Friedrich-Alexander-Universität
Erlangen-Nürnberg

Marie Skłodowska-Curie Actions
Postdoctoral Fellowships

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Lorentz Invariance Violation with KM3NeT/ORCA115

Alba Domi* on behalf of the KM3NeT Collaboration

*ECAP-FAU, Erlangen, Germany (*alba.domi@fau.de*)

11/7/2023 - COST CA18108 Fourth Annual Conference - Rijeka

Lorentz Invariance (LI)

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.

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)

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

Marie Skłodowska-Curie Actions
Postdoctoral Fellowships

- 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:

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

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

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:

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

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

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.

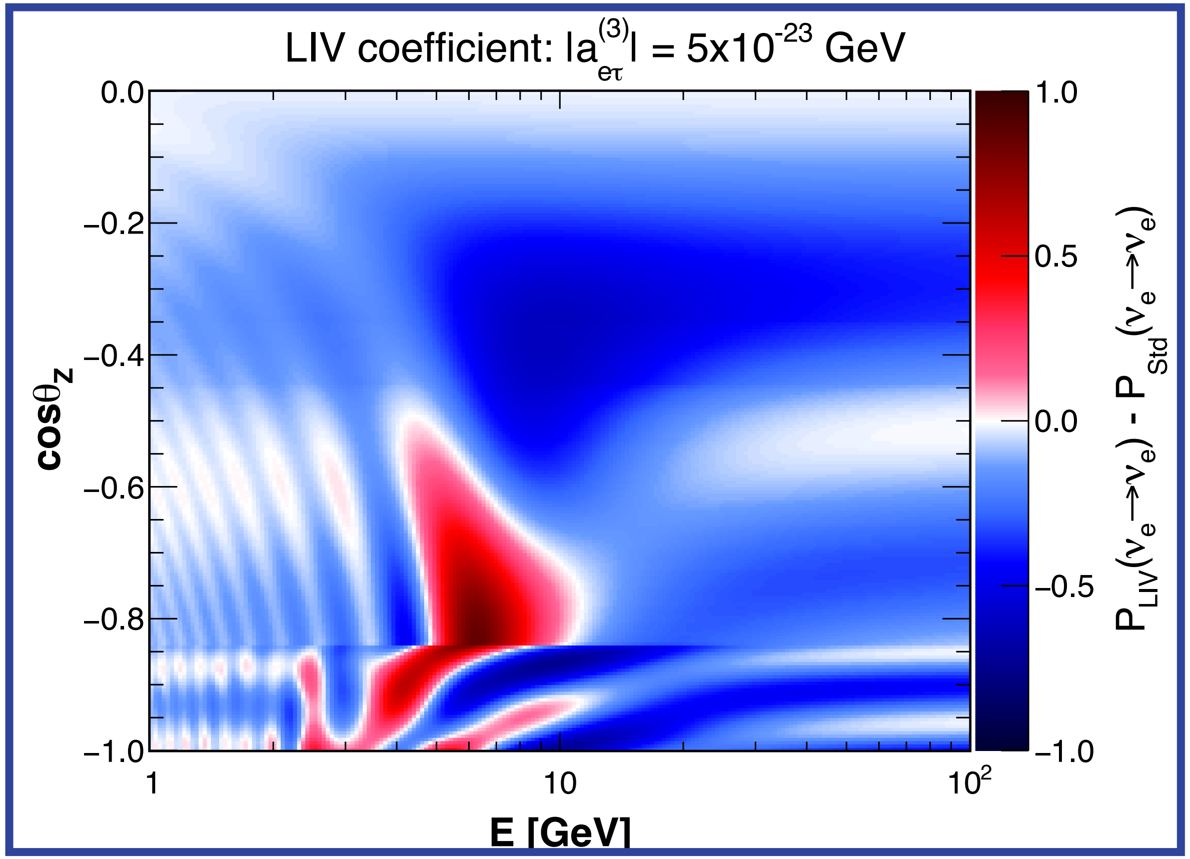
Coefficient	Unit	CPT	Oscillation effect
$\mathring{a}^{(3)}$	GeV	odd	$\propto L$
$\mathring{c}^{(4)}$	-	even	$\propto LE$
$\mathring{a}^{(5)}$	GeV^{-1}	odd	$\propto LE^2$
$\mathring{c}^{(6)}$	GeV^{-2}	even	$\propto LE^3$
$\mathring{a}^{(7)}$	GeV^{-3}	odd	$\propto LE^4$
$\mathring{c}^{(8)}$	GeV^{-4}	even	$\propto LE^5$

