Ultra-High Energy Cosmic Radiation

and what it teaches us about astro- and fundamental physics

- General facts and the experimental situation
- Acceleration ("bottom-up" scenario)
- Cosmic magnetic fields and their role in cosmic ray physics
- The connection with gamma rays and neutrinos
- New interactions and new particles

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http://www2.iap.fr/users/sigl/homepage.html
Further reading:
short review: Science 291 (2001) 73
The cosmic ray spectrum stretches over some 12 orders of magnitude in energy and some 30 orders of magnitude in differential flux: many Joules in one particle!
The structure of the spectrum and scenarios of its origin

- Supernova remnants
- Wind supernovae
- AGN, top-down ??

**Graphical Representation**

- Energy per nucleus $E$ (GeV)
- Intensity $I(E) \times E^{2.5}$ (m$^2$ sr GeV$^{-1.5}$)

- Peaks at $\gamma = 2.7$
- Knee region
- Ankle region
- Tevatron
- LHC
- KASCADE - Grande

- Legend for particles: p (proton), Fe (iron)
Atmospheric Showers and their Detection

Fly's Eye technique measures fluorescence emission. The shower maximum is given by

$$X_{\text{max}} \sim X_0 + X_1 \log E_p$$

where $X_0$ depends on primary type for given energy $E_p$.

Ground array measures lateral distribution. Primary energy proportional to density 600m from shower core.
Lowering the AGASA energy scale by about 20% brings it in accordance with HiRes up to the GZK cut-off, but not beyond.

May need an experiment combining ground array with fluorescence such as the Auger project to resolve this issue.
The southern Auger site is under construction.

Contour of site (3000 km-sq)
In red: engineering array
Circles: average range of the fluorescence det.
Dots: the 1600 detector stations (tanks)
EUSO concept: Detecting air showers from space.
Next-Generation Ultra-High Energy Cosmic Ray Experiments

Exposure after EUSO (in AGASA units)

- AGASA
- HiRes
- Auger (N+S)
- EUSO

Year:
- 1990
- 1992
- 1994
- 1996
- 1998
- 2000
- 2002
- 2004
- 2006
- 2008
- 2010
- 2012
- 2014

Exposure:
- 1
- 10
- 100
- 1000
- 10000
- 100000
- 1000000

After Auger

- 2010
- 2015
- 2020
The Ultra-High Energy Cosmic Ray Mystery consists of (at least) Three Interrelated Challenges

1.) electromagnetically or strongly interacting particles above $10^{20}$ eV loose energy within less than about 50 Mpc.

2.) in most conventional scenarios exceptionally powerful acceleration sources within that distance are needed.

3.) The observed distribution seems to be very isotropic (except for a possible interesting small scale clustering)
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background

\[ E_{\text{th}} = \frac{2m_N m_\pi + m_\pi^2}{4\epsilon} \approx 4 \cdot 10^{19} \text{ eV} \]

⇒ sources must be in cosmological backyard

Only Lorentz symmetry breaking at \( \Gamma > 10^{11} \) could avoid this conclusion.
What the GZK effect tells us about the source distribution (in the absence of strong magnetic deflection)

Observable spectrum for an $E^3$ injection spectrum for a distribution of sources with overdensities of 1, 10, 30 (bottom to top) within 20 Mpc, and otherwise homogeneous.

Possible EUSO measurement

A Possible Euso Measurement
ΔE = ± 15%
Duty cycle = 25%
(Trigger Efficiency is not corrected)

Number of Counts (3 years)

Energy (eV)

"Super-GZK" hypothesis
"GZK" hypothesis
This is the most widely accepted scenario of cosmic ray acceleration. The fractional energy gain per shock crossing depends on the velocity jump at the shock. Together with loss processes this leads to a spectrum $E^{-q}$ with $q > 2$ typically. When the gyroradius becomes comparable to the shock size, the spectrum cuts off.
A possible acceleration site associated with shocks in hot spots of active galaxies.

