Particle Astrophysics
High Energy Neutrinos

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Many thanks to the broad particle astrophysics community for sharing materials online!
Content from: Jordan Goodman - U.Maryland; Francis Halzen - UW-Madison; Jörg R. Hörandel - RU Nijmegen, Nikhef, VU Brussel; Athina Meli - Univ. Athens; Elisa Resconi - TUM; Christian Stegmann - DESY; Yajie Yuan - Flatiron Institute

Jordan Goodman - Gamma ray astronomy with extensive air showers (https://agenda.astro.ru.nl/event/12/contributions/192/)
Jordan Goodman - Recent results from HAWC (https://agenda.astro.ru.nl/event/12/contributions/190/)
Jordan Goodman - Recent results from LHAASO and future arrays (https://agenda.astro.ru.nl/event/12/contributions/189/)
Francis Halzen - https://user-web.loebebo.wisc.edu/~halzen/presentations/Ofomouco22_Halzen.pptx
Jörg R. Hörandel - Historical introduction and basic properties of cosmic rays (https://agenda.astro.ru.nl/event/12/contributions/197/)
Athina Meli - http://www.iexp.desy.de/groups/astroparticle/de/lehre/guest_seminar/meli.pdff
Elisa Resconi - https://campus.fum.de/fumonline/vb/langebot/wb/show/vorlesstyp pessoa#
    https://agenda.astro.ru.nl/event/12/contributions/238/
Christian Stegmann - Ground-based gamma-ray astronomy with imaging air Cherenkov (3 lectures)
Cosmic particle production

**Protons**
Directly produced in the sources

**Photons**
From protons via pion decay
From electrons via inverse Compton scattering

**Neutrinos**
From protons via pion decay
Cosmic ray “standard” scenario (hadronic and leptonic processes)

HADRONIC:
- Proton synchrotron
- Bethe-Heitler pair production
- Photopion ($\pi^+$ component)
- Photopion ($\pi^0$ component)
- Photopion ($\rho$ component)

LEPTONIC:
- Electron synchrotron
- Inverse Compton scattering
- Photon-photon pair production
- Electron-positron annihilation

primary electrons and protons
Cosmic ray ‘standard’ scenario: the secondary products from hadronic mechanisms

Reference:

Interaction of accelerated CR naturally leads to production of neutrinos and gamma rays.

\[ E_p : E_\nu : E_\gamma = 1 : 0.1 : 0.05 \]
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.
charged secondary particles produced as the neutrino disappears

nuclear interaction

- lattice of photomultipliers

neutrino
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track.
- speed of light in water ≈ 3/4 c → shockwave

- lattice of photomultipliers

muon

interaction

neutrino
10,000 times too small to do neutrino astronomy...
ice 1.4 kilometers below geographic South Pole

- find an optically clear medium shielded from cosmic rays
- map its optical properties
- fill with photomultipliers with spacings ~ absorption length
- add data acquisition and computers
• 3 km deep South Pole glacier
• ultra-transparent ice below 1.35 km
• absorption length: 100 ~ 250+ m
High-energy neutrinos - background considerations

downwards (↓↓)
air showers, muons, neutrinos

horizontal (⇔)
air showers, muons, neutrinos

IceCube Horizon

local zenith ~45°

upwards (↑↑)
neutrinos

North
IceCube high energy starting events search

- Identify starting events in the detector by applying an active veto to remove the down-going backgrounds:

  - atmospheric muons identified by using part of the detector in anti-coincidence; can estimate potential contamination by using subsequent detector regions to measure number of muons that evade the other veto layer

  - atmospheric neutrinos: starting outside the detector see above; starting inside the detector tag with a parent atmospheric muon
electron showers ...