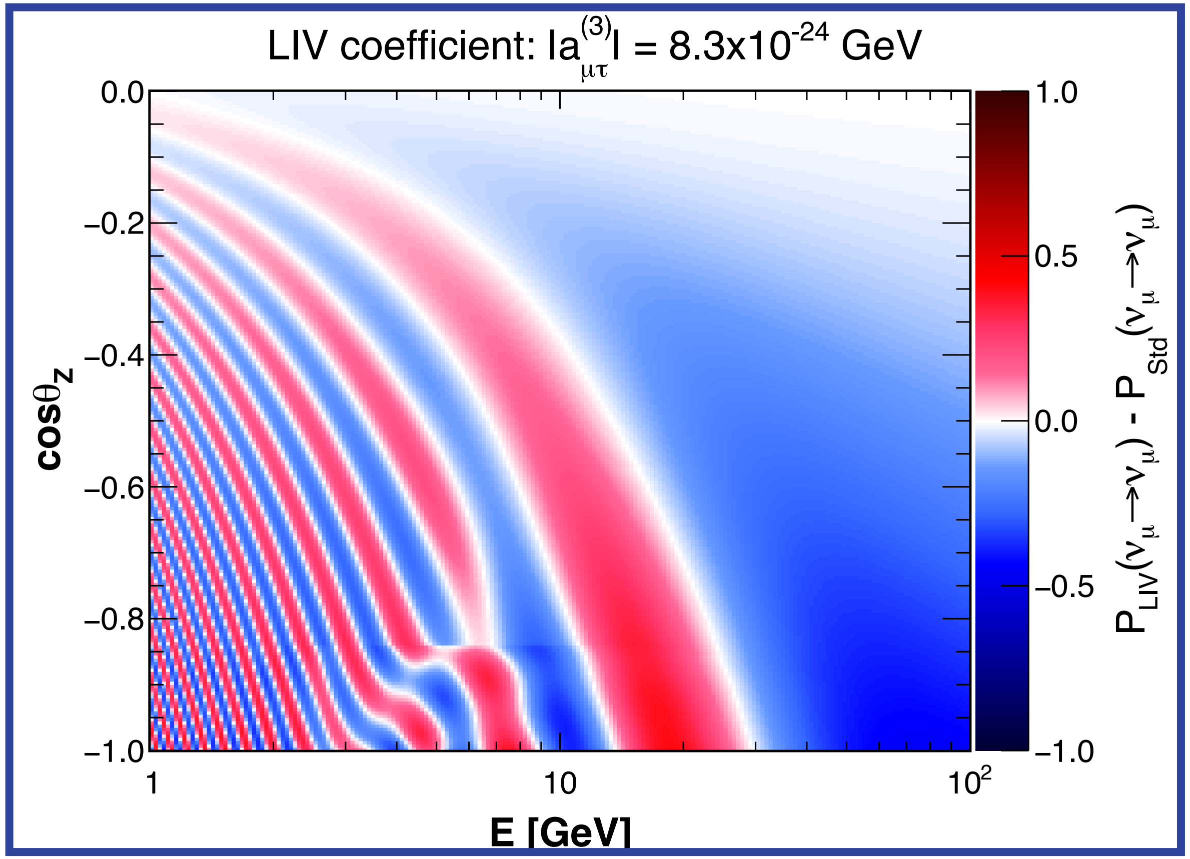
LIV searches with atmospheric neutrinos

Marie Skłodowska-Curie Actions
Postdoctoral Fellowships

- 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, …

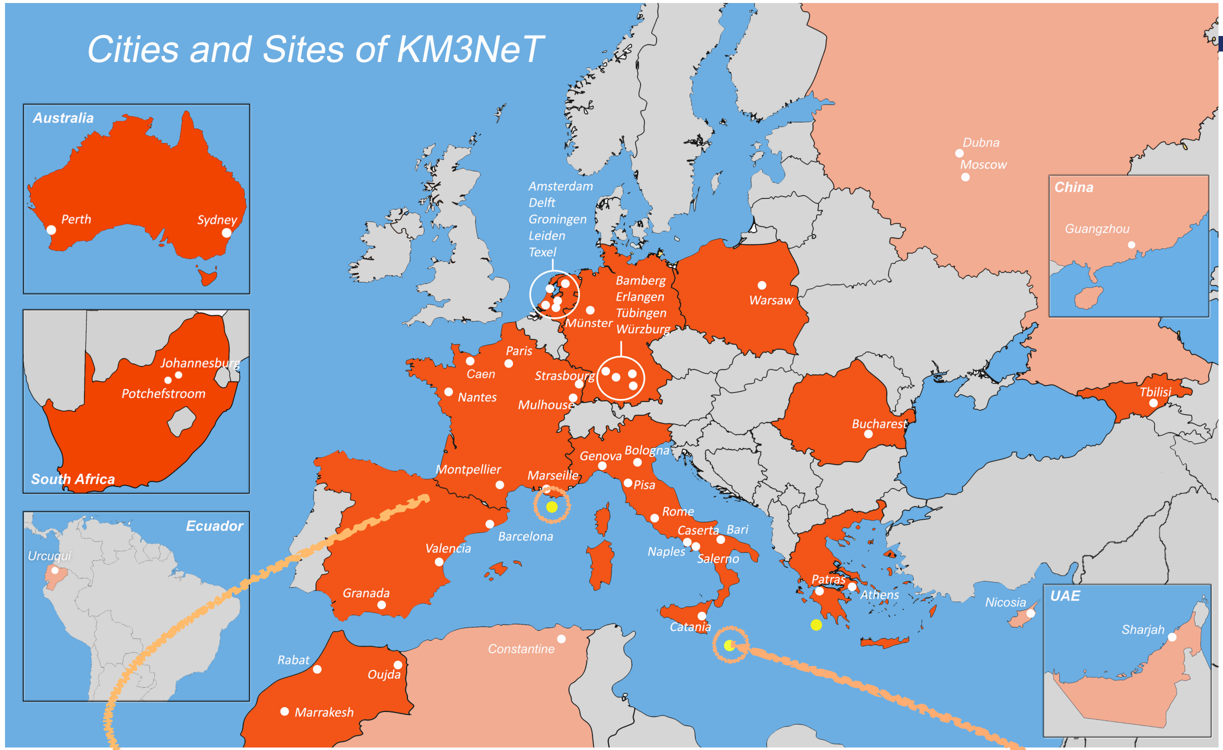
