

Boosted dark matter from semi-annihilations in a neutrino mass model

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Based on Phys. Lett. B **864** 139425 (2025)

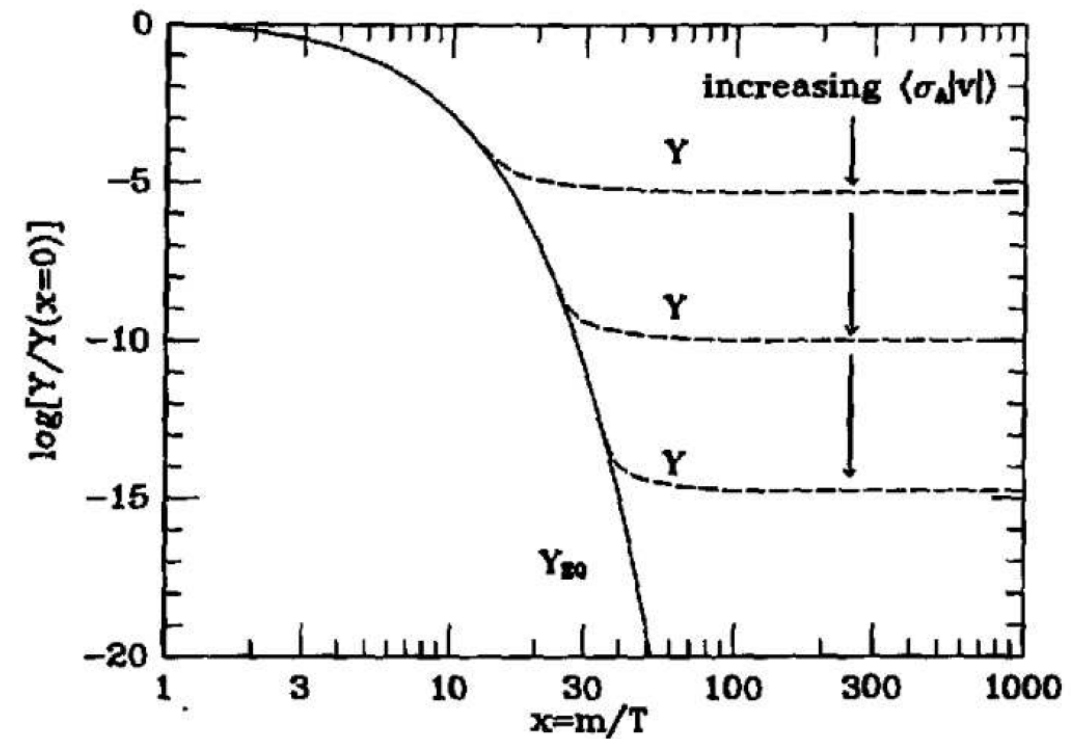
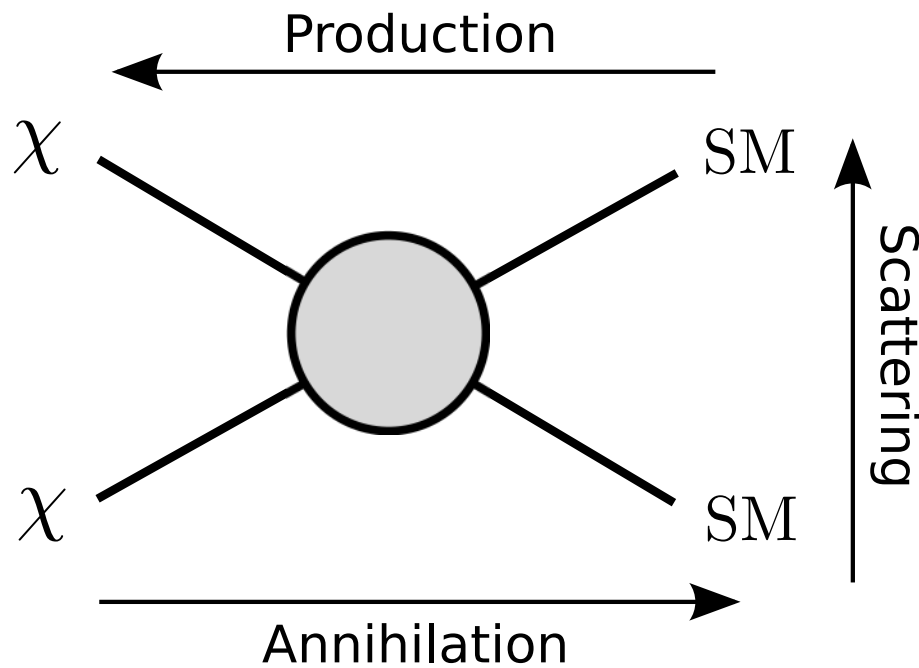
and work in progress with M Fujiwara

Collaborators: B. Betancourt Kamenetskaia, M. Fujiwara, A. Ibarra

Outline

- 1 Thermal dark matter and non-minimal dark sector
- 2 Boosted dark matter from semi-annihilations
PLB **864** 139425 (2025)
- 3 Neutrino mass models (review)
- 4 Model building for boosted dark matter
Work in progress with Motoko Fujiwara
- 5 Summary

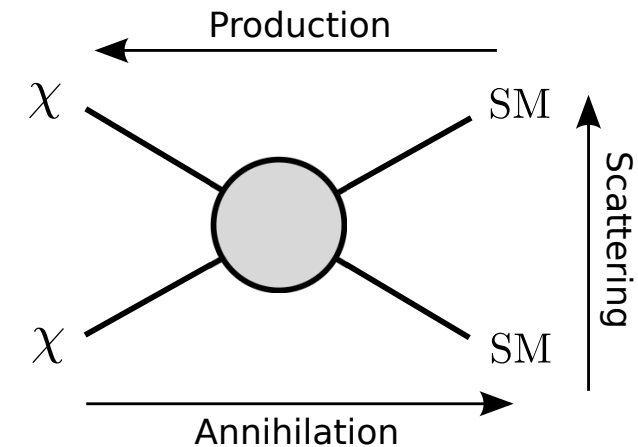
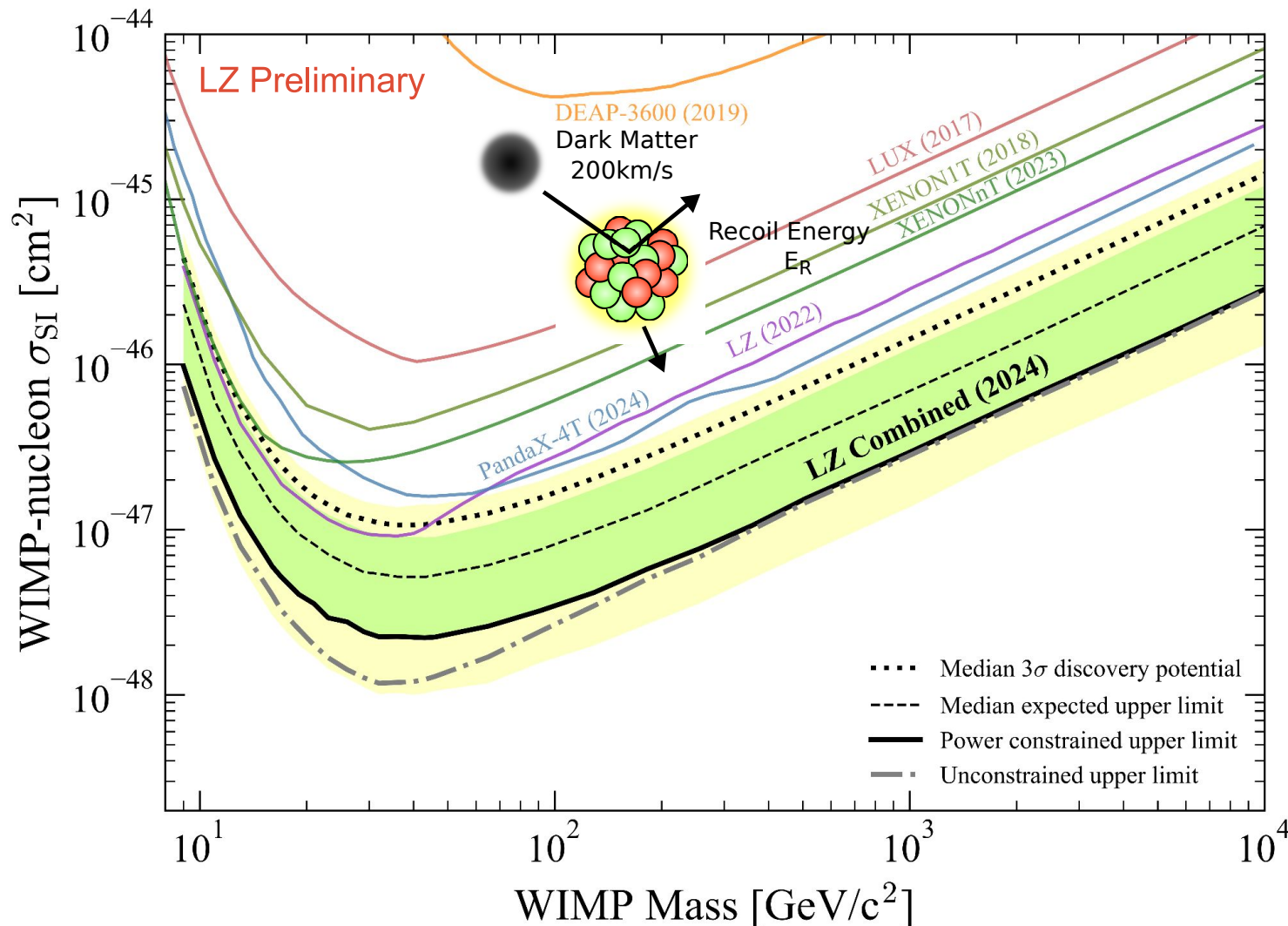
Thermal dark matter



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

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

Status of direct detection experiments



■ $\Omega h^2 = 0.12$
 $\Leftrightarrow \sigma_{\text{el}} \sim 10^{-36} \text{ cm}^2$
 $(\sigma_{\text{el}} \lesssim 10^{-45} \text{ cm}^2)$
 (loop)

LZ talk @ TeVPA2024

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

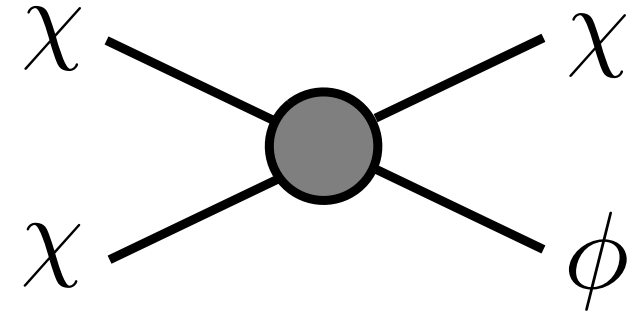
Non-minimal dark sector

$\mathbb{Z}_3$ symmetric DM $\Rightarrow$ cubic coupling $\mathcal{L} \supset \chi^3$

