Latest results from KM3NeT

João Coelho

for the KM3NeT Collaboration

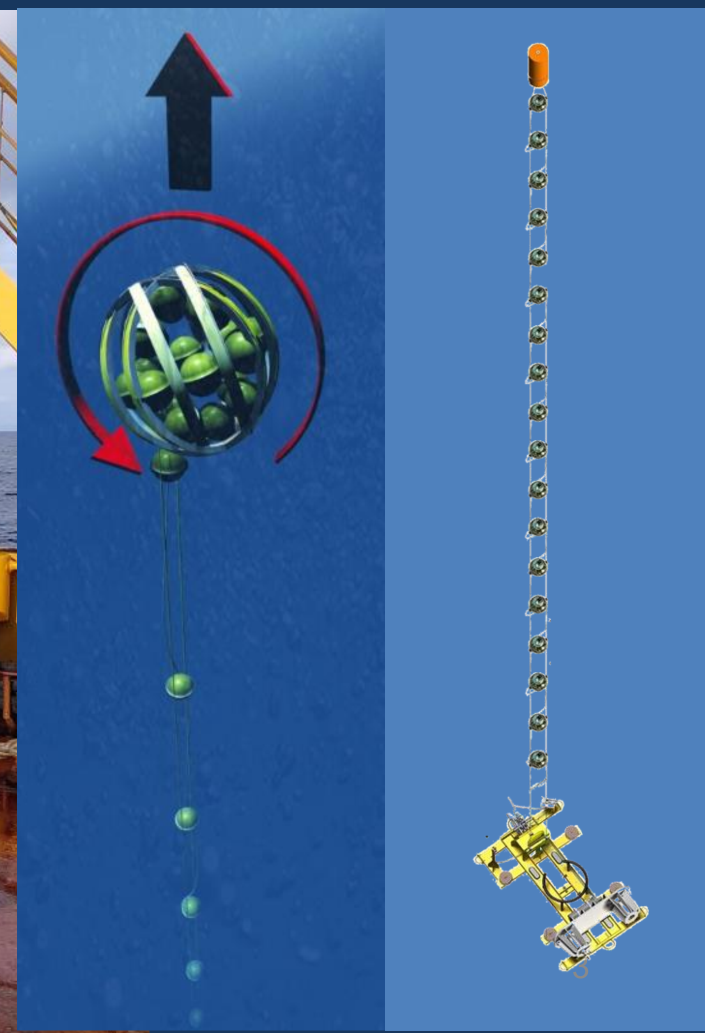
18 June 2024

The KM3NeT Eyes

- KM3NeT is building a series of neutrino telescopes in the Mediterranean Sea
- The KM3NeT DOMs are the eyes of the experiment observing the light around it

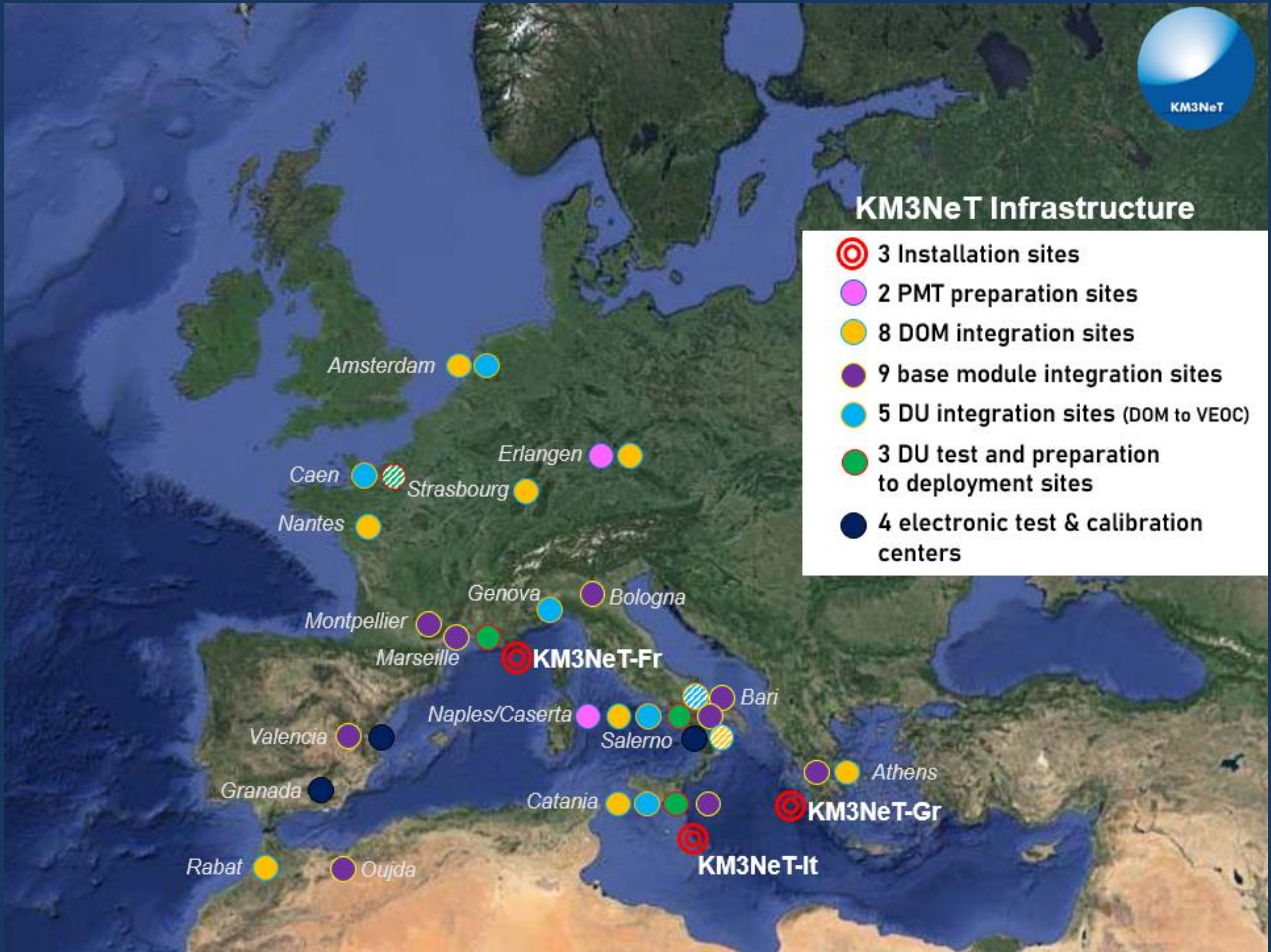
The KM3NeT DU

- 18 KM3NeT DOMs are joined together in a chain to form a Detection Unit (DU)
- DUs are rolled up into a Launcher of Optical Modules (LOM) for deployment at sea
- Once at the bottom, LOM is released and unrolls the DUs into its final vertical position

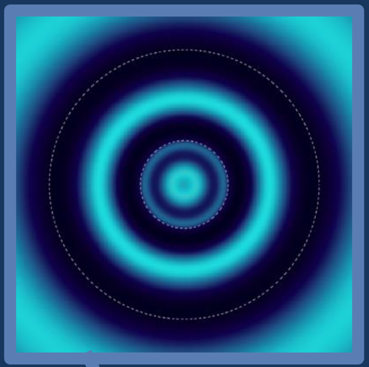


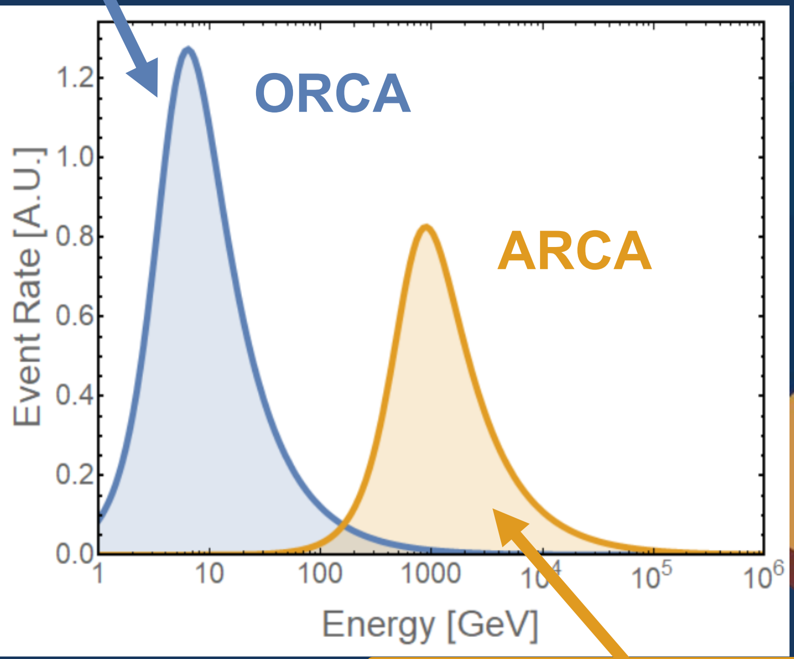
Construction Ongoing

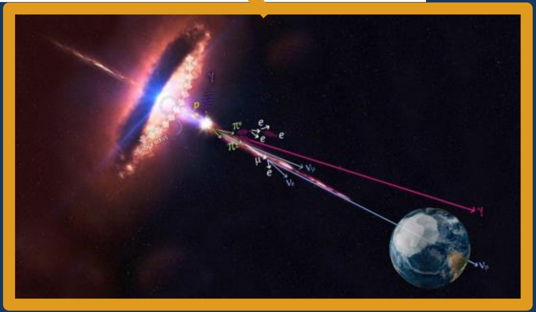
- Multiple integration sites across the world
- More than 1500 DOMs already integrated

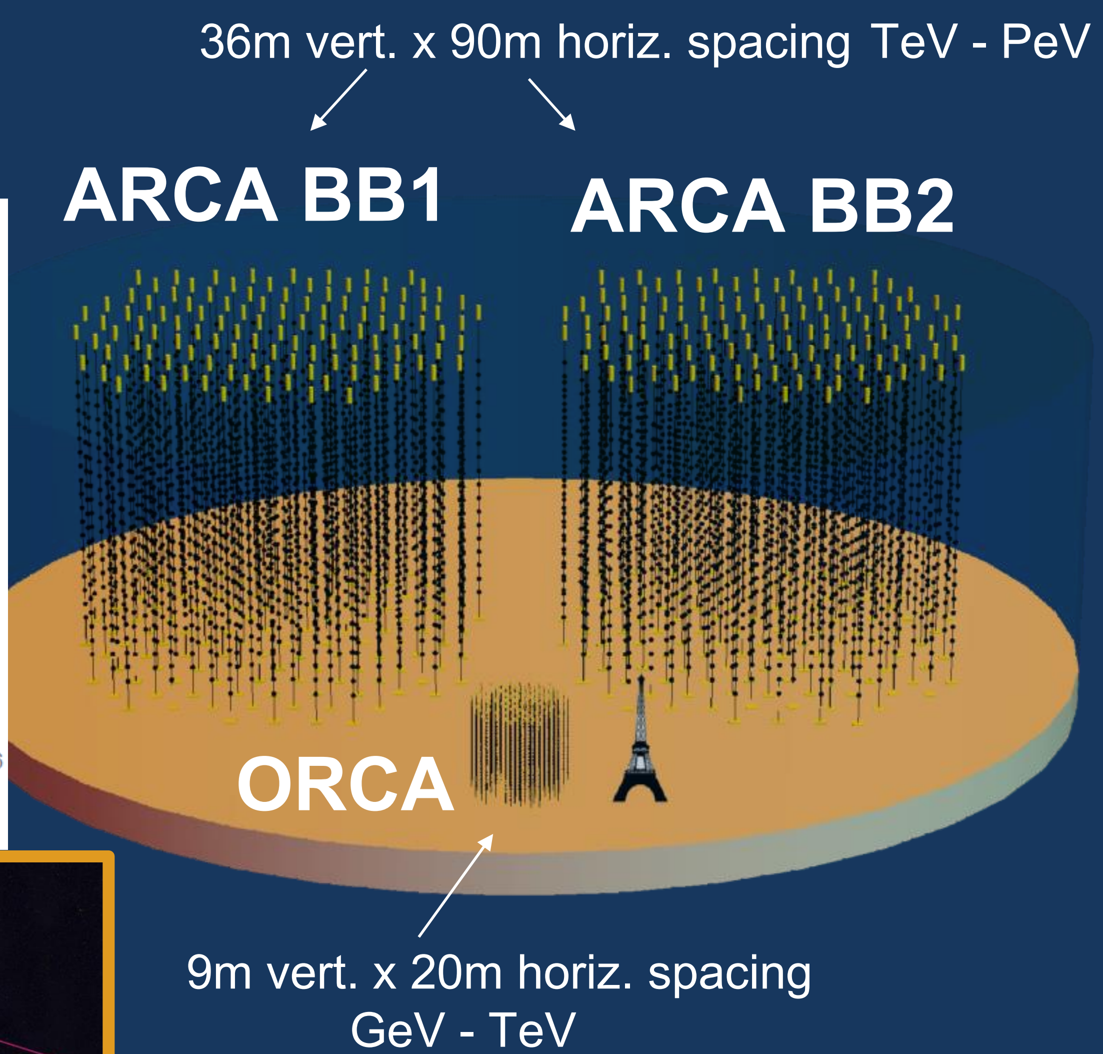


Two Detector Scales



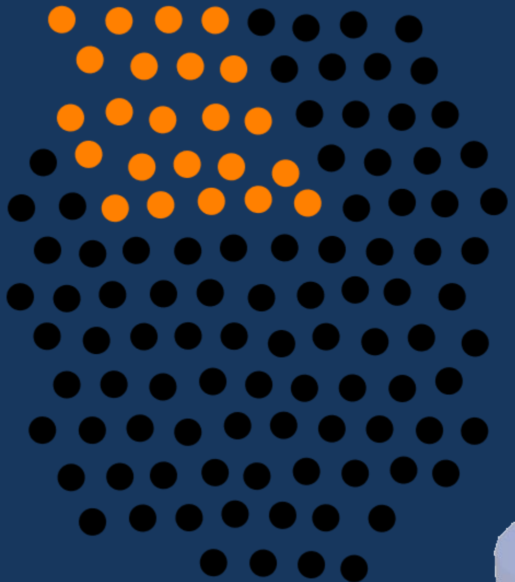






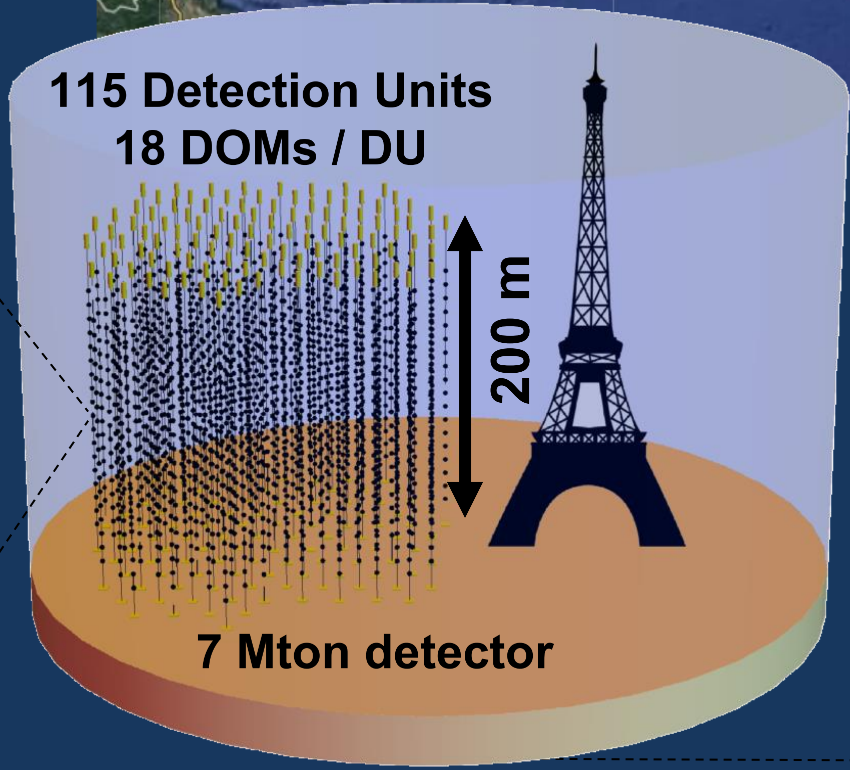
KM3NeT/ORCA

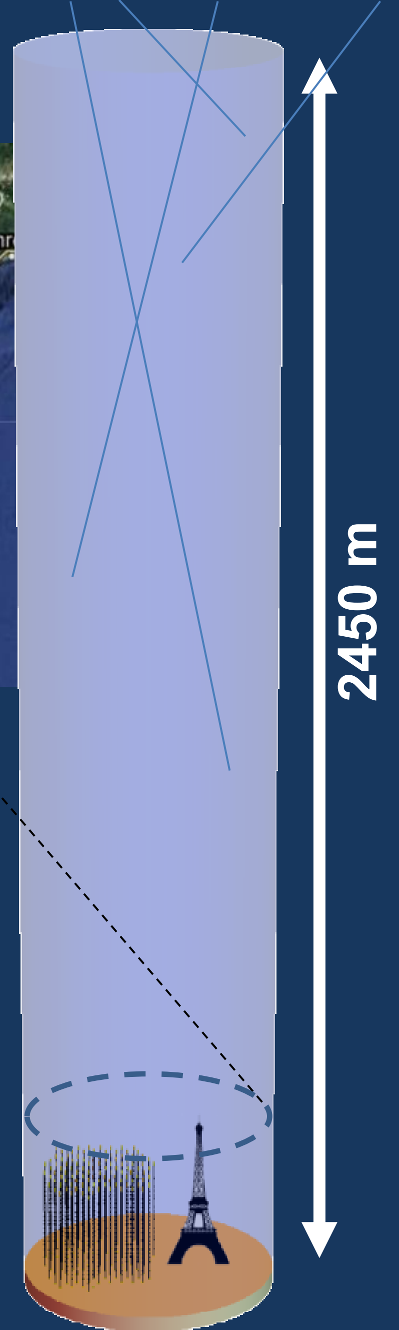
23 DUs Deployed



31x 3'' PMTs

43 cm

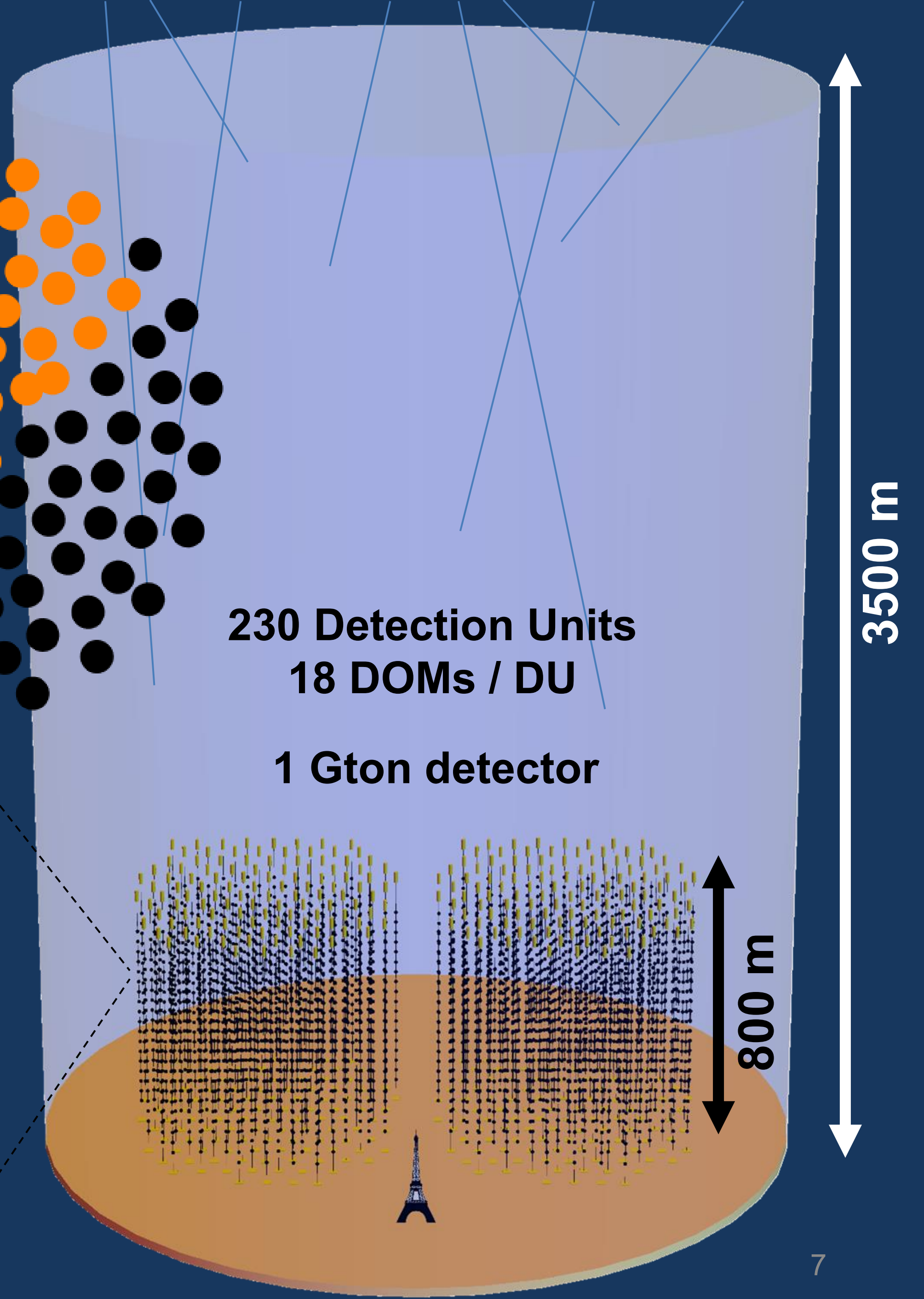




KM3NeT/ARCA

28 DUs Deployed

31x 3'' PMTs

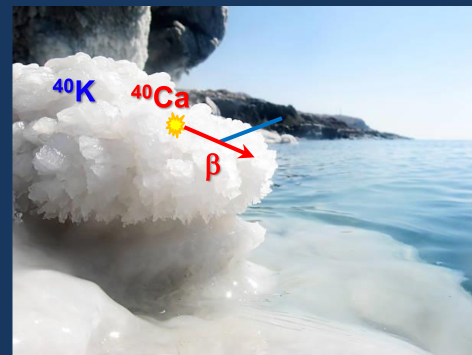


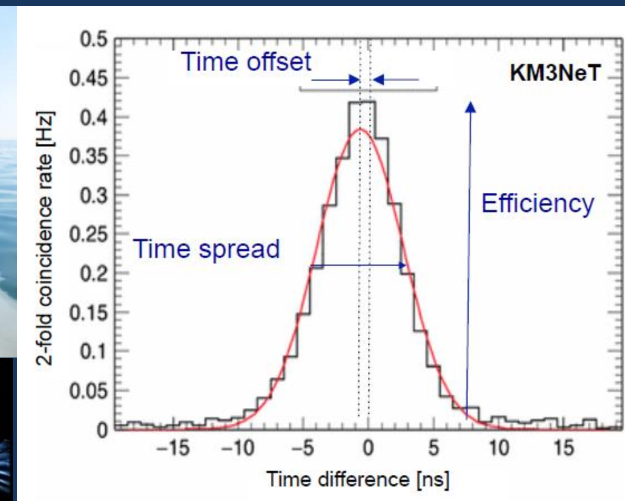
Layer 1: Optical Background

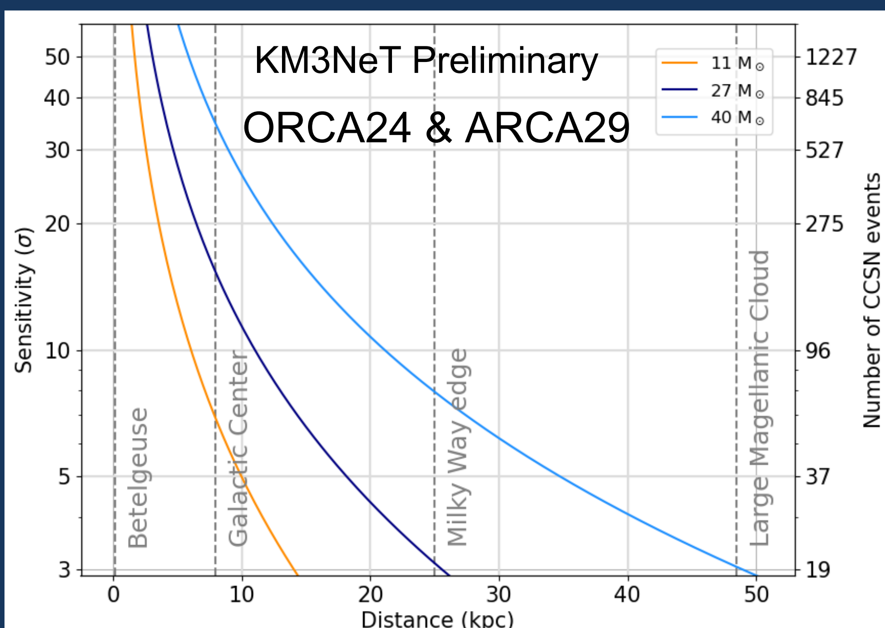
- We turn on our detector and what do we see?
- White noise…

