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Particle Physics with KM3NeT (and ANTARES)

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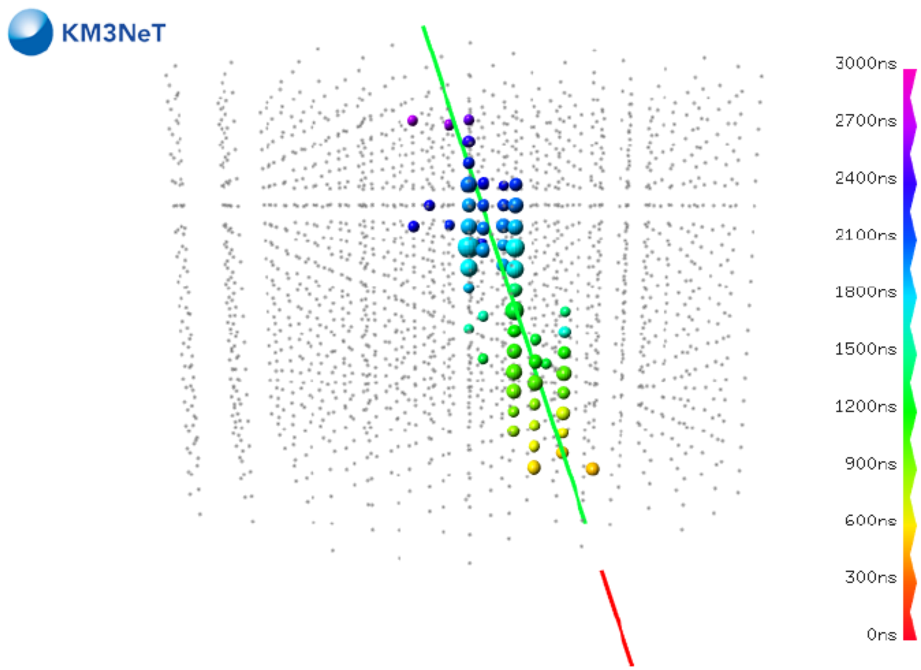
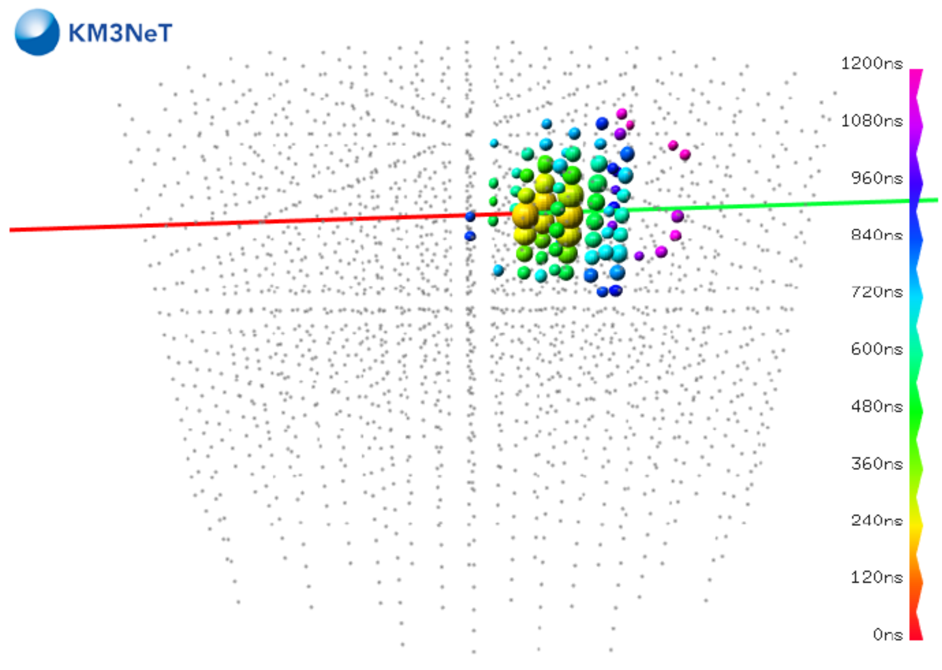
Outline

- Introduction
- Dark matter (including ANTARES)
- Neutrino mass ordering
- Oscillation parameters
- BSM in neutrinos (steriles, non-unitarity, NSI)
- Construction status and plans
- Ideas for the future
- Summary

Introduction

Tracks vs showers



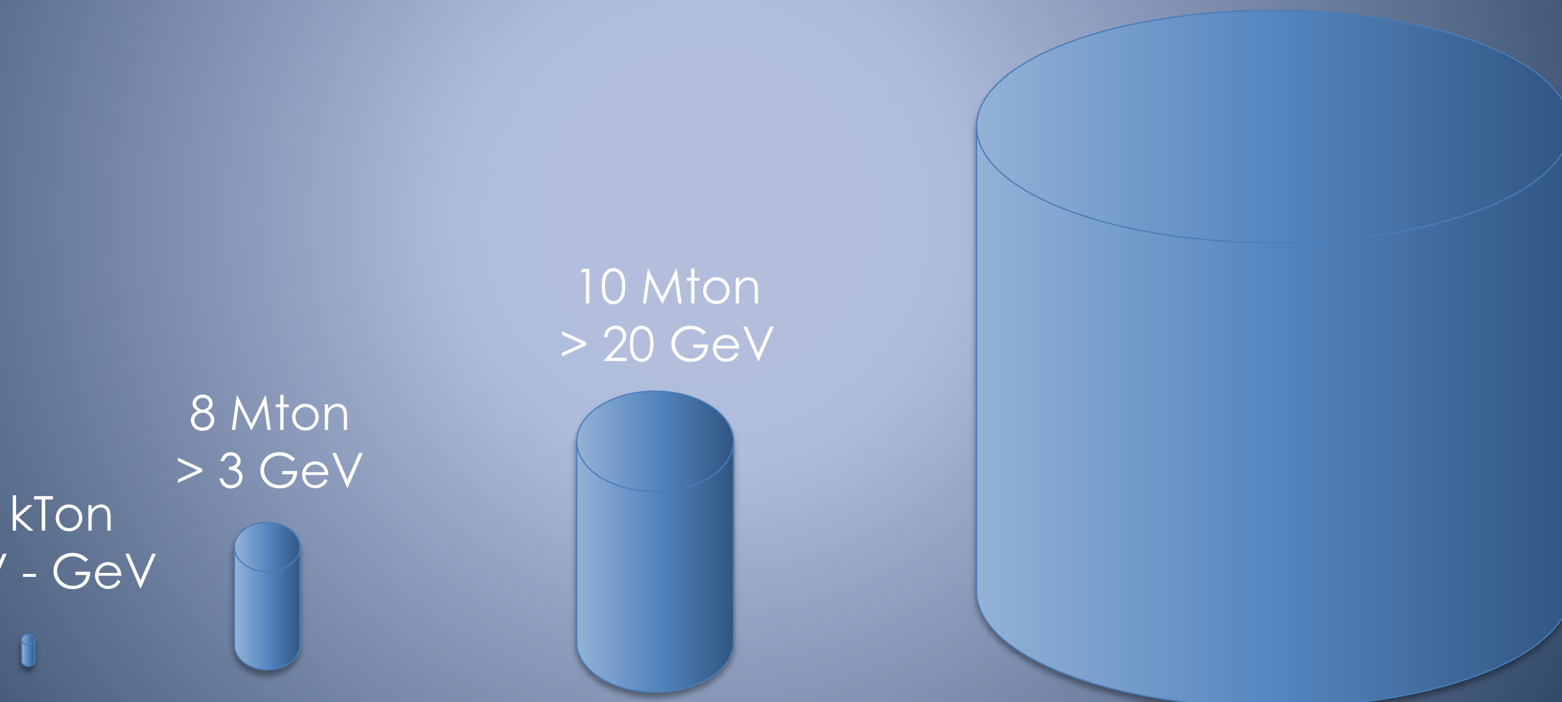


Tracks: CC ν_μ

Showers: CC ν_e, ν_τ and NC

Detector size

Denser detector → Lower energy threshold
Larger detector → More efficient of low fluxes



Scientific Scope

- Origin of cosmic rays
- Hadronic vs. leptonic signatures
- Neutrino mass ordering
- Dark matter

Detector size

Limitation at high energies:
Fast decreasing fluxes E^{-2}, E^{-3}

Limitation at low energies:
-Short muon range
-Low light yield

Detector density

Supernovae

Oscillations-Mass ordering

Dark matter

Astrophysical neutrinos

GZK

MeV | GeV | TeV | PeV | EeV

Other physics: monopoles, nuclearites, Lorentz invariance, etc..