■ Semi-annihilations

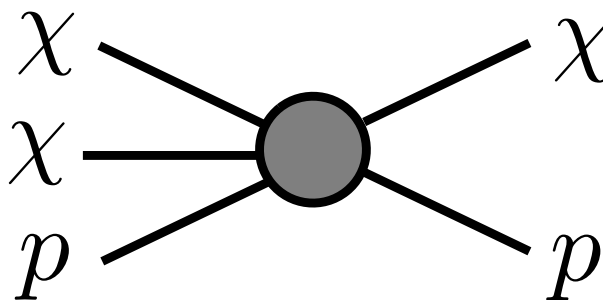
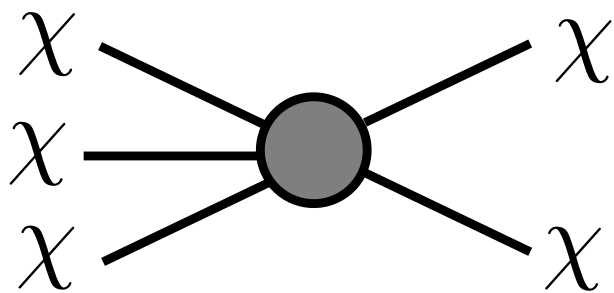
Hambye, JHEP (2009), D'Ermiao, Thaler, JHEP (2010)

$$\chi\chi \rightarrow \bar{\chi}\phi \quad (v_\chi = \mathcal{O}(0.1 - 1))$$



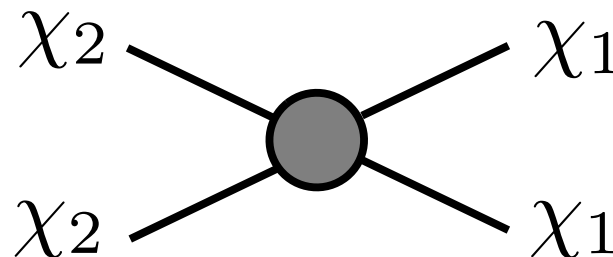
■ SIMP, Co-SIMP Hochberg, Kuflik, Volansky, PRL (2014), Smirnov, Beacom, PRL (2020)

$$\chi\chi\chi \rightarrow \chi\bar{\chi}, \quad \chi\chi p \rightarrow \chi p$$



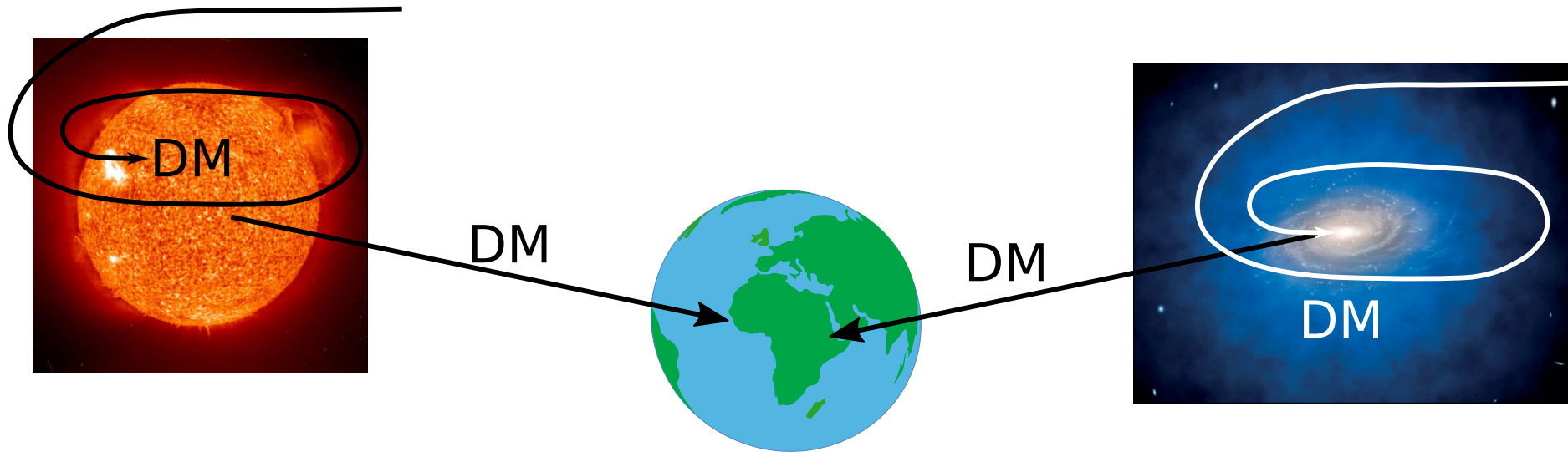
■ Multi-component DM

$$\chi_2\chi_2 \rightarrow \chi_1\chi_1$$



e.g. R. Sheikh, TT, K. Tsumura, 2604.12435 [hep-ph]

DM acceleration



Other acceleration mechanisms and models

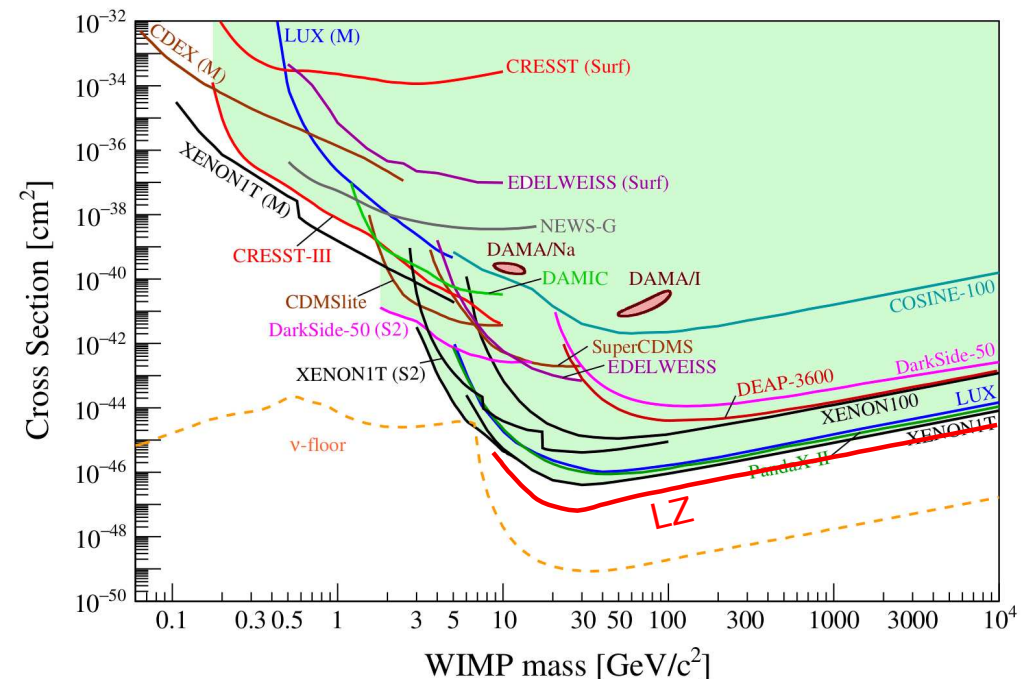
- Scattering with high energy cosmic-rays Bringmann and Pospelov, PRL (2019)
Ema, Sala, Sato, PRL (2019)
- Scattering with Blazar Wang, Granelli, Ullio, PRL (2022)
- Solar reflection Emken, PRD (2022)
- Vacuum decay Cline, Puel, Toma, Wang, PRD (2023), Cline, Puel, Toma, PLB (2024)

Boosted DM from semi-annihilations

Boosted DM from semi-annihilations

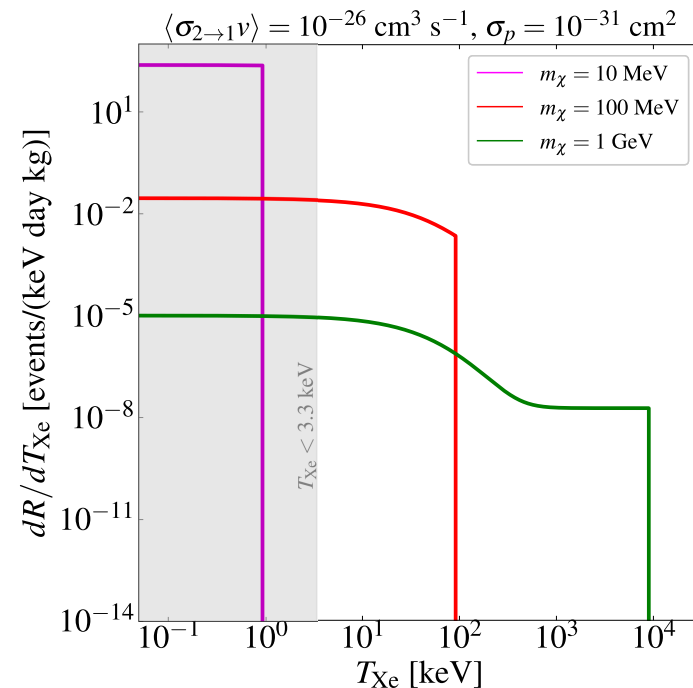
- We focus on $\chi\chi \rightarrow \bar{\chi}\nu \Rightarrow$ Dirac DM
(if $\chi\chi \rightarrow \bar{\chi}\phi \rightarrow \bar{\chi}f\bar{f} \Rightarrow$ strongly constrained by indirect detection)
- DM energy in the final state: $E_\chi = \frac{5}{4}m_\chi$ (monochromatic)
 $\Rightarrow$ Moderate boost factor $\gamma_\chi \equiv \frac{E_\chi}{m_\chi} = \frac{5}{4} = 1.25$ ($v_\chi = 0.6$)
- $\gamma_\chi < \gamma_{\text{Cherenkov}}^{\text{th}} \approx 1.5$
- No deep inelastic scattering
 $\Rightarrow$ simple calculation
- Sub-GeV DM mass range can be target for semi-annihilations.

