Neutrino Oscillations in Dark Matter

Based on arXiv:1909.10478, KYC, Eung Jin Chun and Jongkuk Kim

Ki -Young Choi

성균관대학교
SUNG KYUN KWAN UNIVERSITY

IBS-PNU Joint Workshop on Physics beyond the Standard Model

4-7 December 2019
Paradise Hotel Busan

Contents

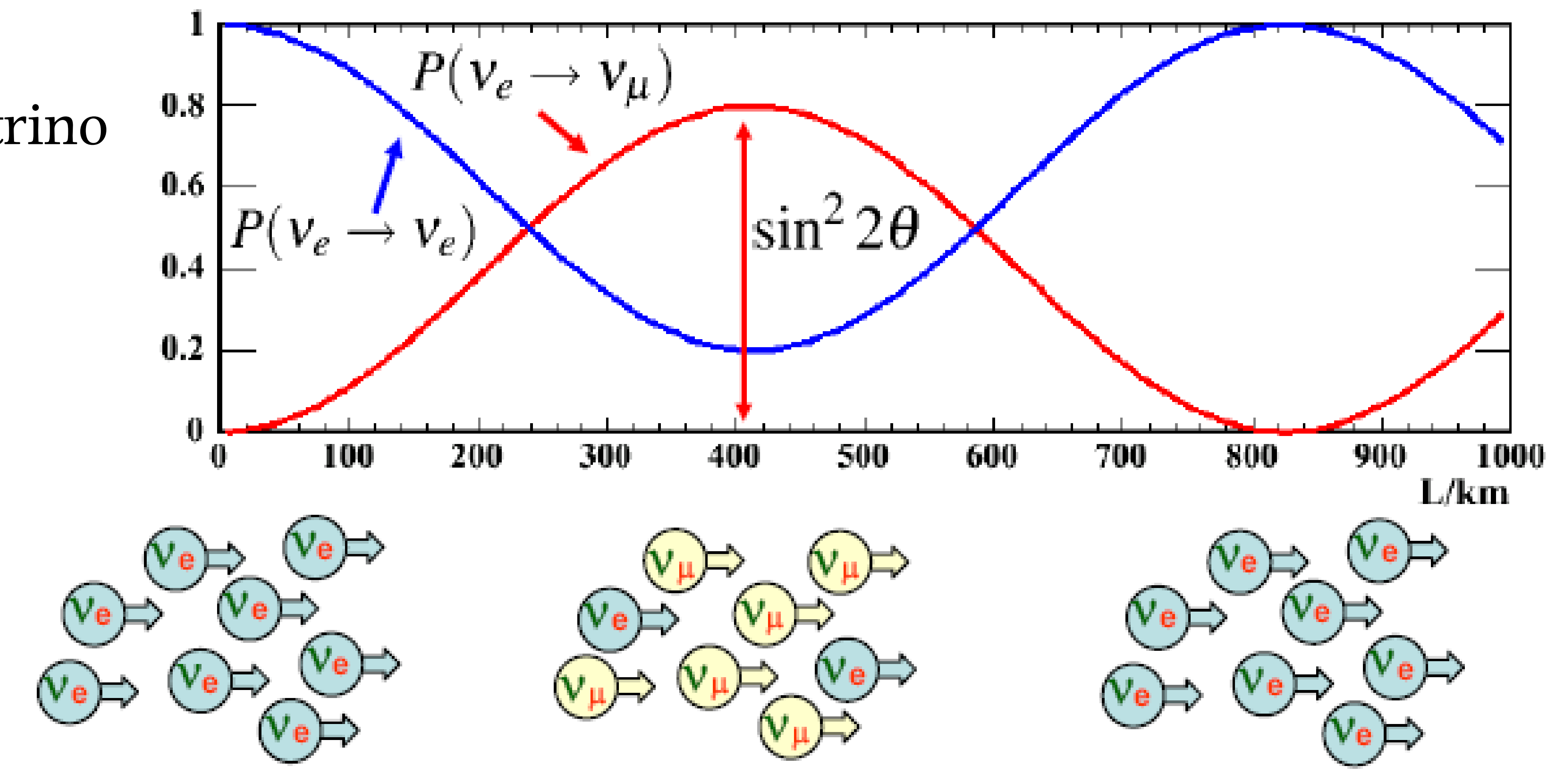
Neutrino Oscillation

Change of flavors with time

For two-body case, $P(\nu_1 \to \nu_2) = |\langle \nu_2(0) | \nu_1(t) \rangle|^2 = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

- e.g. $\Delta m^2 = 0.003\,\mathrm{eV}^2, \quad \sin^2 2\theta = 0.8, \quad E_\nu = 1\,\mathrm{GeV}$

Pure e-neutrino



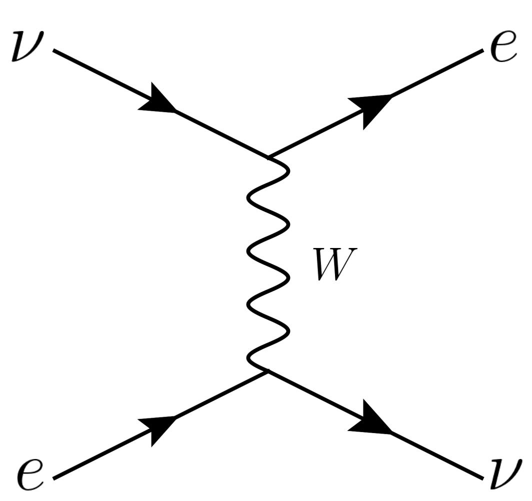
MSW Mechanism

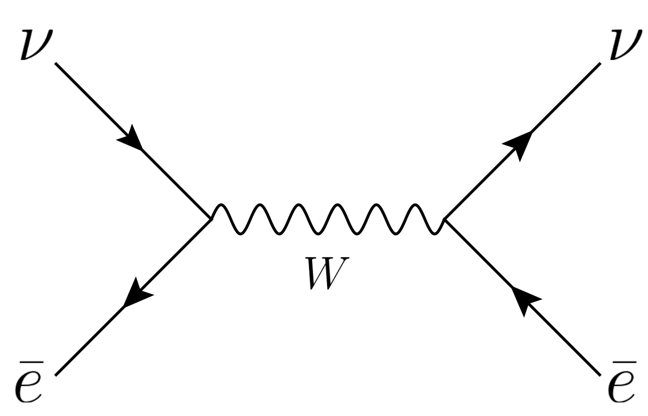
1986 Mikheev and Smirnov proposed a mechanism, which enhance neutrino adiabatic conversion in solar matter based on a theory developed by Wolfenstein. -MSW mechanism

In the matter, due to the interaction with matter, the neutrino mixing changes and adiabatic conversion occurs.

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_M \sin^2(\frac{\Delta m_M^2 x}{4E})$$

with $\sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2}$, $\Delta m_M^2 \equiv \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2}$





$$x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}$$

electron density N_e,

Neutrino Mass Difference

Δm^2_{21} $[10^{-5}\text{ eV}^2] = 7.54^{+0.26}_{-0.22}$ solar neutrino $\sin^2\theta_{12} = 0.308 \pm 0.017$

$|\Delta m^2|$ $[10^{-3}\text{ eV}^2] = 2.43 \pm 0.06$ atm. neutrino $\sin^2\theta_{23} = 0.437^{+0.033}_{-0.023}$

Three masses with two conditions: one is free parameter.

Normal hierarchy

$$m_1 < m_2 < m_3, \quad \Delta m^2_A = \Delta m^2_{31} > 0, \quad \Delta m^2_\odot = \Delta m^2_{21} > 0,$$

$$m_{2(3)} = (m_1^2 + \Delta m^2_{21(31)})^{1/2}.$$

Inverted hierarchy

$$m_3 < m_1 < m_2, \quad \Delta m^2_A = \Delta m^2_{32} < 0, \quad \Delta m^2_\odot = \Delta m^2_{21} > 0,$$

$$m_2 = (m_3^2 + \Delta m^2_{23})^{1/2}, \quad m_1 = (m_3^2 + \Delta m^2_{23} - \Delta m^2_{21})^{1/2}.$$

Why are the Neutrino Oscillations Important?

Two mixing angles requires at least two neutrinos have non-zero mass.

Standard Model is NOT correct.

Standard Model must be extended to include this new physical reality.

