Fermi-LAT Observations of γ-ray Emission Towards the Outer Halo of M31

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Abstract

The outer halo of M31 has a radial extension of ∼300 kpc (i.e. the canonical virial radius), which corresponds to a diameter of 42° on the sky for an M31–Milky Way (MW) distance of 785 kpc. γ-ray emission from M31's outer halo may arise from the interaction of high energy cosmic-rays (CRs) with the radiation field of the stellar halo and/or the circumgalactic gas. Additionally, it may arise from more exotic processes such as dark matter (DM) annihilation or decay. Using 7.6 years of *Fermi*-LAT observations, we make a detailed study of the γ-ray emission between 1–100 GeV towards M31's outer halo, with a total field radius of 60° centered at M31, and we perform an in-depth analysis of the systematic uncertainties related to the observations.

We find evidence for a spherically symmetric excess that appears to be distinct from the conventional MW foreground. We discuss possible interpretations of the excess emission, but emphasize that uncertainties in the MW foreground, and in particular modeling of the H I-related components, have not been fully explored and strongly impact the results. We find that a DM interpretation provides a good description of the emission and is consistent with the DM interpretation of the GC excess. Better understanding of the systematics and complementarity with other DM searches is critical to settle the issue.

Observations

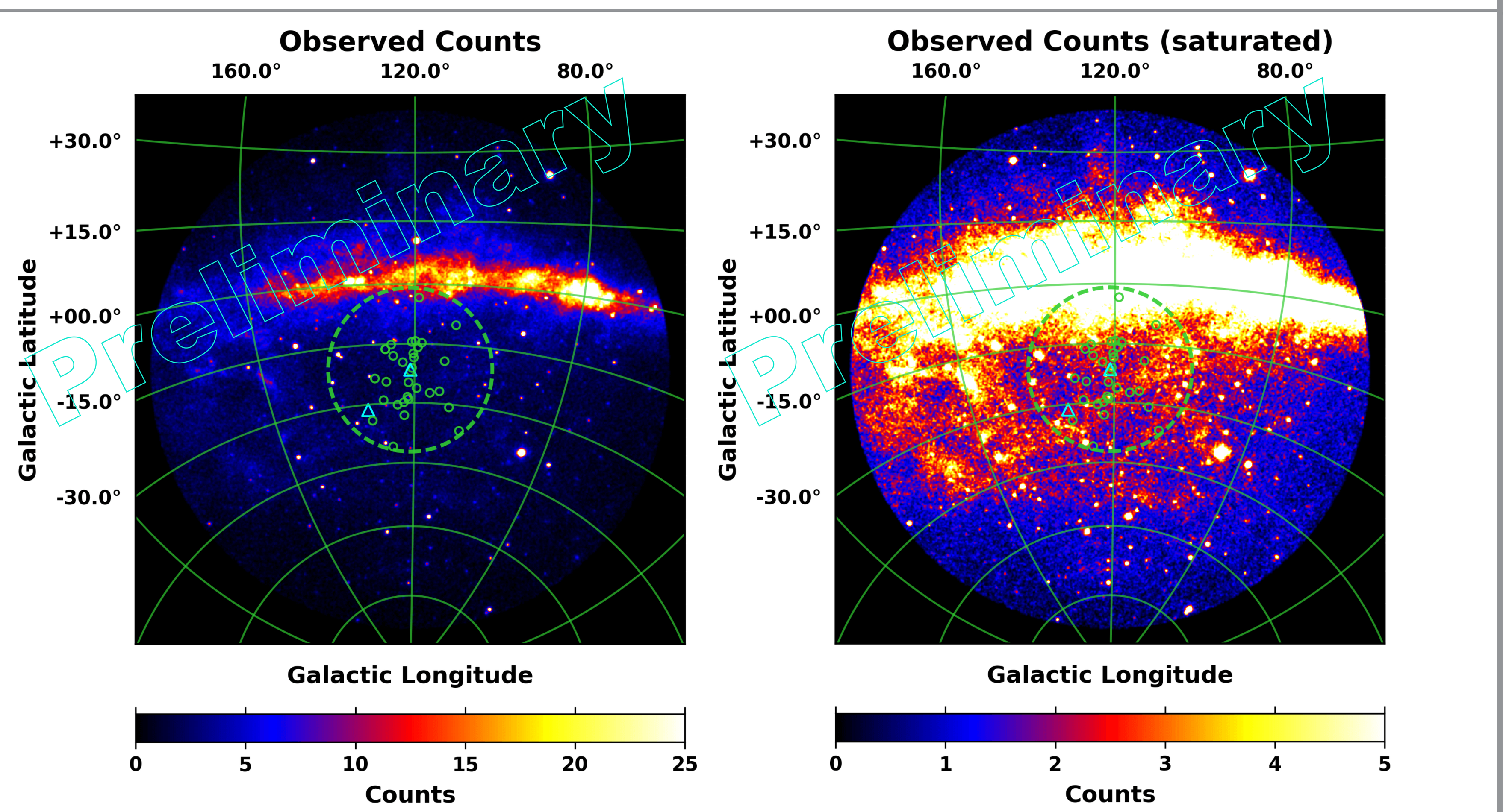

Figure 1: Observed counts (left) and saturated counts (right) for a 60° radius centered at M31. The green dashed circle (21° in radius) corresponds to a 300 kpc projected radius centered at M31, for a MW-M31 distance of 785 kpc, i.e. the canonical virial radius of M31. Also shown is M31's entire population of dwarf galaxies. M31 and M33 are shown with cyan triangles, and the other dwarfs are shown with 1° green circles, each centered at the optical center of the respective galaxy. The sizes of the circles are a bit arbitrary, although they roughly correspond to the PSF (68% containment angle) of *Fermi*-LAT, which at 1 GeV is ∼1°. Most of the MW dwarfs are not detected by *Fermi*-LAT, and likewise we do not expect most of the individual M31 dwarfs to be detected. The primary purpose of the overlay is to provide a qualitative representation of the extent of M31's outer halo, and to show its relationship to the MW disk. Note that ∼3 dwarfs (which are gravitationally bound to M31) reach as far as ∼300 kpc, as seen in the figure.

