Very High Energy Gamma-ray:
the MAGIC telescopes and the CTA project

- Astroparticle Physics
- Very High Energy Gamma-ray
- The MAGIC telescopes
- The future: CTA

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27-01-2014, IMFP, Benasque
Astroparticle Physics
Astroparticle physics

Astroparticle physics, the same as particle astrophysics, is a branch of particle physics that studies elementary particles of astronomical origin and their relation to astrophysics and cosmology. It is a relatively new field of research emerging at the intersection of:

- Particle physics
- Astrophysics
- Cosmology
Cosmic Rays
Victor Hess: Discovery of cosmic rays

Ionized atoms in the atmosphere increase with high. Hence, they have an extraterrestrial origin.
Questions to be answered:

✗ What is the universe made of?
✗ What is dark matter?
✗ Do protons have a finite life time?
✗ What are the properties of neutrinos? What is their role in cosmic evolution?
✗ What do neutrinos tell us about the interior of the Sun and the Earth, and about Supernova explosions?
✗ What is the origin of cosmic rays? What is the view of the sky at extreme energies?
✗ Can we detect gravitational waves? What will they tell us about violent cosmic processes and about the nature of gravity?
The fifth Pillars of Astroparticle Physics

- Cosmic Rays
- Neutrinos
- Gravitational Waves
- High Energy gamma Rays
- Dark Matter
The messengers in Astroparticle Physics

The particles bringing the information are different

- Protons or heavier nuclei
- Electrons and positrons
- Neutrinos
- Photons
- Gravitational waves
- Dark Matter

Complementary informations
The messengers in Astroparticle Physics

The particles bringing the information are different

<table>
<thead>
<tr>
<th>Absorption</th>
<th>Deviation</th>
<th>Detection</th>
</tr>
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<tbody>
<tr>
<td>✓ Protons or heavier nuclei</td>
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<tr>
<td>✓ Dark Matter</td>
<td>?</td>
<td>?</td>
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Complementary informations
Very High Energy Gamma-rays
We get information from many different wavelength

Thermic radiation (black body) produces low energy photons

High Energy photons are generated in other processes: VIOLENT UNIVERS
Cherenkov Telescopes
Cherenkov Telescopes

Gamma-rays interact with particle in the atmosphere and produce the “Extended Air Showers”

Secondary particles travel faster than light → Cherenkov light

Light is collected in the camera
Cherenkov Telescopes

“Imaging Atmospheric Cherenkov Technique”

Whipple telescope (USA) was pioneer on using this technique very successfully between 1969 and 1989.

Comparison between ON and OFF observations allows to see Very High Energy gamma-rays
Cherenkov Telescopes

MAGIC (2004)

VERITAS (2008)

HESS (2003)

The MAGIC telescopes
The MAGIC Telescopes

MAGIC is an Imaging Atmospheric Cherenkov Telescope system consisting of two 17m diameter telescopes, located on Canary island La Palma
The MAGIC Telescopes

**Energy Resolution**

- Energy resolution
- Energy bias

**Angular Resolution**

- 2D Gauss fit, Data
- 2D Gauss fit Monte Carlo
- 68% containment, Data
- 68% containment, Monte Carlo

**Integral Sensitivity**

**Differential Sensitivity**
Supernova Remnants (SNR), the source of cosmic rays?

The W51 Complex

- **W51A & W51B** are star forming regions,
- **W51C** is a medium-age (~30 kyr) SNR at d ~5.5 Kpc
- Possible PWN **CXO J192318.5+1403035** maybe associated with **W51C**
- The SNR interacts with **W51B**
- High Cosmic Ray ionization, ~100xISM value (*Ceccarelli et al. 2011 ApJ 740*)
Supernova Remnants (SNR), the source of cosmic rays?

$^{13}$CO($J=1-0$) 63-72 km/s

21 cm continuum

300 GeV - 1 TeV

$> 1$ TeV
Supernova Remnants (SNR), the source of cosmic rays?

