Non-Acceleration Scenarios for Ultra-High Energy Cosmic Ray

Particle Acceleration in Astrophysical Objects

Krakow June 24-28 2003

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- Neutrinos: The Z-burst effect
- New interactions and new particles
- Lorentz invariance violations
- New physics ("top-down" scenario)

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New Particles and New Interactions

Motivated by possible correlations with high redshift objects:

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<thead>
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<tbody>
<tr>
<td>Farrar, Biermann</td>
<td>radio-loud quasars</td>
<td>~1%</td>
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<tr>
<td>Virmani et al.</td>
<td>radio-loud quasars</td>
<td>~0.1%</td>
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<tr>
<td>Tinyakov, Tkachev</td>
<td>BL-Lac objects</td>
<td>~10^-5</td>
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<tr>
<td>G.S. et al.</td>
<td>radio-loud quasars</td>
<td>~10%</td>
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If this is confirmed, one can only think of 3 possibilities:

1.) Neutrino primaries
   but Standard Model interaction probability in atmosphere is ~10^-5.
   → resonant (Z0) secondary production on massive relic neutrinos: needs extreme parameters and huge neutrino fluxes.
   → strong interactions above ~1TeV: only moderate neutrino fluxes required.

2.) New heavy neutral (SUSY) hadron X_0: m(X_0) > m_N increases GZK threshold.
   but basically ruled out by constraints from accelerator experiments.

3.) New weakly interacting light (keV-MeV) neutral particle
   electromagnetic coupling small enough to avoid GZK effect; hadronic coupling large enough to allow normal air showers: very tough to do.

In all cases: more potential sources, BUT charged primary to be accelerated to even higher energies.
Standard Model neutrino-nucleon cross section

\[ \sigma(\nu N) \ [\text{cm}^2] \]

- \( \nu N \) total, CTEQ4–DIS
- \( \nu N \) CC
- \( \nu N \) NC

\[ E_\nu \ [\text{GeV}] \]
The Z-burst effect

A Z-boson is produced at the neutrino resonance energy

\[ E_{\nu}^{\text{res}} = 4 \cdot 10^{21} \text{ eV} \left( \frac{\text{eV}}{m_{\nu}} \right) \]

“Visible” decay products have energies 10-40 times smaller.

Main problems of this scenario:
* sources have to accelerate up to \(~10^{23}\text{eV}\).
* \(\gamma\)-rays emitted from the sources and produced by neutrinos during propagation tend to over-produce diffuse background in GeV regime.

Fargion, Weiler, Yoshida
The Z-burst mechanism: Sources emitting neutrinos and $\gamma$-rays: Overproduction of GeV $\gamma$-rays

Sources with constant comoving luminosity density up to $z=3$, with $E^2$ $\gamma$-ray injection up to 100 TeV of energy fluence equal to neutrinos, $m_\nu = 0.5$eV, $B = 10^{-9}$ G.
Sources with comoving luminosity proportional to \((1+z)^m\) up to \(z=3\), \(m_\nu=0.5\,\text{eV}\), \(B=10^{-9}\,\text{G}\).
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?
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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

Effective aperture for $\tau$-leptons. Tau-flux $\sim 8.5 \times 10^{-4} \times \tau$-neutrino flux independent of $\sigma_{\nu N}$ for ground-based detectors.

Feng et al., PRL 88 (2002) 161102
Sensitivities of LHC and the Pierre Auger project to microscopic black hole production in neutrino-nucleon scattering

\[ M_D \] = fundamental gravity scale; \[ M_{\text{bh}}^{\text{min}} \] = minimal black hole mass

LHC much more sensitive than Auger, but Auger could “scoop” LHC

Ringwald, Tu, PLB 525 (2002) 135
Lorentz symmetry violations

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

$$E^2 - p^2 \approx m^2 - \xi \frac{p^3}{M_{\text{pl}}} - \zeta \frac{p^4}{M_{\text{pl}}^2} + \ldots,$$

Introducing the standard threshold momentum for pion production, $N + \gamma \rightarrow N\pi$,

$$p_0 = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon},$$

the threshold momentum $p_{\text{th}}$ in the modified theory is given by

$$- \frac{p_0^3}{(m_\pi^2 + 2m_\pi m_N)M_{\text{pl}}} \frac{m_\pi m_N}{(m_\pi + m_N)^2} \left[ 2\xi \left( \frac{p_{\text{th}}}{p_0} \right)^3 + 3\zeta \frac{p_0}{M_{\text{pl}}} \left( \frac{p_{\text{th}}}{p_0} \right)^4 + \ldots \right] + \frac{p_{\text{th}}}{p_0} = 1$$

assuming standard energy-momentum conservation (not necessarily the case).

Idea: For $\xi \sim \zeta \sim 1$ this equation has no solution $\Rightarrow$ No GZK threshold!

Alternative: Top-Down Scenario

Decay of early Universe relics of masses \( \geq 10^{12} \text{ GeV} \)

Benchmark estimate of required decay rate:

\[
\frac{j(E)}{\text{measured flux}} \approx \frac{1}{4\pi} \frac{l(E)}{\text{mean free path}} \frac{dN}{dE} \text{ decay rate} \ rac{\dot{n}_X}{\dot{n}_X} \ rac{dN}{dE} \text{ decay spectrum} ; \text{ now assume } \frac{dN}{dE} \approx \frac{1}{m_X} \left( \frac{E}{m_X} \right)^{-\alpha}
\]

\[
\Rightarrow \dot{n}_X \approx 13 \text{AU}^{-3} \text{yr}^{-1} \left( \frac{E^2 j(E)}{\text{eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}} \right) \left[ \frac{10 \text{Mpc}}{l(E)} \right] \left( \frac{E}{10^{16} \text{GeV}} \right)^{\alpha - 1.5} \left( \frac{m_X}{10^{16} \text{GeV}} \right)^{1 - \alpha}
\]

with \( m_X \) the \( X \)-particle mass.

