Astrophysics and Particle Physics with IceCube and Beyond

PASCOS
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Outline

• The IceCube Neutrino Observatory

• Observations of very high energy neutrinos

• Particle physics with IceCube

• Future Plans: IceCube Gen2
Neutrinos produced as by-product of cosmic ray acceleration near their sources.
IceCube
South Pole Neutrino Observatory

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

IceTop
50 m

1450 m

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

60 DOMs on each string

DeepCore

2450 m

DOMs are 17 meters apart

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

Antarctic bedrock
5 years
IceCube Detector Completion

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Neutrino Signatures

Track
\( \nu_\mu \) CC

- angular resolution <1°
- usually enter IceCube from outside
- factor of 2 resolution on \( E_\mu \) (not \( E_\nu \))

Cascade
\( \nu_e \) CC, \( \nu_x \) NC, low-\( E \) \( \nu_\tau \)

- angular resolution approximately 10°-15°
- 15% resolution on deposited energy

Double Bang (MC)
one high-\( E \) \( \nu_\tau \) topology

- \( \tau \) lepton decay length \( c\tau_\tau \approx 50 \text{ m/PeV} \)
- second cascade at decay vertex (except \( \tau \rightarrow \mu\nu_\mu \), 17% BR)
- not yet observed
atmospheric $\mu$ (~3 kHz)

atmospheric $\nu$ (~5 mHz)

"conventional:" $\pi/K$ decay

"prompt:" charmed mesons, intrinsic charm

astrophysical $\nu$ (~$\mu$Hz)
Atmospheric Muon and Neutrino Veto

- Schönert et al. 2009,
- Gaisser et al. 2014
Astrophysical Neutrinos

- Equal-flavor flux (oscillations) will produce mostly $\nu_e/\nu_\tau$/NC cascades
  - Easiest to identify as astrophysical since most energy deposited in detector

“Bert” 1.04 PeV Aug. 2011


Upward-Going Muon Neutrinos

- Also observe $5.6\sigma$ excess in high-energy $\nu_\mu$ passing through the Earth – completely independent observation channel

- Highest energy neutrino yet: $2.6 \pm 0.3$ PeV deposited in detector
  - *Lower limit on* $E_\nu$

- Up-going track ($\nu_\mu$)
  - Declination $11.5^\circ$, 11/6/14
Where Do They Come From?

Largely isotropic – extragalactic origin

Sub-dominant galactic component cannot be ruled out

Cascade events only

\[ p-value = 18\% \]

ICECUBE PRELIMINARY

4 year high energy starting event sample
Where Do They Come From?

7 year through-going muon neutrino sample
Where Do They Come From?

7 year through-going muon neutrino sample

post-trial p-value 35%
Possible Source Classes

✗ Gamma Ray Bursts

• No more than 1% of the observed HE neutrino flux is associated with GRBs
• However, limits on UHECR-GRB models are constraining but not definitive
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  • No correlation found: < 30% of astrophysical neutrino flux is correlated with 2LAC blazar catalog (even less if weighted by gamma ray emission)
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❓ Starburst Galaxies and other transparent Cosmic Ray Reservoirs
  • Gamma rays co-produced along with neutrinos would exceed residual Fermi-LAT diffuse gamma ray flux not attributable to blazars (Murase et al. 2013, Bechtol et al. 2015)
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Multi-messenger studies underway:
* combining IceCube data with LIGO, Auger, TA, Fermi-LAT, ANTARES, HAWC
* GCN + follow-up searches by MAGIC, VERITAS, HESS, Swift, iPTF, TAROT, Pan-STARRS, MASTER, ASAS-SN
The High Energy Universe

Similar energy injected into the Universe in gamma-rays, neutrinos & UHE cosmic rays!

Fig. adapted from L. Mohrmann
Flavor Ratios

- Astrophysical effects can alter flavor ratio at source
- After oscillations, all sources should wind up inside the triangle – otherwise, new physics required!

