Magnetic field and flavor effects on the neutrino fluxes from cosmic accelerators

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Neutrino production in astrophysical sources

Example: Active galaxy
(Halzen, Venice 2009)

max. center-of-mass energy $\sim 10^3$ TeV
(for $10^{12}$ GeV protons)
Different messengers

- Shock accelerated protons lead to $p$, $\gamma$, $\nu$ fluxes
  - $p$: Cosmic rays: affected by magnetic fields
  - $\gamma$: Photons: easily absorbed/scattered
  - $\nu$: Neutrinos: direct path
Evidence for proton acceleration, hints for neutrino production

- Observation of cosmic rays: need to accelerate protons/hadrons somewhere
- The same sources should produce neutrinos:
  - in the source (pp, pγ interactions)
  - Proton (E > 6 \times 10^{10} \text{ GeV}) on CMB ⇒ GZK cutoff + cosmogenic neutrino flux

(Source: F. Halzen, Venice 2009)
Neutrino detection: IceCube

- Example:
  IceCube at South Pole
  Detector material: ~ 1 km$^3$
antarctic ice

- Completed 2010/11 (86 strings)

- Recent data releases, based on parts of the detector:
  - Point sources IC-40 [IC-22]
  - GRB stacking analysis IC-40
    arXiv:1101.1448
  - Cascade detection IC-22
    arXiv:1101.1692

- Have not seen anything (yet)
  - What does that mean?
  - Are the models wrong?
  - Which parts of the parameter space does IceCube actually test?

http://icecube.wisc.edu/
Neutrino astronomy in the Mediterranean: Example ANTARES

http://antares.in2p3.fr/
When do we expect a \( \nu \) signal?

[Some personal comments]

- Unclear if specific sources lead to neutrino production; spectral energy distribution can be often described by other processes as well (e.g. inverse Compton scattering, proton synchrotron, …)
- However: wherever cosmic rays are produced, neutrinos should be produced to some degree
- There are a number of additional candidates, e.g.
  - „Hidden“ sources (e.g. „slow jet supernovae“ without gamma-ray counterpart)
    (Razzaque, Meszaros, Waxman, 2004; Ando, Beacom, 2005; Razzaque, Meszaros, 2005; Razzaque, Smirnov, 2009)
  - Large fraction of Fermi-LAT unidentified sources?
- From the neutrino point of view: „Fishing in the dark blue sea“? Looking at the wrong places?
- Need for tailor-made neutrino-specific approaches? [unbiased by gamma-ray and cosmic ray observations]
- Also: huge astrophysical uncertainties; try to describe at least the particle physics as accurate as possible!
Where to look for sources?

- Model-independent (necessary) condition: 
  \[ E_{\text{max}} \sim Z e B R \] 
  (Larmor-Radius < size of source)
  - Particles confined to within accelerator!
- Sometimes: define acceleration rate 
  \[ t^{-1}_{\text{acc}} = \eta Z e B/E \] 
  (\( \eta \): acceleration efficiency)
- Caveat: condition relaxed if source heavily Lorentz-boosted (e.g. GRBs)

(Hillas, 1984; version adopted from M. Boratav)
Simulation of sources
Pion photoproduction

Resonant production,
direct production

Multi-pion production

Power law injection spectrum from Fermi shock acc.

Different characteristics (energy loss of protons; energy dep. cross sec.)

Resonant production, direct production

(Mücke, Rachen, Engel, Protheroe, Stanev, 2008; SOPHIA)
Meson photoproduction

- Often used: $\Delta(1232)$-resonance approximation

- Limitations:
  - No $\pi^-$ production; cannot predict $\pi^+ / \pi^-$ ratio (affects neutrino/antineutrino)
  - High energy processes affect spectral shape (X-sec. dependence!)
  - Low energy processes (t-channel) enhance charged pion production

  Charged pion production underestimated compared to $\pi^0$ production by factor of 2.4 (independent of input spectra!)

