Neutrino Oscillations in Dark Matter

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Based on PRD 99, 083018 (2019), Ki-Young Choi, **JKK**, Carsten Rott
Based on arXiv: 1909.10478, Ki-Young Choi, Eung Jin Chun, **JKK**

2019. 10. 10 @ CERN, Swiss

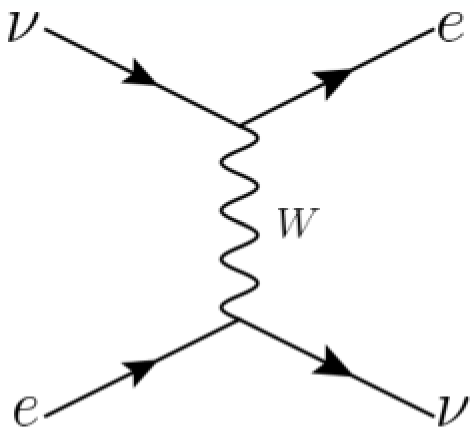
Contents

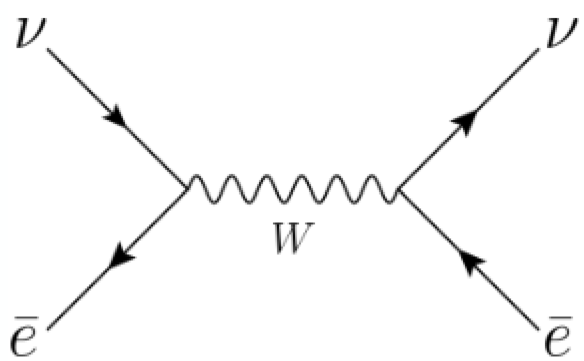
- Neutrino oscillation
  - MSW effect
- Neutrino-DM interaction
  - General formula
  - Dark NSI effect
- Dark Matter Assisted Neutrino Oscillation
- New constraint on neutrino-DM scattering
- Conclusions

Standard MSW effect

- Consider neutrino/anti-neutrino propagation in a general background
  - electron, positron

- **Coherent forward scattering**





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

Standard MSW effect

- Generalized matter potential

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

- Standard matter potential
  - $\epsilon = 1 \; (N_{\bar{e}} = 0)$
  - $m_W^2 \gg 2m_e E_\nu$

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

L. Wolfenstein, 1978
S. P. Mikheyev, A. Smirnov, 1985

- Matter potential @ high energy
  - $V_{\nu,\bar{\nu}}^{SM} \approx \frac{\sqrt{2}G_F m_W^2 (N_e + N_{\bar{e}})}{2m_e E_\nu}$

General formulation

- Equation of motion in the momentum space

$$(\not{p} - \not{\Sigma})u_L = (M^\dagger + \bar{\Sigma}_0)u_R,$$

$$(\not{p} - \bar{\not{\Sigma}})u_R = (M + \Sigma_0)u_L,$$

  - $\not{\Sigma} \equiv \Sigma_\mu \gamma^\mu,\ \bar{\not{\Sigma}} \equiv \bar{\Sigma}_\mu \gamma^\mu,\ \Sigma_0$: corrections

R. F. Sawyer, 1999
P. Q. Hung, 2000
A. Berlin, 2016
S. F. Ge, S. Parke, 2019
H. Davoudiasl, G. Mohlabeng, M. Sulliovan, 2019
G. D'Amico, T. Hamill, N. Kaloper, 2018
F. Capozzi, I. Shoemaker, L. Vecchi 2018

- In a Lorenz invariant medium:
  - $\not{\Sigma} = \not{p}\,\Sigma_1 + \not{k}\,\Sigma_2;\ \bar{\not{\Sigma}} = \not{p}\,\bar{\Sigma}_1 + \not{k}\,\bar{\Sigma}_2,$

- Canonical basis of the kinetic term:

$$u_L \simeq \left(1 + \frac{\Sigma_1}{2}\right)\tilde{u}_L,$$

$$u_R \simeq \left(1 + \frac{\bar{\Sigma}_1}{2}\right)\tilde{u}_R,$$

General formulation

- **The Equation of Motion**

$$(\not{p} - \not{k}\Sigma_2)\tilde{u}_L = \tilde{M}^\dagger \tilde{u}_R,$$
$$(\not{p} - \not{k}\bar{\Sigma}_2)\tilde{u}_R = \tilde{M}\tilde{u}_L.$$

- Correction to the neutrino mass matrix

$$\tilde{M} \simeq \left(1 + \frac{\bar{\Sigma}_1}{2}\right) M \left(1 + \frac{\Sigma_1}{2}\right)$$

