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RESULTS FROM THE AMANDA DETECTOR*

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The Antarctic Muon And Neutrino Detector Array (AMANDA) is a high-energy neutrino telescope based at the geographic South Pole. It is a lattice of photo-multiplier tubes buried deep in the polar ice, which is used as interaction and detection medium. The primary goal of this detector is the observation of astronomical sources of high-energy neutrinos. This paper shows the latest results of the search for a diffuse flux of extraterrestrial ν_μs with energies between 10^{11} eV and 10^{18} eV, ν_μs emitted from point sources and ν_μs from dark matter annihilation in the Earth and the Sun.

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1. Introduction

High-energy cosmic ray particles, gamma rays, nuclei and neutrinos carry valuable astronomical information about high-energy phenomena in the universe in the TeV to the EeV energy range. Although neutrinos are very difficult to detect, they could provide the most natural information about their production sites since they are not deflected by magnetic fields and because they do not suffer from absorption nor within the source nor during propagation.

In this paper the AMANDA detector is described together with its detection principle. The results of the search for extraterrestrial neutrinos, which is the main purpose of the AMANDA experiment, are also discussed. Finally, the AMANDA results obtained in the search for neutrinos induced by neutralino dark matter annihilation in the center of the Earth and the Sun are explained.

2. The AMANDA detector

The AMANDA detector has been built in mainly two phases. The AMANDA-B10 detector was commissioned in 1997 and consists of 302 optical modules (OMs), each containing an 8-inch-diameter Photo Multiplier Tube (PMT) housed in a spherical glass pressure vessel, installed on 10 strings in the ice at the South Pole. These are connected to the surface by an electrical cable that provides the high voltage to the OM and transmits the analog PMT signals from the OM to the surface electronics.

The AMANDA-II detector configuration (see figure 1) was completed in 2000. It consists of 19 strings with a total of 677 OMs arranged in concentric circles, with the ten strings from AMANDA-B10 forming the central core of the enlarged detector. The complete AMANDA high-energy neutrino detector was constructed in a cylindrical volume with an outer diameter of 200 m at a depth between 1500 m and 2000 m below the surface of the Antarctic glacier. The OMs on the new strings are connected via fiber-optical cables

