Neutrino Oscillations in Dark Matter Halo

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

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Contents

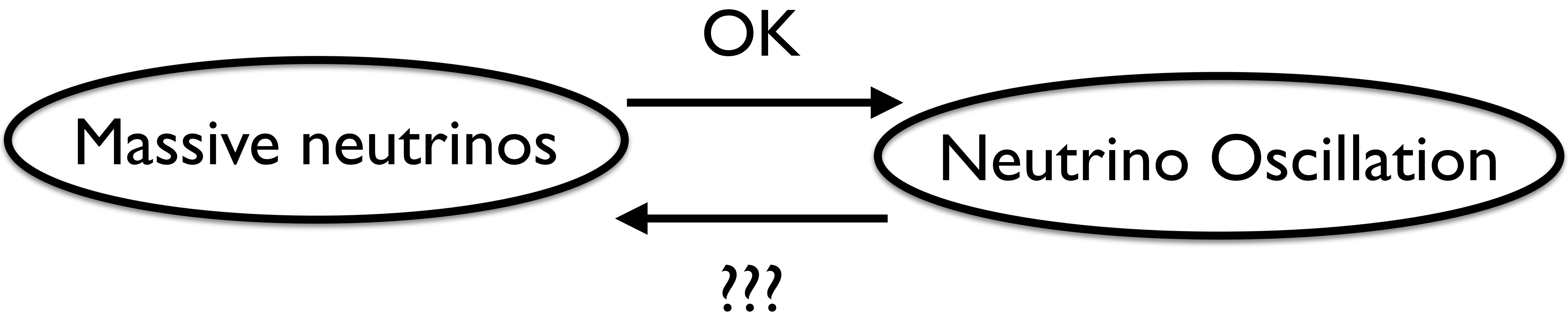
Are Neutrinos massive?

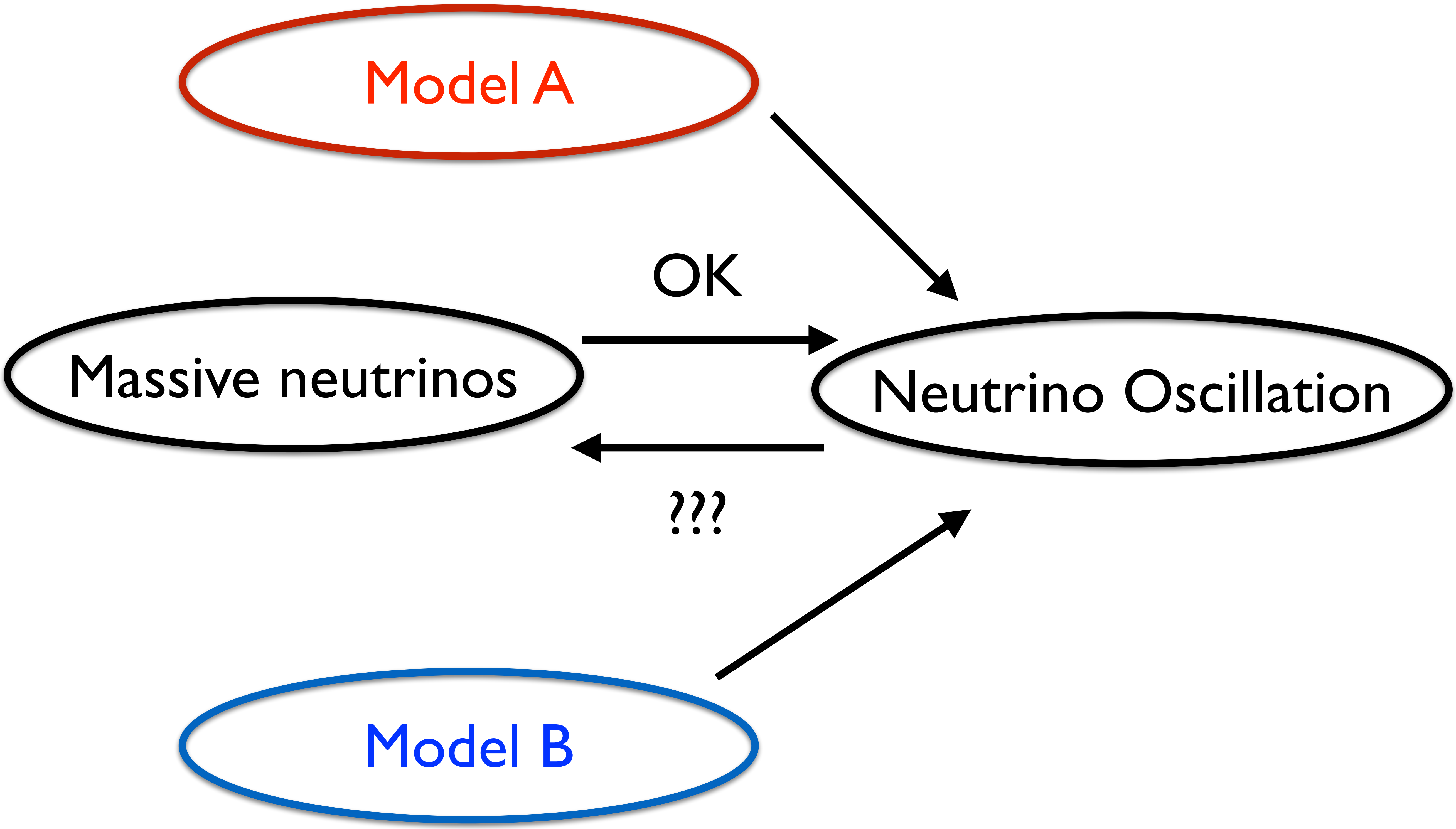
Yes.

Why?

To explain flavor oscillations!

$$\text{Massive neutrinos} \xrightarrow{\text{OK}} \text{Neutrino Oscillation}$$


OK
Massive neutrinos
Neutrino Oscillation
???


Model A
OK
Massive neutrinos
Neutrino Oscillation
???
Model B

Is it possible to explain neutrino oscillations with massless neutrinos?

