OUTLINE

- Introduction: Cosmic Rays and Neutrinos
- The IceCube Neutrino Telescope
- Results from IceCube: Astrophysical Neutrinos
- Conclusions
THE COSMIC-RAY MYSTERY

- Cosmic Rays discovered by Victor Hess (and others) in 1912
- Cosmic Rays spectrum spans 10 decades of energy. Origin still unknown.
  - Galactic CRs: Supernova remnants?
  - Extra-Galactic CRs: AGNs, GRBs, magnetars?

\[ p + \gamma \rightarrow \pi^0 + p \]
\[ 2/3 \rightarrow \gamma \gamma \]
\[ p + \gamma \rightarrow \pi^+ + n \]
\[ 1/3 \rightarrow \nu_\mu + \mu \]
**COSMIC MESSENGERS**

**NEUTRINOS**
They are neutral and weak particles: point to the source carrying information from the deepest parts.

**COSMIC RAYS**
Deflected by magnetic fields ($E < 10^{19}$ eV)

**GAMMA-RAYS**
They point to the sources but they get absorbed and have multiple emission mechanisms

Neutrino Astronomy is THE window to the extragalactic Universe above 100 TeV
DETECTION PRINCIPLE

Northern Sky

Southern Sky

Deep Inelastic Scattering

Cherenkov light

Atmospheric Background

atmospheric $\mu$

$\nu$ induced $\mu$

$\nu_\mu$
THE ICECUBE NEUTRINO OBSERVATORY

IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

See Timo’s talk yesterday

86 strings of DOMs, set 125 meters apart

IceTop

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

IceCube detector

DeepCore

Antarctic bedrock

50 m

1450 m

2450 m

60 DOMs on each string

DOMs are 17 meters apart

RICAP 2016
Juan A. Aguilar
IN-ICE SIGNATURES

Track topology
- Good angular resolution 0.1°
- 1° → Neutrino Astronomy
- Vertex can outside the detector → Increased effective volume

Cascade topology
- All flavors
- Fully active calorimeter → Good energy resolution ±15% deposited energy
- Angular reconstruction possible → ~10° > 100 TeV
Sources may be numerous and faint, hard to resolve individually.

1. Using up-going through-going muon events using Earth as a shield against atmospheric muons.

2. Using the outer layers as an active veto to select starting events.
First evidence (3.7σ) of an extra $\nu_\mu$-based astrophysical component already seen with 2 years of data.

Latest results (5.9σ) with 6 years.

Measured flux:

$$\Phi(E_\nu) = 0.82^{+0.30}_{-0.26} \times 10^{-18} \text{GeV}^{-1} \text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1} (E_\nu/100 \text{ TeV})^{-2.08 \pm 0.13}$$
A multi-GeV event was observed in the through-going muon sample:

**deposited energy**: $2.6\pm0.3$ PeV (lower limit on neutrino energy)

**date**: June 11, 2014

**direction**: $11.48^\circ$ dec / $110.34^\circ$ RA
DIFFUSE: STARTING TRACK EVENTS

- Results from 4 years of data.
- Analysis is sensitive to track and cascade topologies.
- Lower energy threshold

![Graph showing Earth Absorption with 6.5σ for 53(+1) events.](chart)

**Expected background**
- atm. neutrino: $9^{+8.0}_{-2.2}$
- atm. muons: $12.5 \pm 5.1$

**Observed events**
- 53$(+1)$

*arXiv:1510.05223*  
*PoS(ICRC2015)1081*
The measured flux seems to tend towards a soft spectrum driven by lower energy bins (threshold $\sim$ 60 TeV)

Dr. Juan A. Aguilar

**DIFFUSE: STARTING TRACK EVENTS**

Assumption: 1:1:1 flavor ratio, 1:1 neutrino:anti-neutrino

- $E^2 dN/ dE$ vs Neutrino Energy [GeV]
- Differential Spectrum (best-fit, charm component floats to zero)
- Differential Spectrum (fit with charm fixed at IC59 90% C.L.)
- IceCube Preliminary
- $(\text{Waxman-Bahcall}'98)/2$
- 6 years up-going $v_\mu$

*arXiv:1510.05223*
*PoS(ICRC2015)1081*
DIFFUSE: COMPATIBILITY OF RESULTS

![Graph showing data points and lines representing different categories]

- Departing from the single unbroken power-law hypothesis $E^{-\gamma}$?
Only a small region of flavor ratios allowed at Earth after cosmological distances.

Both muon damped and pion decay models allowed. Neutron decay excluded at 3.7σ.

-panic: :compatibility of Results

<table>
<thead>
<tr>
<th>Sources</th>
<th>ν_e</th>
<th>ν_μ</th>
<th>ν_τ</th>
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</thead>
<tbody>
<tr>
<td>Pion Decay</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Muon damped</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Neutron decay</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

ν_e : ν_μ : ν_τ at source
- 0:1:0
- 1:2:0
- 1:0:0

IceCube Preliminary

Through-going muons have **excellent pointing**. Atmospheric neutrino background is small when looking for clusterings in the sky!
Using 6 years through-going sample, best sample for point-source searches. No significant excess found. 

New: Analysis using combined data from ANTARES

See Agustin’s talk next

arXiv:1510.05222
PoS(ICRC2015)1047
Uses a modified version of the standard through-going analysis.
Several other searches performed (galactic plane, transients, etc.)
No significant evidence of clustering was found.
WHERE ARE THE SOURCES? GALACTIC

- Arrival distribution of events limit a galactic component < 50% [Ahlers et al. arXiv:1505.03156].

