A realistic model for DM interactions in the neutrino portal paradigm

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1. Model
2. Constraints
3. Conclusions

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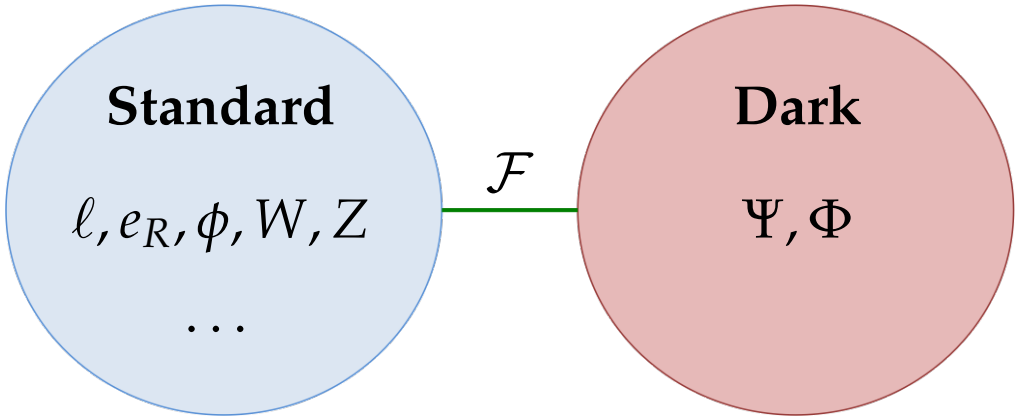
Model

- Simplest realization of the **neutrino portal** paradigm:

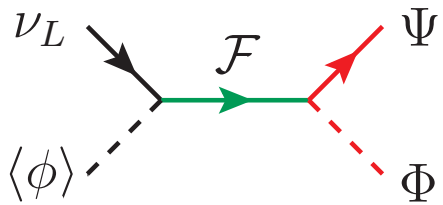


$\mathcal{F}_i$: singlet(s) under $\mathcal{G}_{\rm SM}$, $\mathcal{G}_{\rm DM}$, except fermion number

Ψ, Φ : same transformations under $\mathcal{G}_{\rm DM}$, neutral under $\mathcal{G}_{\rm SM}$

($m_\Psi < m_\Phi \Rightarrow \Psi$ is the DM candidate)

$$\mathcal{O}^{(5)} = (\tilde{\phi}^\dagger \ell)(\overline{\Psi}\Phi)$$



Model

New fields and parameters

$$\mathcal{L} = \overline{\ell}(\mathrm{i}\not{D})\ell + \overline{e}_R \mathrm{i}\not{D} e_R + \overline{\mathcal{F}}(\mathrm{i}\partial\!\!\!/ - M)\mathcal{F} + \overline{\Psi}(\mathrm{i}\partial\!\!\!/ - m_\Psi)\Psi + |\partial\Phi|^2 - m_\Phi^2|\Phi|^2$$

$$-(\overline{\ell}Y^{(e)}e_R\phi + \overline{\ell}Y^{(\nu)}\mathcal{F}\tilde{\phi} + \overline{\Psi}z^\dagger\mathcal{F}\Phi + \mathrm{h.c.}) - \underbrace{\lambda_x|\phi|^2|\Phi|^2}_{\substack{\text{Higgs portal} \\ (m_\Psi > m_\Phi)}}$$

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$$36 = 18(Y^{(\nu)}) + 9(M) + 6(z) + 3(m_\Psi, m_\Phi, \lambda_x)$$
$$\text{phys.}\quad 4 + 20 = \overbrace{4(V) + 3(\eta) + 8(U) + 3(M)} + 3(z) + 3(m_\Psi, m_\Phi, \lambda_x)$$

$$Y^{(\nu)} \equiv \frac{\sqrt{2}}{v} V\eta U M$$

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- Light (n_L) and heavy neutrinos ($N_{L,R}$) of masses M_N from mixing of $(\nu_L, \mathcal{F}_L, \mathcal{F}_R)$

$$\begin{aligned} \mathcal{F} &= U^\dagger(\mathcal{C}U_L\, N_L - \mathcal{S}\, n_L + U_R\, N_R) \\ \nu_L &= V(\mathcal{S}U_L\, N_L + \mathcal{C}\, n_L) \end{aligned} \qquad \mathcal{C} = \frac{\mathbb{1}}{\sqrt{\mathbb{1}+\eta^2}} \qquad \mathcal{S} = \frac{\eta}{\sqrt{\mathbb{1}+\eta^2}}$$

$V = \text{PMNS}$ $\quad \eta = \text{diag}(\eta_i) > 0$ $\quad U \in SU(3)$ $\quad M$ real diagonal

$$U_R^\dagger U M U^\dagger \mathcal{C}^{-1} U_L = M_N = \text{diagonal}$$

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$\Rightarrow$ Modified Z couplings: $\mathcal{L} \supset -\dfrac{g}{2c_W}\overline{n}_L \not{Z}\, \mathcal{C}^2\, n_L + \ldots$

flavor diagonal but non universal

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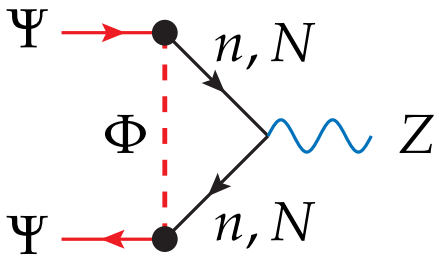

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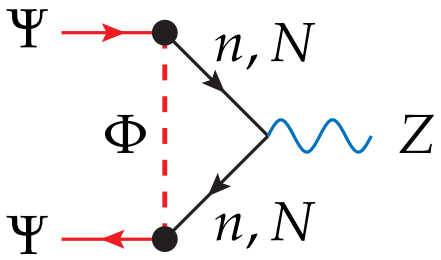
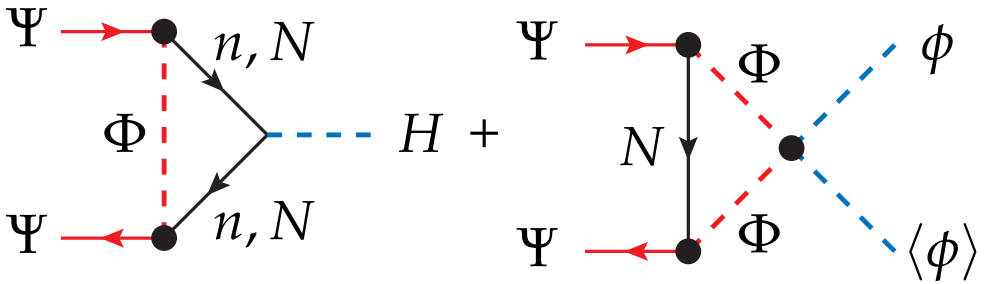


- One-loop $H\Psi\Psi$



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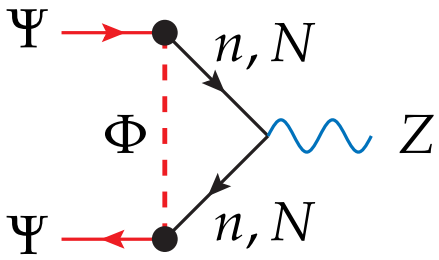

