On the Tau flavor of the cosmic neutrino flux

Yasaman Farzan

School of physics

IPM, Tehran



ν_e	Direct discovery announcement: 1956	Cowan and Reines
ν_μ	Direct discovery announcement: 1962	Lederman, Schwartz, Steinberger
ν_τ	Direct discovery announcement: 2000	DONUT

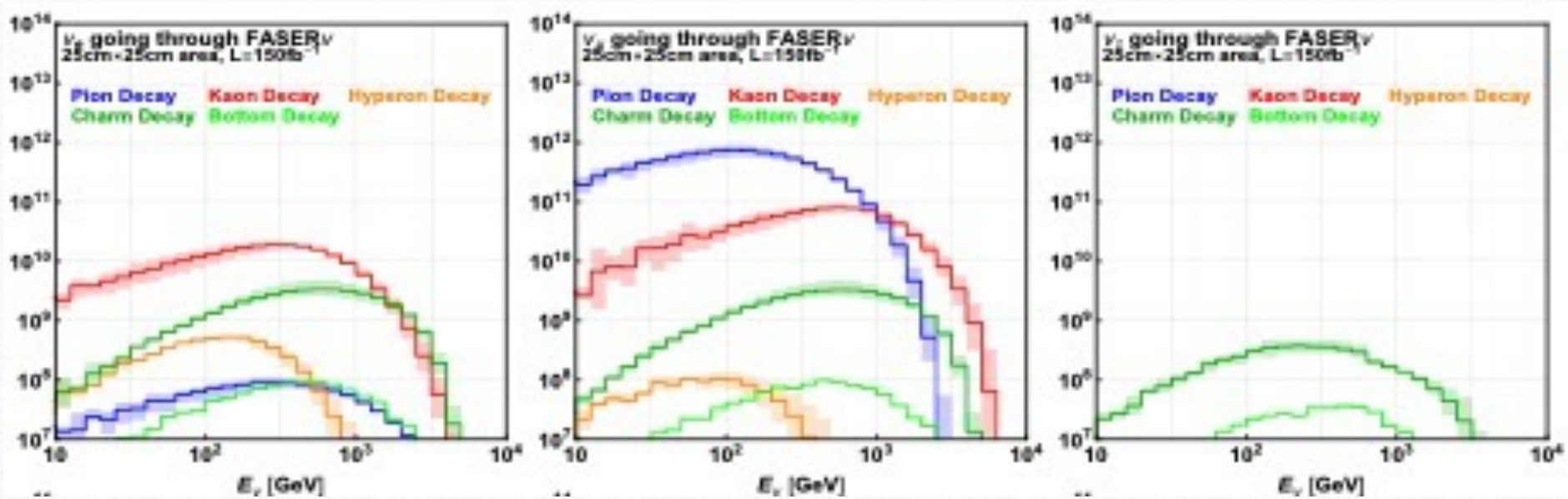
Sources

- Beta decay: $\bar{\nu}_e$
- Fusion in stars: ν_e
- Pion and Kaon decay: $\nu_\mu, \bar{\nu}_\mu$
- Muon decay: $\nu_\mu, \bar{\nu}_\mu$

Reactor neutrinos, solar neutrinos, Earth neutrinos, atmospheric neutrinos, short baseline and long baseline neutrinos

Source for ν_τ

- D-meson decay $m_{D+} = 1869.65 \pm 0.05$ MeV



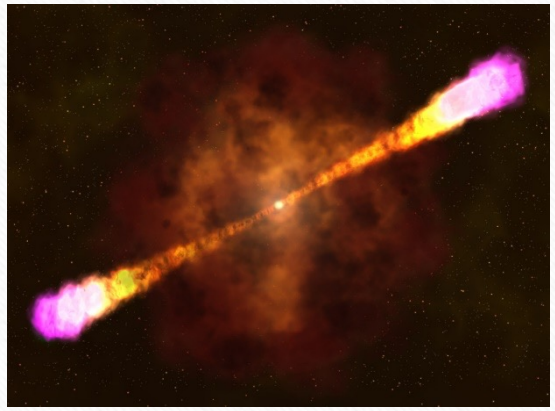
FASER collaboration , *Eur.Phys.J.C* 80 (2020) 1, 61

Source?

AGN



GRB?



Flavor composition at source

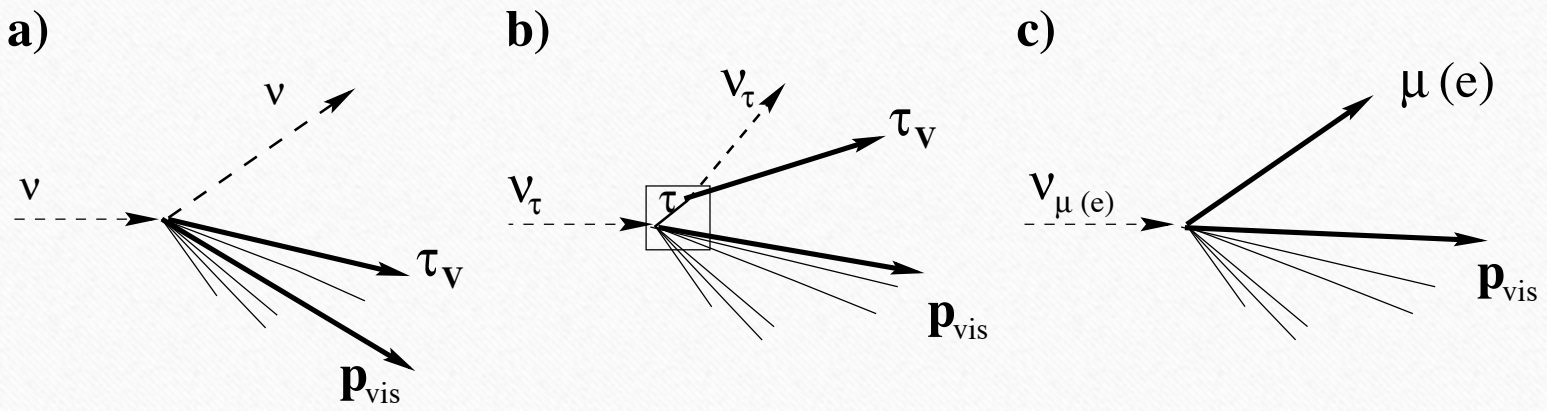
$$p^+p^+ \quad \text{or} \quad p^+ + \gamma \rightarrow .... + \pi^{\pm}, \pi^0$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \quad \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu \quad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

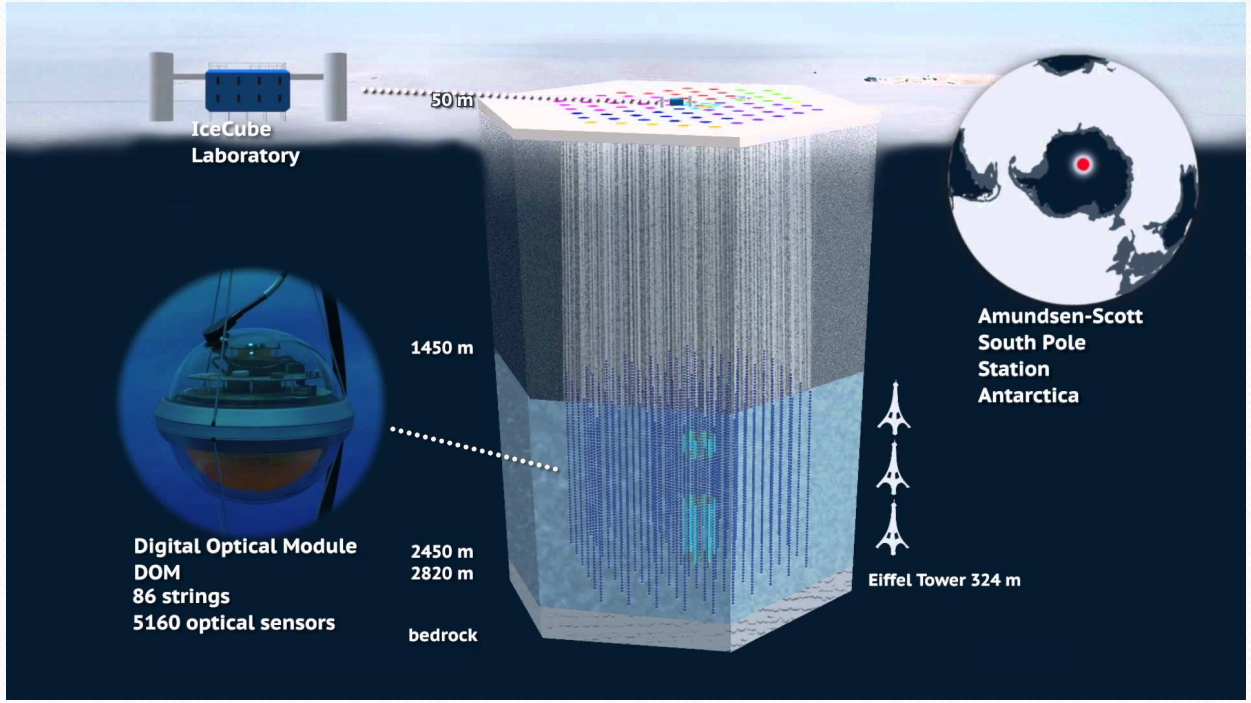
$$F_e^0 : F_\mu^0 : F_\tau^0 = 1 : 2 : 0$$