J. Billard et al., Rept.Prog.Phys. 85 (2022) 5, 056201



Recoil energy spectra

- $\frac{dR_N}{dT_N} = \frac{1}{m_N} \int_{T_\chi^{\min}}^{\infty} \frac{d\sigma_{\chi N}}{dT_N} \frac{d\Phi_\chi}{dT_\chi} dT_\chi$ where $\frac{d\Phi_\chi}{dT_\chi} = \Phi_{\text{BDM}} \delta\left(T_\chi - \frac{m_\chi}{4}\right)$
 $\Phi_{\text{BDM}} \approx 3.2 \times 10^{-3} [\text{cm}^{-2}\text{s}^{-1}] \left(\frac{m_\chi}{100 \text{ MeV}}\right)^{-2} \left(\frac{\langle\sigma_{2\rightarrow 1}v\rangle}{10^{-26} \text{ cm}^3/\text{s}}\right)$
- Mass threshold: $m_\chi^{\min} = \frac{5}{4}m_N \left(\frac{9m_N}{8T^{\text{th}}} - 1\right)^{-1} \left(1 + \frac{3}{5}\sqrt{1 + \frac{2m_N}{T^{\text{th}}}}\right)$
- For XENONnT, $T_{\text{Xe}} = 3.3\text{keV}$
 $\Rightarrow m_\chi^{\min} = 19 \text{ MeV}$
- $R = \sum_N \int \frac{dR_N}{dT_N} dT_N$
 (events/kg/yr)



Attenuation due to overburden

■ Energy loss: $\frac{dT_\chi^z}{dz} = - \sum_N n_N \int_0^{T_\chi^{\max}} T_\chi \frac{d\sigma_{\chi N}}{dT_\chi} dT_\chi$

■ If $m_\chi \ll m_N$, $T_\chi(z) \approx T_\chi(0)e^{-z/\ell}$

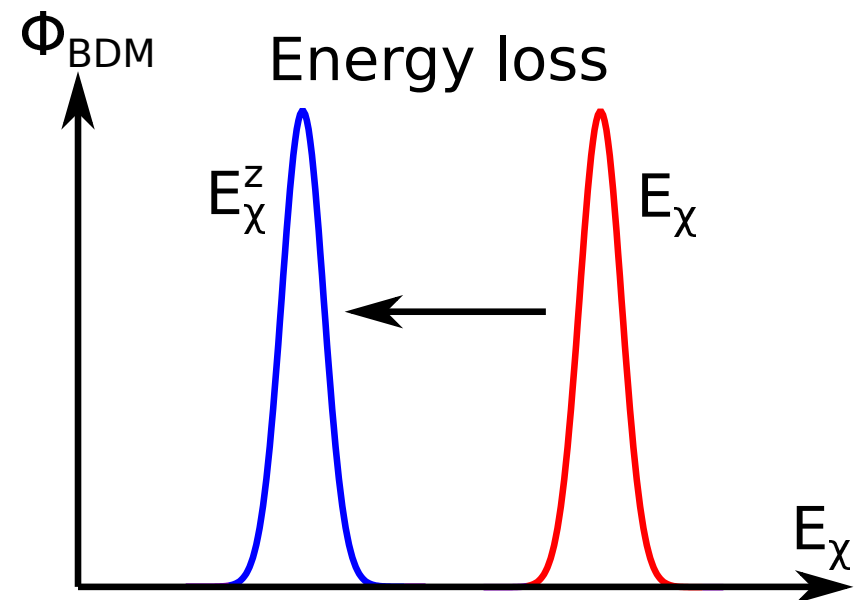
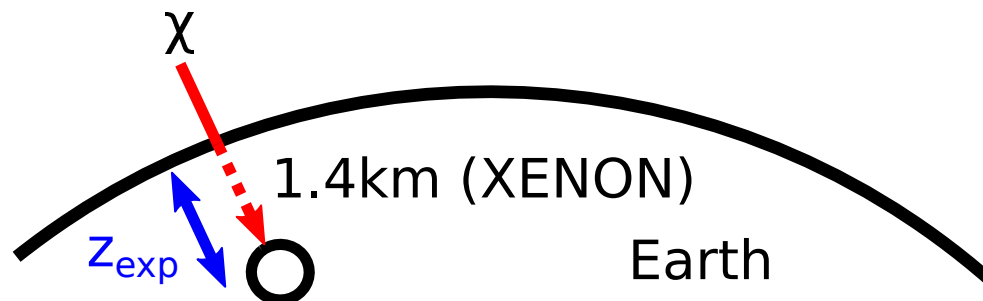
where $\ell \equiv \sigma_p \sum_A 2n_N A_N^2 \left(\frac{m_\chi}{m_N}\right) \left(1 + \frac{m_\chi}{m_p}\right)^2 \left(1 + \frac{m_\chi}{m_N}\right)^{-4}$

■ Soil component:

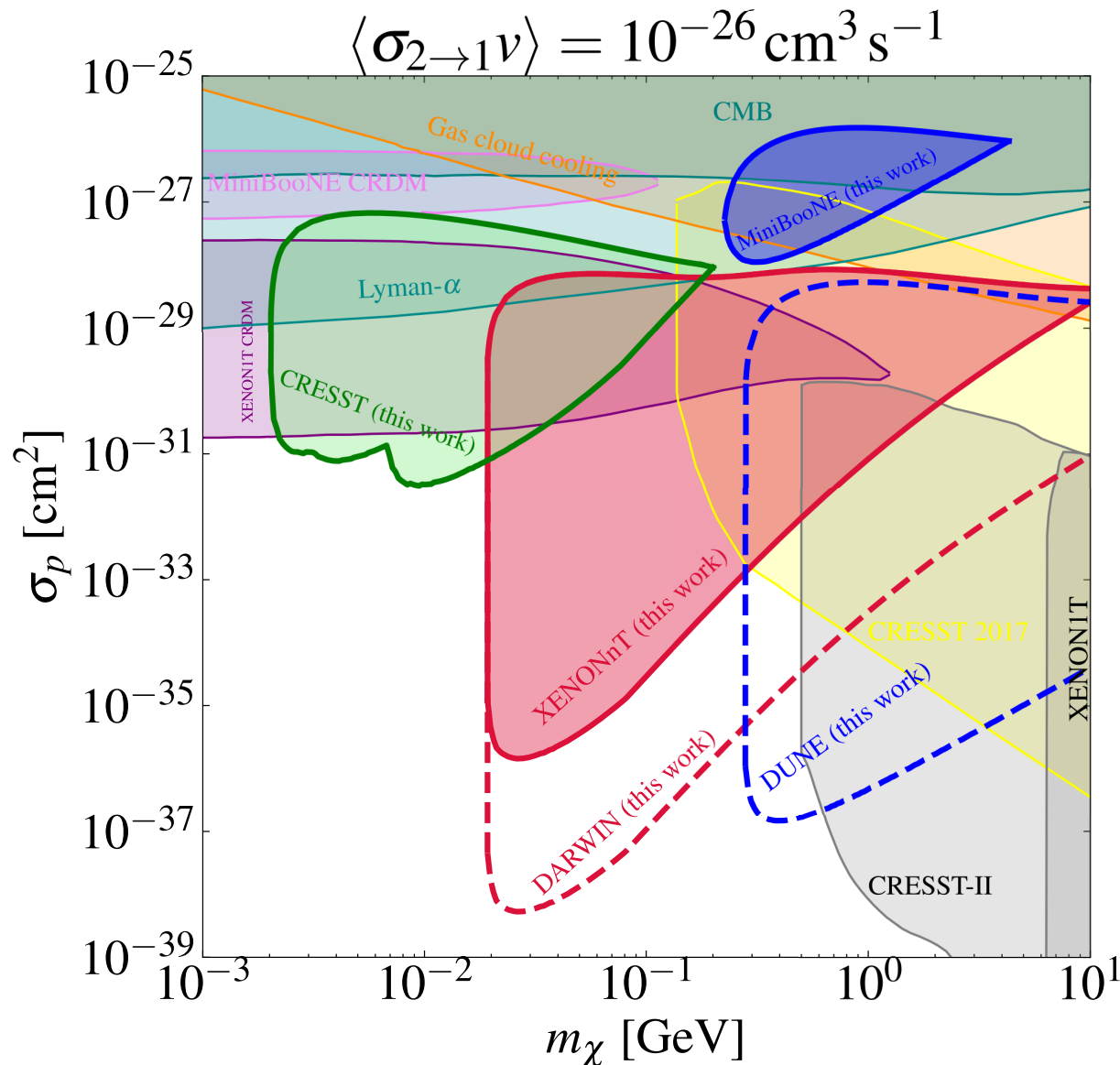
O: 48%, Ca: 30%,

C: 12%, Mg: 5.6%

Density: $\rho = 2.71 \text{ g/cm}^3$



Bounds and future sensitivity for SI cross section



- Large σ_p region is **not** excluded due to strong attenuation.
- The excluded region is sharply cut at a small DM mass due to experimental threshold.
- XENONnT excluded
 $\sigma_p \sim 10^{-35} \text{ [cm}^2\text{]}$ around
 $m_\chi \sim 30 \text{ MeV}$
 DARWIN: $\sigma_p \sim 10^{-38} \text{ [cm}^2\text{]}$
- Coherent enhancement is lost for larger DM mass.

Neutrino mass models

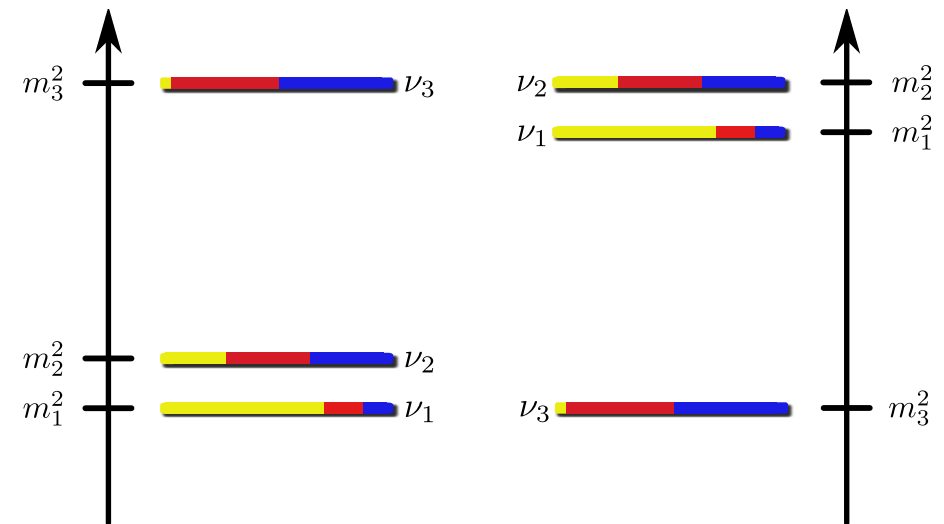
Neutrino masses and mixings

Neutrino masses and mixings are confirmed by the neutrino oscillations.

