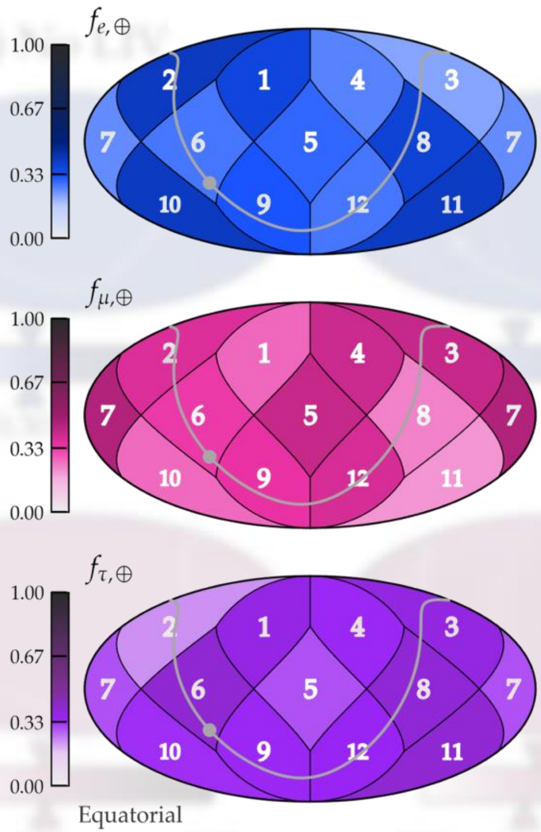

Using Directional Flavour Compositions of High Energy Astrophysical Neutrinos to Constrain Lorentz Invariance Violation

Bernanda Telalovic, Mauricio Bustamante

Niels Bohr Institute
University of Copenhagen

TeVPA Chicago 2024

VILLUM FONDEN

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Outline

1. What are high energy astrophysical neutrinos?
2. How do we know their flavour ratios?
3. How can Lorentz Invariance Violation cause anisotropies?
4. How much can we constrain the effects with data now?

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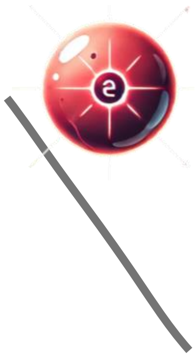
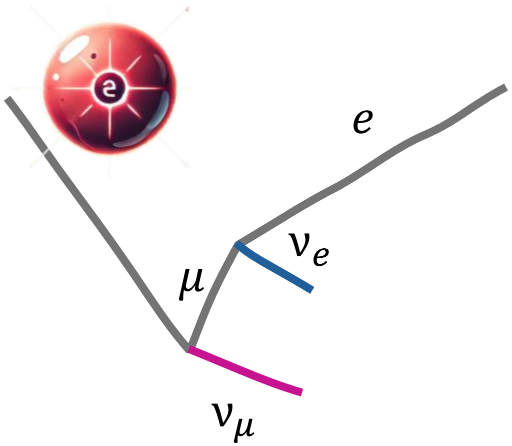
High Energy Astrophysical Neutrinos



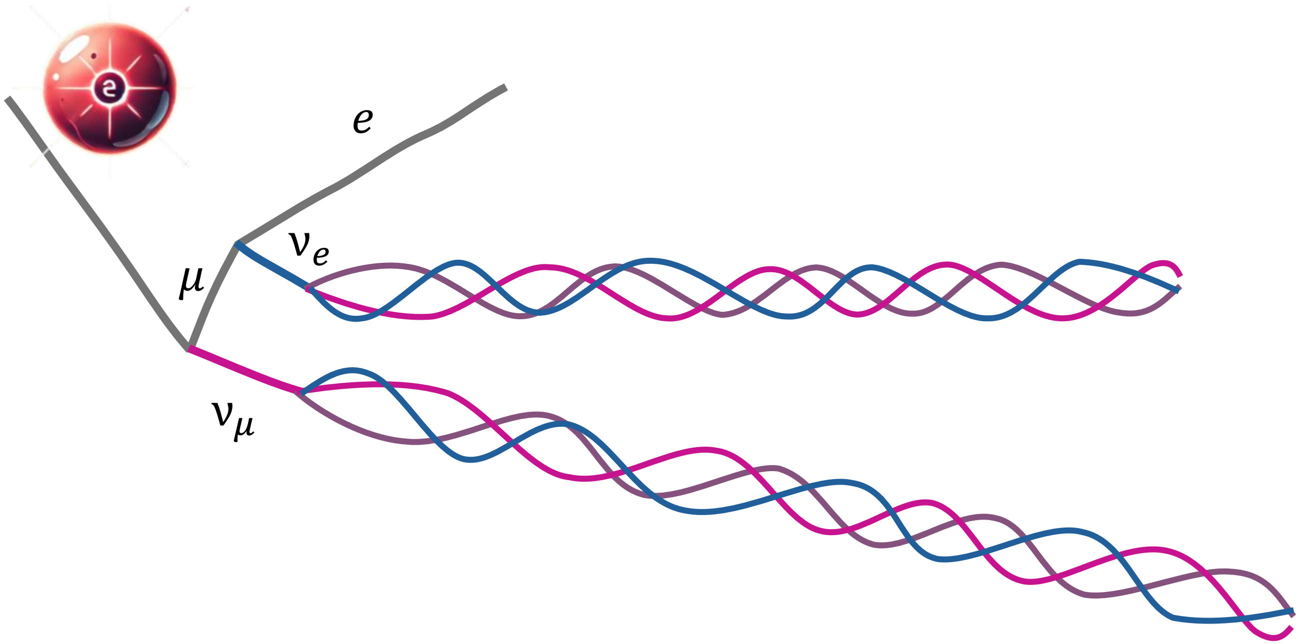
A cosmic ray
produces pions

High Energy Astrophysical Neutrinos



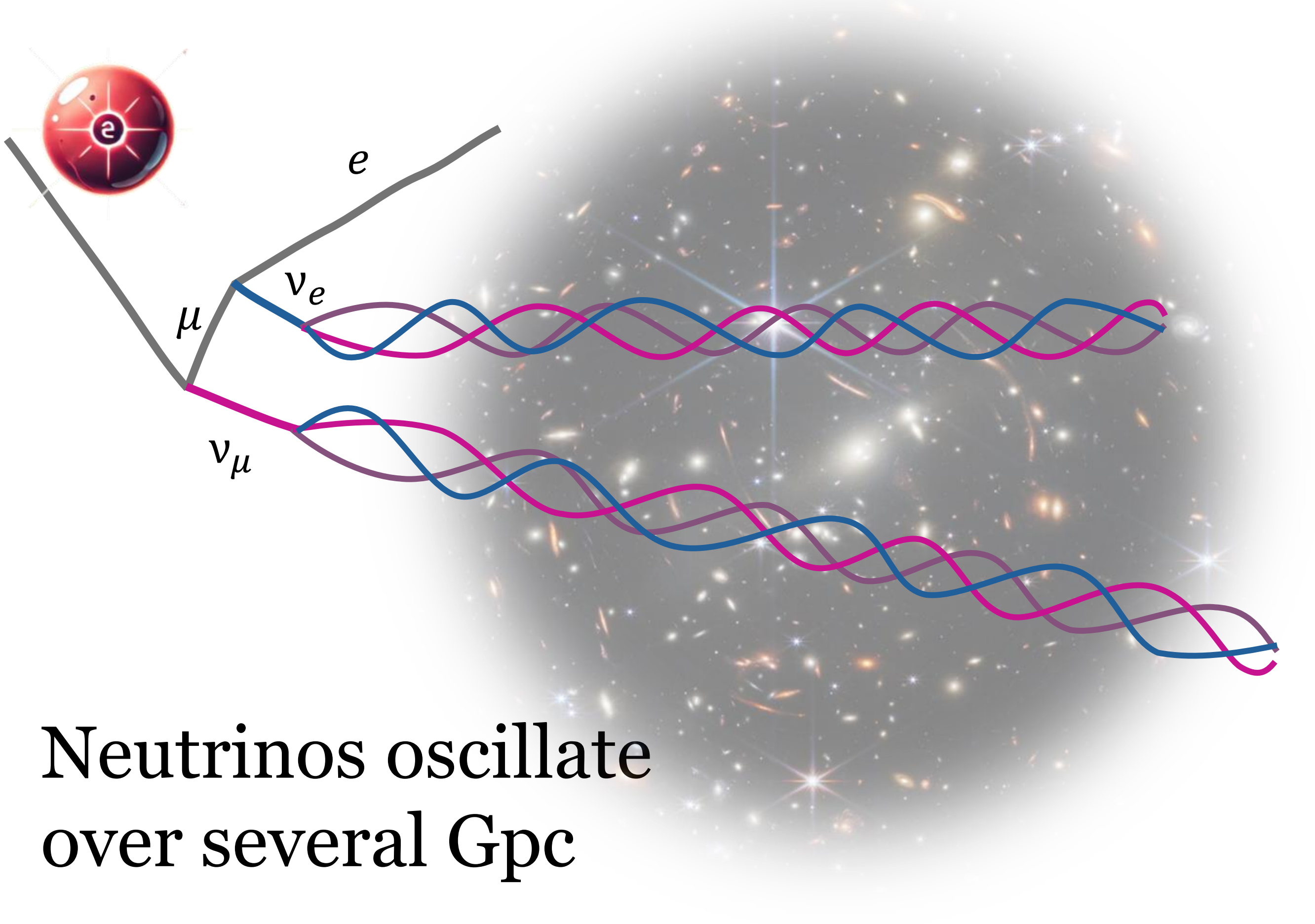
Pions decay to leptons and neutrinos

High Energy Astrophysical Neutrinos



Neutrinos oscillate over several Gpc

High Energy Astrophysical Neutrinos



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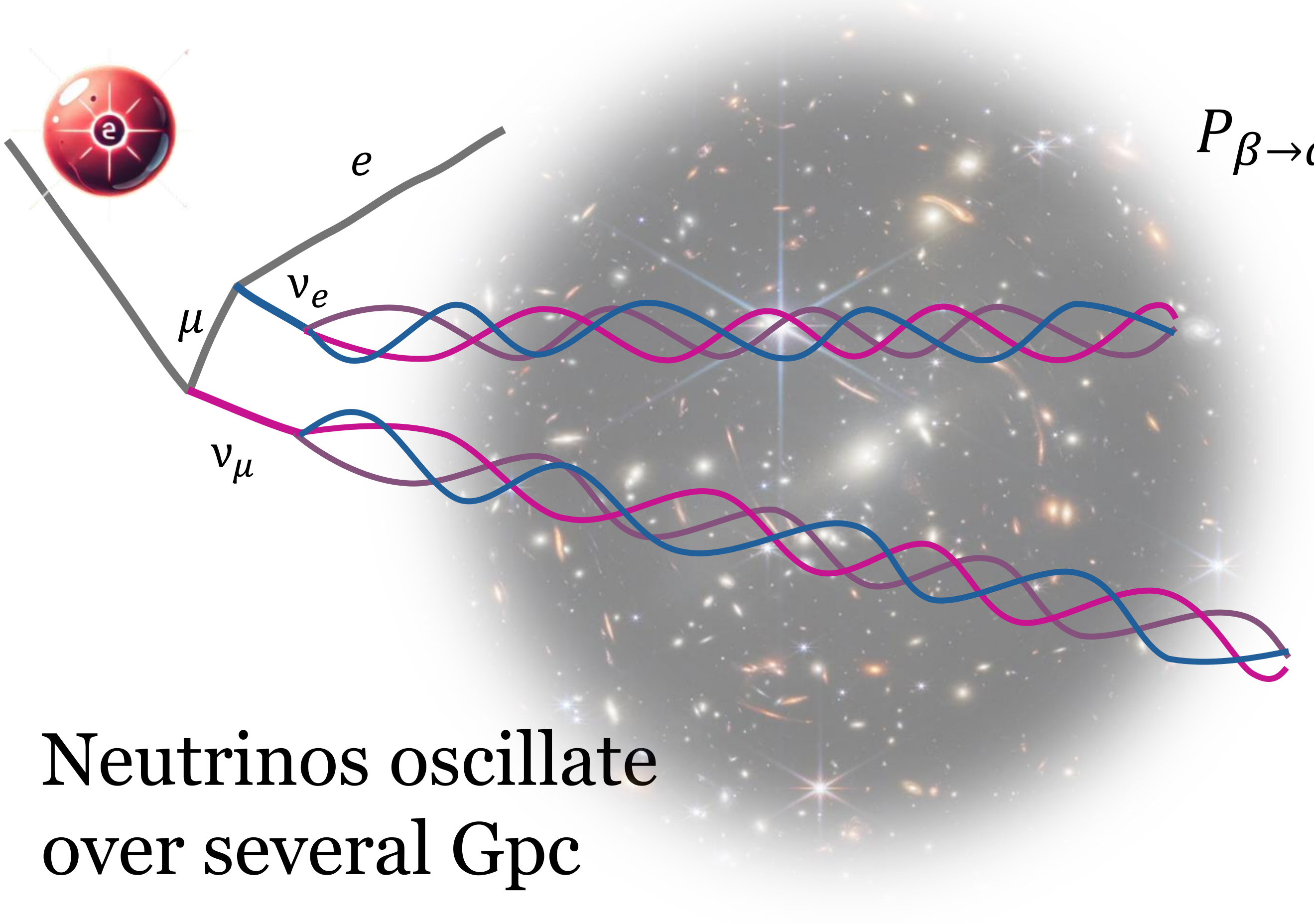