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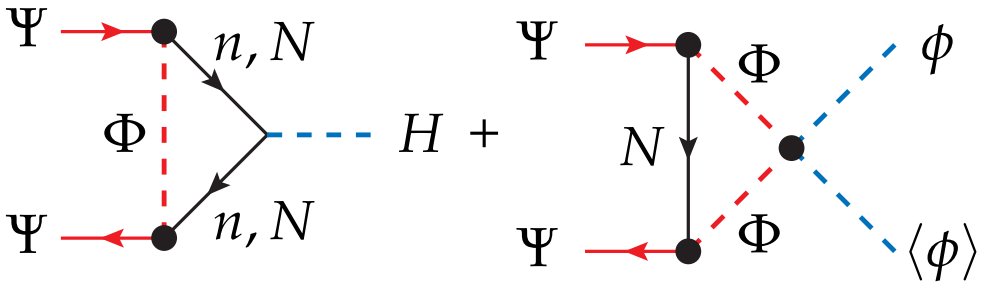

$Z \to$ inv
$H \to$ inv
π, τ decays
Relic abundance
Direct detection
Indirect detection
Collider searches

Model

Quasidegenerate heavy neutrinos

$$\boxed{M_N = \Lambda \mathbb{1} \qquad \eta \ll 1} \quad \Rightarrow \quad \mathcal{C} \approx \mathbb{1} - \tfrac{1}{2}\eta^2 \qquad \mathcal{S} \approx \eta \qquad M \approx \Lambda(\mathbb{1} - \tfrac{1}{2}U^\dagger \eta^2 U)$$

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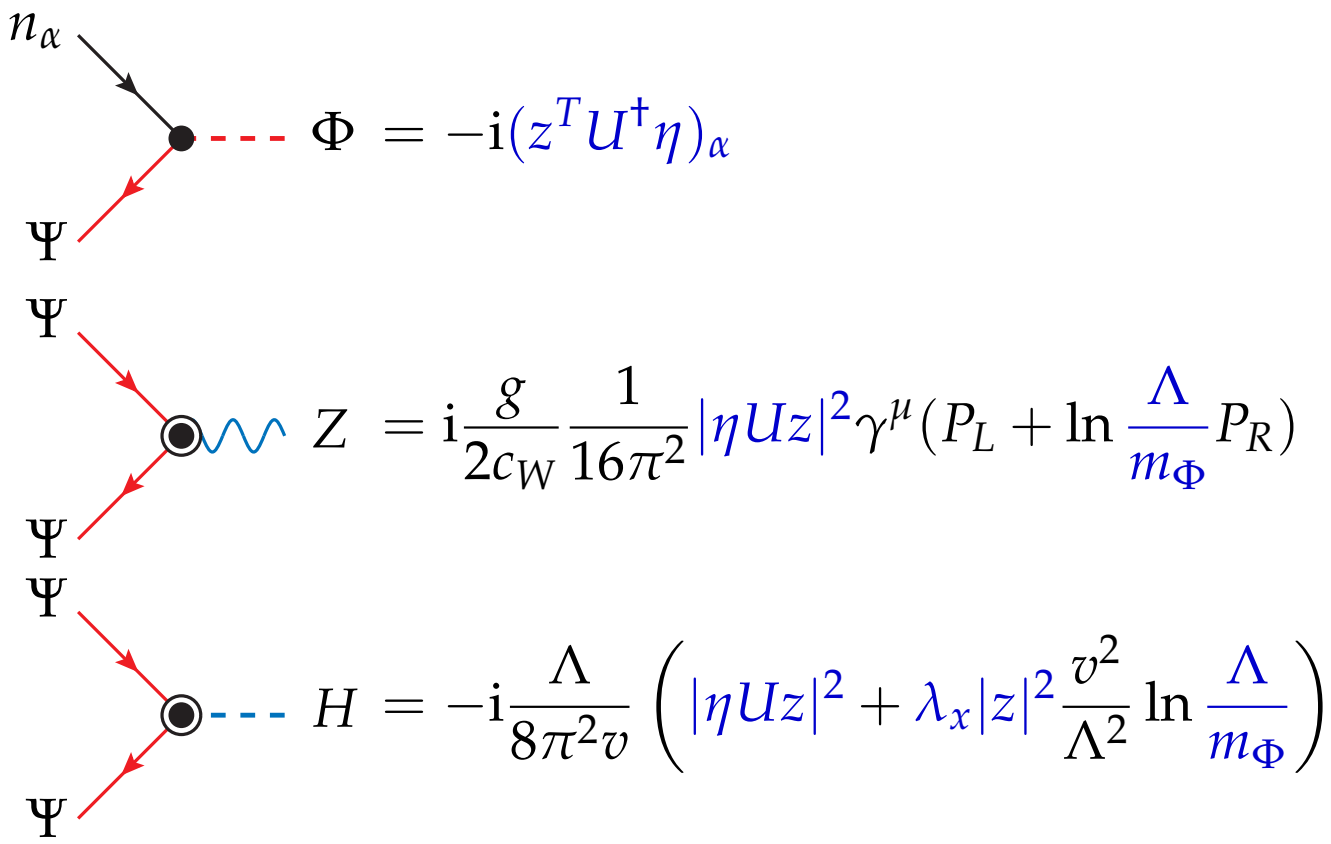
- Just the following 5 parameter combinations appear in DM observables:

$$\Lambda \qquad m_\Psi \qquad m_\Phi \qquad |\eta U z|^2 \qquad \lambda_x |z|^2$$



Constraints | Electroweak

- Z: $\Gamma(Z \to \text{inv}) = \frac{1}{3}\text{Tr}(\mathcal{C}^4)\Gamma_{\text{SM}}(Z \to \text{inv}) \quad \Rightarrow \quad \sum \eta_i^2 < 0.014$ [LEP] (3σ)

