A radiative neutrino mass model with semi-annihilating boosted dark matter

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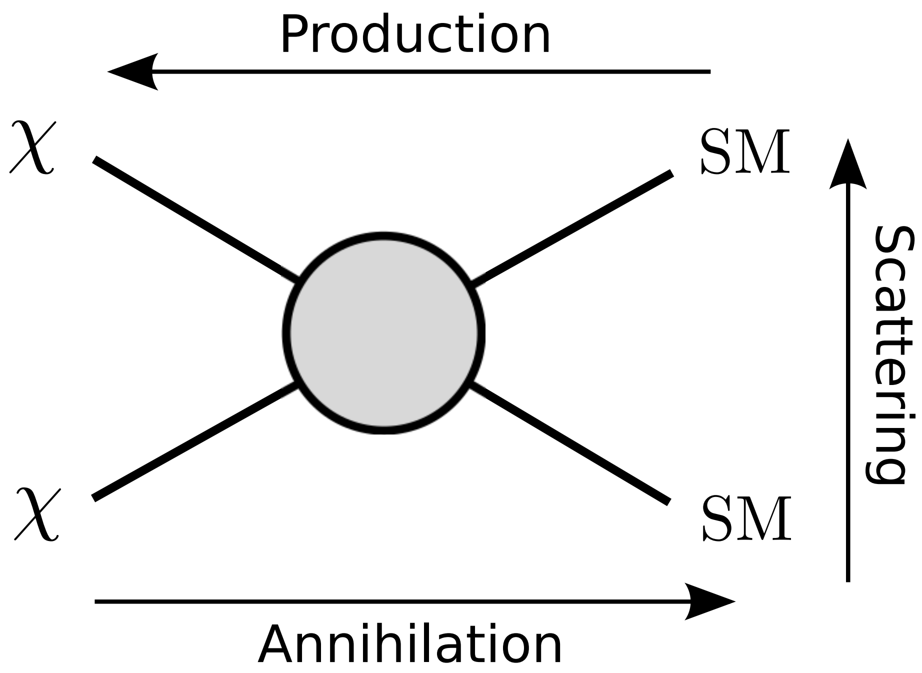
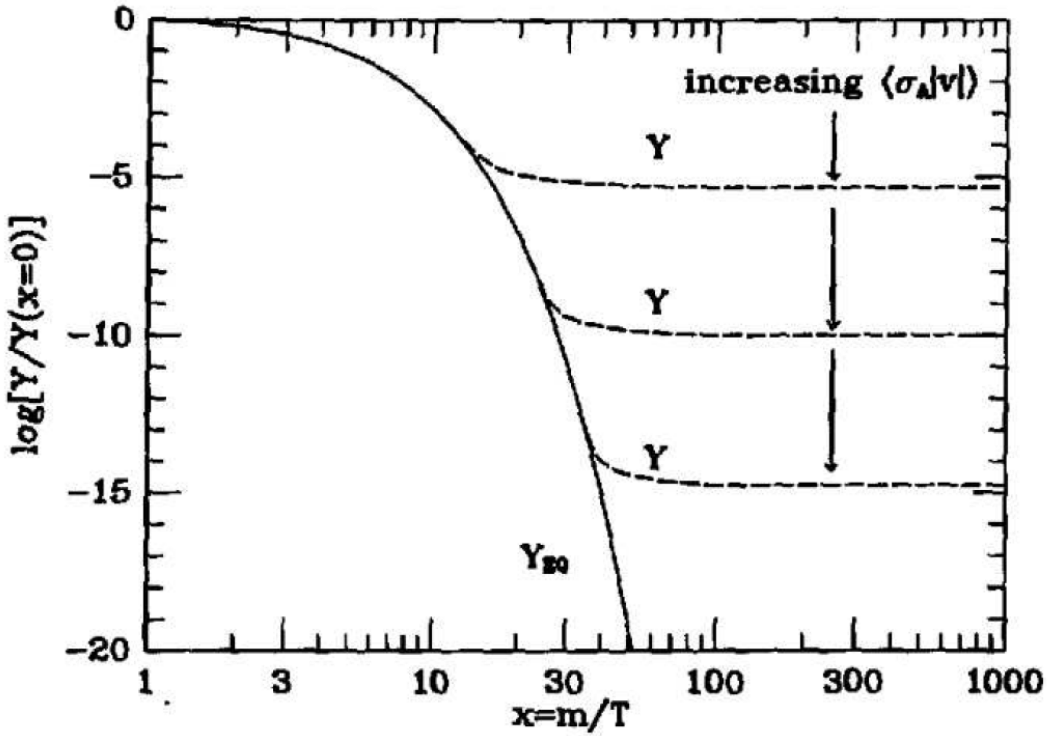
TeVPA2026 @ Tendo, Japan
3rd September 2026

Based on Phys. Lett. B **864** 139425 (2025) [arxiv: 2501.12117 [hep-ph]]
and JHEP **08** 207 (2026) [arxiv:2606.02751 [hep-ph]]
Collaborators: B. Betancourt Kamenetskaia, M. Fujiwara, A. Ibarra

