Neutrinophilic 2HDM and Dark Matter

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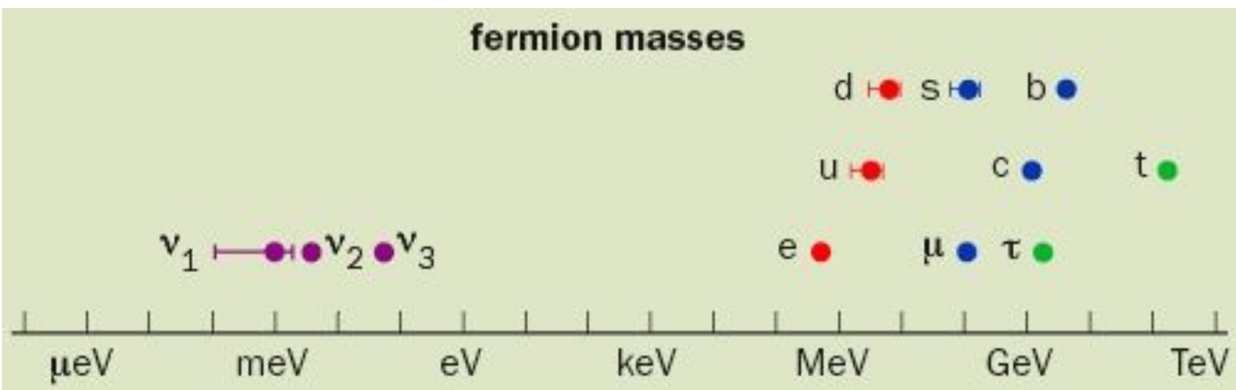
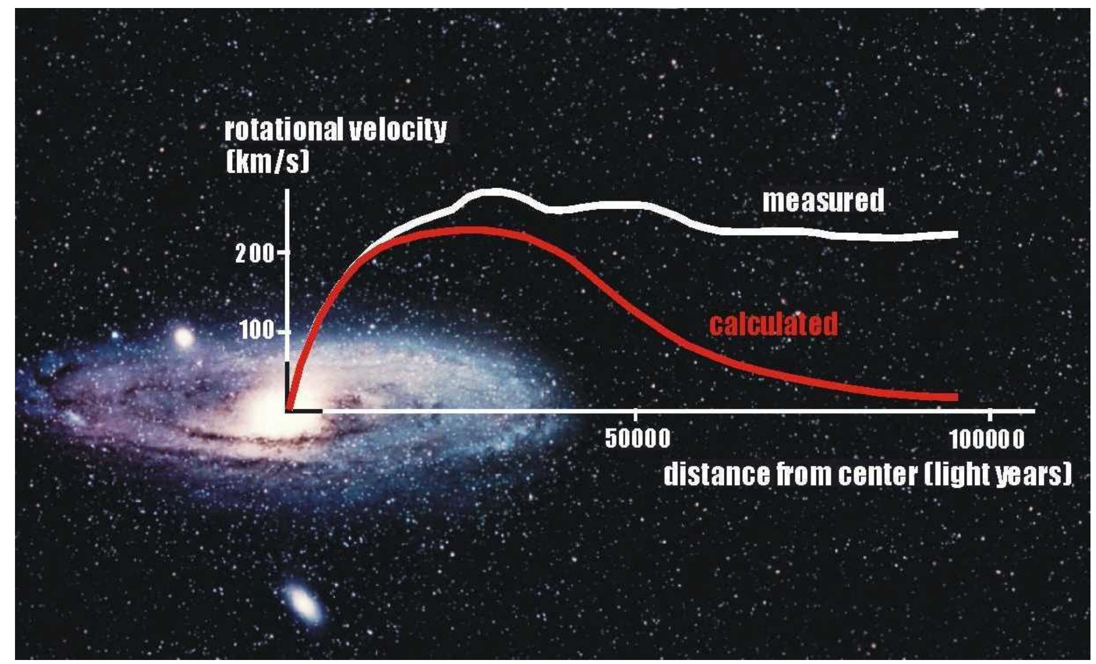
SB, Takaaki Nomura, JHEP 1703 (2017) 059 [arXiv:1611.09145]

Neutrino and Dark Matter

- Two of the SM problems: neutrino mass, dark matter





- Why are neutrinos so light? Are they Dirac or Majorana?

- What is the nature of dark matter?

Neutrino mass: Dirac or Majorana?

