

Discover Cosmic Rays

**INTERNATIONAL
COSMIC DAY**



<https://icd.desy.de>

13/11/2025

*In viaggio con i **raggi cosmici**
tra astrofisica e fisica delle particelle*

Lorenzo Perrone

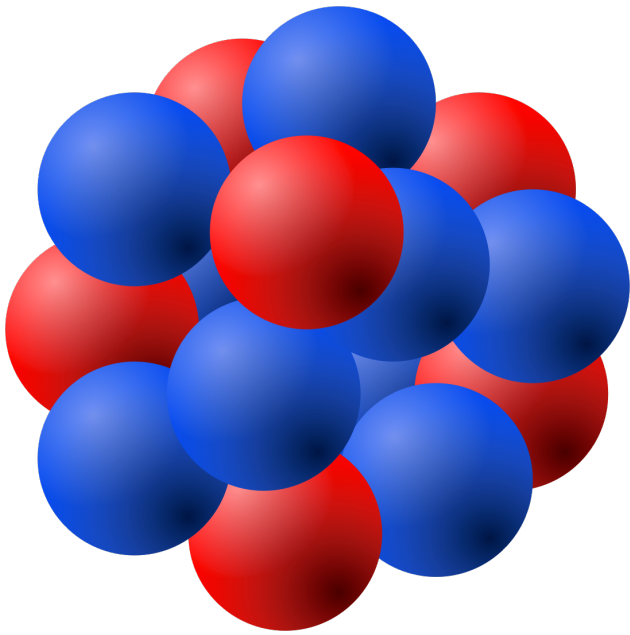
Dipartimento di Matematica e Fisica "Ennio De Giorgi"

Università del Salento e INFN Lecce



ICT-Faculty
UNISALENTO





Raggi cosmici: Nuclei atomici dallo spazio!

 ChatGPT

Cosmic rays are high-energy particles that originate from outer space and travel at nearly the speed of light. They are primarily composed of protons, but can also include heavier atomic nuclei, electrons, and other particles. These rays can come from various sources, including:

1. **Supernova Explosions:** The remnants of explosive stellar events can accelerate particles to high energies.
2. **Active Galactic Nuclei:** Powerful energy emissions from the centers of some galaxies.
3. **Our Sun:** Solar flares and coronal mass ejections release particles into the solar system.
4. **Interstellar Space:** Cosmic rays can travel across vast distances, interacting with the interstellar medium.

When cosmic rays reach the Earth's atmosphere, they collide with atoms, leading to the production of secondary particles. While most cosmic rays are deflected by the Earth's magnetic field, some can reach the surface. Although they can pose risks to astronauts



Raggi Cosmici: perchè?!

sono molto abbondanti in natura

~ 300 particelle/s/m² 20% della radioattività naturale

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

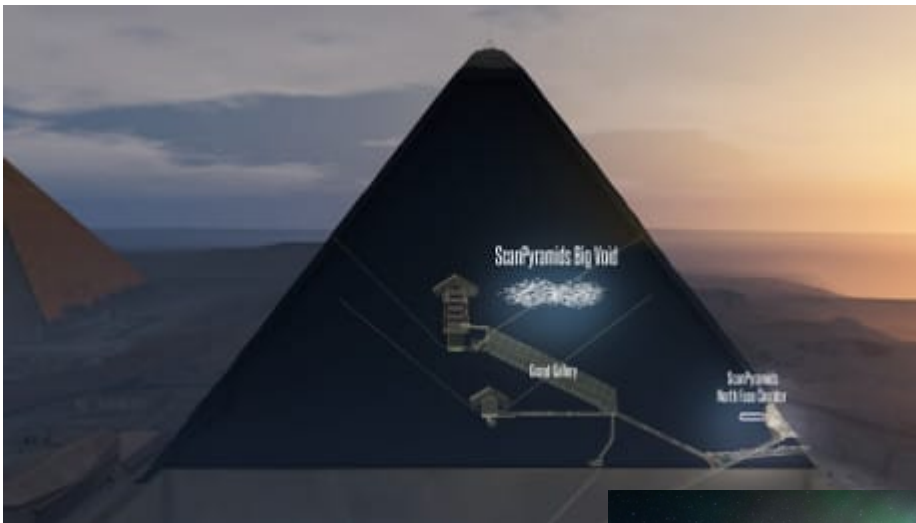
→ studiare le **interazioni** radiazione-materia fino ad energie inaccessibili persino ai moderni acceleratori di particelle

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

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

Raggi cosmici e società

Piramide di Cheope



Aurore polari



Computer quantistici

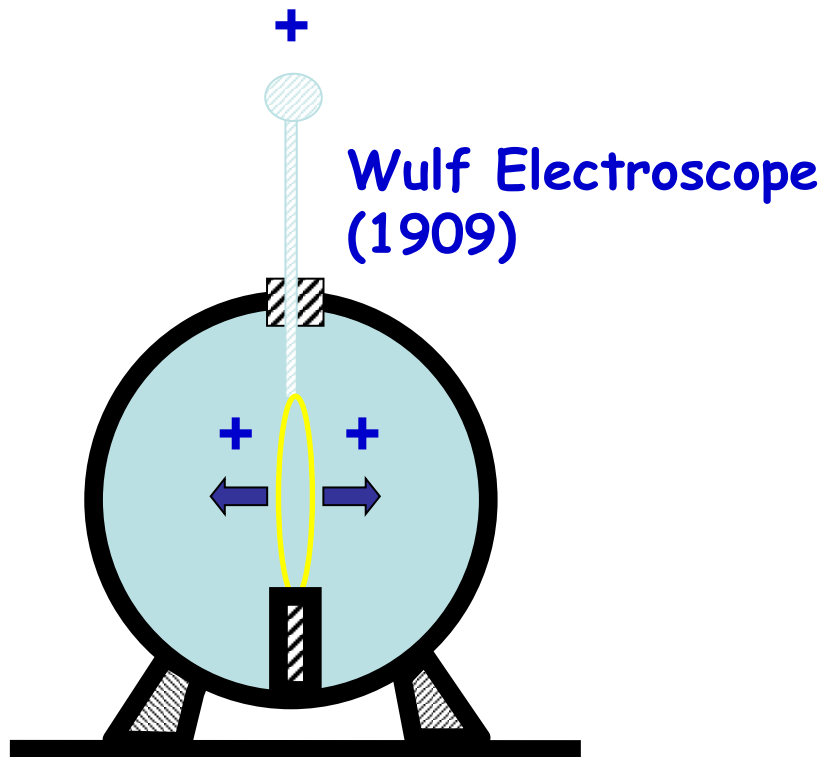




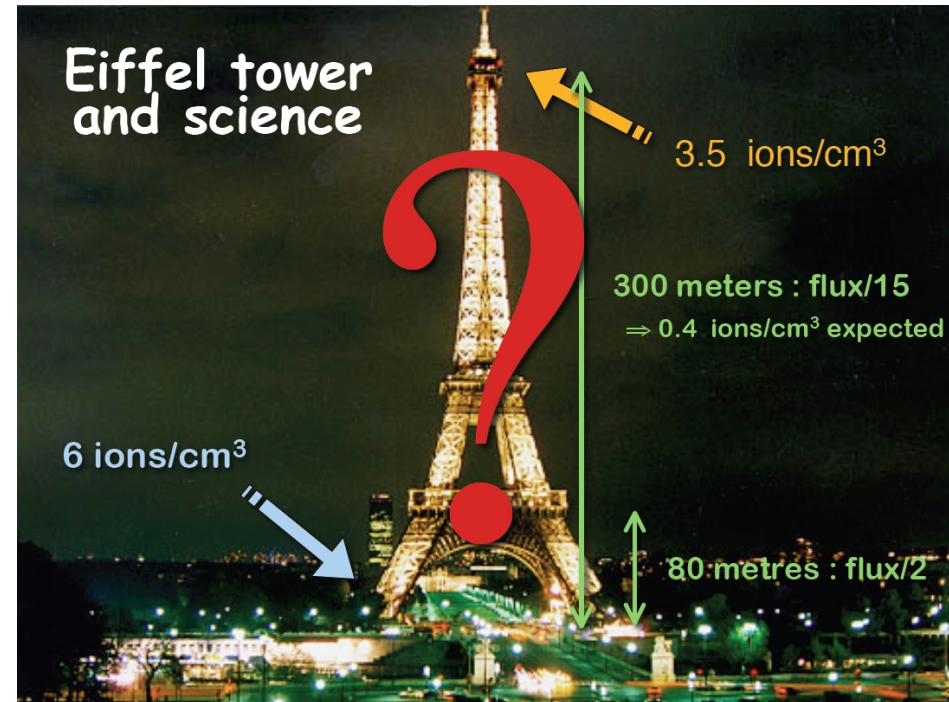
Retrospettiva storica

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



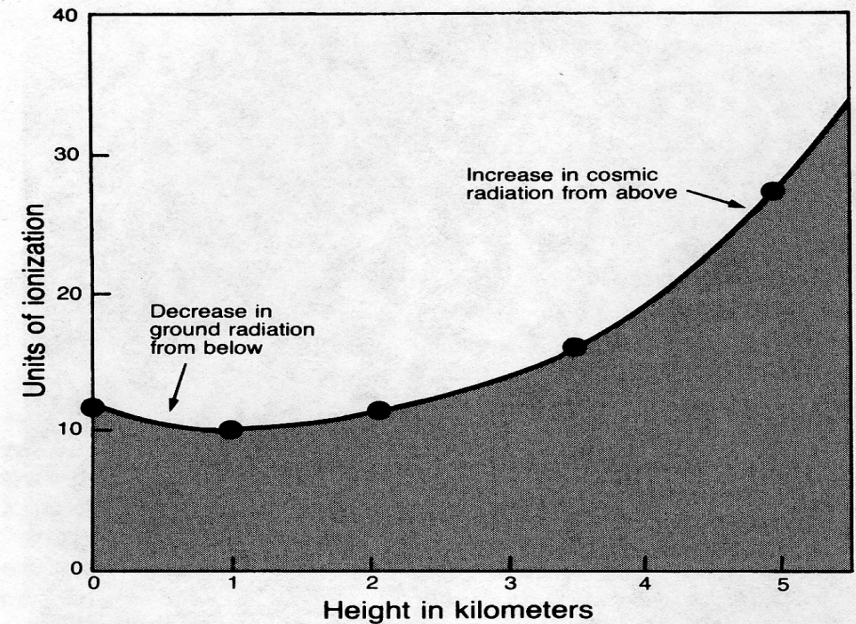
Flusso diminuiva con il crescere della quota ma non come ci si aspettava

Primo problema....

Scoperta dei raggi cosmici!



il volo di Hess (1912)

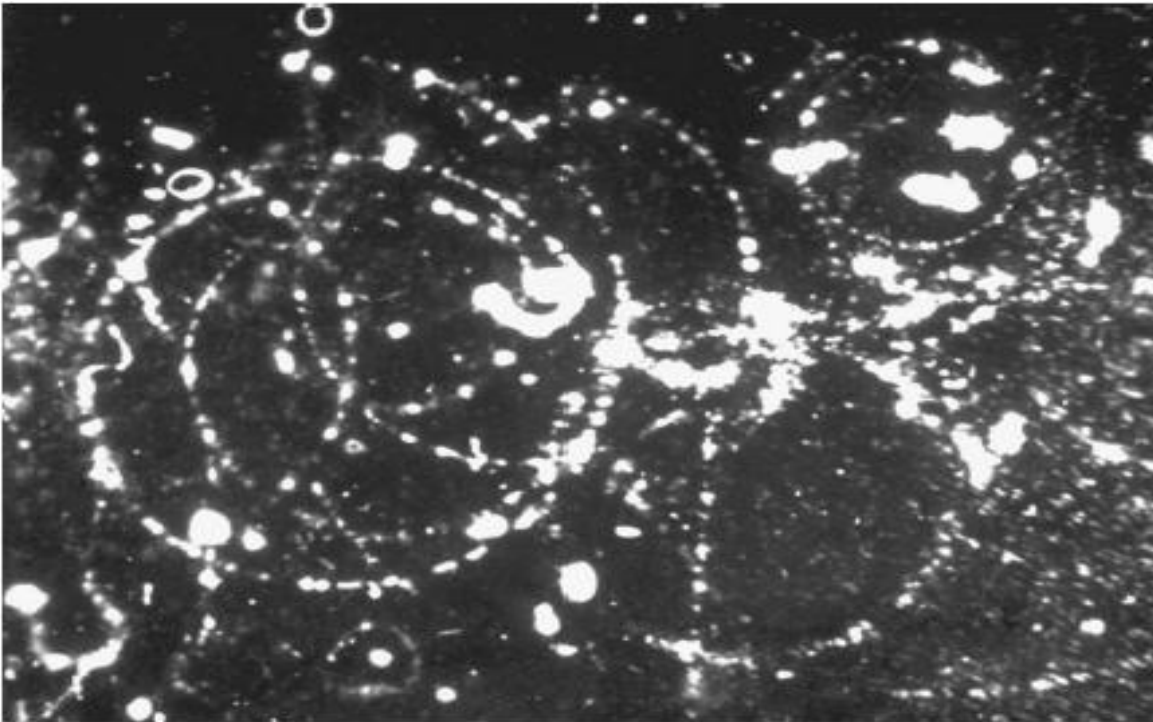


Readings on ionization chamber Victor Hess carried aloft in the Böhmen. Above four kilometers the ionization rose rapidly indicating "that rays of very great penetrating power are entering our atmosphere from above". These cosmic rays contain the only modern samples of matter from outside our solar system 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 $RH \gg 3 \times 10^{17}$. This condition is not satisfied by our galaxy (for which $RH = 5 \times 10^{17}$, 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 $10 \pm 5^\circ$). 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

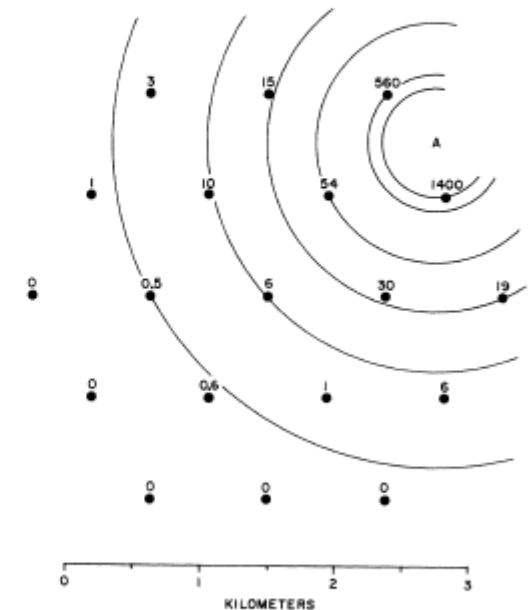
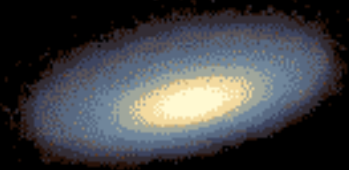


FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-m^2 scintillation detectors. The numbers near the circles are the shower densities (particles/ m^2) registered in this event, No. 2-4834. Point "A" is the estimated location of the shower core. The circular contours about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

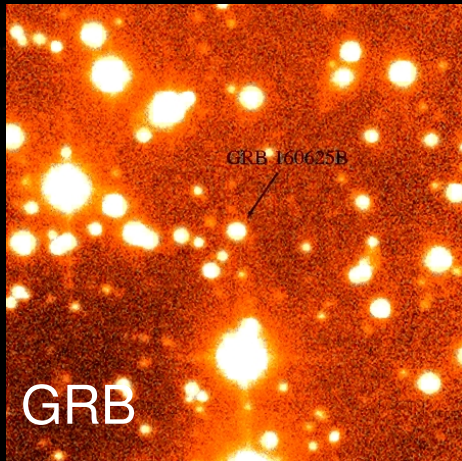
Raggi Cosmici: da dove?



