ULTRAHIGH-ENERGY
COSMIC RAYS
AND
NEW PHYSICS

Jonathan Feng

University of California, Irvine

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Discoveries are made at frontiers.

In particle physics, there are always two frontiers:

- high energy
- high precision

The current frontier: weak scale physics

What do we expect there?

- Supersymmetry
- Strong EW symmetry breaking
- Extra dimensions
- Dark matter
- The unexpected
Hadron Colliders

Livingston plot
Lepton Colliders

Livingston plot
The high energy frontier:

\[ E \sim 10^{19} \text{ eV} \Rightarrow \sqrt{s} = \sqrt{2m_N E} \sim 100 \text{ TeV} \]
THE PLAN

I. The GZK Paradox
   Experiments
   Data
   Solutions

II. UHE $\nu$ Astrophysics
   Fluxes
   Interactions
   Earth-skimming Neutrinos
EXPERIMENTS

Many diverse approaches (in contrast to the collider frontier):

Ground arrays
AGASA, Auger

Fluorescence Detectors (Ground-based)
HiRes, Auger, Telescope Array

Fluorescence Detectors (Space-based)
EUSO, OWL

Neutrino Telescopes (Under-ice)
AMANDA, IceCube

Neutrino Telescopes (Underwater)
ANTARES, NESTOR, NEMO

Radio/Cherenkov
GLUE, RICE, ANITA, SALSA, nuTel

Acoustic
SADCO
UHE cosmic rays $\Rightarrow$ giant air showers:

- initiated at $h \approx 10$ km
- $6 \text{ km}^2$ cross section at Earth’s surface

Main detection techniques at present:

Ground arrays (e.g., AGASA)
- Run at all times
- Detect only shower endpoint

Flourescence detectors (e.g., HiRes)
- Run only on cloudless, moonless nights
- Detect full longitudinal development of shower
Shower picture
AGASA
Auger Observatory  
(Southern site)

Contour of site (3000 km-sq)  
In red: engineering array  
Circles: average range of the fluorescence det.  
Dots: the 1600 detector stations (tanks)
The GZK Paradox

Greisen (1966)
Zatsepin-Kuz’mín (1966)

Extreme energy protons lose energy through

$$p\gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow N\pi$$

Similar behaviors for other particles:
- nuclei photo-dissociate
- $\gamma\gamma_{\text{CMB}} \rightarrow e^+e^-$

No local sources $\Rightarrow E_{\text{cutoff}} \sim 10^{20}$ eV
The ultrahigh-energy AGASA data
The ultrahigh-energy HiRes data

\[ \chi^2/DOF = 40.5/32 \]
\[ XG \text{ Norm} = 2.7(9) \]
\[ XG \gamma = 2.47(9) \]
\[ G \text{ Norm} = 2.2(4) \]
\[ G \gamma = 3 \]
Other UHE data: Fly’s Eye, Yakutsk, Haverah Park

All in all, there is

- Disagreement on flux
- Some evidence for GZK cutoff
- But also excess of super-GZK events

Top-down

Superheavy particles decay.

For example, meta-stable topological defects

\[ \text{TD} \rightarrow \text{hadrons} (\dagger \text{ neutrinos, typically}) \]

Source disappears after decay.
Bottom-up

Requires accelerating source and a mechanism for transporting the energy to our local neighborhood.

For example, $Z$-bursts

Weiler (1997)
Fargion, Mele, Salis (1997)

$$\bar{\nu}_{\text{CNB}} \rightarrow Z \rightarrow 30 \text{ secondaries}$$

$$E_{\text{sh}} \sim \frac{1}{30} \frac{m_Z^2}{2m_\nu} = 1.4 \times 10^{20} \text{ eV} \left[ \frac{\text{eV}}{m_\nu} \right]$$
Prospects for Resolution

Pierre Auger Observatory (2004)

Hybrid detector:

- 3000 km² ground array
- 4 fluorescence detectors

should see $\sim 1000$ events with $E \gtrsim 10^{19.5}$ eV

Energy resolution: $\sim 10\%$

Angular resolution: $\sim 1^\circ$

Will probe GZK feature, clustering, chemical composition, ...
UHE $\nu$ probe dense astrophysical sources, propagate to the Earth unhindered.