Core of Galaxy NGC 4261

Hubble Space Telescope
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image

HST Image of a Gas and Dust Disk

360 Arc Seconds
88,000 LIGHTYEARS

1.7 Arc Seconds
400 LIGHTYEARS
A possible acceleration site associated with shocks formed by colliding galaxies
Arrival Direction Distribution $>4\times10^{19}\text{eV}$ zenith angle $<50\text{deg.}$

- Isotropic on large scales $\rightarrow$ Extra-Galactic
- But AGASA sees clusters in small scale ($\Delta \theta < 2.5\text{deg}$)
  - 1 triplet and 6 doublets (2.0 doublets are expected from random)
  - Disputed by HiRes
Custered component has spectrum $E^{-1.8\pm0.5}$

Possible explanations of clustering:
* point-like sources of charged particles in case of insignificant magnetic deflection
* point-like sources of neutral primaries
* magnetic lensing of charged primaries
1.) Magnetic fields are main players in cosmic ray acceleration.

2.) Cosmic rays up to $\sim 10^{18}$ eV are partially confined in the Galaxy.

Energy densities in cosmic rays, in the galactic magnetic field, in the turbulent flow, and gravitational energy are of comparable magnitude.

The galactic cosmic ray luminosity $L_{\text{CR}}$ required to maintain its observed density $u_{\text{CR}} \sim 1 \text{eV cm}^{-3}$ in the galactic volume $V_{\text{gal}}$, for a confinement time $t_{\text{CR}} \sim 10^7 \text{ yr}$, $L_{\text{CR}} \sim u_{\text{CR}} V_{\text{gal}} / t_{\text{CR}} \sim 10^{41} \text{ erg/sec}$, is $\sim 10\%$ of the kinetic energy rate of galactic supernovae.
3.) The knee is probably a deconfinement effect in the galactic magnetic field as suggested by rigidity dependence measured by KASCADE:
4.) Cosmic rays above \( \sim 10^{19} \text{eV} \) are probably extragalactic and may be deflected mostly by extragalactic fields \( B_{\text{XG}} \) rather than by galactic fields.

However, very little is known about \( B_{\text{XG}} \): It could be as small as \( 10^{-20} \text{G} \) (primordial seeds, Biermann battery) or up to fractions of micro Gauss if concentrated in clusters and filaments (equipartition with plasma).

There is a transition from rectilinear to diffusive propagation over distance \( d \) in a field of strength \( B \) and coherence length \( \Lambda_c \) at an energy roughly given by:

\[
E_c \approx 4.7 \times 10^{19} \left( \frac{d}{10 \text{ Mpc}} \right)^{1/2} \left( \frac{B_{\text{rms}}}{10^{-7} \text{G}} \right) \left( \frac{\lambda_c}{1 \text{ Mpc}} \right)^{1/2} \text{eV}
\]

In this transition regime Monte Carlo codes are in general indispensable.
A particle is registered every time a trajectory crosses the sphere around the observer. This version to be applied for individual source/magnetic field realizations and inhomogeneous structures.

Main Drawback: CPU-intensive if deflections are considerable because most trajectories are “lost”. But inevitable for accurate simulations in highly structured environments without symmetries.
Effects of a single source: Numerical simulations

A source at 3.4 Mpc distance injecting protons with spectrum $E^{-2.4}$ up to $10^{22}$ eV. A uniform Kolmogorov magnetic field, $<B^2(k)> \sim k^{-11/3}$, of rms strength 0.3 µG, and largest turbulent eddy size of 1 Mpc.

Conclusions:
1.) Isotropy is inconsistent with only one source.
2.) Strong fields produce interesting lensing (clustering) effects.
More detailed scenarios of large scale magnetic fields use large scale structure simulations with magnetic fields followed passively and normalized to a few micro Gauss in galaxy clusters. We use an Eulerian, grid-based total-variation-diminishing hydro +N-body code.

