High Energy Analysis and Application to Dark Matter Search

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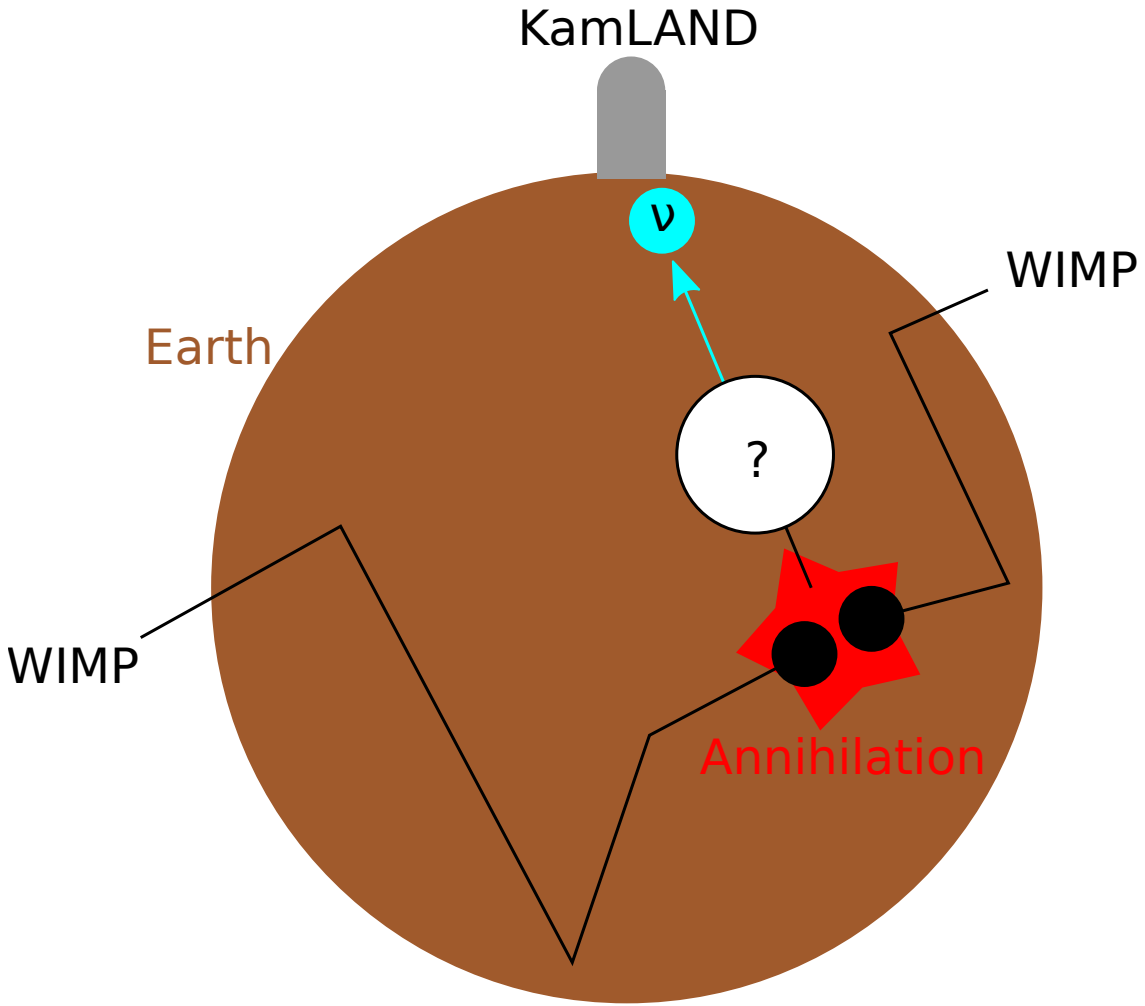
Overview

1. Previous work
2. Signal and background scheme
3. Model building
   - Earth model and neutrino oscillation w/ matter effects
   - Background model (M. Honda tables)
   - Dark matter capture simulation (DarkSUSY)
   - Signal model (WimpSim)
4. Data
   - Data selection
   - Fit Model and Data
   - Dark matter bounds

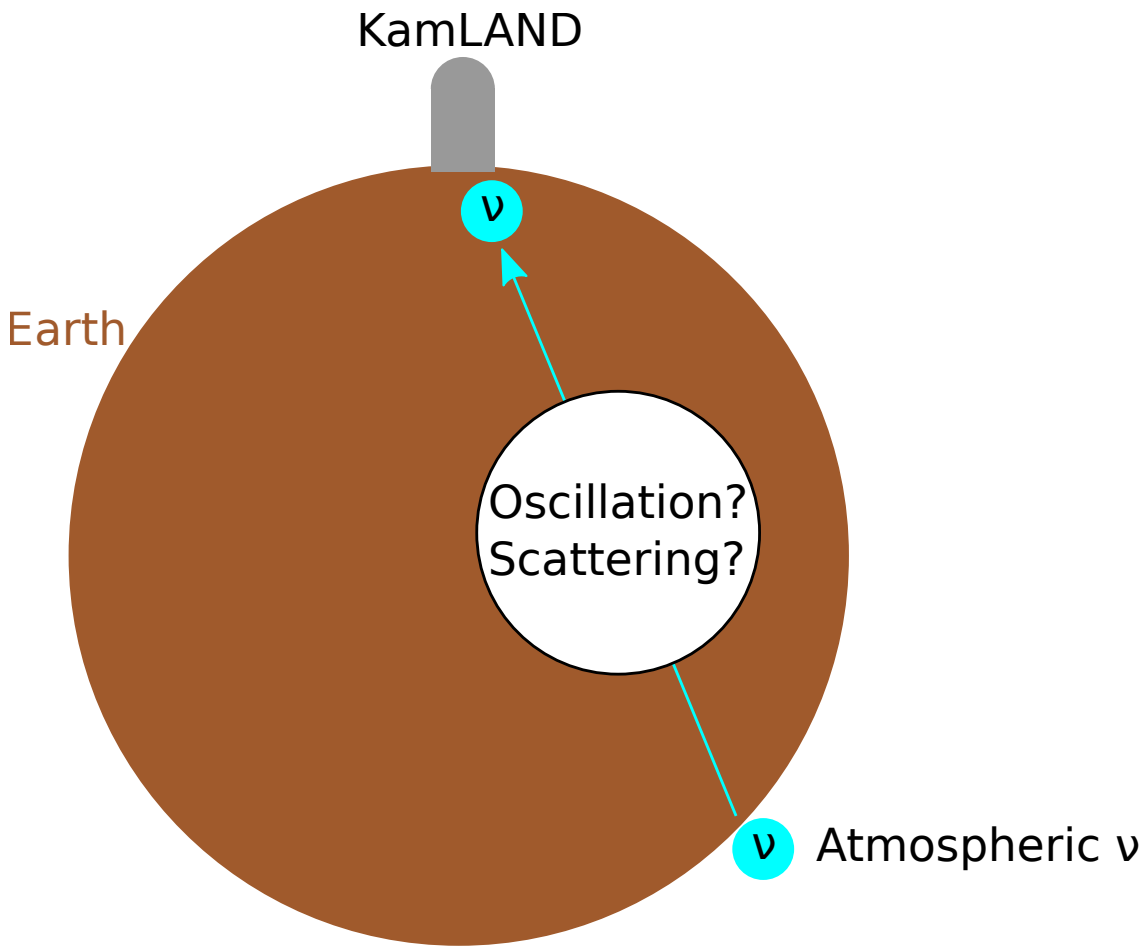
Previously at UCLA I talked about...

- Energy callibration @ high energies using minimum-ionizing cosmic ray μ
- Explored ways to cut PMT prepulsing
  $\Longrightarrow$ conclusion: difficult
  $\Longrightarrow$ useful to keep all gain channel signals
  $\Longrightarrow$ but prepulsing is $\sim$few% effect so ν directionality fitter tuned to be insensitive to prepulsing
- ν directionality fitter tested using MC
  $\Longrightarrow$ fitter valid for energy $>\sim$ 500 MeV

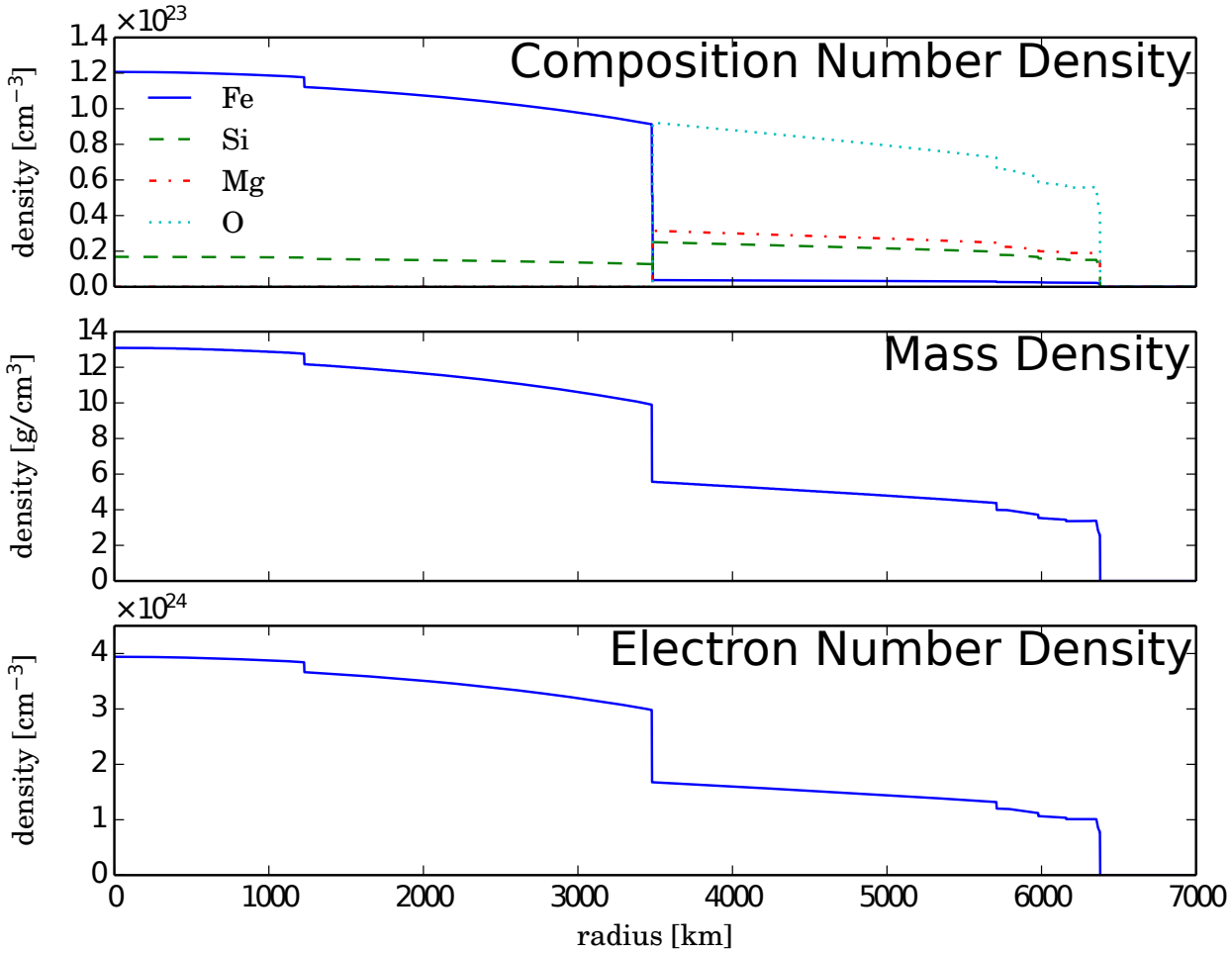
Signal: WIMP annihilation induced ν



Background: Atmospheric ν



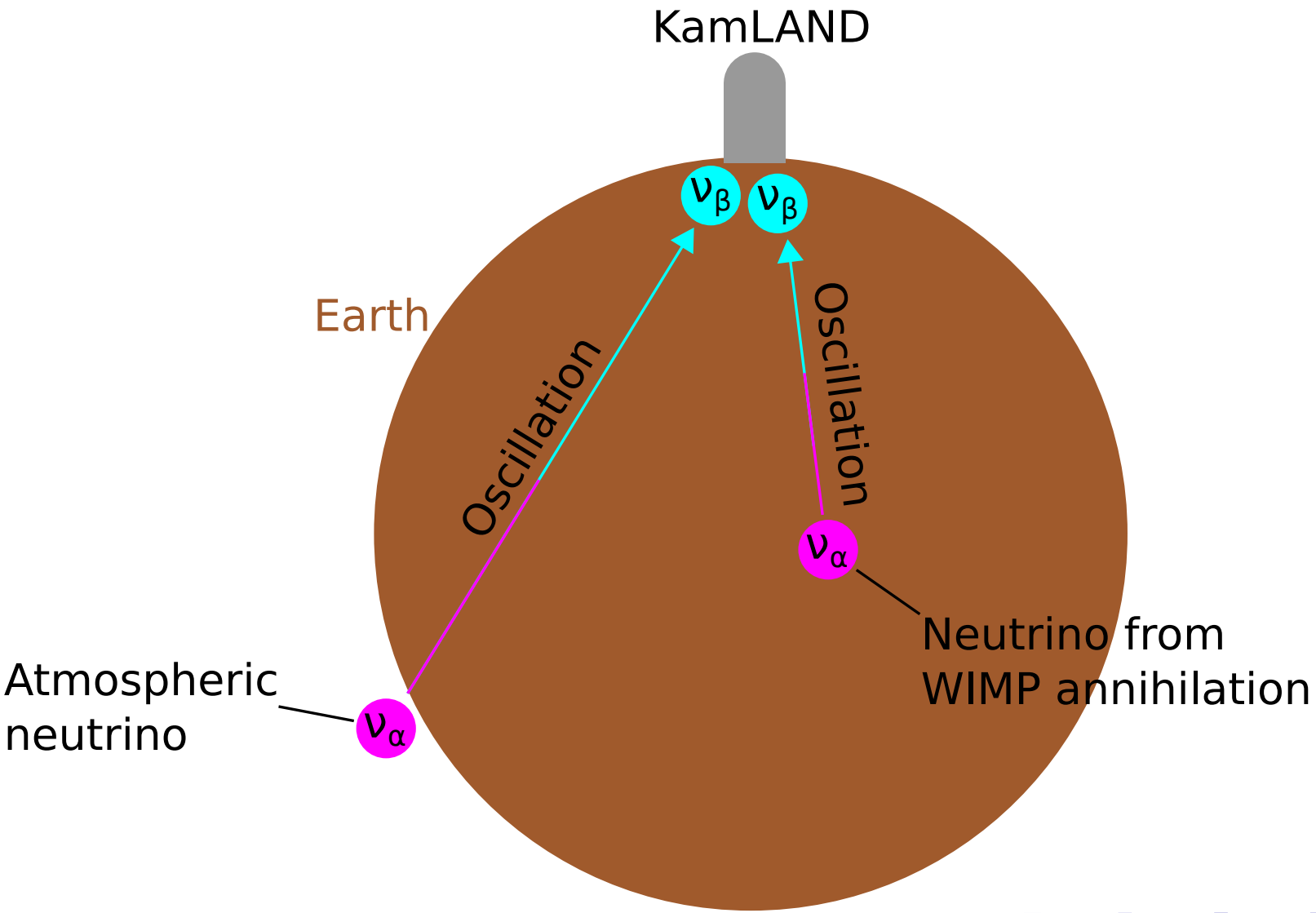
Earth Model (PREM)



