

Astrofisica Nucleare e Subnucleare

UHECR

Spettro dei raggi cosmici (richiamo)

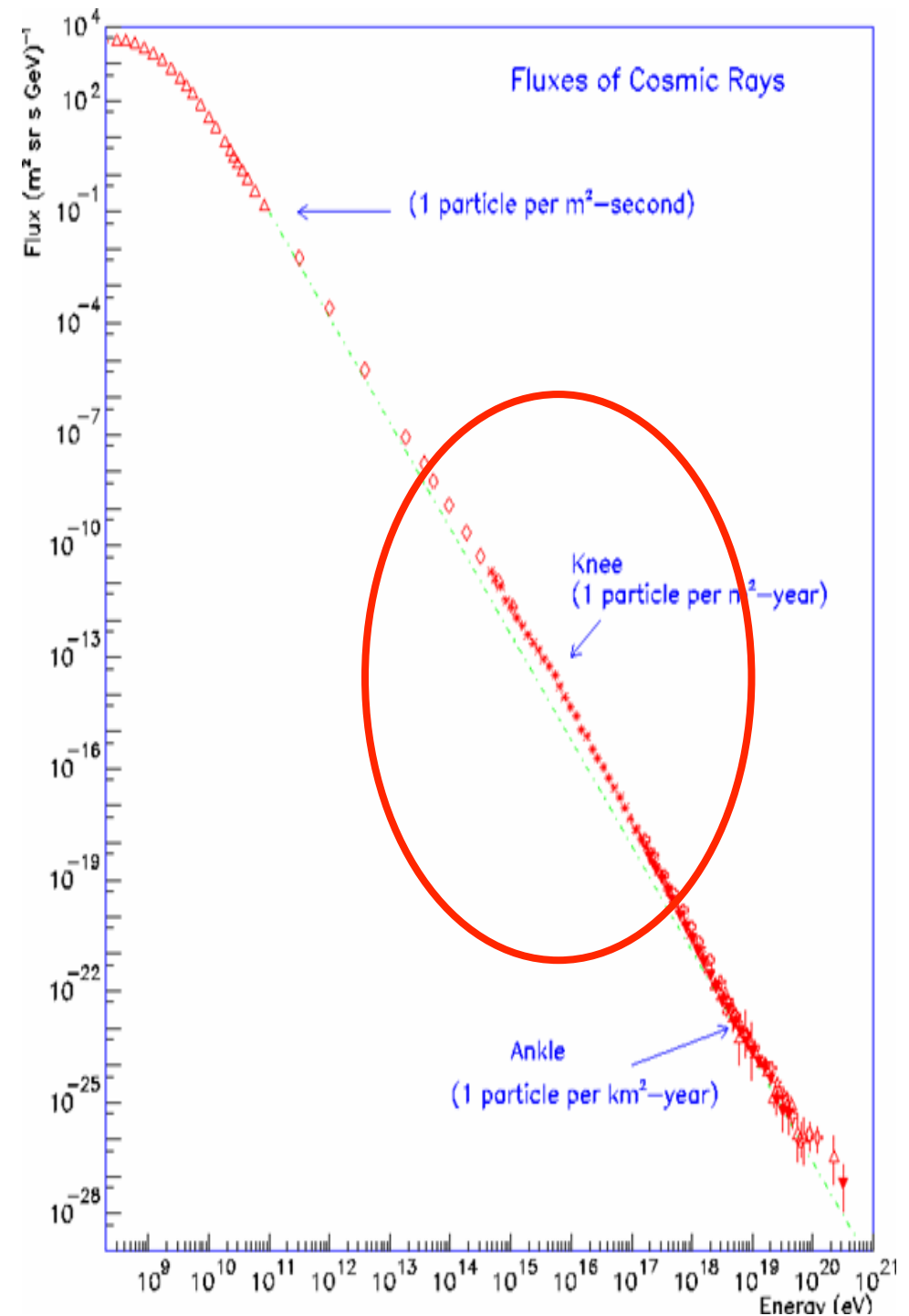
$$\Phi_{\text{TOT}} \sim 1000 \text{ m}^{-2}\text{s}^{-2}\text{sr}^{-1}$$

