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

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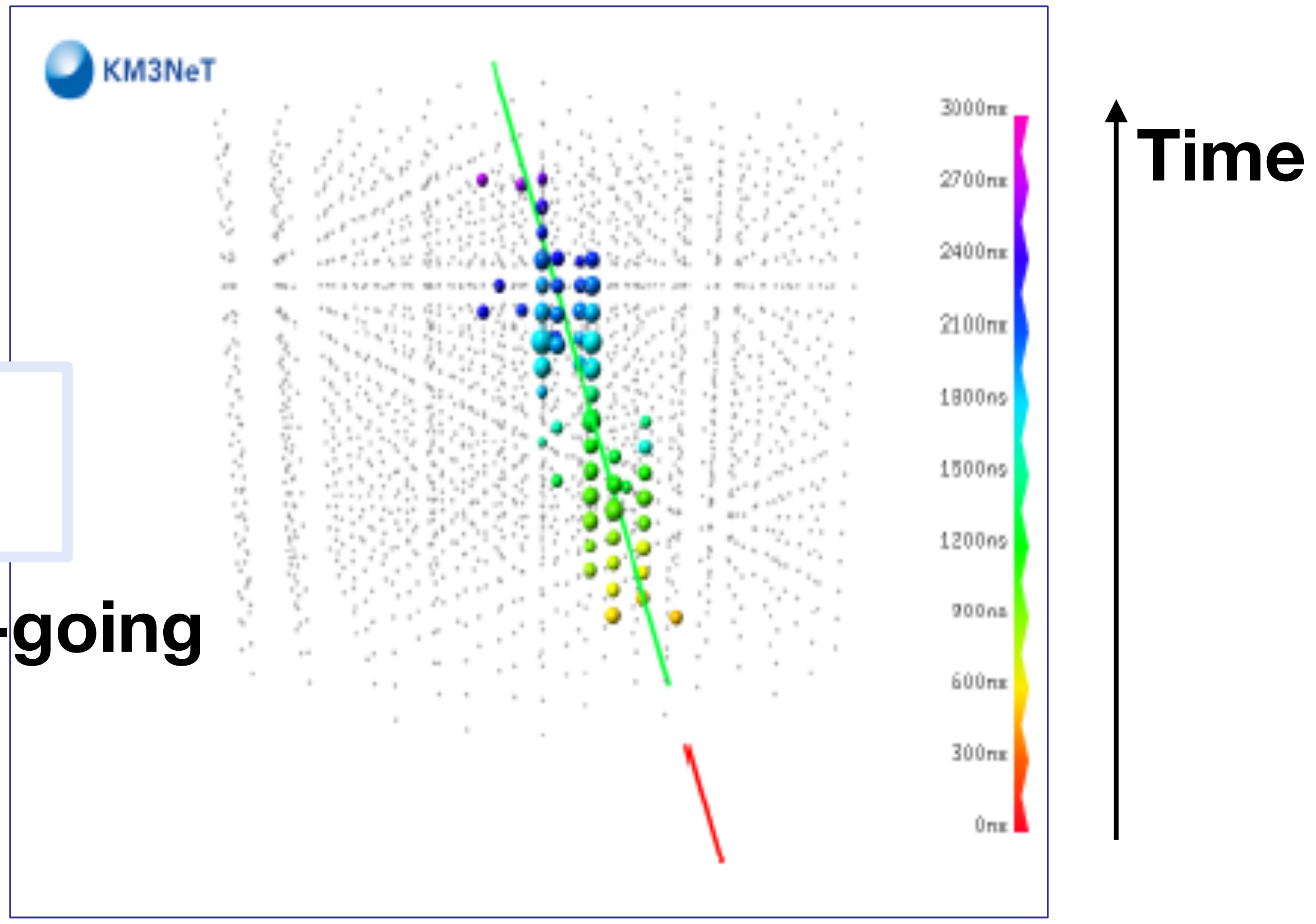
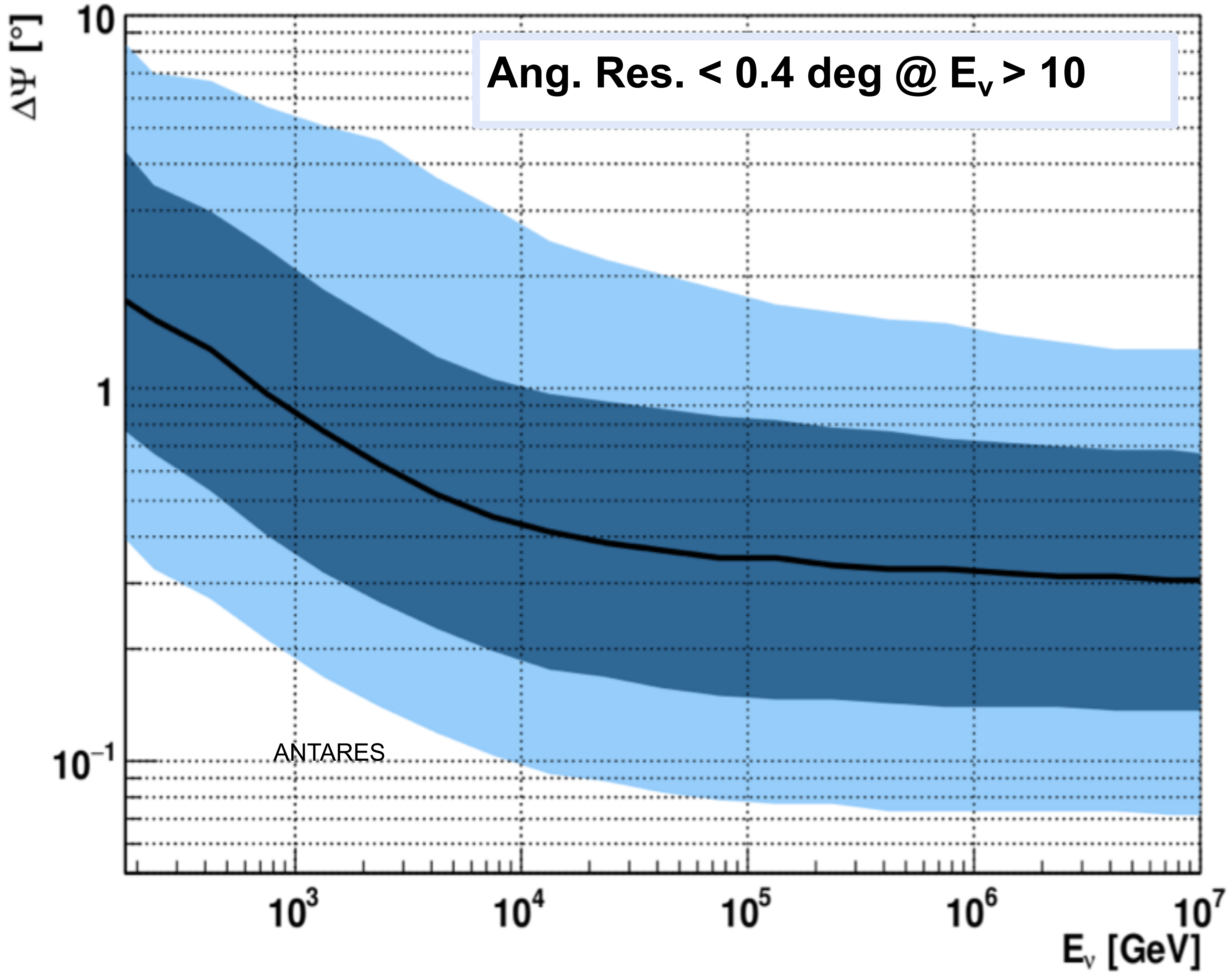
- Running since 2007
- 885 10” PMTs
- 12 lines
- 25 storeys/line
- 3 PMTs / storey
- 0.05 km³ instr. vol.

