KM3NeT/ORCA: Status, first data & perspectives for neutrino oscillation measurements

WIN 2021

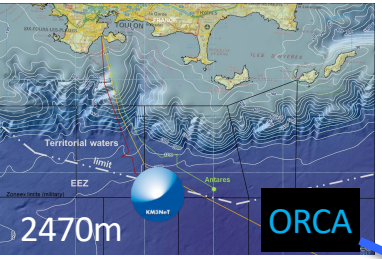
Véronique Van Elewyck
(APC & Université de Paris)

for the
KM3NeT Collaboration

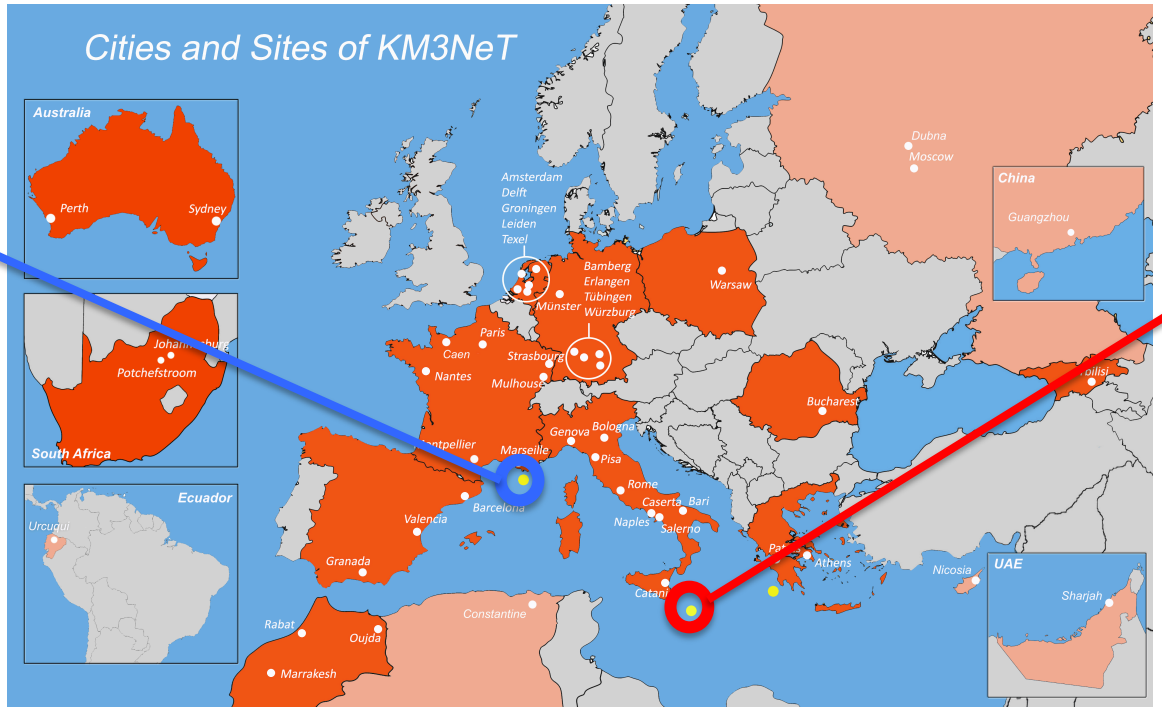
The KM3 Neutrino Telescope

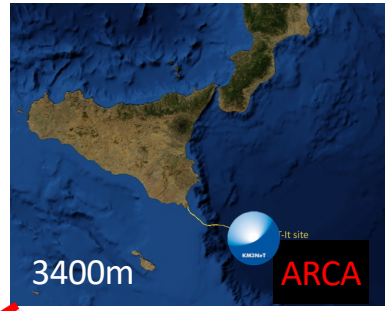
KM3NeT is a distributed research infrastructure with 2 main physics topics:

Oscillations and Astroparticle Research with Cosmics in the Abyss



~40 km offshore
Toulon (France)
close to ANTARES





~100 km offshore
Capo Passero
(Sicily)

📖 *KM3NeT LoI:*
J.Phys.G 43 (2016) 8, 084001

1collaboration, 1 technology, 2 detectors

The KM3NeT Technology

Multi-PMT DOM:

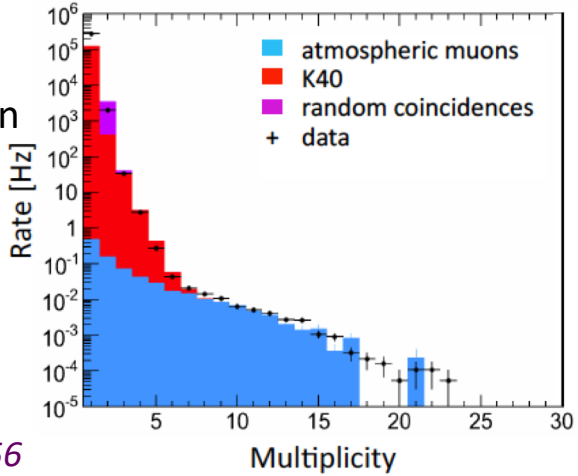
- Digital Optical Module
- 31 x 3” PMTs

(+ reflector rings)

- Gbit/s on optical fiber
- Positioning & timing

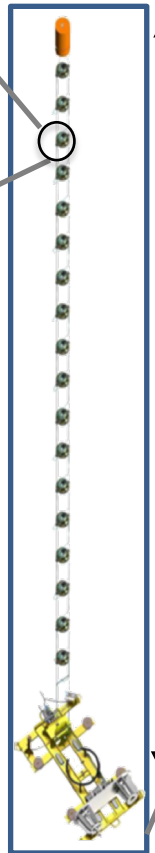
- ~4 π sr coverage
- photon counting
- directional information

single-DOM atmospheric muon detection:

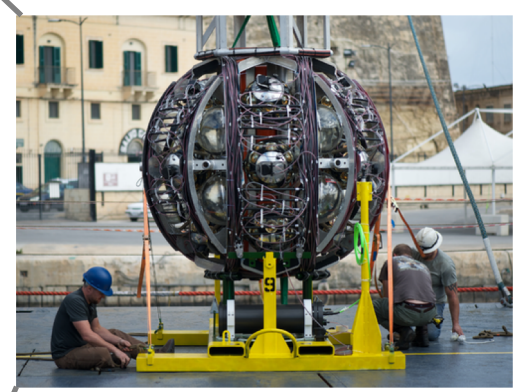


📖 *KM3NeT Collaboration, Eur.Phys.J.C 74 (2014) 9, 3056*

Detection Unit

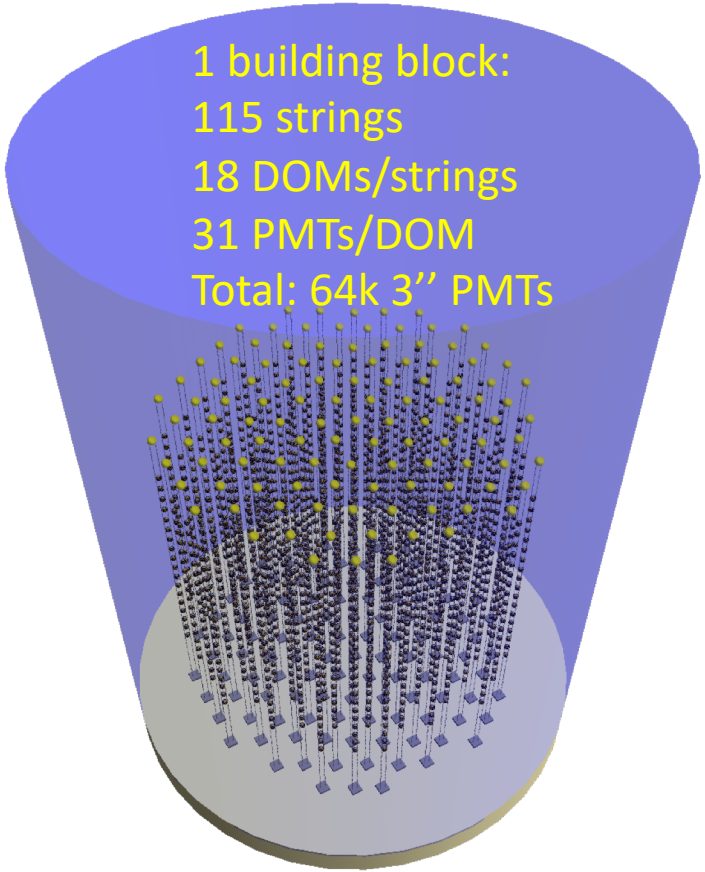


Launcher Module



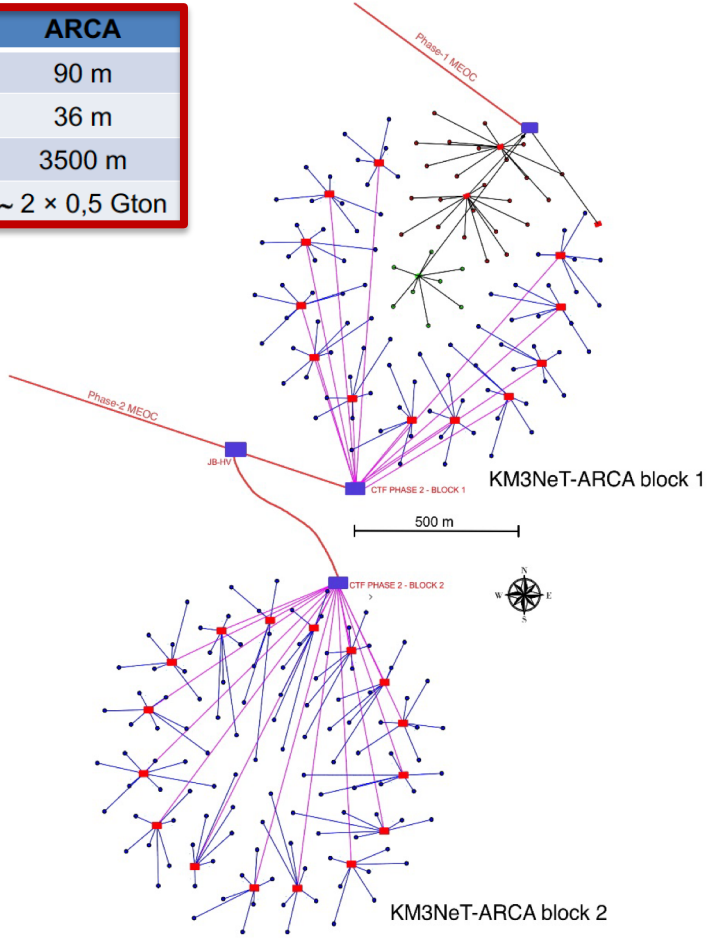
- Rapid deployment
- Multiple strings/sea campaign
- Autonomous/ROV unfurling
- Reusable

