Sources of high-energy neutrinos

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High-energy phenomena in relativistic outflows (HEPRO)

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Contents

• Introduction
• Neutrinos from AGN blazars
• Neutrinos from TDE jets?
• Why are no neutrinos from GRBs seen?
• Summary

Center theme:
What can we learn about cosmic-ray acceleration in relativistic jets from neutrino observations?

Will not tell you how the particles are accelerated, but give you an idea what it needs to describe neutrino and UHECR observations and what the critical issues are …
The Universe in multiple messengers

- Gravitational waves
- Electromagnetic radiation
- Source neutrinos
- Cosmogenic neutrinos
- CMB/CIB

High-energy astrophysical neutrinos are unambiguous evidence for cosmic-ray acceleration!
Detections of astrophysical neutrinos
A selection of results

Focus of this talk: Relativistic outflows

<table>
<thead>
<tr>
<th>Class</th>
<th>Evidence for $\nu$</th>
<th>Related to relativistic jet?</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGN blazars</td>
<td>Widely accepted</td>
<td>Probably ($\Gamma \sim 10-30$)</td>
</tr>
<tr>
<td>Tidal Disruption Events</td>
<td>Several hints</td>
<td>Maybe ($\Gamma \sim 10-100?$)</td>
</tr>
<tr>
<td>Gamma-Ray Bursts</td>
<td>None – why?</td>
<td>Should be! ($\Gamma &gt; 100$)</td>
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</tbody>
</table>
Radiation models and neutrino production

- Neutrino production e.g. through $\Delta$-resonance ($p\gamma$)
  
  $E_\gamma$ [keV] $\sim 0.01 \Gamma^2/E_\nu$ [PeV]

- Interactions described by kinetic equations (one PDE per species)

- Radiation processes include interactions, escape, cooling, injection

- Numerical tool: public soon

- Interaction rate $\sim c N [\text{cm}^{-3}] \sigma [\text{cm}^2]$
  
  Very sensitive to size of radiation zone!

- Neutrino production e.g. through $D$-resonance ($p\gamma$)
  
  $E_\gamma$ [keV] $\sim 0.01 \Gamma^2/E_\nu$ [PeV]

  $E_\nu$ [keV] $\sim 0.05 E_{p,max}$

  $E_\nu$: protons, $E_\gamma$: target photons

- Interaction rate $\sim c N [\text{cm}^{-3}] \sigma [\text{cm}^2]$
  
  Very sensitive to size of radiation zone!

- Interactions described by kinetic equations (one PDE per species)

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Neutrinos from AGN blazars

https://multimessenger.desy.de/
A neutrino from the flaring AGN blazar TXS 0506+056

Sept. 22, 2017:
A neutrino in coincidence with a blazar flare

Observed by Fermi-LAT and MAGIC (blazar flare)

Significance for correlation: $3\sigma$

$z = 0.3365 \pm 0.0010$

Paiano et al, 2018

SED from a multi-wavelength campaign

Color: coincident with neutrino; gray: archival data

Science 361 (2018) 6398
Analysis of archival neutrino (IceCube)

A (orphan) neutrino flare (2014-15) found from the same object in archival neutrino data

During that historical flare:
- Coincident data sparse (since no dedicated follow-up campaign)
- No significant gamma-ray activity


3 ± 5 events excess. Significance: 3.5σ
One zone model results (2017 flare)

Leptonic models

- No neutrinos

Hadronic ($\pi$ cascade) models

- Violate X-ray data

Hybrid or p synchrotron models

- Violate energetics ($L_{\text{edd}}$) by a factor of a few hundred or significantly exceed $\nu$ energy

Baryonic loading $1/f_\nu > 10^4$

see also Cerutti et al, 2018; Sahakyan, 2018; Gokus et al, 2018; Keivani et al, 2018
Theoretical challenge: Where did all the energy go to?

\[ p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & \rightarrow \nu \\ p + \pi^0 & \rightarrow \gamma \end{cases} \]

Comparable amounts of energy

Options for “hiding” the gamma-rays (+electrons):