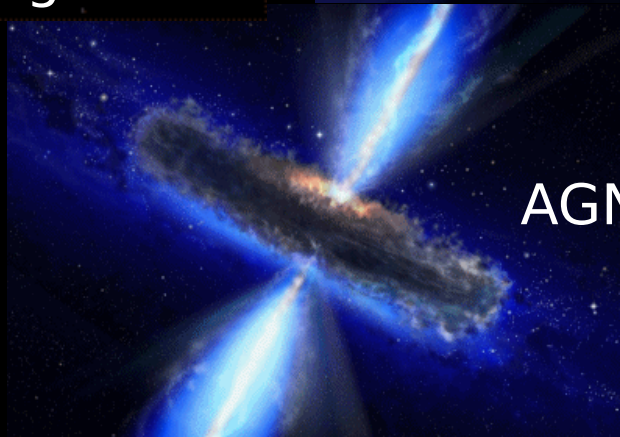
Colliding
galaxies



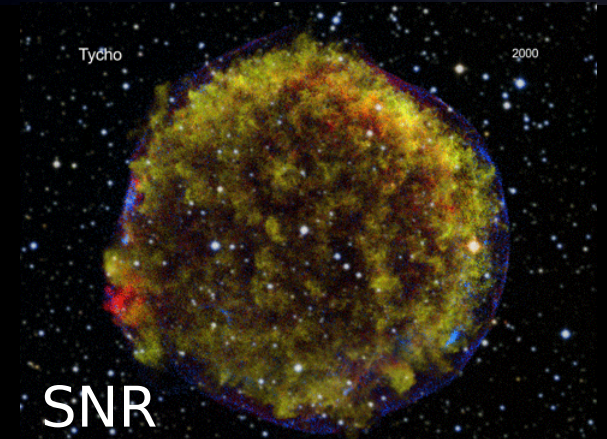
AGN-JETs



GRB

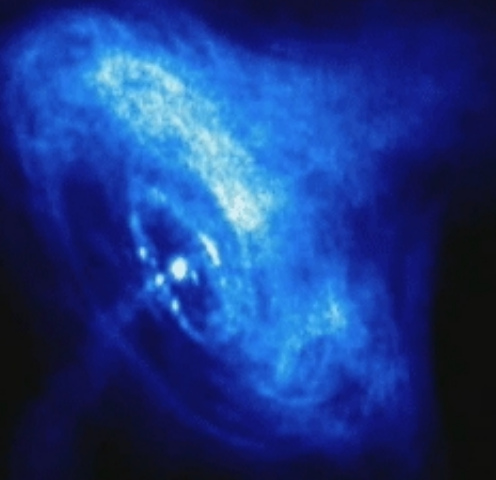


AGN



SNR

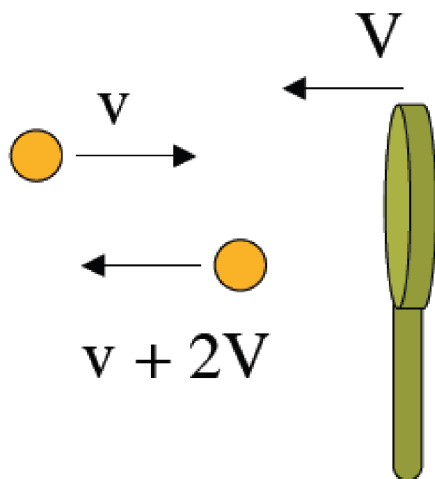
Blazar



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**.

Concetto

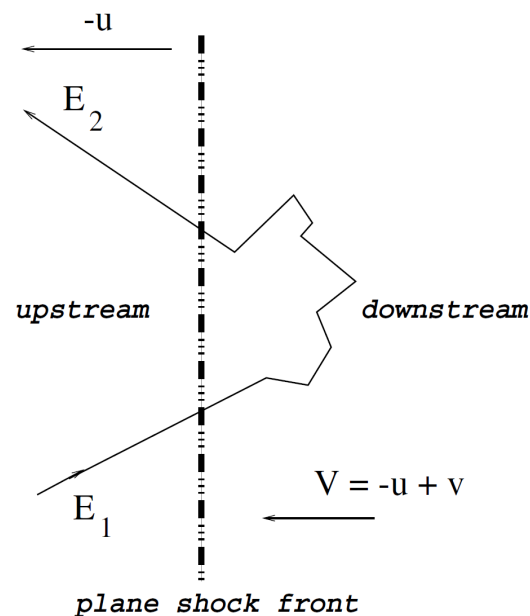


accelerazione

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

La velocità tipica del fronte è:

$$V_s \sim 10^4 \text{ km/s}$$



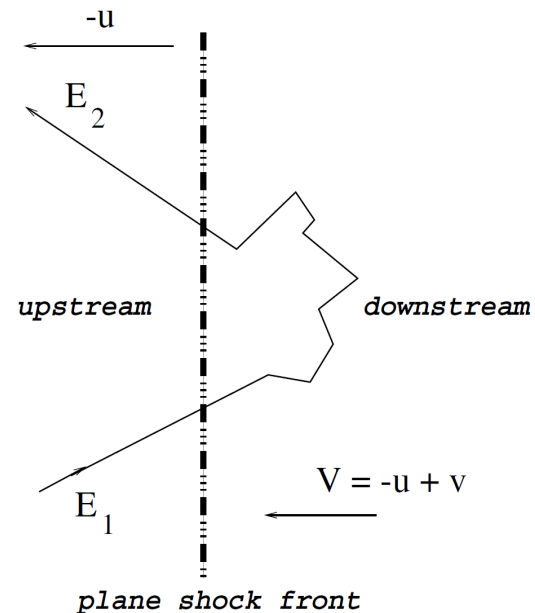
ACCELERAZIONE DEI RAGGI COSMICI

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:

$$V_s \sim 10^4 \text{ km/s}$$

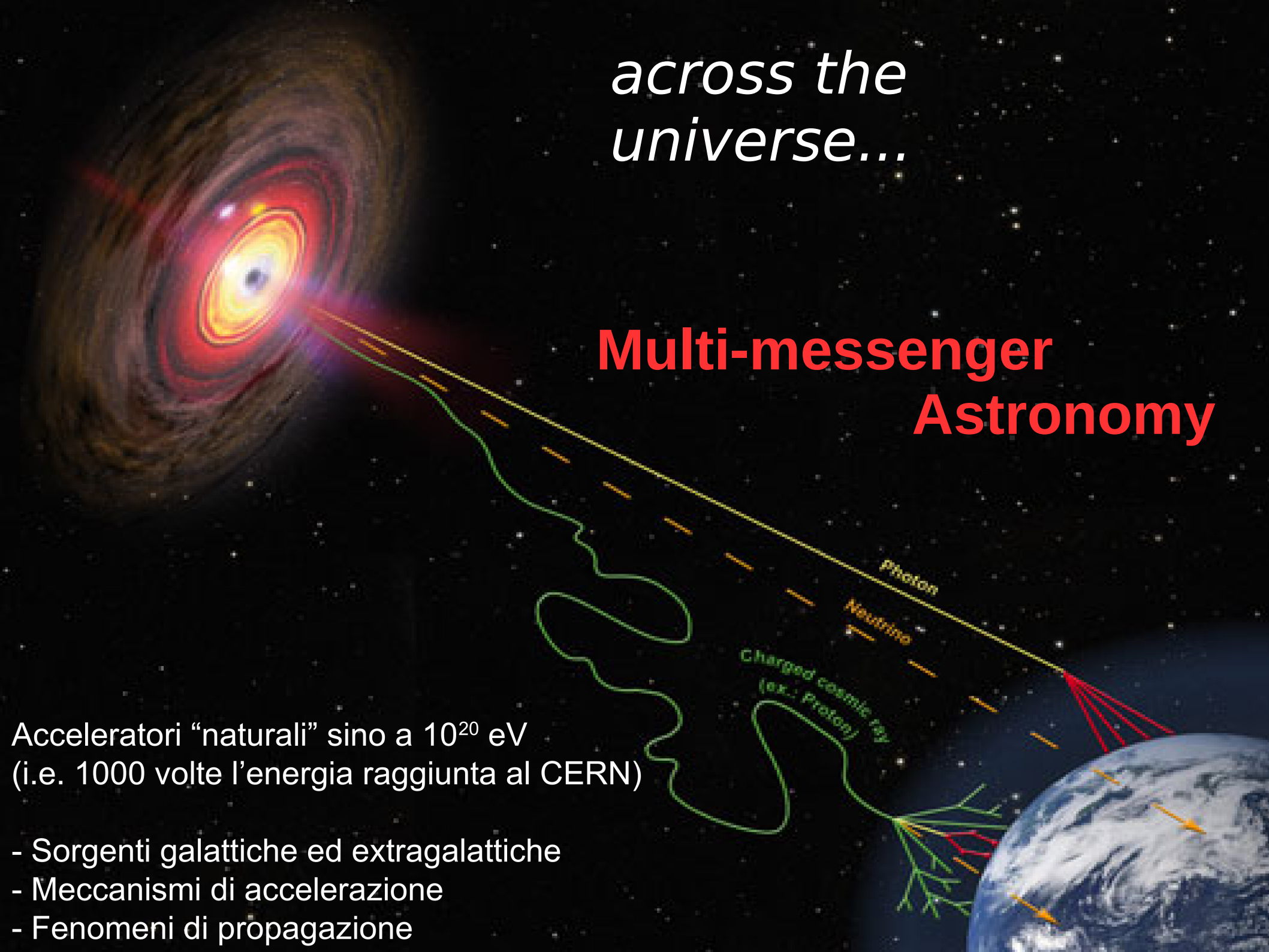


*across the
universe...*

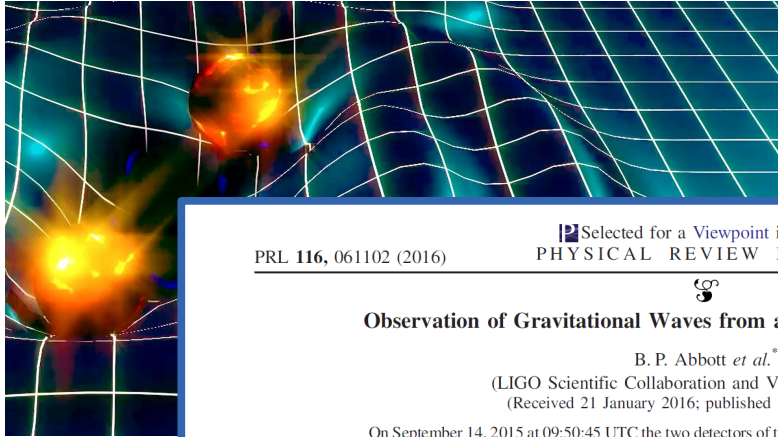
Multi-messenger Astronomy

Acceleratori “natural” 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 !!



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



Observation of Gravitational Waves from a Binary Black Hole Merger

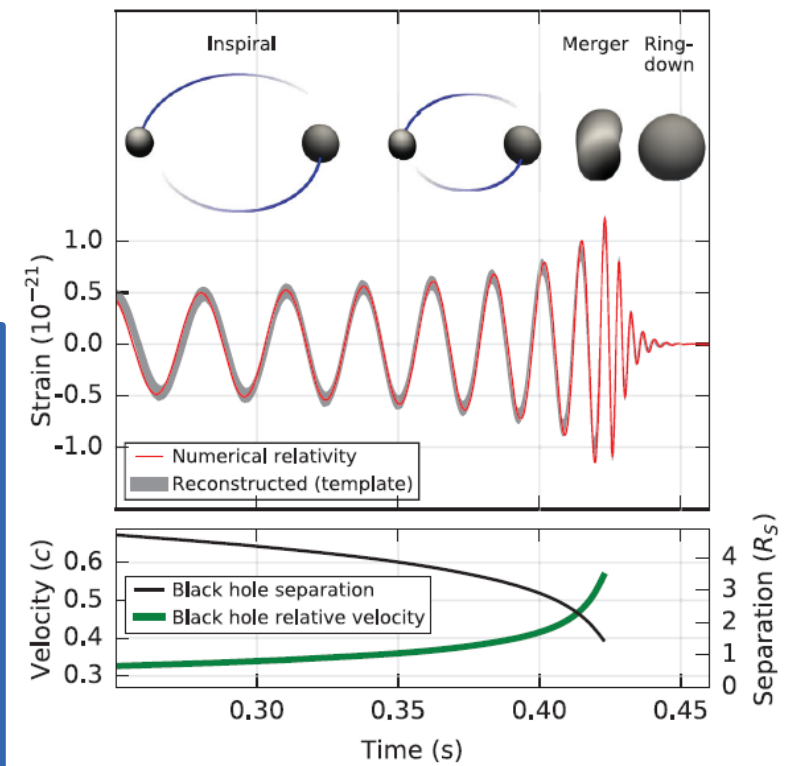
B. P. Abbott *et al.**

(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



PRL 119, 161101 (2017)

Selected for a Viewpoint in Physics PHYSICAL REVIEW LETTERS

week ending 20 OCTOBER 2017



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

B. P. Abbott *et al.**

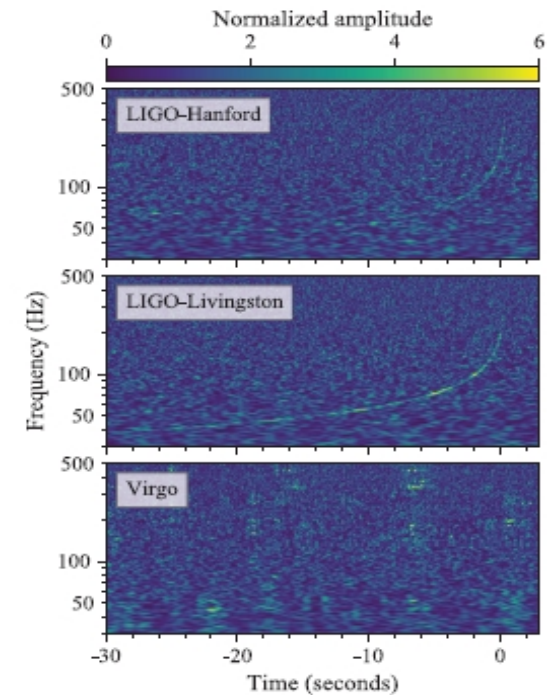
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