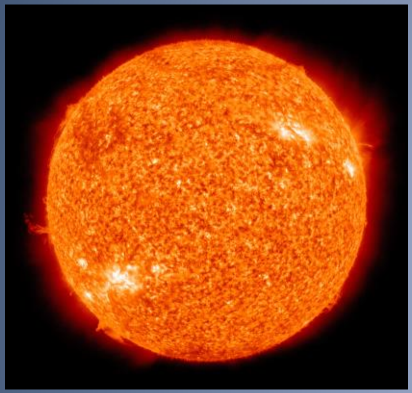
Dark matter

Dark matter detection in NTs

- WIMPs (neutralinos, KK particles) are among the most popular explanations for dark matter
- They would accumulate in massive objects like the Sun, the Earth or the Galactic Centre
- The products of such annihilations would yield "high energy" neutrinos, which can be detected by neutrino telescopes

Dark matter sources for NTs

Sun



Galactic Centre

Dwarf galaxies

Earth

Galactic Halo

Galaxy clusters

Sun: $\sigma_{\chi N}$

Differential neutrino flux is related with the annihilation rate as:

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma}{4\pi d^2}\,\frac{dN_\nu}{dE_\nu},$$

If we assume equilibrium between capture and annihilation in the Sun:

$$\Gamma \simeq \frac{C_\otimes}{2}.$$

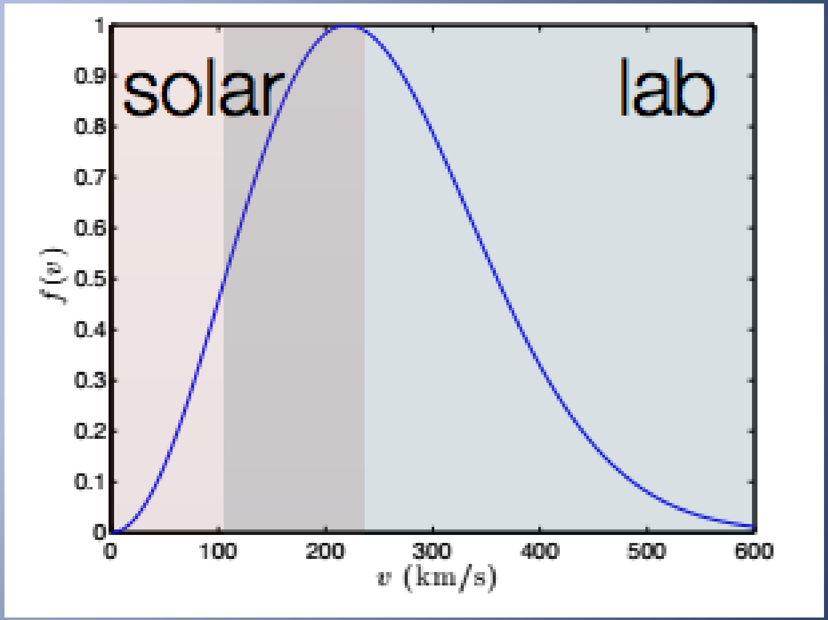
where the capture rate can be expressed as:

$$C_\otimes \simeq 3.35\times 10^{18}\mathrm{s}^{-1} \times \left(\frac{\rho_{\mathrm{local}}}{0.3\,GeV\cdot cm^{-3}}\right) \times \left(\frac{270\,\mathrm{k}m\cdot\mathrm{s}^{-1}}{v_{\mathrm{local}}}\right) \times \left(\frac{\sigma_{H,SD}}{10^{-6}\,\mathrm{pb}}\right) \times \left(\frac{TeV}{M_{\mathrm{WIMP}}}\right)^2,$$

Velocity distributions in the Galactic Halo

$$f(u) = \sqrt{\frac{3}{2\pi}}\frac{u}{v_\odot v_{\rm rms}}\left(\exp\left(-\frac{3(u-v_\odot)^2}{2v_{\rm rms}^2}\right) - \exp\left(-\frac{3(u+v_\odot)^2}{2v_{\rm rms}^2}\right)\right)$$

- Neutrino telescopes (for searches in the Sun) are complementary to direct searches
  - low velocity: easier to capture in the Sun
  - high velocity: large recoils easier at high velocities

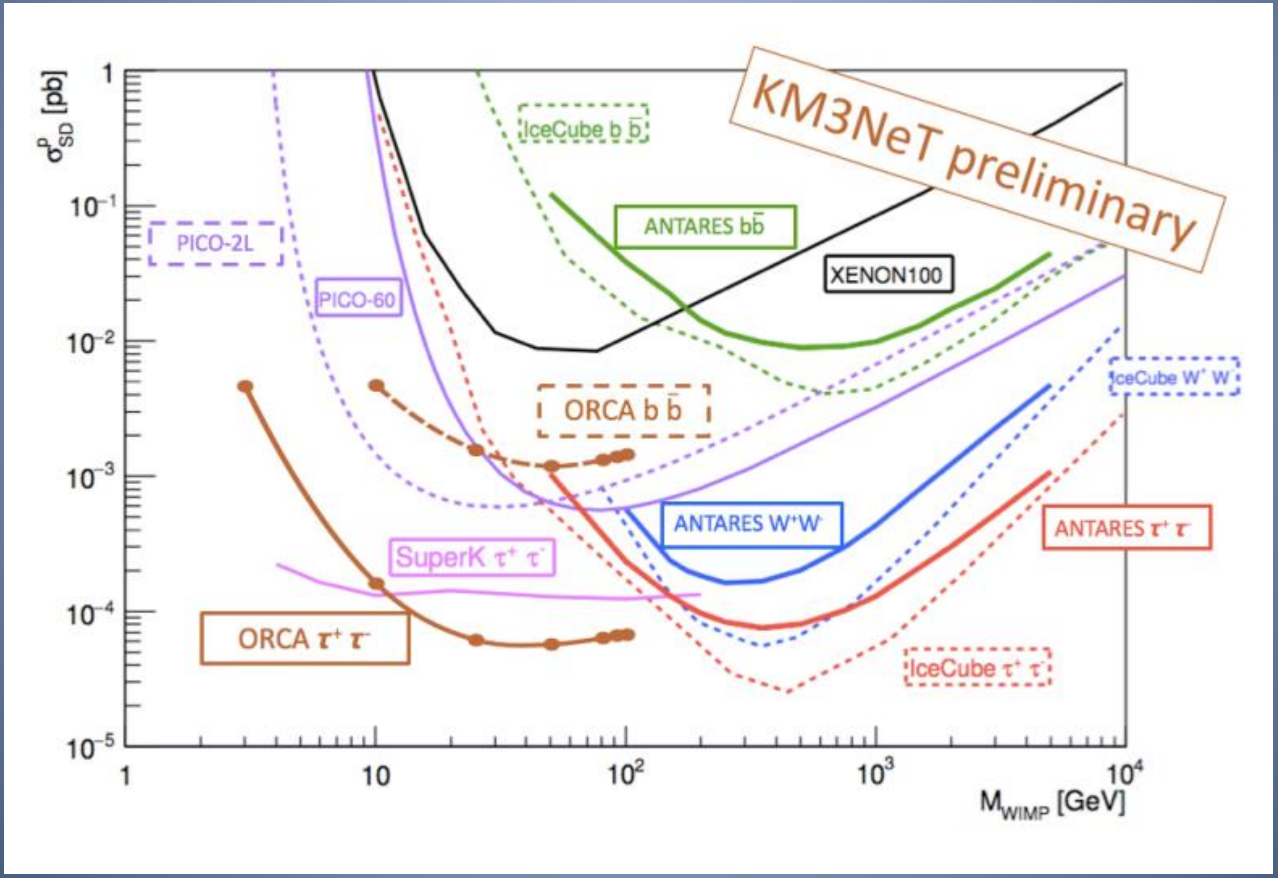


Typically Maxwell distribution of velocities is assumed

Other v distributions: <20% change in C
Choi et al. JCAP 1405 (2014) 049

The Sun

(ANTARES: Physics Letters B, Volume 759 (2016))



Neutrino telescopes: best tool for spin-*dependent* cross section (WIMP-nucleon)

Rate calculation

- Gamma rays, neutrinos:

$$\frac{d\Phi}{dE}(E_\gamma, \psi, \theta, \Delta\Omega) = \boxed{\frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2m_\chi^2}\frac{dN_\gamma^i}{dE_\gamma}} \boxed{\int_0^{\Delta\Omega} d\Omega \int_{\mathrm{l.o.s}} \rho^2(r(s,\psi,\theta))ds.}$$

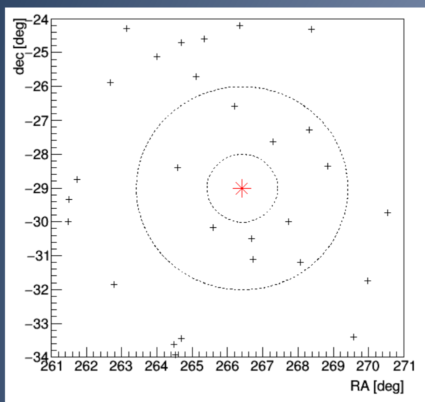
Particle Physics

Dark matter distribution
(J-factor)

