Nuclearite searches with ANTARES

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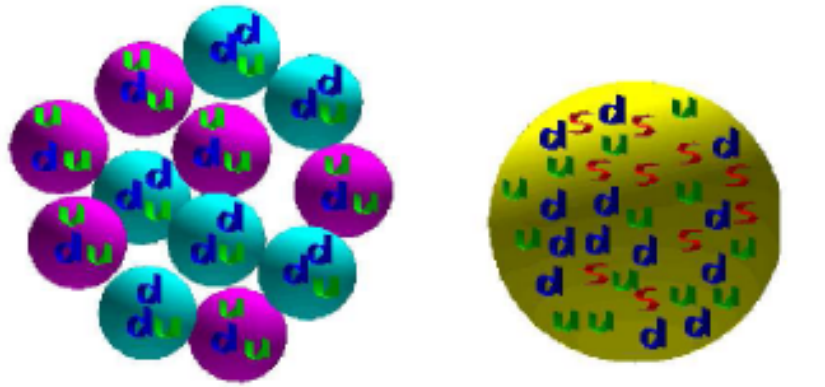
Nuclearites

- lumps of up, down and strange quarks in approximately equal proportion proposed by E. Witten, in *Cosmic separation of phases, Phys. Rev D30, 272, 1984*



- stable, essentially neutral (most or all electrons inside the quark core)
- slow massive particles, $\beta \sim 10^{-3}$
- interact mainly through elastic and quasi-elastic collisions
- in water they produce a thermal shock wave that emits a large amount of black-body radiation at visible wavelengths
- cold dark matter candidates

Nuclearite signal in water

- teorized by A. De Rujula & S.L. Glashow, in *Nuclearites - a novel form of cosmic radiation, Nature 312, 734, 1984*

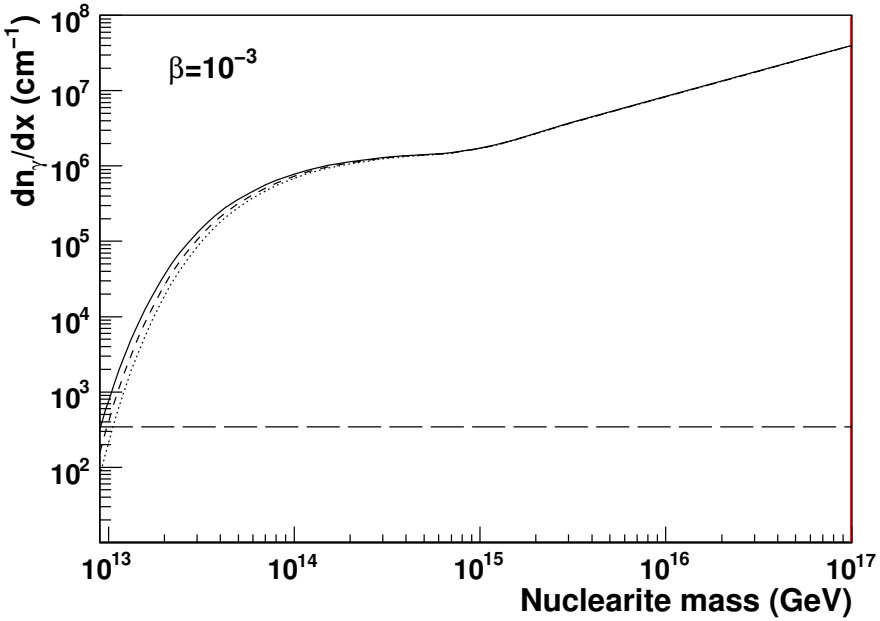
  - energy loss:

$$\frac{dE}{dx} = -\sigma\rho v^2$$

  - number of visible photons per unit path length:

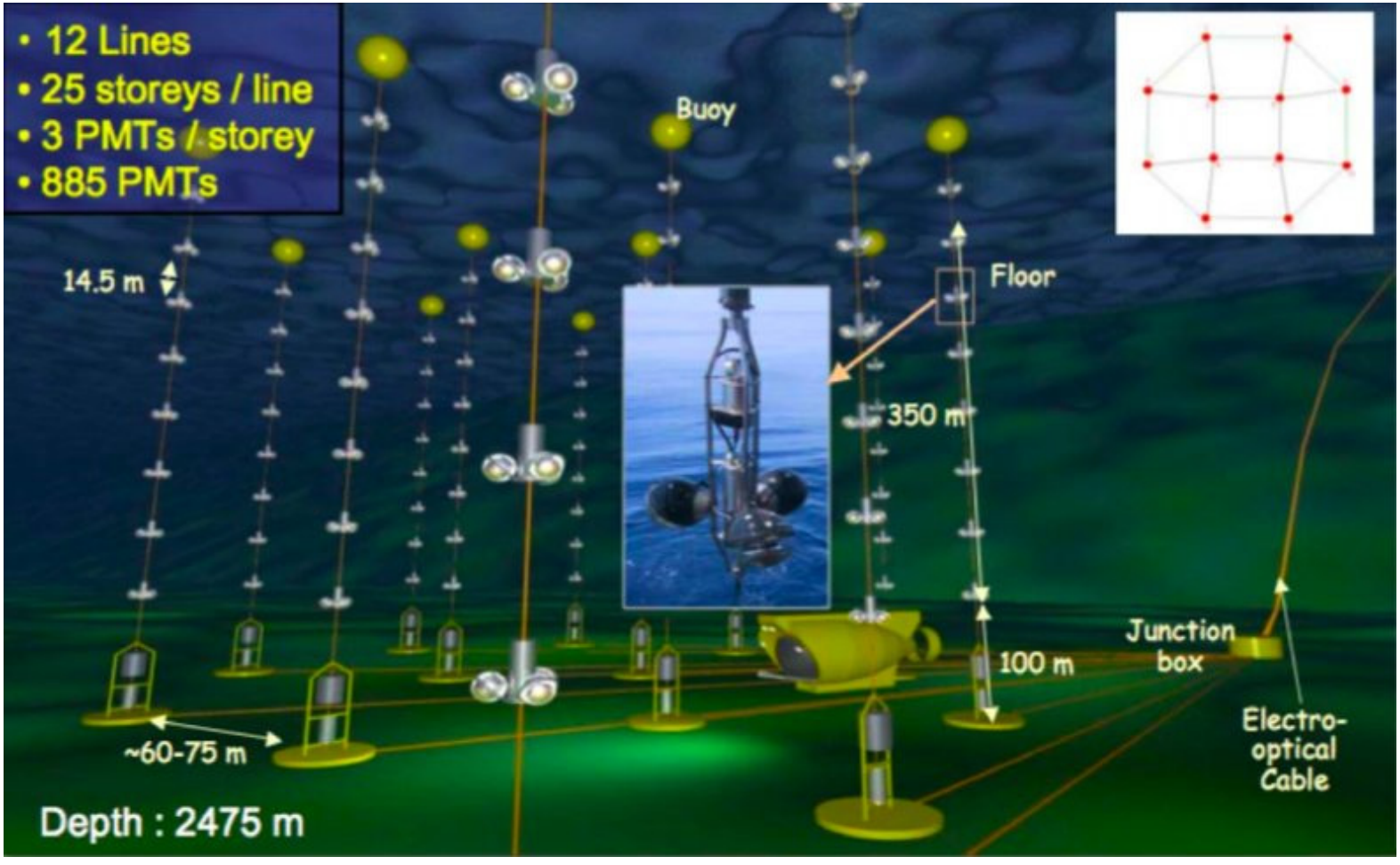
$$\frac{dN_\gamma}{dx} = \eta\frac{dE/dx}{\pi(eV)}$$

  - luminous efficiency: $\eta \simeq 3 \times 10^{-5}$



- light yield of vertically downgoing nuclearites compared to the light expected from relativistic muons of $\beta \sim 1$ (horizontal line)

