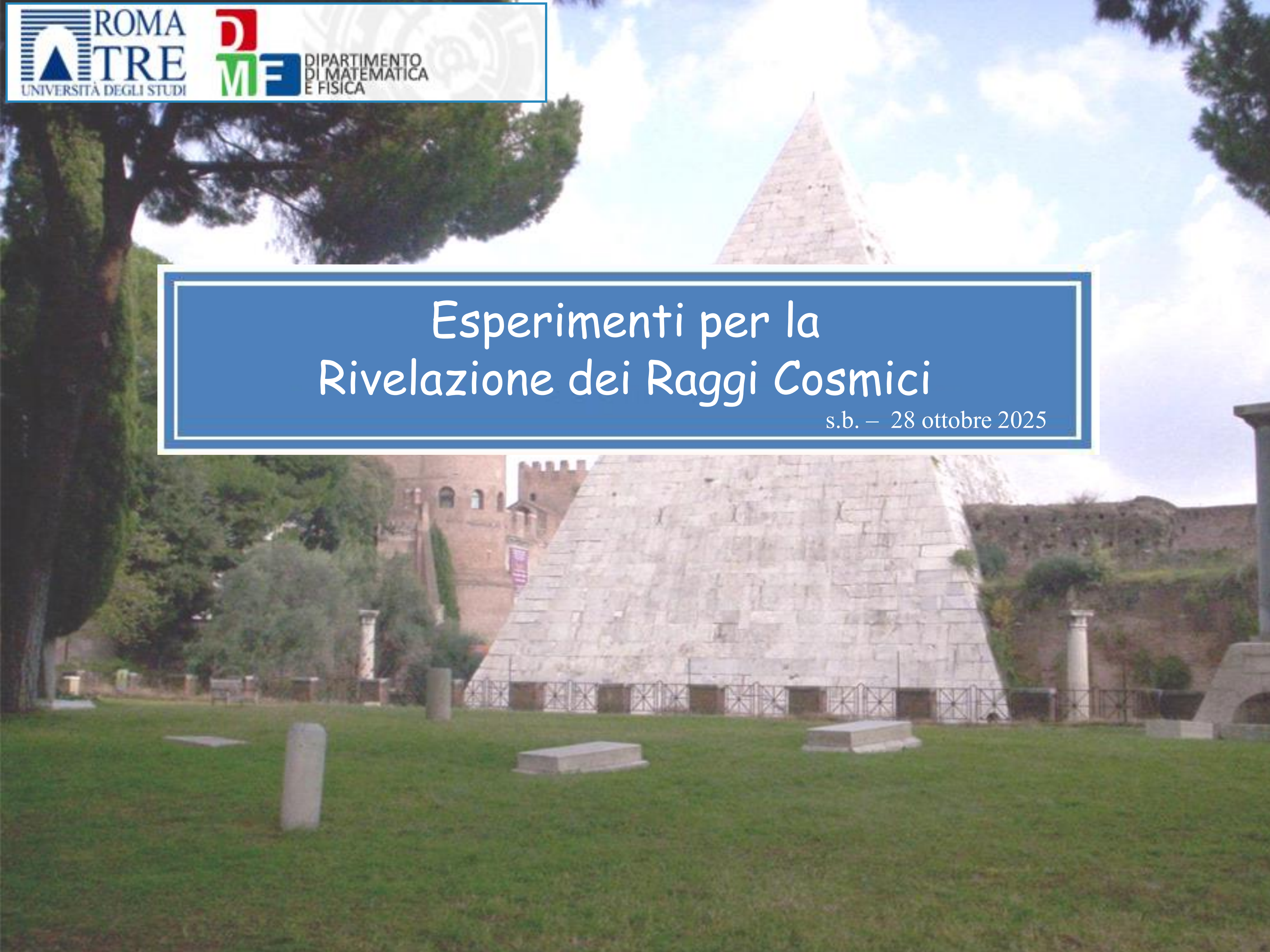


Esperimenti per la Rivelazione dei Raggi Cosmici

s.b. – 28 ottobre 2025

ROMA TRE UNIVERSITÀ DEGLI STUDI
DIPARTIMENTO DI MATEMATICA E FISICA

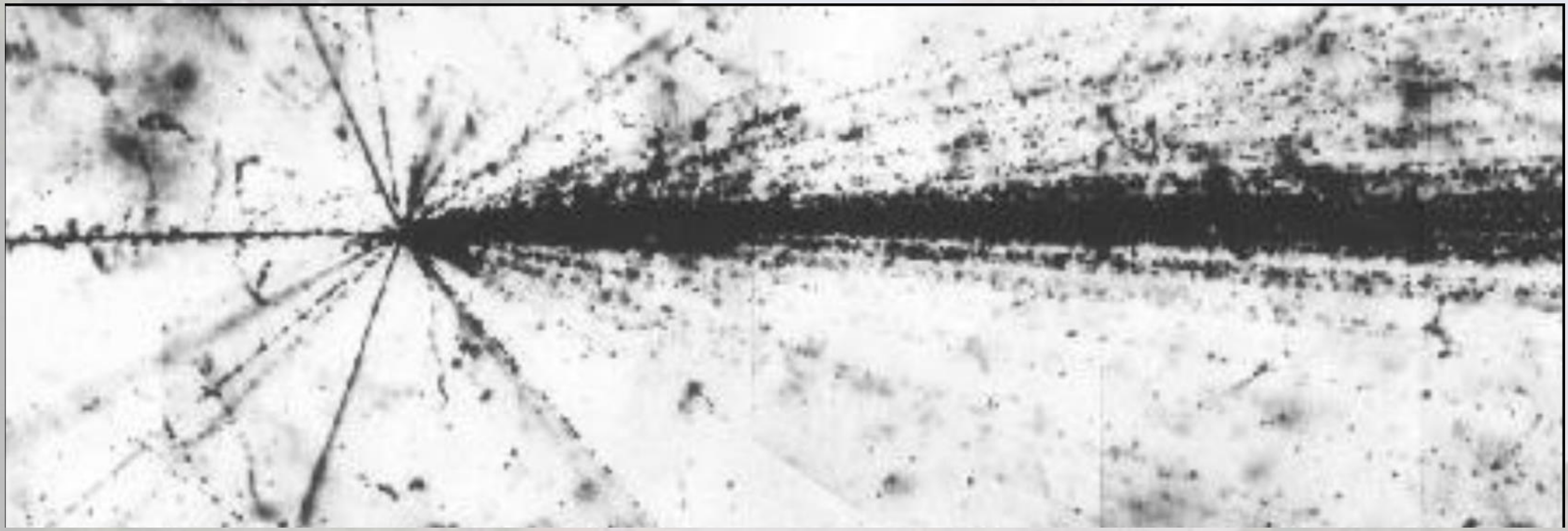
Rivelare i Raggi Cosmici

Rivelazione di Raggi Csomici nello Spazio

Rivelazione di Raggi Cosmici a Terra

Rivelazione di Neutrini

I Raggi Cosmici sono Particelle e per interazione generano alter Particelle



- Posso utilizzare i revelatori descritti da Diego!
    - Come li organizzo?
    - Come costruisco un esperimento?
    - Cosa posso misurare?

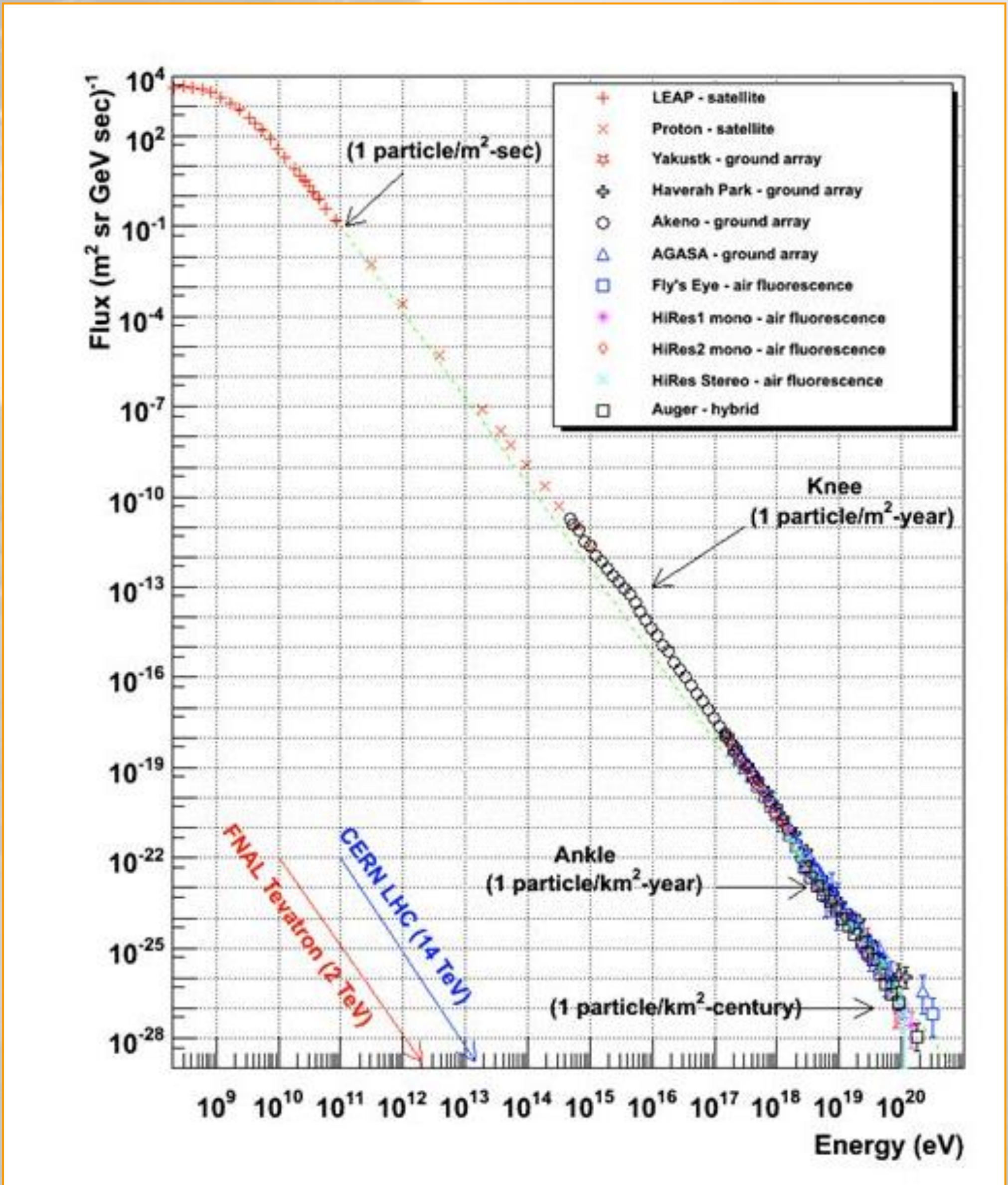
Rivelatori per i Raggi Cosmici (I)

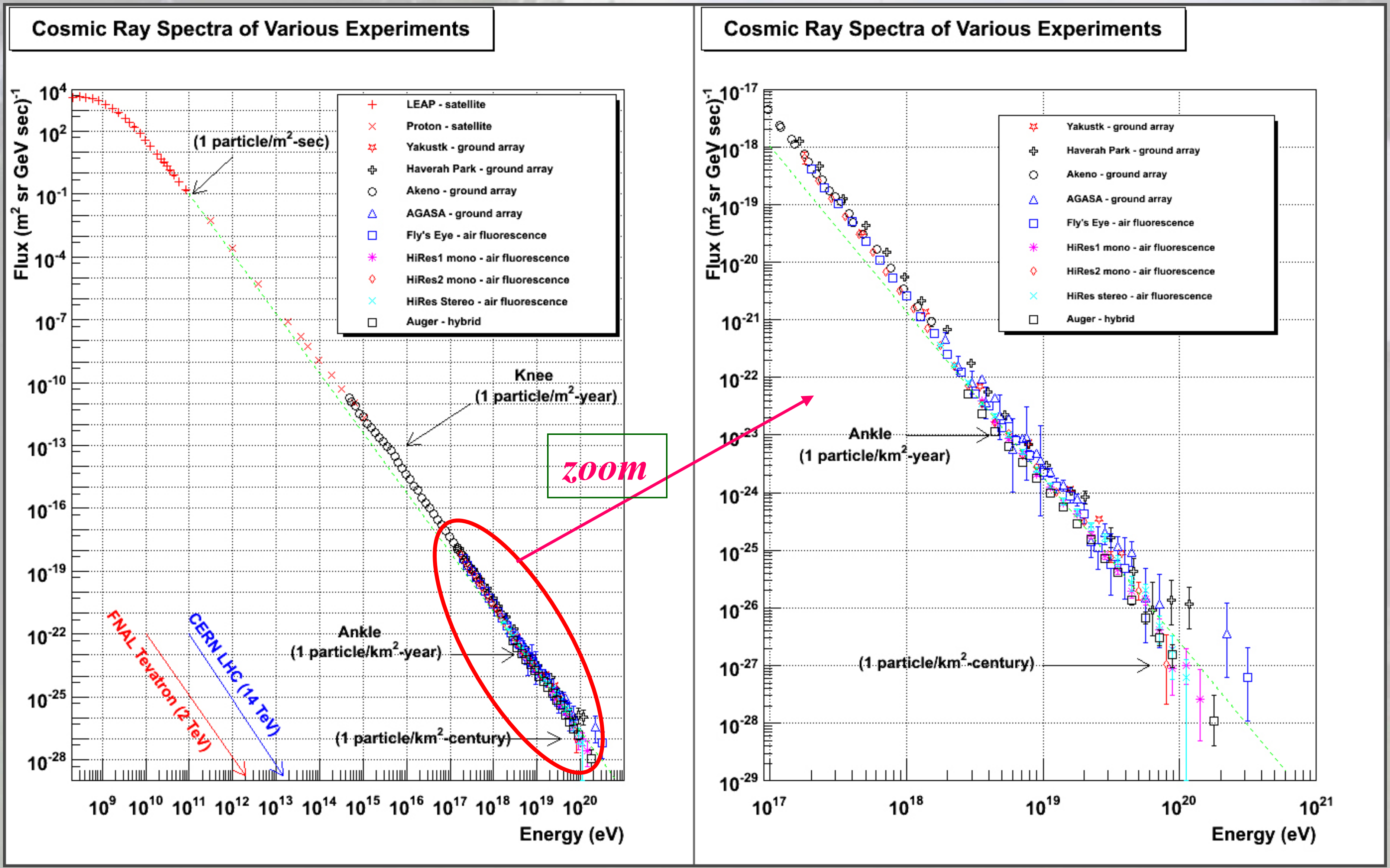
- Lo Scenario Scientifico
  - Quale e’ il loro spettro energetico e la loro composizione
  - Come sono accelerati
  - Posso identificare regioni di provenienza ?

Rivelatori per i Raggi Cosmici (II)

- Misura diretta nello Spazio
  - Esperimenti attuali in presa dati
  - Esperimenti futuri
- Misure a Terra
  - ARGO-YBJ Detector in Tibet (China)
  - LHAASO
  - CTA
  - Auger

Cosmic Rays Spectra and Composition





Cosmic Ray Spectra of Various Experiments
Flux (m² sr GeV sec)⁻¹
(1 particle/m²-sec)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
Knee
(1 particle/m²-year)
zoom
Ankle
(1 particle/km²-year)
(1 particle/km²-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
Energy (eV)
Cosmic Ray Spectra of Various Experiments
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes stereo - air fluorescence
Auger - hybrid
Ankle
(1 particle/km²-year)
(1 particle/km²-century)
Energy (eV)

The Scientific Scenario

«The "Radiation from the Universe" line covers esperiments made in space or at ground aimed at the study of cosmic radiation of any kind. Its scope is at the same time the understanding of the origin, the propagation and the nature of cosmic radiation as well as the study of the Universe itself and its fundamental properties by means of that radiation.»