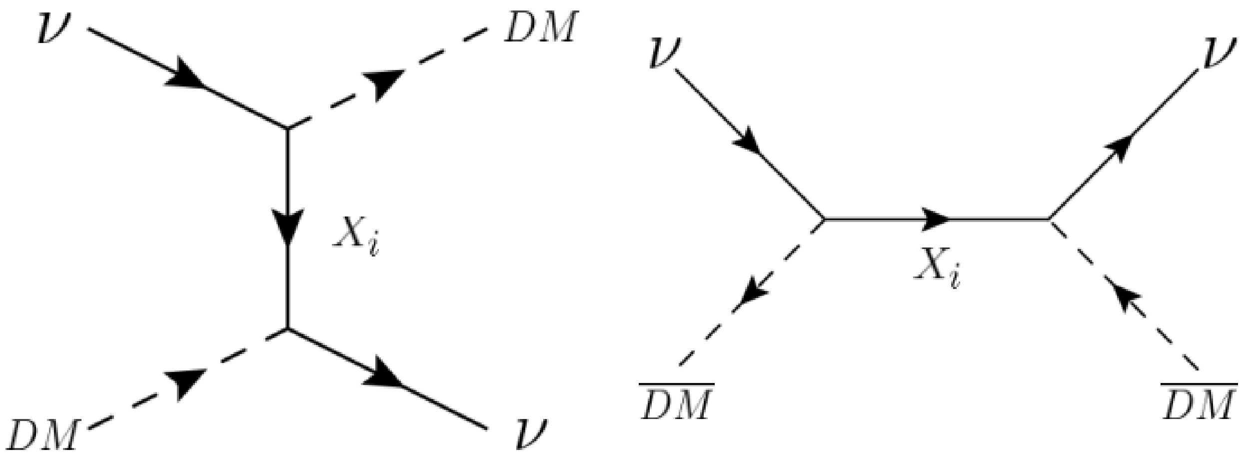
  - Original mass term is modified
  - For large parameter space, the mass correction is subdominant

DM model

- Bosonic DM (ϕ) and fermionic messenger (X_i)
- Lagrangian

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

- **Coherent forward scattering**



General formulation

Ki-Young Choi, Eung Jin Chun, JKK

- Neutrino/ anti-neutrino Hamiltonian

$$H_\nu = E_\nu + \frac{\tilde{M}^\dagger \tilde{M}}{2E_\nu} + k^0 \Sigma_2,$$

$$H_{\bar{\nu}} = E_\nu + \frac{\tilde{M} \tilde{M}^\dagger}{2E_\nu} + k^0 \bar{\Sigma}_2,$$

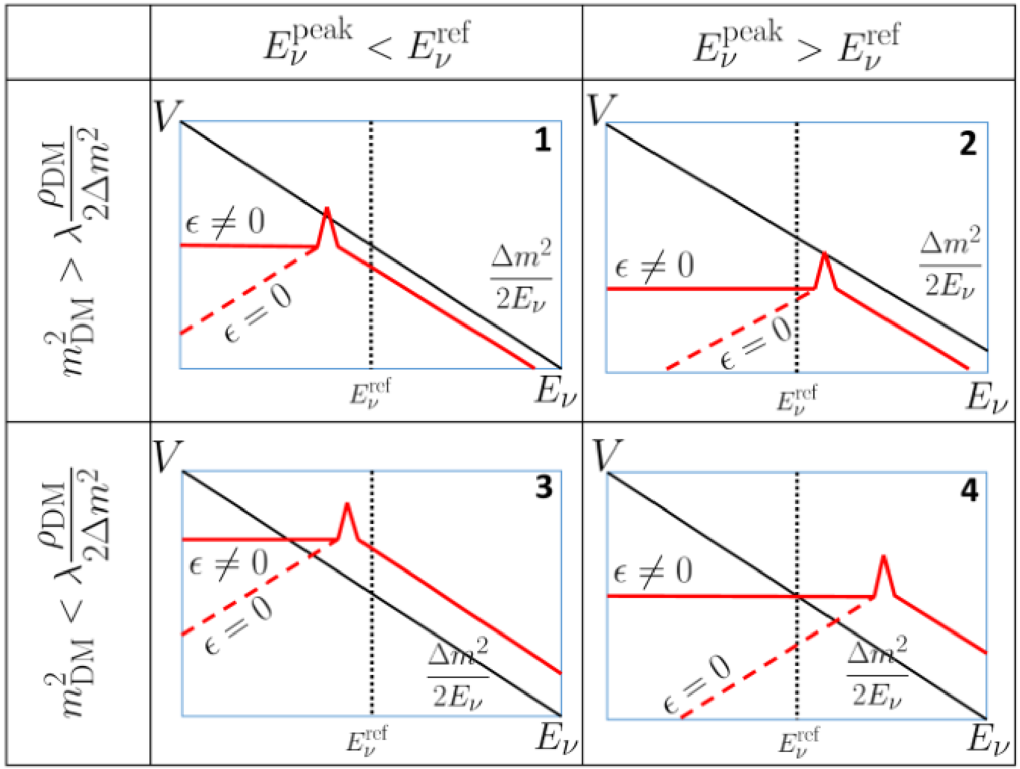
- Corrections

$$\Sigma_1 \,(\text{or } \bar{\Sigma}_1) \simeq \frac{\lambda^{(T)}}{2} \frac{\rho_{DM}}{m_{DM}^2} \frac{\pm\epsilon\, 2 m_{DM} E_\nu - m_X^2}{m_X^4 - 4 m_{DM}^2 E_\nu^2},$$

$$\Sigma_2 \,(\text{or } \bar{\Sigma}_2) \simeq \frac{\lambda^{(T)}}{2} \frac{\rho_{DM}}{m_{DM}^2} \frac{\pm\epsilon\, m_X^2 - 2 m_{DM} E_\nu}{m_X^4 - 4 m_{DM}^2 E_\nu^2},$$

Neutrino potential

Ki-Young Choi, Eung Jin Chun, JKK



- Change of shape:

$$E_\nu^{peak} = \frac{m_X^2}{2m_{DM}}$$

- **Low Energy Limit:**

$$V_{\nu,\bar{\nu}}^{DM} \simeq \pm\epsilon\frac{\lambda^{(T)}}{4}\frac{\rho_{DM}}{m_{DM}^2 E_\nu^{peak}}$$

