0^2} - 1\right]$$

Here m_0 is IDM mass scale



Baryon Asymmetry

Via thermal Leptogenesis

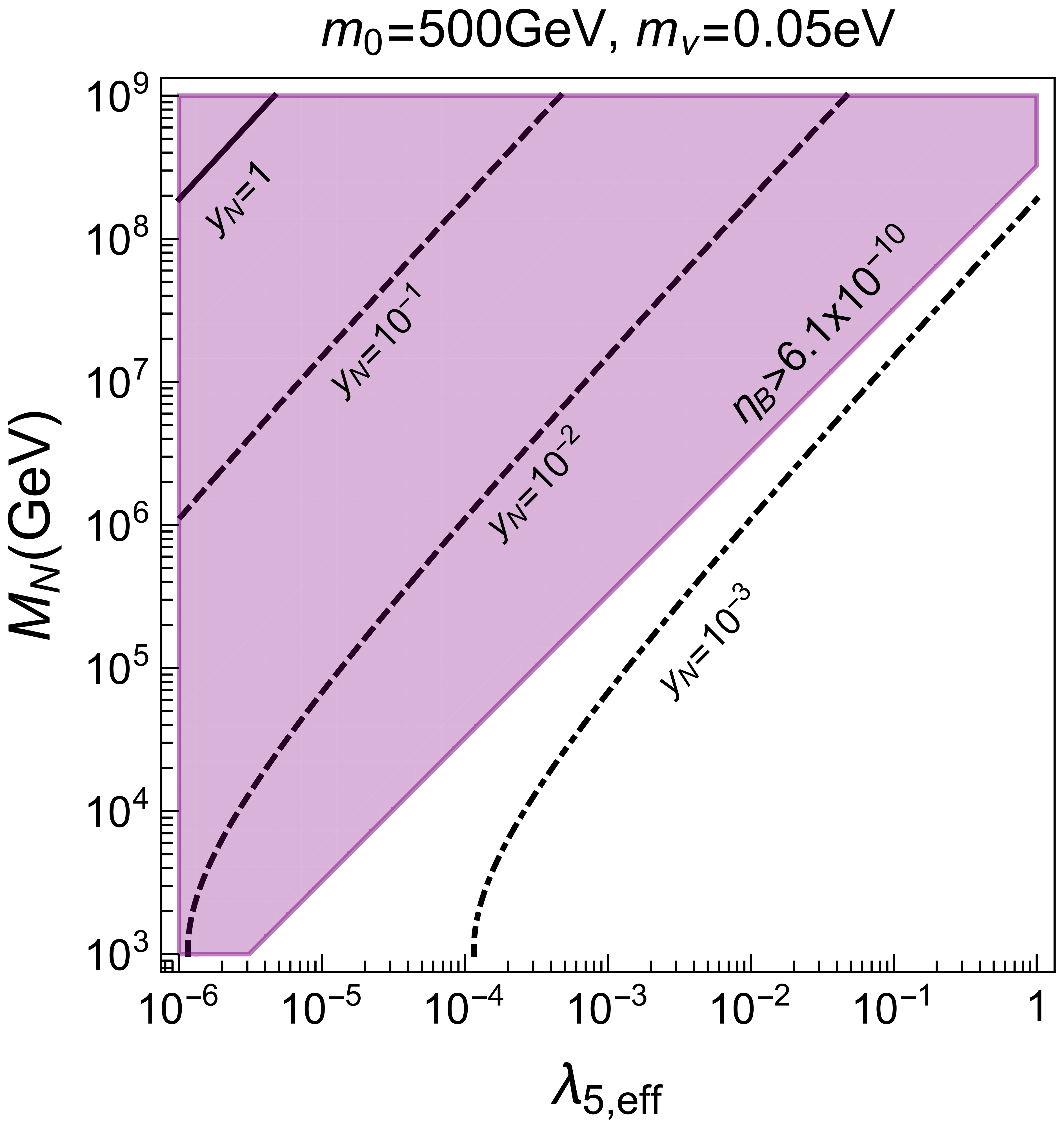
[M. Fukugita, T. Yanagida]

- ➢ baryon-to-photon ratio : $\eta_B = -C\epsilon_1\kappa_1$
- ➢ After optimizing over the Casas-Ibarra parameters

$$\eta_B \simeq 3.8 \times 10^{-10}\left(\frac{M_N}{10^4\,\mathrm{GeV}}\right)\left(\frac{10^{-4}}{\lambda_{5,\mathrm{eff}}}\right)\left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right)$$

[T. Hugle, 1804.09660]

(washout effects from $\Delta L = 2$ process not included)



Theory Constraints

- **Vacuum stability:** quartic part of potential $V_4 \geq 0$ (i.e. co-positivity of matrix X)

$$V_4 = R^T X R, \text{ with } R = [r^2, \rho^2]$$

Such as

$$\{\lambda_1 \geq 0, \lambda_S \geq 0, \frac{\lambda_{H_1 S}}{2} + \sqrt{\lambda_1 \lambda_S} \geq 0\}, \text{ for } \alpha = 0 \text{ and } \beta = 0,$$

