Measurement of the cosmic ray Moon shadow with the ANTARES detector.

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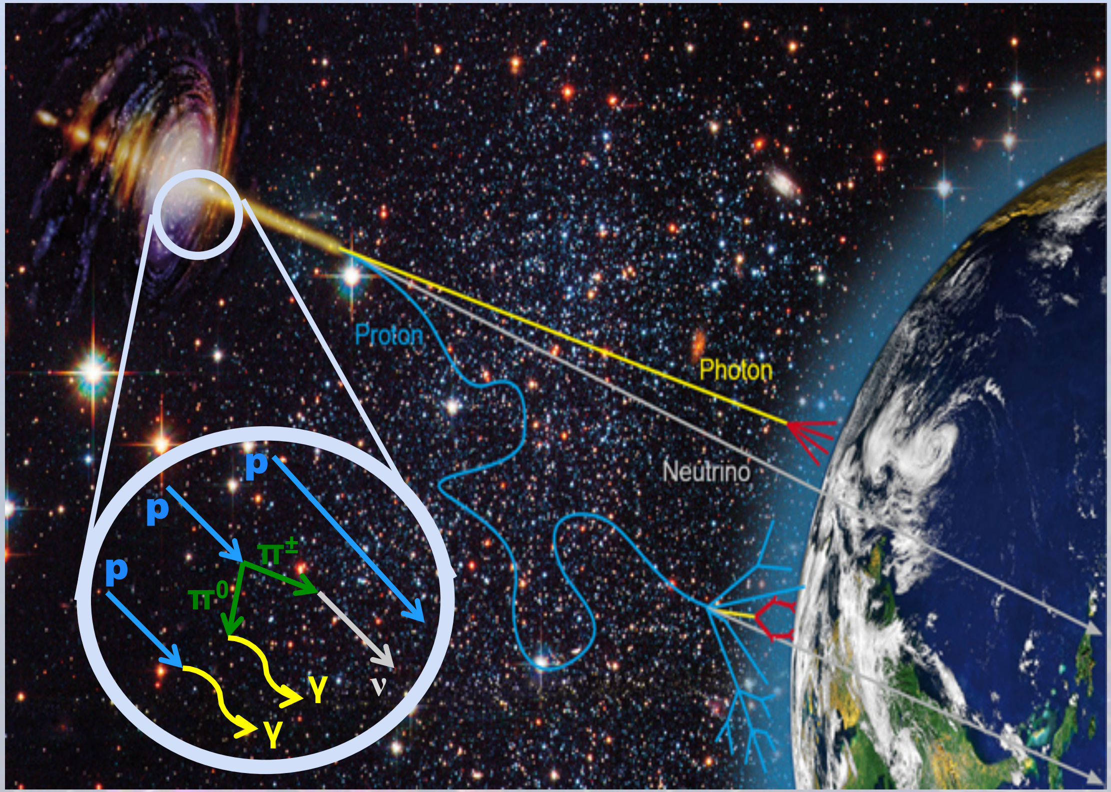
Outline

- Neutrino astronomy
- ANTARES detector
- Moon shadow effect
- Optimization of the event selection
- Moon shadow significance
- Estimation of angular resolution and absolute pointing

Neutrino astrophysics



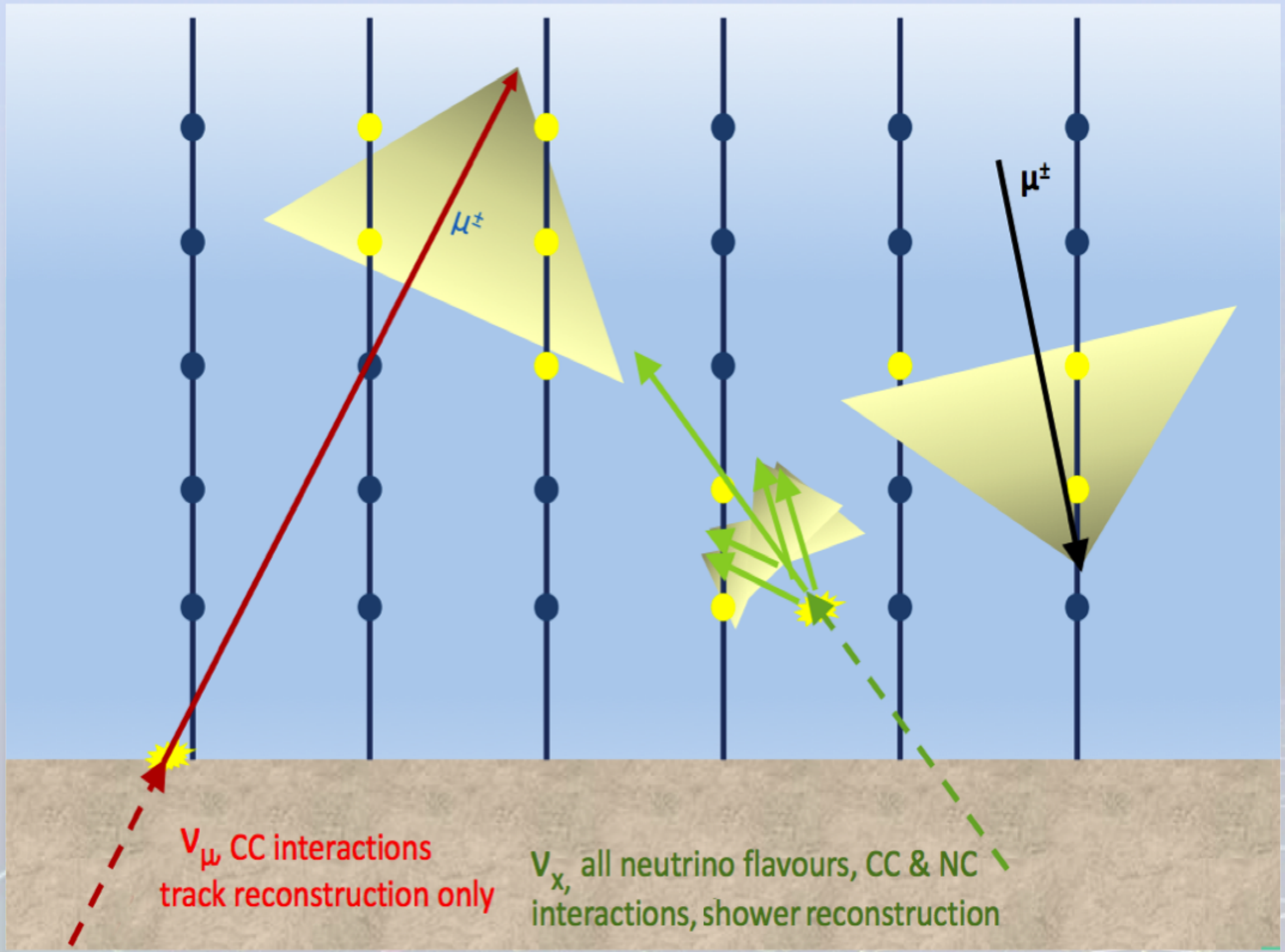
Charged Cosmic Rays
✔ Copiously produced
✘ Directions scrambled by magnetic fields