Misure dirette: 90% p, 9% He, 1% nuclei pesanti

Si estende per 13 ordini di grandezza in energia

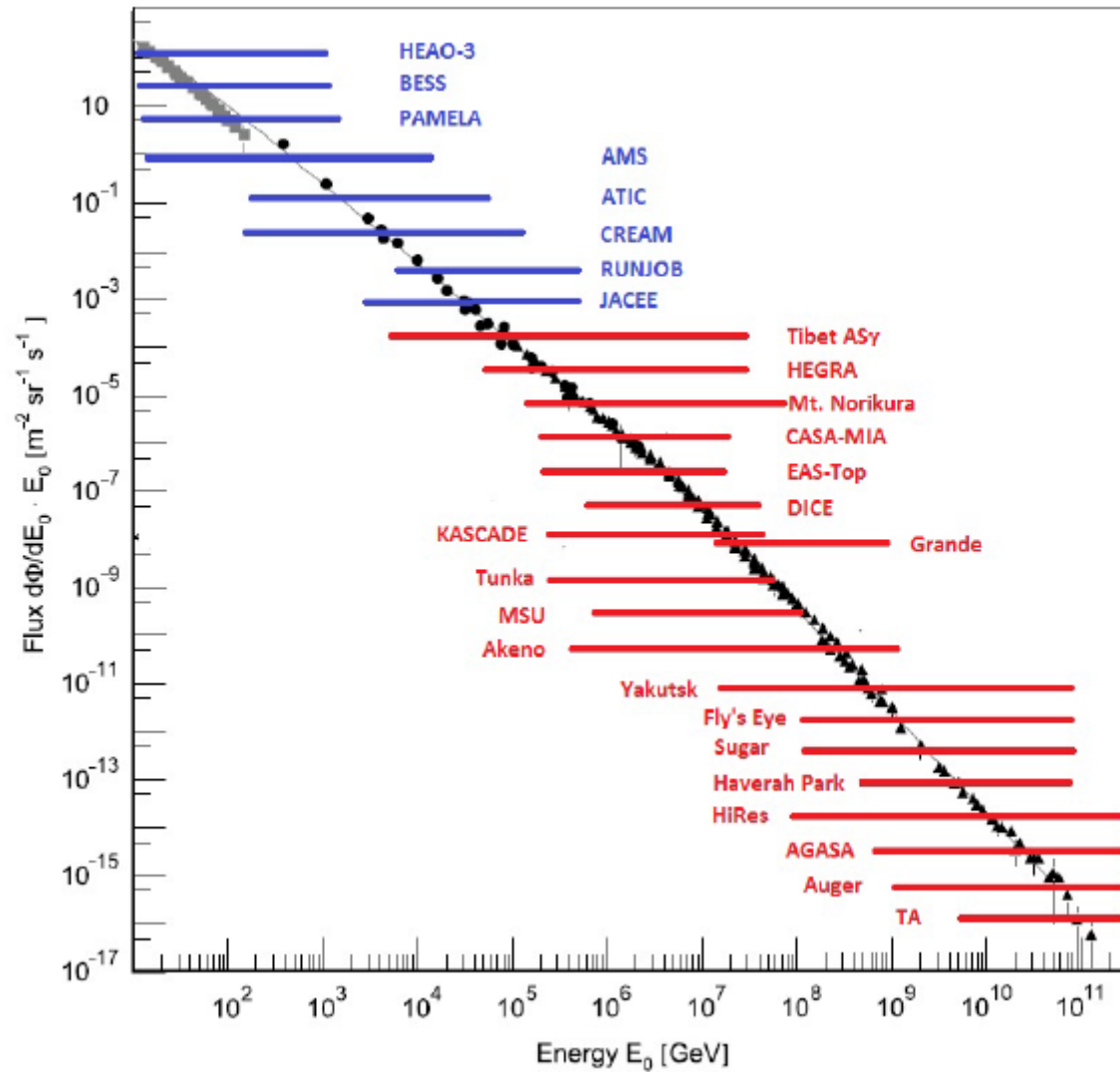
Per 32 ordini di grandezza in flusso

Legge di potenza su tutto lo spettro, con almeno due cambi di pendenza



Metodi di misura dei raggi cosmici

- Misure dirette
 $E < 10^{14}$ eV
- Misure indirette,
 $E > 10^{14}$ eV



KASCADE - Grande

KARlsruhe Shower Core and Array DEtector - Grande

The Detector Array CR

KASCADE-Grande

KASCADE Array

Central Detector

Calorimeter

Trigger Layer

Muon Chambers

GRANDE Array

Piccolo Array

Muon Tracking

LOPES Antenna

CORSIKA

The Collaboration

Institutes

Members

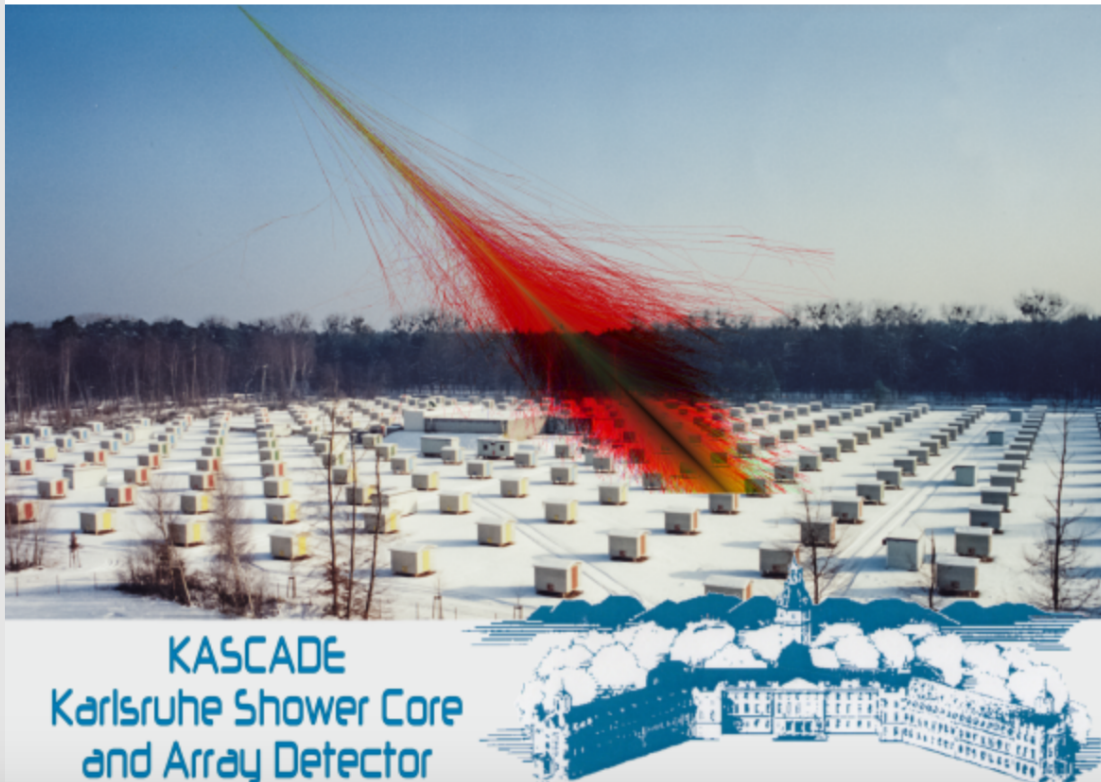


<https://web.ikp.kit.edu/KASCADE/welcome.html>


 KASCADE Cosmic Ray Data Centre (KCDC) / Open β
[KCDC Homepage](#)
[KCDC Regulations](#)
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Welcome to KCDC

The aim of the project **KCDC** (**KASCADE Cosmic Ray Data Centre**) is the installation and establishment of a public data centre for high-energy astroparticle physics based on the data of the KASCADE experiment. KASCADE was a very successful large detector array which recorded data during more than 20 years on site of the KIT-Campus North, Karlsruhe, Germany (formerly Forschungszentrum, Karlsruhe) at 49,1°N, 8,4°E; 110m a.s.l. KASCADE collected within its lifetime more than 1.7 billion events of which some 425.000.000 survived all quality cuts. Initially about 147 million events are available here for public usage.



