Propagation of ultrahigh energy nuclei in clusters of galaxies: survival and secondary emissions

Why look at clusters of galaxies?
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presence of candidate sources of ultrahigh energy cosmic rays AGN (FR-I), but also cosmological shock regions

Best 2004, Gilmour 2009
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an ideal region for secondary emissions (neutrinos, gamma rays)

- strong magnetic field (up to 40 μG in core)  
  *e.g. Carilli & Taylor 2002*
- confinement of cosmic rays of energy \(E < 10^{17}\) eV
- synchrotron emission
- higher IR photon density as compared to the extragalactic background
- high baryonic density
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Auger Coll. 2009
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ultrahigh energy heavy nuclei could be injected at the source

*Anchordoqui et al. 99, 08, Allard & Protheroe 09*

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survival of injected heavy nuclei?

what secondary emission?
Modeling cluster backgrounds and nuclei propagation
Magnetic field, photonic and baryonic density of cluster of galaxies:
(3D MHD simulations by Dubois & Teyssier 2008)

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cool core / non cool core clusters normalization of overall $B$
position of source injection duration
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Propagation in magnetic fields:
semi-analytical propagation code that takes into account small-scale turbulence effects in the central region (K.K. & Lemoine 2008a)
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Interactions with nuclei:
γ-N processes and propagation of secondary nucleons (Allard et al. 05, and SOPHIA, Mucke et al. 1999)
p-N processes: using CONEX, EPOS (hadronic interaction codes to simulate air showers)
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Gamma-ray cascades:
- Treated as post-analysis (method of Murase et al. 2008)
Mixed composition cosmic rays propagating in clusters of galaxies
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hadronic interactions $\lambda_{Ap} \propto A^{-2/3}$, 

+ confinement effects $\tau_{\text{conf}} \propto Z^{1/3} E^{-1/3} B^{1/3}$
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![Graph showing energy spectra and abundance of various components in different core conditions.](image-url)
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Taking into account the limited AGN lifetime

![Graph showing the energy distribution over time with different emission lines and AGN lifetimes.]

- cool core
- $B_c = 10 \, \mu G$
- $t_{AGN} = 10 \, \text{Myr}$

- $H$
- $H^+$
- $\text{CNO}$
- $Z \geq 8$

- $E^2 dN/dE$

- log $E$ [eV]
Taking into account the limited AGN lifetime, the evolution of different elements like H and Z>8 with respect to energy (log E [eV]) is shown for different time points (t = 15 Myr, 24 Myr, 30 Myr, 75 Myr, 231 Myr, 569 Myr). The plots illustrate the distribution of energy (E^2 dN/dE) with time, highlighting the influence of higher confinement times \( t_{conf} \) and spread around \( t_{conf} \), where heavier nuclei escape later from the cluster due to these conditions.
Taking into account the limited AGN lifetime

due to higher confinement times $t_{\text{conf}}$ and spread around $t_{\text{conf}}$, heavier nuclei escape later from cluster

flux diminishes due to spread in time
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but possible cosmic ray afterglow \textit{decorrelated from secondary emissions} when looking at single objects
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But possible cosmic ray afterglow **decorrelated from secondary emissions** when looking at single objects

These effects should not be observed on average (unless there is a nearby source that highly contributes to the total cosmic ray spectrum)
Secondary neutrino emission

AGN luminosity for $E_{\text{min}} = 10^9$ eV and $E_{\text{max}} = 10^{20.5}$ eV: $L_{\text{cr}} = 10^{44}$ erg s$^{-1}$

![Graph showing emission spectra](image)
Secondary neutrino emission

AGN luminosity for $E_{\text{min}} = 10^9$ eV and $E_{\text{max}} = 10^{20.5}$ eV: $L_{\text{cr}} = 10^{44}$ erg s$^{-1}$

KM3Net sensitivity = $2 \times 10^{-9}$ GeV cm$^{-2}$ s$^{-1}$

single source

mixed 2.1

mixed 2.3
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Total UHECR flux compared to observed data

