

# Lezione Fermi 19

*Luciano Maiani, AA 14-15*

## I Raggi Cosmici. 2

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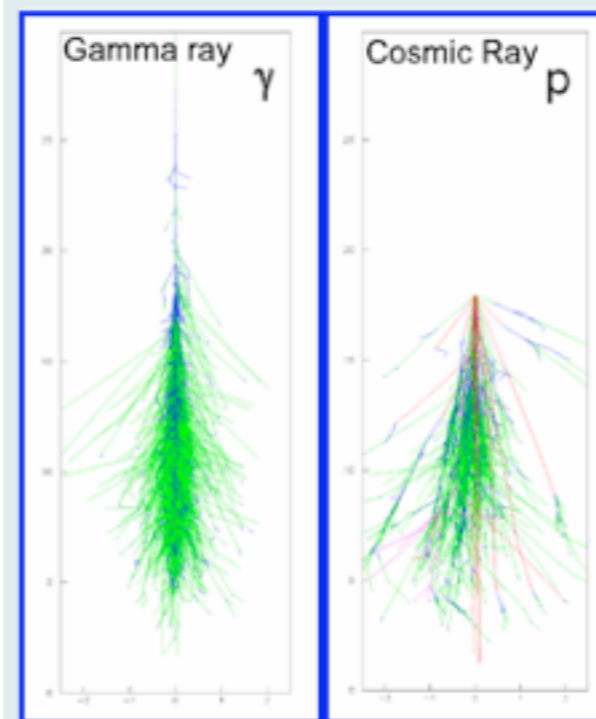
# 1. Astronomia a raggi gamma

- I raggi cosmici primari interagiscono negli strati alti dell'atmosfera e danno luogo a getti di particelle (sciame)
- possiamo distinguere gli sciame iniziati da un fotone da quelli, molto piu' frequenti, iniziati da un particella nucleare: questi ultimi sono piu' "grassi" e hanno una componente penetrante (i muoni) che origina dal decadimento dei mesoni pi;

- gli sciame iniziati da un fotone hanno solo la componente soffice: elettroni e fotoni

- Gli elettroni relativistici, muovendosi nell'atmosfera emettono una luce particolare, luce Cherenkov, che puo' essere raccolta da un telescopio a specchi e inviata su fotomoltiplicatori

## Atmospheric Cherenkov Effect:



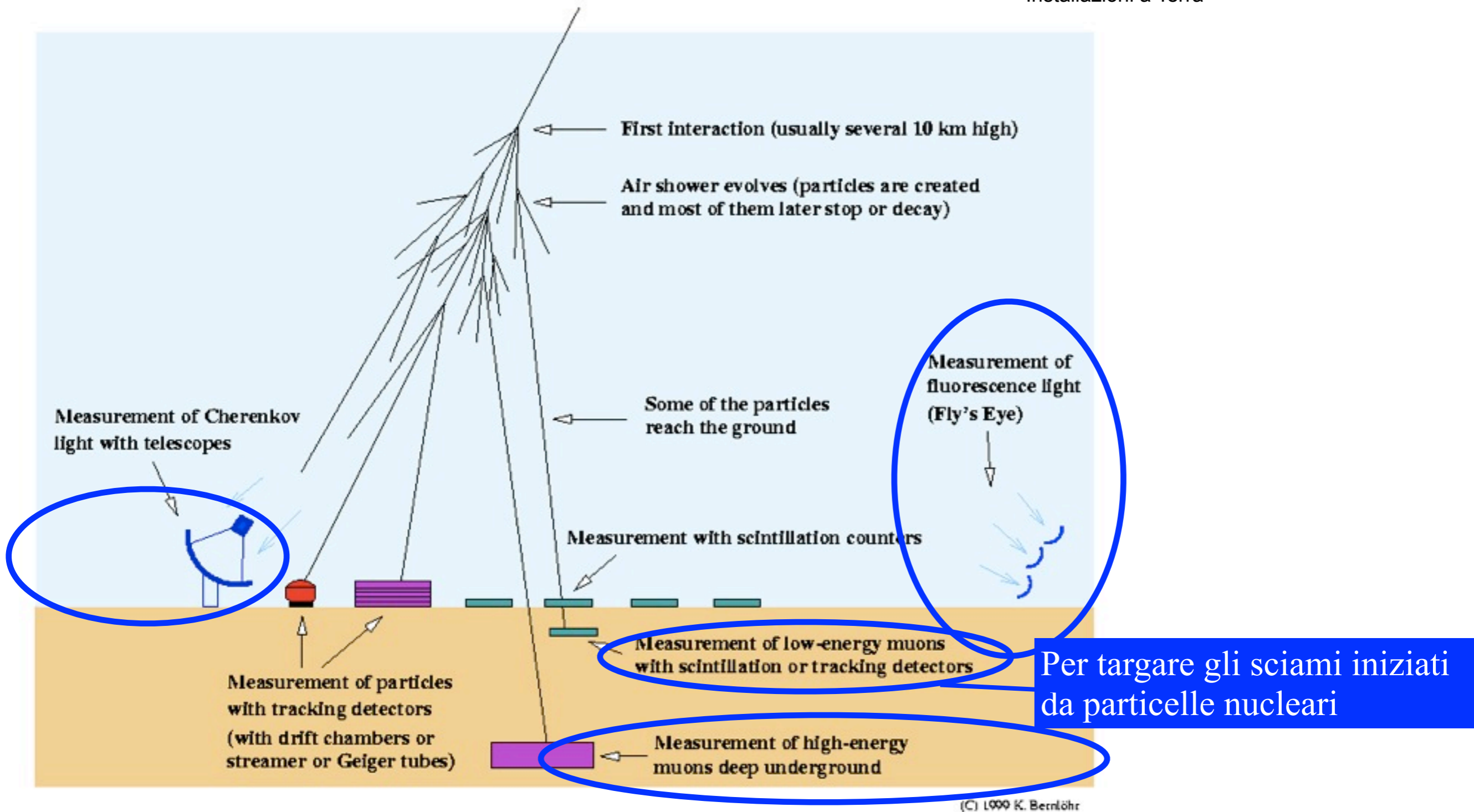
High energy gamma rays and cosmic rays initiate particle cascades as they enter the Earth's atmosphere. Cherenkov light from these air showers can be detected at ground level. Since gamma rays create a unique cascade pattern it is possible to discern between gamma rays and the more abundant background cosmic rays. The graphs at left compare shower structure between gamma rays and protons. The vertical axis is height in the atmosphere (in km). The horizontal axis is lateral position on the group (in units of 100 m). The color coding is gamma,  $e^+/e^-$ ,  $\mu^+/\mu^-$ , hadrons.

- questo e' il principio del Telescopio Cherenkov, scoperto in Inghilterra nel 1952 da Galbraith e Jelley
- un altro metodo di rivelazione e' quello di raccogliere la luce emessa per fluorescenza dagli atomi dell'atmosfera eccitati dal passaggio dello sciame

notte chiare e senza luna, siti ideali in deserti, pampa, altipiani, etc.

## Measuring cosmic-ray and gamma-ray air showers

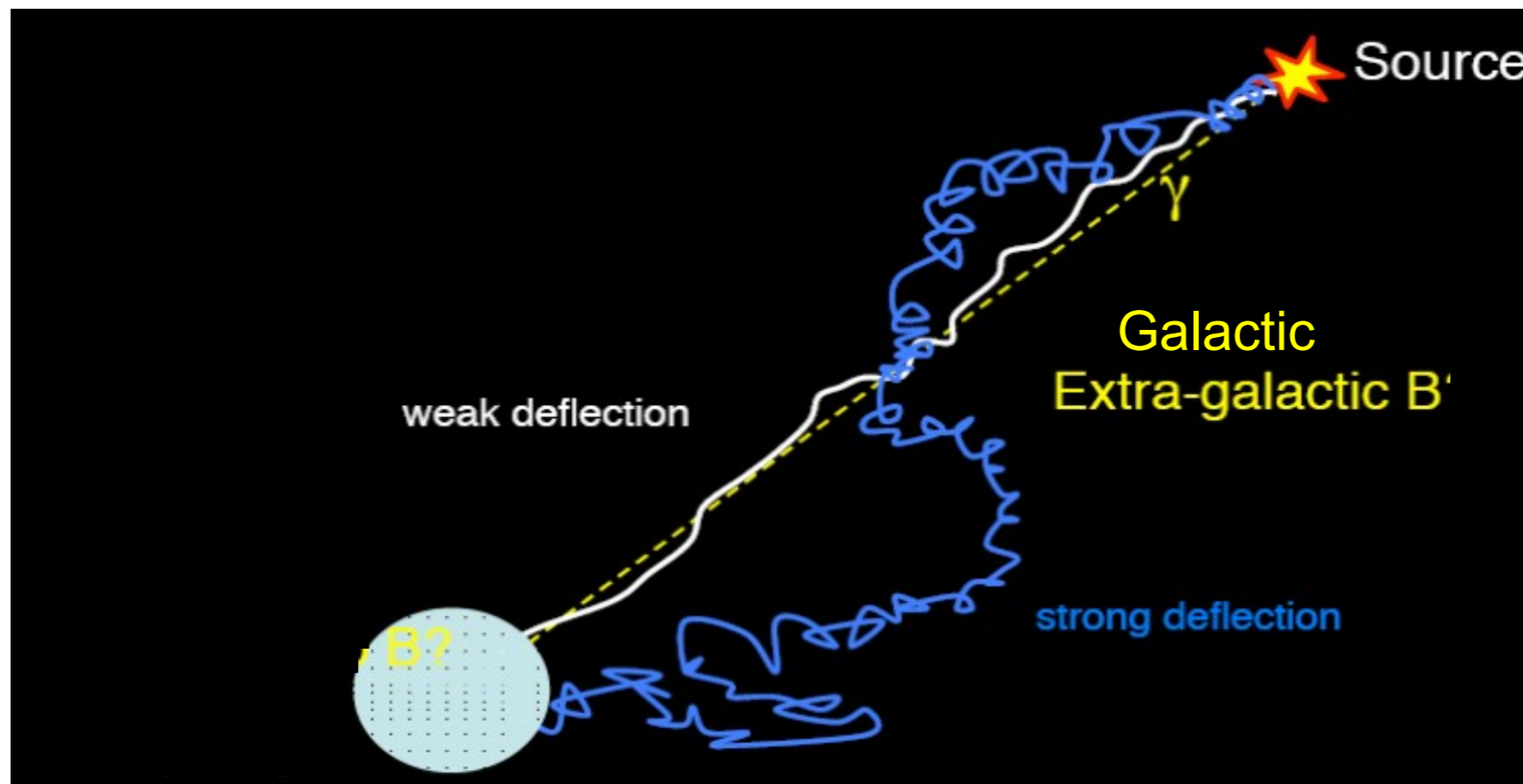
Installazioni a Terra



perche' i gamma ?

## Gamma-rays (and neutrinos) have one big advantage...

...they are not deflected by Galactic and  
extragalactic magnetic fields → direction



Omar Tibolla

Tuxtla Gutierrez, 4<sup>th</sup> of October 2014

- Ci indicano la sorgente
- danno indicazioni sui meccanismi di accelerazione dei raggi cosmici costituiti da particelle nucleari

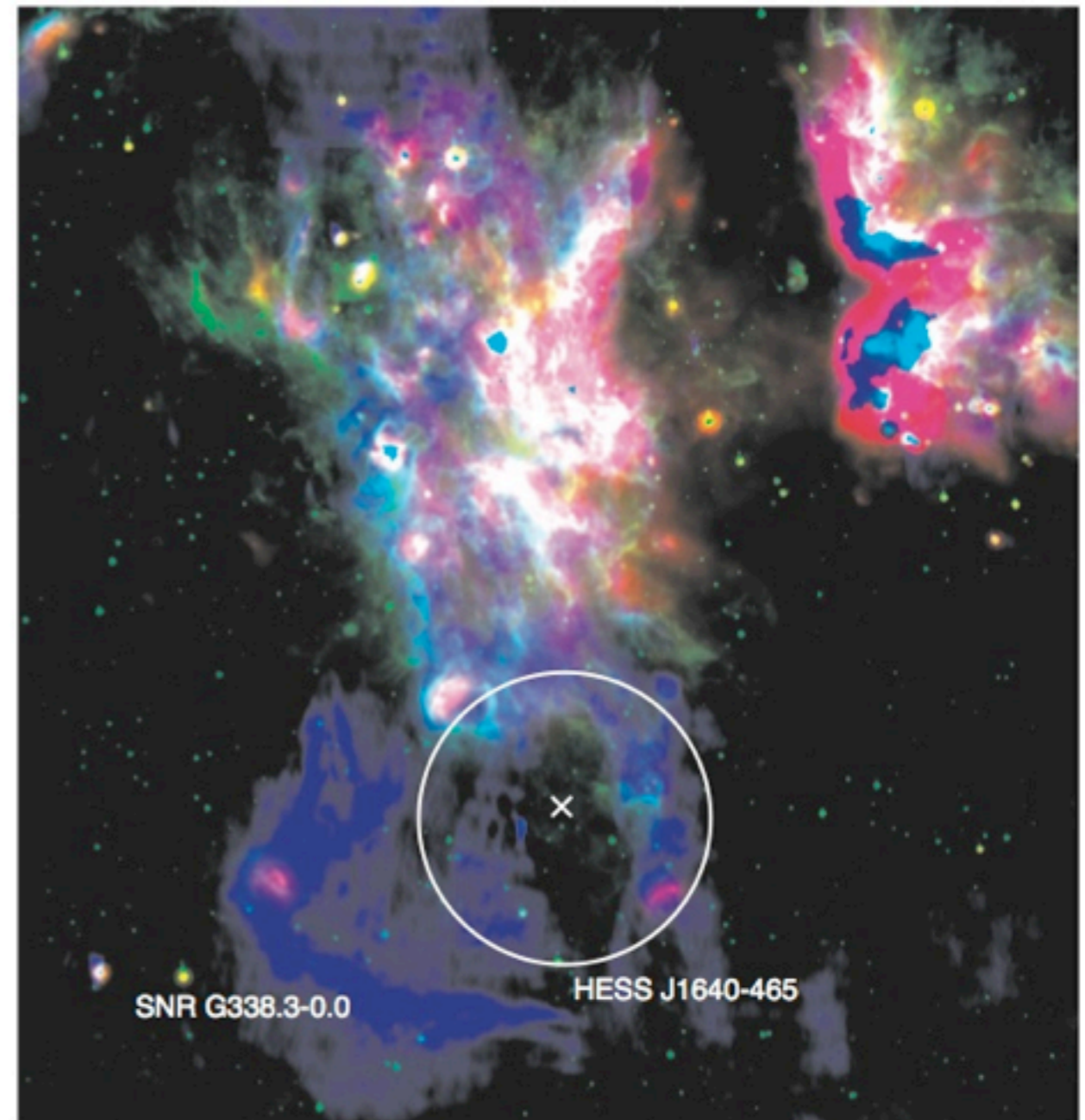


# H.E.S.S.

High Energy Stereoscopic System



- la prima sorgente gamma e' stata scoperta nel 2004 dal telescopio H.E.S.S. situato in Namibia (High Energy Stereoscopic System, ma anche un riconoscimento a Victor Hess, scopritore dei RC)
- 2005: 8 nuove sorgenti
- 2009: piu' di 90 sorgenti con gamma al TeV
- si tratta in maggioranza di SuperNova Remnants (SNR)



Composite image showing radio continuum emission at 610 MHz (in blue) from the region around HESS J1640-465 / SNR G338.3-0.0, and infrared emission at 8  $\mu\text{m}$  (in green) and at 24  $\mu\text{m}$  (in red) taken from the Spitzer Space Telescope GLIMPSE and MIPS GAL surveys, respectively. The white circle marks the position and extension of HESS J1640-465, while the cross indicates the location of the extended X-ray source (Lemiere et al. 2009). From Castelletti et al. (2011)



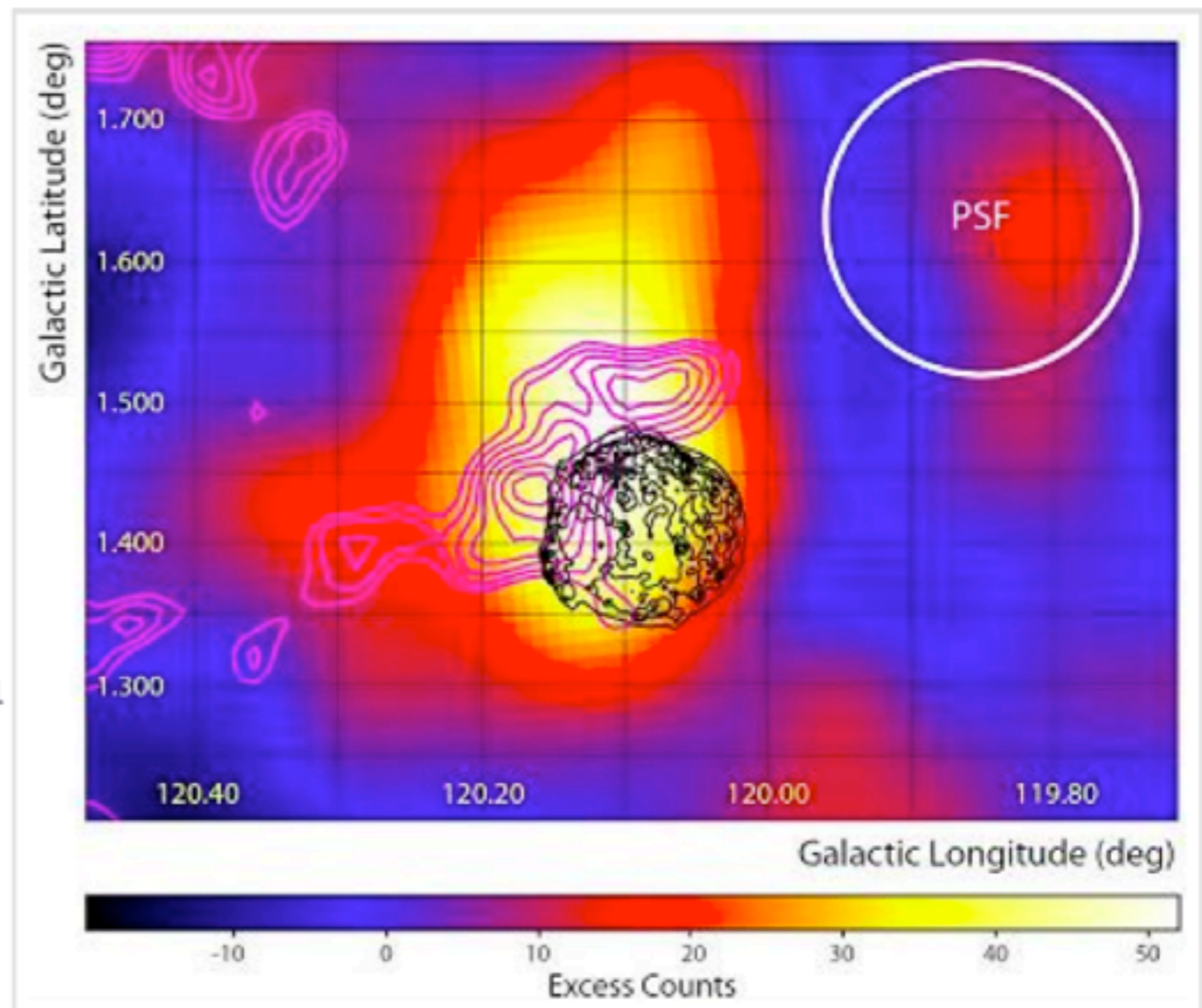
# VERITAS

*Very Energetic Radiation Imaging Telescope Array  
System*

## Important Dates:

- April 2003: Installation of VERITAS prototype telescope at the FLWO Basecamp
- February 2004: First light of VERITAS prototype
- January 2007: Completion of 4 telescope array
- April 27–28 2007: First Light Celebration
- Summer 2009: Displacement of Telescope 1 to new location 1
- Summer 2012: Upgrade of camera PMTs to high-quantum-ef

