Friedrich-Alexander-Universität
Erlangen-Nürnberg

Using galactic neutrinos for constraining Lorentz Invariance violation

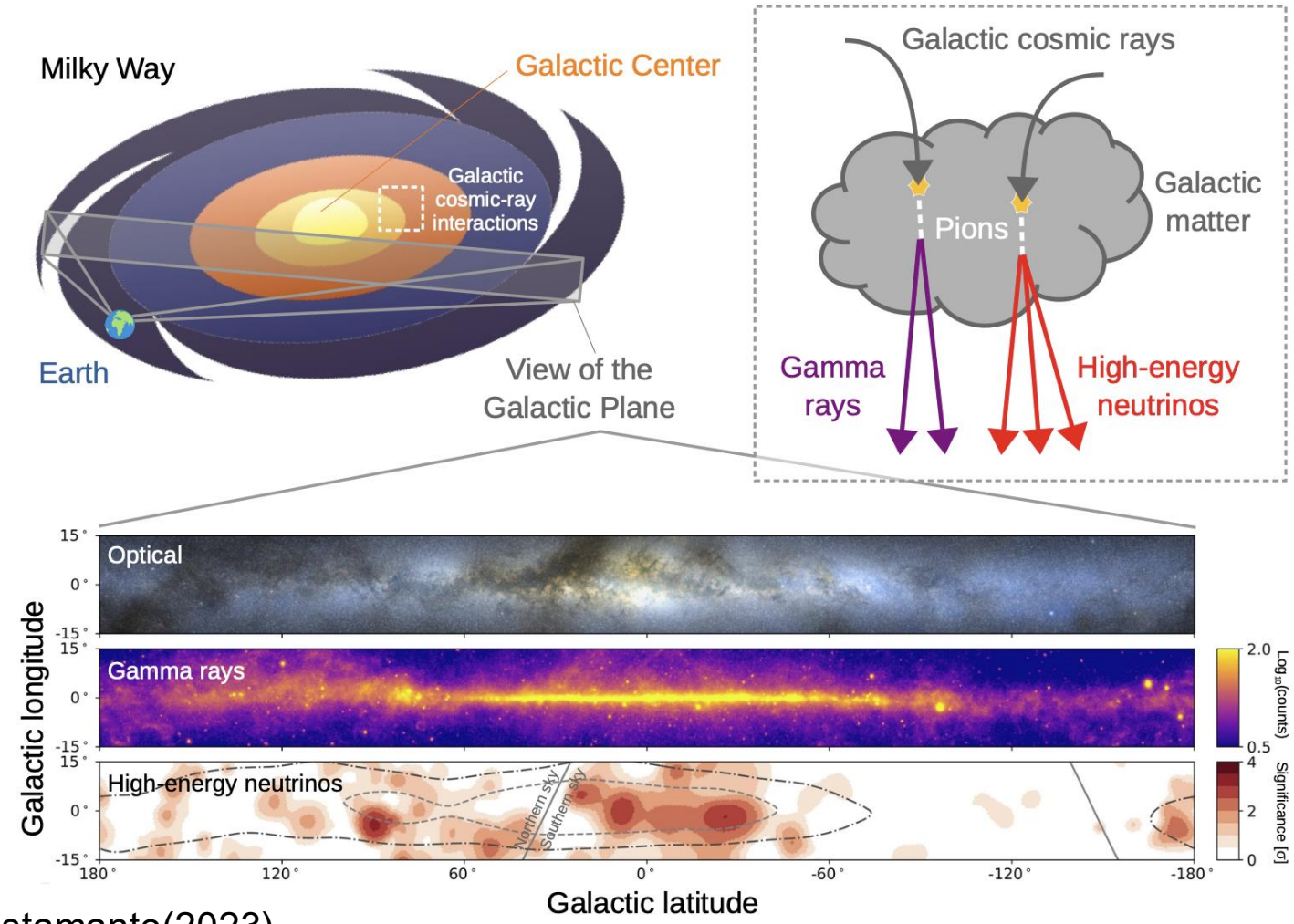
Jelena Celic, Rodrigo Guedes Lang, Stefan Funk

FRANCI meeting 2025

Bamberg, 28.07.2025

The Galactic Plane Seen by IceCube

Using neutrinos for Quantum Gravity Phenomenology



Bustamante(2023)

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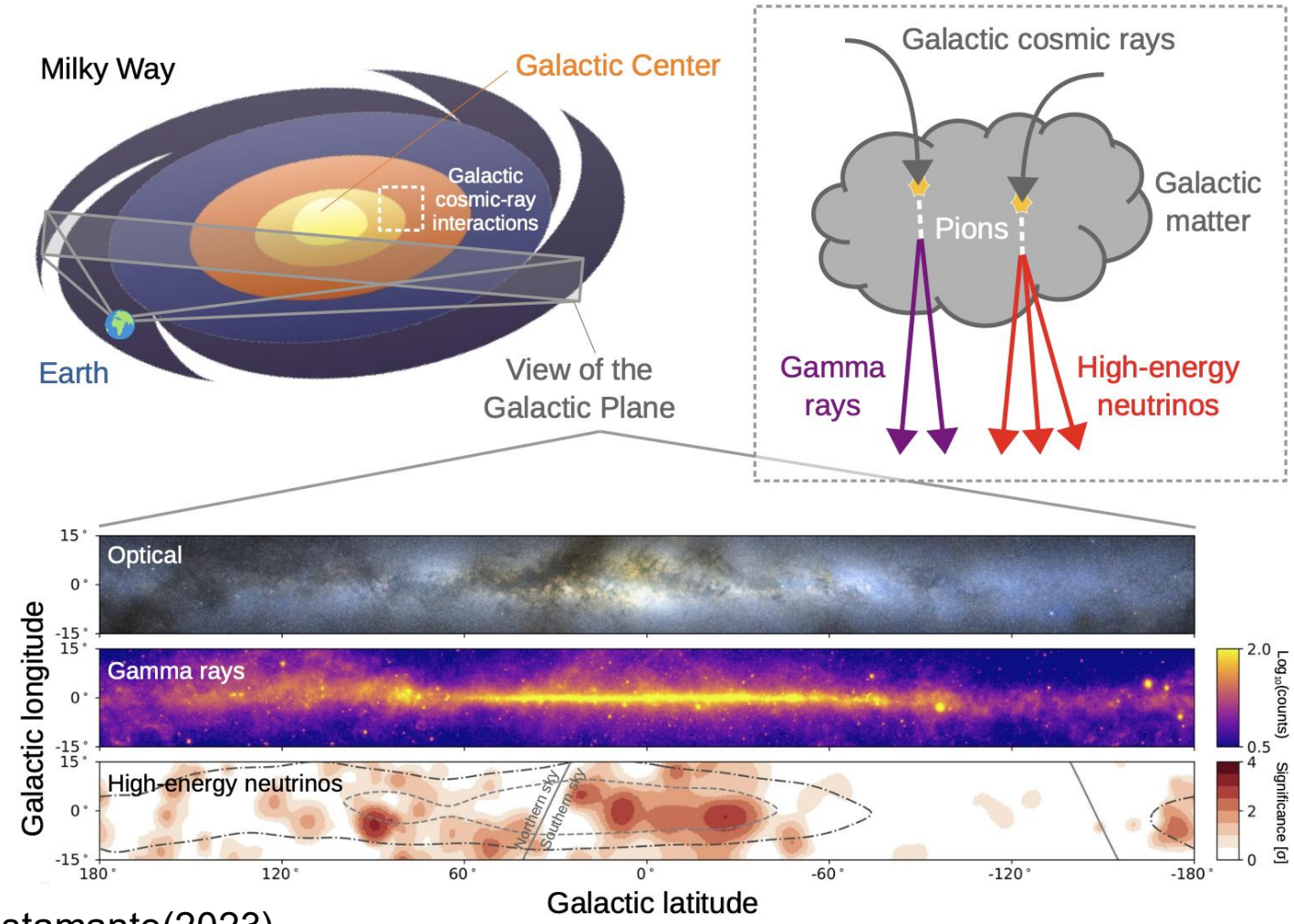

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But: Current models don't agree fully

- Over or underpredict galactic component
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→ **Also seen by other experiments like Baikal-GVD**

