IceCube-DeepCore: Sensitivity study for the Southern Hemisphere.

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Emmy-Noether group: “High-Energy Neutrino Astronomy with IceCube”

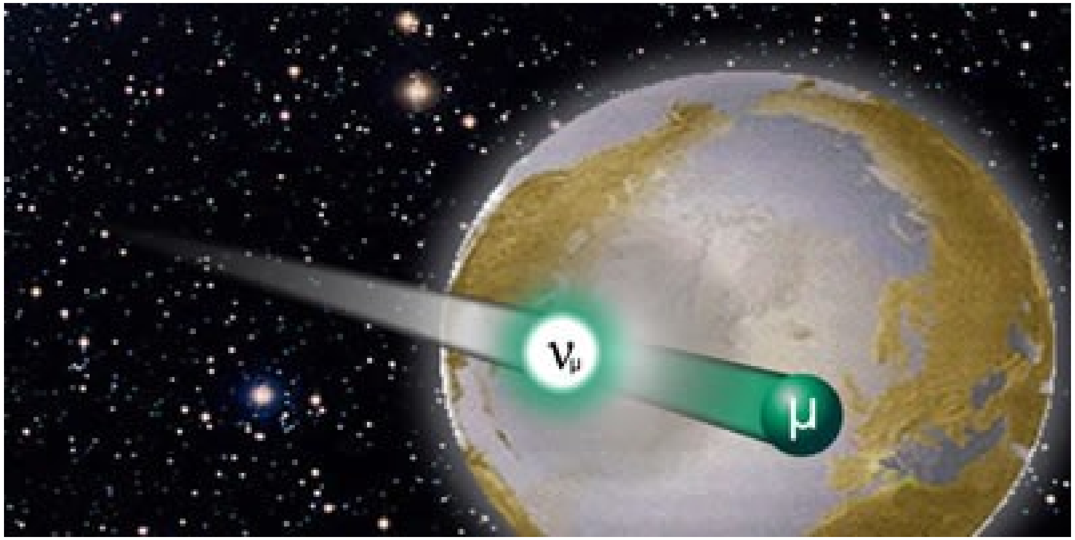
Max-Planck Institute for Nuclear Physics, Heidelberg, Germany

TeVPa Conference, Paris 20 July 2010

MAX-PLANCK-GESELLSCHAFT

IceCube

The view from a Neutrino Telescope

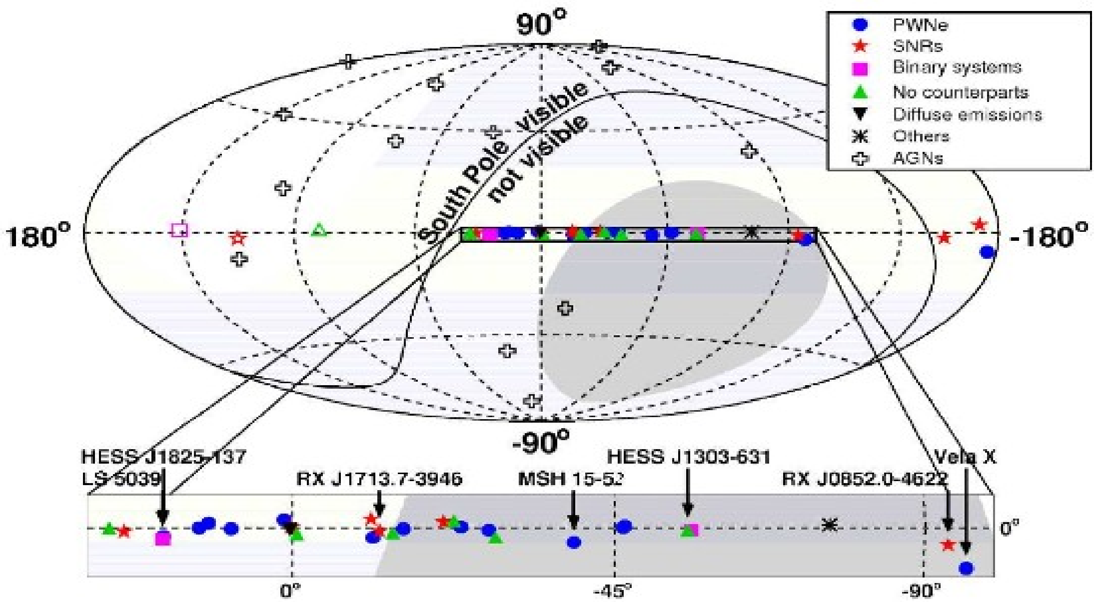


To search for **galactic sources**, a neutrino telescope uses the Earth as a shield against atmospheric muons.

IceCube is at the **South Pole.**

Field of view **(E_ν < 1 PeV):**

Northern Hemisphere.