Aleksic et al. (MAGIC) A&A 541, 2012
Crab Nebula: SNR and Pulsar Wind Nebula (PWN)

Preliminary

$E^2 \frac{dN}{dE dAt}$ [TeV cm$^{-2}$ s$^{-1}$]

- MAGIC stereo data
- Systematic uncertainty
- Variable power-law fit
Crab Nebula: SNR and Pulsar Wind Nebula (PWN)

Aleksić et al. (MAGIC) A&A 540, 2012

\[ E^2 \times dN/dE \ [\ TeV \ cm^{-2} \ s^{-1} ] \]

\[ \text{Energy [ GeV]} \]

\[ \text{Entries 144234} \]
\[ T_{\text{red}} = 4366.8 \text{ min} \]
\[ Z'_{\chi^2} = 128.85 \ (8.6\sigma) \]
\[ H \text{ Test} = 193.33 \ (6.4\sigma) \]
\[ \chi^2/\text{ndf} = 170.19/56 \ (7.7\sigma) \]
\[ N_{\text{ex}} = 1175 \pm 116 \ \text{Sig} = 10.4\sigma \]

\[ \text{Entries 39406} \]
\[ T_{\text{red}} = 4366.8 \text{ min} \]
\[ Z'_{\chi^2} = 59.88 \ (4.5\sigma) \]
\[ H \text{ Test} = 23.88 \ (4.0\sigma) \]
\[ \chi^2/\text{ndf} = 69.79/50 \ (2.4\sigma) \]
\[ N_{\text{ex}} = 419 \pm 68 \ \text{Sig} = 6.2\sigma \]

\[ \text{Entries 74828} \]
\[ T_{\text{red}} = 4366.8 \text{ min} \]
\[ Z'_{\chi^2} = 85.07 \ (5.2\sigma) \]
\[ H \text{ Test} = 55.30 \ (5.7\sigma) \]
\[ \chi^2/\text{ndf} = 116.03/95 \ (5.1\sigma) \]
\[ N_{\text{ex}} = 759 \pm 93 \ \text{Sig} = 8.3\sigma \]
Simple models start to fail: 1ES 1215 + 303

First detection – 2011 January/February
- 2010 observations lower flux
- Simultaneous MWL → High state also in optic and X-Ray
- Simple 1 zone SSC model → extreme values (doppler factor/e⁻ energy distributions)
Multi-year and Multi-Wavelength monitoring: Mrk 401

Several flaring episodes:
- 2008 published
- 2010 analysis ongoing
- 2013 → highest level in VHE

MAGIC, ATel#4976

- Also low state (steady) emission

Aleksic et al. (MAGIC) A&A 542, 2012
Clusters of Galaxies: Perseus the brightest in X-ray
Clusters of Galaxies: Perseus the brightest in X-ray

**NGC1275**

Dominant central galaxy of Perseus

Spectrum with MAGIC

\[ \Gamma = 4.1 \pm 0.7 \]

MAGIC light curve, with MWL

Aleksic et al. (MAGIC) A&A 539, 2012
Clusters of Galaxies: Perseus the brightest in X-ray

IC 310

Originally classified as “head – tail”, MAGIC data suggest a blazar
VHE spectrum very hard
\[ \Gamma = 1.8 \pm 0.1 \]
Day scale variability, new flare in Nov'12

MAGIC, ATel#4976
Clusters of Galaxies: Perseus the brightest in X-ray

Cosmic Rays

Perseus

\[ F_{\gamma}(E) \] [\text{ph}^{-1} \text{s}^{-1} \text{cm}^{-2}]

\[ E \text{ [GeV]} \]

\[ X_{\text{CR}}(R) \text{, scaled to 0.15° UL} \]

\[ X_{\text{CR}}(<R) \text{, scaled to 0.15° UL} \]

\[ X_{\text{CR}}(R) \text{ model} \]

\[ X_{\text{CR}}(<R) \text{ model} \]
Dark Matter searches: The satellite galaxy Segue