The KM3NeT Technology

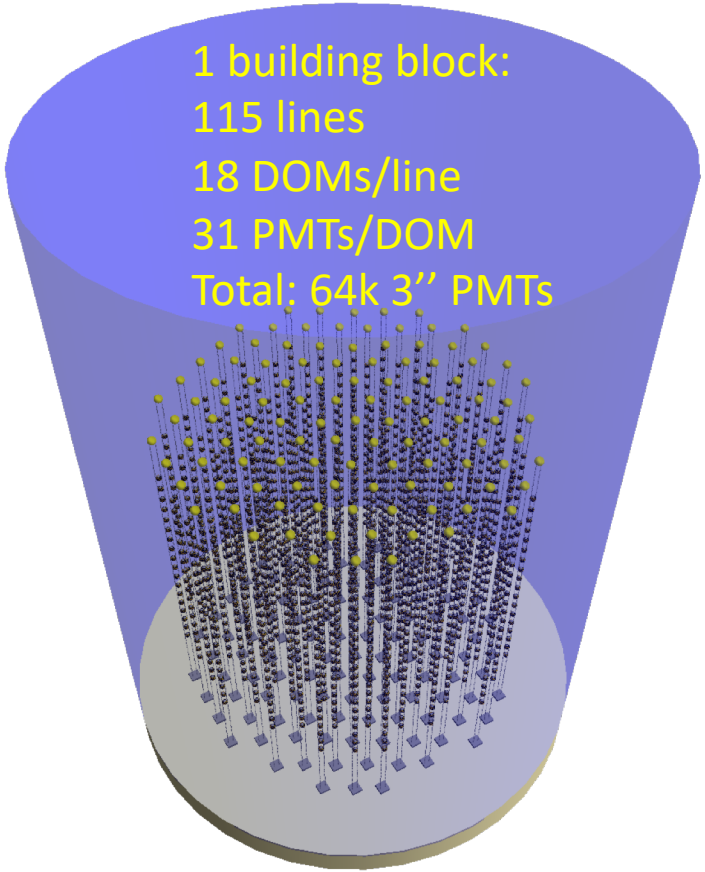


	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	~ 7 Mton	~ 2 × 0,5 Gton

ARCA:
2 building blocks
~Gton instrumented mass



The KM3NeT Technology

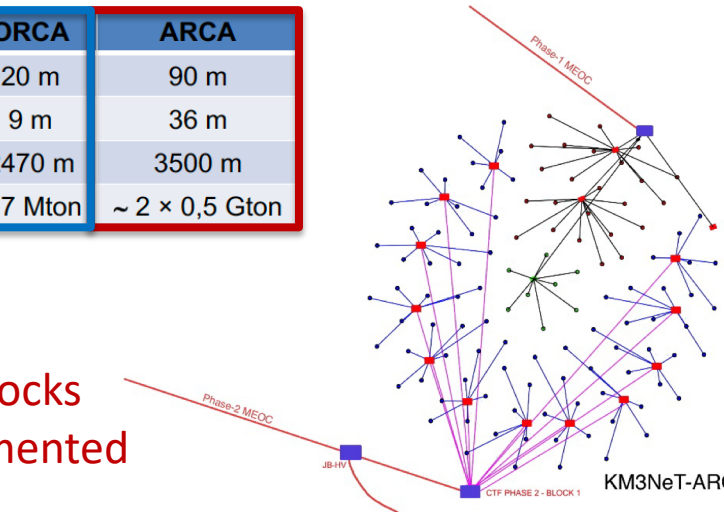


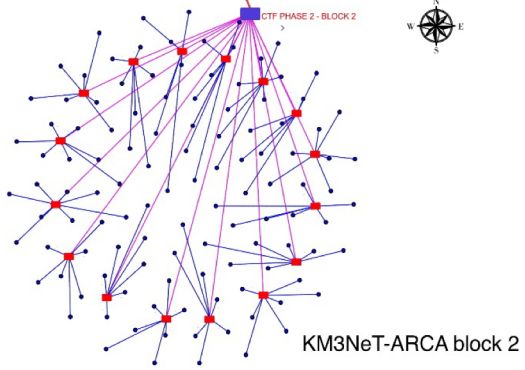
	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	~ 7 Mton	~ 2 × 0,5 Gton

ARCA:
2 building blocks
~1 Gton instrumented mass

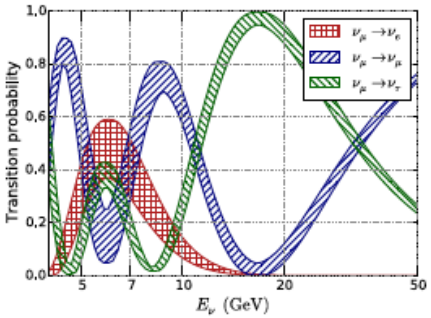
ORCA:
1 building block
~7 Mton instrumented mass

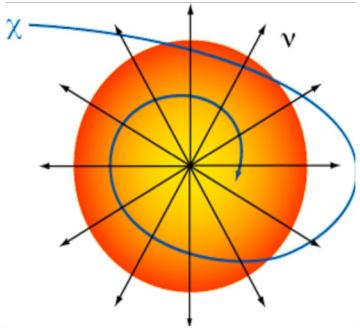
to scale →

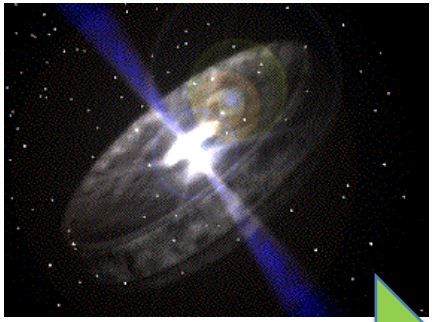




The KM3NeT Science







MeV **GeV** **TeV** **PeV**

Supernova ν

ν Oscillations, Mass ordering

Dark matter, exotics

HE ν astronomy
Cosmic accelerators

ORCA

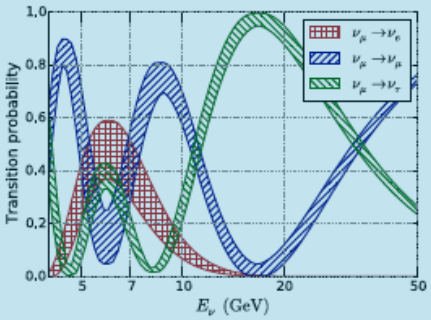
ARCA

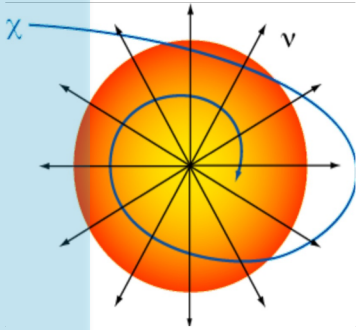
ORCA

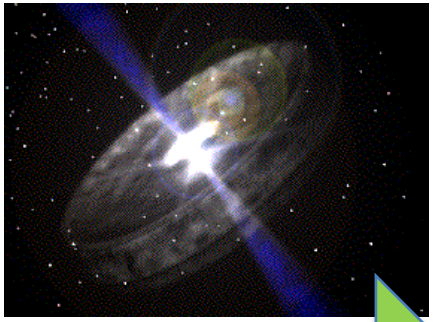
THIS TALK

For ARCA (& ANTARES),
see talk by Sergio Navas
(Astroparticle Physics session)

The KM3NeT Science







MeV — **GeV** — **TeV** — **PeV**

Supernova ν

ν Oscillations, Mass ordering

Dark matter, exotics

HE ν astronomy
Cosmic accelerators

ORCA

ARCA

ORCA

THIS TALK

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(Astroparticle Physics session)

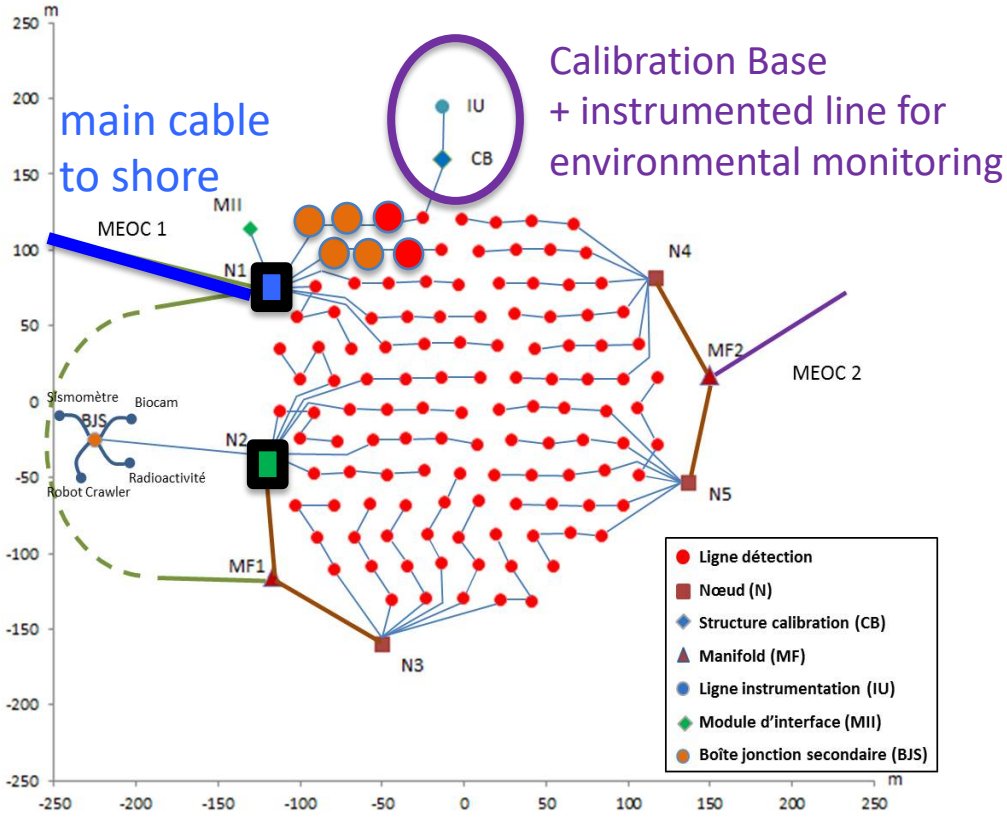
The ORCA detector

ORCA4 since July 2019
~4.5 months data sample
Sanity checks & first physics results
- see later in this talk

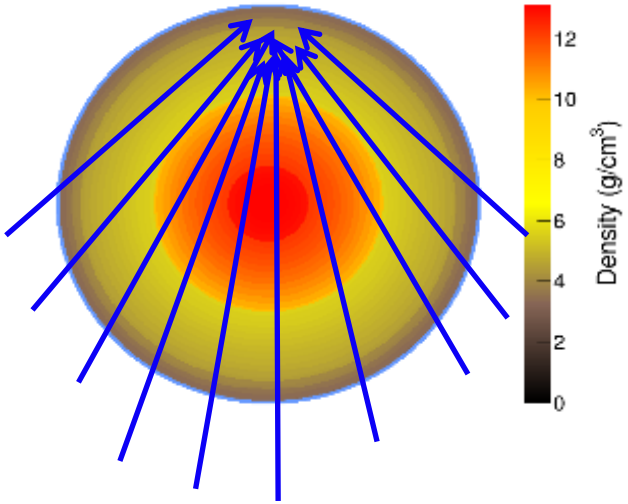
ORCA6 since January 2020
>1 year data on tape, being analyzed

Node2 since October 2020
→ capacity to connect 52 DUs

More sea operations planned for 2021/2022: DUs and Calibration Unit



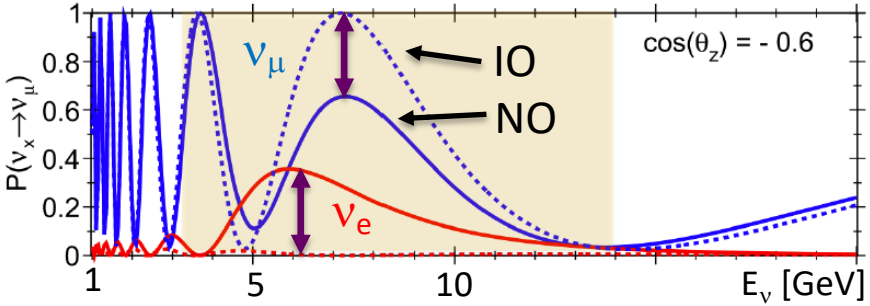
ORCA science goals



❖ Atmospheric neutrino measurement above 1 GeV:
A "free beam of known composition ($\nu_e/\overline{\nu}_e$ and $\nu_\mu/\overline{\nu}_\mu$)
Different energies (few GeV – few 100 GeV)
Different baselines

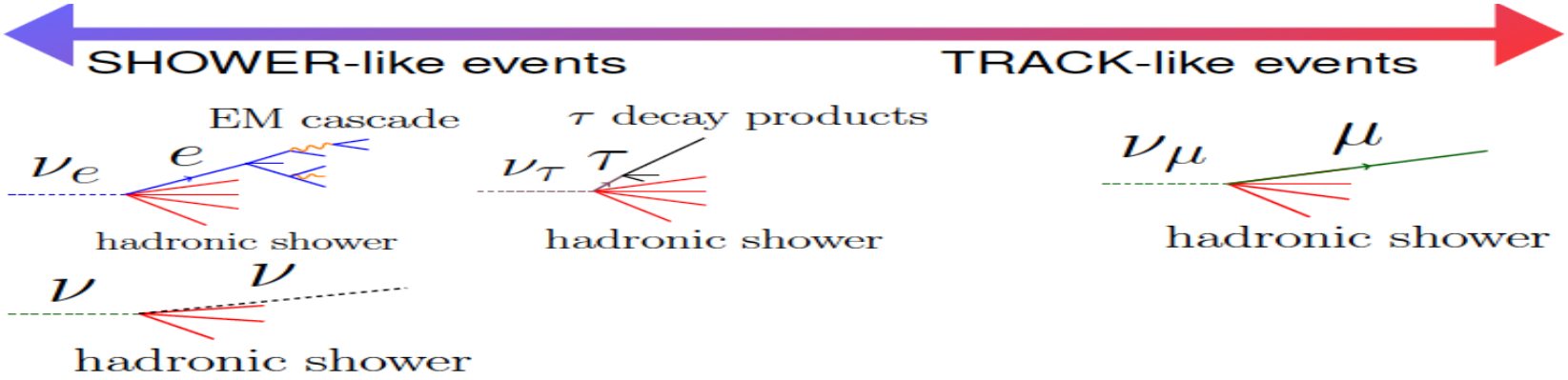
❖ Probe neutrino oscillations in the atmospheric sector: sensitivity to θ_{23} and Δm^2_{31} (+ θ_{13} , δ_{CP})

