Probing the extragalactic cosmic-ray origin with gamma-ray and neutrino backgrounds


PoS (ICRC2017) 516
The UHECRs interact with
1) extragalactic magnetic fields
2) extragalactic photon backgrounds

energy losses

\[ \nu, \gamma \]

\[ \nu, \gamma \]

\[ \nu, \gamma \]

source

Gamma-ray and neutrinos as probe of UHECR sources

ICRC 2017, 12-20 July, Bexco, Busan, Korea
Electromagnetic cascades

- pair production: $N + \gamma \rightarrow N + e^+/e^- \Rightarrow \text{secondary } e^+/-$
- Pion and meson production:
  
  $\pi^0 \rightarrow 2\gamma$
  
  $\pi^+ \rightarrow \mu^+ + \nu_\mu, \mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e \Rightarrow \text{secondary } e^+/-, \gamma$ and $\nu$
  
  $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu, \mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$

=>$\nu$s energy range is PeV-EeV, the $\gamma$-rays cascade down to GeV-TeV

$e + \gamma_{EBL} \rightarrow e^+ + \gamma$ ICS

$\gamma + \gamma_{EBL} \rightarrow e^+ + e^-$ pair production

=>$\text{The cosmic evolution of cosmic-ray sources have a strong influence on the cosmogenic neutrinos and photons fluxes}$
Mixed composition model

Phenomenological mixed composition model:

1) **EGCR**: hard nuclei spectra + spectral index of the proton component $2.0 < \beta < 2.5$
   - The proton spectrum needs to be softer to fit Kascade-GRANDE data => it will contribute significantly to the expected cosmogenic $\gamma$-ray flux
   - "Low-$E_{\text{max}}$" model => less vs due to the lack of cosmic rays accelerated above the pion production threshold

2) **GCR**: rigidity dependent ($E_{\text{max}}(p) = \text{knee energy}$)
Two different models for the Galactic foreground (Ackermann+ 2015)

- **SFGs** (Ackermann et al. 2012, Fermi Collab.)
- **misaligned AGNs** (Inoue 2011)
- **blazars** (Ajello et al. 2015)

sum of all contributions

**UHECR (GRBs) + misAGN + SFG + blazars**

**UHECR (non evol) + misAGN + SFG + blazars**

E\(^2\)J(E) [eV.cm\(^{-2}\).sec\(^{-1}\).sr\(^{-1}\)]

Resulting gamma-ray fluxes (GRB or SFR)

...even compatible with Model A if one consider the uncertainties on the SFG, misAGN and blazars models

+ uncertainties in the Galactic foreground?
What about most recent estimates of PS contributions?

2 recent studies:
- Ackermann et al. 2016 (A16)
- Zechlin et al. 2016 (Z16)
(based on a method by Malyshev & Hogg 2011)

<table>
<thead>
<tr>
<th>Energy bands (in GeV)</th>
<th>(Z16)</th>
<th>(A16)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1.04–1.99</td>
<td>1.99–5.0</td>
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<tr>
<td>( F_{PS} \times 10^{-9} \text{ cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} )</td>
<td>250( ^{+20}_{-40} )</td>
<td>124( ^{+7}_{-25} )</td>
</tr>
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<td>( F_{PS}/F_{EGB} ) (% Model A)</td>
<td>83( ^{+7}_{-13} )</td>
<td>79( ^{+4}_{-16} )</td>
</tr>
<tr>
<td>( F_{PS}/F_{EGB} ) (% Model B)</td>
<td>68( ^{+5}_{-10} )</td>
<td>63( ^{+4}_{-13} )</td>
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<td>( F_{SFG+misAGN} \times 10^{-9} \text{ cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} )</td>
<td>94(_{+100}^{-36})</td>
<td>44(_{+49}^{-18})</td>
</tr>
<tr>
<td>( F_{SFG+misAGN}/F_{EGB} % \text{ Model A} )</td>
<td>31(_{+33}^{-12})</td>
<td>28(_{+31}^{-11})</td>
</tr>
<tr>
<td>( F_{SFG+misAGN}/F_{EGB} % \text{ Model B} )</td>
<td>25(_{+27}^{-10})</td>
<td>23(_{+25}^{-9})</td>
</tr>
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</table>
Allowed cosmological evolutions

- GRB
- HLLAGN
- MLLAGN
- SFR
- BL Lacs
- clusters

TDEs?

