Astrophysics with TeV particles

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(1) TeV gamma-ray astronomy: motivation
Astro-particle physics over 13 orders of magnitude

Radio

Microwave

Infrared

Optical

UV

X-ray

Gamma rays over 9 orders of magnitude

Fermi

CTA

HAWC

IceCube

ARA

0.1 MeV

1 EeV

WIPAC seminar

Justin Vandenbroucke: TeV gamma rays
The non-thermal universe

- CTA
Non-thermal mechanisms of gamma-ray production

(1) Synchrotron (electromagnetic)

(2) Inverse Compton (electromagnetic)

(3) Bremsstrahlung (electromagnetic)

(4) Pion decay (hadronic)
A fifth mechanism to produce gamma rays: exotic particle (e.g. dark matter) rest mass
Cosmic rays, neutrinos, gamma rays (and gravitational waves)
The universe viewed in >1 GeV photons

5 years of data from the Fermi Large Area Telescope
Physics with TeV gamma-ray telescopes

The gamma-ray sky as of 2017

198 TeV sources
3033 GeV sources

Supernova remnants
AGNs
GRBs
Binaries
Dark matter

Starburst galaxies
Cosmic rays
Pulsars
Spacetime

EBL
Axions, …
(2) Techniques for TeV gamma-ray astronomy
The atmosphere is opaque to gamma rays

- Which process will a TeV gamma-ray undergo when it hits the atmosphere?
<table>
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<th>Atmospheric Cherenkov tels.</th>
<th>Particle detector arrays</th>
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<td>EGRET, Fermi</td>
<td>MAGIC, HESS, VERITAS, CTA</td>
<td>Milagro, Tibet array, HAWC</td>
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<td>0.1 - 100 GeV</td>
<td>30 GeV - 70 TeV</td>
<td>100 GeV - 100 TeV</td>
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<td>Space borne: limited in area</td>
<td>Large effective area</td>
<td>Large effective area</td>
</tr>
<tr>
<td>Nearly background free</td>
<td>Excellent background rejection</td>
<td>Very good background rejection</td>
</tr>
<tr>
<td>Large field of view / high duty cycle</td>
<td>Small field of view / low duty cycle</td>
<td>Large field of view / high duty cycle</td>
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<td>All-sky survey and monitoring</td>
<td>Study of known sources</td>
<td>Partial (2/3) sky survey and monitoring</td>
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<td>Extragalactic (AGNs, GRBs), PSRs, MQSO</td>
<td>Deep survey of limited regions</td>
<td>Extended sources</td>
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<td>Dark matter</td>
<td>Morphology of TeV emitters (SNRs, PWN)</td>
<td>Transients (GRBs) &gt; 30 GeV</td>
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<td></td>
<td>High resolution spec. to 30 TeV</td>
<td>Spectra up to 100 TeV</td>
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</table>
The atmosphere as a detector

- Optical frequency (blue) light
- Very short (few ns) exposure to limit night sky background
- Cherenkov cone very narrow, \( \sim 1° \):
  \[
  \theta = \cos^{-1} \frac{1}{n\beta}
  \]
- 1000-1500 hours per year (dark, good weather)
The Whipple 10 m telescope on Mt Hopkins, Arizona

- Pioneer imaging atmospheric Cherenkov telescope
- Discovered the first very-high energy (TeV) astronomical sources
  - Crab Nebula: 1989
  - Markarian 421 (1992): a nearby blazar
  - Markarian 501 (1997): another nearby blazar
The next leap forward: stereo observation
Current generation of (stereo) imaging atmospheric Cherenkov telescopes
Example Cherenkov telescope (looks like astronomy) and “camera” (looks like particle physics)

Telescope:

Segmented mirrors, like optical telescopes, and detect optical light, but do not need as good angular resolution

Camera:

Camera like a particle physics detector:
- Photo-detectors to detect individual photons
- Fast electronics to discriminate the few-nanosecond Cherenkov pulse from the steady night sky
(3) Design and performance
The Cherenkov Telescope Array

**Low energies**
Energy threshold 20-30 GeV
23 m diameter
4 telescopes (South)
4 telescopes (North)

**Medium energies**
100 GeV – 10 TeV
9.5 to 12 m diameter
25 medium-size telescopes (S)
15 medium-size telescopes (N)

**High energies**
10 km² area at few TeV
4 to 6 m diameter
70 small-size telescopes
(S only)
Atmospheric Cherenkov telescopes: 50 hrs
Wide field instruments (Fermi, HAWC): 1 year

Detailed studies related to dish and mirror technology and costs, and the per-channel cost of the detection system, justify the FoV and pixel size for the various telescope designs shown in Figs. 1–5.

The detailed design of these telescopes, their structures, reflectors and cameras, is largely based on well-proven technologies developed for the telescopes of H.E.S.S., MAGIC and VERITAS, yet, significantly improved in terms of reliability, availability, maintainability and safety (RAMS). Some novel design features are extensively tested and benefit greatly from the general experience gained in current projects.

The main design drivers for these telescopes are the following:

**LSTs:**

The desire to rapidly repoint the telescopes for rapid GRB follow-up motivates the choice of a light-weight structure of stiff carbon tubes holding a 23 m diameter reflector, similar to the MAGIC design. At most, four of these telescopes will be used in each CTA observatory. Their design is optimised to reach the best performance with lowest-possible energy threshold. The baseline design has a parabolic mirror with 27.8 m focal length, 4.5 \textdegree/C176 FoV and 0.1 \textdegree/C176 pixels using PMTs (see Fig. 2).

