NOW 2012

• IceCube

• atmospheric and cosmic neutrinos

• the search for the sources of the Galactic and extragalactic cosmic rays
\[ P_{\mu \rightarrow \nu} = \frac{\lambda_\mu}{\lambda_\nu} = n\sigma_v R_\mu \]

- lattice of photomultipliers
- shielded and optically transparent medium
photomultiplier tube
93 TeV muon

Type: NuMu
E(GeV): 9.30e+04
Zen: 40.45 deg
Azi: 192.12 deg
NTrack: 1/1 shown, min E(GeV) == 93026.46
NCasc: 100/427 shown, min E(GeV) == 7.99
energy measurement ($ > 1 \text{ TeV} $)

convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, $dE/dx$, ...)

Run 433700001 Event 0 [0ns, 40000ns]
improving angular and energy resolution
IceCube / Deep Core

- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- < 0.5 degree on-line
- < 0.2 degree off line
- < 30% energy resolution

Digital Optical Module (DOM)
construction of IceCube, year by year…

IC-22": 2007/2008
22 strings / 26 stations

IC-40": 2008/2009
40 strings / 40 stations

IC-59": 2009/2010
59 strings / 59 stations

IC-79": 2010/2011
79 strings / 73 stations

IC-86": 2011 -- ?
86 strings / 81 stations

drilling and deployment

drill and install 60 DOMs in less than 2 days
architecture of independent DOMs

10 inch pmt

LED flasher board

main board

HV board
Digital Optical Module (DOM)

... each DOM, independently collects light signals like this...

... time stamps them with 2 nanoseconds precision and sends them to a computer that sorts them into neutrino events...
Type: PPlus
E(GeV): 1.42e404
Zen: 17.37 deg
Act: 253.00 pug
NTrack: 990/1825 shown, min E(GeV) = 1784.28
NCoset: 100/14225 shown, min E(GeV) = 0.94
... you looked at 10 msec of data!

muons detected per year:

- atmospheric* $\mu \sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu \sim 10^5$
- cosmic $\nu \rightarrow \mu \sim 10$

* 3000 per second ** 1 every 6 minutes
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IceCube.wisc.edu
cosmic neutrinos:

energy: >>> 100 TeV

atmospheric neutrino spectrum to >100 TeV
IceCube 40 + 59 strings out of 86
43339 neutrinos

64230 muons
Total events (IC40+IC59+IC79): 108317 (upgoing) + 146018 (downgoing)
Livetime: 316 days (IC79) + 348 days (IC59) + 375 days (IC40)
oscillations in DeepCore [5.6 sigma]  Andreas Gross

Low-energy sample IC79

- Vertical
- Horizontal

High-energy sample IC79

- MC, std oscillations
- MC, no oscillations
- data

Vertical
\[ \cos(\theta) < -0.55 \]

Horizontal
\[ \cos(\theta) > -0.55 \]
neutrino oscillations in Deep Core

resonance in effective $\theta_{13}$ angle traversing the Earth diameter at 10 GeV

hierarchy $\sin^2(2\theta_{13})=0.1$

$\nu_\tau$ appearance

$\nu_\mu$ disappearance
hierarchy: sign $\Delta_{13}$?
~ 10 GeV : hierarchy revealed by “large” matter effects in the Earth

\[
\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \left[ \cos 2\theta_{13} \pm \frac{\sqrt{2G_F n_e}}{\Delta_{13}} \right]}
\]

(mostly) neutrino + antineutrino -

\[\text{sign } \Delta_{13} : \text{hierarchy !}\]
DeepCore (+6 strings): 11 hits  PINGU (+20 strings): 83 hits

8 GeV muon-neutrino
IceCube drilling to best low background site on Earth:
→ radio-pure ice
→ no seasonal variations (temperature, humidity,…)
→ shielded from cosmic rays by IceCube veto

• DM-ice, DeepCore upgrades

• $1.25M per string of 60 ten inch PMTs (data to your pc, includes logistics)
3+1

matter effect of eV sterile ν's?
number of nu-mu events versus $\cos \theta$ in IceCube 40

$\Delta m^2 = 0.4 \text{ eV}^2$ and $\sin^2 \theta_{34} = 0 \rightarrow 0.5$

Arman Esmaili
Number of Events

\[\sin^2 \theta_{14} = 0.000\]
\[\sin^2 \theta_{24} = 0.100\]
\[\sin^2 \theta_{34} = 0.100\]
\[\Delta m^2_{31} = 0.4 \text{ eV}^2\]
\[\chi^2 = 439.304\]
\[\chi^2_{\text{red}} = 438.764\]