Caveat: Assumes a unified flux!
The Plot Thickens

Combined spectral index: $\gamma = -2.5 \pm 0.1$
High energy tracks: $\gamma = -2.1 \pm 0.1$

$E_\nu > 190$ TeV
Northern sky
all $\nu_\mu$

$E_\nu > 25$ TeV
North + South
mostly $\nu_e$, $\nu_\tau$

Are we seeing a break in
the spectrum, anisotropy,
multiple components,...?
Cosmogenic (BZ) Neutrinos

- Produced when UHECR interact with CMB – primary uncertainty is CR composition

- EHE analysis sensitive to 1 PeV – 2 EeV range

- Non-detection with 6 yr of data becoming a serious constraint on proton fraction of UHE cosmic ray flux
  
  - Limits on mixed or heavy composition more model-dependent
Indirect Searches for Dark Matter

Similar accumulation in Galactic and terrestrial gravitational wells, dwarf spheroidals

Can also probe dark matter decay models, other types of dark matter

Silk, Olive and Srednicki, '85
Gaisser, Steigman & Tilav, '86
Freese, '86
Krauss, Srednicki & Wilczek, '86
Gaisser, Steigman & Tilav, '86
et alia
Leading limits for SD nuclear scattering with massive WIMPs, for most assumed annihilation products.
Oscillations with Atmospheric Neutrinos

• Neutrinos available over a wide range of baselines, few GeV to 10’s of TeV

• Oscillations produce distinctive pattern in energy-angle space
  • Effectively, a range of near to far beams rather than near and far detectors

• Significant matter effects for neutrinos traversing Earth’s core
Probing oscillation physics at a range of baselines and energies not accessible to long-baseline or reactor neutrino experiments
Sterile Neutrinos

• Existence of sterile neutrino state produces MSW resonant $\bar{\nu}_\mu$ disappearance for particular neutrino energy, angle (=matter profile)

  • Location of resonance depends on sterile neutrino mixing parameters

• Fortuitously, preferred range around 1 eV$^2$ leads to resonance at TeV scale – core IceCube energy range
Sterile Neutrino Limits

• Strong constraints on $\theta_{24}$ for $\Delta m^2$ around 0.1–2 eV$^2$
  • $\theta_{14}$ and $\theta_{34}$ assumed to be zero
  • Exclude parameter space favored by appearance experiments
A neutrino facility addressing a wide range of scientific topics spanning GeV-EeV energies

- Gen2 high energy array
- PINGU low energy extension
- Surface air shower/veto array
- Sub-surface radio Cherenkov array
PINGU

- 26 additional, very densely instrumented strings embedded in DeepCore
  - Additional calibration devices to better control detector systematics
- 6 MTon fiducial volume with few GeV energy threshold

Neutrino Physics with PINGU

Determination of the neutrino mass ordering

Measurement of mixing parameters with different method/energy range – Excellent sensitivity to octant of $\theta_{23}$

Precision measurement of $\nu_\tau$ appearance – probe unitarity of PMNS matrix
Summary and Outlook

• IceCube has established the existence of a flux of high energy astrophysical neutrinos with observations in multiple channels
  • Some evidence that the flux may be more complex than an isotropic, equal-flavor power law spectrum
  • Identity of the sources elusive, some candidates ruled out, multi-messenger observations
  • Similar energies in $\nu$, $\gamma$, extragalactic CR fluxes – gives important constraints on origins
  • No observation of cosmogenic (BZ) neutrinos yet

• IceCube is also sensitive to a range of neutrino and BSM physics
  • Neutrino oscillations, sterile neutrinos, dark matter, Lorentz violation, monopoles, etc.

• Planning underway for IceCube-Gen2: accelerate progress toward understanding astrophysical neutrinos, rich neutrino physics and dark matter program with PINGU
Atmospheric Neutrino Veto

- Up-down asymmetry due to veto is an important observable
  - Contributions from charm uncertain – angular distributions critical

Upward-going Muon Neutrinos

Confirmation of the astrophysical neutrino flux in a completely independent data set

Spectrum appears somewhat harder in this data, around $dN/dE \sim E^{-2.0}$ rather than $E^{-2.6}$
Medium Energy Starting Events

*Phys. Rev. D91, 022001 (2015)*

- Lower energies accessible with scaled veto

- Null hypothesis of isotropic, power-law flux not rejected, but we can have fun speculating
- Best-fit (power law): $\gamma = -2.52$
- Best-fit (PL + cutoff): $\gamma = -2.37$, $E_c = 3.1$ PeV
- Best-fit prompt is zero in either case; $-2\Delta \ln L (\text{PL} - \text{PL}+\text{cut}) = 1.54$
Gamma Ray Bursts

