Neutrinos in the Era of Multimessenger Astronomy
francis halzen

- cosmic neutrinos: many independent observations
  → muon neutrinos through the Earth
  → starting neutrinos: all flavors

- the first high-energy cosmic ray accelerator: a rotating supermassive black hole

- from discovery to astronomy: next-generation instruments

- also, a beam for PeV (1,000 TeV) neutrino physics

icecube.wisc.edu
highest energy “radiation” from the Universe: neutrinos and cosmic rays

Universe is opaque above ~100 TeV energy
PeV photons interact with microwave photons (411/cm³) before reaching our telescopes enter: neutrinos
Neutrinos? Perfect Messenger

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

... but difficult to detect
highest energy radiation from the Universe: protons!

high energy
high luminosity

Fly’s Eye 1991
300,000,000 TeV

LHC accelerator should have circumference of Mercury orbit to reach $10^{20}$ eV!
some of the matter falling into a supermassive black hole is accelerated in a jet along its rotation axis.
• fast spinning infalling matter comes in contact with rotating black hole

• spacetime around spinning black hole drags on the field winding it into a tight cone around the rotation axes

• plasma from the accretion disk is then flung out along these lines
Neutrino beams: Heaven & Earth

accelerator is powered by large gravitational energy

supermassive black hole

nearby radiation

\[ p + \gamma \rightarrow n + \pi^+ \]
\[ \sim \text{cosmic ray} + \text{neutrino} \]
\[ \rightarrow p + \pi^0 \]
\[ \sim \text{cosmic ray} + \text{gamma} \]
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ultra-transparent ice below 1.35 km
instrument 1 cubic kilometer of natural ice below 1.45 km
a muon neutrino produces a muon with a range of kilometers

- lattice of photomultipliers

neutrino
neutrinos interacting inside the detector

muon neutrinos filtered by the Earth

total energy measurement all flavors, all sky

astronomy: angular resolution superior (0.2~0.4°)
Cherenkov radiation from PeV electron (tau) shower
> 300 sensors > 100,000 pe reconstructed to 2 nsec
IC190331: 5300 TeV deposited inside the detector

Event 132379/15947448
Time 2019-03-31 06:55:43 UTC
Duration 2269967.8 ns

initial neutrino energy 10~20 PeV
electron and tau neutrinos

\[ E \times E \frac{dN}{dE} \]
electron and tau neutrinos

muon neutrinos

Events vs truncated E GeV: >120 cosmic $v_{\mu}$ per year

$10^2$ $10^4$ $10^6$

Neutrino Energy [GeV]
evidence for non-uniform skymap in 10 years of IceCube data: mostly resulting from 4 extragalactic source candidates

no evidence for neutrinos associated with Galactic sources
\[ \nu \text{ and } \gamma \text{ beams: heaven and earth} \]

- **where are the gamma rays?**
  - **supermassive black hole**
  - **nearby radiation**

\[ p + \gamma \rightarrow n + \pi^+ \]
\[ \sim \text{cosmic ray + neutrino} \]
\[ \rightarrow p + \pi^0 \]
\[ \sim \text{cosmic ray + gamma} \]
Fermi pair spectrometer $\gamma \rightarrow e^+ + e^-$
TeV atmospheric Cherenkov telescopes

HESS, MAGIC, VERITAS
multimessenger astronomy

\[ p + \gamma \rightarrow n + \pi^+ \]
\[ \sim \text{cosmic ray} + \text{neutrino} \]
\[ \rightarrow p + \pi^0 \]
\[ \sim \text{cosmic ray} + \text{gamma} \]
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach Earth.
\( \gamma + \gamma_{\text{CMB}} \rightarrow e^+ + e^- \)
the energy of gamma rays accompanying PeV neutrinos is distributed over the electromagnetic spectrum
$\pi^+ = \pi^- = \pi^0$

Fermi gammas

$E^{-2.15}$

$E^2 J \left[ \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \right]$

$pp$ scenario

SFR evolution

HESE (3yr)

arXiv:1410.1749

Fermi IGRB (2014)

cosmic neutrinos
• energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays
dark sources below 100 TeV not seen in γ’s?

gamma rays cascade in the source to lower energy
target may not be transparent to gamma rays:
gamma rays accompanying IceCube neutrinos lose energy in the source and in the interstellar medium and fragment into lower energy gamma rays, X-rays... that reach earth
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icecube.wisc.edu
from photon at PMT to public neutrino alert: < 1 minute
IceCube 170922
290 TeV

Fermi
detects a flaring blazar within 0.06°

MAGIC
detects emission of
> 100 GeV gammas
Follow-up detections of IC170922 based on public telegrams