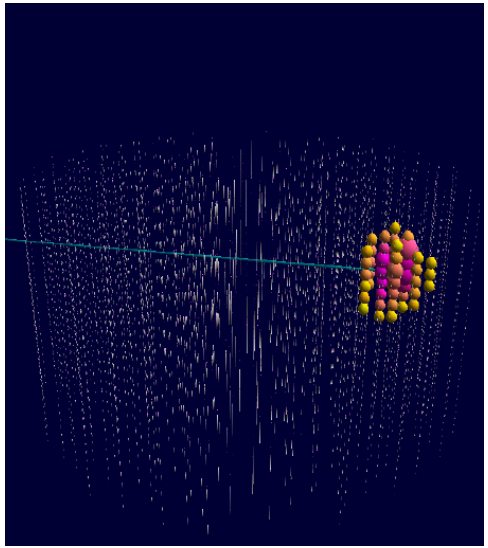
❖ Determine the neutrino mass ordering (IO/NO)
by exploiting matter effects in neutrino oscillations



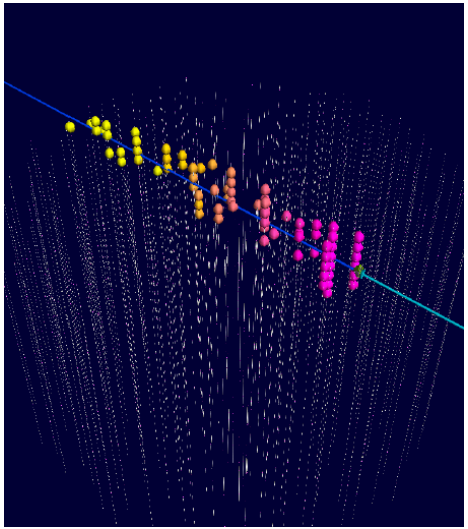
need good event reco/ID performances
+ careful treatment of systematics

ORCA detection principle



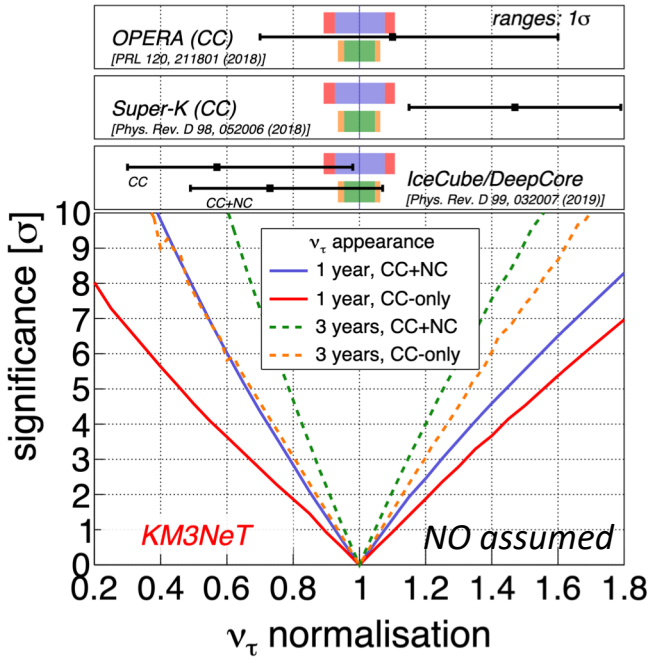


Discrimination of tracks, showers and atmospheric muons (~%) via Random Decision Forests (RDF)



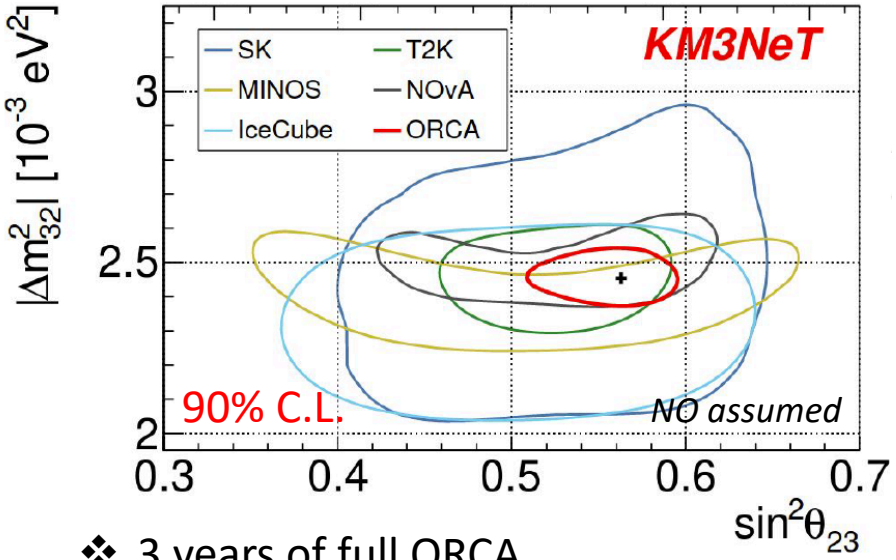
ORCA sensitivity projections

ν_τ appearance



- Confirmation possible after a few months operation with full ORCA
- Fit robust against θ_{23} and mass ordering

Oscillation parameters

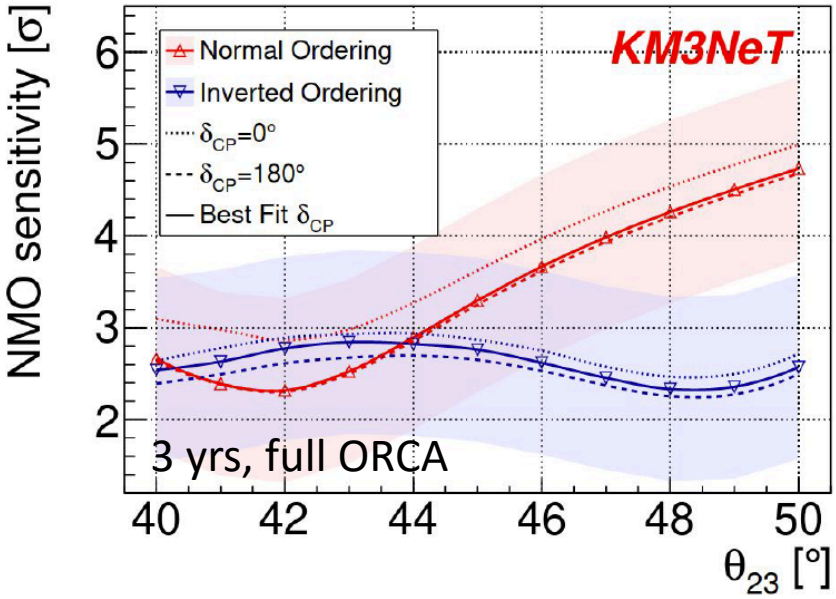


- 3 years of full ORCA
- Normal ordering, $\theta_{23} = 48.6°$ (NuFit v4.1)

📖 *KM3NeT Coll., arXiv: hep-ex/2103.09885 , submitted to EPJ C*

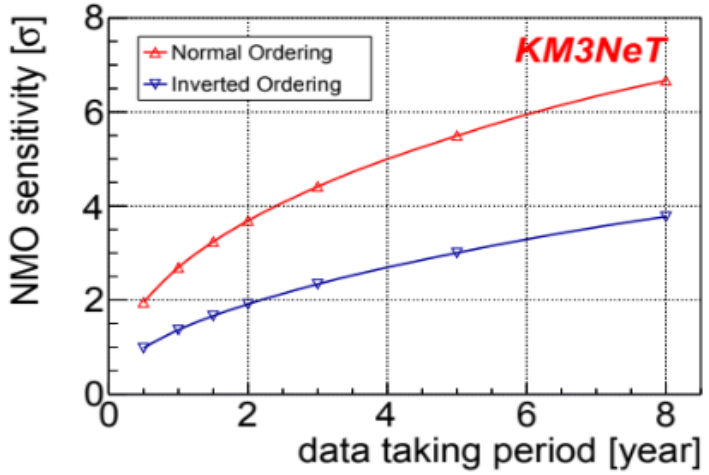
ORCA sensitivity projections

Neutrino mass ordering



68% sensitivity bands (Asimov);
Oscillation parameters from NuFit 4.1

- Favourable scenario: Normal Ordering
→ measurement at 5σ after 4 years
- For Inverted Ordering scenario:
→ measurement at 3σ after 5 years
- moderate impact of δ_{CP} on sensitivity

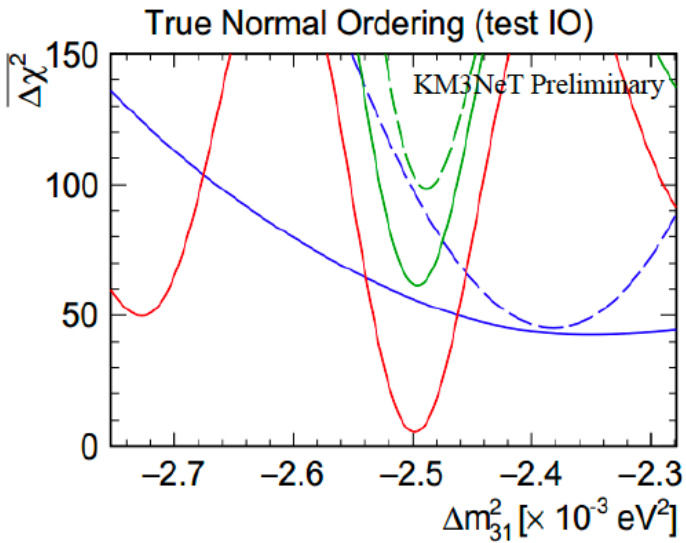


📖 *KM3NeT Coll., arXiv: hep-ex/2103.09885 , submitted to EPJ C*

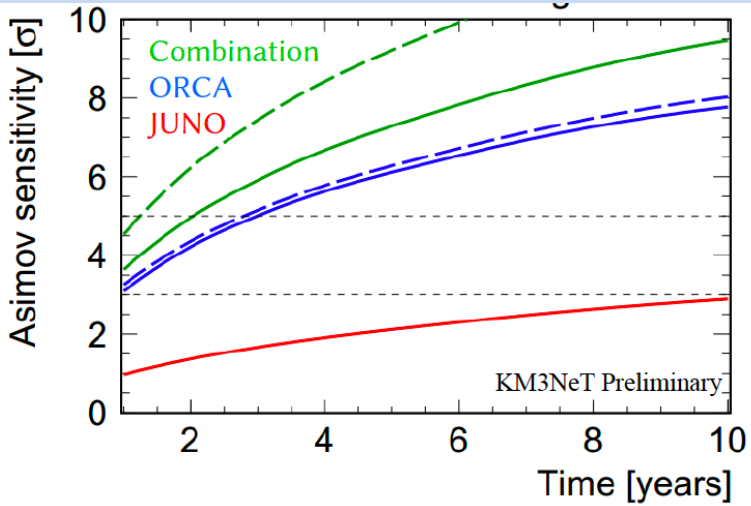
ORCA sensitivity projections

Neutrino mass ordering: combination with JUNO

Tension between the best-fit Δm^2_{31} with a wrong ordering assumption enhances sensitivity when combining ORCA+JUNO



❖ 5σ discrimination achievable for all hierarchy/octant scenarios in < 6 yr
(5σ in 2 years in case of normal ordering)
❖ detail of energy-scale systematic are important

