Constraining the absolute neutrino mass via time-of-flight measurements of the Supernovae electron neutrinos with DUNE

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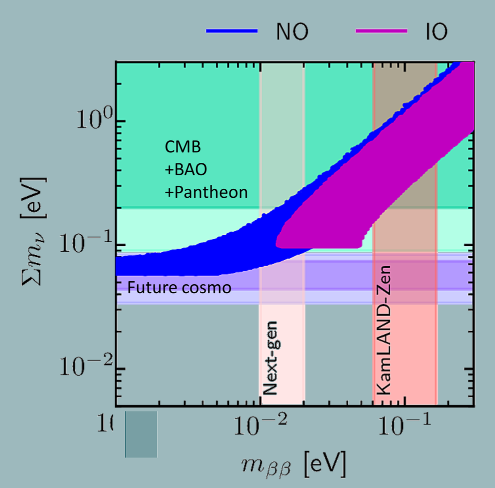
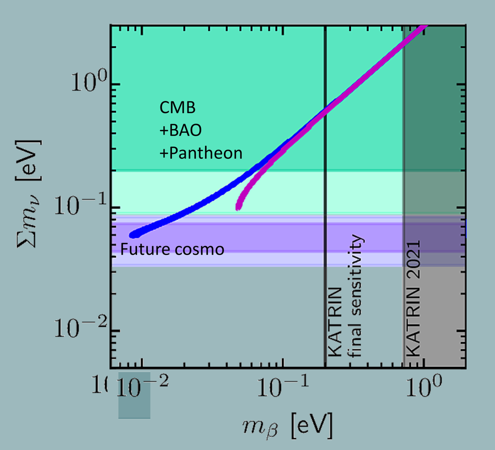
CURRENT LIMITS ON NEUTRINO MASS



From cosmology:
Planck
CMB+BAO - $\Sigma m_\nu < 0.12$ eV (95% CL)

From 0νββ measurements:
KamLAND-Zen
$m_{\beta\beta} < 0.16$ eV (90% CL)

MODEL DEPENDENT



From kinematic measurements:
KATRIN
$m_\beta < 0.8$ eV (90% CL)

Time-of-flight constraints:
Kamiokande-II (SN1987A)
$m_\nu < 5.7$ eV (95% CL)

