Indirect Dark Matter searches with H.E.S.S.

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CEA - Saclay, France
High Energy Stereoscopic System

System of four Imaging Atmospheric Cherenkov Telescopes designed for very high energy ($E_\gamma >100$ GeV) $\gamma$-ray astronomy

MPI Kernphysik, Heidelberg
Humboldt Univ. Berlin
Ruhr-Univ. Bochum
Univ. Hamburg
LSW Heidelberg
Univ. Tübingen
Univ. Erlangen
Ecole Polytechnique, Palaiseau
APC Paris
Univ. Paris VI-VII
Paris Observatory, Meudon
LAPP Annecy
LAOG Grenoble
LPTA Montpellier
DAPNIA Saclay
CESR Toulouse

Durham Univ.
Leeds Univ.
Dublin Inst. for Adv. Studies
Charles Univ., Prague
Yerewan Physics Inst.
North-West Univ., Potchefstroom
Univ. of Namibia, Windhoek
Nicolaus Kopernikus Astr. Center, Warsaw
Jagiellonian University, Cracow
Institute of Nuclear Physics, Warsaw
Space research center, Warsaw

~30 institutes
130 physicists and astrophysicists
Indirect dark matter search

Gamma-ray flux from WIMP annihilation:

\[
\frac{d\Phi_y(\Delta\Omega, E)}{dE} = F_0 \frac{dN_y}{dE} \frac{<\sigma v>}{<\sigma v>_{\text{ref}}} \left(\frac{1\text{ TeV}}{m_{DM}}\right)^2 \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \int_{\text{l.o.s.}} \rho^2(r[s]) \, ds
\]

Angular acceptance

\[\Delta\Omega_{\text{HESS}} = 2 \times 10^{-5} \text{ sr}\]

Particle Physics:
- Cross sections
- Branching ratios
- Differential photon yield
- Mass of the DM particle

Astrophysics: Dark matter halo
- strong dependence on the spatial distribution
- model required for density profile

Gamma spectrum: typically a continuum with an exponential cut-off at the DM particle mass
Dark Matter candidates

• Lots of candidates satisfy WIMP requirements…
• Here, we study two well-known cases:
  - neutralino (SUSY)
  - Kaluza-Klein (UED) particles

The lightest neutralino (LSP):
\[ \tilde{\chi}_1^0 = Z_{11} \tilde{B} + Z_{12} \tilde{W} + Z_{13} \tilde{H}_1^0 + Z_{14} \tilde{H}_2^0 \]
• stable if R-parity conserved
• relic density can accommodate WMAP constraints on CDM
• annihilation spectrum:
  - gamma-ray lines suppressed
  - continuum from \( W^\pm, Z, b, \bar{b} \) hadronisation

The lightest Kaluza-Klein particle (LKP):
\[ B^{(1)} \]
• first KK excitation of the photon
• stable if K-parity conserved
• mass in the range 400-1200 GeV to satisfy WMAP constraints
• annihilation spectrum:
  continuum from charged leptons and quarks
The H.E.S.S. telescope array

Array of four Imaging Atmospheric Cherenkov Telescopes located in Namibia (1800m a.s.l.)

- 13 m diameter telescopes: 107 m² each
- Stereoscopic reconstruction
- Cameras equipped with 960 PMTs
- Large field of view 5°
- Observations on moonless nights, ~1000h/year

- Angular resolution < 0.1°/γ
- Energy threshold (zenith) ~ 100 GeV
- Energy resolution ~ 15%
- Sensitivity: 1% Crab in 25 hours
Potential targets for H.E.S.S.

Searches performed on amplification sites:

- **Galactic Centre:**
  - distance: 8.5 kpc
  - standard $\gamma$-ray emitters $\Rightarrow$ astrophysical background
  - diffuse emission along the galactic plane

- **Galaxy cluster centres:**
  - Virgo (M87), 16.3 Mpc

- **Dwarf spheroidal galaxies:**
  - 4 in 100 kpc

- **Other potential targets:**
  - LMC: $d=50$ kpc, $\Phi($LMC$)/\Phi($GC$) \sim 4\times 10^{-8}$
  - Coma: $d=120$ Mpc, $\Phi($Coma$)/\Phi($GC$) \sim 3\times 10^{-4}$
The Galactic Centre: HESS J1745-290