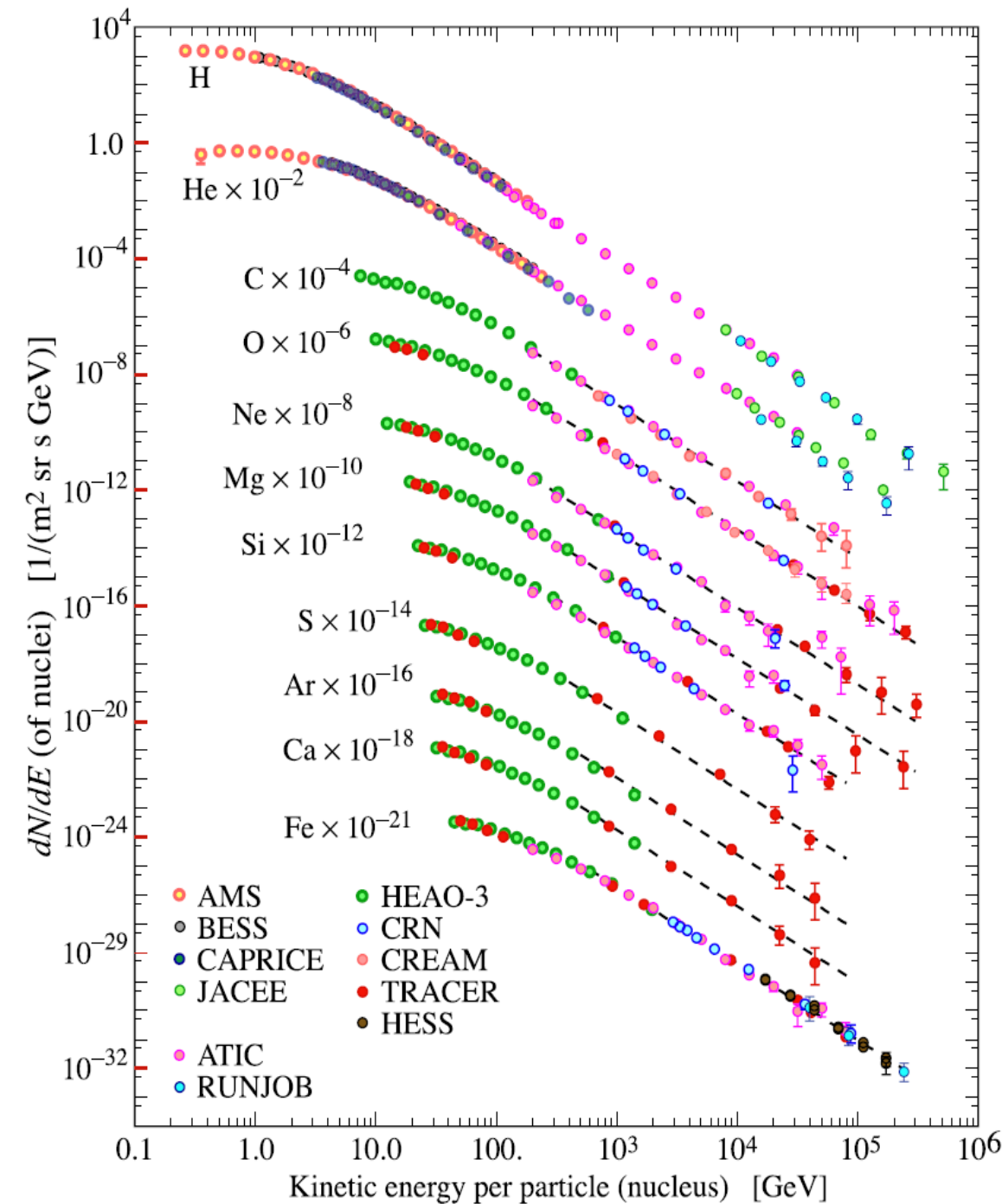
On August 17, 2017 at 12:41 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 30. The source is located in the constellation of Virgo at a luminosity distance of 40^{+8}_{-8} Mpc, or 130^{+40}_{-40} Mpc if the source is at cosmological redshift. The component masses are $1.4^{+0.1}_{-0.1} M_{\odot}$ and $1.3^{+0.1}_{-0.1} M_{\odot}$, in agreement with numerical relativity simulations of the merger of two neutron stars. The total mass of the final object is $2.9^{+0.1}_{-0.1} M_{\odot}$, and the mass difference is $0.1^{+0.1}_{-0.1} M_{\odot}$. The final object is a black hole with a mass of $2.3^{+0.1}_{-0.1} M_{\odot}$ and a dimensionless spin parameter of $0.6^{+0.1}_{-0.1}$. The event provides the first evidence of a link between gravitational-wave counterparts across the sky and the first observation of a neutron star merger. This event provides insight into the equation of state of neutron star matter and the rate of binary neutron star mergers.

**Premio Nobel
2017**

B. Barish R. Weiss and



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

almeno a bassa 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

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

Osservazione diretta (es. Satelliti, Palloni
aerostatici)

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

Osservazione indiretta (sviluppo di sciami
estesi in atmosfera)

EAS: extensive air showers

$$E > 10^{15} \text{ eV}$$

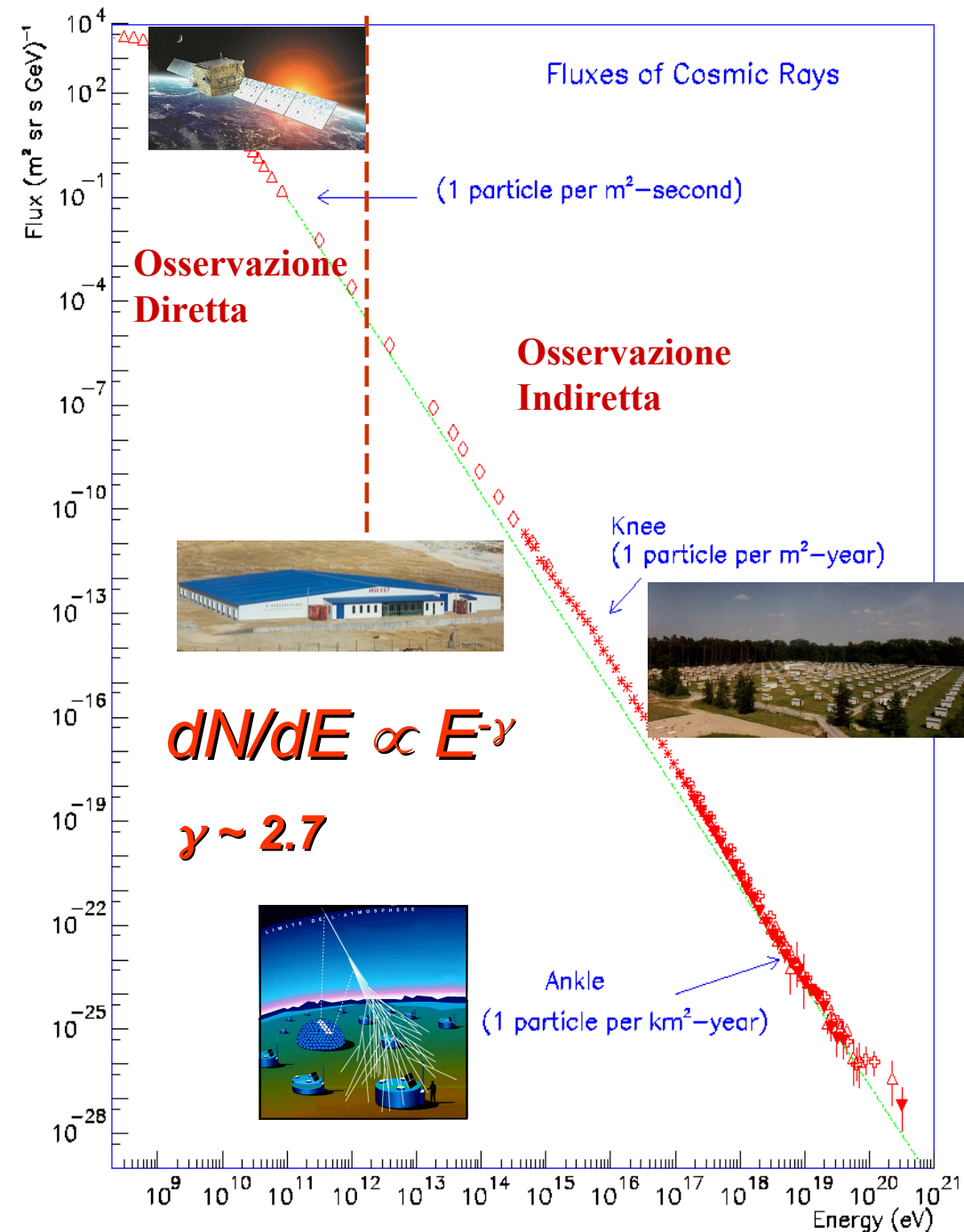
1 particella/m²/anno

$$E > 10^{18} \text{ eV}$$

1 particella/km²/anno

$$E > 10^{20} \text{ eV}$$

1 particella/km²/secolo



The physics case at the highest energies

Ankle

Transition galactic to extra-galactic cosmic rays

“GZK”