Detection

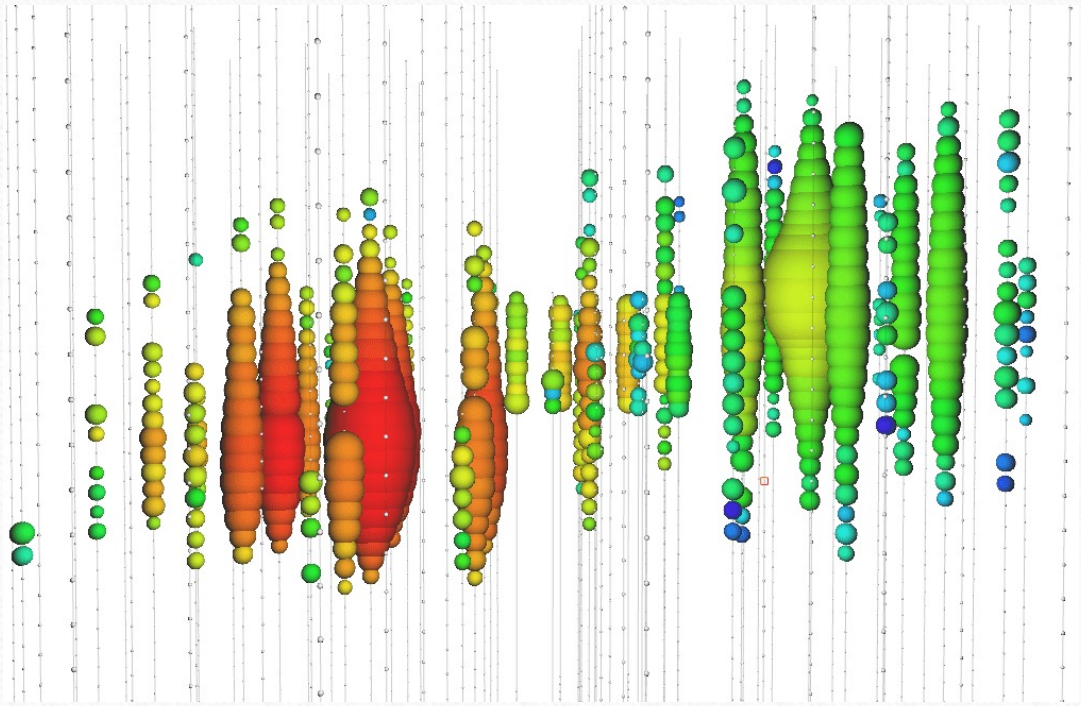


NOMAD collaboration, *Nucl.Phys.B* 611 (2001) 3-39

Ultra-high energy cosmic neutrinos



Double bang



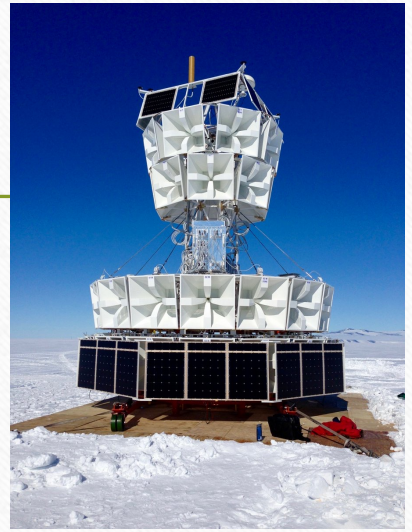
E> 1PeV

ICECUBE collaboration

ANITA

ANtarctic Impulse Transient Antenna (ANITA)

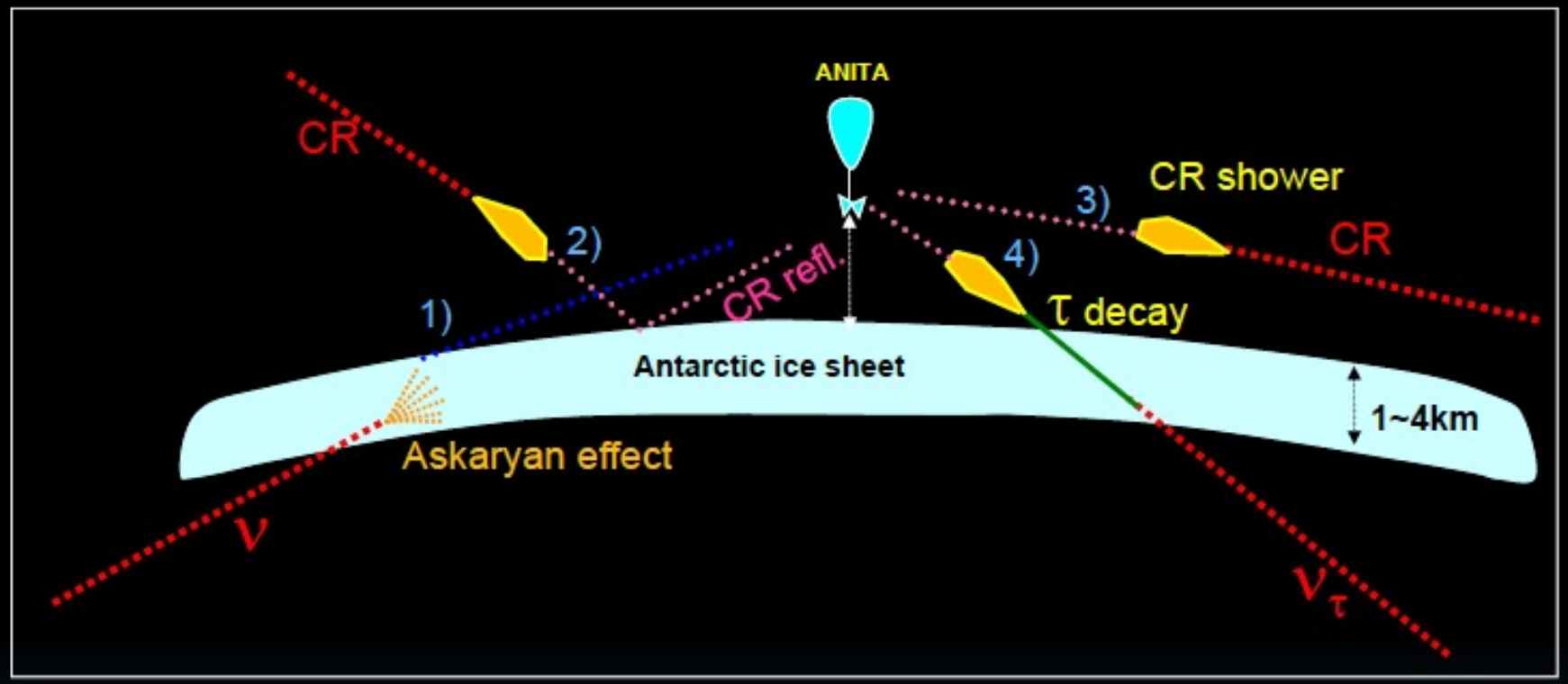
Flying over an altitude of 37 km



Radio detectors



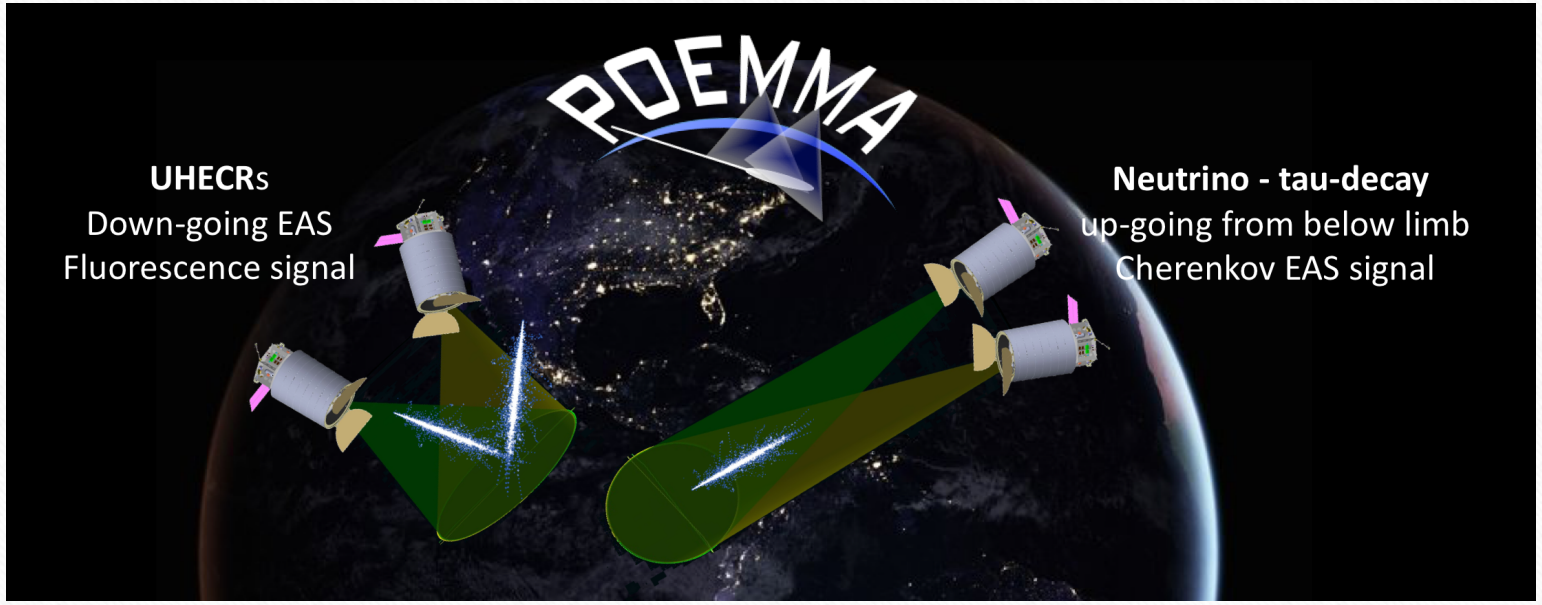
ANITA's signatures



FOLLOWED BY ARA AND ARIANNA

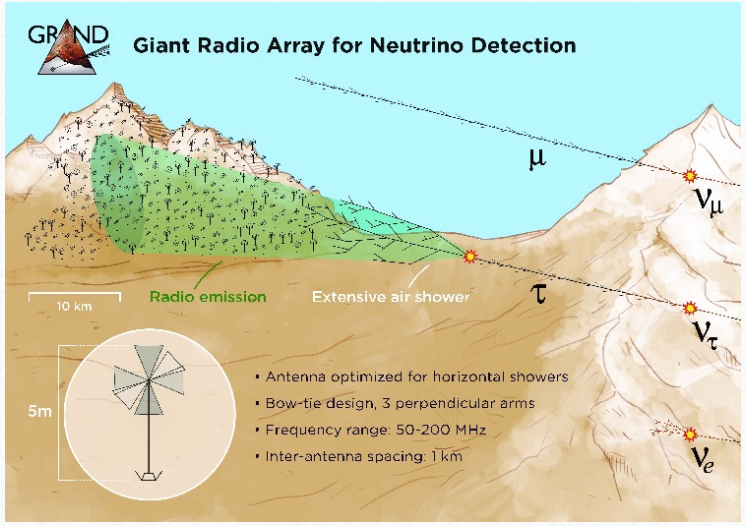
Slides by Jiwoo Nam for ANITA collaboration, ICRC 2017

Higher energy detectors



POEMMA collaboration, *PoS* ICRC2019 (2020) 378, 1909.09466

GRAND



GRAND COLLABORATION, *PoS* ICRC2017 (2018) 996 ARXIV:1708.05128

What are anticipated flavor compositions at cosmic neutrino sources?