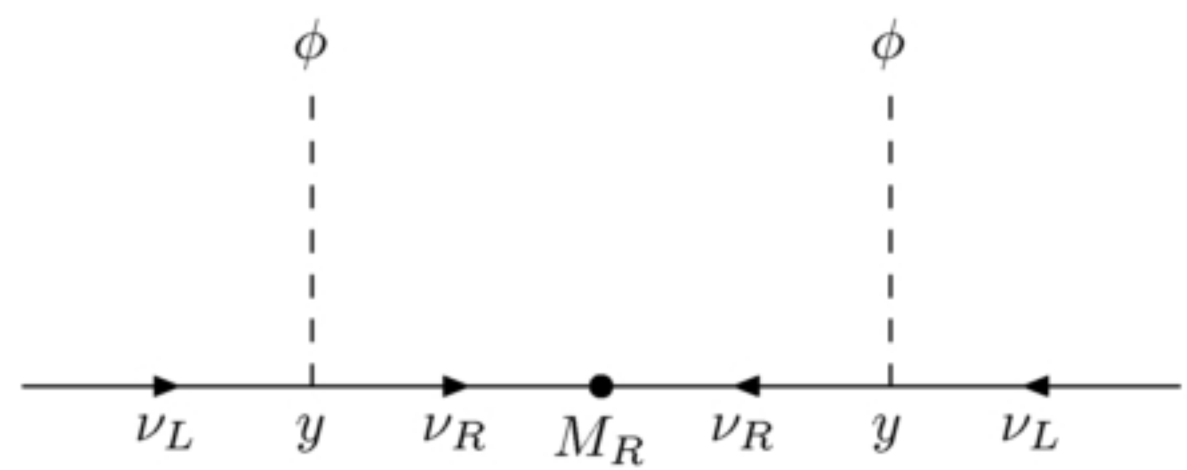
- A model of Dirac neutrino

$$\mathcal{L}_Y = -\overline{Q}_L Y^u \widetilde{\Phi}_2 u_R - \overline{Q}_L Y^d \Phi_2 d_R - \overline{L}_L Y^e \Phi_2 e_R - \overline{L}_L Y^\nu \widetilde{\Phi}_2 \nu_R + h.c.$$

  - Majorana mass term for ν_R may be eliminated by L
  - Neutrino masses➔ $|Y^\nu_{ij}| \lesssim 10^{-11}$
- The most natural scenario for neutrino mass is seesaw mechanism
- Type I seesaw

$$\mathcal{L} = -y_\nu L H \nu_R - \frac{1}{2} M_R \nu_R \nu_R$$

$$m_\nu \sim \frac{y_\nu^2 v^2}{M_R}$$



- Neutrinos are Majorana fermions: can be tested at neutrinoless double beta decay experiments
- If M≫m_{EW}, it is difficult to test at colliders.

Minimal Dirac neutrino model

- Minimal model for Dirac neutrino masses Davidson, Logan (2009)
- ν_R, Φ_1: charge +1 under global $U(1)_X$, all the SM fields neutral
- $U(1)_X$ symmetry forbids Majorana mass terms for ν_R and enforces Φ_1 coupling only to ν_R

$$-\overline{L}_L Y^\nu \widetilde{\Phi}_2 \nu_R \to -\overline{L}_L Y^\nu \widetilde{\Phi}_1 \nu_R$$

- The global $U(1)_X$ is broken softly by $m_{12}^2 \Phi_1^\dagger \Phi_2$

$$v_1 = \frac{m_{12}^2 v_2}{M_A^2}$$

- For M_A~100 GeV, m_{12}~O(100) keV, v_1~eV can be achieved
- $m_{12} \to 0$ restores $U(1)_X$. Small m_{12} is technically natural
- New ew scale scalars can be probed at colliders

Our model

	Scalar Fields			New Fermion	
	Φ_1	Φ_2	S	ν_R	ψ
$SU(2)_L$	**2**	**2**	**1**	**1**	**1**
$U(1)_Y$	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0
$U(1)_X$	2	0	2	2	1

- $U(1)_X$ is spontaneously broken by v_S

$m_{12}{}^2=\mu\langle S\rangle$

$$V(\Phi_1,\Phi_2,S) = -m_{11}^2\Phi_1^\dagger\Phi_1 - m_{22}^2\Phi_2^\dagger\Phi_2 - m_S^2 S^\dagger S - (\mu\Phi_1^\dagger\Phi_2 S + h.c.)$$
$$+\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2 + \lambda_4\Phi_1^\dagger\Phi_2\Phi_2^\dagger\Phi_1 + \lambda_S(S^\dagger S)^2$$
$$+\lambda_{1S}\Phi_1^\dagger\Phi_1 S^\dagger S + \lambda_{2S}\Phi_2^\dagger\Phi_2 S^\dagger S,$$

$$\mathcal{L} \supset -y_{ij}^e\bar{L}_i\Phi_2 e_{Rj} - y_{ij}^\nu\bar{L}_i\tilde{\Phi}_1\nu_{Rj} + h.c,$$

$$\boxed{\mathcal{L} \supset \bar{\psi}i\gamma^\mu\partial_\mu\psi - m_\psi\bar{\psi}\psi - \frac{f}{2}\bar{\psi}^c\psi S^\dagger - \frac{f^*}{2}\bar{\psi}\psi^c S.}$$

$U(1)_X \rightarrow Z_2$ stabilize the DM.

- Neutrino Dirac mass and DM stability are linked together.