MODEL INDEPENDENT

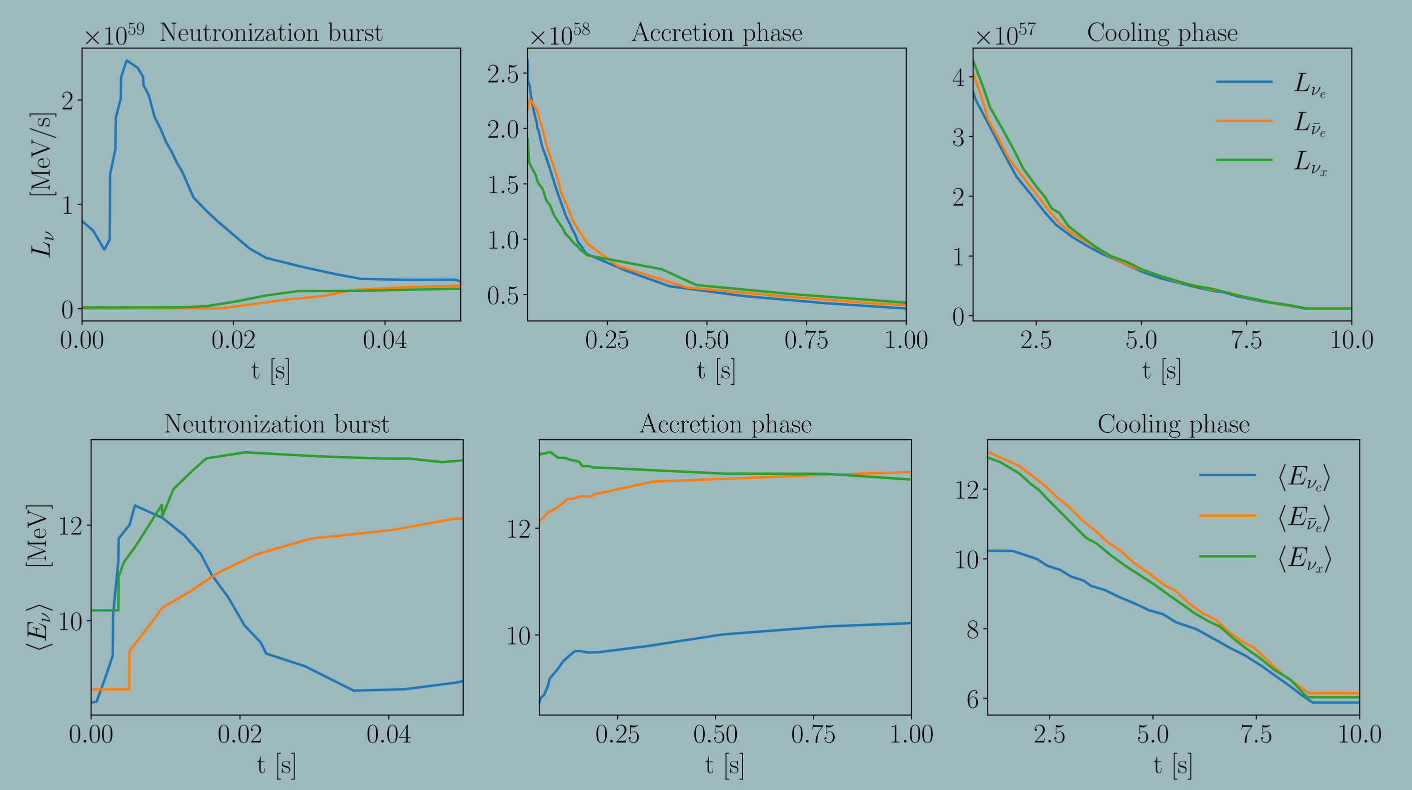
THE DEEP UNDERGROUND NEUTRINO EXPERIMENT

The Deep Underground Neutrino Experiment (DUNE) is a proposed leading-edge neutrino experiment, planning to begin operations in 2026. It will be installed in the Long-Baseline Neutrino Facility, under construction in the United States.

It will consist of two neutrino detectors placed in the world's most intense neutrino beam:

- the Near-detector, hosted at the Fermi National Accelerator Laboratory (Illinois), will study particles interactions near the source of the beam;
- the underground Far-detector, installed 1.300 kilometers downstream of the beam source at the Sanford Underground Research Laboratory (South Dakota), will exploit the Liquid Argon Time Projection Chamber (LArTPC) technology in order to also detect neutrinos of astrophysical origin.

NEUTRINO EMISSION FROM SUPERNOVA BURST



$$\Phi^0_{\nu_\beta}(E,t) = \frac{L_{\nu_\beta}(t)}{4\pi D^2}\frac{\varphi_{\nu_\beta}(E,t)}{\langle E_{\nu_\beta}(t)\rangle} \quad \text{with} \quad \Phi^0_{\nu_\mu}(E,t) = \Phi^0_{\nu_\tau}(E,t) \equiv \Phi^0_{\nu_x}(E,t)$$

$$\varphi_{\nu_\beta}(E,t) = \left[\frac{[\alpha_\beta(t)+1]^{(\alpha_\beta(t)+1)}}{\Gamma(\alpha_\beta(t)+1)\langle E_{\nu_\beta}(t)\rangle}\right]\left(\frac{E}{\langle E_{\nu_\beta}(t)\rangle}\right)^{\alpha_\beta(t)} \exp\left\{\frac{-[\alpha_\beta(t)+1]E}{\langle E_{\nu_\beta}(t)\rangle}\right\}$$

REFERENCES

[1] DUNE collaboration et al. *arXiv:2008.06647.*
[2] E. Di Valentino, S. Gariazzo and O. Mena. *arXiv:2106.15267*
[3] T. J. Loredo and D. Q. Lamb. *arXiv:astro-ph/0107260*
[4] SNOwGLoBES. *https://webhome.phy.duke.edu/~schol/snowglobes/*
[5] A. S. Dighe and A. Y. Smirnov. *arXiv:9907423v2*

Effects of non-zero neutrino mass:

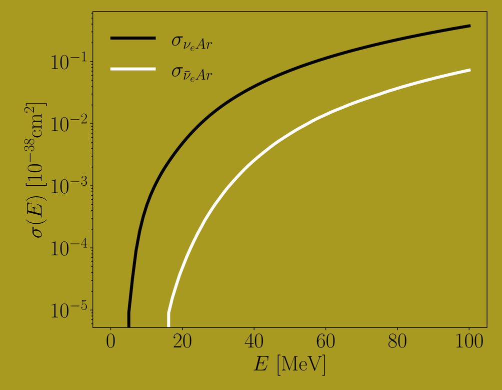
manifest in a time-delay with which neutrinos emitted from the Supernova are detected at the Earth.