Building the IEM with GALPROP

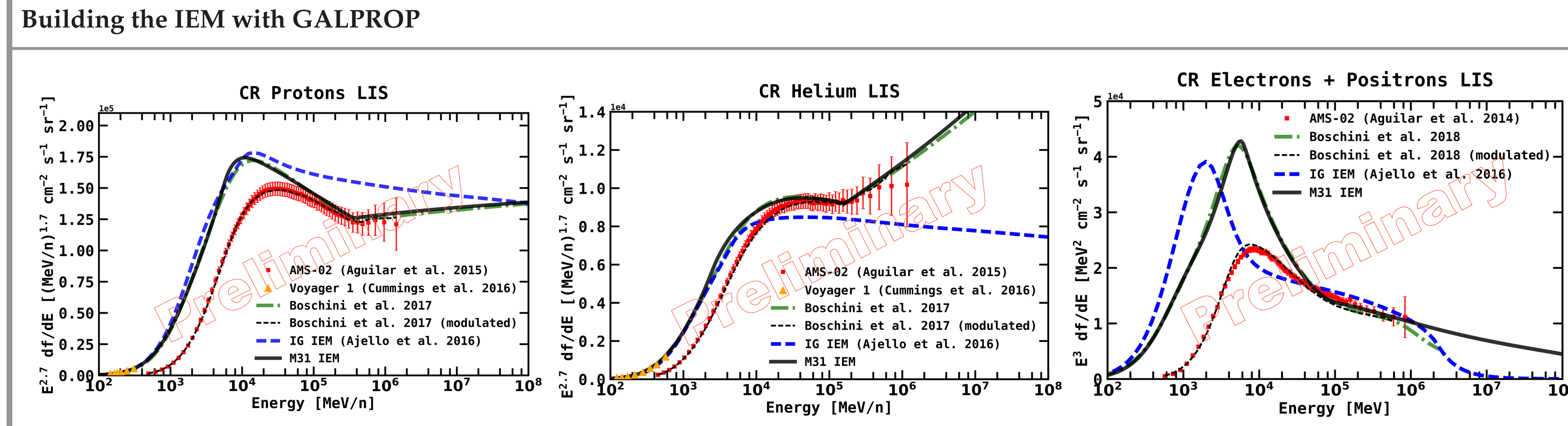

Figure 2: The local interstellar spectra (LIS) for CR protons (left), helium (middle), and all electrons ($e^- + e^+$) (right). The latest AMS-02 measurements from Aguilar et al. 2015 are shown with red squares. The green dashed line shows the results from Boschini et al. 2017,2018, which employ GALPROP and HelMod together in an iterative manner to derive the LIS. We adopt their derived GALPROP CR parameters, and the LIS for our IEM (M31 IEM: solid black line) are roughly the same. The thin dotted black line shows the LIS modulated with HelMod (Boschini et al. 2017,2018). Yellow triangles show the Voyager 1 p and He data in the local interstellar medium (Cummings et al. 2016). Voyager 1 electron data are below 100 MeV and, therefore, are not shown. In addition we show the LIS for the ("Yusifov") IEM in Ajello et al. 2016, which we use as a reference model.