This is not a big number!

Problem of Energetics is trivially solved!
Two types of Top-Down scenarios

1.) long-lived massive free particles ("WIMPZILLA" dark matter)

\[ \Omega_X \approx 10^{-12} \left( \frac{t_X}{10^{10} \text{ yr}} \right) \]

→ Fine tuning problem of normalizing \( \Omega_X/t_X \) to observed flux.
→ predicted \( \gamma \)-ray domination probably inconsistent with data.

2.) particles released from topological defects

scaling \( \Rightarrow \) \( \rho_{\text{defect}} \propto \rho_{\text{critical}} \propto t^{-2} \)

→ Fine tuning problem of normalizing \( \dot{\rho}_X = f \dot{\rho}_{\text{defect}} \propto t^{-3} \) to observed flux.

But for cosmic strings (or necklaces) the Higgs-Kibble mechanism yields

\[ \rho_{\text{string}} \approx v^2 t^{-2}, \text{ with } v = \text{symmetry breaking scale} \]

normalization \( \Rightarrow \sqrt{f} v \approx 10^{13} - 10^{14} \text{ GeV} \)

→ Fine tuning problem only by few orders of magnitude if \( f \approx O(1) \)
→ Absorption in radio background can lead to nucleon domination.
Topological defects are unavoidable products of phase transitions associated with symmetry change

Examples:

1.) Iron:

\[ T > T_{\text{Curie}} : G = SO(3) \]
\[ T < T_{\text{Curie}} : H = SO(2) \]

2.) breaking of gauge symmetries in the early Universe
~1 defect per causal horizon (Higgs-Kibble mechanism)
in Grand Unified Theories (GUTs) this implies magnetic monopole production which would overclose the Universe.
This was one of the motivations that INFLATION was invented.

=> particle and/or defect creation must occur during reheating after inflation.
Microwave background anisotropies implies scale \( H_{\text{inflation}} \approx 10^{13} \text{ GeV} \).

=> natural scale for relics to explain ultra-high energy cosmic rays!
Flux calculations in Top-Down scenarios

a) Assume mode of $X$-particle decay in GUTs

Example: $X \rightarrow l + q + q$ hadronic jets

b) Determine hadronic quark fragmentation spectrum extrapolated from accelerator data within QCD:

modified leading log approximation (Dokshitzer et al.) with and without supersymmetry versus older approximations (Hill). More detailed calculations by Kachelriess, Berezinsky, Toldra, Sarkar, Barbot, Drees: results not drastically different.

Fold in meson decay spectra into neutrinos and $\gamma$-rays to obtain injection spectra for nucleons, neutrinos, and

c) fold in injection history and solve the transport equations for propagation
Schematic MSSM "jet" for an initial squark with a virtuality $Q \sim M_X$. The full circles indicate decays of massive particles, in distinction to fragmentation vertices. The two vertical dashed lines separate different epochs of the evolution of the cascade: at virtuality $Q > m_{\text{SUSY}}$, all MSSM particles can be produced in fragmentation processes. Particles with mass of order $m_{\text{SUSY}}$ decay at the first vertical line. For $m_{\text{SUSY}} < Q < 1 \text{ GeV}$ light QCD degrees of freedom still contribute to the perturbative evolution of the cascade. At the second vertical line, all partons hadronize, and unstable hadrons and leptons decay.

(from M. Drees, e-print hep-ph/0210142)
At the highest energies fluxes in increasing order are: nucleons, \( \gamma \)-rays, neutrinos, neutralinos.
A typical example:

\[ j(E) \sim E^2 \text{[eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] \]

\[ X \rightarrow q + q, \ m_X = 2 \times 10^{14} \text{GeV}, B = 10^{-12} \text{G}, \]

homogeneous sources with \( \dot{\rho}_X \propto t^{-3} \)
Another example only involving neutrino primaries

\[ X \rightarrow \nu + \bar{\nu}, \quad m_X = 10^{14} \text{GeV}, \]

\[ m_{\nu_e} = 0.1 \text{eV}, \quad m_{\nu_\mu} = m_{\nu_\tau} = 1 \text{eV}, \] relic neutrinos of overdensity 50 within 5 Mpc of Earth,

\[ B = 10^{-10} \text{G}, \] homogeneous source distribution with \( \dot{\rho}_X \propto t^{-3} \)
Conclusions

1.) The origin of very high energy cosmic rays is one of the fundamental unsolved questions of astroparticle physics.

2.) The only mechanism involving non-hadronic and non-electromagnetic particles within the Standard Model uses the neutrino as messenger. Unfortunately, this “Z-burst effect” suffers in general from overproduction of $\gamma$-rays in the GeV range.

3.) 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.

4.) Alternatively, the highest energy particles could be linked to decaying relics of the early universe. These “top-down” models can explain only the flux above a few $10^{19}$ eV and predicts a significant $\gamma$-ray and neutrino component.

5.) The coming 3-5 years promise an about 100-fold increase of ultra-high energy data due to experiments that are under either construction or in the proposal stage. This will sort out many of the proposed theoretical scenarios.