- Energetically attractive UHECR source candidates

- Good information from Swift, Fermi – very low background
  - Up-going $\nu_\mu$ track search: 506 northern bursts (4 years)
  - All-flavor cascade search: 257 bursts (1 year)

- Current UHECR-GRB models constrained but not ruled out – but only $\sim 1\%$ of the HE $\nu$ flux can come from GRBs

Active Galactic Nuclei/Blazars

- Stacking limit on Fermi-LAT blazars suggests less than 30% of observed HE astrophysical neutrino flux comes from these sources

- But much more model dependence than for GRBs, e.g. Padovani, Resconi, Petropoulou et al. on HBL Lac objects and time dependence
If neutrino sources produce gamma rays, most of the Fermi isotropic gamma ray background comes from these sources...

...but if blazars don’t produce neutrinos, the remaining gamma ray background is too low for the observed neutrino flux

- Are the neutrino sources opaque to gamma rays?
  - Disfavors some candidates, such as starburst galaxies
- Implies that a significant fraction of the energy in the non-thermal Universe is due to hadronic accelerators

K. Bechtol et al., arXiv:1511.00688
A Galactic Component?

- Scan sky map for excess emission along the Galactic plane
  - *p*-values intriguing, but required emission widths are very large…
Correlations with UHECR?

- Joint analysis of multi-year sky maps from IceCube, Pierre Auger and Telescope Array
  - Complicated by unknown magnetic deflection of cosmic rays
  - Few-percent $p$-value again interesting, but not compelling
How Many Sources Are There?


Point-source equivalent flux if the diffuse flux came from:

100 points in the sky

1000 points in the sky

Slide from Chad Finley, RICAP 2014
Atmospheric Charm

• Global fit to several data sets assuming charm flux of Enberg et al. 2008

• No allowance for contributions of intrinsic/spectator charm
Intrinsic Charm

Halzen and Wille, arXiv:1601.03044

- Normalization chosen to saturate IceCube low-energy observations

![Graph showing event counts in the northern and southern skies](image)

- Observed events in IceCube.
- Additional cosmic neutrino flux is needed to have agreement between the expected and observed events.
- Detection scheme for prompt neutrino leaves little room for an additional cosmic neutrino flux without exceeding the observed events.

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Dark Matter in the Galactic Halo

- Can also search for high energy neutrinos from Galactic halo, dwarf galaxies
  - Gamma ray telescopes generally better for lower masses, small sources
Atmospheric Oscillations with IceCube

- Projection onto \((L/E_\nu)\) for illustration
- Shaded range shows allowed systematics with constraints from current data
  - Systematics-limited; but constraints on systematics are statistics-limited
- Second survival maximum just below DeepCore’s energy threshold

*Phys. Rev D91, 072004 (2015)*
Tau Neutrino Appearance in DeepCore

- Essentially zero intrinsic $\nu_\tau$ flux
- Tau neutrinos from oscillations peak vertically, with specific spectrum
  - Cascade backgrounds are highest near the horizon, broad spectrum

![Graphs showing expected number of events vs L/E (km/GeV) for different neutrino types with and without oscillations.]

- Expected number of events/3 years vs L/E (km/GeV)
  - Track-like and Shower-like categories
  - MC and IceCube Preliminary data

![Graphs showing expected number of events/year vs cos(Zen) for different neutrino types with and without oscillations.]

- Expected number of events/year vs cos(Zen)
This selection targets a clean sample of $\nu_\mu$ CC events and thus misclassifies many $\nu_\mu$ CC events with muons too short to be seen clearly. As a result, the shower sample shows a reduction in rate from the disappearance of these $\nu_\mu$, offset by the appearance of $\nu_\tau$. The $\nu_\tau$ CC cross section is suppressed by the $\tau$ lepton mass and ranges from 25-40% of the $\nu_\mu$ CC cross section in the 10-20 GeV range \cite{11}, implying that the offset is only partial.

Although a few systematics from the $\nu_\mu$ disappearance analysis of Sec. 5.1 are not yet included in this study, as indicated in Table 1, their effect on the $\nu_\mu$ analysis was not large and they are unlikely to affect the $\nu_\tau$ measurement significantly. We will investigate whether re-optimization of the particle ID algorithm would improve the sensitivity of the measurement, but even without further optimization we will obtain world-leading precision on the rate of $\nu_\tau$ appearance with the existing DeepCore data set, as shown in Fig. 7.