$n_{\text{sources}} = 10^{-5}$ Mpc$^{-3}$
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spectral index = 2.3
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**Legend**
- CMB
- cluster IR
- extragal. IR
- hadron

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**Graphs**

- **KM3Net sensitivity:** $2 \times 10^{-9}$ GeV cm$^{-2}$ s$^{-1}$

- **Single source**
- **Mixed 2.1**
- **Mixed 2.3**

- **Total UHECR flux compared to observed data**
  - $n_{\text{sources}} = 10^{-5}$ Mpc$^{-3}$

- **Diffuse neutrino flux**
  - $n_{\text{sources}} = 10^{-5}$ Mpc$^{-3}$
  - Spectral index = 2.3
Secondary neutrino emission

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diffuse neutrino flux

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spectral index = 2.3

various B intensity, profiles, compositions

$B = 0$
Secondary neutrino emission

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mixed 2.3

mixed 2.1

total UHECR flux compared to observed data

$E^2 dN/dE$ [GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$] / $(L_{\text{cr,44}} \times n_s)$

various B intensity, profiles, compositions

source shifted 100 kpc from center

$B = 0$

$E^2 dN/dE$ [GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$]

diffuse neutrino flux

$E^3 dN/dE$ [eV$^2$ m$^{-2}$ s$^{-1}$ sr$^{-1}$] / $(L_{\text{cr,44}} \times n_s)$

$2 \times 10^{-9}$ GeV cm$^{-2}$ s$^{-1}$

KM3Net sensitivity = $2 \times 10^{-9}$ GeV cm$^{-2}$ s$^{-1}$
Secondary neutrino emission

AGN luminosity for $E_{\text{min}} = 10^9$ eV and $E_{\text{max}} = 10^{20.5}$ eV: $L_{\text{cr}} = 10^{44}$ erg s$^{-1}$

KM3Net sensitivity = 2x10$^{-9}$ GeV cm$^{-2}$ s$^{-1}$

IceCube sensitivity (diffuse) = 1.5x10$^{-8}$ GeV cm$^{-2}$ s$^{-1}$

various B intensity, profiles, compositions

source shifted of 100 kpc from center

$B = 0$

diffuse neutrino flux

$n_{\text{sources}} = 10^{-5}$ Mpc$^{-3}$

spectral index = 2.3

total UHECR flux compared to observed data

$n_{\text{sources}} = 10^{-5}$ Mpc$^{-3}$
Gamma ray emission

B = 10 \mu G
spectral index = 2.3
AGN luminosity for E_{\text{min}} = 10^9 \text{ eV} and E_{\text{max}} = 10^{20.5} \text{ eV}: L_{\text{cr}} = 10^{44} \text{ erg s}^{-1}

gamma rays from UHECR injected in a cool core cluster
Gamma ray emission

\[ B = 10 \mu \text{G} \]
\[ \text{spectral index} = 2.3 \]

AGN luminosity for \( E_{\text{min}} = 10^9 \text{ eV} \) and \( E_{\text{max}} = 10^{20.5} \text{ eV} \):
\[ L_{\text{cr}} = 10^{44} \text{ erg s}^{-1} \]

gamma rays from UHECR injected in a cool core cluster

[Graph showing observed and predicted gamma ray emission]

CTA: point source \( \sim 10^{-11} \text{ GeV cm}^{-2} \text{ s}^{-1} \)
Gamma ray emission

\[ \log(E^{-2} \phi [\text{GeV cm}^{-2} \text{s}^{-1}]) \]

- Observed
- CG Escaped
- CG Syn
- Initial \( \gamma \)
- Initial \( e^- e^+ \)

\[
\log(E^{[\text{eV}]})
\]

- B = 10 \( \mu \)G
- spectral index = 2.3
- AGN luminosity for \( E_{\text{min}} = 10^9 \) eV and \( E_{\text{max}} = 10^{20.5} \) eV: \( L_{\text{cr}} = 10^{44} \text{ erg s}^{-1} \)

