why would you want to build a kilometer scale neutrino detector?

IceCube: a cubic kilometer detector

the discovery (and confirmation) of cosmic neutrinos

from discovery to astronomy

IceCube.wisc.edu
TeV γ

cosmic rays

energy (eV)

log[Flux → cm⁻² s⁻¹ sr⁻¹)]

flux of light in the Universe

Radio

CMB

Visible

GeV γ-rays

particle flux in the Universe

LHC

PeV ν

TeV γ

cosmic rays
neutrino as a cosmic messenger:

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- … but difficult to detect
in 1054 a star runs out of nuclear fuel and explodes.
neutrino sky?

IceCube: a discovery instrument
1960 extragalactic cosmic rays

$\gamma + p \rightarrow n + \pi^+$

GZK neutrino

1969 extragalactic cosmic rays
cosmic rays interact with the microwave background

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

cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

1 event per cubic kilometer per year ...but it points at its source!
IceCube
francis halzen

• cosmogenic neutrinos

• the energetics of cosmic ray sources

• neutrinos associated with cosmic rays

• a cubic kilometer detector

• evidence for extraterrestrial neutrinos

• conclusions

IceCube.wisc.edu
the sun constructs an accelerator
challenges of cosmic ray astrophysics:

- dimensional analysis, difficult to satisfy
- accelerator luminosity is high as well

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

\[
E \leq v \ qBR
\]
the sun constructs an accelerator

coronal mass ejection
10 GeV protons
supernova remnants

Chandra Cassiopeia A

gamma ray bursts
fireball calculations challenged
Nature 484 (2012) 351-353

timing/localization from satellites

timing + direction → low background
active galaxy

particle flows near supermassive black hole
Neutrino Beams: Heaven & Earth

- Accelerator is powered by large gravitational energy
- Black Hole Neutron Star
- Radiation and dust

\[ p + \gamma \rightarrow n + \pi^+ \]
\[ \sim \text{cosmic ray + neutrino} \]
\[ \rightarrow p + \pi^0 \]
\[ \sim \text{cosmic ray + gamma} \]
above 100 TeV

- cosmic neutrinos:
  - atmospheric background disappears

\[ \frac{dN}{dE} \sim E^{-2} \]

10—100 events per year for fully efficient 1 km³ detector

100 TeV

atmospheric cosmic
atmospheric neutrinos

(... and muons!)

Atmospheric neutrino source

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]
\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \]
\[ \rightarrow e^- + \bar{\nu}_e + \nu_\mu \]
IceCube: the discovery of cosmic neutrinos
francis halzen

- cosmic ray accelerators
- IceCube: a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube
M. Markov and B. Pontecorvo
1960

M. Markov:
we propose to install detectors
deep in a lake or in the sea and
to determine the direction of
charged particles with the help
of Cherenkov radiation.
- lattice of photomultipliers
- shielded and optically transparent medium
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track
ultra-transparent ice below 1.5 km
IceCube

5160 PMs in 1 km³

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

IceTop
81 Stations
324 optical sensors

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

Eiffel Tower
324 m
photomultiplier
tube -10 inch
architecture of independent DOMs

10 inch pmt

LED flasher board

main board

HV board
... each Digital Optical Module independently collects light signals like this, digitizes them, time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events...
nozzle delivers:
- 200 gallons per minute
- 7 Mpa
- 90 degree C

4.8 megawatt heating plant →
muon track: time is color; number of photons is energy
93 TeV muon: light ~ energy

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

convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)
improving angular and energy resolution

Differential Energy Reconstruction of 5 PeV Muon in IC-86

Monte Carlo Truth
Reconstructed

Total True Energy Loss: 107.9 TeV
Total Reconstructed Energy Loss: 108.8 TeV

1.1 km
Signals and Backgrounds

cosmic ray

...K, charm

atmospheric neutrino

astrophysical neutrino

atmospheric muon
… you looked at 10msec 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
89 TeV

radius $\sim$ number of photons

time $\sim$ red $\rightarrow$ purple
cosmic neutrinos in 2 years of data at 3.7 sigma
above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

\[ \frac{dN}{dE} \sim E^{-2} \]

10—100 events per year for fully efficient detector

100 TeV
highest energy muon energy observed: 560 TeV
\[ \rightarrow \text{PeV } \nu_\mu \]
3 years: $4.3 \sigma$ and more PeV $\nu_\mu$

Reco. muon energy: 950 TeV
Reco. zenith: 90°
Date: Oct. 28 2010
$2.6 \pm 0.3\ \text{PeV}$
IceCube: the discovery of cosmic neutrinos
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1 event per cubic kilometer per year...but it points at its source!
GZK neutrino search: two neutrinos with > 1,000 TeV
tracks and showers

PeV $\nu_e$ and $\nu_\tau$ showers:
- 10 m long
- volume $\sim 5$ m$^3$
- isotropic after 25~50m
size = energy  color = time = direction
reconstruction limited by computing, not ice!
• energy
  1,041 TeV
  1,141 TeV
  (15% resolution)

• not atmospheric: probability of no accompanying muon is $10^{-3}$ per event

→ flux at present level of diffuse limit
✓ select events interacting inside the detector only

✓ no light in the veto region

✓ veto for atmospheric muons and neutrinos (which are typically accompanied by muons)

✓ energy measurement: total absorption calorimetry
...and then there were 26 more...