- **High Energy limit:**

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

Two-flavor oscillation

- The effective Hamiltonian

$$\mathcal{H}_M = \frac{\Delta m^2}{4E}\begin{pmatrix} -(\cos 2\theta - x) & \sin 2\theta + y \\ \sin 2\theta + y & \cos 2\theta - x \end{pmatrix}$$

  - $x \equiv \frac{(V_{\mu\mu} - V_{\tau\tau})/2}{\Delta m^2/4E}, \quad \text{and} \quad y \equiv \frac{V_{\mu\tau}}{\Delta m^2/4E}$

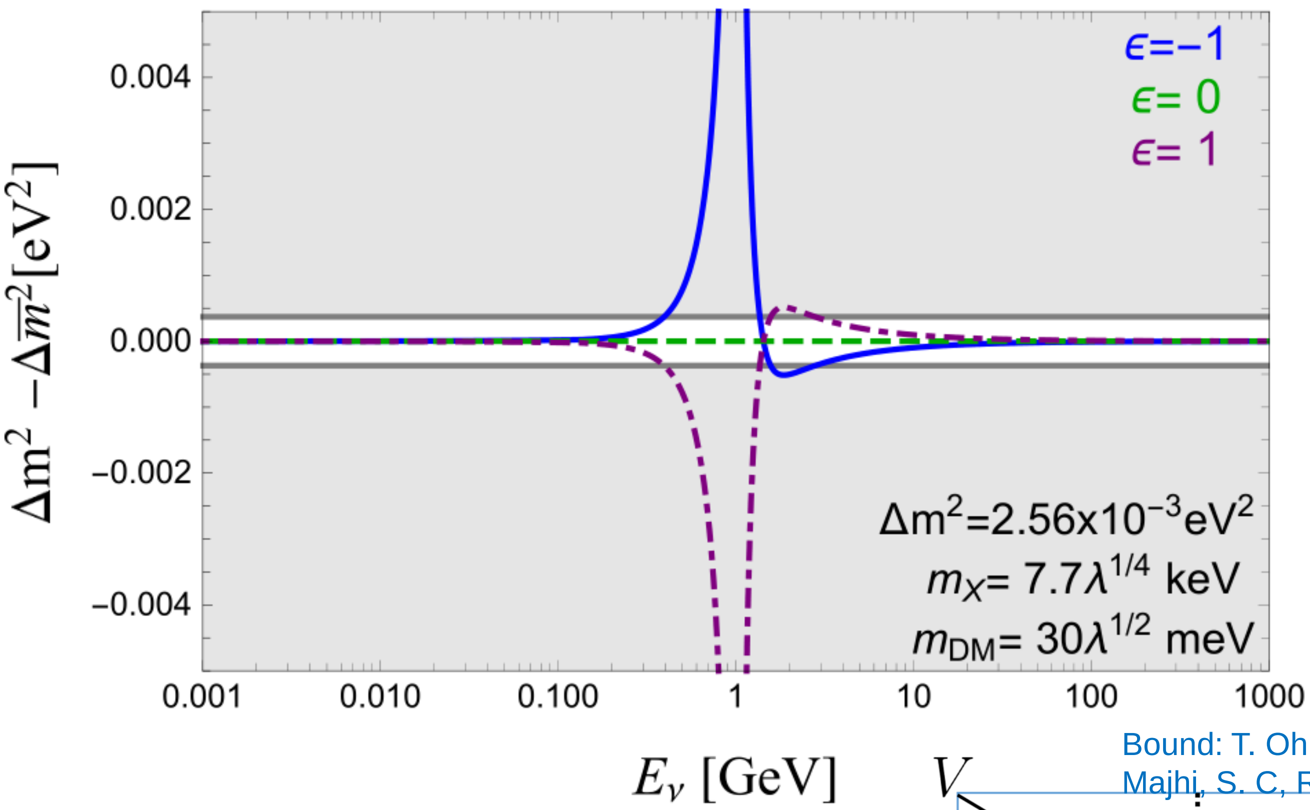
- The mixing angle & mass squared difference in the medium

$$\sin^2 2\theta_M = \frac{(\sin 2\theta + y)^2}{(\cos 2\theta - x)^2 + (\sin 2\theta + y)^2},$$

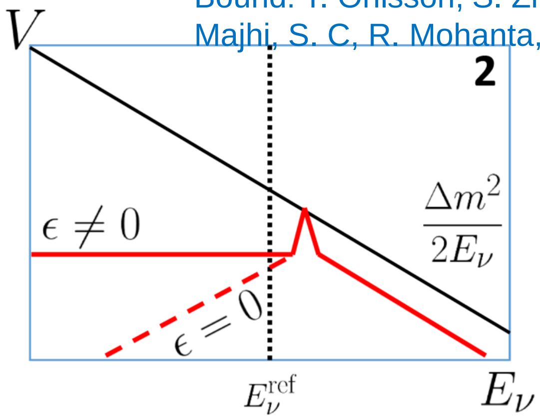
$$\Delta m_M^2 = \Delta m^2 \sqrt{(\cos 2\theta - x)^2 + (\sin 2\theta + y)^2}.$$