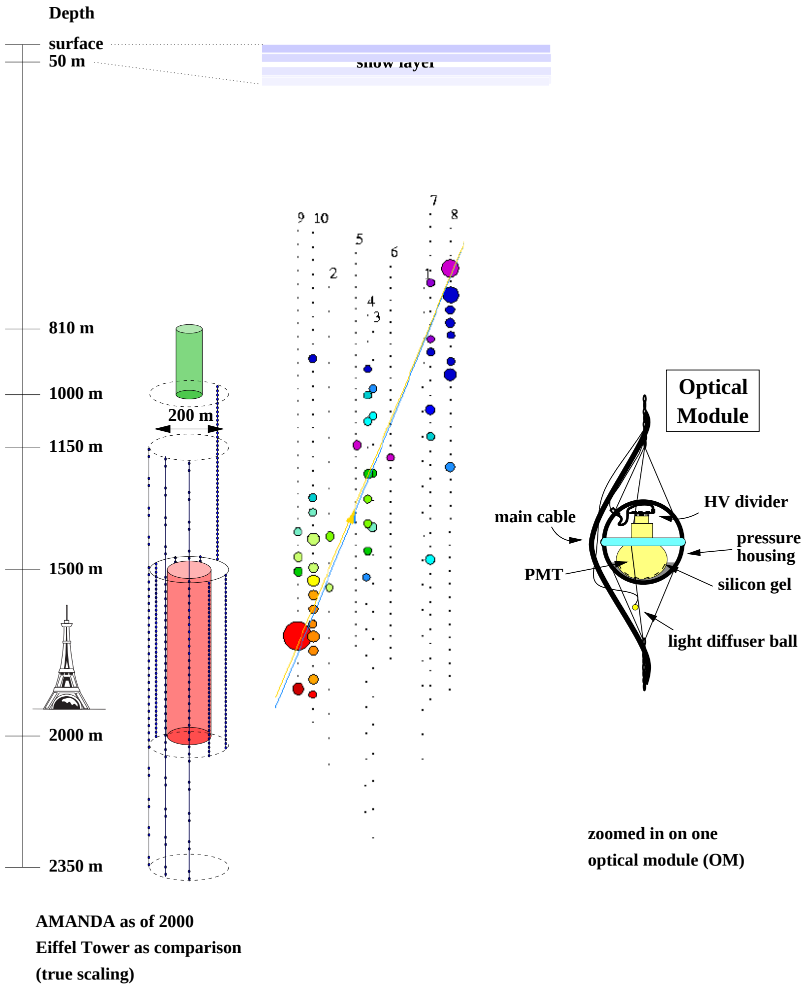

Fig. 1. Schematic view of the geometry of the AMANDA-II detector. The Eiffel Tower is shown to illustrate the scale. The AMANDA-B10 configuration is marked by the shaded cylinder at a depth of 1500 m–2000 m. In the center the signals induced by an up-going muon track are illustrated. This figure shows how the reconstruction program interprets the signals recorded by the detector to reconstruct the muon track. Each dot represents an optical module. Hit optical modules are marked by solid circles. The size of the circles is proportional to the number of photo-electrons detected. The shade of the circles indicates the time. Light shades correspond to early times and dark shades indicate late times. The arrow indicates the direction of the muon. On the right an optical module is enlarged.

allowing high bandwidth transmission of the analog PMT signal. The optical properties of the ice surrounding the detector as well as the time offsets and the detector geometry are determined using both in situ light emitters, installed along the strings, and the data from down-going muons generated in the atmosphere above the detector. The average absorption length at AMANDA-II depths is ~ 110 m and the average scattering length ~ 20 m.

3. Detection principle

An interacting ν_μ produces a muon that can travel long distances through the detector continuously depositing energy by ionization and stochastic interactions, mainly by bremstrahlung and pair production processes. Above 1 TeV, the muon energy can be estimated from the light emission. The Cherenkov light emitted by the energetic muon is picked up by the PMTs and is used for the muon track reconstruction. The angular resolution obtained with AMANDA-II is between 2 and 2.5 degrees after applying quality cuts.

The ν_e and ν_τ channels are somewhat different. The electron from a ν_e-interaction will generate an electro-magnetic cascade, which is confined to a volume of a few cubic meters. The electro-magnetic cascade coincides with the hadronic cascade of the primary interaction vertex. The optical characteristic of this type of event is an expanding spherical shell of Cherenkov photons with a larger intensity in the forward direction. The tau produced in a ν_τ interaction will immediately decay and also generate a cascade. At energies > 1 PeV this cascade is separated by several tens of meters from the cascade of the primary interaction vertex, connected by a single track. This signature of two extremely bright cascades is unique for a high-energy ν_τ and is called a "double bang" event [1]. The direction of electromagnetic and hadronic cascades is presently reconstructed with an accuracy of 30–40 degrees.

Since 2003, the AMANDA-II detector is read out by a Transient Waveform Recorder System (TWR) [2] which should improve the energy resolution for high-energy phenomena and the angular resolution of high-energy muons (muons that cross the array with an excess of 100 TeV).

4. Search for extraterrestrial neutrinos

In the search for extraterrestrial neutrinos, the northern sky is probed for an excess of signal events over the expected background. The Earth is used as a shield against the background events as only up-going tracks are considered. Neutrinos are predicted to be emitted by a variety of galactic and extragalactic sources like supernova remnants, galactic solar mass black holes forming micro-quasars, active galactic nuclei surrounded by sufficiently dense matter and gamma ray bursters. In this section the main background events and the results of the search for astronomical neutrinos are described.

4.1. The atmospheric muon and neutrino background events

The main background events in the search for astrophysical neutrinos are the down-going muons, originating in air showers in the Earth's atmosphere above the detector, that are wrongly reconstructed as up-going muon tracks. This background can be reduced by a set of quality cuts. The atmospheric neutrino events, generated in the northern hemisphere , are an unavoidable background as they can penetrate the Earth from all directions. The atmospheric muons outnumber the neutrino-induced muons by a factor of 10^6 at the detector trigger level. Both down-going atmospheric muons and muons from atmospheric neutrinos are used as AMANDA test beams. They have been extensively studied to understand and calibrate the AMANDA detector and to continuously improve the simulation [4, 5].

