TEV GAMMA-RAY ASTROPHYSICS

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Interstellar radiation spectrum

![Graph showing the intergalactic radiation spectrum with different regions labeled: 2.7K Microwave Background, Radio, Infrared, Visible light, Ultraviolet, X-ray, and Gamma-ray.](image)
High-energy gamma-rays are emitted by non-thermal processes where one cannot define temperature. Elementary process of particle interaction.
Gamma-ray spectrum
High energy electron

High energy electron

High energy proton

High energy electron

Emission from particles accelerated to high energies by non-thermal processes
Gamma-ray interaction with matter

Photoelectric effect

Pair creation

Compton scattering

Evans 1955
Detection of gamma-rays

\[ A \sim 10^4 \text{m}^2 \]
\[ \Omega \sim 10^{-2} \text{sr} \]

~1 m²
~\( \pi \) sr

> TeV gamma-rays

Fermi Gamma-ray Space Telescope (2008 June-)
1952: S. Hayakawa (Prog.Theo.Phys. 8, 571)
   - $\pi^0$ decay gamma-rays during CR propagation
1958: P. Morrison (Nuovo Cim. 7, 858)
   - Synchrotron/Bremsstrahlung/ $\pi^0$ /de-excitation of nuclei/electron-positron annihilation
   - Sun/ Crab/ radio galaxy/ matter-antimatter annihilation
   - $\pi^0$ decay gamma-rays from Crab
1960-64: A.E. Chudakov et al.
   - 1.5m$\phi \times 12$ in Cremea
   - Flux < $10^{-2}$ of prediction by Cocconi
1968: G.G. Fazio et al.
   - Whipple 10m telescope on Mt. Hopkins
   - 3$\sigma$ detection of Crab nebula (Fazio et al. 1972 ApJ 175, L117)
1972: Launch of SAS-2 satellite
Satellite detectors

SAS-2 (1973)  
COS B (1980)  
CGRO/EGRET (1996)  
Fermi (2008)
Pair-conversion telescope

- Photons materialize into matter-antimatter pairs:
  \[ E_\gamma \rightarrow m_{e^+}c^2 + m_{e^-}c^2 \]

- Electron and positron carry information about the direction, energy and polarization of the \( \gamma \)-ray
Early Cherenkov telescopes

Figure 1.2. The Lebedev Institute experiment that operated in the Crimea, c. 1960–64. This was the first major VHE gamma-ray telescope. (Photo: N A Porter.)

Telescopes in Crimea
Figure: Geometric model of emission of Cherenkov radiation for γ-ray and hadron shower.
Air shower development

\[ X_0 : \text{radiation length (37 g/cm}^2\text{ in air)} \]
\[ \varepsilon_0 : \text{critical energy (80 MeV in air)} \]
Cherenkov angle

\[ \cos \theta = \frac{1}{n \beta} \]

\[ \beta = \frac{v}{c} \]

\[ n = 1.0003 \text{ (1 atm)} \]

\[ \Rightarrow \theta = 1.3^\circ \text{ (sea level)} \]

Jelley, 1958

Jelley & Weekes, Sky and Telescope, 1995
Atmospheric transmission

- MODRAN4 calculation by M. Yuasa (2006)

- Observed spectrum:
  - a: Cherenkov
  - b: transmission
  - c: mirror
  - d: QE
  - e: NSB

- MODRAN4 calculation by H. Tsunoo (2002)
Atmospheric Cherenkov Telescope

Cherenkov light from gamma-ray showers

Lateral distribution & Timing distribution

Aharonian & Konopelko 1997
Differentiation of gamma-rays from charged cosmic rays

→ Differentiation of gamma-rays from charged cosmic rays
Shower simulation movies

500 GeV Gamma-ray

2 TeV Proton

Miguel F. Morales, http://scipp.ucsc.edu/milagro/Animations/AnimationIntro.html
Angular resolution
0.25deg → 0.1 deg
Energy resolution
30% → 15%
Better S/N (no local muons)
# Comparison of detection methods