Thermal dark matter

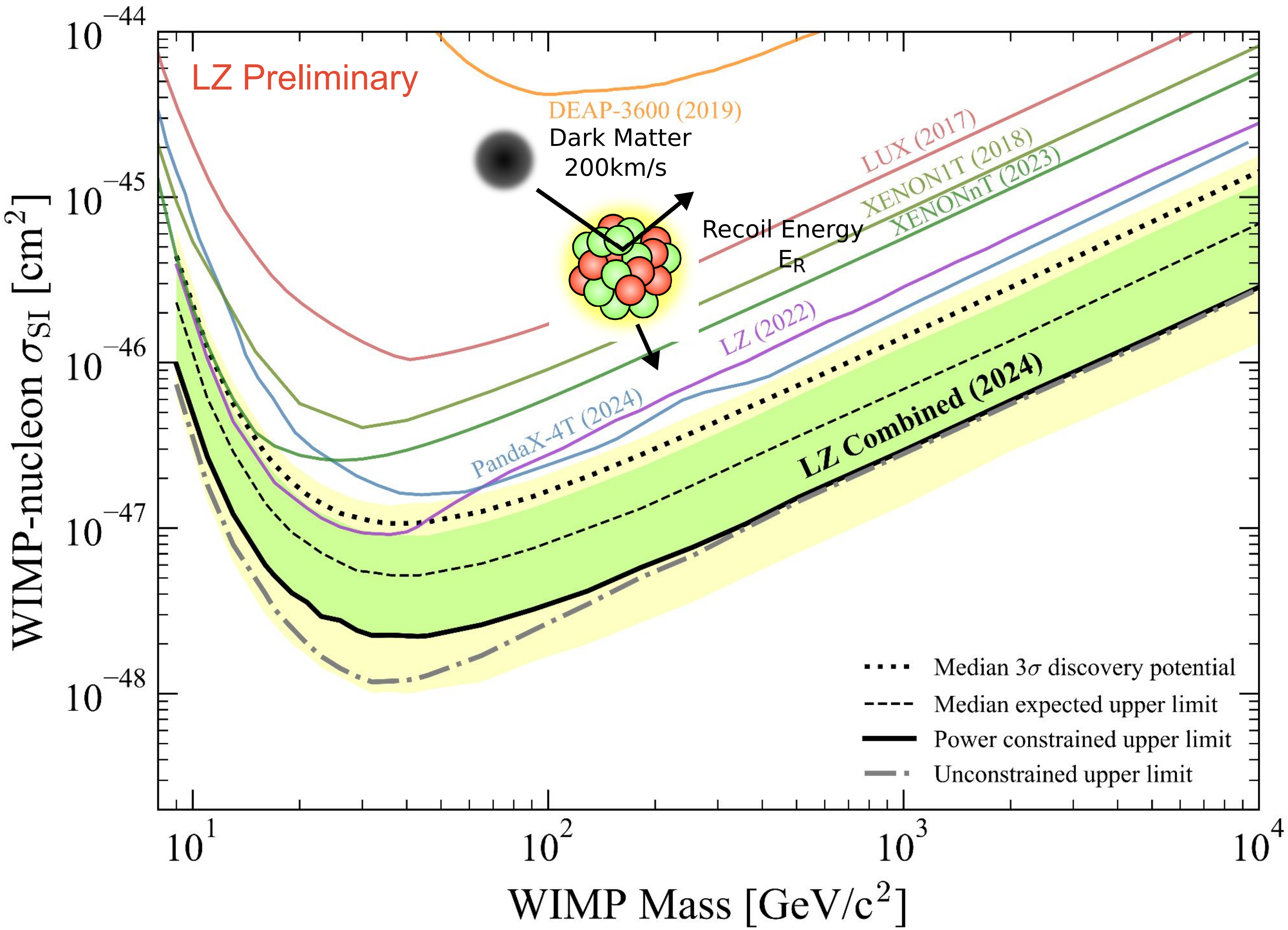


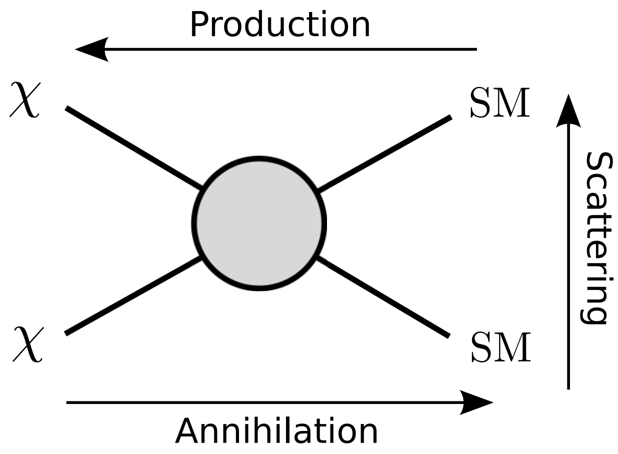


$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_\chi^{\mathrm{eq}2} \right)$$

- Thermalized with SM particles in early universe.
- To get $\Omega_\chi h^2 = 0.12$, roughly $\sigma \sim 1\mathrm{pb} \sim 10^{-26}\mathrm{cm}^3/\mathrm{s} \sim 10^{-36}\mathrm{cm}^2$
  (only log dependent on DM mass)
- Mass range: 10 MeV – 100 TeV

