1. Introduction

2. Neutrinos and Gamma Rays

3. Neutrinos and Cosmic Rays

4. The IceCube Signal

5. Outlook
1. Introduction

• Why Neutrino Astronomy?

• Neutrinos Sources

• Neutrinos and the “High Energy Universe”

[a] Use neutrinos as “messengers” to study the universe. 
“A new way to look at the sky”

[b] Study neutrino propagation, infer fundamental properties of neutrinos
[masses, mixing, ...]
Neutrino Sources

Geo-neutrinos
Solar Neutrinos
SuperNova Neutrinos

\[ E_\nu \approx 1 - 100 \text{ MeV} \]
Neutrino Sources

Cosmological Neutrinos

\[ E_\nu \simeq 10^{-4} \text{ eV} \]

Geo-neutrinos
Solar Neutrinos
SuperNova Neutrinos

\[ E_\nu \simeq 10^6 - 10^8 \text{ eV} \]

Neutrinos from the “High Energy Universe”

\[ E_\nu \simeq 10^{10} - 10^{23} \text{ eV} \]
Neutrino Astrophysics is a very diverse field that extends in a very broad energy range.

**Cosmological Neutrinos**

\[ E_\nu \approx 10^{-4} \text{ eV} \]

**Geo-neutrinos**

**Solar Neutrinos**

**SuperNova Neutrinos**

\[ E_\nu \approx 10^6 - 10^8 \text{ eV} \]

**Dark Matter searches**

\[ E_\nu \approx 10^{10} - 10^{12} \text{ eV} \]

\[ E_\nu \approx 10^{12} - 10^{14} \text{ eV} \]

**Galactic Point Sources**

\[ E_\nu \approx 10^{14} - 10^{16} \text{ eV} \]

**IceCube Signal**

\[ E_\nu \approx 10^{18} - 10^{20} \text{ eV} \]

**GZK neutrinos**

\[ E_\nu \approx 10^{23} \text{ eV} \]

**Decay Supermassive particles**

\[ E_\nu \approx 10^{23} \text{ eV} \]
The ensemble of astrophysical objects, environments and mechanisms that generates very high energy relativistic particles in the Milky Way and in the entire universe.

“High Energy Universe”

4 Messengers

Cosmic Rays, Photons, Neutrinos

Gravitational Waves
2. Neutrinos and Gamma Rays

- Gamma Ray emission: “Leptonic” versus “Hadronic”
- Neutrinos versus Gamma Rays
- Flavor of Astrophysical Neutrinos
- The Gamma Ray Sky
- Gamma Ray absorption
Fundamental Mechanism: Acceleration of Charged Particles to Very High Energy ("non thermal processes") in astrophysical objects (or better "events").

Creation of Gamma Rays and Neutrinos via the interactions of these relativistic charged particles.

"Hadronic"

\[
p + X \rightarrow \pi^+ \pi^- \pi^0 \ldots
\]

\[
\pi^0 \rightarrow \gamma \gamma
\]

\[
\pi^+ \rightarrow \mu^+ \nu_\mu
\]

\[
\rightarrow e^+ \nu_e \bar{\nu}_\mu
\]

"Leptonic"

\[
e^\pm \gamma_{soft} \rightarrow e^\pm \gamma
\]

\[
e^\pm Z \rightarrow e^\pm \gamma Z
\]

\[
e^\pm \vec{B} \rightarrow e^\pm \gamma_{syn}
\]
High Energy Astrophysical Sources:

Astrophysical object (or “event”) that accelerates, and contains (electrically charged) relativistic particles (protons, electrons, nuclei,...)
High Energy Astrophysical Sources:

Astrophysical object (or “event”) that accelerates and contains (electrically charged) relativistic particles (protons, electrons, nuclei, ...)

**Escape:**
Generation of CR

**Interactions:**
Emissions
- gamma rays,
- neutrinos

**Escape:**
Generation of CR
Population of relativistic protons: \( N_p(E_p) \)

Average density of the medium: \( \eta \)

Emission Rates of Photons and Neutrinos:

\[
\dot{N}_{\nu,\gamma}(E) = \int_E^\infty dE_p \ N_p(E_p) \ \left[ \sigma_{pp}(E_p) \ c \eta \right] \ \frac{dN_{\gamma,\nu}(E, E_p)}{dE}
\]

\[ p + X \rightarrow \pi^+ \ \pi^- \ \pi^0 \ldots \]

