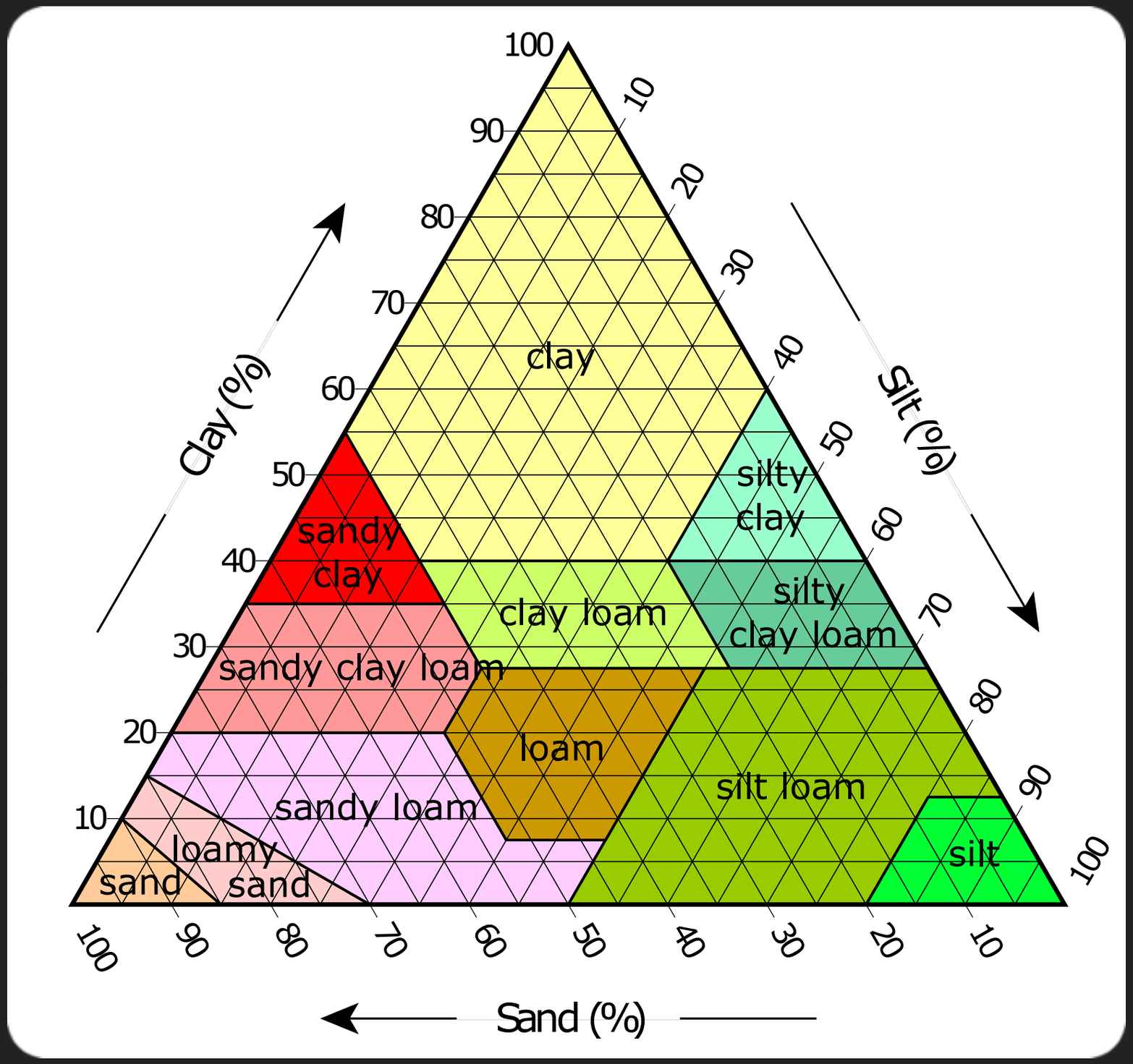
MILO VERMEULEN — 5-8-2020

EIGENNEUT

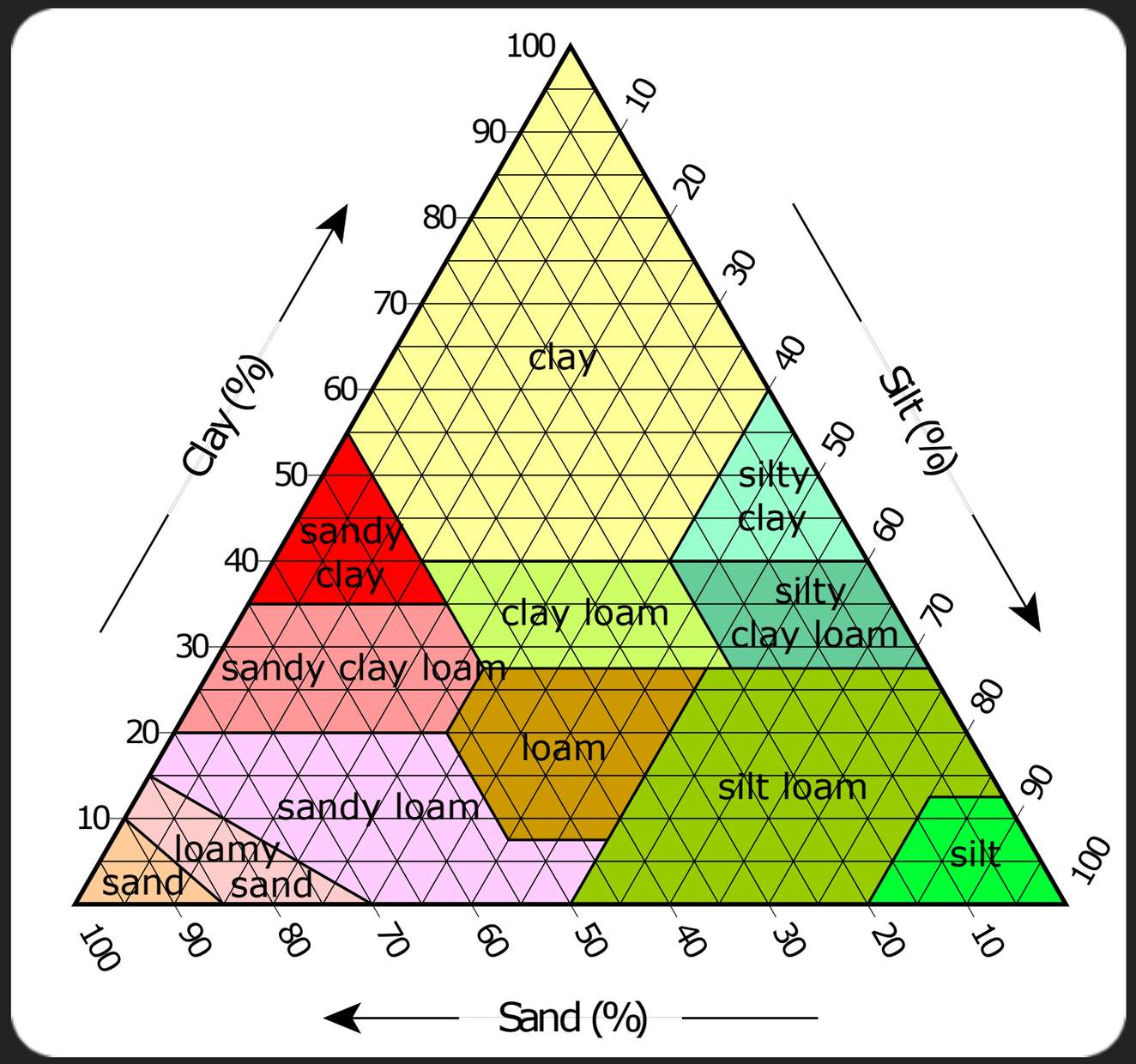
TERNARY GRAPH

USDA soil textural triangle



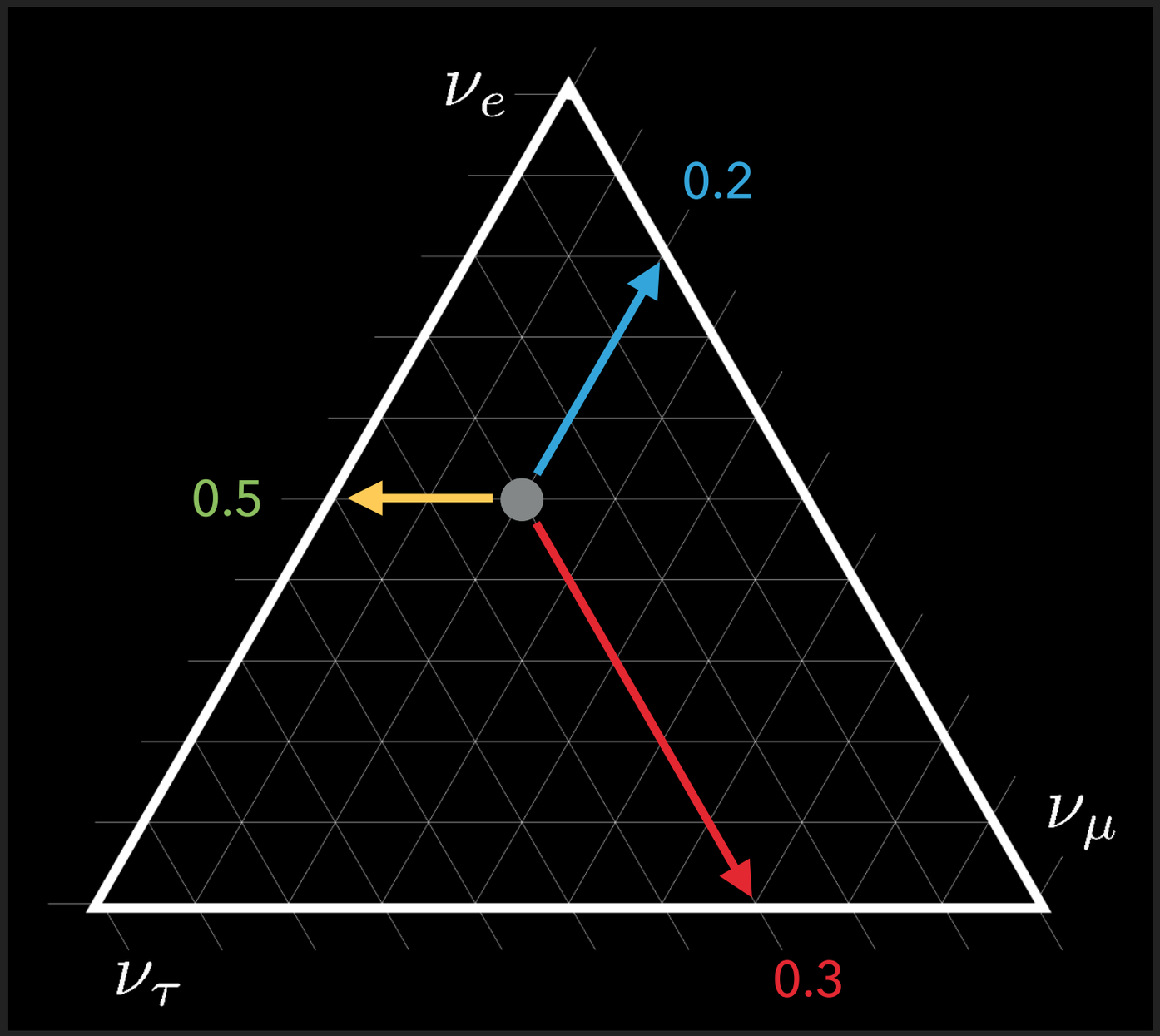
TERNARY GRAPH

- Point in the graph signifies ratio between three components that add up to 100%
- Used in chemistry, solid state physics, etc.
- Relevant example: flavour components of neutrino



