Multimessengers and fundamental physics with ultra-high energy cosmic rays

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Introduction: ultra-high energy cosmic rays

- Charged particles with $E \gtrsim 10^{18}$ eV
- Extragalactic origin
- Flux $\lesssim 1$ particle km$^{-2}$yr$^{-1}$

$\downarrow$

Only indirect observation with extensive air showers in Earth atmosphere

Observed spectrum of cosmic rays


$E^{-2.7}$

32 orders of magnitude

$E^{-3.1}$

12 orders of magnitude

Fluxes of Cosmic Rays

$E = 10^9$ to $10^{12}$ eV

Solar modulation: $10^8 < E < 10^{11}$ eV

Galactic sources: $10^{11} < E < 10^{18}$ eV

Extragalactic sources: $10^{18} < E$
Introduction: observables & problems

Energy spectrum

Spectrum suppression was observed at $E \gtrsim 4 \cdot 10^{19}$ eV


Whether the cut-off is due to GZK effect or due to ending of injection spectrum:

there are no hints for new physics.
UHECR mass composition?

Still not clear from direct EAS measurements

- Low statistics and high systematics with fluorescence observations of EAS
- Moderate statistics but even higher systematics with surface detector observations of EAS

UHECR sources?

Still not clear from direct EAS measurements

- Hard to detect arrival direction: deflection of (charged) CR in galactic magnetic field
Outline: observables & and opportunities

Multimessengers with UHECR

- Secondary UHECR signals: UHE $\gamma$’s & $\nu$’s
  - Not affected by galactic magnetic fields - point directly to the sources
  - Flux depends on UHECR mass composition - independent probe

Fundamental physics with UHECR

- Test for
  - Search for heavy dark matter with UHECR: various signatures
  - Search for axion-like particles — photon conversion: UHE $\gamma$ correlation with Blazars Lacertae

All of this is not yet detected - time to improve sensitivity!
I. Secondary signals from UHECR propagation

- **Nuclei**
  - $A\gamma_b \rightarrow A'N$
  - $A\gamma_b \rightarrow A\pi$
  - $A\gamma_b \rightarrow Ae^+e^-$

- **Protons and neutrons**
  - $N\gamma_b \rightarrow N'\pi$
  - $p\gamma_b \rightarrow pe^+e^-$
  - $n \rightarrow pe^-\bar{\nu}_e$

- **Electron-photon cascades**
  - $e\gamma_b \rightarrow e\gamma$
  - $\gamma\gamma_b \rightarrow e^+e^-$
  - $e$ synchrotron losses

$n,p$ from nuclei

- Photo-desintegration

$\gamma,\nu,n$ from GZK

- from $\beta$-decay

Diffuse

- $\gamma$-background
UHECR propagation: attenuation lengths

Energy loss lengths

IR/Optic background models used here:
- Kneiske et al. astro-ph/1001.2132v1 (dotted line)


M. Kuznetsov
Multimessengers with UHECR
Decay of mesons from $pp$ and $p\gamma$ collisions, e.g.

\[ p + \gamma_b \rightarrow \Delta(1232) \rightarrow p + \pi^0 \rightarrow \gamma + \gamma \]
\[ n + \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ e^+ + \bar{\nu}_\mu + \nu_e \]

$E_\gamma/E_p \simeq 0.1$

$E_\nu/E_p \simeq 0.05$

$E_\nu, E_\gamma \gtrsim 1 \text{ EeV}$

- PeV $\nu$ detected by IceCube — not from GZK
- Only constraints for UHE $\nu$
- Only constraints for UHE $\gamma$
UHE $\nu$ and $\gamma$: probe for UHECR

- **TeV photons**
- **GZK photons**

Gelmini et al. 2007

<table>
<thead>
<tr>
<th></th>
<th>UHE $\nu$</th>
<th>UHE $\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHECR Direction</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>UHECR Source evolution</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>UHECR Local source density</td>
<td>–</td>
<td>+</td>
</tr>
</tbody>
</table>
Diffuse UHE $\gamma$ limits are already probe most optimistic GZK predictions

- A separation between proton and nuclei predictions allows one to probe UHECR composition

There is a way to improve these results
Prospect for target GZK photon search

- Assume that sources of UHECR are trace the Large Scale Structure
- Simulate the UHECR propagation and find distance from which 90% of secondary UHE photons arrives
- Make a cut on this distance and perform a target search for UHE $\gamma$ from LSS directions.