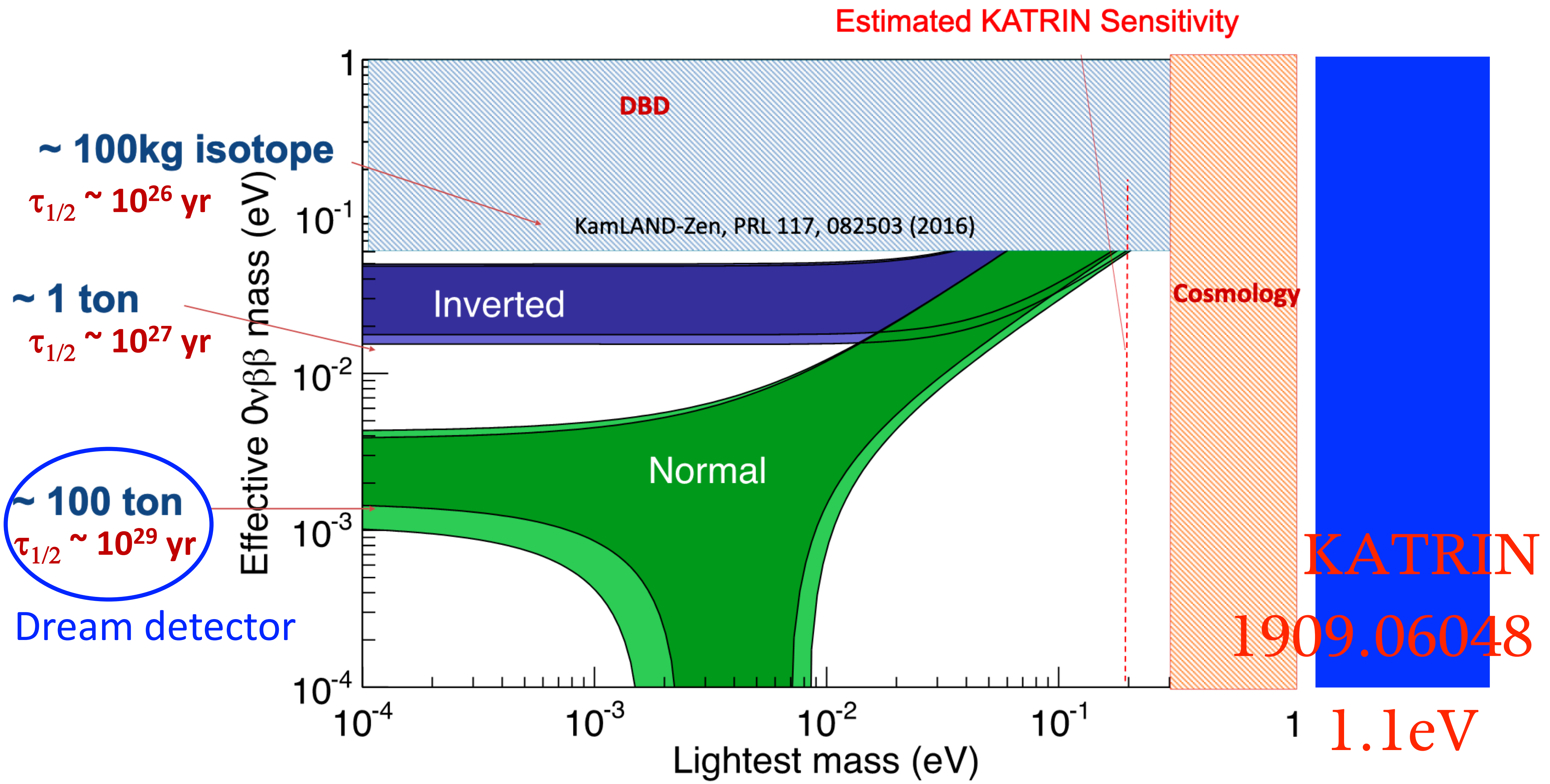
The mechanism which generates neutrino masses is still unknown.

The actual mass of neutrino is still unknown.

The phase of neutrino mixing matrix is still unknown.

Neutrino is Dirac or Majorana?

Neutrino Mass Measurements

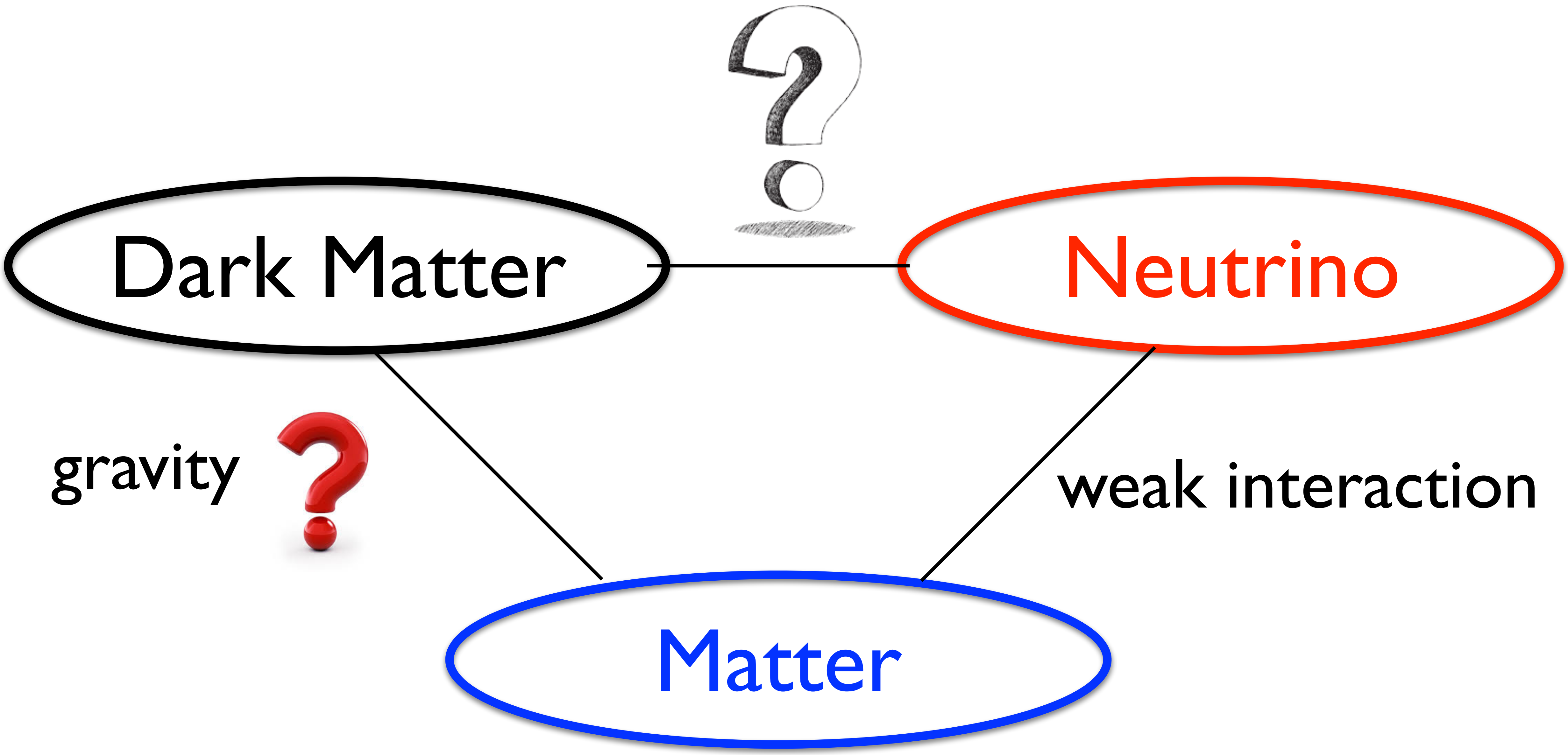


~ 1 ton next generation experiments:

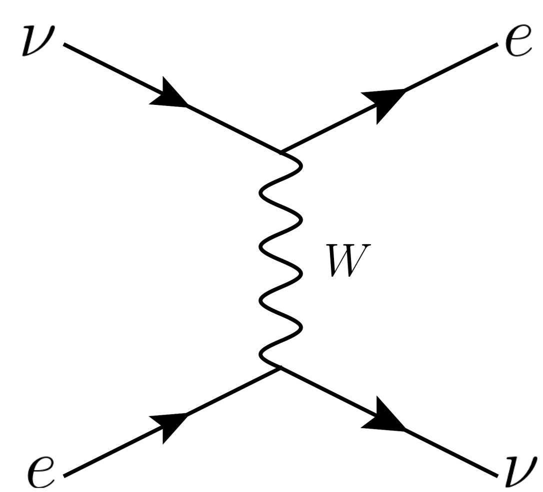
nEXO, NEXT-2.0, PandaX-III 1t, Kamland2-ZEN, SNO+-II, LEGEND-1000, CUPID

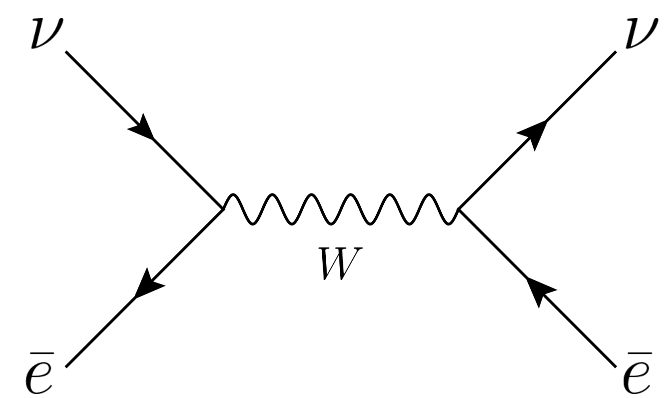
[From Sunny Seo's slide]

Interaction between Matters



Back to the standard MSW effect





Neutrinos can interact with electrons and positrons in matter.