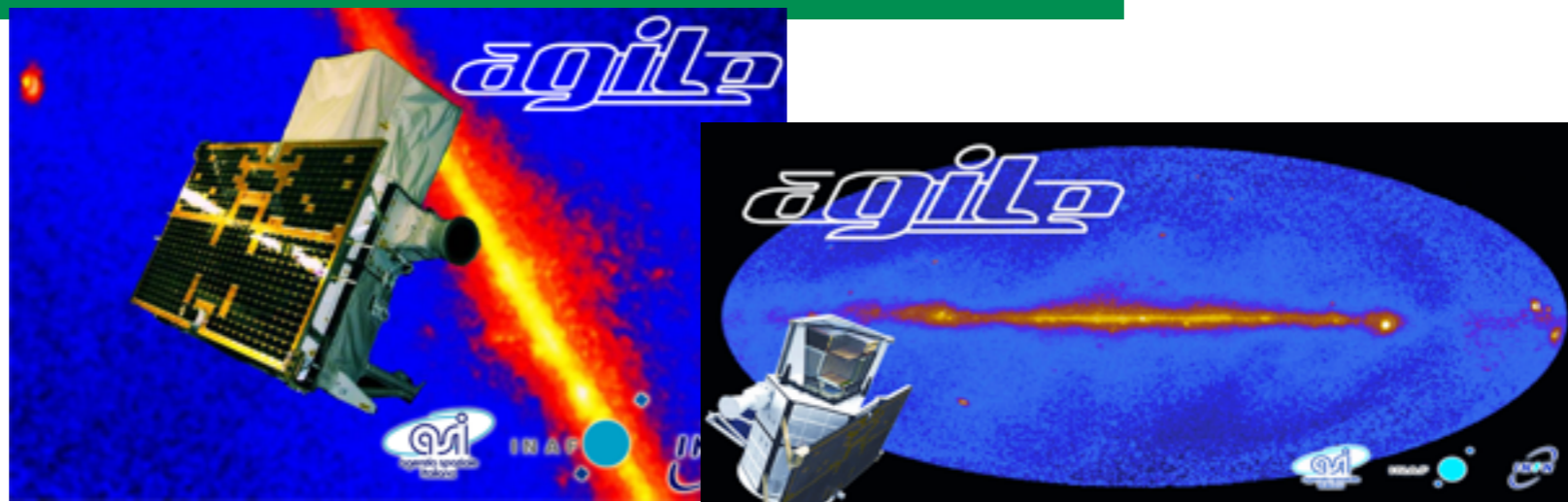
Mount Hopkins, Arizona, USA



VERITAS TeV gamma-ray count map of the region around Tycho's SNR. The color scale indicates the number of excess gamma-ray events from a region, See Figure 1



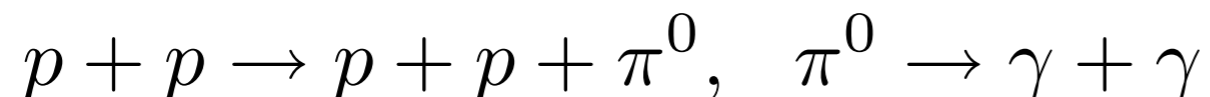
## 2. Astronomia gamma da satellite



- Raggi gamma tra MeV e GeV possono essere osservati, con grande risoluzione, anche da satellite.

- Risultati spettacolari sono stati ottenuti dai satelliti AGILE (italiano, INAF-INFN, 2007) e dal molto più grande FERMI (NASA, 2008), con osservazioni dettagliate su diverse SuperNova Remnants, a partire dalla Crab Nebula.

- Se le SNR sono le sorgenti dei raggi cosmici sotto il ginocchio, il loro ambiente deve essere ricco di protoni di alta energia che producono raggi gamma sul gas circostante attraverso la reazione:



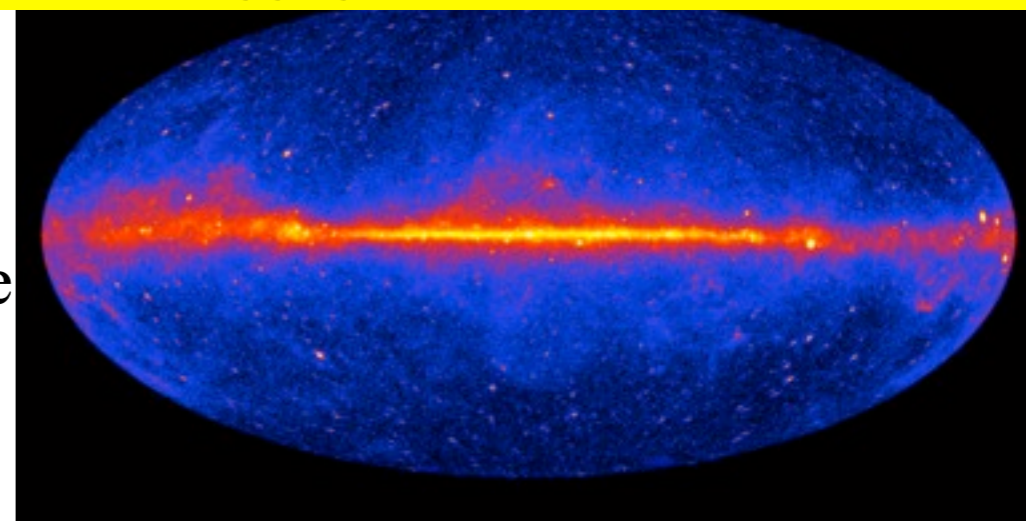
- I raggi gamma dei  $\pi^0$  presentano un picco intorno a  $E_{\text{gamma}} = 200 \text{ MeV}$ : il “proton bump” indica l’inizio della produzione del pione ( $m_{\pi} = 140 \text{ MeV}$ ), ed è ideale per essere osservato da satellite

- ma ... ci sono anche gli elettroni ...



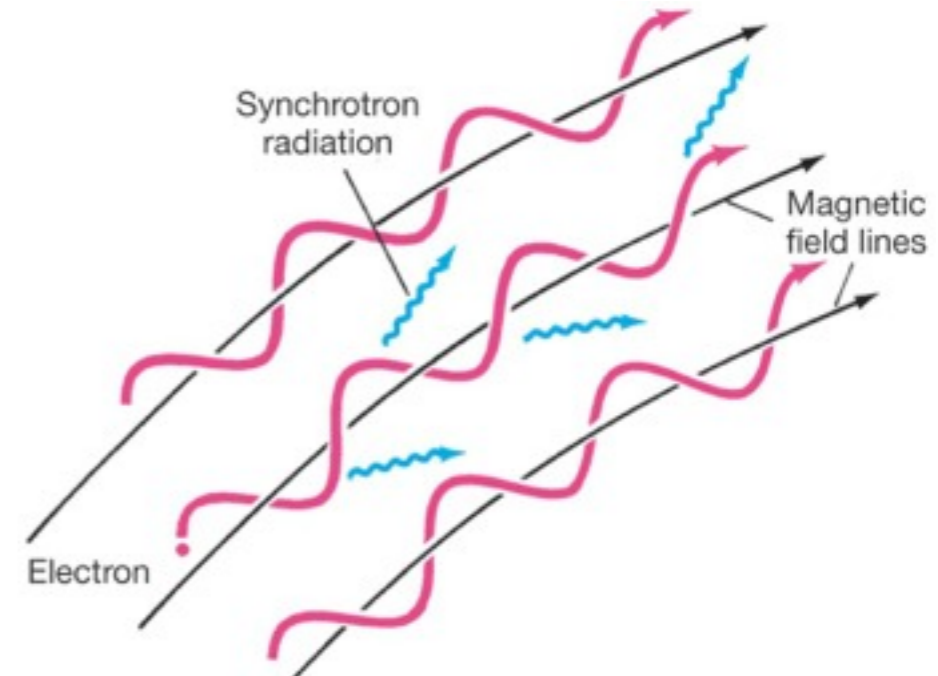
FERMI

Il cielo a raggi gamma osservato da FERMI

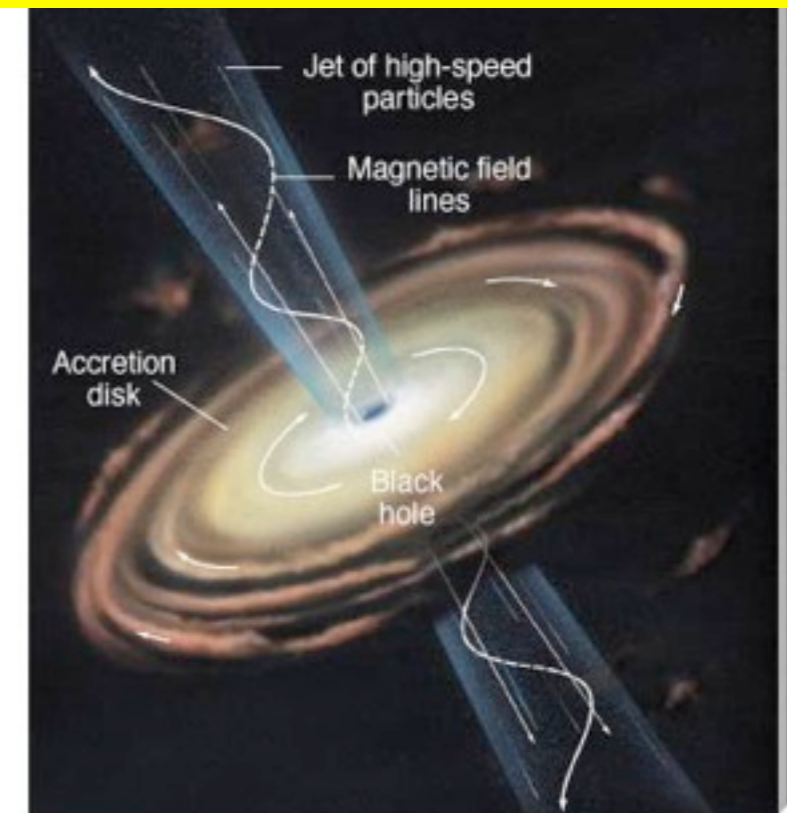


# Il picco dei protoni e il suo fondo

- Le SNR sono popolate anche da elettroni, che possono produrre raggi gamma di alta energia in tre modi
  - gli elettroni che spiraleggiano lungo le linee di forza del campo magnetico irradiano *luce di sincrotrone*
  - *Bremsstrahlung* (irraggiamento conseguente agli urti con i nuclei circostanti)
  - collisione degli stessi elettroni con i fotoni della radiazione di fondo e stellare: *effetto Compton inverso*
- gli stessi meccanismi sono in atto anche in situazioni piu' esotiche, es. dischi di accrezione di buchi neri e potrebbero contribuire ai raggi cosmici di piu' alta energia, di origine extragalattica
- l'emissione di luce di sincrotrone e Compton inverso dalla SNR sono in competizione con il picco dei protoni e difficili da separare
- ci sono gia' un numero di studi interessanti e diverse evidenze "circostanziali"
- ma manca ancora (secondo alcuni, me incluso) un prova stringente che le SNR sono le principali sorgenti di protoni di alta energia.

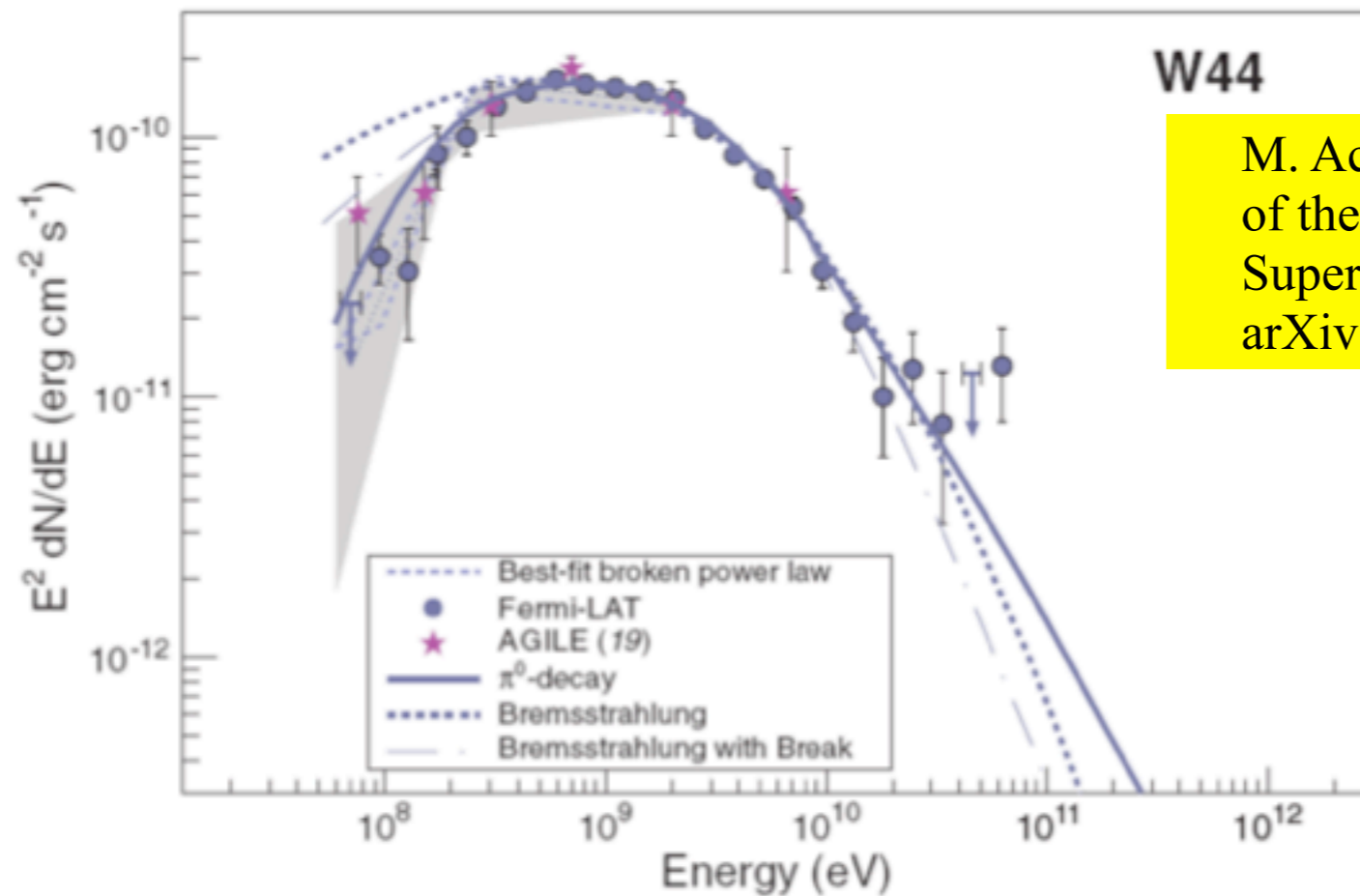


Disco di accrezione di una Black Hole





### 3. Cercando la “pistola fumante”



W44

M. Ackermann, M. Ajello, A. Allafort, et al., Detection of the Characteristic Pion-Decay Signature in Supernova Remnants, *Science* 339 (2013) 807–811. arXiv:1302.3307, doi:10.1126/science.1231160.

Figure 4: Gamma-ray spectrum of W44 as measured with the Fermi LAT, which shows good agreement with pion-decay gamma-ray production model (from [17]).



## The origin of Cosmic-Rays from SNRs: confirmations and challenges after the first direct proof

M.Cardillo<sup>a,\*</sup>, M.Tavani<sup>b,c,d</sup>, A.Giuliani<sup>e</sup>

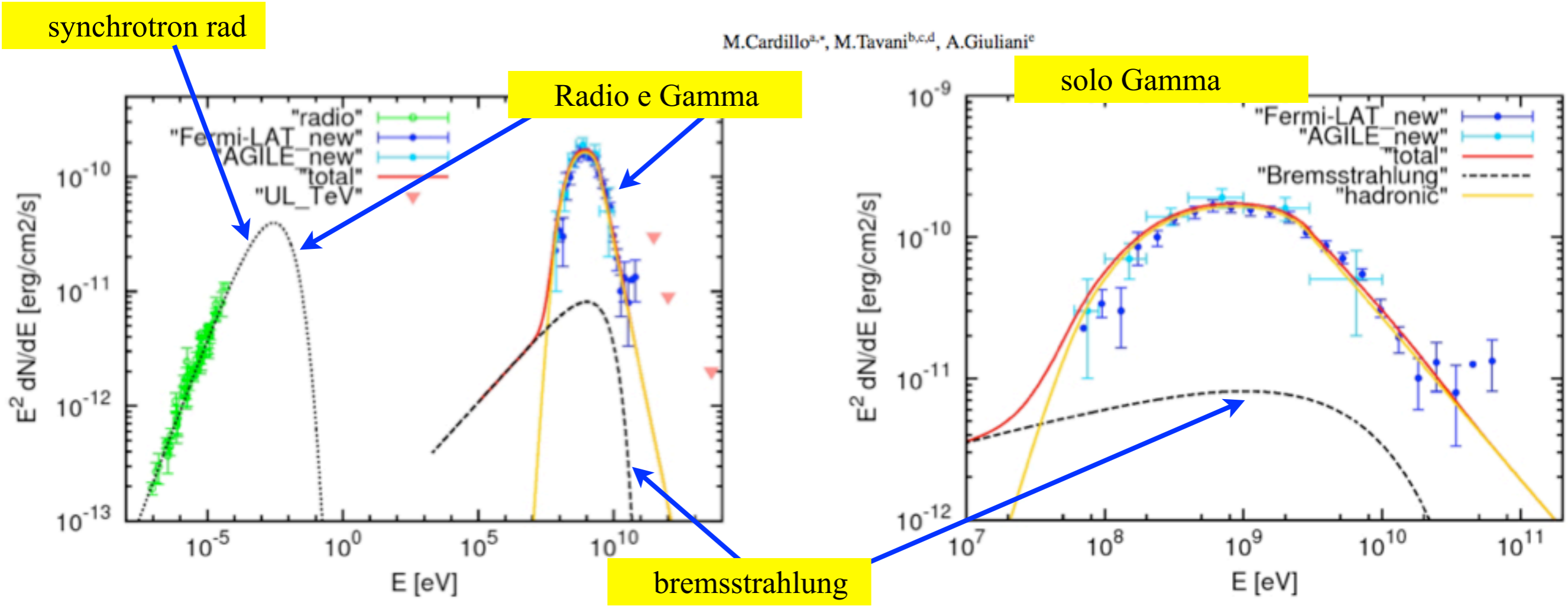


Figure 3: Our best hadronic model, H3, of the broadband spectrum of the SNR W44 that is superimposed with radio and gamma-ray data of Fig. 2. Proton distribution in Eq. 1 with index  $p_1 = 2.2 \pm 0.1$  (for  $E < E_{br}$ ) and  $p_2 = 3.2 \pm 0.1$  (for  $E > E_{br}$ ) where  $E_{br}^p = 20$  GeV. This model is characterized by  $B = 210 \mu\text{G}$  and  $n = 300 \text{ cm}^{-3}$ . We show the neutral pion emission from the accelerated proton distribution discussed in the text. The black curves show the electron contribution by synchrotron (dot) and bremsstrahlung (dashed) emissions; the IC contribution is negligible. The total gamma-ray emission from pion-decay and bremsstrahlung is also shown. **(Left Panel):** SED from radio to gamma-ray band. **(Right Panel):** only gamma-ray part of the spectrum.

