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PANIC’11, MIT
Outline

• Why do we study the Galactic Magnetic Fields (GMF)?
• What is known about the GMF?
• GMF models and cosmic ray composition
• Effects of the GMF on Ultra-High Energy Cosmic Rays (UHECR)
• UHECR anisotropy
• UHECR energy spectrum
• What do we learn?
Why do we study the GMF?

- Charged particles deflected in magnetic fields
- To identify the UHECR sources, we need to correct the effects of the magnetic fields
- There are the Galactic and Extragalactic Magnetic Fields (EGMF) that might affect the UHECR
- EGMF is three orders of magnitude smaller than the GMF
- UHECR deflections due to the EGMF are probably negligible compared to those due to the GMF (for “nearby” sources)
What is known about the GMF?

Well known locally: 1-10 \( \mu \) G, geometry
Poorly known: Large scale, Disk and Halo, Field Reversals

Bisymmetric quadrupole \( \leftrightarrow \) Symmetric Spiral \( \leftrightarrow \) Axisymmetric dipole
GMF models and cosmic ray compositions

- GMF models used: BSS_A, BSS_S, ASS_A, ASS_S, ARING (Stanev model)
- Particles are Protons and Iron nuclei
- 10,000 particles from each of the AGN (Z≤0.018) in the VCV catalog
- 55 < Energy < 150 EeV
- At the source: $dN/dE = E^{-\gamma}$, $\gamma = 2$
- Forward-track the particles through GMF using *CRT code

*Sutherland et al, 2010*
BSS_A GMF Model

- 491 observed proton
- 465 AGN
BSS_S GMF Model

Proton

Iron

Proton

Iron
ASS_A GMF Model
ARING GMF Model

Proton

Iron

Proton

Iron
## Results for Whole Sky

<table>
<thead>
<tr>
<th>GMF Models &amp; particles</th>
<th>N1: observed</th>
<th>deflecttion angle avg</th>
<th>observed angle [AGN-evt] avg</th>
<th>N2: angle&lt;3.1°</th>
<th>N2/N1 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSS_S Proton</td>
<td>536</td>
<td>6.6°</td>
<td>3.3°</td>
<td>282</td>
<td>53 ± 4</td>
</tr>
<tr>
<td>BSS_S Iron</td>
<td>537</td>
<td>64.4°</td>
<td>6.2°</td>
<td>160</td>
<td>30 ± 3</td>
</tr>
<tr>
<td>BSS_A Proton</td>
<td>491</td>
<td>7.6°</td>
<td>3.4°</td>
<td>260</td>
<td>53 ± 4</td>
</tr>
<tr>
<td>BSS_A Iron</td>
<td>467</td>
<td>49.5°</td>
<td>5.8°</td>
<td>151</td>
<td>32 ± 3</td>
</tr>
<tr>
<td>ASS_S Proton</td>
<td>447</td>
<td>9.9°</td>
<td>4.5°</td>
<td>198</td>
<td>44 ± 4</td>
</tr>
<tr>
<td>ASS_S Iron</td>
<td>259</td>
<td>85.6°</td>
<td>7.0°</td>
<td>57</td>
<td>22 ± 3</td>
</tr>
<tr>
<td>ASS_A Proton</td>
<td>489</td>
<td>9°</td>
<td>4.6°</td>
<td>175</td>
<td>36 ± 3</td>
</tr>
<tr>
<td>ASS_A Iron</td>
<td>117</td>
<td>75.3°</td>
<td>10.2°</td>
<td>19</td>
<td>16 ± 4</td>
</tr>
<tr>
<td>ASS+RING Proton</td>
<td>476</td>
<td>5.8°</td>
<td>3.5°</td>
<td>255</td>
<td>54 ± 4</td>
</tr>
<tr>
<td>ASS+RING Iron</td>
<td>124</td>
<td>84.4°</td>
<td>6.9°</td>
<td>31</td>
<td>25 ± 5</td>
</tr>
</tbody>
</table>