Flavor composition at source

$$p^+p^+ \quad \text{or} \quad p^+ + \gamma \rightarrow .... + \pi^{\pm}, \pi^0$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \quad \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu \quad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$F_e^0 : F_\mu^0 : F_\tau^0 = 1 : 2 : 0$$

Flavor composition at source

$$p^+p^+ \quad \text{or} \quad p^+ + \gamma \rightarrow .... + \pi^{\pm}, \pi^0$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \qquad \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu \qquad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

Stopped muon:

$$F_e^0 : F_\mu^0 : F_\tau^0 = 0 : 1 : 0$$

Flavor composition at source

$$n \rightarrow p^{+} e^{-} \bar{\nu}_{e}$$

$$F_{e}^{0} : F_{\mu}^{0} : F_{\tau}^{0} = 1 : 0 : 0$$

Oscillation probability

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_{ij} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \exp^{i\Delta m^2_{ij}/(2E)} \right|^2$$

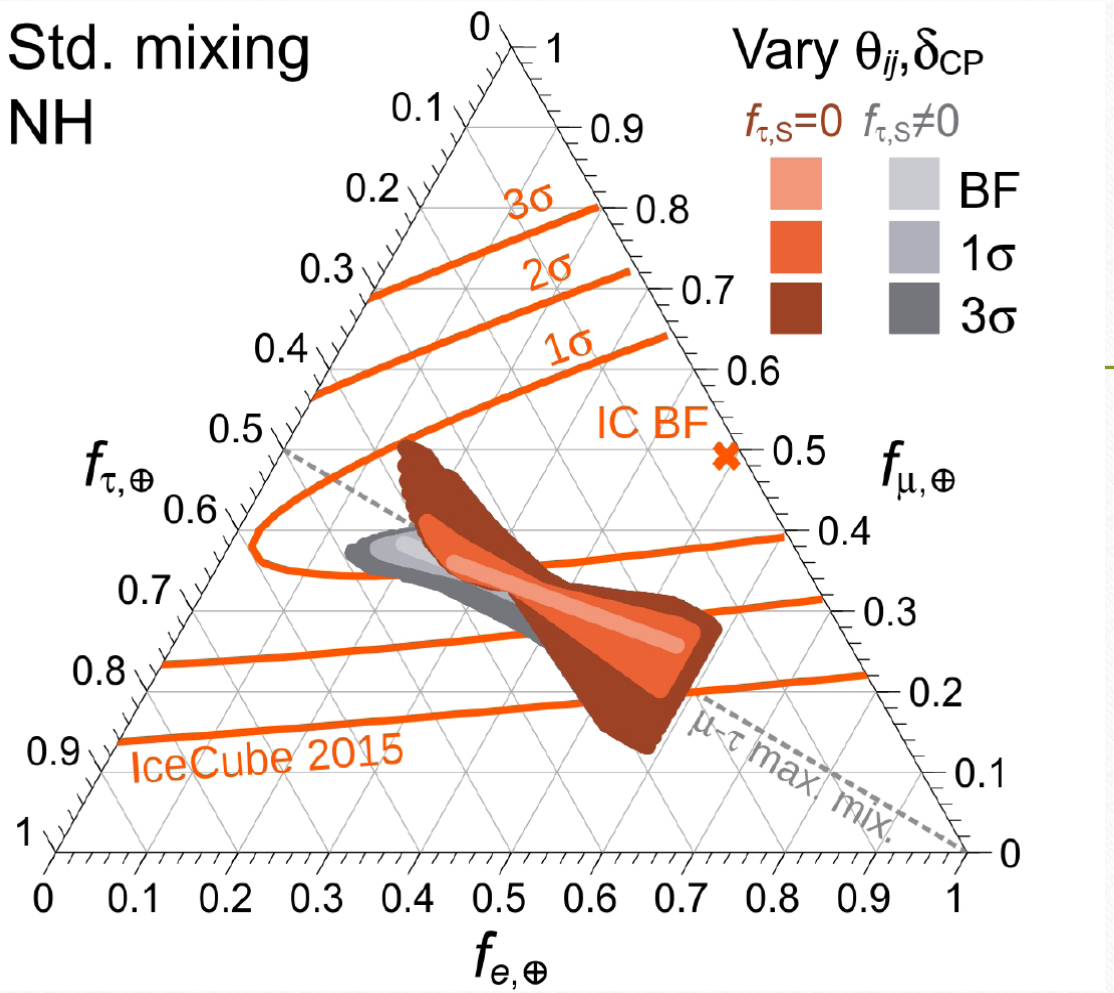
$L \to \infty$

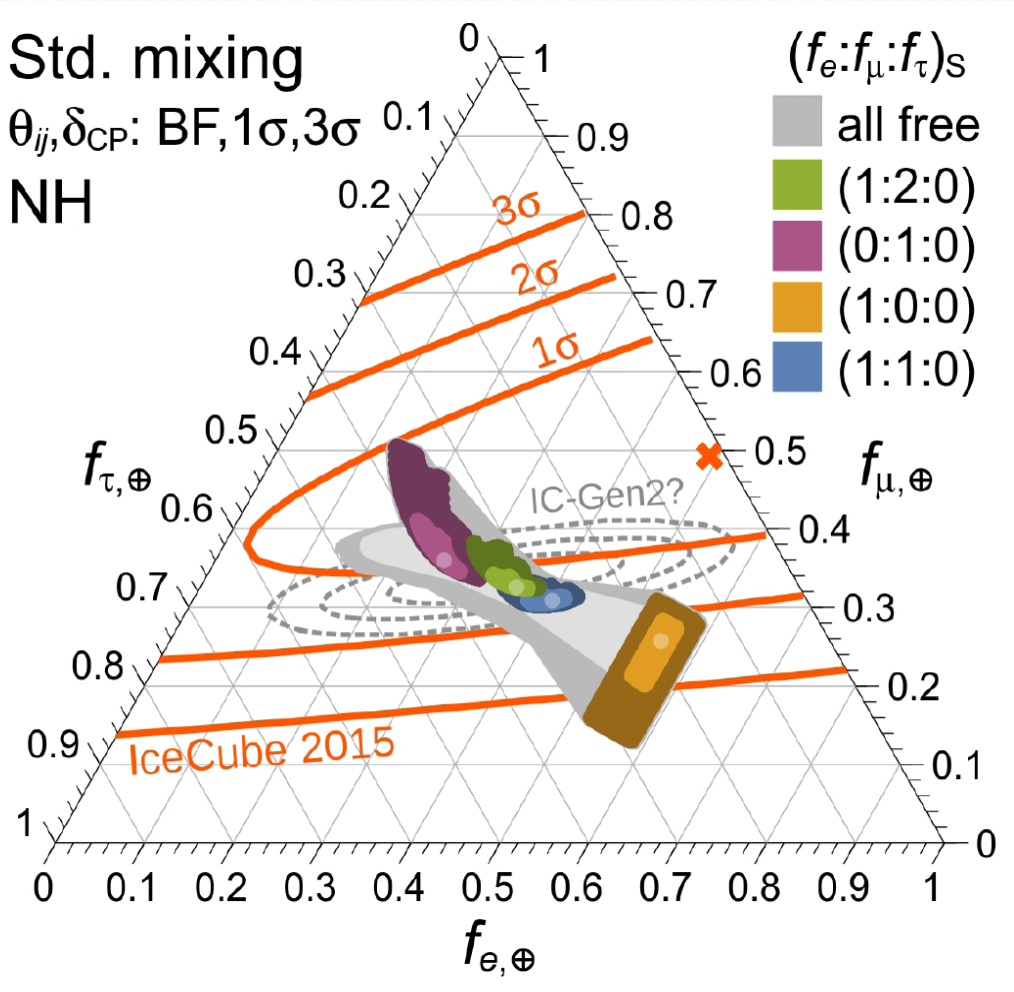
$$P(\nu_\alpha \to \nu_\beta) = \sum_i |U_{\alpha i} U_{\beta i}|^2$$

$$F^\oplus_\alpha = \sum_\alpha P(\nu_\beta \to \nu_\alpha) F^0_\beta$$

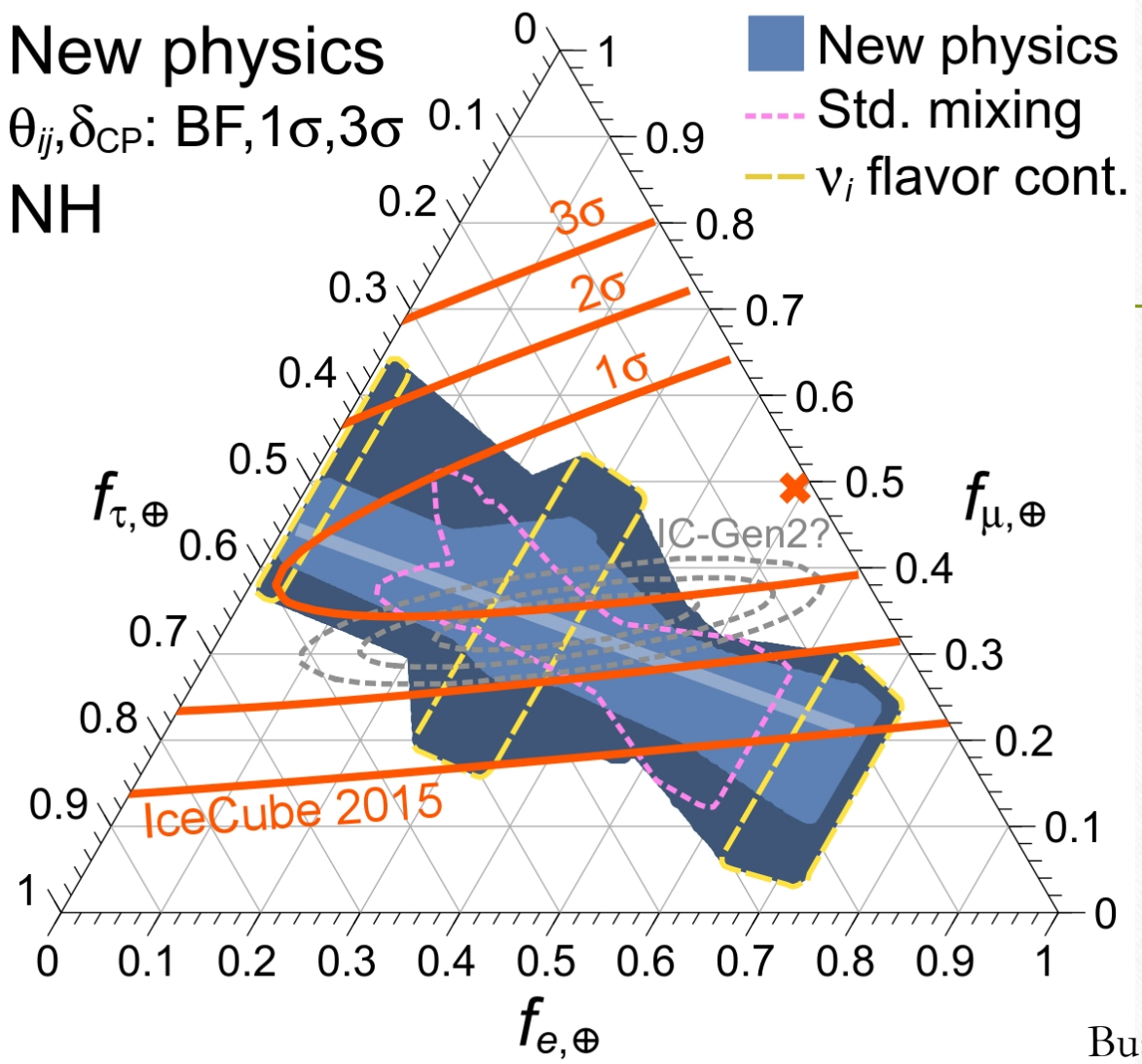
$$F^0_e : F^0_\mu : F^0_\tau = 1 : 2 : 0$$

$$F^\oplus_e : F^\oplus_\mu : F^\oplus_\tau = 1 : 1 : 1$$





Bustamante, Beacom and Winter, PRL 115 (2015) 161302



Arbitrary combinations of incoherent Mass eigenstates

Bustamante, Beacom and Winter, PRL 115 (2015) 161302

SOMETHING UNEXPECTED TO AFFECT THIRD GENERATION

COUPLING TO ULTRALIGHT DM

3+1 OSCILLATION

COUPLING TO ULTRALIGHT DM

- Phenomenology of neutrinos coupled to ultralight dark matter
- Our model
- Phenomenological consequences
- Conclusions