LIV searches with atmospheric neutrinos

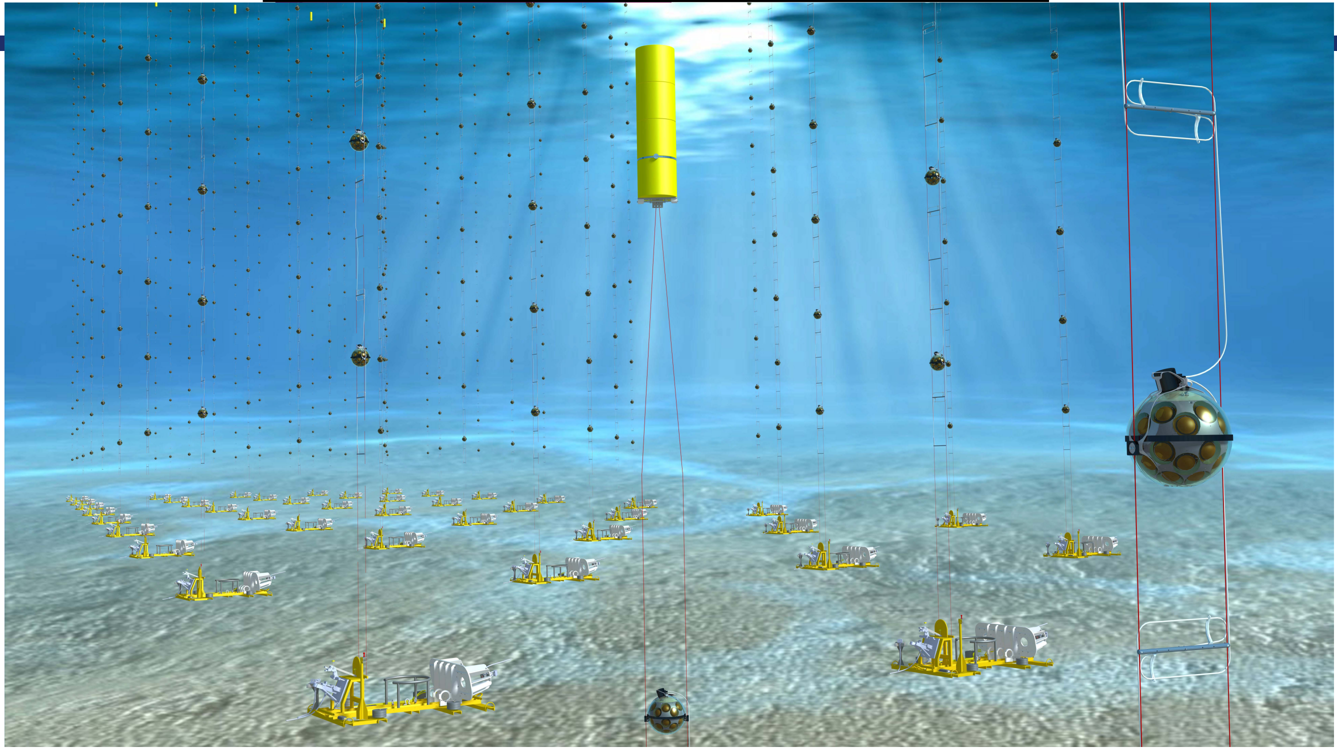




KM3NeT

18 DOMS with 31 3" PMTs FOR EACH LINE

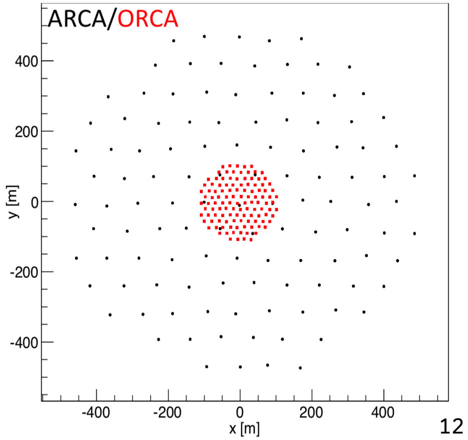




ORCA:
1 dense Building Block
optimised for intermediate energies (1-100 GeV)