Simple relation between neutrino and gamma-ray emissions

\[ \pi^+ \rightarrow \mu^+ \ \nu_\mu \]

\[ \pi^0 \rightarrow \gamma \ \gamma \]

\[ \rightarrow e^+ \ \nu_e \ \bar{\nu}_\mu \]
Neutrino spectra in (chain) pion decay

\[ \pi^+ \rightarrow \mu^+ \quad \nu_\mu \]

\[ \rightarrow \quad e^+ \quad \nu_e \quad \bar{\nu}_\mu \]

\[ \pi^+ \rightarrow \nu_\mu \]

\[ \pi^+ \rightarrow \mu^+ \rightarrow \nu_e \]

\[ x = E_\nu/E_\pi \]
IF the population of relativistic protons inside an astrophysical source is a \textit{power law of exponent \alpha}

$$N_p(E) = K_p \ E_p^{-\alpha}$$

Then (in reasonably good approximation) the neutrino and photon emissions are also power laws with the \textit{same exponent}.

$$\dot{N}_\nu(E) = Q_\nu \ E_\nu^{-\alpha}$$

$$\dot{N}_\gamma(E) = Q_\gamma \ E_\gamma^{-\alpha}$$
Ratio Neutrino-Photon (numerical calculation)

\[ \frac{\phi(\nu)}{\phi(\gamma)} \]

Before \( \nu \) Oscillations

- \( \pi^+ \approx \pi^- \approx \pi^0 \)
- \( \pi^0 / \pi^\pm \approx 1/2 \)
- \( \gamma / \nu \approx 1 \)
- \( \pi^+ / \pi^- \approx 1 \)
- \( \nu / \bar{\nu} \approx 1 \)
$p\gamma$ versus $pp$

Cross section $p + \gamma \rightarrow$ hadrons

Near Threshold: single pion production

$p + \gamma \rightarrow n + \pi^+$
$p + \gamma \rightarrow p + \pi^0$

$\pi^+/\pi^- \gg 1$
$\pi^0/\pi^+ \approx 1$
$\gamma/\nu \approx 2$
$\nu/\bar{\nu} \approx 2$
Energy threshold for photo-production: (creation of a single pion):

\[ s_{p\gamma} \geq (m_p + m_\pi)^2 \]

Minimum photon energy for photo-production of a proton of energy \( E_p \)

\[ \varepsilon_{\text{min}} \propto E_p^{-1} \]

\[ \varepsilon \geq \frac{1}{4 E_p} (2 m_p m_\pi + m_\pi^2) \]

The number of targets is a function of the proton energy.
Proton *interaction probability* per unit time:
[Convolution of cross section with soft photons distributions]

\[
K_{p\gamma}(E_p) = \sigma_{p\gamma} \otimes n_{\gamma}(\varepsilon)
\]

\[
K_{p\gamma}(E_p) = \int d\varepsilon \int_{-1}^{+1} \frac{d\cos \theta_{p\gamma}}{2} (1 - \cos \theta_{p\gamma}) n_{\gamma}(\varepsilon, \cos \theta_{p\gamma}) \sigma_{p\gamma}(\varepsilon_r)
\]

Target photon distribution has approximately a power form:
[main example is Gamma Ray Bursts]

\[
n_{\gamma}(\varepsilon) \propto \varepsilon^{-\beta}
\]

\[
K_{p\gamma}(E_p) \propto E^{\beta}
\]

Interaction probability that grows with energy reflecting the target photon spectral shape
Neutrino emission spectral shape in $p\gamma$ mechanism

\[ N_p(E_p) \propto E_p^{-\alpha} \]

Relativistic protons

\[ n_{\gamma}(\varepsilon) \propto \varepsilon^{-\beta} \]

Target photon field

\[ \dot{N}_{\gamma}(E_{\gamma}) \propto E_{\gamma}^{-\alpha+\beta-1} \]

Neutrino emission

\[ \alpha_{\nu} \approx \alpha - \beta + 1 \]

Spectral index of the neutrinos reflects the spectral indices of the interacting protons and of the target photons
Prediction of the neutrino flux from a source observed in gamma rays

\[ \phi_\gamma(E) \quad \text{to} \quad \phi_{\nu_\alpha}(E) \]
\( \phi_{\gamma}^{\text{leptonic}}(E) + \phi_{\gamma}^{\text{hadronic}}(E) \)

Possible absorption in the source (and in propagation from the source)

\( \phi_{\gamma}(E) \)

Earth

Flavor oscillations (good theoretical control)

\( \phi_{\nu_{\alpha}}(E) \)

Energy extrapolation

Astrophysical source
"Signature" of the hadronic mechanism:

The mass $m_{\pi^0}$ leaves its "imprint" on the photon spectrum.

\[ E_{\gamma,\text{min}} = E_\pi (1 - \beta_\pi) \]
\[ E_{\gamma,\text{max}} = E_\pi (1 + \beta_\pi) \]
Pions of energy $E_\gamma$ can be created only by pions with energy $E_\pi \geq E_{\pi, \text{min}}(E_\gamma)$

\[
E_{\pi, \text{min}}(E_\gamma) = E_\gamma + \frac{m_\pi^2}{4 E_\gamma} = \frac{m_\pi}{2} \left[ \frac{2 E_\gamma}{m_\pi} + \frac{m_\pi}{2 E_\gamma} \right]
\]