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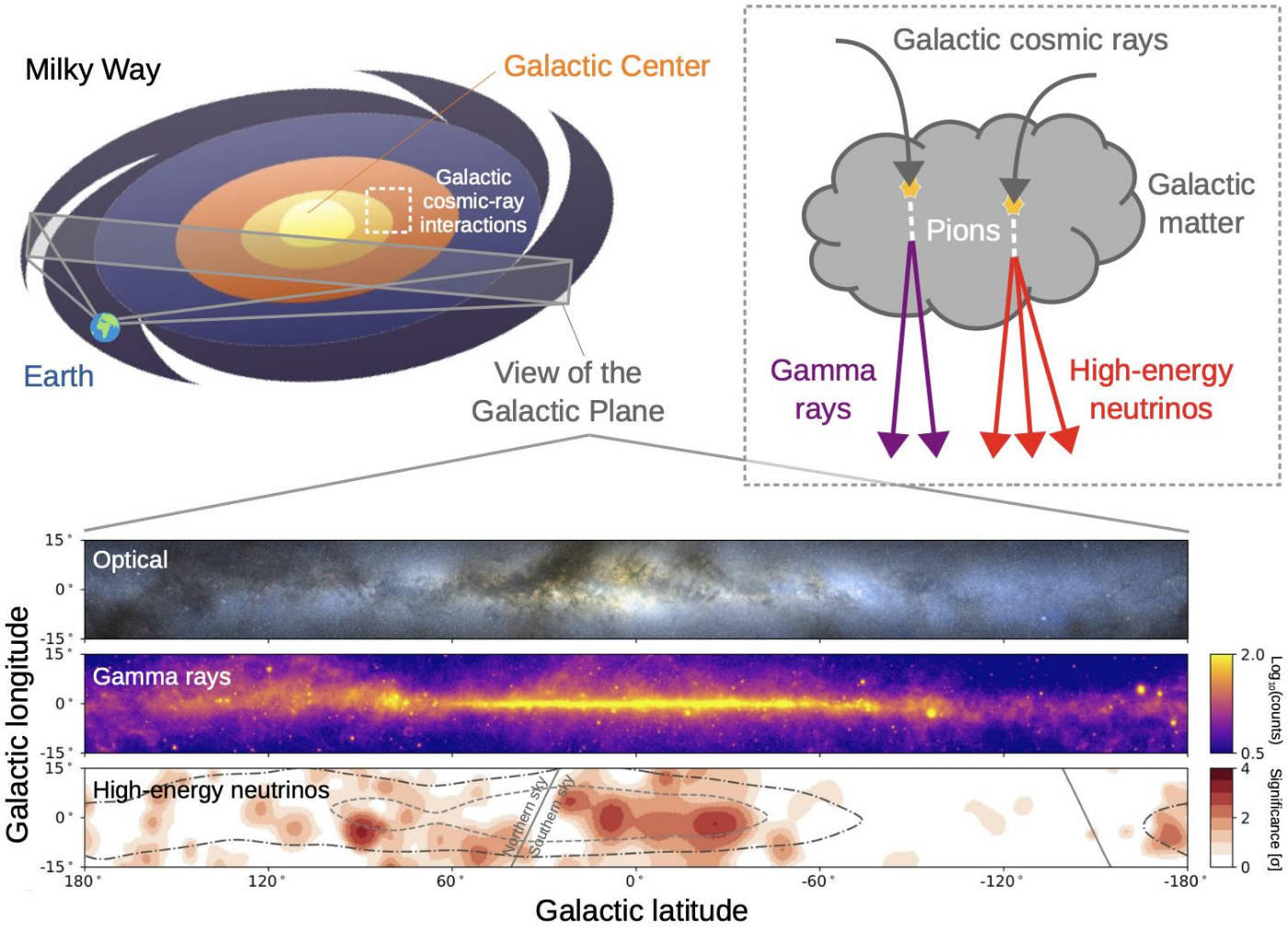

Bustamante(2023)

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Let's test some beyond the Standard model theories!!

Why Quantum Gravity Phenomenology?

Especially why LIV?

The Challenge

•We have a incomplete theory → theory with extentions

•But we **can search for testable effects** that might hint at its nature.

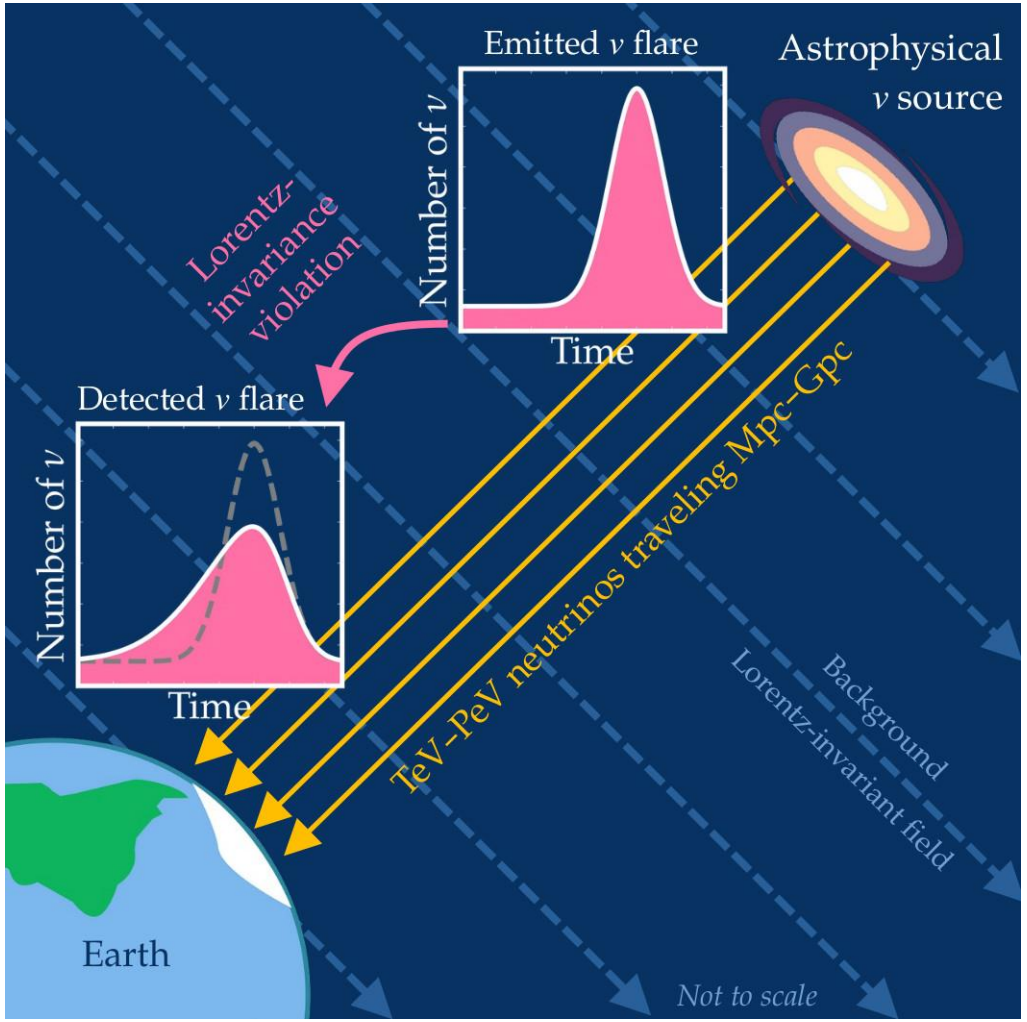
Why look for Lorentz Invariance Violation (LIV)?

•LIV is one of the most widely studied possible effects of quantum gravity.

•Closer to the Planck-Scale($\approx 10^{19} GeV$) → stronger LIV effect

•It could show up in:

- Tiny changes in how fast light travels depending on energy
- Deviations in space-time behavior at very high energies



Bustamante(2024)

Superluminal neutrino decay

Neutrino propagation: “Consistency of Lorentz-invariance violation neutrino scenarios in time delay analyses” by J.M Carmona et al.

Modified dispersion relation for

Neutrinos and Antineutrinos

$$E = |\vec{p}| \left[1 + \left(\frac{|\vec{p}|}{\Lambda}\right)^n\right] ; \qquad E = |\vec{p}| \left[1 + (-1)^n \left(\frac{|\vec{p}|}{\Lambda}\right)^n\right]$$

In the linear case (n = 1) one has **superluminal neutrinos** and **subluminal antineutrinos**

while in the quadratic case (n = 2) both neutrinos and antineutrinos are **superluminal**.

Decay width:

$$\Gamma^{(n)}_{\nu_\alpha \to \nu_\alpha + l + \bar{l}}(E) = 10^{-4} {G_F}^2 \frac{E^{5+3n}}{\Lambda^{3n}} \kappa^{(n)}_{\nu_\alpha, l},$$

→ Paper: Astrophysical (strongly constrained) vs. atmospheric (no effect seen)

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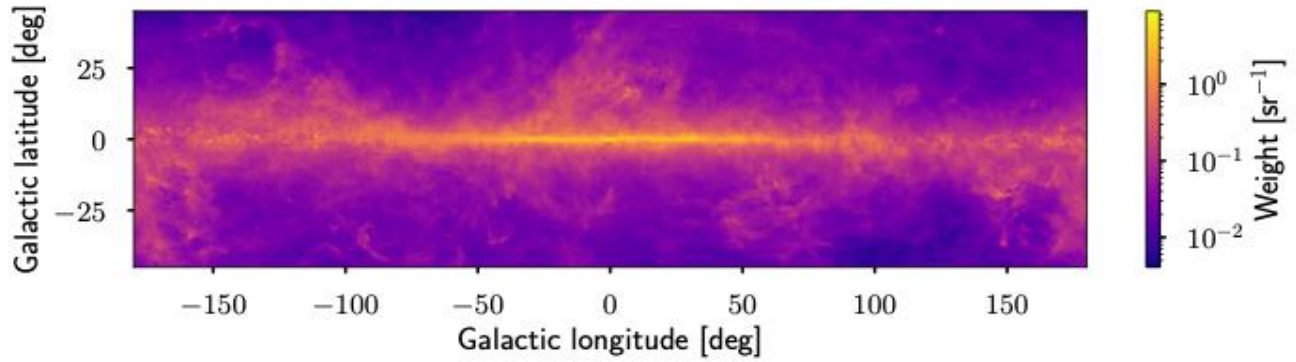
The recipe to replicate the IceCube analysis with OpenData