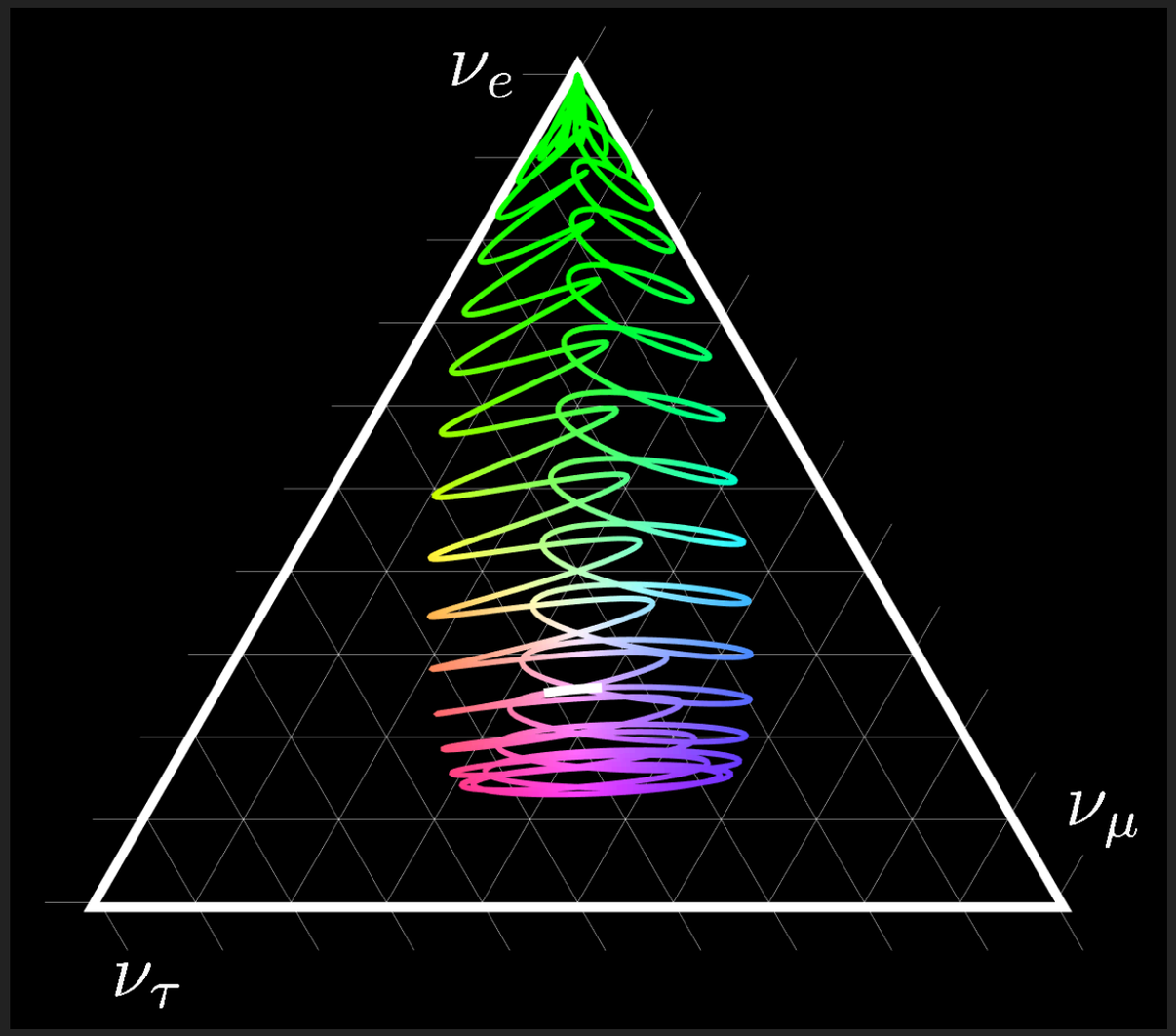
TERNARY GRAPH

- Points in corners are pure flavour states: starting point of any neutrino
- Small demonstration of program



FUNCTIONALITY SUMMARY

- Visualise the evolution of a neutrino in flavour space
- Alter/animate any neutrino oscillation parameter
- Switch between neutrino and antineutrino, normal and inverted mass hierarchy
- Export data to file for 2D plotting



EXPORTING DATA

- Can export oscillation data as a function of E, L or any other parameter (ρ, θ_{ij}, Δm^2_{ij}, δ_{CP})
- Parameters saved to separate file when exporting

