Constraining Vector Dark Matter with Neutrino Experiments

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Introduction

When we think about DM detection, we think of Table-top Experiments or Collider.

Here we will see that Neutrino experiments can be used to detect DM if it interacts with neutrinos.

Flavor eigenstates are NOT mass eigenstates $\Longrightarrow$ Neutrino Oscillation

$$H_{\rm vac} = U_{PMNS} \left[\frac{1}{2E} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} \right] U^\dagger_{PMNS}$$

Introduction

$$\frac{\Delta m^2}{2E_\nu} \sim 10^{-13}\mathrm{eV} \quad \text{For} \quad E_\nu = 1\mathrm{GeV}$$

Colliders are not sensitive to such low energy effects which makes neutrino detectors so interesting.

Propagation through matter prefers particular flavor eigenstate $\Longrightarrow$ MSW Effect

$$H_{\mathrm{MSW}} = \sqrt{2} G_F n_e(x) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Mikheyev, S.P., Smirnov, A.Y. *Il Nuovo Cimento C* **9,** 17–26 (1986)

Our Model

We add a gauge boson which gauges either of the flavor lepton number difference

$$\mathcal{L} \subset -\frac{1}{4}F_D^2 - \frac{1}{2}m_D^2 A_D^2 + i g_{ij} \overline{L_i} \gamma^\mu A_{\mu D} L_j$$

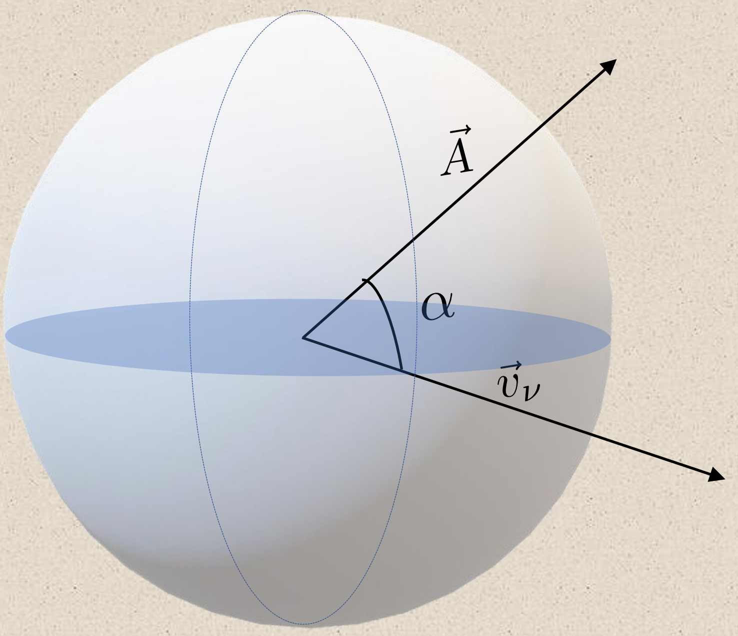
$$L_e - L_\mu \implies g_{ij} \propto \mathrm{diag}(1,-1,0) \qquad L_\mu - L_\tau \implies g_{ij} \propto \mathrm{diag}(0,1,-1)$$

If A is cosmological Dark Matter

$$\vec{A} = \vec{A}_0 \cos\left(m_D t + \phi\right) + \mathcal{O}\left(v_{DM}\right)$$

Our Model

$$H_{\text{int}} = g\vec{A} \cdot \vec{v}_{\nu} + \mathcal{O}(v_{DM})$$



$$H_{\text{tot}} = H_{\text{vac}} + H_{\text{MSW}} + \frac{\sqrt{2\rho}}{m_D} \cos(\omega t + \phi) \cos\alpha \begin{pmatrix} g_{e\mu} & 0 & 0 \\ 0 & g_{\mu\tau} - g_{e\mu} & 0 \\ 0 & 0 & -g_{\mu\tau} \end{pmatrix}$$