$$P_{\beta\to\alpha} \sim \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Neutrinos oscillate
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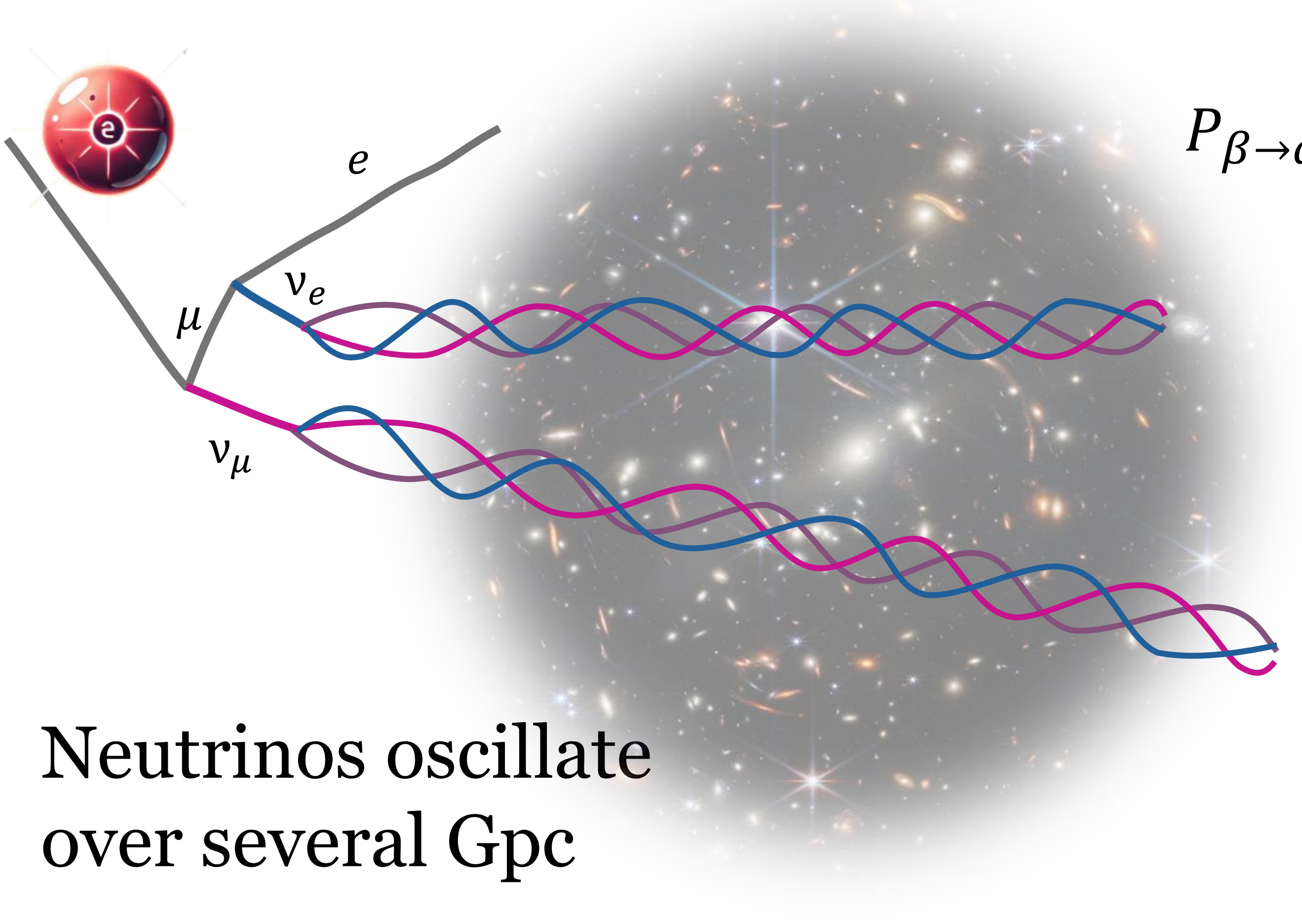
High Energy Astrophysical Neutrinos



$$P_{\beta\to\alpha} \sim \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

↓

$$U = U_{PMNS}$$

Neutrinos oscillate over several Gpc

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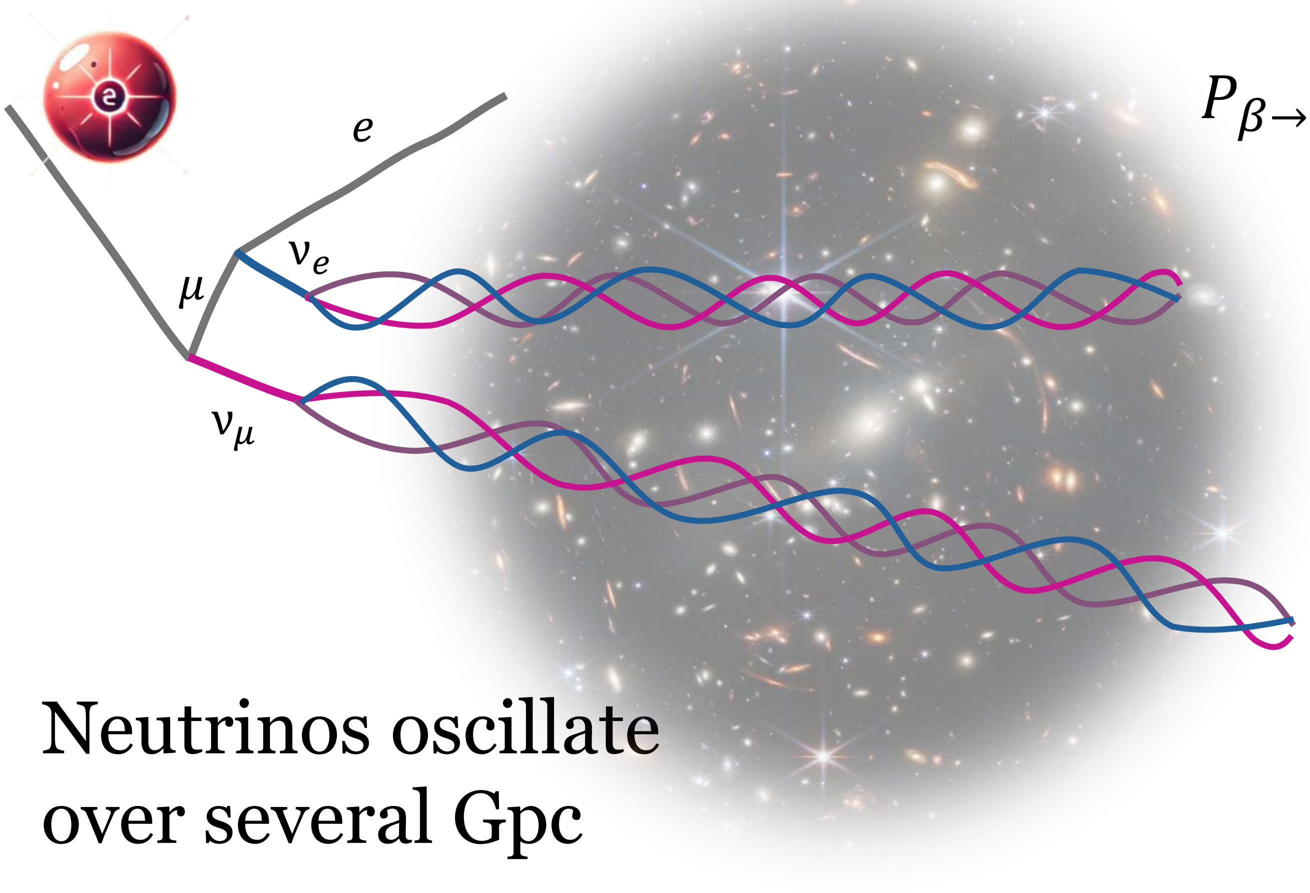
High Energy Astrophysical Neutrinos