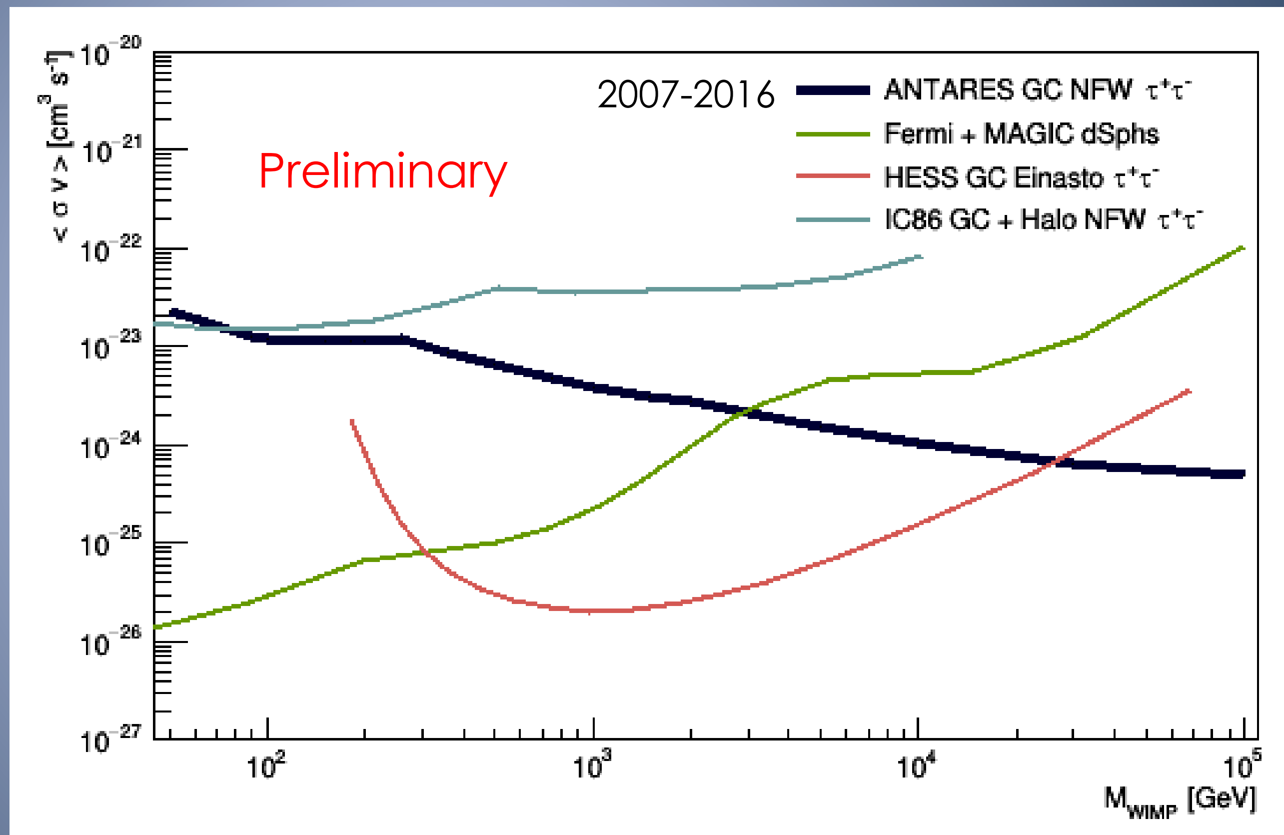
- Cosmic rays:
  - propagation more complex

$$-\mathcal{K}(E)\cdot\nabla^2 n_f - \frac{\partial}{\partial E}\left(b(E,\vec{x})\,n_f\right) + \frac{\partial}{\partial z}\left(\mathrm{sign}(z)\,V_{\mathrm{conv}}\,n_f\right) = Q(E,\vec{x}) - 2h\,\delta(z)\,\Gamma\,n_f$$

Dark Matter: Galactic Center



New data just unblinded!

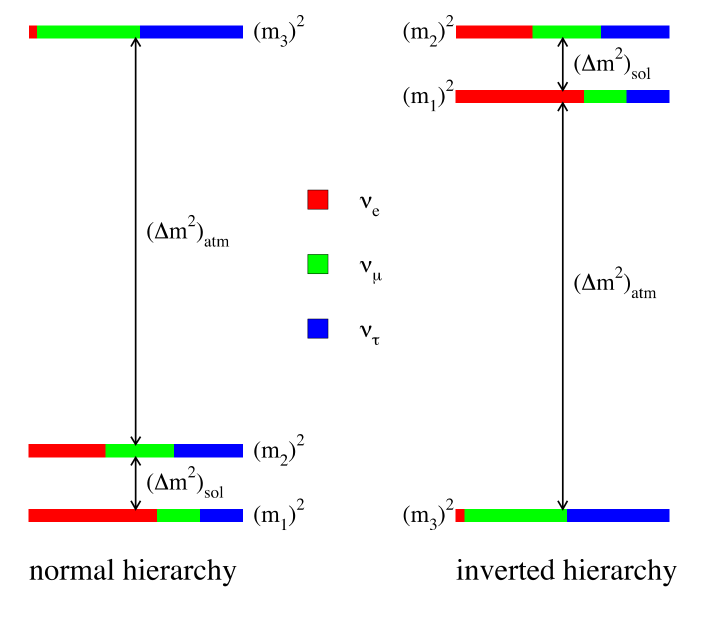


Best limits world wide for WIMP masses above 30 TeV

Neutrino Mass Ordering

Introduction

- Neutrino mass ordering is one of the most relevant unknowns in Particle Physics
  - constrain theoretical models to explain the origin of mass in leptonic sector
- Impact on potential performance of next-generation experiments for
  - CP-phase measurement
  - absolute value of neutrino masses
  - $0\nu\beta\beta$ experiments



NMO in ORCA

- In matter, the sign of Δm^2_{13} is revealed through the CC interactions of ν_e with electrons

$$P^m_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\,\sin^2 2\theta^m_{13}\,\sin^2\left(\frac{\Delta^m m^2_{31}\,L}{4E_\nu}\right),$$

$$\sin^2 2\theta^m_{13} \equiv \sin^2 2\theta_{13}\left(\frac{\Delta m^2_{31}}{\Delta^m m^2_{31}}\right)^2$$

$$\Delta^m m^2_{31} \equiv \sqrt{(\Delta m^2_{31}\,\cos 2\theta_{13} - 2\,E_\nu\,A)^2 + (\Delta m^2_{31}\,\sin 2\theta_{13})^2}\,,$$

- Resonance condition is met for NO (IO) in the neutrino (anti-neutrino) channel when

$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\,\cos 2\theta_{13}}{2\,\sqrt{2}\,G_F\,N_e} \simeq 7\,\mathrm{GeV}\left(\frac{4.5\,\mathrm{g/cm^3}}{\rho}\right)\left(\frac{\Delta m^2_{31}}{2.4\times 10^{-3}\,\mathrm{eV}^2}\right)\cos 2\theta_{13}$$

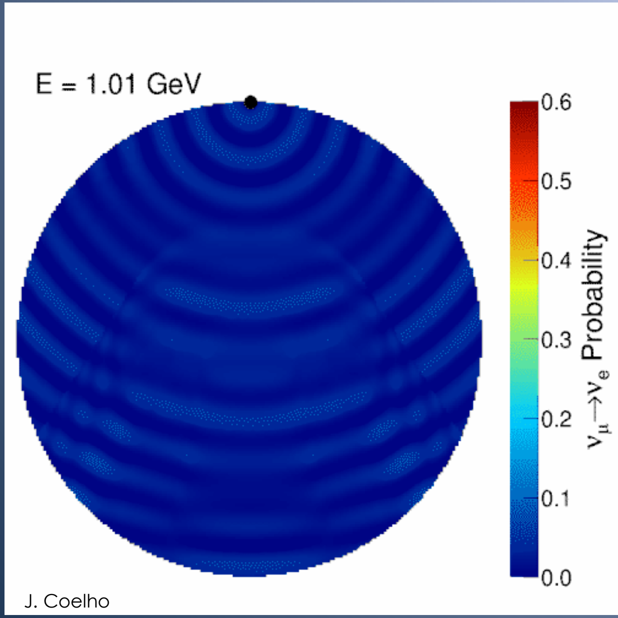
E_{res}~7 GeV for mantle
E_{res}~3 GeV for core

