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ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Lorentz and CPT violation search with on-going and future neutrino experiments

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18/7/2023 - Neutrino workshop IFIRSE

CPT and Lorentz Invariance (& their violations)

Standard Model Extension (SME)

Searches with atmospheric neutrinos & neutrino beams

Searches with astrophysical neutrinos

CPT searches via oscillation parameters measurements

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CPT Invariance

CPT: discrete spacetime symmetry

↓

the three independent operations of charge conjugation (C), parity (P), and time reversal (T), if simultaneously performed, would not modify any measurable property of a physical system.

CPT Invariance

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Why testing it?

CPT invariance is based on three pillars: Lorentz invariance, Hamiltonian hermiticity, and locality

↓

1. CPT allows to probe various cornerstones of physics.
2. CP violation contained in the Standard Model appears to be insufficient for a convincing explanation of the observed baryon asymmetry of the Universe: Planck-size CPT violation may generate a significant overabundance of matter.
3. CPT violations predicted in a variety of QG models attempting to unify GR and SM.

Lorentz Invariance (LI)

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Why testing it?

1. LI underlies both SM and GR -> it represents our understanding of the nature of spacetime.

   ↓

   physical phenomena are observed to be the same by all inertial observers.

2. LI violations predicted in a variety of QG models attempting to unify GR and SM.

CPT & LI

Does the violation of one of them imply the violation of the other?

Not necessarily: https://doi.org/10.1016/j.physletb.2011.03.026 “CPT violation does not lead to violation of Lorentz invariance and vice versa”

Abstract

We present a class of interacting nonlocal quantum field theories, in which the *CPT* invariance is violated while the Lorentz invariance is present. This result rules out a previous claim in the literature that the *CPT* violation implies the violation of Lorentz invariance. Furthermore, there exists the reciprocal of this theorem, namely that the violation of Lorentz invariance does not lead to the *CPT* violation, provided that the residual symmetry of Lorentz invariance admits the proper representation theory for the particles. The latter occurs in the case of quantum field theories on a noncommutative space–time, which in place of the broken Lorentz symmetry possesses the twisted Poincaré invariance. With such a *CPT*-violating interaction and the addition of a *C*-violating (e.g., electroweak) interaction, the quantum corrections due to the combined interactions could lead to different properties for the particle and antiparticle, including their masses.

CPT & LI violations

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FAU

How to test it?

- CPT & LIV: by constraining the Standard Model Extension (SME) coefficients.

- CPT: if violated, the sets of oscillation parameters in neutrino and antineutrino may differ.

CPT and Lorentz Invariance (& their violations)

Standard Model Extension (SME)

Searches with atmospheric neutrinos & neutrino beams

Searches with astrophysical neutrinos

CPT searches via oscillation parameters measurements

Lorentz Invariance Violation (LIV)

How to test it?

- The general effective field theory incorporating LIV and CPT violation is called Standard Model Extension (SME):

↓

LIV terms formed by contracting LIV operators, of a given mass dimension, with a priori unknown coefficients.

- Such coefficients can be experimentally constrained.

……. neutrinos are great candidates!

Lorentz Invariance Violation (LIV)

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FAU

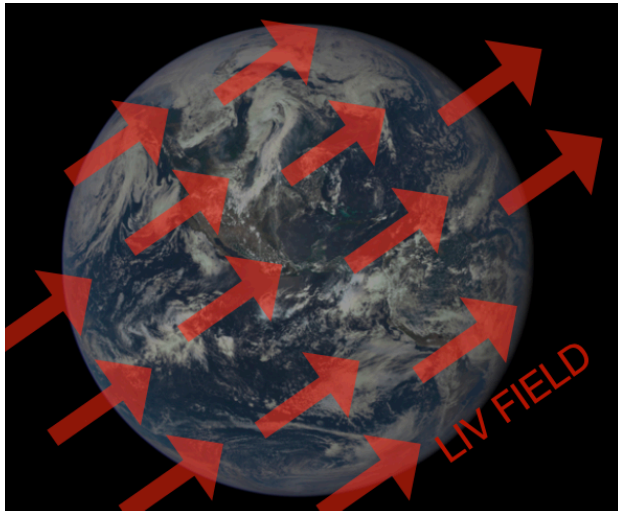
How to test it?

- Many SME-based phenomenological studies with neutrinos focus on the special case of isotropic Lorentz violation (operators that maintain rotation symmetry).

- Models violating rotation symmetry can also be considered: direction-dependent neutrino behavior.

- Several consequences: different results between different terrestrial experiments or for the analysis of experiments involving multiple sources, since the orientation of the neutrino beam or the location of the source relative to the detector can affect neutrino oscillations.

- Rotation-symmetry violation also implies that the Earth daily rotation induces apparent periodic changes of the coefficients which manifest as temporal variations in neutrino oscillations.



LIV with neutrinos

- LIV would affect the evolution of a neutrino system:

$$H = H_0 + H_I + H_{LIV}$$

LIV with neutrinos

- LIV would affect the evolution of a neutrino system:

$$H = H_0 + H_I + H_{LIV}$$

$$H_0 = \frac{1}{2E} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix}$$

LIV with neutrinos

- LIV would affect the evolution of a neutrino system:

$$H = H_0 + H_I + H_{LIV}$$

$$H_I = \pm\sqrt{2}G_F \begin{pmatrix} N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

LIV with neutrinos

- LIV would affect the evolution of a neutrino system:

$$H = H_0 + H_I + H_{LIV}$$

$$H_{LIV} = \begin{pmatrix} \mathring{a}^{(3)}_{ee} & \mathring{a}^{(3)}_{e\mu} & \mathring{a}^{(3)}_{e\tau} \\ \mathring{a}^{(3)*}_{e\mu} & \mathring{a}^{(3)}_{\mu\mu} & \mathring{a}^{(3)}_{\mu\tau} \\ \mathring{a}^{(3)*}_{e\tau} & \mathring{a}^{(3)*}_{\mu\tau} & \mathring{a}^{(3)}_{\tau\tau} \end{pmatrix} - E \begin{pmatrix} \mathring{c}^{(4)}_{ee} & \mathring{c}^{(4)}_{e\mu} & \mathring{c}^{(4)}_{e\tau} \\ \mathring{c}^{(4)*}_{e\mu} & \mathring{c}^{(4)}_{\mu\mu} & \mathring{c}^{(4)}_{\mu\tau} \\ \mathring{c}^{(4)*}_{e\tau} & \mathring{c}^{(4)*}_{\mu\tau} & \mathring{c}^{(4)}_{\tau\tau} \end{pmatrix} + E^2 \mathring{a}^{(5)} - E^3 \mathring{c}^{(6)} + E^4 \mathring{a}^{(7)} - E^5 \mathring{c}^{(8)} + \ldots$$

Isotropic LIV coefficients

- Impact of isotropic LIV coefficients in neutrino oscillations:

Table 1 LIV coefficients: for a comparison, the oscillation effect of H_0 is L/E.

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	$\propto LE^3$
$\mathring{a}^{(7)}$	GeV^{-3}	odd	$\propto LE^4$
$\mathring{c}^{(8)}$	GeV^{-4}	even	$\propto LE^5$

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LIV searches with atmospheric neutrinos

- Atmospheric neutrinos are good candidates for LIV searches:
  - Long baselines (up to Earth diameter)
  - High energies (up to TeV)
- Neutrino detectors can be used, such as KM3NeT, IceCube, ANTARES, Super-Kamiokande, DUNE, …