<table>
<thead>
<tr>
<th>Base</th>
<th>Satellite</th>
<th>Ground</th>
<th>Ground</th>
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</thead>
<tbody>
<tr>
<td>Gamma-ray detection</td>
<td>Direct (pair creation)</td>
<td>Indirect (atmospheric Cherenkov)</td>
<td>Indirect (shower array)</td>
</tr>
<tr>
<td>Energy</td>
<td>&lt; 30 GeV (→ 100 GeV)</td>
<td>&gt;100 GeV (→ 50 GeV)</td>
<td>&gt;3 TeV (→ 1 TeV)</td>
</tr>
<tr>
<td>Pros</td>
<td>High S/N</td>
<td>Large area</td>
<td>24hr operation</td>
</tr>
<tr>
<td></td>
<td>Large FOV</td>
<td>Good Δθ</td>
<td>Large FOV</td>
</tr>
<tr>
<td>Cons</td>
<td>Small area</td>
<td>Low S/N (CR bkgd.)</td>
<td>Low S/N (CR bkgd.)</td>
</tr>
<tr>
<td></td>
<td>High cost</td>
<td>(but imaging overcomes this!)</td>
<td>Moderate Δθ</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
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</table>
Crab: the first TeV source

Whipple 10m telescope

Gamma-ray signal

37ch imaging camera

82hrs, 0.24\gamma/\text{min}
Crab Signal as seen in VERITAS in real time during commissioning

Weekes, Gamma2008, Heidelberg
TeV skymap
TeV skymap

2001

90°

180°

-180°

RX J1713.7-3946

Jim Hinton
ICRC 2007
TeV skymap

2003

RX J1713.7-3946

Jim Hinton
ICRC 2007
TeV skymap
TeV skymap
### Increase of TeV sources

#### "Kifune plot"

<table>
<thead>
<tr>
<th>Class</th>
<th>2003</th>
<th>2005</th>
<th>2007</th>
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<tbody>
<tr>
<td><strong>PWN</strong></td>
<td>1</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>(Pulsar Wind Nebulae)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>SNR</strong></td>
<td>2</td>
<td>3</td>
<td>7</td>
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<tr>
<td>(Subernova remnants)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Binary</strong></td>
<td>0</td>
<td>2</td>
<td>4</td>
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<tr>
<td><strong>Diffuse</strong></td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>AGN</strong></td>
<td>7</td>
<td>11</td>
<td>19</td>
</tr>
<tr>
<td>(Active Galactic Nuclei)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>UnId</strong></td>
<td>2</td>
<td>6</td>
<td>21</td>
</tr>
<tr>
<td>(Unidentified sources)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>12</td>
<td>33</td>
<td>71</td>
</tr>
</tbody>
</table>
* Borders for SNR/PWN/UnID are vague…
Survey region was extended in the years 2005 - 2007

H.E.S.S. Galactic survey

pure scan
400 h

-85° < l < 60°  -2.5° < b < 2.5°

Hoppe 269
H.E.S.S. Galactic survey

Significance of $\gamma$-ray excess

Preliminary

Galactic Centre

New sources found in the survey data

Hoppe 269

Saturated at 20°
Supernova remnants

- Long considered to be primary source for Galactic cosmic rays

**Pros:**
- Energetic enough (10% of SN explosion energy)
- Size of object is large enough \((R \gg r_g)\)
- Many SNRs are bright radio sources: at least electrons are accelerated!

**Cons:**
- Magnetic fields too low to go beyond \(10^{14}\) eV
- Additional problem: adiabatic losses

Cas A by Chandra
Supernova blast wave acceleration

SNR expands into ISM with velocity $V \sim 10^4 \text{ km/s}$.

Drives forward shock at $4/3 V$

Contact discontinuity, $V$

Unshocked ISM

Forward shock

Particle with $E_1$

Unshocked ISM

$u_1 \sim 4/3 V$

$E_2 = \xi E_1$

$T_{SN} \sim 1000 \text{ yrs before slowdown}$

$E_{\text{max}} \sim Z \times 100 \text{ TeV}$
Expected shape of spectrum:

- Differential index $\alpha \sim 2.1$ for diffusive shock acceleration
  - $\alpha_{\text{observed}} \sim 2.7$; $\alpha_{\text{source}} \sim 2.1$; $\Delta \alpha \sim 0.6$
  - $\tau_{\text{esc}}(E) \sim E^{-0.6}$
  - $c \tau_{\text{esc}} \rightarrow T_{\text{disk}} \sim 100$ TeV
  - $\rightarrow$ Isotropy problem

- $E_{\text{max}} \sim \beta_{\text{shock}} Z e \times B \times R_{\text{shock}}$
  - $\rightarrow E_{\text{max}} \sim Z \times 100$ TeV with exponential cutoff of each component
  - But spectrum continues to higher energy:
    - $\rightarrow$ $E_{\text{max}}$ problem

Expect $p + \text{gas} \rightarrow \gamma$ (TeV) for certain SNR

- Need nearby target as shown in picture from *Nature* (April 02)
- Some likely candidates (e.g. HESS J1745-290) but still no certain example
- $\rightarrow$ Problem of elusive $\pi^0 \gamma$-rays
Comparable to PSF (0.09°)


Good keV-TeV Correlation!