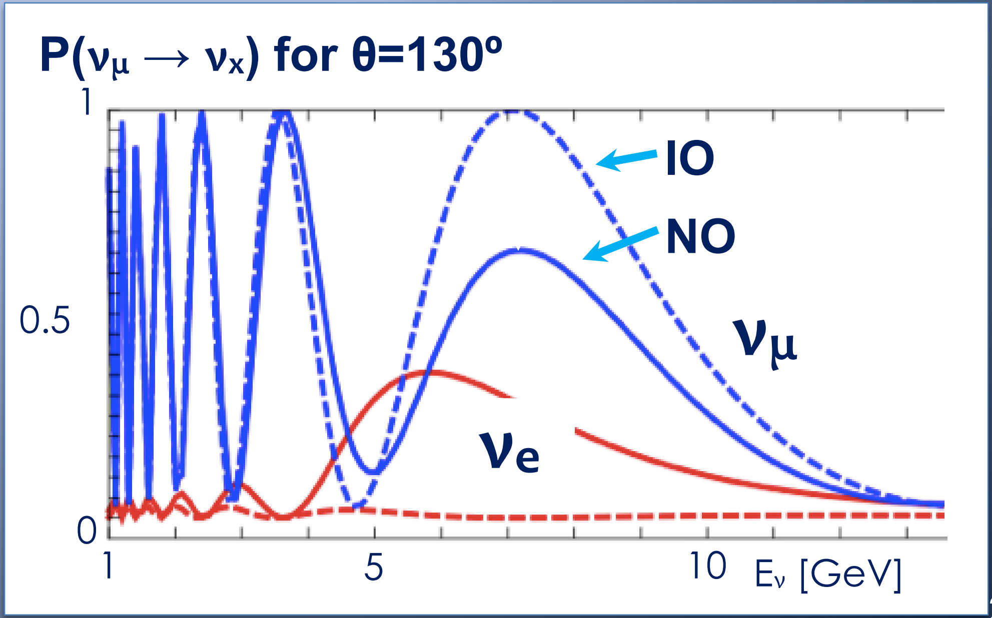
MH with atmospheric neutrinos

- Matter effect in Earth induces ν/anti-ν difference in oscillations
- Examples: PINGU, ORCA, INO (iron tracking calorimeter)
- First maximum for $\nu_\mu \to \nu_\mu$ is at 12 GeV for $L=D_{earth}$
- Could be measurable since at these energies:

$$\sigma(\nu) \approx 2\sigma(\overline{\nu})$$

- Differences in the $(E_\nu, \cos\theta_\nu)$ plane



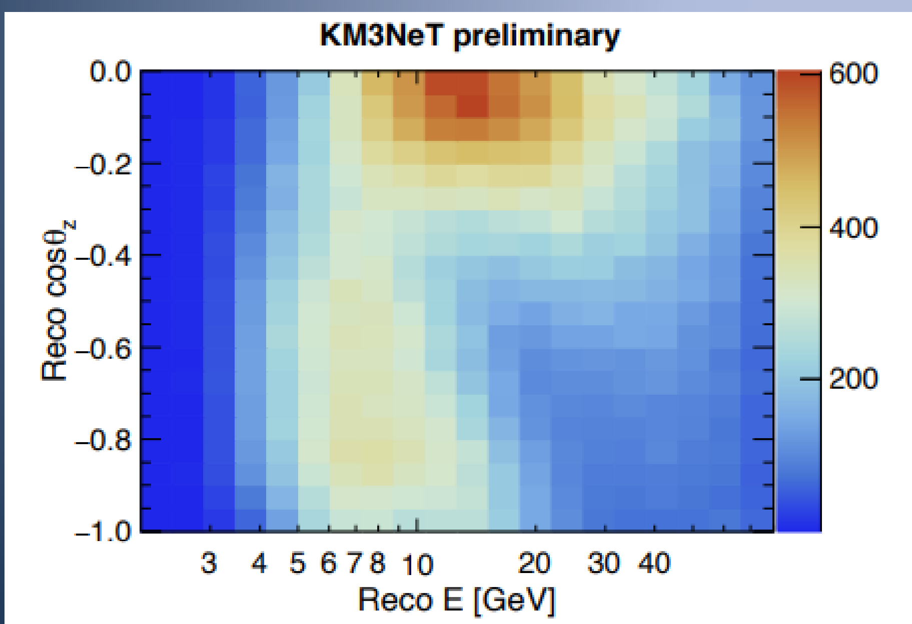


Oscillograms

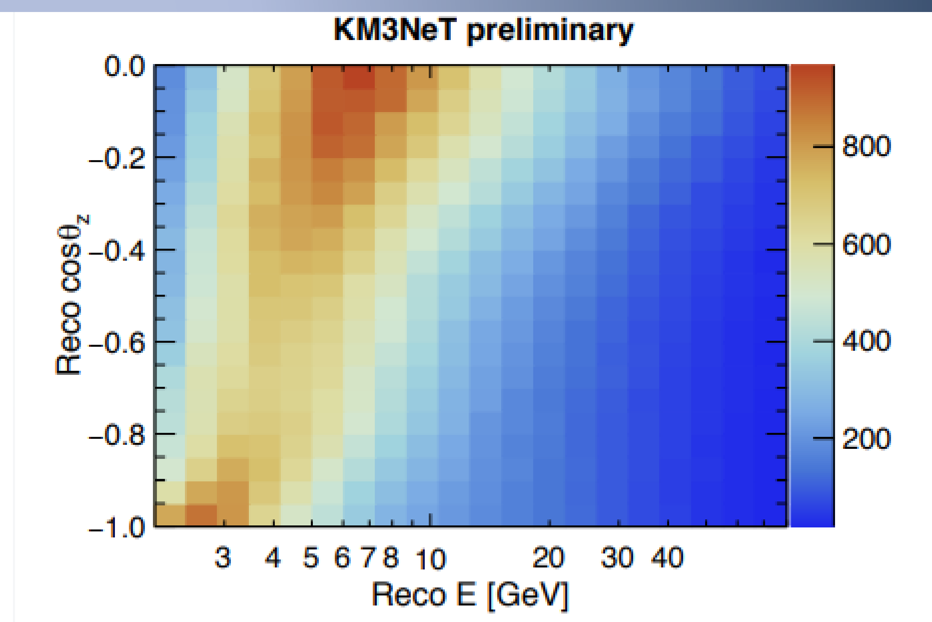
- Finite angular/energy resolutions, uncertainties in oscillation parameters, etc. blur the "theoretical" oscillograms

http://doi.org/10.5281/zenodo.1300771

(number of events in 3 years, NO is assumed)