LIV searches with atmospheric neutrinos

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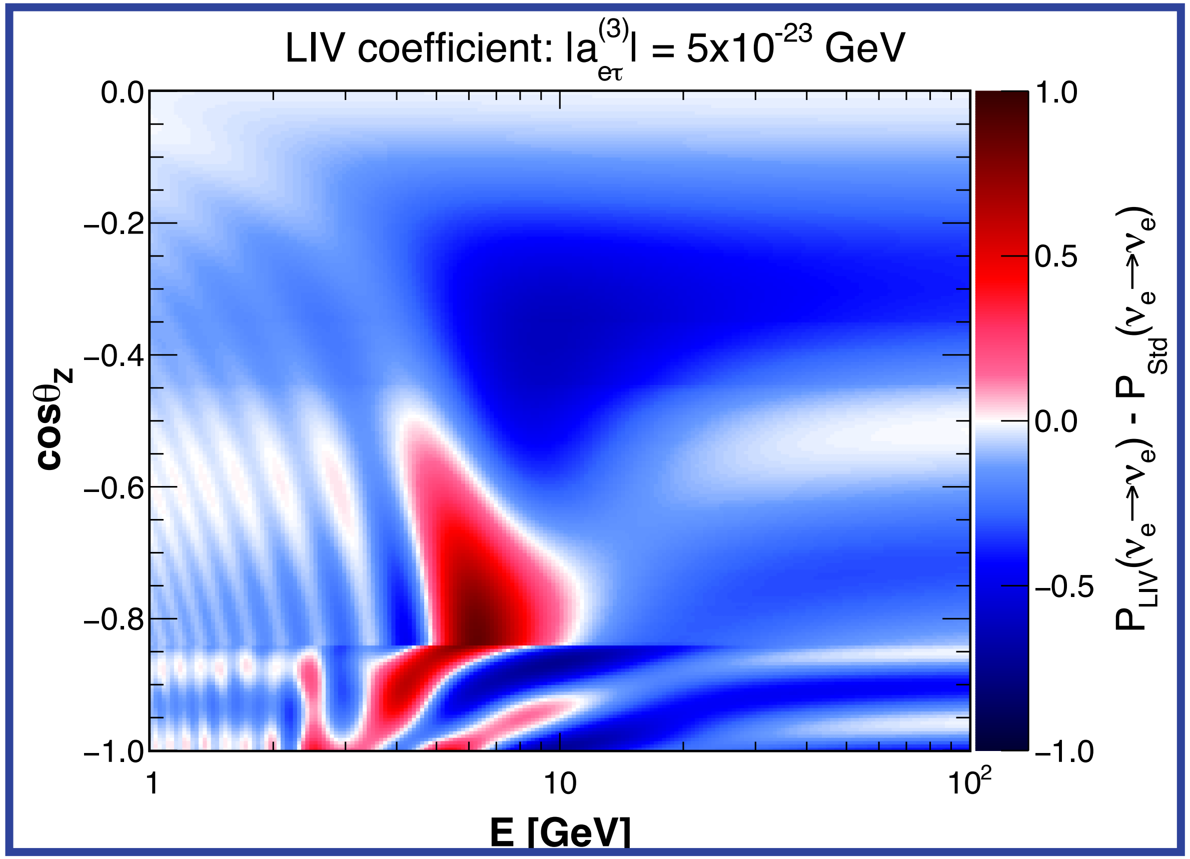

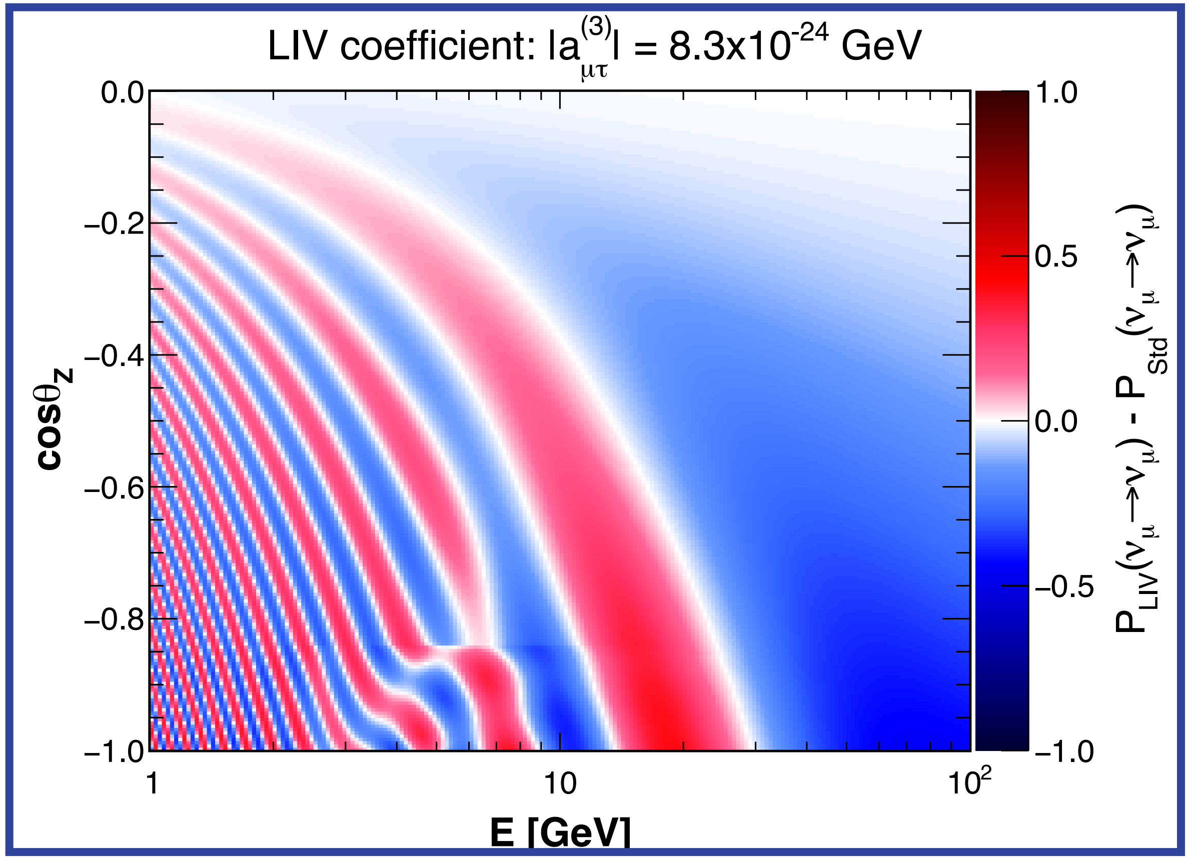

Super-Kamiokande

Isotropic LIV searches with Super Kamiokande

- Analysis from 2015 (*Phys. Rev. D* ***91****, 052003*): use of 4438 days of lifetime (~12 years).

		Live-days FC/PC	Live-days UP-μ	Photo-coverage (%)
SK-I	1996–2001	1,489	1,646	40
SK-II	2002–2005	799	828	19
SK-III	2006–2008	518	635	40
SK-IV	2008–2013	1,632	1,632	40

Isotropic LIV searches with Super Kamiokande

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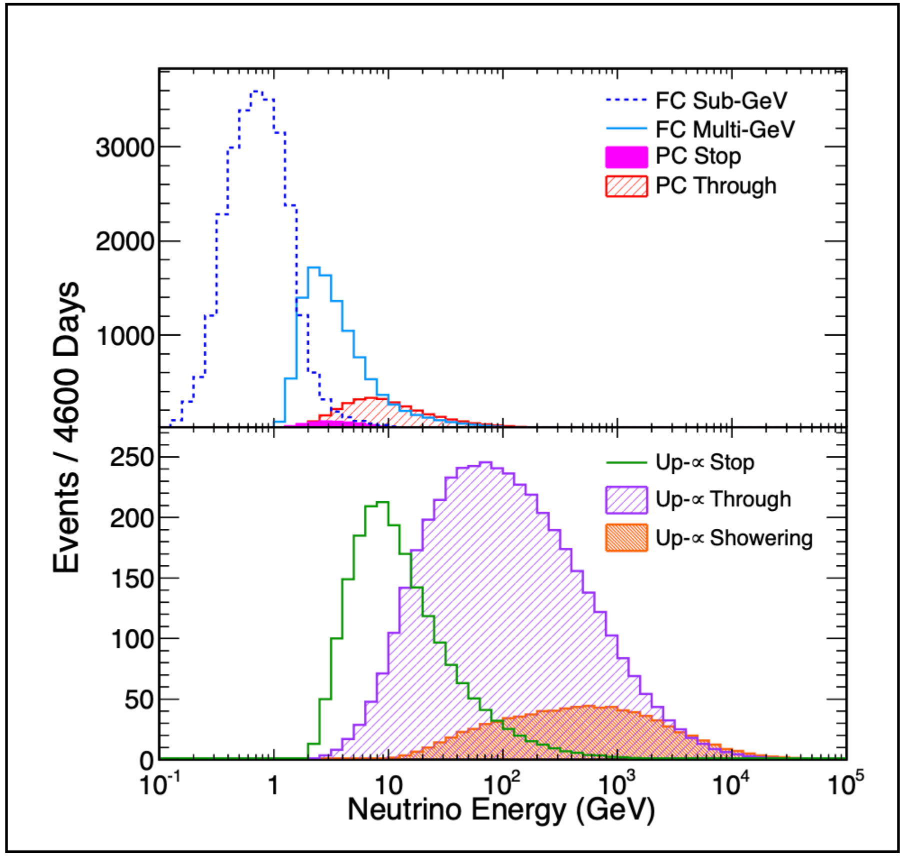
- Three event samples (UP-μ): 1) energies peaked at ~10 GeV; 2) energies peaked at ~100 GeV; energies peaked at ~1 TeV.

