MAGIC dwarf spheroidal galaxies combined limits for WIMP dark matter annihilation

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Outline

1. Indirect Dark Matter searches with Imaging Atmospheric Cherenkov Telescopes
2. The MAGIC telescopes
3. Dark Matter with MAGIC - dSphs
4. Draco and Coma Berenices analyses
5. Combined limits for DM annihilation in dSphs
6. Conclusions and future steps
Indirect DM searches - Theoretical background

GAMMA-RAY FLUX (FROM WIMP ANNIHILATION)

\[
\frac{d \Phi_{\gamma}}{dE} = \frac{d \Phi_{\gamma}^{PP}}{dE} \times J(\Omega)
\]

\[
\frac{d \Phi_{\gamma}^{PP}}{dE} = \frac{\langle \sigma v \rangle}{8 \pi m_{\chi}^2} dN_{\gamma} / dE
\]

PARTICLE PHYSICS FACTOR

ASTROPHYSICAL (J-) FACTOR

\[
J(\Omega) = \int \int_{\Delta \Omega_{\text{los}}} \rho^2(l, \Omega) dl \, d\Omega
\]

ZHАО-HERNIQUST DM PROFILE

\[
\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^\gamma \left[1 + \left(\frac{r}{r_s}\right)^\alpha\right]^{(\beta-\gamma)/\alpha}}
\]

→ NAVARRO-FRENK-WHITE (α=γ=1, β=3)

![Graph showing density profiles](image-url)
Dark matter searches with IACTs
The MAGIC experiment

- 181 members in total
- 12 countries
- Observatorio del Roque de los Muchachos (ORM)
  ~2200m a.s.l., La Palma, Canary Island, Spain
- Two Imaging Atmospheric Cherenkov Telescopes (IACTs) with 17m diameter dishes
- Activity started in 2003, with M1 only (mono data)
- Upgrade to stereo data in 2009, M2 construction
- Energy range: 70GeV-30TeV (with standard trigger), extended down to <20GeV low limit (thanks to the sum-trigger → see G. Ceribella talk) and to >100TeV (in very large zenith angle mode)
- Angular resolution: < 0.08° for energies E≥200GeV
- Fast repositioning: < 30s for 180°
Dark Matter with MAGIC

- Search for **DM over-densities** in the Universe with a low astrophysical background
- Sources in the **northern hemisphere**

**Galactic Halo and the halo around**
- Highest J-factor
- Strong Astrophysical contamination
- Huge uncertainty in core/cusp
- Not optimal hemisphere for MAGIC (high threshold)

**Galaxy Clusters**
- Huge amount of DM but large distance → moderate/low J-factor
- High Astrophysical contamination
- Large uncertainties in baryon feedback and substructure contribution
  - Extended

**Dwarf Galaxies**
- DM dominated (high M/L ratios) and free from Astrophysical background
- Lower uncertainties on the J-factor
- Low J-factor

**BEST CANDIDATES FOR DM ANNIHILATION SEARCHES**
Dark Matter annihilation in dSphs

- Multi-year observations of dwarf spheroidal satellite galaxies with MAGIC for DM searches

- Observational diversification strategy:
  - enlarge the pool of dSphs observed by MAGIC
  - reduce J-factor systematics
  - enrich data sample available with the goal of a joint analysis with Fermi-LAT, HAWC, H.E.S.S. and VERITAS [→ Glory Duck project, see talk of D. Kerszberg]


<table>
<thead>
<tr>
<th>Galaxy</th>
<th>LogJ ± DLogJ ± J-factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segue 1</td>
<td>19.36 ± 0.35 GeV²/cm⁵</td>
</tr>
<tr>
<td>Ursa Major II</td>
<td>19.42 ± 0.42 GeV²/cm⁵</td>
</tr>
<tr>
<td>Draco</td>
<td>19.05 ± 0.21 GeV²/cm⁵</td>
</tr>
<tr>
<td>Coma Berenices</td>
<td>19.02 ± 0.41 GeV²/cm⁵</td>
</tr>
</tbody>
</table>
Draco [RA 17:20:12.4, Dec +57:54:55]
- Data taking: 2018/03/17-2018/09/02
- Tot. amount of good quality data: 52.6h
- Dark time
- Zenith distance: 29-46 deg

Coma Berenices [RA 12:26:59.0 Dec +23:54:15]
- Data taking: 2019/01/29-2019/06/03
- Tot. amount of good quality data: 50.2h
- Dark time
- Zenith distance: 5-36 deg

C. Maggio - MAGIC dSphs DM limits
Extended sources: Donut Montecarlo method

<table>
<thead>
<tr>
<th>TARGET</th>
<th>EXTENSION $\theta_{\text{max}}$ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segue 1</td>
<td>0.35</td>
</tr>
<tr>
<td>Ursa Major II</td>
<td>0.53</td>
</tr>
<tr>
<td>Draco</td>
<td>1.30</td>
</tr>
<tr>
<td>Coma Berenices</td>
<td>0.31</td>
</tr>
</tbody>
</table>