Astroparticle Physics and Multi-Messenger Astrophysics

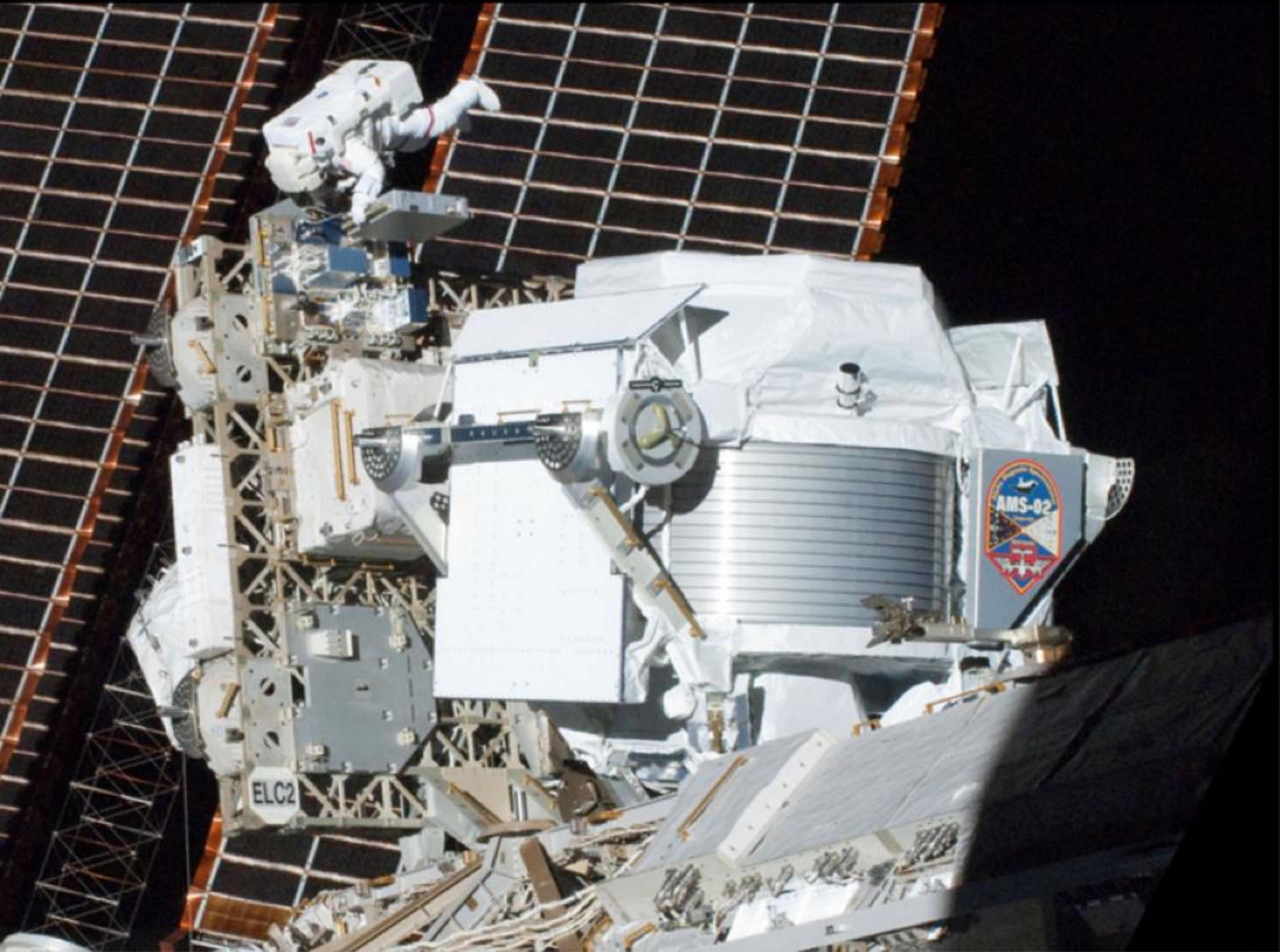
The INFN-CSN2 Strategy document 2018

Misure dirette nello Spazio

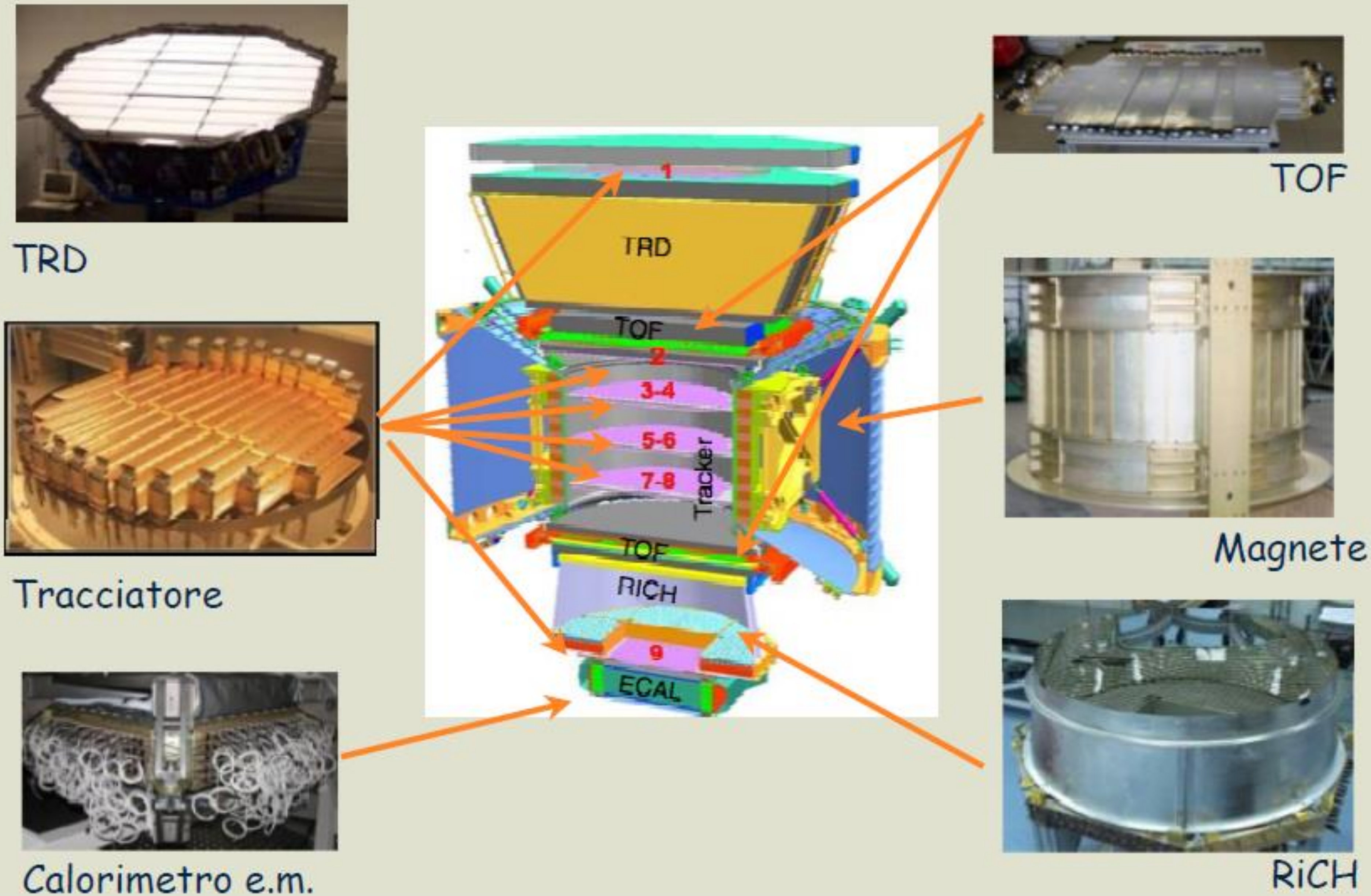
- Esperimenti attuali in presa dati
  - AMS (raggi cosmici carichi)
  - Fermi (raggi gamma)
  - DAMPE
- Esperimenti futuri
  - HERD
  - EUSO

Esperimenti attuali: AMS

- Sulla Stazione Spaziale Internazionale
- Lanciato nel 2011
- https://ams02.space/what-is-ams/ams-in-nutshell


AMS-02
ELC2

AMS2



TRD
Tracciatore
Calorimetro e.m.
1
TRD
TOF
2
3-4
5-6
7-8
Tracker
TOF
RICH
9
ECAL
TOF
Magnete
RiCH

Rivelatore a microstrip di silicio (300 μm)

Basato sulla Ridondanza

TRD	identificazione e^+ e^-
Tracciatore	Z, P
Calorimetro e.m.	Energia di e^+ e^- γ
TOF	Z, E
Magnete (0.15 T)	$\pm$ Z
RiCH	Z, E

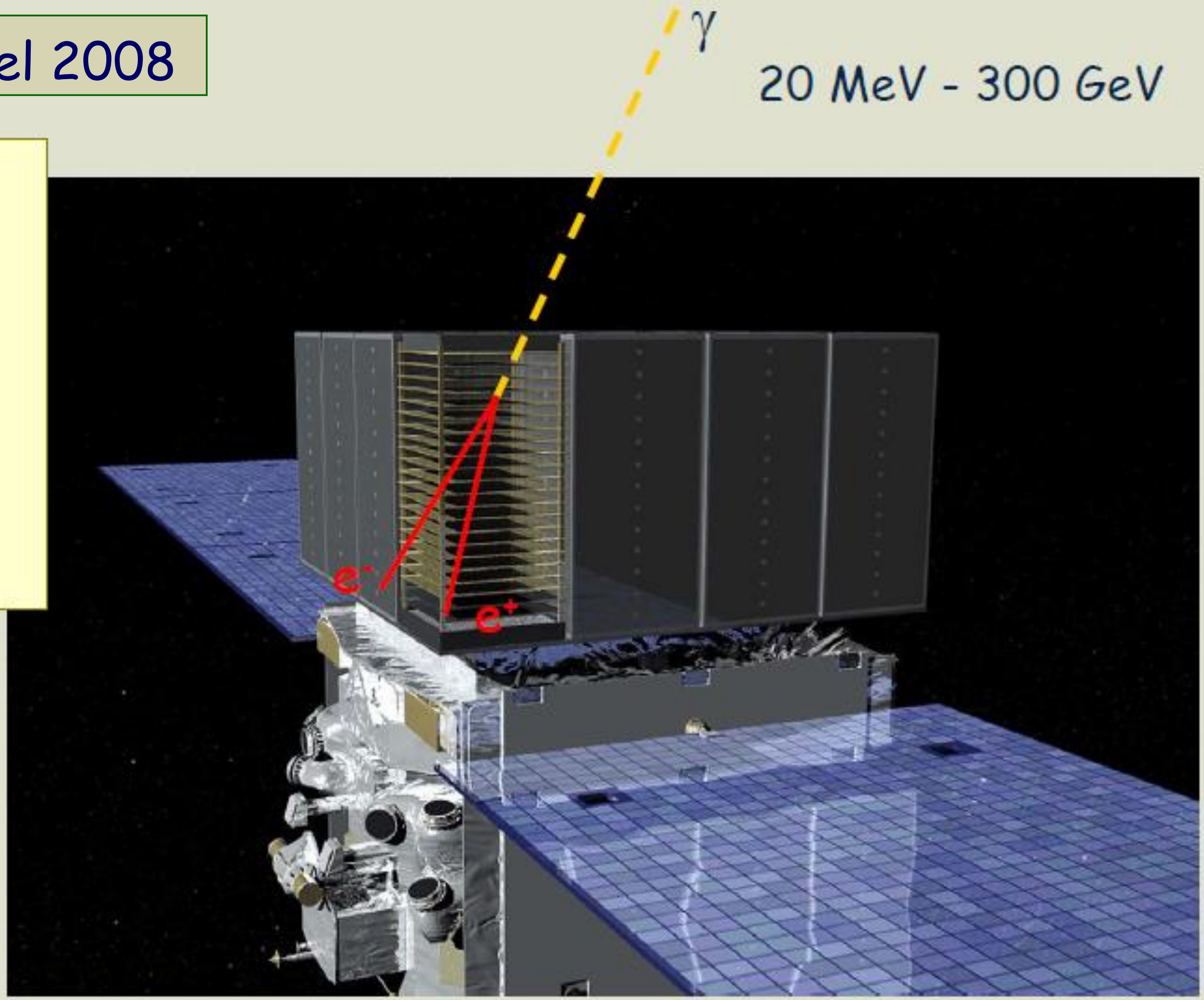
5 anni di dati - 82 miliardi di eventi

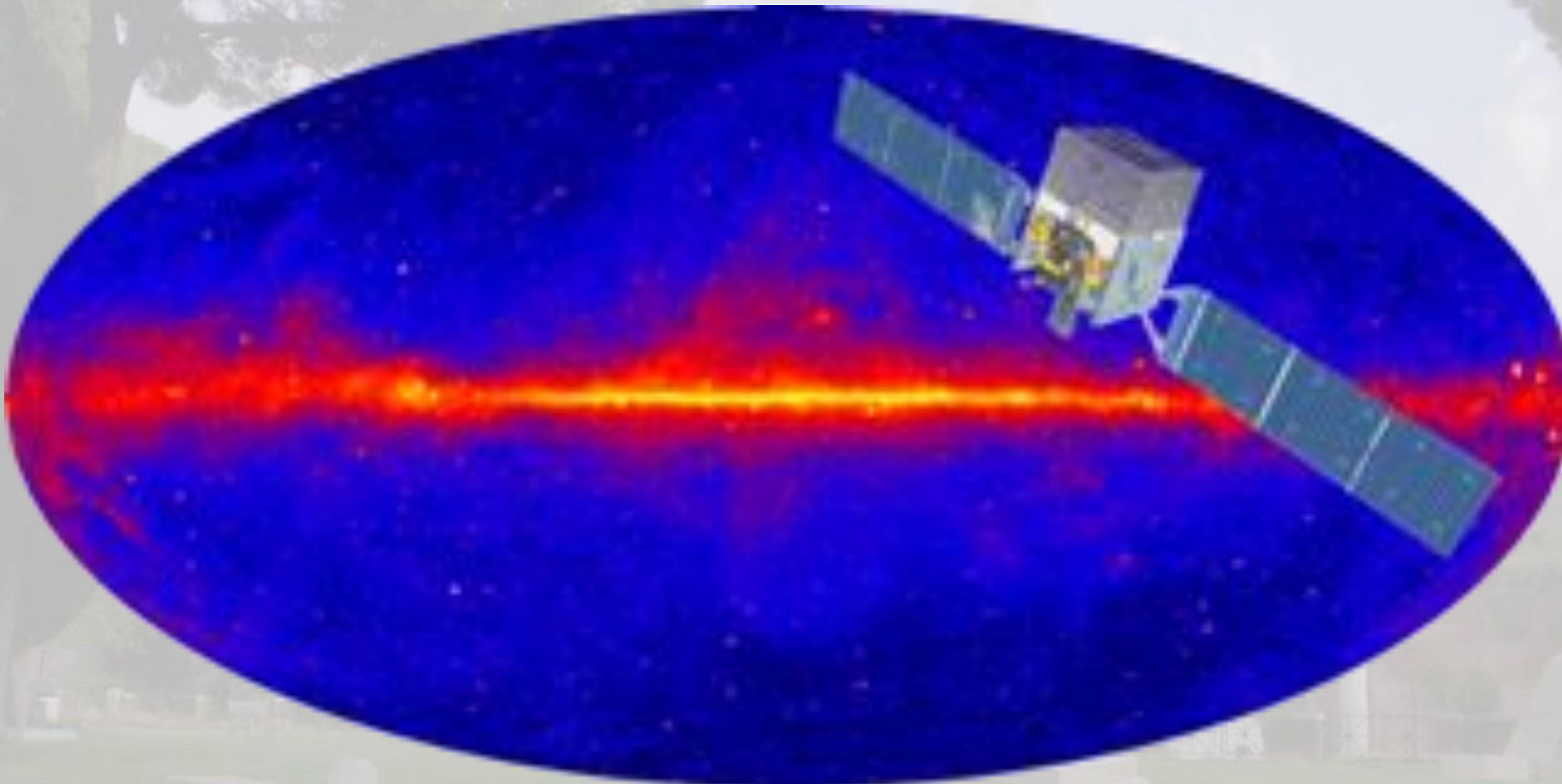
Esperimenti attuali: Fermi

Lanciato nel 2008

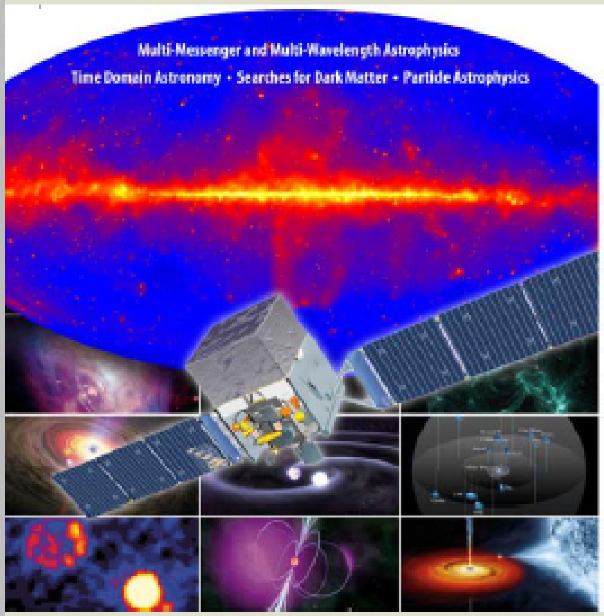
- Grande campo di vista
- Range di energia esteso

20 MeV - 300 GeV





Temi scientifici



- Messaggeri cosmici

  fotoni, elettroni

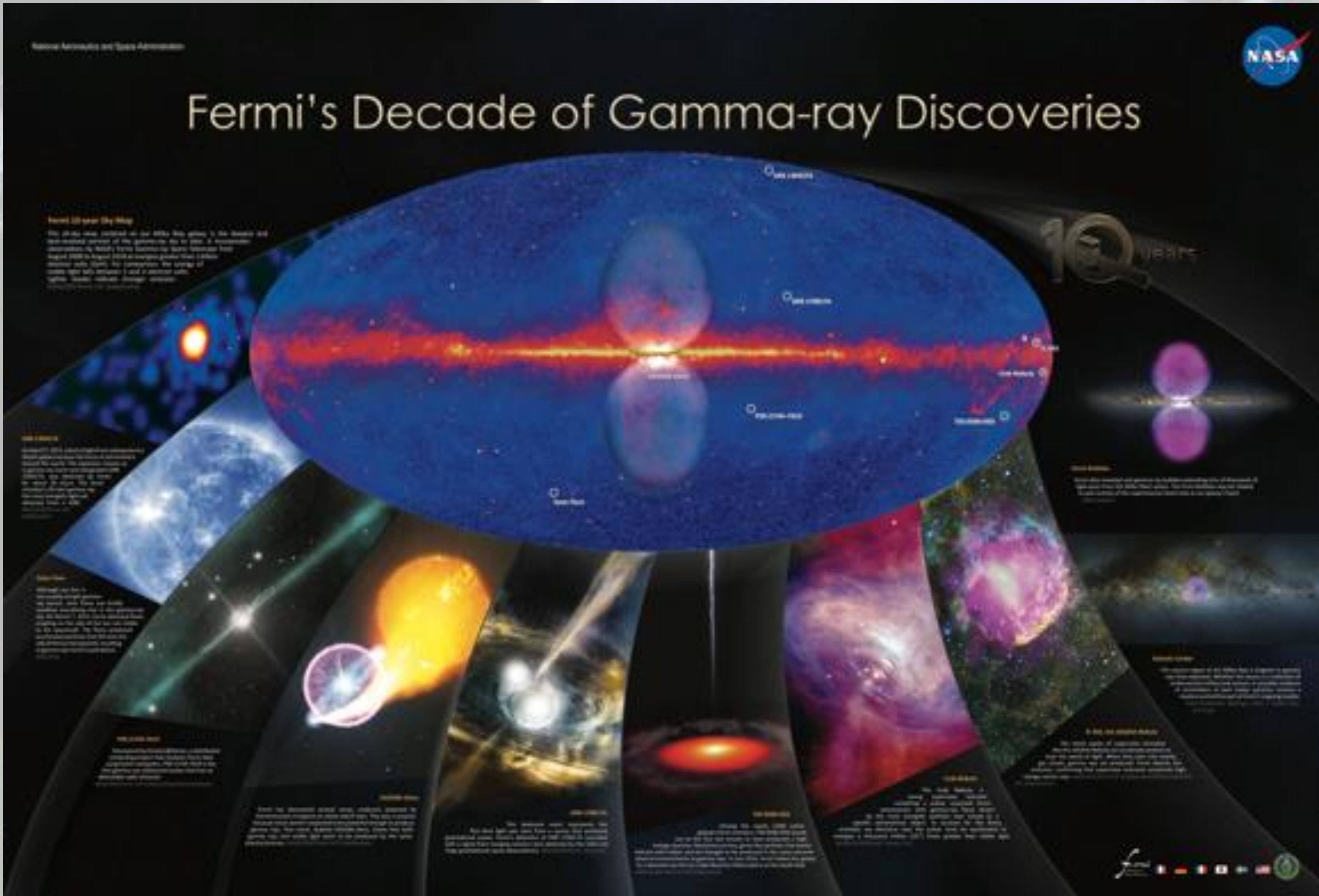
- Astrofisica nel tempo da transienti di decine di microsecondi ad emissioni periodiche di anni

