Are signatures of ultrahigh energy cosmic rays detectable in gamma rays?

K.K., D. Allard and M. Lemoine, submitted to A&A
Why do we care about multi-messenger Astrophysics at UHE?

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- Acceleration (e.g., in shocks)
- Ultrahigh energy cosmic rays
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Auger Coll. 2008
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- Neutrinos
- \( \gamma \) rays

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observable?
what information?

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neutrinos  γ rays
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Fate of gamma rays after their production by UHECRs

\[ \text{CR (10}^{20} \text{eV}) + \gamma_{\text{bg}} \rightarrow e^+e^- + \gamma_{\text{UHE}} \]

**Cascade in IGM**
- interactions with radio/CMB photons
  - \( \gamma \gamma_{\text{bg}} \rightarrow e^+e^- \)
  - Inverse Compton
  - no more interactions
  - \( \gamma \rightarrow \gamma_{\text{TeV-GeV}} \)

**Synchrotron nearby source**
- if source environment sufficiently magnetized
  - \( e^+ \rightarrow \gamma_{\text{GeV}} \)
  - \( B, \text{ synchrotron} \)
  - no more interactions
  - \( \gamma \rightarrow \gamma_{\text{ray halo of limited extension around source}} \)
Fate of gamma rays after their production by UHECRs

\[
\text{CR (10}^20\text{ eV)} \quad + \quad \gamma_{bg} \quad \rightarrow \quad e^+, \quad \gamma_{UHE}
\]

**Cascade in IGM**
- Pair production
  - \( \gamma\gamma_{bg} \rightarrow e^+e^- \)
  - Inverse Compton
    - \( e\gamma_{bg} \rightarrow e\gamma \) \( \rightarrow \quad \gamma\text{TeV-GeV} \)
  - B deflections

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**Homogeneous B:** Flux completely diluted if \( B_{\text{IGM}} > 3 \times 10^{-11} \text{G} \)

*Protheroe 86, Protheroe & Stanev 93, Aharonian et al. 94*
Fate of gamma rays after their production by UHECRs

\[
\text{CR (10}^{20}\text{ eV)} + \gamma_{\text{bg}} \rightarrow \text{e}^+ , \gamma_{\text{UHE}}
\]

\[\gamma_{\text{bg}} \rightarrow e^+ e^- \rightarrow e \gamma_{\text{bg}} \rightarrow e \gamma \rightarrow ... \gamma_{\text{TeV-GeV}}\]

- Pair production
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*K.K. et al. 2010*
Fate of gamma rays after their production by UHECRs

CR \(10^{20} \text{ eV}\) + \(\gamma_{\text{bg}}\) → \(e^+ e^-\) → \(e\gamma_{\text{bg}} \rightarrow e\gamma\) → ... \(\gamma\) TeV-GeV

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*K.K. et al. 2010*

\[
\frac{dN_{\gamma}}{dE_{\gamma}} \approx \frac{f_{1d}(<B_0)}{8\pi d^2} e L_{\text{cr}} \left( \frac{E_{\gamma}}{E_{\gamma,\text{max}}} \right)^{1/2}
\]
Fate of gamma rays after their production by UHECRs

\[ \text{CR (10^{20} \text{eV}) + \gamma_{bg}} \rightarrow e^+ e^- \rightarrow e\gamma_{bg} \rightarrow e\gamma \rightarrow \ldots \ \gamma_{\text{TeV-GeV}} \]

\[ \text{Inverse Compton} \quad \text{no more interactions} \]

**Cascade in IGM**

interactions with radio/CMB photons

**Synchrotron nearby source**

if source environment sufficiently magnetized

\[ e^+ \rightarrow \gamma_{\text{GeV}} \]

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\[ E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \approx f_{1d}(< B_0) L_{\text{cr}} e^{L_{\text{cr}} 2} \left( \frac{E_\gamma}{E_{\gamma,\text{max}}} \right)^{1/2} \]
Fate of gamma rays after their production by UHECRs

\[ \text{CR (10}^{20} \text{eV)} + \gamma_{bg} \rightarrow e^{+} + e^{-} \rightarrow e \gamma_{bg} \rightarrow e \gamma \rightarrow ... \]

\[ \gamma_{\text{TeV-GeV}} \rightarrow \gamma_{\text{UHE}} \]

