Designing a long-baseline experiment to measure CP violation

GMY-aU

GloriaMariyaYuri - across the US

GMY-aP

GloriaMariyaYuri - across the Pacific

Presented by

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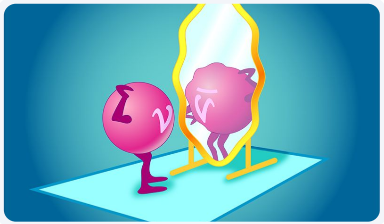
Long-baseline experiments

Long-baseline experiments study neutrino oscillations by directing accelerator neutrino beams toward far detectors over very large distances.

They are key experiments for probing leptonic CP violation, resolving the mass ordering, and making precision measurements of neutrino oscillation parameters.



For this Project:

- **2 MW** beam power (beamline at UCSB)
- **2×10^{21}** POT/yr
- **0.2** forward
- **10 years** run

Parameters to optimize:

- Baseline **L**
- Off-axis angle
- $\nu_\mu/\bar{\nu}_\mu$ splitting
- CPV sensitivity

Vacuum oscillation probability and CP-violating term

Oscillation probability in vacuum:

$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right)\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$
$$\pm 8J_{\mathrm{CP}}\sin\left(\frac{\Delta m^2_{21}L}{4E}\right)\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

CP-violating Jarlskog invariant:

$$J_{\mathrm{CP}} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\sin\delta_{\mathrm{CP}}$$

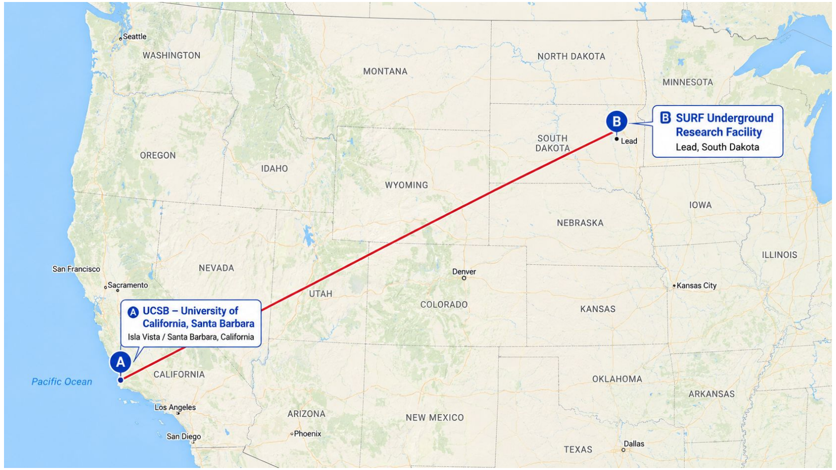
Project Design

GMY-aU: Across-the-US configuration

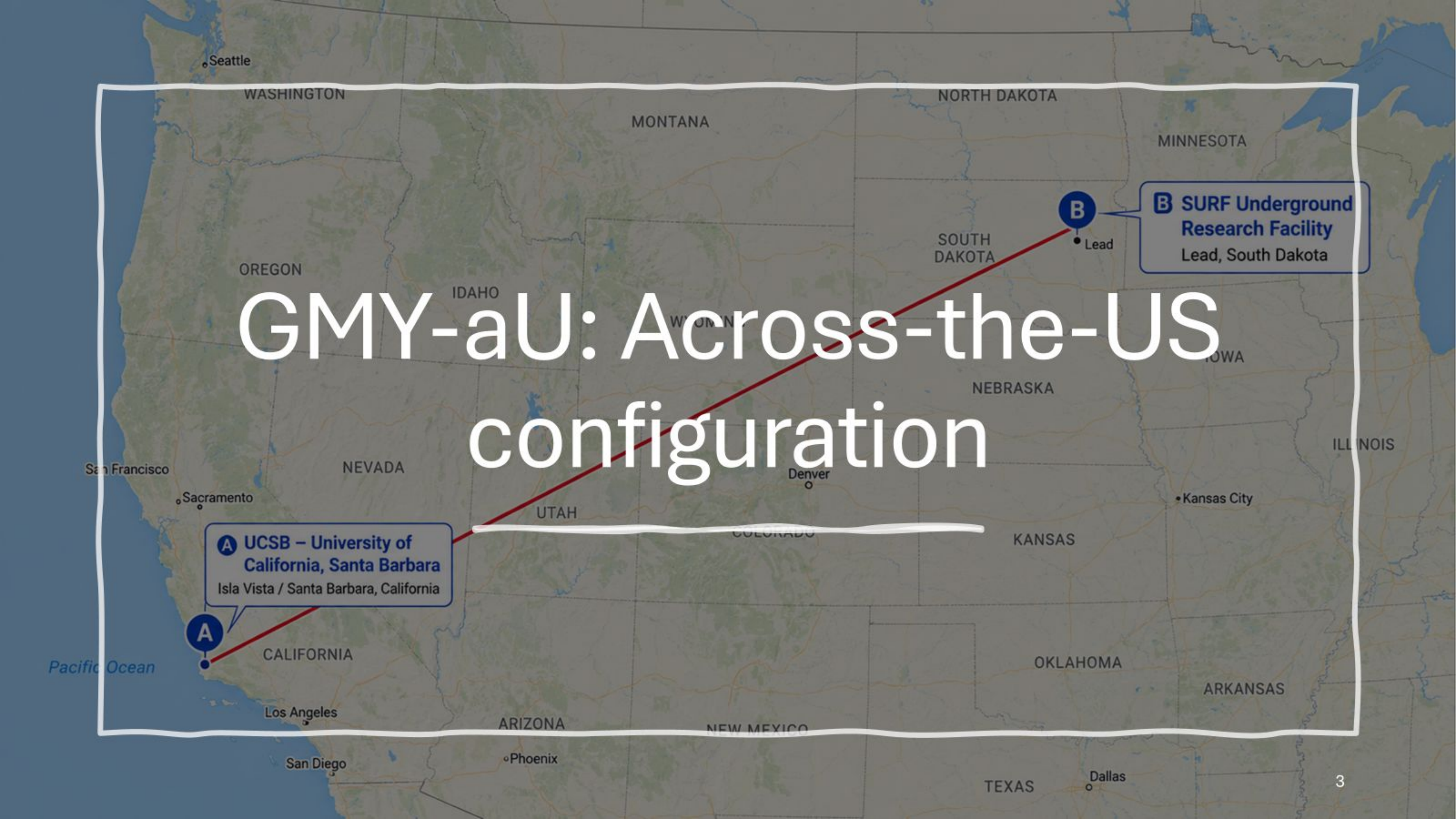
- Baseline: 1800 km, with the far detector at SURF
- Detection efficiency: 0.60
- Assumed matter density: 3.0 g/cm^3
- Beam options tested: on-axis and 0.5° off-axis

