Dark Matter search in dwarf irregular galaxies with the Fermi Large Area Telescope

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To be submitted asap

In collaboration with

Outlook

- Why dwarf irregular (dIrr) galaxies?
- Selected sample
- DM modelling and spatial template
- Data analysis
- Conclusions
Why irregular galaxies?

**Dwarf spheroidal (dSph) galaxies**

- Milky Way satellites
- $d < 0.5$ Mpc

**Pressure supported objects**

(Jeans theory - tidal stripping - phase space function)

DM dominated objects $M_{\text{halo}} = 10^6 - 10^8 \, M_{\odot}$

$10^{14} \text{(Segue 2)} < J\text{-factors} < 10^{19} \text{(Draco)} \, \text{Gev}^2\text{cm}^{-5}$

(within the uncertainty)

With substructures boost of a few

Old star population

and negligible astrophysical background

in gamma rays

**Well-know targets**

for indirect searches of DM

**Dwarf irregular (dIrr) galaxies**

- Local Volume galaxies
- $0.5$ Mpc $< d < 10$ Mpc

**Rotationally supported objects**

(rotation curve)

DM dominated objects $M_{\text{halo}} = 10^8 - 10^{10} \, M_{\odot}$

$10^{14} < J\text{-factors} < 10^{18} \, \text{Gev}^2\text{cm}^{-5}$

With substructures boost up to 10

**Previous work:**

Star forming region

and negligible astrophysical background

in gamma-rays? Yes!


**New targets**

in the context of gamma-ray DM searches
Negligible astrophysical background

Star-forming galaxies detected by Fermi LAT

\[ \log_{10} \left( \frac{L_y}{\text{ergs}^{-1}} \right) = \alpha \log_{10} \left( \frac{L_{\text{IR}}}{10^{10} L_\odot} \right) + \beta \]


dlrrs are here!
7 selected targets

<table>
<thead>
<tr>
<th>Name</th>
<th>Distance [Mpc]</th>
<th>$R_D$ [kpc]</th>
<th>$\log_{10} M_D$ [M$_\odot$]</th>
<th>$l$ [deg]</th>
<th>$b$ [deg]</th>
<th>RC &amp; $M_D$ reference</th>
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<tbody>
<tr>
<td>NGC6822</td>
<td>0.48</td>
<td>0.66</td>
<td>7.0</td>
<td>23.3</td>
<td>-18.4</td>
<td>[28]</td>
</tr>
<tr>
<td>IC10</td>
<td>0.79</td>
<td>0.79</td>
<td>8.1</td>
<td>119.0</td>
<td>-3.3</td>
<td>[33]</td>
</tr>
<tr>
<td>WLM</td>
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<td>7.2</td>
<td>75.9</td>
<td>-73.6</td>
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<tr>
<td>IC1613</td>
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<td>0.64</td>
<td>7.5</td>
<td>129.7</td>
<td>-60.6</td>
<td>[33]</td>
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<tr>
<td>Phoenix</td>
<td>0.44</td>
<td>0.23</td>
<td>6.8</td>
<td>272.2</td>
<td>-68.9</td>
<td>[34, 35]</td>
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<tr>
<td>DDO210</td>
<td>0.9</td>
<td>0.17</td>
<td>5.8</td>
<td>34.0</td>
<td>-31.3</td>
<td>[33]</td>
</tr>
<tr>
<td>DDO216</td>
<td>1.1</td>
<td>0.54</td>
<td>7.2</td>
<td>61.5</td>
<td>-67.1</td>
<td>[33]</td>
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</tbody>
</table>

VG, et al. This work

\[ J(\Delta\Omega, l.o.s.) = \int_0^{\Delta\Omega} d\Omega \int_{l.o.s} \rho^2(r) dl, \]
DM mass modelling

1. **Burkert profile**: Rotation Curve best fit

2. **NFW profile**: $\Lambda$CDM assuming $M_{200}^{\text{Burk}} = M_{200}^{\text{NFW}}$

   $$R_{200} = \left( \frac{3M_{200}}{4\pi\Delta_{200}\rho_{\text{crit}}} \right)^{1/3}$$

   $$c_{200}(M_{200}, z = 0) = \sum_{i=0}^{5} c_i \times \left[ \ln \left( \frac{M_{200}}{h^{-1}M_\odot} \right) \right]^i$$

   $$c \equiv \frac{R_{200}}{r_s}$$

   $$\rho_0 = \frac{2 \Delta_{200} \rho_{\text{crit}} c_{200}}{3 f(c_{200})}$$


3. **Boost due to substructures is included** (expected up to order $\sim 10$)

2D spatial templates with CLUMPY

CLUMPY is a code to compute gamma-ray signals from DM structures. Among other important inputs for indirect DM search, it allows to calculate J-factors (including sub-structures) and fluxes. (Charbonnier et al. (2012), Bonnivard et al. (2016), and Hütten et al. (2018).)