Gamma rays from UHECR injected in a cool core cluster

CTA: point source \( \sim 10^{-11} \) GeV cm\(^{-2}\) s\(^{-1}\)

cluster of R \( \sim 5\)Mpc at 100 Mpc: \( \theta_{\text{source}} \sim 3^\circ \)
Gamma ray emission

- B = 10 μG
- spectral index = 2.3

AGN luminosity for E_{min}=10^9 eV and E_{max} = 10^{20.5} eV: L_{cr} = 10^{44} erg s^{-1}

Gamma rays from UHECR injected in a cool core cluster

CTA: point source \sim 10^{-11} \text{ GeV cm}^{-2} \text{ s}^{-1}

Cluster of R \sim 5 \text{ Mpc} at 100 \text{ Mpc}: \theta_{source} \sim 3^\circ

Fermi: source of some degrees \sim 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1}
Gamma ray emission

Observed
CG Escaped
CG Syn
Initial γ
Initial e⁻e⁺

B = 10 μG
spectral index = 2.3

AGN luminosity for $E_{\text{min}}=10^9$ eV and $E_{\text{max}} = 10^{20.5}$ eV: $L_{\text{cr}} = 10^{44}$ erg s⁻¹

gamma rays from UHECR injected in a cool core cluster

CTA: point source $\sim 10^{-11}$ GeV cm⁻² s⁻¹

cluster of R $\sim$ 5Mpc at 100 Mpc: $\theta_{\text{source}} \sim 3°$

Fermi: source of some degrees $\sim 10^9$ GeV cm⁻² s⁻¹

effects of lower energy cosmic rays ($E < 1$ PeV)

contribution from UHECRs overwhelmed by that of lower energy cosmic rays
Gamma ray emission

\[ \log(E \text{[GeV cm}^{-2} \text{s}^{-1}]) \]

- \( B = 10 \, \mu \text{G} \)
- Spectral index = 2.3

AGN luminosity for \( E_{\text{min}} = 10^{9} \) eV and \( E_{\text{max}} = 10^{20.5} \) eV: \( L_{\text{cr}} = 10^{44} \) erg s\(^{-1}\)

Gamma rays from UHECR injected in a cool core cluster

- **CTA:** point source \( \sim 10^{-11} \) GeV cm\(^{-2}\) s\(^{-1}\)

- Cluster of \( R \sim 5 \) Mpc at 100 Mpc: \( \theta_{\text{source}} \sim 3^\circ \)

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Effects of lower energy cosmic rays (\( E < 1 \) PeV)

Contribution from UHECRs overwhelmed by that of lower energy cosmic rays

**EGRET limit** (point source)
Gamma ray emission

\[ B = 10 \, \mu G \]
\[ \text{spectral index} = 2.3 \]
AGN luminosity for \( E_{\text{min}} = 10^9 \, \text{eV} \) and \( E_{\text{max}} = 10^{20.5} \, \text{eV} \): \( L_{\text{cr}} = 10^{44} \, \text{erg s}^{-1} \)

gamma rays from UHECR injected in a cool core cluster

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\[ \text{EGRET limit} \] (point source)

harder spectral index with \( L = 10^{44} \, \text{erg s}^{-1} \) would overshoot UHECR spectrum
Gamma ray emission

\[ \log(E^{2} \phi) \text{[GeV cm}^{-2} \text{s}^{-1}] \]

- Observed
- CG Escaped
- CG Syn
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- Initial e-e+ 

\[ \log(E \text{[eV]}) \]

- Observed
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\( B = 10 \mu \text{G} \)

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AGN luminosity for \( E_{\text{min}} = 10^{9} \text{eV} \) and \( E_{\text{max}} = 10^{20.5} \text{eV} \): \( L_{\text{cr}} = 10^{44} \text{erg s}^{-1} \)

gamma rays from UHECR injected in a cool core cluster

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cluster of \( R \sim 5 \text{Mpc} \) at 100 Mpc: \( \theta_{\text{source}} \sim 3^\circ \)