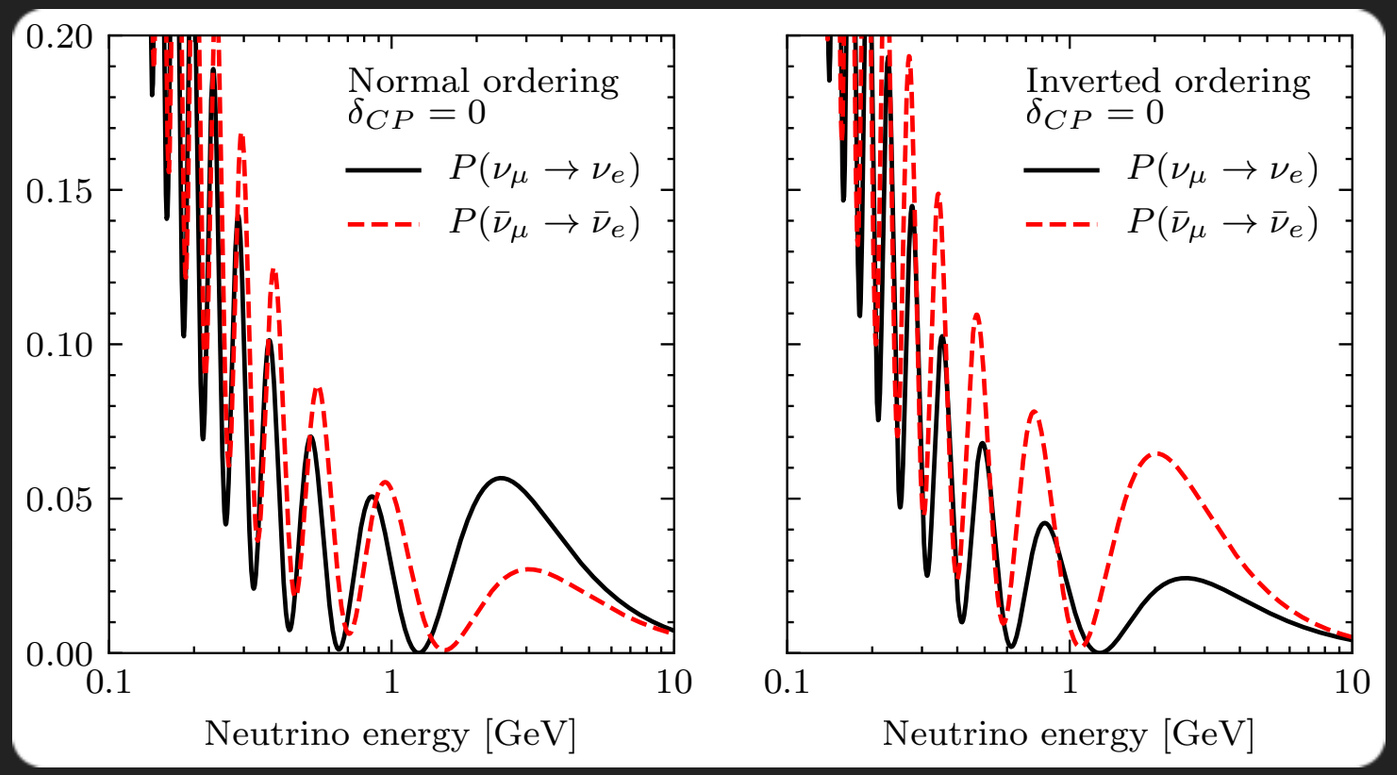
nu.csv

x	nue	numu	nutau
0	0.163769	0.508517	0.327715
0.49995	0.163744	0.508479	0.327776
0.9999	0.16372	0.508442	0.327838
1.49985	0.163696	0.508404	0.3279
1.9998	0.163672	0.508367	0.327961
2.49975	0.163648	0.508329	0.328023
2.9997	0.163623	0.508292	0.328085
3.49965	0.163599	0.508254	0.328147
3.9996	0.163574	0.508217	0.328209
4.49955	0.16355	0.508179	0.328271
4.9995	0.163525	0.508141	0.328334
5.49945	0.1635	0.508104	0.328396
5.9994	0.163475	0.508066	0.328458
6.49935	0.163451	0.508029	0.328521

nuparameters.csv

Parameter	Value
Initial flavour	1
Antineutrino [bool]	1
Energy [GeV]	0.9
Travel distance [km]	1284.9
theta12 [rad]	0.5843
theta23 [rad]	0.738
theta13 [rad]	0.148
Dm21sq [eV^2]	7.5e-05
Dm31sq [eV^2]	-0.002457
dCP [rad]	6.28319
Matter density [kg/m^3]	2848.2