It is a (75 Mpc)$^3$ box, repeated by periodic boundary conditions, to take into account sources at cosmological distances.

We then consider different observer and source positions for structured and unstructured distributions with and without magnetization.

We analyze these scenarios and compare them with data based on large scale multi-poles, auto-correlations, and clustering.

Scenarios of extragalactic magnetic fields using large scale structure simulations with magnetic fields followed passively and normalized to a few micro Gauss in galaxy clusters.


Sources of density $\sim 10^{-5} \text{ Mpc}^{-3}$ follow Baryon density, field at Earth $\sim 10^{-11} \text{ G}$.

Magnetic field filling factors

The spectrum in the magnetized source scenario shows a pronounced GZK cut-off (spectrum shown is for AGASA acceptance).

Deflection in magnetized structures surrounding the sources lead to off-sets of arrival direction from source direction up to >10 degrees up to $10^{20}$ eV in our simulations. This is contrast to Dolag et al., JETP Lett. 79 (2004) 583.

⇒ Particle astronomy not necessarily possible, especially for nuclei!
Comparing predicted autocorrelations for source density = $2.4 \times 10^{-4}$ Mpc$^{-3}$ (upper set) and $2.4 \times 10^{-5}$ Mpc$^{-3}$ (lower set) for an Auger-type exposure.

Deflection in magnetic fields makes autocorrelation and power spectrum much less dependent on source density and distribution!
In the future, a suppressed auto-correlation function will be a signature of magnetized sources.

Comparing predicted autocorrelations for source density $= 2.4 \times 10^{-5} \text{ Mpc}^{-3}$ with (lower set) and without (upper set) magnetization for an Auger-type exposure.

In the future, a suppressed auto-correlation function will be a signature of magnetized sources.
The simulated sky above $4 \times 10^{19}$ eV with structured sources of density $2.4 \times 10^{-5}$ Mpc$^{-3}$: $\sim 10^5$ simulated trajectories above $10^{19}$ eV.

With field

Without field
The simulated sky above $10^{20}$ eV with structured sources of density $2.4 \times 10^{-5}$ Mpc$^{-3}$: $\sim 10^5$ simulated trajectories above $10^{19}$ eV.

With field

Without field
Generalization to Heavy Nuclei: Structured Fields and Individual Sources

Spectra and Composition of Fluxes from Single Discrete Sources considerably depend on Source Magnetization, especially for Sources within a few Mpc.

Source in the center; weakly magnetized observer modelled as a sphere shown in white at 3.3 Mpc distance.

Sigl, JCAP 08 (2004) 012
Iron primaries

With field = blue
Without field = red
Injection spectrum = horizontal line

Composition for iron primaries
Ultra-High Energy Cosmic Rays and the Connection to $\gamma$-ray and Neutrino Astrophysics

accelerated protons interact:

$$ p + \gamma \rightarrow X + \pi^\pm \rightarrow \text{neutrinos} $$

$$ \pi^0 \rightarrow \gamma - \text{rays} $$

$\Rightarrow$ energy fluences in $\gamma$-rays and neutrinos are comparable due to isospin symmetry.

The neutrino spectrum is unmodified, whereas $\gamma$-rays pile up below the pair production threshold on the CMB at a few $10^{14} \text{ eV}$.

The Universe acts as a calorimeter for the total injected electromagnetic energy above the pair threshold. This constrains the neutrino fluxes.

Included processes:

- Electrons: inverse Compton; synchrotron rad (for fields from $pG$ to $10 \text{ ng}$)
- Gammas: pair-production through IR, CMB, and radio backgrounds
- Protons: Bethe-Heitler pair production, pion photoproduction
The total injected electromagnetic energy is constrained by the diffuse $\gamma$-ray flux measured by EGRET in the MeV - 100 GeV regime.