Fermi: source of some degrees \( \sim 10^{-9} \text{GeV cm}^{-2} \text{s}^{-1} \)

effects of lower energy cosmic rays (\( E < 1 \text{ PeV} \))

contribution from UHECRs overwhelmed by that of lower energy cosmic rays

\( s = 2.1, L=10^{42} \text{erg s}^{-1} \)

EGRET limit (point source)

harder spectral index with \( L=10^{44} \text{erg s}^{-1} \) would overshoot UHECR spectrum
Gamma ray emission

\[
\log(E^2 \phi) [\text{GeV} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}]
\]

\[
\log(E) [\text{eV}]
\]

- Observed
- CG Escaped
- CG Syn
- Initial γ
- Initial e⁻e⁺

\(B = 10 \, \mu\text{G}\)
spectral index = 2.3
AGN luminosity for \(E_{\text{min}}=10^9\) eV and \(E_{\text{max}} = 10^{20.5}\) eV: \(L_{\text{cr}} = 10^{44}\) erg s⁻¹

gamma rays from UHECR injected in a cool core cluster

CTA: point source \(\sim 10^{-11}\) GeV cm⁻² s⁻¹
cluster of \(R \sim 5\) Mpc at 100 Mpc: \(\theta_{\text{source}} \sim 3°\)

Fermi: source of some degrees \(\sim 10^9\) GeV cm⁻² s⁻¹

effects of lower energy cosmic rays (\(E < 1\) PeV)
contribution from UHECRs overwhelmed by that of lower energy cosmic rays

\(s = 2.1, L = 10^{42}\) erg s⁻¹

EGRET limit (point source)

harder spectral index with \(L = 10^{44}\) erg s⁻¹ would overshoot UHECR spectrum
question of minimum injection energy
Gamma ray emission

\[ \log(E_{\gamma}^{2} \phi [\text{GeV cm}^{-2} \text{s}^{-1}]) \]

\[ \log(E_{\gamma}^{} [\text{eV}]) \]

Observed
CG Escaped
CG Syn
Initial \( \gamma \)
Initial e-e\(^+\)

Gamma rays from UHECR injected in a cool core cluster

**CTA**: point source \( \sim 10^{-11} \text{ GeV cm}^{-2} \text{s}^{-1} \)

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\[ B = 10 \mu G \]

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Gamma ray emission

\[ \log(\mathcal{E}_2) [\text{GeV cm}^{-2} \text{s}^{-1}] \]

\[ \log(\mathcal{E}) [\text{eV}] \]

- Observed
- CG Escaped
- CG Syn
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**Initial e+e-**

Gamma rays from UHECR injected in a cool core cluster

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\[ B = 10 \mu \text{G} \]

Spectral index \( = 2.3 \)

AGN luminosity for \( E_{\text{min}}=10^9 \text{ eV} \) and \( E_{\text{max}} = 10^{20.5} \text{ eV} : L_{\text{cr}} = 10^{44} \text{ erg s}^{-1} \)

\[ E_{\text{min}} = 10^9 \text{ eV} \]

\[ E_{\text{max}} = 10^{20.5} \text{ eV} \]

\[ L_{\text{cr}} = 10^{44} \text{ erg s}^{-1} \]
Conclusion

We studied the propagation of nuclei in magnetised clusters of galaxies
- using a complete propagation code
- and based on a detailed study of the physical properties of clusters of galaxies.
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The survival of heavy nuclei highly depends on the injection position and on the profile of the magnetic field. Heavy nuclei are more strongly depleted than light nuclei.

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  - using a complete propagation code
  - and based on a detailed study of the physical properties of clusters of galaxies.
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Taking into account the limited lifetime of the central source may lead in some cases to the detection of a cosmic ray afterglow, temporally decorrelated from neutrino and gamma ray emissions.
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The **diffusive neutrino flux** around 1 PeV coming from clusters of galaxies may have a chance to be detected by current instruments. (if source are at the center and $n_s = 10^{-5}$ Mpc$^{-3}$)
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Gamma ray signals coming from **lower energy cosmic rays** ($E < 1 \text{ PeV}$), if they exist, might however be detected by Fermi, for reasonable sets of parameters.