- **Perturbative unitarity:** Eigen values of the $2 \to 2$ scalar scattering matrix

$$\mathcal{E}_1 = \left\{ 2\lambda_1, 2\lambda_2, , 2\lambda_s, 2\lambda_\varphi, \lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + \lambda_4^2} \right\} < 8\pi$$

- **Electroweak Precision:** EW gauge boson self-energy is modified

$$S_{\rm exp} = -0.05 \pm 0.07 \text{ and } T_{\rm exp} = 0.00 \pm 0.06, \text{ for } U = 0$$

[PDG 2024]

Dark Sector Bound

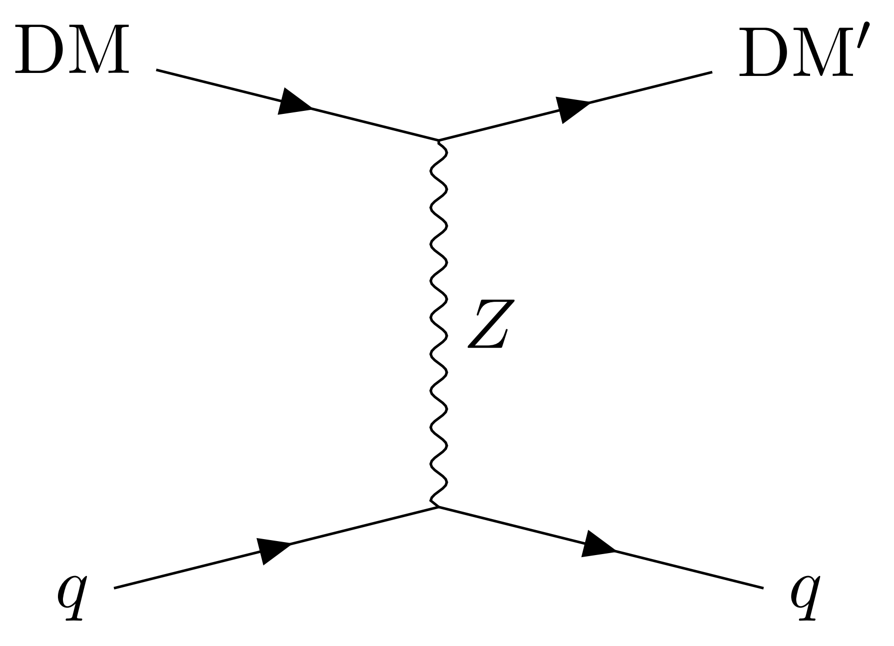
- DM relic density: $\Omega h^2 = 0.1199 \pm 0.0012$