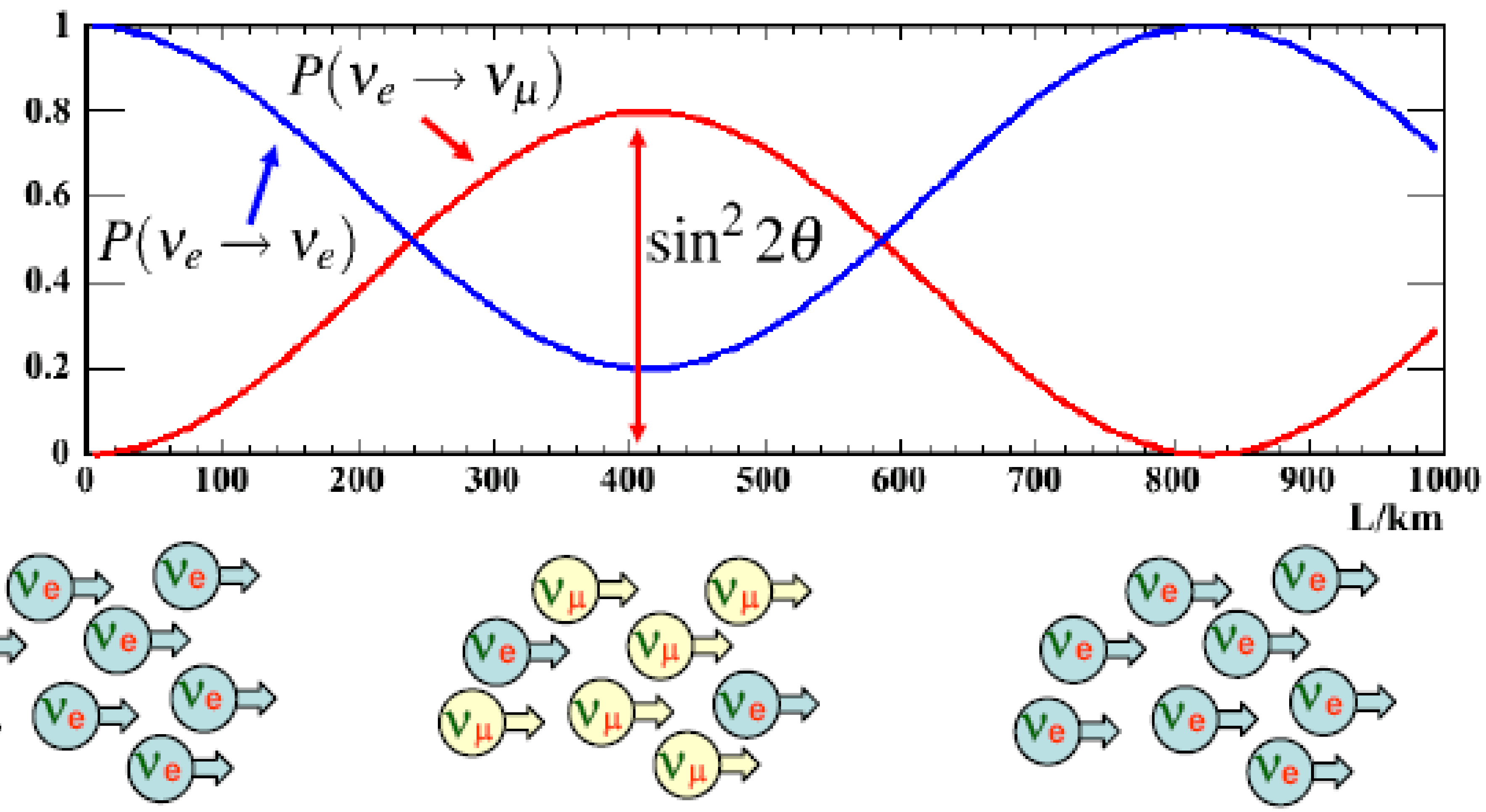
Neutrino Oscillation with massive neutrinos

Change of flavors with time. it can happen if the eigenstates between flavor and mass are different.

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

Pure e-neutrino



Neutrino Mass Difference

$\Delta m^2_{21}\ [10^{-5}\ \text{eV}^{\ 2}] = 7.54^{+0.26}_{-0.22}$ 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

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

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

Hamiltonian for oscillations in the vacuum

In the neutrino flavor space, the oscillation can be described by the Hamiltonian

$$H_{0,\nu} = \frac{1}{2E} U^* \mathrm{diag}(\Delta m^2) U^{\mathrm{t}}$$

with PMNS matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

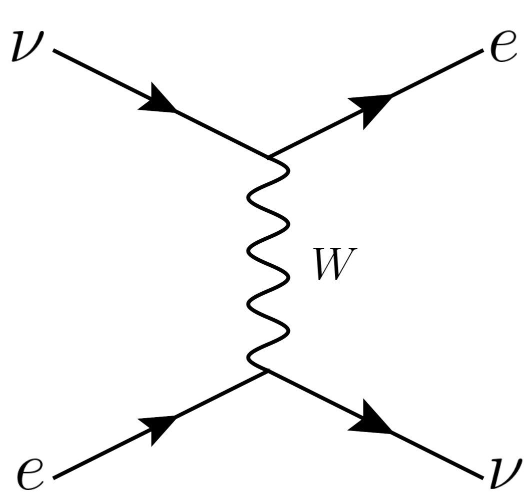
MSW Mechanism in the matter

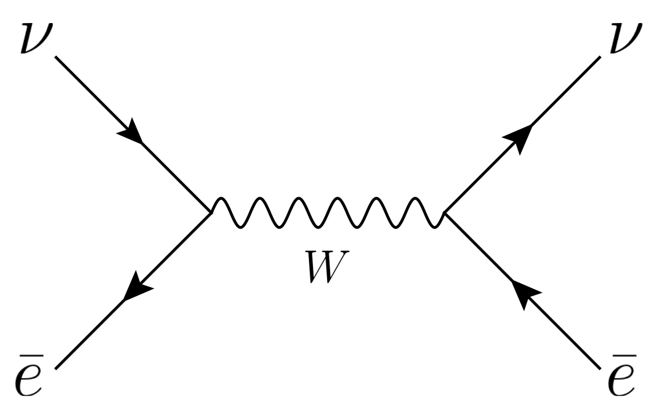
1986 Mikheev and Smirnov proposed a mechanism, which enhance neutrino adiabatic conversion in solar matter based on a theory developed by Wolfenstein. -MSW mechanism

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

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

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





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

electron density N_e,

Hamiltonian in the matter

In the neutrino flavor space,

$$H = H_{0,\nu} + H_{\mathrm{MSW}}$$

with $H_{0,\nu} = \frac{1}{2E} U^* \mathrm{diag}(\Delta m^2) U^{\mathrm{t}}$ **in vacuum**

$$H_{\mathrm{MSW}} = \pm\sqrt{2}\, G_{\mathrm{F}} n_{\mathrm{e}}(\vec{x}) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \text{where} \quad \begin{cases} + & \text{for } \nu \\ - & \text{for } \bar{\nu} \end{cases}$$

in the Sun

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Neutrino mass measurements

No direct mass measurement yet!

Neutrinoless double beta decay [KamLAND-Zen, 2016]

$$\langle m_{\beta\beta}\rangle < (61 - 165)\,\mathrm{meV}$$

KATRIN (Karlsruhe Tritium Neutrino experiment)

$$m_\nu < 1.1\,\mathrm{eV}$$ [1909.06048]