- Solutions:
  - SOPHIA: most accurate description of physics
    Mücke, Rachen, Engel, Protheroe, Stanev, 2000
    Limitations: Often slow, difficult to handle; helicity dep. muon decays!
  - Parameterizations based on SOPHIA
    Kelner, Aharonian, 2008
    Fast, but no intermediate muons, pions (cooling cannot be included)
  - Hümmer, Rüger, Spanier, Winter, 2010
    Fast (~3000 x SOPHIA), including secondaries and accurate $\pi^+/\pi^-$ ratios; also individual contributions of different processes (allows for comparison with $\Delta(1232)$-resonance!)

GRB: $\pi^+$

BB: $\pi^+$

from:
A self-consistent approach

- Target photon field typically:
  - Put in by hand (e.g. obs. spectrum: GRBs)
  - Thermal target photon field
  - From synchrotron radiation of co-accelerated electrons/positrons (AGN-like)

- Requires few model parameters, mainly

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Description</th>
<th>Typical values used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>km (kilometers)</td>
<td>Size of acceleration region</td>
<td>$10^1 \text{ km} \ldots 10^{21} \text{ km}$</td>
</tr>
<tr>
<td>$B$</td>
<td>G (Gauss)</td>
<td>Magnetic field strength</td>
<td>$10^{-9} \text{ G} \ldots 10^{15} \text{ G}$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>1</td>
<td>Universal injection index</td>
<td>1.5 $\ldots$ 4</td>
</tr>
</tbody>
</table>

- Purpose: describe wide parameter ranges with a simple model; **minimal set of assumptions for $\nu$?!**
Optically thin to neutrons

Model summary

Dashed arrows: include cooling and escape

\[ Q_e(E) \rightarrow N_e(E) \rightarrow Q_\gamma(E) \rightarrow N_\gamma(E) \rightarrow N_p(E) \rightarrow Q_p(E) \]

Dashed arrow: Steady state
Balances injection with energy losses and escape

\[ Q(E) = - \frac{\partial}{\partial E} \left( \frac{E N(E)}{t_{loss}} \right) + \frac{N(E)}{t_{esc}} \]

Injection \hspace{1cm} Energy losses \hspace{1cm} Escape

\[ Q(E) \ [\text{GeV}^{-1} \text{cm}^{-3} \text{s}^{-1}] \] per time frame

\[ N(E) \ [\text{GeV}^{-1} \text{cm}^{-3}] \] steady spectrum

\[ Q_{\nu_e}(E) \quad \text{from } \mu^+ \]
\[ Q_{\nu_\mu}(E) \quad \text{from } \mu^+ \]
\[ Q_{\bar{\nu}_e}(E) \quad \text{from } \mu^- \]
\[ Q_{\bar{\nu}_\mu}(E) \quad \text{from } \mu^- \]

\[ N_{\nu_\mu}(E) \]
\[ N_{\bar{\nu}_\mu}(E) \]
\[ N_{\nu_e}(E) \]
\[ N_{\bar{\nu}_e}(E) \]

\[ Q_{\pi^+}(E) \]
\[ N_{\pi^+}(E) \]
\[ Q_{\mu_R^+}(E) \]
\[ N_{\mu_R^+}(E) \]
\[ Q_{\mu_L^+}(E) \]
\[ N_{\mu_L^+}(E) \]

\[ Q_{\pi^-}(E) \]
\[ N_{\pi^-}(E) \]
\[ Q_{\mu_R^-}(E) \]
\[ N_{\mu_R^-}(E) \]
\[ Q_{\mu_L^-}(E) \]
\[ N_{\mu_L^-}(E) \]

\[ Q_{\nu_\mu}(E) \quad \text{from } \mu^- \]
\[ Q_{\bar{\nu}_e}(E) \quad \text{from } \mu^- \]

**An example: Primaries**

TP 3: $\alpha=2$, $B=10^3$ G, $R=10^{9.6}$ km

- **Meson production described by**

  \[ Q_b(E_b) = \int \frac{dE_p}{E_p} N_p(E_p) \int d\varepsilon N_\gamma(\varepsilon) R_b(x, y) \]

  \[
  x = \frac{E_b}{E_p}, \quad y = \frac{(E_p\varepsilon)}{m_p}
  \]