No signal

→ For some cases most constraining limits (general or from SpheD)
→ Still … many models alive (more than killed)
The future: CTA
A world wide collaboration

Currently:
28 countries, 80 institutions  1138 members
Expected Performance for CTA

Design done aiming at:

- Full sky coverage: 2 sites, one in each hemisphere
- Sensitivity improved by factor ~10
- Large energy range: < 30 GeV to > 100 TeV
- Improved energy and angular resolution and accuracy
The Cherenkov Telescope Array concept
The Cherenkov Telescope Array concept

Low energy
Few 23 m telescopes
4.5° FoV
~2000 pixels
~ 0.1°
The Cherenkov Telescope Array concept

Low energy
Few 23 m telescopes
  4.5° FoV
~2000 pixels
  ~ 0.1°
The Cherenkov Telescope Array concept

**Medium energy**

About twenty 12 m telescopes

$\sim 8^\circ$ FoV

$\sim 2000$ pixels

$\sim 0.2^\circ$
The Cherenkov Telescope Array concept

Medium energy
About twenty 12 m telescopes
\(~8^\circ\) FoV
\(~2000\) pixels
\(~0.2^\circ\)
The Cherenkov Telescope Array concept

High energy
Fifty + 4.3 m telescopes
9.6° FoV
Compact Silicon Camera
~ 0.25
The Cherenkov Telescope Array concept

High energy
Fifty + 4.3 m telescopes
9.6° FoV
Compact Silicon Camera
~ 0.25
The Cherenkov Telescope Array concept

Low energy
~4 x 23 m CT
4.5° FoV
~2000 pixels
~ 0.1°

Medium energy
~20 x 12 m CT
~8° FoV
~2000 pixels
~ 0.2°

High energy
~50 x 4.3 m CT
9.6° FoV
Silicon Camera
~ 0.25
The Cherenkov Telescope Array concept

- SNR/PWN
- Binaries
- Radio Gal.
- Blazars
- Pulsars
- Colliding Winds
- StarBurst
- Clusters
- GRBs
- +Dark Matter
The Cherenkov Telescope Array (CTA) concept

Data from CTA can also provide information on fundamental physics:

- Indirect Detection of Dark Matter
- Charged Particles Measurement
- Axion Like Particles
- Lorentz Invariance Violation
- Interaction of UHE Cosmic-Rays
- Extragalactic Background Light
- Cosmology
The Cherenkov Telescope Array concept

- Possibility to answer many questions still open both on Astro and Fundamental Physics.
- Some measurements will be complementary to other instruments
- But ... CTA is unique at least in:
  
  **Short time scale phenomena at VHE**
  
  **Sky survey at the highest energies**
Spain in CTA

Tenerife

Warning: map not quite accurate!

proposals for sites received 6/2011 (S) and 1/2012 (N)!
evaluation and downselection to few sites in 2012!
final selection in 2013!
Spain in CTA

Tenerife

Warning: map not quite accurate!

proposals for sites received 6/2011 (S) and 1/2012 (N)!
evaluation and downsampling to few sites in 2012!

Delayed until March 2014
Astroparticle Physics is a very active field that is still growing.

Very High Energy Gamma-ray provides information:
- Astro Physics
- Fundamental Physics (particles physics)
- Cosmology

The MAGIC telescopes have had a leading role in the field (with VERITAS and HESS) and will continue producing first-class results until CTA becomes real.
Backup
Neutrins

✗ Postulat d'existència (Wolfgang Pauli 1930)
Partícula molt lleugera necessària per mantenir lleis de conservació a la desintegració β.

✗ Primera confirmació experimental: 1956

✗ Neutrins extraterrestres: Sol i SN 1987A
Matèria fosca

No emet ni reflecteix prou radiació electromagnètica per poder-se detectar directament.