- Materia Oscura

  WIMP e ALPs

- Astro-particelle

  siti e accelerazione dei raggi cosmici

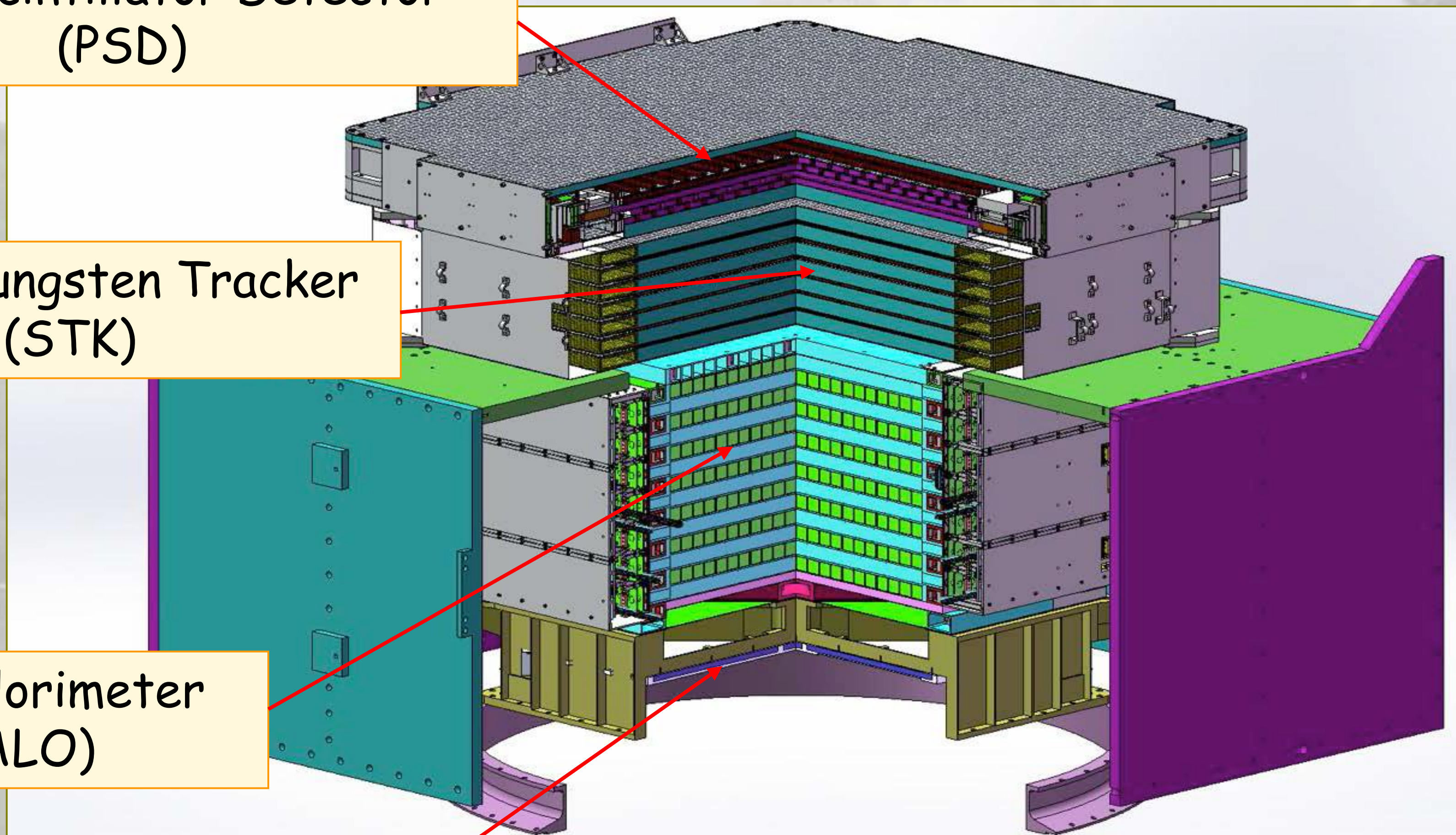

Fermi's Decade of Gamma-ray Discoveries
NASA

Esperimenti attuali: DAMPE

Obiettivi

- Studio dello spettro di elettroni e fotoni di origine cosmica;
- Studio dei raggi cosmici (protoni e nuclei).
  Spettro e composizione;
- Astronomia gamma ad alta energia;
- Ricerca di Dark Matter
- Fenomeni esotici e non attesi

Satellite Cinese - Lanciato nel 2015


Plastic Scintillator Detector (PSD)
Silicon-Tungsten Tracker (STK)
BGO Calorimeter (CALO)
Neutron Detector (NUD)

nature
International journal of science

LETTER

doi:10.1038/nature24475

Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of electrons and positrons

DAMPE Collaboration*

High-energy cosmic-ray electrons and positrons (CREs), which lose energy quickly during their propagation, provide a probe of Galactic high-energy processes[1–7] and may enable the observation of phenomena such as dark-matter particle annihilation or decay[8–10]. The CRE spectrum has been measured directly up to approximately 2 teraelectronvolts in previous balloon- or space-borne experiments[11–16], and indirectly up to approximately 5 teraelectronvolts using ground-based Cherenkov γ-ray telescope arrays[17,18]. Evidence for a spectral break in the teraelectronvolt energy range has been provided by indirect measurements[17,18], although the results were qualified by sizeable systematic uncertainties. Here we report a direct measurement of CREs in the energy range 25 gigaelectronvolts to 4.6 teraelectronvolts by the Dark Matter Particle Explorer (DAMPE)[19] with unprecedentedly high energy resolution and low background. The largest part of the spectrum can be well fitted by a 'smoothly broken power-law' model rather than a single power-law model. The direct detection of a spectral break at about 0.9 teraelectronvolts confirms the evidence found by previous indirect measurements[17,18], clarifies the behaviour of the CRE spectrum at energies above 1 teraelectronvolt and sheds light on the physical origin of the sub-teraelectronvolt CREs.

The Dark Matter Particle Explorer (DAMPE; also known as 'Wukong' in China), which was launched into a Sun-synchronous orbit at an altitude of about 500 km on 17 December 2015, is a high-energy particle detector optimized for studies of CREs and γ-rays up to about 10 TeV. The DAMPE instrument, from top to bottom, consists of a plastic scintillator detector, a silicon–tungsten tracker-converter detector, a bismuth germanium oxide (BGO) imaging calorimeter, and a neutron detector[19]. The plastic scintillator detector measures the charge of incident particles with a high nuclear resolution up to atomic number $Z = 28$, and aids in the discrimination between photons and charged particles. The silicon–tungsten tracker-converter detector measures the charge and trajectory of charged particles, and reconstructs the direction of γ-rays converting into e^+e^- pairs. The BGO calorimeter[20], with a total depth of about 32 radiation lengths and about 1.6 nuclear interaction lengths, measures the energy of incident particles and provides efficient CRE identification. The neutron detector further improves the electron/proton discrimination at teraelectronvolt energies[19]. With the combination of these four sub-detectors, DAMPE has achieved effective rejection of the hadronic cosmic-ray background and much improved energy resolution for CRE measurements[19]. In 2014 and 2015 the DAMPE engineering qualification model (see Methods) was extensively tested using test beams at the European Organization for Nuclear Research (CERN). The test beam data demonstrated excellent energy resolution for electrons and

proton background are therefore crucial for reliable measurement of the CRE spectrum. As the major instrument onboard DAMPE, the BGO calorimeter ensures a well contained development of electromagnetic showers in the energy range of interest. The electron/proton discrimination method relies on an image-based pattern recognition, as adopted in the ATIC experiment[23]. It exploits the topological differences of the shower shape between hadronic and electromagnetic particles in the BGO calorimeter. This method, together with the event pre-selection procedure, is found to be able to reject >99.99% of the protons while keeping 90% of the electrons and positrons. The details of electron identification are presented in Methods (for example, in Extended Data Fig. 1 we show the consistency of the electron/proton discrimination between the flight data and the Monte Carlo simulations). Figure 1 illustrates the discrimination power of DAMPE between electrons and protons with deposited energies of 500–1,000 GeV, using the BGO images only.

The results reported in this work are based on data recorded between 27 December 2015 and 8 June 2017. Data collected while the satellite was passing the South Atlantic Anomaly has been excluded from the analysis. During these approximately 530 days of operation, DAMPE recorded more than 2.8 billion cosmic-ray events, including around 1.5 million CREs above 25 GeV. Figure 2 shows the corresponding CRE spectrum measured from the DAMPE data (see Table 1 for more details), compared with previously published results from the space-borne experiments AMS-02[14] and Fermi-LAT[16], as well as the ground-based experiment of the H.E.S.S. Collaboration[17,18]. The contamination

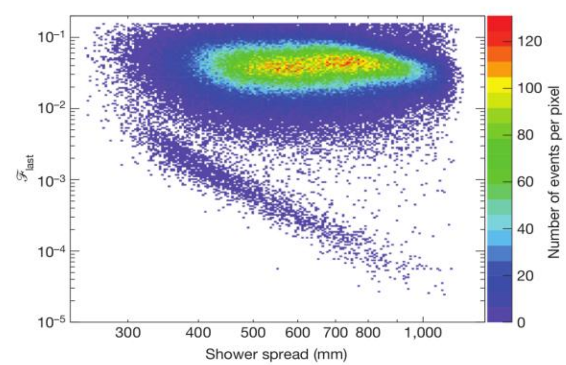


Figure 1 | Discrimination between electrons and protons in the

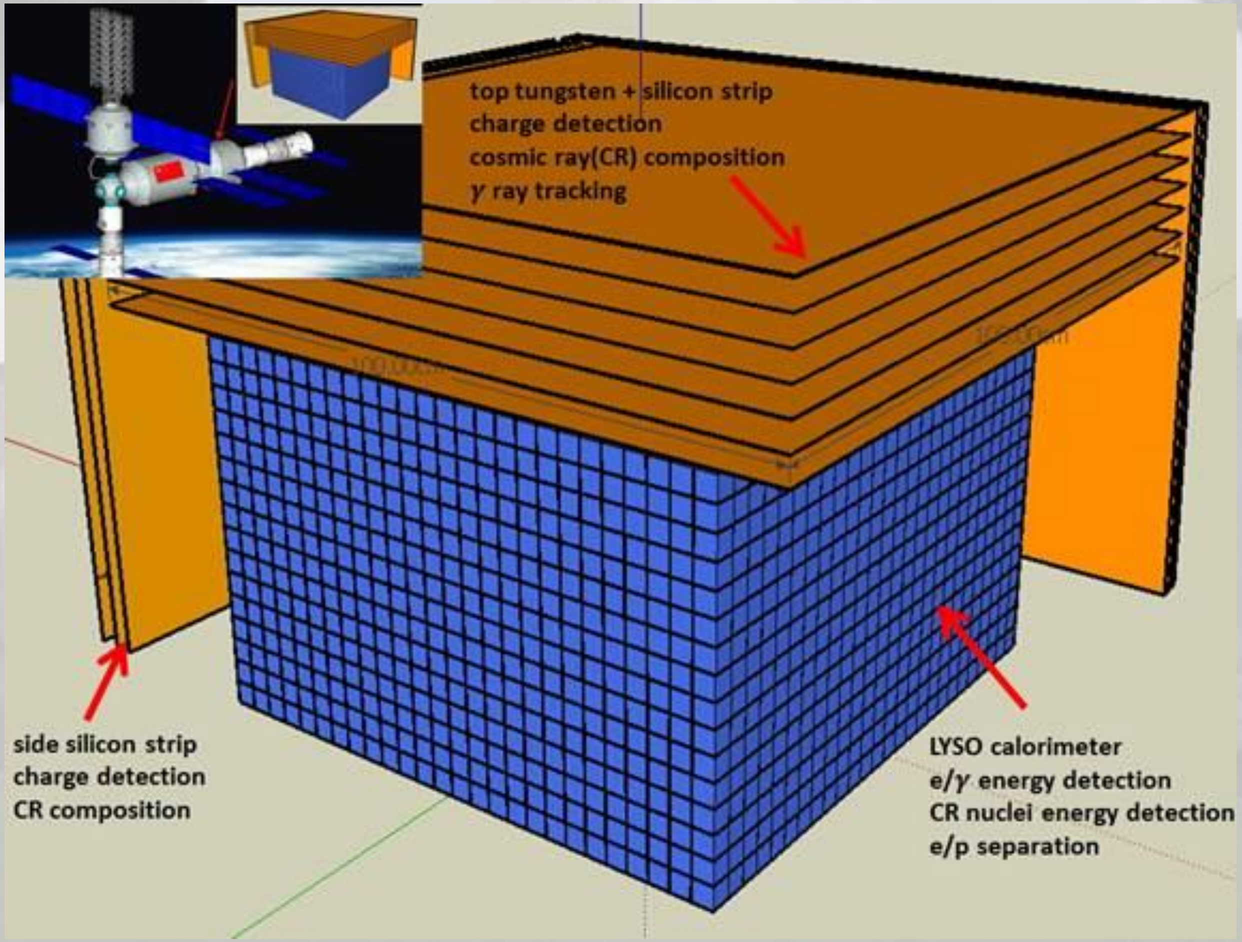
Esperimenti Futuri: HERD

10-15 m^2 sr yr

Calorimetro

Tracciatore a silici

scintillatore plastico

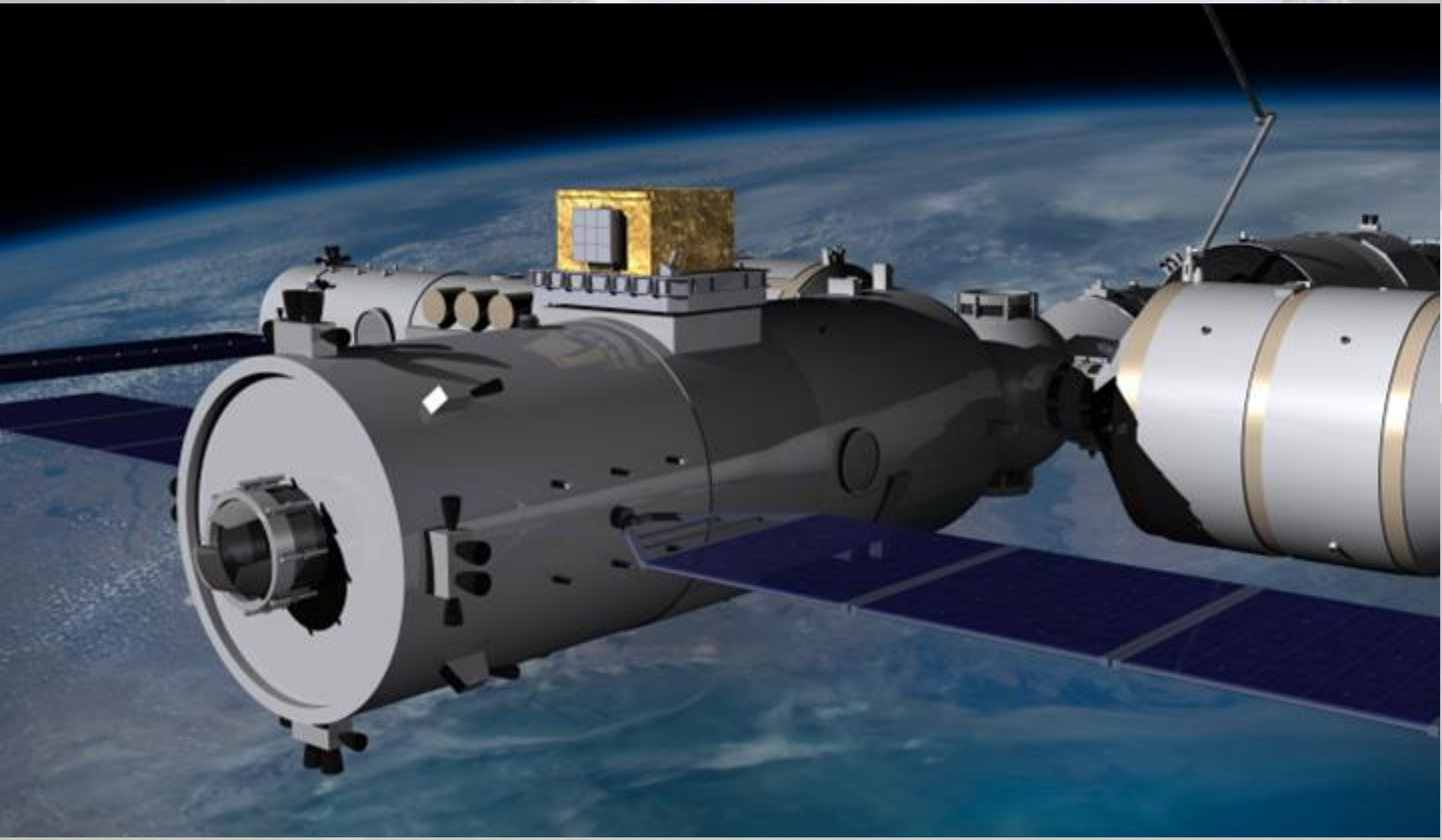


http://herd.ihep.ac.cn/

Caratteristiche

- Charge measurement (dE/dx in PSD, STK and BGO)
- Tungsten converter (pair production)
- Precise tracking (silicon strips)
- Thick calorimeter (BGO bars)
- Hadron rejection (neutron detector)

L'apparato permette la rivelazione di elettroni e gamma tra 10 GeV e 10 TeV e protoni e nuclei nell'intervallo 50 GeV - 500 TeV, con una eccellente risoluzione in energia, precisione di tracciamento e capacita' di identificazione.



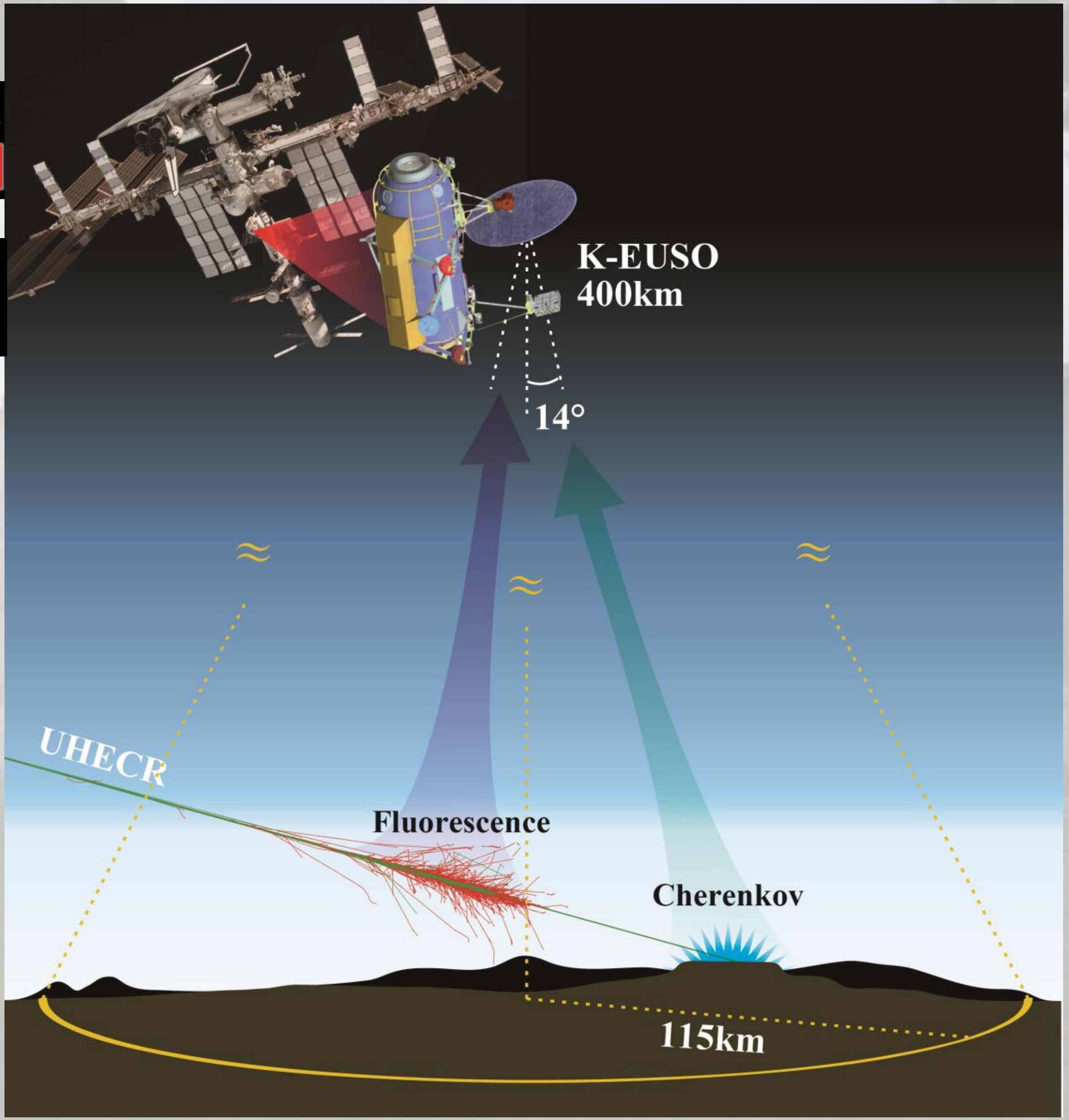
Satellite Cinese - Lancio previsto nel 2027

