MASTER YOUR PHYSICS CONFERENCE
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GAMMA-RAY ASTROPHYSICS
IN A MULTI-MESSENGER CONTEXT

16 June 2021
WHY THE SKY IS DARK?

Olber’s paradox (XIX century): In a static, infinite Universe every line of sight should eventually intercept the surface of a star, so the sky should be as bright as a stellar surface.

Solution:
- finite speed of light: we can see only galaxies where light has had the time to reach us;
- Finite age of universe in the Big Bang cosmology;
- Expansion of the universe: stars only radiate for finite time, limiting the energy density of the background light)
The expanding universe

Extragalactic Background Light (EBL)
THE SKY IS PERVERDED OF RADIATION!

The CMB is a picture of the Universe 380’000 yr after the Big Bang.
The Extragalactic Background Light (EBL) encodes the output of galaxy formation evolution.

Dole et al., 2006; Dole 2010 HDR; Béthermin et al., 2012; Dole & Bethermin (in prep)
MULTI-WAVELENGTH ASTRONOMICAL OBSERVATIONS

The electromagnetic spectrum

Electromagnetic opacity of the atmosphere

Rayons Gamma, X et ultra-violets bloqués par la haute atmosphère (observation depuis l'espace).

Lumière visible observable depuis la Terre mais un peu de distorsion atmosphérique.

La plupart des rayons infra-rouge sont absorbés par des gaz atmosphériques (observation depuis l'espace).

Ondes radio observables depuis la Terre.

Très grandes longueurs d'onde bloquées.
THE MULTI-WALENGTH SKY

Radio Continuum (408 MHz)  Bonn, Jodrell, Bashe, and Parcels

Atomic Hydrogen  21 cm Dickey-Lockman

Molecular Hydrogen  115 GHz Columbus-GISS

X-Ray  0.25, 0.75, 1.5 KeV ROSAT/SPC

Gamma Ray  >100 MeV CGRO/EGRET

Infrared  12, 60, 100 μm IRIS

Near Infrared  1.25, 2.2, 3.5 μm COBE/DIRBE

Optical  A. Mullinger Photomosaic

https://mwmw.gsfc.nasa.gov/mmw_allsky.html
http://www.chromoscope.net

Planck 10-0.3 mm
COSMIC MICROWAVE RADIATION

Blackbody spectrum with $T = 2.7 \, ^\circ\text{K}$

angular resolution between $0.5^\circ - 0.08^\circ \Rightarrow \Delta T/T \sim 2 \times 10^{-6}$
THE ACCELERATORS SKY IN THE TEV SEEN BY FERMI-LAT


30 MeV-300 GeV
THE MULTI-WAVELENGTH OBSERVATIONS: THE CRAB NEBULA

Historical Supernova remnant observed in the year 1054 by Chinese Astronomers

Credit: NASA/CXC/SAO (X-ray), Paul Scowen and Jeff Hester (Arizona State University) and the Mt. Palomar Observatories (optical), 2MASS/UMass/IPAC- Caltech/NASA/NSF (infrared), and NRAO/AUI/NSF (radio)

<table>
<thead>
<tr>
<th>X-ray</th>
<th>Optical</th>
<th>Infrared</th>
<th>Radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ $10^4$ eV</td>
<td>~ few eV</td>
<td>~ 1 eV</td>
<td>~ $10^{-4}$ eV</td>
</tr>
</tbody>
</table>

Credit: NASA/CXC/SAO (X-ray), Paul Scowen and Jeff Hester (Arizona State University) and the Mt. Palomar Observatories (optical), 2MASS/UMass/IPAC- Caltech/NASA/NSF (infrared), and NRAO/AUI/NSF (radio)
Opening windows to the unexpected...

Extend 23’000 light-years above the plane of the Milky Way, energy ~1-100 GeV; enough cool gas to create 2M x M_{Sun}, counterpart of WMAP haze (Planck).