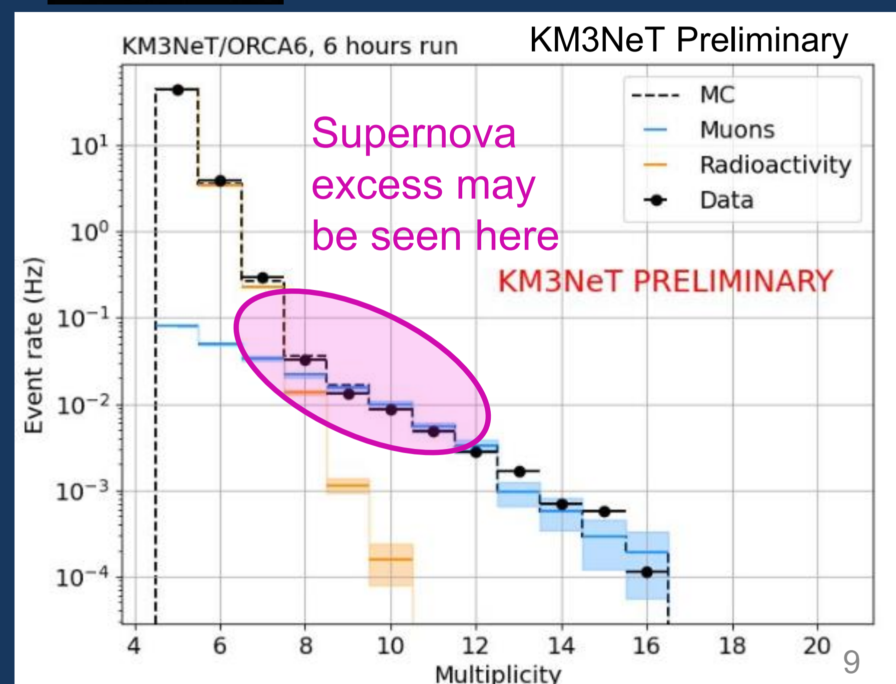
Layer 1: Optical Background

- 7 kHz random background, mostly from ^{40}K decays
- Constant natural source to calibrate the charge and timing of PMTs
- Can use single DOM variables to search for supernova neutrino bursts









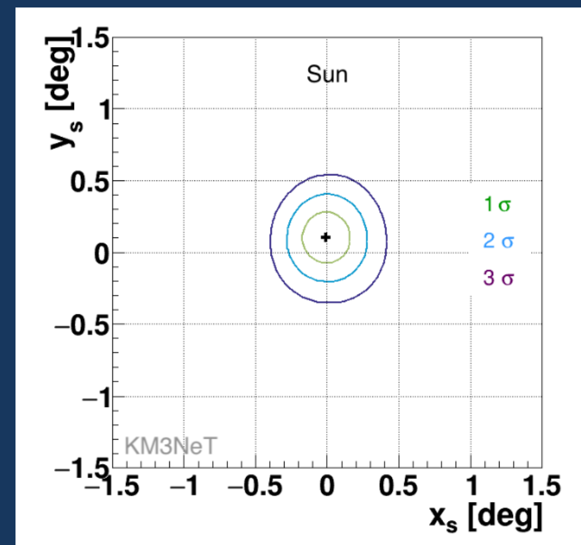
See poster 357

Layer 2: Cosmic Rays

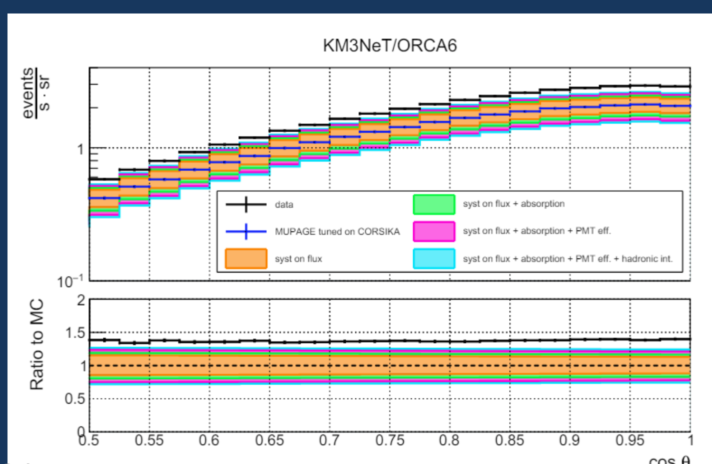
- Once optical noise is filtered, we see particles…

Layer 2: Cosmic Rays

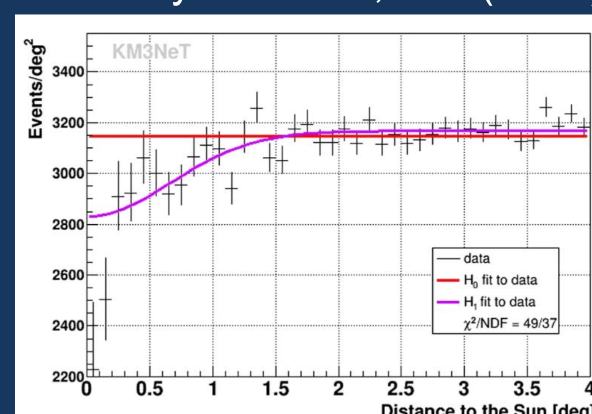
- Mostly muons coming from above
- Signal from Cherenkov light with distinct space-time correlation between DOMs
- Reconstruction based on simultaneous fit of light for each PMT in the detector according to PDFs from physics hypotheses
- Excellent source of particles for calibration:
  - Timing calibration between DOMs and DUs
  - Orientation calibration with Sun and Moon shadows
  - Measurement of water properties from stopping muons
- Also exploring cosmic ray physics:
  - Muon deficit puzzle
  - Mass composition of cosmic rays
  - Hadron composition of air showers
  - Constraining models of neutrino production in the atmosphere



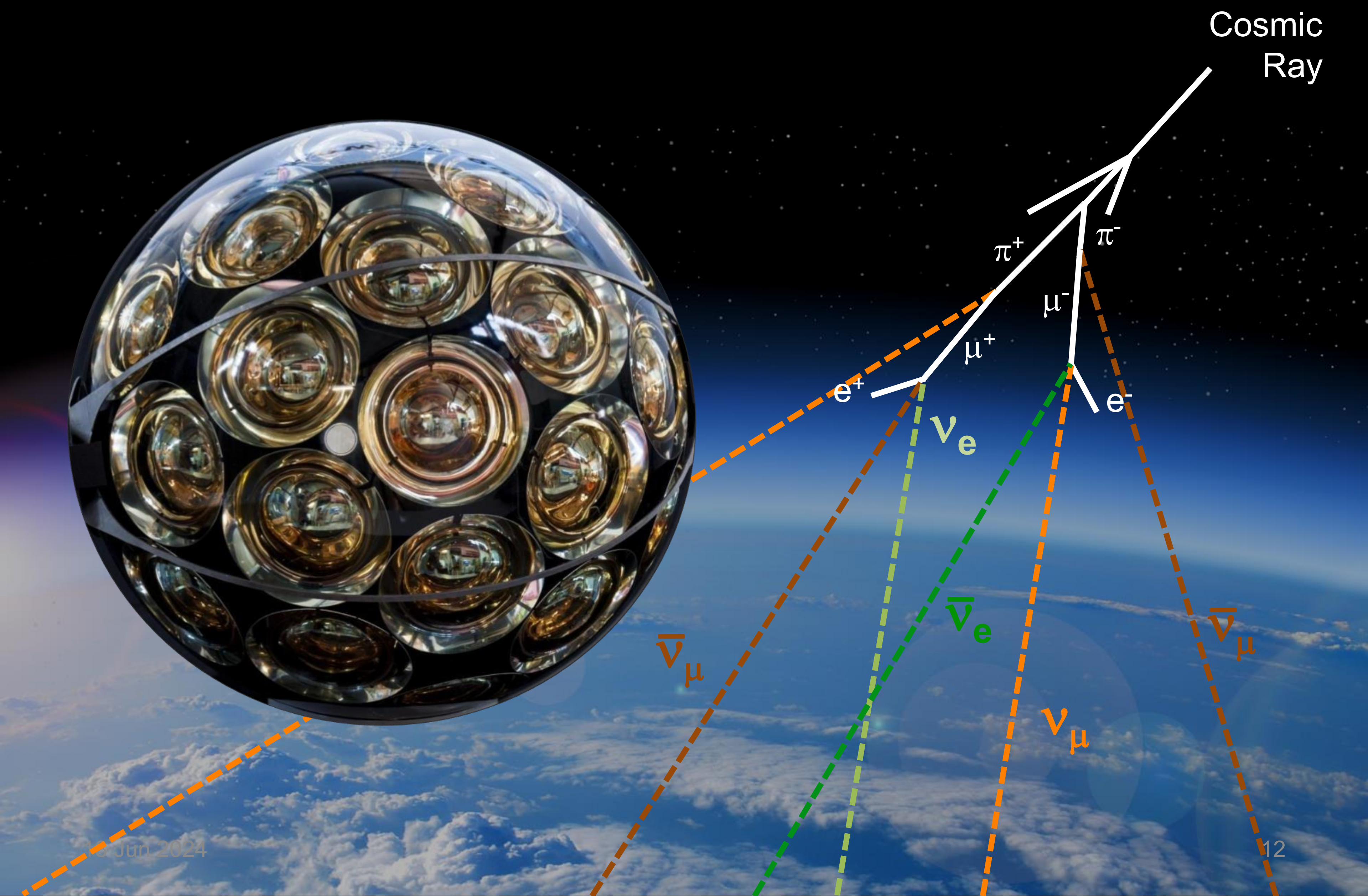
Eur. Phys. J. C 83, 344 (2023)



https://arxiv.org/abs/2403.11946

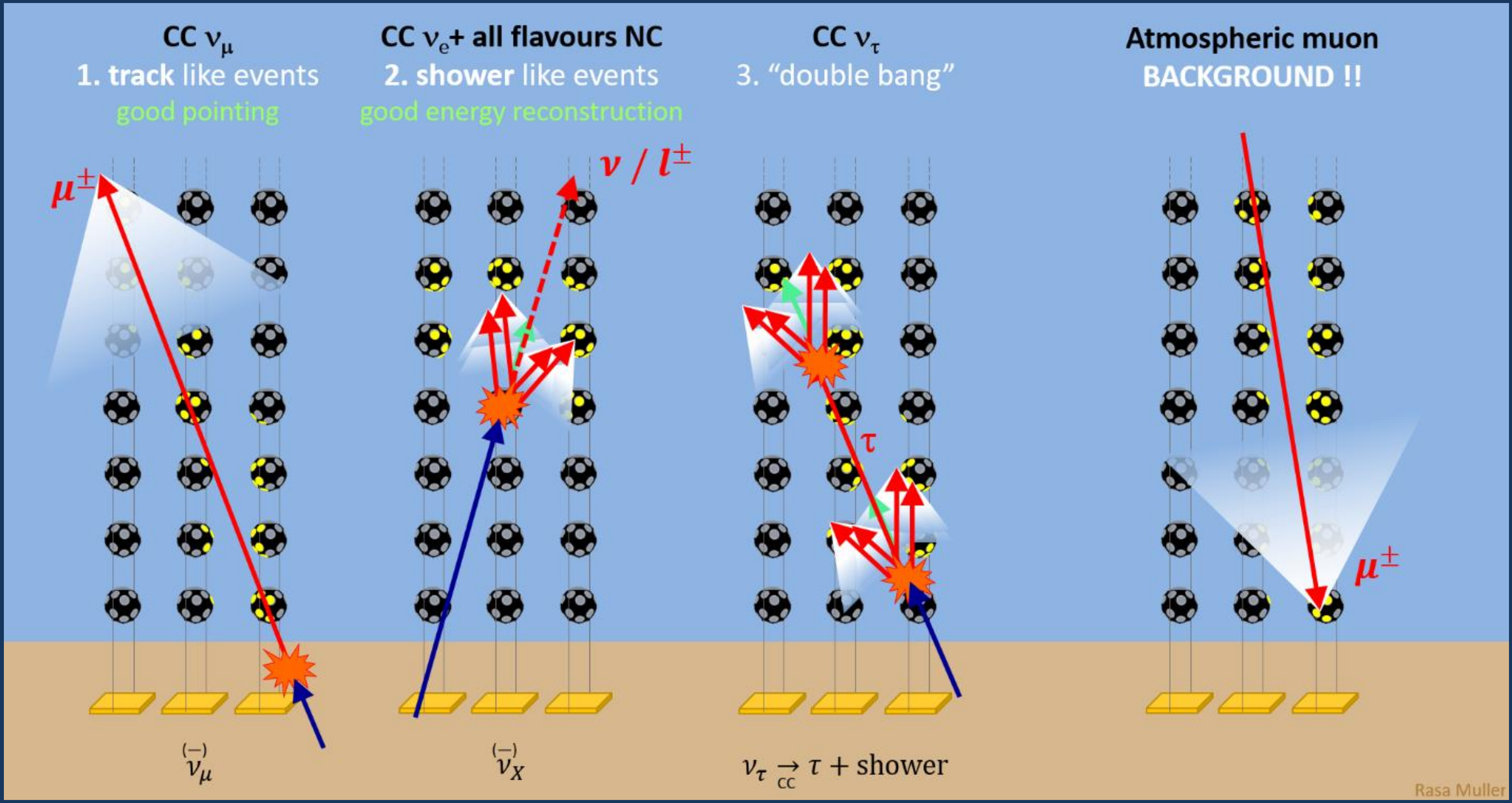


Layer 3: Atmospheric Neutrinos



Layer 3: Atmospheric Neutrinos

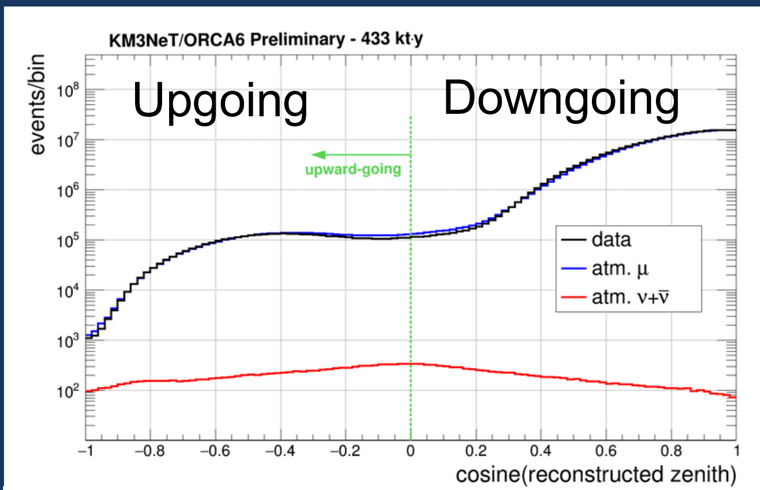
- The Earth is a great cosmic ray shield, but neutrinos don't care
- Distinct patterns of light can be used to identify neutrino flavours and background