PeV $\nu_e$ and $\nu_\mu$
showers:

- 10 m long
- volume $= 5 \text{ m}^3$
- isotropic after 25~50 m
size = energy

color = time = direction
IceCube high energy starting events search
...and then there were 26 more...

data: 86 strings one year
IceCube high energy starting events search

Starting Event Spectrum

- Background Atmospheric Muon Flux
- Bkg. Atmospheric Neutrinos ($\nu_\tau$)
- Background Uncertainties
- Atmospheric Neutrinos 30% CL Charm ($\nu_\mu$)
- Bkg + Signal Best Fit 1 Component Astrophysical ($E^{-2.3}$)
- Bkg + Signal Best Fit 2 Component Astrophysical
- Data

IceCube Preliminary

Events per 2018 Days

Deposited EM-Equivalent Energy in Detector (TeV)

1.0 PeV

1.1 PeV

2.0 PeV
cascade reconstruction
muon neutrino flux filtered by the Earth: atmospheric vs cosmic
tau neutrino production and decay

tau decay length:
\[ \gamma c t = 50 \text{m per PeV} \]
tau decay length: 50m per PeV

2014 Event

\[
\frac{(E_1 - E_2)}{(E_1 + E_2)} = -0.80
\]

9 TeV

80 TeV

17 m

event found in 3 different analyses
a cosmic tau neutrino with 17m lifetime

light from nutau interaction and tau decay

WORK IN PROGRESS

Bright DOMs are excluded from this analysis
oscillations of PeV neutrinos over cosmic distances to 1:1:1

oscillating PeV neutrinos (7.5 years starting events)
First observation of a Glashow Resonance Event

Partially contained event with energy 6.3 PeV

Resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron
First observation of a Glashow Resonance Event

Glashow resonance: anti-ν_\text{e} + atomic electron \rightarrow real W

- partially-contained PeV search
- deposited energy: 5.9\pm0.18 PeV
- visible energy is 93%
- \rightarrow resonance: E_V = 6.3 PeV

work on-going
The story of a neutrino...

IceCube-170922A and TXS 0506+056

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability of being of astrophysical origin. The event was identified by the Extremely High Energy (EHE) track event selection. The IceCube detector was in a normal operating state.
IceCube 170922
290 TeV
Fermi detects a flaring blazar within 0.06°
MAGIC detects emission of $>100$ GeV gammas

IceCube 170922
290 TeV
Fermi detects a flaring blazar within 0.06°
The story of a neutrino... and a blazer

Following the direction of this neutrino 4 billion light years back into the distant sky we found an active supermassive black hole (blazar); the first compelling source for high energy neutrinos, and hence cosmic rays!

- 3 major press conference (US, Germany, Japan)
- more than 2,000 articles, videos and radio/podcasts to date, including major news (BBC, CNN, FoxNews, Frankfurt Allgemeine, NYtimes, Washington Post,...), specialized, and children's programming
The story of a neutrino... and a blazar

Spectral Energy Distribution — Sept/Oct 2017

- Extensive broad-band follow-up measurements
- Inferred ~300 TeV neutrino emission has $\nu E_{\nu}$ of same order as H.E. V.H.E. gamma rays
- NB: observations not strictly contemporaneous
global robotic network of optical telescopes connects TXS 0506+056 to IC170922A in the time domain

"MASTER found the blazar in the off-state after one minute and then switched to on-state two hours after the event. The effect is observed at a 50-sigma significance level"

Optical Observations Reveal Strong Evidence for High Energy Neutrino Progenitor

gamma rays in 2017 at the time the neutrino is produced? consistent with an obscured source, not a blazar

- MAGIC, HESS and VERITAS: TeV flux is highly variable and there is no TeV gamma ray emission at the time the neutrino is produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- confirmed by MASTER: the blazar switches from the "off" to "on" state 2 hours after the neutrino
The story of a number of neutrinos and a blazar...

IceCube-170922A and TXS 0506+056
multimessenger observations in the time domain
change of flux 2 hours after 170922 neutrino
source is quiet 10 previous and 3 following years
Sources of high-energy astrophysical neutrinos...

Evidence for non-uniform sky map in 10 years of IceCube data:
mostly resulting from 4 extragalactic source candidates.
Example of non-jetted AGN: NGC 1068

Seyfert 2 type AGN
Star burst activity
Outflow

Outflows regulating star formation and galaxy quenching, can drive active star formation, accretion onto galactic nuclei, AGNs). Cold gas outflows contain the raw material from which stars are formed.

