Measuring the atmospheric neutrino oscillation parameters and constraining the 3+1 neutrino model with ten years of ANTARES data

Abstract

The ANTARES neutrino telescope has been optimised to study high energy neutrinos coming from Galactic and extra-galactic astrophysical objects. Additionally, at neutrino energies of the order of a few tens of GeV, the detector allows to study the phenomenon of atmospheric muon neutrino disappearance due to neutrino oscillations. In a similar way, constraints on the 3+1 neutrino model, which foresees the existence of a sterile neutrino, can be inferred. Using data collected by the ANTARES neutrino telescope from 2007 to 2016, a new measurement of Δm^2_{32} and θ_{23} has been performed - which is consistent with world best-fit values - and constraints on the 3+1 neutrino model have been derived.

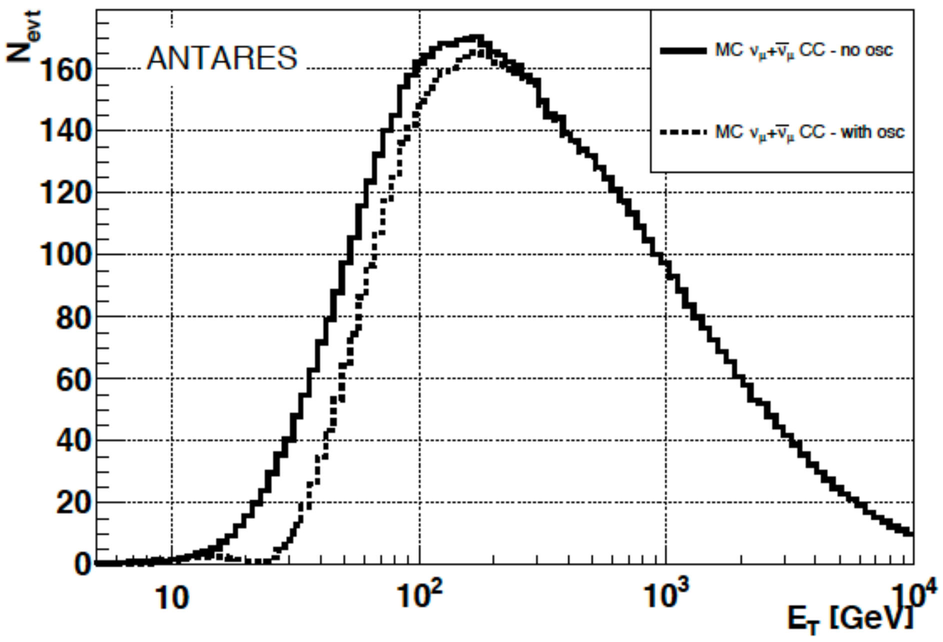
$$P_{\nu_\mu \to \nu_\mu} \sim 1 - 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) \sin^2(\frac{\Delta m_{32}^2 L}{4E})$$

$$U_{\mu 3} = \sin\theta_{23}\cos\theta_{13}$$

$$\Delta m_{32}^2 = m_3^2 - m_2^2$$

If only 2 generations: $P = \sin 2\theta \ \sin(1.27 \ \Delta m^2 \ \frac{L}{E})^{\ 2}$ (eV, km, GeV)

So for L = 12000 km and Δm^2 = 2.5 x 10^{-3} eV^2: max oscillation at E = 25 GeV



Antares paper: look only at muon neutrino disappearance.
(Why no showers?)

Neutrino generator: GENHEN
Muon generator: MUPAGE

Sensitivity only for E > 20 GeV

Two neutrino reconstruction methods:

A: χ^2 fit. Events either single-line (SL) or multi-line (ML)
B: chain of fits with a final likelihood fit

