The High Energy Universe:

Opportunities for Astrophysics, Particle Physics, and Cosmology

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1. Introduction

- There is a high energy universe: **Gamma rays** have been identified up to energies \( E \lesssim \text{few} \times 10^3 \text{ GeV} \)

- Cosmic rays have been observed up to energies \( E \lesssim \text{few} \times 10^{11} \text{ GeV} \)

- 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?
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Outline:

2. Observations at ultrahigh energies

3. Non-observations at ultrahigh energies

4. The future ...

5. Conclusions
2. Observations at ultrahigh energies

- **Spectrum:** Large statistical and systematic uncertainties

  ⇐ low flux

  ⇐ energy from shower simulations

![Graph showing energy spectrum](Ahlers et al. '05)
2. Observations at ultrahigh energies

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- Crucial improvement by **PAO**:
  - huge size ⇒ better statistics
  - hybrid observations ⇒ better energy calibration through Fly’s Eye technique, direction from ground array

[www.auger.org]
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[Ahlers *et al.* ‘05]
2. Observations at ultrahigh energies

- Angular distribution: $\approx$ isotrop

Cosmic rays above $\sim 10^{8.6}$ GeV, the "second knee", dominantly protons

Assume that CR's in $10^{8.6-11}$ GeV range originate from isotropically distributed extragalactic proton sources, with simple power-law injection spectra $\propto E^{-\gamma_i} (1 + z)^n$ [Berezinsky et al. '02-'05; ...; Ahlers et al. '05]

Good fit; inelastic interactions with CMB ($e^+ + e^-$ "dip"; $\pi$ "bump") visible; some post-GZK events [Greisen; Zatsepin, Kuzmin '67]

$^h$GC

AGASA
2. Observations at ultrahigh energies

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- **Composition:** Large uncertainty
  $\leftarrow$ studies rely on simulations
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[Berezinsky...'02-'05;...;Ahlers et al. '05]

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• Possible sources of these protons: GRB, AGN, . . .
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• **Shock acceleration:**
  – $p$’s, confined by magnetic fields, accelerate through repeated scattering by plasma shock fronts

\[ p \rightarrow \gamma, \nu, \pi, n (\text{diffusion from source}) \]

Neutrinos as diagnostic tool:
– $\nu$’s from sources ($p\gamma \rightarrow n + \pi$) close to be measured
– Cosmogenic neutrino flux (from $p\gamma \rightarrow N\pi$) dominates above $10^9$ GeV

\[
\begin{align*}
\rho &\rightarrow e^+ + e^- + \nu_{\mu} + \bar{\nu}_{\mu} \\
\pi^- &\rightarrow \mu^- + e^- + \nu_{\mu} + \bar{\nu}_{\mu}
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[Ahlers PhD in prep.]
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**Hillas-plot**

(candidate sites for $E=100$ EeV and $E=1$ ZeV)

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$E_{\text{max}}$ ZBL (Fermi)

$E_{\text{max}}$ ZBL* (Ultra-relativistic shocks-GRB)

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[Ahlers et al. ‘05]

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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)

$\approx$ under control (←HERA)

$\Rightarrow$ Search for enhancements in $\sigma_{\nu N}$ beyond (perturbative) SM:

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

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  [Tu '04]

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\[ \text{[Fodor,Katz,AR,Tu '03; Han,Hooper '03]} \]
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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; ..]

Recent quantitative analysis:
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  ◦ Best current limits from exploitation of RICE search results

  [Kravchenko et al. [RICE] ’02,03]

[www2.phys.canterbury.ac.nz/rice]

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  ◦ 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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Strongly interacting neutrino scenarios

- 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:

\[ \Rightarrow \text{Strongly interacting neutrino scenario for the post-GZK events} \]

[Berezinsky, Zatsepin '69]

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

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

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4. The future ...

