IceCube constraints on Violation of Equivalence Principle

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based on D. Fiorillo, G. Mangano, S. Morisi, O. Pisanti, arXiv:2012.07867

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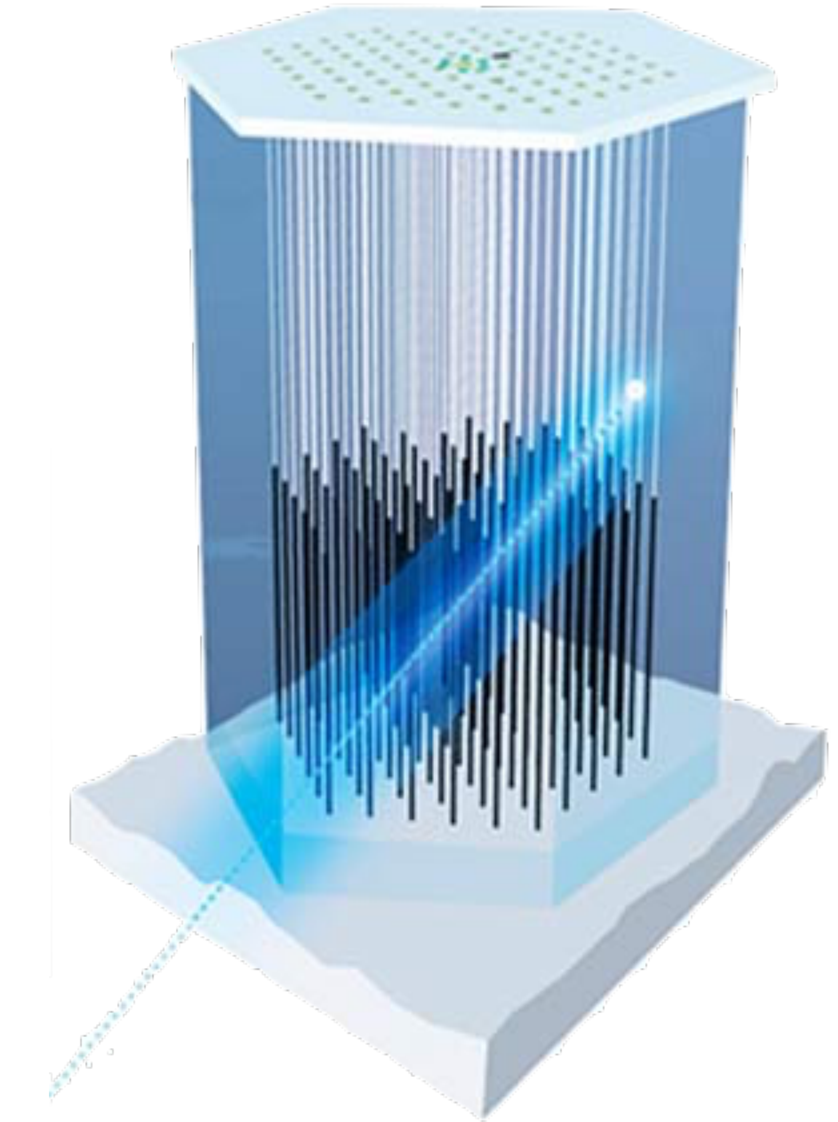
Violation of Equivalence Principle (VEP)

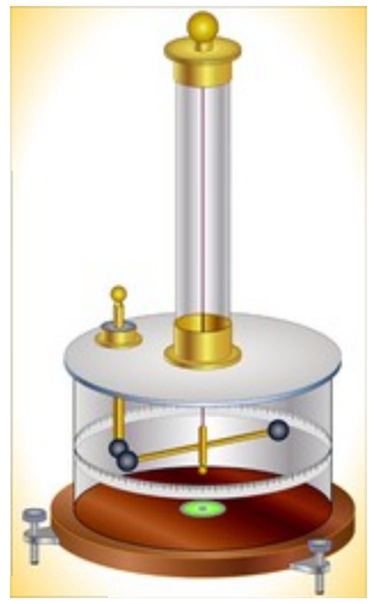
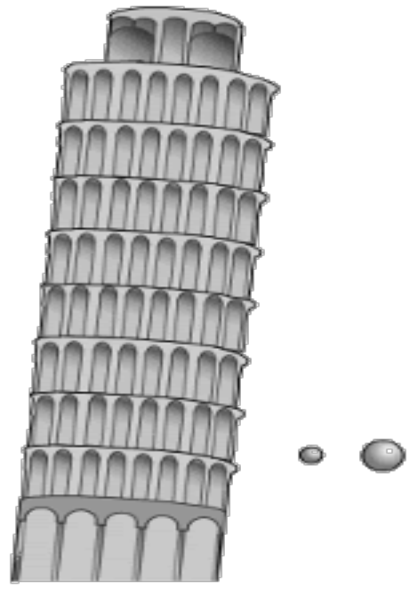
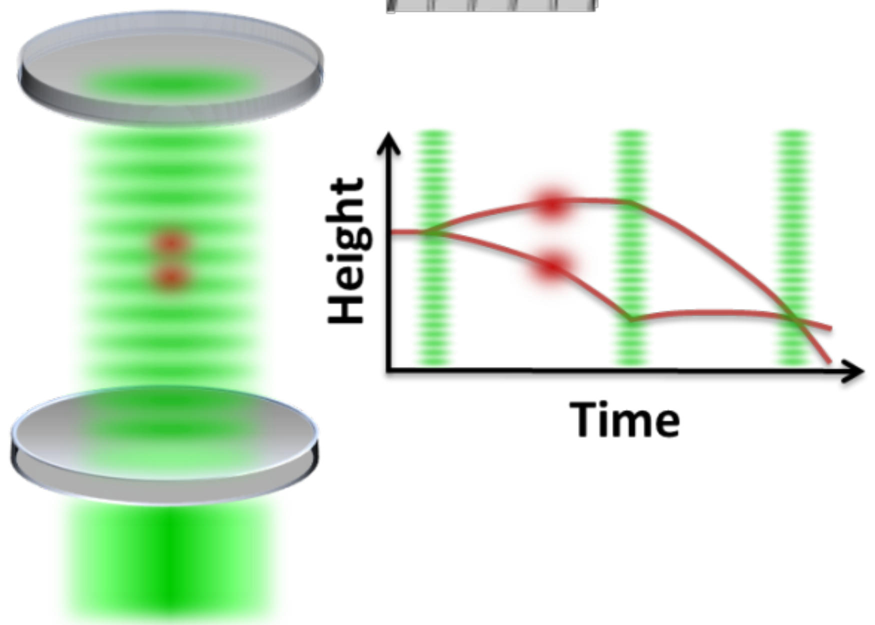
General Relativity

Equivalence Principle
All particles couple equally to the gravitational field



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

Testing the Equivalence Principle can guide toward complete theory

		$\delta G/G$
	Lab experiments	$10^{-13} - 10^{-14}$
	Free fall	$10^{-10} - 10^{-15}$
	Atom interferometry	$10^{-9} - 10^{-15}$

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VEP and high energy neutrinos

Why does VEP influence neutrinos?