KASCADE
 Karlsruhe Shower Core
 and Array Detector

Institute for Nuclear Physics (IKP)

KIT Campus North

Address:

 Institute for Nuclear Physics
 Karlsruhe Institute of Technology
 Hermann-v.Helmholtz-Platz 1
 D-76344 Eggenstein-
 Leopoldshafen

Postal Address:

 Institute for Nuclear Physics
 Karlsruhe Institute of Technology
 Postbox 3640
 D-76021 Karlsruhe

Phone: +49/721/608-23546

Fax: +49/721/608-23548

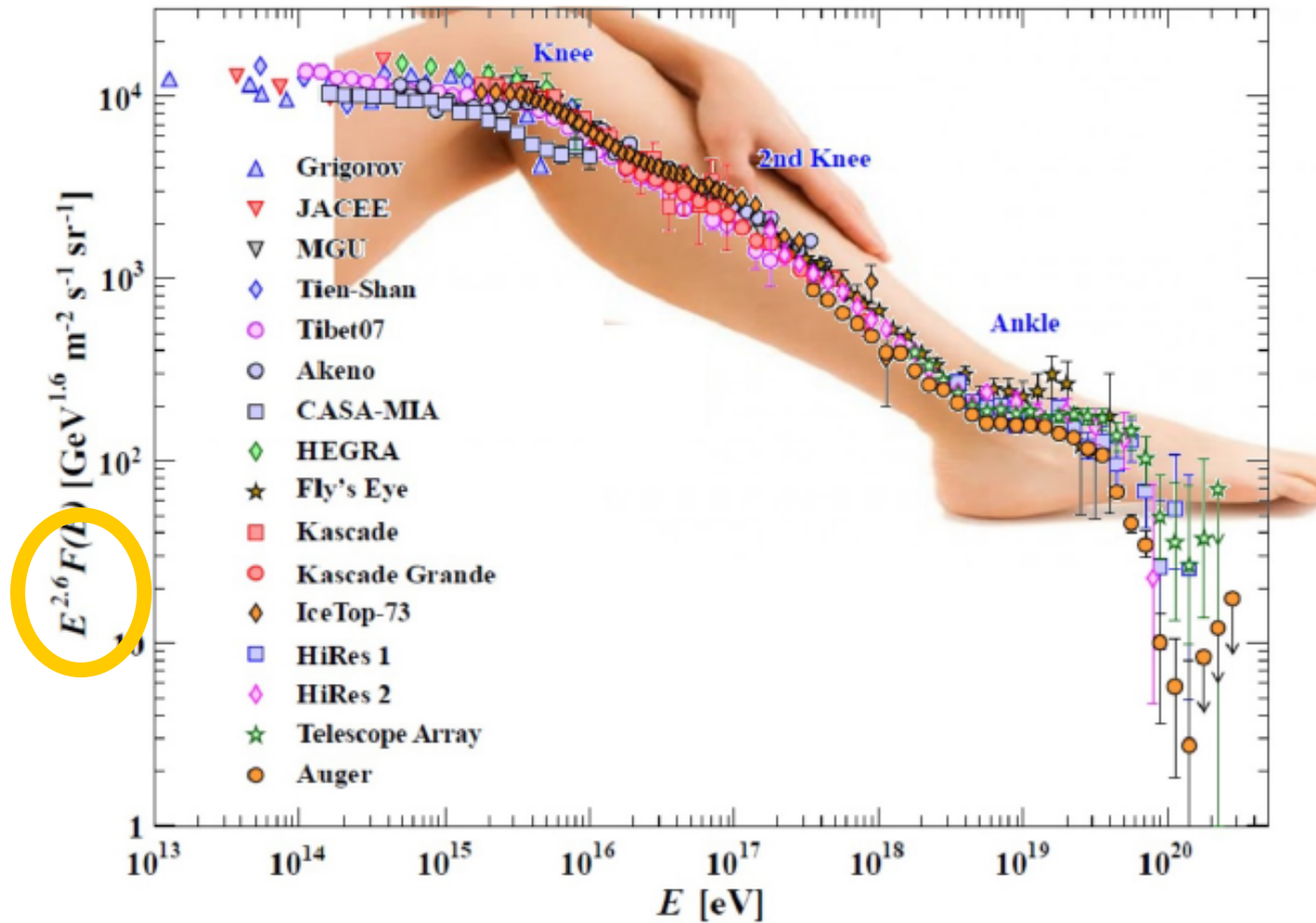
E-Mail:

[ikp-kcdc\[at\]lists.kit.edu](mailto:ikp-kcdc[at]lists.kit.edu)