The matter potential within matter is

$$V^{SM}_{\nu,\bar{\nu}} = \sqrt{2} G_F (N_e + N_{\bar{e}}) \frac{\pm\epsilon\, m_W^4 - 2 m_W^2 m_e E_\nu}{m_W^4 - 4 m_e^2 E_\nu^2}$$

with electron asymmetry $\epsilon \equiv (N_e - N_{\bar{e}})/(N_e + N_{\bar{e}})$

$$\pm\sqrt{2} G_F N_e$$

\+ for neutrino

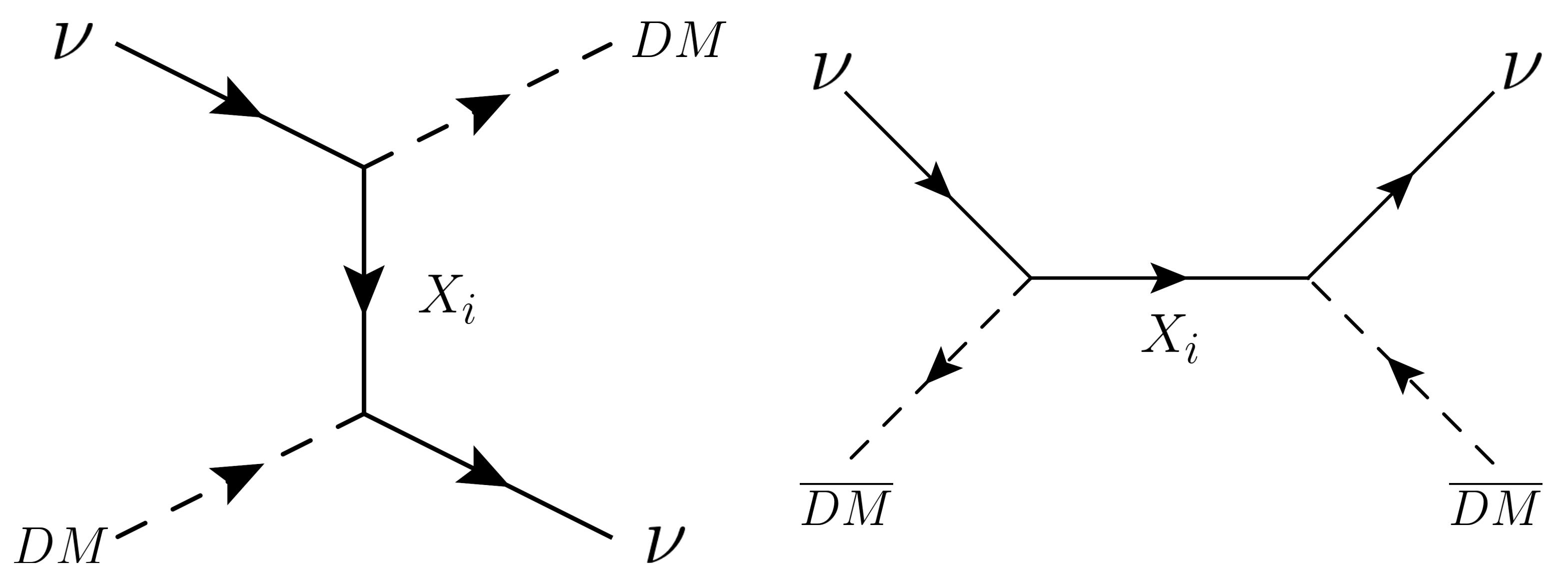
\- for anti-neutrino

$\epsilon = 1\,(N_{\bar{e}} = 0)$ $m_W^2 \gg 2 m_e E_\nu$

Ki-Young Choi, Sungkyunkwan University, Korea

Neutrinos in Dark Matter

$$\mathcal{L}_{int} = g_{\alpha i} \bar{f}_i P_L \nu_\alpha \phi^* + h.c.$$



[arXiv:1909.10478, KYC, Eung Jin Chun and Jongkuk Kim]

$$V^{DM}_{\nu,\bar{\nu}} \simeq \frac{\lambda^{(T)}}{2} \frac{\rho_{DM}}{m_{DM}} \frac{\pm \epsilon\, m_X^2 - 2 m_{DM} E_\nu}{m_X^4 - 4 m_{DM}^2 E_\nu^2}$$

with DM asymmetry $\epsilon \equiv \frac{N_{DM} - N_{\overline{DM}}}{N_{DM} + N_{\overline{DM}}}$,

cf) wrong sign in [1904.02518, Ge, Murayama]

Effective Hamiltonian

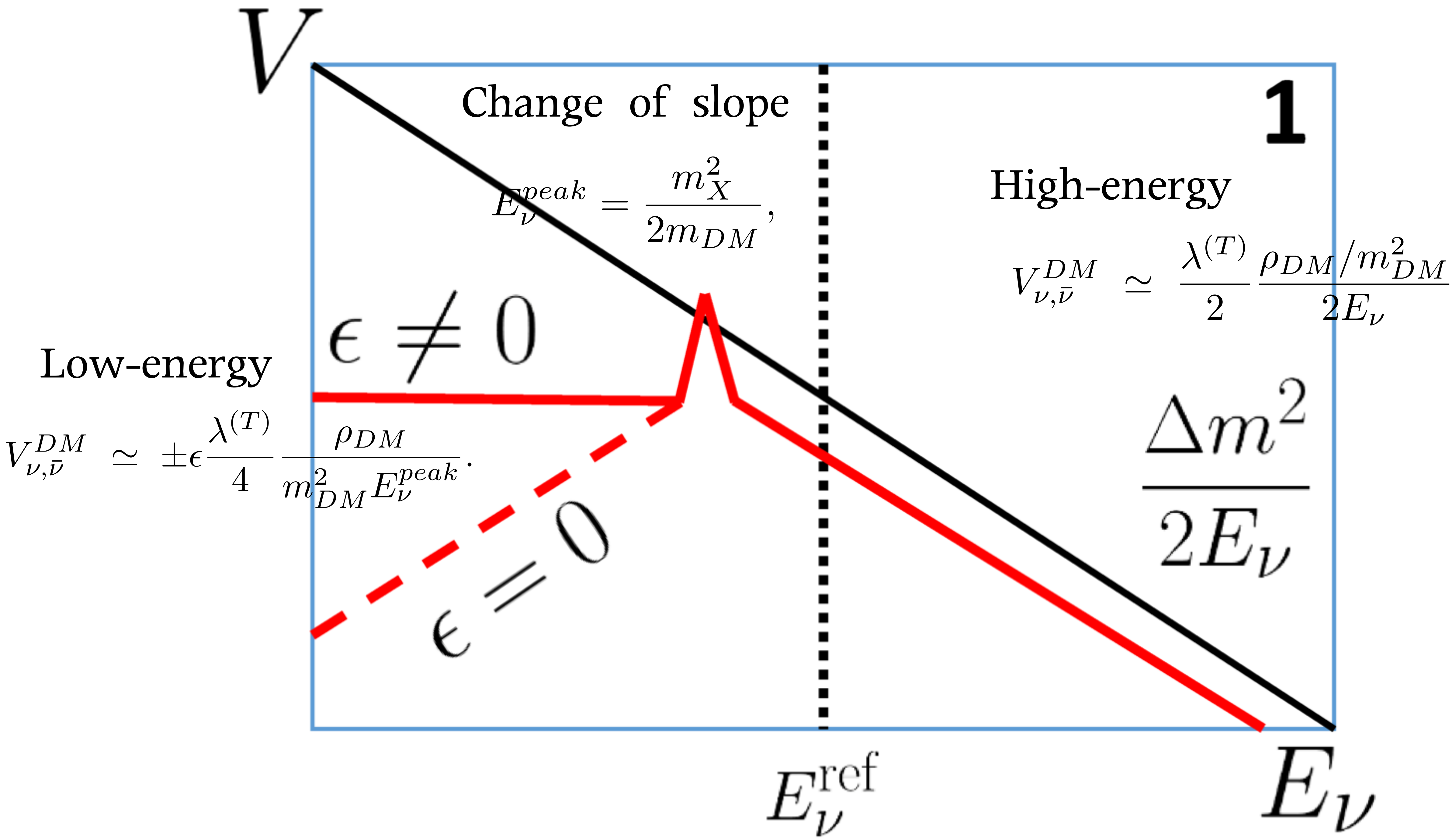
The effective Hamiltonian for the neutrino (anti-neutrino) oscillation

$$H_\nu = E_\nu + \frac{\tilde{M}^\dagger \tilde{M}}{2E_\nu} + V_\nu^{DM},$$

$$H_{\bar{\nu}} = E_\nu + \frac{\tilde{M} \tilde{M}^\dagger}{2E_\nu} + V_{\bar{\nu}}^{DM},$$