High Energy Gamma Rays
✔ Produced both by hadronic and leptonic mechanisms
✘ Absorbed on dust and radiation

UltraHigh Energy Cosmic Rays
✔ Not strongly deflected by magnetic field
✘ Limited by GZK cut-off

Neutrinos ✔ Not affected by magnetic fields and radiation, not absorbed by matter
✘ Very low interaction cross section

Neutrino detection principle

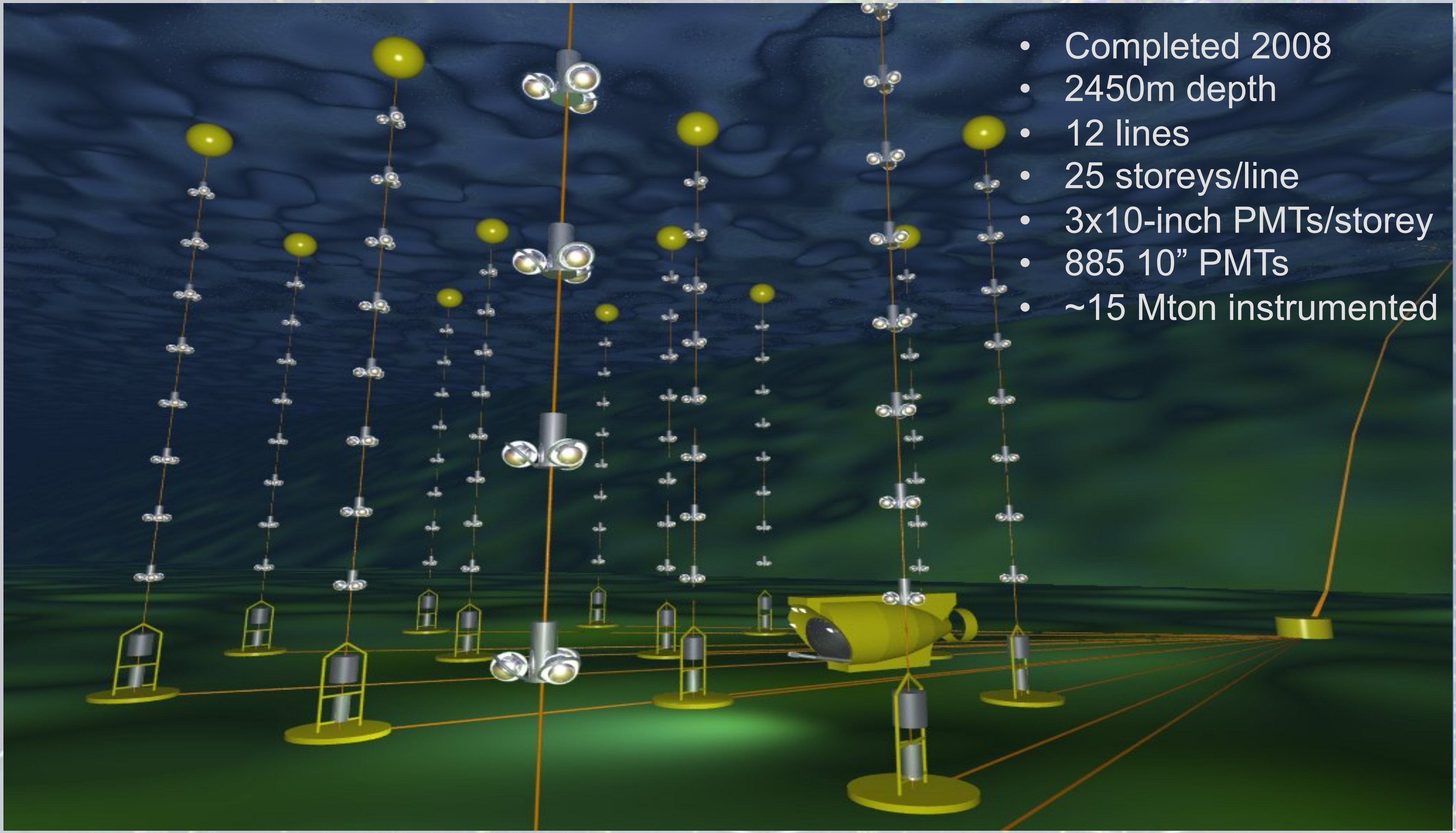


An array of PMT detects the Cherenkov light induced by the particles produced in the neutrino interaction