- $\Delta m_{21}^2 = 7.49 \times 10^{-5} \text{ [eV}^2\text{]}, \Delta m_{31}^2 = 2.513 \times 10^{-3} \text{ [eV}^2\text{]}$ (Normal hierarchy)
- Large mixing angles of the PMNS matrix [Esteban et al., \[arXiv:2410.05380 \[hep-ph\]\]](#)
 $\sin^2 \theta_{12} = 0.308, \sin^2 \theta_{23} = 0.470, \sin^2 \theta_{13} = 0.02215.$

Remaining problems

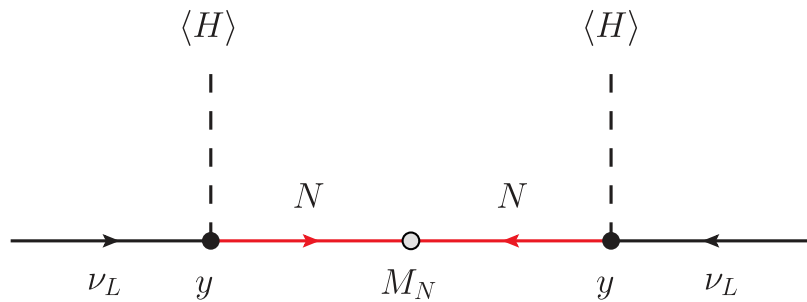
- Mass ordering (NH or IH?)
- Neutrinos are Dirac or Majorana?
- How much is CP phase?
 $\delta_{\text{CP}} = 212_{-41}^{+26} [^\circ]$ for NH,
 $\delta_{\text{CP}} = 274_{-25}^{+22} [^\circ]$ for IH
 $\Rightarrow$ CP conservation? or maximal violation?



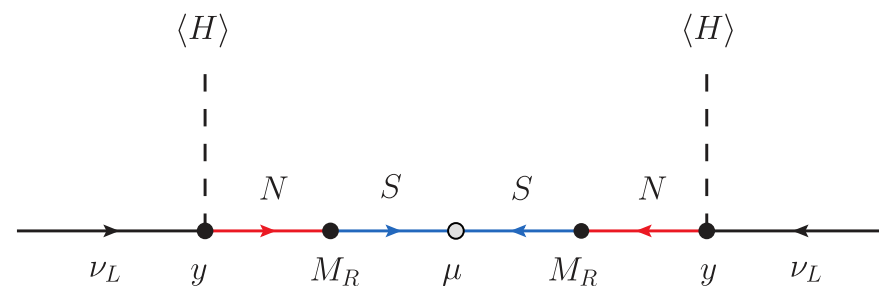
Neutrino mass generation mechanisms

- Type-I, II, III seesaw, Inverse seesaw, Linear seesaw, radiative seesaw etc.

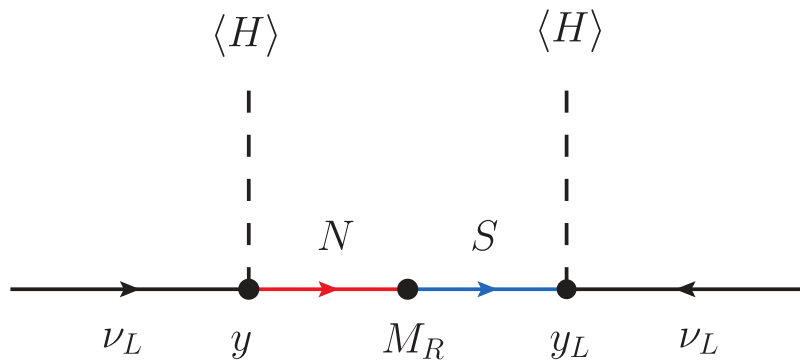
Phys.Rev.D 101 (2020) 7, 075032 [arXiv:1912.08858 [hep-ph]]



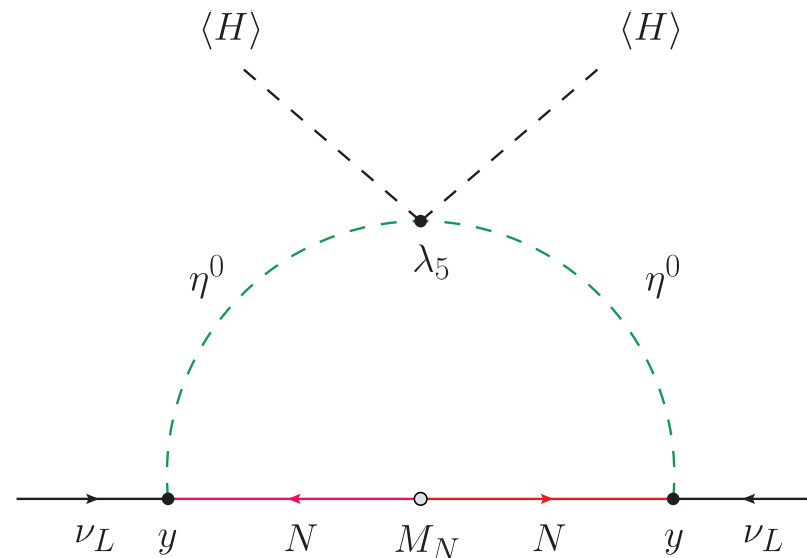
Type-I seesaw



Inverse seesaw



Linear seesaw



Radiative seesaw

Neutrino Mass Generation (tree level)

- Seesaw mechanism (Type I, Type II, Type III...)

In Type I seesaw, heavy right-handed neutrinos N_R are introduced.

$$\begin{aligned}\mathcal{L} &= -H^\dagger \bar{\ell}_L y_\nu N_R - \frac{1}{2} \bar{N}_R^c M N_R + \text{h.c.} \\ &\rightarrow -\bar{\nu}_L m_D N_R - \frac{1}{2} \bar{N}_R^c M N_R + \text{h.c.} \quad m_D = y_\nu \langle H \rangle\end{aligned}$$

Mass matrix

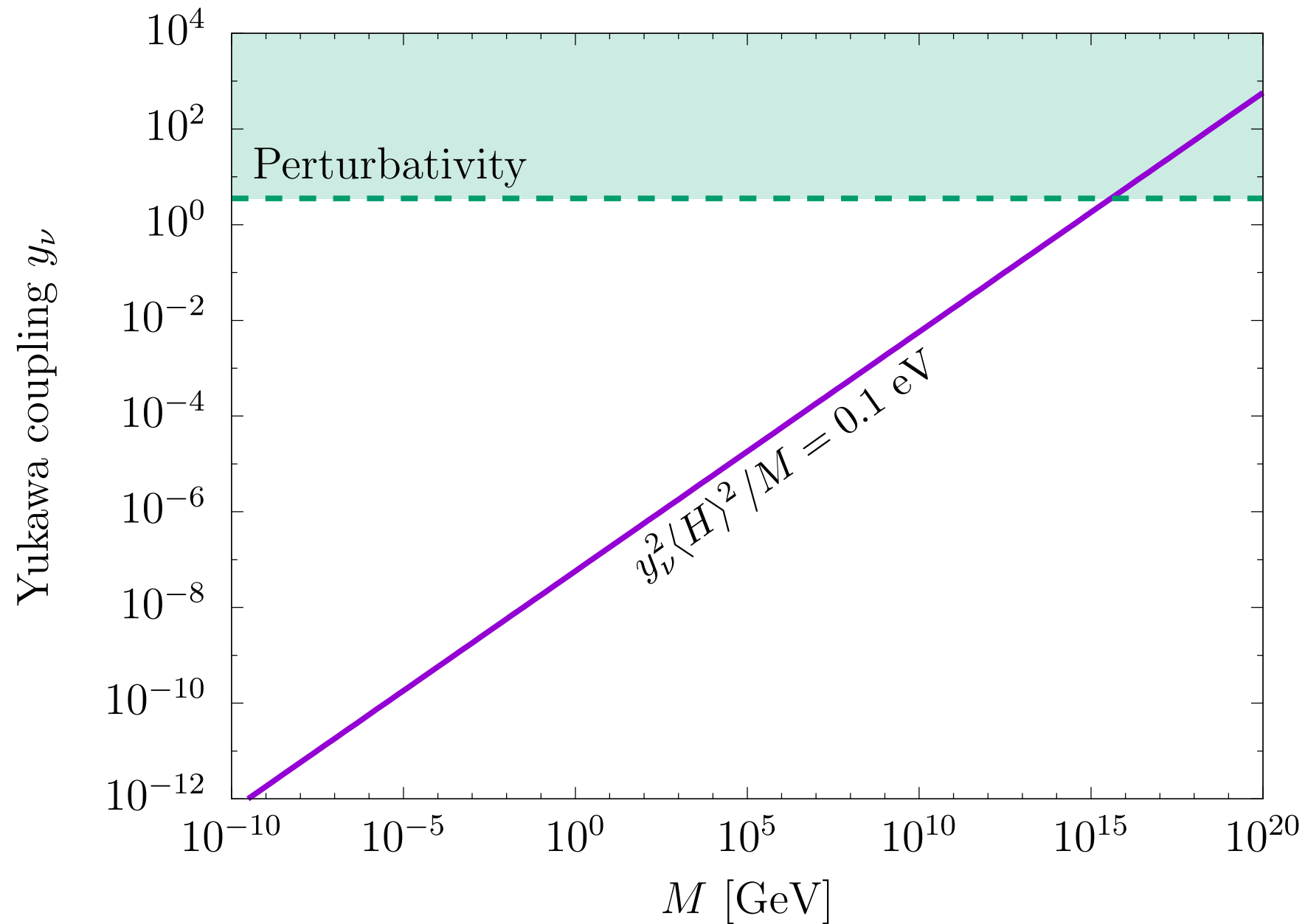
$$\begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \rightarrow m_\nu = -m_D M^{-1} m_D^T + \dots$$

(if $m_D \ll M$)