**Cascade in IGM**

interactions with radio/CMB photons

\[ \gamma_{bg} \rightarrow e^{+} + e^{-} \rightarrow e \gamma_{bg} \rightarrow e \gamma \rightarrow ... \]

**Inverse Compton**  no more interactions

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*K.K. et al. 2010*

\[ E_{\gamma}^{2} \frac{dN_{\gamma}}{dE_{\gamma}} \approx f_{1d}(< B_{0}) e^{- \frac{L_{\text{sr}}}{8 \pi d^{2}}} e^{e_{\gamma} \left( \frac{E_{\gamma}}{E_{\gamma,\text{max}}} \right)^{1/2}} \]

**homogeneous magnetized sphere around source**

*Gabici & Aharonian 06*

filaments, inhomogeneous B

*K.K. et al. 2010*
Explore influence of astrophysical parameters on gamma ray signal

Chemical compositions for UHECR: protons, Galactic mixed, iron, [mixed + low $E_{p,max}$]

Various extragalactic magnetic field configurations (intensity, contrast, ...)

adapted from Allard et al. 08
Interactions of nuclei with cosmic backgrounds + multimessengers ($\gamma, \nu$)

Allard et al. 05, SOPHIA (Mücke et al. 1999), EPOS (Werner et al. 06), CONEX (Bergmann et al. 07)

Gamma-ray cascades

Explore influence of astrophysical parameters on gamma ray signal

Chemical compositions for UHECR: protons, Galactic mixed, iron, [mixed + low $E_{p,\text{max}}$]

Various extragalactic magnetic field configurations (intensity, contrast, ...)

adapted from Allard et al. 08

... using a complete propagation and interaction code


Propagation in magnetic fields  
K.K. & Lemoine 2008a
**Synchrotron component**
+ cascaded component: flux \( \times \) a few

\[
L_{cr}(E > 10^{19} \text{ eV}) = 10^{42} \text{ erg s}^{-1}
\]

average type of source: fits Auger spectrum for \( n_{\text{sources}} = 10^{-5} \text{ Mpc}^{-3} \)

distance to observer \( d = 100 \text{ Mpc} \)
\( E_{\text{max}} = 10^{20.5} \text{ eV} \), spectral index = 2.3

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**Extragalactic magnetic field configurations**

**Chemical compositions of primary UHECR**
Synchrotron component
+ cascaded component: flux x a few

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**Extragalactic magnetic field configurations**

**Chemical compositions of primary UHECR**

**flux ultimately depends on injected energy at the source robustness** according to B and composition.
**Synchrotron component**
+ cascaded component: flux x a few

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**Extragalactic magnetic field configurations**

**Chemical compositions of primary UHECR**

![Graph showing synchrotron spectra for different magnetic fields and injection spectra.](image-url)
**Synchrotron component**
+ cascaded component: flux $\times$ a few

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average type of source: fits Auger spectrum for $n_{\text{sources}} = 10^{-5} \text{ Mpc}^{-3}$

distance to observer $d = 100 \text{ Mpc}$

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**Extragalactic magnetic field configurations**

**Chemical compositions of primary UHECR**
Synchrotron component
+ cascaded component: flux x a few
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L_{cr}(E>10^{19} \text{ eV}) = 10^{42} \text{ erg s}^{-1}
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average type of source: fits Auger spectrum for \( n_{\text{sources}} = 10^{-5} \text{ Mpc}^{-3} \)
distance to observer \( d = 100 \text{ Mpc} \)
\( E_{\max} = 10^{20.5} \text{ eV}, \) spectral index = 2.3

Fermi: \( \sim 10^{-10} \text{ GeV cm}^{-2} \text{ s}^{-1} (\theta_{\text{source}}/1^\circ) \)

CTA: \( \sim 10^{-11} \text{ GeV cm}^{-2} \text{ s}^{-1} (\theta_{\text{source}}/0.1^\circ) \)

flux ultimately depends on injected energy at the source
**robustness** according to B and composition.

detectable only if:
- particularly powerful source (rare)
- close-by source (Cen A?)
Case of particularly powerful sources

\[ L_{cr,19} = 10^{44} \text{ erg s}^{-1} \]
\[ d = 100 \text{ Mpc} \]

\[ L_{cr,19} = 10^{46} \text{ erg s}^{-1} \]
\[ d = 1 \text{ Gpc} \]