Neutrino flux upper limit for opaque sources determined by EGRET bound.

Neutrino flux upper limit for transparent sources more strongly constrained by primary cosmic ray flux at $10^{18} - 10^{19}$ eV (Waxman-Bahcall; Mannheim-Protheroe-Rachen)
1.) Neutrino primaries but Standard Model interaction probability in atmosphere is $\approx 10^{-5}$. 

\[ \text{\textasciitilde} \text{resonant (Z}_0\text{) secondary production on massive relic neutrinos: needs extreme parameters and huge neutrino fluxes.} \]

2.) New heavy neutral (SUSY) hadron $X_0$: $m(X_0) > m_N$ increases GZK threshold. 

\[ \text{\textasciitilde} \text{but basically ruled out by constraints from accelerator experiments.} \]

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.

\[ \text{\textasciitilde} \text{strong interactions above \sim 1TeV: only moderate neutrino fluxes required.} \]

Avoiding the GZK Cutoff

If correlated sources turn out to be farther away than allowed by pion production, one can only think of 4 possibilities:

4.) Lorentz symmetry violations.

The Z-burst effect

A Z-boson is produced at the neutrino resonance energy $\nu \nu \sim mE^2 = veV_0^{104}$

\[ \text{\textasciitilde} \text{Visible decay products have energies 10-40 times smaller.} \]

Fargion, Weiler, Yoshida

Main problems of this scenario:

* sources have to accelerate up to $\approx 10^{23} eV$.

* $\gamma$-rays emitted from the sources and produced by neutrinos during propagation tend to over-produce diffuse background in GeV regime.

The 7-hurst effort

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

\[10^{-30} \quad 10^{-31} \quad 10^{-32} \quad 10^{-33} \quad 10^{-34} \quad 10^{-35} \quad 10^{-36} \quad 10^{-37} \quad 10^{-38} \]

$E_\nu [\text{GeV}]$

\[10 \quad 100 \quad 1000 \quad 10^4 \quad 10^5 \quad 10^6 \quad 10^7 \quad 10^8 \quad 10^9 \quad 10^{10} \quad 10^{11} \quad 10^{12} \]
The Z-burst mechanism: Relevant neutrino interactions

\[ \nu_i \bar{\nu}_i \rightarrow \Sigma f \bar{f} \]
\[ \nu_i \bar{\nu}_j \rightarrow \nu_i \nu_j \]
\[ \nu_i \nu_j \rightarrow \nu_i \nu_j \]
\[ \nu_i \nu_i \rightarrow \nu_i \nu_i \]
\[ \nu_i \bar{\nu}_i \rightarrow \nu_i \bar{\nu}_i \]
\[ \nu_i \bar{\nu}_j \rightarrow l_i \bar{l}_j \]
\[ \nu_i \nu_i \rightarrow l_i \bar{l}_j \]
\[ \nu_e \gamma \rightarrow e^- W^+ \]
Neutrinos:

- \( s \)-channel \( Z^0 \)-production: \( \nu_i \bar{\nu}_i \to Z^0 \to f \bar{f} \) where \( f \) is any fermion (including hadronic fragmentation in case of quarks)

\[
\begin{align*}
\begin{array}{c}
\text{f}^- \\
-\text{p}_f \\
\text{p}_f \\
\text{f}^+ \\
\end{array}
\end{align*}
\]

\( Z_0 \) \( q = k_v + k_b \)

\[
\frac{d\sigma_s}{d\mu^*} = \frac{G_F^2 s}{16\pi} \frac{M_Z^4}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \left[ g_V^2 (1 + \mu^*)^2 + g_A^2 (1 - \mu^*)^2 \right],
\]

where \( \mu^* = \cos(\text{scattering angle in center of mass}) \), \( \Gamma_Z \) = width of \( Z^0 \), \( g_V = t_3 - q \sin \theta_W^2 \) and \( g_A = -q \sin \theta_W^2 \) with \( t_3 \) = weak isospin and \( q \) = charge.

