Helmholtz-Hochschul Nachwuchsgruppe **VH-NG-205**

"Multi-messenger studies of point sources of cosmic rays using data from IceCube"

2009 Activity Report

Group members

Staff:	Dr. Elisa Bernardini
Post-doctoral fellows:	Dr. Pratik Majumdar
Graduate Students (supervisor E. Bernardini):	Robert Lauer Konstancja Satalecka Jose Luis Bazo Alba Robert Franke
Summer Students	Victoria Parra Osorio, Jörn Mahlsted

Group Status Overview

Elisa Bernardini and Konstancja Satalecka went both on maternity leave (March 2009 - March 2010 and July 2009 – January 2010 respectively). Pratik Majumdar left the group in December 2009.

Summary of the Main Activities

The main programmatic points of this group is the development of the multi-messenger approach. The activities are organized in three working packages:

A. *Search for point sources of neutrinos with IceCube*
B. *Development of Neutrino triggered Target of Opportunity (NToO) observations with MAGIC and IceCube*
C. *Study of gamma-ray emission of Blazars, with MAGIC*

The main achievements reached in 2009 for each point are summarized in what follows.

A. Search for point sources of neutrinos with IceCube

A1. Development of a novel concept in the search for point sources of neutrinos extending the sensitivity to multi-PeV energies

One of the goals of the group was the enhancement of the sensitivity to point sources of neutrinos with ultra-high energies (above 100 TeV and up to the EeV region). This was made possible or the first time in 2008/2009 by including downward-going events from above the horizon, since upward-going neutrinos at these energies are absorbed when traveling through Earth. The analysis developed in 2009 is the first to demonstrate that the dominating background of atmospheric muons, reaching IceCube from above, can be suppressed to a level that allows a point source search. In late December 2008, a major goal of this work was achieved by unblinding data collected with 22 IceCube strings. An all-sky scan showed no significant excess of events above background expectations. A second test of 28 neutrino source candidates, mostly Active Galactic Nuclei selected according to EGRET gamma-ray flux measurements with respect to hadronic models like [A.M. Atoyan and C.D. Dermer

(2004)], was also compatible with the background hypothesis. These results led to upper limits on neutrino fluxes. They are currently the best constraints for point source emissions at and above PeV energies in the southern sky.
The results were first presented in 2009 in Heidelberg on the workshop High-Energy Gamma-rays and Neutrinos from Extra-Galactic Sources [R. Lauer et al. Int. J. Mod. Phys. D, 18:1587, (2009)]. The journal publication appeared in November 2009 in Physical Review Letters [R. Abbasi et al. Phys. Rev. Lett., 103:221102, (2009)].
The method of using energy-sensitive cuts to suppress the atmospheric background for neutrino searches above the horizon has since then been adopted as the new standard for IceCube point source analyses.

The group performed a follow-up analysis to test a model of neutrino flares in the blazar 3C279, motivated by results from MAGIC [E. Aliu et al. (2008)] and predictions in [A. Reimer (2009)]. This was based on the same IceCube event selection as in the journal publication but included also the use of arrival times of neutrino candidates.
Due to the location of 3C279 in the southern sky, this approach was the first that could cover the most interesting neutrino energy range above a few PeV. The resulting limit was included in [Phys. Rev. Lett., 103:221102, (2009)]. It is shown in Figure 1, which also illustrates the model prediction. While this result is a first glance discouraging (a flux an order of magnitude higher compared to the model prediction is required to be observed in this data set), it is noteworthy to emphasize that the particular flare analyzed may be not the most favorable in neutrinos, due to its large transparency in gamma-rays which may indicate less dense target matter for neutrino production. In any case, it is important to recognize the effort being put in developing more physics motivated analyses.