Mass difference between ν&ν̄

Ki-Young Choi, Eung Jin Chun, JKK



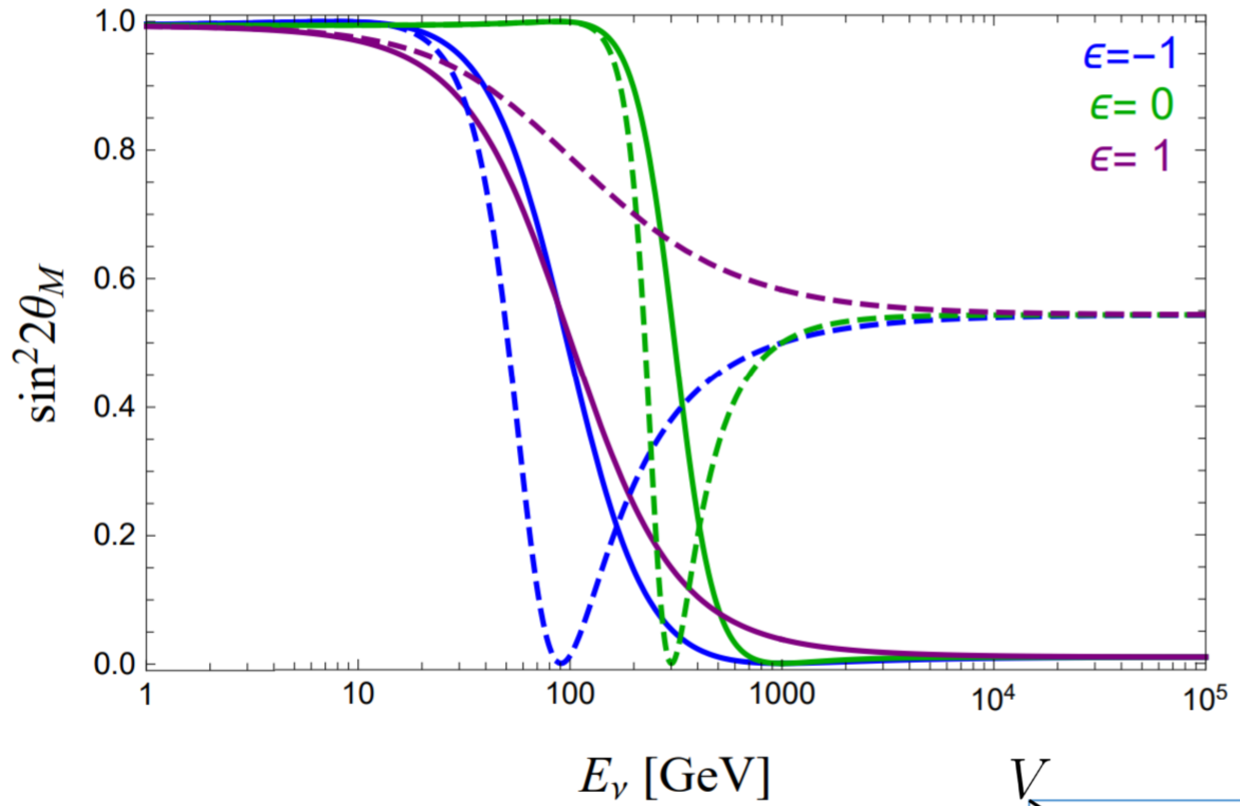
Bound: T. Ohlsson, S. Zhou, 2015, R. Majhi, S. C, R. Mohanta, 2019



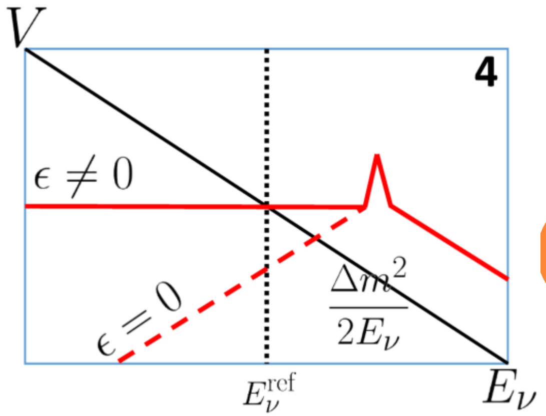
- $E_\nu^{Peak} = 1$GeV
- $x \to 0.75$ @ High Energy limit

Modified mixing angle

Ki-Young Choi, Eung Jin Chun, JKK



- $E_\nu^{Peak} = 1\text{TeV}$
- Solid line: $x \to 10, y \to\ 0$
- Dashed line: $x \to 10, y \to 10$

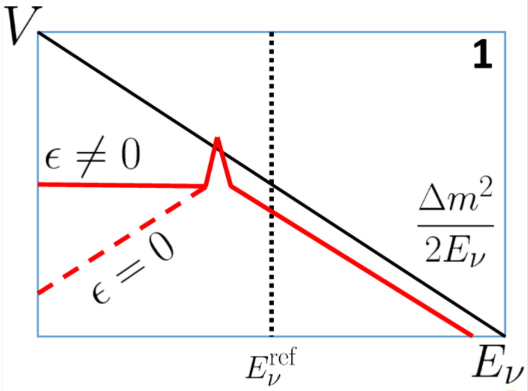


DM assisted neutrino oscillation

Ki-Young Choi, Eung Jin Chun, JKK

- In the case of $m_X^2 \ll 2m_{DM}E_\nu$ **(Peak energy << 1MeV)**

$$V_{\nu,\bar{\nu}}^{DM} \simeq \frac{\lambda^{(T)}}{2}\frac{\rho_{DM}/m_{DM}^2}{2E_\nu} \approx \frac{3\times10^{-3}\mathrm{eV}^2}{2E_\nu}\lambda^{(T)}\left(\frac{20\mathrm{meV}}{m_{DM}}\right)^2$$



- $$\lambda = \frac{2m_{DM}^2}{\rho_{DM}}U^*\mathrm{diag}(\Delta m^2)U^T, \simeq \begin{pmatrix} 0.026 & 0.091 & 0.085 \\ 0.091 & 0.381 & 0.408 \\ 0.085 & 0.408 & 0.477 \end{pmatrix}\left(\frac{20\mathrm{meV}}{m_{DM}}\right)^2\left(\frac{0.3\,\mathrm{GeV\,cm}^{-3}}{\rho_{DM}}\right)$$

- Standard neutrino oscillation can occur from the symmetric DM effect even for **massless neutrino**.