ANTARES detector



Frame of the analysis

ANTARES data

- 2007 & 2008 data (5, 9, 10, 12 line configurations), $\sim$ 310 active days

Trigger selection

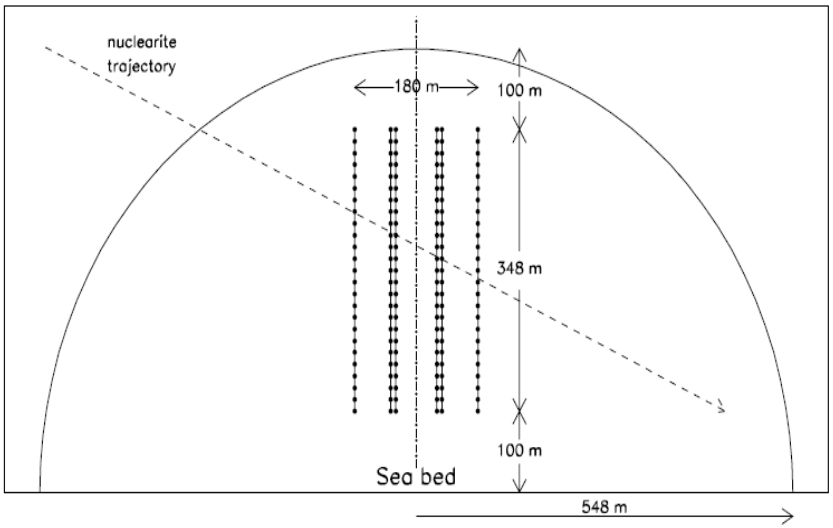
- L0 hit - basic information of a signal detected by a PMT, above a pre-defined threshold (typically 0.3 pe)
- L1 hit - local coincidence - two L0 hits within 20 ns in the same storey, or a single hit with a large amplitude (high threshold = 3 or 10 pe)
- directional trigger (DT) - 5 L1 hits correlated in space and time (2007 & 2008 data)
- cluster trigger (CT) - two clusters of two L1 hits in adjacent and next-to-adjacent storeys, within 2.2 μs window (2008 data)
- event information collected in an extended time window called snapshot (that adds 2.2 μs before the first triggered hit and 2.2 μs after the last triggered hit)

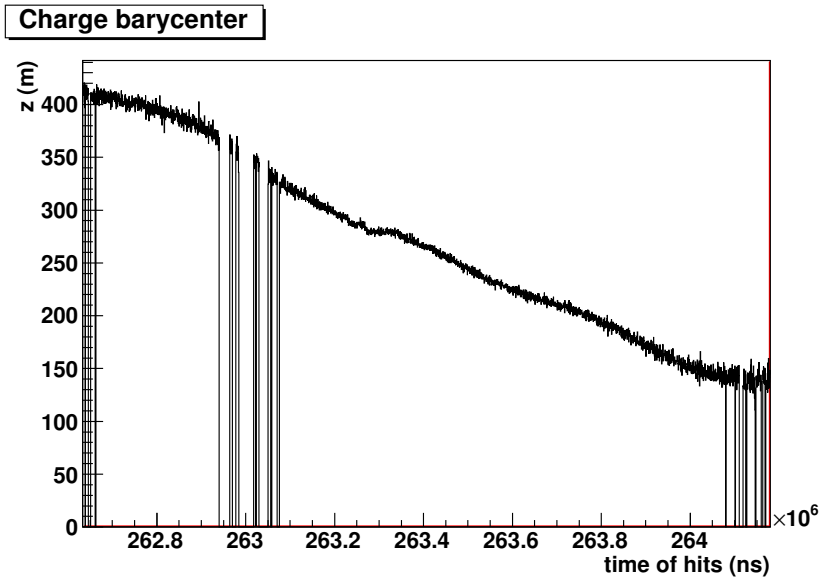
Blinding strategy

- search strategy established on MC simulations
- validate the simulation on a fraction (15%) of the available data

