Searching for \textit{FERMI} $\gamma$-Ray Diffuse Extragalactic Signal via Cross-Correlations with LSS

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collaboration with
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• Searching for isotropic $\gamma$-ray background signal
• Separating unresolved sources contributions
• Clarifying the origin of IGRB
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Theoretical Background

• Cross-correlation between the extragalactic background and the fluctuation of discrete LSS sources

\[ C^{ij}_l = \frac{2}{\pi} \int k^2 P(k) \left[ G^i_l(k) \right] \left[ G^j_l(k) \right] dk \]

\[ G^i_l(k) = \int \rho_\gamma(z) b_\gamma(z) D(z) j_1[k \chi(z)] dz \]

\[ \rho_\gamma(z) \equiv \int_{L_{\text{MIN}}}^{L_{\text{MAX}}(z)} \Phi_j(L_\gamma, z) L_\gamma \frac{(1 + z)^{-\mu_j(L_\gamma)}}{H(z)} dL_\gamma \]

\[ \mu(L_\gamma) = \mu^* + \beta \times \left( \log_{10}(L_\gamma) - 46 \right) \]

\[ I_j(>E) \equiv \int E \frac{dI_j}{dE} dE = \frac{cE^{2-\Gamma_j}}{4\pi} \int \rho_\gamma(z) dz \]
Unresolved Sources

- **Specific type of unresolved sources**
  - Flat Spectrum Radio Quasars (FSRQs)
  - BL Lacertae objects (BL Lacs)
  - Star-Forming Galaxies (SFGs)
  - Misaligned AGNs (mAGNs)
Bias & Luminosity Density

- **FSRQs:**

\[ b_{\text{FSRQ}}(z) = 0.42 + 0.04(1 + z) + 0.25(1 + z)^2 \]

- **BL Lacs:**

- **SFGs:**

\[ b_{\text{SFG}} = 1 \quad I(E) \propto E^{-\Gamma} \]

- **mAGNs:** The redshift distribution is similar with SFGs that peak at \( z \sim 2 \). The bias is high, however, the constraint is very poor now.

<table>
<thead>
<tr>
<th>Model</th>
<th>( A^a )</th>
<th>( \gamma_1 )</th>
<th>( L_*^b )</th>
<th>( \gamma_2 )</th>
<th>( z_c^* )</th>
<th>( p_1^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLLacs1 LDDE</td>
<td>( 3.39 \times 10^4 )</td>
<td>0.27</td>
<td>0.28</td>
<td>1.86</td>
<td>1.34</td>
<td>2.24</td>
</tr>
<tr>
<td>BLLacs2 LDDE</td>
<td>( 9.20 \times 10^2 )</td>
<td>1.12</td>
<td>2.43</td>
<td>3.71</td>
<td>1.67</td>
<td>4.50</td>
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<tr>
<td>FSRQ LDDE</td>
<td>( 3.06 \times 10^4 )</td>
<td>0.21</td>
<td>0.84</td>
<td>1.58</td>
<td>1.47</td>
<td>7.35</td>
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</table>

<table>
<thead>
<tr>
<th>( \tau )</th>
<th>( p_2 )</th>
<th>( \alpha )</th>
<th>( \mu^* )</th>
<th>( \beta )</th>
<th>( \sigma )</th>
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</thead>
<tbody>
<tr>
<td>4.92</td>
<td>-7.37</td>
<td>( 4.53 \times 10^{-2} )</td>
<td>2.10</td>
<td>( 6.46 \times 10^{-2} )</td>
<td>0.26</td>
</tr>
<tr>
<td>0.0</td>
<td>-12.88</td>
<td>( 4.46 \times 10^{-2} )</td>
<td>2.12</td>
<td>( 6.04 \times 10^{-2} )</td>
<td>0.26</td>
</tr>
<tr>
<td>0.0</td>
<td>-6.51</td>
<td>0.21</td>
<td>2.44</td>
<td>0.0</td>
<td>0.18</td>
</tr>
</tbody>
</table>
FERMI-LAT Flux Maps

• Best experiment to investigate nature of IGRB
  – Wide Energy Range: 20MeV ~ >300GeV
  – Excellent Angular Resolution: ~ 0.1° above 10GeV
  – Large Field of View: ~ 2.4 sr
  – Efficient rejection of background from charged particles

• Final Flux Maps:
  – 60 months of data: 2008 ~ 2013
  – Using *P7REP_CLEAN* event selection: reduce cosmic-ray background contamination
  – Reducing the contamination from the bright Earth limb emission
  – Producing the corresponding exposure maps and dividing the count maps by exposure maps in three energy ranges: > 0.5GeV, > 1GeV, > 10GeV
  – Using both back-converting and front-converting events
Masks used to subtract contaminations

