KM3NeT/ORCA

status & perspectives for ν oscillation and mass hierarchy measurements

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Birmingham group particle physics seminar
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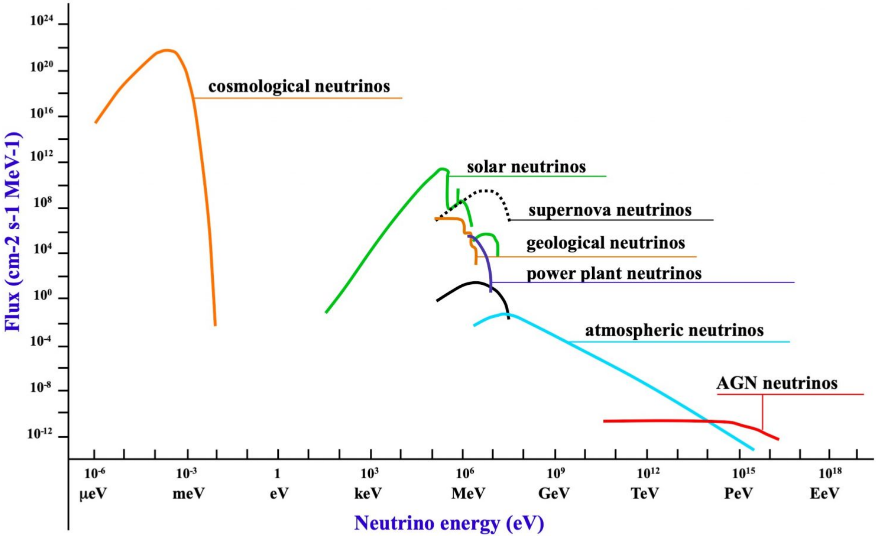
NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Funded by: NATIONAL SCIENCE CENTRE POLAND grant 2015/18/E/ST2/00758

Outline

Neutrino sources

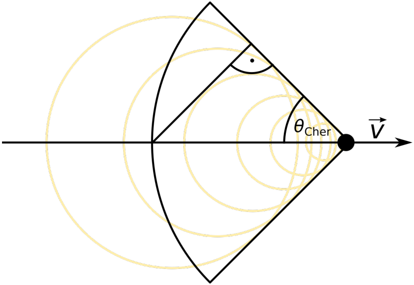


Neutrino interactions

Possible interactions:

- gravitational
- weak:
  - charged current (CC) : $\nu_l + N \xrightarrow{W^\pm} l + X$
  - neutral current (NC) : $\nu_l + N \xrightarrow{Z^0} \nu_l + X$
  - elastic scattering (ES) : $\nu_l + l \xrightarrow{W^\pm/Z^0} \nu_l + l$
- ν oscillations

Electrically charged interaction products may produce Cherenkov light:



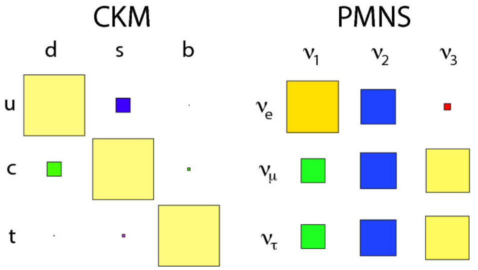
Neutrino oscillations in vacuum

Mixing of neutrino mass and flavour states:

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

U_{PMNS} - Pontecorvo-Maki-Nakagawa-Sakata matrix

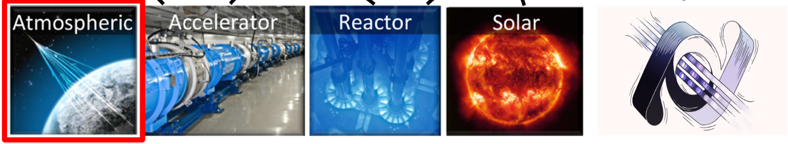
- NOT diagonal like CKM for quarks!
- not measured as precisely as CKM
- CKM = Cabibbo–Kobayashi–Maskawa



U_{PMNS} parametrization

The usual PMNS parametrization:

$$U_{\alpha i} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}} \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}} \underbrace{\begin{bmatrix} e^{\frac{i\alpha_1}{2}} & 0 & 0 \\ 0 & e^{\frac{i\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Only if } \nu\text{'s are Majorana}} \quad (1)$$

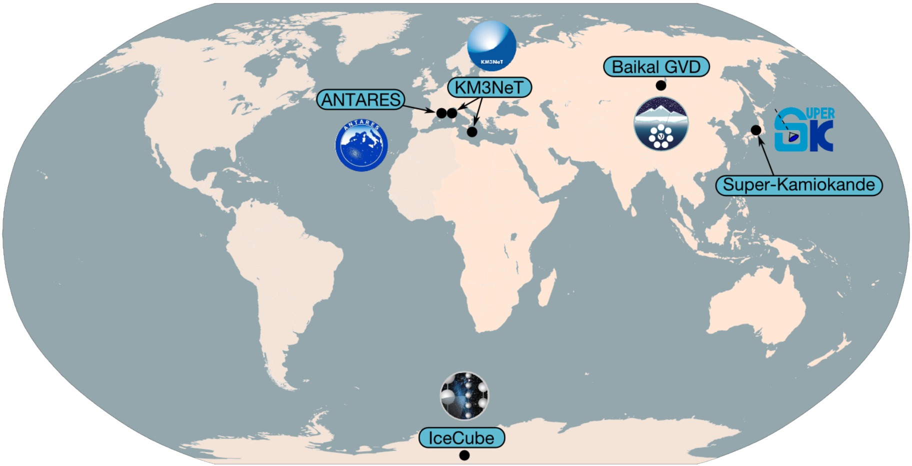


where $c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$, δ – CP-violating phase (charge-parity) and α_1, α_2 – Majorana phases.

Oscillation probability for 2ν case:

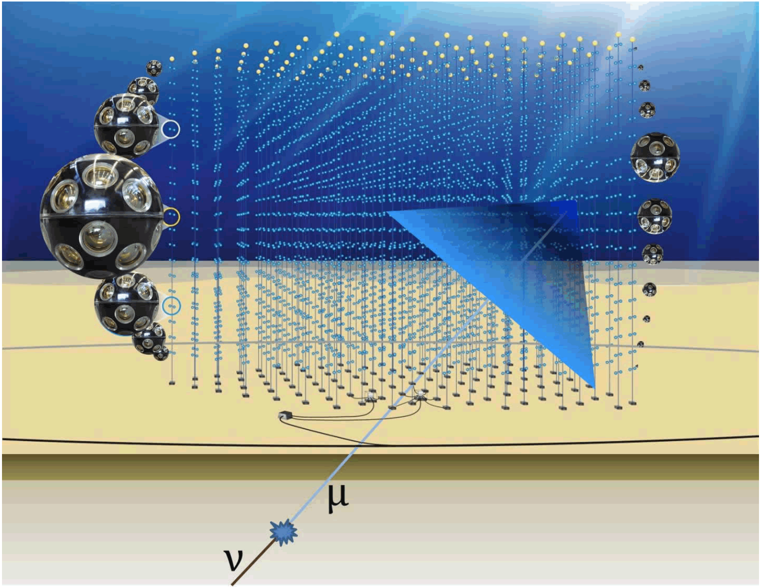
$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2 2\theta_{ij} \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) \quad (1)$$

Water Cherenkov neutrino telescopes



Outline

Principle of detection (upgoing ν_μ example)

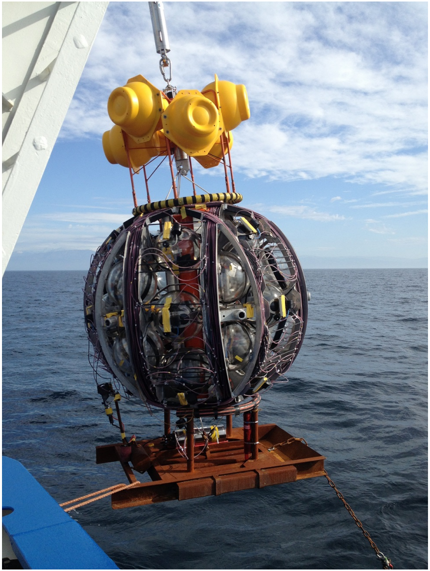


Light sensors

DOM:
Digital Optical Module
(31 3" PMTs + electronics etc.)

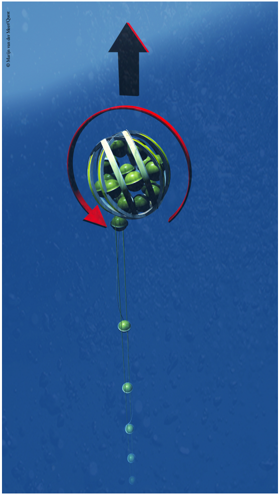
PMT:
Photomultiplier Tube

DOM arrangement



DU: Detection Unit (string with 18 DOMs)

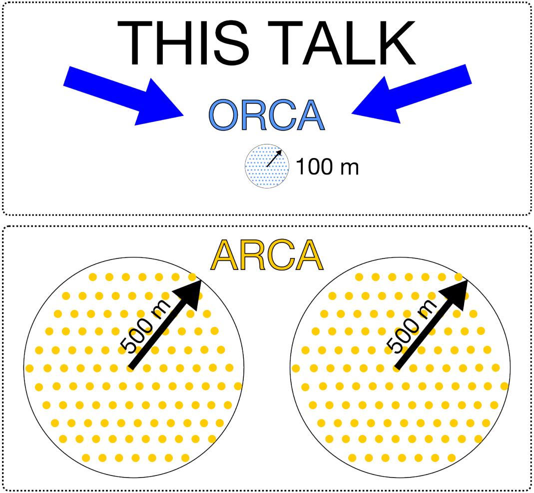
https://youtu.be/omlFkdCkbYk



ORCA6 $\Longleftrightarrow$ ORCA with 6 DUs

Detector comparison

ORCA – Oscillation Research with Cosmics in the Abyss (**main goal**: m_ν ordering)



Depth	Volume
2.5 km	0.006 km^3 (6 Mton)
3.5 km	1 km^3 (1 Gton)

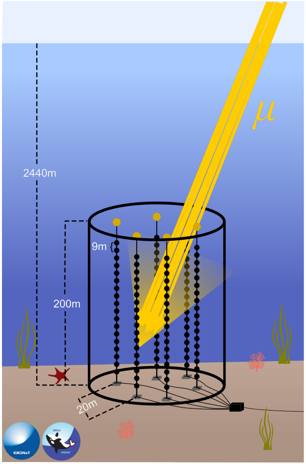
ARCA – Astroparticle Research with Cosmics in the Abyss (**main goal**: ν_{astro})