Lower bounds on dark matter mass

- Standard thermal production: $m_{DM} > \text{few } keV$
- Gunn-Tremaine bound on fermionic dark matter: $m_{DM} > 400\ eV$
- Lower bound on bosonic dark matter: $m_{DM} > 10^{-22}\ eV$

de Broglie wavelength

$$\lambda_{\rm dB} = 2\pi/(m_{\rm DM}\, v)$$

Fuzzy dark matter

$\lambda_{dB} \sim$ Galaxy core

Hu, Barkana and Gruzinov, PRL 85 (2000); Suarez, Robles and Matos, Astrophys Space Sci Proc 38 (2014) 107;
Rindler-Daller and Shapiro, Mod Phys Lette A 29; Chavanis, PRD 84 (2011) 43531;
Marsh, Phys Rep 643 (2016);
Hui, Ostriker, Tremaine and Witten, PRD 95 (2017) 043541

Classical limit

$$\lambda_{dB} \sim n_{DM}^{-1/3} = \left(\frac{m_{DM}}{\rho_{DM}}\right)^{1/3}$$

Real scalar:

$$\phi = A\cos(m_{DM}t)$$

Complex scalar:

$$\phi = A\,\cos\left(m_{\rm DM}\,t\right) + i\,B\,\sin\left(m_{\rm DM}\,t + c\right)$$

Equating T^{00} with $\rho_{\rm DM}$:

$$A^2 = \frac{2\rho_{DM}}{m_{DM}^2}$$

$$A^2 + B^2 = \frac{\rho_{\rm DM}}{m_{\rm DM}^2}$$

Neutrino oscillations as a probe of light scalar dark matter

- A. Berlin, PRL 177 (2016) 231801

$$-\mathcal{L} \supset \frac{1}{2}\, m_\phi^2\, \phi^2 + \frac{1}{2}\, m_i\, \bar{\nu}_i\, \nu_i + g_\phi\, \phi\, \bar{\nu}_1\, \nu_2 + \cdots$$

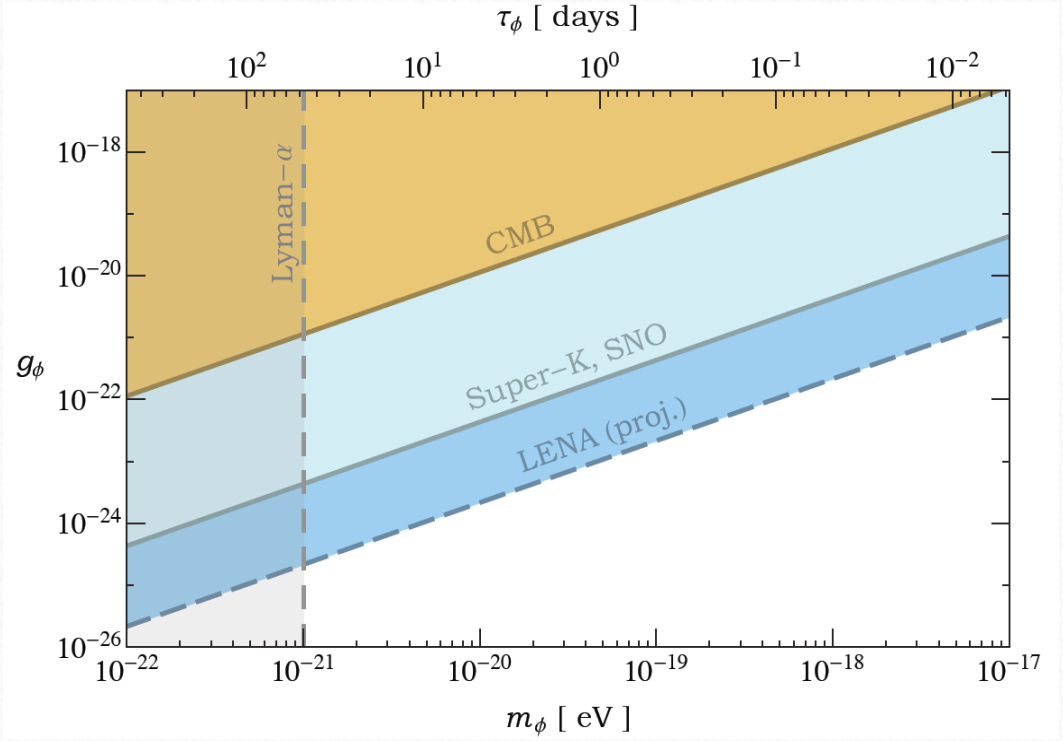
$$\phi(x) \simeq \frac{\sqrt{2\,\rho_{\rm DM}\,(x)}}{m_\phi}\, \cos\left[\, m_\phi\, (t - \vec{v}\cdot\vec{x})\,\right]$$

$$\sin\theta_{12}(t) \simeq \sin\theta_{12} + \frac{\cos\theta_{12}}{\Delta m_{12}}\, \frac{g_\phi\, \sqrt{2\,\rho_{\rm DM}}}{m_\phi}\, \cos m_\phi\, t$$

$$\Phi_{\rm eff} = \Phi^{(0)} + \Phi^{(1)}\, \cos m_\phi\, t$$

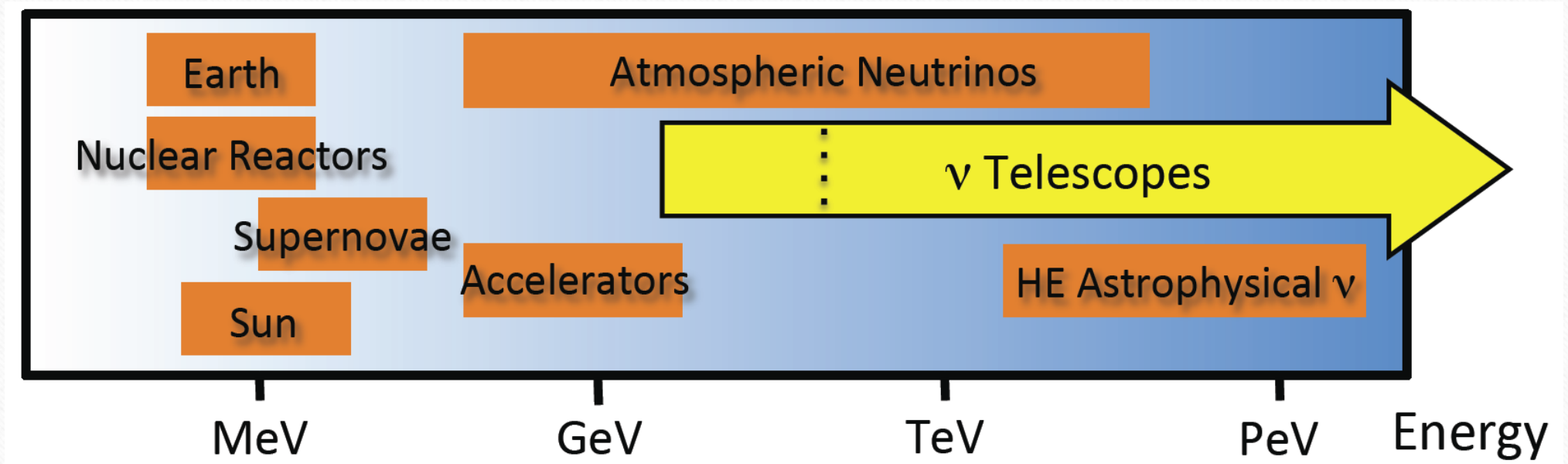
$$\frac{\Phi^{(1)}}{\Phi^{(0)}} \simeq 2\, \cot\theta_{12}\, \frac{g_\phi\, \sqrt{2\,\rho_{\rm DM}}}{m_\phi\, \Delta m_{12}}$$

Bounds from time modulation of solar neutrinos



Time varying effects

- Krnjaic, Machado and Necib, PRD 97 (2018) 075017: JUNO and DUNE
- Brdar, Kopp, Liu, Prass and Wang, PRD97 (2018) 43001: T2K and solar


Earth
Nuclear Reactors
Supernovae
Sun
Atmospheric Neutrinos
ν Telescopes
Accelerators
HE Astrophysical ν
MeV
GeV
TeV
PeV
Energy

Effective Lagrangian

Y.F. and Palomares-Ruiz, "Flavor of cosmic neutrinos preserved by ultralight dark matter," *Phys.Rev.D* 99 (2019) 5, 051702

$$i\,\frac{g_\alpha}{\Lambda^2}(\phi^\dagger\partial_\mu\phi-\phi\,\partial_\mu\phi^*)(\bar{\nu}_\alpha\gamma^\mu\nu_\alpha)$$

$$V_\alpha\,\nu_\alpha^\dagger\nu_\alpha$$

$$\left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right)\left(\frac{a_\alpha}{\Lambda^2}\right)\nu_\alpha^\dagger\nu_\alpha$$

$$\Delta V \gg \Delta m^2/E_\nu$$

$$V_e \neq V_\mu \neq V_\tau$$

Effective dark matter mass

$$V_\alpha \, \nu_\alpha^\dagger \nu_\alpha = \left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right) \left(\frac{g_\alpha}{\Lambda^2}\right) \bar{\nu}_\alpha \gamma^0 \nu_\alpha$$

$$H_{\rm DM} = H_{\rm vac} \pm {\rm diag}(V_e, V_\mu, V_\tau)$$

$$H_{\rm vac} = M_\nu^2 / 2E_\nu$$

Irrelevant for low energy neutrinos

Local DM density

$\sim 0.3\ \mathrm{GeV/cm^3}$

$\rho_{DM}|_{\text{outside halo}} \sim 10^{-5} \rho_{DM}|_{\text{inside halo}}$

$$\frac{\Lambda^2/\Delta g}{(20\ \mathrm{PeV})^2} \ll \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)\left(\frac{10^{-21}\ \mathrm{eV}}{m_{\mathrm{DM}}}\right) \times \left(\frac{10^{-3}\ \mathrm{eV}^2}{\Delta m^2\ \cos 2\theta}\right)\left(\frac{\rho_{\mathrm{DM}}}{0.3\ \mathrm{GeV/cm^3}}\right)$$

- In a halo, $\Delta m^2_{31}/(E_\nu), \Delta m^2_{21}/(E_\nu) \ll V_\alpha - V_\beta$

Effective mass (energy) eigenstates $=$ flavor eigenstate



No Oscillation

Adiabaticity condition

$$d\rho_{\rm DM}/dx \;<\; \Delta m^2_m/(4\,E_\nu)$$

$$2\,E_\nu\,\Delta V_{\rm res} = \Delta m^2\,\cos 2\theta$$

$$\left|\frac{d\rho_{\rm DM}/dx}{\rho_{\rm DM}}\right|_{\rm res} \ll \Delta V_{\rm res}\,\tan^2 2\theta$$

$$\sim 5\times 10^4\,{\rm pc}^{-1}\left(\frac{\sin^2 2\theta}{\cos 2\theta}\right)$$

Result

$$\rho_{DM}\big|_{\text{outside halo}} \sim 10^{-5}\rho_{DM}\big|_{\text{inside halo}}$$

If the source and detector are both located in dark matter halo, the original flavor ratios are maintained

$$(F^0_{\nu_e} : F^0_{\nu_\mu} : F^0_{\nu_\tau}) = (1:2:0) \quad \Rightarrow \quad (F^{\oplus}_{\nu_e} : F^{\oplus}_{\nu_\mu} : F^{\oplus}_{\nu_\tau}) = (1:2:0)$$

Will low energy neutrinos be affected, too?

