Detecting a dark matter contribution to the extragalactic γ-ray background

Scientific rationale The *Fermi*-LAT has revolutionized our understanding of the γ-ray sky at GeV energies while Imagining Atmospheric Cherenkov Telescopes (IACTs) (e.g., H.E.S.S., VERITAS and HAWC) cover the TeV band. One of the greatest achievements of the *Fermi*-LAT is the precise measurement of 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 IGRB.

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]). A sizeable contribution could be due to misaligned Active Galactic Nuclei (MAGN). These sources are less luminous than blazars but, since are much more numerous, the collective γ-ray emission could explain 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 the interaction of Dark Matter (DM) particles. Cosmology and Astrophysics provide convincing evidences 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 strategy to search for DM.

In Fig. 1 we show the contribution of each source population to the IGRB as derived in [6][1]. The different source populations contribute with about the same flux to the IGRB at 1 GeV. The contribution of blazars, that are traditionally divided into BL Lacertae (BL Lacs) and Flat Spectrum Radio Quasars (FSRQs), is known at 30% level while the contribution of SFG and MAGN at 40 and 50% level respectively[2]. These large uncertainties reduce the sensitivity of searches targeting the DM contribution to the IGRB. We need to improve significantly the prediction of γ-ray emission from these sources at least to the 20% level in order use the IGRB as a promising target for the detection of DM.

I propose to use future *Fermi*-LAT catalogs, data and a multi-pronged approach to find the most precise yet determination of the contribution of extragalactic sources to the IGRB. This result will improve our understanding for the composition of the IGRB, will provide the space density and cosmological evolution of AGN and SFGs and will enable us to find signatures or derive severe limits for the DM production of γ rays. We plan to release all results and tools that we are going to produce with this proposal. We think that this would be an important service for the comunity 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 CTA [7], e-ASTROGAM [8] or ComPair [9].

General methodology Below we list the different techniques that we are 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, almost a factor of two more sources than the 3FGL catalog). I will use these catalogs to re-evaluate the luminosity function and cosmological evolution of blazars. The luminosity

[1]Similar results have been found in [3]

[2]The uncertainty level is relative to the average contribution of each source population.

[3]`https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/`

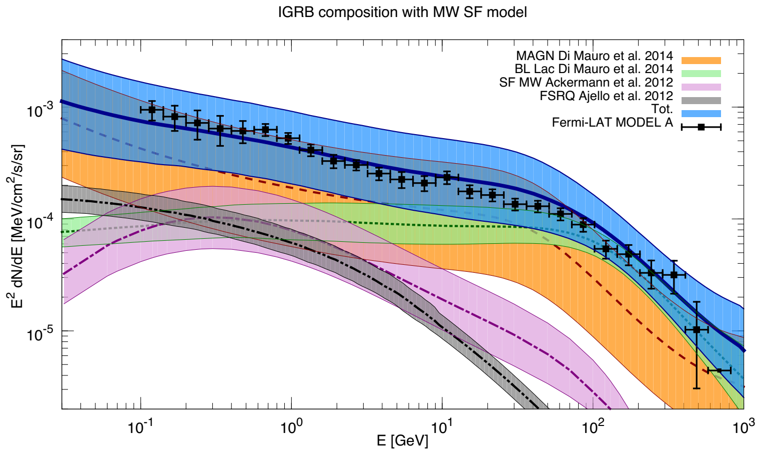

Figure 1: γ-ray emission from unresolved sources, along with data for the IGRB [1]. Lines and relevant uncertainty bands represent the contribution from the following source populations: orange dashed for MAGN, green dotted for BL Lacs, grey double dot-dashed for FSRQs, purple dot-dashed for SFG, and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

function is the number 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 best-fit of the luminosity function parameters is found by comparing, through a maximum-likelihood estimator, the number 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, IACTs (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 enable us to estimate the spectrum and cosmological evolution of the extragalactic background light that affects the propagation of very-high-energy γ rays [11].

The current estimations of the luminosity function of blazars are based on the 1FGL and 2FGL (see, e.g., [10, 3, 12]). The future 4FGL will have about three times the number of sources, and thus of blazars, with respect to the 1FGL and 2FGL. **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 contribution of these sources to the IGRB with a precision of 10%.**

Efficiency corrections and photon statistics. The luminosity function method is model-dependent since you have to assume a shape for it. 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 cataloged sources and are model-independent. The drawback of these methods is that you can not distinguish between different source populations since you derive the source count distribution of all sources in the extragalactic sky that are 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 that are dominated by blazars [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 photons [13].

