Gamma-Ray Astronomy
from the Ground

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No – we haven't discovered dark matter, yet
Yes – we have discovered sources of cosmic rays
Yes – we have detected the optical extra-galactic background light
Yes – we are sensitive to new physics (LIV/ALPs)
Yes – there are at least 160 Gamma-ray sources detected from ground
Yes – upgrades and new experiments are coming
Blessing: Large collection area
Curse: Huge background
Two strategies (complementary → hybrid):
- Air Cherenkov imaging technique
- Non imaging technique (particle/light sampling)
300 Water Cherenkov detectors on a 22 000 m² surface at high altitude (4100 m a.s.l.)

100% duty cycle, 1 srad

Fully operational since 3/2015

Data will be public >2017

Sparse outrigger extension for improved >10 TeV sensitivity
H.E.S.S. - Phase II

- Since 7/2012: 4x12m telescopes + 28 m telescope (“CT5”)
- Energy range 30 GeV – 100 TeV
- Major upgrade of CT1-CT4 cameras ongoing
MAGIC$^2$: 2 x 17 m IACTs

- Improved triggering scheme → reduced threshold of ~35 GeV
- 4fold improvement of Sensitivity
- Correction of data for changes of the atmosphere with LIDAR
VERITAS: 4 x 12 m IACTs

- Upgrades of PMTs in 2012
- Observations with moon light
Improvements/Sensitivity

[Graph showing improvements in sensitivity over time and the number of sources detected.]
TeV Sky as of now

Already 162 detected sources reported in the TeV Catalog in August 2015!
65 sources are extragalactic - 70 are Galactic - 27 UNID
Highlights: Galactic plane

- Gamma-rays from the survey – comparison HESS and HAWC, 3000 hrs of HESS, 64 sources + 13 complex source regions
Highlights: Galactic plane

Gamma-rays from the survey – comparison HESS and HAWC, 3000 hrs of HESS, 64 sources + 13 complex source regions

H.E.S.S. (2015) Preliminary

HAWC-111, 280 days
Diffuse emission from the inner Galaxy

Masking sources

Inclusive flux (|b|<2°)

Diffuse flux (|b|<2°)
Diffuse emission from the inner Galaxy (HESS)

Comparison (red lines)
Emission from CR-Gas interaction

Diffuse flux (|l|<70°)

Inclusive flux (|l|<70°)

Masking sources

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Population studies...

Pulsar wind nebulae
[Klepnser et al. 2015]

Shell-type Supernova remnants
[Hahn et al. 2015]

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H.E.S.S. preliminary

Luminosity $L_{\text{LHE}}$ [erg/s]
Spin-down Power $\dot{E}$ [erg s$^{-1}$]

$L_{\text{LHE}}/L_{\text{Radio}}$
Age

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Crab nebula

- New measurements from the ground → very good overlap / consistency with Fermi-LAT
- Difficult time for models (none fit..)

R. Zanin et al. 2015
Shell-type supernova remnants

- Spectra not consistent with the hadronic scenario
- Interesting new developments in spatially resolved spectra

Tycho SNR

B-field map

amburg.de
Galactic center: Pevatron

- CR density + spectrum
Galactic center: arch!

HESS contours on Chandra image

H.E.S.S.
(Lemièrè et al. 2015)

VERITAS, E>2 TeV
(Smith et al. 2015)

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Dark matter searches

- No detection – but limits are improving
- New combinations: Fermi-LAT combined with MAGIC

Main targets:
- Inner Galaxy (halo)
- Dwarf galaxies (including newly identified obj.)
- Dark halo objects (unid. Fermi-LAT sources)

Rico et al. 2015
Large Magellanic cloud

- PWN N157B
  Crab-like (lower B-field)
- 30 Dor C
  Superbubble
- N 132 D
  SNR
- But:
  no detection from SN1987A
Other Galaxies: AGN

- Common understanding (Synchrotron/IC): Gamma-rays from accelerated electrons in relativistic outflows