Accelerated particles and gamma-ray spectrum

Proton
- \( \Pi^0 \) decay
- Flat spectrum above 100MeV

Electron
- Synchrotron X-rays
- Inverse Compton gamma-rays

p/e ratio problem

\( E^2 \frac{dF}{dE} \)

\( \text{Energy} \)
Hard power-law + cutoff (?): $\sim E^{-2} \exp(-E/E_{\text{max}})$

**SNR spectrum**

**Electron model**

RX J1713.7-3946

Aharonian et al. 2006

**Proton model**

RX J0842.0-4622

Enomoto et al. 2006

Berezhko & Voelk 2007

NO definitive answer for accelerated particles!
Identification of particles is not easy.

Fig. 12.—Pion-decay and IC emission for a range of $n_H$ and $B_0$. In the top panel, the heavy curves are pion decay, the light curves are IC, and $\epsilon_{\pi\gamma} = 36\%$ and $B_0 = 15 \mu G$ in all cases. The strong dependence of pion decay on ambient density $n_H$ is evident. The middle panel shows IC, and the bottom panel shows pion decay for $n_H = 0.1 \text{ cm}^{-3}$, with $B_0$ varying from 3 $\mu G$ (solid curves) to 15 $\mu G$ (dashed curves) to 60 $\mu G$ (dotted curves). For comparison to the $\pi^0$, we show in the bottom panel the IC emission for $B_0 = 60 \mu G$ (light dotted curve). The particle distributions producing the emission in the bottom two panels are those shown in the top panel of Fig. 11.

Difficult in the GeV-TeV region if magnetic field is strong!
Variation in \sim 1\text{yr} time scale  
→ Need > 1mG ! (locally)  
→ Protons produce TeV gamma-rays!?  

Counter arguments: Y.But et al. , arXiv:0801.4954
SNRs interacting with clouds?

IC443

[12CO]

W28

[90cm]

Evidence of proton acceleration?


[H.E.S.S., Aharonian et al., A&A, in press]
SN1006

Chandra and H.E.S.S. Morphology

- Chandra map smoothed by the H.E.S.S. PSF and oversampled with 0.1°
- H.E.S.S. map with Chandra contours

- Independent analysis methods confirm the detection of the NE rim of SN 1006 at about 6 sigma in the region pre-defined in the 2004 H.E.S.S. upper limit paper
- Compatibility with non-thermal X-ray morphology very good
- Given the flux level of ~1% Crab, both leptonic and hadronic scenarios are reasonable
Pulsar nebulae

- Major group in Galactic TeV sources
  - 18/71 by Hinton (2007ICRC)
  - Associated with relatively young (<10^5 years) and large spin-down pulsars
- Extended \( O(10pc) \), displaced from pulsars
- Gamma-rays via inverse Compton by electrons?
Pulsar nebula: energy-dependent morphology

- HESS J1825-137 associated with energetic pulsar
- Spectral steepening seen away from the pulsar
- Very likely this is evidence for cooling of electrons in the Nebula
  - Seen in several X-ray PWN
- A first in gamma-ray astronomy!

Shrinks!
Simulations of Pulsar Wind Nebula

Contact Discontinuity

Reverse Shock

Forward Shock

Pulsar wind Shock

PWN Shock

Displacement due to pulsar kick?
More pulsar nebulae...

- HESS J1833-105
  - Djannati-Atai et al., ICRC2007

- HESS J1846-029
  - Hoppe et al., ICRC2007

- HESS J1912-012
  - Djannati-Atai et al., ICRC2007

- HESS J1718-385
  - Carrigan et al., ICRC2007

- HESS J1809-193
  - Komin et al., ICRC2007

- HESS J1837-069

- 70.5ms PSR (ATel1392)
Figure 3: **Top:** $P - \dot{P}$ diagram for pulsars: all ATNF pulsars (black), with detected X-ray PWN (brown), with a known corresponding SNR (blue), potentially associated to an EGRET source (green), associated to a H.E.S.S. VHE PWN (red). **Bottom:** Energy output for the selections used at the top.
Pulsed emission from Crab

→Favors outer-gap model rather than polar-cap model
Gamma-ray binaries

LSI +61 303 (VERITAS/MAGIC)

$P_{\text{orb}} \approx 26.5\text{day}$

- MAGIC

- VERTAS

V.A. Acciari et al., arXiv:0802.2363

LS 5039 (H.E.S.S.)