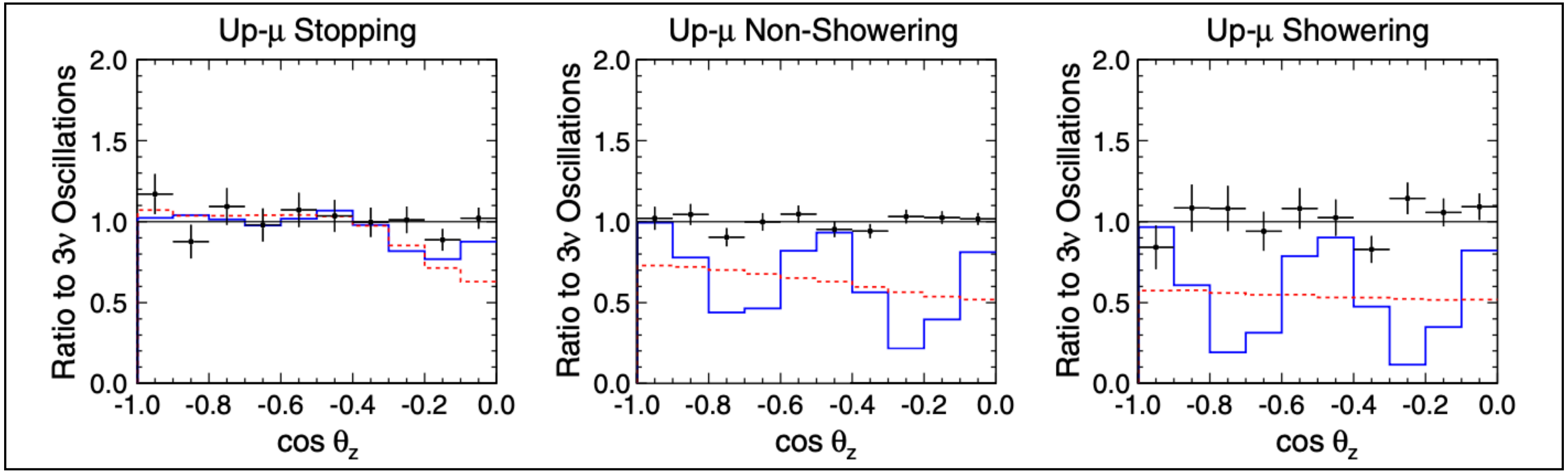


*Phys. Rev. D **91**, 052019*

Isotropic LIV searches with Super Kamiokande

- Main result: no LIV observation.

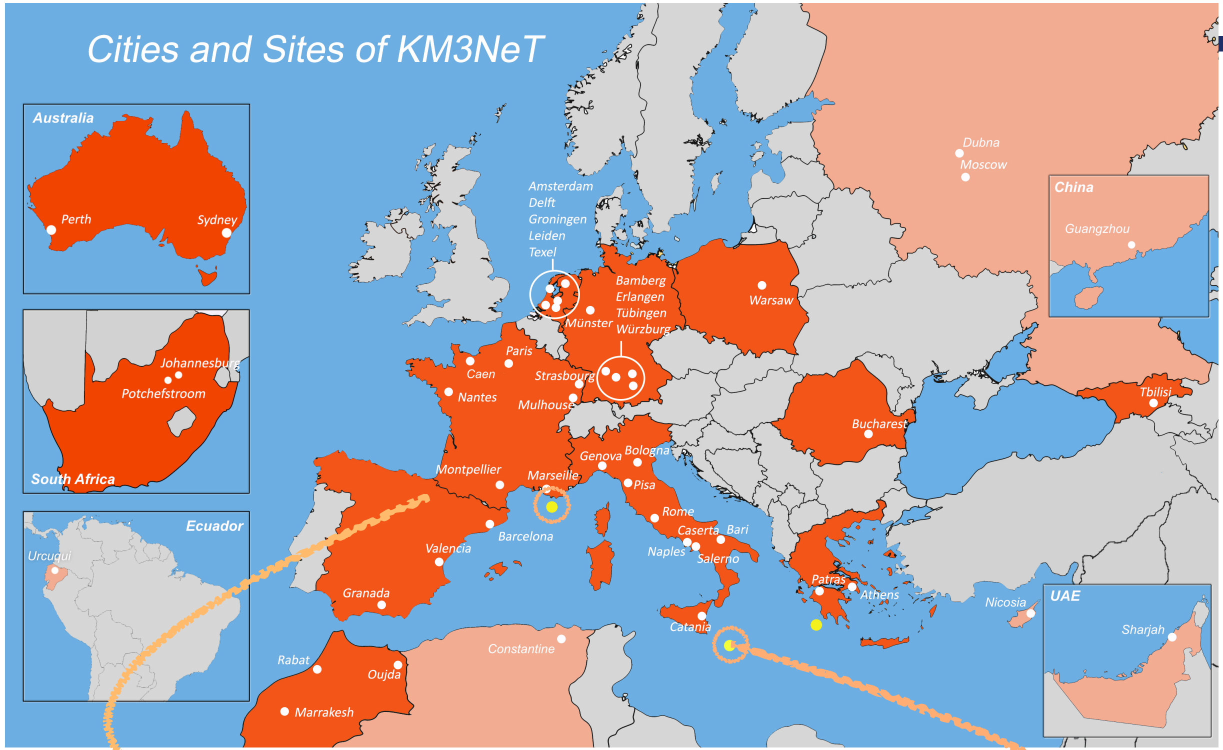
- Constraints on dimension 3-4 coefficients of the SME.

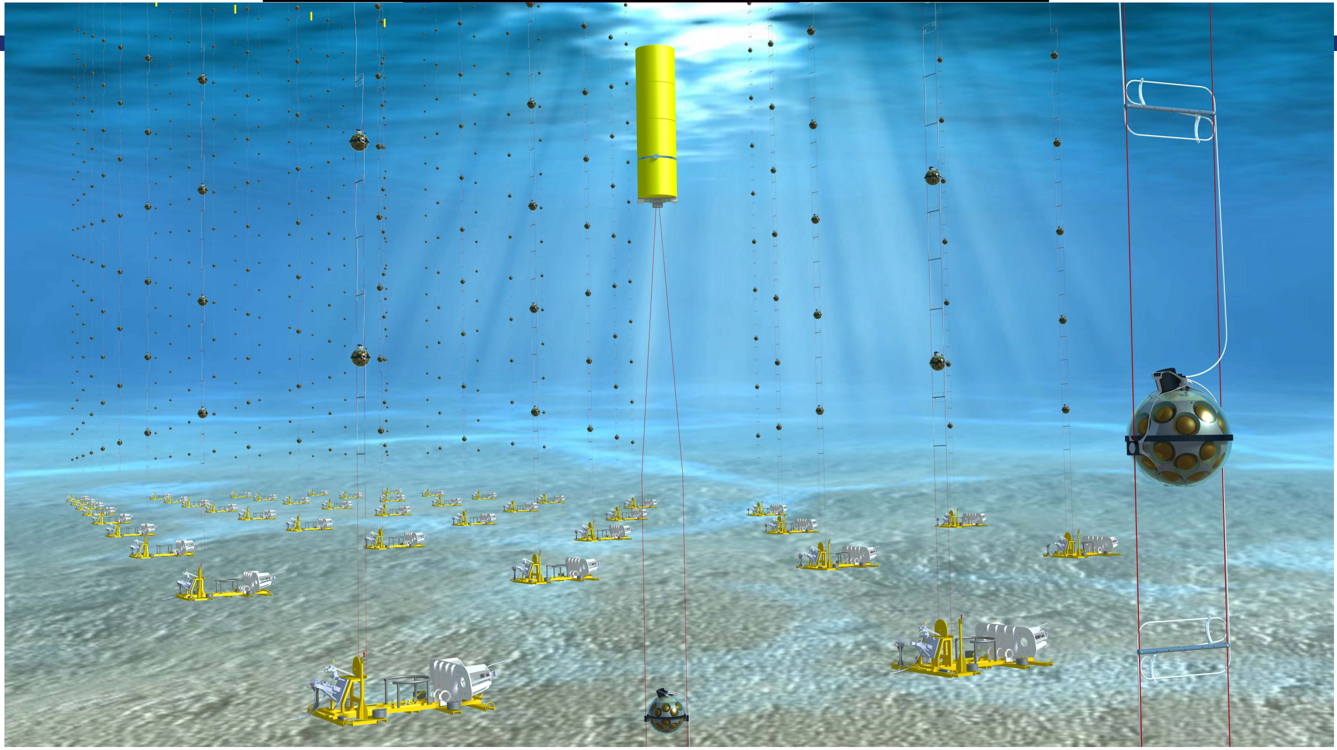


KM3NeT

KM3NeT

18 DOMS with 31 3” PMTs FOR EACH LINE

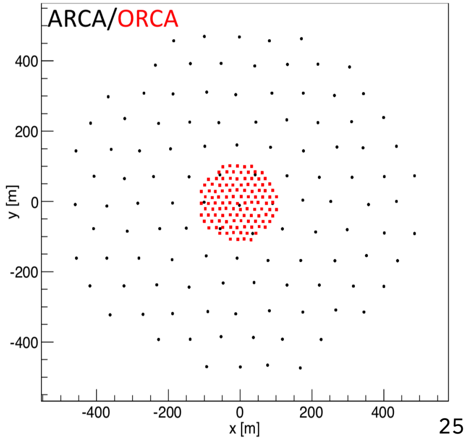




ORCA:
1 dense Building Block
optimised for intermediate energies (1-100 GeV)

ARCA:
2 sparse Building Blocks optimised for high energies (>1 TEV)