Finkbeiner et al., 2010; Karen Yang, Ruszkowski, Zweibel et al, 2018
...AND OF PARTICLES!
CONTENTS OF TWO LECTURES

▸ What are cosmic rays and why we study them?

▸ The new astronomy: multi-messenger high energy astrophysics

▸ Gamma-Ray and neutrino high-energy telescopes
COSMIC RAY HISTORY

- <1909: 3 hypothesis for observed discharge of electroscope: Wilson had visionary idea on extraterrestrial radiation (e.g. Sun), radiation from radioactive elements in the Earth crust or atmosphere.

- 1910 Wulf: inclusive measurements from Eiffel Tower.

- A. Gockel (Swiss, 1909-1911): with a Wolf-type electroscope on 3 balloon flights discovers that the radiation discharging the electrosopes not from ground but increases with altitude. Wrong interpretation: gamma-rays from radioactive sources in the atmosphere.

- V.F. Hess (1912, Nobel prize with Anderson in 1936) reaches 5000 m of altitude and interprets results as due to a **ionising radiation that increases with altitude**.

http://www.desy.de/2012vhess
Kolhörster took more data between 1911-1914 up to 9 km improving Hess results.

Millikan studied the penetration properties in water and atmosphere and called the radiation ‘cosmic rays’ (1928)

These facts, combined with the further observation made both before and at this time, that within the limits of our observational error the rays came in equally from all directions of the sky, and supplemented finally by the facts that the observed absorption coefficient and total cosmic ray ionisation at the altitude of Muir Lake predict satisfactorily the results obtained in the 15.5 km. balloon flight, all this constitutes pretty unambiguous evidence that the high altitude rays do not originate in our atmosphere, very certainly not in the lower ninetenths of it, and justifies the designation ‘cosmic rays,’ the most descriptive and the most appropriate name yet suggested for that portion of the penetrating rays which come in from above. We shall discuss just how unambiguous the evidence is at this moment after having presented our new results.

These represent two groups of experiments, one carried out in Bolivia in the High Andes at altitudes up to 15,400 ft. (4620 m.) in the fall of 1926, and the other in Arrowhead Lake and Gem Lake, California, in the summer of 1927.
COSMIC RAY MEASUREMENTS

Direct detection balloon-borne or satellite experiments generally use energy per nucleon on x-axis, the natural variable for studying propagation of nuclei because energy per nucleon is conserved in spallation processes.

Indirect measurements: Since air shower measurements are calorimetric in nature, the natural energy variable to use is total energy per nucleus.

AMS on space station

ANITA at South Pole

IceTop at South Pole

Figure from M. Spurio’s book, Particles & Astrophysics
Particles per unit of surface, unit of time, unit of solid angle, unit of energy \([\text{m}^2 \text{ s sr GeV}]^{-1}\). The spectrum spans 12 orders of magnitude in energy and 24 in intensity. Below the knee:

\[
\frac{dN}{dE} = 1.8 \times 10^4 (E/1\text{GeV})^{-2.7} \text{nucleons m}^2 \text{s sr GeV}^{-1}
\]

**\(E_{\text{knee}} \sim Z \times 3 \text{ PeV}\)**

**\(E_{\text{ankle}} \sim 5 \times 10^{19} \text{ eV}\)**

Notice:

\[
\log \left( \frac{dN}{dE} \right) = \log[A] - \alpha \cdot \log[E]
\]

Since the spectrum is steep, we multiply by \(E^{\beta}\):

\[
\log \left( E^{\beta} \frac{dN}{dE} \right) = \log[A] - (\alpha - \beta) \cdot \log[E]
\]
The spectral features: The Knee and the Ankle

The changes of slope are connected to changes of sources and/or propagation features.