GMY-aP: Across-the-Pacific configuration

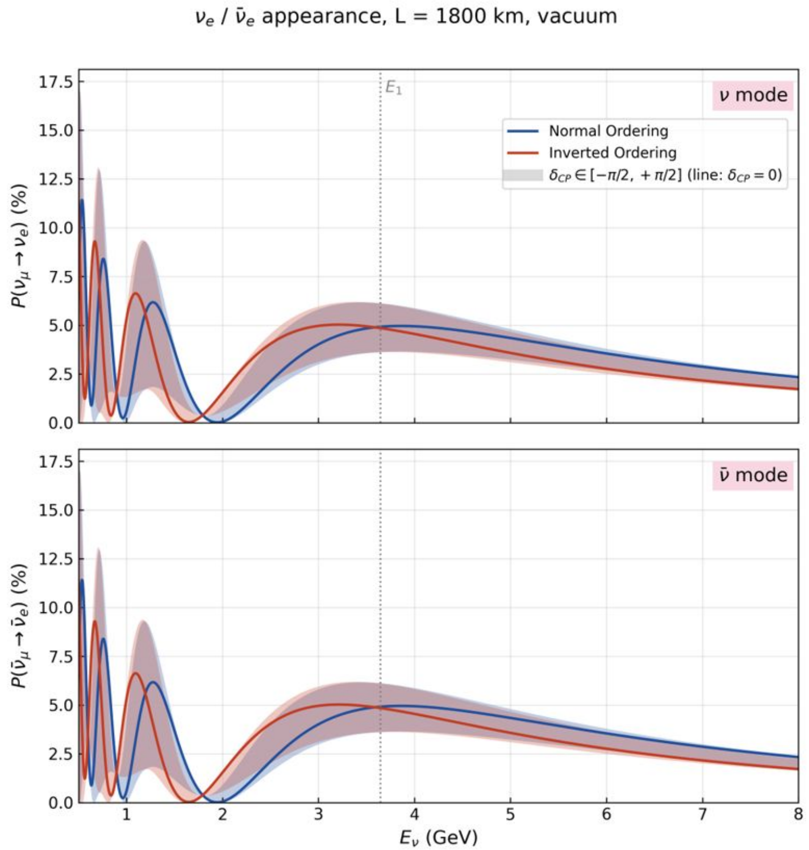
- Baseline: 8119 km, with the far detector near Super-Kamiokande
- Detection efficiency: 0.60
- Assumed density: 1.02 g/cm^3, using a sea-water approximation
- Beam option tested: on-axis



GMY-aU: Across-the-US configuration



First oscillation maximum for GMY-aU



The first oscillation maximum occurs when

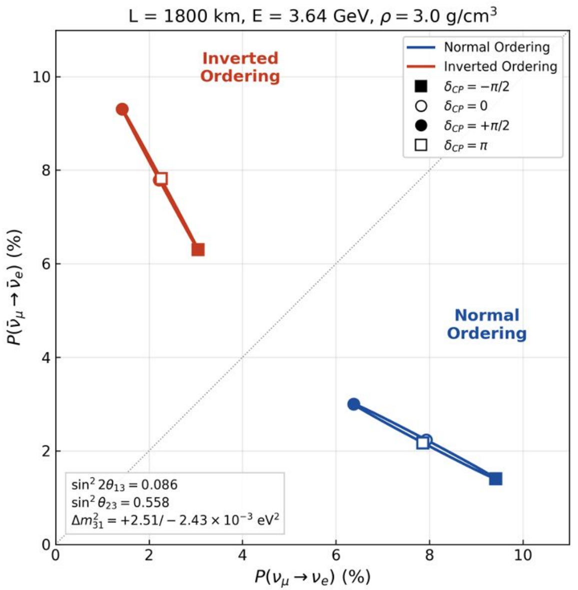
$$\Delta m^2_{13} \times \frac{L}{4E} = 1.267 \Delta m^2_{13} [eV^2] \frac{L[km]}{E[GeV]} = \frac{\pi}{2}$$

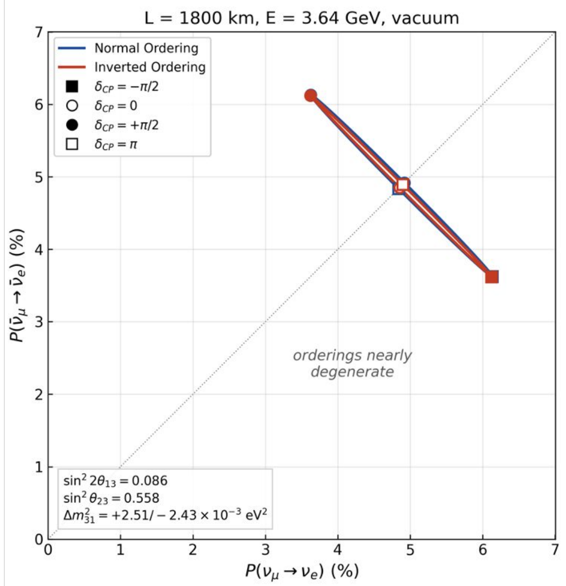
$$\Delta m^2_{13} \approx 2.5 \times 10^{-3} eV^2$$

$$E = 3.64 GeV$$

Matter effects

The ellipses show the neutrino probability versus antineutrino probability as δ_{CP} changes. The separation between normal and inverted ordering comes from matter effects.





