Indirect dark matter searches with the Cherenkov Telescope Array

Jennifer Gaskins
GRAPPA, University of Amsterdam
for the CTA Consortium

For more details, please see:


Atmospheric Cherenkov Telescopes

- Pair-production detector: detects charged particle events as well as gamma rays.
- Can identify cosmic-ray electron and positron events; in general, cannot determine charge on an event-by-event basis.

Image credit: H.E.S.S. Collaboration
The Cherenkov Telescope Array

- next-generation gamma-ray observatory with > 100 telescopes
- open observatory
- designed to operate for 30 years
- Northern and Southern sites
  - Southern: in Chile, near Paranal
  - Northern: La Palma, Canary Islands, Spain
- 31 nations, ~ €297M (construction costs)

Image credit: CTA Collaboration
The Cherenkov Telescope Array

Array configuration assumed for results shown here:

- CTA Southern Site (area covered by the array of telescopes: ~4 km²):
  - 4 large-size telescopes
  - 24 medium-size telescopes
  - 72 small-size telescopes

- CTA Northern Site (area covered by the array of telescopes: ~0.4 km²):
  - 4 large-size telescopes
  - 15 medium-size telescopes

Current and future capabilities

**angular resolution (80% containment radius)**

![Graph showing angular resolution (80% containment radius) vs. Energy](image)

- **CTA South**
- **MAGIC**
- **VERITAS**
- **Fermi LAT Pass 8**
- **HAWC**

**Figure 1.1** – Comparisons of the performance of CTA with selected existing gamma-ray instruments. Top: differential flux sensitivity for five independent five standard deviation detections per decade in energy. Additional criteria applied are to require at least ten detected gamma-rays per energy bin and a signal/noise ratio of at least 1/20. Bottom: angular resolution expressed as the 80% containment radius of reconstructed gamma rays (the resolution for CTA North is similar).

Courtesy of CTA Consortium 2015
Current and future capabilities

sensitivity vs energy

![Graph showing sensitivity vs energy for different instruments.](https://www.cta-observatory.org/)

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Courtesy of CTA Consortium 2015
IACTs vs Fermi LAT

- IACTs have a large irreducible cosmic-ray background whereas the LAT can reject charged CRs at high efficiency

  ➡ this is a major challenge for searches for extended signals, such as dark matter annihilation in the Inner Galaxy
Anomalies!

Credit: Jester @ http://resonaances.blogspot.com
Anomalies!

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indirect detection
Anomalies!

indirect detection

Credit: Jester @ http://resonaances.blogspot.com
Dark matter search targets for CTA

The Galactic halo

Image credit: JG 2008

Milky Way satellites


The Large Magellanic Cloud

Image credit: NASA
Galactic halo projected sensitivity

500h, Einasto, different channels

500h, bb, different profiles

Carr et al. 2015 (CTA Consortium)
LMC projected sensitivity

340h
200 GeV threshold
different profiles
and channels

(statistical errors only)
Satellites projected sensitivity

500h, Sculptor, different channels

500h, bb, different dSph

(prospects for indirect dark matter searches with CTA)

J. Carr

require 525 hours to probe cuspy profile DM distributions and the thermal annihilation cross-section. In the CTA Galactic Centre Key Science Programme a further 300 hours are proposed for astrophysics covering up to latitudes 10° from the GC and data are also expected from the extragalactic surveys. These observations should be done in the first three years of CTA operation with high priority.

The sensitivity predictions for observations in the Galactic Halo are shown in Figure 1. The left plot shows the sensitivity for different annihilation modes (99, τ⁺τ⁻, W⁺W⁻), and the right plot for various dark matter halo profiles satisfying stellar dynamics as indicated in the caption.

3.2 Dwarf Spheroidal Galaxies

The dwarf spheroidal galaxies (dSphs) of the Local Group could give a clear and unambiguous detection of dark matter [17]. They are gravitationally bound objects and are believed to contain up to O(10³) times more mass in dark matter than in visible matter, making them widely discussed as potential targets. Being small and distant many of the dwarf galaxies will appear as near point sources in CTA and hence the nuisance of the instrumental background is much reduced. Although being less massive than the Milky Way or the LMC, they are also environments with a favourably low astrophysical gamma-ray background making the unambiguous identification of a DM signal easier compared to the Galactic Centre or LMC. Further, the J-factors integrated over the small source have less dependence on the DM profile assumed than the extended sources.

Neither astrophysical gamma-ray sources (supernova remnants, pulsar wind nebulae...) nor gas acting as target material for cosmic rays, have been observed in these systems.