Naturalness and spectra

- Small v_1 results from small $\mu \ll v_2, v_S$(~EW scale)

$$v_1 \simeq \frac{\mu \langle S \rangle v_2}{m_A^2}$$

- μ=0 increases the symmetry: $U(1)_S$ where only S is charged➔ small μ is technically natural

Scalar spectrum

- Scalar field decomposition

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + h_1 + i a_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + i a_2) \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}} r_S e^{i \frac{a_S}{v_S}}$$

- Pseudo-scalar

$$A \simeq a_1 - \frac{v_1}{v_2} a_2 - \frac{v_1}{v_S} a_S \approx a_1$$:Physical pseudo-scalar

$$G^0 \simeq \frac{v_1}{v_2} a_1 + a_2 \approx a_2$$:NG eaten by Z

$$a \simeq \frac{v_1}{v_S} a_1 + a_S \approx a_S$$:Physical Goldstone boson

$$m_A^2 \simeq \frac{1}{2}\left(-2m_{11}^2 + (\lambda_3 + \lambda_4) v_2^2 + \lambda_{1S} v_S^2\right)$$: ew scale

Scalar spectrum

- Scalar field decomposition

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + h_1 + ia_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + ia_2) \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}} r_S e^{i\frac{a_S}{v_S}}$$

- Charged scalar

$$H^\pm \simeq \phi_1^\pm - \frac{v_1}{v_2}\phi_2^\pm \approx \phi_1^\pm$$:Physical charged scalar

$$G^\pm \simeq \frac{v_1}{v_2}\phi_1^\pm + \phi_2^\pm \approx \phi_2^\pm$$:NG eaten by $W^\pm$

$$m_{H^\pm}^2 \simeq m_A^2 - \frac{1}{2}\lambda_4 v_2^2$$: ew scale

Scalar spectrum

- Scalar field decomposition

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + h_1 + i a_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + i a_2) \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}} r_S e^{i\frac{a_S}{v_S}}$$

$$r_S = v_S + \rho$$

- Neutral scalar

$$M_H^2 = \begin{pmatrix} 2\lambda_1 v_1^2 + \frac{\mu v_2 v_S}{\sqrt{2} v_1} & (\lambda_3 + \lambda_4) v_1 v_2 - \frac{\mu v_S}{\sqrt{2}} & \lambda_{1S} v_1 v_S - \frac{\mu v_2}{\sqrt{2}} \\ (\lambda_3 + \lambda_4) v_1 v_2 - \frac{\mu v_S}{\sqrt{2}} & 2\lambda_2 v_2^2 + \frac{\mu v_1 v_S}{\sqrt{2} v_2} & \lambda_{2S} v_2 v_S - \frac{\mu v_1}{\sqrt{2}} \\ \lambda_{1S} v_1 v_S - \frac{\mu v_2}{\sqrt{2}} & \lambda_{2S} v_2 v_S - \frac{\mu v_1}{\sqrt{2}} & 2\lambda_S v_S^2 + \frac{\mu v_1 v_2}{\sqrt{2} v_S} \end{pmatrix}$$

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \\ \rho \end{pmatrix}$$

Higgs portal SB, P. Ko, W.I.Park(2012)

Constraints and ΔN_{eff}

- Invisible Z decay with strongly constrains $Z \to H_i\, a$ decay. Can be suppressed either by small mixing or by assuming $m_{Hi} > m_Z$. P. H. Frampton, M. C. Oh, T. Yoshikawa (2002)

- $i g_{\bar{e}ea}\, a\, \bar{e}\gamma_5 e$: Stellar energy loss process $\gamma e \to ea$

  constrains $g_{\bar{e}ea} \lesssim 10^{-12}$ D. Chang, et.al. (1988)

  In our model, $g_{\bar{e}ea} \simeq m_e v_1/(v v_S) \approx 2 \times 10^{-16} (v_1/1\,\mathrm{eV})(100\,\mathrm{GeV}/v_S)$

- When $\lambda_{2S} = 0.005$ and $m_{H_3} = 500$ MeV Weinberg (2013)

  the Goldstone boson decouples after muon decouples and ΔN_{eff}=0.39, solving 3.4σ discrepancy between Hubble Space Telescope and Planck measurements of H_0.

Dark sector

$$\mathcal{L} \supset \bar{\psi} i\gamma^\mu \partial_\mu \psi - m_\psi \bar{\psi}\psi - \frac{f}{2}\bar{\psi}^c \psi S^\dagger - \frac{f^*}{2}\bar{\psi}\psi^c S.$$

- After S gets VEV, ψ splits into two Majorana fermions $\psi_\pm^c = \psi_\pm$

$$\psi_+ = \frac{1}{\sqrt{2}}\left(\psi' + \psi'^c\right), \quad \psi_- = \frac{-i}{\sqrt{2}}\left(\psi' - \psi'^c\right), \qquad \left(\psi = \psi' e^{i\frac{a_S}{2v_S}} \right)$$

with masses $m_\pm = m_\psi \pm \frac{f v_S}{\sqrt{2}}$ DM: ψ_- stable due to remnant Z_2

- In terms of mass eigenstates,

$$\mathcal{L} \supset \frac{1}{2}\sum_{\alpha=\pm} \bar{\psi}_\alpha \left[i\gamma^\mu\partial_\mu - m_\pm \right]\psi_\alpha - \frac{i}{4v_S}\left[\bar{\psi}_+\gamma^\mu\psi_- - \bar{\psi}_-\gamma^\mu\psi_+ \right]\partial_\mu a_S$$
$$- \frac{f}{2\sqrt{2}}\rho\left[\bar{\psi}_+\psi_+ - \bar{\psi}_-\psi_- \right].$$

Higgs portal int.

