Scientific rationale The *Fermi*-LAT has revolutionized our understanding of the γ-ray sky at GeV energies. One of the greatest achievements of the *Fermi*-LAT is the precise measurement of the energy spectrum and the anisotropy of the so-called Isotropic Diffuse γ-Ray Background (IGRB) [1, 2]. The IGRB is a quasi-isotropic emission attributed to the combination of unresolved sources and a possible truly diffuse background. It was first measured a few decades ago but its exact composition is still a mystery.

The bulk of the IGRB is likely the emission from unresolved, i.e. undetected, blazars that are the most numerous population of sources in *Fermi*-LAT catalogs (see, e.g., [3]). Blazars are traditionally divided into BL Lacertae (BL Lacs) and Flat Spectrum Radio Quasars (FSRQs), A sizeable contribution could be due to misaligned Active Galactic Nuclei (MAGN). These sources are less luminous than blazars but, because they are much more numerous, the collective γ-ray emission could explain a significant part of the IGRB (see, e.g., [4]). Finally, Star-Forming Galaxies (SFGs) produce γ rays through the interaction of cosmic rays with the interstellar medium (see, e.g., [5]). A fraction of the IGRB can originate from truly diffuse mechanisms such as the interaction of Dark Matter (DM) particles. Cosmology and Astrophysics provide convincing evidence that DM constitutes 26% of the energy content of the Universe and detecting γ rays produced from this elusive form of matter is one of the most promising strategies to search for DM.

In Fig. 1 we show the contribution of each source population to the IGRB as derived in [6][1]. The contribution of blazars, SFGs and MAGN to the IGRB integrated above 1 GeV is: $(39^{+15}_{-13})\%$, $(45^{+70}_{-30})\%$ and $(14^{+13}_{-7})\%$, respectively. Therefore, the fraction of the IGRB that is truly unresolved is between 0 and 52%. These large uncertainties reduce the sensitivity of searches targeting the DM contribution to the IGRB. However, given the large size of the putative DM annihilation signal, improving significantly our knowledge for total contributions of these astrophysical components to the IGRB flux would make this particular probe highly competitive with other searches [7].

We propose to use future *Fermi*-LAT catalogs, data and a multi-pronged approach to obtain a determination for the fraction of the contribution of extragalactic sources to the IGRB with a precision of 10%. This result will improve our knowledge of the IGRB composition and will provide the space density and cosmological evolution of AGN and SFGs. Moreover, will enable us to find signatures or derive stringent limits for a DM contribution. Our analysis is conceived to detect DM particles with cross sections well below the thermal one for a wide range of DM masses. We plan to release all results and tools that we are going to produce with this proposal. We believe that this would be an important service for the community that could use our products for their own analysis of *Fermi* data and to create the basis for analysis of data from future missions data such as Amego[2], CTA [8] and e-ASTROGAM [9].

General methodology Below we list the different techniques we will planning to use in order to achieve our goals.

Luminosity function and SED of blazars. New catalogs of γ-ray sources will be available from the *Fermi*-LAT (see the preliminary version of the 4FGL[3] with about 5600 sources). We will use these catalogs to re-evaluate the luminosity function and cosmological evolution of blazars. The luminosity function is the number density of sources as a function of redshift and γ-ray luminosity and it is the key ingredient for the estimation of γ-ray emission from blazars. The luminosity function parameters are found by com-

[1] Similar results have been found in [3] [2] `https://asd.gsfc.nasa.gov/amego/index.html`
[3] `https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/`