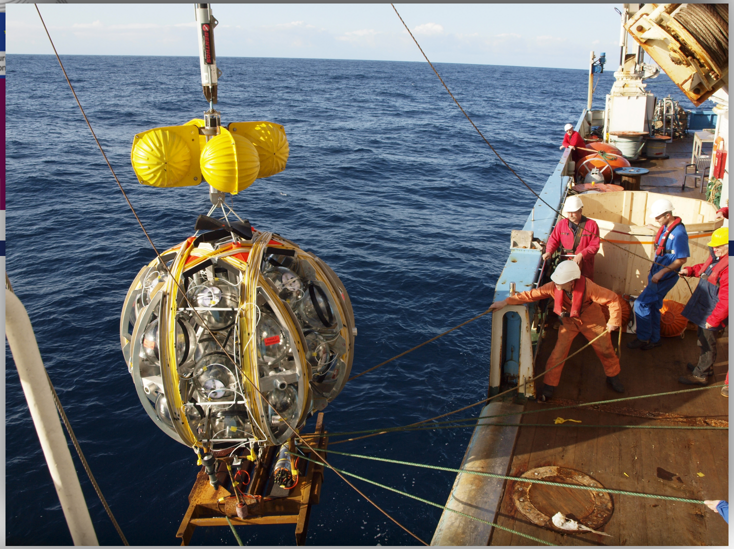
	ORCA	ARCA
String spacing	20 m	90 m
Vertical spacing	9 m	36 m
Depth	2470 m	3500 m

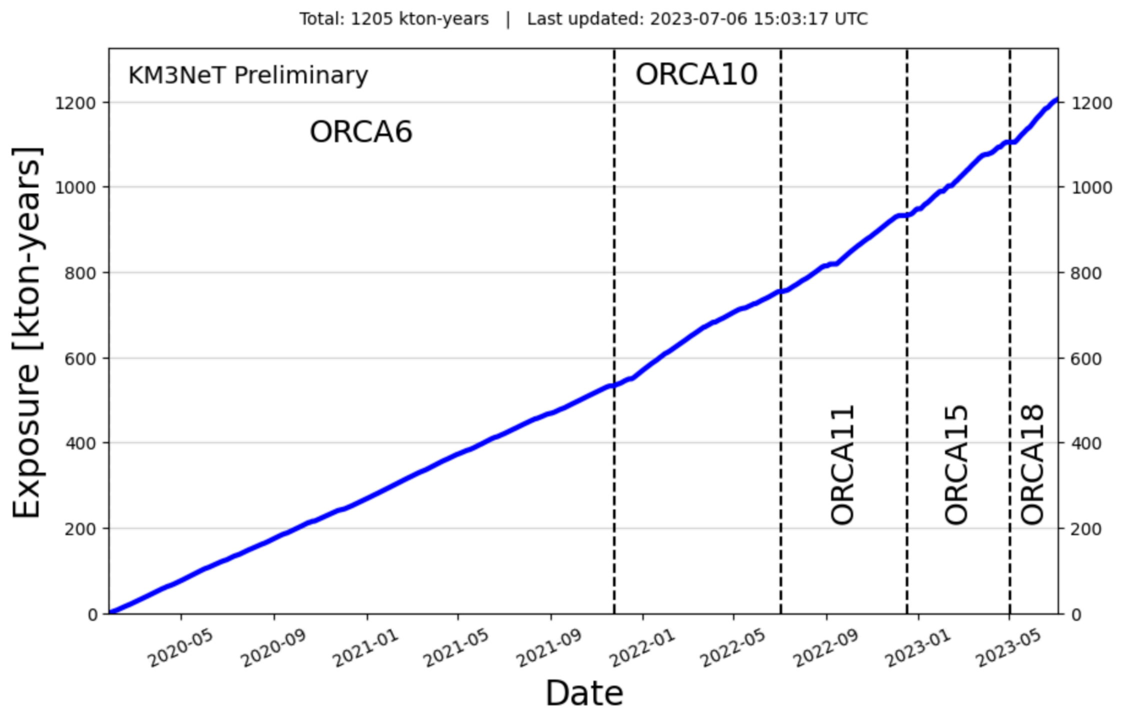


KM3NeT

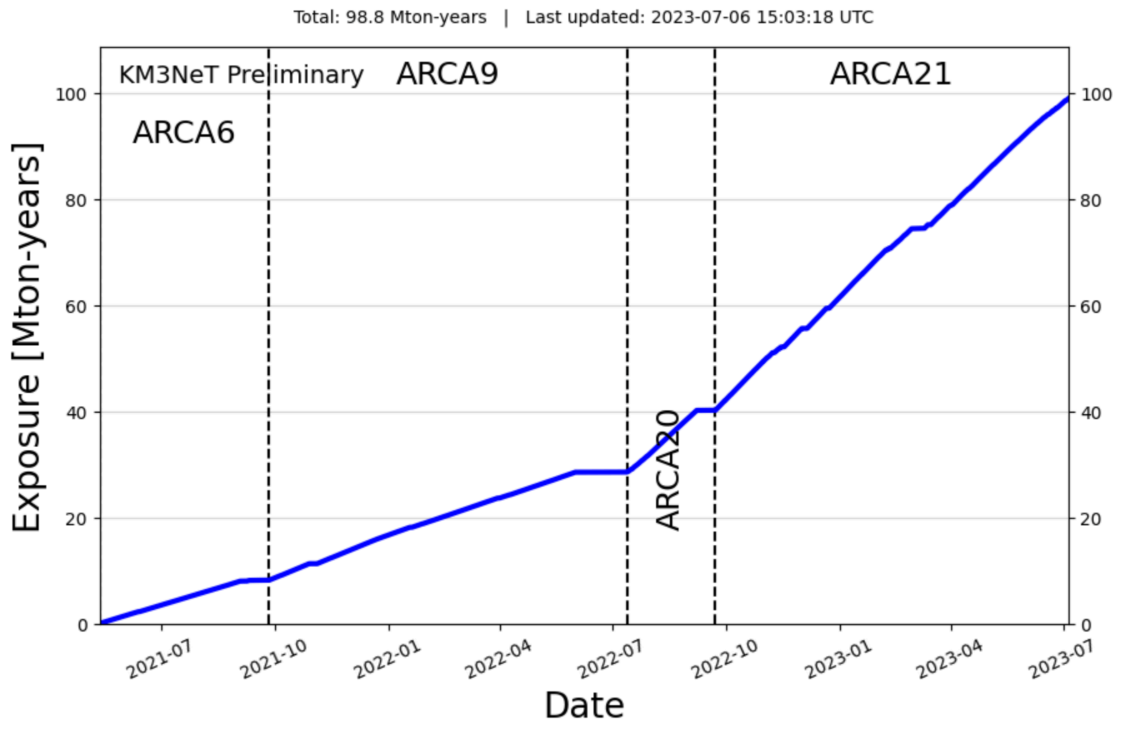
Modular deployment.

18 ORCA-DUs and 21 ARCA-DUs currently taking data!





Cumulative instrumented exposures of ORCA in kton-years.

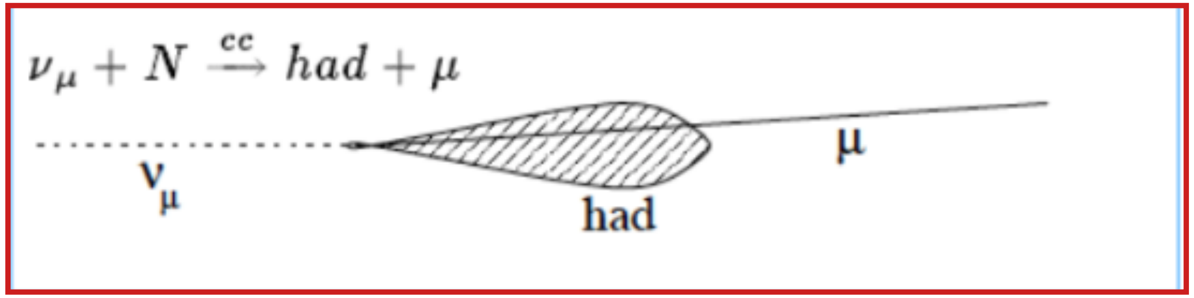


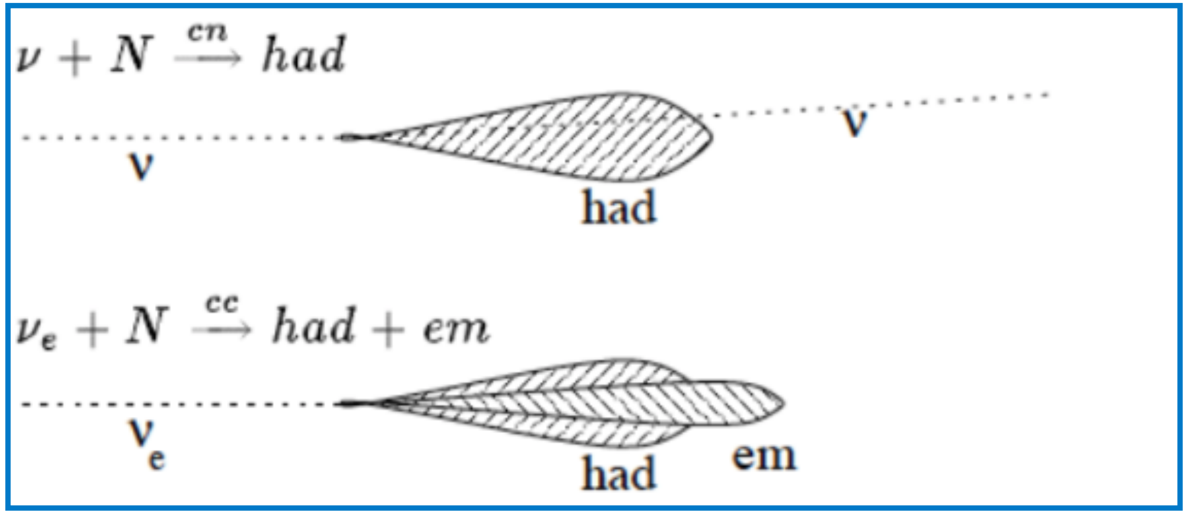
Cumulative instrumented exposures of ARCA in Mton-years.