- IceCube: September 22
- Swift: September 26
- Fermi, ASAS-SN: September 28
- SALT, Kapteyn: October 7
- MAGIC: October 4
- Liverpool, AGILE: September 29
- Kanata, NuSTAR: October 12
- VLA: October 17
- Subaru: October 25

MASTER robotic telescope: after 73 seconds
multiwavelength campaign launched by IC 170922

IceCube, Fermi –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, Swift, VLA, VERITAS

• neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43° Dec 5.72°

• Fermi-LAT: flaring blazar within 0.06° (7x steady flux, daily variations)

• MAGIC: TeV source in follow-up observations

• follow-up by more telescopes

• → IceCube archival data (without look-elsewhere effect)

• → Fermi-LAT archival data
search in archival IceCube data:

- 150-day flare in December 2014 of 19 events (bkg < 6)
- spectrum $E^{-2.2}$
- $L_\nu > 10^{47}$ erg/s
we identified a source of high energy cosmic rays: the active galaxy (“blazar”) TXS 0506+056 at a redshift of 0.33 at ten times further distance, it outshines nearby active galaxies: is it special? extensive multiwavelength campaign allows us to study the first cosmic accelerator a problem: theory
we know that this cosmic accelerator is a cosmic ray source
- blazar modeling well understood
- add protons (7 → 14 parameters)
We finally understand weak interactions

CP VIOLATION

Cabibbo 1966
IC170922
blazar model
14 parameters
<< 1 neutrino
IC170922
blazar model
14 parameters
<< 1 neutrino

2014-15 neutrino burst
Neutrino Beams: Heaven & Earth

\[ p + \gamma \rightarrow n + \pi^+ \]

\[ \rightarrow \text{cosmic ray + neutrino} \]

\[ \text{supermassive black hole} \]

\[ \text{target} \]

\[ \rightarrow \text{a neutrino source needs an accelerator and a target} \]

\[ \rightarrow \text{the target may be opaque to gamma rays} \]
an efficient neutrino source is opaque to gamma rays

- efficiency for producing neutrinos: $L_\nu \sim \tau_{p\gamma} L_p$

- requires large opacity of the target’s proton $\tau_{p\gamma}$

- gamma ray opacity is $10^2$ times higher $\tau_{\gamma\gamma} \simeq 10^2 \tau_{p\gamma}$

- blazars are highly efficient gamma ray emitters, cannot be efficient neutrino sources

- imaging by radio interferometry and optical robotic telescopes to the rescue!
neutrino

gamma ray

radio

[Garrappa+, 2019]
TXS 0506+056

- beyond 5 mas the jet loses its tight collimation…
- jet found a target after ~tens of pc

Theory confirms observations:

- jet star interaction?
- jet-jet encounter in a galaxy merger?

core brightening observed in a radio burst that started 5 years ago

core expands with superluminal velocity

1912.01743v1
[astro-ph.GA]
analysis of 16 VLBA observations
MOJAVE 15 GHz
2009-18
global robotic network of optical telescopes connects TXS 0506+056 to IC170922A

“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”
MASTER robotic network
optical observations
TXS 0506+056 since 2005
blue panels: expanded time axis years → seconds

time variation of flux times signal-to-noise

hour-scale variability of the source after neutrino emission
theory: not a “vanilla” blazar

what is the target found in the radio and optical images?

blueprint of TXS accelerator still evolving

is cosmic ray origin really connected to blazars or do other sources also turn into TXS-type neutrino beam dumps?

multimessenger astronomy is “subtle but not malicious”

some other intriguing events: 190730, 191001, 200107...
IC 190730: 300 TeV
• coincident with PKS 1502+106
• radio burst

Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz

ATel #12996; S. Kiehlmann (IoA FORTH, OVRO), T. Hovatta (FINCA), M. Kadler (Univ. Würzburg), W. Max-Moerbeck (Univ. de Chile), A. C.S. Readhead (OVRO) on 7 Aug 2019; 12:31 UT

Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started in 2014, which is currently reaching an all-time high of about 4 Jy, since the beginning of the OVRO measurements in 2008. A similar 15 GHz long-term outburst was seen in TXS 0506+056 during the neutrino event IceCube-170922A.
the two highest energy IceCube alerts are coincident with radio flares
IC191001 in coincidence with the tidal disruption of a star?

IC191001 close to luminous TDE of the Zwicky Transit Factory

Discovered in April 2019 by ZTF, lots of data! Neutrino arrived ~175 days post-discovery.

Relatively early/bright plateau, consistent with accretion disk formation.

As for most TDEs, well-described by thermal emission ($T \sim 10^{4.6}$ K, $R \sim 10^{14.5}$ cm, $L_{\text{peak}} \sim 10^{44.5}$ erg s$^{-1}$)
next attraction: gravitational waves + neutrinos?