**MSTs:**

The MST design is a blend between the H.E.S.S. and VERITAS concepts for a 12 m diameter Davies–Cotton reflector, optimised for reliability, simplicity and cost-saving, given that of the order of 30 such telescopes will be used at each site. The optical design foresees 16 m focal length, 7–8 \textdegree/C176 FoV and 0.18 \textdegree/C176 pixels (Fig. 3). Currently a full-scale prototype is under construction. In addition to these telescopes, CTA is exploring a design for a dual-mirror MST. This design might become a first extension of the southern CTA array, where as many as 36 telescopes could complement the baseline MST array. It has a Schwarzschild-Couder optics providing a 10 \textdegree/C176 FoV and a very small plate scale. The latter allows for much finer pixelation and the use of much cheaper photo sensors (either multi-anode photomultiplier tubes or Silicon photomultipliers) in the camera. This is a completely new concept for IACTs and a prototype to prove its viability is being constructed (Fig. 4).

**SSTs:**

A rather large number (35–70, depending on cost) of small-size telescopes spread out over a large area are needed to reach the desired sensitivity at the highest energies. Therefore, the cost per telescope is one of the strongest drivers in the choice of the technology. In principle the SSTs could be designed as a simplified and downscaled version of the MSTs. However, the need for a large FoV due to the large inter-telescope spacing, would lead to the cost of the camera dominating the total SST cost. Therefore, different solutions are being explored (Fig. 5). Possibilities are, for instance, the use of compact dual-mirror Schwarzschild–Couder (SC) optical design, with a very small plate scale (allowing for a small and thus inexpensive camera) or Davies–Cotton telescopes with cameras using the same new and inexpensive photosensor technologies that are proposed for the SC MST design. At present, different prototypes of both options are being developed to evaluate the feasibility and cost.
(4) Prototype telescope construction
New technologies for high performance: dual mirror optics, silicon photomultipliers, multi-channel waveform digitizers

- Allows (1) better optical angular resolution over wide (8° diameter) field of view (2) small camera
- Small focal plane well suited for modern dense, highly integrated photo-detectors (silicon photomultipliers) and electronics (application-specific integrated circuits)
- Improved gamma-ray angular resolution and background rejection allow qualitatively improved sensitivity
Simulated shower images for two-mirror vs. one-mirror telescope design

Example 1 TeV gamma-ray shower as seen by one-mirror or two-mirror telescope

DC telescope (~2k 0.16° pixels)

SC telescope (~10k 0.06° pixels)

Both images zoomed in (2° across, compared to 8° field of view)
Schwarzschild-Couder (dual-mirror) Telescope prototype construction underway

- NSF-funded prototype at VERITAS site in Arizona
- Full primary mirror, full mechanics, full secondary mirror, partial camera
- Silicon photomultipliers and readout electronics for one full sub-field (25 modules)
- Sub-system production and testing underway now
- Prototype commissioning in 2017
VERITAS site
at 4,200 ft altitude on Mount Hopkins in Arizona
Prototype construction in Arizona

http://cta-psct.physics.ucla.edu

live web cam
Prototype construction in Arizona

http://cta-psct.physics.ucla.edu
live web cam
Prototype construction in Arizona

http://cta-psct.physics.ucla.edu

live web cam
Camera integration and testing in Chamberlin (first floor lab)
Camera integration and testing in Chamberlin (first floor lab)

integrated camera  focal plane sensors
SCT camera in Chamberlin hall: first recording of light with full camera last week!
(5) Scientific prospects: highlights
Where does dark matter accumulate in the Universe?
Search for neutrinos and/or gamma rays from these:

- Center of Sun
- Center of Earth
- Galactic halo
- Dwarf galaxies
- Center of Galaxy
- Galaxy clusters
Fermi dwarfs & CTA Galactic center will cover entire mass range down to thermal cross section.
Opening up the time domain

Field of view, duty cycle also matter

Physics 301
Justin Vandenbroucke: TeV astro
Multi-messenger astronomy

Fermi
SKA
LIGO
HAWC
IceCube
LSST
Conclusion and outlook

• The Cherenkov Telescope Array will study astrophysics and particle physics with the highest energy photons ever detected.

• CTA will provide important discoveries and constraints concerning dark matter, astrophysical particle accelerators, transient bursts, electrons and positrons, and Lorentz invariance.

• Simultaneous operation with Fermi, HAWC, LIGO, IceCube, SKA, LSST and other wide-field observatories will enable discovery through multiple messengers and transients.

• See also Distributed Electronic Cosmic-ray Observatory, DECO (use your smart phone to detect particles) [https://wipac.wisc.edu/deco](https://wipac.wisc.edu/deco).

• Undergraduate research opportunities available: justin.vandenbroucke@wisc.edu.
Extra slides
Rapid follow up of transients: receiving and issuing multi-messenger alerts

- Telescopes can slew in $<$30 seconds
- Astrophysical neutrinos: search for electromagnetic counterpart, to identify neutrino (and cosmic ray) origins
- Gravitational waves: TeV emission from black hole or neutron star mergers (including those producing gamma-ray bursts)
- Gamma-ray burst light curves and spectra with high statistics per burst
- Triggers from optical/IR/radio transient factories: tidal disruption events, fast radio bursts, supernova shock breakout, ...
- Galactic transients inc. novae, Crab nebula flares (up to 100 TeV)
- Real-time analysis ($<$30 sec) for serendipitous transient detection and alerting other observatories
- 8° field of view per telescope, can cover larger areas with tiling or divergent pointing
AMS measurement of positron fraction and constraints on its anisotropy

- Positron fraction (integrated from 16 to 350 GeV) shows no anisotropy
- Dipole anisotropy < 0.036 (95% confidence)
Magnetic deflection in Earth’s field along trajectory from Moon is \( \sim 1.5° \) at 1 TeV (depending on viewing direction and location on Earth).

