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Understanding the Galactic Center Gamma-Ray Excess: Theory Prospects

Thematic Areas:

■ (CF1) Dark Matter: Particle Like
■ (TF09) Astro-Particle Physics and Cosmology

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Abstract:
An excess of GeV gamma rays from the Galactic Center has been definitively detected by the Fermi Gamma-Ray Space Telescope. The leading explanations for this Galactic Center Excess (GCE) are a new population of millisecond pulsars or annihilating dark matter. Conclusively determining the origin of these gamma rays will either furnish the first evidence of dark matter interactions with the Standard Model, or will establish the existence of a new population of pulsars. We discuss the actions that can be taken to solve this problem, focusing in this LoI on advances in the theoretical understanding and treatment of the signal. This includes improving the modeling of astrophysical diffuse, extended, and point-source emission; understanding the limitations and characterizing the uncertainties of current fitting methods, and encouraging development of new methods; and calculating and finding complementary signals that can increase or decrease our confidence in an astrophysical or non-Standard Model explanation of the excess.

Improving Diffuse Models: Astrophysical gamma-ray emission arises from processes which we classify as "diffuse", "extended", or "point-like." Each of these requires improved modeling, which will come from improved analytical understanding and dedicated computational resources.

The dominant source of photons in the GeV energy range observed by gamma-ray telescopes like Fermi-LAT is the Galactic diffuse emission (GDE). It arises due to cosmic rays, accelerated from a variety of mechanisms, impacting regions of gas, dust, and starlight that are concentrated in the center of the Galaxy. The GDE must be understood before we can draw conclusions about the GCE. Building up new GDE models is a complicated task requiring new modeling techniques, fits to new multi-wavelength data, and substantial computing resources. One critical improvement will be increasing the resolution of gas maps. Most available gas maps in the literature assume circular orbits of interstellar gas, some amount of temporal stability, and certain tracers of only limited completeness and fidelity. The central molecular zone (CMZ) is particularly problematic to model. Separately, inverse Compton scattering (ICS) requires an improved understanding of: star-forming regions and the distribution and intensity of associated light; the propagation of leptons, which are susceptible to Galactic winds and other local phenomena; and the energetics, stability, and associated signals of transient injection [1–3]. To this end, we must make use of (local) cosmic-ray observations from the Alpha Magnetic Spectrometer (AMS-02) on board the International Space Station, as well as broad multi-messenger observations from radio to MeV and TeV energies, which will constrain the ICS emission and disentangle its degeneracies with synchrotron.

Presently, these ingredients are converted to gamma-ray emission maps assuming cylindrical symmetry of cosmic ray diffusion, but resolving the mystery of the GCE calls for anisotropic, three-dimensional modeling of diffuse emission. Promising initial work [4;5] remains impeded by computational challenges. Hydrodynamic simulation of interstellar gas [6–8] provides a viable way forward to resolve the distribution of gas in a region where the gas orbits are highly non-circular. Ultimately, these modeling and computational strides are urgently required to reduce the (correlated) systematic GDE emission uncertainties.

Fitting Methods: While the GCE is detected at a very high statistical significance, the systematic uncertainty is large, deriving from the significant underlying uncertainties on the GDE, extended sources, and point sources. Characterizing the GCE in the presence of these large systematic uncertainties is a crucial step for the near-term future. One well-developed method for characterizing the excess is the non-Poissonian template fit (NPTF) [9–11], but recent demonstration of bias in NPTF results has called into question some of the conclusions [12–14]. While efforts to reduce the susceptibility of NPTF results to diffuse mismodeling have commenced [15;16], substantial additional theoretical effort will be required before we can draw final conclusions based on the NPTF. For example, the NPTF does not yet incorporate energy information; spectral information could play a determining factor in how we interpret the NPTF results.

Wavelet-based approaches to the data [17–20] offer a different perspective on the GCE. These approaches seek to increase the signal-to-noise for a given GCE hypothesis [17;20] and/or reduce systematic background uncertainties [18;19] at the cost of reducing statistical significance. While these approaches are so far inconclusive, they have furnished evidence that a millisecond pulsar population with a luminosity function described by a power law with a constant index across many decades in luminosity, once considered a leading alternative to dark matter annihilation [21–26], is not a viable candidate to explain the GCE [20].