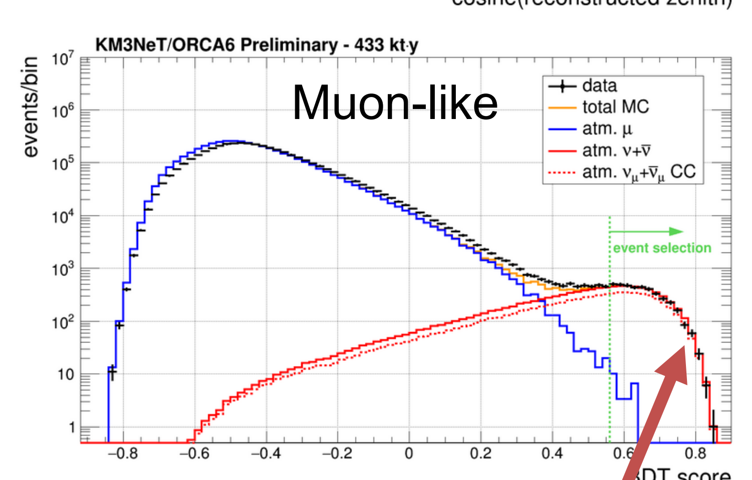


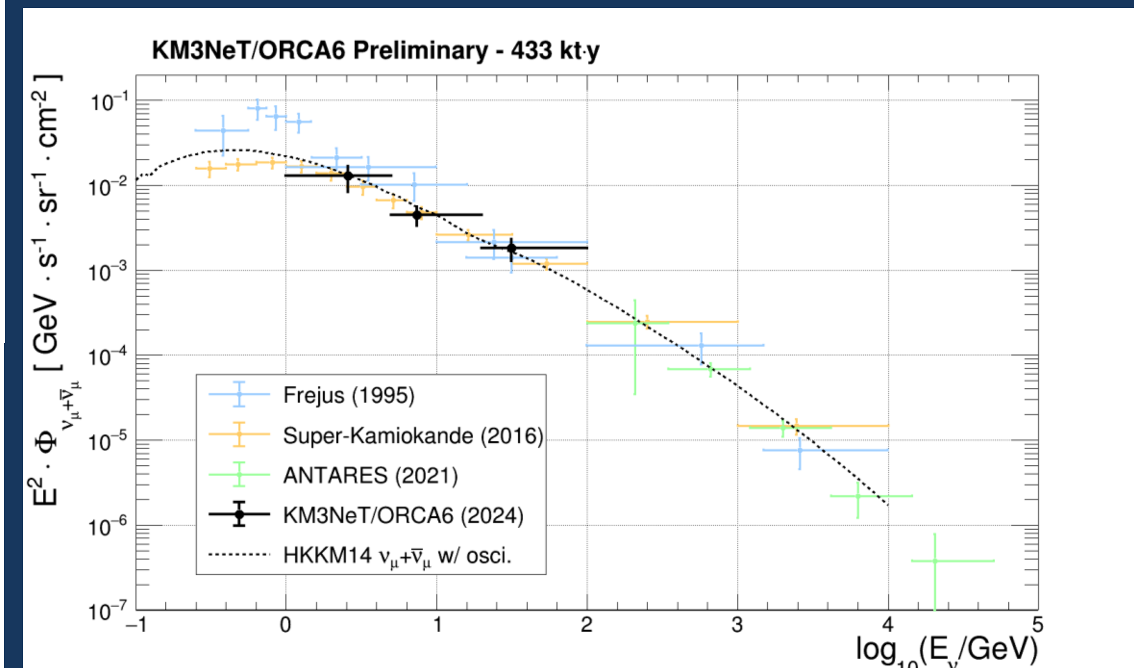
See also posters 178 and 632

Layer 3: Atmospheric Neutrinos

- First KM3NeT measurement of atm. Neutrino flux consistent with world data







Neutrino-like

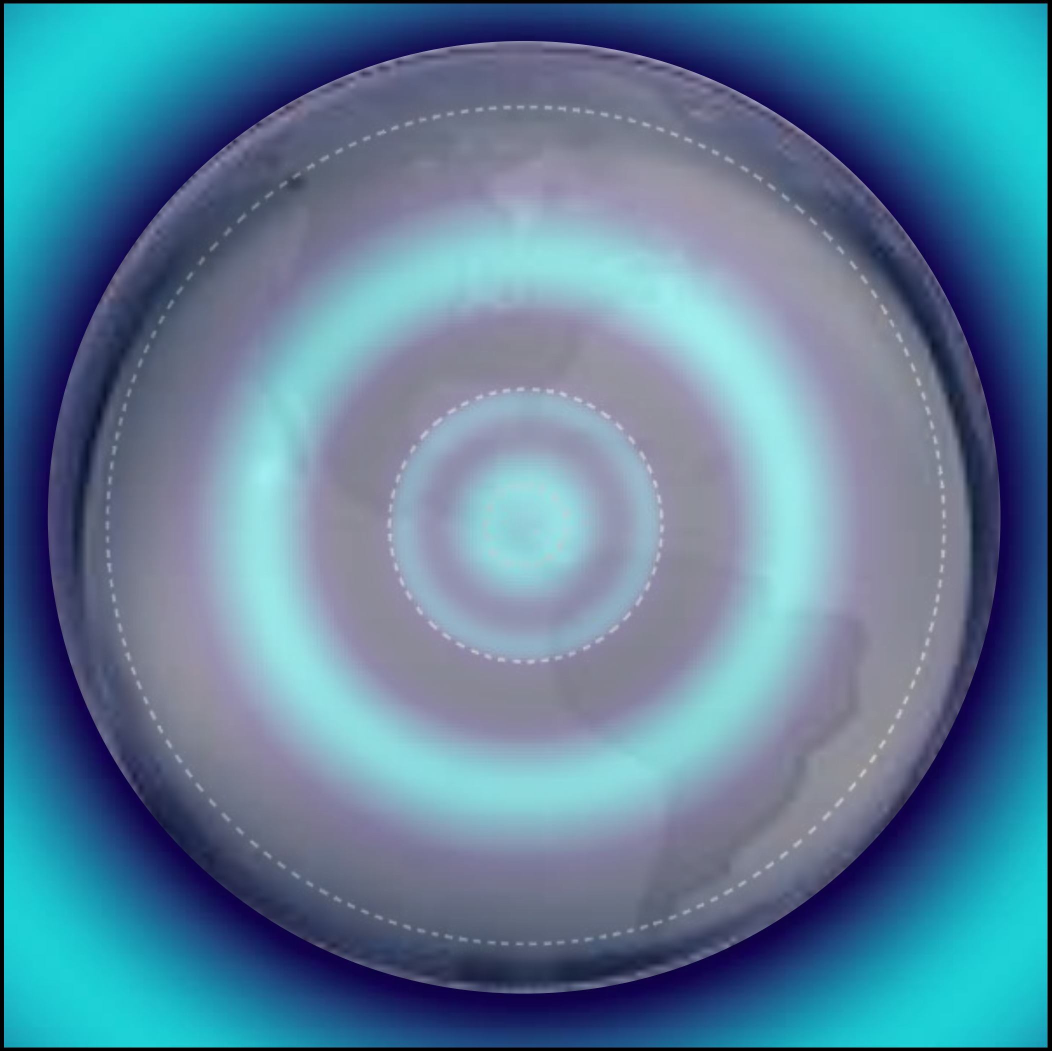
See poster 401

Neutrino Oscillations

- If you look carefully…

Neutrino Oscillations

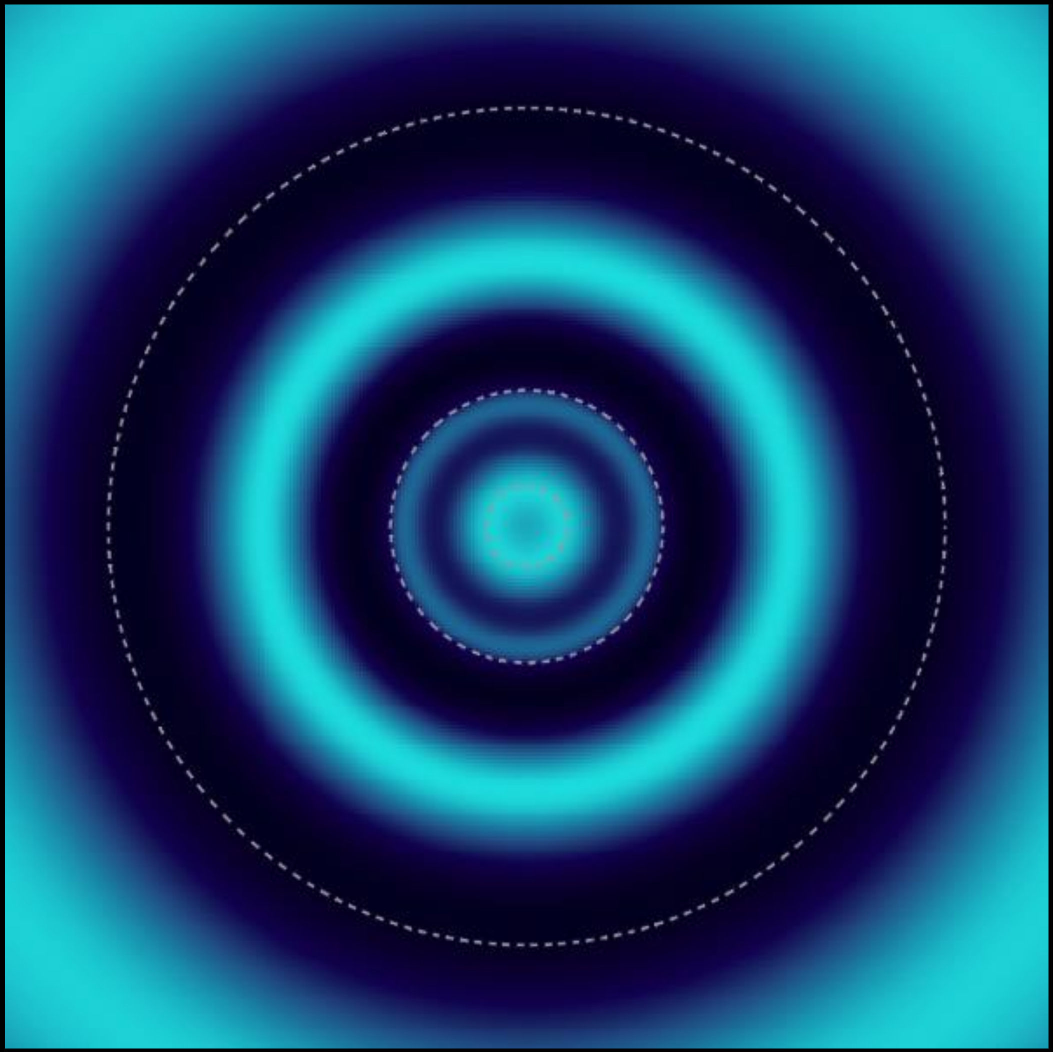
- If you look carefully, there will be rings of neutrinos…



Muon neutrinos at 4 GeV

Neutrino Oscillations

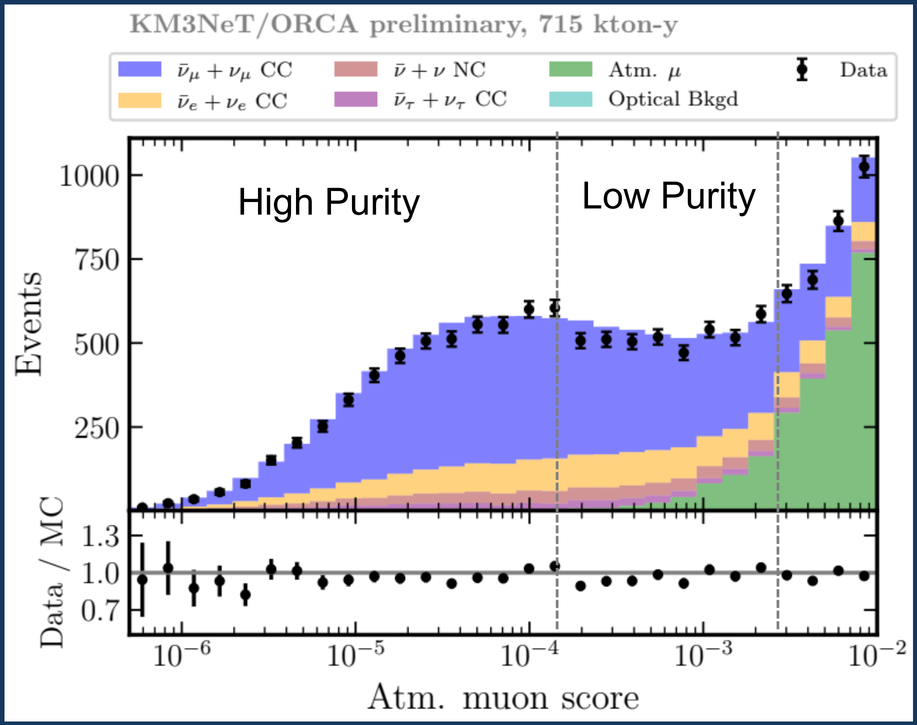
- If you look carefully, there will be rings of neutrinos…

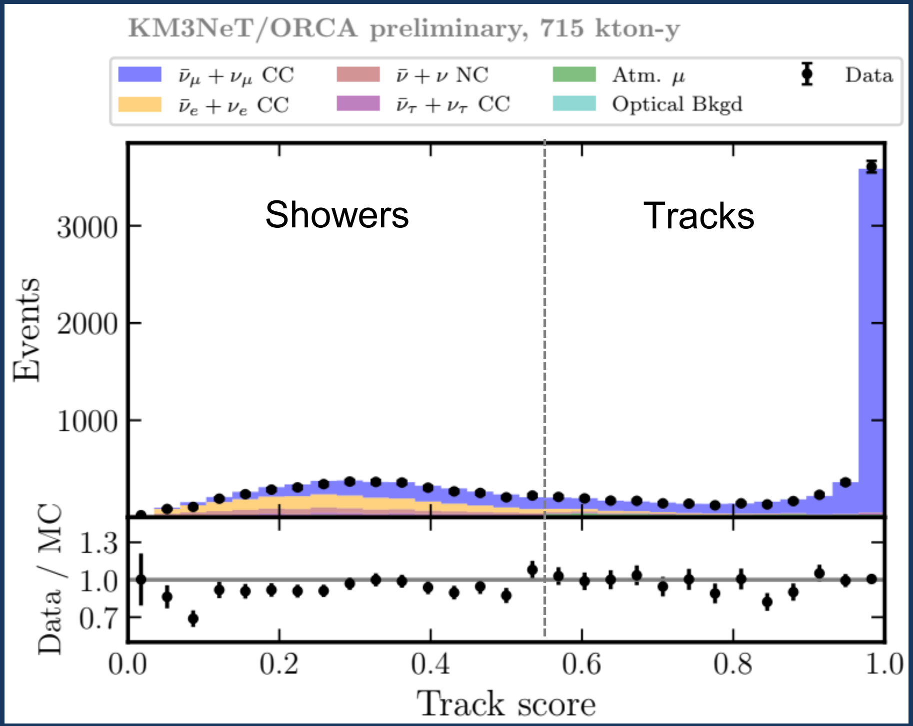


Muon neutrinos at 4 GeV

Event Selection

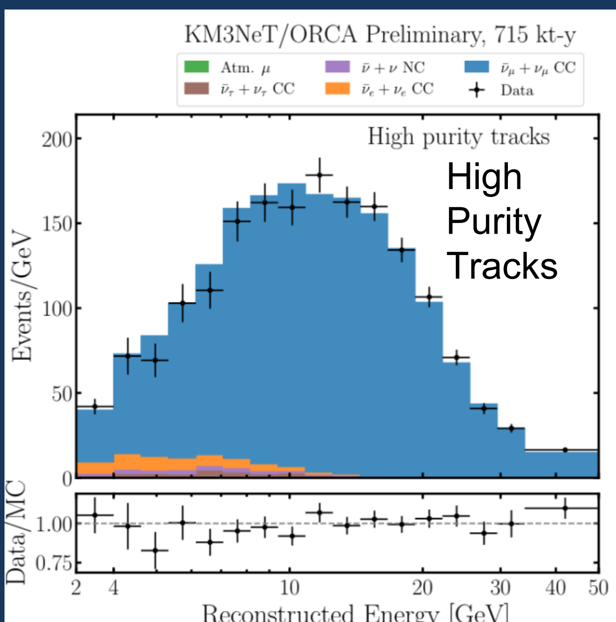
- We employ BDTs to summarize reconstructed quantities into background scores
- 3 selection regions are defined: High purity tracks, low purity tracks, and showers
- Excellent agreement between data and simulation for neutrinos and atm. muons

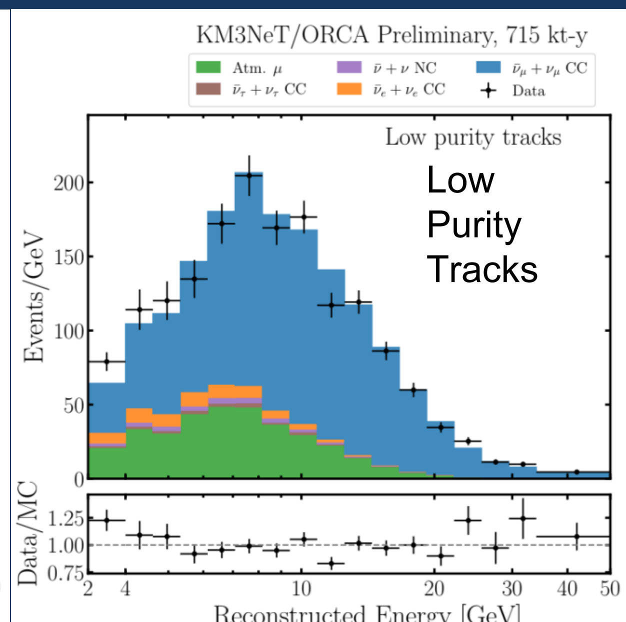


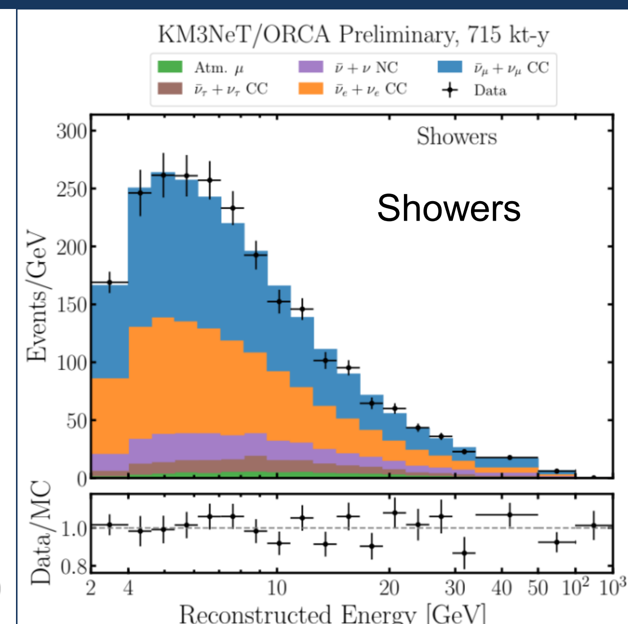


Event Selection

- 9751 neutrino candidates in our selection with similar numbers in each class
- 97% pure ν_μ-CC sample in high purity track-like class
- 91% accuracy in classifying ν_e-CC events as showers
- ~1300 ν_e-CC events expected in shower-like sample

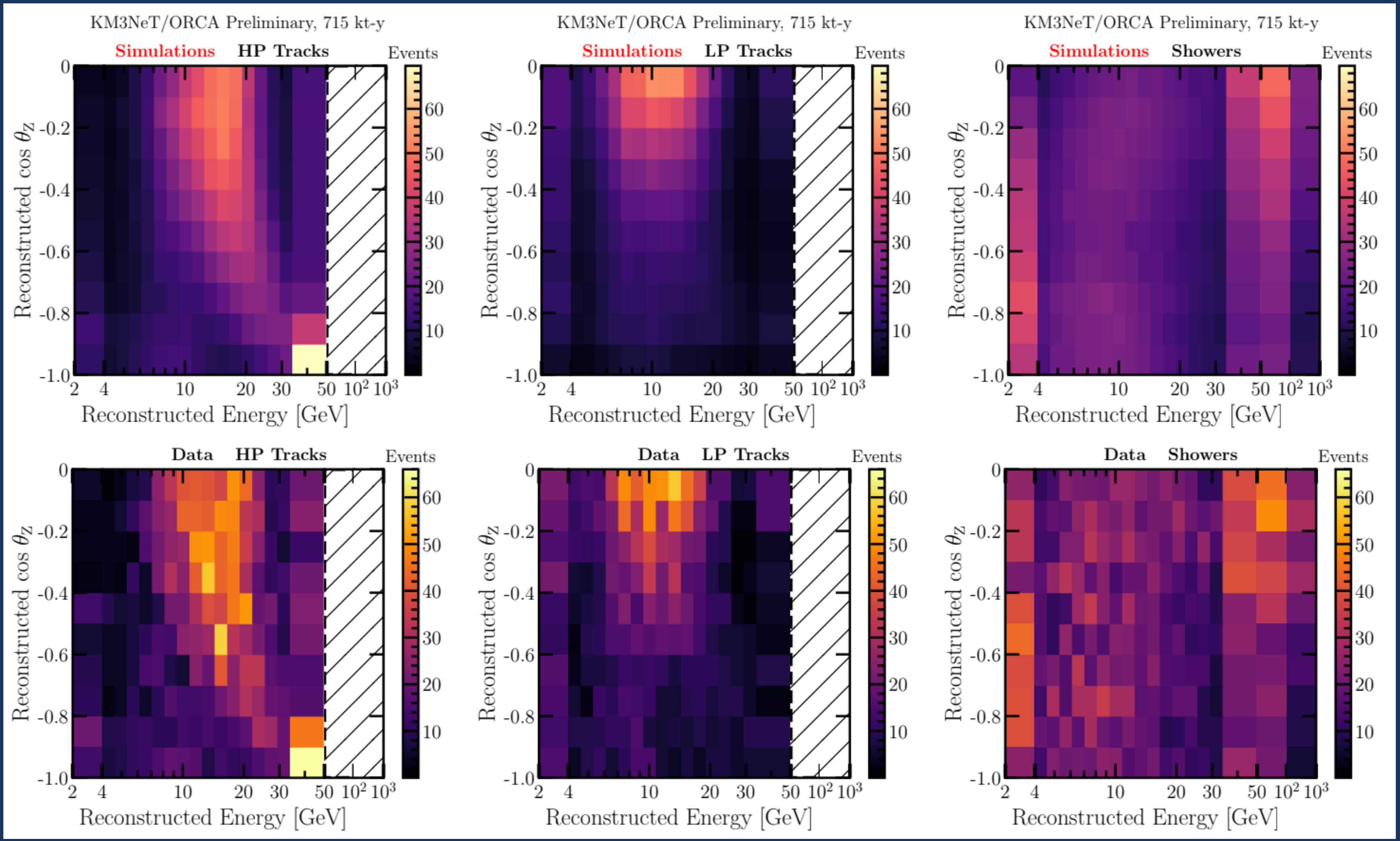






Oscillation Patterns

- Analyze data in 2D space of energy and direction
- Oscillation best fit describes data very well (-2logL p-value: 41%)



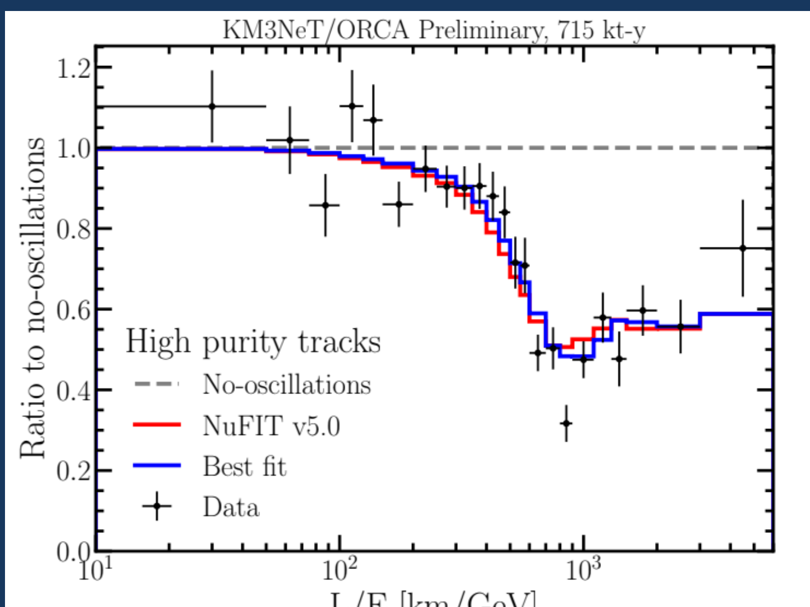
Improved Measurement

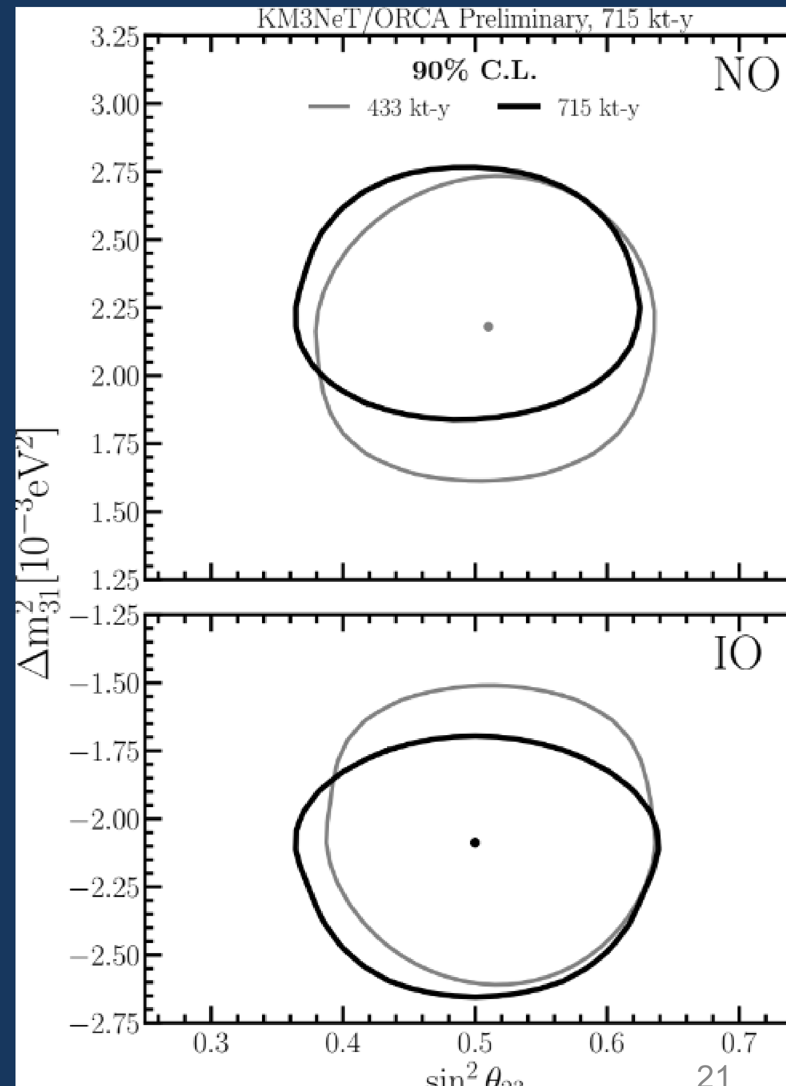
- New measurement uses 715 kt-y of data (65% increase over 2023 dataset)
- Clear oscillation pattern in L/E
- Slight preference for Inverted Ordering (IO)

