Linking Electromagnetic Observations to Neutrino Astrophysics

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AGNs, SNRs, GRBs...

**Gamma rays**
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

**Neutrinos**
They are weak, neutral particles that point to their sources and carry information from deep within their origins.

**Cosmic rays**
They are charged particles and are deflected by magnetic fields.

Image credit: IceCube coll.
Hunting Cosmic Neutrinos
A pre-condition for likely astrophysical VHE neutrino sources is that they are also sources of VHE cosmic rays

Such sources could also be naturally related to the sources of ultra-high energy cosmic rays (UHECRs) observed by the Auger and TA cosmic ray arrays

NB: We still cannot prove those energies. For the currently detected maximum neutrino energies of $\sim< 3\text{ PeV}$ it is only necessary to have sources capable of accelerating CRs up to $\sim< 100\text{ PeV}$

(e.g., Mészáros 2017, ARNPS, 67, 45; Böttcher 2019 Galaxies, 7, 20 for a review)
Astrophysical ν point sources

Neutrinos are becoming a mature means to explore our Universe


Isotropically distributed: suggests a (dominant) extragalactic origin

Astrophysical Extragalactic Scenarios

- **Cosmic-ray Accelerators**
  
  Neutrinos produced within the CR source, mesons are typically produced by interactions of CRs with radiation

  - **Gamma-ray bursts**
    (e.g. Waxman & Bahcall 97, Murase et al. 06, Cholis & Hooper 13, Liu & Wang 13, Murase & Ioka 13, Winter 13, Senno, Murase & Meszaros 16)

  - **Active Galactic Nuclei**
    (e.g. Stecker et al. 91, Mannheim 93/95, Reimer 2012, Kalashev, Kusenko & Essey 13, Stecker 13, Murase, Inoue & Dermer 14, Dermer, KM & Inoue 14, Tavecchio et al. 14, Kimura, Murase & Toma 15, Padovani et al. 15, Wang & Li 1, Lamastra 2017)

- **Cosmic-ray Reservoirs**
  
  Neutrinos produced by inelastic hadronuclear collisions while confined within the environment surrounding the CR source

  - **Starburst galaxies**
    (e.g., Loeb & Waxman 06, Thompson+ 07; Murase, Ahlers & Lacki 13, Katz et al. 13, Liu+ 14, Tamborra, Ando & Murase 14, Anchordoqui+ 14, Senno+ 15)

  - **Galaxy groups/clusters**
    (e.g., Berezinsky+ 97, KM et al. 08, Kotera+ 09 // Murase, Ahlers & Lacki 13, Fang & Olinto 16)
$\gamma - \nu$ connection: strategies

- Limits on source density inferred by non-observation of neutrino multiplets

Kowalski, 2014; Ahlers, Halzen, 2014; Murase, Waxman, 2016
Tempting Neutrino/Gamma-rays connection
\( \gamma - \nu \) connection: strategies

**Correlation with known catalogs**

- 3LAC (>100 MeV, 4 years); 2FHL (>50 GeV, 6 years); 2WHSP (most complete list of HSP)

- None of the three blazar catalogs tested showed any significant evidence for a neutrino signal above background expectations.

- All the outcomes from the three catalog stacking analyses are fully compatible with background fluctuations.

IceCube - PoS(ICRC2017)994
Search for neutrino emission correlated with g-ray flares

A previous suspect

The high-peaked BL Lac object 1ES 1959+658:

- “Orphan” VHE flaring episode on June 4th, 2002 (WHIPPLE)
- Three neutrino events were found to arrive during the flaring episode (AMANDA); one within a few hours of the gamma ray observations
- Exhibited major flares in VHE gamma rays in the spring of 2016 (Buson+ Atel #9010, Fermi-LAT, FACT, MAGIC and VERITAS coll.)
- Test for time-clustering of neutrinos with IceCube
  - No significant emission neither by integrating over the whole flaring episode, nor by testing for clusters on shorter time scales

Search for neutrino emission temporally consistent with g-ray blazars:


No compelling neutrino excess pointed out
A Suggestive Hint

PKS 1424-418 (FSRQ)
Fermi-LAT gamma-ray counts map (>100 MeV)

Kadler+ 2016 Nature Physics 12, 807
IceCube Alert – IC170922A

“EHE” through-going track selection in the real-time alert system

| TITLE: | GCN/AMON NOTICE |
| NOTICE_DATE: | Fri 22 Sep 17 20:55:13 UT |
| NOTICE_TYPE: | AMON ICECUBE EHE |
| RUN_NUM: | 130033 |
| EVENT_NUM: | 50579430 |
| SRC_RA: | 77.2853d {+05h 09m 08s} (J2000), 77.5221d {+05h 10m 05s} (current), 76.6176d {+05h 06m 28s} (1950) |
| SRC_DEC: | +5.7517d {+05d 45' 06"} (J2000), +5.7732d {+05d 46' 24"} (current), +5.6888d {+05d 41' 20"} (1950) |
| SRC_ERROR: | 14.99 [arcmin radius, stat+sys, 50%] |
| DISCOVERY_DATE: | 18018 JD, 268 DOI, 17/09/22 (yy/mm/dd) |
| DISCOVERY_TIME: | 75270 SOD {20:54:30.43} UT |
| REVISION: | 0 |
| N_EVENTS: | 1 [number of neutrinos] |
| STREAM: | 2 |
| DELTA_T: | 0.0000 [sec] |
| SIGMA_T: | 0.0000e+00 [dn] |
| ENERGY: | 1.1998e+02 [TeV] |
| SIGNALNESS: | 5.6507e-01 [dn] |
| CHARGE: | 5784.9552 [pe] |
Fermi-LAT detection of candidate counterpart
Tanaka, Buson+ Atel #10791

IC-170922A

- 290 TeV (>183 TeV)
- *signalness* ~50%
What can we learn from IC170922A?

*IceCube, Fermi, MAGIC+ Science 361, 146 2018*
Multi-Messenger SED

Models producing neutrinos and gamma-rays through the same proton population, predict too high neutrino energies!

(Cerruti et al.: 1807.04335)
Photo-pion Models for TXS 0506+056

Models producing neutrinos and gamma-rays require leptonic-dominated gamma-ray production!


“Neutrino flare” 2014/2015

- IceCube archival search found 3.5sigma excess positionally consistent with the same blazar
TXS 0506+056 Light Curve

“Neutrino flare”

Gamma rays

Optical
γ-ray SED for 2014/15 period

• Compatible with quiescence (Garrappa, Buson, Franckowiak, ASAS-SN, IceCube coll. 2019)

• but see also Padovani+2018
MWL SED – TXS 0506+056

2014-15 ν flare

IC 170922A limits
Simultaneous Multi-Messenger SED (TXS 0506+056 “neutrino flare”)

Photo-Hadronically Produced Neutrinos from TXS 0506+056?

Photo-Pion Production / Energetics

$p\gamma$ interactions are strongly dominated by single-pion production through the $\Delta^+$ resonance at an energy of $E_{\Delta^+} = 1232\text{MeV}$

At $\Delta^+$ resonance energy, the $\gamma$ and $p$ energies obey the relation:

$$s = E_p' E_t' (1 - \beta_p' \mu) \sim E_p' E_t' \sim E_{\Delta^+}^2 = (1232 \text{MeV})^2$$

and

$$E'_\gamma \sim 0.05 E'_p$$

$\Rightarrow$ To produce IceCube neutrinos ($\sim 100 \text{TeV} \rightarrow E_\nu = 10^{14} E_{14} \text{ eV}$):

(i.e., $E'_\nu = 10 E_{14} \delta_{1\text{}}^{-1} \text{ TeV}$)

Need protons with $E'_p \sim 200 E_{14} \delta_{1\text{}}^{-1} \text{ TeV}$ ($<$ UHECRs energy)

and target photons with $E'_t \sim 1.6 E_{14}^{-1} \delta_{1\text{}} \text{ keV}$ (X-ray band)
The $p\gamma$ Efficiency Problem

- Same target photon field for photo-pion production can also **absorb** any co-spatially produced $\gamma$-rays via $\gamma\gamma$ absorption.