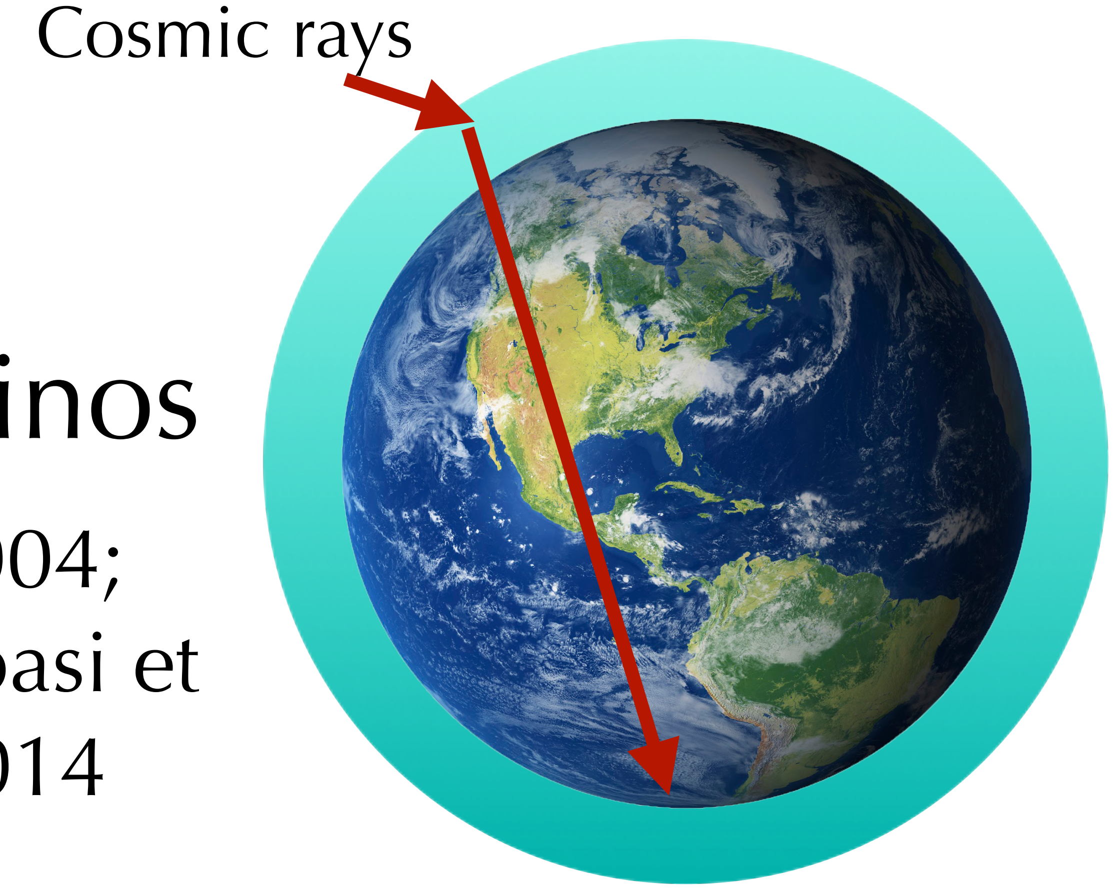
$$\nu \longrightarrow \begin{cases} \xrightarrow{\nu_1} & G'_1 = \gamma_1 G \\ \xrightarrow{\nu_2} & G'_2 = \gamma_2 G \\ \xrightarrow{\nu_3} & G'_3 = \gamma_3 G \end{cases}$$

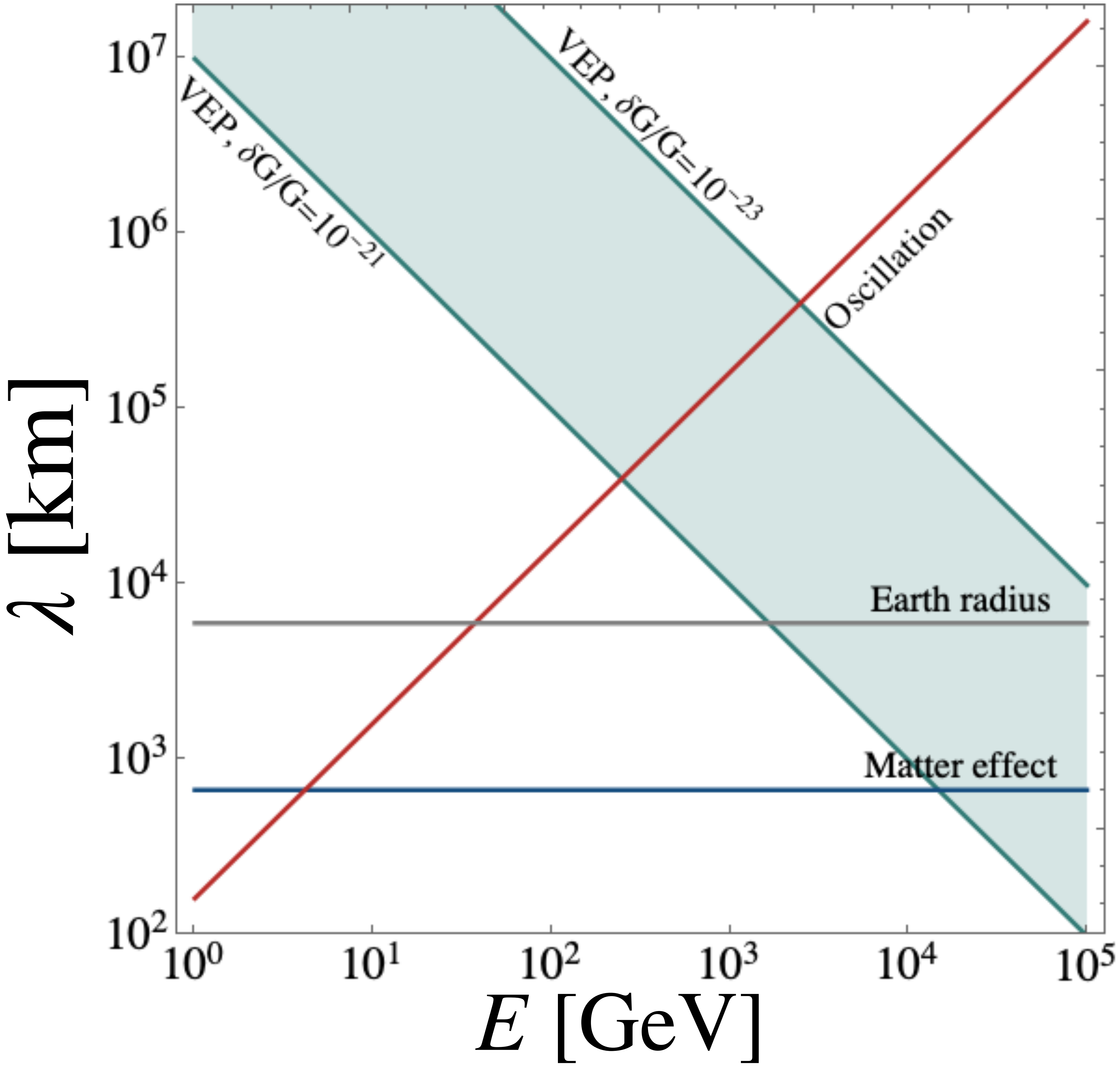
Dephasing leads to oscillations

$$E \gtrsim 1 \text{ TeV}$$

Atmospheric neutrinos

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





VEP-induced oscillations

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

Flavor basis

Mass term

Matter term

VEP term

U PMNS matrix

p neutrino momentum

ϕ gravitational potential (in natural units)

VEP-induced oscillations

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

Flavor basis

Mass term

Matter term

VEP term

$$\Gamma = \begin{pmatrix} \gamma_1 & 0 & 0 \\ 0 & \gamma_2 & 0 \\ 0 & 0 & \gamma_3 \end{pmatrix} \xrightarrow{\text{Only differences can cause physical effects}} \Gamma = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \gamma_{21} & 0 \\ 0 & 0 & \gamma_{31} \end{pmatrix}$$