Event selection: from method A passing cut, else from method B passing cut

Determine track length L_μ , then: $E_{reco} = L_\mu \times 0.2\,\mathrm{GeV/m}$

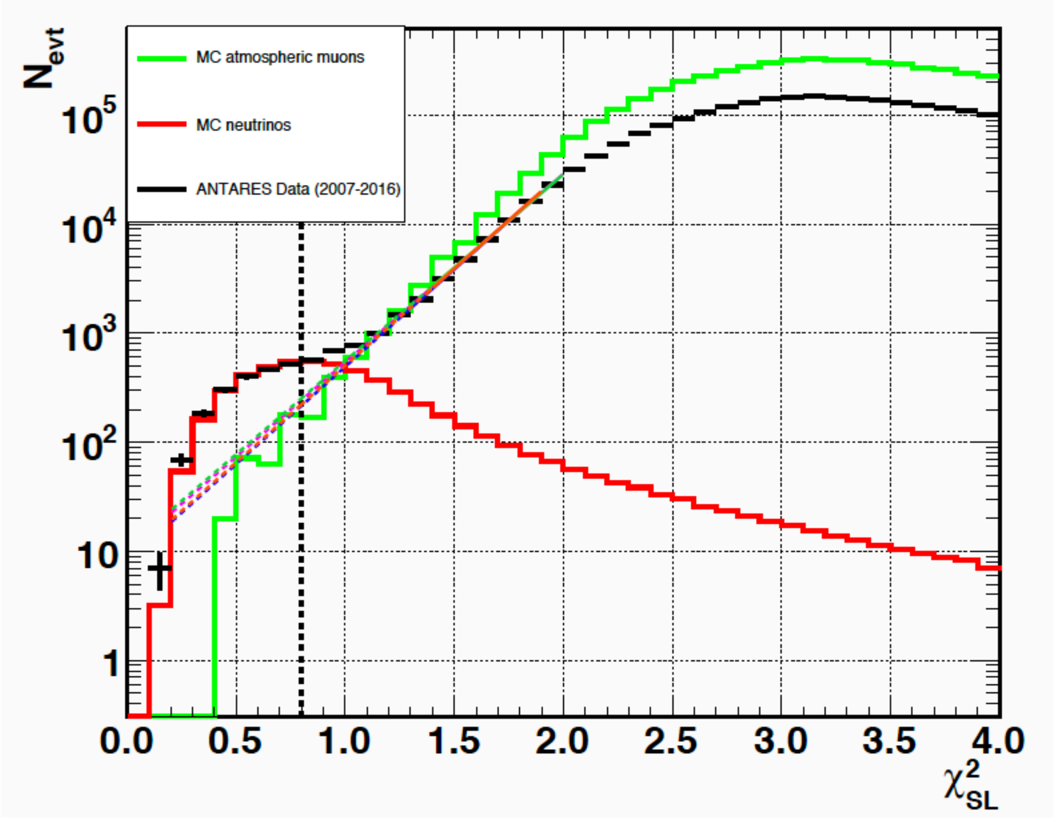
Q: What about tracks that start/end outside Antares?
Would it not be better to restrict to contained events?

Is there a difference in resolution (angle/track length) between methods A and B?

How many events are selected by A, and how many by B?
How many events are SL, and how many ML?

What is the energy resolution anyway?

Atmospheric muon background is estimated from data:



Using sample A SL only (?)

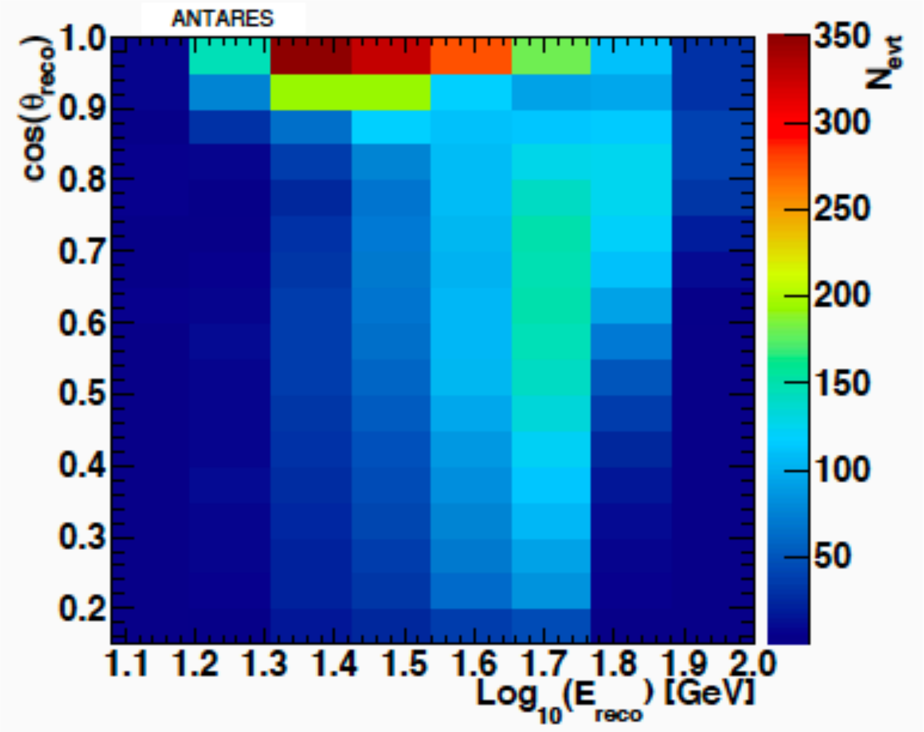
Extrapolating to A (SL+ML) + B: N_μ = 740 ± 120