- Red: No sterile
- Green: Sterile
- Blue: Data
$\sin^2 \theta_{14} = 0.000$
$\sin^2 \theta_{24} = 0.100$
$\sin^2 \theta_{34} = 0.150$
$\Delta m^2_{41} = 0.4 \text{ eV}^2$
$\chi^2 = 698.593$
$\chi^2_{\text{red}} = 655.973$

No sterile
Sterile
Data

Number of Events

$\cos(\theta)$
$\sin^2 \theta_{14} = 0.000$
$\sin^2 \theta_{24} = 0.100$
$\sin^2 \theta_{34} = 0.200$
$\Delta m^2_{41} = 0.4 \text{ eV}^2$
$\chi^2 = 767.372$
$\chi^2_{\text{red}} = 762.402$

- **No sterile**
- **Sterile**
- **Data**
$\sin^2 \theta_{14} = 0.000$
$\sin^2 \theta_{24} = 0.100$
$\sin^2 \theta_{34} = 0.450$
$\Delta m^2_{31} = 0.4 \text{ eV}^2$
$\chi^2 = 326.895$
$\chi^2_{\text{red}} = 320.294$

- Red: No Sterile
- Green: Sterile
- Blue: Data
SYSTEMATICS !!!

- K/π ratio
- zenith acceptance of modules
- ice
- CR flux, composition

[IceTop helps]
zenith angle distribution 40-string data

Preliminary

Events per bin

Simulation with shape error
Data with statistical error

Cos(\theta_z)
Cos(Zenith) Distributions

Simulation

Data

59 strings
NOW 2012

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sources accommodating the observed energy budget

Galactic: supernova remnants?
extragalactic: gamma ray bursts? active galaxies?
shock acceleration (solar flare)

flows of charged particles result in large B-fields

coronal mass ejection

$\rightarrow$

10 GeV particles
Hillas formula:

- accelerator must contain the particles

\[ R_{gyro} \left( = \frac{E}{vqB} \right) \leq R \]

\[ E \leq v \ qBR \]

- dimensional analysis, difficult to satisfy
galactic cosmic rays 10^{-12} \text{ erg cm}^{-3}

410 photons of 2.7 K per cm^3 or 10^{-12} \text{ erg cm}^{-3} 
\sim 0.5 \text{ eV cm}^{-3}
cassiopeia A supernova remnant in X-rays

gravitational energy released is transformed into acceleration when particles cross high B-fields
collapse of massive star produces a **gamma ray burst**

**spinning black hole**

shocks produced in the outflow of the spinning black hole: electrons (and protons ?)
diffuse flux limit

\[
E^2 \frac{d\phi}{dE} \text{[GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] \n\]

- AMANDA $\nu_\mu$ 2000-2003 90\%CL limit
- ANTARES $\nu_\mu$ 07-09 90\%CL limit
- IC40 $\nu_\mu$ 90\%CL limit
- IC59 $\nu_\mu$ sensitivity
- IC59 $\nu_\mu$ 90\%CL limit (prelim.)
- IC40 atmospheric unfolding
- Honda2006 $\nu_\mu$
- Honda2006 $\nu_\mu$ + Enberg et al.

- Waxman-Bahcall upper bound 2011
- WB11 upper bound no evolution
- Mannheim 1995
- BBR I 2005 steep spectra sources
- Stecker AGN (Seyfert) 2005
- High Peaked BL Lac (max) Mucke 2003
- Prompt GRB Razzaque et al. 2008

IC59 limit
IC40 limit
IC59 sensitivity

Preliminary

Anne Schukraft
NOW 2012

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• the search for the sources of the Galactic and extragalactic cosmic rays
cosmic rays interact with the microwave background

\[ p + \gamma \rightarrow n + \pi^+ \quad \text{and} \quad p + \pi^0 \]

cosmic rays disappear, neutrinos appear

\[ \pi \rightarrow \mu + \nu_\mu \rightarrow \{ e + \nu_\mu + \nu_e \} + \nu_\mu \]

\[ E_\nu \geq 2 \times 10^6 \text{TeV} \]