The end of the spectrum:
GZK cut-off
All stable elements of the periodic table are found in galactic CRs

The CRs composition is similar to the elements in the Sun indicating that they have stellar origin

H, He directly accelerated in stars. Li, Be, B are secondary nuclei produced in the spallation of heavier elements (C and O). Also Mn, V, and Sc come from the fragmentation of Fe.

The zig-zag is due to the fact that nuclei with odd Z and/or A have weaker bounds and are less frequent products of thermonuclear reactions.
Large Hadron Collider:
\[ E_{\text{max}} = c \cdot e \cdot B \cdot R = 7 \times 10^{12} \text{eV} \]

9593 superconducting magnets at -271.3 °C accelerate protons to collide in 4 points instrumented to analyse matter and its constituents in which it decomposes at these extreme conditions similar to \(3 \times 10^{15}\) seconds after the Big Bang (\(\sim 15\) TeV correspond to abt. \(10^{17}\) Kelvin)
THE NON-THERMAL ACCELERATORS

coronal mass
ejection
10 GeV protons

Chandra
SN 1006
COSMIC ACCELERATORS

An LHC with the radius of the Mercury orbit could accelerate protons to $10^{20}$ eV = $10^7 \times$ LHC!
MESSENGER ACCELERATION: THE HILLAS’ PLOT

\[ F_L = qvB = m \frac{v^2}{R} \]

Imposing that the Larmor is equal to the accelerating region

\[ R = R_{\text{acc}} \]

We find the maximum energy at which the charged relativistic particle with \( q = Ze \) can be accelerated

\[ E_{\text{max}} \simeq Z \left( \frac{B}{\mu G} \right) \left( \frac{R_{\text{source}}}{\text{kpc}} \right) \times 10^9 \text{ GeV} \]

For jets with Lorentz factor \( \Gamma \), \( E_{\text{max}} \approx \Gamma ZBR \) (maximum energy depends on cosmic ray charge \( Z!! \))
In a SN gravitational energy released is transformed into acceleration of particles \( \rightarrow \) E\(^{-2}\) spectrum

For an isotropic source the emitted energy density is connected to energy flux:

\[
\rho_E = 4\pi \int_{1\ \text{GeV}}^{1\ \text{PeV}} \frac{E\ dN}{\beta c\ dE} dE \sim \frac{1\ eV}{cm^2} \sim \frac{B^2}{8\pi}
\]

If 10\% of the energy of the ejecta of all SNR in the Galaxy goes into acceleration of CRs the spectrum to the knee is explained.
EXTRAGALACTIC ACCELERATORS

Centaurus A

**Chandra X-ray**
**DSS Optical**
**NRAO Radio Continuum**
**NRAO Radio (21-cm)**
The end of the spectrum of CRs could be due to GZK cutoff and/or effect of sources exhausting their energy. The GZK cut-off is due to proton interactions. The threshold for production of delta resonance is around $5 \times 10^{19}$ eV.
The generic model of a cosmic ray accelerator
Multi-messengers

Astroparticle Physics Nowadays

Neutrino GW Gamma-ray Astrophysics
Gamma-ray detection

From ground

Imaging Air Cherenkov Telescopes (IACT)

- atmosphere is calorimeter
- Sets of mirrors focus Cherenkov pool light into fast camera in focus
- ~10% duty cycle due to Moon and weather and exposed mirrors
- decreasing efficiency by order of 2% due to mirror deterioration

Table from De Angelis, Mallamaci, arXiv:0805.05642

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Fermi</th>
<th>IACTs</th>
<th>EAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range</td>
<td>20 MeV–200 GeV</td>
<td>100 GeV–50 TeV</td>
<td>400 GeV–100 TeV</td>
</tr>
<tr>
<td>Energy res.</td>
<td>5–10%</td>
<td>15–20%</td>
<td>~ 50%</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>80%</td>
<td>15%</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td>FoV</td>
<td>4π/5</td>
<td>5 deg × 5 deg</td>
<td>4π/6</td>
</tr>
<tr>
<td>PSF (deg)</td>
<td>0.1</td>
<td>0.07</td>
<td>0.5</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>1% Crab (1 GeV)</td>
<td>1% Crab (0.5 TeV)</td>
<td>0.5 Crab (5 TeV)</td>
</tr>
</tbody>
</table>