MAGIC PSF < 0.1deg

TEVPA 2019

DONUT MONTECARLO METHOD

JCAP 1803 (2018) 009
MAGIC DM full-likelihood analysis

Output of the first analysis steps:
- gamma-like events from source (ON) and background (OFF) region
- Instrument Response Function:
  - energy migration matrix \( G(E,E') \)
  - effective area \( A(E) \)
- ON/OFF normalization factor \( \tau \)

\[ \rightarrow \text{FULL LIKELIHOOD ANALYSIS} \]

Inputs for the final analysis:
- used only positive values for the tested flux (parameter of interest) \( g(<\sigma v>,J) \)
- take into account a systematic uncertainty of 1.5\% for the background evaluation (\( \tau \))
- 300 simulations (of the Null-hypothesis) for each source

\[ L(<\sigma v>;\nu|(D)) = L(g(<\sigma v>,J);b,\tau|(N_{ON},N_{OFF})_{j=1,...,N_{bins}}) \cdot J(J|J_{obs},\sigma) \]

Where \( g \) is the expected number of gamma rays (detected with reconstructed energy \( E' \)):

\[ g(<\sigma v>,J) = T_{obs} \int_{E'_{min}}^{E'_{max}} dE' \int_{0}^{\infty} dE \frac{d\Phi}{dE}(<\sigma v>,J) A(E) G(E,E') \]

For more details have a look at J. Aleksić, J. Rico, M. Martinez paper JCAP 1210 (2012) 032.
Draco upper limits on the $<\sigma v>$ of WIMPs

Tot. eff. Time: 52.6 h, used only positive values for the reconstructed gamma-events, took into account a systematic error of 1.5%, 300 simulations to compute the 1 and 2 sigma bands
Coma Berenices upper limits on the $<\sigma v>$ of WIMPs

Tot. eff. Time: 50.2 h, used only positive values for the reconstructed gamma-events, took into account a systematic error of 1.5%, 300 simulations to compute the 1 and 2 sigma bands
## MAGIC observed dSphs

<table>
<thead>
<tr>
<th>TARGET</th>
<th>DATA TAKING PERIODS</th>
<th>OBS. TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segue 1</td>
<td>2011/01/28 2013/05/12</td>
<td>158 h</td>
</tr>
<tr>
<td>Ursa Major II</td>
<td>2014/12/17 2016/04/29</td>
<td>95 h</td>
</tr>
<tr>
<td>Draco</td>
<td>2018/03/17 2018/09/02</td>
<td>52 h</td>
</tr>
<tr>
<td>Coma Berenices</td>
<td>2019/01/29 2019/06/03</td>
<td>50 h</td>
</tr>
</tbody>
</table>
Combined limits for DM annihilation

- Total observation time: 355h and 300 simulations to compute the 1 and 2 sigma bands
Comparison with previous MAGIC results
Comparison with other experiments

The curves for H.E.S.S., HAWC, Veritas and Fermi have been taken from PoS (ICRC2019) 033
Conclusions and future steps

- very fruitful campaign on dwarf spheroidal galaxies with MAGIC

- reached the best $\langle \sigma v \rangle$ limit with the MAGIC telescopes for the annihilation of WIMPs:

5.2206x10$^{-24}$ cm$^3$/s for the $b\bar{b}$ channel @2TeV DM mass and 9.5239x10$^{-25}$ cm$^3$/s for the $\tau^+\tau^-$ channel @700GeV DM mass

- the results will be published soon

- still very active working group → new projects foreseen

- results used for the Glory Duck project

- improvement of the sensitivity with LST (CTA)
Thank you for your attention!
**Backup**

**Θ² PLOTS FOR DRACO AND COMA BERENICES**

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**Left Plot**: 
- Time: 51.68 h
- $N_{\text{on}} = 203$; $N_{\text{off}} = 202.9 \pm 11.7$
- $N_{\text{ex}} = 0.1 \pm 18.5$
- Significance (Li&Ma) = 0.01σ

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**Right Plot**: 
- Time: 49.49 h
- $N_{\text{on}} = 244$; $N_{\text{off}} = 238.0 \pm 12.7$
- $N_{\text{ex}} = 6.0 \pm 20.2$
- Significance (Li&Ma) = 0.30σ

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C. Maggio - MAGIC dSphs DM limits
\[ \rho(r) = \rho_s \exp \left\{ -d_n \left[ \left( \frac{r}{r_s} \right)^{1/n} - 1 \right] \right\} \]

**EINASTO DM PROFILE**

\[ \rho(r) = \frac{\rho_s r_s^3}{(r + r_s)(r^2 + r_s^2)} \]

**BURKERT DM PROFILE**