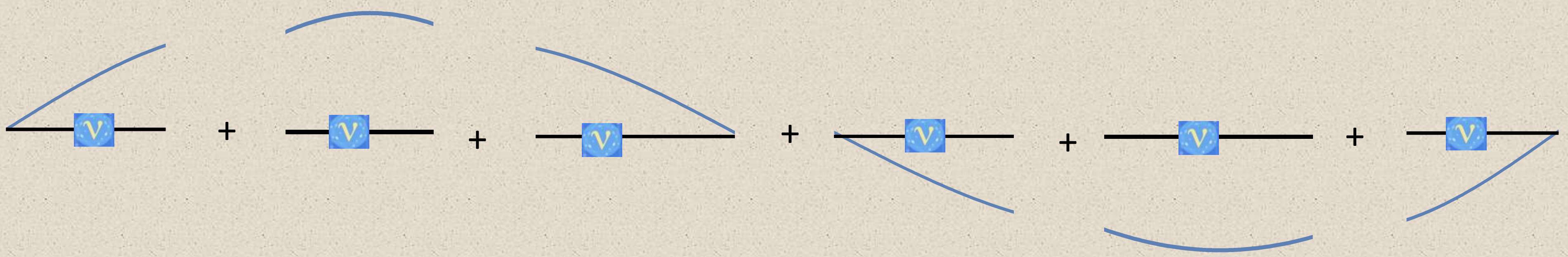
Time Average

The easiest effect to detect is time averaged response.

$$\Delta^{(1)} P_{\nu_\alpha \to \nu_\beta} \propto \langle g A \cos(m_D t + \phi) \rangle = 0$$

$$m_D L \ll 1$$

$$\Delta^{(2)} P_{\nu_\alpha \to \nu_\beta} \propto \langle g^2 A^2 \cos(m_D t + \phi)^2 \rangle \sim \frac{g^2 \rho_{\rm DM}}{m_D^2} L^2$$

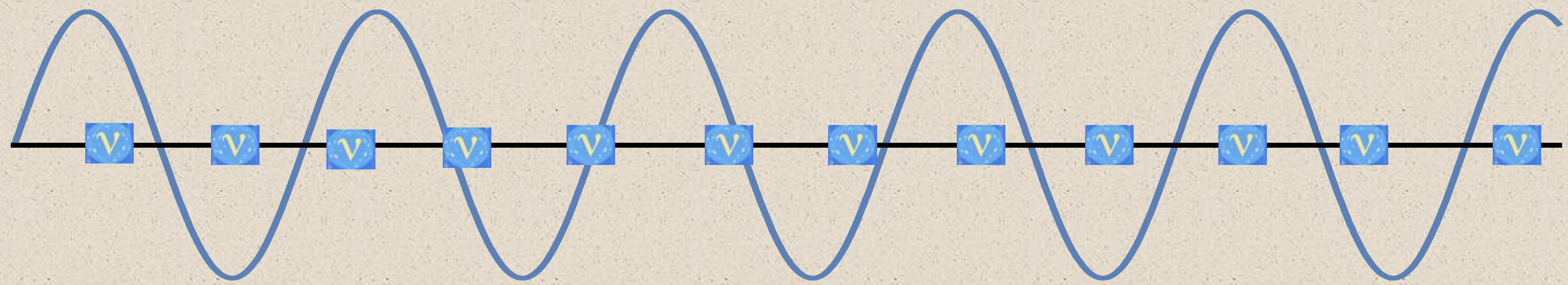


For a fixed uncertainty, limits on g gets weaker for higher mass with slope 1.