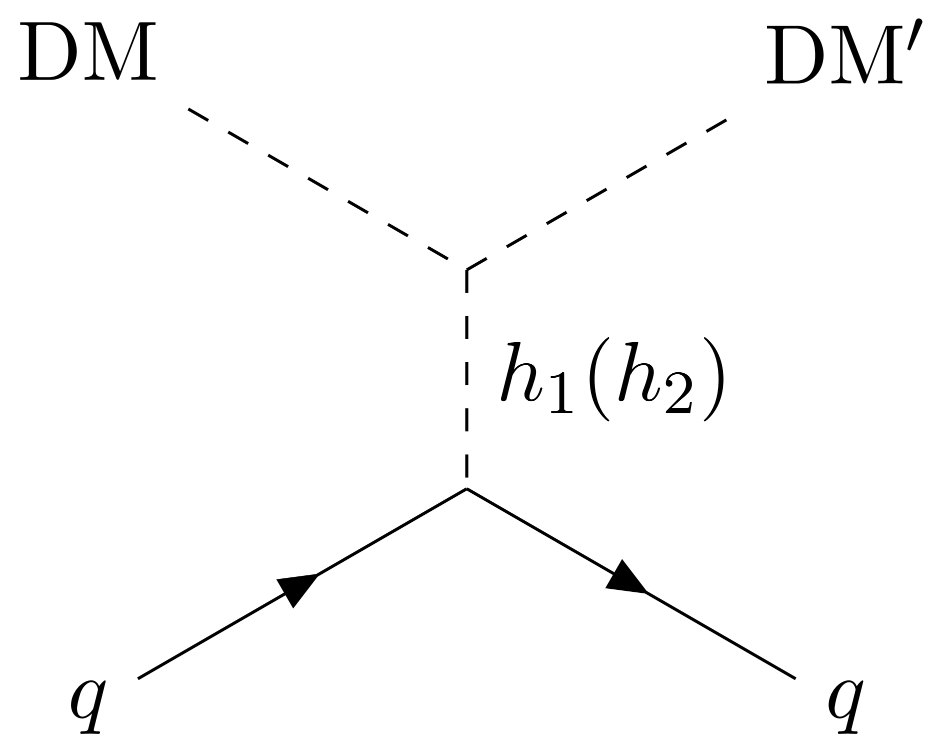
Additional channels

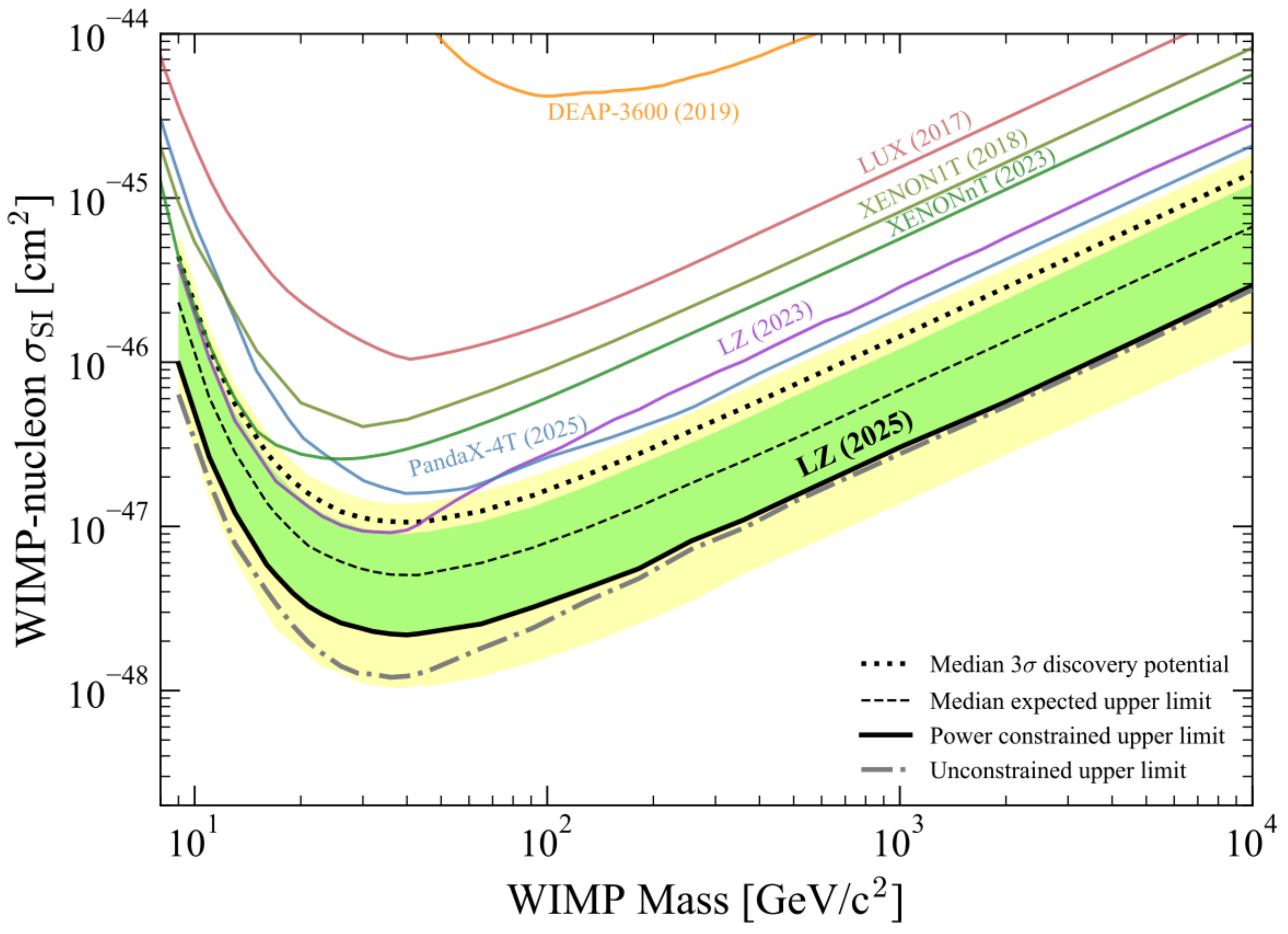
Annihilation $$\mathrm{DM}\ \mathrm{DM} \to SM\ SM, h_2 h_2, h_1 h_2$$

co-annihilation $$DM\ DM' \to SM\ SM, h_2 h_2, h_1 h_2$$

- Direct detection:







$\Delta m > 100$ KeV kinematically suppressed

- Indirect detection:

$$\mathrm{DM}\ \mathrm{DM} \to h_2 h_2, \quad h_2 \to \gamma\gamma$$

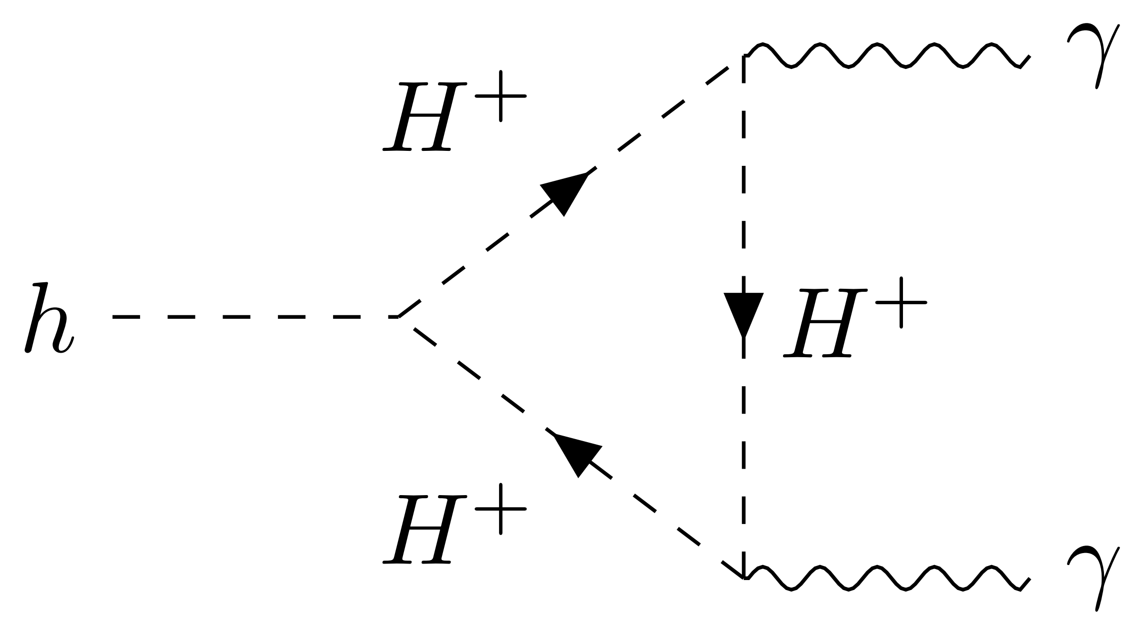
Good sensitivity at CTA expected

Collider Bound

- **LEP:** $e^+e^- \to H^+H^-/H_iA_i$ $\boxed{M_{H^\pm} > 70\,\mathrm{GeV}}$ [JHEP 08 (2007) 026]

For $|M_{H_1} - M_{A_1}| \geq 8\,\mathrm{GeV}$ $\boxed{M_{H_1} \leq 80\,\mathrm{GeV} \text{ and } M_{A_1} \leq 100\,\mathrm{GeV}}$ [PRD 2009]

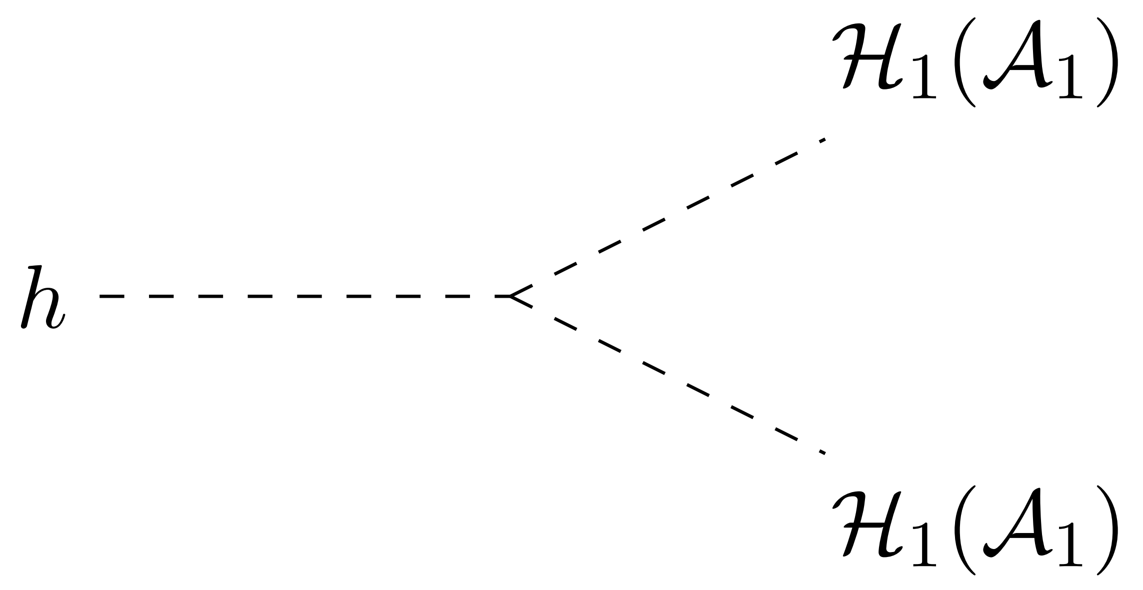
- **Higgs signal strength:** $\boxed{\mu_{\gamma\gamma} = 1.1 \pm 0.06}$ [PDG 2024]



$$\mu_{\gamma\gamma} = \frac{\sigma}{\sigma^{\mathrm{SM}}}\frac{\mathrm{Br}(h\to\gamma\gamma)}{\mathrm{Br}^{\mathrm{SM}}(h\to\gamma\gamma)} = \cos^2\alpha\,\frac{\mathrm{Br}(h\to\gamma\gamma)}{\mathrm{Br}^{\mathrm{SM}}(h\to\gamma\gamma)}$$

