# Search for Lorentz invariance violation with ANTARES and KM3NeT/ORCA6


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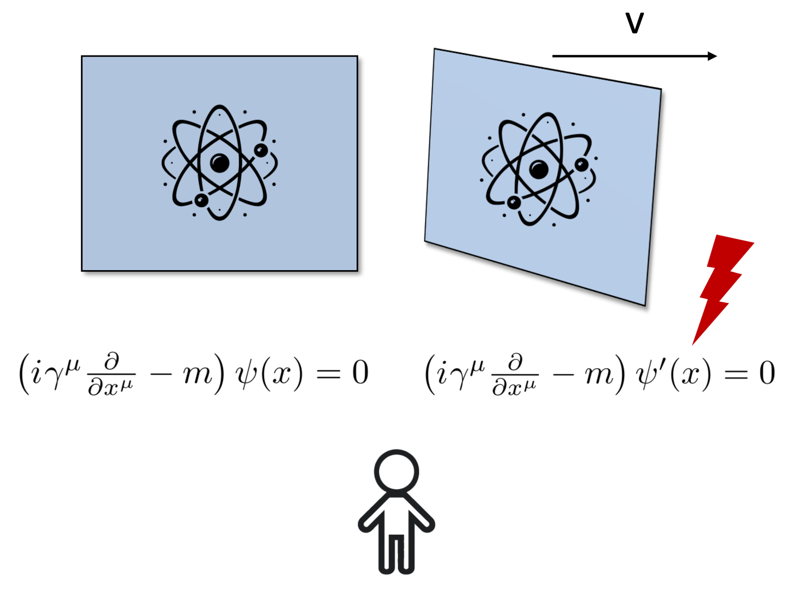
## Lorentz invariance violation (LIV)

- Lorentz invariance states that the outcome of an experiment is:
  - the same for two inertial observers watching the same experiment
  - independent of the inertial laboratory in which it is performed
- LIV preserves observer-independence, but violates the second condition
- LIV is allowed in many theories beyond the Standard Model




*Observer cannot use the same equations to describe identical experiments in different laboratories*

## Standard Model Extension (SME)

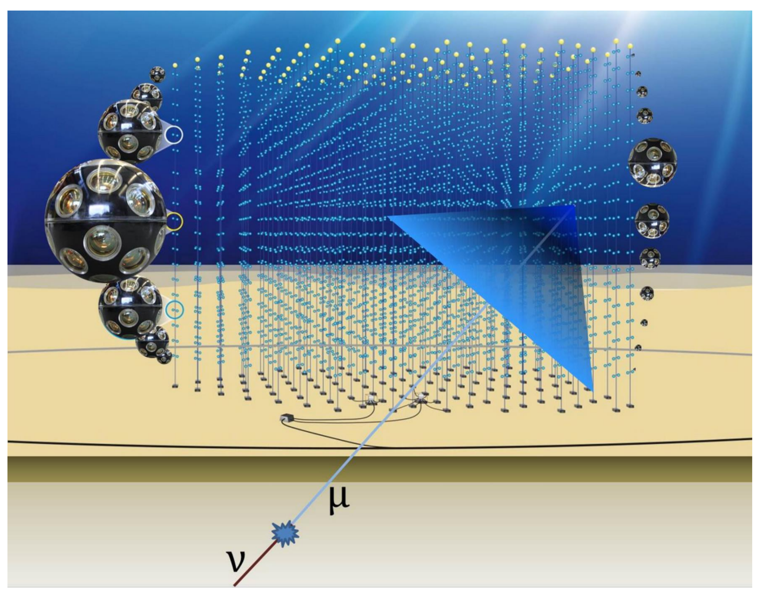
- An extension of the Standard Model including all possible LIV operators[1]
- Focus on isotropic LIV models that preserve rotational invariance in a preferred frame
- General LIV Hamiltonian for neutrinos introducing complex-valued LIV coefficients[2]:

$$H_{LIV} = \begin{pmatrix} \mathring{a}^{(3)}_{ee} & \mathring{a}^{(3)}_{e\mu} & \mathring{a}^{(3)}_{e\tau} \\ \mathring{a}^{(3)*}_{e\mu} & \mathring{a}^{(3)}_{\mu\mu} & \mathring{a}^{(3)}_{\mu\tau} \\ \mathring{a}^{(3)*}_{e\tau} & \mathring{a}^{(3)*}_{\mu\tau} & \mathring{a}^{(3)}_{\tau\tau} \end{pmatrix} - \frac{4}{3}E \begin{pmatrix} \mathring{c}^{(4)}_{ee} & \mathring{c}^{(4)}_{e\mu} & \mathring{c}^{(4)}_{e\tau} \\ \mathring{c}^{(4)*}_{e\mu} & \mathring{c}^{(4)}_{\mu\mu} & \mathring{c}^{(4)}_{\mu\tau} \\ \mathring{c}^{(4)*}_{e\tau} & \mathring{c}^{(4)*}_{\mu\tau} & \mathring{c}^{(4)}_{\tau\tau} \end{pmatrix} + E^2\mathring{a}^{(5)} - E^3\mathring{c}^{(6)} + \dots$$

- Nonzero LIV coefficient implies deviations from standard oscillations
- Mass dimension determines oscillation dependence on baseline L and energy E
- Focus on mass dimension up to six

| Coefficient | Unit | CPT | Oscillation effect |
|---|---|---|---|
| $\mathring{a}^{(3)}$ | GeV | odd | $\propto L$ |
| $\mathring{c}^{(4)}$ | - | even | $\propto LE$ |
| $\mathring{a}^{(5)}$ | $GeV^{-1}$ | odd | $\propto LE^2$ |
| $\mathring{c}^{(6)}$ | $GeV^{-2}$ | even | $\propto LE^3$ |

## Experiment descriptions




*Artist impression of completed KM3NeT/ORCA*

- **KM3NeT/ORCA**
  - Cherenkov neutrino telescope under construction in the Mediterranean Sea
  - It will consist of 115 Detection Units (DUs)
  - Focus here on subdetector KM3NeT/ORCA6 operated with six DUs from Jan. 2020 – Nov. 2021
- **ANTARES**
  - Cherenkov neutrino telescope operated in the Mediterranean Sea from 2007 to 2022
  - It consisted of 12 lines

## Analysis method

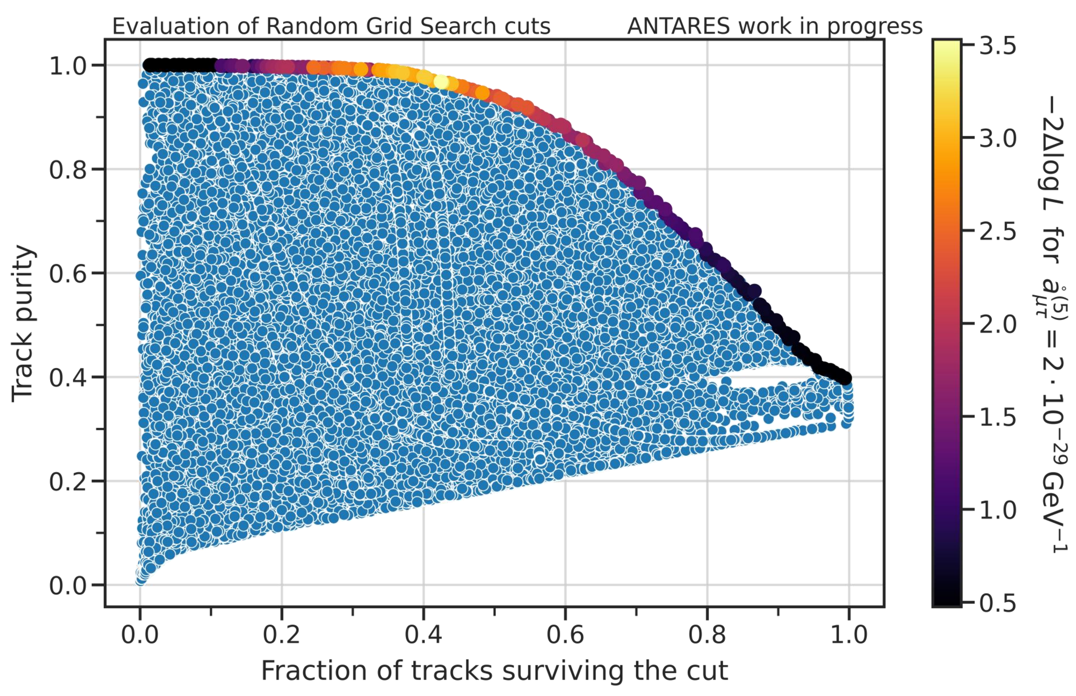
- Analysis uses 2D binning in reconstructed energy and zenith angle
- Models assuming LIV are fitted to data by minimizing negative log-likelihood
- Standard oscillation parameter values from NuFit v5.0 global fit (with SK)
- Systematic flux parameters for KM3NeT/ORCA6 on the right
- Parameters with a * are currently kept fixed in ANTARES