Neutrino Oscillation Parameters (PDG 2014)

- $\sin^2(2\theta_{12}) = 0.846 \pm 0.021 \rightarrow \theta_{12} = 33.45^\circ$
- $\sin^2(2\theta_{13}) = (9.3 \pm 0.8) \times 10^{-2} \rightarrow \theta_{13} = 8.88^\circ$
- $\sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018} \rightarrow \theta_{23} = 44.09^\circ$ (normal hierarchy)
- $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\,\text{eV}$
- $\Delta m^2_{31} = (2.52 \pm 0.06) \times 10^{-3}\,\text{eV}$ (normal hierarchy)

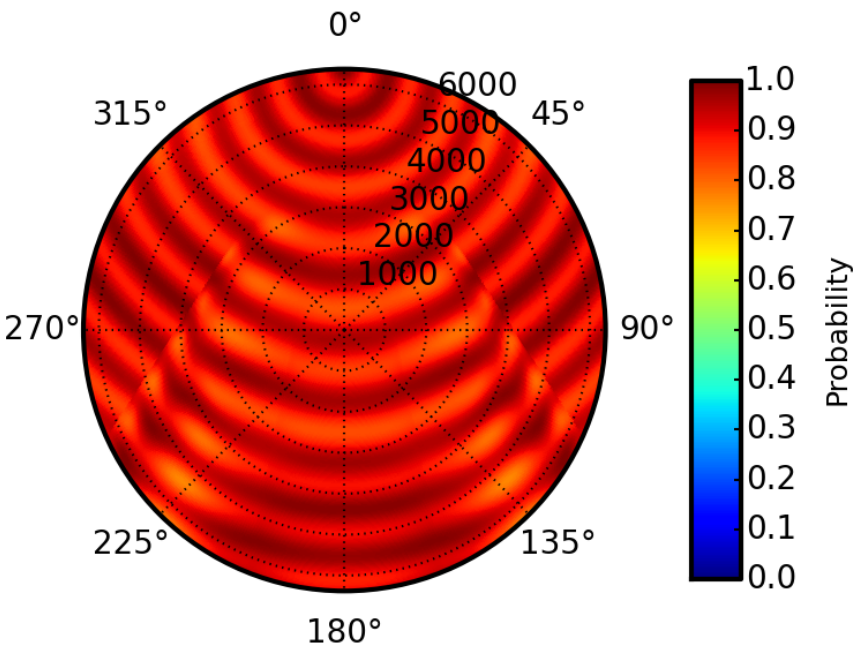
ν produced in Earth or atmosphere will oscillate by the time it reaches KamLAND



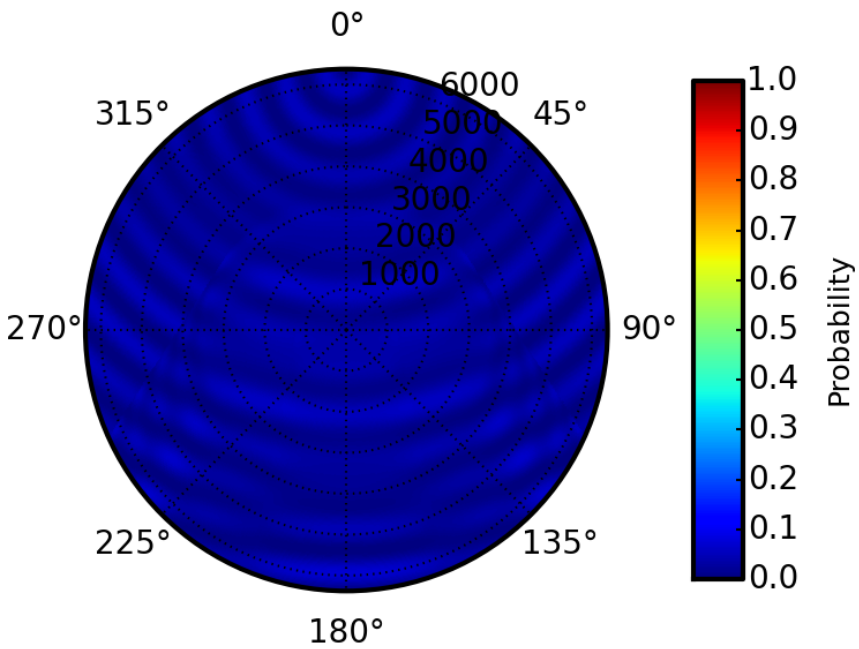
ν oscillation probability at 1 GeV

KamLAND is at radius $= 6378\,\text{km}$ and angle $= 0°$.
Following is cross-section of Earth through Earth center and KamLAND.
Color represents oscillation probability $P(\nu_\alpha \to \nu_\beta)$ for ν_α created in Earth and ν_β arriving at KamLAND.

(a) $\nu_e \to \nu_e$



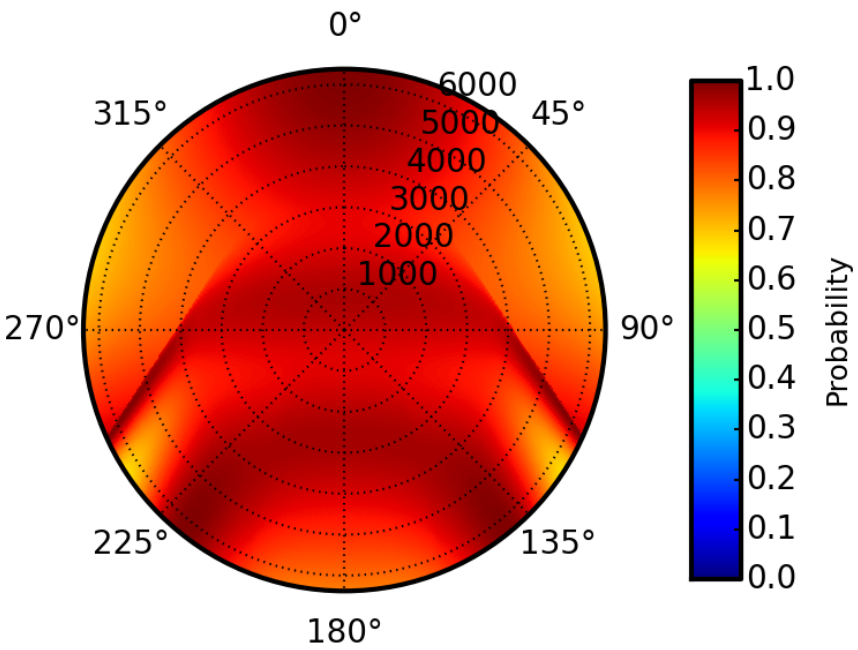
(b) $\nu_e \to \nu_\mu$



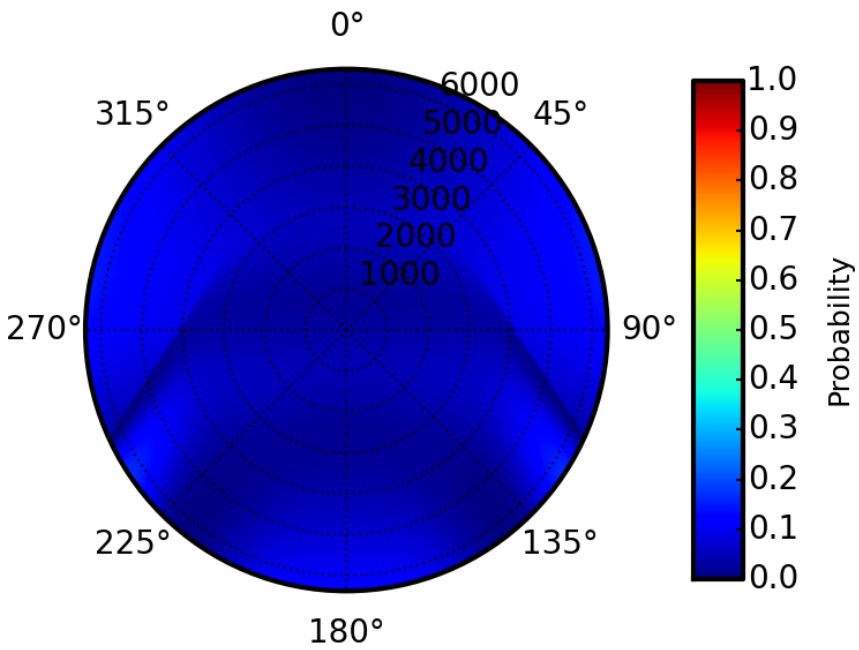
ν oscillation probability at 10 GeV

KamLAND is at radius = 6378 km and angle = 0°.
Following is cross-section of Earth through Earth center and KamLAND.
Color represents oscillation probability $P(\nu_\alpha \to \nu_\beta)$ for ν_α created in Earth and ν_β arriving at KamLAND.

(a) $\nu_e \to \nu_e$

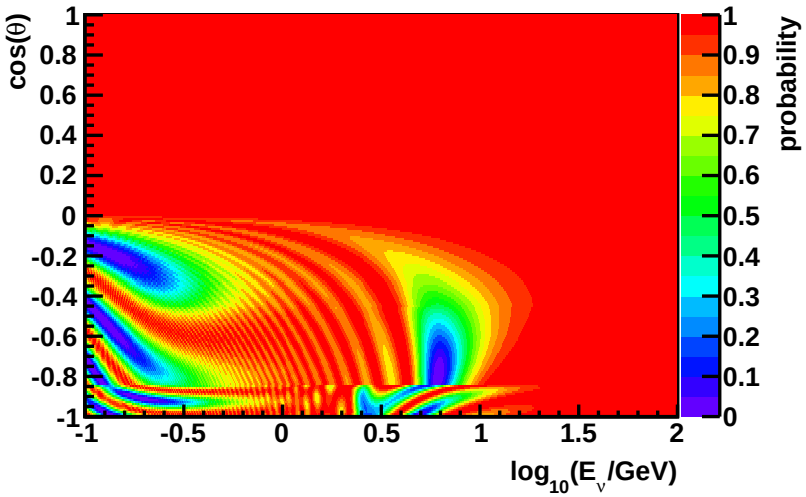


(b) $\nu_e \to \nu_\mu$

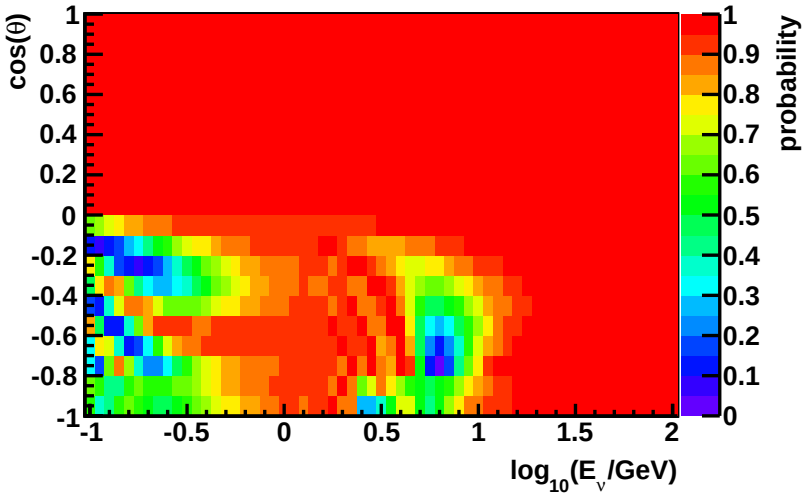


Oscillation Probability for Atmospheric ν Background

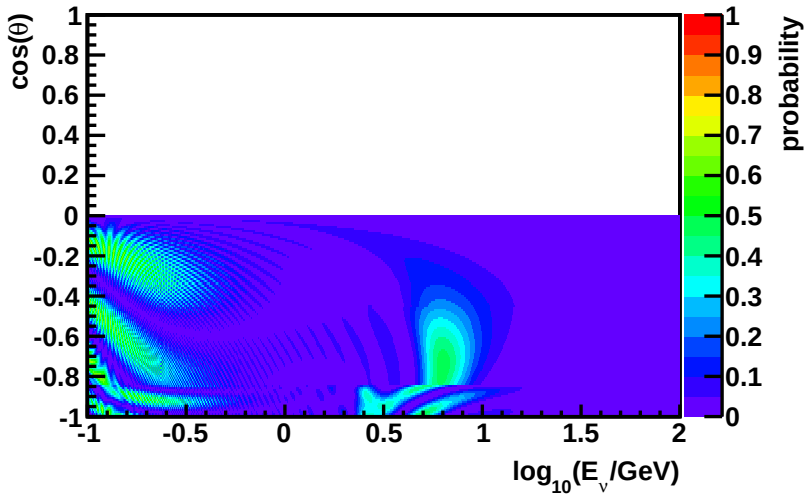
(a) $\nu_e \to \nu_e$



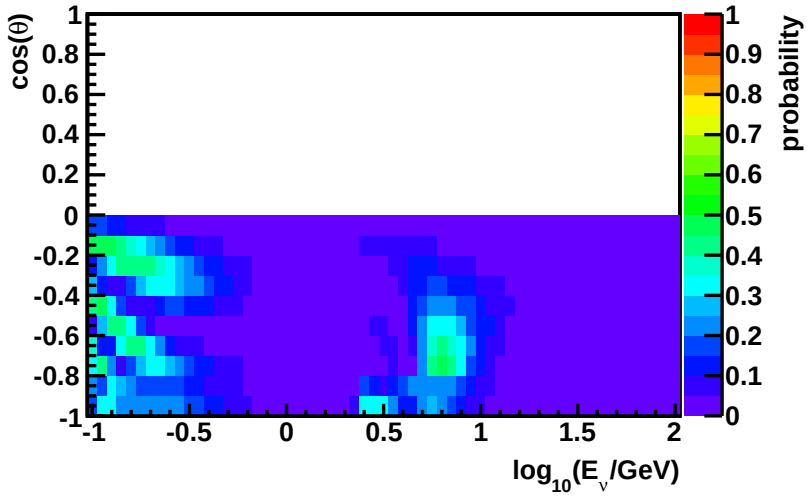
(averaged to Honda bins)