Refer to A. Kouchner’s general talk

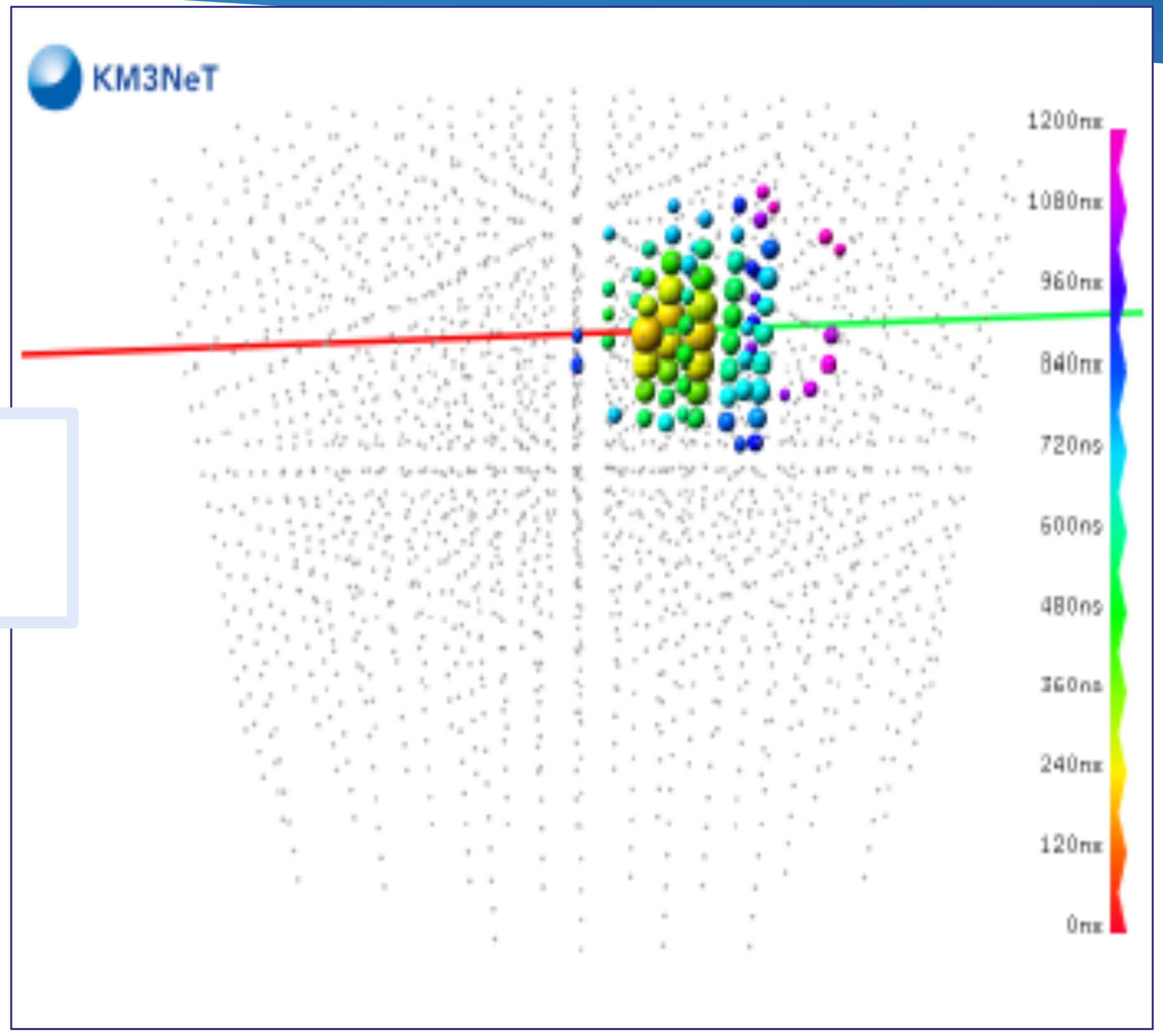
TRACKS:
ν_μ CC

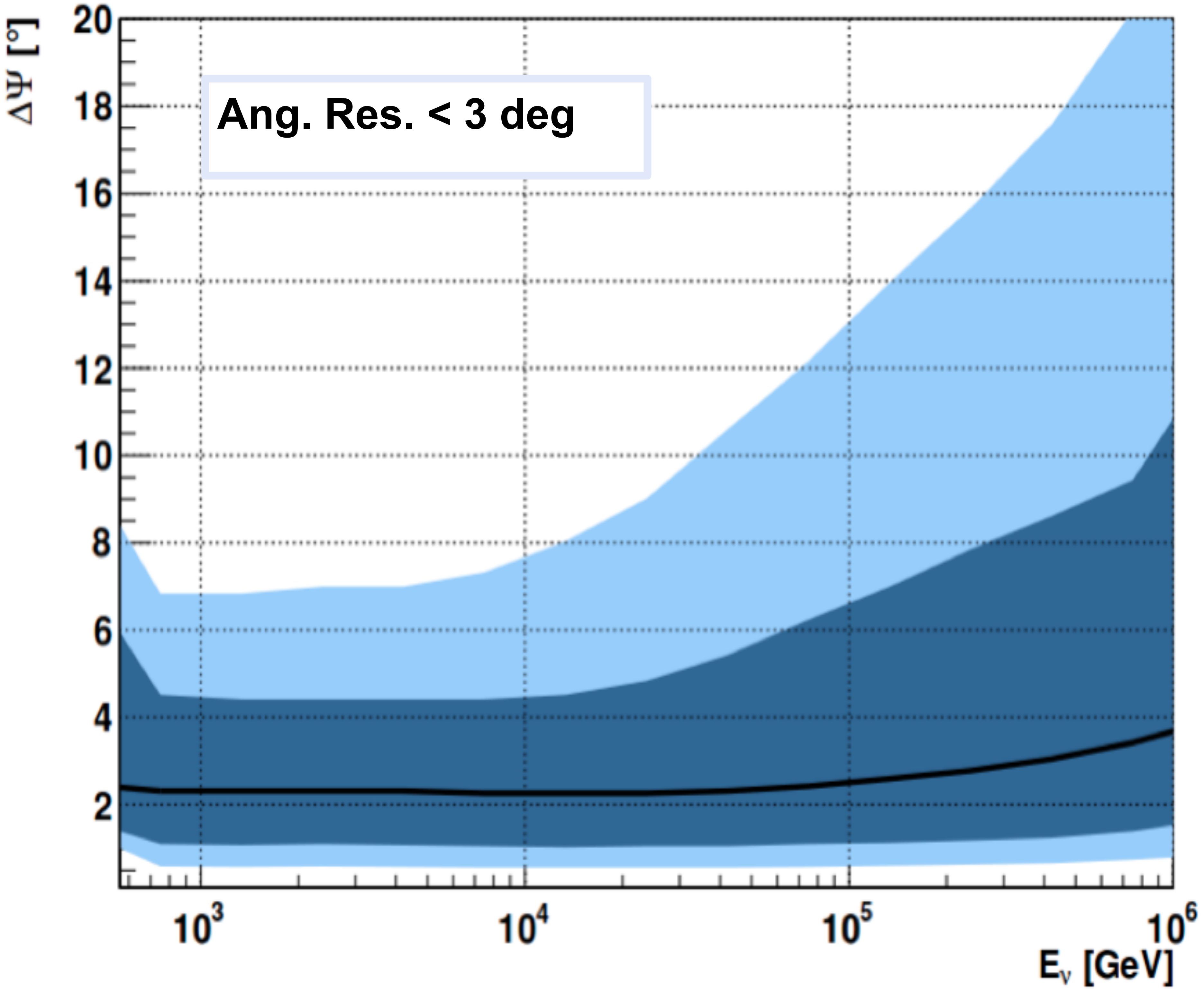
Essentially upward-going





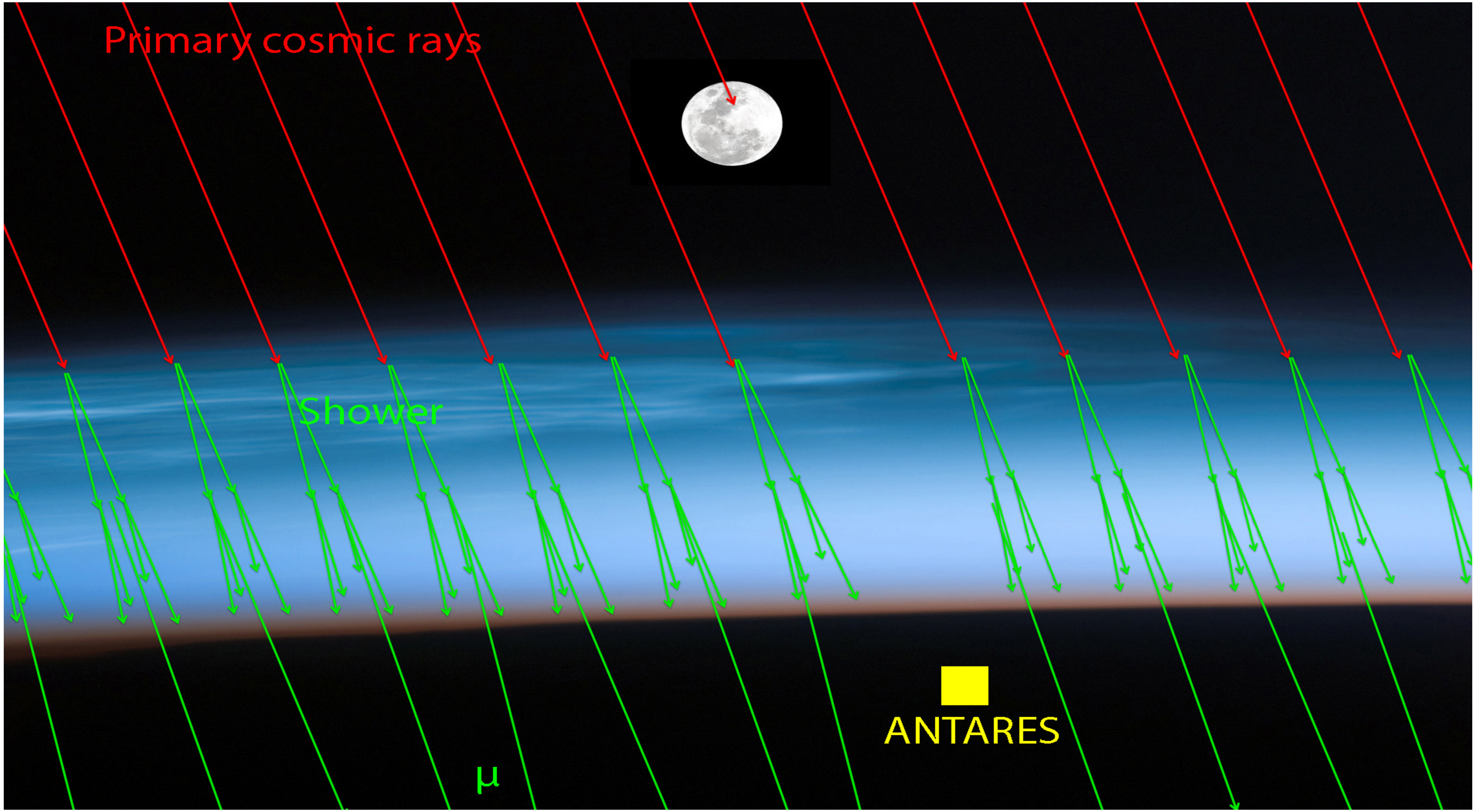
SHOWERS:
ν_e CC, ν_{all} NC





Exploiting the Moon Shadow:

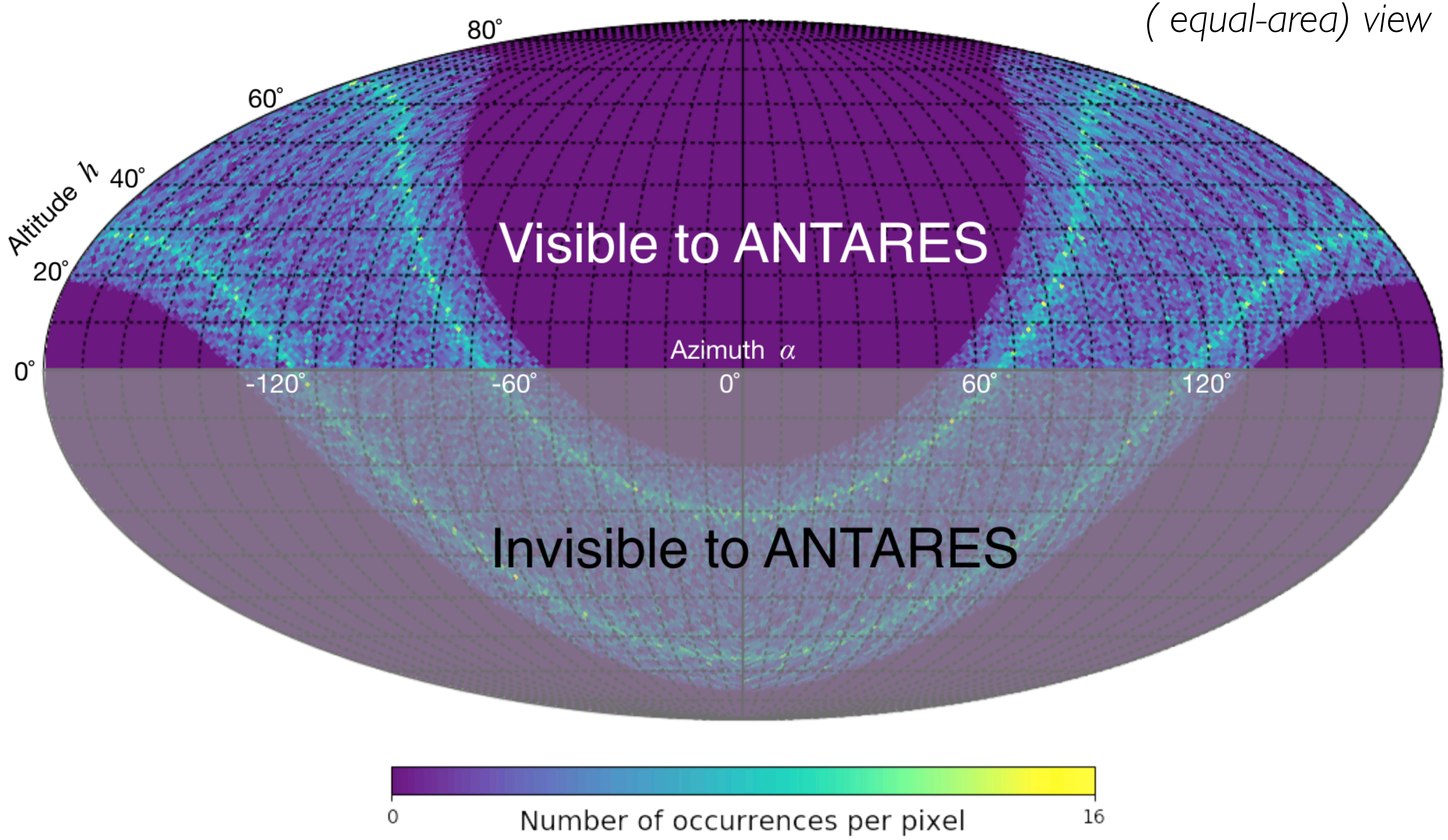
deficit in the atmospheric muon flux in the direction of the Moon induced by absorption of cosmic rays.



Note: down-going tracks!

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

Mollweide horizontal coordinates (equal-area) view



The dedicated MC:

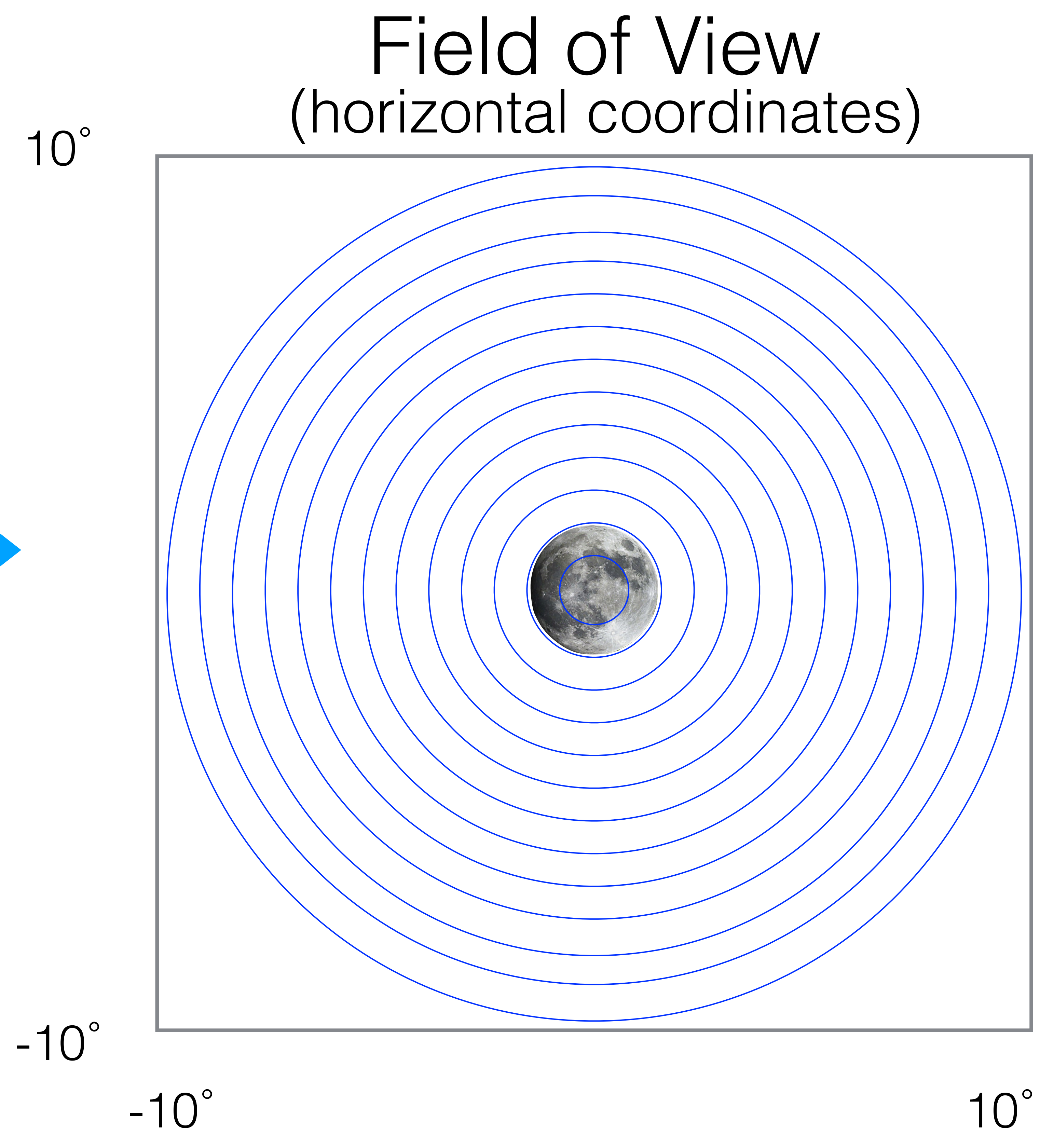
- Run by Run approach.
- Muon generation and propagation.
- Cherenkov light stimulated by the muon and its propagation up to the PMT.
- Optical background ⇒ bioluminescence and radioactive isotopes (mainly ^{40}K) present in sea water.
- Detector response.
- Event reconstruction.
- Computation of track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

Two different *Run-by-Run* MC simulation sets are prepared:

- Without the shadowing effect;
- Considering the shadowing effect (removing the muons generated within the Moon disk).

