The Dark Side of H.E.S.S.

Dark Matter Search with Cherenkov Telescopes

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VHE γ-ray astronomy
... a new window to the universe
VHE $\gamma$-ray astronomy

... a new window to the universe

resolve sources
VHE $\gamma$-ray astronomy
... a new window to the universe

$E_\gamma^{-2}$

$E_\gamma^{-3.3}$

$\text{dN/dE (cm}^{-2} \text{s}^{-1} \text{TeV}^{-1})$

H.E.S.S.
Aharonian et al. 2007

do spectroscopy
VHE γ-ray astronomy
... a new window to the universe

PKS 2155-304
H.E.S.S.
Aharonian et al. 2007

measure flux variability
VHE $\gamma$-ray sky in 2009
... more than 75 sources known
VHE $\gamma$-ray sky in 2009

... more than 75 sources known
(Some) topics of VHE $\gamma$-ray astronomy

**Astrophysics**
- Which are the cosmic PeVatrons?
- How do they work?
- Acceleration, emission, propagation

**Fundamental Physics**
- Indirect Dark Matter searches
- Energy dependence of speed of light

**Cosmology**
- Extragalactic Background Light
  $\rightarrow$ star formation in the early universe
- Galaxy clusters as storehouses of cosmic rays
Windows for Astronomy

- Radio
- Infrared
- Optical
- X-ray
- Soft Gamma
- VHE Gamma
Detection Principle

Gamma Ray

Atmosphere

Particle Shower
Detection Principle

Atmosphere

Particle Shower

Gamma Ray

Cherenkov Light

10 $\gamma$-rays / m² yr from the Crab nebula
but > 50,000 m² detection area
$\rightarrow$ flux of > 1 $\gamma$-ray / min

~ 120 m
Detection Principle

- Gamma Ray
- Atmosphere
- Particle Shower
- Cherenkov Light

$\sim 120 \text{ m}$
Particle Shower Detection Principle

Atmosphere

Cherenkov Light

- Image intensity → $\gamma$-ray energy
- Image form → background reduction
- Image orientation → $\gamma$-ray direction

~ 120 m
Detection Principle

Atmosphere

Particle Shower

Cherenkov Light

Camera

- stereo reconstruction
  → improved direction
  → background reduction
  → low energy threshold

~ 120 m
Cherenkov Telescopes World Map

VERITAS 10/2006

H.E.S.S. 12/2003

MAGIC 08/2004

Cangaroo III 03/2004
H.E.S.S. Details

- 4 telescopes
  120 m spacing
  107 m² mirror surface each

- energy threshold \(\sim 100 \text{ GeV}\)
  energy resolution \(< 15 \%\)

- angular resolution \(\sim 0.1^\circ\)
  pointing accuracy \(< 20''\)

- sensitivity (5σ):
  5% of Crab in 1 h
  1% of Crab in 25 h
  HEGRA: 5% of Crab in 100 h

- 1000 h of observations / year
  during moonless nights
The H.E.S.S. Cameras

- 960 pixels (0.16° per pixel)
- 5° field of view
- Sensitive photomultipliers
- Fast readout and trigger electronics
Need for short exposures
...to reduce night-sky background

1 TeV gamma-ray vertical

K. Bernlöhr
Background Reduction & Control

- (one of) the most critical issue for analysis
- vital for significance calculation
- vital for flux determination

2 types of background

- cosmic ray hadrons
  - produce air showers somewhat similar to gamma rays
  - about $10^4$ more hadrons than gamma rays

- cosmic ray electrons
  - showers very similar to gamma rays
  - flux suppressed at TeV energies

3 stages of reduction

- suppression at trigger level
- reduction by image shape analysis
- subtraction by background modeling
H.E.S.S. Trigger

- 4x single telescope pixel threshold trigger
typical rates 500-800 Hz

- multiplicity-2 system trigger
typical system rate 150-250 Hz

- system trigger provides
  efficient background reduction
  and lower threshold
Energy Threshold

- 160 GeV @ zenith for standard cuts
- strong zenith angle dependence
- optical degradation is shifting up thresholds

Aharonian et al. (2006)
Cosmic Rays...
...main background for Cherenkov astronomy

- Ratio $\gamma$/hadron $\approx 1/1000$
- Cuts on image parameters $\rightarrow$ 99.9% background reduction
- Remaining S/B $\sim 1..10$, depending on source strength and source size
Background Modeling

- remaining background is subtracted on statistical basis:

\[ N_{\text{excess}} = N_{\text{on}} - \alpha N_{\text{off}} \]

- ideally, control background is taken
  - contemporaneously
  - same position in camera
  - same sky region
  - with large event statistics
  - same image-parameter phase space

- not all criteria can be met at the same time

- favoured background model depends on type of analysis (detection, morphology, spectrum...)