- **$h \to$ inv decay rate:** [PDG 2024]

$$\boxed{\mathrm{Br}(\mathrm{h} \to \mathrm{invisible}) < 0.107}$$



Benchmark

No mixing Small mixing

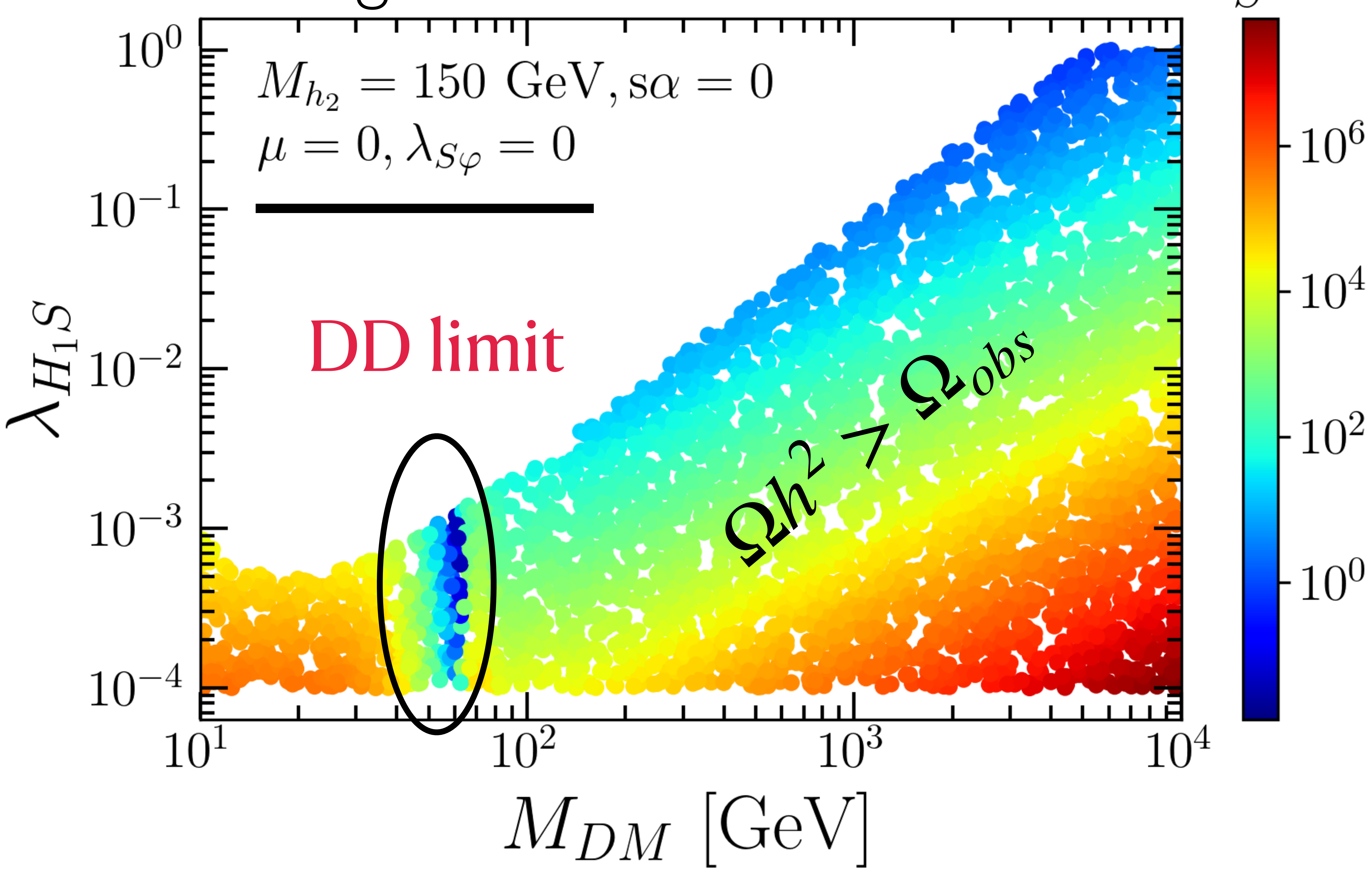
Parameters	Scenario I	Scenario II	Bi-Maximal	Maximal	Scenario IV
$(m_{H_0}/\mathrm{GeV})^2$	31623^2	$[1, 10^8]$	$[1, 10^8]$	$[1, 10^8]$	$[1, 10^8]$
$(m_S/\mathrm{GeV})^2$	$[1, 10^8]$	$[10^{10}, 10^{20}]$	m_2^2	m_2^2	$[1, 10^8]$
κ/GeV	0	$-m_S$	$-[10^{-4}, 1]$	$-[10^{-4}, 1]$	$[1, 10^6]$
μ/GeV	$0(-1)$	0	0	$[1, 10^4]$	10^2
v_φ/GeV	106	$[10^2, 10^9]$	10^3	10^3	10^4
m_{h_2}/GeV	150	150	150	150	150
λ_2	0	$[10^{-4}, 4\pi]$	$[10^{-4}, 4\pi]$	$[10^{-4}, 4\pi]$	$[10^{-4}, 4\pi]$
λ_S	0	$[10^{-4}, 4\pi]$	$[10^{-4}, 4\pi]$	$[10^{-4}, 4\pi]$	$[10^{-4}, 4\pi]$
$\lambda_{H_1\varphi}$	0	0	0	0	0
λ_{H_2S}	0	$[10^{-4}, 4\pi]$	$[10^{-4}, 4\pi]$	$[10^{-4}, 4\pi]$	$[10^{-4}, 4\pi]$
λ_{H_1S}	$[10^{-4}, 1]$	$[10^{-4}, 4\pi]$	$[10^{-4}, 4\pi]$	$[10^{-4}, 4\pi]$	$[10^{-4}, 4\pi]$
λ_4	-0.01	$-[10^{-4}, 4\pi]$	$-[10^{-6}, 4\pi]$	$-[10^{-6}, 4\pi]$	$-[10^{-4}, 4\pi]$
λ_3	0.1	$[10^{-4}, 4\pi]$	$\lambda_{H_1S} - \lambda_4$	$\lambda_{H_1S} - \lambda_4$	$[10^{-4}, 4\pi]$
$\lambda'_{S\varphi}$	0	$[10^{-4}, 4\pi]$	$[10^{-7}, 10^{-3}]$	$[10^{-7}, 10^{-3}]$	$[10^{-4}, 4\pi]$
κ'/GeV	0	$[0.005, 6.2 \times 10^9]$	$[0.5 \times 10^{-4}, 0.5]$	$[0.5 \times 10^{-4}, 0.5]$	$[0.5, 6.2 \times 10^4]$
$\lambda_{S\varphi}$	$[10^{-2}, 4\pi]$	$[10^{-4}, 4\pi]$	$[10^{-4}, 1]$	$[10^{-4}, 1]$	$[10^{-4}, 1]$
$\lambda_{H_2\varphi}$	4π	$[10^{-4}, 4\pi]$	$\lambda_{S\varphi}$	$\lambda_{S\varphi} - 4\mu/v_\varphi$	0