The IceCube 22-strings event selection served also as basis for a study of correlations between neutrinos and the arrival directions of charged cosmic rays at ultra-high energies, as reported by the Pierre Auger Observatory and the HiRes experiment. The cosmic rays have energies above 10^{19} eV and can be expected to be only slightly deflected by galactic magnetic fields, thus pointing to sites of hadronic acceleration. A method to search for a correlation of neutrinos with the directions of the highest energy cosmic rays was developed and applied to IceCube 22-strings data.
An excess of events with significance 2.35 σ and a probability of 1% to occur due to a random fluctuation was found. Despite intriguing, this result is interpreted as being compatible with background-only expectations. Currently, the extension of this search to include new data taken with 40 IceCube strings is under development.

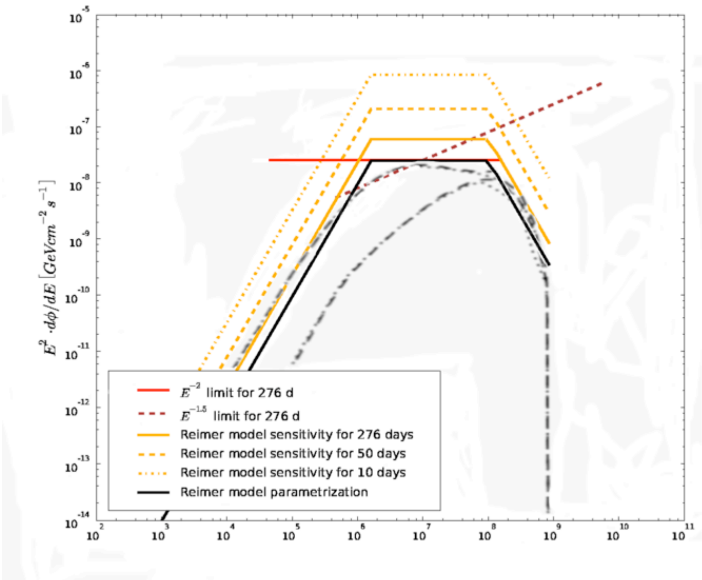


Figure 1: Flux upper limit from the flare search from 3C279 on IceCube 22-strings data.

A2. Time-dependent search for neutrinos with IceCube ("un-triggered searches")

The group developed a time variable method to look for neutrino flares from pre-defined directions in the whole sky using IceCube data. This analysis was based on work previously done by the group on AMANDA data [K. Satalecka et al. (2007)]. The new version of this time-clustering algorithm implements a maximum likelihood approach (un-binned method), found to deliver higher discovery probabilities. The background and signal probability density functions of the un-binned method include, besides the usual spatial term, an energy term that further helps to discriminate background from signal. This algorithm provides a search for significant neutrino flares over time-scales that are not fixed a-priori and that are not triggered by multi-wavelength observations (the latter subject is covered in Madison).
The improvement in discovery chance as compared to time-integrated searches can be judged from Figure 2, which illustrates the number of signal events which are necessary to deliver a 5 σ discovery, as a function of the assumed flare duration. While on time-scales as long as several days time-integrated and time-variable searches are comparable, on short time scale (days or less) the signal flux necessary to obtain a detection is decreased of a factor up to 3. This of course applies only in case the neutrino emission is variable in time.
The method was applied to data from 22-strings of IceCube (May 2007- April 2008: 276 days of uptime). A pre-defined list of 10 bright and variable astrophysical sources was analyzed (Table 1). The highest excess was recorded from the direction of 3C 454.3 (also referred to as the "Crazy Diamond"), which exhibited variability in GeV photons in the period analyzed [S. Vercellone et al (2009)]. The result is however compatible with a background fluctuation, therefore upper limits on the neutrino fluence from these sources were derived (see Table 1). These results were presented at the 31st ICRC [J.L. Bazo Alba et al. (2009)].
A follow-up analysis using data from 40-strings of IceCube was performed. In this case, the southern sky could be included for the first time. 40 sources were selected, based on information on GeV photon emission provided by FERMI (absolute luminosity and time-variability index). Also in this case no statistically significant excess was found and upper limits were reported. Results are shown here as fluence limits (Figure 4) and significance map (Figure 5).