$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3}\mathrm{eV}^2, & \mathrm{IO} \\ [2.10, 2.37] \times 10^{-3}\mathrm{eV}^2, & \mathrm{NO} \end{cases}$$

$$\sin^2\theta_{23} = 0.50 \pm 0.07$$

$$2\log(\mathcal{L}_{IO}/\mathcal{L}_{NO}) = 0.61$$





See poster 358

Improved Measurement

- Already providing relevant information with exposure equivalent to only 37 days of full ORCA detector
- Fully consistent with world data

$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3}\mathrm{eV}^2, & \mathrm{IO} \\ [2.10, 2.37] \times 10^{-3}\mathrm{eV}^2, & \mathrm{NO} \end{cases}$$

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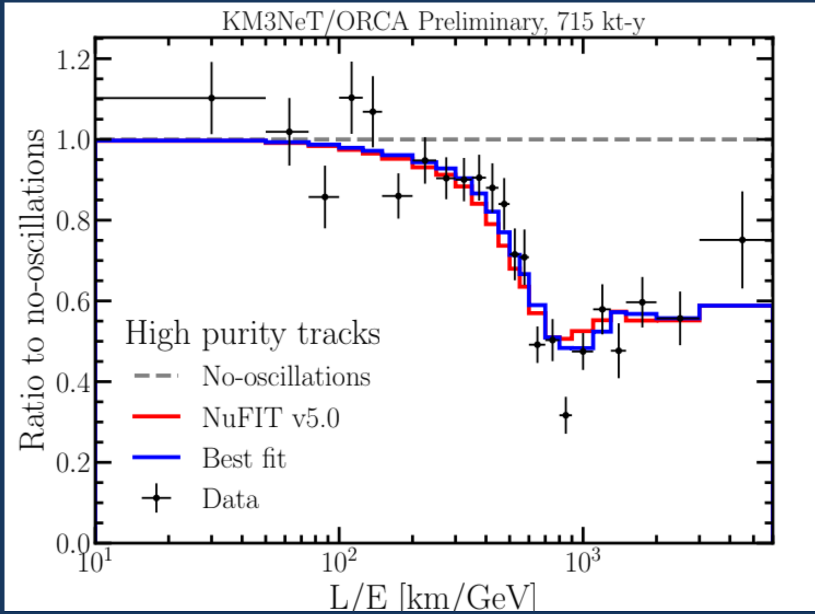
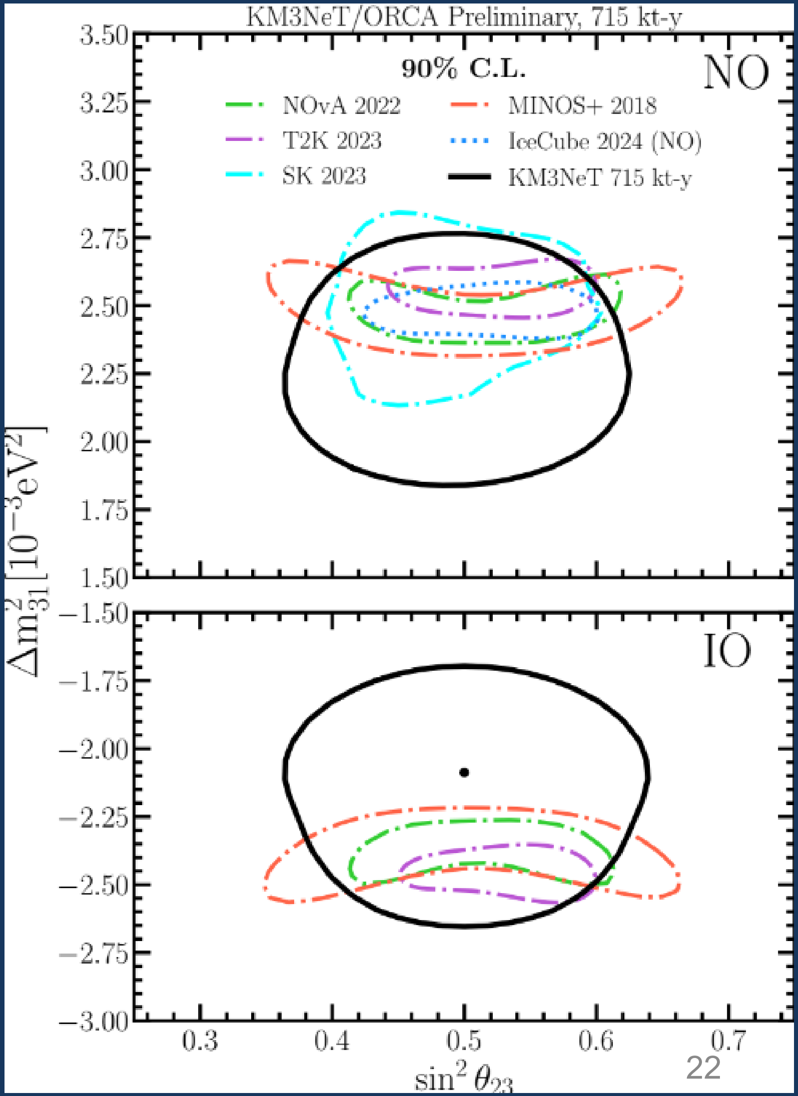
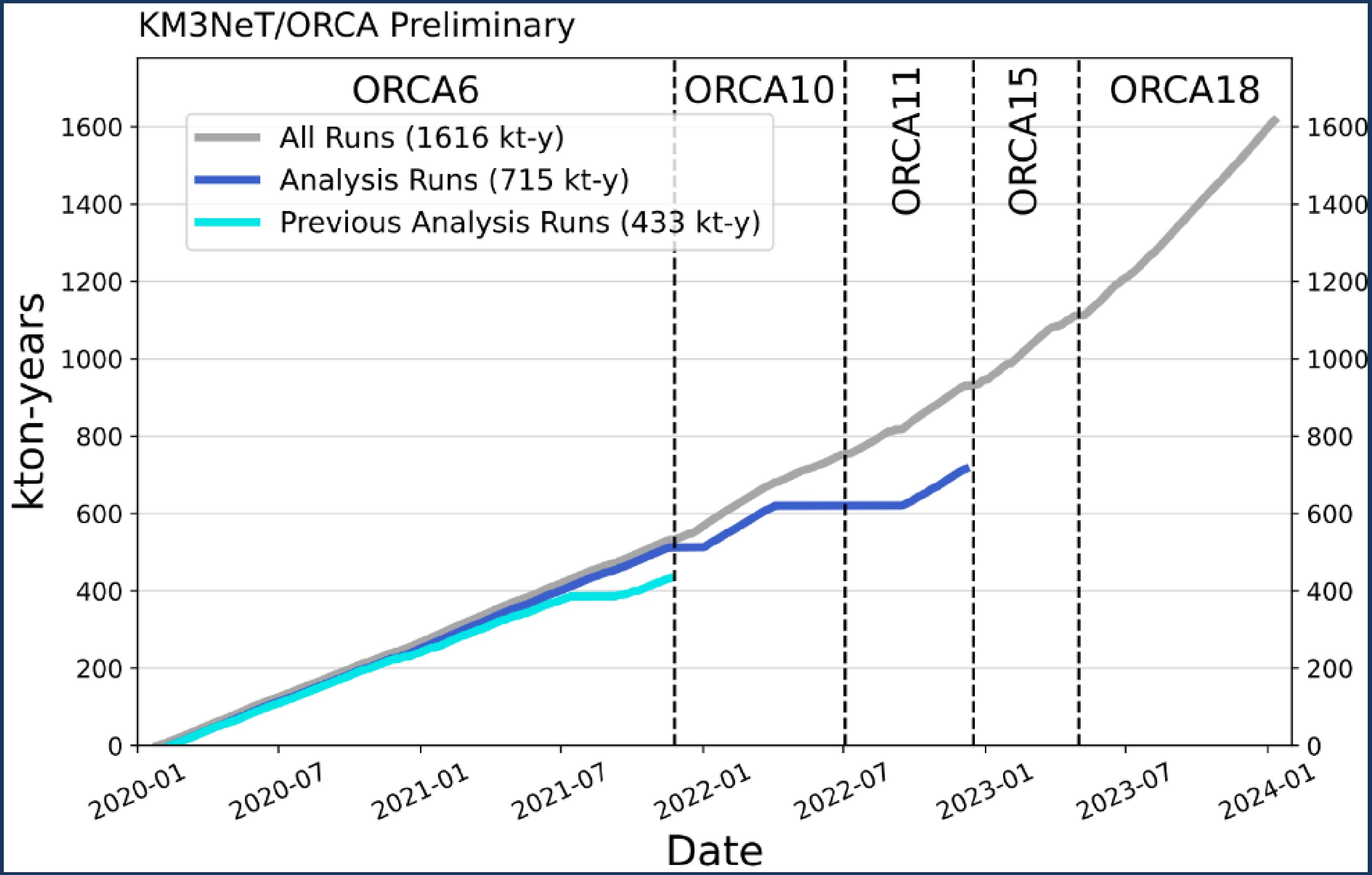




See poster 358

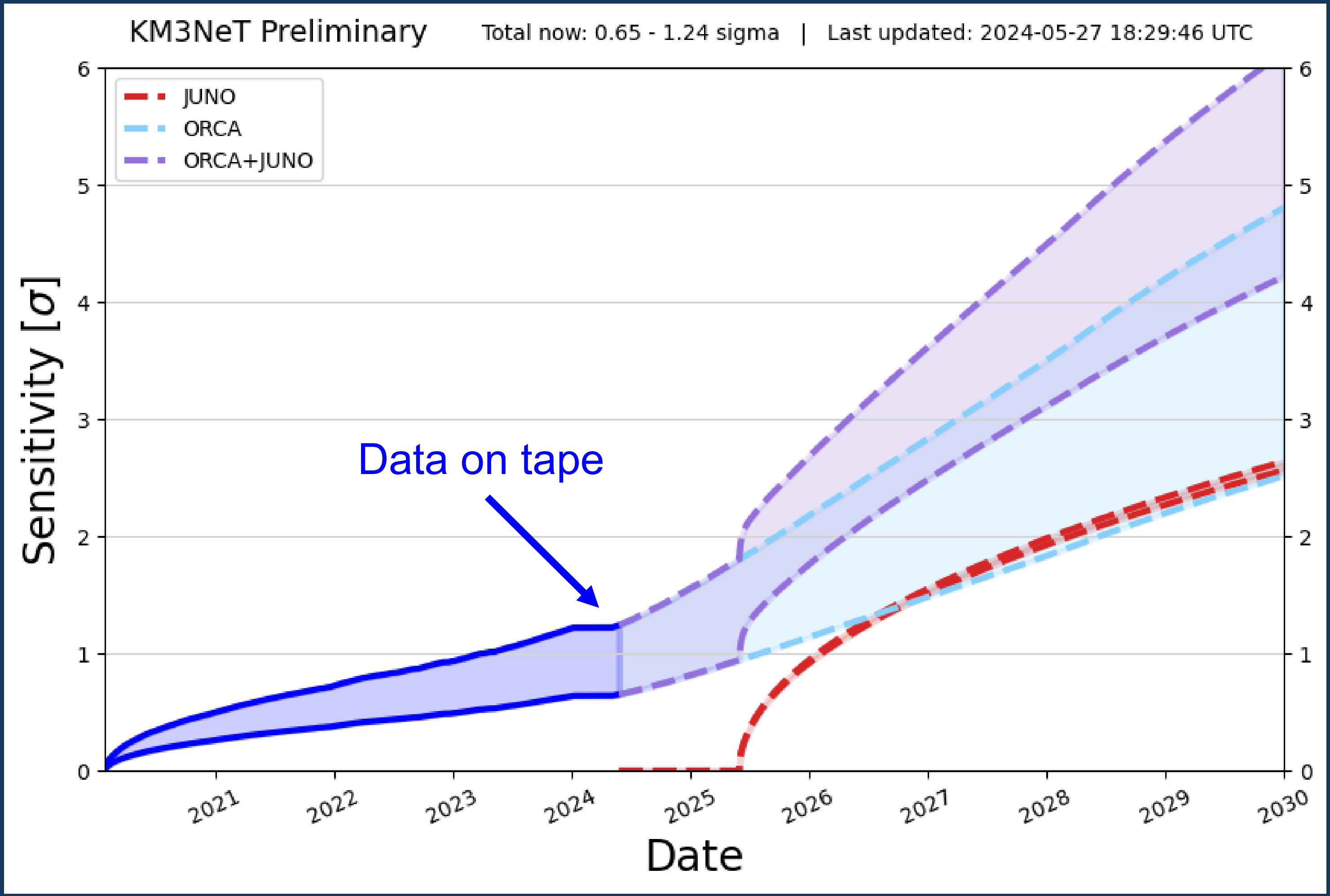
Data Already Here

- Already collected and processed more than 1.6 Mt-y of data
- Current analysis only covers the first half of this data, prioritized in data processing
- Expect to update these results very soon with remaining available data



And More Data is Coming

- Current projections including detector construction schedule show 5σ NMO determination in reach within this decade when combined with JUNO

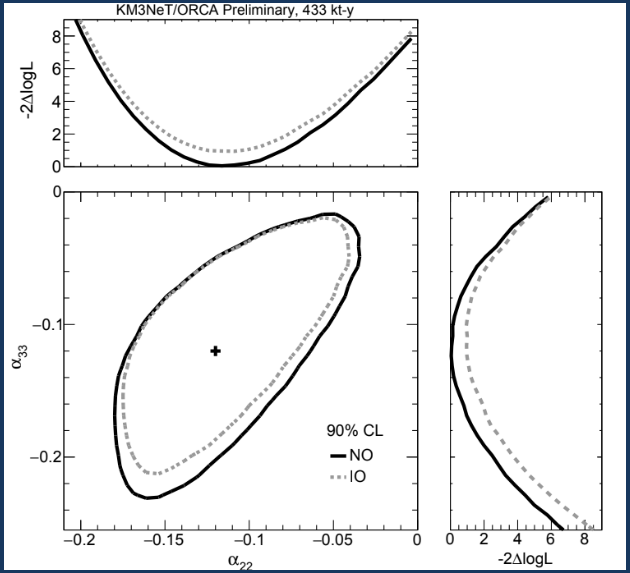


See talk by J. Brunner on Thursday

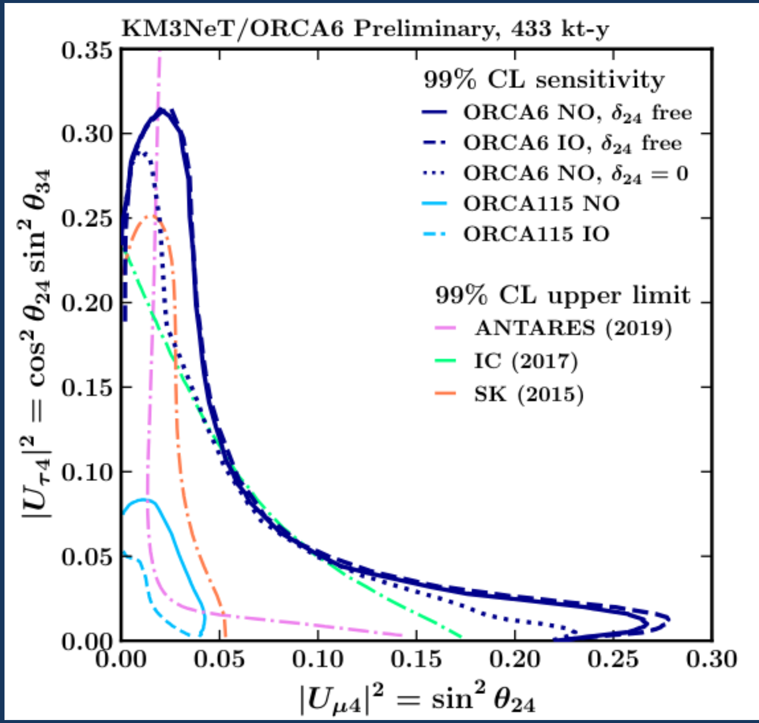
New Physics Models

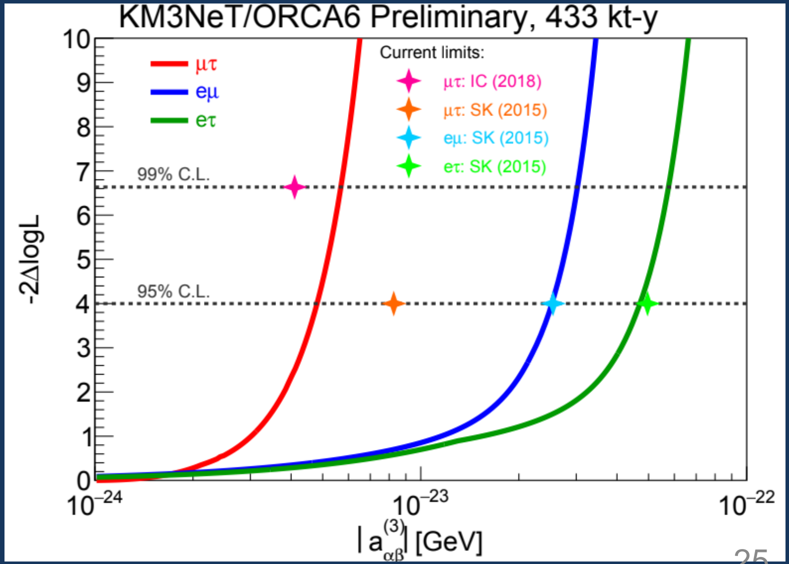
- Many other alternative models can be explored with the same datasets
- Some examples in posters today and on Friday