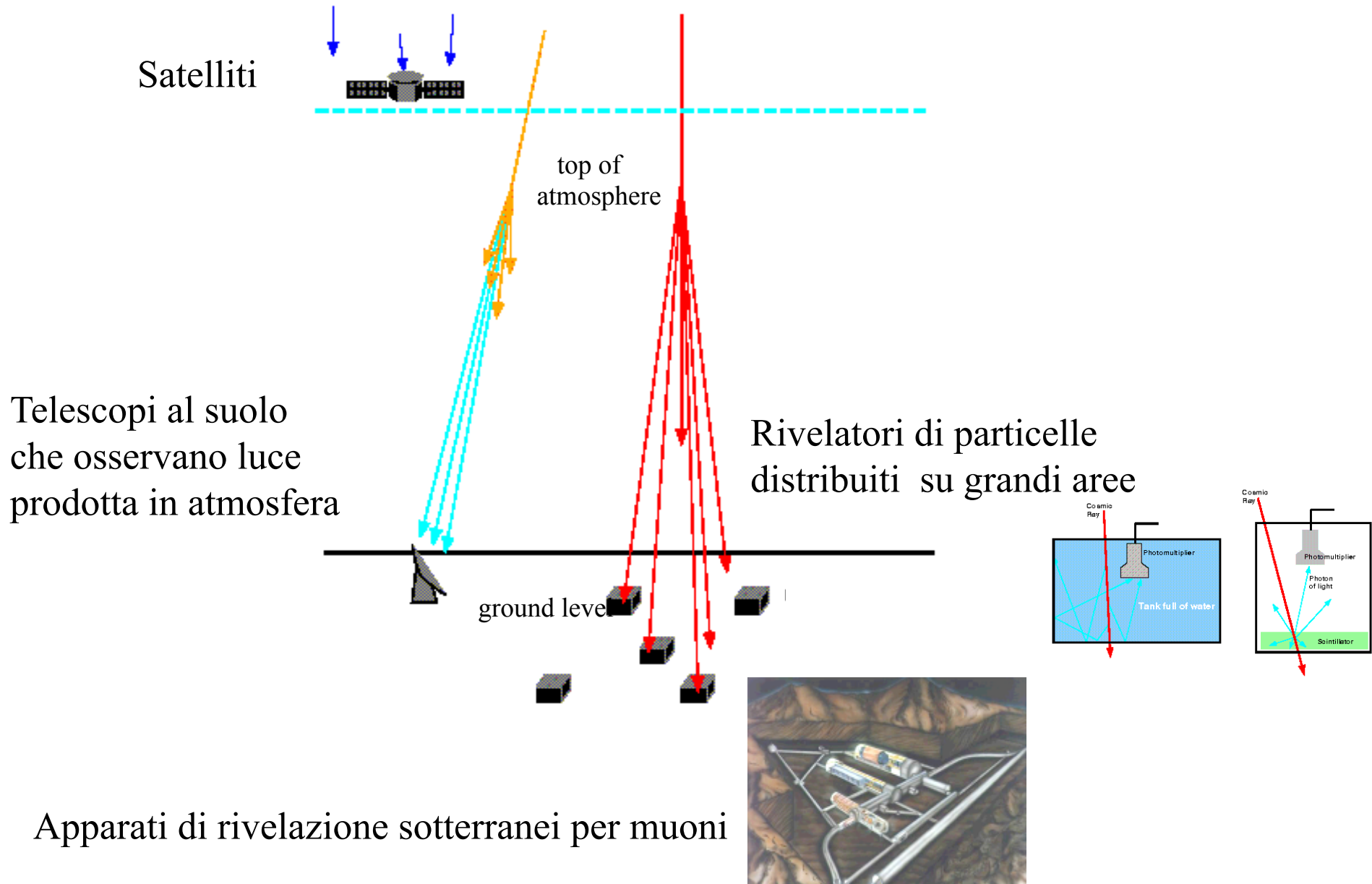
Downloads

[KCDC Manual \(english\)](#)
<https://kcdc.ikp.kit.edu>

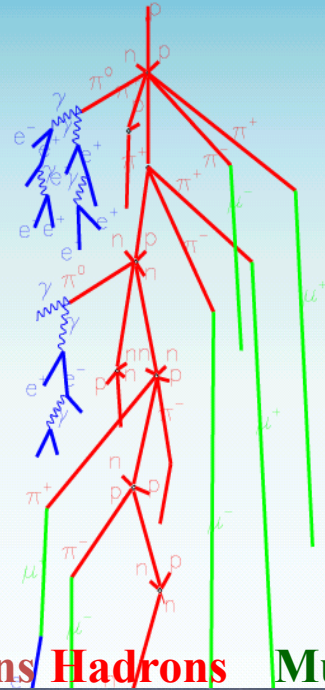
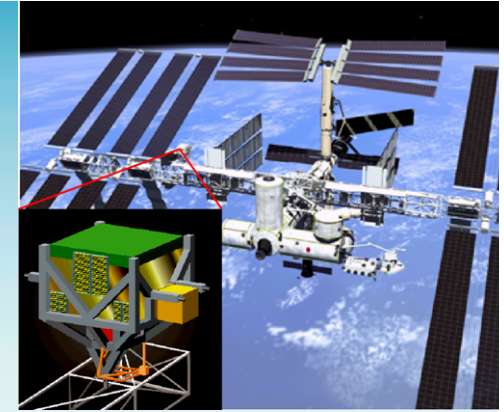
The Knee in the Energy Spectrum of Cosmic Rays



Rivelatori di raggi cosmici



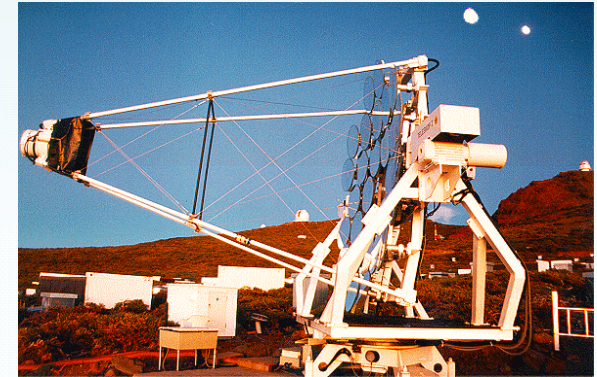
Observation of cosmic rays



Electrons Hadrons Muons



Fluorescence light



Cerenkov light
(imaging & non-imaging)