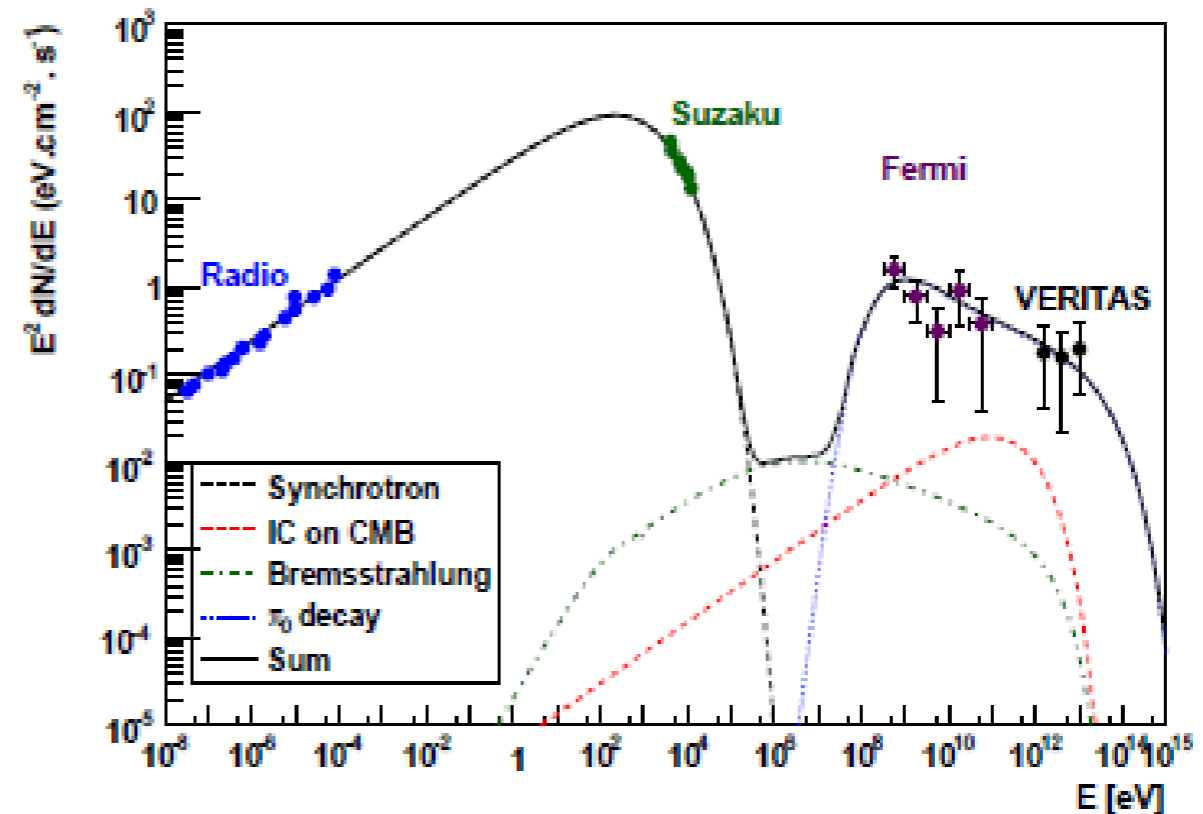


# Note (IMPORTANT):

Among the Femi LAT SNRs sample, a very important discovery is represented by Tycho.

In the case of Tycho, leptonic models are basically disproved (!!!); i.e. Tycho represents the “smoking gun”, the “hadronic fingerprint”, i.e. the answer to a 60-100 years old question!

So everything would look solved and every question answered...BUT...



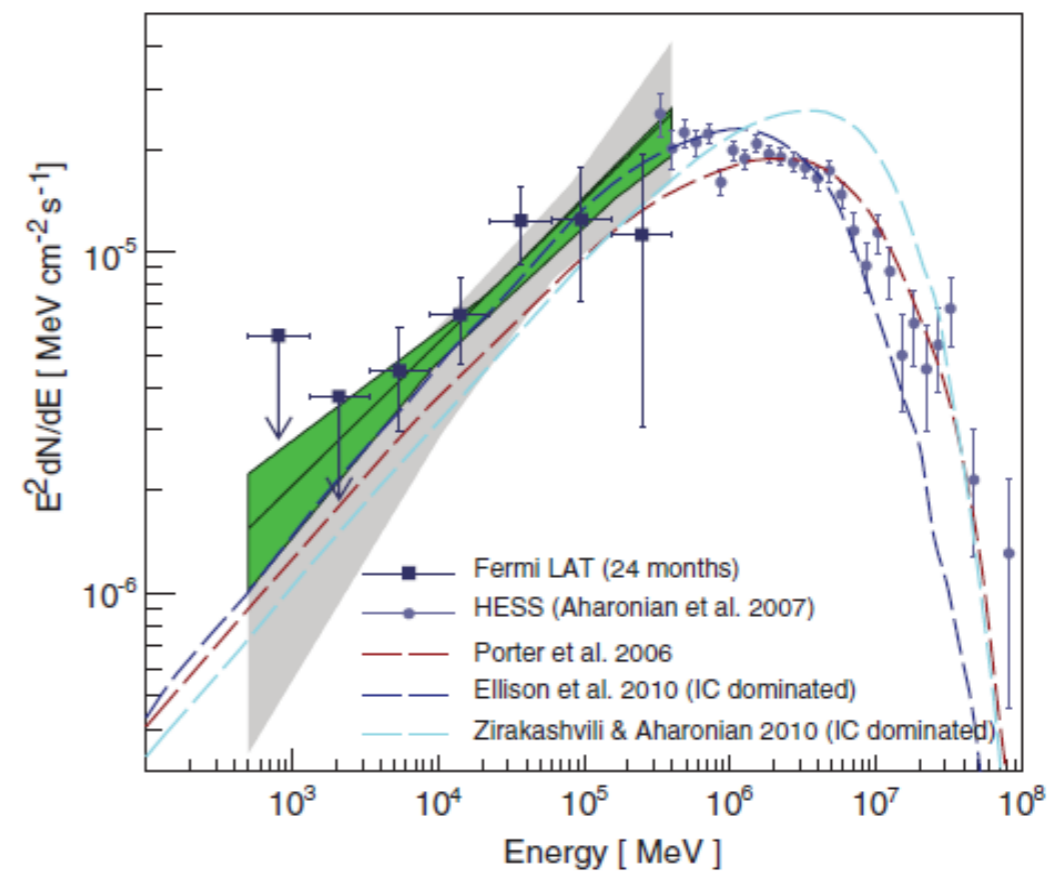
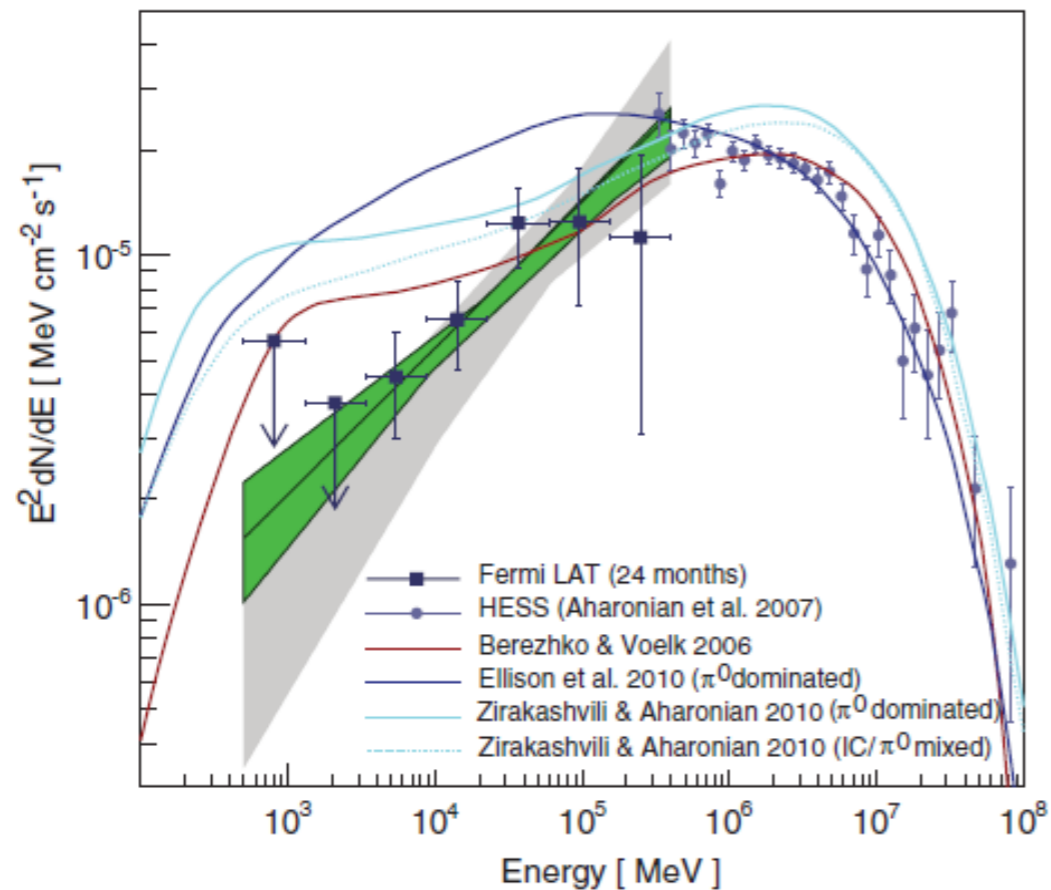
Omar Tibolla

Tuxtla Gutierrez, 4<sup>th</sup> of October 2014

...but

Some shell-type SNRs seem leptonic..

E.g. **RX J1713.7-3946** , one of the most promising targets and moreover one of the best threatened by theoretical models...



Omar Tibolla

Tuxtla Gutierrez, 4<sup>th</sup> of October 2014



## Other possibilities...

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In order to close possible gaps, people search for other possibilities...

Looking the high energy sky (i.e. the “non-thermal sky”), the dominant population is not represented by shell-type SNRs...

Among the known sources, **Pulsar Wind Nebulae (PWNe)** is the most numerous. And indeed it was proposed that at the termination shock of the Pulsar Wind, also hadrons could be accelerated as well as leptons (e.g. [Bednarek & Protheroe 1997, PRL, 79, 2616](#) ; [Atoyan & Aharonian 1996, MNRAS, 278, 525](#) ; [Cheng et al. 1990, J. Phys. G, 16, 1115](#) ; [Bednarek & Bartosik 2003, A&A, 405, 689](#)).

But the most numerous population in absolute terms is represented by **Unidentified sources**. In fact almost 50% of the TeV Galactic sources are still unidentified; at GeV energies, 67% of EGRET sources were unidentified and also with the newer generation of gamma-ray satellites we have the same result: in fact, at low Galactic latitudes ( $b < 10$  deg), 62% of the Fermi LAT detected sources have no formal counterpart.

*Hence understanding the high energy unidentified sources could be a crucial brick in solving the whole riddle of Cosmic Rays origin.* And the correlation with PWNe could be very close, at least for the so called “dark sources”.

## 4. Un fenomeno spettacolare: Fermi Bubbles

In 2010, two gigantic spherical bubbles of high energy emission were detected to the north and the south of the Milky Way core, using data of the *Fermi Gamma-ray Space Telescope*.

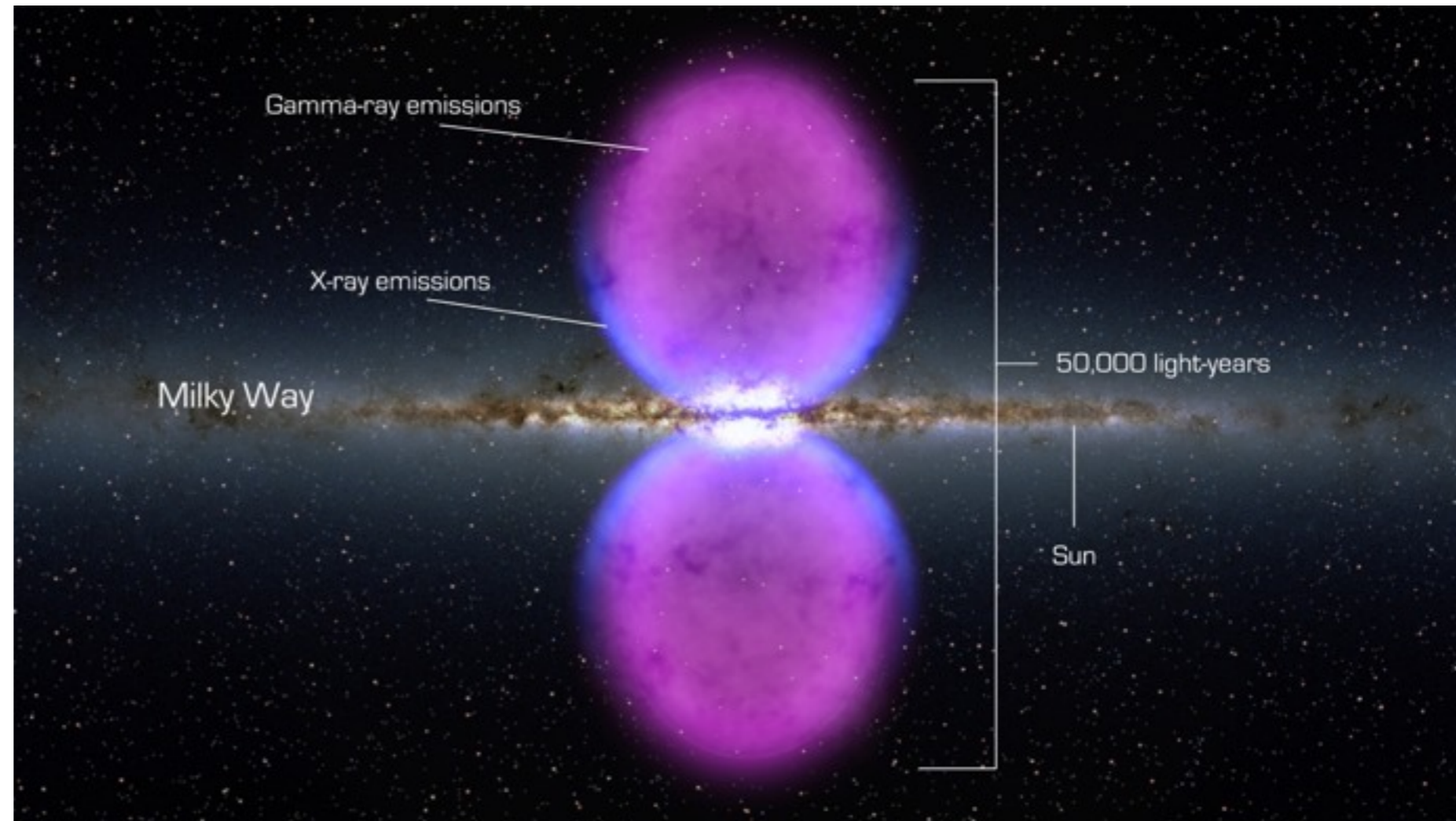
The diameter of each of the bubbles is about 25,000 light-years (7.7 kpc); they stretch up to Grus and to Virgo on the night-sky of the southern hemisphere.

Subsequently, observations with the Parkes Telescope at radio frequencies identified polarized emission that is associated with the Fermi bubbles.

These observations are best interpreted as a magnetized outflow driven by star formation in the central 640 ly (200 pc) of the Milky Way.

Later, on January 5, 2015, NASA reported observing an X-ray flare 400 times brighter than usual, a record-breaker, from Sagittarius A\*, a black hole in the center of the Milky Way.

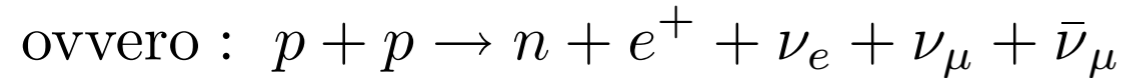
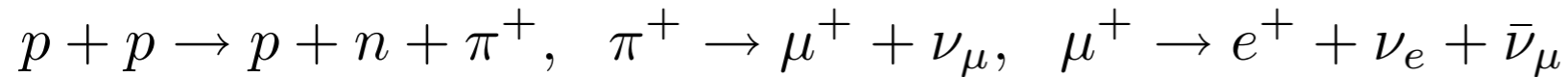
The unusual event may have been caused by the breaking apart of an asteroid falling into the black hole or by the entanglement of magnetic field lines within gas flowing into Sagittarius A\*, according to astronomers.