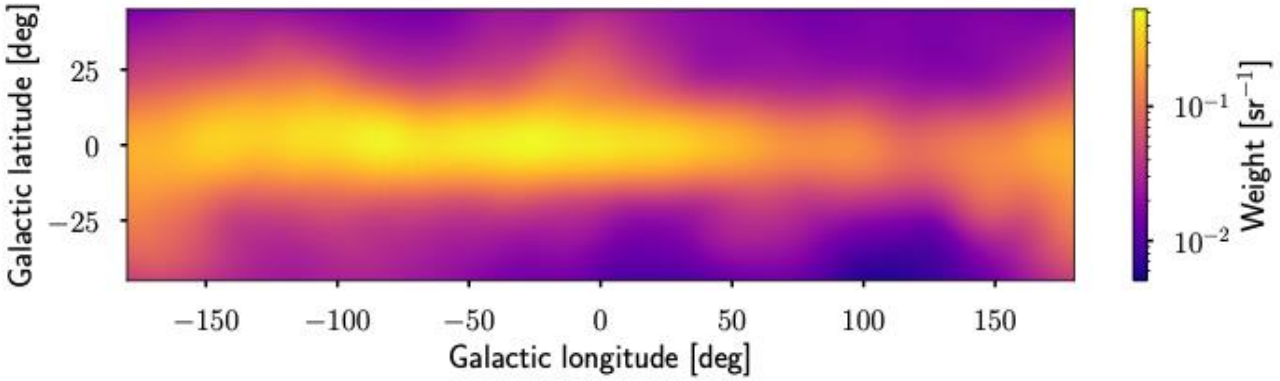
Or at least to get close to the IceCube publication

Starting point of the analysis



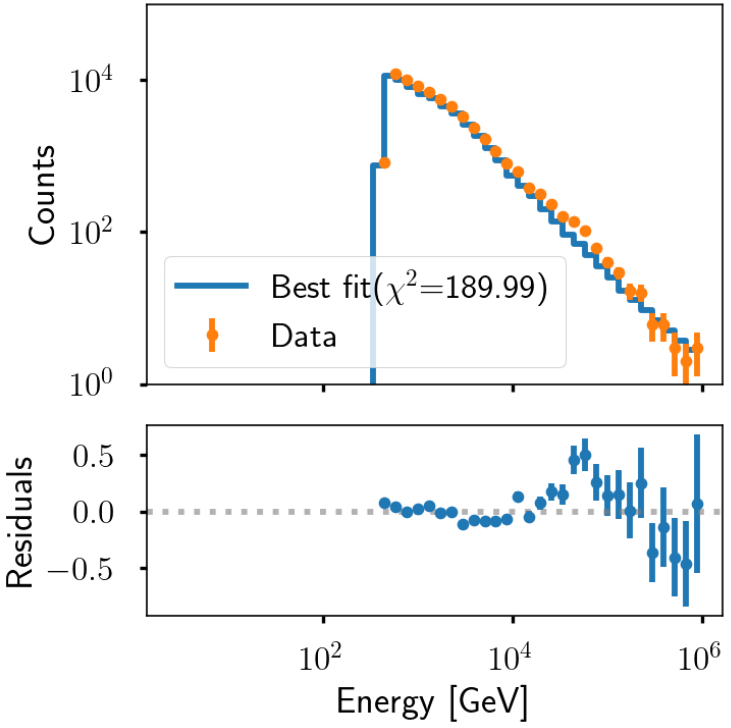
Effective area &
Angular uncertainty of IceCube

Angular distribution and ν Analysis Expectation in LI case



- **No energy dependence in the spatial distribution**
- Assumed Broken power law

$$\Phi(E) = \Phi_0 \cdot \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-\gamma_s}$$



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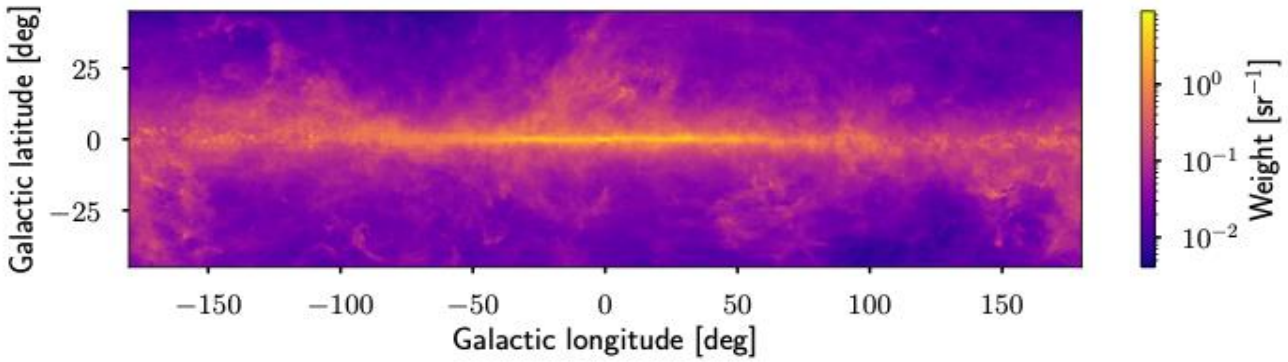

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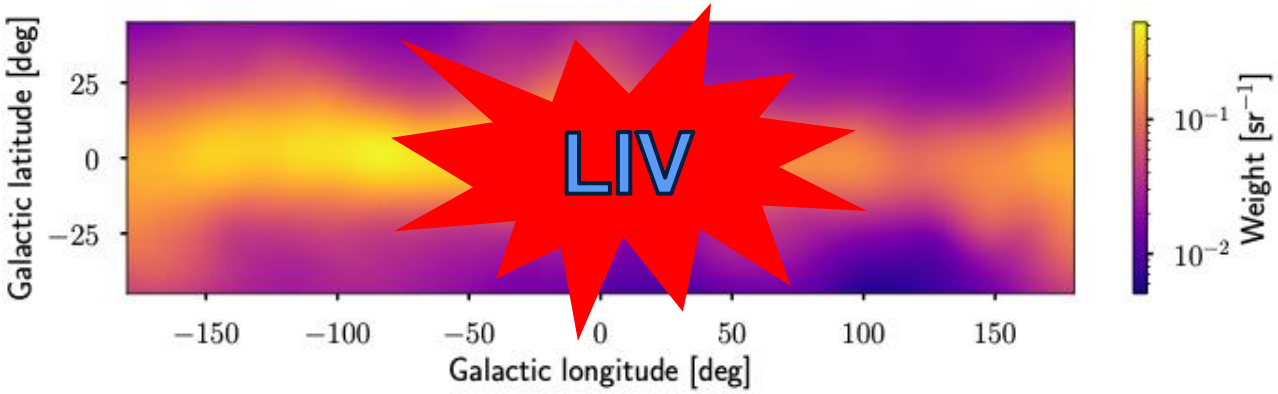

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LIV

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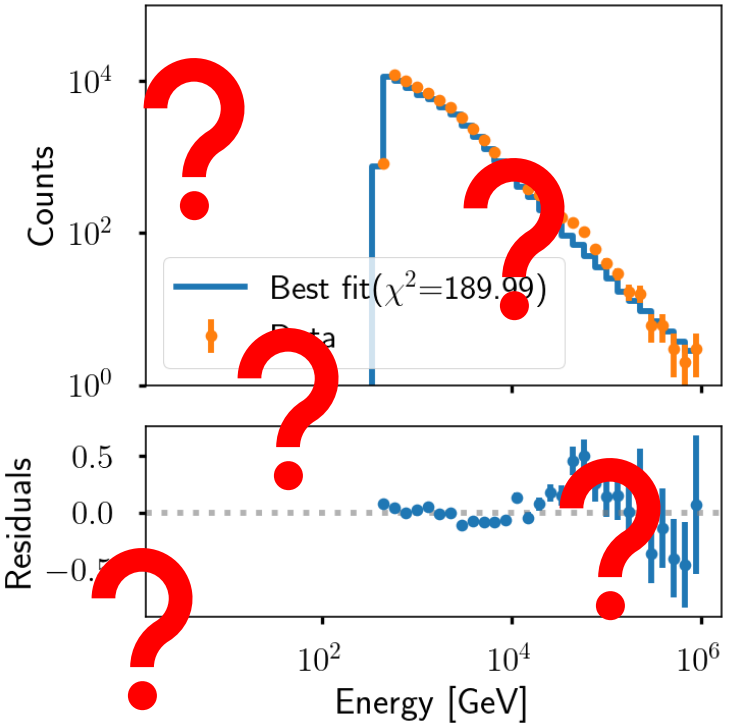
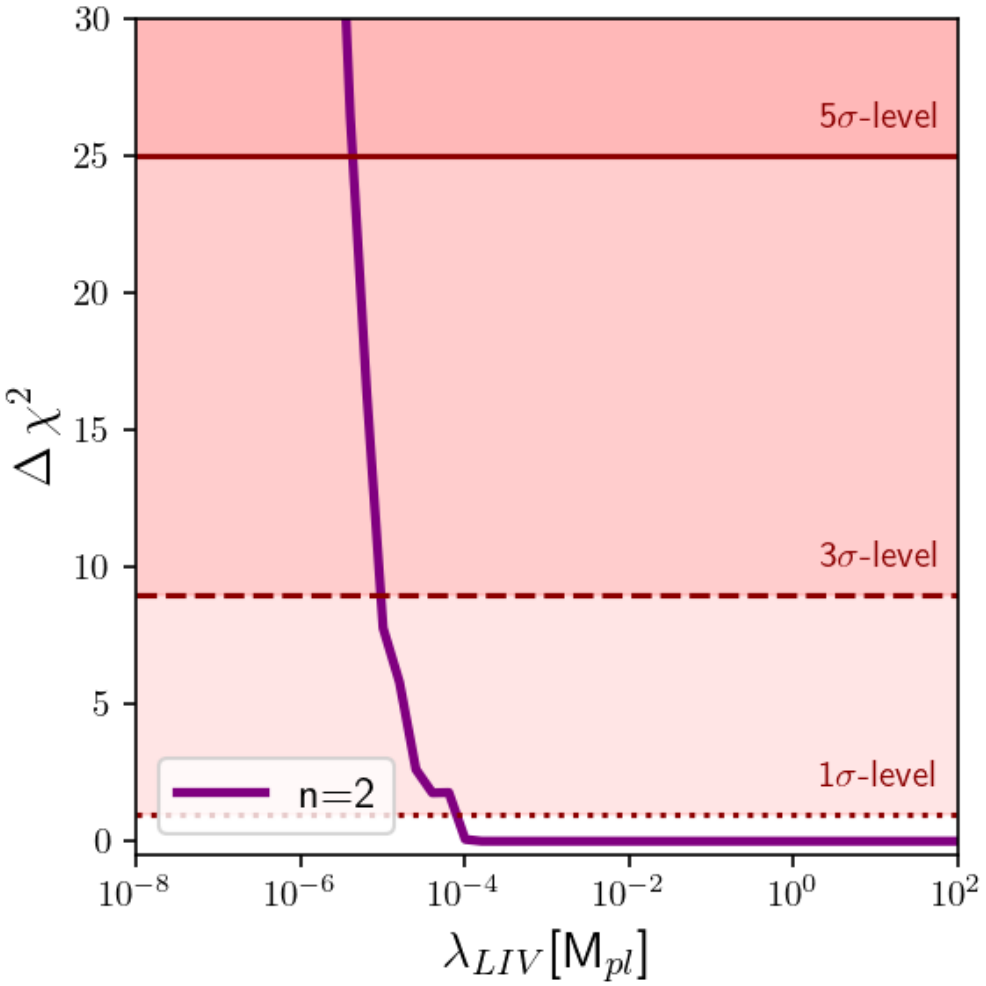