- Reprocessed into \( E \) ranges without data during flare? (e.g. MeV range)
  - \( n + \pi^+ \rightarrow \nu \)
  - \( p + \pi^0 \rightarrow \gamma \)
  - \( \rightarrow \) Implies low radiation density (\( \gamma \)-rays escape)
  - Energetics more challenging

- Leave source + dumped into the background light?
  - \( \rightarrow \) Requires additional model ingredients
  - Implies low radiation density (\( \gamma \)-rays escape)
  - Energetics more challenging

- Absorbed or scattered in some opaque region, e.g. dust/gas/radiation?
  - \( \rightarrow \) Requires additional model ingredients
  - see e.g. Wang et al, 2018; Murase et al, 2018

Electromagnetic data during neutrino flare sparse (colored)

Hardening in gamma-rays? (red shaded region)

Padovani et al, 2018; Garrappa et al, arXiv:1901.10806
Systematic modeling
of 324 AGN blazars

Spectral energy distribution benefits from hadronic contributions in about 1/3 of all cases.

Energy crisis for cosmic-ray acceleration?

- Substantial fraction of Eddington luminosity has to go into non-thermal protons. In many cases super-Eddington.

Theoretical comments/questions

- The electron parameters ($E_{e,\text{min}}, E_{e,\text{max}}, \gamma_e$, even escape) are often free parameters → Self-consistent description?
  e.g. Zech, Lemoine, 2021

- The proton parameters (esp. $E_{p,\text{min}}, \gamma_p$) are often chosen ad hoc. (l.h.s: 100 GeV, $E^{-1}$) → Harder spectra and higher $E_{p,\text{min}}$ can mitigate the energy problem → Are $E_{e,\text{min}}$ and $E_{p,\text{min}}$ connected?

- Can such high baryonic loadings be justified from theoretical arguments?

Are super-Eddington accretion flares somehow connected with cosmic-ray acceleration?

- Baryonic loading (non-thermal $L_p/L_e \sim 10^1$-$10^5$, significantly dropping with luminosity → No energy-equipartition!

Neutrinos from TDEs

Tidal Disruption Events

Is there a connection with a relativistic outflow?

https://www.desy.de/e409/e116959/e119238/media/9170/TDE_DESY_SciComLab_sound_080p.mp4
How to disrupt a star

Fundamentals
• Force on a mass element in the star (by gravitation) ~ force exerted by the SMBH at distance (tidal radius)
  \[ r_t = \left(\frac{2M}{m}\right)^{1/3} R \approx 8.8 \times 10^{12} \text{ cm} \left(\frac{M}{10^6 M_\odot}\right)^{1/3} \frac{R}{R_\odot} \left(\frac{m}{M_\odot}\right)^{-1/3} \]
• Has to be beyond Schwarzschild radius for TDE (otherwise swallowed as a whole)
  \[ R_s = \frac{2MG}{c^2} \approx 3 \times 10^{11} \text{ cm} \left(\frac{M}{10^6 M_\odot}\right) \]
• From the comparison \( r_t > R_s \) and demographics, one obtains (theory) \( M < \approx 2 \times 10^7 M_\odot \) (lower limit less certain …)
  Hills, 1975; Kochanek, 2016; van Velzen 2017

Theory: A unified model?
• Supported by MHD simulations; here \( M_{SMBH} = 5 \times 10^6 M_\odot \)
• Jet formation depends on SMBH spin
• Average mass accretion rate \( \dot{M} \approx 10^2 L_{\text{Edd}} \)
  • ~ 20% of that into jet
  • ~ 3% into bolometric luminosity
  • ~ 20% into outflow
  Dai, McKinney, Roth, Ramirez-Ruiz, Coleman Miller, 2018
Relativistic jets from TDEs

Radio observations

Interesting signals in about 1/3 of all cases. Evolving radio signals interpreted as outflow or jet:

A new example: AT2022cmc

- Extremely luminous
- Non-thermal spectra in X-rays
- Associated with on-axis (or slightly off-axis) relativistic jet

- $\Gamma \sim$ few to 90 (!) (one model AT2022cmc)
- Typical assumption $\Gamma \sim 10$

