AGN as neutrino sources
from IceCube to radio neutrino telescopes

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Astrophysical neutrino observations

- Diffuse neutrino flux observed above atmospheric background (first observed in 2013)

- Astrophysical neutrinos observed with energy up to ~50 PeV

- No strong correlation with known point sources
- No significant clustering observed yet
  -> Stacking limits, multiplet constraints

- But some hints of neutrino sources have already emerged (e.g. TXS 0506+056, PKS 1502+106)
Astrophysical neutrino observations

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Future radio detection of extreme-high-energy (EHE) neutrinos

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Cosmic ray interactions and the multi-messenger picture

- **Multi-messenger astrophysics**: attempting to unveil *common origin* to different cosmic radiations

- **Evidence** of a fraction of ultra-high-energy cosmic rays *heavier than protons*
Active Galactic Nuclei (AGNs)

- Lorentz factor $\Gamma$
- Relativistic jet
- Supermassive black hole
- Thin accretion disk
- Dust torus

Picture courtesy NASA, Dana Berry/Skyworks Digital
Active Galactic Nuclei (AGNs)

- Lorentz factor $\Gamma$
- Radio galaxy
- Hercules A (Hubble+VLA)
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Picture courtesy NASA, Dana Berry/Skyworks Digital
Active Galactic Nuclei (AGNs)

- Lorentz factor $\Gamma$
- radio galaxy
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Credit: NASA/HST

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blazar

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dust torus

one-zone models

Lorentz factor $\Gamma$

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Blazar family overview

Flat-Spectrum Radio Quasars (FSRQs)

Credit: Bill Saxton, NRAO/AUI/
Blazar family overview

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Blazar gamma-ray luminosity [erg/s]

blazar redshift

Blazar family overview

Flat-Spectrum Radio Quasars (FSRQs)

BL Lacs

PKS 1502+106: example of a leptohadronic model

Protons accelerated to ~PeV (source frame)
-→ neutrinos peak at ~PeV (observer frame)
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Gamma-ray - neutrino correlation

**XR, Garrappa, Gao, Paliya, Franckowiak & Winter, accepted in ApJ**
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TXS 0506+056 (2014/15 IceCube signal)

Protons accelerated to 100 TeV (source frame)

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Cascades "dump" the gamma rays into the MeV range (X-ray- neutrino connection)  

Entirely hadronic

TXS 0506+056 (2014/15 IceCube signal)

CRs and neutrinos from the entire blazar population

CRs and neutrinos from the entire AGN population

\[
\nu \text{ production efficiency}
\]

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\]

\[
\epsilon_{\nu} \sim 10^{-3} - 10^{-1}
\]

\[
L_{\gamma} [\text{erg/s}]
\]

\[
\epsilon_{\text{UHECR}} \sim 10^{-3} - 10^{-1}
\]

\[
L_{\gamma} [\text{erg/s}]
\]

CRs and neutrinos from the entire AGN population

![Diagram showing neutrino production efficiency and UHECR efficiency for BL Lacs and FSRQs.](image)

- **Neutrino Production Efficiency**
  - BL Lacs: Increases with increasing gamma-ray luminosity $L_\gamma$[erg/s].
  - FSRQs: Slightly lower efficiency compared to BL Lacs.

- **UHECR Efficiency**
  - BL Lacs: Constant efficiency across gamma-ray luminosity $L_\gamma$[erg/s].
  - FSRQs: Decreases with increasing gamma-ray luminosity $L_\gamma$[erg/s].

Makes **lack of neutrino-source correlations** even more intriguing.

Indicates **decoupling** between neutrino and CR sources.
### CRs and neutrinos from the entire AGN population

<table>
<thead>
<tr>
<th>Scenario 1: AGN accelerate CRs up to max 10 PeV</th>
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- Can explain IceCube sub-PeV to PeV flux

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CRs and neutrinos from the entire AGN population

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The CR-neutrino connection

Cosmic rays

$E^3 J$ [GeV$^2$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$]

$E$ [GeV]

XR, Heinze, Palladino, van Vliet, Winter, submitted to PRL
The CR-neutrino connection

EHE neutrino flux:
- Possibly at a level detectable by IceCube Gen2, GRAND 200k
- **Source neutrinos** should outshine cosmogenic
- Dominated by **bright FSRQs** (only ~600 objects resolved by Fermi-LAT)

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**Cosmic rays**

**Neutrinos**

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Conclusion

Recent IceCube from the directions of known AGN are generally supported by multi-messenger modeling of cosmic-ray interactions.

Current challenges in the modeling point towards more sophisticated models -> which in turn require more multi-wavelength coverage and higher neutrino statistics.

If AGN accelerate CRs to 100 TeV - 10 PeV: may explain the IceCube diffuse flux -> hypothesis will soon be challenged by stacking limits and multiplet constraints.

If AGN accelerate UHECRs: may produce UHE neutrinos at levels detectable by future radio neutrino telescopes; these will be source neutrinos from a few powerful quasars -> favourable to directionality studies, time domain searches.
Backup
CRs and neutrinos from the entire blazar population

\[ \epsilon_{\nu} \]

\[ \epsilon_{\text{UHECR}} \]

\[ L_\gamma \text{[erg/s]} \]

CRs and neutrinos from the entire blazar population

![Graphs showing CRs and neutrinos from blazars](image_url)
Blazars as sources of the IceCube neutrinos?

**Diffuse neutrino flux**

- BL Lacs must have high baryonic loadings to power the IceCube neutrino flux.
- FSRQ contribution must be highly suppressed not to violate stacking bounds.

**Baryonic loading**

- FSRQs contribution must be highly suppressed not to violate stacking bounds.
- BL Lacs must have high baryonic loadings to power the IceCube neutrino flux.

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Neutrinos and CRs from the blazar family

Bright blazars are good neutrino emitters

Dim blazars are good CR emitters

Makes lack of neutrino-source correlations even more challenging

TXS 0506+056: the first neutrino blazar?

Muon track observed on Sep 22, 2017 (energy of 23.7±2.8 TeV)

Simultaneous gamma-ray flare

Evidence for 13±5 neutrinos from the same source back in 2014-15

Aartsen et al., 2018, Science 361, eeat1378

The 2017 neutrino event

Example of lepto-hadronic model:

X-rays from hadronic cascades constrain the baryonic loading of the source, but 0.2 neutrinos per year can be explained.
The 2014/15 neutrino flare of TXS 0506+056 — constraints

The graph shows the distribution of energy vs. frequency for different energy regimes: µeV, meV, eV, keV, MeV, GeV, TeV, and PeV. The data points are labeled with energy levels and corresponding energy distributions. The graph includes constraints from Padovani++, Swift BAT, Fermi LAT, and IceCube 2018. The 2017 gamma-ray level is indicated, and there is a note that 0.2 neutrino events per year are expected.
One-zone model

Explain up to 2 neutrinos without violating X- and gamma-ray fluxes

External-field (FSRQ-like) model

In-source cascades "dump" the hadronic photons into the MeV range (cf. Reimer++ 2019 ApJ 881)

TeV spectrum too soft due to photon annihilation with the disk emission

Model can explain up to 5 neutrino events (still 2 σ discrepancy with observation)

This result emphasizes the need for
• Better multi-wavelength blazar data
• Realistic numerical modeling

Assume a disk luminosity consistent with observations [Padovani et al. MNRAS 484 (2019)]