NEUTRINO TELESCOPES

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Gelmini, Kusenko & Weiler, Through Neutrino Eyes, Scientific American, May 2010


A full collection of references on Neutrinos (an incredible database!): http://www.nu.to.infn.it/
CONTENTS

- Mediterranean Detectors
- Detection medium
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SSI 2010, Aug 10
IceCube: 86 strings, 60 OMs/string, 17 m between OMs, 125 m between strings
DeepCore of IceCube: 8 of the strings with high QE PMTs
IceTop: 80 stations of 2 tanks with 2 modules
Technological challenge: Drilling technique

- Avg. time to deep drill hole: 41 hrs
- Avg. hole depth: 2452 m
- Avg. drilling rate: 1.7 m/min
- Avg. fuel per hole: 5,520 gal
- Drill thermal power output: 4.7 MW
- Avg. string deployment time: 8 hrs
IceCube Construction

1996/2000 Seasons - AMANDA
2004/2005 Season - First String
2005/2006 Season - 8 Strings
2006/2007 Season - 13 Strings
2007/2008 Season - 18 Strings
2008/2009 Season - 16 to 19 Strings
2009/2010 Season - 20 strings!!
2010/2011 Season - remaining 7

Currently →
79 out of 86 strings are taking data
Digital Optical Module (DOM)

- **PMT**: 10 inch Hamamatsu
- **Power consumption**: 3 W
- **Digitize at 300 MHz for 400 ns with custom chip**
- **40 MHz for 6.4 µs with fast ADC**
- **Dynamic range**: 200pe/15 nsec
- **Send all data to surface over copper 2 sensors/twisted pair**.
- **Flasherboard with 12 LEDs**
- **Local HV**

**Clock stability**: $10^{-10} \approx 0.1 \text{ nsec} / \text{sec}$

**Synchronized to GPS time every** $\approx 10 \text{ sec}$

**Time calibration resolution** = 2 nsec

Digitized Waveform
Visibility for different locations

AMANDA / IceCube (South Pole)

ANTARES (43° N)

1.5 \pi sr common view per day

galactic coordinates
Installation:
Junction Box - Dec 2002
Line 1 - March 2006
Line 5-1 - Dec 2007
Line 11-12 - May 2008
885 PMTs on 12 lines
Basic detector element: storey

Optical Beacon for timing calibration (blue LEDs) 1/4 floors

Local Control Module (in the Ti-cylinder)

17" glass sphere
10" PMT Har. R7081-20
14 stages

Hydrophone RX

NIM A578/3 (2007)

NIM A555 (2005)
Technological challenges
KM3NeT: towards a km3 in the Med

2 detectors of 100-300 strings → capital investment
220 M€uro, 2-3% operation/yr

Other European large investment in Astroparticle: CTA

Flexible tower tested in Feb 2010

Triangle structure

new: 31x 3-inch high QE PMT cathode area 3 x 10-inch PMTs, single penetrator, 140 mW

classical: 8-inch high QE PMT
Where?
and timeline

2 km
Optical Properties of ice/water

Light propagating in a medium is **absorbed** and **scattered**.

$$I = I_0 \frac{A}{4\pi R^2} e^{-R/\lambda_{\text{att}}}$$

$$\frac{1}{\lambda_{\text{att}}} = \frac{1}{\lambda_{\text{abs}}} + \frac{1}{\lambda_{\text{scatt}}}$$

$$\lambda_{\text{eff}} \approx \frac{\lambda_{\text{scatt}}}{1 - \langle \cos \theta \rangle}$$

Scattering is the main factor limiting the angular resolution together with PMT TTS and electronics resolution.

Sea water: $\lambda_{\text{att}} \sim 50$ m $\lambda_{\text{abs}} \sim 50-60$ m $\lambda_{\text{eff,scatt}} > 200$ m @ 450 nm

Polar ice: $\lambda_{\text{abs}} \sim 110$ m $\lambda_{\text{eff,scatt}} \sim 20$ m @ 400 nm

Ice scattering and absorption is depth dependent

Muon ‘radiography’ of ice

*Figure: A 3D plot showing the effective scattering coefficient, depth, and wavelength for different ice conditions.*
Optical Background

Typical SPE rate: 60 – 120 kHz caused by bioluminescence and $^{40}$K decay (~ 40 kHz) with some ~MHz bursts due to macro-organisms. Burst fraction correlated with current and seasonal dependent.