| Fit parameter | Prior uncertainty |
|---|---|
| Energy Scale* | 9% |
| Overall Norm | Free |
| Shower Norm* | Free |
| HP Track Norm | Free |
| Spectral Index | 0.3 |
| HE Light Simulation* | 20% |
| Muon Norm* | Free |
| NC Norm | 20% |
| $\nu_\tau$-CC Norm | 20% |
| $\nu_e/\overline{\nu}_e$ | 7% |
| $\nu_\mu/\nu_e$ | 2% |
| $\overline{\nu}_\mu/\nu_\mu$ | 5% |
| $\nu_{hor}/\nu_{ver}$ | 2% |

- Off-diagonal coefficients are tested one by one, starting with the lowest mass dimension
- On-diagonal coefficients have strongly correlated oscillation effects

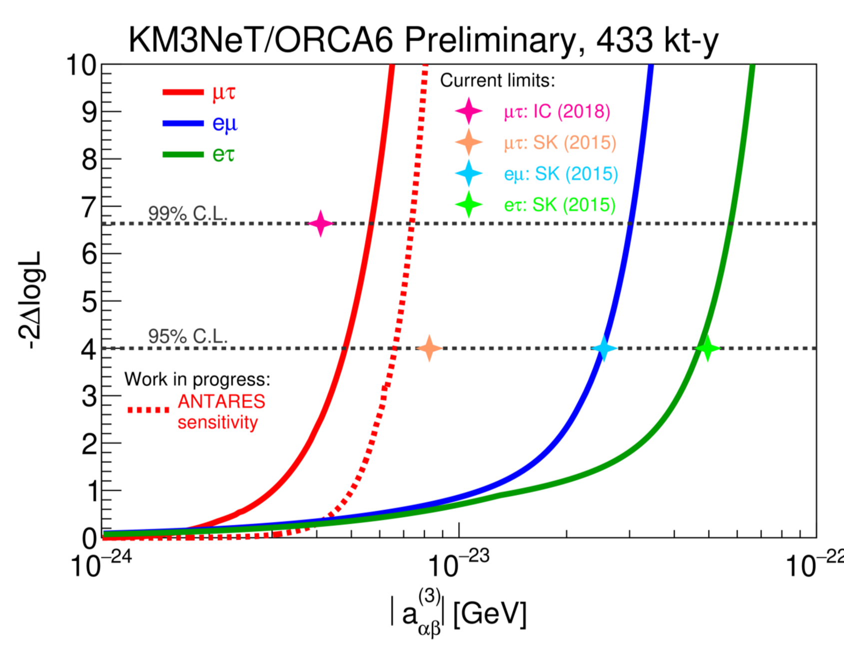
## Event selection

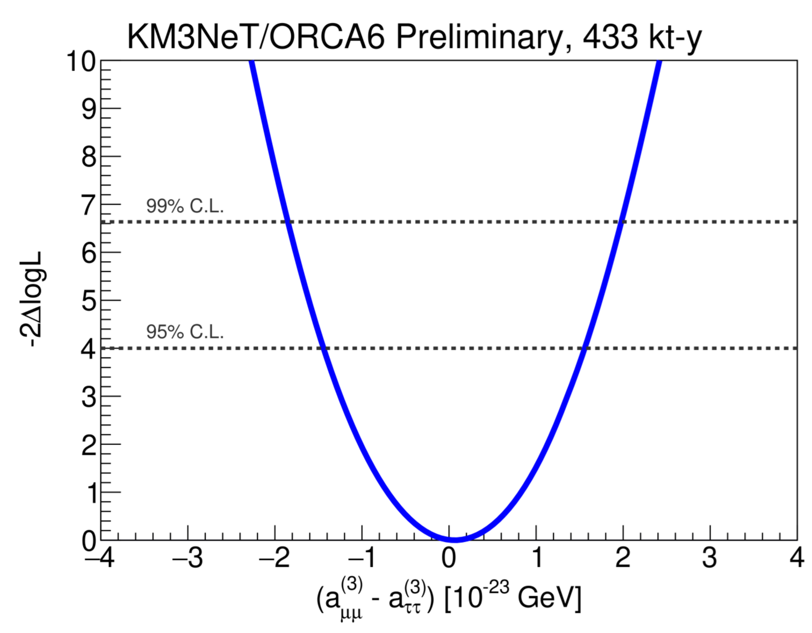
- **KM3NeT/ORCA6**
  - Events are sorted into three different classes: high-purity neutrino-induced muon tracks, low-purity tracks, and showers
  - Boosted decision tree scores determine the class of an event
  - Most events have energies between 2 GeV and 100 GeV
- **ANTARES**
  - Only high-purity track class is used so far
  - Event class determined by set of cuts
  - Random grid search[3] tries out and evaluates 100k cuts