Cosmology

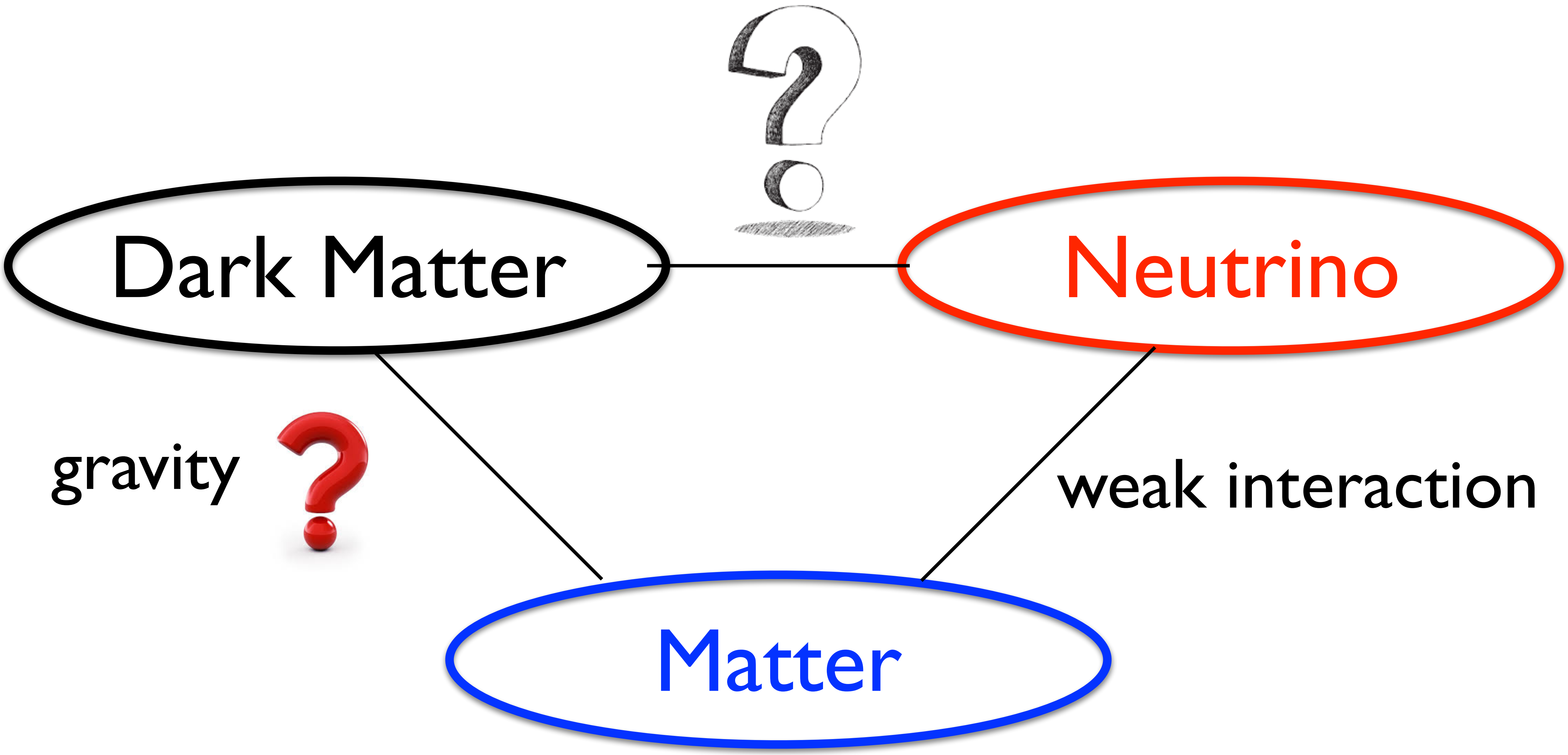
$$\sum_j m_j < (0.340 - 0.715)\ \mathrm{eV}$$

[Planck collaboration, 2016]

Neutrino oscillations are well described by the non-vanishing neutrino mass.

However there is no direct evidence for the neutrino mass.

Interaction between Matters



Hamiltonian in the dark matter

$\boxed{\text{SM + neutrino mass}}$

$$H = H_{\mathrm{MSW}} + H_0^\nu$$

with

$$H_{0,\nu} = \frac{1}{2E} U^* \mathrm{diag}(\Delta m^2) U^{\mathrm{t}}$$

$\boxed{\text{SM + DM}}$

massless neutrinos

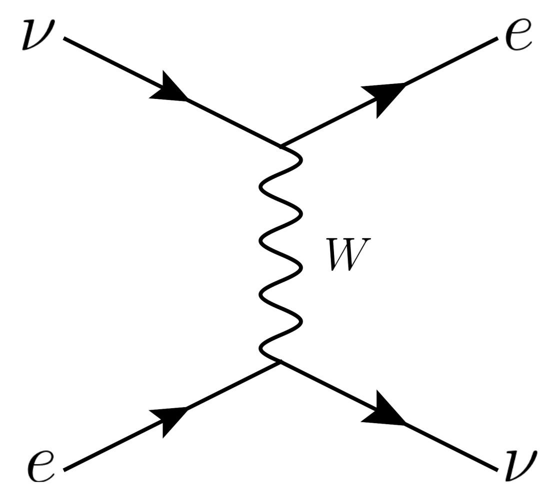
$$H = H_{\mathrm{MSW}} + V_\nu^{DM}$$

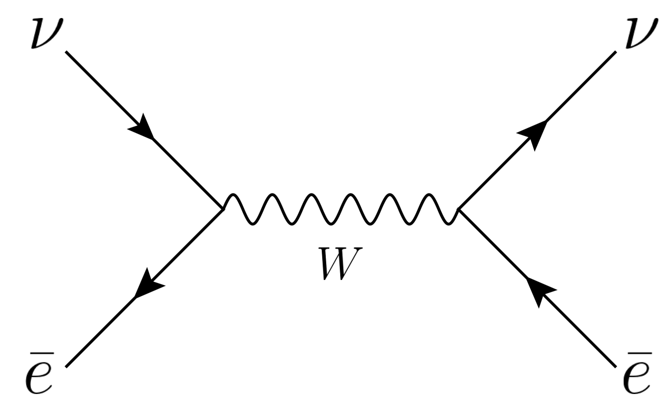
with $V_\nu^{DM} = H_{0,\nu}$

but V_ν^{DM} comes from
DM-neutrino interactions

$$H_{\mathrm{MSW}} = \pm\sqrt{2}\, G_{\mathrm{F}} n_{\mathrm{e}}(\vec{x}) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \text{where} \quad \begin{cases} + & \text{for } \nu \\ - & \text{for } \bar{\nu} \end{cases}$$

Back to the standard MSW effect





Neutrinos can interact with electrons and positrons in matter.