$$t_i = t_{\text{det}} + t_{\text{off}} - \frac{D}{2c}\left(\frac{m_\nu}{E_{\nu_i}}\right)^2$$

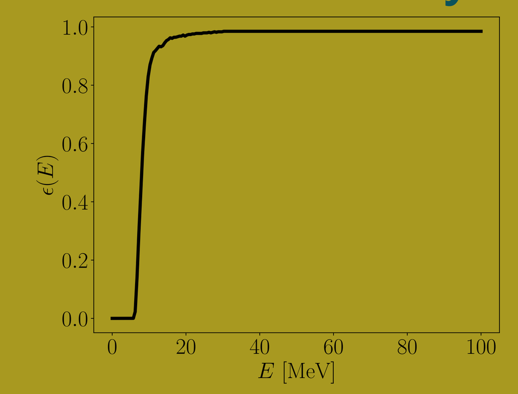
Interaction channels in LArTPC:

$$\nu_e\ {}^{40}\text{Ar} \longrightarrow e^-\ {}^{40}\text{K}^*$$
$$\bar{\nu}_e\ {}^{40}\text{Ar} \longrightarrow e^+\ {}^{40}\text{Cl}^*$$

Cross section



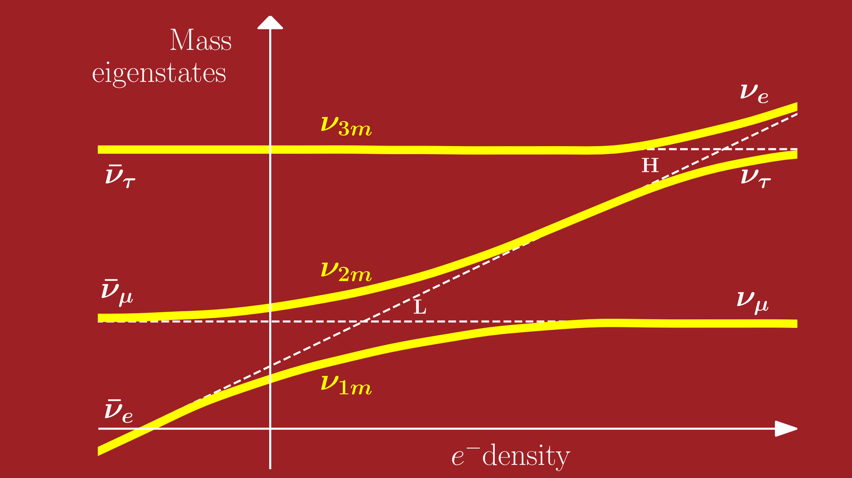
DUNE efficiency



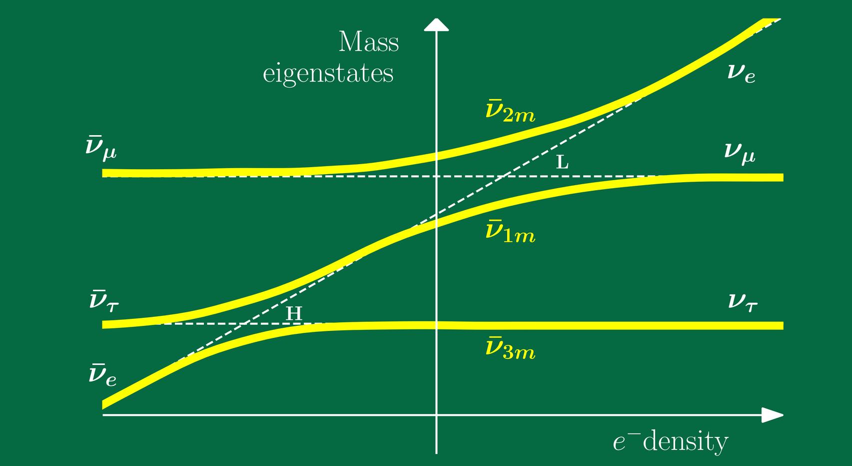
Signal rate at the detector:

$$R(t,E_{\nu_e}) = N_{\text{target}} M_d \sigma_{\nu_e Ar}(E_{\nu_e})\Phi_{\nu_e}(t,E_{\nu_e})\epsilon(E_{\nu_e})$$