(b) $\nu_e \to \nu_\mu$

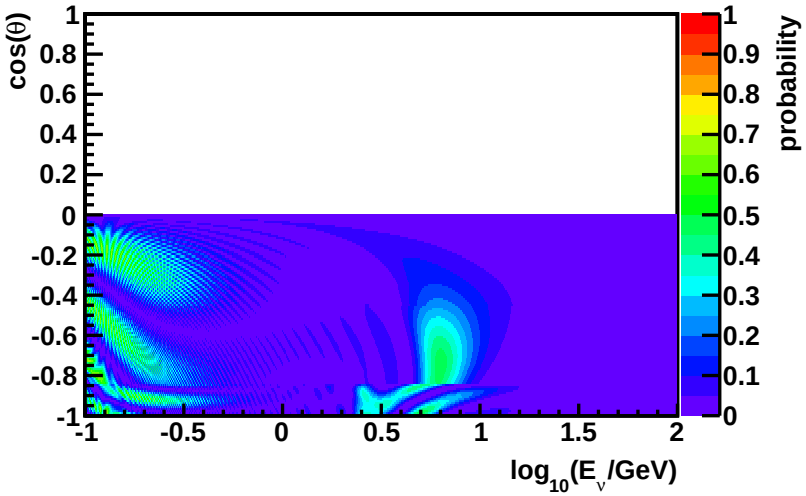


(averaged to Honda bins)

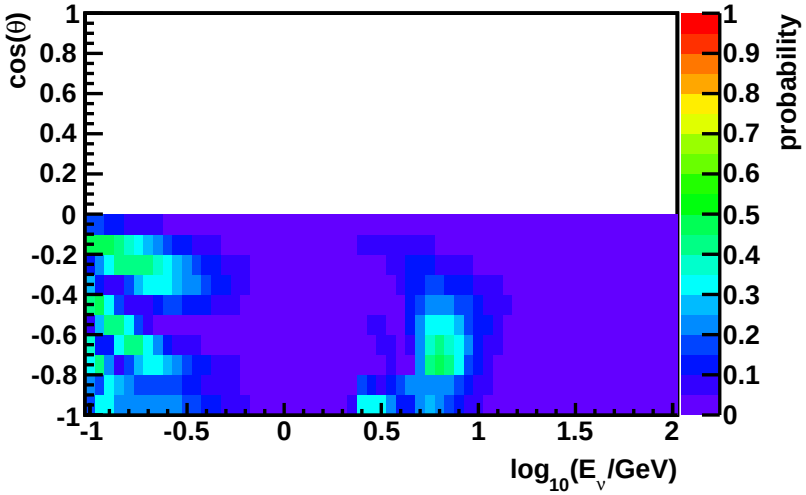


Oscillation Probability for Atmospheric ν Background

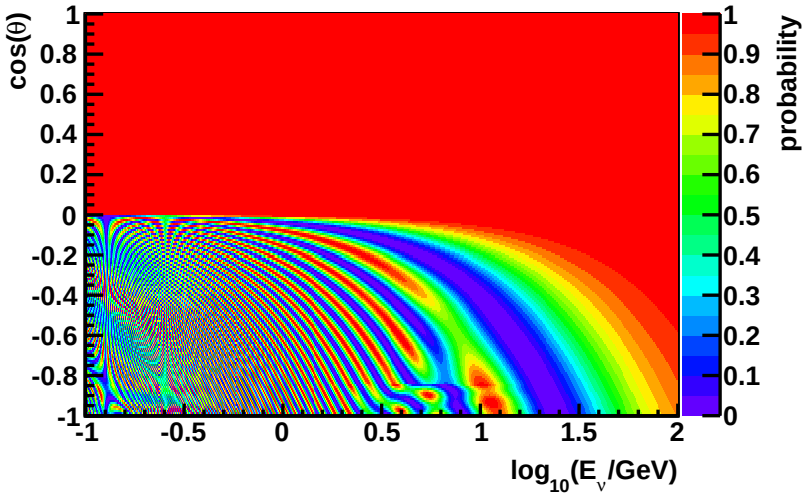
(a) $\nu_\mu \to \nu_e$



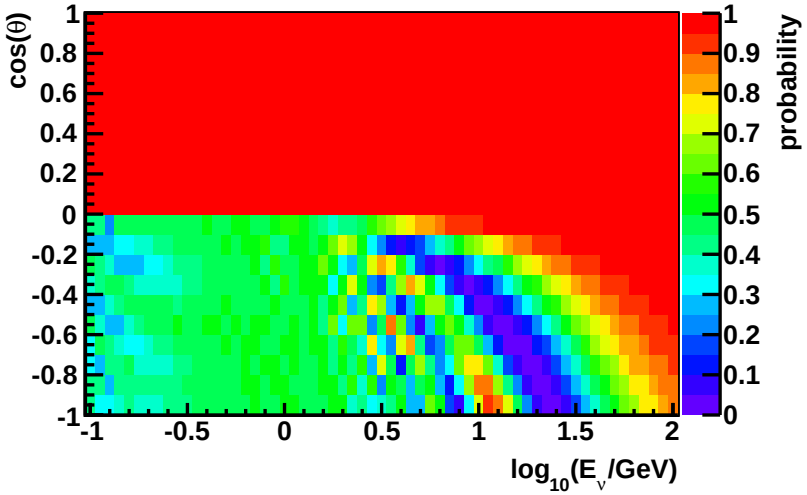
(averaged to Honda bins)



(b) $\nu_\mu \to \nu_\mu$

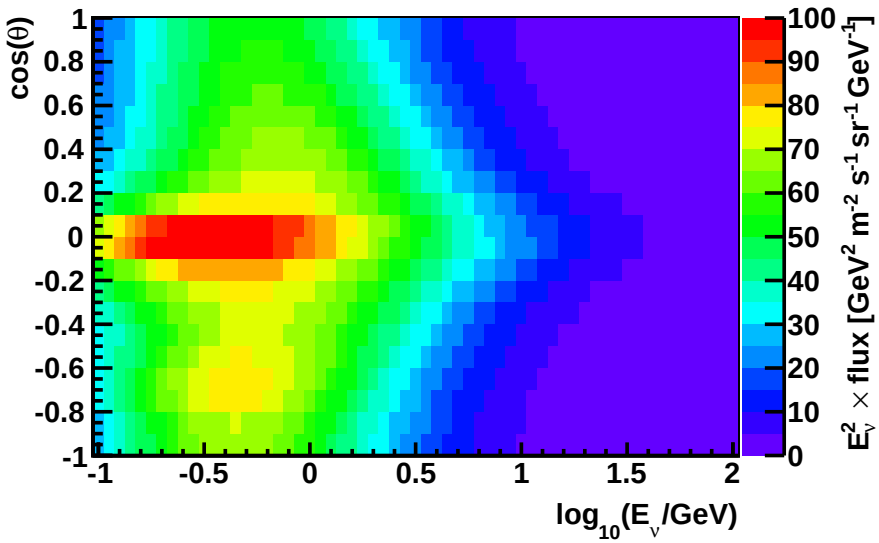


(averaged to Honda bins)

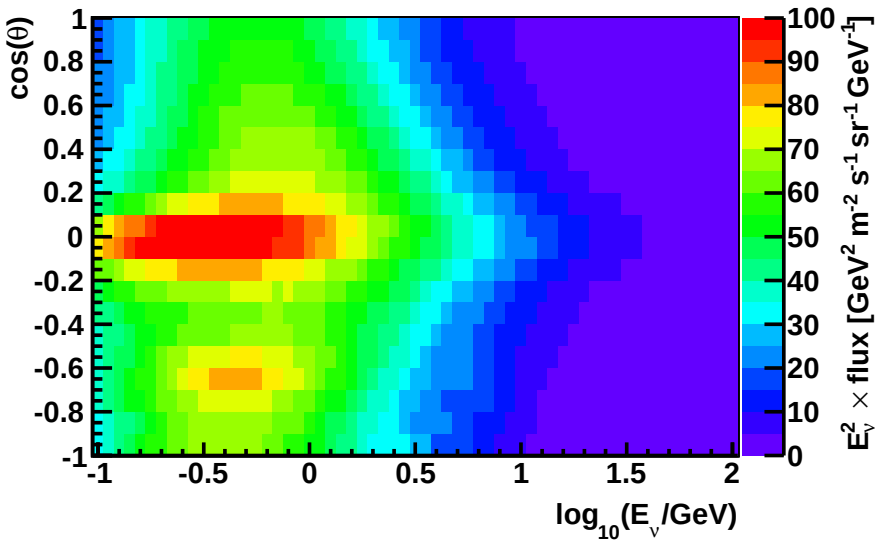


Atmospheric ν_e Background

w/o oscillation

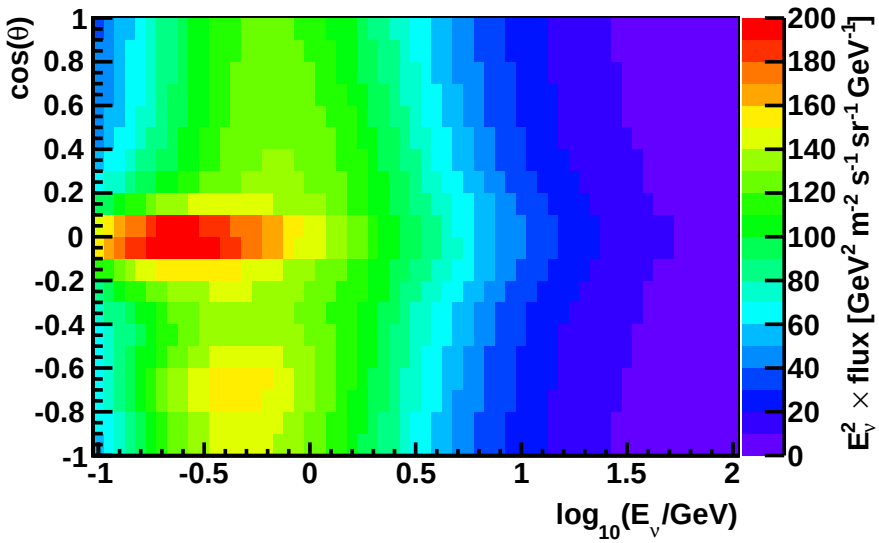


w/ oscillation

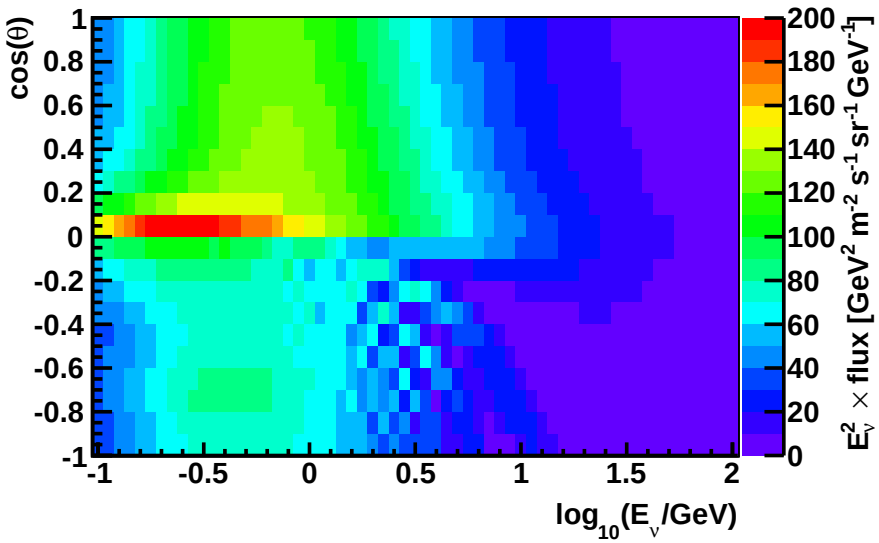


Atmospheric ν_μ Background

w/o oscillation

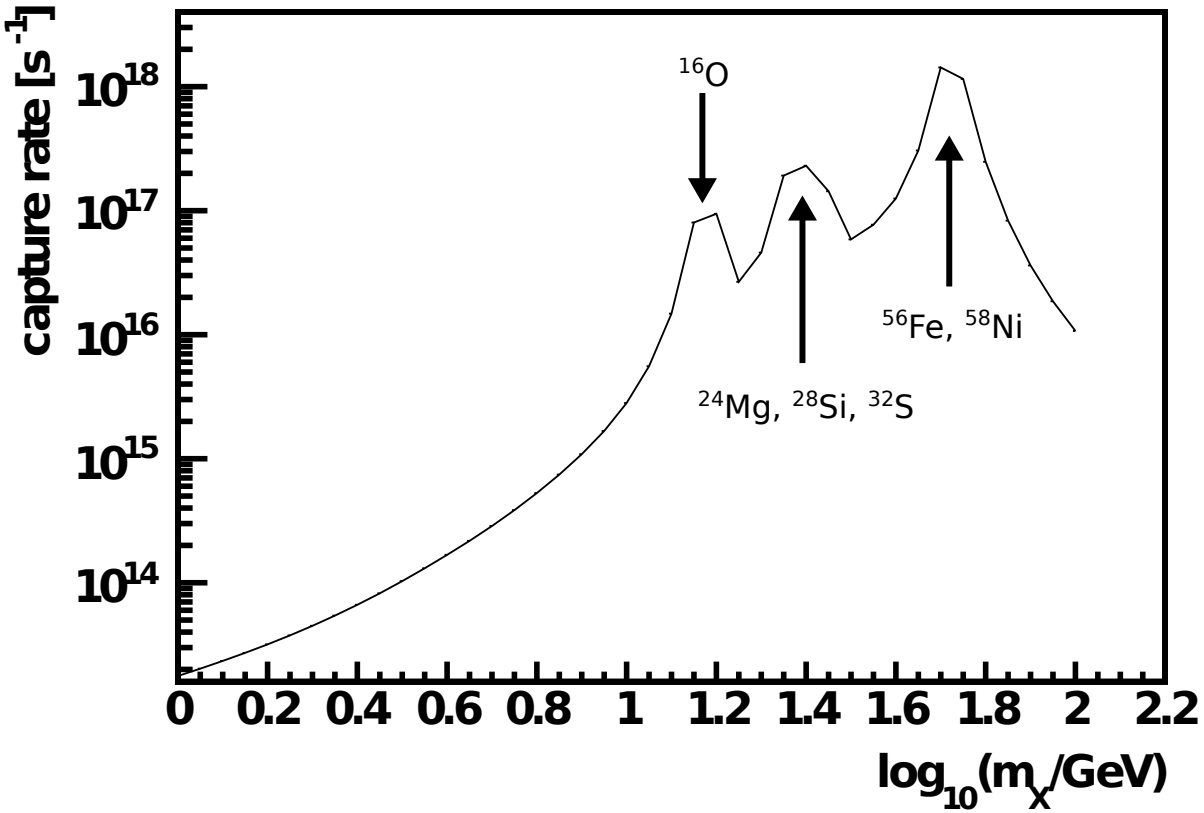


w/ oscillation



Dark Matter Capture in Earth

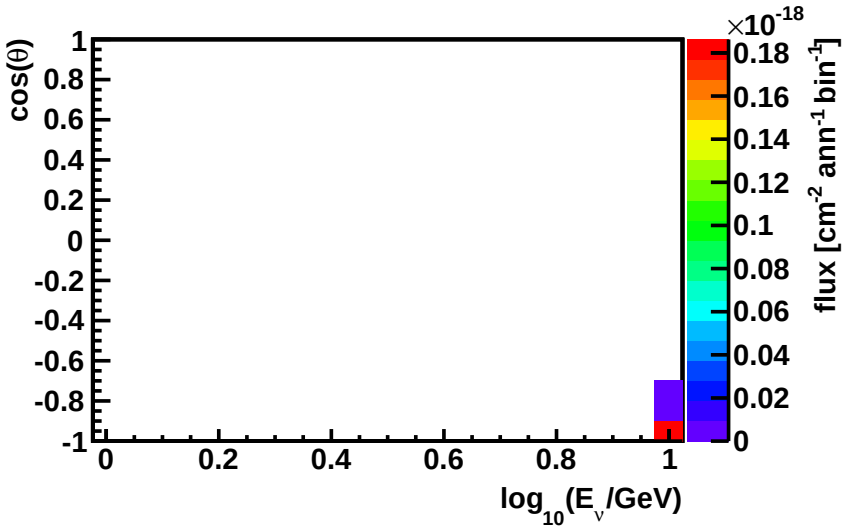
Spin-independent cross-section $\sigma_{\mathrm{SI}} = 1 \times 10^{-40}\,\mathrm{cm}^2$



