Bound on a flux of ultra-high energy neutrinos in a scenario with extra dimensions

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Plan of the talk

- Diffuse flux of cosmic neutrinos
- Neutrino events at the Pierre Auger Observatory (PAO)
- Scenario with flat extra dimensions
- Neutrino-nucleon scattering in the ADD model
- Bound on diffuse flux of ultra-high energy (UHE) neutrinos
- Expected number of neutrino events at the PAO
- Conclusions
Detection of signals from cosmic UHE neutrinos will allow:

- to discover cosmic rays (CR) point sources
- to define their position, in particular, to constrain the position of the GW sources
- to understand mechanisms of CR acceleration
- to give information on the nature of the primaries
- to define energy boundary between galactic and extragalactic parts of CR spectrum
- to measure cosmic neutrino flux, flavor ratio, and UHE neutrino-nucleon cross section
**Diffuse flux of cosmic neutrinos**

“Guaranteed” cosmogenic neutrino flux

\[ p + \gamma_{CMB} \rightarrow n + \pi^+ \]

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

\[ \mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e \]

**Flavor ratio:** \( \nu_e : \nu_\mu : \nu_\tau = 1:2:0 \)

**After oscillation:** \( \nu_e : \nu_\mu : \nu_\tau = 1:1:1 \)

**Benchmark WB bound on neutrino production in optically thin sources**

(single flavor, \( 10^{13} \text{ eV} < E_\nu < 10^{20} \text{ eV} \))

(Waxman & Bahcall, PRD 64 (2001) 023002)

\[ E_\nu^2 \frac{dN}{dE_\nu} = 2.33 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \]
Neutrino detector IceCube: first observation of astrophysical neutrinos in the range 6.3 TeV-980 TeV

(IceCube Collab., PRL 113 (2014) 101101)

IceCube diffuse neutrino flux
(single flavor, 25 TeV<E_\nu< 1.4 PeV) (1PeV = 10^{15} eV)

(IceCube Collab., PRD 91 (2015) 022001)

\[
\frac{dN}{dE_\nu} = 2.06 \times 10^{-18} (E_0/E_\nu)^\gamma \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}
\]

\[E_0 = 10^5 \text{GeV}, \quad \gamma = 2.46\]

(flux is consistent with the WB bound)
Surface Detector (SD) array: 1600 water-Cherenkov detectors spread over an area of 3000 km² (a bit larger than the country of Luxemburg)
Two types of UHE neutrino induced air showers at the Pierre Auger Observatory

Downward-going high zenith angle (DG) and up-going Earth-skimming (ES) neutrinos
Inclined showers (with zenith angle 75°-90°) are initiated by cosmic neutrinos, not by protons (nuclei)

Inclined shower induced by hadronic interactions high in the atmosphere (upper panel) and deep inclined shower (lower panel)

(PAO Collab. PRD 84 (2011) 122005)
Upper limit to the normalization of the diffuse flux of UHE neutrinos from the PAO (red line), along with fluxes in several cosmogenic models (with protons as primaries)

(\textit{PAO Collab., PRD 91 (2015) 092008})
Single-flavor limit to diffuse flux of UHE neutrinos from PAO
\((10^{17} \text{ eV} < E_\nu < 2.5 \cdot 10^{19} \text{ eV})\)

\((\text{PAO Collab., PRD 91 (2015) 092008})\)

\[ E_\nu^2 \frac{dN}{dE_\nu} < 6.4 \cdot 10^{-9} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]

IceCube diffuse neutrino flux if extrapolated to 1 EeV \((10^{18} \text{ eV})\)

\[ E_\nu^2 \frac{dN}{dE_\nu} = 0.3 \times 10^{-9} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]
The best-fit IceCube astrophysical all-flavor neutrino flux

(PDG, Chin. Phys. C, 40 (2016) 100001)
Mergers of black holes are potentially environment for accelerating CRs to ultra-high energies
UHECRs can interact with the surrounding matter or radiation to produce UHE gamma rays and neutrinos

\[ (Kotera \text{ and Silk, Astr. J. Lett. (2016) 823}) \]

