IceCube-DeepCore: Sensitivity study for the Southern Hemisphere.

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The view from a Neutrino Telescope

To search for galactic sources, a neutrino telescope uses the Earth as a shield against atmospheric muons.

IceCube is at the South Pole.

Field of view ($E_\nu < 1$ PeV):
Northern Hemisphere.

Young shell-type supernova remnants are (among) the best candidate galactic neutrino sources.

Southern Hemisphere:
At least 5 SNRs have been detected + Galactic Center + Many sources to be identify
**The link to Gamma-Ray Astronomy**

**Benchmark source:** SNR RXJ 1713.7-3946  
**Right Ascension:** 17:13:00 h  
**Declination:** -39:45:00 deg  
Very young and the brightest SNR of the Southern Hemisphere

The measured gamma ray spectrum allows to estimate the neutrino spectrum, in the case that they are produced in proton-proton interactions [astro-ph]arxiv: 0607286 (2007).

How to open the field of view of IceCube to the Southern Hemisphere for galactic neutrino sources with a soft-spectrum?

\[
\frac{dN}{dE_\nu} = 15.52 \left( \frac{E_\nu}{1 \text{ TeV}} \right)^{-1.72} e^{-\sqrt{\frac{E_\nu}{1.35}}} 10^{-12} \text{ TeV}^{-1} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}
\]
1. Requirements to observe Galactic Neutrino Sources with soft spectra:
   a. Optimize IceCube for low neutrino energies (<100 TeV).
      → *IceCube-DeepCore subarray*
   b. Open the field of view of IceCube to the hemisphere directly above the telescope.
      → *Atmospheric Muon Veto*
   c. Reduce the background of atmospheric neutrinos which dominates over the expected signal.
      → *Atmospheric Neutrino Veto*

2. Discovery Potential to RXJ 1713.7-3846

3. Sensitivity to RXJ 1713.7-3846

4. Conclusion and future perspectives
DeepCore is a compact Cherenkov detector at the bottom center of IceCube (see Per Olof Hulth talk “DeepCore Design and Initial Performances”)

- DeepCore consists of 6 additional strings of 360 high quantum efficiency photo-tubes.

- **Denser spacing** of the photo-tubes compared to IceCube.

- Detector is **complete** since January 2010.

- **Two additional strings** will be deployed in 2011.

**Purpose:**

- Provide new capabilities compared to AMANDA-II (decommissioned in May 2009)

- Enhance the sensitivity of IceCube for **low energies** (< 1 TeV).

- Lower the detection threshold of IceCube by an order of magnitude to **below 10 TeV**.
The Atmospheric muon Veto

Veto atmospheric muons while keeping a good passing rate of starting neutrinos.

Events with hits in the veto region (shaded) are treated as atmospheric muon background. Events with hits in the fiducial region are signal.

Fiducial Volume: cylinder around String 36. R=200m, H=350m (6 DC strings + 7 surrounding IC strings.)

Sources: [astro-ph]:0907.2263 and Sebastian Euler.'s thesis.
**Atmospheric muon Veto: L1 & L2 cuts**

- **Level 1 cuts** aim to reduce the atmospheric background for 4 orders of magnitude, before reconstruction, using only the topology of the hits.

  → Keep events with **hits only in the Fiducial Region**
  → Background rejection: $\sim 5 \times 10^{-4}$

- **Level 2 cuts** are based on the output of the vertex reconstruction algorithm.

  **LLHR** – Likelihood for the track to be starting inside the Fiducial Volume.

  The reconstructed vertex position is described by the **Z-coordinate** and the **radius $R$** from the center of IceCube-DeepCore:

  \[ R = \sqrt{(X_{\text{vertex}} - 46m)^2 + (Y_{\text{vertex}} + 34.5m)^2} \]

  → Background rejection: $10^{-6}$-$10^{-7}$

  **Rmq**: The vertex reconstruction works with the true track information.
L2 Cuts: Optimization for Point Source searches

Reject atmospheric muon background while keeping the maximum number of signal events starting inside IceCube-DeepCore.