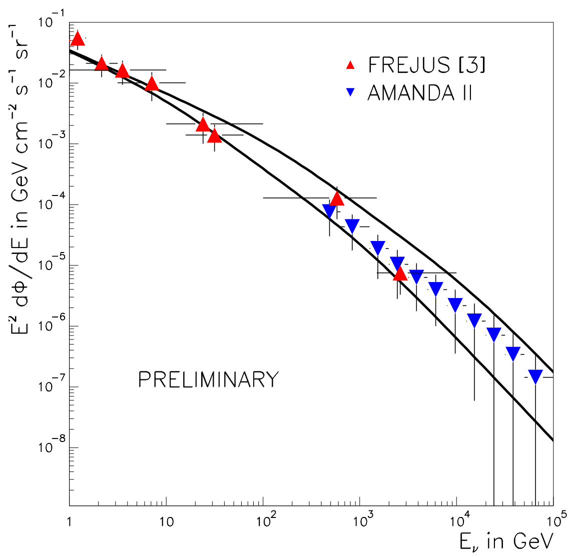

Fig. 2. Spectrum of atmospheric neutrinos determined with the AMANDA-II and Fréjus experiment [3]. The lines show the horizontal and vertical atmospheric neutrino flux parametrizations according to Volkova *et al.* [7]. The error bars give the statistical error from the unfolding procedure plus an overall systematic uncertainty.

A new method has been developed in [5] to reconstruct the neutrino energy spectra based on neural networks. A sample of 570 neutrino events has been selected from the raw data, taken by the AMANDA-II detector in 2000, by applying optimized point source cuts [6] and a zenith veto at 10 degrees below the horizon. The comparison with background simulations predicts a contamination of mis-reconstructed atmospheric muons of $\sim 3\%$. Figure 2 shows the resulting atmospheric neutrino spectrum that has been measured up to 100 TeV. The AMANDA-II results are complementary to those obtained by the Fréjus experiment [3] and are in good agreement with the atmospheric neutrino flux parametrizations according to Volkova *et al.* [7].

4.2. Diffuse flux of high-energy muon-neutrinos

In the search for a diffuse flux of high-energy neutrinos an excess of neutrino events with high energy is looked for on top of the atmospheric neutrino spectrum. This method is based on the fact that atmospheric neutrinos have a rather soft energy spectrum (spectral index $\sim E^{-3.7}$), while neutrinos from astrophysical sources are expected to have a harder spectrum ($\sim E^{-2}$). The low-energy events are suppressed by selections on energy-related parameters to improve the sensitivity.

The energy-dependent transmission of neutrinos through the Earth determines the strategy of the analysis. In the TeV–PeV neutrino energy range, one searches for a diffuse excess in the flux of up-going muon-neutrinos. In the analysis [8] of the data taken in 1997 by the AMANDA-B10 detector, the number of observed hits in the detector is used as a measure of energy, *i.e.* muons from extraterrestrial neutrinos would appear as an excess of neutrino events at higher hit multiplicities as illustrated in figure 3. The experimental data are consistent with the expectation from atmospheric neutrinos. The final event sample was selected with an energy-sensitive cut ($N_{\rm ch} > 56$) optimizing the detector sensitivity. As no excess was observed, a 90% confidence level upper limit of

$$E^2\Phi(E) < 8.4 \times 10^{-7} \mathrm{GeV cm^{-2} s^{-1} sr^{-1}} \quad (1)$$

within the sensitive neutrino energy region from 6 to 1000 TeV is obtained.

Taking the additional data taken by the AMANDA-II detector until 2002 into account, a 90 % confidence level upper limit of $E^2\Phi(E) < 10^{-7}\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$ is expected. This sensitivity will further test model predictions and observations at this level may exclude certain theoretical predictions on the neutrino flux [9, 10].