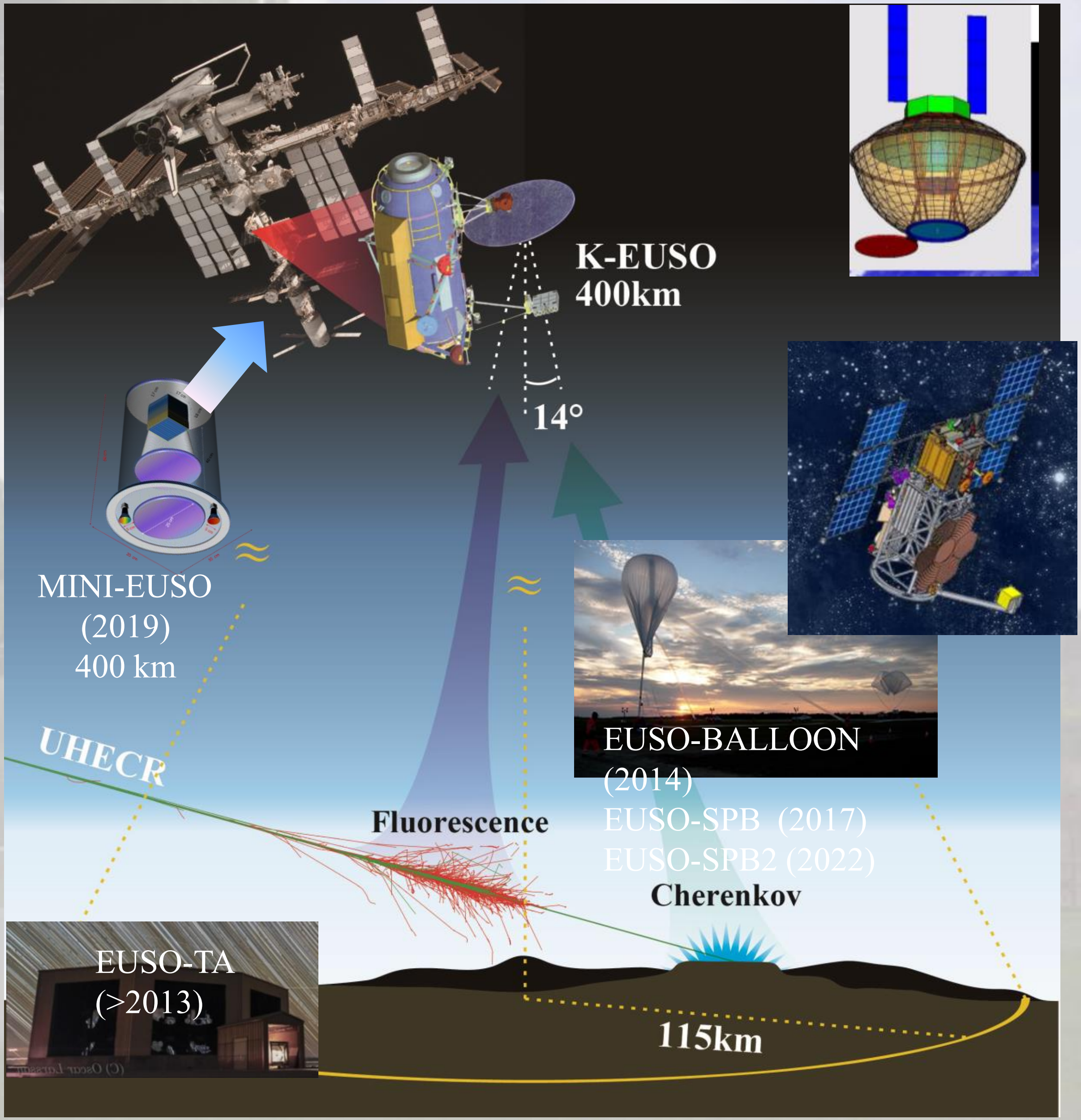
Temi scientifici

HERD(High Energy Cosmic Radiation Detection) facility is one of the Cosmic Lighthouse Program onboard China's Space Station, planned to be launched and assembled in 2020. The main science objectives of HERD onboard china's space station are detecting dark matter particle, study of cosmic ray composition and high energy gamma-ray observations. The main constraints imposed on HERD are: total weight less than around 2 tons and total power consumption less than around 2 kilowatts.

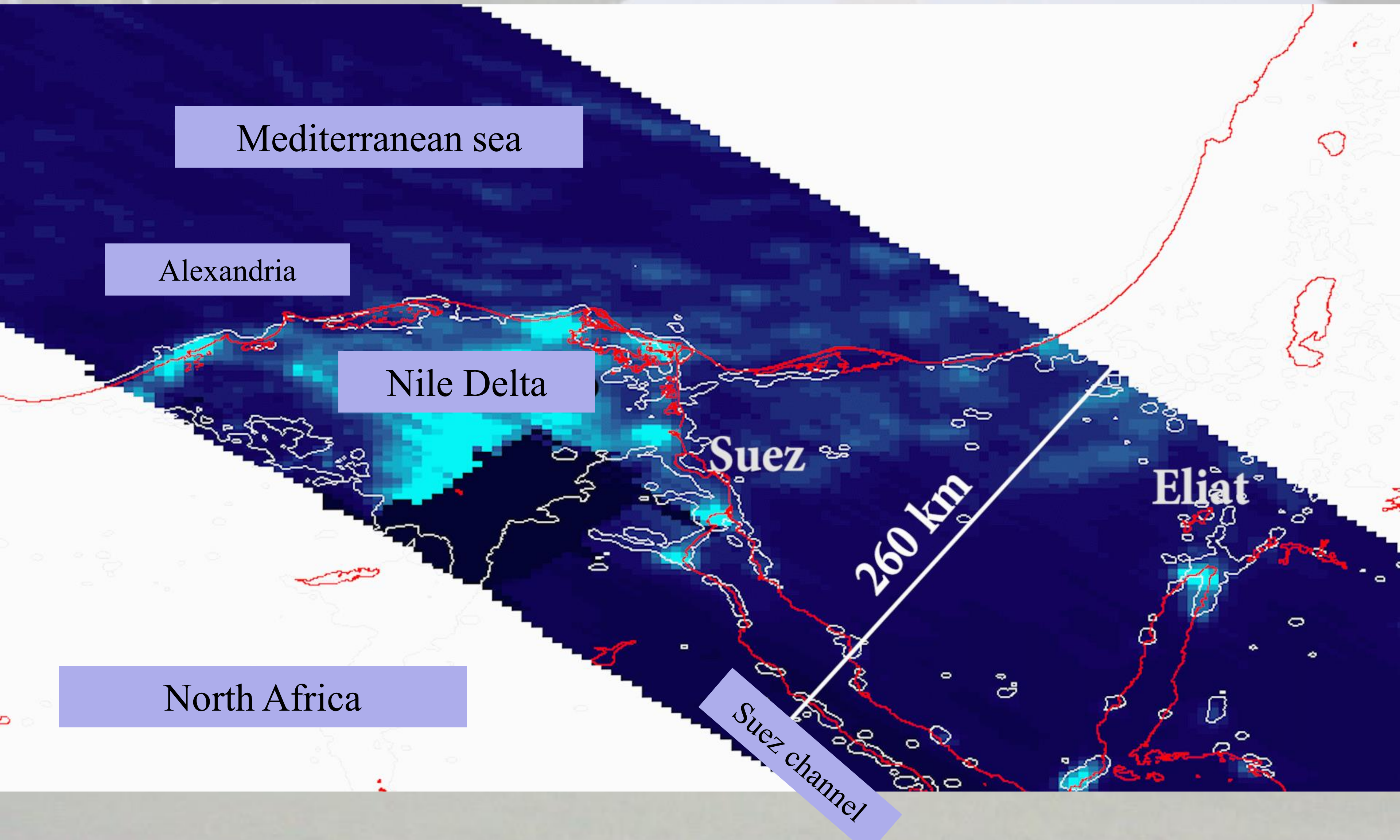
To achieve HERD's science objectives, HERD must have the capability of accurate electron and gamma-ray energy and direction measurement (tens of GeV – 10TeV), adequate cosmic ray energy measurement with charge determination (up to PeV).

Esperimenti Futuri: EUSO




K-EUSO
400km
14°
MINI-EUSO
(2019)
400 km
UHECR
Fluorescence
EUSO-BALLOON
(2014)
EUSO-SPB (2017)
EUSO-SPB2 (2022)
Cherenkov
EUSO-TA
(>2013)
115km

Egypt and Suez Channel



Rivelatori a Terra

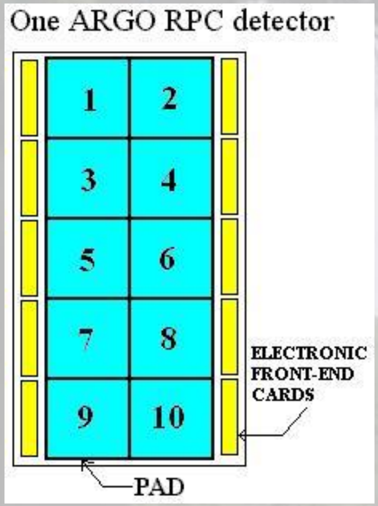
- ARGO-YBJ Detector in Tibet (China)
- LHAASO
- CTA
- Auger

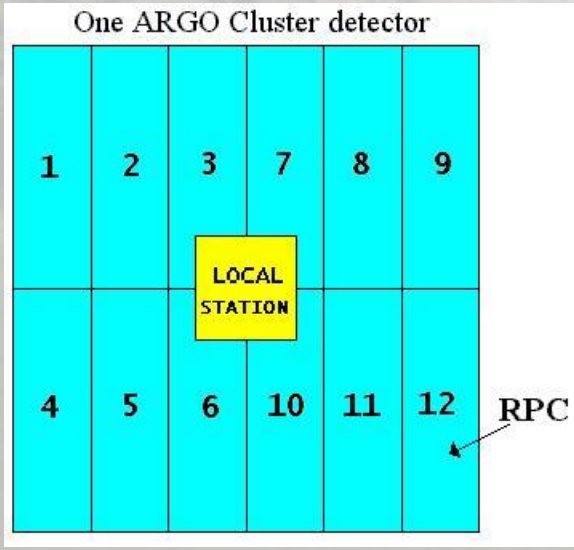
ARGO-YBJ

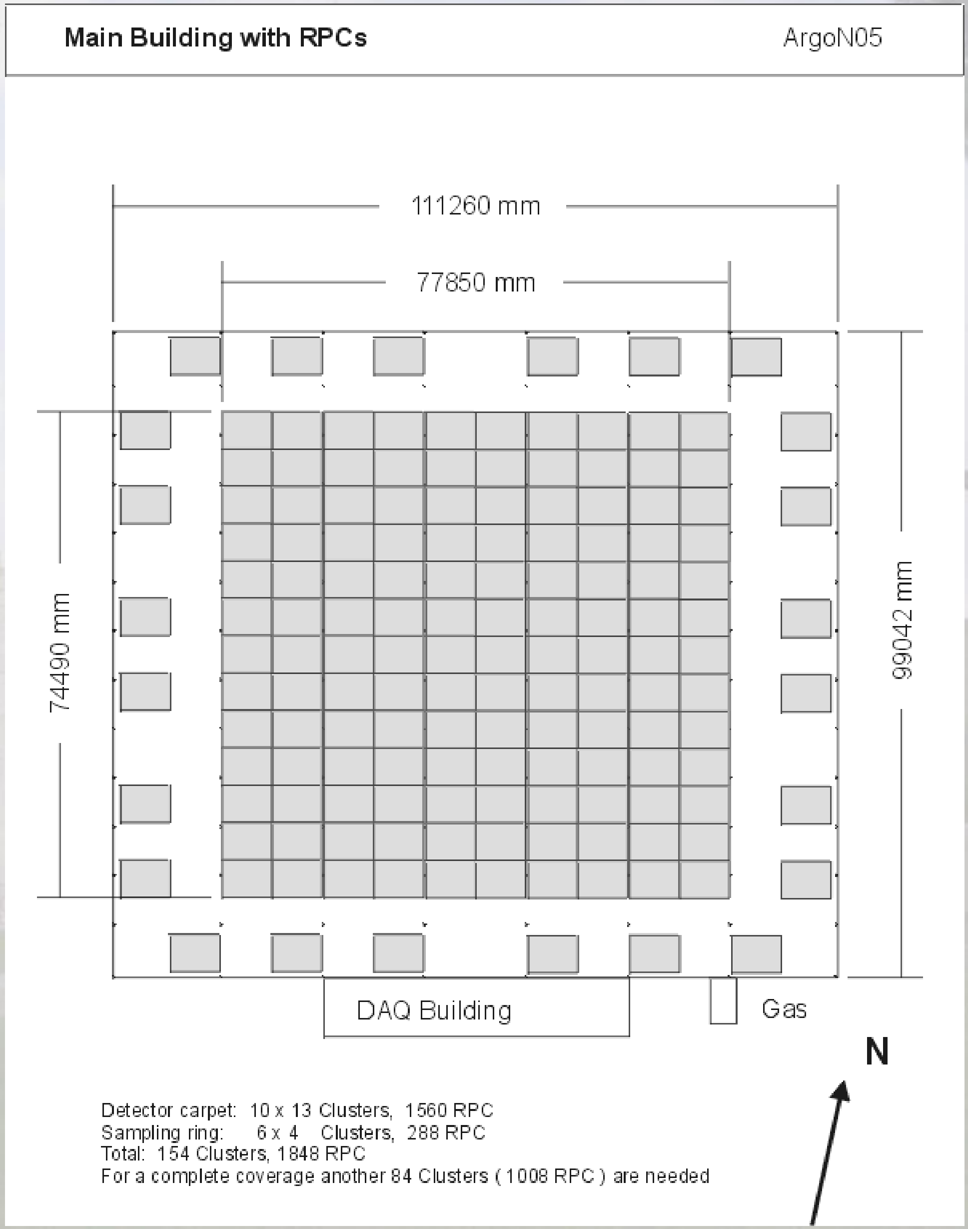
Installato in Tibet (China) vicino a Lhasa a 4300 m

- The Detector
  - Structure
  - Performance
  - Scientific Goals
- Some results in the field of Cosmic Rays
  - The knee of Cosmics Rays
  - A Bayes unfolding procedure
  - The result

The Detector: Structure







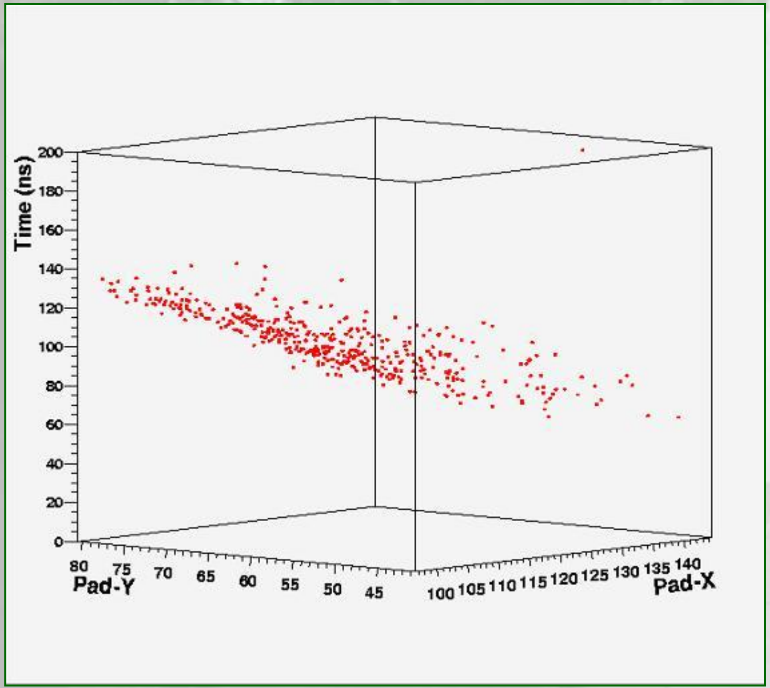
The Detector: Performance

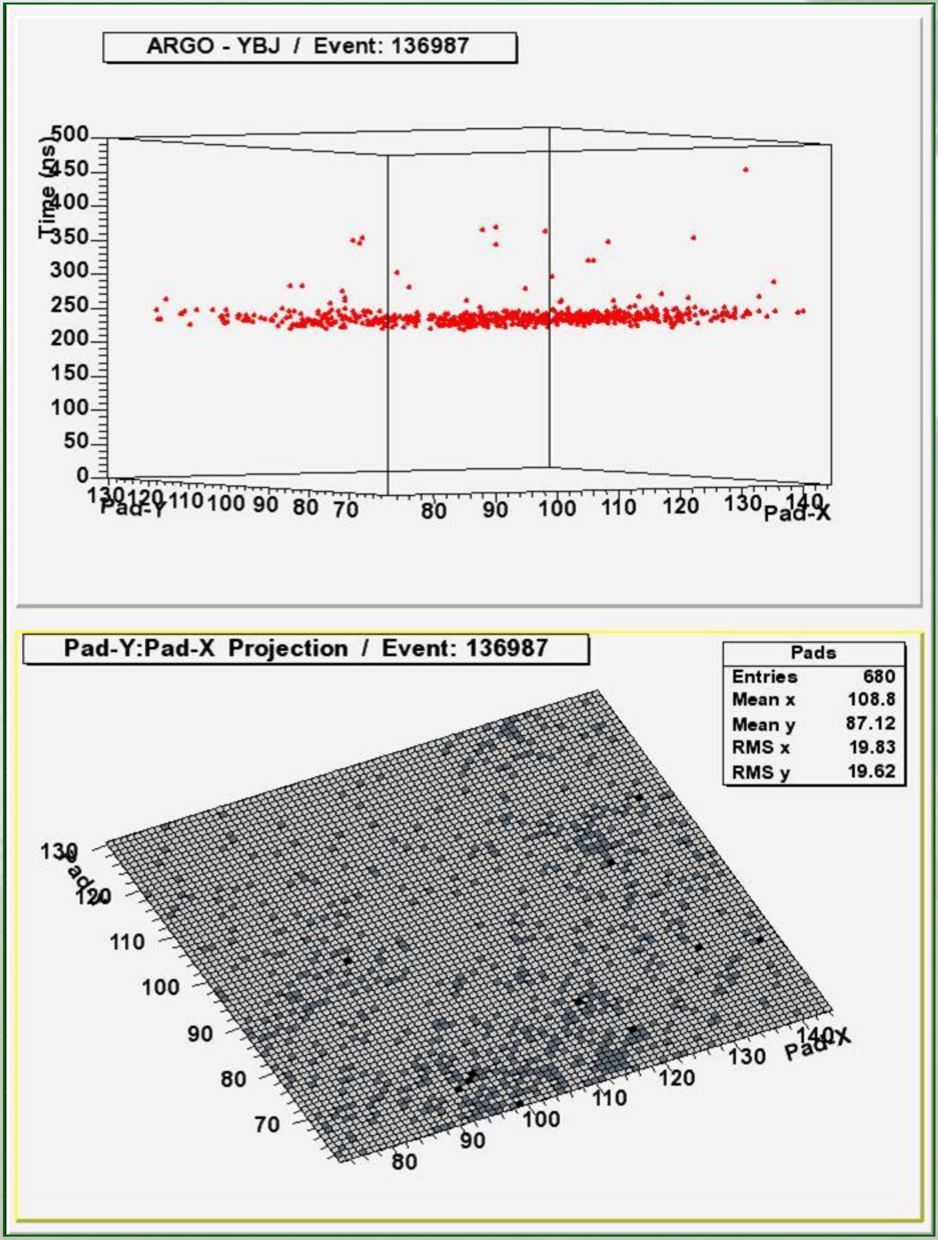
- altezza sul livello del mare > 4000 m (E_{th} ~ 100 GeV)
- grande area attiva del rivelatore (~ 6000 m^2)
- immagine dello sciame ad alta granularità (~ 0.3 m^2)
- risoluzione temporale ~ 1 ns ($\Rightarrow$ ris. ang. ~ 1^o)
- ciclo di funzionamento 100 %