Status of direct detection experiments





- $\Omega h^2 = 0.12$

  $\Leftrightarrow \sigma_{\mathrm{el}} \sim 10^{-36}$ cm^2

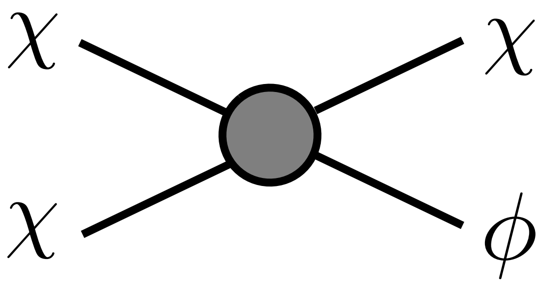
  ($\sigma_{\mathrm{el}} \lesssim 10^{-45}$ cm^2)

  (loop)

LZ talk @ TeVPA2024

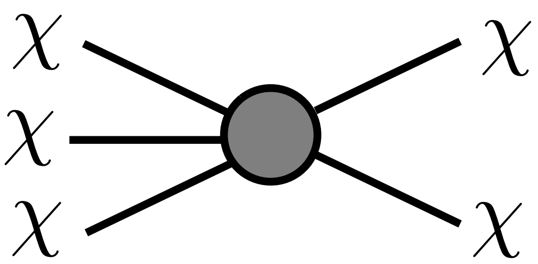
- LZ gives the strongest bound 2.2×10^{-48} cm^2 at 43 GeV.
- Low sensitivity at low DM mass due to experimental threshold

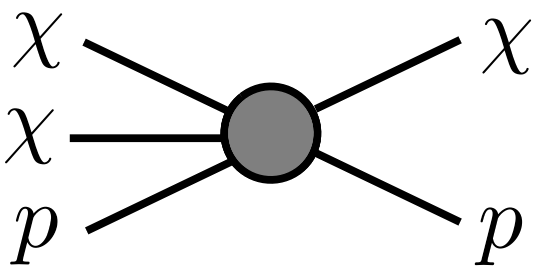
Boosted DM



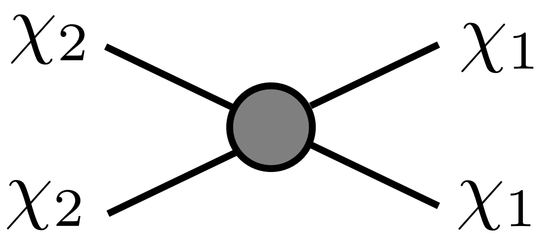
- Semi-annihilations
  Hambye, JHEP (2009), D'Ermao,. Thaler, JHEP (2010)
  $\chi\chi \to \overline{\chi}\phi \ (v_\chi = \mathcal{O}(0.1-1))$
  $\mathbb{Z}_3$ symmetric DM $\Rightarrow$ cubic coupling $\mathcal{L} \supset \chi^3$

- SIMP, Co-SIMP Hochberg, Kuflik, Volansky, PRL (2014), Smirnov, Beacom, PRL (2020)
  $\chi\chi\chi \to \chi\overline{\chi}$, $\chi\chi p \to \chi p$