1-D histogram for each of the two MC samples:

distribution of events as a function of the angular distance δ with respect to the Moon.



- Detailed Run-by-Run MC within the FoV
- Coarser Run-by-Run MC for larger area

The used **test-statistics**

H_0= No Moon

$$\lambda = -2\log\frac{L_{H_1}}{L_{H_0}} = 2\sum_{i=ring}\left[\mu_i - \nu_i + n_i \ln\frac{\nu_i}{\mu_i}\right]$$

H_{1}=Moon

10^6 **pseudo-experiments** **assuming different selection criteria**

Fixed power of the test (defining the critical region)

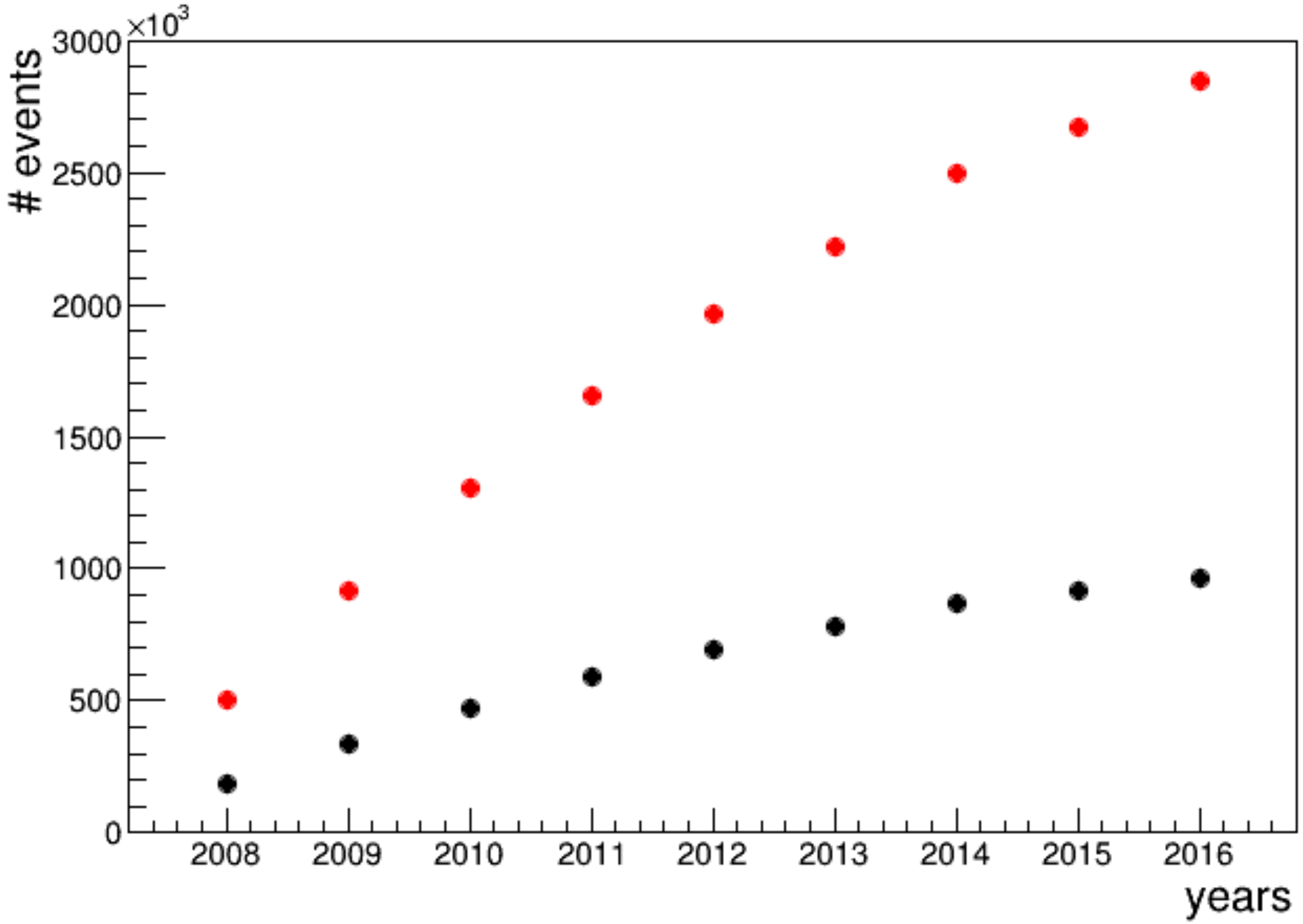
α size of the test

Optimal cuts for the largest expected significance

$\lambda_{cut} = -6.15$

