Physics of Neutrinos at Ultra High Energies

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“The UHE Universe: a vision for the next decade”
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1. Introduction

• Existing observatories for Ultra High Energy Cosmic $\nu$'s provide sensible upper bounds on flux

• Upcoming decade: progressively larger detectors for UHEC$\nu$'s

$\Rightarrow E \geq 10^{16}$ eV:

  $\rightarrow$ Astrophysics of cosmic rays

$\Rightarrow E \geq 10^{17}$ eV:

  $\rightarrow$ Particle physics beyond LHC

$\Rightarrow E \geq 10^{21}$ eV:

  $\rightarrow$ Cosmology: relics of phase transitions; absorption on big bang relic neutrinos

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Further content:

2. Sources and fluxes of UHEC neutrinos
3. Fundamental physics opportunities of UHEC neutrinos
4. Conclusions
2. Sources and fluxes of UHEC neutrinos

- Paradigm for **astrophysical** extragalactic source of protons and neutrinos: **shock acceleration**
  - \( p \)'s, confined by magnetic fields, accelerate through repeated scattering by plasma shock fronts
  - production of \( \pi \)'s and \( n \)'s through collisions of the trapped \( p \)'s with ambient plasma produces \( \gamma \)'s, \( \nu \)'s and CR's (\( n \) diffusion from source)
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  $\Rightarrow E_\nu \gtrsim 10^{20}$ eV (super-GZK) $\nu$’s:
  ← yet unknown acceleration sites
  ← other acceleration mechanism
  ← **decay of superheavy particles**

[Barbot, Drees '02]

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Top-down scenarios for super-GZK neutrinos

- Existence of superheavy particles with $10^{12} \text{ GeV} \lesssim m_X \lesssim 10^{16} \text{ GeV}$, produced during and after inflation through e.g.
  - decomposition of topological defects from late phase transitions into their constituents

[Ringeval, Sakellariadou, Bouchet '06]
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[Aloisio, Berezinsky, Kachelriess ’04]
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[Kolb, Chung, Riotto '98]
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  - particle creation in time-varying gravitational field
  \[ \Rightarrow \text{super-GZK } \nu \text{'s from decay or annihilation of superheavy dark matter (for } \tau_X \gtrsim \tau_U) \]

[Aloisio, Berezinsky, Kachelriess '04]

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Top-down scenarios for super-GZK neutrinos

- How generic?
  - **Topological defects**: generic prediction of symmetry breaking (SB) in GUT’s, and even fundamental string theory, e.g.
    * $G \rightarrow H \times U(1)$ SB: monopoles
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[Rajantie ‘03]
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\[ SO(10) \rightarrow ^1 4C \ 2_L \ 2_R \]

\[
\begin{cases}
1 & \rightarrow & 3C \ 2_L \ 2_R \ 1_{B-L} \\
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[Jeannerot,Rocher,Sakellariadou '03]
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[Berezinsky '05]
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  - **Superheavy dark matter:** need symmetry to prevent fast $X$ decay
    - gauge $\Rightarrow X$ stable
    - discrete $\Rightarrow$ stable or quasi-stable
3. Fundamental physics opportunities with UHEC neutrinos

- $C_{\nu}$'s with $E_\nu \gtrsim 10^8$ GeV probe $\nu N$ scattering at $\sqrt{s_{\nu N}} \gtrsim 14$ TeV (LHC)

- Perturbative Standard Model (SM) $\approx$ under control (← HERA)

  [Gandhi et al. '98; Kwiecinski et al. '98; ...]

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  - Kaluza-Klein, black hole, p-brane or string ball production in TeV-scale gravity models

\[ \text{[AR '03]} \]
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$[\text{Fodor,Katz,AR,Tu '03; Han,Hooper '03}]$
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TeV scale physics with UHEC neutrinos

\[ \frac{dN}{dt} \propto \int dE_\nu F_\nu(E_\nu) \sigma_{\nu N}(E_\nu) \]

\[ \Rightarrow \] Non-observation of deeply-penetrating particles, together with lower bound on \( F_\nu \) (e.g. cosmogenic \( \nu \)'s)

\[ \Rightarrow \] upper bound on \( \sigma_{\nu N} \)

[Berezinsky, Smirnov '74; Morris, AR '94; Tyler, Olinto, Sigl '01; ...]

Recent quantitative analysis:

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• Recent quantitative analysis:

  [Anchordoqui,Fodor,Katz,AR,Tu '04]

  ◦ Best current limits from exploitation of RICE search results

    [Kravchenko et al. [RICE] '02,03]

  ◦ Auger will improve these limits by one order of magnitude

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TeV scale physics with UHEC neutrinos

• Bounds exploiting searches for deeply-penetrating particles applicable as long as $\sigma_{\nu N} \lesssim (0.5 \div 1) \text{ mb}$

• For even higher cross sections, e.g. via sphaleron or brane production:

⇒ Strongly interacting neutrino scenario for the post-GZK events

[Berezinsky, Zatsepin '69]

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Quantitative analysis:

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- Very good fit to CR data
- Need steeply rising cross section, otherwise clash with nonobservation of deeply-penetrating particles

[Ahlers,A.R.,Tu ’05]
[AR ’03;Han,Hooper ’04] - - - sphalerons
[Anchordoqui,Feng,Goldberg ’02] - - - p-branes
[Burgett,Domokos,Kovesi-Domokos ’04] ...string excitations

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GUT scale physics with super-GZK neutrinos

- Strong impact of measurement for
  - particle physics
  - cosmology

[Fodor, Katz, AR, Weiler, Wong, in prep.]

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    * window on early phase transition
    * Hubble expansion rate $H(z)$
    * existence of the big bang relic neutrino background ($\nu_B$)

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[Adriano Ringwald, DESY]

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4. Conclusions

- Exciting times for ultrahigh energy cosmic rays and neutrinos:
  - many observatories under construction
  ⇒ appreciable event samples

- Expect strong impact on
  - astrophysics
  - particle physics
  - cosmology