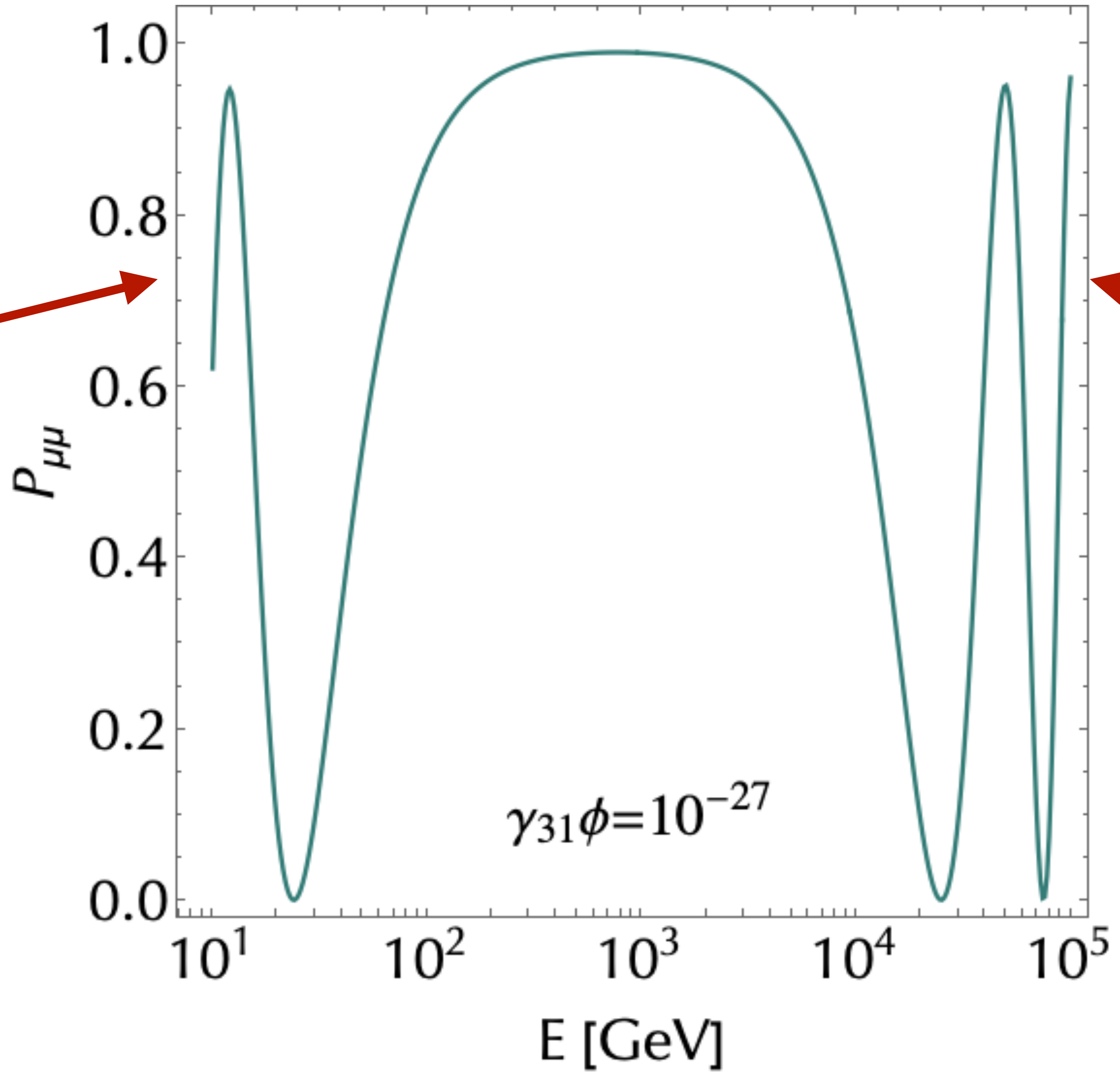
Simple benchmark choice: gravity couples (diagonally) to mass eigenstates