Composició desconeguda.
Ones gravitacionals

Fluctuacions de la curvatura de l'espai temps que es propaga en forma d'ona.

\[ \frac{dh}{h} \sim 10^{-20} \]
Cosmic rays

- 1 particle / m² s
- 1 particle / m² any
- 1 particle / km² any
HESS 1857+026

Unidentified HESS source \cite{Aharonian2008}\textsuperscript{a}
Young energetic pulsar PSR J1858+0245 later discovered \cite{Hessels2008}\textsuperscript{b}
Point-like source \cite{Rousseau2012}\textsuperscript{c}

\textsuperscript{a} Aharonian et al. 2008 A&A 477
\textsuperscript{b} Hessels et al. 2008 ApJ 662
\textsuperscript{c} Rousseau et al 2012 A&A 544

Morphology and spectrum → Hint for PWN
Upper limits on Magnetars

### 4U 0142+61
- \( L_x \sim 10^{35}\) erg s\(^{-1}\) (among the brightest)
- B on surface: \(1.3 \cdot 10^{14}\) G
- Distance: \(3.5 \pm 0.4\) kpc
- MAGIC: 17h in 2008, mono data
- 95% upper limit at \(E > 200\) GeV:
  \[ \sim 0.5\%\text{ C.U.} \]

### 1E 2259+586
- \( L_x \sim 0.3 \cdot 10^{35}\) erg s\(^{-1}\)
- B on surface: \(0.59 \cdot 10^{14}\) G
- Distance: \(4.0 \pm 0.8\) kpc
- MAGIC: 8h in 2010, stereo data
- 95% upper limit at \(E > 200\) GeV:
  \[ \sim 0.6\%\text{ C.U.} \]

Similar UL with half of the time.
Binary Systems

**LS I +61 303**
- Observed with MAGIC since 2005
- No spectral variability detected
- Low flux state detected in 2009
- Back to high state in 2011

**HESS J0632+057**
- Monitored with MAGIC since 2010
- February 2011 → 6σ in 5.6 hours
- \( \sim 4\%\) C.U.
New MAGIC sources

1ES 0806+524
Observation triggered high optic state (KVA)
16 hours in Feb'11

Daily variability $\Gamma = 2.0 \pm 0.3$

1ES 1727+502
HBL at $z=0.055$
13 hours 2011 → 5.5σ
No variability
$\Gamma = 3.2 \pm 0.4$

MS1221.8+2452
High Synchrotron peaked BL Lac
4 hours 1$^{st}$ of May
Flare of PG 1553 +113

BL Lac object with unknown redshift
Estimated ~ 0.4
(Prandini et al 2011, Danforth et al. 2010)

- First detected in 2005
  (HESS/MAGIC)

- February-May 2012:
  - About 50 $\sigma$ in 17 hours
  - Strong flare ~1 C.U. at 100 GeV
  - Complete MWL picture

<table>
<thead>
<tr>
<th>Year</th>
<th>Flux ($E &gt; 150$ GeV) [$cm^{-2} s^{-1}$]</th>
</tr>
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<tbody>
<tr>
<td>2007</td>
<td>(1.40±0.38)×10^{-11} [2]</td>
</tr>
<tr>
<td>2008</td>
<td>(3.70±0.47)×10^{-11} [2]</td>
</tr>
<tr>
<td>2009</td>
<td>(1.63±0.45)×10^{-11} [2]</td>
</tr>
<tr>
<td>2012 (pre-flare)</td>
<td>(5.03±0.25)×10^{-11} [2]</td>
</tr>
<tr>
<td>2012 (flare)</td>
<td>(9.63±0.37)×10^{-11}</td>
</tr>
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</table>
FSRQs

3c 279
- Discovered in VHE by MAGIC in 2006
- Seen again in 2007
- Monitoring and ToO in 2011

Upper limits below previous detections

PKS 1510 -089
- Discovered in VHE by HESS in 2009
- MAGIC observations (Feb-Apr'12) triggered by Fermi/LAT
- 21 hours $\rightarrow$ 5.7 $\sigma$
The end