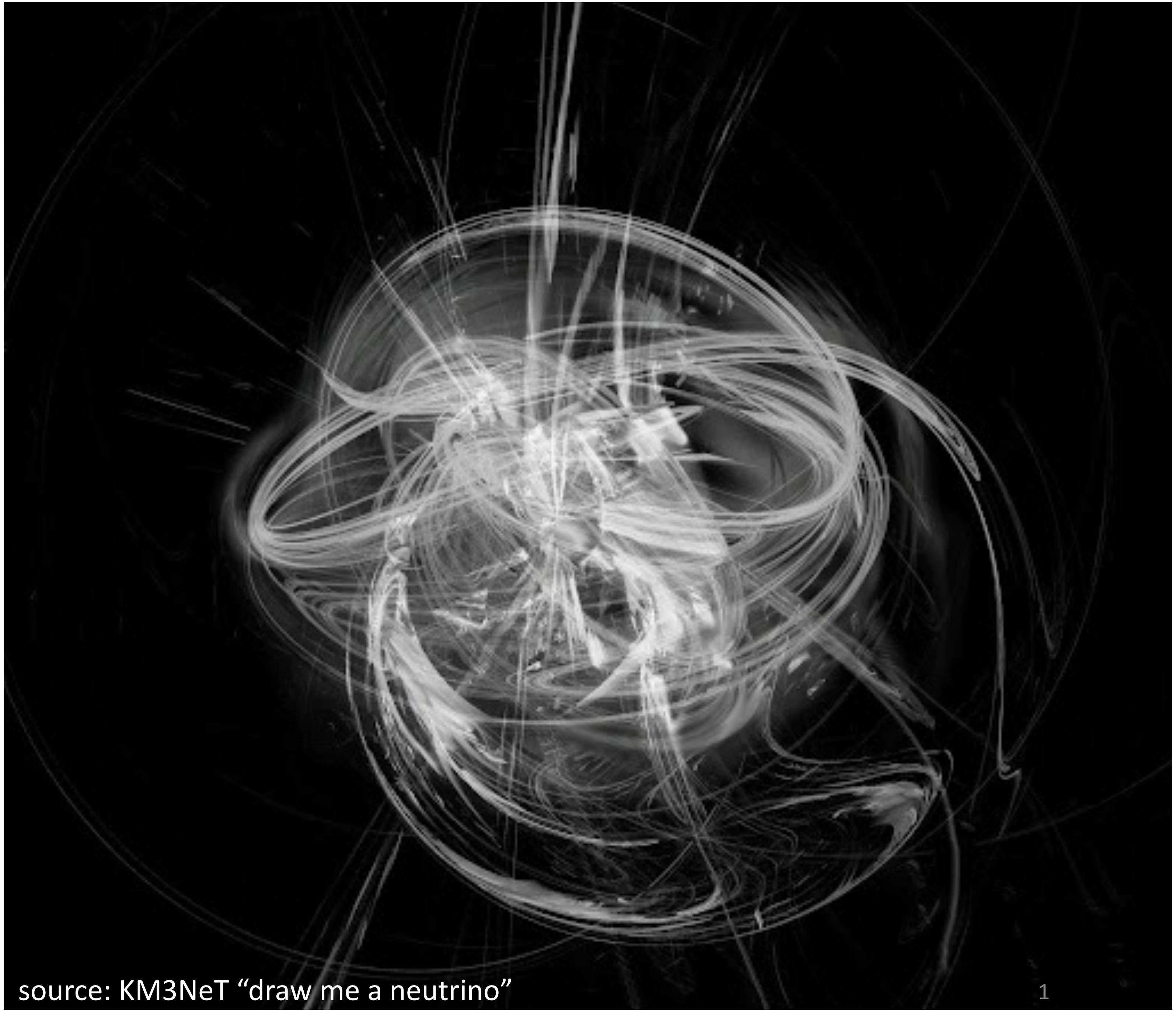
Neutrino Physics



source: KM3NeT “draw me a neutrino”

Neutrino physics deserves a prominent place in the next European Strategy.

The neutrino sector provides the most significant (if not the only) evidence that the Glashow-Salam-Weinberg + Brout-Englert-Higgs model is incomplete;
neutrinos have small but non-zero mass, lepton flavour is violated.

It is possible to extend the SM to generate neutrino masses, but there is no unique prescription, nor is there any reason to prefer one. All include at least one new particle.

The mixing between neutrino mass- and flavour states is WILD, for one angle close to maximal. What is the relation between quark masses/mixings and lepton masses/mixings?

It is likely that there is significant CP-violation in the neutrino sector,
offering a path towards a better understanding of the baryon-asymmetry in the Universe.

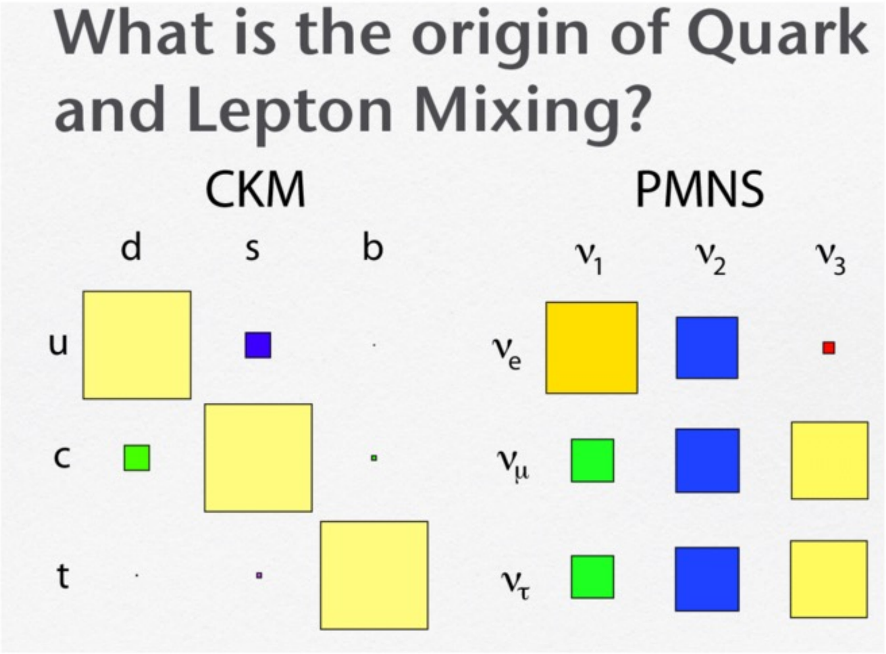
Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{\mu 1} & U_{\tau 1} \\ U_{e2} & U_{\mu 2} & U_{\tau 2} \\ U_{e3} & U_{\mu 3} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

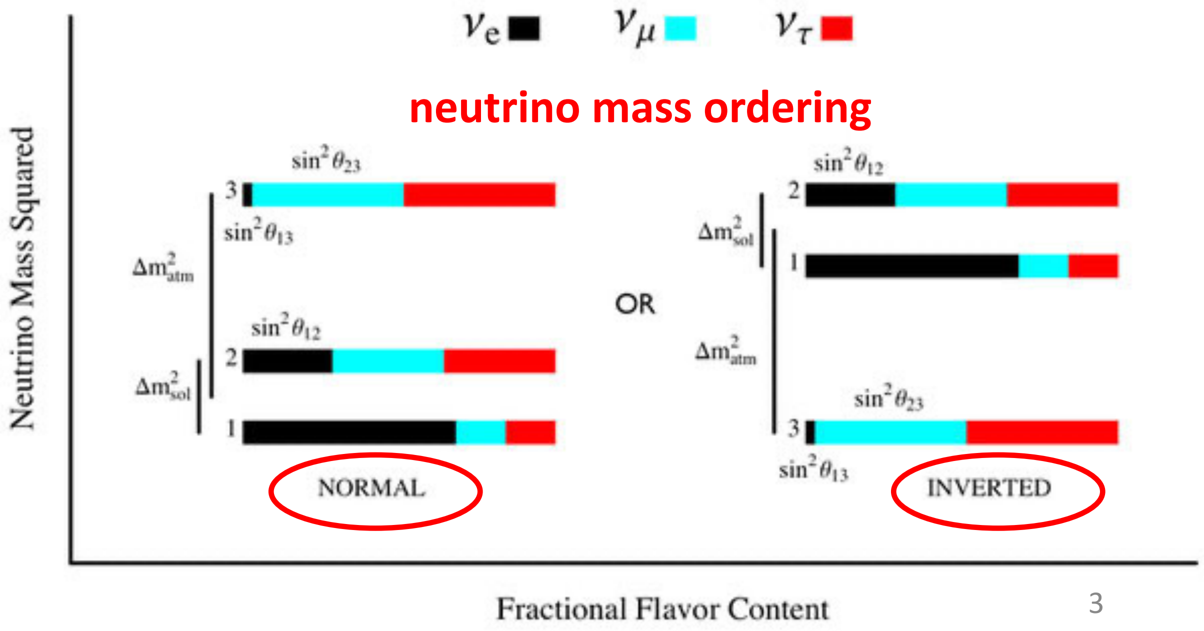
$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_{i=1}^{N_\nu} U_{i\alpha}^\dagger U_{\beta i} e^{-i m_i^2 L/2E} \right|^2$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