$$U = \tilde{U}$$

VEP-induced oscillations

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

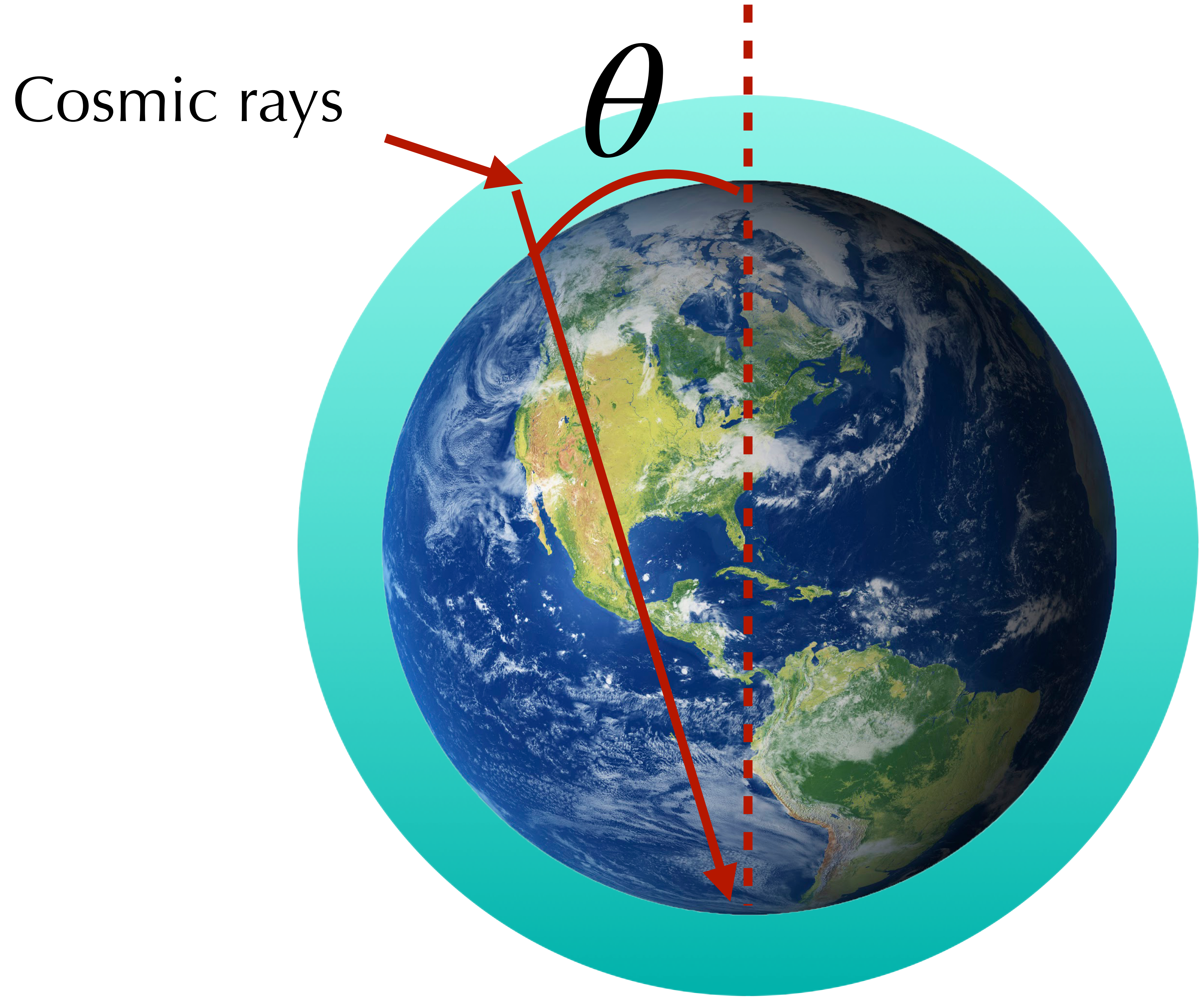
Conventional oscillations



VEP-dominated oscillations

VEP and atmospheric neutrinos

Model of atmospheric fluxes from Honda et al., 2006



Gravitational potential dominated by Great Attractor

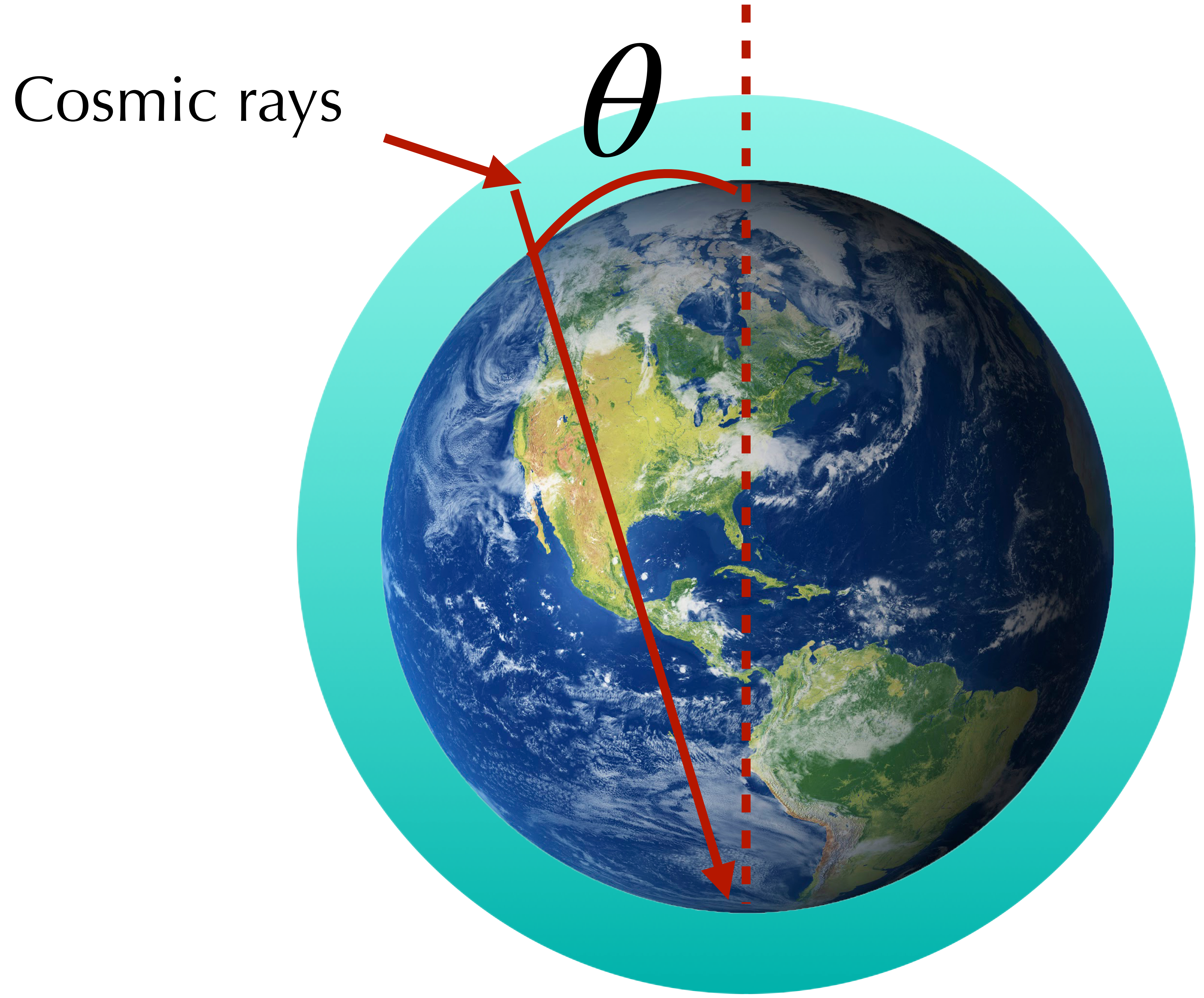
$$\phi \sim 10^{-5}$$

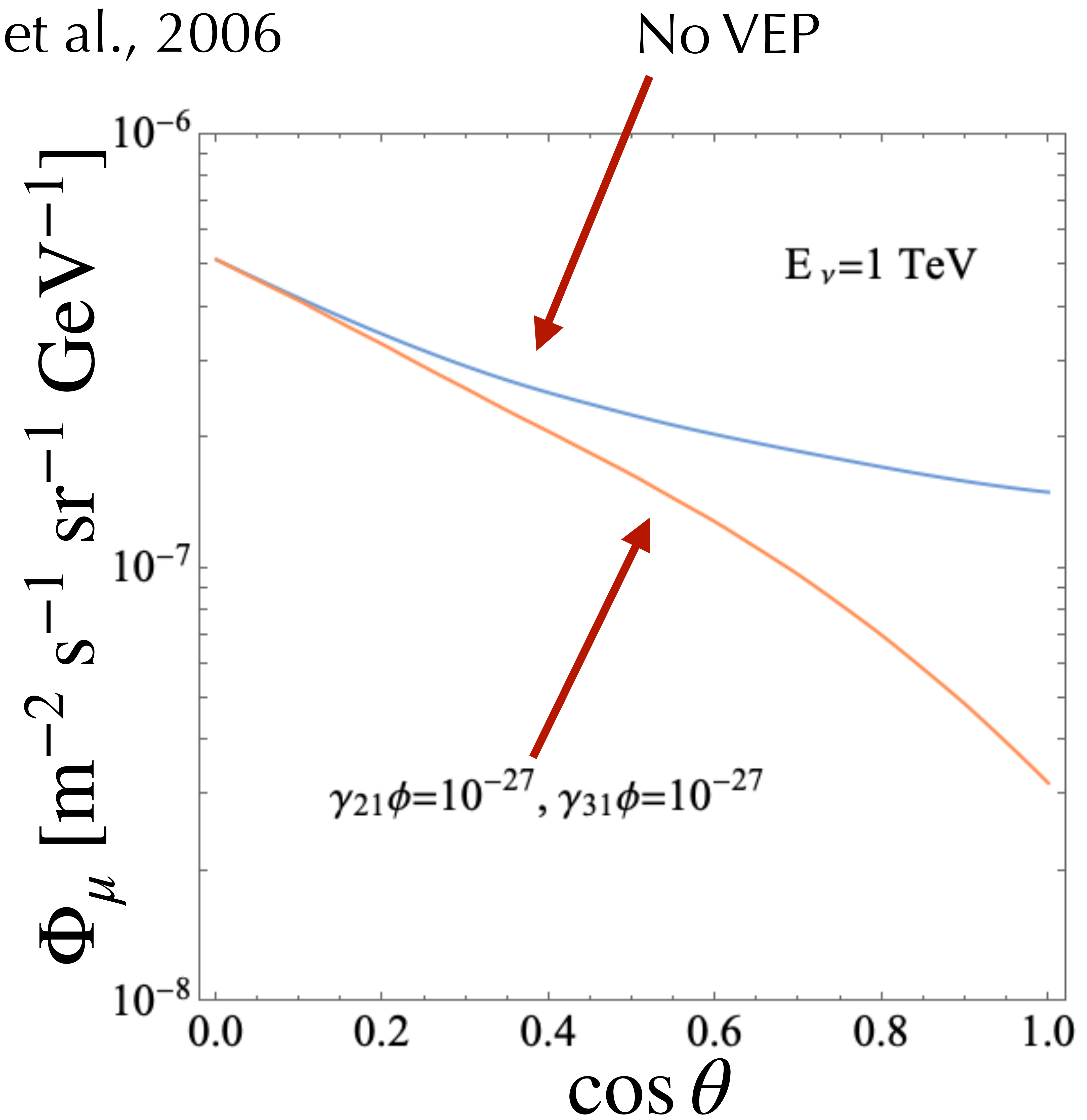
Earth gravitational potential negligible ($\phi \sim 10^{-9}$)