In the PeV–EeV energy range, one searches for a diffuse excess in the flux of down-going muons and muons close to the horizon. At PeV energies,

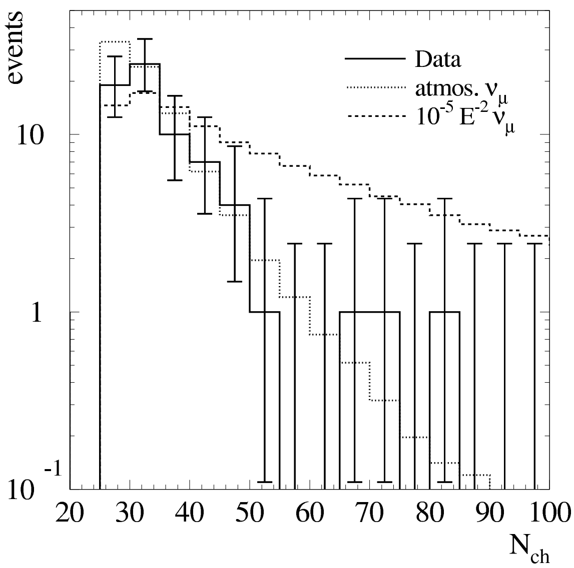

Fig. 3. Distribution of the number of hit PMTs ($N_{\rm ch}$) for the selected up-going muon events. In addition simulations for atmospheric neutrinos and AGN neutrinos, assuming a spectrum of $d\phi/dE = 10^{-5}E^{-2}$ cm^{-2}s^{-1}sr^{-1}GeV, are illustrated.

the Earth is essentially opaque to neutrinos and a search for extraterrestrial sources must focus on almost horizontal events, where the expected signal accumulates. Data taken in 1997 by the AMANDA-B10 detector was searched for muon-neutrinos with energies above 10 PeV [11]. The background events are large muon bundles from down-going atmospheric air shower events. In this search no excess of events above background have been observed and an upper limit at 90% confidence level to an assumed E^{-2} muon–neutrino flux at the detector of

$$E^2\,\Phi(E) < 7.2 \times 10^{-7}\mathrm{GeV cm^{-2}s^{-1}sr^{-1}} \tag{2}$$

has been set in the region 2.5 PeV $< E_\nu <$ 5.6 EeV. This is currently the most restrictive experimental limit placed by any neutrino detector at these energies.

In [12] the search for electro-magnetic and/or hadronic showers induced by a diffuse flux of high-energy neutrinos (80 TeV to 7 PeV) using the data collected with the AMANDA-II detector during the year 2000 has been performed. The result is a preliminary 90% confidence level upper limit of

$$E^2\,\Phi(E) < 9 \times 10^{-7}\mathrm{GeV cm^{-2}s^{-1}sr^{-1}} \tag{3}$$

on a diffuse flux of extraterrestrial electron-, tau- and muon-neutrinos following an E^{-2} spectrum and consisting of an equal mix of all flavors.

4.3. Search for extraterrestrial muon-neutrino point sources

In the search for point sources one looks for an excess of up-going muon tracks in particular directions in the sky. Point sources are expected to provide a hard spectrum ($\sim E^{-2}$). The selection is therefore optimized for high energies to suppress atmospheric neutrinos. Figure 4 shows the skyplot, sub-divided into 300 bins ($\sim 7° \times 7°$), of 1557 muon tracks extracted from

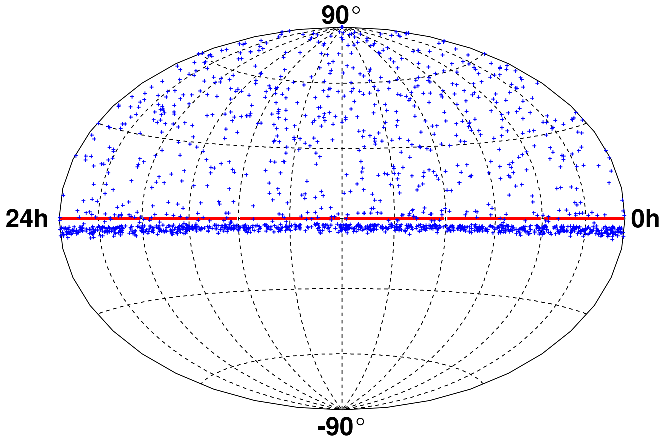

Fig. 4. Skyplot in equatorial coordinates of 1557 AMANDA-II events recorded in the year 2000. The thick band of events below the horizon shows the onset of the down-going cosmic ray muon background contamination.