(How big an extrapolation is this?)

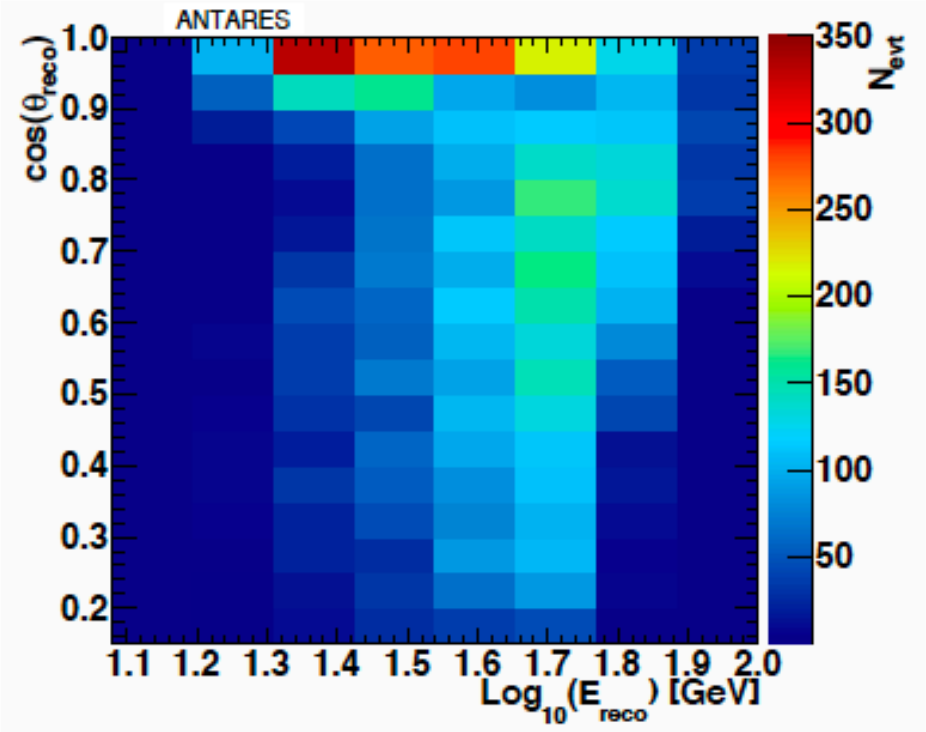
From MC: expect 7590 CC neutrino events if no oscillations (+bg: 8330)

6870 CC neutrino events with oscillations (+bg: 7610)

Data: 7710



MC, no oscillations



Data

(It is really hard to interpret this plot, in my opinion)

Oscillation parameters are extracted from a fit to the above 2D distribution:

$$-2\log L = 2\sum_{i,j}[N_{i,j}^{MC}(\bar{p},\bar{\eta}) - N_{i,j}^{Data}\cdot\log N_{i,j}^{MC}(\bar{p},\bar{\eta})] + \sum_k \frac{(\eta_k - <\eta_k>)^2}{\sigma_{\eta_k}^2}$$

p are the oscillation parameters, η the systematic uncertainties (with a prior)

Standard oscillation analysis:

Name	Prior	Fit
Δm^2_{32} [10^{-3} eV^2]	FREE	2.0± 0.3
θ_{23} [°]	FREE	45 ± 12
N_ν	FREE	0.82 ± 0.09
$\nu/\overline{\nu}$ [σ]	0.0±1.0	1.1 ± 0.6
$\Delta\gamma$	0.0± 0.05	-0.003 ± 0.036
N_μ	740 ± 120	415 ± 22
θ_{13} [°]	8.41± 0.28	8.41± 0.28
M_A [σ]	0.0±1.0	0.01 ± 0.98

6 sources of systematics

IceCube DeepCore:

TABLE I. Table of nuisance parameters along with their associated priors, if applicable. The right two columns show the results from our best fit for normal mass ordering and inverted mass ordering, respectively.