[symmetry for “reflections” around $E_\gamma = m_\pi/2$ ]

![Graph showing the relationship between $m_\pi$ and $E_\pi$](image)
Spectrum symmetric around $E_\gamma = \frac{m_{\pi^0}}{2}$

High energy cutoff:
Reflects a possible cutoff in the Proton spectrum
Detection of the characteristic pion-decay signature in Supernova Remnants
The Gamma Ray sky

- Diffuse Galactic Flux
- Galactic Sources
- Extragalactic Sources
\[ E_\gamma \geq 100 \text{ MeV} \]
1. Ensemble of (quasi)-point sources

2. Diffuse Galactic Flux

(80% of photons around 1 GeV)

(generated by cosmic rays magnetically confined in the Milky Way)

3. Isotropic flux.

(attributed to an ensemble of unresolved extragalactic sources)
50% of flux
+/- 5 degrees
around equator

energy range 200 MeV to 100 GeV
Galactic Diffuse flux spectral shape

\[ \phi_{\gamma}^{\text{diffuse}}(E_\gamma) \propto E_\gamma^{-2.70} \]

\[ \alpha_{\gamma}^{\text{diffuse}} \approx 2.70 \pm 0.05 \]

Decomposition (by FERMI) of the diffuse Galactic flux
Angular distribution of the diffuse Galactic emission

$E_\gamma = 12 \text{ GeV}$

$\phi(\Omega) / \phi_{GC} = 0.5, 0.25, 0.1, 0.05$
Galactic Latitude distribution

![Graph showing Galactic Latitude distribution](image)

Galactic Longitude distribution

![Graph showing Galactic Longitude distribution](image)
3rd FERMI Catalog

E > 100 MeV

3034 sources
3034 3rd catalog sources  [approximately 440 are galactic]
TeV Sky $170 \rightarrow 200$ Sources

blue-to-red colors $\rightarrow 0.1$ GeV – Fermi gamma-ray sky
HESS survey of Galactic Plane [ICRC 2015] 77 “firm identifications”
Gamma Ray Absorption:

\[ \gamma + \gamma \rightarrow e^+ + e^- \]

\[ x = \frac{s}{4m_e^2} = \frac{E_\gamma \varepsilon (1 - \cos \theta_{\gamma\gamma})}{2m_e^2} \]

\[ \sigma^{\text{max}}_{\gamma\gamma} \approx 0.2554 \sigma_{\text{Th}} \]

\[ \approx 1.70 \times 10^{-25} \text{ cm}^2 \]
Gamma Ray absorption (intergalactic space)

Astronomy $E > 100$ TeV: Galactic Astronomy

$P_{\text{surv}} (E, d)$

Mrk 421
$z = 0.03$

$d = 10, 30$ kpc
$d = 1, 3, 5, 10, 120$ Mpc

$E_\gamma$ (TeV)
Extragalactic Gamma Ray flux

\[ \phi_\gamma(E) E^2 \text{ [GeV/(cm}^2\text{s}\text{sr}]} \]

Extragalactic gamma ray flux

- a: No evolution
- b: SFR Madau–Dickinson
The Gamma Ray Sources:

SNR
Pulsars
MicroQuasars

AGN
GRB's

Wonderful Beasts in the Sky
Johannes Kepler,
*De Stella Nova in Pede Serpentarii*
(1606)
The CRAB Nebula

1 minute = 0.58 pc
= 1.8 \times 10^{18} \text{ cm}
Superluminal Motions in microQuasars in our Galaxy

GRS1915+105

Observations in radio

$\lambda = 3.5$ cm

“Two pairs of bright radio condensations”
CENTAURUS A

First object imaged with Cosmic Rays?
The Galactic Center
(extends to 1 PeV)
GRB: associated with a subset of SN Stellar Gravitational Collapse
What has Fermi found: The LAT two-year catalog

- Blazars: 57%
- Supernova remnants: 4%
- Globular clusters, high-mass binaries, normal galaxies and more: 1%
- Pulsars: 6%
- Non-blazar active galaxies: 1%
- Unknown: 31%

575 (31%)
Many unassociated sources...

