Gamma Rays

Part 2: Results & CTA
Fermi Satellite

LAT: 10 MeV - 300 GeV
BGO: ....
GBM: 10 keV-1 MeV

≈ 1 m² 2.5 sr
LAT: 10 MeV - 300 GeV

> 5000 sources 50 MeV - 1 TeV
> 5000 GRBs
NASA’s Fermi telescope reveals best-ever view of the gamma-ray sky

"direct identification"  "excess of events"

Satellite experiment: 100 MeV - 100 GeV
point sources, extended sources and diffuse emission, ...

Credit: NASA/DOE/Fermi LAT Collaboration
Satellite experiment: 100 MeV - 100 GeV
point sources, extended sources and diffuse emission, ...
Gamma Ray Bursts

Fermi GRBs as of 171126

2218 GBM GRBs
139 LAT GRBs
In Field-of-view of LAT (1163)
Out of Field-of-view of LAT (1055)
The Fermi Bubble

... a remnant of recent activity of our galaxy?
Fermi Bubble

Fermi Loop
Major gamma-ray flare from Crab Nebula
(April 2011)

Crab was always seen as the “standard candle”
Spectrum varies with time. Allows study of the "dynamic processes" of particle acceleration.
Fermi: LIV test: GRB

Fermi LAT+GBM:
QG energy scale $> 1.2 \ E_{\text{Planck}}$
(linear dep. of the speed of light on energy)

... plus many more exciting results.
100s of papers...
Search for “dark matter” with gamma rays.

DM particles should cluster in gravitational potentials
e.g. in centre of galaxies

They could annihilate and produce gamma rays
with \( E_\gamma \approx m_{DM} \)

i.e. line emission

\[
\chi \chi \rightarrow \gamma \gamma, \; \gamma Z, \; \gamma h
\]

\[
\text{BR}(\chi \chi \rightarrow \gamma \gamma) \sim \alpha^2_{\text{em}} \sim 10^{-4}
\]
Understand the gamma ray sky ...

... before claiming Dark Matter
search in several, theoretically suggested, regions for emission from DM
Indication of an emission line from the galactic centre at $E \approx 130$ GeV

Reg4 (SOURCE), $E_\gamma = 129.8$ GeV

Signal counts: $57.0$ (4.63$\sigma$)

$p$-value = 0.46, $\chi^2_{\text{red}} = 22.1/22$

$4.6 \sigma$ (?)
Blob of emission from the galactic centre in the 120-140 GeV range

Fig. 3.— All-sky CLEAN 3.7 year maps in 5 energy bins, and a residual map (lower right). The residual map is the 120 - 140 GeV map minus a background estimate, taken to be the average of the other 4 maps where the average is computed in $E^2dN/dE$ units. This simple image was produced by John Beatty and Scott Beatty.
HAWC High Energy Catalog

7 candidate sources, energy > 56 TeV, energy spectra forth coming

➤ Acceleration mechanisms: hadronic or leptonic?
➤ Correlation with neutrinos?
➤ Prospects for testing Lorentz Invariance Violation.
Multisource Fitting Example: Hunting for CR Acceleration in SFRs with HAWC
Latest Survey: HAWC 11/2014-04/2018

>39 candidate sources, pivot energy ~ 7 TeV

Crab at 17σ in 8 years.

Galactic Plane Observations over the Years

- **Milagro (2000-2008)**
- **HAWC Pass 1 (2013-2014, partial array, candidates)**
  - Preliminary

Milagro was located near Los Alamos, New Mexico
- different sensitivity by declination along Galactic plane.
Current imaging Cherenkov telescopes
TeVCat

now: >200 sources (> 100 GeV)
gal. / extragal. / unid.

background image:
Fermi sky map (MeV-GeV)

gamma ray emission is present wherever there are shocks and relativistic flows

Source Types

- PWN
- XRB PSR Gamma BIN
- HBL IBL FRI FSRQ LBL AGN (unknown type)
- Shell SNR/Molec. Cloud
- Starburst
- DARK UNID Other
- uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL Lac (class unclear) WR
TeV astronomy highlights