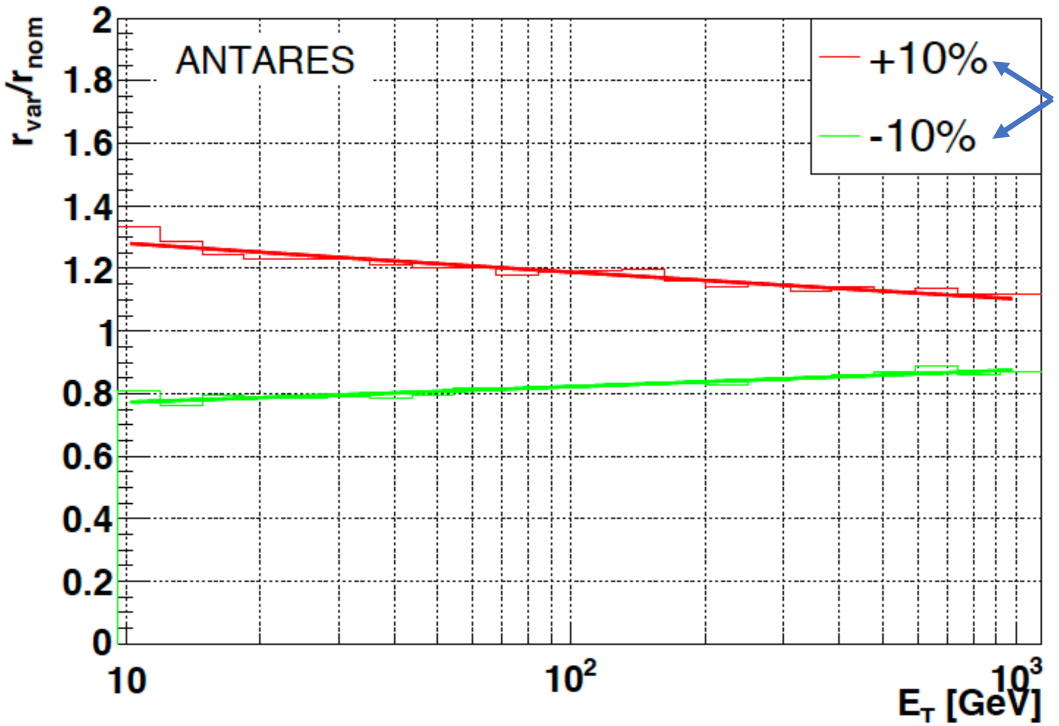
Parameters	Priors	Best Fit NO	Best Fit IO
Flux and cross section parameters			
Neutrino event rate [% of nominal]	no prior	85	85
$\Delta\gamma$ (spectral index)	0.00±0.10	-0.02	-0.02
M_A (resonance) [GeV]	1.12±0.22	0.92	0.93
$\nu_e + \bar{\nu}_e$ relative normalization [%]	100±20	125	125
NC relative normalization [%]	100±20	106	106
Hadronic flux, energy dependent [σ]	0.00±1.00	-0.56	-0.59
Hadronic flux, zenith dependent [σ]	0.00±1.00	-0.55	-0.57
Detector parameters			
overall optical eff. [%]	100±10	102	102
relative optical eff., lateral [σ]	0.0±1.0	0.2	0.2
relative optical eff., head-on [a.u.]	no prior	-0.72	-0.66
Background			
Atm. μ contamination [% of sample]	no prior	5.5	5.6

Detector uncertainties (photon detection, water absorption) are included in N_ν and $\Delta\gamma$

2nd parameter contains both neutrino/antineutrino ratio and upwards/horizontal ratio uncertainties