(August 17, 2017 neutron star merger: jet not aligned)
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• the first high-energy cosmic ray accelerator: a rotating supermassive black hole

• from discovery to astronomy: next-generation instruments: x 5~10 (PeV) and x100 (EeV)

• also, a beam for PeV neutrino physics

icecube.wisc.edu
ANTARES

Running since 2007
885 10” PMTs
12 lines
25 storeys/line
3 PMTs / storey
2500 m deep

450 m

40 km to shore

Junction Box

Interlink cables

ANTARES
Lake Baikal experiment reaches 0.35 km$^3$
KM3NeT: 6 strings operating stably for one year

completion: 14 units 2024
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the first Glashow resonance event:
anti-$\nu_e$ + atomic electron $\rightarrow$ real W at 6.3 PeV
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
- Energy measurement understood
- Identification of anti-electron neutrinos
tau decay length = γ c τ = 50m per PeV
a cosmic tau neutrino: livetime 17m

* Bright DOMs are excluded from this analysis
high-energy starting events – 7.5 yr

WORK IN PROGRESS

oscillations of PeV neutrinos over cosmic distances to 1:1:1
neutrino astronomy 2020

• it exists

• more neutrinos, better neutrinos

• closing in on cosmic ray sources
THE ICECUBE COLLABORATION
THE ICECUBE COLLABORATION
overflow sides
IC200107A: The “DNN-starting-track Neutrino”

High-charge HESE event, did not qualify as alert
(see SplineMPE direction...)

Good starting track, confirmed by Theo’s DNN

Signalness ~65% (Not reported).

Posted in **GCN circular**.

Coincident with “extreme blazar”.

Followed Up In 7 GCNs + 3 ATELs + 3 Papers:

- **ZTF** (Non-detection)
- **Fermi GBM** (Non-detection)
- **Integral** (Non-detection)
- **HAWC** (Non-detection)
- **Fermi-LAT** (Nothing coincident, no new sources)
- **Swift** (ATEL, ATEL)
- **IceCube (FRA)** (p_2 = 0.04)
- **LBT** (Redshift) (Coincident Extreme Blazar, flaring)
10 years of IceCube data: evidence for non-uniform skymap, mostly resulting from 4 source candidates

why not seen before?
one of 3 prominent sources at 100 TeV
energy in the Universe in gamma rays, neutrinos and cosmic rays
Apparent superluminal core expansion and limb brightening in the candidate neutrino blazar TXS 0506+056

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Submitted: November 28, 2019; Accepted: December 3, 2019

ABSTRACT

Context. IceCube has reported a very-high-energy neutrino (IceCube-170922A) in a region containing the blazar TXS 0506+056. Correlated gamma-ray activity has led to the first high-probability association of a high-energy neutrino with an extragalactic source. This blazar has been found to be in a radio outburst during the neutrino event.

Aims. Our goal is to probe the sub-millisecond properties of the radio jet right after the neutrino detection and during the further evolution of the radio outburst.

Methods. We have performed target-of-opportunity very-long-baseline interferometry imaging observations at 43 GHz frequency, corresponding to 7 mm in wavelength, with the Very Long Baseline Array two and eight months, respectively, after the neutrino event.

Results. We produced two images of the radio jet of TXS 0506+056 at 43 GHz with angular resolutions of (0.2 × 1.1) mas and (0.2 × 0.5) mas, respectively. The source shows a compact, high brightness temperature core (albeit not approaching the equipartition limit, Readhead [1994]) and a bright and originally very collimated inner jet. Beyond about 0.5 mas from the mm-VLBI core, the jet loses this tight collimation and expands rapidly. During the months after the neutrino event associated with this source, the overall flux density is rising. This flux density increase happens solely within the core. Notably, the core expands in size with apparent superluminal velocity during these six months so that the brightness temperature drops by a factor of three in spite of the strong flux density increase.

Conclusions. The radio jet of TXS 0506+056 shows strong signs of deceleration and/or a spine-sheath structure within the inner 1 mas (corresponding to about 70 pc to 140 pc in deprojected distance) from the mm-VLBI core. This structure is consistent with theoretical models that attribute the neutrino and gamma-ray production in TXS 0506+056 to interactions of electrons and protons in the highly-relativistic jet spine with external photons originating from a slower-moving jet region. Proton loading due to jet-star interactions in the inner host galaxy is suggested as the possible cause of deceleration.

new physics?

if not...

every model for the astrophysical source ends up in the triangle

\[ \nu_\tau \lor \nu_\mu \lor \nu_e \]
upgrade/Gen2

- neutrino oscillation at PeV energy
- test of the 3-neutrino scenario
- neutrino physics BSM