<table>
<thead>
<tr>
<th>$E_\gamma$, EeV</th>
<th>max. flux $R_{90%}$</th>
<th>min. flux $R_{90%}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>310 Mpc</td>
<td>350 Mpc</td>
</tr>
<tr>
<td>10</td>
<td>140 Mpc</td>
<td>170 Mpc</td>
</tr>
<tr>
<td>30</td>
<td>45 Mpc</td>
<td>40 Mpc</td>
</tr>
</tbody>
</table>
Prospect for target GZK photon search: parameter dependence

$\gamma$-flux depends on:

- Primary proton injection spectrum (moderately)
- Value of extragalactic magn. field (strongly)
- Model of interstellar radio background (strongly)

The most promising energy region for UHECR composition probe is $E_\gamma > 10^{18.5}$ eV. But attenuation for this region is the smallest

$\Downarrow$

LSS $\simeq$ whole sky

$\Downarrow$

Some source weighting is needed for target search
Prospect for target GZK photon search: sensitivity improvement

Rough estimate of sensitivity improvement is $Q \equiv 4\pi / \Omega_{\text{LSS}}$
With angular resolution $\sigma = 1.92^\circ$ at $E_\gamma > 30EeV$ and without source weighting:

$Q \simeq 1.5$

 Flux weighting and angular resolution improvement is needed for more efficient UHE $\gamma$ search
II. Fundamental physics with UHECR: axion-like particles

- Correlations of UHECR with distant Blazars Lacertae (BL Lacs) were observed by HiRes experiment
- The significance of result is $3.5\sigma$
- Still not excluded by modern experiments

P-value vs. angular distance from sources

<table>
<thead>
<tr>
<th>Cosmic ray</th>
<th>BL Lac</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$, deg.</td>
<td>$\delta$, deg.</td>
<td>name</td>
</tr>
<tr>
<td>17.8</td>
<td>−12.5</td>
<td>RBS 0161</td>
</tr>
<tr>
<td>48.5</td>
<td>5.8</td>
<td>RX J03143+0620</td>
</tr>
<tr>
<td>118.7</td>
<td>48.1</td>
<td>TXS 0751+485</td>
</tr>
<tr>
<td>123.8</td>
<td>57.0</td>
<td>RX J08163+5739</td>
</tr>
<tr>
<td>137.2</td>
<td>33.5</td>
<td>Ton 1015</td>
</tr>
<tr>
<td>162.6</td>
<td>49.2</td>
<td>MS 10507+4946</td>
</tr>
<tr>
<td>169.3</td>
<td>25.9</td>
<td>RX J11176+2548</td>
</tr>
<tr>
<td>209.9</td>
<td>59.7</td>
<td>RX J13598+5911</td>
</tr>
<tr>
<td>226.5</td>
<td>56.5</td>
<td>SBS 1508+561</td>
</tr>
<tr>
<td>229.0</td>
<td>56.4</td>
<td>SBS 1508+561</td>
</tr>
<tr>
<td>253.7</td>
<td>39.8</td>
<td>RGB J1652+403</td>
</tr>
<tr>
<td>265.3</td>
<td>46.7</td>
<td>OT 465</td>
</tr>
<tr>
<td>300.2</td>
<td>65.1</td>
<td>1ES 1959+650</td>
</tr>
</tbody>
</table>
BL Lac – UHECR correlation properties

- $E > 10^{19}$ eV
- Small separation angle ($\sim 0.8^\circ$) between BL Lacs and UHECR: not possible with charged particles due to gal.magnetic field
- Sources are too distant: indications for the anomalous high attenuation length of neutral particles
- The fraction of correlated events is $\eta \sim 2\%$: consistent with recent diffuse UHE $\gamma$ limits
- The only viable explanation is UHE$\gamma \rightarrow ALP \rightarrow UHE\gamma$ conversion

Fairbairn et al. 2009
How to test this result?