$P_{\text{orb}} \approx 3.9\text{day}$

Black hole binary: $M_{BH} \sim 21M_\odot$, $M_\star \sim 30M_\odot$
Relativistic jet $v > 0.6c$: “microquasar”
MAGIC 40hr obs.
4.9$\sigma$ seen in one 79 min. time slice
Estimated significance: 4.1$\sigma$ after correction for statistical trials
Emission from binaries

**Microquasar**
- Companion star
- Ultraviolet and optical emission
- Accretion disk
- Relativistic jets
- Compact object of center

**Binary Pulsar**
- Pulsar
- Be star
- Cometary radio emission
- Disk outflow
- γ-rays

**Mirabel 2006**

**Sidro 574**

Microquasar: particles (electrons or hadrons) are accelerated in a jet

Bosch-Ramon et al. (2006), Romero et al. (2007)

γ-rays produced in the shock where the wind of the young pulsar and the wind of the Be star collide

Dubus (2006), Dhawan et al. (2006)
Stellar cluster Westerlund 2

- Young open stellar cluster
  - Dozen O-stars
  - Two Wolf-Rayet stars (~80M☉ each)
- Extended gamma-ray emission covering (but offset from) Westerlund 2 by HESS
- Due to collective effects of stellar winds in the cluster?
- A new source class?

Galactic center \(\approx\) Sgr A*

HESS data 2003-2004 towards galactic centre. (We await 2005-6 data eagerly...)

Energy spectrum is not consistent with dark matter annihilation signal!

Steady (time-independent) spectrum, pointlike within HESS angular resolution, could be Moore cusp instead of NFW?

But: Probably too high energy (and wrong shape of spectrum) for WIMP annihilation explanation

L. Bergström, CTA meeting, Jan. 2008
Gamma-ray signal from DM annihilation at the Galactic center

Indirect detection through γ-rays. Three types of signal:

- Continuous from π⁰, K⁰, ... decays and
- Monoenergetic line and
- Internal bremsstrahlung from QED process.

Enhanced flux possible thanks to halo density profile and substructure (as predicted by CDM)

Good spectral signatures! Unfortunately, large uncertainties in the predictions of absolute rates.
Galactic center ridge

Spectrum is harder than CR spectrum!


Two types:
1) No compelling counterparts
2) Dark in other wavelengths
## TeV-GeV relation?

### Coincident sources

<table>
<thead>
<tr>
<th>EGRET source</th>
<th>VHE γ-ray source</th>
<th>Potential Counterpart</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3EG J1639-4702</td>
<td>HESS J1640-465</td>
<td>G338.3-0.0 (SNR/PWN)</td>
</tr>
<tr>
<td>3EG J1744-3011</td>
<td>HESS J1745-303</td>
<td></td>
</tr>
<tr>
<td>3EG J1800-2338</td>
<td>HESS J1801-233</td>
<td>W28 (SNR)</td>
</tr>
<tr>
<td>3EG J1826-1302</td>
<td>HESS J1825-137</td>
<td>G18.0-0.7 (PWN)</td>
</tr>
<tr>
<td>3EG J1824-1514</td>
<td>HESS J1826-148</td>
<td>LS 5039 (Binary)</td>
</tr>
</tbody>
</table>

### Outside the H.E.S.S. GPS

<table>
<thead>
<tr>
<th>EGRET source</th>
<th>VHE γ-ray source</th>
<th>Potential Counterpart</th>
</tr>
</thead>
<tbody>
<tr>
<td>3EG J0241+6103</td>
<td>MAGIC J0240+613</td>
<td>LSI+61 303 (Binary)</td>
</tr>
<tr>
<td>3EG J0617+2238</td>
<td>MAGIC J0616+225</td>
<td>IC443 (SNR/PWN)</td>
</tr>
<tr>
<td>3EG J0634+0521</td>
<td>HESS J0632+058</td>
<td>Monoceros</td>
</tr>
<tr>
<td>3EG J1420-6038</td>
<td>HESS J1420-607</td>
<td>Kookaburra (PWN)</td>
</tr>
</tbody>
</table>

