Testing Neutrino Properties with Astrophysics and Cosmology

- High Energy Neutrinos: The connection to high energy cosmic and gamma-rays
- Testing Oscillation Parameters and Source Physics
- Testing Physics beyond the Standard Model: Cross Sections at PeV scales, Lorentz symmetry violation
- Neutrinos in Cosmology

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Supernova remnants have been seen by HESS in γ-rays: The remnant RXJ1713-3946 has a spectrum \( \sim E^{-2.2} \): \( \Rightarrow \) Charged particles have been accelerated to \( > 100 \) TeV. Also seen in 1-3 keV X-rays (contour lines from ASCA)

Aharonian et al., Nature 432 (2004) 75
Identifying galactic sources from their secondary gamma-ray signatures

Supernova remnant RXJ1713.7-3946 seen by HESS
Shell-type supernova remnant RCW 86 seen by HESS
Summary of neutrino production modes
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background.

\[ E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 4 \cdot 10^{19} \text{ eV} \]

\( \Rightarrow \) sources must be in cosmological backyard.

Only Lorentz symmetry breaking at \( \Gamma > 10^{11} \) could avoid this conclusion.
Secondary γ-rays and neutrinos mostly produced by pp interactions in this model.

Expected neutrino fluxes above TeV \(\sim 10^{-9} - 10^{-7} \text{ GeV cm}^{-2}\text{s}^{-1}\)

F. Aharonian et al., astro-ph/0508658
The universal photon spectrum

(log[Flux/(erg cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)]) vs log(E/eV))

- Radio
- CMB
- IR
- Visible
- UV
- X-rays
- \(\gamma\)-rays
- \(\gamma\)-wall

TeV
CERN/Fermilab
Cosmic-rays

(\(\gamma\) after Ressell & Turner ‘90)
The „grand unified“ neutrino energy flux spectrum

From the European ASPERA roadmap
The „grand unified“ differential neutrino number spectrum
Ultra-High Energy Cosmic Rays and the Connection to $\gamma$-ray and Neutrino Astrophysics

accelerated protons interact:
\[
p + \gamma \rightarrow X + \pi^\pm \rightarrow \text{neutrinos} \]
during propagation ("cosmogenic") or in sources (AGN, GRB, ...)

\[\Rightarrow \text{energy fluences in } \gamma \text{-rays and neutrinos are comparable due to isospin symmetry.}\]
Neutrino spectrum is unmodified, $\gamma$-rays pile up below pair production threshold on CMB at a few $10^{14}$ eV.

Universe acts as a calorimeter for total injected electromagnetic energy above the pair threshold.

\[\Rightarrow \text{neutrino flux constraints.}\]
Theoretical Limits, Sensitivities, and “Realistic” Fluxes: A Summary

Armengaud and Sigl
Current upper limits on diffuse neutrino fluxes

T. de Young for ICECUBE, arXiv:0910.3644
Limits and future Sensitivities to UHE neutrino fluxes

A. Haungs, arXiv:0811.2361
Centaurus A as a possible local UHECR source
Pierre Auger events from Centaurus A?

Moskalenko et al., arXiv:0805.1260

Rachen, arXiv:0808.0349
Centaurus A was recently seen by H.E.S.S.
Centaurus A as Multimessenger Source

\[ E^2 \text{ acceleration of protons around the core} \]

\[ E^2 \text{ acceleration of protons in the jet} \]

Kachelriess, Ostapchenko, Tomas, arXiv:0805.2608
Oscillation parameters, source physics, neutrino decay and decoherence
Collective effects in supernova neutrino oscillations
Neutrino-nucleon cross sections
Quantum Gravity effects
For $n$ neutrino flavors, eigenstates $| \nu_i \rangle$ of mass $m_i$ and interaction eigenstates $| \nu_\alpha \rangle$ are related by a unitary $n \times n$ matrix $U$:

$$
| \nu_\alpha \rangle = \sum_i U_{\alpha i} | \nu_i \rangle
$$

If at $t=0$ a flavor eigenstate $| \nu_\alpha \rangle = \sum_i U_{\alpha i} | \nu_i \rangle$ is produced in an interaction, in vacuum the time development will thus be

$$
| \nu(t) \rangle = \sum_i U_{\alpha i} e^{-iE_i t} | \nu_i \rangle = \sum_{i, \beta} U_{\alpha i} U_{\beta i}^* e^{-iE_i t} | \nu_\beta \rangle.
$$