N_ν 20% lower than in prior, 1.1 sigma pull in neutrino/antineutrino ratio, N_μ 2.7 sigma lower than in prior

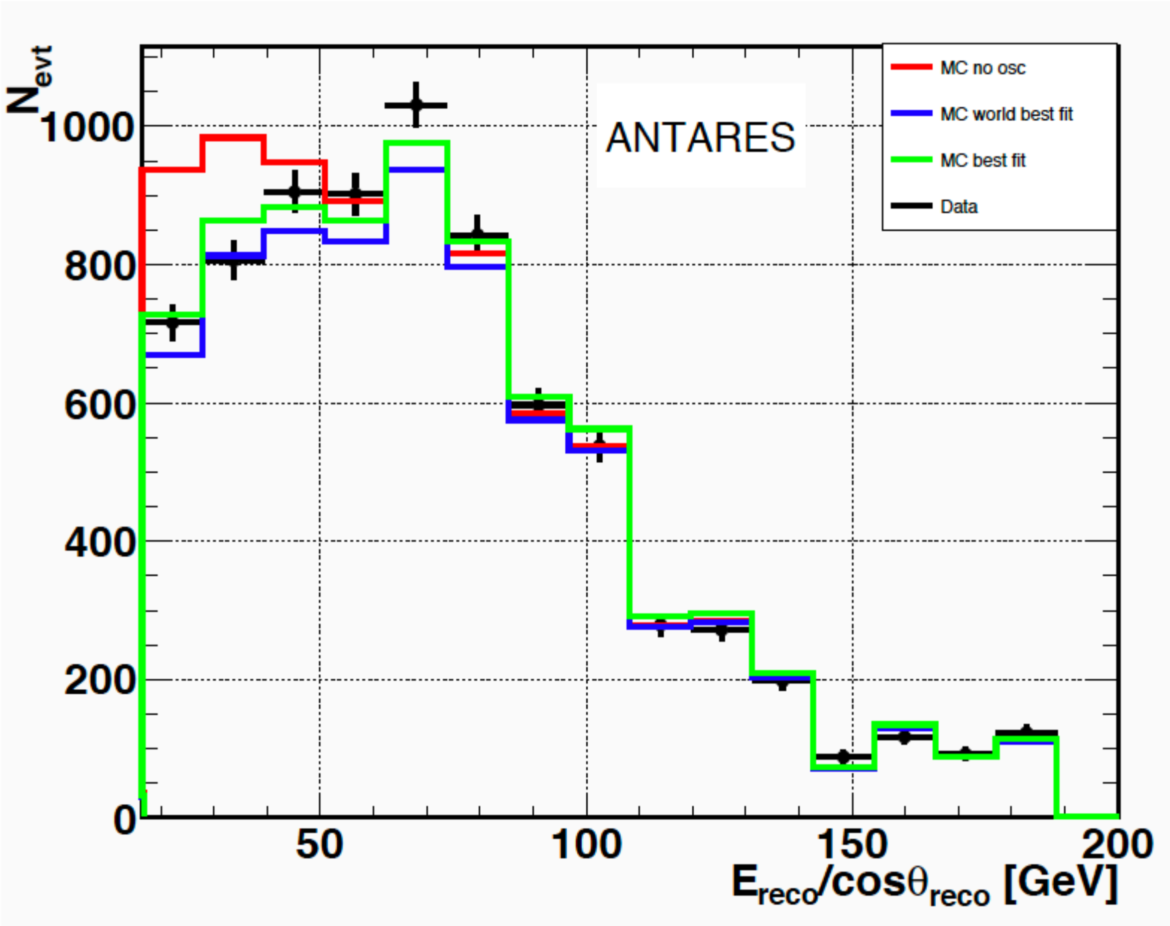
Ratio of event rates



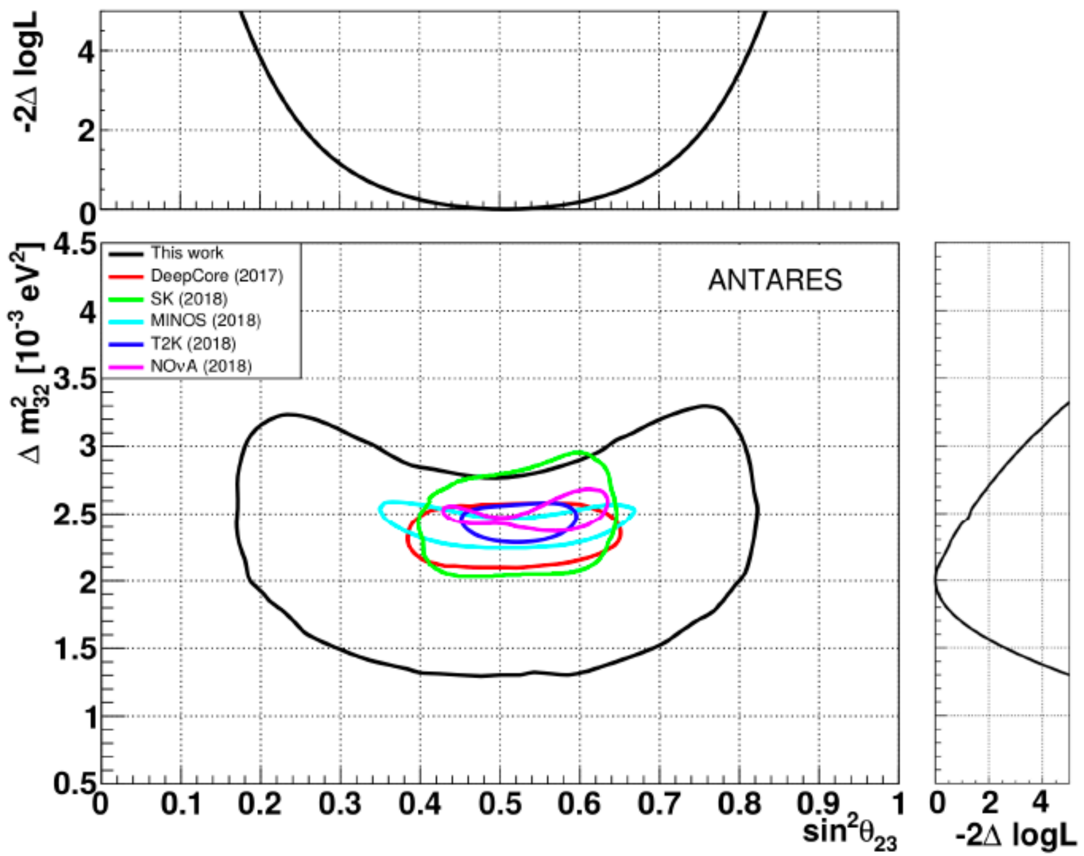
photon detection efficiency

$$f_\gamma(E) = A_\gamma \cdot E_T^{B_\gamma}$$

A_γ is incorporated in N_ν, B_γ in $\Delta\gamma$



N_evt
MC no osc
MC world best fit
MC best fit
Data
ANTARES
E_reco/cosθ_reco [GeV]