Spectral LIV limits
→ all-sky flux normalization fit

LIV Constrains

Spectral limits

σ-level	n=2
1σ	$6.310 \cdot 10^{-5}$ M_{Pl}
3σ	$6.310 \cdot 10^{-6}$ M_{Pl}
5σ	$3.981 \cdot 10^{-6}$ M_{Pl}



$(M_{pl} \approx 10^{19} GeV)$

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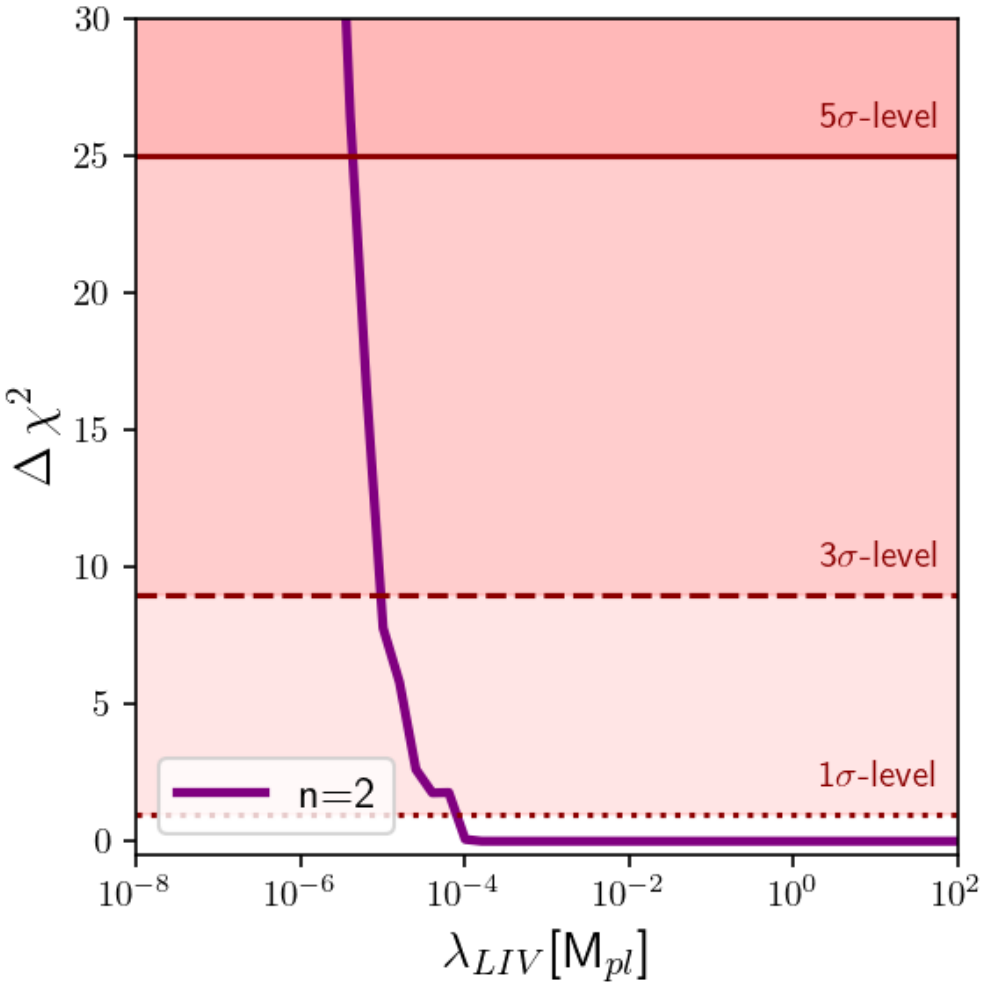

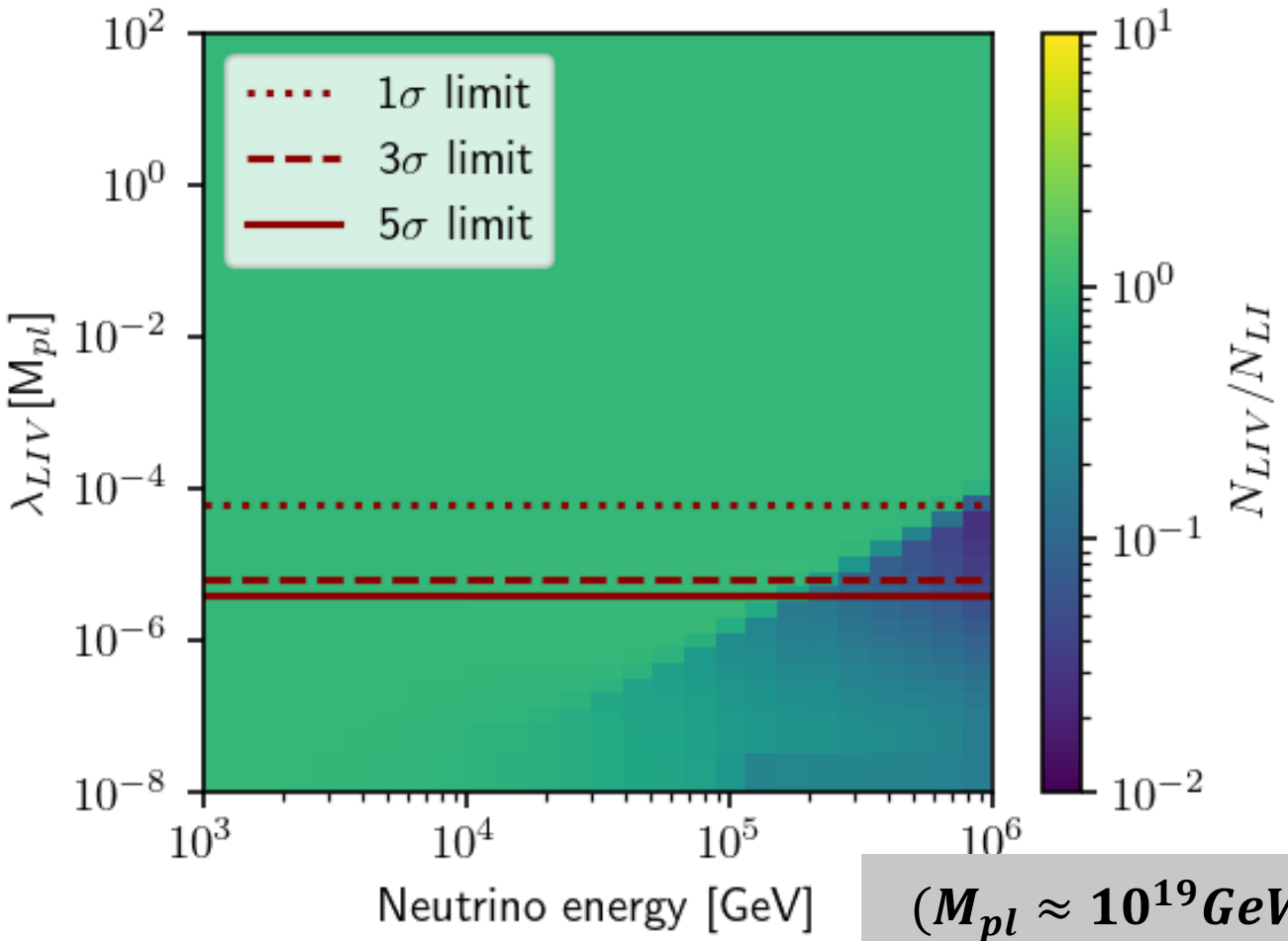

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What about the direction of the neutrinos?