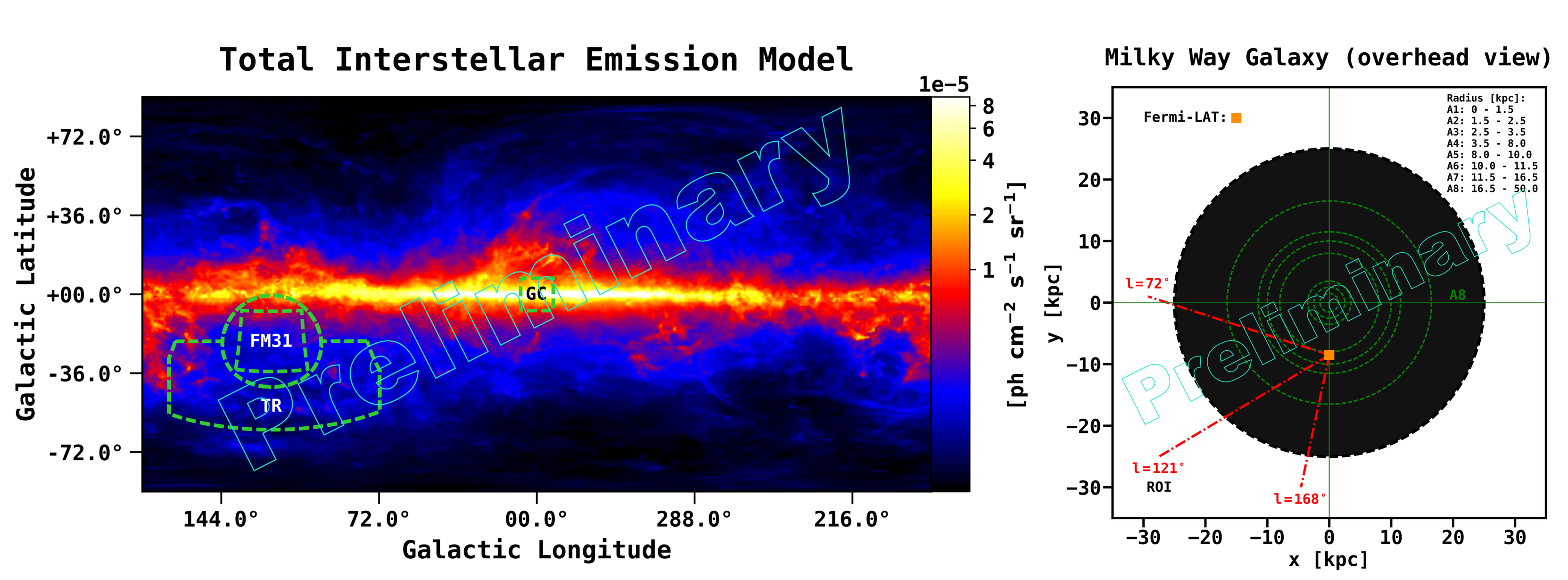

Figure 3: Left: The total interstellar emission model (IEM) for the MW integrated in the energy range 1–100 GeV. The color corresponds to the intensity, and is shown in logarithmic scale. The model has contributions from π^0-decay, (anisotropic) IC emission, and Bremsstrahlung. Overlaid is the region of interest (ROI) used in this analysis. From the observed counts we cut a 84° × 84° region, which is centered at M31. The green dashed circle is the 300 kpc boundary corresponding to M31's canonical virial radius. We label the field within the virial radius as field M31 (FM31), and the region outside (and south of latitudes of −21.57°) we label as the tuning region (TR). Longitude cuts are made on the ROI at $l = 168°$ and $l = 72°$. For reference we also show the Galactic center region (GC), which corresponds to a 15° × 15° square centered at the GC. **Right:** Schematic of the eight concentric circles which define the annuli (A1–A8) in the IEM. The ranges in Galactocentric radii are reported in the legend. Note that the full extension of A8 is not shown. Only A5–A8 contribute to the Galactic foreground emission for the field used in this analysis.