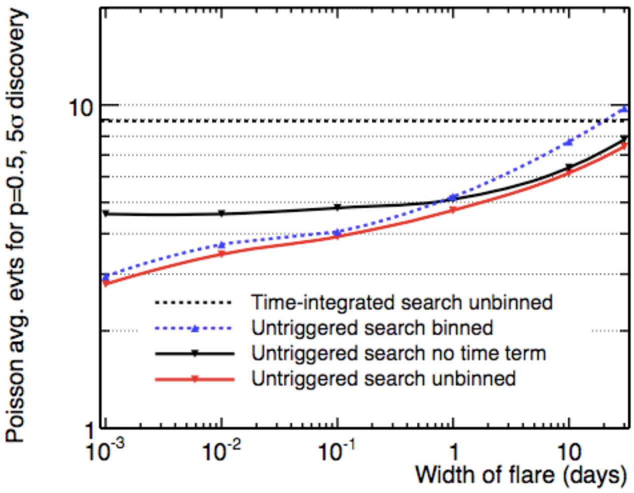


Figure 2: Poisson average number of events required to yield a 5 sigma excess in 50% o the trials, as a function of the flare duration. Different analysis methods are compared: time-integrated search (dashed black line), time-clustering search, based on an angular binned test on the event directions (blue), time-clustering search with a max. likelihood method without a time-term in the signal probability density function (black) and a time-clustering search with a max. likelihood method implementing both an energy and a time-term in the probability density function (red, finally used for the analysis).

Table 1: Results for pre-defined variable astrophysical source candidates using the time clustering algorithm and IC22 data.

Source	dec [°]	ra [°]	p-value	Δt (days)	Fluence Limit (GeV/cm^2)
GEV J0540-4359	-44.1	84.7	0.54	7.08	29.8
GEV J1626-2502	-25.5	246.4	0.41	22.8	22.8
GEV J1832-2128	-21.1	278.4	0.64	4.49	12.0
GEV J2024-0812	-7.6	306.4	1	3.55	3.7
3C 279	-5.8	194.1	0.52	0.19	3.3
3C 273	2.0	187.3	0.84	1.97	0.37
CTA 102	11.7	338.1	0.27	3.7	1.42
GEV J0530+1340	13.5	82.7	0.82	3.48	0.47
3C 454.3	16.1	343.5	0.047	0.5	2.22
GEV J0237+1648	16.6	39.7	0.59	1.99	1.08

Note.- The flare duration of the best cluster is given by Δt. The fluence upper limit is calculated by integrating $d\Phi/dE \times E$ over the 90% energy range and Δt, assuming a neutrino energy spectrum of E^{-2}.

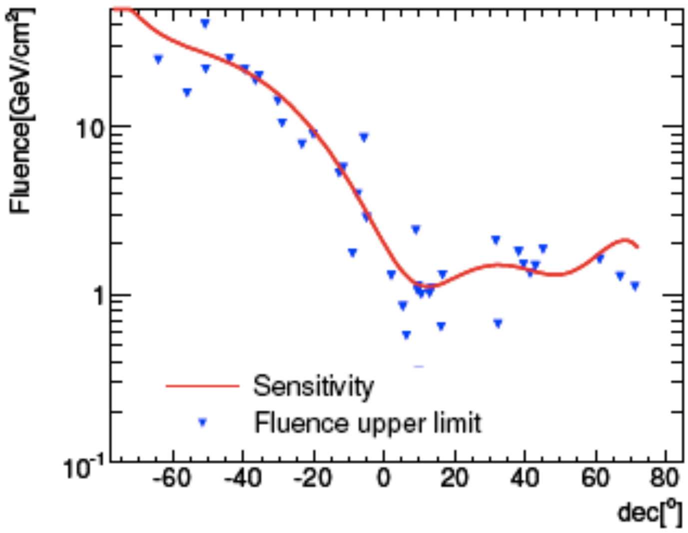


Figure 4: Fluence upper limits of the 40 selected sources as function of declination. The red line represents the median sensitivity.