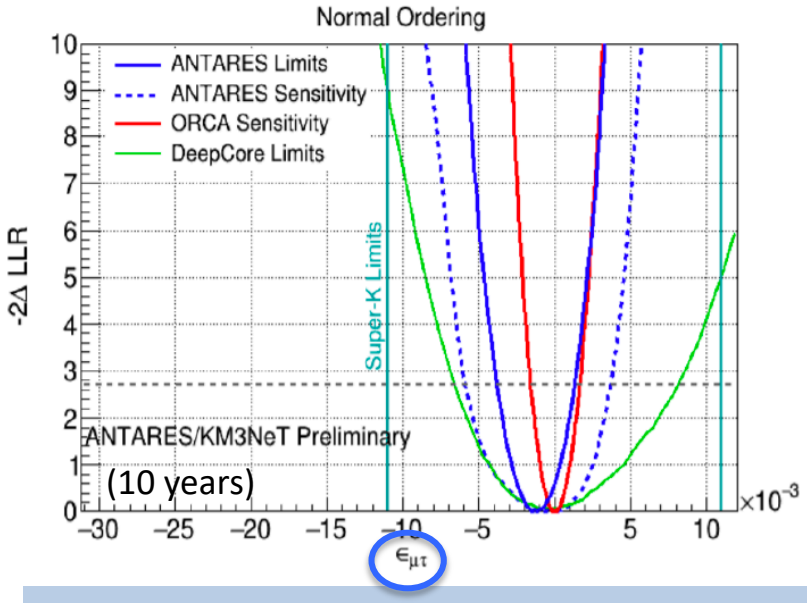


☞ *See talk by Nhan Chau, VLVnT 2021*

Oscillation parameters from NuFit 4.1

ORCA sensitivity projections

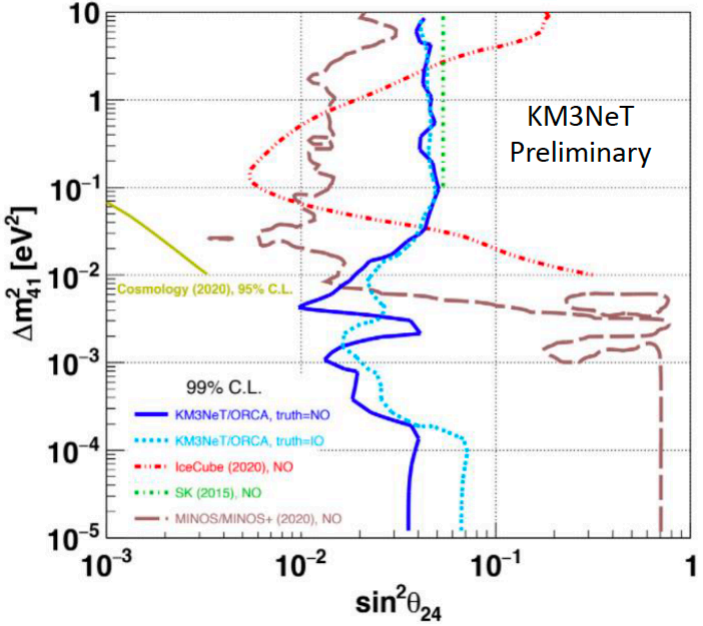
Non-standard ν interactions



❖ expected x3 improvement on already competitive limits of ANTARES

❖ expected 1% precision on full NSI Hamiltonian

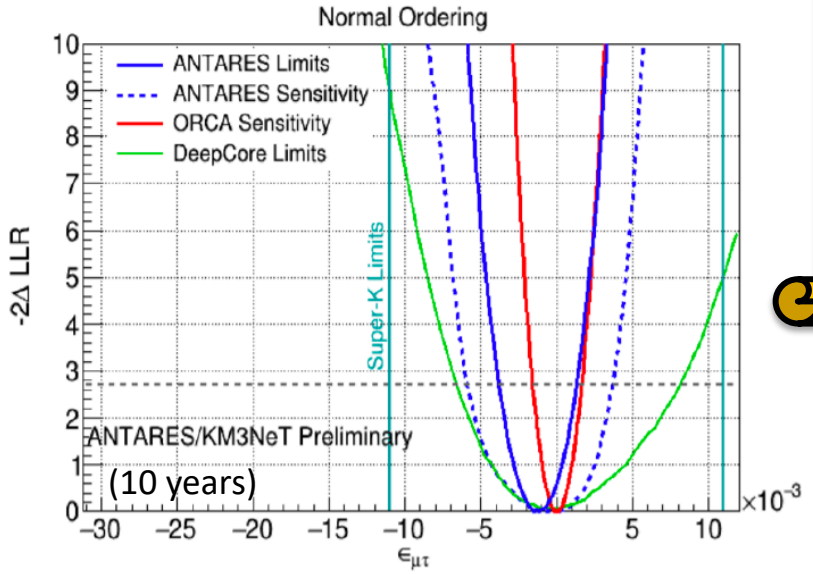
Sterile ν



❖ expected world-leading sensitivity on $|U_{\tau 4}|^2$ and test of low Δm^2_{41}

ORCA sensitivity projections

Non-standard ν interactions

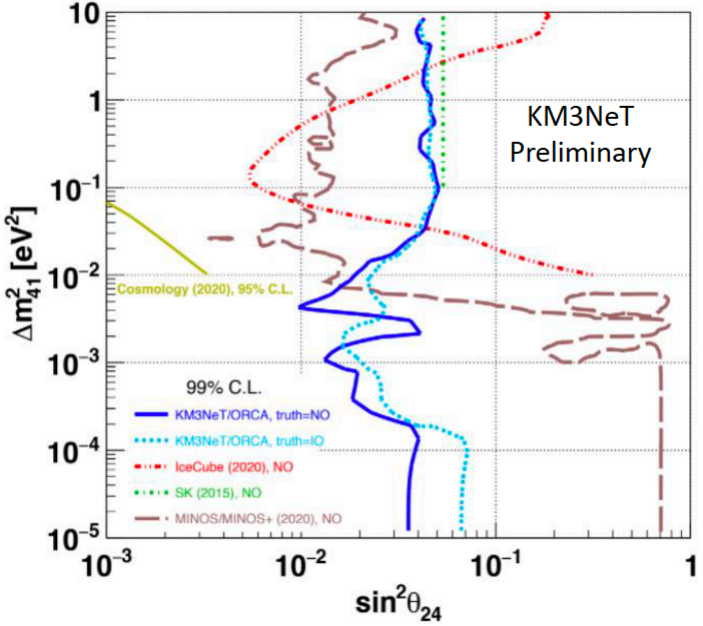


❖ expected x3 improvement on already competitive limits of ANTARES

❖ expected 1% precision on full NSI Hamiltonian

See virtual poster by Joao Coelho (same session)

Sterile ν



❖ expected world-leading sensitivity on $|U_{\tau 4}|^2$ and test of low Δm^2_{41}

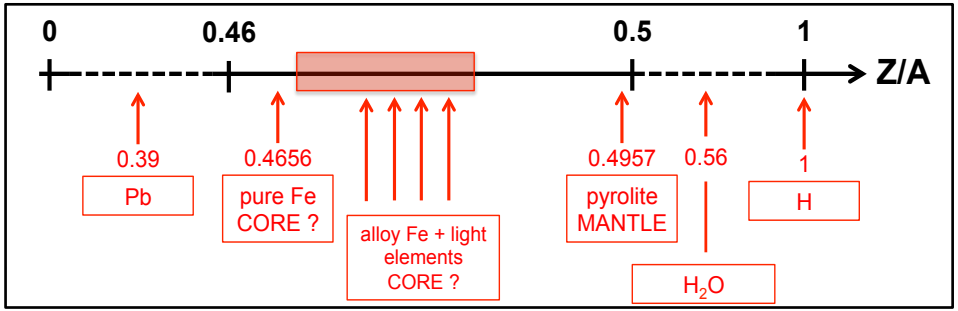
ORCA sensitivity projections

Atmospheric neutrino oscillations

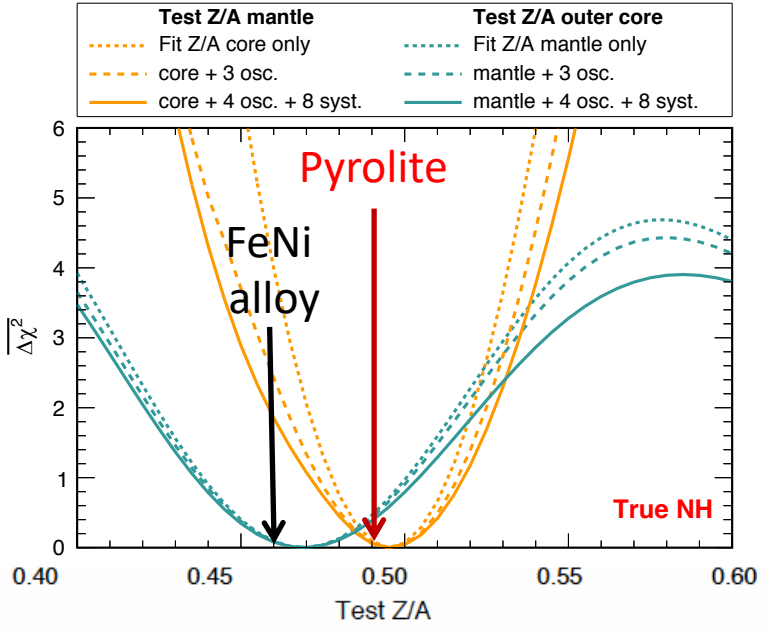
$$N_e = \frac{N_A}{m_n} \times \frac{Z}{A} \times \rho_{matter}$$

from geophysics

Constrain $\frac{Z}{A} = \sum_i w_i \frac{Z_i}{A_i}$



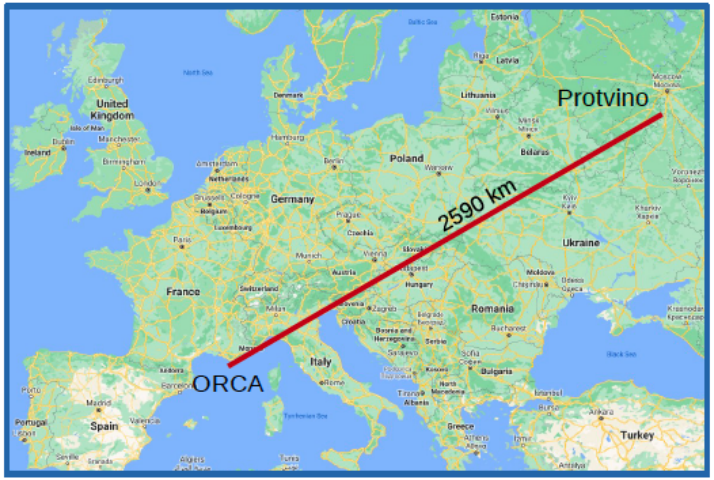
❖ 1σ sensitivity on Z/A after 10 years:
5% in mantle
6% in outer core
(systematics included, MC response & PID)



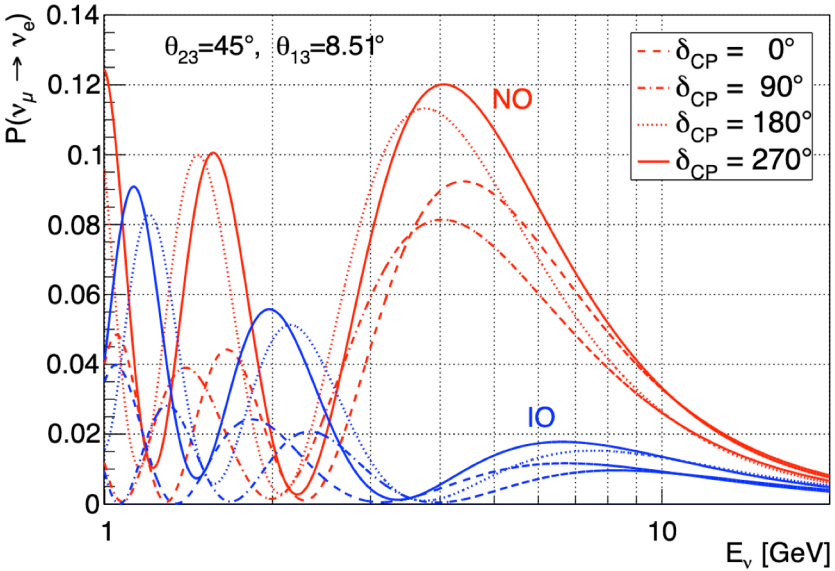
S. Bourret [KM3NeT Coll.], EPJ Web Conf. 207 (2019) 04008

A neutrino beam to ORCA ?