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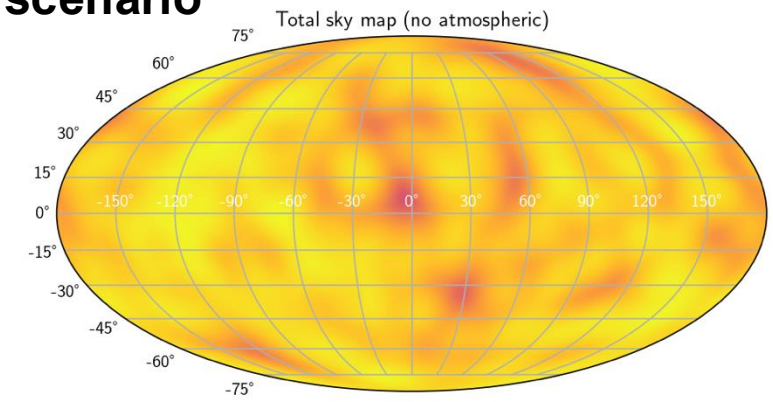
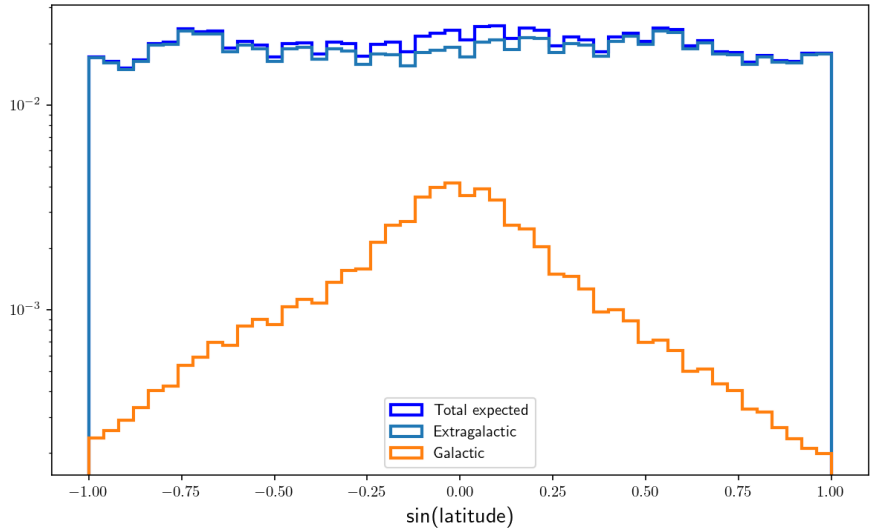
→ not possible for us, but we have an idea

Directional expectation above 100 TeV

Another way how to constrain LIV

LI scenario





LIV scenarios

Directional expectation above 100 TeV

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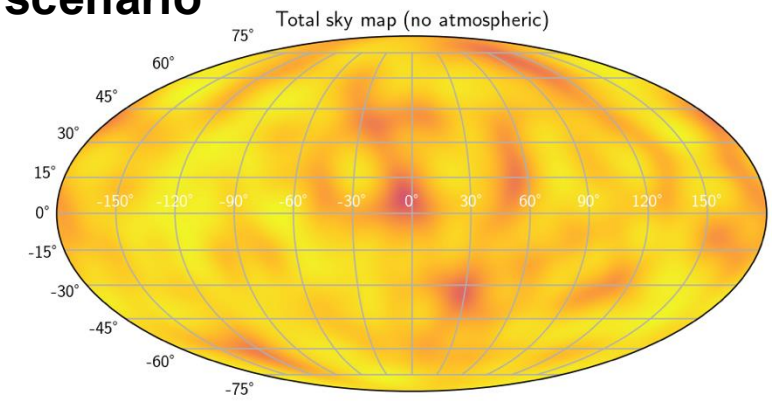

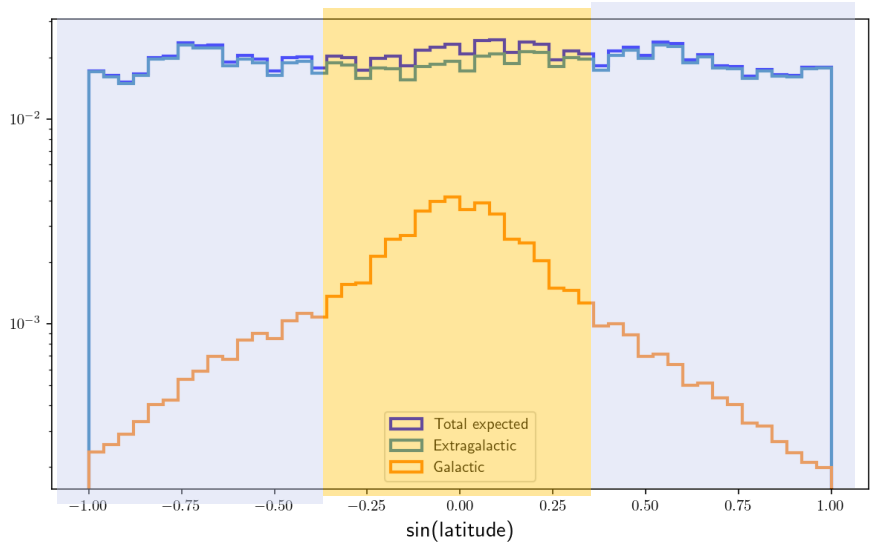

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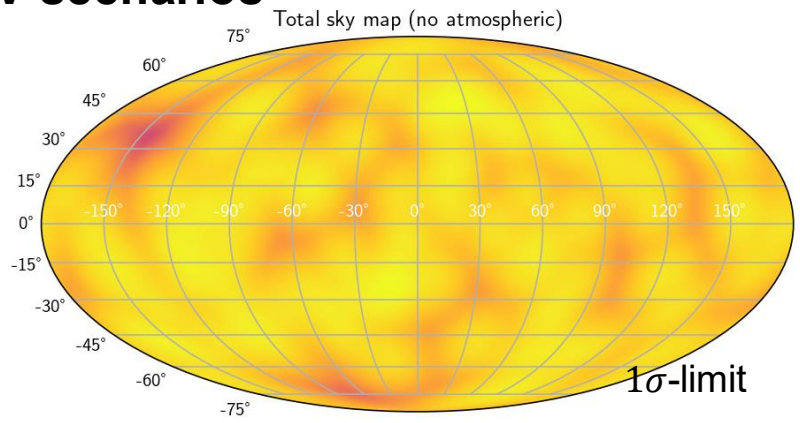