This implies the following transition probabilities

$$
P (\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_i U_{\alpha i} U_{\beta i}^* e^{-iE_i t} \right|^2
$$

For flavors $\alpha$ injected with relative weights $w_\alpha$ at the source, the flux of flavor $\beta$ at the observer is then (averaged over the oscillations)

$$
\phi_\beta (E) \propto \sum_\alpha w_\alpha P (\nu_\alpha \rightarrow \nu_\beta) \approx \sum_{\alpha, i} w_\alpha |U_{\alpha i}|^2 |U_{\beta i}|^2.
$$
Examples for standard mixing parameters:

Sensitivity to source physics: When both pions and muons decay before loosing energy, then $w_e : w_\nu : w_\tau \simeq \frac{1}{3} : \frac{2}{3} : 0$ and thus $\phi_e : \phi_\mu : \phi_\tau \simeq \frac{1}{3} : \frac{1}{3} : \frac{1}{3}$

If pions but not muons decay before loosing energy then $w_e : w_\mu : w_\tau \simeq 0 : 1 : 0$

and thus $\phi_e : \phi_\mu : \phi_\tau \simeq \frac{1}{5} : \frac{2}{5} : \frac{2}{5}$

For unstable mass eigenstates introduce a factor $\exp\left[-(m_i/\tau_i)(t/E)\right]$.

In normal hierarchy if $\nu_2$ and $\nu_3$ decay completely, then $\phi_e : \phi_\mu : \phi_\tau \simeq \frac{3}{4} : \frac{1}{8} : \frac{1}{8}$

In inverted hierarchy if $\nu_1$ and $\nu_2$ decay completely, then $\phi_e : \phi_\mu : \phi_\tau \simeq 0 : \frac{1}{2} : \frac{1}{2}$

For quantum decoherence on scales smaller than $t$ one always has $\phi_e : \phi_\mu : \phi_\tau \simeq \frac{1}{3} : \frac{1}{3} : \frac{1}{3}$
Injection of pions of energy $\epsilon_{\pi}$ with spectrum $\propto \epsilon_{\pi}^{-2}$ with energy losses $\epsilon_{\pi} \propto \epsilon_{\pi}^{2}$. $\epsilon_{0,\mu}$ is the energy at which decay equals synchrotron loss.

Observed Muon to Non-Muon Ratios can be sensitive to oscillation parameters

For a source optically thick to muons but not to pions: Pions decay right away, but muons loose energy by synchro before decaying

Oscillation phase is 
\( \frac{L \Delta m^2}{4 E_n} \)
Numbers indicate \( \Delta m^2/eV^2 \).
Collective Neutrino Oscillations in Supernovae

In a supernova neutrino self-interactions contribute to the refractive indexWhich leads to interesting collective effects:

Most relevant are the (unknown) atmospheric hierarchy $\Delta m^2_{\text{atm}}$ and $\Theta_{13}$
Schematic example for the inverted hierarchy

\[ P_z = \frac{F(\nu_e) - F(\nu_x)}{F_0(\bar{\nu}_e) - F_0(\bar{\nu}_x)} \]

\[ \bar{P}_z = \frac{F(\bar{\nu}_e) - F(\bar{\nu}_x)}{F_0(\bar{\nu}_e) - F_0(\bar{\nu}_x)}. \]

for the initial flux hierarchy \( F_0(\nu_e) > F_0(\bar{\nu}_e) > F_0(\nu_x) = F_0(\bar{\nu}_x) \)
corresponding to initial energy hierarchy \( \langle \epsilon_0(\nu_e) \rangle > \langle \epsilon_0(\bar{\nu}_e) \rangle > \langle \epsilon_0(\nu_x) \rangle = \langle \epsilon_0(\bar{\nu}_x) \rangle \)
Note: In inverted hierarchy, bipolar oscillations occur for arbitrarily small $\Theta_{13}$. This can be used as experimental test by observing a supernova with mega-ton detectors that are mostly sensitive to electron-antineutrinos.
The spectral split is governed by lepton number conservation for both flavors separately:

Anti-neutrinos swap completely; to compensate, neutrinos can only swap partially because:

\[ |F(\nu_x) - F(\nu_e)| > |F(\bar{\nu}_x) - F(\bar{\nu}_e)| \]
\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

Following Dasgupta, Dighe, Mirizzi,, arXiv:0802.1481 relate fluxes \(F(\bar{\nu}_e)\) at detector to fluxes \(F_0(\bar{\nu}_e)\) at neutrino-sphere:

No swapping of \(\bar{\nu}_e\) and \(\bar{\nu}_\tau\)' if either normal hierarchy or inverted hierarchy with \(\sin^2 \theta_{13} \geq 10^{-3}\) (such that bipolar transition followed by adiabatic MSW):

\[
F(\bar{\nu}_e) \approx \cos^2 \theta_{12} F_0(\bar{\nu}_e) + \sin^2 \theta_{12} F_0(\bar{\nu}_\mu')
\]

Swapping of \(\bar{\nu}_e\) and \(\bar{\nu}_\tau\)' if inverted hierarchy with \(\sin^2 \theta_{13} \leq 10^{-5}\) (such that bipolar transition followed by non-adiabatic MSW) with \(F_0(\bar{\nu}_\tau') = F_0(\bar{\nu}_\mu')\):

\[
F(\bar{\nu}_e) \approx \cos^2 \theta_{12} F_0(\bar{\nu}_\tau') + \sin^2 \theta_{12} F_0(\bar{\nu}_\mu') = F_0(\bar{\nu}_\tau')
\]

For Earth matter effects \(\cos^2 \theta_{12} \rightarrow P(\bar{\nu}_\mu' \rightarrow \bar{\nu}_e)\)
Probes of Neutrino Interactions beyond the Standard Model

Note: For primary energies around $10^{20}$ eV:

- Center of mass energies for collisions with relic backgrounds
  ~100 MeV - 100 GeV → physics well understood
- Center of mass energies for collisions with nucleons in the atmosphere
  ~100 TeV - 1 PeV → probes physics beyond reach of accelerators

Example: microscopic black hole production in scenarios with a TeV string scale:

- For neutrino-nucleon scattering with $n=1,...,7$ extra dimensions,
  from top to bottom

This increase is not sufficient to explain the highest energy cosmic rays, but can be probed with deeply penetrating showers.

Feng, Shapere, PRL 88 (2002) 021303
However, the neutrino flux from pion-production of extra-galactic trans-GZK cosmic rays allows to put limits on the neutrino-nucleon cross section:

Comparison of this $N\gamma$- ("cosmogenic") flux with the non-observation of horizontal air showers results in the present upper limit about $10^3$ above the Standard Model cross section.

Future experiments will either close the window down to the Standard Model cross section, discover higher cross sections, or find sources beyond the cosmogenic flux. How to disentangle new sources and new cross sections?
Solution: Compare rates of different types of neutrino-induced showers

Deeply penetrating (horizontal)

Earth-skimming

Figure from Cusumano
Earth-skimming $\tau$-neutrinos

Air-shower probability per $\tau$-neutrino at $10^{20}$ eV for $10^{18}$ eV (1) and $10^{19}$ eV (2) threshold energy for space-based detection.

Comparison of earth-skimming and horizontal shower rates allows to measure the neutrino-nucleon cross section in the 100 TeV range.

Kusenko, Weiler, PRL 88 (2002) 121104
Probes of Quantum Gravity Effects with Neutrinos

Dispersion relation between energy $E$, momentum $p$, and mass $m$ may be modified by non-renormalizable effects at the Planck scale $M_{\text{Pl}}$, 

$$p^2 + m^2 = E^2 \left[ 1 - \sum_{n=1}^{\infty} \eta_n \left( \frac{E}{m_{\text{Pl}}} \right)^n \right]$$

where most models, e.g. critical string theory, predict $\eta=0$ for lowest order. For the $i$-th neutrino mass eigenstate this gives

$$p_i \approx E + \frac{m_i^2}{2E} + \frac{1}{2} \sum_{n=1}^{\infty} \eta_n^{(i)} \frac{E^{n+1}}{m_{\text{Pl}}}$$