M_d = *40* kton of LAr



$$\Phi^{\text{NO}}_{\nu_e} = p^{\text{NO}}\Phi^0_{\nu_e} + (1-p^{\text{NO}})\Phi^0_{\nu_x}$$
$$p^{\text{NO}} = |U_{e3}|^2$$



$$\Phi^{\text{IO}}_{\nu_e} = p^{\text{IO}}\Phi^0_{\nu_e} + (1-p^{\text{IO}})\Phi^0_{\nu_x}$$
$$p^{\text{IO}} = |U_{e2}|^2$$

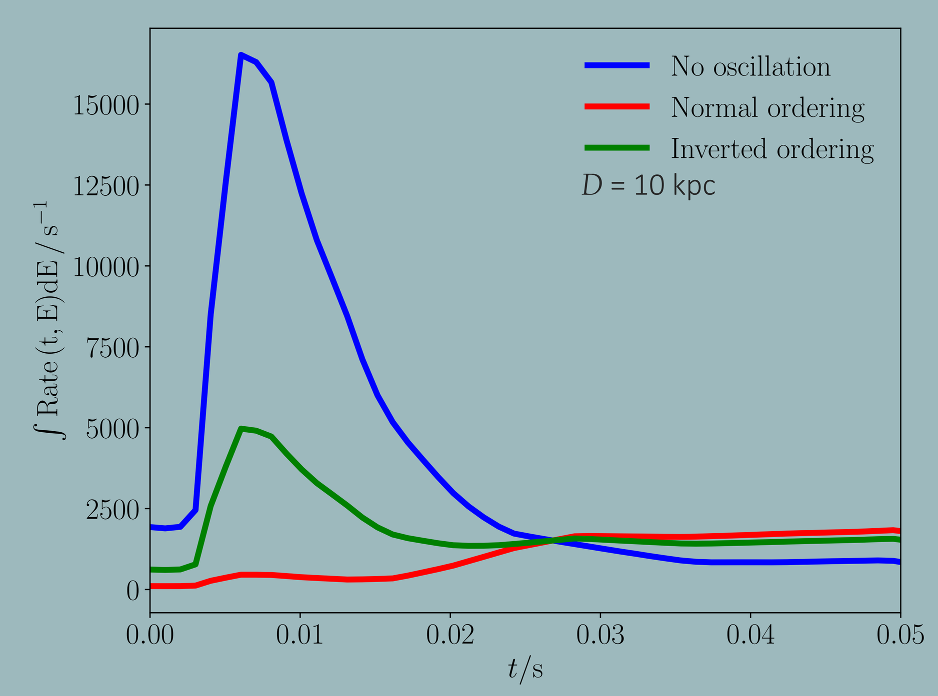
The assumed Likelihood:

$$\mathcal{L} = \prod_{i=1}^{N_d} e^{R(t_i)}\left[\int R(t_i,E)\mathcal{G}_i(E)\mathrm{d}E\right]$$

Estimation of theoretical bounds:

$$\chi^2(m_\nu) = -2\log\mathcal{L}$$
$$\Delta\chi^2(m_\nu) = \chi^2(m_\nu) - \chi^2_{min}$$

EXPECTED EVENT RATES IN DUNE FOR A GALACTIC SUPERNOVA BURST



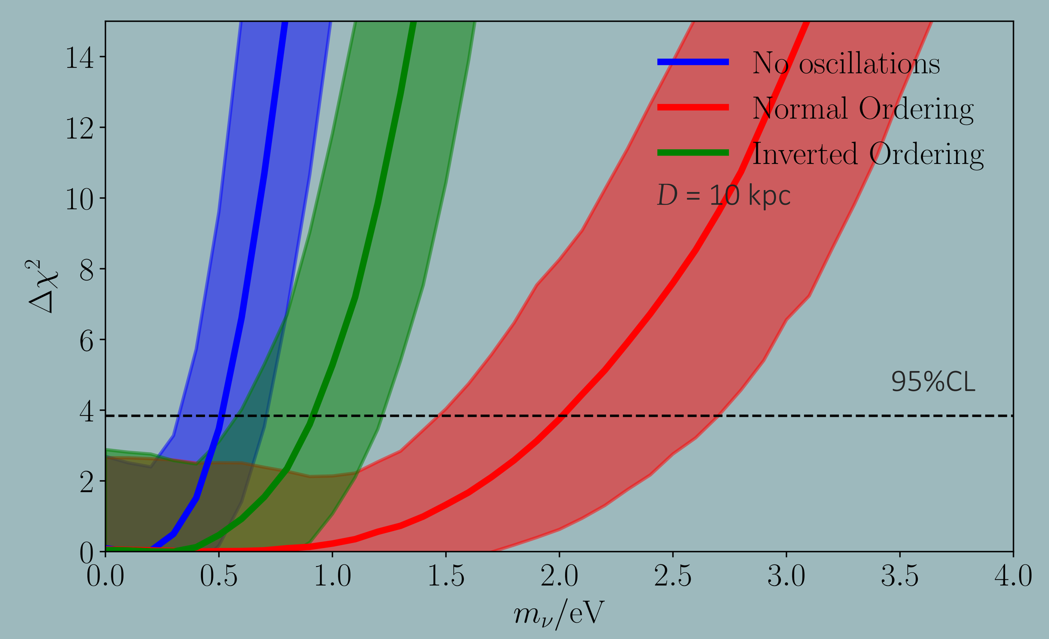
Considering the 9s time window of the Supernova neutrinos emission, the expected number of electron neutrino interactions in DUNE considering all possible oscillations scenarios are,