![Graph showing energy flux distribution](chart.png)
Extended H.E.S.S. survey

Extended H.E.S.S. GPS
- $-85^\circ < l < 60^\circ$
- $-3^\circ < b < 3^\circ$
- Scan mode: 400 h
- Detected 50+ Galactic sources of VHE gamma-rays
- ICRC 2007, DPG 2008, Gamma08
H.E.S.S. galactic plane survey

- HESS J1714-385 (SNR CTB 37A)
- HESS J1713-381 (SNR CTB 37B)
- HESS J1442-623 (SNR RCW 86)
- HESS J1356-654 (Offset PWN)
- HESS J1503-582 (FVW?)
- HESS J1848-018 (SFR W 43, WR 121a?)
- HESS J1849-000 (PWN)
# Extragalactic TeV sources

<table>
<thead>
<tr>
<th>Name</th>
<th>Discovered</th>
<th>Year</th>
<th>$z$</th>
<th>Contributions</th>
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<tbody>
<tr>
<td>M 87</td>
<td>HEGRA</td>
<td>2003</td>
<td>0.004</td>
<td>VERITAS-Colin, HESS-Beilicke, MAGIC-Milagro-Smith, VERITAS-Fegan, +</td>
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<tr>
<td>Mrk 421</td>
<td>Whipple</td>
<td>1992</td>
<td>0.031</td>
<td>TACTIC-Godambe, MAGIC-Paneque, + MAGIC-Wagner</td>
</tr>
<tr>
<td>Mrk 501</td>
<td>Whipple</td>
<td>1996</td>
<td>0.034</td>
<td></td>
</tr>
<tr>
<td>1ES 2344+514</td>
<td>Whipple</td>
<td>1998</td>
<td>0.044</td>
<td></td>
</tr>
<tr>
<td>Mrk 180</td>
<td>MAGIC</td>
<td>2006</td>
<td>0.046</td>
<td>MAGIC-Mazin, MAGIC-Hayashida</td>
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<tr>
<td>1ES 1959+650</td>
<td>TA</td>
<td>2002</td>
<td>0.047</td>
<td></td>
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<tr>
<td>BL Lac</td>
<td>MAGIC</td>
<td>2006</td>
<td>0.069</td>
<td>MAGIC-Hayashida</td>
</tr>
<tr>
<td>PKS 0548-322</td>
<td>HESS</td>
<td>2006</td>
<td>0.069</td>
<td>HESS-Superina</td>
</tr>
<tr>
<td>PKS 2005-489</td>
<td>HESS</td>
<td>2005</td>
<td>0.071</td>
<td>HESS-Costamante</td>
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<tr>
<td>PKS 2155-304</td>
<td>Durham</td>
<td>1999</td>
<td>0.116</td>
<td>HESS-Punch, CANGAROO-Sakamoto, +</td>
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<tr>
<td>H 1426+428</td>
<td>Whipple</td>
<td>2002</td>
<td>0.129</td>
<td>VERITAS-Krawczynski</td>
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<td>1ES 0229+200</td>
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<td>2007</td>
<td>0.140</td>
<td>HESS-Raue</td>
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<td>2005</td>
<td>0.150</td>
<td>HESS-Costamante</td>
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<td>1ES 1218+304</td>
<td>MAGIC</td>
<td>2005</td>
<td>0.182</td>
<td>MAGIC-Hayashida</td>
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<td>1ES 0347-121</td>
<td>HESS</td>
<td>2007</td>
<td>0.188</td>
<td>HESS-Puelhofer</td>
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<td>MAGIC</td>
<td>2007</td>
<td>0.212</td>
<td>MAGIC-Mazin</td>
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<td>PG 1553+113</td>
<td>HESS/MAGIC</td>
<td>2005</td>
<td>?</td>
<td>MAGIC-Wagner, HESS-Benbow</td>
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<tr>
<td>3C 279</td>
<td>MAGIC</td>
<td>2007</td>
<td>0.536</td>
<td>MAGIC-Teshima</td>
</tr>
</tbody>
</table>

*8 new AGN*
Emission from AGNs

FSRQ
BL Lac

Synchrotron peak
Inverse Compton peak

Electron model
Fossati et al. 1998

Proton model
Muecke et al. APh 18, 2003
Fast time variation

PKS 2155−304
z = 0.116
July 28, 2006
Peak flux ~15 x Crab
~50 x average
Luminosity ~10^{12} x Crab
Doubling times
67, 116, 173, 178 ±50 s
R_{BH}/c \sim 1...2 \times 10^4 s