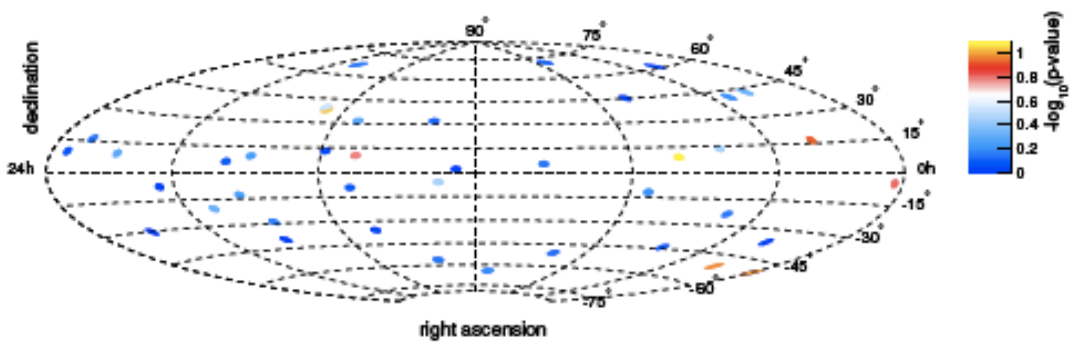


Figure 5: P-values in the sky of the selected 40 sources for IC40.

B. Development of Neutrino triggered Target of Opportunity (NToO) observations with MAGIC and IceCube

Progress was made in 2009 in the development of a neutrino-triggered follow up program involving IceCube and MAGIC. An IceCube online filter was developed together with the optical follow-up team (M. Kowalski's group), that selects high quality up-going muon tracks at the South Pole. Due to the computing power restraints at the Pole this selection is necessary before more extensive reconstruction algorithms can be run. The Online Level2 filter form also the basis of the optical follow program. As the point source analysis on IceCube now covers the full sky the Online Level 2 filter for the 77-string configuration of IceCube that will start in April 2010 was extend to cover also the full Southern Sky ("Down-going events"). This will allow to extend the reach of the follow-up programs also above the horizon.

To ensure that follow-up alerts are only send when the detector is in stable running conditions, an online stability monitoring program was implemented at the South Pole. This is based on the idea that one compares different detector trigger and filter rates to their running averages to be sensitive to possible problems at the various stages of detector and DAQ operations. The trigger and filter rates are measured on very short time scales to be able to say something about the stability on time frames shorter than a full detector run (usually 8 hours). The rates are filled in a database directly at the Pole to be accessible for the follow-up program. In the future the information gained from this short term monitoring will also be included in the general detector monitoring. A plot of the online Level 2 filter rates for the year 2009 is shown in Figure 6.