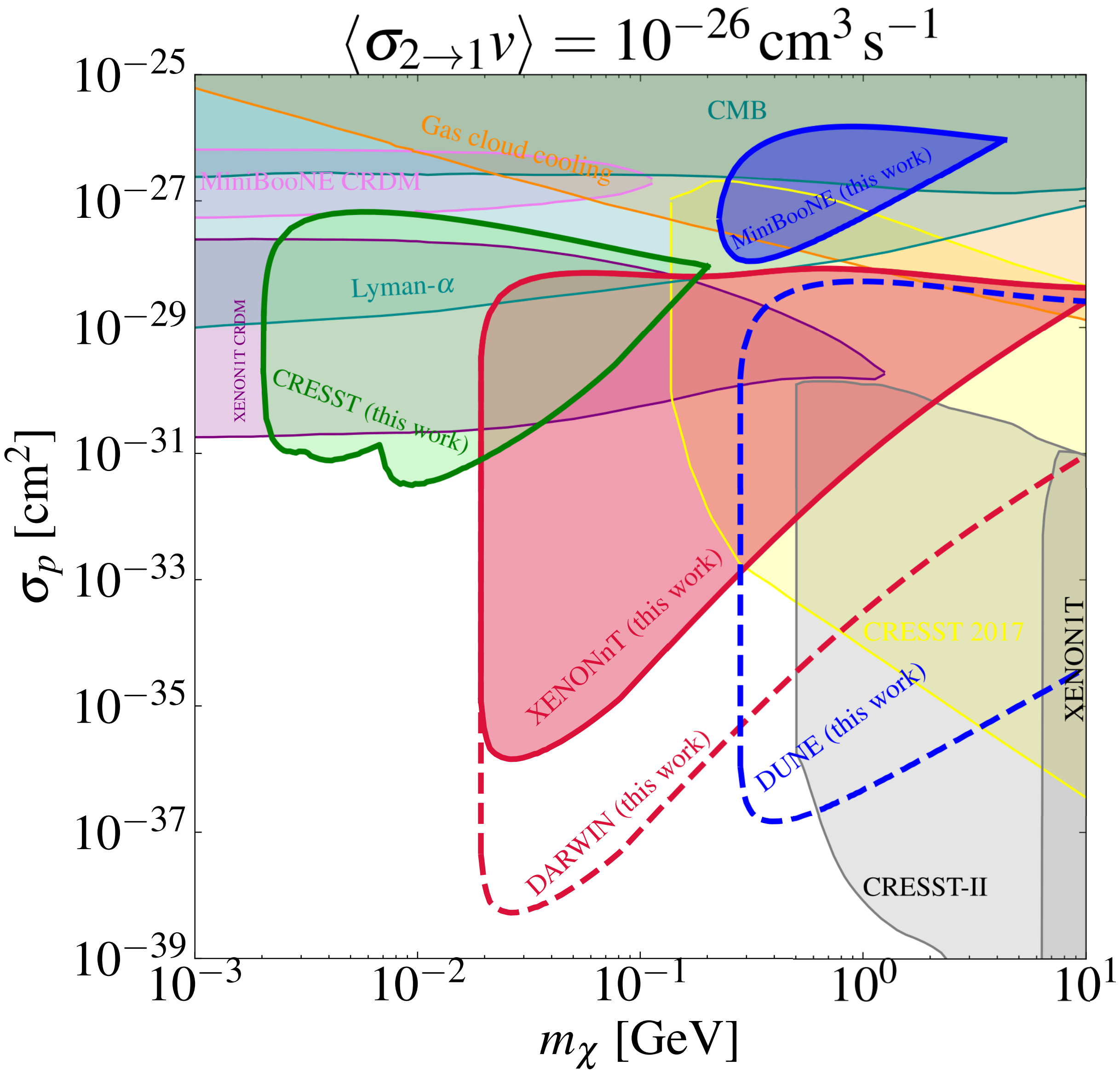


- Multi-component DM
  $\chi_2\chi_2 \to \chi_1\chi_1$
  e.g. R. Sheikh, TT, K. Tsumura, 2604.12435 [hep-ph]



Our previous work

Betancourt Kamenetskaia et al., PLB 864 (2025), [2501.12117 [hep-ph]]



- Model independent study
- The excluded region is sharply cut at a small DM mass due to experimental threshold.
- XENONnT excluded $\sigma_p \sim 10^{-35}$ [cm^2] around $m_\chi \sim 30$ MeV DARWIN: $\sigma_p \sim 10^{-38}$ [cm^2]
- Coherent enhancement is lost for larger DM mass.
- What model can realize this scenario?

Model building

Model building

Ma, PLB 662 (2008), Aoki, TT, JCAP 09 016 (2014)

	L_L	e_R^c	ψ_L	ψ_R^c	H	Σ	η	χ
SU(2)$_L$	**2**	**1**	**1**	**1**	**2**	**1**	**2**	**1**
U(1)$_Y$	–1/2	1	0	0	1/2	0	1/2	0
Global U(1)$_L$	1	–1	–1/3	–5/3	0	2	2/3	2/3
Remnant $\mathbb{Z}_3$	0	0	1	–1	0	0	1	1
Spin	1/2	1/2	1/2	1/2	0	0	0	0

Lagrangian

$$\mathcal{L} = \overline{\psi}_i i\partial\!\!\!/ \psi_i + |\partial_\mu \Sigma|^2 + |D_\mu \eta|^2 + |\partial_\mu \chi|^2 - \mathcal{V}(H, \Sigma, \eta, \chi)$$

$$- \left(y_\alpha H^\dagger \overline{e}_\alpha L_\alpha + (y_\nu)_{i\alpha} \eta \overline{\psi}_i P_L L_\alpha + \frac{(y_L)_{ij}}{2} \chi \overline{\psi_i^c} P_L \psi_j + (y_\Sigma)_i \Sigma \overline{\psi}_i P_L \psi_i + \text{h.c.} \right)$$

- $\mathcal{V}(H, \Sigma, \eta, \chi) \supset \lambda_{H\Sigma} |H|^2 |\Sigma|^2 + \tilde{\mu}_\chi \left(H^\dagger \eta \right) \chi^* + \dfrac{\tilde{\lambda}_\chi}{3!} \Sigma^* \chi^3 \Rightarrow \dfrac{\tilde{\lambda}_\chi \langle \Sigma \rangle}{3!} \chi^3$
- Global U(1)$_L \Rightarrow \mathbb{Z}_3$

Mass spectra

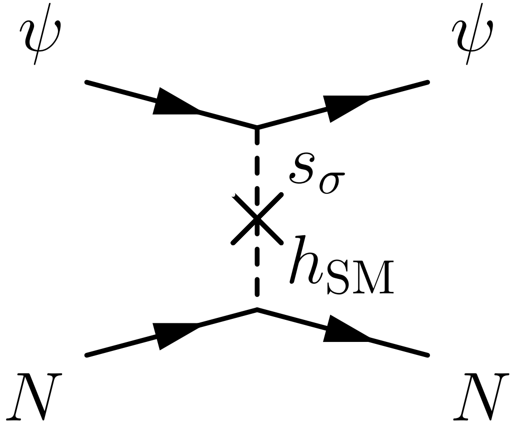
- $H = \begin{pmatrix} 0 \\ \frac{v+h_{\mathrm{SM}}}{\sqrt{2}} \end{pmatrix}, \quad \Sigma = \dfrac{v_\sigma + \sigma + iJ}{\sqrt{2}}, \quad \eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}, \quad \chi = \chi$

  pNGB: $m_J = \mathcal{O}(100)$ GeV $\quad \dfrac{1}{M_P^2}\Phi^4\Sigma^2 + \text{h.c.} \Rightarrow \dfrac{\langle\Phi\rangle^4}{M_P^2}\Sigma^2 + \text{h.c.}$

