Pierre Auger Observatory Master Classes 18/03/2025

Raggi cosmici di altissima energia

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Sezione INFN Lecce

Raggi Cosmici: perchè?!

sono molto abbondanti in natura

~ 300 particelle/s/m^2 20% della radioattività naturale

→ scoprire la natura di **sorgenti astrofisiche** galattiche ed extragalattiche e dei meccanismi di produzione ed accelerazione di particelle

→ studiare le **interazioni** radiazione-materia fino ad energie inaccessibili persino ai moderni acceleratori di particelle

→ messaggeri di **fisica potenzialmente nuova** (materia ed energia oscura)

→ contengono le **particelle più energetiche dell'Universo**

Raggi cosmici e società

Piramide di Cheope

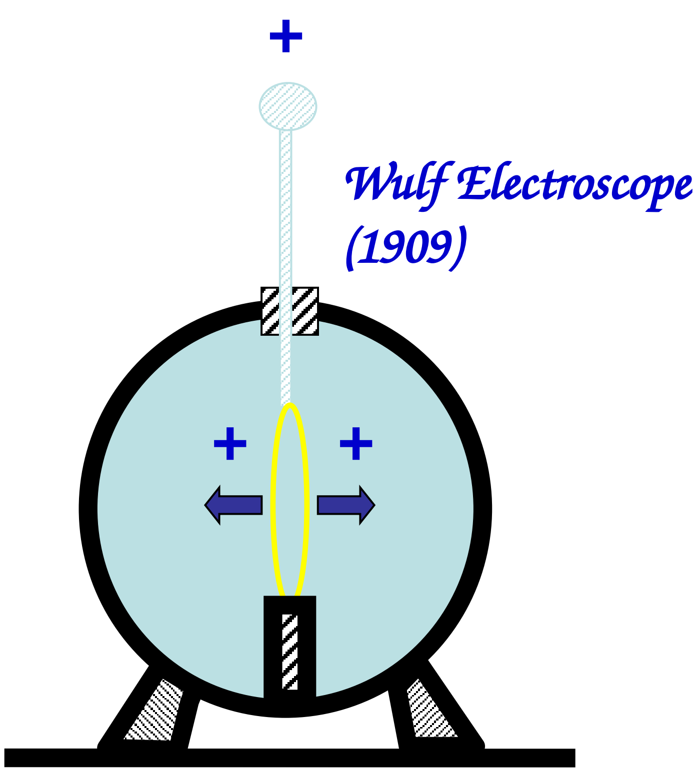
Aurore boreali

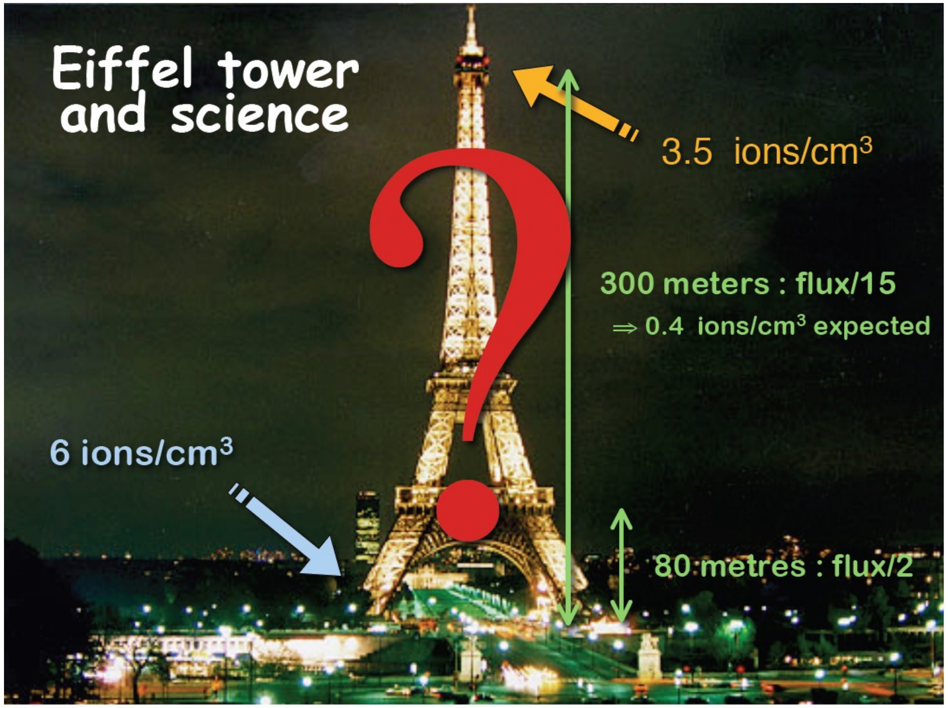
Computer quantistici

Retrospettiva storica

1896- 1903: Scoperta della radioattività naturale (H. Bequerel) e prime misure (E. Rutherford)

1910: T. Wulf va sulla torre Eiffel e misura la concentrazione radioattiva ad alta quota utilizzando un elettroscopio.





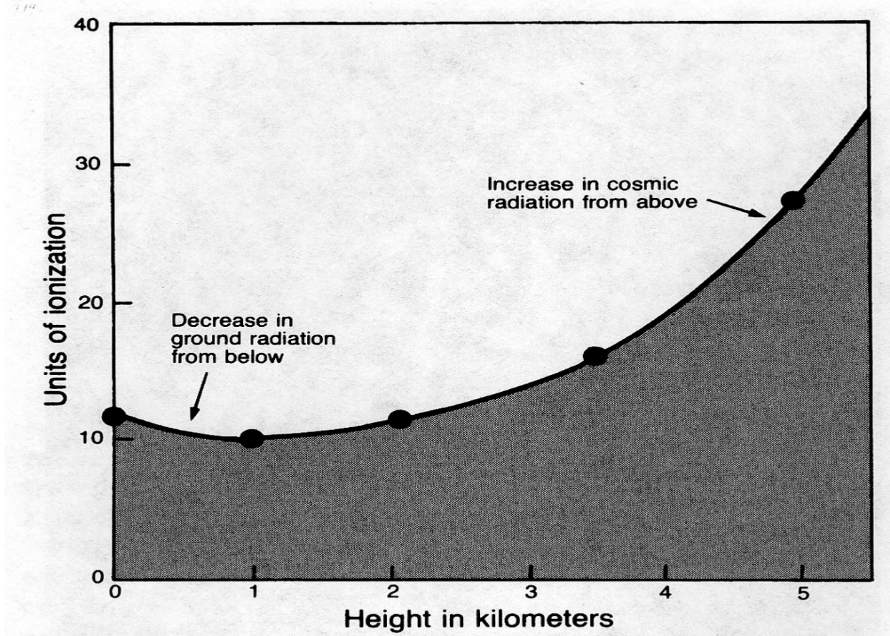
Allo stesso tempo **Pacini** in Italia effettuava delle misure simili a diverse profondità nel mare di fronte a Livorno

Flusso diminuiva con il crescere della quota ma non come ci si aspettava

Primo problema….

Scoperta dei raggi cosmici!

il volo di Hess (1912)

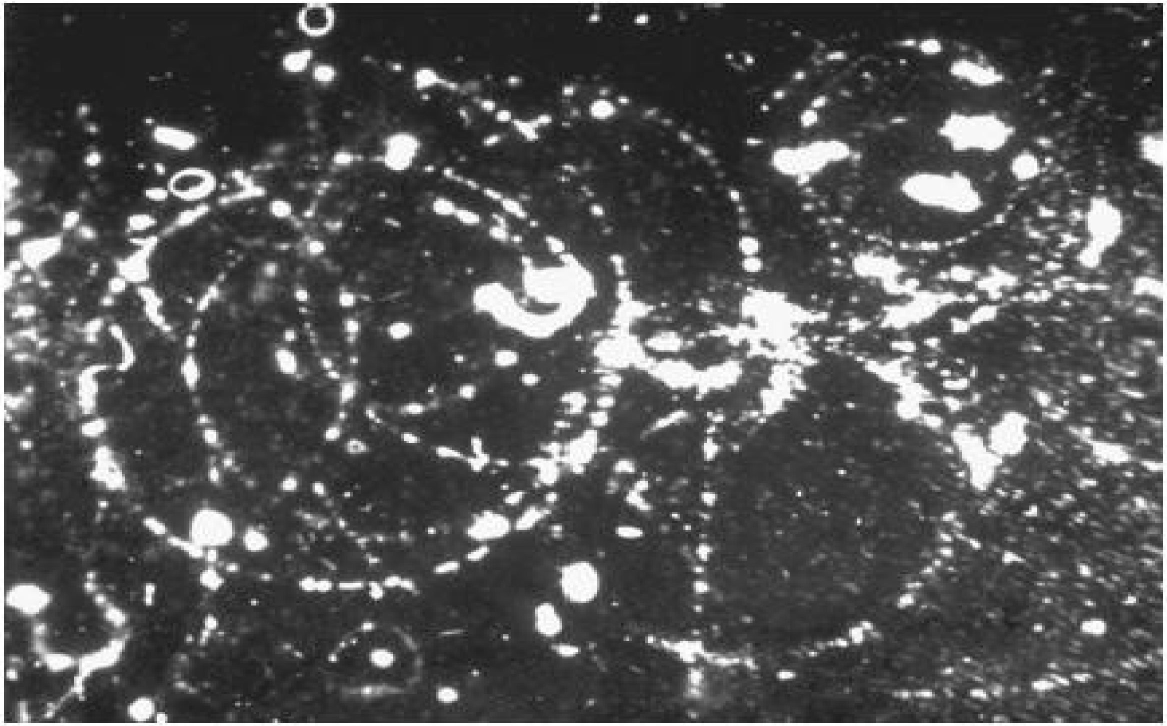


Readings on ionization chamber Victor Hess carried aloft in the Böhmen. Above four kilometers the ionization rose rapidly indicating "that rays of very great penetrating power are entering our atmosphere from above". These cosmic rays contain the only modern samples of matter from outside our solar system which can be investigated directly.

I raggi cosmici provengono dallo spazio (flusso aumenta con la quota)

Raggi Cosmici: di cosa si tratta?

1932: Millikan vs Compton: fotoni o particelle cariche?



D. Skobeltsyn: foto dei RC in una camera a nebbia con campo magnetico

Inizia la fisica delle particelle!

1932: Carl Anderson, scopre il positrone (antimateria)

1937: Neddermeyer e **Anderson,** scoprono il muone

1940's: altre scoperte, pioni e particelle strane

particelle cariche!

Extensive Cosmic-Ray Showers

PIERRE AUGER
In collaboration with
P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON
Paris, France

Pierre Auger

LONG DISTANCE COINCIDENCES

If two or three counters are arranged in coincidence in free air, a small number of coincidences is observable, due to "air showers" and this number decreases quickly when the horizontal distance of the counters is increased. Schmeiser and Bothe have studied these local showers with counter separations up to half a meter.[2] If the distance is increased further, the

CONCLUSION

One of the consequences of the extension of the energy spectrum of cosmic rays up to 10^{15} ev is that it is actually impossible to imagine a single process able to give to a particle such an energy. It seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of a very great extension.

John Linsley

Energia delle particelle fino a 10^{20} eV !!

[14 TeV è la massima energia raggiunta nei laboratori del CERN]

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

Analysis of a cosmic-ray air shower recorded at the MIT Volcano Ranch station in February 1962 indicates that the total number of particles in the shower (Serial No. 2-4834) was 5×10^{10}. The total energy of the primary particle which produced the shower was 1.0×10^{20} eV. The shower was about twice the size of the largest we had reported previously (No. 1-15832, recorded in March 1961).[1]

The existence of cosmic-ray particles having such a great energy is of importance to astrophysics because such particles (believed to be atomic nuclei) have very great magnetic rigidity. It is believed that the region in which such a particle originates must be large enough and possess a strong enough magnetic field so that $RH \gg (1/300) \times (E/Z)$, where R is the radius of the region (cm) and H is the intensity of the magnetic field (gauss). E is the total energy of the particle (eV) and Z is its charge. Recent evidence favors the choice $Z = 1$ (proton primaries) for the region of highest cosmic-ray energies.[2] For the present event one obtains the condition $RH \gg 3\times10^{17}$. This condition is not satisfied by our galaxy (for which $RH \approx 5\times10^{17}$, halo included) or known objects within it, such as supernovae.

The technique we use has been described elsewhere.[1] An array of scintillation detectors is used to find the direction (from pulse times) and size (from pulse amplitudes) of shower events which satisfy a triggering requirement. In the present case, the direction of the shower was nearly vertical (zenith angle $10\pm5°$). The values of shower density registered at the various points of the array are shown in Fig. 1. It can be verified by close inspection of the figure that the core of the shower must have struck near the point marked "A," assuming only (1) that shower particles are distributed symmetrically about an axis (the "core"), and (2) that the density of particles decreases monotonically with increasing distance from the axis. The observed densities

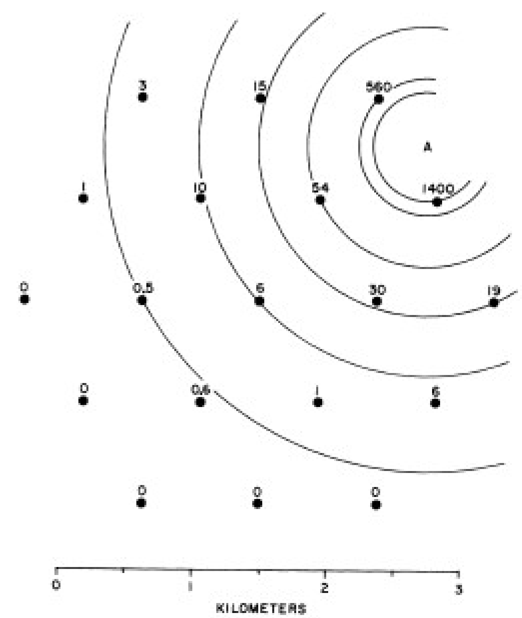
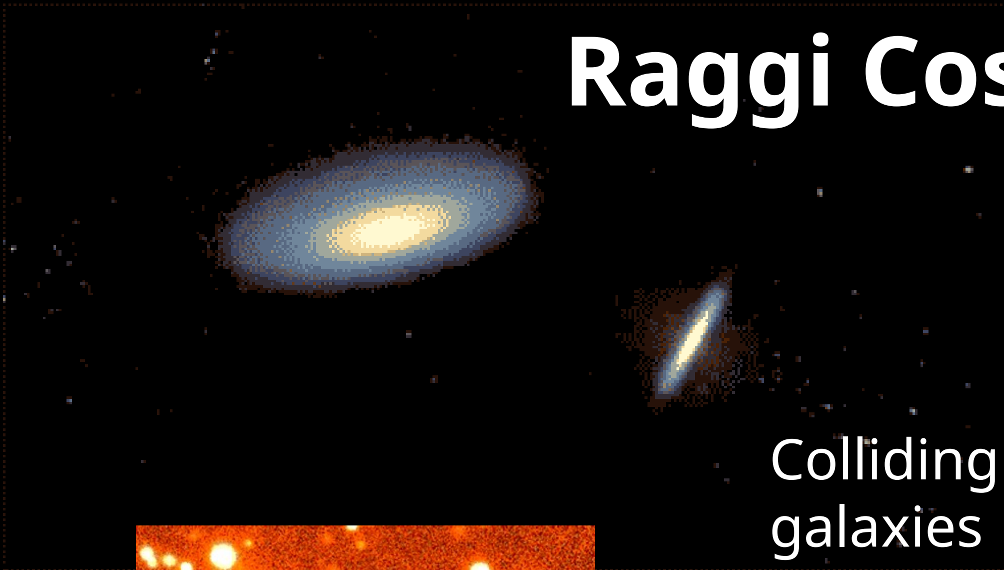
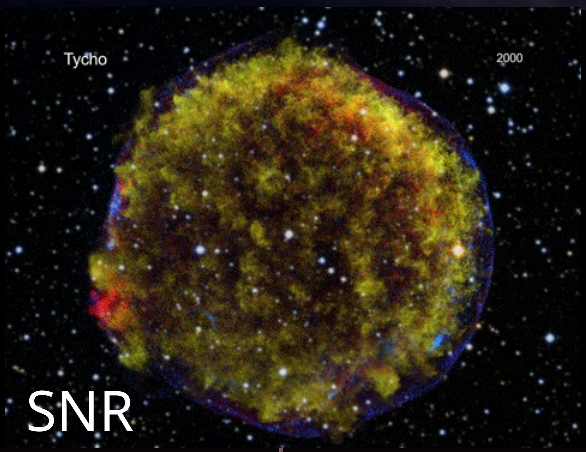


FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-m^2 scintillation detectors. The numbers near the circles are the shower densities (particles/m^2) registered in this event, No. 2-4834. Point "A" is the estimated location of the shower core. The circular contours about that point aid in verifying the core location by inspection.

