Multi-messenger Astronomy with high-energy Neutrinos

Anna Franckowiak

HELMHOLTZ Young Investigators
N3AS Seminar, Berkeley, 15.2.2022
IceCube
South Pole Neutrino Observatory

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

50 m

IceTop

86 strings of DOMs, set 125 meters apart

1450 m

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

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

2450 m

IceCube detector

DeepCore

Antarctic bedrock

60 DOMs on each string
DOMs are 17 meters apart
Event Signatures

“shower“ events: neutrinos interacting inside the detector

“track“ events: muon neutrinos filtered by the Earth

total energy measurement to 10%, all flavors, all sky

astronomy: angular resolution superior (0.2°~0.4°)
Multi-messenger Diffuse Flux

Similar energies in gamma rays, neutrinos & cosmic rays injected into our Universe!
Where to the neutrinos come from?
Where do the Neutrinos come from?

Sky map of likely cosmic neutrinos > 30 TeV (2010 - 2016)

Compatible with an isotropic distribution
→ extragalactic origin of cosmic neutrinos
IceCube Target of Opportunity Program

Public alerts since April 2016

- Single high-energy muon track events (> ~100 TeV)
- “Gold” alert stream: 10 / yr, ~5 / yr of cosmic origin
- Median latency: 30 sec

Goal: Find electromagnetic counterpart
IC-170922A – a 290 TeV Neutrino

Signalness: 56.5%
IC-170922A – a 290 TeV Neutrino
Fermi-LAT finds Flaring Source
Fermi-LAT finds Flaring Blazar, TXS 0506+056

Among 50 brightest Fermi blazars (3%)
Fermi-LAT finds Flaring Blazar, TXS 0506+056

Among 50 brightest Fermi blazars (3%)
Fermi-LAT finds Flaring Blazar, TXS 0506+056

Among 50 brightest Fermi blazars (3%)

3 sigma significance including trials
> 6 PeV protons accelerated in the source
Do gamma-ray blazars produce all diffuse neutrinos?
**Fermi Blazars**

Gamma rays tell us *where* to look for neutrinos
**Fermi Blazars**

Gamma rays tell us **where** to look for neutrinos

**Fermi gamma-ray sky**

Correlation study of 3 years of IceCube data and 862 **Fermi-LAT blazars**

**Fermi-LAT blazars** can only be responsible for a **small fraction** of the observed $\nu$'s.
**Fermi Blazars**

Gamma rays tell us **where** to look for neutrinos

- **Fermi gamma-ray sky**

Correlation study of 3 years of IceCube data and 862 *Fermi*-LAT blazars

- **Multiple Populations?**
Other possible sources?
Tidal Disruption Events

~50 TDEs identified, 3 jetted TDEs
The Zwicky Transient Facility (ZTF)

Mt. Palomar in California
1.3 m Mirror
The Zwicky Transient Facility (ZTF) – giant field of view

**Diagram:**
- **DES,** 2.5 deg²
- **SDSS,** 3 deg²
- **PTF/iPTF,** 7.3 deg²
- **PS1,** 7 deg²
- **LSST,** 9.6 deg²
- **ZTF,** 47 deg²
- **250 x full moon**
ZTF Follow-up Pipeline

1. high-energy neutrino alert arrives

2. Observe with ZTF

3. Follow-up with AMPEL
   

4. Trigger further follow-up observations

Reject stars, planets, artifacts, asteroids

Reject unrelated transients (e.g. Type Ia Supernovae)
Neutrino IC191001A (200 TeV)

$\nu F_\nu$ [erg cm$^{-2}$ s$^{-1}$]

$\nu L_\nu$ [erg s$^{-1}$]

Time since $\nu$ [d]

$g$ (464 nm) $\rightarrow$ r (658 nm)
Neutrino IC191001A (200 TeV)

ZTF history

R. Stein et al., Nature Astronomy 2021
Neutrino IC191001A (200 TeV)

Archival data

R. Stein et al., Nature Astronomy 2021
Neutrino IC191001A (200 TeV) coincident with Tidal Disruption Event AT2019dsg

Distance: $z = 0.05$ (d=230Mpc)
Neutrino IC191001A (200 TeV) coincident with Tidal Disruption Event AT2019dsg aka as “Bran Stark”

Distance: $z = 0.05$ (d=230Mpc)
Neutrino IC191001A (200 TeV) coincident with Tidal Disruption Event AT2019dsg aka as “Bran Stark”

Distance: $z = 0.05$ (d=230Mpc)
Neutrino IC191001A (200 TeV) coincident with Tidal Disruption Event AT2019dsg aka as “Bran Stark”

Distance: $z = 0.05 \ (d = 230\text{Mpc})$

**Chance coincidence:** 0.2% to find a TDE that bright (including trials)
Radio Data reveal long-lasting activity of central engine

\[ \dot{E} = 2 \times 10^{43} \text{ erg/s} \]

\[ \dot{R} = 0.12c \]
Various Neutrino Production Scenarios

- Soft X-ray TDEs
- (iv) \( \nu \) Radio
- (i) \( \nu \) X-rays
- (ii) \( \nu \)
- Ambient matter
- Outflow (wind)
- Shock
- X-rays
- Optical/UV
- Debris stream
- Disk
- BH
- Corona
- Jet
- Debris stream

Hayasaki, Nature Astronomy 2021
Second interesting source! AT2019fdr / “Tywin” coincident with IC200530A

Extreme flare in a narrow-line Seyfert 1 galaxy, classified as likely TDE

Optical lightcurve of Tywin compared to Bran Stark

$\nu L_\nu$ [$\text{erg s}^{-1}$]

$10^{42}$ $10^{43}$ $10^{44}$

58500 58600 58700 58800 58900 59000 59100 59200

Date [MJD]

Tywin

Bran

IceCube-191001A

IceCube-200530A

$p = 3.44 \times 10^{-4} \ (3.4 \sigma)$

$z = 0.267$

Are TDEs emerging as new source class?

S. Reusch et al. arXiv:2111.09390
Extend search to sample of accretion flares with strong dust echos

Systematic search for coincidence between IceCube public alerts and optical flares that show post-peak neoWISE infrared flares

→ Third coincidence: AT2019aalc (Lancel)

Unified population of accretion flares as new neutrino source class?
Efficient Acceleration at Eddington Limit?

• These three associated events could produce a significant part of the IceCube high-energy neutrino flux:
  \[ 19^{+22}_{-12}\% \ (90\% \text{CL}) \]
• **But:** “Normal” AGN outshine TDEs by two orders of magnitude – why are we not dominated by those?!
• All sources are close to the Eddington limit

→ Very efficient neutrino production in TDEs?

S. Van Velzen et al. arXiv:2111.09391
Next Generation Neutrino Telescopes

- Neutrino sources on the southern sky
- Today's neutrino telescopes
- 5x better sensitivity in the TeV-PeV energy range
- Neutrinos bei EeV Energien

**KM3NeT / Baikal-GVD** (construction started)

**IceCube-Gen2** (Phase 1 started)

**ARA/ARIANNA, RNO, Gen2-Radio** (proposals in)
Summary

unique messengers from the high-energy Universe
Summary

Neutrinos can reveal the sources of high-energy cosmic rays
Summary

Sources still unknown → Electro-magnetic counterparts are crucial to identify the sources. First compelling candidates found!