- Conclusion: About 1% of all TDEs have relativistic jets (not necessarily pointed in our direction, i.e., “TDE blazars”)

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Andreoni et al, Nature 612 (2022) 7940, 430; Pasham et al, Nature Astron. 7 (2023) 1, 88
Neutrinos from TDEs

Analysis

- Three neutrinos associated with TDE candidates
  van Velzen et al, arXiv:2111.09391
- Overall significance: 3.7σ
  van Velzen et al, arXiv:2111.09391

Common features:

- All three TDEs exhibit strong dust echoes in the infrared range
- All three TDEs have been detected in X-rays (not so frequent for TDEs!)
- All three TDEs exhibit neutrino time delays order $10^7$ s wrt BB peak
- All three neutrinos arrived at the peak of the dust echoes

Possible interpretation:

- What if ... the dust echo itself (IR) is the target for cosmic ray interactions?
- Consequence (from $p\gamma$ interactions): $E_p > 1.6$ EeV ($T_{IR}/0.1$ eV)$^{-1}$
  (for nuclei: rigidity $R > 1.6$ EV)
- Compatible with UHECR fits, e.g. $R_{\text{max}} \sim 1.4$-3.5 EV. Coincidence?
- Points towards interactions of UHECRs
  Winter, Lunardini, ApJ 948 (2023) 1, 42
**Possible particle acceleration sites**

1. **Jets (on-axis, off-axis, choked)**

2. **Disk**
   - Hayasaki & Yamazaki, 2019

3. **Corona**
   - Murase et al, 2020

4. **Winds, outflow, stream-stream collisions**
   - Murase et al, 2020; Fang et al, 2020; Wu et al, 2021

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Probably neutrinos not associated with on-axis jets (constraints from radio signals).

But: hypothesis “jetted TDEs ~ neutrino-emitting TDEs” roughly consistent with neutrino diffuse flux at highest energies powered by TDEs

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Winter, Lunardini, ApJ 948 (2023) 1, 42
Example: A jetted concordance scenario for AT2019dsg

Addresses energetics issue, but challenged by radio observations

Early:
\( t - t_{\text{peak}} < 17 \text{ d} \)

Late:
\( t - t_{\text{peak}} >> 17 \text{ d} \)

Why no neutrinos from GRBs?

Focus on prompt phase, internal shocks

Source: NASA
**Multimessenger bounds**

Gamma-ray observations (e.g. Fermi, Swift, etc)

Neutrino observations (e.g. IceCube, ANTARES)

Use timing, directional and energy information to reduce backgrounds

Cannot power observed diffuse flux!

But: 1% contribution possible

Fudge factor:

Baryonic loading $1/f_e$

(energy injected into non-thermal protons vs. electrons)

Required value to power UHECRs depends on:

- $p$ spectrum, $E_{p,\text{min}}$
- $1/f_e$
- UHECR escape mechanism
- Electron cooling efficiency
- Local GRB rate
- Peak of GRB luminosity function

Stacking vs. GRB 221009A

Murase, Mukhopadhyay, Kheirandish, Kimura, Fang, 2022; see also Ai, Gao, 2022

IceCube, Nature 484 (2012) 351; Fig. from update: ApJ 843 (2017) 112
The vanilla one-zone prompt model

Quantitative studies require description of UHECR data (here: ankle model)

- Can describe UHECR data, but:
  - Scenario is constrained by neutrino non-observations

- Conclusion robust after extensive parameter space studies (e.g. different energy ranges)

Possible caveats:
- Low-luminosity GRBs
- Large R (magnetic reconnection?)

Biehl, Boncioli, Fedynitch, Winter, arXiv:1705.08909
Back to the roots: Outflow models

Continuous outflow: $t'_{\text{dyn}} = R_c / (c \Gamma)$

Discrete outflow: $t'_{\text{dyn}} = \Gamma l_m / c$

One zone approximation:
$\tau_v \sim l_m / c$ (variability timescale)
$R_C \sim \Gamma^2 d$ (distance to catch up)
Often: $d \sim l \rightarrow R_C \sim c \Gamma^2 \tau_v$

From:
- Bustamante, Baerwald, Murase, Winter, Nature Commun. 6 (2015) 6783
A unified engine model with free injection compositions

Systematic parameter space study requires model which can capture stochastic and continuous engine properties

**Model description**

- Lorentz factor ramp-up from $\Gamma_{\text{min}}$ to $\Gamma_{\text{max}}$, stochasticity ($A_\Gamma$) on top

**Description of UHECR data**

Describes UHECR data over a large range of parameters!