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

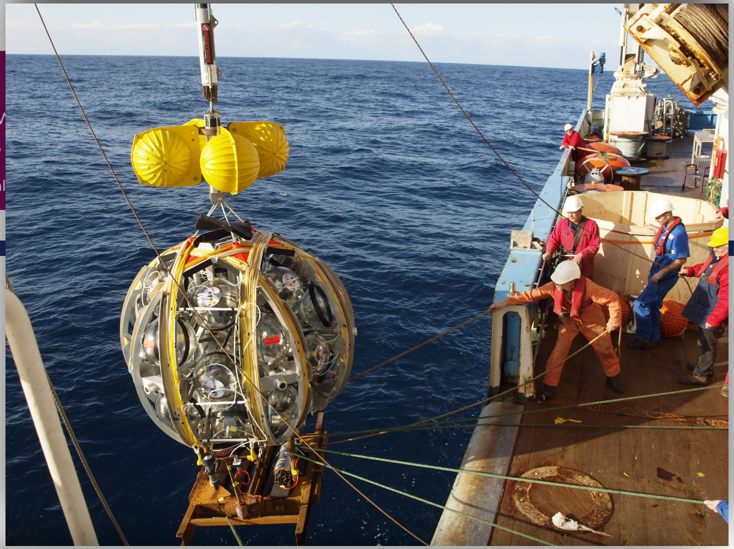
	ORCA	ARCA
String spacing	20 m	90 m
Vertical spacing	9 m	36 m
Depth	2470 m	3500 m

