# Sterile Neutrino Portal Dark Matter with Z3 Symmetry

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# Relations between Sterile Neutrino and Dark Matter

① The sterile neutrino can be decaying dark matter when $m_N \sim$ keV.

Tightly constrained by $N \to \nu\gamma$

② The sterile neutrino can be stable dark matter and act as mediator for neutrino mass.

Scotogenic mechanism, LFV constraints

⋆ The most popular dark matter candidate: WIMP.

Tightly constrained by direct detection

③ The sterile neutrino can be the mediator for dark sector:

- Small nucleon scattering cross section for direct detection.
- Large cosmic flux for indirect detection.
- Promising signature of $N$ at colliders.

⋆ The interactions are determined by the symmetry :

Z2 , Z3 , $U(1)_{B-L}$, A4,...

# The Model

⋆ The Dark Sector : a scalar singlet $\phi$ and a fermion singlet $\chi$, which transform as $\chi \to e^{i2\pi/3}\chi, \phi \to e^{i2\pi/3}\phi$.

⋆The Yukawa interaction takes the form of

$$-\mathcal{L}_Y = \left(y_\nu \overline{L}\tilde{H}N + y_N \phi \bar{\chi} N + h.c.\right) + y_\chi \phi \overline{\chi^c}\chi. \tag{1}$$

⋆The scalar potential under the exact $Z_2/Z_3$ symmetry is

$$\begin{aligned} V &= -\mu_H^2 H^\dagger H + \mu_\phi^2 \phi^\dagger \phi + \lambda_H (H^\dagger H)^2 + \lambda_\phi (\phi^\dagger \phi)^2 \\ &\quad + \lambda_{H\phi}(H^\dagger H)(\phi^\dagger \phi) + \left(\frac{\mu}{2}\phi^3 + h.c.\right). \end{aligned} \tag{2}$$

The blue terms are interactions in the $Z_2$ symmetry, and the red terms are new in the $Z_3$ symmetry.

# Z3 Fermion DM

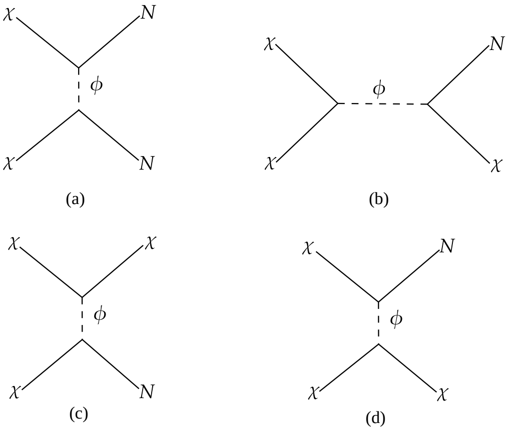



Figure: The secluded channel $\chi\chi \to NN$ appears in $Z_2$ model, meanwhile the semi-annihilation channel $\chi\chi \to N\chi$ is new in $Z_3$ model.

$$\frac{dY_\chi}{dz} = -\frac{\lambda}{z^2}\langle\sigma v\rangle_{\chi\chi\to NN}\left(Y_\chi^2 - (Y_\chi^{eq})^2\right) - \frac{\lambda}{2z^2}\langle\sigma v\rangle_{\chi\chi\to N\chi}\left(Y_\chi^2 - Y_\chi^{eq} Y_\chi\right) \quad (3)$$

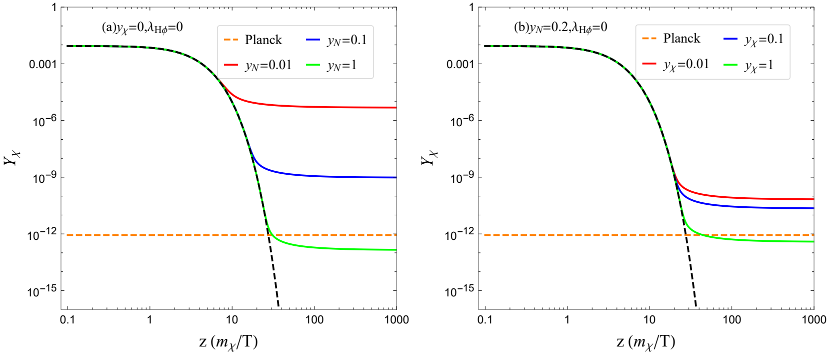
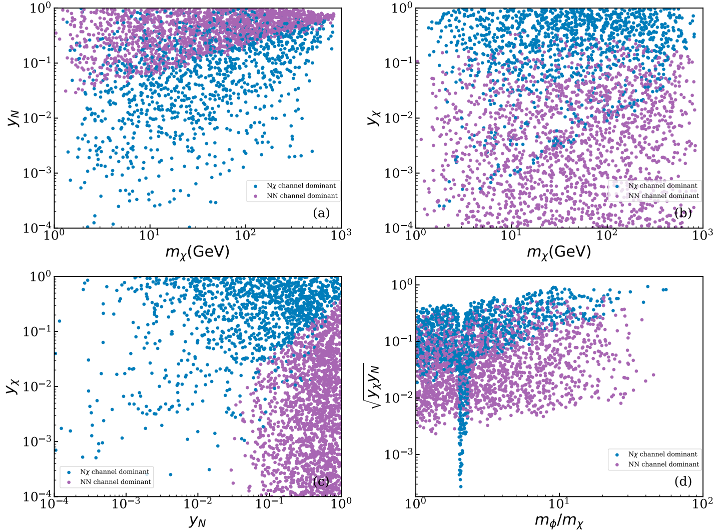