$$\frac{\delta G}{G} \sim 10^{-22} \longrightarrow \gamma\phi \sim 10^{-27}$$

VEP and atmospheric neutrinos

Model of atmospheric fluxes from Honda et al., 2006





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

$$\left.\begin{array}{l}\text{IC79}\\ \\ \text{IC86-11}\end{array}\right\}\ \text{Aartsen et al., 2017}$$

IC86-12/18 Aartsen et al., 2020

$$\chi^2(\gamma_{21}\phi, \gamma_{31}\phi, \alpha, \beta) =$$

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

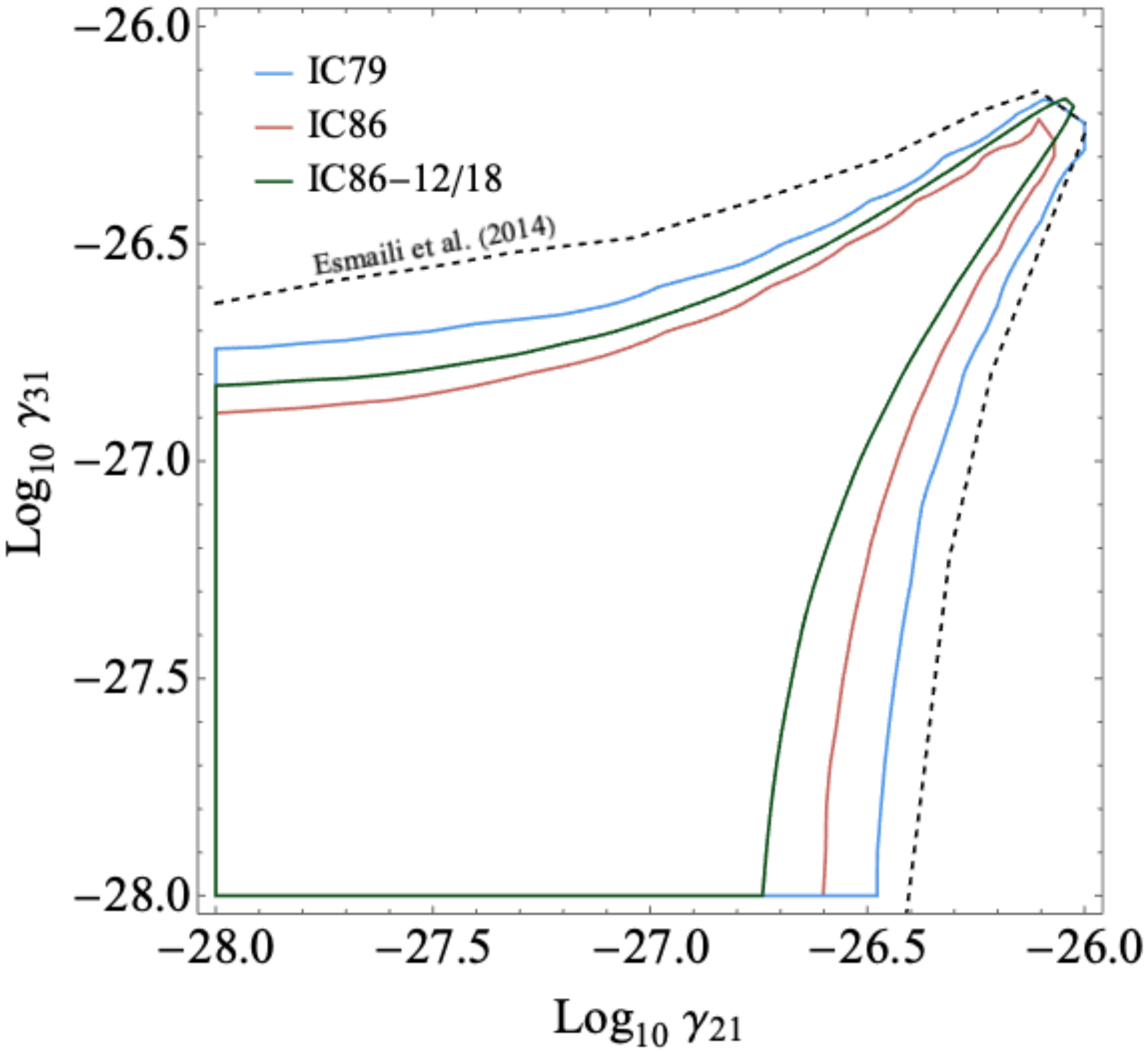
$$\frac{(1-\alpha)^2}{\sigma_\alpha^2} + \frac{\beta^2}{\sigma_\beta^2}$$