DM assisted neutrino oscillation

Work in progress

- **Predictions**
- No observation in the absolute neutrino mass
  - - neutrinoless double beta decay
  - - cosmological observation of the sum over neutrino mass
- Asymmetric oscillation in the neutrino and anti-neutrino
  - - Thanks to anisotropic velocity of DM on the Earth, the matter potential has asymmetry
  - - Annual modulation of neutrino oscillation
- Directional dependence of neutrino oscillation
  - - Matter potential oscillates depending on time

DM-neutrino interactions

- **Constraints**

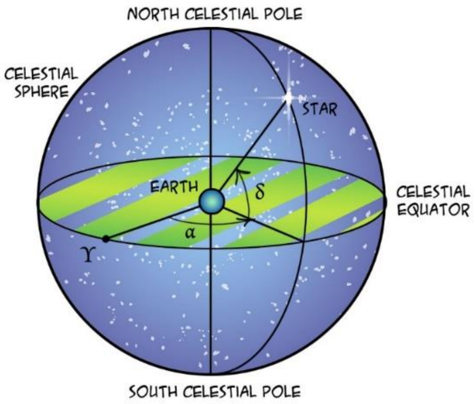
	Early Universe	**Present Universe**
$\langle \sigma_{\mathrm{DMDM} \to \nu\nu} v \rangle$	-DM relic density -Neutrino reheating : Neff, BBN	Neutrino flux
$\sigma_{\mathrm{DM}\nu \to \mathrm{DM}\nu} v$	-CMB anisotropy -Large Scale Structure	Supernovae-1987A **IceCube-170922A** **Ki-Young Choi, JKK, Carsten Rott** - Neutrino flux suppression - Neutrino flux anisotropy

IceCube-170922A

- **Icecube-170922A**
  - Right ascension: 77.42, Declination: 5.72
  - Neutrino Energy: 290 TeV
  - TXS 0506+056 determined to be z = 0.3365
  - 1421 Mpc

