Blazars as Potential High-Energy Neutrino Sources

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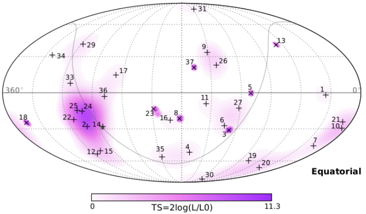
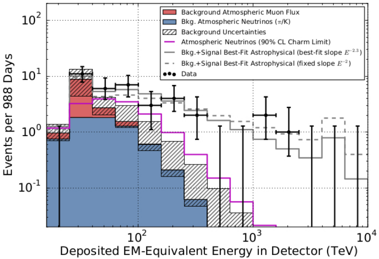
Fermi summer school
Lewes Delaware 2016

Evidence for a high-energy extraterrestrial neutrino signal



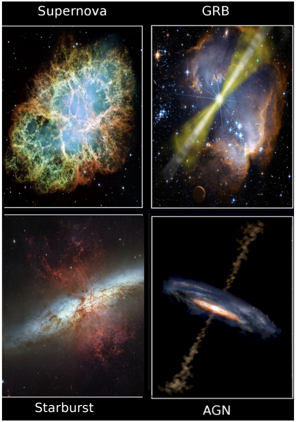
Credit: IceCube Collaboration 2014



But:

- What are the sources for the IceCube Neutrino Signal?

What are potential sources of extraterrestrial Neutrinos?

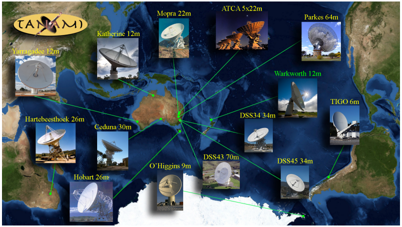


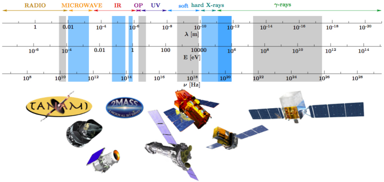
Starburst galaxies and AGN remain as potential source candidates as shown in:

- Krauß et al. 2014
- Padovani et al. 2016
- Waxman 2015

THE TANAMI PROGRAM

- Multiwavelength Monitoring of $\sim$ 90 AGN Jets South of $\delta < -30°$





- Includes the radio- and γ-ray brightest AGN in the IceCube PeV neutrino fields

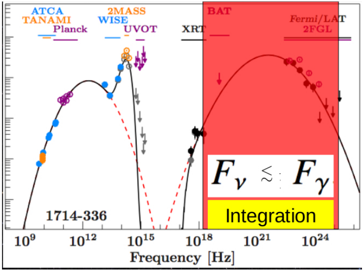
Which are the most promising sources?

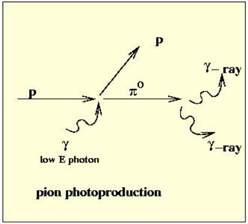
Pion Photoproduction:

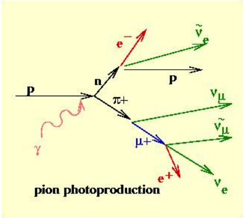
Maximum Neutrino Output:

$$F_\gamma = \frac{1}{3}F_\pi + \frac{1}{4}\cdot\frac{2}{3}F_\pi\frac{1}{2}F_\pi$$
$$F_\nu = \frac{2}{3}\cdot\frac{3}{4}F_\pi = \frac{1}{2}F_\pi$$
$$F_\gamma = F_\nu$$

- See Kadler,et al. 2016, arXiv:1602.02012



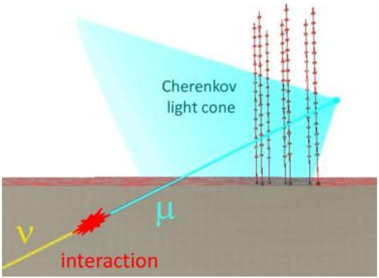




Credit: Mücke et al. 2000

Neutrino Detection

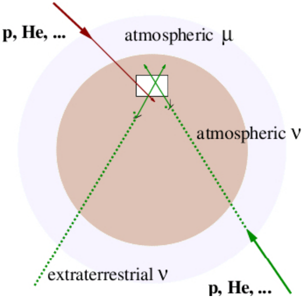
- Indirect detection via secondary particles (μ or e)
- Resulting particle emits Cherenkov light
- Cherenkov light is finally detected by an array of light sensors.