Normalization

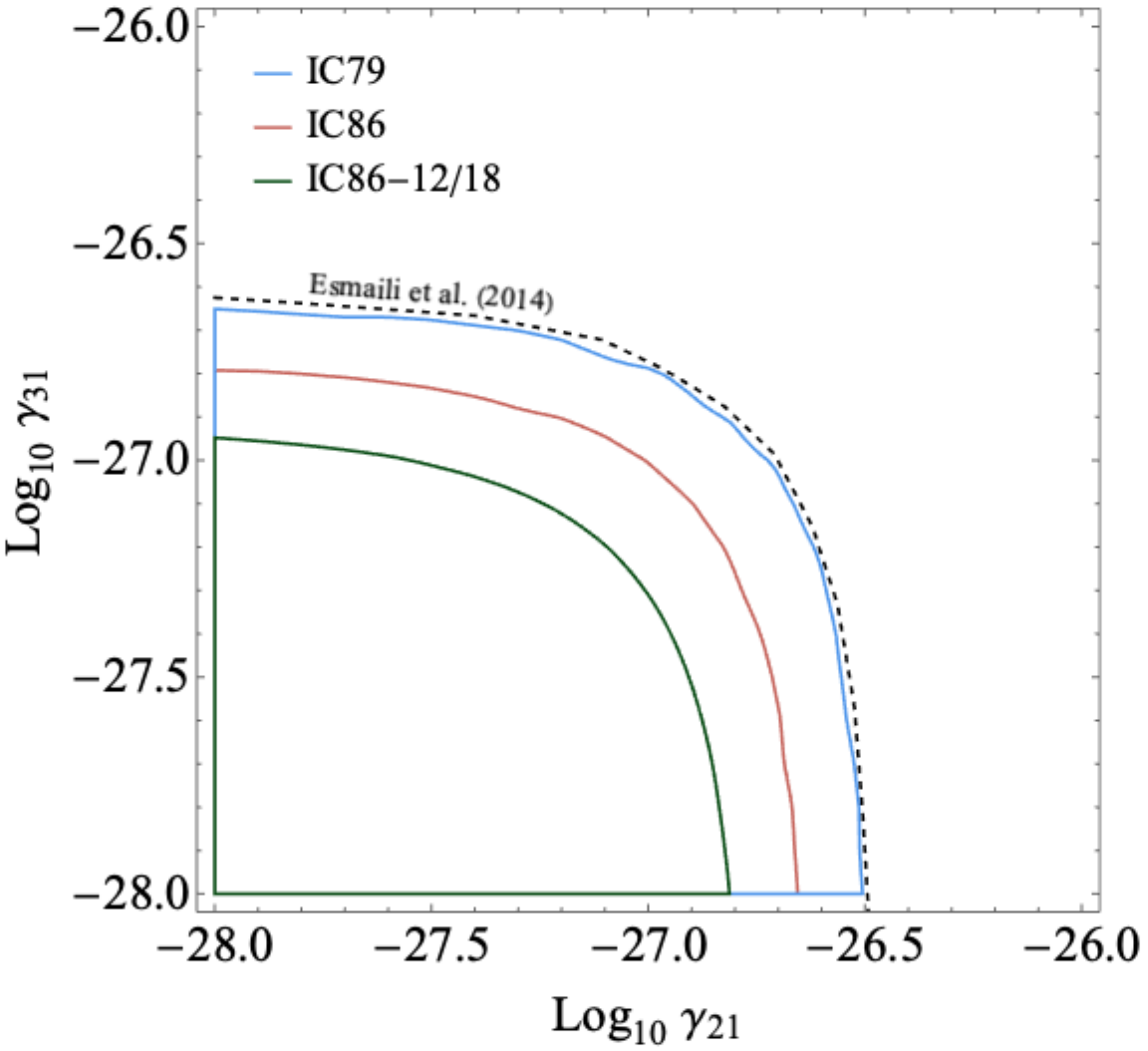
Angular distribution

Constraints from atmospheric neutrinos

γ_{21}, γ_{31} have same signs



γ_{21}, γ_{31} have opposite signs



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Gravitational basis

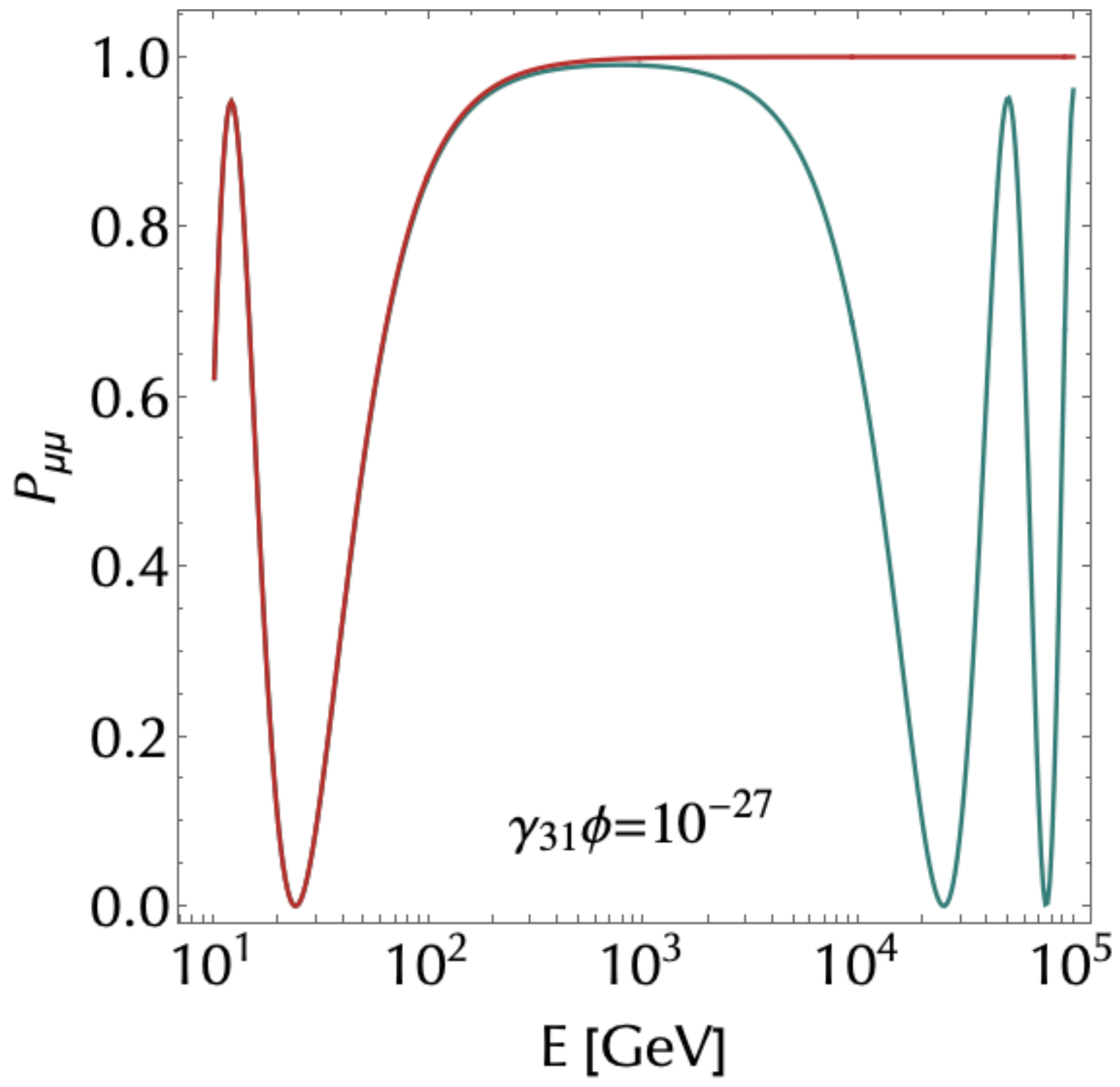
Simple benchmark choice: gravity couples (diagonally) to mass eigenstates

What happens for different choices?