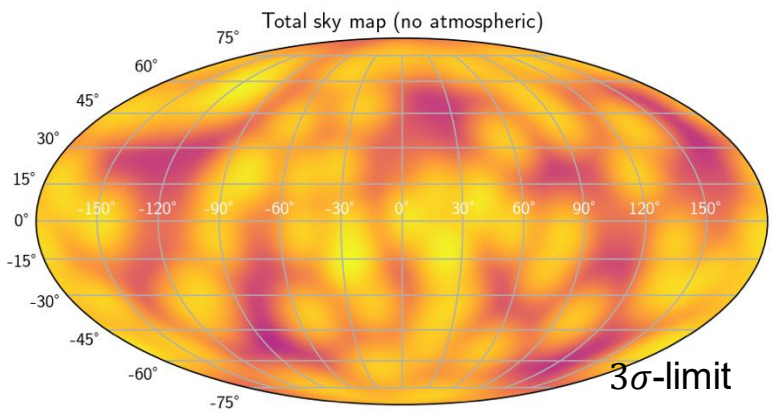

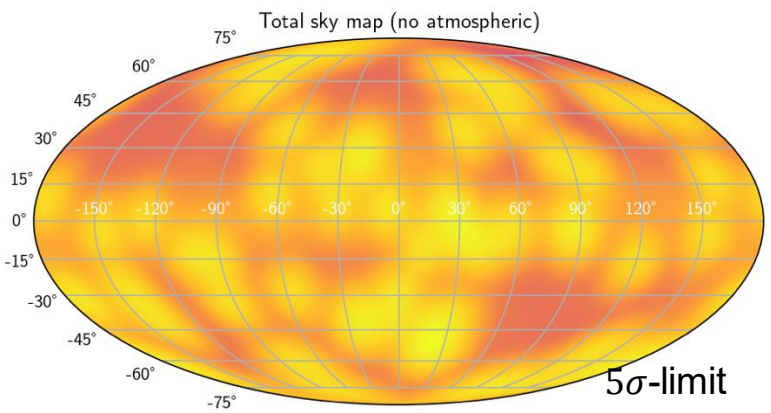

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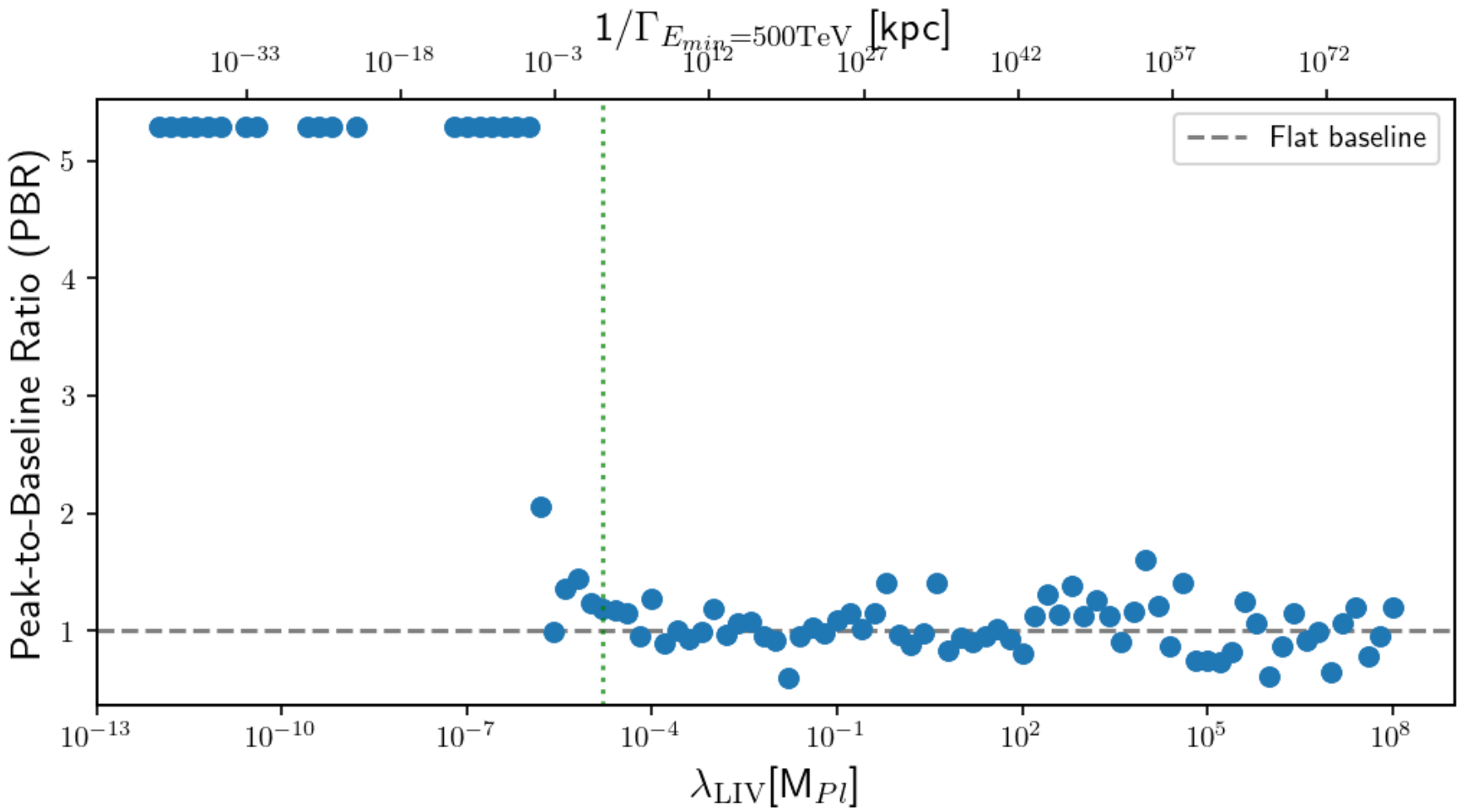


Green dotted line

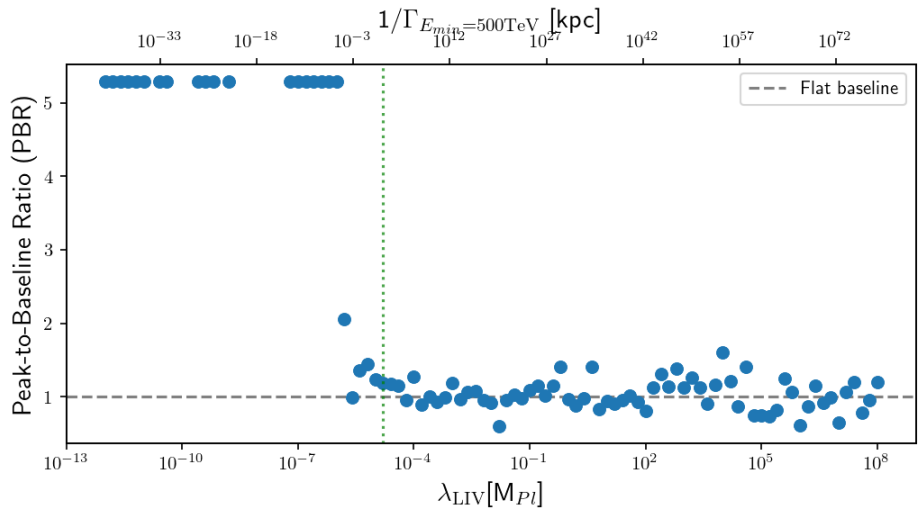
= Half the size of the Milky Way

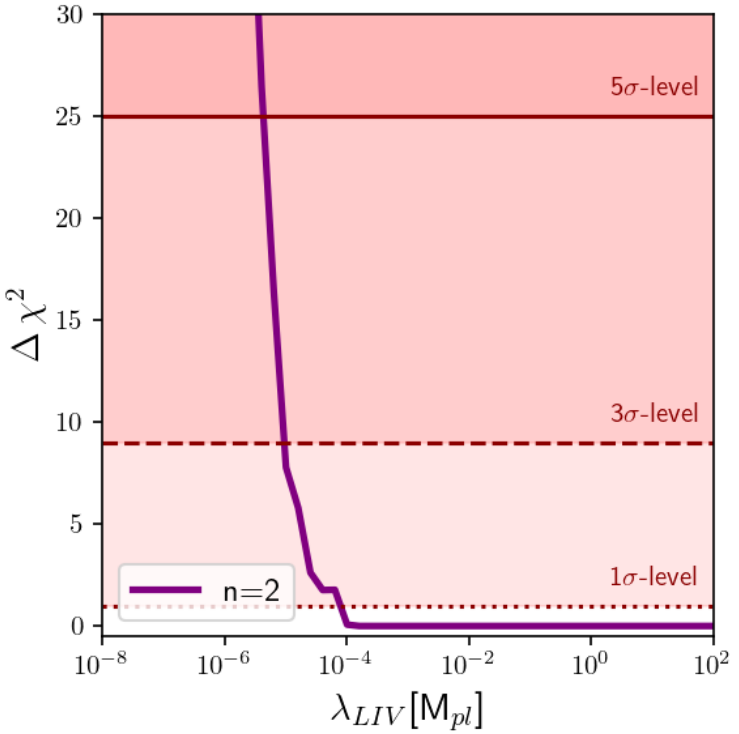
$(M_{pl} \approx 10^{19} GeV)$

Let's sum everything up

Conclusion and Outlook

- **The galactic neutrino model doesn't match with the data above 200 TeV → Opportunity to test LIV**
- **Under LIV (depending on the n-order): superluminal decay of neutrinos (& antineutrinos)**
- **Constrained for n=2: but to $10^{-5} - 10^{-6} M_{pl}$ can be discarded (only spectral)**
- **Proposed metric for directional constrains: the stronger LIV gets, less isotropic skymap**





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Thanks for your attention?
Questions?

LIV in the weak sector

Overview of the processes

Propagation

Modified neutrino dispersion relation

Signatures:
- **Time-of-flight differences** from astrophysical sources
- **Modified energy spectra**
- **Decay-like behavior** at high energies

Focus of my work

Production

Energy-momentum conservation at the vertex in weak decays (e.g., pion → muon + neutrino).

Signatures are e.g.:

- **Suppression or enhancement** of decay channels
- **Threshold shifts** or cutoff in the neutrino energy spectrum

Oscillation

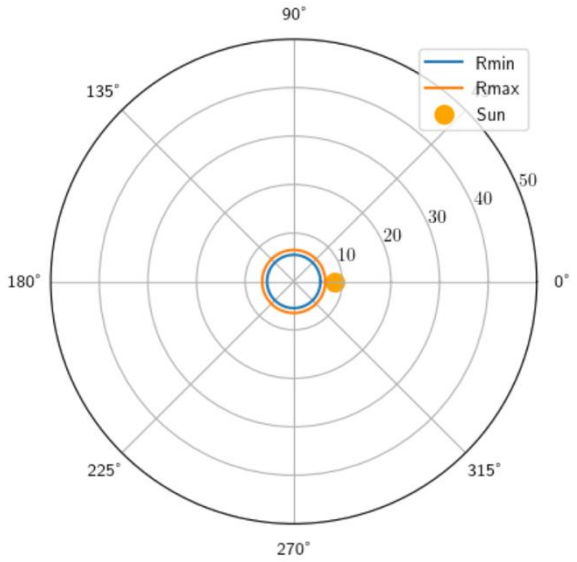
Effective Hamiltonian gets extra LIV terms → changes oscillation probabilities.

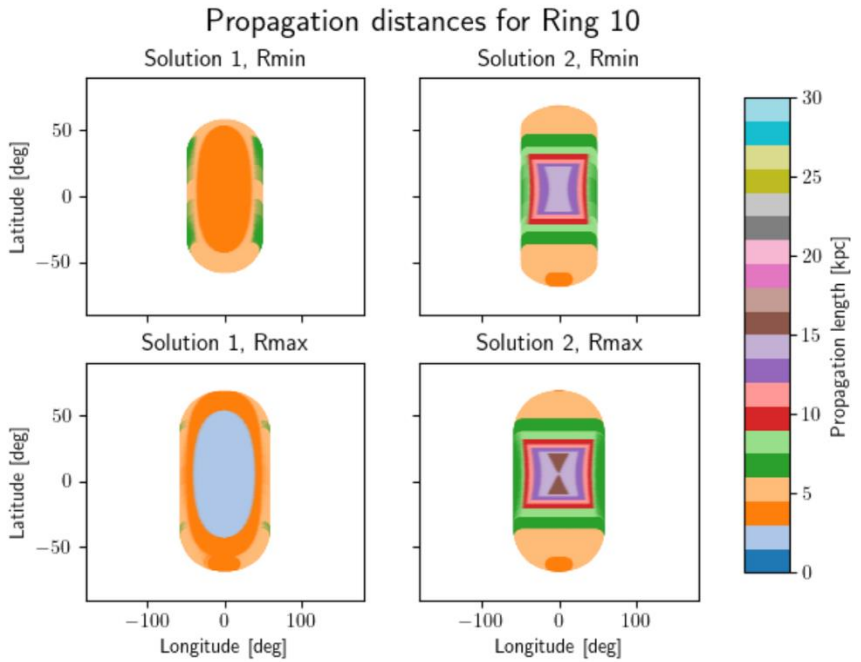
Signatures e.g.
- **Energy-dependent deviations** from standard mixing
- **Directional asymmetries** in oscillation patterns