- Rewritten by mass eigenstates

$$\begin{pmatrix} \sigma \\ h_{\mathrm{SM}} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} s \\ h \end{pmatrix}$$

$$\begin{pmatrix} \chi \\ \eta^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \varphi \\ \tilde{\varphi} \end{pmatrix}$$



- Mixing angles

  $\sin\theta \propto \lambda_{H\Sigma}$

  $\sin\alpha \propto \tilde{\mu}_\chi$

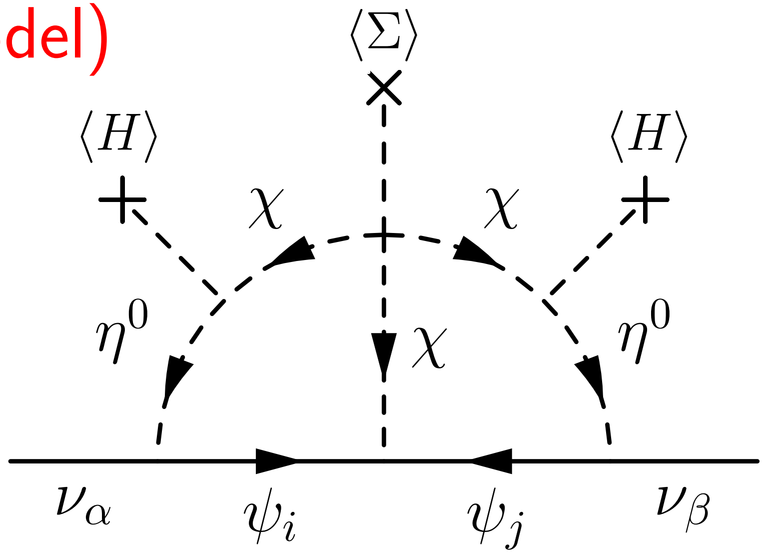
- Fermion masses

  $M_i = (y_\Sigma)_i v_\sigma / \sqrt{2}$

Neutrino masses

- $$(m_\nu)_{\alpha\beta} \approx \frac{\tilde{\lambda}_\chi v_\sigma \sin^2 2\alpha \cos^2\alpha}{4\sqrt{2}(4\pi)^4} \sum_{i,j} (y_\nu)_{i\alpha}(y_L)_{ij}(y_\nu)_{j\beta} I_{\text{loop}}$$

  μ_χ (original model) $\Leftrightarrow$ $\frac{\tilde{\lambda}_\chi v_\sigma}{\sqrt{2}}$ (extended model)



- Diagonalization:
  $U^T m_\nu U$ = diag(m_1,m_2,m_3)
  with PMNS matrix U

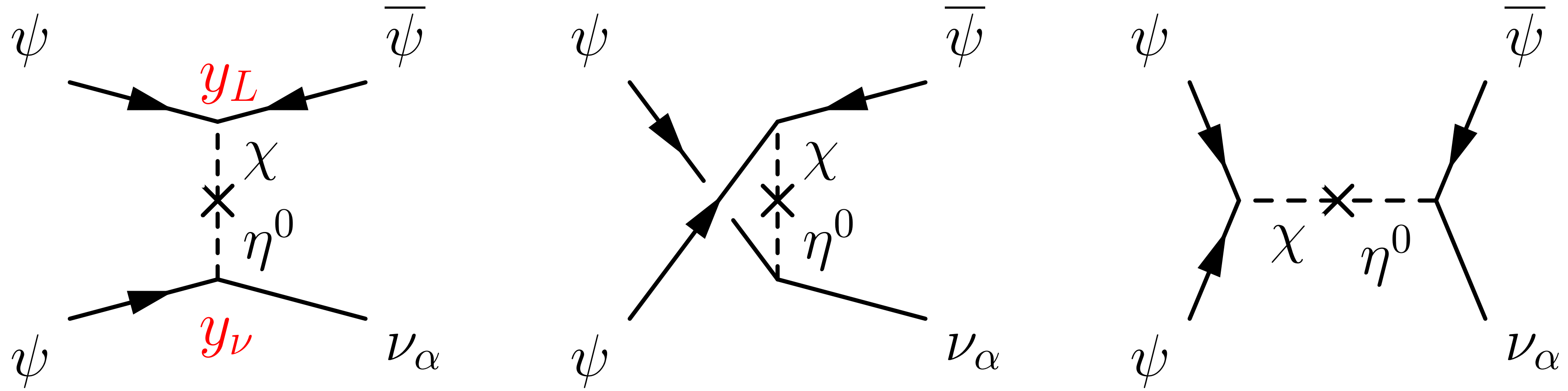
- Correlation with DM coupling (assuming diagonal y^ν)

$$(y_L)_{11} = 0.2\left(\frac{0.01}{(y_\nu)_{1e}\sin 2\alpha}\right)^2\left(\frac{1\text{ GeV}}{\tilde{\lambda}_\chi v_\sigma}\right)\left(\frac{0.1}{I_{\text{loop}}}\right)\left(\frac{(m_\nu)_{ee}}{10^{-2}\text{ eV}}\right)$$