(Systematically studied)

Inferred neutrino fluxes from the parameter space scan

Prompt neutrino flux possibly testable with IceCube-Gen2, cosmogenic one in future radio instruments

The different messengers “prefer” different production regions; one zone therefore no good approximation for neutrino production

Interpretation of the results and open issues

- The required injection composition is derived: more than 70% heavy (N+Si+Fe) at the 95% CL (here: non-thermal energy fractions)

- Self-consistent energy budget requires kinetic energies larger than $10^{55}$ erg – perhaps biggest challenge for UHECR paradigm?

<table>
<thead>
<tr>
<th>$E_{v}$</th>
<th>$E_{\text{esc}}$ (escape)</th>
<th>$E_{\text{HECR}}$ (in-source)</th>
<th>$E_{\text{HECR}}$ (in-source, UHECR)</th>
<th>$E_{p}$</th>
<th>$E_{\text{kin,init}}$ (isotropic-equivalent)</th>
<th>Dissipation efficiency $\epsilon_{\text{diss}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.67x10^{52} erg</td>
<td>2.01x10^{53} erg</td>
<td>3.70x10^{53} erg</td>
<td>7.81x10^{59} erg</td>
<td>2.90x10^{55} erg</td>
<td>0.28</td>
</tr>
<tr>
<td>SR-OS</td>
<td>8.00x10^{52} erg</td>
<td>2.10x10^{53} erg</td>
<td>4.62x10^{54} erg</td>
<td>2.18x10^{50} erg</td>
<td>3.00x10^{55} erg</td>
<td>0.22</td>
</tr>
<tr>
<td>SR-LS</td>
<td>8.21x10^{52} erg</td>
<td>1.85x10^{53} erg</td>
<td>3.97x10^{53} erg</td>
<td>1.28x10^{51} erg</td>
<td>4.50x10^{55} erg</td>
<td>0.13</td>
</tr>
<tr>
<td>WR-MS</td>
<td>4.27x10^{52} erg</td>
<td>1.60x10^{53} erg</td>
<td>3.57x10^{53} erg</td>
<td>1.79x10^{51} erg</td>
<td>7.81x10^{55} erg</td>
<td>0.14</td>
</tr>
<tr>
<td>WR-HS</td>
<td></td>
<td></td>
<td></td>
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</table>

- Light curves may be used as engine discriminator

<table>
<thead>
<tr>
<th>Engine</th>
<th>Light curves</th>
<th>$t_{\text{obs}} - R_{c}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR-OS</td>
<td>More pulse-like</td>
<td>correlated</td>
</tr>
<tr>
<td>SR-LS</td>
<td>More stochastic</td>
<td>uncorrelated</td>
</tr>
<tr>
<td>WR-MS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WR-HS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Hadronic signatures in the electromagnetic spectrum

Example: Energetic GRB with $E_{\gamma,\text{iso}} \sim 10^{54}$ erg, single pulse, synchrotron (fast) cooling dominated SED, large $R_C \sim 10^{16}$ cm

Impact of baryonic loading:

→ Neutrino production dominated by low photon energies
→ Hadronic contributions enhance neutrino production
→ High peak neutrino energies

Summary and open issues
... from neutrino observations and the UHECR connection

Generic observations and open issues for acceleration models with relativistic outflows

- Neutrino production requires very efficient energy transfer into non-thermal protons. Are neutrino flares related to super-Eddington accretion events?
- Acceleration theory: Hard acceleration spectra or large $E_{p,\text{min}}$ can mitigate the energy crisis. Is there a connection with $E_{e,\text{min}}$?
- What does the required injection composition tell us about the UHECR acceleration?
- How do UHECRs escape from the source?