Credit: NASA/Goddard Space Flight Center
Extragalactic Flux: Resolved + unresolved sources

\[ \phi_{\text{tot}} \left( 10^{-6} \text{ cm}^{-2} \text{s}^{-1} \right) \]

\[ \phi[10-100 \text{ GeV}] \left( \text{cm}^{-2} \text{s}^{-1} \right) \]

\[ |\sin(b_{\text{gal}})| > 0.4 \]

Unresolved isotropic Flux

PKS 0426–380
PKS 2155–304
S5 0716+71
Mkn 421
PKS 0537–441
3C 454.3
Extragalactic Flux: Resolved + unresolved sources

Extragalactic flux dominated by “blazars” [AGN]

Brightest source in the sky (3C454.3) 1.8 % of extragalactic light
Angle integrated components of the Gamma Ray Sky

\[ \Phi_{\gamma,\gamma}(E) E^2 \text{ [GeV/(cm}^2\text{s)]} \]

- a: \( \gamma \) IceCube HESE
- b: \( \gamma \) IceCube muons
- c: \( \gamma \) Galactic diffuse
- d: \( \gamma \) extragalactic
- d': \( \gamma \) extragal. sources
- e: \( \gamma \) Galactic sources
- f: TeVCat Gal. sources

\( E \) (GeV)
3. Neutrinos and Cosmic Rays

- Galactic and Extragalactic Cosmic Rays
- Cosmic Ray versus Neutrino emission
High-energy cosmic ray spectrum

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)

Scaled flux $E^{-2.5} J(E)$ (m$^{-2}$ sec$^{-1}$ sr$^{-1}$ eV$^{1.5}$)

Knee(s) transition galactic-extragalactic

Low energy EAS measurements (high-altitude)

Highest energy cosmic rays

HERA (e+p), RHIC (p+p), Tevatron (p+p), LHC (p+p)
Kascade-Grande results

"Iron Knee"

\[ E_{\text{knee}}(Z) = Z \ E_{\text{knee}}(p) \]

Extragalactic Cosmic Rays become dominant at lower energy

\[ E^* < E_{\text{ankle}} \]
4. The IceCube Signal

- Atmospheric Foreground
  - “Conventional flux” ($\pi^\pm$, $K$ decay)
  - “Prompt flux” (charm decay)
- Galactic versus Extragalactic
- Resolved versus Unresolved sources
- Neutrino Point Sources
High Energy Starting Events

4 years data

Track [(small) black circles]
Showers [ (large) blue circles]

Galactic equator

\( E_{\text{vis}} \gtrsim 30 \text{ TeV} \)
First evidence for an extra-terrestrial h.e. neutrino flux
First evidence for an extra-terrestrial h.e. neutrino flux.

3 “PeV events” carry most of the statistical significance for an excess.
Upgoing (neutrino induced) Muons

IC2012-2014

Rate per Bin / Hz

Muon Energy Proxy / GeV

Upgoing muon events

$E_\mu \gtrsim 200$ TeV

Interpretation offered by IceCube collaboration:
(of the HESS events)

There is an excess of neutrino events over the foreground of atmospheric neutrinos.

Consistent with an isotropic (extragalactic) flux

with equal intensity for all 3 flavors (e, mu, tau) [little sensitivity to the nu/antinu ratio.]

Simple Power Law:

\[ \phi_\nu^{\text{astro}} (E) = \phi_0 E^{-2.50 \pm 0.09} \]
Estimates of the (equal-flavor) astrophysical flux

\[ \phi^\text{astro}_\nu (E) = \phi^\text{HESE}_0 E^{-2.50\pm0.09} \]

\[ \phi^\text{astro}_\nu (E) = \phi^\mu_0 \uparrow E^{-2.13\pm0.13} \]
Systematic Effect?

Break in the Spectrum

Two components in the spectrum

Anisotropy?

[Galactic + extragalactic components]
Compare the **Neutrino Signal** to **Gamma Ray fluxes**.
Compare the *Neutrino Signal* to *Gamma Ray fluxes*

IceCube Signal *higher* than extrapolations of extragalactic flux

*New class of “hidden” sources?*

If IceCube contains a Galactic Component. what is its origin?
(Testable) Assumptions:

1. Equal flavor

2. Isotropy (extragalactic flux)
Space averaged flavor transition probability

Neutrinos created in volume of sufficiently large linear size

\[ X_{\text{source}} \gg \frac{E}{|\Delta m_{jk}^2|} \]

Oscillating terms average to zero
\[ \langle P(\nu_\alpha \rightarrow \nu_\beta) \rangle = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 \]

\[ \frac{1}{2} \begin{pmatrix} 1 - 2v & v & v \\ v & (1 - v)/2 & (1 - v)/2 \\ v & (1 - v)/2 & (1 - v)/2 \end{pmatrix} \approx \begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix} \]

\[ \theta_{13} \approx 0 \]

\[ \theta_{23} \approx 45^\circ \]

\[ v = \cos^2 \theta_{12} \sin^2 \theta_{12} \approx 0.2 \]

\[ \begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \]

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]

\[ \rightarrow e^+ \nu_e \overline{\nu}_\mu \]
“Standard mechanism”
\[
\begin{pmatrix}
1 \\
2 \\
0
\end{pmatrix}
\Rightarrow
\begin{pmatrix}
1 \\
1 \\
1
\end{pmatrix}
\text{ much more “astrophysically plausible”}
\]