Background Modeling
- Ring Background -

- Off-Region: ring around On-Region
- Off-Events subtracted from On-Events
  - proper area factor
  - acceptance correction
- insensitive to linear gradients in background
- applicable all over the field of view (Sky Maps, morphology)
- not very well suited for spectra due to acceptance correction
Background Modeling
- Reflected Region Background -

- Off-Region: ring of circular regions around observation position (same distance as On-Region)
- Observation position must be outside the On-Region
- no acceptance correction needed assuming radially symmetric acceptance
- insensitive to systematics of acceptance determination
- very well suited for spectra
H.E.S.S. Galactic Plane Scan including re-observations

Pulsar Wind Nebulae
H.E.S.S. Galactic Plane Scan including re-observations

Classification from Aharonian, Buckley, Kifune and Sinnis (2008)

Binary Systems
H.E.S.S. Galactic Plane Scan
including re-observations

Galactic Centre

Classification from Aharonian, Buckley, Kifune and Simnis (2008)
H.E.S.S. Galactic Plane Scan including re-observations

Classification from Aharonian, Buckley, Kifune and Sinnis (2008)
Indirect Dark Matter Searches
The Early Days...

- Large velocity dispersion among Coma cluster galaxies → Zwicky 1933
- Galactic rotation curves hard to explain with luminous matter only → Babcock 1939 (Andromeda)

... and 75 years later

- High-redshift supernova surveys
- Large-scale structure of the universe
- CMBR fluctuations → $\Lambda$CDM Standard Model of Cosmology → need CDM for structure formation

- Dark Matter accounts for
  - 22% of energy content
  - 85% of total matter

We know that we don't know, but with great precision
Particle Dark Matter

- Almost all models extensions of the SM need (quasi-)stable, massive particles

<table>
<thead>
<tr>
<th>Particle</th>
<th>Spin</th>
<th>Mass Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axion</td>
<td>0</td>
<td>μeV - meV</td>
</tr>
<tr>
<td>Inert Higgs Doublet</td>
<td>0</td>
<td>50 GeV</td>
</tr>
<tr>
<td>Sterile Neutrino</td>
<td>1/2</td>
<td>keV</td>
</tr>
<tr>
<td>Neutralino</td>
<td>1/2</td>
<td>10 GeV – 10 TeV</td>
</tr>
<tr>
<td>Kaluza-Klein UED</td>
<td>1</td>
<td>TeV</td>
</tr>
</tbody>
</table>

Bergström (2009)

- Velocity-averaged annihilation cross section at the time of freeze-out ($v/c \approx 0.2 – 0.3$)

$$\langle \sigma v \rangle = 2.8 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

- Galaxy today: $v/c \approx 10^{-3}$
  → significant enhancement possible, especially if bound state exists
Final states

- Too many models on the market:
  → two SM particles: $e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, $W^+W^-$, $b\bar{b}$, $p\bar{p}$
  → >4 SM particles: $4e$, $4\mu$, $4\tau$, $4\pi$

- Branching ratios do depend on DM particle mass

- Depends on type of process:
  annihilation vs. decay
  → mainly concentrate on annihilation here

- Usually continuum spectra, but line emission possible (can be loop-suppressed)
Expected Flux

\[
\Phi = \int \int \frac{1}{\tau} \frac{\rho_{DM}}{M_{DM}} \frac{dN_y}{dE_y} \ d\Omega \ d\Omega
\]

\[\langle \sigma v \rangle = 2.8 \times 10^{-26} \text{ cm}^3 \text{s}^{-1} : \text{cross section at freeze-out}\]

\[\rho_{DM} = 0.3 \text{ GeV cm}^{-3} : \text{local energy density}\]

\[\text{BF: boost factor}\]

(Sommerfeld, sub-structure...)

Messengers

- γ-rays, neutrinos
  → sensitivity drops with 1/θ
  → observe spikes in DM profile

- electrons/positrons
  → diffusion-dominated
  → measure diffuse flux

- Diffuse γ-rays from Inverse Compton
Galactic Dark Matter Distribution

- Form of DM halo critical for detection
  → e.g. large differences in density at GC, sub-structure
- More an issue for $\gamma$-rays than for electrons
- More an issue for annihilation than for decay

Barger (2009)
The Centre of the Milky Way
The Centre of the Milky Way

H.E.S.S. (55 hours)

H.E.S.S. J1745-290
point-like < 1.2' (95% CL)

G 0.9+0.1

3EG J1746-2851

3EG J1744-3011

Aharonian et al. (2006)
The Centre of the Milky Way

H.E.S.S. 2004 (55 hours)

H.E.S.S. J1745-290
point-like < 1.2' (95% CL)