⇩

The measurement of position and time of the detected photon allows the reconstruction of the direction and the energy of the event

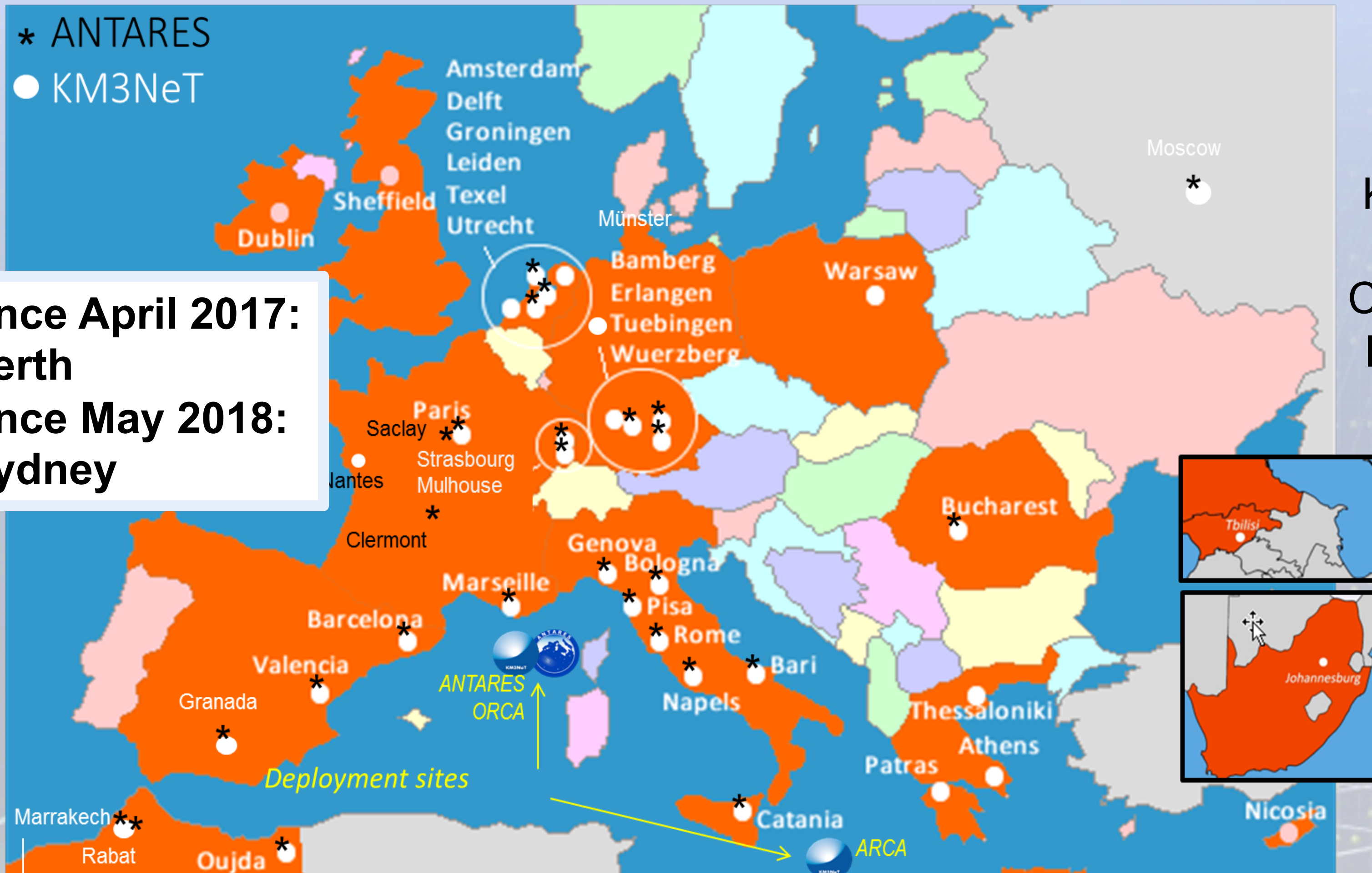
The ANTARES detector



- Completed 2008
- 2450m depth
- 12 lines
- 25 storeys/line
- 3x10-inch PMTs/storey
- 885 10” PMTs
- ~15 Mton instrumented

ANTARES & KM3NeT collaborations

- **since April 2017: Perth**
- **since May 2018: Sydney**



2 sites:
Toulon, FR
ANTARES
KM3NeT/ORCA

Capo Passero, IT
KM3NeT/ARCA

3d site
under study
(Pylos,GR)