  (summed over a number of interaction types)

  - Only product normalization enters in pion spectra as long as synchrotron or adiabatic cooling dominate

- **Maximal energy of primaries (e, p) by balancing energy loss and acceleration rate**

  \[
  t_{\text{acc}}^{-1} = \eta \frac{c^2 e B}{E}
  \]

- **Hillas condition often necessary, but not sufficient!**

Hümer, Maltoni, Winter, Yaguna, 2010
Maximal proton energy (⇒ UHECR) often constrained by proton synchrotron losses

Sources of UHECR in lower right corner of Hillas plot?

Hümmer, Maltoni, Winter, Yaguna, 2010
Secondary spectra ($\mu$, $\pi$, $K$) become loss-steepend above a critical energy.

$E_c = \sqrt{\frac{9\pi\epsilon_0 m^5 c^5}{\tau_0 e^4 B^2}}$

- $E_c$ depends on particle physics only ($m$, $\tau_0$, and $B$)
- Leads to characteristic flavor composition
- Any additional cooling processes mainly affecting the primaries will not affect the flavor composition
- Flavor ratios most robust prediction for sources?
- The only way to directly measure $B$?
Flavor composition at the source
Astrophysical neutrino sources produce certain flavor ratios of neutrinos ($\nu_e : \nu_\mu : \nu_\tau$):

- **Pion beam source** (1:2:0)
  Standard in generic models

- **Muon damped source** (0:1:0)
  at high E: Muons loose energy before they decay

- **Muon beam source** (1:1:0)
  Cooled muons pile up at lower energies (also: heavy flavor decays)

- **Neutron beam source** (1:0:0)
  Neutron decays from $p\gamma$
  (also possible: photo-dissociation of heavy nuclei)

> At the source: Use ratio $\nu_e / \nu_\mu$ (nus+antinus added)
However: flavor composition is energy dependent!

Muon beam $\Rightarrow$ muon damped

Energy window with large flux for classification

Undefined (mixed source)

Pion beam

Typically $n$ beam for low E (from $p\gamma$)

Pion beam $\Rightarrow$ muon damped

Behavior for small fluxes undefined

- All relevant regions recovered
- GRBs: in our model $\alpha=4$ to reproduce pion spectra; pion beam $\Rightarrow$ muon damped
  (confirms Kashti, Waxman, 2005)
- Some dependence on injection index

Hümmer, Maltoni, Winter, Yaguna, 2010
Neutrino propagation and detection
Neutrino propagation

- Key assumption: Incoherent propagation of neutrinos

- Flavor mixing:  \[ P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2 \]

- Example: For \( \theta_{13} = 0 \), \( \theta_{23} = \pi/4 \):

\[
\begin{pmatrix}
\nu_{e}^\text{source} \\
\nu_{\mu}^\text{source} \\
\nu_{\tau}^\text{source}
\end{pmatrix} = \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} \quad \rightarrow \quad \begin{pmatrix}
\nu_{e}^\text{Earth} \\
\nu_{\mu}^\text{Earth} \\
\nu_{\tau}^\text{Earth}
\end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}
\]

- NB: No CPV in flavor mixing only!
  But: In principle, sensitive to \( \text{Re} \exp(-i \delta) \sim \cos \delta \)
Neutrino detection: Muon tracks

- Number of events depends on neutrino effective area and observ. time $t_{\text{exp}}$:

$$N = \int dE \, \text{Exp}(E, \delta) \frac{dN(E)}{dE} = \int dE A_{\nu}^{\text{eff}}(E, \delta) \, t_{\text{exp}} \frac{dN(E)}{dE}$$

- Neutrino effective area $\sim$ detector area $\times$ muon range ($E$); but: cuts, uncontained events, ...

- Time-integrated point source search, IC-40 (arXiv:1012.2137)
- Differential limit $2.3 \frac{E}{(A_{\text{eff}} t_{\text{exp}})}$ illustrates what spectra the data limit best

\[ \delta = (60^\circ, 90^\circ) \text{ upgoing} \]

Atlantic IC-40 $\nu_\mu$

Auger 2004-2008 Earth skimming $\nu_\tau$

(Winter, arXiv:1103.4266)
Which point sources can specific data constrain best?