ORCA detector

KM3NeT-ORCA:

- **location**:
  - 40km offshore Toulon (France)
  - coords: 42°48' N 06°02' E
- optimized for E_ν range: few - 100GeV
- full config: ORCA115

ORCA6 (with 6 DUs):

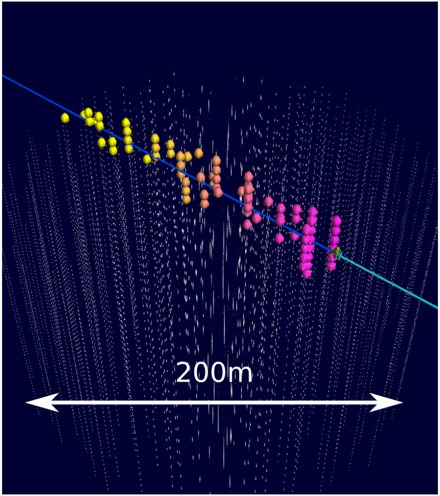


https://youtu.be/AjQx8NpQJ8Y

Event topologies (ORCA115 simulation)

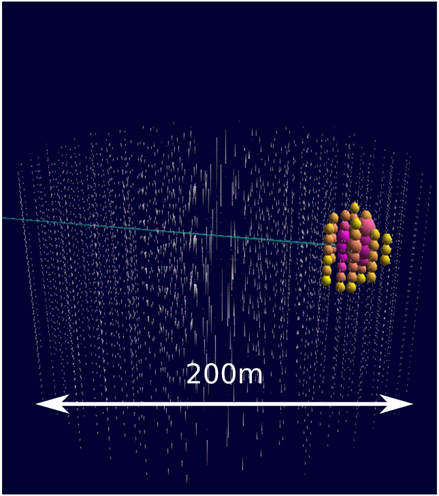
tracks

(CC: ν_μ ,ν_τ ($\tau \to \mu$))



showers

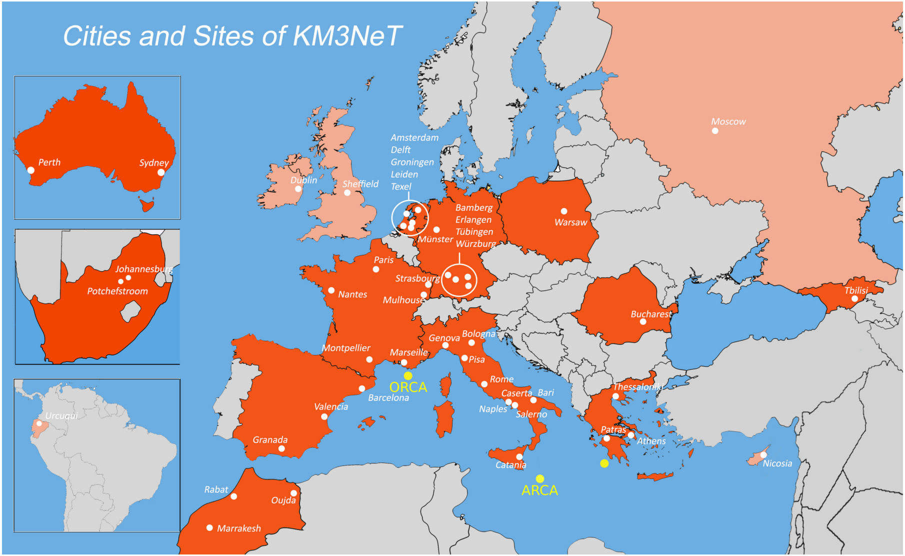
(NC: $\nu_{e,\mu,\tau}$, CC: ν_e, ν_τ ($\tau \nrightarrow \mu$))



Ball size $\to$ # hit PMTs on a DOM

color $\to$ time

The KM3NeT Collaboration



KM3NeT – The Cubic Kilometre (km^3) Neutrino Telescope

KM3NeT-PL Group

- Piotr Mijakowski (coordinator)
  - Conference and Outreach Commitee member
  - Institute Board and Review & Resources Board representative

- Rafał Wojaczyński (post-doc)
  - GC WIMP search sensitivity for ORCA
  - self-veto studies

- Piotr Kalaczyński (PhD student)
  - atm. ν/μ CORSIKA simulations & data comparisons
  - prompt μ analysis

Outline

Current status of ORCA detector

KM3NeT-ORCA:

- **configuration**:
  - 6 DUs since January 2020
  - new DU planned in Dec
  - full detector: 115 DUs (in 2025)
- remote operation → COVID-proof
- First ν candidates (already shown in https://youtu.be/AjQx8NpQJ8Y)
- 6 DUs opertional for 6 months celebration:

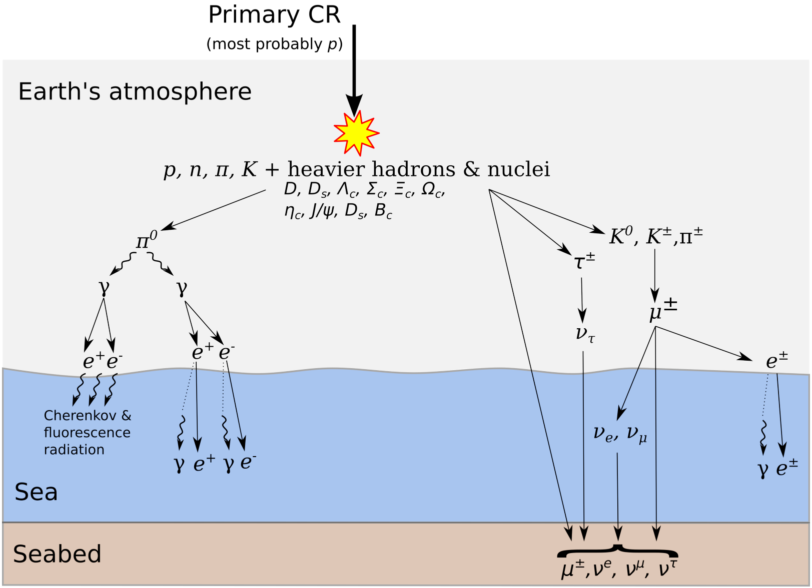
  Route 66: https://youtu.be/nkXg8g31SdU
  6 strings, 6 months: https://youtu.be/gxToAs6IQ68

Outline

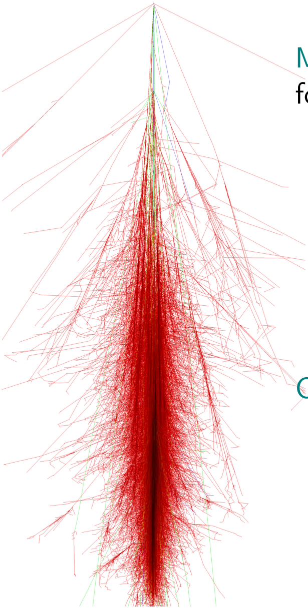
Outline

- atm. muon rate
- atm. neutrino flux

Extensive Air Showers (EAS)



EAS simulations in KM3NeT



MUPAGE – atmospheric MUons from PArametric formulas: a fast GEnerator for neutrino telescopes

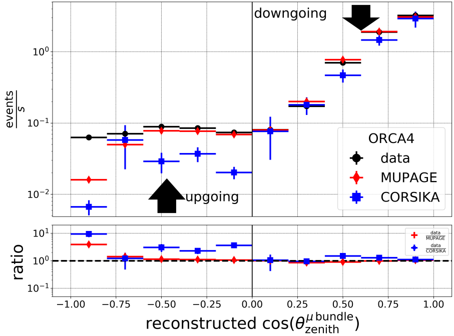
- developed for ANTARES
- fast muon MC generator
- based on parametric formulas and MACRO measurements
- parameters can be freely tuned

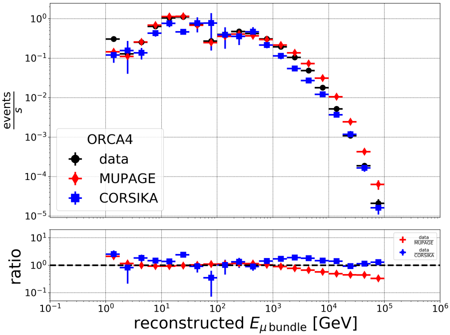
CORSIKA – COsmic Ray SImulations for KAscade

- developed for KASCADE experiment (Karlsruhe)
- full simulation of air showers
- customizable (models, primaries, etc.)

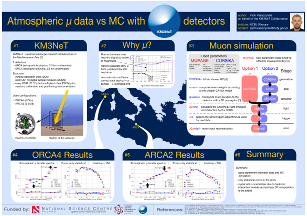
Atmospheric muon rate measurement

author: Piotr Kalaczyński (me ☺)





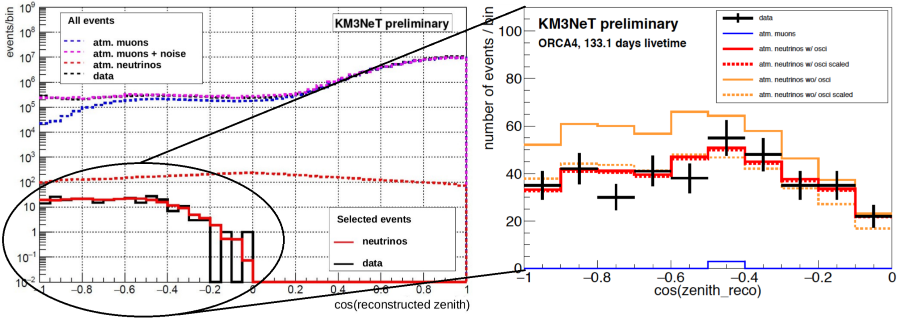
- from poster #316 @Neutrino2020
- **livetime**: 35d (10.-11.2019) with 4 DUs
- **obs. rate**: $455\text{k}\frac{\mu}{\text{day}}$ ($\sim 0.03 \cdot \text{rate @sea level}$)
- errors only stat. (syst. in progress)



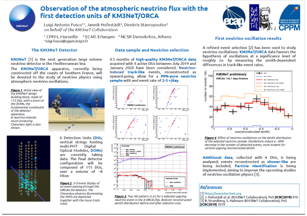
Atmospheric neutrino flux measurement

authors: Luigi Antonio Fusco, Jannik Hofestädt, Dimitris Stavropoulos

ν_{atm} selection | oscillations



- from poster #363 @Neutrino2020
- **livetime**: 4.5m (07.2019-01.2020) with 4 DUs
- **purity**: 99 %
- **observed rate**: $3\frac{\nu}{\text{day}}$
- oscillations hypothesis favoured ($p = 0.17$)!