- Electron, positron shadows are displaced in opposite directions.
- In our ultra-relativistic regime (>100 GeV), protons and positrons deflect the same amount.
- Measured proton, positron shadows have different size and position due to different pointing resolution and energy reconstruction.
Simulated CTA positron Moon shadow in various energy bins

Example templates used in multi-component fit

- 100-147 GeV
- 215-316 GeV
- 2-3 TeV

- Above ~3 TeV: deflected Moon shadow starts to overlap true Moon position
- Below ~0.3 TeV: dim shower difficult to detect above background moonlight; large deflection requires separate telescope pointing
Simulated CTA positron spectrum measurement

- Model: Mertsch & Sarkar with $R_{\text{max}} = 10$ TV
- 100 hours of CTA observation

![Graph showing electron and positron spectra with model data and observational data from CTA and AMS]
Gamma rays from dark matter annihilation in the cosmos

- **Galactic center halo**
  - Large expected signal (J factor)
  - Large astrophysical backgrounds, but they can be distinguished from smooth halo shape
  - Large uncertainty on dark matter density (squared)
  - Probably the best target

- **Dwarf spheroidal galaxies**
  - Much more mass (DM) than light (stars)
  - Little/no astrophysical background from cosmic rays
  - Smaller J factor than halo
  - Smaller uncertainty on dark matter distribution

- **Galaxy clusters**

- **Milky Way subhalos**

- Prioritization among dark matter targets is underway (while maintaining flexibility for new targets such as dwarf spheroidals)
Modular, hierarchical camera design

(1) Full camera: 9 sub-fields
8° (0.81 m) diameter for 11,328 pixels
(24 telescopes will have 272k channels)

(2) Sub-field: 25 modules

(3) Camera module:
- 16 SiPM tiles
- 64 image pixels
- 16 trigger pixels
- 4 TARGET chips
- Each pixel is 0.067° (6 mm) square

Each telescope has more pixels than VERITAS, MAGIC, and H.E.S.S. combined
Simple calculation: Cherenkov light pool from infinite vertical shower

- At high altitude, density is small, index of refraction is close to 1, and Cherenkov angle is small
- Towards ground level, each of these increases
- Light pool of radius ~120-140 m on ground
Galactic plane survey

Entire plane surveyed to < 3.8 mCrab - several 100’s of sources
Galactic particle accelerators

Surveys of:
- Galactic center
- Galactic plane
- LMC

Current Galactic VHE sources (with distance estimates)
CTA will precisely measure the total electron + positron spectrum

- Cosmic ray electrons and positrons provide important constraints on cosmic ray production and propagation and on dark matter
- CTA will measure total electron + positron spectrum up to 30-100 TeV (depending on its shape)
- CTA will also measure anisotropy by comparing different sky directions
Gamma-ray bursts at very-high energy

Simulated spectrum

S. Inoue et al. for CTA, Astroparticle Physics
43 (2013) 252-275
# VHE GALACTIC SURVEYS

## Previous Surveys

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Hemisphere</th>
<th>Galactic Plane Coverage</th>
<th>Energy (GeV)</th>
<th>Sensitivity (mCrab)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H.E.S.S.-I</td>
<td>S</td>
<td>$-70^\circ &lt; l &lt; 60^\circ$, $</td>
<td>b</td>
<td>&lt; 2^\circ$</td>
</tr>
<tr>
<td>VERITAS</td>
<td>N</td>
<td>$67^\circ &lt; l &lt; 83^\circ$, $-1^\circ &lt; b &lt; 4^\circ$</td>
<td>$\gtrsim 300$</td>
<td>20 – 30</td>
</tr>
<tr>
<td>ARGO-YBJ</td>
<td>N</td>
<td>Northern Sky</td>
<td>$&gt; 300$</td>
<td>240 – 1000</td>
</tr>
<tr>
<td>HEGRA</td>
<td>N</td>
<td>$-2^\circ &lt; l &lt; 85^\circ$, $</td>
<td>b</td>
<td>&lt; 1^\circ$</td>
</tr>
<tr>
<td>Milagro</td>
<td>N</td>
<td>Northern Sky</td>
<td>$&gt; 10,000$</td>
<td>300 – 500</td>
</tr>
</tbody>
</table>

## Present/future Surveys

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Hemisphere</th>
<th>Energy Threshold</th>
<th>Angular Resolution</th>
<th>Pt. Source Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTA</td>
<td>N, S</td>
<td>125 GeV</td>
<td>$\sim 0.10^\circ$ at 300 GeV</td>
<td>2 – 4 mCrab</td>
</tr>
<tr>
<td>HAWC</td>
<td>N</td>
<td>2 TeV</td>
<td>0.30°</td>
<td>20 mCrab</td>
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</table>

**CTA GPS:**  
Full-plane survey with graded exposure  
Wide energy range and unprecedented angular resolution  
Order of magnitude improvement in sensitivity
GPS SENSITIVITY

Entire plane surveyed to < 3.8 mCrab - several 100’s of sources
New dwarf galaxies continue to be discovered, particularly in Southern hemisphere

