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Understanding the Galactic Center Gamma-Ray Excess: Observational 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. Solving this problem is of pressing importance; we may either find the first evidence of dark matter interactions with the Standard Model, or confirm 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 observations that can be performed now or in the future. This includes new observations of the pulsar candidates in radio, X-ray, gravitational waves, or with TeV gamma rays. For dark matter, this includes understanding complementary signals as they may appear in other wavelengths and experiments, as well as improving of models of DM profiles for the Milky Way.

Understanding the shape of the GCE energy spectrum: The shape of the GCE gamma-ray energy spectrum can help reveal its origin. While the best-fit parameters for annihilating dark matter (DM) and millisecond pulsars (MSPs) are predicted to produce a comparable spectrum, they differ most in their predictions below $\sim$GeV energies. At such energies, Fermi-LAT's point spread function substantially degrades, introducing large systematics that obscure the low-energy part of the spectrum. To detect meaningful deviations at the low-energy end, new MeV gamma-ray telescopes are required. New telescopes such as eASTROGAM [1] and AMEGO [2], will be more sensitive to this part of the spectrum, and therefore may be able to differentiate the two hypotheses. The expected sensitivity to point sources with eASTROGAM is a factor of 2 better for extragalactic objects than 10 years of Fermi data, for a 1-year observation (1.2×10^{-12} erg/cm^2/s vs 2.8×10^{-12} erg/cm^2/s at 100 MeV) [1]. An additional GCE hypothesis, other than DM or MSPs, is a cosmic-ray outburst event. Compared to MSPs and DM, outburst activity from the GC can endure energy losses that soften the energy spectrum at further distances from the GC [3;4], producing a marked difference in the spatial dependence of the signal. While currently the spectrum seems invariant in its position and shape [5], disfavoring an outflow event, an important task is to reduce large systematic uncertainties. Lastly, if the GCE is produced by the stellar bulge rather than DM, as is favored in some studies [6–9], more detailed spectral analyses would be needed to determine any remaining potential DM contributions.

Understanding the GCE pulsar luminosity function: If the GCE arises from MSPs, their luminosity function provides a handle on the number of expected GCE MSPs. It is important to understand if there is conflict between potential GCE MSPs with the MSP luminosity function of known pulsars in globular clusters or the disk [10–15]. Wavelet studies have set constraints on the potential GCE pulsar luminosity function [14], requiring a very large number of new pulsars to explain the GCE. A better understanding of the total number of pulsars/MSPs in the MW may set a strong bound on the luminosity function. The luminosity function can also be used to determine the number of expected detections in X-ray. While being spun-up by a stellar companion to become a MSP, MSPs exist for a time as a low-mass X-ray binary (LMXB). If one expects a similar MSP birth for the GCE and the MW's globular cluster population, the ratio of MSPs to LMXBs should be similar. The number of LMXBs already detected in the GCE region can be used to estimate the size of the population of GCE MSPs, and the number of LMXBs has found to be severely too low compared to the required number of MSPs to explain the GCE [14;16]. However, multiple MSP formation channels exist, leading to potentially different MSP populations in the GC and globular clusters. More detailed studies (dynamical evolution, population synthesis, etc) will be needed to shed light on the MSP populations. This includes in M31, where the LMXB population and its spatial extent can be measured better than the MW [17].

Improving models of Milky Way DM density: The intensity of the DM annihilation signal is dependent on the DM density profile. The latest results from hydrodynamic simulations of galaxy formation seem to consistently point towards a flattening of the DM profile in the inner Galaxy, with a less steep cusp than a standard NFW profile [18;19]. However, the uncertainties are large at the GC, where N-body simulations are limited in resolution; further improvements in these simulations are needed.