The Detector: Scientific Goals

- Astronomia Gamma
- Misura del rapporto tra il flusso di antiprotoni/protoni
- Gamma Ray Bursts
- Spettro dei Raggi Cosmici primari
- Fisica Solare

Some results in the field of Cosmic Rays

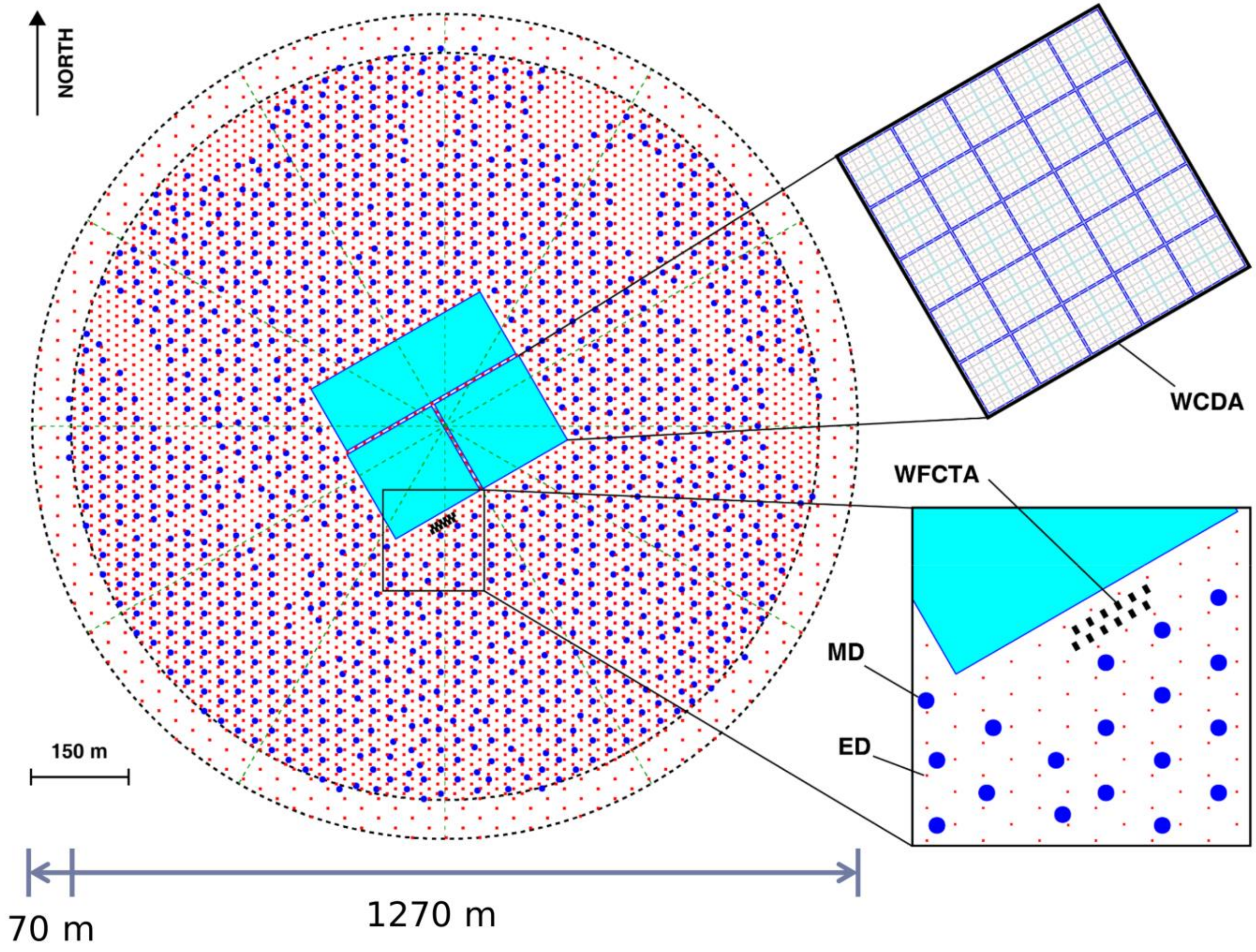


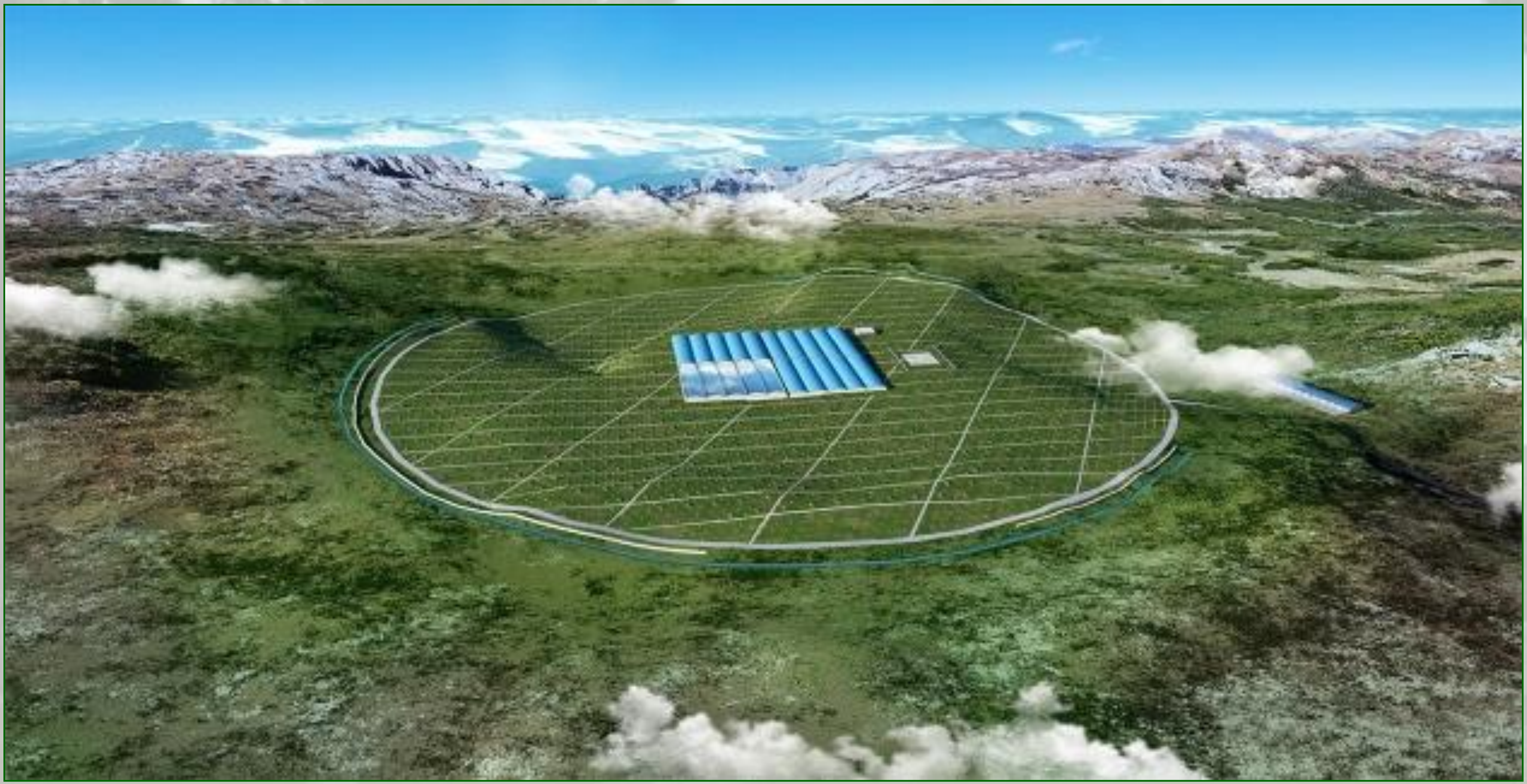


- The knee of Cosmics Rays
- A Bayes unfolding procedure
- The result

LHAASO

Layout of LHAASO Detectors





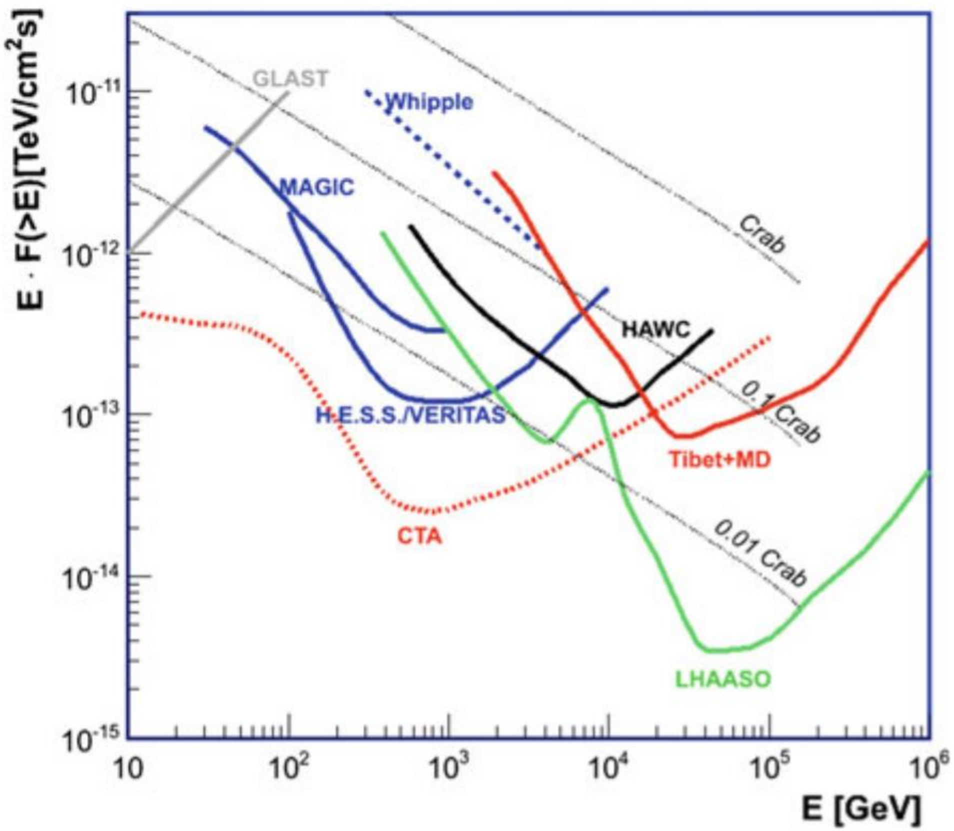
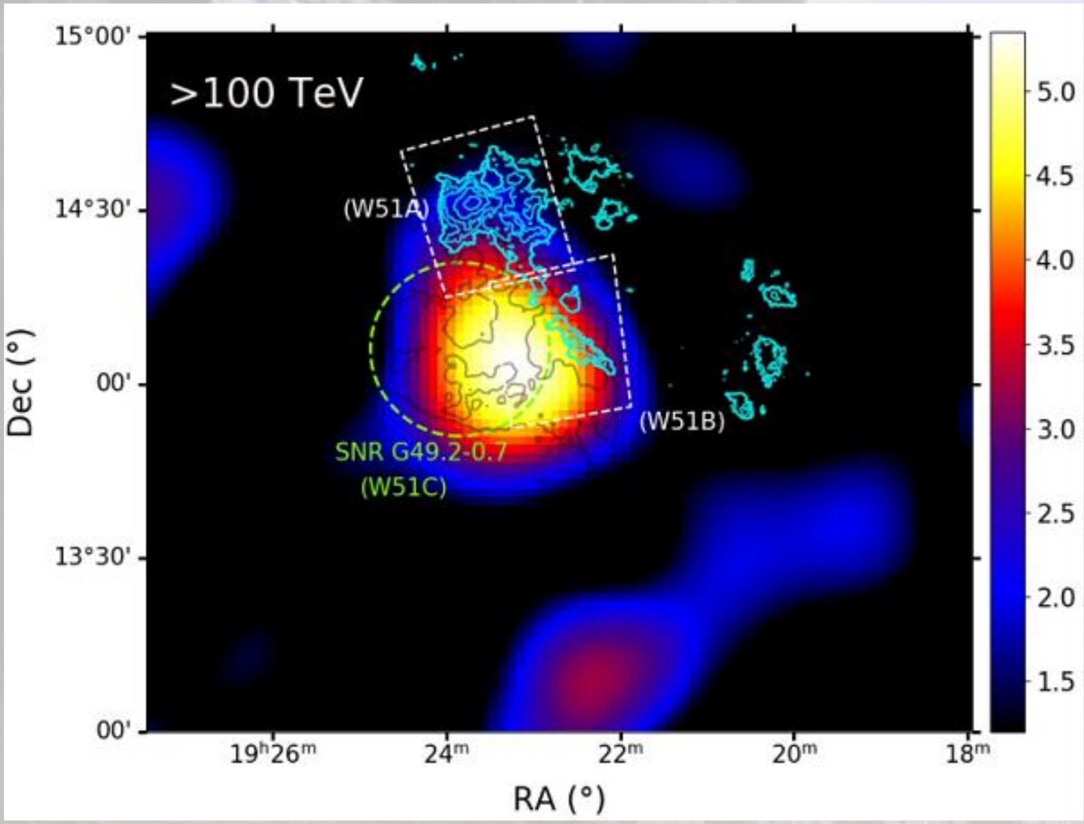
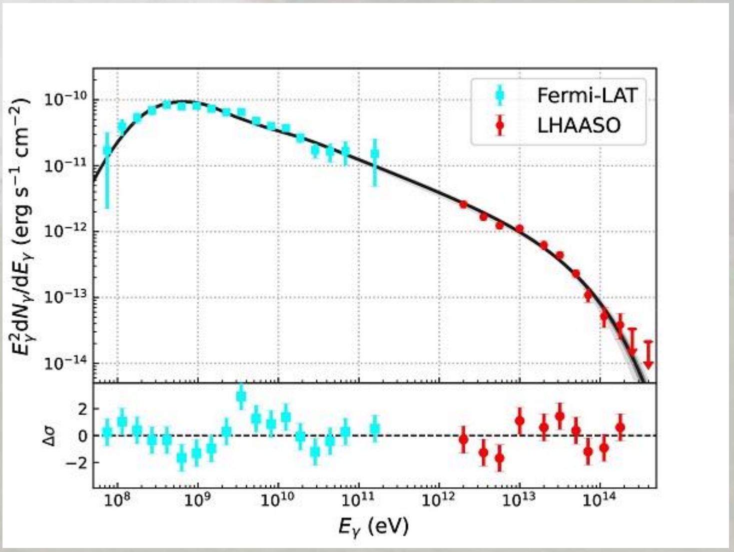


Fig. 5 The energy flux sensitivities of the current and future ground-based detectors—the IACT and EAS arrays in the energy range 10^{10}–10^{16} eV

W51 Un acceleratore di Raggi Cosmici





LHAASO sotto la neve

CTA

https://www.ctao.org/it/

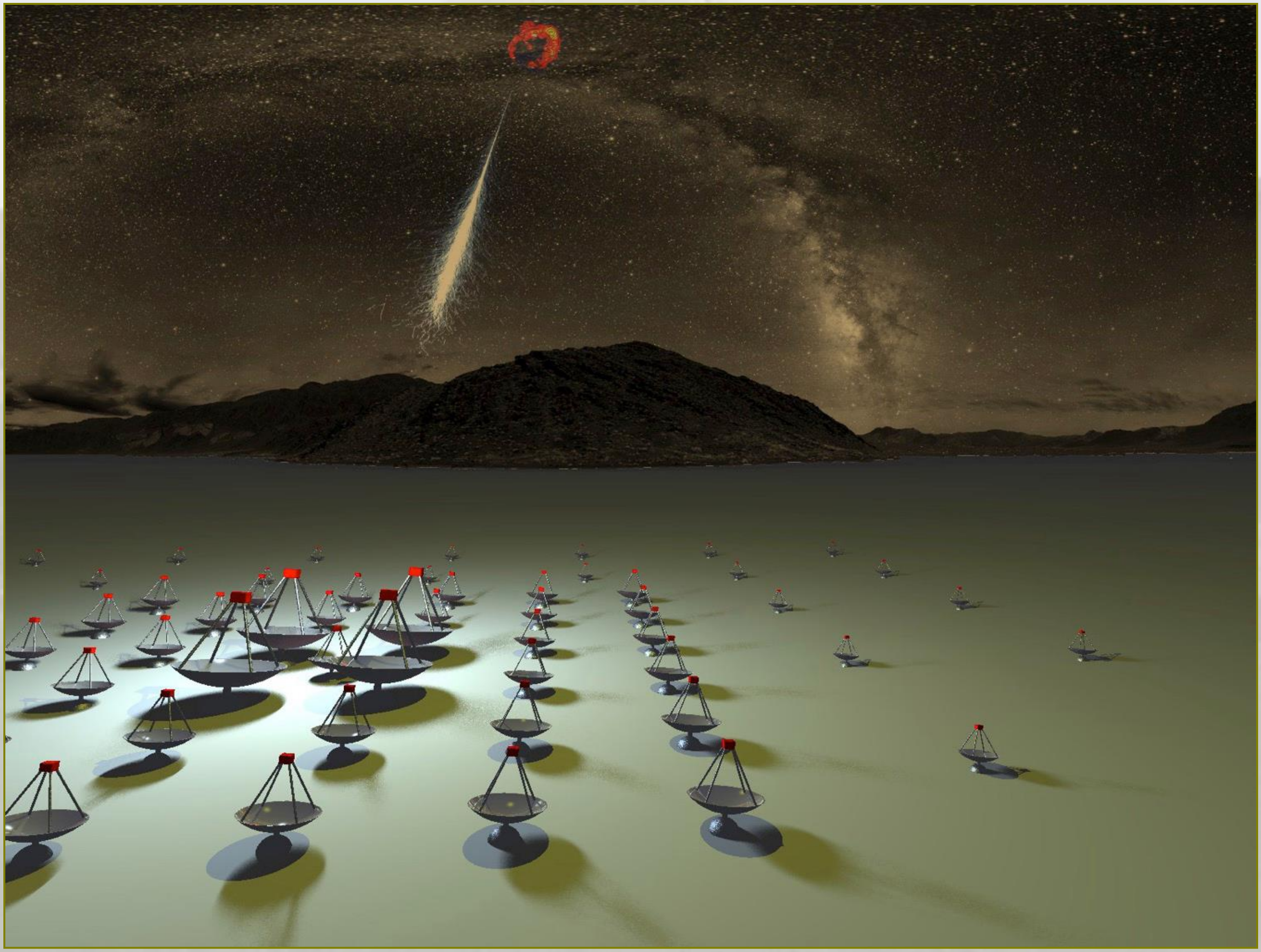
Rivelatori Cerenkow (3 tipi)

Piu' di 100 Telescopi

Area ~ 10 km2

Soglia ~ 20-30 GeV

Misure sino a E ~ 10 TeV



Obiettivo principale e' lo studio del cielo a raggi γ

Pero' la collaborazione lavora su tre item di interesse per i RC:

i) studio dei siti di accelerazione

ii) misura dello spettro dei nuclei

iii) misura dello spettro di elettroni

i) studio dei siti di accelerazione

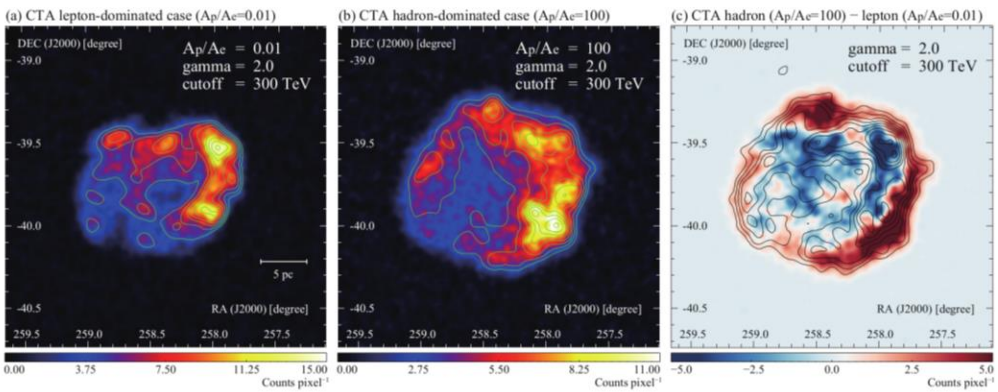


Figure 1.6 – Simulated CTA images of the TeV-bright supernova remnant RX J1713−3946 for different emission scenarios, showing the power of CTA to differentiate between these scenarios. Reproduced from [25].