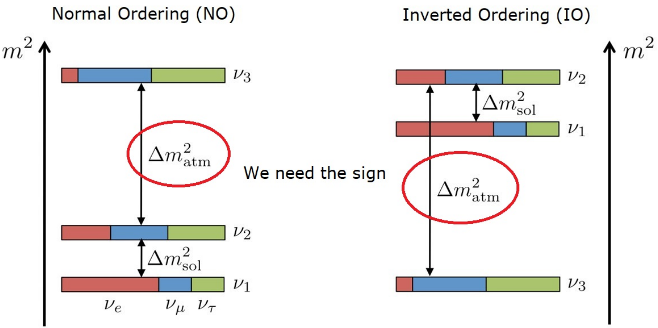


Outline

Outline

- ν mass ordering
- mixing parameters
- ν_τ appearance
- sterile neutrinos
- core-collapse SNe
- DM from the Sun

Neutrino Mass Ordering (NMO)

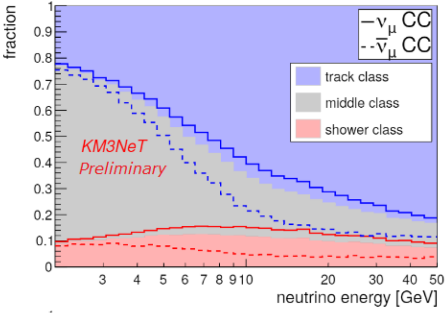


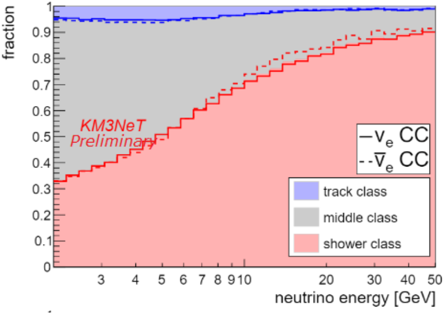
credit: JUNO Collaboration / JGU-Mainz

Analysis idea:

- traversing the Earth enhances $P_{\nu_\mu \longleftrightarrow \nu_e}$ for NO and $P_{\bar{\nu}_\mu \longleftrightarrow \bar{\nu}_e}$ for IO at $E \lesssim 15\,\text{GeV}$
- KM3NeT does not distinguish ν and $\bar{\nu}$ events
- $\sigma_{\text{interaction}}$ and atm. flux are bigger for ν than for $\bar{\nu}$
  ↪ net effect on oscillation patterns

Event classes in NMO analysis





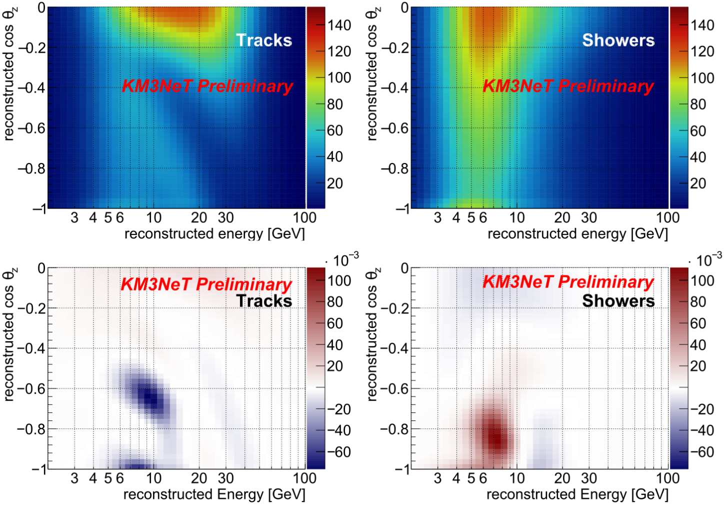
- **reco**: max $\mathcal{L}$ (vertex, dir, E, t)
- **cuts**: containment, upgoing, quality
- **background suppression**: random decision forests (RDF)

- **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**

Oscillation patterns in NMO analysis

Null (NO) distribution

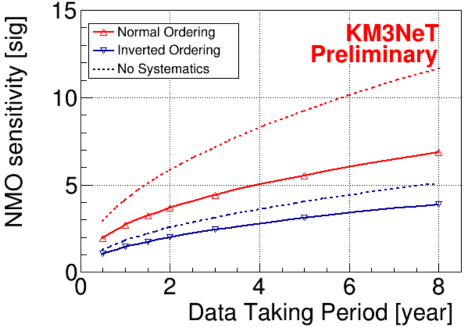
Minimized TS

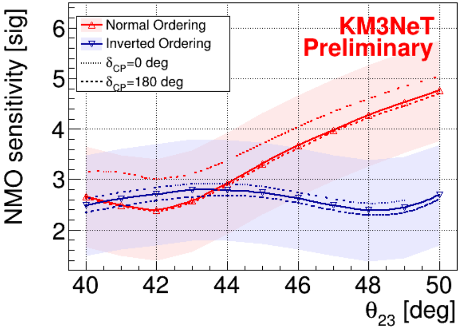


$$\text{Sensitivity} = \sum_{\text{bins}} |\text{minimized TS}|$$

Neutrino Mass Ordering (NMO) sensitivity

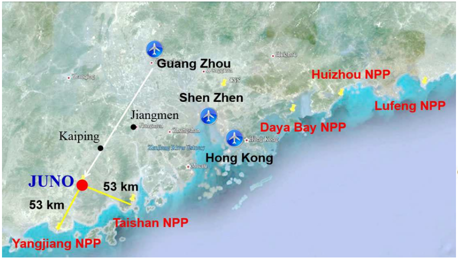
author: Mathieu Perrin-Terrin

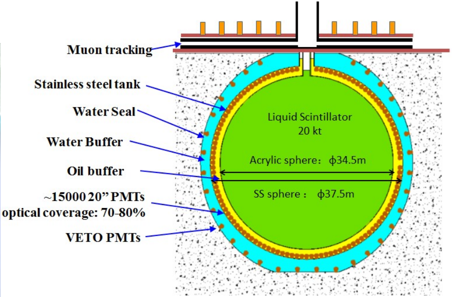




- **parameters**: NuFit 4.1
- **MC**: 3y of full ORCA (115 DUs)
- for NO: 5σ after 4y
- paper in preparation

JUNO experiment

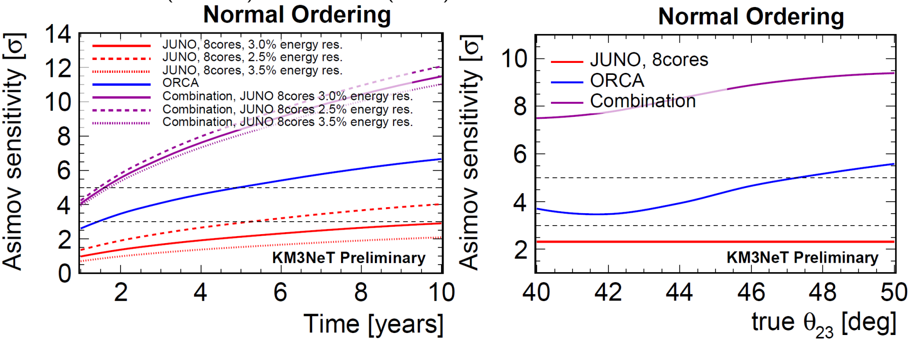




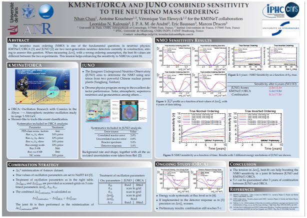
- Jiangmen Underground Neutrino Observatory (JUNO)
- reactor experiment in China
- **main goal**: precision θ_{13} measurement
- **sensitive to**: atmospheric, geo- and supernova ν's
- scheduled to start taking data in 2021

NMO sensitivity for ORCA + JUNO

authors: Nhan Chau (KM3NeT) and L. Kalousis (JUNO)



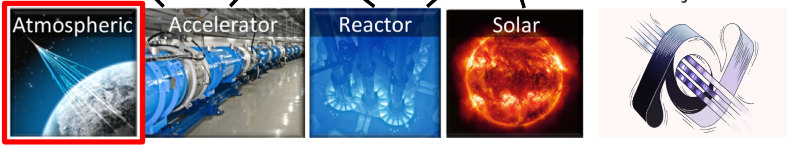
- from poster #480 @Neutrino2020
- tension between the best-fit Δm^2_{31} with a wrong ordering assumption enhances the sensitivity
- **method**: χ^2 minimization of an Asimov dataset
- **parameters**: NuFit 4.0
- for NO: 5σ after 1y (7.5σ after 4y)



Atmospheric mixing parameters (reminder)

The usual PMNS parametrization:

$$U_{\alpha i} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}} \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}} \underbrace{\begin{bmatrix} e^{\frac{i\alpha_1}{2}} & 0 & 0 \\ 0 & e^{\frac{i\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Only if } \nu\text{'s are Majorana}} \quad (1)$$



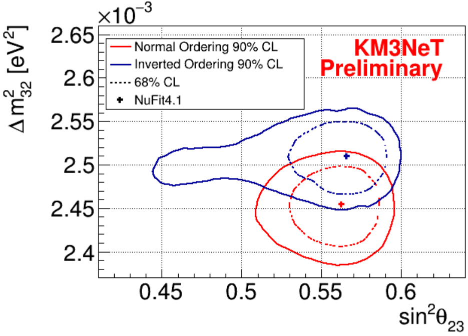
where $c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$, δ – CP-violating phase (charge-parity) and α_1, α_2 – Majorana phases.