27 previously known
Discovered in past 2 years: 22 by DES and 5 by others

- DES much deeper than previous searches
- DES (and SkyMapper, Pan-STARRS, LSST) will continue to provide new dwarfs, potentially with excellent J factors
• Sensitivity predicted for three known dwarf galaxies
• Southern: Sculptor
• Northern: Segue 1, Ursa Minor
• Many new dwarf galaxies are being discovered, particularly in the Southern hemisphere thanks to DES and LSST
• Some new dwarf galaxies already have J factor comparable to the best known previously

Doro et al. for CTA, APP 2012 (1208.5356)
Resolving extragalactic sources: Cen A

Fermi LAT >200 MeV background-subtracted counts map of Cen A

Fermi LAT PSF at 10 GeV
CTA PSF at 100 GeV (≥2 images)
CTA PSF at 300 GeV (≥10 images)
(68% containment)
Fermi limits will improve with more time and new dwarfs discovered by Southern surveys

- Known dwarfs mostly in Northern hemisphere (Sloan survey)
- Current and future surveys (DES, LSST) will increase number of known dwarfs
- New surveys will increase sky coverage by factor $\sim 3$
Gamma-ray Cherenkov Telescope (GCT) prototype

Inaugurated December 1, 2015

Inaugurated December 1, 2015
Gamma-ray Cherenkov Telescope (GCT) prototype
First Cherenkov light at a CTA (prototype) telescope recorded by Gamma-ray Cherenkov Telescope (GCT)

- November 26, 2015 in Meudon, France
- Pointing away from City of Light and nearly full Moon
- 12 events in 5 minutes
- 32 modules of 64 pixels each (2.048 kilopixel camera)
- Most events were due to cosmic-ray air showers
- Image shows maximum light in each pixel among 100 frames
Gamma-ray Cherenkov Telescope (GCT) prototype
Time allocation and community access

Potential scenario

<table>
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<th>Year</th>
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<td>10</td>
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- **Community**: All CTA data will be fully open after a proprietary period.
- **Consortium**
- **Key Science Projects**

*of scientists from nations contributing to CTA construction and operations
Project Phases

- **Pre-Construction Phase**
  - Finish End of 2016
- **Pre-Production Phase**
  - 2017 - 2018
- **Production Phase**
  - 2019 - 2024

Current Phase
- Pre-Construction Phase

Current Timeline

- Jul 2015
- Oct 2015
- Jan 2016
- Apr 2016
- Jul 2016
- Oct 2016
- Jan 2017
- Apr 2017

- Site Negotiations Begin
- Instrument Contribution Expressions of Interest Received
- Initial Evaluation of Resources
- International Agreement
- Call for Offers
- Headquarters Site Decision
- Initial Design Acceptance
- Work Begins On Site
- Financial Ability to Continue
Prototype telescopes

• SST-1M (Krakow, Poland)
• SST-2M ASTRI (Serra la Neve, Sicily)
• GCT (Meudon, France)
• MST (Adlershof, Germany)
• SCT (Mt Hopkins, USA)
• LST (La Palma, Spain)
Effective area

Fermi LAT

CTA

1 m²

10⁶ m²
Angular resolution

![Angular Resolution vs Energy Graph]

- **Angular Resolution** $\theta_{68}$ (degrees)
- **Energy** (TeV)
- **Angular Resolution** $\theta_{68}$ vs. Energy (TeV)

- **Fermi**: 
- **HESS**: 
- **CTA**: 
- **HAWC**:

*Note: The graph illustrates the angular resolution for different gamma-ray observatories as a function of energy. The solid line represents CTA, showing significantly better angular resolution compared to Fermi, HESS, and HAWC.*
The sensitivity of gamma-ray detectors is determined by three basic characteristics: the effective collection area, residual background, and angular and energy resolution. This is due to inherent fluctuations in the shower production in the atmosphere for showers initiated by low energy primaries.

The study presented here uses the curves for an altitude field-of-view, and 32 telescopes of 7 m diameter with a 10 k/m² on the ground rate and angular resolution, all of which are typically a large issue, even for CTA as shown in [16]. Contrary to the Fermi-LAT, this might be overly conservative. Due to analysis improvements and hardware performance and telescope array

The sensitivity model such as GRBs.

The sensitivity is relevant when aiming to detect a new source, and the sensitivity may be limited by statistical fluctuations of the background. The instrument point-spread functions (PSFs) are assumed to be Gaussian for simplicity, with the 68% containment in the Fermi-LAT data above 10 GeV. The likelihood method is used.

For the ground-based instruments a 5% systematic error on the background is representative of the isotropic diffuse emission relevant for high Galactic latitude sources. As previously stated we ignore the Galactic diffuse emission which is justified, given its diminishing importance in the Fermi-LAT data above 10 GeV. The likelihood method is used.

Source extension studies described in Section 5, where a full treatment is used. This approach is used throughout except for the case of the Fermi-LAT, where an energy-dependent aperture is used. To match the sensitivity achieved in the Fermi-LAT data above 10 GeV, the likelihood method is used. The instrumental background is determined from cosmic-ray interactions in our Galaxy in that energy range. Therefore longer observations do not help the CTA to the dominance of systematic errors for CTA in the overlapping energy range, longer observation times do not significantly shift the accuracy.

