Fermi-LAT observations of \( \gamma \)-ray emission towards the outer halo of M31

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We find evidence for an extended excess that appears to be distinct from the conventional MW foreground, having a total radial extension upwards of ~120-200 kpc from the center of M31...
CRs in the interstellar medium

Gamma rays:
- Trace the whole Galaxy
- Line of sight integration
- Only major species (p, He, e)

CR measurements:
- Detailed information on all species
- Only one location
- Solar modulation

Modeling is a must!
Original motivation

✧ Pre-GALPROP (before ~1997)
  ✧ Leaky-box type models: simple, but not physical
  ✧ Many different simplifying assumptions – hard to compare
  ✧ Many models, each with a purpose to reproduce data of a single instrument
  ✧ No or few attempts to make a self-consistent model

✧ Two key concepts are forming the basis of GALPROP

I. One Galaxy – a self-consistent modeling:
   Various kinds of data, such as direct CR measurements including primary and secondary nuclei, electrons and positrons, γ-rays, synchrotron radiation, and so forth, are all related to the same astrophysical components of the Galaxy and, therefore, have to be modeled self-consistently

II. As realistic as possible:
   The goal for GALPROP-based models is to be as realistic as possible and to make use of all available astronomical and astrophysical information, nuclear and particle data, with a minimum of simplifying assumptions
Components of GALPROP

✧ Propagation, diffusive acceleration, convection, energy losses…
✧ Numerically solves transport equations for all cosmic ray species (stable + long-lived isotopes + pbars + leptons ~90) in 2D or 3D
✧ Derives the propagation parameters corresponding to the assumed transport phenomenology and source distribution
✧ Cosmic ray source distribution(s)
✧ Detailed gas distribution from HI and CO gas surveys (energy losses from ionization, bremsstrahlung; secondary production; γ-rays from π0-decay, bremsstrahlung)
✧ Interstellar radiation field (inverse Compton losses/γ-rays for e±)
✧ B-field models
✧ Nuclear & particle production cross sections + the reaction network (cross section database + LANL nuclear codes + phenomenological codes)
Andromeda galaxy M31 – a closest spiral

- Similar to the Milky Way at 778 kpc
- Provides an external view on our own Galaxy
- Large size on the sky $3^\circ \times 1^\circ$ – easy to resolve
- The rotation curve remains constant over large distances – large content of DM
- Virial radius $\sim 300$ kpc

Rubin & Ford 1970

from Vera Rubin, 2006
The interstellar emission model for the MW (1-100 GeV):

- $\pi^0$-decay + (anisotropic) inverse Compton + Bremsstrahlung

“Square” region is M31 field (28°×28°)

“TR” labels the test region

Schematic of the eight concentric circles which define the annuli (A1-A8) in the MW foreground model. Only A5-A8 contribute to the Galactic foreground emission for the field used in this analysis.
Production of high energy $\gamma$-rays

- $pp \rightarrow \pi^0(2\gamma)+X$ – production and decay of neutral pions $\pi^0$ and Kaons $K^0$
- Inverse Compton Scattering
- Bremsstrahlung
- Synchrotron emission
Tuning to local CR measurements

- We use latest AMS-02 and Voyager data
- Heliospheric propagation is calculated using the dedicated HelMod code (Boschini et al. 2017, 2018)
- LIS – local interstellar spectrum
- IG – inner Galaxy LAT paper (tuned to old CR data)
γ-ray maps for $\pi^0$-decay for different rings (GALPROP) – 1

HI gas

H II, H$_2$ gas
γ-ray maps for anisotropic IC for different rings (GALPROP) –2

(Local) Anisotropic Inverse Compton Emission, A5

AIC/IC Flux Ratio

Anisotropic Inverse Compton Emission, A6-A7

AIC IC Flux Ratio

Anisotropic Inverse Compton Emission, A8

Anisotropic/isotropic ratio illustrates the importance of the effect that reaches a factor of 1.7 for certain directions and is non-uniform on the sky
Flux and fractional count residuals for the fit in the TR and FM31.

- The fractional residuals (FM31) show an excess between 3-20 GeV reaching a level of 4%.
- Residuals at HE is due to the spectral approximation of the 3FGL sources.
3FGL sources: Spectral changes at HE

3FHL J0617.2+2234e (IC443)

3FHL J0205.5+6449 (PSR J0205+6449)

3FHL J1104.4+3812 (Mkn 421, z = 0.03)

3FHL J0222.6+4302 (3C 66A)

$V=\text{variable}$
2D residuals in Tuning Region

✧ Test region demonstrates spatially uniform distribution of the residuals
✧ The fit is used to fix the isotropic background normalization
✧ The isotropic background derived in different regions shows moderate spectral variations, while overall shape remains the same
FM31: Spatial residuals

- Spatial count residuals (data – model) resulting from the baseline fit in FM31 for three different energy bands. Smoothed using 1° Gaussian kernel. The pixel size is 0.2°×0.2°
- The “arc” structure is clearly seen in the 1st and 2nd pixels (see the Arc Template on the left)
- M33 is in the bottom left angle
- Dashed circle – “spherical halo” of 117 kpc radius (8.5°)
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Arc flux and residuals

Simultaneous fit of the arc template with other components

Power-law (left) and power-law with exponential cutoff (right) spectral fits are unable to flatten the residuals in the range 3-20 GeV

The right panel shows a separate fit of two parts of the arc (North and South)

The index of the arc emission has a value ~2.0-2.4, notably flatter than other components
2D residuals after the Arc fit

✧ Subtraction of the Arc template flattens the 2D residuals, which show no obvious residual structure
What is the arc? Loops, loops, loops...

✧ There are ~17 so-called Loops found on the sky in radio and polarized radio emission; some of them are seen in $\gamma$-rays (e.g., famous Loop I)

✧ Loops or Spurs are large structures covering a significant part of the sky – their origin is unknown

✧ A part of the shell of Loop III seems to be associated with the north part of the arc, and Loops II and IIIIs are covering the entire ROI

✧ The Arc could be a part of the old Loop III or other Loops; hard spectrum – particle acceleration
Adding M31 components: all-component fit

Three spherically symmetric templates centered at M31 are added to the model: inner galaxy (IG), spherical halo (SH), and far outer halo (FOH).

Templates are given PLEXP spectral models and fit simultaneously with other components of the IEM, including the arc template. Two fit variations are performed, amounting to two different variations in the arc template: full arc with PL, arc north and south with PLEXP.

IG, SH, and FOH are detected at the significance levels of 7σ, 7σ, and 5σ, respectively. Results for the two fit variations are similar.

Spectral shapes (SH, FOH) are noticeably different from other components.
Excess in different foreground models

- A systematic excess is observed between 3–20 GeV at the level of 3–5% independently on the background (foreground) model used.
- Absent only in case of the foreground model that is built using the LAT data itself, yet with free index (FSSC index scaled).

Interestingly, isotropic component has a “bump” in the same energy range as the observed excess.

- Dark Matter halo around the Milky Way?
Spectrum of the excess and interpretation

- Spectral shape is not resembling other CR-related components
- FM31: properties of the extended (DM?) halo remain highly uncertain
- Consistent with DM interpretation of the Galactic center excess (requires a large boost factor)
- Decaying DM looks more natural
The big picture (illustrative)

MW-M31-like pairs (example) from Garrison-Kimmel et al. (2018)
The problem of dark matter (hidden mass) and its detection

Thanks!