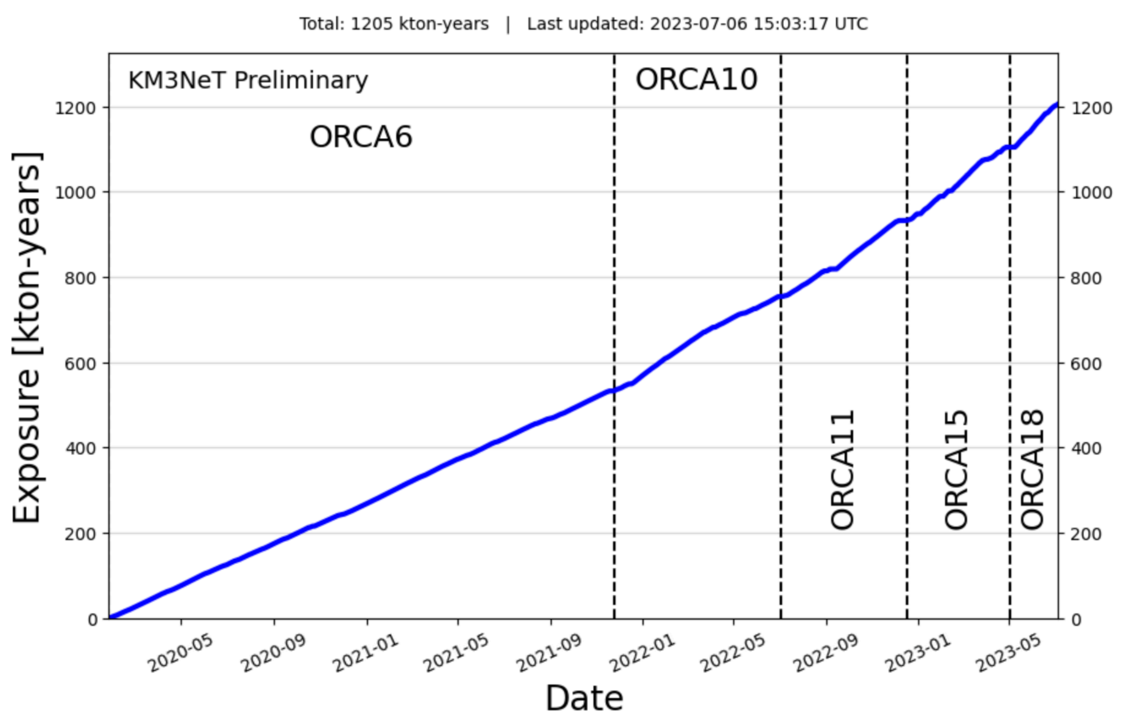


KM3NeT

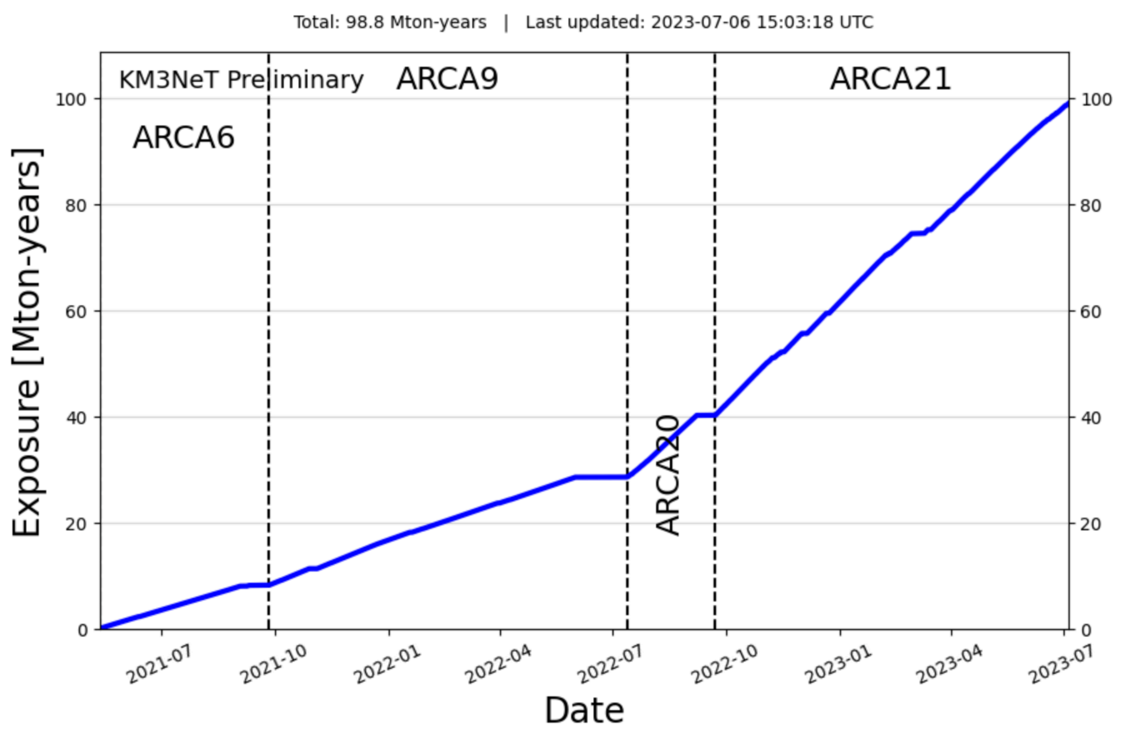
Modular deployment.

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





Cumulative instrumented exposures of ORCA in kton-years.

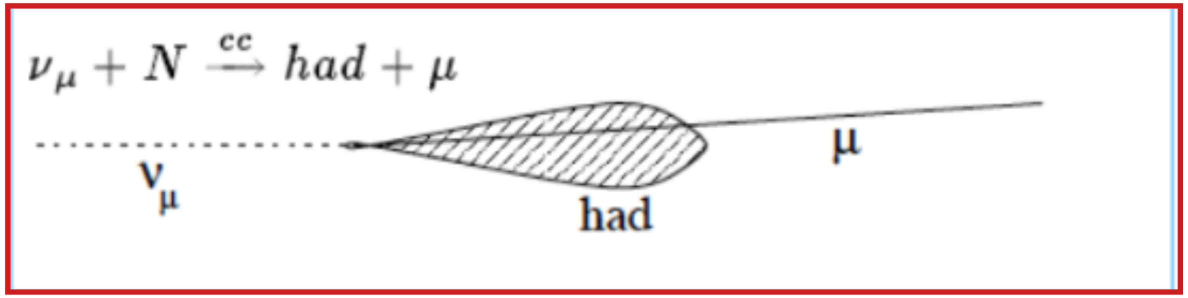


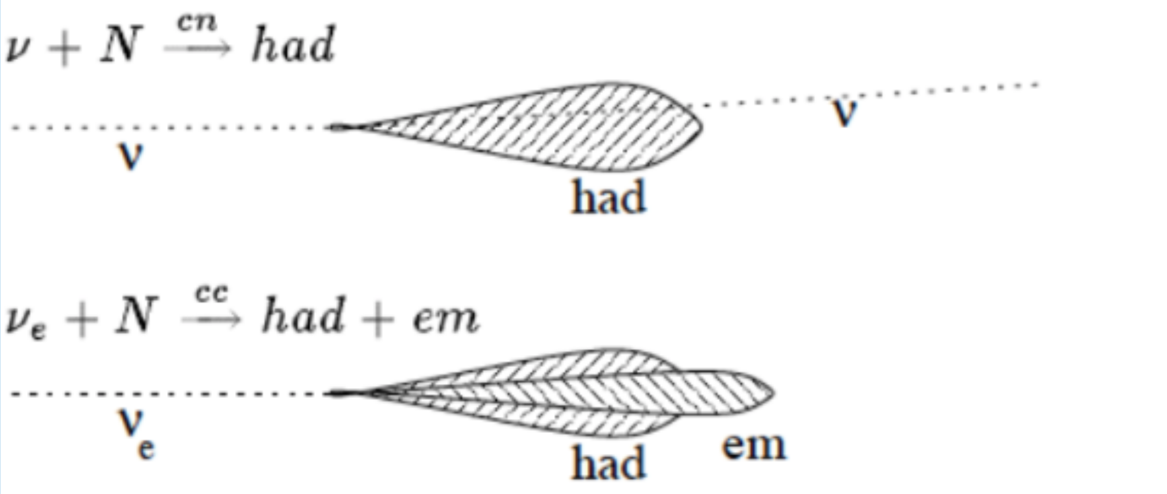
Cumulative instrumented exposures of ARCA in Mton-years.