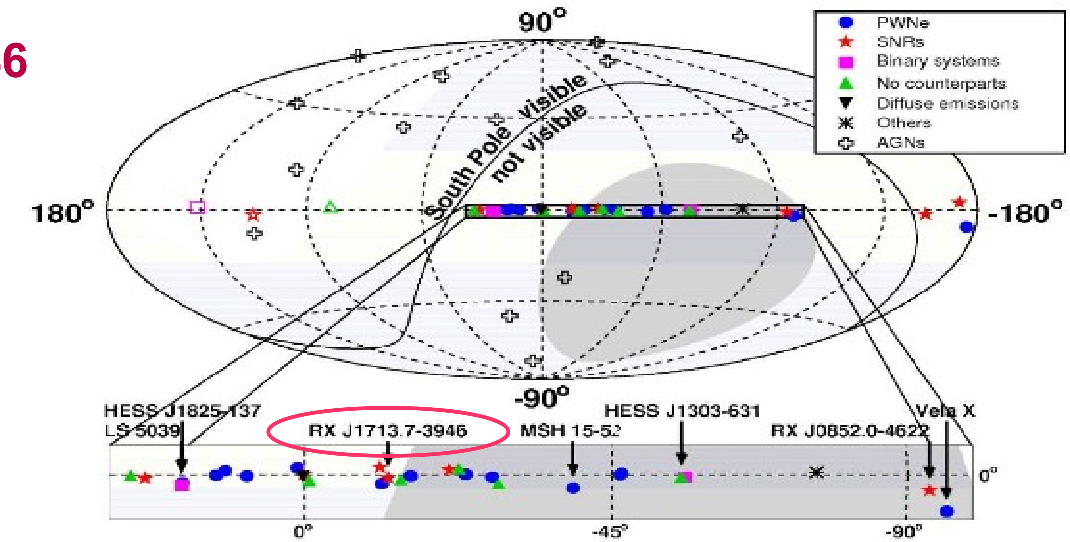


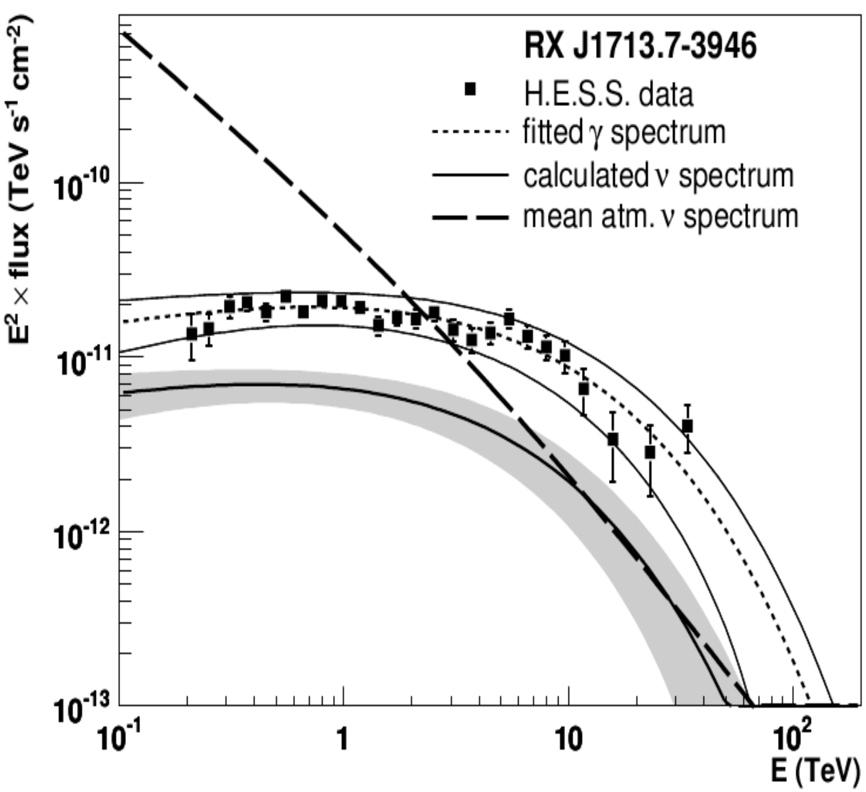
Southern Hemisphere:

At least **5 SNRs** have been detected
+
Galactic Center
+
Many **sources to be identified**

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?

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

OUTLINE

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***

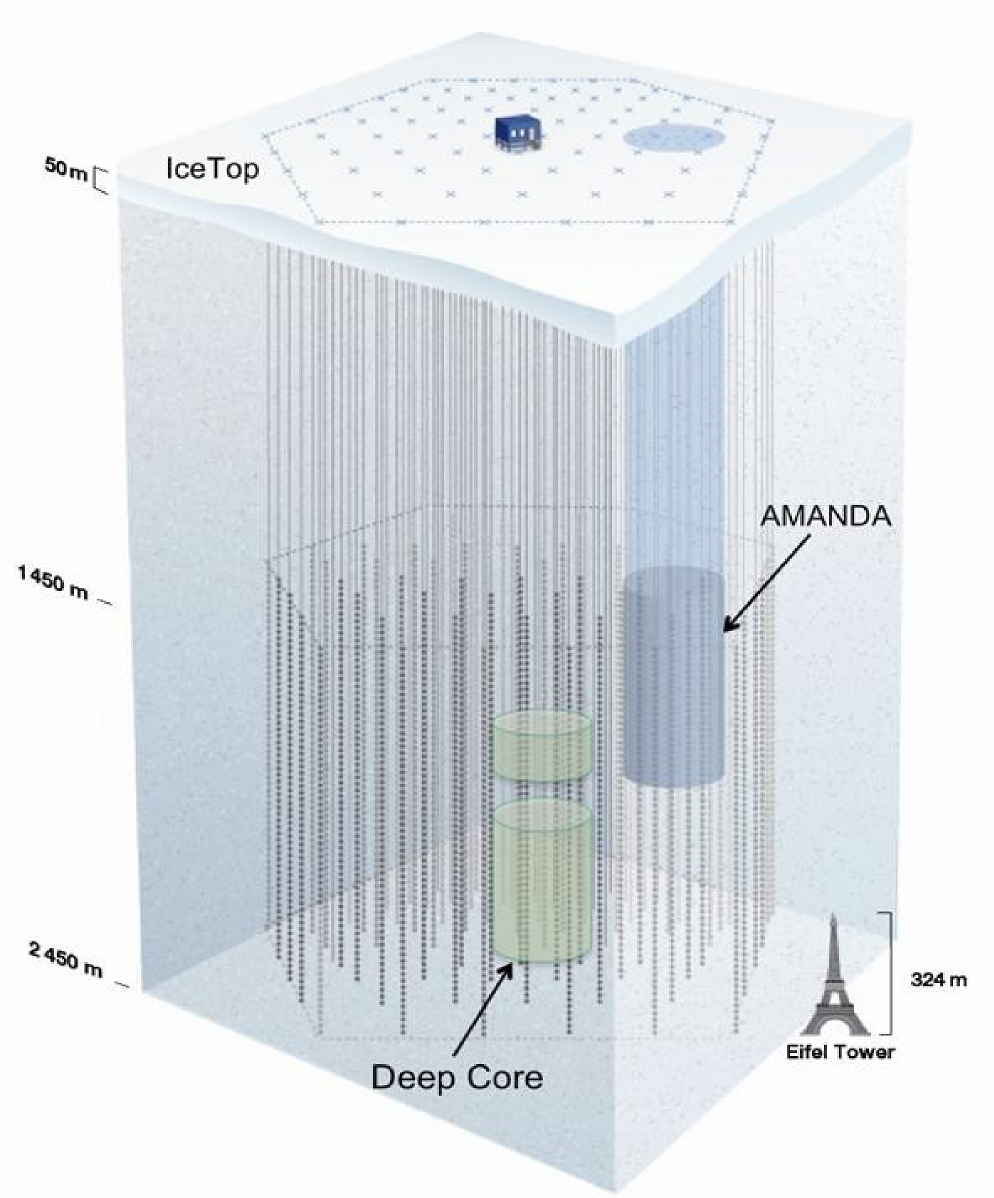
2. Discovery Potential to RXJ 1713.7-3946

3. Sensitivity to RXJ 1713.7-3946

4. Conclusion and future perspectives

The IceCube-DeepCore neutrino telescope

DeepCore is a compact Cherenkov detector at the bottom center of **Icecube.**
(*cf. Plenary talk of D.Williams, Status of the IceCube Neutrino Observatory*)