<table>
<thead>
<tr>
<th>Topic</th>
<th>Journal</th>
<th>Volume</th>
<th>Year</th>
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<td>432</td>
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<td>101</td>
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+ many papers in other journals

… a booming field.
young (~10 ky) pulsars with large spin-down power magnetised relativistic winds

morphology

SED: GeV - TeV connection
SNR - PWN connection
electron cooling
population studies

~30 pulsar wind nebulae (PWN)

TeV PWNe
GeV PWNe

Crab
e.g. HESS J1825-137

source of wind

270 GeV to 35 TeV

spatially resolved spectra
Gamma Ray Sources

RX J1713.7-3946, a supernova remnant shell
Supernova Remnant RX J1713.7-3946

The graph shows the energy distribution of gamma rays from the supernova remnant RX J1713.7-3946, with measurements from various instruments including ASCA, Suzaku, EGRET, and HESS. The energy range is depicted on a logarithmic scale from meV to TeV, with the flux density in units of (cm$^2$/s).
HESS: gal. centre

CRs with mol. clouds
A PeV-atron in the Galactic centre

Nature 531, 476-479 (2016)

H.E.S.S. 2016:
diffuse emission in Galactic Centre Ridge region

Presence of protons of $\approx 10^{15}$ eV

Dataset: 2004 - 2015
PeV-atron in the Galactic Centre. Constant injection over at least $10^3$ years. Current luminosity of GC is not enough.

Very hard emission, no cutoff, untypical for extended emission

Cosmic ray density profile using matter densities from molecular line surveys.
BL Lac object $z = 0.116$
bursts on minute scales
$\Gamma \geq 100$ are required
Extragalactic Background light

The Gamma-Ray Horizon \( \gamma_{\text{TeV}} + \gamma_{\text{IR}} \rightarrow e^+e^- \)

Mean Free Path

- Whole universe visible
  - Beamed sources, time variability
- Precision study of local EG sources, resolved morphology
- Precision study of galactic CR sources, up to the knee

Cherenkov Telescopes

- UV
- NIR
- FIR
- Radio
- CMB
- Cen A
- Mrk 421
- M 31
- GC
- 3C 279
analyse absorption features in the spectra of distant sources.
universe is surprisingly transparent.
Gamma Rays are ubiquitous:

- many sources / source types
- complex structures in space, time and energy
- test extreme end of high-energy phenomena
- complement observations at longer wavelengths
  with other particles

The Imaging Atmospheric Cherenkov technique
is not yet at its limit:

Big improvements are possible with existing technology.
**Science Scope:**

**Cosmic energetic particles**
- Origin of the galactic cosmic rays
- Also UHECR signatures
- Role of ultra-relativistic particles in clusters of galaxies, AGN, Starbursts…
- The physics of (relativistic) jets and shocks

**Fundamental Physics**
- Dark Matter annihilation / decay
- Lorentz Invariance violation

**Cosmology**
- Cosmic FIR-UV radiation, cosmic magnetism
The future with

An advanced facility for ground-based gamma-ray astronomy.

CTA is the global, next-generation project with largely enhanced performance and energy range two observatories (South and North),

probing the extreme universe with huge potential for high-energy astronomy and fundamental physics.
Boosting sensitivity & resolution: Arrays of Cherenkov telescopes

- Single telescope
- Shower light pool
- 300 m
- Sweet spot
Core array: mCrab sensitivity in 0.1–10 TeV range
Low-energy section energy threshold of some 10 GeV (a) bigger dishes or
Low-energy section energy threshold of some 10 GeV (a) bigger dishes or (b) dense packing / high-QE sensors
High-energy section
10 km$^2$ area at
> 100 TeV energies

Not to scale!
CTA

10× more sensitive than current instruments
+ much wider energy coverage and field of view
substantially better angular and energy resolution

*telescopes: ~100 (3 sizes)*

Design: 2008-12,
Prototypes: 2013-16,
Construction: 2016-21
From current arrays to CTA

- light pool radius $R \approx 100-150$ m
  - typical telescope spacing

Sweet spot for best triggering and reconstruction:
- large detection area
- more images per shower
- lower trigger threshold
CHERENKOV IMAGING IMPROVEMENTS