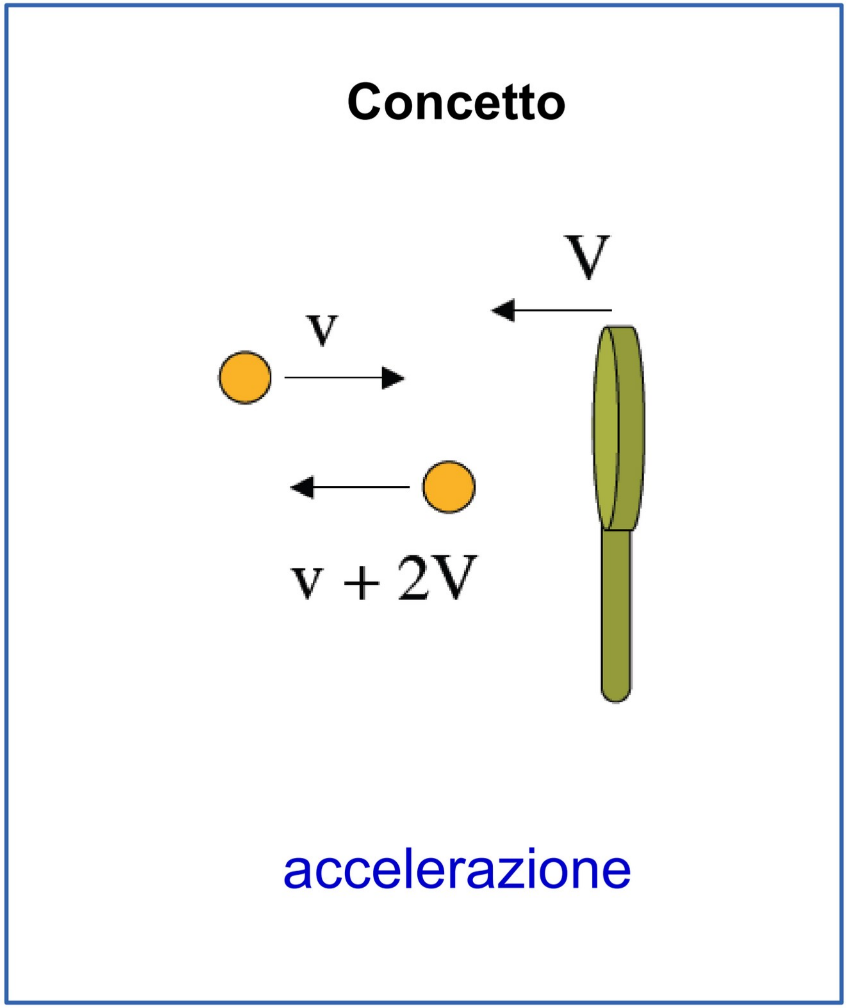
Raggi Cosmici: da dove?





ACCELERAZIONE DEI RAGGI COSMICI

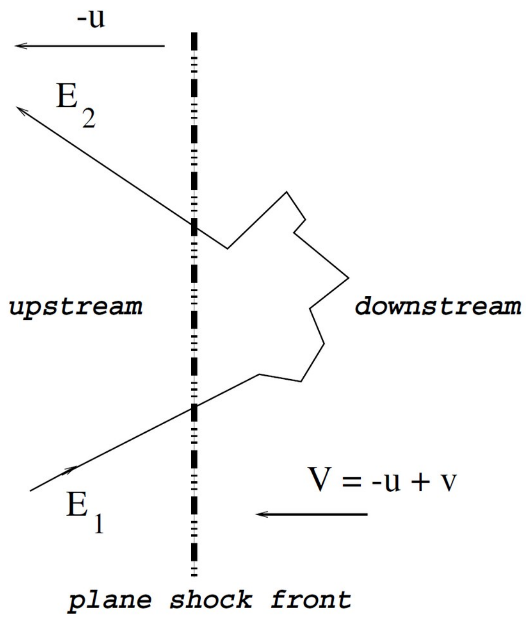
In fisica delle particelle l'energia viene misurata in **elettronVolt (eV)**.
È definito come l'energia persa da un elettrone che attraversa una d.d.p. di 1 V
Sono molto usati i suoi multipli **keV**, **MeV**, **GeV**, **TeV**.



Le particelle guadagnano energia attraversando fronti di materia in moto generato da fenomeni molto energetici (supernovae shock).

La velocità tipica del fronte è:

$$V_s \sim 10^4 km/s$$



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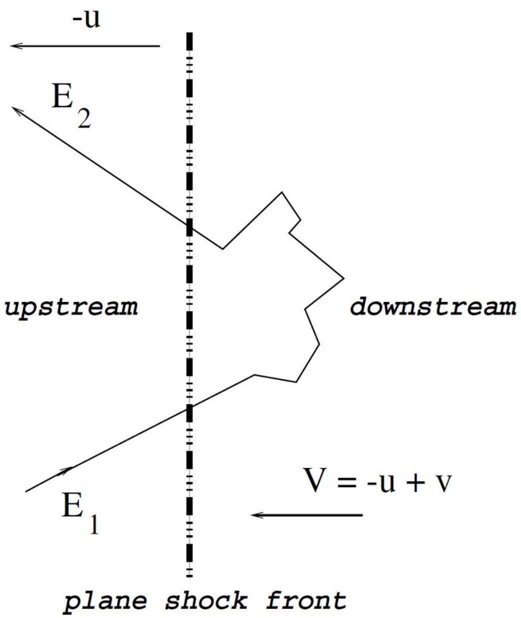
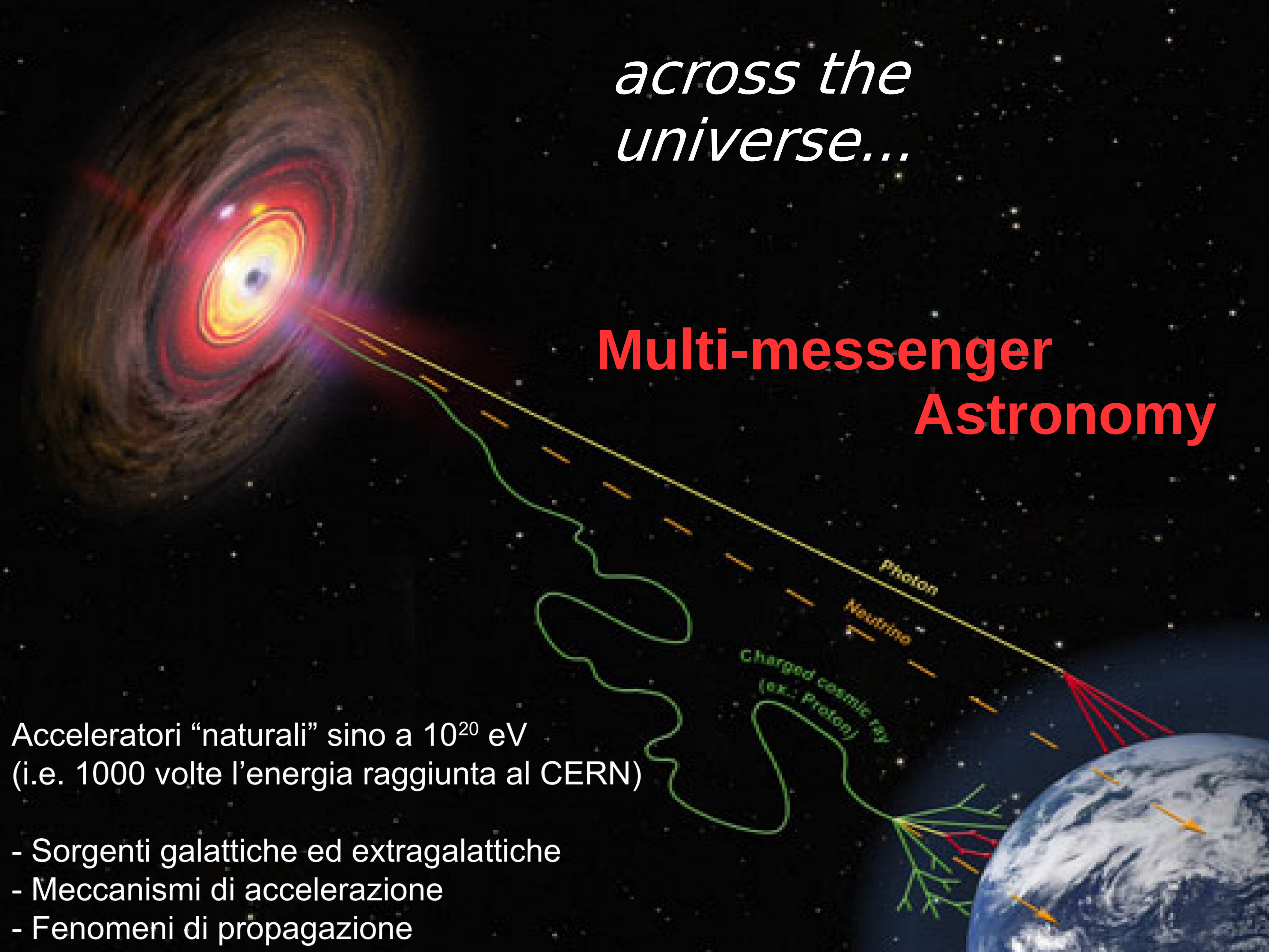


across the universe...

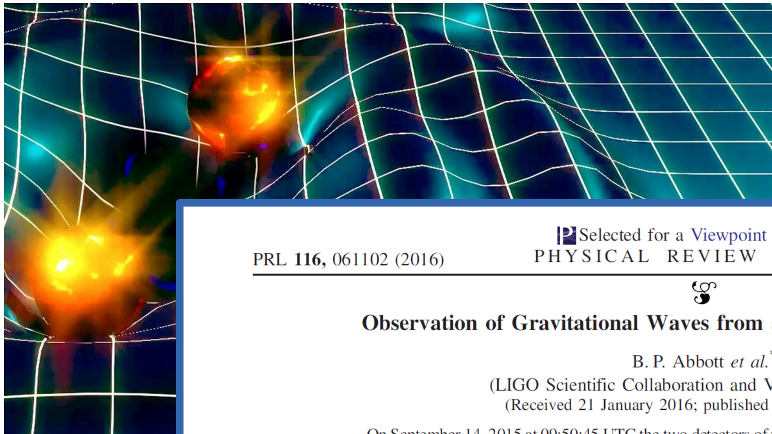
Multi-messenger Astronomy



Acceleratori "naturali" sino a 10^{20} eV
(i.e. 1000 volte l'energia raggiunta al CERN)

- Sorgenti galattiche ed extragalattiche
- Meccanismi di accelerazione
- Fenomeni di propagazione

Onde Gravitazionali !!



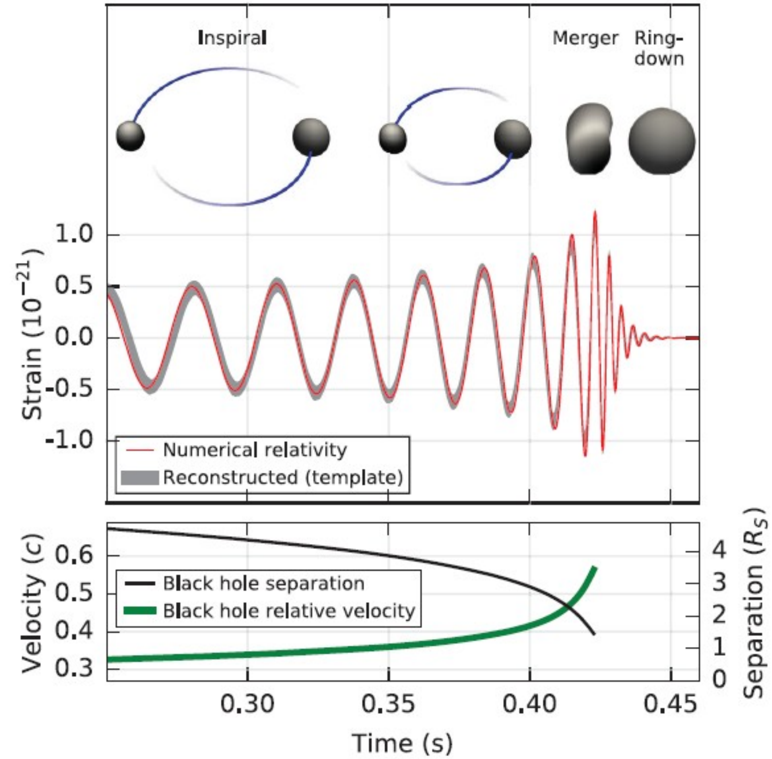
Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102



Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

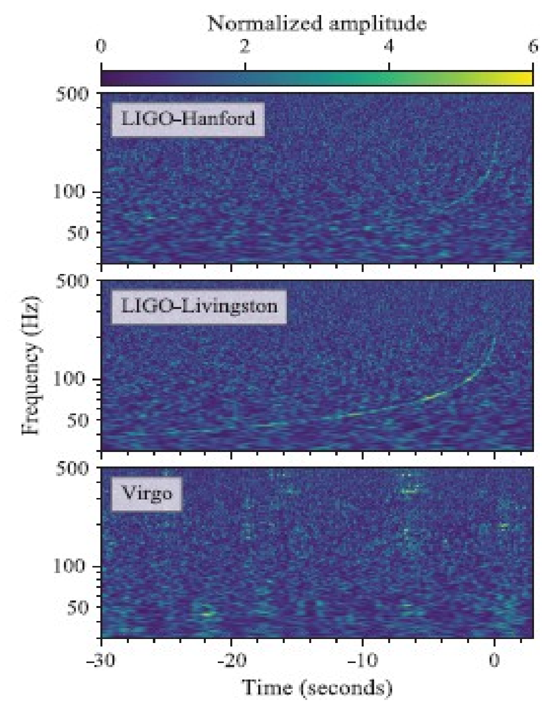
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; re... manuscript received ... October 2017; published 16 October 2017)

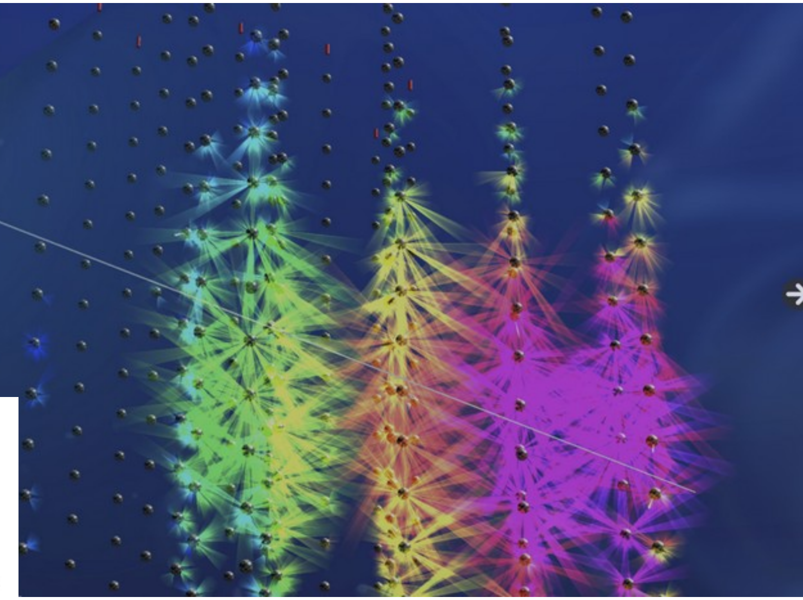
On August 17, 2017 at 12:41 ... C the Advance... and Advan... gravitational-wave detectors made their first observat... ...ary neutro... ...al. Th... 170817, was detected with a comb... signal-to-nois... ...4 ar... of less than one per 8.0×10^4 years... 0.86 and 2.26 $M_\odot$, in agreement with m... ...s to the ...ferred in binary neutron stars... total mass of the ... $2.74^{+0.04}$ ... probability) and had a ... signal yet. The ... coalescence, ... evidence of a link between ... nt counterparts across ... this event as a neutro... observation provides insight into astro...

Premio Nobel 2017

B. Barish R. Weiss and



2025 → Neutrino cosmico a circa 10^{17} eV



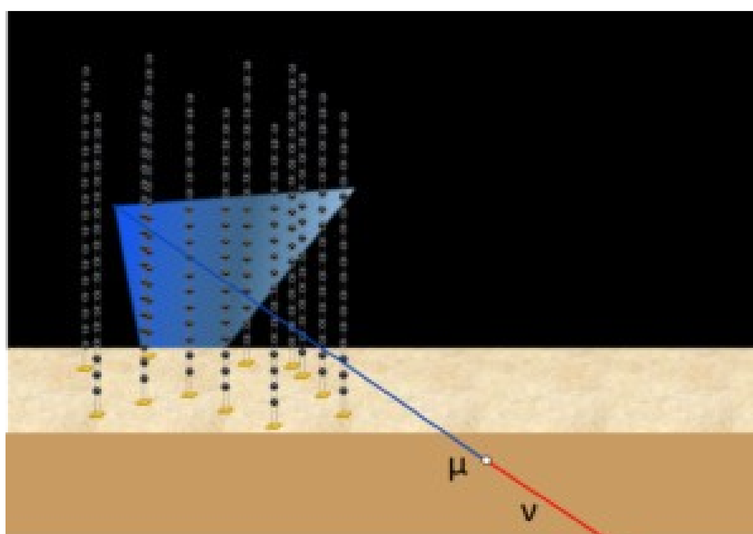
Discover the amazement of KM3-230213A, the most energetic neutrino ever detected!