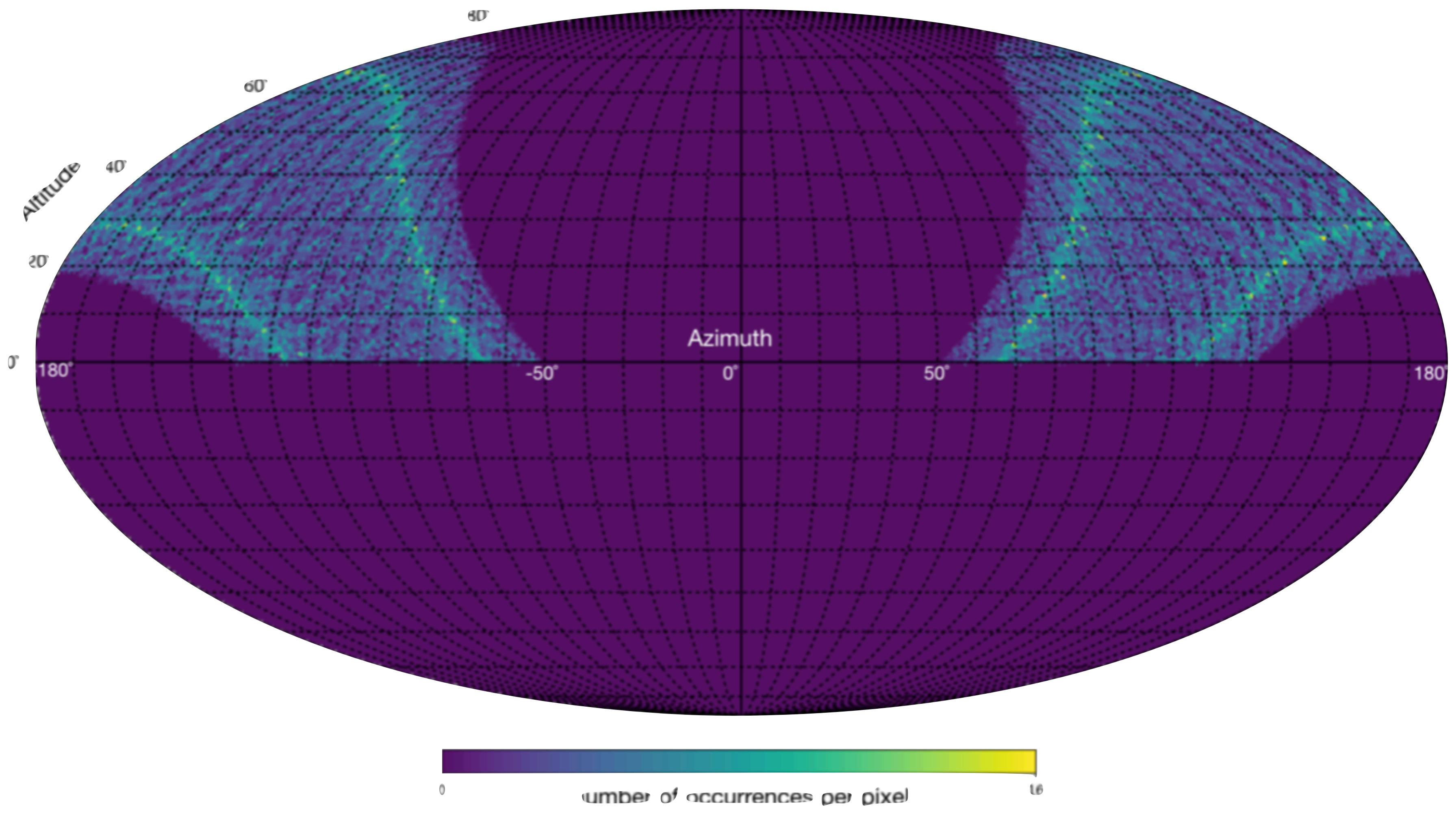
$\alpha = 3.6\times10^{-4}$

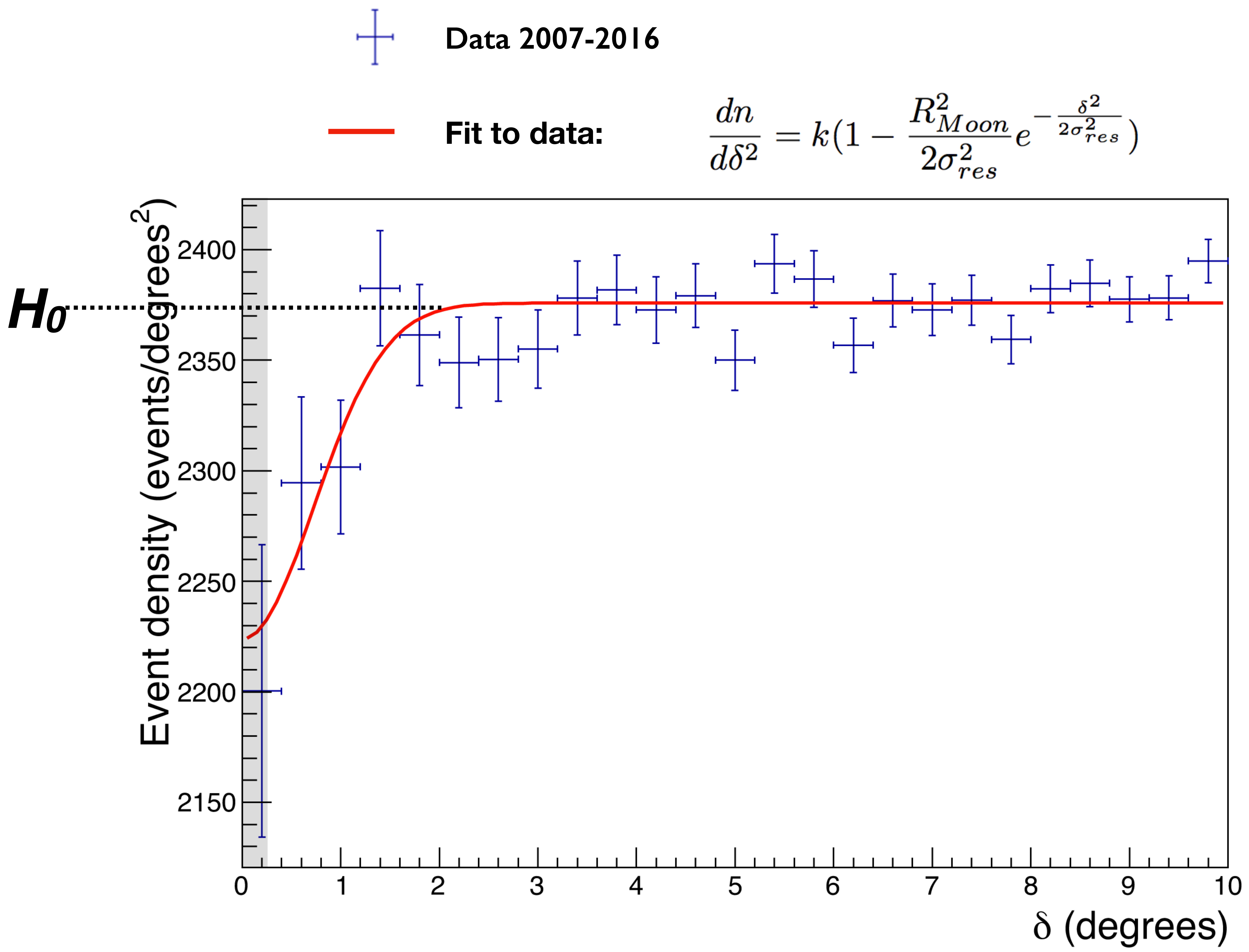
expected significance = 3.4 σ



● All reconstructed data (no cuts: ~**2x10⁶** events)

● Selected reconstructed data (after quality cuts: ~ **9.7x10⁵** events)





Fit constraint: $R_{Moon} = 0.26^\circ$

Fitted value: angular resolution for down-going muons

$$\sigma_{res} = 0.73^\circ \pm 0.14^\circ$$

Deficit significance = 3.3 σ

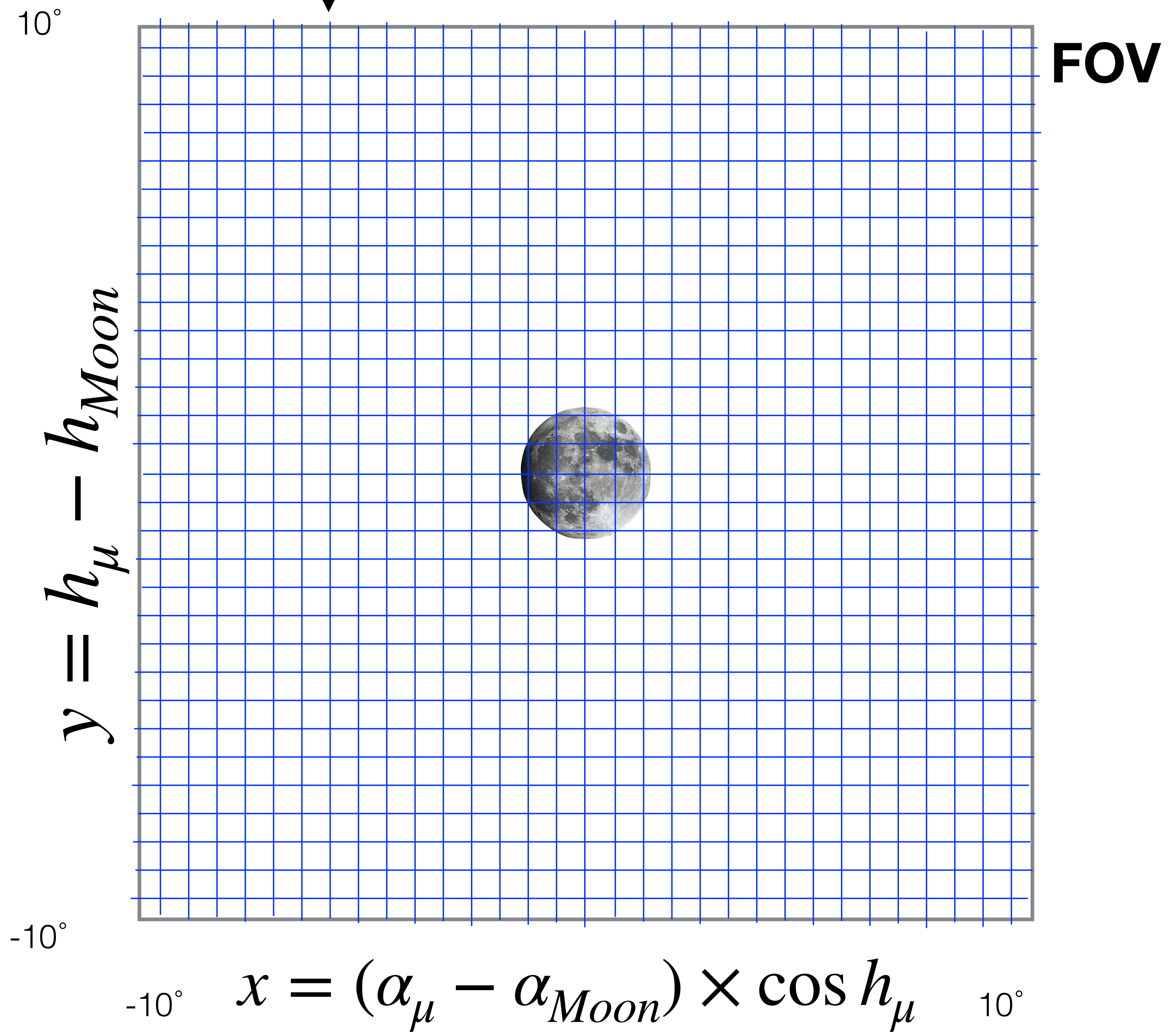
Again, *the same* ***test-statistics***

$$\lambda = -2\log\frac{L_{H_1}}{L_{H_0}} = 2\sum_{i=bin}\left[\mu_i - \nu_i + n_i \ln\frac{\nu_i}{\mu_i}\right]$$