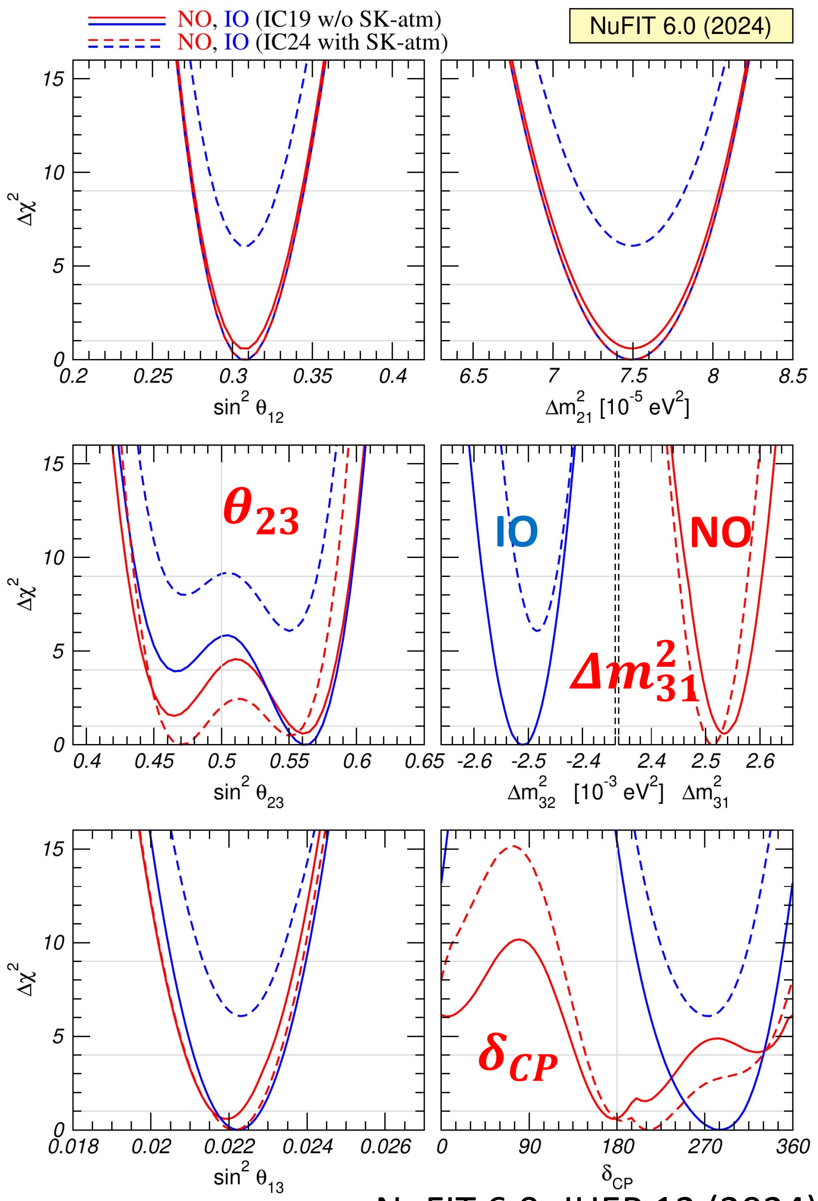
only for Majorana neutrinos



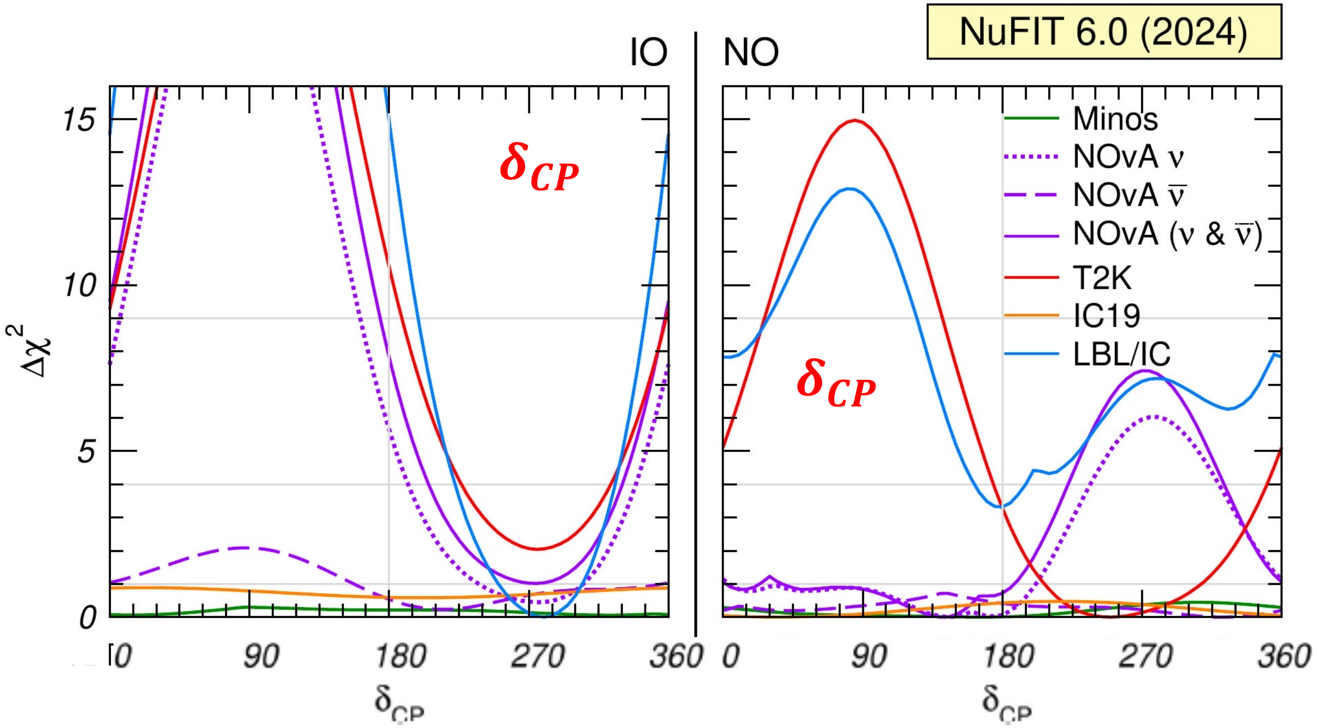
size of mixing matrix elements

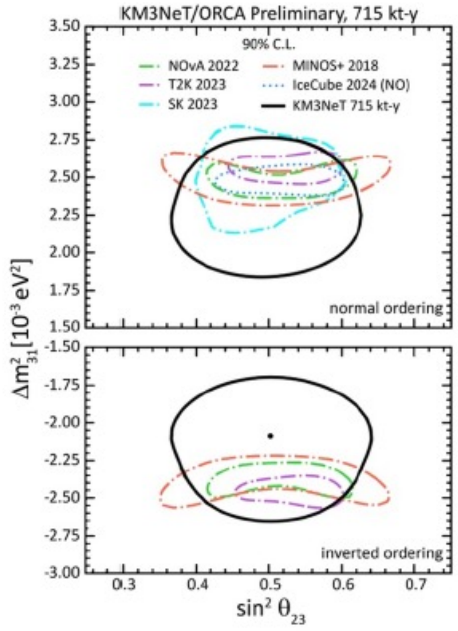


Neutrino Oscillations anno 2025

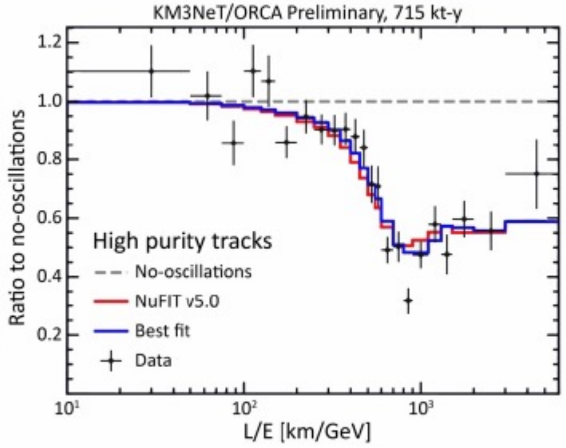


NuFIT 6.0, JHEP 12 (2024) 216





KM3NeT first results with 6-11 lines



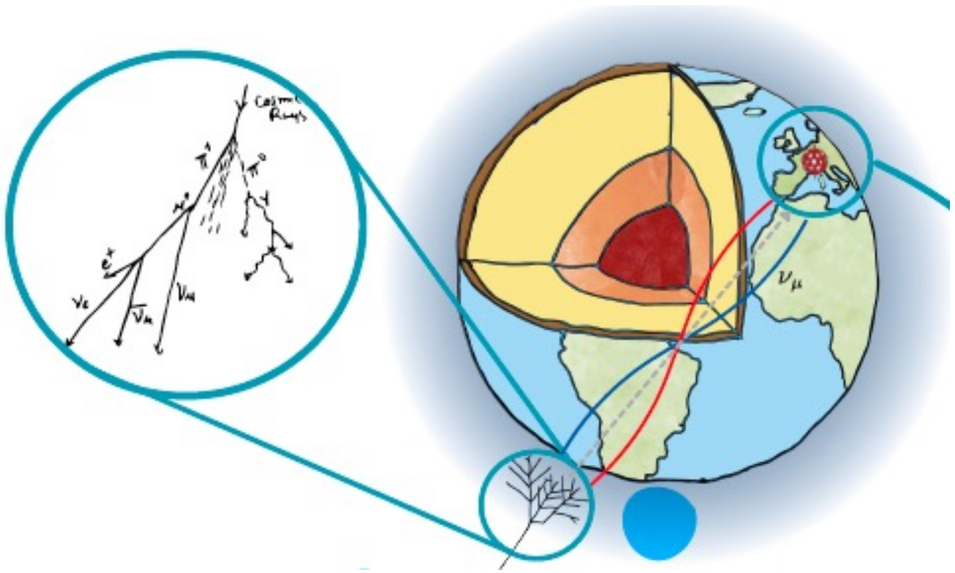
Today:
ORCA 24 DUs
ARCA 33 DUs

(full: 115/230)

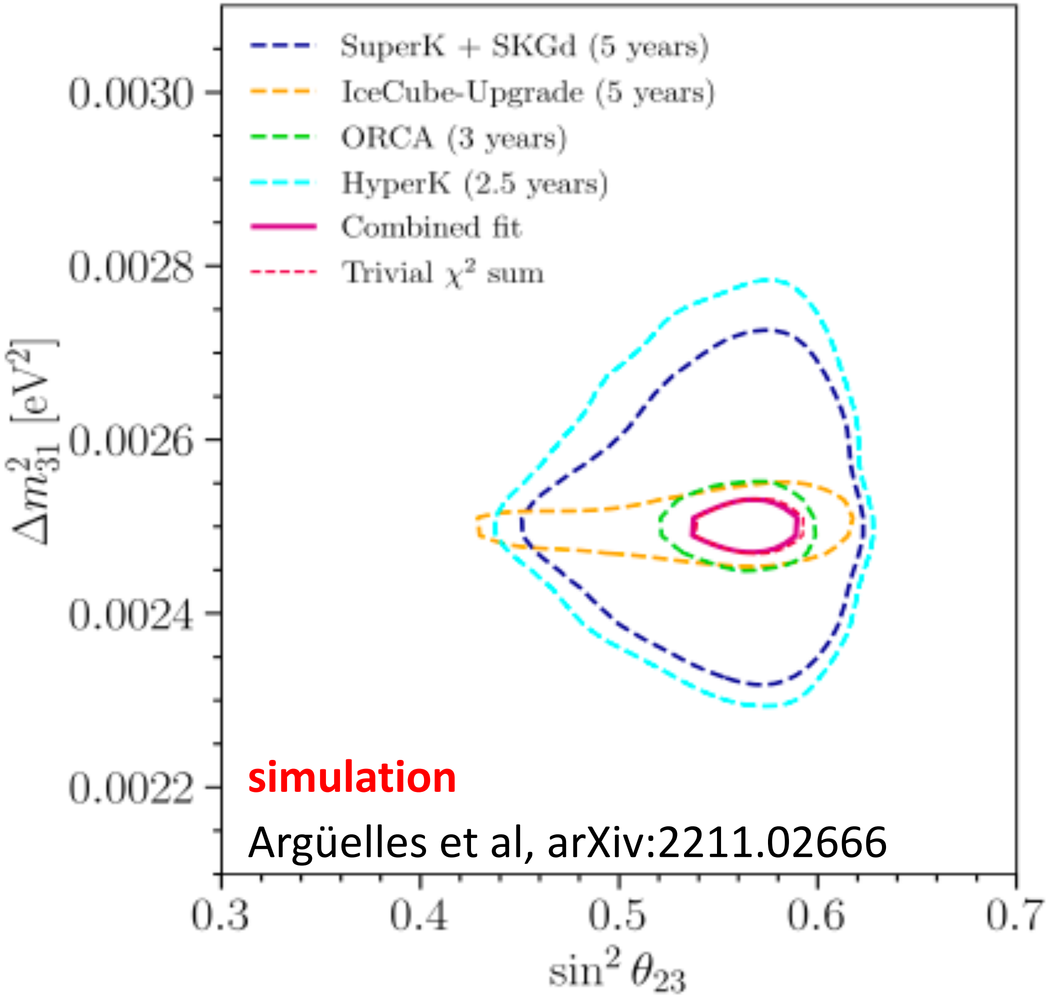
KMS3NeT

(Nikhef involved in ground-breaking work for all parts of KM3NeT)