“Muon absorption”
\[
\begin{pmatrix}
0 \\
1 \\
0
\end{pmatrix}
\Rightarrow
\begin{pmatrix}
v \\
(1-v)/2 \\
(1-v)/2
\end{pmatrix}
\approx
\begin{pmatrix}
0.2 \\
0.4 \\
0.4
\end{pmatrix}
\]

Very high magnetic field

“Neutron decay”
\[
\begin{pmatrix}
1 \\
0 \\
0
\end{pmatrix}
\Rightarrow
\begin{pmatrix}
1-2v \\
v \\
v
\end{pmatrix}
\approx
\begin{pmatrix}
0.6 \\
0.2 \\
0.2
\end{pmatrix}
\]

Nuclear fragmentation
Include
best fit of oscillation parameters
(delta dependence)

Significant presence of tau-neutrinos
Possibility of “Modifications” of the neutrino flux during propagation.

Investigate:
Flavor Oscillations (with very long path-lengths)

Neutrino Decay [with very long lifetimes]

\[ z \approx 1 \quad \Delta m^2 \approx 10^{-18} \left( \frac{E}{100 \text{ TeV}} \right) \text{ eV}^2 \]

Important difficulty:
Properties of the neutrinos at the source must be sufficiently well understood.
Questions:

1. Is the signal of astrophysical neutrinos real? (or is the background/foreground poorly estimated)?

1a. Could the signal be contaminated by a non negligible contribution of atmospheric neutrinos?

2. Is the signal entirely extragalactic? Or does it contain a non negligible Galactic component?

3. If most of the signal is extragalactic, what can we say about the sources?

3a. If there is a Galactic (perhaps subdominant) component, what is its nature?
$$\phi_{\nu_\alpha}(E, \Omega) = \phi_{\nu_\alpha}^{\text{atm. standard}}(E, \Omega) + \phi_{\nu_\alpha}^{\text{atm. charm}}(E, \Omega) + \phi_{\nu_\alpha}^{\text{astro. extragalactic}}(E, \Omega) + \phi_{\nu_\alpha}^{\text{astro. Galactic}}(E, \Omega)$$
Each component of the neutrino flux has characteristics:

- Flavor composition
- Angular distribution
- Energy distribution
Geometry of Particle Decay

Long lifetime $\pi^\pm K$

Zenith angle dependence

$P_{\text{dec}}(E) \propto \frac{1}{\ell_{\text{dec}}} \propto \frac{m}{E}$

$\phi_\nu(\theta_z) \propto \frac{1}{\cos \theta_z}$
Conventional atmospheric neutrinos

νₑ ≈ νμ/40
ντ ≈ 0

Angular distr.

Horizontal/Vertical ≈ 10

Energy distr. \( \phi_\nu(E) \)

“Prompt” atmospheric neutrinos

νₑ ≈ νμ
ντ ≈ νμ/10

\( D_s^+ \to \tau^+ \nu_\tau \)

Isotropic

Astroph. neutrinos

νₑ ≈ νμ
ντ ≈ νμ

Isotropic [if extragal.]

“Hard”
Separation of "Atmospheric Charm"

Astrophysical components more challenging

Energy distr.

Angular distr.

Flavor

Conventional atmospheric neutrinos

"Prompt"

ν_e ≈ ν_μ
ν_τ ≈ ν_μ

Isotropic [if extragal.]

"Hard"

Astroph. neutrinos
Angle integrated Neutrino fluxes $\nu + \bar{\nu}$
Angle integrated Neutrino fluxes $\nu + \bar{\nu}$

Charm decay component
"All Nucleon flux" \[ \phi_N(E_0) = \sum_A A^2 \phi_A(E_0, A) \]

\[ \phi_A(E) \simeq K_A E^{-\alpha} \]

\[ K_A A^{-\alpha+2} \]

\[ \alpha \approx 2.7 - 3 > 2 \]

Nuclei contribution to neutrino production is suppressed

Uncertainty associated to the determination of the cosmic ray composition.
Dynamics of charm production in hadronic interactions

Perturbative QCD calculation (gluon fusion dominant)
Recent measurements of charm cross section at LHC (small phase space coverage).
Prompt neutrino fluxes from atmospheric charm

Rikard Enberg,¹ Mary Hall Reno,² and Ina Sarcevic¹,³

Calculation used as reference by IceCube

Note: Uncertainties = Primary Flux * Charm production
A. Bhattacharya, R. Enberg, M. H. Reno, I. Sarcevic and A. Stasto, 
“Perturbative charm production and the prompt atmospheric neutrino flux in light of RHIC and LHC,” 
JHEP 1506, 110 (2015) 

R. Gauld, J. Rojo, L. Rottoli, S. Sarkar and J. Talbert, 
“The prompt atmospheric neutrino flux in the light of LHCb,” 
JHEP 1602, 130 (2016) 
[arXiv:1511.06346 [hep-ph]].

