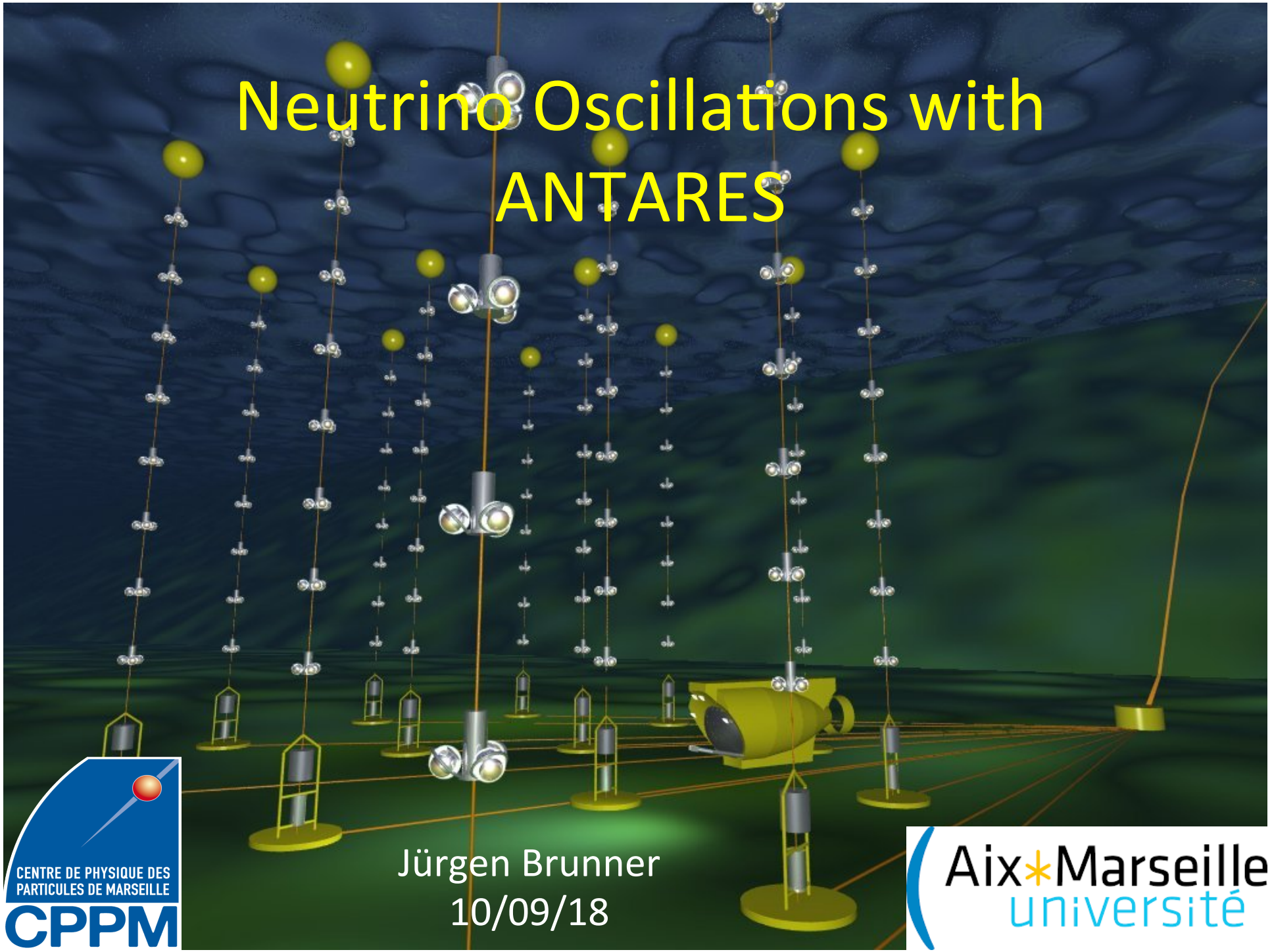
Neutrino Oscillations with ANTARES

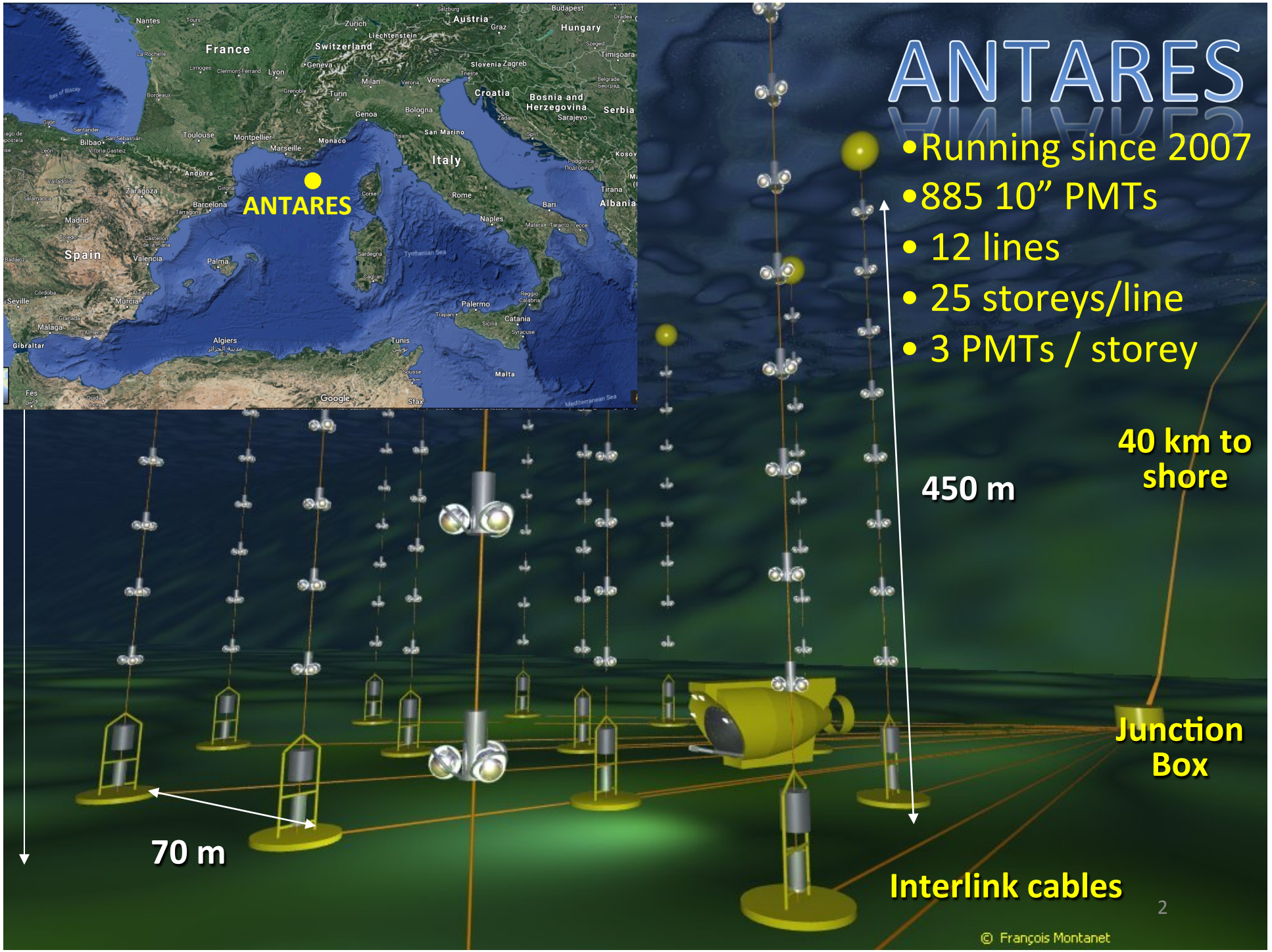


Jürgen Brunner

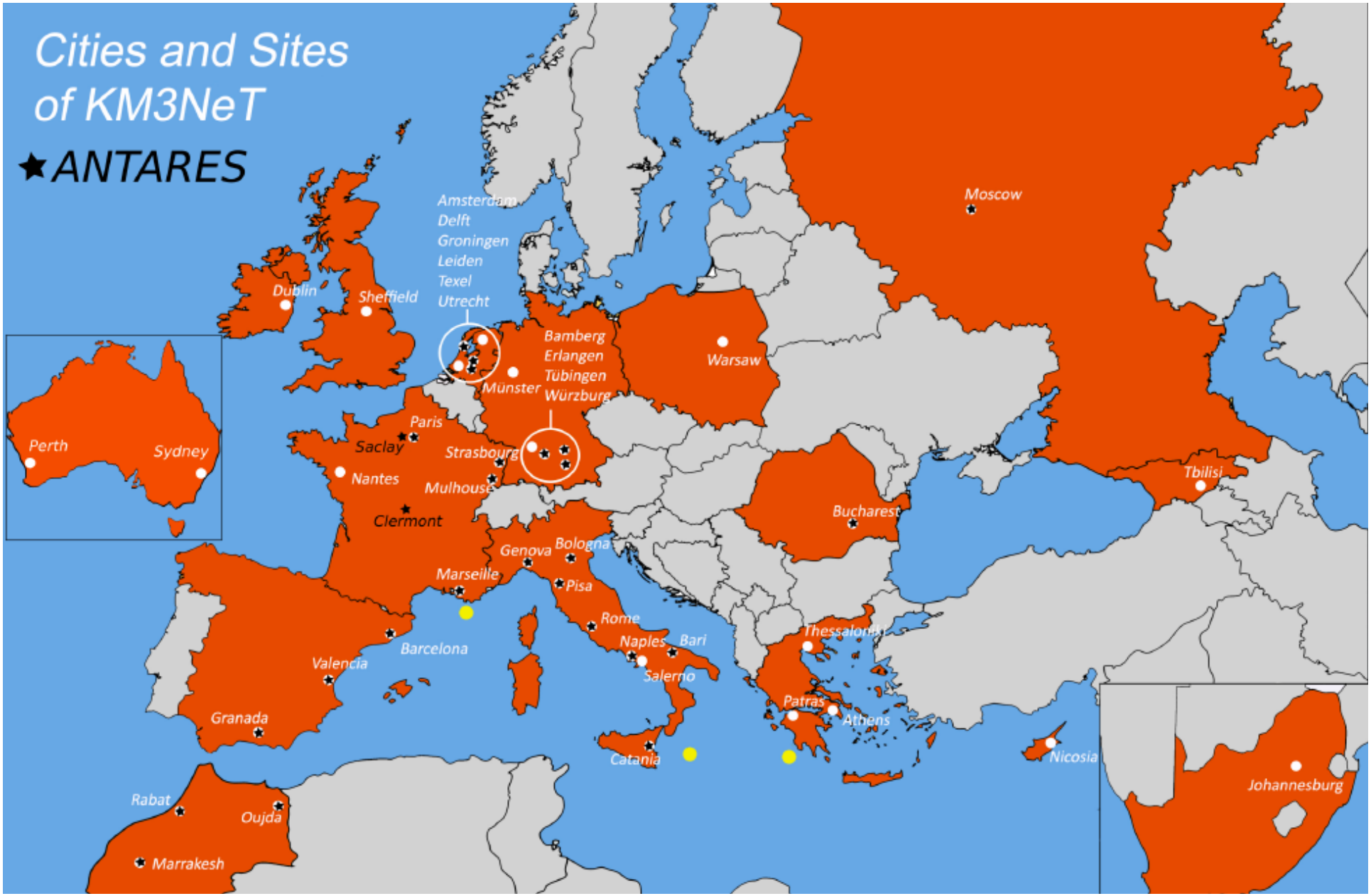
10/09/18

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

Aix*Marseille université

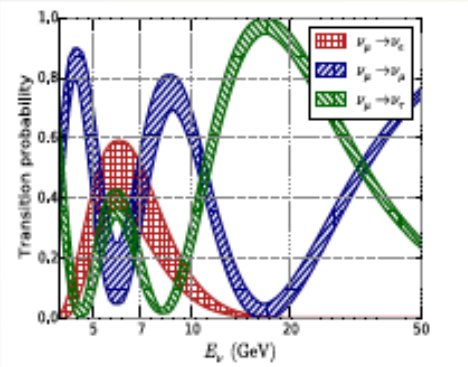

ANTARES
•Running since 2007
•885 10” PMTs
• 12 lines
• 25 storeys/line
• 3 PMTs / storey
ANTARES
40 km to shore
450 m
Junction Box
70 m
Interlink cables
© François Montanet
France
Switzerland
Austria
Hungary
Slovenia
Croatia
Bosnia and Herzegovina
Serbia
Italy
Spain
Monaco
Andorra
Malta
Tunisia
Algeria
Gibraltar
Google