G 0.9+0.1

Diffuse emission
15 sigma (55h)

Aharonian et al. (2006)
Diffuse Emission

... enhanced cosmic ray density

- Not just passive illumination
  - enhanced flux for > 1 TeV
  - photon index ~2.3

- Similar index as HESS 1745-290
  - everywhere in the region

- Many sources of electrons?
  - strong cooling: expect compact sources
  - should be strong X-ray emitters but not observed
Diffuse Emission
... molecular cloud association

- Lack of $\gamma$-rays for $l > 1^\circ$
- Injection of protons at GC
- Assume $k \approx 3$ kpc$^2$ Myr$^{-1}$ for TeV protons
  $\rightarrow$ injection $10^4$ years ago
- Fits age of Sgr A East
HESS J1745-290
... not much room for Dark Matter


NFW Dark Matter: \( \rho \propto r^{-1} \)

H.E.S.S. PSF

radial source profile fits NFW DM at first glance, but...

\[
F_\gamma \propto \frac{dN_\gamma}{dE} \langle \sigma \cdot v \rangle \int dl \frac{\rho^2}{m_{DM}^2}
\]
HESS J1745-290
... not much room for Dark Matter


- radial source profile fits NFW DM at first glance, but...
  ... point-like after subtraction of diffuse emission

- DM density stronger peaked than $r^{-1.2}$ (99% CL)
HESS J1745-290
... not much room for Dark Matter

- energy spectrum: straight powerlaw exponential cutoff: $E_c > 9$ TeV @ 95% CL
- curved annihilation spectra
  + “uncomfortably large” masses in MSSM
- 10% DM contribution not ruled out
  $\rightarrow$ derived limits on $<\sigma v>$ do not constrain models
Dwarf Galaxies

- High mass/luminosity ratio
- Most extreme DM dominated environments
Sagittarius Dwarf

- Satellite galaxy in the Local Group
- 24 kpc distance, so close-by
- Several Galactic disk crossings → likely disrupted w/o large DM content
- Galaxy core is point-like for H.E.S.S.

- No significant signal detected

→ derive flux upper limit (95% CL):

\[ F(>250\text{GeV}) < 3.6 \times 10^{-12} \text{cm}^{-2} \text{s}^{-1} \]

or less than 56 γ-rays...
Sagittarius Dwarf

- Used both NFW and “cored” profile adjusted to object parameters
- Calculate pMSSM annihilation cross section limits
- Can constrain some models depending on core profile
- WMAP compliant models still viable

\[
\langle \sigma v \rangle^{95\text{CL}} = \frac{4 \pi}{T} \frac{m_{\text{DM}}^2}{J \Delta \Omega} \frac{N_{95\text{CL}}^{\gamma}}{\int_0^{m_{\text{DM}}} A_{\text{eff}}(E_\gamma) \frac{dN}{dE_\gamma} dE_\gamma}
\]

Aharonian et al. (2008)
Other Dwarf Galaxies

- ULs hardly constrain models
- Large uncertainty from astrophysical parameters
Dark Matter from IMBHs

- black holes of intermediate mass ($100 \, M_{\text{sun}} < M_{\text{BH}} < 10^6 \, M_{\text{sun}}$)
- may power ultra-luminous X-ray sources
- formation procedure highly debated but leads to formation of DM overdensities
- search in H.E.S.S. scan data for point-like sources
Dark Matter from IMBHs

- Can calculate analytically DM profile of the “mini spike”
- expect to see DM from 50-100 IMBHs
  - for full halo coverage
  - for uniform exposure of 25 hours in each sky bin
- inner scan region
  - $-30^\circ < l < 60^\circ$
  - $-3^\circ < b < 3^\circ$
- expect to see 4.3 IMBHs for 400 hours of H.E.S.S. exposure
- 3 point-like sources detected
  - all compatible with being astrophysical sources
- obtain 90% limit on $<\sigma v>$

$\sigma v = 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1}$

$10^{15} < \Phi_{\gamma}(E>100 \text{ GeV}) < 10^{-8}$
**Dark Matter from IMBHs**

- Determine true H.E.S.S. sensitivity map of inner scan region

- Use 200 Monte-Carlo representations of Milky-Way halos

- Search for detections → expect to see $4.3 \pm 2.3$ mini spikes
Dark Matter from IMBHs

- There is some potential to exclude single models
- But large uncertainties from IMBH formation models
Electrons and Positrons
Diffuse Electron (+positron) Spectrum

- Electrons: only small fraction of cosmic rays
- Suffer severely from synchrotron and inverse compton losses
  → TeV electrons must come from local sources
  → steep spectrum $\sim E^{-3.3}$