% all contributions to EGB Model A
% all contributions to EGB Model B

Band 4 (10.4 - 50 GeV)
Central value of PS+misAGN+SFG models

Central value of PS+misAGN+SFG models
Resulting neutrinos fluxes

**mixed composition**

- GRB (as main UHECR sources)
- non evol. (as main UHECR sources)
- IceCube
- ARIANNA (5 yrs)
- GRAND (3 yrs)

**pure protons**

- GRB (as main UHECR sources)
- non evol. (as main UHECR sources)
- FR-II (as main UHECR sources)
- IceCube
- ARIANNA (5 yrs)

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Summary

- The mixed composition model is compatible with the spectrum and composition data (Globus, Allard, Parizot Phys. Rev. D 92, 021302) and is consistent with the anisotropy constraints on galactic protons (Tinyakov +16)

- We showed that this model is compatible with both the most recent Fermi-LAT measurements and with current IceCube limits (Globus, Allard, Parizot & Piran ApJ Letters, 839, 2) Only very strong evolution (FR-II) are excluded by the current observations

- There is a large uncertainty in the Galactic foreground subtraction => neutrinos will help us to distinguish between models (proton "dip" model seems to be already ruled out for SFR and stronger evolution see Heinze +16)
thank you
BACK-UP
The model provides a good description of the evolution of the composition

Prediction: the dominant class of nuclei between $\sim 6 \times 10^{18}$ eV and $\sim 5 \times 10^{19}$ eV should be CNO
Extragalactic $\gamma$-ray sources

- **resolved**: blazars
- **unresolved**: misaligned AGNs, SFGs, ...
- **truly diffuse in origin**:  
  - the electromagnetic cascades initiated by both very high energy $\gamma$-rays and UHECRs interacting with the EBL  
  - dark matter annihilation/decay

![EGRB spectrum by Fermi Large Area Telescope (Fermi LAT) collaboration between 100 MeV and 820 GeV](Ackermann et al. 2015)
Comparison with total EGB

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<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$F_{\text{UHECR}}$ ((\times 10^{-10} \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}))</td>
<td>GRB</td>
<td>170</td>
</tr>
<tr>
<td>SFR</td>
<td>200</td>
<td>140</td>
</tr>
<tr>
<td>non evol</td>
<td>42</td>
<td>30</td>
</tr>
<tr>
<td>$F_{\text{UHECR}}/F_{\text{EGB}}$</td>
<td>GRB</td>
<td>4.6</td>
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<tr>
<td>SFR</td>
<td>5.3</td>
<td>7.1</td>
</tr>
<tr>
<td>non evol</td>
<td>1.1</td>
<td>1.6</td>
</tr>
<tr>
<td>$F_{(\text{UHECR+PS+SFG+misAGN})}/F_{\text{EGB}}$</td>
<td>GRB</td>
<td>97</td>
</tr>
<tr>
<td>SFR</td>
<td>98</td>
<td>93</td>
</tr>
<tr>
<td>non evol</td>
<td>94</td>
<td>87</td>
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% Model B

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</tr>
<tr>
<td>$F_{\text{UHECR}}/F_{\text{EGB}}$</td>
<td>GRB</td>
<td>5.7</td>
</tr>
<tr>
<td>SFR</td>
<td>6.5</td>
<td>8.9</td>
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<tr>
<td>non evol</td>
<td>1.4</td>
<td>1.9</td>
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% Model A

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<tr>
<td>$F_{(\text{UHECR+PS+SFG+misAGN})}/F_{\text{EGB}}$</td>
<td>GRB</td>
<td>120</td>
</tr>
<tr>
<td>SFR</td>
<td>121</td>
<td>116</td>
</tr>
<tr>
<td>non evol</td>
<td>116</td>
<td>109</td>
</tr>
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(considering the mean values of the SFG+misAGN models)