Oscillation probability for 2ν case:

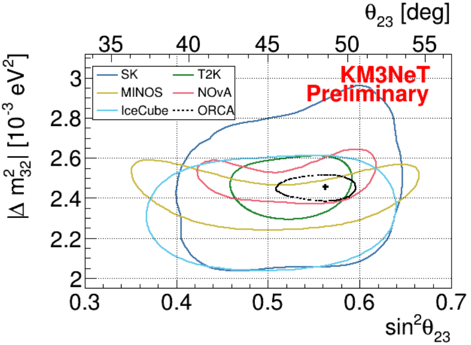
$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2 2\theta_{ij} \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) \quad (2)$$

Sensitivity to Δm^2_{32} and θ_{23}

author: Mathieu Perrin-Terrin



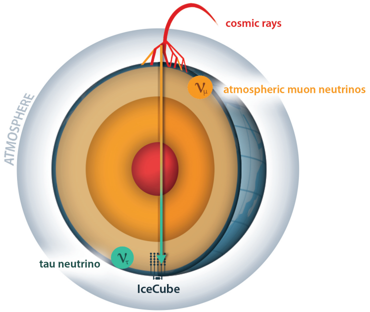
Assuming NO



- **motivation:**
  - improve the precision on Δm^2_{32}, θ_{23}
  - determine the octant of θ_{23}
- **method**: max. likelihood
- **parameters**: NuFit 4.1
- **MC**: 3y of full ORCA (115 DUs)
- paper in preparation

ν_τ appearance concept

credit: the IceCube Collaboration



ν_τ appearance:

- confirmation of oscillations (no other way to produce ν_τ)
- first measured by OPERA (Phys. Rev. Lett. 115, 121802 (2015))
- observed statistically by SK and IceCube

τ normalization[1]: measure of the unitarity[2] of U_{PMNS}
(τ norm$\neq 1$ means new physics)

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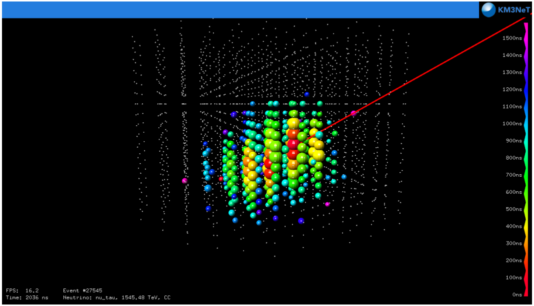
[1] τ normalization$= \frac{\#\text{detected}\,\nu_\tau}{\#\text{expected}\,\nu_\tau\,\text{from standard oscillations}}$

[2] $U^* U = \mathbb{I}$

ν_τ signal

Example of ν_τ signature (double bang):



1st "bang": $\nu_\tau + N \to \tau + X$
2nd "bang": $\tau \to \nu_\tau + X'$ or
$\tau \to \nu_\tau + e + \bar{\nu}_e$
problems:

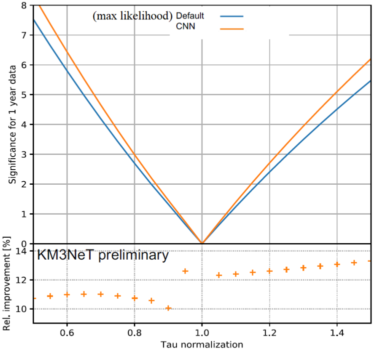
- rare events
- "bangs" hard to separate

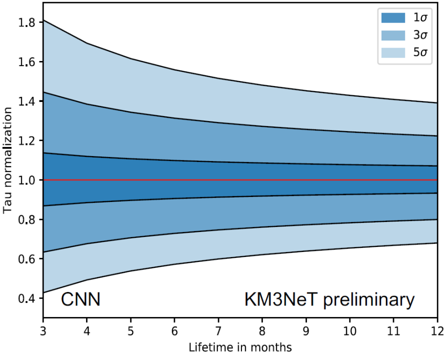
There are other signatures, but generally hard to extract the ν_τ's.

$\Longrightarrow$ Solution: look at statistical excess due to taus!

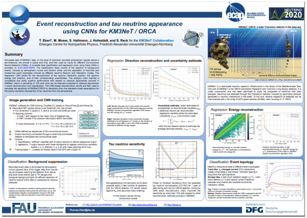
ν_τ appearance results

authors: Michael Moser and Thomas Eberl





- from poster #202 @Neutrino2020
- fit robust against θ_{23} and mass ordering
- CNN's outperform max $\mathcal{L}$ by >10% in constraining deviations from expected τ normalization (=1)
- confirmation of τ appearance possible within few months of operation with full ORCA



Sterile neutrinos (mini-intro)

Sterile ν simplest scenario (3+1):

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = U_{3+1} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

$\hookrightarrow$ new mixing parameters: θ_{i4}, Δm^2_{i4} $(i = 1,2,3)$, δ_{i4} $(i = 1,2,3)$

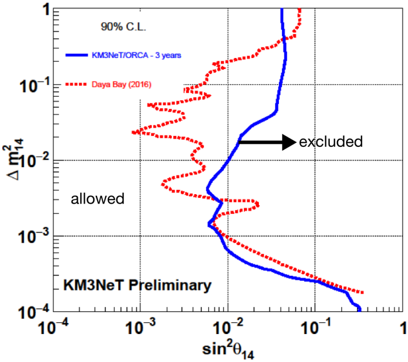
■ - standard U_{PMNS}

■ - sterile

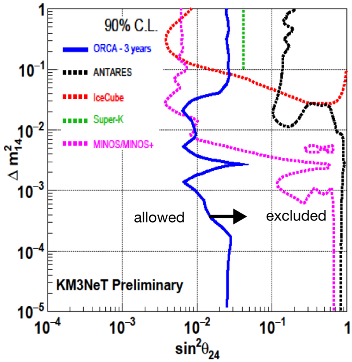
Exclusion limits on sterile mixing parameters

authors: Tarak Thakore, Alba Domi and Joao Coelho

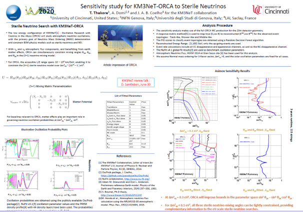
θ_{24} and θ_{34} fitted, $\delta_{24} = 0$



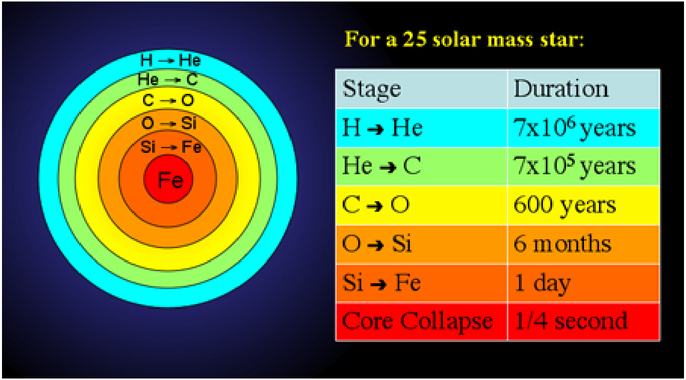
θ_{14} and θ_{34} fitted, $\delta_{24} = 0$



- from poster #179 @Neutrino2020
- **method**: χ^2 minimization of an Asimov dataset
- **MC**: 3y of full ORCA (115 DUs)
- **scenario**: 3+1
- **assumptions**: NO, $\Delta m^2_{41} > 0$, NuFit 4.1 (Δm^2_{21}, θ_{12})



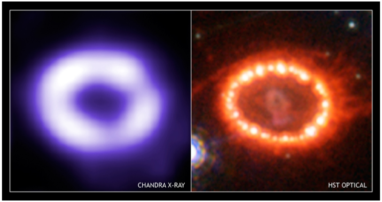
Core-collapse Supernovae (CCSN)



Stage	Duration
H → He	7x10^6 years
He → C	7x10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

CCSN:

- 99% of $E_{\text{grav}} \dashrightarrow \nu$ when γ cannot escape
- Explosion mechanism not fully understood
- First and only observation: 24 ν from SN1987A →



Detecting a CCSN with neutrinos

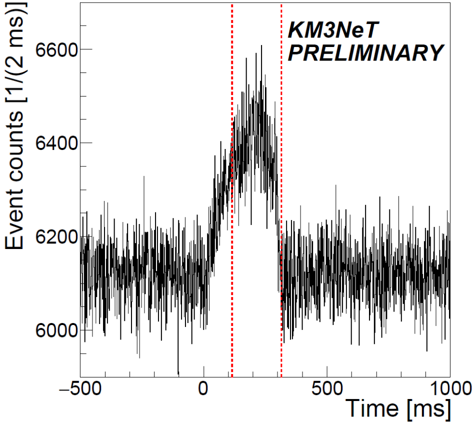
There are 2 ways to detect:

- measure the ν
- look at the PMT background rate

CCSN produce MeV ν's

KM3NeT has few GeV threshold → 2nd approach

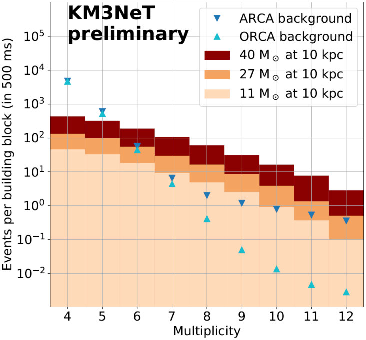
authors: Marta Colomer, Massimiliano Lincetto, Vladimir Kulikovskiy, Damien Dornic and Alexis Coleiro



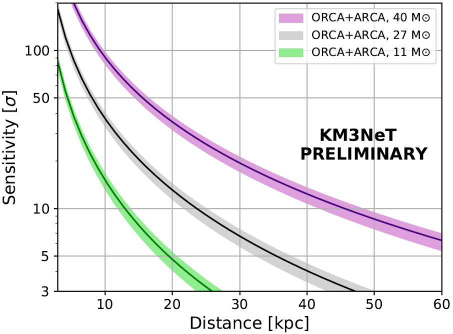
CCSN detection sensitivity

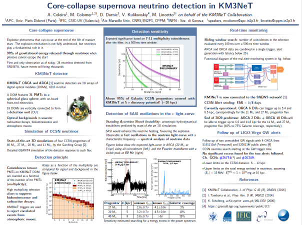
authors: Marta Colomer, Massimiliano Lincetto, Vladimir Kulikovskiy, Damien Dornic and Alexis Coleiro

1 building block



full ORCA&ARCA, multiplicity 7-11, 500ms window





- from poster #245 @Neutrino2020
- **multiplicity** - number of hit PMTs on a DOM
- >95% of galactic CCSN progenitors at 5σ (20kpc)
- ORCA6 can trigger up to 5.4 (9.5) kpc for 11 (27) $M_\odot$ progenitors

Dark matter (DM)