Oscillation probability in matter :

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\left[\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\right]\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\left[\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\right]\Delta_{31}\left[\frac{\sin(aL)}{aL}\right]\Delta_{21}\cos(\Delta_{31}+\delta_{\mathrm{CP}})$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\left[\frac{\sin^2(aL)}{(aL)^2}\right]\Delta_{21}^2$$

$$\boxed{\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}}$$

$$\boxed{a = \frac{G_F N_e}{\sqrt{2}}}$$

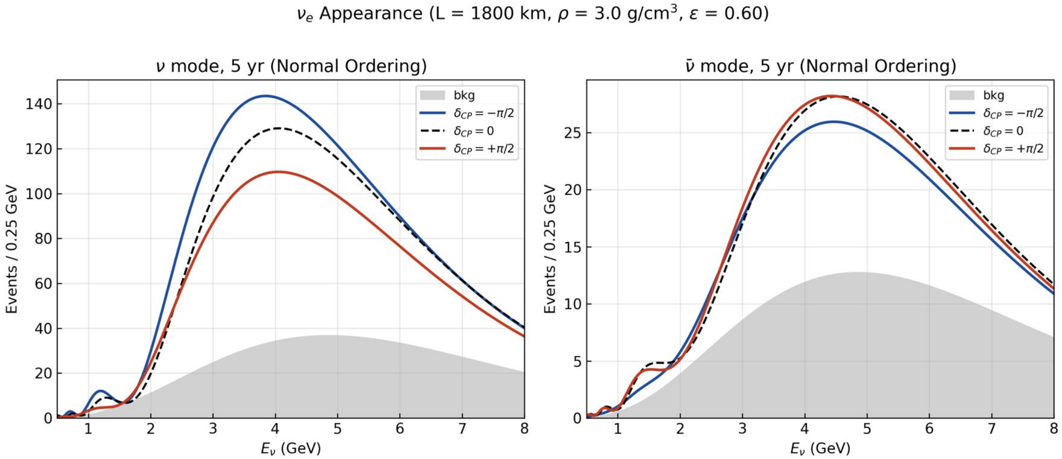
Choosing the off-axis angle

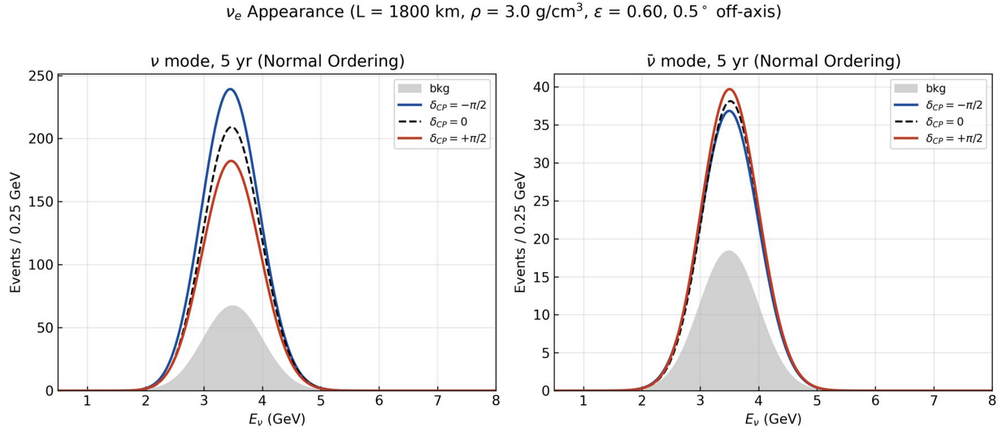
$$E_\nu = \frac{(1 - m_p^2/m_\pi^2)E_\pi}{1 + \gamma^2\theta^2}$$