\textbf{PAO: no neutrinos from the GW sources}

\[ (PAO \text{ Collab., PRD 94 (2016) 122007}) \]

Upper bound on the diffuse single-flavor flux integrated over population of GW sources

\[ (Kotera \text{ and Silk, Astr. J. Lett. (2016) 823}) \]

\[ E_\nu^2 \frac{dN}{dE_\nu} = (1.5 - 6.9) \times 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]
SM: $\sigma_{\nu N}$ is small and rises slowly with energy

The total CC cross sections for neutrinos (left figure) and antineutrinos (right figure)  
*(Cooper-Sarkar & Sarkar, JHEP 080 (2008) 075)*

Significant (dominating) contribution from “new physics” is expected at ultra-high neutrino energies
**Scenario with large flat extra dimensions (ADD model)**

(Arkani-Hamed, Dimopoulos and Dvali, Antoniadis, 1998)

Parameters of the model: number of extra dimensions \( n \) (\( D=4+n \)), D-dimensional gravity scale \( M_D \), compactification radius \( R_c \)

Hierarchy relation:

\[
M_{Pl}^2 = (2\pi R_c)^n M_D^n + 2
\]

Masses of KK gravitons:

\[
m_n = n/R_c
\]

Interaction Lagrangian on the brane:

\[
L(x) = -\frac{1}{M_{Pl}} \sum_{n=1}^{\infty} h^{(n)}(x) T^{\mu \nu}(x)
\]
Scattering of UHE neutrinos in ADD model

Transplanckian region

\[ E_V > 10^{17} \text{eV}, \sqrt{s} \gg M_D, -t \]

Sum of the ladder diagrams in the eikonal approximation. Wavy lines represent the exchange of \( D \)-dimensional gravitons

Scattering amplitude in the eikonal approximation

\[ A_{\text{eik}}(s, t) = -2i s \int_0^\infty dbb J_0(b\sqrt{-t}) \{1 - \exp[i\chi(s, b)]\} \]

\[ -t = q^2 \]
Eikonal scattering phase

\[ \chi(b) = \frac{1}{2s} \int \frac{d^2q}{(2\pi)^2} e^{iqb} A_{Bom}(q^2) \]

\[ \chi(b) = \left( \frac{b_c}{b} \right)^n \]

\[ b_c = \left( \frac{(4\pi)^{n/2-1}s \Gamma(n/2)}{2M_D^{n+2}} \right)^{1/n} \]

\( (Giudice, Rattazzi and Wells, Nucl. Phys. B 630 (2002) 293) \)

\[ q << b_c^{-1}, \quad \frac{d\sigma_{\text{eik}}}{dt} \sim \frac{\sigma_{\text{BH}}}{s} \left( \frac{s}{M_D^2} \right)^{(n+2)^2/n(n+1)} \]

\[ q >> b_c^{-1}, \quad \frac{d\sigma_{\text{eik}}}{dt} \sim \frac{\sigma_{\text{BH}}}{s} \left( \frac{s}{-t} \right)^{n+2/n+1} \]

Geometric black-hole cross section

\[ \sigma_{\text{BH}} = \pi R_S^2 \]

\[ R_S \sim \left( \frac{\sqrt{s}}{M_D^{n+2}} \right)^{1/(n+1)} \]
D-dimensional Planck scale:

\[ G_D = \frac{(2\pi)^{n-1} \hbar^{n+1}}{4c^{n-1}M_D^{n+2}} \]

Planck length:

\[ \lambda_{Pl} = \left( \frac{G_D \hbar}{c^3} \right)^{\frac{1}{n+2}} \]

Quantum gravity effects become important at distances below \( \lambda_{Pl} \)

In the limit \( \hbar \to 0 \), with \( G_D \) and \( \sqrt{s} \) fixed, \( M_D \) vanishes

Transplanckian regime corresponds to a classical limit (\( b > R_s \))

\[ \sqrt{s} \gg M_D, \quad R_s \gg \lambda_{Pl}, \quad \theta \sim (R_s / b)^{n+1} \]