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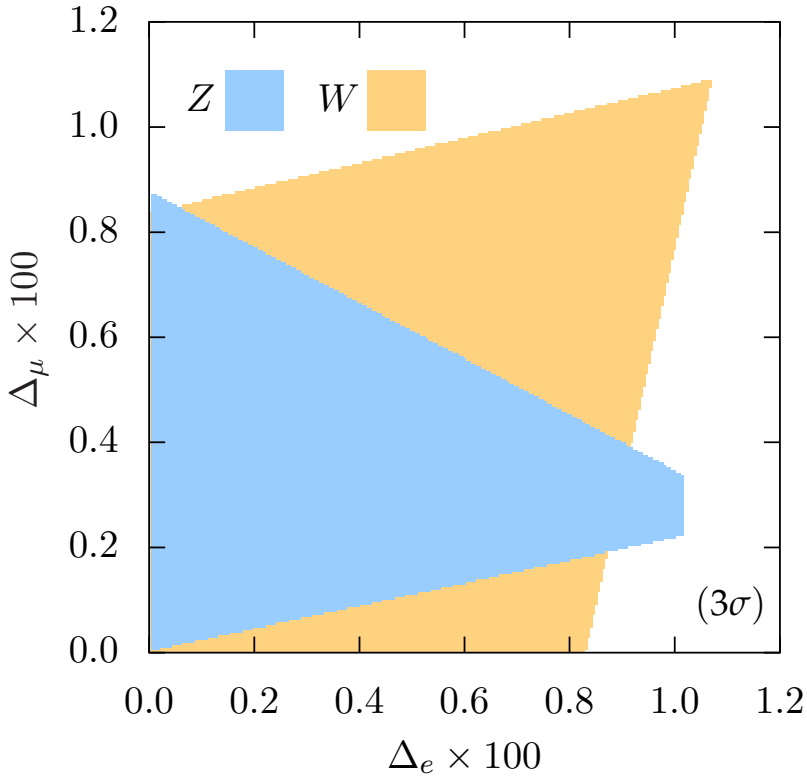
- W: $\overline{\ell}_\alpha \nu_\alpha = \overline{\ell}_\alpha \; V\mathcal{C} \; \nu_\alpha = \overline{\ell}_\alpha [V(\mathbb{1} - \frac{1}{2}\eta^2)]_{\alpha i} n_i \quad \Rightarrow \quad \Delta_\alpha = [V\eta^2 V^\dagger]_{\alpha\alpha} = \sum_i |V_{\alpha i}|^2 \eta_i^2$

$$\Gamma(\pi \to \ell_\alpha \overline{\nu}_\alpha) = (1 - \Delta_\alpha)\, \Gamma_{\text{SM}}$$
$$\Gamma(\ell_\alpha \to \ell_\beta \overline{\nu}_\alpha \nu_\beta) = (1 - \Delta_\alpha - \Delta_\beta)\, \Gamma_{\text{SM}}$$



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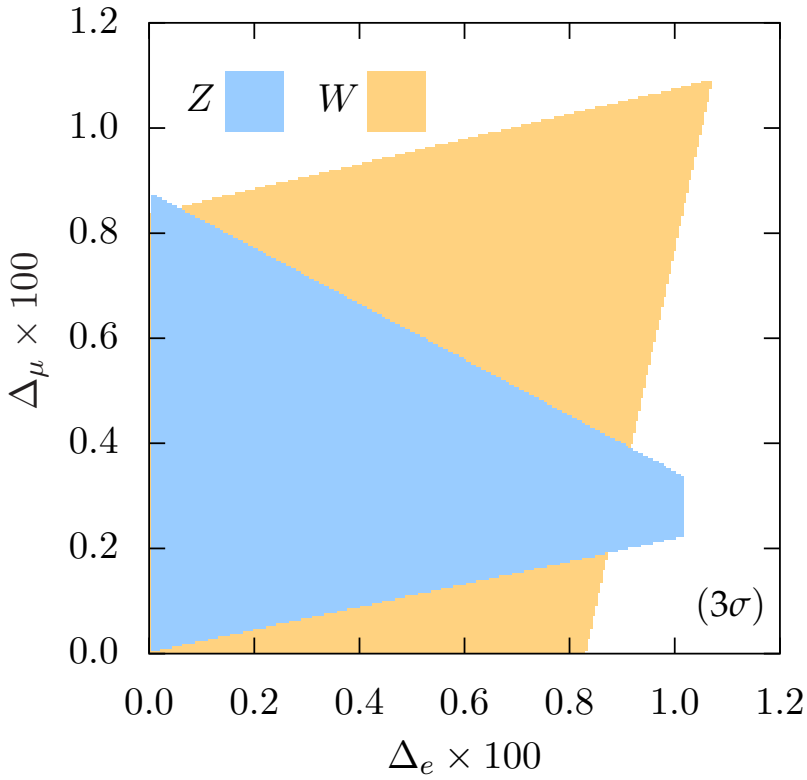
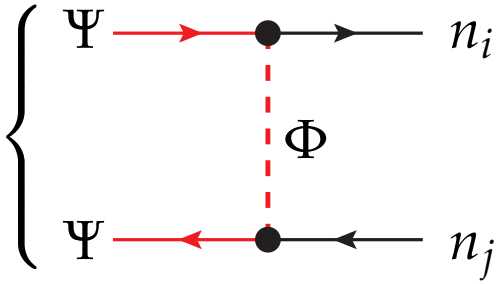


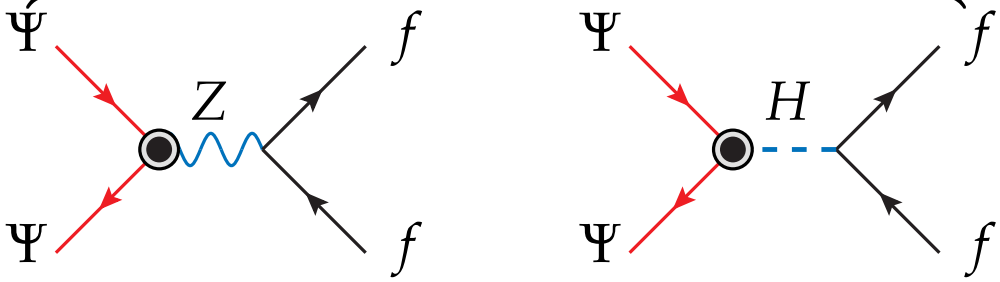
- H: $\Gamma(H \to \text{inv})$ (if $m_\Psi < m_H/2$) $\quad \Rightarrow \quad \frac{v}{\Lambda}\left|\,|\eta U z|^2 \frac{\Lambda^2}{v^2} + \lambda_x |z|^2 \frac{\Lambda}{m_\Phi}\right| < 1.7$ [ATLAS] (90% C.L.)

DM

$\Psi\overline{\Psi}$ annihil. $\Rightarrow$



$\Downarrow\ \Psi\mathcal{N} \to \Psi\mathcal{N}$



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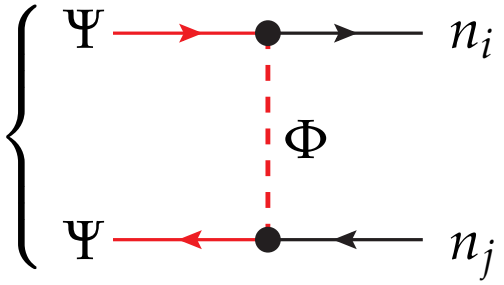

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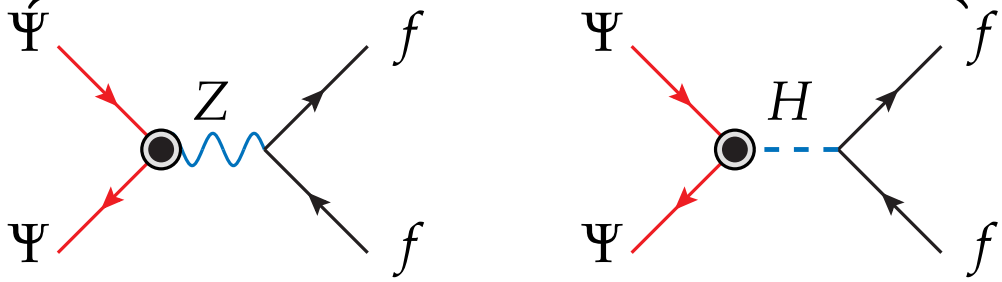