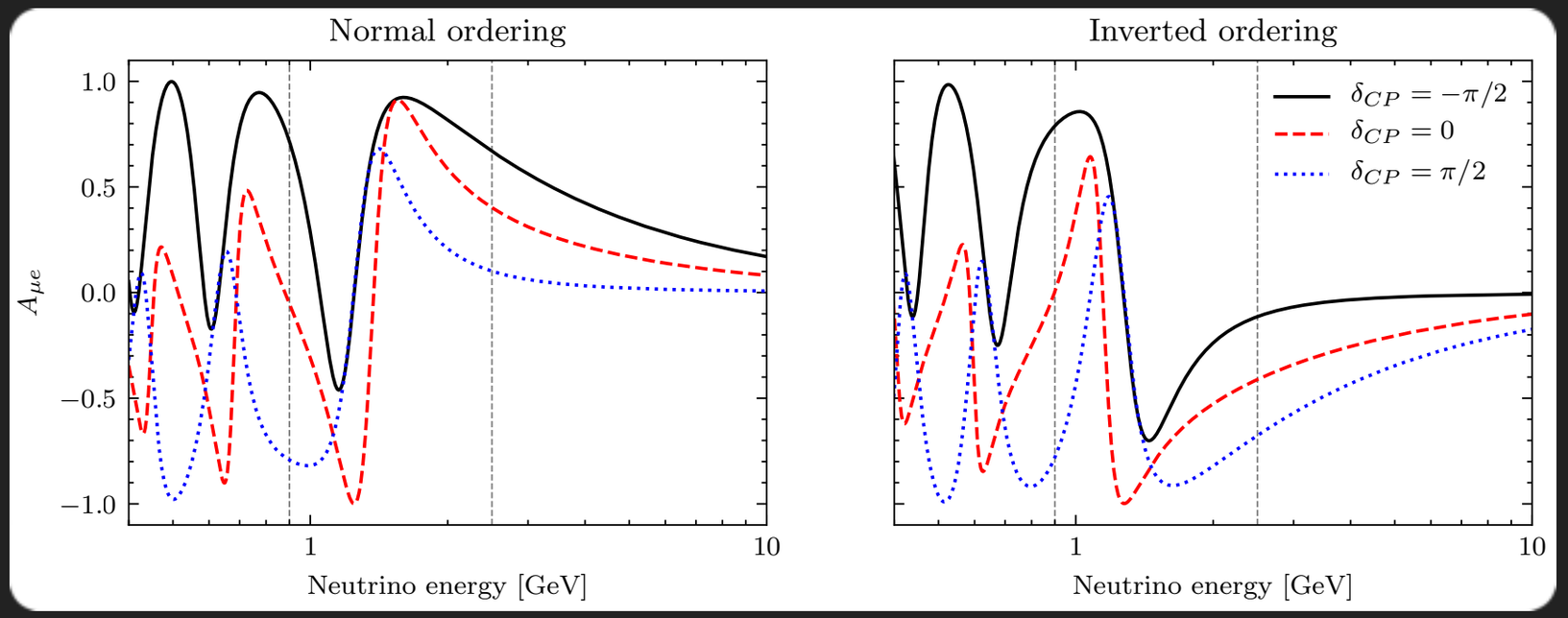
EXAMPLE PLOTS



Energy spectrum of neutrino appearance at DUNE FD

Appearance asymmetry at DUNE FD

$$A_{\mu e} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$



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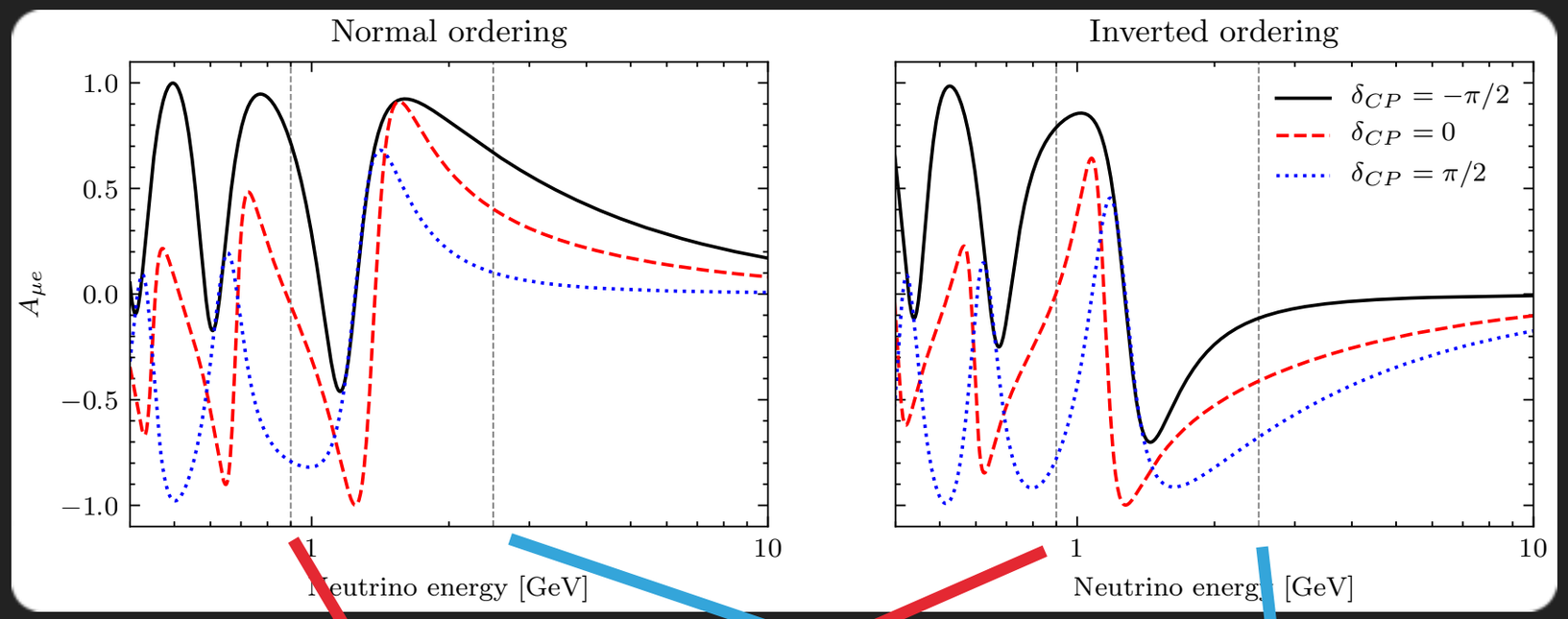
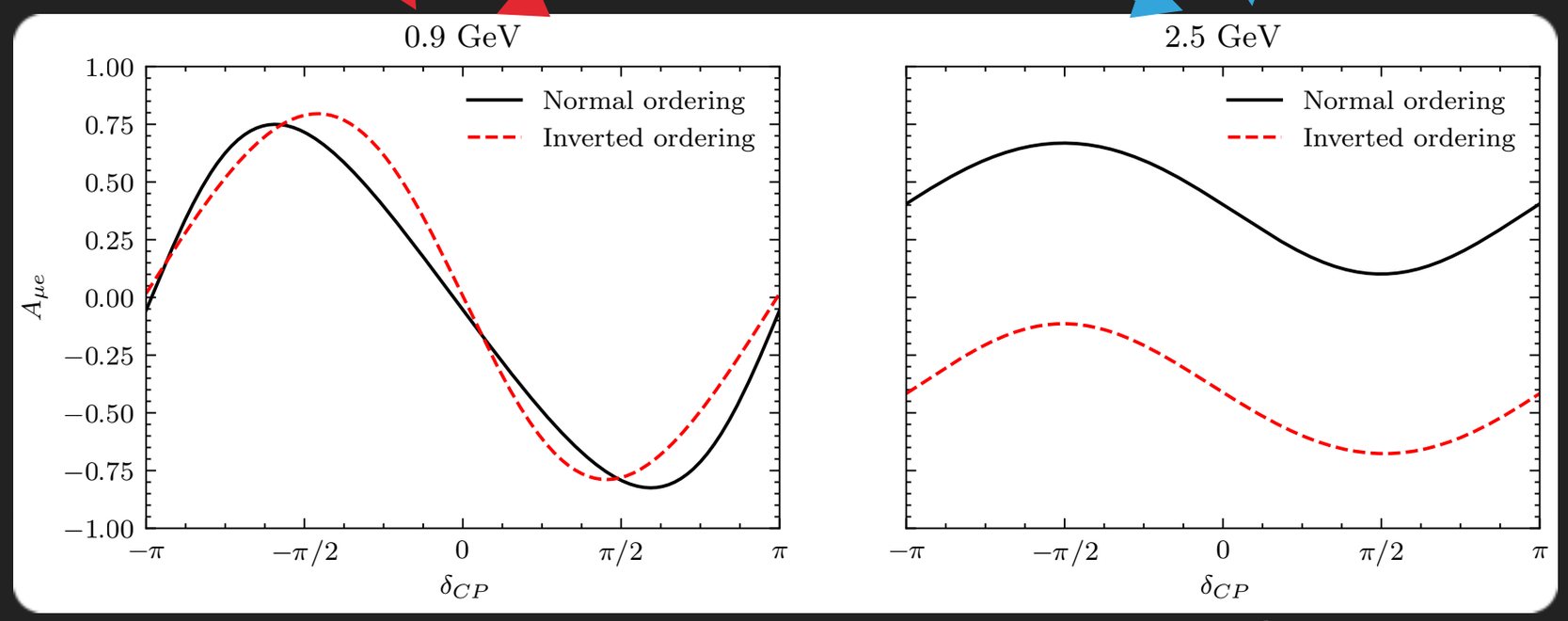