Event topologies in the GeV energy range

Tracks: ν_μ^{CC}, ν_τ^{CC} ($\tau \rightarrow \mu$)

Showers: ν_e^{CC}, ν^{NC}, ν_τ^{CC} ($\tau \rightarrow \mu$)



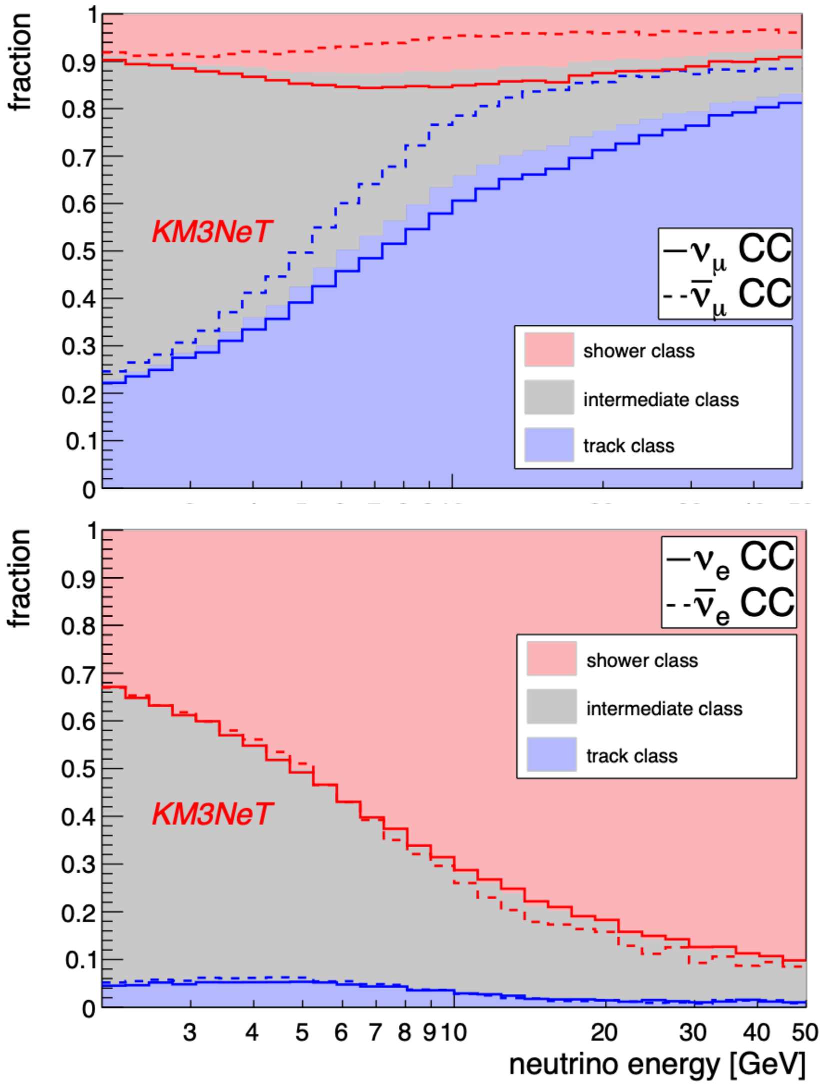


L ~ 4 m x E/GeV

L ~ 0.9 + 0.36 ln(E/GeV) m

LIV searches with ORCA115

- Event selection: Random Decision Forest classifier with binary decision trees trained to classify:
  - neutrinos vs atmospheric muons
  - neutrinos vs noise
  - tracks vs showers: **3** topologies based on track_score **p**:
    - Tracks (track preselection & p > 0.7),
    - Middles (shower preselection & 0.3 < p ≤ 0.7),
    - Showers (shower preselection & p ≤ 0.3).



LIV searches with ORCA115

- ORCA115 sensitivity evaluation with:
  - Events up to 20 GeV.
  - Assuming NO and NuFit 5.2 parameters values (with SK):

	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}	$\Delta m^2_{21}(\mathrm{eV}^2)$	$\Delta m^2_{31}(\mathrm{eV}^2)$
NO	0.303	0.451	0.02225	232°	7.41×10^{-5}	2.507×10^{-3}

LIV searches with ORCA115

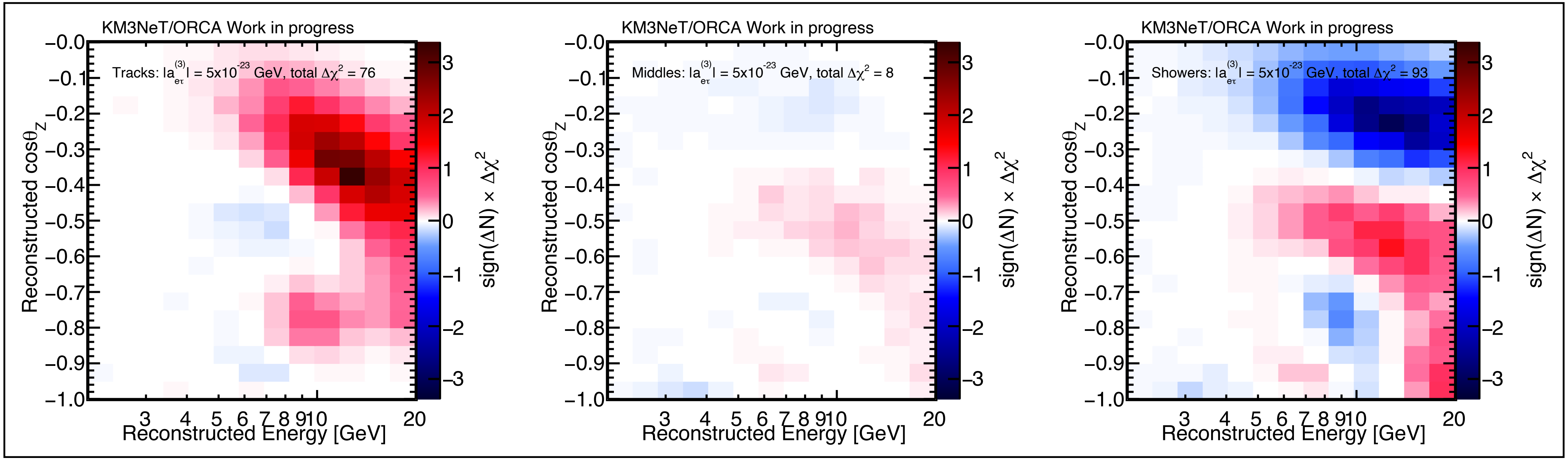
- Fitted parameters and their priors:

Parameter	Gaussian Prior ($\mu \pm \sigma$)
$\nu_e/\bar{\nu}_e$	0 ± 0.07
$\nu_\mu/\bar{\nu}_\mu$	0 ± 0.05
ν_e/ν_μ	0 ± 0.02
NC Scale	No prior
Energy Scale	1 ± 0.05
Energy Slope	No prior
Zenith Angle Slope	0 ± 0.02
Track Normalisation	No Prior
Intermediate Normalisation	No Prior
Shower Normalisation	No Prior
Δm^2_{31}	No prior
θ_{13}	$\theta_{13} \pm 0.13^\circ$
θ_{23}	No prior

LIV searches with ORCA115

- LIV impact on events distribution:

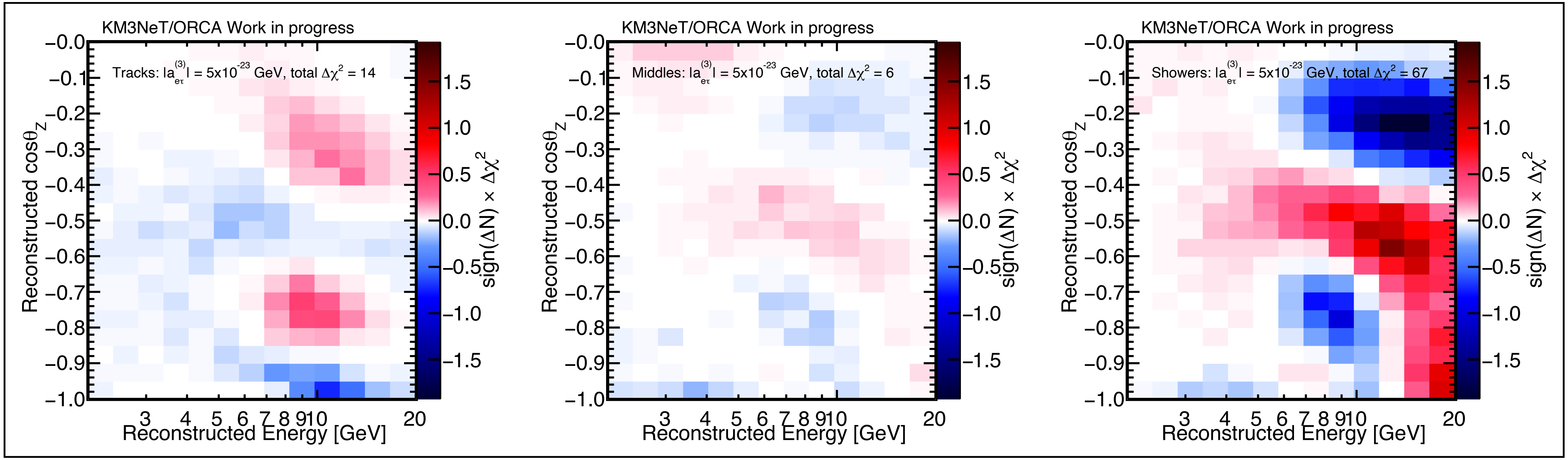
$$\Delta\chi^2 = \frac{(N_{\rm LIV} - N_{\rm Std})|N_{\rm LIV} - N_{\rm Std}|}{N_{\rm LIV}},$$



LIV searches with ORCA115

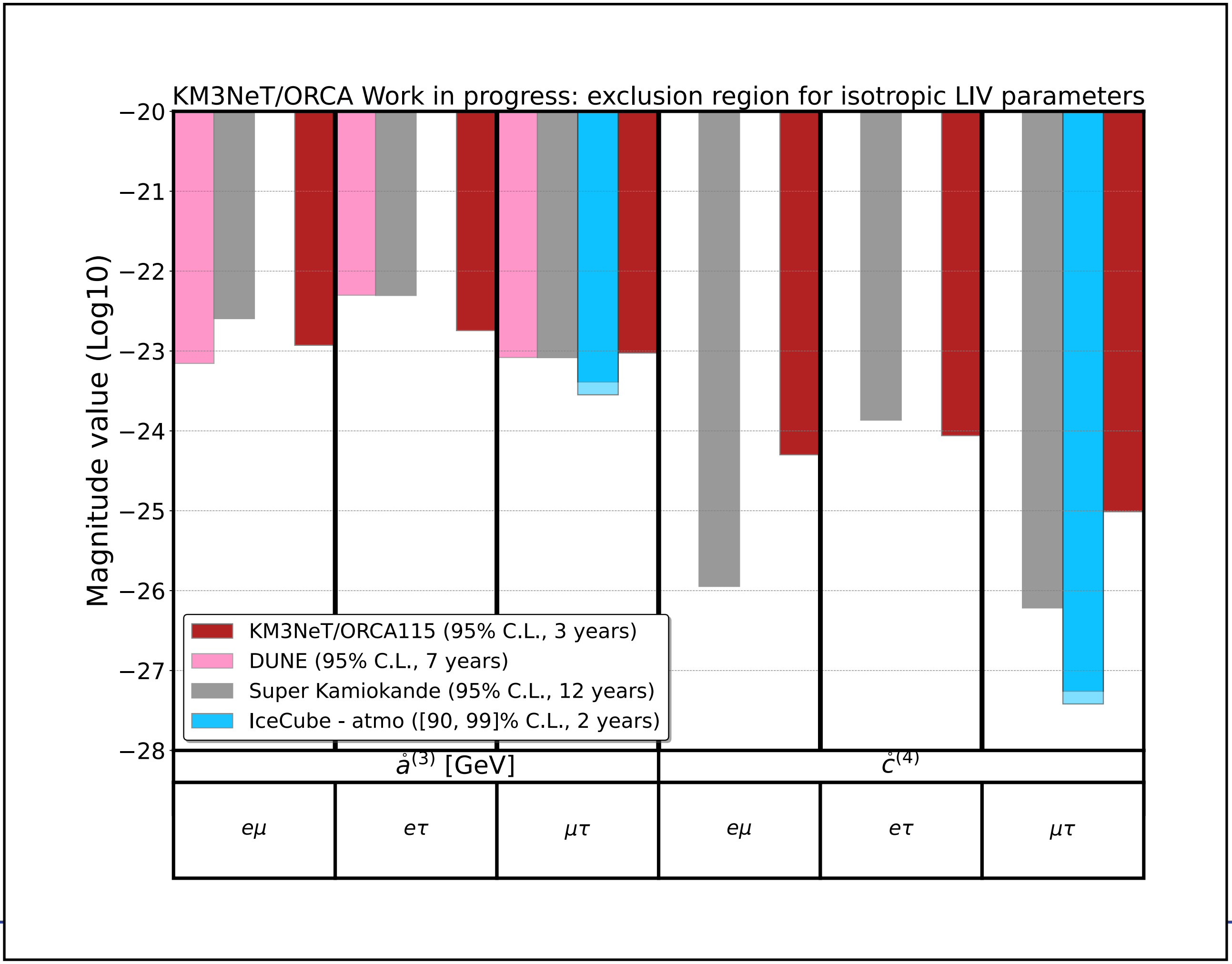
- LIV impact accounting for systematics:

$$\Delta\chi^2 = \frac{(N_{\rm LIV} - N_{\rm Std})|N_{\rm LIV} - N_{\rm Std}|}{N_{\rm LIV}},$$



LIV searches with ORCA115

- ORCA115 sensitivity for 3 years of assumed data taking



DUNE: Physics Letters B 788, 308-315 (2019)

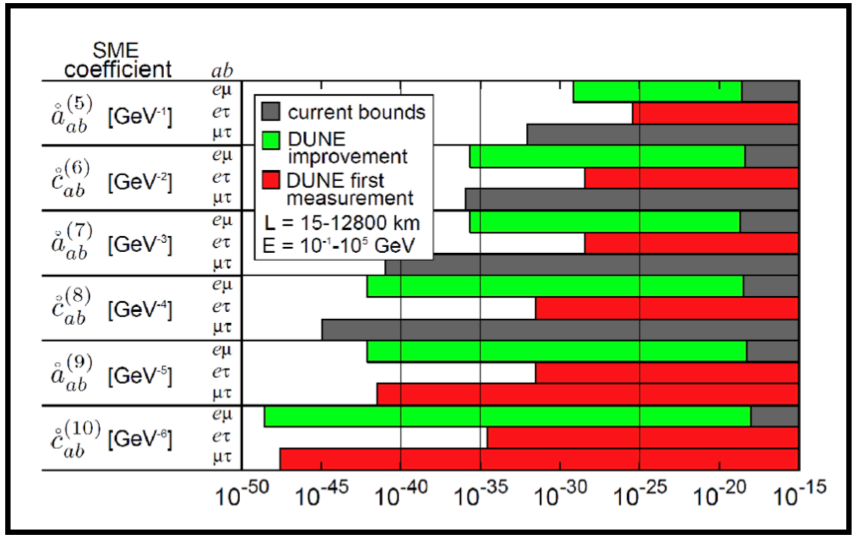
SK: Phys. Rev. D 91, 052003 (2015)

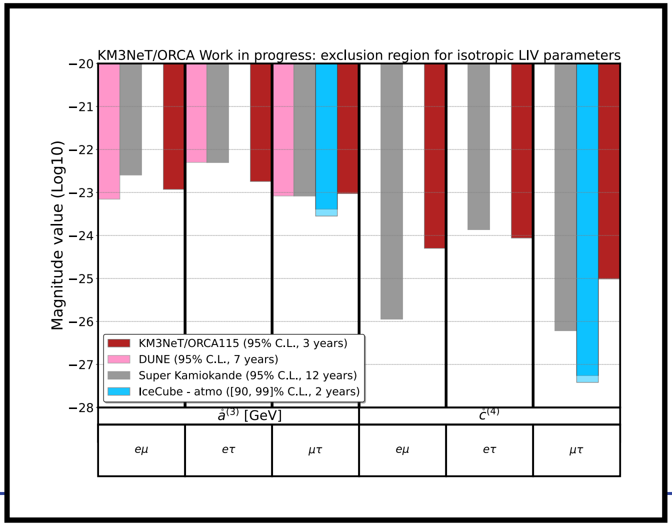
IC-atmo: *Nat. Phys* **14**, 961–966 (2018)

DUNE

LIV searches with DUNE

- Two parallel works performed for DUNE:
- One with atmospheric neutrinos (*European Physical Journal C 81 (2021) 322*): sensitivity for higher dimension coefficients.
- One with neutrino beam (*Physics Letters B 788, 308-315 (2019)*): sensitivity for dimension 3-4 coefficients.