- Improved imaging: larger fov, finer pixels
- Large dish
- Stereoscopy
- Large arrays
- High-QE PMTs, silicon sensors
- Novel optics concepts
- Extremely detailed simulation models
- Atmospheric monitoring and modeling
- Use of pixel waveforms
- Image fitting
- Deep neural networks
- Run-wise simulations
The Gamma-Ray Horizon

\[ \gamma_{\text{VHE}} + \gamma \rightarrow e^+e^- \]

- Whole universe visible
- Beamed sources, time variability
- Precision studies of local EG sources, resolved morphology
- Precision studies of galactic CR sources, up to the knee

Mean Free Path

- LSTs
- NIR
- FIR
- MSTs
- SSTs
- CMB
- Radio

- UV
- NIR
- FIR
- Radio

- 3C 279
- Mrk 421
- Cen A
- M 31
- GC

Energy:
- 10 GeV
- 100 GeV
- 1 TeV
- 10 TeV
- 100 TeV
- 1 PeV
- 10 PeV
- 100 PeV
- 1 EeV
- 10 EeV
- 100 EeV

Distances:
- 10 kpc
- 100 kpc
- 1 Mpc
- 10 Mpc
- 100 Mpc
- 1 Gpc
- 10 Mpc
- 100 Mpc
- 1 Gpc
- 10 EeV
- 100 EeV

Redshifts:
- z=5
- z=1
- z=0
One observatory with two sites

Chile

La Palma

mid latitude, large, flat area, 
~2 km altitude, 
good seeing, easy access, ...
Paranal, Chile  (ESO site, Atacama desert)
Baseline Arrays

South: 4 LSTs  25 MSTs  70 SSTs

North: 4 LSTs  15 MSTs

full energy range

mainly low energies
Sensitivity to point sources
3 telescope sizes for a wide energy coverage

Sensitivity (in units of Crab flux) for detection in each 0.2-decade energy band
Angular Resolution:

\(< 0.1^{\circ}\) for \(\geq 5\) images

or for \(E > 100\) GeV \((\geq 4\) images\)
... allows study of morphologies
CTA observation modes

- very deep field
- deep field
- monitoring
- deep field
- survey mode
CTA and Fermi

Good complementarity, covering 6 orders of mag. in energy.

(Steady sources)
Variability and Short-Timescale Phenomena
(flares, GRBs, ... all sorts of transients)

![Graph showing the differential flux for Fermi-LAT and CTA with lines for different energies (25 GeV, 40 GeV, 75 GeV). The graph indicates an improvement by a factor of $10^4$.](image-url)
Performance: Sensitivity

E \cdot \text{Integral Sensitivity} (\text{erg cm}^{-2} \text{s}^{-1})

\begin{align*}
10^{-14} & \quad 10^{-13} \\
10^{-12} & \\
\end{align*}

\begin{align*}
-2 & \quad -1.5 \quad -1 \quad -0.5 \quad 0 \quad 0.5 \quad 1 \quad 1.5 \quad 2
\end{align*}

\begin{align*}
\log_{10}(E/\text{TeV}) \quad \uparrow \quad 1 \text{ TeV}
\end{align*}

goal sensitivity

\begin{align*}
B & \\
C & \\
E & \\
\end{align*}

\begin{align*}
\text{scale} \quad 1 \text{ km}
\end{align*}
**Threshold:**
limited by number of Ch. photons collected
- larger telescopes,
- dense packing of tels.
- better photo detectors

**Medium region:**
limited by signal / BG
- better BG rejection,
- improved ang. resolution,
- better photon statistics

**High energies:**
limited by statistics
- large array
Performance: angular and energy resolution

$1-2\degree$ for $E > 1\text{ TeV}$
(fundamental limit: $\sim 10\arcsec$)

$<10\%$ for $E > 1\text{ TeV}$
CTA will be the ultimate instrument …

… for surveys ~400x faster than H.E.S.S.