The scientific and technical details are illustrated in the publication:

The KM3NeT Collaboration, Observation of an ultra-high-energy cosmic neutrino with KM3NeT

Nature **638**, 376–382 (2025) (DOI: 10.1038/s41586-024-08543-1)

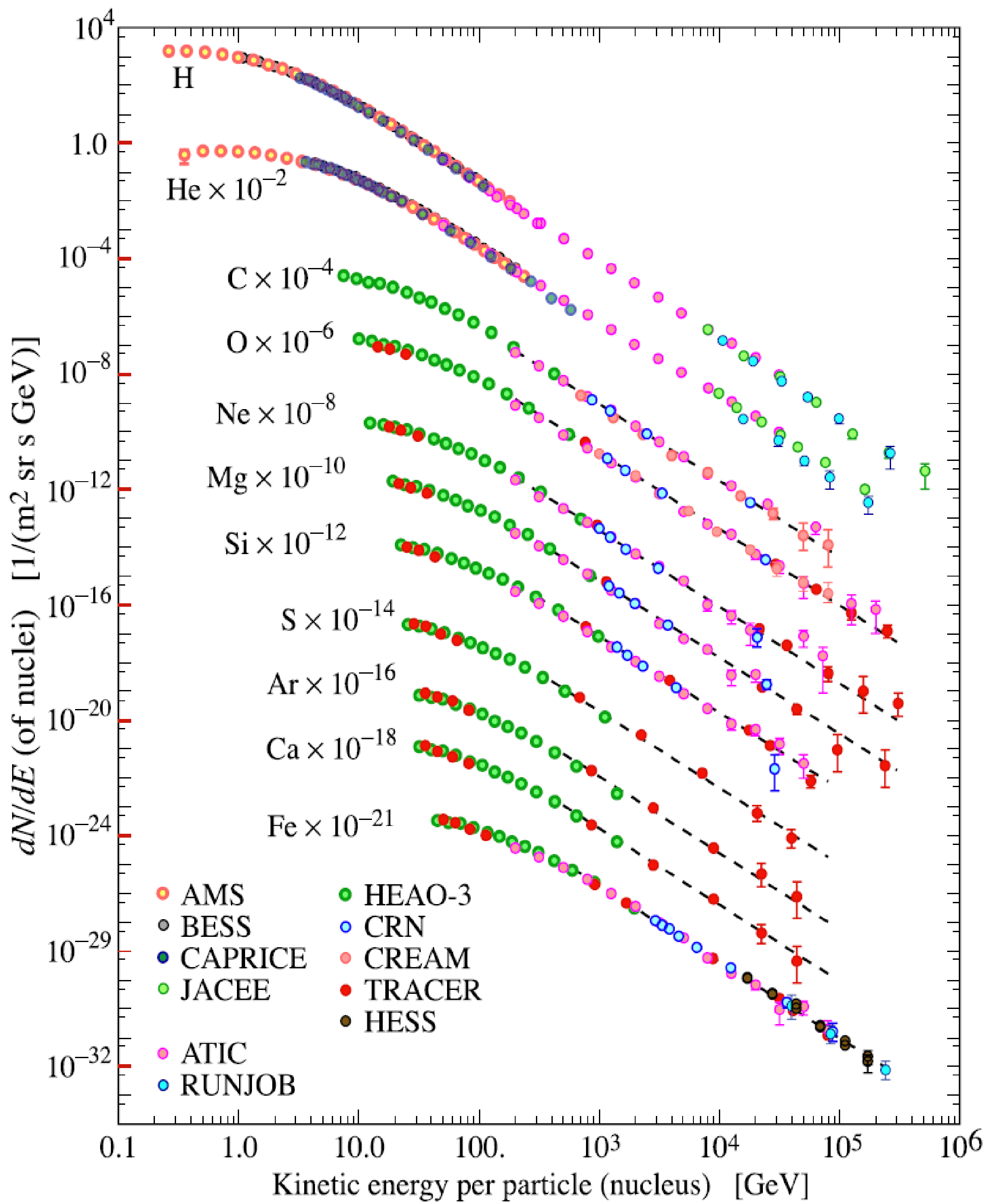
Observation of an ultra-high-energy cosmic neutrino with KM3NeT



The KM3NeT Collaboration*✉

The detection of cosmic neutrinos with energies above a teraelectronvolt (TeV) offers a unique exploration into astrophysical phenomena[1–3]. Electrically neutral and interacting only by means of the weak interaction, neutrinos are not deflected by magnetic fields and are rarely absorbed by interstellar matter: their direction indicates that their cosmic origin might be from the farthest reaches of the Universe. High-energy neutrinos can be produced when ultra-relativistic cosmic-ray protons or nuclei interact with other matter or photons, and their observation could be a signature of these processes. Here we report an exceptionally high-energy event observed by KM3NeT, the deep-sea neutrino telescope in the Mediterranean Sea[4], which we associate with a cosmic neutrino detection. We detect a muon with an estimated energy of 120^{+110}_{-60} petaelectronvolts (PeV). In light of its enormous energy and near-horizontal direction, the muon most probably originated from the interaction of a neutrino of even higher energy in the vicinity of the detector. The cosmic neutrino energy spectrum measured up to now[5–7] falls steeply with energy. However, the energy of this event is much larger than that of any neutrino detected so far. This suggests that the neutrino may have originated in a different cosmic accelerator than the lower-energy neutrinos, or this may be the first detection of a cosmogenic neutrino[8], resulting from the interactions of ultra-high-energy cosmic rays with background photons in the Universe.

Composizione chimica



All'energia del GeV

~ 79% protoni

~ 15% nuclei di elio

~ 5% nuclei più pesanti

~ 1% elettroni liberi

~ 10^{-5} 10^{-4} antiprotoni

- prodotti da sorgenti **galattiche** a bassa energia e da sorgenti **extragalattiche** ad altissima energia

- isotropi

ma esistono misure di tracce di anisotropia a livello di 10^{-3} al TeV

L'Intensità dei RC decresce con l'energia

Particelle cariche e nuclei atomici provenienti dallo spazio

$E < 10^{12} - 10^{14}$ eV

Osservazione diretta (es. Satelliti, Palloni aerostatici)

$E > 10^{12} - 10^{14}$ eV

Osservazione indiretta (sviluppo di sciami estesi in atmosfera)

EAS: extensive air showers

$E > 10^{15}$ eV

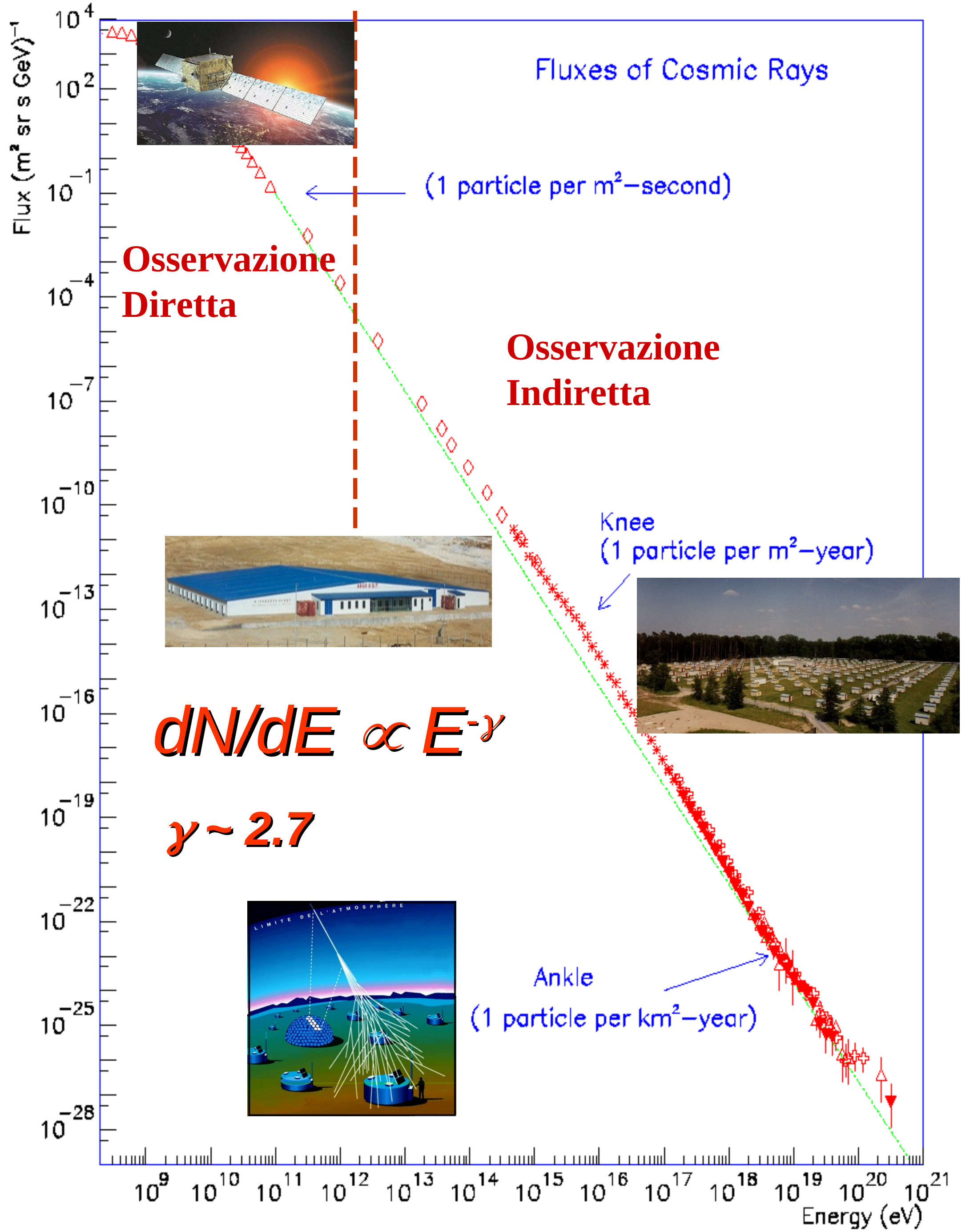
1 particella/m^2/anno

$E > 10^{18}$ eV

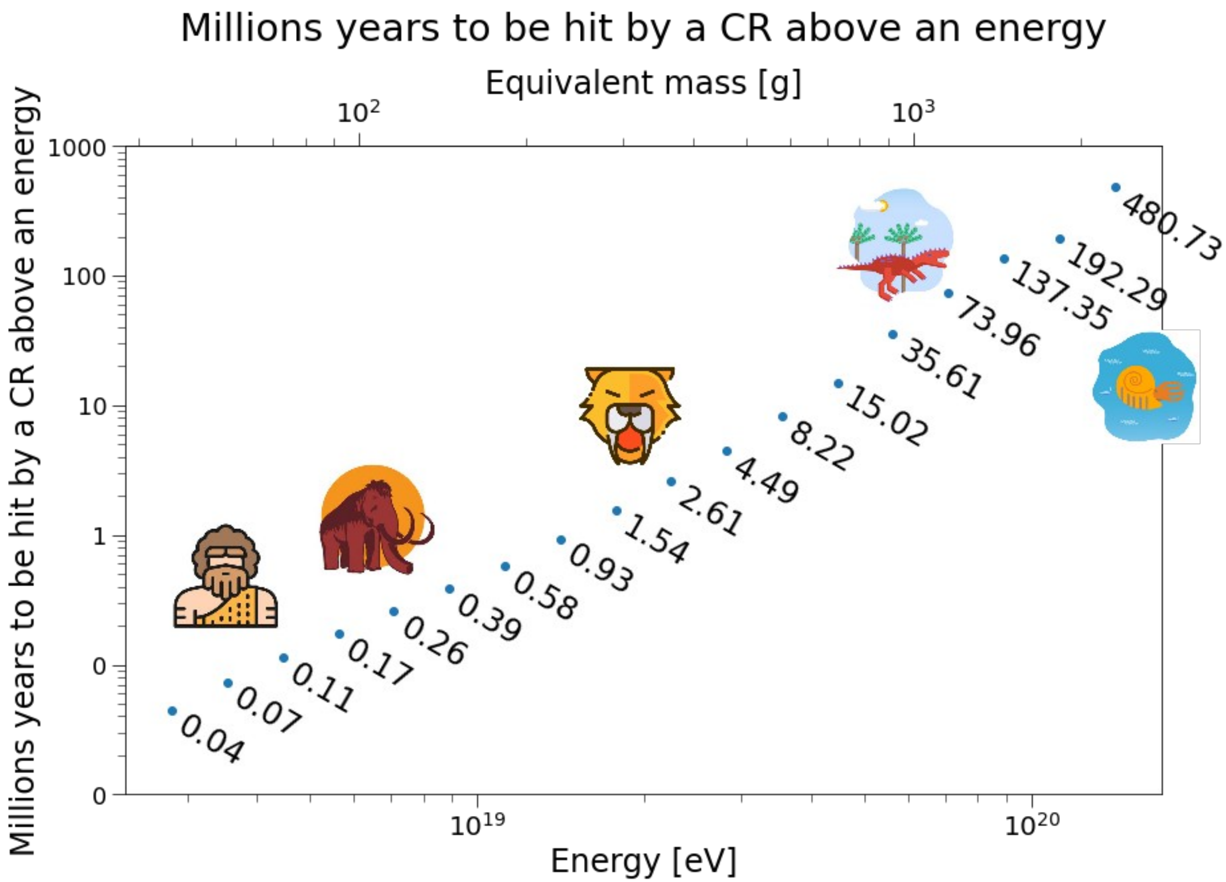
1 particella/km2/anno

$E > 10^{20}$ eV

1 particella/km2/secolo

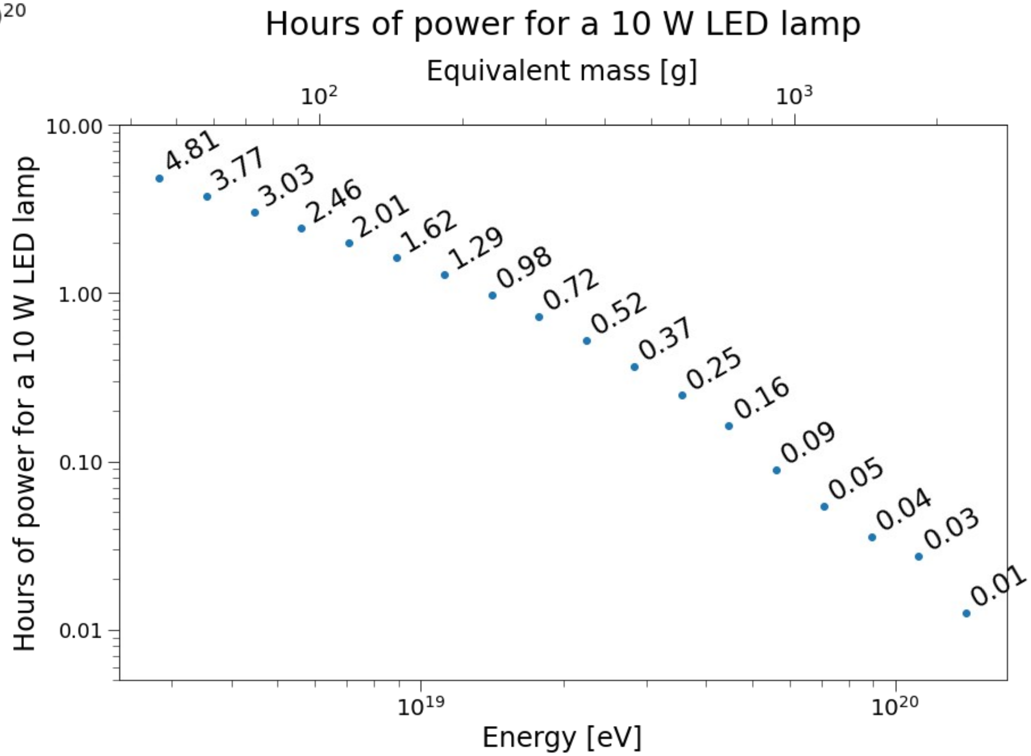


https://opendata.auger.org/



Tempo necessario per essere colpiti da un raggio cosmico

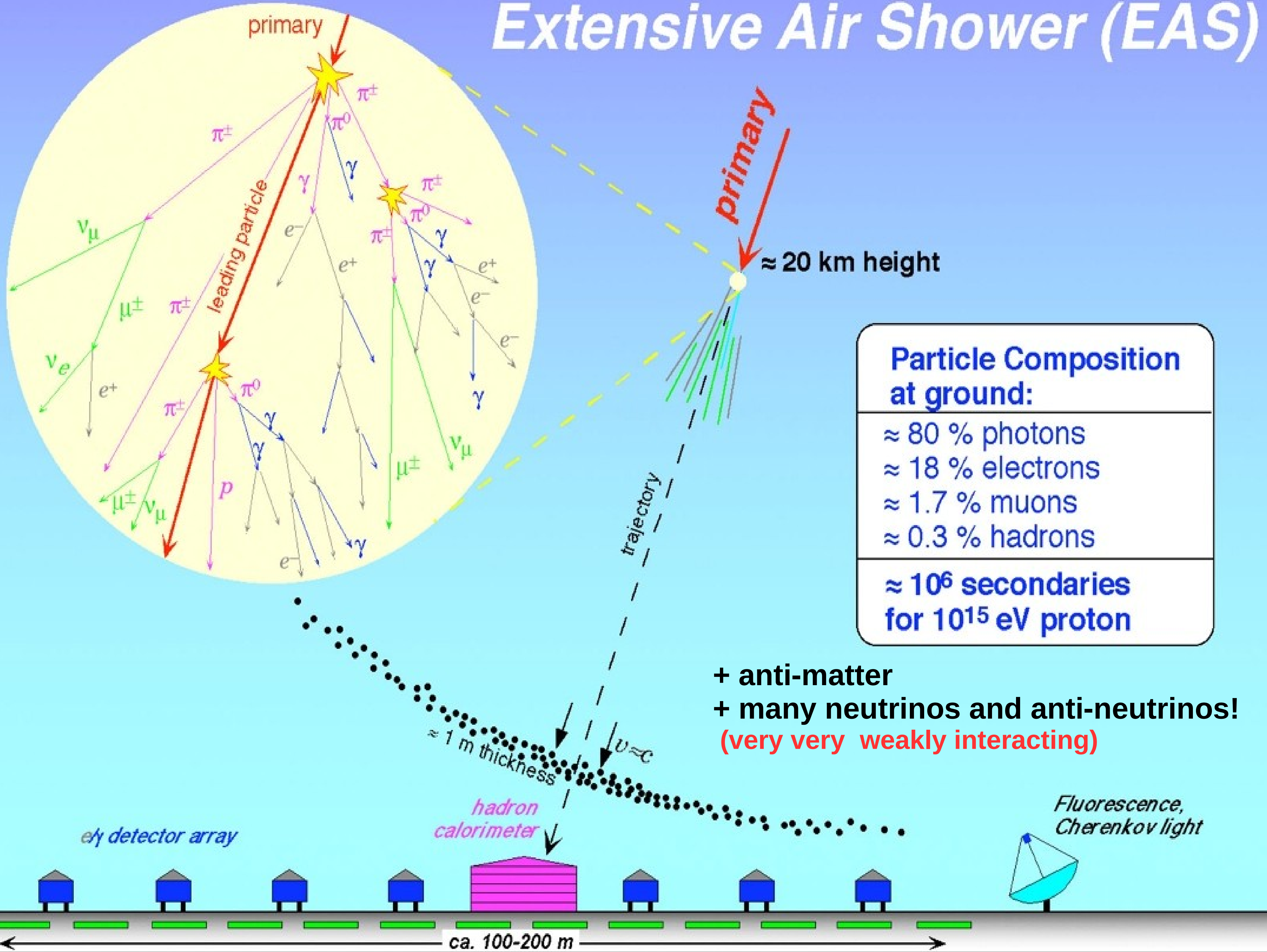
Centinaia di milioni di anni a 10^{20} eV!!