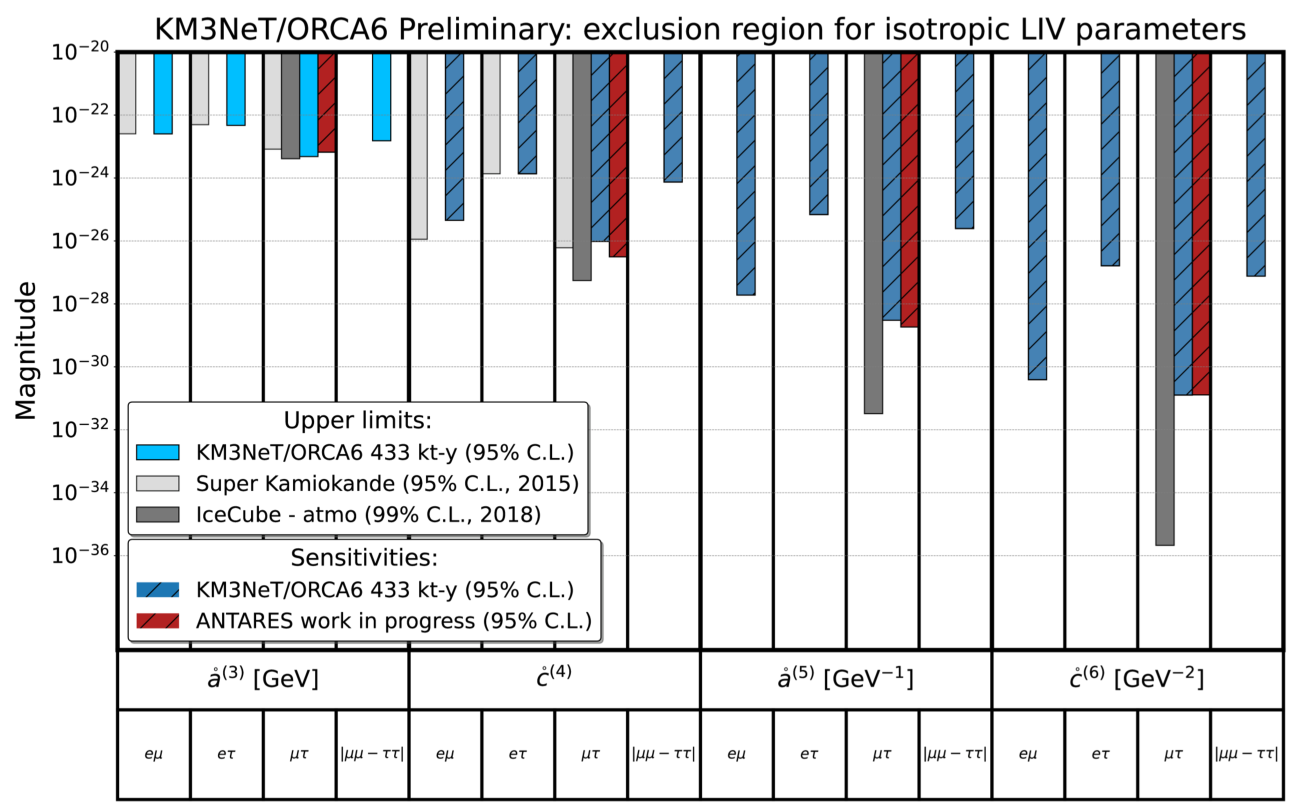

  - Best cuts form Pareto front
  - Color of Pareto front cut indicates $\chi^2$ resulting from fit to LIV model with $\mathring{a}^{(5)}_{\mu\tau} = 2\cdot10^{-29}\,GeV^{-1}$
  - Pareto front cut achieving the highest $\chi^2$ defines high-purity tracks
  - Most events have energies between 100 GeV and 1 TeV

## Results




**We aim to put the first constraints on several LIV coefficients!**




## References


[1]Colladay, Kostelecký (1998): Phys. Rev. D 58, 116002

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