[Numerical calculation: SARAH,CalcHEP,MicroOmegas]

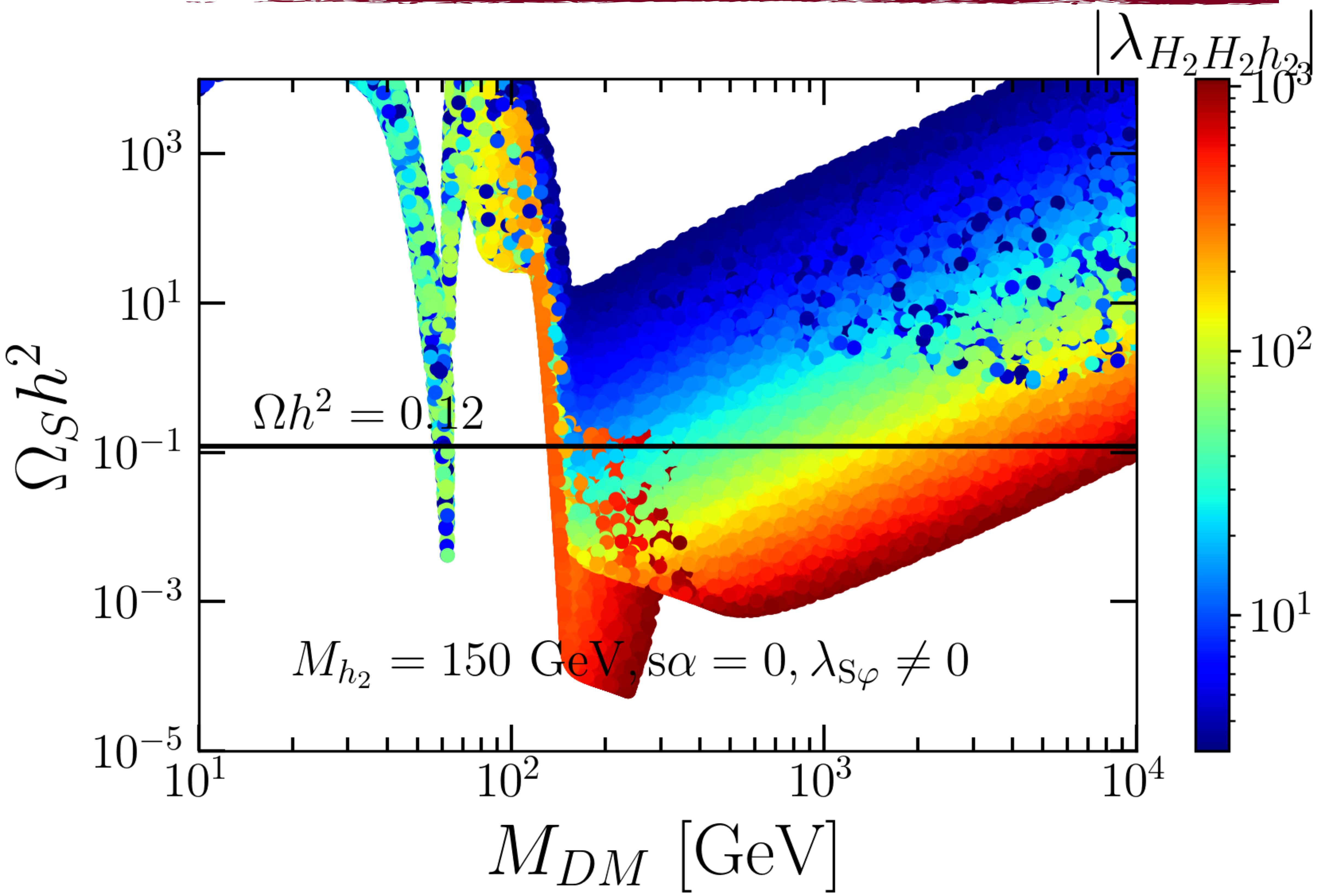
Scenario-1

- $\kappa = \kappa' = 0$ (no mixing b/w Dark Scalars) Neutrino mass is zero
- $m_{H_2} < m_{A_2}, m_{A_2} < m_{H_1} = m_{A_1}$:
  $\rightarrow H_2$ is singlet like DM

Singlet Scalar DM

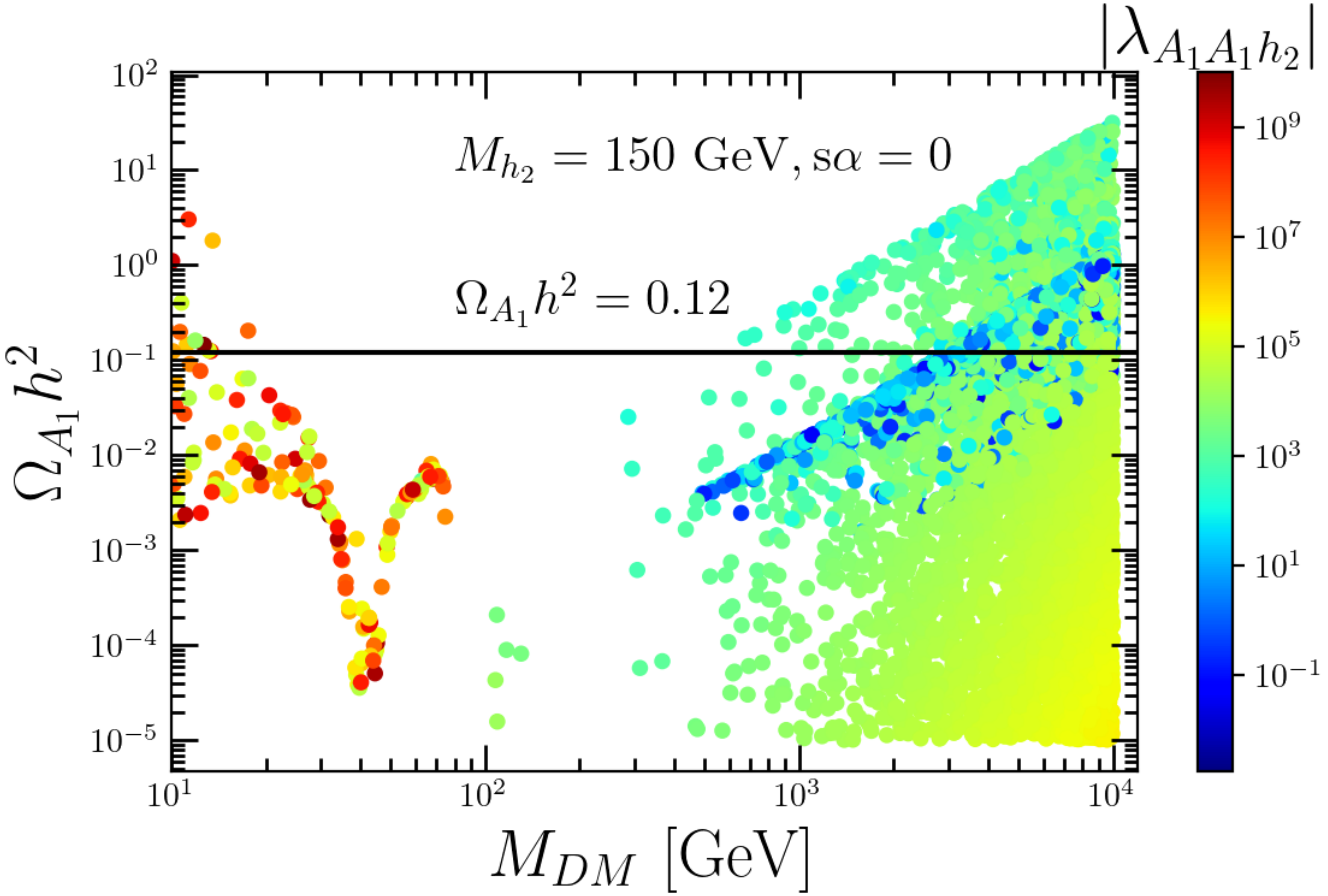


$H_2H_2 \rightarrow h_2h_2$
Is crucial to set observed relic density



Scenario-II

- $\kappa \neq \kappa' \neq 0$ (small mixing b/w Dark Scalars) Neutrino mass non-zero
- $m_{H_2}, m_{A_2} > m_{H_1} > m_{A_1}$: $\rightarrow A_1$ is doublet like DM
- $\lambda_{H_2\varphi} = 0$: $\rightarrow$ Inert Doublet model
- $\lambda_{H_2\varphi} \neq 0$: Observed relic can be adjusted in the overabundance regime of IDM via additional channel $\mathrm{A_1A_1} \rightarrow h_2h_2$, which **opens up wider parameter space**