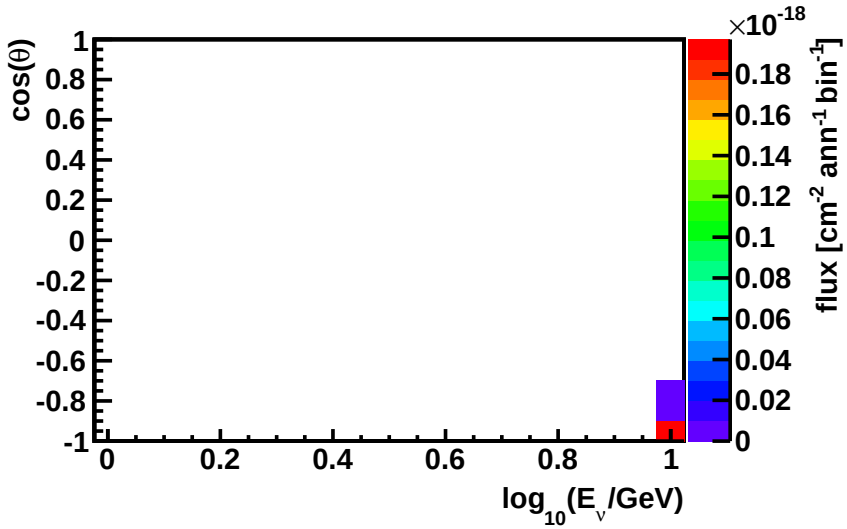
Signal from $m_\chi = 10\,\mathrm{GeV}$, $\chi\overline{\chi} \to \nu_e\overline{\nu_e}$

(Generated from 10^7 $\chi\overline{\chi}$ annihilations)

ν_e flux



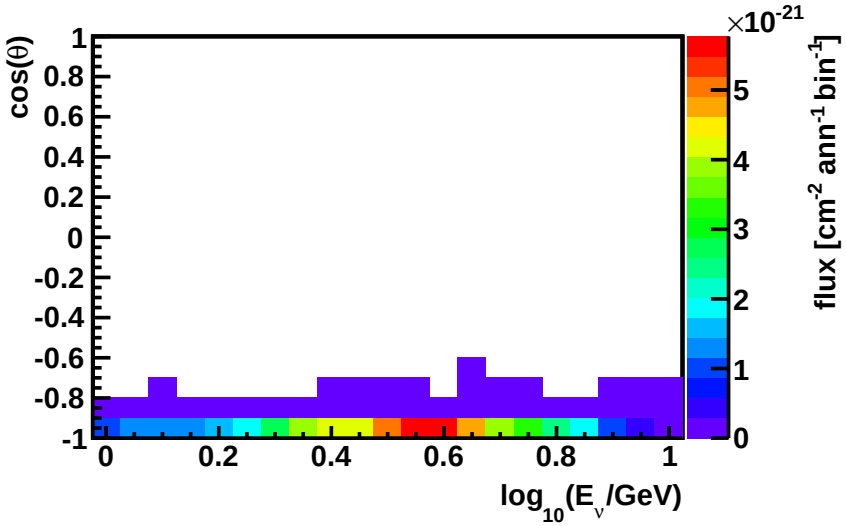
$\overline{\nu}_e$ flux



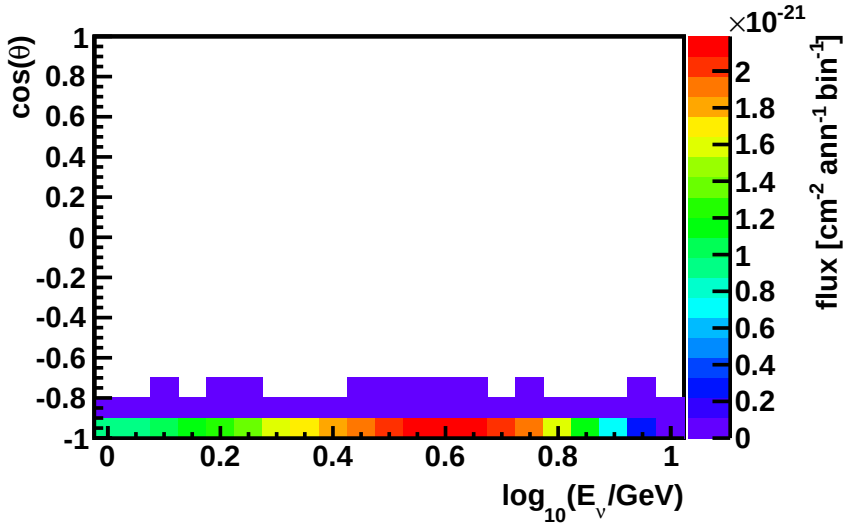
Signal from $m_\chi = 10\,\mathrm{GeV}$, $\chi\overline{\chi} \to \tau\overline{\tau}$

(Generated from 10^7 $\chi\overline{\chi}$ annihilations)

ν_e flux



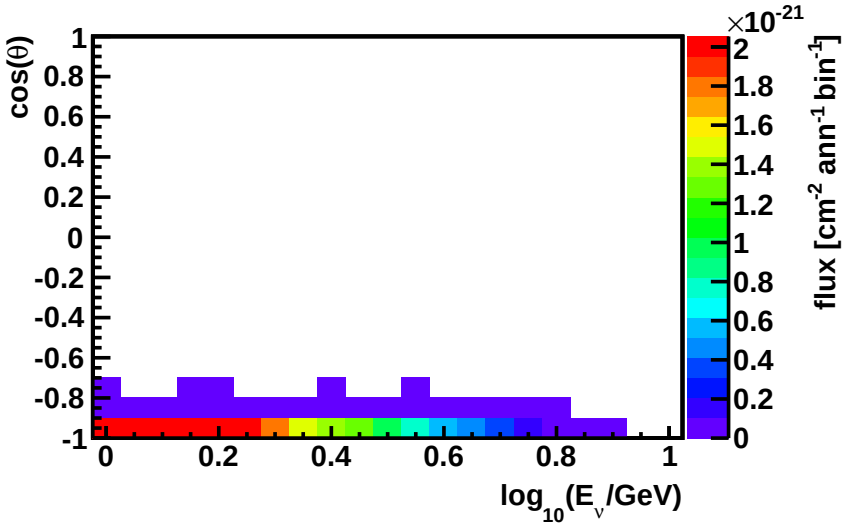
$\overline{\nu}_e$ flux



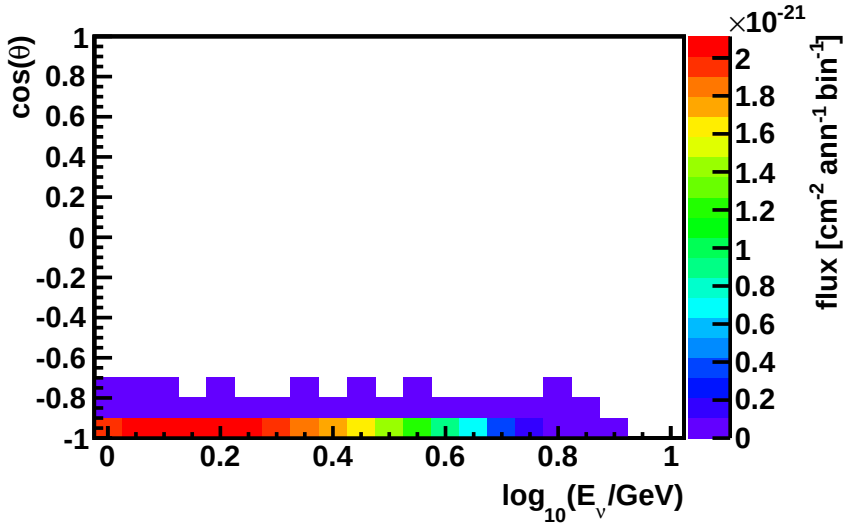
Signal from $m_\chi = 10\,\mathrm{GeV}$, $\chi\overline{\chi} \to b\overline{b}$

(Generated from 10^7 $\chi\overline{\chi}$ annihilations)

ν_e flux



$\overline{\nu}_e$ flux

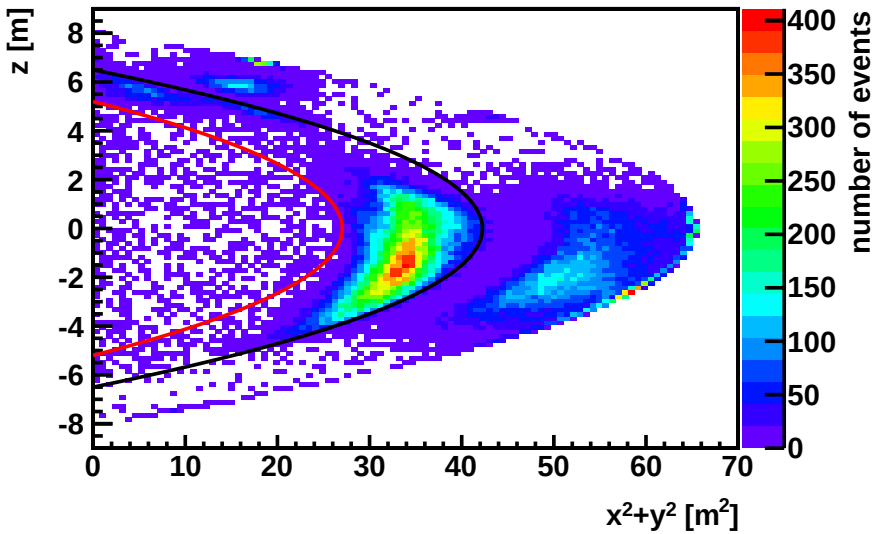


Data Selection

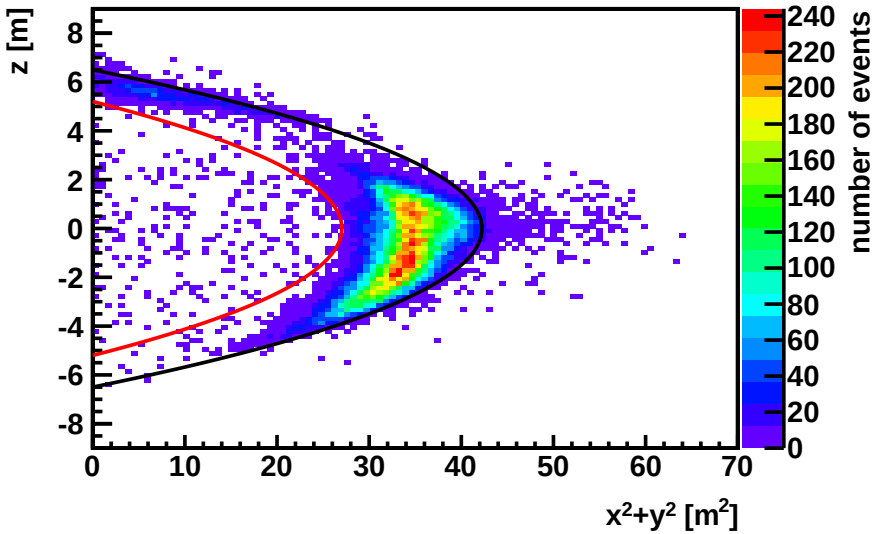
- Runs: 1330 to 12 475
- Total Live Time: 3671 days
- Selection Criteria: $\mathrm{nHit}_{\mathrm{OD}} < 5$, $E_{\mathrm{Kat}} >= 1\,\mathrm{GeV}$