- from U70-Protvino (Russia) to ORCA (P2O)
- up to 450 kW beam power
- Baseline 2595 km



- First oscillation maximum ~5 GeV
- Sensitivity to mass ordering and CP violation

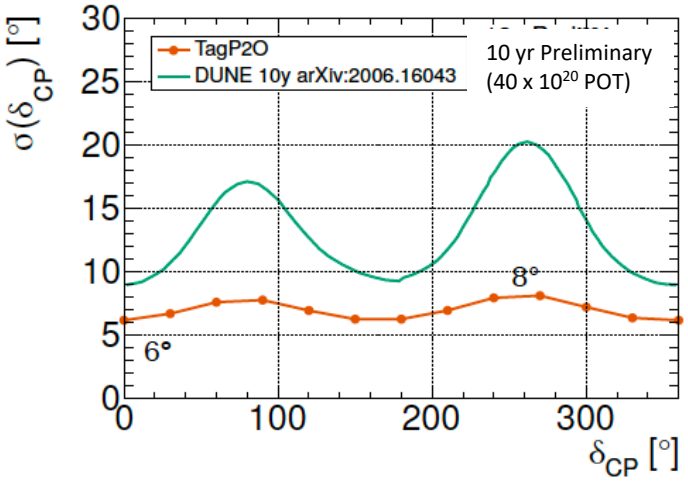


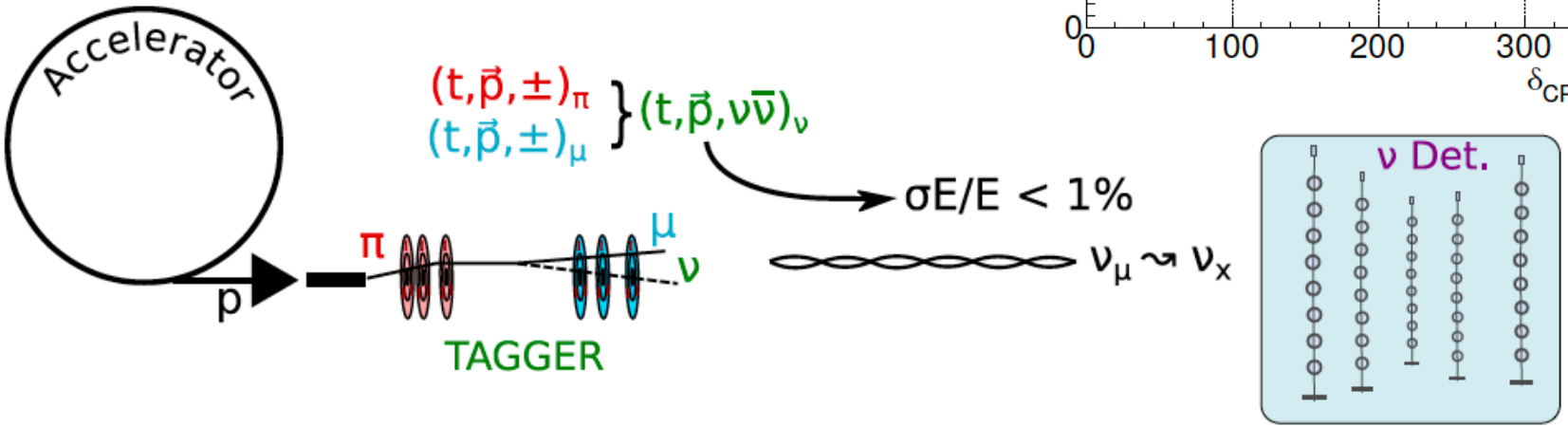
📖 *P2O LoI: Eur.Phys.J.C 79 (2019) 9, 758*

A neutrino beam to ORCA ?

- from U70-Protvino (Russia) to ORCA (P2O)
- up to 450 kW beam power
- Baseline 2595 km
- New idea: use a tagged beam

→ Improved & quasi-uniform sensitivity to δ_{CP}

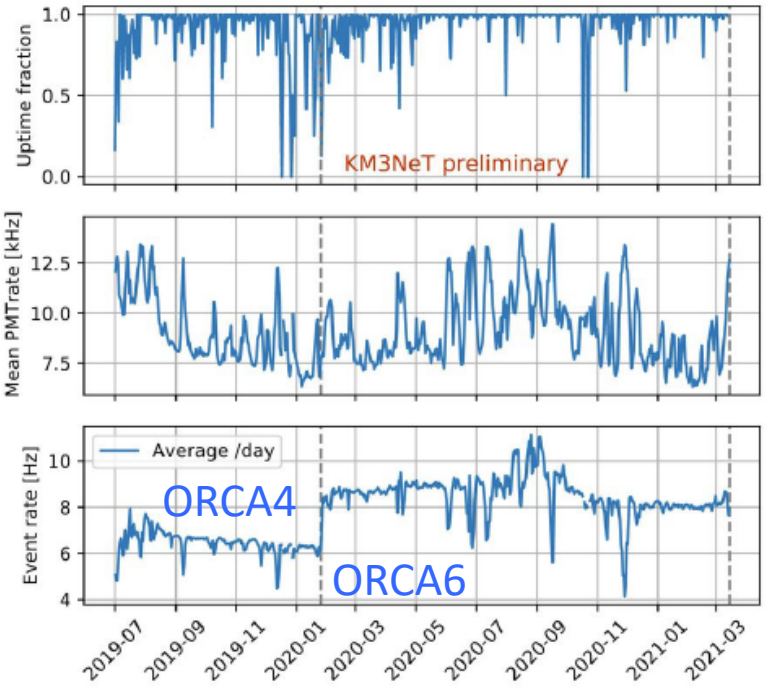




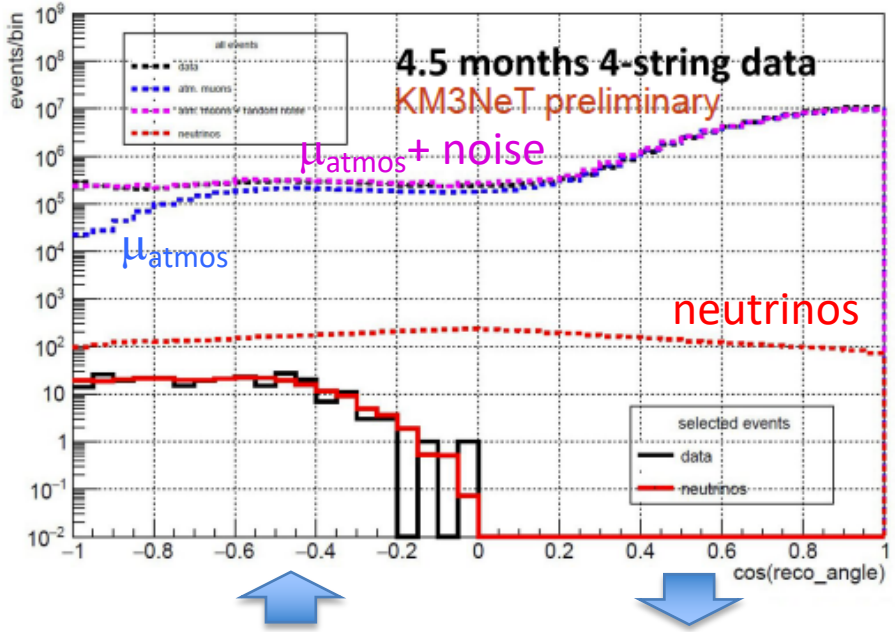
☞ *See talk by Mathieu Perrin-Terrin, VLVnT 2021*

ORCA4: first results

- Stable data taking since mid-2019
- Uptime 91% (2019) → 99% (2021)
- Good stability of trigger



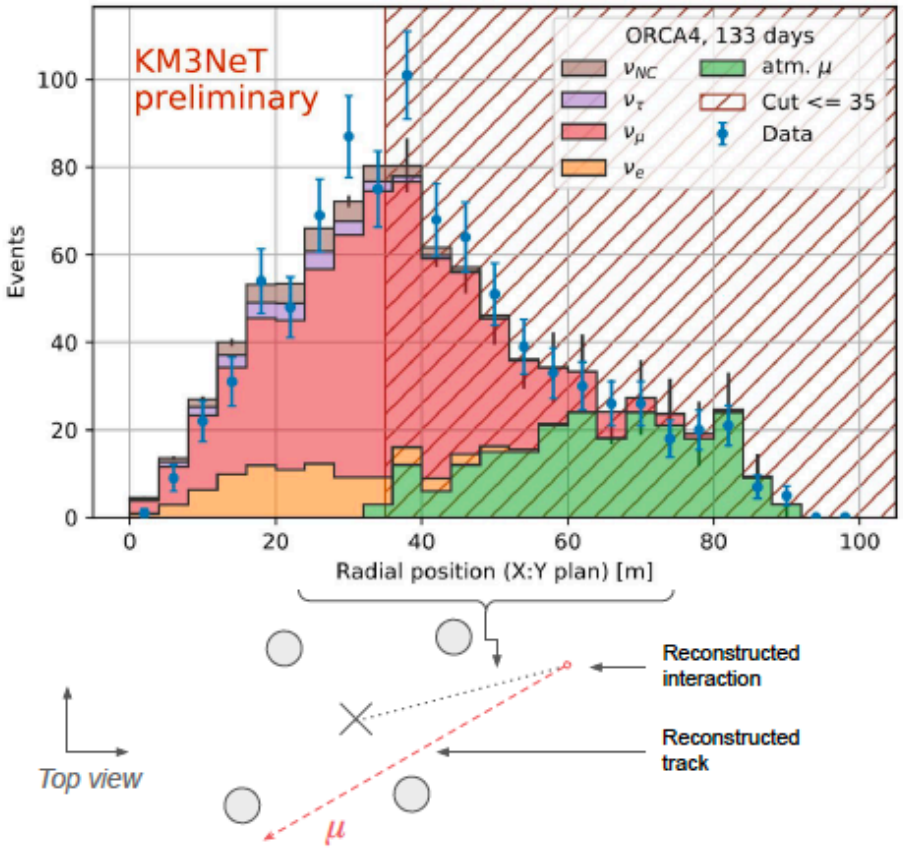
- ORCA4 data sample: 133.1 days
- Good data-MC agreement



~600 000 muons/day
~40 neutrinos/day

☞ *See talk by Vincent Pestel [KM3NeT Coll.], VLVnT 2021*

ORCA4: first results



❖ Neutrino selection:

- Upgoing tracks
- Track quality parameter
- « containment » condition on reconstructed vertex

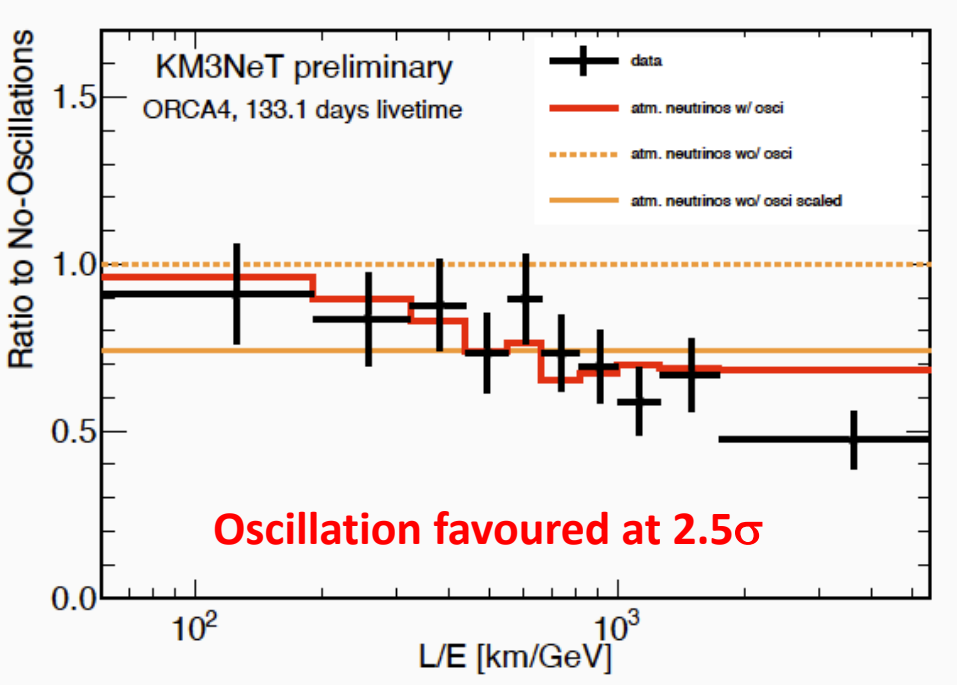
➡ High-purity neutrino sample:

• Data	2.86	± 0.15 /day
• ν_{atm}	2.92	± 0.02 /day
• $\nu_{atm\ (no\text{-}osc)}$	3.94	± 0.03 /day
• μ_{atm}	0.02	± 0.02 /day

Only stat.