- The $p\gamma$ cross section is several orders of magnitude smaller than the $\gamma\gamma$ absorption cross section.

- Efficient $p\gamma$ neutrino (and $\gamma$-ray) production requires that the optical depth for relativistic protons to interact with the target photon field, $\tau_{p\gamma} \sim 1$,

=> optical depth of the emission region to $\sim$ GeV photons is $\tau_{\gamma\gamma} \sim 310 \tau_{p\gamma} >> 1$

$\Rightarrow$ Photons with $E_\gamma \sim$ GeV – TeV are heavily absorbed
$\Rightarrow$ EM cascade emission at lower energies
Photo-Hadronically Produced Neutrinos From TXS 0506+056?

- **Hypothesis:**
  - Neutrino (0.3-3 PeV range) flux at a similar level of the observed gamma-ray flux

- **Aims:** Constraining the neutrino production parameters as much model-independent as possible
  - *No assumptions on the origin of the target photon field for particle-photon interactions*

- **Primers:**
  - Neutrinos and photons originate photo-hadronically in the Jet
  - Target radiation field in the jet is isotropic
  - Linear cascades

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**Reimer, Bottcher, Buson sub. to ApJ**

- Target photons: $n_{ph}(\varepsilon) \sim \varepsilon^{-\alpha}$, $\varepsilon_{\text{min}} = 10$ keV, $\varepsilon_{\text{max}} = 60$ keV, $\alpha = 1$
- Proton spectrum: $n_{p}(E) \sim E^{-\alpha_{p}}$, $E_{\text{max}} = 30$ PeV, $\alpha_{p} = 2.0$
Simulate pair cascades initiated by secondary γ-rays and electrons/positrons

Energy density of the target photon field

Energy density of the protons

Size of the emitting region

Doppler factor

Changes in the doppler factor shift in energy the distribution; and one needs to change a bit the target photon field. Good thing is that for any choice of doppler factor, one can always find a combination of parameters that works.
Synchrotron-supported Cascades

Ruled out by MWL spectra
(over-predicting either Fermi-LAT or X-ray / radio fluxes)

Reimer, Bottcher, Buson sub. to ApJ
Feasible scenario

- $\tau_{\gamma\gamma} << 1$: minimal photon flux produced along with the gamma-flux co-spatially
- $\tau_{\gamma\gamma} >> 10$: significant internal absorption in > GeV/VHE energy range
- Bulk of LAT-flux can not be produced co-spatially with neutrino-flux

In principle, allowed by MWL spectra:
Significantly below observed fluxes

=> No neutrino – $\gamma$-ray correlation expected!

Compton-Supported Cascades

Reimer, Bottcher, Buson sub. to ApJ
Production, Origin of Target Photons

Stationary UV / soft X-ray target photon field external to the jet is plausible

- Possible sources of external UV / soft X-ray target photons, e.g.,:
  - BLR (Padovani+ 2019 MNRAS, 484, 104)
  - Slow-moving sheath (Tavecchio & Ghisellini 2005)
  - Accretion flow (ADAF, Righi+ 2019 MNRAS, 483, 127)

(see also Rodrigues+ 2018, arXiv:181205939)
Desiderata for Future Progresses

• Multi-messenger + time-domain is a promising path to reveal the origin of neutrinos (and potentially cosmic rays)

• More high-energy neutrinos! (IceCube increasing the event statistic)

• Future observatories will improve sensitivity and statistics, e.g., IceCube-Gen2, KM3NeT, AMEGO, ASTROGAM, CTA ...

Garrappa, Buson, Franckowiak+ arXiv:190110806
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THANKS

Garrappa, Buson, Franckowiak+ arXiv:190110806
BACK UP
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