\( b < R_s \) \quad black hole production

QUARKS-2018, Valday, Russia, June 1, 2018
BSM: $\sigma_{\nu N}$ rises more rapidly than in SM as neutrino energy grows

The total neutrino-nucleon cross sections for $n=2$ (left panel) and $n=6$ (right panel) with different values of the gravity scale $M_D$. 
Exposures of the SD of the Pierre Auger Observatory

Exposures of the SD array of the Pierre Auger Observatory for the period equivalent to 6.4 years of continuous operation as a function of the neutrino energy

\[ N_{ev} = \int \frac{dN}{dE_{\nu}} E( E_{\nu} ) dE_{\nu} \]

(PAO Collab., PRD 91 (2015) 092008)
DG neutrinos: enhanced interaction cross-section increases exposure:

\[ \mathcal{E}_{BSM}^{DG} = \mathcal{E}_{SM}^{DG} \frac{\sigma_{SM} + \sigma_{BSM}}{\sigma_{SM}} \]

ES neutrinos: enhanced interaction cross-section suppresses exposure:

\[ \mathcal{E}_{BSM}^{ES} = \mathcal{E}_{SM}^{ES} \left( \frac{\sigma_{CC}}{\sigma_{CC} + \sigma_{BSM}} \right)^2 \]

(Anchordoqui et al, PRD 82 (2010) 043001)
The exposures for the SD array of the PAO for the DG neutrino events with zenith angle $75^\circ < \theta < 90^\circ$ for different values of the gravity scale $M_D$. Left panel: $n=2$. Right panel: $n=6$. 
The exposures for the SD array of the PAO for the ES neutrino events for different values of the gravity scale $M_D$.
Left panel: $n=2$. Right panel: $n=6$. 

Exposures of the Earth-skimming neutrino events in the ADD model
The expected ratio of the ES events to the DG events (with zenith angle $75^\circ < \theta < 90^\circ$) at the SD array of the PAO as a function of $M_D$ and $n$. 

$\frac{N_{ev}(ES)}{N_{ev}(DG)} \approx 6$ (PAO Collab., 2015)
Bound on diffuse flux of UHE neutrinos

Diffuse neutrino flux:

\[ \frac{dN}{dE_\nu} = k E_\nu^{-2} \]

- number of observed events = 0
- number of expected background events = 0

Upper limit on signal events:

\[ N_{up} = 2.39 \]

Upper limit on k:

\[ k = \frac{N_{up}}{\int E(E_\nu) E_\nu^{-2} dE_\nu} \]

(PAO Collab., PRD 91 (2015) 092008)
The upper bound on the flux normalization $k$ in the ADD model as a function of $M_D$ at fixed values of $n$


\[
\frac{dN}{dE_{\nu}} = k \times E_{\nu}^{-2}
\]
The upper bound on the flux normalization $k$ in the ADD model as a function of $n$ at fixed values of $M_D$:

Expected number of events induced by UHE neutrinos with the Auger flux

Expected number of neutrino events at the SD of the PAO for a period equivalent of 2•6.4 years of PAO working continuously
Expected number of events induced by UHE neutrinos with the IceCube flux

Expected number of neutrino events at the SD of the PAO for a period equivalent of $2 \times 6.4$ years of PAO working continuously
Conclusions

- In the scenario with flat EDs, the upper limit on the diffuse UHE neutrino flux is calculated as a function of the number of extra dimensions $n$ and the D-dimensional Planck scale $M_D$.

- This limit turned out to be more stringent than the PAO upper limit for $M_D < 3 \text{ TeV} (2.4 \text{ TeV})$, if $n = 2$ (6), as well as for $M_D = 2.3 \text{ TeV}$, if $n \leq 3$ or $n \geq 6$.

- For large values of the gravity scale, $M_D \geq 4 \text{ TeV}$, our bound, on the contrary, exceeds the PAO bound for all $n$.