The Crab Nebula is shown as dashed grey curves. Compton measurements for the brightest persistent TeV source, the Crab Nebula function curves have been used. As comparison, the synchrotron and Inverse Compton components of the diffuse emission have been determined by the off-phase, this might be overly conservative. Due to the high energy range, the determination of a source. While HAWC's performance in these quantities is focused, HAWC is not competitive with the Fermi-LAT and CTA for the aforementioned goals. In the energy range at which this study is focused, HAWC is not shown in Fig. 1 as different.
More telescopes means more contained showers detected by multiple telescopes

VERITAS type

4 x 3.5° FoV

25 x 8° FoV

61 x 8° FoV
1200 members from 170 institutes in 32 countries
Signal and background spectra

- Cherenkov spectrum
- convolved Cherenkov spectrum (MAPMT)
- convolved Cherenkov spectrum (MPPC)
- NSB spectrum

Arbitrary Units vs. Wavelength (nm)
What could dark matter annihilate/decay to?

- Neutrinos
- Gamma rays
- Electrons, positrons
- Protons, antiprotons
- Deuterons, antideuterons
FACT has observed air showers with full Moon in center of camera

Simulated positron vs. proton Moon shadow shape (100-147 GeV)
Axion-like particles

- CTA is sensitive to axions /axion-like particles (ALPs) through ALP-photon conversion in magnetic fields.
- ALPs can imprint signatures on the spectra of active galactic nuclei.
- CTA will test a unique region of phase space, including a region in which they would behave as cold dark matter.
10 to 300 times improved sensitivity to Lorentz invariance violation

Potential of GUT scale physics to reveal itself in LIV effects

Variable gamma-ray sources (pulsars, AGN, and GRB) provide the most stringent tests of LIV effects in the photon dispersion relation

CTA will provide 10 to 300 times improved sensitivity on LIV tests

\[
\begin{align*}
c'(E) &= c + a \cdot \frac{E}{E_{LIV}} + b \cdot \left( \frac{E}{E_{LIV}} \right)^2 \\
\Delta t_1 &= \frac{d}{c} \cdot \frac{E_h - E_l}{E_{LIV}} \\
\Delta t_2 &= \frac{d}{c} \cdot \frac{3}{2} \cdot \frac{E_{h}^2 - E_{l}^2}{E_{LIV}^2}
\end{align*}
\]

Current best limits from Fermi-LAT

(arXiv: 1305.3463)
US contribution doubles the collection area of the array (from 25 to 49 telescopes) and nearly doubles the sensitivity.

Equivalent to a factor of 3–4 reduction in observing time: Makes possible results impossible with the baseline array.

CTA expected performance: point source sensitivity

Point Source Sensitivity
50 hour observation

CTA Baseline
CTA Baseline + US Extension
Fermi 10yr
1 mCrab
+ U.S. Enhancement

Ratio
Energy [log_{10}(E/GeV)]

Justin Vandenbroucke: TeV astro
Counting Moon observation time available

- Moon phase < 0.5: 51%
- Sun zenith > 108°: 38%
- Moon zenith < 50°: 22%
- Moon zenith < 50° and sun zenith > 108° and moon phase < 0.5: 0.39% (34 hrs per year)
64-pixel camera module

30 cm length
5.2 cm width (square)
233 g without photo-sensor
64-pixel camera module

- 30 cm length
- 5.2 cm width (square)
- 233 g without photo-sensor
- < 10 W for 64 channels (without photo-detector)
- Prototype module used TARGET 1 and MAPMT
- Prototype SCT camera will use TARGET 7 and SiPM
Sensor module has active temperature stabilization for stable SiPM gain

- SiPM temperatures stabilized to ±0.25 °C
- Peltier element consumes 2-3 W per 64-channel module

Cold (0° C - 20° C)

Warm (≥ 25° C)

- Air flow to cool electronics

- Peltier
- Delrin
- Heat sink
- thermistor
- insulating foam (not shown)
- copper
Camera mechanical structure

Sensor module

Front-end electronics

Carbon fiber posts

Lattice

Module Cages

Backplane motherboard

Bulkhead

Three-axis stage controller outside of camera housing for overall camera positioning/focusing

Cooling achieved with fans blowing parallel to front-end boards
US focus in CTA: dual-mirror (Schwarzschild-Couder) telescope design

- Allows (1) better optical angular resolution over wide (8° diameter) field of view (2) small camera focal plane
- Small focal plane well suited for modern dense, highly integrated photo-detectors (MAPMTs and SiPMs) and electronics (application-specific integrated circuits)
- Improved gamma-ray angular resolution and background rejection allow qualitatively improved sensitivity
Camera design for US dual-mirror CTA telescopes

(1) Full camera: 9 sub-fields
8° (0.8 m) diameter for 11,328 pixels

(2) Sub-field: 25 modules

(3) Camera module:
• 2” SiPM
• 64 analog pixels
• 16 trigger pixels
• 4 TARGET chips
• Each pixel is 0.067° (6 mm) square

Each telescope has more pixels than VERITAS, MAGIC, and HESS combined
Modules for pSCT
Example model: secondary $e^\pm$ production and acceleration in supernova remnants

Mertsch & Sarkar
PRD 90, 061301 (2014)
Indirect detection would provide smoking gun confirmation of particle nature of dark matter

Simulation of whole sky in gamma rays from dark matter based on Via Lactea II (Pieri et al. PRD 2011)
γ-ray Shower
Energy: 1 TeV
Impact Distance: 100m

Proton Shower
Energy: 3.16 TeV
Impact Distance: 0m

Camera images
CTA expected performance: angular resolution

- US telescopes: good angular resolution across wide field of view
  - 0.1° at 100 GeV
  - 0.04° at 1 TeV
  - 0.02° at 10 TeV
  - 0.01° at 100 TeV
- Enables good background (proton) rejection
- Enables morphological studies of Galactic sources
- Reduces source confusion
CTA expected performance: angular resolution