M. V. Garzelli et al. [PROSA Collaboration], 
“Prompt neutrino fluxes in the atmosphere with PROSA parton distribution functions,” 
arXiv:1611.03815 [hep-ph].

R. Laha and S. J. Brodsky, 
“IC at IC: IceCube can constrain the intrinsic charm of the proton,” 

F. Halzen and L. Wille, 
“Charm contribution to the atmospheric neutrino flux,” 
Possibility of "Intrinsic charm"

Qualitative idea:
Large component of charm in the Proton Parton Distribution Function.

\[ pp \rightarrow \Lambda_c + D^- + \ldots \]
\[ pp \rightarrow \Lambda_c + \overline{D}^\circ + \ldots \]

\[ |\Lambda_c\rangle = [cud] \]
\[ |D^-\rangle = [\overline{cd}] \]
\[ |\overline{D}^\circ\rangle = [\overline{cu}] \]
On the Charm Contribution to the Atmospheric Neutrino Flux

Francis Halzen and Logan Wille

*Wisconsin IceCube Particle Astrophysics Center and Department of Physics, University of Wisconsin, Madison, WI 53706, USA*

We revisit the estimate of the charm particle contribution to the atmospheric neutrino flux that is expected to dominate at high energies because long-lived high-energy pions and kaons interact in the atmosphere before decaying into neutrinos. We focus on the production of forward charm particles which carry a large fraction of the momentum of the incident proton. In the case of strange particles, such a component is familiar from the abundant production of $K^+\Lambda$ pairs. These forward charm particles can dominate the high-energy atmospheric neutrino flux in underground experiments. Modern collider experiments have no coverage in the very large rapidity region where charm forward pair production dominates. Using archival accelerator data as well as IceCube measurements of atmospheric electron and muon neutrino fluxes, we obtain an upper limit on forward $D^0\Lambda_c$ pair production and on the associated flux of high-energy atmospheric neutrinos. We conclude that the prompt flux may dominate the much-studied central component and represent a significant contribution to the TeV atmospheric neutrino flux. Importantly, it cannot accommodate the PeV flux of high-energy cosmic neutrinos, nor the excess of events observed by IceCube in the 30–200 TeV energy range indicating either structure in the flux of cosmic accelerators, or a presence of more than one component in the cosmic flux observed.


Non perturbative mechanism could be the dominant for neutrino production (non-negligible effect)
On the Charm Contribution to the Atmospheric Neutrino Flux

Francis Halzen and Logan Wille

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University of Wisconsin, Madison, WI 53706, USA

We revisit the estimate of the charm particle contribution to the atmospheric neutrino flux that is expected to dominate at high energies because long-lived high-energy pions and kaons interact in the atmosphere before decaying into neutrinos. We focus on the production of forward charm particles which carry a large fraction of the momentum of the incident proton. In the case of strange particles, such a component is familiar from the abundant production of $K^{+}\Lambda$ pairs. These forward charm particles can dominate the high-energy atmospheric neutrino flux in underground experiments. Modern collider experiments have no coverage in the very large rapidity region where charm forward pair production dominates. Using archival accelerator data as well as IceCube measurements of atmospheric electron and muon neutrino fluxes, we obtain an upper limit on forward $\bar{D}^0\Lambda_c$ pair production and on the associated flux of high-energy atmospheric neutrinos. We conclude that the prompt flux may dominate the much-studied central component and represent a significant contribution to the TeV atmospheric neutrino flux. Importantly, it cannot accommodate the PeV flux of high-energy cosmic neutrinos, nor the excess of events observed by IceCube in the 30–200 TeV energy range indicating either structure in the flux of cosmic accelerators, or a presence of more than one component in the cosmic flux observed.

F. Halzen and L. Wille,
“Charm contribution to the atmospheric neutrino flux,”

Note the conclusion
Very similar point on possible role of non-perturbative contribution to charm production [P.L. astro-ph/1308.2086]. (with (very speculative) possibility of larger flux)
Atmospheric neutrino self veto

Two cases

1. Stefan Schönert et al.
   Can be evaluated analytically

2. Veto by an unrelated $\mu$
   --also applies to $\nu_e$
   Requires Monte Carlo or numerical integration

Experimental detection of charm component.

Tom Gaisser
Effect of VETO: rejection of atmospheric neutrinos

$\sin(\delta) = -\cos(\theta)$ at the South Pole
Effect allows to separate atmospheric charm from isotropic astrophysical.

Some neutrinos are absorbed in the Earth.

Graph showing interactions per km$^3$ yr$^{-1}$ $E_\nu > 100$ TeV.