- Relevant terms for DM phenomenology:

$$\mathcal{L} \supset -\frac{f}{2\sqrt{2}}\rho(\bar{\psi}_+\psi_+ - \bar{\psi}_-\psi_-) - \frac{i}{4v_S}\left[\bar{\psi}_+\gamma^\mu\psi_- - \bar{\psi}_-\gamma^\mu\psi_+ \right]\partial_\mu a \longrightarrow \text{Noble GB int.}$$
$$- \mu_{SS}\rho^3 + \frac{1}{v_S}\rho\partial_\mu a\partial^\mu a - \mu_{1S}\rho\left(\phi_1^+\phi_1^- + \frac{1}{2}(h_1^2 + a_1^2) \right) - \frac{\mu_{2S}}{2}\rho h_2^2,$$

$$\boxed{\mu_{SS} \equiv \lambda_S v_S, \ \mu_{1S} \equiv \lambda_{1S} v_S \text{ and } \mu_{2S} \equiv \lambda_{2S} v_S}$$

DM relic density

Four scenarios depending on the interaction strength of dark scalar, ρ:

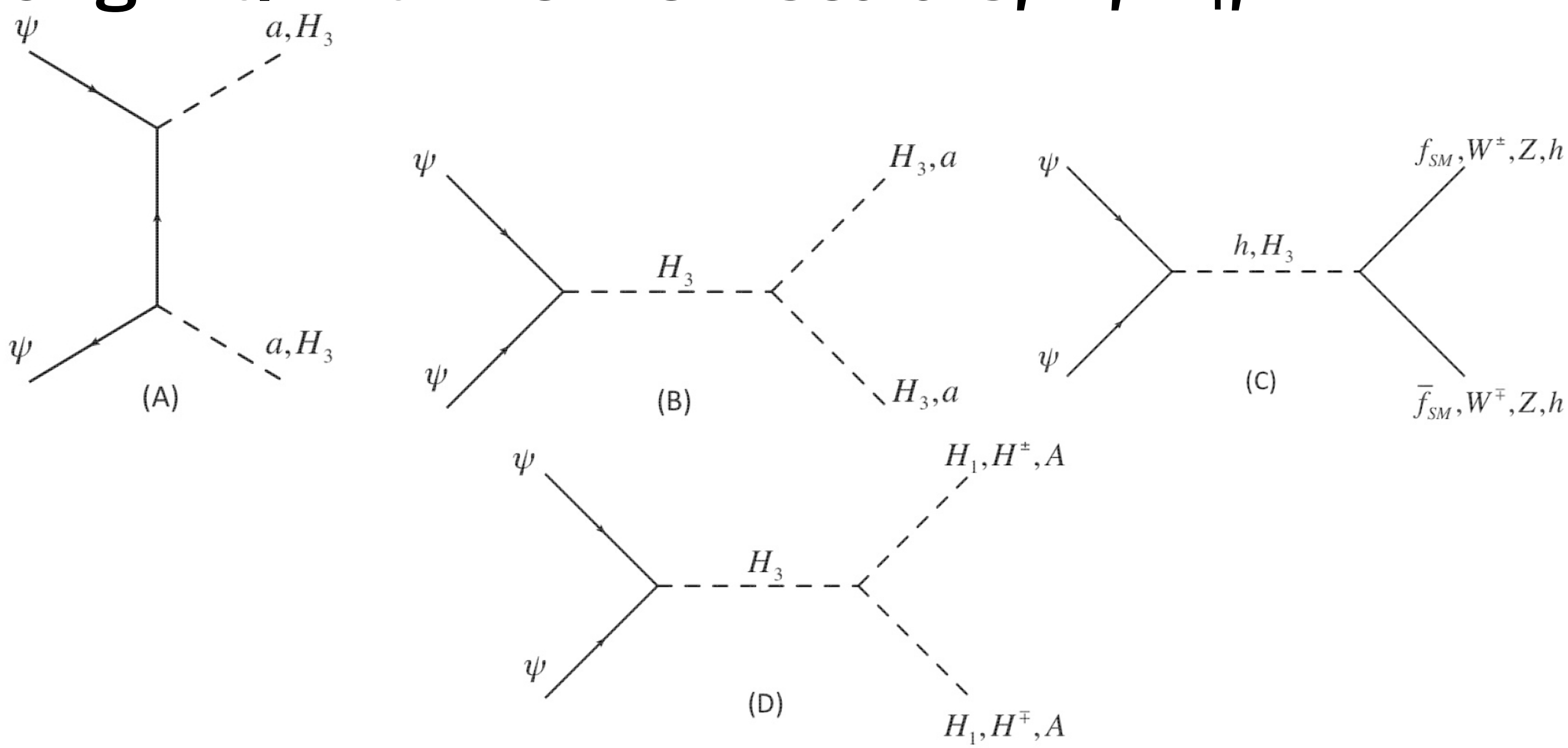
$$S = \frac{1}{\sqrt{2}}(v_S + \rho)e^{i\frac{a_S}{v_S}}$$

(I) Strong int. with DM

(II) Strong int. with DM & strong self int.