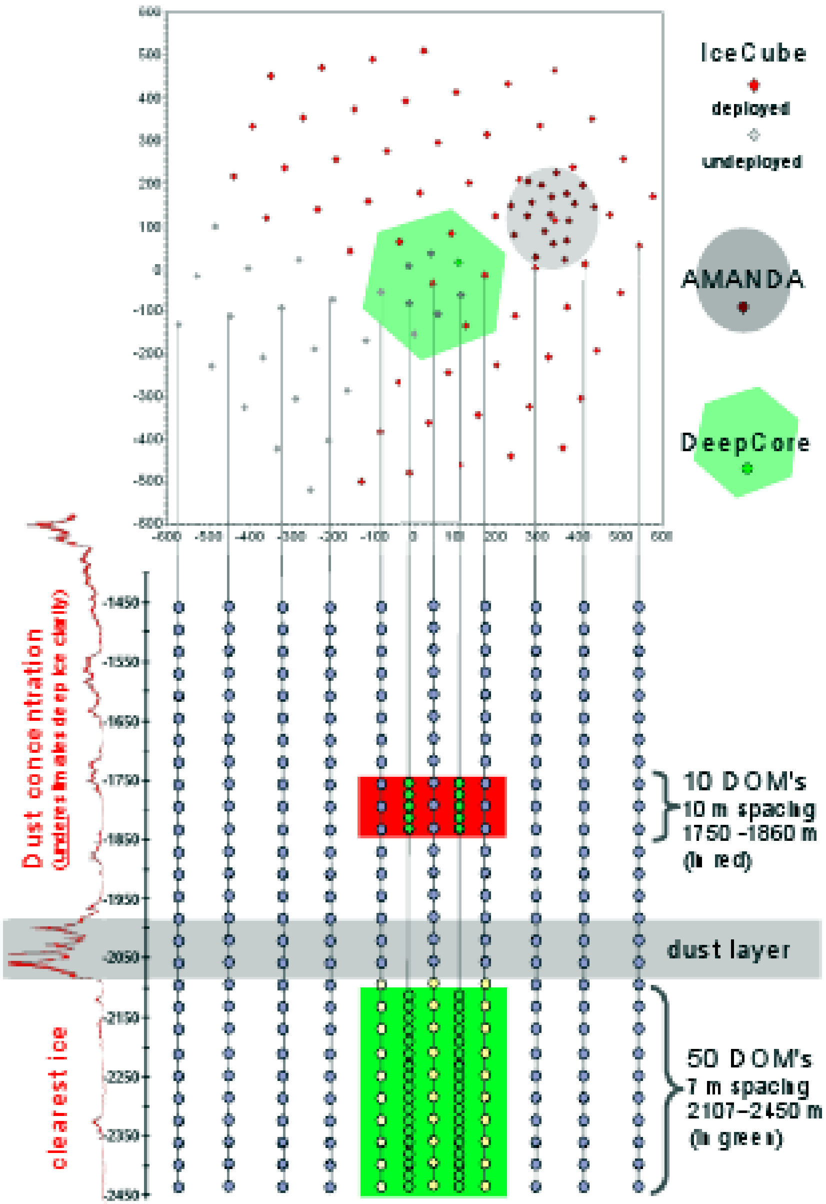
- DeepCore consists of 6 additional strings of 360 **high quantum efficiency photo-tubes.**
- **Denser spacing** of the photo-tubes compared to IceCube**.**
- Detector is **complete** since January 2010.
- **Two additional strings** will be deployed in 2011.

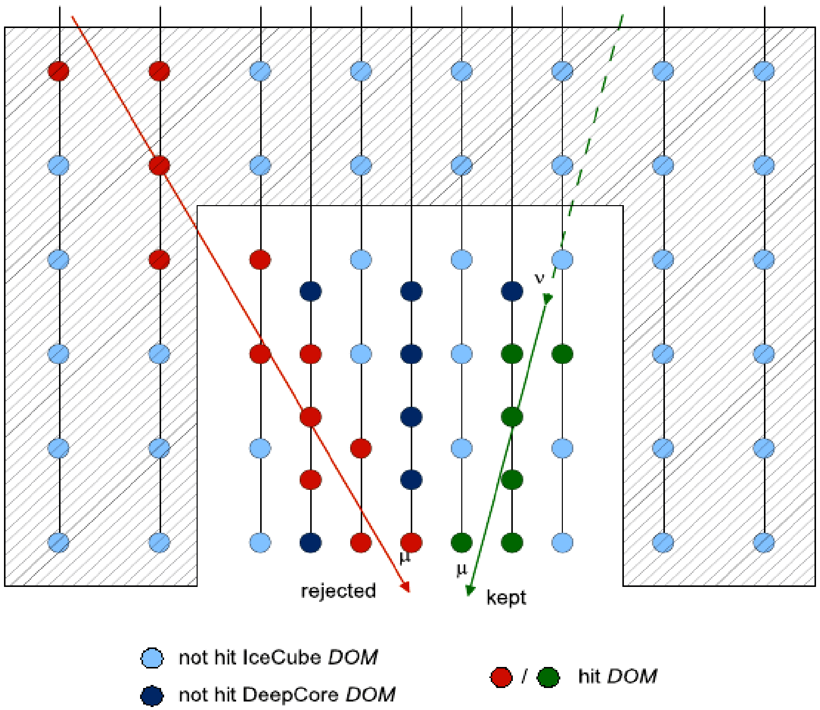
Purpose:

- Provide new capabilities compared to AMANDA (decomissioned 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 Volume***

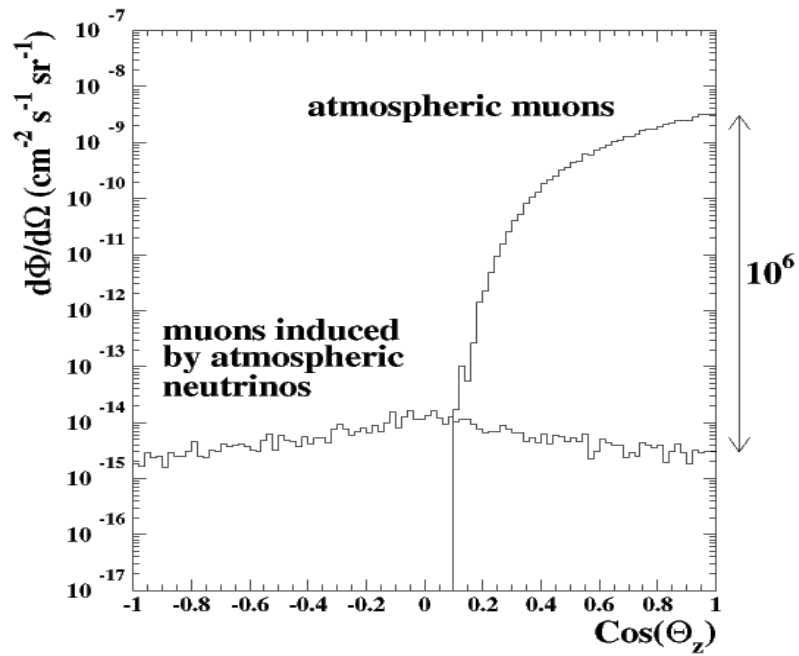
→ Background rejection: **~ 5 x 10^{-4}**