Track channel

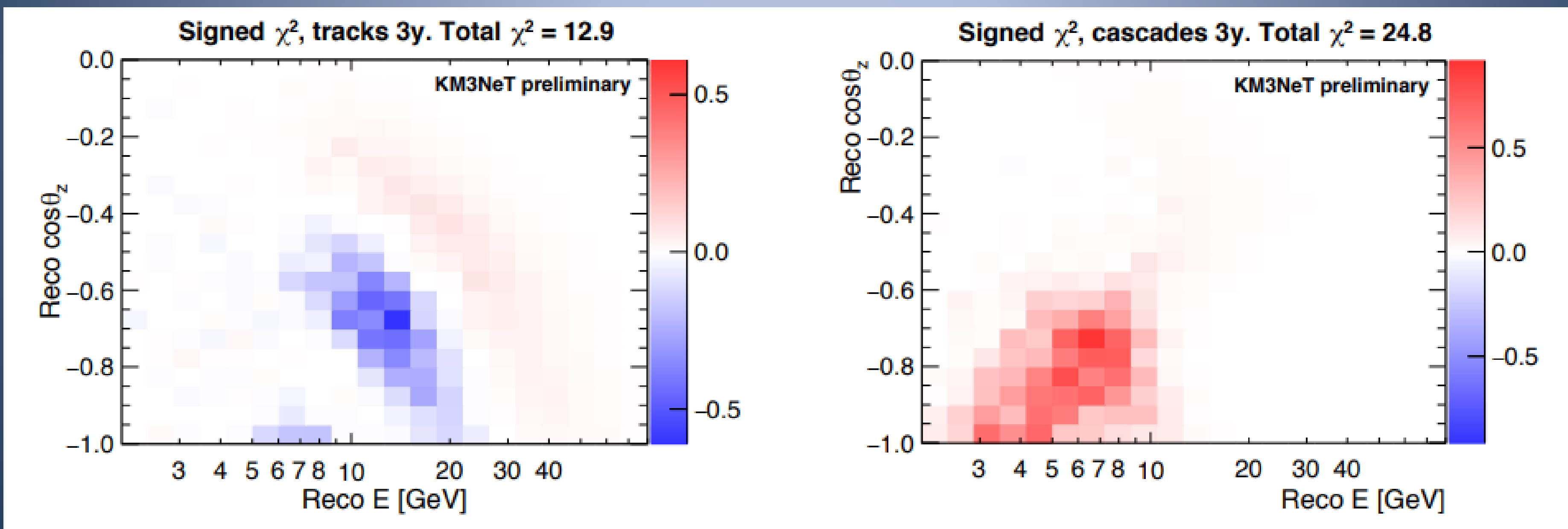


Cascade channel

Oscillograms

$\chi 2 = (N_{NO} - N_{IO})\,|N_{NO} - N_{IO}|\,/N_{NO}$

http://doi.org/10.5281/zenodo.1300771

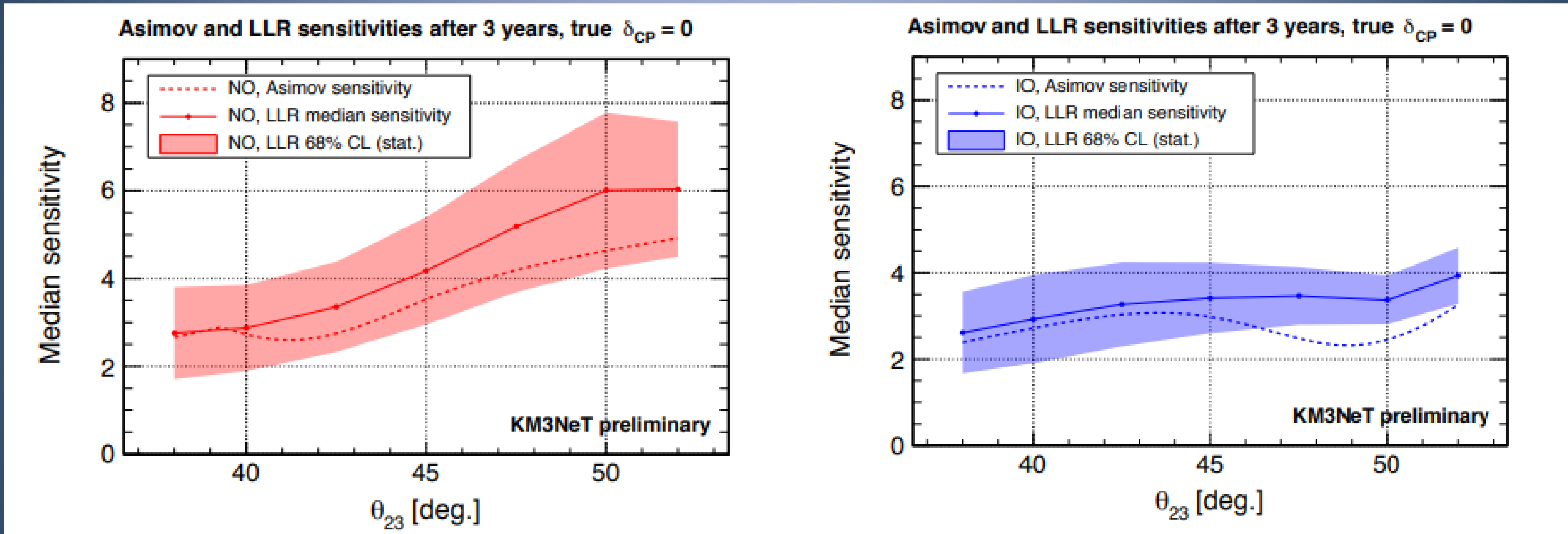


Track channel

Cascade channel

Sensitivity to NMO (ORCA)

http://doi.org/10.5281/zenodo.1300771



Likelihoods are maximized over a set of nuisance parameters:

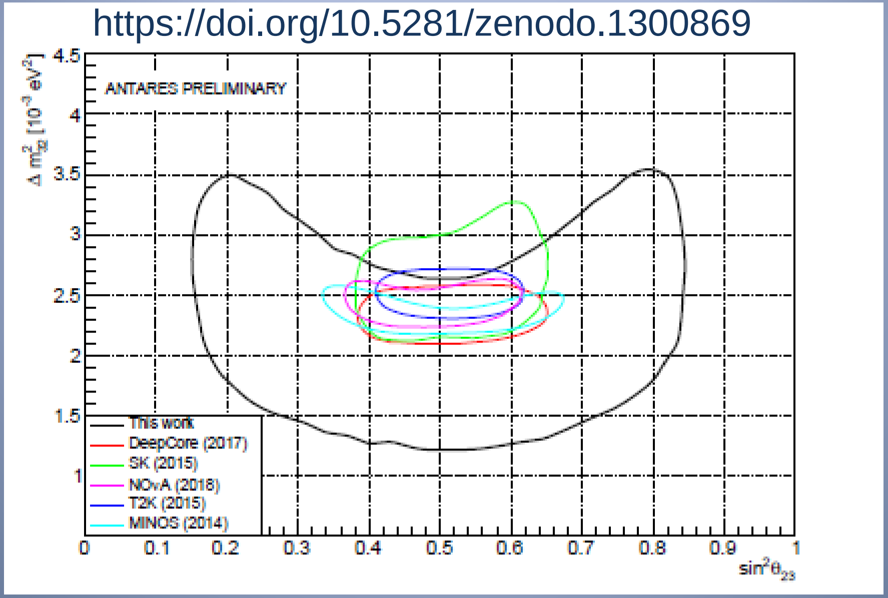
$$TS = -2 \cdot \ln \frac{\max \mathcal{L}_{\mathrm{NO}}}{\max \mathcal{L}_{\mathrm{IO}}} = \chi^2_{\min}(\mathrm{NO}) - \chi^2_{\min}(\mathrm{IO})$$

parameter	*treatment*	*true value*	*prior*
$\lvert\Delta M^2\rvert$ (eV^2)	fitted	$2.48\,10^{-3}$	free
Δm^2_{21} (eV^2)	fix	$7.53\,10^{-5}$	–
θ_{13} (°)	fitted	8.42	0.26
θ_{12} (°)	fix	33.4	–
θ_{23} (°)	fitted	38 – 52	free
δ_{CP}	fitted	$0, 2\pi$	free
Flux spectral tilt	fitted	0	free
$\nu/\bar{\nu}$ skew	fitted	0	0.03
Tracks normalisation	fitted	1	free
Cascades normalisation	fitted	1	free
NC events normalisation	fitted	1	0.10

Oscillation parameters

ANTARES on neutrino oscillations

- Data: 2830 days (2007-2016)
- 7710 events (track-like)
- Non-oscillation discarded at 4.6σ

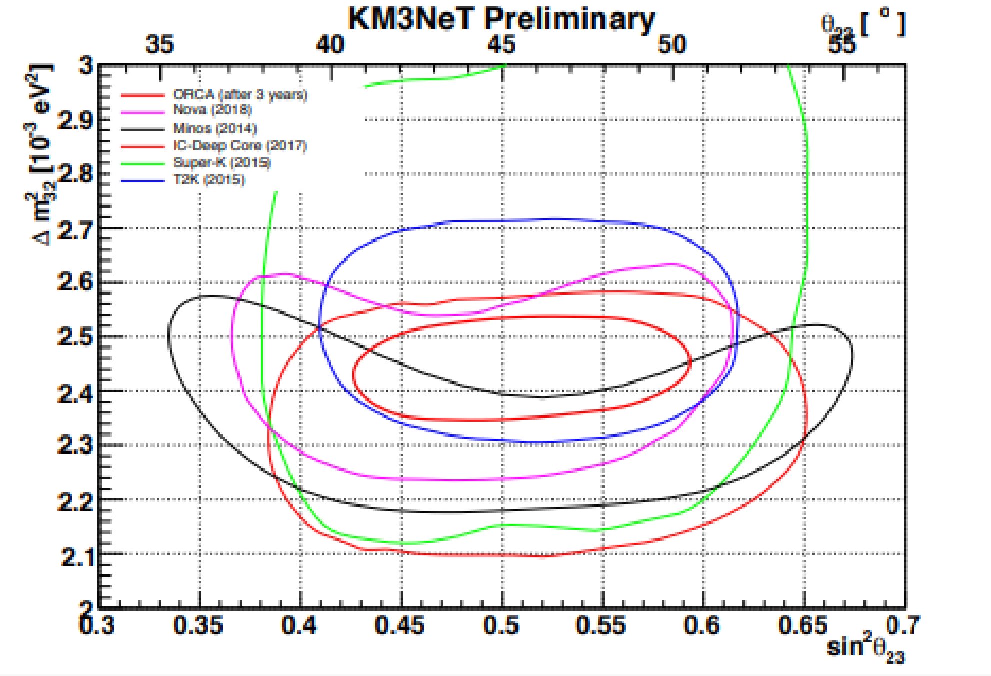


See also for previous analysis: Phys. Lett. B 714 (2012) 224-230 → First time neutrino oscillations were observed in neutrino telescopes