End of the spectrum

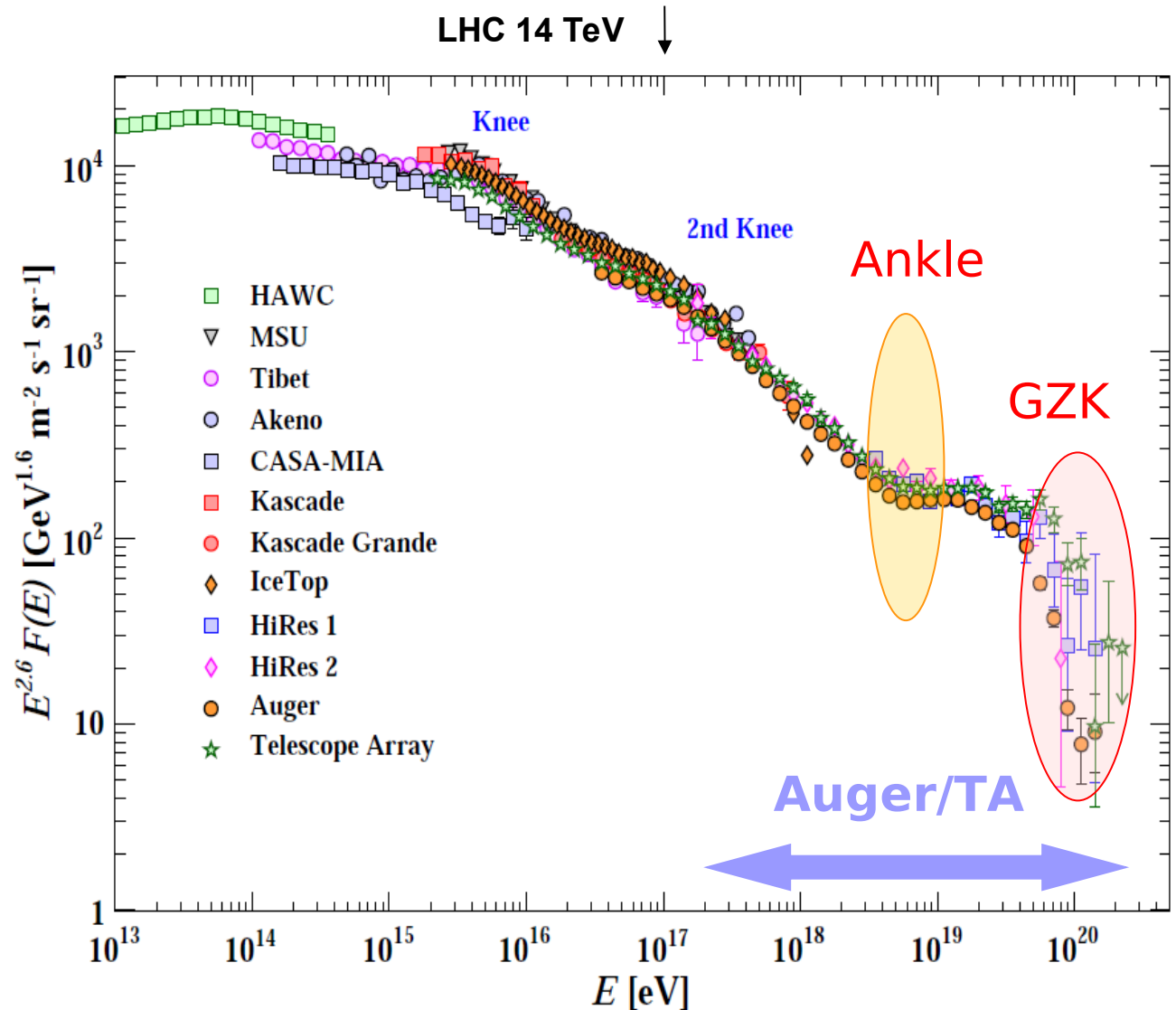
Energy spectrum

Arrival directions

Composition

Search for photon and neutrinos as primary cosmic rays

Hadronic physics

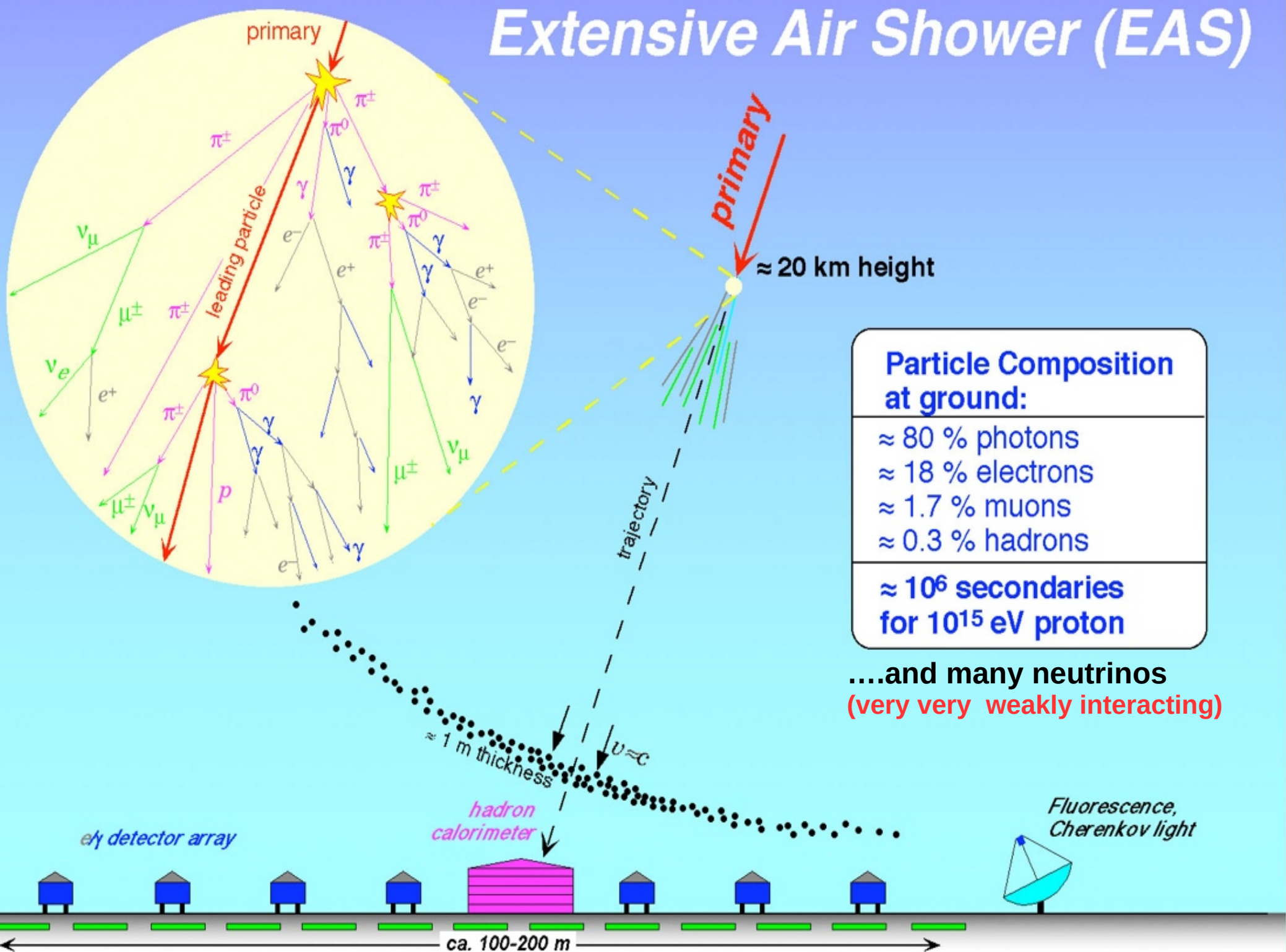


Particle Data Group

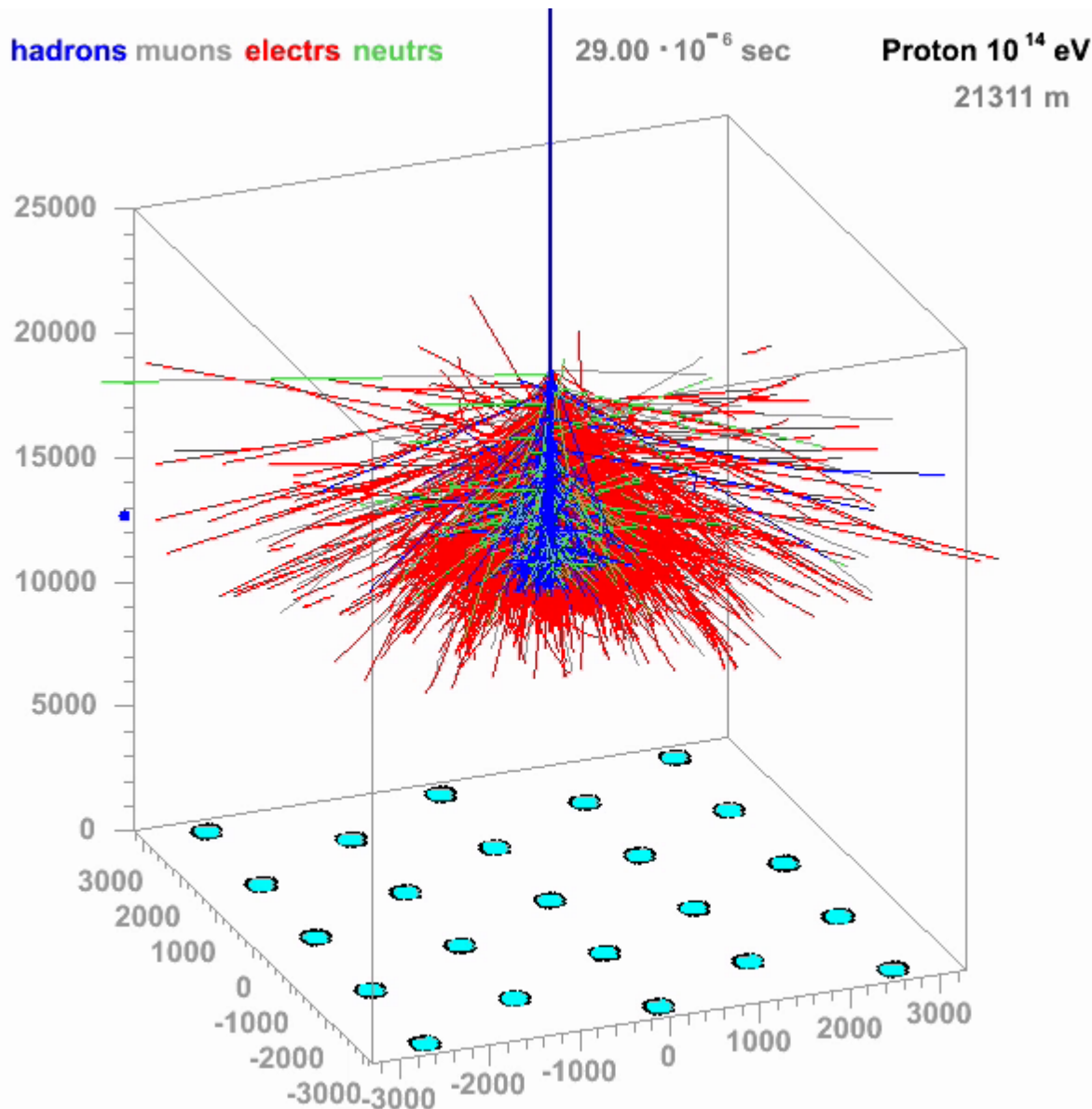
**Cosa fanno i raggi
cosmici quando
entrano nell'atmosfera
terrestre?**



Extensive Air Shower (EAS)

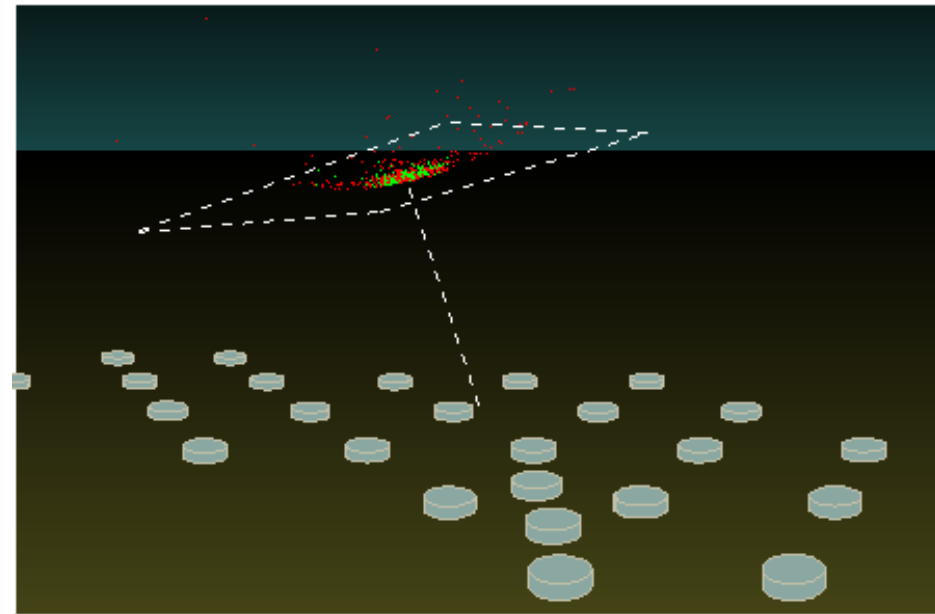


Raggi Cosmici “simulati”

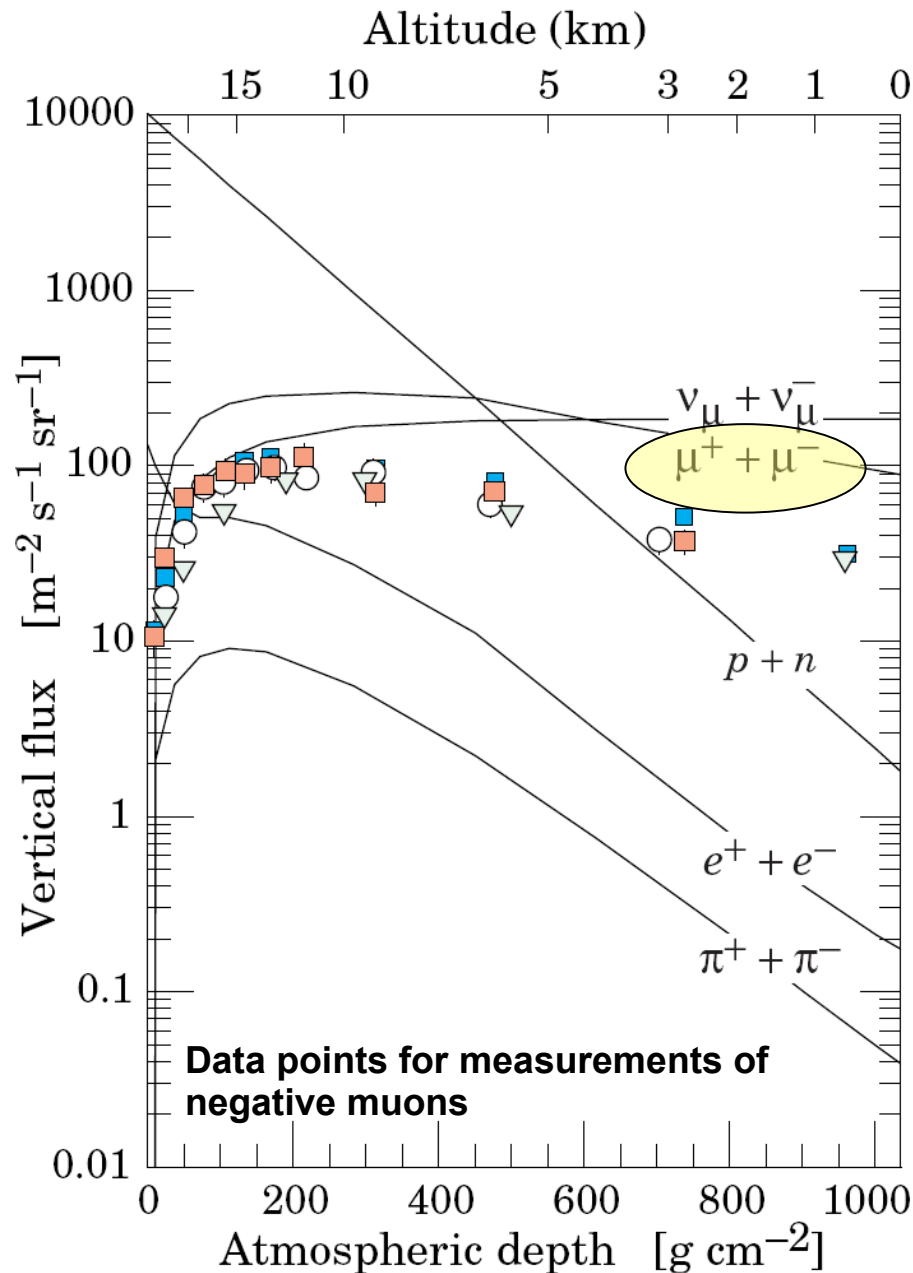


Simulazioni Monte Carlo:

- interazioni
- rivelatore



Raggi cosmici nell'atmosfera



Flusso verticale dei raggi cosmici nell'atmosfera con $E > 1 \text{ GeV}$

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

$\sim 1\text{-}2 \text{ muoni/cm}^2/\text{min}$

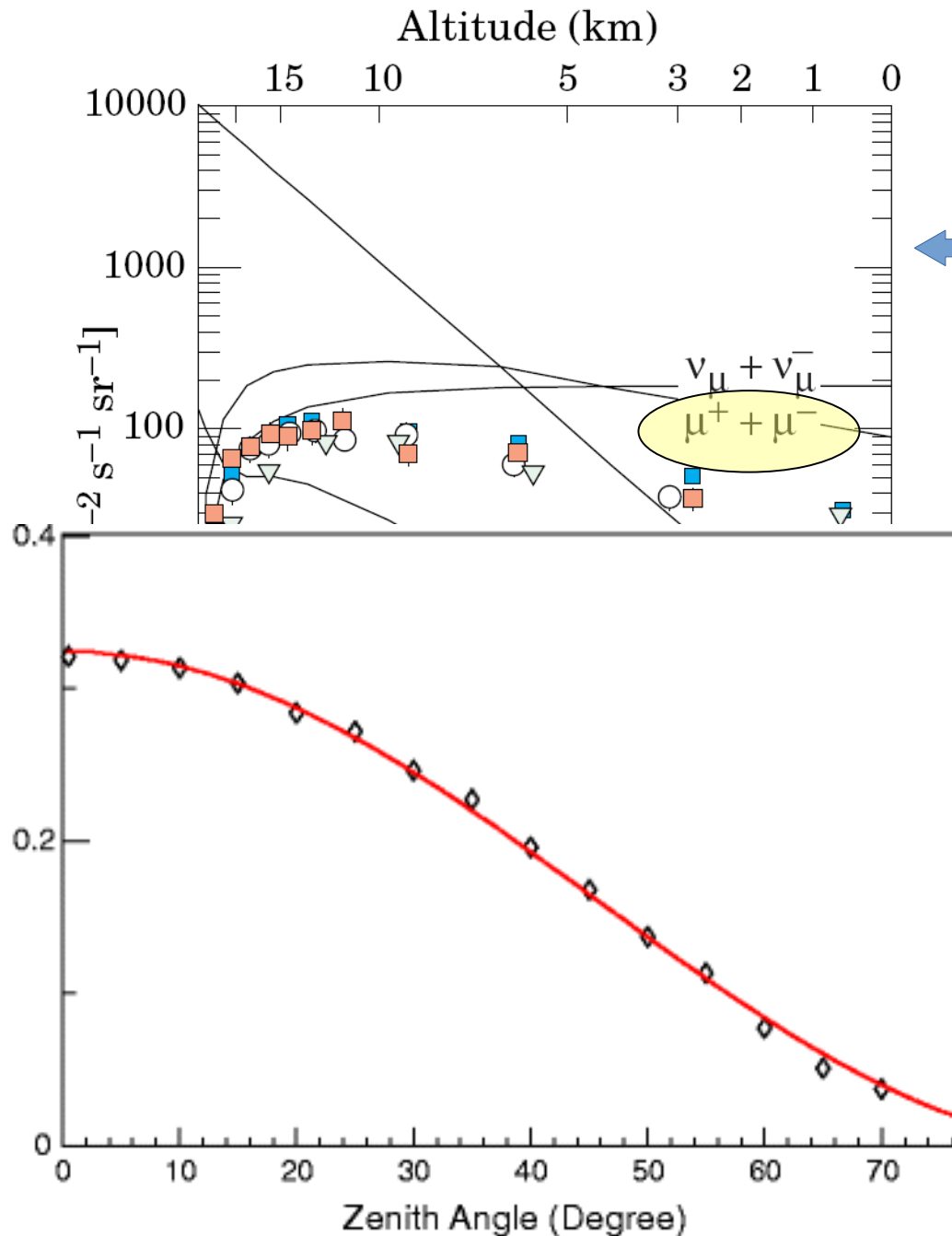
Sono prodotti a circa 15 km di quota

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)

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

$\sim 1\text{-}2 \text{ muoni/cm}^2\text{/min}$

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)

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 ($\sim 3000 \text{ km}^2$)

Fluorescence detector

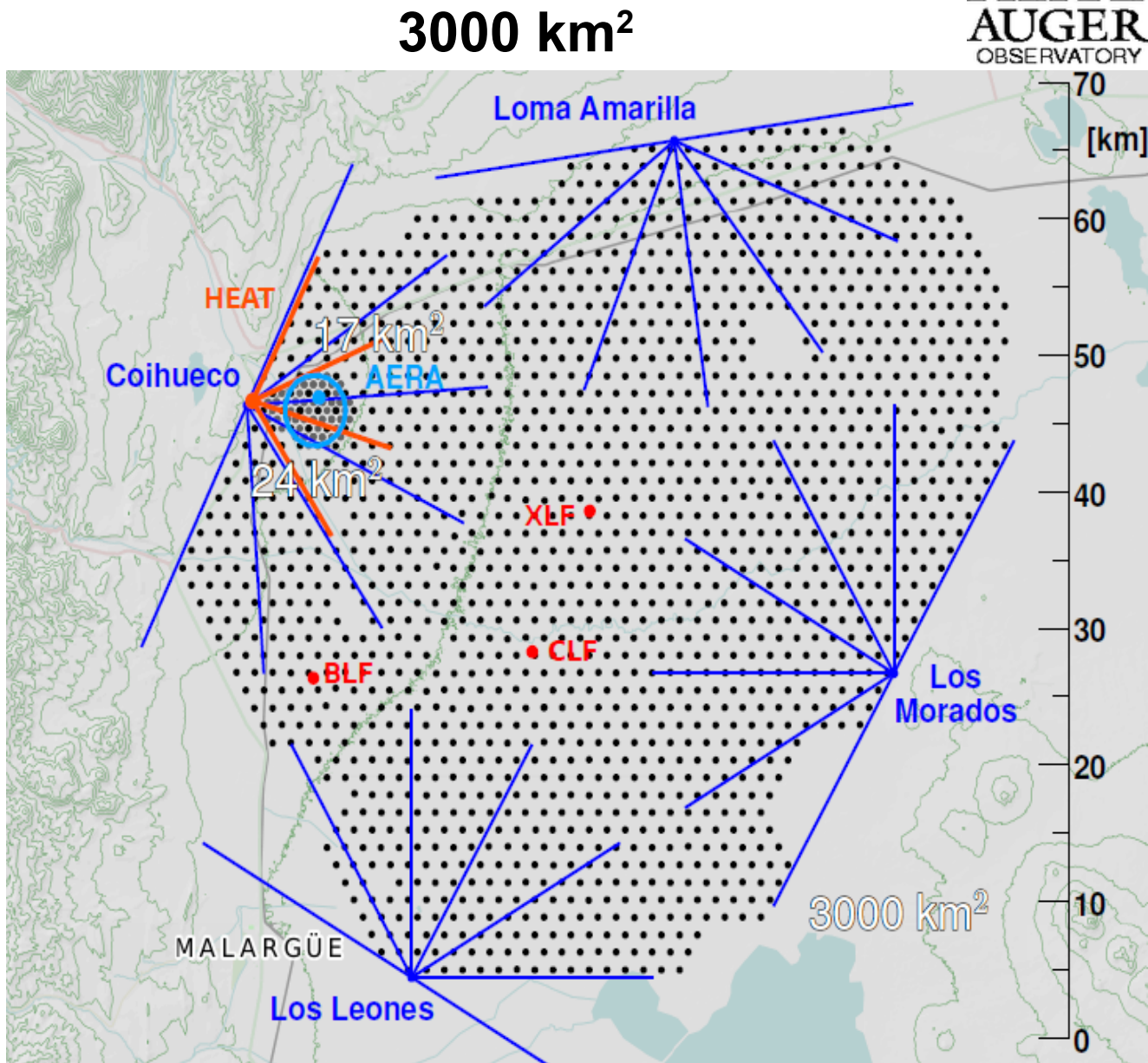
4+1 buildings overlooking the array (24+3 telescopes)

Radio detector

153 Radio Antenna $\rightarrow$ AERA

Low energy extensions

- Dense array (24 km^2) plus muon detectors $\rightarrow$ AMIGA
- 3 further high elevation FD telescopes $\rightarrow$ HEAT



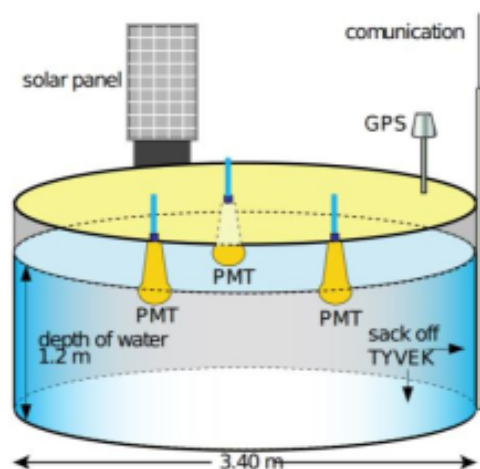
L'Osservatorio Pierre Auger nel Salento



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
($\sim 3000 \text{ km}^2$).