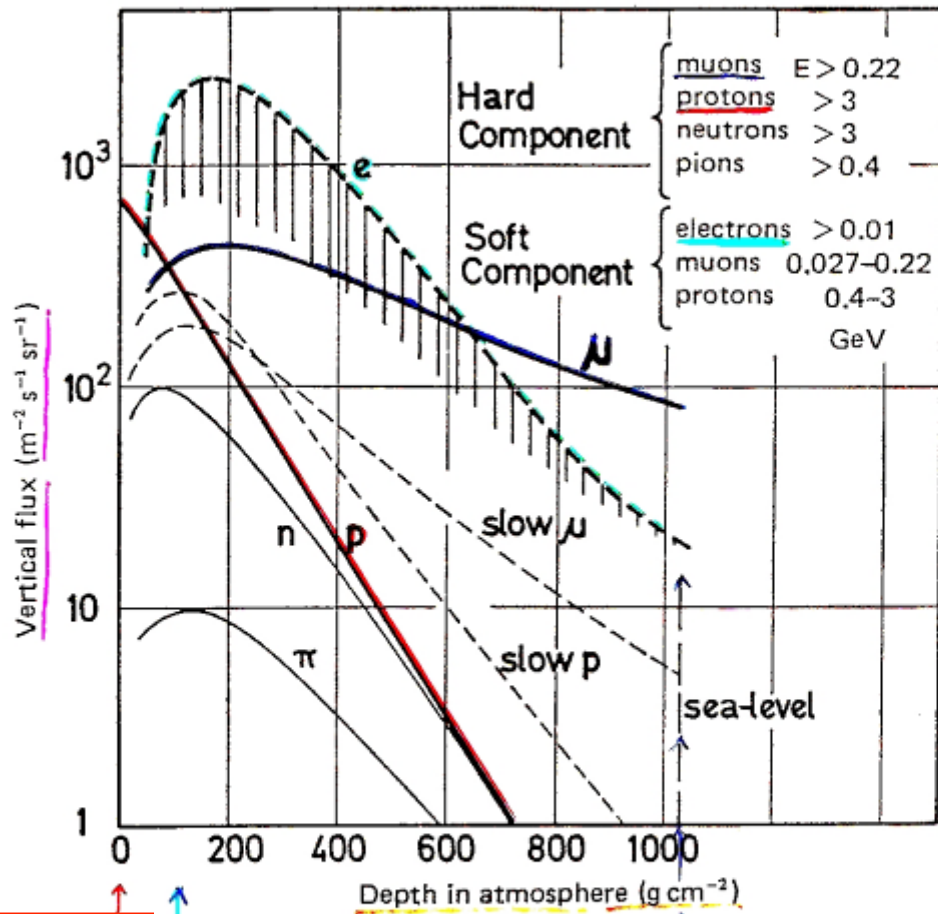
Neutrinos



Muons

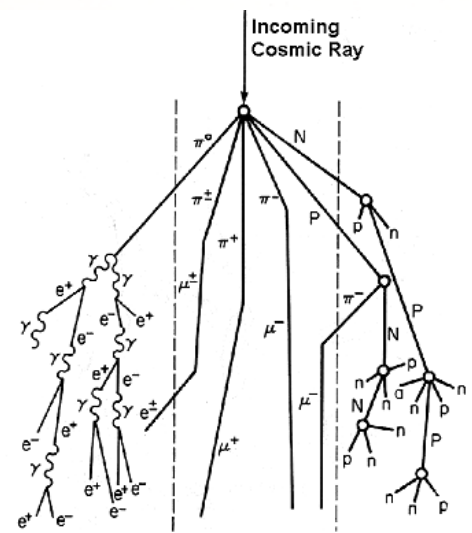
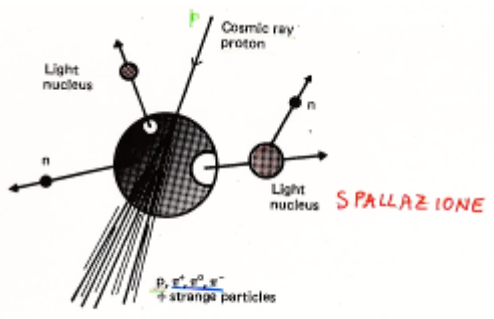
Sciami estesi in Atmosfera

- L'interazione di un primario in Atmosfera origina uno sciame di particelle con 3 componenti:
 - Elettromagnetica (EM)
 - Muoni
 - adroni
- Le Energie dei RC molto maggiori delle E raggiungibili con acceleratori. E' possibile esplorare interazioni adroniche in regioni cinematiche non ancora studiate.
- Tevatron: protoni e antiprotoni collidono frontalmente con energia nel CdM pari a $\sqrt{s} = 2TeV$
- LHC: protoni protoni "head-on" con $\sqrt{s} = 14TeV$



$3000 m^{-2} s^{-1} sr^{-1}$

$100 m^{-2} s^{-1} sr^{-1}$



KEY

P	Proton	e	Electron
n	Neutron	μ	Muon
π	Pion	γ	Photon

Spazio

Pfozter maximum @ ~ 20 km

Livello del mare

Flusso verticale di Raggi Cosmici vs. profondita' nell' atmosfera

NOTE: $\tau(\mu) = 2.2 \mu s$

$c\tau(\mu) = 2.2 \cdot 10^{-6} s \cdot 3 \cdot 10^8 ms^{-1} = 660 m$

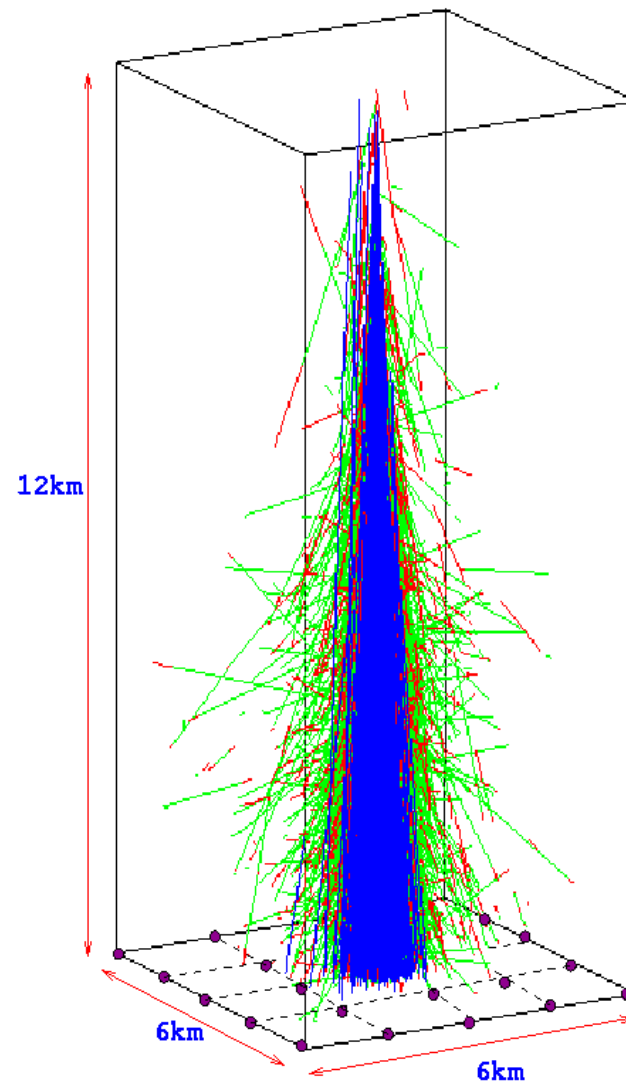
$E = \gamma mc^2$

$\tau = \gamma \tau_0 \Rightarrow \gamma > 20$

RELATIVISTIC

$w_\mu = 10^5 MeV/c^2$

A 10 EeV Extensive Air Shower (EAS)