Figure 2. Left: Sensitivity for σv from observation on the classical dwarf galaxy Sculptor for different annihilation modes as indicated. Right: Sensitivity for 500 h observation on the classical dSphs Draco and Sculptor, and the ultra-faint dwarf galaxies Segue 1 and Coma Berenices as indicated. Dashed lines correspond to ±1σ on the J-factors. Sensitivity is computed assuming the 99< annihilation mode and statistical errors only are taken into account.

Due to the larger available sample of spectroscopically measured stars, the classical dwarf galaxies such as Draco, Ursa Minor, Carina, and Fornax have significantly smaller uncertainties on the J-factor than the ultra-faint galaxies [17]. However several of the ultra-faint galaxies (e.g. Segue 1, Ursa Major II, and...
Comparison of targets

CTA Halo/Sculptor: 30 GeV threshold

CTA LMC: 200 GeV threshold

(statistical errors only)

SYSTEMATICS MUST BE CONTROLLED EXTREMELY WELL TO ACHIEVE STATISTICALLY-POSSIBLE SENSITIVITY

Carr et al. 2015 (CTA Consortium)
Spectral information

using full spectral information in analysis improves sensitivity at moderate/high dark matter masses

(now included in recent CTA projections shown here)
Morphological information

using full morphological information (as opposed to simple ON-OFF techniques) in analysis improves sensitivity

(under study for implementation in future CTA analyses)

see also Lefranc et al. 2015 for impact of spectral and morphological analysis

Galactic halo, 100h, comparison of analyses

![Graph showing self-annihilation cross-section vs. DM particle mass]

- CTA Ring method
- CTA Morph. analysis
- CTA Morph. analysis (3% syst.)
- CTA Morph. analysis (0.3% syst.)
- HESS GC
- Fermi-LAT dSph
- Doro et al. 2013, CTA
- Wood et al. 2013, CTA
- Pierre et al. 2014, CTA

Silverwood et al. 2014

$\chi\chi \rightarrow b\bar{b}$, 100 hours

DM particle mass $m_\chi$ [GeV]

Self-annihilation cross-section $\sigma_{\chi\chi}$ [cm$^3$ s$^{-1}$]

$10^{-21}$ $10^{-22}$ $10^{-23}$ $10^{-24}$ $10^{-25}$ $10^{-26}$
Summary

- CTA will improve dramatically on existing sensitivity to DM annihilation for a range of interesting DM masses
- for many annihilation channels CTA will test the canonical thermal relic annihilation cross section if the Galactic halo density profile is NFW/Einasto
- while less promising, the LMC and Milky Way satellite galaxies are complementary targets with different uncertainties
- understanding and controlling systematics will be key for interpreting a possible detection or placing constraints using any targets
Additional slides
Calculating indirect signals
(for particles that propagate directly to the observer without deflection, attenuation, or secondary production)

Differential intensity = particle physics term “K” • astrophysics term “J”

ANNIHILATION:

\[ K_{\text{ann}} = \frac{dN}{dE} \frac{\langle \sigma v \rangle}{2m^2_\chi} \]
\[ J_{\text{ann}}(\psi) = \frac{1}{4\pi} \int_{los} ds \rho^2(s, \psi) \]

DECAY:

\[ K_{\text{decay}} = \frac{dN}{dE} \frac{1}{m_\chi \tau_\chi} \]
\[ J_{\text{decay}}(\psi) = \frac{1}{4\pi} \int_{los} ds \rho(s, \psi) \]
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dark matter particle mass

DECAY:

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differential intensity = particle physics term “K” • astrophysics term “J”

ANNIHILATION:

\[ K_{\text{ann}} = \frac{dN}{dE} \frac{(\sigma v)}{2m^2_\chi} \]

\[ J_{\text{ann}}(\psi) = \frac{1}{4\pi} \int_{\text{los}} ds \, \rho^2(s, \psi) \]

average of pair annihilation cross section times relative velocity

DECAY:

\[ K_{\text{decay}} = \frac{dN}{dE} \frac{1}{m_\chi \tau_\chi} \]

\[ J_{\text{decay}}(\psi) = \frac{1}{4\pi} \int_{\text{los}} ds \, \rho(s, \psi) \]
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dark matter particle lifetime
Calculating indirect signals
(for particles that propagate directly to the observer without deflection, attenuation, or secondary production)

differential intensity = particle physics term “K” • astrophysics term “J”

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\[ J_{\text{ann}}(\psi) = \frac{1}{4\pi} \int_{los} ds \rho^2(s, \psi) \]

dark matter density

DECAY:

\[ K_{\text{decay}} = \frac{dN}{dE} \frac{1}{m_\chi \tau_\chi} \]

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The multi-wavelength Inner Galaxy