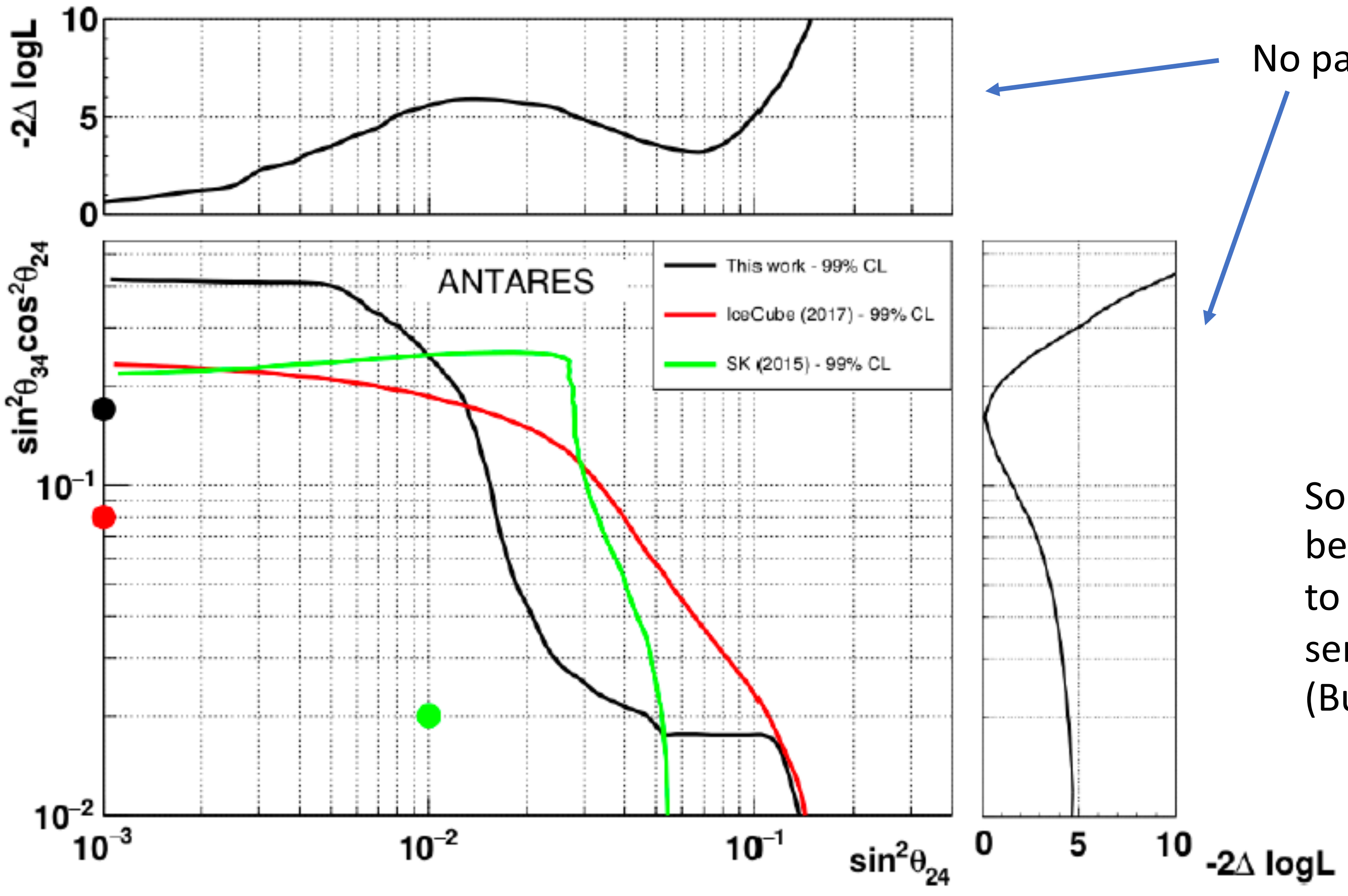
-2Δ logL
This work
DeepCore (2017)
SK (2018)
MINOS (2018)
T2K (2018)
NOvA (2018)
ANTARES
Δ m²_32 [10⁻³ eV²]
sin²θ_23
-2Δ logL

Sterile neutrinos:

3+1 neutrino model: one new mass splitting Δm^2_{41}, three new mixing angles, two new phases

From LSND/MiniBoone/reactor expts: expect Δm^2_{41} of order 1 eV^2
But large Δm^2 imply fast oscillations, everything smears out. Therefore fix it.
θ_{14} and δ_{14} fixed at zero, since mostly affect ν_e

Name	Prior	Fit	
θ_{24} [°]	FREE	0.9 ± 1.8	
θ_{34} [°]	FREE	24 ± 4 (*)	← Yuck
N_ν	FREE	0.81 ± 0.09	
$\nu/\overline{\nu}$ [σ]	0.0 ± 1.0	1.1 ± 0.6	
$\Delta\gamma$	0.00 ± 0.05	-0.001 ± 0.035	
Δm^2_{32} [$10^{-3}\,eV^2$]	2.46 ± 0.14	2.49 ± 0.13	← Not free anymore
θ_{23} [°]	FREE	49 ± 7	
δ_{24} [°]	FREE	0 ± 120	
θ_{13} [°]	8.41 ± 0.28	8.41 ± 0.28	
M_A [σ]	0.0 ± 1.0	0.1 ± 1.0	