$$P_{\beta\to\alpha} \sim \sum_i |U_{\alpha i}|^2 \left|U_{\beta i}\right|^2$$

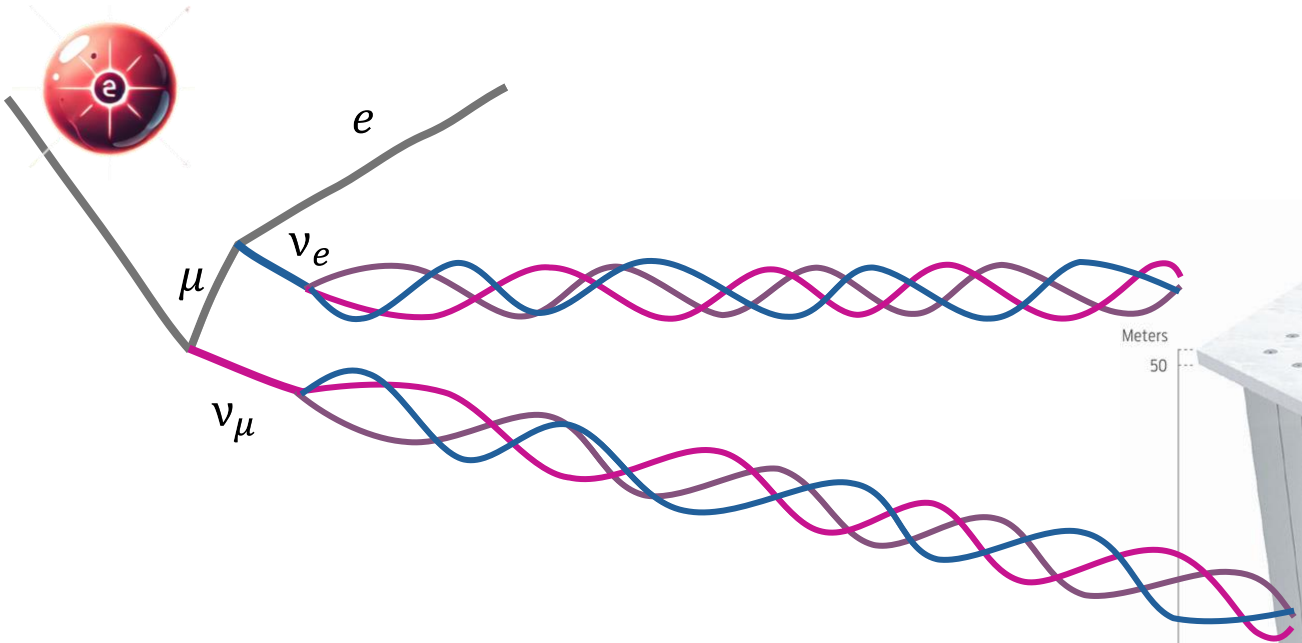
↓

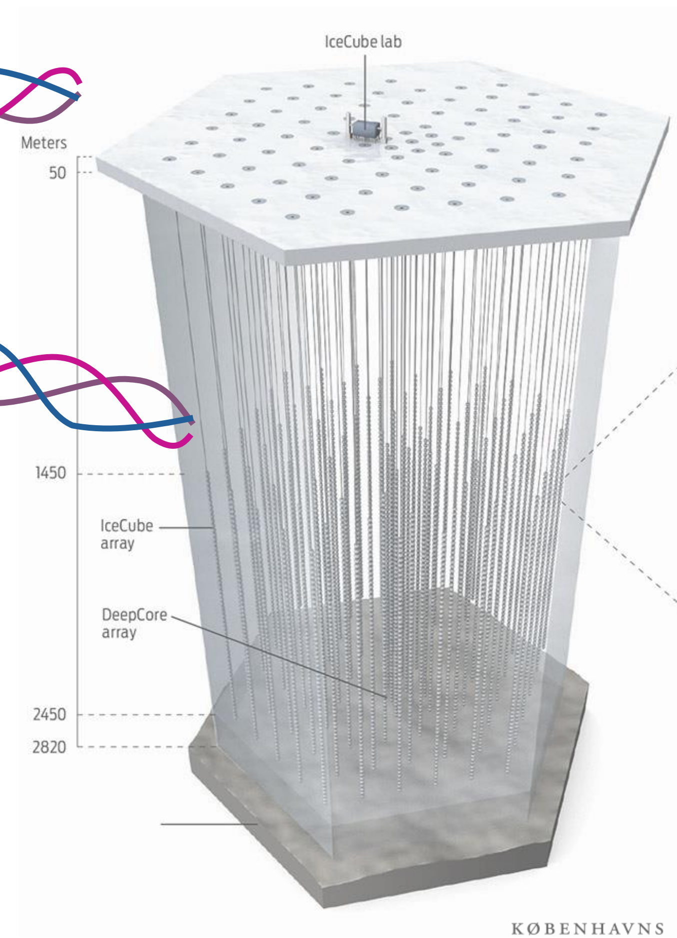
$$U = U_{PMNS}$$

New physics: different U

Neutrinos oscillate over several Gpc

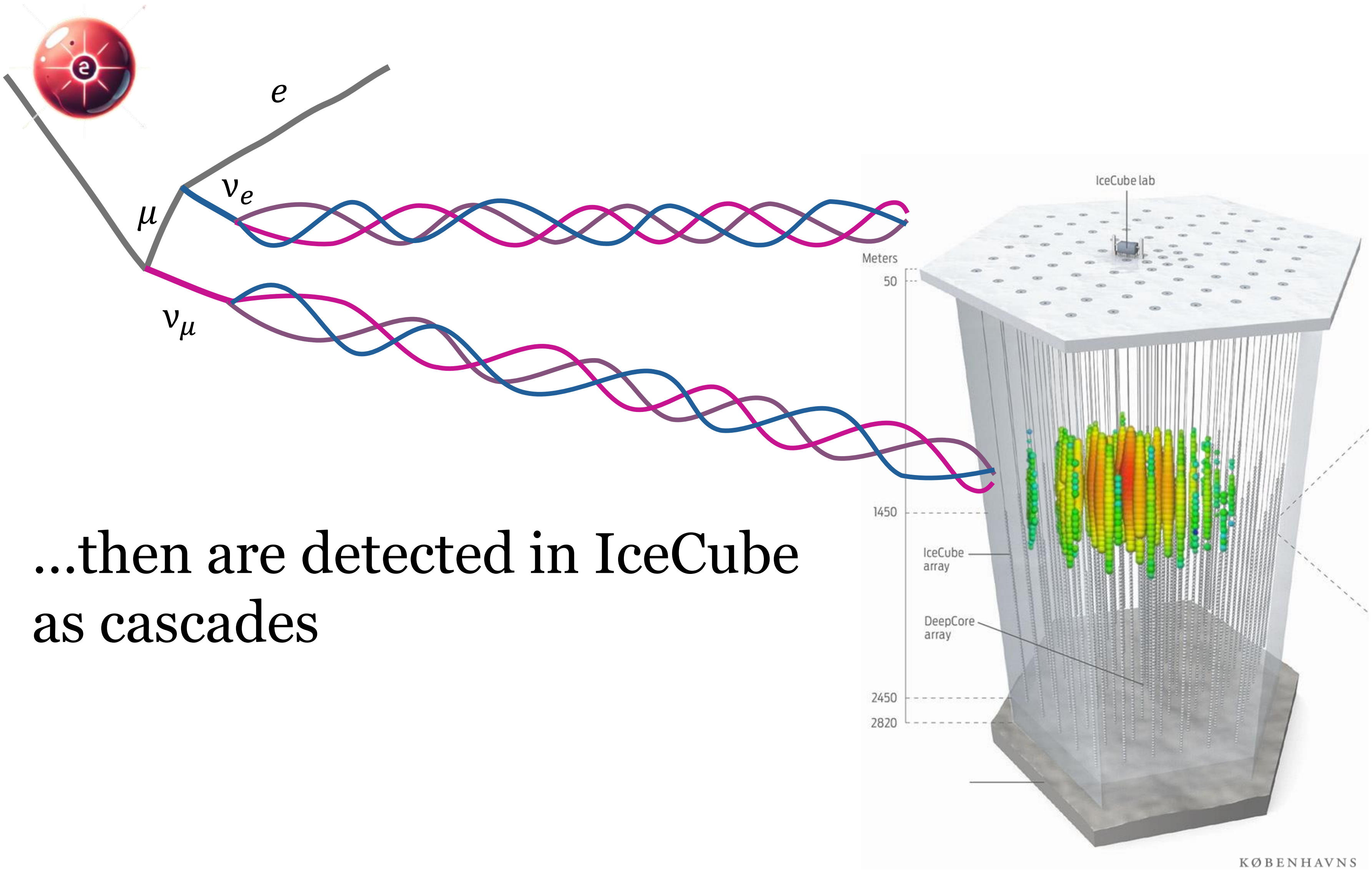
High Energy Astrophysical Neutrinos





…then are detected in IceCube as

High Energy Astrophysical Neutrinos



…then are detected in IceCube as cascades

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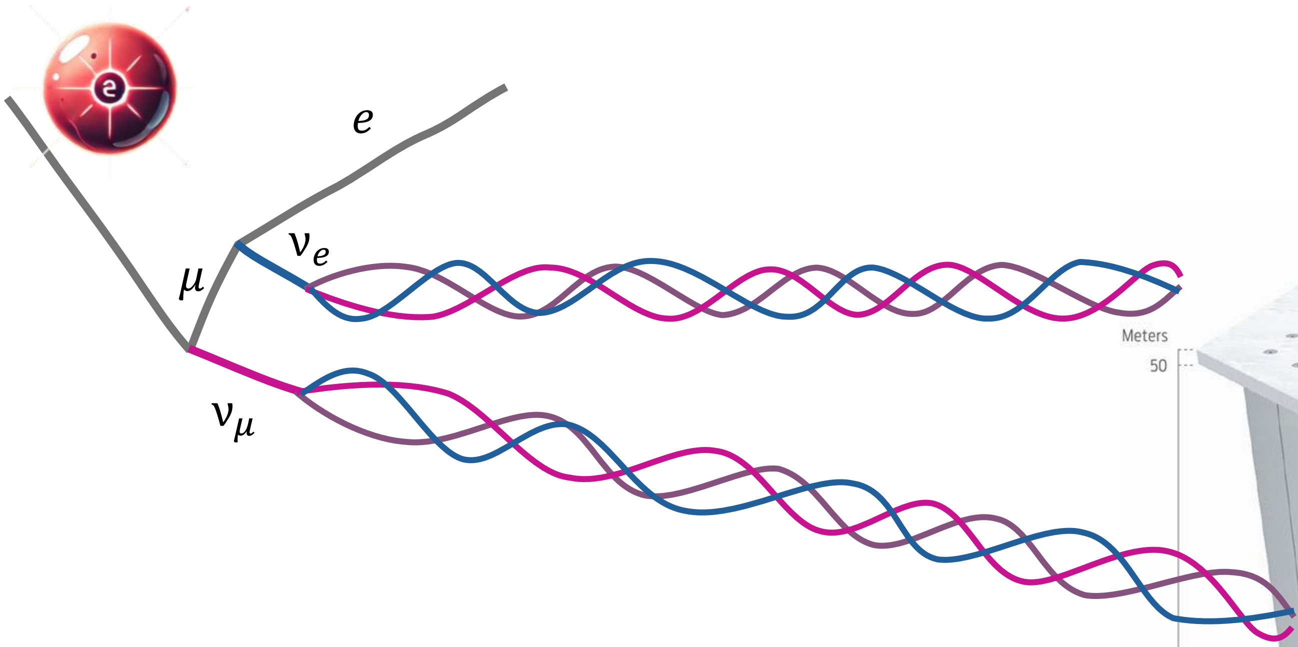
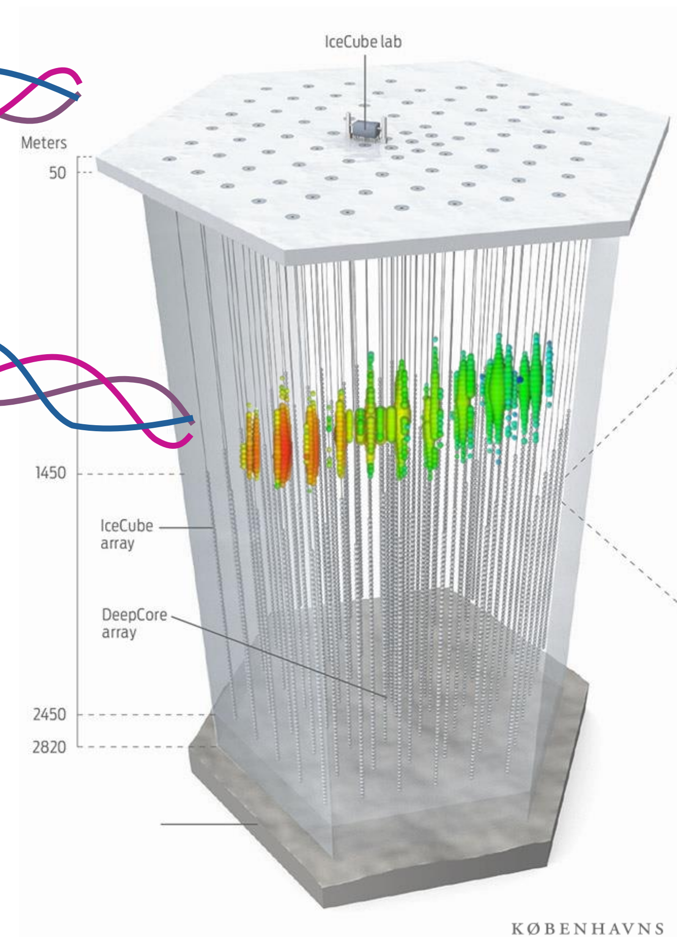
High Energy Astrophysical Neutrinos





…then are detected in IceCube as cascades, tracks

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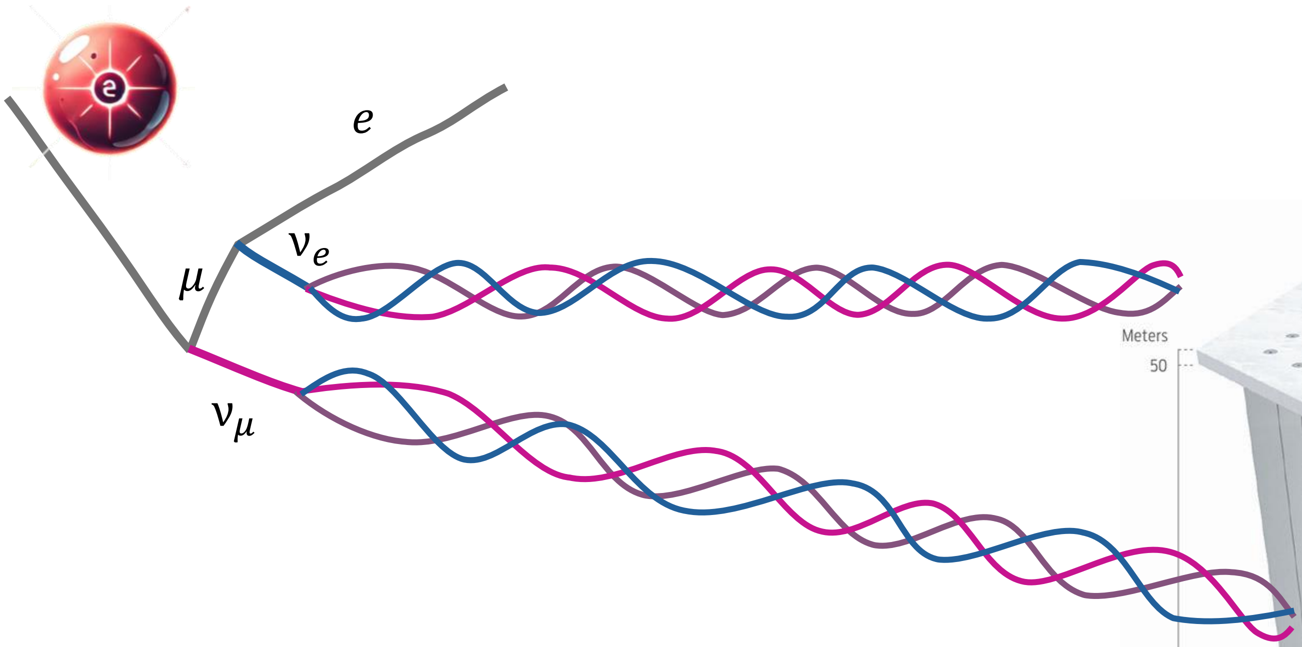
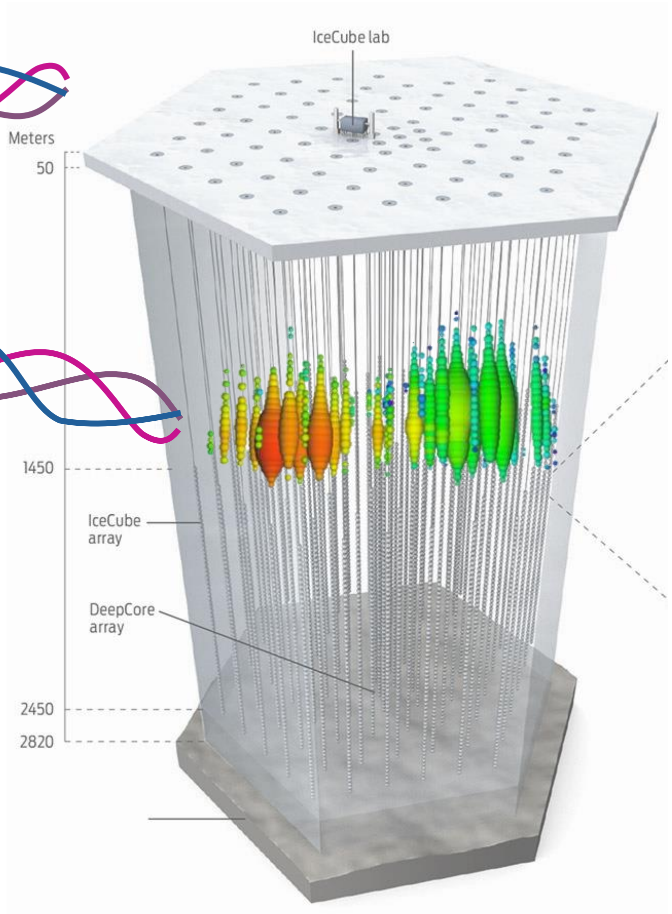
High Energy Astrophysical Neutrinos