Nuclearite signal inside the ANTARES detector

- nuclearite simulated masses: 3×10^{13}, 10^{14}, 10^{15}, 10^{16}, 10^{17} GeV

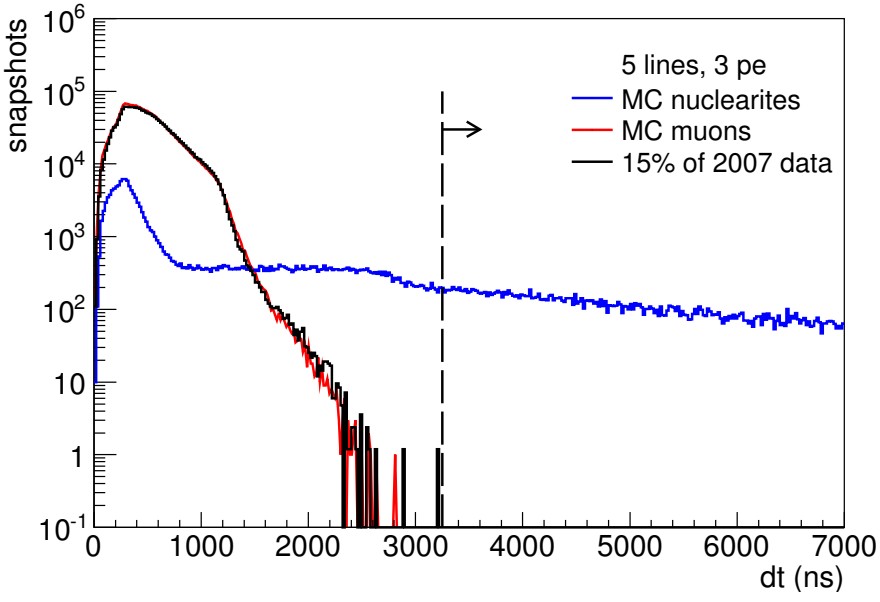




- the crossing time of a nuclearite event would be much longer (about 1 ms) than the typical muon crossing time (2.2 μs)
- the isotropic light emitted by nuclearites would induce a succession of fake muon-like signals recorded in both distinct and merged snapshots (merging takes place whenever two triggers occur within 2.2 μs)

First level cuts: C1

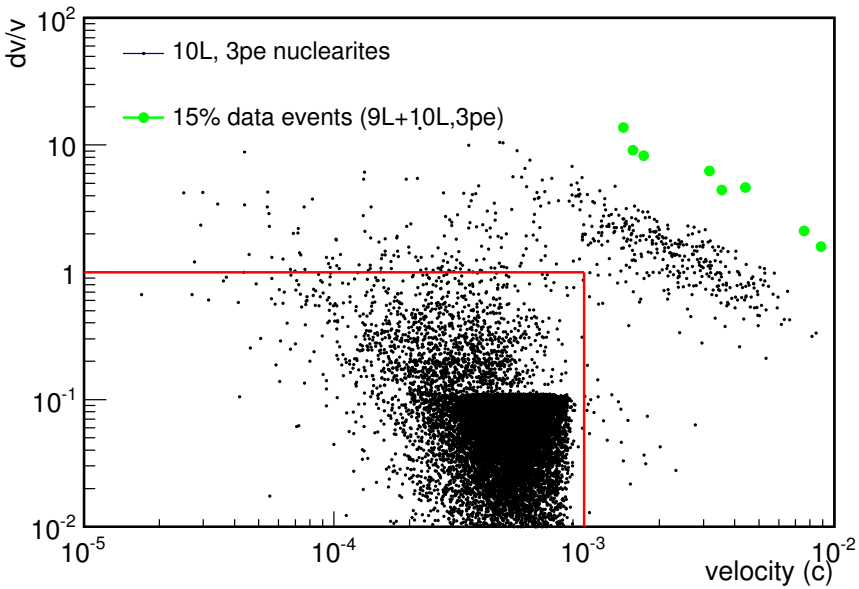
- discriminative variable: snapshot core duration, C1=dt=Tmax-Tmin (ns), with Tmax and Tmin the time of the last and the first triggered (L1) hits
- remove the main background due to downgoing atmospheric muons