~40 institutes
14 countries

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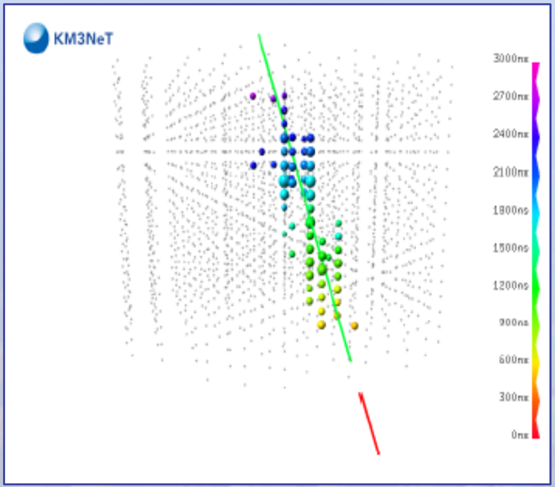
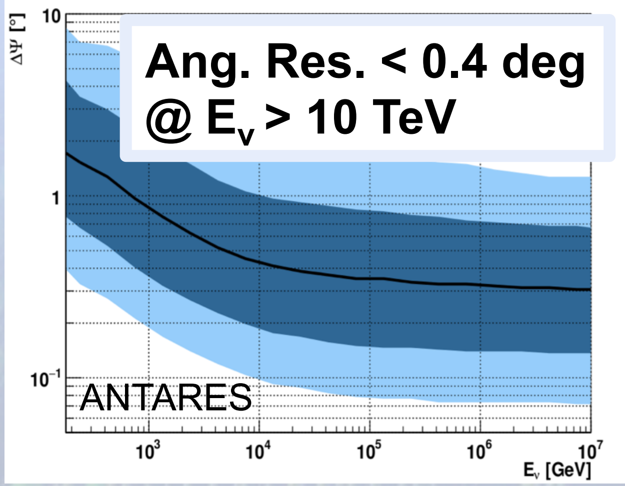
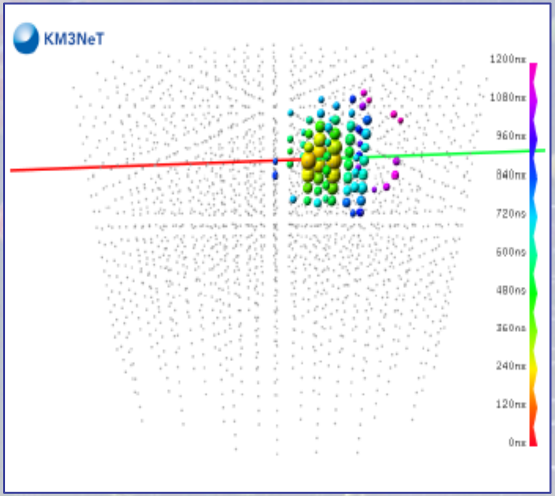
ANTARES neutrino angular resolution