ORCA best suited for “standard oscillations” 2-100 GeV, but there is also oscillation physics in ARCA



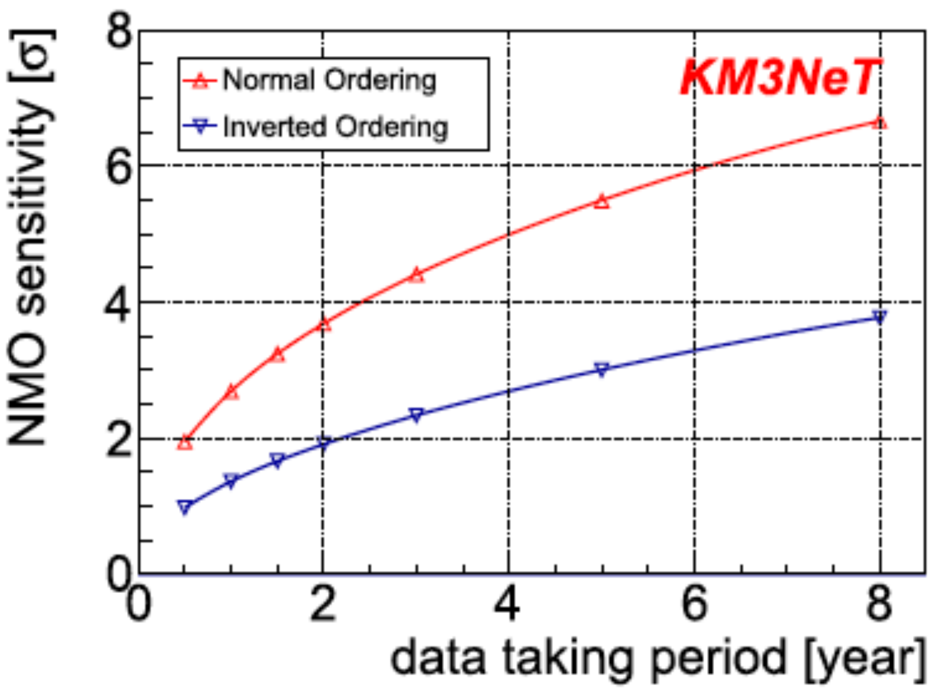
Atmospheric neutrinos
Long baselines, large matter effect
Flux with mix of $\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$
Large detectors (ORCA 7 Mton water): high statistics



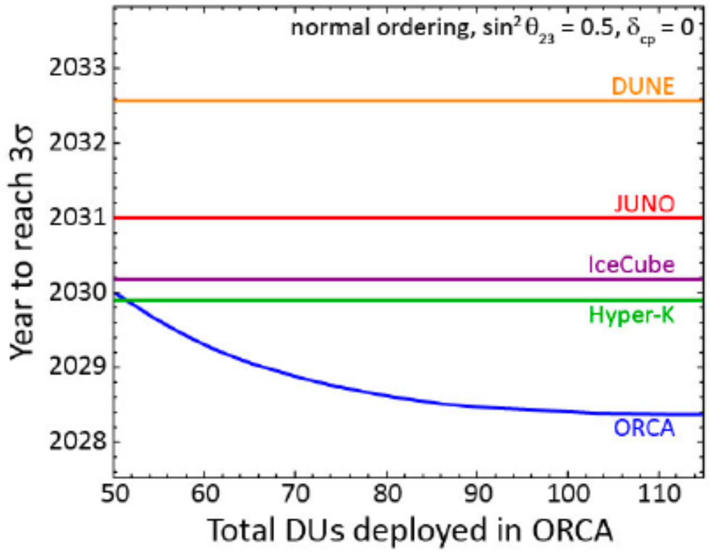
Neutrino telescopes will dominate θ_{23} determination, and full ORCA will dominate the neutrino telescopes

(Also: first very large sample of tau neutrinos)