Time Average

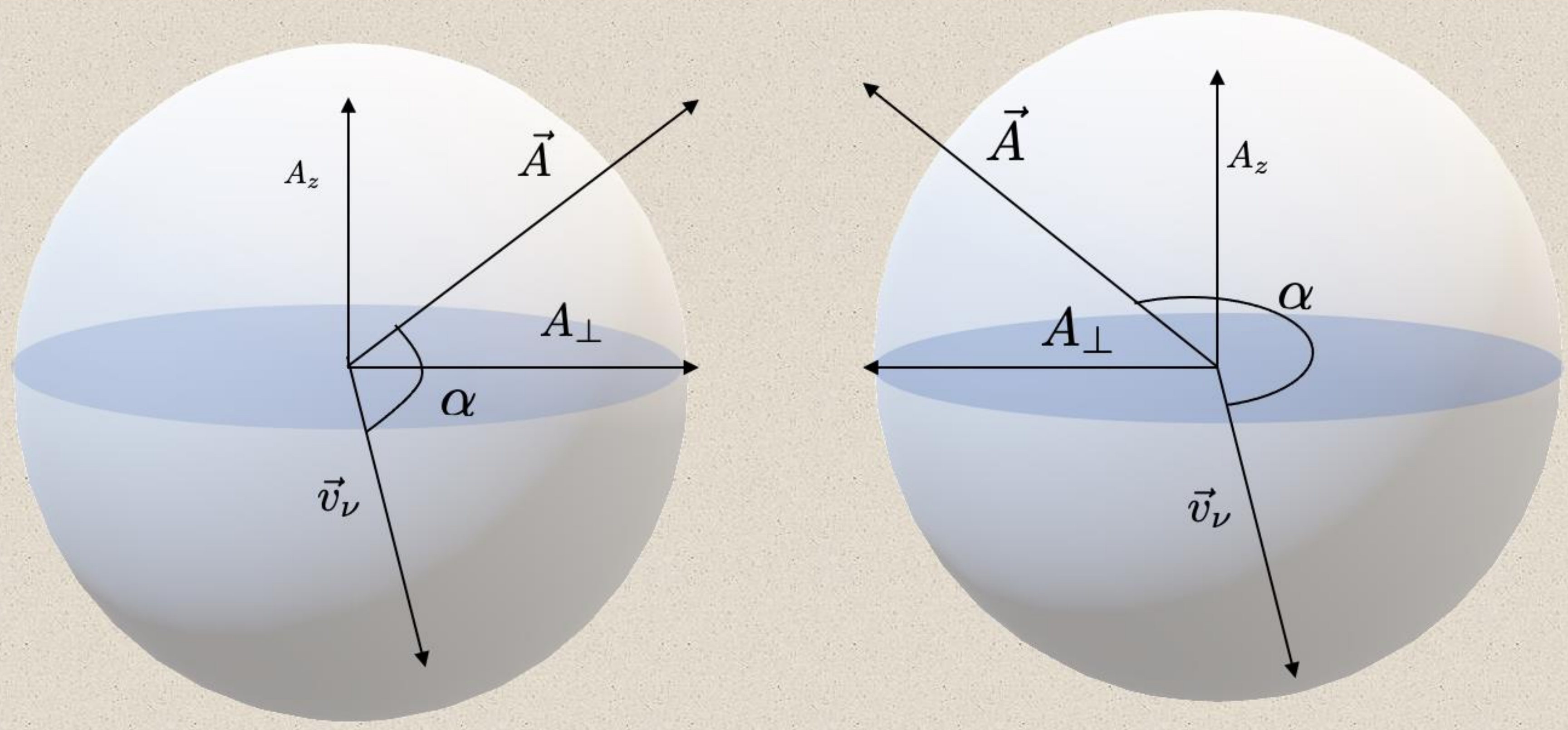
$$\Delta^{(2)} P_{\nu_\alpha \to \nu_\beta} \propto \langle\langle g^2 A^2 \cos(m_D t + \phi)^2 \rangle_L \rangle \sim \frac{g^2 \rho_{\rm DM}}{m_D^4} \qquad\qquad m_D L \gg 1$$

For heavier mass, the limits weakens much faster.



Daily Modulation

$$\vec{A} = \left(A_z \hat{z} + A_\perp \hat{\perp} \cos \omega_E t\right) \cos(m_D t + \phi) \qquad \vec{v}_\nu = \left(v_{\nu,z} \hat{z} + v_{\nu,\perp} \hat{\perp}\right)$$



Daily Modulation + Time Average

$$\Delta^{(1)} P_{\nu_\alpha \to \nu_\beta} \propto \langle g\vec{A} \cdot \vec{v_\nu} \rangle_{\omega_E} = A_z v_{\nu,z} \cos(m_D t + \phi) \neq 0$$

Daily average picks up the polar component, not 0

$$\Delta^{(1)} P_{\nu_\alpha \to \nu_\beta} \propto \langle\langle g\vec{A} \cdot \vec{v_\nu} \rangle_{\omega_E} \rangle = 0$$

$$\Delta^{(2)} P_{\nu_\alpha \to \nu_\beta} \propto \langle\langle \left(g\vec{A} \cdot \vec{v_\nu} \right)^2 \rangle_{\omega_E} \rangle = \frac{1}{2} g^2 \left(A_z^2 v_{\nu,z}^2 + \frac{1}{2} A_\perp^2 v_{\nu,\perp}^2 \right)$$