On axis $$E_\nu = 0.43 E_\pi$$

Off-axis $$E_\nu = \frac{0.43 m_\pi}{2\theta}$$

$$E_\nu = 3.6 GeV \quad \theta \simeq 8.3 mrad \simeq 0.5^\circ$$





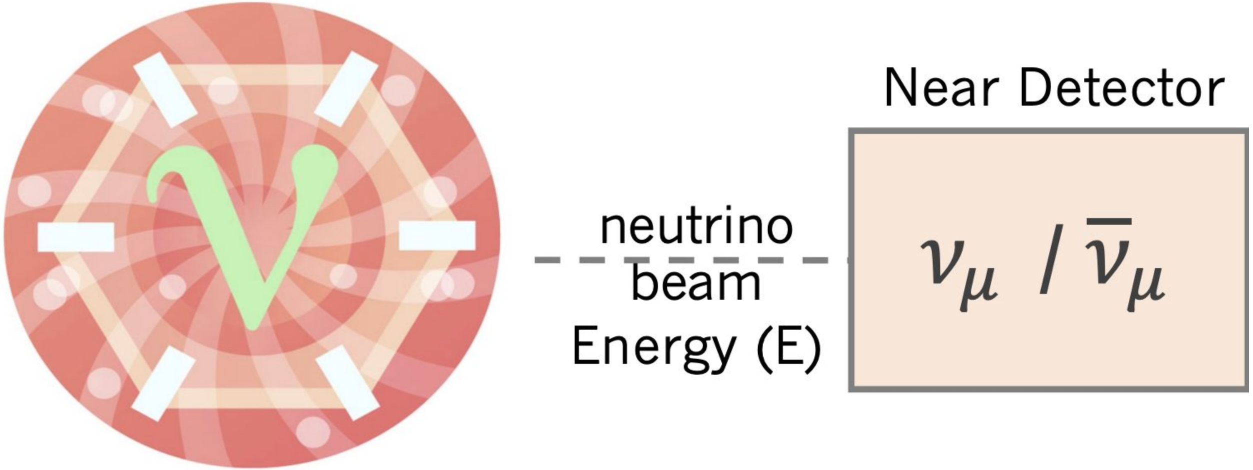
Off-axis beam:

- Cleaner, narrower energy spectrum
- Peak closer to the first oscillation maximum
  - Fewer events
  - Less spectral information
  - Lower CP sensitivity in our simulation

Chosen design: on-axis

Placing the near detector

- Placed around 600 m–1 km from the beam source.
- Measures the beam before significant oscillations occur.
- Constrains the neutrino flux, energy spectrum, cross sections, intrinsic beam backgrounds, and detector response.
- Similar technology to the far detector helps reduce near-to-far systematic uncertainties.



Run Plan: 5 Years + 5 Years

5+5 YEAR EXPOSURE AS A COMPROMISE

$$\sigma_\nu \simeq 2\sigma_{\bar\nu} \qquad N_{\bar\nu} \simeq \frac{1}{4} N_\nu$$

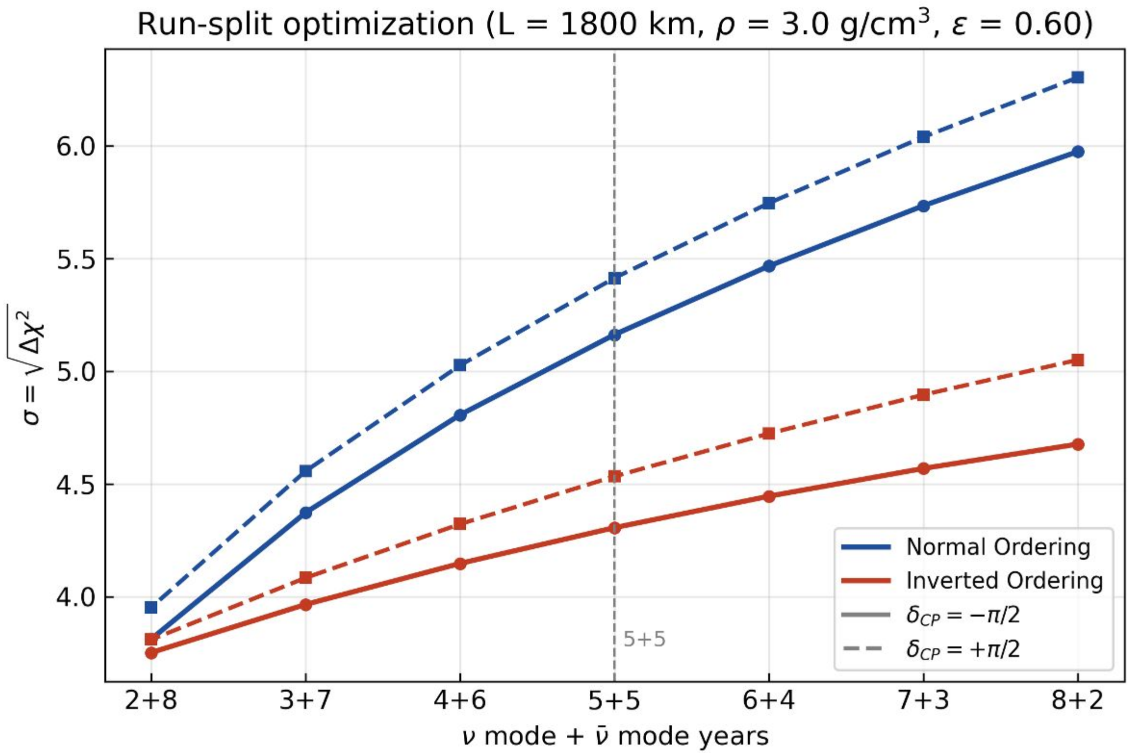
CPV is measure comparing

$$\nu_\mu \to \nu_e \quad \text{and} \quad \bar\nu_\mu \to \bar\nu_e$$

Equal running provides comparable exposure in both modes, even though fewer antineutrino events are collected.