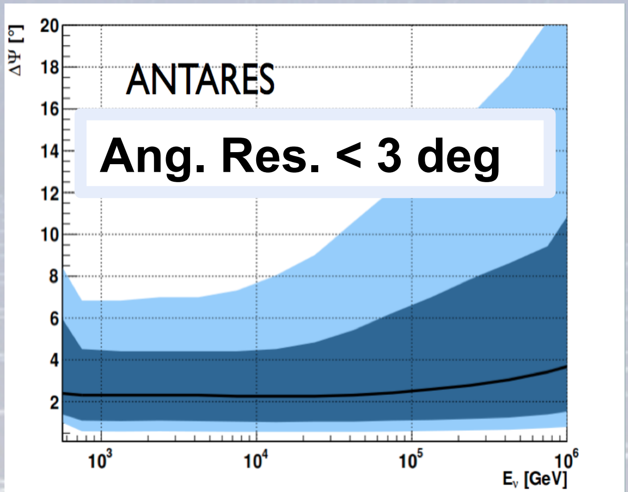
TRACKS:
ν_μ CC





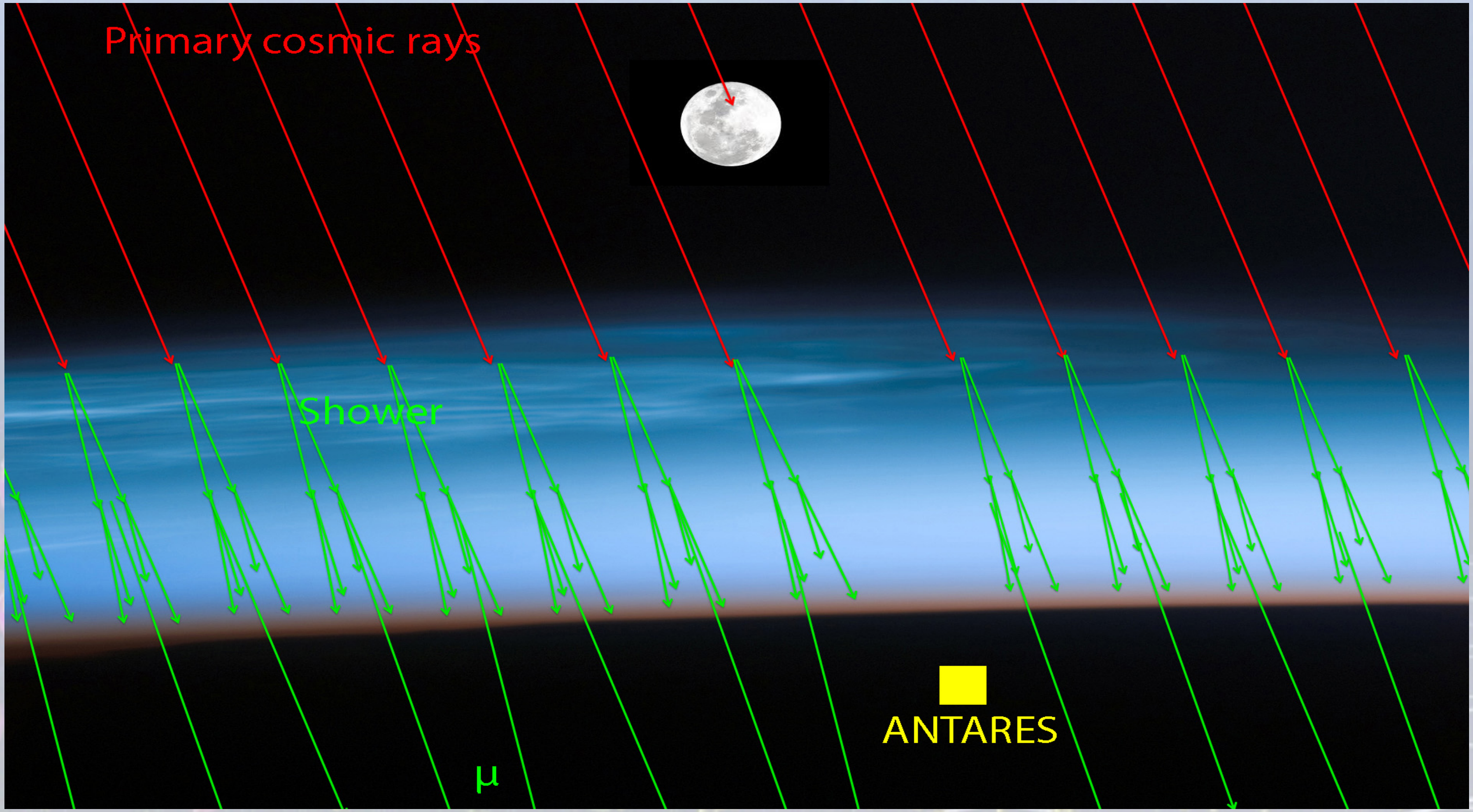
SHOWERS:
ν_e CC, ν_{all} NC





Moon shadow effect

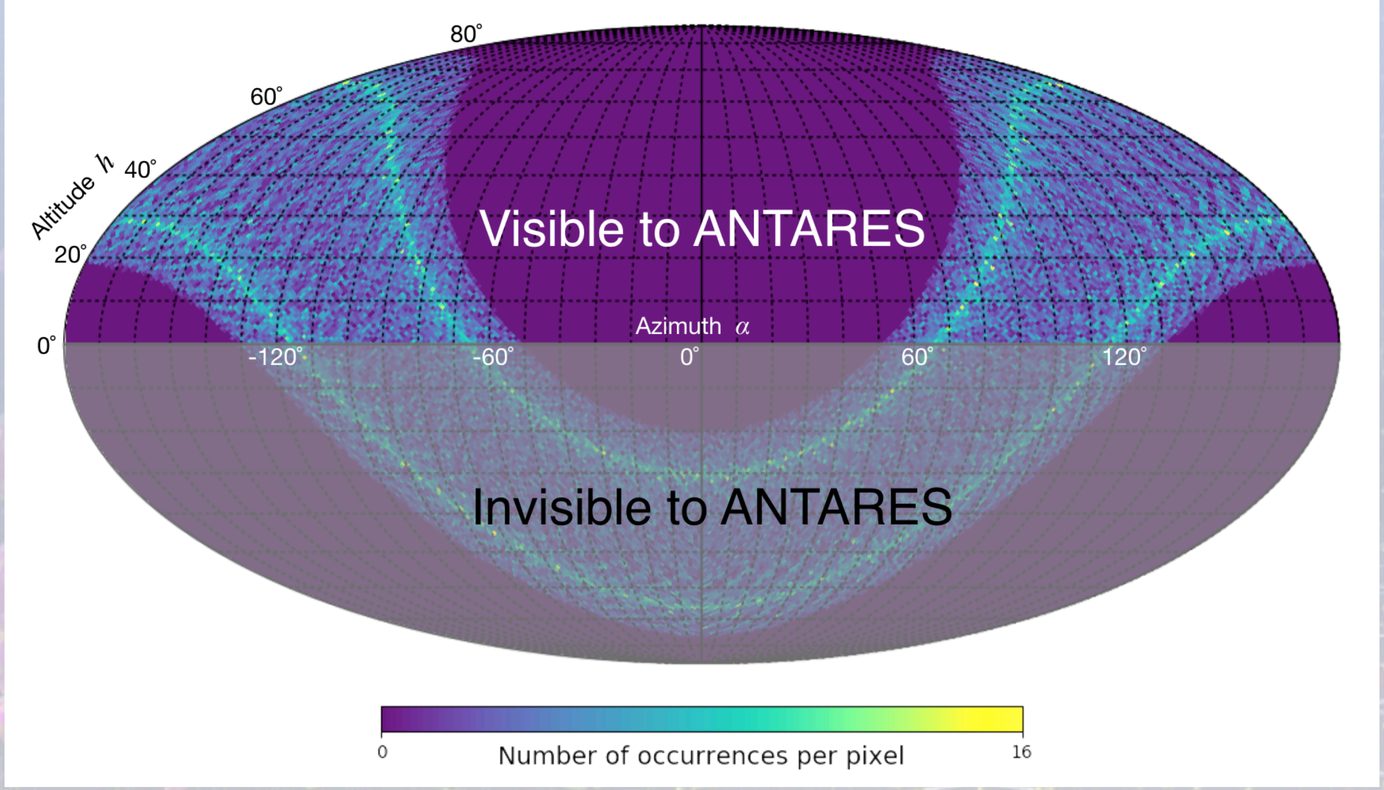
One possibility to measure the pointing accuracy is to analyse the shadow of the Moon, i.e. the deficit in the atmospheric muon flux in the direction of the Moon induced by absorption of cosmic rays.



Moon shadow effect

Data taking corresponding to years 2007-2016
Total live time: 3128 days

Moon position in the analysed period



Optimization of the event selection with Monte Carlo simulations

A dedicated Monte Carlo simulation has been developed.