## 5. Un segnale non ambiguo: neutrini!

Le interazioni nucleari possono anche portare a neutrini che provengono dai decadimenti di pioni e muoni



la rivelazione di neutrini di 200 MeV da SNR sarebbe la vera “pistola fumante” del meccanismo di accelerazione dei raggi cosmici

per ora, rivelatori di neutrini ( $E > 8 \text{ TeV}$ ) energia sono in funzione sotto il ghiaccio in Antartide (Ice Cube) o sono in progetto a grande profondità in mare (NEMO, Capo Passero, Sicilia)

37 eventi di neutrino osservati da IceCube, nessun addensamento

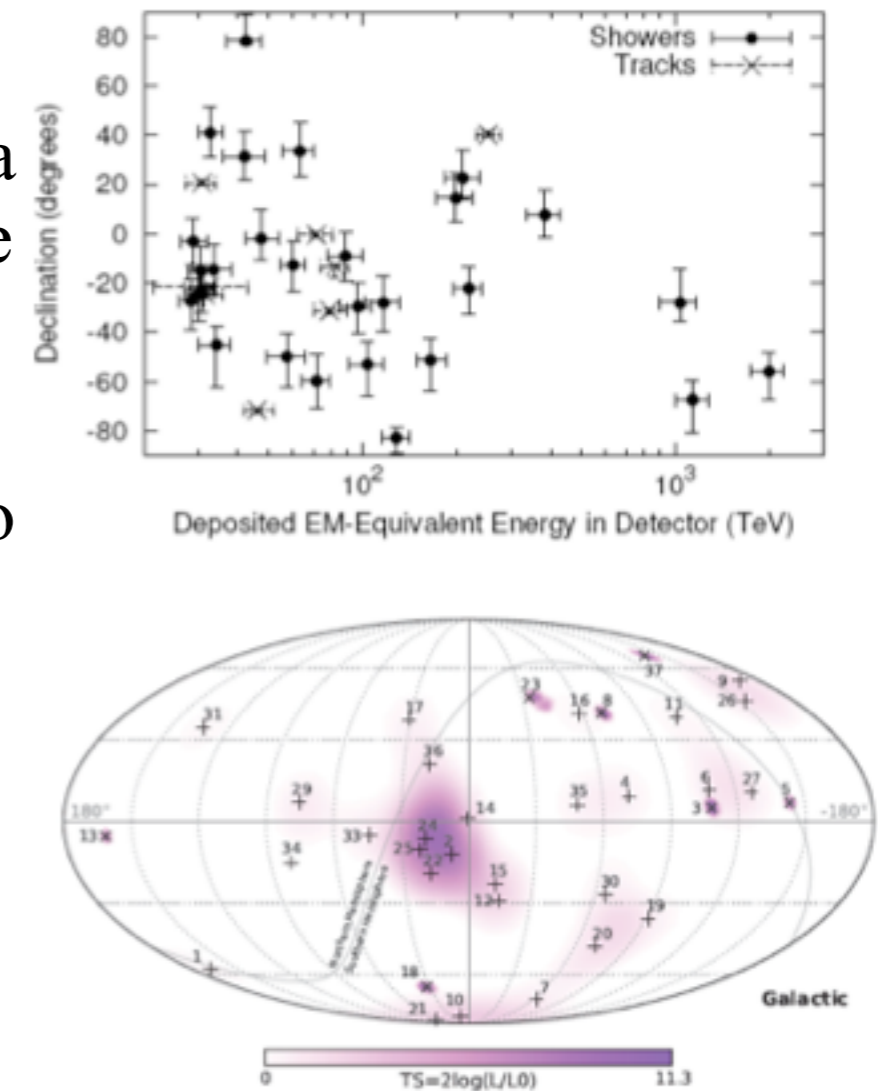
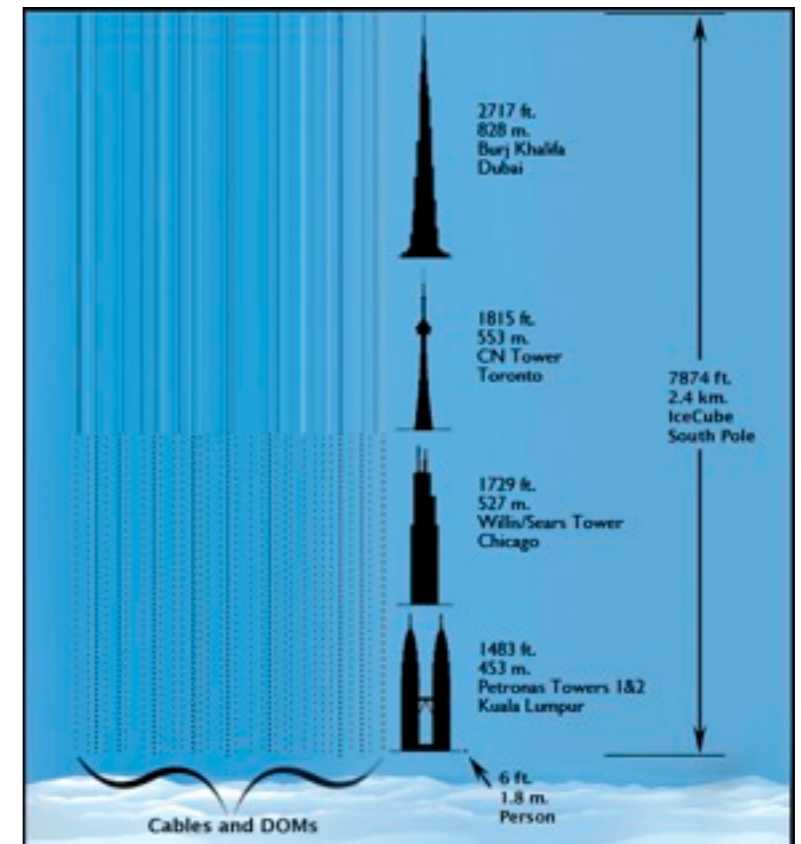
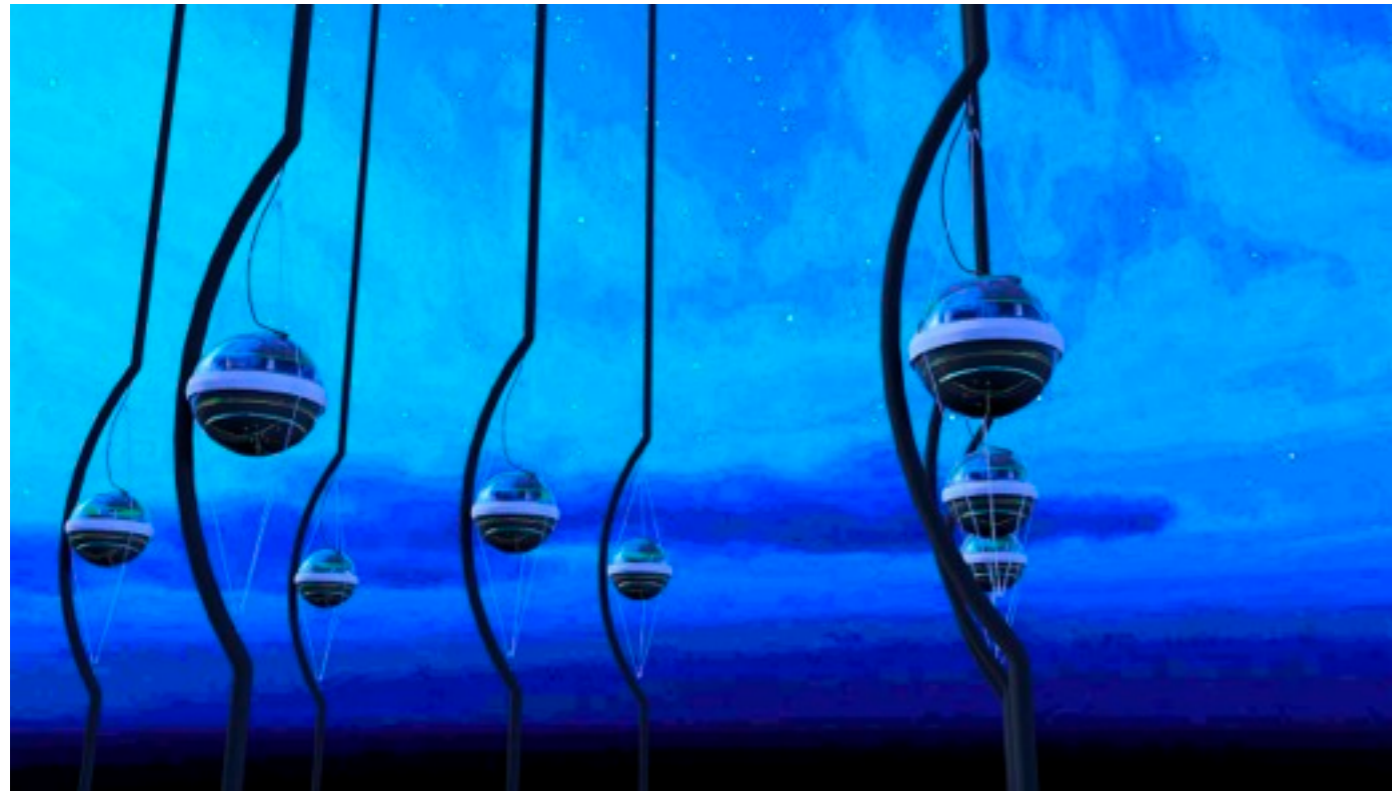


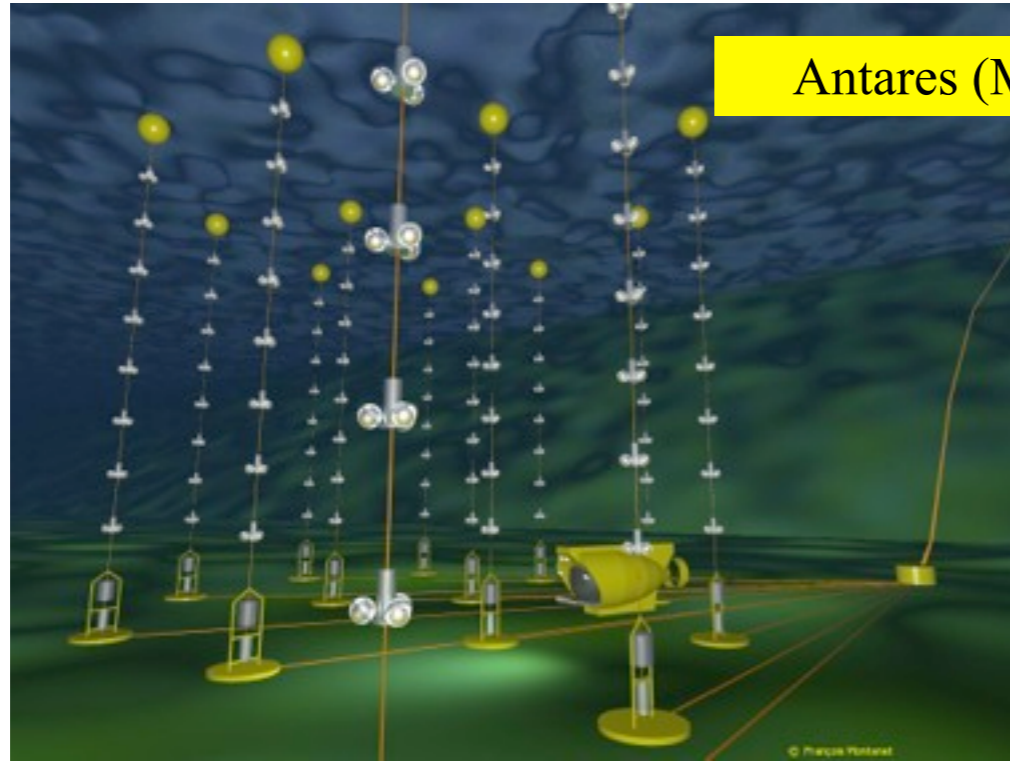
Figure 8: Deposited energies of the VHE neutrinos and their arrival directions (from [38]).

# IceCube

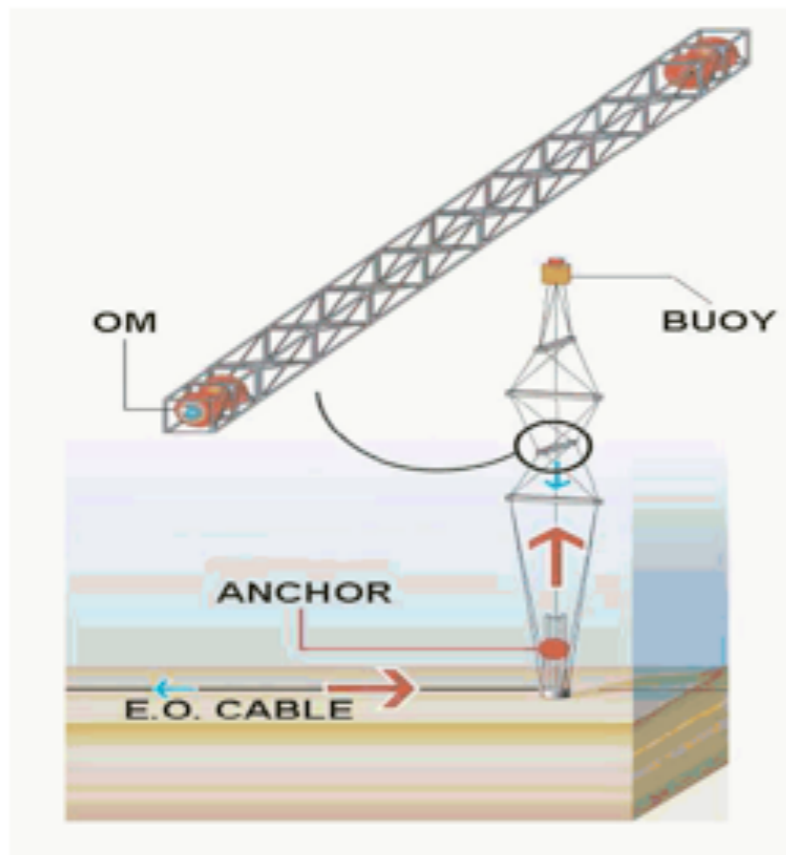
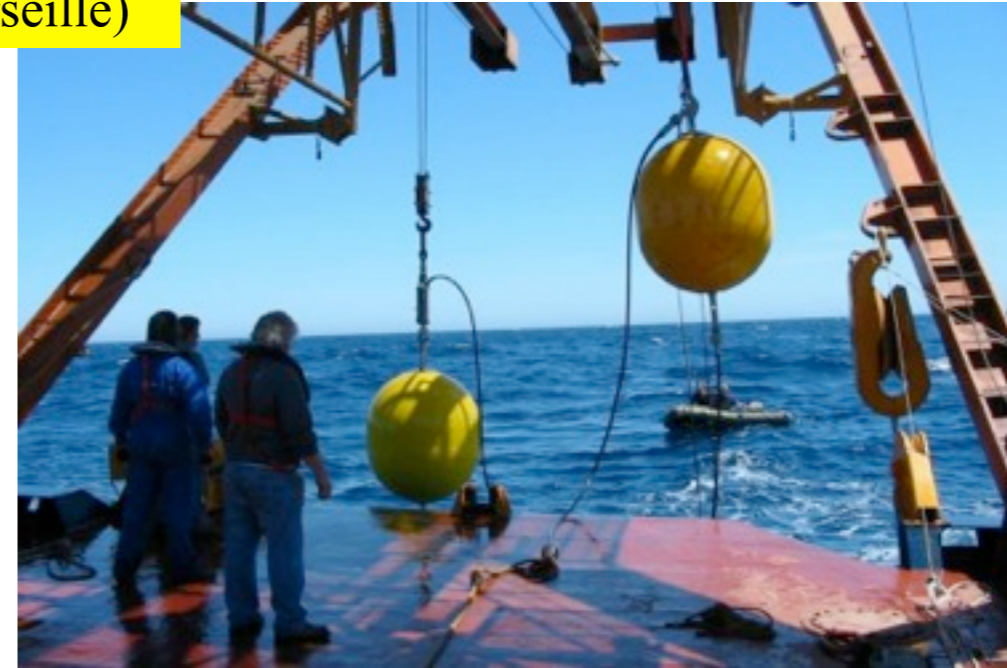




# Antares e NEMO



Antares (Marseille)



NEutrino  
Mediterranean  
Observatory



La "mini-torre" di NEMO

Il deployment della "mini-torre"

## 6. Ultra High Energy cosmic rays

- Meccanismo di accelerazione: molte ipotesi
  - campi magnetici ruotanti delle pulsar, o dei dischi di accrezione
  - campi magnetici nei Gamma Ray Burst
  - -??????
- I raggi cosmici UHE, anche se protoni, sono poco deflessi dai campi magnetici intergalattici, la direzione di provenienza potrebbe puntare alla sorgente
- attenuazione su distanze di Mpc a Gpc potrebbe diventare importante alle energie in cui si hanno probabilita' di collisione inelastica sui fotoni del fondo cosmico
- la probabilita' di collisione di una particella dei raggi cosmici, es. protone, e' misurata dalla cosiddetta *sezione d'urto*,  $\sigma$ , una grandezza con la dimensione di una superficie [ $\sigma$ ]= cm<sup>2</sup>
- cui corrisponde una *lunghezza di attenuazione*:  $L = \frac{1}{n\sigma}$  dove n=numero di bersagli/cm<sup>3</sup>, ad es. il numero dei fotoni del fondo cosmico e' circa n=400/cm<sup>3</sup>,
- alle energie per cui  $\sigma$  aumenta, ad es. quando l'energia rende possibile una nuova reazione, L diminuisce e i RC che vengono da distanze >L sono assorbiti



# Lunghezza di attenuazione cosmica, limite GZK

- la reazione  $p + \gamma \rightarrow p + e^+ + e^-$  avviene per energie del protone superiori a (Lez. 18)

$$E_{pair} = \frac{(m_p + 2m_e)^2 - m_p^2}{4\omega} \approx \frac{m_p m_e}{\omega} \approx 2 \cdot 10^{18} \text{ eV}$$

e corrisponde a  $L \sim 1000 \text{ Mpc}$  ( $\sigma$  piccola)

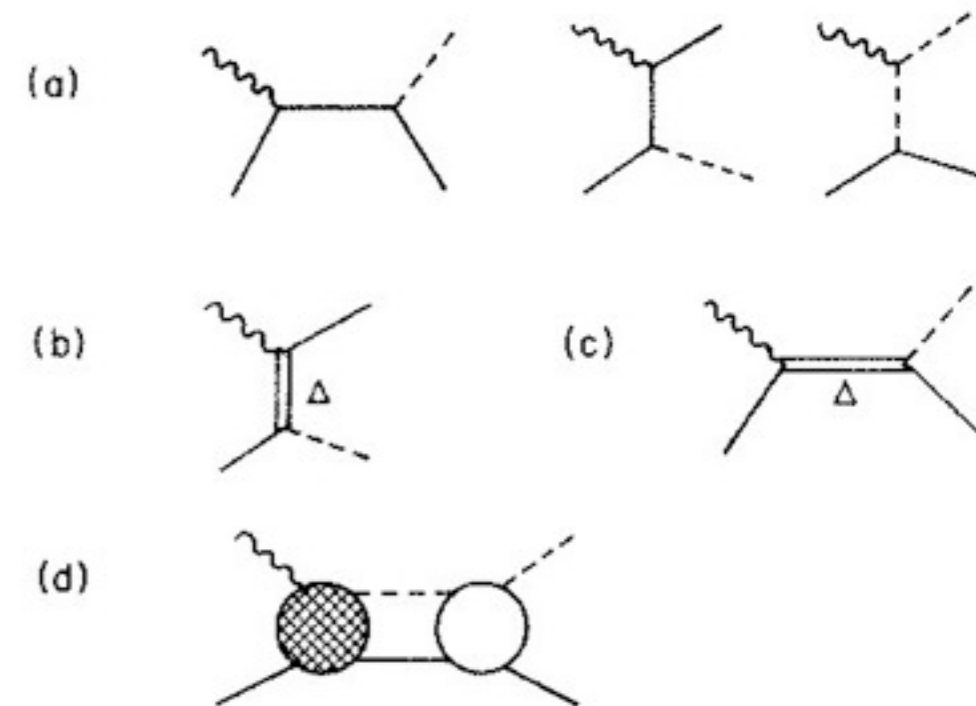
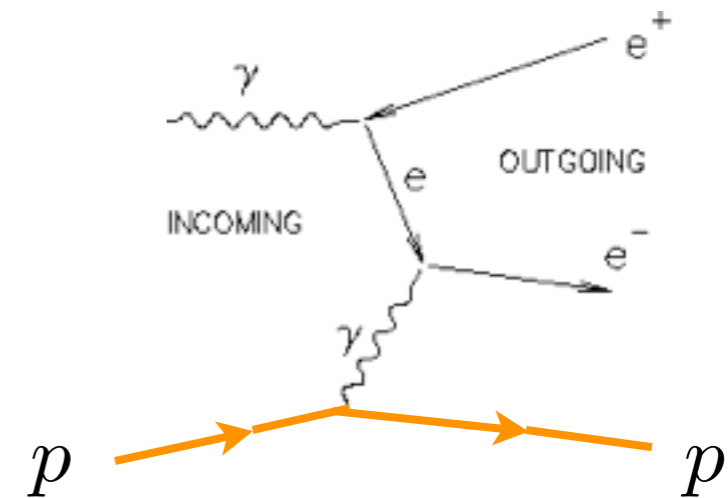
- La reazione  $p + \gamma \rightarrow p + \pi^0$  richiede

$$E_{phot} = \frac{(m_p + m_\pi)^2 - m_p^2}{4\omega} \approx \frac{m_p m_\pi}{2\omega} \approx 2 \cdot 10^{20} \text{ eV}$$

e corrisponde a  $L \sim 100 \text{ Mpc}$  ( $\sigma$  circa 10 volte superiore)