The matter potential within matter from the forward elastic scattering,

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

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

in the Sun

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

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

$+$ for neutrino

- for anti-neutrino

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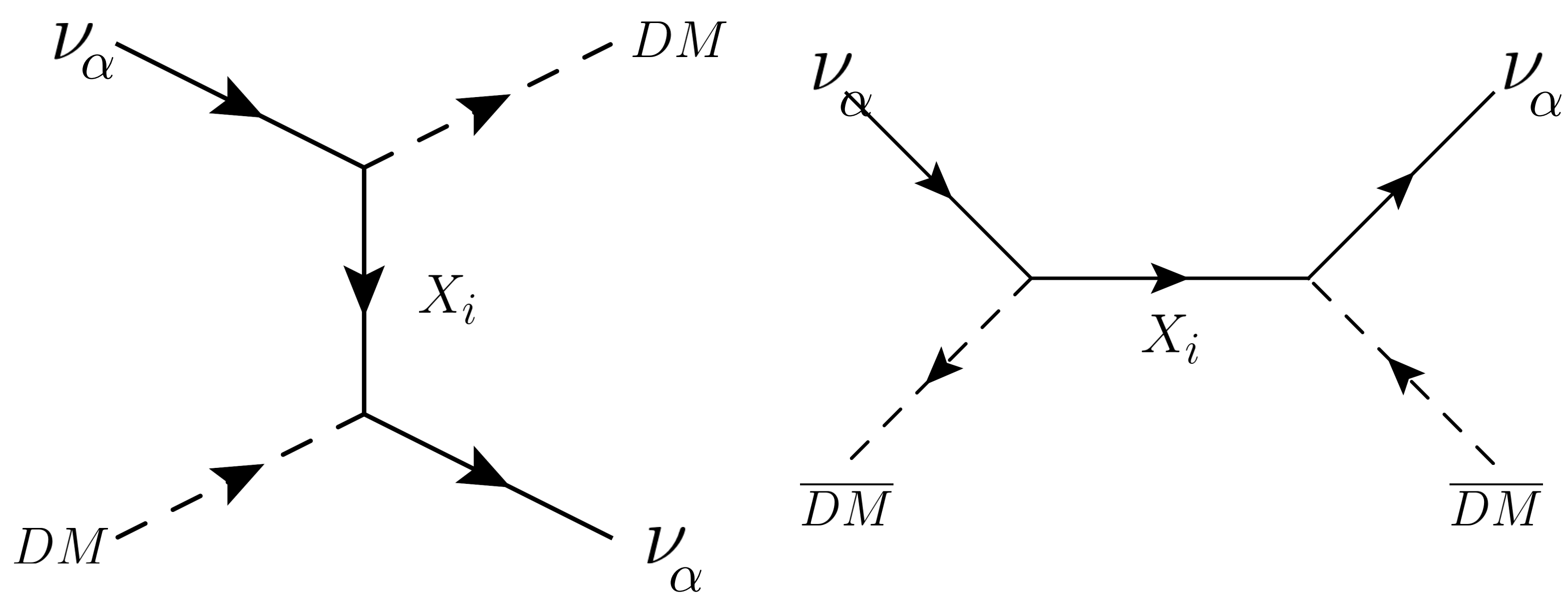
Neutrinos in Dark Matter halo

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



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

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

$\lambda_{\alpha\beta} \equiv g^*_{\alpha i}g_{\beta i}/2$ with DM asymmetry $\epsilon \equiv \dfrac{N_{DM} - N_{\overline{DM}}}{N_{DM} + N_{\overline{DM}}}$,

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

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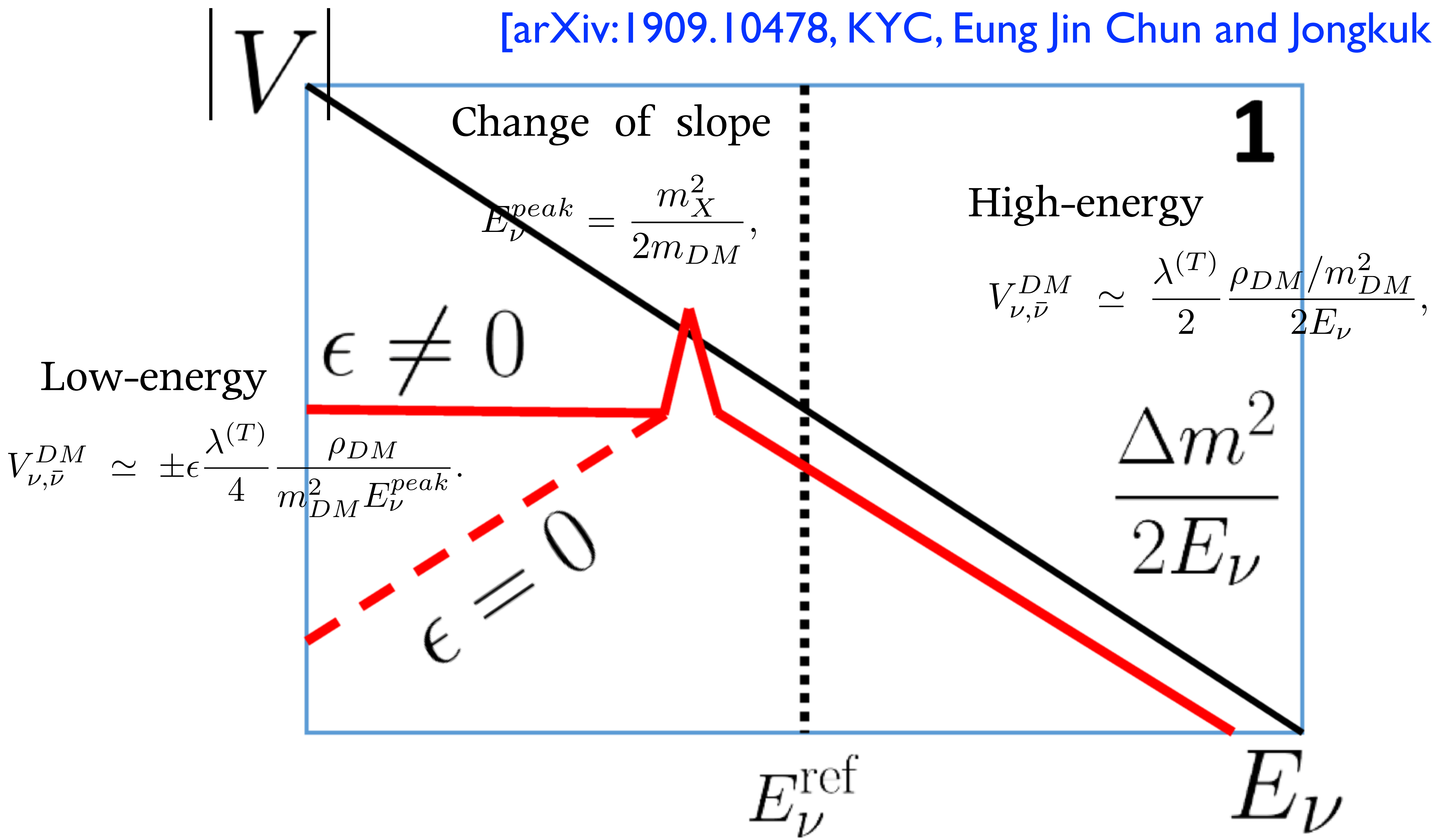
Neutrino matter potential in Dark Matter

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



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First, when $\epsilon = 0$

Neutrino Oscillations can be explained with massless neutrinos,

through

DM-neutrino interactions!

Dark Matter Assisted Neutrino Oscillation

$\epsilon = 0$

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

$$V^{DM}_{\nu,\bar{\nu}} \simeq \frac{\lambda^{(T)}}{2} \frac{\rho_{DM}/m^2_{DM}}{2E_\nu} \;\; = \;\; H_{0,\nu} = \frac{1}{2E} U^* \mathrm{diag}(\Delta m^2) U^t$$

for $E_\nu \gg 1\,\mathrm{MeV}$ (or for $E_\nu^{peak} = \dfrac{m_X^2}{2m_{DM}} \ll 1\,\mathrm{MeV}$)

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

$\lambda_{\alpha\beta} \equiv g^*_{\alpha i} g_{\beta i}/2$ [arXiv:1909.10478, KYC, Eung Jin Chun and Jongkuk Kim]

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

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.

Directional dependence of (anti-)neutrino oscillation

- Due to the anisotropic velocity of DM on Earth, the matter potential depends on the neutrino direction.

Modulated oscillation in the neutrino and anti-neutrino

- Annual modulation of (anti-)neutrino oscillation.