- in absence of flavour oscillations: **~ 859 events**;
- in the Normal ordering (NO) oscillation scheme: **~ 1372 events**;
- in the Inverted ordering (IO) oscillation scheme: **~ 1228 events**.

Focusing on the *neutronization burst*, occurring during the first *50ms* after the Supernova explosion, we expect to detect,

- in absence of flavour oscillations: **~ 201 events**;
- assuming the NO oscillation scheme: **~ 54 events**;
- assuming the IO oscillation scheme: **~ 95 events**.

EXPECTED NEUTRINO MASS CONSTRAINTS IN DUNE



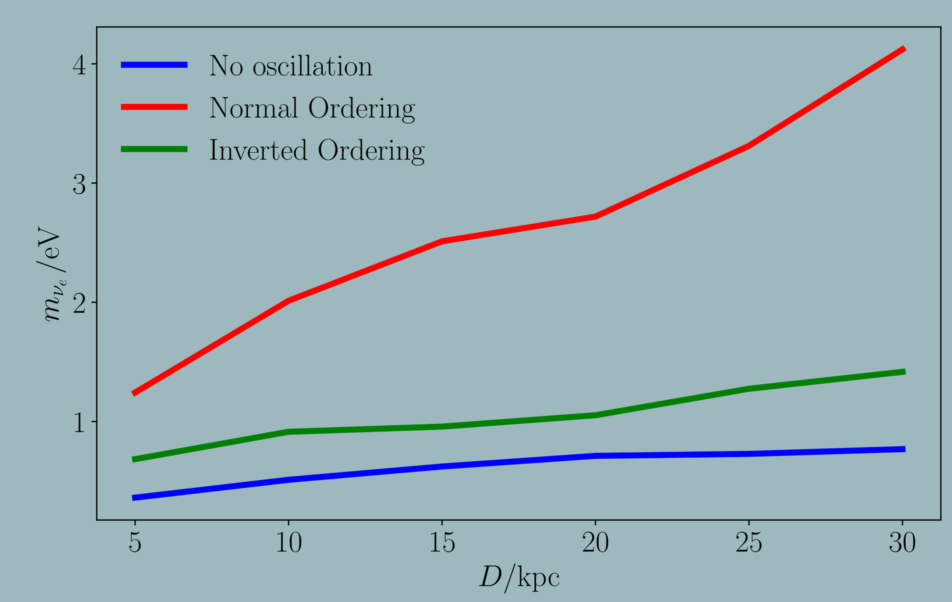
The sensitivity bounds reached by DUNE in constraining the Supernova electron neutrino mass

$$m_{\nu_e} = \sqrt{\sum_{i=1,2,3}|U_{ei}|^2 m_i^2}$$

at 95% CL in each oscillation scenario are,

- in absence of flavour oscillations: **m_{ν_e} < 0.51 eV;**
- in the NO oscillation scheme: **m_{ν_e} < 2.01 eV;**
- in the IO oscillation scheme: **m_{ν_e} < 0.91 eV.**