- ~ 100 h of data taking 2003 → 2005
- excess ~ 60σ
- compatible with a point-like source

Position relative to SgrA*:
\[ \delta \theta = 5'' \pm 10'' \text{ (stat) } \pm 20'' \text{ (syst)} \]

radio contours (90 cm)

- constant flux: 1 \( \gamma \)/minute
- no significant fluctuation (10 mn → 1 year)
- flare sensitivity: 2.5 (6hours) → 0.75 (1month)
- no significant periodicity (28mn → 1year)

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HESS J1745-290: spectral constraints

2004 data:
- Power-law spectrum: $\Gamma = 2.29 \pm 0.09 \pm 0.15$
- Exponential cut-off limit: $E_{\text{cut}} > 6\text{TeV}$ (95% C.L.)

⇒ Heavy WIMPs required, not favored by theory
⇒ Low energy data not well fitted
HESS J1745-290: exclusion plots

- MSSM limit: $\langle \sigma v \rangle \leq (1-10) \times 10^{-24} \text{ cm}^3\text{s}^{-1}$
- KK limit: $\langle \sigma v \rangle \leq 10^{-24} \text{ cm}^3\text{s}^{-1}$

Sensitivity @95% C.L.

MSSM+WMAP predictions

MSSM predictions

KK Predictions

NFW profile

pMSSM predictions: DarkSUSY4.1

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A TeV signal from M87 (Virgo cluster)

- 13σ detection in 89h (2003-2006)
- Point-like source: < 3’ (99% C.L.)
- Power law spectrum:
  - $\Gamma = 2.22 \pm 0.25$ (2005)
  - $\Gamma = 2.62 \pm 0.35$ (2004)
- Temporal variability

- Active galaxy, black hole $3.2 \times 10^{-9} \, M_{\text{sun}}$
- Distance: 16.3 Mpc
- Jet axis 20-40 deg. from line of sight
- Detected by HEGRA (2003)
Variability of the TeV signal from M87

- Long term variability ~1 year (3.2σ)
- Short term variability ~2 days (4σ)
- Emission region size < ~50 R_s ⇒ production site: black hole?

Dark matter predictions:
- m_χ=1 TeV, MSSM, \( \chi \chi \rightarrow WW \)
  with Moore profile:
  \( \Phi(>730\text{GeV}) \sim 10^{-16} \text{ cm}^{-2}\text{s}^{-1} \)
  - 1000 times lower than observed…

Short term and long term variability exclude the whole signal to be of Dark Matter origin
Satellite galaxies of the Milky Way

Sextans dw

Ursa Minor dw

Canis Major dw

Draco dw


Canis Major: 7 kpc (2007)

HESS observations:

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The Sagittarius dwarf galaxy

- discovered in 1994
- distance 24 kpc
- on the opposite side of the Galactic Centre
- core out of the galactic plane

Majewski et al., 2003
The Sagittarius dwarf galaxy

- Spheroidal galaxy with nucleus
- Coïncidence in position with the globular cluster M54
- Tidally distorted
- M/L > 50 in outer part of galaxy

2 components in the luminous profile
- compact component: «cusp»
  - core size: $r_c = 1.5$ pc
  - fit to density $\rho \propto r^{-\alpha} \Rightarrow \alpha = 2.68$
  - too large for a black hole ($\alpha = 1.75$)
- large scale component: King model $r_K = 1.6$ kpc

- Velocity dispersion roughly constant over scales of degrees:
  - Central value $(11.4$ km/s$)^2$
  - Recent measurement: $(8$ km/s$)^2$
    (Saggia 2005)

The signal is expected to come from the region of 1.5 pc
$\Rightarrow$ much smaller than the H.E.S.S. PSF: search for a point-like signal
Sagittarius dwarf: data analysis

- Target position: RA = 18h54m40s Dec = -30d27m05s (J2000)
- Centre of the globular cluster M54

- 25 runs after data selection in 2006
- Mean zenith observation angle: 19°
- 11 live hours after quality checks
- Combined (Hillas+Model) analysis

No significant $\gamma$ excess at the target position
Limits on the $\gamma$–ray flux from Sagittarius dwarf
and sensitivity calculation