We plan to perform this analysis on 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. The major uncertainty in the composition of the IGRB comes from 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 SFGs and MAGN 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 use together the information derived for detected and undetected sources to reduce significantly the uncertainties in the correlation between γ-ray and radio or infrared luminosities that as a consequence will provide a more precise estimate of the contribution of SFGs and MAGN to the IGRB.

Stacking analysis of the γ-ray emission from MAGN and SFGs. We propose to apply a stacking analysis of the γ-ray emission from MAGN detected in radio energies and unresolved by *Fermi*-LAT. The stacking analysis for SFGs detected in infrared will be performed with an other proposal submitted in the *Fermi* GI cycle 11 (P.I. V.S. Paliya and Co.I. M. Ajello and M.Di Mauro). We will use the most updated radio and infrared catalogs of MAGN and SFGs. We will select only sources detected with a $TS < 25$[4]. Point sources with a $TS > 25$ are in fact included in *Fermi* catalogs and are thus officially detected. We will run an analysis for the search of γ-ray emission from a point source with a given photon flux and index stacking the photons from all sources in our sample. This technique is able to detect the γ-ray emission from a population of faint point sources because even if each source contributes with a few photons the total emission from the entire sample will produce a significant flux. This stacking analysis will be applied to samples of sources binned in radio (for MAGN) or infrared luminosities (for SFGs) in order to calculate for each bin the detection or an upper limits for the γ-ray luminosity.

The results for the luminosity correlations derived from the stacking analysis of γ-ray undetected sources and for the numerous list of γ-ray detected sources will be used to reduce the uncertainty for the contribution of SFGs and MAGN to the IGRB to the 20% level.

Signatures or limits for the contribution of DM to the IGRB. The analyses described

[4]The TS is defined as twice the difference in log-likelihood between the null hypothesis (i.e., no source present) and the test hypothesis: $TS = 2(\log \mathcal{L}_{\mathrm{test}} - \log \mathcal{L}_{\mathrm{null}})$.

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 senstivitiy. N-body simulations predict that DM is distributed in the Universe with main halo and substructures in each Galaxy. A possible contribution of γ rays from DM is thus made of three components with a distinct morphology: a Galactic smooth DM distribution, Galactic substructures and an extragalactic component. 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 [14, 3] and all future N-body simulation results.

In our analysis we will first perform a fit to *Fermi*-LAT IGRB data changing 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_{DM}), we will add as a free parameter in the fit the annihilation cross section of DM ($\langle\sigma v\rangle$), in addition to the ones for astrophysical sources. The goodness of fit of this analysis 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 [15]. We have shown that with future *Fermi*-LAT catalogs we will be able to reduce by 30-50% the uncertainty for 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.

Contribution of MAGN to the IGRB. As explained before, one of the greatest source of uncertainty for the interpretation of the IGRB is the contribution of MAGN and in order to reduce it we need a numerous sample of 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 [16] and FRIICAT [17]). We eliminated from these catalogs sources that also appear in the blazar catalog BZCAT [18] or in SFG catalogs [19, 20]. 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 enable to know the dN/dS for almost three orders of magni-

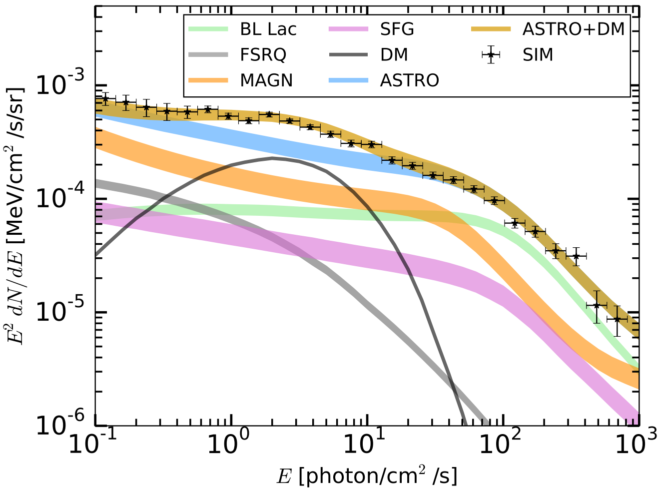

Figure 2: γ-ray emission from FSRQs, BL Lacs, MAGN, SFGs, as in Fig. 1 but with an uncertainty of the different population of the 10% for blazars and 20% for SFGs and MAGN. A contribution from extragalactic DM annihilating into $b\bar{b}$ with $M_{\rm DM} = 100$ GeV and $\langle\sigma v\rangle = 10^{-26}$ cm^3/s. The total contribution for the sum of source population contribution and DM is depicted with gold band.