Non-Unitary Mixing



Sterile Neutrinos

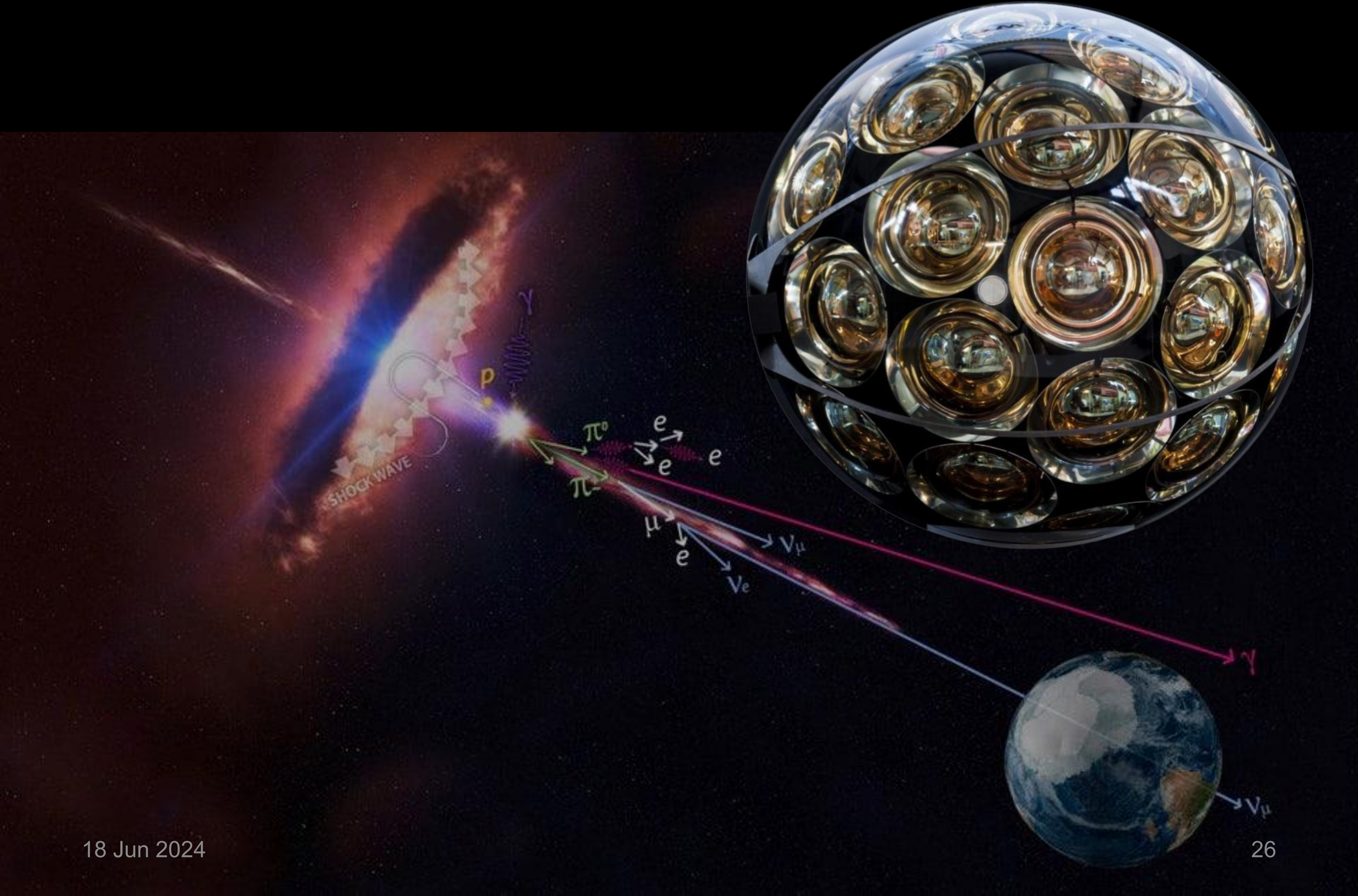




Lorentz Invariance Violation

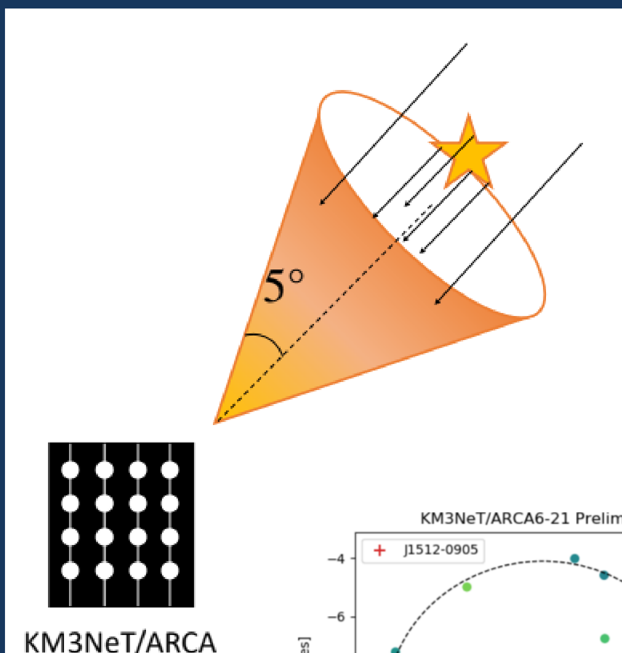
See posters 224, 341 and 529

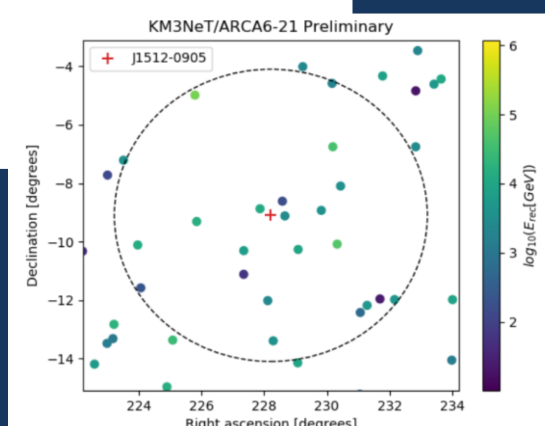
Astrophysical Neutrinos

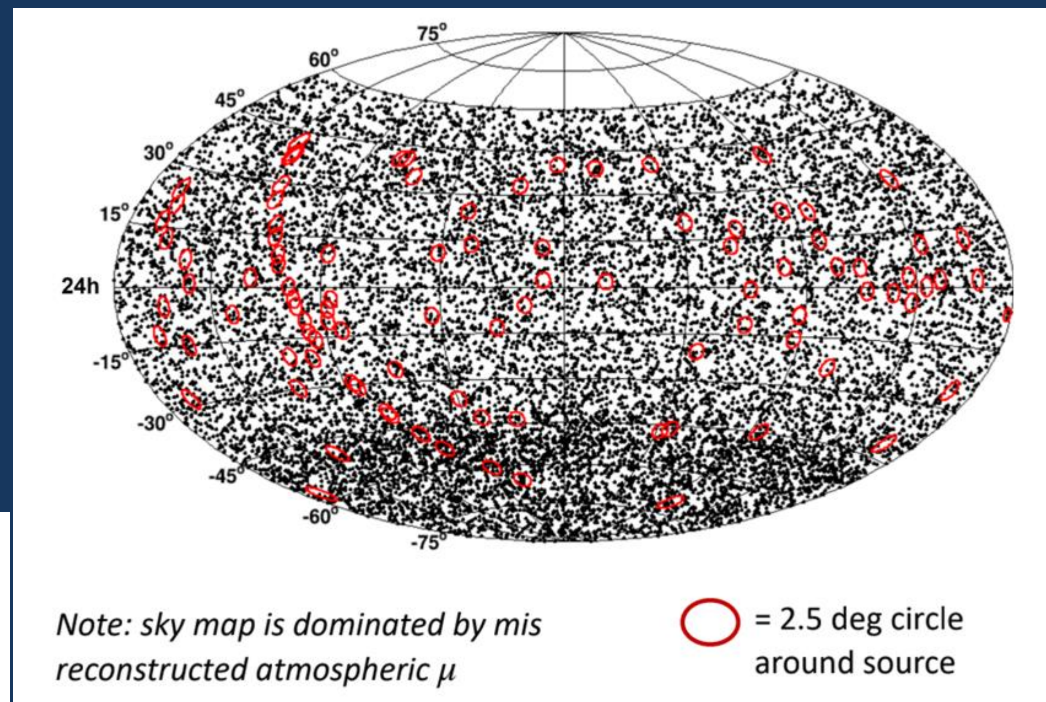


The Final Layer

- Underneath a large atmospheric neutrino foreground, we search for cosmic neutrinos
- Localized sources may provide a higher concentration
- Look for excess of events within 5 degrees of known objects of interest

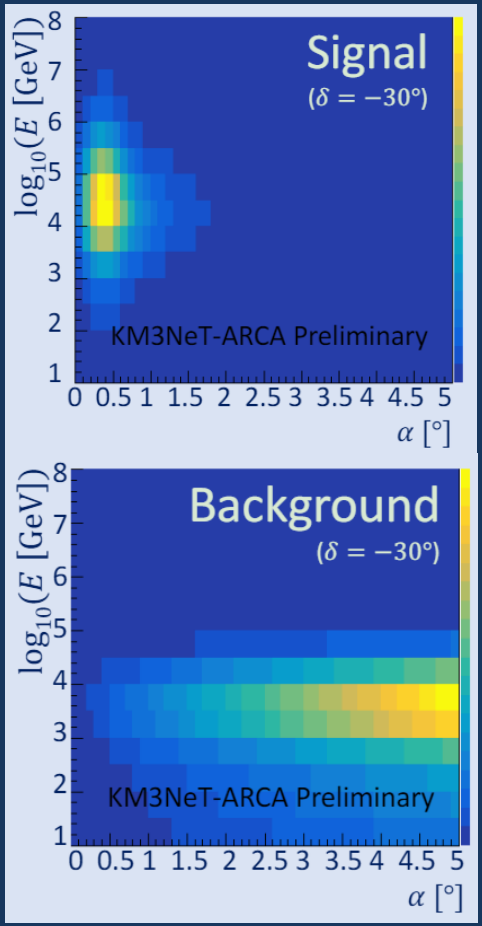


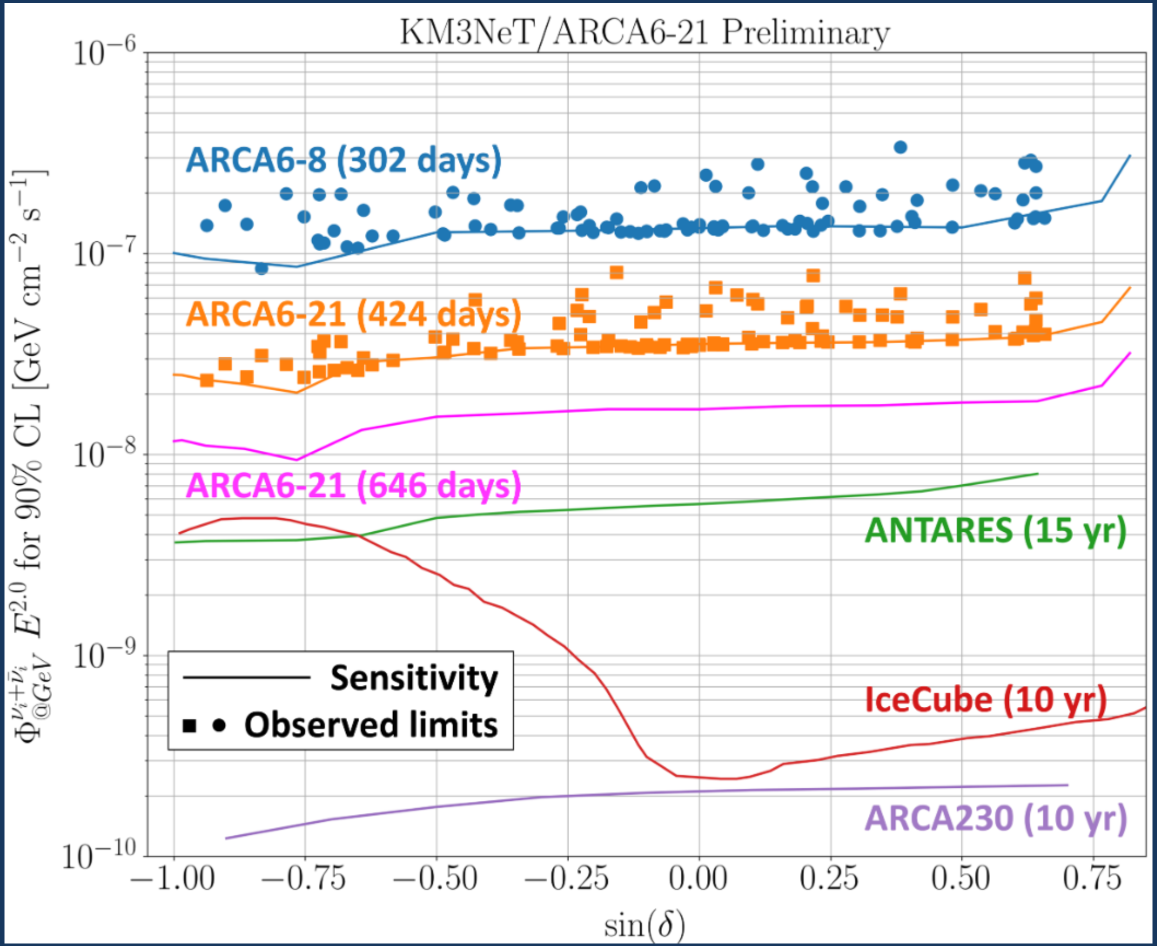




Point Source Analysis

- Analysis done in 2D space of energy and distance from the source
- KM3NeT sensitivity improving fast and approaching ANTARES soon

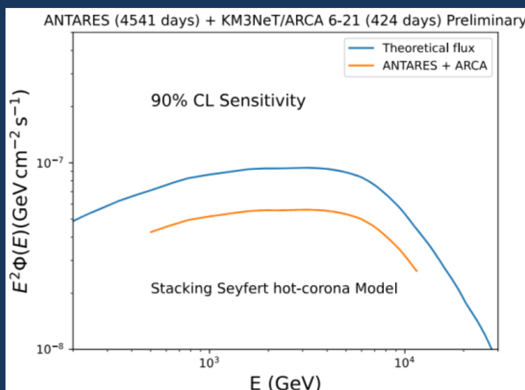


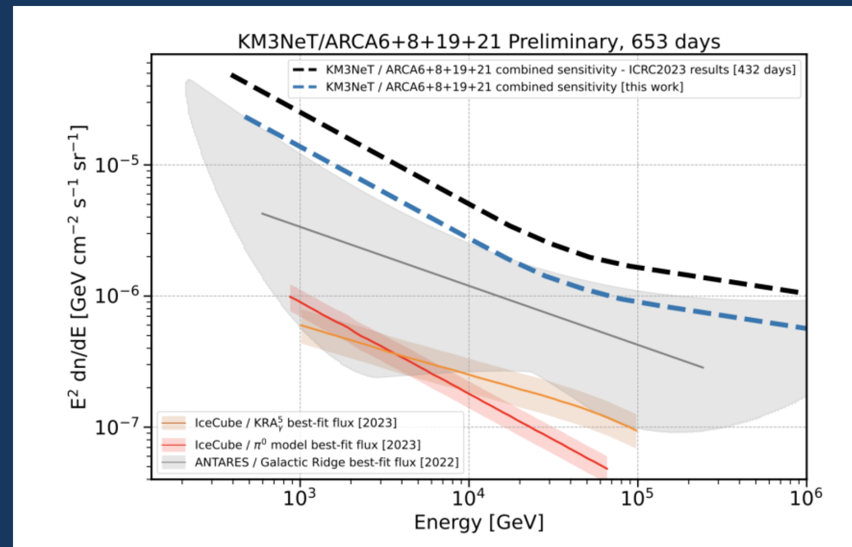


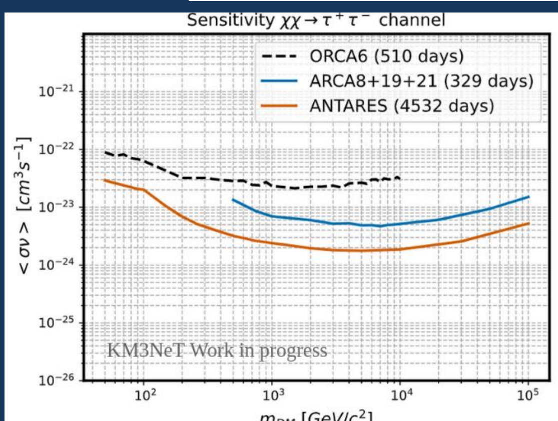
See poster 195

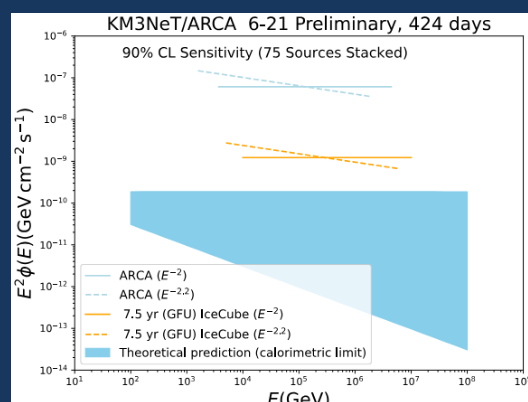
Further Tactics

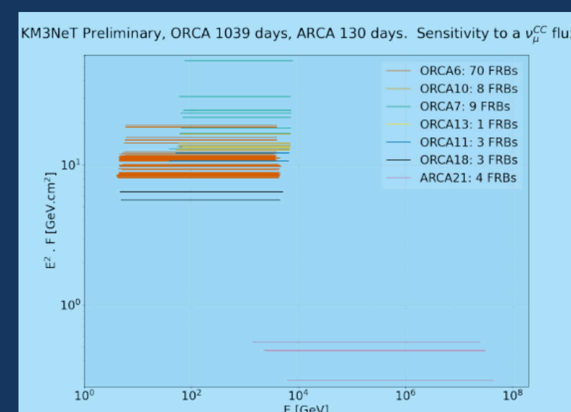
- Individual sources may be faint
- Pool statistics from multiple known sources for extra power
- Look for transient sources with known time window to further reduce background
- Focus on nearby galactic neutrinos
- Also search for Dark Matter







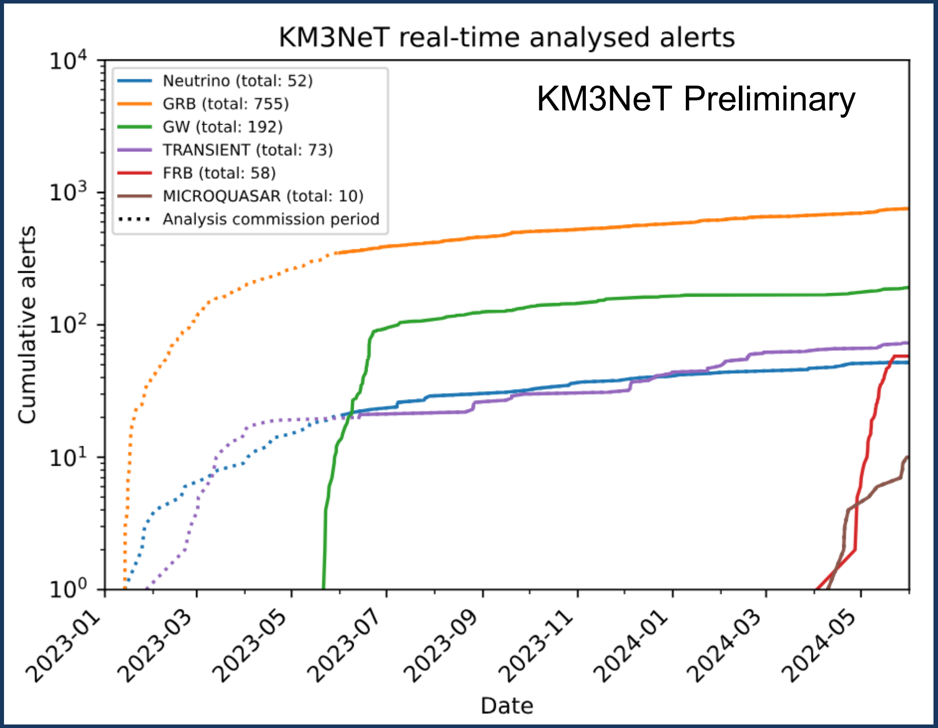


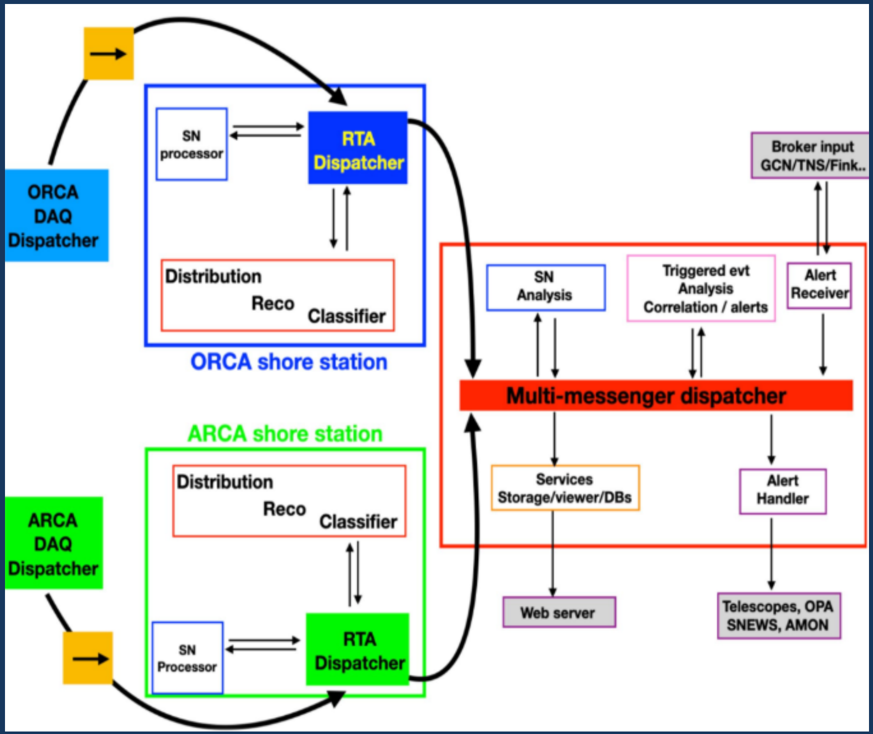


See posters 180, 211, 213, 254, and 633

Multi-Messenger

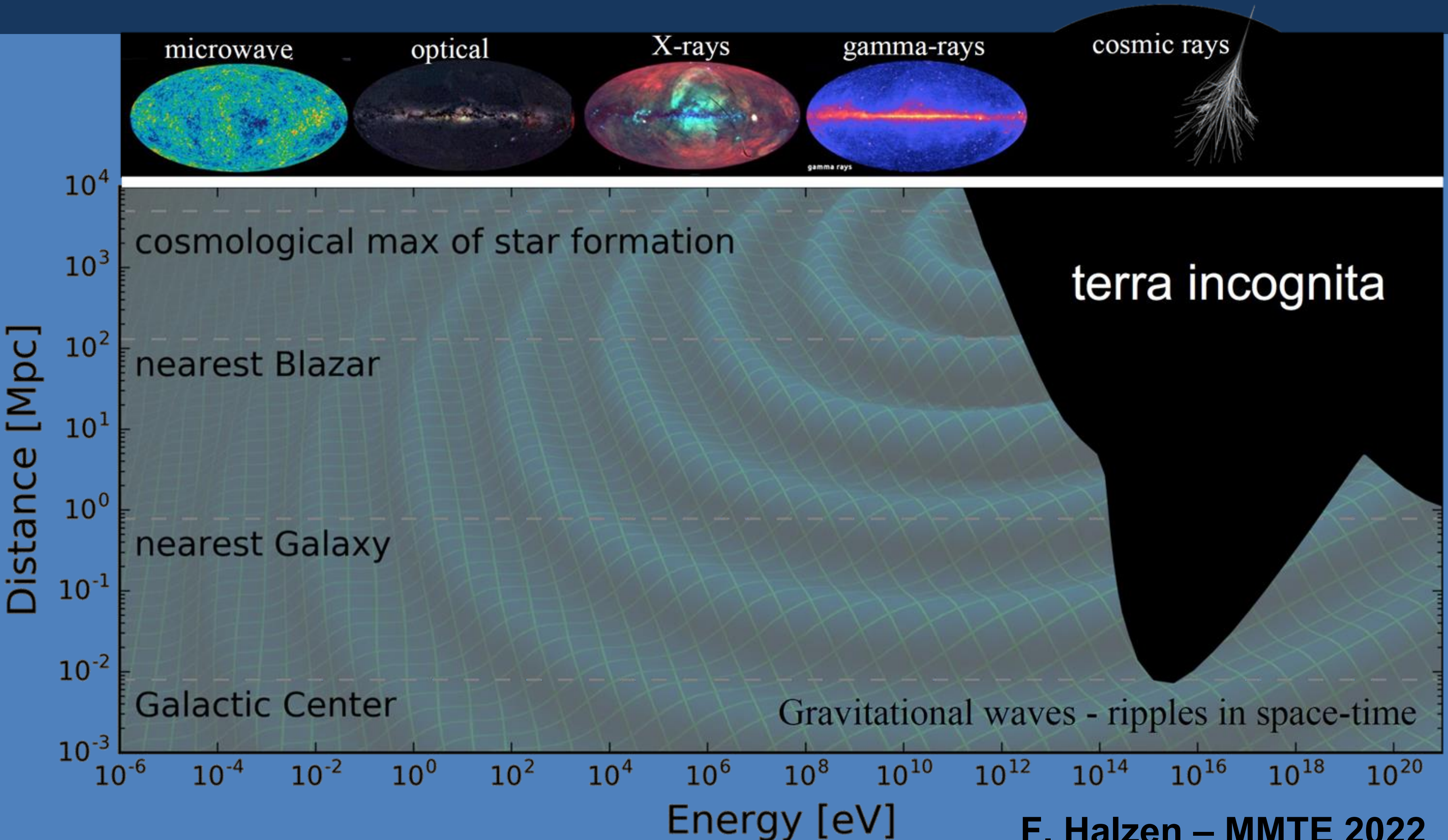
- A real time analysis of events is also underway
- KM3NeT already receiving and investigating alerts from multiple observatories
- No significant signals observed so far in received alerts
- Preparing online system to start sending alerts from KM3NeT later this year