- Astrophysical $\nu$
- Prompt $\nu_\mu + \nu_e$
- Conventional $\nu_\mu$
- Conventional $\nu_e$

Equation: $\sin(\delta) = -\cos(\theta)$ at the South Pole.
Absorption of neutrinos in the Earth

\[ E_\nu = 10^4, 10^5, 10^6, 10^7 \text{ GeV} \]
My (very “conservative”) comment:

The possibility that a charm component is a non negligible contamination to the lower energy part of the IceCube signal is unlikely but not impossible.

The possibility of performing experimental studies in the very forward region at LHC is certainly desirable.

[in a program of experimental studies that is also of interest for the modeling of UHECR cosmic ray showers]

Preliminary studies are being made [workshop SAS@LHC (small angle spectrometer)@LHC]
Does the IceCube signal have a Galactic component?
IceCube 4-years HESE events

Galactic plane

Celestial coordinates

Galactic coordinates

horizon
Does the IceCube signal have a Galactic component?

There are models where the signal is entirely of Galactic origin.


Expected angular distribution
Very large (100 kpc) halo of cosmic rays

[Inspired (to a large extent) by the observations of the “Fermi Bubbles”]
My own analysis

E > 100 TeV

Excess of events close to Galactic disk?

Prediction of isotropic flux

\[ \sin b_{\text{gal}} \]
Excess from Galactic Equator?
Several works discuss models where the IceCube signal has a Galactic and an ExtraGalactic component:

A. Palladino and F. Vissani, 
“Extragalactic plus Galactic model for IceCube neutrino events,” 

A. Palladino, M. Spurio and F. Vissani, 
“On the IceCube spectral anomaly,” 
JCAP **1612**, no. 12, 045 (2016) 

G. Pagliaroli, C. Evoli and F. L. Villante, 
“Expectations for high energy diffuse galactic neutrinos for different cosmic ray distributions,” 
JCAP **1611**, no. 11, 004 (2016) 
Compare the *Neutrino Signal* to *Gamma Ray fluxes*

If IceCube contains a Galactic Component, what is its origin?

CR in the Galaxy harder than what observed at the Sun?
Important implication of Models with a Galactic component:

A gamma ray counterpart to the neutrino signal is reduced (and distorted) by absorption effects but is detectable by future gamma ray telescopes. [and perhaps should already have been detected]

[Note that the IceCube signal emerges at E=30 TeV – 1 PeV, a region where the Gamma ray telescopes have not studied in depth]
Survival Probabilities for Gamma Rays

Absorption pattern has two maxima

\[ E_{\gamma} \simeq 150 \text{ PeV} \]
[from dust emitted radiation]

\[ E_{\gamma} \simeq 2.2 \text{ PeV} \]
[from CMBR]

Potential for the measurement of the diffuse Gamma Ray flux

Detector features:
- Effective area $A_0 = 1 \text{ km}^2$
- $\gamma$-ray detection efficiency $\varepsilon_0 = 1$
- Observation time $T_0 = 1 \text{ year}$
- Latitude $30^\circ \text{ N}$
- Maximum zenith angle $45^\circ$

Minimum observable flux (5 $\sigma$)
$F_{\text{min}}(A_0,\varepsilon_0, T_0)$ for different values of $f$

$f = \text{background rejection factor}$

Minimum flux for any $A$, $\varepsilon$ and $T$:
$F_{\text{min}}(A,\varepsilon, T) = F_{\text{min}}(A_0,\varepsilon_0, T_0) \sqrt{\frac{A_0 T_0}{A T} \frac{\varepsilon_0}{\varepsilon}}$

S.Vernetto
Extragalactic Sources

\[ \phi_{\nu}^{\text{extra}}(E) = \sum_{j} \phi_{j}(E) \]

Extragalactic flux formed by an ensemble of discrete sources.

Identification of the class of sources
Extragalactic Sources

Flux observed at the Earth from source at redshift $z$

$$\phi(E, z) = \frac{1}{4\pi r^2(z)} q[E(1 + z)]$$

"comoving distance" of the source $r(z)$

"energy redshift"

$$r(z) = \frac{1}{H(z')} \int_{0}^{z} \frac{dz'}{\sqrt{1 + \Omega_r (1+z')^4 + \Omega_m (1+z')^3 + \Omega_\Lambda}}$$
Ensemble of identical sources that fill homogeneously the universe.