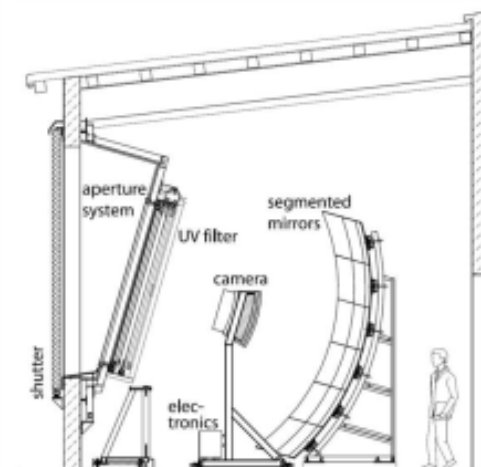
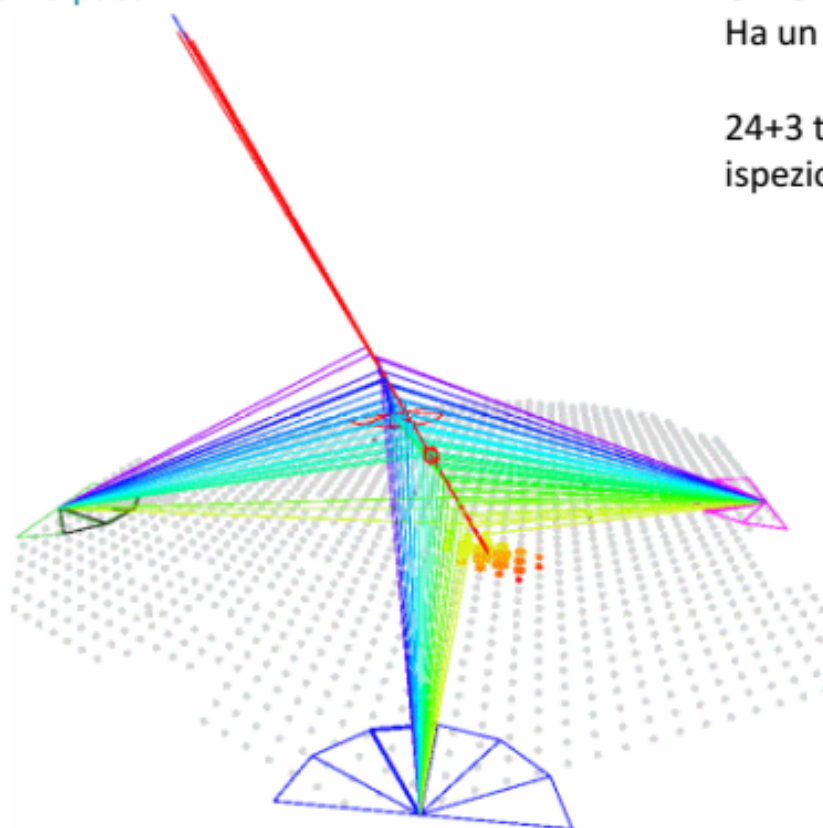
Ha un duty cycle del 100%.

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

Detector di fluorescenza (FD):

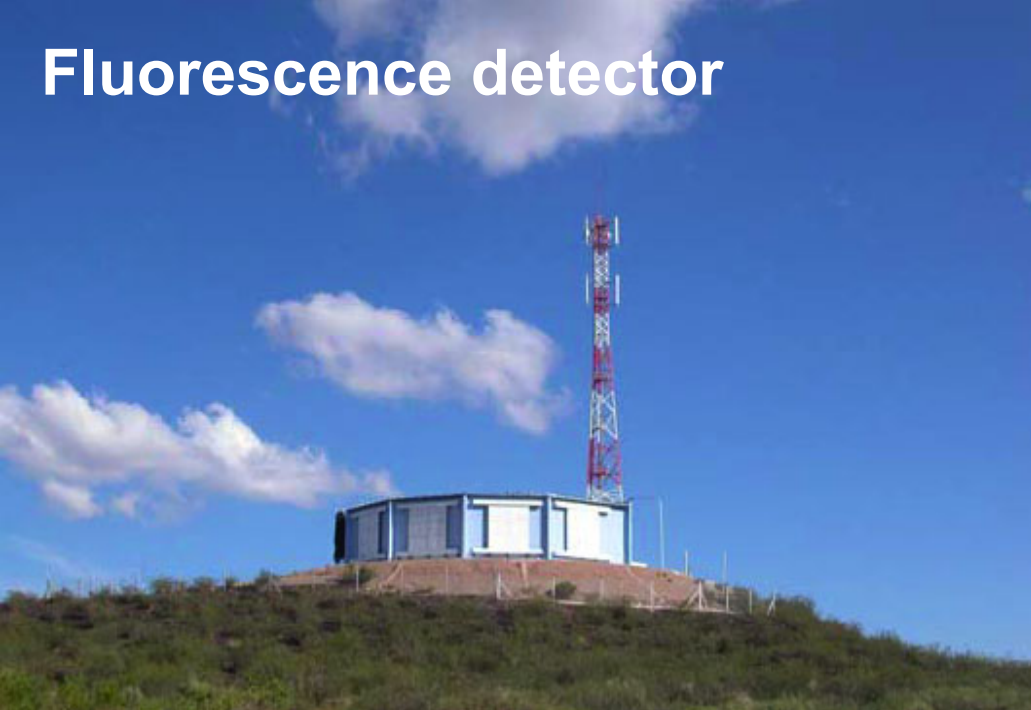
Offre misure dell'energia calorimetrica.
Ha un duty cycle di circa il 15%

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.

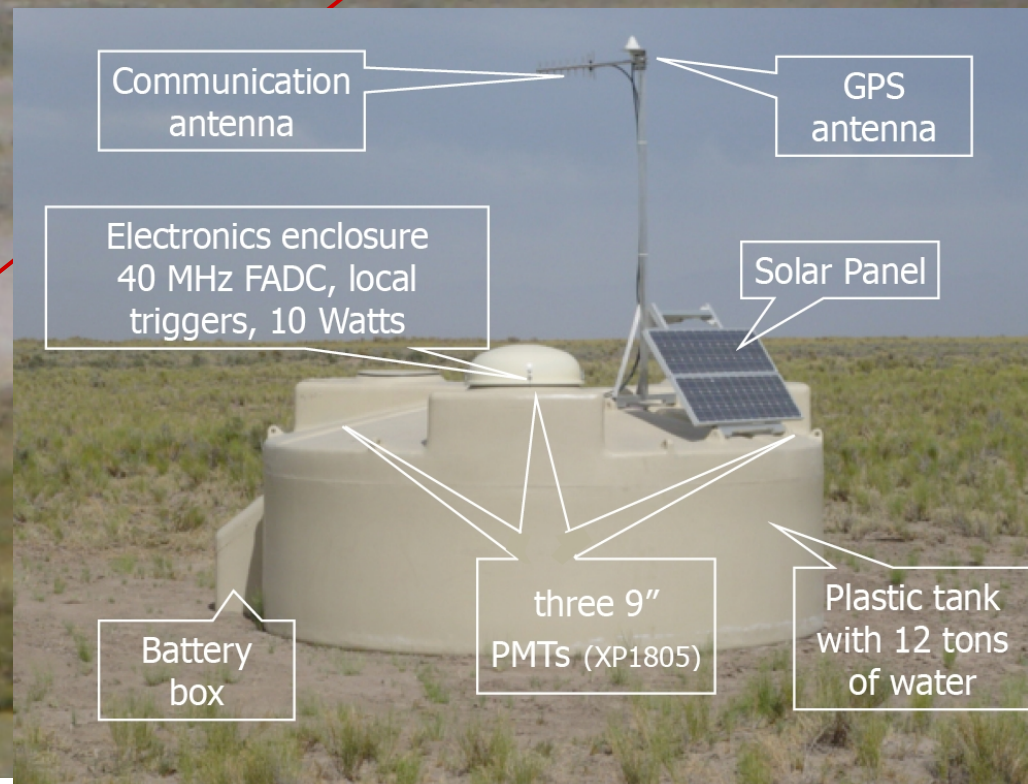
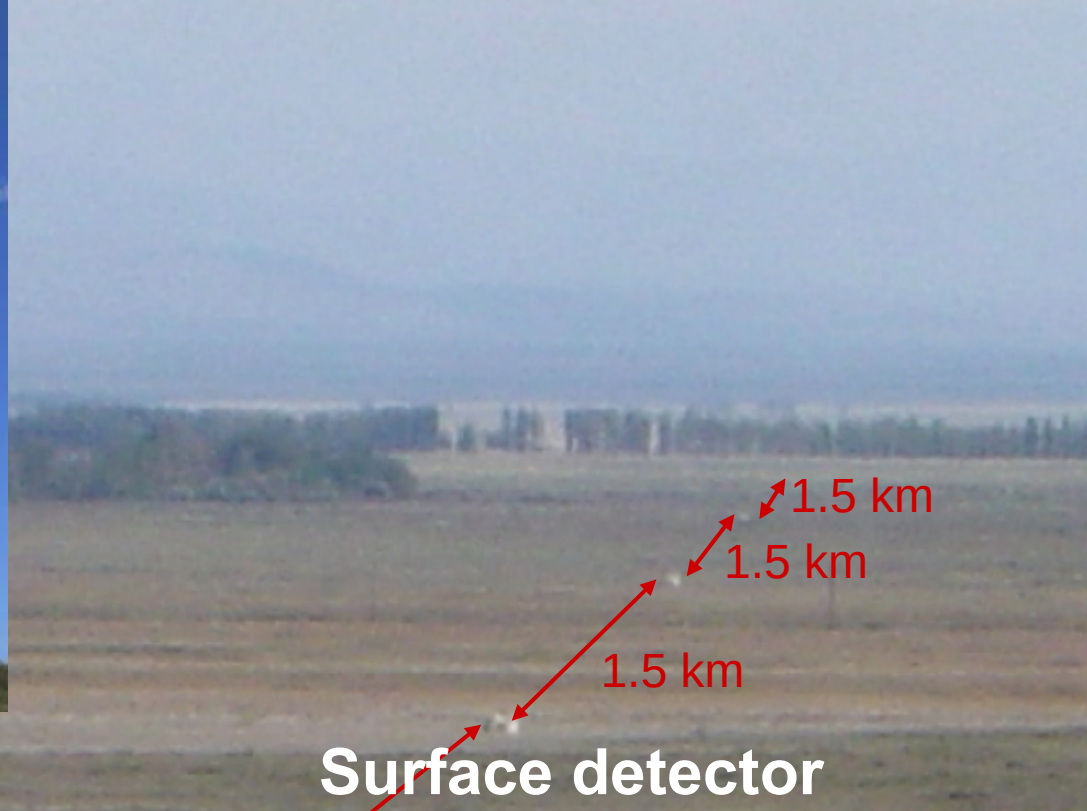
Fluorescence detector



Radio detector



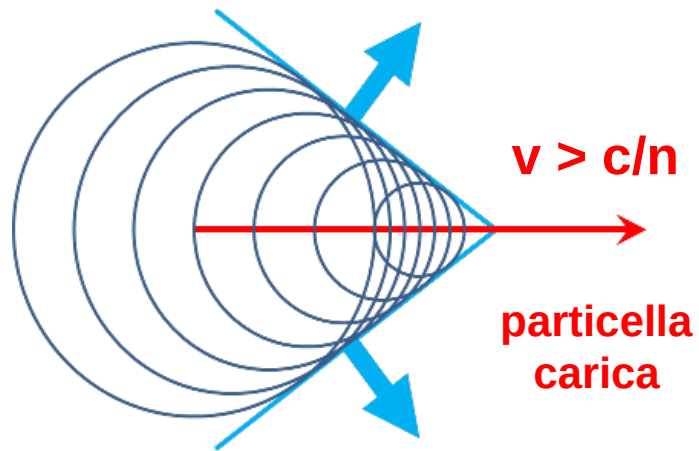
Surface detector



Non è sempre facile...