See posters 375 and 511

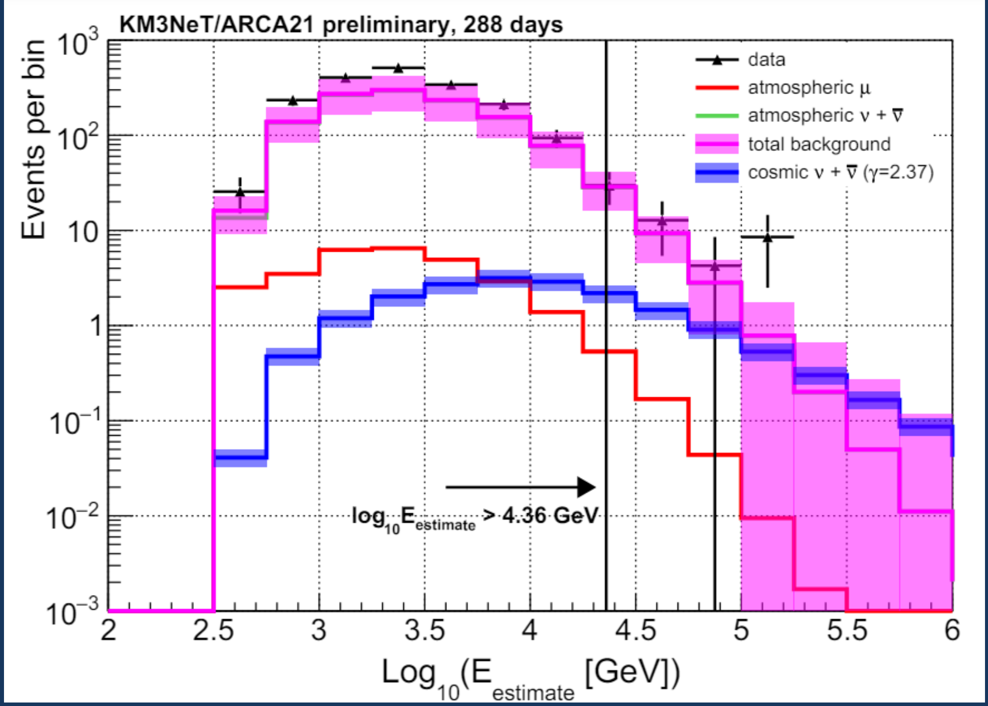
The Unknown

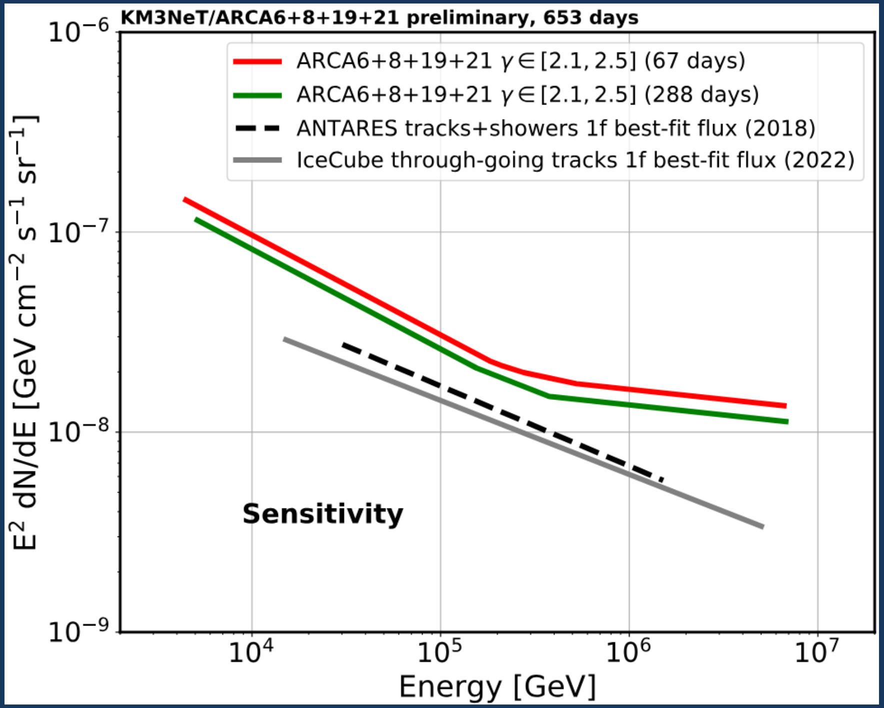


F. Halzen – MMTE 2022

Diffuse Analysis

- Search for cosmic neutrinos via high-energy excess over the atmospheric background
- Atmospheric neutrinos expected to taper off above 100 TeV scale
- Sensitivities updated with 221 more days of ARCA21 data (4x larger than 2023 result)



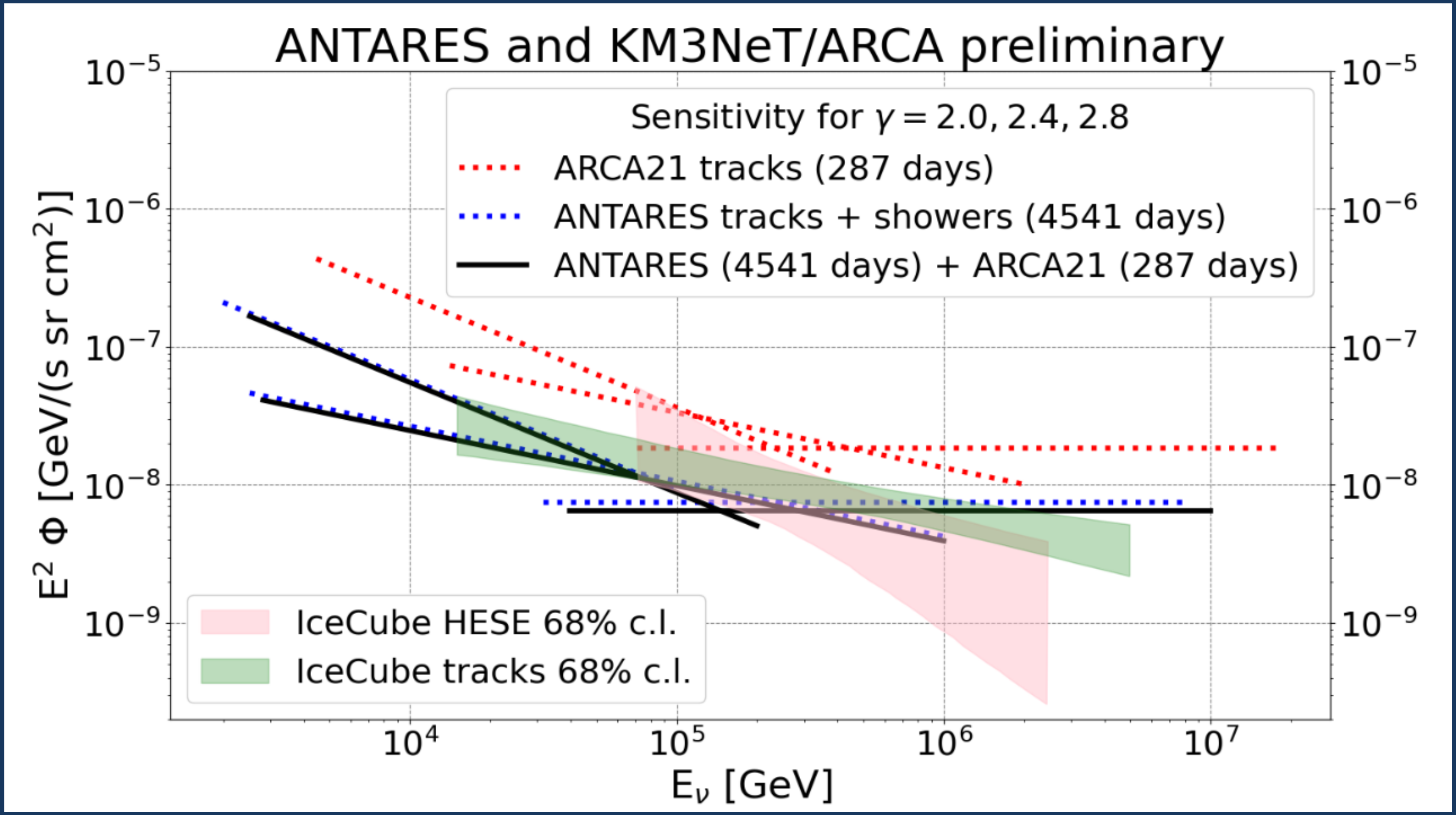


Data and MC scaled up from 67 day sample

See poster 633

Diffuse Analysis

- Diffuse flux already observed by IceCube
- ARCA and ANTARES joining forces to confirm the full sky flux



See poster 225

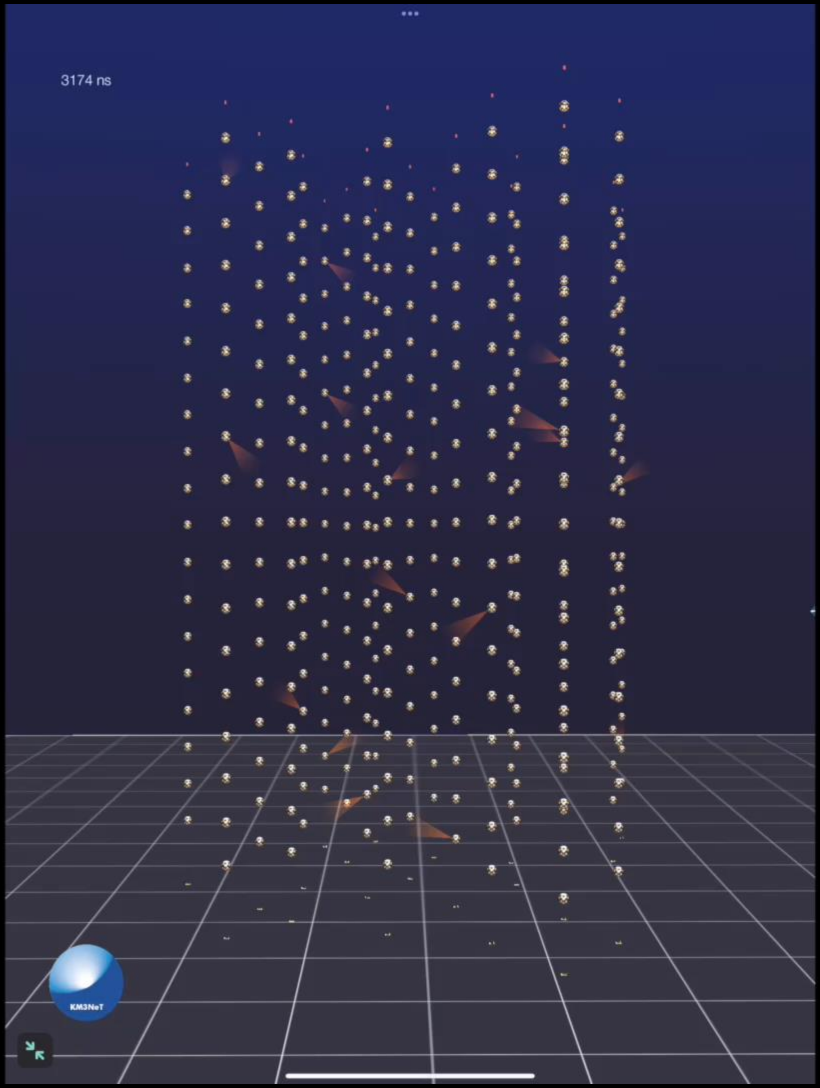
Uncharted Territory

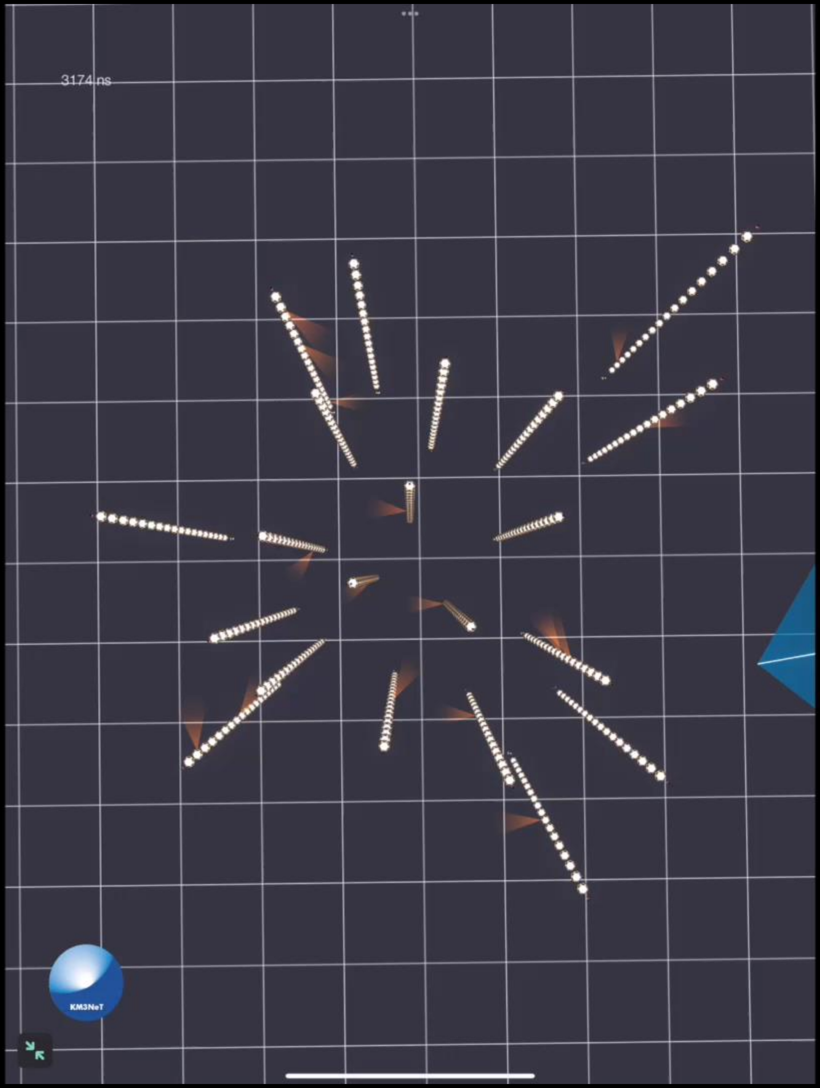
At the highest energies, there's darkness…

Uncharted Territory

At the highest energies, there's darkness… most of the time

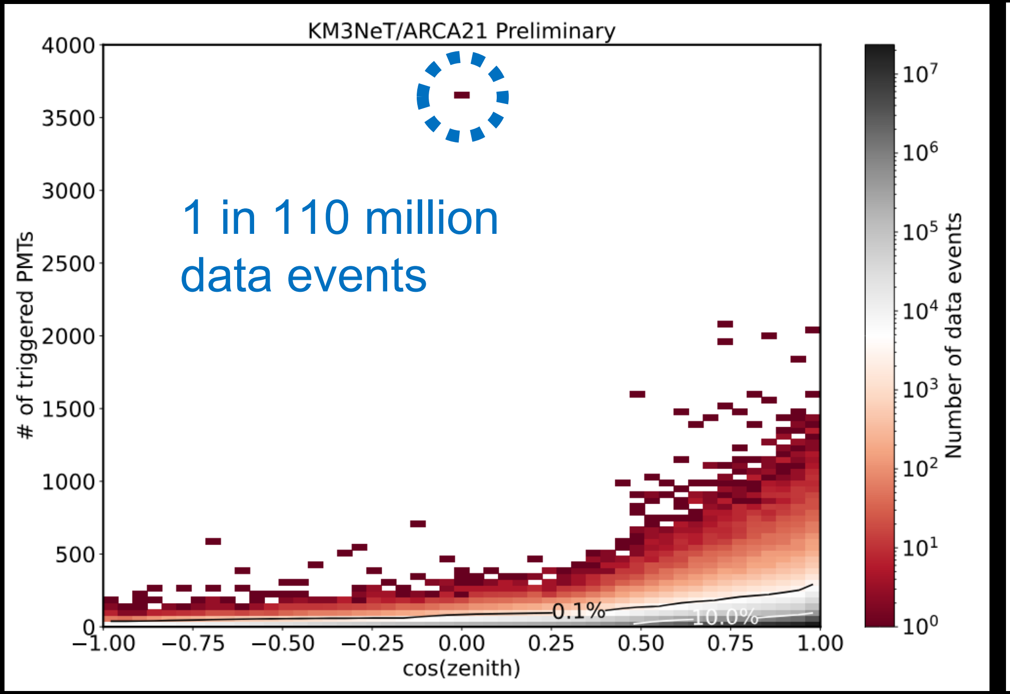
Uncharted Territory

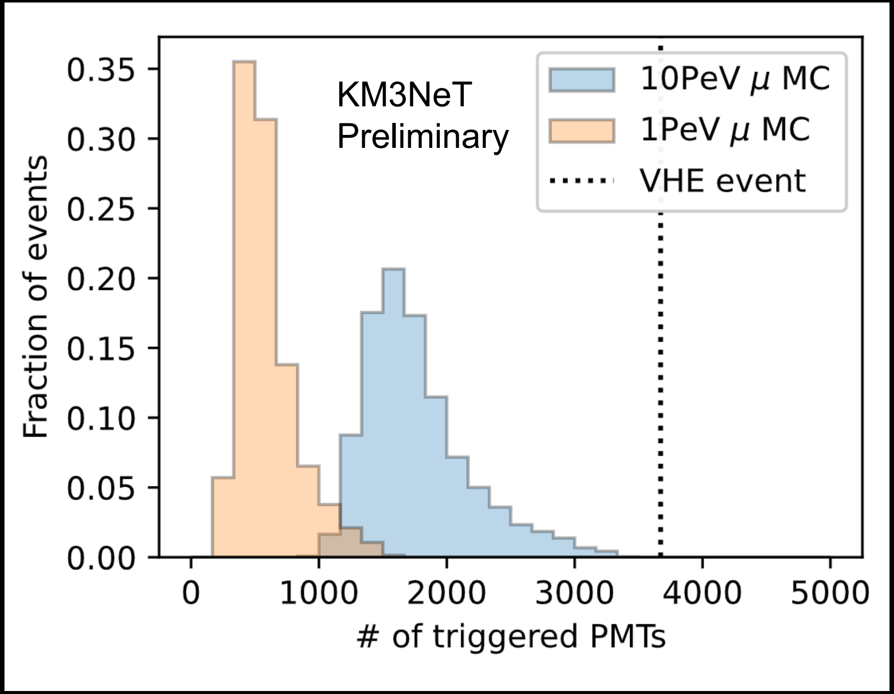




Uncharted Territory

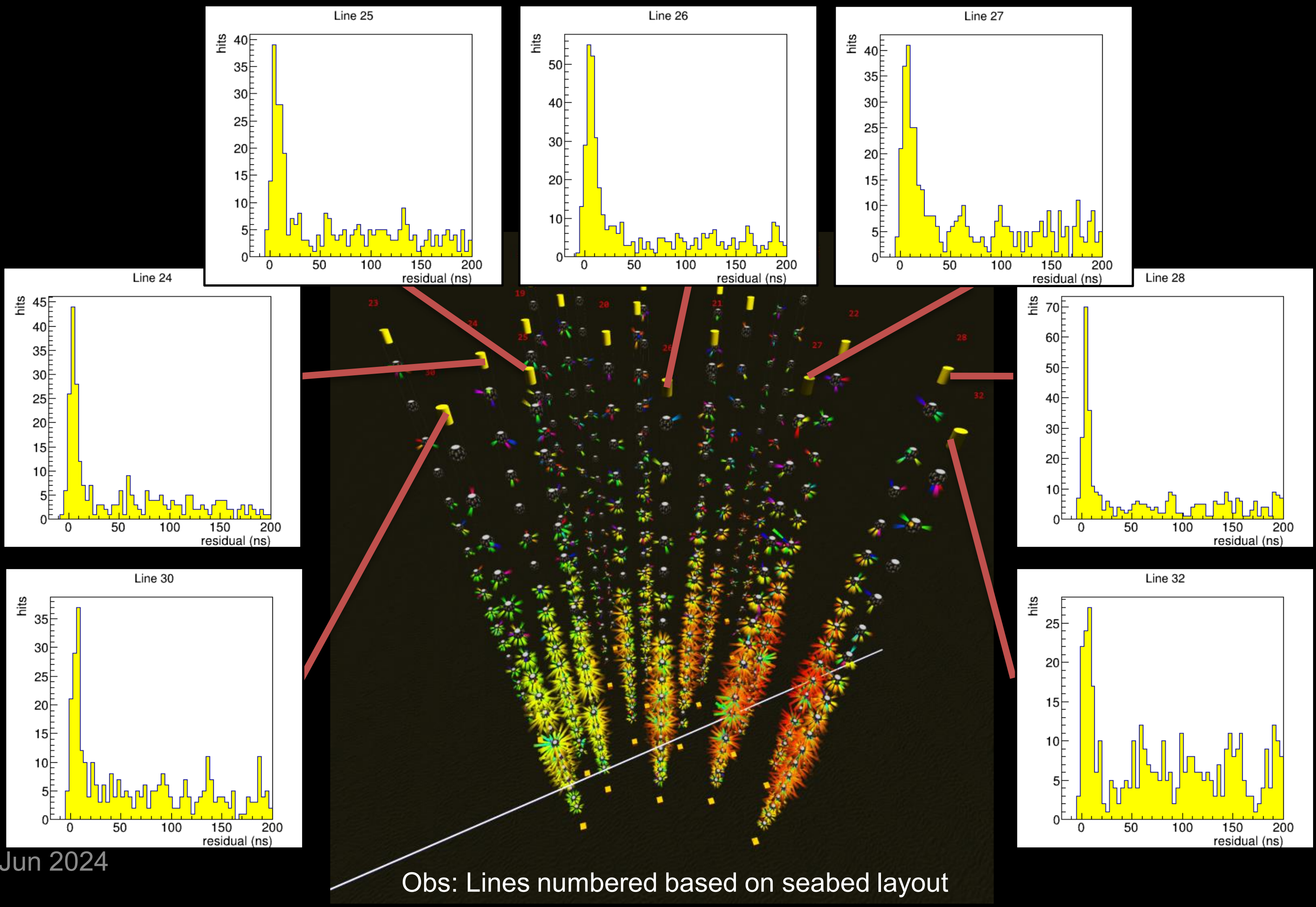
- Significant event observed with huge amount of light
- Horizontal event (1° above horizon) as expected since earth opaque to neutrinos at PeV scale
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light
  - Likely multiple 10's of PeV