It includes:

- Muon generation and propagation
- Cherenkov light stimulated by the muon and its propagation up to the PMT
- Optical background → bioluminescence and radioactive isotopes (mainly 40K) present in sea water
- Detector response
- Event reconstruction
- Computation of track quality parameters

Optimization of the event selection

Two different MC simulation sets are prepared:

- Considering the shadowing effect
- Without the shadowing effect

In the last one, the Moon shadow is obtained by removing the muons generated within the Moon disk.

For each of the two MC samples, a one dimensional histogram is built with the distribution of events as a function of the angular distance δ with respect to the Moon.

Optimization of the event selection

A test statistic is defined

$$\lambda = -2 \log \frac{L_{H_1}}{L_{H_0}}$$

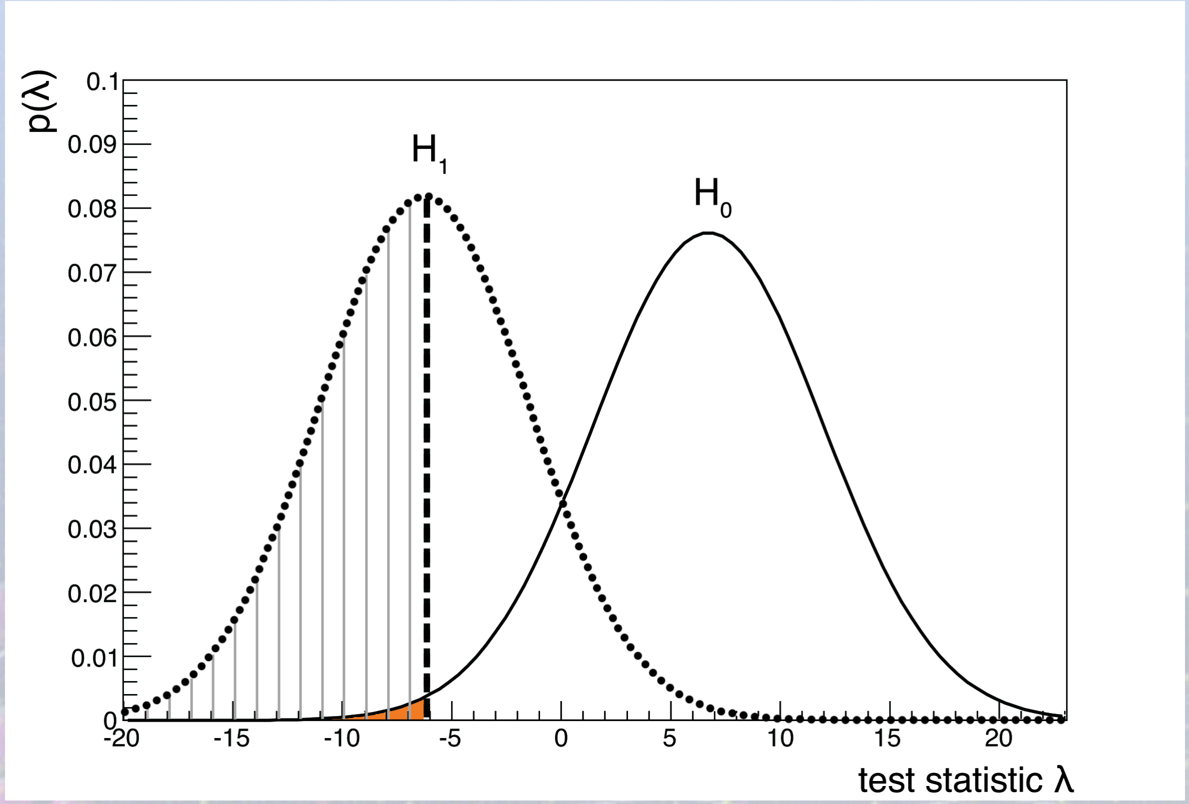
where L_{H0} and L_{H1} are the likelihoods obtained under the "No Moon shadow" hypothesis H_0 and "Moon shadow" H_1 hypothesis.

The distribution of λ assuming the two different hypotheses is obtained using10^6 pseudo-experiments.

Several hypothesis tests are performed assuming different selection criteria in order to derive the cuts that maximize the expected significance