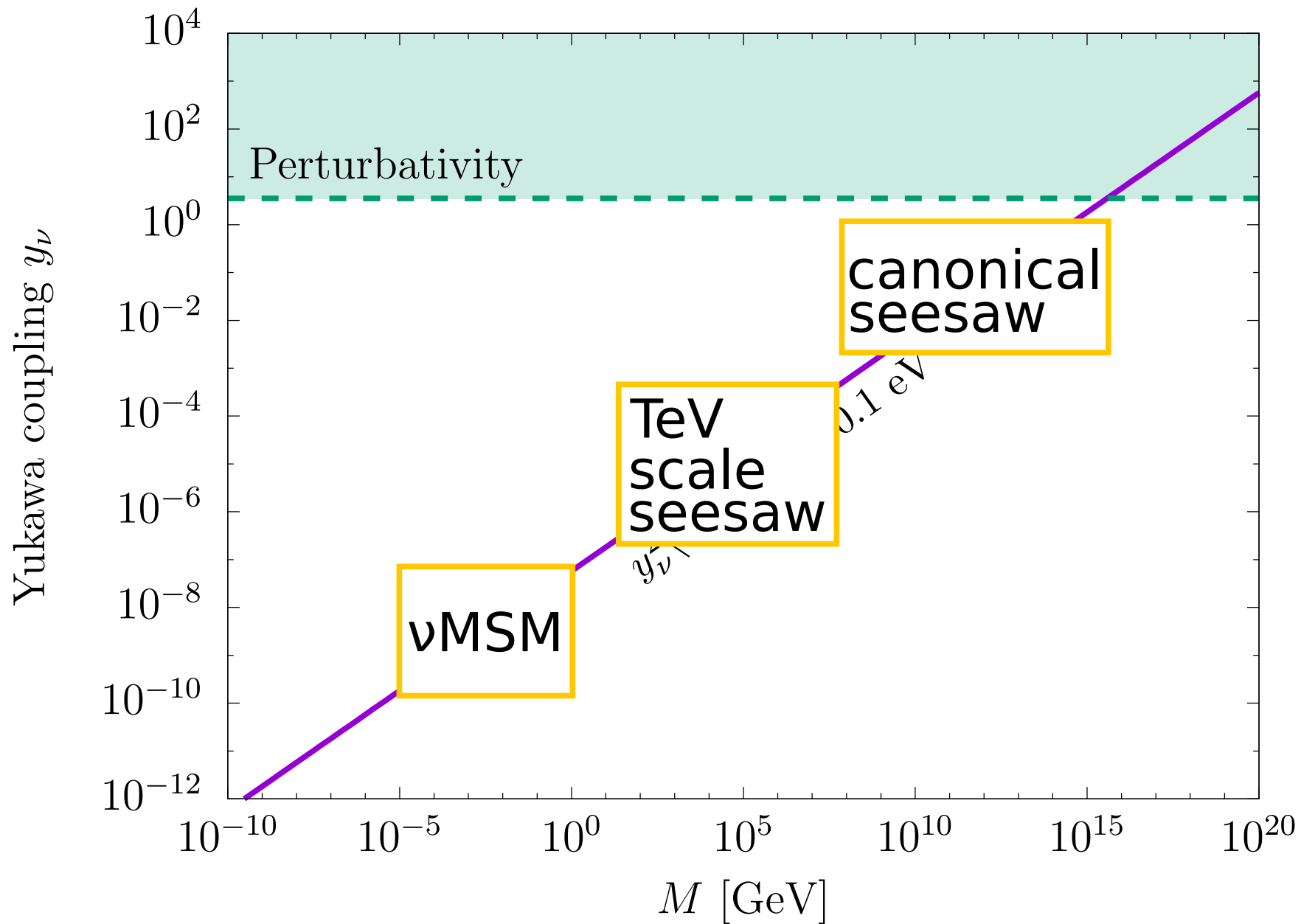
Typical scale

- If Yukawa coupling is $\mathcal{O}(1)$, $m_D \sim 100 \text{ GeV}$ and $M \sim 10^{14} \text{ GeV}$.
 $\Rightarrow$ Collider search cannot reach.

Type-I seesaw mechanism



Type-I seesaw mechanism



Scotogenic Model (Ma-Tao Model) Ma, PRD (2006), Tao, PRD (1996)

(skotos = darkness in Greek)

New particles

	N_i	η
$SU(2)_L$	1	2
$U(1)_Y$	0	1/2
$\mathbb{Z}_2$	-1	-1

- Neutrino mass generation at one-loop level
Benchmark model for radiative ν masses
- Inert η : $\langle \eta \rangle = 0$
- DM candidates: N_1 and η^0
- No mixing between H and η

Lagrangian

$$\mathcal{L} = |D_\mu \eta|^2 + \frac{1}{2} \overline{N_i} (i \not{\partial} - M_i) N_i - y_{i\alpha} \eta \overline{N_i} L_\alpha + \text{h.c.} - \mathcal{V}(\phi, \eta)$$

$$\begin{aligned} \mathcal{V}(\phi, \eta) = & m_H^2 |H|^2 + m_\eta^2 |\eta|^2 + \frac{\lambda_1}{2} |H|^4 + \frac{\lambda_2}{2} |\eta|^4 \\ & + \lambda_3 |H|^2 |\eta|^2 + \lambda_4 (H^\dagger \eta) (\eta^\dagger H) + \frac{\lambda_5}{2} \left[(H^\dagger \eta)^2 + (\eta^\dagger H)^2 \right] \end{aligned}$$

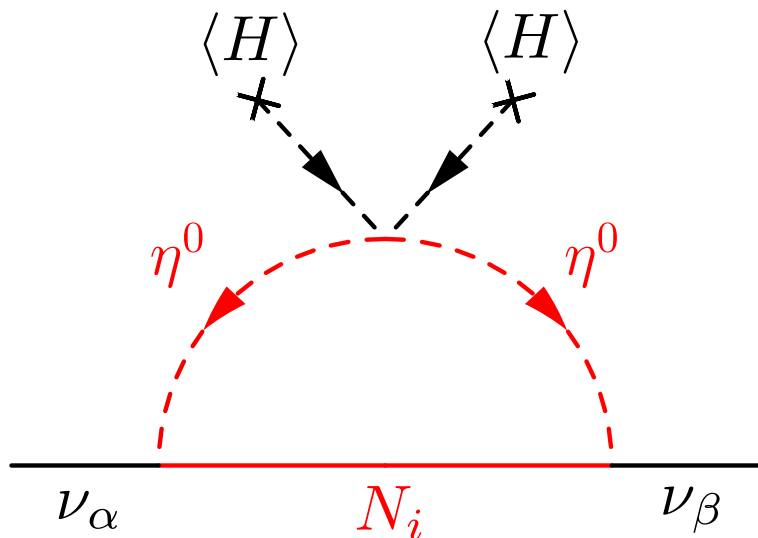
Neutrino masses

After electroweak symmetry breaking, η^0 splits into η_R and η_I .

$$\eta^0 = \frac{\eta_R + i\eta_I}{\sqrt{2}} \quad (\text{mass eigenstates}), \quad m_R^2 - m_I^2 = 2\lambda_5 \langle H \rangle^2$$

$$(m_\nu)_{\alpha\beta} = \sum_{i=1}^3 \frac{y_{i\alpha} y_{i\beta} M_i}{2(4\pi)^2} \left[\frac{m_R^2}{m_R^2 - M_i^2} \log \left(\frac{m_R^2}{M_i^2} \right) - \frac{m_I^2}{m_I^2 - M_i^2} \log \left(\frac{m_I^2}{M_i^2} \right) \right]$$

$$\equiv (y^T \Lambda y)_{\alpha\beta}$$



■ Neutrino mass scale $m_\nu \sim 0.1$ eV

■ Diagonalization

$$U_{\text{PMNS}}^T m_\nu U_{\text{PMNS}} = \text{diag}(m_1, m_2, m_3)$$

$\Rightarrow$ Casa-Ibarra parametrization

$$y = \sqrt{\Lambda}^{-1} R \sqrt{\hat{m}_\nu} U_{\text{PMNS}}^\dagger$$

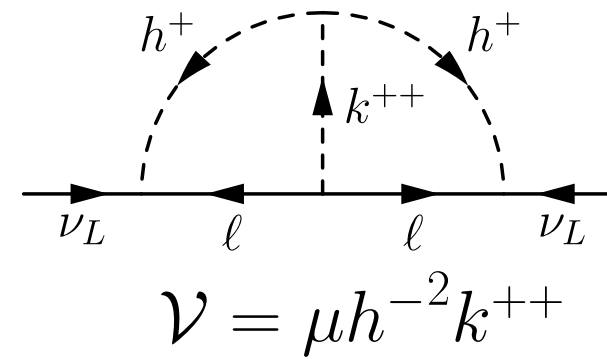
Radiative models

■ Zee-Babu model (1986)

Zee, Nucl. Phys. B 264, 99 (1986);

Babu, Phys. Lett. B 203, 132 (1988)

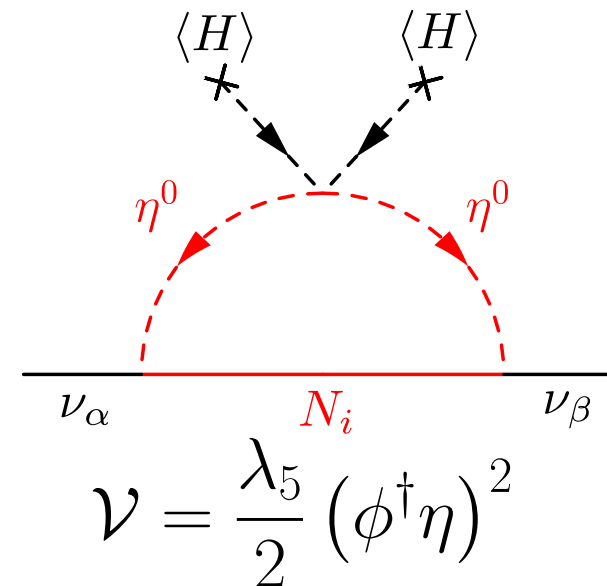
	$SU(2)_L$	$U(1)_Y$
h^+	1	1
k^{++}	1	2



- Neutrino mass (2-loop level)

■ Ma-Tao model (2006) [hep-ph/0601225](#) (Scotogenic model) [Z. Tao PRD \(1996\)](#)

	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
N_i	1	0	-1
η	2	1/2	-1



- Neutrino mass (1-loop level)
- DM candidates (N_1 or η^0)

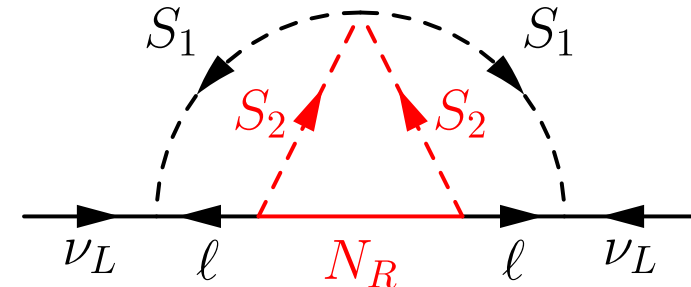
Radiative models

■ Krauss-Nasri-Trodden model (2002)

	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
S_1^+	1	1	+1
S_2^+	1	1	-1
N_R	1	0	-1

- Neutrino mass (3-loop level)
- DM candidate (N_R)

hep-ph/0210389



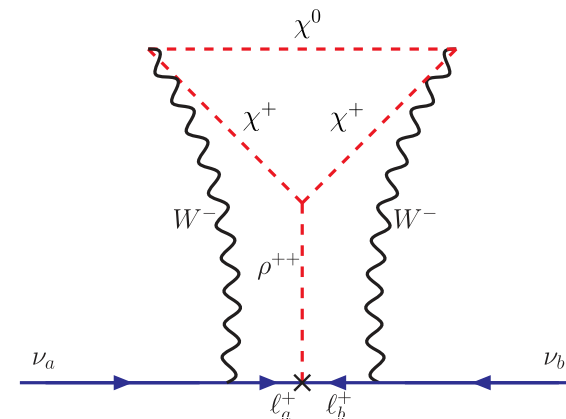
$$\mathcal{V} = \lambda_s (S_1^+ S_2^-)^2$$

■ Gustafsson-No-Rivera model (2012)

	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
Φ_2	2	1/2	-1
S^+	1	1	-1
ρ^{++}	1	2	+1

- Neutrino masses (3-loop level)
- DM candidate (inert doublet)

arXiv:1212.4806



Cocktail diagram

$$\mathcal{V} = \mu \rho^{++} S^- S^- + \lambda_5 \left(\Phi_1^\dagger \Phi_2 \right)^2$$

$\mathbb{Z}_3$ symmetric neutrino mass model $\Rightarrow$ semi-ann.