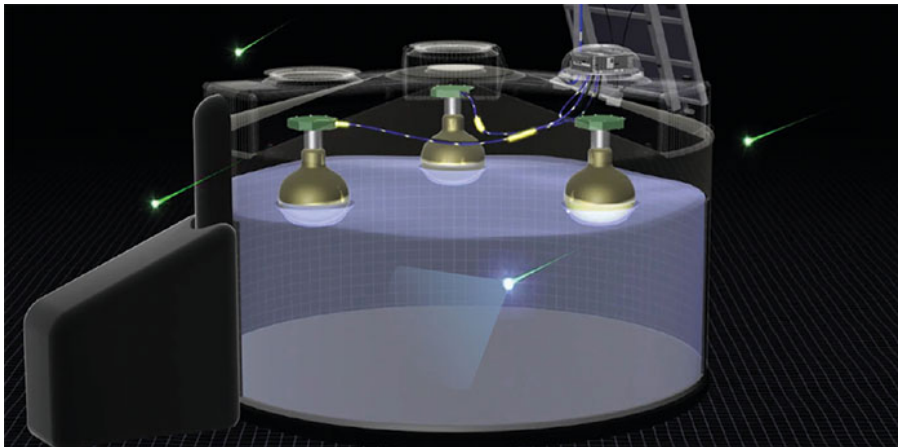


L'effetto Cherenkov

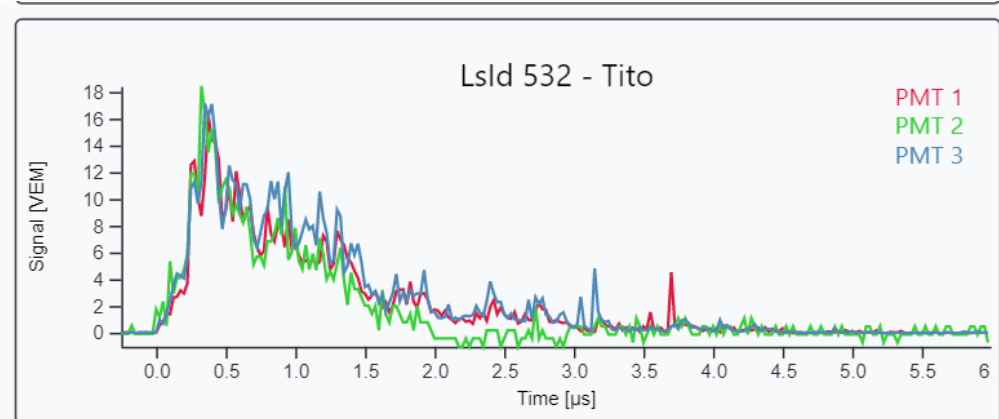


CONO LUCE CHERENKOV

Angolo in aria 1.4° in Acqua 41.2°

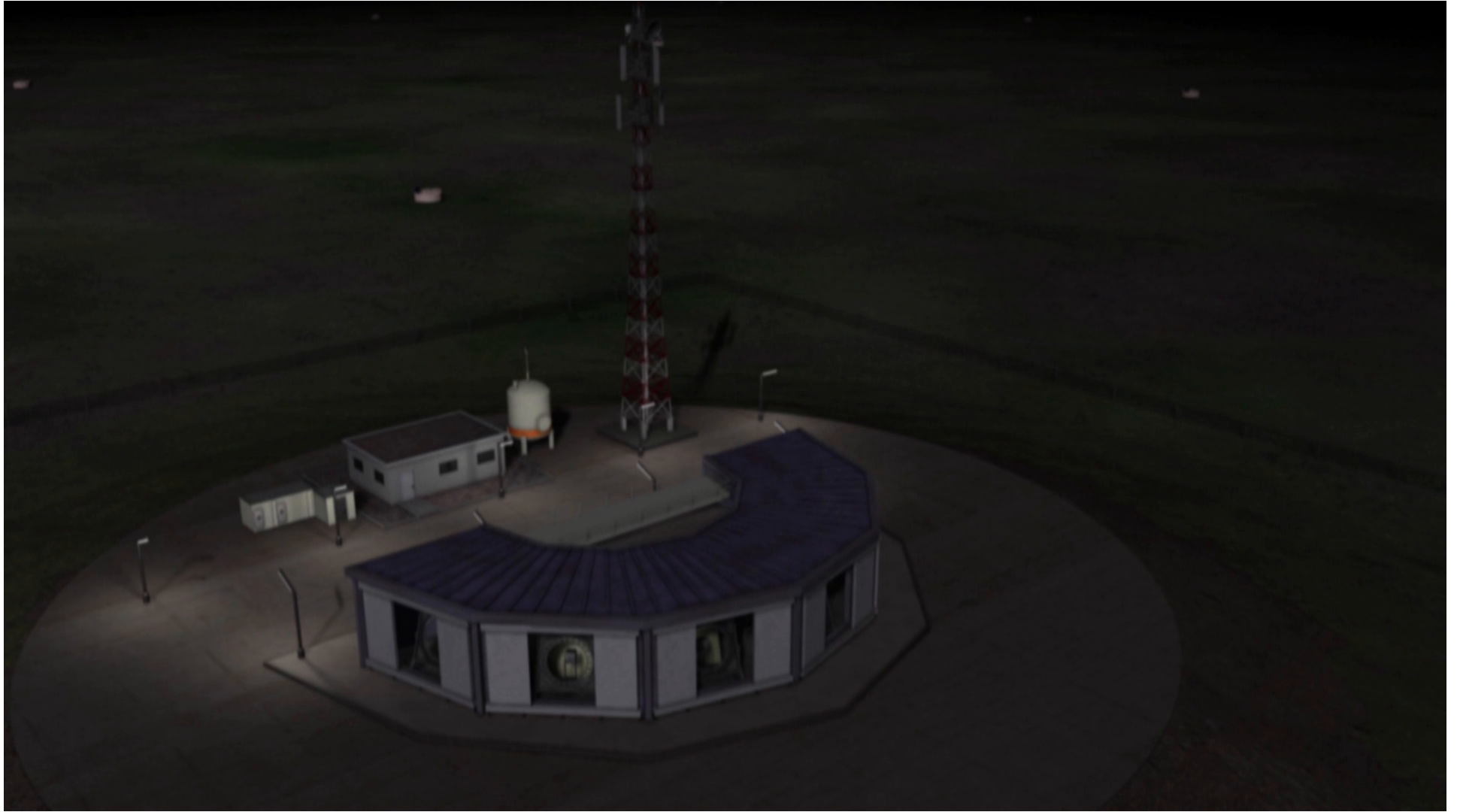


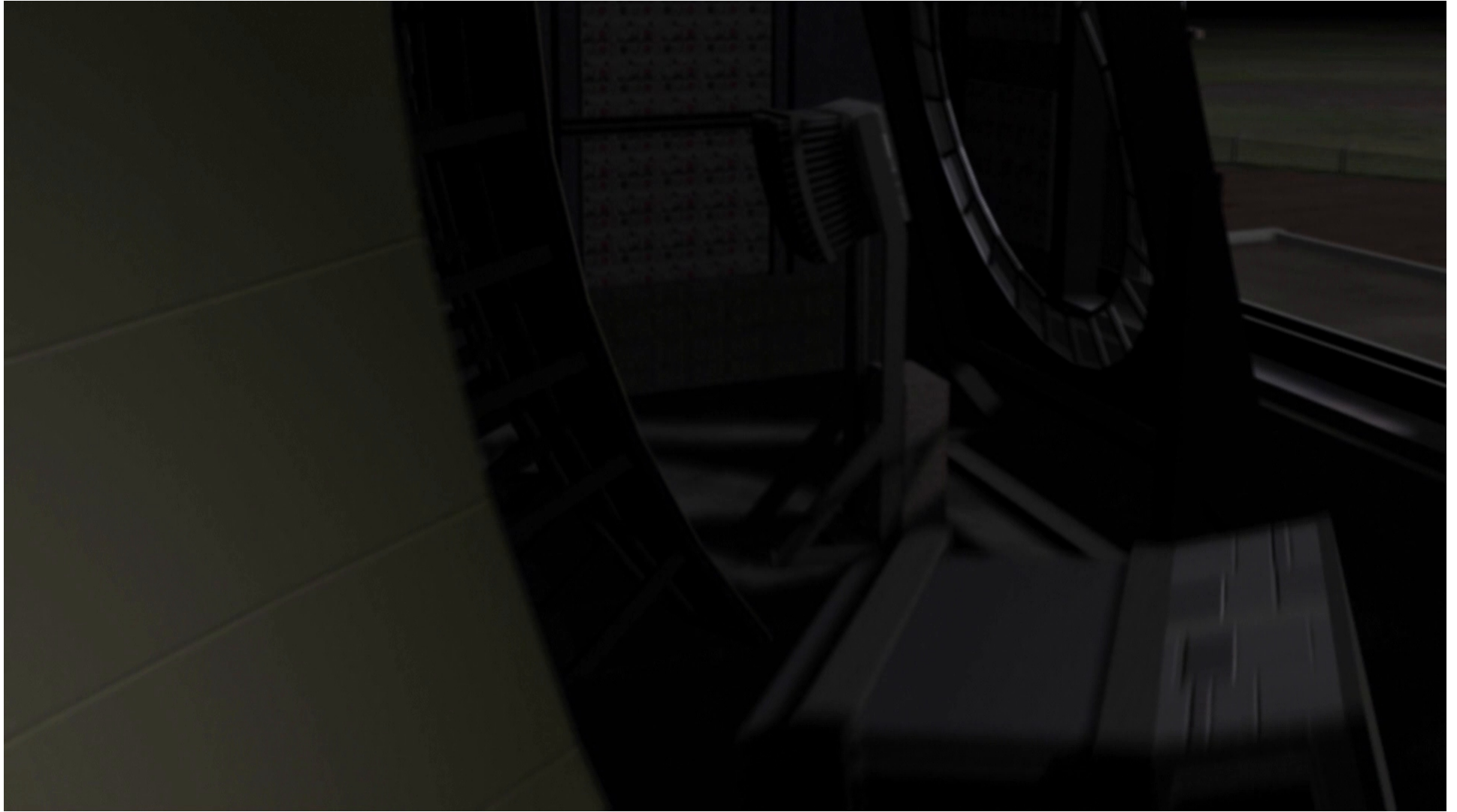
Stazione Cherenkov



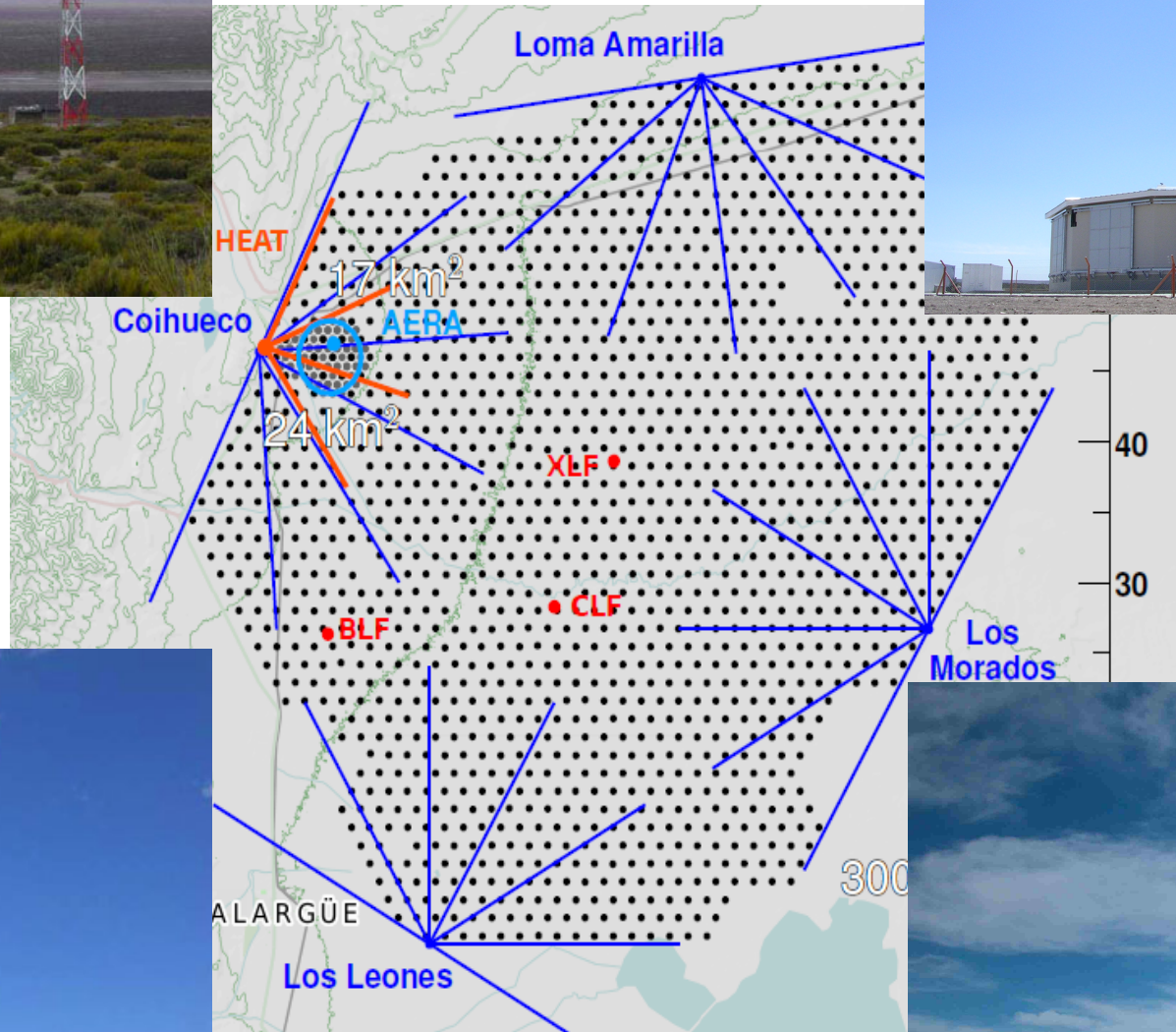
Segnale nei PMT



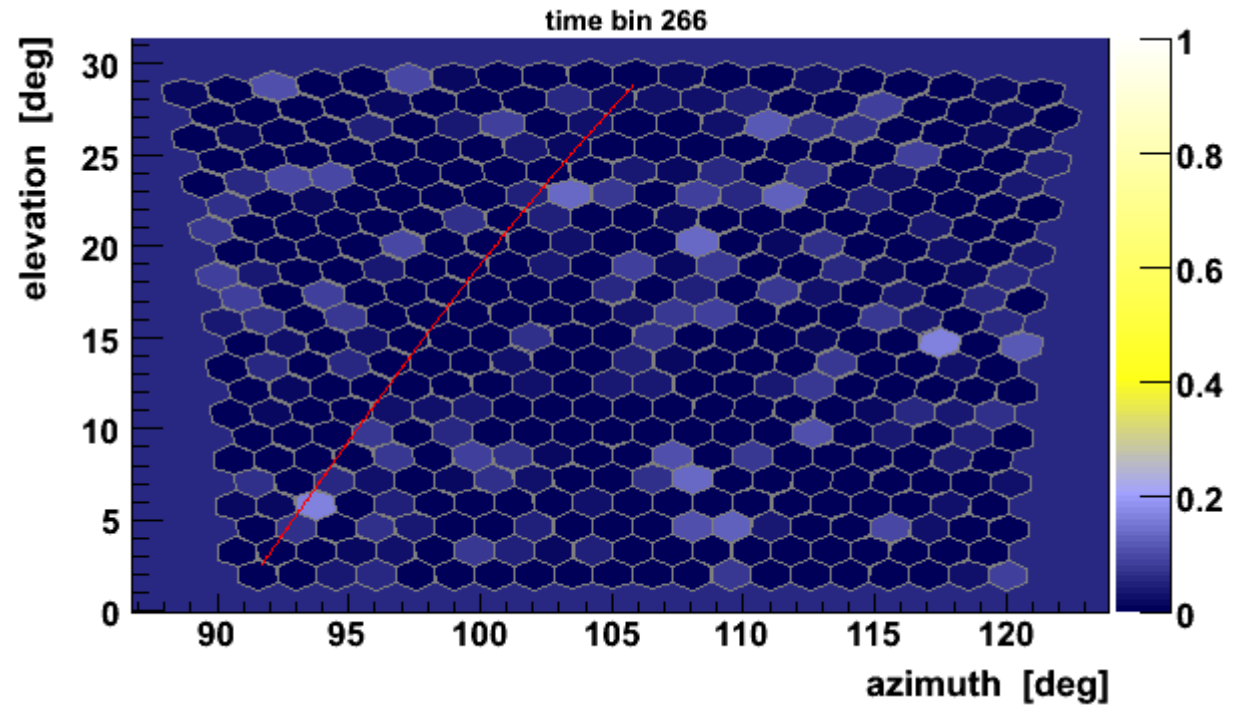
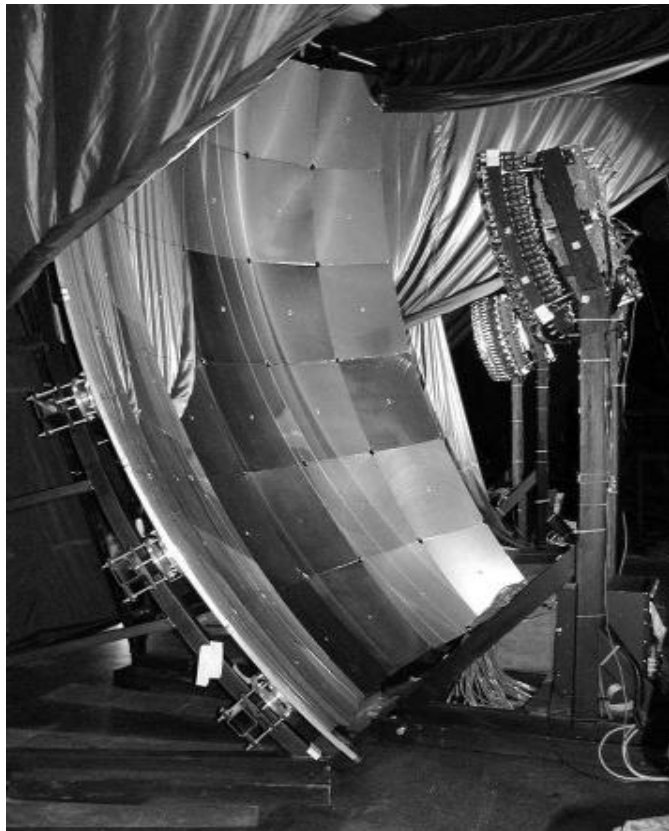
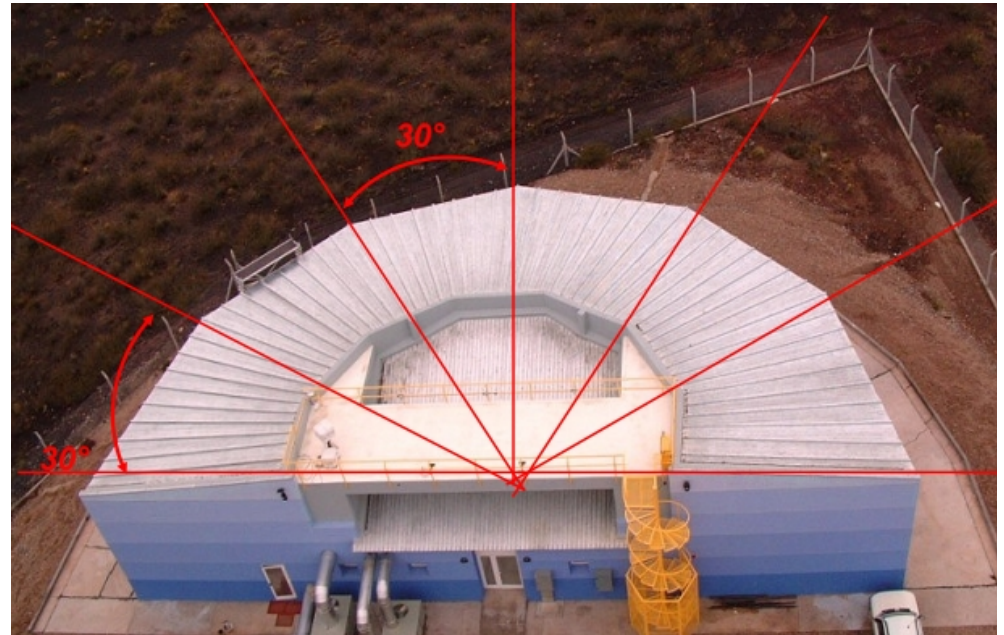
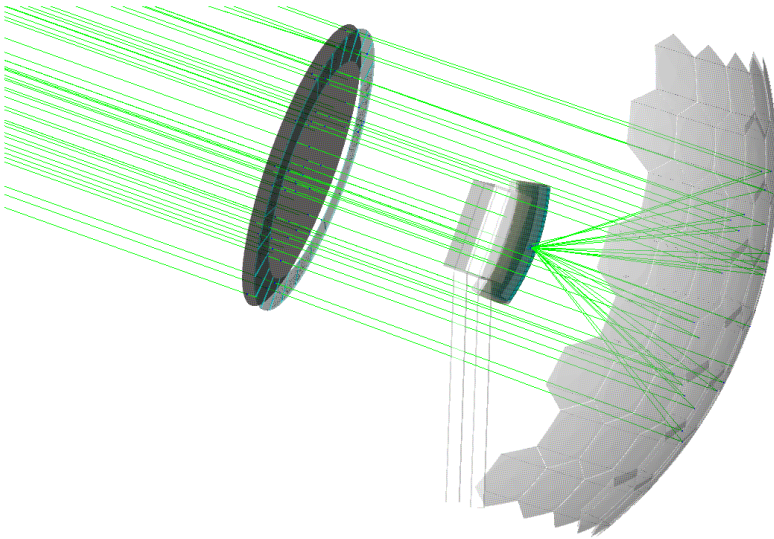