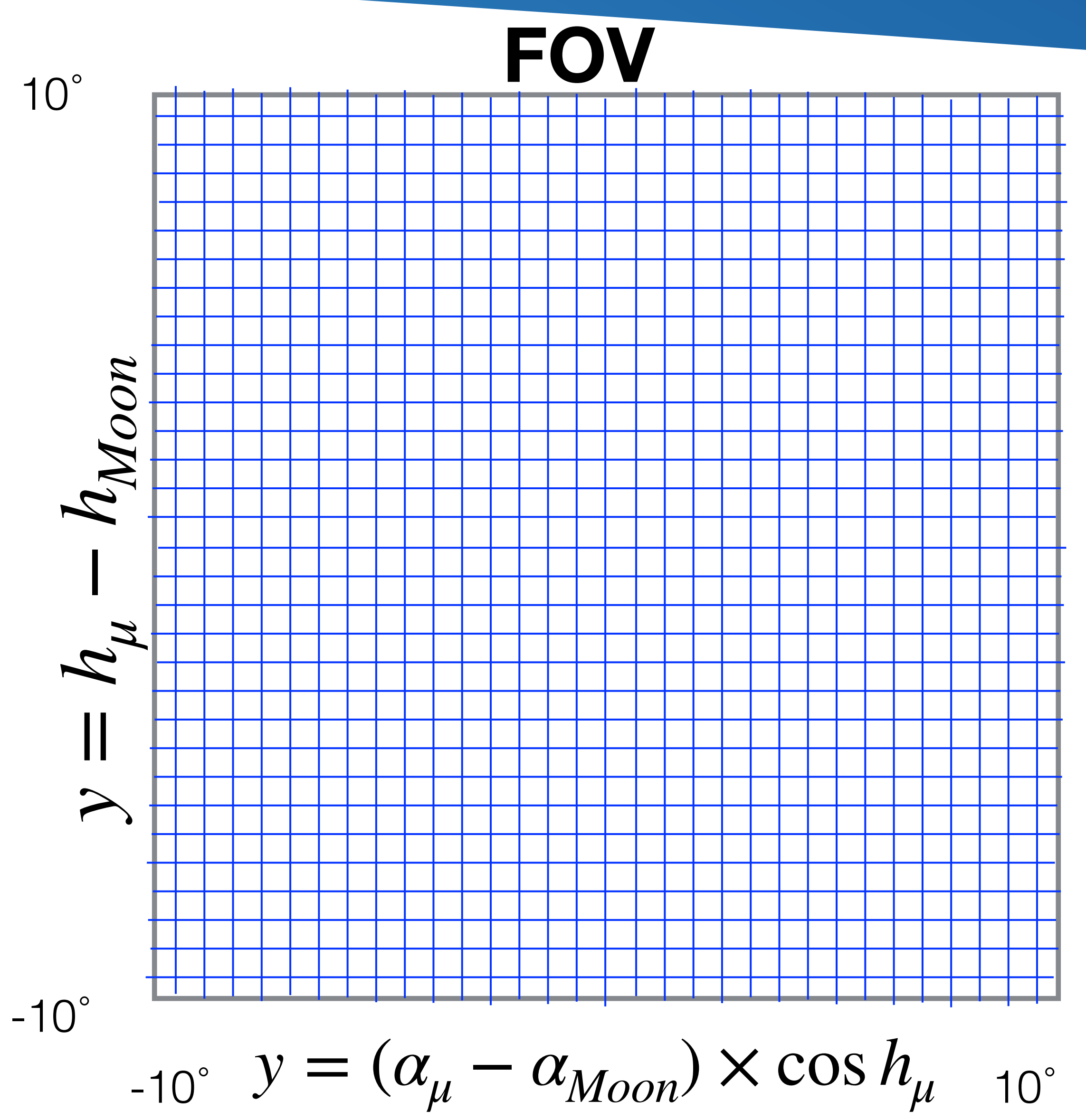
H_0= No Moon

H_1=Moon

Real data measurements



H_0 PDF: $p_2(x,y)$, off zone: **4h after** the Moon



$$p_2(x, y, \overrightarrow{k} \,|\, H_0) = k_0 + k_1 x + k_2 x^2 + k_3 y + k_4 y^2$$

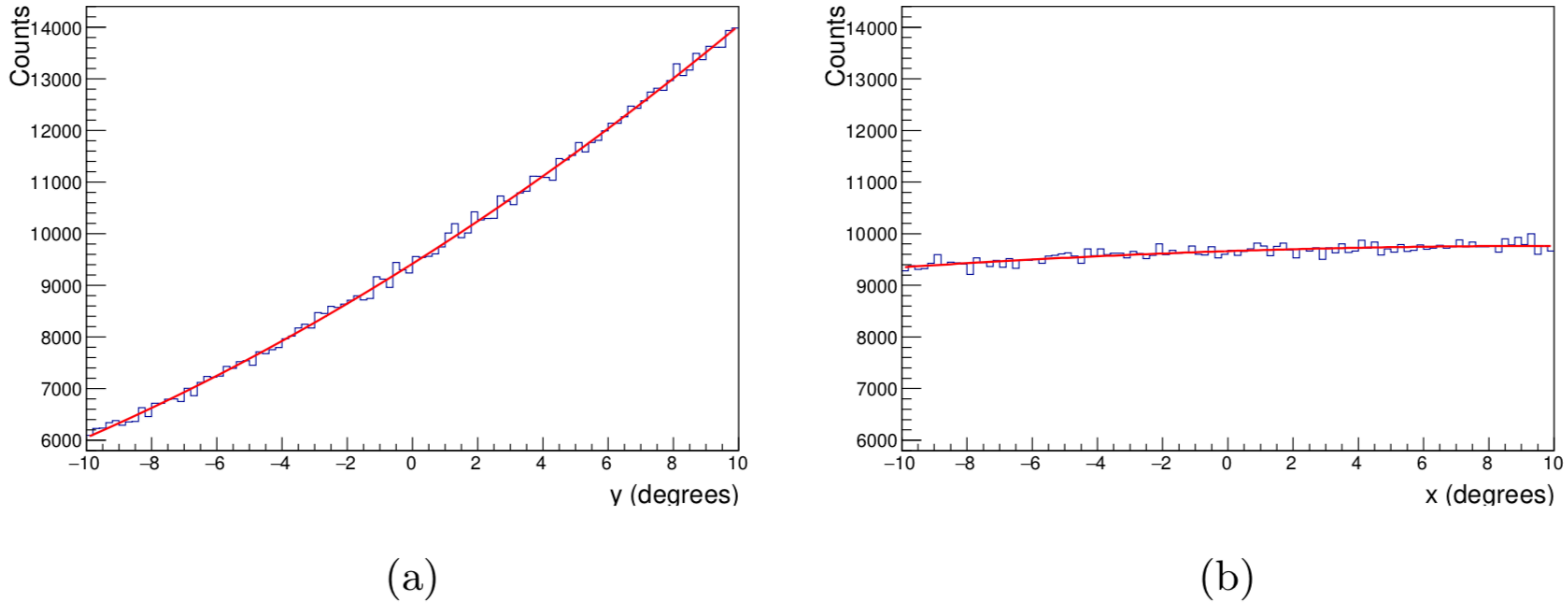
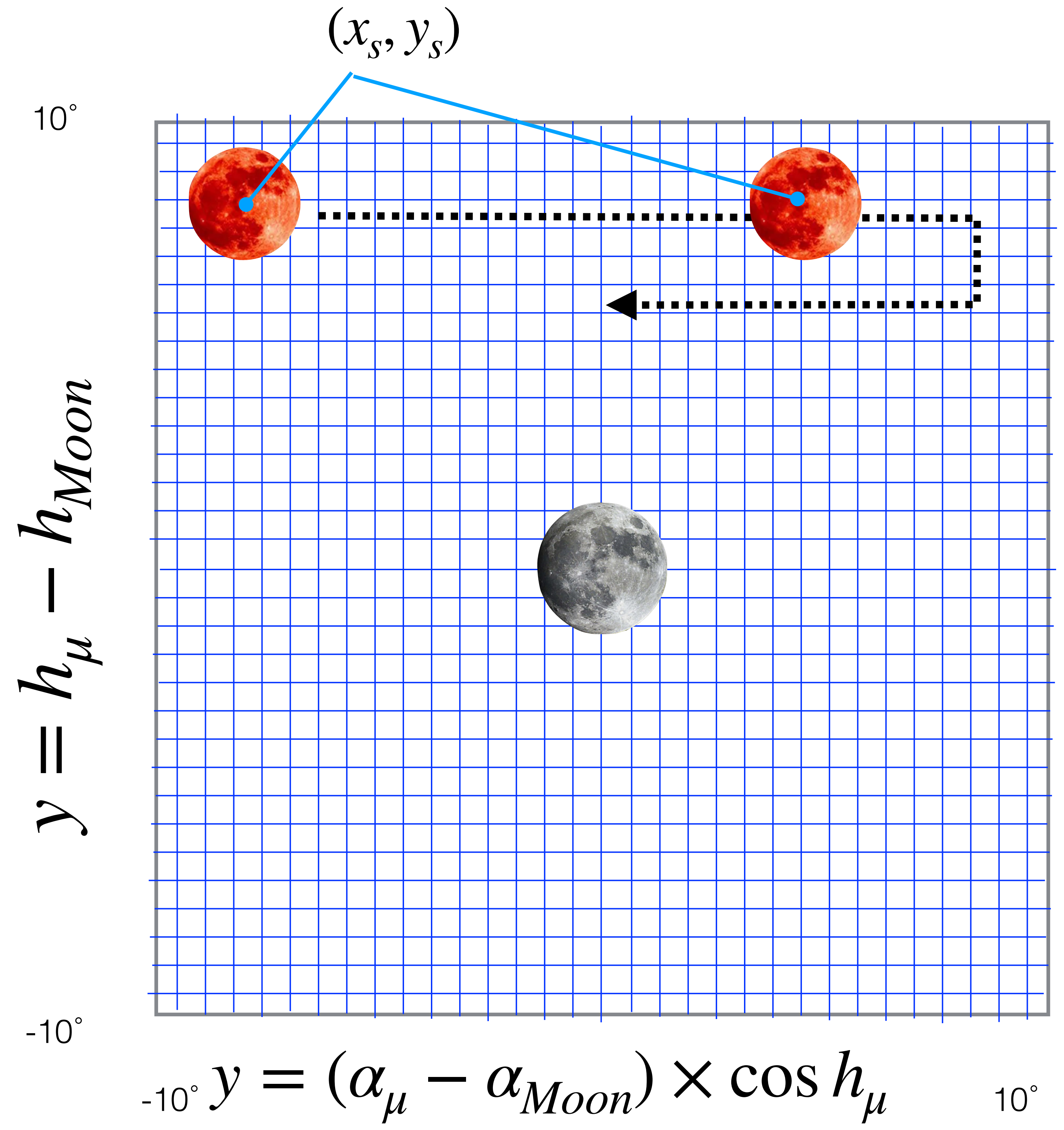


Figure 4: Marginalisation of the measured 2-D event distributions, in absence of the Moon (H_0), for the Field of View coordinates $x = \delta\alpha \times \cos h_\mu$ and $y = h_\mu - h_{\text{Moon}}$.