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

	L_L	e_R^c	ψ_L	ψ_R^c	H	η	χ
$SU(2)_L$	2	1	1	1	2	2	1
$U(1)_Y$	$-1/2$	1	0	0	$1/2$	$1/2$	0
$\mathbb{Z}_3$	0	0	1	-1	0	1	1
Spin	$1/2$	$1/2$	$1/2$	$1/2$	0	0	0

Lagrangian

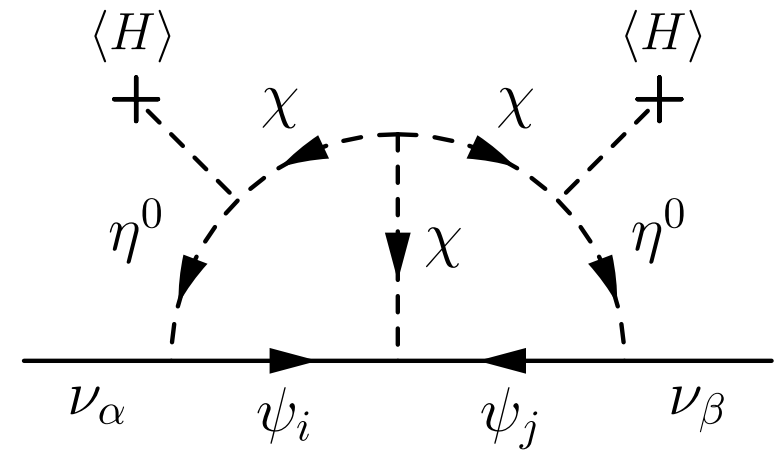
$$\mathcal{L} = \bar{\psi}_i (i\not{\partial} - M_i) \psi_i + |D_\mu \eta|^2 + |\partial_\mu \chi|^2 - \mathcal{V}(H, \eta, \chi) \\ - \left(y_\alpha H^\dagger \bar{e}_\alpha L_\alpha + y_{i\alpha}^\nu \eta \bar{\psi}_i P_L L_\alpha + \frac{y_{ij}^L}{2} \chi \bar{\psi}_i^c P_L \psi_j + \frac{y_{ij}^R}{2} \chi \bar{\psi}_i^c P_R \psi_j + \text{h.c.} \right)$$

■ $\mathcal{V}(H, \eta, \chi) \supset \tilde{\mu}_\chi (H^\dagger \eta) \chi^* + \frac{\mu_\chi}{3!} \chi^3$
 $\Rightarrow \eta^0$ - χ mixing ν masses
 $\sin \alpha$

Neutrino masses

- $(m_\nu)_{\alpha\beta} \approx \frac{\mu_\chi \sin^2 2\alpha \cos^2 \alpha}{4(4\pi)^4} \sum_{i,j} y_{i\alpha}^\nu y_{ij}^L y_{j\beta}^\nu I_{\text{loop}}$

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



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

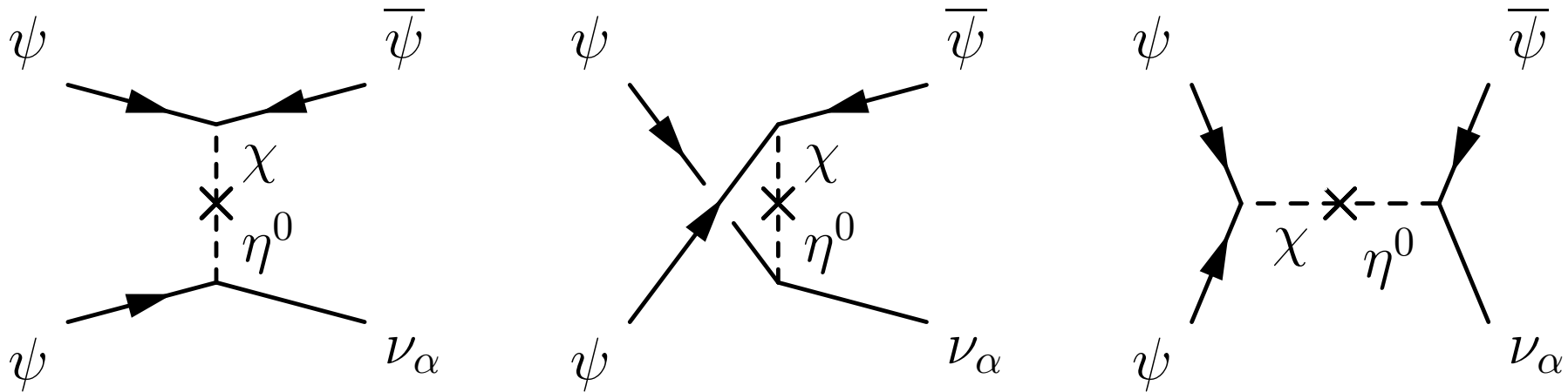
$$y_{11}^L = 0.2 \left(\frac{0.01}{y_{e1} \sin 2\alpha} \right)^2 \left(\frac{1 \text{ GeV}}{\mu_\chi} \right) \left(\frac{0.1}{I_{\text{loop}}} \right) \left(\frac{(m_\nu)_{ee}}{10^{-2} \text{ eV}} \right)$$

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

Dark matter

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

- Semi-annihilation: $\psi\psi \rightarrow \bar{\psi}\nu_\alpha$



- Good: semi-annihilations are naturally involved.

- But DM is leptophilic

$\sigma_{\psi e}$ is too small to be detected.

$\Rightarrow$ an extension of the model is needed.

$$\sigma_{\psi e} = \frac{(y_\nu)_{e1}^4 m_\psi^2 m_e^2}{16\pi m_\eta^4 (m_\psi + m_e)^2} \leq \mathcal{O}(10^{-50}) \text{ [cm}^2\text{]}$$

Z_3 symmetric neutrino mass model

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

$$\mathcal{L} = \bar{\psi}_i i \not{\partial} \psi_i + |\partial_\mu \Sigma|^2 + |D_\mu \eta|^2 + |\partial_\mu \chi|^2 - \mathcal{V}(H, \Sigma, \eta, \chi) \\ - \left(y_\alpha H^\dagger \bar{e}_\alpha L_\alpha + y_{i\alpha}^\nu \eta \bar{\psi}_i P_L L_\alpha + \frac{y_{ij}^L}{2} \chi \bar{\psi}_i^c P_L \psi_j + y_i^\Sigma \Sigma \bar{\psi}_i P_L \psi_i + \text{h.c.} \right)$$

$$\blacksquare \mathcal{V}(H, \Sigma, \eta, \chi) \supset \lambda_{H\Sigma} |H|^2 |\Sigma|^2 + \tilde{\mu}_\chi (H^\dagger \eta) \chi^* + \frac{\tilde{\lambda}_\chi}{3!} \Sigma^* \chi^3 \Rightarrow \frac{\tilde{\lambda}_\chi \langle \Sigma \rangle}{3!} \chi^3$$

$$\blacksquare \text{Global } U(1)_L \Rightarrow \mathbb{Z}_3$$

Mass spectra

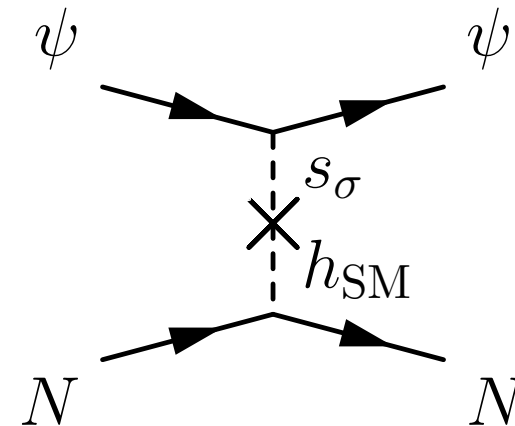
$$\blacksquare H = \begin{pmatrix} 0 \\ \frac{v+h_{\text{SM}}}{\sqrt{2}} \end{pmatrix}, \quad \Sigma = \frac{v_\sigma + \sigma + iJ}{\sqrt{2}}, \quad \eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}, \quad \chi = \chi$$

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

■ Mass eigenstates

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

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



■ Mixing angles

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

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

■ Fermion masses

$$M_i = y_i^\Sigma v_\sigma$$

Neutrino masses

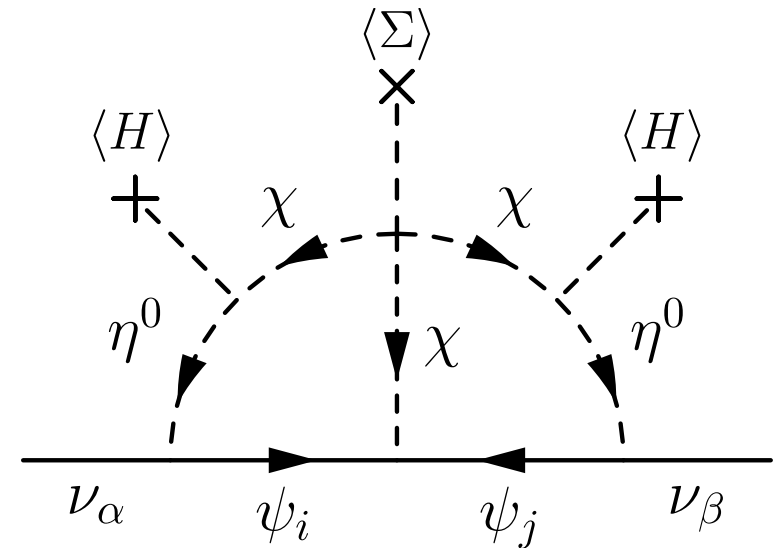
- $(m_\nu)_{\alpha\beta} \approx \frac{\tilde{\lambda}_\chi v_\sigma \sin^2 2\alpha \cos^2 \alpha}{4\sqrt{2}(4\pi)^4} \sum_{i,j} y_{i\alpha}^\nu y_{ij}^L y_{j\beta}^\nu I_{\text{loop}}$