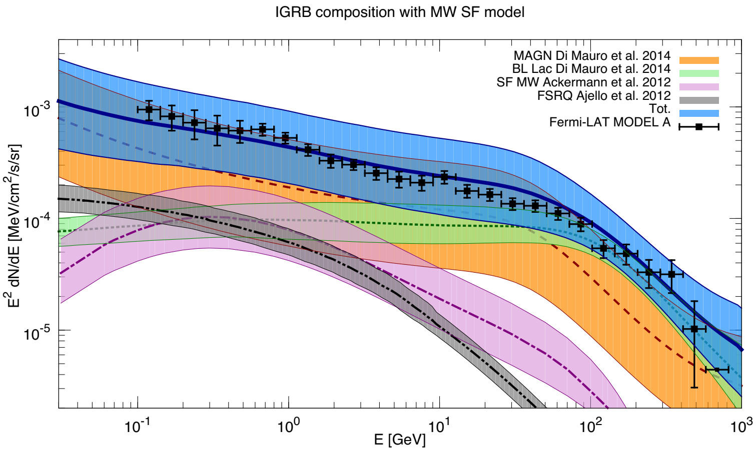

Figure 1: γ-ray flux from unresolved sources, along with IGRB data [1]. Lines and relevant uncertainty bands represent the contribution from the following source populations: orange dashed for MAGN, green dotted for BL Lacs, grey double dot-dashed for FSRQs, purple dot-dashed for SFG, and blue solid for the sum of all the contributions [6].

paring, through a maximum-likelihood estimator, the numbers of expected objects to the observed number while accounting for selection effects in the survey [10].

An important ingredient for the determination of γ-ray emission from blazars is the estimate of their Spectral Energy Distribution (SED). We plan to use SED data from *Fermi*-LAT, ground-based γ-ray observatories (such as CTA, H.E.S.S., VERITAS and HAWC) and X-ray experiments (e.g. Swift, Chandra and NuSTAR) on individual sources to model their SEDs in a wide energy range. This study will also result in estimates of the spectrum and cosmological evolution of the extragalactic background light that affects the propagation of very-high-energy γ rays [11].

The current estimates for the luminosity function of blazars are based on the 1FGL and 2FGL catalogs (see, e.g., [10, 3, 12]). The upcoming 4FGL will have about three times the number of sources as the 1FGL and 2FGL catalogs. **Using this more numerous sample of blazars we plan to find the blazar luminosity function and SED and we will be able to calculate the fraction for the contribution of these sources to the IGRB with a precision of 4%.**

Efficiency corrections and photon statistics. The luminosity function method is model-dependent in the sense that the functional form of the luminosity function is assumed based on model predictions. Moreover, it relies on sources of *Fermi*-LAT catalogs. We plan to use two additional complementary techniques to find the contribution of blazars to the IGRB: efficiency corrections and photon statistics. These methods do not depend on extrapolations, reach a sensitivity below the limits of the LAT catalogs and are model independent. The drawback of these additional methods is that they cannot distinguish between different source populations since they derive the source count distribution of all sources in the extragalactic sky, which is dominated by blazars.

With efficiency corrections, simulations of the γ-ray sky are generated to calculate the efficiency for detection of sources with a given photon flux S. The efficiency is then used to correct the source count distribution of cataloged sources and to find the real (i.e., intrinsic) dN/dS of extragalactic sources [13]. Efficiency corrections use information down to the flux of the faintest source in the catalog while pixel photon count statistics reach even lower fluxes. Specifically, the pixel photon count statistics method calculates the number of photons per pixel, and thus includes information from unresolved sources contributing even a single photon [13].

We plan to perform this analysis on at least 10 years of LAT data and in at least eight energy bins between 0.1-1000 GeV. This will enable us to evaluate more precisely than ever before the energy-dependence of blazar contribution to the IGRB. That will, in turn, be a powerful tool to understand the SED of the source populations (SFGs or MAGN) and/or diffuse processes (e.g., DM particle interactions) that contribute to the IGRB along with blazars.

Contribution of MAGN and SFGs to the IGRB: luminosity correlations. The majority of the uncertainty in the composition of the IGRB is due to SFGs and MAGN [6] (see Fig. 1). This is due to the limited sample of MAGN and SFGs detected in γ rays and to the uncertain correlation between γ-ray and infrared or radio luminosities. Indeed, the γ-ray luminosity function is estimated from measurements at these lower energies where the samples of SFGs and MAGN contain hundreds of sources [5, 4].