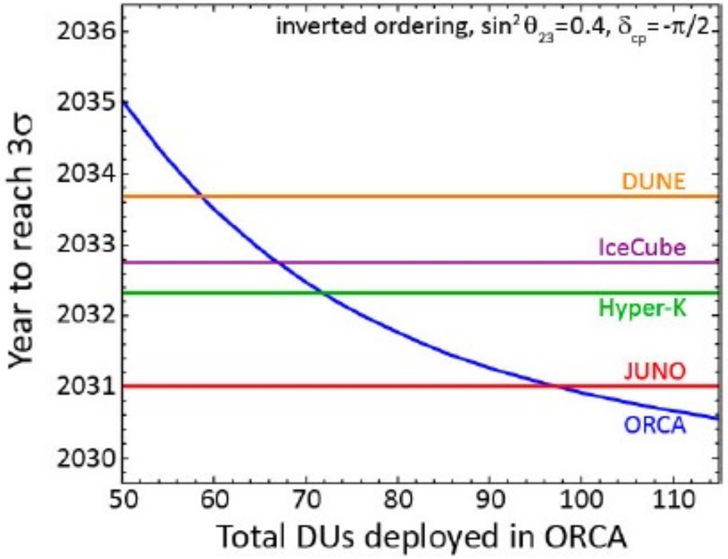
KM3NeT neutrino mass ordering



ORCA, 115 DUs [*Eur. Phys. J. C* **82,** 26 (**2022**)]



3 sigma
average scenario
for oscillation
parameters



3 sigma
worst-case scenario
for oscillation
parameters

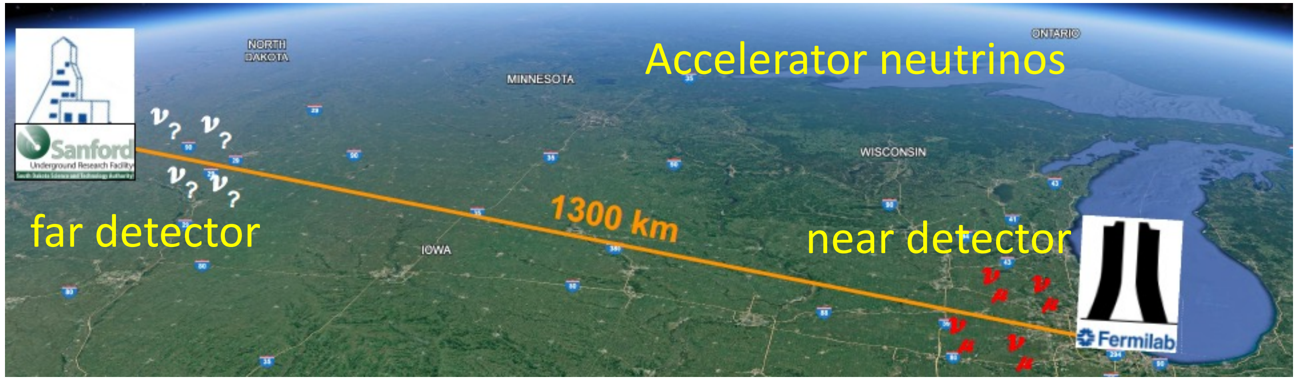
J. Coelho,
KM3NeT internal

ORCA will have an excellent shot at being the first single experiment to determine the NMO, if it grows sufficiently large sufficiently fast.

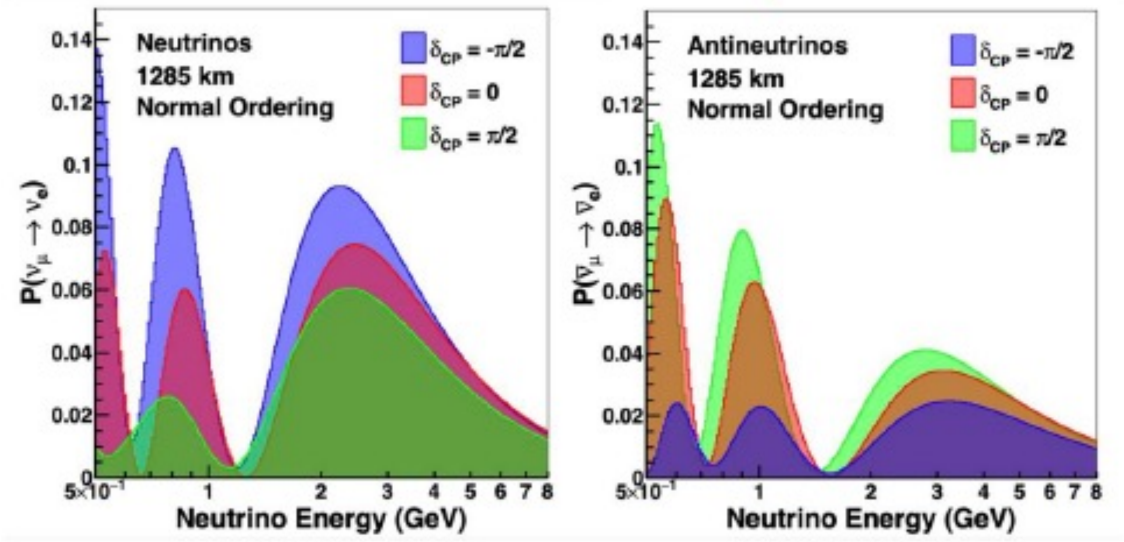
ORCA is not able to measure CP-violation, unless a (tagged) neutrino beam is sent to ORCA (e.g. P2O)

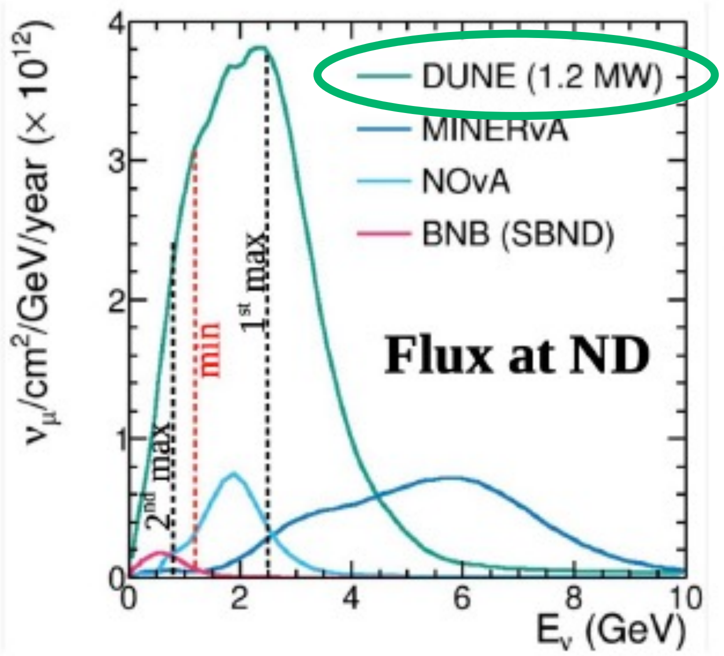
Deep Underground Neutrino Experiment (DUNE)