- No effect for solar, atmospheric, supernova core collapse or terrestrial neutrinos

$$\Delta m^2_{31}/E_\nu, \Delta m^2_{21}/E_\nu \gg V_\alpha - V_\beta$$

Underlying model

$L_\alpha - L_\beta$ gauge symmetry

$$i\, g_\phi \left(\phi^* \partial^\mu \phi - \phi\, \partial^\mu \phi^*\right) Z'_\mu$$

$$Z'_\mu \sum_\alpha g_\alpha\, \bar{L}_\alpha \gamma^\mu L_\alpha$$

Anomaly cancelation

$$g_e + g_\mu + g_\tau = 0,$$

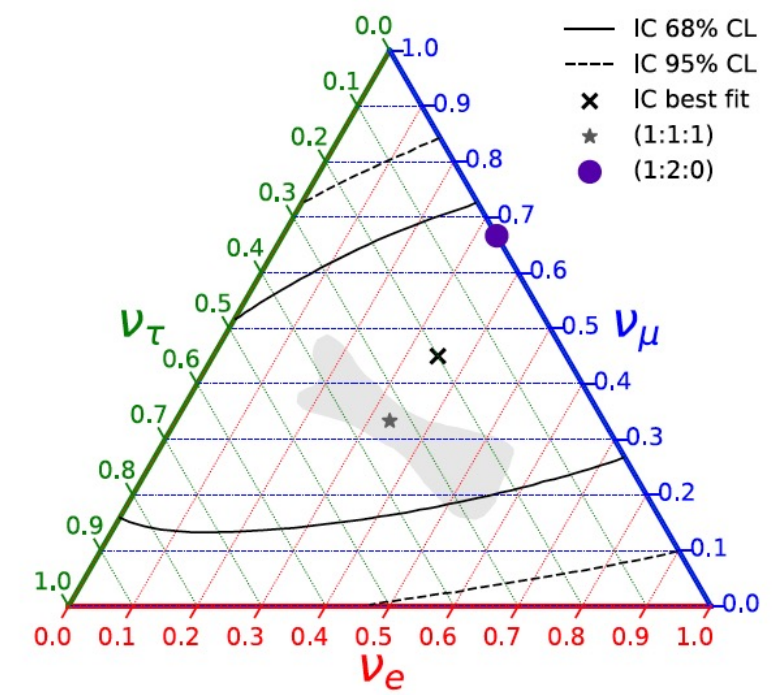
$$g_e^3 + g_\mu^3 + g_\tau^3 = 0$$

$$i\, \frac{g_\alpha}{\Lambda^2} (\phi^\dagger \partial_\mu \phi - \phi\, \partial_\mu \phi^*)(\bar{\nu}_\alpha \gamma^\mu \nu_\alpha)$$

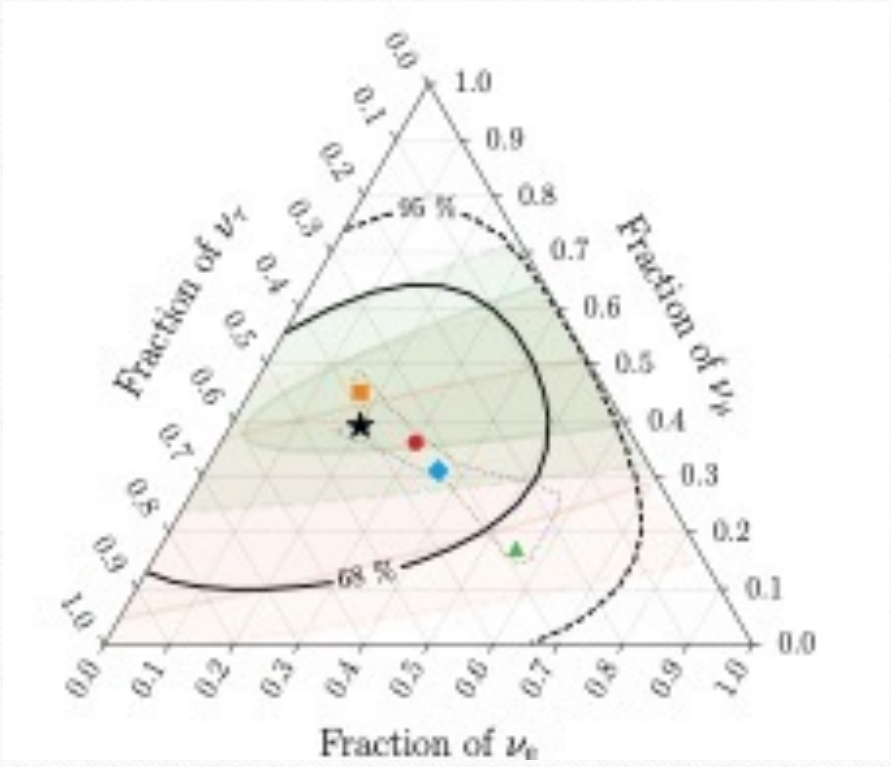
$$\Lambda^2 = \frac{m_{Z'}^2}{g_\phi}$$

Y.F. and Palomares-Ruiz, "Flavor of cosmic neutrinos preserved by ultralight dark matter," *Phys.Rev.D* 99 (2019) 5, 051702

Our results



YF and Palomares-Ruiz, *Phys.Rev.D* 99 (2019) 5, 051702



ICECUBE collaboration, 2011.03561

Bound

$$\frac{g_\alpha}{\Lambda^2}\frac{\rho_{DM}}{m_{DM}} \ll \frac{\Delta m^2_{31}}{2E_\nu} \sim 10^{-18}\ eV.$$

$E_\nu \sim \text{PeV}$

$$(g_\alpha/\Lambda^2)(\rho_{DM}/m_{DM}) \sim 10^{-19}\ eV$$

No effect for PeV neutrinos
Significant effect for EeV

Y.F., "On the flavor of the cosmic neutrino flavor," JHEP 07 (2021) 174, arXiv:2105.03272

Cosmogenic neutrinos

$$p^+ + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+.$$

$$(F_{\nu_e} : F_{\nu_\mu} : F_{\nu_\tau}) = (1 : 2 : 0)$$

Mean free path: 6 Mpc

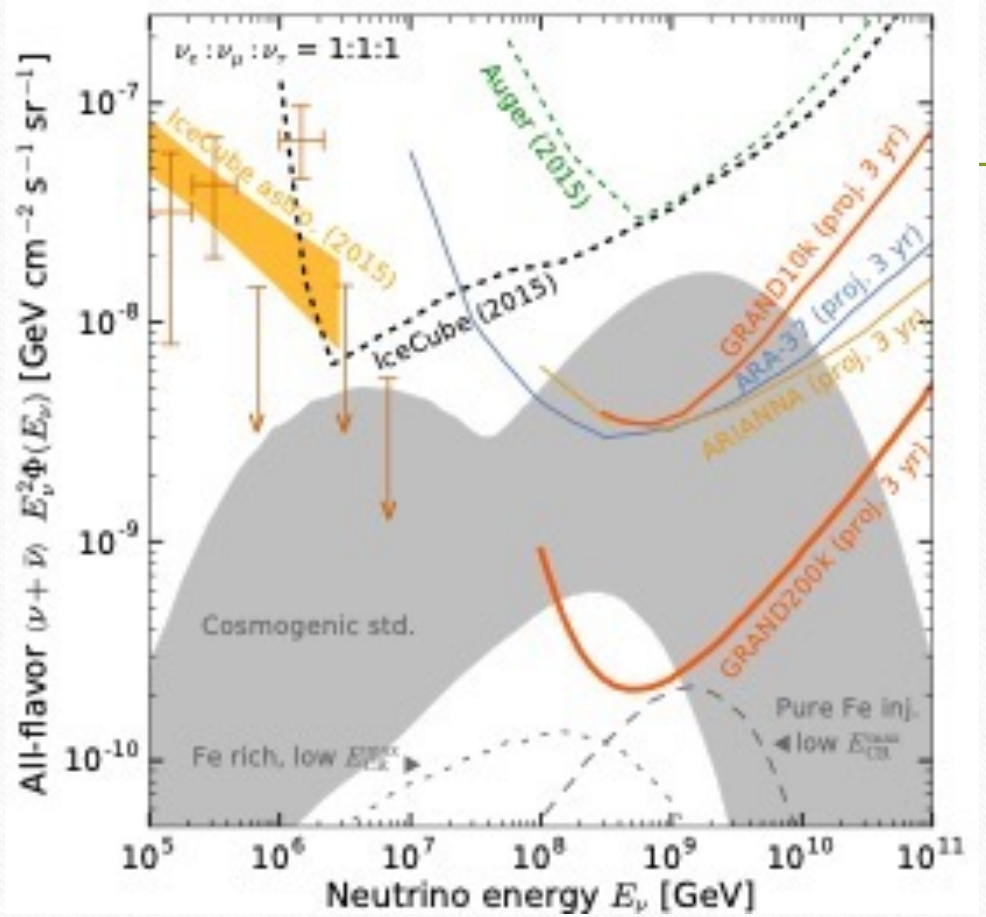
R. Ruffini, G. V. Vereshchagin and S. S. Xue, Astrophys. Space Sci. 361 (2016)