Neutrino Experiment

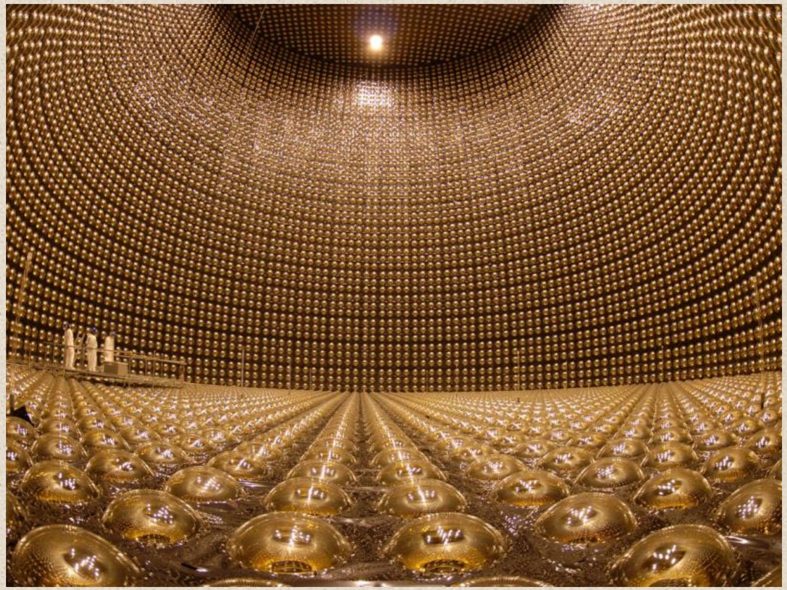
Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\lvert\Delta m^2_{31,32}\rvert$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\lvert\Delta m^2_{31,32}\rvert$, θ_{13},δ_{CP}
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\lvert\Delta m^2_{31,32}\rvert$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	δ_{CP}	θ_{13} , θ_{23}

We prefer neutrinos with higher energy to suppress the vacuum oscillation $\sim \frac{\Delta m^2}{E_\nu}$

We want good statistics, which is hard to obtain for extragalactic neutrinos.

The best existing experiment is Super K. An exciting upcoming one is DUNE.

Super Kamiokande



Stainless steel tank of $50m^3$ ultrapure water.

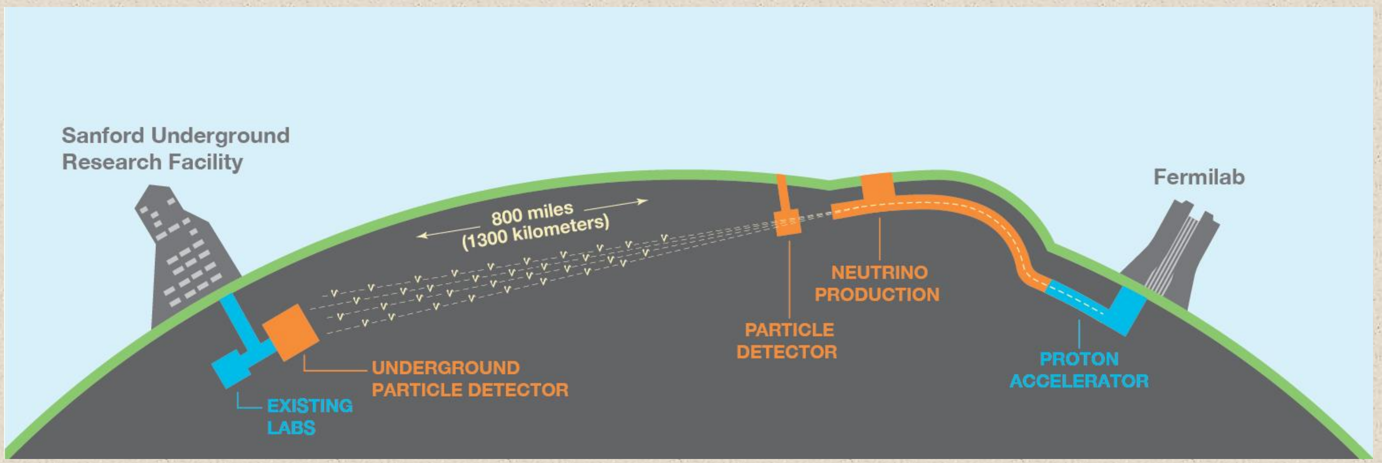
Inside the tank are mounted 13000 PMTs.

Neutrinos are detected through Cherenkov radiation.

Sensitive to a wide range of neutrino energy

Suzuki, Y. The Super-Kamiokande experiment. *Eur. Phys. J. C* **79,** 298 (2019)

DUNE



DUNE is a neutrino experiment under construction.