Given the advances and challenges listed above, it is timely to reconsider our fitting methodologies. Convolutional neural networks [27;28], perhaps extended to approximate Bayesian computation and likelihood-free inference, offer one such path to weigh in on the GCE. Probabilistic cataloging [29;30] improves spatial resolution at the cost of a large-scale computational challenge. Extending fits to simultaneously utilize rich multi-wavelength data can constrain the origins of the GCE, especially given expected observational strides.

Improving Extended and Point-Like Templates: Astrophysical emission components other than the semisteady-state GDE will be important for understanding the GCE. For example, the Fermi Bubbles are extended gamma-ray lobes that dominate emission at high latitudes and high energies. Their low-latitude extension, where they are potentially degenerate with the GCE, may be spectrally and morphologically distinct from their well-observed high-latitude component. Understanding the origin of the Fermi Bubbles will be critical to utilizing extended templates for these gamma rays in sky regions that are relevant for the GCE. Two other extended emission components that lie along the Galactic plane[19], and which have as yet undetected counterparts in other wavelengths, call for improved modeling as well.

Similarly, the Galactic stellar bulge must be modeled in greater fidelity before we can make final conclusions about the nature of the GCE. State-of-the-art bulge models were obtained using[31] VISTA Variables Via Lactea (VVV) data to study the population of Red Clump (RC) giants in the Galactic bulge. The SkyFACT algorithm[31;32] has been used to obtain a non-parametric model of the spatial distribution of the RC giant stars in the Galactic bulge. These new (peanut-like) templates may provide a significantly better fit[31] to the data than the boxy bulge templates[33]. Some studies in fact indicate a preference for a stellar bulge over spherically symmetric emission at the Galactic center[7;8;34;35]. Understanding the sensitivity of these results to fitting choices, systematically accounting for possible degeneracies with other emission including point sources and the Fermi Bubbles, and, ultimately, interpreting the implications for dark matter annihilation are of utmost importance, and it is important to test the Galactic bulge templates with current fitting techniques (discussed in more detail below). Dynamical evolutionary modeling of the bulge combined with population synthesis modeling of gamma-ray populations[36;37] will constrain what astrophysical source classes can explain and help provide theoretical guidance on interpretation of gamma-ray detections.

Before assigning a final interpretation to the GCE, we must also understand in a data-driven way if the GCE itself is significantly asymmetric with respect to any spatial axes, as appears compatible with recent theoretical investigations[13;14]. Higher fidelity numerical simulations, using insights and constraints from the Gaia satellite, can be used to understand the allowed morphologies of a dark matter signal, for instance. Alternately, ideas from image processing can dissect the data in novel ways, allowing access to new aspects of the GCE without forward modeling.

Finally, other gamma-ray emission components such as isotropic emission and complete point source catalogs are also critical for understanding the GCE. These will principally improved from the observational perspective, but theoretical advances will need to consistently incorporate these data in their entirety.

Complementary Signals: Understanding the implications of annihilating dark matter in other search channels is important. Here we highlight a few routes for confirming or testing the origin of the GCE.
Anti-nucleus production – Dark matter annihilation that produces a bright gamma-ray signal will also produce anti-nuclei at observable, but highly uncertain, rates[38;39]. Improving this situation will require improved modeling and incorporation of novel accelerator-based data sets.
Dwarf Spheroidals – Lower-background regions of the sky with high dark matter content have great bearing on interpretations of the GCE. Recent strides in modeling the density profiles of classical dwarf-spheroidal galaxies (dSphs)[40] are important to extend to ultra-faint objects (more of which are discovered all the time[41]), which potentially have similarly high or higher J-factors for dark matter annihilation[42]. Simultaneously, it is critical to accurately account for the systematic uncertainties incurred by using these targets[43].
Extragalactic Emission – Gamma-ray emission from the M31 bulge exhibits some similarities with the GCE[34;44]; improved observations and theoretical studies might shine some light on the origin of the gamma-ray emission in bulges of star-forming galaxies. Somewhat related, it is also possible the signal at high latitudes within the Milky Way (away from the Inner Galaxy) would be observable[45;46].
Other Wavelengths – Dark matter annihilation would produce a population of energetic e^+e^- pairs. The signal from the synchrotron losses of these leptons[47] would be important to model and hopefully observe with a future MeV gamma-ray satellite.

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