Space-based: 0.1 - 100 GeV Large FoV and duty cycle

EAS: $\gtrsim 1$ TeV

- collect Cherenkov radiation produced by charged particles in water tanks or ponds equipped with photosensors
- > 90% duty cycle and large FoV
- Needs water purification and recycling (HAWC, LHAASO)
- Future Southern Widefield Gamma-ray Observatory (SWGO)

Table from De Angelis, Mallamaci, arXiv:0805.05642
Imaging Air Cherenkov Telescopes

C. Galbreith & J. Jelley, when visiting the Harwell Air Shower Array in UK in 1952, used a 5 cm PMT mounted on the focal plane of a 25 cm parabolic mirror in a garbage can. They observed oscilloscope triggers from light pulses that exceeded the average night-sky background every 2 min. In 1953, from the polarisation and spectral distribution, they confirmed P. Backett’s assertion that Cherenkov light is produced by charged CRs in the atmosphere on top of the night sky background.

In 1959 G. Cocconi proposed to measure TeV gamma-rays using air shower detectors.

Trevor Weekes (1940-2014)
Whipple: first image of the Crab Nebula in 1989, the most studied TeV source

Eckart Lorenz (1938-2014)
HEGRA+AIROBICC, MAGIC arrays
High-energy sources in the years

https://github.com/sfegan/kifune-plot
Gamma-ray sources from space: 10 GeV-100 GeV

Fermi 8 yr catalogue (4FGL) 50 MeV - 300 GeV 5064 sources, 62% blazars, 1.5% 2.7% SNR & PWN, 4.7% Pulsars

Space-based experiments accesses redshift $Z < 2.5$

Ground based detectors accesses redshift $Z < 1.5$.

At PeV energy only the Galactic plane is visible!

(can be used to measure EBL, EG magnetic fields and search for axions!)
Gamma-ray sources from ground

Currently 232 sources in $Z < 1.5$
Imaging Cherenkov technology
When the measurement is stereoscopic the background is largely reduced and the source is observed in a $S/N$ regime not $S/\sqrt{N}$ and $E_{th} \propto 1/A_{mirror}$ rather than $E_{th} \propto 1/\sqrt{A_{mirror}}$.

CTA North in La Palma, Canarian Islands

Baseline: 0 LST + 15 MST + 50 SST
Future: 4 LST + 25 MST + 70 SST

CTA South at Paranal, Chile

Baseline: 4 LST + 5 MST
Future: 4 LST + 15 MST
The Northern array of CTAO
Its camera
The SST-1M

✓ **Dish** = 4 m
✓ **FoV** = 9°
✓ **f/D** = 1.4

Pixel size = $4 \cdot \min(\sigma_x, \sigma_y) = 0.24°$
Camera size ($D_c$) = 88 cm
Pixel size (linear) = 2.32 cm
$n_p = 1296$ pixels
The mini-telescope

- Arrival time [ns]
- ADC counts HG
- ADC counts LG

- Observation campaign @ OFXB in Saint Luc (Valais, Switzerland)
- Trigger rate scan to determine acquisition threshold

144 pixels camera
Readout system based on CITIROC custom adapted version
Telescope structure

Ekoume et al, JINST 15 (2020) 04, P04004
e-Print: 1912.05894 [astro-ph.IM]
Gamma-astronomy `themes’

- Understanding of the origin of the cosmic rays in a multi-messenger context

- Probing extreme environments, such as neutron stars, black holes and gamma-ray bursts, the physics of the jets and how particles are accelerated by them;

- The Galactic plane Survey (deep survey 2 faster by ~100 than current generation);

- Exploring frontiers in physics, such as the nature of Dark Matter in the Galactic Centre

https://arxiv.org/abs/1709.07997
Commissioning LST-1

The neutron star pulsations at the centre of the Crab Nebula. P2/P1 >1 indicates a large threshold.