Known TeV-emitting source classes where CTA data will have a transformational impact on our understanding include PWN, gamma-ray binaries, colliding-wind binaries, massive stellar clusters, starburst galaxies and active galaxies. There is clearly huge potential for the discovery of new classes of accelerators, with emission from clusters of galaxies (see Chapter 13) as one of the most exciting possibilities.

10.1.1 Scientific Objectives

The scientific goals of this KSP appeal directly to the fundamental question of the origin of the cosmic-ray sea that fills our Galaxy.

1. Where and how in the Galaxy are cosmic rays accelerated up to PeV energies?
2. Are we sitting in a particular location of the Galaxy, or do the cosmic rays form a uniform sea within the whole Galaxy?
3. What is the distribution of PeVatrons in the Galaxy?
4. Do young shell-type SNRs accelerate hadronic cosmic rays up to PeV energies?
5. If so, up to which energies and how effective is this acceleration?

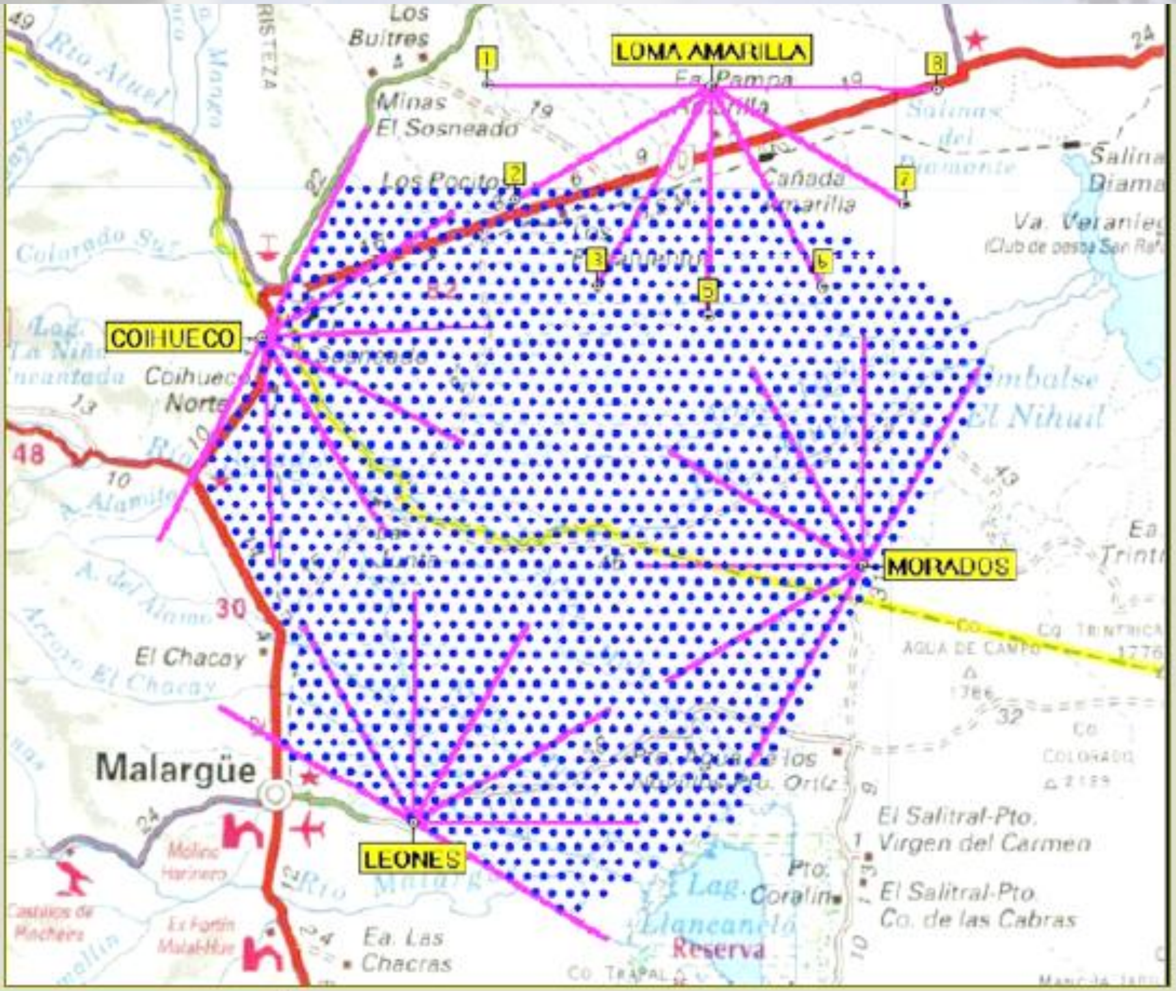
AUGER

Rivelatore a terra

Tecnologie multiple

Operativo dal 2008

Il Sito



Obiettivi

- *Direzione di arrivo*
- *Energia*
- *Composizione chimica*

dei raggi cosmici di altissima energia

Due tecniche di misura ***indipendenti** e **complementari**:*

- **Un array di 1600 stazioni di superficie SD su un'area di 3000 km^2**

- **4 rivelatori di luce di fluorescenza FD**

Southern hemisphere (3000 km^2)
Malargüe (Mendoza), Argentina

Obiettivo di Auger

Studio della radiazione cosmica di altissima energia

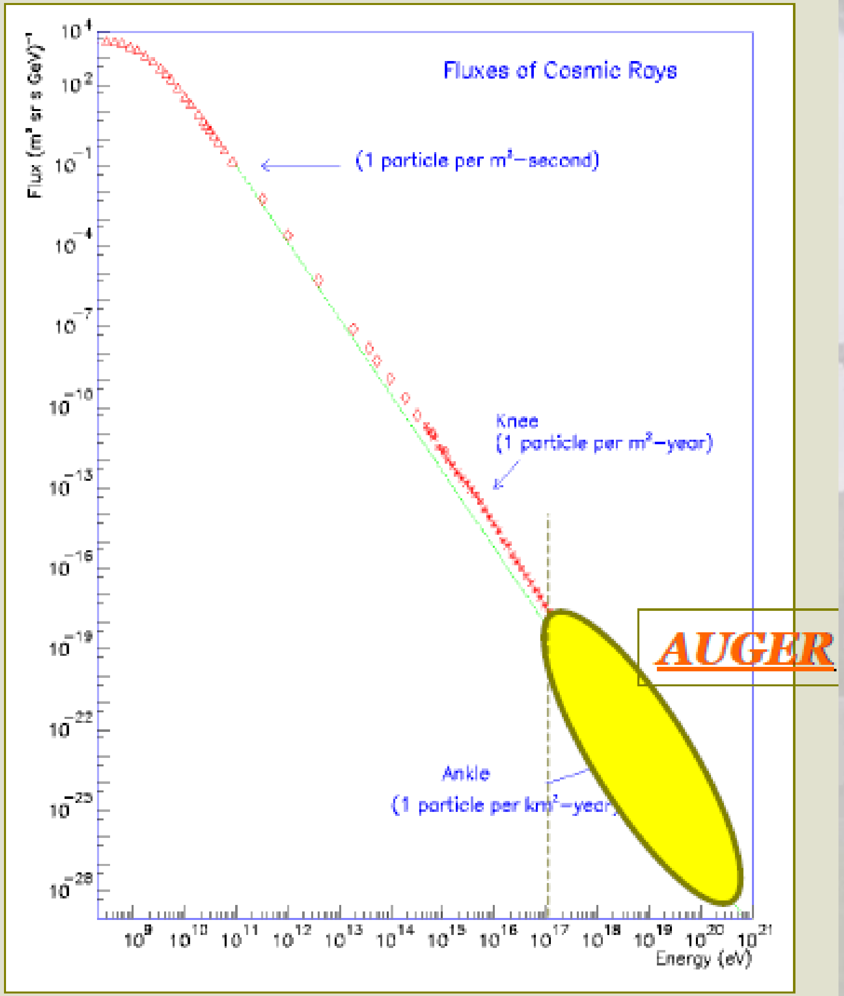
(10^{17}-10^{21}) eV

Flusso ad E>$10^{19.5}$ eV molto basso

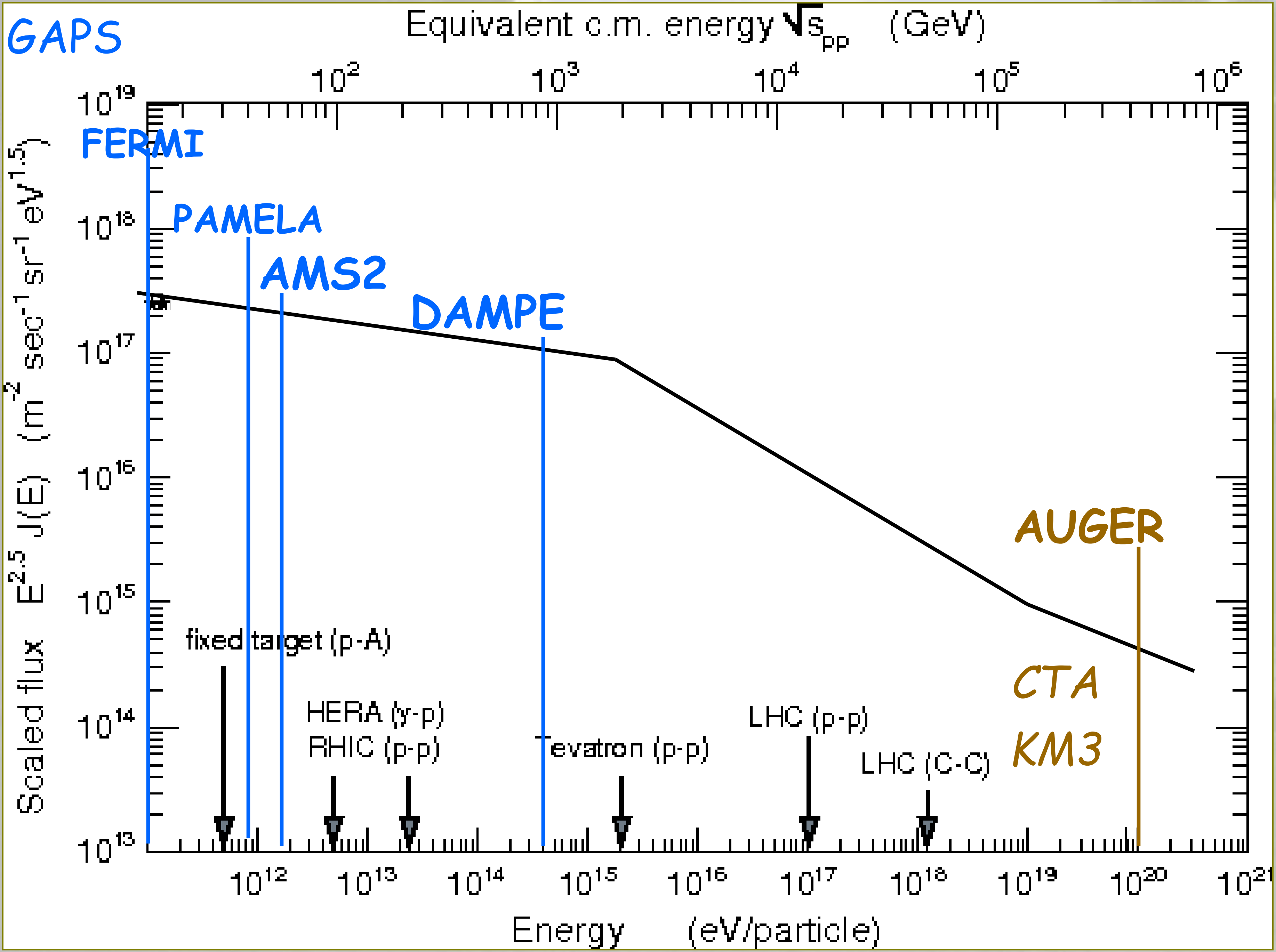
1 particella/(km^2 sr secolo)

Apparato di grandi dimensioni:
3000 km^2 (Auger)

30 eventi/anno



In sintesi....

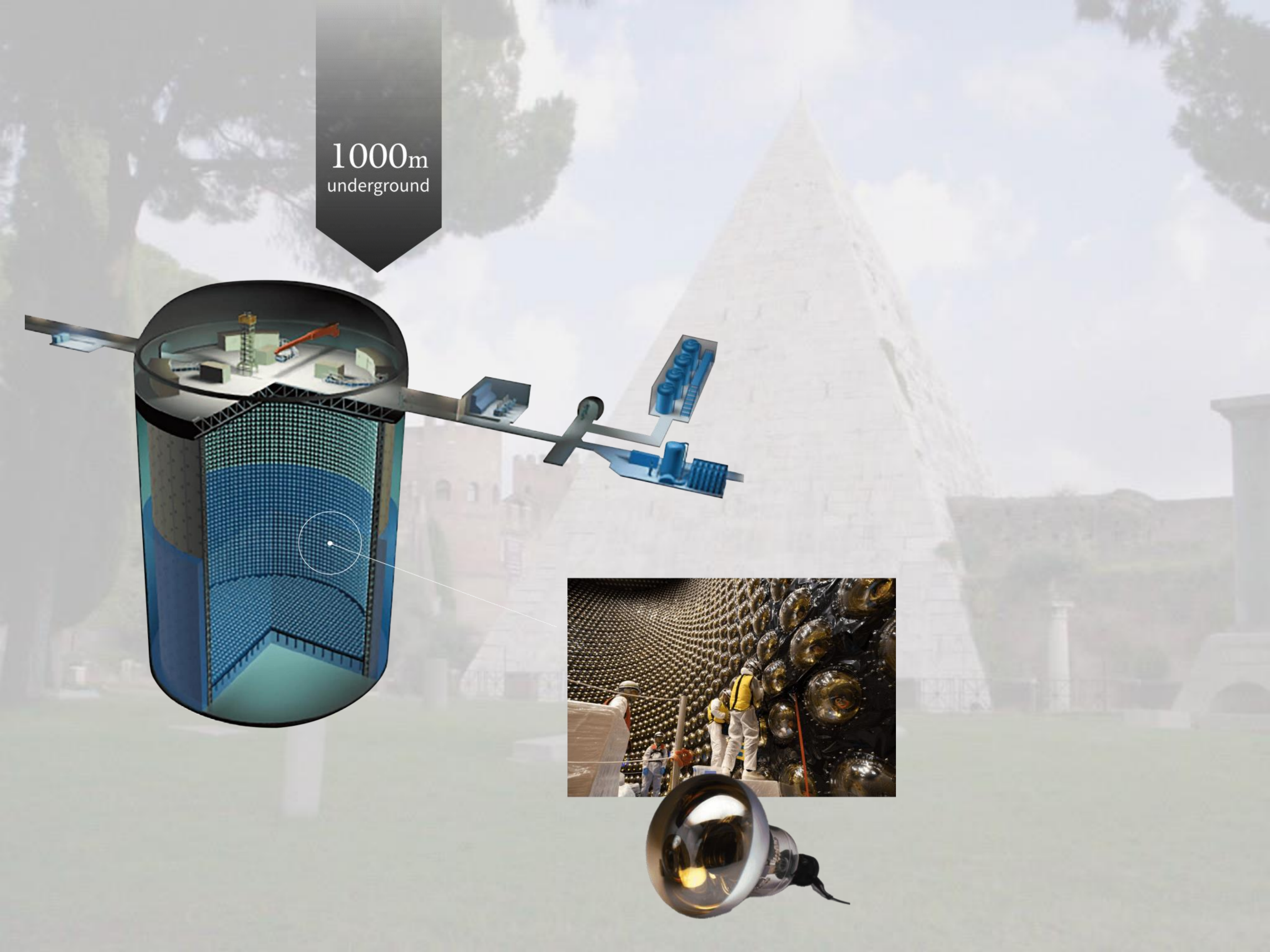

GAPS
Equivalent c.m. energy √s_pp (GeV)
10^2
10^3
10^4
10^5
10^6
10^19
10^18
10^17
10^16
10^15
10^14
10^13
FERMI
PAMELA
AMS2
DAMPE
AUGER
CTA
KM3
Scaled flux E^2.5 J(E) (m^-2 sec^-1 sr^-1 eV^1.5)
fixed target (p-A)
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
LHC (C-C)
10^12
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Energy (eV/particle)