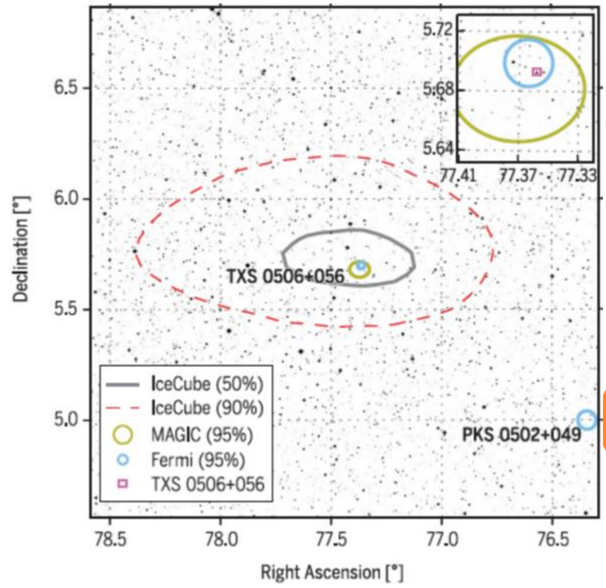
IceCube 2018 Science

S. Paiano et al, ApJL 2018



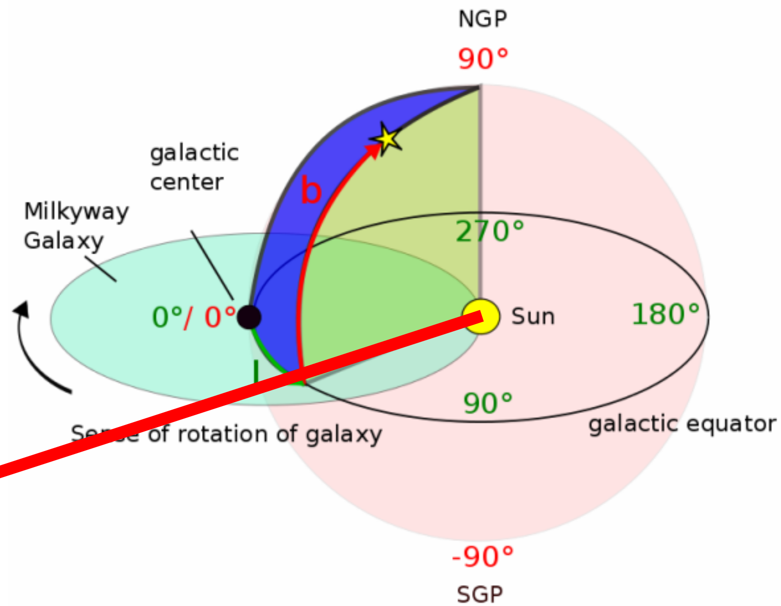
- Equatorial coordinate system

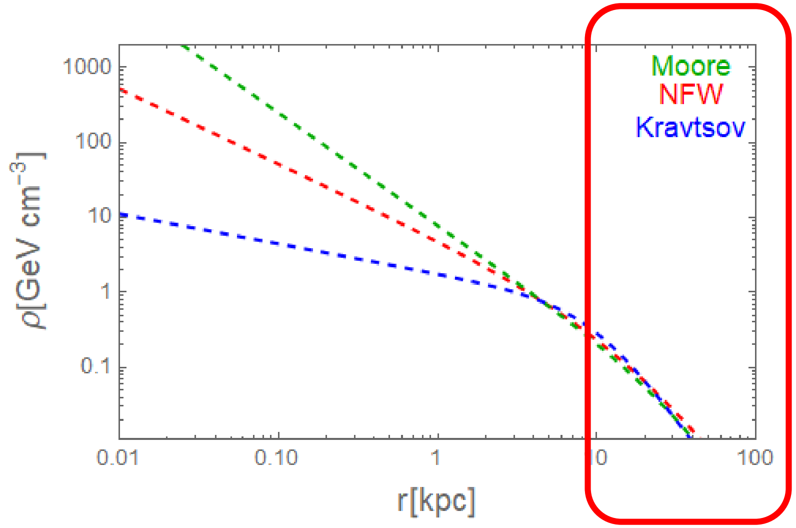
- Mean-free path
  - $$\lambda_{\mathrm{MFP}} = \frac{1}{n_X \sigma(\nu X \to Y)}$$
  - X can be **DM**

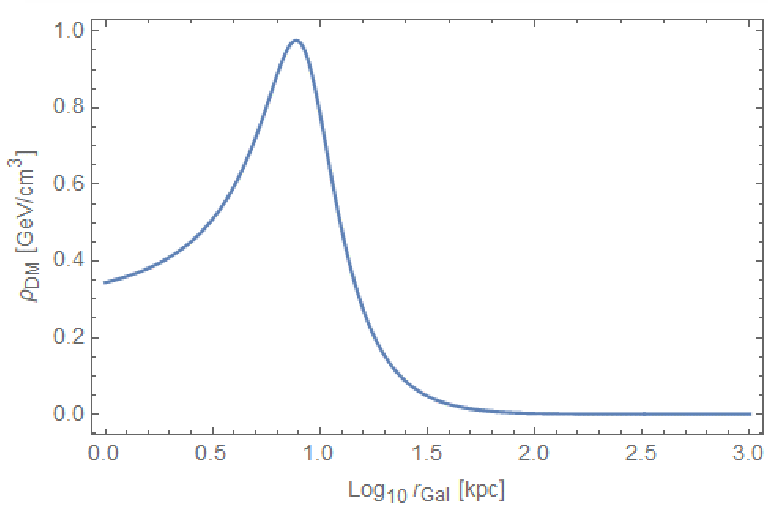


Galactic coordinate

- Icecube-170922A
  - b = -19.6 degree
  - l = 15.4 degree
- **Not** travel through GC
  - **Not depends on DM profile**







Dissipation of neutrino flux

- The interaction of neutrinos with DM can suppress the flux of neutrinos along the path from the Blazar to Earth
  - Scattering cross section → **constant**

$$\Phi = \Phi_0 e^{-\int_{\text{path}} \sigma n(\mathbf{x}) dl}$$

- The suppression depends on the DM-v scattering cross section as well as the DM number density along the path

- $$\int_{\text{path}} \sigma n(\mathbf{x}) dl \lesssim 1$$

Dissipation of neutrino flux

- The suppression can be divided into two contributions

$$\int_{\text{path}} \sigma n(\mathbf{x})dl = \int_{\text{los}} n(z)\sigma dl + \int_{\text{los}} \sigma n_{\text{gal}}(\mathbf{x})dl,$$
$$= \boxed{\frac{\sigma}{M_{\text{dm}}}\left(\int_{\text{los}} \rho(z)dl\right.} + \left.\int_{\text{los}} \rho_{\text{gal}}(\mathbf{x})dl\right)$$

- Suppression from the cosmological DM
  - Cosmological DM energy density is determined by Planck 2018 data
    - $\rho_{\text{dm}}(z) = 1.3\times 10^{-6}(1+z)^3\,\text{GeV}/\text{cm}^3$ **Planck 2018**
  - $$\int_{los} \rho(z)\,dl = \int \rho(z)\frac{cdt}{dz}dz,$$
    $$\simeq 7.2\times 10^{21}\,\text{GeV}/\,\text{cm}^2.$$

Dissipation of neutrino flux

- The suppression can be divide into two contributions

$$\int_{\text{path}} \sigma n(\mathbf{x}) dl = \int_{\text{los}} n(z)\sigma dl + \int_{\text{los}} \sigma n_{\text{gal}}(\mathbf{x}) dl,$$

$$= \frac{\sigma}{M_{\text{dm}}} \left(\int_{\text{los}} \rho(z) dl + \int_{\text{los}} \rho_{\text{gal}}(\mathbf{x}) dl \right)$$

- Galactic DM
  - NFW DM profile ← $\rho_{\text{gal}}(\mathbf{x}) = \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$
  - $\int_{los} \rho_{\text{gal}}(\mathbf{x}) dl \simeq 3.8 \times 10^{22}\,\text{GeV}/\,\text{cm}^2$