Optimization of the event selection

Distribution of test statistic λ

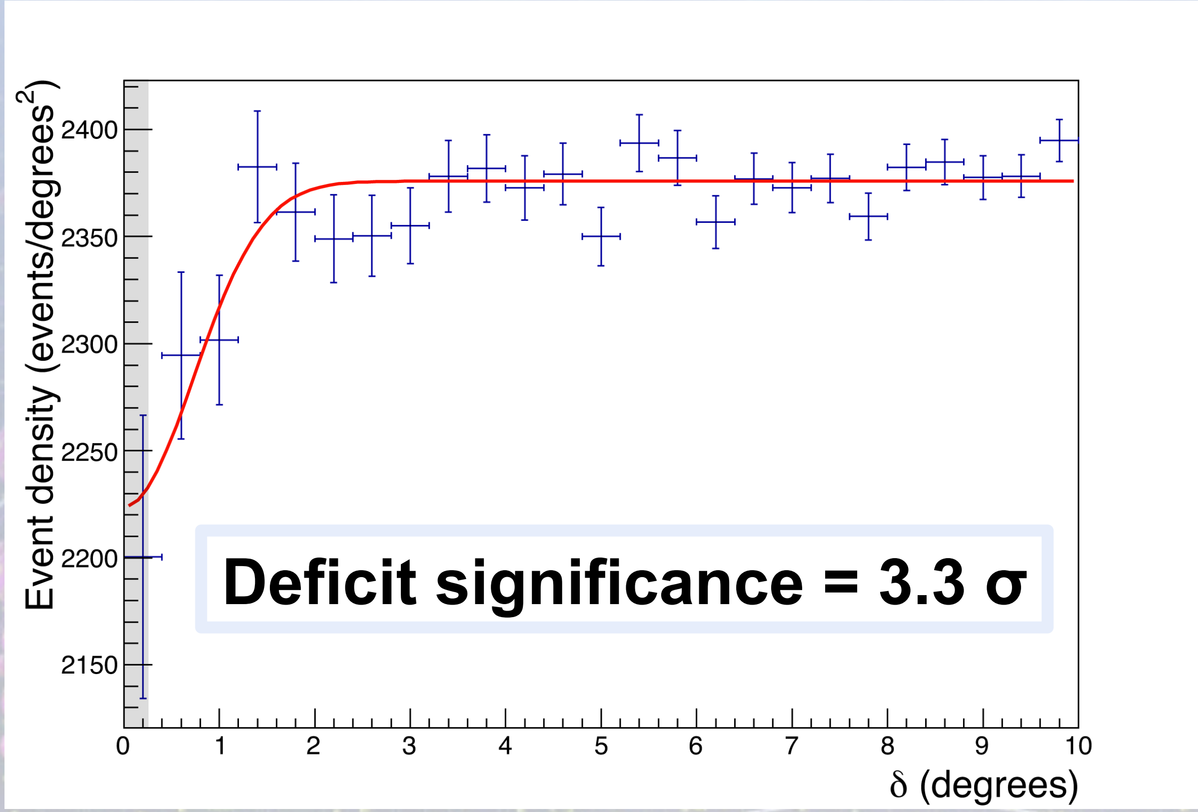


The filled-coloured area corresponds to an expected median significance of 3.4 σ for the Moon shadow effect

Moon shadow significance

The optimized quality cuts are applied to the data sample collected in the period 2007-2016

Event density vs. Angular distance



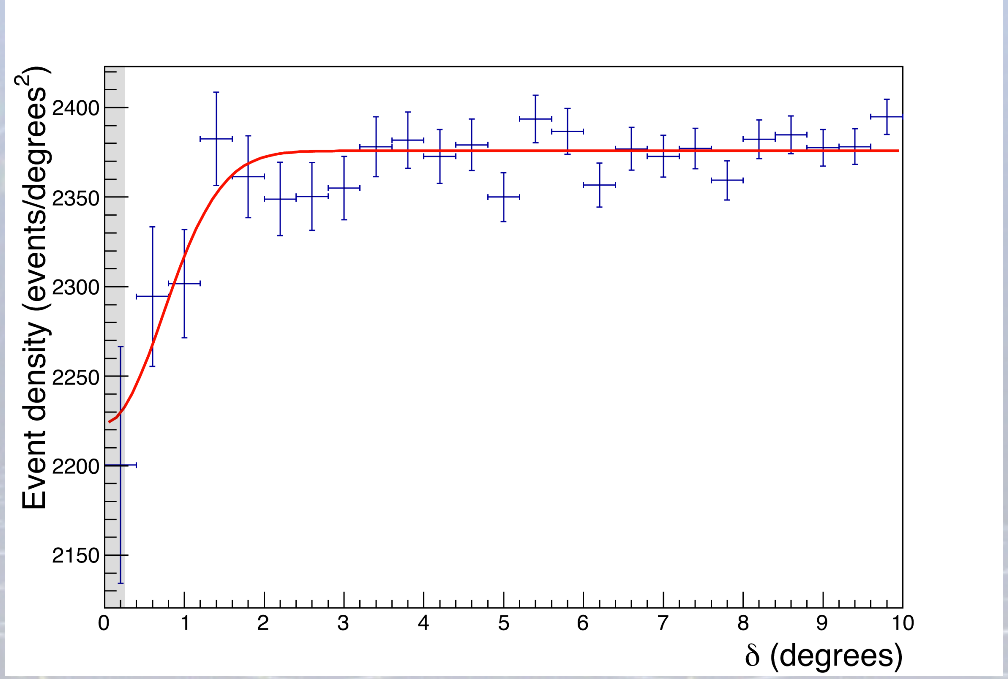
Angular resolution evaluation

The event distribution has been fitted to evaluate the angular resolution of the detector for downgoing muons

Fitted function

$$\frac{dn}{d\delta^2} = k\left(1 - \frac{R^2_{Moon}}{2\sigma^2_{res}} e^{-\frac{\delta^2}{2\sigma^2_{res}}}\right)$$

Angular resolution:
0.73°±0.14°



Absolute pointing

The selected events are subdivided in a grid of 0.2°×0.2° squared bins within the range [−10°,10°] in azimuth and zenith.

All possible absolute pointing displacements are considered within the field of view centred on the nominal position of the Moon.

The test statistic function

$$\lambda = -2 \log \frac{L_{H_1}}{L_{H_0}}$$

is computed, but H_1 hypothesis assumes the Moon shadow in a different bin of the field of view each time

Absolute pointing

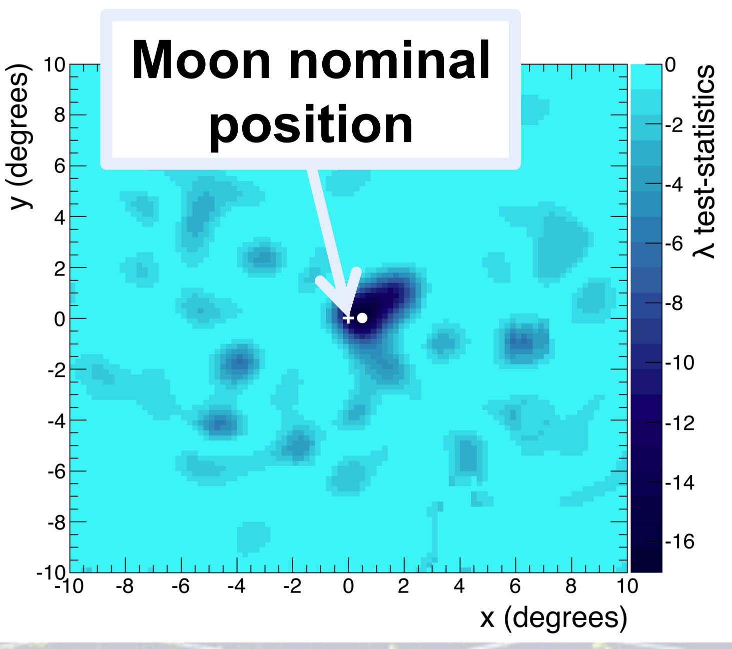
For each bin of the field of view the test statistic function λ is minimized fitting the function