- **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:

$$R=\sqrt{\left(X_{vertex}-46\text{m}\right)^2+\left(Y_{vertex}+34.5\text{m}\right)^2}\ .$$

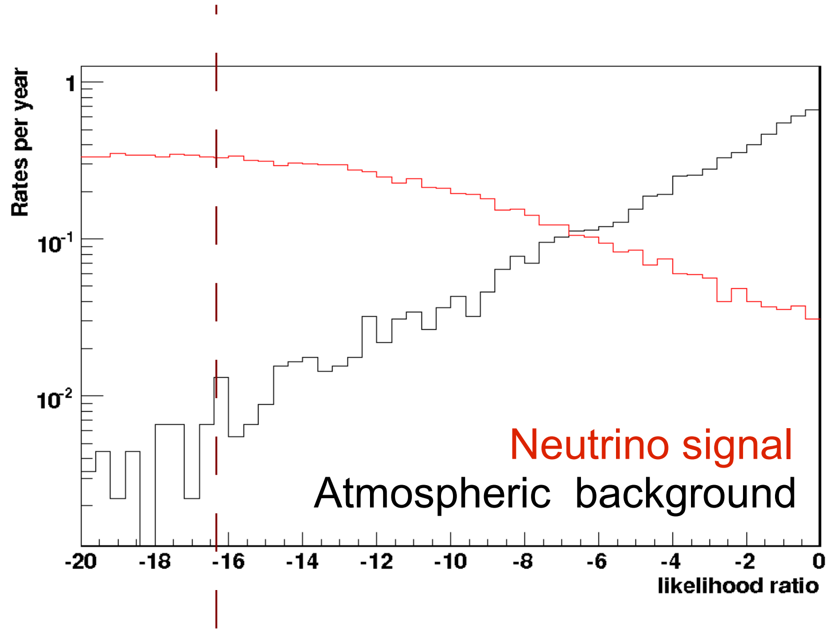
→ Background rejection: ~ **10^{-6}**

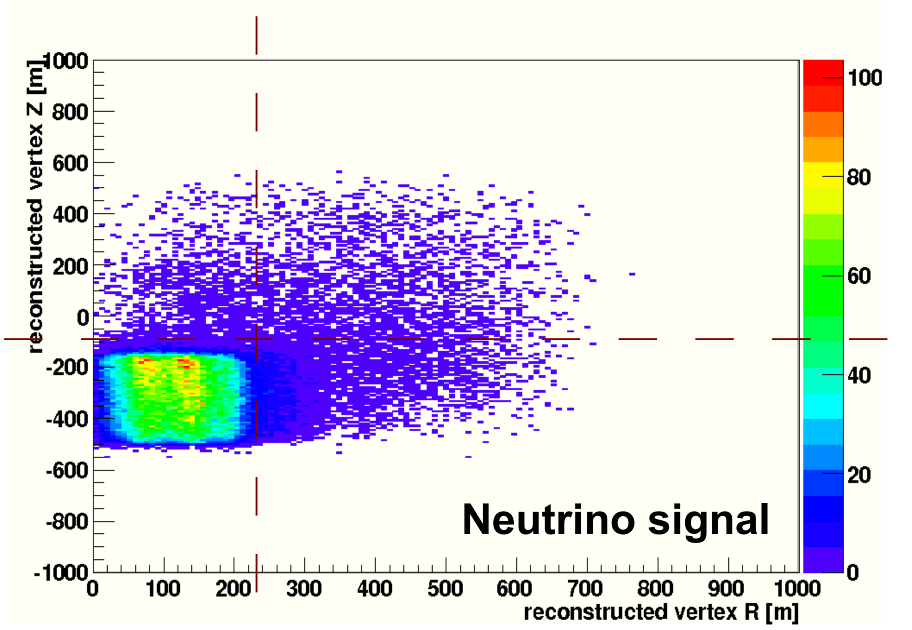


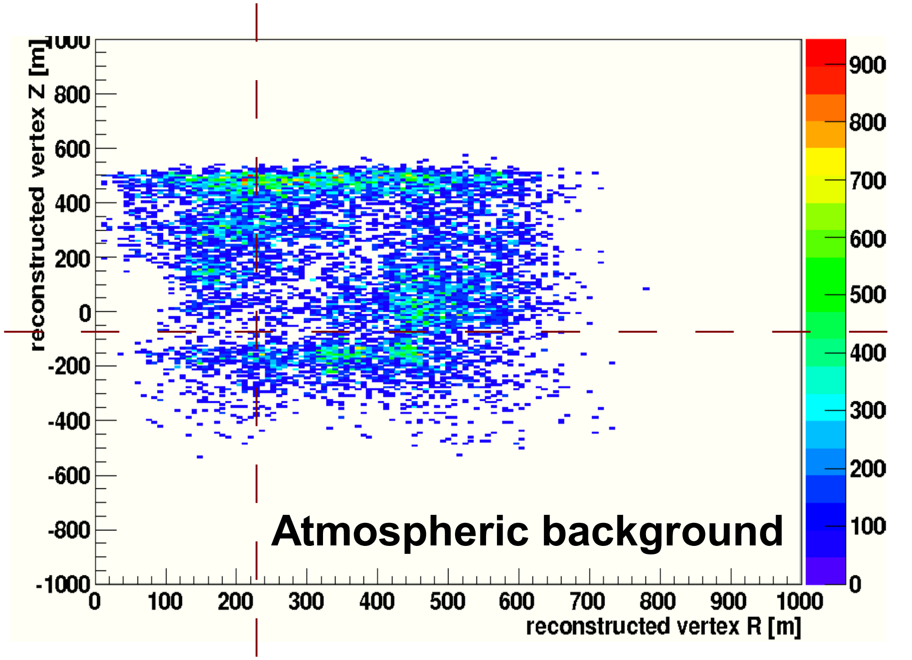
<u>Rmq</u>: The vertex reconstruction works with the true track information.