**Fluxes**

GZK is a ‘guaranteed’ source:

$$p\gamma_{\text{CMB}} \rightarrow n\pi^{+} \rightarrow pe^{-}\bar{\nu}_{e} + e^{+}\nu_{e}\bar{\nu}_{\mu} + \nu_{\mu}$$

![Graph showing the flux distribution with energy and differential flux on the y-axis and energy on the x-axis.](image)

Stecker (1979)
Hill, Schramm (1985)
Protheroe, Johnson (1996)
Engel, Seckel, Stanev (2001)
The GZK paradox also motivates many new $\nu$ possibilities. For example,

- $\text{TD} \rightarrow \nu$
- $Z$-bursts requires $\nu$ primaries

\[
\begin{align*}
\pi \text{ photoproduction} & \\
Z \text{ bursts} & \\
\text{Topological defects} & \\
\text{AGN} & 
\end{align*}
\]
Interactions

SM $\nu$ interactions are very weak

For $E_\nu \gtrsim 10^8$ GeV:

- No upgoing $\nu$s
- Quasi-horizontal atmospheric showers
  $\sim 0.1 - 1$ event/year at Auger

Capelle, Cronin, Parente, Zas (1998)
Diaz, Shellard, Amaral (2001)
$\nu s \Rightarrow$ deep quasi-horizontal showers.

Far inclined showers (thousands per year)
- Flat and thin shower front
- Narrow signals
- Time alignment

Deep inclined showers (~few per year?)
- Curved and thick shower front
- Broad signals

FIG. 6. Schematic representation of a UHE air shower, and of its placement with respect to the ground and the Auger array. A “far inclined” shower is likely to be due to a hadronic cosmic ray, whereas a “deep inclined” shower can only be caused by a neutrino.

Coutu, Bertou, Billoir (1999)
New Physics

New interactions may greatly enhance $\nu$ interactions.

An example: Extra dimensions

The gauge hierarchy problem may be phased as

Why is $m_e \ll M_{Pl}$?

Why is $F_{EM} = \frac{e^2}{r^2} \gg G_N \frac{m_e^2}{r^2} = \frac{m_e^2}{M_{Pl}^2 r^2} = F_{gravity}$?

Why is gravity so weak?

Perhaps gravity and EM have same intrinsic strength, but gravity is diluted by propagating in extra dimensions.
For example, for 5 spacetime dimensions,

\[ F \sim \begin{cases} \frac{m_1 m_2}{M_5^3 r^3}, & r \ll L \\ G_N \frac{m_1 m_2}{r^2}, & r \gg L \end{cases} \]

Matching at \( r \sim L \) \( \Rightarrow \)

\[ M_5^3 L \approx (10^{19} \text{ GeV})^2 \]

\( L \) big in Planck units \( \Rightarrow M_5 \ll 10^{19} \text{ GeV} \).

Then the graviton has Kaluza-Klein partners of small mass \( \sim 1/L \).

These mediate \( \nu N \rightarrow \nu X \) through \( t \)-channel graviton exchange. These effects are important for UHE neutrinos.
Neutrino cross sections enhanced by extra dimension effects.

Alvarez-Muniz, Halzen, Han, Hooper (2001)

Nussinov, Shrock (1998)
Jain, McKay, Panda, Ralston (2000)
Tyler, Olinto, Sigl (2000)
Neutrino searches

Hadronic showers are those initiated by hadrons
EM showers are initiated by $e$ or $\gamma$

At AGASA: $\mathcal{E}_{\text{had}} > \mathcal{E}_{\text{EM}}$
At Fly’s Eye: $\mathcal{E}_{\text{had}} \approx \mathcal{E}_{\text{EM}}$

Total exposures for hadronic showers at AGASA (solid),
EM showers at AGASA (dashed), and all showers at
Fly’s Eye (dotted).