- The expected number of DG and ES neutrino events at the PAO is estimated both for the PAO bound and for the IceCube neutrino flux extrapolated to PAO energies (for $2 \cdot 6.4$ years of continuous operation).
Thank you for attention
Back-up slides
<table>
<thead>
<tr>
<th>Diffuse flux Neutrino model</th>
<th>Expected number of events (1 January 2004–20 June 2013)</th>
<th>Probability of observing 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmogenic—proton, FRII [33]</td>
<td>~4.0</td>
<td>~1.8 x 10^{-2}</td>
</tr>
<tr>
<td>Cosmogenic—proton, SFR [33]</td>
<td>~0.9</td>
<td>~0.4</td>
</tr>
<tr>
<td>Cosmogenic—proton, Fermi-LAT, $E_{\text{min}} = 10^{19}$ eV [34]</td>
<td>~3.2</td>
<td>~4 x 10^{-2}</td>
</tr>
<tr>
<td>Cosmogenic—proton, Fermi-LAT, $E_{\text{min}} = 10^{17.5}$ eV [34]</td>
<td>~1.6</td>
<td>~0.2</td>
</tr>
<tr>
<td>Cosmogenic—proton or mixed, SFR &amp; GRB [9]</td>
<td>~0.5–1.4</td>
<td>~0.6–0.2</td>
</tr>
<tr>
<td>Cosmogenic—iron, FRII [33]</td>
<td>~0.3</td>
<td>~0.7</td>
</tr>
<tr>
<td>Astrophysical $\nu$ (AGN) [35]</td>
<td>~7.2</td>
<td>~7 x 10^{-4}</td>
</tr>
<tr>
<td>Exotic [36]</td>
<td>~31.5</td>
<td>~2 x 10^{-14}</td>
</tr>
</tbody>
</table>

*(PAO Collab., PRD 91 (2015) 092008)*
Efficiencies of the SD array depends on: the neutrino energy $E_\nu$, the incident zenith angle $\theta$ and interaction depth in the atmosphere $D$ (DG events), or the altitude $h$ (ES events)

Once efficiencies are obtained, exposure involves:
SD array aperture and $\nu$ interaction probability at the depth $D$, energy $E_\nu$ and the search period $T$ (DG events)
SD array aperture, probability density function of tau emerging from the Earth with energy $E_\tau$, probability of tau decaying at the altitude $h$ and the search period $T$ (ES events)
The $s^2$ dependence of the graviton-exchange Born term renders the sum of exchanges dominant with respect to the inelastic diagrams (see third diagram on this figure)
Ordinary gauge theory: no classical limit

Different properties of spin-2 and spin-1 exchange – because energy itself plays the role of charge in gravity
The total neutrino-nucleon cross sections for $M_D = 2.3$ TeV (left panel) and $M_D = 4$ TeV (right panel) with two values of the number of extra dimensions $n$
Effective mass apertures $A_i$ for DG neutrinos of the PAO Surface Detector in units of $[g \, s \, sr]$ 

(*PAO Collab.*, **PRD** 84 (2011) 122005)

Exposure of the SD for DG neutrinos: 

$$E(E_\nu) = \sum_i \sigma_i(E_\nu) A_i(E_\nu)/m_N$$
Expected and observed 95% CL exclusion limits on $M_D$ in the ADD scenario for different values of $n$

*(CMS Collab., EPJC 78 (2018) 291)*
The 95% CL lower limits on minimum semiclassical black hole mass as a function of the Planck scale $M_D$, for several benchmark models

The 95% CL lower limits on minimum quantum black hole mass as a function of the Planck scale $M_D$, for several benchmark models (bound in the RS1 scenario is also shown)

Neutrino-nucleon charged-current cross section, averaged for neutrino and antineutrino, from different predictions

*(Bustamante and Connolly, arXiv:1711.11043)*
All-particle cosmic-ray energy spectrum
Energy spectrum derived from the Surface detector (SD) and hybrid data at the Pierre Auger Observatory (PAO)

(PAO Collab., ICRC, 2015)
Average depth of shower maxima as a function of energy

(PAO Collaboration, PRD 96(2017)122003)
Detection of air showers by the Surface Detector (SD) of the PAO
Lay out of the Telescope Array extension (TA× 4)