Neutrino potential due to Dark Matter

[arXiv:1909.10478, KYC, Eung Jin Chun and Jongkuk Kim]

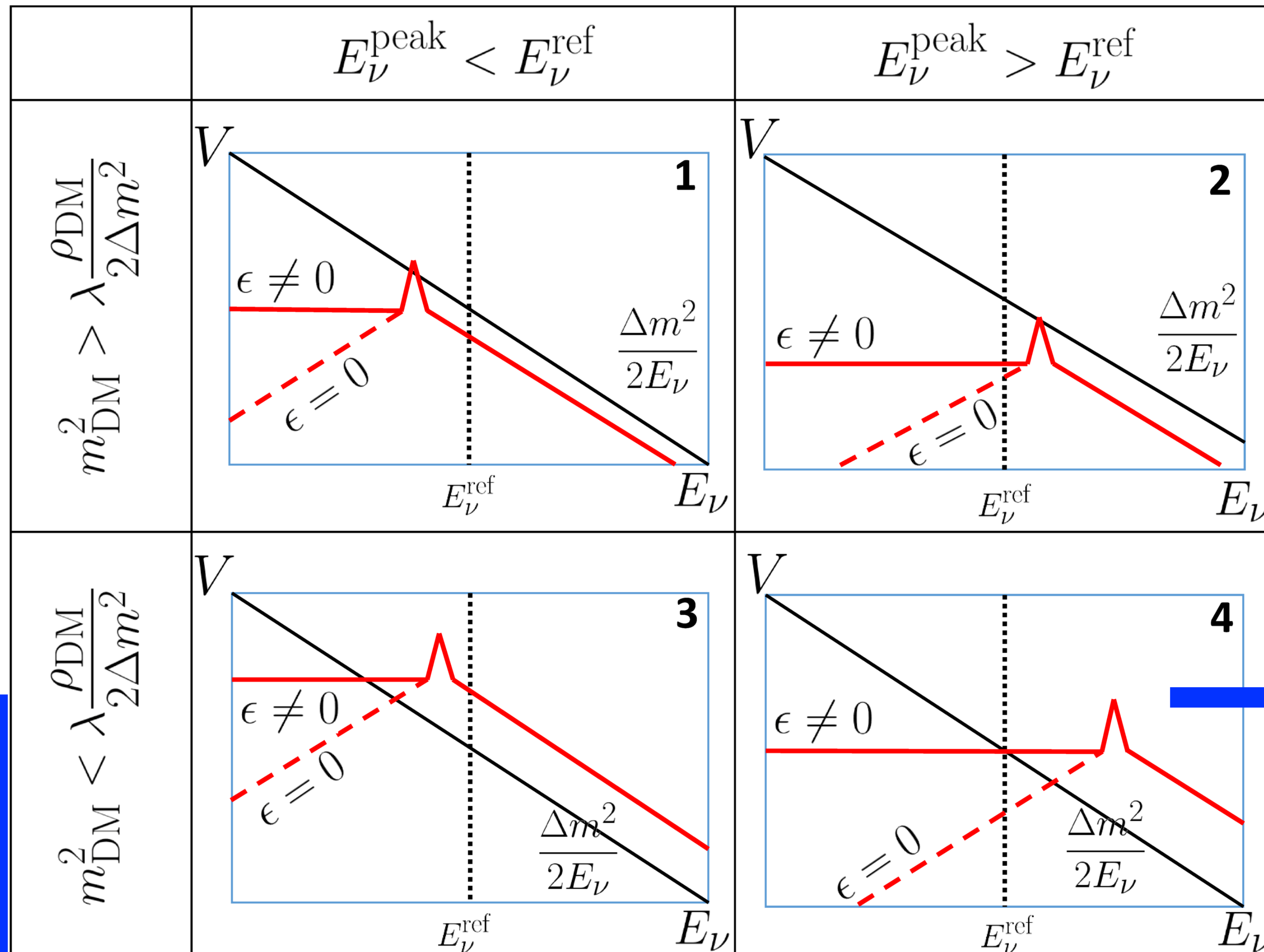


New observations?

[arXiv:1909.10478, KYC, Eung Jin Chun and Jongkuk Kim]

Anomalous neutrino experiments

Ruled-out by neutrino experiments



HE neutrino experiments

Dark Matter asymmetry in the neutrino oscillation

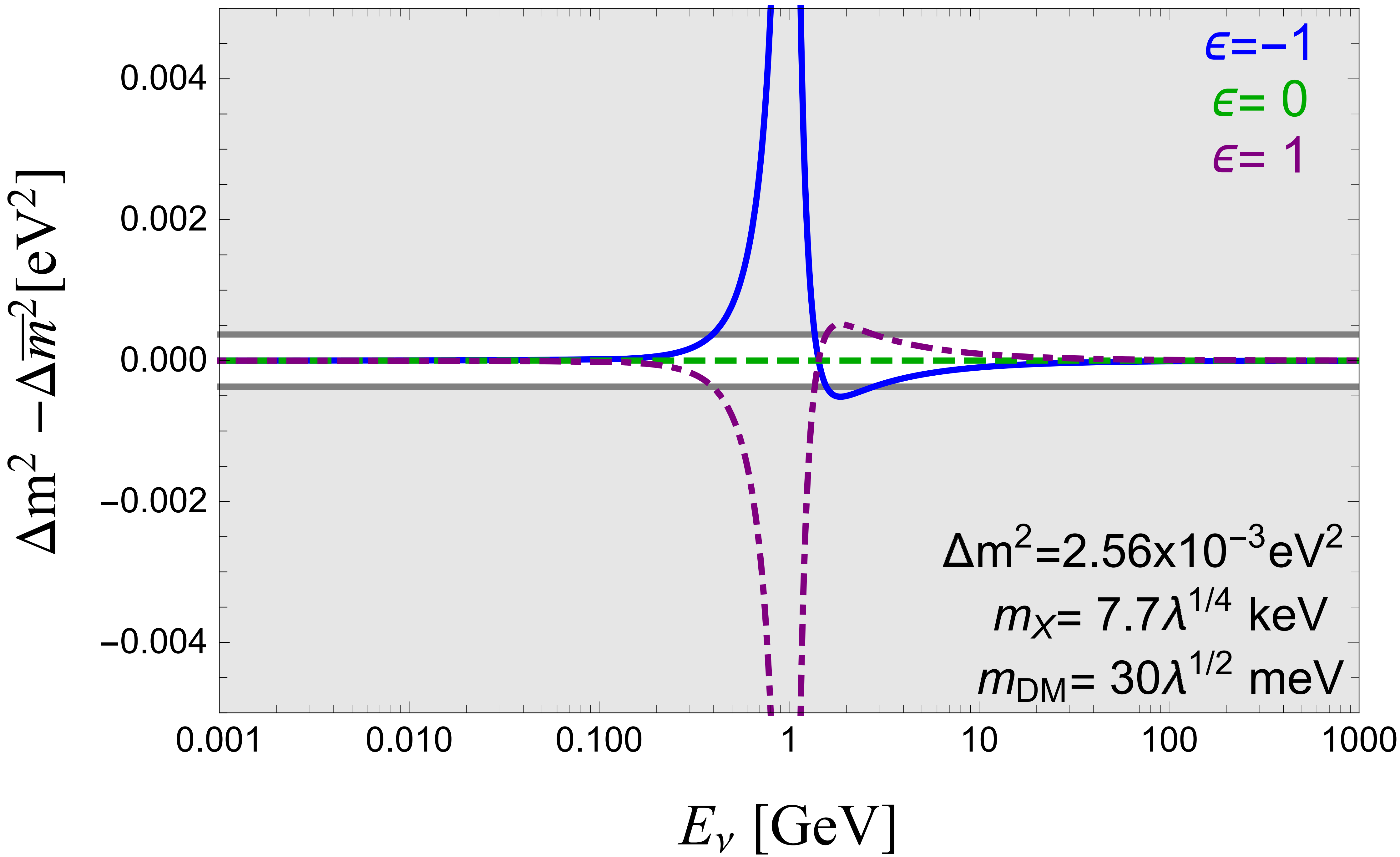
Asymmetric oscillations between neutrino and anti-neutrino

- Neutrino and antineutrino have different sign in the potential, since the background DM is asymmetric.