L2 Cuts: Optimization for Point Source search

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







R < 180m, Z < -210 and LLHR < -16

Background rejection: **10^{-6}**

Signal passing rate: ~ 50%

$$Purity = \frac{Signal}{Signal + Atmospheric\, muon\, background} > 98\%$$

Atmospheric neutrino veto

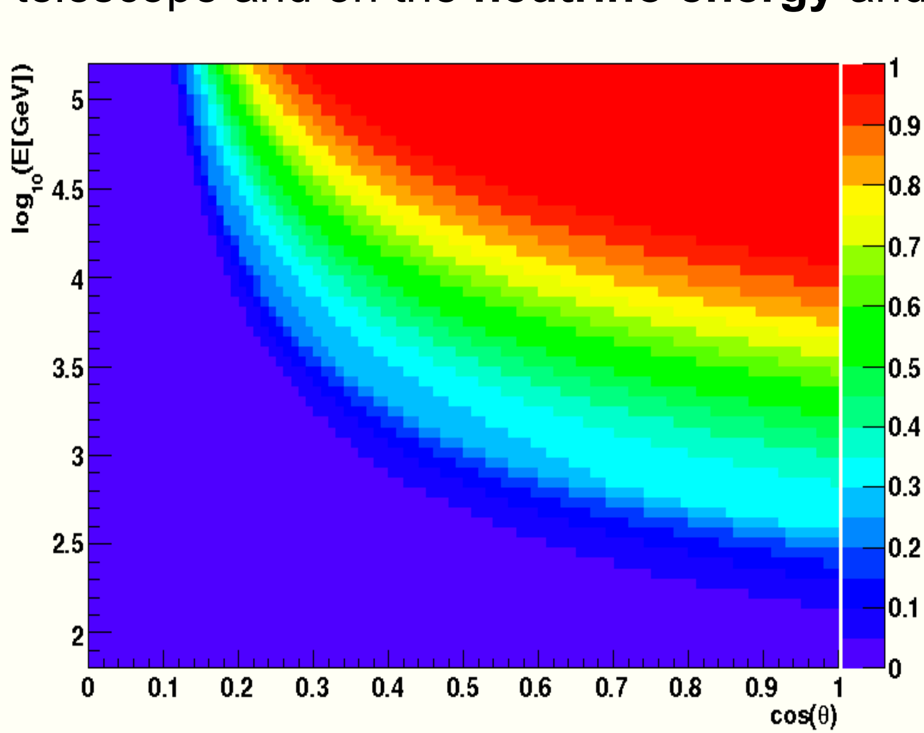
Phys.Rev.D79,043009 (2009) [astro-ph]: 0812.4308, S.Schonert et al.

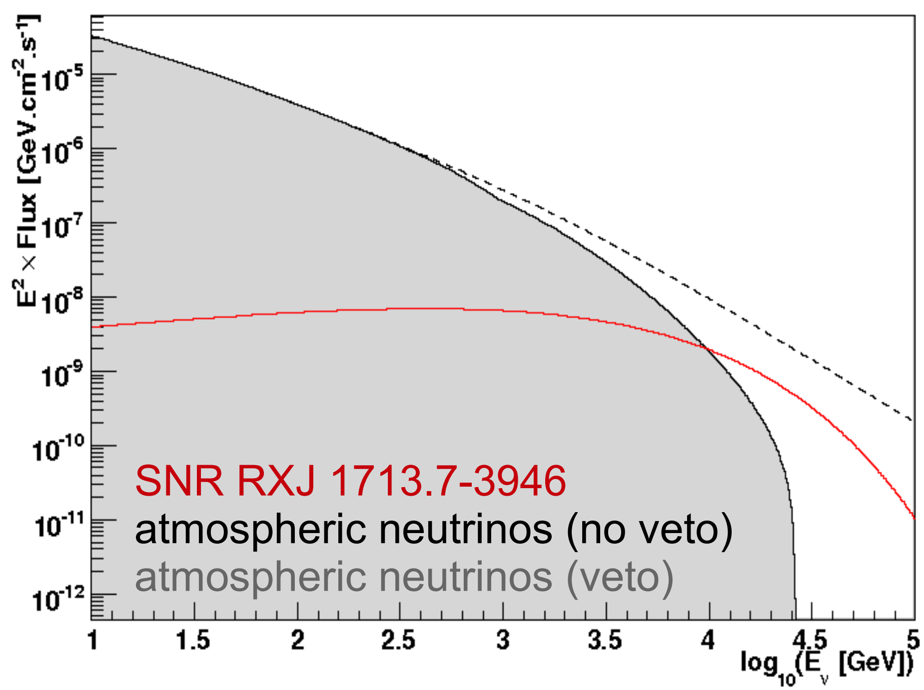
- At **Tev-PeV energies**, the opening angle between a downward-going atmospheric ν_μ and the μ produced by the decay of the same parent meson in the atmosphere is very small.

→ a downward-going atmospheric ν_μ has a **certain probability** to reach the detector accompanied by its partner μ .

→ veto a downward-going atmospheric ν_μ by the detection of a correlated atmospheric μ.

- The veto performances depend on the **atmospheric muon veto** efficiency, the **depth** of the telescope and on the **neutrino energy** and **direction**.





Point source analysis: SNR RXJ 1713.7-3946

- **Monte Carlo simulations** with **IceCube 80-strings** and **DeepCore 6-strings** configurations.
- Keep events in a **zenith band of width 10º** around the source: ***45.25º < θ < 55.25º***
- Background: - atmospheric neutrinos (conventional flux, Honda 2006) *< 2600 events*

  - atmospheric muons (CORSIKA) *< 20 events*
- Signal: muon-neutrinos starting inside IceCube-DeepCore: 2800 events
- Signal events are distributed according to:

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

- 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 are under development:

➞ Angular resolution of IceCube-DeepCore:

σ= 2º (mean AMANDA angular resolution)

Neutrino energies considered: ***100 GeV < E_ν < 1 PeV***.

Unbinned Likelihood Ratio method

J. Braun et al., Astropart.Phys.29:299-305 (2008)

- The events are given a probability to belong to the source with a certain uncertainty **σ**.

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

Source PDF with **σ**: DeepCore angular resolution (***2º***)

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

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

Background PDF with **ω**: solid angle of the zenith band.

- The **Likelihood** for a source to be at location Xs with a strength Ns 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: **<N_s> = 0 - 60 events**.

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

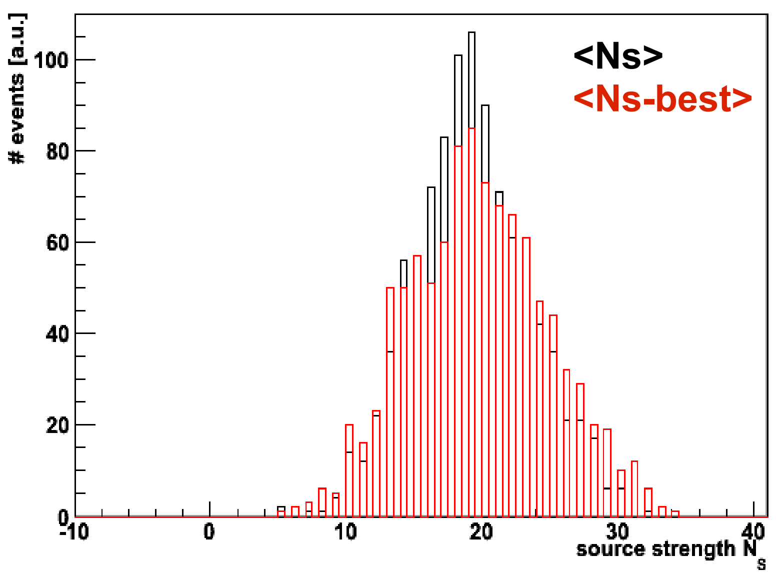
- Downward fluctuations of the background:

$-10 < N_s < 60$

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

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

FLUXSCALE = 1000



- For each experiment we record the **test statistic λ** to determine the **significance** of an observed deviation from the null hypothesis.