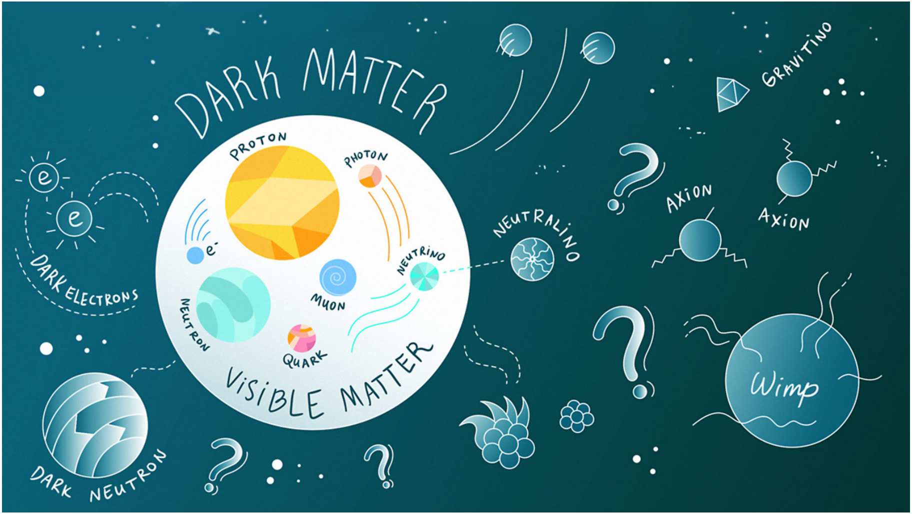


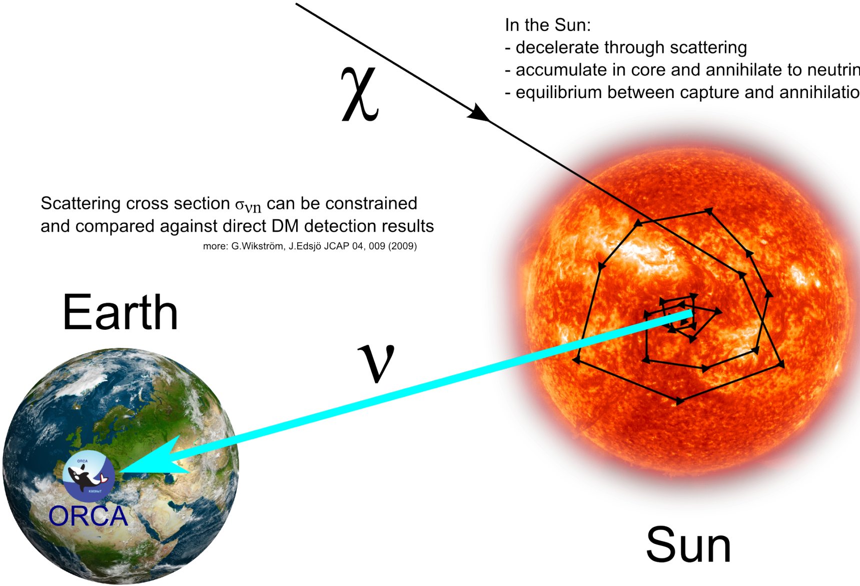
Illustration by Sandbox Studio, Chicago with Ana Kova

DM from the Sun

In the Sun:
- decelerate through scattering
- accumulate in core and annihilate to neutrinos
- equilibrium between capture and annihilation

Scattering cross section $\sigma_{\nu n}$ can be constrained and compared against direct DM detection results

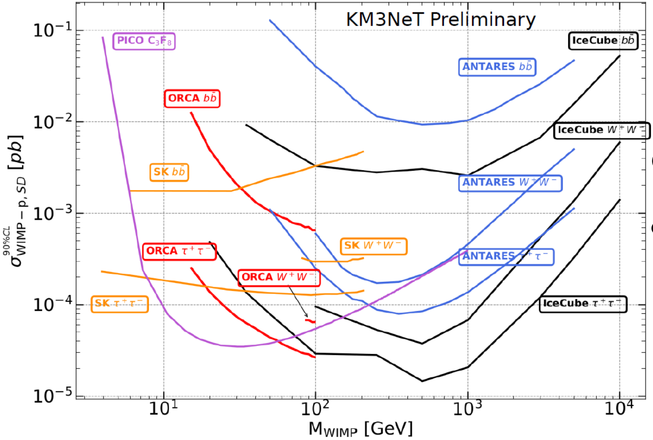
more: G.Wikström, J.Edsjö JCAP 04, 009 (2009)



DM from the Sun sensitivity

authors: Daniel Lopez-Coto, Sergio Navas and Juande Zornoza
spin-dependent (coupling to splin; mainly for odd A)

ORCA 115 (5 years), ANTARES (2007-2012), IceCube (2011-2014), SK (1996-2012), PICO (2016-2017)



ORCA: sensitivity

others: limits from data

- **search**: indirect
- **DM particle**: WIMP (neutralino χ)
- **method**: $\log \mathcal{L}$ maximization
- **MC**: 5y with full ORCA (115 DUs)
- **used topology**: only tracks

Outline

Potential upgrades

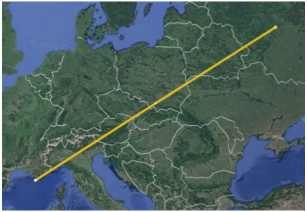
Goal: measure δ_{CP}

Super-ORCA:

- ~10x denser
- improved E and θ resolution
- more details in PoS(ICRC2019)911 (arXiv:1907.12983)

Protvino to ORCA (P2O):

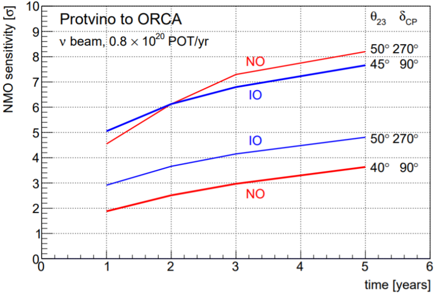
- neutrino beam from Protvino (near Moscow)
- 2595km baseline
- **LoI:** Eur. Phys. J. C (2019) 79: 758 (arXiv:1902.06083)



Both: Protvino to Super-ORCA
Timeline: undefined

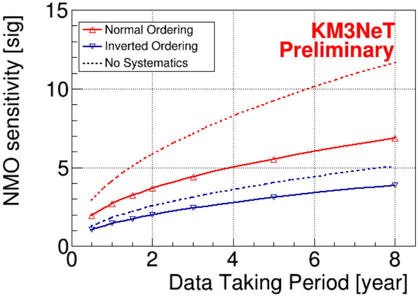
P2O sensitivity to the NMO

P2O



(for the 90kW beam)

ORCA

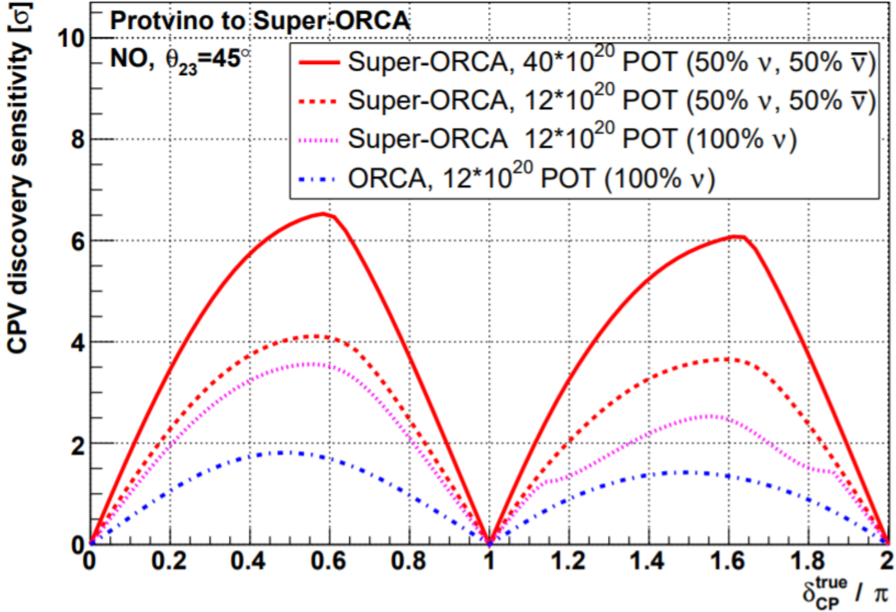


$\theta_{23} = 48.6°$, $\delta_{CP} = 221.0°$ (NO),

$\theta_{23} = 48.8°$, $\delta_{CP} = 282.0°$ (IO),

- improved overall performance

P2O sensitivity to δ_{CP}: ORCA vs Super-ORCA



Outline

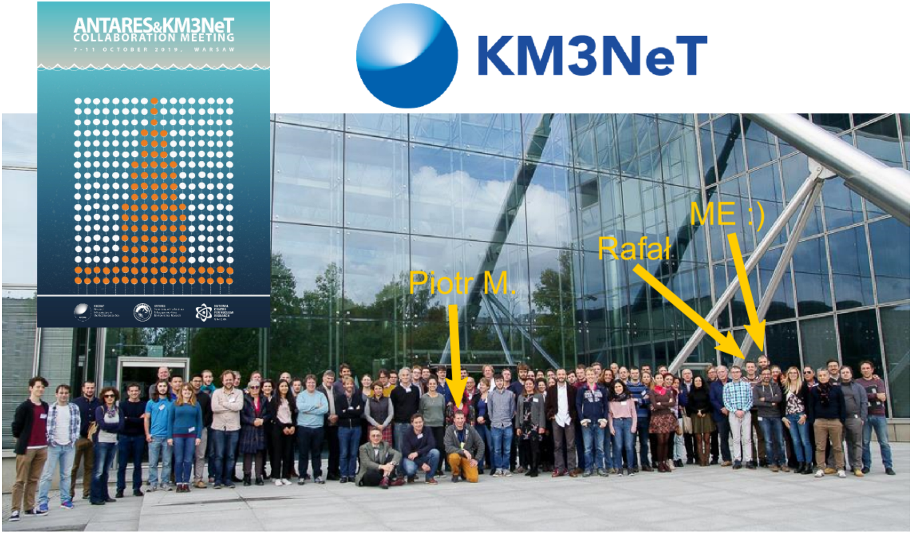
1. Neutrinos
2. KM3NeT
3. ORCA status
   - Measurements with ORCA4 (with 4 DUs)
   - Sensitivity studies for ORCA115 (with 115 DUs)
   - Potential detector upgrades
4. Summary

Summary

- Detector:
  - ORCA6 running stably
  - new DU expected in December 2020
- Data analyses:
  - ORCA4:
    - first measurements
    - we see the oscillations!
  - ORCA6: analyses ongoing
- Sensitivity studies for ORCA115
  - promising results
  - world-first NMO measurement possible!
  - not all shown!

Take-home message:
ORCA lives and bites hard.
Exciting physics ahead!

Thank you for your attention. Any questions?