(III) Strong int. with SM Higgs (=Higgs portal model)

(IV) Strong int. with new ew scalars, A, H_1, $H^{\pm}$



DM relic density

Four scenarios:

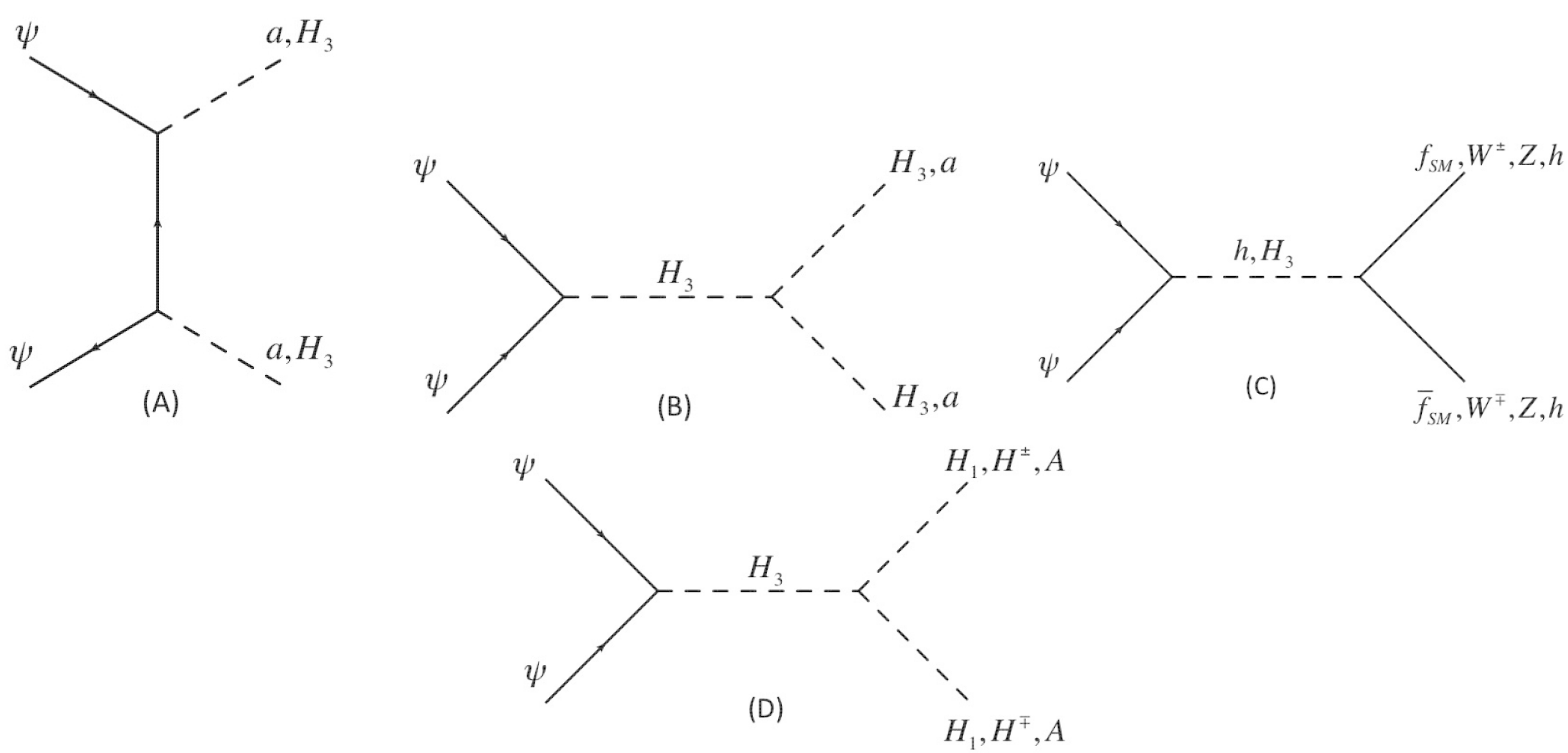
(I) $f \le \sqrt{4\pi}\ \mu_{1S,2S,SS} \ll 0.1$ GeV