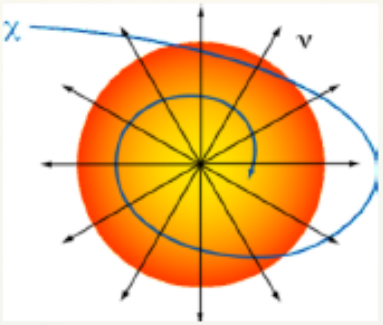
ANTARES & KM3NeT Collaboration

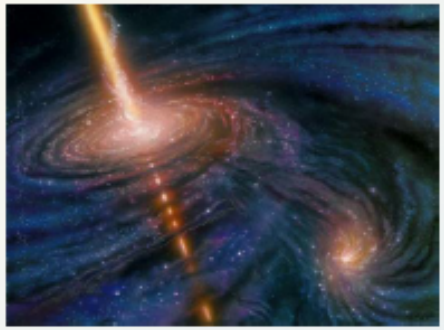


ANTARES (KM3NeT) Physics Program

- Large variety of topics
- Many orders of magnitude in neutrino energy



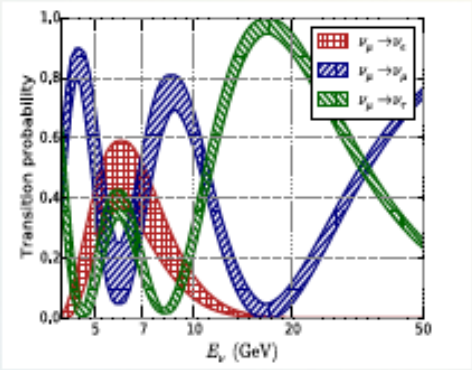




Low Energy	Medium Energy	High Energy
3 GeV < E_ν < 50 GeV	10 GeV < E_ν < 1 TeV	E_ν > 1 TeV
ν Oscillations	Dark Matter searches + Exotic searches	Cosmic neutrinos Origin & production mechanism of HE CR

ANTARES (KM3NeT) Physics Program

- Large variety of topics
- Many orders of magnitude in neutrino energy



Talks Wednesday afternoon
→M. Spurio (ANTARES)
→R. Coniglione (KM3NeT)