~1 event per cubed kilometer per year
$E_{\text{min}} = 10^{18} \text{ eV}$

![Graph showing particle energy $E^2 J$ versus energy $E$ for different detectors.](image-url)
GZK neutrinos: > 41,000 photons near the horizon

number of channels > 300

Energy of incoming particle \( \propto \) Energy-losses in detector \( \propto \) number of photo electrons (NPE)

- Optimization based MC and MC verification based on 10% experimental ‘burn’ sample

unblinding: 2 events in the signal region
tracks and showers

- Muon track
- Cascade
- Cherenkov light
Zenith 2.68676
Azimuth 1.66995
1.1 and 1.3 PeV < 35% systematic error

directions soon

flux at present level of diffuse limit

largest bkgd: atmospheric charm < 0.2 evts
no air shower
The collapse of a massive star produces a gamma-ray burst. Neutrinos are produced in the interactions of fireball protons (cosmic rays) with synchrotron photons.
Decays to PeV neutrino

\[ p + \gamma \rightarrow n + \pi^+ \]

Decays to cosmic ray

GRB: one neutrino per cosmic ray observed
collide cosmic rays of GRB origin with fireball and microwave photons

\[ p + \gamma \rightarrow n + \pi^+ \text{ and } p + \pi^0 \]

cosmic rays from n-decay
GRB origin of cosmic rays challenged

$\pi^0$ gamma rays after cascading in the microwave background

$\pi^+$ neutrinos
• Using satellite information (time and direction, GCN)

Off-time ➔ On-time (blind) ➔ Off-time

\[ T_0 \]

prompt background

precursor (\(~100\) s) model independent (several hours)

very low background \(\rightarrow\) 1 event can be significant!

• 98 bursts (northern sky) observed with IceCube 59 strings
• Individual modeling of neutrino fluxes (fireball model)
aligned with SWIFT
angular accuracy 0.2
energy 109 TeV
<table>
<thead>
<tr>
<th>Model</th>
<th>Predicted $\nu$</th>
<th>Fractional Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Fireball (CR-normalized)</td>
<td>$\gtrsim 84$</td>
<td>0.04</td>
</tr>
<tr>
<td>Waxman 2003 (CR-normalized)</td>
<td>27</td>
<td>0.11</td>
</tr>
<tr>
<td>Guetta et al. ($\gamma$-normalized)</td>
<td>14</td>
<td>0.21</td>
</tr>
</tbody>
</table>
active galaxy

particle flows near supermassive black hole
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Galactic plane in 10 TeV gamma rays:
supernova remnants in star forming regions

$n_{cr}(>\text{TeV}) \sim 10^{14} \text{ cm}^{-3}$

1 proton cm$^{-3}$

Southern Hemisphere Sky

milagro
neutrinos from supernova remnants:
molecular clouds as beam dumps
neutral pions are observed as gamma rays
charged pions are observed as neutrinos

\[ \nu_\mu + \overline{\nu}_\mu = \gamma + \gamma \]
Cygnus region : Milagro

translation of TeV gamma rays into TeV neutrinos :

$3 \pm 1 \nu$ per year in IceCube per source
5σ in 5 years of IceCube ...
IceCube image of our Galaxy > 10 TeV
without oscillations

with oscillations

3+1 neutrinos?

IceCube

science
conclusions

• Hess 1912.... and still no conclusion

• the instrumentation is in place …

• … supernova remnants, cosmogenic ν and GRB are in very close range !

• first 86-string unblinding: two >PeV events
The IceCube Collaboration

39 Institutions
~220 collaborators

International Funding Agencies

- Fonds de la Recherche Scientifique (FRS-FNRS)
- Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
- Federal Ministry of Education & Research (BMBF)
- German Research Foundation (DFG)
- Deutsches Elektronen-Synchrotron (DESY)
- Knut and Alice Wallenberg Foundation
- Swedish Polar Research Secretariat
- The Swedish Research Council (VR)
- University of Wisconsin Alumni Research Foundation (WARF)
- US National Science Foundation (NSF)
muon astronomy
Total events (IC40+IC59+IC79): 108317 (upgoing) + 146018 (downgoing)
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muon astronomy: nearby Galactic source(s)?

20 TeV

- Anisotropy changes in phase and amplitude with energy.

400 TeV

2 PeV

"diffusive" picture of nearby Galactic source(s)

IceCube

IceCube/IceTop
the rare high energy particles at the end of the spectrum are produced by the closest source
ON SUPER-NOVAE

BY W. BAADE AND F. ZWICKY

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

Communicated March 19, 1934
conclusions

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