Constraining neutrino-DM interactions with Milky Way dwarf spheroidals and supernova neutrinos

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Introduction

- DM-model

Motivation

- Why study DM-neutrino interaction?
  - It may provide insights in understanding abnormalities of neutrinos from SM
  - It constraints DM interaction model with neutrinos

- New Physics
  - How neutrinos effects gives feedback to dwarf galaxy-sized subhalos are not fully understood.

Background

Assumptions:

- Standard cosmological model (ΛCDM)
- DM is cold, collisionless, not self-interacting

Core–Cusp Profile

- NFW profile
- Cusp profile (predictions) vs. Core profile (observation)

- $\rho(r) = \frac{\rho_s r_s^3}{(r_c+r)(r_s+r)^2}$
- core: $\mathrm{r}_c \neq 0$
- cusp: $\mathrm{r}_c = 0$ (NFW profile)

Methods

Goal: derive expression of upper limit of neutrino-DM cross-section

We need:

1. CCSNe neutrino number
2. Constrain energy injection from CCSNe neutrinos
3. Mass losing bound
4. Energy fraction cross-section bound

CCSNe neutrino number

- $E_{\nu,tot} = 3 \times 10^{53}$erg for each supernova
- Number of CCNSe is given by

$$\mathcal{N}_{\mathrm{CCSNe}} = M_* \frac{\int_{8\,\mathrm{M}_\odot}^{100\,\mathrm{M}_\odot} \xi(m)\,dm}{\int_{0.1\,\mathrm{M}_\odot}^{100\,\mathrm{M}_\odot} m\,\xi(m)\,dm},$$

$$\xi(m) \propto \begin{cases} m^{-0.3}, & \text{if } m \leq 0.08\,\mathrm{M}_\odot, \\ m^{-1.3}, & \text{if } 0.08\,\mathrm{M}_\odot < m \leq 0.5\,\mathrm{M}_\odot, \\ m^{-2.3}, & \text{if } 0.5\,\mathrm{M}_\odot < m, \end{cases}$$

Calculate the injection energy

$$\frac{M(r)}{M_0} = \begin{cases} \ln(1+\tilde{r}) - \frac{\tilde{r}(2+3\tilde{r})}{2(1+\tilde{r})}, x = 1 \\ \frac{x^2 \ln(1+\tilde{r}/x) + (1-2x)\ln(1+\tilde{r})}{(1-x)^2} - \frac{\tilde{r}}{(1+\tilde{r})(1-x)}, x \neq 1 \end{cases}$$

here M_0 is the total mass of the halo, $\tilde{r} \equiv r/r_s$, and $x = r_c/r_s$

$$W = -4\pi G_N \int_0^{r_{200}} r\,\rho(r)\,M(r)\,dr,$$

$$\Delta E = \frac{W_{\rm core} - W_{\rm cusp}}{2},$$

- core: $r_c \neq 0$
- cusp: $r_c = 0$

Gravitational bounded

- To avoid DM become gravitational unbounded after interacting with neutrino, we can place a constrain on the mass regime of DM particle

$$\frac{1}{2} m_\chi v_{\rm esc}^2 = \frac{\int_{0\,\rm GeV}^{1\,\rm GeV} F_\nu(E_\nu)\, 2E_\nu^2/(2E_\nu + m_\chi)\, dE_\nu}{\int_{0\,\rm GeV}^{1\,\rm GeV} F_\nu(E_\nu) dE_\nu},$$

- Solving this give us the allowed regime of DM particle mass, and for the strongest bounded subhalo Fornax, $m_\chi = 130$GeV.

Mass losing bound

- To form the core profile which we see today, the mass losing will provide a bound on the cross-section, as the mass lose can relate to the magnitude of cross-section.
- We can write down the formula to calculate cross-section of DM-neutrino by some simple argument, the results is

$$\langle \sigma_{\nu-\mathrm{DM}}(m_\chi \le m_{\chi,\mathrm{lim}}) \rangle = \frac{\eta}{\Sigma_{\mathrm{DM}}} = \frac{\Delta M_{\mathrm{lim}}}{m_\chi \, \Sigma_{\mathrm{DM}} \, \mathcal{N}_{\nu,\mathrm{tot}}}, \\ = \frac{\Delta M_{\mathrm{lim}}}{\mathcal{N}_{\nu,\mathrm{tot}} \int_0^{r_c} \rho_{\mathrm{NFW}}(r) dr,}$$

- Notice that this result is independent to the mass of DM.