No neutrinos detected so far.
Neutrino flux limits

Model-independent (squares) and model-dependent (solid lines) upper limits on the total neutrino flux $E_\nu d\Phi_\nu / dE_\nu$ from AGASA and Fly’s Eye. Also shown are bounds from GLUE (circles), RICE (dashed), and the GZK flux (dash-dotted), and the Z-burst prediction.

Anchordoqui, Feng, Goldberg, Shapere (2002)
Neutrino interaction limits

Model-independent upper limits on $\sigma_{\nu N}$ for inelasticity $y = 1$ (filled squares) and $y = 0.1$ (open squares). Also shown is a maximal BH cross section, and the SM cross sections.

Anchordoqui, Feng, Goldberg, Shapere (2002)
EARTH-SKIMMING NEUTRINOS

The atmosphere is a poor $\nu$ detector. Exploit Earth as large volume converter:

$\nu_\ell \rightarrow \ell$ in the Earth, $\ell$ detected in the Earth.

Previously, $\pi \rightarrow \nu_\ell \Rightarrow$ two possibilities:

$\ell = \mu$: standard “up-going” $\nu$ signal. Detection in neutrino telescopes (AMANDA, IceCube, ANTARES, etc.)

$\ell = e$: Cascades generate radio waves through the Askaryan effect. Detection for $\nu$s passing through Earth and moon.

Zas, Halzen, Stanev (1991)
Gorham, Saltzberg et al. (2001)
After 1998: \( \ell = \tau \) is equally likely.

Athar (2000)

\( \nu \to \ell \) in the Earth, \( \ell \) escapes, is detected in Earth’s atmosphere.

Bjorken
Fargion
Domokos, Kovesi-Domokos
Bertou, Billoir, Deligny, Lachaud, Letessier-Selvon (2001)
Feng, Fisher, Wilczek, Yu (2001)
Kusenko, Weiler (2001)

Exploits

- Earth as large volume converter
- Atmosphere as large volume detector
- \( \tau \) lifetime \( \Rightarrow \) \( \tau \) travels \( \sim 10 \) km, just right!
Optimal angle

\[ \theta_{\text{opt}} : \int_{0}^{2R_{\oplus}} \cos \theta_{\text{opt}} \frac{dz'}{L_{CC}'(E_{\nu}, \theta_{\text{opt}}, z')} \equiv 1 \]

\( \theta < \theta_{\text{opt}}: \nu \) shadowed
\( \theta > \theta_{\text{opt}}: \nu \) rarely converts

Neutrinos must be within \( \sim 3^\circ \) of horizontal.
Decay length is

\[ \lambda_\tau = c T_\tau \frac{E_\tau}{m_\tau} \approx 49 \text{ km} \frac{E_\tau}{10^9 \text{ GeV}} \]

Taus lose energy through bremsstrahlung, pair production, photonuclear interactions.

\[ E_\tau \rightarrow 0.1 E_\tau \text{ in 11 km.} \]

Dutta, Reno, Sarcevic, Seckel (2000)

So taus travel \( \sim 10 \) km in Earth, but decay not far from surface.
Apertures

Effective apertures at Fly’s Eye (dotted), HiRes (solid), and Telescope Array (dashed).

Apertures rise with energy until time dilation causes decay to be too high for detection (curvature of Earth).

Aperture and flux peaks coincide.

Result: $\mathcal{O}(1)$ event/year at Auger for ‘guaranteed’ flux.
Measuring $\sigma(\nu N \rightarrow \ell X)$

Rates for quasi-horizontal showers (horizontal air showers, HAS) and Earth-skimming showers (upward air showers, UAS) as functions of $\sigma$.

Kusenko, Weiler (2001)
CONCLUSIONS

Many interesting issues in UHE Cosmic rays:

- An outstanding problem

  GZK paradox is still puzzling

- The continuation of a rich research program

  The dawn of UHE \( \nu \) astrophysics

- Potential for fundamental breakthroughs at Nature’s collider

  The energy frontier: \( \sqrt{s} \gtrsim 100 \text{ TeV} \)

  Construction cost: $0

  Operating budget: $0/yr

Only good ideas required!