Reconstructed Vertex

Reconstructed energy $> 30\,\mathrm{MeV}$

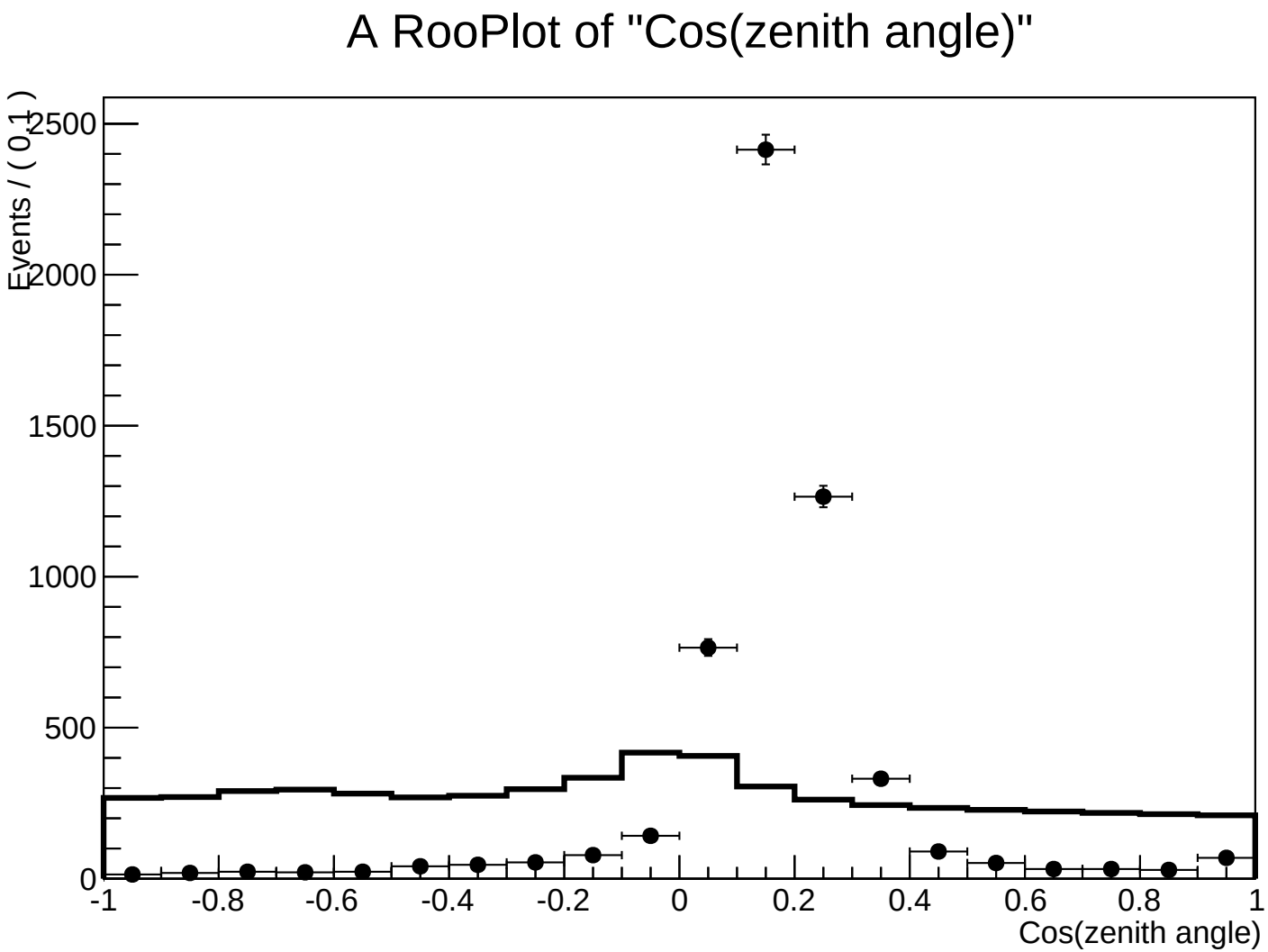


Reconstructed energy $> 1\,\mathrm{GeV}$

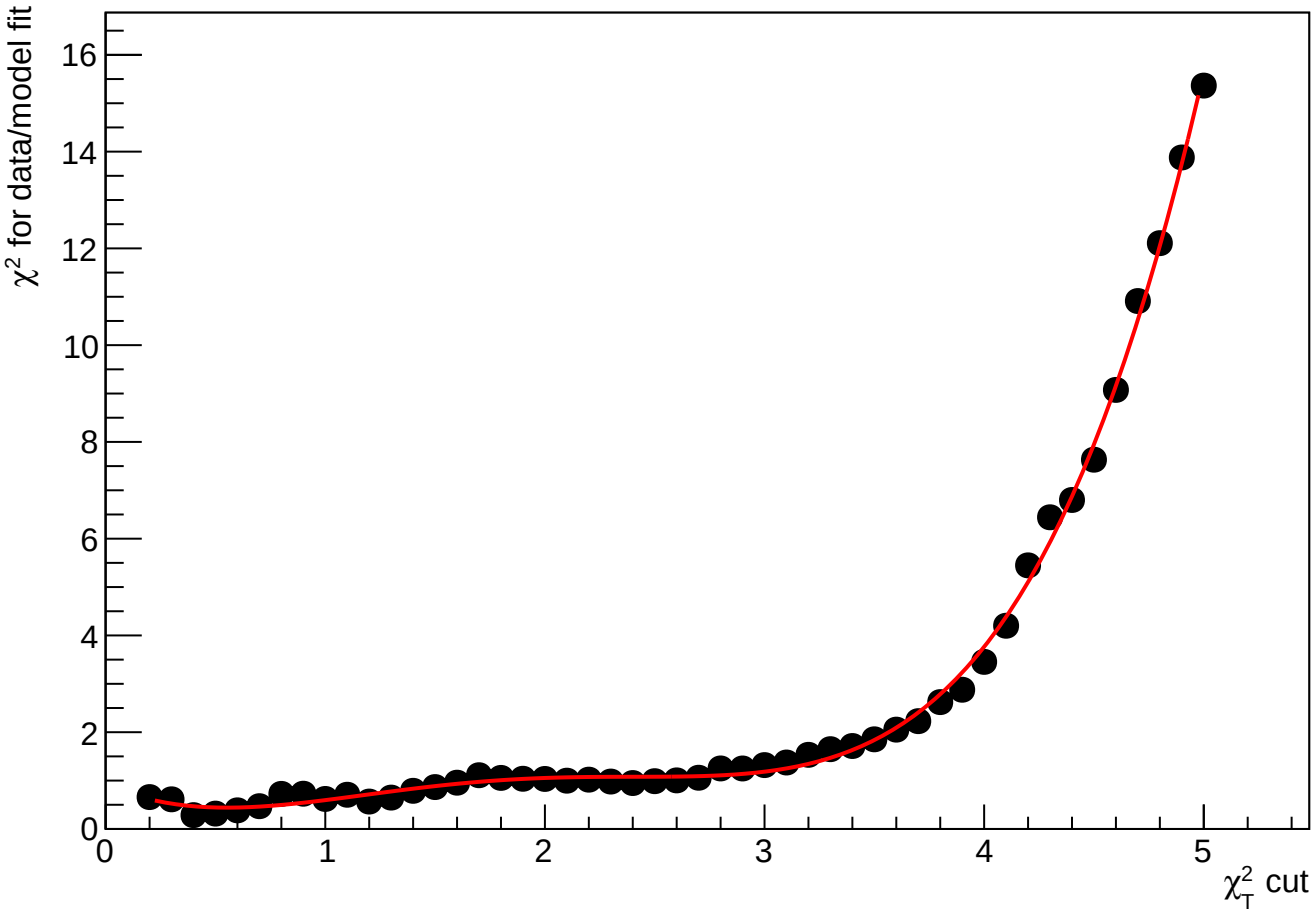


- Black line: 6.5 m radius balloon
- Red line: 5.2 m radius fiducial volume
- T2K veto applied by Shimizu-san

Fit data to background model

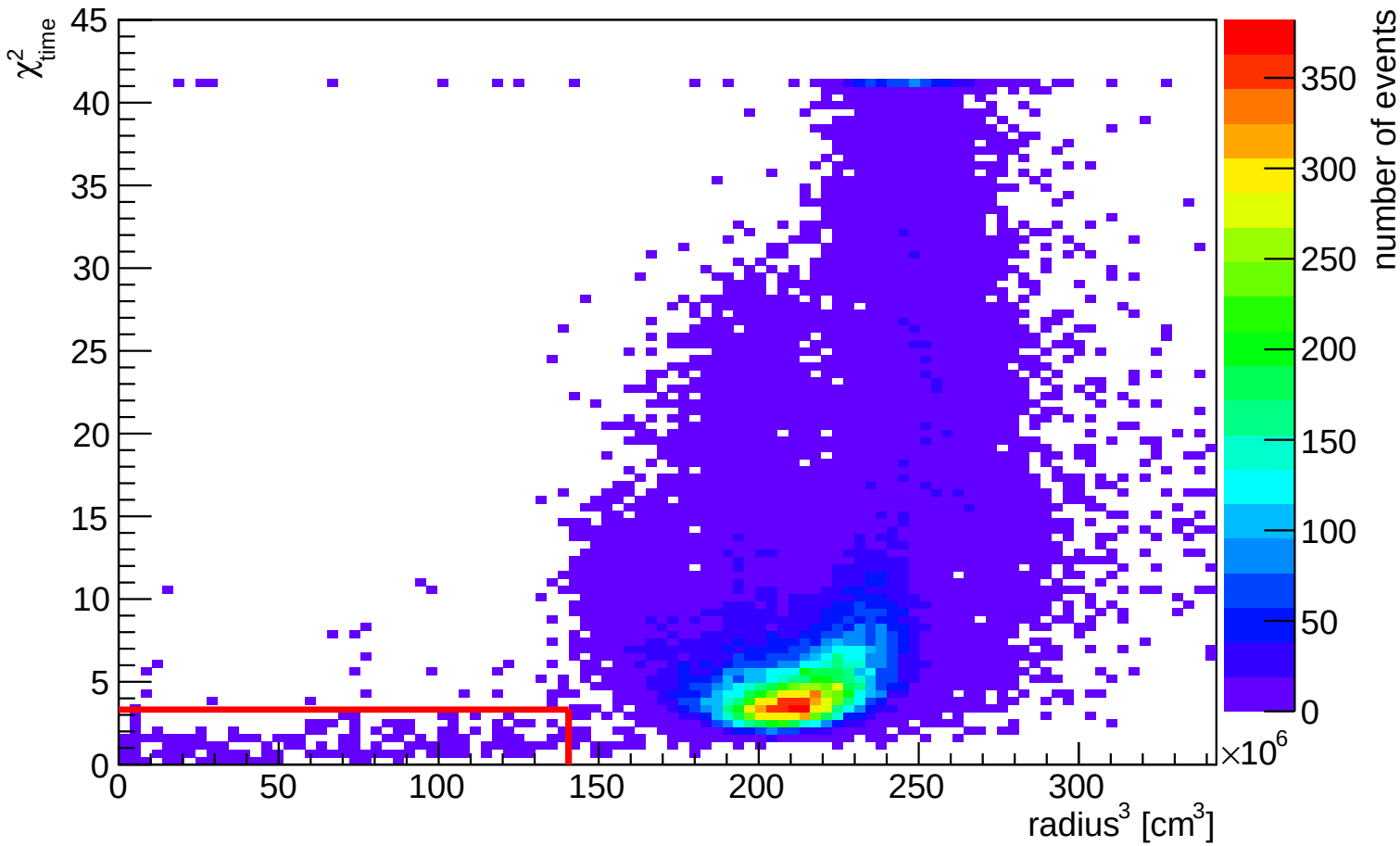


χ^2 of data/model fit vs χ^2_{time} cut



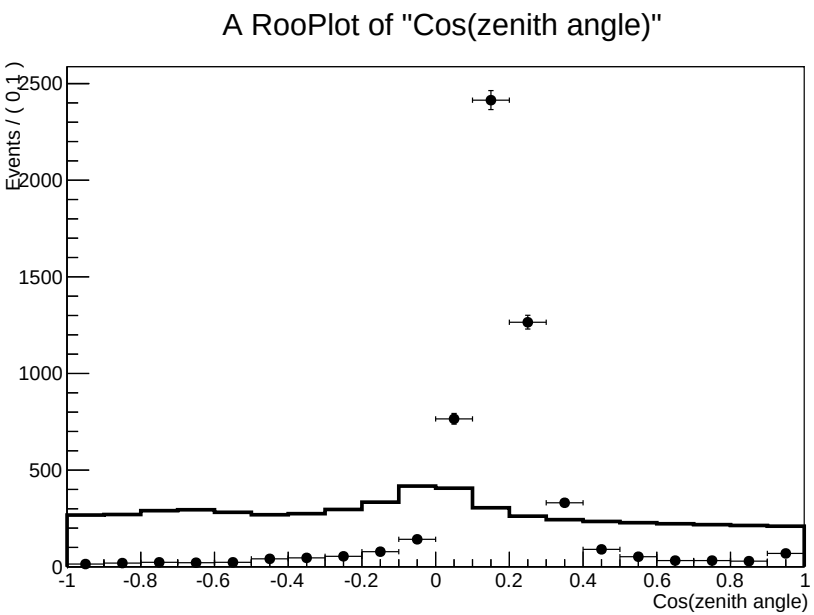
At 90 % confidence level χ^2_{T} cut $= 3.32$

Vertex χ^2_{time} (test of event point-likeness)

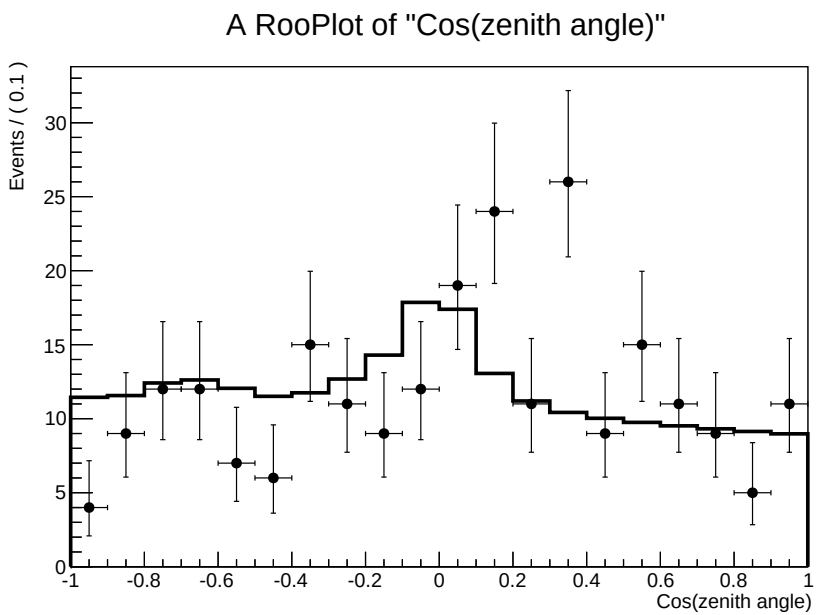


Fit data to background model (with χ^2_T cut)