It is possible with large statistics of modern UHECR experiments and their sensitivity to UHE $\gamma$

The sensitivity needed was estimated

\[ Q = \frac{S}{\sqrt{B}} \sim \frac{\eta \sqrt{NF}}{\sigma} \]

where $N$ is number of detected events, $\sigma$ is angular resolution of experiment, $F$ is geographical factor of experiment and $\eta$ is fraction of UHE photons among detected events.
Probe of BL Lac – UHE $\gamma$ correlation with modern experiments

$$Q = \frac{S}{\sqrt{B}} \sim \frac{\eta \sqrt{NF}}{\sigma}$$

- **Geography:** the majority of BL Lacs are located in the Northern Hemisphere:
  \(F_{\text{HiRes}} = 1.38; F_{\text{TA}} = 1.41; F_{\text{Auger}} = 0.53\).
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➤ **Angular resolution for $\gamma$:** larger for FD experiments:
$\sigma_{\text{HiRes}} = 0.6^\circ; \sigma_{\text{TA SD}} = 2.65^\circ; \sigma_{\text{Auger hybrid}} = 0.7^\circ.$
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- **Number of events:** $N_{\text{SD}}$ is $\sim 10$ times larger than $N_{\text{FD}}$. 
Probe of BL Lac – UHE $\gamma$ correlation with modern experiments

\[ Q = \frac{S}{\sqrt{B}} \sim \frac{\eta \sqrt{NF}}{\sigma} \]

**Main problem:**

Energy reconstruction: for fluorescence detectors the energy scale for protons is the same as for photons. For SD it is not so.  

\[ \text{Log}_{10}(E_{\text{rec}}/E) \]

\[ -1 \quad -0.5 \quad 0 \quad 0.5 \quad 1 \]

Therefore, the same cut on $E_\gamma$ yields different $\gamma$ fraction:

$\eta_{\text{HiRes}} \approx 2\%$; $\eta_{\text{TA SD}} \approx 0.5\%$; $\eta_{\text{Auger}} \approx 0.1\%$.

I will discuss a possible probe with TA SD.
Prospect for probe of BL Lac – UHE $\gamma$ correlation with TA SD

TA SD reconstruction improved with Neural Net (preliminary).

- Angular resolution for $\gamma$: $\sigma = 2.65^\circ \rightarrow \sigma = 2.13^\circ$
- $p - \gamma$ classification: cut the UHECR sample to increase $\eta$: $\eta \simeq 0.5\% \rightarrow \eta \simeq 68\%$

Resulting sensitivity improvement comparing to HiRes (preliminary):

$$\frac{Q_{\text{TA SD NN}}}{Q_{\text{HiRes}}} \approx 2.7$$

Therefore,

- TA can either confirm the BL Lac – UHE $\gamma$ correlation with significance $> 5\sigma$ or
- constrain the total UHE $\gamma$ fraction from BL Lac to $\eta \simeq 0.5\%$ with 95\%C.L.
III. Dark matter and UHECR

- Standard thermal WIMP DM was not detected yet
- IceCube observed several PeV $\nu$ that cannot be a product of WIMP annihilation
- Can it be a product of heavy DM decay?
Heavy dark matter (HDM)

Particles $X$ with mass $M_X \gg 100$ TeV and lifetime $\tau \gg 10^{10}$ yr

Kuzmin, Rubakov '97; Berezinsky et al. '97; Birkel, Sarkar '98

1. Naturally to generate non-thermally in the early Universe:
   - Non-stationary gravitational fields
   - Non-equilibrium plasma
   - Inflaton decay (preheating)

2. Particle concentration is too low $\Rightarrow$ non-accessible for direct detection
   ($\sigma_{AX}^{\text{est.}} \sim 10^{-55} \text{cm}^2$)

3. Indirect detection sensitive only to decay, but not to annihilation: $\sigma_{\text{ann.}} \lesssim \frac{1}{M_X^2}$

4. Consider masses $10^6 \leq M_X \leq 10^{16}$ GeV (although there are some mass constraints from cosmology)
Can we probe HDM with UHECR?