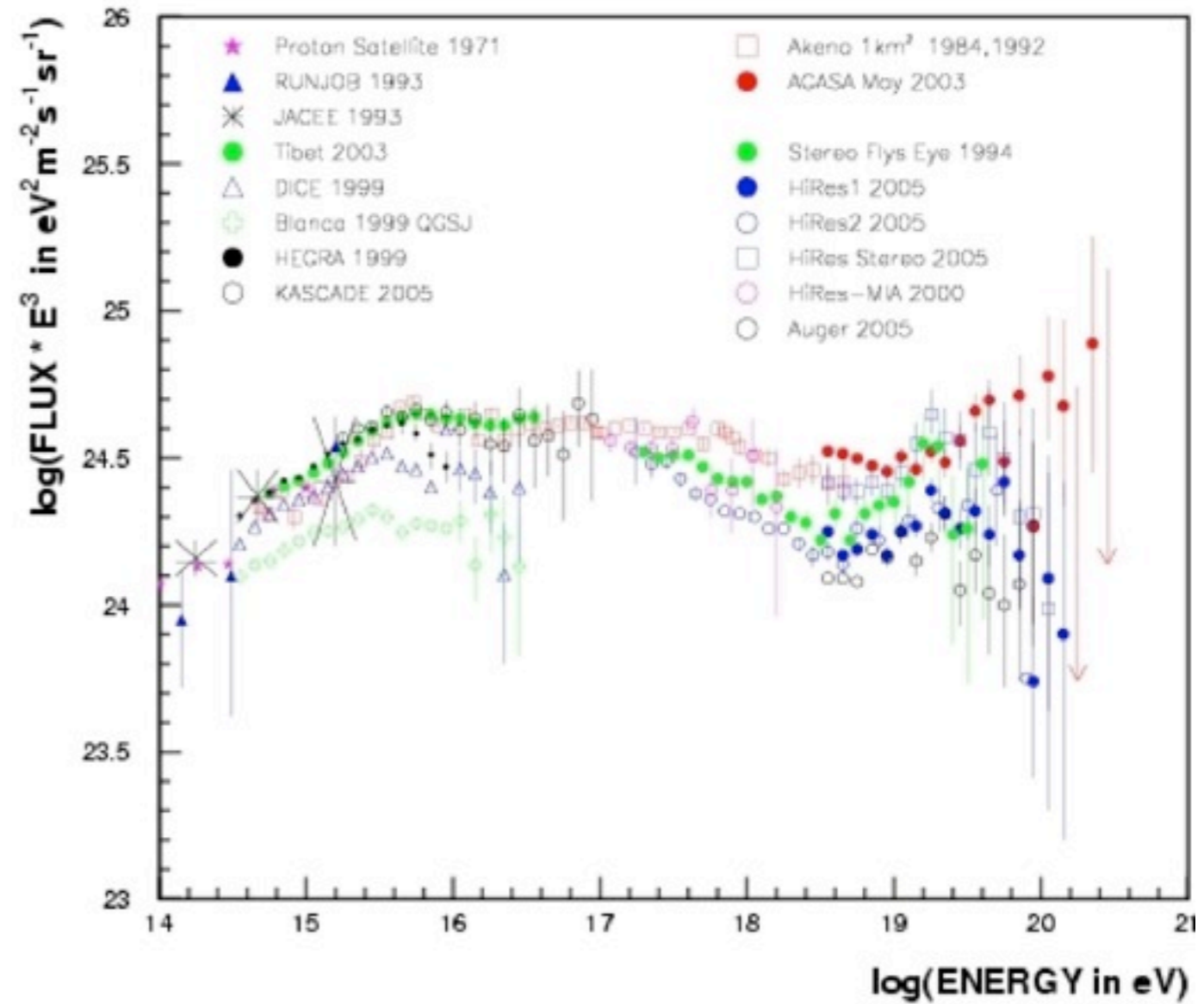
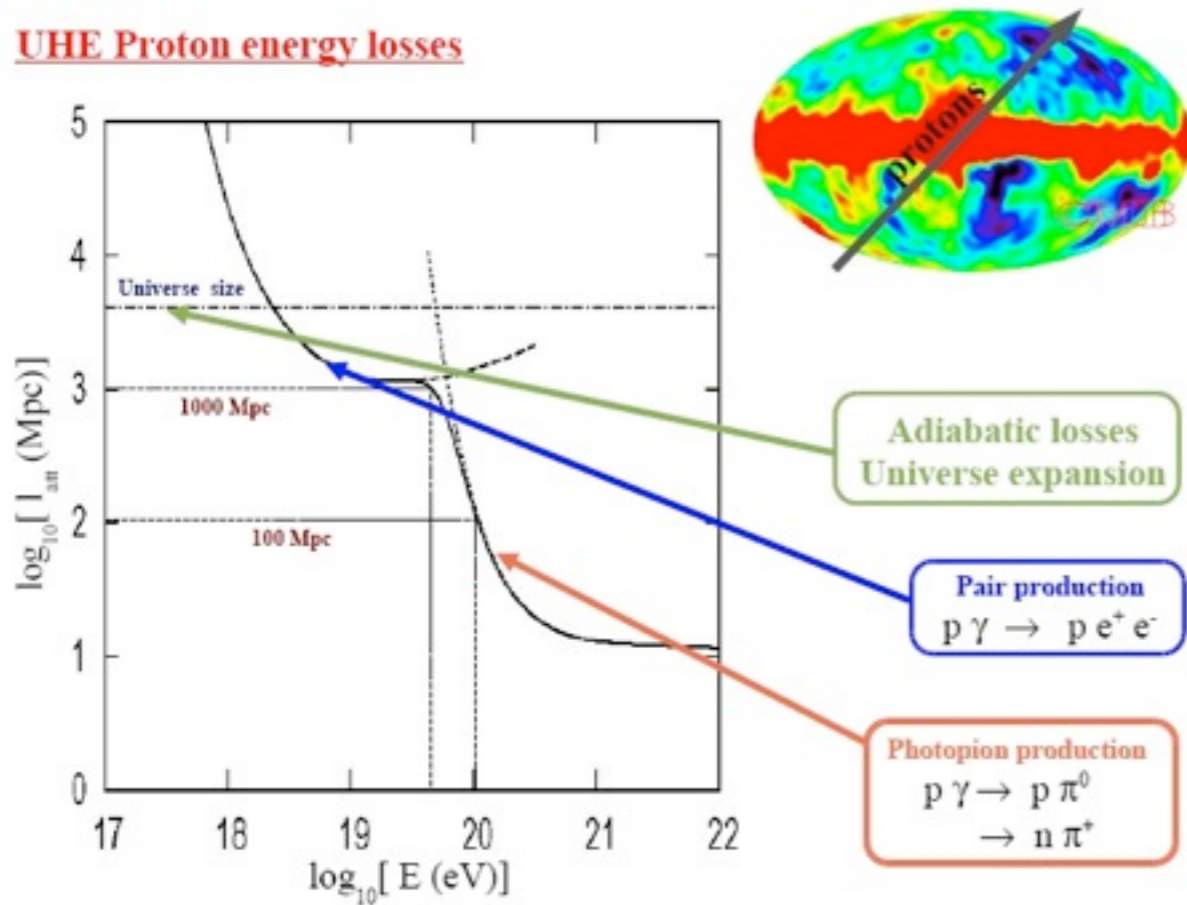
- il fatto che i raggi cosmici di energia superiore a circa  $10^{20} \text{ eV}$  non possano provenire da distanze superiori alle dimensioni dei cluster di galassie implica una brusca diminuzione della loro abbondanza e quindi un calo nello spettro dei RC con energie sopra la caviglia, noto come “limite GZK” (Greisen, Zatsepin, Kuzmin)

??? l'eventuale osservazione di raggi cosmici di energia superiore al limite GZK, potrebbe indicare una violazione della invarianza relativistica ??????