… for transients at 25 GeV, $10^4$x better than Fermi

Two observatories (S+N) for full-sky coverage.
CTA prognosis: $>1000$ new sources

galactic disc

HESS
$+60 \ldots -120^\circ$

CTA prognosis:

$\sim600$ sources

galactic + extragalactic: $\geq 1000$ sources
Gamma-Ray Astronomy goes “mainstream”! 167
existing telescopes of different sizes

MAGIC 17 m

HESS I 12 m

HESS II 28 m
to scale
SCHWARZSCHILD COUDER TELESCOPE (SCT)

Single-mirror
MST

Dual-mirror
SCT

Back side of secondary mirror

V. V. Vassiliev, S. J. Fegan, P. F. Brousseau
Astropart. Phys. 28:10, 2007

9.7 m primary
5.4 m secondary

11328 x 0.07° SiPMT pixels

Secondary (5.4 m diam.)

Focal plane

0.07° pixels
8° FOV

Primary (9.7 m diam.)
Large Size Telescope Prototype

Ground breaking on La Palma
SST Prototypes

at Cracow

don Sicily
SST Prototype at Meudon

First images from a dual mirror telescope
# Tels. technical data

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<th>Telescope</th>
<th>Large</th>
<th>Medium</th>
<th>Small</th>
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<tr>
<td></td>
<td>LST</td>
<td>MST</td>
<td>SCT</td>
</tr>
<tr>
<td>Number North array</td>
<td>4</td>
<td>15</td>
<td>TBD</td>
</tr>
<tr>
<td>Number South array</td>
<td>4</td>
<td>25</td>
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## Optics

<table>
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<tr>
<th>Optics</th>
<th>Parab. mirror</th>
<th>Davies-Cotton</th>
<th>Schwarzschild-Couder</th>
<th>Davies-Cotton</th>
<th>Schwarzschild-Couder</th>
<th>Schwarzschild-Couder</th>
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<tr>
<td>Primary mirror diameter (m)</td>
<td>23</td>
<td>13.8</td>
<td>9.7</td>
<td>4</td>
<td>4.3</td>
<td>4</td>
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<tr>
<td>Secondary mirror diameter (m)</td>
<td>–</td>
<td>–</td>
<td>5.4</td>
<td>–</td>
<td>1.8</td>
<td>2</td>
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<tr>
<td>Eff. mirror area after shadowing (m²)</td>
<td>368</td>
<td>88</td>
<td>40</td>
<td>7.4</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Focal length (m)</td>
<td>28</td>
<td>16</td>
<td>5.6</td>
<td>5.6</td>
<td>2.15</td>
<td>2.28</td>
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## Focal plane instrumentation

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<th>Photo sensor</th>
<th>PMT</th>
<th>PMT</th>
<th>silicon</th>
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<td>Pixel size (degr.), shape</td>
<td>0.10, hex.</td>
<td>0.18, hex.</td>
<td>0.07, square</td>
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<td>Field of view (degr.)</td>
<td>4.5</td>
<td>7.7/8.0</td>
<td>8.0</td>
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<tr>
<td>Number of pixels</td>
<td>1855</td>
<td>1764/1855</td>
<td>11328</td>
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<tr>
<td>Signal sampling rate</td>
<td>GHz</td>
<td>250 MHz / GHz</td>
<td>GHz</td>
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## Structure

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<th>Mount</th>
<th>alz-az, on circular rail</th>
<th>alt-az positioner</th>
<th>alt-az positioner</th>
<th>alt-az positioner</th>
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<tr>
<td>Structural material</td>
<td>CFRP / steel</td>
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<td>steel</td>
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<td>Weight (full telescope, tons)</td>
<td>100</td>
<td>85</td>
<td>~85</td>
<td>9</td>
<td>15</td>
<td>8</td>
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<tr>
<td>Max. time for repositioning (s)</td>
<td>20</td>
<td>90</td>
<td>90</td>
<td>60</td>
<td>80</td>
<td>60</td>
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Technological challenges:

CTA:  
– 30 years of operation ***
  – in a desert environment, exposed to wind & weather
  – earthquake proof

– Opt. & mech. precision (not too good)
  – minimal operating costs ($\ll 10\%$ invest/yr) ***

– robust, quick construction,***
  error-free operation, easy to maintain***

– cheap, light-weight, long-lived mirrors
– cheap, efficient photo sensors
– low-power electronics, cooling, computing
  ....