- \( t \)-channel \( W^\pm \)-exchange, e.g. \( \nu_i \bar{\nu}_j \to l_i \bar{l}_j \), where \( l_i \) is leptonic partner of \( \nu_i \):

\[
\begin{align*}
\begin{array}{c}
\text{f}^- \\
\text{p}_f \\
\text{W} \\
-\text{p}_f \\
\text{f}^+ \\
\text{q} = k_v - p_f \\
\text{v} \\
\bar{\nu}_b \\
\end{array}
\end{align*}
\]

\[
\frac{d\sigma_t}{d\mu^*} = \frac{G_F^2 s}{4\pi} \frac{M_W^2 (1 + \mu^*)^2}{(s(1 - \mu^*)/2 + M_W^2)}
\]
The Z-burst mechanism: Sources emitting neutrinos and $\gamma$-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, $m_\nu=0.5eV$, $B=10^{-9}$ G.

Kalashev, Kuzmin, Semikoz, Sigl, PRD 65 (2002) 103003
The Z-burst mechanism: Exclusive neutrino emitters

Sources with comoving luminosity proportional to $(1+z)^0$ up to $z=3$, $m_\nu=0.33\text{eV}$, $B=10^{-9}\text{ G}$.
For homogeneous relic neutrinos GLUE+FORTE2003 upper limits on neutrino flux above $10^{20}$ eV imply (see figure).

$$\sum m_{\nu_i} \geq 0.3 \text{ eV}$$

Cosmological data including WMAP imply

$$\sum m_{\nu_i} \leq 0.6 \text{ eV}$$

Solar and atmospheric neutrino oscillations indicate near degeneracy at this scale

$$\Rightarrow \sum m_{\nu_i} \leq 0.2 \text{ eV}$$

For such masses local relic neutrino overdensities are $< 10$ on Mpc scales. This is considerably smaller than UHECR loss lengths => required UHE Neutrino flux not significantly reduced by clustering.
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 $\rightarrow$ physics well understood

- **Center of mass energies for collisions with nucleons in the atmosphere**
  ~100 TeV - 1 PeV $\rightarrow$ 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:

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?

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.

Ringwald, Tu, PLB 525 (2002) 135
Solution: Compare rates of different types of neutrino-induced showers

Deeply penetrating (horizontal)

Earth-skimming

Earth

ATMOSPHERE

Figure from Cusumano
Air-shower probability per τ-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
1.) The origin of very high energy cosmic rays is one of the fundamental unsolved questions of astroparticle physics. This is especially true at the highest energies, but even the origin of Galactic cosmic rays is not resolved beyond doubt.

2.) Acceleration and sky distribution of cosmic rays are strongly linked to the in part poorly known strength and distribution of cosmic magnetic fields.

3.) Deflection angles are currently hard to quantify.

4.) Sources are likely immersed in magnetic fields of fractions of a microGauss. Such fields can strongly modify spectra and composition even if cosmic rays arrive within a few degrees from the source direction.
5.) Pion-production establishes a very important link between the physics of high energy cosmic rays on the one hand, and $\gamma$-ray and neutrino astrophysics on the other hand. All three of these fields should be considered together.

6.) There are many potential high energy neutrino sources including speculative ones. But the only guaranteed ones are due to pion production of primary cosmic rays known to exist: Galactic neutrinos from hadronic interactions up to $\sim 10^{16}$ eV and “cosmogenic” neutrinos around $10^{19}$ eV from photopion production. Flux uncertainties stem from uncertainties in cosmic ray source distribution and evolution.

7.) The highest neutrino fluxes above $10^{19}$ eV are predicted by top-down models, the Z-burst, and cosmic ray sources with power increasing with redshift. However, extragalactic top-down models and the Z-burst are unlikely to considerably contribute to ultra-high energy cosmic rays.