Dark Matter asymmetry in the neutrino oscillation

Second, when $\boxed{\epsilon \neq 0}$

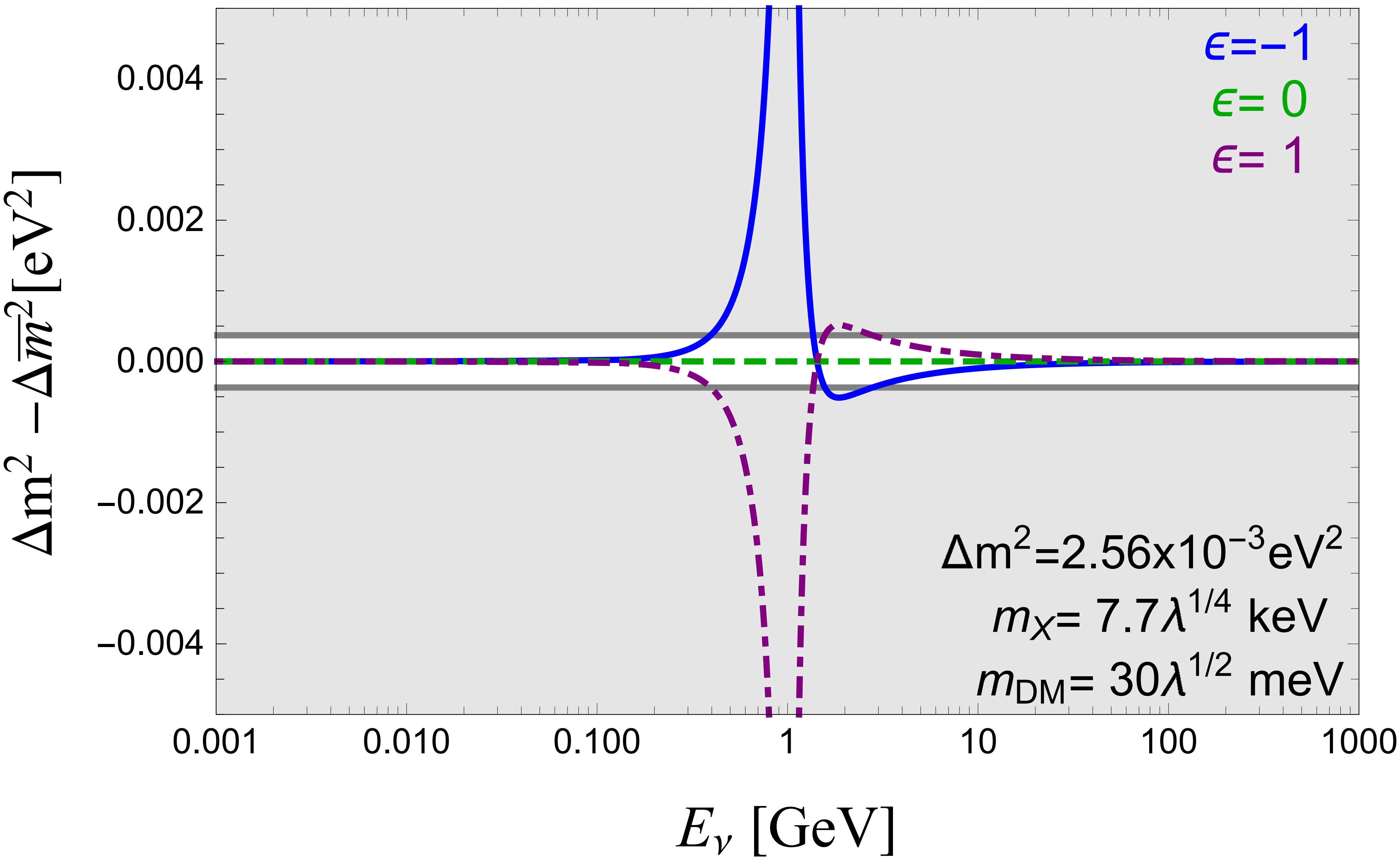
Asymmetric oscillations between neutrino and anti-neutrino

- Neutrino and antineutrino have different correction 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 in a different way.

- 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]

Constraints on DM-neutrino interaction

	Early Universe	Present Universe
$\langle \sigma_{\mathrm{DMDM} \to \nu\nu} v \rangle$	- DM relic density - Neutrino reheating : BBN, Neff	- neutrino flux enhancement
$\sigma_{\mathrm{DM}+\nu \to \mathrm{DM}+\nu}$	- 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

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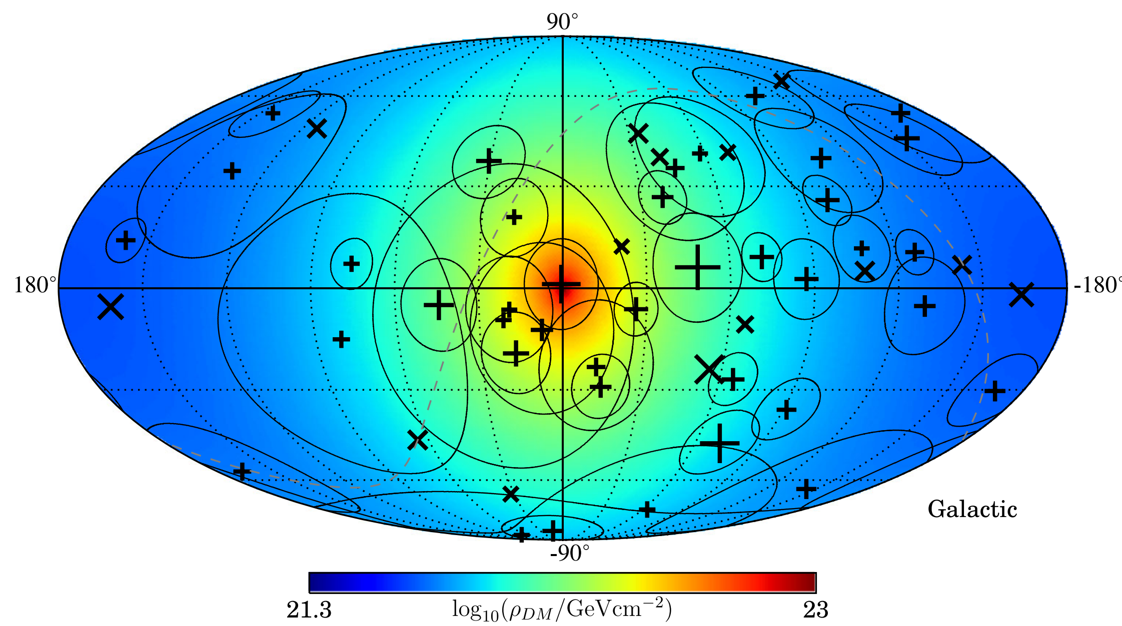
Astrophysical Neutrinos