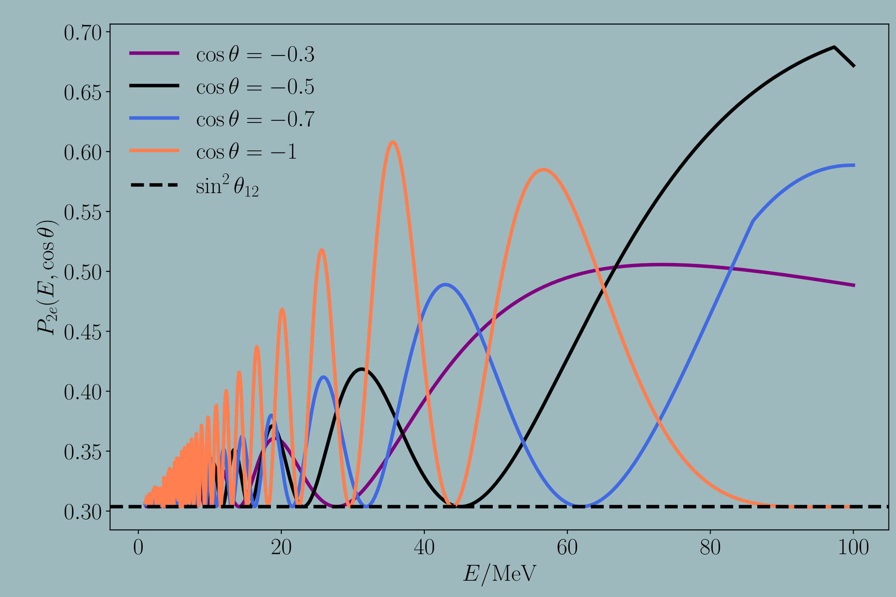
DEPENDENCE ON THE SUPERNOVA DISTANCE



95% CL bounds on Supernova electron neutrino mass obtained by varying the Supernova distance from the Earth.

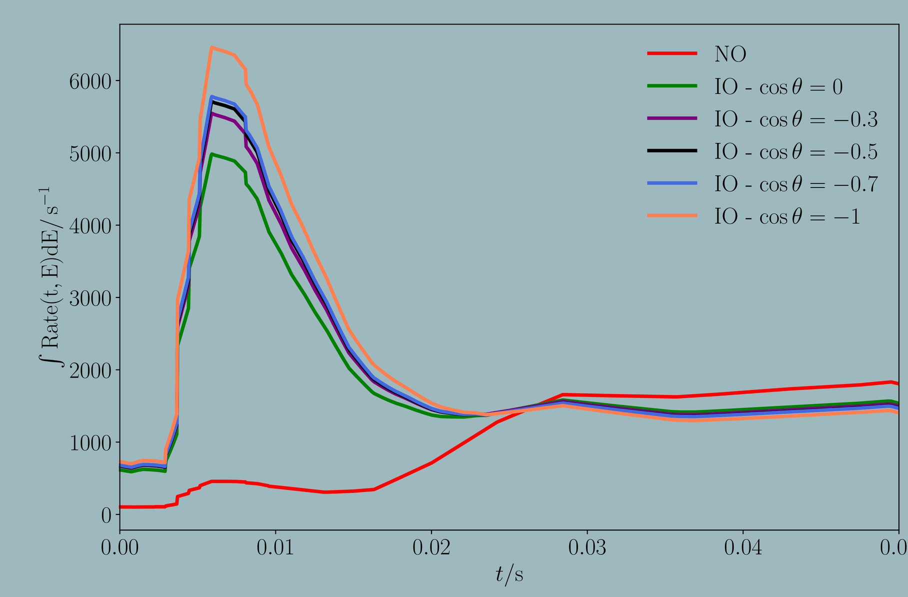
EFFECTS OF PROPAGATION IN THE EARTH MATTER

$$P_{2e} = \sin^2\theta_{12} + \sin^2\theta^m_{12}\sin(2\theta^m_{12} - 2\theta_{12})\sin^2\left(\frac{\Delta m^2_{12}\sin(2\theta_{12})}{\sin(2\theta^m_{12})}\frac{L(\cos\theta)}{4E}\right) \longrightarrow \begin{array}{l}\Phi^{\oplus\text{NO}}_{\nu_e} = \Phi^{\text{NO}}_{\nu_e}\\ \Phi^{\oplus\text{IO}}_{\nu_e} = P_{2e}\Phi^0_{\nu_e} + (1-P_{2e})\Phi^0_{\nu_x}\end{array}$$



Assuming a constant density along the whole neutrino path in the Earth matter:

cosθ = -0.3 : **~ 100**
cosθ = -0.5 : **~ 101**
cosθ = -0.7 : **~ 102**
cosθ = -1 : **~ 107**



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