Mass losing bound

- By the formula, we can get the cross-section of DM-neutrino interaction, and this result is valid only if DM particle mass less than 130 GeV.

Energy injection bound

- With the case the dark matter are gravitational unbounded, we can use the relativistic collision formula to calculate the **maximum fraction of energy** being transferred to the dark matter.
- Like the case in gravitational bounded DM, the cross-section is given by:

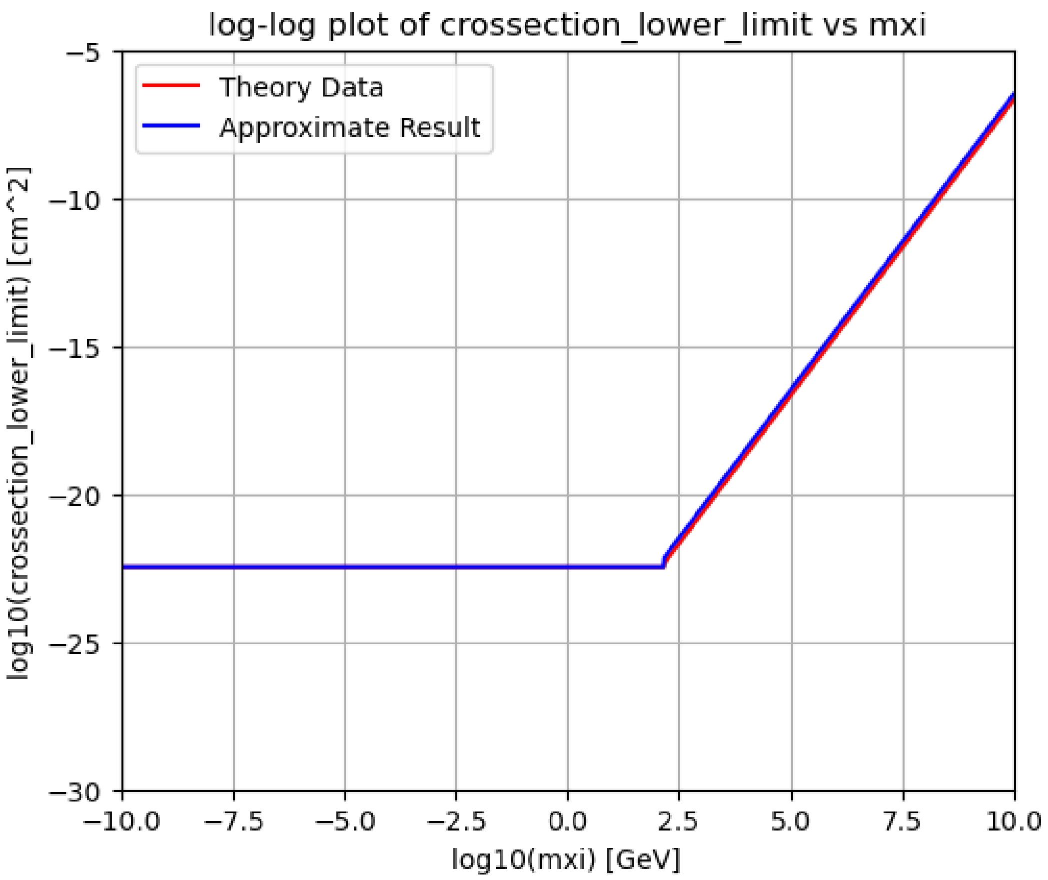
$$\sigma_{\nu-\mathrm{DM}}(m_\chi > m_{\chi,\mathrm{lim}}) = \frac{\varepsilon}{f_{\max}\,\Sigma_{\mathrm{DM}}},$$

Cross-section upper-limit

$$\langle \sigma_{\nu-\mathrm{DM}} \rangle \approx \begin{cases} 3.4 \times 10^{-23}\ \mathrm{cm}^2, & m_\chi \leq 130\,\mathrm{GeV}, \\ 3.2 \times 10^{-27}\ \left(\frac{m_\chi}{1\,\mathrm{GeV}}\right)^2\ \mathrm{cm}^2, & m_\chi > 130\,\mathrm{GeV}. \end{cases}$$

The cross-section upper limit-DM mass

- Use Fornax to be the upper-limit of cross-section.