Rate of coincidences used to calibrate the detector and adjust thresholds and gain of PMTs.
Positioning of lines in the sea

6 months

Distance measurement between a system of acoustic emitters and receivers every 2m.
Compass: heading
Accelerometer: tilt

Precision of positioning of PMTs < 10 cm
Detector parameters

- Reconstruction of Events
- Neutrino interaction and Muon energy losses
- Effective area and Response curve
- Telescope Point Spread Function
- Energy resolution

Major Physics Items with NTs

- Diffuse fluxes
- Point sources
  - Flares from GRBs, AGNs SGRs
- Cosmic rays
  - DM searches: WIMP and Magnetic Monopoles
- SN monitoring
- Atmospheric neutrino oscillations
Event topologies

Muon neutrino
a) $E_\mu = 10$ TeV $\sim 90$ hits

b) $E_\mu = 6$ PeV $\sim 1000$ hits

$E \sim dE/dx$, $E > 1$ TeV
Energy Res. : $\log(E) \sim 0.3$
Angular Res.: $0.8 - 2$ deg

Electron neutrino

$E = 375$ TeV

Energy Res. $\log(E) \sim 0.1 - 0.2$
Poor Angular Resolution

Tau neutrino

$E = 10$ PeV

Double-bang signature above $\sim 1$ PeV
Very low background
Pointing capability
Best energy measurement

$\nu_\tau + N \rightarrow \tau + ...$

$300$ m

$\tau \rightarrow \nu_\tau +$ hadrons
IceCube-40 cascade event
A muon bundle in 40-strings of IceCube and IceTop no reconstruction of multiple tracks (not enough photocathode coverage)!

Big detector, huge events!
Multiple events in same readout frame
Muons and neutrinos in ANTARES

June 2007 – Dec 2008
5+10+12 lines
341 active day
1062 upward neutrino candidates
Teresa Montaruli, UW-Madison

Calibration beams

IceCube-22 Data vs. Monte Carlo Simulation Data

- Cosmic Ray Induced Muons
- Coincident Cosmic Ray Induced Muons
- Neutrinos
- All Simulated Muons & Neutrinos
- IceCube-22 Data
Atmospheric neutrino fluxes

For $E > 100 \text{ GeV/cos} \theta$ and $\theta < 70^\circ$

$$\frac{dN_{\mu}}{dE_{\mu} d\Omega} \approx 0.14 \frac{E_{\mu}^{2.7}}{\text{cm}^2 \text{s sr GeV}}$$

$$\times \left\{ \frac{1}{1 + \frac{E_{\mu} \cos \theta}{115 \text{ GeV}}} + \frac{0.054}{1 + \frac{E_{\mu} \cos \theta}{850 \text{ GeV}}} \right\}$$

- pions
- kaons
the valence contribution dominates at low energy and the neutrino and anti-neutrino cross section become identical at HE.
Absorption in the Earth and regeneration

\[ P_{\text{survival}} = \exp\left(-\frac{l}{\lambda_\nu}\right) \]
\[ \lambda_\nu = 1/(\rho N_A \sigma_\nu(E_\nu)) \]

Absorption probability in the Earth vs \( E_\nu \)
(for CC interactions only)

\[ \frac{d\sigma}{dE} = \rho N_A \sigma_\nu(E_\nu) \]

\[ \text{Average number of CC and NC interactions in the Earth for vertical } \nu_\tau \]


Muon energy losses

Muon range

Survival probability (stochastic nature)

critical energy in water
\sim 1 \text{ TeV}
Effective area and response function

Neutrino Event Energy Distributions

- atmNu, 90% in range (2.4, 4.2)
- $E^3$, 90% in range (2.5, 4.7)
- $E^{2.5}$, 90% in range (2.9, 5.4)
- $E^2$, 90% in range (3.5, 6.5)

Effective Area

Neutrino-nucleon cross-section

$$N_\nu = \int V_{\text{eff}}(E_\nu, \theta_\nu, \phi_\nu) (\rho N_A) \sigma(E_\nu) \frac{d\Phi_\nu}{dE_\nu d\Omega_\nu} dE_\nu d\Omega_\nu$$

Target nucleon density

$$A_{\text{eff}}^\nu = V_{\text{gen}} \times \frac{N_{\text{zzz}}(E_\nu, \theta_\nu, \phi_\nu)}{N_{\text{gen}}(E_\nu, \theta_\nu, \phi_\nu)} \times (\rho N_A) \sigma(E_\nu) \times P_{\text{earth}}(E_\nu, \theta_\nu)$$

Event rate

$$N_\mu = \int A_{\text{eff}}^\nu(E_\nu, \theta_\nu, \phi_\nu) \frac{d\Phi_\nu}{dE_\nu d\Omega_\nu} dE_\nu d\Omega_\nu$$

Neutrinos flux model

Shadowing effect

absorption in the Earth
Telescope standard candle: the moon shadow

Primary CR average energy around $10^5$ GeV

G.W. Clark, 1957

IceCube results in I. Taboada’s talk
POINT SPREAD FUNCTION

PSF: angle between nu and reco mu

IC86: 0.3° for 1-10 PeV and 0.5° for 10-100 TeV.