Even in presence of DM

$$(F_{\nu_e} : F_{\nu_\mu} : F_{\nu_\tau}) = (1 : 2 : 0)$$



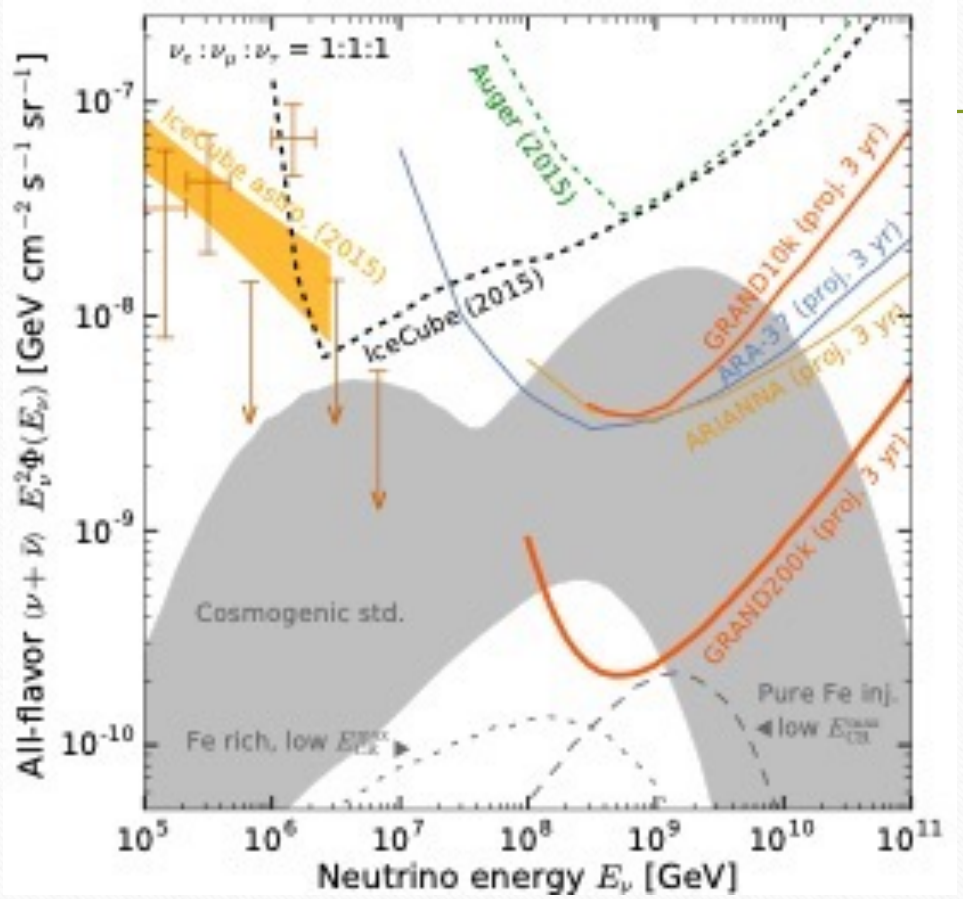
$$F_e^{\oplus} : F_\mu^{\oplus} : F_\tau^{\oplus} = 1 : 1 : 1$$



GRAND collaboration,
PoS ICRC2017 (2018) 996
1708.05128

GRAND will see only tau neutrino

ARA and ARIANNA will see all types of neutrinos



Possiblities:

GRAND does not observe neutrino flux

But ARA and ARIANNA do

Hint for our scenario with

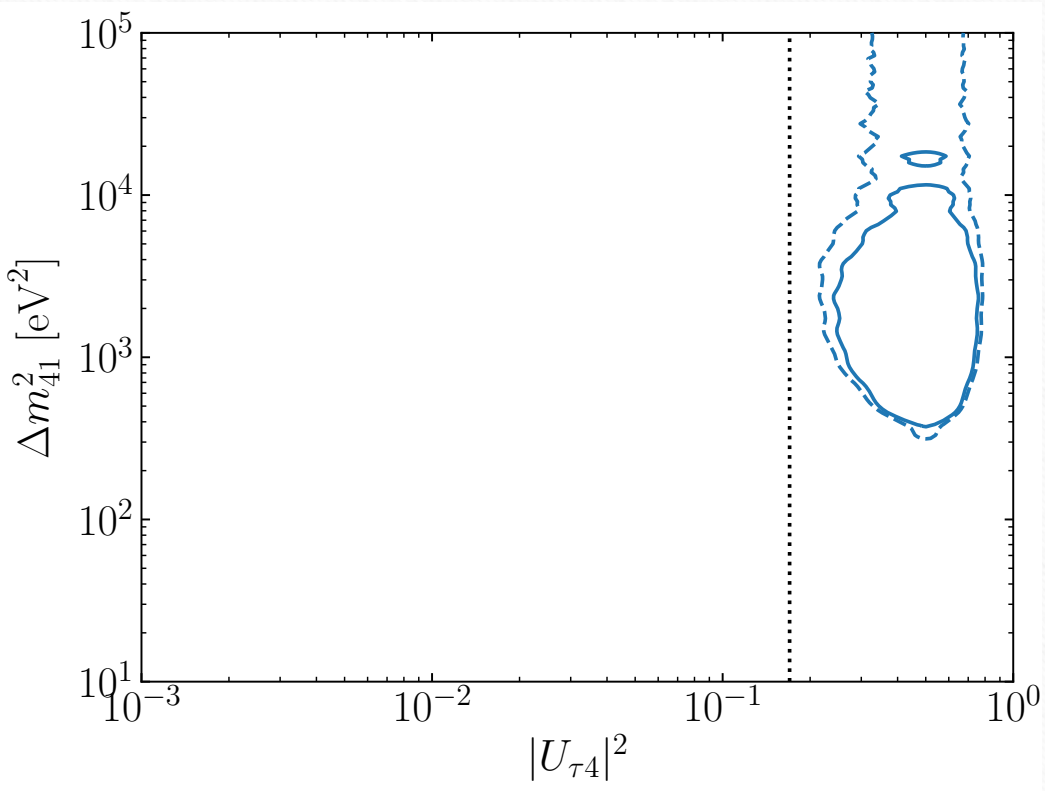
$(g_\alpha/\Lambda^2)(\rho_{DM}/m_{DM}) \sim 10^{-19}\ eV$

No cosmogenic (origin is within halo)

Second scenario

Sterile neutrinos mixed with the Tau neutrino

3+1 scenario



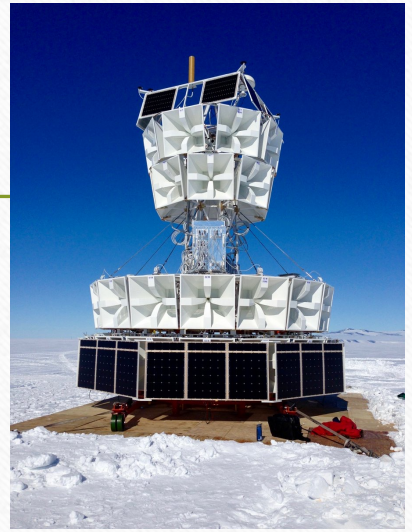
NOMAD collaboration, NPB 611 (2001) 3, PLB 570 (2003) 19; Dentler et al., JHEP 08 (2018) 10

FASER collaboration , *Eur.Phys.J.C* 80 (2020) 1, 61

ANITA

ANtarctic Impulse Transient Antenna (ANITA)

Flying over an altitude of 37 km



Radio detectors



Two anomalous events

TABLE I: *ANITA-I,-III anomalous upward air showers.*

event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon.[(1)]	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3°, 159.62 \pm 0.7°$	$-35.0 \pm 0.3°, 61.41 \pm 0.7°$
RA, Dec[(2)]	282.14064, +20.33043	50.78203, +38.65498
E_{shower}[(3)]	0.6 ± 0.4 EeV	$0.56^{+0.3}_{-0.2}$ EeV

ANITA collaboration, PRL 117 (2017) 071101

Extensive Air Shower (EAS)

ANITA collaboration, PRL 121 (2018), no 16, 161102

Event characteristics

- Zenith angles: $117.4° \pm 0.3°$ and $125° \pm 0.3°$
- Chord sizes: 5800 km and 7300 km
- Energies 0.6 ± 0.4 EeV and $0.56^{+0.4}_{-0.2}$ EeV

Mean free path for neutrino

- The mean free path in mantle for neutrinos of energy of EeV

500-800 km << chord size → Neutrinos will be absorbed.

The probability of neutrinos passing the Earth is ~ 10^{-9} .

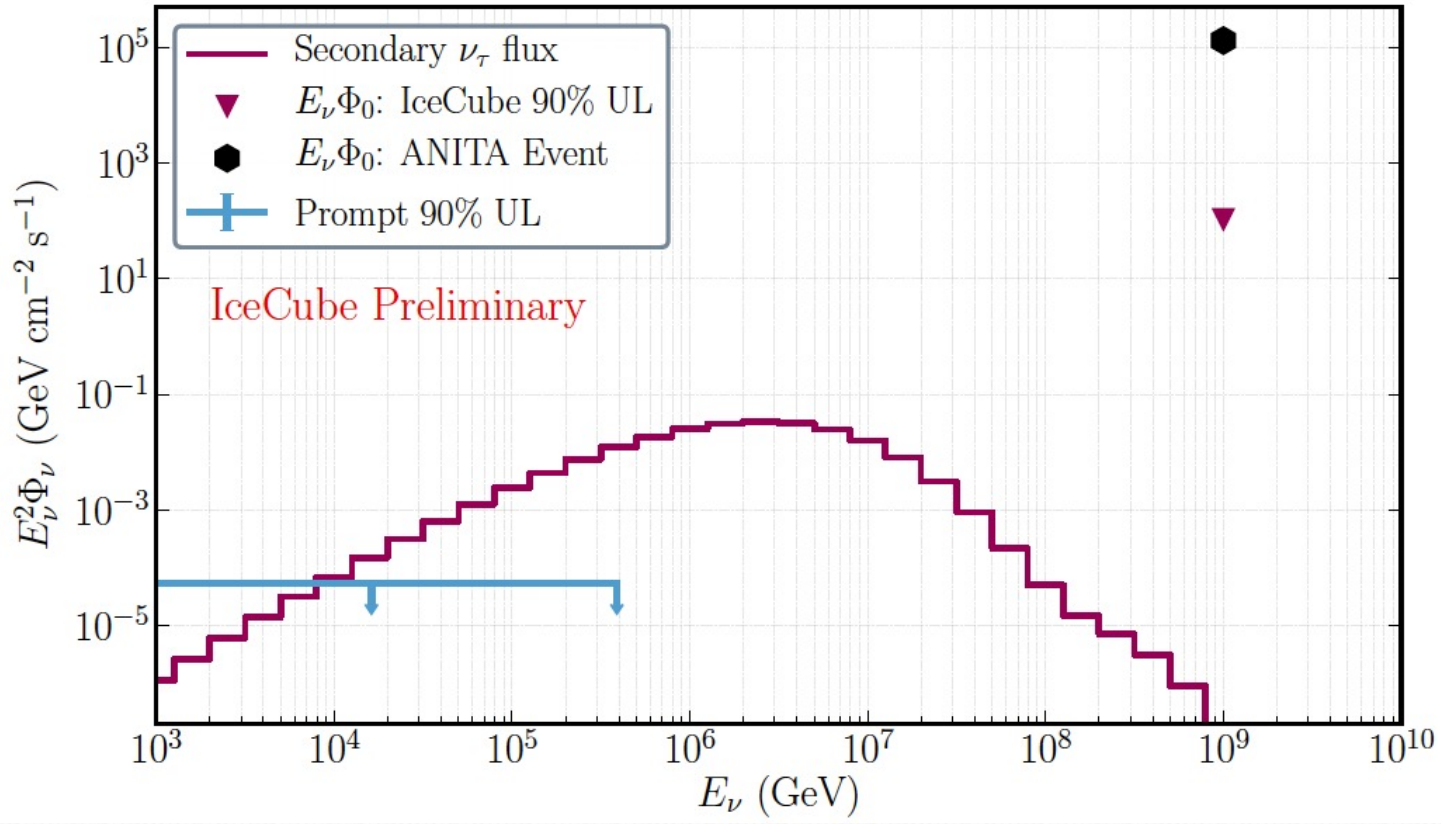
Neutrino recreation

$$\nu_\tau \rightarrow \tau \rightarrow \nu_\tau \rightarrow \ldots \rightarrow \nu_\tau$$