- US telescopes: good angular resolution across wide field of view
  - 0.1° at 100 GeV
  - 0.04° at 1 TeV
  - 0.02° at 10 TeV
- Enables good background (proton) rejection
- Enables morphological studies of Galactic sources
- Reduces source confusion
- Improves subtraction of discrete sources for study of extended sources such as Galactic center halo
Chile

- **10 meter and (pictured) 30 meter weather towers**
- Measuring temperature, humidity, pressure, wind
- 3D anemometers at several heights: wind speed and profile
- All-sky camera for cloud monitoring
- Seismometer
- Sun and moon photometer for measuring absorption and scattering of light
The total electron + positron spectrum

Abdo et al., PRL 102, 181101 (2009)
Ackermann et al., PRD 82, 092004 (2010)
Indirect, direct, and accelerator dark matter searches are complementary

M. Cahill-Rowley et al. – Snowmass white paper, arXiv:1305.6921
Cherenkov Telescope Array capabilities: total electron + positron anisotropy

Anisotropy:

arXiv:1304.1792
Prototype single-mirror mid-size CTA telescope in Germany
Cherenkov Telescope Array capabilities: positron fraction with Moon shadow

- Measure total electron + positron spectrum precisely to ~100 TeV
- CTA expected to detect Moon shadow in electrons in ~5 hours
- Use Moon shadow to separate electrons and positrons: two shadows separated by ~1.5° at ~1 TeV
- Silicon photomultipliers particularly well suited: can look in direction of bright moonlight
Three mechanisms of cosmic-ray electron and positron production

1. Interaction of cosmic-ray protons with diffuse interstellar gas (believed to dominate)

2. Primary astrophysical sources (e.g. pulsars)

3. Dark matter annihilation or decay
Freeze-out of dark matter particles

From A. Ibarra @ Zurich February 2010
Simulated CTA array

Array “2A”: 4 LST, 24 MST, 35 SST
Effective area of CTA array geometry 2A

- Assuming nominal (extragalactic) NSB
- Cuts optimized for gamma-ray point sources
Gamma ray vs. neutrino spectra from WIMP annihilation

Gamma rays

\( \gamma \) prompt spectra

- Hard: \( e^+e^-, \mu^+\mu^-, \tau^+\tau^- \)
- Soft: \( b\bar{b}, t\bar{t}, W^+W^- \)

Neutrinos

IceCube 1406.6868

- Hard: \( W^+W^-, \mu^+\mu^-, \nu\bar{\nu} \)
- Soft: \( b\bar{b} \)

Spectra calculated with PPPC 4 DM ID [Cirelli et al. 2010]

Justin Vandenbroucke: TeV astro 104
Uncertainty of dark matter distribution in Milky Way

- Uncertainty in both shape and normalization
- Local density (0.2-0.4 GeV/cm³) can be used to normalize
- Gamma-ray flux scales with density squared
Gamma-ray bursts at very-high energy

Detection rate depends on slewing to target quickly

Simulated spectrum measurement for example burst

GRB 090902B-like, $z=1.0$
$t_0=50$ sec, F08 EBL, exposure 50 sec

S. Inoue et al. for CTA, Astroparticle Physics 43 (2013) 252-275
Milky Way dark matter distribution

Search Region

15 pc  150 pc

DM Density [GeV cm$^{-3}$]

NFW  
Einasto ($\alpha = 0.17$)  
isothermal  
NFW (C&U 2010)  
Einasto (C&U 2010)  
68% CI (NFW C&U 2010)  
68% CI (Einasto C&U 2010)
The presence of simulations for both north and south pointings for each site, which can be separately characterised, plus the presence of a range of sites, means that the effects of magnetic field and altitude on sensitivity can indeed be decoupled. Fits to the derived PPUT values have been performed for both the DESY and MPIK analyses, with consistent results on relative PPUT. Here we describe the MPIK fit, which is used in the derivation of the final PPUT values. Note that an additional simulation set was produced at 500 m altitude (with the same geomagnetic field as Aar) to constrain the behaviour of the altitude dependence at the low altitude end.

The model was fit in two steps to the southern site PPUTs. The first step assumed that the PPUT degrades with increasing component \( B_{\text{perp}} \) of the geomagnetic field, where \( B_{\text{perp}} \) is the component perpendicular to the shower axis, which dominates the deflection of shower particles moving along the shower axis. The values of \( B_{\text{perp}} \) differ for North and South pointings; the respective values are listed in cols. 4 and 5 of Table 18. Figure 8 shows for all available altitudes (500 m, 1640 m, 2662 m, 3600 m) and analysis methods the relative difference in PPUT values between the two viewing directions (to the north and south) and the corresponding difference in \( B_{\text{perp}} \). The results are well described by a linear dependence, with PPUT decreasing by about 1% per \( 1^\circ \) in \( B_{\text{perp}} \) (the line obviously has to go through the origin). The dependence is parametrized as:

\[
\text{PPUT} = \text{PPUT}_0 - k B_{\text{perp}}.
\]

The second step was to fit a parabola to the eight PPUT values corrected to zero B-field. In total, the model thus used four fit parameters for eight PPUT data points. When excluding the hypothetical 500 m site, a linear fit of zero-B-field PPUT values would be of similar quality, although without predictive power for altitudes below 1640 m. Figure 9 shows the data used for the fit, and the best fit curve for zero B-field. The best fit final expression is:

\[
\text{PPUT} = 1.52 - (|\text{Altitude} - 330 \text{ m}|/5600 \text{ m})^2.5 - |B_{\text{perp}}|/75 \times 10^3.
\]

The index is rather poorly constrained, with equally good fits for values of 2.0 and 2.5, but with very little impact on the predicted PPUT for a range of altitude from 1.5-3.0 km.