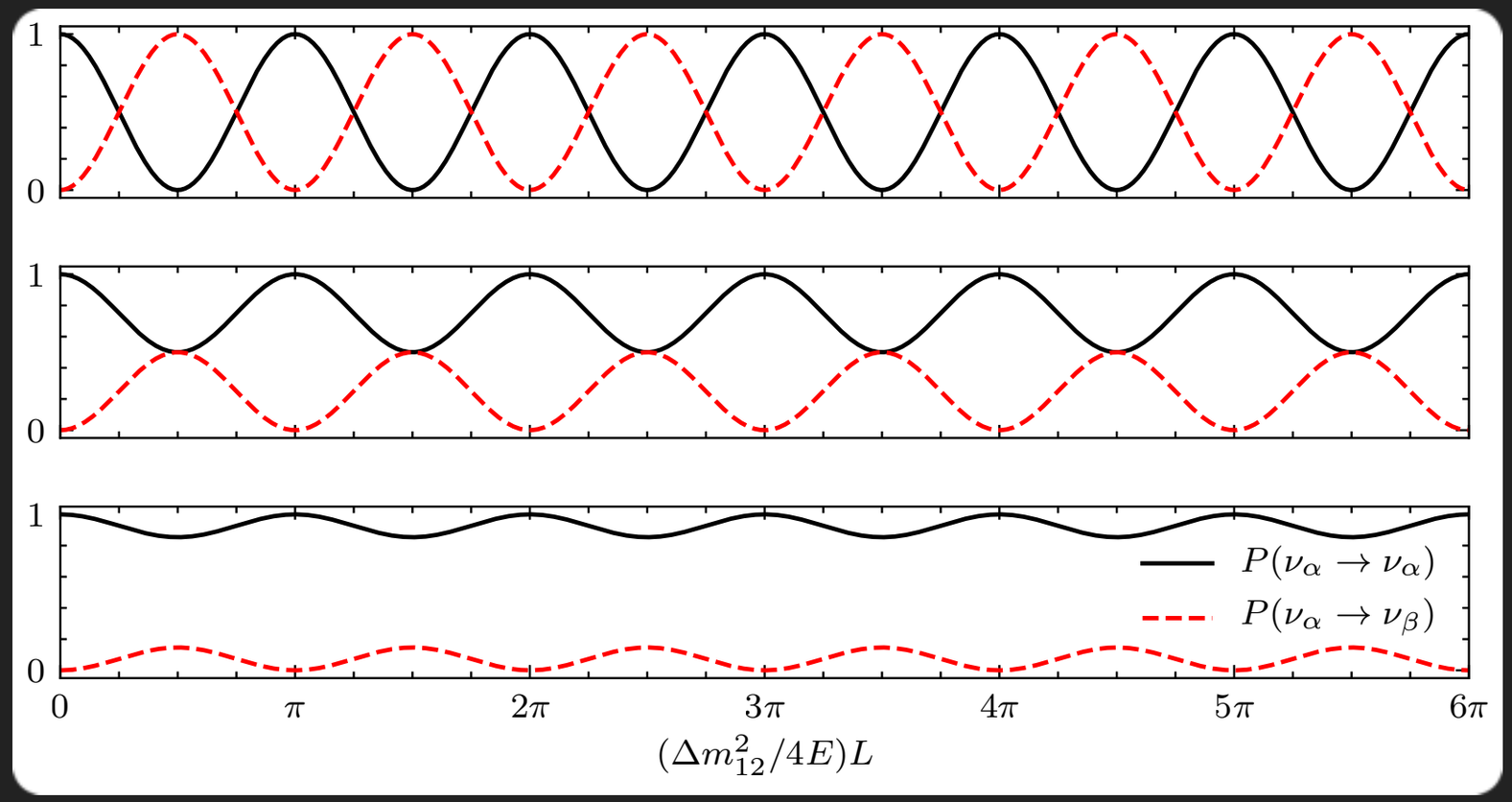


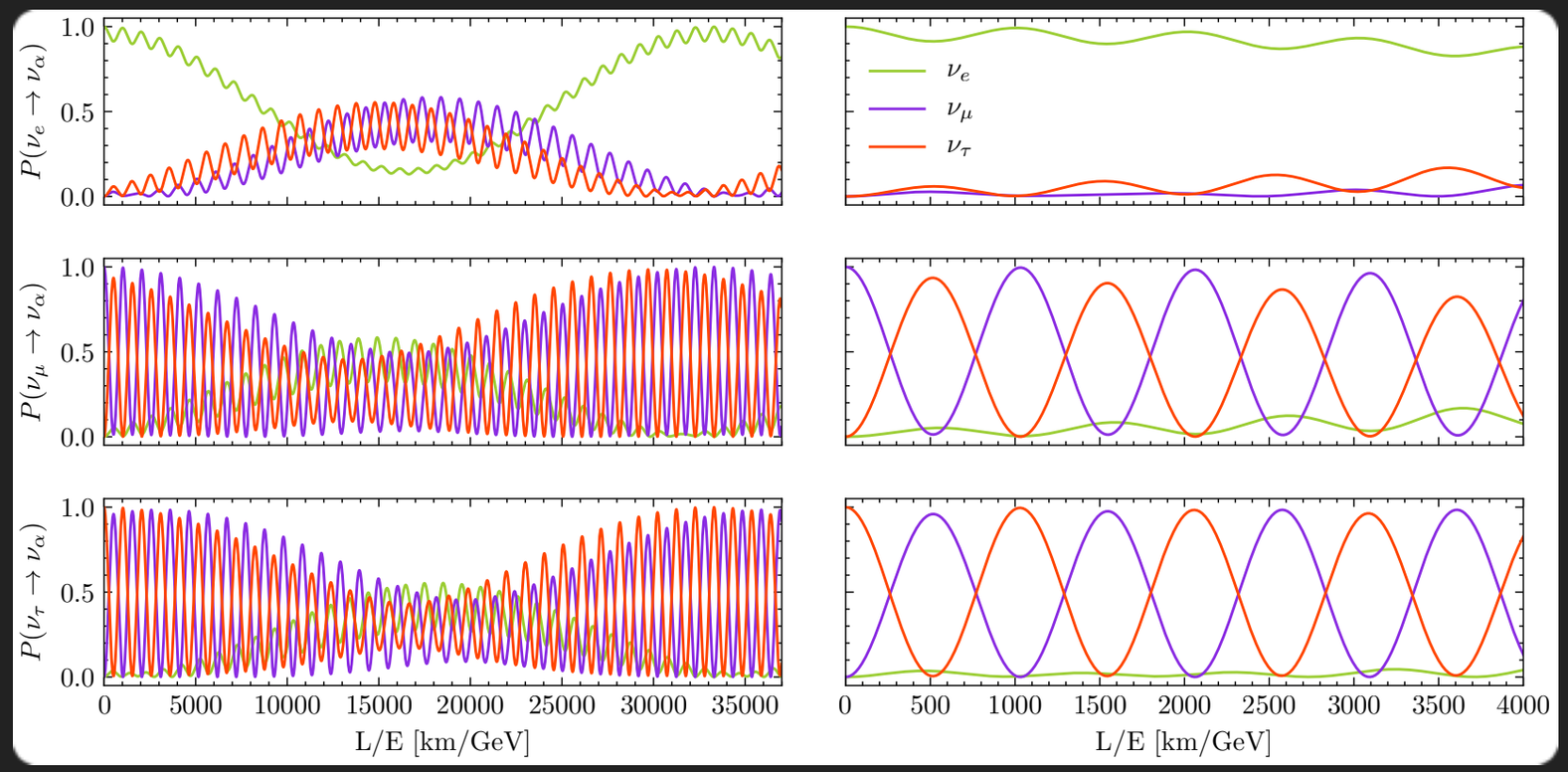
Measure δ_{CP} regardless of ordering