...then are detected in IceCube as cascades, tracks or double cascades



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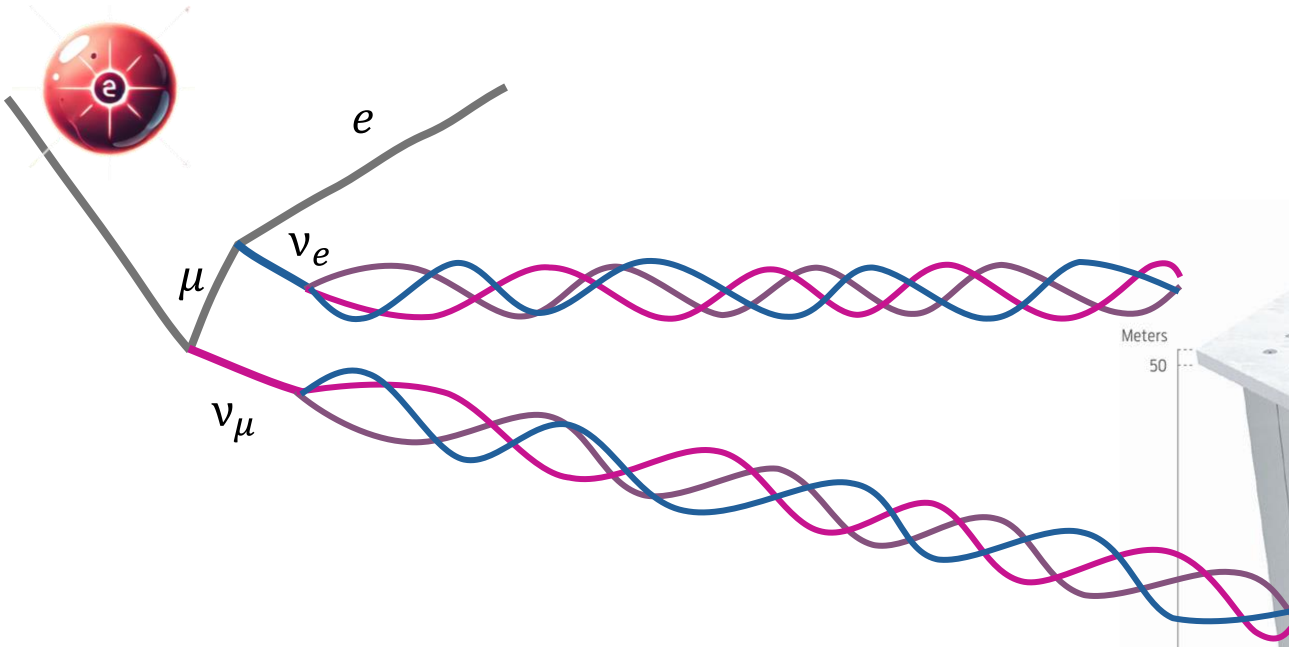
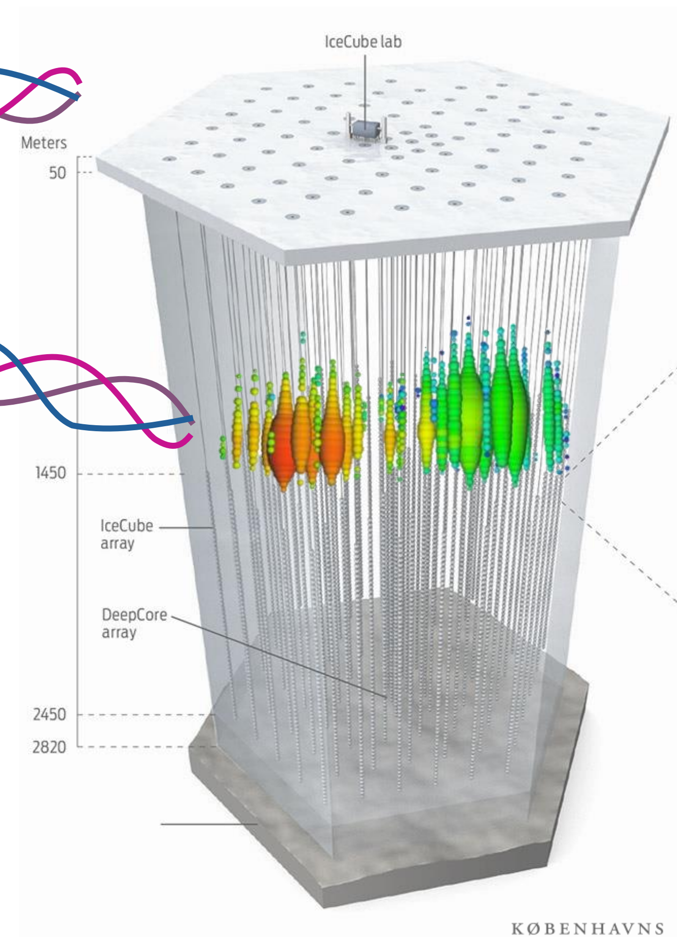
High Energy Astrophysical Neutrinos





depending on the neutrino flavour

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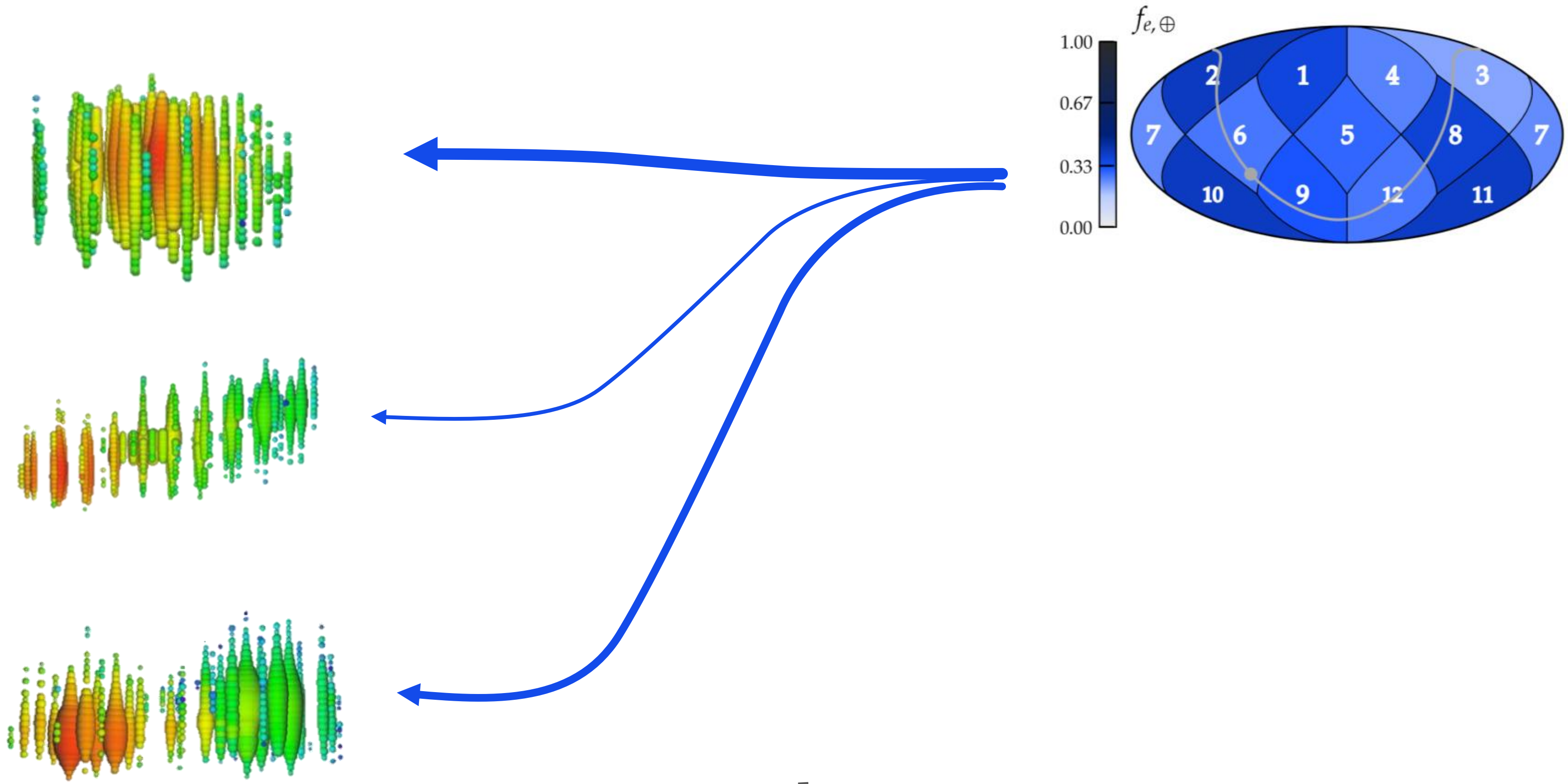
Directional Flavour Ratios in HESE data

We can reconstruct neutrino energy, direction and **flavour**



not to scale

See: https://arxiv.org/abs/2310.15224

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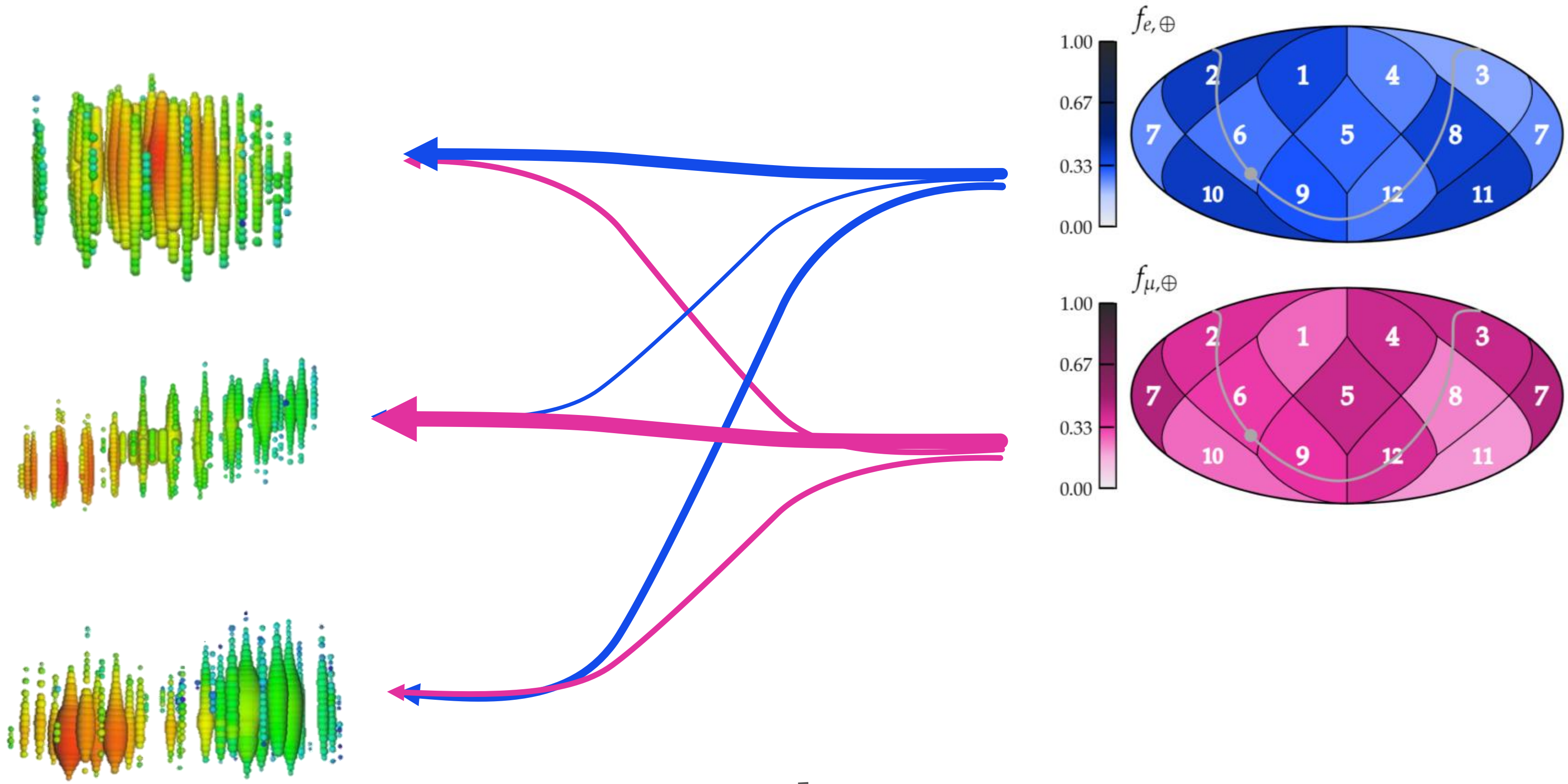

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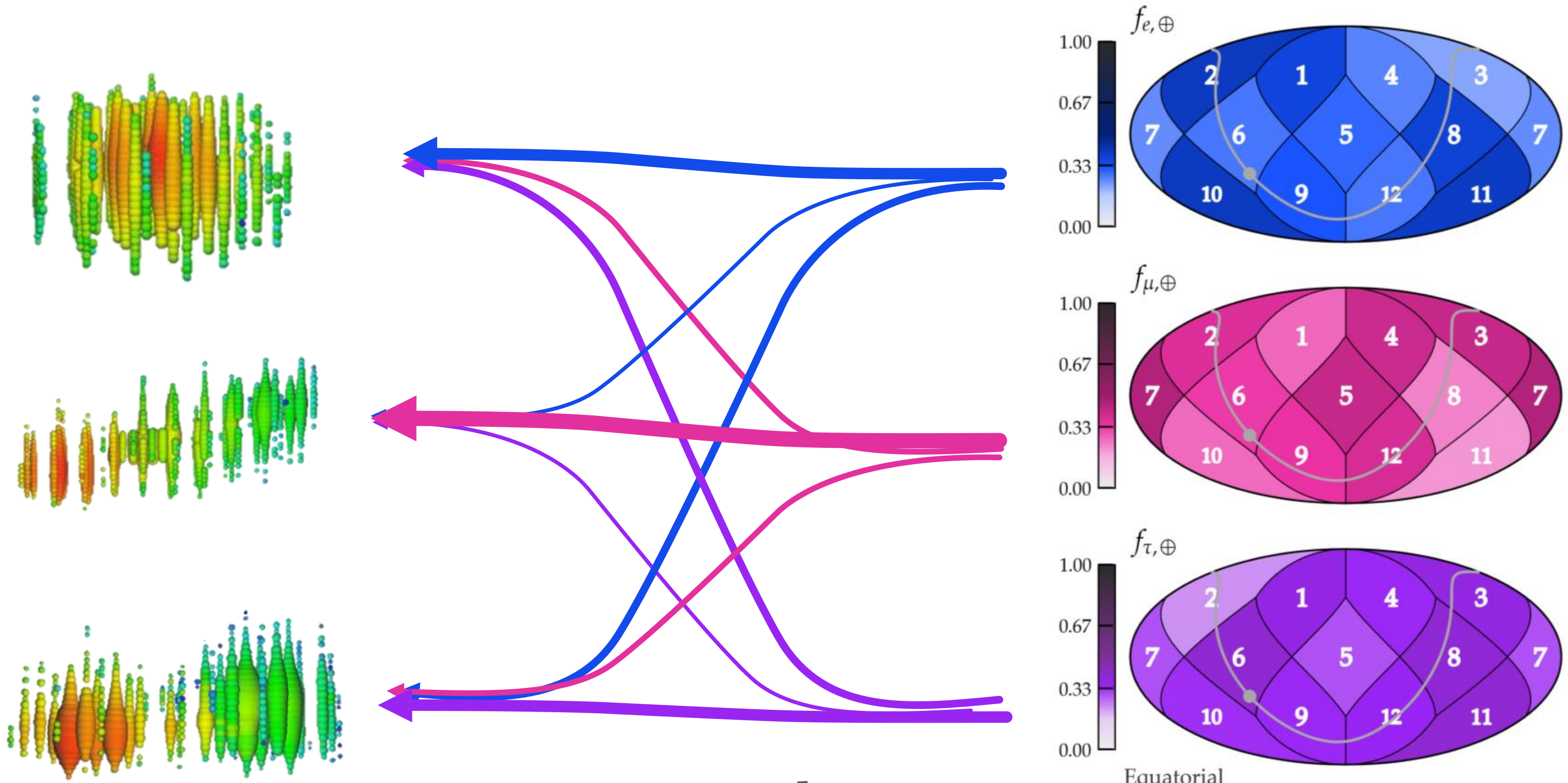