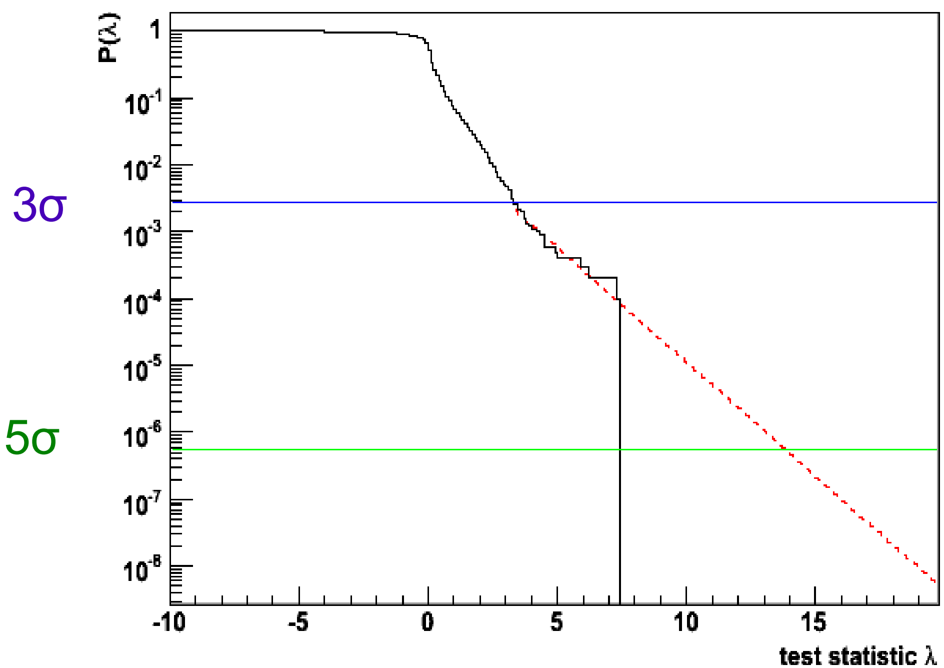
$$\lambda = -2.\text{sign}(\hat{N}_S).\log\frac{L(\vec{X}_S, 0)}{L(\vec{X}_S, \hat{N}_S)}$$

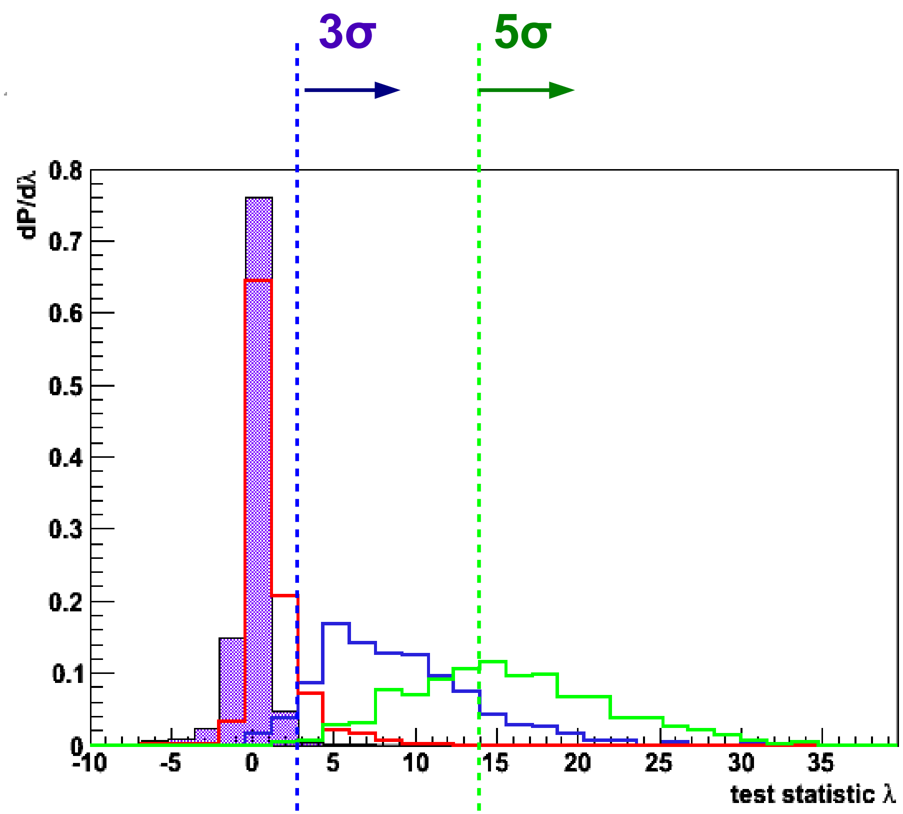
$H_0 = L(\vec{X}_S, 0)$ The data consists only of background events.

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

Significance and discovery potential

Procedure





λ = 3.4 λ = 13.9

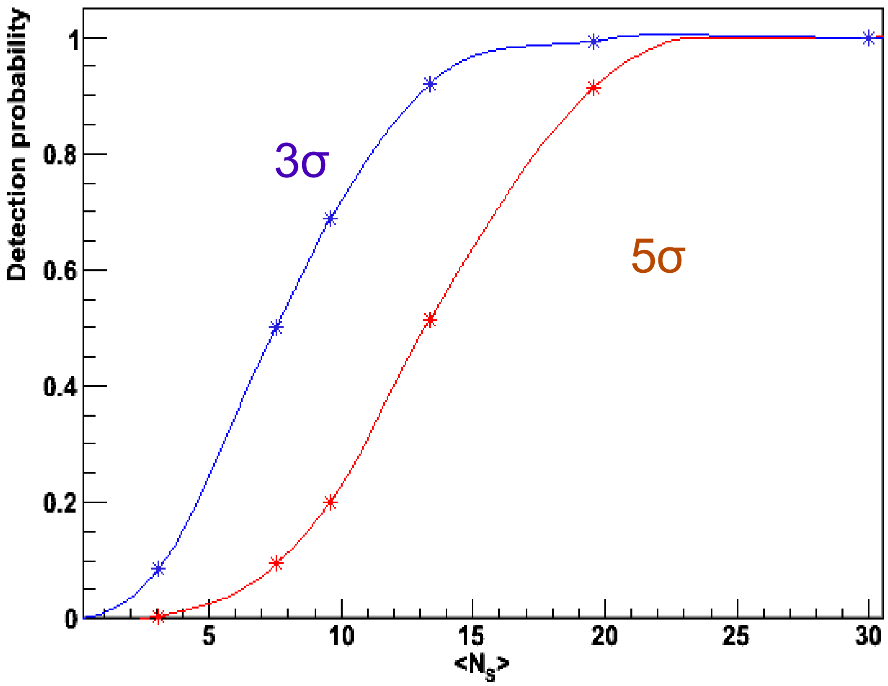
- The integral distribution of λ for the background alone is calculated at the location of the source.