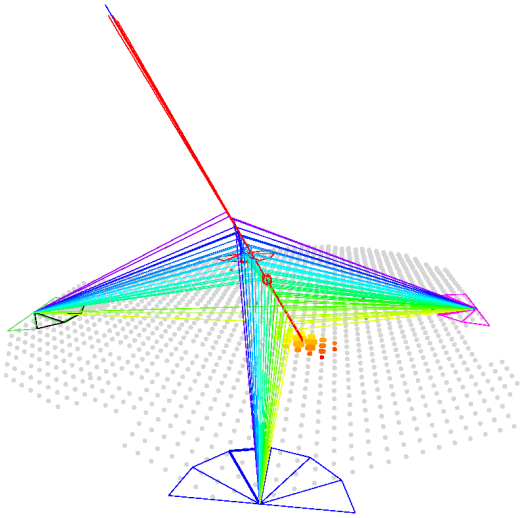
I rivelatori di fluorescenza (FD)



Il rivelatore di fluorescenza



Il design ibrido



Profilo longitudinale

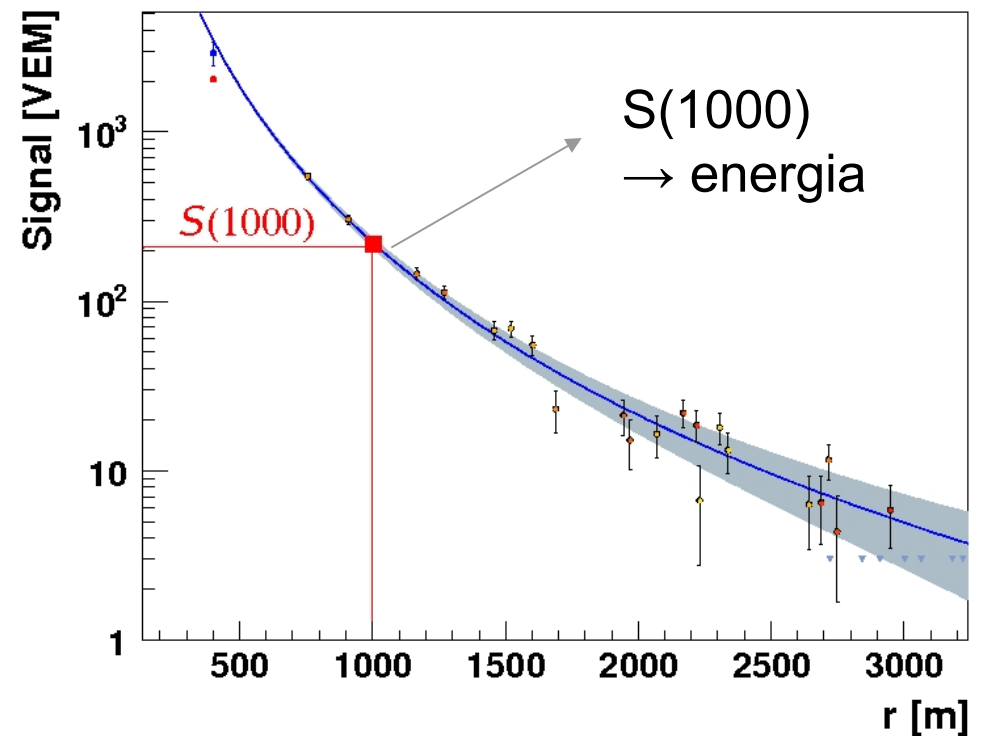
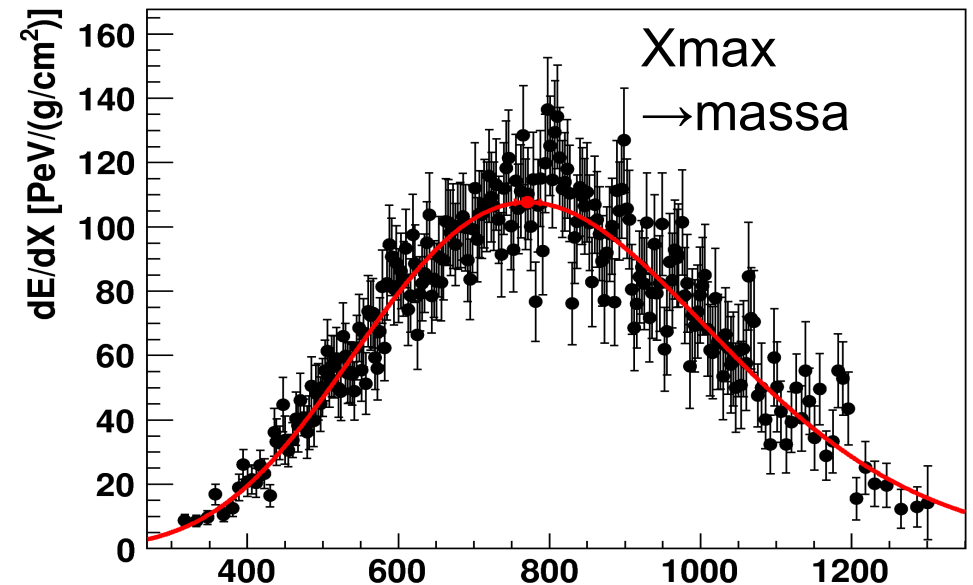
FD – misura calorimetrica

- duty cycle ~ 15%

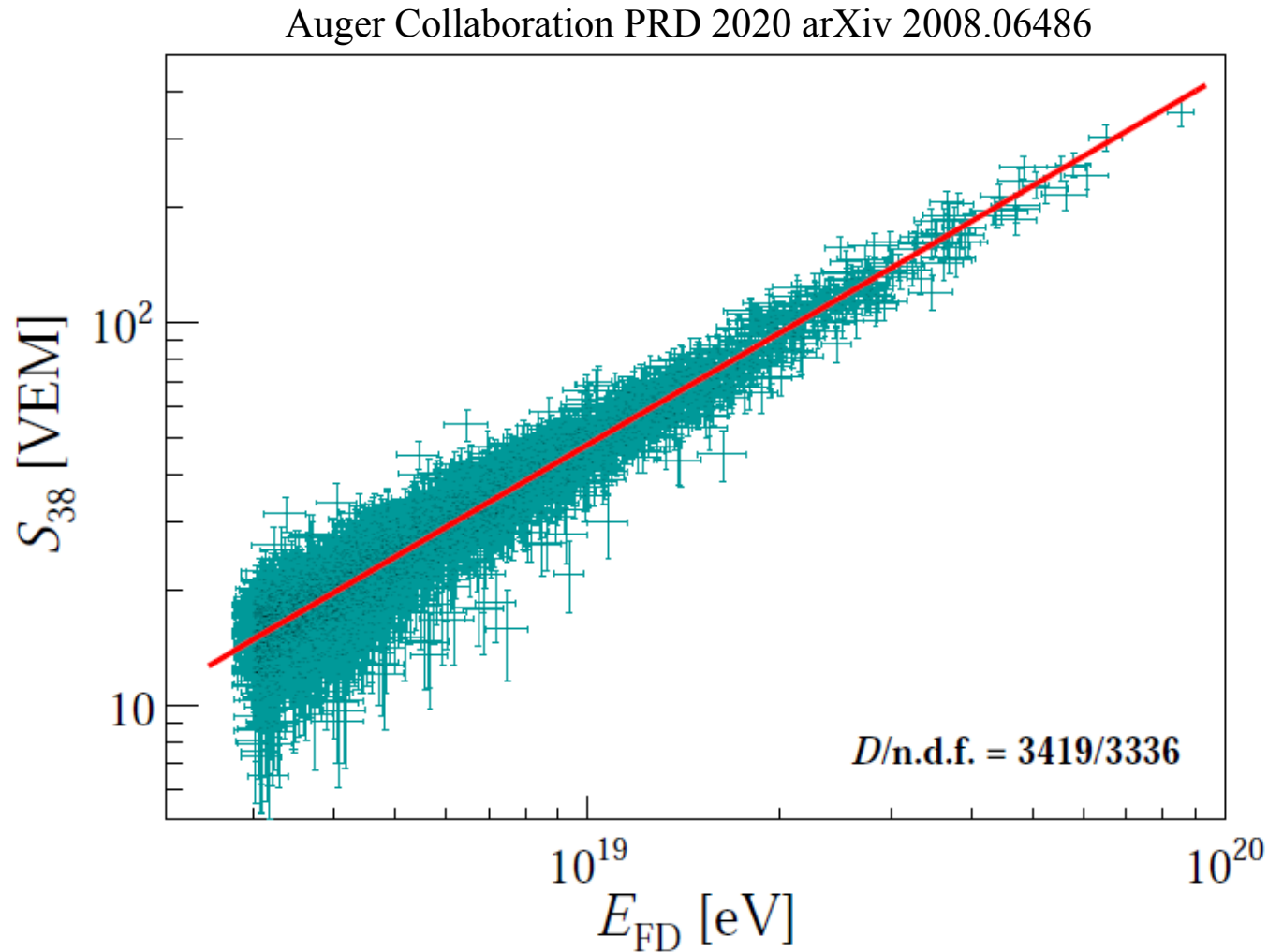
Densità di particelle a terra

SD - duty cycle ~ 100%

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



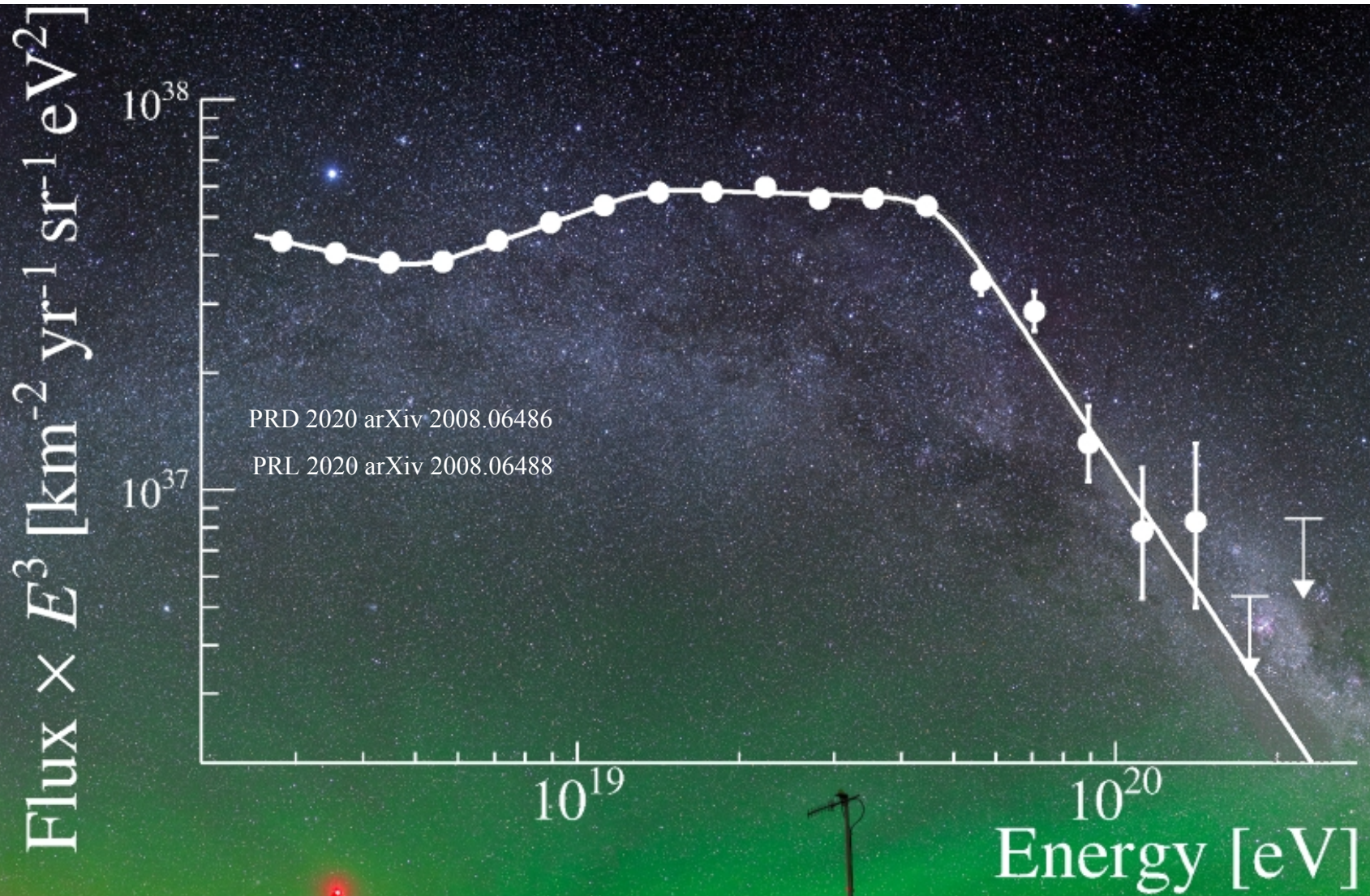
Calibrazione degli eventi del rivelatore di superficie