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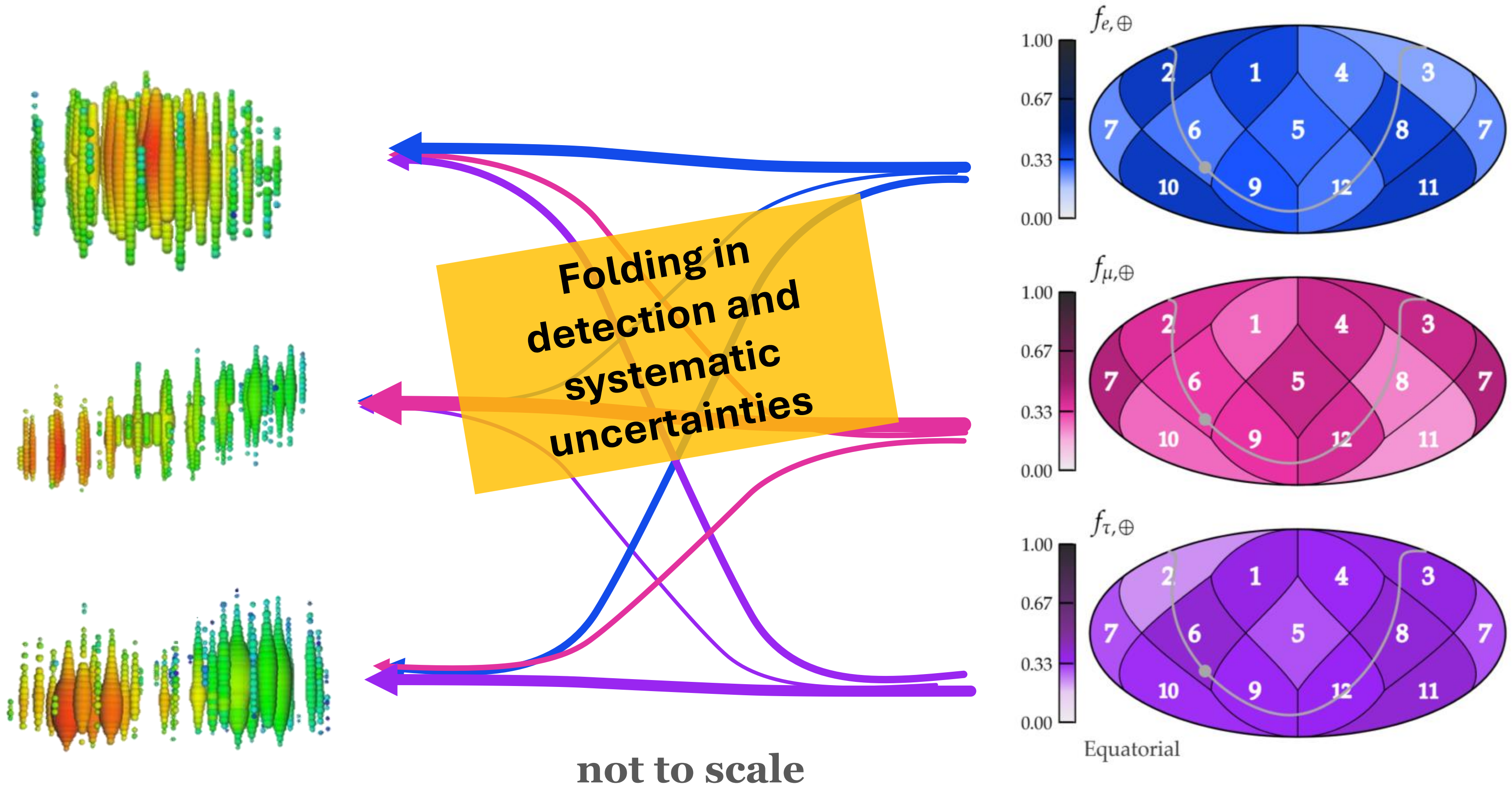

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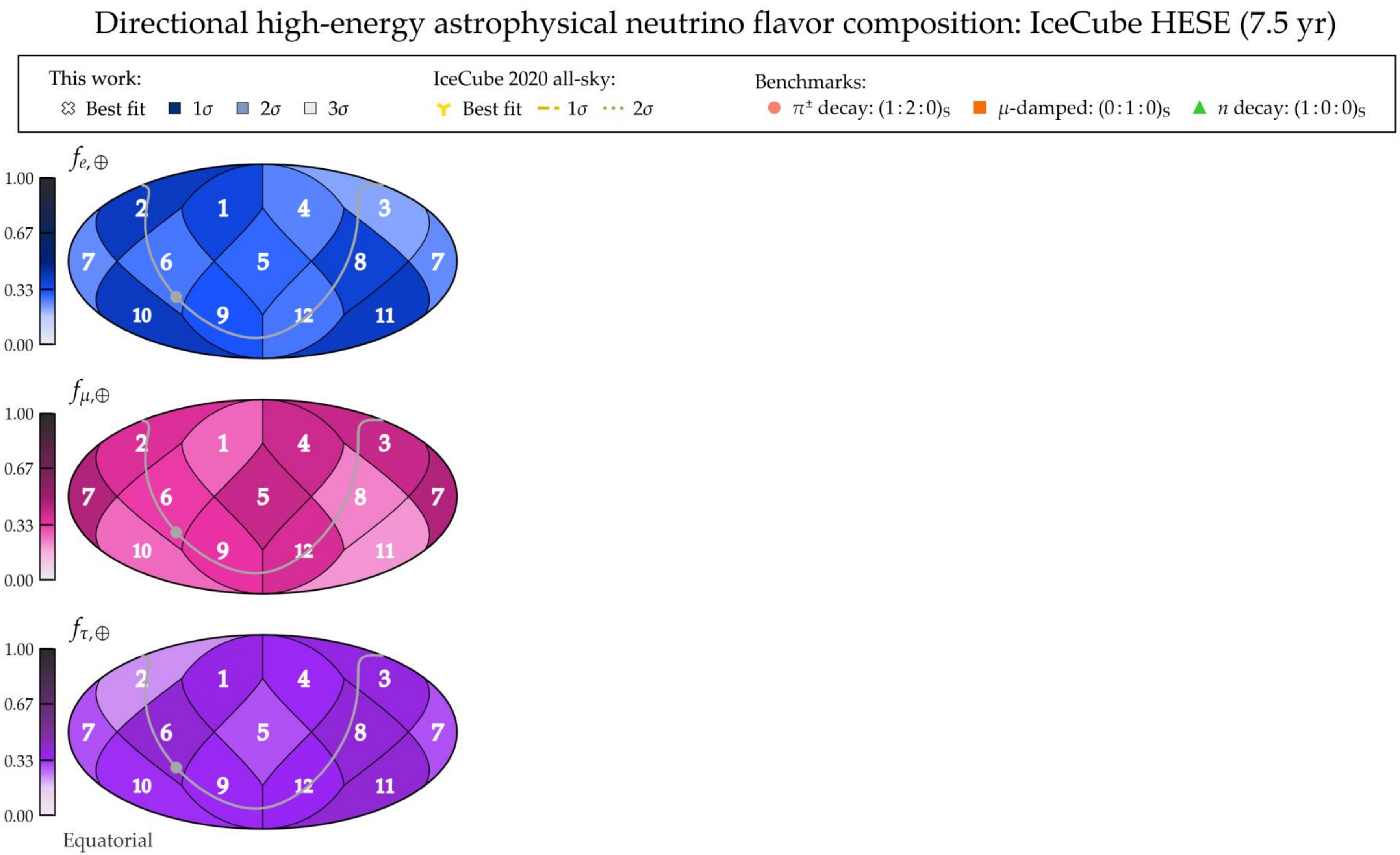

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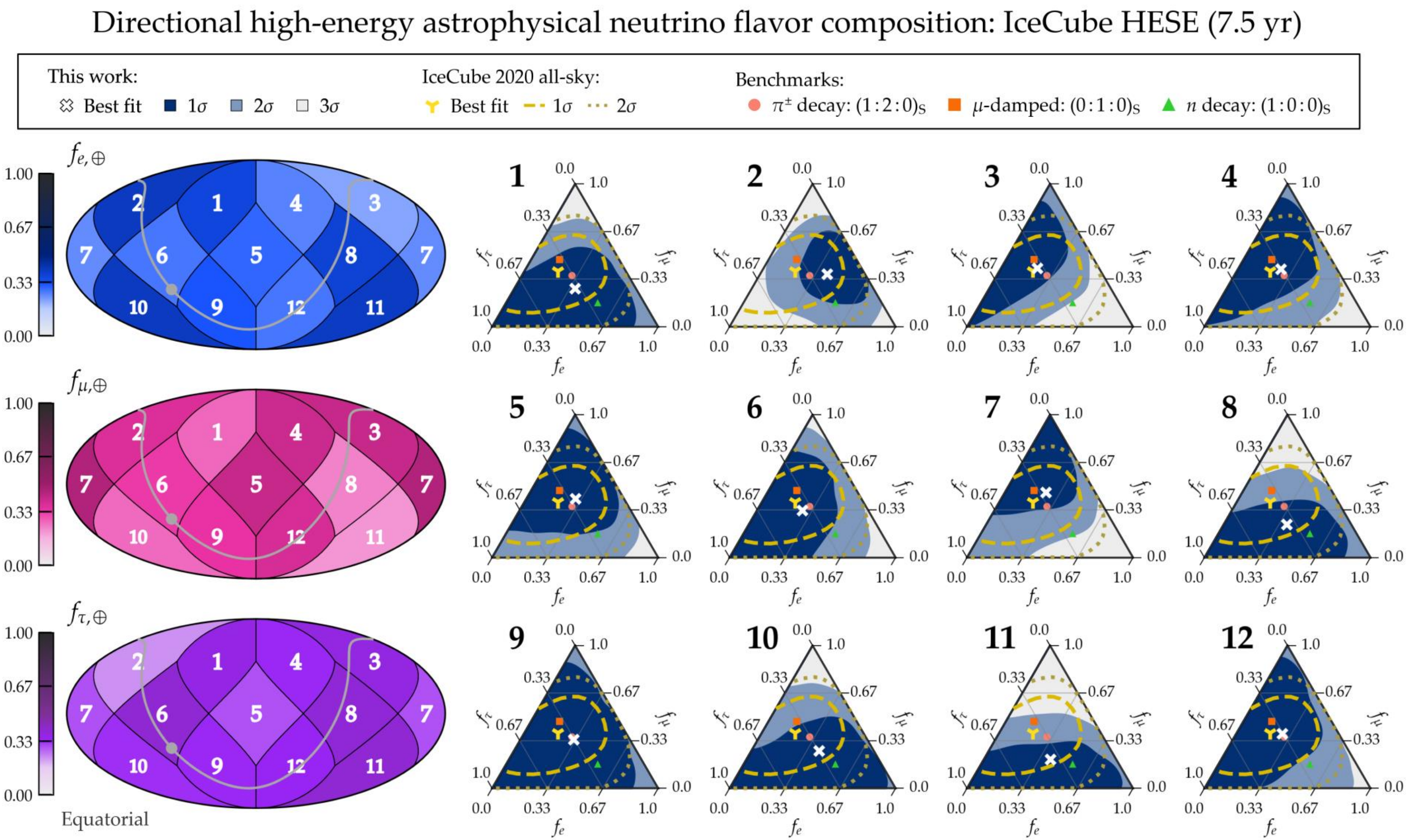