$\Rightarrow$ `FeynRules`, `CALCHEP`, `MicrOmegas`

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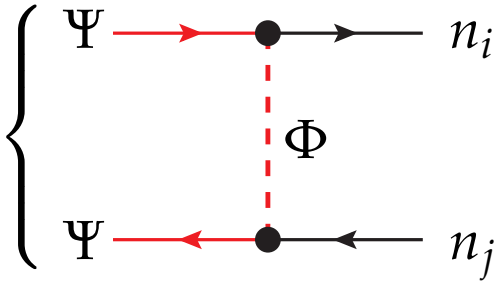

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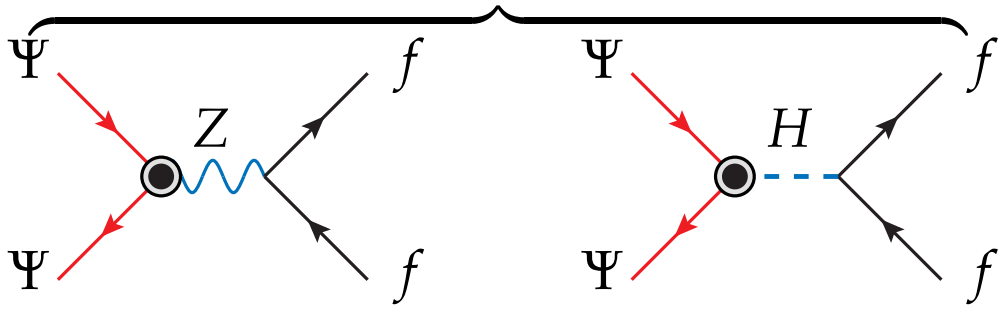

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Parameter scan: Λ m_Ψ m_Φ $|\eta U z|^2$ $\lambda_x |z|^2$

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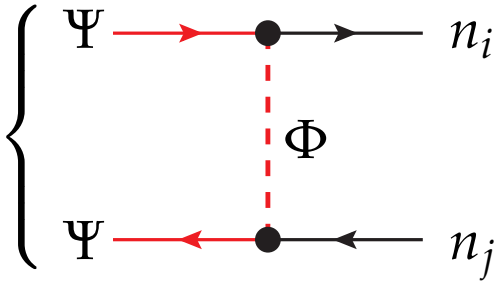

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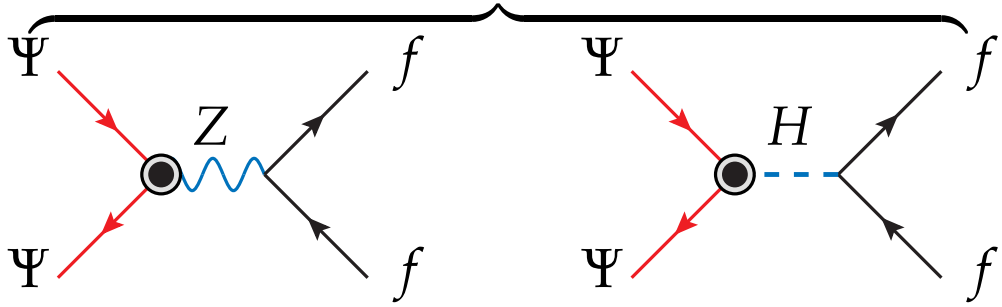

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$$200\ \text{GeV} \leq \Lambda \leq 10\ \text{TeV} \qquad \text{(heavy neutrinos)}$$

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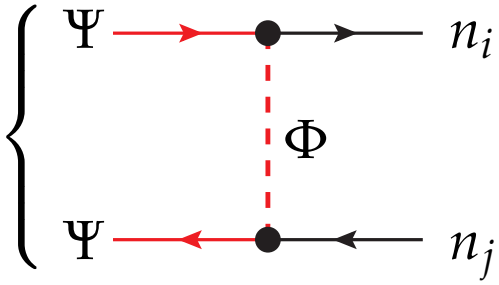

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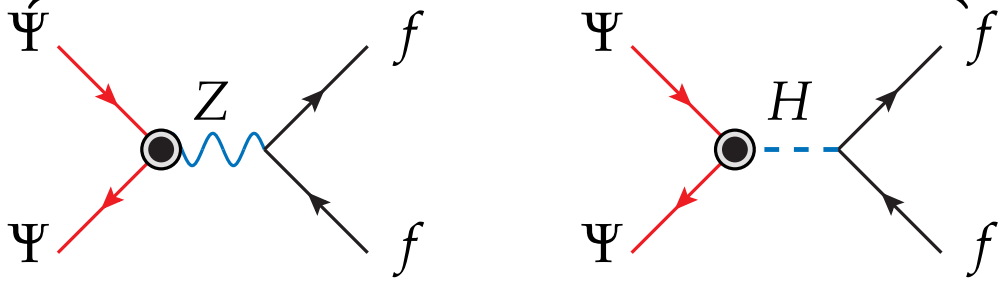