Data (Trigger Level)

Signal Region

Events per 662 days

Total Charge (PE)

Veto Region Charge (PE)

Veto

data: 86 strings one year
...and then there were 26 more...

Data (Trigger Level)
Signal Region

Events per 662 days

Data: 86 strings one year
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration*

A 2004 TeV neutrino interaction at the IceCube detector is shown. The interaction point, the location of the neutrino, and the direction of the muon are marked.

28 High Energy Events

2004 TeV event in year 3

doubled the data since 2013
total charge collected by PMTs of events with interaction inside the detector
confirmation!
flux of muon neutrinos through the Earth

neutrinos of all flavors interacting inside IceCube

4 year 7 sigma
430 TeV
1 event:
\sim 5 \text{ sigma}
discovery

> \text{PeV } \nu_\mu
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• beyond IceCube
4 year HESE

ICECUBE PRELIMINARY

where do they come from?
oscillate over cosmic distances to 1:1:1
• we observe a diffuse extragalactic flux

• a subdominant Galactic component cannot be excluded

• where are the PeV gamma rays that accompany PeV neutrinos?
hadronic gamma rays?

\[ \pi^+ = \pi^- = \pi^0 \]
electromagnetic cascades in CMB

hadronic gamma rays
\[ \pi^+ = \pi^- = \pi^0 \]

Fermi gammas

\[ E^{-2.15} \]

Pp scenario

SFR evolution

HESE (3yr)

arXiv:1410.1749

Fermi IGRB (2014)

Cosmic neutrinos
towards lower energies: a second component?

warning:
- spectrum may not be a power law
- slope depends on energy range fitted

PeV neutrinos absorbed in the Earth
1.01 \times \text{atmospheric } \pi/K \nu \\
+ 1.47 \times \text{penetrating } \mu \\
+ 2.24 \left( \frac{E}{100 \text{ TeV}} \right)^{-2.49} \\
\times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}

Southern sky \\
-1.0 < \sin \delta \leq -0.2

Northern sky \\
-0.2 < \sin \delta \leq 1.0
• we have observed a flux of neutrinos from the cosmos whose properties correspond in all respects to the flux anticipated from PeV-energy cosmic accelerators that radiate comparable energies in light and neutrinos

• hadronic accelerators are not a footnote to astronomy; they generate a significant fraction of the energy in the non-thermal Universe

• gamma ray sources predict neutrinos. We are close to identifying point sources.
even for Galactic sources the photon to neutrino conversion implies that we are close to detecting neutrinos from known high energy gamma ray emitters
even for Galactic sources the photon to neutrino conversation implies that we are close to detecting neutrinos from known high energy gamma ray emitters
photon to neutrino conversation implies that we are close to detecting neutrinos from known high energy gamma ray emitters
<table>
<thead>
<tr>
<th>Type</th>
<th>Origin</th>
<th>Flux Seen by</th>
<th>Min #Events</th>
<th>Max #Events</th>
<th>flux ratio</th>
<th>Integration bound [TeV]</th>
<th>cut off</th>
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<tbody>
<tr>
<td>MGRO J2031+41</td>
<td>UNID</td>
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<td>2.5</td>
<td>3.9</td>
<td>-</td>
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<tr>
<td>MGRO J2019+37</td>
<td>PWN</td>
<td>Galactic</td>
<td>3.2</td>
<td>6.6</td>
<td>-</td>
<td>1-10^3</td>
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<td>UNID</td>
<td>Galactic</td>
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<td>Markarian 421</td>
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<td>2.7</td>
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<td>0.1-Infinity</td>
<td>-</td>
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<td>PWN</td>
<td>Galactic</td>
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<td>0.9</td>
<td>0.08</td>
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<td>Blazar</td>
<td>Extragalactic</td>
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<td>0.3</td>
<td>0.2</td>
<td>0.1-Infinity</td>
<td>-</td>
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<tr>
<td>W Comae</td>
<td>Blazar</td>
<td>Extragalactic</td>
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<td>2.2</td>
<td>1.9</td>
<td>0.2-Infinity</td>
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<td>Markarian 501</td>
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<td>19</td>
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<td>0.15-Infinity</td>
<td>-</td>
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<td>3C 279</td>
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<td>Extragalactic</td>
<td>0.1</td>
<td>0.7</td>
<td>1.5</td>
<td>0.25-Infinity</td>
<td>-</td>
</tr>
<tr>
<td>1ES 0229+200</td>
<td>Blazar</td>
<td>Extragalactic</td>
<td>0.3</td>
<td>1.2</td>
<td>0.1</td>
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<td>M 82</td>
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<td>Extragalactic</td>
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<td>0.9</td>
<td>0.02</td>
<td>0.35-Infinity</td>
<td>-</td>
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<td>NGC 1257</td>
<td>Starburst</td>
<td>Extragalactic</td>
<td>0</td>
<td>0.2</td>
<td>0.18</td>
<td>0.1-Infinity</td>
<td>-</td>
</tr>
</tbody>
</table>