The `standard candle' of gamma-ray astronomy

P2 > P1 at $E > 50$ GeV

Eth > 100 GeV


320 hours

Pulsed emission up to 1.5 TeV!

MAGIC data
LHAASO: Large High Altitude Air Shower Observatory

Aerial photograph of LHAASO (Image by IHEP)

80’000 m² water pools
WCDA,
~200 GeV-20 TeV and
~9mCU @ few TeV

KM2A with EM & muon detectors
> 10 TeV

Lightguides produced in Switzerland

WFCTA
Crab Nebula a clear PeVatron with secondary gammas > 100 TeV; also seen by HAWC and Tibet ASγ with no cut-off above 400 TeV indicating that primary electrons can reach above 0.1 PeV.

WCDA: 0.45° (<0.2°) @ 1 TeV (>6 TeV) with the pointing accuracy < 0.05°. Significance in image 4-77σ

\[ \phi(E) = \phi_0 \left( \frac{E}{3 \text{ TeV}} \right)^{-\alpha - \beta \ln \left( \frac{E}{3 \text{ TeV}} \right)} \]

\[ \phi_0 = (2.32 \pm 0.19) \times 10^{-12} \text{ cm}^{-2} \text{ TeV}^{-1} \text{ s}^{-1} \]

\[ \alpha = 2.57 \pm 0.06, \beta = 0.02 \pm 0.05 \]
### PeVatron candidates (> 100 TeV)

12 young massive star clusters and supernova remnants, PWN, 1 yet unidentified. $E_{\text{max}} = 1.42 \text{ PeV}$ for LHAASO J2032+4102 Cygnus cocoon!!

<table>
<thead>
<tr>
<th>source name</th>
<th>R.A.</th>
<th>dec</th>
<th>Significance (σ)</th>
<th>$E_{\text{max}}$ (PeV) above 100 TeV</th>
<th>Flux (± error) at 100 TeV (CU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHAASO J0534+2202</td>
<td>83.55</td>
<td>22.05</td>
<td>17.8</td>
<td>0.88 ± 0.11</td>
<td>1.00(0.14)</td>
</tr>
<tr>
<td>LHAASO J1825-1326</td>
<td>276.45</td>
<td>-13.45</td>
<td>16.4</td>
<td>0.42 ± 0.16</td>
<td>3.57(0.52)</td>
</tr>
<tr>
<td>LHAASO J1839-0545</td>
<td>279.95</td>
<td>-5.75</td>
<td>7.7</td>
<td>0.21 ± 0.05</td>
<td>0.70(0.18)</td>
</tr>
<tr>
<td>LHAASO J1843-0338</td>
<td>280.75</td>
<td>-3.65</td>
<td>8.5</td>
<td>0.26 $^{+0.16}_{-0.10}$</td>
<td>0.73(0.17)</td>
</tr>
<tr>
<td>LHAASO J1849-0003</td>
<td>282.35</td>
<td>-0.05</td>
<td>10.4</td>
<td>0.35 ± 0.07</td>
<td>0.74(0.15)</td>
</tr>
<tr>
<td>LHAASO J1908+0621</td>
<td>287.05</td>
<td>6.35</td>
<td>17.2</td>
<td>0.44 ± 0.05</td>
<td>1.36(0.18)</td>
</tr>
<tr>
<td>LHAASO J1929+1745</td>
<td>292.25</td>
<td>17.75</td>
<td>7.4</td>
<td>0.71 $^{+0.16}_{-0.07}$</td>
<td>0.38(0.09)</td>
</tr>
<tr>
<td>LHAASO J1956+2845</td>
<td>299.05</td>
<td>28.75</td>
<td>7.4</td>
<td>0.42 ± 0.03</td>
<td>0.41(0.09)</td>
</tr>
<tr>
<td>LHAASO J2018+3651</td>
<td>304.75</td>
<td>36.85</td>
<td>10.4</td>
<td>0.27 ± 0.02</td>
<td>0.50(0.10)</td>
</tr>
<tr>
<td>LHAASO J2032+4102</td>
<td>308.05</td>
<td>41.05</td>
<td>10.5</td>
<td>1.42 ± 0.13</td>
<td>0.54(0.10)</td>
</tr>
<tr>
<td>LHAASO J2108+5157</td>
<td>317.15</td>
<td>51.95</td>
<td>8.3</td>
<td>0.43 ± 0.05</td>
<td>0.38(0.09)</td>
</tr>
<tr>
<td>LHAASO J2226+6057</td>
<td>336.75</td>
<td>60.95</td>
<td>13.6</td>
<td>0.57 ± 0.19</td>
<td>1.05(0.10)</td>
</tr>
</tbody>
</table>