**R < 110m, Z < -250 and LLHR < -17**
Background rejection: $10^{-7}$
Signal passing rate: 24%

**R < 180m, Z < -210 and LLHR < -16**
Background rejection: $10^{-6}$
Signal passing rate: 46%

**R < 250m, Z < -140 and LLHR < -8**
Background rejection: $10^{-5}$
Signal passing rate: 85%
Point source analysis: SNR RXJ 1713.7-3946

- **Monte Carlo simulations** with IceCube 80-strings and DeepCore 6-strings configurations.

- Signal events are distributed according to:

\[
\frac{dN}{dE_{\nu}} = 15.52 \left( \frac{E_{\nu}}{1 \text{ TeV}} \right)^{-1.72} e^{-\sqrt{\frac{E_{\nu}}{1.35}}} \times 10^{-12} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}.
\]

- Keep signal events in a **zenith band of** 10° around the source: \(45.25^\circ < \theta < 55.25^\circ\) for neutrino energies \(10 \text{ GeV} < E < 10^{10} \text{ GeV}\).

- Atmospheric neutrino background: conventional flux following Honda 2006 computations.

- Atmospheric muon background generated with CORSIKA.

- Gaussian **source PSF**:

\[
S_i = \frac{1}{2 \pi \sigma^2} e^{-\frac{|\vec{x}_i - \vec{x}_S|}{2 \sigma^2}}.
\]

**Track reconstruction algorithms under development**

\[
\sigma = 2^\circ \quad \text{(mean AMANDA angular resolution)}
\]

Neutrino energies considered: \(100 \text{ GeV} < E_{\nu} < 1 \text{ PeV}\).
At Tev-PeV energies, the opening angle between the $\nu_\mu$ and the secondary $\mu$ is very small.

→ an atmospheric neutrino has a certain probability to reach the detector accompanied by its partner muon.

- Veto downward-going atmospheric neutrinos by the detection of a correlated muon.

- The veto performances depend on the atmospheric muon veto efficiency, the depth of the telescope and on the neutrino energy and direction.
The events are given a probability to belong to the source with a certain uncertainty $\sigma$.

$$S_i = \frac{1}{2\pi\sigma^2} e^{-\frac{|\mathbf{x}_i - \mathbf{x}_S|}{2\sigma^2}}$$

Source PDF with $\sigma$: DeepCore angular resolution ($2^\circ$)

The probability for an event to be an atmospheric background event is given by:

$$B_i = \frac{1}{\omega_{band}}$$

Background PDF with $\omega$: solid angle of the zenith band.

The **Likelihood** for a source to be at location $X_S$ with a strength $N_S$ is therefore:

$$L = \prod_N \frac{N^S}{N} S_i + \left(1 - \frac{N^S}{N}\right) B_i$$

$N$: total number of events (signal + background)

The likelihood $L$ is maximized to obtain the best estimate of the number of signal events.
Test Statistic

- Mean source strength: **0-40 events**.

→ Scale the flux model by a factor **FLUXSCALE**.

- Downward fluctuations of the background: \((Ns < 0)\)

- Signal + Background simulation: **1000** experiments for each **FLUXSCALE**.

- Background alone: **10000** experiments with randomized azimuth.

For each experiment we record the **test statistic** \(\lambda\) to determine the **significance** of an observed deviation from the null hypothesis.

\[
\lambda = -2.\text{sign}(\hat{N}_S) \cdot \log \frac{L(\hat{X}_S, 0)}{L(\hat{X}_S, \hat{N}_S)}
\]

\(H_0 = L(\hat{X}_S, 0)\) The data consists only of background events.

\(H_S = L(\hat{X}_S, \hat{N}_S)\) The data consists of \(\hat{N}_S\) signal events from the source and background events.
Significance and discovery potential

Procedure

- The integral distribution of $\lambda$ for the background alone is calculated at the location of the source.

- The values of $\lambda$ corresponding to $3\sigma$ and $5\sigma$ are calculated.

- The discovery potential at $3\sigma$ and $5\sigma$ are the number of experiments with $\lambda$ above the $3\sigma$ and $5\sigma$ threshold, respectively.
Detection Probability

- 3σ and 5σ confidence level detection probability vs. Poisson mean number of source signal events (atmospheric muon background rejection: $10^{-6}$).