ORCA: Sensitivity to Δm^2_{23} and $\sin^2\theta_{23}$

- Precision: 2% for Δm^2_{23} and 5% for $\sin^2\theta_{23}$ (90%CL)

http://doi.org/10.5281/zenodo.1300771

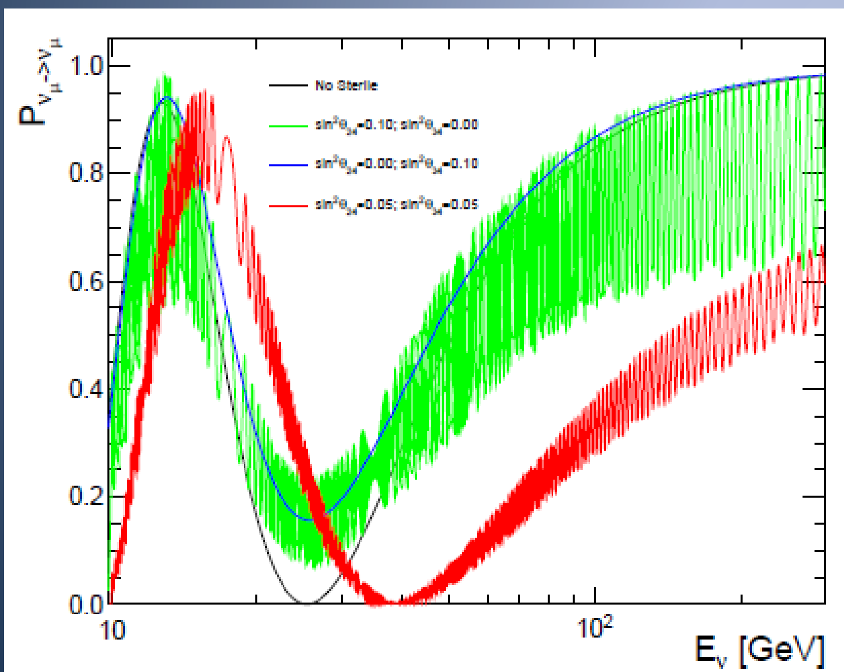


(NO assumed, δ_{CP}=0)

BSM in neutrinos

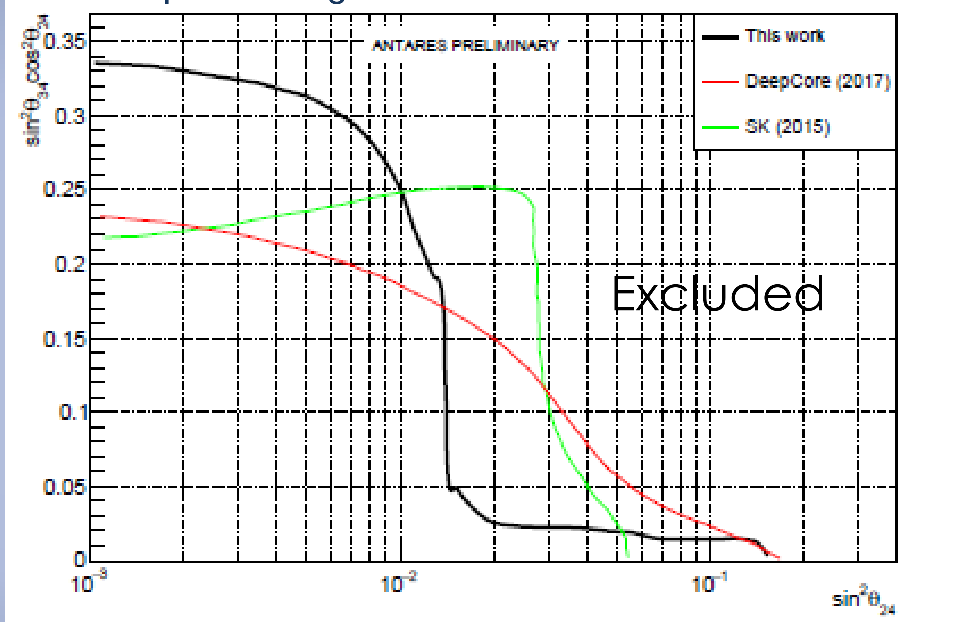
Sterile neutrinos with ANTARES

Distortion in the pattern of oscillations of vertical upgoing muon neutrinos by the existence of sterile neutrinos (3+1 model)



Atmospheric neutrino oscillation may be affected at energies 20-30 GeV

https://doi.org/10.5281/zenodo.1300869



Same data set and fitting procedure used for the standard oscillation analysis

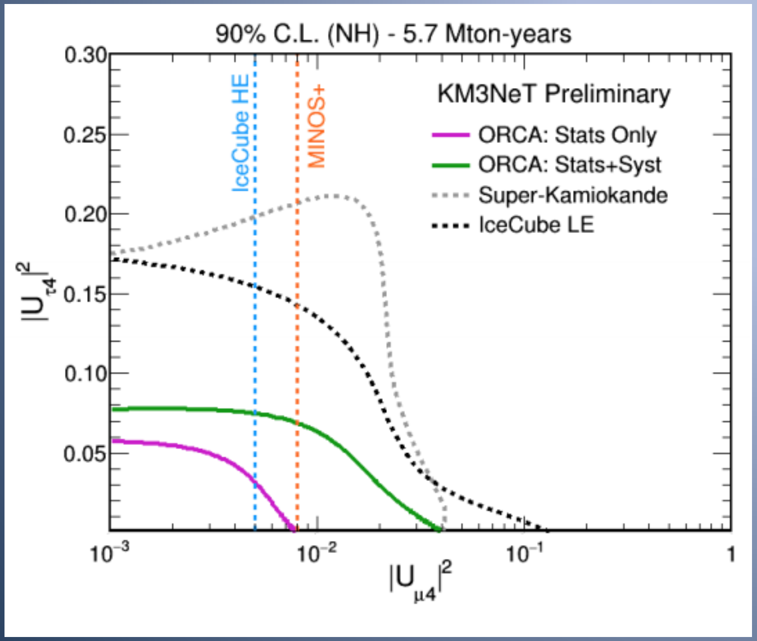
δ_{CP} and δ_{24} left unconstrained in the fit

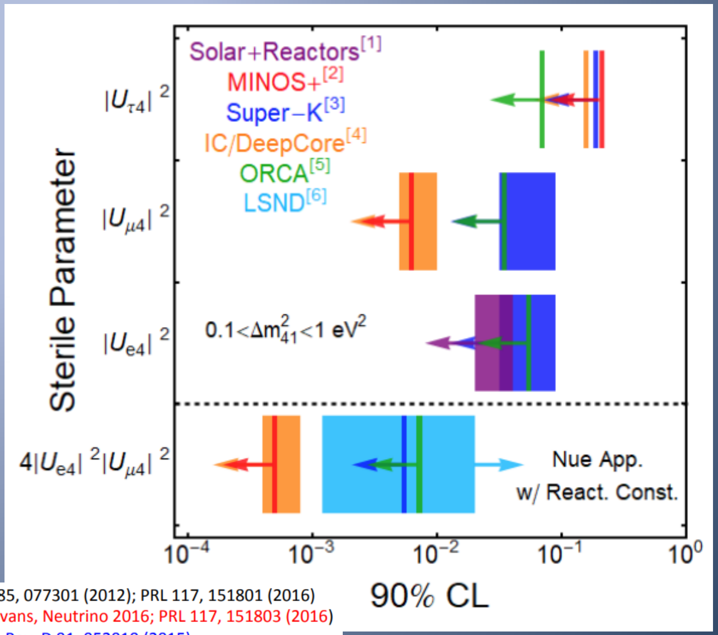
Δm^2_{41} fixed at 0.5 eV^2

ORCA: Light sterile neutrinos

- After only one year, factor two of improvement in sensitivity for $U_{\tau 4}$ wrt SuperK and IceCube

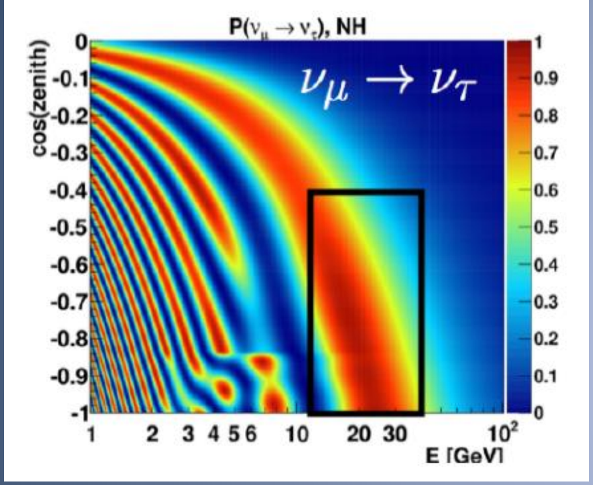
$$H_{sterile} = U \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} & 0 \\ 0 & 0 & 0 & \frac{\Delta m^2_{41}}{2E} \end{pmatrix} U^\dagger \pm \sqrt{2} G_F \begin{pmatrix} n_e & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & n_n \end{pmatrix}$$