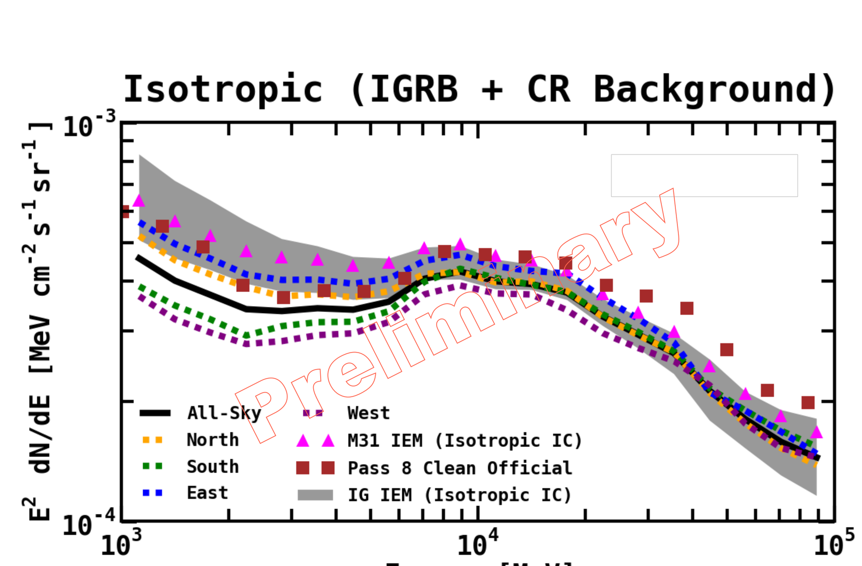

Figure 4: The spectrum of the isotropic component has a dependence on the IEM and the ROI used for the calculation, as well as the data set. For the M31 IEM (which uses the AIC sky maps) we calculate the **All-Sky** (solid black line) isotropic component in the following region: $|b| \geq 30°$, $45° \leq l \leq 315°$. We also calculate the isotropic component in the different sky regions: **North**: $b \geq 30°$, $45° \leq l \leq 315°$ (orange dashed line); **South**: $b \leq -30°$, $45° \leq l \leq 315°$ (green dashed line); **East**: $|b| \geq 30°$, $180° \leq l \leq 315°$ (blue dashed line); and **West**: $|b| \geq 30°$, $45° \leq l \leq 180°$ (purple dashed line). Magenta triangles show the all-sky isotropic component for the M31 IEM derived using the isotropic IC formalism. The brown squares show the official FSSC isotropic spectrum (iso_P8R2_CLEAN_V6_v06). The grey band is our calculated isotropic systematic uncertainty for the IG IEM (which uses the isotropic IC formalism).