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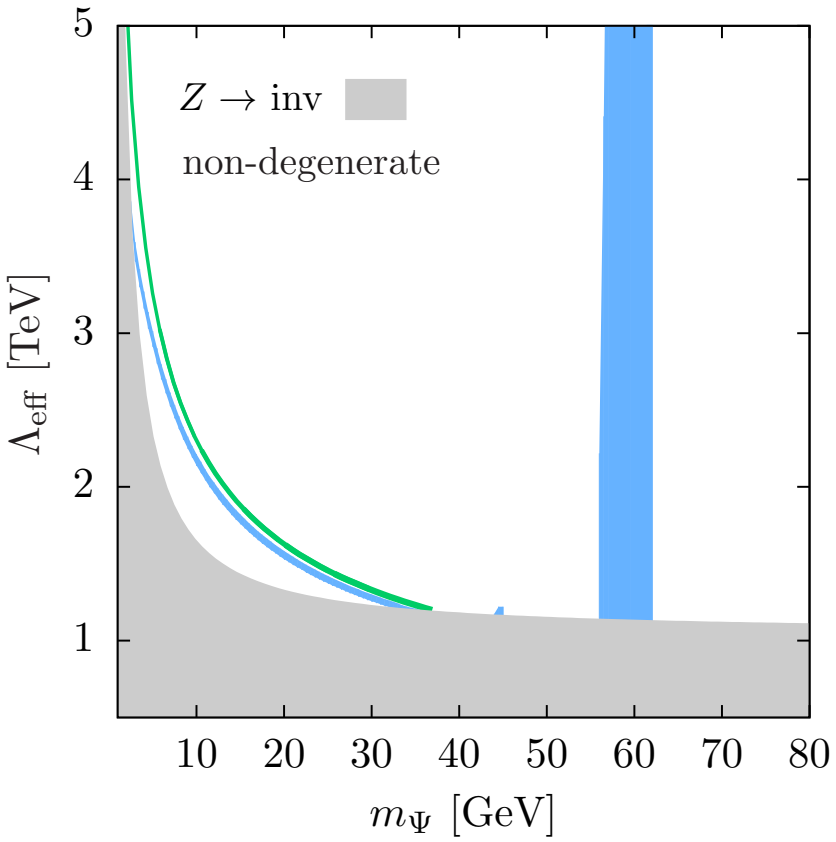
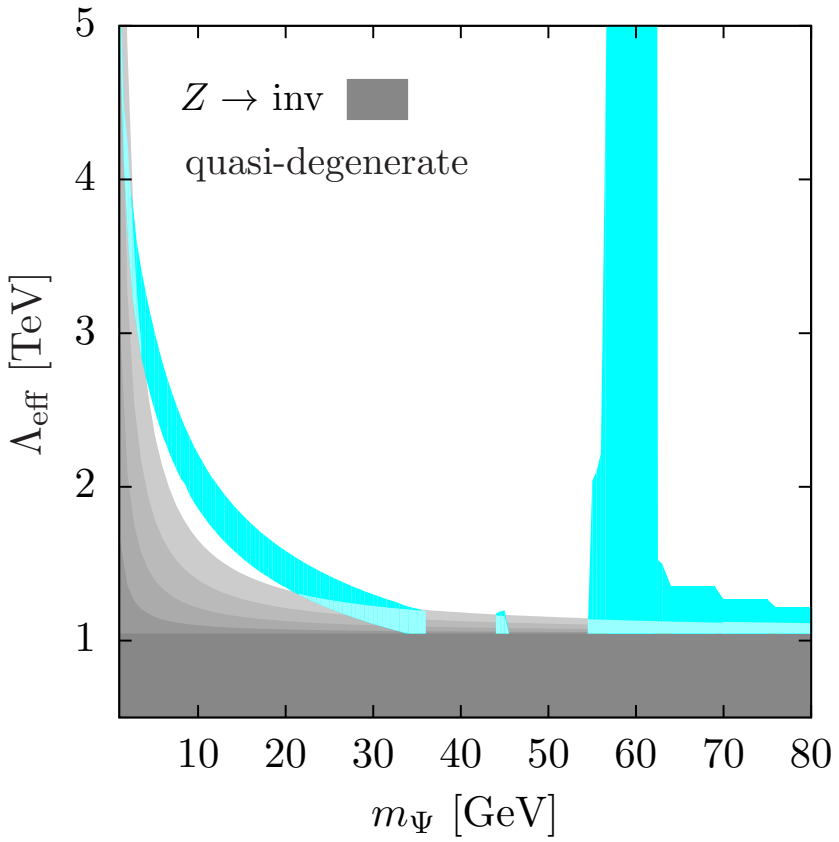
- non-degenerate: $m_\Psi + 10\ \text{GeV} \leq m_\Phi$
- quasi-degenerate: $m_\Psi < m_\Phi < m_\Psi + 10\ \text{GeV}$

DM **Relic abundance**

$$\Omega_\Psi h^2 = 0.1198 \pm 0.026\ (3\sigma)\ \text{[Planck]}$$





dominant $\quad \langle \sigma v \rangle_{\Psi\overline{\Psi}\to\nu\bar{\nu}} = \dfrac{(v/\Lambda_{\rm eff})^4}{256\pi m_\Psi^2} \qquad \Lambda_{\rm eff} = \dfrac{v/\sqrt{2}}{|\eta U z|}\sqrt{\dfrac{m_\Psi^2 + m_\Phi^2}{m_\Psi^2}}$

$$\langle \sigma v \rangle_{\Psi\overline{\Psi}\to f\bar{f}} = \underbrace{(\sigma_0)_Z}_{S-\text{wave}} + \frac{T}{m_\Psi}\underbrace{(\sigma_0)_H}_{P-\text{wave}} \qquad \langle v \rangle \sim T^{1/2}$$

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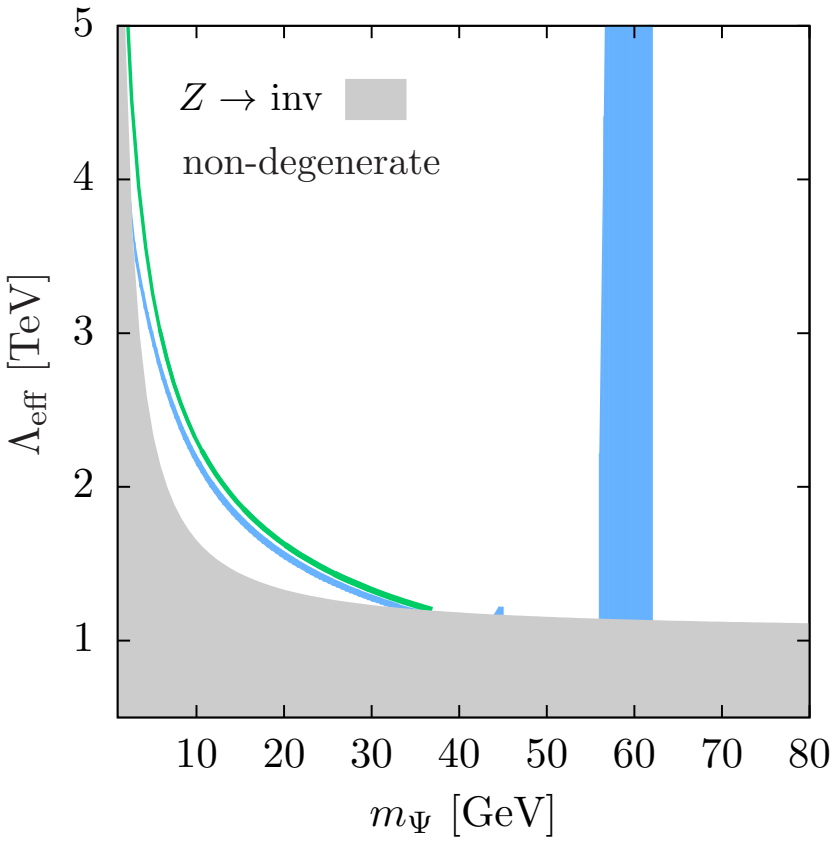