# GZK: teoria e esperimenti pre *Pierre Auger Observatory*

**UHE Proton energy losses**

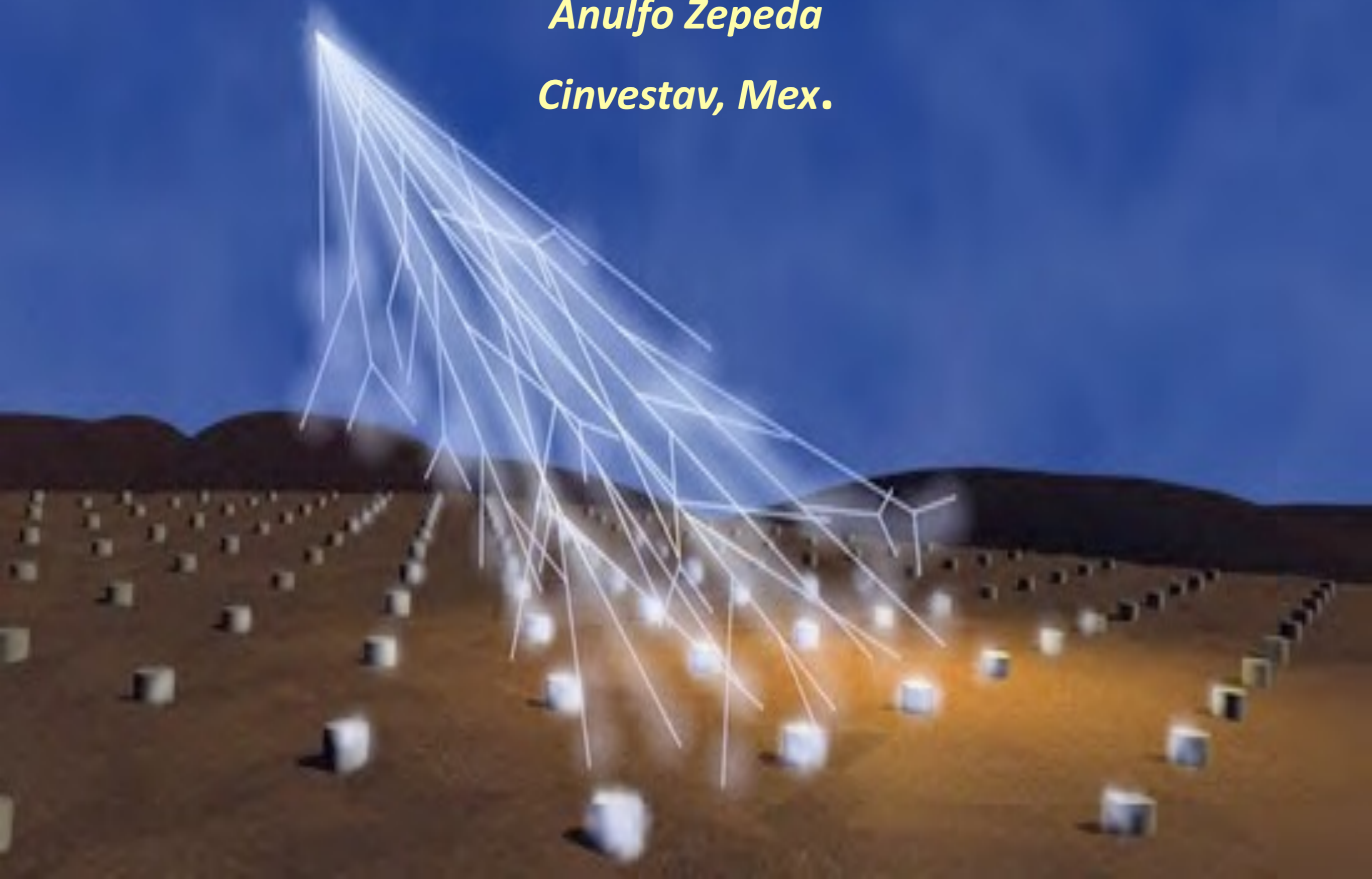




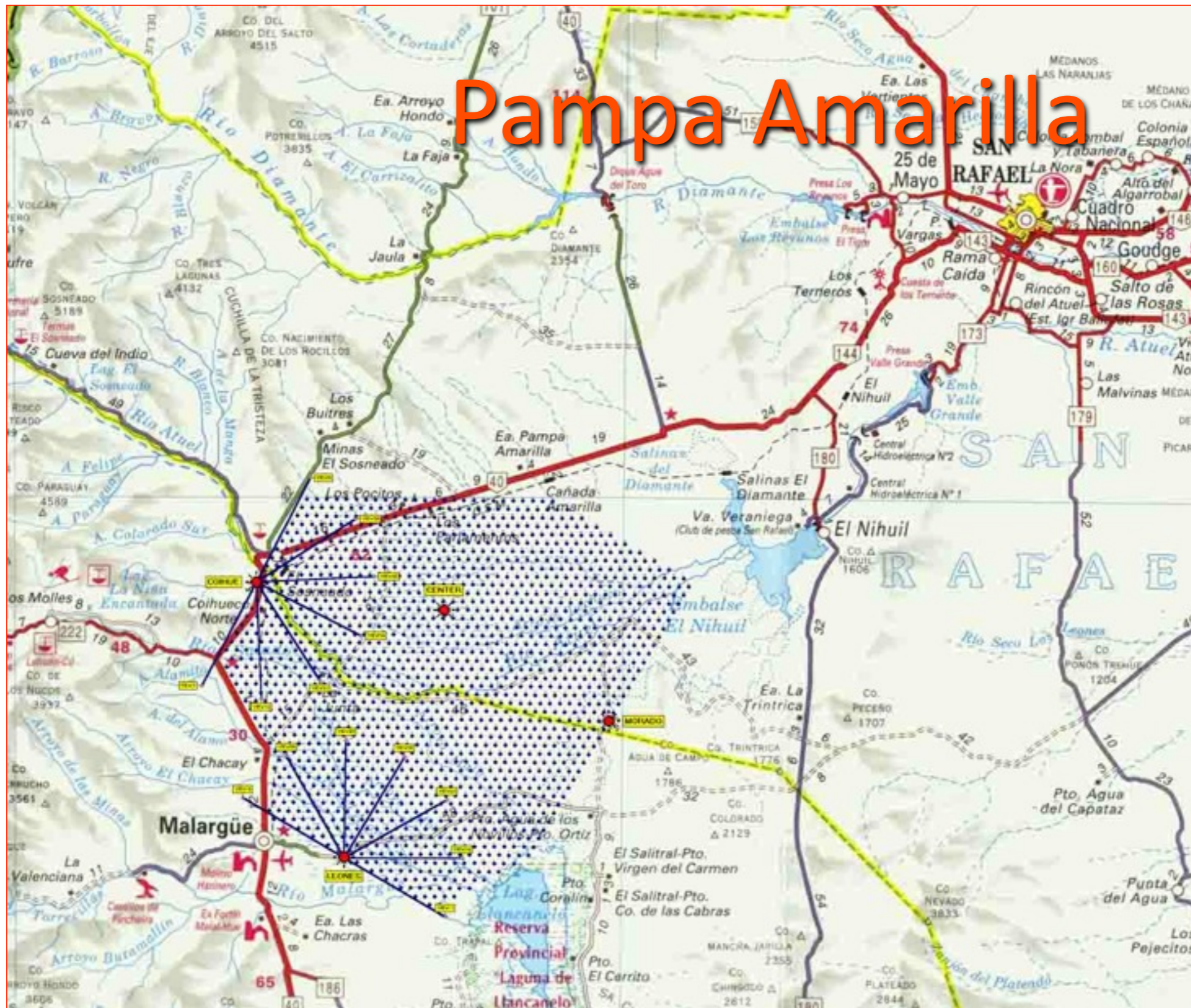
# 7. The Pierre Auger Observatory

*Anulfo Zepeda*

*Cinvestav, Mex.*



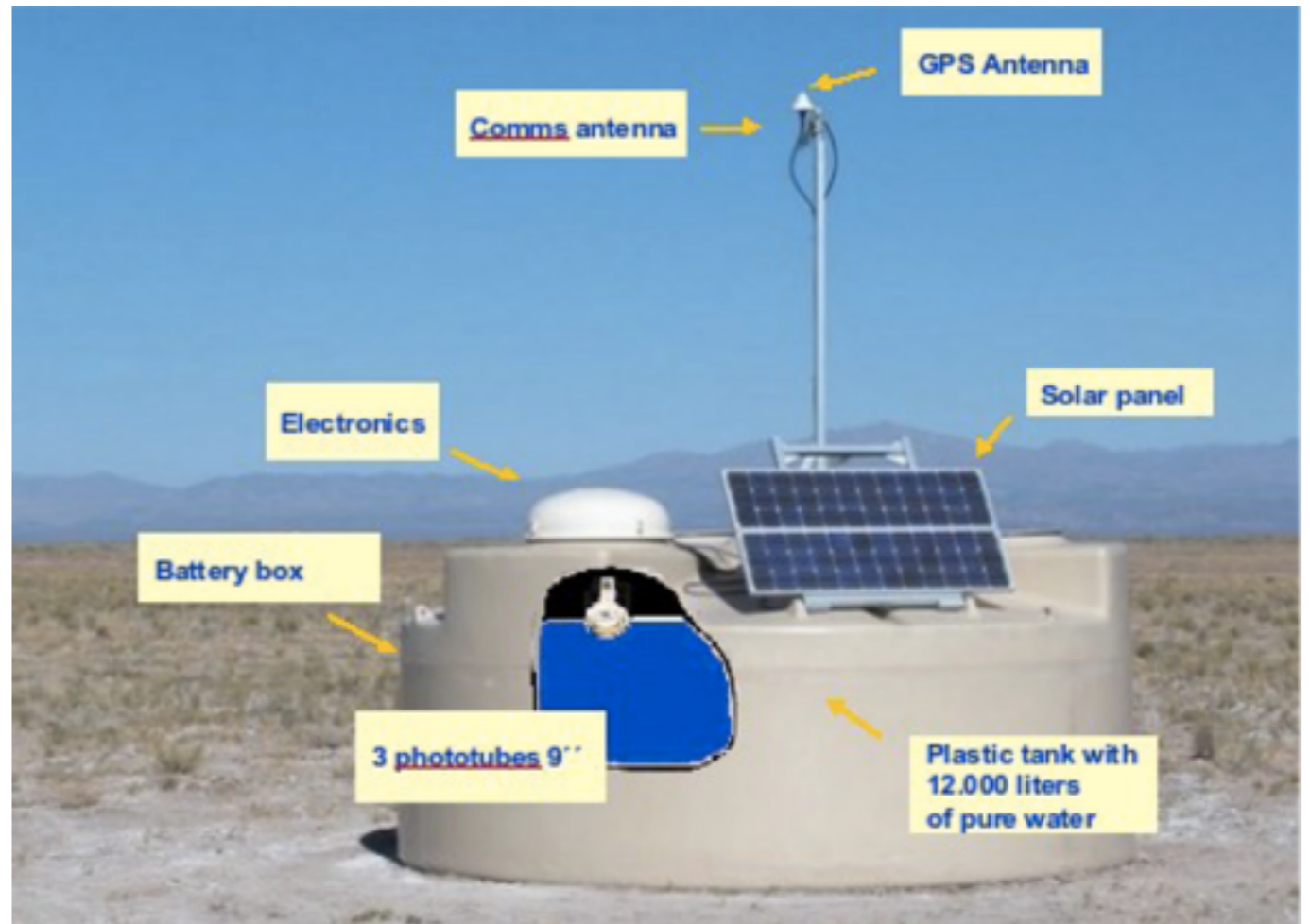


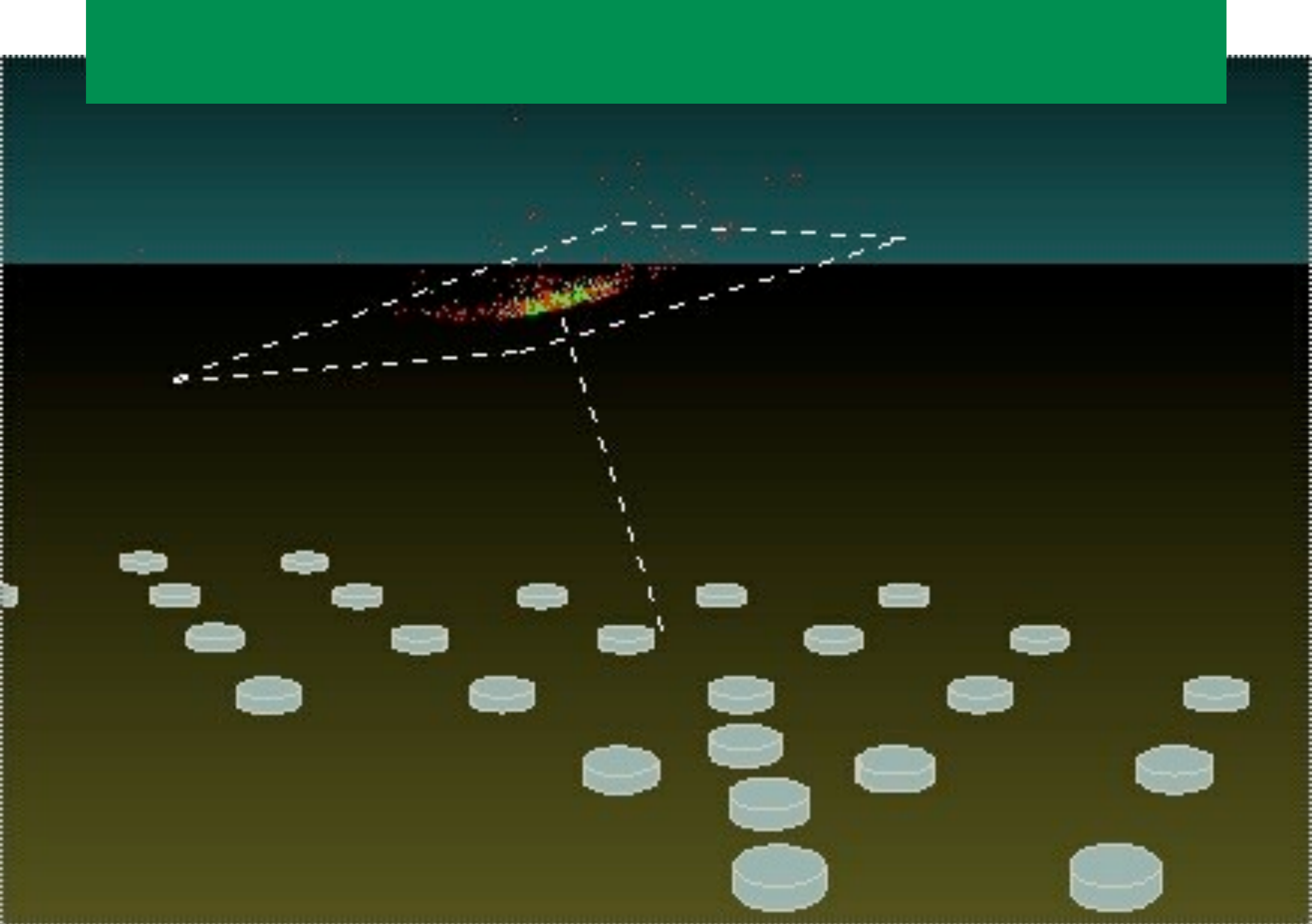


1300-1400 msnm

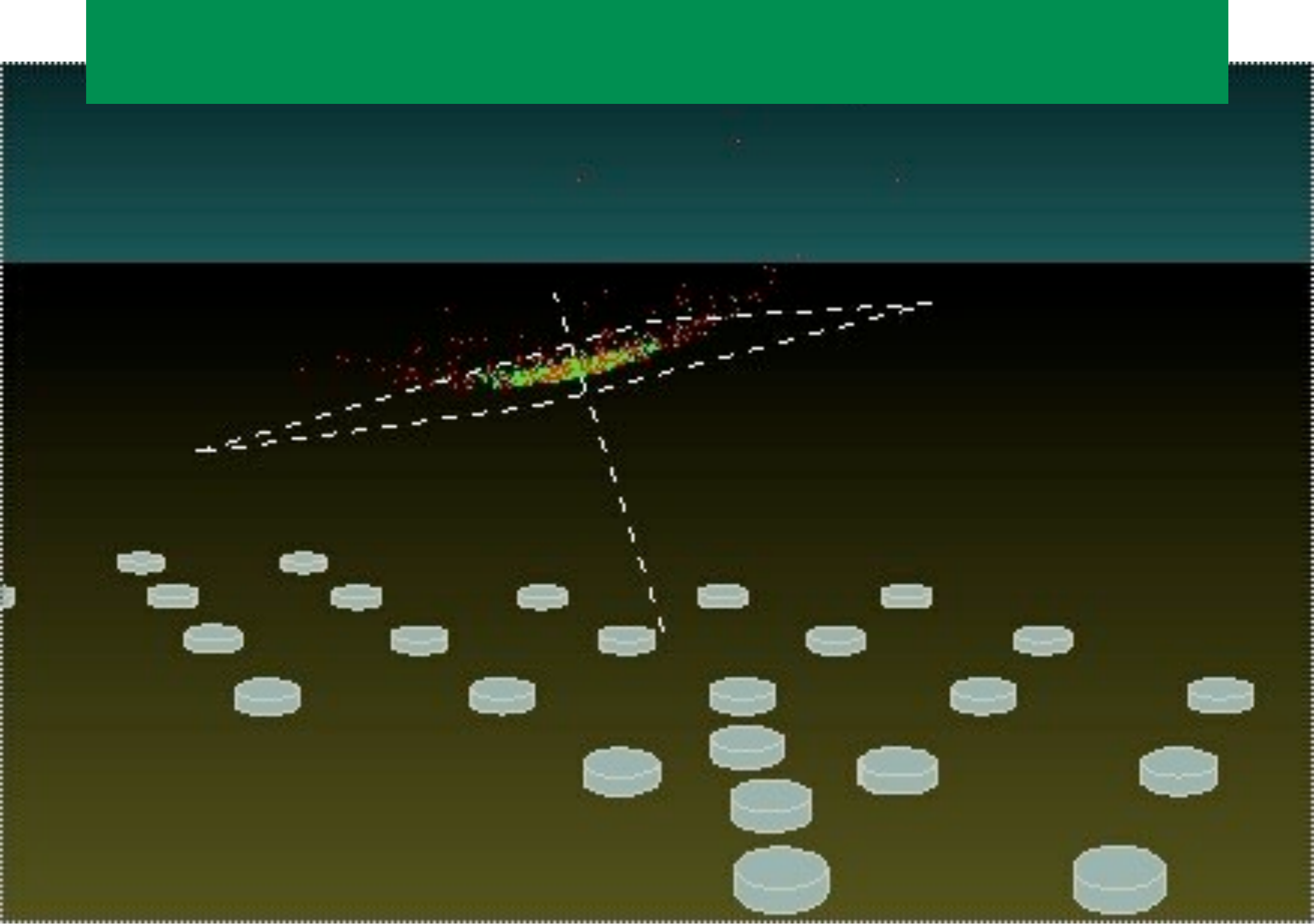


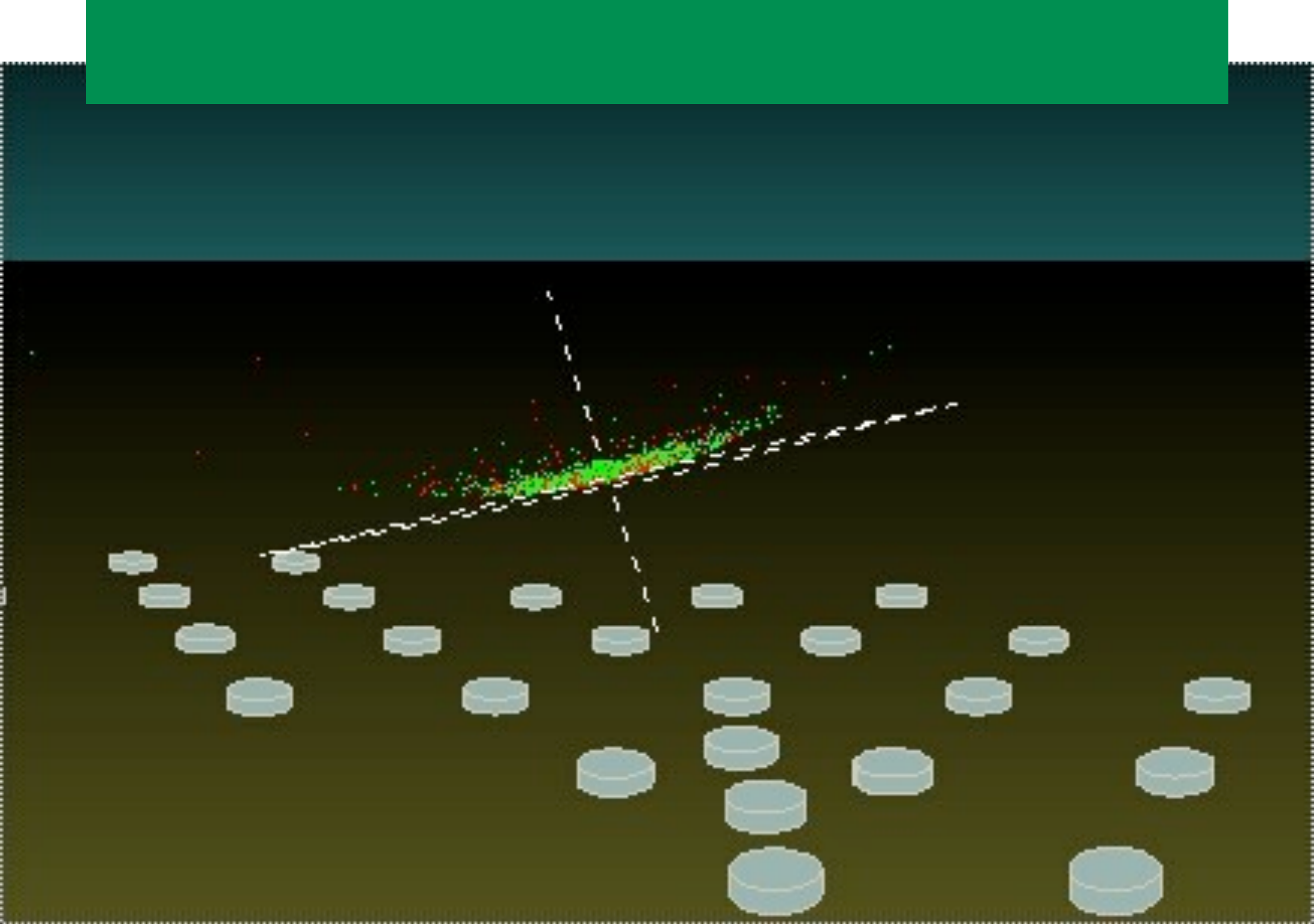
# surface detector

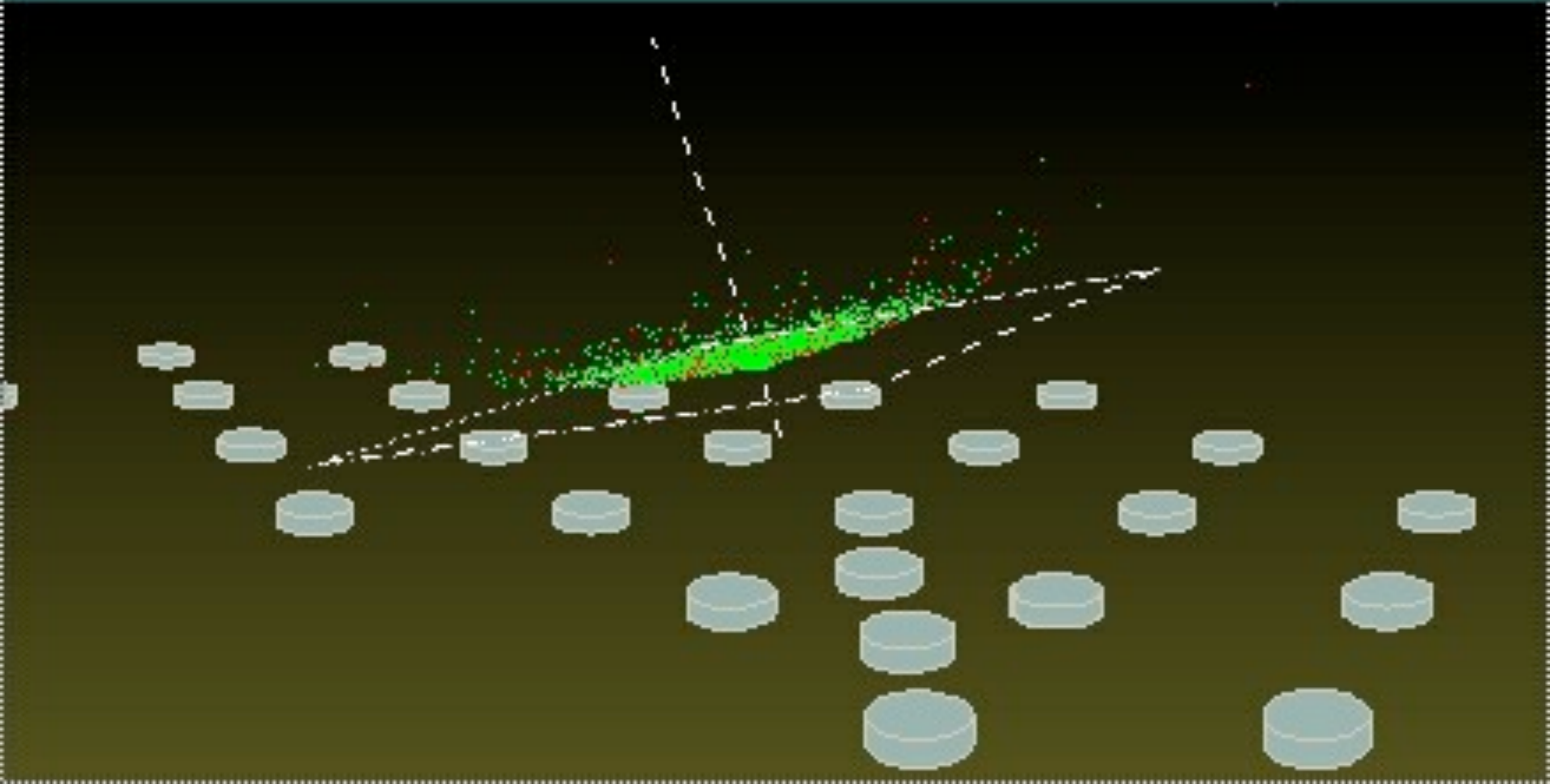




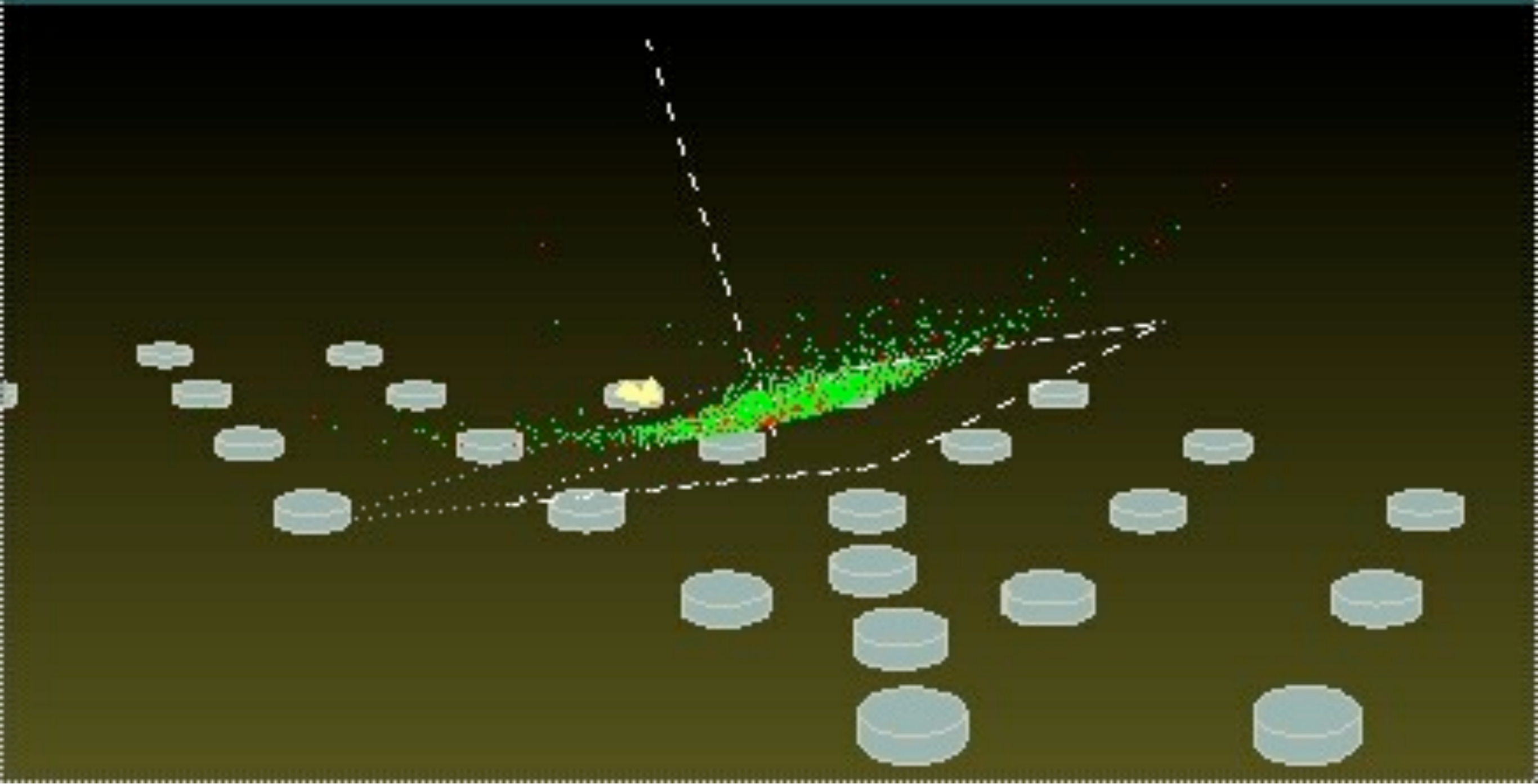


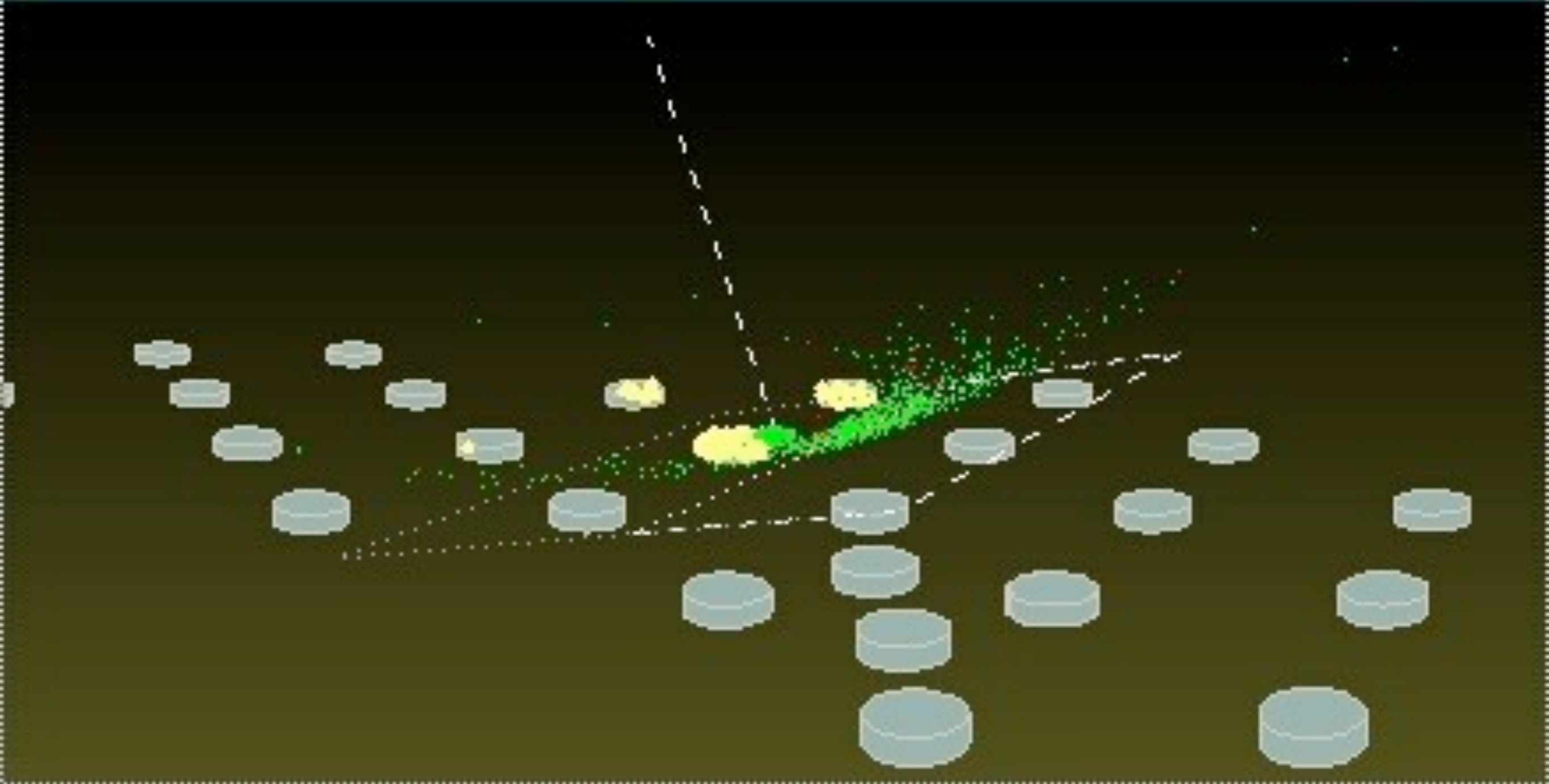


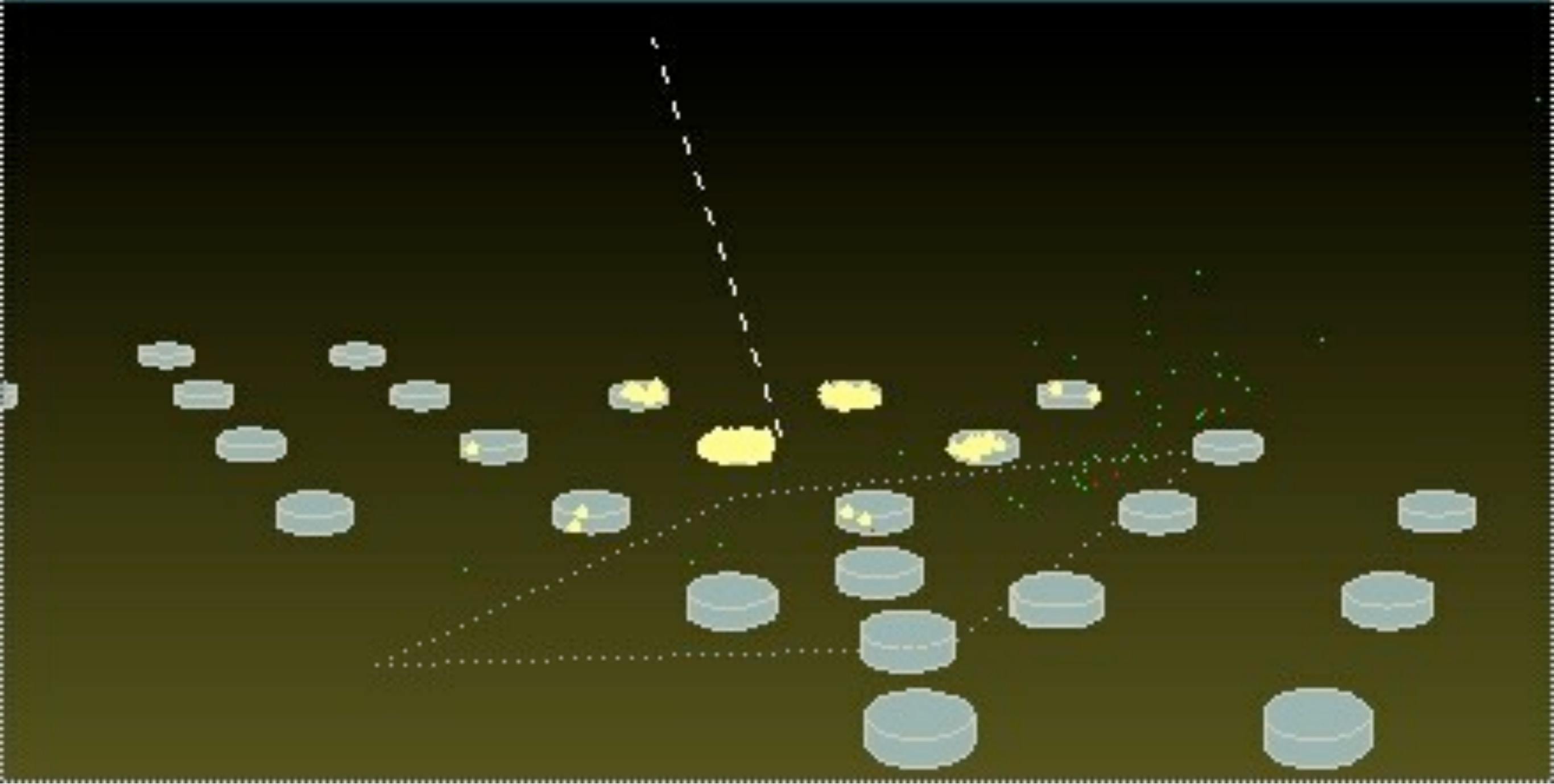