As the $Z$ boson width establishes that it couples to only three light neutrino species \cite{11}, $\nu_\mu$ oscillating to new types of neutrinos will not contribute to the NC rate and thus $\nu_\tau$ NC events are included in the $\nu_\tau$ rate measurement in Fig. 7, although we also plan to report rates and significances based on $\nu_\tau$ CC events only, for comparison to other measurements \cite{85, 86}.

This measurement will be an important test of the unitarity of the PMNS mixing matrix, complementary to other searches for physics beyond the Standard Model in the neutrino sector; alternatively, under the assumption of unitarity measurement of the appearance rate provides an interesting test of assumptions of lepton universality used to calculate the $\nu_\tau$ cross section. This analysis will be the focus of Dr. de André.

Figure 6: Impact of $\nu_\tau$ appearance on the reconstructed L/E distributions for events classified as track-like (left) and shower-like (right). The two peaks in each plot are due to down-going and up-going neutrons. Tau neutrinos have minimal impact on track-like events, so both down-going neutrinos and tracks serve as control samples for clustering systems. The effect of $\nu_\tau$ appearance, primarily CC events, is clearly visible in the up-going shower sample in the right-hand plot.

Figure 7: Expected precision with which the rate of $\nu_\tau$ appearance can be measured as a function of exposure, compared to existing (1$\sigma$) measurements. The standard expectation corresponds to a value of 1.0. With 3 years of data already available, DeepCore’s measurement will be the world’s most precise.

Expected sensitivity based on MC data challenges, analysis underway.
Supernova Detection with IceCube

- Inverse beta decay at $\mathcal{O}(10$ MeV)
  
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \]

  - Some impact from positron annihilation and neutron capture
  
  - Produces $\sim$2000 Cherenkov photons per neutrino

- May detect $\sim$1 photon from neutrinos near strings
  
  - Elevated detector “noise” rate proportional to deposited energy
Supernova Detection

![Graph showing supernova detection with data and theoretical models]

- **data with muon subtraction**
- **data**
- **Huedepohl Ahlers NH**
- **Lawrence Livermore Ahlers NH**

(following radial distribution of progenitors in the Milky Way)
Coverage

- High significance throughout Milky Way, detectable in LMC
Supernova Observations

- High statistics measurement of energy-weighted neutrino light curve
  - Little information on spectrum or neutrino/antineutrino ratio
- Useful in conjunction with measurements from other detectors

![Graph showing neutrino light curve with Lawrence-Livermore and O-Ne-Mg 1D models. Assumed distance: 10 kpc. Statistical precision marked.]
Mass Ordering from Supernovae
IceCube Dark Noise

- Contributions from thermal emission, afterpulses, correlated emission from glass(?) and muons
- Gradual decrease as PMTs settle down after light exposure

Suppressed by artificial deadtime
Magnetic Monopoles

- Very bright, slow tracks – also relevant for Q-balls, nuclearites, etc.

Regular light deposition, after correction for ice

Irregular pattern due to bremsstrahlung, etc.
Magnetic Monopoles

- World’s leading flux limits for a wide range of monopole $\beta$
Surface Veto Array

- Potential to greatly enhance usable target for $\nu_\mu$ by directly detecting air showers that could produce atmospheric neutrinos.
  - Several technologies under investigation (scintillators, air Cherenkov)
Possible Gen2 Timeline

Potential to improve performance/reduce cost with new technologies under investigation
PINGU Cost Estimate

<table>
<thead>
<tr>
<th></th>
<th>Cost (20 Strings)</th>
<th>Cost (26 Strings)</th>
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</thead>
<tbody>
<tr>
<td>Drill refurbishment</td>
<td>$5M</td>
<td>$5M</td>
</tr>
<tr>
<td>Deployment (labor)</td>
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<td>$5M</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>$25M</td>
<td>$33M</td>
</tr>
<tr>
<td>Management &amp; other costs</td>
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<tr>
<td>Total</td>
<td>$39M</td>
<td>$47M</td>
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<tr>
<td>Fuel</td>
<td>146,000 gal</td>
<td>190,000 gal</td>
</tr>
</tbody>
</table>

(excl. contingency)

- Bulk of instrumentation expected to come from non-US partners
- Redesign reduces costs through
  - Enabling use of refurbished IceCube hot-water drill: $11M
  - Labor costs for eliminated third Pole season: $3M
  - Savings on per-string costs (fuel, cables): ~$8M