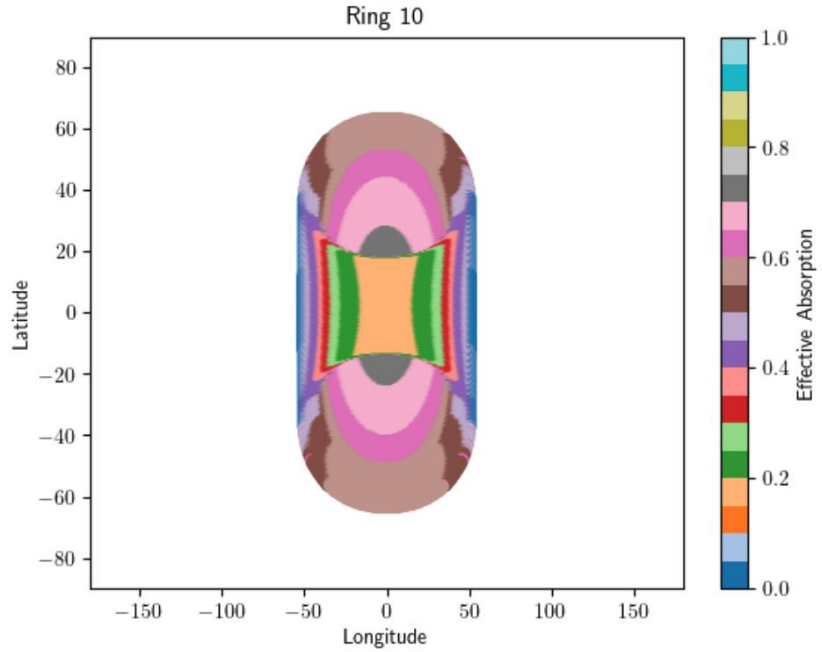
At ECAP ongoing work in the neutrino group and QG theory group

The recipe to set LIV constrains (Part 1)

The galactic plane expected neutrino distributions







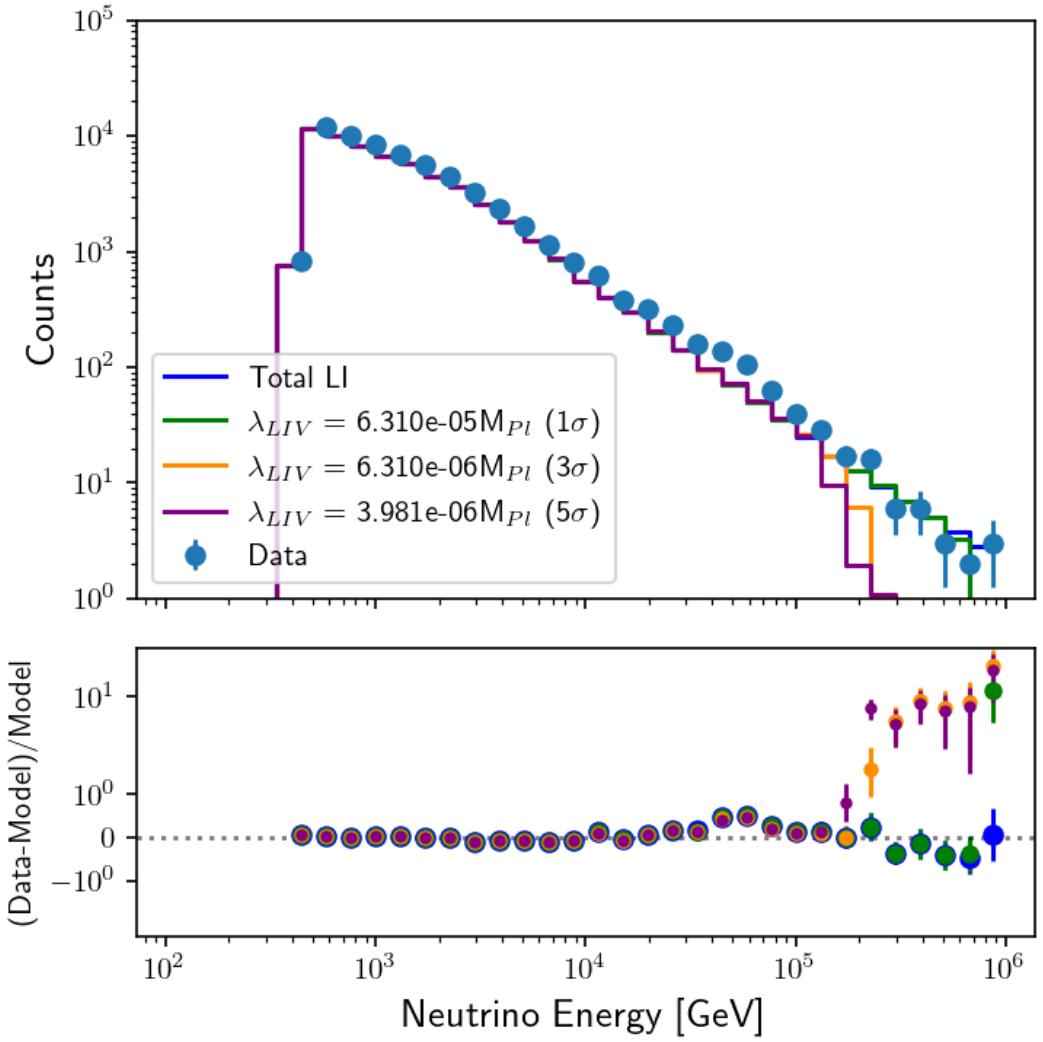
$$\frac{\int_\Omega \int_{l_1}^{l_2} dl d\Omega \rho(\vec{x}) e^{-l/\Gamma}}{\int_\Omega \int_{l_1}^{l_2} dl d\Omega \rho(\vec{x})} = \frac{\int_{l_1}^{l_2} l^2 e^{-l/\Gamma}}{\int_{l_1}^{l_2} l^2} = I(l_1, l_2)$$

$$I(l_1, l_2) := \frac{\Gamma e^{-l/\Gamma\left(2\Gamma^2+2\Gamma l+l^2\right)}\Big|_{l_1}^{l_2}}{\frac{l^3}{3}\Big|_{l_1}^{l_2}}$$

$$a_{\text{eff}}(\theta, \phi, \Gamma, \rho_{\min}, \rho_{\max}) = \begin{cases} I\left(l^{(1)}_{\rho_{\max}}, l^{(1)}_{\rho_{\min}}\right) + I\left(l^{(2)}_{\rho_{\min}}, l^{(2)}_{\rho_{\max}}\right) & , \text{for } \tilde{\mathrm{N}} = (2,2) \\ I\left(0, l^{(1)}_{\rho_{\min}}\right) + I\left(l^{(2)}_{\rho_{\min}}, l^{(2)}_{\rho_{\max}}\right) & , \text{for } \tilde{\mathrm{N}} = (2,1) \\ I\left(l^{(1)}_{\rho_{\max}}, l^{(2)}_{\rho_{\max}}\right) & , \text{for } \tilde{\mathrm{N}} = (1,2) \\ I\left(l^{(1)}_{\rho_{\min}}, l^{(1)}_{\rho_{\max}}\right) & , \text{for } \tilde{\mathrm{N}} = (1,1) \\ I\left(l^{(1)}_{\rho_{\max}}, l^{(2)}_{\rho_{\max}}\right) & , \text{for } \tilde{\mathrm{N}} = (0,2) \\ I\left(0, l^{(1)}_{\rho_{\min}}\right) & , \text{for } \tilde{\mathrm{N}} = (1,0) \\ I\left(0, l^{(1)}_{\rho_{\max}}\right) & , \text{for } \tilde{\mathrm{N}} = (0,1) \text{ and } \rho_{\min} < \mathrm{x_E} < \rho_{\max} \\ 0 & , \text{otherwise} \end{cases}.$$