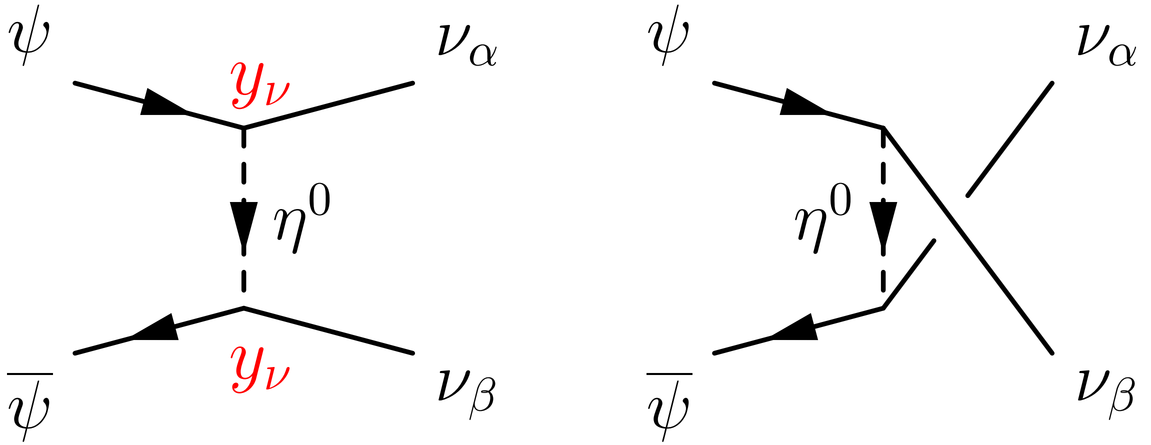
Dark matter

DM: the lightest fermion $\psi \equiv \psi_1$

- Semi-annihilation: $\psi\psi \to \overline{\psi}\nu_\alpha$ (s-wave)



- Standard annihilation: $\psi\overline{\psi} \to \nu_\alpha\nu_\beta$ (s-wave)



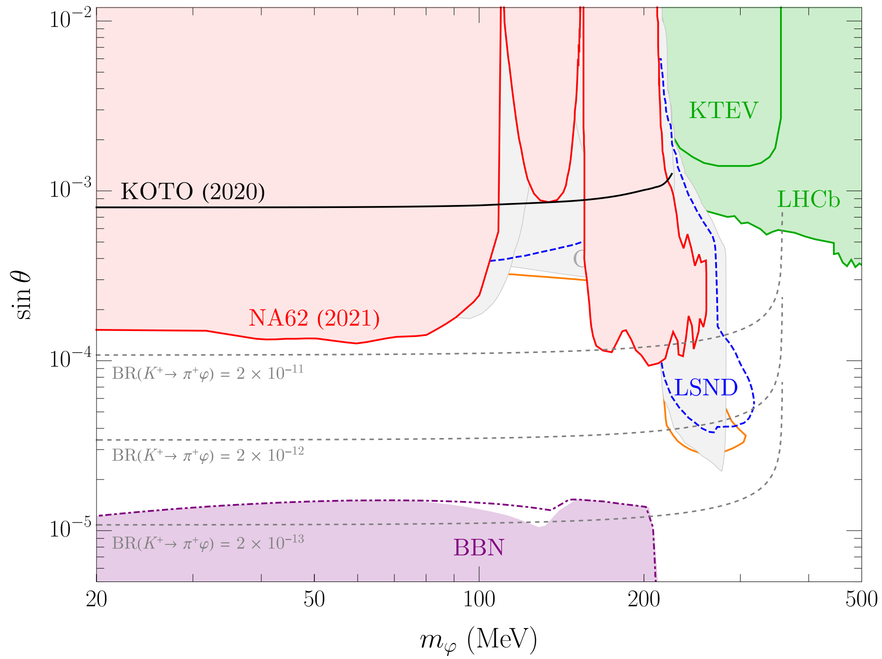
Constraints

- Neutrino masses and mixings $\Rightarrow$ $m_\nu \propto y_\nu^T y_L y_\nu$ (mixing)
- Lepton flavor violation $\ell_\alpha \to \ell_\beta \gamma$ $\Rightarrow$ Roughly diagonal y_ν

$$\mathrm{Br}(\ell_\alpha \to \ell_\beta\gamma) \simeq \frac{\alpha_{\mathrm{em}}}{768\pi G_F^2 m_\eta^4} \left|(y_\nu)_{1\alpha}(y_\nu)_{1\beta}^*\right|^2$$