‘...photons exceeding 1 PeV from it, can be treated as evidence of the operation of massive stars as hadronic PeVatrons. The leptonic (IC) origin of radiation can be excluded because of the lack of brightening of the gamma-ray image towards Cygnus OB2. A decisive test for the acceleration of protons, presumably via collisions of the stellar winds, and continuous injection into the circumstellar medium over million-year timescales, would be the derivation of hard injection spectra and radial dependence of the density of UHE protons’

Nature paper (press release on May 17): Detection of Ultra-high Energy Photons up to 1.4 PeV from 12 Gamma-ray Sources
The generic model of a cosmic ray accelerator

T. De Young
Reactions in matter accelerators

Gamma-ray astronomy - Neutrino Astronomy and cosmic rays
HADRONIC SIGNATURES IN SPECTRAL EMISSION DISTRIBUTION

Leptonic scenario: red and blue

Hadronic scenario: pion decay

energy flux
$E^2 \frac{d}{dE} \sim \nu F(\nu)$

synchrotron radiation from electrons
$\frac{dE}{dt}_{Sy} = k \gamma_e^2 U_{mag} \sim \gamma_e^2 B^2$

Inv. Compton scattering by the same electrons
$\frac{dE}{dt}_{IC} = k \gamma_e^2 U_{rad}$
HADRONIC SUPERNOVAE

IC 443

W44

Fermi, Science 2013
Nov. 2013. Currently, more than 8 yrs are available and a negligible probability that these high energy neutrinos are originating in the atmosphere.
A DIFFUSE FLUX
On Sep. 2015 the LIGO interferometers transmitted the `chirp’ of coalescent BHs with 36 and 29 solar masses. This sound traversed the Earth. The waves are perturbations of gravitational field produced by a cataclysmic astrophysical event and are an important confirmation of the Einstein Theory of gravitation.

The frequency of GWs is a sound.
The first event of BH-BH merger: raw data!

GW arrived first at L1 and then after $6.9 - 0.4 + 0.5$ ms at H1.

A direct detection which requires only a pass band filter in 35–350 Hz!

Fit to simple formulas bring a lot of information!

At first order, the rate of change of the frequency is

$$\frac{df}{dt} = \frac{96\pi^{8/3} (GM)^{5/3} f^{11}}{5 c^5},$$

And the chirp mass

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}.$$ 

The polarization of the waves provides the angle of emission
And the distance is a multiple of the laser wavelength

Templates are calculated from General Relativity for NS-NS / BH-BH mergers and matched to data (matched template technique)