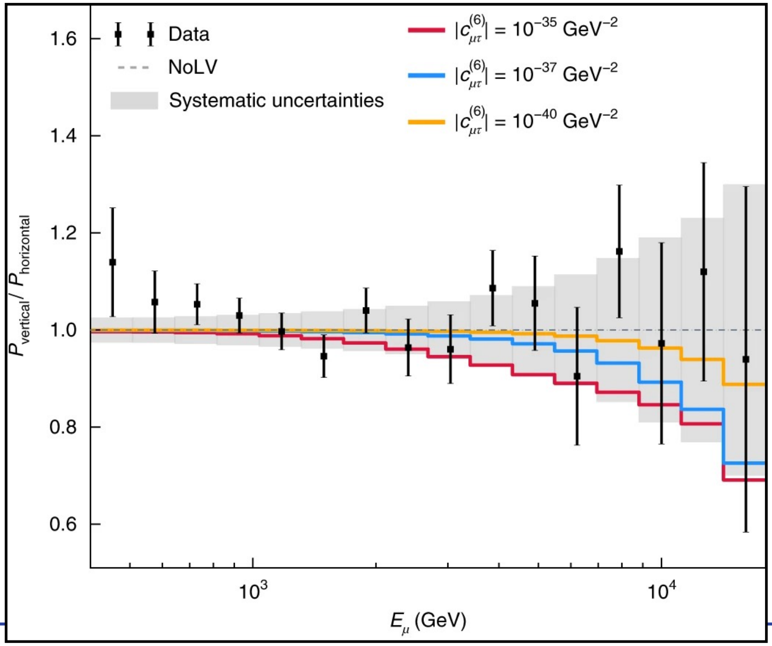


IceCube

LIV searches with IceCube

- Best constraints with atmospheric neutrinos come from IceCube analysis (*Nat. Phys* ***14**, 961–966 (2018)*).

- High energy events: 400 GeV - 18 TeV.



LIV searches with IceCube

- Best LIV constraints with atmospheric neutrinos come from IceCube analysis (*Nat. Phys* ***14**, 961–966 (2018)*).
- High energy events: 400 GeV - 18 TeV.
- Main result: NO LIV OBSERVATION -> strongest upper limits using atmospheric neutrinos.
- However, for higher dimension coefficients, astrophysical neutrinos play a leading role.

CPT and Lorentz Invariance (& their violations)

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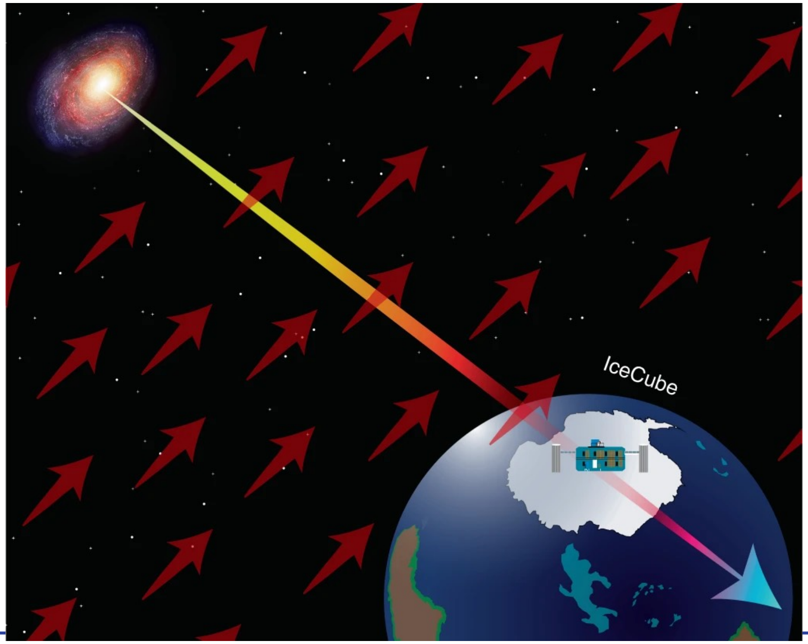
LIV searches with IceCube

- Best LIV constraints come from IceCube analysis with astrophysical neutrinos (*Nat. Phys.* **18**, 1287–1292 (2022)).

- Very high energy events: 60 TeV - 2 PeV.



LIV searches with IceCube

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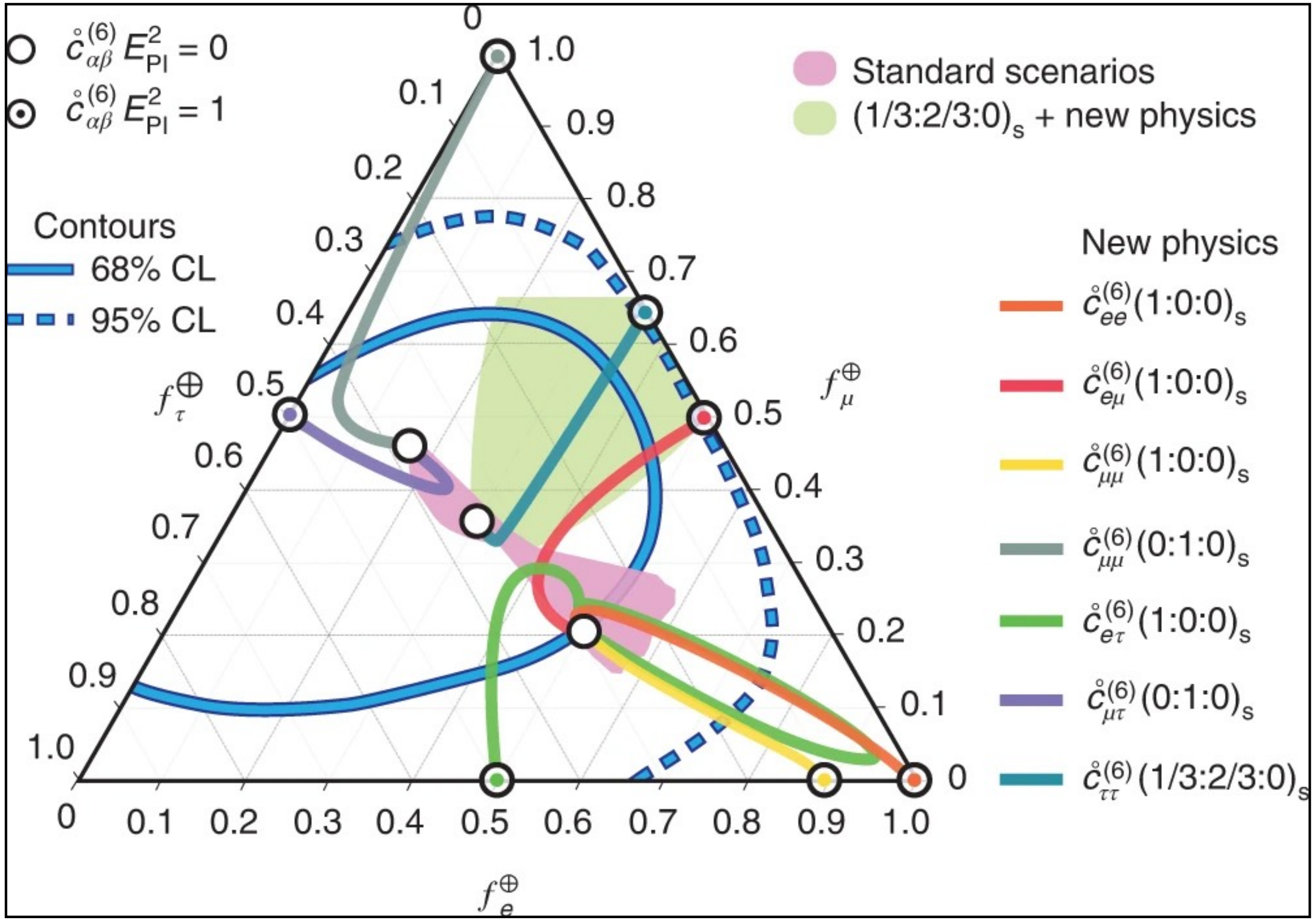
- Very high energy events: 60 TeV - 2 PeV.
- Observable: measured flavour ratio.



LIV searches with IceCube

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- Observable: measured flavour ratio.
- Main result: NO LIV OBSERVATION -> strongest upper limits in the neutrino sector.
- However, results depend on the knowledge of the initial flavour composition at the source.