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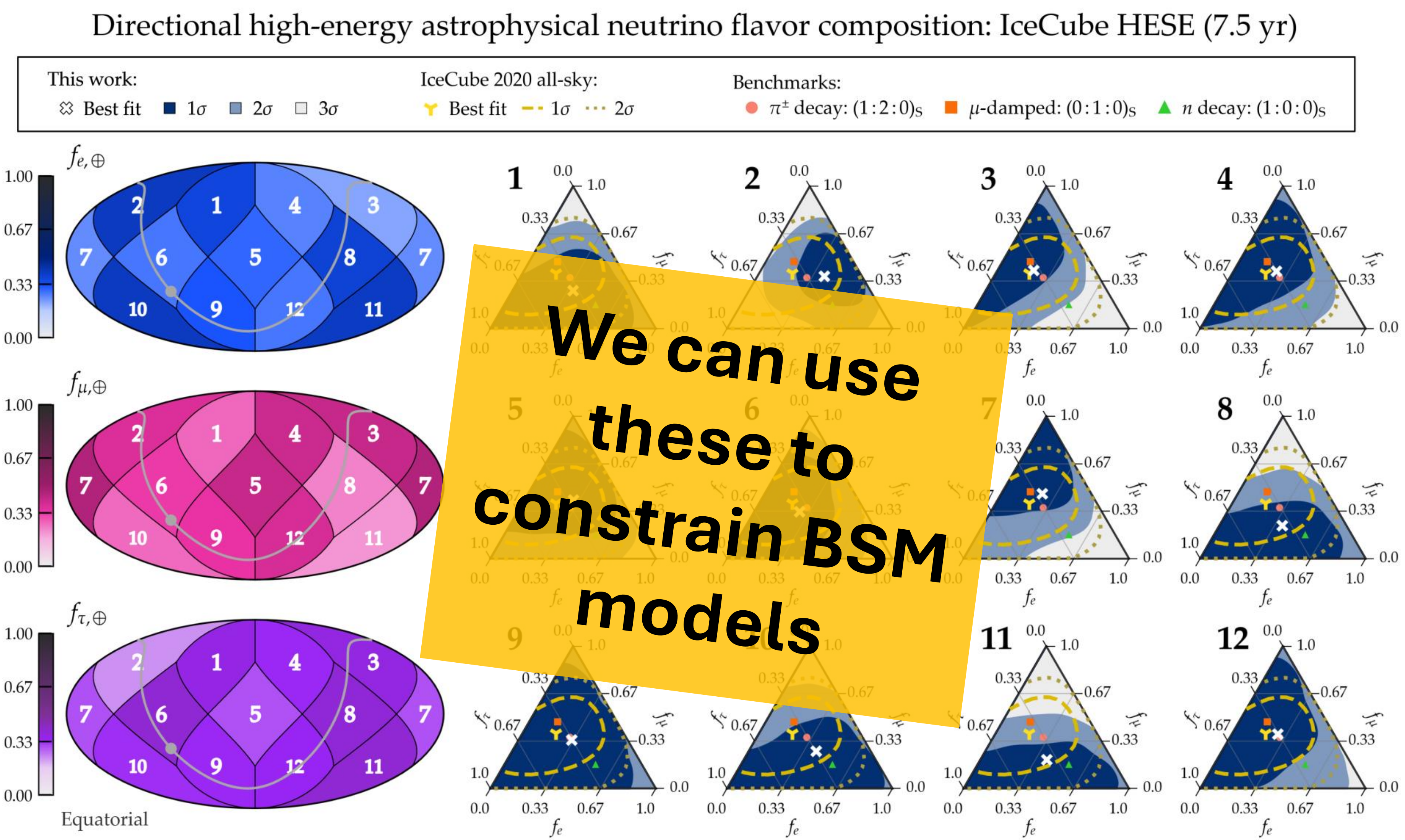

See: https://arxiv.org/abs/2310.15224

Flavour ratios?

f_α - ratio of flavour $\alpha = e, \mu, \tau$ at Earth

$$f_\alpha = \frac{\Phi_\alpha}{\sum_\beta \Phi_\beta} \qquad \text{with} \qquad \sum_\alpha f_\alpha = 1$$

Φ_α - flux/amount of ν_α neutrinos

- energy integrated: TeV–PeV (HESE range)
- time integrated: 7.5 years at IceCube

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How do we model the flux at Earth?

$$\frac{d\Phi_\alpha}{dE\,dz} = \Phi_0 \rho_0 H_0^{-1} \times [E(z+1)]^{2-\gamma} \times \frac{\rho(z)}{h(z)(z+1)^2} \times \sum_\beta P_{\beta\to\alpha} f_{\beta,S}$$

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constants

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constants

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Energy–redshift dependence

changes all-flavour flux shape

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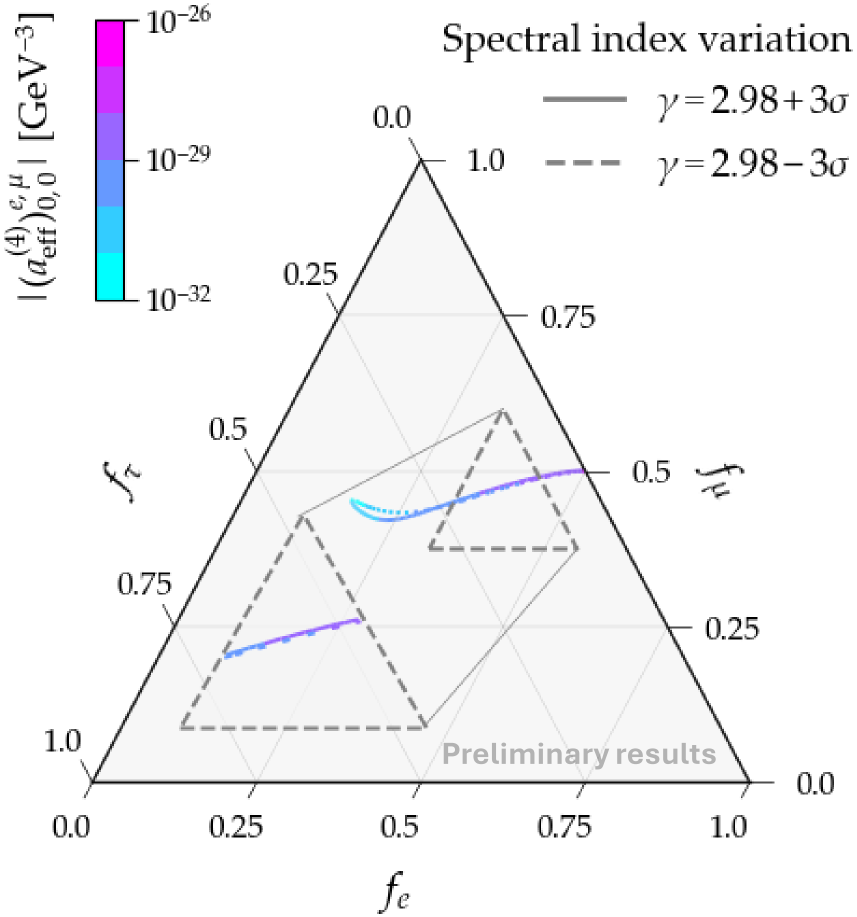
Spectral index



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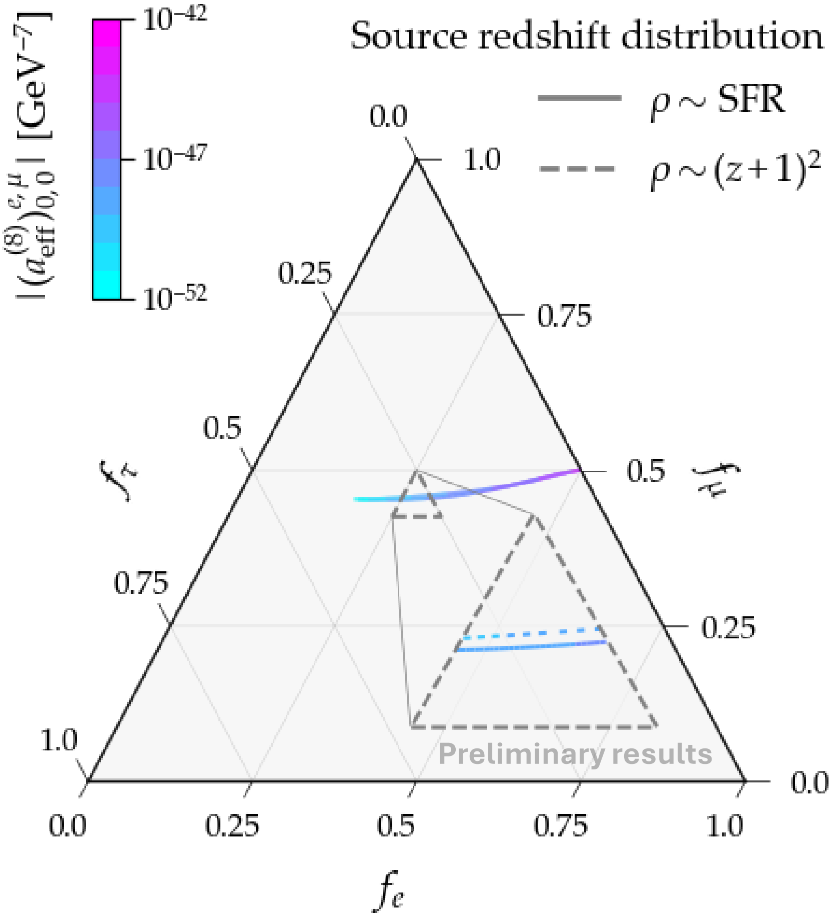
Source distribution over redshift



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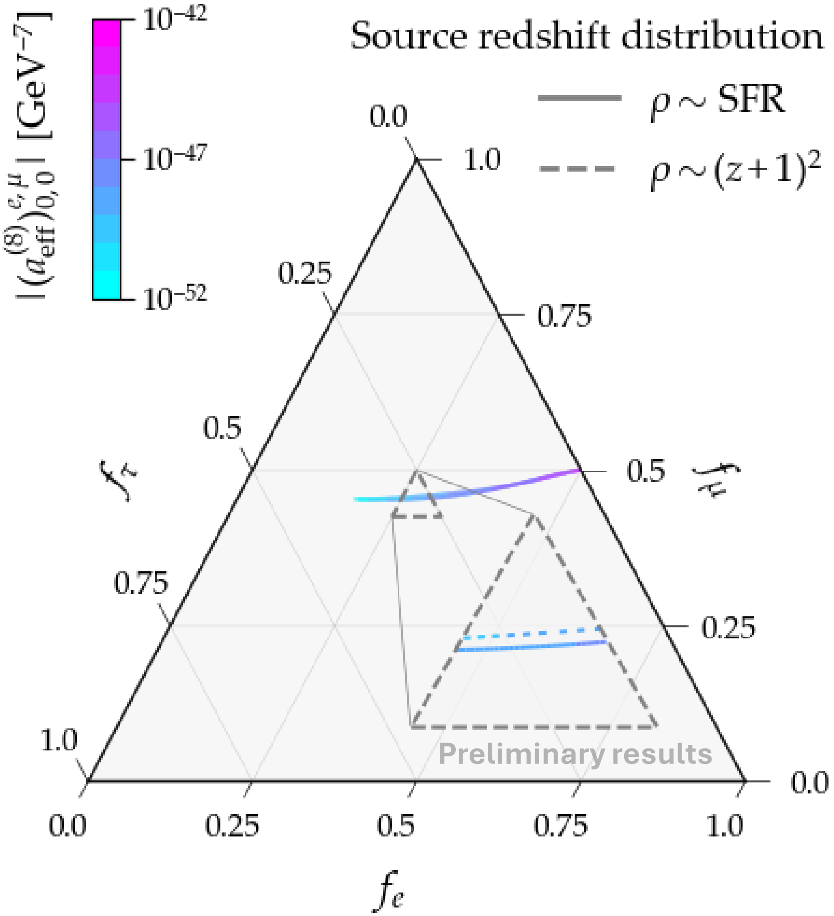
So far, no anisotropies are introduced!

Source distribution over redshift



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Anisotropy in flavour oscillation

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Anisotropy in flavour oscillation

$$H_{tot} = \frac{1}{2E} U_{PMNS} M U_{PMNS}^\dagger + H_{LIV}$$

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How do we model the flux at Earth?

$$\frac{d\Phi_\alpha}{dE\,dz} = \Phi_0 \rho_0 H_0^{-1} \times [E(z+1)]^{2-\gamma} \times \frac{\rho(z)}{h(z)(z+1)^2} \times \sum_\beta \boldsymbol{P_{\beta\to\alpha}} f_{\beta,S}$$

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Averaged over long distances

$$P_{\beta\to\alpha} \sim \sum_i |U_{\alpha i}|^2 \left|U_{\beta i}\right|^2$$

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How do we model the flux at Earth?

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U diagonalises H_{tot}

Anisotropy in flavour oscillation

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Lorentz Invariance Violation

$$P_{\beta\to\alpha} \sim \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Lorentz Invariance – no preferred inertial reference frame

Violation – there is a preferred inertial reference frame

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Lorentz Invariance Violation

$$P_{\beta\to\alpha} \sim \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

$$H_{LIV} = \sum_{d=2}^{\infty} E^{d-2} \sum_{\ell=0,m}^{d-1} \hat{a}_{\ell,m}^{(d)} Y_{\ell,m} + h.c.$$

Parametrises any preferred reference frame in the Universe

See: Standard Model Extension https://arxiv.org/abs/1112.6395

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Lorentz Invariance Violation

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Energy dependence

See: Standard Model Extension https://arxiv.org/abs/1112.6395

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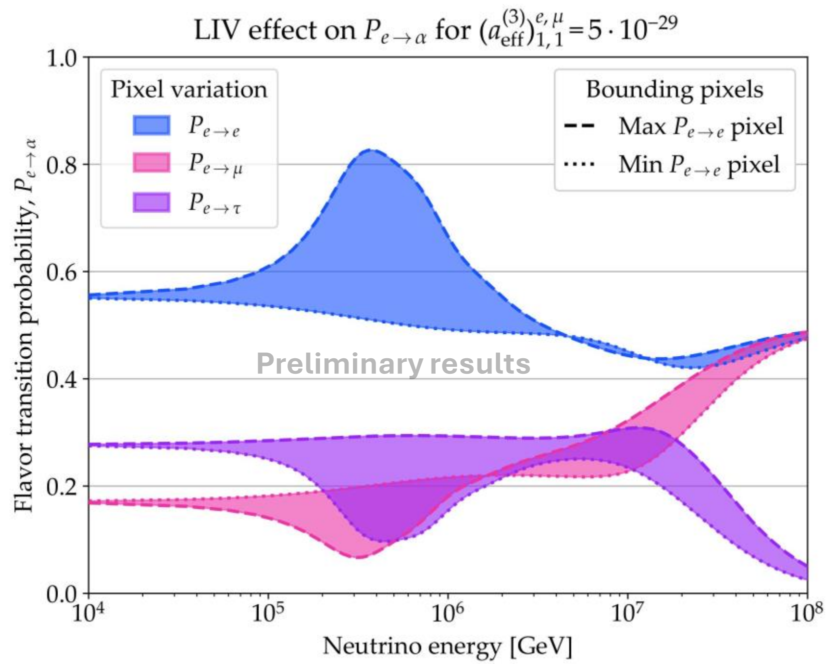
Energy dependence