- Combined with SM mass term, the DM potential is added or subtracted, which changes the oscillation.

- Anomalous asymmetry in the neutrino and antineutrino may give hints on the DM-neutrino interaction and asymmetry of DM

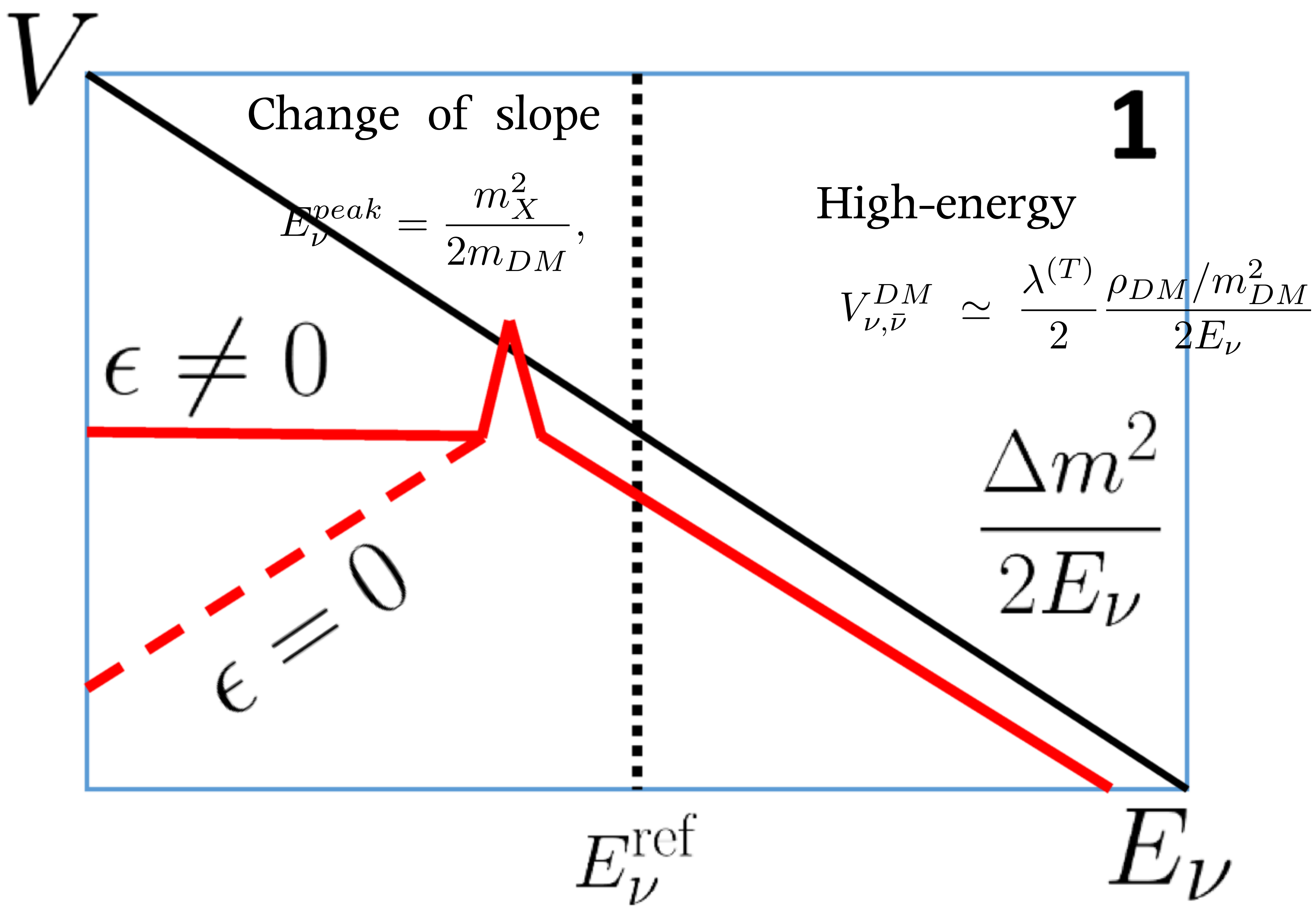
Asymmetry in the oscillations



[arXiv:1909.10478, KYC, Eung Jin Chun and Jongkuk Kim]

When DM symmetric? $\epsilon = 0$

$\epsilon = 0$



Ki-Young Choi, Sungkyunkwan University, Korea

Neutrino Oscillations can be explained with massless neutrinos?

With

DM-neutrino interactions!

Dark Matter Assisted Neutrino Oscillation

$\epsilon = 0$

When the neutrino peak energy is smaller than 1 MeV

$$E_\nu^{peak} = \frac{m_X^2}{2m_{DM}} \ll 1\ \text{MeV}$$

and the DM induced matter potential is the same as neutrino mass effect

$$V_{\nu,\bar{\nu}}^{DM} \simeq \frac{\lambda^{(T)}}{2} \frac{\rho_{DM}/m_{DM}^2}{2E_\nu} = \frac{\Delta m^2}{2E_\nu}$$

Neutrino oscillations can be explained only with DM-neutrino interactions even with massless neutrinos.

[arXiv:1909.10478, KYC, Eung Jin Chun and Jongkuk Kim]

$$\begin{aligned} \lambda &= \frac{2m_{DM}^2}{\rho_{DM}} U^* \text{diag}(\Delta m^2) U^T \qquad (20) \\ &\simeq \begin{pmatrix} 0.026 & 0.091 & 0.085 \\ 0.091 & 0.381 & 0.408 \\ 0.085 & 0.408 & 0.478 \end{pmatrix} \left(\frac{m_{DM}}{20\text{meV}}\right)^2 \left(\frac{0.3\,\text{GeV}\,\text{cm}^{-3}}{\rho_{DM}}\right), \end{aligned}$$

Dark Matter Assisted Neutrino Oscillation

Predictions [Work in progress]

No measurement of the absolute neutrino mass:

- Single beta decay (KATRIN), neutrinoless double beta decay, cosmological observation of neutrino mass.

Modulated oscillation in the neutrino and anti-neutrino

- Due to the anisotropic velocity of DM on Earth, the matter potential has time dependence.
- Annual modulation of (anti-)neutrino oscillation.

Directional dependence of (anti-)neutrino oscillation

- Matter potential has correction.

Constraints on DM-neutrino interaction

	Early Universe	Present Universe
$\langle \sigma_{\rm DMDM \to \nu\nu} v \rangle$	- DM relic density - Neutrino reheating : BBN, Neff	- neutrino flux enhancement
$\sigma_{\rm DM+\nu \to DM+\nu}$	- CMB anisotropy - Large Scale Structure	- SN1987-A, IC170922A - neutrino anisotropy - neutrino flux suppression - neutrino flavor oscillation
model-dependent coupling		- mono-jet, mono-lepton - invisible Z decay