10^{20} eV → energia di una pallina da tennis servita a circa 100 km/h


Cosa fanno I raggi cosmici quando entranto nell’atmosfera terrestre?

Extensive Air Shower (EAS)



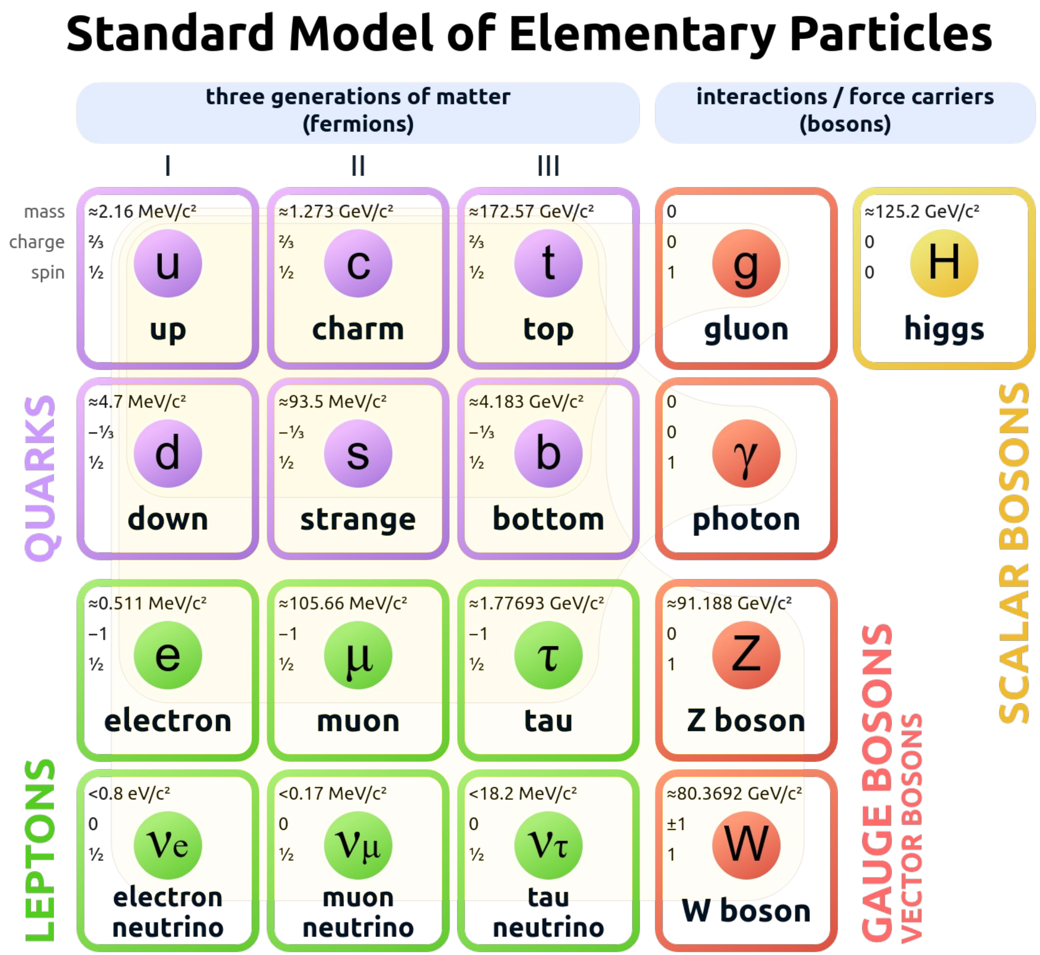
Particle Composition at ground:

≈ 80 % photons
≈ 18 % electrons
≈ 1.7 % muons
≈ 0.3 % hadrons

≈ 10^6 secondaries for 10^{15} eV proton

+ anti-matter
+ many neutrinos and anti-neutrinos!
(very very weakly interacting)

Secondary particles in the extensive air showers:
→ an insight in the mysterious world of subatomic particles



Particles in the shower:

→ matter, anti-matter and radiation

- electrons/positrons (leptons)

- photons

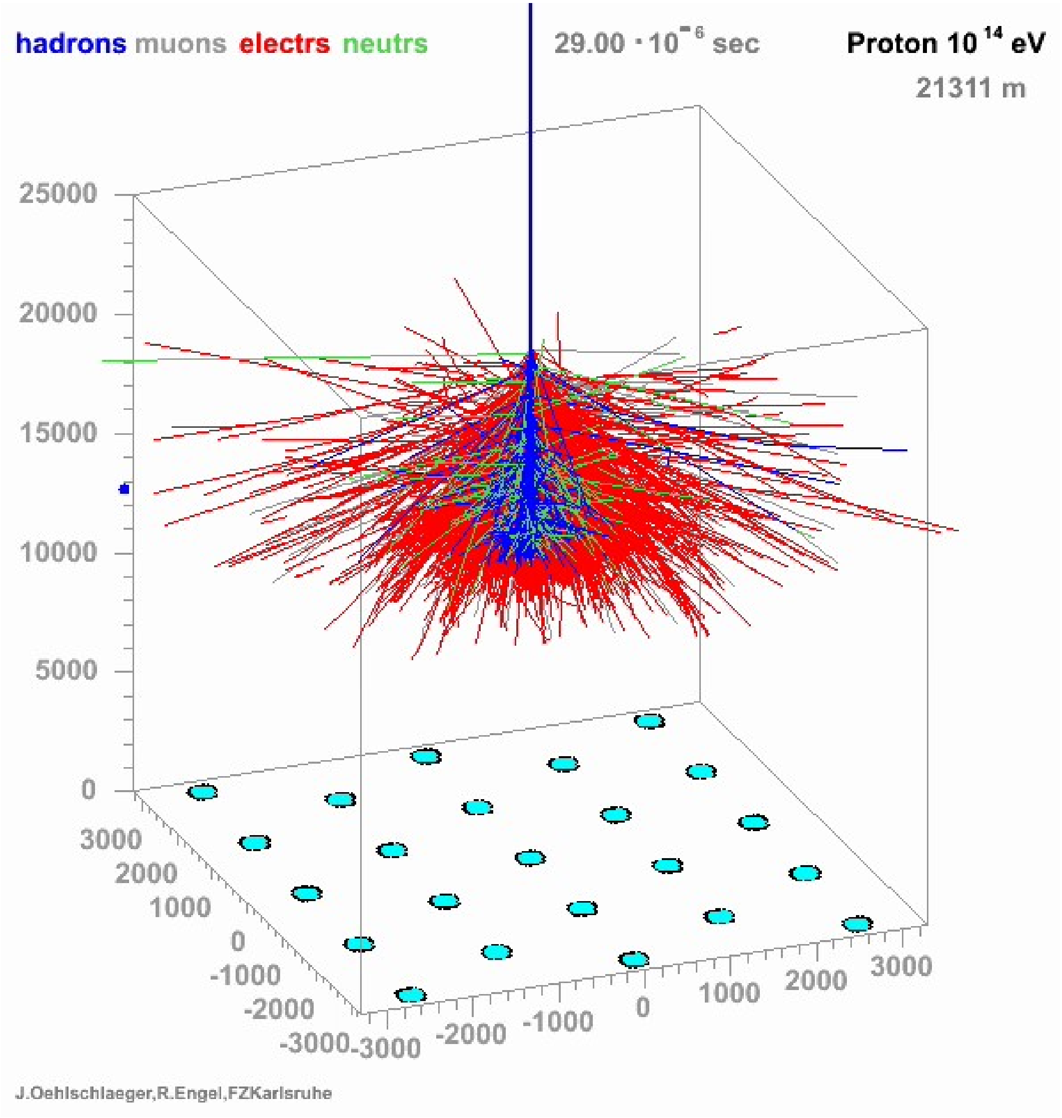
- hadrons

- positive/negative muons (leptons)

- neutrinos and anti-neutrinos weakly interacting, they may travel through the entire Earth

Proton → uud (three quarks)
Neutron → ddu (three quarks)

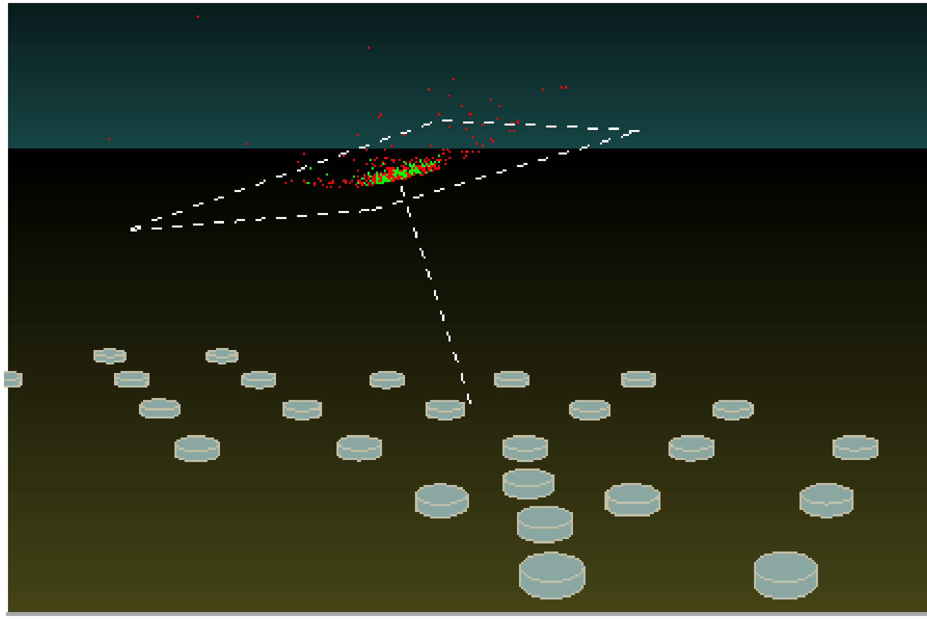
Raggi Cosmici “simulati”



Simulazioni Monte Carlo:

→ interazioni

→ rivelatore



L’Osservatorio Pierre Auger in Argentina

The Pierre Auger Observatory

500 members, 17 countries

Surface detector

an array of 1660 Cherenkov stations on a 1.5 km hexagonal grid (~ 3000 km²)

Fluorescence detector

4+1 buildings overlooking the array (24+3 telescopes)

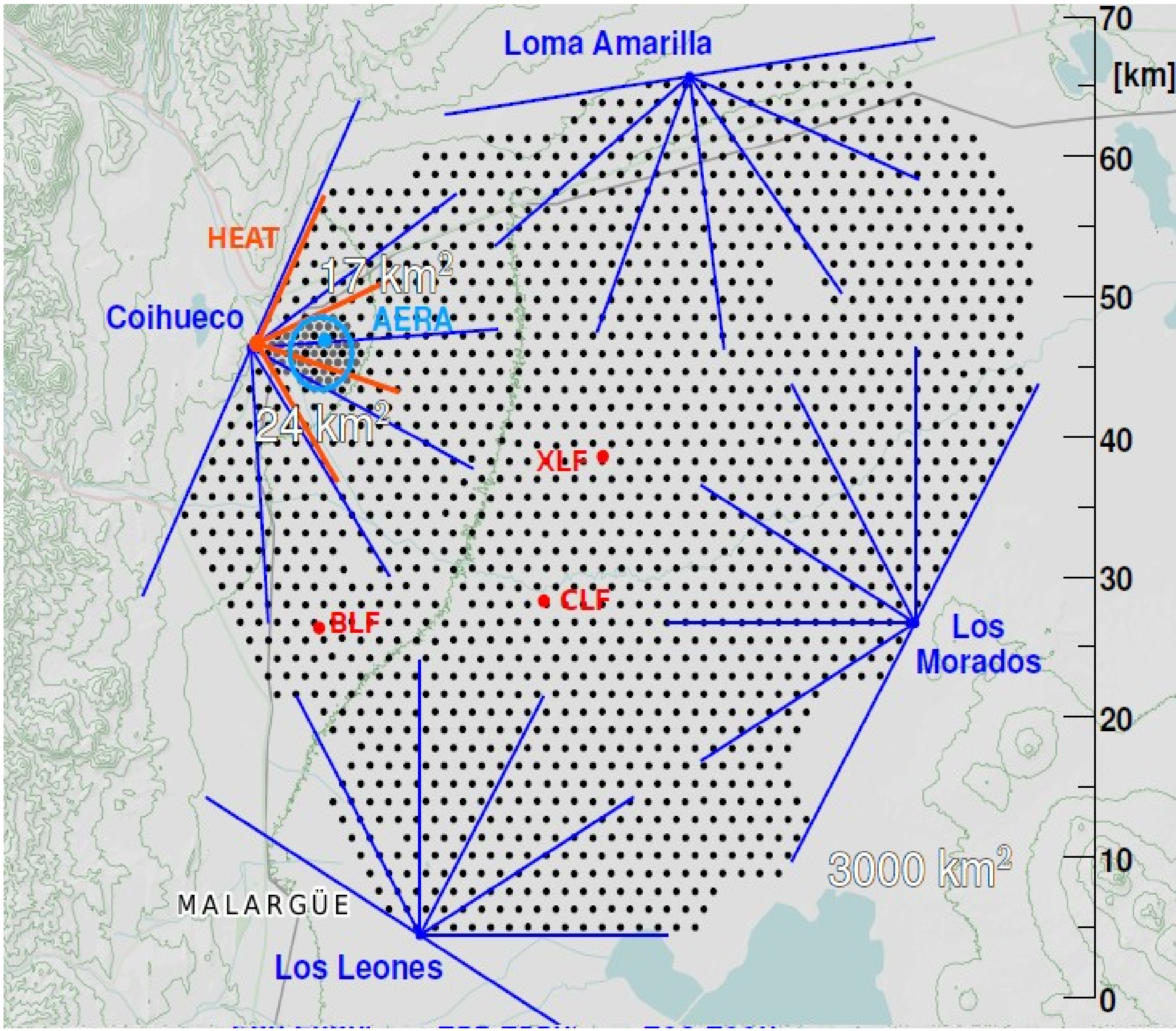
Radio detector

153 Radio Antenna → AERA

Low energy extensions

- Dense array (24km²) plus muon detectors → AMIGA
- 3 further high elevation FD telescopes → HEAT

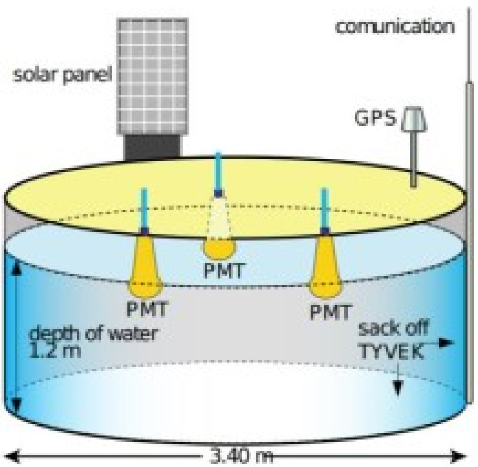
3000 km²



L’Osservatorio Pierre Auger nel Salento

L’Osservatorio Pierre Auger

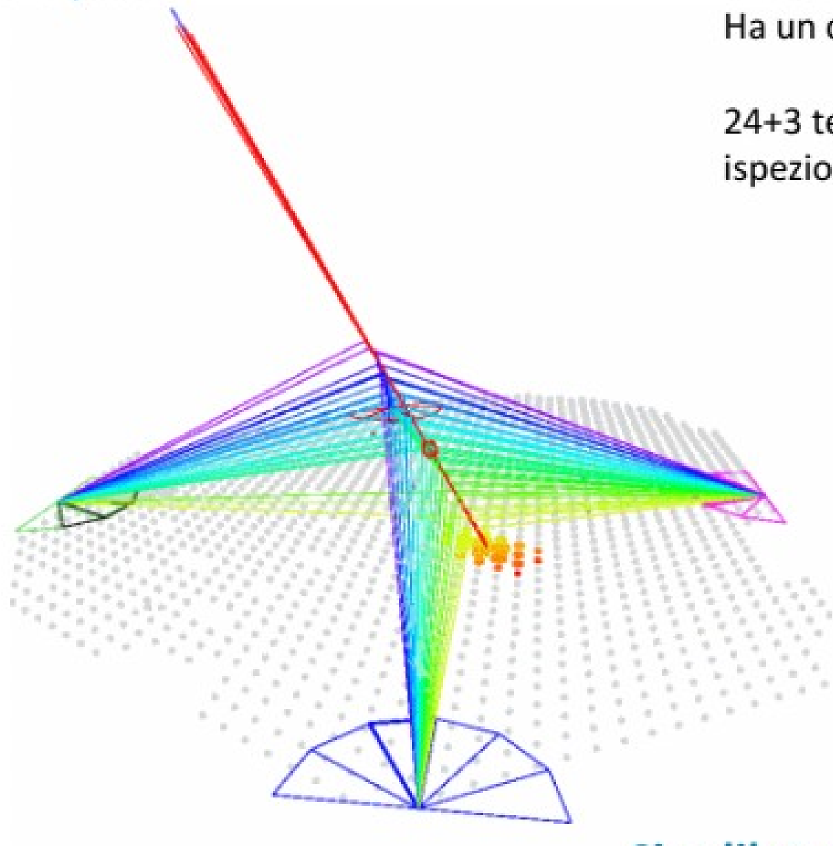
Situato in Argentina, provincia di Mendoza (1400 m s.l.m.)
Collaborazione di circa 500 membri da 18 paesi.



