Cosmic Accelerators:
Gamma Rays, Neutrinos and
The Dawn of Multimessenger Astrophysics

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The Multiwavelength Milky Way
The Universe in Multiwavelength Light
What did we learn?

Element Origins

Merging Neutron Stars
Dying Low Mass Stars
Exploding Massive Stars
Exploding White Dwarfs
Big Bang
Cosmic Ray Fission

Speed of Gravity

\[ -3 \times 10^{-15} \leq \frac{\Delta v}{\nu_{\text{EM}}} \leq +7 \times 10^{-16} \]

Tested Equivalence Principle of Gravity:
Ruled out many theories of modified gravity to explain dark matter

H_0 = 70^{+12}_{-8} \text{ km/s/Mpc}
The Multimessenger Universe

Cosmic Explosions
What is creating these ultra-high energy particles?

99% protons

Galactic

Extra-Galactic
Neutrinos are the smoking gun signature for hadronic acceleration.

Goal:
Find neutrinos coming from an extra-galactic source.
Searching for Neutrino Sources

Large trials factor when looking only at neutrinos, multiwavelength data can identify potential sources!
Sources that produce high-energy photons
Fermi observes over 2000 blazars

>300 MeV over 3 months in 2008
IceCube: Alerts starting in April 2016

IC-170922A: 290 TeV Neutrino
Redshift: 0.3365±0.0010 (3.7 billion light years)

Among 50 brightest blazars
Fermi-LAT Counts Map with IceCube Sky position

MAGIC Counts Map with IceCube Sky position
Spectra of TXS 0506+56 across all wavelengths and messengers
Light Curve of TXS 0506+56 across all wavelengths and messengers
Looking back at the IceCube data

13±5 above the background of atmospheric neutrinos, 3.5\sigma
Modeling the Multimessenger Universe

• “Interpretation of the coincident observation of a high energy neutrino and a bright flare”, Gao, Fedynitch, Winter, Pohl, arXiv:1807.04275

• “A multiwavelength view of BL Lacs neutrino candidates”, Righi, Tavecchio, Pacciani, arXiv:1807.04299

• “The blazar TXS 0506+056 associated with a high-energy neutrino: insights into extragalactic jets and cosmic ray acceleration”, MAGIC Collaboration, arXiv:1807.04300


• “Blazar Flares as an Origin of High-Energy Cosmic Neutrinos?” Murase, Oikonomou, Petropoulou, arXiv:1807.04748
Electromagnetic Spectrum
Neutrino Spectrum
The Multimessenger Universe

Cosmic Accelerators

Cosmic Explosions
Summary

A source of cosmic-ray acceleration has been identified

Era of Multimessenger Astrophysics!

Fermi serves as a bridge between electromagnetic observations and the new messengers: Neutrinos and gravitational waves
Thank you
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

1450 m

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

2450 m

IceTop
86 strings of DOMs, set 125 meters apart

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

100 m

DeepCore
DOMs are 17 meters apart

60 DOMs on each string

Antarctic bedrock
How Likely is it a Chance Probability?

**Step I:** Draw a random neutrino from a representative sample of high-energy muon-track events.

**Step II:** Are there any extragalactic Fermi sources close in space to the neutrinos?

**Step III:** What is the gamma-ray energy flux in the time bin when the neutrino arrives?
How Likely is it a Chance Probability?

\[ TS = 2 \log \frac{\mathcal{L}(n_s = 1)}{\mathcal{L}(n_s = 0)} = 2 \log \frac{S}{B} \]

- Pre-trials p-value: 4.1σ
- Post-trials p-value: 3.0σ
How does this compare to stacking limit?

- **Stacking:**
  - Upper limit of 27% of the diffuse flux fit between 10 TeV and 100 TeV with a soft $E^{-2.5}$ spectrum
  - Upper limit of 40% and 80% for an $E^{-2}$ spectrum (compatible with the diffuse flux fit $>200\text{TeV}$)

- Allowed contribution by blazars as a population is larger, because it would include the contribution of unresolved blazars

- Averaged over 9.5 years, the neutrino flux of TXS 0506+056 by itself corresponds to 1% of the astrophysical diffuse flux, and is fully compatible with the blazar catalog stacking results