Note: would be consistent with a heavy composition at UHE (Auger?)
Case of particularly powerful sources

$L_{\text{cr,19}} = 10^{44} \text{ erg s}^{-1}$

$d = 100 \text{ Mpc}$

$E^2 \phi(E) (\text{eV}^2/\text{m}^2\text{s}\text{sr})$

* * flux integrated up to angular extension $\theta$

$L_{\text{cr,19}} = 10^{46} \text{ erg s}^{-1}$

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**Case of particularly powerful sources**

- Flux integrated up to angular extension $\theta$

- **Fermi/CTA at 10 GeV:**
  \[ \sim 10^{-10} \text{ GeV cm}^{-2} \text{ s}^{-1} \left( \frac{\theta_{\text{source}}}{1^\circ} \right) \]

- **$L_{\text{cr,19}} = 10^{46} \text{ erg s}^{-1}$**
  \[ d = 1 \text{ Gpc} \]

- **$L_{\text{cr,19}} = 10^{44} \text{ erg s}^{-1}$**
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Case of particularly powerful sources

Extended emission (NOT pointlike) ensures that the gamma emission is an **UHECR signature**.
Distinguishable from leptonic/hadronic contribution produced inside the source.

\[ L_{\text{cr,19}} = 10^{44} \text{ erg s}^{-1} \]
\[ d = 100 \text{ Mpc} \]

Fermi/CTA at 10 GeV:
\~ 10^{-10} \text{ GeV cm}^{-2} \text{ s}^{-1} (\theta_{\text{source}}/1^{\circ})

\[ L_{\text{cr,19}} = 10^{46} \text{ erg s}^{-1} \]
\[ d = 1 \text{ Gpc} \]
for synchrotron emission:
  extended and strong magnetic field necessary

-> lobes of Cen A?
  $B_{\text{lobes}} \sim 1 \mu G, l_{\text{coh}} \sim 20 \text{kpc}, R_{\text{lobe}} \sim 100 \text{kpc}, L_{\text{cr,19}} \sim 3 \times 10^{39} \text{erg s}^{-1}$

7 degrees in the sky -> sensitivity loss of $\theta_{\text{source}}/\theta_{\text{PSF}} \sim 7$

$$F_{\text{lobe,10 TeV}} \sim \left(\frac{d_{\text{Cen A}}}{d_{\text{fil}}}ight)^{-2} \frac{L_{\text{Cen A}}}{10^{42} \text{erg/s}} \frac{R_{\text{lobe}}}{5 \text{Mpc}} F_{\text{fil,10 GeV}}$$

**total decrease of factor $\sim 10^3$ compared to average sources -> hardly observable**

UHE photons could be detectable with Auger *Taylor et al. 09*
expected rate of $>10^{19}$ eV photons from Cen A, assuming it is responsible for 10% of the $6 \times 10^{19}$ eV flux: **0.2–0.3 events/yr**
Are signatures of UHECR detectable in gamma rays?

K.K., D. Allard, M. Lemoine, submitted to A&A

We studied the detectability of UHECR signatures in gamma rays, taking into account major astrophysical constraints:

- source environment
- magnetic configuration in the Universe
- types of emission: EM cascade, synchrotron emission
- UHECR composition
- source luminosity
- observed UHECR spectrum

Flux ultimately depends on injected energy at the source (robust according to B, composition, ...).

Our conclusions on detectability:

- average type of sources not observable by current and upcoming instruments (2 orders of magnitude)
- powerful sources:
  \[ L_{19} = 10^{44} \text{ erg s}^{-1} \text{ at } 100 \text{ Mpc at limit of observed CR spectrum}, \]  would produce a detectable \( \gamma \) halo of \( \sim 2^\circ \)
  \[ L_{19} = 10^{46} \text{ erg s}^{-1} \text{ at } 1 \text{ Gpc produce } 10\% \text{ of observed CR spectrum}, \]  and a detectable \( \gamma \) halo of fract. of deg.
  Note: halo = clear signature of UHECR

- close-by sources: Cen A
  synchrotron radiation due to injection of UHECR in lobes not observable
  UHE emission potentially observable with Auger if Cen A is responsible for 10% of the \( 6 \times 10^{19} \) eV flux