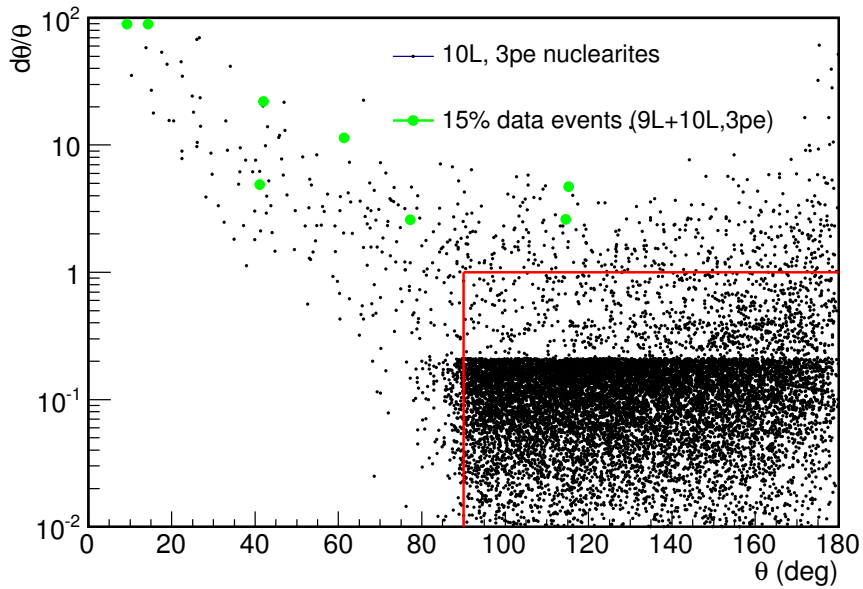


Detector	C1 cut (ns)
5L, DT,10 pe	2500
5L, DT, 3 pe	3250
10L, DT, 10 pe	3200
10L, DT, 3 pe	3500
10L, DT, CT, 3 pe	4200
9L, DT, CT, 3 pe	4250
9L, DT, CT, 10 pe	3350
12L, DT, CT, 10 pe	4000
12L, DT, CT, 3 pe	4750

Second level cuts: C2

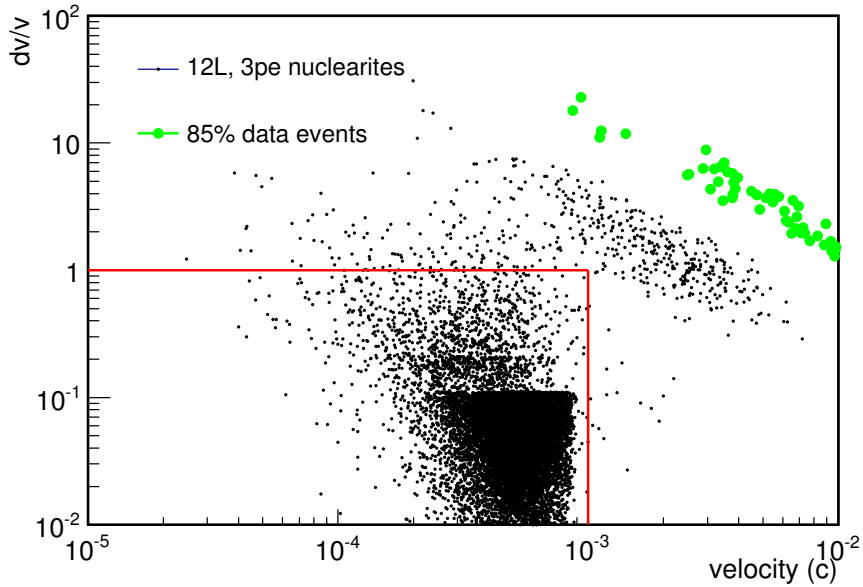
- 11 events found in the 15% data sample (in 4 out of 9 configurations) after the first cut
- reconstruction of the particle tracks based on the charge barycenter vs time distributions
- C2 cuts chosen to comply with the characteristic topology of nuclearites
- C2 cuts: reconstructed $v < 10^{-3}c$, $dv/v < 1$, zenith angle $\theta > 90°$ and $d\theta/\theta < 1$