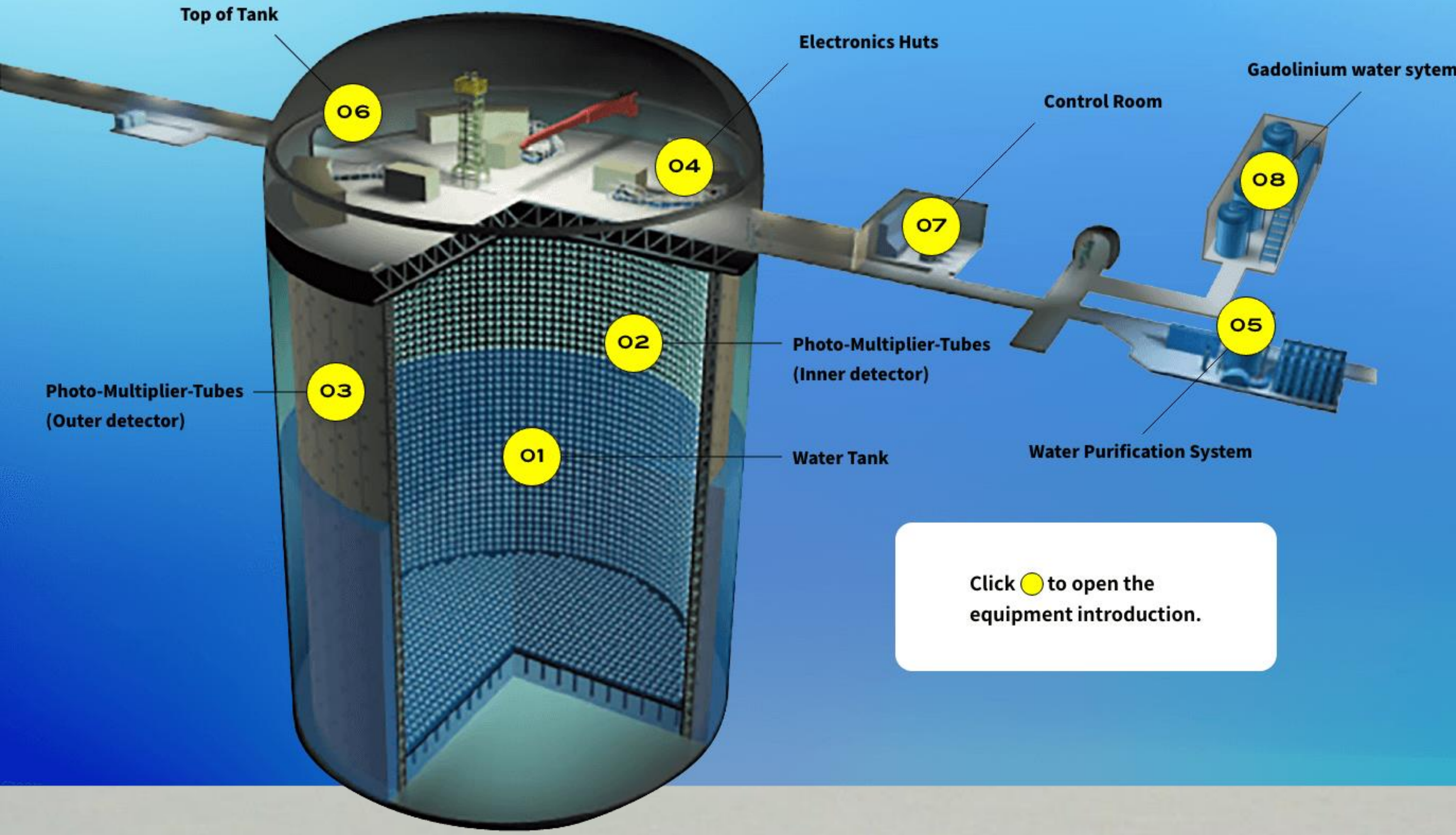
Rivelatori per Neutrini

- Kamiokande
- KM3
- IceCube
- Juno

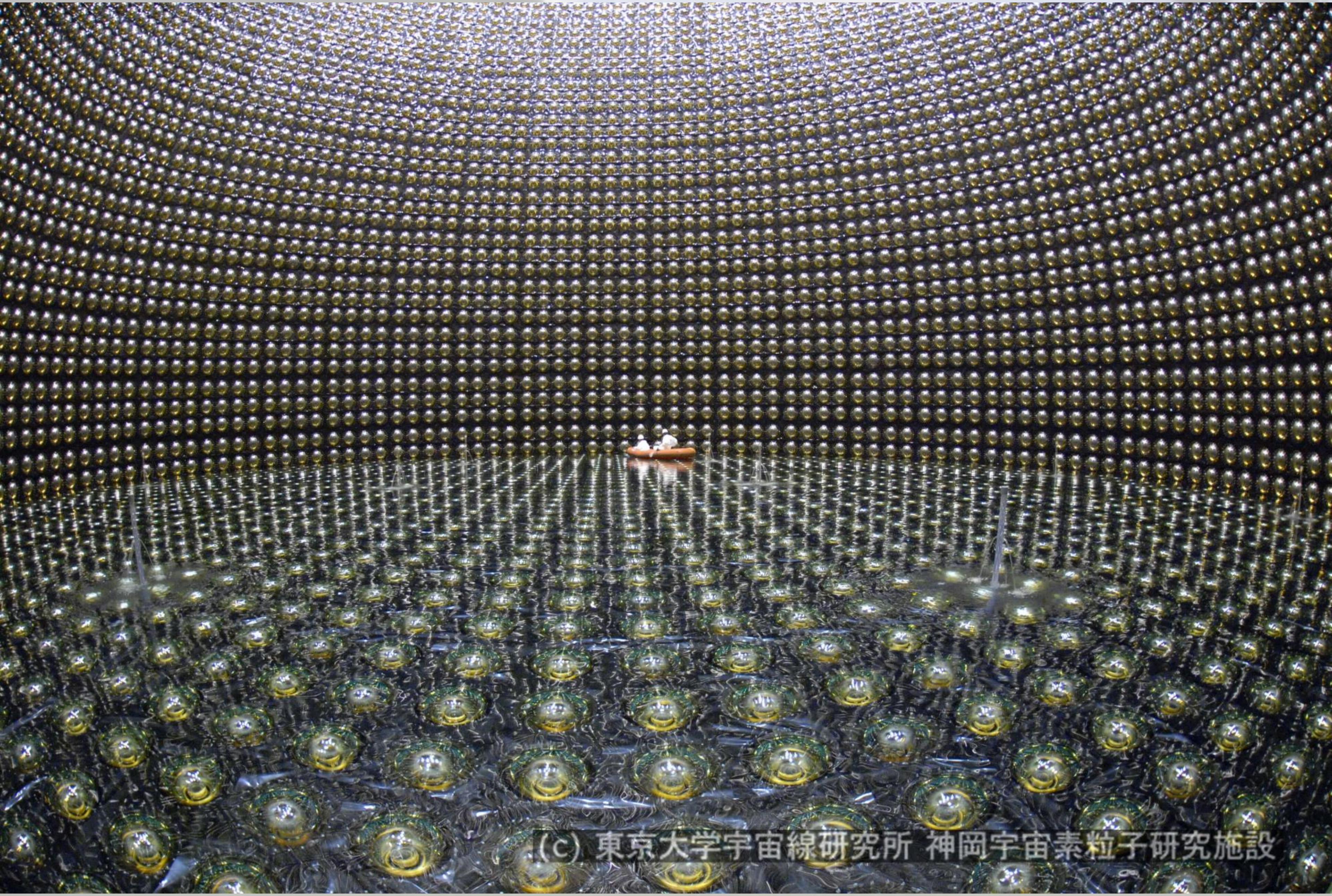
Kamiokande in Giappone

- Kamiokande – 3000 ton – dal 1983 al 1996
- SuperKamiokande – 50000 ton – dal 1996
- HyperKamiokande (in costruzione)
  - 260000 ton – dal 2027 (?)


1000m
underground



Click ◯ to open the
equipment introduction.


(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

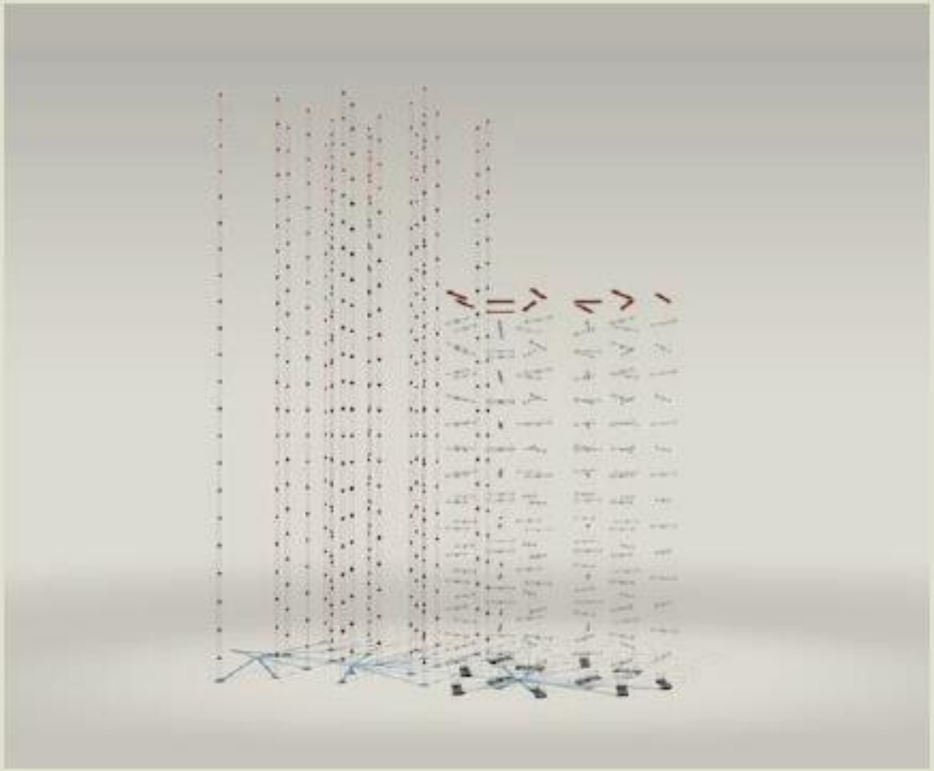
KM3

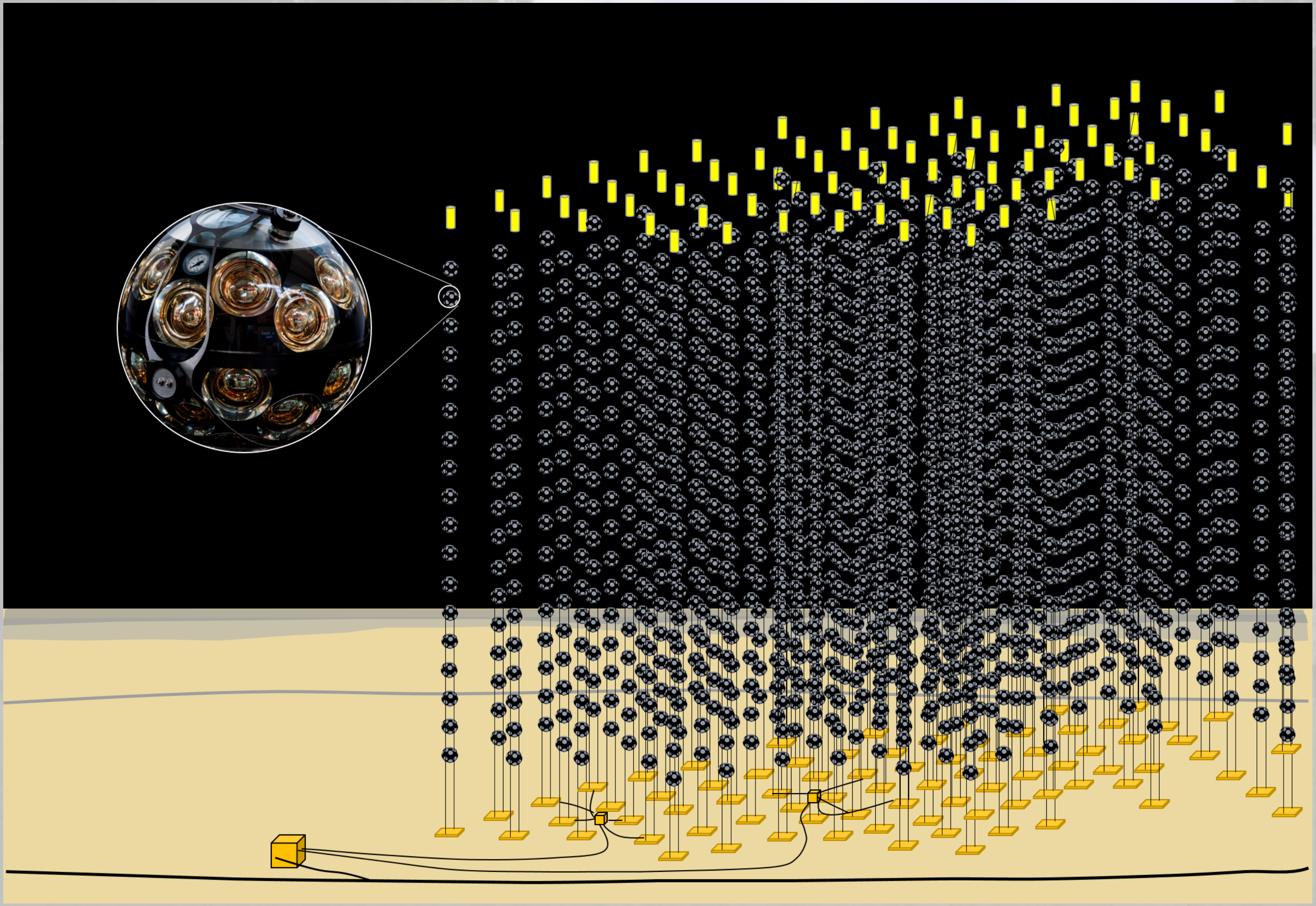
Rivelatore per Neutrini di alta energia

In corso di installazione a Porto Palo

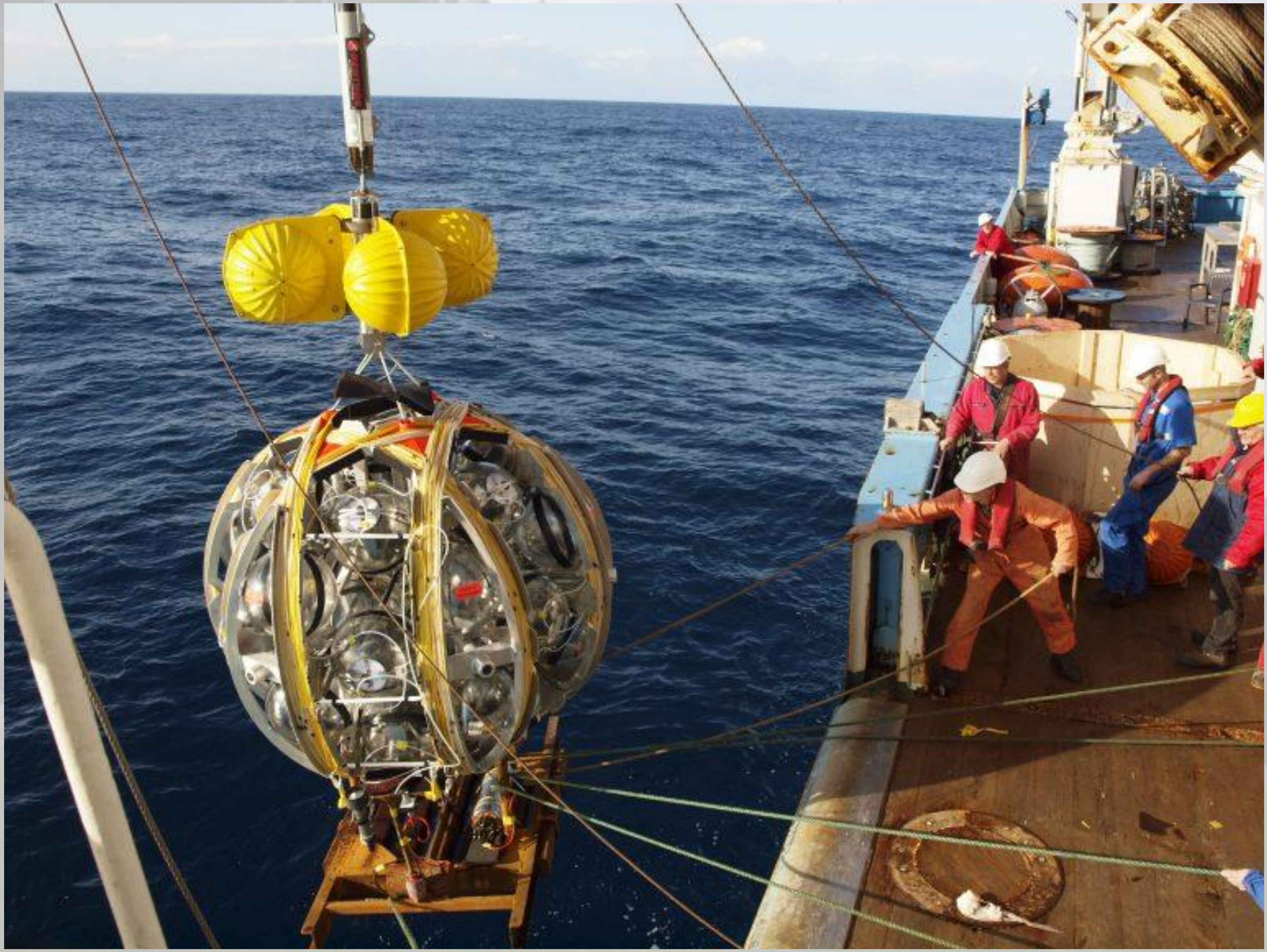
Operativo dal 2020

Circa 3000 m di profondita'






© Marijn van der Meer/Quest



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

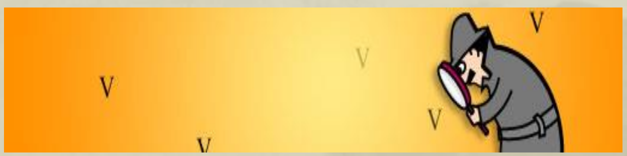
The scientific and technical details are illustrated in the publication:

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)

JUNO

- Neutrinos from reactors
  - Kamland in Japan
  - JUNO in China
  - .....

some Km



JUNO: A Reactor based experiment

The location

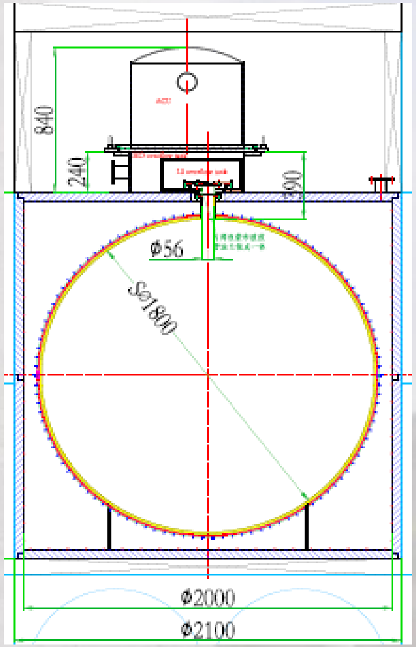
20 kton LS
Inner Vessel: ϕ35.4m
Out Vessel: ϕ40 m
Muon Tracker
Outer Vessel
Water Pool
20 kton pure water
6 kton mineral oil
20” PMTs
Veto PMTs