$$P \sim 10^{-7}$$

See however, Cumming et al, arXiv:1910.00992

Bounds from AUGER and ICECUBE

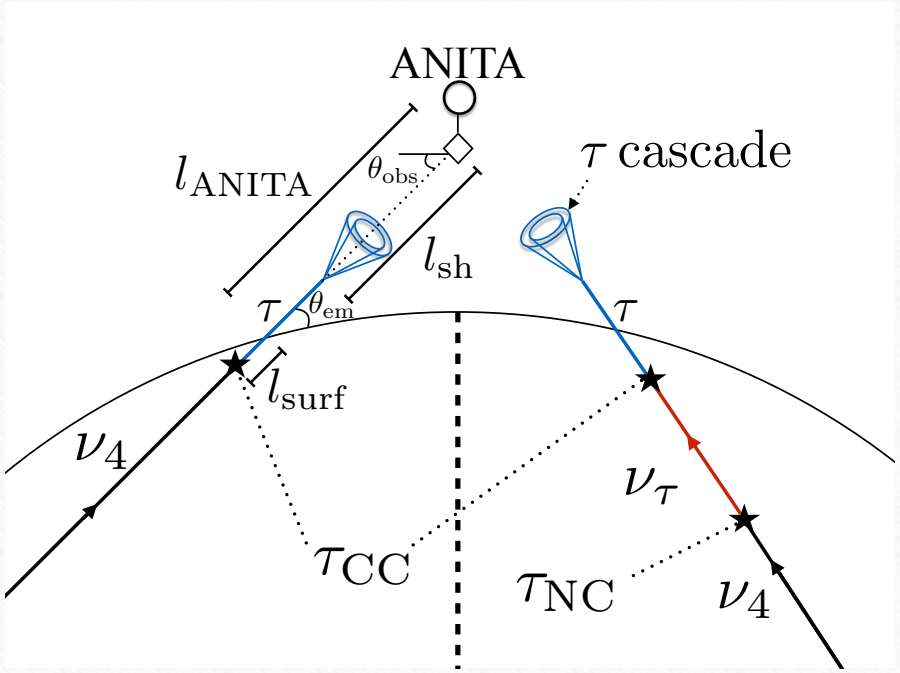


Transient source

ICECUBE collaboration,
arXiv: 1908.08060

See also, Safa, Pizzuto, Arguelles, Halzen, Hussain, Kheirandish, Vandenbroucke,
JCAP 01 (2020) 012
arXiv: 1909.10487

- J. F. Cherry and I. M. Shoemaker, Phys. Rev. D 99 (2019) no.6



Mass eigenstates

$$|\nu_1\rangle = U_{e1}|\nu_e\rangle + U_{\mu 1}|\nu_\mu\rangle + \cos\alpha U_{\tau 1}|\nu_\tau\rangle - \sin\alpha U_{\tau 1}|\nu_s\rangle$$

$$|\nu_2\rangle = U_{e2}|\nu_e\rangle + U_{\mu 2}|\nu_\mu\rangle + \cos\alpha U_{\tau 2}|\nu_\tau\rangle - \sin\alpha U_{\tau 2}|\nu_s\rangle$$

$$|\nu_3\rangle = U_{e3}|\nu_e\rangle + U_{\mu 3}|\nu_\mu\rangle + \cos\alpha U_{\tau 3}|\nu_\tau\rangle - \sin\alpha U_{\tau 3}|\nu_s\rangle$$

$$|\nu_4\rangle = \sin\alpha|\nu_\tau\rangle + \cos\alpha|\nu_s\rangle.$$

Misconception

Cross section of $\nu_4 = |U_{\tau 4}|^2 \sigma(\nu_\tau + \text{nucleus})$

Mean free path of $\nu_4 = |U_{\tau 4}|^{-2} \times$ (Mean free path of ν_τ)~5000 km

500 km



~~The flux will survive and produce tau.~~

Misconception

Cross section of $\nu_4 = |U_{\tau 4}|^2 \sigma(\nu_\tau + \text{nucleus})$

Mean free path of $\nu_4 = |U_{\tau 4}|^{-2} \times$ (Mean free path of ν_τ)~5000 km

500 km

In the limit, $\Gamma R_\oplus \gg 1$ and $\Delta M^2 R_\oplus / E_\nu \ll 1$

$|\nu_4\rangle = \sin\alpha |\nu_\tau\rangle + \cos\alpha |\nu_s\rangle.$ → $\cos\alpha |\nu_s\rangle$

$|\nu_i\rangle$ → $-\sin\alpha U_{\tau i} |\nu_s\rangle.$

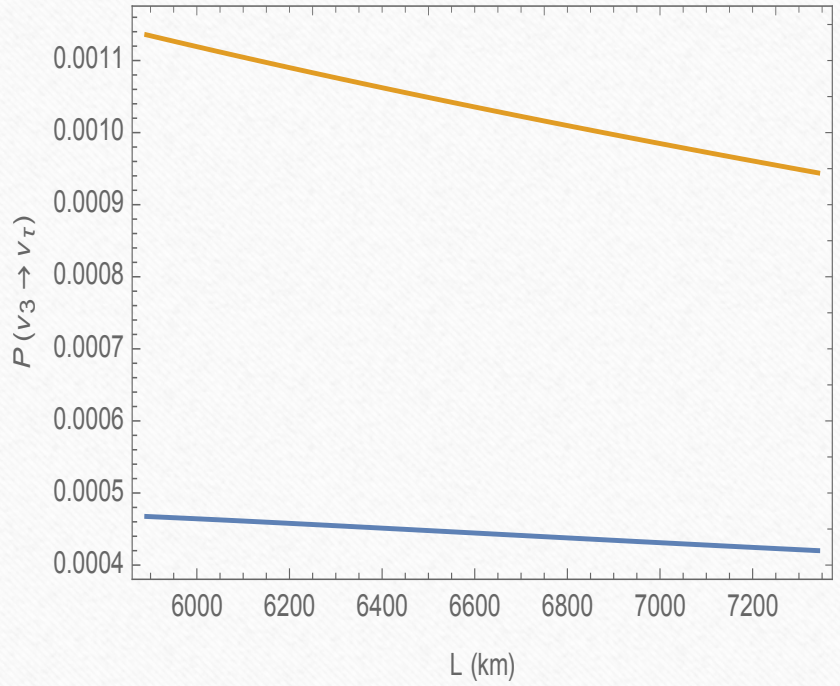
Evolution in presence of scattering

$\psi^T = (\nu_e,\ \nu_\mu,\ \nu_\tau,\ \nu_s)$

$\Gamma =$ scattering rate

$$
\begin{aligned}
i\frac{d\psi}{dt} = \Big[& U \cdot \mathrm{diag}(0, \Delta m^2_{21}/(2E_\nu), \Delta m^2_{31}/(2E_\nu), \Delta M^2/(2E_\nu)) \cdot U^\dagger \\
& + \mathrm{diag}(\sqrt{2}G_F(N_e - N_n/2), -\sqrt{2}G_F N_n/2, -\sqrt{2}G_F N_n/2, 0) \\
& - i\ \mathrm{diag}(\Gamma/2, \Gamma/2, \Gamma/2, 0)\Big]\,\psi
\end{aligned}
$$

Simultaneous oscillation and scattering



E_ν =EeV,

$\rho = 4.5$ gr/cm^3

SM cross section $\sim 1.1 \times 10^{-32}$ cm^2

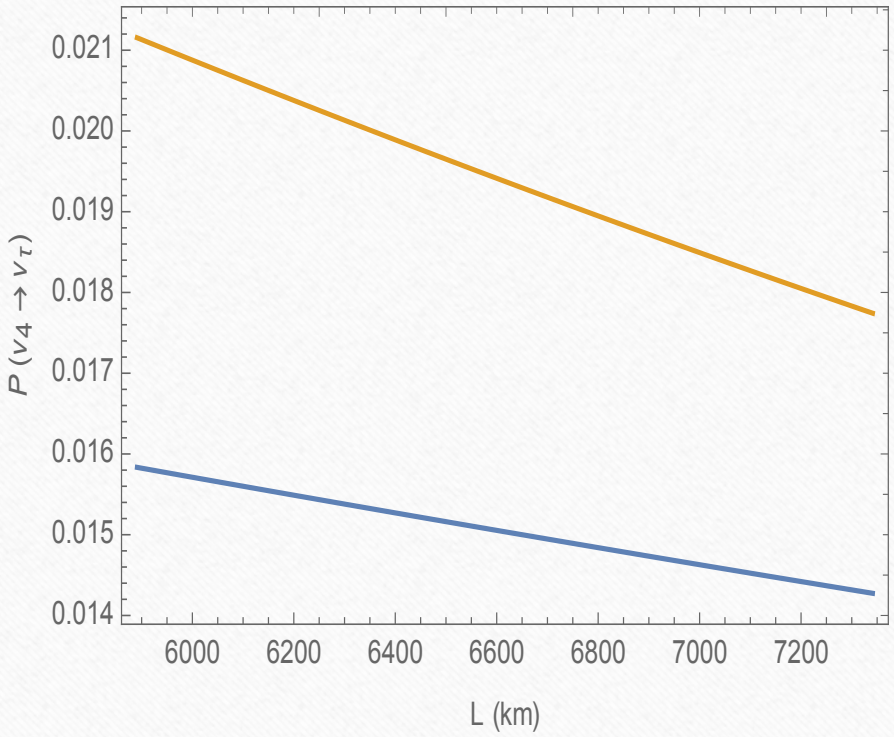
$\Rightarrow \Gamma = 0.003$ km^{-1}

$|U_{\tau 4}|^2 = \sin^2\alpha = 0.1$ and $\Delta M^2/2E_\nu = 0.35\Gamma$

$\sqrt{\Delta M^2} = 643$ eV.