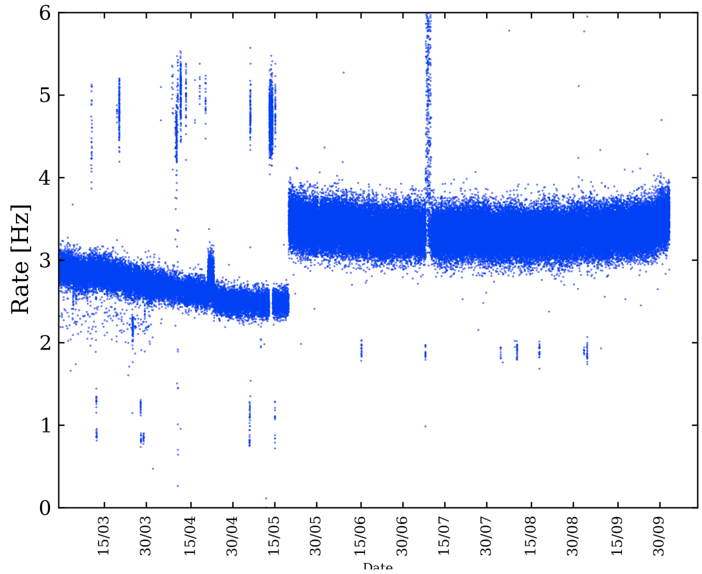


Figure 6: Rate of the Level 2 Online filter from March 2009 till September 2009. The data for IceCube in its 59-string configuration (from May 2009 onwards) has been measured online at the South Pole.

Based on the Online L2 filter for IC59 and the additional reconstructions that were run on these events at the Pole a neutrino selection was implemented. Figure 7 shows the effective are reached with that selection.

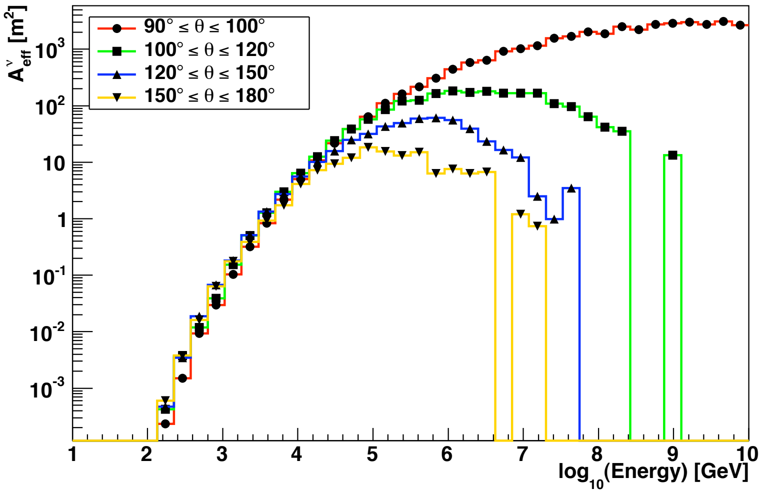


Figure 7: Effective area for the online neutrino selection based on the Online Level 2 filter for IceCube in its 59-string configuration.

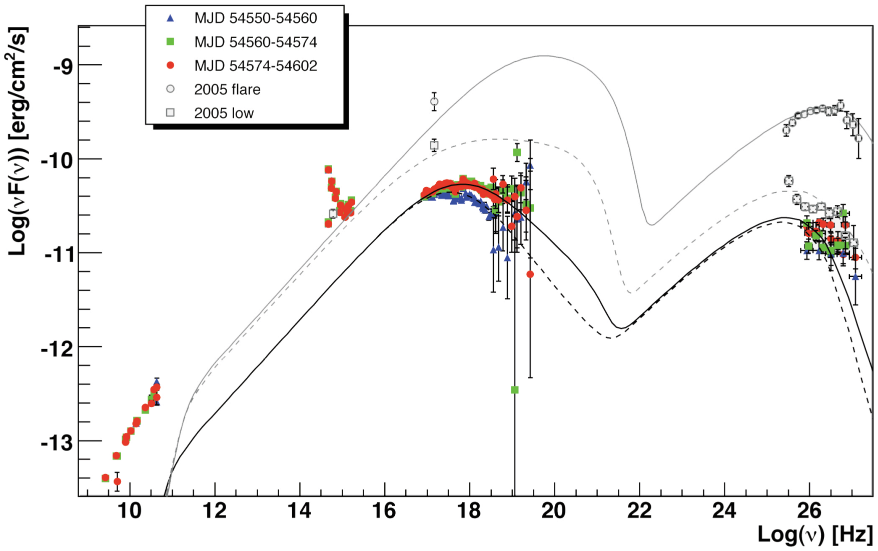
To be able to select events from pre-defined directions, assess the multiplet significance and finally send the alert message to the MAGIC telescope a software infrastructure had to be implemented at the Pole and in the North.