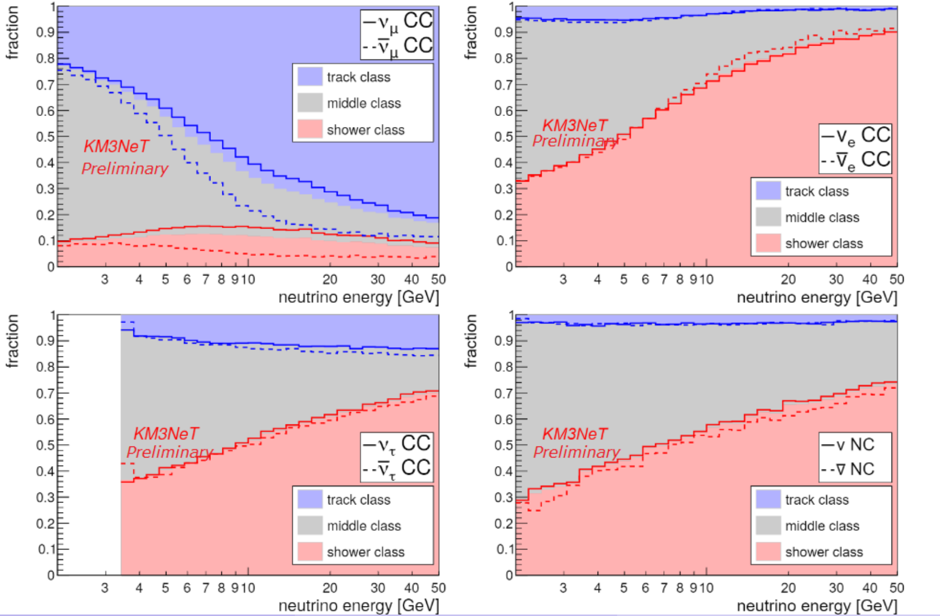
ARCA - why 2 blocks?

- sensitivity to galactic sources is not reduced for 2 building blocks, provided they are large enough (at least 0.5km^3 each)
- more optimal for regional funding and human resources
- complies with the technical specifications for the construction and operation

Core-collapse Supernovae (CCSN)

- $\Delta t \simeq 10 - 20$ms @10kpc, depending on the progenitor
- dedicated CCSN MC for the signal of a single DOM
- for bgd we use data directly
- No significant excess found for GCN #26751(retracted) and #26249 alerts

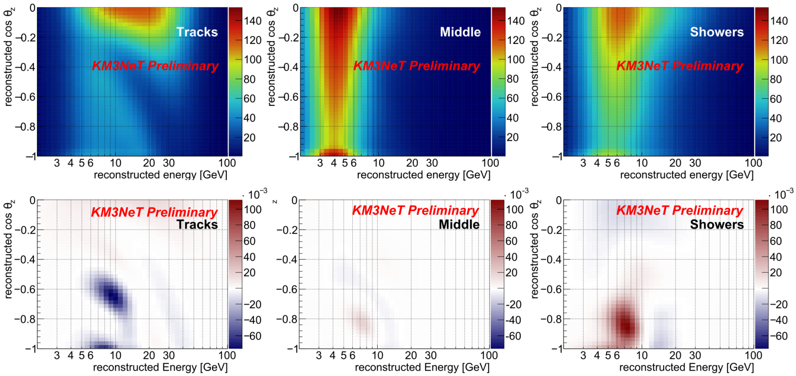
Event classes in NMO analysis



Oscillation patterns in NMO analysis

Null (NO) distribution

Minimized TS



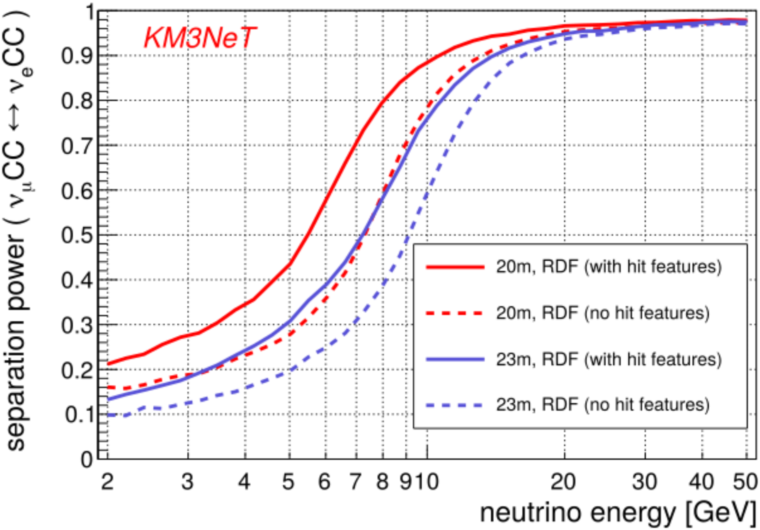
$$\text{Sensitivity} = \sum_{\text{bins}} |\text{minimized TS}|$$

NMO TS formula

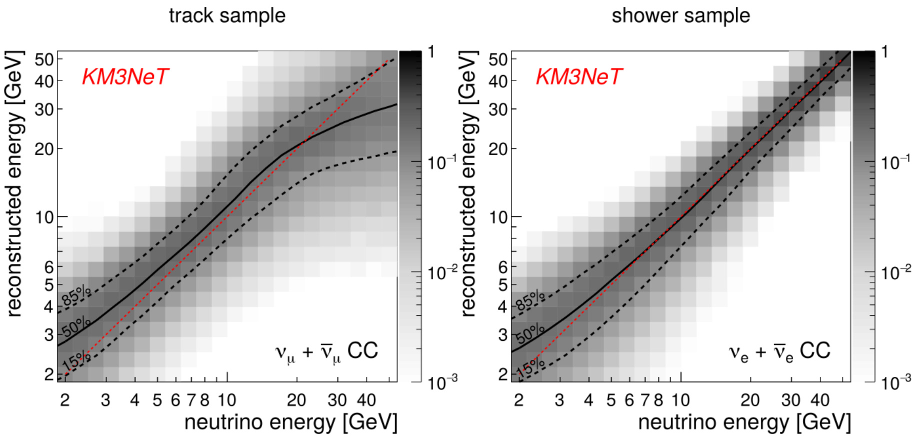
$$\mathcal{L}_0^2 = \sum_{i \in [\mathrm{E^{rec}},\ \cos\theta_z^{rec}]} \mathcal{L}_{0,i}^2 = \sum_{i \in [\mathrm{E^{rec}},\ \cos\theta_z^{rec}]} -2.0 \times (n_i^{\mathrm{alt}} - n_i^{\mathrm{null}} - n_i^{\mathrm{alt}} \ln \frac{n_i^{\mathrm{alt}}}{n_i^{\mathrm{null}}}), \quad (3)$$

$$\mathsf{TS} : \mathcal{L}_{eff}^2 = \mathcal{L}_0^2 + \sum_{i \in parameters} \frac{(p_i^{exp} - p_i^{obs})^2}{\sigma_i^2} \quad (4)$$

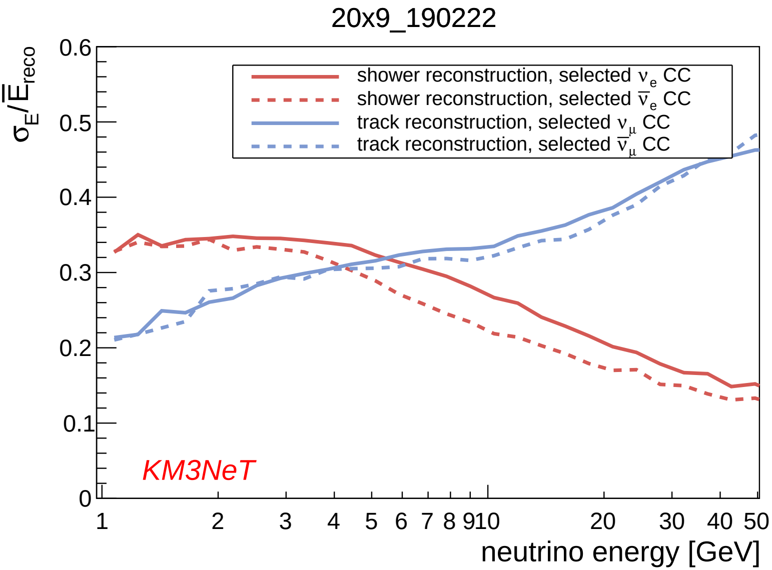
NMO separation power (tracks vs showers)