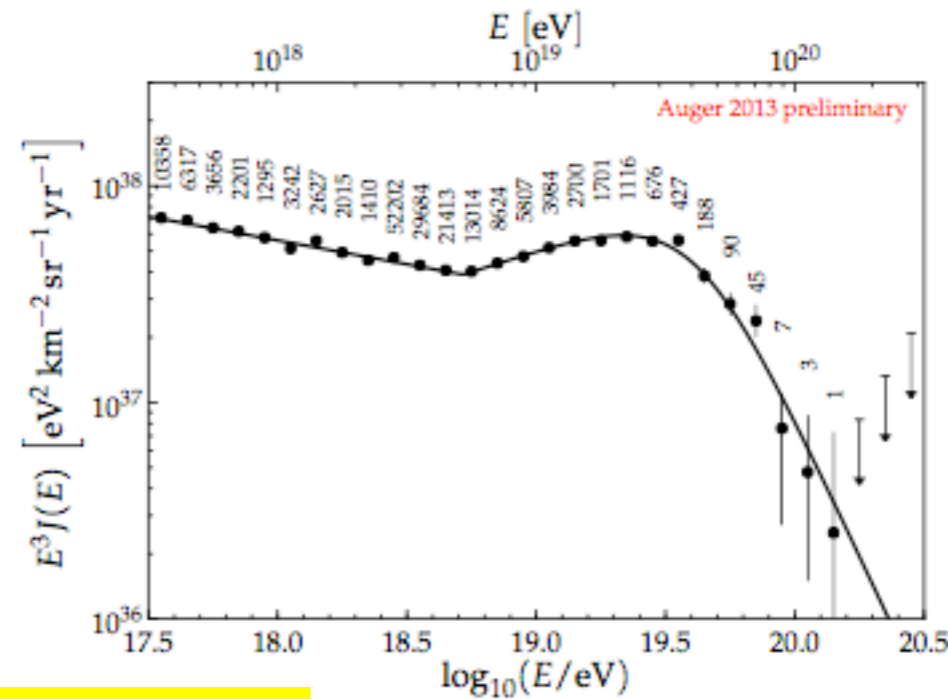
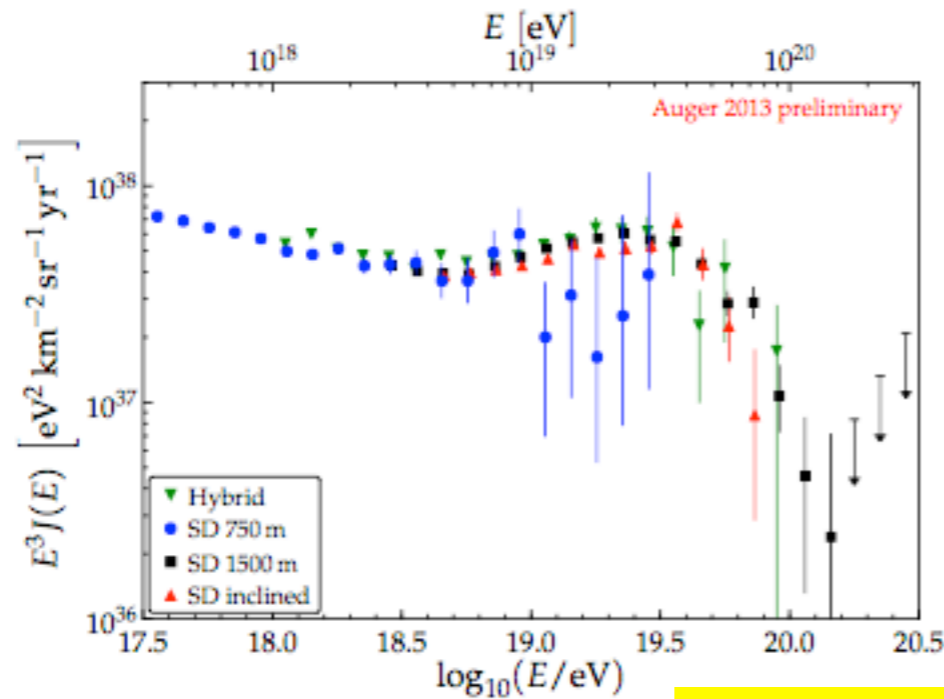
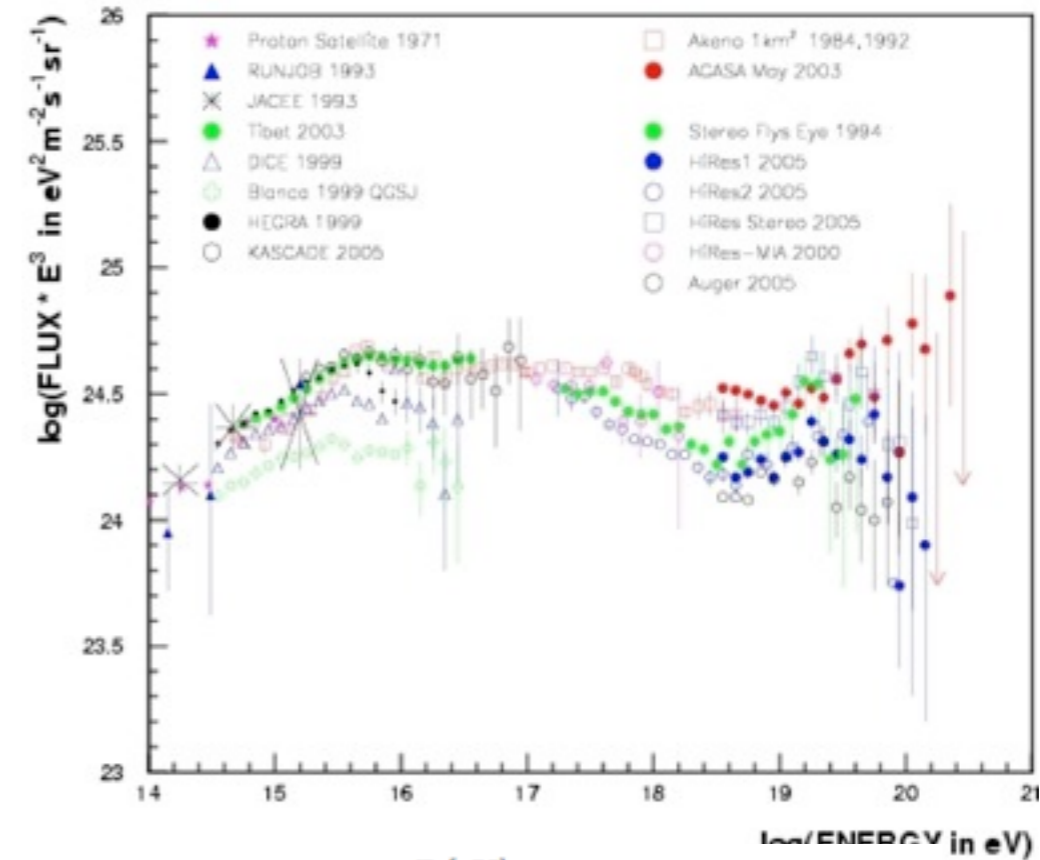
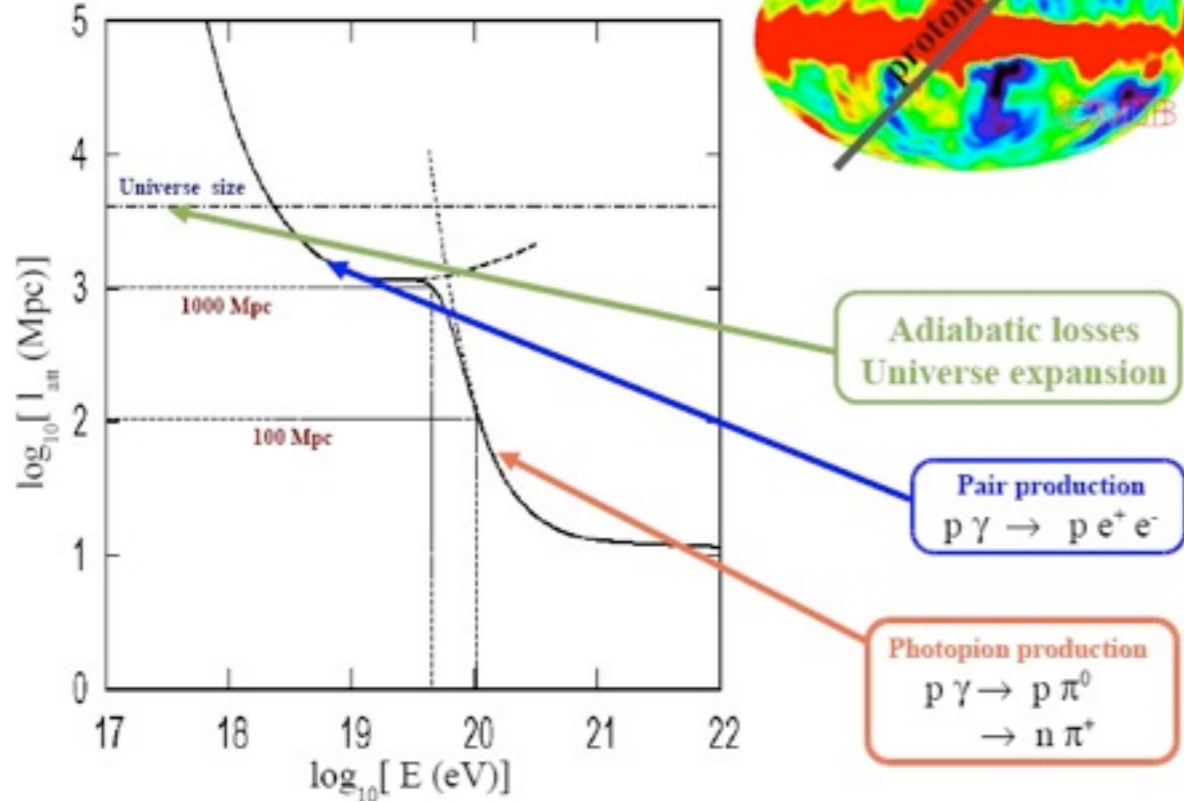






# 8. GZK: gli esperimenti all'OPA confermano il limite !

## UHE Proton energy losses

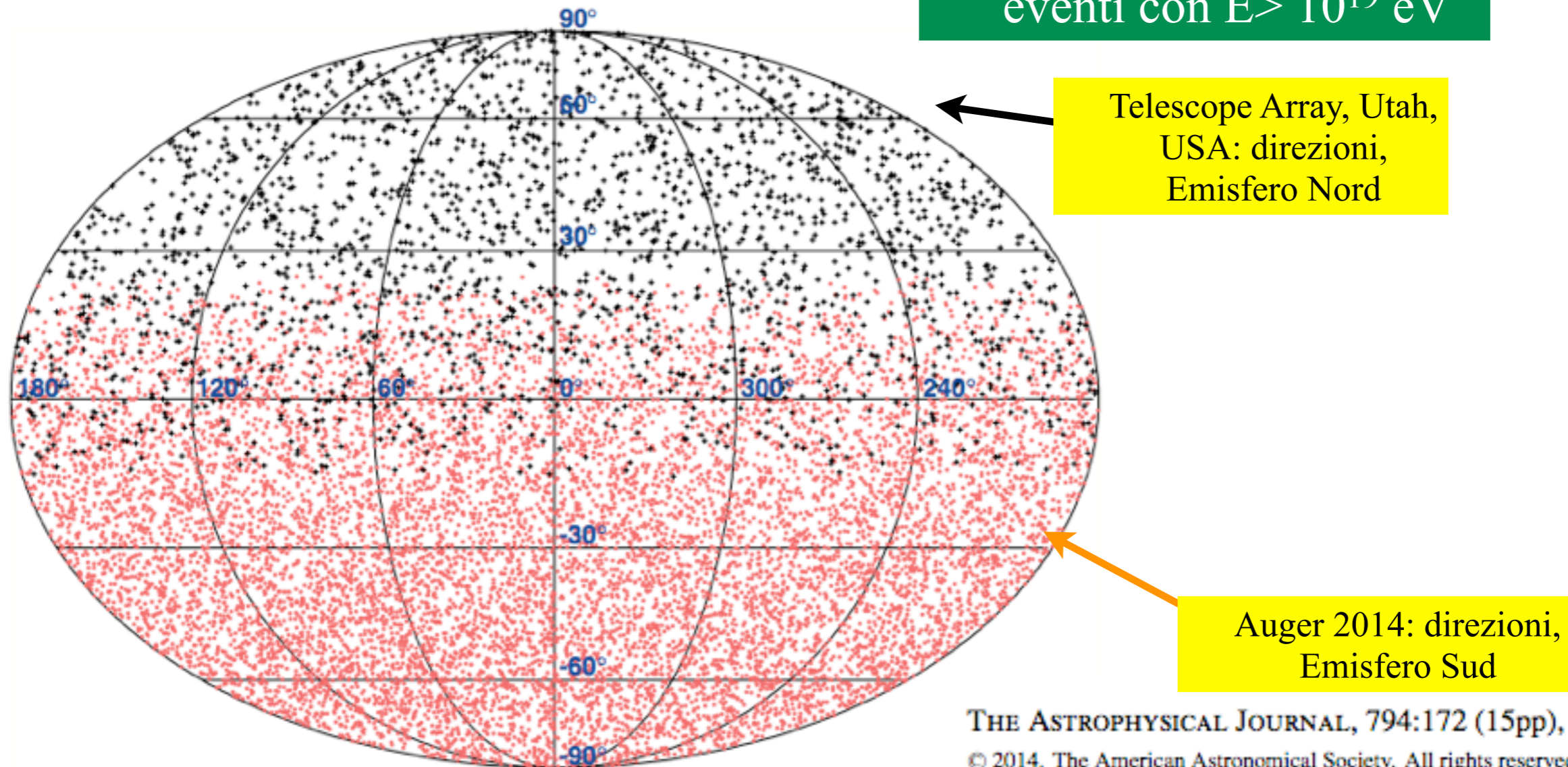


### Auger 2013: spectrum

**Figure 1.** Left: The energy spectra obtained from hybrid events, and from data of the 750 m and 1500 m SD arrays for vertical and inclined showers measured at the Auger Observatory. Right: The combined spectrum, with the number of events shown in each energy bin. The arrows represent upper limits at an 84% confidence level [5].