C. Study of gamma-ray emission of known objects with MAGIC

The group participated in the observation campaigns for Cycle 5 (which is the first cycle with stereo observations) with the following proposals:

1. **Monitoring of known AGN TeV sources**
2. **Observations of 3C273 with MAGIC Telescopes**
3. **Neutrino Triggered follow-up observations**

The **AGN monitoring program** aims at providing unbiased measurements of the long term flux variability. In particular: since most of the data is expected to be taken during low flux levels, it will increase the hitherto scarce statistics taken during quiescent states. This provides input to constrain theoretical models. In addition, it enables the determination of flaring state probabilities, essential to estimate the statistical significance of possible correlations between flaring states and other observables such as neutrino events. The selected AGNs are in the field-of-view of the neutrino observatory IceCube which is continuously observing the northern hemisphere with a yearly improving sensitivity. Moreover, the proposed measurements are well suited to trigger multi-wavelength ToO observations, which are based on high GeV/TeV gamma ray flux levels.
This activity is a continuation of the "bright Blazars monitoring campaign" from Cycles 3 and 4. The group was involved in the analysis of data on the Blazars Markarian 501 and 1ES 1959+650 data. Results were presented at the 31st ICRC [K. Satalecka et al, arXiv: 0907.0893 (2009)]. Paper summarizing observations of Markarian 501, Markarian 421 and 1ES 1959 from Cycles 3-5 in preparation.
Part of this data was also collected during multi-wavelength campaigns, which cover several orders of magnitude in energy. In 2009 a dedicated study of the spectral energy distribution (SED) was carried out. Results are shown in Figure 8 (published in D. Kranich et al. arXiv: 0907.1098). The model code was developd by [Tavecchio et al. (2001)]. It is able to accurately reproduce the data at X-ray energies. The discrepancy between the model and the data at lower energies (radio, optical) can be caused by synchrotron radiation from additional, cooler electron populations which could be present at different locations in the jet. In comparison to the historical 2005 SED, the model parameters (the size of the emission region, the Doppler factor, the magnetic field, the electron energy distribution) have changed significantly. In the framework of two populations of electrons, this result suggests that the population of cool electrons does not vary with time while the population of electrons responsible for the X-ray (Synchrotron) and gamma-ray (Inverse Compton) emission is very dynamic.



This line of activity is being continued 2010 as well (observation Cycle VI), with improved concepts by monitoring of the source behavior not only in gamma-rays but also other wavelengths (with a "multi-wavelength monitoring"). This requires a huge effort, involving many instruments.

The **observations of 3C273** could unfortunately not take place, due to limited observation time available and not optimal conditions for the observations (visibility, bad weather).

For the **neutrino triggered follow-up program** (NToO, se previous section) an observation proposal was submitted). We requested 20 hours of maximum observation time with MAGIC. The IceCube alert system was however not yet finalized during this observation Cycle and no alert was issued. The proposal for the next Cycle has just been resubmitted.

Teaching

“Astroparticle Physics” at the Humboldt University in Berlin, by E. Bernardini, Winter Semester 2008/2009.