- **Incidentally** both contributions from cosmological DM and Milky Way DM are very comparable
  - Very tiny cosmological DM density is compensated by the long distance

New constraint

Ki-Young Choi, JKK, Carsten Rott

- Demand less than **90% suppression** of the flux
  - $\int \sigma n dl \lesssim 2.3$
- DM-v scattering cross section
  - The identification of the source can allow the precise evaluation of the neutrino flux change due to DM- v scattering cross section
- $\sigma / M_{\rm dm} \le 5.1 \times 10^{-23} {\rm cm}^2/{\rm GeV}$
  - @ $E_\nu = 290 \ {\rm TeV}$

Known constraints

- **Lyman-alpha**

C. Boehm, R. Wilkinson arXiv: 1401.7597

  - DM stays in equilibrium with primordial plasma for longer time due to elastic scattering and undergoes acoustic oscillations
  - Suppresses matter perturbations and reduces the amount of small scale structures today
  - constant cross section: $\sigma_{\mathrm{el}} < 10^{-36} \left(\frac{m_{\mathrm{DM}}}{\mathrm{MeV}}\right) \mathrm{cm}^2$
  - T-dependent cross section: $\sigma_{\mathrm{el}} < 10^{-48} \left(\frac{m_{\mathrm{DM}}}{\mathrm{MeV}}\right) \left(\frac{T_\nu}{T_0}\right)^2 \mathrm{cm}^2$

$$T_0 = 2.35 \times 10^{-4}\ \mathrm{eV}$$

- This constraint can be applied for neutrino energy at around 100 eV.

Known constraints

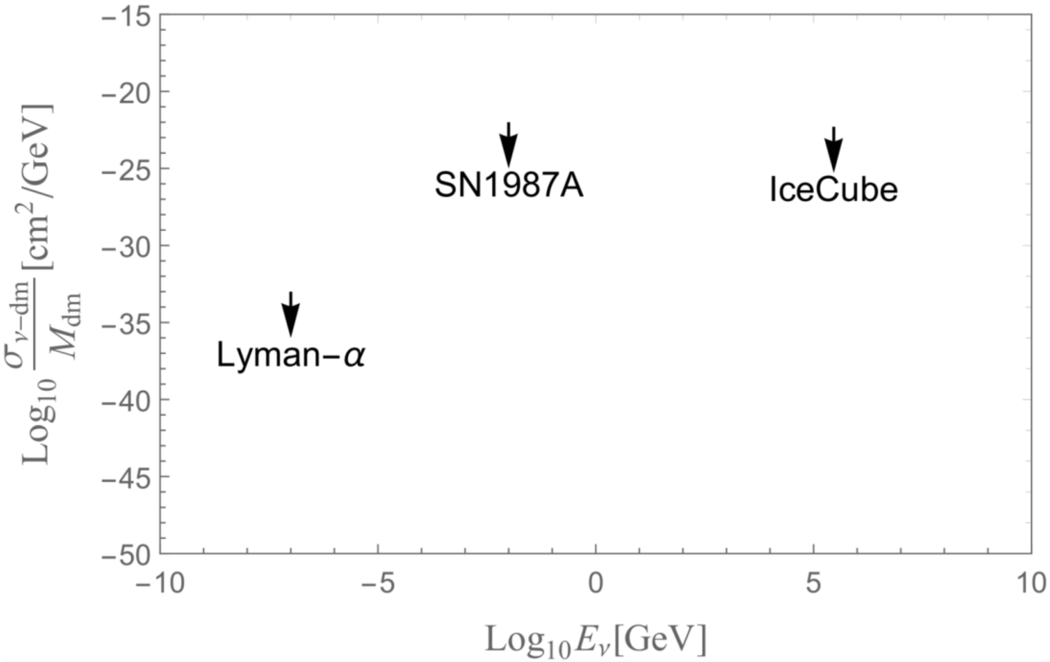
G. Barbiellini, G. Cocconi, 1987

- **SN1987A**
  - Neutrino energies ~ 10 MeV
  - Distance ~ 50 kpc

- ν-DM interaction can be constrained
- This constraint can be applied for neutrino energy at around 10 MeV.

Neutrino energy	$\sigma / M_{\rm dm}[\rm cm^2/GeV]$
~ 100 eV	6×10^{-31}
~ 100 eV	10^{-33}
10 MeV	10^{-22}