Figure: The evolution of fermion dark matter abundance in different major annihilation channels. The orange horizontal lines correspond to the Planck observed abundance for $m_{DM} = 500$ GeV.

# Samples with correct relic density for fermion DM.



# Z3 Scalar DM

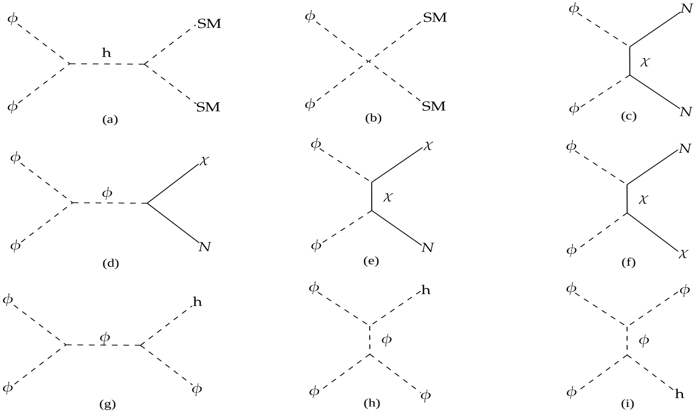



Figure: $Z_2$ model: $\phi\phi \to$ SM$, NN$, new in $Z_3$ model: $\phi\phi \to \chi N, h\phi$.

$$
\begin{aligned}
\frac{\mathrm{d}Y_\phi}{\mathrm{d}z} = & -\frac{\lambda}{z^2}\langle\sigma v\rangle_{\phi\phi\to \mathrm{SM}}\left(Y_\phi^2-(Y_\phi^{\mathrm{eq}})^2\right)-\frac{\lambda}{2z^2}\langle\sigma v\rangle_{\phi\phi\to h\phi}\left(Y_\phi^2-Y_\phi^{\mathrm{eq}}Y_\phi\right) \\
& -\frac{\lambda}{z^2}\langle\sigma v\rangle_{\phi\phi\to NN}\left(Y_\phi^2-(Y_\phi^{\mathrm{eq}})^2\right)-\frac{\lambda}{2z^2}\langle\sigma v\rangle_{\phi\phi\to N\chi}\left(Y_\phi^2-\frac{(Y_\phi^{\mathrm{eq}})^2}{Y_\chi^{\mathrm{eq}}}Y_\chi\right)
\end{aligned}
\quad (4)
$$

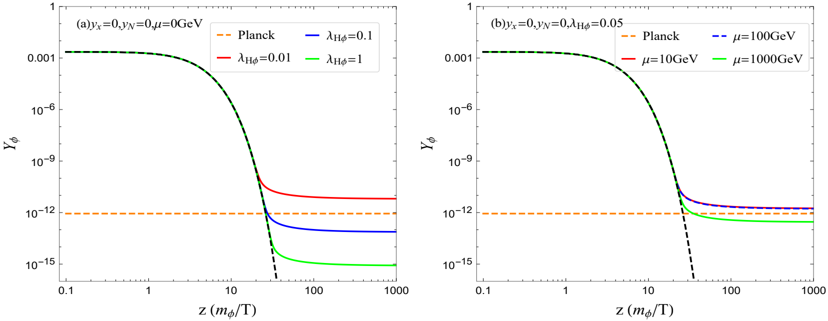
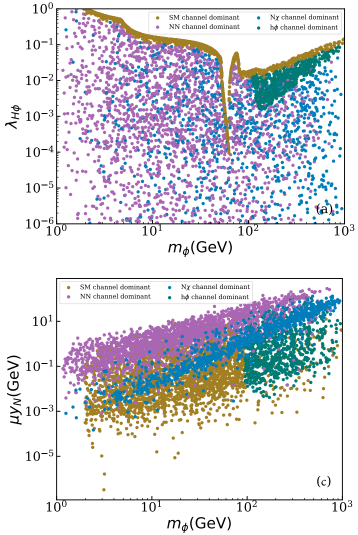