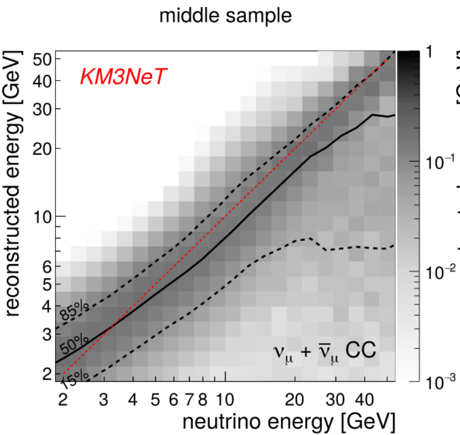
NMO E reconstruction

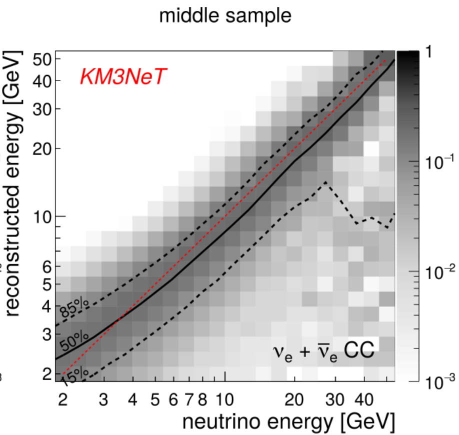


NMO E resolution

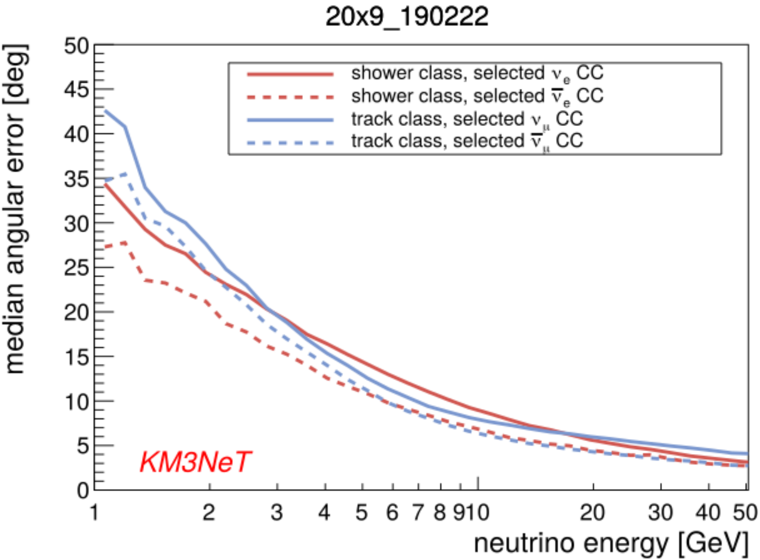


NMO E reconstruction

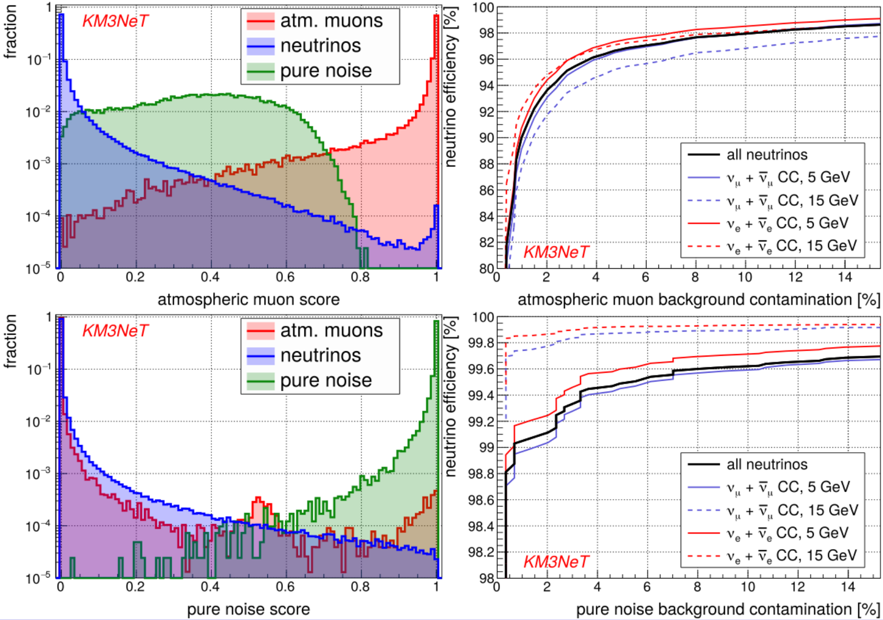




NMO angular resolution



NMO muon and noise suppression



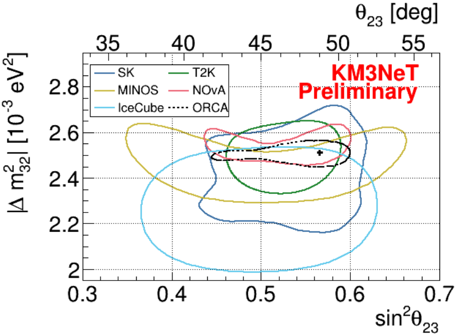
NMO priors

Parameter	Null Hypothesis Values NO	Null Hypothesis Values IO	Constraints
Δm^2_{32}	2.528×10^{-3} eV^2	2.436×10^{-3} eV^2	free
δ_{CP}	221.0°, 0°, 180.0°	282.0°, 0°, 180.0°	free
θ_{13}	8.60°	8.64°	±0.13°
Δm^2_{21}	7.39×10^{-5} eV^2		fixed
θ_{12}	33.82°		fixed
θ_{23}	[40°–50°]		free

Sensitivity to Δm^2_{32} and θ_{23} priors

Parameter	Null Hypothesis Values		Constraints
	NO	IO	
δ_{CP}	221.0°	282.0°	free
θ_{13}	8.60°	8.64°	±0.13°
Δm^2_{21}	7.39×10^{-5} eV^2		fixed
θ_{12}	33.82°		fixed
θ_{23}	[40°–50°]		fixed
Δm^2_{32}	$[2.2 \times 10^{-3}; 2.8 \times 10^{-3}]$ eV^2		fixed

Sensitivity to Δm^2_{32} and θ_{23} comparison for IO



(Assuming IO)

References:

- M. G. Aartsen et al. (IceCube Collaboration), '*Measurement of Atmospheric Neutrino Oscillations at 6–56 GeV with IceCube DeepCore*', Phys. Rev. Lett. 120 (2018), p. 071801, doi:10.1103/PhysRevLett.120.071801
- K. Abe et al., '*Atmospheric neutrino oscillation analysis with external constraints in Super-Kamiokande I-IV*', Phys. Rev. D 97.7 (2018), p. 072001, doi: 10.1103/PhysRevD.97.072001, arXiv: 1710.09126 [hep-ex]
- K. Abe et al., '*Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations*', Nature 580.7803 (2020), pp. 339–344, doi: 10.1038/s41586-020-2177-0, arXiv: 1910.03887 [hep-ex]
- Adam Aurisano, '*Recent Results from MINOS and MINOS+*', June 2018. doi: 10.5281/zenodo.1286760, url: https://doi.org/10.5281/zenodo.1286760
- M.A. Acero et al., '*First Measurement of Neutrino Oscillation Parameters 543 using Neutrinos and Antineutrinos by NOvA*', Phys. Rev. Lett. 123.15 544 (2019), p. 151803, doi: 10.1103/PhysRevLett.123.151803, arXiv: 545 1906.04907 [hep-ex]

Neutrino oscillations in matter

Presence of electrons affects the Hamiltonian:

$$H_{\text{eff}} = H_{\text{vacuum}} + \underbrace{\sqrt{2} G_{\text{F}} n_e}_{\text{MSW}}$$

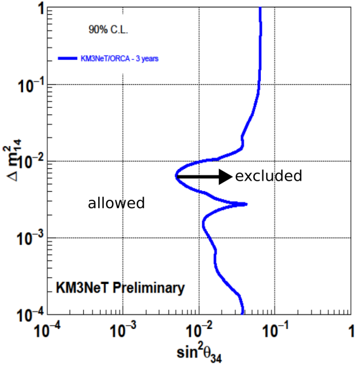
Modified 2ν oscillation probability:

$$P_{\alpha \to \beta} = \sin^2 2\theta_{\text{M}} \sin^2 \left(\frac{\Delta m^2_{\text{M}} L}{4E} \right), \tag{5}$$

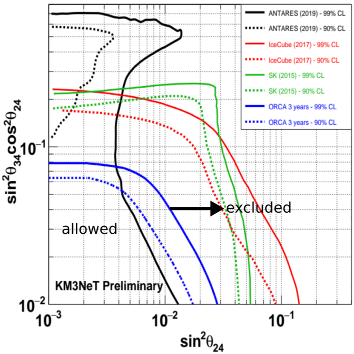
where $\sin^2 2\theta_{\text{M}} = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2}$, $\Delta m^2_{\text{M}} = \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2}$
with $x = \frac{2\sqrt{2} G_{\text{F}} n_e E}{\Delta m^2}$ (G_{F} – Fermi constant, n_e – electron number density).
θ_{M} and Δm^2_{M} are the effective angle and mass square difference respectively.

Exclusion limits on sterile mixing parameters

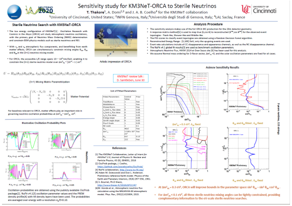
θ_{14} and θ_{24} fitted, $\delta_{24} = 0$



$\Delta m^2_{41} = 0.3\,\text{eV}^2$, $\delta_{24} = 0$



- from poster #179 @Neutrino2020
- **method**: χ^2 minimization of an Asimov dataset
- **MC**: 3y with full ORCA (115 DUs)
- **model**: 3+1
- **assumptions**: NO, $\Delta m^2_{41} > 0$, NuFit 4.1 (Δm^2_{21}, θ_{12})



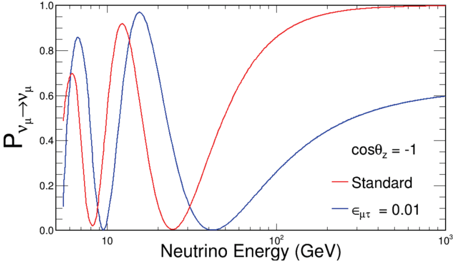
Non-Standard Interactions (NSI) (mini-intro)

NC NSI of ν_α with matter fermions (e, u, d) distort the standard ($\varepsilon_{\alpha\beta} = 0$) MSW effect:

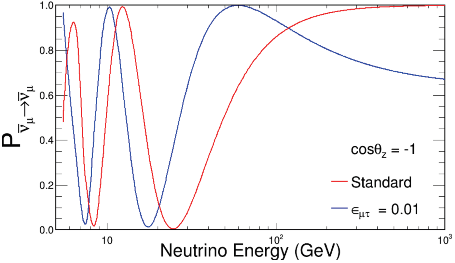
(arXiv:1907.00991v2)

$$H_{\text{eff}} = \frac{1}{2E} U_{\text{PMNS}} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix} U^\dagger_{\text{PMNS}} + \sqrt{2} G_{\text{F}} N_e \begin{bmatrix} 1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{bmatrix}$$

neutrinos

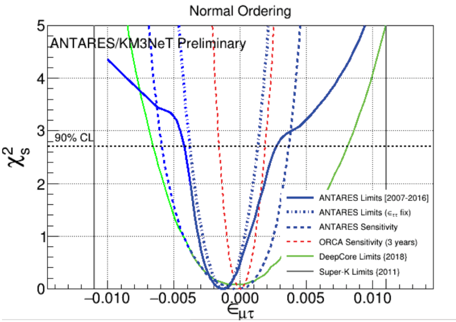


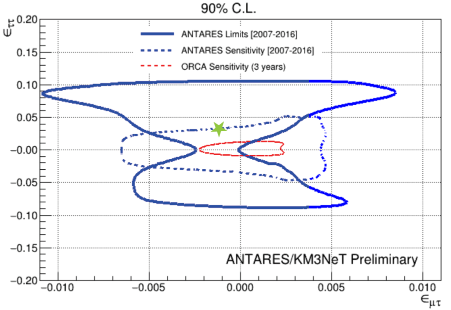
antineutrinos



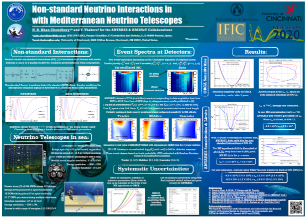
Non-Standard Interactions (NSI)

author: Nafis Rezwan Khan Chowdhury, Tarak Thakore





- from poster #178 @Neutrino2020
- **method**: χ^2 minimization of an Asimov dataset
- **MC**: 3y with full ORCA (115 DUs)