Low Energy
3 GeV < E_ν < 50 GeV

Medium Energy
10 GeV < E_ν < 1 TeV

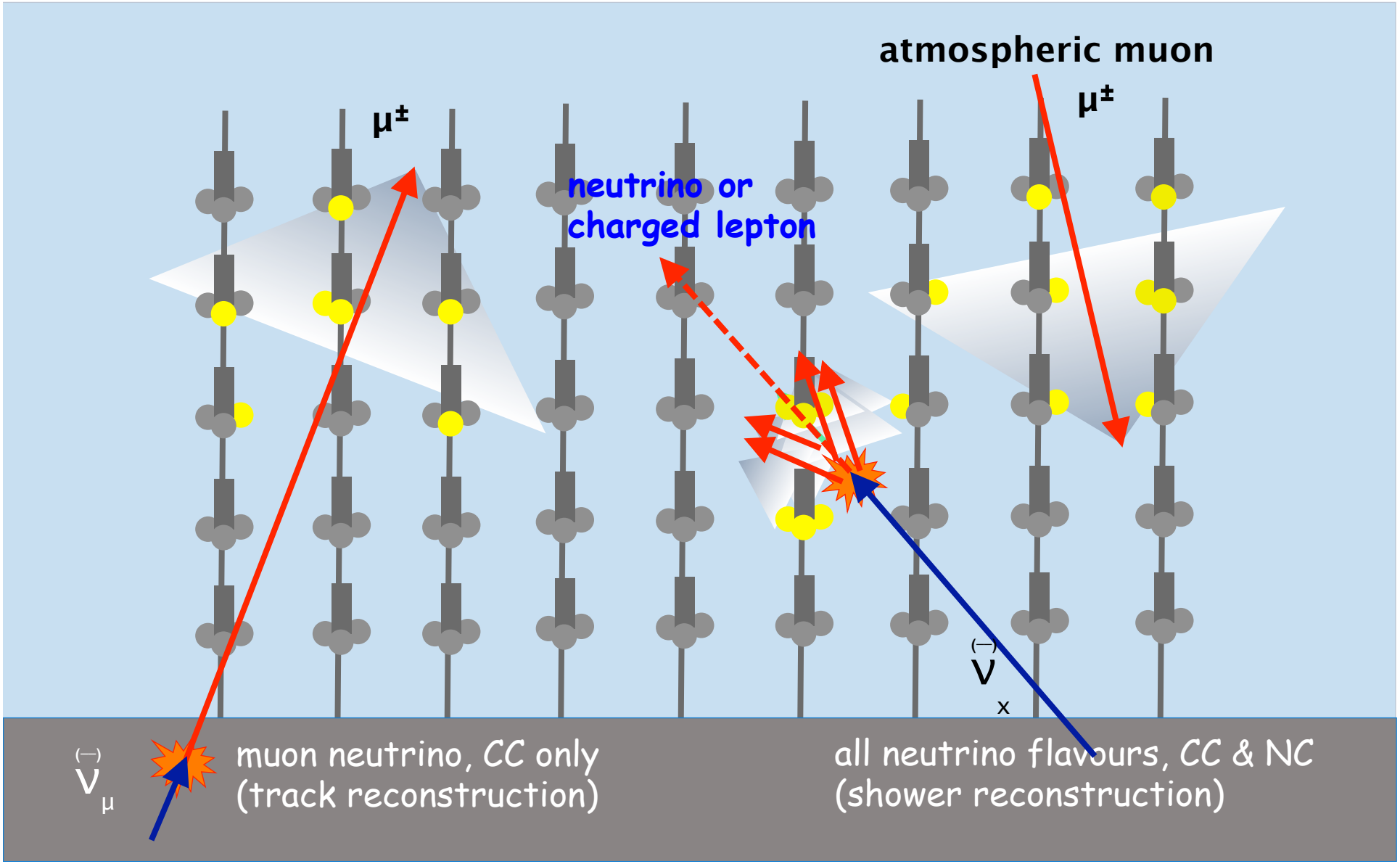
High Energy
E_ν > 1 TeV

ν Oscillations

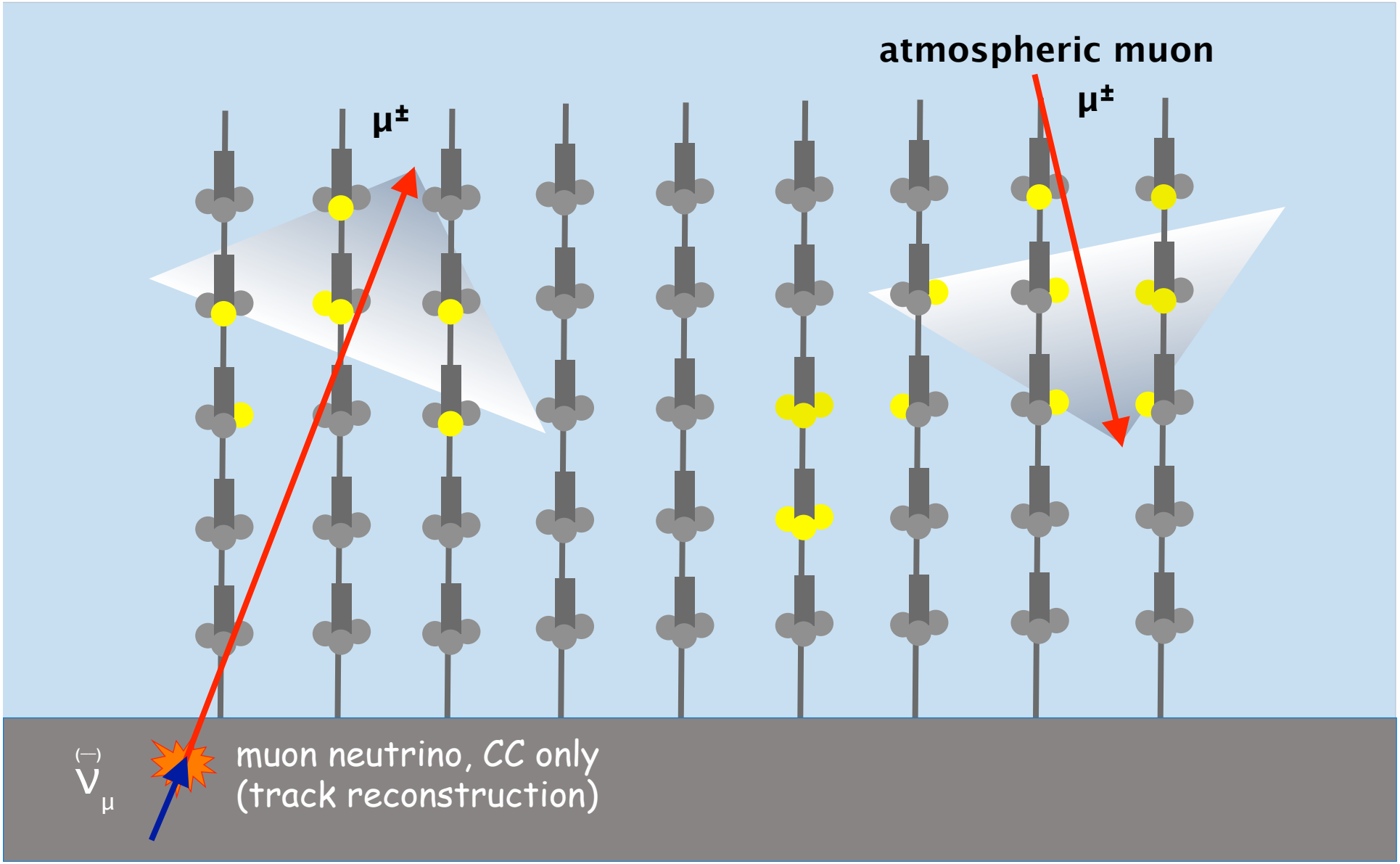
Dark Matter searches
+ Exotic searches

Cosmic neutrinos
Origin & production
mechanism of HE CR

Neutrino Signatures



This analysis : track signature only



Simulations Signal & Background

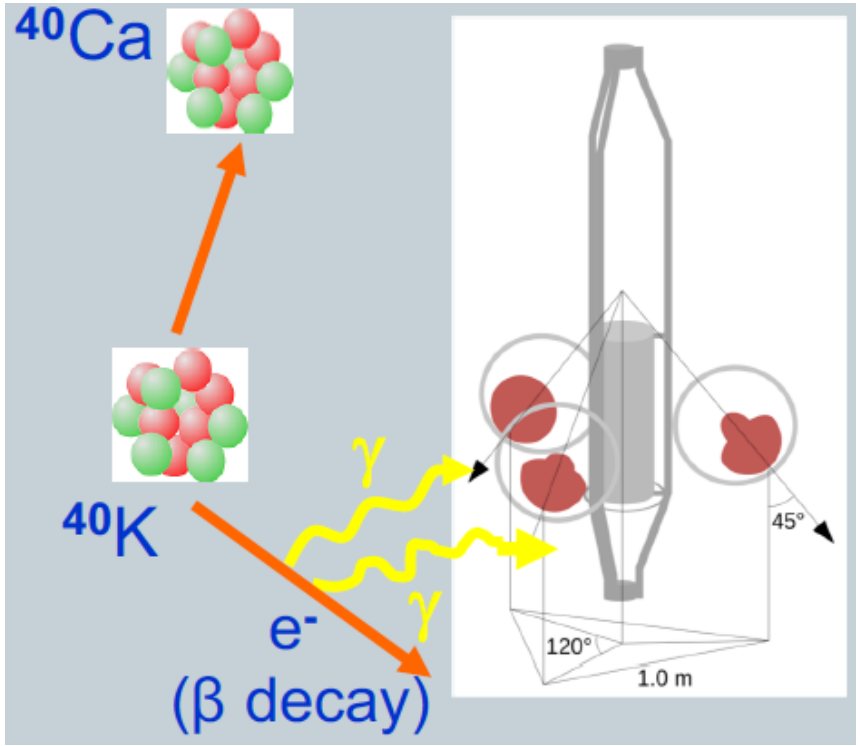
- Signal :
  - ν_μ-CC interaction, atmospheric neutrinos
- Background
  - ν_e-CC interaction, NC, atmospheric neutrinos
  - Atmospheric muons
- Flux : Honda (Frejus, solar minimum)
- Cross sections
  - QE, resonant, DIS (Genhen - Antares package)
- Atmospheric Muons
  - MUPAGE (parametrisation)

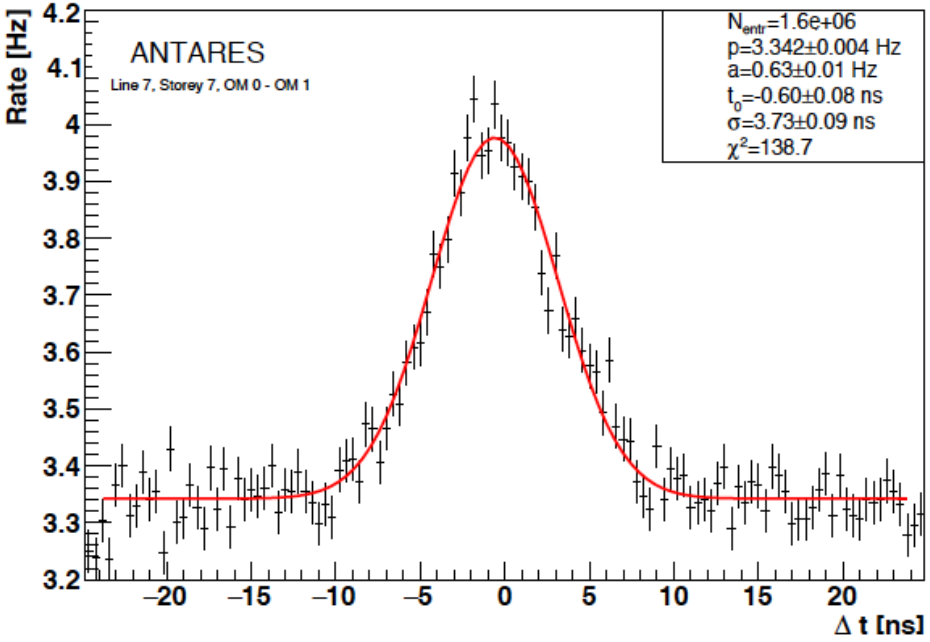
Simulations

- Data taking conditions evolve
  - Optical background time dependent
  - PMT efficiencies
- Run-by-run Monte Carlo takes into account these changes with fine-grained sampling
- Optical background monitored on 100msec level for each individual optical module
- Optical module efficiencies monitored with ^{40}K

Optical module efficiency - ^{40}K method

- Measure coincidence signals from same decay in the vicinity of a storey
- Radioactivity : constant calibration source

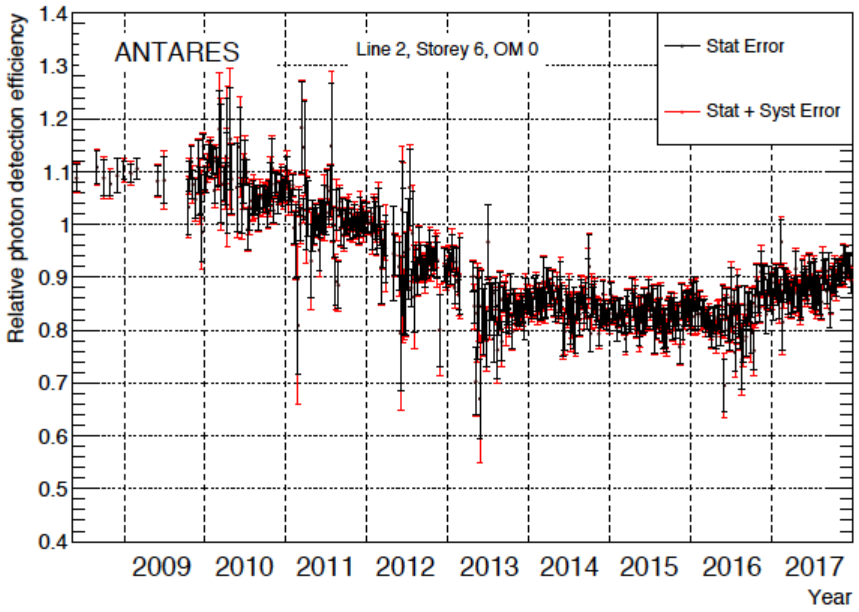




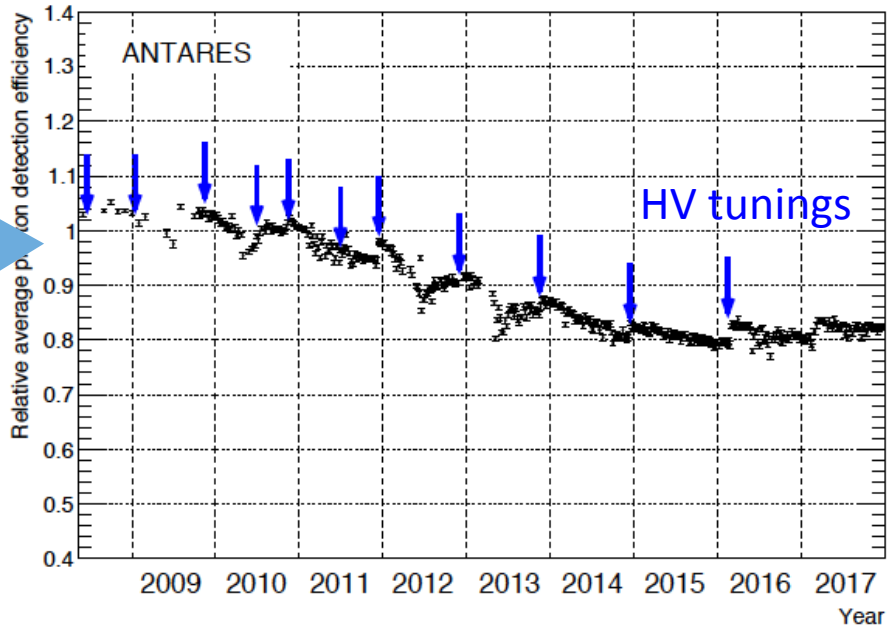
Long term evolution of OM efficiency

- Efficiency monitoring on weekly basis
- 20% loss in 10 years

Example of one optical module



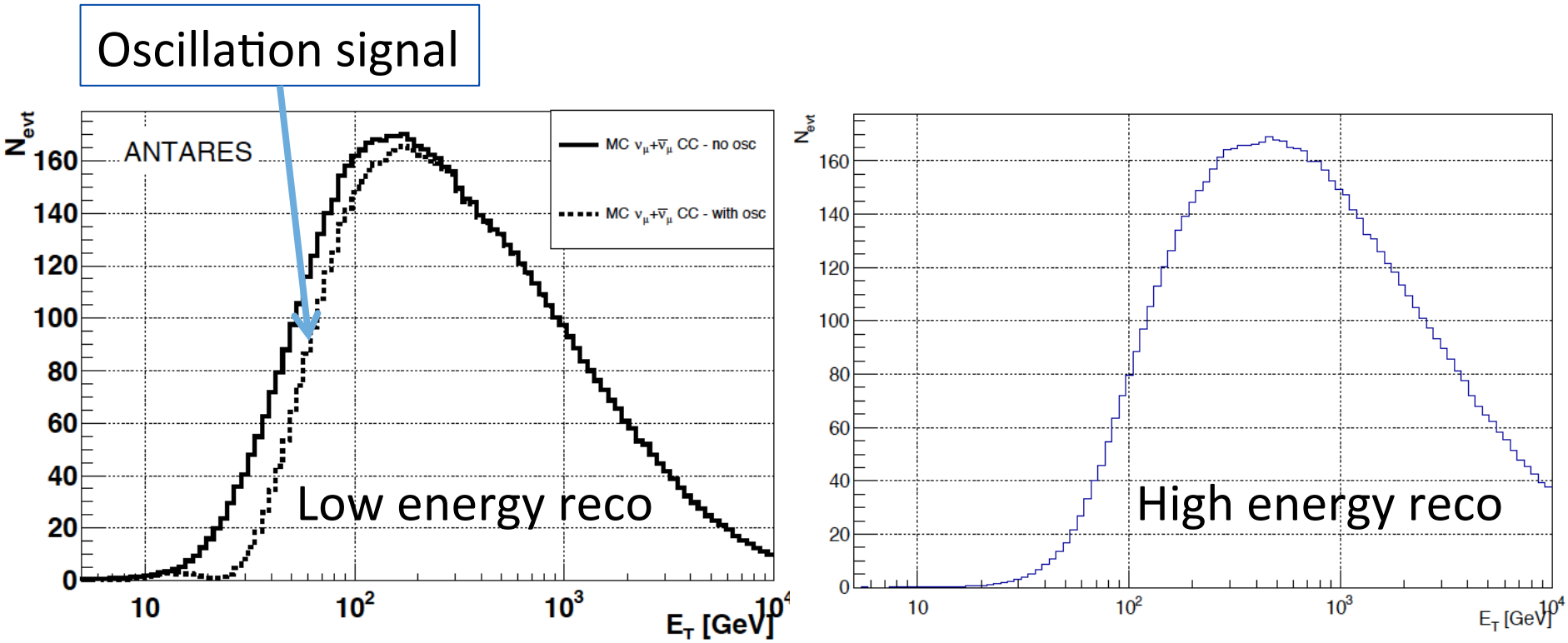
Full detector average



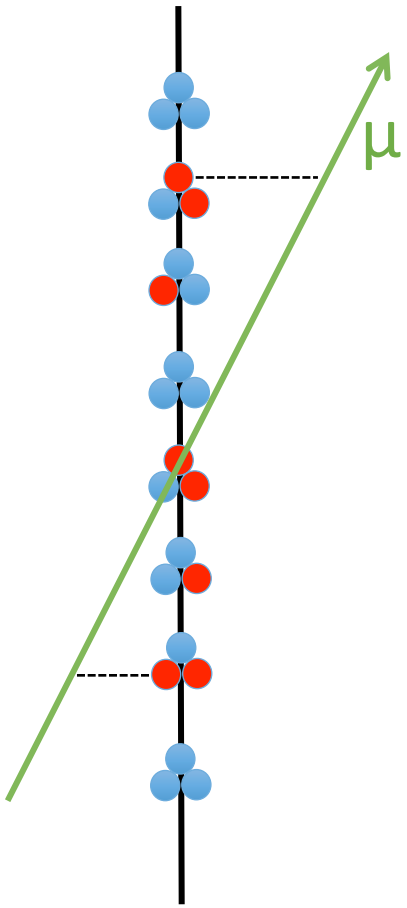
Antares collab., Eur. Phys. J. C (2018) 78:669