*** improved wrt. existing instruments
CTA Consortium

33 countries
88 parties
202 institutes
1308 members (438 FTE)

Argentina, Armenia, Australia, Austria, Brazil, Bulgaria, Canada, Chile, Czech Republic, Croatia, Finland, France, Germany, Greece, India, Italy, Ireland, Israel, Japan, Mexico, Namibia, Netherlands, Norway, Poland, Slovenia, Spain, South Africa, **Sweden**, Switzerland, Thailand, UK, Ukraine, USA
Main Science Themes:

**Cosmic Particle Acceleration**
- Particle acceleration
- Particle propagation
- Impact of rel. particles on their environment

**Probing Extreme Environments**
- Processes close to neutron stars and black holes
- Processes in relativistic jets, winds and explosions
- Cosmic voids

**Physics frontiers**
- Nature & distribution of Dark Matter
- Lorentz-Invariance at high energies
- Axion-like particles
- Exotics
### CTA Key Science Projects

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<td>Relativistic Cosmic Particles</td>
<td>What are the sites of high-energy particle acceleration in the universe?</td>
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<td>What are the mechanisms for cosmic particle acceleration?</td>
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<td>What role do accelerated particles play in feedback on star formation and</td>
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<td>Probing Extreme Environments</td>
<td>What physical processes are at work close to neutron stars and black</td>
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<td>holes?</td>
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<td>What are the characteristics of relativistic jets, winds and explosions?</td>
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<td>How intense are radiation fields and magnetic fields in cosmic voids,</td>
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<td>and how do these evolve over cosmic time?</td>
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<td>Exploring Frontiers in Physics</td>
<td>What is the nature of Dark Matter? How is it distributed?</td>
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<td>Are there quantum gravitational effects on photon propagation?</td>
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CTA is a new, powerful observatory for ground-based gamma-ray astronomy

- has a huge science potential (for a moderate price)
- offers an attractive mix of discovery potential and a wealth of “guaranteed” good astrophysics,
- complements data from other wavelengths / messengers
- is almost production ready,
- first funding is in hand / construction start very soon ...

CTA will considerably advance our knowledge on high-energy astrophysics and cosmic accelerators.

https://www.cta-observatory.org
More Details:

Design Concepts for the Cherenkov Telescope Array
CTA
An Advanced Facility for Ground-Based High-Energy Gamma-Ray Astronomy
The CTA Consortium
May 2010

“Design Concepts for the Cherenkov Telescope Array”
120 pages
Exp. Astronomy 32 (2011) 193-316

“Seeing the High-Energy Universe with the Cherenkov Telescope Array”
24 articles, 356 pages
Astroparticle Physics 43 (2013) 1-356

general info: www.cta-observatory.org

ICRC The Astroparticle Physics Conference
July 30 - August 6, 2015
The Hague, The Netherlands

CTA Contributions to the 34th ICRC 2015, Den Haag
60 papers
arXiv:1508.05894
Key Science Projects

Contents
1. Introduction to CTA Science
2. Synergies
3. Core Programme Overview
4. Dark Matter Programme
5. KSP: Galactic Centre
6. KSP: Galactic Plane Survey
7. KSP: LMC Survey
8. KSP: Extragalactic Survey
9. KSP: Transients
10. KSP: CosmicRayPeVatrons
11. KSP: Star Forming Systems
12. KSP: Active Galactic Nuclei
13. KSP: Clusters of Galaxies
14. Capabilities beyond Gamma Rays
15. Simulating CTA
Synergies with other existing and upcoming instruments

<table>
<thead>
<tr>
<th>Year</th>
<th>CTA Prototypes</th>
<th>Science Verification</th>
<th>User Operation</th>
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<tbody>
<tr>
<td>2014</td>
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<td>2025</td>
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</table>

**Low Frequency Radio**
- LOFAR
- MWA
- VLITE on JVLA
- MWA (upgrade)
- FAST
- (2018? LOBO)

**Mid-Hi Frequency Radio**
- JVLA, VLBA, eMerlin, ATCA, EVN, JVN, VKN, VERA, LBA, GBT...
- (many other smaller facilities)
- SKA1&2 (Lo/Mid)
- ASKAP
- Kat7 --> MeerKAT --> SKA Phase 1