<table>
<thead>
<tr>
<th>Site</th>
<th>Altitude [m]</th>
<th>Horizontal</th>
<th>Perpendicular - 20 deg. Zenith</th>
<th>B [microtesla]</th>
<th>HESS</th>
<th>MAGIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leoncito</td>
<td>2662</td>
<td>19.9</td>
<td>14.4</td>
<td>23.0</td>
<td>18.7</td>
<td>19.1</td>
</tr>
<tr>
<td>Aar</td>
<td>1640</td>
<td>10.9</td>
<td>1.7</td>
<td>18.8</td>
<td>10.2</td>
<td>15.6</td>
</tr>
<tr>
<td>SAC</td>
<td>3600</td>
<td>20.9</td>
<td>16.6</td>
<td>22.7</td>
<td>19.6</td>
<td>19.6</td>
</tr>
<tr>
<td>Armazones</td>
<td>2500</td>
<td>21.4</td>
<td>17.0</td>
<td>23.1</td>
<td>20.1</td>
<td>20.0</td>
</tr>
<tr>
<td>HESS</td>
<td>1800</td>
<td>12.0</td>
<td>2.3</td>
<td>18.5</td>
<td>10.4</td>
<td>16.5</td>
</tr>
<tr>
<td>SPM</td>
<td>2434</td>
<td>25.2</td>
<td>36.8</td>
<td>10.6</td>
<td>23.7</td>
<td>28.5</td>
</tr>
<tr>
<td>Meteor Crater</td>
<td>1680</td>
<td>23.5</td>
<td>36.8</td>
<td>7.4</td>
<td>22.1</td>
<td>28.2</td>
</tr>
<tr>
<td>Yavapai</td>
<td>1670</td>
<td>23.6</td>
<td>36.8</td>
<td>7.6</td>
<td>22.2</td>
<td>28.2</td>
</tr>
<tr>
<td>Tenerife</td>
<td>2290</td>
<td>30.8</td>
<td>36.9</td>
<td>21.0</td>
<td>28.9</td>
<td>31.0</td>
</tr>
</tbody>
</table>

Table 18: Summary of different magnetic field values for the candidate sites. The average perpendicular \( B \) is given for vertical showers (labelled 'Horizontal'), for 20º to the north to the south and the average of these two values (labelled 'Average'), and averaged over the pointing distributions (2D distributions in altitude, azimuth) for HESS and MAGIC.
Energy budget of the Galaxy

- Visible starlight: 0.3 eV/cm³
- Magnetic fields: 0.3 eV/cm³
- CMB: 0.3 eV/cm³
- Cosmic rays: 1 eV/cm³
HESS extends constraints to higher mass using Galactic center observations

PRL 106, 161301 (2011)
Fermi and CTA together will cover the entire range of dark matter WIMP masses
Fermi non-detection of dwarf galaxies strongly constrains dark matter

Cross section upper limit is now below that expected if WIMPs are produced thermally in early Universe (3 x 10^{-26} cm^3/s)

PRL 107, 241302 (2011)
Fermi Bubbles

- Huge structures, $\pm 50^\circ$ from Galactic plane (residual maps after subtracting Gal. diffuse)
- Synchrotron from energetic particles from past Sgr A* or star formation activity?
Search for spectral lines from dark matter annihilation

Abdo et al., PRL 104:091302 (2010)

- Integrate diffuse flux over most of sky (exclude Galactic latitudes more than 10° from plane except keep 20° x 20° square centered on Galactic center), one year of data
- Search for lines in 30 to 200 GeV mass range
- Line width due to Fermi energy resolution
- Scan line energy and set flux upper limit at each energy
Simulated shower images for two-mirror vs. one-mirror telescope design

Example 1 TeV gamma-ray shower as seen by one-mirror or two-mirror telescope

DC telescope (~2k 0.16° pixels)
SC telescope (~10k 0.06° pixels)
Both images zoomed in (2° across, compared to 8° field of view)
PASAG and Astro 2010 strongly endorsed CTA

- **PASAG**
  - “Given the great excitement in the field and the success of the technique, a more ambitious and **likely very highly productive** concept for the future is an array of many (~50) atmospheric Cherenkov telescopes distributed over a square km.”

- **Astro 2010**
  - **Ranked among top 4 priorities for large ground-based projects**
  - “The last decade has seen the coming of age of very high energy (TeV) astronomy... Further progress is now dependent on building a larger facility exploiting new detector technology and a larger field of view so that the known sources can be studied in more detail and the number of sources can be increased by an order of magnitude.”
  - “**The promise of this field is so high that continued involvement is strongly recommended.**”
  - “Increasing the sensitivity of atmospheric Cherenkov telescopes by another order of magnitude is our top priority for exploring the nature of dark matter.” (Panel on Particle Astrophysics and Gravitation)
γ-ray Shower
Energy: 1 TeV
Impact Distance: 100m

Proton Shower
Energy: 3.16 TeV
Impact Distance: 0m

Camera images
9 candidate sites

- **South:**
  - Aar, Namibia: private farmland 1600 masl
  - Khomas Highland, Namibia
  - Chile
  - El Leoncito, Argentina
  - San Antonio de los Cobres, Argentina

- **North:**
  - Meteor Crater, Arizona, United States
  - Yavapai Ranch, Arizona, United States
  - San Pedro Martir, Mexico
  - Teide, Tenerife, Canary Islands
Two-Mirror Atmospheric Cherenkov Telescope: The Schwarzschild-Couder Telescope (SCT)