- The values of λ corresponding to 3σ and 5σ are calculated.

- The discovery potential at 3σ and 5σ are the number of experiments with λ above the 3σ and 5σ threshold, respectively.

Discovery Fluxes: SNR RXJ 1713.7-3946

• 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 C.L.:

$$\begin{cases} \bar{\mu}(50\%, 3\sigma) = 7.656 \; events \\ \bar{\mu}(50\%, 5\sigma) = 13.17 \; events \; . \end{cases}$$

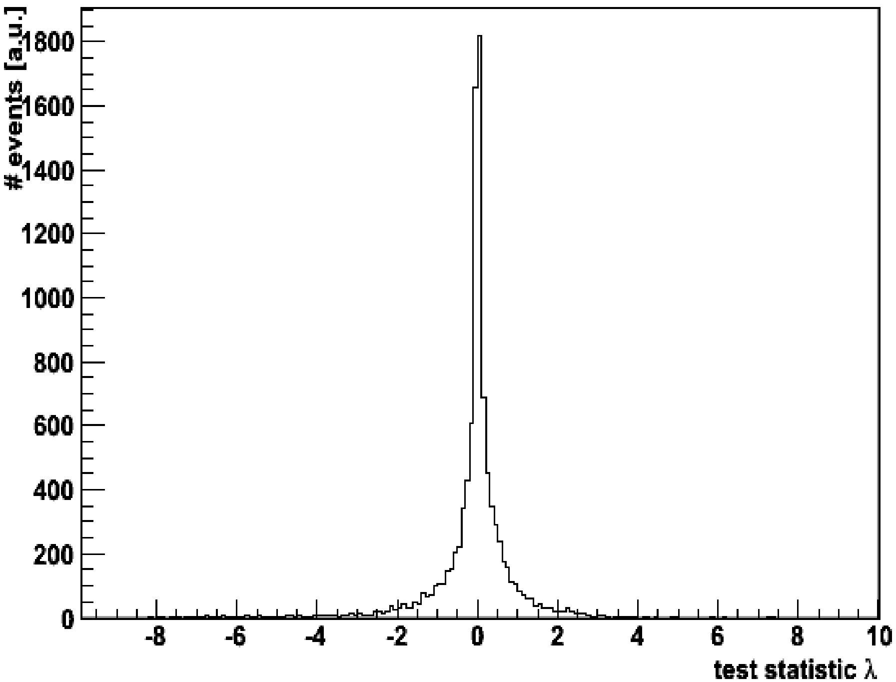
<u>DISCOVERY FLUXES (after one year)</u>:

$$\phi_{50\%,3\sigma} \leq 4.00 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10} \; TeV^{-1} \cdot cm^{-2} \cdot sr^{-1} \cdot s^{-1}$$

$$\phi_{50\%,5\sigma} \leq 6.96 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10} \; TeV^{-1} \cdot cm^{-2} \cdot sr^{-1} \cdot s^{-1}$$

Sensitivity to SNR RXJ 1713.7-3946

Neyman 90% C.L. Upper Limit (*Amsler et al. 2008*)



Distribution of λ for background alone

$\lambda_{Median} \sim 0.00$

<u>Neyman-Pearson lemma:</u>

Reject H_0 if $P(\lambda > \lambda_{Median} \mid H_0) = 90\%$

H_0 – Null hypothesis.

The data consists only of background

H_1 – The data consists of signal and background.

→ **μ90% = 5.86 events**

<u>Sensitivity at the 90% C.L (after one year)</u>:

$$\phi_{90\%} \leq 2.84 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}\, TeV^{-1} \cdot cm^{-2} \cdot sr^{-1} \cdot s^{-1}$$

Influence of the Atmospheric Neutrino Veto

Improvement Discovery Potential/Sensitivity of ~ 40%

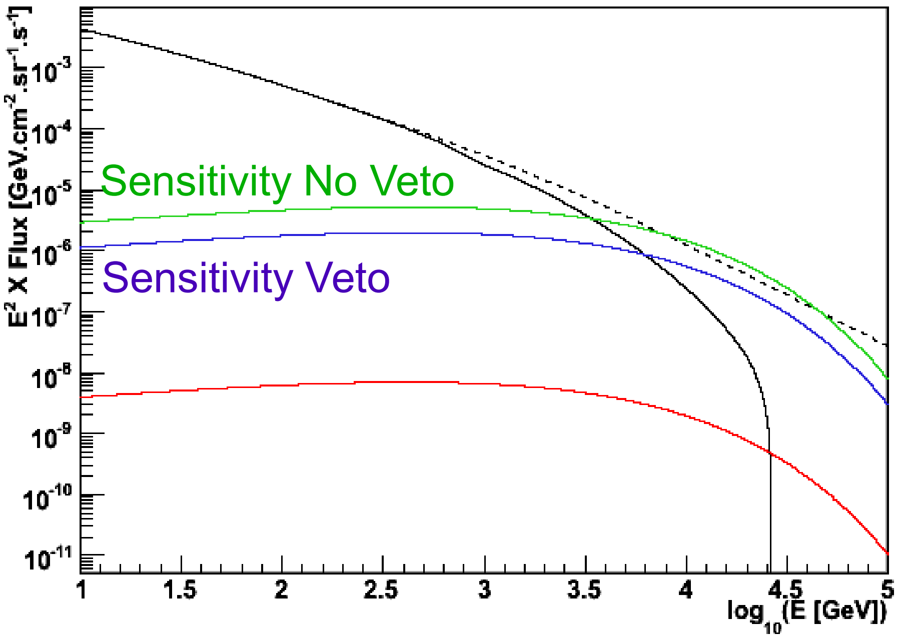
Discovery Fluxes after 1 year (unit: $TeV^{-1}.cm^{-2}.sr^{-1}.s^{-1}$):

$$\phi_{50\%,3\sigma} \leq 1.22 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-9} \longrightarrow \phi_{50\%,3\sigma} \leq 4.00 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$$

ν Atmo Veto

$$\phi_{50\%,5\sigma} \leq 2.46 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-9} \longrightarrow \phi_{50\%,5\sigma} \leq 6.96 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$$

Sensitivity after 1 year at the 90% C.L (unit: $TeV^{-1}.cm^{-2}.sr^{-1}.s^{-1}$):



(1) green line: $\phi_{90\%} \leq 7.42 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-9}$

(2) blue line: $\phi_{90\%} \leq 2.84 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$

- red line: expected signal flux
- dashed line: atmospheric neutrino flux (no veto)
- black line: atmospheric neutrino flux