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

- Diagonalization:

$$U^T m_\nu U = \text{diag}(m_1, m_2, m_3)$$

with PMNS matrix U



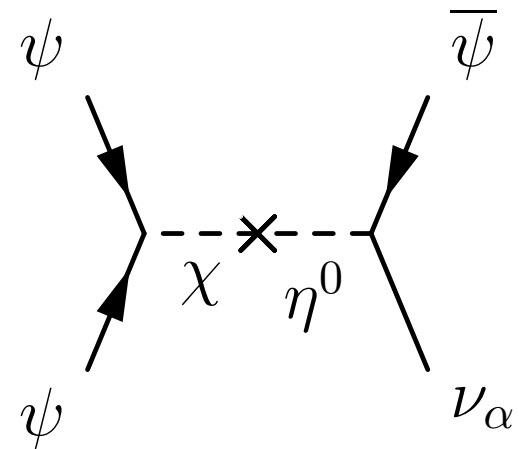
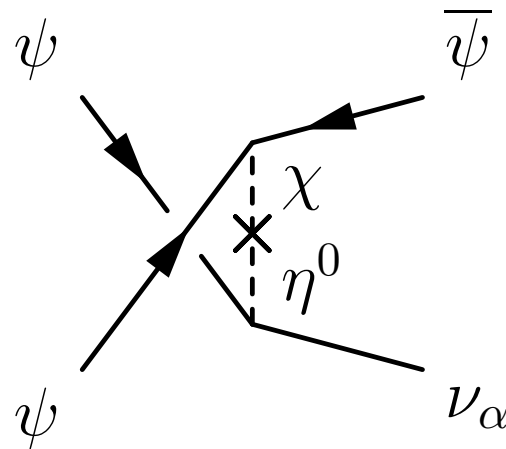
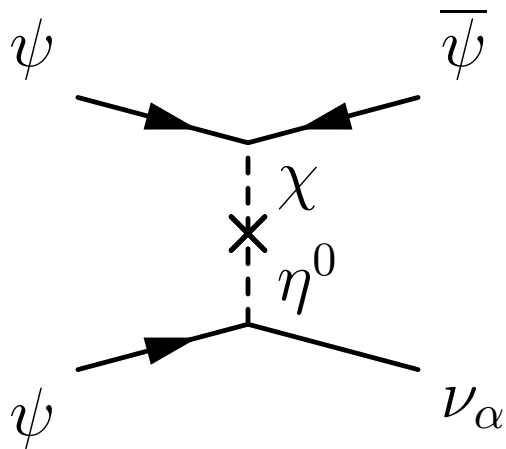
- Correlation with DM coupling (assuming diagonal y^ν)

$$y_{11}^L = 0.2 \left(\frac{0.01}{y_{e1} \sin 2\alpha} \right)^2 \left(\frac{1 \text{ GeV}}{\tilde{\lambda}_\chi v_\sigma} \right) \left(\frac{0.1}{I_{\text{loop}}} \right) \left(\frac{(m_\nu)_{ee}}{10^{-2} \text{ eV}} \right)$$

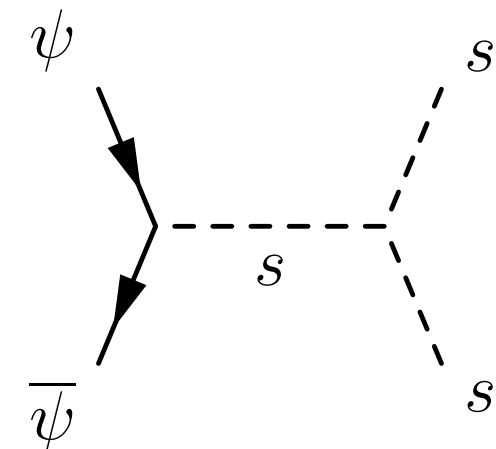
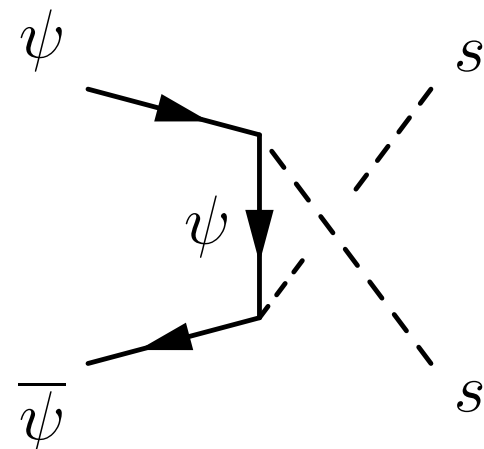
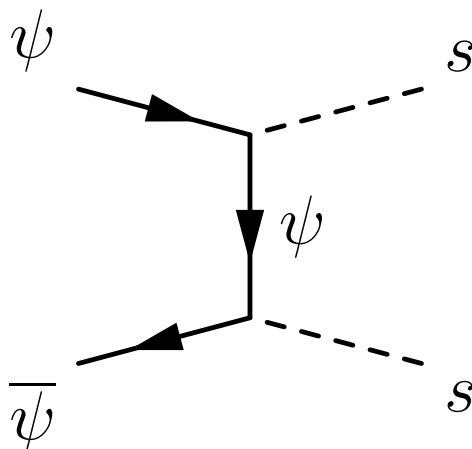
Dark matter

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

- Semi-annihilation: $\psi\psi \rightarrow \bar{\psi}\nu_\alpha$



- Standard annihilation: $\psi\bar{\psi} \rightarrow ss$ (p-wave)

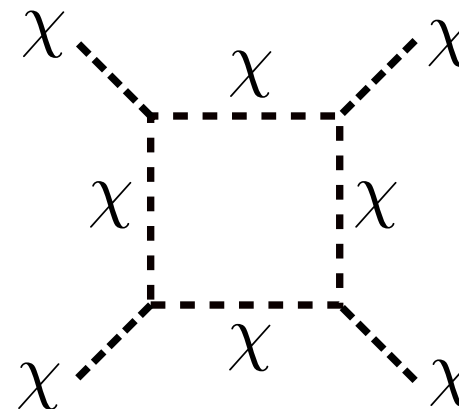


Constraints

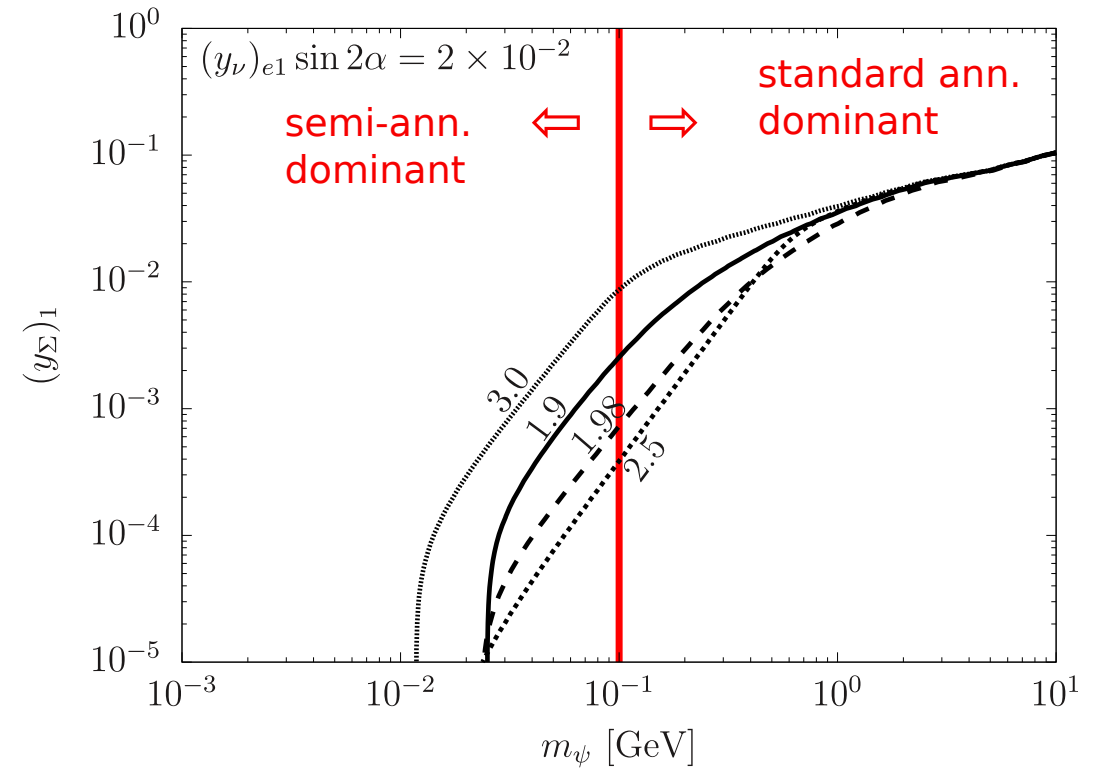
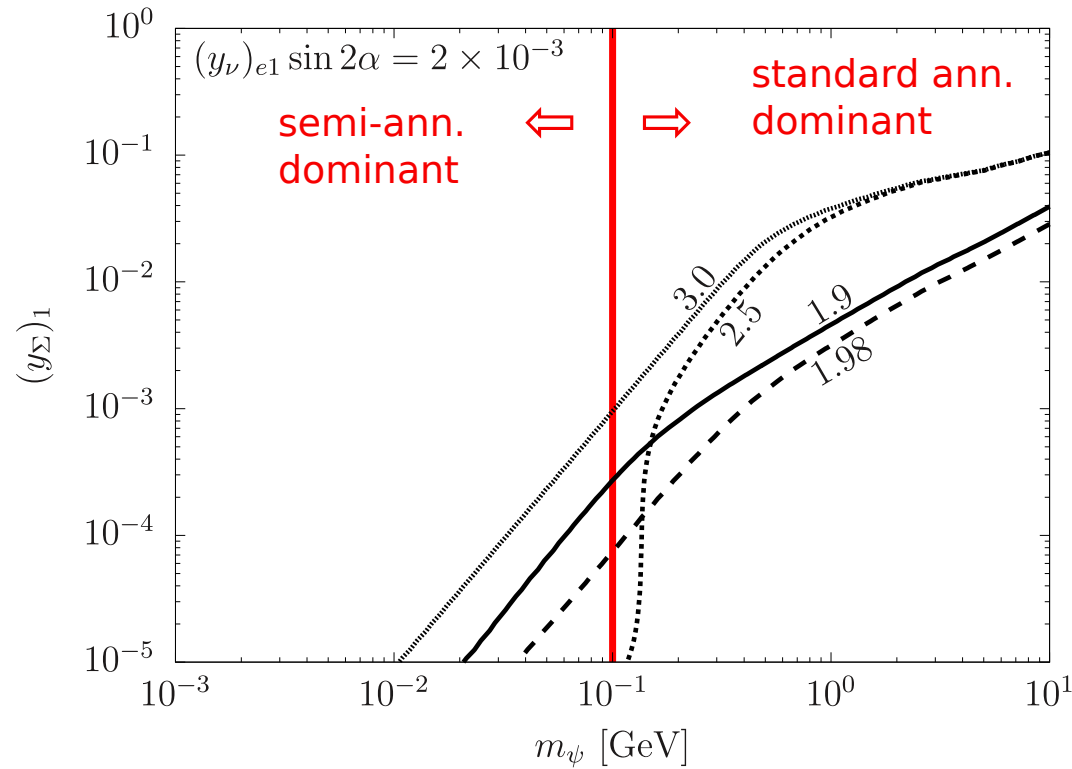
- Neutrino masses and mixings $\Rightarrow m_\nu \propto y^L$ (mixing)
- Lepton flavor violation $\ell_\alpha \rightarrow \ell_\beta \gamma \Rightarrow$ Roughly diagonal y^ν