Measure ordering regardless of δ_{CP}

EXAMPLE PLOTS

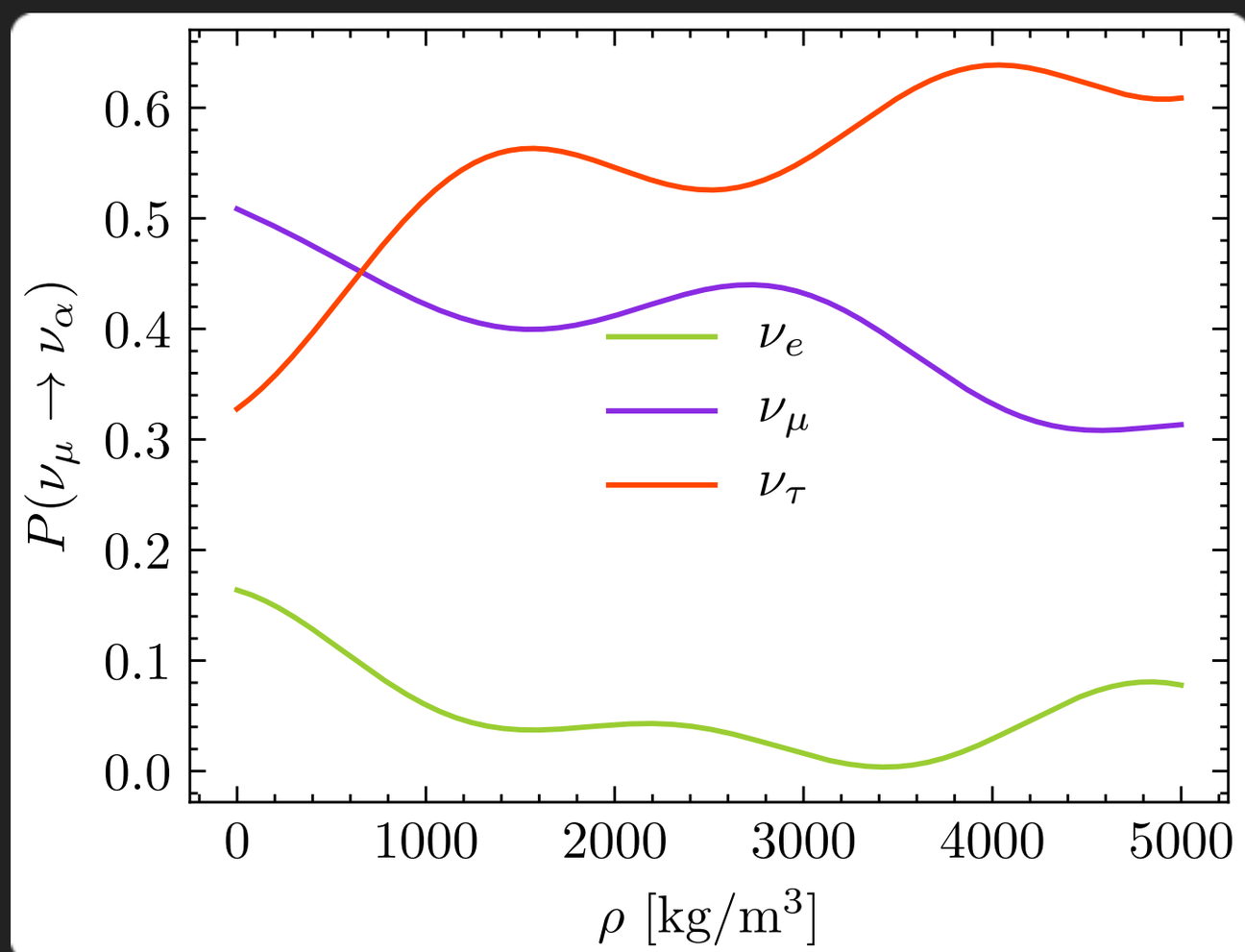
- Two and three-neutrino oscillation over distance