**Sub/Millimeter Radio**
- JCMT, LLAMA, LMT, IRAM, NOEMA, SMA, SMT, SPT, Nanten2, Mopra, Nobeyama...
- (many other smaller facilities)
- ALMA
- EHT (prototype --> full ops)
- SKA1&2 (Lo/Mid)

**Optical Transient Factories/Transient Finders**
- Palomar Transient Factory
- (~2017) Zwicky TF
- PanSTARRS1 --> PanSTARRS2
- BlackGEM (Meerlicht single dish prototype in 2016)
- LSST (buildup to full survey mode)

**Optical/IR Large Facilities**
- VLT, Keck, GTC, Gemini, Magellan...
- (many other smaller facilities)
- HST
- JWST
- WFIRST
- GMT

**X-ray**
- Swift (incl. UV/optical)
- XMM & Chandra
- NuSTAR
- IXPE
- ATHERA (2028)

**Gamma-ray**
- ASTROSAT
- HXMT
- NICER
- eROSITA
- SVOM (incl. soft gamma-ray + optical ground elements)
- XARM

**Grav. Waves**
- Advanced LIGO + Advanced VIRGO (2017)
- (upgrade to include LIGO India)
- LHAASO
- Einstein Tel.

**Neutrinos**
- IceCube (SINCE 2011)
- KAGRA
- ANTARES
- KM3NET-1
- KM3NET-2 (ARCA)
- IceCube-Gen2?
- KM3NET-3

**UHE Cosmic Rays**
- Telescope Array --> upgrade to TAx4
- Pierre Auger Observatory --> upgrade to Auger Prime
LHAASO
Sichuan, China, 4410 m asl

5195 Scintillators
- 1 m² each
- 15 m spacing

1171 Muon Detectors
- 36 m² each
- 30 m spacing

3000 Water Cherenkov Cells
- 25 m² each

12 Wide Field Cherenkov Telescopes
SGSO

an enlarged version of HAWC in the South

Dense core area ≈ LHAASO
$E^2 dN/dE = \nu F_{\nu}$

[erg/cm$^2$s]

SENsITIVITY (STEADY SOURCES)

adapted from www.cta-observatory.org; J. Goodman, COSPAR 2018; Z. Cao, La Palma 2018
The Gamma-Ray Horizon

\[ \gamma_{\text{VHE}} + \gamma \rightarrow e^+e^- \]

- Whole universe visible
- Beamed sources, time variability
- Precision studies of local EG sources, resolved morphology
- Precision studies of galactic CR sources, up to the knee

### Energy Ranges and Distances

- **10 GeV** to **100 GeV**
- **1 TeV**
- **10 TeV**
- **100 TeV**
- **1 PeV**

### Images and Object Labels

- **3C 279**
- **Cen A**
- **Mrk 421**
- **M 31**
- **GC**

### Distance Scales

- **10 kpc**
- **100 kpc**
- **1 Mpc**
- **10 Mpc**
- **100 Mpc**
- **1 Gpc**
## Multi-Messenger Physics:

<table>
<thead>
<tr>
<th>Category</th>
<th>Instruments/Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>LOFAR, ALMA, SKA …</td>
</tr>
<tr>
<td>optical</td>
<td>VLT, GMT, eELT, LSST, …</td>
</tr>
<tr>
<td>X-rays</td>
<td>SWIFT, XMM, SVOM, …</td>
</tr>
<tr>
<td>Gamma rays (keV-GeV)</td>
<td>Fermi, DAMPE, …</td>
</tr>
<tr>
<td>Gamma rays (TeV)</td>
<td>HAWC, LHAASO, <strong>CTA</strong></td>
</tr>
<tr>
<td>neutrinos</td>
<td>IceCube/Gen2, KM3NeT</td>
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<tr>
<td>gravitational waves</td>
<td>Adv Ligo, KAGRA, Ligo-India</td>
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</table>

Many complementary / contemporary experiments.
28 high-energy $\nu$s
Clear evidence for astrophysical origin ($>5\sigma$)
Neutrinos create charged particles which in turn produce Cherenkov light.