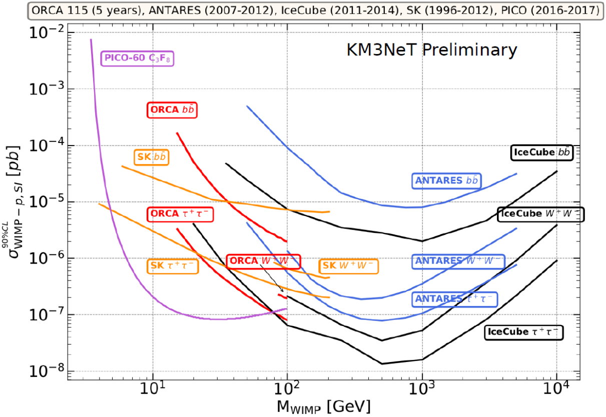


Dark matter (DM) from the Sun

authors: Daniel Lopez-Coto, Sergio Navas and Juande Zornoza

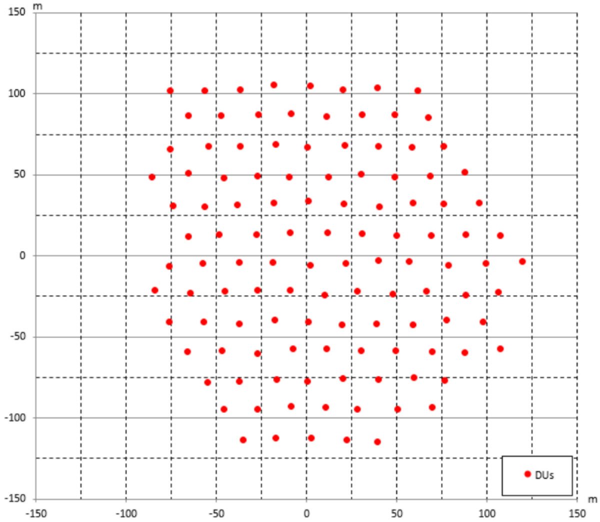
spin-dependent (coupling to splin; mainly for odd A)

spin-independent (coupling to mass)

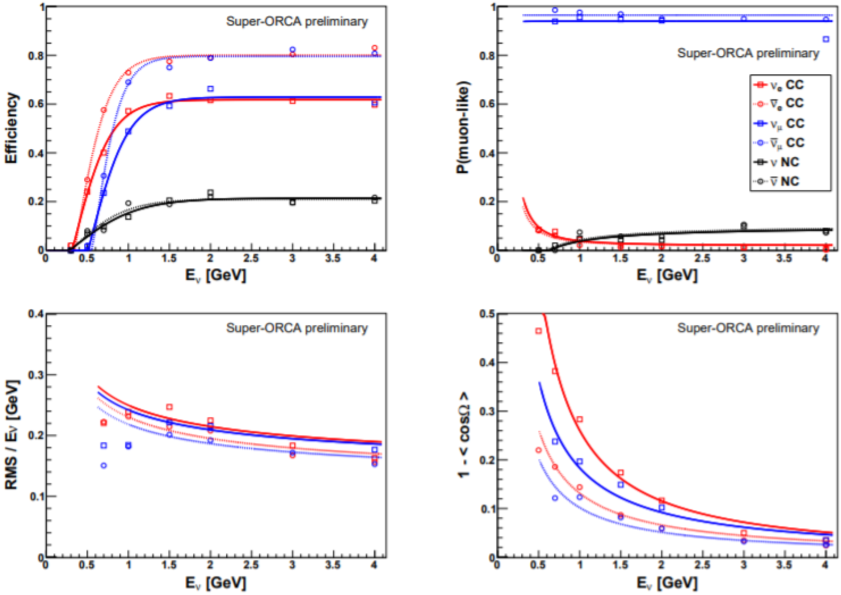


- **search**: indirect
- **DM particle**: WIMP (neutralino χ)
- **method**: $\log \mathcal{L}$ maximization
- **MC**: 5y with full ORCA (115 DUs)
- **used topology**: only tracks

The actual ORCA footprint

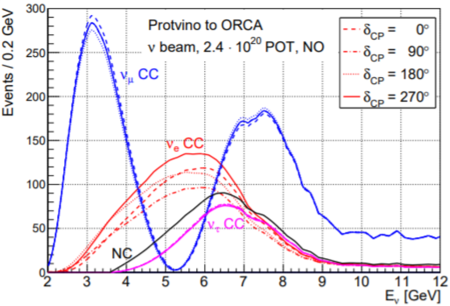


Super-ORCA expected detector performance

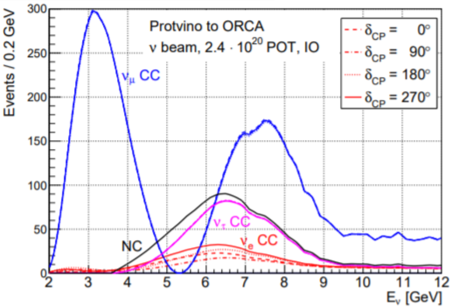


P2O spectra for NO and IO

NO



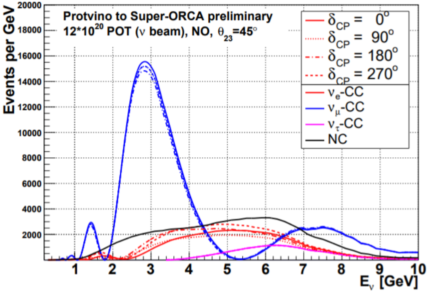
IO



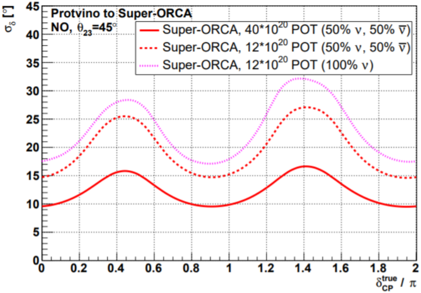
Plots for 3y with the 90kW beam

P2(S-)O expected performance

E distribution at Super-ORCA

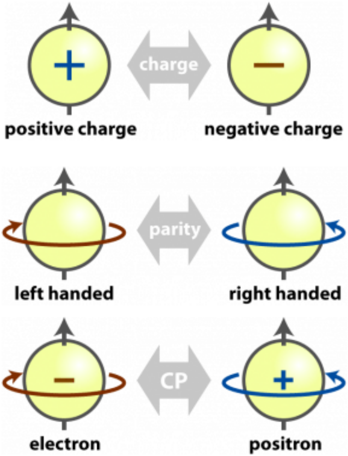


1σ-resolution on δ_{CP}



Plots for 3y with the 450kW beam

CP symmetry

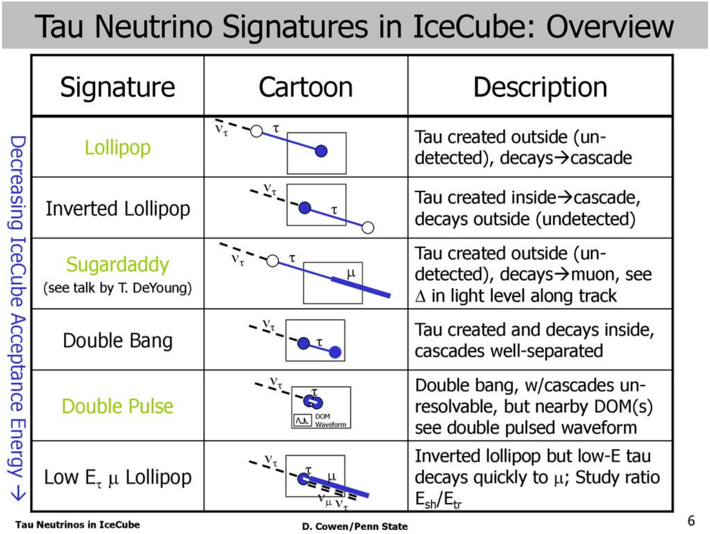

charge
positive charge
negative charge
parity
left handed
right handed
CP
electron
positron

CORSIKA simulation settings

Settings used for simulations:

- **hadronic interaction models**:
  - HE : SIBYLL 2.3
  - LE: GHEISHA 2002d
- **Charmed** particles handled explicitly
- 5 **primaries**: p, He, C, O, Fe
- **statistics**: $5{\cdot}10^6$ showers per primary
- $10^3 < \frac{E_{\text{primary}}}{\text{GeV}} < 10^9$

Other ν_τ signatures (in IceCube)



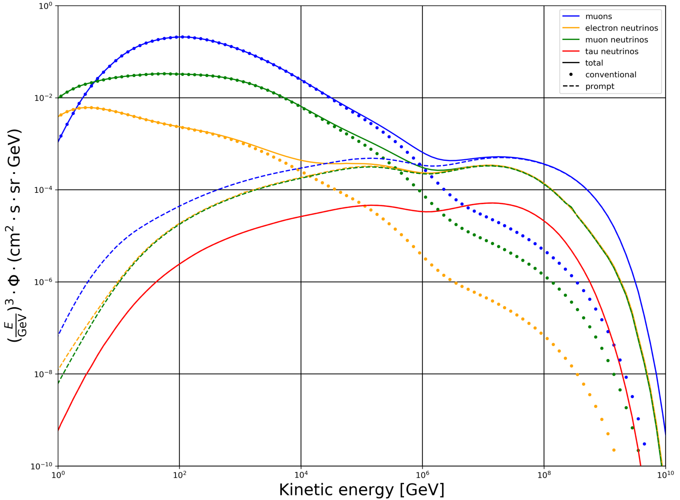
Tau Neutrino Signatures in IceCube: Overview

Signature	Cartoon	Description
Lollipop	ν_τ, τ	Tau created outside (un-detected), decays→cascade
Inverted Lollipop	ν_τ, τ	Tau created inside→cascade, decays outside (undetected)
Sugardaddy (see talk by T. DeYoung)	ν_τ, τ, μ	Tau created outside (un-detected), decays→muon, see Δ in light level along track
Double Bang	ν_τ, τ	Tau created and decays inside, cascades well-separated
Double Pulse	ν_τ, τ, DOM Waveform	Double bang, w/cascades un-resolvable, but nearby DOM(s) see double pulsed waveform
Low E_τ μ Lollipop	ν_τ, τ, μ, ν_μ ν_τ	Inverted lollipop but low-E tau decays quickly to μ; Study ratio E_{sh}/E_{tr}

Decreasing IceCube Acceptance Energy →

Tau Neutrinos in IceCube D. Cowen/Penn State 6

Atmospheric spectrum at the sea [MCEq]



https://mceq.readthedocs.io/en/latest/index.html