Detector di superficie (SD):

Array di 1660 detector Cherenkov disposti su una griglia esagonale ($\sim 3000\ \mathrm{km}^2$).

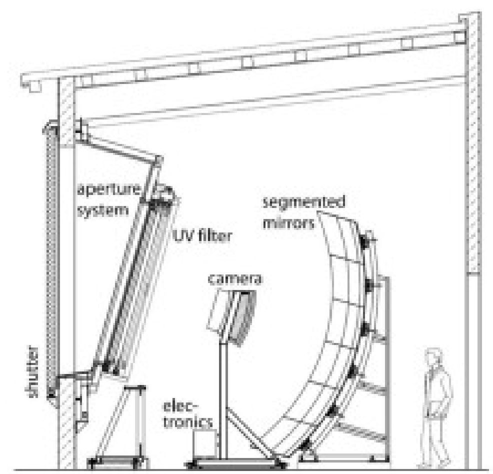
Ha un duty cycle del 100%.



Detector di fluorescenza (FD):

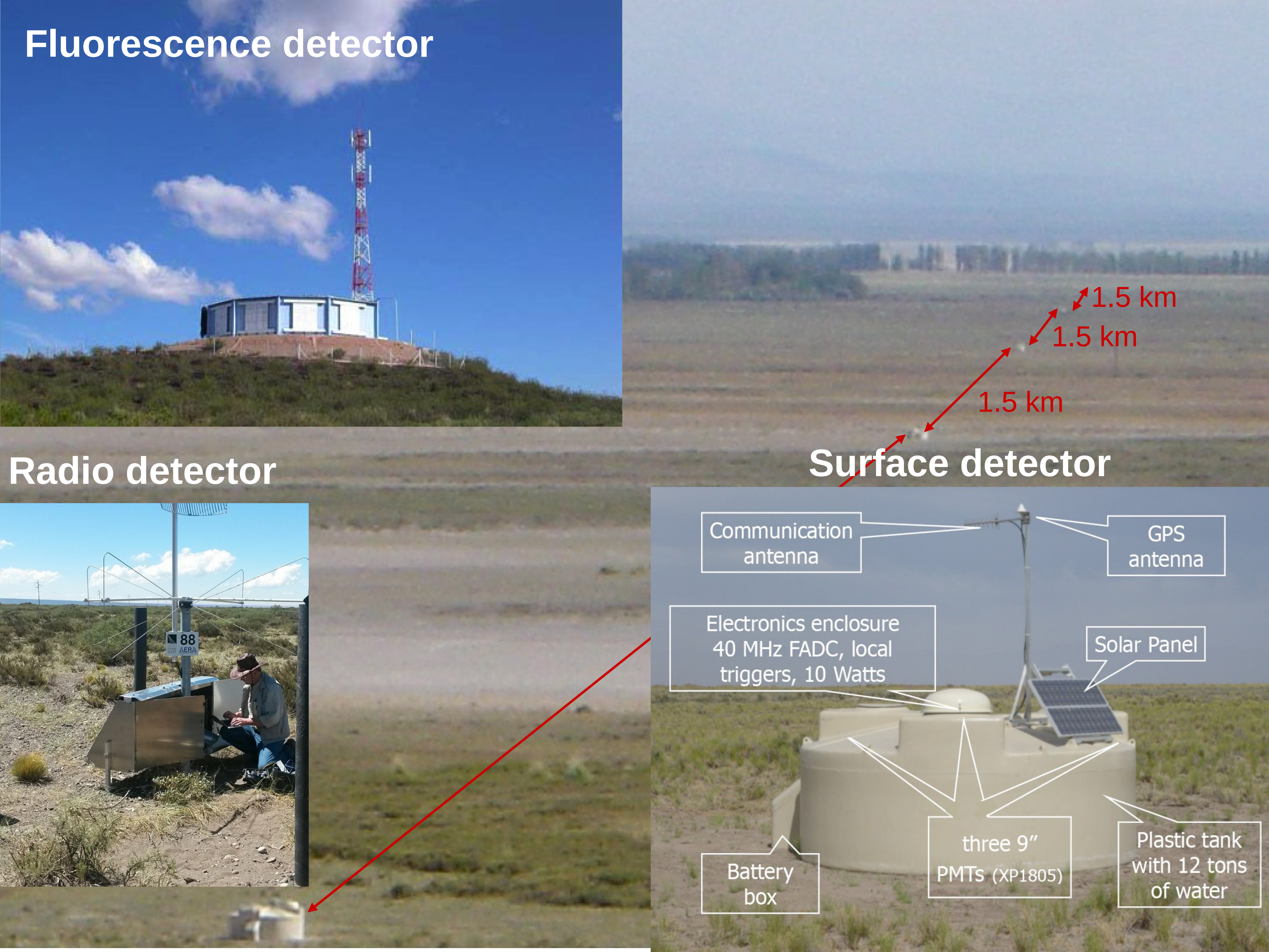
Offre misure dell’energia calorimetrica.
Ha un duty cycle di circa il 15%

24+3 telescopi alloggiati in 4+1 siti che ispezionano l’area sopra l’array.



Si calibrano le misure fatte tramite SD attraverso quelle fatte da FD.

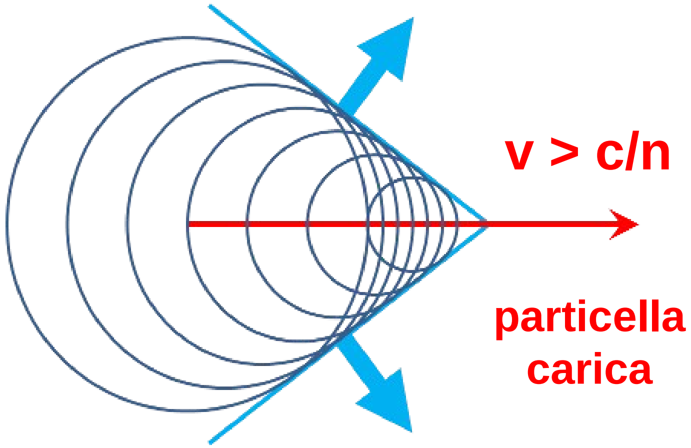
Un upgrade del detector è in fase di realizzazione per accrescere la performance nella misura della composizione chimica



Fluorescence detector
Radio detector
88
AERA
Surface detector
1.5 km
1.5 km
1.5 km
Communication antenna
GPS antenna
Electronics enclosure 40 MHz FADC, local triggers, 10 Watts
Solar Panel
three 9” PMTs (XP1805)
Plastic tank with 12 tons of water
Battery box

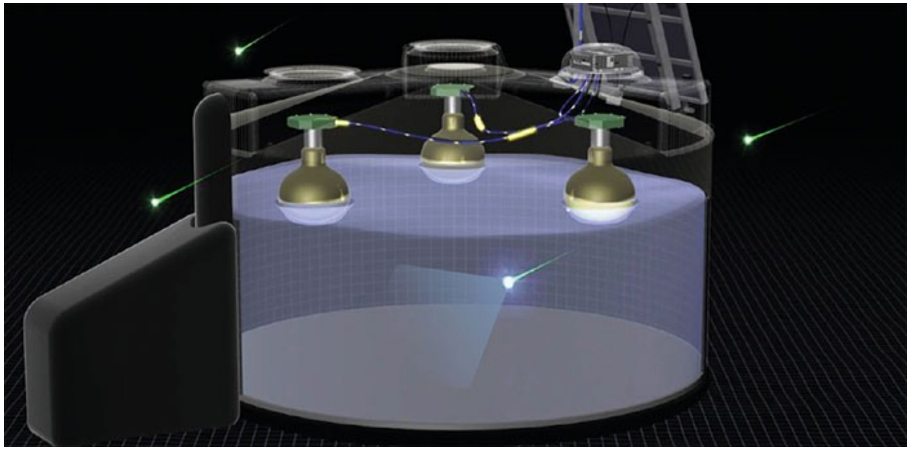
Non è sempre facile...

L’effetto Cherenkov

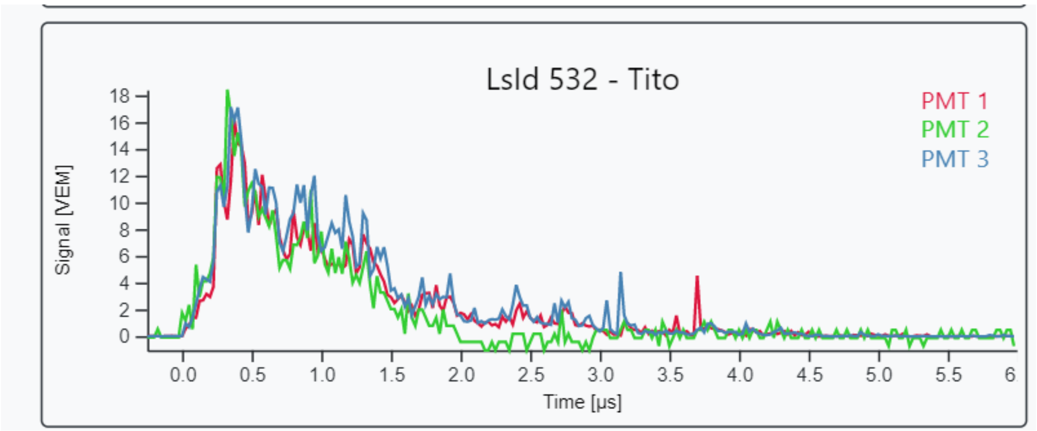


CONO LUCE CHERENKOV

Angolo in aria 1.4° in Acqua 41.2°

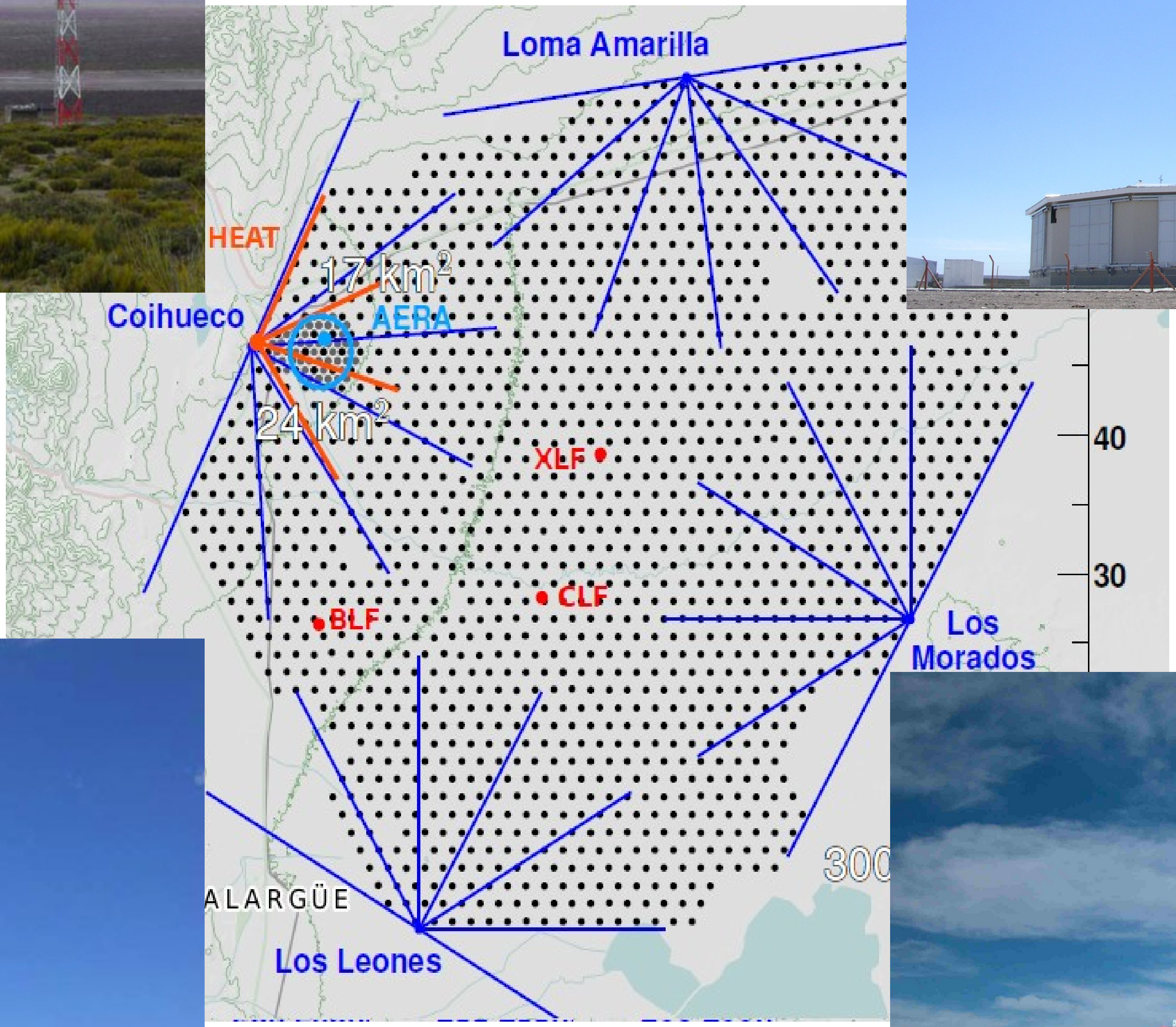


Stazione Cherenkov

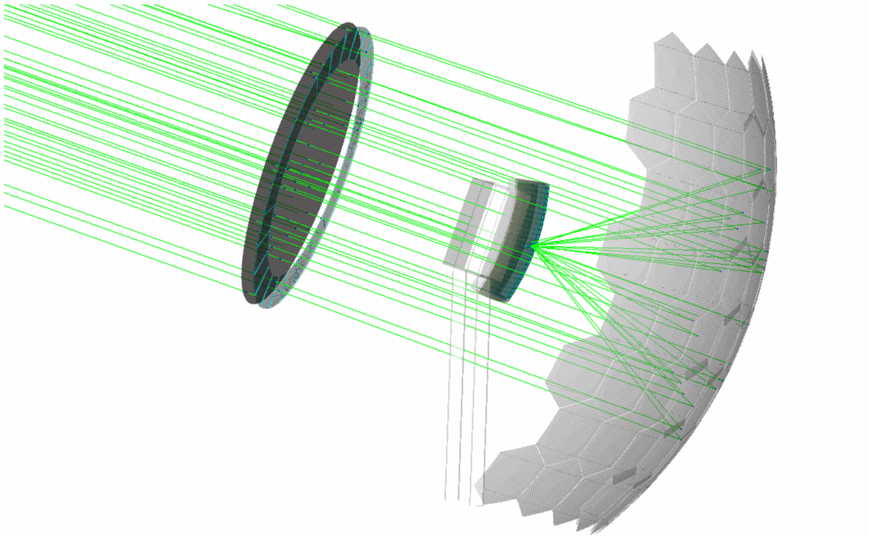


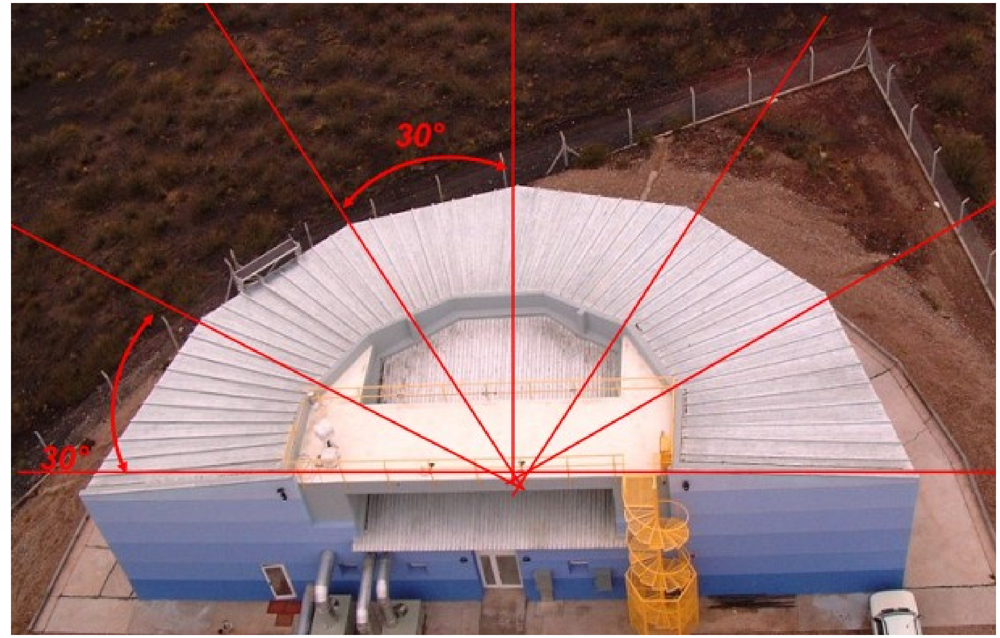
Segnale nei PMT

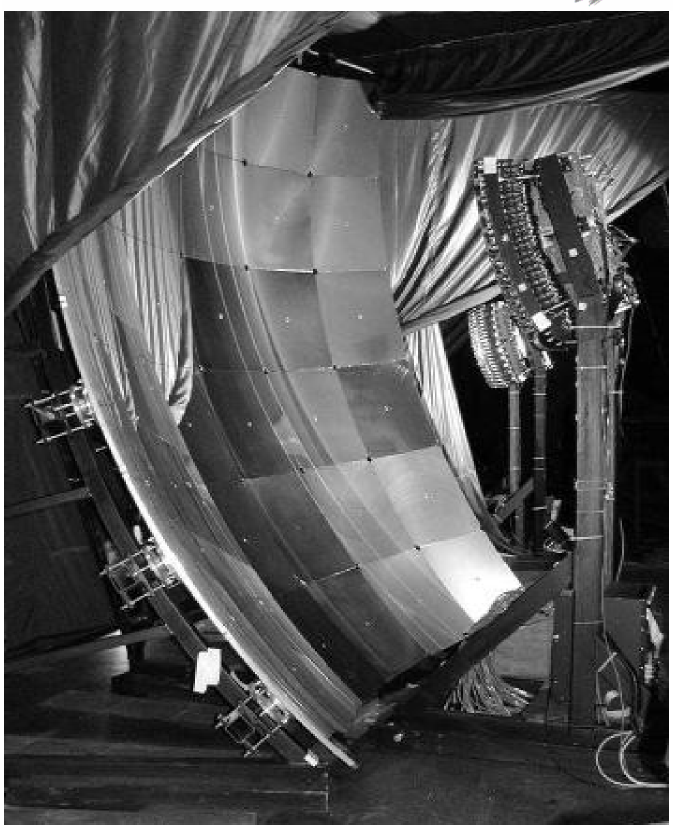
I rivelatori di fluorescenza (FD)