- No significant $\gamma$-ray excess at the target position
  $\Rightarrow$ 95% C.L. upper limit on the number of $\gamma$-ray above 250 GeV
    (Feldman & Cousins method)
  with $N_{ON} = 437$ $N_{OFF} = 4270$ $\alpha=10.1$
  $N_{\gamma}^{95\% \text{C.L.}} = 56$

- Given the acceptance of the detector for Sgr dwarf observations:
  $\Phi_{\gamma}(E_{\gamma} > 250 \text{GeV}) < 3.6 \times 10^{-12} \text{cm}^{-2}\text{s}^{-1} \text{ (95\% C.L.)}$

- The 95% C.L. limit on $N_{\gamma}$ provides a 95% C.L. limit on the velocity-
  weighted cross section for a given DM profile

\[ \langle \sigma v \rangle_{\text{min}}^{95\% \text{C.L.}} = \frac{4\pi}{T_{\text{obs}}} \frac{m_{DM}^2}{\bar{J}(\Delta \Omega) \Delta \Omega} \int_{0}^{m_{DM}} \frac{N_{\gamma}^{95\% \text{C.L.}}}{A_{\text{eff}}(E_{\gamma}) \frac{dN_{\gamma}}{dE_{\gamma}}} \]
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Modelling Sagittarius dwarf dark matter halo

- Start from Jeans equation:
  *Method based on Evans, et al., 2004*

- Observables:
  - $\rho$: luminous density,
  - $<v_r^2>$: radial velocity dispersion

- Unknown: $M$: total mass, $\beta$: anisotropy

- 2 widely different types of DM halo profiles:
  - NFW profile: fit of $(A, r_s)$ parameters to $<v_r^2>$
  - Cored profile: $<v_r^2>$ assumed to be flat, $(8 \text{ km/s})^2$

- Analytic resolution of the Jeans equation

\[
M(r) = r <v_r^2> \left( \frac{d \ln \rho}{d \ln r} + \frac{d \ln <v_r^2>}{d \ln r} - 2\beta \right)
\]

- Assume anisotropy $\beta = 0$
  - solve for $M(r)$ to get $\rho_{\text{dark}}$
  OR
  - fit DM halo parameters to $<v_r^2>$

<table>
<thead>
<tr>
<th>Halo type</th>
<th>Parameters</th>
<th>$\bar{J}$ (10^{24}\text{GeV}^2\text{cm}^{-5})</th>
<th>Fraction of signal in $\Delta\Omega = 2 \times 10^{-5}\text{sr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cusped NFW halo</td>
<td>$r_s = 0.2 \text{ kpc}$</td>
<td>2.2</td>
<td>93.6%</td>
</tr>
<tr>
<td></td>
<td>$A = 3.3 \times 10^7\text{M}_\odot$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cored halo</td>
<td>$r_c = 1.5 \text{ pc}$</td>
<td>75.0</td>
<td>99.9%</td>
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<tr>
<td></td>
<td>$v_a = 13.4 \text{ km s}^{-1}$</td>
<td></td>
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</tr>
</tbody>
</table>

Table 1
Constraints on neutralino dark matter: exclusion plots

Sensitivity curve at 95% C.L.

- pMSSM models obtained with DarkSUSY4.1
  ⇒ large scan of the parameter space

Some pMSSM models with higgsino-like neutralino excluded in the case of the cored profile

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Constraints on Kaluza-Klein dark matter: exclusion plots

Some KK models providing a relic density compatible with WMAP constraints are excluded in the case of the cored profile.

\[ \langle \sigma v \rangle = \frac{95 g_i^4}{324 \pi m_{LKP}^2} \approx \frac{1.7 \times 10^{-26}}{m_{LKP}/\text{TeV}} \text{ cm}^3/\text{s}. \]
Conclusions

- Present dark matter searches:
  - **Galactic Centre**: strong signal, probably not dark matter origin
  - **M87**: strong variable signal, dark matter origin excluded
  - **Sagittarius dwarf**: strong constraints for a cored profile
    - on pMSSM models: \( \langle \sigma v \rangle \sim 2 \times 10^{-25} \text{ cm}^3\text{s}^{-1} \)
    - on Kaluza-Klein models: \( \langle \sigma v \rangle \sim 4 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \)

- Future searches with H.E.S.S. 2 (2008)
  - large telescope: Ø28m
  - lower energy threshold: ~20 GeV

⇒ Access to large part of MSSM models