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

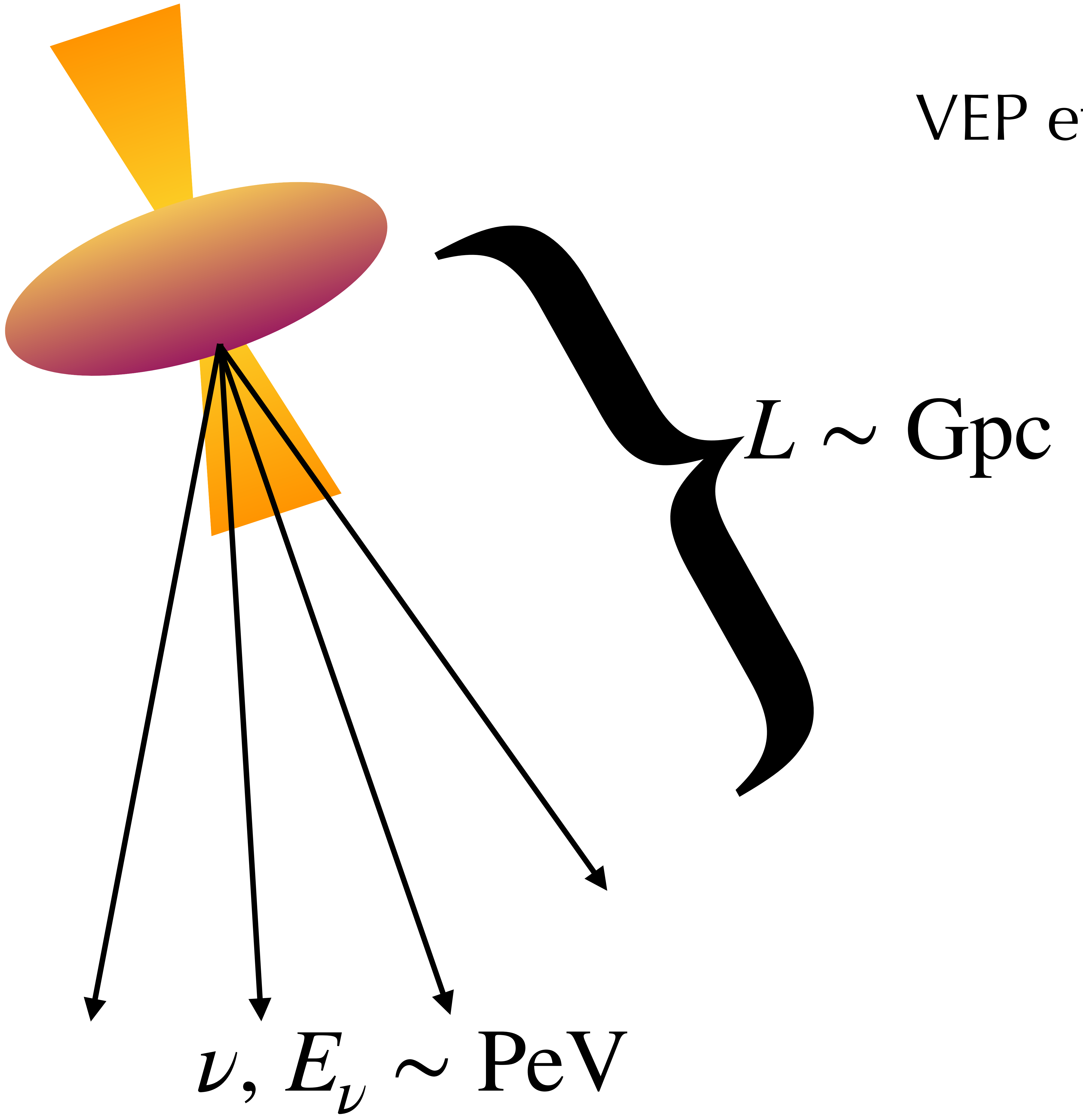
Parameterized by 3 mixing angles, 1 phase

Extreme benchmark choice: gravity couples (diagonally) to flavor eigenstates → VEP oscillations are inhibited



Atmospheric neutrinos cannot constrain all choices!