Scattering cross section

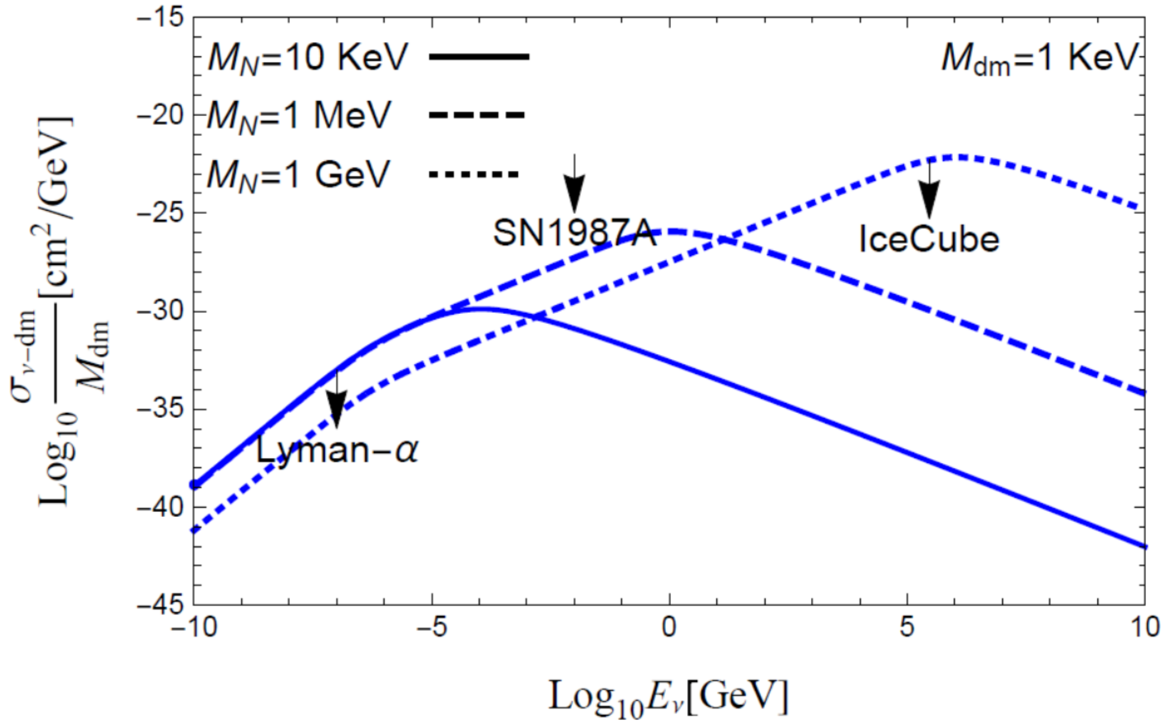


Complex scalar DM model

Ki-Young Choi, JKK, Carsten Rott

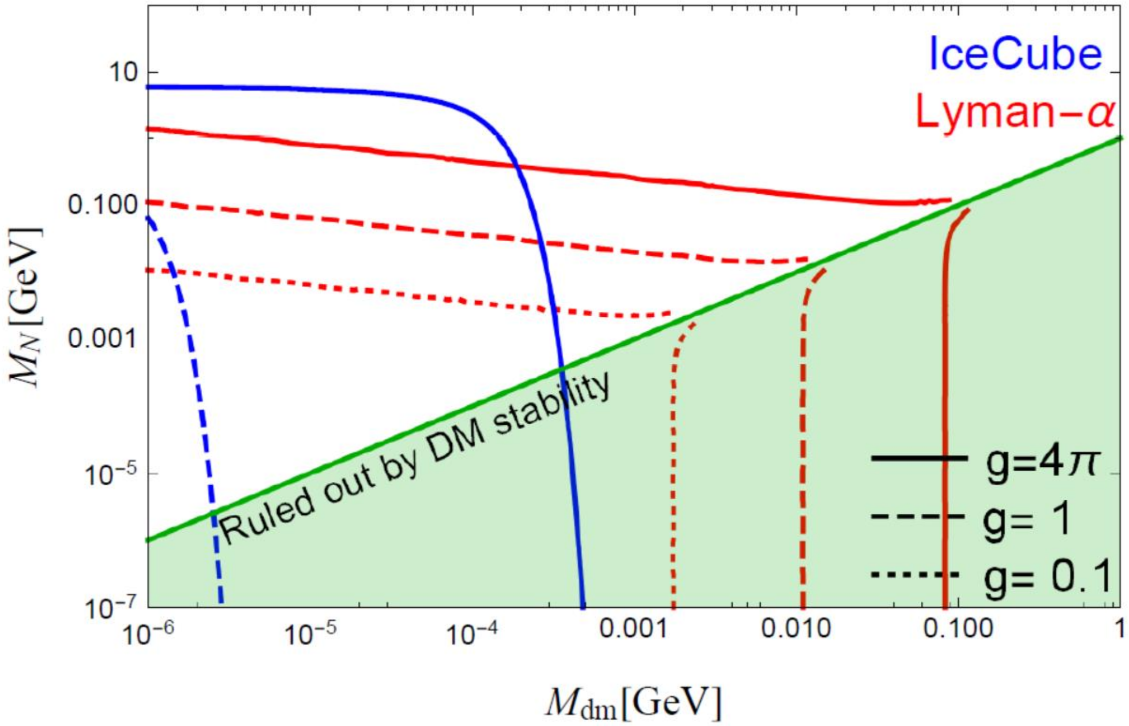
- A fermion mediator
  - $\mathcal{L}_{\rm int} = -g\chi\overline{N}\nu_L + {\rm h.c.},$

- Scattering cross section vs neutrino energy



Complex scalar DM model

Ki-Young Choi, JKK, Carsten Rott



- Upper & right region are allowed
  - Blue: IceCube-170922A
  - Red: Lyman alpha
- Green region: ruled out by DM stability

Conclusions

- A systematic study of neutrino oscillations in a medium of DM

- **DM assisted neutrino oscillation**
  - DM interaction with neutrino can explain neutrino oscillation

- **New constraint** on DM-ν scattering
  - Obtained from Icecube-170922A

- $\sigma/M_{\rm dm} \leq 5.1 \times 10^{-23} {\rm cm}^2/{\rm GeV}$
  - @ $E_\nu = 290$ TeV

Conclusions

- A systematic study of neutrino oscillations in a medium of DM

Thank you.

  - Obtained from IceCube-170922A

- $\sigma/M_{\rm dm} \leq 5.1 \times 10^{-23} {\rm cm}^2/{\rm GeV}$
  - @ $E_\nu = 290$ TeV