IC40: 0.6° for 1-10 PeV
0.5° for 10-100 TeV.
ANGULAR RESOLUTION AND STRING CONFIGURATION

Currently most results of IceCube are presented for 40 strings (I. Taboada’s talk)
ENERGY RESOLUTION

About a factor of 2 on an event by event basis

But spectral reconstruction helped by large lever arm in energy (NTs measure over many decades of energy!)
Unfolding techniques can be used to account for energy resolution (see spectrum of atmospheric neutrinos in Taboada’s talk).
**BLIND ANALYSIS**

**Cut definition:** cuts should be defining maximizing sensitivity or discovery potential prior looking at the effect on data that may include the signal.

**Search of rare events:** statistical fluctuation may bias the choice of experimenter so **data challenge method** helps when high statistics of equivalent samples to the real experiment is used.

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**Blind Analysis in Particle Physics, PHYSSTAT2003, Aarn Roodman, physics/0312102**

**Blind Analysis, P.F. Harrison**

**Blind Search for the Real Sample: Application to the origin of UHECRs, B.J. Stern and J. Poutanen, astro-ph/0501677**

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From Particle Data Group

![Graphs showing statistical means and lifetimes](image)

World average $K_S^0$ and $B^\pm$ mean lifetime vs PDG publication year.
LIKELIHOOD METHOD: PROBABILITY DENSITY FUNCTIONS FOR SIGNAL AND BACKGROUND

\[ L(x_s, \gamma, n_s) = \prod P_i(|x_i - x_s|, E_i, \gamma, n_s) \]

likelihood function

\[ B(x_i, E_i) = P_{BkgDec}(x_i) P_{BkgMue}(\delta_i, E_i) \]

background PDF

PDF for background comes from data \(\Rightarrow\) significance is solid

Signal PDF with free parameters to fit maximizing S/B

\[ P_i(|x_i - x_s|, E_i, \gamma) = \frac{1}{2\pi\sigma_i^2} \exp \left( - \frac{|x_i - x_s|^2}{2\sigma_i^2} \right) P_{SigMue}(E_i|\delta_i, \gamma) \]

\[ S_i(|x_i - x_s|, E_i, \gamma) = \frac{n_s}{n_{tot}} S_i(|x_i - x_s|, E_i, \gamma) + \left( \frac{1 - n_s}{n_{tot}} \right) B(x_i, E_i) \]

individual event probability: weight of events

\[ \log \lambda = \log \left( \frac{L(x_s, \hat{\gamma}, \hat{n}_s)}{L(n_s = 0)} \right) \]

Test statistics. Extract fit parameters that minimize test statistics

TEST OF HYPOTHESIS AND SIGNIFICANCE

Check if the test statistics looks reasonable depending on your dofs!

The probability to reject $H_0$ in favor of $H_1$ is called the power of the test

$$\text{power} \equiv P(\lambda \in \omega | H_1)$$

CL defines the rejection region

Probability that $H_0$ is wrongly rejected

$$1 - CL \equiv P(\lambda \in \omega | H_0)$$

At a fixed level of significance, the power of the test corresponds to the sensitivity for discovering the signal and it depends on the level of separation between the test statistic distributions for $H_0$ and $H_1$. The mean number of events for discovery at 5$\sigma$ for 50% of trials (scrambled maps).
When the background is randomly distributed in time and the signal is expected to be small compared to the background (not around the Poles): scramble only right ascension = time and take real declination and other variables of events (e.g., energy proxy).

If the background in the off-on source region have the same properties a signal can be looked for as an unexpected feature of the background.


EXTENDING THE FOV OF NTS

It does not matter what background is used...but how much it is matters for reasons of CPU and intensity of signal between background

IceCube-40 skymap (Taboada’s talk)
Point Sources: The Progress

factor $\sim 1000$

from my PhD thesis (15 years)!
Where do we stand?

- **RX J1736.7-3946-like model**: (Morlino et al., arXiv:0903.4565) @ Crab location dec = 22°
  - discovery x 13
  - exclusion x 3.2

- **3C 279**: dec = -5° active flare for 330 d (Reimer et al., arXiv:0810.4864)
  - discovery x 3.1
  - exclusion x 1.2

- **MGRO 1852+01 at dec=0.5°**: E^{-2} up to 40 TeV (Halzen et al, arXiv:0902.1176)
  - discovery x 12.3
  - exclusion x 3.1

![Graph showing flux prediction and discovery/exclusion limits](image)
INDIRECT DETECTION OF DM WITH NEUTRINOS

$\rho_\chi$  $\chi$  $<\sigma_A v>$

$\sigma_{\text{scatt}}$  $\chi$  Earth

$\Gamma_{\text{capture}}$  $\chi\chi \rightarrow c\bar{c}, b\bar{b}, t\bar{t}, \tau^+\tau^-, W^\pm, Z^0, H^\pm H^0$  $\rightarrow \nu\nu$