Ki-Young Choi, Sungkyunkwan University, Korea

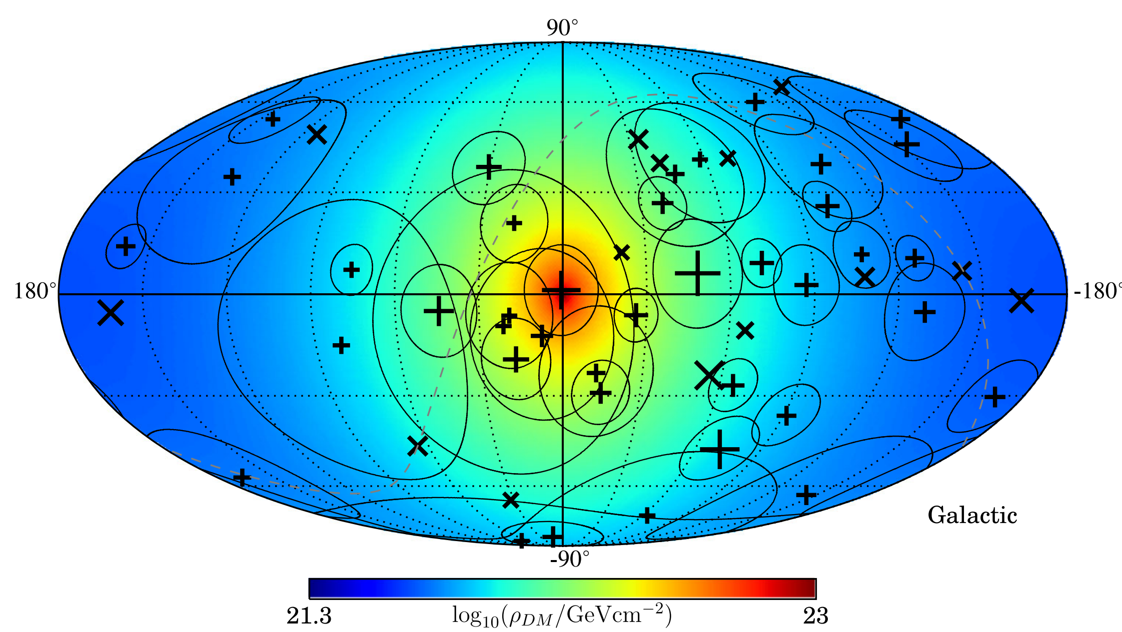
Astrophysical Neutrinos

- Suppression of the astrophysical neutrino flux

- SN1987A constrains the interaction at the energy around MeV
[Raffelt, 1996] [Mangano, Melchoirri, Serra, Cooray, Kamionkowski, 2006]

$$\frac{\langle \sigma_{dm-\nu} |v| \rangle}{m_{dm}} \lesssim 10^{-25}\ \mathrm{cm}^2\ \mathrm{MeV}^{-1} \quad \text{at } E \sim 10\ \text{MeV}$$

- Anisotropy of the neutrino flux through the Milky DM halo
[Arguelles, Kheirandish, Vincent, 2017]

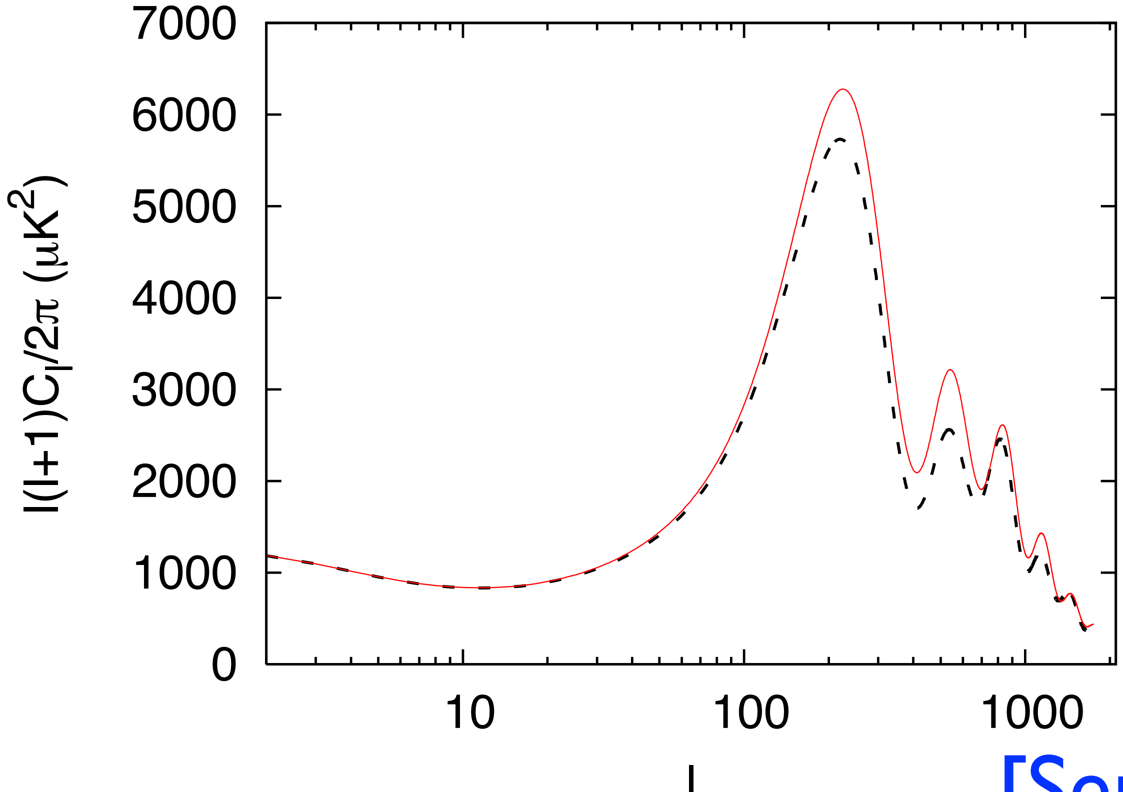


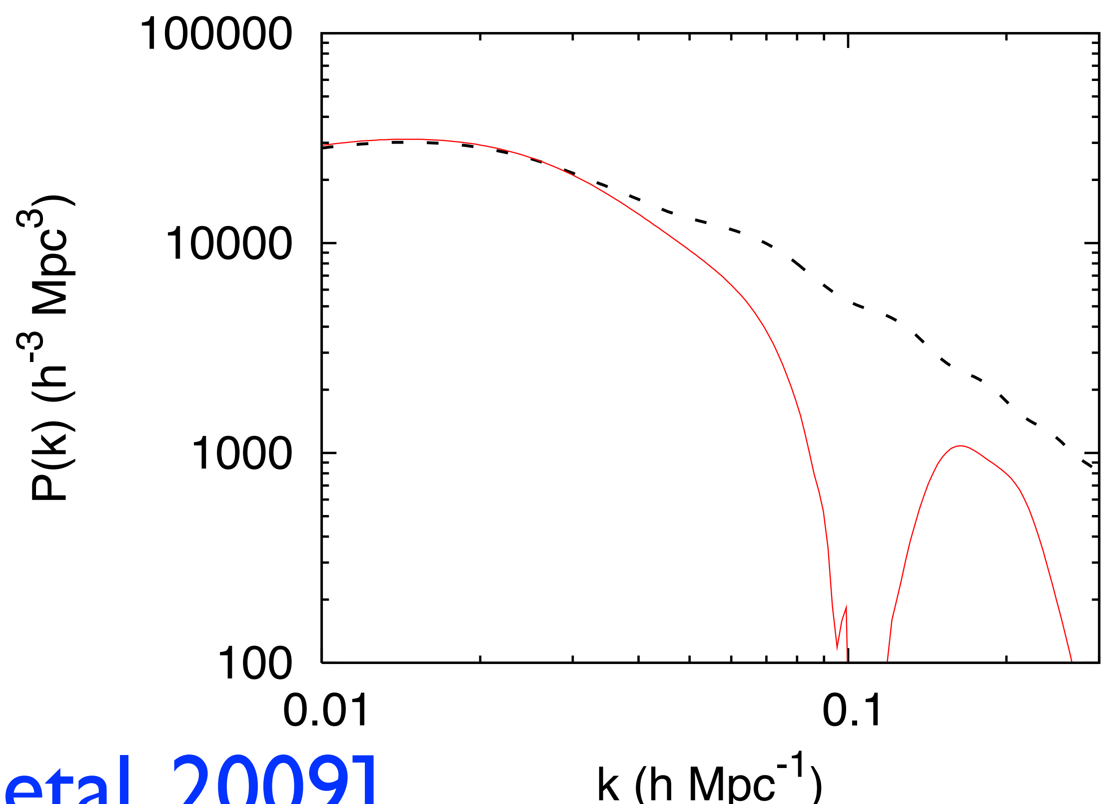
Ki-Young Choi, Sungkyunkwan University, Korea

Constraints from Cosmology

- The density perturbation does not grow in the kinetic equilibrium of DM, and then grow after decoupling.