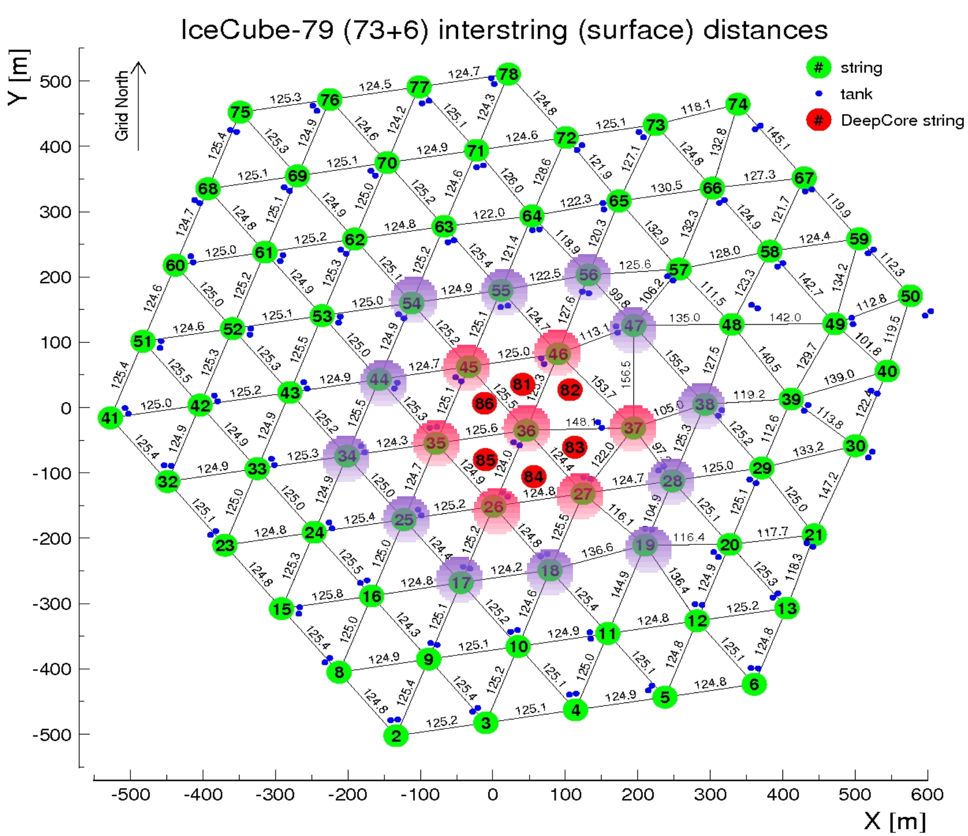
Influence of the L2 cuts and the geometry of the Fiducial Volume

Fiducial Volume 13 strings (Radius=200m, Height=350m):

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%



Fiducial Volume 25 strings (Radius=400m, Height=350m):

Increase in atmospheric muons (after L1 cuts): +82%
Increase in starting signal events (after L1 cuts): +53%

Background rejection **10^{-5}**

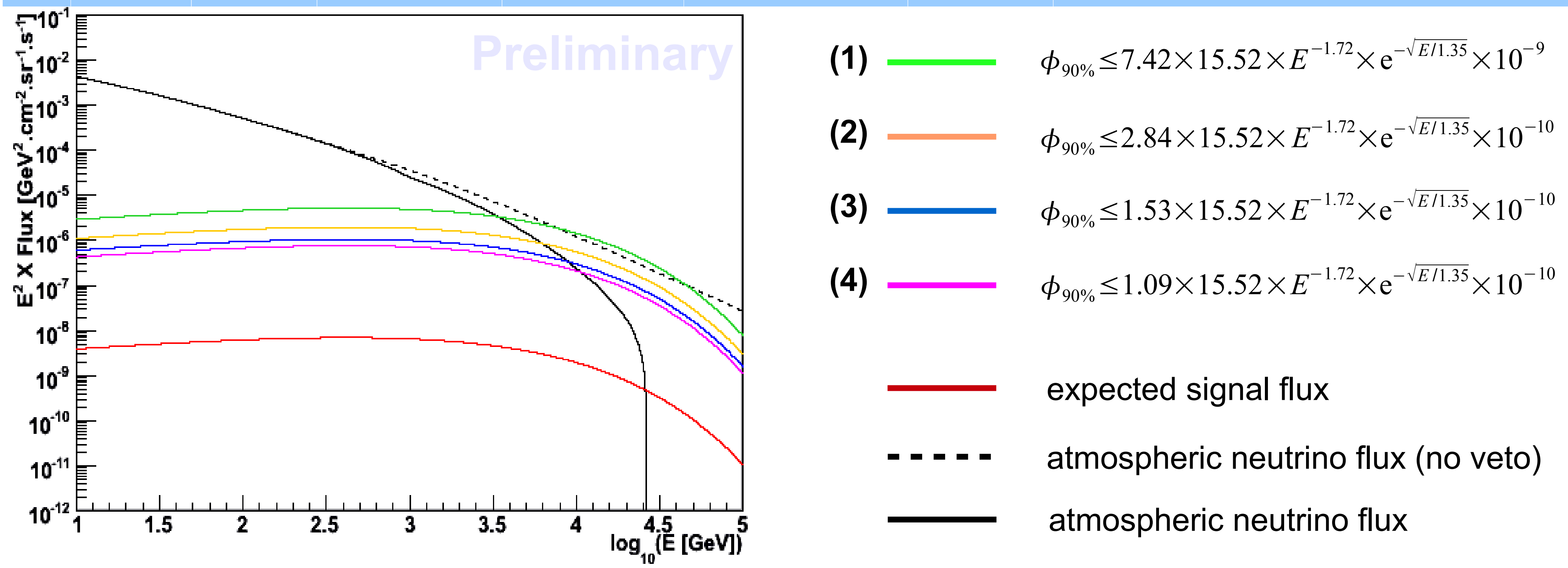
Signal passing rate: 52%

R < 190m, Z < -140 and LLHR < -7

Sensitivity to SNR RXJ 1713.7-3946

After one year, at the 90% C.L.

Nr	FV 13	FV 21	Bg rejection 10^{-6}	Bg rejection 10^{-5}	Atmospheric neutrino veto	Energy cut: E_ν>100 GeV	Sensitivity [$TeV^{-1}cm^{-2}.sec^{-1}$]
1	X	0	X	0	0	0	$\phi_{90\%} \leq 7.42 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-9}$
2	X	0	X	0	X	X	$\phi_{90\%} \leq 2.84 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$
3	X	0	0	X	X	X	$\phi_{90\%} \leq 1.53 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$
4	0	X	0	X	X	X	$\phi_{90\%} \leq 1.09 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$



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.

→ **Sensitivity to SNR RXJ 1713.7-3946 improved by 40%**.

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.

- 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 region) 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 (after February 2011).

Thank you!

EXTRA SLIDES