☞ *See talk by Vincent Pestel [KM3NeT Coll.], VLVnT 2021*

ORCA4: first results

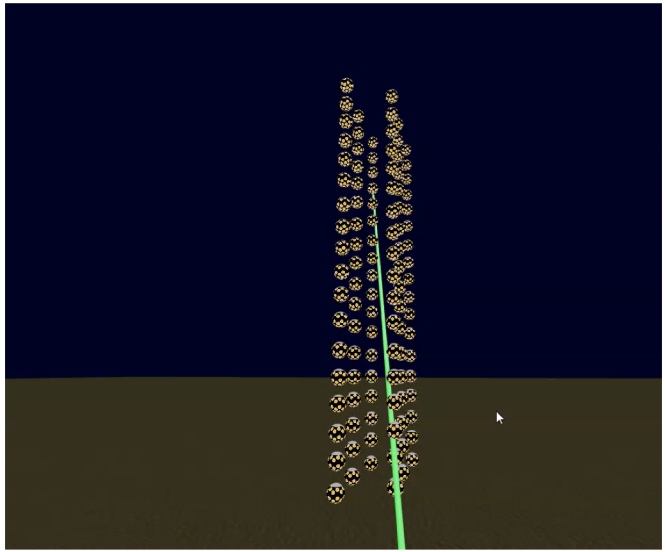


Binning adjusted for similar statistical uncertainties per bin

- First preliminary measurement
  Honda atmospheric flux + NuFit 4.0
  Flux normalization free
- Good data/MC agreement
- Statistically limited
- No track/shower separation:
  all events reconstructed as tracks
- resolutions (energy/direction) limited by small size of detector

☞ *See talk by Vincent Pestel [KM3NeT Coll.], VLVnT 2021*

Outlook



Stay tuned !

Collaborators welcome !

❖ Already 10x more neutrinos on tape with ORCA6; data sample being analyzed

❖ Detector construction proceeding and ramping up despite of CoViD:
~30 DUs expected by early 2022

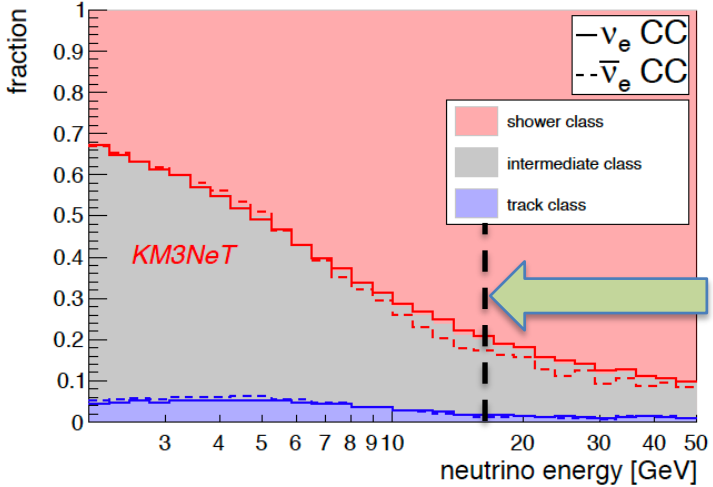
BACKUP SLIDES

ORCA reconstruction/PID

- **reco**: max $\mathcal{L}$ (vertex, dir, E, t)
- **cuts**: containment, upgoing, quality
- **background suppression**: random decision forests (RDF)

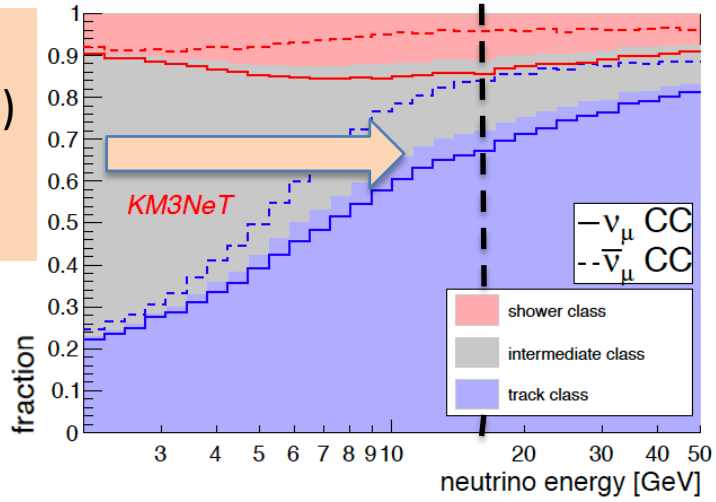
event classes:

- **shower**:
  - passes shower selection
  - track score<0.3
- **middle**:
  - passes shower selection
  - 0.3<track score<0.7
- **track**:
  - passes track selection
  - track score>0.7



At 15 GeV:
70% (85%) ν_μ^{CC} ($\overline{\nu}_\mu^{CC}$) correctly classified as tracks

At 15 GeV:
<5% $\overline{\nu}_e^{CC}$ wrongly classified as tracks



KM3NeT Coll., arXiv: hep-ex/2103.09885 , submitted to EPJ C

ORCA NMO analysis

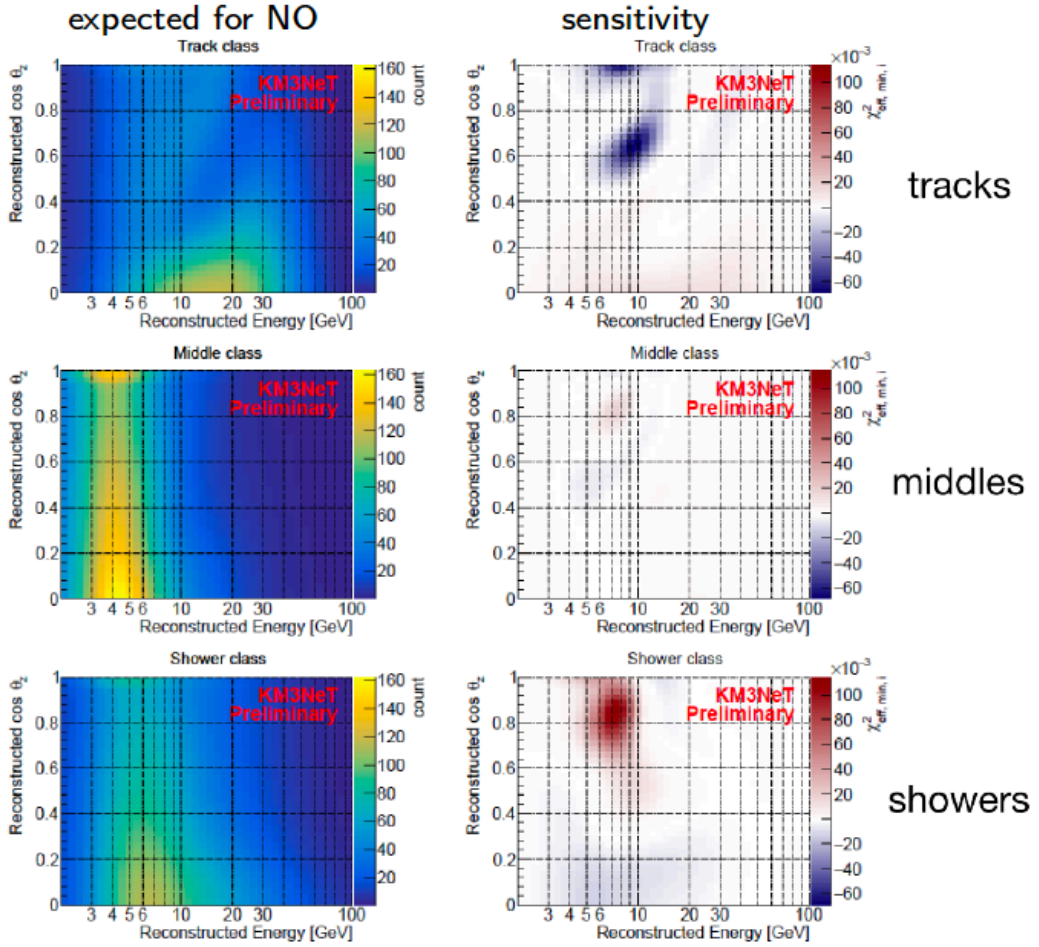
left:
expected distributions after 3y

right:
sensitivity to the NMO (NO confronted against IO)

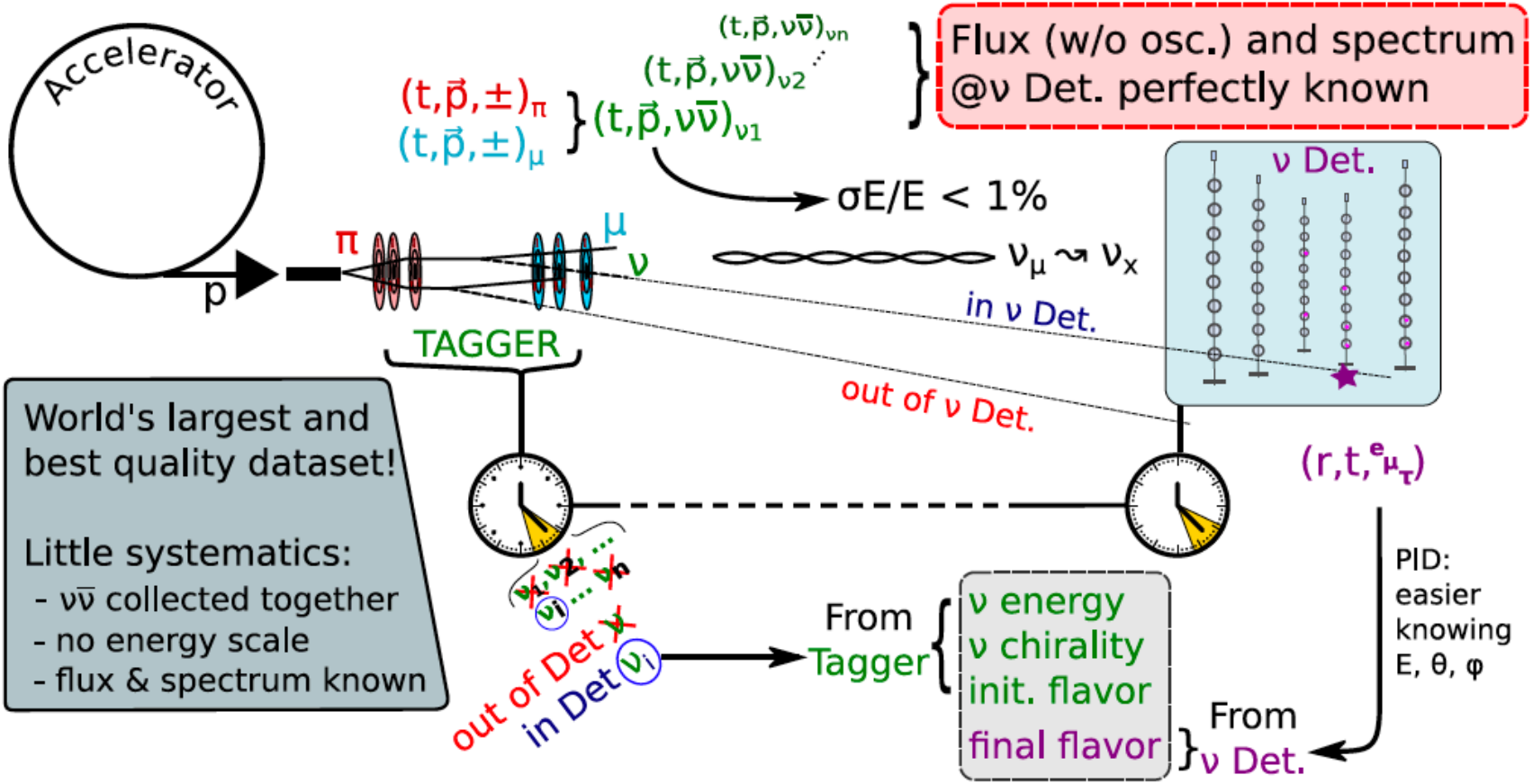
sensitivity obtained by minimizing a Test Statistic

bins: 40x40

(Asimov dataset)