- Suppression of the astrophysical neutrino flux

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

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

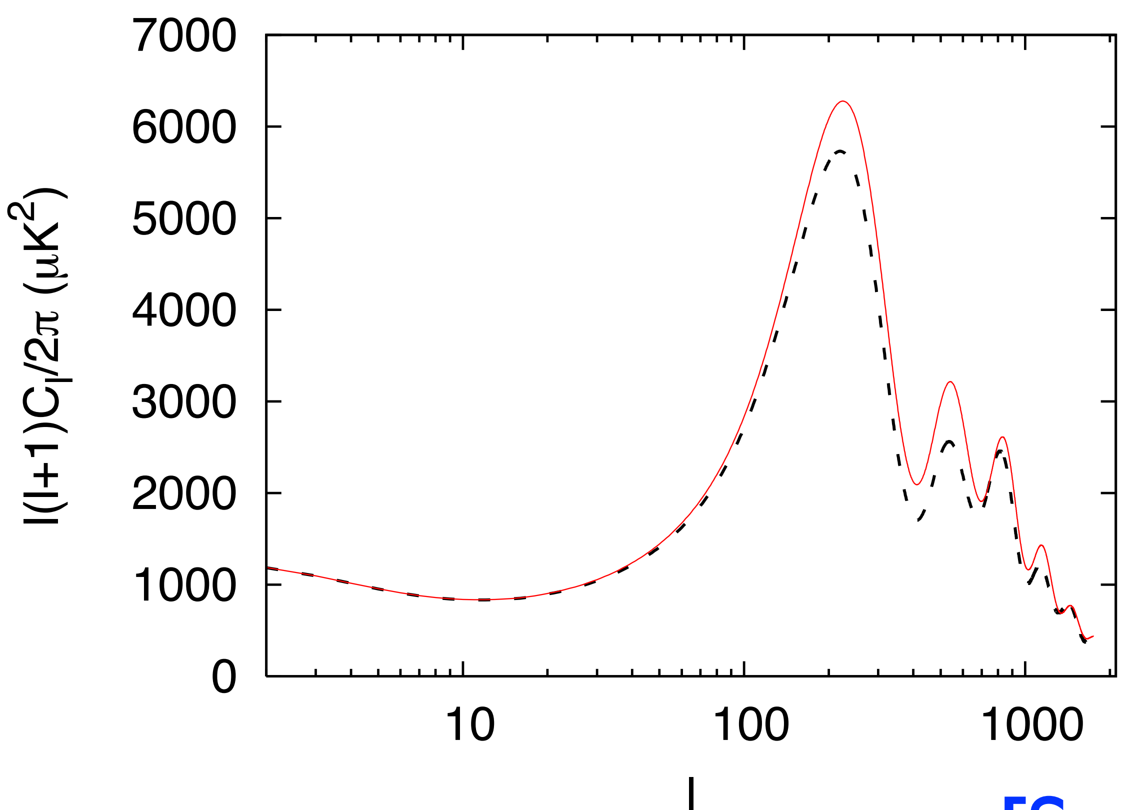
- Anisotropy of the neutrino flux through the Milky DM halo
  [Arguelles, Kheirandish, Vincent, 2017]

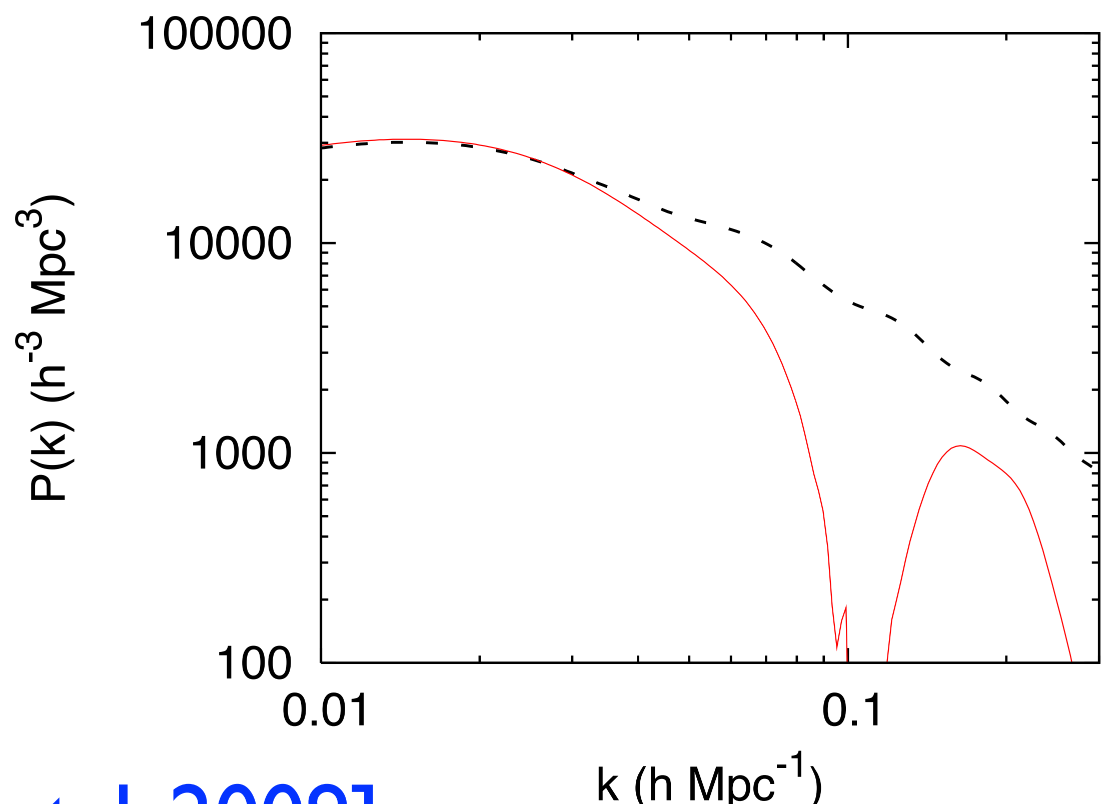


Constraints from Cosmology

- 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

Multi-messenger neutrino IC-170922A (Blazar TXS 0506+056)

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

$$\boxed{\sigma / M_{\rm dm} \lesssim 5.1 \times 10^{-23}\, {\rm cm}^2 / \,{\rm GeV} \quad {\rm at} \quad E_\nu = 290\,{\rm TeV}}$$