Reconstruction Methods – Tracks only

- Two Low-energy methods combined
- Enhanced efficiency below 200 GeV
- signal region for neutrino oscillations remains at threshold
- ~10% depletion of expected event rate



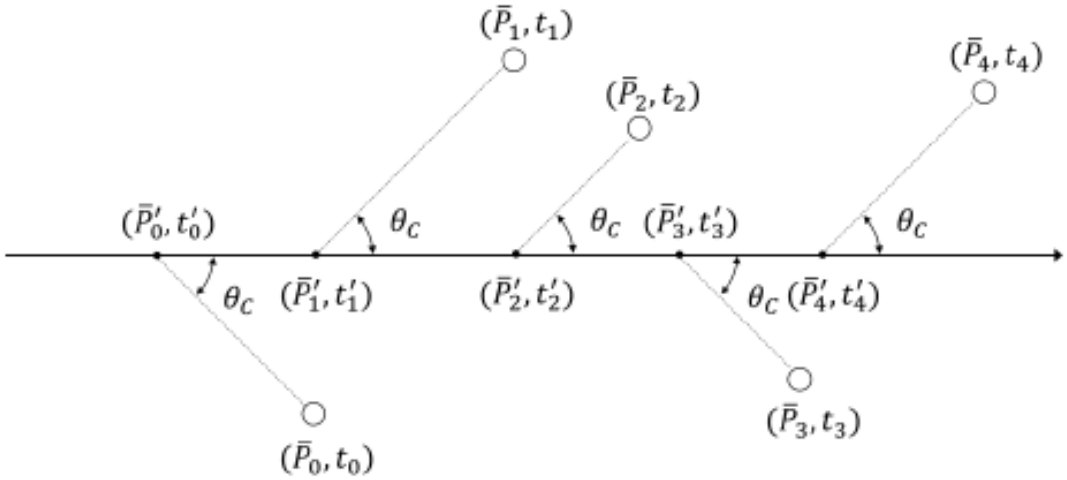
Reconstruction Methods 1



Strict hit selection ("direct" hits) + χ^2 minimization

Single-line versus Multi-line reconstruction

Muon length (=energy) from projected reco-track



Reconstruction Method 2

- Scan of many track hypotheses in angular phase space
- Selection of up versus down-going based on hit multiplicity

Down-going muon

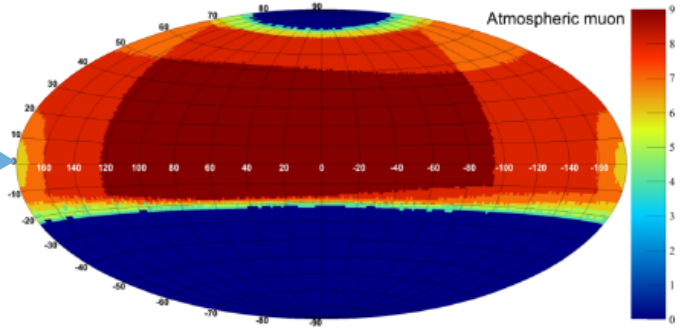
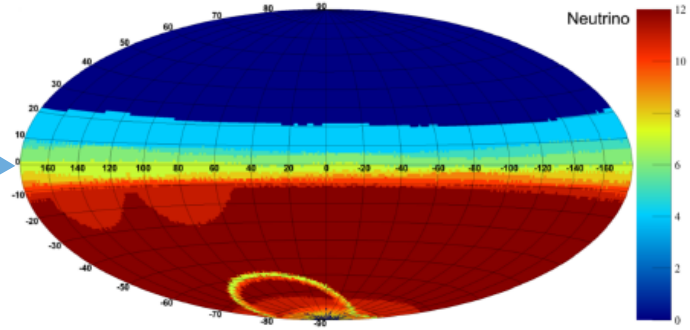


Figure 4.10: Sky-map with the N_{hits} grid for an atmospheric muon.

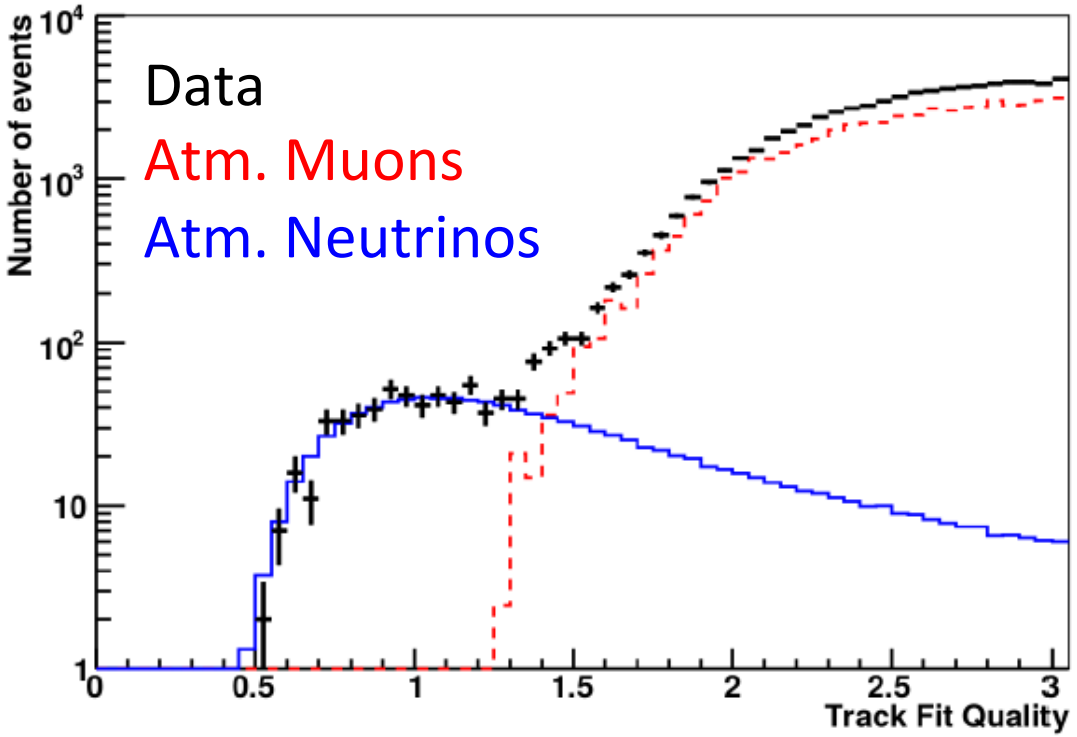
Hit multiplicity of angular scan

Up-going neutrino



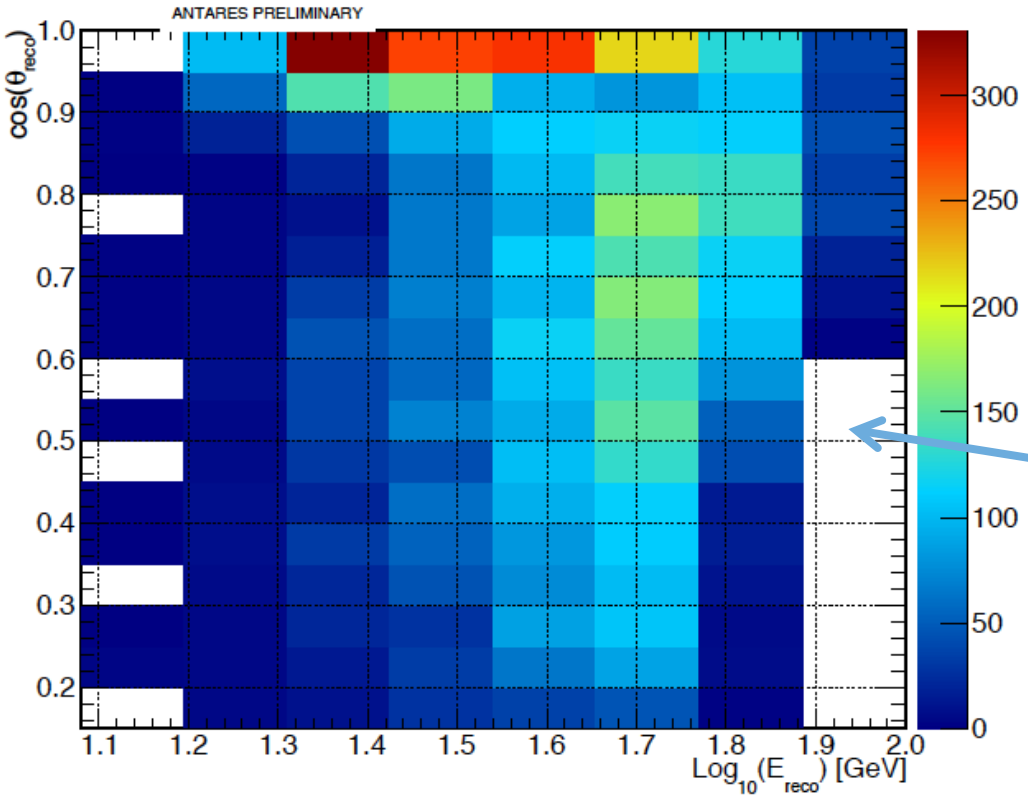
Selection of clean neutrino signal

- Up-going track candidates
- Cut on track quality
- Example from 2008 data Reco 1



Total data sample

- 10 years of data (2007-2016) - 2830 days of lifetime
- 7710 events selected
- A binned likelihood fit (Poisson statistics) is performed in two dimensions ($\log_{10}(E_{reco})$, $\cos\theta_{23}^{reco}$)