- Existing observatories for Extremely High Energy Cosmic $\nu$'s

GLUE: Goldstone Lunar Ultra-high energy neutrino Experiment

[http://www.physics.ucla.edu/moonemp/public/]
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**GLUE:** Goldstone Lunar Ultra-high energy neutrino Experiment

![Diagram of cosmic ray event](image-url)

[Source: Gorham et al. '04]
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**FORTE:** Fast On-orbit Recording of Transient Events

[nis-www.lanl.gov/nis-projects/forte/]
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[Lehtinen et al. ‘04]

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**ANITA-LITE:**
Prototype of ANtarctic Impulsive Transient Antenna

[www.phys.hawaii.edu/anita/web/index.htm]
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[cosray2.wustl.edu/tiger/index.html]
4. The future ...

- Existing observatories for Extremely High Energy Cosmic $\nu$'s provide sensible upper bounds on flux.

![Graph showing energy vs. flux for different observatories.

$E^2 F_{eV m^{-2} s^{-1} sr^{-1}}$ vs. $E_{eV}$]

$E \geq 10^{16}$ eV: $\rightarrow$ Astrophysics of cosmic rays

$E \geq 10^{17}$ eV: $\rightarrow$ Particle physics beyond LHC

$E \geq 10^{21}$ eV: $\rightarrow$ Cosmology: relics of phase transitions; absorption on big bang relic neutrinos.
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- Upcoming decade: progressively larger detectors for EHEC$\nu$'s

ANITA:

[www.ps.uci.edu/anita/]

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WSRT: WeSterbork Radio Telescope

[Bacelar, ARENA Workshop ‘05]
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LOFAR:

[www.lofar.org]
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Top-down scenarios for EHEC 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

[Ref: 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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  $\Rightarrow$ EHEC $\nu$’s from decay or annihilation of superheavy dark matter (for $\tau_X \gtrsim \tau_U$)
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![Graph showing log$_{10}(E^3 I)$ vs log$_{10}(E/eV)$, with different curves for $I_{\nu}^{\text{halo}}$, $I_{\nu}^{\text{tot}}$, $I_{\gamma}^{\text{halo}}$, $I_{\nu}^{\text{extr}}$.](image)

[Berezinsky, Kachelriess, Vilenkin ’97]
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  $\Rightarrow$ EHEC $\nu$’s from topological defects

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

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

![Graph showing dN/dx vs. x for photons, neutrinos, electrons, and protons with $m_X = 10^{11}$ GeV](image)
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  - DGLAP evolution from experimental initial distributions at e.g. $\mu = m_Z$

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\[ [\text{Fodor,Katz '01}] \]
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$\Rightarrow$ Reliably predicted!

[Aloisio, Berezinsky, Kachelriess '04]

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

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[Aloisio, Berezinsky, Kachelriess '04]
Top-down scenarios for EHEC neutrinos

- How natural?
  - **Superheavy dark matter**: need symmetry to prevent fast $X$ decay
    - gauge $\Rightarrow$ $X$ stable
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    * $G \rightarrow H \times U(1)$ SB: monopoles
    * $U(1)$ SB: ordinary or superconducting strings

[Rajantie '03]
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    - $G \rightarrow H \times U(1) \rightarrow H \times Z_N$ SB: monopoles connected by strings
Top-down scenarios for EHEC neutrinos

- Strong impact of measurement for
  - Particle physics
  - Cosmology

[Figure showing the energy distribution of EHEC neutrinos with energy $E$ and flux $F$ in units of $E^2 F$ for different years (2005 and 2015).]

[Fodor, Katz, AR, Weiler, Wong, in prep.]
Top-down scenarios for EHEC neutrinos

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    * GUT parameters, e.g. $m_X$
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  - particle physics
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[Barbot, Drees '02]
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    * $\nu N$ scattering at $\sqrt{s} \gg$ LHC
  
  - **cosmology**

![Graph](Tu '04)
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    * Hubble expansion rate $H(z)$
    * existence of the big bang relic neutrino background ($C\nu B$)
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5. Conclusions

• Exciting times for extremely high energy cosmic rays and neutrinos:
  – many observatories under construction
  ⇒ appreciable event samples

• Expect strong impact on
  – astrophysics
  – particle physics
  – cosmology