Constraints to energy flux density

\[
\phi = \int E \frac{dN(E)}{dE} dE
\]

(Winter, arXiv:1103.4266)
Measuring flavor?

- In principle, flavor information can be obtained from different event topologies:
  - Muon tracks - $\nu_\mu$
  - Cascades (showers) – CC: $\nu_e$, $\nu_\tau$, NC: all flavors
  - Glashow resonance (6.3 PeV): $\overline{\nu}_e$
  - Double bang/lollipop: $\nu_\tau$ (sep. tau track)
    (Learned, Pakvasa, 1995; Beacom et al, 2003)

- In practice, the first (?) IceCube „flavor“ analysis appeared recently – IC-22 cascades (arXiv:1101.1692)

Flavor contributions to cascades for $E^{-2}$ extragalactic test flux (after cuts):
  - Electron neutrinos 40%
  - Tau neutrinos 45%
  - Muon neutrinos 15%
  - Electron and tau neutrinos detected with comparable efficiencies
  - Neutral current showers are a moderate background
Flavor ratios at detector

- At the detector: define observables which
  - take into account the unknown flux normalization
  - take into account the detector properties

- Example: Muon tracks to showers
  Do not need to differentiate between electromagnetic and hadronic showers!

\[
\hat{R} = \frac{\phi^\mu_{\text{Det}}}{\phi^e_{\text{Det}} + \phi^\tau_{\text{Det}}}
\]

- Flavor ratios have recently been discussed for many particle physics applications

(for flavor mixing and decay: Beacom et al 2002+2003; Farzan and Smirnov, 2002; Kachelriess, Serpico, 2005; Bhattacharjee, Gupta, 2005; Serpico, 2006; Winter, 2006; Majumard and Ghosal, 2006; Rodejohann, 2006; Xing, 2006; Meloni, Ohlsson, 2006; Blum, Nir, Waxman, 2007; Majumar, 2007; Awasthi, Choubey, 2007; Hwang, Siyeon, 2007; Lipari, Lusignoli, Meloni, 2007; Pakvasa, Rodejohann, Weiler, 2007; Quigg, 2008; Maltoni, Winter, 2008; Donini, Yasuda, 2008; Choubey, Niro, Rodejohann, 2008; Xing, Zhou, 2008; Choubey, Rodejohann, 2009; Esmaili, Farzan, 2009; Bustamante, Gago, Pena-Garay, 2010; Mehta, Winter, 2011….)
Parameter uncertainties

- Basic dependence recovered after flavor mixing

- However: mixing parameter knowledge ~ 2015 (Daya Bay, T2K, etc) required

Hümmer, Maltoni, Winter, Yaguna, 2010
New physics in R?

\[
\hat{X}(E) = \frac{\Phi^0_e(E)}{\Phi^0_\mu(E)}
\]

\[
\hat{R} \equiv \frac{\Phi^\text{Det}_\mu}{\Phi^\text{Det}_e + \Phi^\text{Det}_\tau} = \frac{P_{e\mu}(E) \hat{X}(E) + P_{\mu\mu}(E)}{[P_{ee}(E) + P_{e\tau}(E)] \hat{X}(E) + [P_{\mu e}(E) + P_{\mu\tau}(E)]}
\]

\[
P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\beta i}|^2 |U_{\alpha i}|^2 D_i(E) \quad \text{with} \quad D_i(E) = \exp \left(-\frac{\hat{\alpha}_i L}{E} \right)
\]

(Example: [invisible] neutrino decay)

Mehta, Winter, JCAP 03 (2011) 041; see also Bhattacharya, Choubey, Gandhi, Watanabe, 2009/2010

1 Stable state

1 Unstable state
Glashow resonance?
Glashow resonance

... at source

- **pp**: Produce $\pi^+$ and $\pi^-$ in roughly equal ratio
- **pγ**: Produce mostly $\pi^+$
  - Glashow resonance (6.3 PeV, electron antineutrinos) as source discriminator?