No χ^2_T cut



χ^2_T cut $= 3.32$



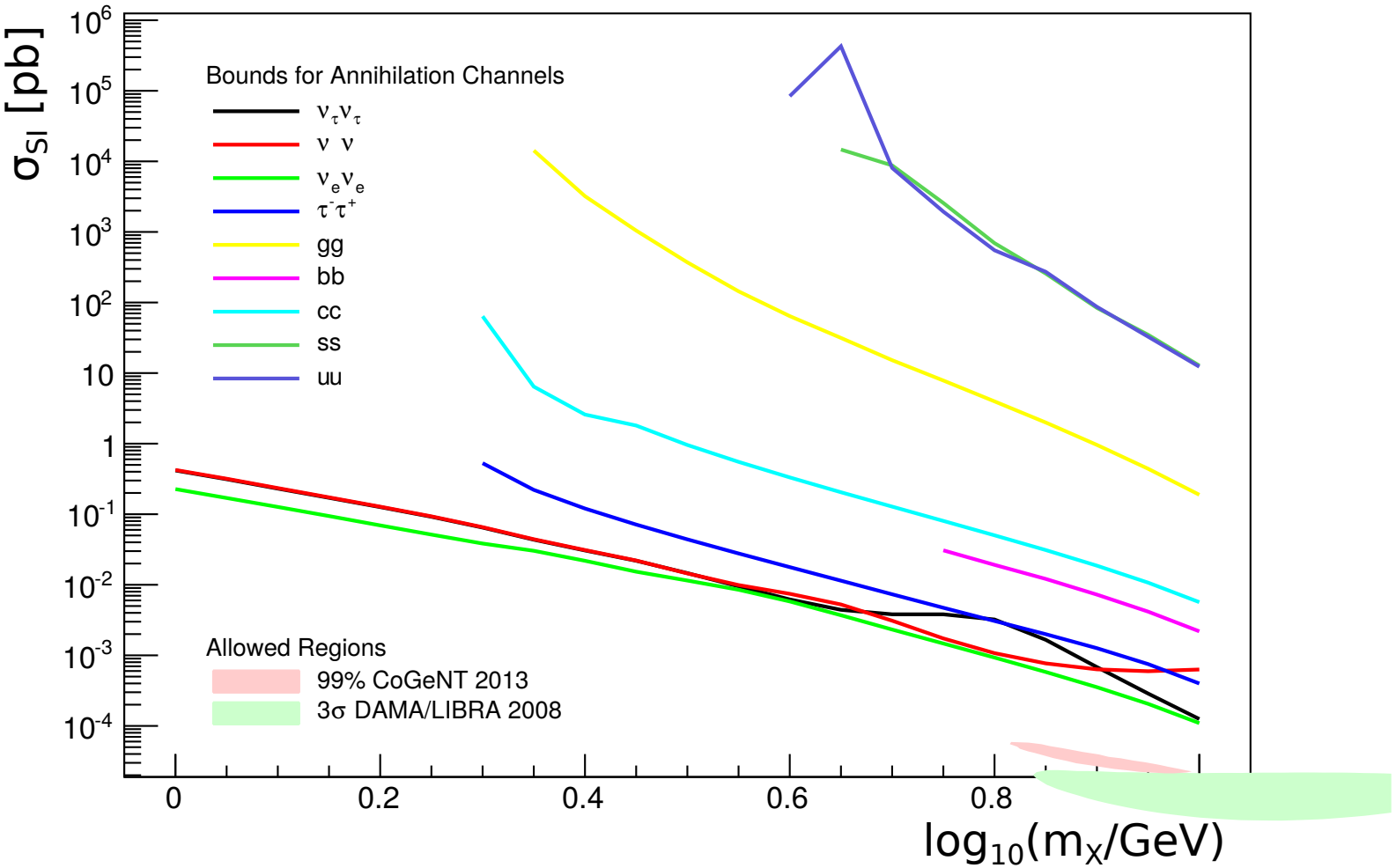
Event rate equation

$$\mathrm{rate}_{\mathrm{signal}} = \Gamma_{\mathrm{A}} \times \sum_{\substack{\mathrm{channel}=i \\ \nu-\mathrm{flavor}=\alpha}} \left[B_i \int dE_\alpha \frac{dN_{i,\alpha}}{dE_\alpha} \frac{\sigma_{\mathrm{effective}}(E_\alpha)}{4\pi R_{\mathrm{Earth}}^2} \right]$$

- $\Gamma_A = \frac{1}{2}\Gamma_C$ ($\chi\overline{\chi}$ annihilation rate at equilibrium)
- $\Gamma_C = \sigma_{\chi-\mathrm{nucleon}} C_0$ (χ capture rate)
- E_α (energy of neutrino for flavor α)
- $N_{i,\alpha}$ (neutrino yield of flavor α per annihilation for channel i)
- $\sigma_{\mathrm{effective},\alpha}(E_\alpha)$ (effective detector cross-section)
- R_{Earth} (radius of Earth)

$\therefore$ 90 % C.L. bound on $\mathrm{rate}_{\mathrm{signal}} \implies$ 90 % C.L. bound on $\sigma_{\chi-\mathrm{nucleon}}$

WIMP σ_{SI} bounds (90 % C.L.)



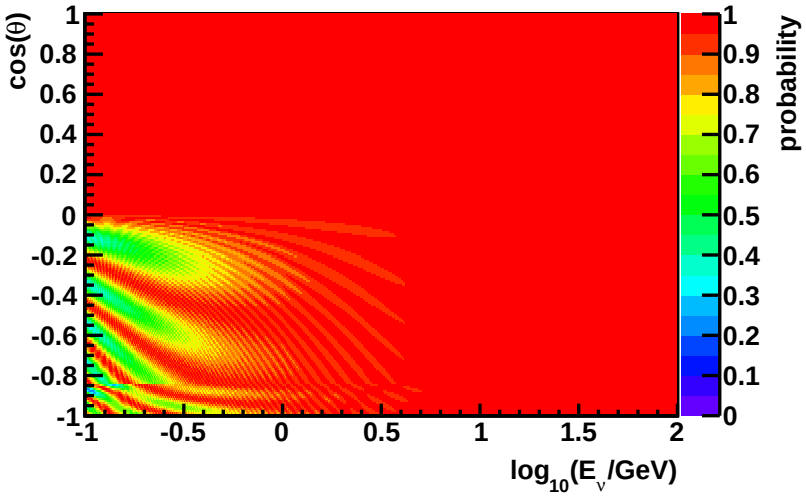
To do

- KLG4 high energy simulation taking a long time (now $\sim$half done, $\sim$4 months more using $\sim$100 cores)
  $\Longrightarrow$ need to discuss with simulation expert to optimize KLG4 for large amount of photons or continue running as is
- OD inefficiency for μ-veto
  $\Longrightarrow$ maybe need to simulated μ background and fit to data instead of finding a χ^2_T cut to reduce μ background

Backup Slides

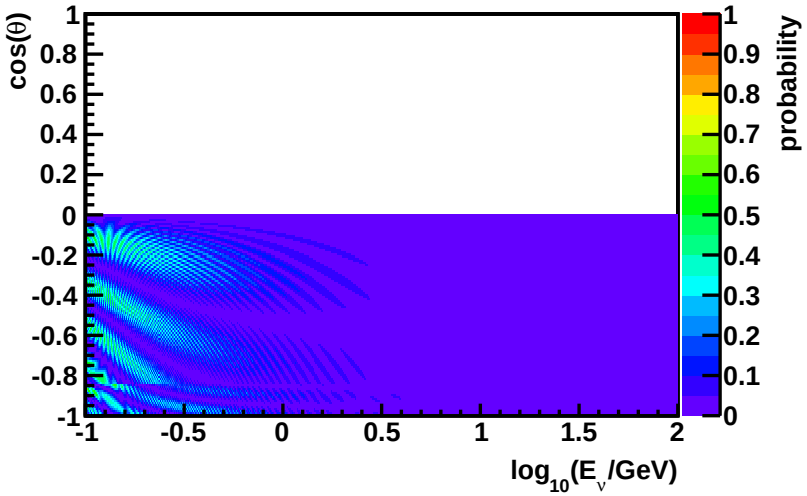
Oscillation Probability for Atmospheric ν Background

$\overline{\nu}_e \rightarrow \overline{\nu}_e$

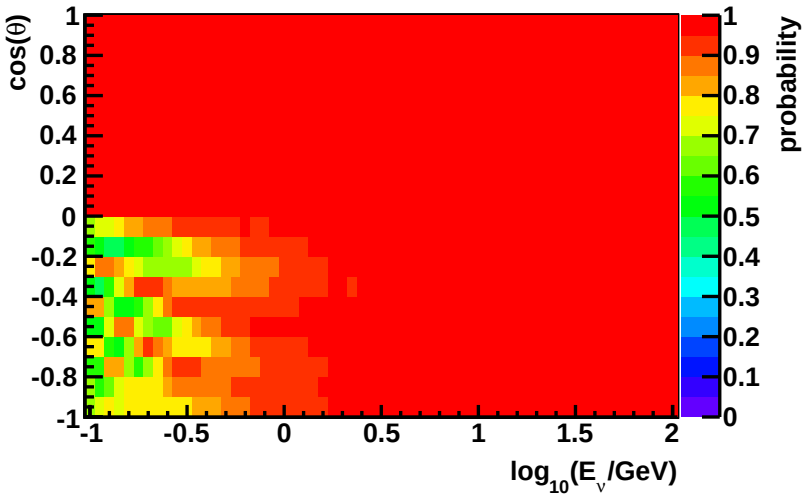


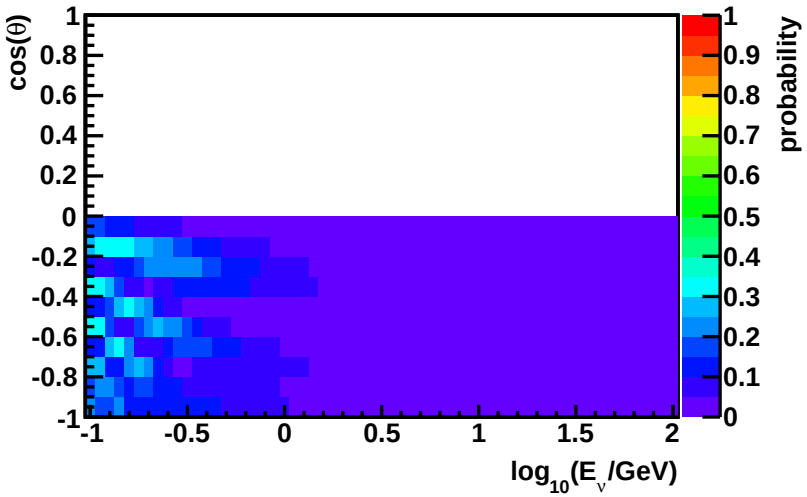
(averaged over Honda bins)

$\overline{\nu}_e \rightarrow \overline{\nu}_\mu$



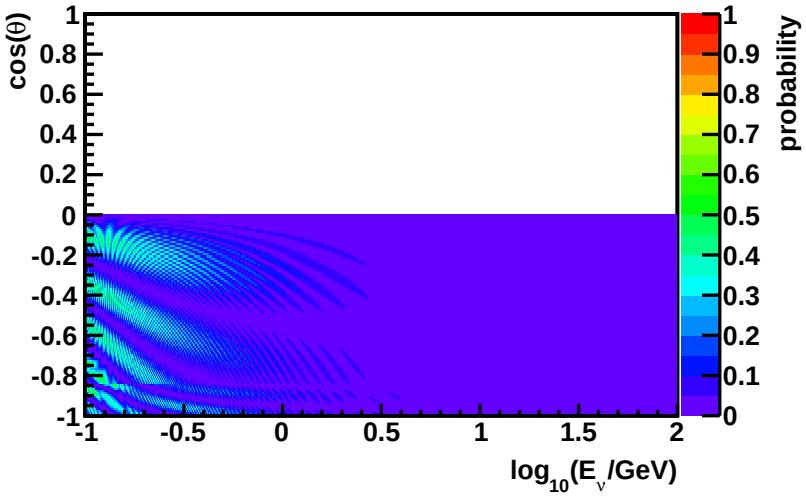
(averaged over Honda bins)



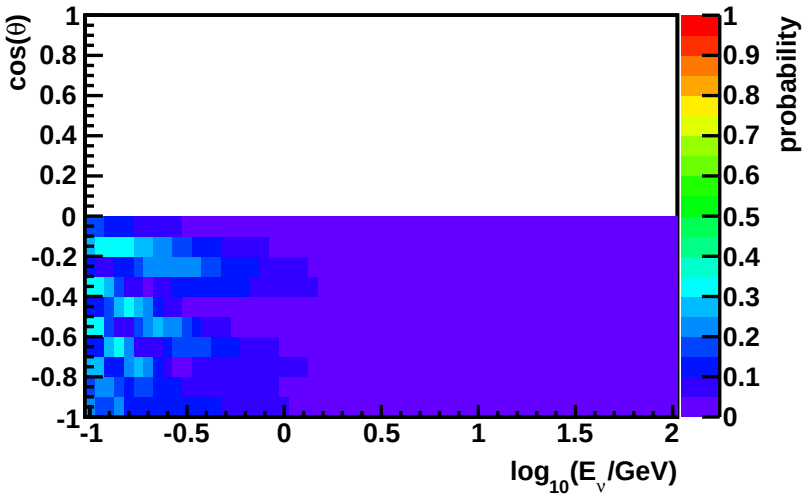


Oscillation Probability for Atmospheric ν Background

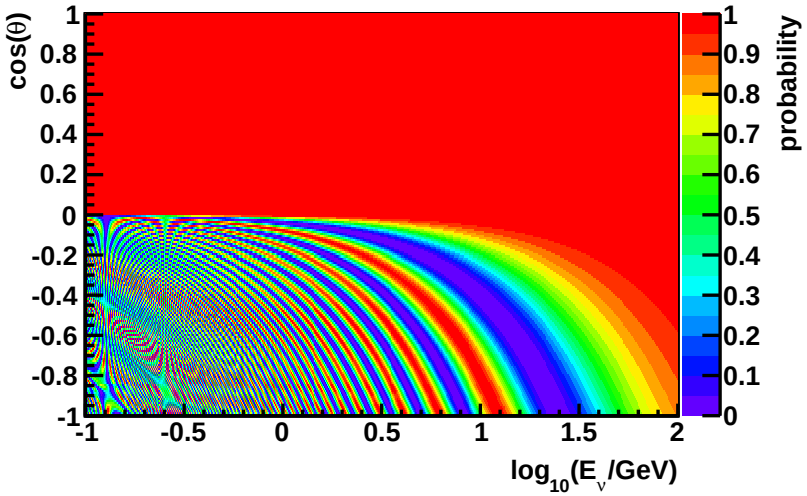
(a) $\overline{\nu}_\mu \to \overline{\nu}_e$



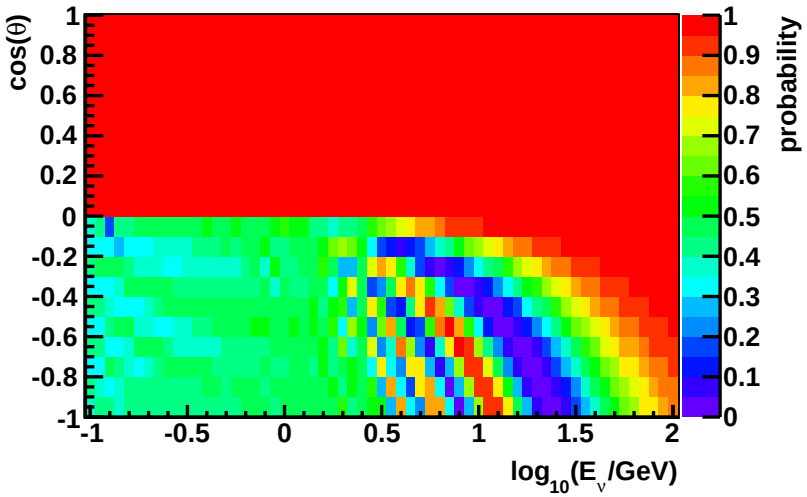
(averaged over Honda bins)