VLA @ 330 MHz

HESS > 380 GeV

Figure 1

identified EGRET source 3EG J1744

subtraction: extended emission spatially coincident with the un-

the map shown in Fig. 1b. Two significant features are apparent after

model for point-like emission at the position of these excesses yields

LETTERS

are derived from 55 hours of data consisting of dedicated observations of Sgr

as dashed green ellipses

composite supernova remnant G0.9

in 'events' and is dimensionless. White contour lines indicate the density of

observed r.m.s. extension in latitude of 0.2

J0852.0

for the shell-type supernova remnants RXJ1713.7–3946 (ref. 22) and RX

the ability of HESS to map extended

applied here to improve signal/noise and angular resolution. We note that

any residual emission at the position of the point-like

and has a statistical significance of 14.6 standard deviations. The absence of

threshold of the maps is 380 GeV, owing to the tight

excess observed along the Galactic plane consists of

reconstructed

as can be seen in the Galactic latitude slices shown in Fig. 2. The

emission extending along the Galactic plane for roughly 2

latitude (x

y

þ

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20

¼

0.20

j

g

8

corresponds to a scale of

VHE

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2422 (ref. 23). The white contours are evenly spaced and show

j

b

g

8

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g

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8

from the problem of 'standard' CO lines

is estimated to be 10

acceleration (hadronic) cosmic rays in any part of our Galaxy has been

Centre cosmic-ray population above the cosmic-ray 'sea' that fills the

cosmic-ray interactions are small, cosmic rays themselves (corrections due to scaling violations in the

in the region. In the case of a power-law energy distribution the

density by the same factor. The size of the enhancement increases

density of cosmic rays with multi-TeV energies exceeds the local

masses of interstellar gas, structured in a number of overlapping

molecular clouds in this region, as traced by their CO emission and in

thick for these lines and hence the total mass of clouds may be

is the angular distance from the Galactic Centre.

19

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erg in the energy range 4–40 T eV or

can estimate the expected

the moment that the Galactic Centre cosmic-ray flux and spectrum

solar neighbourhood (where an

ray spectrum near the Galactic Centre with a spectral index close to

2.3, significantly harder than in the solar neighbourhood (where an

94)-ray emission is unique and provides a compelling case for an origin

energy required to accelerate this additional component

accelerated (hadronic) cosmic rays in any part of our Galaxy has been

in total if the measured spectrum extends from 10

929)-ray source G0.9

scenario, any epoch of cosmic-ray production must have occurred in

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Sensitivity to gamma-ray lines

energy resolution vs energy

CTA South

ΔE/E (68% containment) vs energy Er [TeV]

Courtesy of CTA consortium 2015
Sensitivity to gamma-ray lines

Figure 4.8

Comparison of allowed models from [59] for the dominant modes: \( W^+ W^- \), \( b \bar{b} \), \( t \bar{t} \), and \( \tau^+ \tau^- \) in the four panels as indicated with the corresponding sensitivities as calculated in their paper. The colour code shows the value of dominant branching fraction for each point (The stars mark the particular benchmark points discussed in Ref. [59]).

Figure 4.9

Sensitivity of CTA to monochromatic gamma-ray signals from dark matter annihilation, with \( E = M_{DM} \), after 500 h of observation of a region with 1 deg around the Galactic Centre using an unbinned likelihood analysis (blue line) and a differential sensitivity analysis (orange curve) assuming an Einasto profile. For comparison, the currently best limits from Fermi [110] (black triangles) and H.E.S.S [111] (red dots) are also shown, along with the much discussed line-like feature at around 130 GeV [112, 113] (magenta star). The dashed lines also show the mean upper-limits obtained in case of a Burkert profile. The natural scale for monochromatic gamma-ray signal is highlighted as a black shaded area.

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Courtesy of CTA consortium 2015
## Proposed search strategy

### Table 4.1 – Strategy for dark matter observations over ten years with CTA. The first three years are devoted to the deep observation of the Galactic Centre (GC) together with the observation of the best ultra-faint dwarf galaxy. In case of non-detection of the GC, observations starting in the fourth year focus on the most promising target at that time to provide legacy constraints.

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galactic halo</td>
<td>175 h</td>
<td>175 h</td>
<td>175 h</td>
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<tr>
<td>Segue 1 (or best) dSph</td>
<td>100 h</td>
<td>100 h</td>
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</tr>
</tbody>
</table>

*in case of detection at GC, large $\sigma_v$*

| Segue 1 (or best) dSph | 150 h  | 150 h  | 150 h  | 150 h  | 150 h  | 150 h  | 150 h  | 150 h  | 150 h  | 150 h  |
| Galactic halo          | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  |

*in case of detection at GC, small $\sigma_v$*

| Galactic halo          | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  |

*in case of no detection at GC*

| Best Target            | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  | 100 h  |

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