Event topologies

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

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



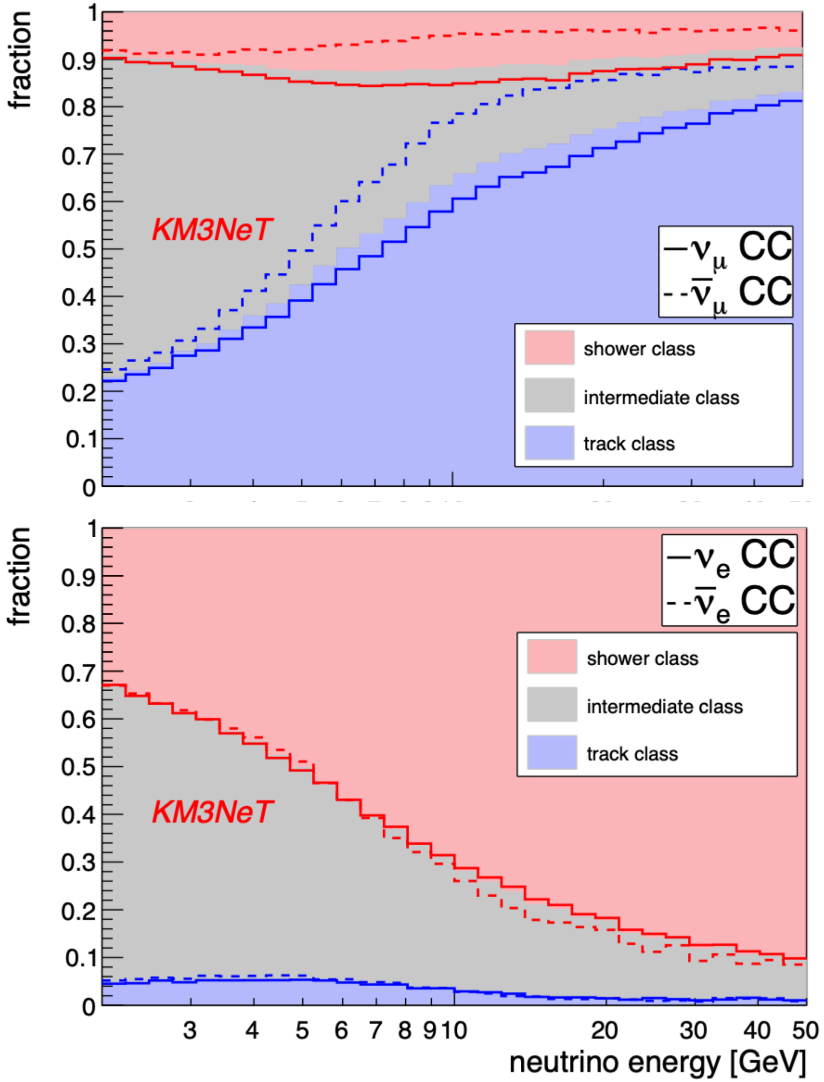


L ~ 4 m x E/GeV

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

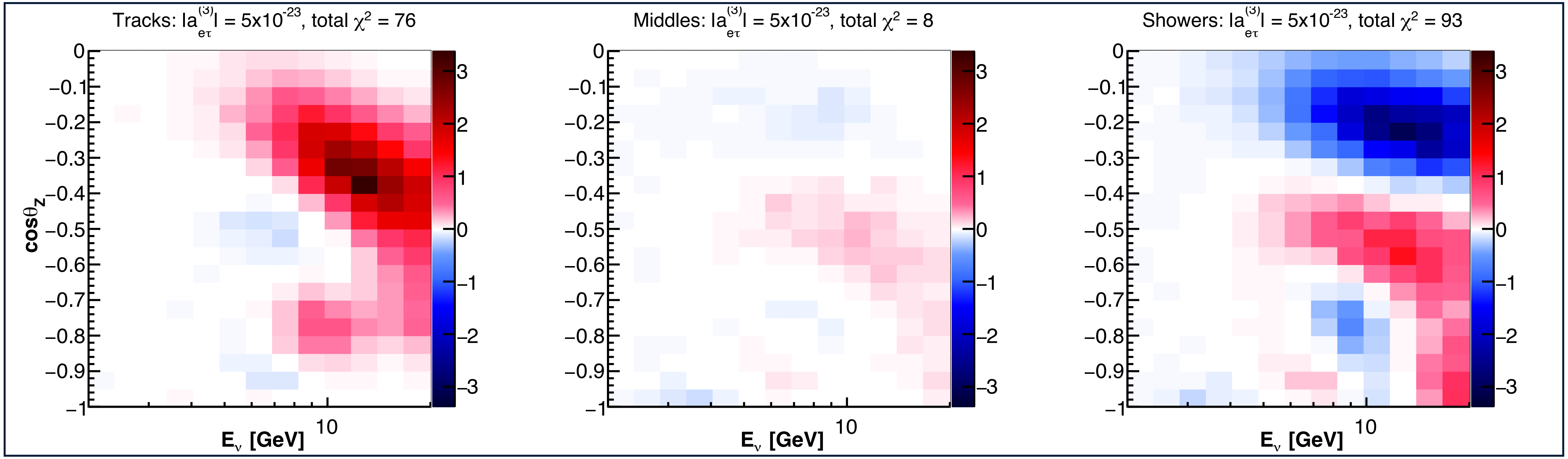
- Fitted parameters and their priors:

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:

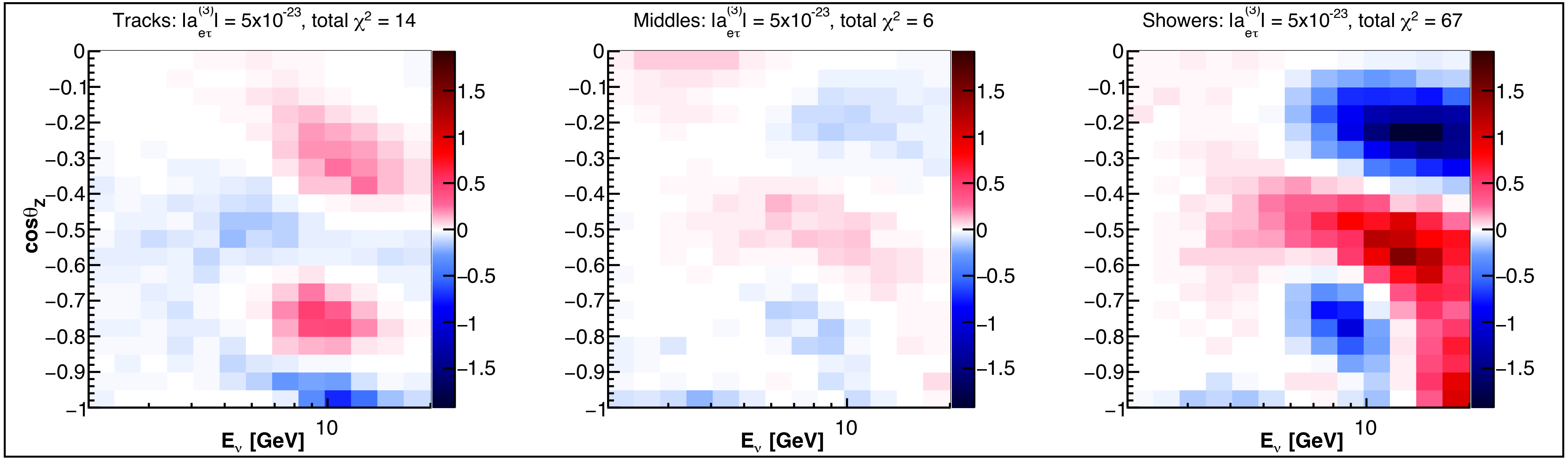
$$\chi^2 = \frac{(N_{\rm LIV} - N_{\rm Std})|N_{\rm LIV} - N_{\rm Std}|}{N_{\rm LIV}},$$



LIV searches with ORCA115

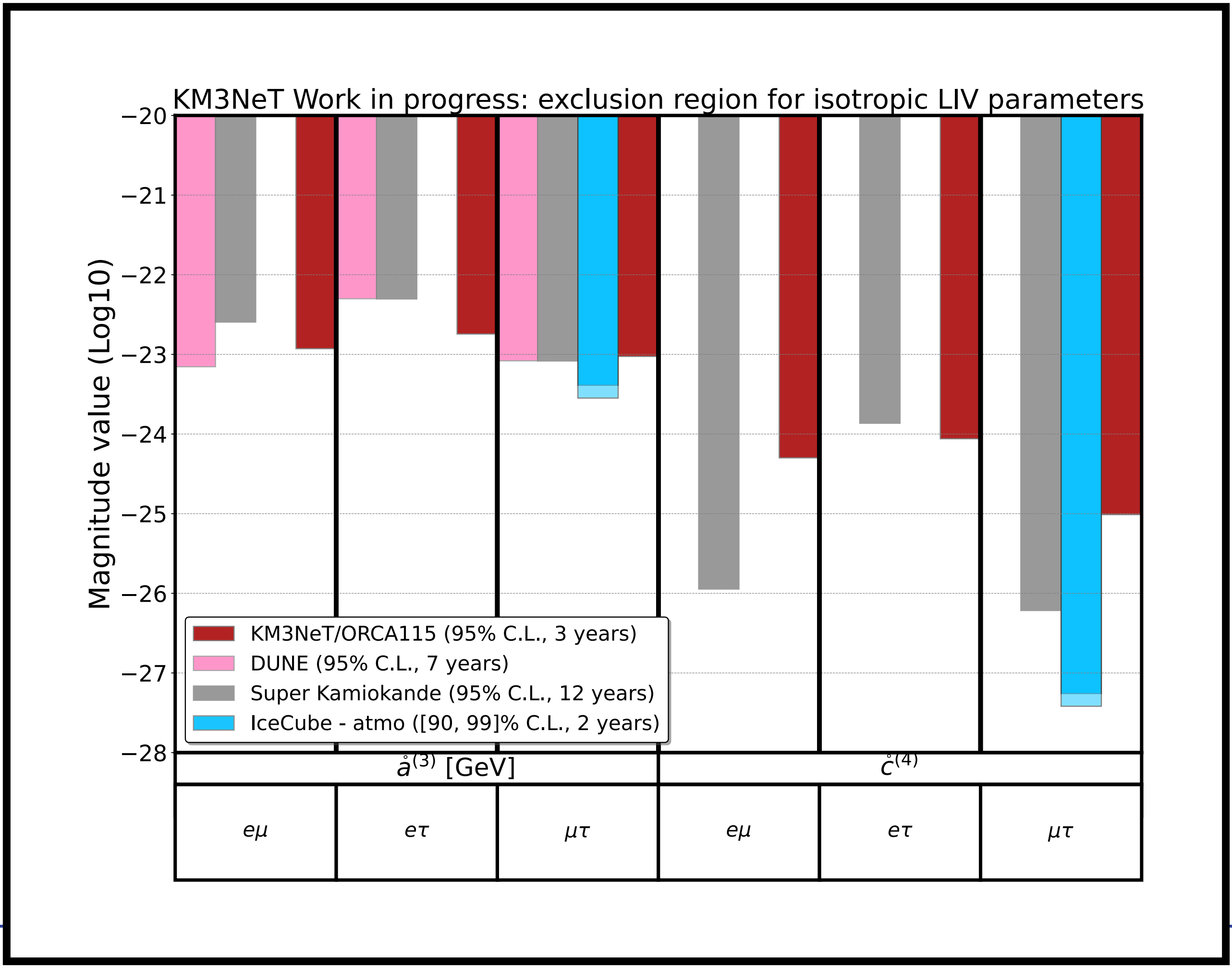
- LIV impact accounting for systematics:

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



LIV searches with ORCA115

- ORCA115 sensitivity for 3 years of assumed data taking

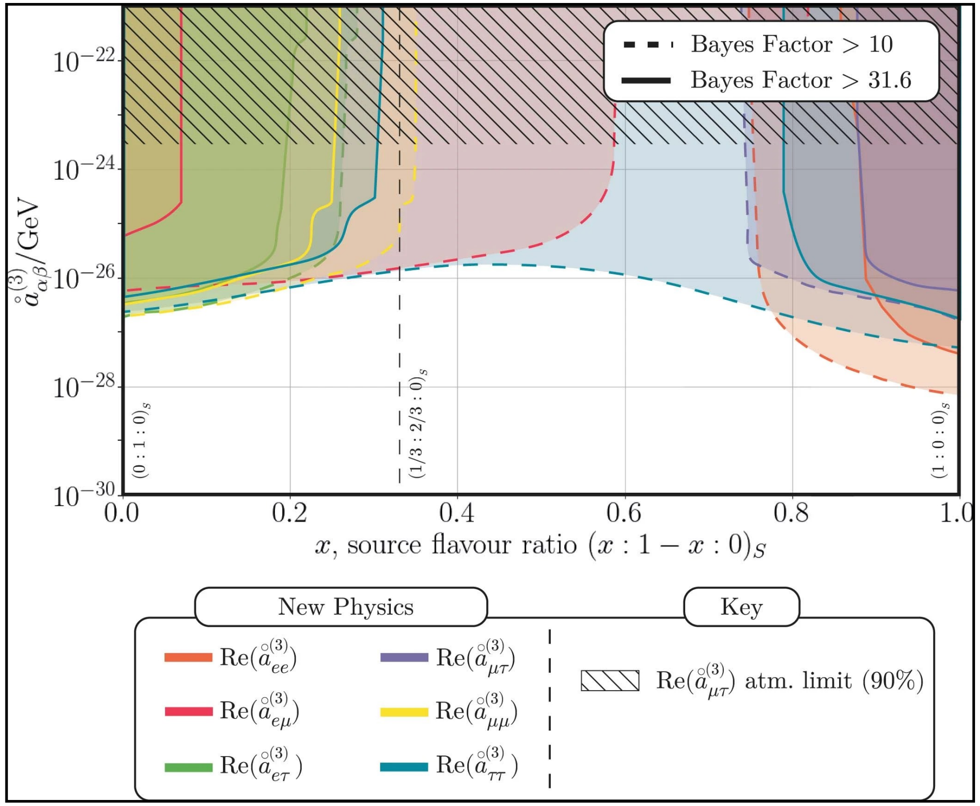


DUNE: Physics Letters B 788, 308-315 (2019)
SK: Phys. Rev. D 91, 052003 (2015)
IC-atmo: *Nat. Phys* **14**, 961–966 (2018)

LIV with atmo/astro neutrinos

- *Nat. Phys.* **18**, 1287–1292 (2022): strongest LIV constraints obtained with astrophysical neutrinos.
- Such constraints depend on the source flavour ratio model.
- Atmospheric neutrinos represent a complementary probe for LIV.

Nat. Phys. **18**, 1287–1292 (2022)



LIV searches with ORCA115

- First preliminary analysis of ORCA115 using low energy events (E_{RECO} < 20 GeV) shows a good potential to constrain regions of the parameter space not yet constrained by current experiments.
- The analysis will be extended to higher dimensions by including higher energy events.
- This work is part of the MSCA grant QGRANT (ID 101068013) with the goal of performing a global LIV analysis with KM3NeT+ANTARES+IceCube data.