At Fermilab, neutrinos are produced for decay of pions.

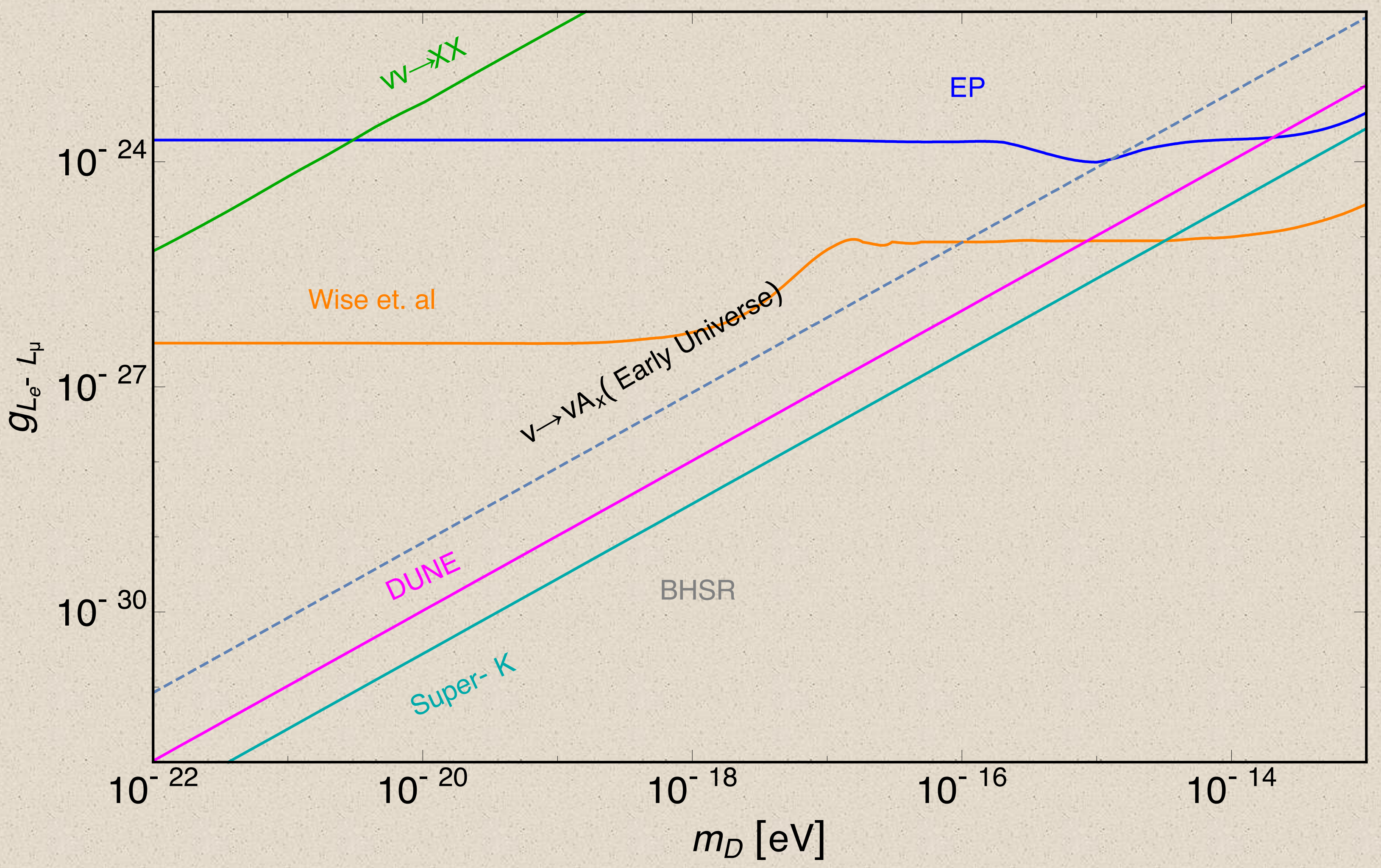
The far detector is located at Sanford, about 1300km away.

The far detector is sensitive to neutrinos with energy 0.5-8.0 GeV

It will observe about 2000 events over 3.5 years.