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

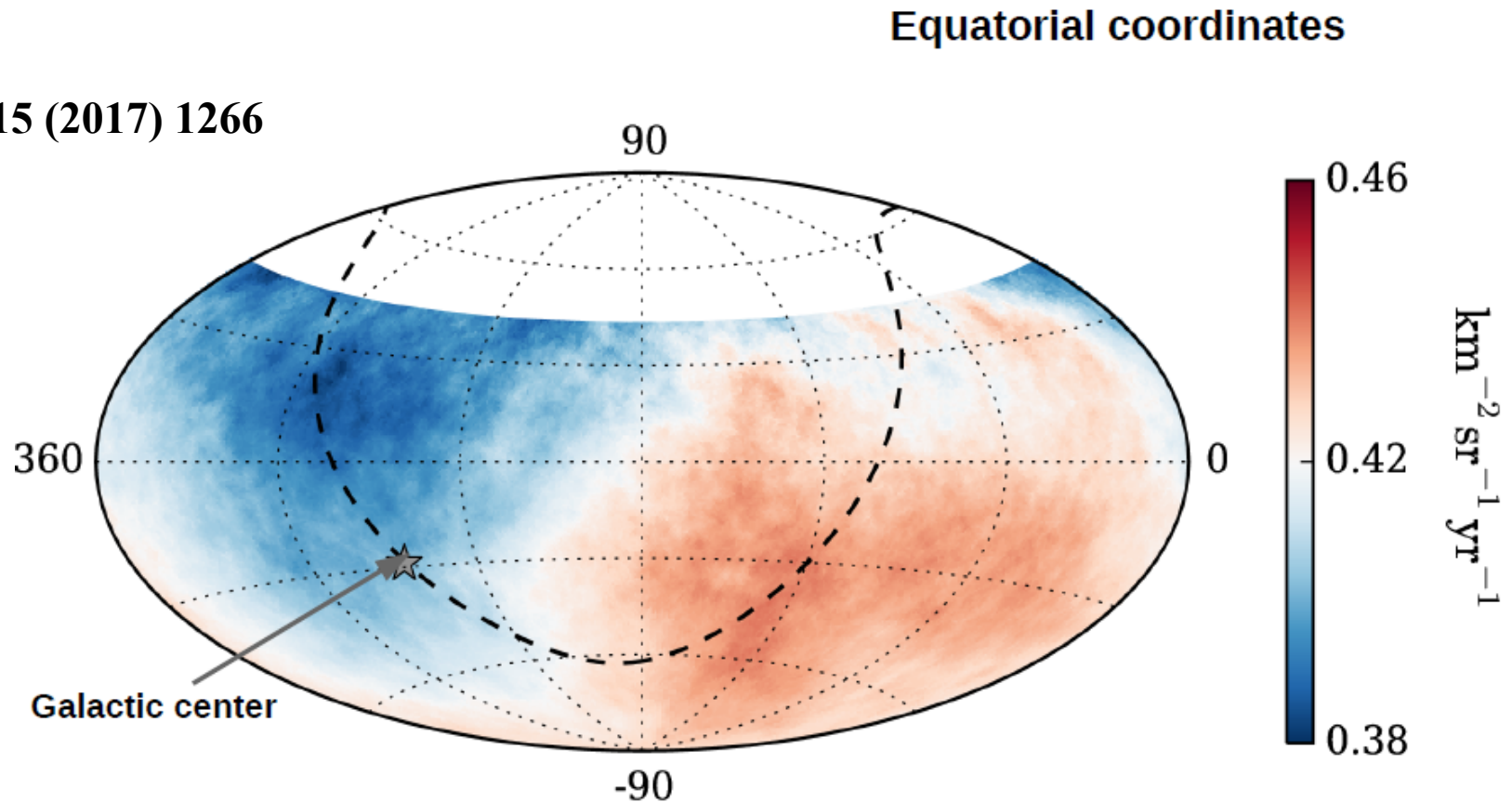


$$E_{\text{max}}/\text{EeV} \sim Z (B / \mu\text{G}) (R / \text{kpc})$$

$$\theta \sim Z / E$$

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 multi messaggeri (e molte collaborazioni!)

THE ASTROPHYSICAL JOURNAL LETTERS, 850:L35 (18pp), 2017 December 1

© 2017. The American Astronomical Society.

OPEN ACCESS

<https://doi.org/10.3847/2041-8213/aa9aed>



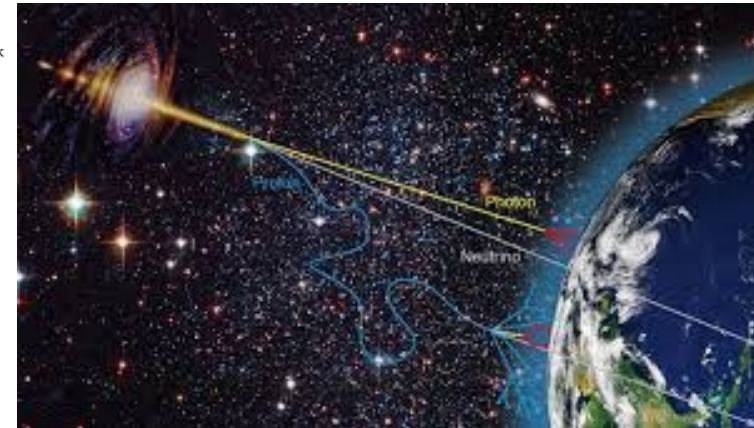
Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

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 burst was detected. We further carried out an extended search in the direction of the GRB localization period following the merger, but found no evidence of high-energy neutrino emission. These results constrain mechanisms in relativistic outflows driven by the binary neutron star merger model predictions of short GRBs observed at a large off-axis angle.



THE ASTROPHYSICAL JOURNAL LETTERS, 850:L35 (18pp), 2017 December 1

Albert et al.

ALLARMI

Osservazione con tutti i rivelatori

- a diverse frequenze

- in diverse finestre temporali

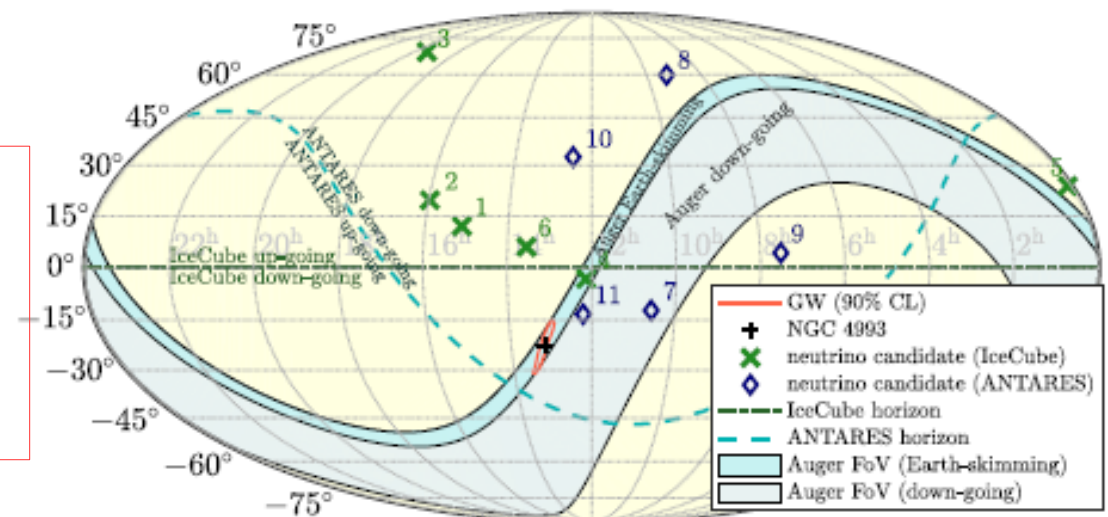
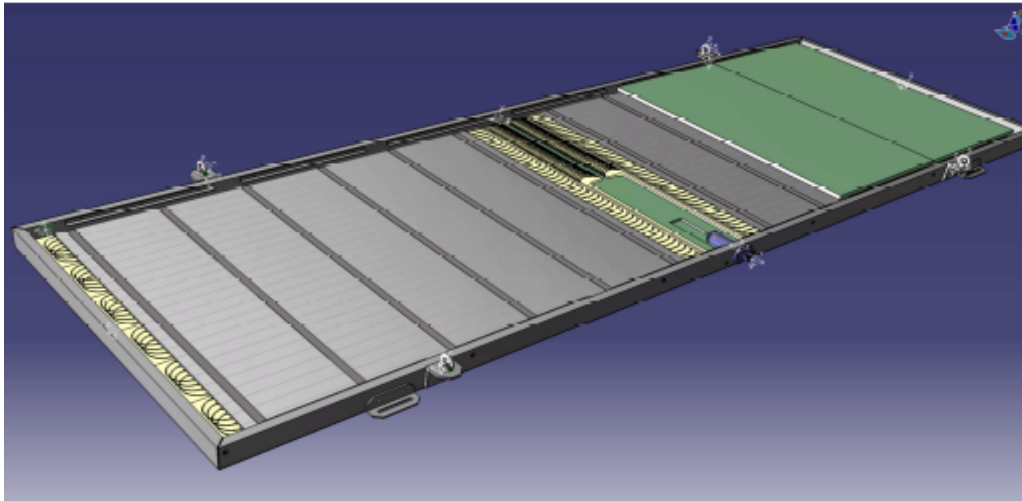


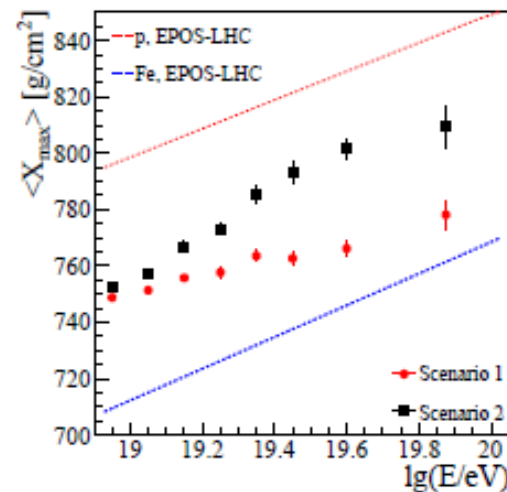
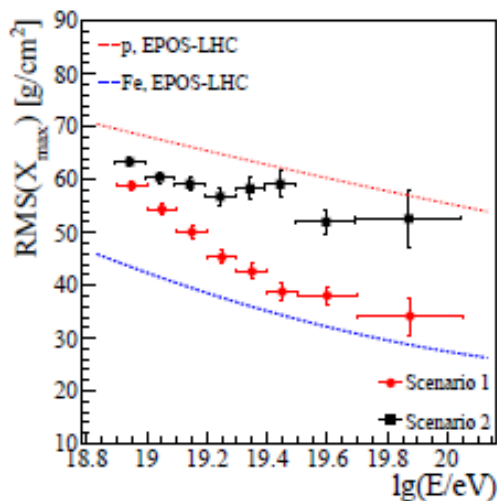
Figure 1. Localizations and sensitive sky areas at the time of the GW event in equatorial coordinates: GW 90% credible-level localization (red contour; Abbott et al. 2017b), direction of NGC 4993 (black plus symbol; Coulter et al. 2017b), directions of IceCube's and ANTARES's neutrino candidates within 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 73.7° 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



In più

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

Scenario 1 : massima rigidità

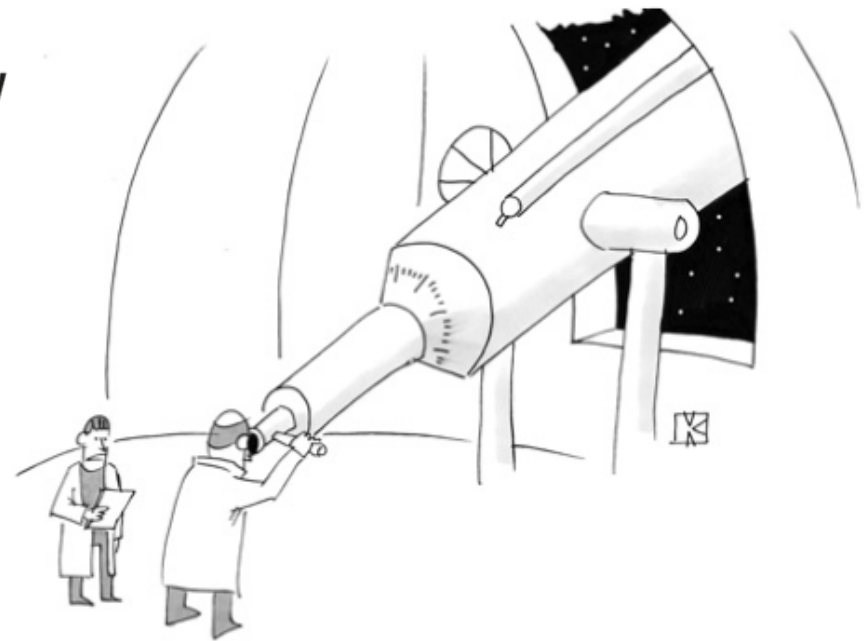
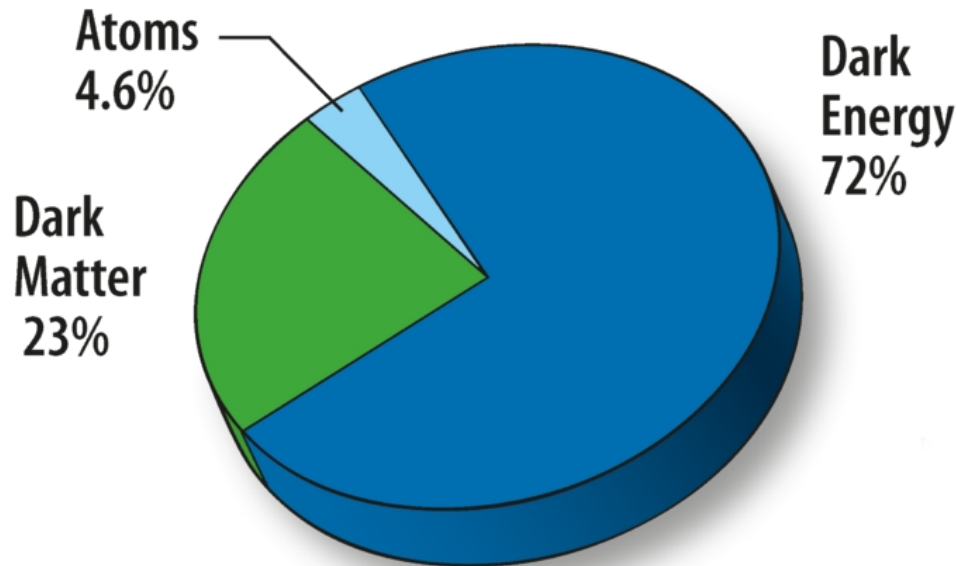
Scenario 2: photo-disintegrazione

“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



The IPPOG Collaboration: <https://ippog.org>



[About](#) [Resources](#) [Activities](#) [News](#) [Events](#) 

Activities

International Masterclasses

Global Cosmics

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.