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

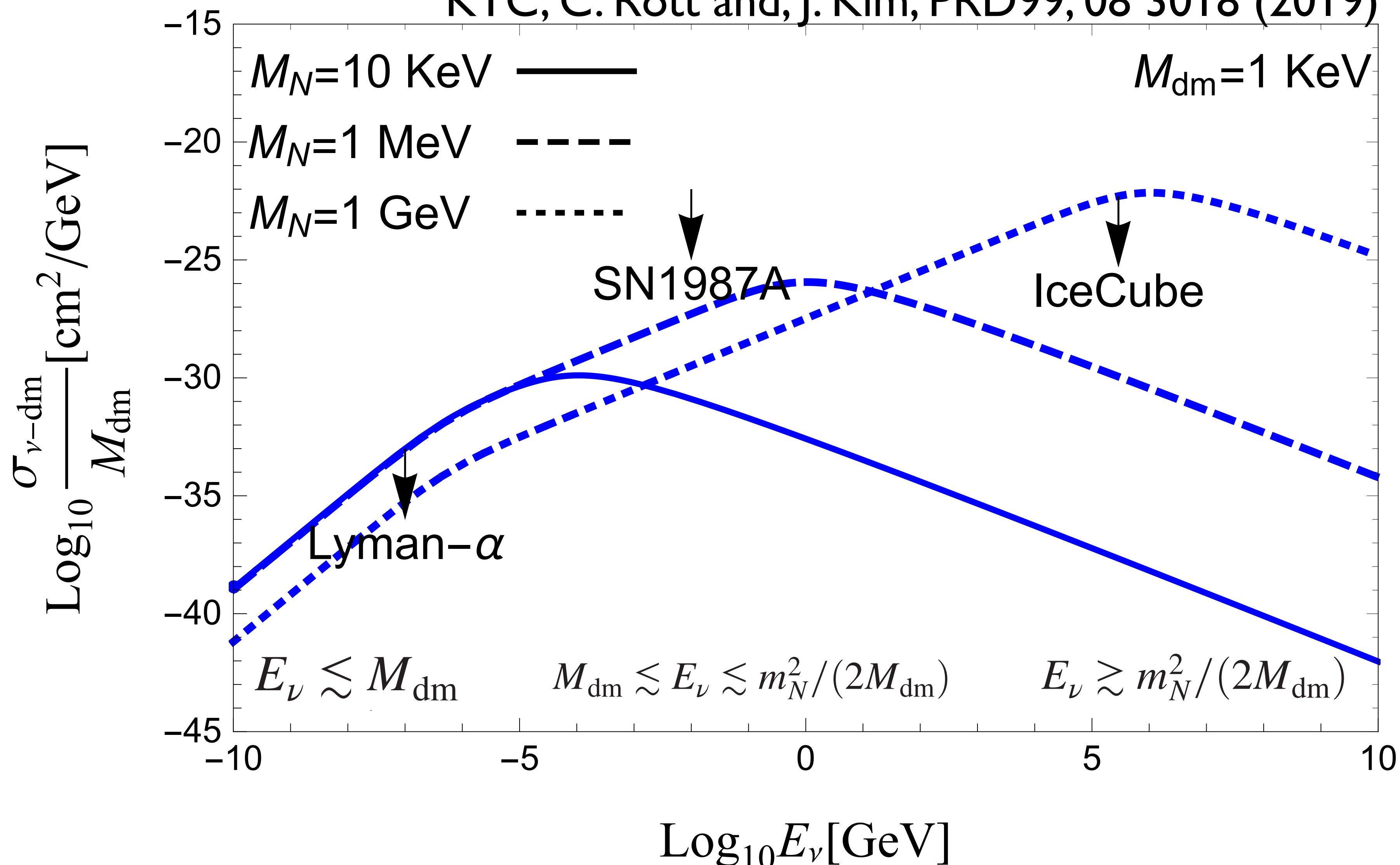
Complex Scalar DM with fermion mediator

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

χ dark matter

N massive fermion

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



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

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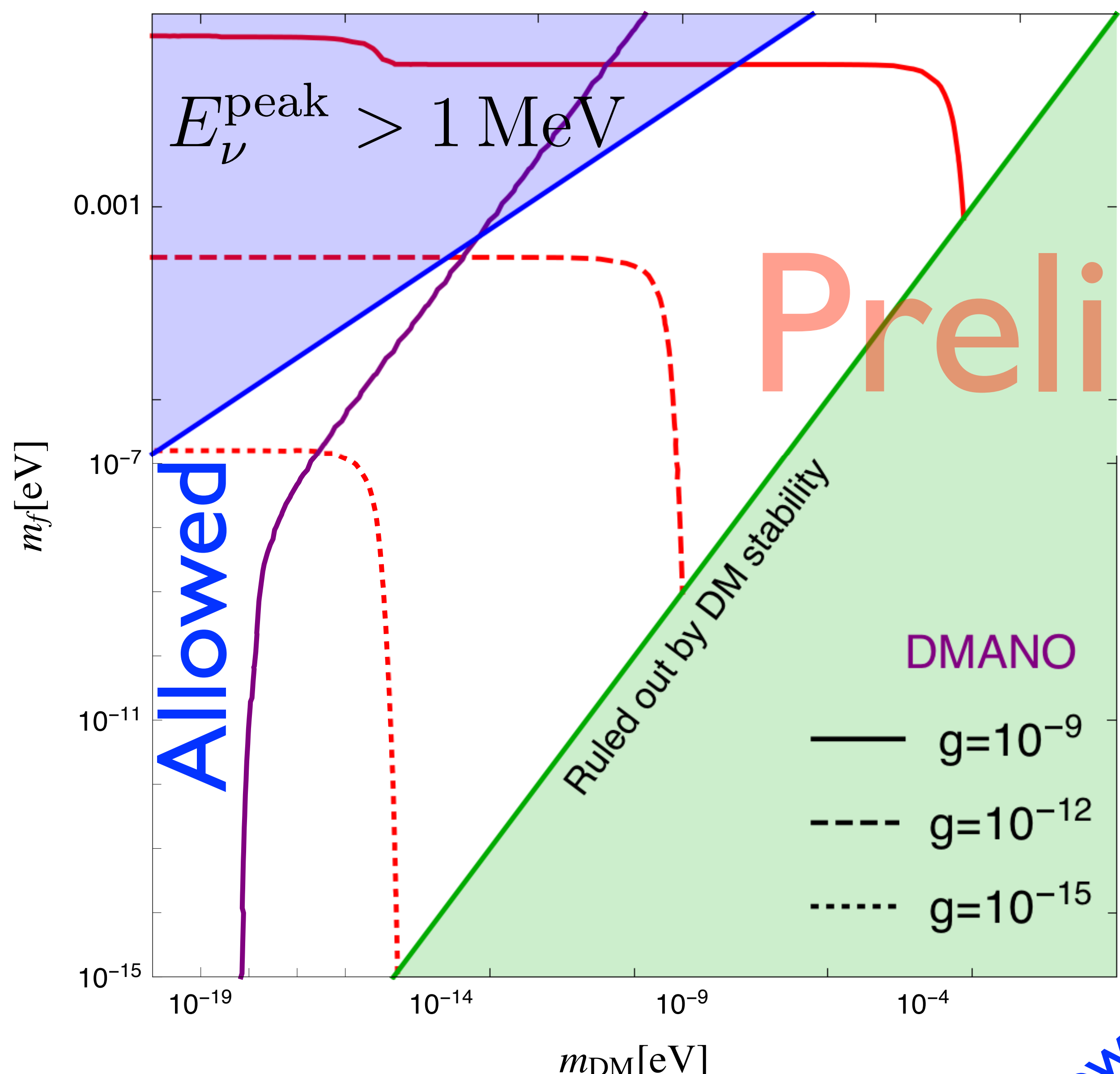
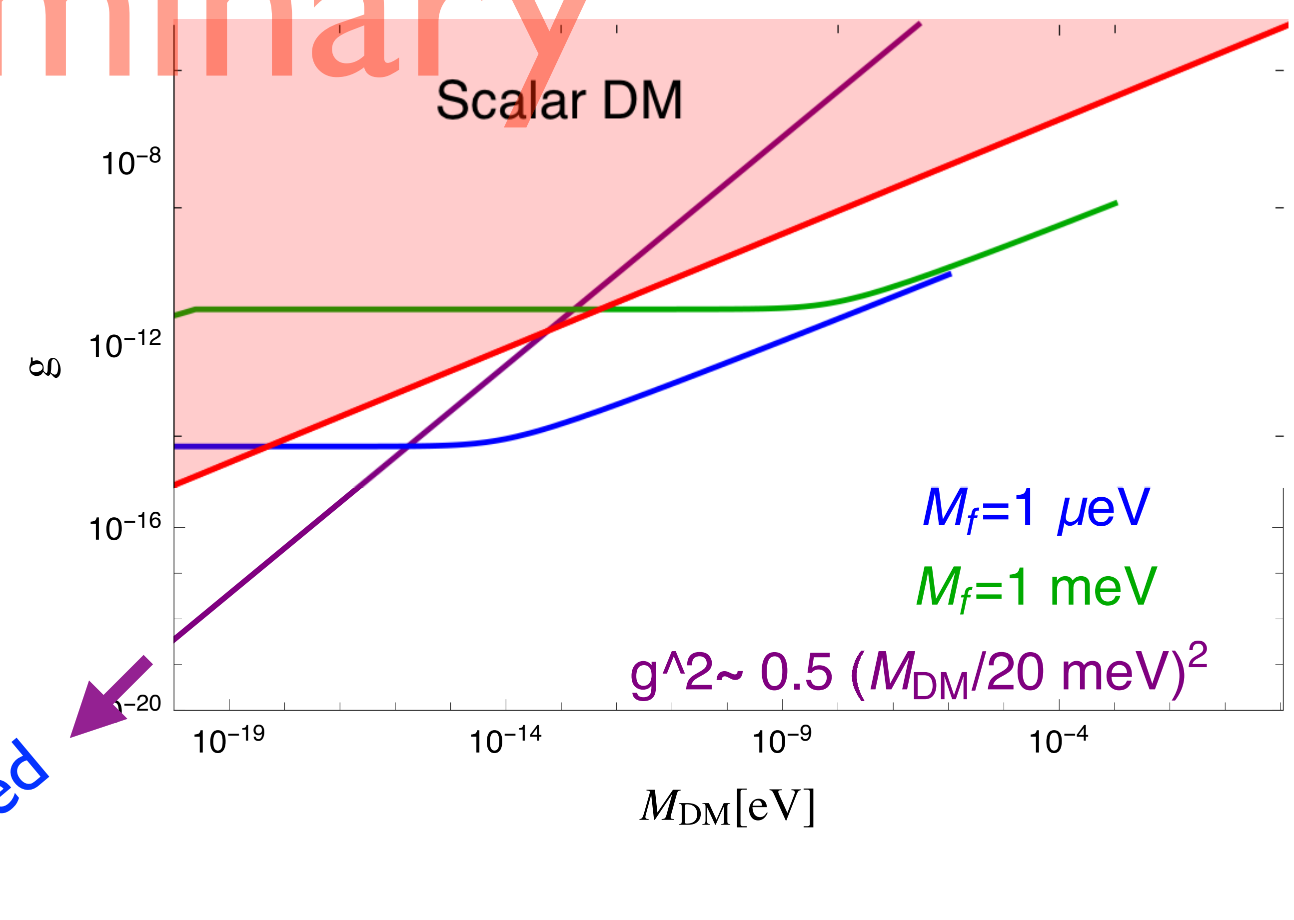
Cosmological/astrophysical constraints on DMANO model [Work in progress]