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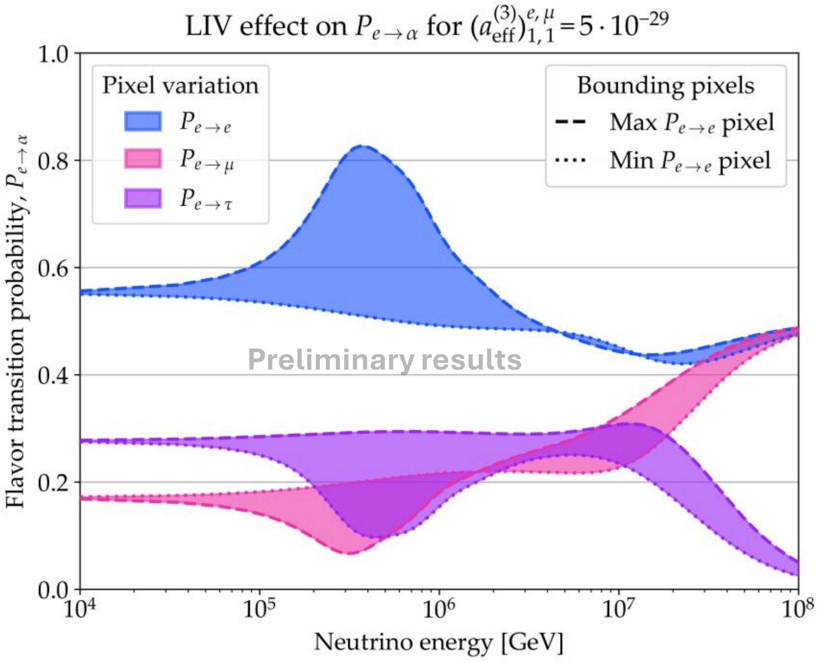
Energy dependence

effect is strongest
at resonance



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Angular dependence

See: Standard Model Extension https://arxiv.org/abs/1112.6395

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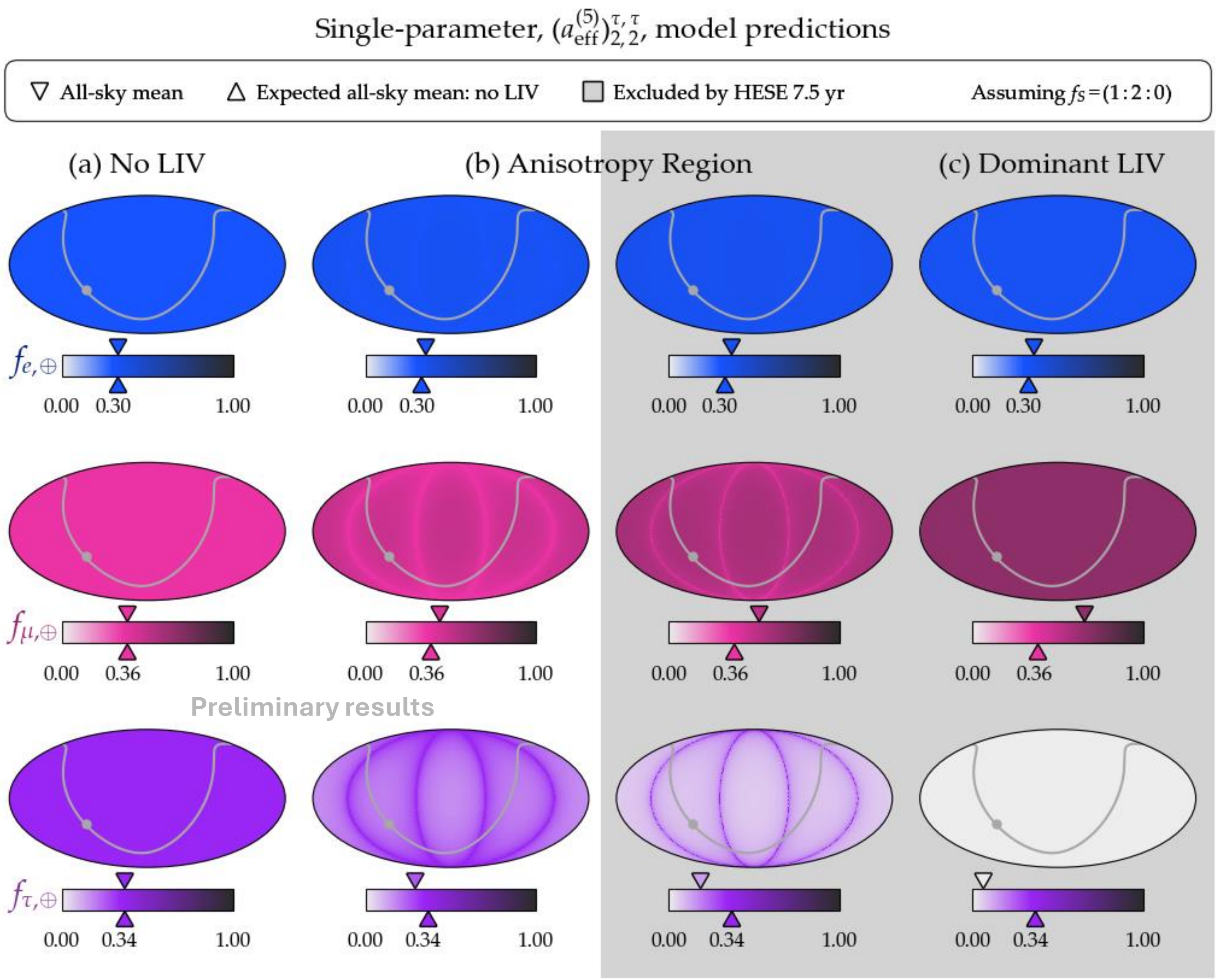

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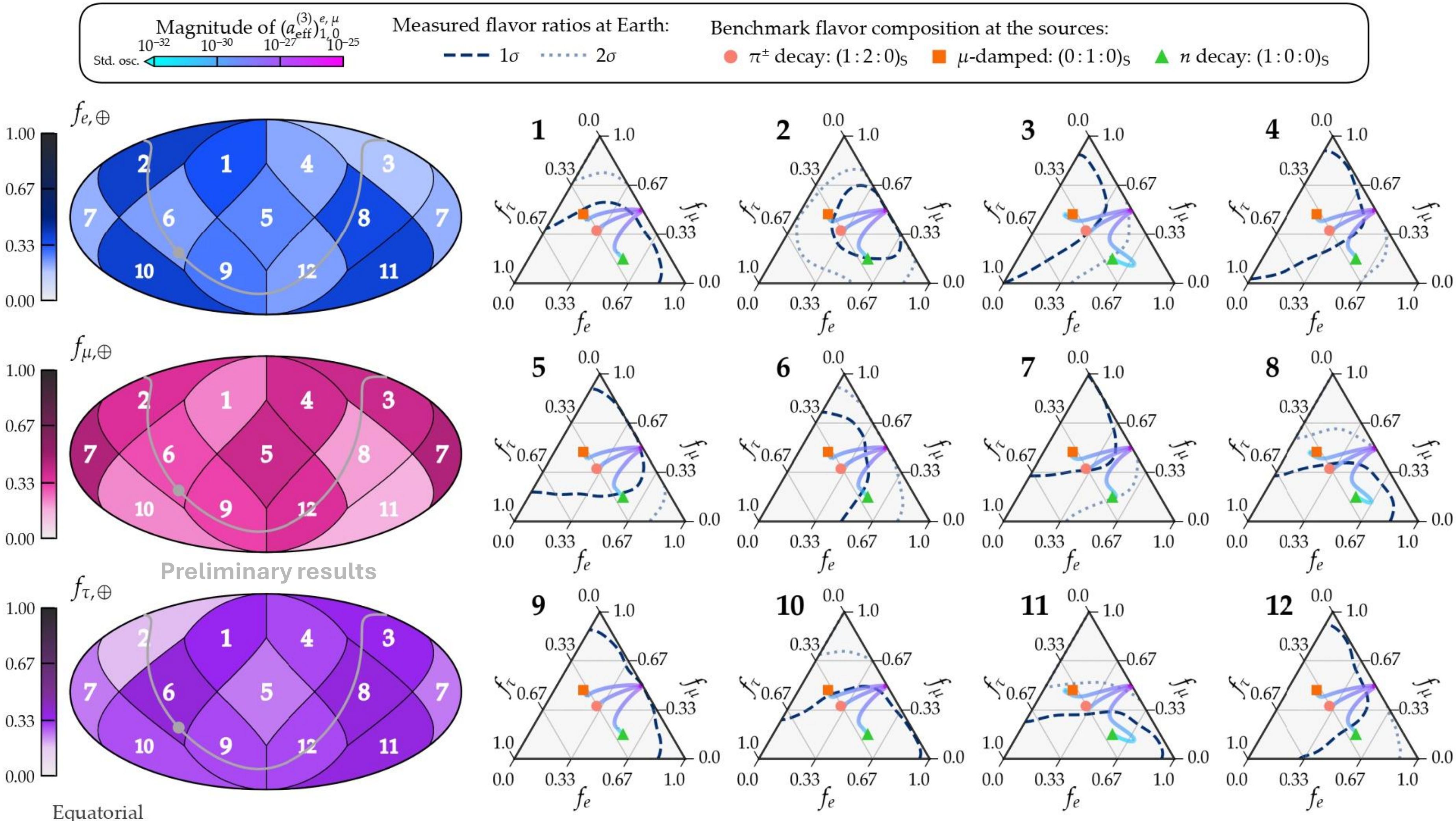
How do they manifest?

Lorentz-violating high-energy neutrino flavor anisotropy (IceCube HESE 7.5 years)



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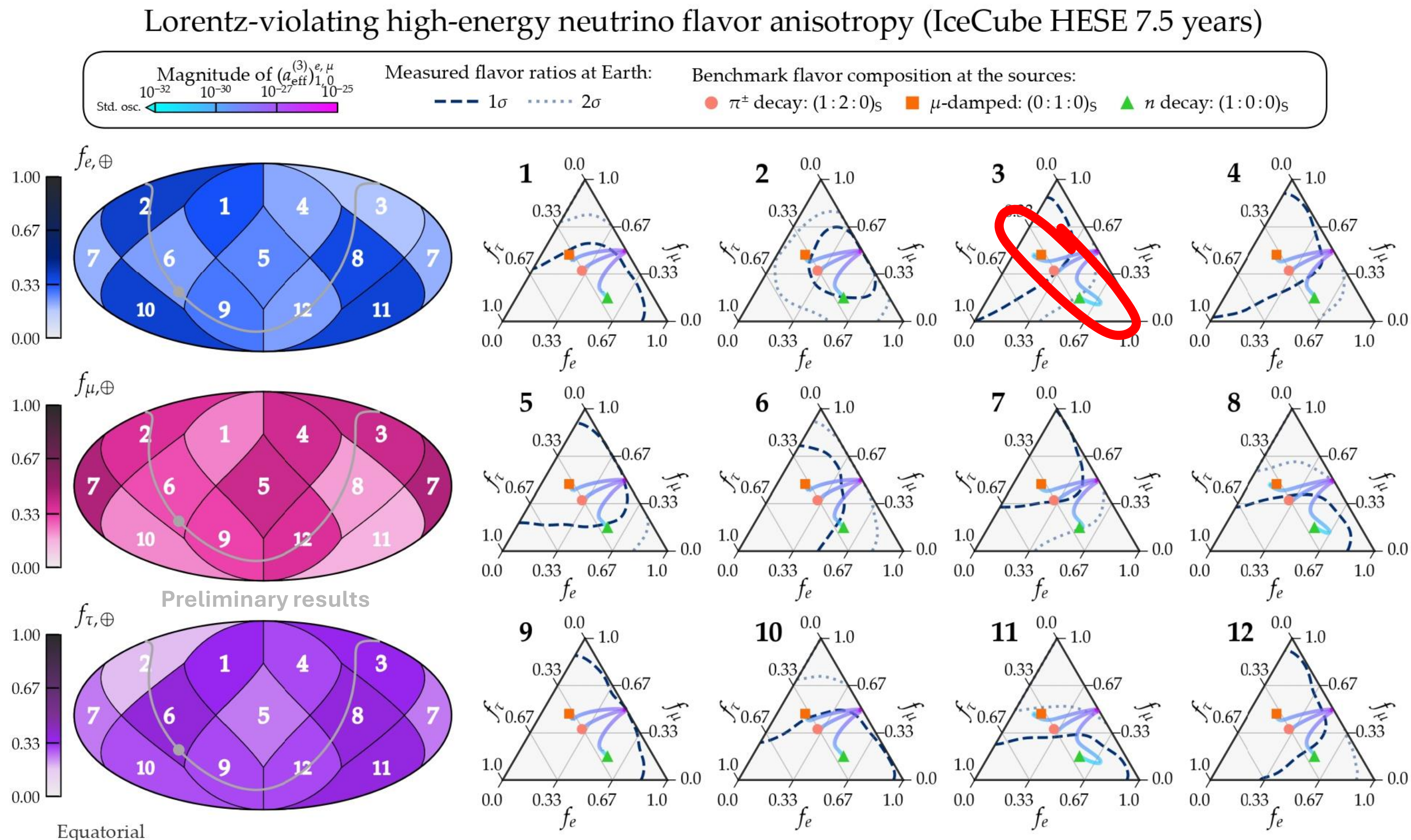

How do we model the flux at Earth

$$\frac{d\Phi_\alpha}{dE\ dz} = \Phi_0 \rho_0 H_0^{-1} \times [E(z+1)]^{2-\gamma} \times \frac{\rho(z)}{h(z)(z+1)^2} \times \sum_\beta P_{\beta\to\alpha}\, f_{\beta,S}$$

What flavours are produced?