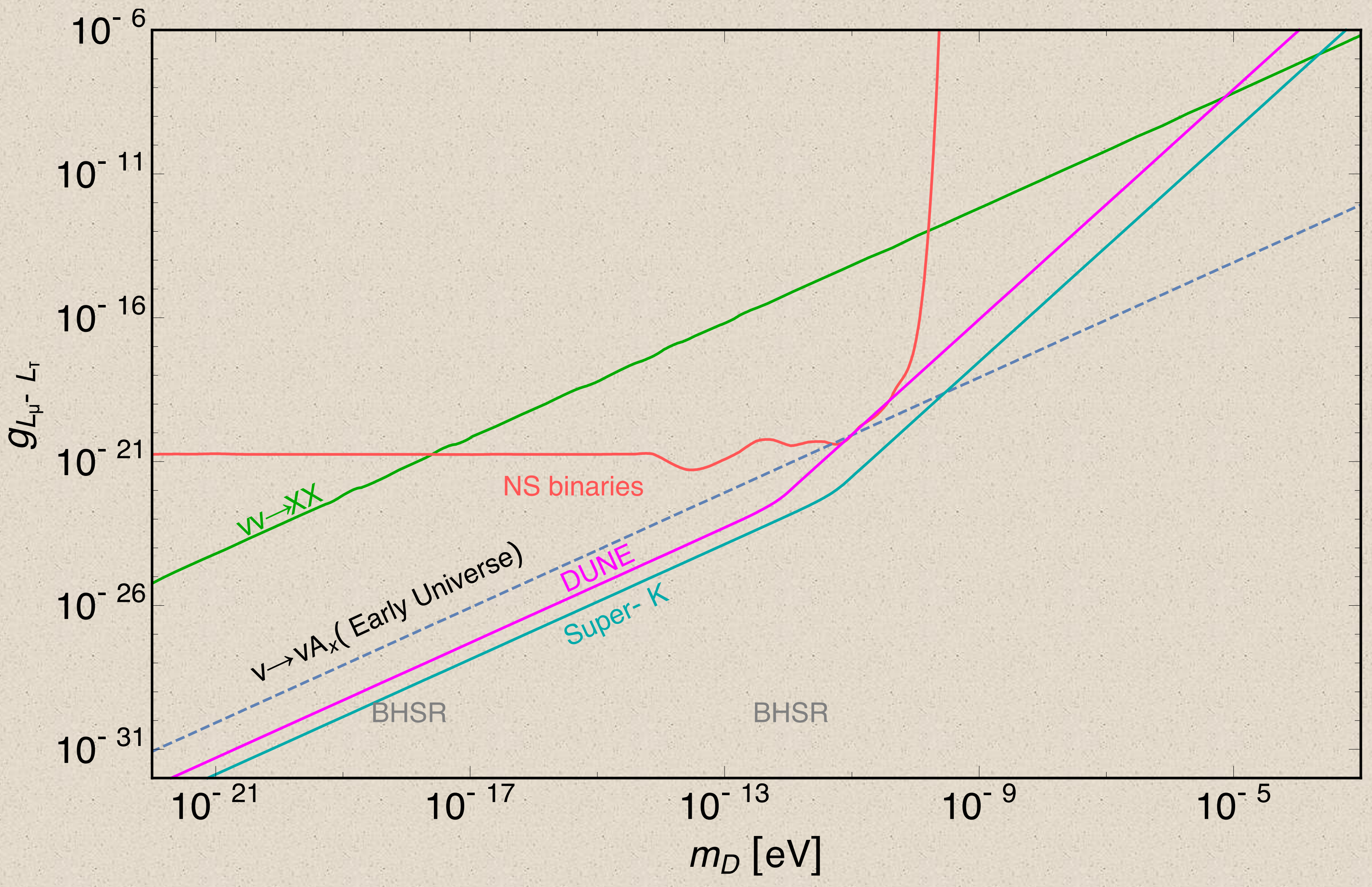
DUNE Collaboraion, arxiv 1601.05471

$L_e - L\mu$ Bound



νν→XX
EP
Wise et. al
ν→νA_x(Early Universe)
DUNE
BHSR
Super- K
10^-24
10^-27
10^-30
g_{Le- Lμ}
10^-22
10^-20
10^-18
10^-16
10^-14
m_D [eV]

$L_\mu - L\tau$ Bound



Summary

➢Neutrino experiment are sensitive to dark matter interacting with neutrinos.

➢Existing and upcoming neutrino experiments can constrain DM parameter space not accessible to other experiments and observations.

➢It would be interesting to observe the phase dependent DM effect.

Thank you