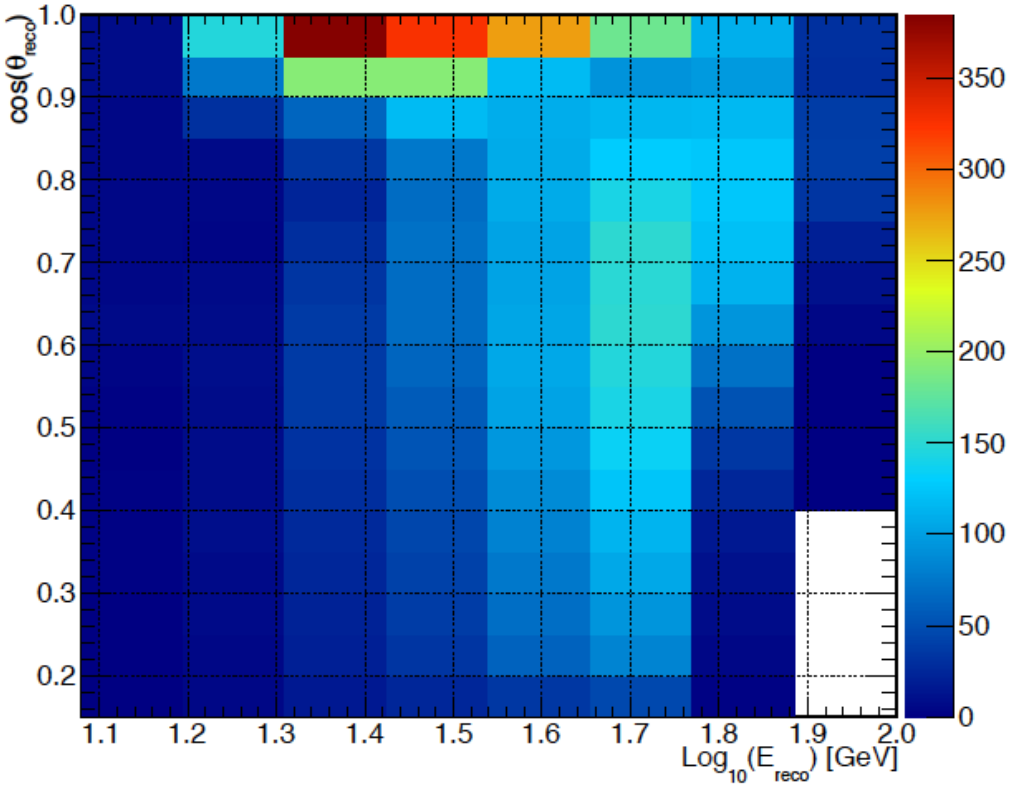


Size of detector

Total MC sample

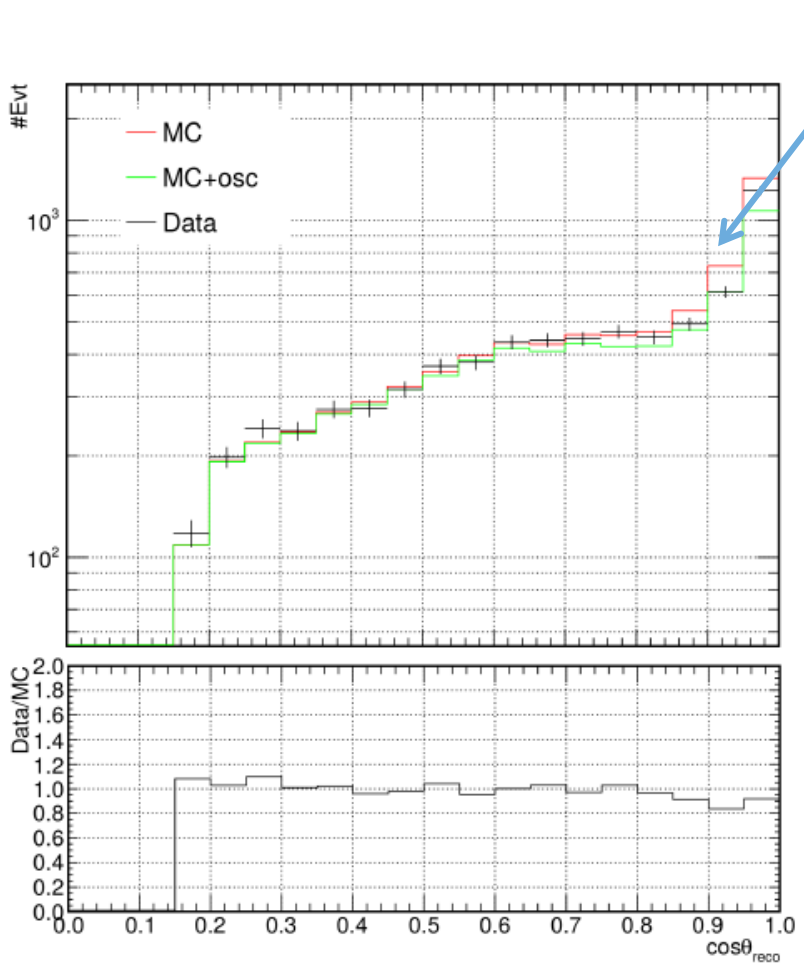
- Contributions :

$\nu_\mu + \bar{\nu}_\mu$ CC	7591.4 ± 5.3
Atm μ	351.0 ± 32.4
$\nu_e + \bar{\nu}_e$ CC + NC	39.3 ± 0.2
Signal Strength	716.4 ± 7.6



Sanity check

- Zenith angle distribution data/MC comparison
- Good agreement (MC without oscillations)

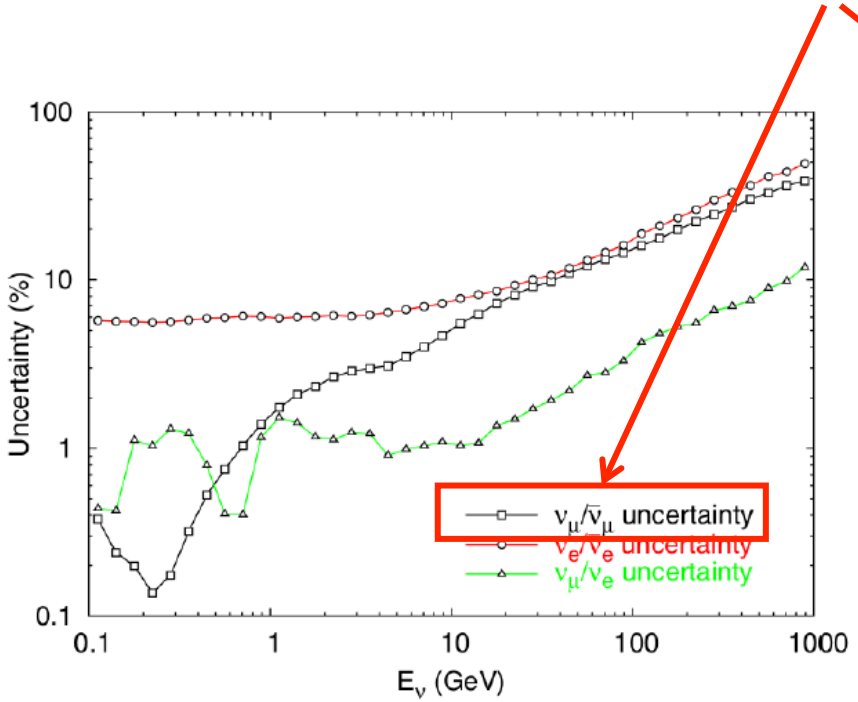


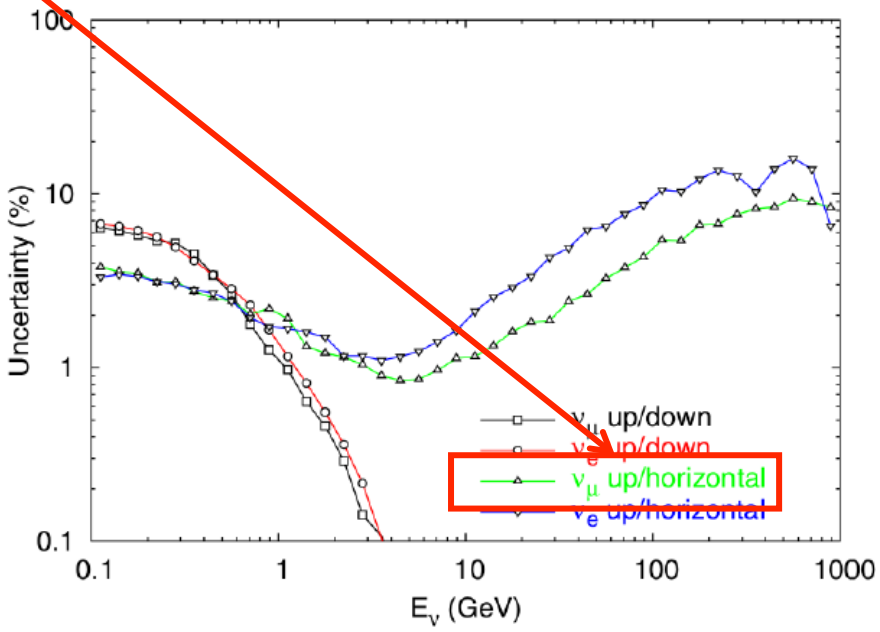
Systematics - generics

- Unconstrained normalization for neutrinos
  - Combined effect of flux, deep inelastic x-sec, detector
- Spectral index variations with 5% prior
  - Combined effect of flux, deep inelastic x-sec, detector
- Cross section from Genie
  - Leading effect M_A (resonances) E-dependent variation
- θ_{13} with prior from reactor data
- θ_{12} , Δm_{21}^2 , δ_{CP} fixed (no sensitivity)

Further flux systematics

- Neutrino/anti-neutrino ratio and up/horizontal ratio
- From G. D. Barr et al., Phys. Rev. D 74 (2006) 094009.
- Implementation from IceCube, kindly provided by Th. Stuttard
- Two ratios are important for this analysis (correlated)

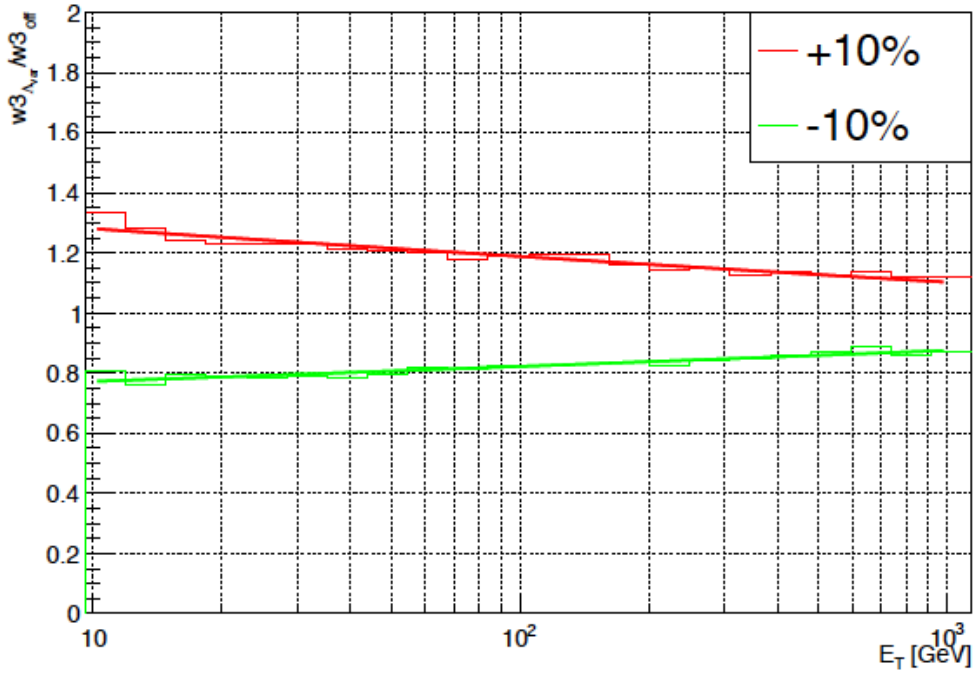




Detector Systematics

- 10% Variation of Optical Module efficiency
- Well described by norm + spectral index modification