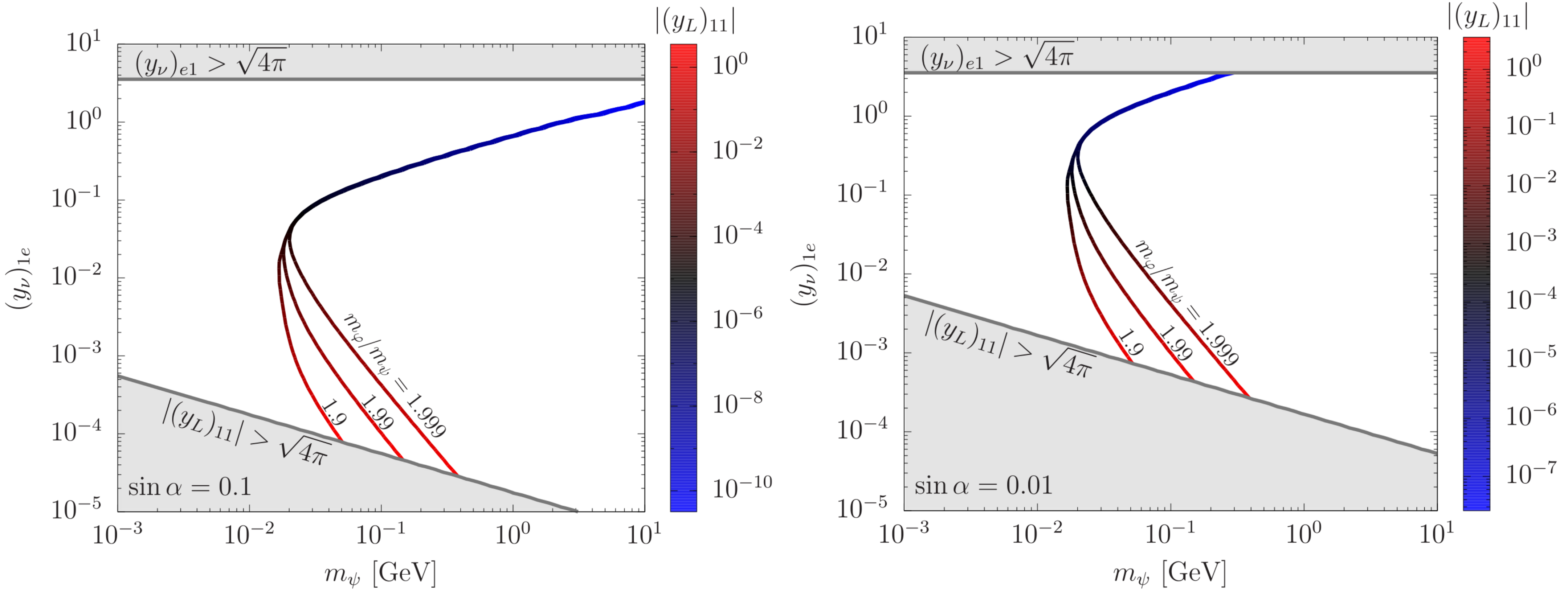
- Electroweak precision test ($\Delta\rho$ and Z invisible decay $Z \to \varphi^*\varphi$)
  $\Rightarrow$ $m_\varphi \ll m_{\tilde{\varphi}} \approx m_\eta \sim$ TeV and $\sin\alpha \lesssim 0.39$
- Higgs mixing angle $\sin\theta$: $K^+ \to \pi^+\nu\bar{\nu}$
  $\Rightarrow$ $10^{-5} \lesssim \sin\theta \lesssim 10^{-4}$
- BBN: $\tau_s \lesssim$ 1s $\Rightarrow$ $m_s \gtrsim$ 1 MeV
- Potential stability

$$\lambda_\chi - \frac{1}{96\sqrt{3}\pi}\left(\frac{\tilde{\lambda}_\chi v_\sigma}{m_\chi}\right)^4 \gtrsim 0$$



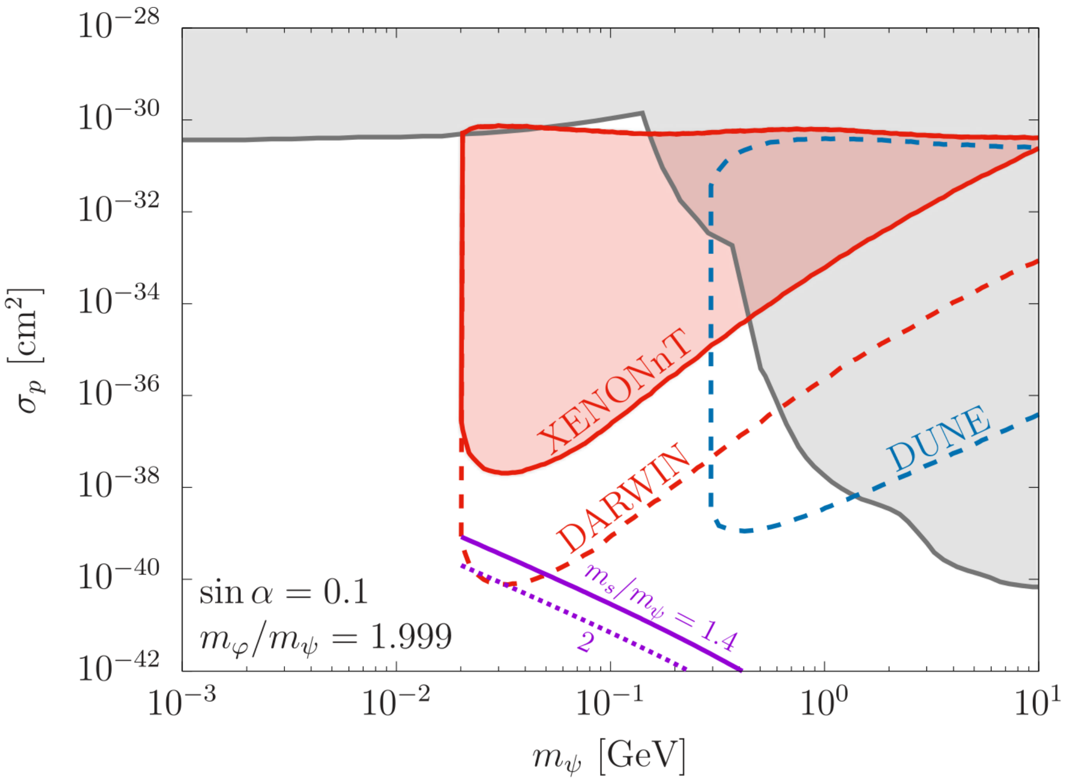
E. Goudzovski et al., Rep. Prog. Phys. 86 016201 [arxiv:2201.07805 [hep-ph]]