Results

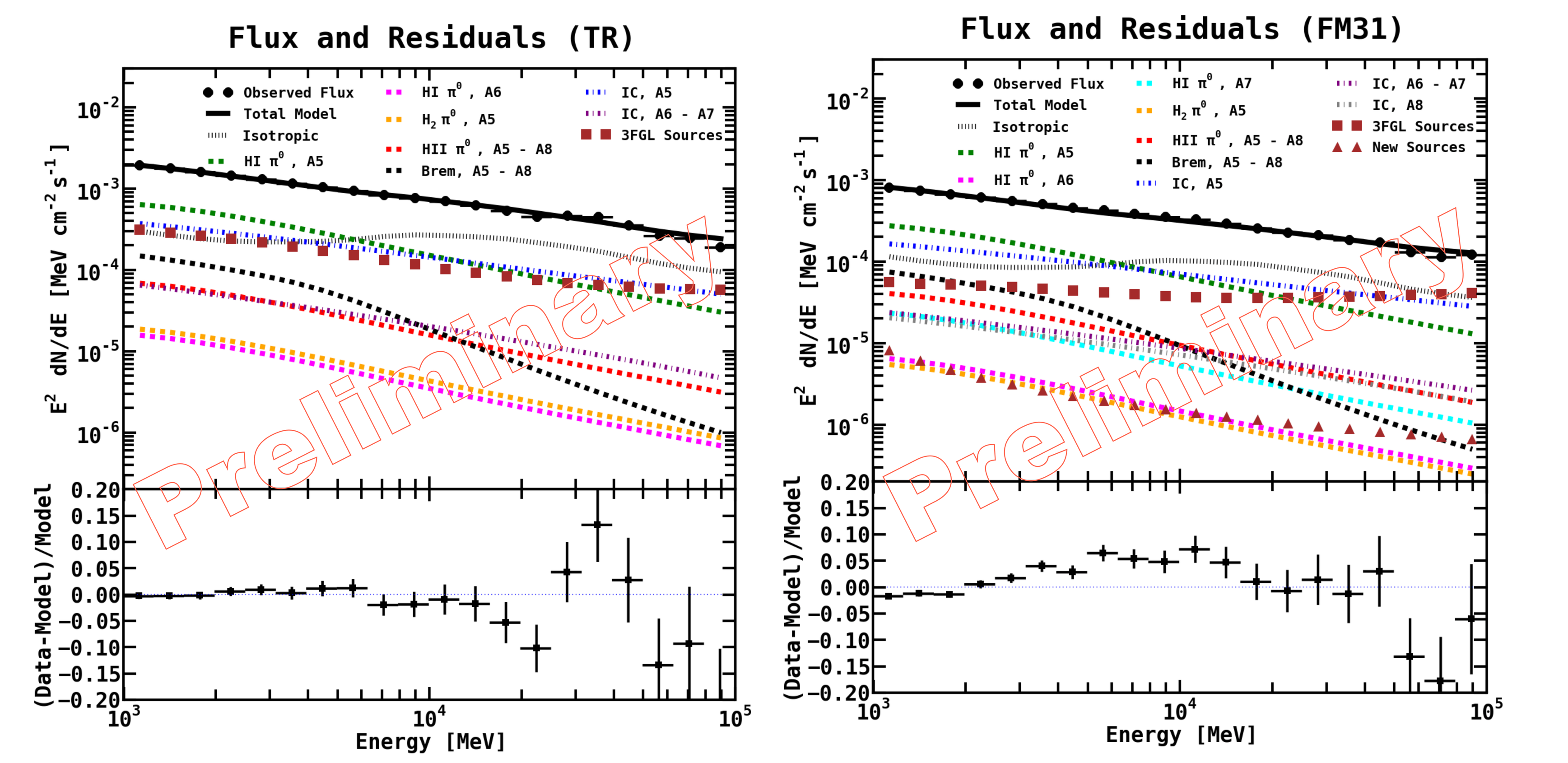

Figure 5: Left: Flux (upper panel) and fractional count residuals (lower panel) for the fit in the TR. The residuals show fairly good agreement over the entire energy range. **Right:** Flux (upper panel) and fractional count residuals (lower panel) for the baseline fit in FM31. The fractional residuals show an excess between ∼3–20 GeV reaching a level of ∼4%. Above and below this range the data is being over-modeled as the fit tries to balance the excess with the negative residuals.