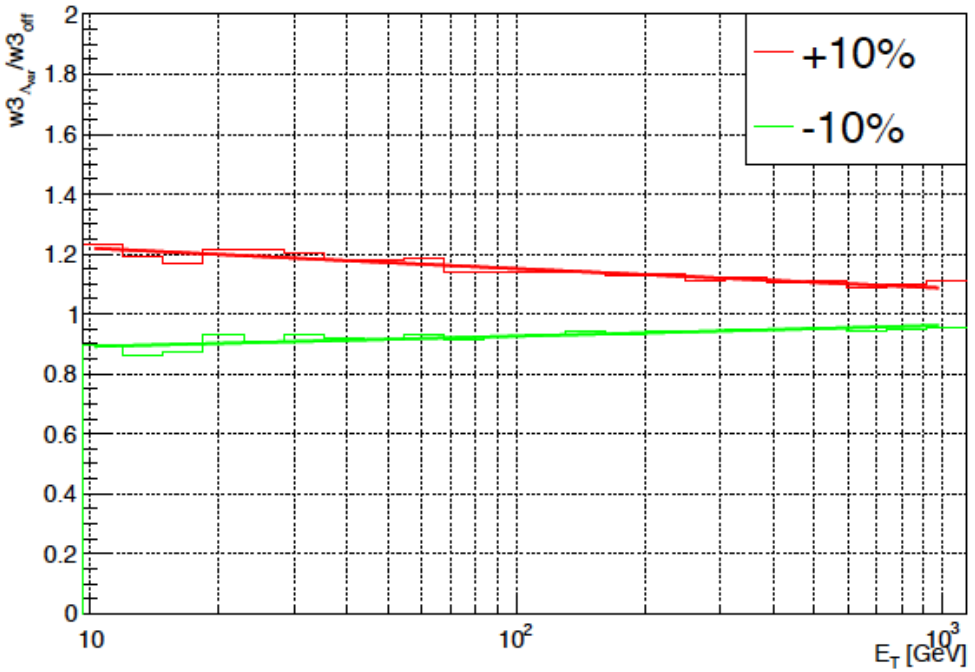
	Norm	γ
+10%	1.34	-0.03
−10%	0.73	0.03



Detector Systematics

- 10% Variation of water absorption
- Well described by norm + spectral index modification

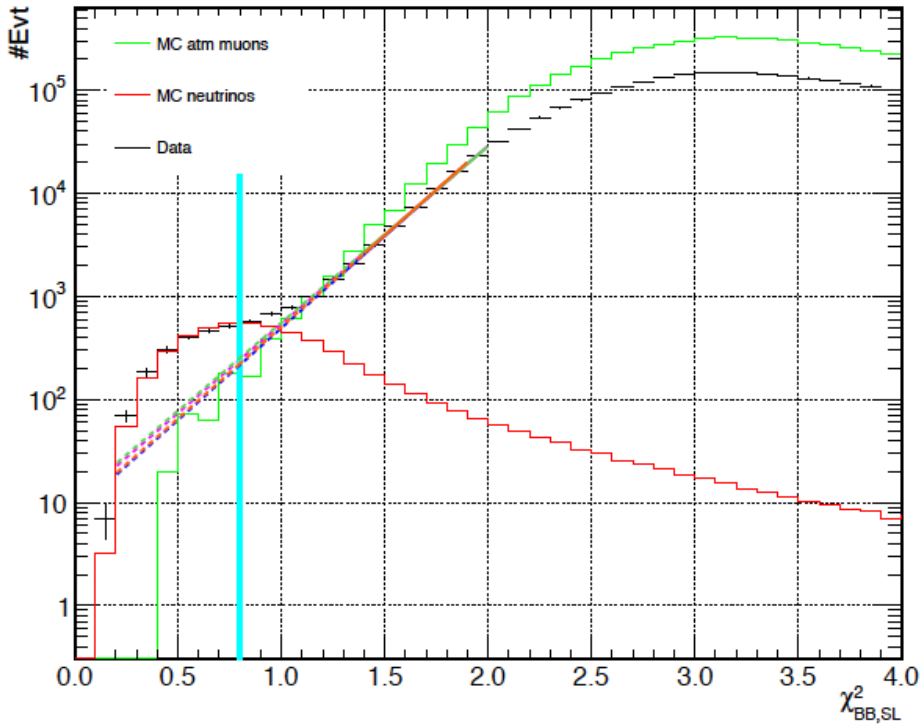
	Norm	γ
+10%	1.29	-0.02
−10%	0.86	0.02



Atmospheric muons systematics

- Extrapolated into signal region from track quality parameter of up-going fits
- Resulting rate + error used as prior for atmospheric muons

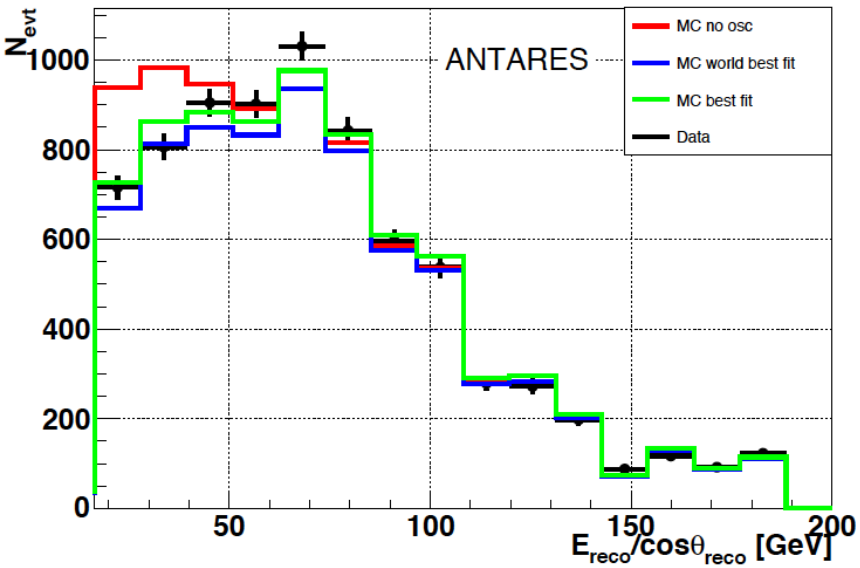
Example plot
Single-line Fits



Results standard oscillation fit

- θ_{23} close to maximal mixing, Δm_{32}^2 slightly on low side
- Normalisation 18% low, correlated with pull in nu/nubar
- No spectral distortion
- Strong pull on atmospheric muons → back to MC value

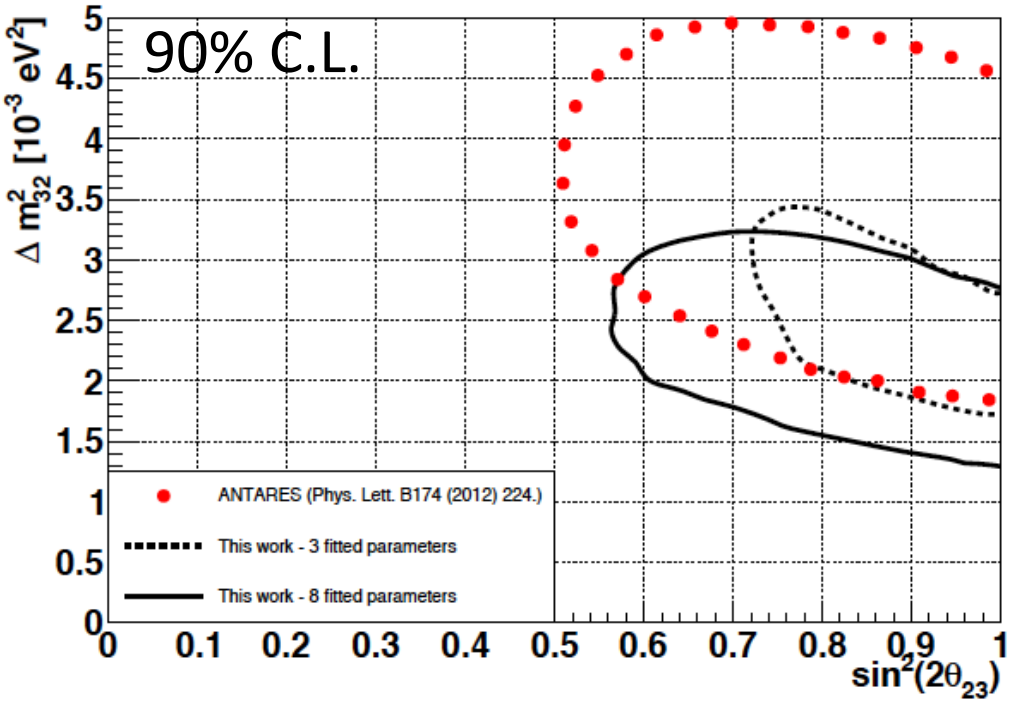
Name	Prior	Fit
N	FREE	0.82 ± 0.09
Δm^2_{32} $[10^{-3}\,\mathrm{eV}^2]$	FREE	2.0± 0.3
θ_{23} [°]	FREE	45.4 ± 12.1
θ_{13} [°]	8.41± 0.28	8.41± 0.28
$\Delta\gamma$	0.0± 0.05	-0.003 ± 0.036
M_A^{CCRES} $[\sigma]$	0.0±1.0	0.008 ± 0.98
$\nu/\overline{\nu}$ $[\sigma]$	0.0±1.0	1.08 ± 0.60
N_μ [%]	742 ± 119	415 ± 22



The E/cosθ plot illustrates the oscillation effect
The fit is NOT performed on this 1D distribution