Detecting pulsar candidates in other wavelengths: The GCE signal presents in GeV gamma rays. However, if the GCE is powered by MSPs, they may be detectable in other wavelengths. Some directions are:

Detecting pulsar candidates in radio– If the GCE is powered by MSPs, they may also pulse into radio. This signal is challenging to find with traditional single-dish telescopes, such as the Greenbank Telescope. However, there are very good prospects with the already operating Very Large Array (VLA), and MeerKAT [20] as well as SKA in the future. If one uses the disk population to calibrate the bulge source modeling, then no or a few detections with already achievable sensitivity would imply that either there is no bulge population or that its radio properties (namely flux distribution) are substantially different from disk pulsars. There are however, complexities in interpreting a null observation of bulge pulsars. It is possible that all pulsars producing the GCE are radio quiet, although it is not clear how naturally can we expect that to happen. Improvement of radio-gamma pulsar theory, observation, and modeling is required. Furthermore, higher confidence in the point source methods and any localization would help interpret such searches.

Detecting pulsar candidates with TeV-scale γ-ray telescopes– Pulsar candidates may efficiently accelerate $e^{\pm}$ pairs. Evidence of this process is found in mild evidence for TeV halos around MSPs in HAWC observations (e.g.,[21]), correlation between radio luminosity and far-infrared observation in star-forming-galaxies[22], and high-energy tail of the GCE[23]. The $e^{\pm}$ pairs injected by a putative MSPs population in the GC could produce detectable TeV-scale inverse-Compton (IC) emissions. While prompt γ rays from MSPs would trace the MSPs spatial distribution, the IC counterpart would exhibit an energy-dependent spatial morphology. The predicted IC spectra for MSPs distributed as the Galactic bulge vs NFW^2 profile are indistinguishable, but their spatial morphologies have recognizable features at TeV energies[24]. Such differences may be used by future high-energy γ-ray detectors such as CTA to provide a viable TeV-scale handle for the MSP origin of the GCE. Due to gradual aging, MSPs may not be as bright as usually assumed, increasing the number of required MSPs and creating potential dynamical problems due to the increased mass budget of the required bulge MSP population[25], though scenarios without disrupted globular clusters are also considered[15].

Detecting pulsar candidates with gravitational waves– Although quite distant in the future, 3rd generation GW ground-based telescopes have the potential to detect the cumulative signal from a population of bulge MSPs from the GC direction[26], as dominating contribution to the Galactic stochastic GW background. For the time being, analysis of already available data can set (not yet competitive) limits on pulsar ellipticity.

Finding a consistent DM signal elsewhere: To corroborate a potential DM explanation of the GCE, a signal consistent with DM needs to appear in other experiments and observables. Some targets are:
Dark matter in dwarf spheroidal galaxies– Dwarf Spheroidal Galaxies are very DM dense environments, with low γ-ray background, making them ideal targets for DM annihilation searches. Currently, no conclusive signal is seen in dwarfs, though the limits that arise here are consistent with a DM signal from the GCE[27]. Systematics in background estimation at the dwarf position are traditionally not taken into account, but worsen the limits by another factor 2-3[28]. While Fermi will not obtain much improved results due to statistics, improvements are expected by finding more dwarfs with DES and Rubin, allowing a significantly increased sample. Radio and X-rays can also set limits on annihilating DM, especially from dwarfs, though these can depend on magnetic field structure of targets, and sizeable systematics need to be improved[29;30].

Dark matter in Andromeda– An extended excess of gamma rays has been detected toward Andromeda (M31)[31]. This signal is potentially consistent with the GCE, however, its interpretation is complicated primarily by the difficult to model MW foreground. For Fermi-LAT, the limited effective area and poor angular resolution $<\sim$GeV are also an issue[32]. CTA will observe M31 and might detect high energy ($>\sim$ 50 GeV) counterpart from the M31 bulge, but it is not guaranteed since it could be too faint/too extended. New generation instruments such as e-ASTROGAM or AMEGO might give further clues on the origin of this emission and its possible common features with the GCE.

Antiproton and antinuclei signals– An excess has been identified in the spectrum of cosmic-ray antiprotons at energies of $5-20$ GeV[33;34]. Intriguingly the range of dark matter models accommodating the antiproton excess is similar to those which could generate the excess of GeV-scale gamma rays[33–35], even though these two indirect dark matter probes are sensitive to different systematic uncertainties. An additional excess has been identified, in AMS anti-nuclei events[36]. Ongoing AMS and future GAPS anti-nuclei searches can inform us about the possible DM mass, annihilation channel and cross-section in association to both the CR antiprotons GeV excess and the GCE[36].

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