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary black hole mass</td>
<td>$36^{+5}<em>{-4} M</em>\odot$</td>
</tr>
<tr>
<td>Secondary black hole mass</td>
<td>$29^{+4}<em>{-4} M</em>\odot$</td>
</tr>
<tr>
<td>Final black hole mass</td>
<td>$62^{+4}<em>{-4} M</em>\odot$</td>
</tr>
<tr>
<td>Final black hole spin</td>
<td>$0.67^{+0.05}_{-0.07}$</td>
</tr>
<tr>
<td>Luminosity distance</td>
<td>$410^{+160}_{-180}$ Mpc</td>
</tr>
<tr>
<td>Source redshift, $z$</td>
<td>$0.09^{+0.03}_{-0.04}$</td>
</tr>
</tbody>
</table>

**Total Energy Radiated in GW:**

$$3.0^{+0.5}_{-0.5} M_\odot c^2$$

**Peak GW Luminosity:**

$$3.6^{+0.5}_{-0.4} \times 10^{56} \text{ erg/s}$$

*The most luminous event ever observed*

*First observation of the largest known stellar mass BH ($>25 M_\odot$)*

*First observation of a binary black hole (BBH) system and BBH merger*
Aug 17th 2017 at 12:41 UTC Advanced LIGO-Virgo detected a binary neutron star inspiral

Resulting mass $90\text{M}_\odot$

$2.73 < M_{\text{Total}} < 3.29 \text{M}_\odot$

Two mass interval

$0.86 < m_i < 2.26 \text{M}_\odot$

Luminosity distance

$$D_L = 40^{+8}_{-14} \text{ Mpc}$$

A GRB event, 1.7 sec after…

First direct evidence that BNS mergers are progenitors of short GRB

Optical counterpart in host galaxy NGC4993

Optical/infrared/UV counterpart detected

First identification of a kilonova
The multi-messenger event!

GW 170817 - photon connection

Figure from M. Branchesi’s presentation at Neutrino Telescopes 2021

GSSI Colloquia: A. Bonanno and M. Maggiore this year
NEUTRINO TELESCOPE

- 10,000,000,000 atmospheric muons
- 100,000 atmospheric neutrinos
- 10 cosmic neutrinos (per year and km³)
IceCube sent an alert including the direction of an event $\sim 3 \times 10^{14}$ eV in only 43 sec. Fermi discovered blazar a 0.06° distance from the IceCube event in a flaring state. In a follow up, MAGIC detected gamma rays of $> 300$ GeV energy from the source. The probability that this is not a casual coincidence is about $3.5\sigma$.

IceCube found a second flare in 2014-15.
The 22/08/2017 IceCube alert event (not a neutrino, but a muon)!

IC220817: $23.7 \pm 2.8$ TeV **visible energy** in the detector from number of photoelectrons in PMTs, 15 arcmin error (50% containment), signalness 56.5% (**GOLDEN alerts: ~10 /yr with signalness > 50%**)

**Muon Energy proxy:** muon energy at detector entrance: 
~52 TeV = **is a lower limit to the total muon energy** since the muon passes through the detector.

The corresponding **corresponding to a most probable neutrino energy ~290 TeV. Upper limit at 90% CL is 4.5 PeV (7.5) PeV)** for a spectral index of -2.13 (-2).

https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon
Photon - neutrino multi-messenger event

$F_x \sim 10^{-12} \text{ erg/(cm}^2 \text{ s)}$

IC 170922A

2014-15 $\nu$ flare

M.G. Aartsen et al. *Science* 361

Asen Christov, PhD Thesis UNIGE
Interestingly...variability matters!

MASTER found the TXS 0506+056 in a quiet state 73 s after the IceCube 2017 event, but 2 hr after they observed an increase of optical flux at 50σ level (biggest variation since 2005!)

3 high variability episodes (up to hour scale): in 2006 (IceCube had 1 string), Apr. 2015 (IceCube flare 9/2014-3/2015) and 9/2017

Le véritable voyage de découverte ne consiste pas à chercher de nouveaux paysages, mais à avoir de nouveaux yeux.

The real voyage of discovery consists not in seeking new landscapes, but in having new eyes. *(Marcel Proust)*