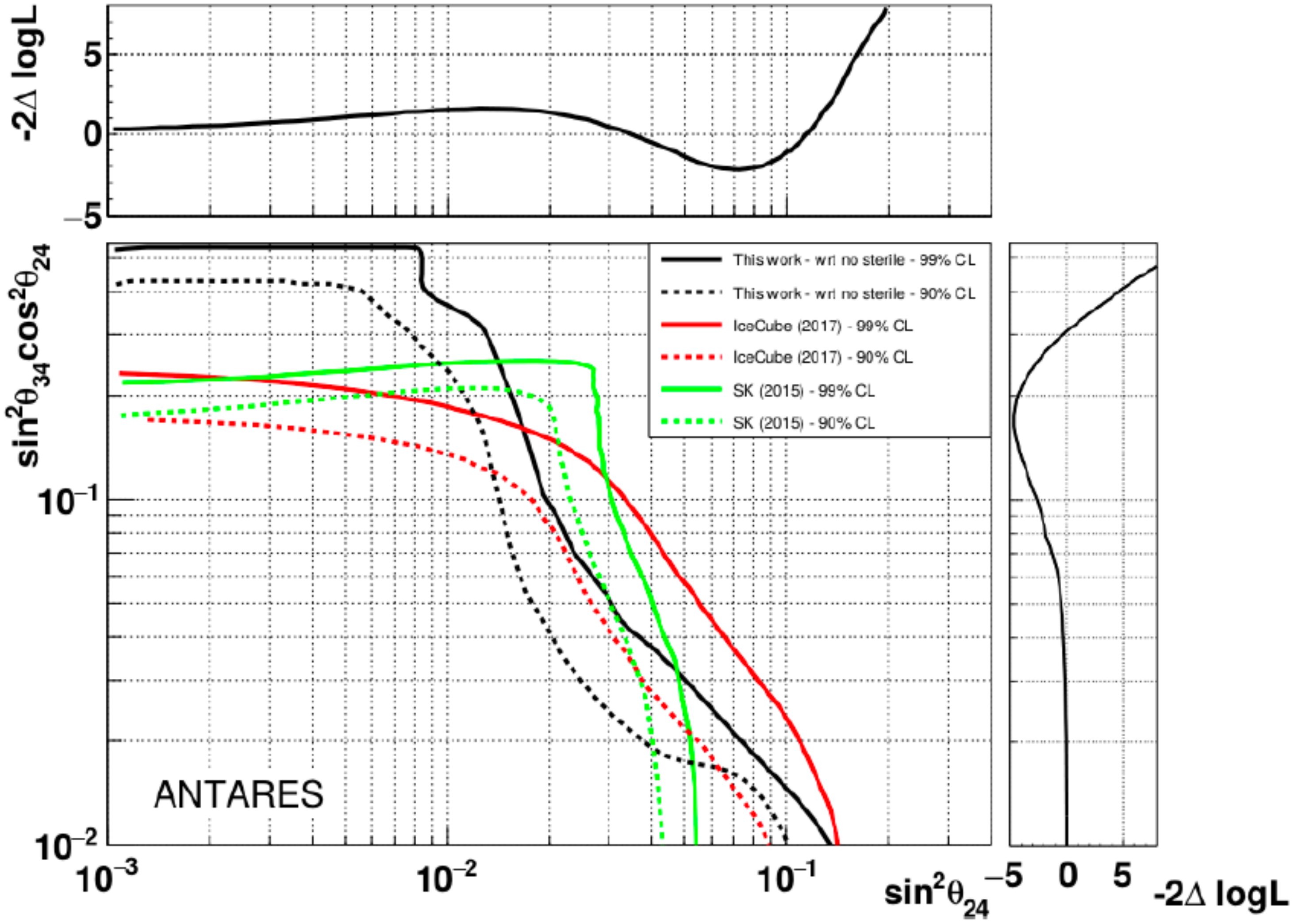
No parabola

$$|U_{\mu 4}|^2 = \sin^2\theta_{24}$$

$$|U_{\tau 4}|^2 = \sin^2\theta_{34}\cos^2\theta_{24}$$

Some differences in fit details between the 3 experiments may to some extent explain different sensitivities.
(But no proof given)

99% CL?
Quote asymmetric error for θ_{34} ?



Why is Antares competitive in sterile neutrino limits, but not in standard oscillation?

Better explain difference between figure 8 and figure 7?