Alternative Option

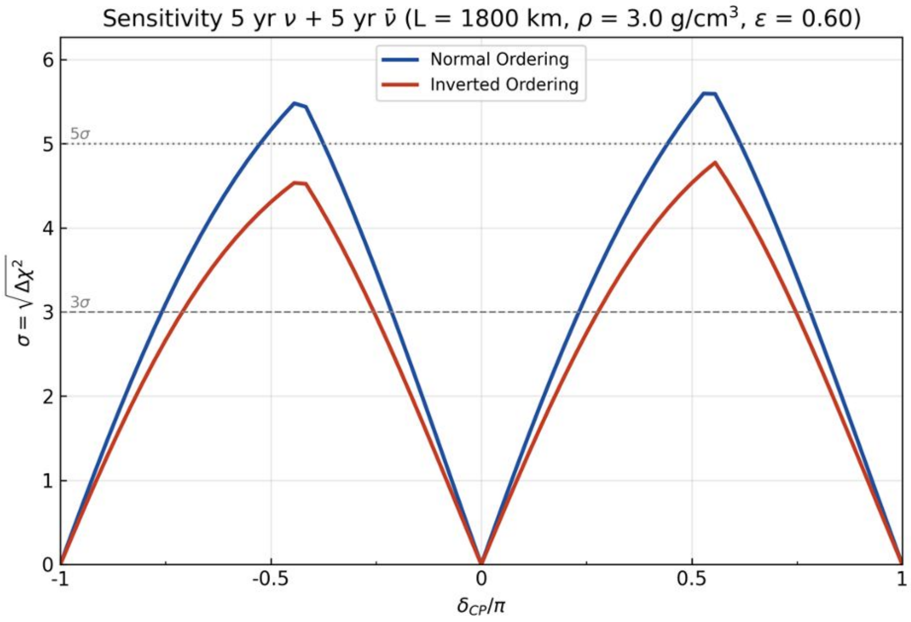
A 7-year ν + 3-year anti-ν split would maximize the total number of events but would reduce the statistical power of the antineutrino sample.

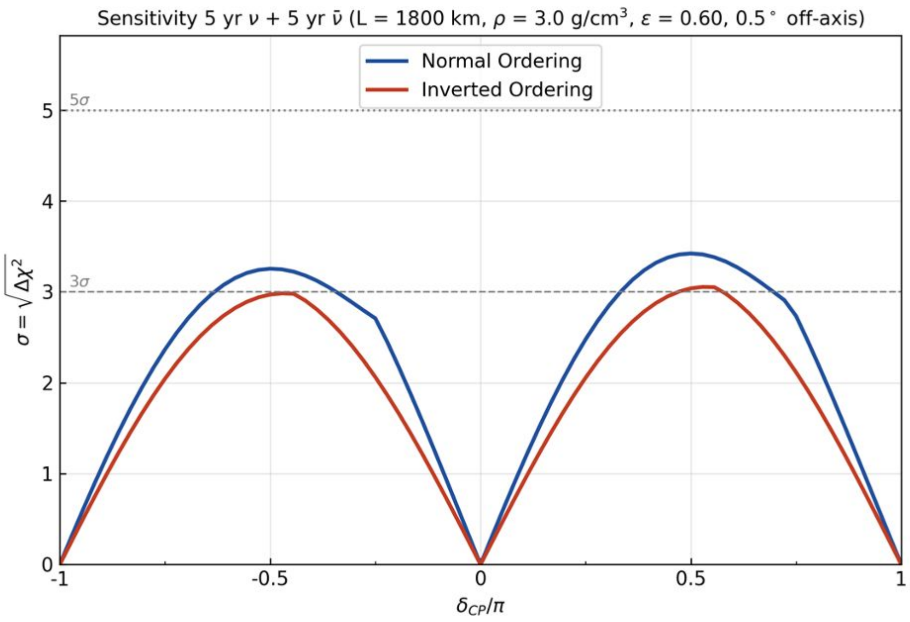


The sensitivity:

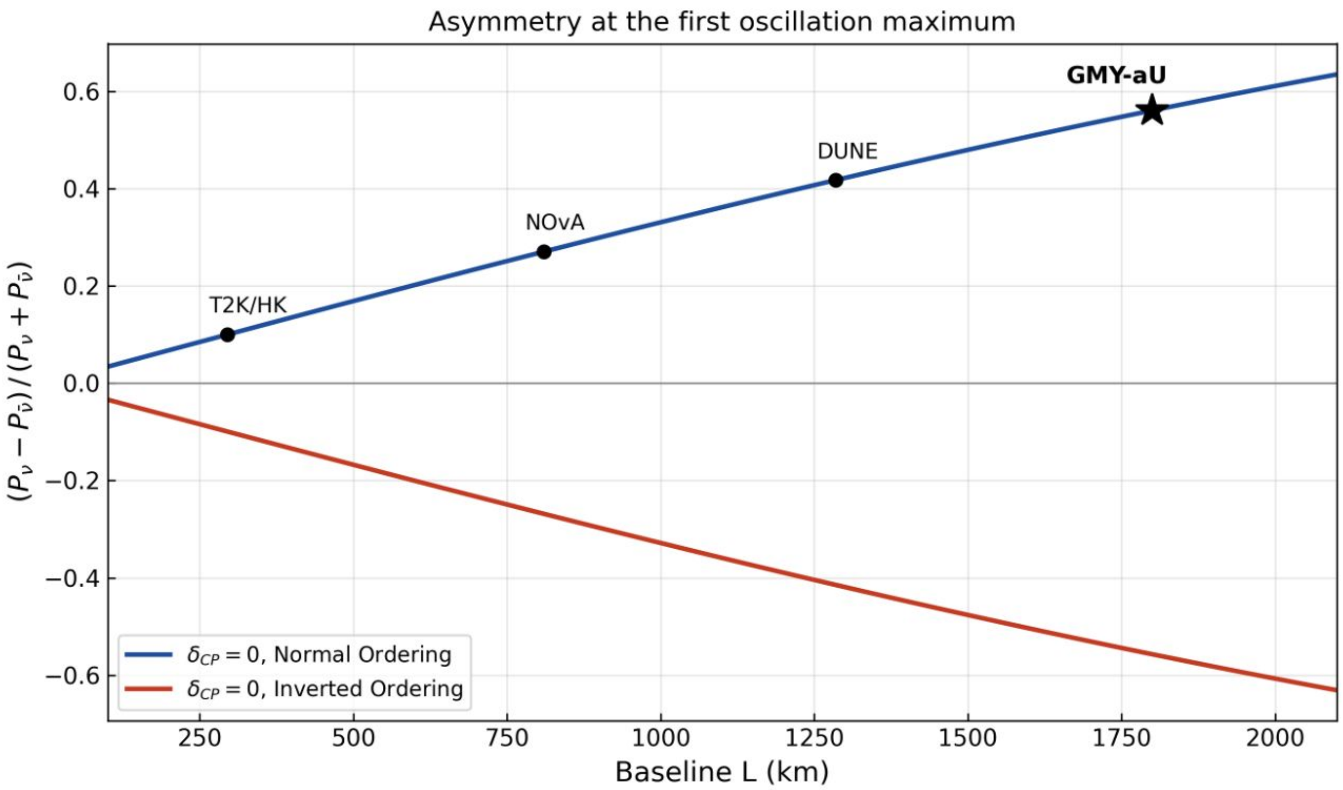
$$\sigma \simeq \sqrt{\Delta\chi^2} \qquad \Delta\chi^2 = \chi^2(\delta_{CP} = 0, \pi) - \chi^2(\delta_{CP})$$