The « standard » oscillation term becomes comparable to the new terms at energies

$$E \approx m_{\text{Pl}} \left( \frac{\Delta m^2}{m_{\text{Pl}}^2 \eta_n} \right)^{\frac{1}{n+2}} \approx 0.2 \cdot 2 \times 10^4, 1.8 \times 10^7, 1.7 \times 10^9 \text{ GeV}$$

for $n=1, 2, 3, 4$, respectively, and $\Delta m^2=10^{-3} \text{ eV}^2$, for which ordinary Oscillation length is $\sim 2.5(E/\text{MeV}) \text{ km}$.

Other possible effects: Decoherence of oscillation amplitude with exp(-αL):
Assume galactic neutron sources, L~10 kpc, giving exclusively electron-anti-neutrinos before oscillation. After oscillation the flavor ratio becomes 1:0:0 → 0.56:0.24:0.20 without decoherence, but 0.33:0.33:0.33 with decoherence.

At E~1 TeV one has a sensitivity of α~10^{-37} GeV (somewhat dependent on energy dependence of α)

Modification of GZK neutrino flux by Lorentz Invariance Variation

Example: If a neutrino with energy $E_{obs}$ is observed, the constraint

$$\eta_2 \leq \left( \frac{E_{obs}}{6 \times 10^{18} \text{ eV}} \right)^{-\frac{13}{4}}$$

results, otherwise neutrino would decay on short length scale.

Mattingly et al., arXiv:0911.0521
Cosmological Structure Formation and Neutrino Mass

The transfer function determines power spectrum at small (Mpc) scales

The fact that freely streaming neutrinos suppress the large scale galaxy power $\Delta P_m/P_m = -8\Omega_\nu/\Omega_m$ allows to put a (somewhat model dependent) limit on the sum of neutrino masses.

Future weak lensing surveys (cosmic shear) are expected to bring sensitivity down to the 0.05 eV level.

Hannestad, astro-ph/0602058
## Some Recent Cosmological Limits on Neutrino Masses

<table>
<thead>
<tr>
<th>Study</th>
<th>( \Sigma m_\nu / \text{eV} ) (limit 95%CL)</th>
<th>Data / Priors</th>
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<tbody>
<tr>
<td>Hannestad 2003</td>
<td>( 1.01 )</td>
<td>WMAP-1, CMB, 2dF, HST</td>
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<td>[astro-ph/0303076]</td>
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<td>Spergel et al. (WMAP) 2003</td>
<td>( 0.69 )</td>
<td>WMAP-1, 2dF, HST, ( \sigma_8 )</td>
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<td>Crotty et al. 2004</td>
<td>( 1.0 ) and ( 0.6 )</td>
<td>WMAP-1, CMB, 2dF, SDSS &amp; HST, SN</td>
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<td>[hep-ph/0402049]</td>
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<td>Hannestad 2004</td>
<td>( 0.65 )</td>
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<td>[hep-ph/0409108]</td>
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<td>WMAP-1, SDSS, Bias, Ly-( \alpha ) data from SDSS sample</td>
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*after G. Raffelt*
Conclusions

1.) Pion-production establishes a very important link between the physics of high energy cosmic rays on the one hand, and γ-ray and neutrino astrophysics on the other hand.

2.) There are many potential high energy neutrino sources including speculative ones. But the only guaranteed ones are due to pion production of primary cosmic rays known to exist: Galactic neutrinos from hadronic interactions up to $\sim 10^{16}$ eV and “cosmogenic” neutrinos around $10^{19}$ eV from photopion production. Good experimental prospects to detect them in near future.

3.) Flavor composition of ultra-high energy neutrinos can test the source physics as well as possibly physics beyond the Standard Model.

4.) Collective supernova neutrino oscillations probe the neutrino mass hierarchy.
5.) At energies above $\sim 10^{18}$ eV, the center-of-mass energies are above a TeV and thus beyond the reach of accelerator experiments. Especially in the neutrino sector, where Standard Model cross sections are small, this probes potentially new physics beyond the electroweak scale, including possible quantum gravity effects.

6.) Cosmological relic neutrinos are a very sensitive probe for the neutrino mass.