H_1 PDF: $p_2(x, y, \vec{k} \,|\, H_0) - \frac{A_M}{2\pi\sigma_{res}^2} e^{-\frac{(x-x_s)^2+(y-y_s)^2}{2\sigma_{res}^2}}$

Free parameter

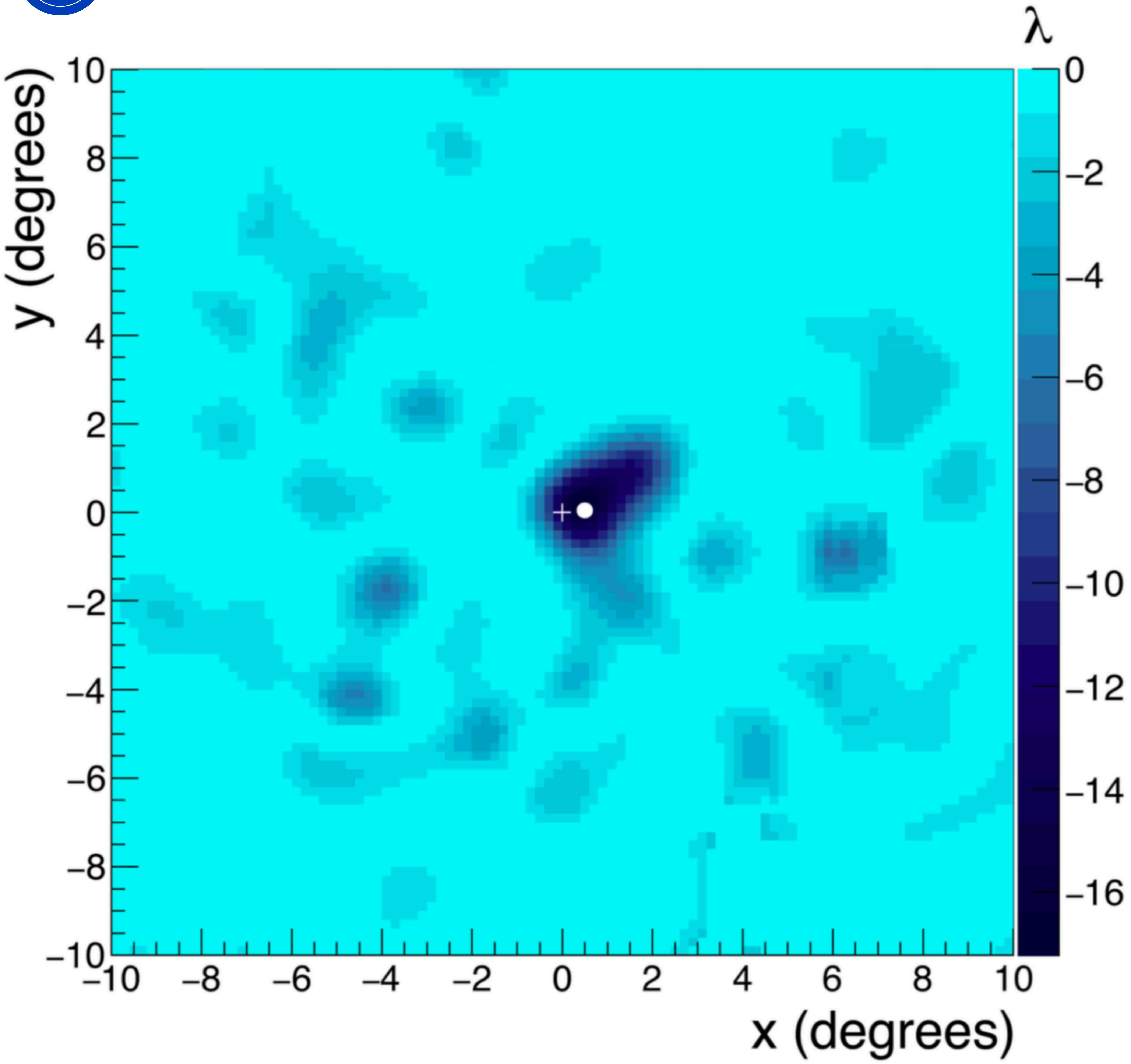
fixed from 1-D analysis $\sigma_{res} = 0.73^{\circ} \pm 0.14^{\circ}$



Assumed the Moon in a given bin (x_s,y_s), λ_{best} is computed optimising A_M .

By varying the assumption on the Moon position, it is possible to build a λ_{best} map across the FOV

… see next slide…



Best position: (+0.5,+0.1)

λ_{min} =−17.05

A_M =20.3 ±5.0

Nominal position: (0,0)

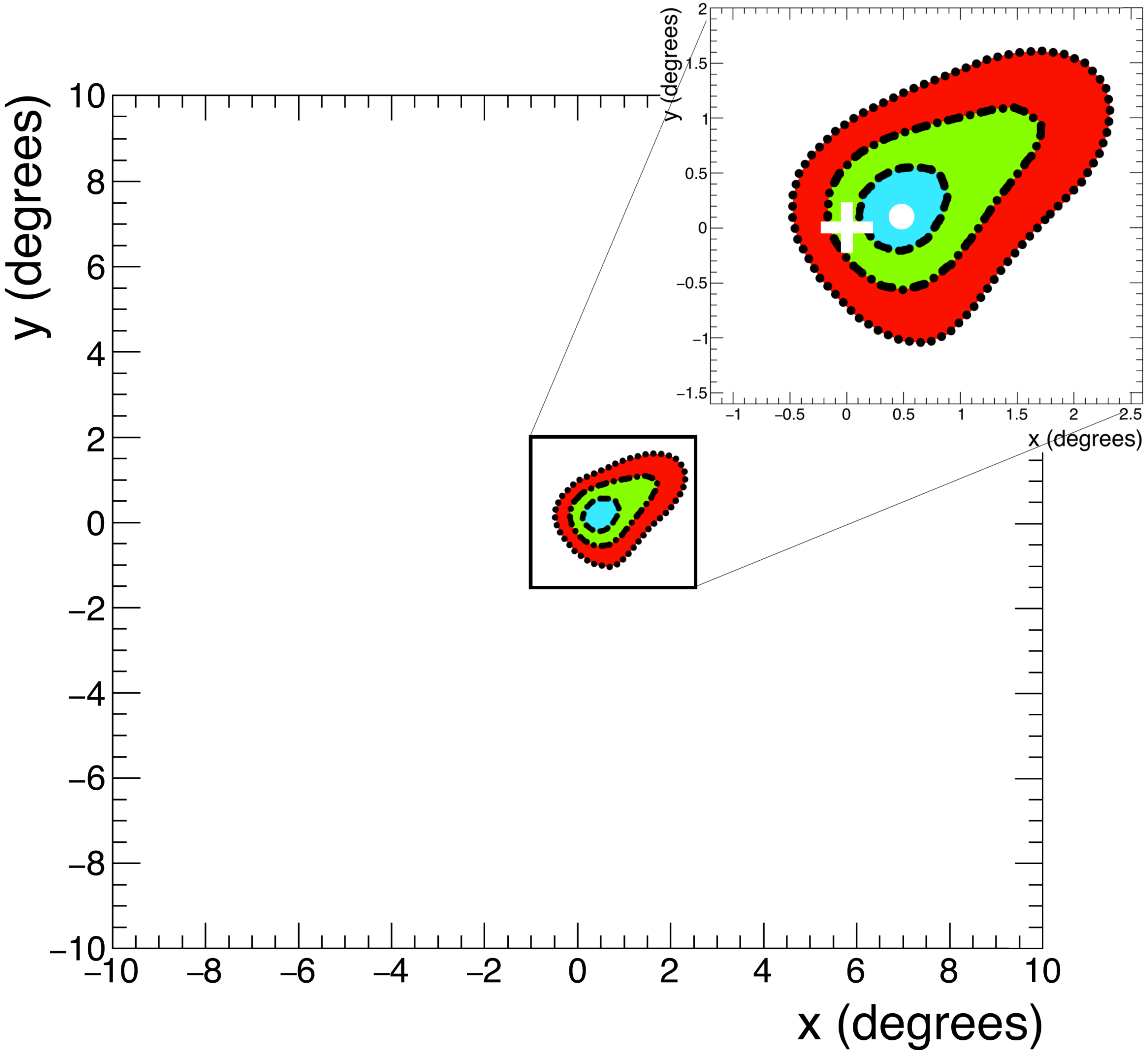
λ_{nom} =−13.37

A_M =19.0 ±5.0

Fixed the grid-bin, the λ PDF→ χ^2(1 dof)

⇓

Significane of Moon 3.5 **σ**



- 68,27% C.L.
- 95,45% C.L.
- 99,73% C.L.