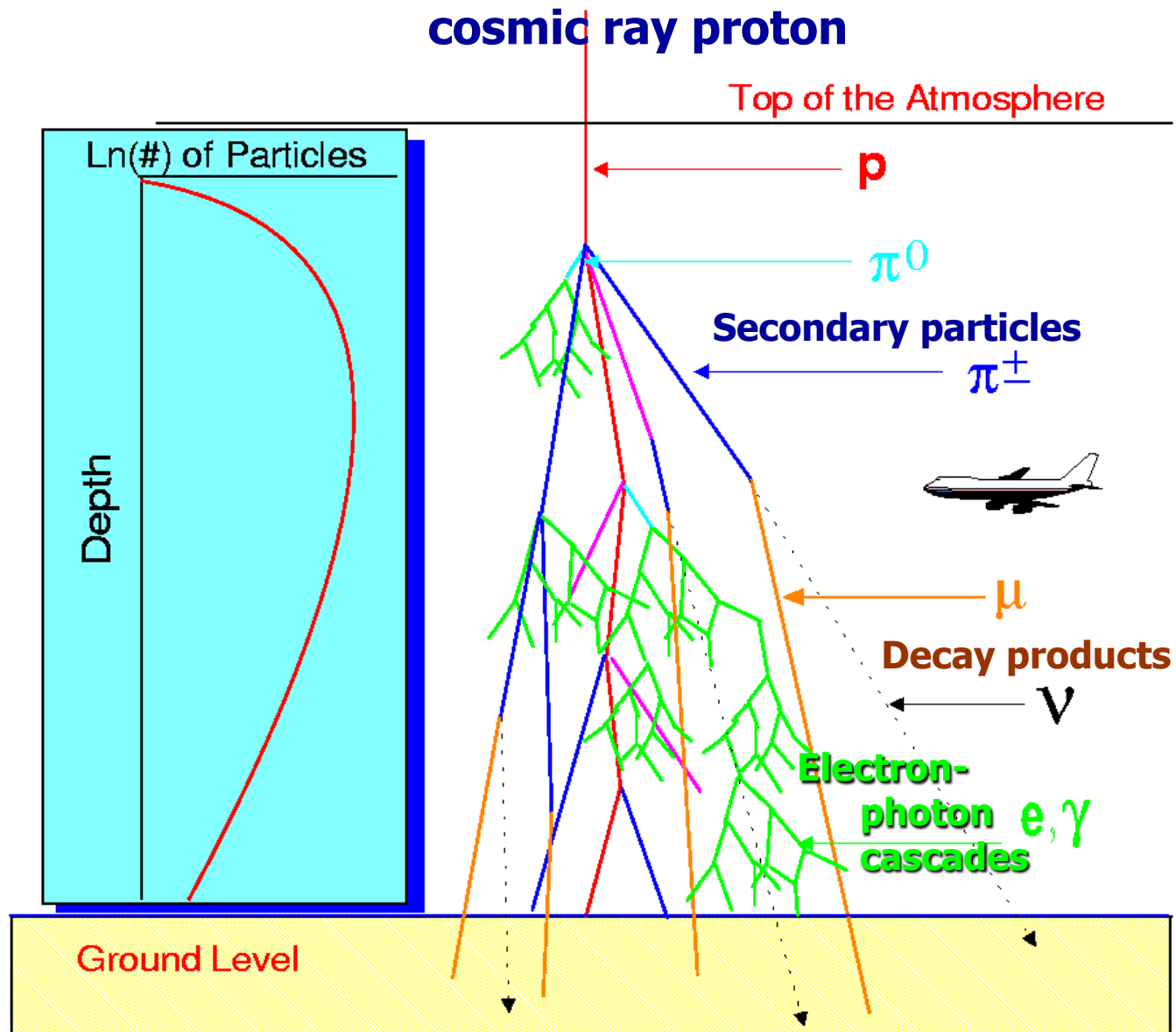


100 billion particles at sea level

photons, electrons (99%), muons (1%)

● Ground Array stations

Le componenti dello sciame



CORSIKA Simulation

QGSJET/EGS4

proton

$E=10^{14}$ eV

iron nucleus

50 km

40 km

30 km

20 km

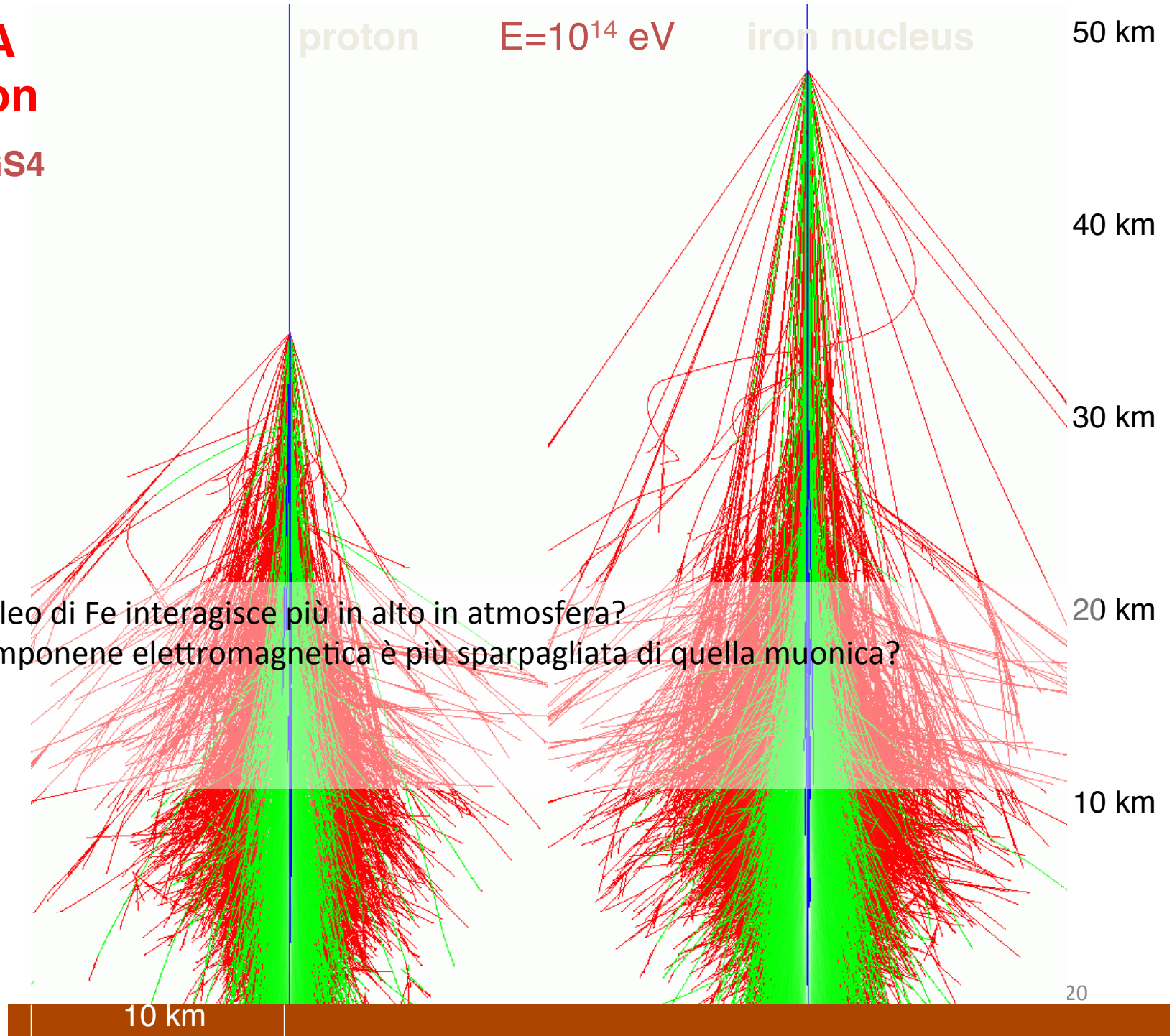
10 km

Perchè il nucleo di Fe interagisce più in alto in atmosfera?
Perchè la componente elettromagnetica è più sparpagliata di quella muonica?