Figure: The evolution of Scalar dark matter abundance

# Samples with correct relic density for scalar DM.



# Invisible Higgs decay.

- ⋆ ATLAS limit on invisible Higgs decay: $\text{Br}_{\text{inv}} < 0.11$.
- ⋆ The theoretical Higgs invisible decay widths into dark matter :

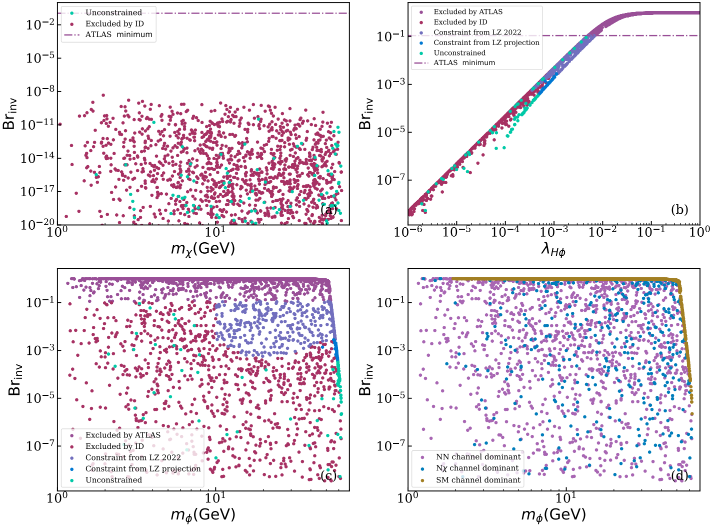
$$\Gamma(h \to \phi\phi) = \frac{\lambda_{H\phi}^2 v^2}{8\pi m_h}\sqrt{1 - \frac{4m_\phi^2}{m_h^2}}, \tag{5}$$

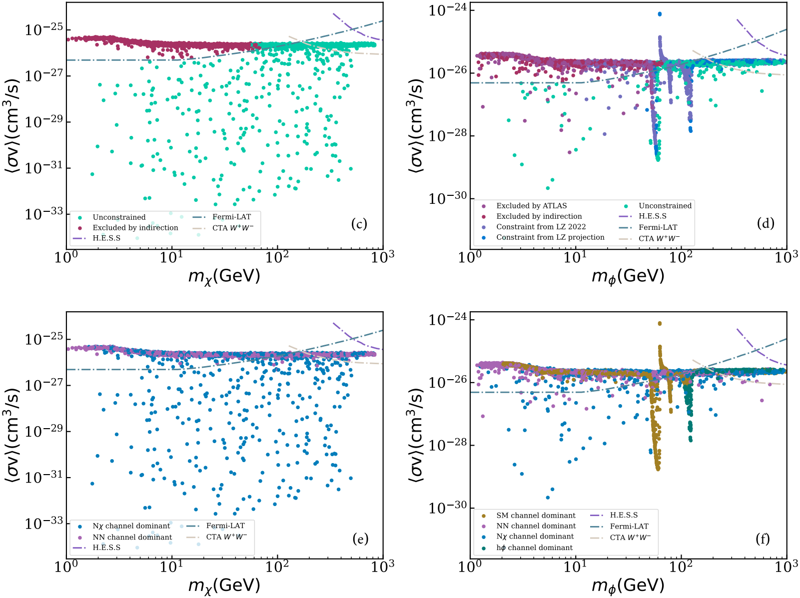
$$\Gamma(h \to \bar{\chi}\chi) = \frac{m_h (\lambda_{H\chi}^{eff})^2}{8\pi}\left(1 - \frac{4m_\chi^2}{m_h^2}\right)^{3/2}, \tag{6}$$

where the one-loop effective $h\bar{\chi}\chi$ coupling is

$$\lambda_{H\chi}^{eff} = \lambda_{H\phi}\frac{y_N^2}{16\pi^2}\frac{m_N}{(m_\phi^2 - m_N^2)^2}\left(m_\phi^2 - m_N^2 + m_N^2 \log\frac{m_N^2}{m_\phi^2}\right). \tag{7}$$