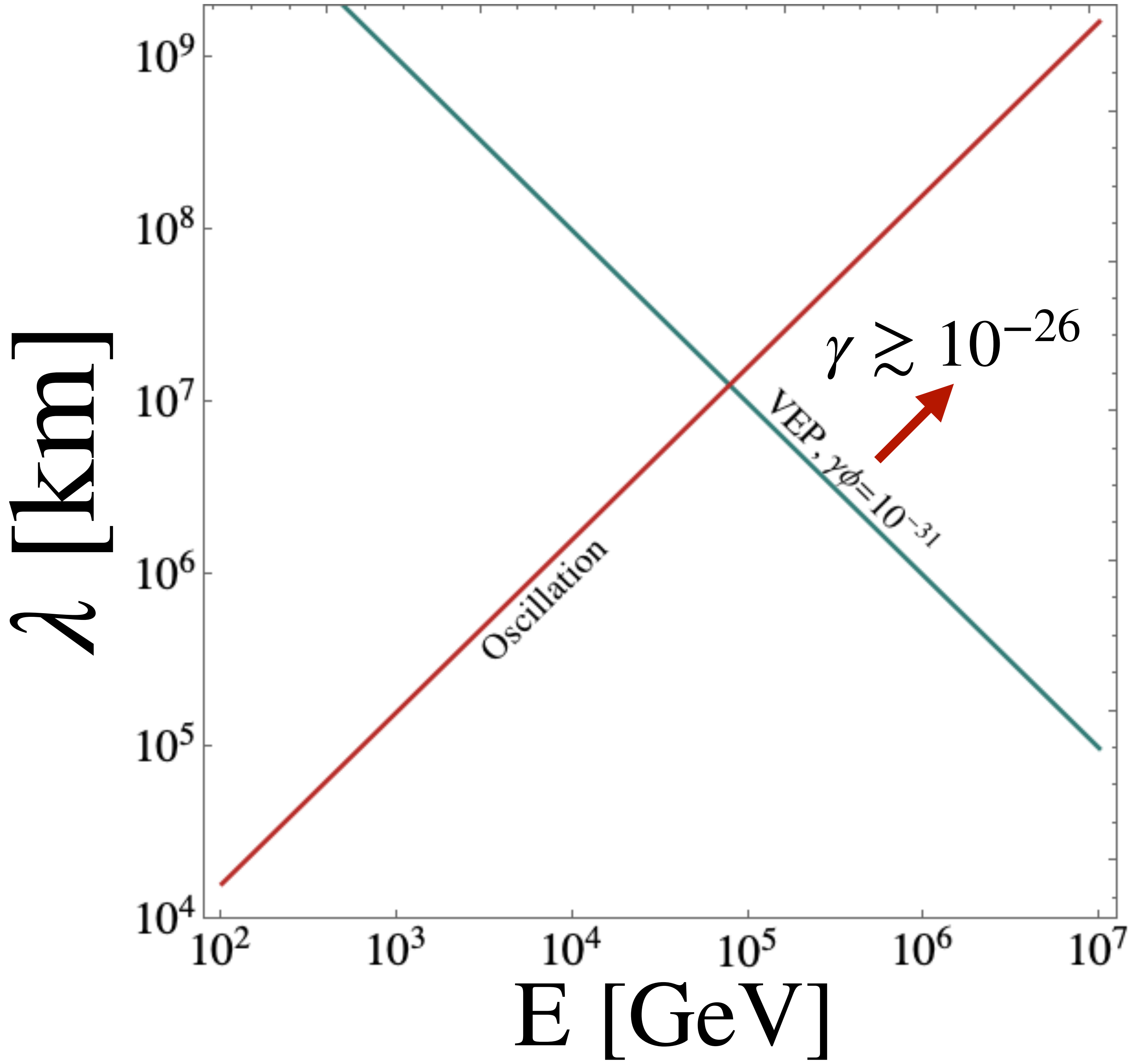
VEP and astrophysical neutrinos



VEP effects depend on gravitational field structure

Minakata et al. 1996

Simple scenario model independent



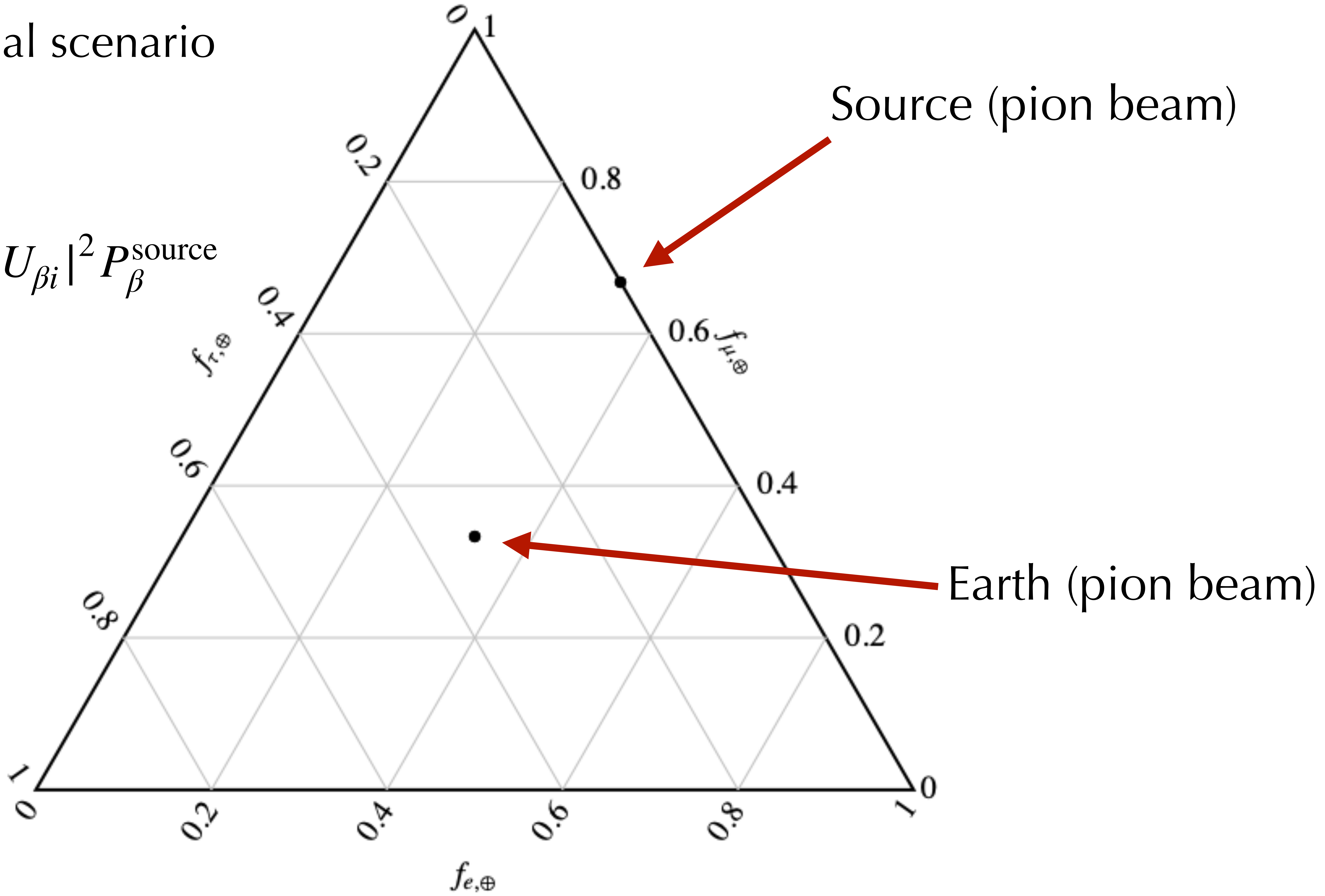
$\phi \sim 5 \times 10^{-6}$

VEP-dominated oscillations

VEP and astrophysical neutrinos

Conventional scenario

$$P_\alpha^{\text{Earth}} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2 P_\beta^{\text{source}}$$



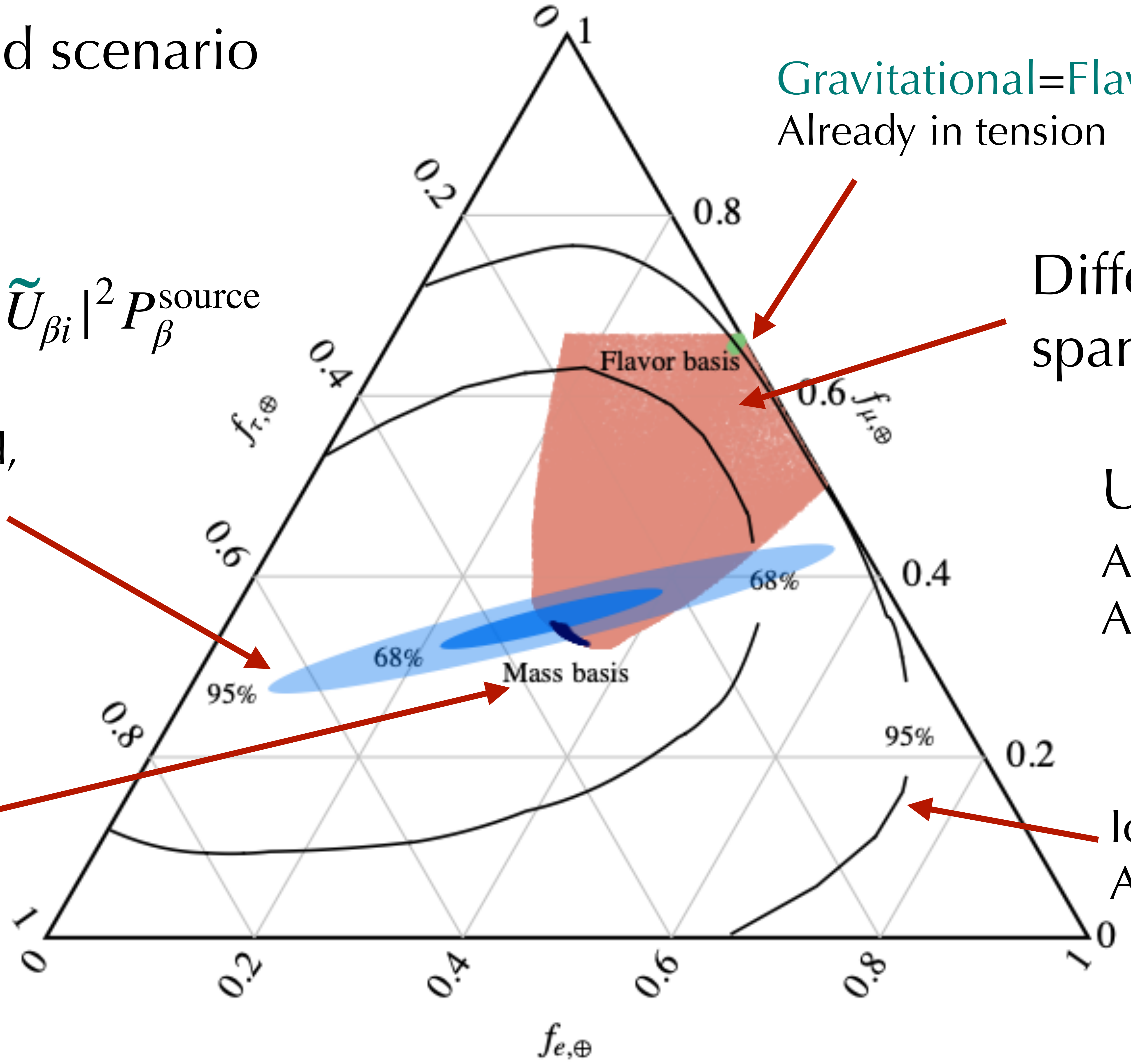
VEP and astrophysical neutrinos

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!



Gravitational=Flavor
Already in tension

Different choices of $\tilde{U}$ span the region

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

IceCube,
Abbasi et al., 2020

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?

$$\nu_e \quad \nu_\mu \quad \nu_\tau$$

Three neutrino states

$$\nu_a = \sum_\beta \tilde{U}^*_{\beta a} \nu_\beta \xrightarrow{\gamma_a} \phi$$

Different coupling strengths

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