the AMANDA-II 2000 data [13]. The sub-sample of 699 muon tracks coming from below the horizon is dominated by atmospheric neutrino-induced events, with a remaining non-neutrino background contamination of less than 10%. The sensitivity of the AMANDA-II detector is of the order of $\Phi_\nu^{\rm lim} \approx 0.23 \times 10^{-7} {\rm cm}^{-2}{\rm s}^{-1}$ (declination averaged), which is 4–5 times better than that of the AMANDA-B10 detector [14]. This is a result of its larger effective area and its improved angular resolution. A binned search for excesses in the northern hemisphere and a study of pre-selected sources did not indicate any statistically significant excess above the background expectation. In Table I the upper limits derived for a few pre-selected northern hemisphere blazars and microquasars are listed. For the microquasar SS433 the limit is close to the theoretical prediction made in [15].

TABLE I

Preliminary 90 % confidence level upper limits on candidate sources. Dec. is the source declination in degrees and R.A. is the right ascension in hours. Neutrino limits $\Phi_\nu^{\rm lim}$ are for an assumed E^{-2} spectral shape, integrated above $E_\nu = 10$ GeV, in units of $10^{-8}\text{cm}^{-2}\text{s}^{-1}$ using the data taken in 1997 and 1999 (AMANDA-B10) and 2000 (AMANDA-II).

Candidate	Dec. [°]	R.A. [h]	$\Phi_\nu^{\rm lim}$ 1997	$\Phi_\nu^{\rm lim}$ 1999	$\Phi_\nu^{\rm lim}$ 2000
SS433	5.0	19.20	—	—	0.7
M 87	12.4	12.51	17.0	—	1.0
Crab Nebula	22.0	5.58	4.2	9.2	2.4
Markarian 421	38.2	11.07	11.2	3.7	3.5
Markarian 501	39.8	16.90	9.5	7.6	1.8
Cygnus X-3	41.0	20.54	4.9	5.2	3.5
Cassiopeia A	58.8	23.39	9.8	10.4	1.2

5. Indirect search for neutralino dark matter

If dark matter in the Universe is constituted by super-symmetric particles in the form of neutralinos then these can accumulate gravitationally in the center of the Earth or the Sun and annihilate pairwise therein. This annihilation process generates a neutrino flux that can be measured as up-going near-vertical muon tracks or horizontal muon tracks respectively in a detector like AMANDA. These muons will result in an excess on top of the atmospheric neutrino spectrum.

No statistically significant excess of up-going muon tracks induced by the annihilation of neutralinos in the center of the Earth has been found in the data taken by the AMANDA-B10 detector during 1997 [16] and 1999 [17]. Figure 5 shows the upper limits on the neutrino-induced muon flux coming from the annihilation of neutralinos in the center of the Earth, including the systematic uncertainties, as a function of the neutralino mass. The AMANDA results of the 1999 data analysis [17] are shown in addition to the published AMANDA upper limits obtained in the 1997 data analysis [16]. The current upper limits from the neutrino telescopes Baksan [18], MACRO [19] and SuperKamiokande [20] and the anticipated sensitivity for the future neutrino telescope Icecube [21] are indicated as well. All upper limits have been calculated for a muon energy threshold of 1 GeV. The dots and crosses represent the model predictions from the Minimal Supersymmetric extension of the Standard Model (MSSM), calculated with the DarkSUSY package [22, 23]. The Earth is believed to capture WIMPs not dominantly from the Milky Way halo directly, but instead from a distribution of WIMPs that have diffused around in the solar system due to gravitational interactions with the planets in the solar system. Recently, doubts have been raised about the life time of these WIMP orbits due to solar capture. In [24] this issue has been investigated and compared to earlier estimates. It is found that the WIMP velocity distribution is significantly suppressed below about 70 km/s which results in a suppression of the capture rates mainly for heavier WIMPs (above $\sim$ 100 GeV). As a result, the annihilation rates, and thus the neutrino fluxes, are reduced even more than the capture rates. At high masses (above $\sim$ 1 TeV), the suppression is almost two orders of magnitude. This suppression will make the detection of neutrinos from heavy WIMP annihilations in the Earth much harder compared to earlier estimates. Models that are excluded by the current direct detection limit set by the Edelweiss experiment [25] are indicated by circles, while models that are not excluded are represented by crosses. This figure shows that AMANDA can only exclude model predictions from the MSSM that are already excluded by the Edelweiss experiment.