Credit: NASA/JPL-Caltech
The AGN component in NGC1068

radiatively inefficient accretion flows:
acceleration of electrons and protons
in the high field regions associated
with the accretion disk and the optically
thick corona (0.1 pc) emitting most of the X-rays

In the core is the target for neutrino production
and gamma-ray obscured

Black hot corona: ultrahot gas

Accretion disk

Credit: NASA/Caltech
Sources of high-energy astrophysical neutrinos... coming next?

Observation of high-energy neutrinos coincident with gravitational wave events
Sources of high-energy astrophysical neutrinos... coming next?

LIGO run O4 commenced May 2023
August 17, 2017 neutron star merger did not have the jet aligned with Earth
Grand unified neutrino spectrum (integrated over direction and flavour)

Neutrino energy flux $E\phi$ [cm$^{-2}$ s$^{-1}$]

Energy $E$ [eV]

- CNB
- Solar (thermal)
- Solar (nuclear)
- Reactors
- Geoneutrinos
- DSNB
- Atmospheric
- IceCube data (2017)
- Cosmogenic
The Askaryan effect vs radio

- In a shower: many particles
  - Charge separation produces a current

- Number of particles is a function of height above ground

- The current changes as function of time/height
- A changing current causes electromagnetic emission

The Askaryan effect vs radio


**Ultra-High Energy (UHE) cosmic rays and neutrinos:**

*coherent radio pulse* from the excess of electrons in a shower developing in a dense dielectric and non-absorptive medium. The signal is the radiation due to the charge excess of a shower in a linear dielectric medium such as ice, salt, or silica sand.

Emitted power goes with the square of the particle energy (experimentally confirmed in accelerators): promising idea for the detection of UHE particles.

Radio power is absorbed quickly by a small admixture of liquid water, so the natural medium should be dry, such as salt domes, or better yet, frozen to a solid state.
The Askaryan effect vs radio: detection via antennas in the shallow ice (South Pole, Greenland)

The Askaryan effect vs radio: detection via antennas in the shallow ice (South Pole, Greenland)

- After lots of proof-of-principle experiments: first scale-up to large array

https://indico.t5.physik.tum.de/event/708/attachments/0/61313/Ankreisung_TUchemnitz.pdf
The Askaryan effect vs radio: detection via antennas in the shallow ice (South Pole, Greenland)


One can fly a balloon with antennas and maximize the volume observed (ANITA project)
The Askaryan effect vs radio:
ANITA I-IV (ANTARCTIC IMPULSE TRANSIENT ANTENNA)


ANITA I (2006-2007)
- trigger rate: 4 - 5 Hz
ANITA II (2008-2009)
ANITA III (2014)
ANITA IV (2018)
High-Energy Neutrinos ... IceCube Upgrade

Science drivers:

- Enhanced capability for GeV atmospheric neutrino detection at ~few GeV; world-leading measurement of tau neutrino normalization for direct text of unitarity of the PMNS mixing matrix

- Advanced calibration devices to reduce ice systematic uncertainties -> recalibration of the full array.
- Re-analyze more than 15 years of IceCube data with substantially improved angular and energy resolutions (~factor 2 improvement)
- Enhanced neutrino event pointing (source discovery)
High-Energy Neutrinos ... Global View

- **Plan: > 1km³**
  - **Currently 2**
  - **Pathfinder strings**

- **0.01km³**

- **BAIKAL-GVD**

- **Plan: > 1km³**
  - **Currently 0.4km³**

- **1km³**

- **Pathfinder**

- **In Planning**

- **KM3Net**
  - **Plan: > 1km³**
  - **Currently 6/230 strings**

- **ICECUBE GEN2**
  - **Plan: Multi-km³**

- **ICECUBE**
  - **Currently 1km³**

- **P-ONE**
  - **Pathfinder strings**
High-Energy Neutrinos ... KM3NeT
High-Energy Neutrinos ... KM3NeT
High-Energy Neutrinos … GVD
High-Energy Neutrinos ... Global view

- IceCube
- GVD, Russia
- KM3NeT, Sicily
- ONC, Canada
- Galactic center/plane
- TXS 0506+056