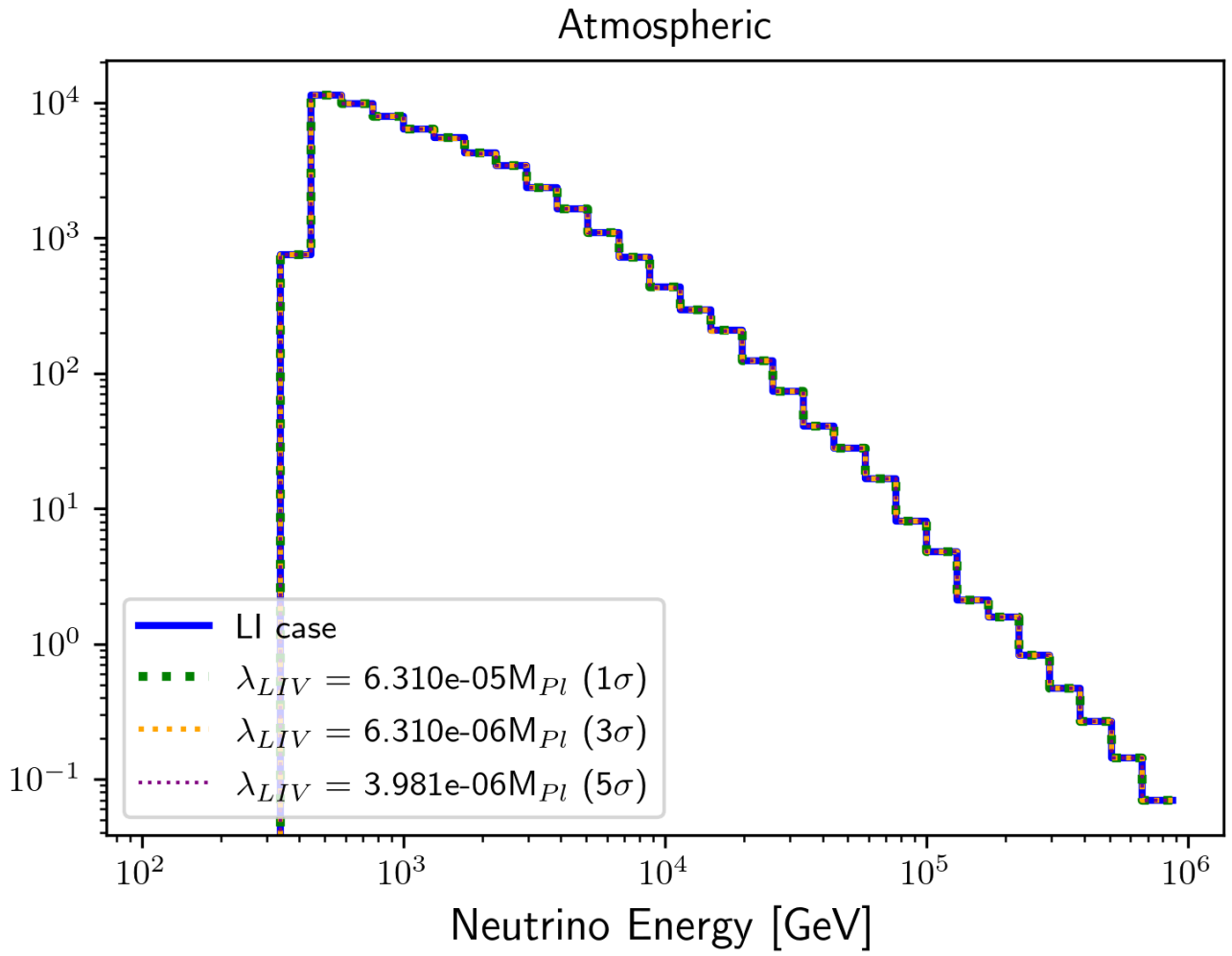
LIV constrains (Part 1)

Spectrum LI vs. LIV scenario (1,3,5 sigma)



Spectrum comparison

Contributions to the spectrum (1 sigma, 3 sigma, 5 sigma)



As stated in paper:

- atmospheric model is due to small propagation distances not affected

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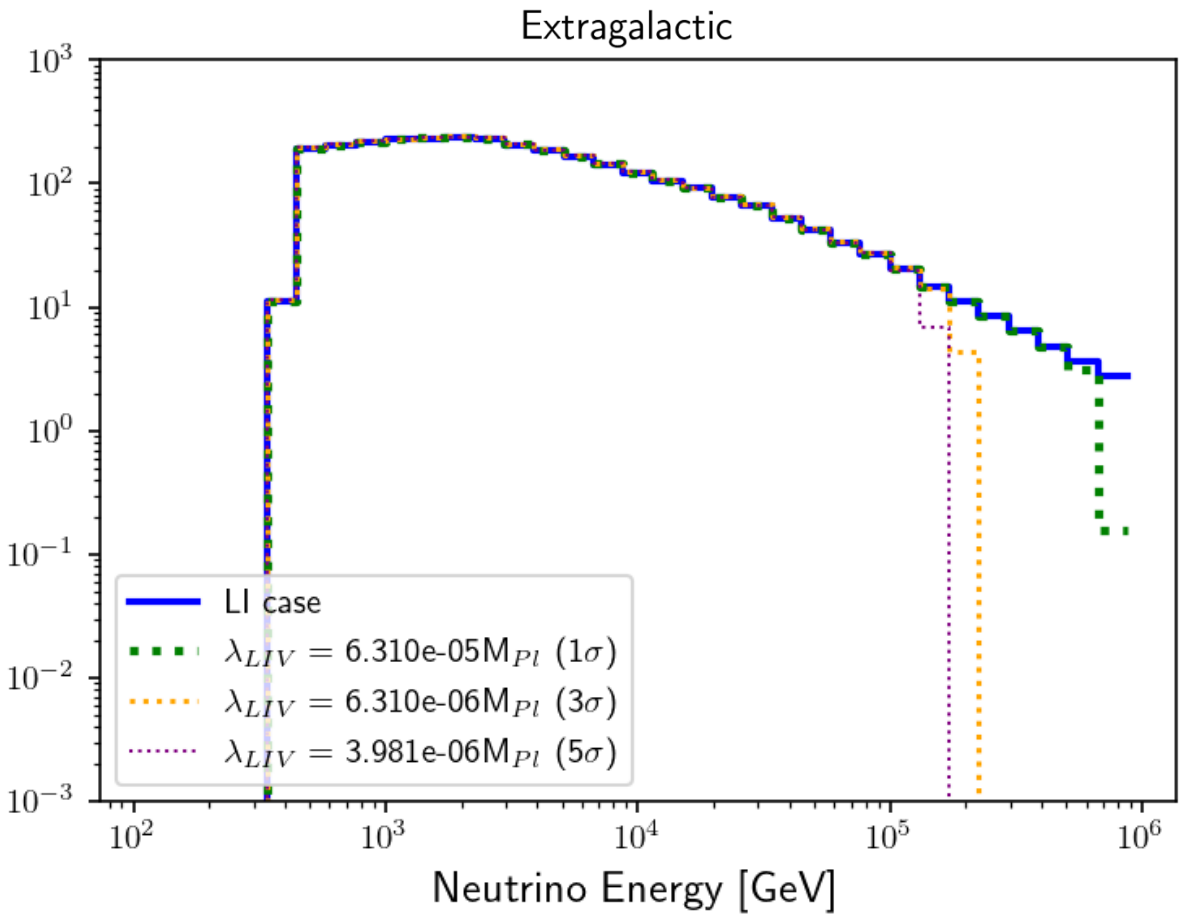

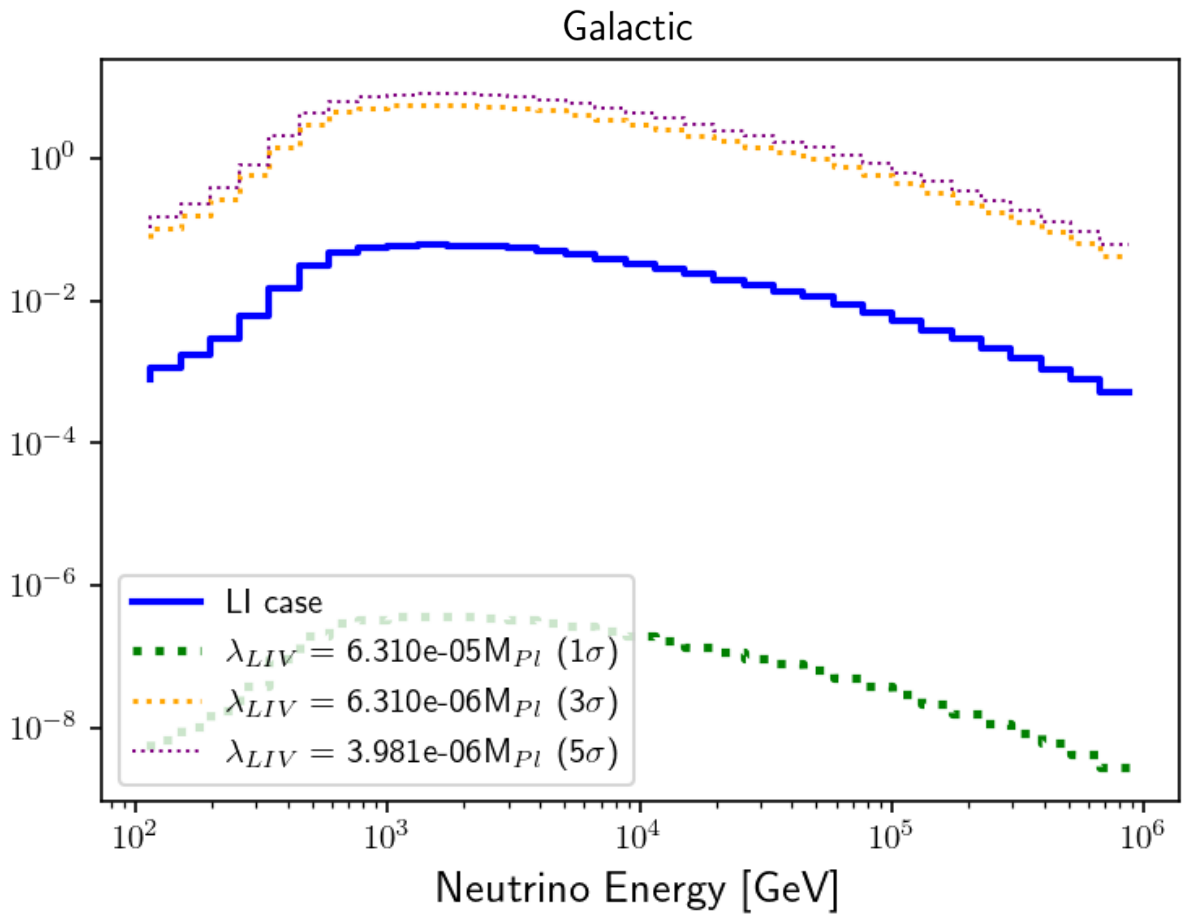

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