- The power spectrum of DM from CMB and LSS can constrain the scattering cross section of DM with neutrinos





[Serra etal, 2009]

Constraint on the DM-neutrino interaction

Requiring less than 90% suppression of the flux $\int \sigma n dl \lesssim 2.3$

$$\frac{\sigma}{M_{\rm dm}} \lesssim 2.3 \times \left(\rho_0 L + \int_{los} \rho_{\rm gal}(\mathbf{x}) dl \right)^{-1}$$

We obtain the upper bound on the cross section/mass as

$$\sigma / M_{\rm dm} \lesssim 5.1 \times 10^{-23}\, {\rm cm}^2 / \,{\rm GeV}$$

$$\text{at} \quad E_\nu = 290\,{\rm TeV}$$

KYC, C. Rott and, J. Kim, PRD99, 08 3018 (2019)

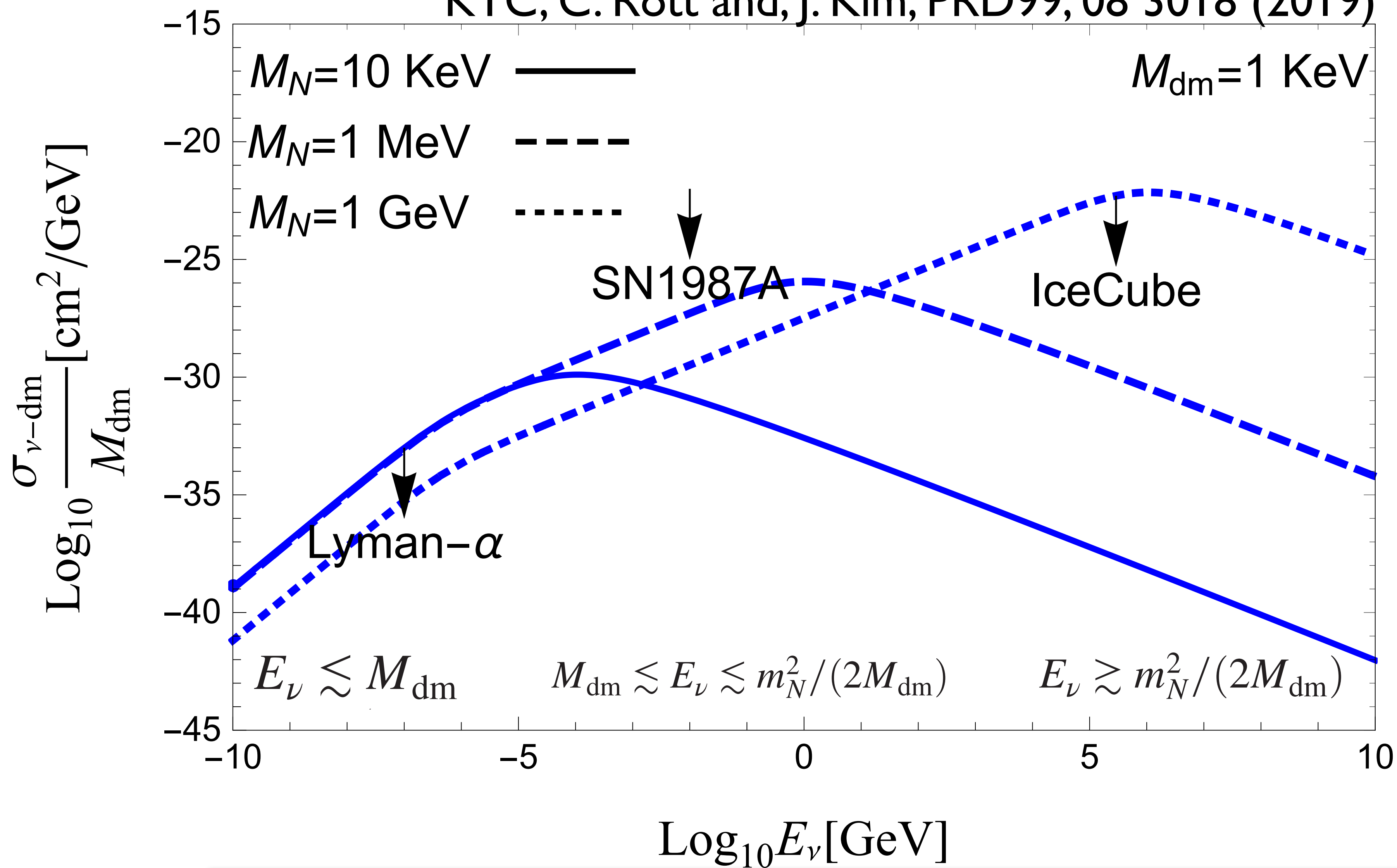
Complex Scalar DM with fermion mediator

$$\mathcal{L}_{\rm int} = -g\chi\overline{N}\nu_L + \text{h.c.}$$

χ dark matter

N massive fermion

KYC, C. Rott and, J. Kim, PRD99, 08 3018 (2019)



$$\sigma/M_{\rm dm} \lesssim 5.1\times10^{-23}\ \text{cm}^2/\ \text{GeV} \quad \text{at} \quad E_\nu = 290\,\text{TeV}$$

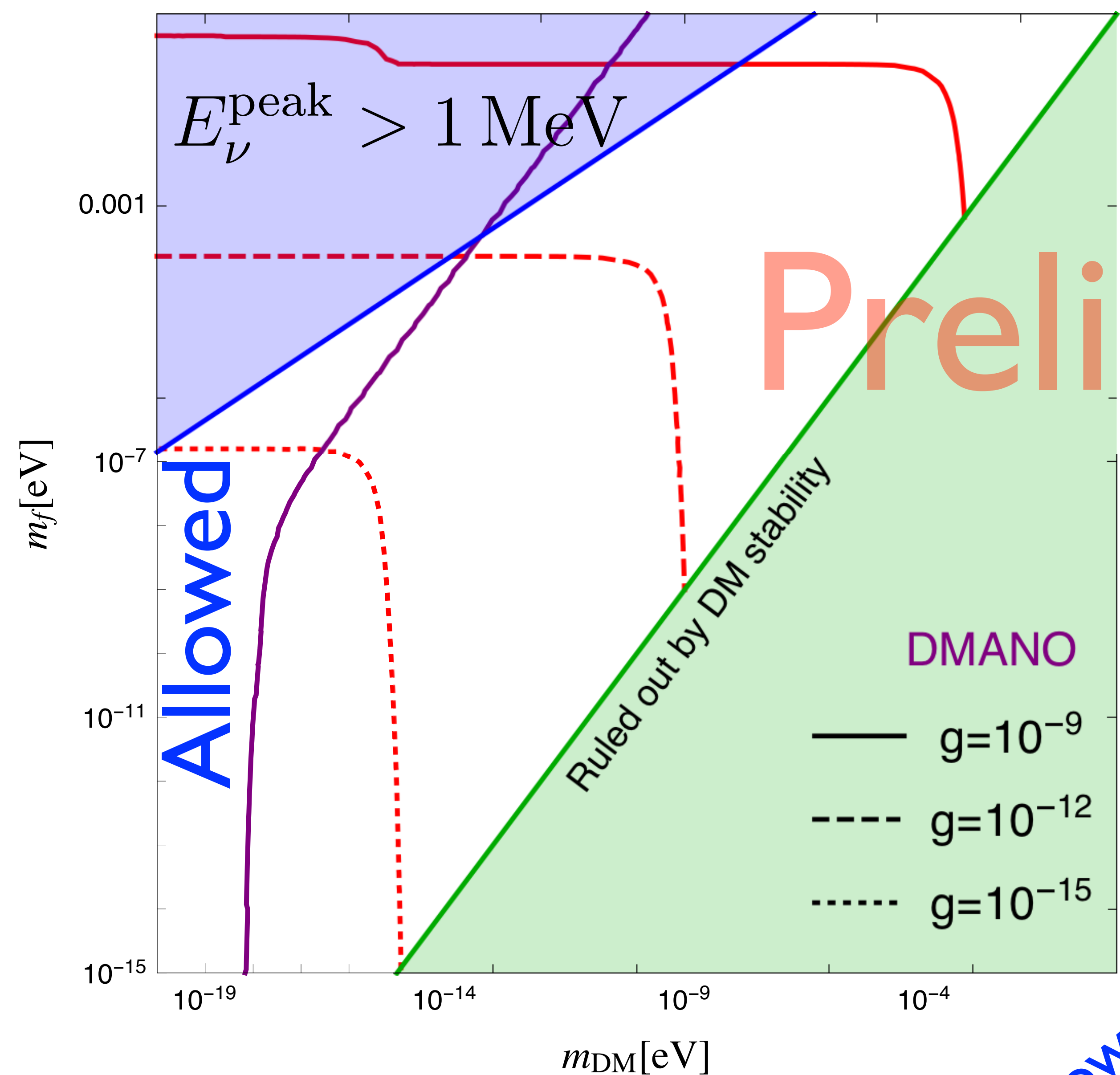
Ki-Young Choi, Sungkyunkwan University, Korea