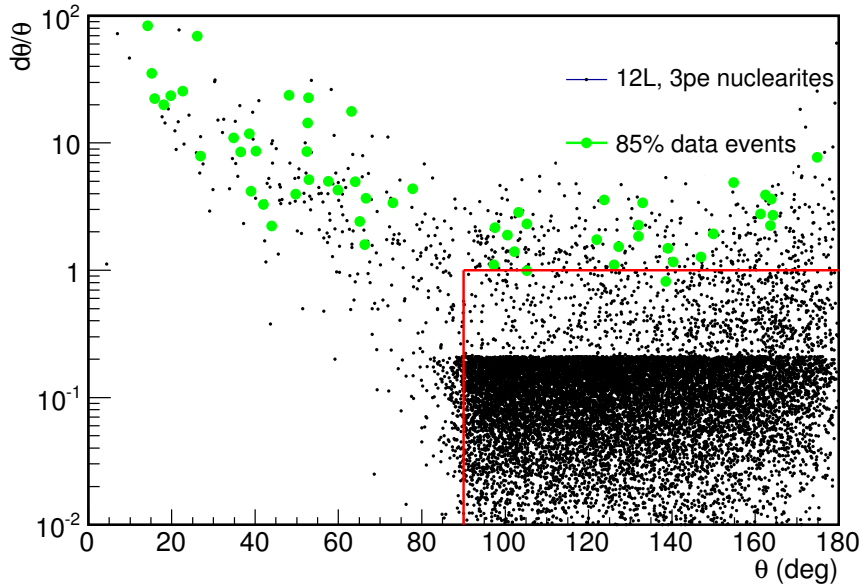




Unblinding results

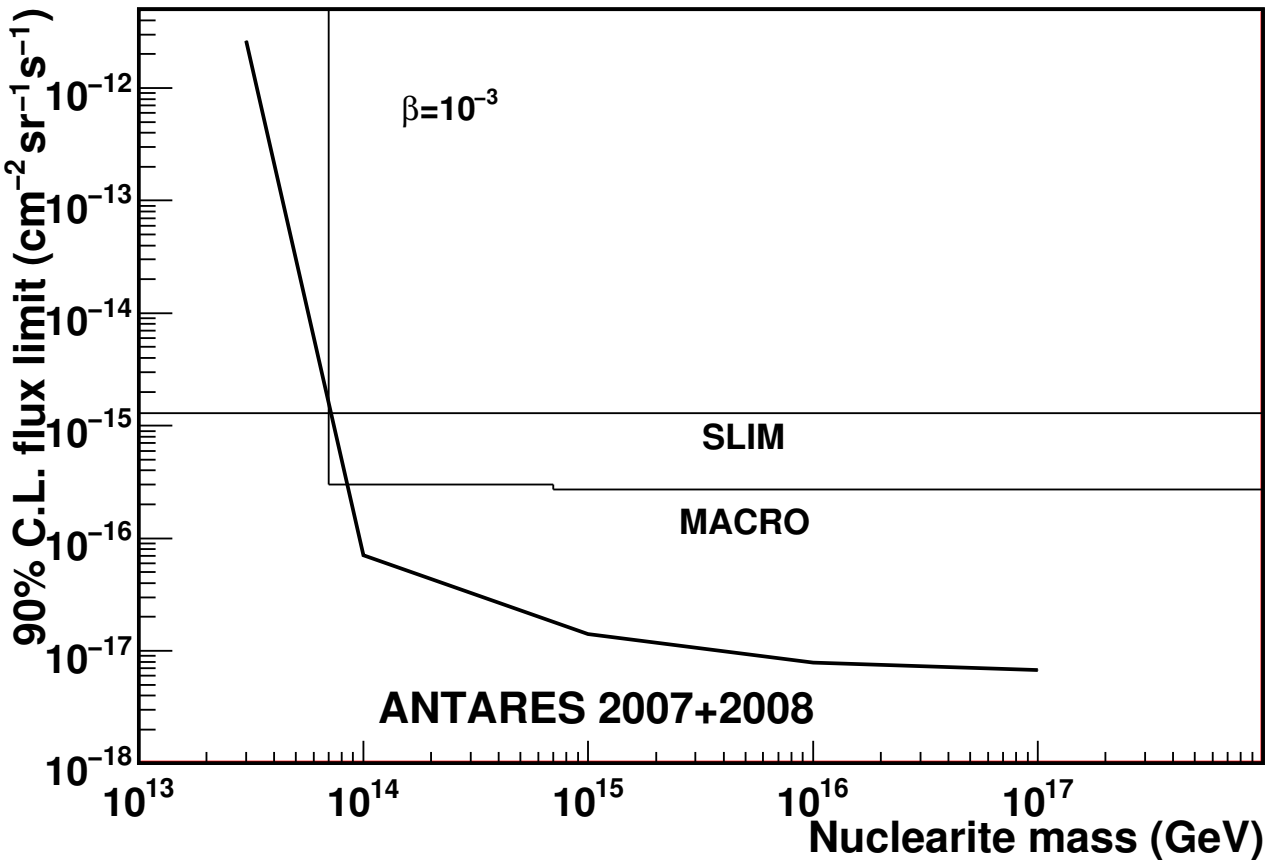
- outlier events remained in the 85% data samples after the first cut
- these events may be produced by short episodes of high bioluminescence activity recorded in the selected data runs and not accounted for in MC simulations





- no events survived both selection cuts in the remaining 85% data

ANTARES flux upper limit to downgoing nuclearites, 310 active days from 2007 and 2008



Conclusions

- ANTARES detector is sensitive to downgoing nuclearites, even when using triggers designed for relativistic particles
- ANTARES improves the MACRO upper limit by more than one order of magnitude for nuclearite masses greater than 10^{15} GeV