(II) $f \le \sqrt{4\pi}$ and $\mu_{SS} \gg \mu_{1S,2S}$

(III) $f < 0.8$ and $\mu_{2S} \gg \mu_{1S,SS}$

(IV) $f < 0.8$ and $\mu_{1S} \gg \mu_{2S,SS}$

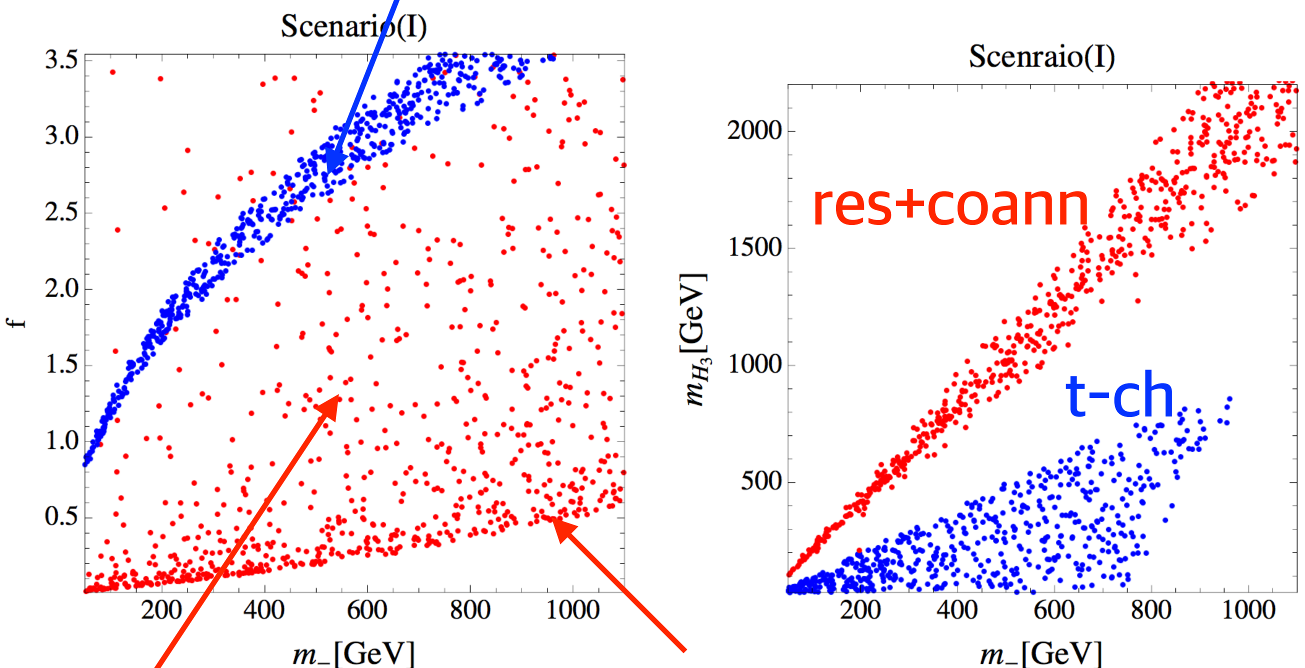
$$
\begin{aligned}
\text{For all scenario}: &\quad m_- \in [50, 1100]\ \text{GeV}, \quad m_{H_3} \in [30, 2200], \quad v_S = 1000\ \text{GeV},\\
\text{scenario (I)}: &\quad f \in [0.1, \sqrt{4\pi}], \quad \mu_{1S} = \mu_{2S} = \mu_{SS} = 10^{-3}\ \text{GeV},\\
\text{scenario (II)}: &\quad f \in [0.01, \sqrt{4\pi}], \quad \mu_{SS} \in [0.1, m_{H_3}]\ \text{GeV}, \quad \mu_{1S} = \mu_{2S} = 10^{-3}\ \text{GeV},\\
\text{scenario (III)}: &\quad f \in [0.01, 0.8], \quad \mu_{2S} \in [0.1, m_{H_3}]\ \text{GeV}, \quad \mu_{1S} = \mu_{SS} = 10^{-3}\ \text{GeV},\\
\text{scenario (IV)}: &\quad f \in [0.01, 0.8], \quad \mu_{1S} \in [0.1, m_{H_3}]\ \text{GeV}, \quad \mu_{2S} = \mu_{SS} = 10^{-3}\ \text{GeV},\\
&\quad m_{H_1} = m_{H^\pm} = m_A \in [70, m_\psi]\ \text{GeV},
\end{aligned}
$$