Number of signal events needed on top of the background to achieve a 50% chance of detection at the 3 and 5 σ:

$$\bar{\mu}(50\%, 3\sigma) = 7.656 \text{ events}$$

$$\bar{\mu}(50\%, 5\sigma) = 13.17 \text{ events}.$$
## Discovery Fluxes: SNR RXJ 1713.7-3946

### 3 σ confidence level:

<table>
<thead>
<tr>
<th>Nr</th>
<th>Bg rejection $10^{-6}$</th>
<th>Bg rejection $10^{-5}$</th>
<th>Atmospheric neutrino veto</th>
<th>Energy cut: $E_\nu &gt; 100$ GeV</th>
<th>Sensitivity [TeV$^{-1}$cm$^{-2}$sec$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\phi_{90%} \leq 1.22 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-9}$</td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>$\phi_{90%} \leq 4.00 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>$\phi_{90%} \leq 2.49 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$</td>
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### 5 σ confidence level:

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<th>Nr</th>
<th>Bg rejection $10^{-6}$</th>
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<th>Atmospheric neutrino veto</th>
<th>Energy cut: $E_\nu &gt; 100$ GeV</th>
<th>Discovery Flux [TeV$^{-1}$cm$^{-2}$sec$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\phi_{90%} \leq 2.46 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-9}$</td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>$\phi_{90%} \leq 6.96 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>$\phi_{90%} \leq 4.33 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$</td>
</tr>
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Sensitivity to the SNR RXJ 1713.7-3946

Procedure

- Use **Feldman and Cousins** [1] ordering principle based on likelihood ratios.

- Construct confidence belts (Poisson process with background) using the **test statistic** $\lambda$ as observable.

  → Determine the value of the mean source strength $<\hat{N}_S>$ which maximize $P(\lambda, <N_s>)$.

  → Evaluate the ratio of the two likelihoods:

  $$ R = \frac{P(\lambda, <N_s>)}{P(\lambda, <\hat{N}_S>)} $$

  → Values of $\lambda$ are added for a given $<N_s>$ to the acceptance region in decreasing order or $R$, until the sum of $P(\lambda, <N_s>)$ meets or exceeds 90% C.L.

- Upper limits are converted into upper flux limits with the corresponding **FLUXSCALE** factors.

- The sensitivity is the average upper flux limit obtained from the distribution of $\lambda$ for background alone $P(\lambda, 0)$

**Sensitivity to SNR RXJ 1713.7-3946**

<table>
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<th>Nr</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\phi_{90%} \leq 1.19 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-9}$</td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>$\phi_{90%} \leq 4.65 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>$\phi_{90%} \leq 2.41 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$</td>
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**Expected signal flux**

$\phi_{90\%} \leq 1.19 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-9}$

**Atmospheric neutrino flux (no veto)**

$\phi_{90\%} \leq 4.65 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$

**Atmospheric neutrino flux**

$\phi_{90\%} \leq 2.41 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$
CONCLUSIONS and OUTLOOK

- An innovative and exploratory approach to Neutrino Astronomy is under development to observe steady soft-spectra galactic neutrino sources.

- A very preliminary sensitivity to the benchmark source RXJ 1713.7-3946 has been presented.

- The atmospheric muon veto and IceCube-DeepCore can be used to open the field of view of IceCube to the Southern Hemisphere below 1 PeV.

- The atmospheric neutrino veto can be used to discriminate part of the source signal (depending on the source location and the neutrino energy) from the background of atmospheric neutrinos.
NEXT STEPS

- Develop dedicated simulations (based on CORSIKA) to assess the atmospheric neutrino veto capability in practice.

- Include muon track and energy reconstruction algorithms.
  → Determine IceCube-DeepCore angular resolution as a function of the energy.

- Study the influence of different fiducial volume geometries (asymmetric volume, ect...)

- Include energy term in the likelihood maximization (expected improvement of about 30%) as described in J.Braun et al., Astroparticle Physics 29 (2008) 299-305

- Estimate the sensitivity to other astrophysical objects of interest (H.E.S.S. SNRs, Galactic Center) throughout the Southern Hemisphere.

- Investigate potential extensions of IceCube-DeepCore to enhance the sensitivity.

- Analysis of the first data from the complete IceCube-DeepCore subarray in combination with the complete IceCube telescope.