Further constrains on gamma-ray diffuse emission reduces up to a 25% of the neutrino flux [Gaggero et al. arXiv:1505.00227]

- An extra-galactic component needs to be invoked.
WHERE ARE THE SOURCES? EXTRA-GALACTIC

STAR FORMING GALAXIES

- Too many neutrinos to be from Star Forming Galaxies (diffuse γ-ray limited by the non-blazar component of the EGB).
- Blazar population study indicates at most 25% of neutrinos from 2LAC Blazars.
- Gamma-Ray Bursts? Prompt emission also excluded based on IceCube results.
- So, what’s left? Hidden sources?

Bechtol et al. arXiv:1511.00688

BLAZARS

RICAP 2014 Proceedings
Paper in preparation

Bechtol et al. arXiv:1511.00688
MULTIMESSENGER: REALTIME FRAMEWORK

Follow-Up Observations

Analysis

IceCube has 99% duty cycle and all-sky coverage.

X-Rays
Swift

γ-Rays
VERITAS

Optical
PTF

Fast response

IceCube

arXiv:1510.05222
PoS(ICRC2015)1069

Juan A. Aguilar
**MULTIMESSENGER: GRAVITATIONAL WAVES**

- LIGO discovered gravitational waves!
- IceCube/ANTARES did a follow-up of LIGO GW150914
- No neutrino association found (expected from BH mergers)
- A **fast-response analysis** is being put in place to respond quickly to this kind of astronomical events.


See Imre’s talk next session

**Three off-source low-energy neutrinos within ± 500 s**
### MULTIMESSENGER: ICECUBE HESE EVENTS

<table>
<thead>
<tr>
<th>TITLE:</th>
<th>GCN/AMON NOTICE</th>
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<tbody>
<tr>
<td>NOTICE_DATE:</td>
<td>Wed 27 Apr 16 23:24:24 UT</td>
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<tr>
<td>NOTICE_TYPE:</td>
<td>AMON ICECUBE HESE</td>
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<tr>
<td>RUN_NUM:</td>
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<tr>
<td>EVENT_NUM:</td>
<td>67093193</td>
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<td>SRC_RA:</td>
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<td>SRC_ERROR:</td>
<td>35.99 [arcmin radius, stat+sys, 90% containment]</td>
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<tr>
<td>SRC_ERROR50:</td>
<td>0.00 [arcmin radius, stat+sys, 50% containment]</td>
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<tr>
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<tr>
<td>DISCOVERY_TIME:</td>
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<tr>
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<tr>
<td>N_EVENTS:</td>
<td>1 [number of neutrinos]</td>
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<tr>
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<tr>
<td>DELTA_T:</td>
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<tr>
<td>SIGMA_T:</td>
<td>0.0000 [sec]</td>
</tr>
<tr>
<td>FALSE_POS:</td>
<td>0.0000e+00 [s^-1 sr^-1]</td>
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<tr>
<td>PVALUE:</td>
<td>0.0000e+00 [dn]</td>
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<tr>
<td>CHARGE:</td>
<td>18883.62 [pe]</td>
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<td>SIGNAL_TRACKNESS:</td>
<td>0.92 [dn]</td>
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<td>SUN_POSTN:</td>
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<tr>
<td>SUN_DIST:</td>
<td>145.82 [deg] Sun_angle= 10.3 [hr] (West of Sun)</td>
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<tr>
<td>MOON_POSTN:</td>
<td>282.67d {+18h 50m 41s} -18.11d {-18d 06' 31&quot;}</td>
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<tr>
<td>MOON_DIST:</td>
<td>49.62 [deg]</td>
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<tr>
<td>GAL_COORDS:</td>
<td>20.70, 41.68 [deg] galactic lon,lat of the event</td>
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<tr>
<td>ECL_COORDS:</td>
<td>236.19, 29.39 [deg] ecliptic lon,lat of the event</td>
</tr>
<tr>
<td>COMMENTS:</td>
<td>AMON_ICECUBE_HESE.</td>
</tr>
</tbody>
</table>

- An alert system based on HESE track-like events.
- Expected ~ 4 alert notices per year (1 astrophysical, 3 background)
- One event found few weeks after the system was put in place! (ST ~ 0.9)
MULTIMESSENGER: REACTIONS TO ICECUBE-160427A

- GCN 19364 - Fermi Gamma-Ray Burst Monitor - No detection
- GCN 19360 - Fermi LAT - 5 unrelated blazars
- GCN 19361 - HAWC - no detection
- GCN 19362 - MASTER - no detection
- GCN 19377 - VERITAS - no detection
- GCN 19392 - iPalomar Transient Factory - 3 transients, all AGN
- GCN 19427 - FACT Cherenkov TeV Telescope - no detection
- GCN 19426 - Interplanetary Network - no detection
- GCN 19381 - Pan-STARRS - 7 SN candidates, one consistent with type Ic supernova.
ICECUBE-GEN2 A VISION FOR THE FUTURE

PINGU
Further in-fill
Lower the energy threshold few GeV
Neutrino Mass Hierarchy
Dark Matter + Solar Flares

High Energy Array (HEA)
Extension of IceCube array
Look for high-energy events
GZK and astrophysical neutrinos

Radio Array: 100-300 km$^2$ for extremely high energies ($\geq 10^{18}$ eV)

Surface Veto: Air shower detector with 75 km$^2$ / 100 TeV threshold

CONCLUSIONS

- The future exploration of the high energy universe belongs to Neutrino Astronomy.
- IceCube has started to characterize the observed astrophysical neutrino flux.
- Future discoveries will be only possible with multimessenger campaigns. IceCube is actively interconnected in the realtime network sending and receiving alerts.
- Different components (IceTop-2, HEA, Radio Array,...) will make IceCube-Gen2 a global neutrino observatory.
- Many other analysis results not presented here: Dark Matter, Oscillations, Sterile Neutrinos, Cosmic Ray Anisotropy,...