We plan to calculate the γ-ray emission of the SFG and MAGN source populations using future *Fermi*-LAT catalogs (e.g., 4FGL) that will include many more sources belonging to these source classes since SFGs and MAGN are on average faint γ-ray sources. We will derive the correlation of γ-ray and radio (for MAGN) or infrared (for SFGs) luminosity using this more numerous than before sample of γ-ray sources. For MAGN and SFGs that are not detected by *Fermi*-LAT we will calculate upper limits for their γ-ray luminosity. We will combine the information derived for detected and undetected sources to reduce significantly the uncertainties in the correlation between γ-ray and radio or infrared luminosities which will allow a more precise estimate of the contribution of SFGs and MAGN to the IGRB.

Contribution of MAGN and SFGs to the IGRB: cross correlations. We propose to study the contribution of MAGN and SFGs searching for cross correlations between IGRB photons and catalogs of extragalactic sources. Since SFGs and MAGN are faint sources and thousands of these objects have been detected in radio (for MAGN) and IR (for SFGs), if they contribute significantly to the IGRB they should leave an imprint in the IGRB. This signature can be detected as correlations between IGRB photons and the position of these sources in low-energy catalogs. This analysis has been successfully used in the past to find a correlation at 16.3σ significance between the IGRB and the NRAO VLA catalog (NVSS) of radio sources [14]. We plan to apply the cross-correlation analysis to at least 10 years of data and in at least 8 energy bins between 0.1 GeV to 1 TeV using the same method as in [14]. We will mask the sources in the future 4FGL catalog, the Galactic plane and the regions such as the *Fermi* Bubble and Loop I that are known Galactic contributors. We will search for cross correlations between the IGRB and catalogs of SFGs and MAGN such as: 3CRR Bright Sample, the MRC 1 Jy Sample, the MS4 Sample and the BRL Sample, the FRICAT [15] and FRIICAT [16]) for MAGN and [17, 18] for SFGs. We will use the cross-correlation signal to find the γ-ray luminosity function for MAGN and SFGs starting from the one in radio and IR. **The results for the luminosity correlations derived from undetected and detected sources and for their luminosity function found with the cross-correlation analysis will be used to determine the fraction of the SFG and MAGN contribution to the IGRB at the 3% and 9% level, respectively.**

Signatures or limits for the contribution of DM to the IGRB. The analyses described above will provide the most precise estimation of the contribution of extragalactic sources to the IGRB and they will permit us to search for DM signals in the IGRB with greatly improved sensitivity. N-body simulations predict that DM is distributed in the Universe with a main halo and substructures in each galaxy. A possible contribution of γ rays from

DM is thus made of three components with distinct morphologies: a Milky Way smooth DM distribution, Milky Way substructures and an extragalactic component from other galaxies. The extragalactic DM annihilation signal is isotropic to a large degree while the smooth Galactic and Galactic substructure components are more concentrated toward the center of our Galaxy. We plan to include the contribution of each of these components following [19, 3] and any upcoming N-body simulation results.

In our analysis we will first perform a fit to *Fermi*-LAT IGRB data optimizing the parameters that affect the γ-ray emission of AGN and SFGs. Then, we will add the γ-ray emission from Galactic and extragalactic DM (see, e.g, [6, 3]). For a fixed DM mass ($M_{\rm DM}$), we will add as a free parameter in the fit the annihilation cross section of DM ($\langle \sigma v \rangle$). The goodness of fit from this analysis is compared to the one with astrophysical sources only will provide the significance for the contribution of DM. We will perform this analysis for different DM annihilation and decay channels and for DM masses between the energy threshold of the DM candidate and 10 TeV. The result of this analysis will be either the signature of a DM contribution, if the fit to *Fermi*-LAT data improves significantly with the addition of this component, or will provide upper limits for $\langle \sigma v \rangle$ as a function of the DM mass and annihilation or decay channel.