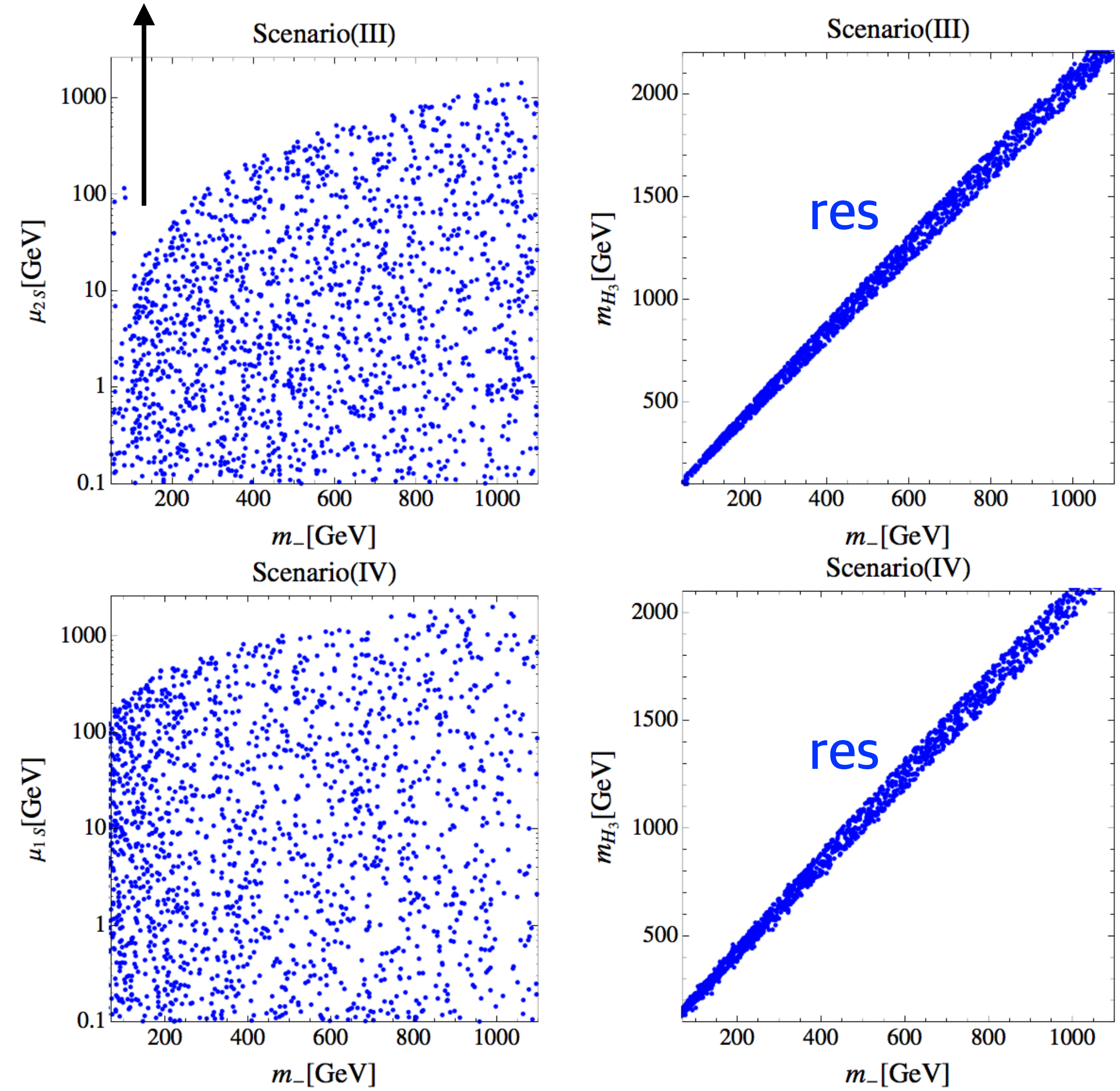


$m_- > m_{H_3}$

$\psi_-\psi_- \to H_3H_3, aa$
$\psi_-\psi_+ \to H_3a$

Higgs mixing angle,
invisible decay constraint $s_\theta < 0.2$



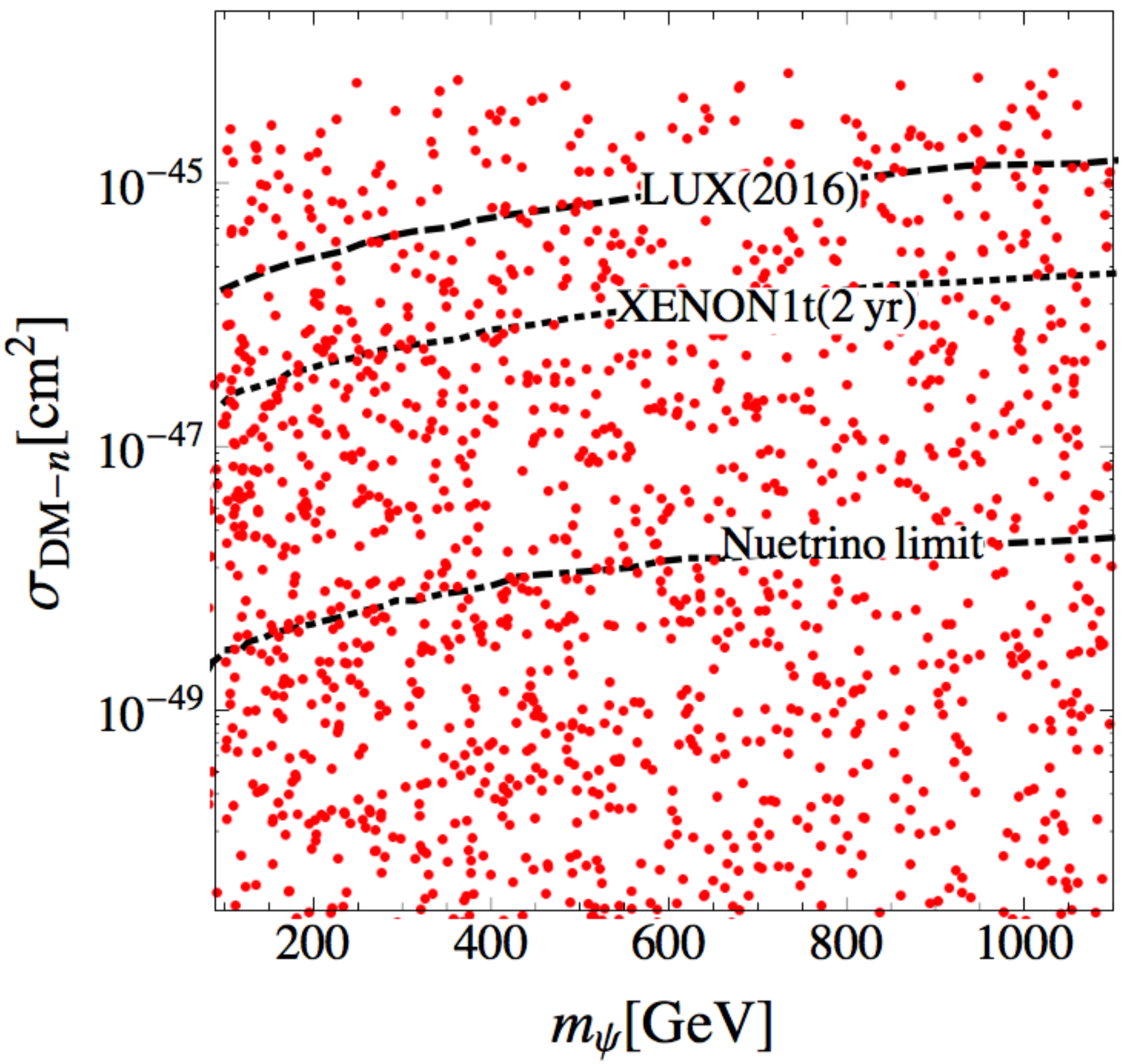


$\psi_-\psi_- \to H_3 \to aa$ $\psi_-\psi_+ \to H_3a$

$m_- + m_+ > m_{H_3} > m_-$

- For (I) either s-channel aa or t-channel diagrams important
- (II) is similar to (I); additional $\psi_-\psi_- \to H_3 \to H_3H_3$ is subdominant
- For (III,IV) s-channel H_3 resonance regions dominate