Sure!
For large enough $M_X$ and any decay channel hadronic / electroweak cascade develops

\[\downarrow\]

The final state contains all stable SM particles.

\[\downarrow\]

There is a number of signatures in UHECR

- Dipole in UHECR spatial distribution
- Flux of UHE $\gamma$
- Flux of UHE $\nu$
Decay for two primary channels: $X \rightarrow q\bar{q}$ and $X \rightarrow \nu\bar{\nu}$

$X \rightarrow q\bar{q}$ yields the softest injection spectrum in both $\gamma$ and $\nu$; $X \rightarrow \nu\bar{\nu}$ — the hardest.

Analytical calculation with fragmentation functions and DGLAP equations

*Aloisio et al. '03; Kachelriess, Kalashev & MK '18.*
► For UHE $\gamma$ flux only the galactic DM contribution is relevant. For $\nu$ — both galactic and extragalactic.

► Take into account $\gamma \rightarrow e^+ e^- \rightarrow \gamma$ cascades on cosmic photon backgrounds. 

Kalashev, Kido ’14.
High energy gamma-rays: observational data

$F_{\gamma}(E > E_{\text{min}})$, km$^{-2}$sr$^{-1}$yr$^{-1}$

$E_{\text{min}}$, eV

KASCADE
CASA-MIA
EAS-MSU
KASCADE-Grande
Yakutsk
Auger
TA

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High energy gamma-rays: constraints on heavy dark matter

Constraints on DM lifetime from comparison of the DM model $\gamma$-flux with the high-energy $\gamma$ limits

$X \rightarrow q\bar{q} \rightarrow \gamma$

$X \rightarrow \nu\bar{\nu} \rightarrow \gamma$
High energy neutrino: observational data

Highest energy observed event has $E \approx 2\ \text{PeV}$, for higher energies upper-limits are set

*IceCube ’18, Auger ’15*
High energy neutrino: constraints on heavy dark matter

Explanation of IceCube highest energy events by decay of HDM with $M_X \gtrsim 10^8$ GeV is ruled out by non-observation of UHE $\gamma$
Cosmic-ray anisotropy: observations

Observable: amplitude of dipole in harmonic analysis over right ascension

\[ J(\alpha, E) = a_0(E) + \sum_n \left[ a_n(E) \sin(n\alpha) + b_n(E) \cos(n\alpha) \right] ; \quad r_1(E) = \sqrt{a_1^2 + b_1^2} \]
Cosmic–ray anisotropy: constraints on HDM

UHECR anisotropy probes heavy dark matter not so efficient as UHE $\gamma$ and $\nu$ limits.
Prospects of indirect search for heavy dark matter

How large is the anisotropy of cosmic–rays induced by the allowed heavy dark matter?

- Running experiments are more sensitive to dark matter decay gamma-rays than to the respective anisotropy.
- The detected CR anisotropy is not of DM origin.
- Vise-versa, future orbital UHECR detectors assumed to be more sensitive to HDM induced UHECR anisotropy than to UHE $\gamma$ signal.
Conclusions

UHECR is a viable probe for fundamental physics and an interesting target for multimessenger studies

- UHECR sources and composition can be probed with UHE $\gamma$ rays
- Photon–ALP mixing hypothesis can be tested indirectly by modern UHECR observatories
- Decaying heavy dark matter can be efficiently searched for with UHE $\gamma$ ray observation

Thank you!
Backup slides
Deflection in galactic magnetic field:

\[
\frac{\Delta \Theta}{Z} \sim 2.5 \frac{100 \text{EeV}}{E} \frac{B}{3 \mu \text{G}}
\]

Extragalactic magnetic field in voids:

\[
\frac{\Delta \Theta}{Z} \lesssim 0.4 \frac{100 \text{EeV}}{E} \frac{B}{0.1 \text{nG}} \frac{\sqrt{L\lambda_{\text{cor}}}}{10 \text{Mpc}}
\]

Recent constraints on \( B_{\text{EG}} \) and its correlation length \( \lambda_{\text{cor}} \):

\[
10^{-17} \text{G} \lesssim B_{\text{EG}} \lesssim 10^{-9} \text{G}
\]

\[
\lambda_{\text{cor}} \gtrsim 1 \text{pc}
\]

R. Durrer & A. Neronov 2013