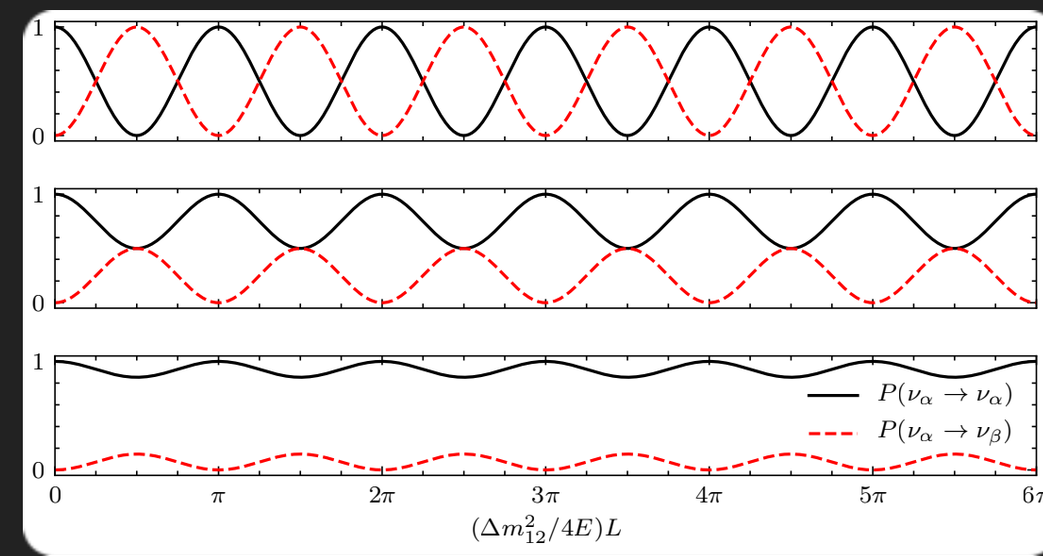


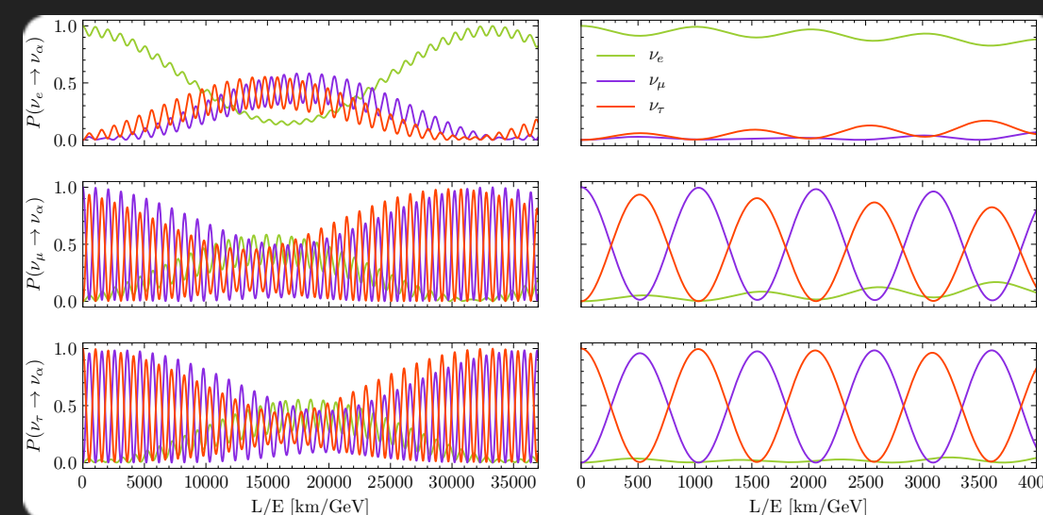


EXAMPLE PLOTS

- Three-neutrino oscillation as a function of earth density(?)
- Endless possibilities





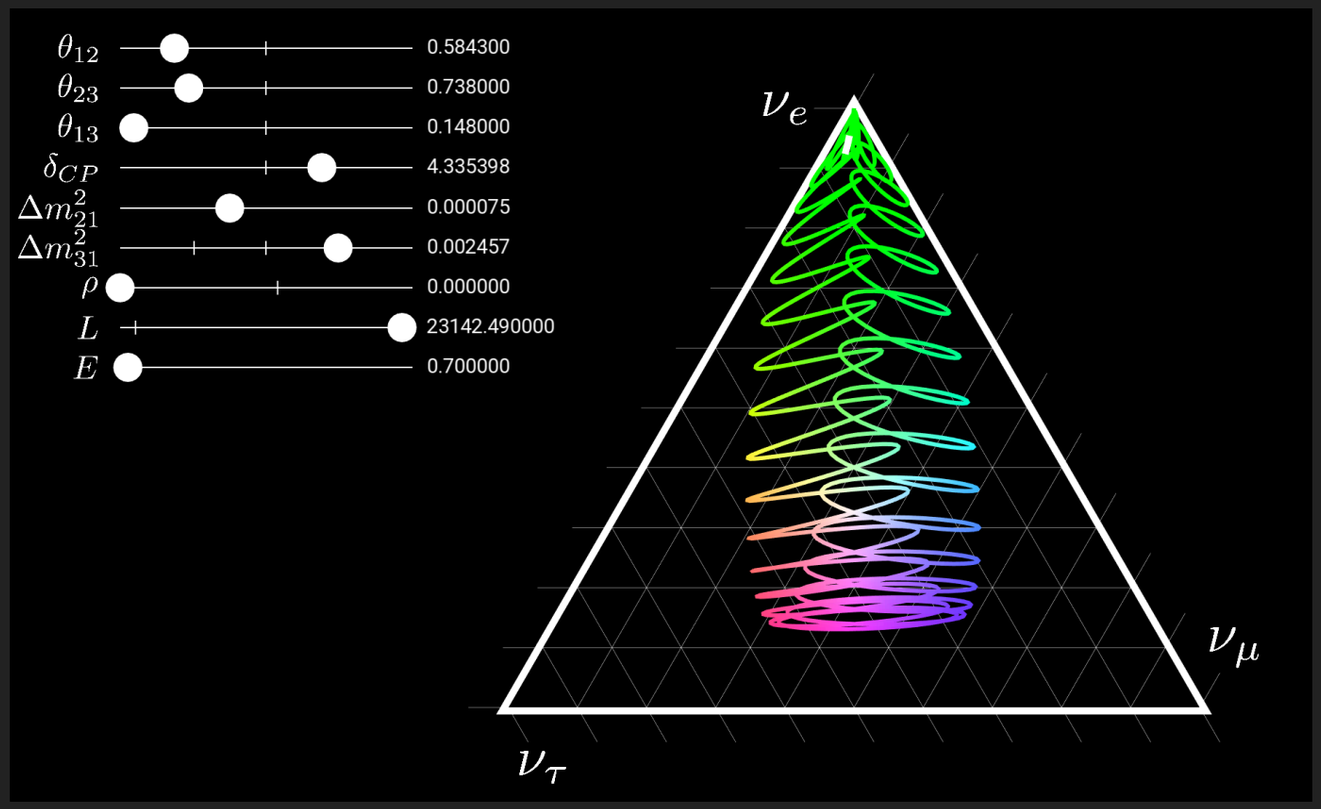


2.5 GeV initial ν_μ at a distance of 12,500 km

BASIC INFORMATION

- Program written in C++, built using CMake
- Tested on macOS and Ubuntu
- Dependencies: SFML 2 for drawing, Eigen 3 for matrix operations
- Everything custom-made

Check it out on GitHub!
https://github.com/mivermeu/EigenNeut



BACKUP

INNER WORKINGS

- General case: $|\nu_\alpha(x)> = Ue^{-iHx}U^\dagger|\nu_\alpha(0)>$
- Vacuum case:
  $H = \text{diag}(E_1, E_2, E_3) \quad \Rightarrow \quad e^H = \text{diag}(e^{E_1}, e^{E_2}, e^{E_3})$
- Matter case (using Lie product formula):
  $H = H_0 + UVU^\dagger \quad \Rightarrow \quad e^H = \lim_{N\to\infty}\left(e^{H/N}Ue^{V/N}U^\dagger\right)^N$
  where $H_0 = \text{diag}\left(E_1, E_2, E_3\right), \quad V = \text{diag}\left(\sqrt{2}G_F n_e, 0, 0\right)$
- Use time-costly exponential function when exporting oscillation data instead of Lie product formula approximation