Deep Survey of Segue 1 with MAGIC
★ Dark Matter Searches with MAGIC
★ Observations
★ Dedicated analysis
★ Results
★ Conclusions
Active efforts in indirect dark matter searches

- **Galactic Center**

- **Galaxy Cluster**

- **Dwarf Spheroidals**
  Segue 1 (30 h): JCAP 06 (2011) 035

- **Subhalos**
All existing publications on dark matter searches with mono data

**Goal:** Improve our best (published) limits by a factor 10

- **Stereo system** since 2009
  - Major upgrade finished in 2012
- **Long-term observational campaign** on best dark matter candidate
- **Dedicated analysis approach**
Segue 1

 SEGUE = Sloan Extension for Galaxy Understanding and Exploration

- The most dark matter dominated object known so far
- The least luminous galaxy
- Close, no background, Northern hemisphere

<table>
<thead>
<tr>
<th>Segue 1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinates</td>
<td>(10^h 07^m 04^s), (+16^\circ 04' 55'')</td>
</tr>
<tr>
<td>Distance</td>
<td>(23\pm2) kpc</td>
</tr>
<tr>
<td>Number of resolved stars</td>
<td>71</td>
</tr>
<tr>
<td>Magnitude</td>
<td>(-1.5^{+0.6}_{-0.8})</td>
</tr>
<tr>
<td>Apparent magnitude</td>
<td>13.8(\pm0.5)</td>
</tr>
<tr>
<td>Luminosity</td>
<td>(340 , L_\odot)</td>
</tr>
<tr>
<td>Mass</td>
<td>(5.8^{+82}<em>{-31} \times 10^5 , M</em>\odot)</td>
</tr>
<tr>
<td>(M/L)</td>
<td>(\sim 3400 , M_\odot/L_\odot)</td>
</tr>
<tr>
<td>Half-light radius</td>
<td>29(^{+8}_{-5}) pc</td>
</tr>
<tr>
<td>System velocity</td>
<td>208.5(\pm0.9) km/s</td>
</tr>
<tr>
<td>Velocity dispersion</td>
<td>3.7(^{+1.4}_{-1.1}) km/s</td>
</tr>
<tr>
<td>Mean [Fe/H]</td>
<td>(-2.5)</td>
</tr>
</tbody>
</table>
Observations

★ January 2011 – February 2013
★ Low zenith angle (13 – 35 deg)
★ Wobble mode

★ Different telescope configurations(!):
  ➤ Jan 2011 – May 2011: 47.0 h
  ➤ Jan 2012 – Feb 2012: 12.3 h
  ➤ Mar 2012 – May 2012: 51.3 h
  ➤ Nov 2012 – Feb 2013: 47.5 h
Observations

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Total effective observation time: 157.9 h

The deepest survey of any dSph by any IACT!
$L(N_{\text{EST}}, M(\theta) \mid N_{\text{OBS}}, E_1, \ldots, E_{N_{\text{OBS}}}) = \frac{N_{\text{EST}}^N_{\text{OBS}}}{N_{\text{OBS}}!} e^{-N_{\text{EST}}} \times \prod_{i=1}^{N_{\text{OBS}}} P(E_i; M(\theta))$

$N_{\text{OBS}}, N_{\text{EST}}$ – total measured and estimated number of events

$E, E'$ – measured and true energy

$M(\theta)$ – model with parameters $\theta$

Measured and estimated spectral distributions

JCAP 10 (2012) 032

J. Aleksic - Segue I with MAGIC
A priori assumption on the expected spectral shape \(\rightarrow\) maximum advantage of potential features

- Unbiased, stable, robust

- Significant improvement with respect to the conventional analysis

- Straightforward combination of results from different instruments / sources

\[
\mathcal{L}_T(M(\theta)) = \prod_{i=1}^{N_{\text{inst}}} \mathcal{L}_i(M(\theta))
\]
Full Likelihood Analysis

- **Response function**: calculated for each observation period separately
- **Background spectral shape**: modeled from the Segue 1 observations
- **Signal spectral shape**: few models of dark matter annihilation and decay:
  - Secondary photons
  - Monochromatic line
  - Virtual Internal Bremsstrahlung
  - Gamma-ray boxes