Caveats:
- Multi-pion processes produce $\pi^-$
- If some optical thickness, $n\gamma$ "backreactions“ equilibrate $\pi^+$ and $\pi^-$
- Neutron decays fake $\pi^-$ contribution
  - May identify “pγ optically thin source“ with about 20% contamination from $\pi^-$, but cannot establish pp source!

Sec. 3.3 in Hümer, Maltoni, Winter, Yaguna, 2010; see also Xing, Zhou, 2011
Additional complications:

- Flavor mixing (electron antineutrinos from muon antineutrinos produced in $\mu^+$ decays)
- Have to know flavor composition (e.g. a muon damped pp source can be mixed up with a pion beam $p\gamma$ source)
- Have to hit a specific energy (6.3 PeV), which may depend on $\Gamma$ of the source

Sec. 4.3 in Hümmer, Maltoni, Winter, Yaguna, 2010
On GRB neutrino fluxes
Example: GRB stacking

- Idea: Use multi-messenger approach

  GRB gamma-ray observations (e.g. Fermi GBM, Swift, etc)

  Neutrino observations (e.g. IceCube, …)

  Coincidence!

- Predict neutrino flux from observed photon fluxes event by event

  Observed: broken power law (Band function)

(Source: NASA)

(Example: IceCube, arXiv:1101.1448)
Gamma-ray burst fireball model: IC-40 data meet generic bounds


Generic flux based on the assumption that GRBs are the sources of (highest energetic) cosmic rays

- Does IceCube really rule out the paradigm that GRBs are the sources of the ultra-high energy cosmic rays?

(see also Ahlers, Gonzales-Garcia, Halzen, 2011 for a fit to data)
Waxman-Bahcall, reproduced

- Reproduced original WB flux with similar assumptions
- Additional charged pion production channels included, also $\pi^-$!
Fluxes before/after flavor mixing

Re-analysis of fireball model

- Correction factors from:
  - Cosmological expansion (z)
  - Some crude estimates, e.g. for \( f_\pi \) (frac. of E going pion production)
  - Spectral corrections (compared to choosing the break energy)
  - Neutrinos from pions/muons

- Photohadronics and magnetic field effects change spectral shape

\[ \text{Baerwald, Hümmer, Winter, PRD83 (2011) 067303} \]

- Conclusion (preliminary): Fireball flux ~ factor of five lower than expected, with different shape

\[ \text{(Hümmer, Baerwald, Winter, in prep.)} \]
Systematics in aggregated fluxes

- IceCube: Signal from 117 bursts “stacked” (summed) for current limit (arXiv:1101.1448)
  - Is that sufficient?

- Some (preliminary) results:
  - $z \sim 1$ “typical” redshift of a GRB
    - Flux overestimated if $z \sim 2-3$ assumed (unless $z$ measured)
  - Peak contribution in a region of low statistics
    - Probability to be within 20% of the diffuse flux is (roughly)
      - 40% for 100 bursts
      - 50% for 300 bursts
      - 70% for 1000 bursts
      - 95% for 10000 bursts
    - Need $O(1000)$ bursts for reliable stacking limits!

(Baerwald, Hümmer, Winter, in prep.)
Summary

- Particle production, flavor, and magnetic field effects change the shape of astrophysical neutrino fluxes
  - Description of the „known“ (particle physics) components should be as accurate as possible for data analysis; e.g. GRBs

- Flavor ratios, though difficult to measure, are interesting because
  - they may be the only way to directly measure B (astrophysics)
  - they are useful for new physics searches (particle physics)
  - they are relatively robust with respect to the cooling and escape processes of the primaries (e, p, γ)

- The flux shape and flavor ratio of a point source can be predicted in a self-consistent way if the astrophysical parameters can be estimated, such as from a multi-messenger observation
  (R: from time variability, B: from energy equipartition, α: from spectral shape)

- Even for point sources searches experiments such as Auger are useful, since they (in principle) test the parameter region relevant for the UHECR in our model