**Muon-tracks**
- good pointing (<1 degree)
- large event rates due to long muon tracks

**Neutrino signatures**
- Neutrinos create charged particles
- These charged particles produce Cherenkov light
Particle cascades

$\nu_e, \nu_\tau$

good energy resolution,
little background

signature of $\nu_e$

375 TeV

signature of $\nu_\tau$

$\nu_\tau + N \rightarrow \tau^\pm$...

$\tau \rightarrow \nu_\tau + \text{hadrons}$

$\tau^\pm$ (300 m track!)
First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A.

After the IceCube neutrino event EHE 170922A detected on 22 Sep 2017 (GCN circular #21935), Fermi-LAT measured a linearly polarized gamma-ray excess from the blazar TXS 0506-56 (05 06 23.9670, +05 41 45.3270) (2009). Lu et al., Astron. J. 138, 1905-1912 (2010)), located 6 arcmin from the EHE 170922A estimated direction (Ah 410841). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observation from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATel, 20733, 20734, 20735, 20736, 20737, 20738, 20739. The MAGIC team presents these observations are R. Moriyama (Rutgers, New Jersey, USA), M. Bernhardt (llw.lmu.de), G. Bernardini (lina.bernhardini/bochum.de), K. Bänsch (kompetenz entering/berchtesgaden.de). MAGIC is a system of two 17-meter Imaging Atmospheric Cherenkov Telescopes located at the Observatorio Roque de los Muchachos on the Canary Island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.
A neutrino event in IceCube
High-energy, through going track

IC170922A
Alert sent
Sep 22, 2017
via Realtime stream

Coincident observations by
Fermi-LAT and MAGIC

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

Further Swift-XRT observations of IceCube 170922A

ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

Joint Swift XRT and NuSTAR Observations of TXS 0506+056

MAXI/GSC observations of IceCube-170922A and TXS 0506+056

VLA Radio Observations of the blazar TXS 0506+056 associated with the IceCube-170922A neutrino event

Science 361 (2018) no.6398, eaat1378
IC170922A / TXS 0506+56
First evidence for a neutrino point source

Archival search
• Check historical IceCube data for pileup of neutrinos from direction of TXS 0506+56
• Look for clustering in time

Inconsistent with background-only hypothesis at the $3.5\sigma$ level

Independent of the 2017 alert when looking in this specific direction!
Gravitational Waves:

Event GW150914: Merger of two black holes 29 and 36 solar masses 1.3 x 10^9 light years away

New messenger in the multi-messenger approach to high-energy astrophysics.

Do grav. events produce also other measurable outputs (light, neutrinos, gamma rays)? Some might …
Another first: neutron star merger (NS-NS)

2017: LIGO detected the first binary Neutron-Star merger: GW170817 - this time with an electro magnetic counterpart.
The follow-up of GW170817

Real-time Multi-Messenger Astronomy @ DESY

Gamma ray follow-up of NS/NS merger GW170817

- H.E.S.S. first ground-based pointing telescope on target, 5 hours after the event
- DESY PhD students happened to be on shift in Namibia, they scanned the uncertainty region within three nights
- 3 of the lead authors of the H.E.S.S. paper (Abdalla et al 2017) from DESY
Summary: Gamma Ray Astronomy

- 1948: first ideas
- 1989: first source
- 2000: ~10 sources, ~10 collaborators
- 2010: ~100 sources, ~100 collaborators
- 2030: ~1000 sources, ~1000 collaborators

Cherenkov Telescopes are the best means of studying $\gamma$-rays at energies 50 GeV ... 300 TeV.

Astrophysics in the GeV ... >300 TeV range will see major scientific progress with Fermi, CTA and many other experiments.

41 years! (thanks to very dedicated physicists)
Astroparticle Physics

- Astroparticle Physics is an exciting field.
- Highest energy particles are rare & difficult to detect
  ... but new experiments (with increased sensitivity) are getting better
  in detecting these particle and identifying their sources.
- The most-energetic CRs, gamma rays & neutrinos
  come likely from the same, most violent environments
  in the universe. (Multi-messenger approach)

- Four new windows in Astronomy:
  TeV gamma rays, Neutrinos, Gravitational waves, Cosmic rays

Bright future with many challenges for bright young scientists.