The High Energy Universe: Observations and Implications

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1. Introduction

- There is a high energy universe:
  **Gamma rays** have been identified up to energies $E \lesssim \text{few} \times 10^3$ GeV
  - Cosmic rays have been observed up to energies $E \lesssim \text{few} \times 10^{11}$ GeV
- It is under active observation:
  - Gamma ray observatories: e.g. H.E.S.S., MAGIC
  - Air shower detectors: e.g. Pierre Auger Observatory
  - Neutrino telescopes: e.g. IceCube
- Attack fundamental questions:
  - What is it made of? What are the cosmic accelerators? Can we exploit them also for particle physics?

[M. Martinez ’05]
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[www.auger.org]
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Outline:

2. Observations at ultrahigh energies

3. Non-observations at ultrahigh energies

4. Future observations at ultrahigh energies

5. Conclusions
2. Observations at ultrahigh energies

- **Spectrum:** Large statistical and systematic uncertainties
  - low flux
  - energy from shower simulations

[Ahlers et al. ‘05]

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- Assume that CR’s in $10^{8.6,11}$ GeV range originate from isotropically distributed extragalactic proton sources, with simple power-law injection spectra $\propto E_i^{-\gamma}(1 + z)^n$

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  \[ \text{[Berezinsky...'02-'05;...; Ahlers et al. ‘05]} \]

$\Rightarrow$ Good fit; inelastic interactions with CMB ($e^+e^-$ “dip”; $\pi$ “bump”) visible; some post-GZK events?

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\[ \text{[Ahlers et al. ‘05]} \]

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[Ahlers PhD in prep.]
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**Hillas-plot**
(candidate sites for $E=100$ EeV and $E=1$ ZeV)

- Neutron star
- GRB
- Protons (100 EeV)
- Protons (1 ZeV)
- White dwarf
- SNR
- Galactic disk-halo
- Clusters
- Colliding galaxies

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• **Neutrinos as diagnostic tool:**
  - $\nu$'s from sources ($p\gamma \rightarrow n + \pi$'s) close to be measured
  - Cosmogenic neutrino flux (from $p\gamma_{\text{CMB}} \rightarrow N\pi$'s) dominates above $10^9$ GeV

[Ahlers et al. ‘05]
3. Non-observations at ultrahigh energies

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

[Graph showing $E^2 J(E)$ vs $E$ with various fluxes and limits marked.

[Ahlers et al. '05]
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- Perturbative Standard Model (SM) $\approx$ under control (← HERA)
  
  [Gandhi et al. '98; Kwiecinski et al. '98; ...]

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  - Electroweak sphaleron production ($B + L$ violating processes in SM)

![Graph showing the cross-section $\sigma_{\nu N}$ vs. $E_\nu$]
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  - Electroweak sphaleron production ($B + L$ violating processes in SM)
  - Kaluza-Klein, black hole, $p$-brane or string ball production in TeV scale gravity models
  - ... 

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“Model-independent” upper bounds on $\sigma_{\nu N}$

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

$\Rightarrow$ 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;..]

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

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- Recent quantitative analysis:
  - 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
    [Anchordoqui,Fodor,Katz,AR,Tu ’04]

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4. Future observations at ultrahigh energies

- Existing observatories for Extremely High Energy Cosmic neutrinos provide sensible upper bounds on flux

\[ E \geq 10^{16} \text{eV} \rightarrow \text{Astrophysics} \]
\[ E \geq 10^{17} \text{eV} \rightarrow \text{Particle physics beyond LHC} \]
\[ E \geq 10^{21} \text{eV} \rightarrow \text{Cosmology: relics of phase transitions; absorption on big bang relics} \]
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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.
  - particle creation in time-varying gravitational field

[Kolb, Chung, Riotto '98]
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- decomposition of topological defects, formed during preheating, into their constituents

[Tkachev,Khlebnikov,Kofman,Linde ‘98]
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  ⇒ super-GZK $\nu$'s from decay or annihilation of superheavy dark matter (for $\tau_X \gtrsim \tau_U$)
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[Ref. [Berezinsky, Kachelriess, Vilenkin '97]]
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  $\Rightarrow$ super-GZK $\nu$’s from topological defects

[Bhattacharjee,Hill,Schramm ’92]
Top-down scenarios for super-GZK neutrinos

• **Injection spectra**: fragmentation functions $D_i(x, \mu)$, $i = p, e, \gamma, \nu$, determined via
  – Monte Carlo generators

\[ [\text{Birkel, Sarkar '98}] \]
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[Fodor, Katz '01]
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\[ [\text{Aloisio, Berezinsky, Kachelriess '04}] \]
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  - for superheavy dark matter, injection nearby: $j_\nu \sim j_\gamma \sim j_p$

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- **Spectra at Earth**:
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  - for topological defects, injection far away: $j_\nu \gg j_\gamma \sim j_p$

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- **How natural?**
  - **Superheavy dark matter:** need symmetry to prevent fast $X$ decay
    - gauge $\Rightarrow X$ stable
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[Berezinsky '05]

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Top-down scenarios for super-GZK neutrinos

- Strong impact of measurement for
  - particle physics
  - cosmology

[Fodor, Katz, AR, Weiler, Wong, in prep.]
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[Barbot, Drees '02]
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[Fodor, Katz, AR, Weiler, Wong, in prep.]

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5. 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