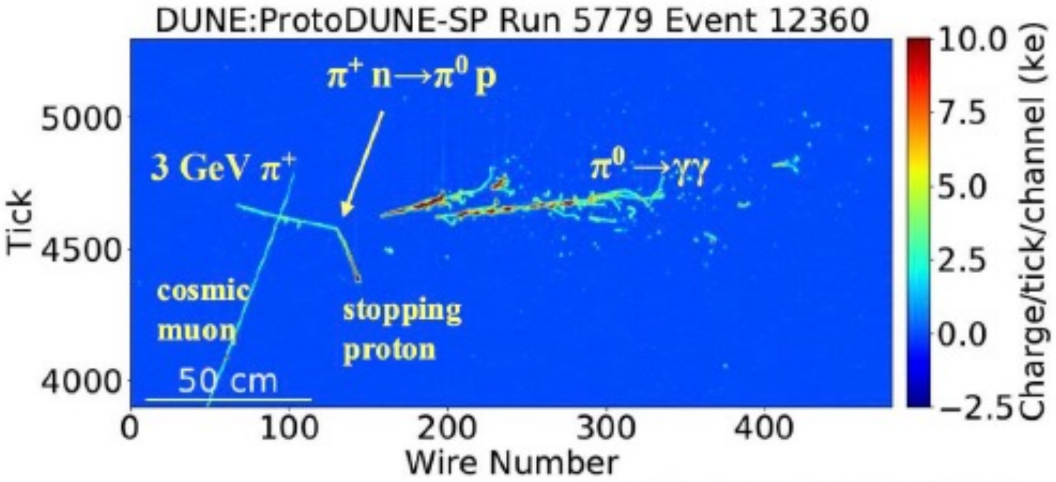
+ LBNF: Long Baseline Neutrino Facility



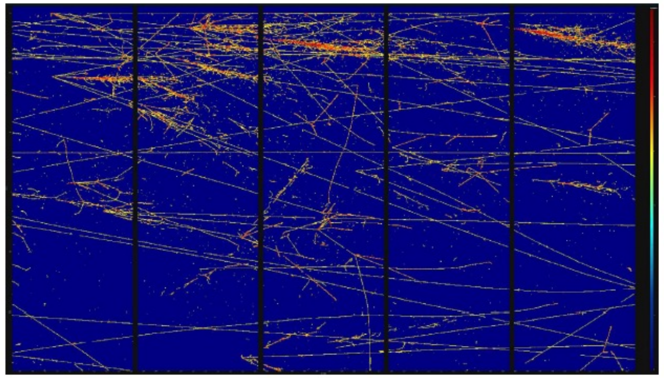
detect 1st and 2nd oscillation maximum







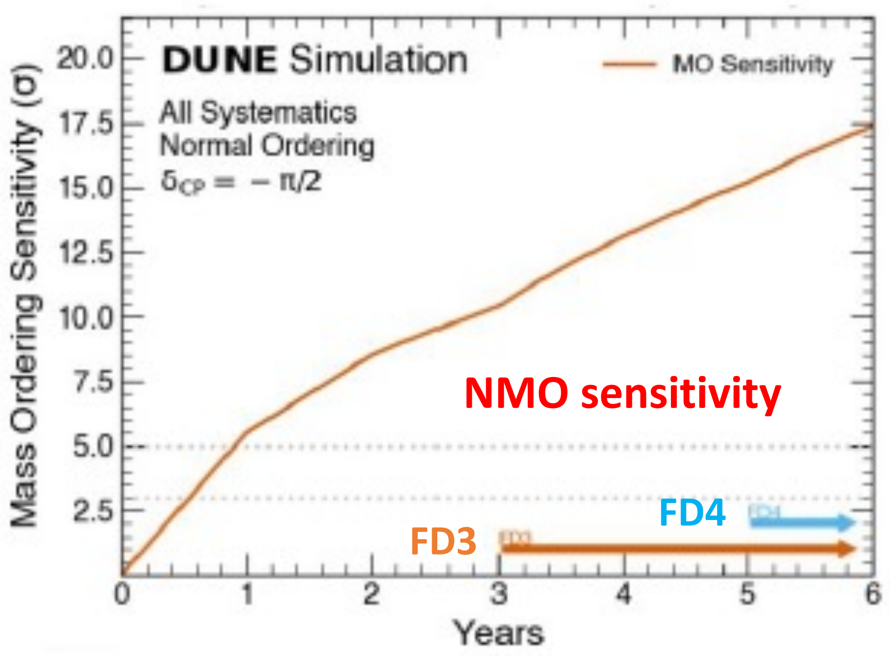
Liquid argon TPC: exquisite reconstruction of final states.

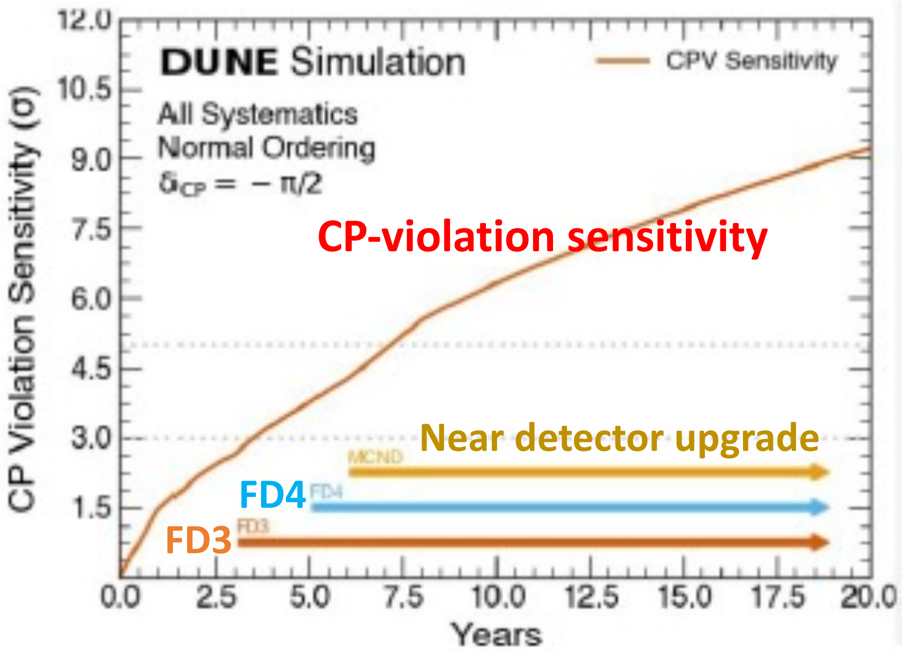


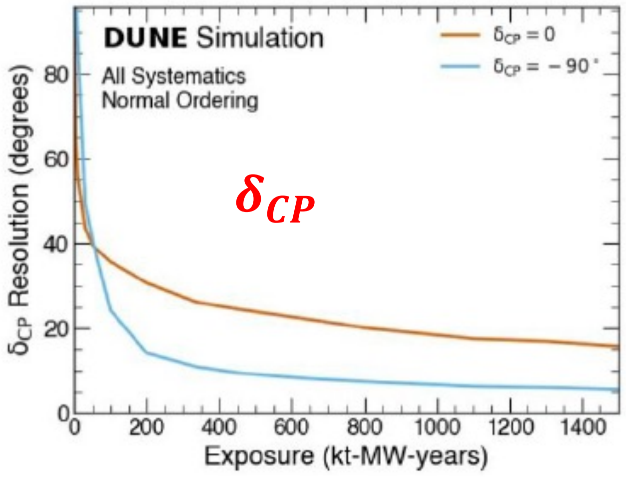
Neutrino event pile-up in the near detector

DUNE

FD = far detector, modules with each up to 17 kton liquid argon







Phase 1: 1.2 MW beam, 2 far detector modules, near detector LAr TPC: <u>highest priority level in US P5 strategy</u>

Phase 2 (P5 recommendation): upgraded beam (ACE-MIRT), 3rd far detector module, upgraded near detector

Beyond that: 4th far detector module with possibly different technology, broadened physics scope

Neutrino physics is dominant part of FNAL strategy, and DUNE is priority

DUNE

Building & Site Infrastructure work until mid-2025

Far detector installation

Physics w/ Far Detector Natural neutrino sources

2024 — 2025 — 2025-26 — 2026-27 — 2028 — 2029 — 2031

Far site excavation

Cryostat warm structure on its way to US from CERN to be installed

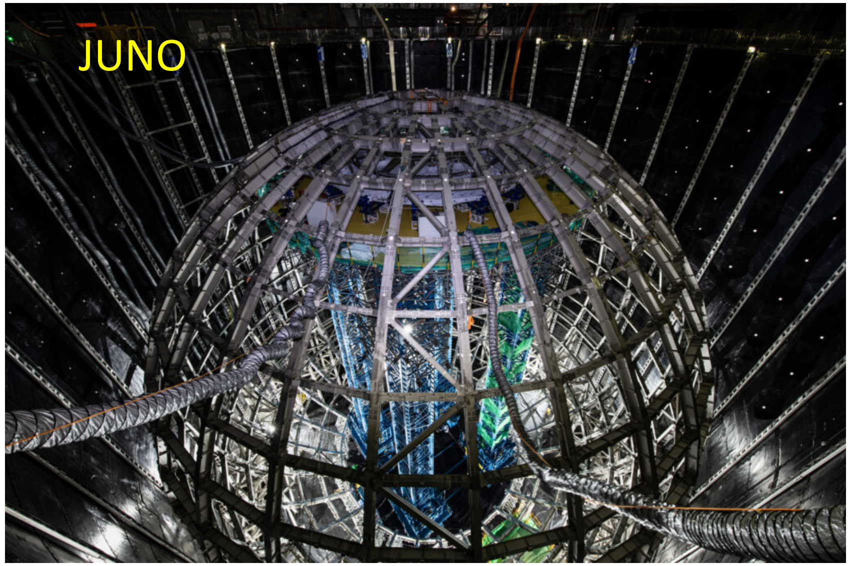
Purge and fill with argon

Beam + Near Detector

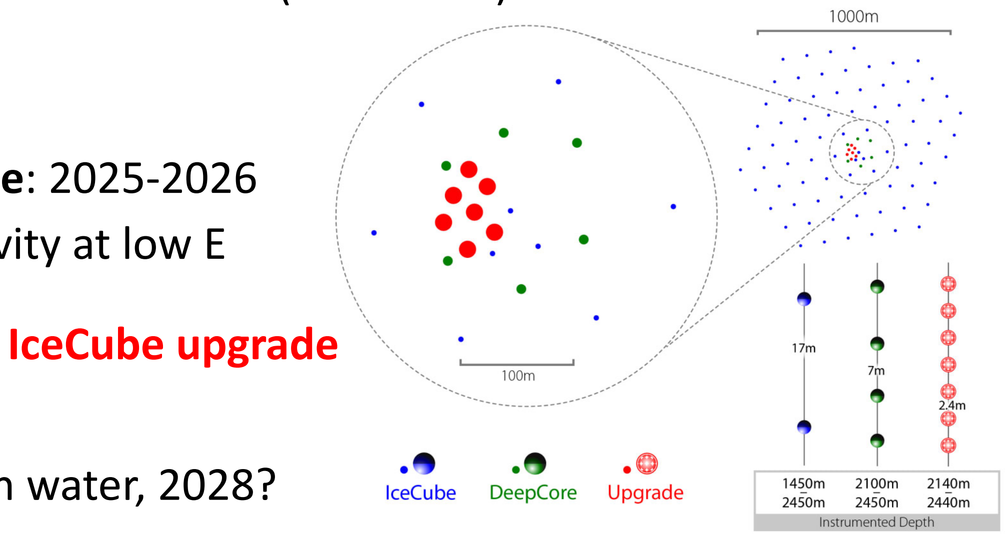
The neutrino experiment landscape (other than KM3NeT/DUNE)

T2K: still taking data, to be superseded by T2HK: only small improvements towards the asymptote
NOvA: could still be taking data, but NuMi beam not operational now, expect not much data until FNAL switches to LBNF

JUNO: start by end of 2025? Reactor neutrinos, excellent energy resolution needed for Δm^2_{31}. Would need about 6 years for 3 sigma NMO determination. Combined analysis ORCA+JUNO(+IceCube?) also considered.