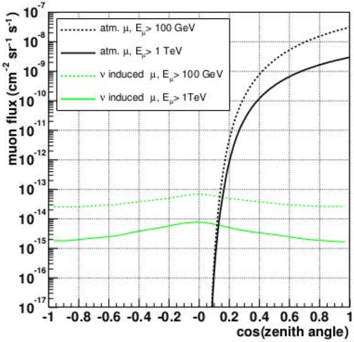
Credit: Ageron et al. 2011

Neutrino Detection

- Atmospheric background



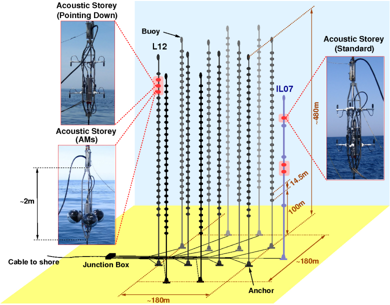
Credit: Katz & Spiering 2012

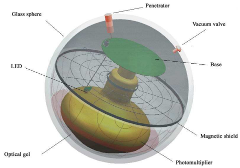


Credit: Okada 1994

The ANTARES Detector:

- located in 2500 m depth
- 12 vertical detection lines (a $\approx$ 450 m)
- 885 optical modules (OMs)
- 25 storeys per line (a 3 OMs)





Video

Time correlated analysis

- Select sources which are promising in F_γ of the southern Sky
- Unbinned Maximum likelihood analysis:

$$L(n_s) = \prod_{i=1}^{N} \left[\frac{n_s}{N} S_i + (1 - \frac{n_s}{N}) B_i \right]$$

n_s unknown contribution of the signal events

N number of events

S_i signal probability density

B_i background probability density

Time correlated analysis

Maximize the likelihood of the data

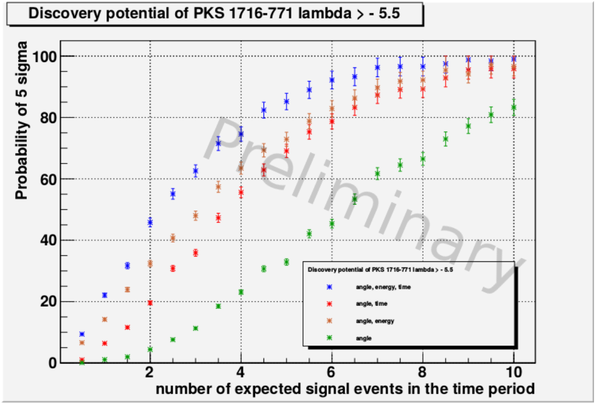
$$L(n_s) = \prod_{i=1}^{N} \left[\frac{n_s}{N} S_i + (1 - \frac{n_s}{N}) B_i \right]$$

$$S_i = N_i(\alpha) \times T_i(t) \times E_i^s$$
$$B_i = E_i^b$$

- $N_i(\alpha)$ direction dependent term
- E_i^s or E_i^b energy dependent term
- $T_i(t)$ time dependent term

Discovery potential

Probability for 5 σ discovery:



$\Rightarrow$ Best result for using γ and ν correlation

Summary

- Integrated flux of FSRQs can explain the IceCube PeV signal Kadler,et al. 2016, arXiv:1602.02012
- Major number of point source analysis are in time integrated mode
  $\Rightarrow$ Time correlation between γ and ν increases detection probability
- Application to TANAMI flaring blazar sample in preparation

GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

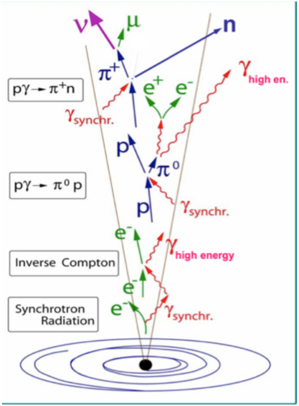
Backup

Neutrino Production in AGN Jets

Lepto-hadronic acceleration model:

$$p + nucleus \rightarrow \pi + X \qquad (\pi = \pi^{\pm}, \pi^0)$$

$$p + \gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} \pi^0 + p \\ \pi^{+} + n. \end{cases}$$



Credit: Katz & Spiering 2012

Neutrino Production in AGN Jets

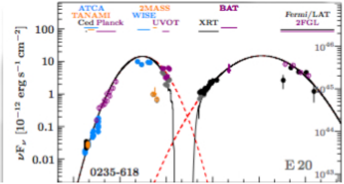
The resulting pions further decay into:

$$\pi^0 \rightarrow \gamma + \gamma$$

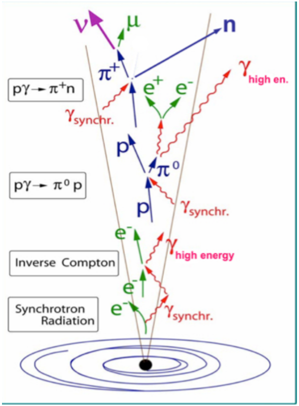
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu \text{ (or } \bar{\nu_\mu}\text{)}$$

$$\mu^+ \rightarrow e^+ + \bar{\nu_\mu} + \nu_e$$

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu_e}$$



Credit: Krauß et al. 2014, A&A 566, L7



Credit: Katz & Spiering 2012

TANAMI Blazars in the First Two PeV-Neutrino Fields

- Maximum-possible neutrino flux from blazars can explain observed PeV events

But:

- No individual source bright enough for a direct association

Source	$F_\gamma(\mathrm{erg\,cm^{-2}\,s^{-1}})$	events
0235−618	$\left(1.0^{+0.5}_{-0.5}\right)\times10^{-10}$	$0.19^{+0.04}_{-0.04}$
0302−623	$\left(3.4^{+0.7}_{-0.7}\right)\times10^{-11}$	$0.06^{+0.01}_{-0.01}$
0308−611	$\left(7.5^{+2.9}_{-2.9}\right)\times10^{-11}$	$0.14^{+0.05}_{-0.05}$
1653−329	$\left(4.5^{+0.5}_{-0.5}\right)\times10^{-10}$	$0.86^{+0.10}_{-0.10}$
1714−336	$\left(2.4^{+0.5}_{-0.6}\right)\times10^{-10}$	$0.46^{+0.10}_{-0.12}$
1759−396	$\left(1.2^{+0.3}_{-0.2}\right)\times10^{-10}$	$0.23^{+0.50}_{-0.40}$
Total		1.9 ± 0.4

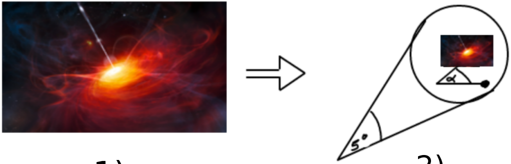
Background sources

- Atmospheric background
- Optical background
  - ^{40}K decay
  - bioluminescent organisms

⇒ Produce MC that models highly variable environmental conditions in the deep Sea
(Run by Run MC)