- Balloon/satellite data available at $< 1$ TeV

- Electron showers similar to gamma showers
- H.E.S.S. can measure at even higher energies
  → large detection area
  → but large backgrounds

- Gamma background
  → observe extragalactic fields
  → if any, at most 50% gamma contamination

- Cosmic Ray background
  → special rejection technique
Diffuse Electron (+positron) Spectrum

- Electrons are isotropic
  → no geometric background subtraction

- Random Forest:
  train machine learning algorithm on shower image parameters
  → needs electron/hadron simulations

- For each shower, RF determines “electron likeness” parameter $\zeta \in [0;1]$

- For $\zeta > 0.9$, total background suppression is $10^{-6}$

- Remaining background
  → Fit $\zeta$-distribution with combination of electron/proton simulations
  → result depends on hadronic interaction model (Sybill/QGSJet)
Diffuse Electron (+positron) Spectrum

- One fit per energy band to derive electron spectrum

- Two analyses recently published:
  - high energies: 600 GeV – 5 TeV (hard cuts for best reconstruction)
Diffuse Electron (+positron) Spectrum

- Spectral index $3.9 \pm 0.1 \pm 0.3$
  → steepening compared to GeV energies

- After energy scale uncertainty compatible with previous measurements: $\Gamma = 3.1$ with cut-off at 2.1 TeV

- Existence of TeV electrons implies local electron source → PWN? DM?
Break in spectrum:
\[ \Gamma_1 = 3.0 \pm 0.1 \pm 0.3 \]
\[ \Gamma_2 = 4.1 \pm 0.3 \pm 0.3 \]
\[ E_B = 0.9 \pm 0.1 \text{ TeV} \]

- No indication of feature similar to ATIC
- Compatible to FERMI within energy shift uncertainty

Aharonian et al. 2009

\[ \Delta E \pm 15\% \]
• Attempt to fit electron results with DM annihilation spectra
• Relic DM density: 0.3 GeV/cm$^3$
• Assume $<\sigma v> = 3 \cdot 10^{-26}$ cm$^3$/s
• Isothermal Galactic halo profile
• Standard electron diffusion
• GALPROP to simulate astrophysical electron background
• Use H.E.S.S. data as upper limits

DM DM $\rightarrow$ e$^+$e$^-$ gives too hard/peaked electron spectrum
DM DM $\rightarrow$ $\tau^+\tau^-$ gives too soft electron spectrum

Either direct decay into muons, or via light scalar (N3, AH4) viable
Large boost-factors needed to explain large fluxes
DM $\rightarrow e^+e^-$ gives too hard/peaked electron spectrum
DM $\rightarrow \tau^+\tau^-$ gives too soft electron spectrum
Either direct decay into muons, or via light scalar (N3, AH4) viable
Large boost-factors needed to explain large fluxes
Photon and Neutrino Constraints

- γ-rays test constrain DM scenarios on sub-kpc scales
  → Galactic Centre
  → Galactic Centre diffuse
  → local clumps of DM (dwarf galaxies, IMBH)
  → sensitive to halo profile

- ...and on Galactic scales
  → IC photons from DM electrons
  → do not overproduce FERMI diffuse Galactic γ-ray flux

- Neutrino bounds from Super-K Galactic Centre observations
  → constraints on μ, τ final states
  → sensitive to halo profile

Meade et al. (2009)
arXiv:0905.0480
Photon and Neutrino Constraints

Meade et al. (2009)  
arXiv:0905.0480
Photon and Neutrino Constraints

Meade et al. (2009)
arXiv:0905.0480
The Future: CTA

- **Concept**
  - an IACT array *observatory*
  - an order of magnitude more sensitive than HESS: 1 mCrab
  - wide energy coverage: $O(10) \text{ GeV} - O(100) \text{ TeV}$
  - possibly sites in the south and north

- **Consortium**
  - largely European
  - HESS + MAGIC + many others
  - 15 countries currently involved

- **Currently in design phase**
  - Prototype construction in 1-2 years

- **High priority in European road maps:**
Array Simulations

- Up to 97 telescopes
- Individual sub-arrays
- Different altitudes above sea level
- Different pixel sizes
- Different pixel technology

Aims:
- Physics performance
- Cost optimisation
Array Simulations

- 4+85: good all-purpose instrument
- 4 big telescopes → low energies
- 85 small telescopes → highest energies
Summary

- VHE γ-ray instruments reach critical sensitivity to do real astronomy
- Indirect Dark Matter searches don't constrain models yet
- H.E.S.S. Measurements do constrain models when performing global fits to all available data
- CTA will offer much deeper exposures of DM overdensities + provide better energy coverage
- Uncertainties in halo profiles remain a significant problem in this field
- Will LHC detect signature of new physics?
Thank you!