Refereed Journal Publications

- MAGIC TeV Gamma-Ray Observations of Markarian 421 during Multiwavelength Campaigns in 2006, MAGIC Collaboration (J. Aleksić et al.), Astron. Astrophys. subm. 2009 December 23.
- Simultaneous multi-frequency observation of the unknown redshift blazar PG 1553+113 in March-April 2008, MAGIC Collaboration (J. Aleksić et al.), Astron. Astrophys. subm. 2009 November 6.
- Correlated X-ray and Very High Energy emission in the gamma-ray binary LS I +61 303, MAGIC Collaboration (H. Anderhub et al.), Astrophys. J. 706 (2009) L27.
- MAGIC observation of the GRB 080430 afterglow, MAGIC Collaboration (J. Aleksić et al.), submitted for publication to Astron. Astrophys. 2009 October 13.
- Simultaneous Multiwavelength Observation of Mkn501 in a Low State in 2006, MAGIC Collaboration (H. Anderhub et al.), Astrophys. J. 705 (2009) 1624.
- THE JUNE 2008 FLARE OF MARKARIAN 421 FROM OPTICAL TO TEV ENERGIES, AGILE, GASPWEBT, MAGIC,VERITAS Collaborations, (I. Donnarumma et al.), Astrophys. J. Lett. 691, L13 (2009).
- Suzaku and Multi-wavelength Observations of OJ 287 during the Periodic Optical Outburst in 2007, KANATA and MAGIC Collaboration (H. Seta et al.), PASJ, accepted, arXiv:0906.0234 (2009).

- First Neutrino Point-Source Results From the 22 String IceCube Detector, IceCube Collaboration (R. Abbasi et al.), Astrophysical J. Lett. 701, L47 (2009).
- MAGIC upper limits to the VHE gamma-ray flux of 3C454.3 in high emission state, MAGIC Collaboration (H. Anderhub et al.), Astron. Astrophys. in press.
- Discovery of a very high energy gamma-ray signal from the 3C 66A/B region, AGILE, MAGIC Collaboration (E. Aliu et al.), Astrophys. J. Lett. 692, 29 (2009).
- Radio Imaging of the Very-High-Energy gamma-Ray Emission Region in the Central Engine of a Radio Galaxy, The VLBA 43 GHz M 87 Monitoring Team and MAGIC, H.E.S.S. and VERITAS Collaborations (V.A. Acciari et al .), Science 325, 444 (2009).
- Search for VHE gamma-ray emission from the globular cluster M13 with the MAGIC telescope, MAGIC Collaboration (H. Anderhub et al.), ,Astrophys. J. 702, 66 (2009).
- IMPROVING THE PERFORMANCE OF THE SINGLE-DISH CHERENKOV TELESCOPE MAGIC THROUGH THE USE OF SIGNAL TIMING, MAGIC Collaboration (E. Aliu et al.), Astropart. Phys. 30, 293 (2009).
- Upper limits on the VHE gamma-ray emission from the Willman 1 satellite galaxy with the MAGIC Telescope, MAGIC Collaboration (E. Aliu et al.), Astrophys.J. 697, 1299 (2009).
- PERIODIC VERY HIGH ENERGY GAMMA-RAY EMISSION FROM LS I+61O 303 OBSERVED WITH THE MAGIC TELESCOPE, MAGIC Collaboration (J. Albert et al.), Astrophys. J. 693, 303 (2009).
- The IceCube Data Acquisition System: Signal Capture, Digitization, and Time stamping, IceCube Collaboration (R. Abbasi et al.), Nucl. Instrum. Meth. A601, 294 (2009).
- Search for High-Energy Muon Neutrinos from the "Naked-Eye" GRB 080319B with the IceCube Neutrino Telescope, IceCube Collaboration (R. Abbasi et al .), Astrophys. J. 701, 1721 (2009).
- Discovery of Very High Energy gamma-rays from the blazar S5 0716+714, MAGIC Collaboration (H. Anderhub et al .), Astrophys. J. Lett., submitted, arXiv:0907.2386.
- Determination of the Atmospheric Neutrino Flux and Searches for New Physics with AMANDA-II, IceCube Collaboration (R. Abbasi et al.), Phys. Rev. D79, 102005 (2009).
- Limits on a Muon Flux from Neutralino Annihilations in the Sun with the IceCube 22-string Detector, IceCube Collaboration (R. Abbasi et al.), Phys. Rev. Lett. 102, 201302 (2009).