IceCube upgrade: 2025-2026
increase sensitivity at low E



Hyper-K: 200 kton water, 2028?

Cosmology: putting significant constraints on sum of neutrino masses now
inverted ordering becoming disfavoured. But: needs cosmological assumptions (Λ CDM)

Neutrinoless double beta decay: also sensitive to mass ordering, in particular inverted ordering
But: neutrino must be Majorana, and uncertainties in nuclear matrix elements

Beyond oscillations

Neutrino physics does not stop when NMO is settled and CP-violation discovered.

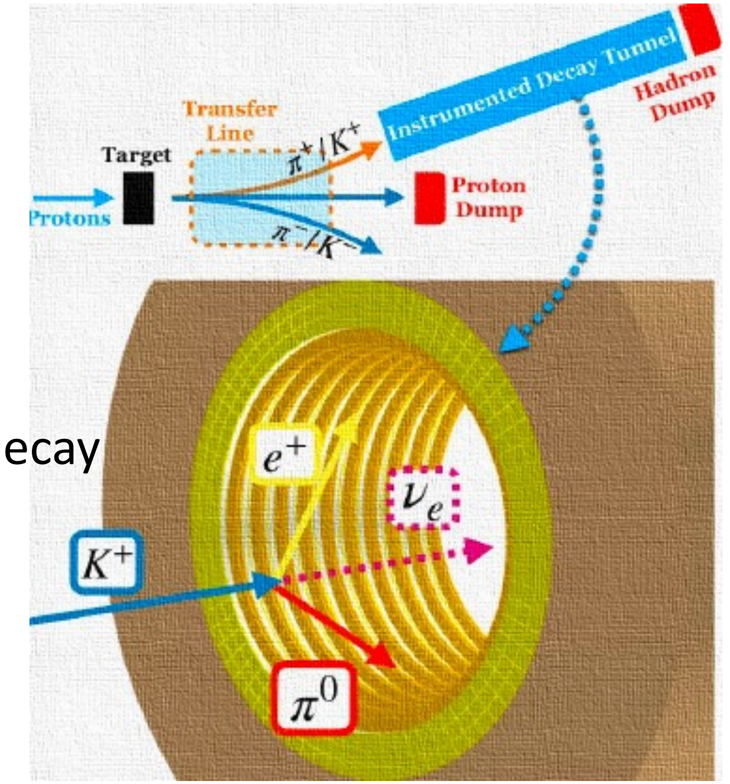
We need a comprehensive multi-experiment multi-observable analysis to test the 3-flavour paradigm, understand neutrino masses and mixings, determine Majorana character, search for new physics.
Many frictions in current data!

> Neutrinos don't interact a lot,
> But everything is connected:
> You can't do it alone
>
> Peter B. Denton (BNL)

Neutrino telescopes can contribute significantly: large statistics, long baselines, large matter effect.

DUNE (LAr TPC) has exquisite capability to reconstruct many different final states and verify consistency of results in a wide range of measurements.
The DUNE near detector will collect the world's largest neutrino interactions data set.

Future neutrino beams

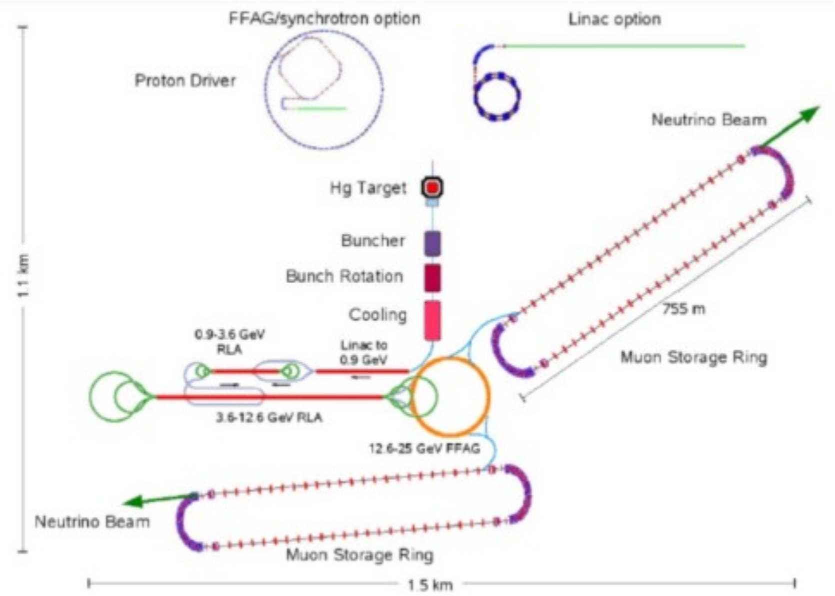


Tagged neutrino beams

ENUBET: Enhanced Neutrino Beams from Kaon Tagging

ν_e and ν_μ flux determination from tagging positrons and antimuons from π/K decay

future: precision timing for a tagged beam, fast silicon detecors
associate individual neutrinos with their production vertex



Neutrino Factory

intense, collimated, pure neutrino beam

"natural" side-product from a muon storage ring (e.g. for muon collider)

European Strategy (part 1)

Neutrino physics deserves a prominent place in the next European Strategy.

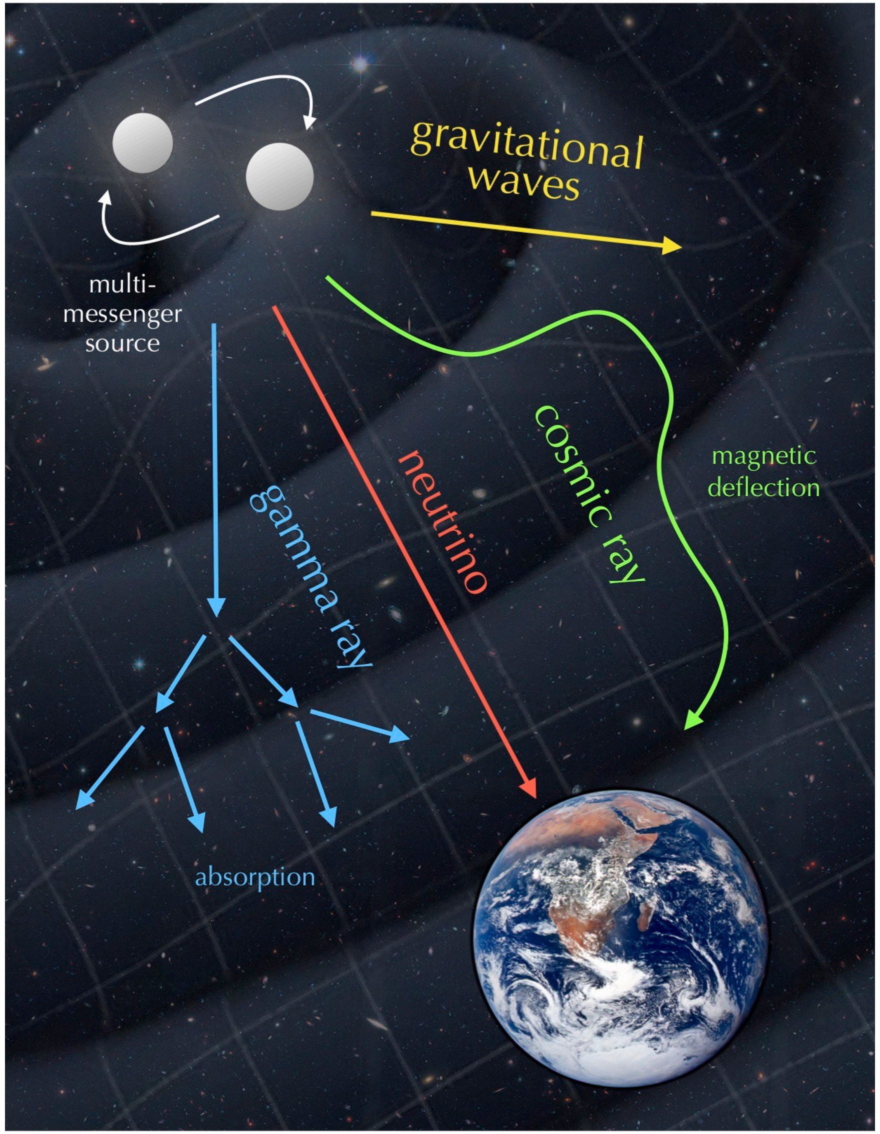
CERN is full member of DUNE, with significant contributions to prototyping/R&D (neutrino platform, ProtoDUNE), cryostat, DAQ, computing etc.