LIV searches with IceCube

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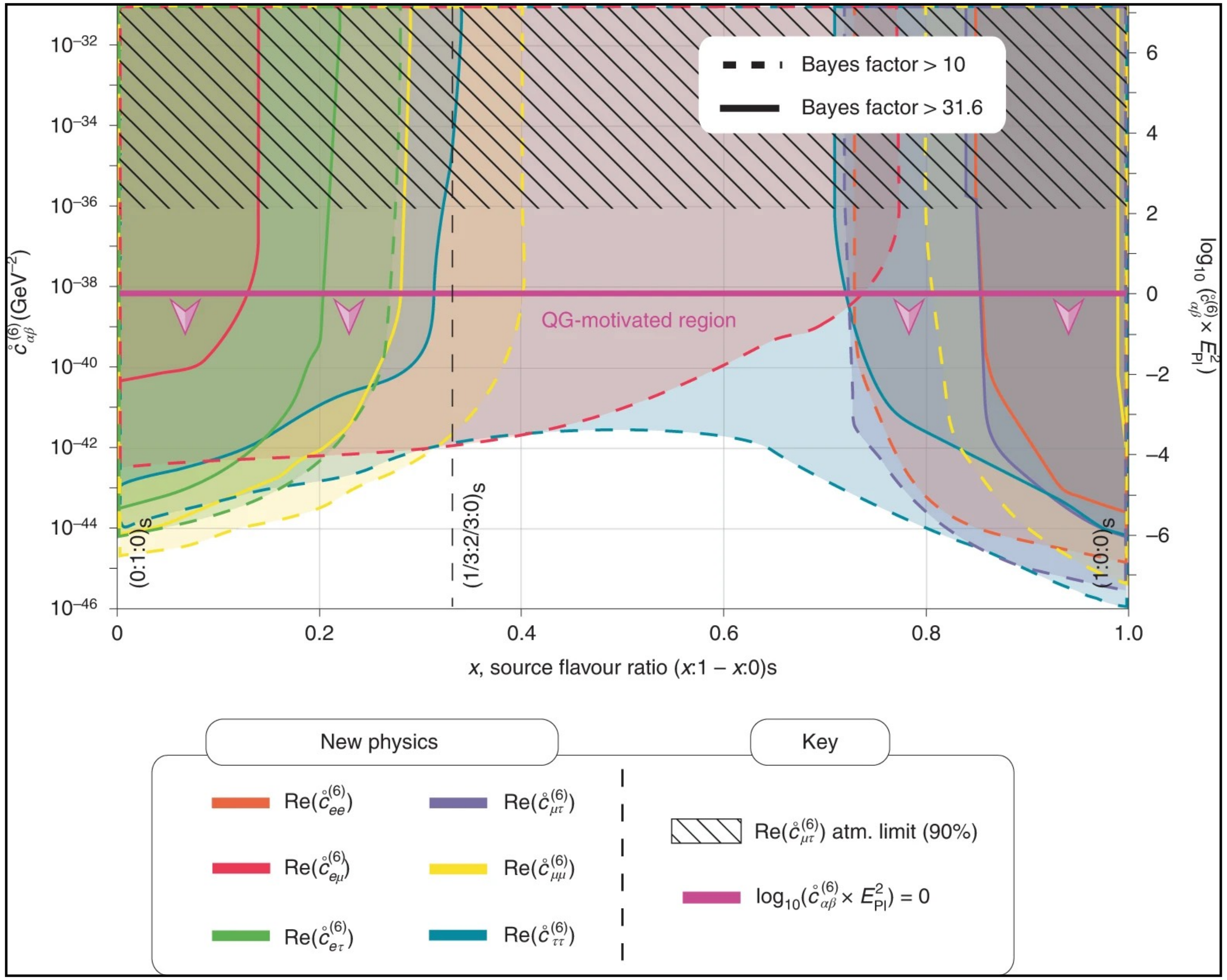

LIV with atmo/astro/beam neutrinos

- Astrophysical neutrino constraints depend on the source flavour ratio model.

- Atmospheric neutrinos & neutrino beams represent a complementary probe for LIV.

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CPT violation via oscillation params

- *Phys. Rev. D* ***107****, 016013*: under CPT symmetry

$$P_{\nu_\alpha \to \nu_\beta} \xrightarrow{\text{CPT}} P_{\overline{\nu}_\beta \to \overline{\nu}_\alpha} = P_{\nu_\alpha \to \nu_\beta}$$
$$= f(\theta_{12},\ \theta_{13},\ \theta_{23},\ \delta_{\text{CP}},\ \Delta m^2_{21},\ \Delta m^2_{31}).$$

- If CPT is violated:

$$P_{\nu_\alpha \to \nu_\beta} = f(\theta_{12},\ \theta_{13},\ \theta_{23},\ \delta_{\text{CP}},\ \Delta m^2_{21},\ \Delta m^2_{31}),\ \neq\ P_{\overline{\nu}_\beta \to \overline{\nu}_\alpha} = f(\overline{\theta}_{12},\ \overline{\theta}_{13},\ \overline{\theta}_{23},\ \overline{\delta}_{\text{CP}},\ \Delta \overline{m}^2_{21},\ \Delta \overline{m}^2_{31}),$$

- Experiments with the atmospheric neutrino and accelerator-based neutrino sources can precisely measure the $(\theta_{23},\ \overline{\theta}_{23},\ \Delta m^2_{31},\ \Delta \overline{m}^2_{31})$ parameters.

CPT violation via oscillation params

- *Phys. Rev. D **107**, 016013*: synergy between T2K & NOvA & JUNO.

- A-LBL experiments use the highly intense beam of the al-most pure muon neutrinos ν_μ and muon anti-neutrinos $\bar{\nu}_\mu$ via disappearance.

$$\mathcal{A}^{\rm CPT}_{\mu\mu} = P_{\nu_\mu\to\nu_\mu} - P_{\bar{\nu}_\mu\to\bar{\nu}_\mu}$$

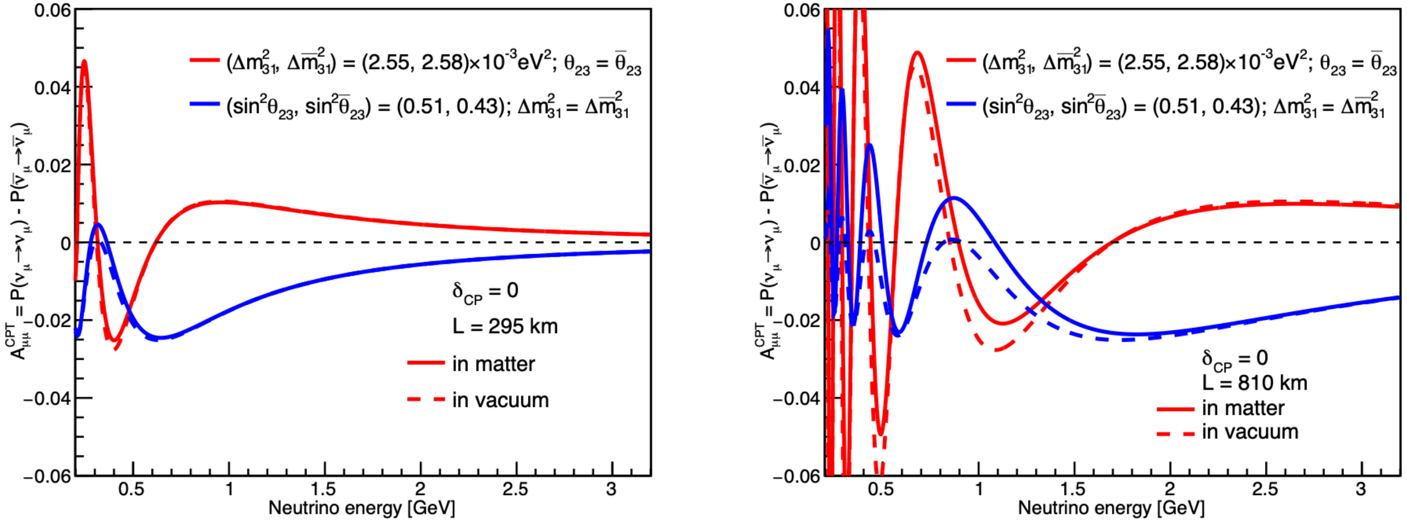

FIG. 1: CPT asymmetries in *disappearance* channels for T2K baseline L = 295 km (left) and NOνA baseline L = 810 km (right). The differences in solid lines and dashed lines indicate extrinsic CPT effects caused by matter.

CPT violation via oscillation params

- *Phys. Rev. D* ***107**, 016013*: synergy between T2K & NOvA & JUNO.

- The primary driving parameters are $(\theta_{23},\ \overline{\theta}_{23},\ \Delta m^2_{31},\ \Delta\overline{m}^2_{31})$

- Analysis expected by 2028.

	3σ C. L. upper limits	
Experiments	$\lvert\delta_{\nu\overline{\nu}}(\Delta m^2_{31})\rvert$	$\lvert\delta_{\nu\overline{\nu}}(\sin^2\theta_{23})\rvert$
T2K-II	$2.0 \times 10^{-4}\ \mathrm{eV}^2$	0.14
T2K-II+NOνA-II	$1.2 \times 10^{-4}\ \mathrm{eV}^2$	0.10
T2K-II+NOνA-II+JUNO	$5.3 \times 10^{-5}\ \mathrm{eV}^2$	0.10

Current bound derived from global fit:

$2.5 \times 10^{-4}\mathrm{eV}^2$

Summary

- Neutrinos are a powerful probe for CPT & LI violations.
- Both can be probed by considering the SME.
- CPT can also be probed by precisely measuring neutrino/antineutrino oscillation parameters.
- Atmospheric neutrinos & neutrino beams are complementary candidates to cosmic neutrinos for probing such effects.
- How can we improve current analyses?
    - Increasing the statistics.
    - Extending current isotropic LIV analyses with sidereal ones.

In this respect, European Union has founded the Marie Curie grant QGRANT (ID 101068013) with the goal of performing a global LIV analysis with KM3NeT+ANTARES+IceCube data (isotropic + sidereal)… stay tuned!