YF, "On the Tau flavor of the cosmic neutrino flux"
JHEP 07 (2021) 174, arXiv 2105.03272

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Scaling with mixing

$$\Delta M^2/(2E_\nu) \sim \Gamma, \Rightarrow \begin{cases} P(\nu_3 \to \nu_\tau) \sim 0.1 \sin^4 \alpha \\ P(\nu_4 \to \nu_\tau) \sim 0.1 \sin^2 \alpha \end{cases}$$

$$\Delta M^2/E_\nu \gg R_\oplus^{-1}, \Rightarrow \begin{cases} P(\nu_4 \to \nu_\tau) \simeq P(\bar{\nu}_4 \to \bar{\nu}_\tau) \sim 0.01(\sin^2 \alpha/0.1) \\ P(\nu_3 \to \nu_\tau) \simeq P(\bar{\nu}_3 \to \bar{\nu}_\tau) \to 0. \end{cases}$$

$$(F_{\nu_e} : F_{\nu_\mu} : F_{\nu_\tau} : F_{\nu_s}) = (1 : 2 : 0 : 0)$$

$$(F_{\nu_e} : F_{\nu_\mu} : F_{\nu_\tau} : F_{\nu_s}) = (1 : 1 : 1 : 0)$$

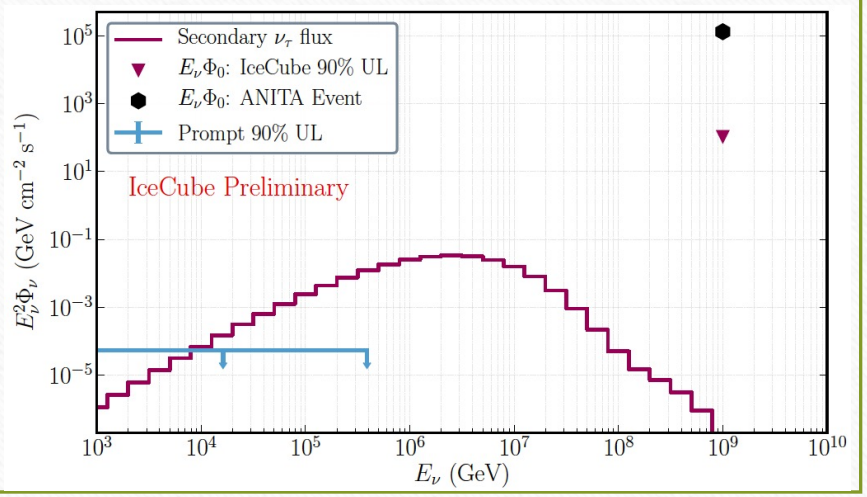
with a normalization of F at arrival.

$$\nu_\tau \to \tau \to \nu_\tau \to \ldots \to \nu_\tau$$

The bound on F for EeV energies is 10^{-7} cm^{-2}.

Safa et al., *JCAP* 01 (2020) 012

ICECUBE collaboration, arXiv: 1908.08060



The bound on F for EeV energies is 10^{-7} cm^{-2}.

$$FP(\nu_3 \to \nu_\tau) \sim 0.1F \sin^4 \alpha$$

10^{-10} cm^{-2}.

acceptance of ANITA is $\sim 2 \times 10^9$ cm^2

<1 events at ANITA

The bound on F for EeV energies is 10^{-7} cm^{-2}.

$$FP(\nu_3 \to \nu_\tau) \sim 0.1 F \sin^4 \alpha$$

$$F \sim 10^{-7} \text{ cm}^{-2}$$

$$\sin^2 \alpha \sim 0.1$$

$$\Delta M^2/(2E_\nu) \sim (0.1 - 1)\Gamma$$

A powerful
Transient source of cosmic neutrinos



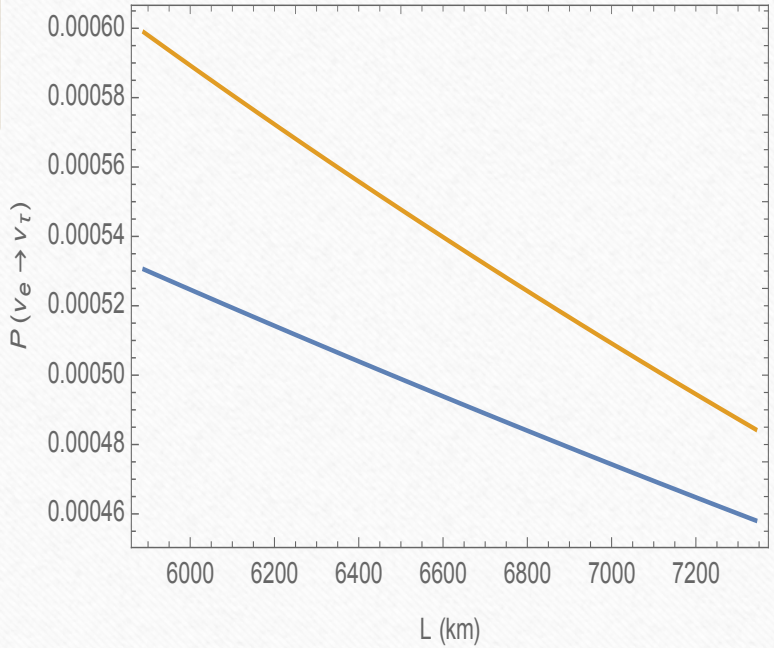
POEMMA, EeV tau neutrinos

Concurrent PeV tau neutrinos by ICECUBE

Violation of unitarity of PMNS matrix

Both 3+1 and coupling to ultralight DM

- At Earth surface: $P(\nu_e \to \nu_\tau)|^{\oplus}_{surface} = 2|U_{\tau 4}|^2|U_{e4}|^2 = 4 \times 10^{-3} \frac{|U_{\tau 4}|^2}{0.1} \frac{|U_{e4}|^2}{0.02}.$



Bound from regeneration is relaxed

$V_\alpha \gg \Delta m^2_{31}/(2E_\nu)$ but still $V_\alpha \ll \Delta M^2/(2E_\nu)$

$|U_{\tau 4}|^2 = 0.1$ and $|U_{e4}|^2 = 0.02$.

Bounds from ICECUBE and ANITA events

$$F\Gamma \int_0^L P(\nu_e \to \nu_\tau)|^{\oplus}_{cross}[x]dx \sim 0.01F,$$

Reinterpretation of ICECUBE bound on regenerated tau neutrino:

$0.01F < 10^{-7}\ \mathrm{cm}^{-2}$ ⇒ $F < 10^{-5}\ \mathrm{cm}^{-2}$

$$FP(\nu_e \to \nu_\tau)|^{\oplus}_{cross} Acc = 10 \frac{F}{10^{-5}\ \mathrm{cm}^{-2}} \frac{P(\nu_e \to \nu_\tau)}{0.0005} \frac{Acc}{2 \times 10^9\ \mathrm{cm}^2}.$$

ANITA anomalous events can be readily explained.

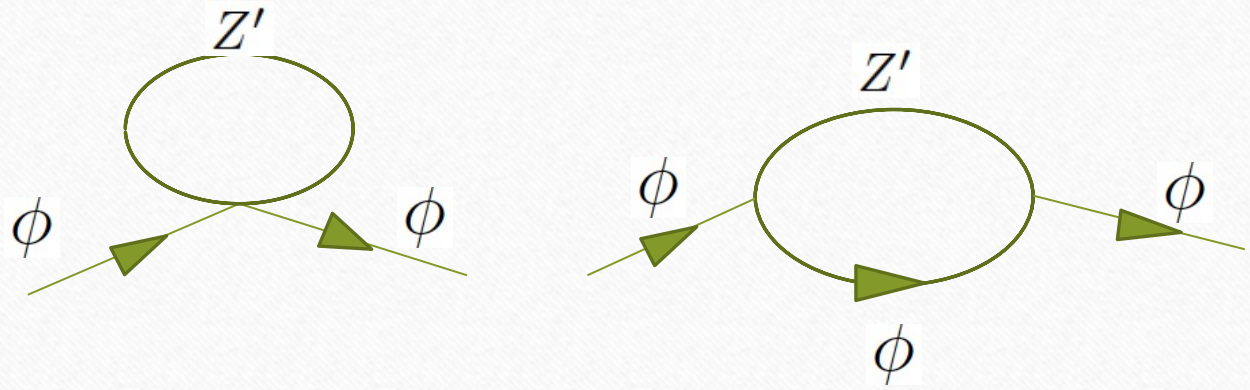
Summary

- The ν_τ detection will play a key role in studying high energy (EeV) cosmic neutrino flux.
- Flavor diagonal but non-universal coupling to ultra-light DM ⇨ maintaining the original flavor ratio at a source located within DM halo
- Relaxes the bound from ICECUBE on transient neutrino flux of EeV energy coming from the tau-neutrino regeneration in Earth
- 3+1 scheme with $\Delta M^2 R_\oplus / E \sim 1$ can open hope for EeV ν_τ from deep down earth despite absorption

Dominance of DM effects

$$\frac{m_{Z'}}{\sqrt{\Delta g\, g_\phi}} \ll 20\ \mathrm{PeV} \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{1/2} \left(\frac{10^{-21}\ \mathrm{eV}}{m_{\mathrm{DM}}}\right)^{1/2}$$

Radiative correction



$$\delta m_\phi^2 \sim \frac{m_{Z'}^2 g_\phi^2}{16\pi^2}$$

Naturalness: $m_\phi \gtrsim m_{Z'} g_\phi/(4\pi)$

$m_{Z'} \lesssim 0.01$ eV and $g_\alpha \sim g_\phi \gtrsim 10^{-18}$

$\mathcal{L}_\mu - \mathcal{L}_\tau$ gauge symmetry $\qquad g_e = 0 \qquad V_e = 0$ and $V_\mu = -V_\tau$

Neutrino decay

$$\nu_i \to \nu_j \phi\phi \text{ or even } \nu_i \to \nu_j Z'.$$

$$m_{Z'} \lesssim 0.01 \text{ eV and } g_\alpha \sim g_\phi \gtrsim 10^{-18}$$

Too large lifetime

Force between DM

- Repulsive force (like gauge coupling) stable
- Attractive force (like Yukawa coupling) unstable

Chavanis, PRD84 (2011) 043531

Our scenario

$$\phi = A\,\cos\left(m_{\rm DM}\,t\right) + i\,B\,\sin\left(m_{\rm DM}\,t + c\right)$$

$$A^2 + B^2 = \frac{\rho_{\rm DM}}{m_{\rm DM}^2}$$

$$J_0^\phi = i\,\left(\phi^*\,\partial_0\phi - \phi\,\partial_0\phi^*\right) = 2\,m_{\rm DM}\,A\,B\,\cos c$$

$$J_0^\phi \;=\; \rho_{\rm DM}/m_{\rm DM} \;=\; n_{\rm DM}$$

Recent lower bounds

- Rotation curve of nearby galaxies and dwarf galaxies

Bar, Blas, Blum and Sibiryakov, PRD 98 (2018); Marsh and Pop, Mon Not Roy Astron Soc 451 (2015); Gonzalez –Morales et al, Mont Not Roy. Astron Soc 472 (2017); Urena-Lopez, Robles and Matos, PRD 96 (2017)

- Hydrodynamical simulation and Lyman alpha

Irsic et al, PRL 119 (2017); Armengaud et al, Mon Not Roy Astron Soc 471 (2017); Kobayashi et al, PRD96 (2017); Nori et al, arXiv:1809.09619

$$m_{DM} > 10^{-21}\ \mathrm{eV}$$