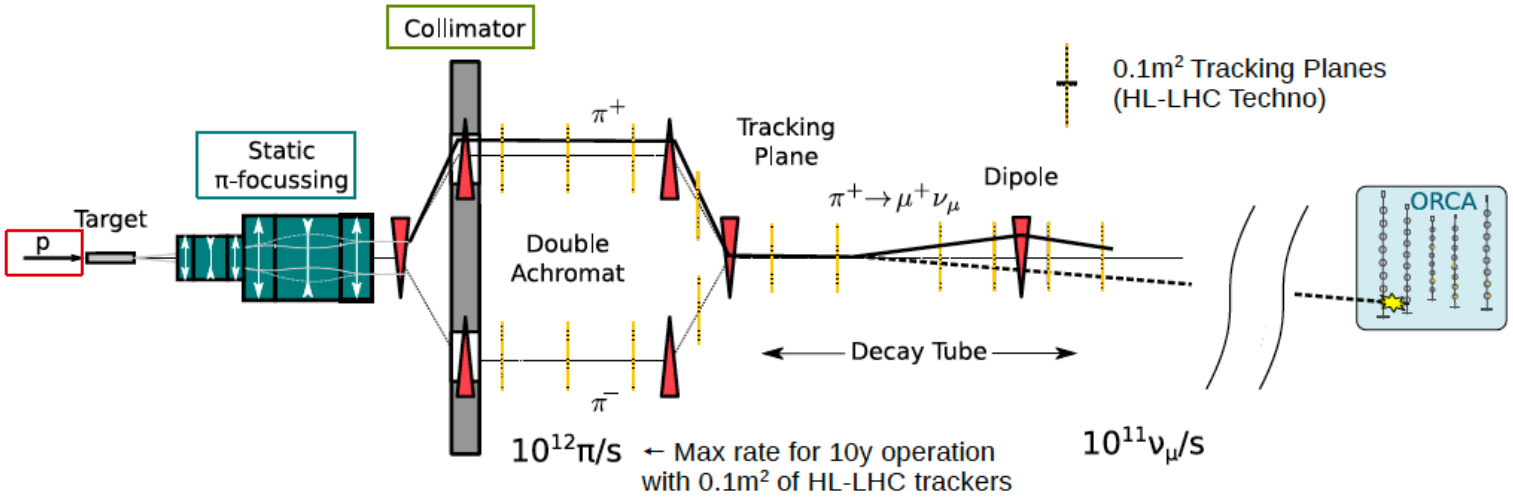
Protvino to ORCA: a tagged neutrino beam



Protvino to ORCA: a tagged neutrino beam

Beam Line Sketch for a TAGGED LBLNE

- **Slow extraction (few sec.)** & **beam cleaning** to reduce π rate
- **Static π+ and π- Focussing Devices** replace conventional horns
- **Beam size** around **0.1 m²** to match HL-LHC trackers specs.



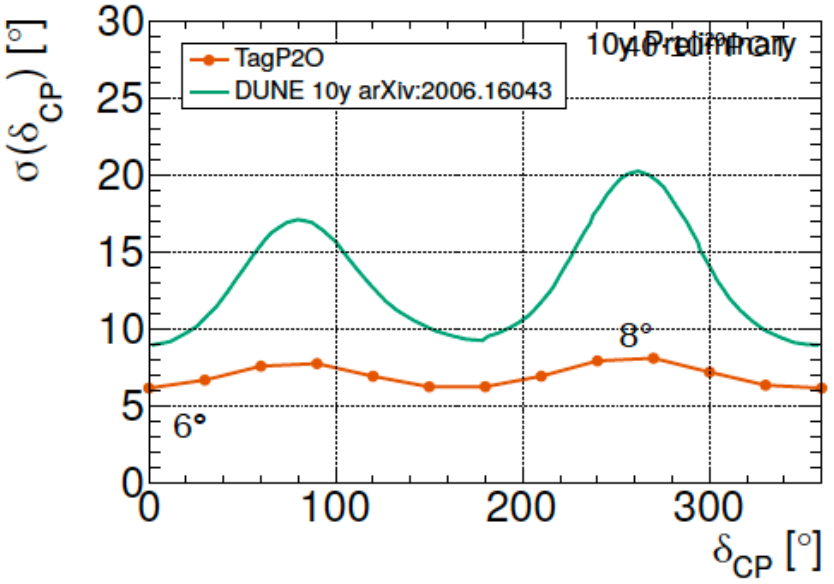
Protvino to ORCA: a tagged neutrino beam

Precision to δ_{CP} at P2O

- **Systematics** on oscillation parameters, cross section & normalisation (free)

θ13 ± 0.15°	ντ ± 10%
θ23 ± 2°	NC ± 5%
Δm^2_{31} ± 5e-3eV²	νe=νμ ± 5%

- **Conservative** estimates:
  no PID improvement with respect to atmospheric ν was considered
- δ_{CP} precision **stable** over all values
- **<8° precision** can be achieved!
- **<5°** achievable with larger detectors



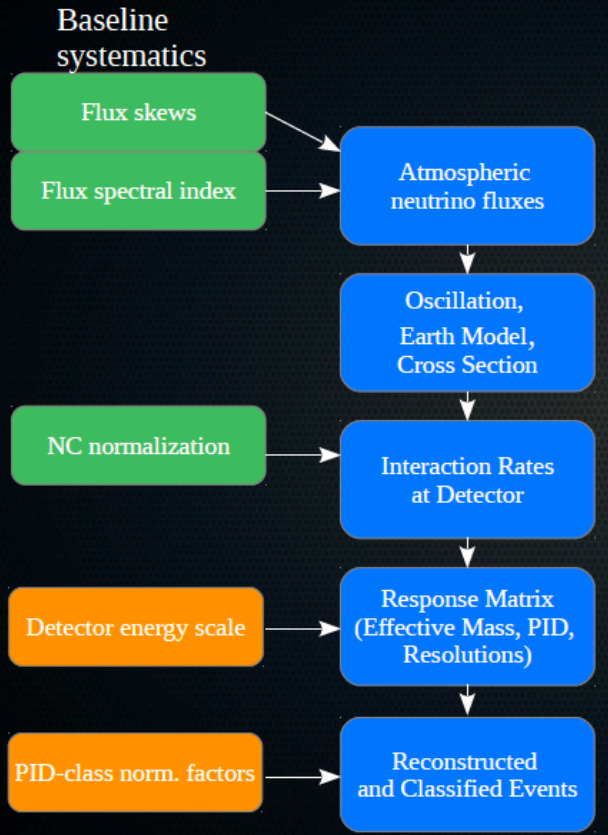
ORCA/JUNO combined sensitivity for NMO

Combination of ORCA and JUNO

- χ^2 minimization of Asimov dataset.
- Combination on Δm^2_{31} and θ_{13} using a scanned grid:

$$\chi^2(\Delta m^2_{31}, \theta_{13}) = \chi^2_{\text{JUNO}}(\Delta m^2_{31}, \theta_{13}) + \chi^2_{\text{ORCA}}(\Delta m^2_{31}, \theta_{13}) + \frac{\left(\sin^2\theta_{13} - \sin^2\theta^{GF}_{13}\right)^2}{\sigma^2_{\sin^2\theta^{GF}_{13}}}$$

Osc. parameter	JUNO	ORCA
θ_{13}	grid scan	
Δm^2_{31}	grid scan	
θ_{23}	x	fitted
Δm^2_{21}	fitted	*fixed*
θ_{12}	*fixed*	*fixed*
δ_{CP}	x	fitted

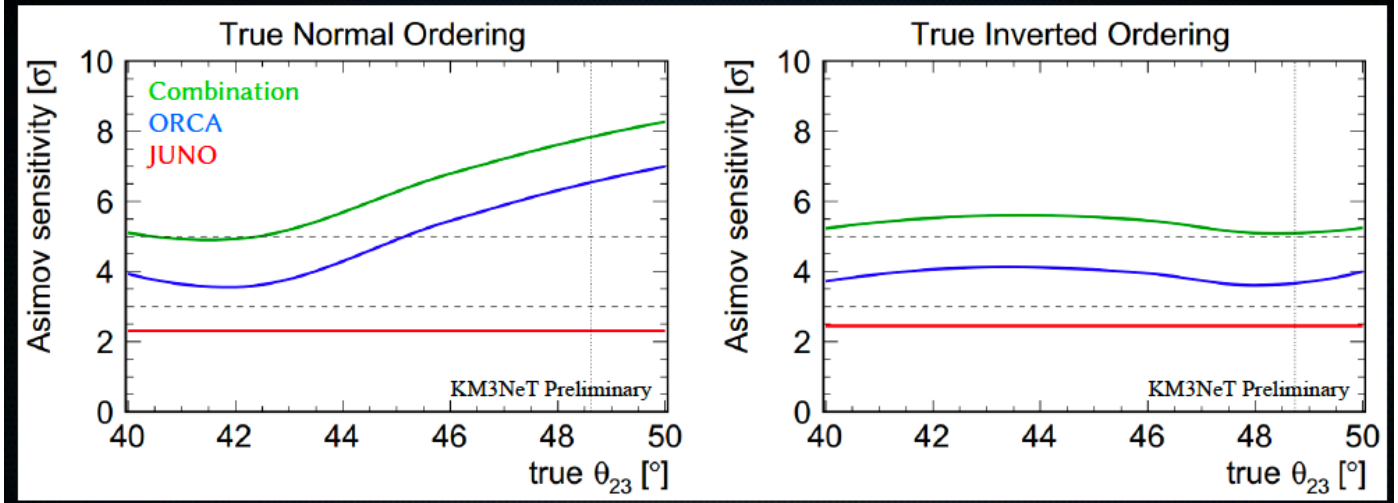


[4] J.Phys.G 43 (2016) 8, 084001 - Letter of intent for KM3NeT 2.0

☞ *See talk by Nhan Chau[KM3NeT Coll.& JUNO members], VLVnT 2021*

ORCA/JUNO combined sensitivity for NMO

θ_{23} dependence, 6 years of data taking



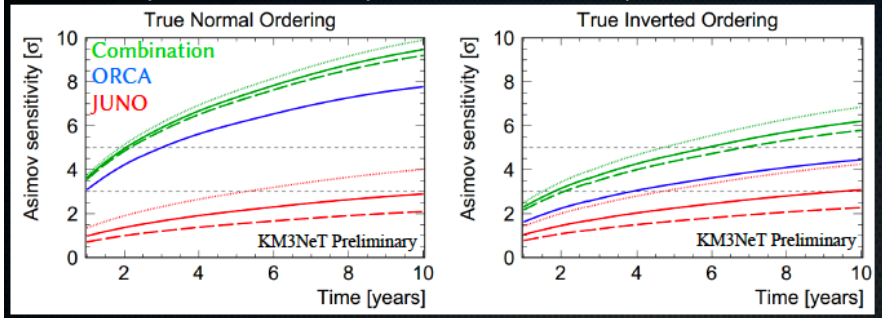
- θ_{23} dependence driven by ORCA sensitivity
- The combination ensures 5σ after 6 years regardless of the true value of θ_{23} and the true NMO

☞ *See talk by Nhan Chau[KM3NeT Coll.& JUNO members], VLVnT 2021*

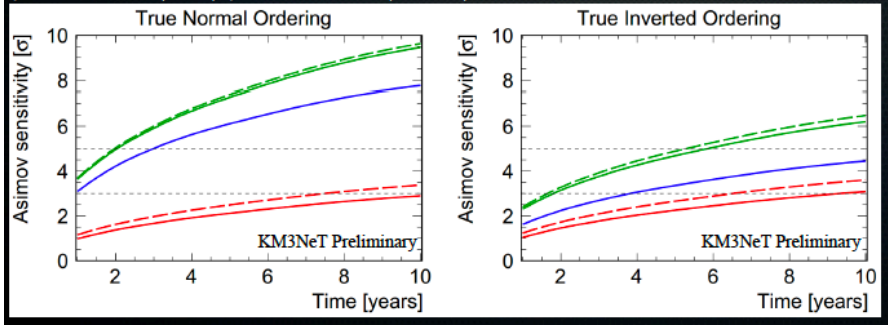
ORCA/JUNO combined sensitivity for NMO

Energy resolution in JUNO and 10 cores scenario

Nominal: $3.0\%\sqrt{E/\mathrm{MeV}}$(solid) $2.5\%\sqrt{E/\mathrm{MeV}}$(dotted) $3.5\%\sqrt{E/\mathrm{MeV}}$(dashed)



JUNO 8 cores (solid), JUNO 10 cores (dashed)



The boost relies on the difference between the JUNO and ORCA best-fit of Δm^2_{31} rather than NMO sensitivity of each experiment.