P-value of the shift: 0.23.
A statistical fluctuation.

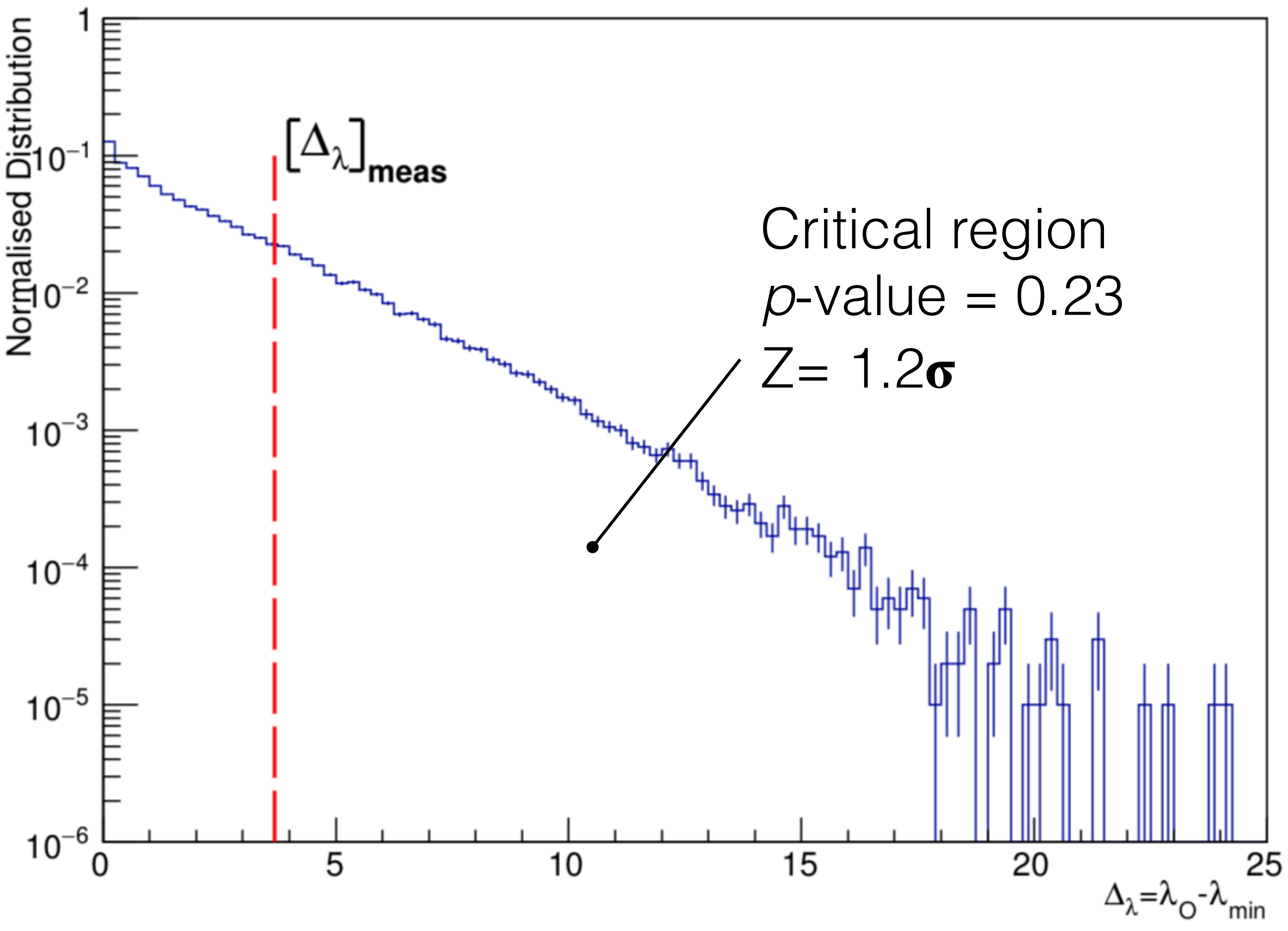
- The angular resolution and the absolute pointing are fundamental for a neutrino telescope
- The Moon shadow effect has been exploited to evaluate the pointing performance of ANTARES
- The 2007-2016 ANTARES data have been analysed (arXiv:1807.11815, submitted to EPJC)
- Moon shadow significance: 3.5
- Angular resolution for down-going muons = 0.73° ± 0.14°
- No evidence of pointing shift
- Sun shadow analysis is on-going

SPARE SLIDES

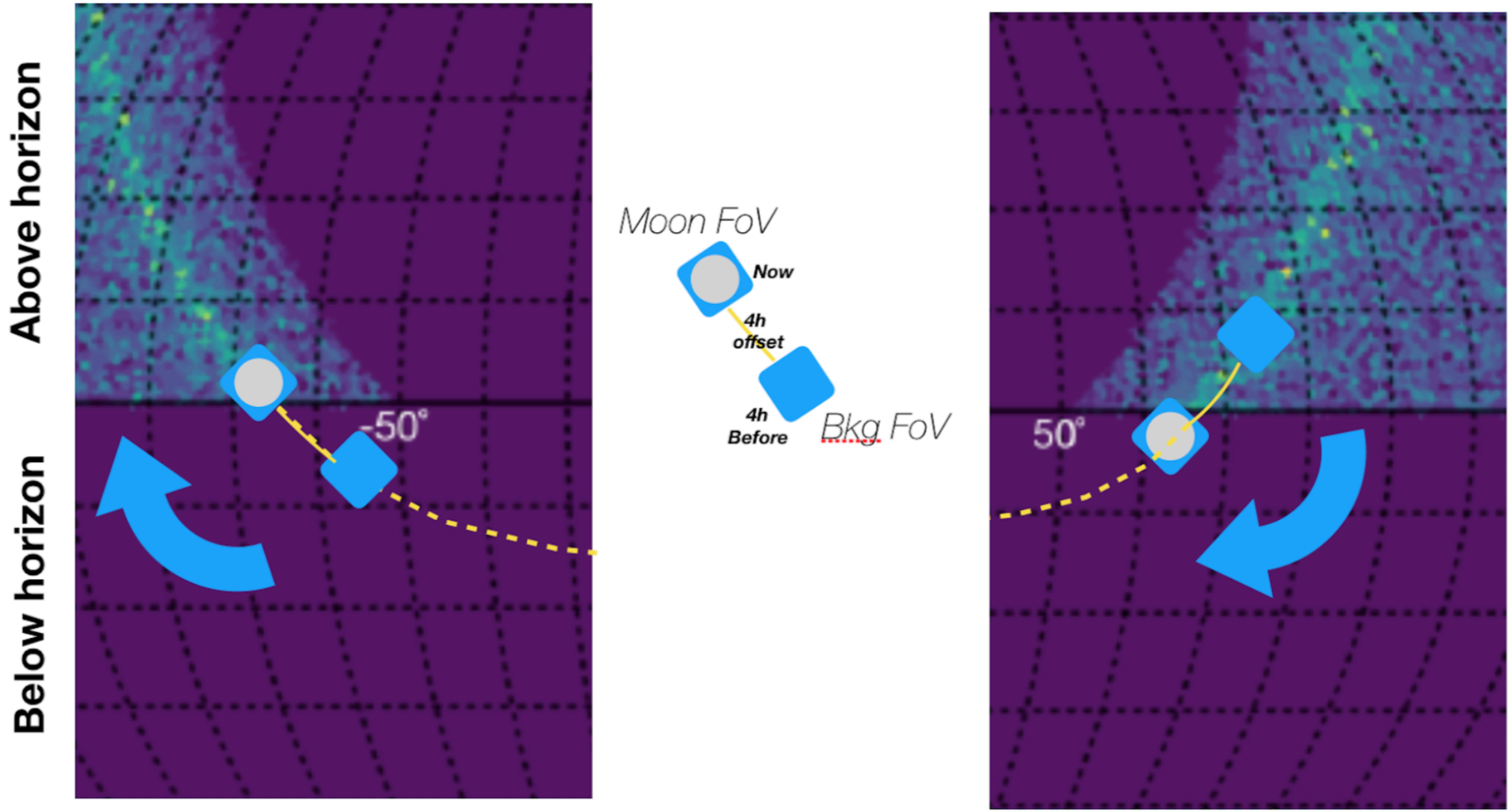
We reuse the Pseudo Experiment (PE) technique to determine the distribution of $\Delta_\lambda = \lambda_O - \lambda_{min}$

- $\lambda_O \rightarrow$ the λ-value in $O \equiv (0,0)$,
- $\lambda_{min} \rightarrow$ the minimum λ-value all-over the FoV

For each PE, the Moon is assumed in the center of the FoV, $O \equiv (0,0)$



Interpretation of the observed shift as a statistical fluctuation


Above horizon
Below horizon
-50°
Moon FoV
Now
4h
offset
4h
Before
Bkg FoV
50°

34 European Institutes

8 Extra-European Institutes