The minimum and maximum expected number of events from interesting sources in 5 years of IC86. The neutrino fluxes are estimated from Gamma ray flux assuming pp interaction at the source. The flux ratio is Integrated Gamma ray flux above threshold energy divided by 90% confidence level neutrino flux limit from 4-year point search of IceCube with a factor 2. The flux used for the W Comae is based on the fitted flux of the flares in different years.
• we observe a diffuse extragalactic flux
• active galaxies, most likely blazars, or starburst galaxies?
• correlation to catalogues should confirm this
IceCube: the discovery of cosmic neutrinos
francis halzen

- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube
• a next-generation IceCube with a volume of 10 km$^3$ and an angular resolution of $< 0.3$ degrees will see multiple neutrinos and identify the sources, even from a “diffuse” extragalactic flux in several years

• need 1,000 events vs 100 now

• discovery instrument $\rightarrow$ astronomical telescope
most transparent medium in nature, and in the lab

absorption length of Cherenkov light

$\lambda_a(400 \text{ nm}) \text{ [m]}$ vs. depth [m]

$\leftarrow >100\text{m} \rightarrow$

$\leftarrow 220\text{m} \rightarrow$
we are limited by computing, not the optics of the ice
measured optical properties ⏮ twice the string spacing

(increase in threshold not important: only eliminates energies where the atmospheric background dominates)

Spacing 1 (120m):
IceCube (1 km$^3$) + 98 strings (1.3 km$^3$) = 2.3 km$^3$

Spacing 2 (240m):
IceCube (1 km$^3$) + 99 strings (5.3 km$^3$) = 6.3 km$^3$

Spacing 3 (360m):
IceCube (1 km$^3$) + 95 strings (11.6 km$^3$) = 12.6 km$^3$
instrumented volume: x 10
same budget as IceCube

PINGU infill
40 strings
GeV threshold

120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing
did not talk about:

- measurement of atmospheric oscillation parameters
- supernova detection
- searches for dark matter, monopoles,…
- search for eV-mass sterile neutrinos
- PINGU/ORCA
- ….
one half million atmospheric neutrinos...
one half million atmospheric neutrinos…

- neutrino oscillations hierarchy
- non-standard neutrino interactions $\delta c/c < 10^{-27}$
- earth matter resonance for eV sterile neutrino

DeepCore
eV sterile neutrino $\rightarrow$ Earth MSW resonance for TeV neutrinos

In the Earth for sterile neutrino $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$
oscillations at 20 GeV
SuperK

\[ \sim 1 \text{ GeV} \]

**Average energies**
- FC: \( \sim 1 \text{ GeV} \), PC: \( \sim 10 \text{ GeV} \), UpMu: \( \sim 100 \text{ GeV} \)

IceCube

\[ 6 \text{ GeV} < E_{\text{reco}} < 56 \text{ GeV} \]
and with PINGU...

(soon using PINGU methods)
Outlook:

- capitalize on discovery
- astronomy guaranteed
- neutrino physics at low cost and short timescale
- neutrinos are never boring!

from discovery to astronomical telescopes:
parallel development in the Mediterranean

ANTARES → KM3NeT
Baikal → GVD
IceCube: a discovery instrument

neutrinos?
• 6 different data samples based on data from 2008 – 2012
• different strategies to suppress the atm. $\mu$ background
• large samples of track-like and cascade-like events

assuming isotropic astrophysical flux and $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$ at Earth $\to$

unbroken power-law between 25 TeV and 2.8 PeV
spectral index $-2.5 \pm 0.09$ (-2 disfavored at 3.8 $\sigma$)
flux at 100 TeV $(6.7 \pm 1.2) \times 10^{-18}$ (GeV $\cdot$ cm$^2$ $\cdot$ s $\cdot$ sr)$^{-1}$

the best fit flavor composition disfavors 1:0:0 at source at 3.6 $\sigma$
new physics?
only otherwise...
every model ends up in the triangle
Glashow resonance events per year:

<table>
<thead>
<tr>
<th>$\Phi_{\nu_e}$ [GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$]</th>
<th>interaction type</th>
<th>pp source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.0 \times 10^{-18} (E/100,\text{TeV})^{-2.0}$</td>
<td>GR</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>DIS</td>
<td>0.09</td>
</tr>
<tr>
<td>$1.5 \times 10^{-18} (E/100,\text{TeV})^{-2.3}$</td>
<td>GR</td>
<td>0.38</td>
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<tr>
<td></td>
<td>DIS</td>
<td>0.04</td>
</tr>
<tr>
<td>$2.4 \times 10^{-18} (E/100,\text{TeV})^{-2.7}$</td>
<td>GR</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>DIS</td>
<td>0.01</td>
</tr>
</tbody>
</table>

$\overline{\nu}_e + e^- \rightarrow W$
ANTARES → KM3NeT
distribution of the parent neutrino energy corresponding to the energy deposited by the secondary muon inside IceCube