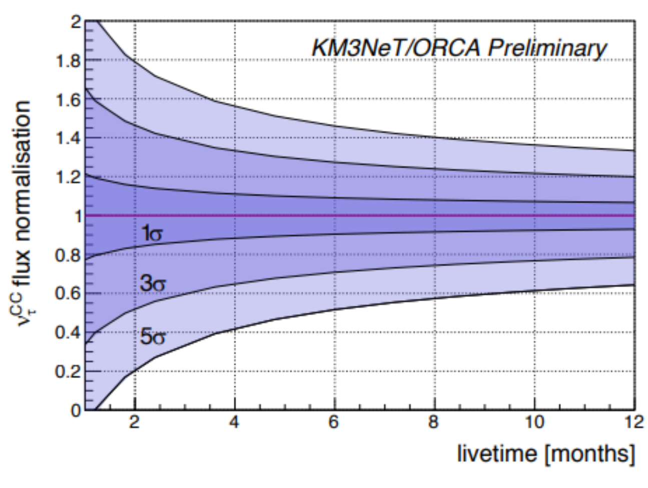
[1] PRD 85, 077301 (2012); PRL 117, 151801 (2016)
[2] J. J. Evans, Neutrino 2016; PRL 117, 151803 (2016)
[3] Phys. Rev. D 91, 052019 (2015)
[4] PRL 117, 071801 (2016); arXiv:1702.05160 (2017)
[5] KM3NeT-ORCA Preliminary
[6] Phys. Rev. D 64, 112007 (2001)

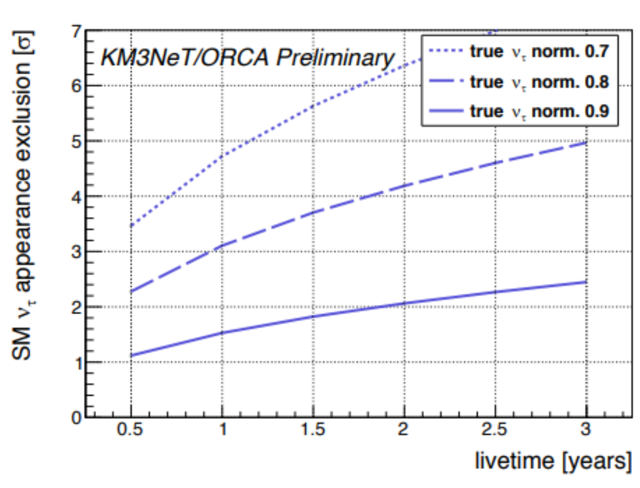
ORCA: Unitarity with tau neutrinos

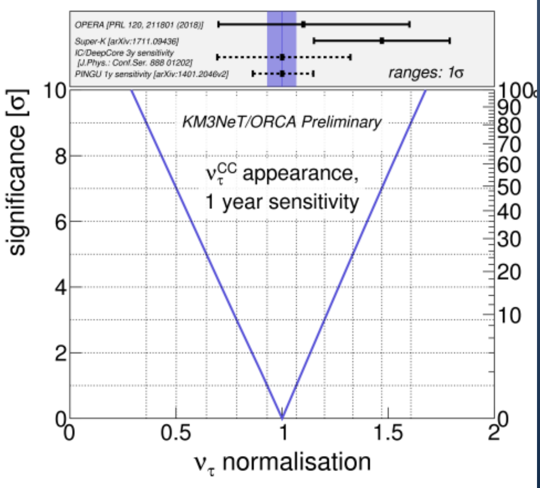


- About 3000 ν_τ/year (CC) in ORCA → test on unitarity
- In one year, rates constrained to 10% (world data precision now at 30%)
- After three years, deviations above 20% in normalization can be excluded at 5σ

https://doi.org/10.5281/zenodo.1292823



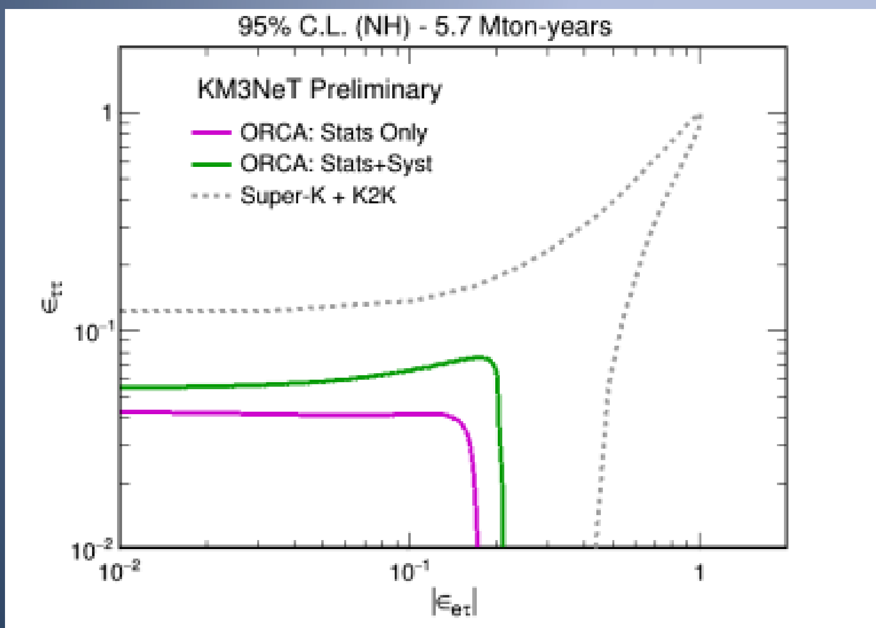


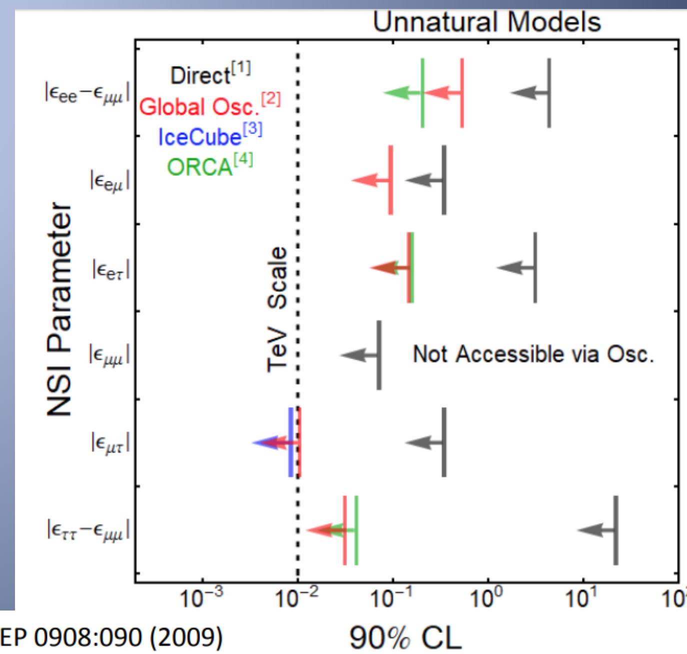


ORCA: Non-standard interactions

- Effects of non-standard interactions could be observable in ORCA, with limits competitive from oscillations and more than factor 10 better direct

$$H_{NSI} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger \pm \sqrt{2} G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$





[1] JHEP 0908:090 (2009)
[2] JHEP 1309:152 (2013)
[3] Phys. Rev. D 97, 072009 (2018)
[4] KM3NeT-ORCA Preliminary

Construction status and plans

APPEC Endorsement

- **KM3NeT "strongly endorsed"** by **APPEC** (Astroparticle Physics European Consortium)in its new European Astroparticle Physics Strategy for **2017-2026**
- Reminder: KM3NeT also included in **ESFRI** Roadmap for "scientific excellence and maturity"


nature International weekly journal of science

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Davide Castelvecchi

16 November 2017

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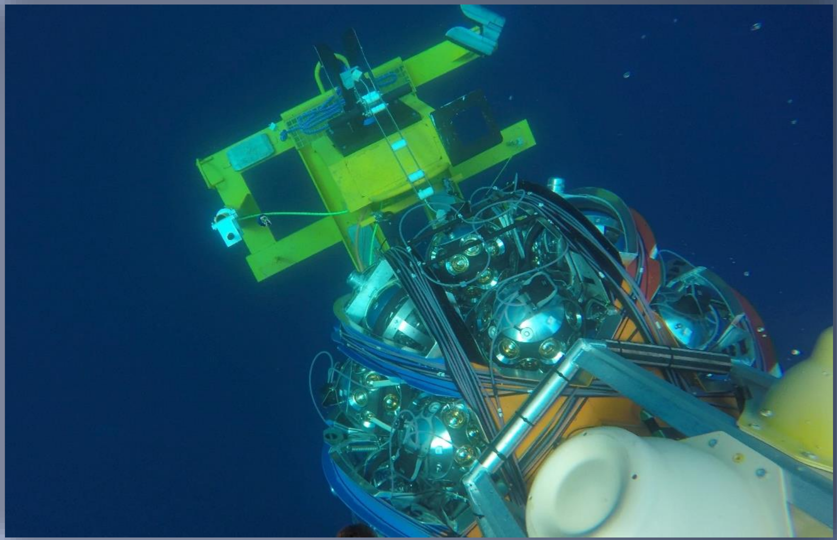
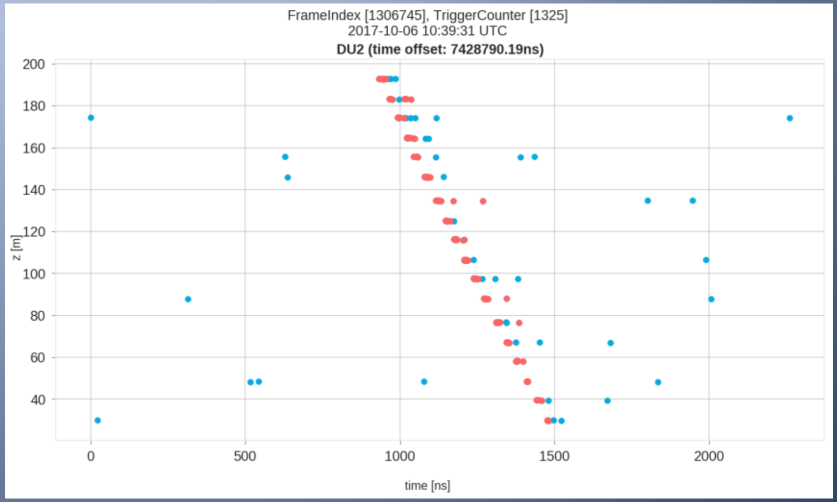
Nature | 29 November 2017