Neutrinos from AGN blazars
- Some convincing evidence
- Strong parameter constraints from SED on that zone
- Low neutrino production efficiency
- Certainly no energy equipartition $e$-$p$, super-Eddington accretion needed?

Neutrinos from TDE jets?
- Several hints for neutrinos from TDEs
- TDE jets interesting because they can address the energetics issue
- However, so far no clear identification of a jetted TDE with a neutrino

Neutrinos from GRBs
- Expected if GRBs are the sources of the UHECRs. Requires relatively high kinetic energies!
- So far no GRB neutrino seen
- One zone models constrained, but does not rule out UHECR paradigm in multi-zone models yet
One zone description of spectral energy distribution (AGN)

... can describe SED (with significant excess of $L_{\text{edd}}$), but no more than two neutrino events

Energy deposited in MeV range and absorbed in EBL (here about 80% absorbed, 20% re-processed for $E_\gamma > \text{TeV}$)

Primary electron processes (synchrotron and inverse Compton) dominate nowhere in this model!

TDE observations (general)

• Optical-UV (blackbody): Mass fallback rate typically exhibits a peak and then a $\sim t^{-5/3}$ dropoff over a few hundred days.

• X-rays: Only observed in rare cases (here about 4 out of 17). X-ray properties very different.

• Radio: Interesting signals in about 1/3 of all cases. Evolving radio signals interpreted as outflow or jet.

Neutrino production efficiency in GRBs

- Pion production efficiency $f_\pi (\sim 0.2 \tau_{pr})$ from photon energy density:

$$u'_\gamma \equiv \int \epsilon' N'_\gamma(\epsilon')d\epsilon' = \frac{L_\gamma}{4\pi c \Gamma^2 R^2}$$

$$f_\pi \propto \frac{c t'_\text{dyn} L_\gamma}{\hat{\epsilon}_\gamma R^2 \Gamma} \sim \frac{L_\gamma t_v}{\hat{\epsilon}_\gamma R^2} \sim \frac{L_\gamma}{\hat{\epsilon}_\gamma R \Gamma^2} \sim \frac{L_\gamma}{\hat{\epsilon}_\gamma \Gamma^4 t_v}$$

Typical photon energy (where photon number density peaks):

$$\hat{\epsilon}_\gamma \sim \epsilon_{\gamma, \text{br}}$$

or harder below break (not achievable for synchrotron emission …)

- Production radius $R$ and luminosity $L_\gamma$ are the main control parameters for the particle interactions [for fixed $t_v$] → Neutrino production, EM cascade from secondaries, nuclear disintegration, etc.

  - Internal shock model (multi-zone, discrete outflow).
  - Magnetic reconnection models (two different scales).
  - Internal shock model (cont. outflow).
  - Photospheric models?
  - Magnetic reconnection models (two different scales).

  e.g. Guetta et al, 2003; He et al, 2012; Zhang, Kumar, 2013; Biehl et al, arXiv:1705.08909 (Sec. 2.5); Pitik et al, 2021
Back to the drawing board: Multi-collision models

The GRB prompt emission comes from multiple zones (one GRB)

Observations

- The collision radius can vary over orders of magnitude
- The different messengers prefer different production regions; one zone therefore no good approximation
- The neutrino emission can be significantly lower
- The engine properties determine the nature of the (multi-messenger) light curves, and where the collisions take place
- Many aspects studied, such as impact of collision dynamics, interplay engine properties and light curves, dissipation efficiency etc.

Bustamante, Baerwald, Murase, Winter, Nature Commun. 6 (2015) 6783;
see also Globus et al, 2014+2015;
earlier works e.g. Guetta, Spada, Waxman, 2001 x 2
Application to GRB 221009A

- Baryonic loading $1/f_e \sim 3$ consistent with UHECR paradigm, LHAASO photons from EBL interactions, ~energy equipartition
- Intermittent engine $t_{\text{var}} \sim 1s$, quiescent period ~ 200s, $R_C \sim 10^{16}$ cm
- Spectrum does not carry significant hadronic signatures; neutrino spectra consistent with non-observation