$\Gamma_{\text{annihilation}}$

1. $\chi$ - flux

$\Phi_\chi = n_\chi v = \frac{\rho_\chi}{m_\chi} v$

For $m_\chi = 500 GeV$  $\Phi_\chi \sim 1.4 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$

2. solar cross section

$\Sigma_{\text{sun}} = n \sigma_{\chi p} = \frac{M_{\text{sun}}}{m_p} \sigma_{\chi p}$

$\sim [1.2 \times 10^{57}] [10^{-41} \text{ cm}^2] \sim 1.2 \times 10^{16} \text{ cm}^2$

3. Capture rate by the sun

$C_{\text{Sun}} = \Phi_\chi \Sigma_{\text{Sun}} = 1.7 \times 10^{20} \text{ s}^{-1}$

$0.3 \text{ GeV cm}^{-3}$

230 km/s
NEUTRINO FLUXES FROM THE SUN

Rate change of the WIMPs in the Sun due to the capture rate and annihilation rate

\[ \dot{N}(t) = C_{\text{Sun}} - A_{\text{Sun}} N(t)^2 \]

The annihilation rate is

\[ A_{\text{Sun}} = \frac{\langle \sigma v \rangle}{V_{\text{eff}}} \]

effective volume of the Sun from matching the core T of the Sun with the gravitational potential

\[ V_{\text{eff}} = 5.7 \times 10^{27} \text{ cm}^3 \left( \frac{100 \text{ GeV}}{m_\chi} \right)^{3/2} \]

The present WIMP annihilation rate is:

\[ \Gamma_A = \frac{1}{2} A_{\text{Sun}} N(t_{\text{Sun}})^2 = \frac{1}{2} C_{\text{Sun}} \tanh^2 \left( \sqrt{C_{\text{Sun}} A_{\text{Sun}} t_{\text{Sun}}} \right) \]

\[ t_{\text{Sun}} \sim 4.5 \text{ billion yrs} \]

Neutralinos in the halo are accreted onto the Sun and their number is depleted due to annihilation. Capture and annihilation come to equilibrium on a time scale much shorter than the age of the solar system:

\[ \Gamma_A = \frac{1}{2} C \]

so the annihilation rate is determined by the capture rate and not by the annihilation cross sec

\[ \Phi_\nu \propto \Gamma_A \propto C_{\text{Sun}} = \Phi_{\chi} \Sigma_{\text{Sun}} = 1.4 \times 10^{20} \text{ s}^{-1} \]

500 GeV WIMP
NEUTRINO EVENT RATE FROM THE SUN

\[ \Phi_\nu \propto \Gamma_A \propto C_{Sun} = \Phi_\chi \Sigma_{Sun} = 1.4 \times 10^{20} \text{ s}^{-1} \]

500 GeV WIMP

Number of neutrino pairs from annihilation:

\[ N_\nu \sim C_{Sun} = 2\Gamma_A \]

Distance Sun-Earth \( \sim 1.5 \times 10^{13} \text{ cm} \)

Approximate: the flux of neutrinos (of each type) from neutralino annihilation in the Sun is proportional to the annihilation neutrino spectra \( dN_i/dE \) for each channel with branching ratio \( B_F \).

\[
\left( \frac{d\Phi_\nu}{dE} \right) = \frac{\Gamma_A}{4\pi R^2} \sum_F B_F \left( \frac{dN_i}{dE} \right)_{F,i} \left( E_\nu, E_{in} \right)
\]

Taking an intermediate value of \( 5 \times 10^{-3} \text{ m}^2 \)

Event rate \( \sim A_\nu \otimes \Phi_\nu \sim 5 \times 10^{-8} \text{ cm}^{-2}\text{s}^{-1} \times 10\text{cm}^2 \sim 15 \text{ events/yr} \)
MORE PRECISE CALCULATIONS

Allowed region (68% & 95% cl) of Constrained Minimal supersymmetric Standard Models for the neutralino. If IceCube does not discover WIMPs and direct detectors do not find anything for the CMSSM would be disfavored

http://arXiv.org/pdf/0906.0366

\[ \sigma_p^{SI} \gtrsim 0.9 \times 10^{-8} \text{ pb} \]
Direct-Indirect Detection

IceCube 22 strings, effective livetime $10^4$ d
PRL 102 (2009) 201302
AMANDA, J. Braun at ICRC2009

Xenon 10 spin dependent
PRL 101 (2008)

DAMA allowed
KIMS
CDMS
Xe10 for
2 form factors

pure n
pure p

Preliminary
CONCLUSIONS

Neutrino Telescopes are a tremendous adventure. We can open a new window on the universe!