JUNO: A Reactor based experiment

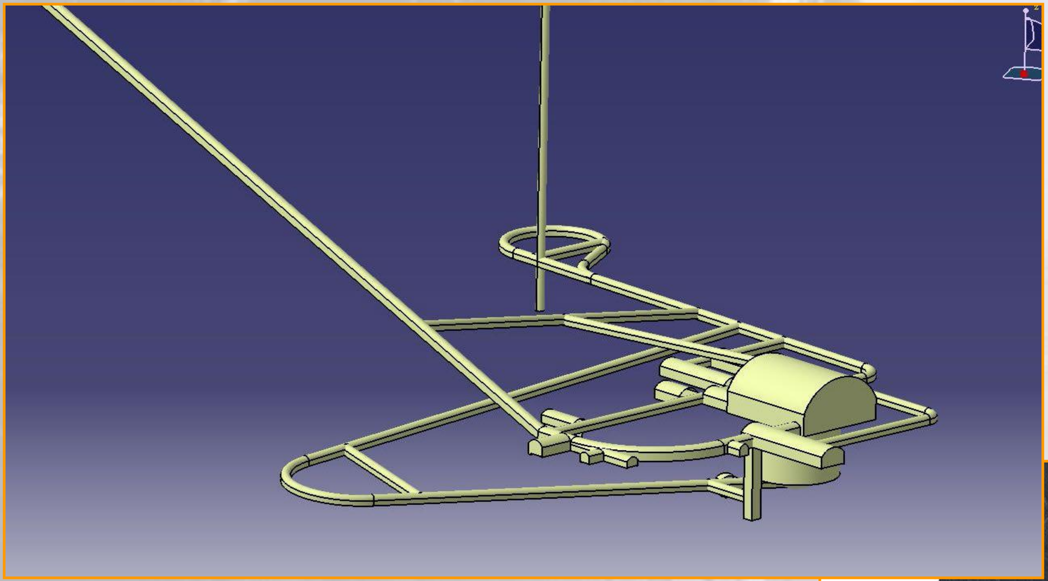
"Near" and "Main" Detector

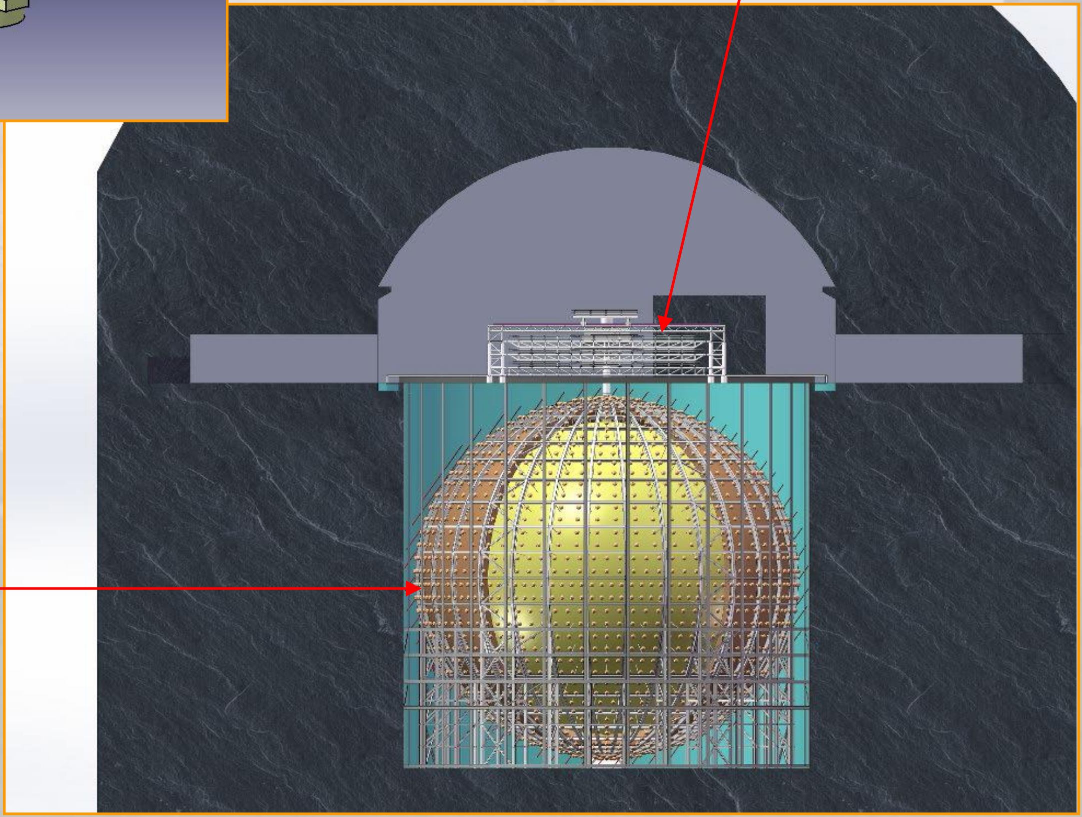
TAO Detector (Near)

- 2.6 ton Gd-LS in a spherical vessel
  1-ton FV, 4000 ν's/day
- 10 m^2 SiPM of 50% PDE
  Operate at -50°C
- Laboratory in a basement at -10 m, 30-35 m from Taishancore (4.6 GW)
- Plan to be online in parallel with JUNO



JUNO Detector (Main)





experimental hall

overburden ~ 700 m

pool

JUNO: The Detector

Calibration

Top Tracker
(OPERA TT)

Central detector

Acrylic Sphere

SS latticed shell

18000 20" PMT
25000 3" PMT

Water Cherenkov
~2000 20" PMT

Pool ID 43.5 m

Electronics

Filling +
Overflow

Acrylic Sphere:
ID: 35.4m
Thickness:12cm
SSLS:
ID: 40.1m
OD: 41.1m

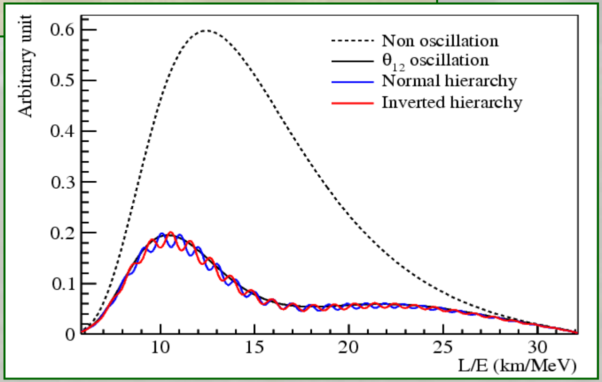
Water pool
ID: 43.5m
Height: 44m
Water Depth:
43.5m

JUNO: Scientific Discover Potentialities

Main Scientific Purpose: Neutrino Mass Hierarchy

"The main goal of JUNO is to establish **the neutrino mass hierarchy** by analyzing the spectrum of the antineutrino inverse β decay on proton. To obtain this result, the experimental spectrum will be compared with the theoretical one, which is a function of the oscillation parameters and of the mass hierarchy."

Juno Collaboration, Universe 4 (2018) 126



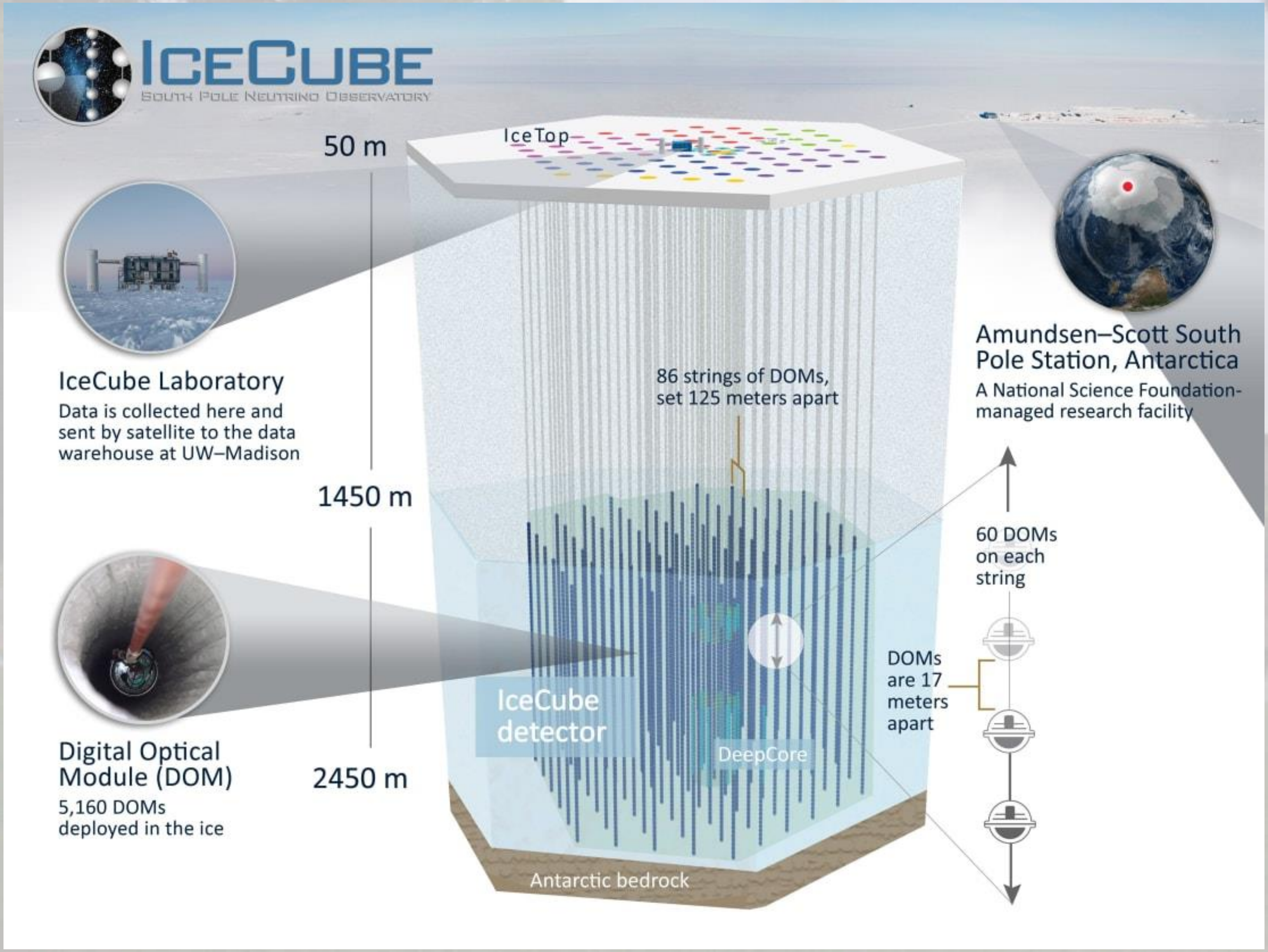
Other Scientific Purposes

- Supernova Neutrinos
- Solar Neutrinos
- Geoneutrinos

Anything else...

The detector should start data collection in 2026

IceCube


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
Antarctic bedrock

Detector Design

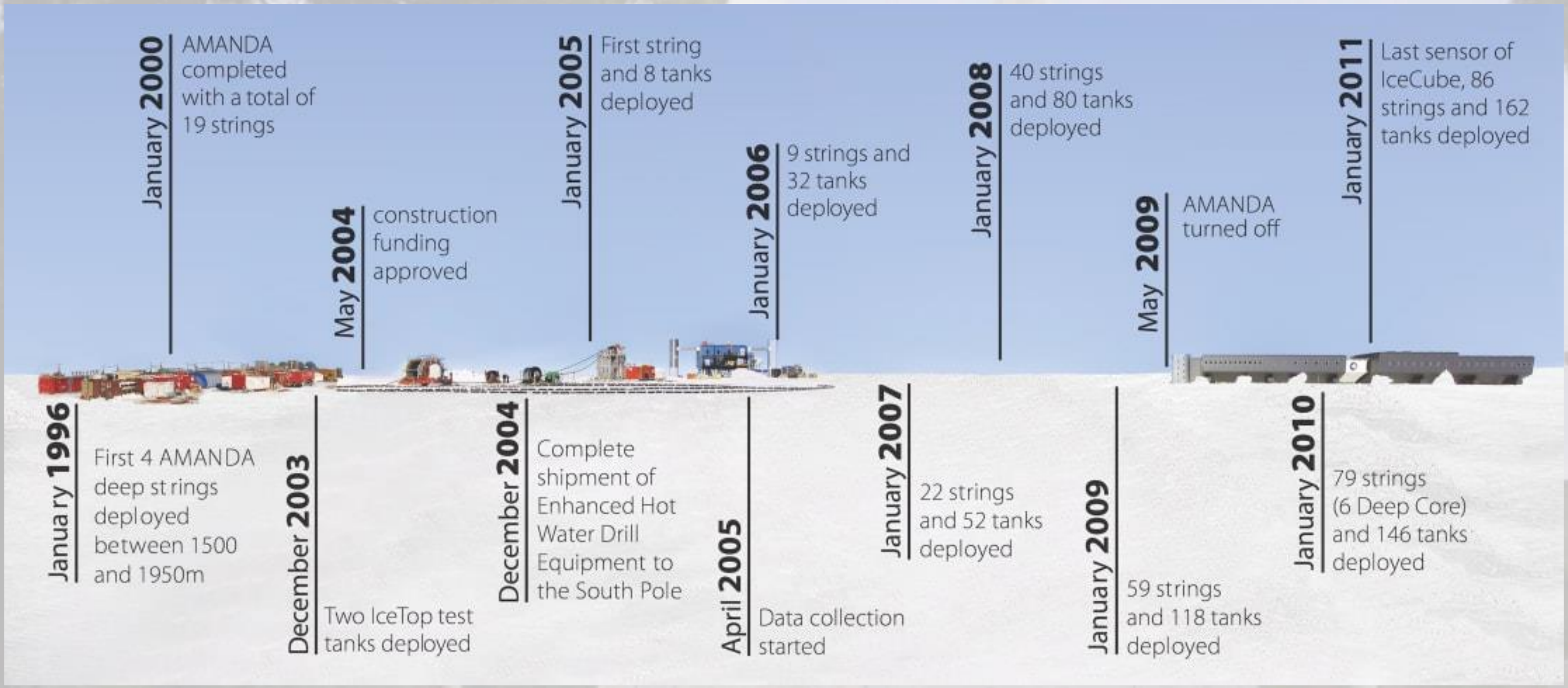
1 gigaton of instrumented ice

5,160 light sensors, or digital optical modules (DOMs), digitize and time-stamp signals

1 square kilometer surface array, IceTop, with 324 DOMs

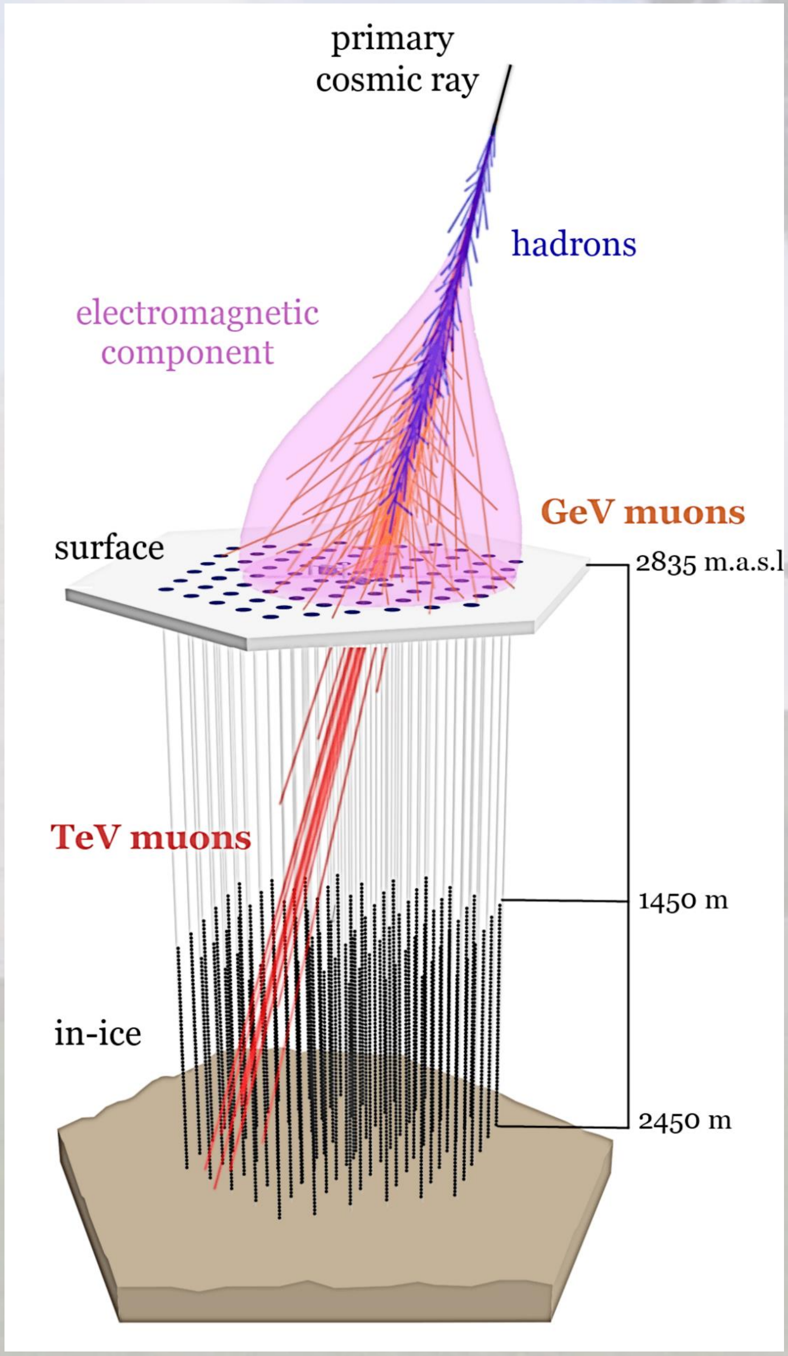
2 nanosecond time resolution

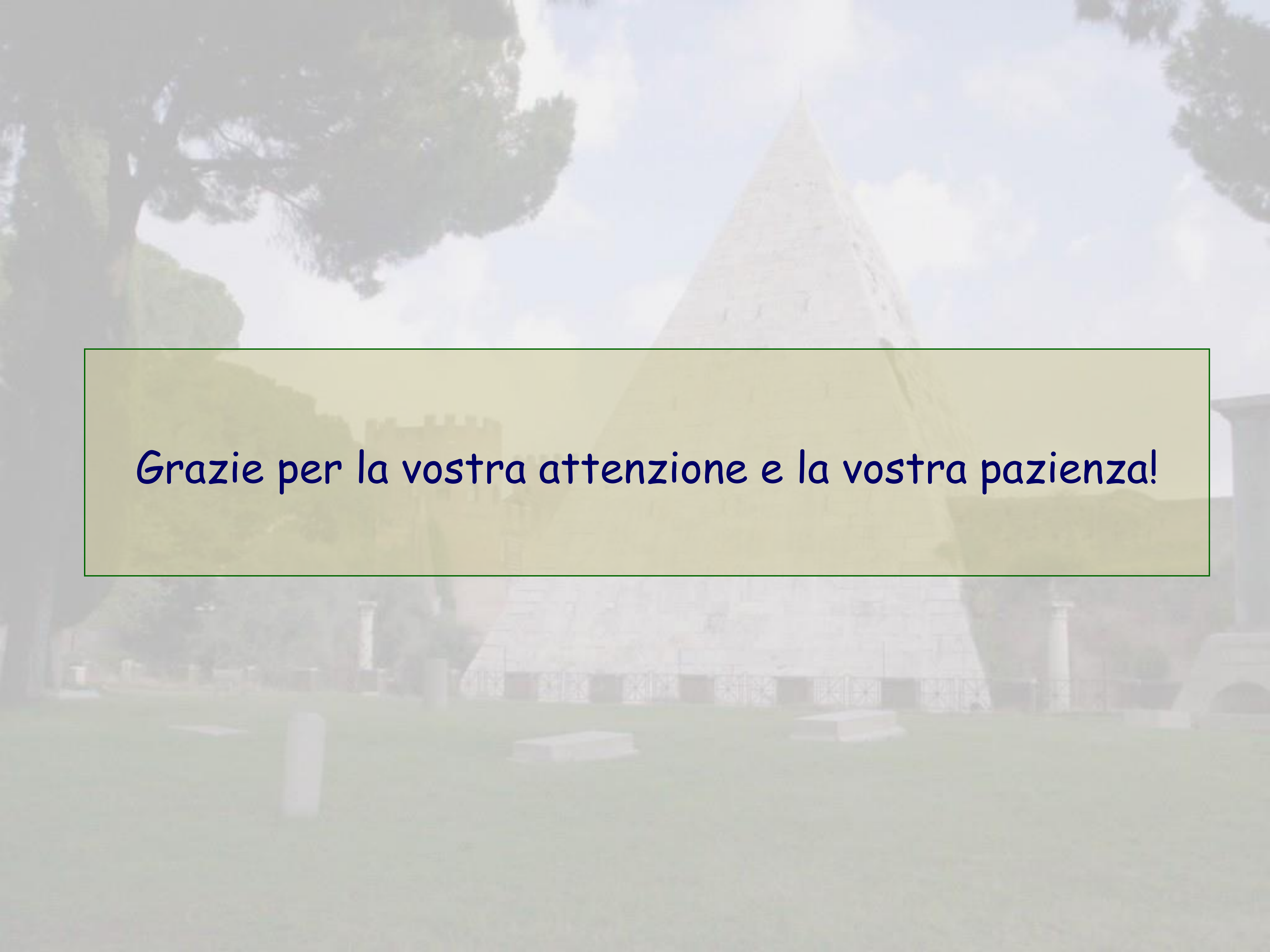
IceCube Lab (ICL) houses data processing and storage and sends 100 GB of data north by satellite daily



Tempo e impegno necessario per costruire un rivelatore!

Ecco nuovamente
i Raggi Cosmici!





Grazie per la vostra attenzione e la vostra pazienza!