[Graphs showing the spectral energy distribution (SED) and fractional variability, with data points and labels indicating different observations such as Swift-XRT, NuSTAR, VERITAS, Fermi-LAT, and Metsahovi.]
(at least) two surprises

- Variability time scale too short ($t_{\text{var}} < r_s/c$) for supermassive black holes
- PKS 2155-304 ($M \sim 10^9 M_{\odot}$ but $t_{\text{var}} = 2'$) (HESS coll. 2009)
- IC 310 (MAGIC coll. 2014), no beaming, but $t_{\text{var}} < 4'$
Discovery of gamma-ray emission from B0218+357 with MAGIC (Sitarek et al. 2015)

Delayed signal from grav. Lensing. Variable ratios?

Observation of micro-lensing would constrain the size of the emission region to be $\sim 10^{15}$ cm and its velocity to be sub-luminal.

B0218+357
Z=0.944
Lens at z=0.684
Delay of 11d
More surprises?

Absorption of gamma-rays due to pair-production on the extra-galactic background light (EBL) – however spectra are hardening?

DH&Jacholkowska (2015)
New sources discovered:
PKS 1441+25 (z=0.939)  
(MAGIC and VERITAS)
B0218+357 (z=0.944)  
(MAGIC 2015)

PKS 1441+25 (z=0.939)  
(MAGIC prel.)
Searching for Lorentz-invariance breaking

Dispersion relation of Photons modified:

\[ E^2 \simeq p^2 c^2 \times \left[ 1 - \sum s_{\pm} \left( \frac{E}{E_{QG}} \right)^n \right] \]

Energy/distance dependent delay + modified absorption (shift of threshold)

<table>
<thead>
<tr>
<th>Property</th>
<th>GRBs</th>
<th>AGNs</th>
<th>Pulsars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redshift</td>
<td>&lt; 8.2</td>
<td>&lt; 0.8</td>
<td>0</td>
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<tr>
<td>Energy range</td>
<td>&lt; 100 GeV</td>
<td>&lt; 10 TeV</td>
<td>&lt; 300 GeV</td>
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<tr>
<td>Relevant time scales</td>
<td>10-100 msec</td>
<td>1-10 min</td>
<td>10 msec</td>
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<td>Intrinsic effects</td>
<td>known</td>
<td>moderate</td>
<td>under control</td>
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<tr>
<td>Best results</td>
<td>GRB 090510</td>
<td>PKS 2155-304</td>
<td>CRAB</td>
</tr>
<tr>
<td></td>
<td>(Fermi)</td>
<td>(H.E.S.S.)</td>
<td>(VERITAS)</td>
</tr>
</tbody>
</table>
Searching for light pseudoscalars (Axion-like particles)

- Spectroscopic signatures

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Gamma-ray bursts

- Not detected, yet
- Just wait a little bit, either HAWC or fast response IACTs (MAGIC, HESS II) will detect them
**New instruments: CTA**

### The Cherenkov Telescope Array (CTA)

- > 1200 members
- 194 Institutes from 31 countries
- 2 sites selected:
  - North (La Palma, Spain)
  - South (Paranal, Chile)

Initial construction could start in 2016
Early science: towards the end of the decade

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*M. Lemoine-Goumard, 34th ICRC, The Hague, 6th August 2015*
Towards lower energies

MACE

- High altitude air Cherenkov detection (Hanle site)
- Non-imaging (HAGAR)
- Imaging (MACE)
Towards higher energies: LHAASO

- Air shower array 1 km²
- 75 000 m² of Water Cherenkov Detector array
- 12 Wide field imaging air Cherenkov telescopes
Towards Higher energies: TAIGA

- Non-imaging air Cherenkov detector field (currently \(\sim 0.5 \text{ km}^2\)), upgradable to \(\sim 5 \text{ km}^2\)

- Planned upgrade: imaging air Cherenkov telescopes with 8° f.o.v.
Gamma-ray astronomy – rich phenomenology of cosmic-ray accelerators

Fundamental sciences – unique sensitivity to propagation effects and massive self-annihilating dark matter

Impact on low-energy astrophysics: constraining star formation

Extreme acceleration in relativistic environment
End of presentation