$$\frac{A}{2\pi\sigma_{res}^2} e^{-\frac{(x-x_s)^2+(y-y_s)^2}{2\sigma_{res}^2}}$$

Value of λ for each bin in the FoV →

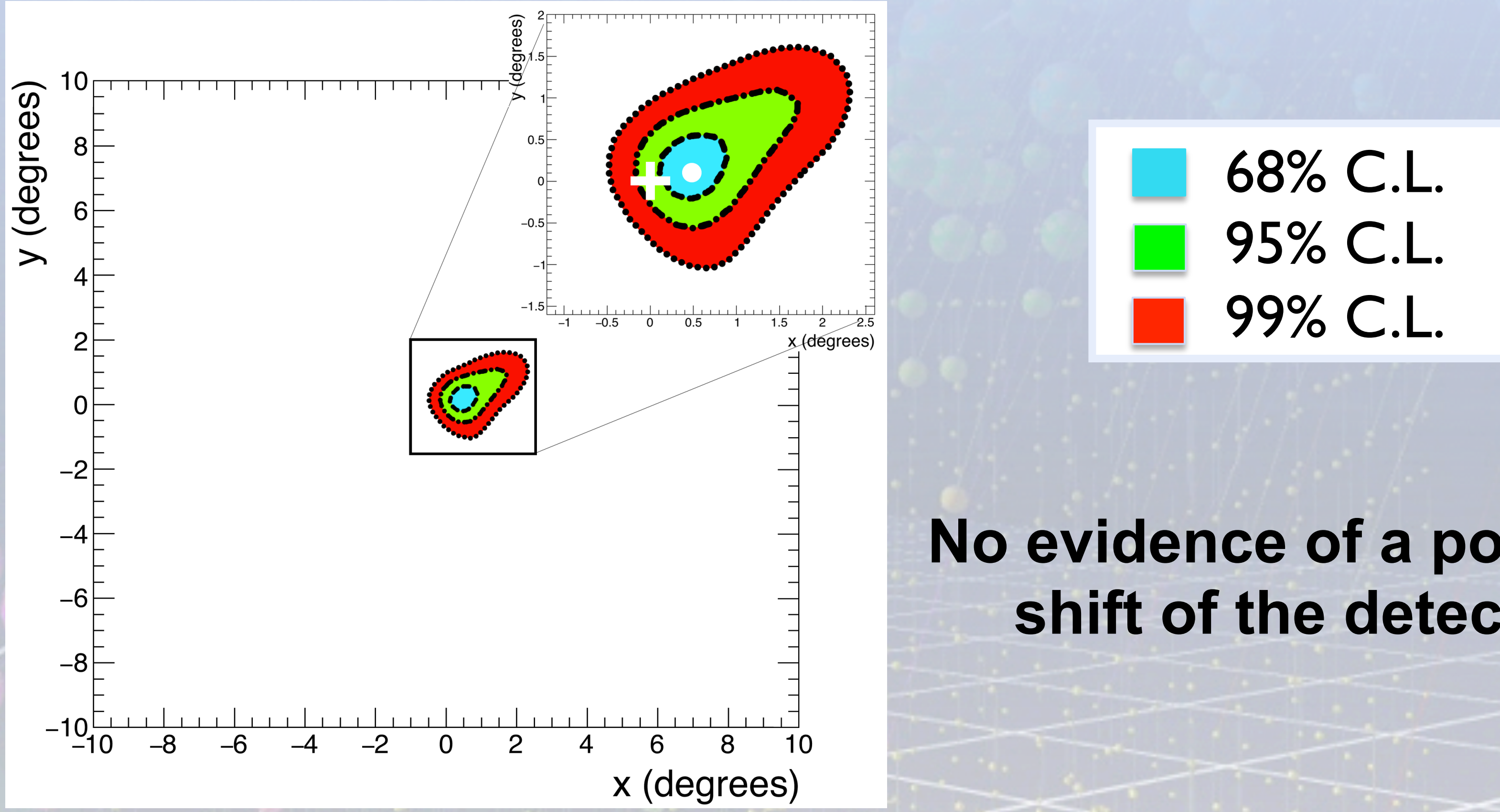
λ_{min} = -17.05
in the bin [0.5°,0.1°]

Moon shadow significance: 3.5 σ



Absolute pointing

The confidence region of the ANTARES absolute pointing for down-going muons can be derived from the λ distribution



No evidence of a pointing shift of the detector

Conclusion

- The angular resolution and the absolute pointing are fundamental for a neutrino telescope
- The Moon shadow effect has been exploited to evaluate the pointing performance of ANTARES
- The 2007-2016 ANTARES data have been analysed (arXiv:1807.11815, submitted to EPJC)
- Moon shadow significance: 3.5 σ
- Angular resolution for down-going muons = 0.7°
- No evidence of pointing shift
- Sun shadow analysis is on-going