• Applying a **Galactic latitude cut** \(|b| > 30^\circ\) to reduce the impact of the Galactic emission
• Excluding the region associated with the **Fermi Bubbles and the Loop I structure** located at high Galactic latitude
• Removing pixels placed at the positions of all **resolved sources**
• Using **Galactic diffuse emission model** to subtract from the observed emission to obtain the cleaned maps
• Subtracting the contributions from **solar and lunar emission** along the ecliptic
• Removing all contributions from **multipoles up to \(\ell = 10\)** to reduce spurious signals at large scales
Maps and Masks

residuals $E > 500$ MeV

residuals $E > 1$ GeV

residuals $E > 10$ GeV

mask
LSS Galaxies Sources

• We consider five LSS catalogs:
  – Low z: 2MASS, SDSS DR8 Main galaxies, SDSS DR8 LRGs
  – High z: SDSS DR6 QSOs, NVSS

\[
G_i^j (k) = \int \frac{dN(z)}{dz} b_j(z) D(z) j_1 [k \chi(z)] dz,
\]
FERMI x QSO Result

- At $\Theta < 1^\circ$, observe a cross-correlation signal that is more significant in the low-energy band.
- Observations are consistent with theoretical predictions.

\[
TS = \chi_0^2 - \chi_{bf}^2
\]
FERMI x NVSS Result

Fermi-NVSS 500MeV

Fermi-NVSS 1GeV

Fermi-NVSS 10GeV

Fermi-NVSS 500MeV

Fermi-NVSS 1GeV

Fermi-NVSS 10GeV
FERMI x NVSS Result

- Detecting a strong signal at $\Theta < 1^\circ$ and $\gamma > 100$

- Due to a one-halo term, or part of NVSS sources are also themselves γ-ray emitters.

- All models match to the data at $\Theta > 1^\circ$ well.
FERMI x 2MASS Result

- Observing the CCF and CAPS signal at $\Theta < 10^\circ$ and $\ell < 200$ at about 3.5\sigma.
- Contribution from BL Lacs to IGRB diffuse emission is suppressed at low redshift.

\[
\begin{array}{cccc}
\text{2MASS} & \chi^2_{bf} & \sigma & TS \\
8.3 & 3.4 & 11.5 \\
3.7 & 3.6 & 12.8 \\
5.1 & 1.6 & 2.7 \\
\text{2MASS} & \chi^2_{bf} & \sigma & TS \\
6.2 & 3.6 & 12.9 \\
10.6 & 4.4 & 19.4 \\
2.0 & 2.1 & 4.5 \\
\end{array}
\]
FERMI x MGs Result

The diagrams illustrate the results of Fermi-MG 500MeV, Fermi-MG 1GeV, and Fermi-MG 10GeV, showing multipole $l$ vs. $10^{10}|C_l|$ [cm$^{-2}$ s$^{-1}$ sr$^{-1}$] and angle $\theta$ vs. $10^9 C_{\theta}(\|)$ [cm$^{-2}$ s$^{-1}$ sr$^{-1}$]. The data is categorized into BLLacs1, FSRQs, SFGs1, and SFGs2.
FERMI x LRGs Result

Fermi-LRG 500MeV

Fermi-LRG 1GeV

Fermi-LRG 10GeV
• Searching for isotropic γ-ray background signal
• **Separating unresolved sources contributions**
• Clarifying the origin of IGRB
Chisq. Analysis
Summary

- Constraints from objects at low redshifts, like 2MASS and SDSS galaxies, strongly suggest the SFGs dominates the IGRB.
- All models that include a contribution from SFGs provide a significantly better fit than those in which the IGRB is contributed to by AGNs only.
- In all models explored, the IGRB contribution from AGNs is subdominant. When SFGs are included among the IGRB sources, the AGN contribution is consistent with zero.
FERMI-LAT x LSS

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Dark Matter Interpretation

• The combined emission from SFGs, BL Lacs, and FSRQs does not account for whole diffuse IGRB signal completely at low redshifts.

• A certain level of emitted radiation from dark matter annihilation or decay could also contribute the unresolved diffuse IGRB signal.

• We compared the predicted angular cross-correlation between the γ-ray emission induced by DM annihilation or decay in different channels and the distribution of 2MASS galaxies with the measured CCFs between these objects and the Fermi-LAT γ-ray maps (all energy bands together).
Conclusions

• A WIMP DM contribution can fully explain the observed FERMI x 2MASS cross-correlation.

• A canonical WIMP with a mass in the 10–100 GeV range, an annihilation rate around the thermal value, and a realistic model for DM halo and sub-halo properties reproduce both the size and shape of the measured angular cross-correlation.

• The cross-correlation technique is more sensitive to a DM signal than other probes used so far.

see Alessandro Cuoco’s talk tomorrow in DM session
✓ Searching for isotropic γ-ray background signal
✓ Separating unresolved sources contributions
? Clarifying the origin of IGRB (Needs more data)
Thanks!