DM direct detection



- Only scenario (III) has tree-level contribution to DD via Higgs portal

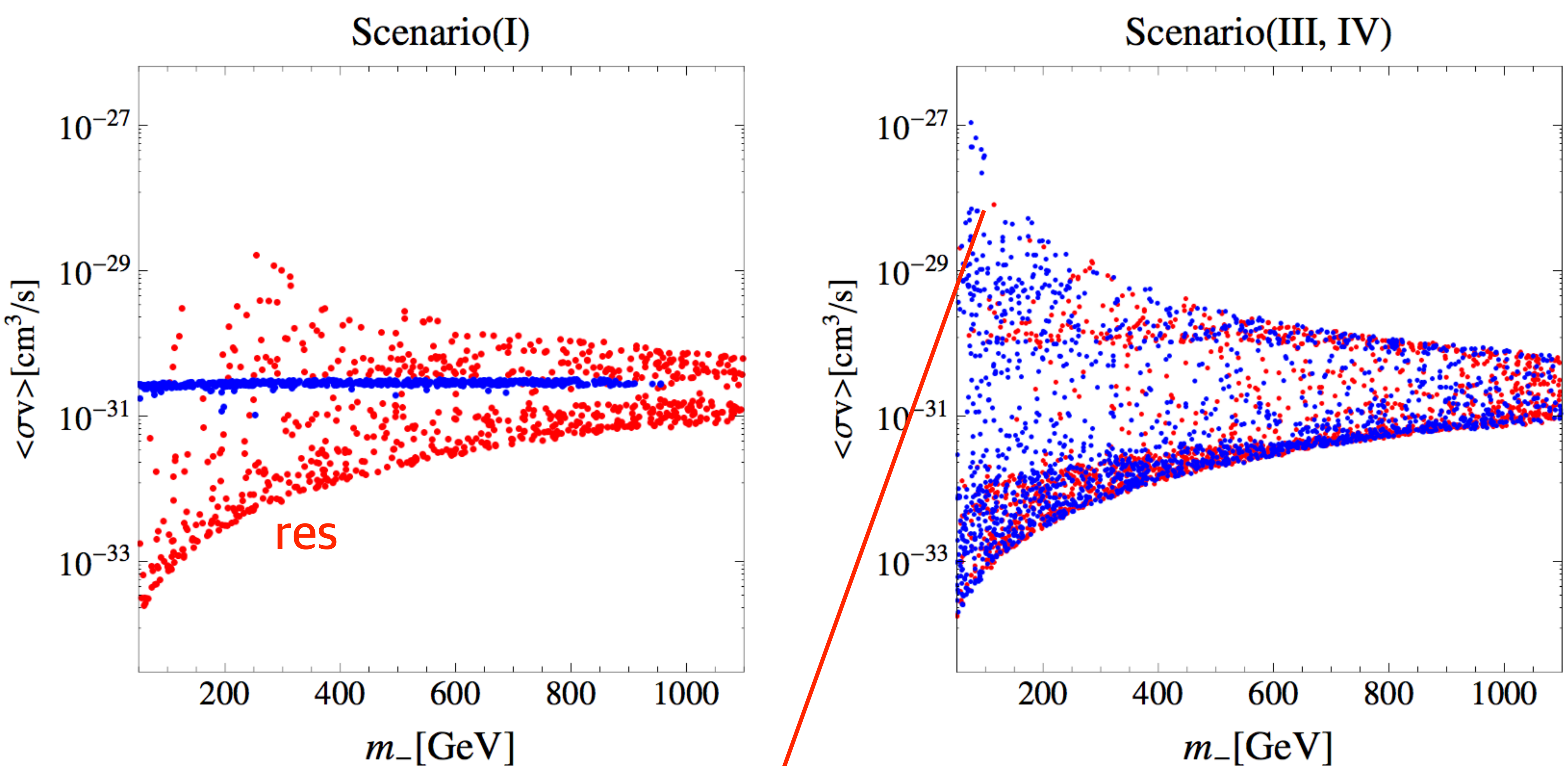
$$\sigma_{\rm SI}(\psi N \to \psi N) = \frac{1}{2\pi}\frac{\mu_{N\psi}^2 f_N^2 m_N^2 f^2 s_\theta^2 c_\theta^2}{v^2}\left(\frac{1}{m_h^2} - \frac{1}{m_{H_3}^2}\right)^2$$

- suppressed by mixing angle θ constraint from LHC

DM indirect detection

- p-wave suppressed

(red, blue)



suppressed due to $s_\theta < 0.2$

Conclusions

- Extended a Dirac neutrino model to include DM
- Global $U(1)_X$ forbids both Majorana masses of ν_R and guarantees the stability of DM
- Relic abundance of DM can be explained while DD and ID cross sections are suppressed
- Can be tested at neutrinoless double beta decay experiments or at collider searches of ew scalars