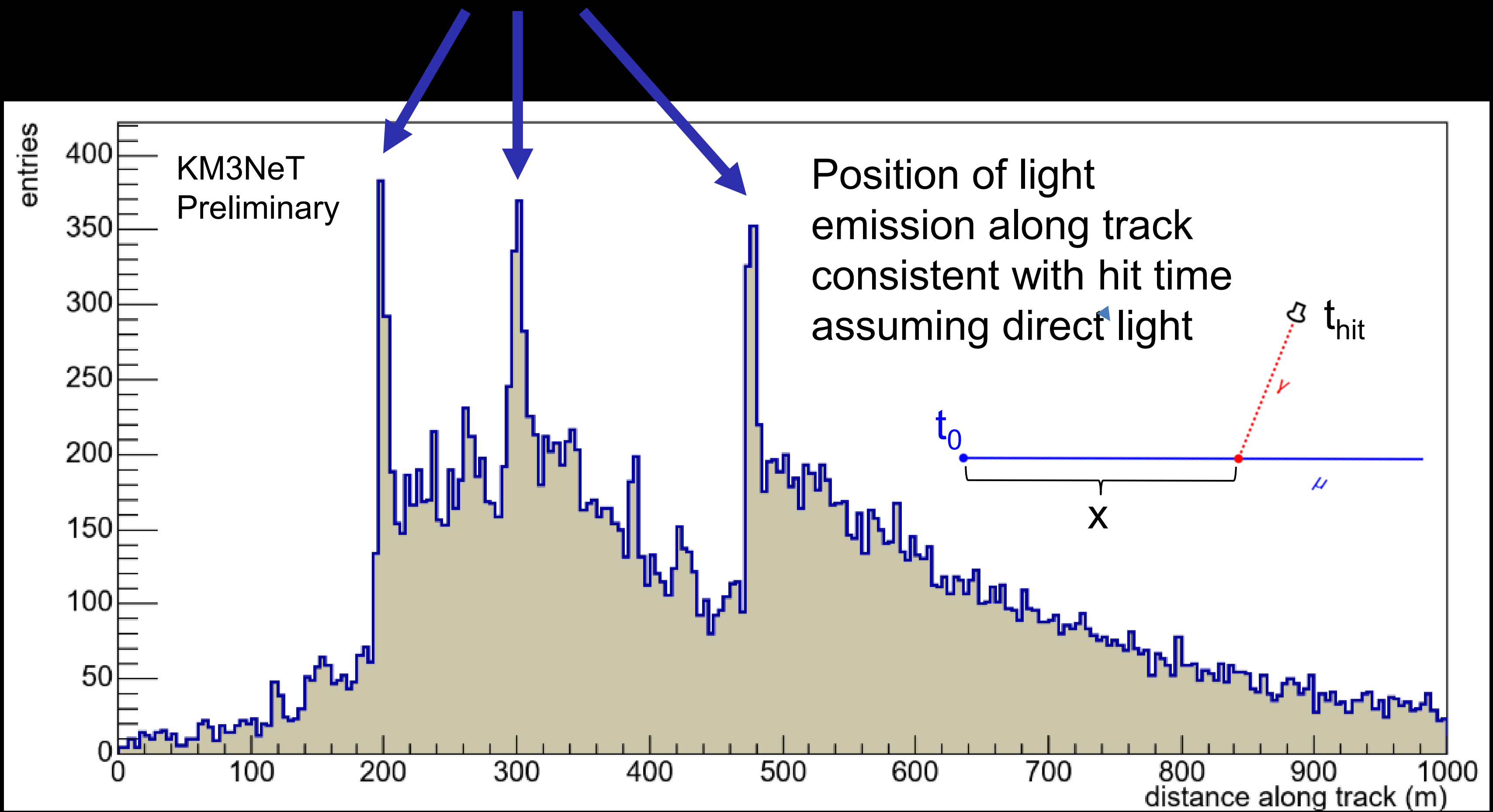
Uncharted Territory

- Event is well reconstructed as a high energy muon crossing entire ARCA21 detector



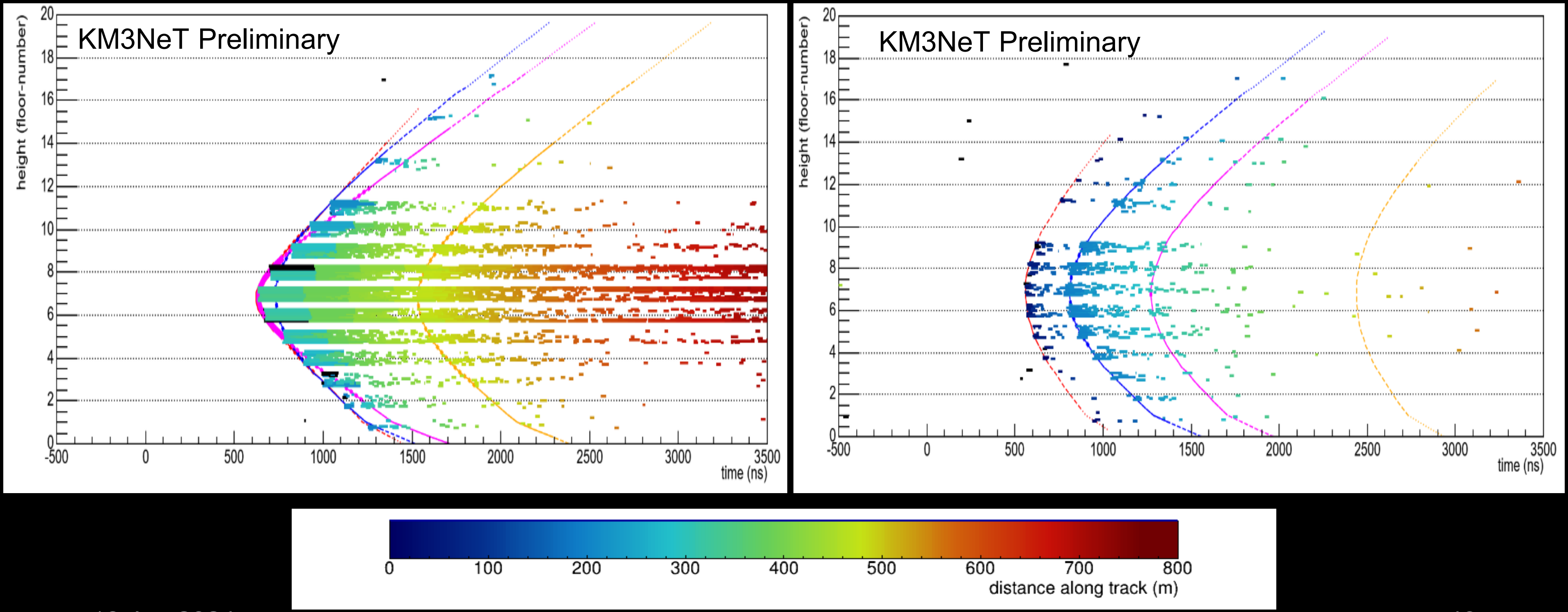
Uncharted Territory

- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons



Uncharted Territory

- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons
- Space-time distribution of light consistent with shower hypothesis associated with these energy depositions
- Low scattering is key to observing this richness of detail



Conclusion

- KM3NeT has been taking high quality data during construction phase
- The KM3NeT detectors explore the physics of multiple layers of light seen by the multi-PMT DOM design

- New improved oscillation results and much more data to come
- Strong matter effects open a window to exciting new physics models

- Searches for astrophysical sources are under way

- An unprecedented event was observed in rich detail
- Likely multiple 10's of PeV
- Further investigations on energy and origin of this event underway

- Stay tuned!

Posters

- For more details on many of these analyses, look for our posters:

Tuesday (Now):

225. Diffuse and point source search with KM3NeT/ARCA and ANTARES neutrino telescopes
BARBARA CAIFFI (Istituto Nazionale di Fisica Nucleare)

633. All-sky and Galactic Ridge diffuse astrophysical neutrino flux search with KM3NeT/ARCA6-8-19-21 data
Luigi Antonio Fusco (Istituto Nazionale di Fisica Nucleare)

254. Model-Dependent and Independent Stacking Search for Seyfert Neutrino Emission with the KM3NeT/ARCA and ANTARES Detectors
Walid Idrissi Ibnsalih (Istituto Nazionale di Fisica Nucleare)

213. Search for high energy neutrinos in KM3NeT in coincidence with Fast Radio Bursts
Félix Bretaudeau (KM3NeT Collaboration)

211. Stacking Search for Ultra-Luminous Infrared Galaxies with KM3NeT/ARCA Detector
Antonio Ambrosone (Istituto Nazionale di Fisica Nucleare)

195. Time-integrated search for astrophysical neutrino emission with 2 years of KM3NeT/ARCA data
Maurizio Spurio (Istituto Nazionale di Fisica Nucleare)

Posters

- For more details on many of these analyses, look for our posters:

Tuesday (Now):

375. The KM3NeT real-time analysis framework
Massimo Mastrodicasa (Università degli Studi di Roma "La Sapienza" and INFN-Roma)

511. Results of the follow-up of external triggers with KM3NeT
Ilaria Del Rosso (Istituto Nazionale di Fisica Nucleare)

357. KM3NeT’s sensitivity to the next core-collapse supernova
Isabel Astrid Goos (APC)

632. GNNs applications in KM3NeT/ARCA
Alessandro Veutro (Istituto Nazionale di Fisica Nucleare), Maria Rosaria Musone (Istituto Nazionale di Fisica Nucleare)

178. Introducing a Simultaneous Track+Shower Reconstruction Algorithm, dedicated for KM3NeT/ORCA
Dr Brían Ó Fearraigh (University of Genoa)

341. First measurement of light sterile neutrino mixing parameters with KM3NeT/ORCA
Louis Bailly-Salins (LPC Caen (CNRS/IN2P3))

224. Non unitary neutrino mixing with KM3NeT/ORCA
Luc Cerisy (CPPM)

Posters

- For more details on many of these analyses, look for our posters:

Friday:

401. Measurement of the atmospheric muon neutrino flux with KM3NeT/ORCA6
Louis Bailly-Salins (LPC Caen (CNRS/IN2P3))

358. Updated measurement of atmospheric neutrino oscillation parameters with KM3NeT/ORCA
Santiago Peña Martínez (APC)

529. Search for Lorentz invariance violation with ANTARES and KM3NeT/ORCA6
Lukas Hennig (Erlangen Centre for Astroparticle Physics (ECAP), Friedrich-Alexander-Universität Erlangen-Nürnberg)

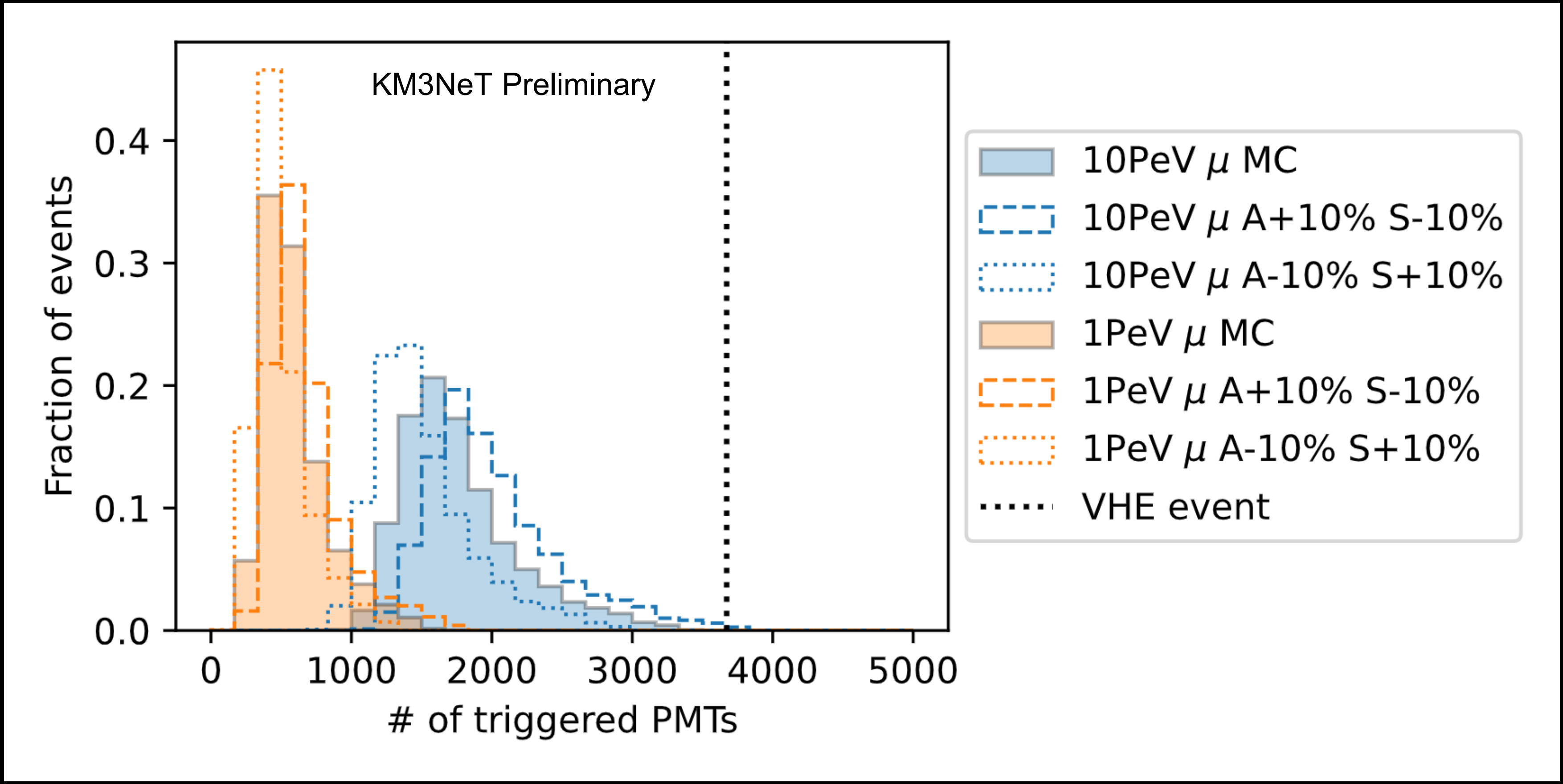
180. WIMP dark matter searches in the Galactic Centre with KM3NeT
Adriana Bariego Quintana (IFIC (CSIC-UV))

Thank you!

NIOZ
Koninklijk Nederlands Instituut
voor Onderzoek der Zee

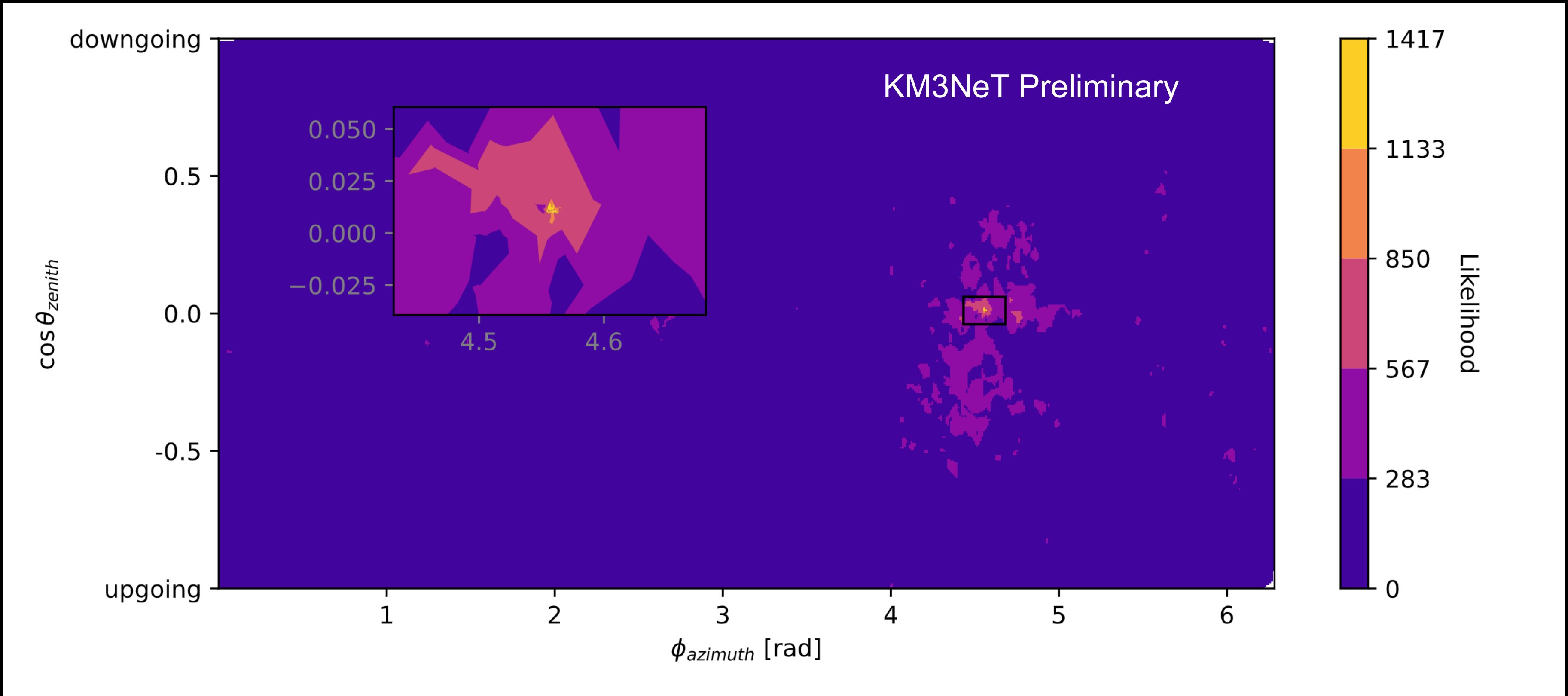
Uncharted Territory

- Uncertainty from water properties impacts PMT count
- One of many factors in establishing an uncertainty on the energy

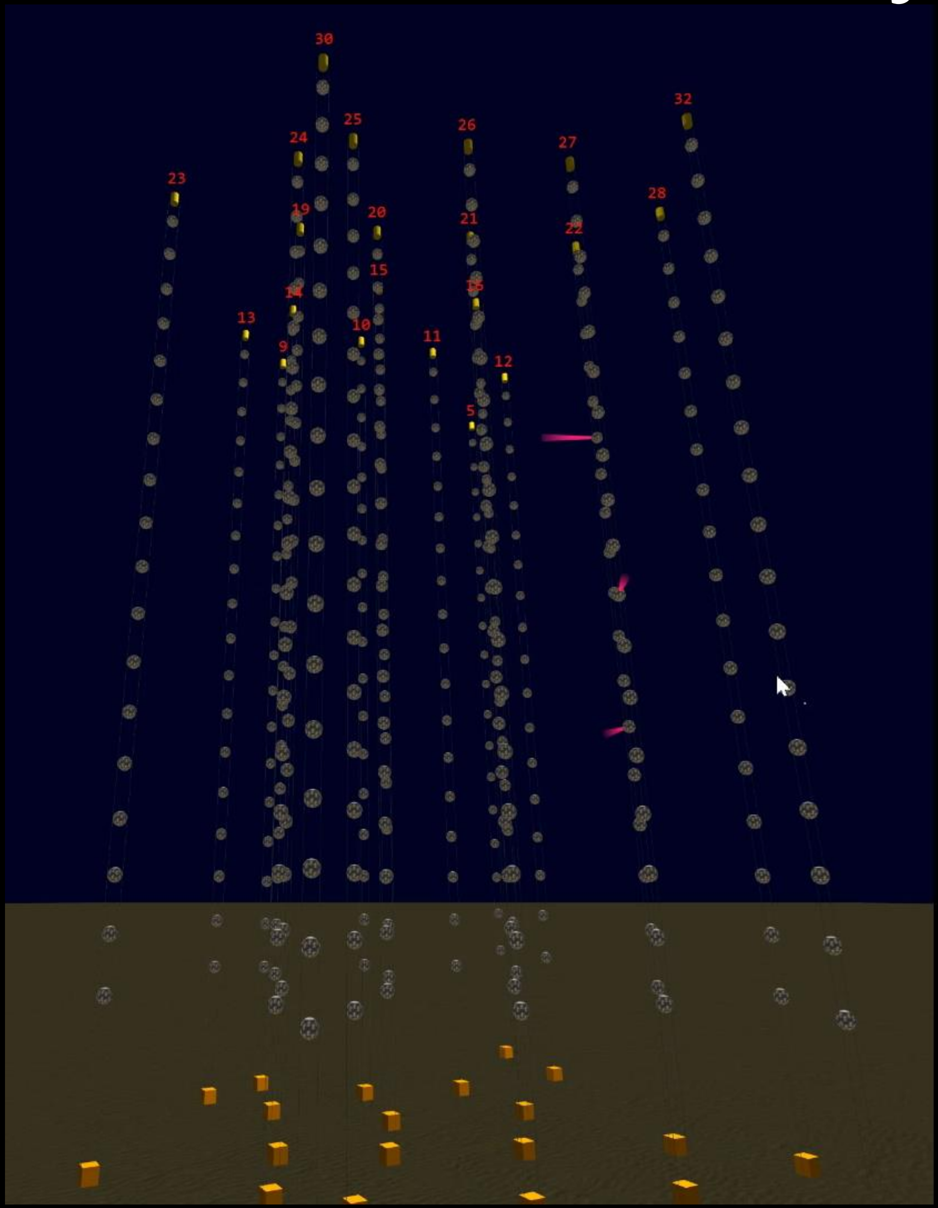


Uncharted Territory

- Local direction reconstruction very well established
- No other solutions are consistent with the data