First ORCA line installed



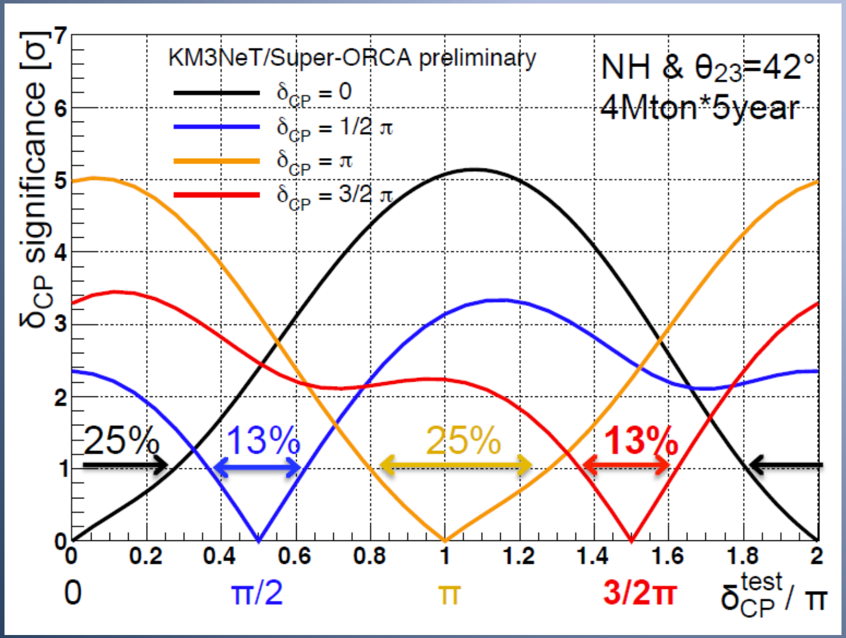


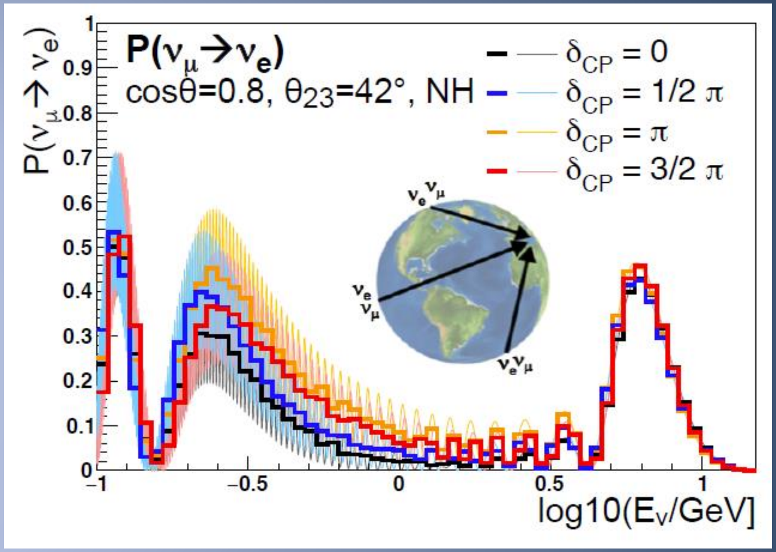
Ideas for the future

Super-ORCA

- Goal: measuring δ_{CP}
- x10 denser than ORCA

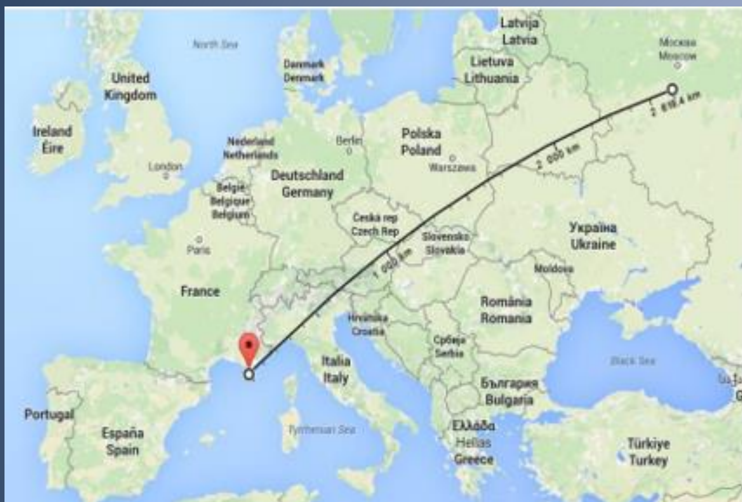
http://doi.org/10.5281/zenodo.1292936





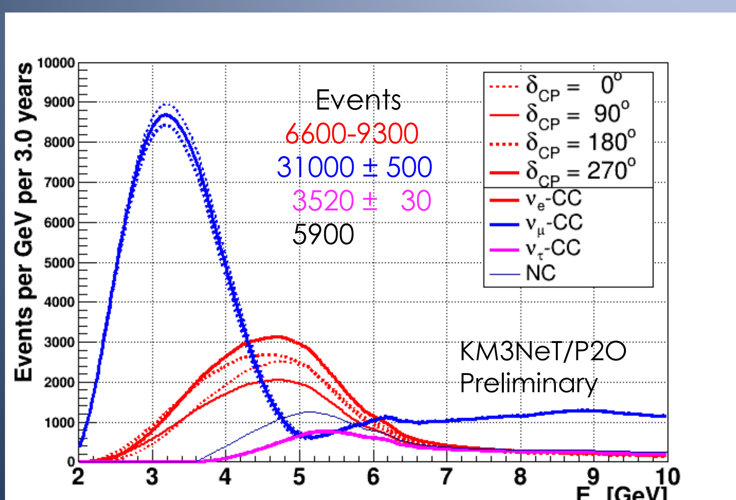
- 60-70% disfavoured with >2σ
- Complementary to long-baseline experiments:
  - better for 0.5π and 1.5 π

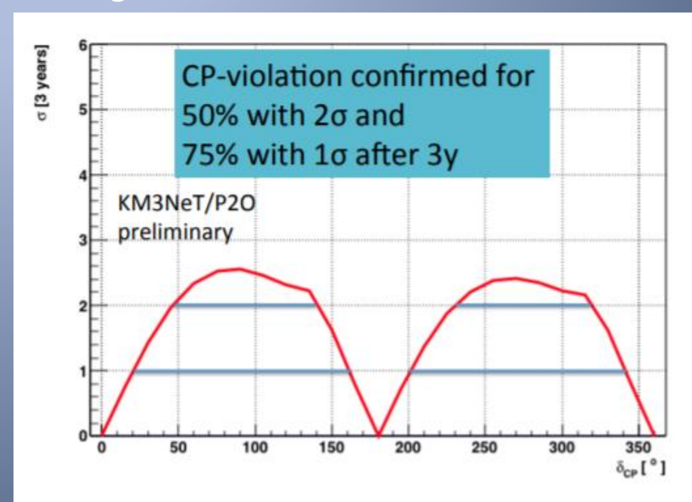
P2O: Protvino to ORCA



- Goal: neutrino mass ordering and CP violation
- Method: to look for appearance in 2590 km from Protvino U70 accelerator
- Proposal: construct a neutrino beam of 2-7 GeV
- 3 years at 450kW running → variation of 3300 in number of ν_e events for different CP phases
- NMO: >5σ for all combination of parameters

http://doi.org/10.5281/zenodo.1300743





Summary

- Neutrino astronomy is an extraordinary tool for both Astroparticle and Particle Physics
- ANTARES has showed the feasibility of the technique in water and produced relevant results on particle physics: dark matter, neutrino oscillations, monopoles
- Great potential for KM3NeT in many areas: neutrino mass ordering, oscillation parameters, dark matter, sterile, NSI...
- First lines of KM3NeT already installed
- Plans for the future: SuperORCA, P2O
- Rich physics harvest already gathered, but much more to come...


Thanks for your attention!
TL 509049