- $m_\chi$ in the 100 GeV – 10 TeV (200 GeV – 20 TeV) range
- $\text{Br} = 100\%$
- Einasto density profile
Secondary Photons

\[ \chi \chi \rightarrow b \bar{b} \]

\[ \langle \sigma v \rangle \text{ [cm}^2 \text{s]} \]

- A / W1
- A / W2
- B1 / W1
- B1 / W2
- B2 / W1
- B2 / W2
- C / W1
- C / W2
- Combined

\[ 10^{-20} \]

\[ 10^{-21} \]

\[ 10^{-22} \]

\[ 10^{-23} \]

\[ 10^{-24} \]

\[ 10^{-25} \]

\[ 10^2 \]

\[ 10^3 \]

\[ 10^4 \]

\[ m_\chi \text{ [GeV]} \]

Preliminary
Secondary Photons

This work
MAGIC mono
Fermi-LAT
VERITAS

Preliminary
Secondary Photons

This work
MAGIC mono
Fermi-LAT
VERITAS

Secondary Photons

<\sigma v> [cm^3 s^{-1}]

MAGIC mono, 30 h Segue 1

\chi\chi \rightarrow b\bar{b}

m_\chi [GeV]

Preliminary
Secondary Photons

This work
MAGIC mono
Fermi-LAT
VERITAS

VERITAS, 50 h Segue I

\( \chi \chi \rightarrow b \bar{b} \)
Secondary Photons

This work
MAGIC mono
Fermi-LAT
VERITAS

Preliminary

Fermi-LAT, 2 yrs of 10 dSphs

\[ \chi \rightarrow b\bar{b} \]

[Graph showing production rate vs. mass for different experiments: This work, MAGIC mono, Fermi-LAT, VERITAS]
Secondary Photons

Preliminary

Strongest limit above 1 TeV from dSphs

\[ \chi \chi \rightarrow b \bar{b} \]
Secondary Photons

This work
MAGIC mono
Fermi-LAT
VERITAS
H.E.S.S. (qq)

Preliminary

H.E.S.S., 112 h Galactic Halo

\( \chi \chi \rightarrow b \bar{b} \)

\[ \langle \sigma v \rangle \quad [\text{cm}^3\text{s}^{-1}] \]

\[ \begin{array}{cccc}
10^{-20} & 10^{-21} & 10^{-22} & 10^{-23} \\
10^{-24} & 10^{-25} & 10^{-26} & 10^{-27} \\
10^{-28} & 10^{-29} & 10^{-30} & 10^{-31} \\
10^{-32} & 10^{-33} & 10^{-34} & 10^{-35} \\
\end{array} \]

\( m_\chi \text{ [GeV]} \)
Secondary Photons

\[ \langle \nu \rangle \rightarrow \mu^+ \mu^- \nabla \chi \rightarrow \mu^+ \mu^- \]

\[ \langle \nu \rangle \rightarrow \tau^+ \tau^- \nabla \chi \rightarrow \tau^+ \tau^- \]

This work
MAGIC mono
Fermi-LAT
VERITAS

Preliminary

Preliminary
Secondary Photons

This work

MAGIC mono

Fermi-LAT

VERITAS

Preliminary

Strongest limit above 300 GeV from dSphs

Strongest limit above 450 GeV from dSphs

EPS-HEP, Stockholm J. Aleksic - Segue I with MAGIC July 18th 2013
Secondary Photons