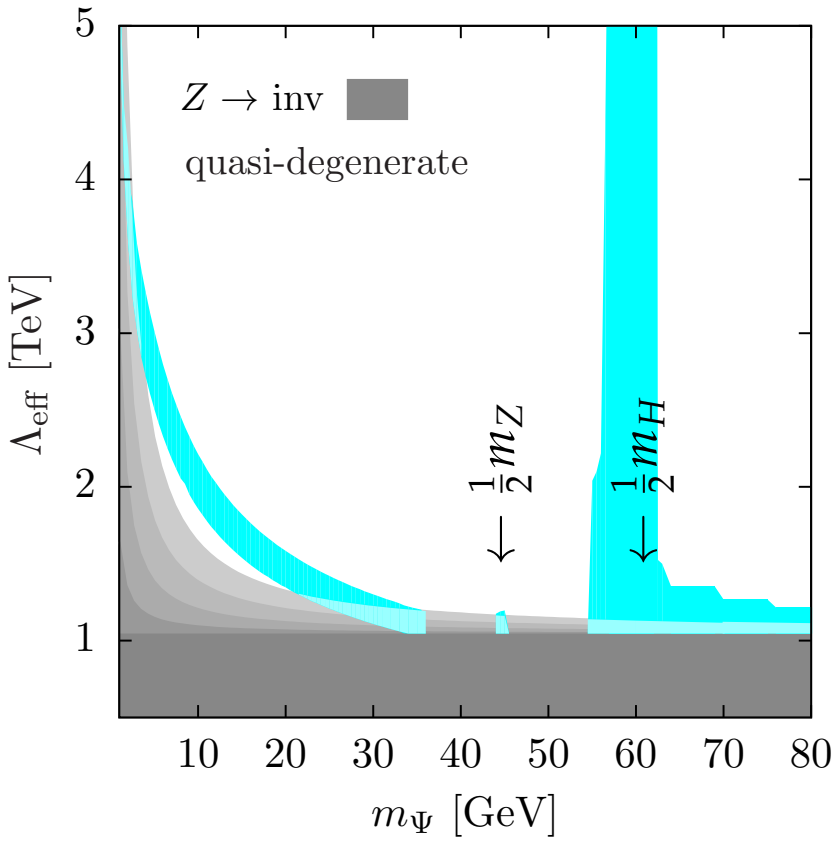

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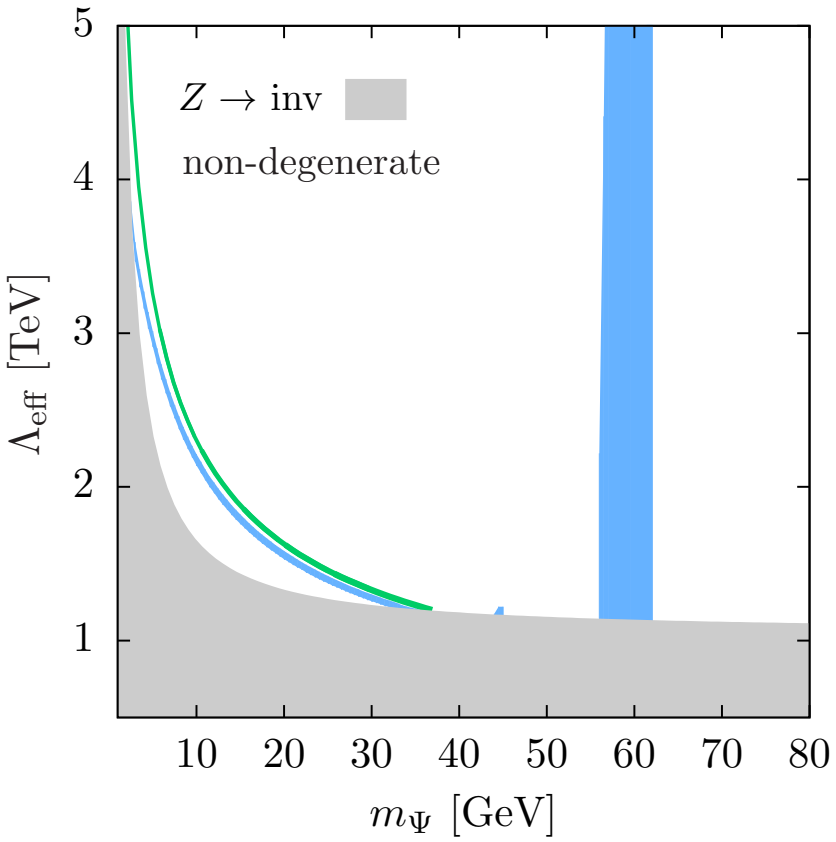
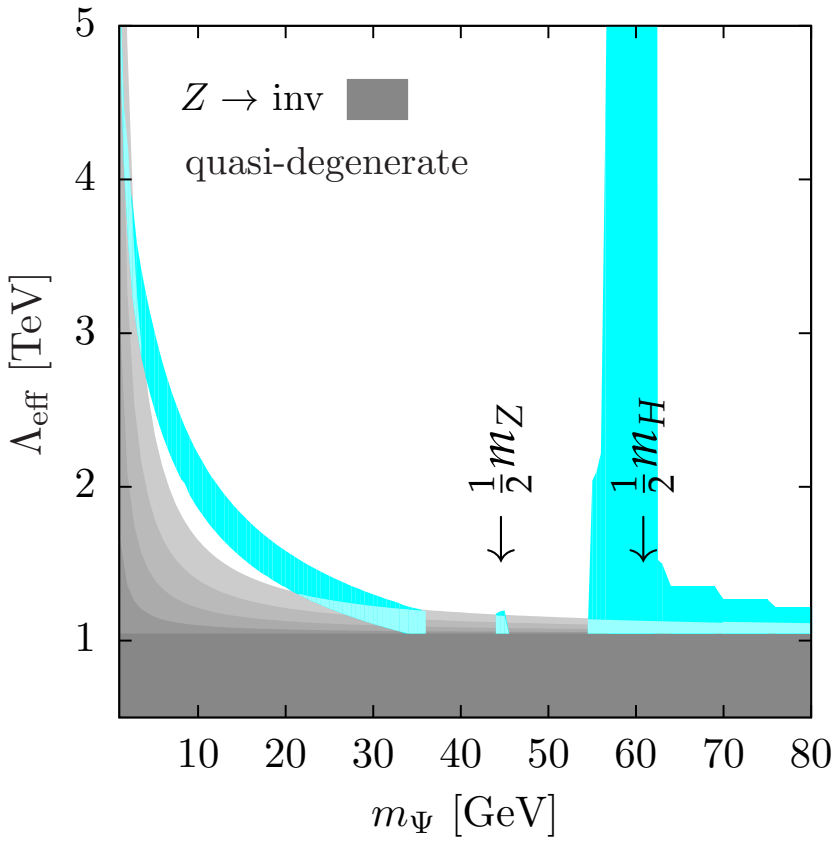