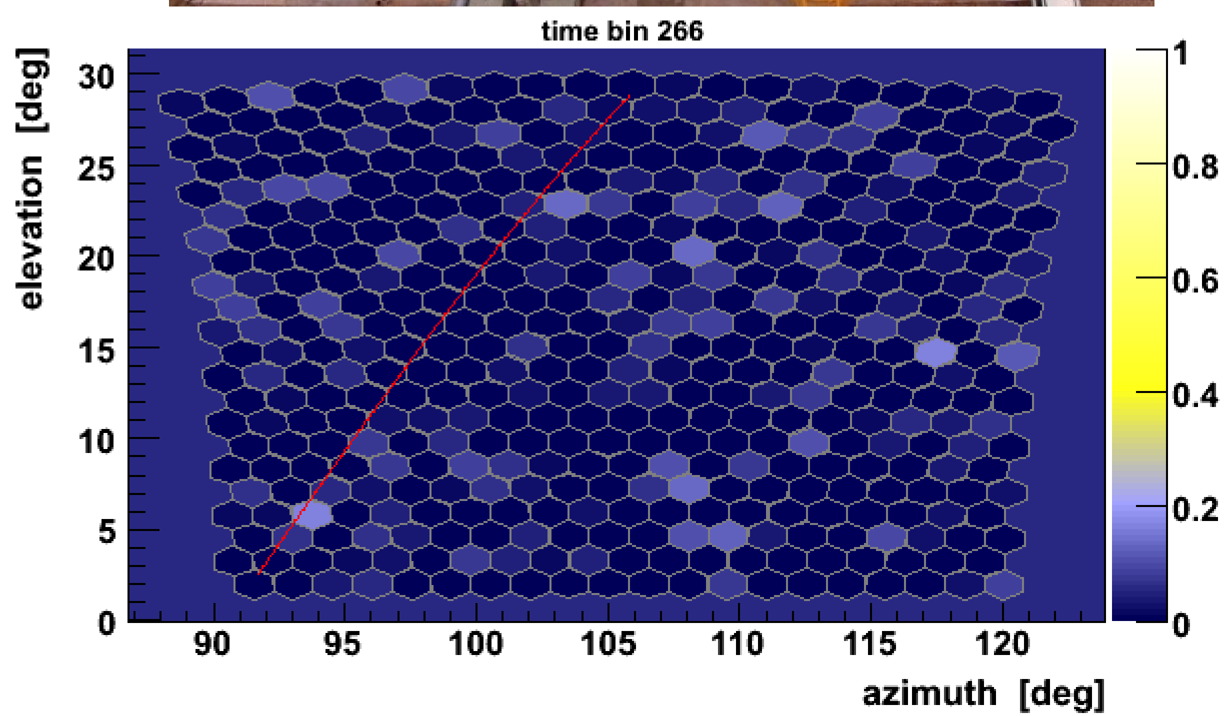


Il rivelatore di fluorescenza

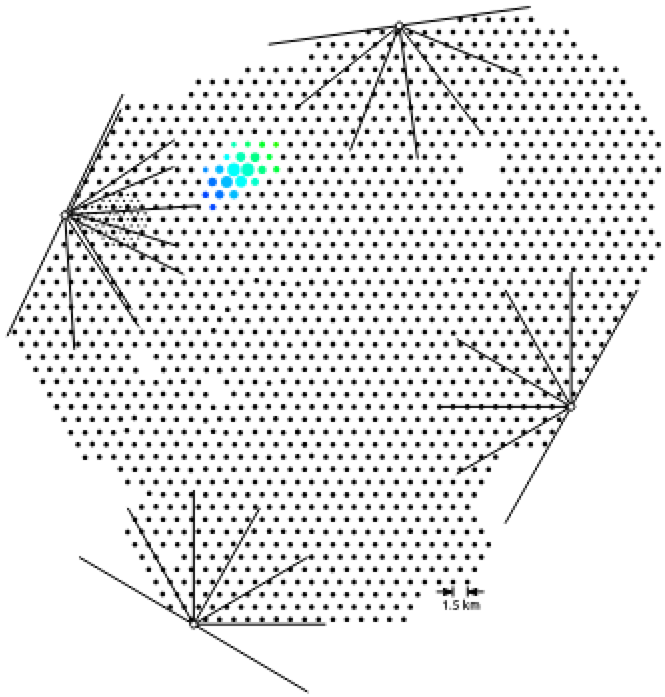


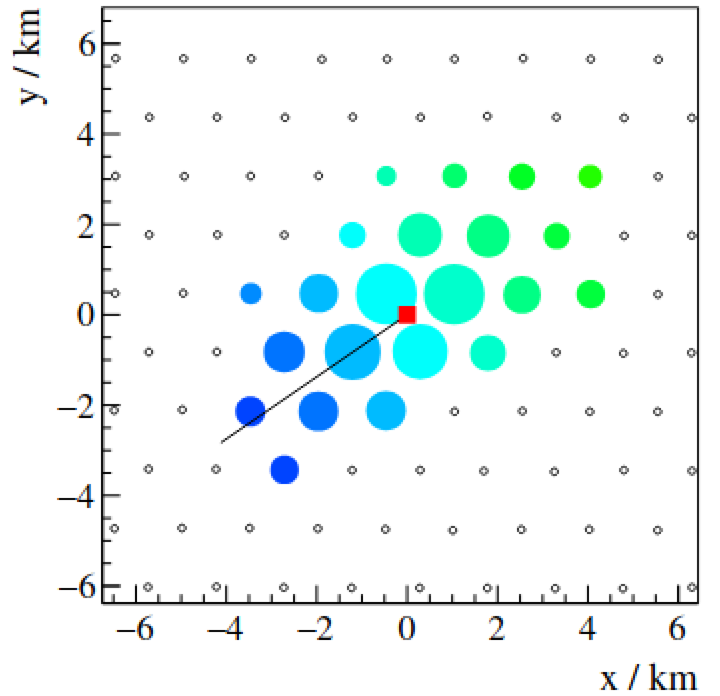


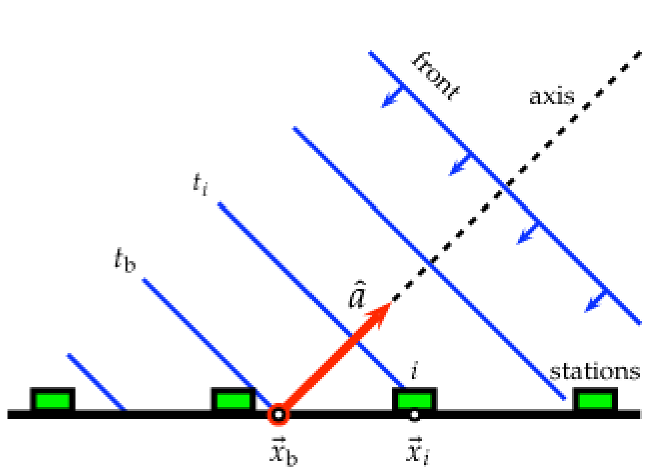


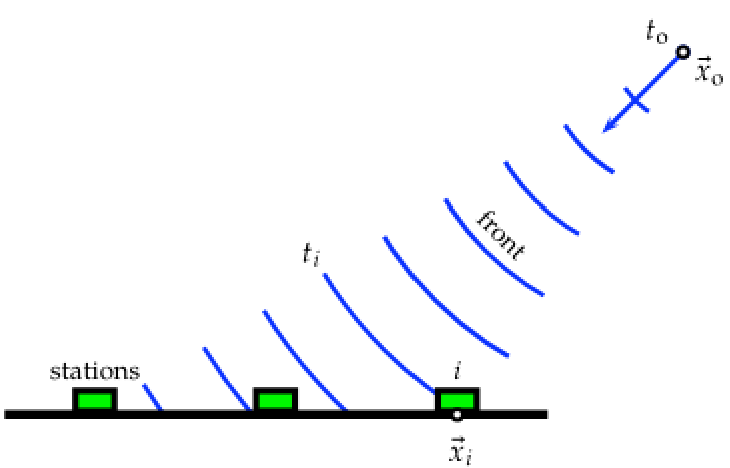


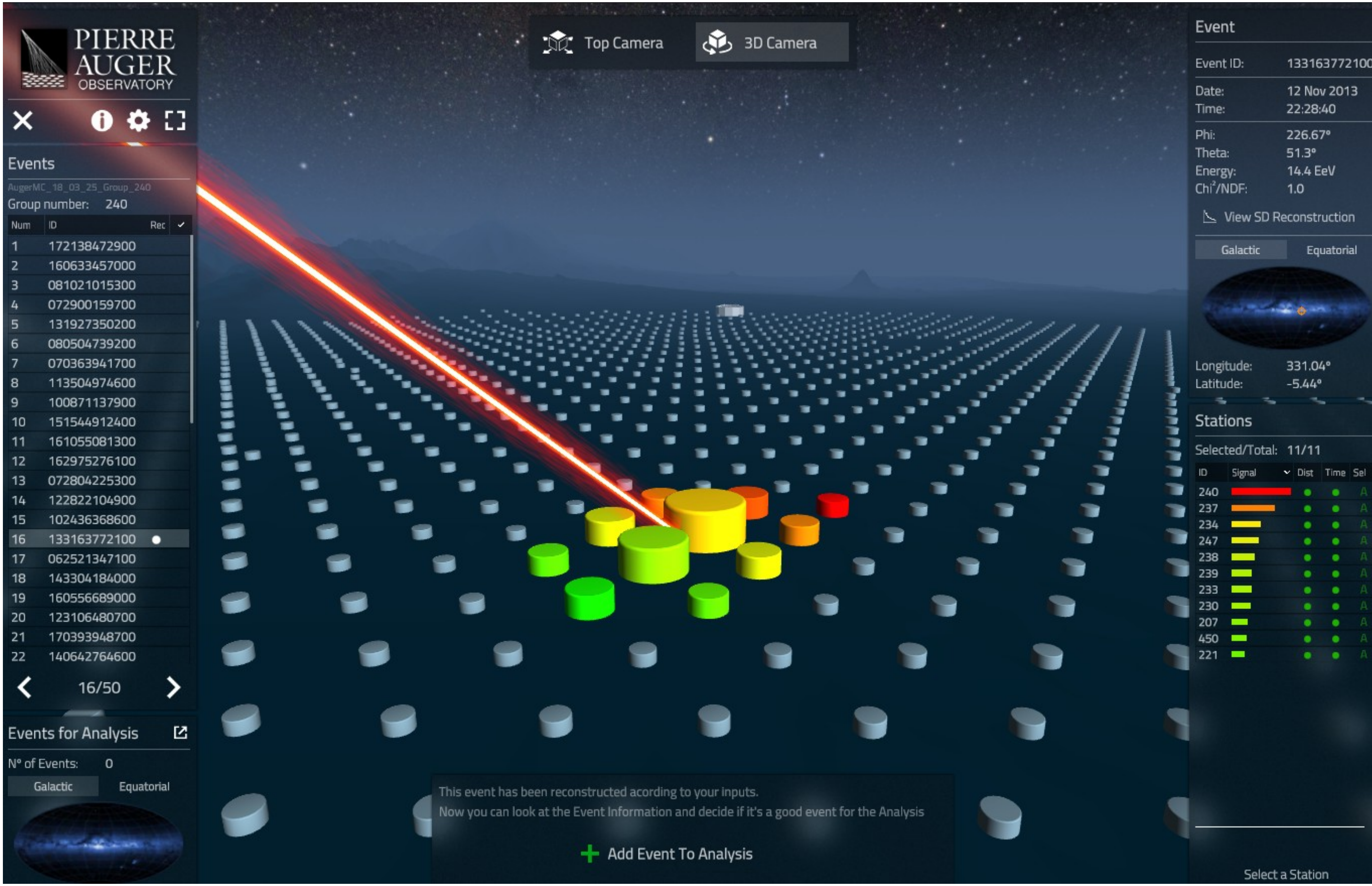
Ricostruzione nel rivelatore di superficie



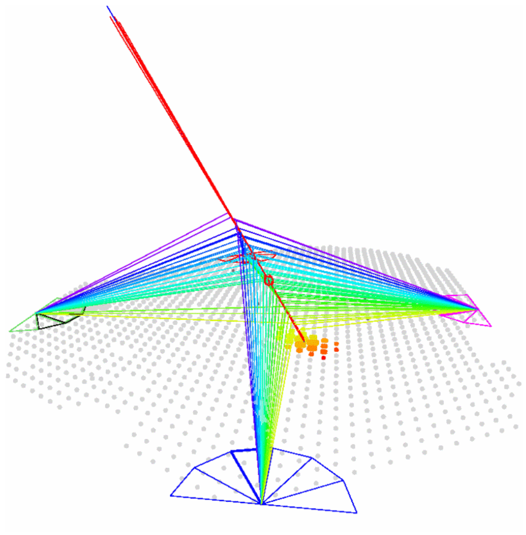


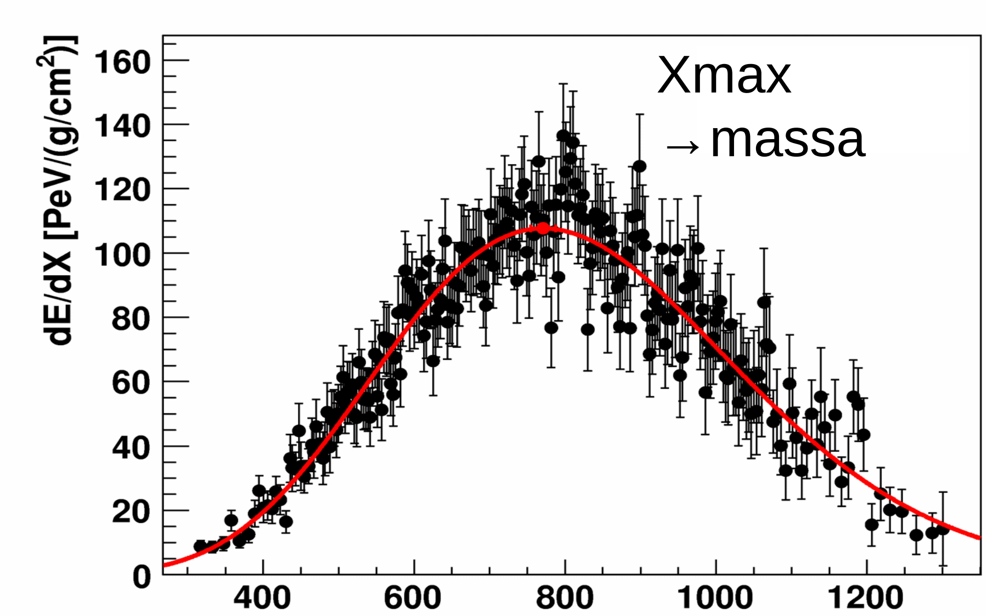




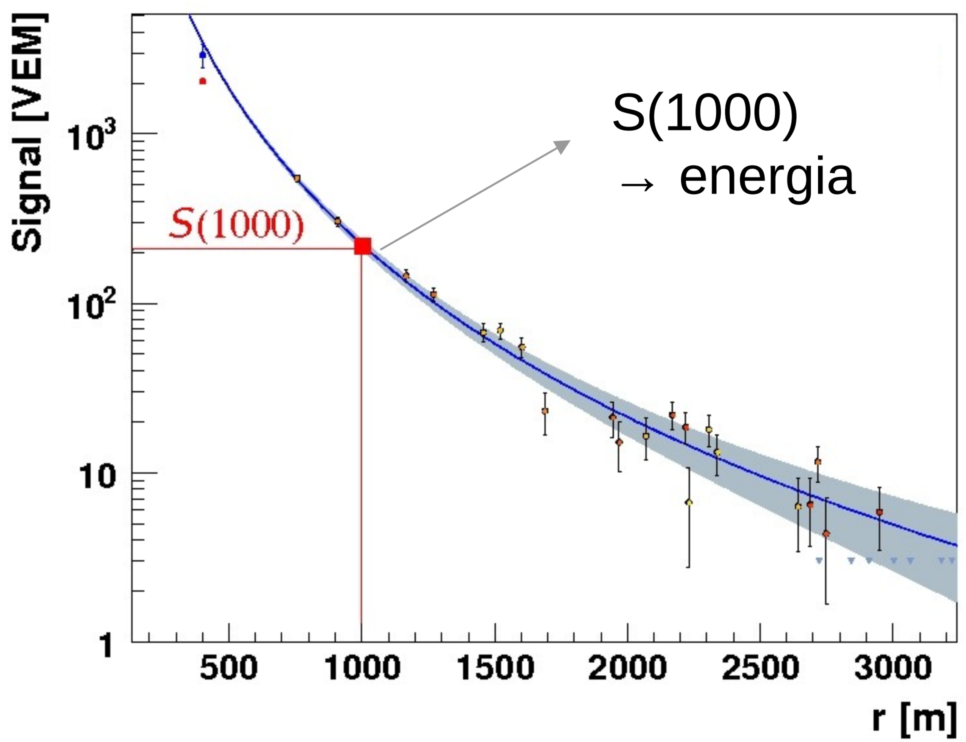

PIERRE AUGER OBSERVATORY
Top Camera
3D Camera
Events
AugerMC_18_03_25_Group_240
Group number: 240
Num ID Rec
1 172138472900
2 160633457000
3 081021015300
4 072900159700
5 131927350200
6 080504739200
7 070363941700
8 113504974600
9 100871137900
10 151544912400
11 161055081300
12 162975276100
13 072804225300
14 122822104900
15 102436368600
16 133163772100
17 062521347100
18 143304184000
19 160556689000
20 123106480700
21 170393948700
22 140642764600
16/50
Events for Analysis
Nº of Events: 0
Galactic
Equatorial
Event
Event ID: 133163772100
Date: 12 Nov 2013
Time: 22:28:40
Phi: 226.67°
Theta: 51.3°
Energy: 14.4 EeV
Chi²/NDF: 1.0
View SD Reconstruction
Galactic
Equatorial
Longitude: 331.04°
Latitude: -5.44°
Stations
Selected/Total: 11/11
ID Signal Dist Time Sel
240
237
234
247
238
239
233
230
207
450
221
Select a Station
This event has been reconstructed acording to your inputs.
Now you can look at the Event Information and decide if it's a good event for the Analysis
Add Event To Analysis