# Invisible Higgs decay.





(c)
Unconstrained
Excluded by indirection
H.E.S.S
Fermi-LAT
CTA $W^+W^-$
$\langle\sigma v\rangle(\mathrm{cm}^3/\mathrm{s})$
$m_\chi(\mathrm{GeV})$
(d)
Excluded by ATLAS
Excluded by indirection
Constraint from LZ 2022
Constraint from LZ projection
Unconstrained
H.E.S.S
Fermi-LAT
CTA $W^+W^-$
$\langle\sigma v\rangle(\mathrm{cm}^3/\mathrm{s})$
$m_\phi(\mathrm{GeV})$
(e)
$N\chi$ channel dominant
NN channel dominant
H.E.S.S
Fermi-LAT
CTA $W^+W^-$
$\langle\sigma v\rangle(\mathrm{cm}^3/\mathrm{s})$
$m_\chi(\mathrm{GeV})$
(f)
SM channel dominant
NN channel dominant
$N\chi$ channel dominant
$h\phi$ channel dominant
H.E.S.S
Fermi-LAT
CTA $W^+W^-$
$\langle\sigma v\rangle(\mathrm{cm}^3/\mathrm{s})$
$m_\phi(\mathrm{GeV})$

# Direct Detection

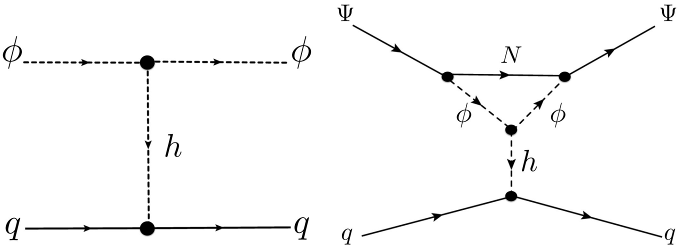
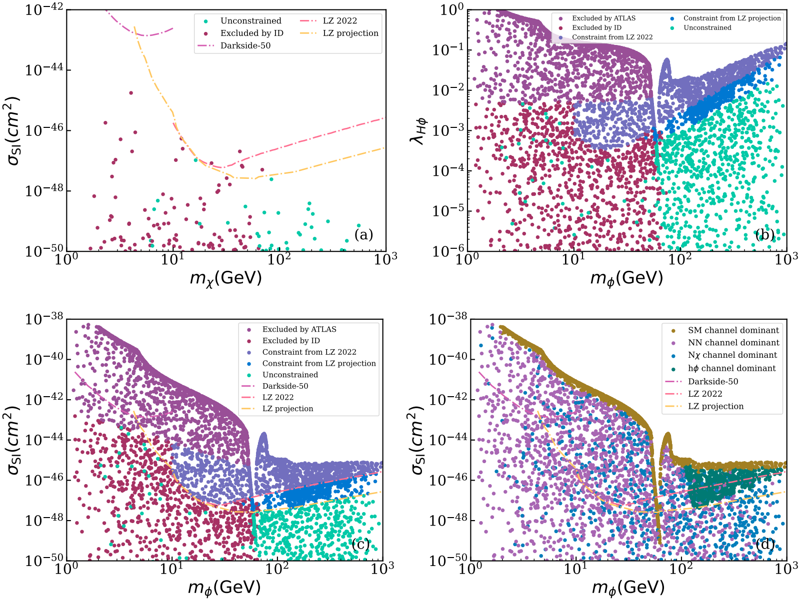



Figure: Elastic scattering diagrams. The cross sections are:

$$\sigma^{\rm SI}_{\phi n} = \frac{\lambda^2_{H\phi}}{\pi m_h^4}\frac{m_n^4 f_n^2}{(m_\phi + m_n)^2}\ , \tag{8}$$

$$\sigma^{\rm SI}_{\chi n} = \frac{(\lambda^{eff}_{H\chi})^2}{\pi m_h^4}\frac{m_n^4 m_\chi^2 f_n^2}{(m_\chi + m_n)^2}\ , \tag{9}$$

# Direct Detection



# Conclusion

⋆ The $Z_3$ symmetry leads to new terms as $y_\chi \phi \overline{\chi^c} \chi$ and $\left(\frac{\mu}{2}\phi^3 + h.c.\right)$.
⋆ Semi-annihilation channels $\chi\chi \to N\chi, \phi\phi \to \chi N, h\phi$ enlarge the viable parameter space.

| Dark Matter | Symmetry | $h \to$ inv | $m_{\rm DM} \lesssim 50$ GeV | Future CTA | Beyond CTA | Direct Detection |
|---|---|---|---|---|---|---|
| $\chi$ | $Z_2$ | ✗ | ✗ | ✓ | ✗ | ✗ |
| | $Z_3$ | ✗ | ✓ | ✓ | ✓ | ✗ |
| $\phi$ | $Z_2$ | ✗ | ✗ | ✓ | ✗ | ✓ |
| | $Z_3$ | ✓ | ✓ | ✓ | ✗ | ✓ |

Table: Different signatures for the $Z_2$ and $Z_3$ symmetric model.