(b) $\overline{\nu}_\mu \to \overline{\nu}_\mu$

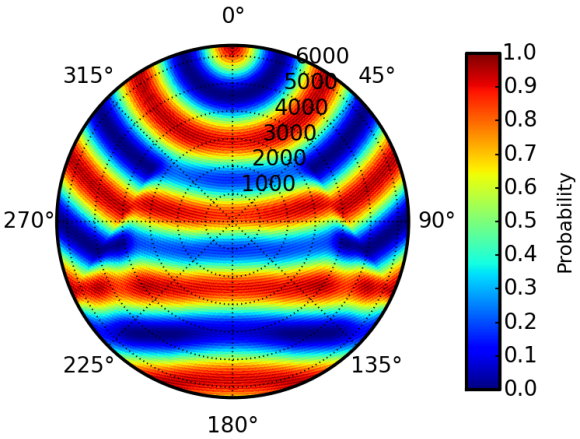


(averaged over Honda bins)

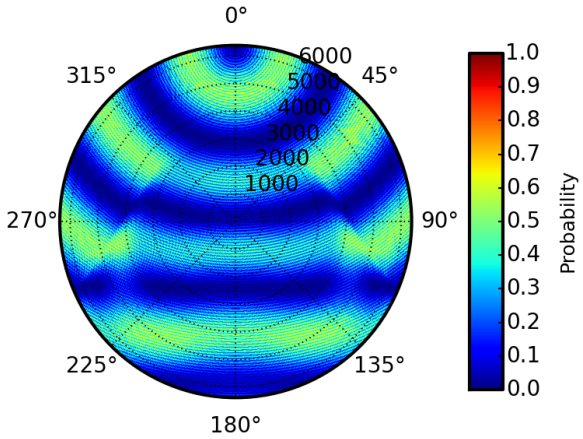


ν_e oscillation probability at 0.1 GeV

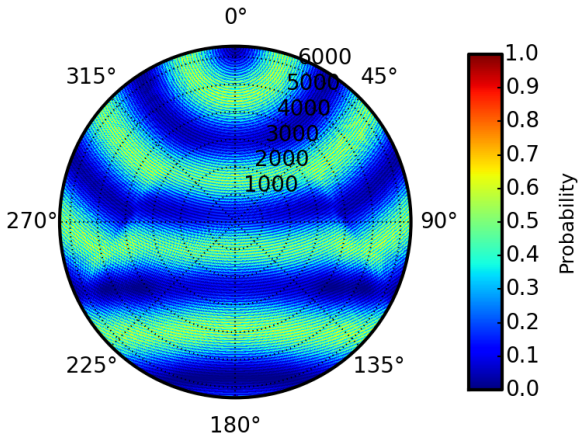
(a) $\nu_e \to \nu_e$



(b) $\nu_e \to \nu_\mu$

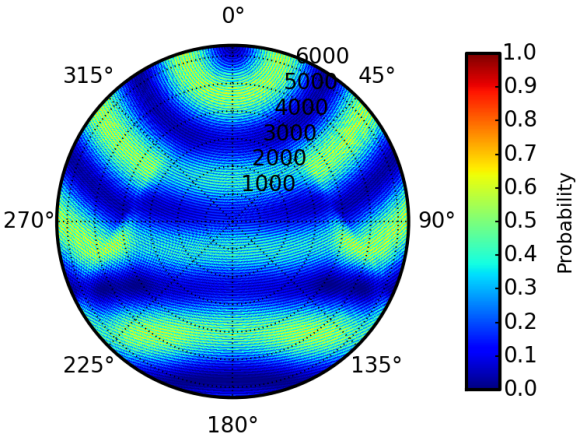


(c) $\nu_e \to \nu_\tau$

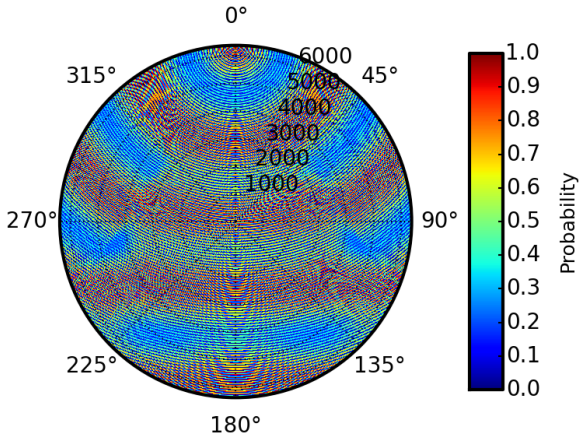


ν_μ oscillation probability at 0.1 GeV

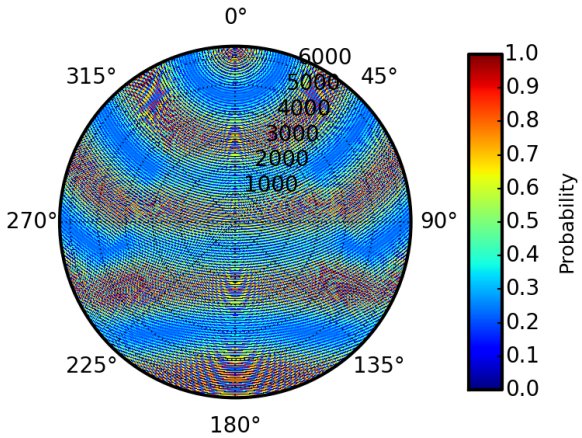
(a) $\nu_\mu \to \nu_e$



(b) $\nu_\mu \to \nu_\mu$

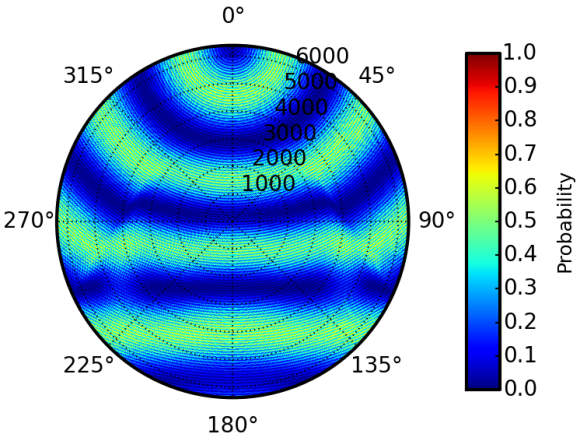


(c) $\nu_\mu \to \nu_\tau$

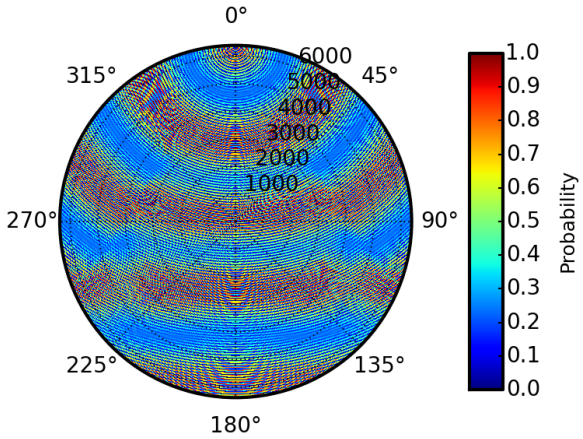


ν_τ oscillation probability at 0.1 GeV

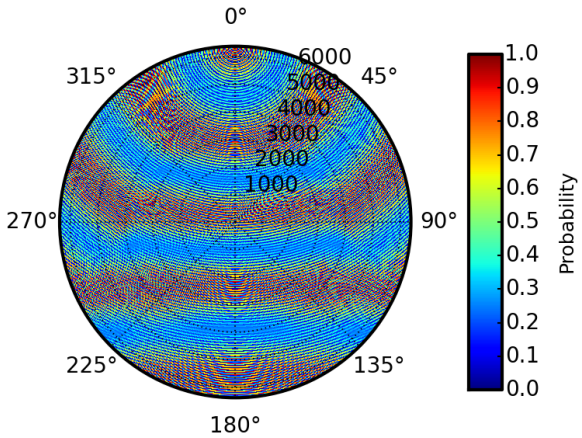
(a) $\nu_\tau \to \nu_e$



(b) $\nu_\tau \to \nu_\mu$

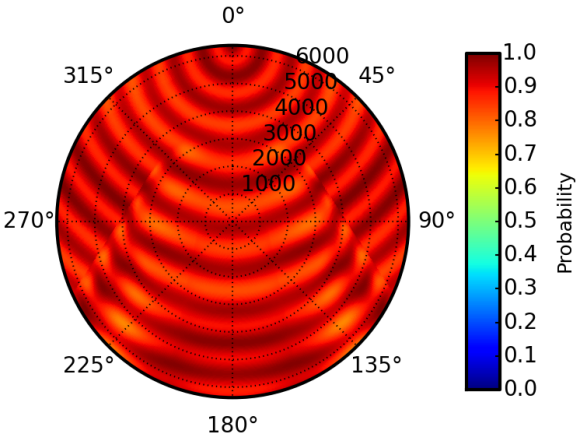


(c) $\nu_\tau \to \nu_\tau$

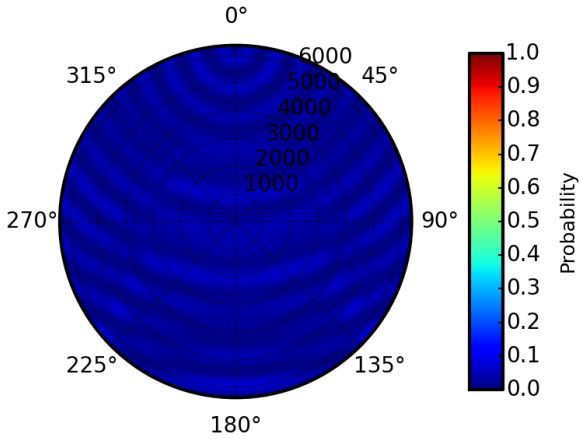


ν_e oscillation probability at 1.0 GeV

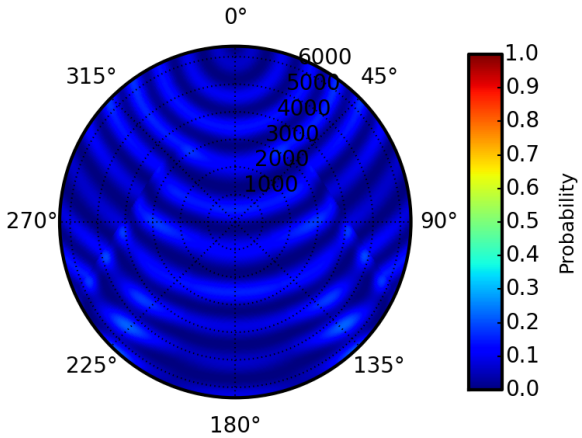
(a) $\nu_e \to \nu_e$



(b) $\nu_e \to \nu_\mu$

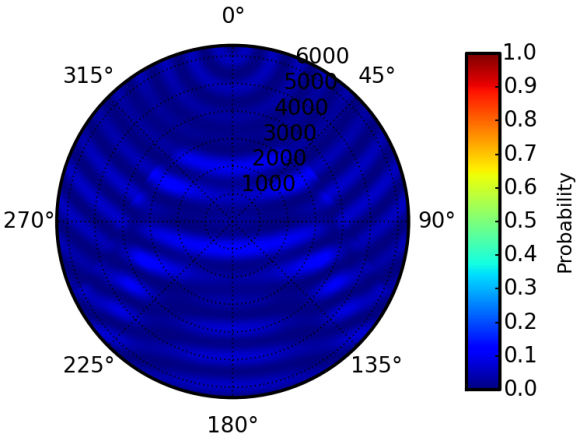


(c) $\nu_e \to \nu_\tau$

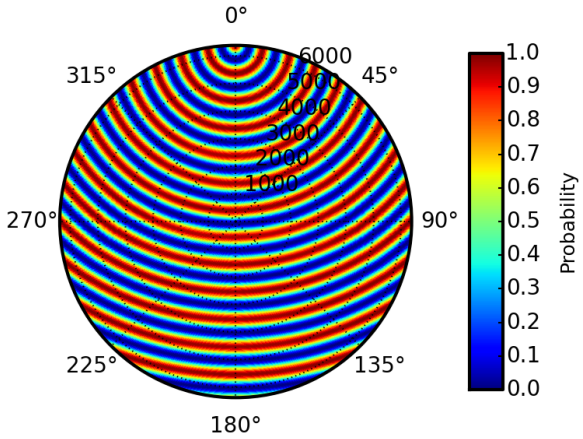


ν_μ oscillation probability at 1.0 GeV

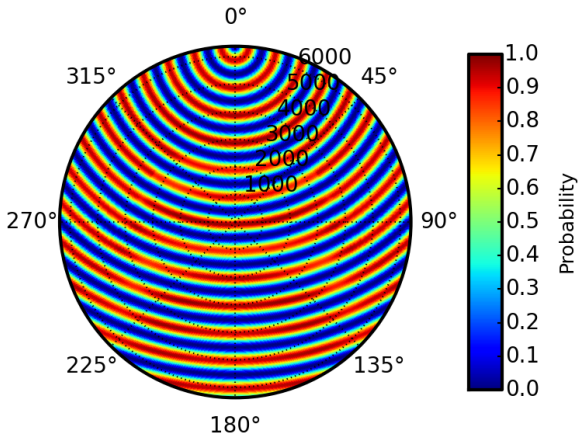
(a) $\nu_\mu \to \nu_e$



(b) $\nu_\mu \to \nu_\mu$

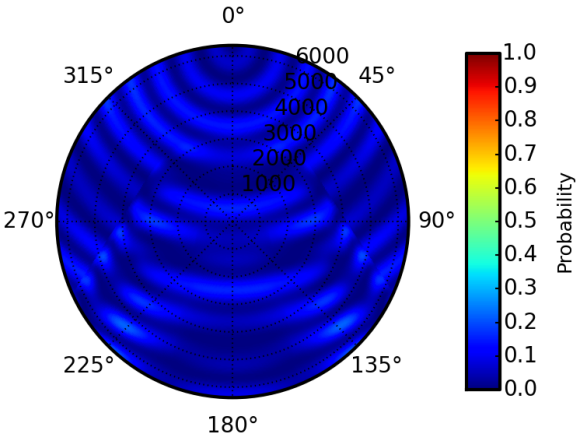


