IceCube constraints on Violation of Equivalence Principle

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Violation of Equivalence Principle (VEP)

Equivalence Principle
All particles couple equally to the gravitational field

General Relativity

Testing the Equivalence Principle can guide toward complete theory

δG/G

Lab experiments $10^{-13} - 10^{-14}$

Free fall $10^{-10} - 10^{-15}$

Atom interferometry $10^{-9} - 10^{-15}$

IceCube can constrain at the level of $10^{-22}$

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VEP and high energy neutrinos

Why does VEP influence neutrinos?

\[ \nu \rightarrow \begin{cases} \nu_1 \\ \nu_2 \\ \nu_3 \end{cases} \]

- \( G'_1 = \gamma_1 G \)
- \( G'_2 = \gamma_2 G \)
- \( G'_3 = \gamma_3 G \)

Dephasing leads to oscillations

\( E \gtrsim 1 \text{ TeV} \)

Cosmic rays

Atmospheric neutrinos

Gonzalez-Garcia et al., 2004; Battistoni et al., 2005; Abbasi et al., 2009; Esmaili et al., 2014
VEP-induced oscillations

\[ i \frac{d\nu}{dl} = \left( \frac{UM^2U^\dagger}{2p} + V + 2\phi p\tilde{U}\tilde{\Gamma}\tilde{U}^\dagger \right) \nu \]

- **Flavor basis**
- **Mass term**
- **Matter term**
- **VEP term**

- **\( U \)**: PMNS matrix
- **\( p \)**: neutrino momentum
- **\( \phi \)**: gravitational potential (in natural units)
VEP-induced oscillations

\[ i \frac{d\nu}{dl} = \left( \frac{U M^2 U^\dagger}{2p} + V + 2\phi p \Gamma \tilde{U} \Gamma \tilde{U}^\dagger \right) \nu \]

Flavor basis
Mass term
Matter term
VEP term

\[
\Gamma = \begin{pmatrix}
\gamma_1 & 0 & 0 \\
0 & \gamma_2 & 0 \\
0 & 0 & \gamma_3
\end{pmatrix} \quad \text{Only differences can cause physical effects}
\]

\[
\Gamma = \begin{pmatrix}
0 & 0 & 0 \\
0 & \gamma_{21} & 0 \\
0 & 0 & \gamma_{31}
\end{pmatrix}
\]

Simple benchmark choice: gravity couples (diagonally) to mass eigenstates

\[ U = \tilde{U} \]

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VEP-induced oscillations

\[ i \frac{d\nu}{dl} = \left( \frac{U M^2 U^\dagger}{2p} + V + 2\phi p \tilde{\Gamma} \tilde{U}^\dagger \right) \nu \]

Conventional oscillations

VEP-dominated oscillations
VEP and atmospheric neutrinos

Model of atmospheric fluxes from Honda et al., 2006

Gravitational potential dominated by Great Attractor

\[ \phi \sim 10^{-5} \]

Earth gravitational potential negligible
(\[ \phi \sim 10^{-9} \])

\[ \frac{\delta G}{G} \sim 10^{-22} \]

\[ \gamma \phi \sim 10^{-27} \]
VEP and atmospheric neutrinos

Model of atmospheric fluxes from Honda et al., 2006

No VEP

\[ \Phi_\mu \left[ \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1} \right] \]

\[ E_\nu = 1 \text{ TeV} \]

\[ \gamma_{21} \phi = 10^{-27}, \gamma_{31} \phi = 10^{-27} \]
VEP and atmospheric neutrinos

Model of atmospheric fluxes from Honda et al., 2006

Analysis on IC40 and IC79  
Esmaili et al., 2014

Analysis on through-going muons  
Aartsen et al., 2017

\[
\chi^2(\gamma_{21}\phi, \gamma_{31}\phi, \alpha, \beta) = \\
\sum_i \left[ \frac{N_i^{\text{data}} - \alpha(1 + \beta(0.5 + \cos \theta))N_i^{\text{th}}}{\sigma_{i,\text{stat}}^2 + \sigma_{i,\text{sys}}^2} \right]^2 + \\
\frac{(1 - \alpha)^2}{\sigma_{\alpha}^2} + \frac{\beta^2}{\sigma_{\beta}^2}
\]

Normalization  
Angular distribution

Aartsen et al., 2017

Aartsen et al., 2020
Constraints from atmospheric neutrinos

\( \gamma_{21}, \gamma_{31} \) have same signs

\( \gamma_{21}, \gamma_{31} \) have opposite signs
Gravitational basis

Simple **benchmark** choice: gravity couples (diagonally) to mass eigenstates

What happens for different choices?

$\tilde{U}$ connects gravitational and flavor eigenstates

Parameterized by 3 mixing angles, 1 phase

Extreme **benchmark** choice: gravity couples (diagonally) to **flavor** eigenstates

VEP oscillations are inhibited

Atmospheric neutrinos cannot constrain all choices!
VEP and astrophysical neutrinos

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

$\{ L \sim \text{Gpc} \}$

VEP effects depend on gravitational field structure

Minakata et al. 1996

Simple scenario model independent

$\phi \sim 5 \times 10^{-6}$

VEP-dominanted oscillations

$\lambda \ [\text{km}]$

$E \ [\text{GeV}]$

$\gamma \gtrsim 10^{-26}$
VEP and astrophysical neutrinos

Conventional scenario

\[ P^\text{Earth}_\alpha = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2 P_\beta^\text{source} \]
VEP and astrophysical neutrinos

VEP-dominated scenario

\[ P_{\alpha}^{\text{Earth}} = \sum_{i} |\tilde{U}_{\alpha i}|^2 |\tilde{U}_{\beta i}|^2 P_{\beta}^{\text{source}} \]

IceCube-Gen 2 estimated, Bustamante et al., 2019
See also Shoemaker et al., 2016; Song et al., 2020

\[ \tilde{U} = U \]
Gravitational=Mass
Cannot be distinguished!

Unitarity bounds
Arguelles et al., 2015; Ahlers et al., 2018

Gravitational=Flavor
Already in tension

Different choices of \( \tilde{U} \) span the region

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Conclusions

- VEP in the neutrino sector can be tested by IceCube observations
- Complementarity between two approaches
  - Atmospheric neutrinos constrain at the level of $\gamma \phi \sim 10^{-27}$ for some choices of the gravitational basis
  - Astrophysical neutrinos constrain at the level of $\gamma \phi \sim 10^{-31}$ for other choices of the gravitational basis
Backup slides
VEP and high energy neutrinos

Why does VEP influence neutrinos?

Three neutrino states

$$\nu_a = \sum_\beta \bar{U}_{\beta a} \nu_\beta$$

Different coupling strengths

$$\gamma_a$$

Gravitational potential

Simple benchmark case: mass eigenstates couple differently to gravity

$$E^2(1 + 2\gamma_a \phi) - p^2(1 - 2\gamma_a \phi) = m_a^2$$

Modified dispersion relation