CP sensitivity for GMY-aU

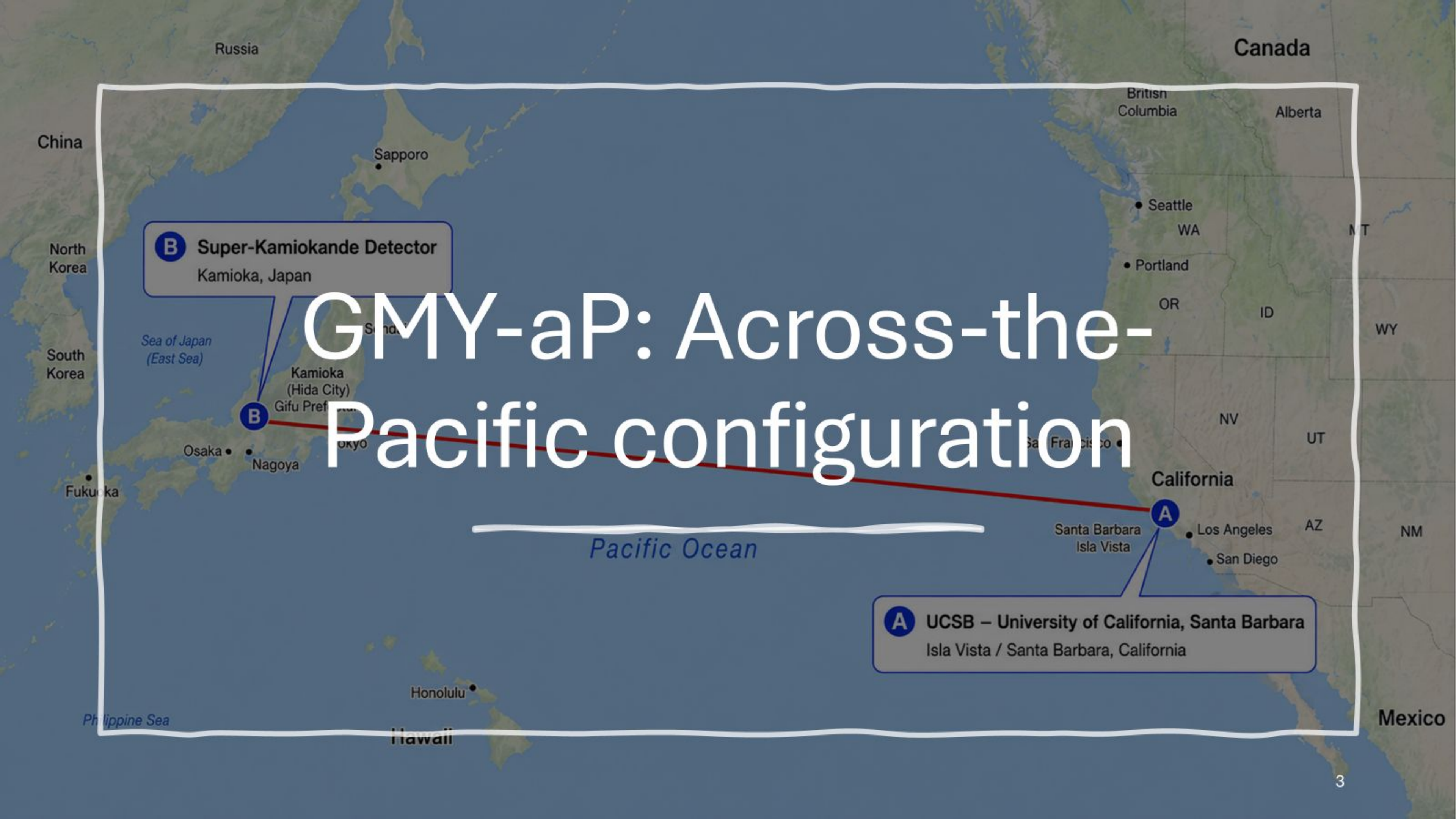




GMY-aU weakness



GMY-aP: Across-the-Pacific configuration



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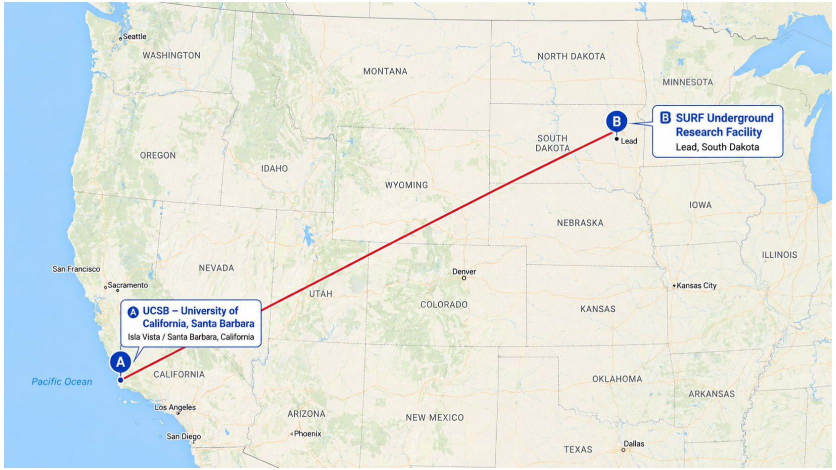