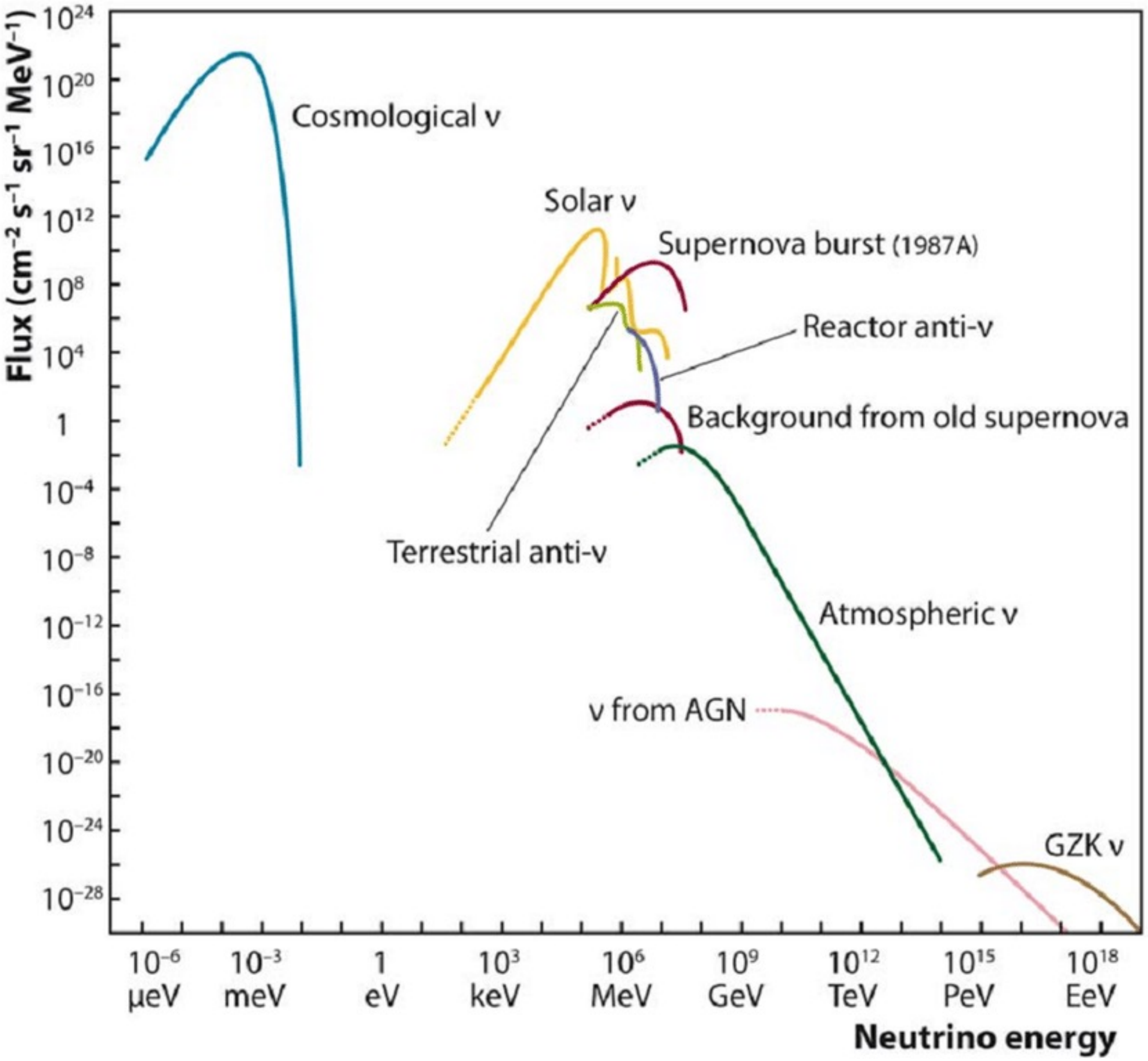
The ESPP should support the P5 strategy in the US, by recommending timely completion of full DUNE and LBNF beamline.

The ESPP should support R&D for future neutrino beams:
tagged beams and neutrino beams from a muon storage ring.

(Dutch contribution to DUNE: computing, DAQ/ProtoDUNE (past), near detector (prototype data analysis, light readout))

Neutrinos from the cosmos





Neutrino astronomy

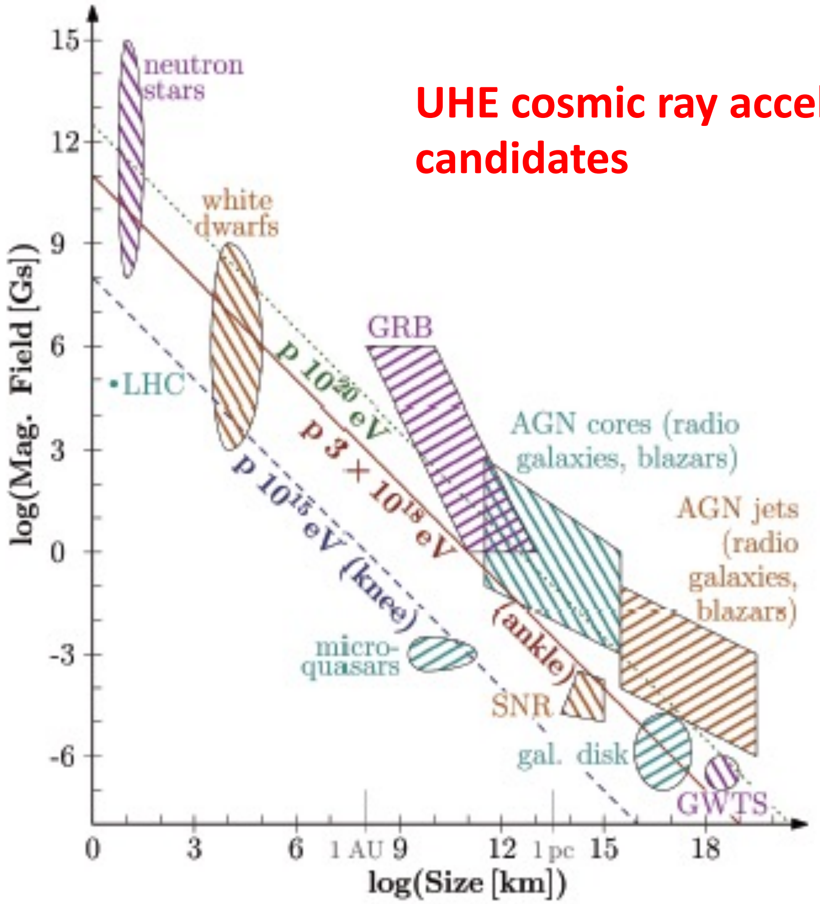
Goal: find sources of cosmic neutrinos, from low energy (core-collapse supernovae and dark matter) to ultra-high energy.

High-energy neutrino sources are also the accelerators of high-energy cosmic rays.

A few hints for sources have emerged from IceCube: NGC 1068, blazar TXS 0506+056, the galactic plane.
Significance still somewhat marginal.
Source modeling appears difficult.

KM3NeT: largest project in Northern Hemisphere, excellent resolution.