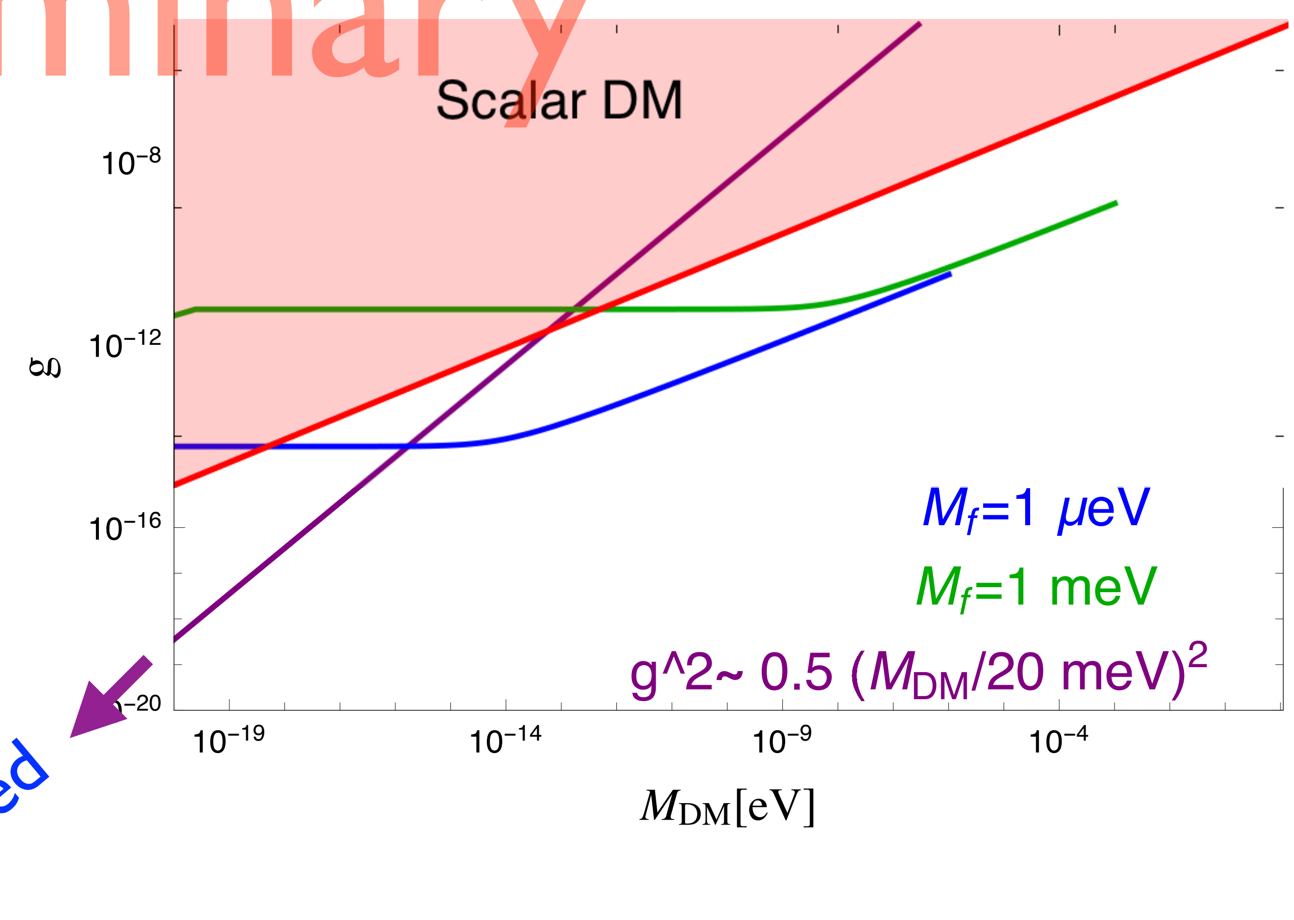
Cosmological/astrophysical constraints on DMANO model [Work in progress]

$$g \sim 3 M_{\rm dm} / \,{\rm eV}$$

$$m_X < \sqrt{10^6\,{\rm eV}\, M_{\rm dm}}$$

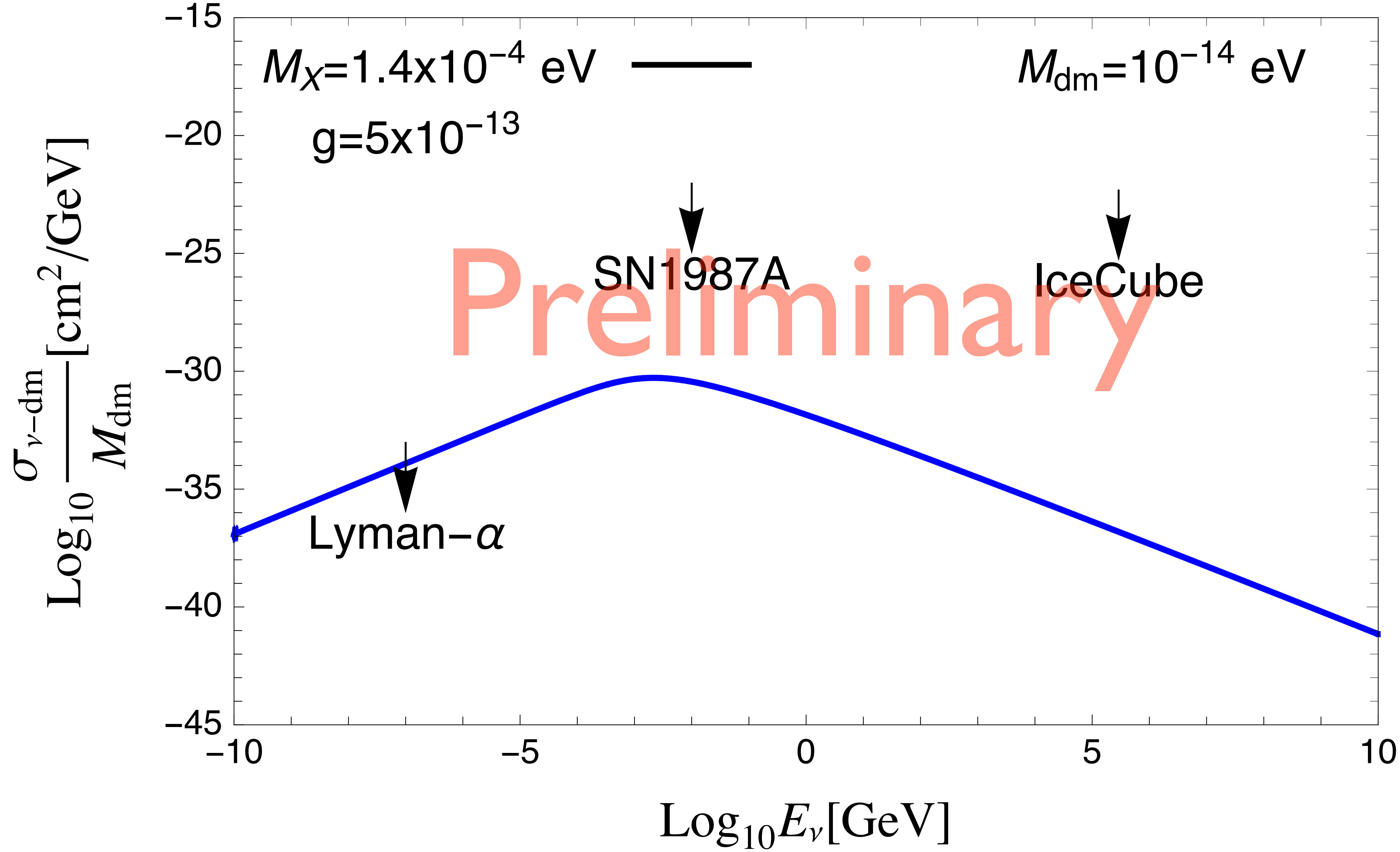
Preliminary





Ki-Young Choi, Sungkyunkwan University, Korea

Cosmological/astrophysical constraints on DMANO model



Ki-Young Choi, Sungkyunkwan University, Korea

Discussion

1. Neutrinos in Dark Matter:

   DM interactions with neutrino affect the neutrino oscillation with energy dependence.

2. DM asymmetry may be encoded in the neutrino oscillations: ($\epsilon \neq 0$)

   Anomalies in the (anti)neutrino oscillations

3. Does DM-neutrino interaction can explain solely the neutrino oscillations with massless neutrinos? $\epsilon = 0$

   Due to the cosmological/astrophysical constraints, very small mass of DM and interaction is needed.

Thank You!