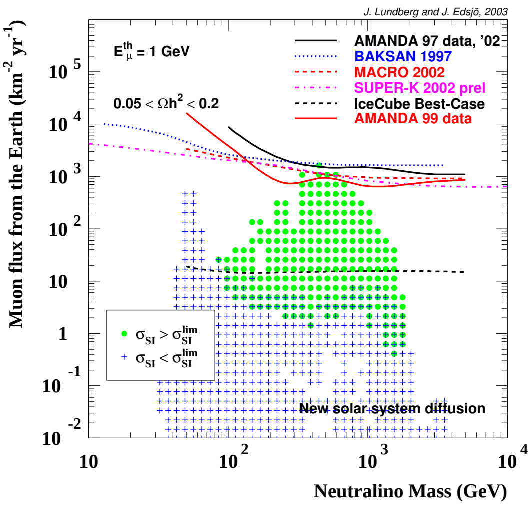

Fig. 5. The upper limits on the ν_μ flux from the center of the Earth set by AMANDA, Baksan [18], MACRO [19] and Super-Kamiokande [20] and the MSSM model predictions on the neutrino-induced muon flux coming from the annihilation of neutralinos in the center of the Earth taking WIMP diffusion in the solar system into account as a function of the neutralino mass. Also shown is the estimated sensitivity for Icecube [21] ($\sim$ 10 years of live time).

The search for neutralinos in the center of the Sun was not possible with the AMANDA-B10 detector due to the limited resolution close to the horizon. The improved reconstruction performance with respect to horizontal tracks of the AMANDA-II detector makes this analysis feasible. The

AMANDA-II sensitivity is fairly competitive with the results of the direct searches on Earth as illustrated in figure 6. This can be explained by the fact that the Sun is effective in capturing WIMPs thanks to the spin-dependent WIMP-hydrogen interaction, while the Earth mostly accretes WIMPs by spin-independent interactions.

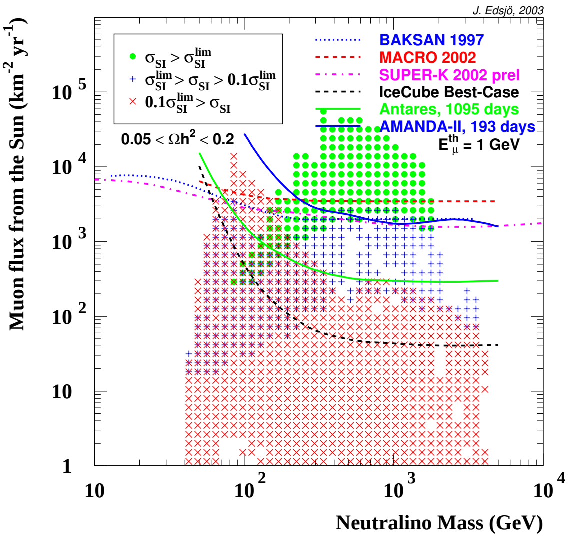

Fig. 6. The upper limits on the ν_μ flux from the center of the Sun set by Baksan [18], MACRO [19] and Super-Kamiokande [20] and the MSSM model predictions on the neutrino-induced muon flux coming from the annihilation of neutralinos in the center of the Sun as a function of the neutralino mass. The results based on AMANDA-II (193 days of live time), Icecube [21] (5 years of live time) and Antares [26] (3 years of live time) are sensitivities.

6. Conclusions

The AMANDA experiment has continuously been taking data since 1997. The feasibility of an under-ice telescope has been proven by more than seven years of successful operation. AMANDA has reached the sensitivity to observe astrophysical neutrinos required by most optimistic models. The events observed by the AMANDA detector in the different analyzes, covering different fields and energy ranges from 50 GeV up to several EeV, correspond to the background expectations. Upper limits are derived which are competitive or even better than those obtained by similar experiments.

The Icecube detector [21], which will consist of 4800 PMTs deployed on 80 vertical strings, is expected to be completed around 2010. It will allow to reach ~ 1 km^2 effective telescope area above an energy of 1 TeV with an angular resolution of well below 1 degree.

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