Static Euclidean universe: Infinite flux ("Kepler Olbers Paradox")

\[
\left( \frac{1}{4\pi R^2} \right) \left( 4\pi R^2 \Delta R \right)
\]

All spherical shells contribute equally to the flux
\[ \frac{\phi_{\text{cumul}}}{\{n_s (c/H_0)^3\}} \]

\[ \phi_* = \frac{q_s}{4\pi (c/H_0)^2} \]
Resolved sources

Contribution of all unresolved sources
Extragalactic Flux: Resolved + unresolved sources

Extragalactic flux dominated by "blazars" [AGN]

Brightest source in the sky (3C454.3) 1.8% of extragalactic light
IceCube study of correlations with the FERMI 2LAC

\[ E^2 \frac{d\Phi}{dE_{\nu\mu}} \left[ \text{GeV}^{-1} \text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1} \right] \]

Neutrino Energy [GeV]

\[ 10^{-6} \quad 10^{-7} \quad 10^{-8} \quad 10^{-9} \quad 10^{-10} \]

2LAC Blazar Upper Limit
- \( \Gamma_{SI} = -2.5, E_\nu > 10 \text{ TeV} \)
- \( \Gamma_{SI} = -2.2, E_\nu > 10 \text{ TeV} \)

equal weighting
\( \gamma \)-weighting

Astrophysical Diffuse Flux

19% - 27%
7%
M. Kadler et al.,
"Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event."
Nature Phys. 12, no. 8, 807 (2016)

\(\gamma\)-ray light curve of PKS B1424–418.
5. Outlook

- What can we learn with astrophysical neutrinos?
Modern physics in a classical setting – the Neutrino Telescopes Workshop in Venice’s Palazzo Loredan.

Venezia 1989
II Neutrino Telescope Workshop
Picking up high energy neutrinos from distant sources is a major goal for the underground detectors (muons induced by atmospheric neutrinos are seen and their spectra are in reasonable agreement with calculations). The expected mechanisms for particle acceleration in binary stars and other systems, together with present data from high energy gamma ray telescopes, require that detectors intercepting neutrinos from distant point sources would have to be very large, bigger than $10^4$ sq m, with good angular resolution, one degree or better, for the induced muons.

One natural solution to have cheap large area and volume is to go deep underwater and detect the muons by means of Cherenkov light. The DUMAND collaboration, after a successful test demonstrating the feasibility of an experiment 4000 m deep (June 1988, page 29), is about to set up its nine-string array off Hawaii. Meanwhile Soviet groups are at work in Lake Baikal and in the Mediterranean, and a US proposal aims at instrumenting an Arkansas lake for a combined neutrino- and gamma-ray telescope.
DUMAND idea

1978: 1.26 km³
22,698 OMs

1980: 0.60 km³
6,615 OMs

1982: 0.015 km³
756 OMs

1988: 0.002 km³
216 OMs
Observation of muons using the polar ice cap as a Cerenkov detector

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DETECTION of the small flux of extraterrestrial neutrinos expected at energies above 1 TeV, and identification of their astrophysical point sources, will require neutrino telescopes with effective areas measured in square kilometres—much larger than detectors now existing1–3. Such a device can be built only by using some naturally occurring detecting medium of enormous extent: deep Antarctic ice is a strong candidate. A neutrino telescope could be constructed by drilling holes in the ice with hot water into which photomultiplier tubes could be placed to a depth of 1 km. Neutrinos would be recorded, as in underground neutrino detectors using water as the medium, by the observation of Cerenkov radiation from secondary muons. We have begun the AMANDA (Antarctic Muon and Neutrino Detector Array) project to test this idea, and here we describe a pilot experiment using photomultiplier tubes placed into Arctic ice in Greenland. Cerenkov radiation from muons was detected, and a comparison of count rate with the expected muon flux indicates that the ice is very transparent, with an absorption length greater than 18 m. Our results suggest that a full-scale Antarctic ice detector is technically quite feasible.


Neutrino Astrophysics has made extraordinary progress

More in general: Multi-messenger Astrophysics is demonstrating to be a vibrant field, and our understanding of the “High Energy Universe” is making rapid progress.
GW150914: the signal

- Top row left – Hanford
- Top row right – Livingston
- Time difference ~ 6.9 ms with Livingston first
- Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)
- Third Row – residuals
- Bottom row – time frequency plot showing frequency increases with time (chirp)
from : Eugenio Coccia
Figure 1. Snapshots at representative times of the evolution of a binary neutron-star merger. The density is shown in yellow-red, with magnetic-field lines superimposed. The sequence begins with $t = 7.5$ msec, followed by $t = 13.8$ msec, $t = 15.26$ msec, and finally $t = 26.5$ msec.

M. Kadler et al.,
"Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event."
Nature Phys. 12, no. 8, 807 (2016)
VLBA radio images of M87 at 43 GHz

Radio Imaging of the Very-High-Energy γ-Ray Emission Region in the Central Engine of a Radio Galaxy

The VERITAS Collaboration, the VLBA 43 GHz M87 Monitoring Team, the H.E.S.S. Collaboration, the MAGIC Collaboration
The opening up of Gravitational Wave Astronomy is a remarkable new development, hopefully the “dream” of merging information from multi-messenger studies will turn into reality in a future that is not so distant.

It is essential to pursue multi-messenger studies in a coherent and coordinated form, because the different methods offer complementary information, required to develop a complete understanding.