Small impact of JUNO energy resolution on the combined analysis.

Small impact of 2 additional reactors to the combination.

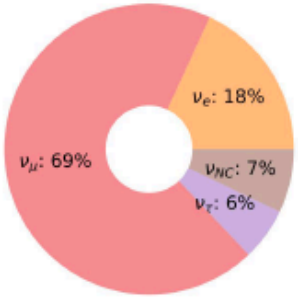
☞ *See talk by Nhan Chau[KM3NeT Coll.& JUNO members], VLVnT 2021*

ORCA4 data analysis: zenith distribution

Good agreement with Monte-Carlo

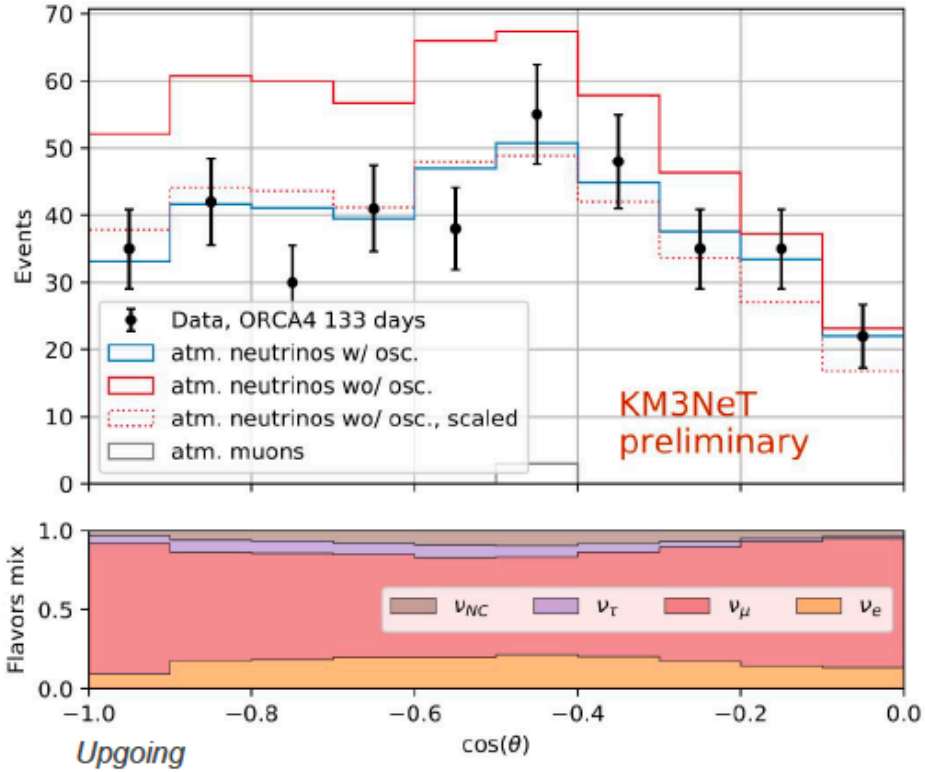
Consistency with data

- MC with neutrino oscillation :
  - p = 0.78
- MC no-oscillation, scaled to data:
  - p = 0.17



ν_μ dominated sample

- No PID applied yet
- Only "track" reconstruction



☞ *See talk by Vincent Pestel [KM3NeT Coll.], VLVnT 2021*

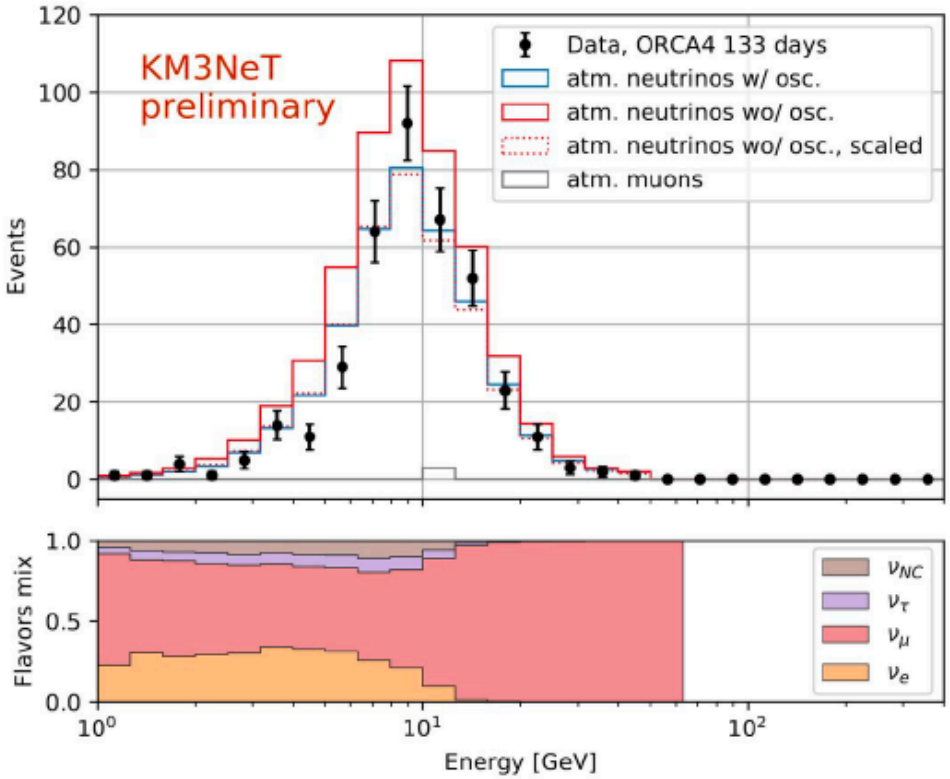
ORCA4 data analysis: energy distribution

Simple energy estimator : track length

- Consider track at MIP
  - dE/dX = 0.25 GeV/m
- Good agreement

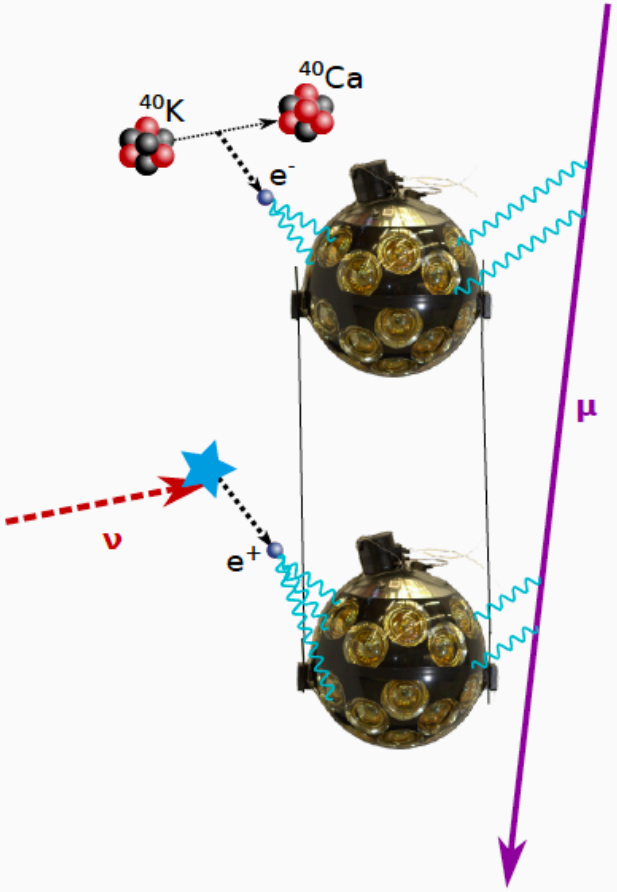
Energy peaking around 10 GeV

- Detector geometry effect
- 10 GeV ~ 40m tracks
- Reduce drastically energy sensitivity to oscillations



☞ *See talk by Vincent Pestel [KM3NeT Coll.], VLVnT 2021*

KM3NeT potential for SN neutrino detection



CCSN ν **low-energy interactions**, small tracks of $\sim$ 0.5 cm per MeV; mostly detected as **local coincidences on a single DOM**. Higher mean energy than radioactive decays.

The number of PMTs hit in a coincidence is defined as **multiplicity**.

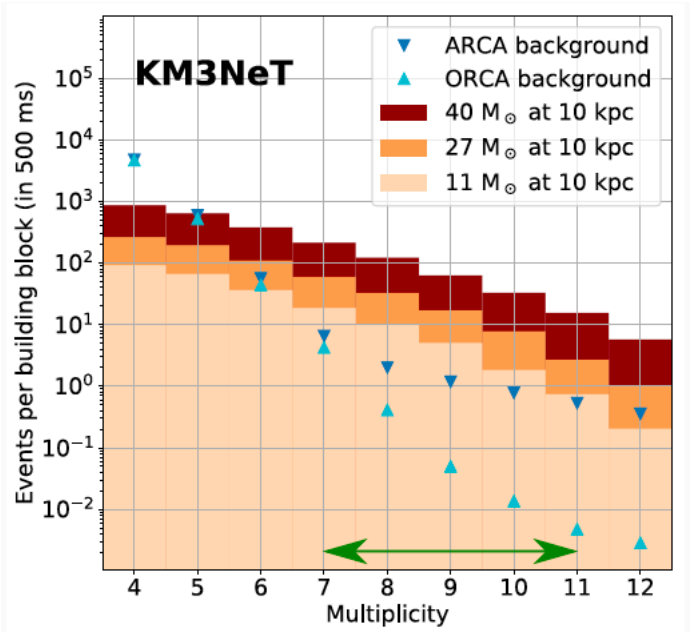
Search for a population of coincidences in excess above the backgrounds.

Study outline:

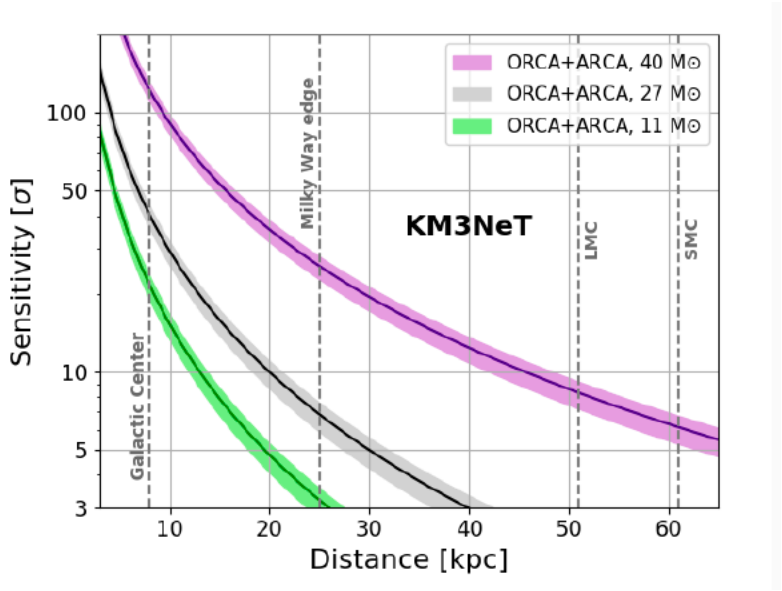
1. characterise the multiplicity distribution of the CCSN ν signal;
2. define a technique to suppress the correlated signals from atm. μ;
3. find the multiplicity selection providing the best sensitivity.

☞ *See talk by Massimiliano Lincetto [KM3NeT Coll.], VLVnT 2021*

KM3NeT potential for SN neutrino detection



500 ms time window to cover the accretion phase. Expected number of events for signal and background after muon rejection in one KM3NeT building block.



Discovery potential for 95% of Galactic CCSNe in the most conservative scenario (green band).

Maximisation of the 5σ discovery horizon → choice the **7–11 multiplicity range**.

Publication: *pre-print* `arXiv:2102.05977`, *accepted by EPJ-C.*

☞ *See talk by Massimiliano Lincetto [KM3NeT Coll.], VLVnT 2021*