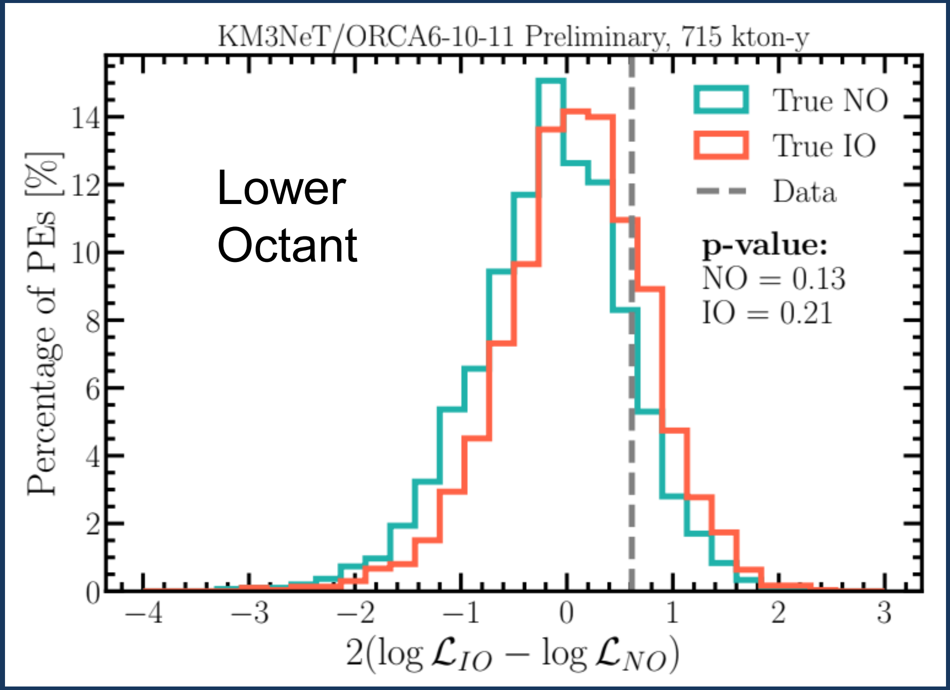


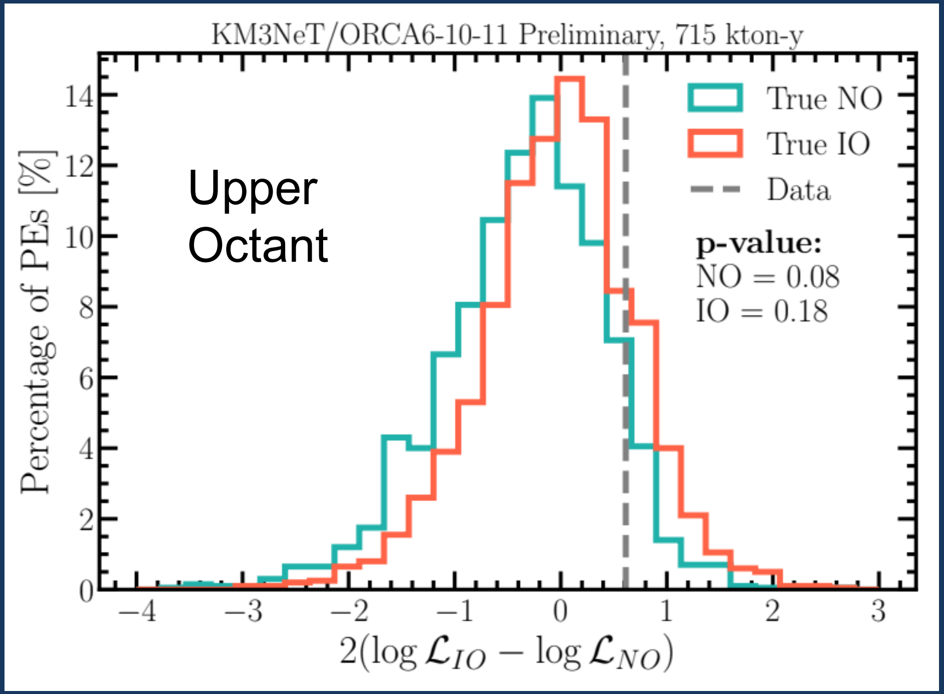
Uncharted Territory



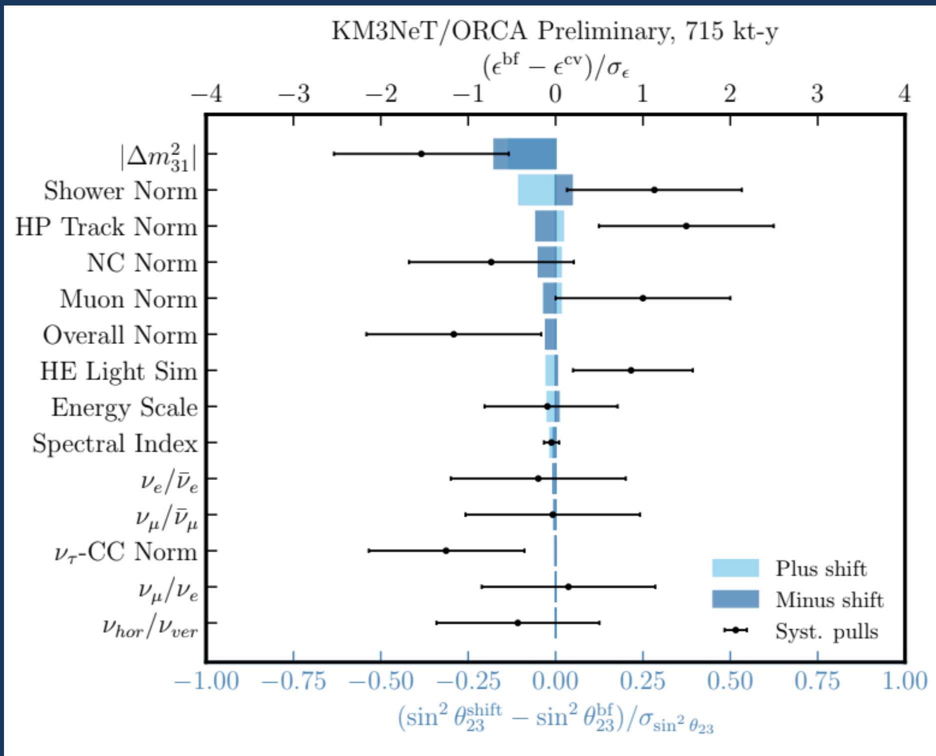
NMO Significance

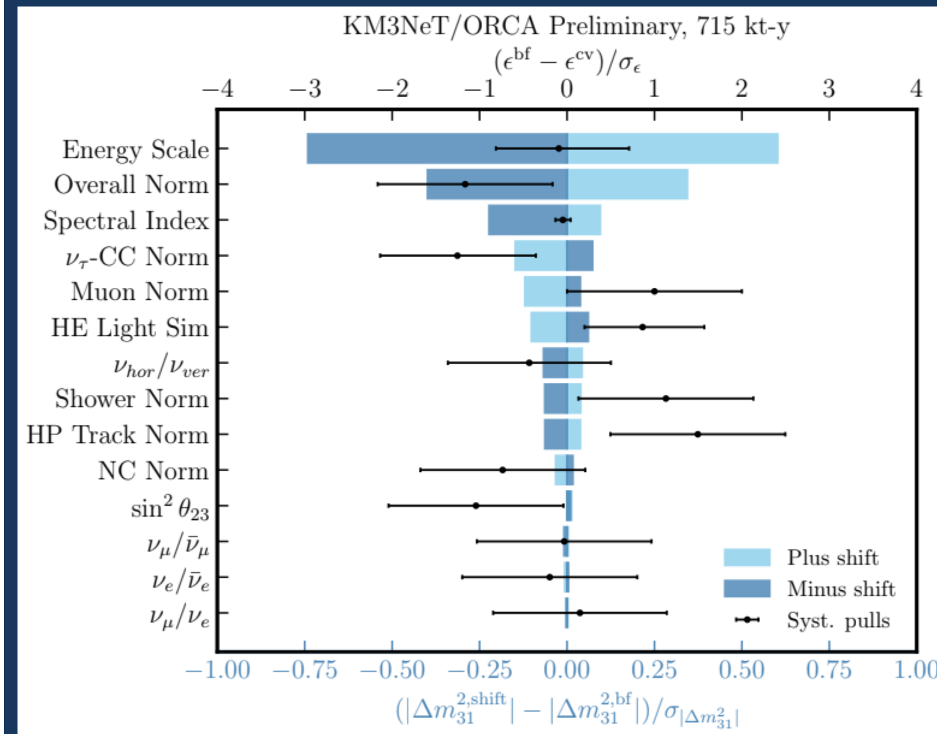
- Conversion from -2logL to p-value depends on choice of nuisance parameters
- At NuFIT 5.0 best fit, NO hypothesis disfavoured at 1.7σ / 1.5σ in (UO/LO)
- IO preference slightly stronger than expected (18%/21% p-value in UO/LO)
- Working towards a more general statement as a function of $\sin^2\theta_{23}$





Systematic Uncertainties





$\sin^2\theta_{23}$ dominated by statistics

Δm^2_{31} impacted mostly by uncertainty on energy scale

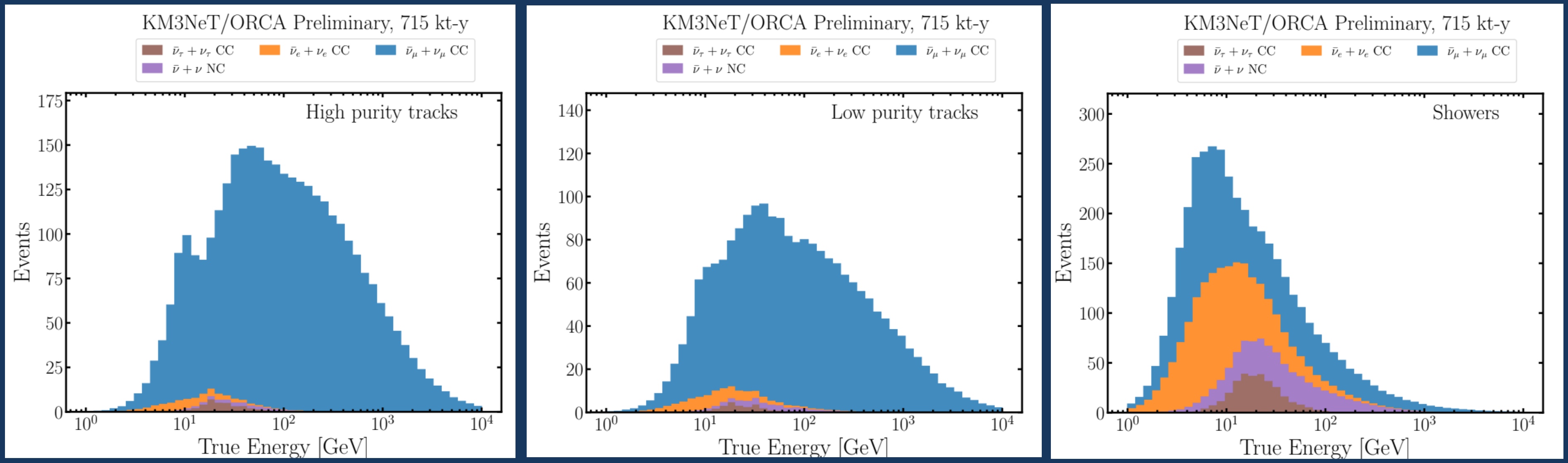
Dominated by uncertainties on water properties

Event Breakdown

Selection	HP Tracks	LP Tracks	Showers	Total
ν_μ CC	2166	1232	1266	4664
$\bar{\nu}_\mu$ CC	1103	618	495	2216
$\nu_\mu + \bar{\nu}_\mu$ CC	3269	1850	1761	6880
ν_e CC	38	49	907	994
$\bar{\nu}_e$ CC	19	23	415	457
$\nu_e + \bar{\nu}_e$ CC	57	72	1322	1451
ν_τ CC	19	13	155	187
$\bar{\nu}_\tau$ CC	10	6	63	79
$\nu_\tau + \bar{\nu}_\tau$ CC	29	19	218	266
ν NC	16	23	367	406
$\bar{\nu}$ NC	5	7	108	120
$\nu + \bar{\nu}$ NC	21	30	475	526
Background	2	421	205	628
Best fit MC	3378	2392	3981	9751
Total Data	3378	2390	3983	9751

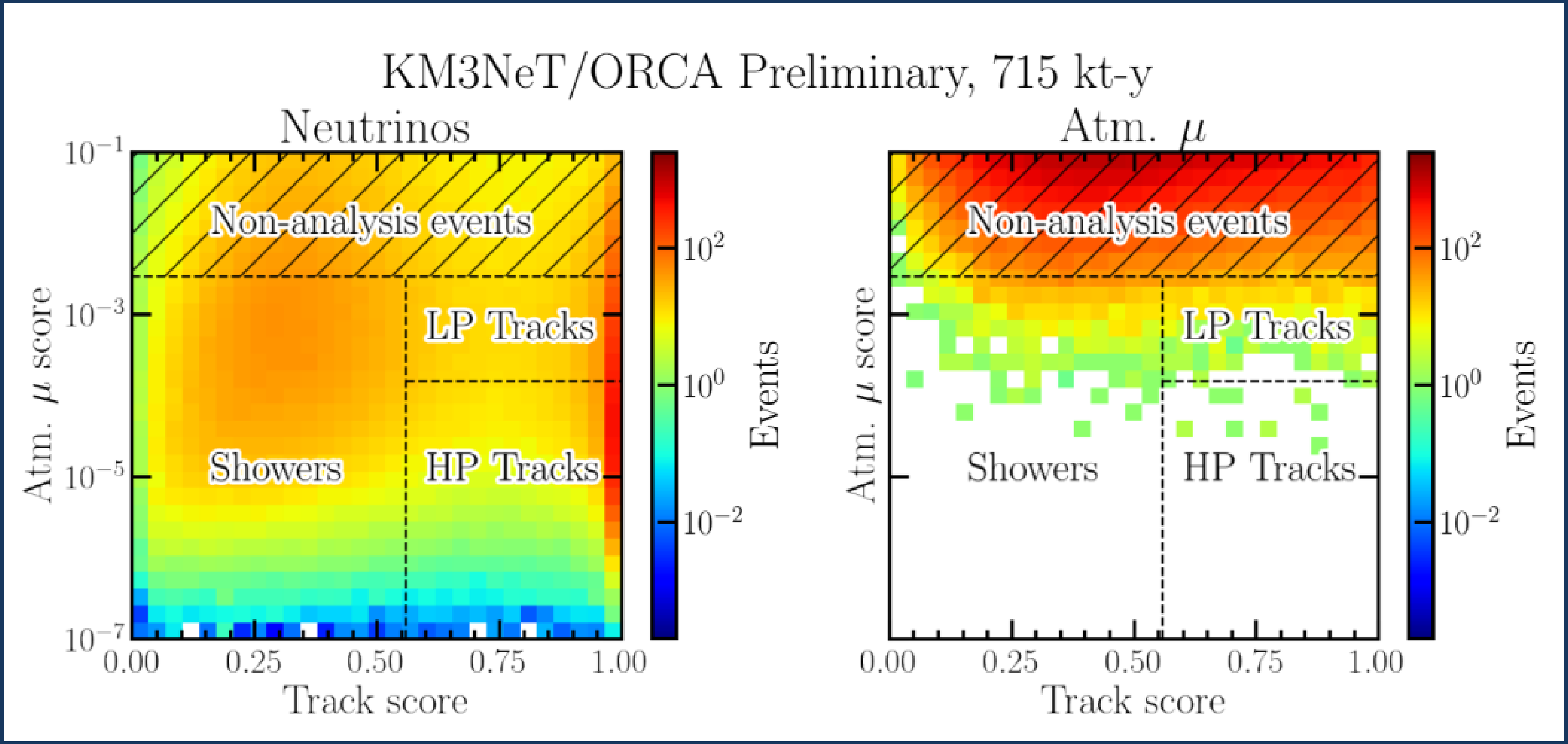
True Energy

- Long tail of high energy events in track-like samples
- Peak of distribution at a few tens of GeV



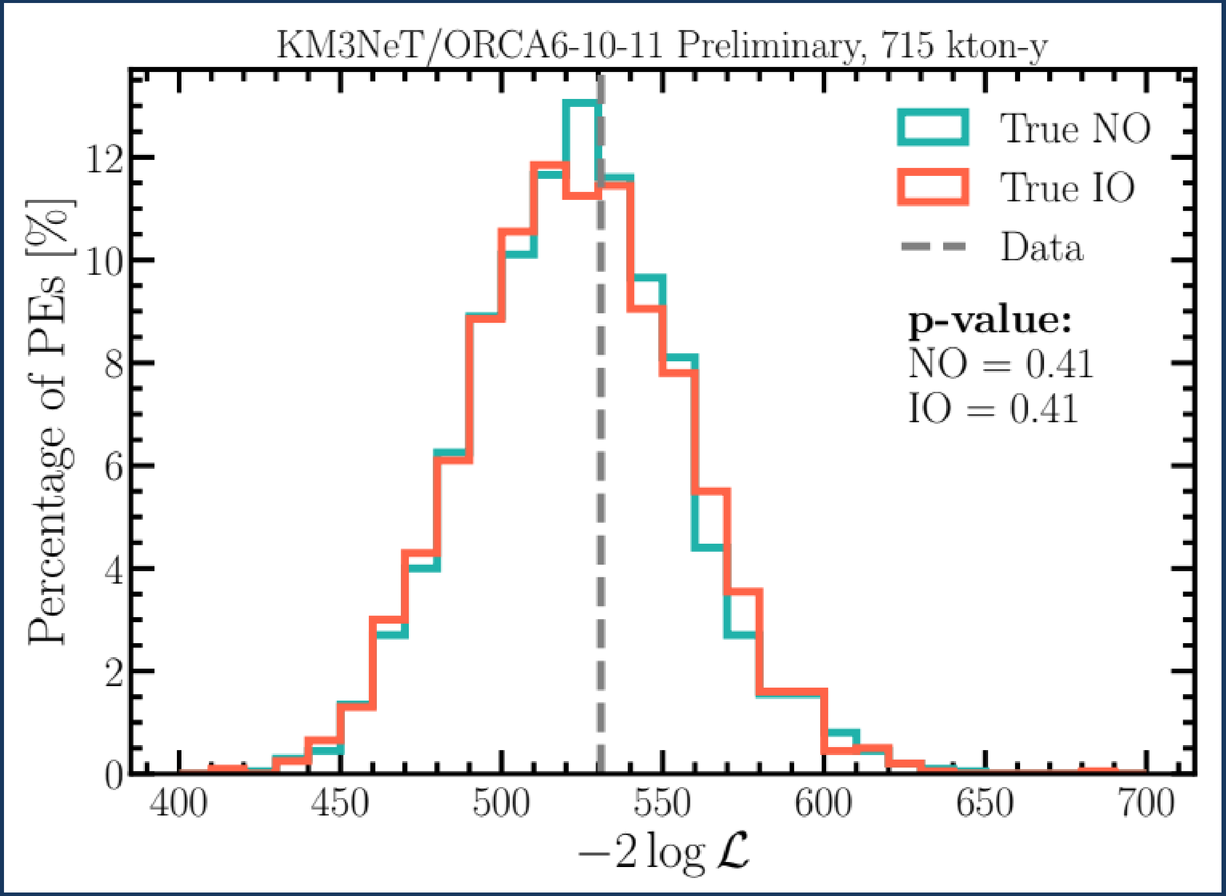
Class Definitions

- Tile the 2D space of track and atm. Muon BDT scores
- Prioritized a very pure track-like sample



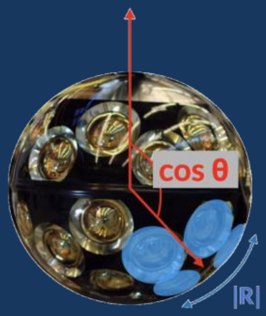
Goodness-of-Fit

- Data total likelihood value consistent with toy simulations

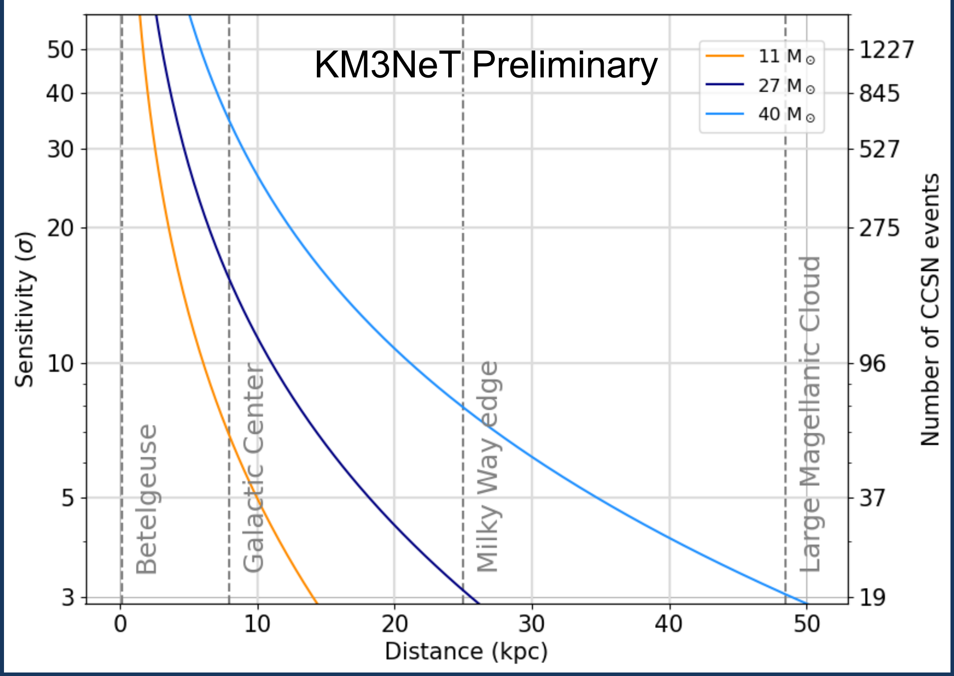


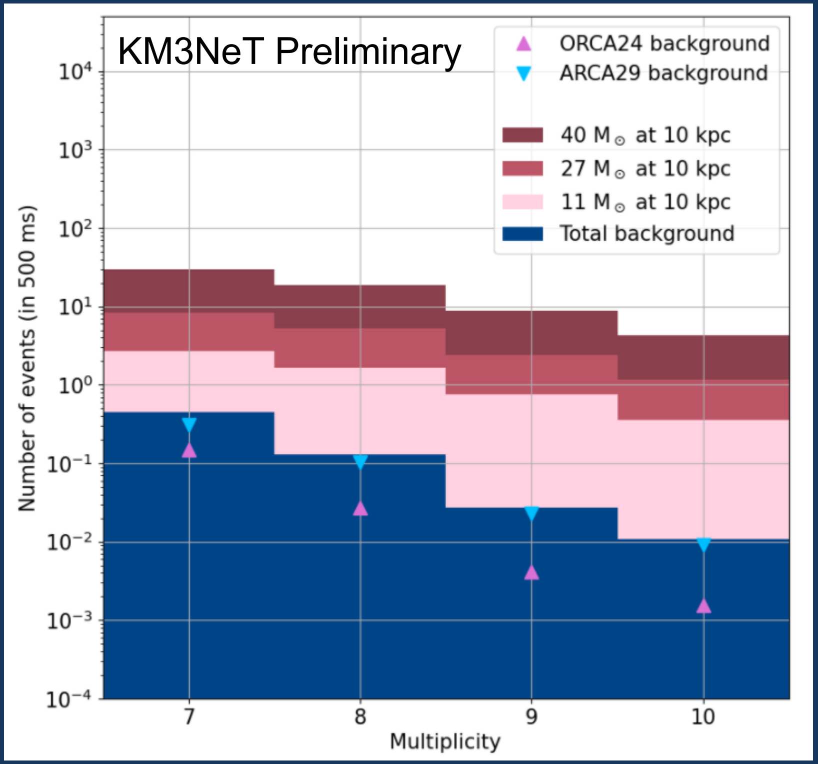
Layer 1: Optical Background

- Supernova neutrinos can be explored at the DOM level
- Characteristic multiplicity shape can be explored
- Other DOM level characteristics also explored
- If a supernova happens in the Galaxy, we're ready!



ORCA24 & ARCA29





See poster 357