Fast variation ↔ Acceleration site & mechanism
Observed spectrum is affected by integalactic absorption!

$$\gamma_{\text{TeV}} + \gamma_{\text{IR}} \rightarrow e^+ + e^-$$

Mean free path for $e^+e^-$ pair production


We cannot discriminate source spectrum and integalactic absorption!
Unfolding source spectra

Some models can be rejected

Assume not harder than $E^{-1.5}$
Upper limits: fluctuation/direct measurements
Lower limits: source counts
3C279 at $z=0.538$

Fig. 1. Light curves. MAGIC (top) and optical R-band data (bottom) obtained for 3C 279 from February to March 2006. The long-term baseline for the optical flux is at 3 mJy.

Fig. 2. Spectrum of 3C 279 measured by MAGIC. The gray area includes the combined statistical (1σ) and systematic errors, and underlines the marginal significance of detections at high energy. The dotted line shows compatibility of the measured spectrum with a power law of photon index $\alpha = 4.1$. The blue and red triangles are measurements corrected on the basis of the two models for EBL density, discussed in the text.
Redshift distribution of blazars

Model Fit to Blazar Redshift Distribution

Fit parameters for the FSRQs are $\Gamma = 8$ and comoving directional luminosity $L = 10^{40}$ ergs sr$^{-1}$ s$^{-1}$; EC statistics

Fit parameters for the BL Lacs are $\Gamma = 5$ and $L = 10^{42}$ ergs sr$^{-1}$ s$^{-1}$; syn/SSC statistics
Redshift distribution of blazars

More AGNs as energy threshold goes lower!
Clustering of galaxies: upper limits

H.E.S.S.: Domainko et al., ICRC2007

Perseus

A2029

Coma

A4038


CANGAROO-III: Kiuchi et al., ICRC2007
Air shower arrays

Tibet AS$_\gamma$ (Japan-China, 4300 m a.s.l.)

Milagro (US+, 2630 m a.s.l.)

Atmospheric Cherenkov Telescopes
- Energy Range: 0.05-50 TeV
- Area: > $10^4$ m$^2$
- Background Rejection: > 99%
- Angular Resolution: 0.05°
- Energy Resolution: ~15%
- Aperture: 0.003 sr
- Duty Cycle: 10%
- High Resolution Energy Spectra
- Precision Study of Known Sources
- Source Location & Morphology
- Deep Surveys of Limited Regions of Sky

Extensive Air Shower Arrays
- Energy Range: 0.1-100 TeV
- Area: > $10^4$ m$^2$
- Background Rejection: > 95%
- Angular Resolution: 0.3° - 0.7°
- Energy Resolution: ~50%
- Aperture: > 2 sr
- Duty Cycle: > 90%
- Unbiased Complete Sky Survey
- Extended Sources
- Transient Objects (GRB’s)
- Multi-Wavelength/Messenger Observations
Air shower arrays: results

- 7 year map
- $\gamma$/hadron cut raises median energy to 20 TeV
- 3 new sources significant post trials

Abdo, ICRC 2007

Wang, ICRC 2007
Gamma-ray skymap

(background: Fermi Gamma-ray Space Telescope Firstlight data [>100 MeV])
Under construction

H.E.S.S. II

28m

MAGIC II

85m
Future projects

CTA (Cherenkov Telescope Array): EU++

AGIS (Advanced Gamma-ray Imaging System): USA++

Option:
Mix of telescope types

~10 central Huge telescopes
~100 Medium + Small Telescopes

(by J. Buckley, Wash.U.)

Picture: Courtesy of W. Hofmann
Data: H.E.S.S. catalog

$\log N - \log S$ relation

$N \propto S^{-2/3}$

$\times 2$ (North/South)

$\downarrow$

1000 TeV sources if mCrab!
High energy window of the Universe is now open!
- Additional 2-3 decades of the photon spectrum
- Wider variety of sources than expected
  \(\rightarrow\) Cosmic accelerators are ubiquitous!
- Much work left to understand their physics
- Also: cosmology, fundamental physics

Hoping to detect other class of sources...
- Pulsars
- Star-forming galaxies, mergers
- Dwarf galaxies and dark matter
- Ultraluminous IR galaxies
- Clusters of galaxies
- Gamma-ray bursts
Thank you!

CANGAROO-III telescopes, Woomera, South Australia