This work
Fermi-LAT
H.E.S.S

Preliminary

$\tau_\chi \ [s]$

$10^{-29}$
$10^{-28}$
$10^{-27}$
$10^{-26}$
$10^{-25}$
$10^{-24}$

$m_\chi \ [GeV]$ $10^{-3}$ $10^{-4}$

$\chi \rightarrow \mu^+\mu^-$

$\tau_\chi \ [s]$

$10^{-29}$
$10^{-28}$
$10^{-27}$
$10^{-26}$
$10^{-25}$
$10^{-24}$

$m_\chi \ [GeV]$ $10^{-3}$ $10^{-4}$

$\chi \rightarrow \tau^+\tau^-$

EPS-HEP, Stockholm

J. Aleksic - Segue I with MAGIC

July 18th 2013
Secondary Photons

Preliminary

PAMELA best-fit

Fermi-LAT, 2 yrs isotropic data

H.E.S.S., 15 h Fornax Cluster

Preliminary

This work

Fermi-LAT

H.E.S.S.
Secondary Photons

This work
Fermi-LAT
H.E.S.S

Strongest limit from IACTs
Close to the best-fit value
Monochromatic Line

\[ \langle \nu \rangle \left[ \text{cm}^3 \text{s}^{-1} \right] \]

- \( 10^{-29} \) to \( 10^{-25} \)

This work
H.E.S.S.
Fermi-LAT

Preliminary

\( \chi \chi \rightarrow \gamma \gamma \)

\( m_{\chi} \) [GeV]
Monochromatic Line

This work
H.E.S.S.
Fermi-LAT

Preliminary

H.E.S.S., 112 h Galactic Halo

Fermi-LAT, 3.7 yrs GC region

$\chi\chi \rightarrow \gamma\gamma$

$\langle N \rangle$ [cm$^3$ s$^{-1}$]

10$^{-3}$
10$^{-4}$
10$^{-5}$
10$^{-6}$
10$^{-7}$
10$^{-8}$
10$^{-9}$
10$^{-10}$
10$^{-11}$
10$^{-12}$
10$^{-13}$

$m_\chi$ [GeV]

10
10$^2$
10$^3$
10$^4$

J. Aleksic - Segue I with MAGIC

EPS-HEP, Stockholm

July 18th 2013
Monochromatic Line

This work
H.E.S.S.
Fermi-LAT

Preliminary

130 GeV line

$\langle \nu \rangle$ [cm$^3$ s$^{-1}$]

$m_\chi$ [GeV]

$\chi \chi \rightarrow \gamma \gamma$
Virtual Internal Bremsstrahlung

- Mass splitting parameter $\mu$:
  
  $$
  \mu = \left( \frac{m_\eta}{m_\chi} \right)^2
  $$

- Degenerate $\mu$ values
- Extended spectrum; softened peak
Virtual Internal Bremsstrahlung

\[ \langle \sigma v \rangle [\text{cm}^3\text{s}^{-1}] \]

- \[ 10^{-23} \]
- \[ 10^{-24} \]
- \[ 10^{-25} \]
- \[ 10^{-26} \]

- \[ m_\chi \text{ [GeV]} \]

- \[ \mu = 1.05 \]
- \[ \mu = 1.50 \]
- \[ \mu = 2.00 \]

Preliminary
Virtual Internal Bremsstrahlung

Preliminary \( \langle \sigma v \rangle \) [cm\(^3\) s\(^{-1}\)]

\[
\begin{align*}
&\text{Up to factor 50 improvement with VIB} \\
&\langle \sigma v \rangle [\text{cm}^3 \text{s}^{-1}] \\
&\quad \mu = 1.05 \\
&\quad \mu = 1.50 \\
&\quad \mu = 2.00
\end{align*}
\]

\[1 \times 10^{-25} \text{ cm}^3 \text{s}^{-1}\]
Conclusions

★ 157.9 h of Segue 1 observations with MAGIC: **deepest ever survey** of any dSph with any IACT

★ **Complex combined analysis** (different configurations)

★ **Dedicated analysis, optimized for spectra with features**

★ **Strongest limits** on various models of dark matter annihilation/decay **from dSph with IACT**

★ **Above certain** $m_\chi$, **strongest limits from dSphs**
Integral sensitivity $[\text{cm}^{-2}\text{s}^{-1}]$

- MAGIC
- CTA
- VERITAS

Crab and Crab fractions:
- 10% Crab
- 1% Crab
- 0.1% Crab

$E_{\text{th}}$ $[\text{GeV}]$ range:
- $10^2$ to $10^3$