Il design ibrido





Profilo longitudinale
FD – misura calorimetrica
- duty cycle ~ 15%

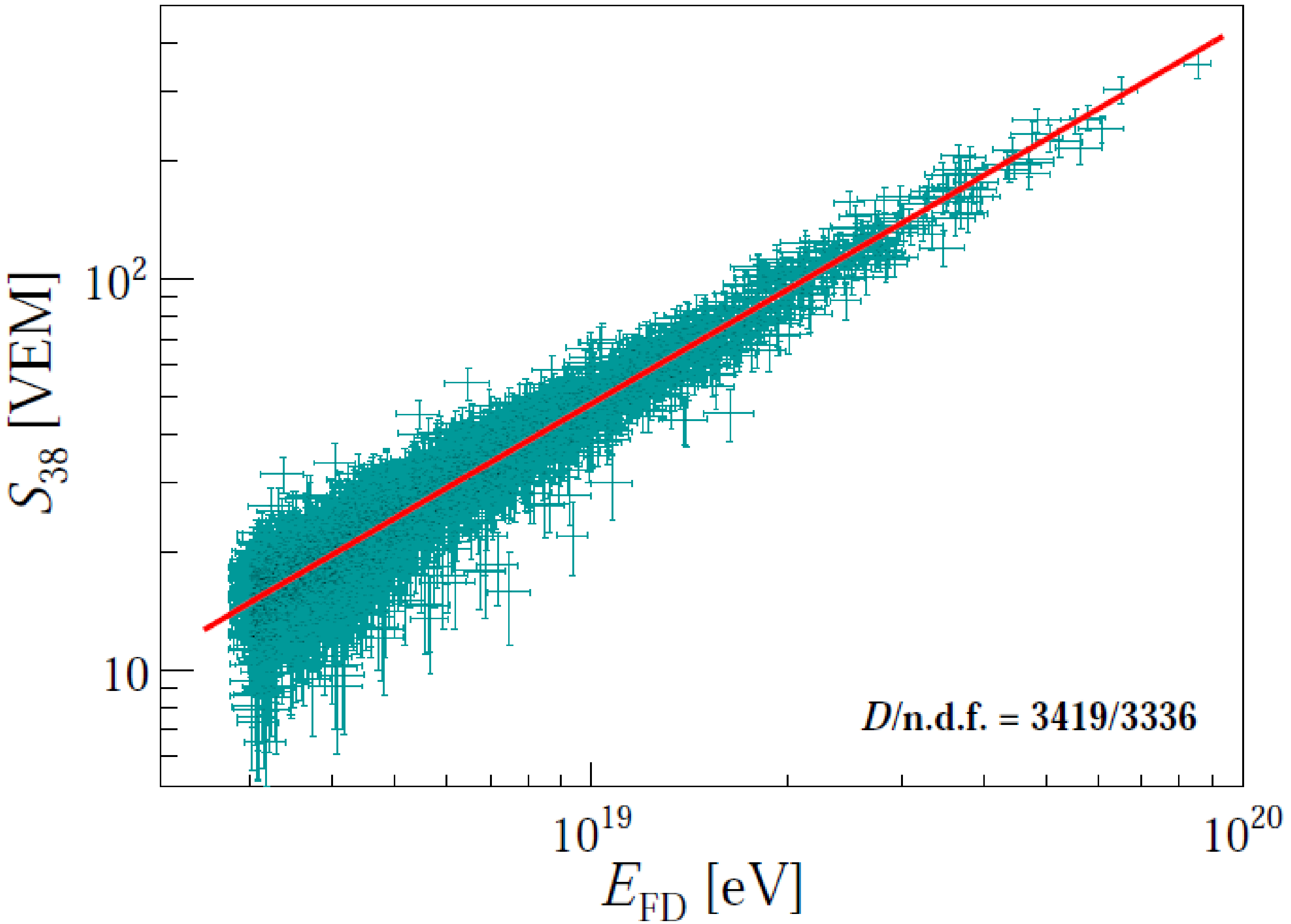


Densità di particelle a terra
SD - duty cycle ~ 100%

Usa la scala di energia dell'FD per calibrare l'intero data sample SD

Calibrazione degli eventi del rivelatore di superficie

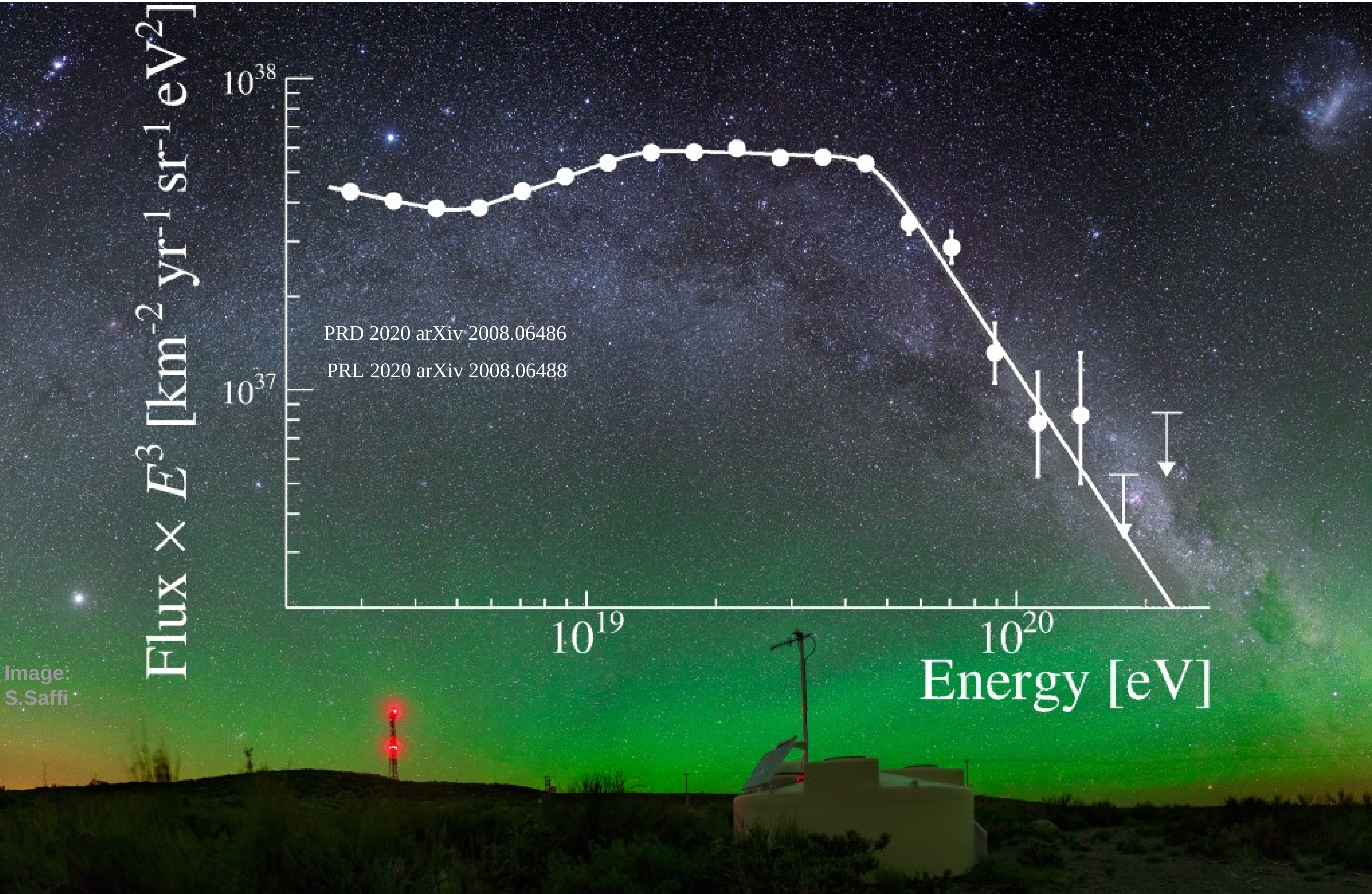
Auger Collaboration PRD 2020 arXiv 2008.06486



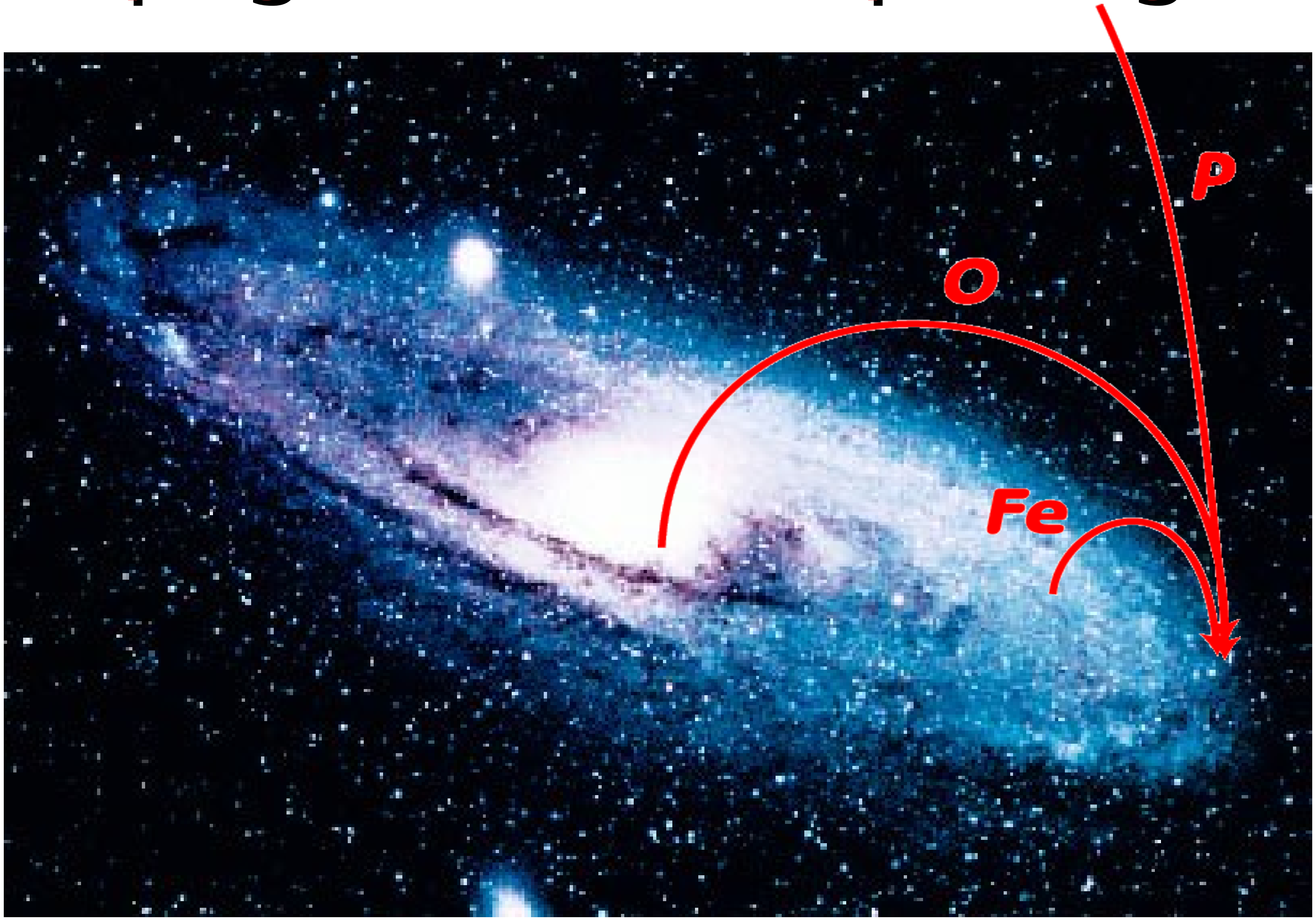
Utilizzare le misure molto precise di energia provenienti dal rivelatore di fluorescenza per calibrare I segnali del rivelatore di superficie

Massimizzando I benefici delle due tecniche !!

Lo spettro energetico



Propagazione: campi magnetici

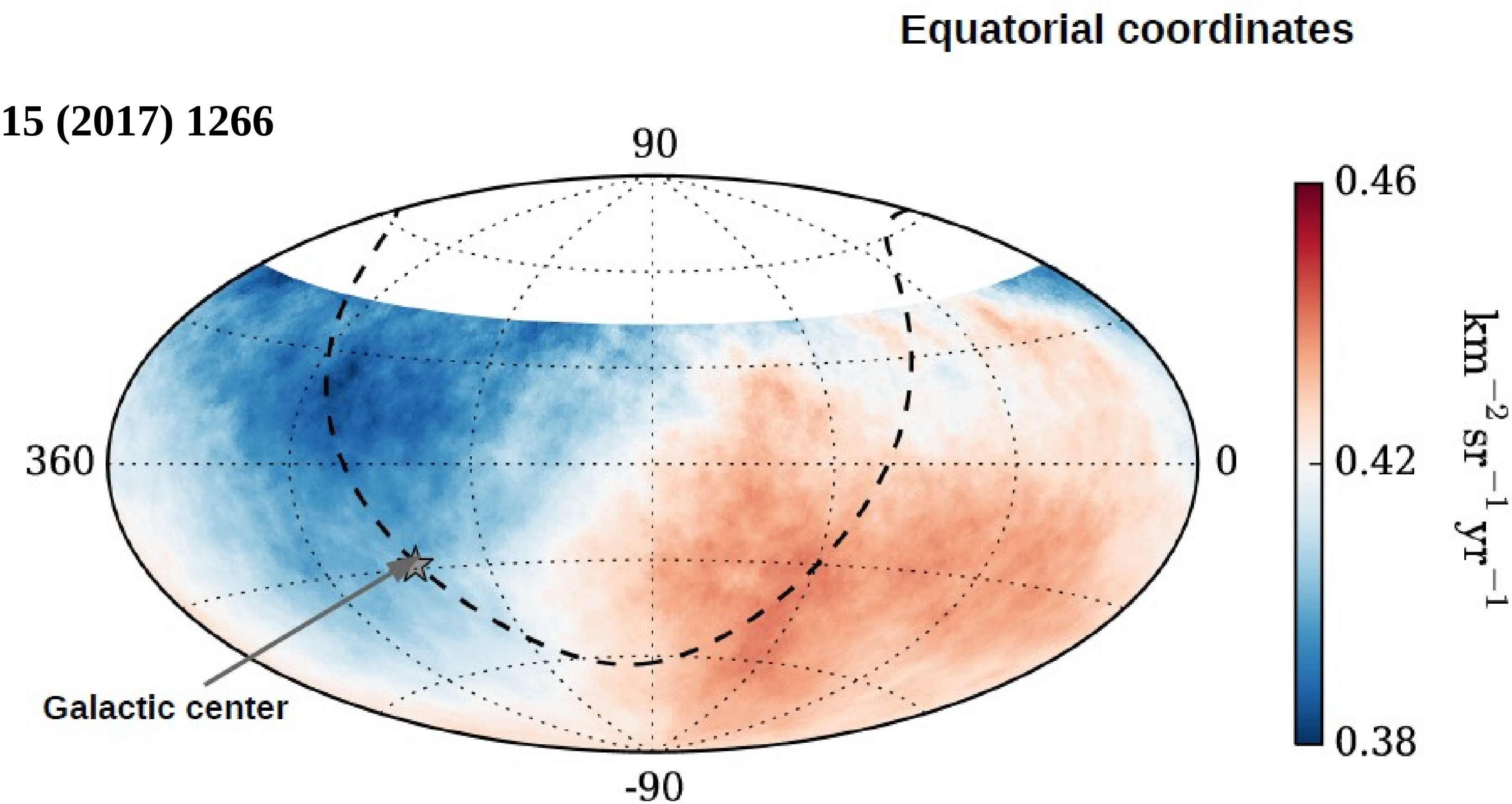


$\mathbf{E_{max}}/EeV \sim \mathbf{Z}\ (\mathbf{B}/\mu G)\ (\mathbf{R}/kpc)$

$\theta \sim \mathbf{Z} / \mathbf{E}$

Distribuzione delle direzioni di arrivo ad alte energie

Science 315 (2017) 1266



Rivelazione di una tangibile anisotropia

Altissima significatività statistica (> 5 sigma)

Origine extragalattica dei raggi cosmici ad alte energie

Uno sforzo comune:
astronomia a molti messaggeri (e molte collaborazioni!)

The Astrophysical Journal Letters, 850:L35 (18pp), 2017 December 1 https://doi.org/10.3847/2041-8213/aa9aed

OPEN ACCESS

CrossMark

Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration,
and LIGO Scientific Collaboration and Virgo Collaboration
(See the end matter for the full list of authors.)