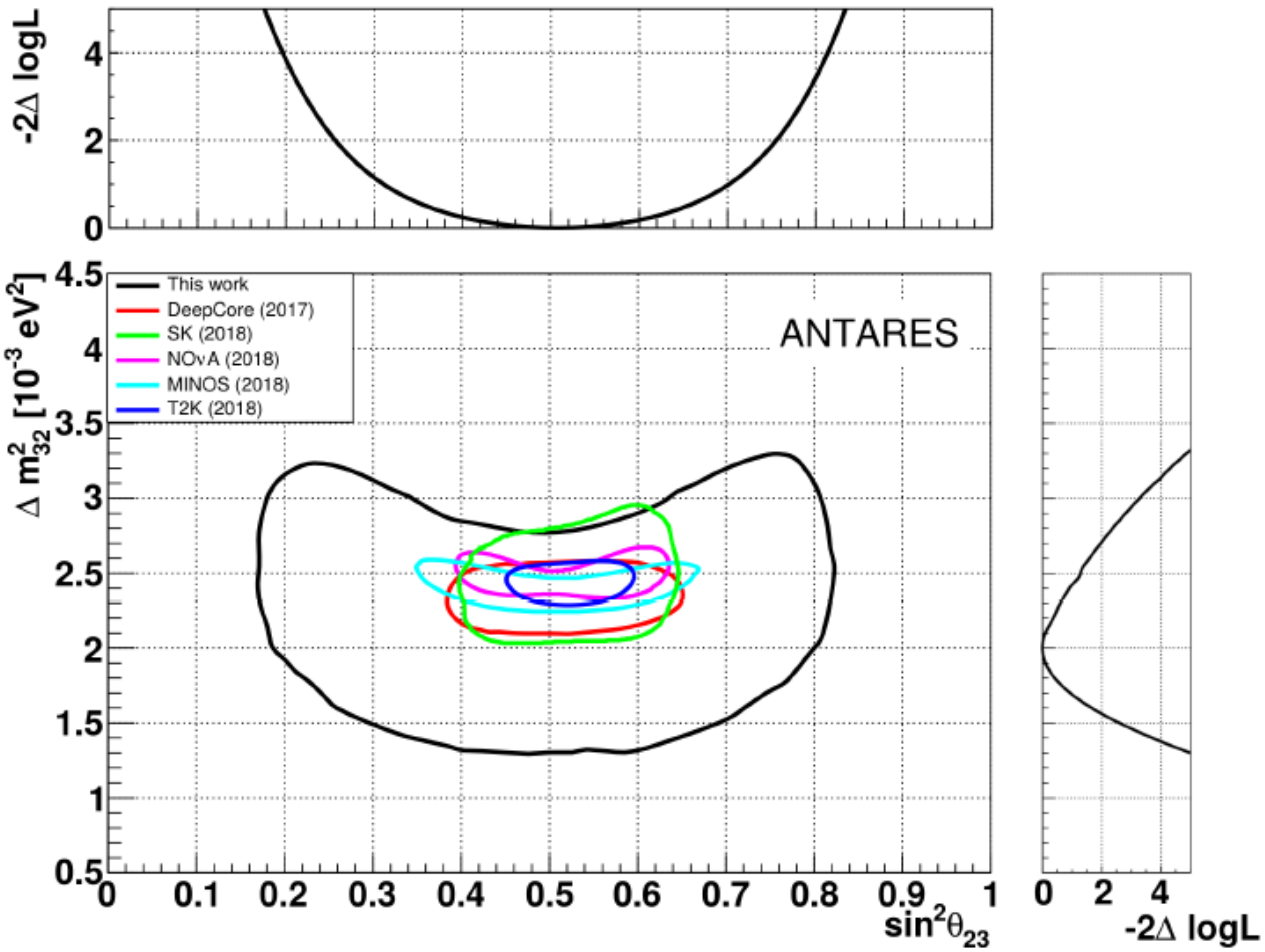
Comparison with earlier Antares result

- Factor three larger data sample
- Many more systematics taken into account
- Still significant improvement
- No-oscillation hypothesis excluded at 4.6σ
  - was 2.2σ in former analysis



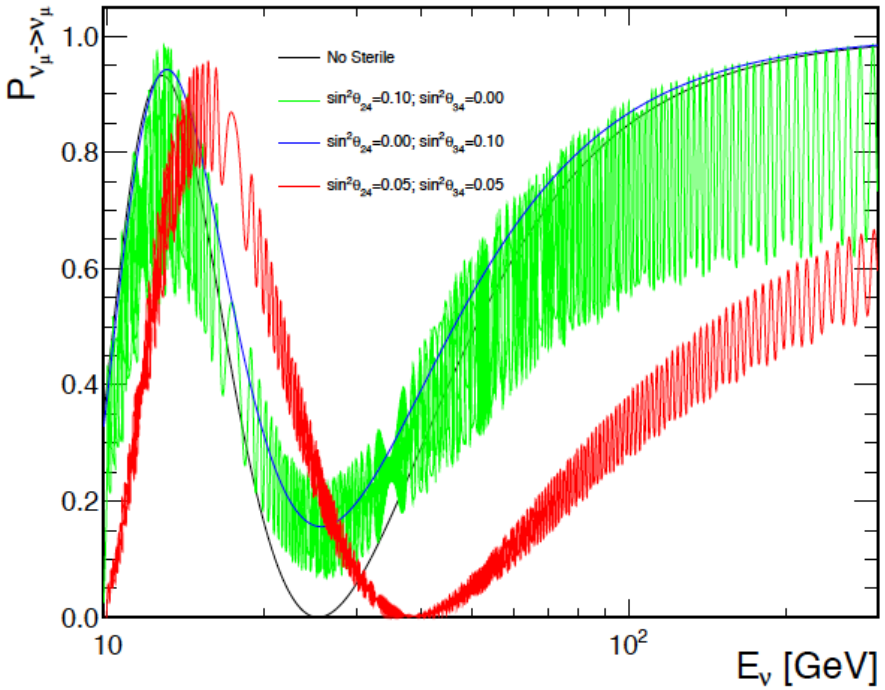
Comparison with world data

- Antares compatible but not competitive
- Oscillation Measurement with world highest energy threshold



Search for sterile Neutrinos

- Same data sample, similar fit
- 3+1 model with $\Delta m^2_{41} > 0.5\ eV^2$ → no sensitivity to Δm^2_{41}
- Combination of $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$ modifies oscillation minimum
- Only few limits on $|U_{\tau 4}|^2$ exist so far
- Relevant energy range extended → good for Antares



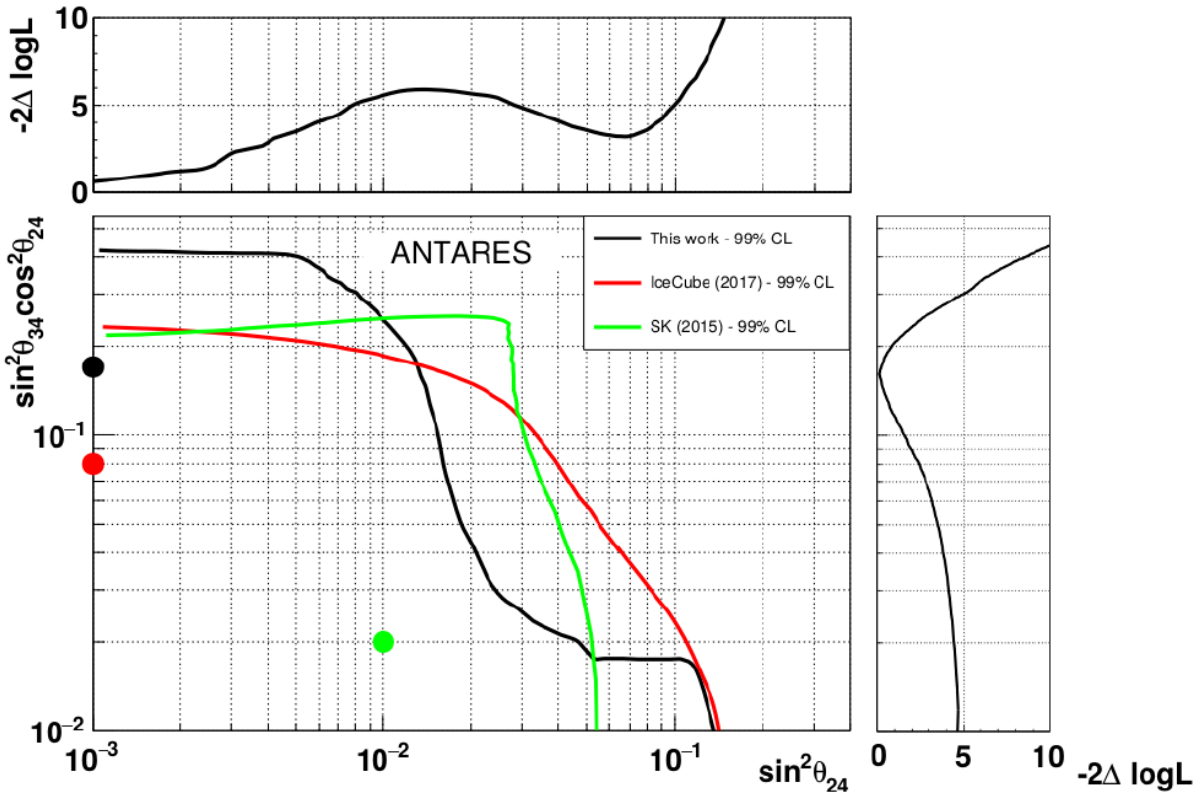
Results Sterile Fit

- Three new fit parameters θ_{24} , θ_{34} , δ_{24}
- No sensitivity to θ_{14} , δ_{14}
- Δm_{32}^2 with prior from global fit

Name	Prior	Fit
N	FREE	0.81 ± 0.09
θ_{24} [°]	FREE	0.94 ± 1.84
θ_{34} [°]	FREE	24.14 ± 3.88
δ_{24} [°]	FREE	0 ± 115
Δm^2_{32} [10^{-3} eV^2]	2.46 ± 0.14	2.49 ± 0.13
θ_{23} [°]	FREE	48.77 ± 7.03
θ_{13} [°]	8.41 ± 0.28	8.41 ± 0.28
$\Delta\gamma$	0.00 ± 0.05	-0.001 ± 0.035
X_{sec} [σ]	0.0 ± 1.0	0.11 ± 0.99
$\nu/\overline{\nu}$ [σ]	0.0 ± 1.0	1.09 ± 0.61

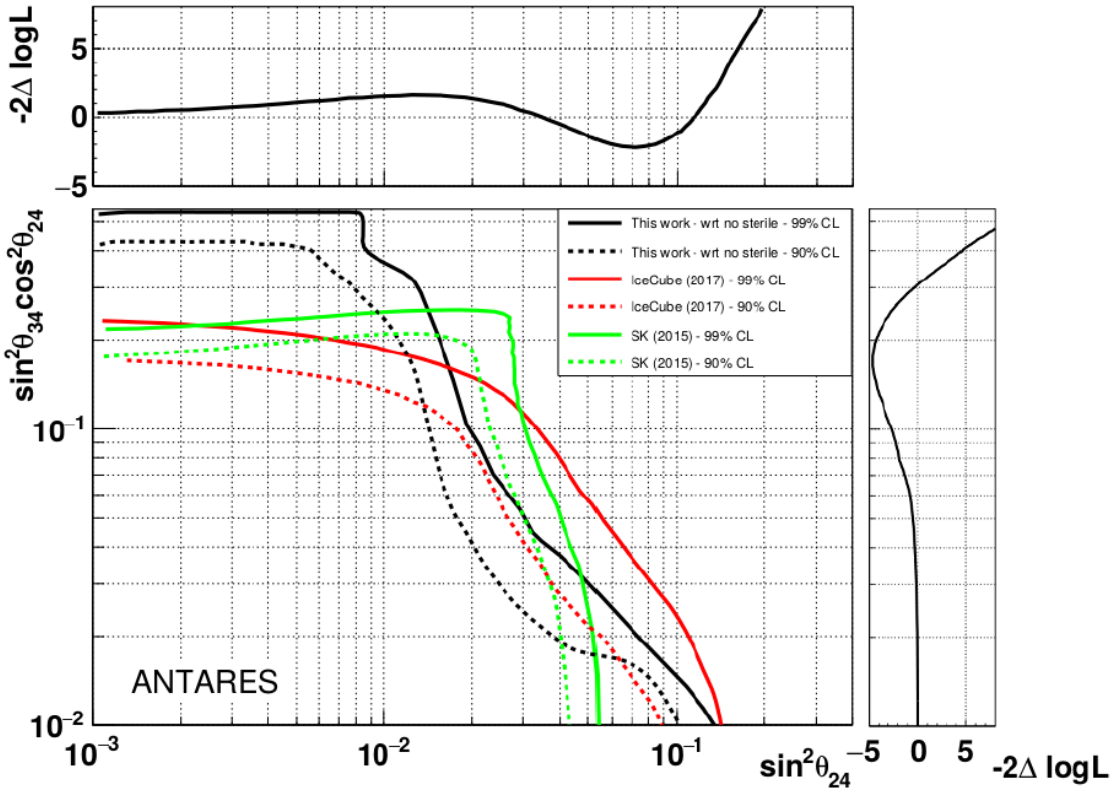
Comparison to SuperK & IceCube

- 99% C.L. limits with respect to best fit point
- Antares improves limits from IC & SuperK (larger E range)
- Some degeneracy between $\theta_{23} \leftrightarrow \theta_{24}$ and $\theta_{23} \leftrightarrow \theta_{34}$
- Best fit point not at “no-sterile” for all experiments