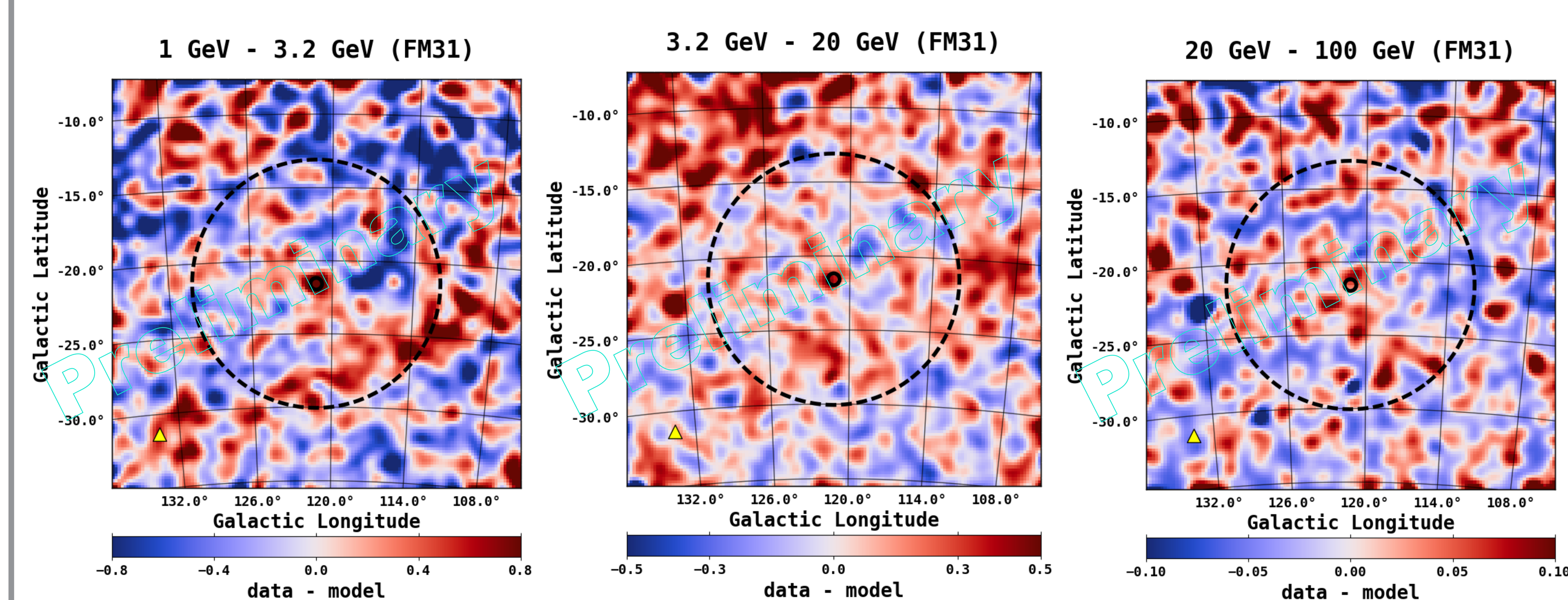

Figure 6: Spatial count residuals (data − model) resulting from the baseline fit in FM31 for three different energy bands, as indicated above each plot. The energy bins are chosen to coincide with the excess observed in the fractional residuals. The color scale corresponds to counts/pixel, and the pixel size is 0.2° × 0.2°. The images are smoothed using a 1° Gaussian kernel. This value corresponds to the PSF (68% containment angle) of *Fermi*-LAT, which at 1 GeV is ∼1°. For reference, the position of M33, $(l, b) = (133.61°, -31.33°)$, is shown with a yellow triangle. We eventually add to the model three symmetric M31-related templates, as discussed below. The boundaries for these templates are overlaid to the residual maps. The solid black circle (0.4° in radius) shows the boundary for the inner galaxy template. The dashed black circle (8.5° in radius) shows the boundary for the spherical halo template. The far outer halo template covers the remaining extent of the field. Further details are given in Figure 8.