- $\rho_{host}$: DM density distribution in the host halo
- $\rho_{sub}$: DM density distribution inside the sub-halos
- SRD: sub-halos radial distribution within the host
- $\alpha$: slope of the sub-halo mass function (SHMF), i.e. the distribution in mass of the population of sub-halos.

\[
\frac{dN}{dM} \propto M^{-\alpha}
\]
Integrated Astrophysical J-factors

- **MIN** = Burkert without substructure
- **MED** = Burkert accounting for substructure, with alpha=1.9 for the index of subhalo mass function (SHMF)
- **MAX-BUR** = Burkert accounting for substructure, with alpha=2.0 for the SMHF index
- **MAX-NFW** = NFW accounting for substructure, with alpha=2.0 for the SMHF index

<table>
<thead>
<tr>
<th>Name</th>
<th>$\log_{10} J_{MIN}$ GeV$^2$cm$^{-5}$</th>
<th>$\log_{10} J_{MED}$ GeV$^2$cm$^{-5}$</th>
<th>$\log_{10} J_{MAX-BUR}$ GeV$^2$cm$^{-5}$</th>
<th>$\log_{10} J_{MAX-NFW}$ GeV$^2$cm$^{-5}$</th>
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<tr>
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<td>17.86</td>
<td>18.40</td>
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<td>IC10</td>
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<td>18.53</td>
<td>18.33</td>
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<tr>
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<td>17.10</td>
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<td>17.24</td>
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<tr>
<td>DDO216</td>
<td>15.45</td>
<td>15.72</td>
<td>15.83</td>
<td>15.73</td>
</tr>
</tbody>
</table>

$J(\Delta \Omega, l.o.s.) = \int_0^{\Delta \Omega} d\Omega \int_{l.o.s} \rho^2(r) dl,$

- $\text{Boost}_{MED} = 0.6-3.4$
- $\text{Boost}_{MAX-B} = 1.1-4.8$
Fermi-LAT data analysis

- We performed the analysis to each individual ROI using the corresponding CLUMPY template for each of the models, and adding the sources from the 4FGL-DR1 catalog.
- 11 years of LAT data, Fermipy v0.19.0 and ScienceTools v1.3.7 are used.
- Benchmark pipeline used for previous Fermi-LAT dSphs analyses applied (Ackermann+2011; 2014; 2015; Drlica-Wagner+15; Albert+17).
- Combined likelihood analysis of the full sample.
- Considered annihilation channels: $b\bar{b}, \tau^+\tau^-, W^+W^-$. 

Galactic diffuse emission:
gll_iem_v07

Isotropic contribution:
P8R3_SOURCEVETO_V3_v1.txt

- No significant emission detected. Small local excesses with pre-trials $TS \approx 8-10$
The most stringent constraints are obtained for IC10 and NGC6822, independently of the adopted DM profile.
Fermi-LAT data analysis

Stacked results for different DM models

IC10 dominates the combined limits
The observed mismatch can be easily attributed to the small local TS excesses found for some objects in our sample at the relevant energies. These are pre-trials, local excesses, also probably due to a mismodeling of the involved Galactic foregrounds.
Conclusions

• First extended analysis of dIrr galaxies with 11 years of Fermi-LAT data in the context of DM searches.

• Substructures models applied to dIrrs boost the J-factor up to $\sim 5$.

• The combined analysis of 7 dIrrs give the best limits at low masses. They are a factor 4-5 far from thermal cross section and a factor 10 from the constraints obtained by the analysis of dSphs.

• A better understanding of baryonic physics by means of hydrodynamical simulations and its comparison with the available observational data would help in order to reach a complete understanding of the kinematics of these objects.

• New and better targets could be found, both as potential discovery of new objects and by collecting more and more spectral data and RC measurements of already known dIrrs.
Thank you
where $dN(m)/dm$ is the subhalo mass function for a halo of mass $M$, $dN(m)/dm = A/M(m/M)^{-\alpha}$. The normalization factor is equal to $A = 0.012$ for a slope of the subhalo mass function $\alpha = 2$ and to $A = 0.03$ for $\alpha = 1.9$ (Sánchez-Conde & Prada 2014), and was chosen so that the mass in the resolved substructure amounts to about 10 percent of the total mass of the halo as found in recent simulations (Diemand et al. 2007b; Springel et al. 2008). Note

Results for 100 simulations of the null signal

Results of the analysis of 100 simulations with an injected signal in the M31 ROI

\[ m_\chi = 100 \text{GeV} \quad <\sigma v> = 10^{-25} \text{cm}^3\text{s}^{-1} \]