$$\text{Br} \approx \frac{\alpha_{\text{em}}}{768\pi G_F^2 m_\eta^4} |(y^\nu)_{1\alpha} (y^\nu)_{1\beta}^*|^2$$
- Electroweak precision test ($\Delta\rho$ and Z invisible decay $Z \rightarrow \varphi^* \varphi$)
 $\Rightarrow m_\varphi \ll m_{\tilde{\varphi}} \approx m_\eta \sim \text{TeV and } \sin \alpha \lesssim 0.39$
- Higgs mixing angle $\sin \theta$: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
 $\Rightarrow 10^{-5} \lesssim \sin \theta \lesssim 10^{-4}$
- BBN: $\tau_s \lesssim 1\text{s} \Rightarrow m_s \gtrsim 1 \text{ MeV}$
- Potential stability

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

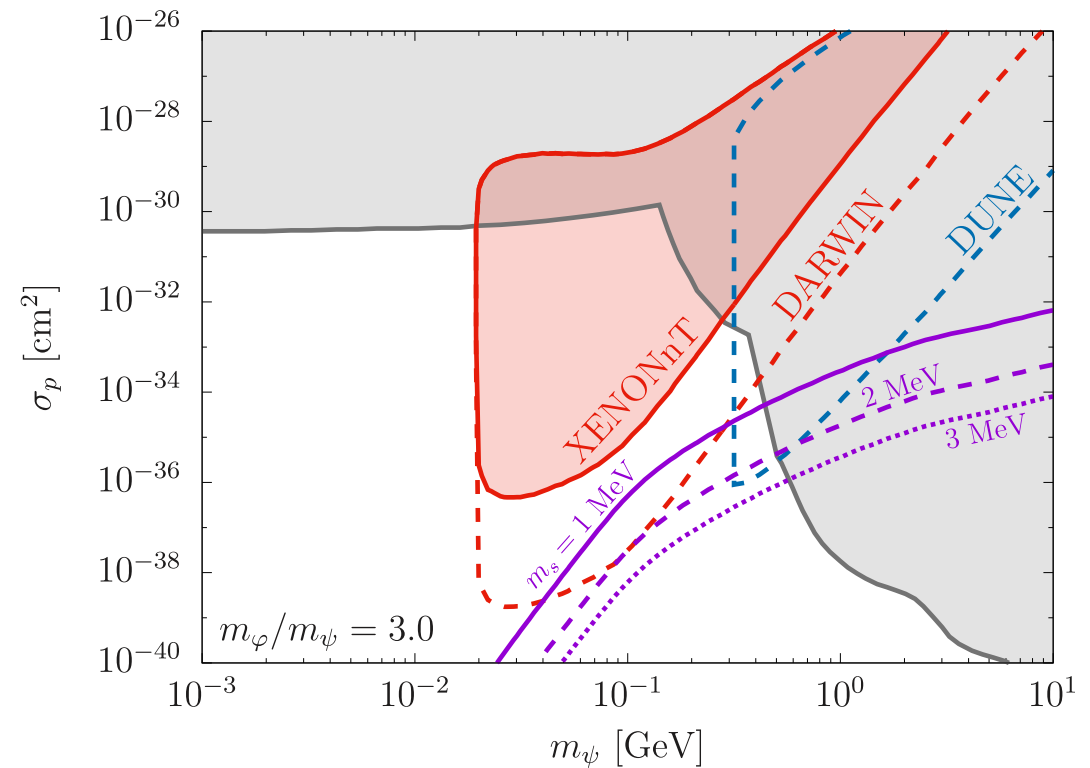
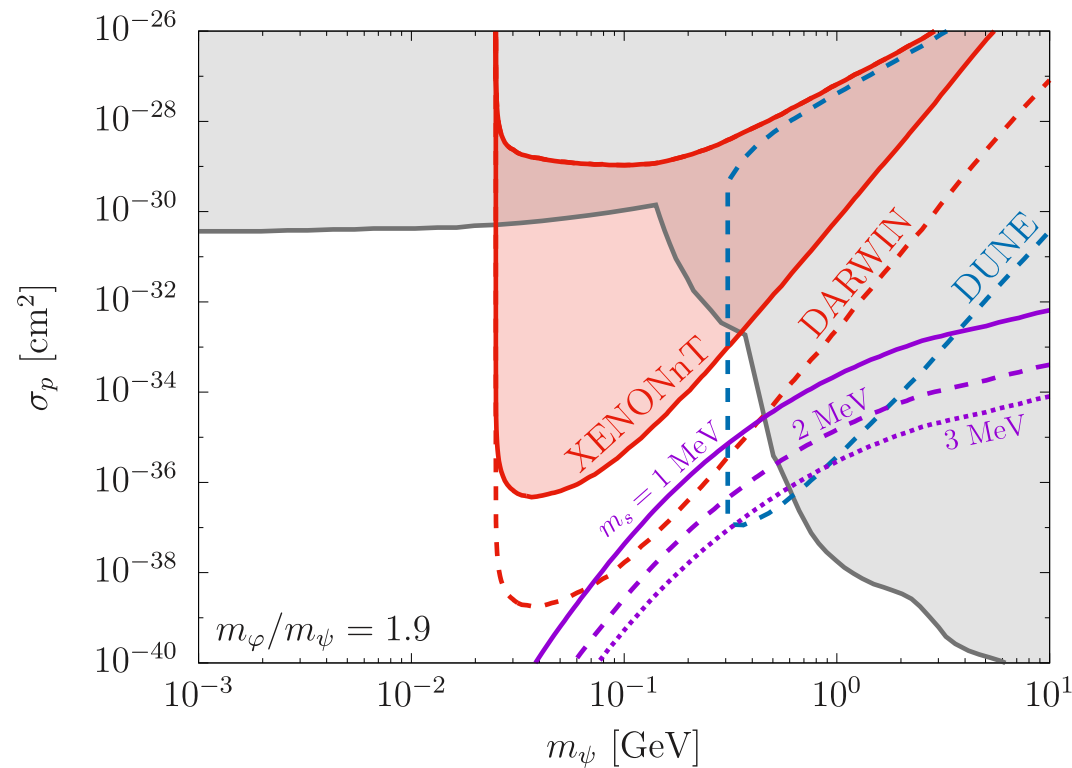


Relic abundance

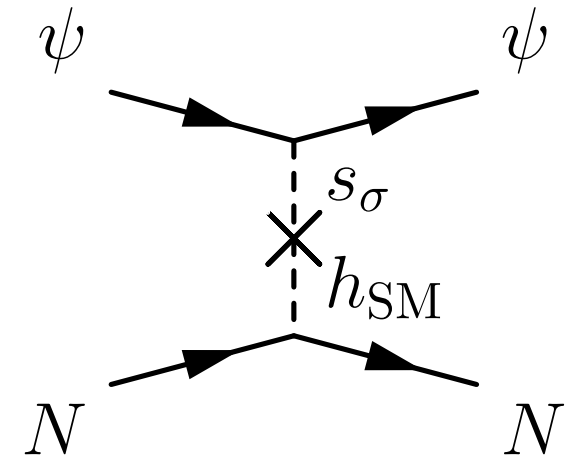


- $m_s = \mathcal{O}(1)$ MeV, $\sin \theta = 10^{-4}$
 $m_\varphi/m_\psi = 1.9, 1.98$ (resonance), 2.5, 3.0
- $\psi\psi \rightarrow \bar{\psi}\nu_\alpha \gg \psi\bar{\psi} \rightarrow ss$ for $m_\psi \lesssim 0.1$ GeV
 $\psi\psi \rightarrow \bar{\psi}\nu_\alpha \ll \psi\bar{\psi} \rightarrow ss$ for $m_\psi \gtrsim 0.1$ GeV

Boosted DM search from semi-ann. ($\psi\psi \rightarrow \bar{\psi}\nu$)



- Scattering with nucleons $\psi N \rightarrow \psi N$
- Testable by **DARWIN** and **DUNE**
- $\text{Br}(\mu \rightarrow e\gamma) \sim 10^{-14}$ (close to exp.)
assuming $\frac{\text{off diag}}{\text{diag}} = 0.1$



Summary

- 1 Conventional thermal DM scenarios are strongly constrained.
- 2 Semi-annihilations accelerate DM coming from Galactic Center.
- 3 We found experimental sensitivity for BDM in sub-GeV mass range through XENON and DUNE.
- 4 A concrete model was built with loop induced neutrino masses.
- 5 A light mediator $\sim \mathcal{O}(\text{MeV})$ is needed to enhance σ_p .

Future work

- Matter antimatter asymmetry?
- A specific realization of pandemic DM?

Bringmann et al., PRL 127 (2021) 19, 19 [2103.16572 [hep-ph]]