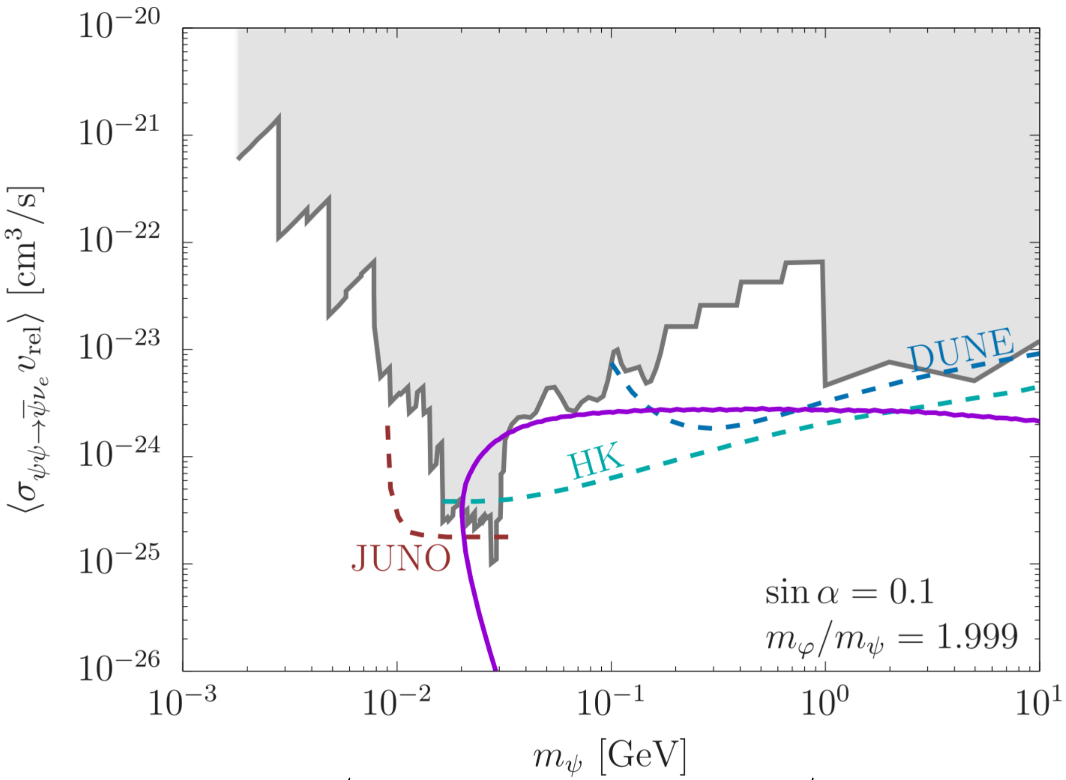
Relic abundance



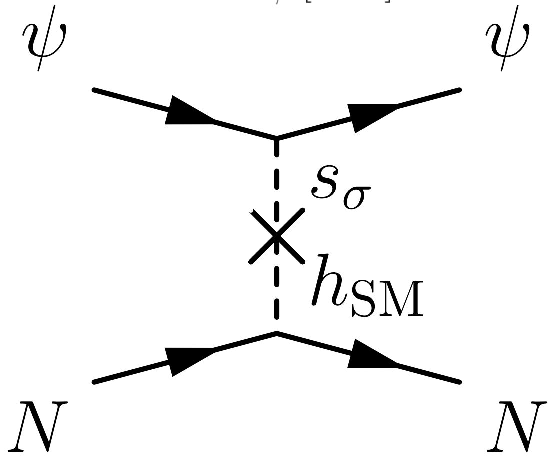
- $1.4 m_\psi \lesssim m_s \lesssim 2 m_\psi$, $\sin\theta = 10^{-4}$
  $m_\varphi / m_\psi = 1.9, 1.99, 1.999$ (close to resonance)
- $\psi\psi \to \overline{\psi}\nu_\alpha \gg \psi\overline{\psi} \to \nu_\alpha\nu_\beta$ (red region)
  $\psi\psi \to \overline{\psi}\nu_\alpha \ll \psi\overline{\psi} \to \nu_\alpha\nu_\beta$ (blue region)

BDM and ν searches from semi-ann. $(\psi\psi \to \overline{\psi}\nu)$





- Scattering with nucleons $\psi N \to \psi N$
- BDM and ν can be detected simultamenously by DARWIN and Hyper-K with $\mathcal{O}(0.1)\%$ tuning.



Summary

1. Conventional thermal DM scenarios are strongly constrained.
2. Semi-annihilations accelerate DM coming from Galactic Center, that can be an exotic DM signal (boosted DM).
3. A concrete model was built with loop induced neutrino masses.
4. We found the produced BDM and neutrino can be detected through DARWIN and HK at the same time, respectively.