Feasibility of the project *Contribution of blazars to the IGRB and limits for DM.* Forecasts for the contribution of extragalactic sources to the IGRB and for the limits on a DM contribution with 15 years of LAT operations have been published in [7]. We have shown that with future *Fermi*-LAT catalogs we will be able to reduce by 30-50% the uncertainty of the contribution of extragalactic sources to the IGRB (see left panel of Fig. G.33). We have also calculated that with a significant improvement in the modeling of the IE we will be able to reduce the systematic uncertainties of the IGRB and we will be able to find limits for DM that rule out the thermal cross section up to 200 GeV. These limits will be as good as the stacking analysis of clusters or of Milky Way Dwarf Spheroidal Galaxies [7].

Contribution of MAGN to the IGRB. As explained before, one of the greatest sources of uncertainty for the interpretation of the IGRB is the contribution of MAGN and in order to reduce it we need a large sample of such sources in future *Fermi* catalogs. We investigated this considering these radio catalogs of MAGN: 3CRR Bright Sample, the MRC 1 Jy Sample, the MS4 Sample and the BRL Sample, the FRICAT [15] and FRIICAT [16]). We eliminated from these catalogs sources that also appear in the blazar catalog BZCAT [20] or in SFG catalogs [17, 18]. We have then performed a dedicated γ-ray analysis with the *Fermi* Science Tools in the energy range 0.1-1000 GeV and for 100 months of data. The result of this analysis is that we find a sample of 46 MAGN, more than twice the sample detected in the 3FGL, demonstrating the viability of our proposal.

Source count distribution of blazars derived with efficiency correction and photon statistics. We performed in [21] an analysis of the source count distribution of blazars derived with efficiency corrections and photon statistics methods (1pPDF) using the third *Fermi* catalog of hard sources (3FHL) detected at $E > 10$ GeV [22]. We selected sources located at Galactic latitude $|b| > 20°$. The efficiency correction and photon statistics methods give compatible results and they allow determination of the dN/dS for almost three orders of magnitude. The sensitivity of the two methods is $\sim 10^{-11}$ ph cm^{-2} s^{-1} and summing the flux of cataloged sources and the contribution of unresolved sources we find that (42 ± 8)% of the IGRB is explained with blazars. This result has remarkable consequences because the remaining 58% of the IGRB should be given by an unresolved population of faint sources such as SFGs and/or MAGN or from a truly diffuse emission mechanism like DM

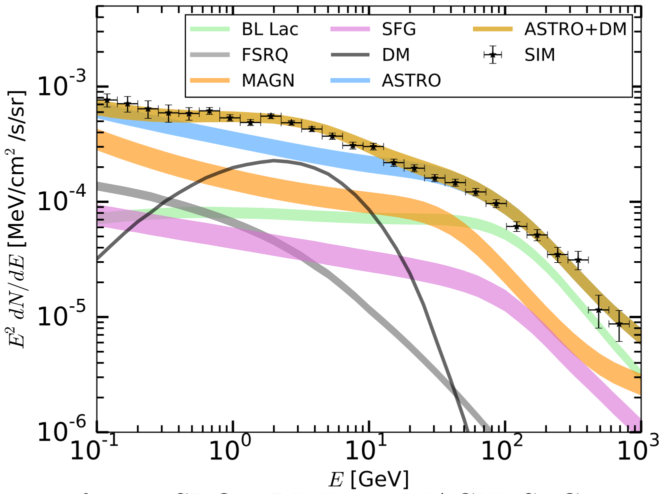

Figure 2: γ-ray emission from FSRQs, BL Lacs, MAGN, SFGs, as in Fig. 1 but with an uncertainties for the fraction of their contribution to the IGRB that is 4% for blazars, 3% for SFGs and 9% for MAGN. A contribution from extragalactic DM annihilating into $b\bar{b}$ with $M_{\rm DM}$ = 100 GeV and $\langle\sigma v\rangle = 10^{-26}$ cm^3/s. The sum of the source population contributions and the DM annihilation signal is depicted as the gold band.

particle interactions.