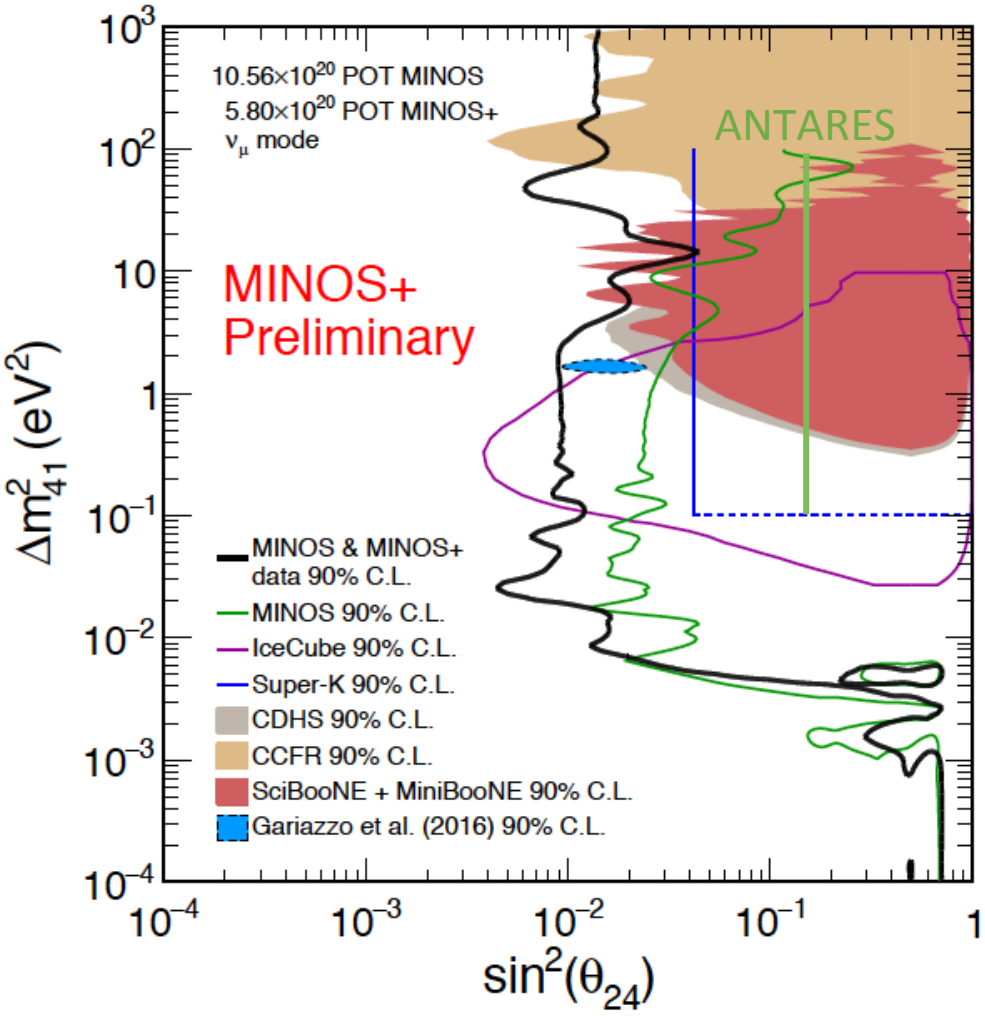
Comparison to SuperK & IceCube

- 90% & 99% C.L. limits with respect to no sterile (for Antares)
- Antares still improves limits from IC & SuperK
- 1-dim limits 90% C.L. $|U_{\mu 4}|^2 < 0.14$ and $|U_{\tau 4}|^2 < 0.36$



Comparison with muon disappearance results

- Plot from recent MINOS+ analysis



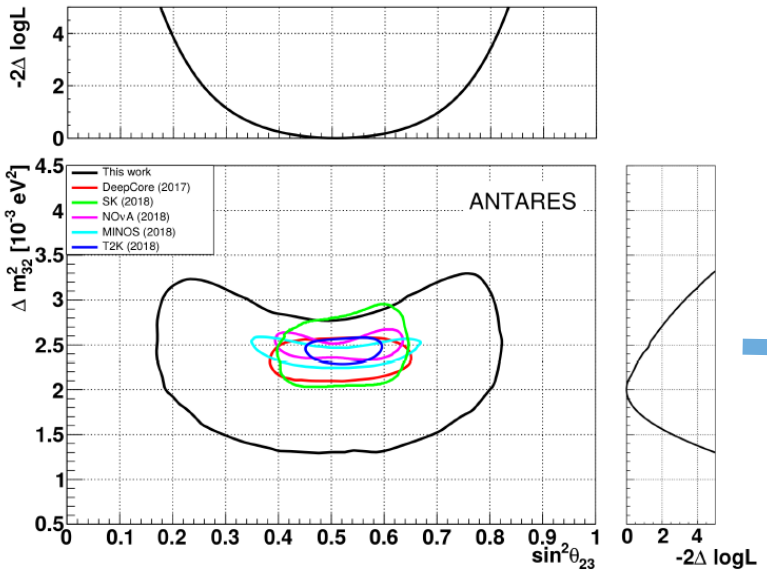
Conclusion

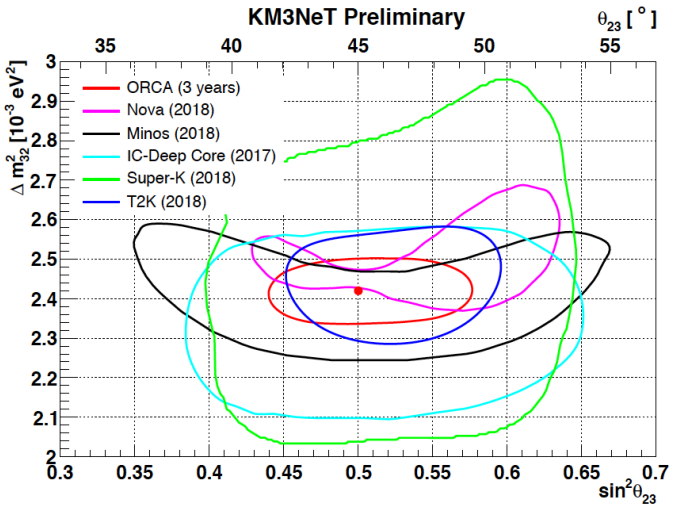
- 10 years atmospheric neutrinos of Antares analyzed
- Atmospheric neutrino oscillation measurement performed with $E_\nu > 20$ GeV
- Sterile 3+1 model tested
- Limits on $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$ derived
- Earlier limits from SuperK & IceCube improved for some combinations of parameters

- Where to go from here ???

Outlook

- Next generation :KM3NeT/ORCA
  - much denser detector
  - Lower energy threshold





→ See plenary talk D. Samtleben tomorrow

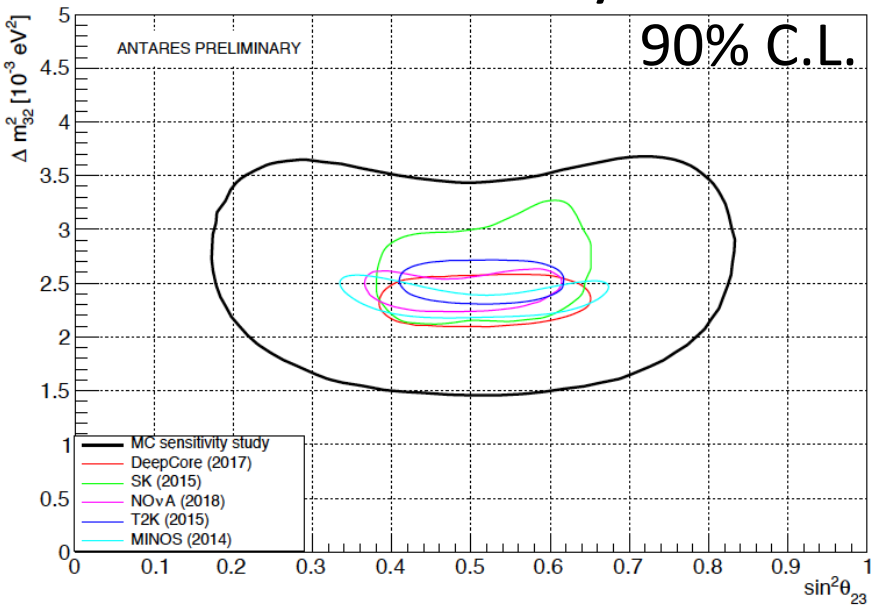
backup

- backup

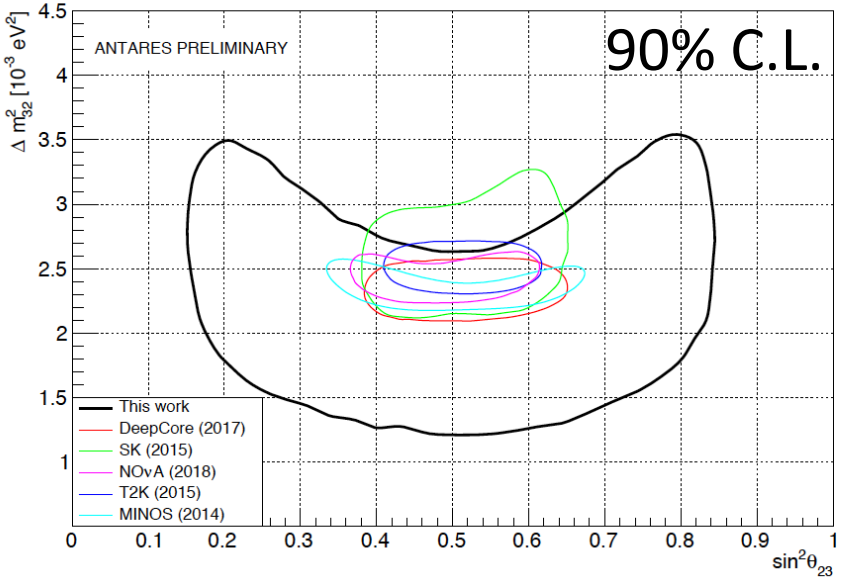
Results Standard Oscillations

- Result comparable to sensitivity estimate
- Data prefer slightly lower value of Δm_{32}^2

Sensitivity



Result



Energy resolution

- Exclusively from muon range