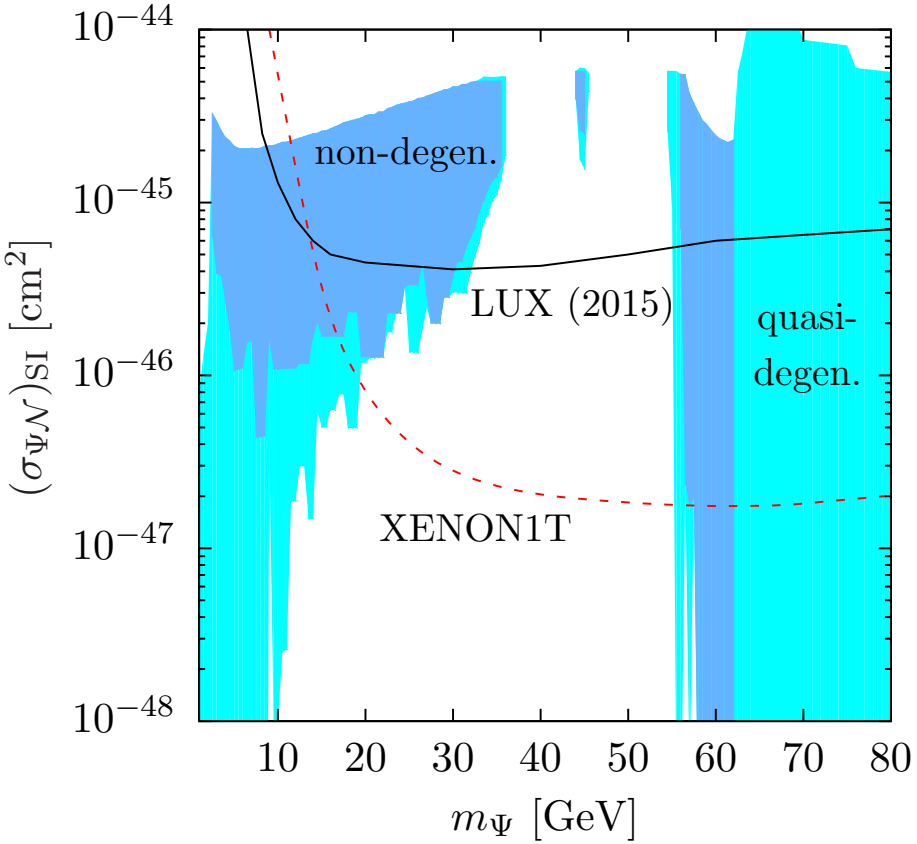


← Coannihilation:
$\Psi\Phi \to We, Z\nu, H\nu$
$\Phi\Phi \to HH, WW, ZZ$

$$\text{dominant} \quad \langle \sigma \mathrm{v} \rangle_{\Psi\overline{\Psi} \to \nu\bar{\nu}} = \frac{(v/\Lambda_{\text{eff}})^4}{256\pi m_\Psi^2} \qquad \Lambda_{\text{eff}} = \frac{v/\sqrt{2}}{|\eta U z|} \sqrt{\frac{m_\Psi^2 + m_\Phi^2}{m_\Psi^2}}$$

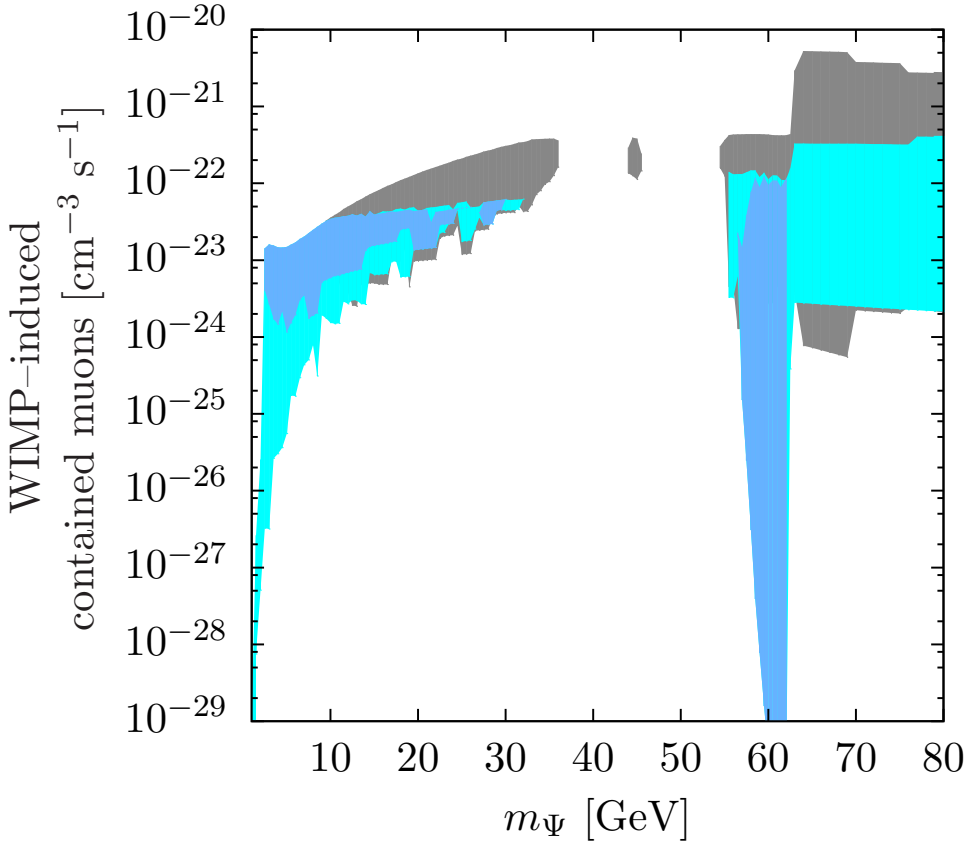
$$\langle \sigma \mathrm{v} \rangle_{\Psi\overline{\Psi} \to f\bar{f}} = \underbrace{(\sigma_0)_Z}_{S-\text{wave}} + \frac{T}{m_\Psi} \underbrace{(\sigma_0)_H}_{P-\text{wave}} \qquad \langle \mathrm{v} \rangle \sim T^{1/2}$$

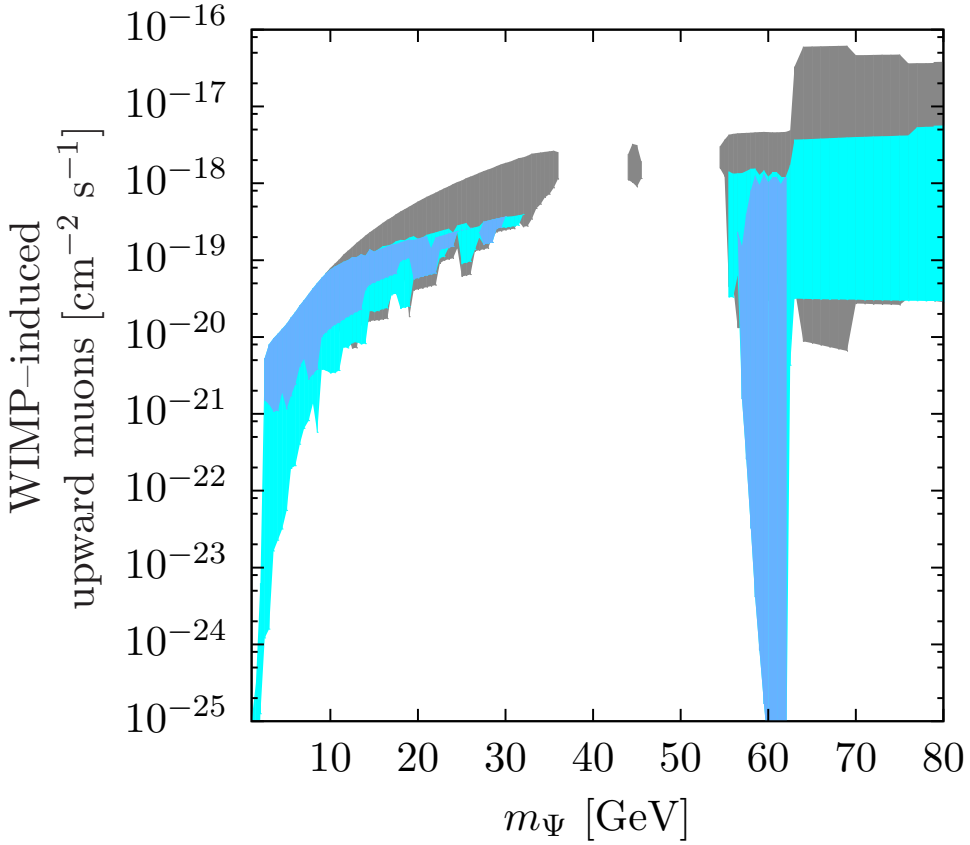
DM **Direct detection** $\Psi\mathcal{N} \to \Psi\mathcal{N}$