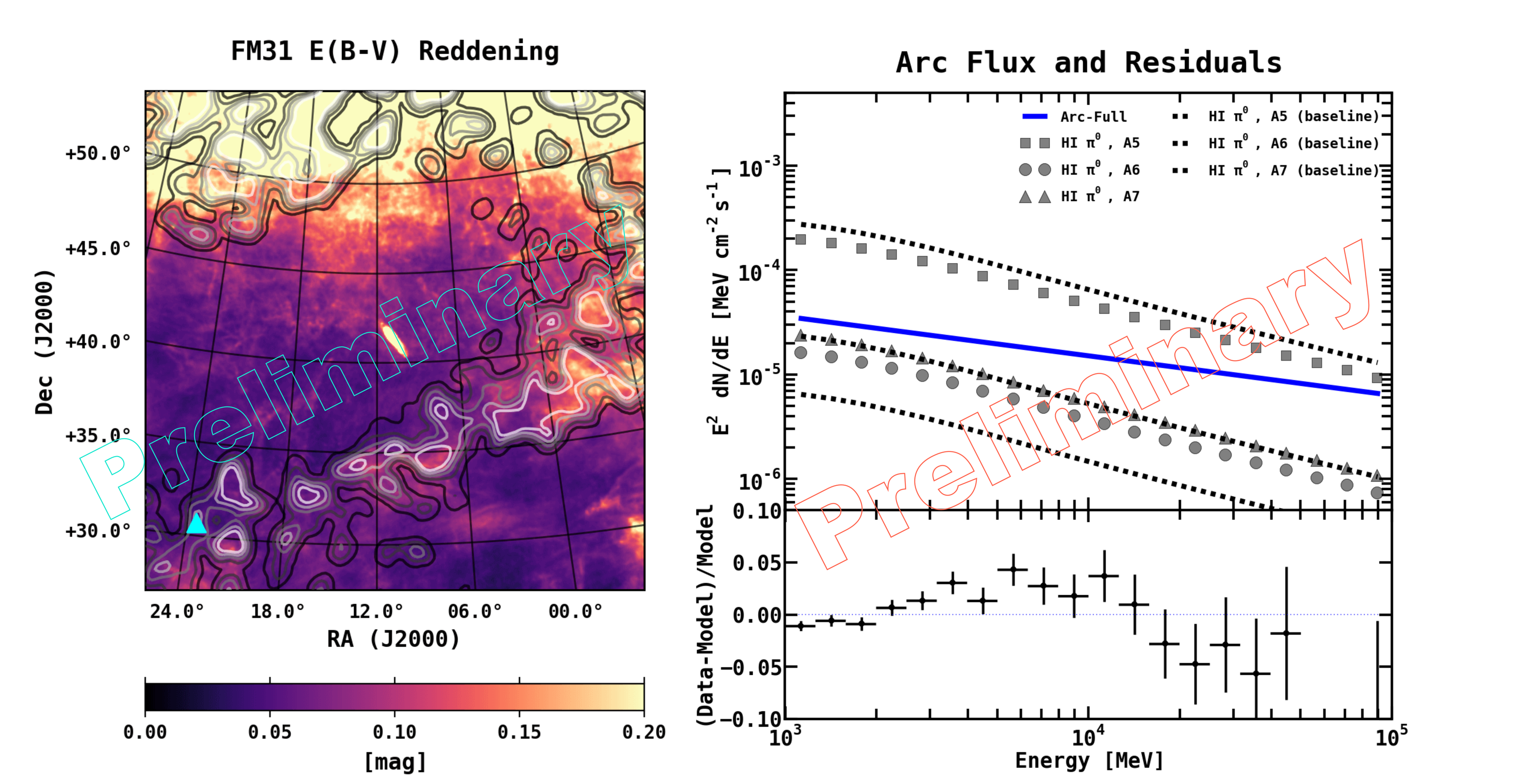

Figure 7: Left: The dust reddening map for FM31 from Schlegel et al. 1998. Overlaid are contours for the arc template, which is added to the model to account for the arc feature observed in the residuals, likely related to inaccuracies in the foreground model (at least the upper portion of the arc). The cyan triangle shows the (projected) position of M33. **Right:** Spectra and fractional energy residuals resulting from the arc fit. The arc component is given a power law spectrum, and the normalization is fit simultaneously with the other components in the region, just as for the baseline fit. The blue solid line is the best-fit spectrum for the arc template. The bottom panel shows the remaining fractional residuals. Downward pointing blue and green triangles give upper-limits. The arc template is unable to flatten the excess between ∼3–20 GeV.