Scenario-III

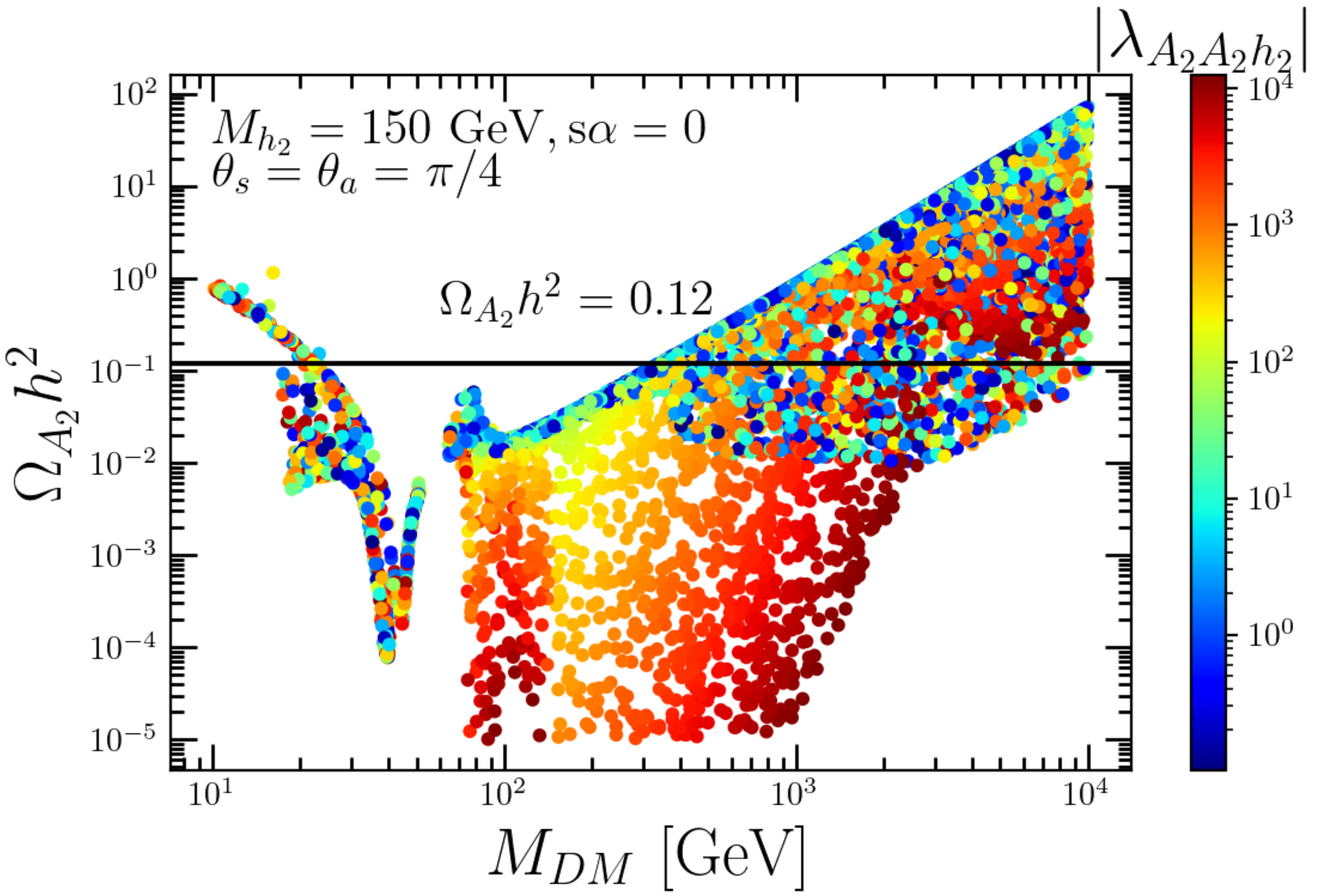
- θ_s and/or $\theta_a = \pi/4$ (Maximal mixing b/w Dark Scalars)

Neutrino mass non-zero

- $for\ \theta_s = \theta_a = \pi/4 \to m_{H_0} = m_a = m_s,\ if\ \kappa\kappa' < 0,$ $\to A_2$ is mixed DM

$A_2A_2 \to h_2h_2$

Can have dominant contribution to the annihilation cross section



Summary

- We proposed Z4 model to explain neutrino mass, Dark matter and Baryon Asymmetry.
- As a consequence of Z_4 breaking, a small effective LNV interaction is generated which is crucial for neutrino mass generation at one-loop level.
- Presence Scalar φ gives additional DM annihilation modes, ID signal and opens up wider parameter space where DM relic can be adjusted to observed value.

Thank You!!