Example of a detectable DM contribution to the IGRB. We consider the average γ-ray emission from blazars, SFGs and MAGN as in Fig. 1 with an uncertainty of each contribution as reported in the goals of this proposal. We thus fix the uncertainty for the fraction of the blazar, SFG and MAGN contribution to the IGRB at 4%, 3% and 9%, respectively. We then add the contribution of extragalactic DM annihilating into $b\bar{b}$ with $M_{\rm DM}$ = 100 GeV and $\langle\sigma v\rangle = 10^{-26}$ cm^3/s for a model provided in [19]. **This candidate has a cross section that is 2 times below the thermal cross section and would contribute at 25% of the IGRB.** The result is shown in Fig. 2. The IGRB data points are mock data created by rescaling the errors of the published ones [1] by a factor of the square root of time for 10 years of data. The data have been renormalized by a factor of 0.83 due to the greater flux resolved by point sources in the preliminary 4FGL with respect to the 4FGL. **It is clearly visible from this example that with this proposal we will be able to detect the γ-ray emission from a DM candidate that is compatible with current DM bounds (see, e.g., [23]).** Here we are reporting only the contribution of extragalactic DM from the main halo of Galaxies. Adding the Galactic main halo and substructures the signal would be even larger.

Data and Tools provided for the community. Our proposal involves the creation of a large amount of data and tools that we will release to the public. We plan to incorporate the tools to the `FermiPy` Python package[4] and we will upload the data to its GitHub repository and into the FSSC. These products will include:

- The list of blazars, SFGs and MAGN that we will use for our analysis. We plan to keep our list periodically updated with newly found redshift measurements, with the most up-to-date SEDs, classification (FRI or FRII for MAGN, FSRQ or BL Lacs for blazars) and with infrared or radio luminosities.
- The measurements for the γ-ray anisotropy and flux generated by SFGs, MAGN and blazars. We will update these estimates when new *Fermi*-LAT catalogs are released or cataloged sources are newly associated with these source classes.

[4] `http://fermipy.readthedocs.io/en/latest/`

- The source count distribution at different fluxes and in energy bins calculated with efficiency correction and 1PDF methods.

We will provide all the codes that we will employ in our projects with dedicated documentation including: evaluation of the luminosity function of blazars, simulation and analysis of γ-ray data, evaluation of detection efficiency and source count distribution for blazars, tools to calculate the γ-ray emission from DM. **The community will benefit in the near term and long term from using our products to make their own analyses of new *Fermi*-LAT data and of data from future γ-ray experiments such as Amego, CTA and e-ASTROGAM.**

Summary, Timeline of the Project and Budget The composition of the IGRB is an open problem in astrophysics. We will undertake deep searches for a signature of a DM contribution over the next two years. **The first year** will be devoted to the calculation of the luminosity function of blazars using the 4FGL, and to the determination of their source count distribution applying the efficiency correction and photon statistics methods to at least 10 years of *Fermi*-LAT data. This research will produce an estimate for the fraction of blazar contribution to the IGRB at the 4% level. **In the second year** we will reduce to 3% and 9% level the uncertainties associated to the fraction of the SFG and MAGN contribution to the IGRB. This will be achieved using new *Fermi*-LAT catalogs and employing a cross correlation-study between the IGRB and SFGs and MAGN catalogs. The work performed in this proposal will enable the most precise ever estimation of the contribution of extragalactic sources to the IGRB and will permit us to search for a signature or bounds for DM production of γ rays.

Given the substantial data analysis effort, we request two years funding to support for the PI ($\sim$ 50%), for two conferences per year and publication charges. Including overheads we request a budget of 120k$ per year. The PI M. Di Mauro and CO-Is M. Ajello, V. Paliya, S. Manconi and H. Zechlin will be directly in charge of the analysis.Co-Is E. Charles, F. Donato and S. Digel will provide both technical and the scientific input.

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