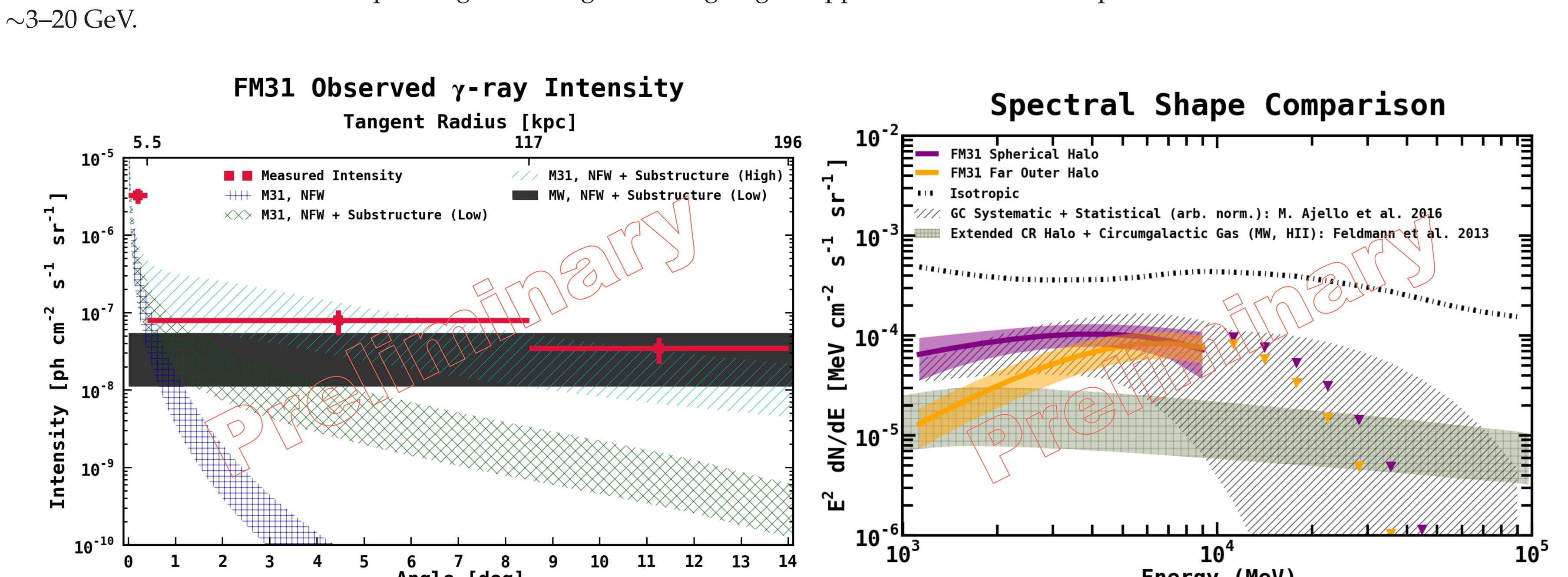

Figure 8: We model M31 and its outer halo with three symmetric uniform templates centered at M31. The inner disk (inner galaxy) has a radial extension of 0.4° (5.5 kpc projected radius). The intermediate ring (spherical halo) has a radial extension from $0.4° < r \leq 8.5°$ (117 kpc projected radius), and it encloses a majority of M31's globular cluster population and stellar halo, as well as a large lopsided H I cloud centered in projection on M31, possibly associated with the M31 system, i.e. the M31 cloud. The outer ring (far outer halo) covers the remaining extent of our primary M31 field (FM31), corresponding to a total projected radius of ∼200 kpc. The boundaries for the M31-related components are shown in Figure 6. The fit also includes the arc template. The M31-related components (inner galaxy, spherical halo, and far outer halo) are detected at the significance levels of 7σ, 7σ, and 5σ, respectively. We discuss plausible interpretations of the observed residual emission, but emphasize that uncertainties in the MW foreground, and in particular modeling of the H I-related emission, have not been fully explored and strongly impact the results. **Left:** Radial intensity profile for the M31-related components. For reference, we compare the radial profile to expectations for DM annihilation in the line of sight, including the contribution from the MW halo. **Right:** Spectral shape comparison to the Galactic center excess (for an arbitrary normalization), as observed in Ajello et al. 2016. Also shown is a prediction for CRs interacting with the ionized gas of the circumgalactic medium from Feldmann et al. 2013. Note that the prediction is for a MW component, but we are primarily interested in a spectral shape comparison. For reference, the isotropic component is plotted as well.