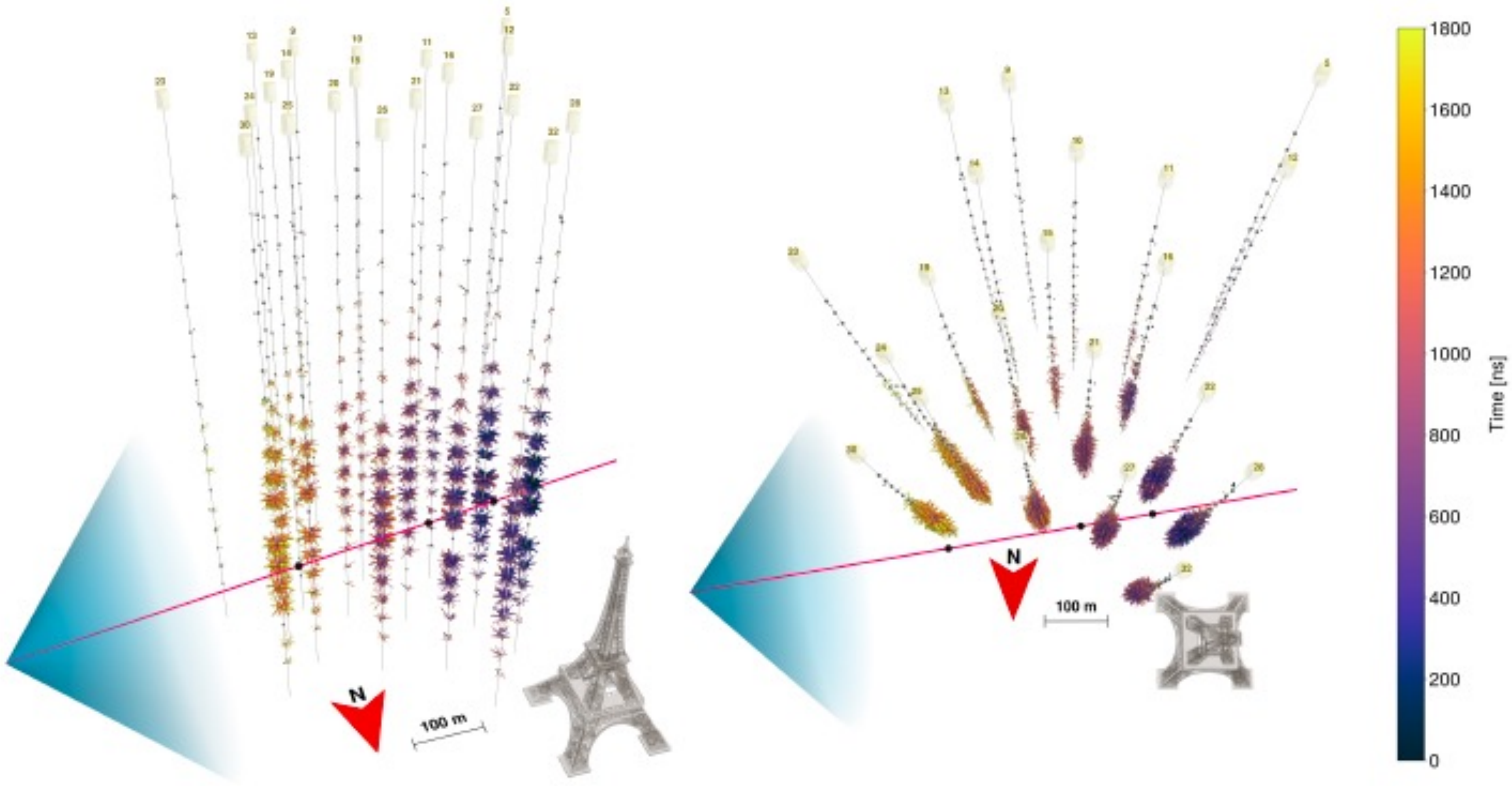
Landscape: IceCube, KM3NeT, Baikal-GVD.
Future: P-ONE, IceCube-Gen2, Chinese projects.



UHE cosmic ray accelerator candidates

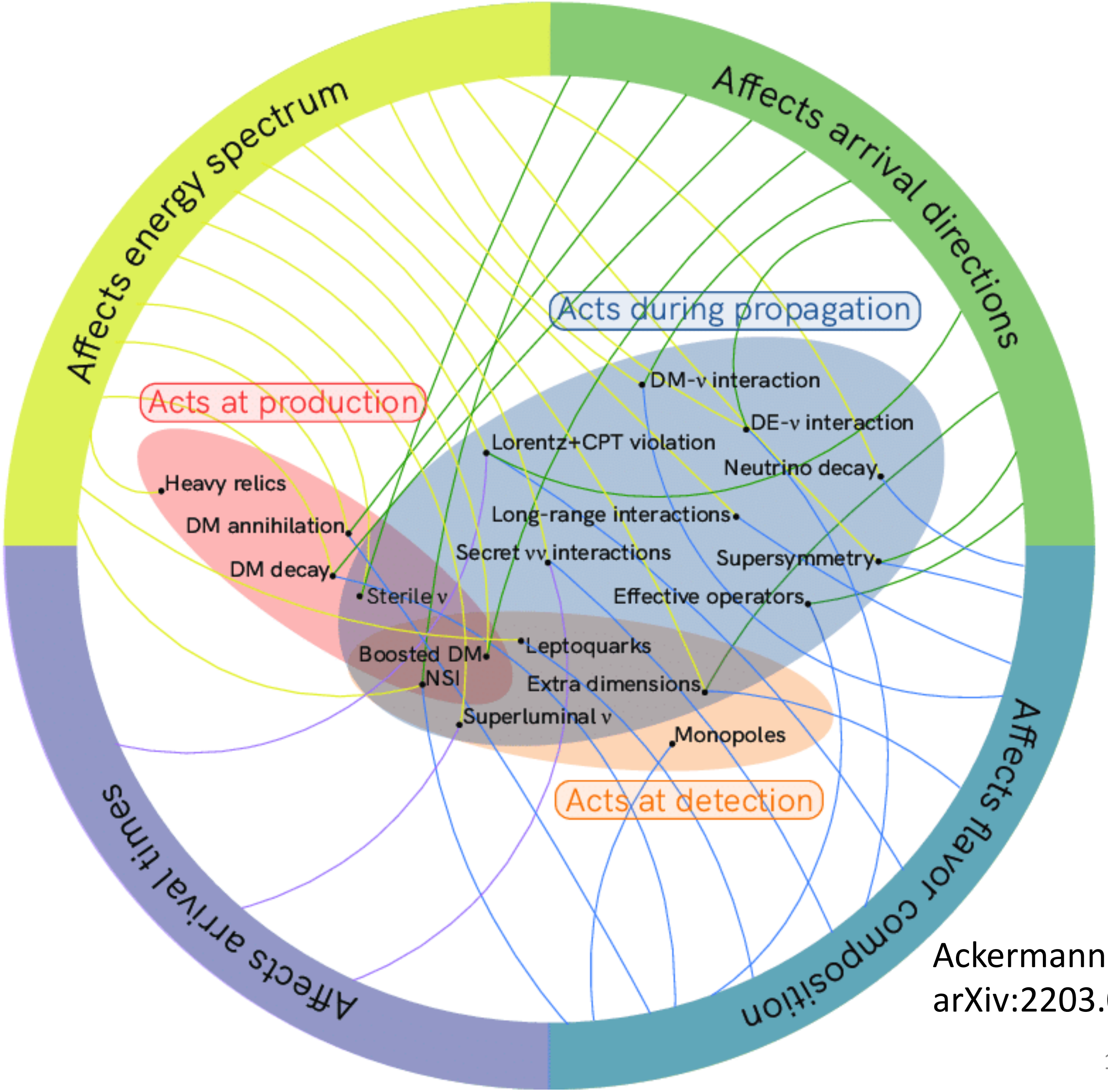
UHE neutrinos (> 100 PeV): different technology for **much larger detectors**: radio, or acoustic detection

Ultra-high energy neutrino observed by KM3NeT



KM3-230213A: a (>> 10 PeV) muon, horizontally through the ARCA detector; very likely from a neutrino.
Would be the highest-energy neutrino ever observed, touching the cosmogenic regime of the spectrum.
Nature paper to appear mid-February.

Cosmic neutrinos also test models of new physics



Ackermann et al.
arXiv:2203.08096

Synergy

Multimessenger astronomy: combining information from neutrinos with gamma rays, X-rays, visible light, radio, charged cosmic rays, gravitational waves.
This is a <u>must</u> to understand sources.

Cosmic rays: atmospheric neutrinos originate from cosmic ray showers; measurement of high-energy neutrinos in those showers could help resolve puzzles.
Radio detection of cosmic rays: also sensitive to VHE/UHE neutrino showers.

Interaction cross sections at high energy: "prompt" neutrinos from charm decay, information on nucleon structure functions.

New physics searches: complementary to colliders or fixed-target expts.

European Strategy (part 2)

The European Strategy should acknowledge and promote the role of astroparticle physics experiments in advancing our knowledge of the subatomic world.

It would help APP experiments if CERN would play a more supportive and coordinating role.

- alignment of funding agencies
- oversight by a CERN scientific committee (an LHCC for APP?)
- legal support
- support for procurements
- access to electronics and mechanical design/prototyping
- support in data processing and computing

We believe this would also help CERN: portfolio enrichment, risk spreading

Prepared statements

"Measurements of neutrino masses and mixings, the CP-violating angle in the neutrino sector, tests of the three-flavour paradigm and searches for new physics in the neutrino sector are crucial for the progress of particle physics and must have a prominent place in the European strategy."

For the Dutch input to the strategy, the previous statement to be followed up by: "These objectives are the goal of the DUNE experiment, as well as the European KM3NeT project".

And:

"Neutrinos offer independent and complementary access to the study of astrophysical and cosmological phenomena, and large-volume neutrino telescopes must be part of the European astroparticle physics strategy. CERN should play a more supportive and coordinating role for European astroparticle physics."

And:

"CERN should support R&D for future neutrino beams, including tagged neutrino beams."