# Distribuzione nel cielo delle direzioni di arrivo degli UHE CR

eventi con  $E > 10^{19}$  eV

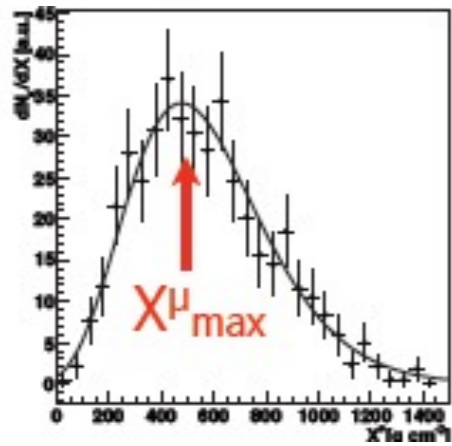


**Figure 7.** Arrival directions of Auger (red points in the south hemisphere) and Telescope Array events (black crosses in the northern hemisphere) above  $10^{19}$  eV in equatorial coordinates, using a Mollweide projection. (A color version of this figure is available in the online journal.)

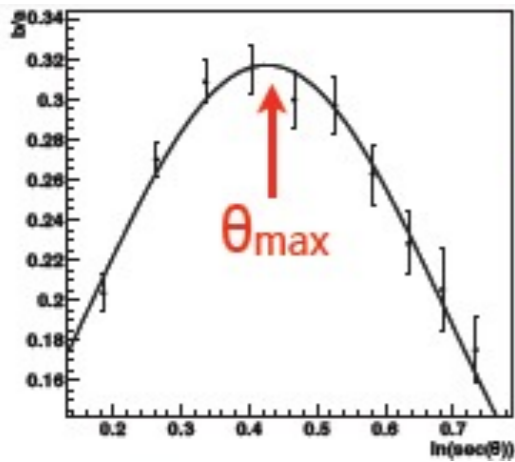
Con la risoluzione attuale, non si vedono sorgenti



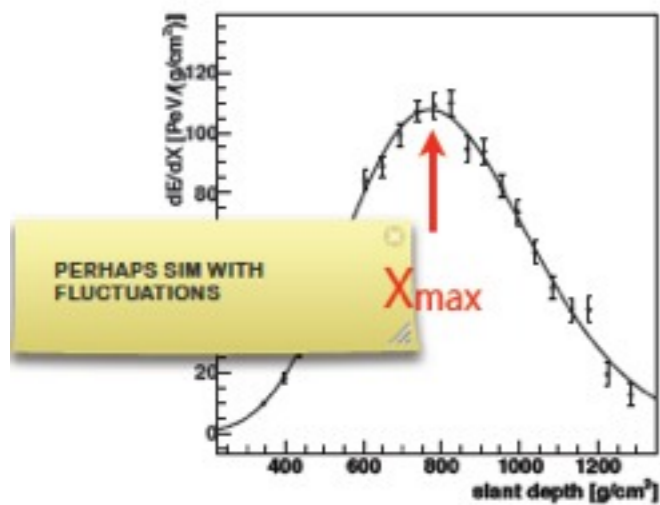
# Comparison of Methods



Muon Production Depth from timing differences

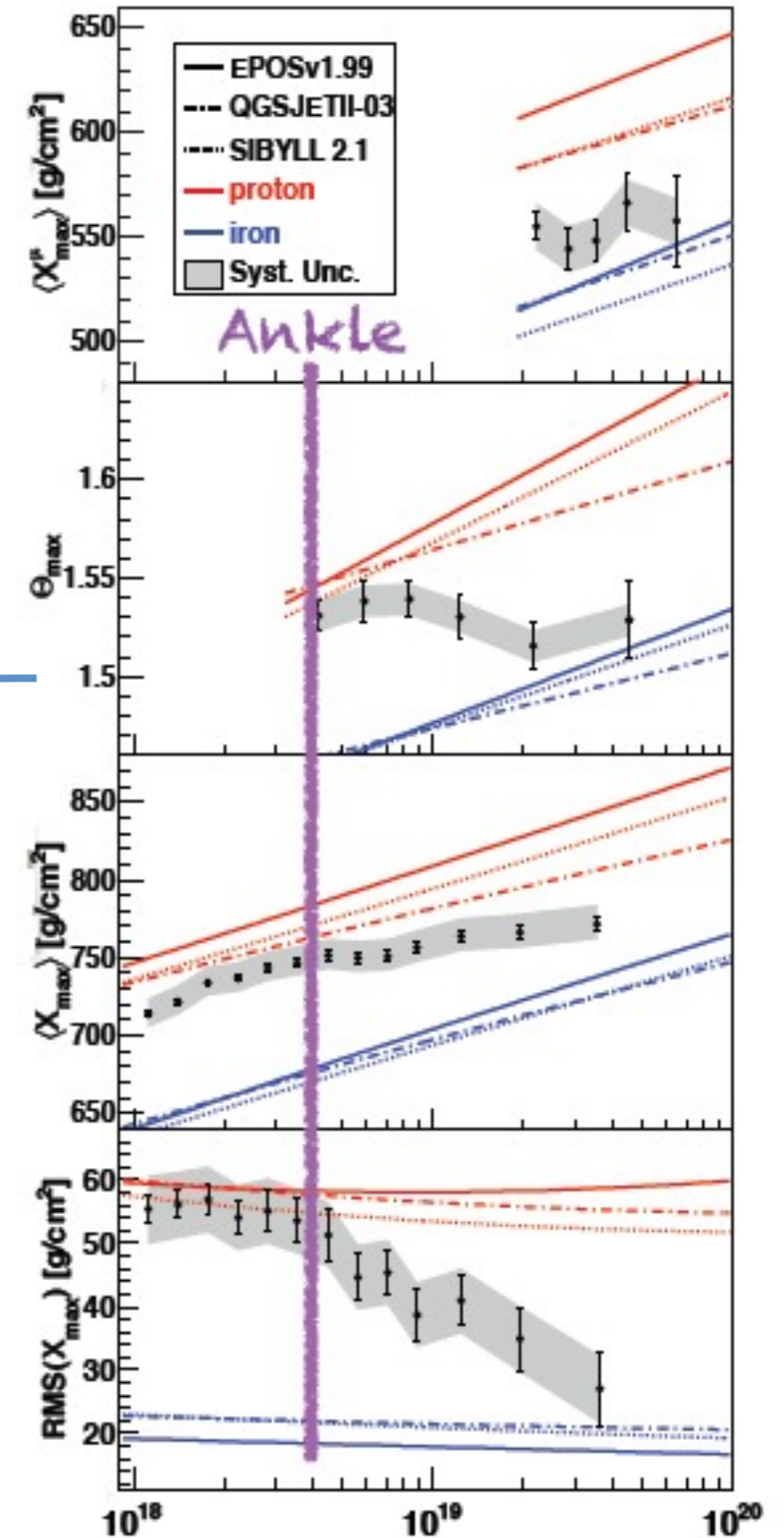


Shower Maximum from asymmetry of rise times

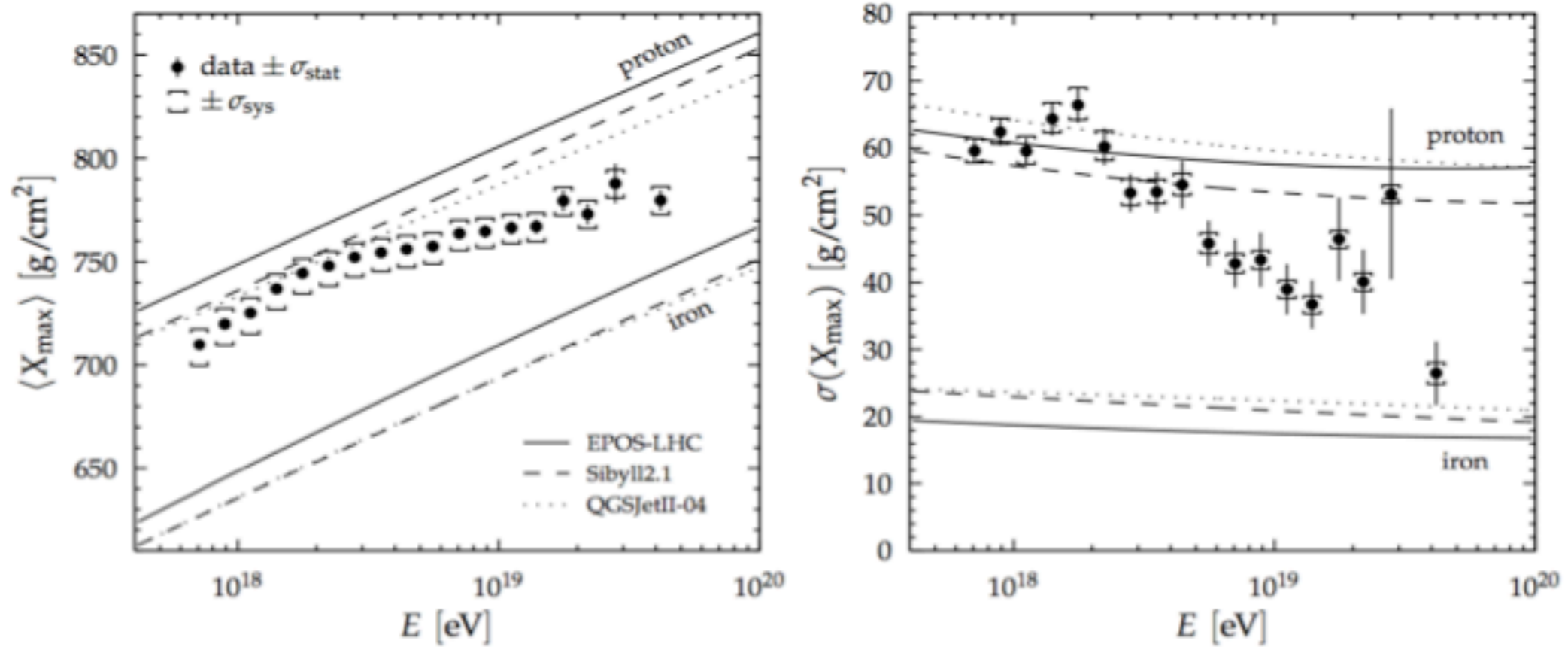


RMS( $X_{max}$ ) from FD

$X_{max}$  from FD



# Composition



**Figure 2.**  $\langle X_{\max} \rangle$  and its RMS as a function of energy, compared to the predictions of the most recent, post-LHC, air shower simulations using different hadronic interaction models (see text) [10].



## 9. Nel futuro: Cherenkov Telescope Array

- In corso di realizzazione, 10 km<sup>2</sup>, 30/70 telescopi, grande collaborazione internazionale (per Italia, INAF e INFN)
- sito Sud: scelta tra Chile (deserto di Atacama-ESO) e Namibia, nel 2015
- candidati sito Nord: Utah, Isole Canarie, Mexico
- fase preparatoria, primi dati tra 5-8 anni

### **Detectors**

- The lowest-energy photons (20–200 GeV) will be detected with a few large telescopes of 23 m diameter.
- Intermediate energies, from about 200 GeV to 1 TeV, will be covered with some 25 medium-size telescopes of 12 m diameter.

### **Physics Goals**

- 1 Cosmic particle acceleration.** Gamma rays are emitted by high energy particles accelerated in cosmic particle accelerators. How and where particles are accelerated, how they propagate, and how they impact their environment and influence cosmic evolution is poorly understood.
- 2 – Extreme environments in the Cosmos.** Gamma rays are produced near neutron stars and black holes in relativistic jets and cosmic explosions. Propagating through cosmic voids, gamma rays provide the opportunity for scientists to probe the radiation fields and magnetic fields in these voids.
- 3 – Physics frontiers.** Gamma rays enable searches for annihilating Dark Matter particles, new tests of Einstein's theory of relativity, or the search for the long-predicted axion particles.

# CTA, immagini

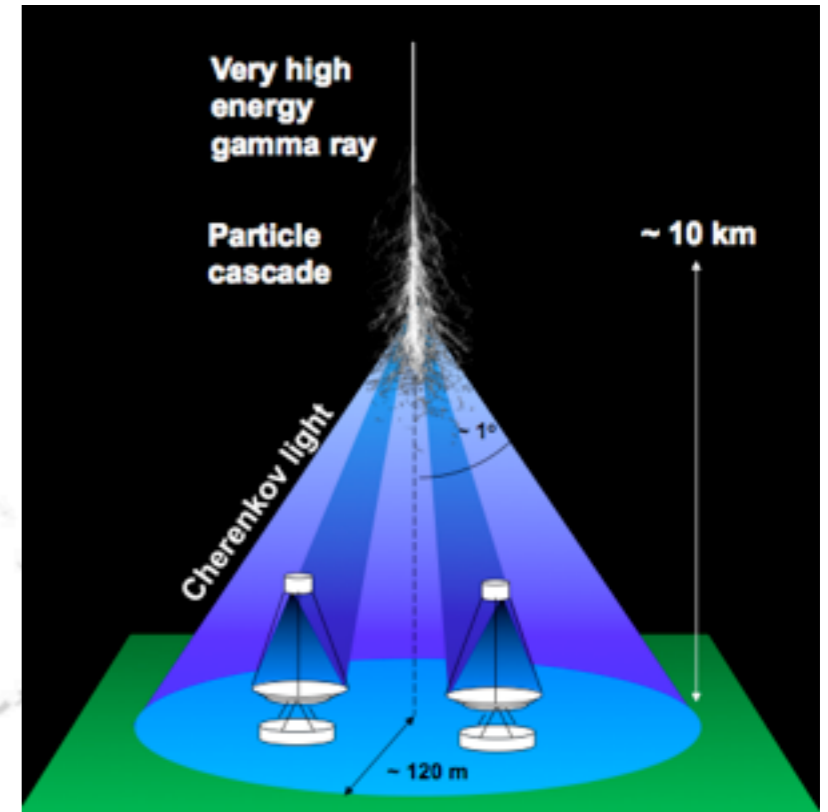


Figure 4: Countries with research groups participating in the CTA Consortium.

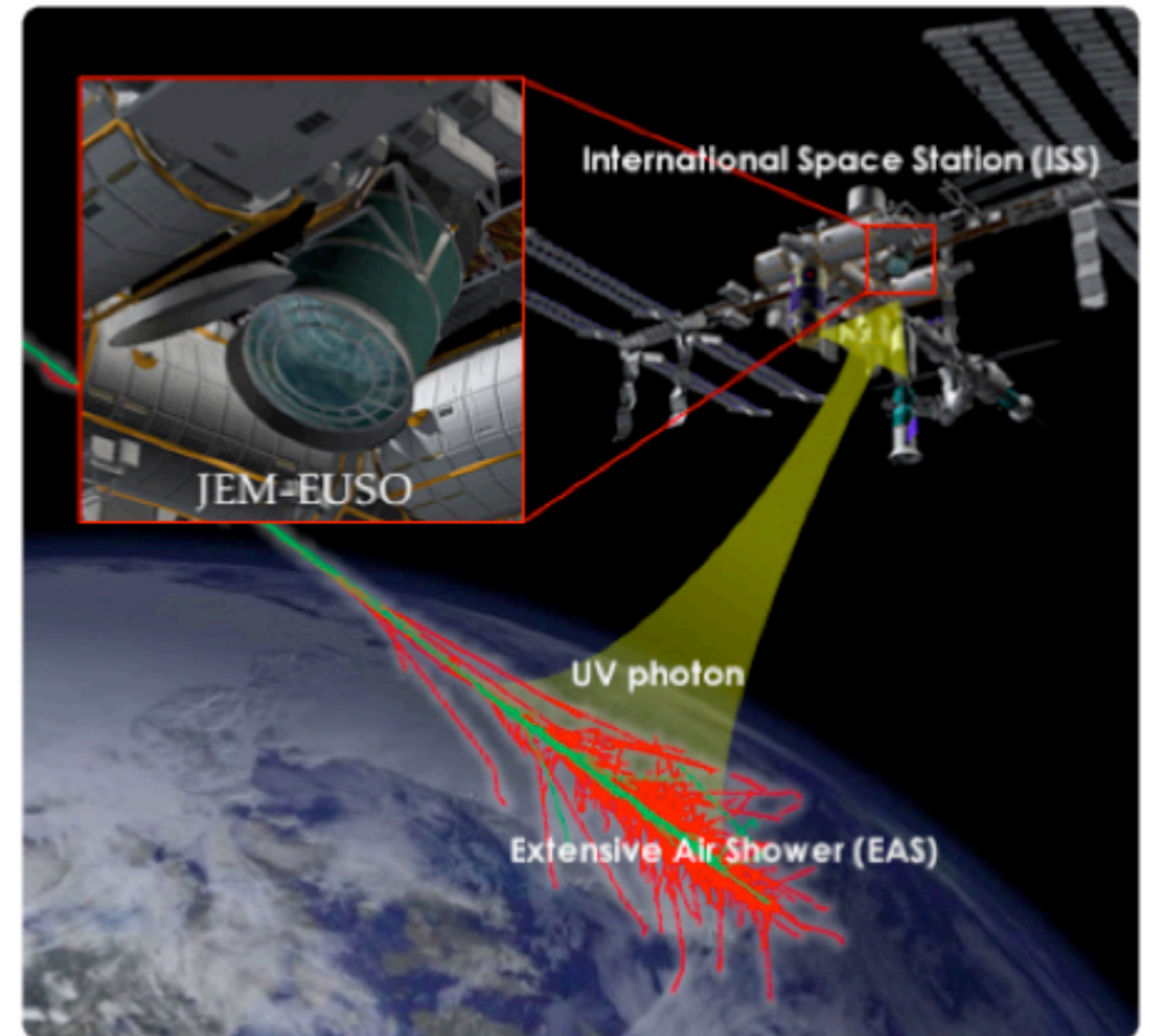


Credits: DESY/Milieu Science Comm./Exocart



# Nel futuro: EUSO

The planned JEM-EUSO (Extreme Universe Space Observatory onboard the ISS Japanese Experimental Module) will measure the energy spectra of cosmic rays up to the range of  $10^{21}$  eV and will search for direction to their sources. It will observe the extensive air showers generated in the atmosphere by high energy cosmic ray primary particle from the space. The instantaneous aperture of the telescope will exceed by one order the aperture of the largest ground based detectors. JEM-EUSO apparatus is a large telescope with a diameter of 2.5 m with fast UV camera.



*JEM-EUSO is a downward looking telescope project, which will be onboard the International Space Station (Credit JEM-EUSO collaboration).*