Method

Positional information $N_i(\alpha)$



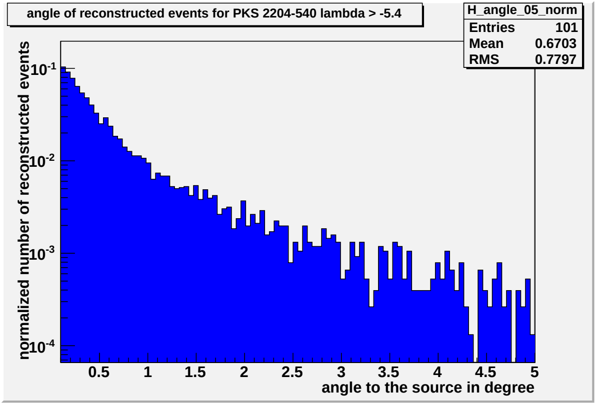
1) 2)

1. Position of source in equatorial coordinates
2. Define 5 deg search cone around the source

$\Rightarrow$ α: Angle between an event and the center of the cone

Method

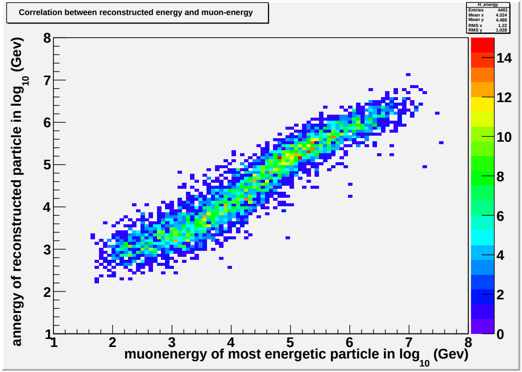
Positional information $N_i(\alpha)$



- signal case: Take normalized hight of this histogram
- background case: Take angle from uniform distribution $\propto \sin(\alpha)$

Method

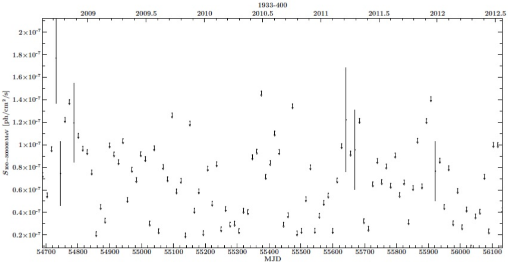
Energy information E_i



- x-axes: energy of muon
- y-axes: reconstructed energy of muon

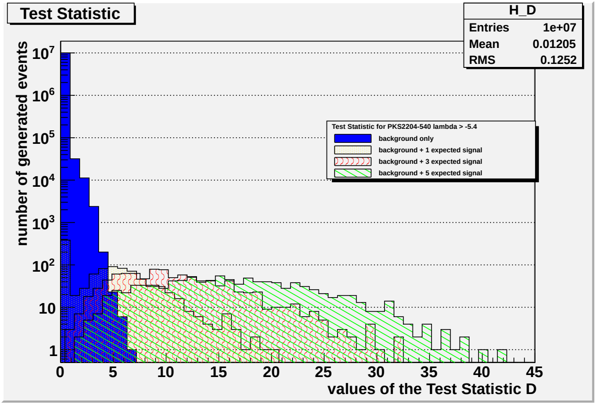
Method

Timing information $T_i(t)$



- signal case: Choose time from Lightcurve
- background case: Choose time randomly

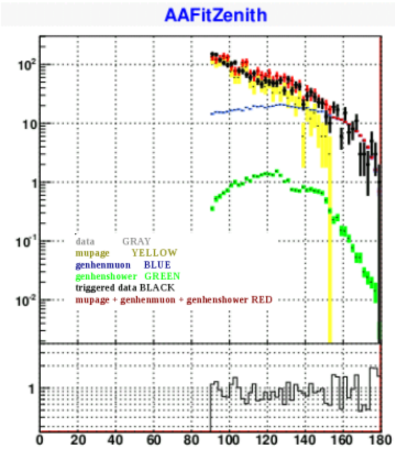
Test Statistic



$$D = 2Log\left[\frac{L(\hat{n}_s)}{L(n_s = 0)}\right] \quad (1)$$

Data MC comparison for rbrMC

Data MC comparison for PKS 1716-771



- MC models data in an appropriate way