23 % for isotropic sky
Southern Sky: BSS_S GMF Model

(using Auger Exposure)
## Results for Southern Exposure

<table>
<thead>
<tr>
<th>GMF Models &amp; particles</th>
<th>N3: observed</th>
<th>deflection angle avg</th>
<th>observed angle [AGN-evt] avg</th>
<th>N4: angle&lt;3.1°</th>
<th>N4/N3 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSS_S Proton</td>
<td>203</td>
<td>6.6°</td>
<td>3.4°</td>
<td>103</td>
<td>51 ± 6</td>
</tr>
<tr>
<td>BSS_S Iron</td>
<td>171</td>
<td>70.1°</td>
<td>7.3°</td>
<td>50</td>
<td>29 ± 5</td>
</tr>
<tr>
<td>BSS_A Proton</td>
<td>181</td>
<td>8.7°</td>
<td>3.6°</td>
<td>93</td>
<td>51 ± 6</td>
</tr>
<tr>
<td>BSS_A Iron</td>
<td>171</td>
<td>51.5°</td>
<td>6.2°</td>
<td>55</td>
<td>32 ± 5</td>
</tr>
<tr>
<td>ASS_S Proton</td>
<td>156</td>
<td>11.1°</td>
<td>4.9°</td>
<td>63</td>
<td>40 ± 6</td>
</tr>
<tr>
<td>ASS_S Iron</td>
<td>113</td>
<td>85.8°</td>
<td>6.7°</td>
<td>22</td>
<td>19 ± 4</td>
</tr>
<tr>
<td>ASS_A Proton</td>
<td>175</td>
<td>8.8°</td>
<td>4.7°</td>
<td>57</td>
<td>33 ± 5</td>
</tr>
<tr>
<td>ASS_A Iron</td>
<td>38</td>
<td>69.8°</td>
<td>12°</td>
<td>4</td>
<td>10 ± 5</td>
</tr>
<tr>
<td>ASS+RING Proton</td>
<td>163</td>
<td>6.2°</td>
<td>3.6°</td>
<td>85</td>
<td>52 ± 7</td>
</tr>
<tr>
<td>ASS+RING Iron</td>
<td>42</td>
<td>85.4°</td>
<td>6.3°</td>
<td>9</td>
<td>22 ± 8</td>
</tr>
</tbody>
</table>
Results for Southern Sky compare to the Whole Sky

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<thead>
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<th>GMF Models &amp; particles</th>
<th>N4/N3 (%)</th>
<th>N2/N1 (%)</th>
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<tr>
<td>BSS_S Proton</td>
<td>51 ± 6</td>
<td>53 ± 4</td>
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<td>BSS_A Proton</td>
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<td>53 ± 4</td>
</tr>
<tr>
<td>BSS_A Iron</td>
<td>32 ± 5</td>
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<td>ASS_S Proton</td>
<td>40 ± 6</td>
<td>44 ± 4</td>
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<tr>
<td>ASS_S Iron</td>
<td>19 ± 4</td>
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<td>ASS_A Iron</td>
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<tr>
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23 % for isotropic sky
Observed Energy Spectrum

- Galactic magnetic field can influence the observed energy spectrum
- Does the GMF deflect lower energy events more?
- Does the observed energy spectrum change at lower energies?
Energy Spectrum - BSS_S GMF Model

\[ \frac{dN}{dE} \propto E^{-\gamma} \]

Input spectrum: \( \gamma = 2.00 \)

Fitted \( \gamma = 1.66 \pm 0.15 \)

\( \Delta \gamma = -0.34 \pm 0.15 \)
Observed Energy Spectrum

BSS_S

\[ \Delta \gamma = -0.34 \pm 0.15 \]

\[ \Delta \gamma = 0.24 \pm 0.15 \]

ASS_A

\[ \Delta \gamma = 0.26 \pm 0.17 \]

\[ \Delta \gamma = -0.18 \pm 0.32 \]

ARING

\[ \Delta \gamma = 0.12 \pm 0.17 \]

\[ \Delta \gamma = -1.94 \pm 0.32 \]
Observed Energy Spectrum, Lower Energies

- BSS_S
  - $\Delta \gamma = -0.34 \pm 0.15$
  - $\Delta \gamma = 0.24 \pm 0.15$

- ASS_A
  - $\Delta \gamma = 0.26 \pm 0.17$
  - $\Delta \gamma = -0.18 \pm 0.32$

- ARING
  - $\Delta \gamma = 0.12 \pm 0.17$
  - $\Delta \gamma = -1.94 \pm 0.32$
These plots are for Events with separation angle $< 3.1^\circ$ of an AGN in VCV catalog (Correlated Events)
What do we learn?

• The results are GMF model-dependent.
• For protons the ratio of events correlating is between 33-54% (isotropy= 23%)
• For iron nuclei the ratio is between 10-32%
• Observed energy spectrum does slightly change depending on the model
• Observed energy spectrum does not change significantly at lower energies