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What flavours are produced?

- assume negligible ν_τ production
- otherwise, stay agnostic

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$$f_S = (f_{e,S}, 1 - f_{e,S}, 0)$$

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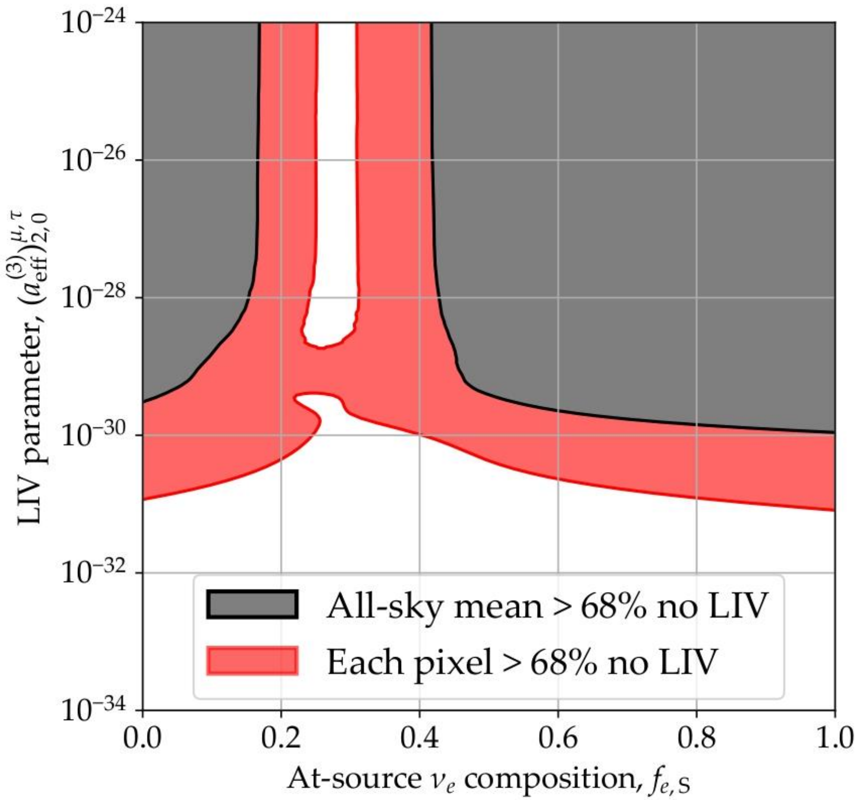

Bayesian Procedure

$$\frac{d\Phi_\alpha}{dE\ dz}$$

Bayesian Procedure

$$\frac{d\Phi_\alpha}{dE\,dz} \xrightarrow{\int dEdz} \Phi_\alpha$$

Bayesian Procedure

$$\frac{d\Phi_\alpha}{dE\,dz} \xrightarrow{\int dE dz} \Phi_\alpha \longrightarrow f_\alpha$$

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Bayesian Procedure

$$\frac{d\Phi_\alpha}{dE\,dz} \xrightarrow{\int dEdz} \Phi_\alpha \longrightarrow f_\alpha \longrightarrow \mathcal{L} = \prod_{\text{pixels}} \int_\omega p\left(f_{\vec{\alpha}}(\omega)\right) \pi(\omega)$$

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Bayesian Procedure

$$\frac{d\Phi_\alpha}{dE\,dz} \xrightarrow{\int dEdz} \Phi_\alpha \longrightarrow f_\alpha \longrightarrow \mathcal{L} = \prod_{\text{pixels}} \int_\omega \boldsymbol{p}\left(f_{\vec{\alpha}}(\omega)\right) \pi(\omega)$$

p - measurement in each pixel

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Bayesian Procedure

$$\frac{d\Phi_\alpha}{dE\,dz} \xrightarrow{\int dEdz} \Phi_\alpha \longrightarrow f_\alpha \longrightarrow \mathcal{L} = \prod_{\text{pixels}} \int_\omega p\big(f_{\vec{\alpha}}(\omega)\big)\,\pi(\omega)$$

p - measurement in each pixel

$f_{\vec{\alpha}}$ - predicted flavour ratio in that pixel

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Bayesian Procedure

$$\frac{d\Phi_\alpha}{dE\,dz} \xrightarrow{\int dE dz} \Phi_\alpha \longrightarrow f_\alpha \longrightarrow \mathcal{L} = \prod_{\text{pixels}} \int_\omega p\left(f_{\vec{\alpha}}(\omega)\right) \boldsymbol{\pi}(\omega)$$

p - measurement pdf in each pixel

$f_{\vec{\alpha}}$ - predicted flavour ratio in that pixel

π - priors on all parameters

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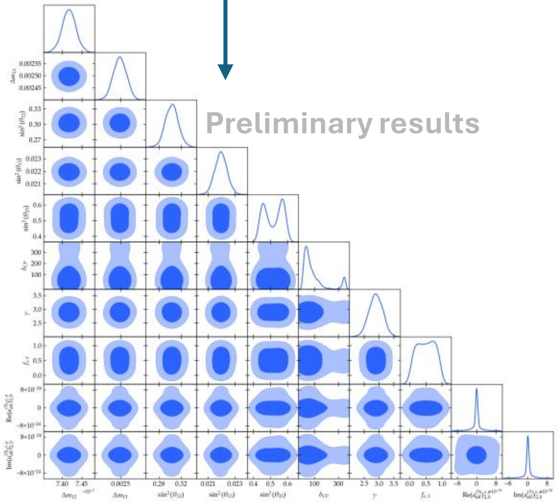

Preliminary results

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Bayesian Procedure

We fit each H_{LIV} parameter one-at-a-time

$$d = 2, \ldots, 8$$

for each $d > 3$, there are $9d^2$ parameters

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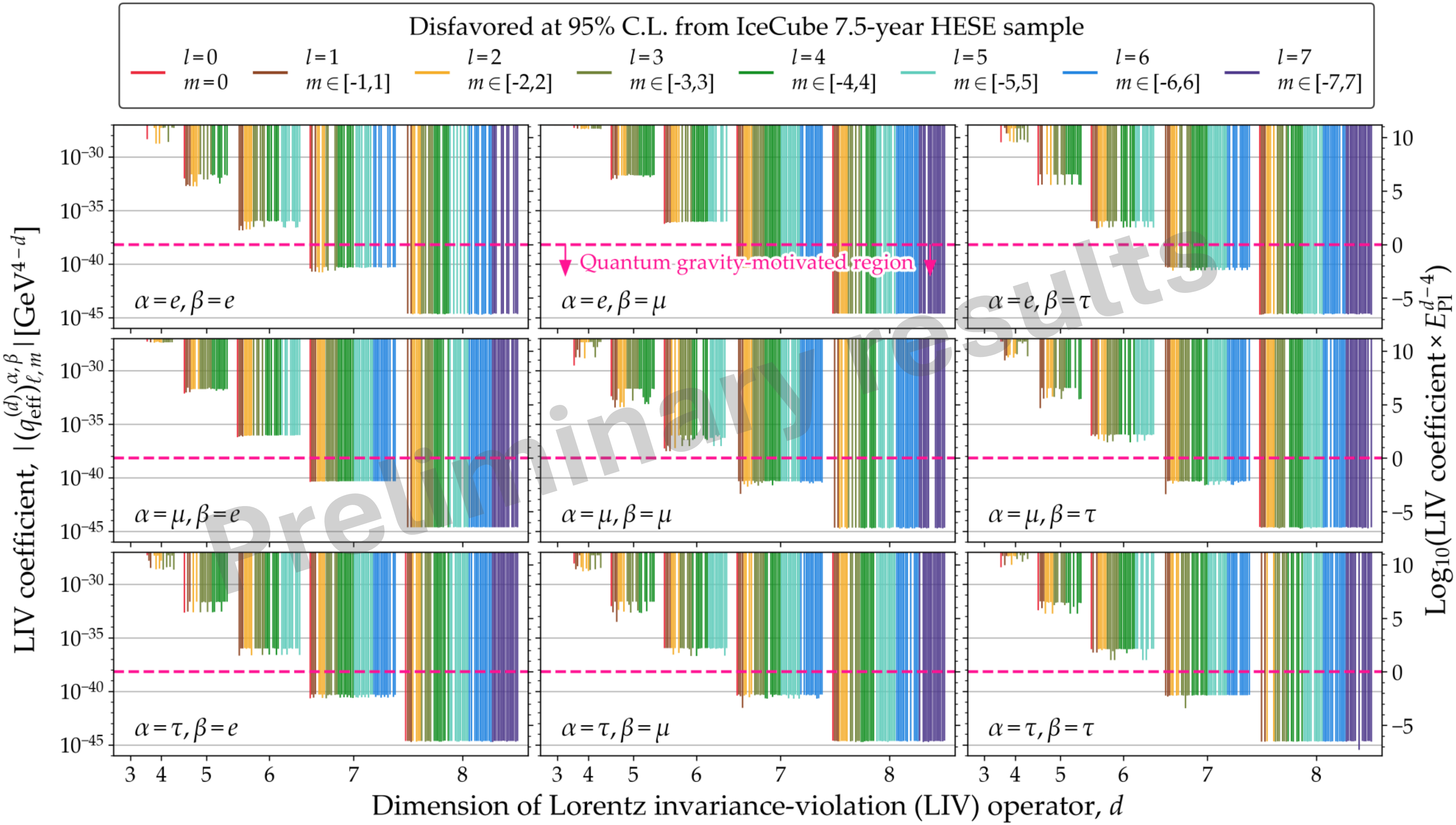
Results

Results



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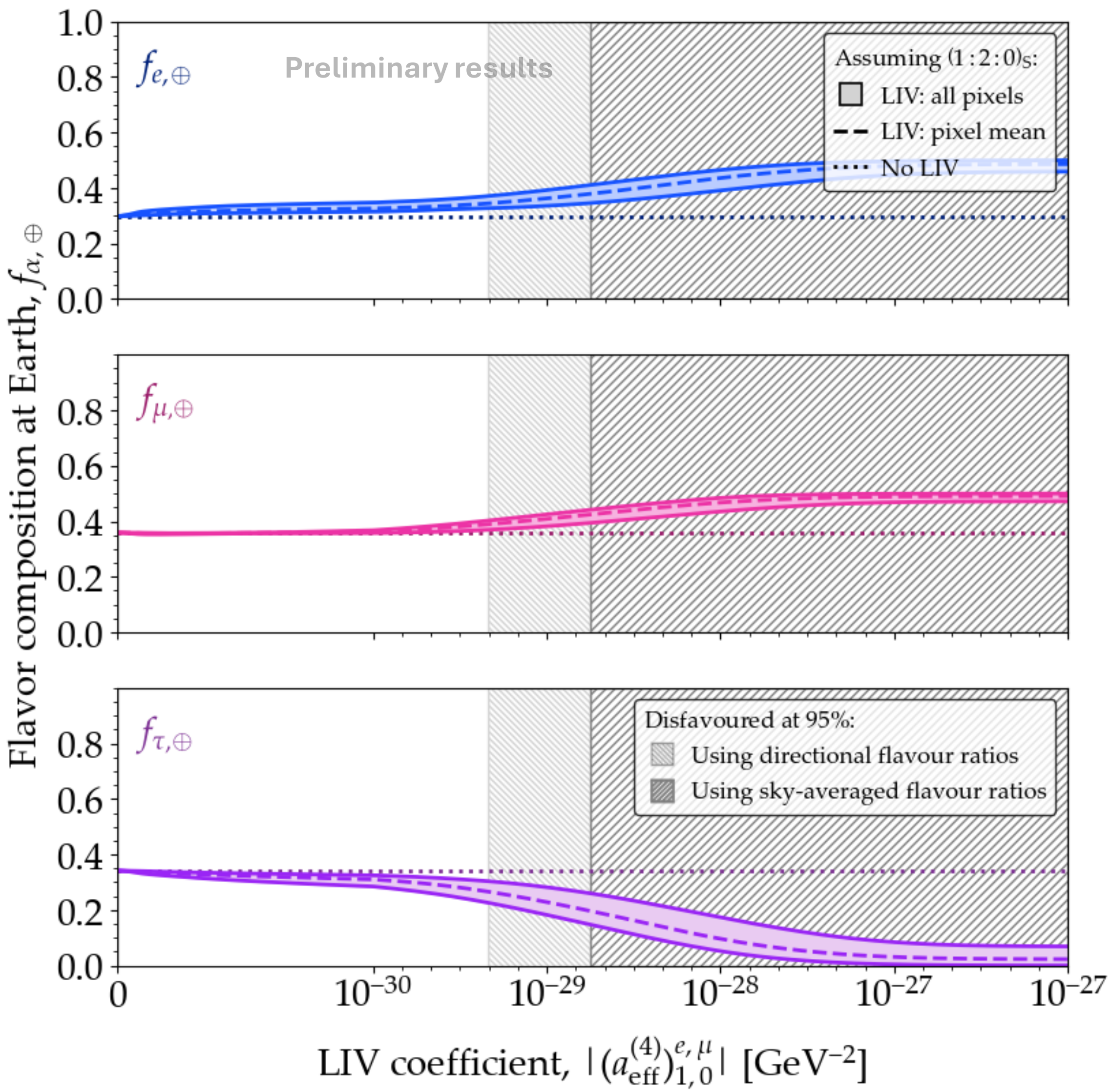
Directional info helps!



Take Home Message

Higher cosmic energies are
opening the window into
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TeV-and-beyond neutrinos have a lot to teach us