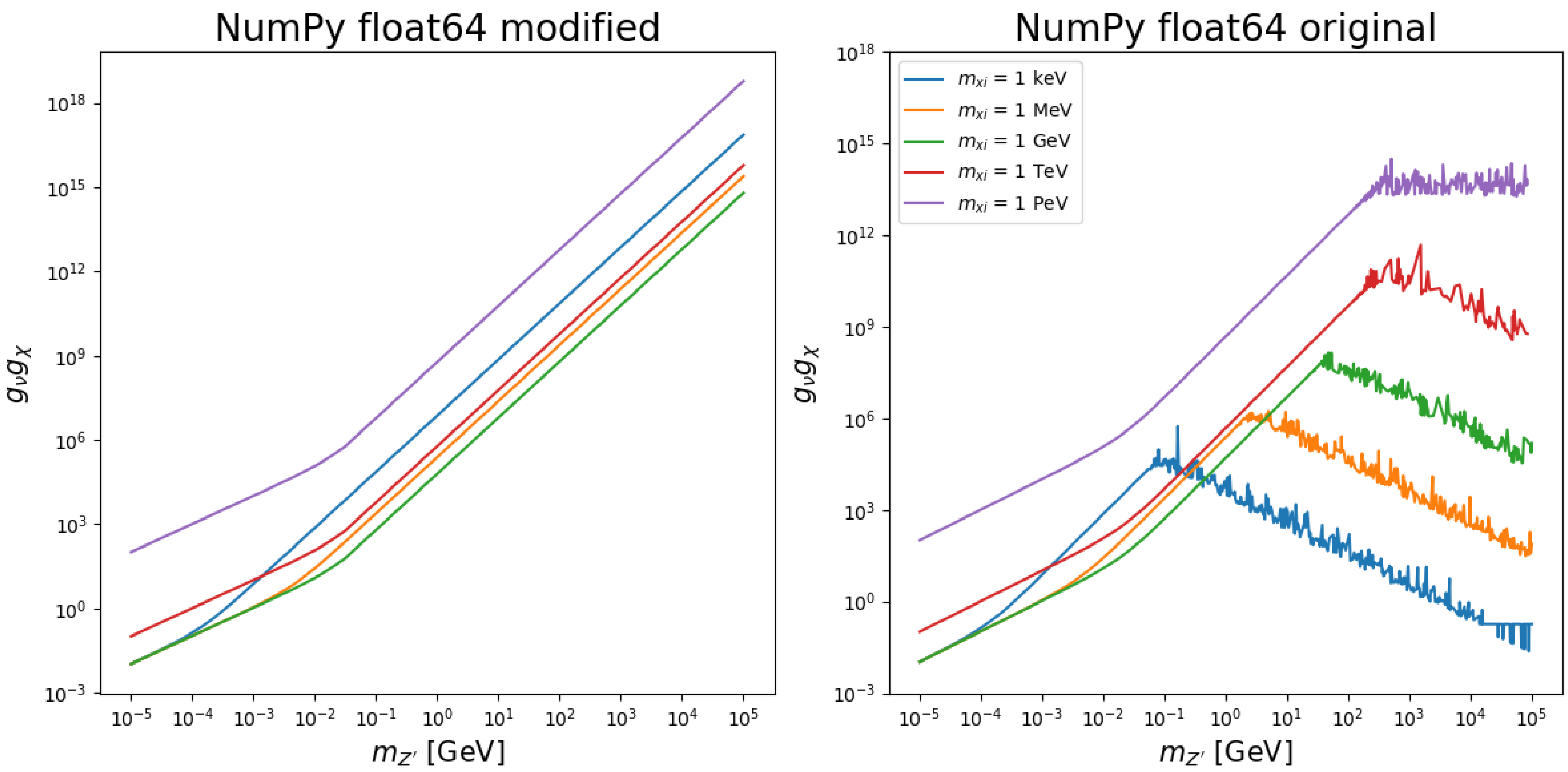


Results

- Z' model

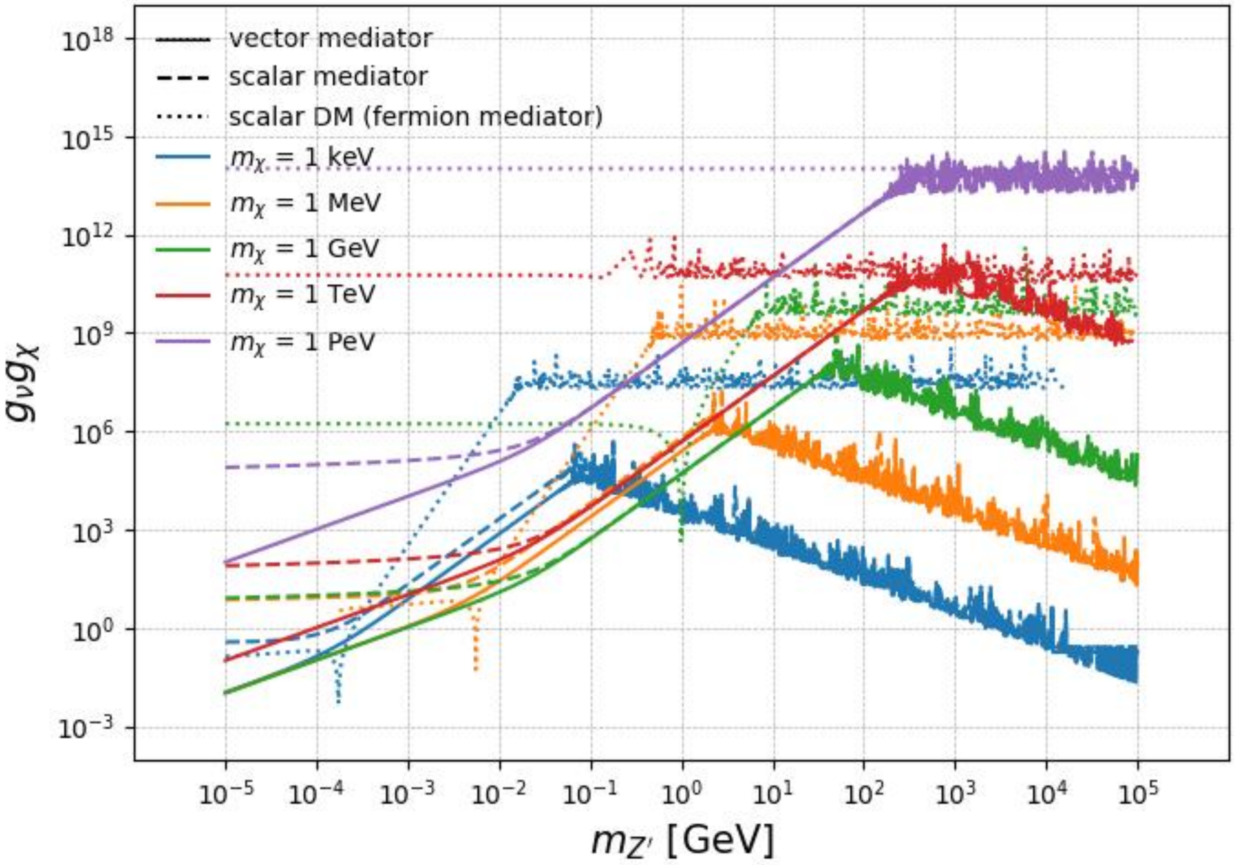
$$\sigma_{\nu-\mathrm{DM}} = \frac{(g_\nu g_\chi)^2}{16\pi E_\nu^2 m_\chi^2}\left[(m_{Z'}^2 + m_\chi^2 + 2E_\nu m_\chi)\log\left(\frac{m_{Z'}^2(2E_\nu + m_\chi)}{m_\chi(4E_\nu^2 + m_{Z'}^2) + 2E_\nu m_{Z'}^2}\right)\right.$$
$$\left. + 4E_\nu^2\left(1 + \frac{m_\chi^2}{m_{Z'}^2} - \frac{2E_\nu(4E_\nu^2 m_\chi + E_\nu(m_\chi^2 + 2m_{Z'}^2) + m_\chi m_{Z'}^2)}{(2E_\nu + m_\chi)(m_\chi(4E_\nu^2 + m_{Z'}^2) + 2E_\nu m_{Z'}^2}\right)\right]$$