(c) $\nu_\mu \to \nu_\tau$

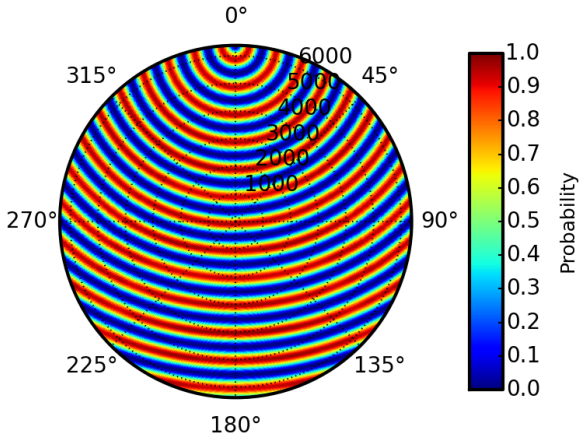


ν_τ oscillation probability at 1.0 GeV

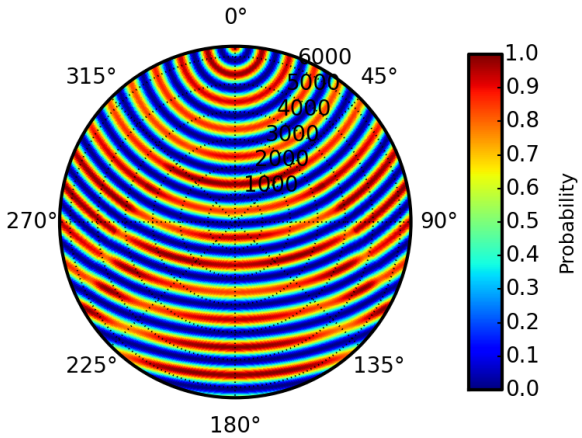
(a) $\nu_\tau \rightarrow \nu_e$



(b) $\nu_\tau \rightarrow \nu_\mu$

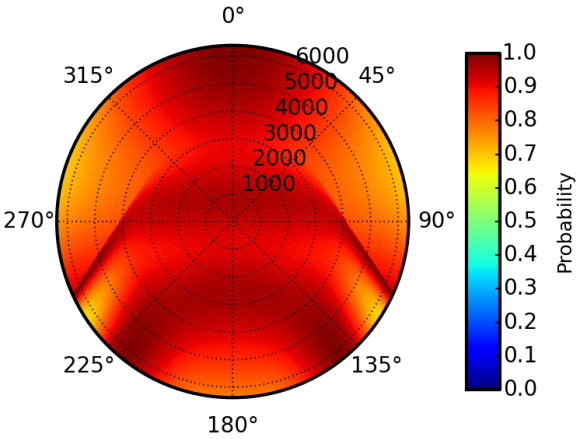


(c) $\nu_\tau \rightarrow \nu_\tau$

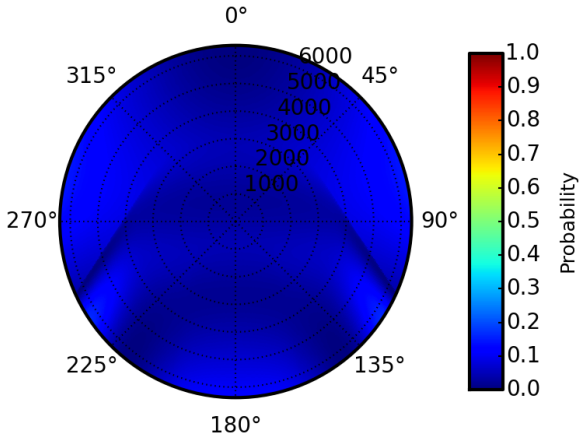


ν_e oscillation probability at 10.0 GeV

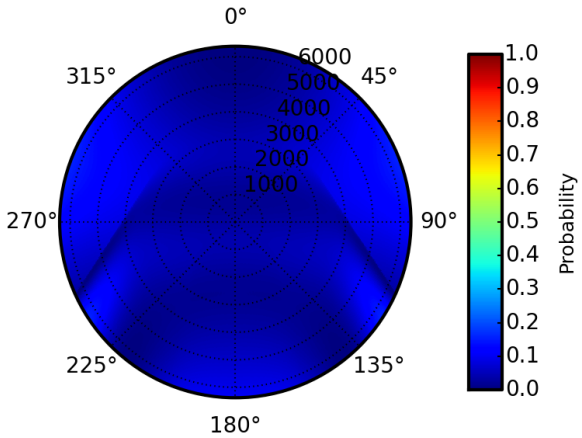
(a) $\nu_e \to \nu_e$



(b) $\nu_e \to \nu_\mu$

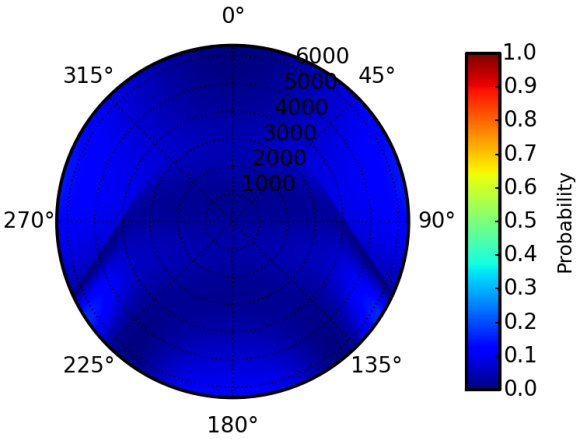


(c) $\nu_e \to \nu_\tau$

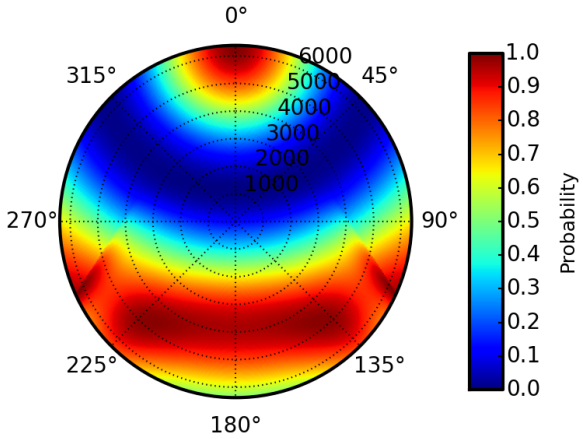


ν_μ oscillation probability at 10.0 GeV

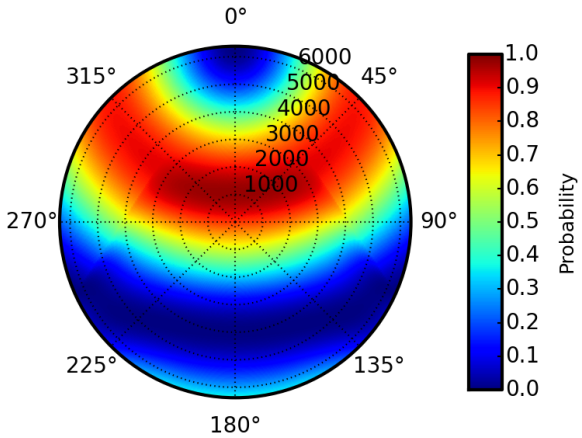
(a) $\nu_\mu \to \nu_e$



(b) $\nu_\mu \to \nu_\mu$

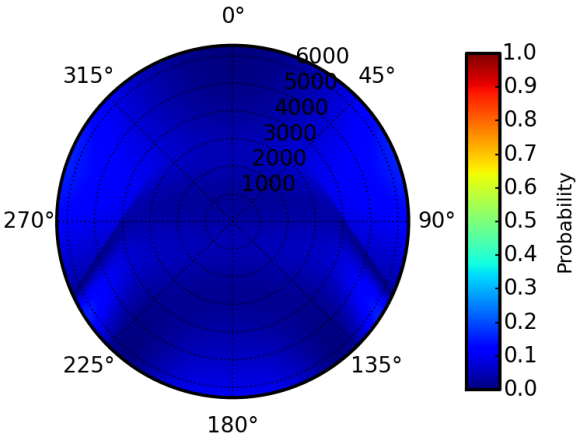


(c) $\nu_\mu \to \nu_\tau$

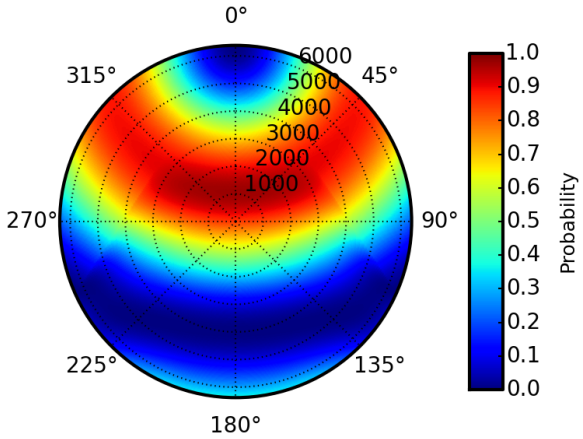


ν_τ oscillation probability at 10.0 GeV

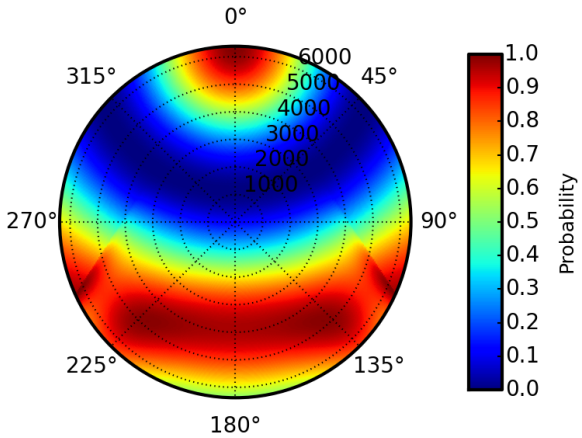
(a) $\nu_\tau \rightarrow \nu_e$



(b) $\nu_\tau \rightarrow \nu_\mu$

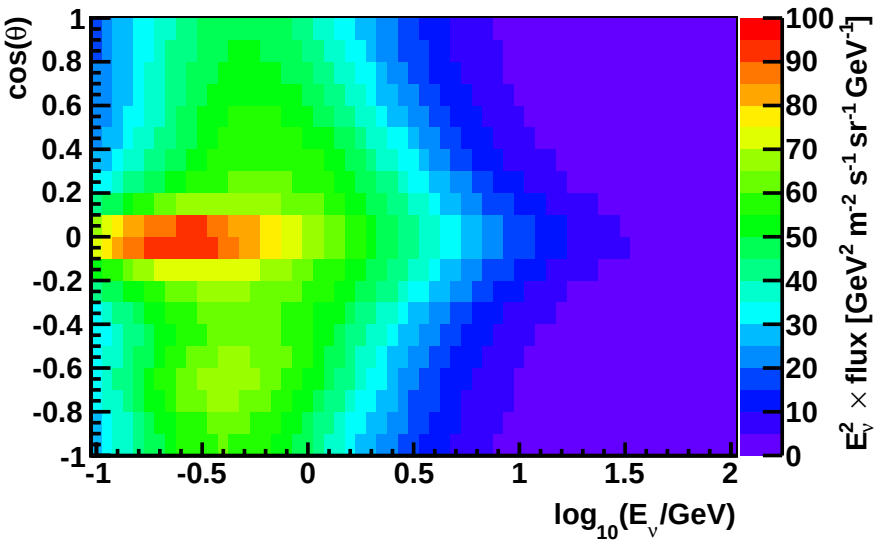


(c) $\nu_\tau \rightarrow \nu_\tau$

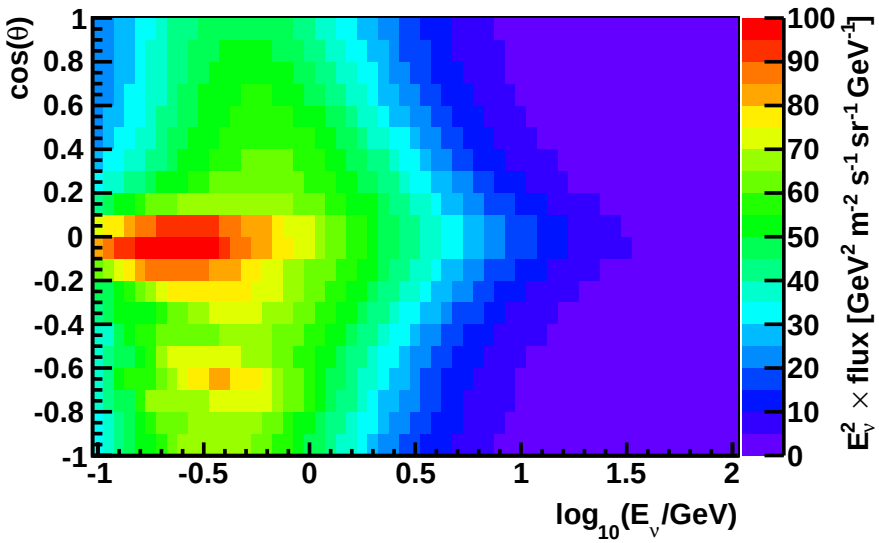


Atmospheric $\overline{\nu}_e$ Background

(a) w/o oscillation

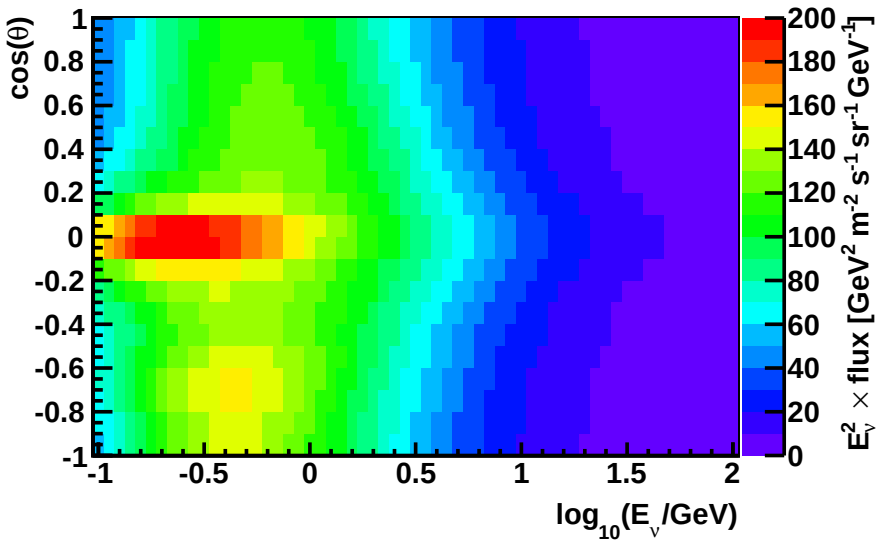


(b) w/ oscillation



Atmospheric $\overline{\nu}_\mu$ Background

(a) w/o oscillation



(b) w/ oscillation