Received 2017 October 15; revised 2017 November 9; accepted 2017 November 10; published 2017 November 29

Abstract

The Advanced LIGO and Advanced Virgo observatories recently discovered gravitational waves from a binary neutron star inspiral. A short gamma-ray burst (GRB) that followed the merger of this binary was also recorded by the *Fermi* Gamma-ray Burst Monitor (*Fermi*-GBM), and the Anti-Coincidence Shield for the Spectrometer for the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*), indicating particle acceleration by the source. The precise location of the event was determined by optical detections of emission following the merger. We searched for high-energy neutrinos from the merger in the GeV–EeV energy range using the ANTARES, IceCube, and Pierre Auger Observatories. No neutrinos directionally coincident with the source were detected within ±500 s around the merger time. Additionally, no MeV neutrino bu
further carried out an extended search in the direction of t
period following the merger, but found no evidence of
mechanisms in relativistic outflows driven by the binary ne
model predictions of short GRBs observed at a large off-a

ALLARMI

Osservazione con tutti i rivelatori

- a diverse frequenze

- in diverse finestre temporali

The Astrophysical Journal Letters, 850:L35 (18pp), 2017 December 1 Albert et al.

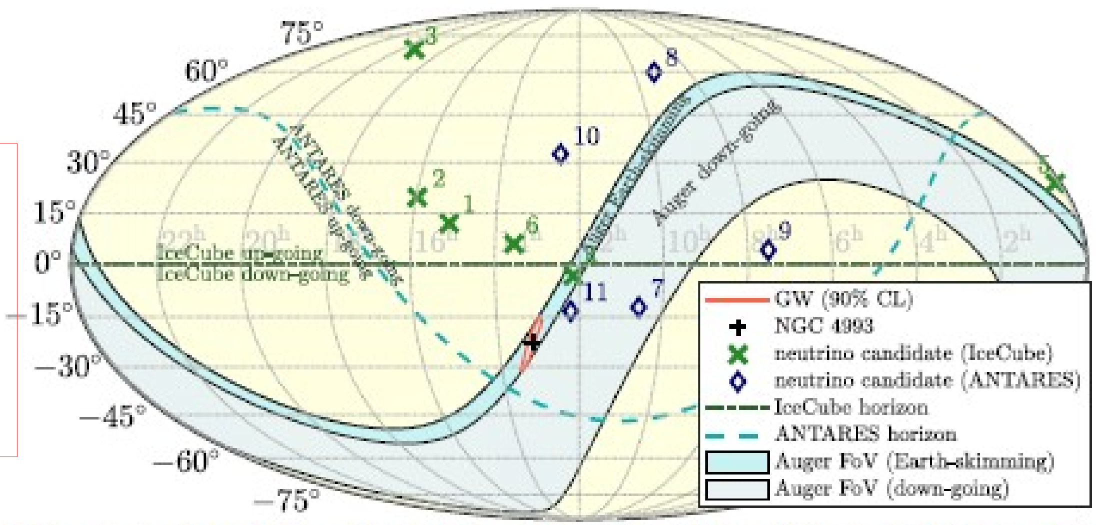
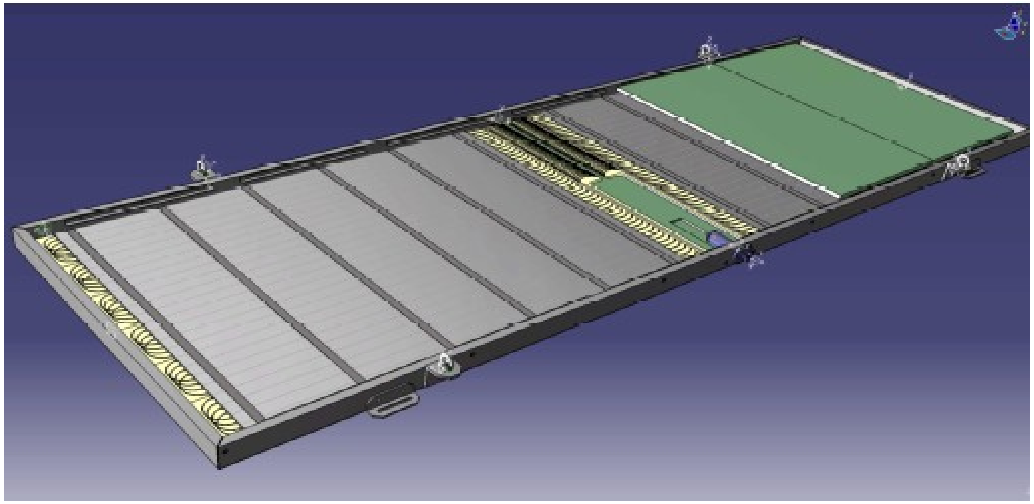


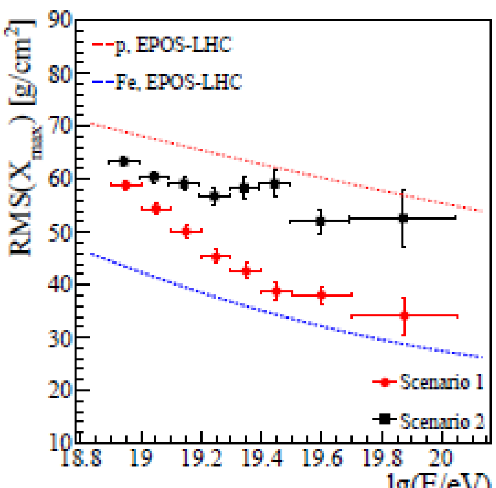
Figure 1. Localizations and sensitive sky areas at the time of the GW event in equatorial coordinates: GW 90% credible-level localization (red contour; Abbott et al. 2017b), direction of NGC 4993 (black plus symbol; Coulter et al. 2017b), directions of IceCube's and ANTARES's neutrino candidates within 500 s of the merger (green crosses and blue diamonds, respectively), ANTARES's horizon separating down-going (north of horizon) and up-going (south of horizon) neutrino directions (dashed blue line), and Auger's fields of view for Earth-skimming (darker blue) and down-going (lighter blue) directions. IceCube's up-going and down-going directions are on the northern and southern hemispheres, respectively. The zenith angle of the source at the detection time of the merger was 73°.8 for ANTARES, 66°.6 for IceCube, and 91°.9 for Auger.

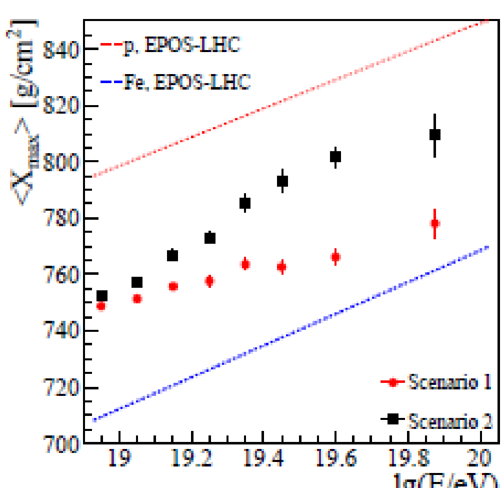
AugerPrime

Scintillatori di area 3.8 m^2 (1 cm spessore) sopra ogni stazione dell'array di superficie



Scintillatori sensibili alla componente elettromagnetica dello sciame





Scenario 1 : massima rigidità

Scenario 2: photo-disintegrazione

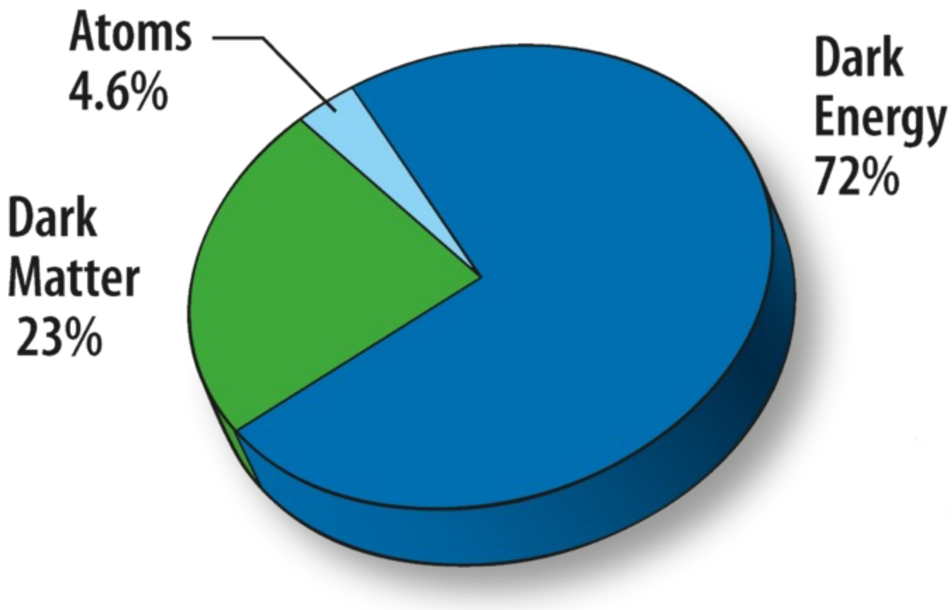
In più
- elettronica veloce
- estensione del range dinamico
- cross check con i rivelatori di muoni sotto terra

“Take home message”

Fisica dei raggi cosmici naturalmente interdisciplinare (astrofisica, astronomia, fisica delle particelle elementari).

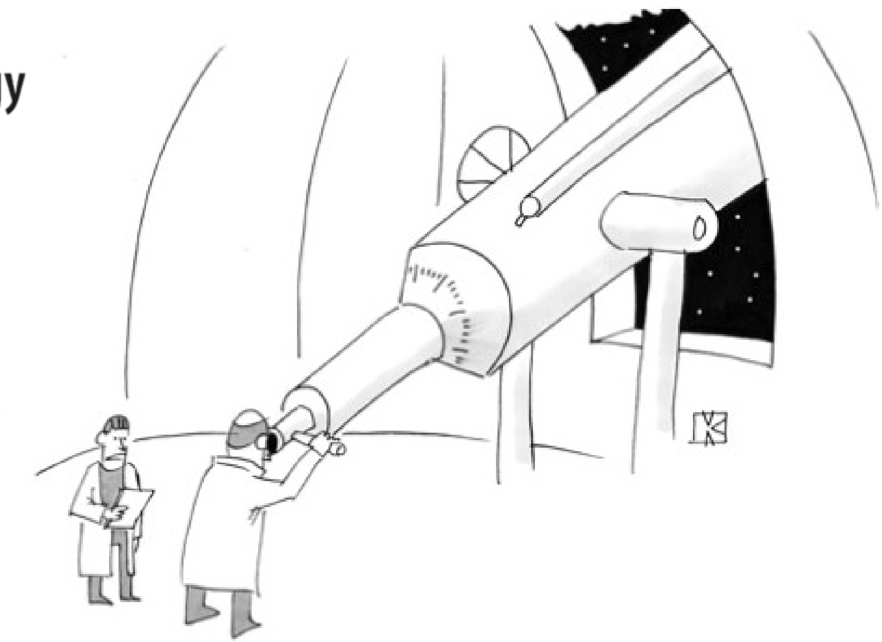
Molti problemi ancora aperti:

- **Origine e meccanismi di produzione** non completamente svelati
- **Composizione chimica** alle energie estreme ancora controversa



Il mondo a noi accessibile

E' SOLO IL 5%!!



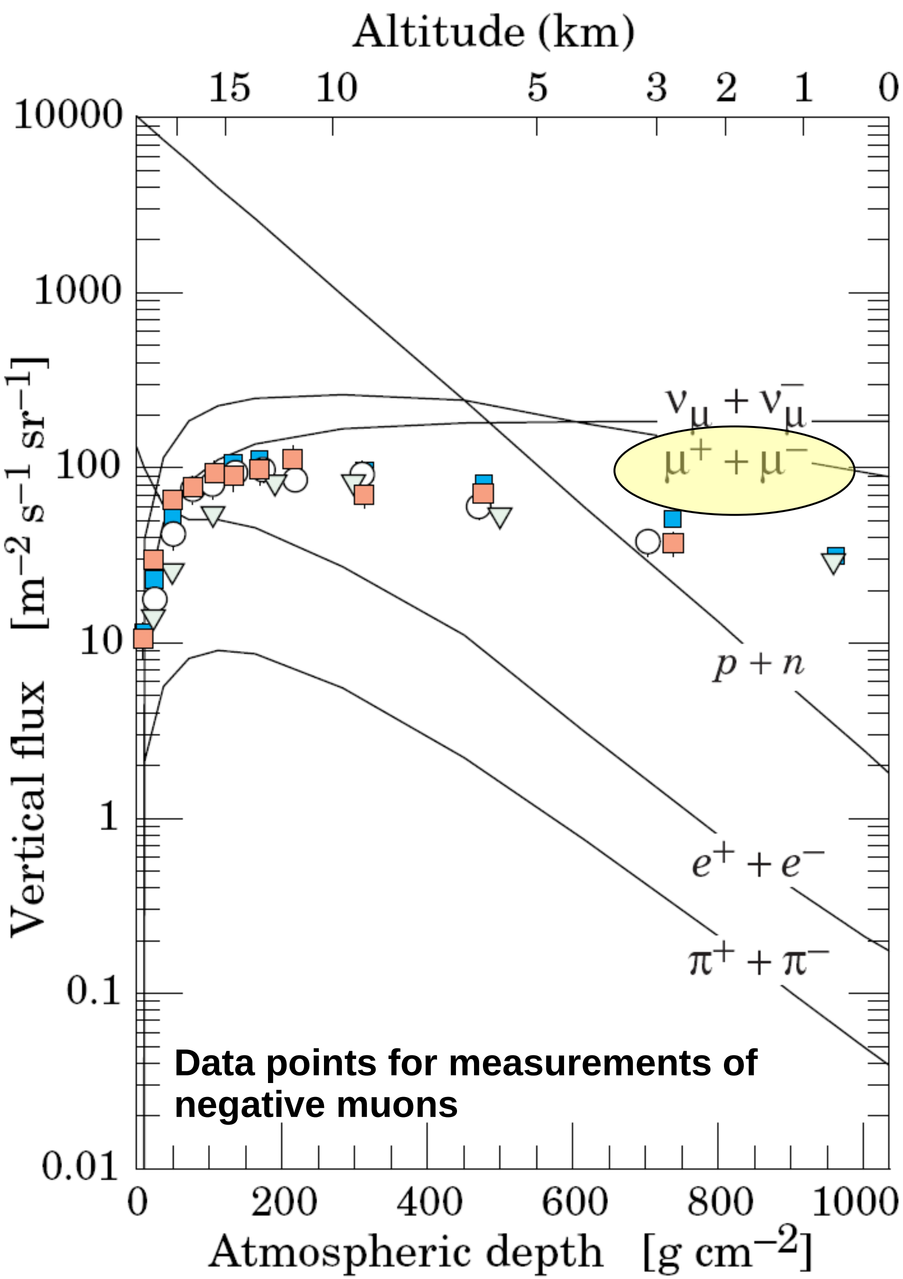
“ That isn't dark matter, sir - You just forgot to take off the lens cap.”

…eventually a bright future

[Tom Gauld, Department of mind-blowing theories, Canongate Books, 2020]

https://youtu.be/dcNxkiz_hec

Raggi cosmici nell'atmosfera



Flusso verticale dei raggi cosmici nell'atmosfera con E > 1 GeV

I muoni dominano il flusso dei raggi cosmici al livello del mare

~ 1-2 muoni/cm²/min

Sono prodotti a circa 15 km di quota

L'energia media a terra è circa 4 GeV

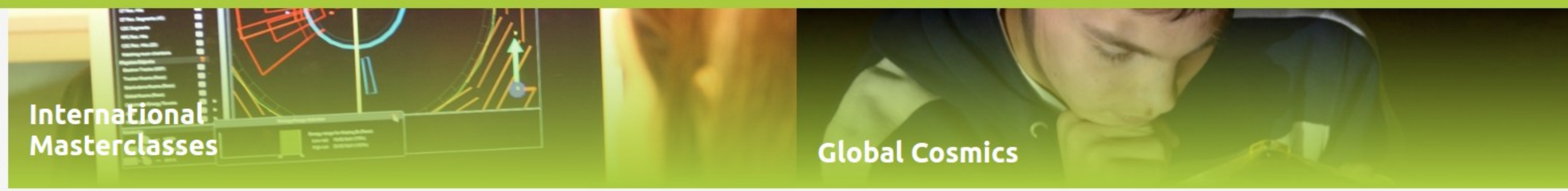
La distribuzione angolare è proporzionale a **$\cos^2\theta$**

….e ovviamente una valanga di neutrini e anti neutrini (difficilissimi da osservare, interagiscono pochissimo con la materia)

The IPPOG Collaboration: htpps://ippog.org

About Resources Activities News Events

Activities



Projects and competitions

International

- Girls, do Physics! 11/02/2019 - 08/03/2019
- Particles 4U 21/11/2017 - 21/02/2018

National

- Creating Ambassadors for Science in Society 18/06/2018 - 21/06/2021
- Music Festival Pohoda in Slovakia 11/07/2019 - 13/07/2019
- Music Festival Colours of Ostrava in Czech Republic 17/07/2019 - 20/07/2019
- Universal Science Festival 05/08/2020

ABOUT

Organisational Structure

IPPOG is an **International Collaboration** bound by a Memorandum of Understanding. It is governed by a **Collaboration Board** comprising representatives of the Members (countries, international particle physics laboratories and experiments) and Associate Members (national laboratories).

Coordination Team: One or two **IPPOG Chair(s)** is/are elected by the Collaboration Board for up to two 3-year terms. They direct activities by leading the **Core Team (**Scientific Secretary and other staff). The **Programme Coordinators** run the International Masterclass and Global Cosmics programmes.