- LUX excludes Z resonance region
- Non-degenerate: Cross sections larger than 10^{-46} cm^2 unless $m_\Psi \sim m_H/2$
- Quasi-degenerate: large parameter space available

DM **Indirect detection** DM annihilation in the Sun





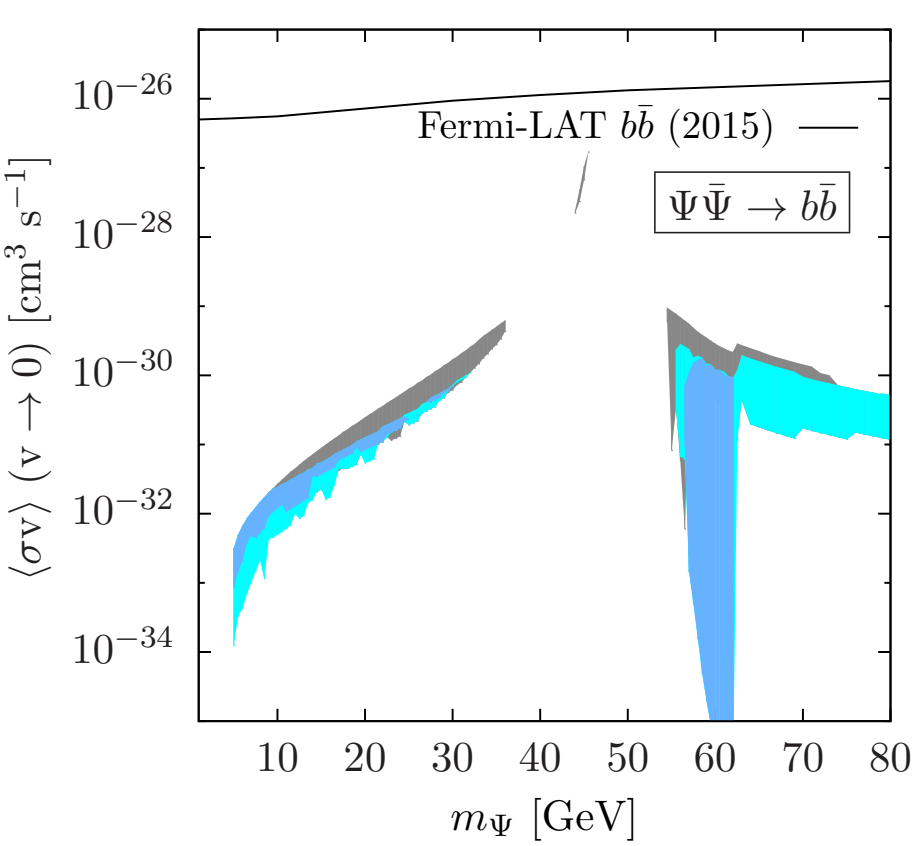
- Neutrino line $E_\nu = m_\Psi$:

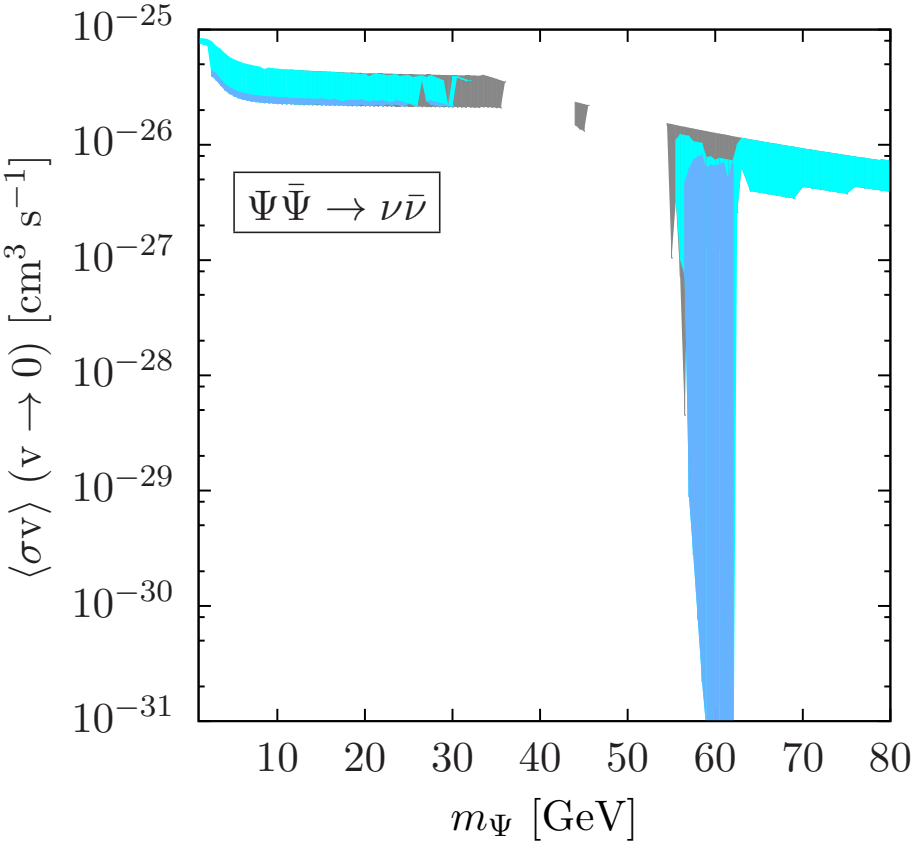
$$\mathrm{d}N/\mathrm{E}_{\nu_i} \sim \frac{1}{2} C_\Psi \delta(E_{\nu_i} - m_\Psi) \qquad C_\Psi \sim \sigma_{\Psi\mathcal{N}} \times \rho^{\mathrm{DM}}_{\mathrm{local}}$$

[exp sensitivity: IceCube ($E_\nu > 100$ GeV) Super-K (up-muons $\gtrsim 10^{-14}$ cm^{-2} s^{-1})]

DM **Indirect detection**

Annihilation cross sections for two channels





- Into charged fermions (1-loop):
  H-mediated is P-wave, suppressed w.r.t. to Z-mediated (S-wave)
  (safe from Fermi-LAT)

- Into neutrinos (tree-level):
  Poorly measured
  (Super-K?)

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