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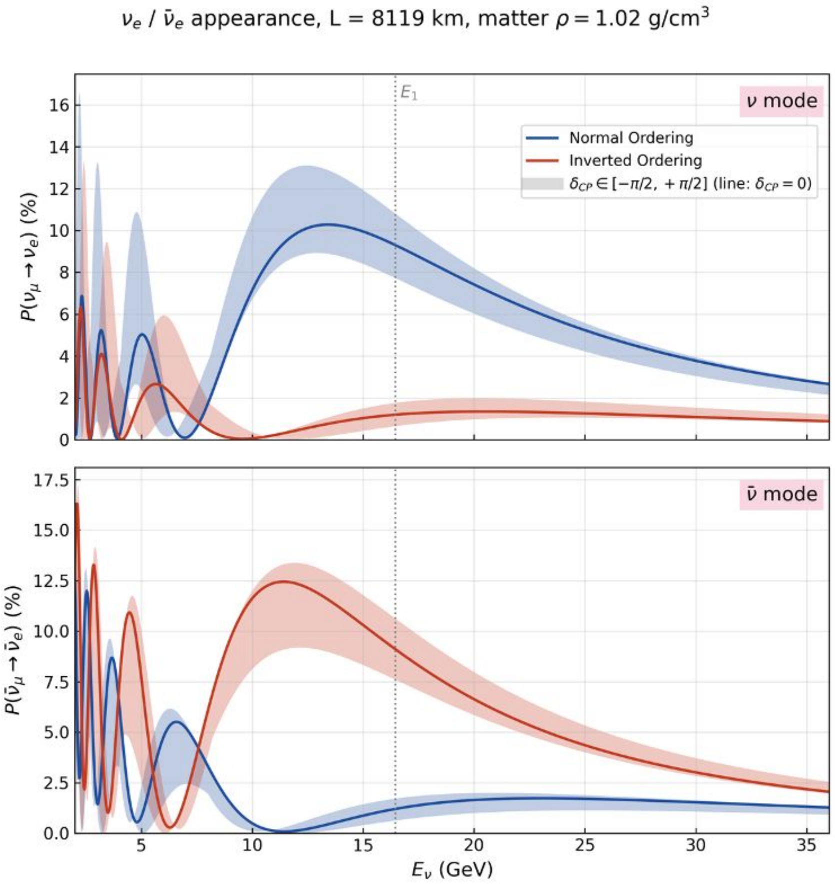

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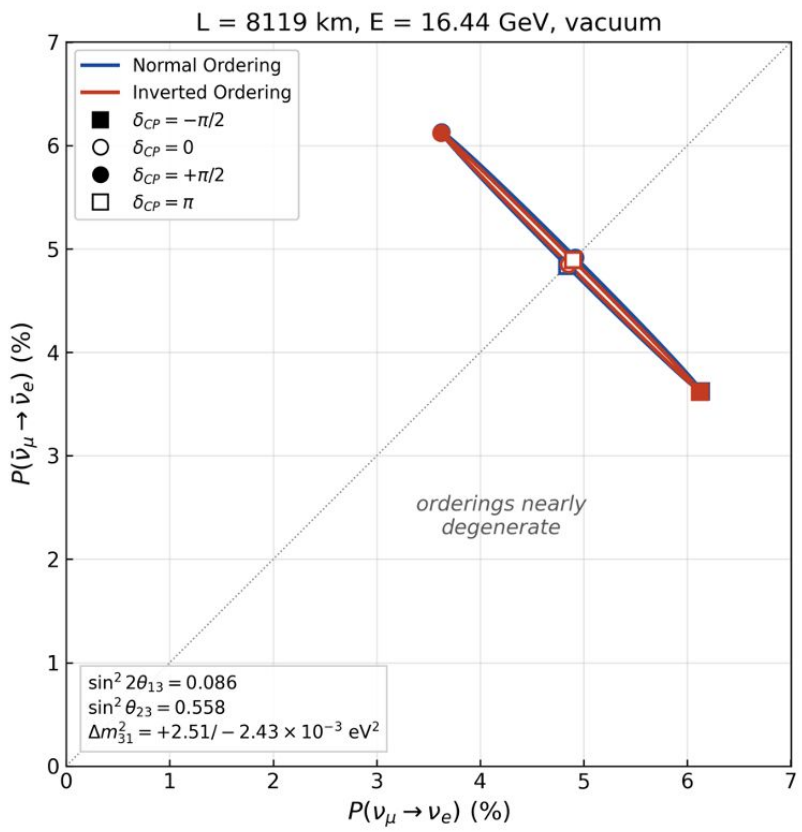
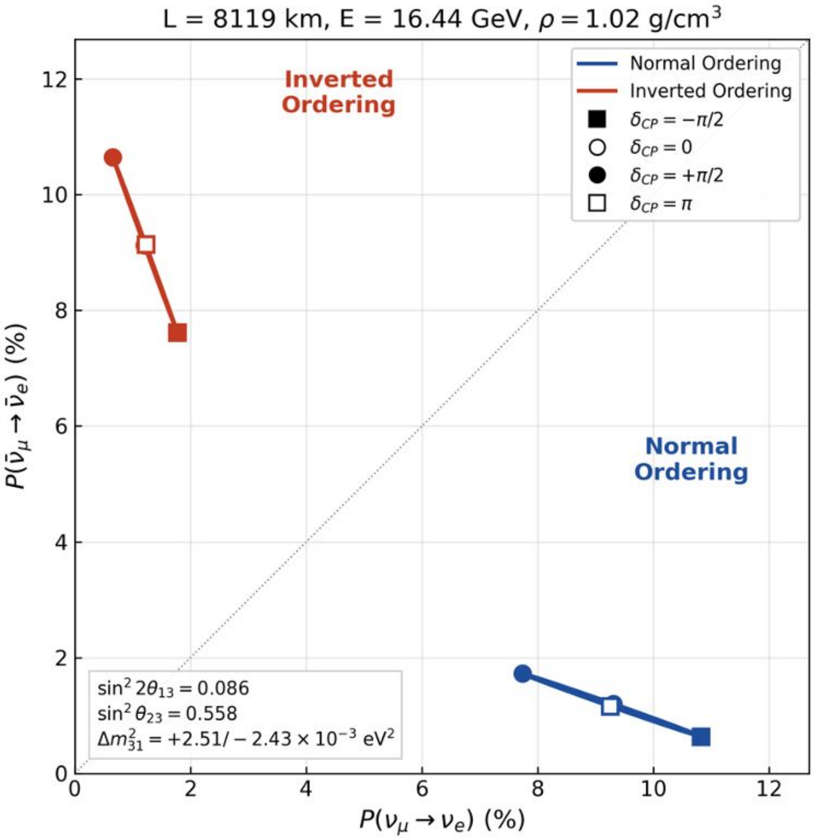
$$\boxed{E = 16.44 GeV}$$