- Innovative U.S. design key to boosting CTA performance
- Corrects aberrations providing higher resolution, wider field
- Small plate scale enables SiPM camera
- Deep analog memory waveform samplers to minimize dead-time and allow flexible triggering
- High level of integration into ASICs allows dramatic cost savings (<$80 per channel) and high reliability (11,328 channels)
- Overall cost comparable to baseline single-mirror medium-sized telescope
- Adopted now by European groups also for small-sized telescopes
A fifth mechanism to make $\gamma$ rays

Exotic particle (e.g. dark matter) rest mass
Gamma rays probe the extreme, non-thermal, Universe

- Dark Nebula
- Dim, young star
- Our Sun
- Globular Cluster

CMB

Accretion Disk

Thermal Processes

- Radio
- Microwave
- Infrared
- Visible
- Ultraviolet
- X-ray
- Gamma ray

eV keV MeV GeV TeV

Extreme Universe

Physics 301
Justin Vandenbergroucke: TeV astro
Combining indirect, direct, and accelerator WIMP searches

![Graph showing the sensitivity of various searches in the LSP mass vs scaled SI cross section plane for the pMSSM model sample.](image)

Cahill-Rowley et al. PRD 91, 055011 (2015)
Moon spectrometer technique: past, present, future

- Initial work by ARTEMIS
- MAGIC and VERITAS have continued the technique
- Challenge with PMTs: large NSB near Moon
- ~35 hours per year observable

- CTA has sensitivity necessary to measure $e^{\pm}$ shadows
- Larger effective area
- Better gamma-hadron separation
- Larger field of view
- SiPM-based CTA cameras expected to observe well in moonlight
- Capabilities of PMT-based CTA cameras require further study

Justin Vandenbroucke: Positron fraction with CTA

Physics 301
TARGET chip for triggering and waveform digitization

- Application-specific integrated circuit featuring switched capacitor array analog sampling followed by self-triggered digitization
- Designed by Gary Varner (U Hawaii)
- 1.0 or 0.5 GSa/sec analog sampling per channel
- ~380 MHz analog bandwidth
- 16 channels per chip
- 16,384 cells of analog memory per channel
- Self triggering with analog sum trigger (sum of 4 channels)
- LVDS trigger output
- Currently characterizing version 7 (to be used for prototype SCT)
- ~10 bits effective (1.9 V range, 2 mV noise)
Gamma-ray angular resolution vs. energy for single-mirror vs. double-mirror telescope arrays

- 21 single-mirror telescopes
- 61 dual-mirror telescopes
- 61 dual-mirror telescopes

T. Jogler et al. (CTA), ICRC 2013

arXiv:1307.5905
Camera design for Schwarzschild-Couder telescopes

- Excellent optical resolution, small plate scale of dual-mirror telescope well matched to fine pixelation supported by silicon photomultipliers and TARGET readout electronics
- 11,328 6x6 mm² pixels (temperature-stabilized silicon photomultipliers)
- Pixel size 0.067° (high-resolution imaging)
- Readout directly behind focal plane
- 1 GSa/s, 10 bits effective (TARGET 7)
- 3 kW power budget
- Shares many common components with the Compact High Energy Camera for CTA Small Size Telescopes

8° field of view, 81 cm diameter
Gamma-ray angular resolution vs. energy for single-mirror vs. double-mirror telescope arrays

- 21 single-mirror telescopes
- 61 dual-mirror telescopes
- 61 dual-mirror telescopes

T. Jogler et al. (CTA), ICRC 2013
arXiv:1307.5905
Telescope images with single-mirror vs. dual-mirror design

**Single-Mirror Telescope Images**
- 8° field of view
- 0.18° pixels
- 1,570 channels

**Two-Mirror Telescope Images**
- 8° field of view
- 0.067° pixels
- 11,328 channels

**Signal:** γ-ray Shower
**Energy:** 1 TeV

**Background:** Proton Shower
**Energy:** 3.2 TeV

Justin Vandenbroucke: TeV astro
GPS IMPLEMENTATION

- **Strategy**
  - Both CTA-S and CTA-N
  - Dark time, full arrays, zenith < 45°
  - Double-row pointing scheme with 3° spacing; LST participation still under study
  - Sensitivity-graded with deepest exposure in the inner, Cygnus and Carina regions
  - Carried out over ten years, but with significant exposure in Years 1-2 to provide early bright-source list (Year 2) and first catalog (Year 3)
  - Transients detected are followed-up in context of Transients KSP
  - Total time: 1020 h (S), 600 h (N)
Fermi dwarfs & CTA Galactic center will cover entire mass range down to thermal cross section
CTA will test a wide range of dark matter models with Galactic center halo and dwarf galaxy observations
Camera module based on fast, modern, highly pixelated photo-detectors and readout electronics

30 cm length
5.2 cm width (square)
233 g without photo-sensor
H.E.S.S. constraints on WIMP annihilation from Galactic center halo observations

Signal and background regions

HESS, PRL 106, 161301 (2011)
Silicon photomultipliers

- Operate at much lower voltage (~70 V) than PMTs
- Hamamatsu S12642-0404PA-50 selected for first sub-field of prototype SCT
- 3x3 mm² SiPMs in 4x4 matrix, 50 µm cell size
- Through-silicon via technology (low dead space: 21% with 54 mm module pitch)
- Peak photon detection efficiency (PDE) @ 450 nm is ~40% at center of one pixel
- 415 devices (400 for prototype telescope, plus 15 spares) received in past two months