Coupling Constant- mediator boson mass

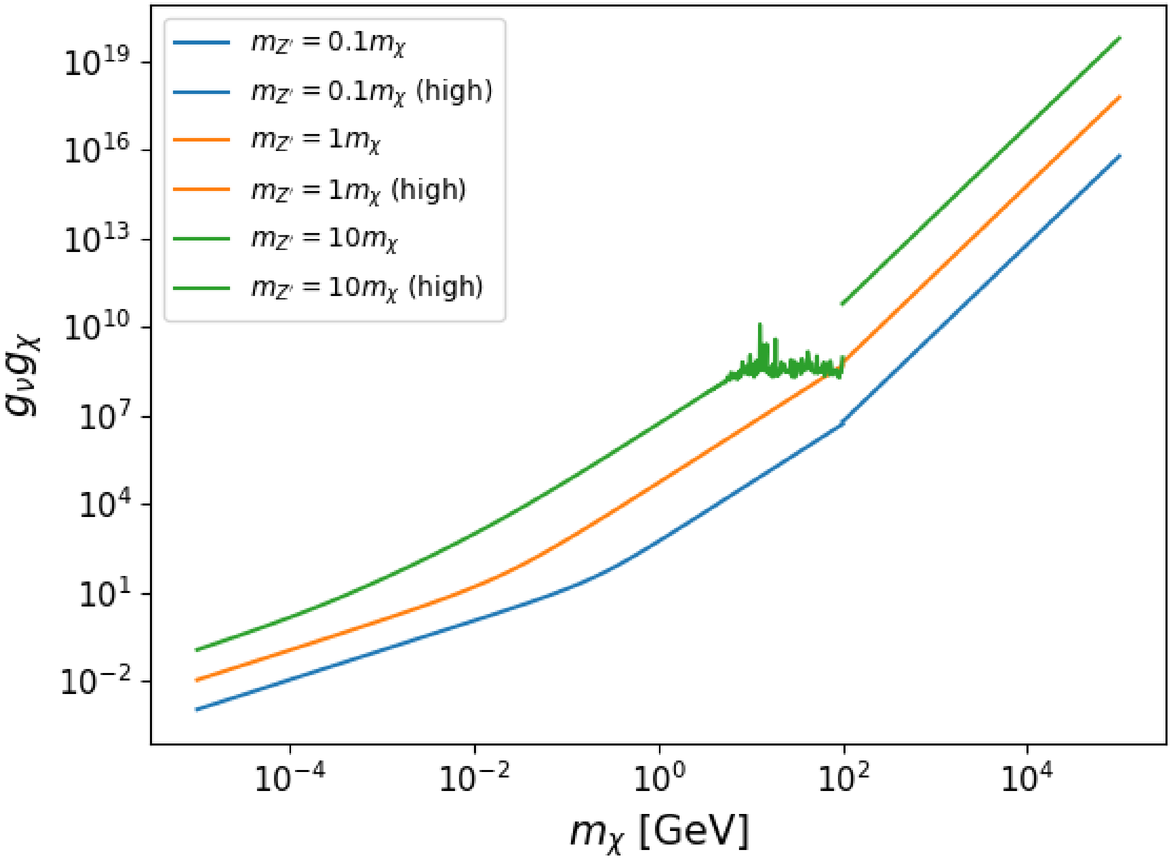


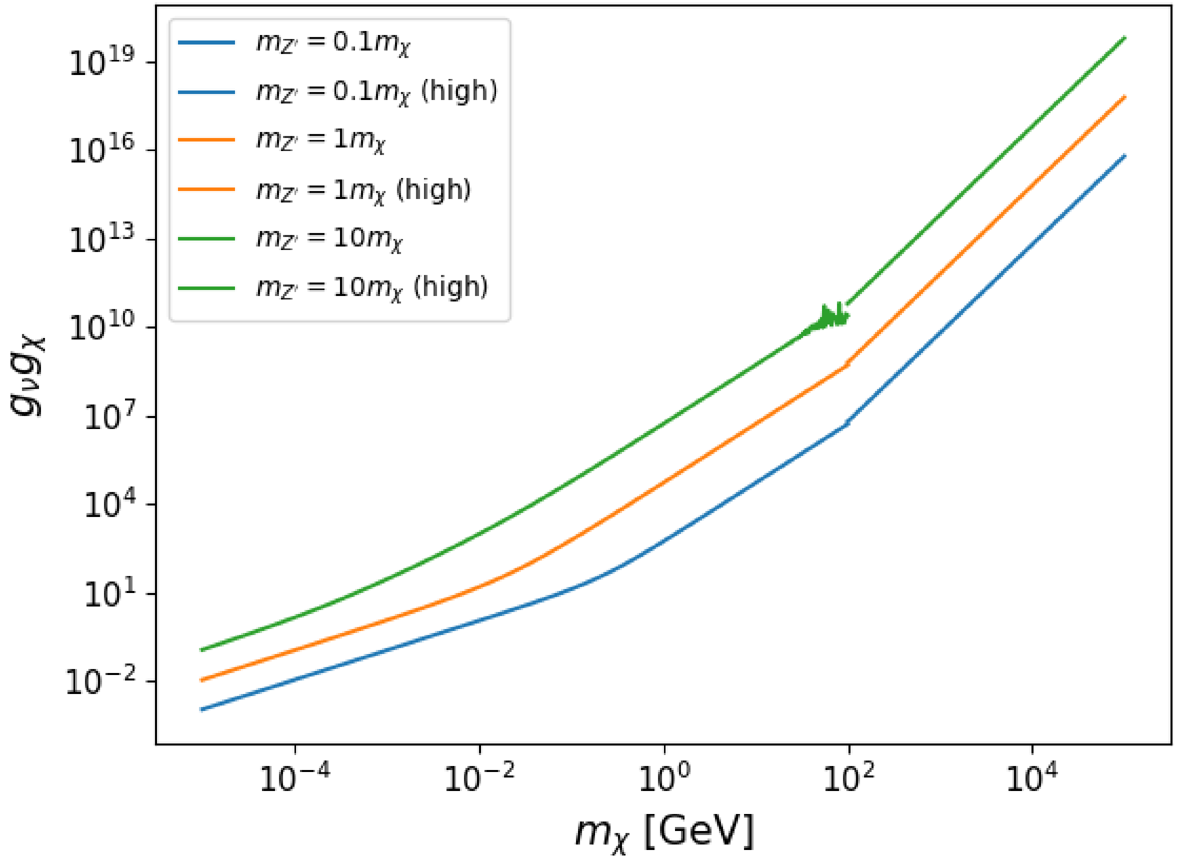
Compare Different Interaction model

- Vector mediator
- Scalar mediator
- Fermion mediator(scalar DM)



Coupling Constant- DM mass





$m_{Z'} = 0.1m_\chi$
$m_{Z'} = 0.1m_\chi$ (high)
$m_{Z'} = 1m_\chi$
$m_{Z'} = 1m_\chi$ (high)
$m_{Z'} = 10m_\chi$
$m_{Z'} = 10m_\chi$ (high)
10^{19}
10^{16}
10^{13}
10^{10}
10^{7}
10^{4}
10^{1}
10^{-2}
$g_\nu g_\chi$
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
m_χ [GeV]

Thanks for Listening

References

- arXiv:2402.08718 [hep-ph]