Matter effects





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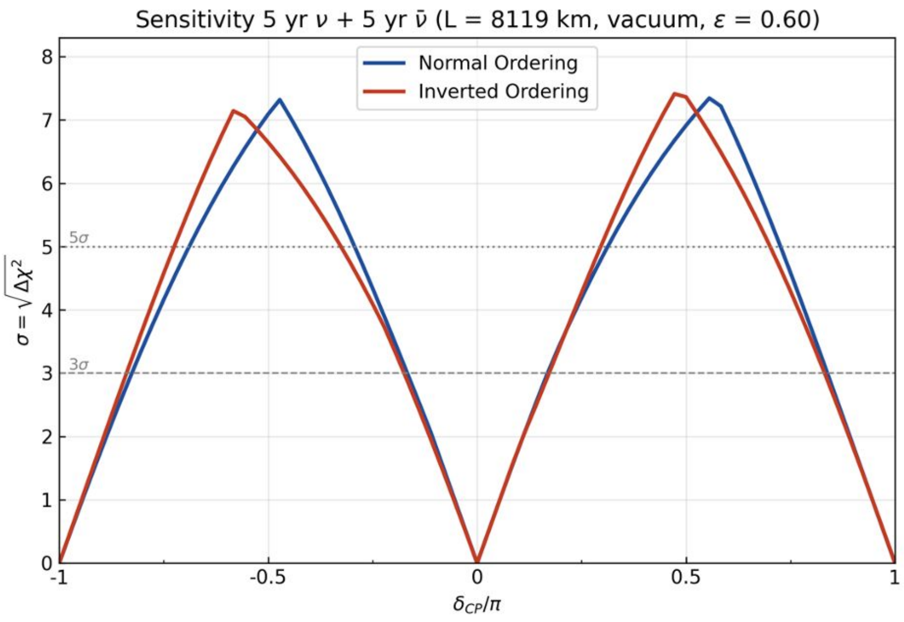

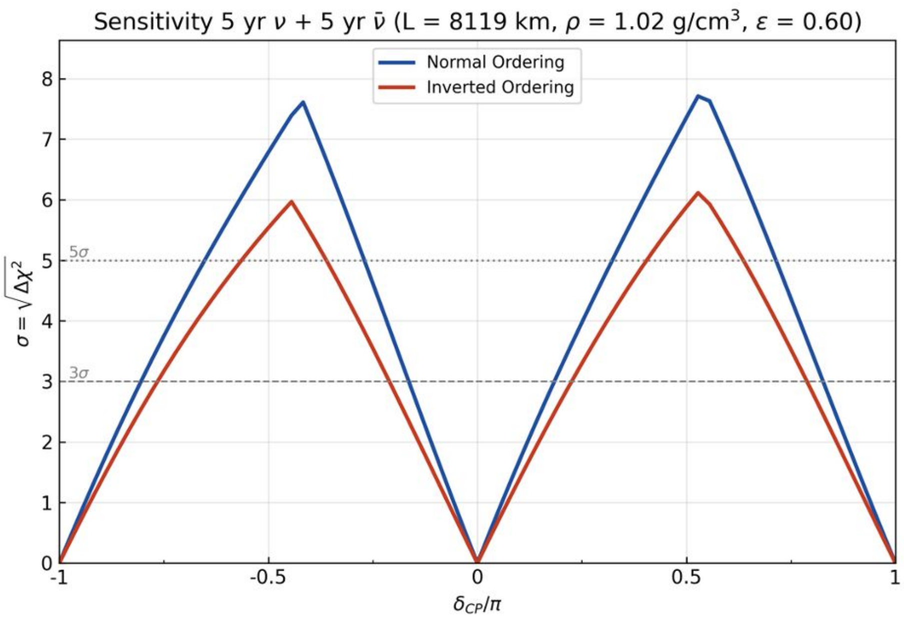

GMY-aP weakness