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

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





Preliminary

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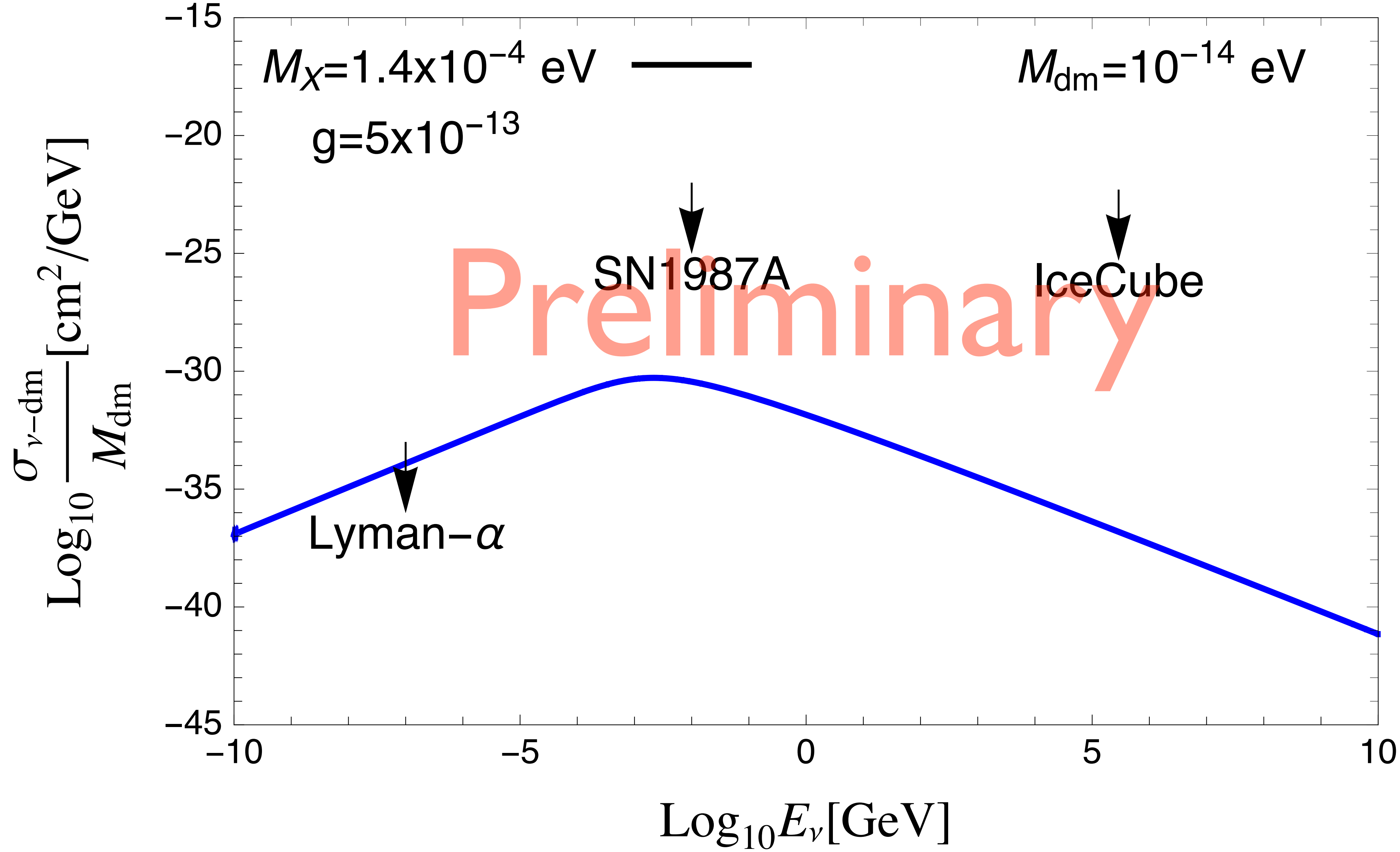
Cosmological/astrophysical constraints on DMANO model



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Discussion

1. Neutrinos in Dark Matter:

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

2. DM-neutrino interaction may explain the neutrino oscillations even with massless neutrinos. $\epsilon = 0$

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

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

   Anomalies in the (anti)neutrino oscillations.

Thank You!