tude. The sensitivity of the two methods is around $\sim 10^{-11}$ ph cm^{-2} s^{-1} and summing the flux of cataloged sources and the contribution of unresolved sources we find that 42% of the IGRB is explained with blazars. This result has remarkable consequences because the remaining 48% of the IGRB should be given by an unresolved population of faint sources such as SFGs and/or MAGN of from a truly diffuse emission mechanism like DM 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 to be 10% for FSRQs and BL Lacs and 20% for SFGs and MAGN. 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 [14]. The result is shown in Fig. 2. The IGRB datapoints are mock data created rescaling the errors of the published ones [1] for 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 points 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 comunity. Our research project involves the creation of a large amount of data and tools that we plan to release to the public. 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 discovered redshift measurements, with the most updated shape of their SED, classification (FRI or FRII for MAGN, FSRQ or BL Lacs for blazars) and with infrared or radio luminosities.
- The theoretical predictions for the γ-ray anisotropy and flux generated by SFGs, MAGN and blazars. We will update these estimates once new *Fermi*-LAT catalogs

will be released or new γ-ray sources will be associated to these source classes.

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

We will provide all the codes that we will employ in our projects with dedicated documentation including:

- the program we will use to find the luminosity function of blazars,
- to simulate and analyze γ-ray data,
- to find the efficiency and the source count distribution of blazars and
- the set of tools that we will employ to calculate the γ-ray emission from DM.

The comunity will have a great benefit from using our products to make their own analyses of new *Fermi*-LAT data and to data of future γ-ray experiments such as CTA [7], e-ASTROGAM [8] or ComPair [9].

Summary, Timeline of the project and Budget The composition of the IGRB is an open problem in astrophysics and we plan to find possible signatures of a DM contribution using this proposal that has a timeline of 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 10 years of *Fermi*-LAT data. This research will produce an estimate for the contribution of blazar to the IGRB at the 10% level. **In the second year** we will reduce to the 20% level the uncertainties associated to the contribution of SFGs and MAGN. This will be achieved using new *Fermi*-LAT catalogs and employing a stacking analysis of γ-ray undetected sources. We will take the results of the stacking analysis of SFGs derived with an other program proposed at this cycle of the *Fermi* GI (P.I. V.S. Paliya and Co.I. M. Ajello and M.Di Mauro). The work performed in the previous analyses will enable us to have the most precise ever estimation of the contribution of extragalactic sources to the IGRB and will permit in the second year to search for signatures 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. Diegel will provide both technical and the scientific input.

References

[1] M. Ackermann *et al. ApJ*, vol. 799, no. 1, p. 86, 2015.

[2] M. Ackermann *et al. PRD*, vol. 85, no. 8, p. 083007, 2012.

[3] M. Ajello *et al. ApJ*, vol. 800, no. 2, p. L27, 2015.

[4] M. Di Mauro *et al. ApJ*, vol. 780, p. 161, 2014.

[5] M. Ackermann *et al. ApJ*, vol. 755, p. 164, 2012.

[6] M. Di Mauro and F. Donato *PRD*, vol. 91, p. 123001, 2015.

[7] R. A. Ong in *Proceedings ICRC 2017*, 2017.

[8] V. Tatischeff *et al. Proc. SPIE Int. Soc. Opt. Eng.*, vol. 9905, p. 99052N, 2016.

[9] A. A. Moiseev *et al.* 2015.

[10] M. Ajello *et al. ApJ*, vol. 751, p. 108, 2012.

[11] M. Ackermann *et al. Science*, vol. 338, p. 1190, 2012.

[12] M. Di Mauro *et al. ApJ*, vol. 786, p. 129, 2014.

[13] M. Ackermann *et al. PRL*, vol. 116, no. 15, p. 151105, 2016.

[14] M. Cirelli *et al. JCAP*, vol. 1103, p. 051, 2011.

[15] E. Charles *et al. Phys. Rept.*, vol. 636, pp. 1–46, 2016.

[16] A. Capetti, F. Massaro, and R. D. Baldi *A&A*, vol. 598, p. A49, 2017.

[17] A. Capetti, F. Massaro, and R. Baldi *A&A*, vol. 601, p. A81, 2017.

[18] E. Massaro *et al. Astrophys. Space Sci.*, vol. 357, no. 1, p. 75, 2015.

[19] D. B. Sanders *et al. Astron. J.*, vol. 126, p. 1607, 2003.

[20] Y. Gao and P. M. Solomon *ApJ*, vol. 606, pp. 271–290, 2004.

[21] M. Di Mauro *et al. arXiv: 1711.03111*, 2017.

[22] M. Ajello *et al. ApJS*, vol. 232, no. 2, p. 18, 2017.

[23] A. Albert *et al. ApJ*, vol. 834, no. 2, p. 110, 2017.