e/γ
 μ
 h

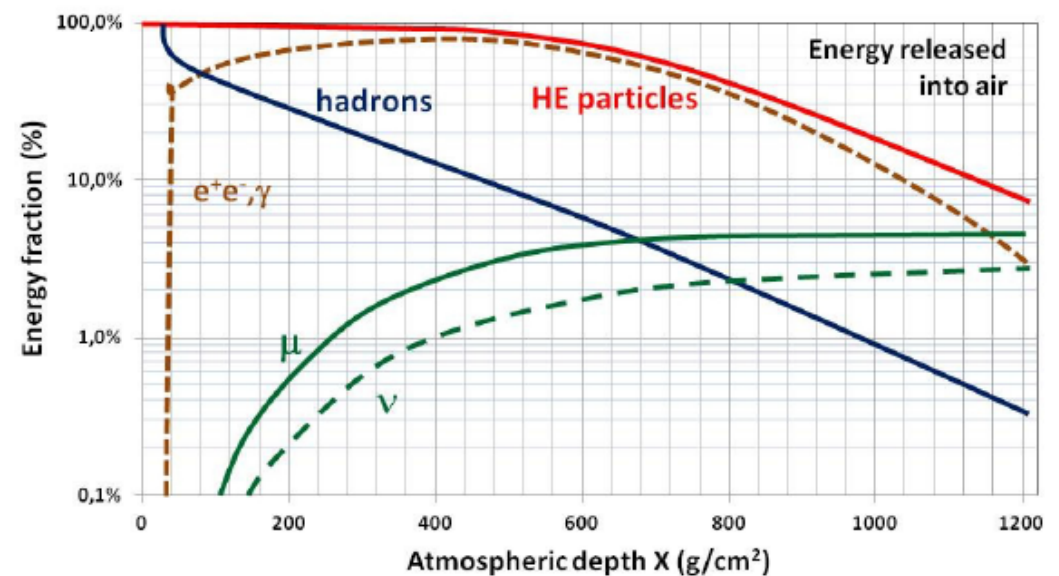
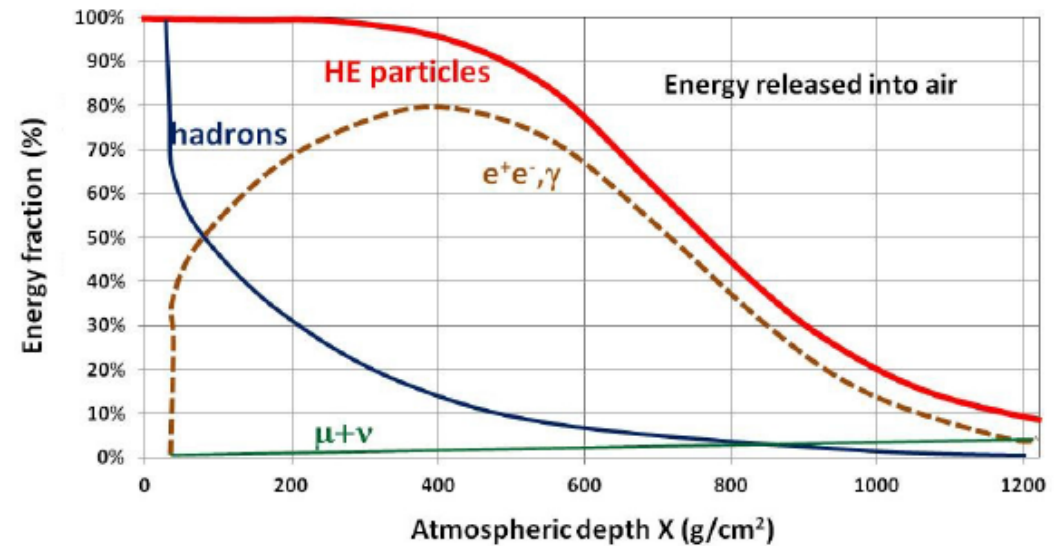
10 km

20



Caratteristiche generali dello sciame

- Gli adroni vengono esponenzialmente attenuati
- Lo sciame EM si sviluppa esponenzialmente sino ad un massimo, la cui profondità aumenta con E_0 (E primario)
- Sulla superficie terrestre (ed underground), prevalentemente muoni



Caratteristiche generali dello sciame

- Un altro modo di vedere le cose:

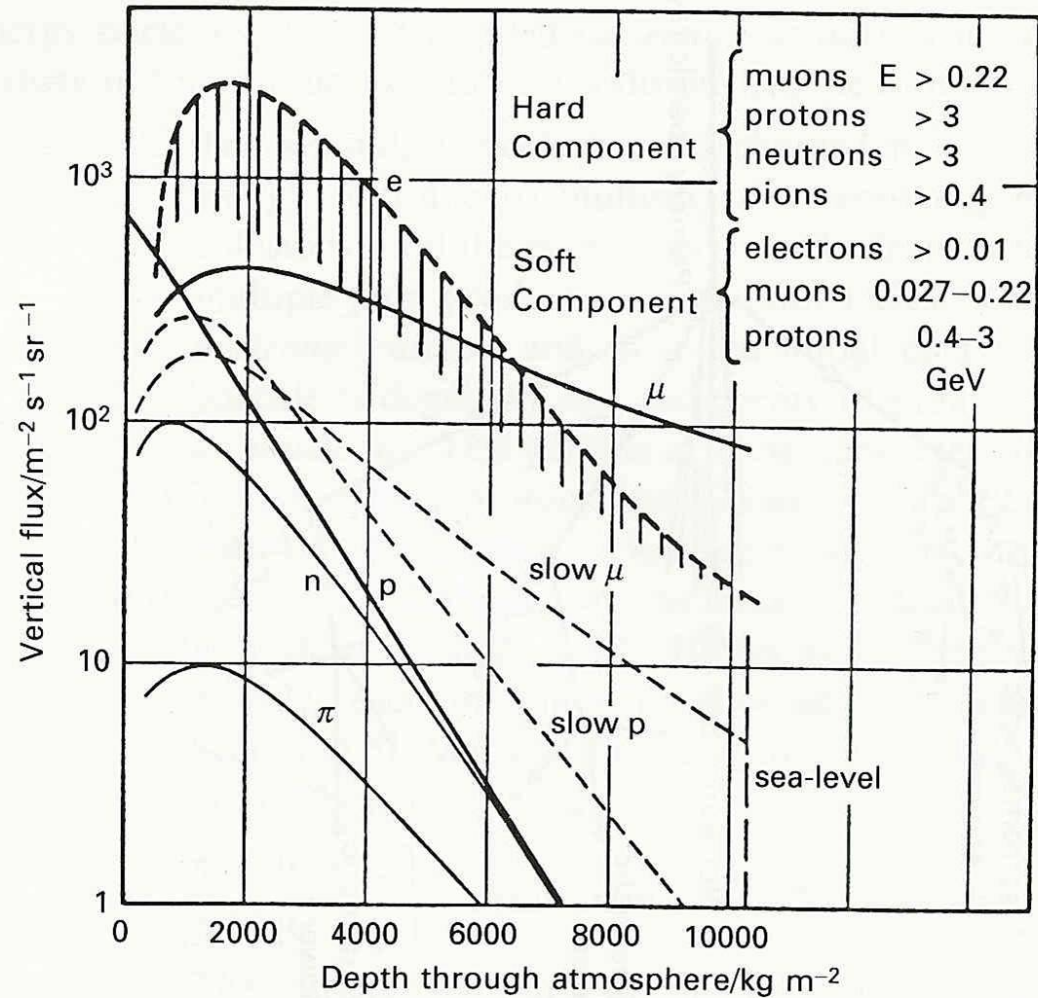


Figure 5.12. The vertical fluxes of different components of cosmic rays in atmosphere. (From A. M. Hillas (1972). *Cosmic rays*, page 50, Oxford: Pe

“Superposition” model

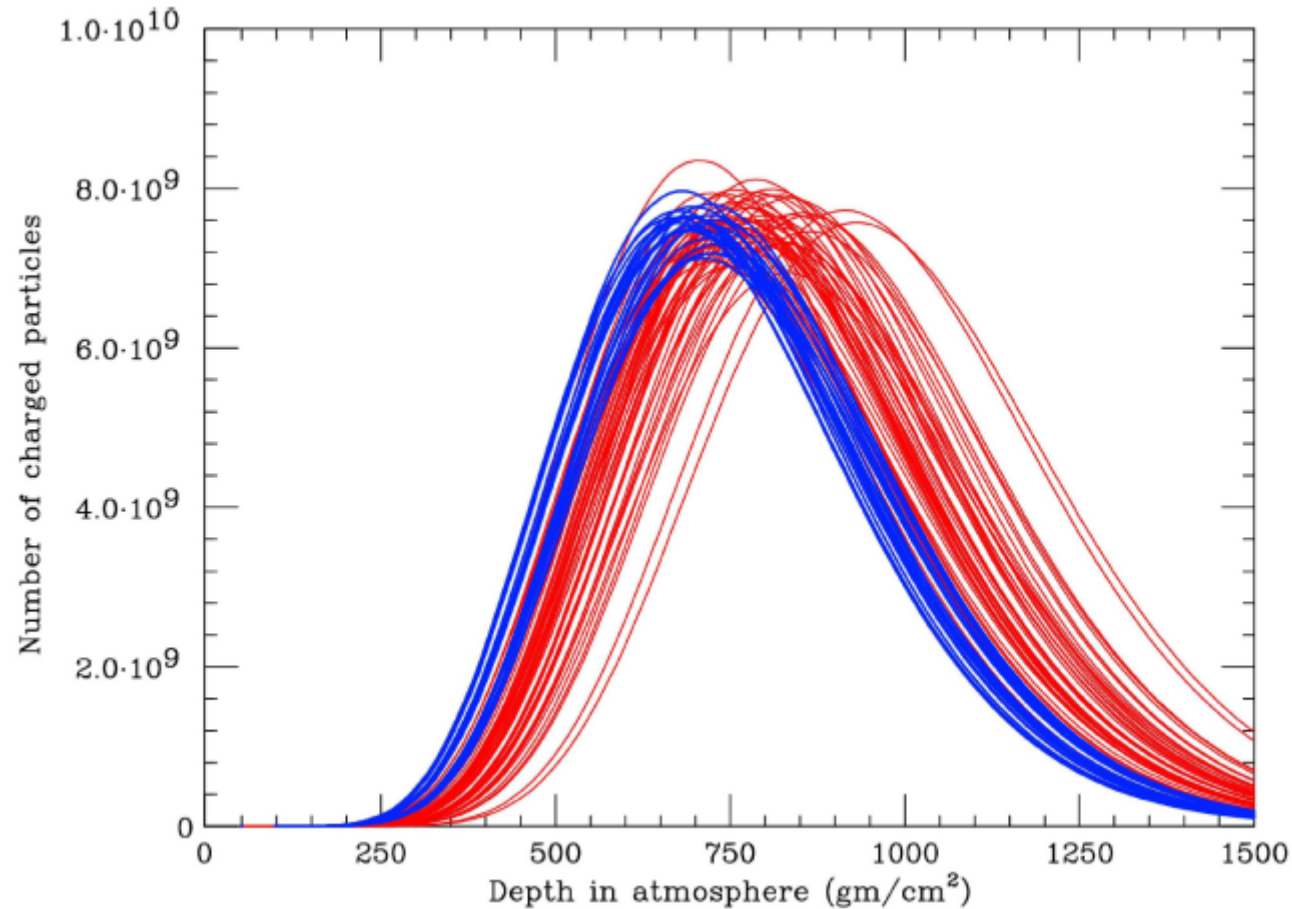
- The superposition model assumes that a nucleus with atomic mass number \mathbf{A} and energy \mathbf{E}_0 is equivalent to A individual single nucleons, each with energy \mathbf{E}_0/\mathbf{A} , each acting independently
- Number of particles at the maximum:

$$N_{\max}(\mathbf{p}) = E_0/E_c \quad \rightarrow \quad N_{\max}(\mathbf{A}) = A \times [(E_0/A)E_c] = N_{\max}(\mathbf{p}) !!$$

- The depth in atmosphere of the shower maximum :

$$X_{\max}(\mathbf{A}) = X_f + X_0 \ln(E_0/AE_c) = X_{\max}(\mathbf{p}) - X_0 \ln A$$

An air shower initiated by He, O and Fe nuclei of the same total energy reach maximum 50, 100 and 150 g/cm² earlier than that initiated by a proton with the same energy

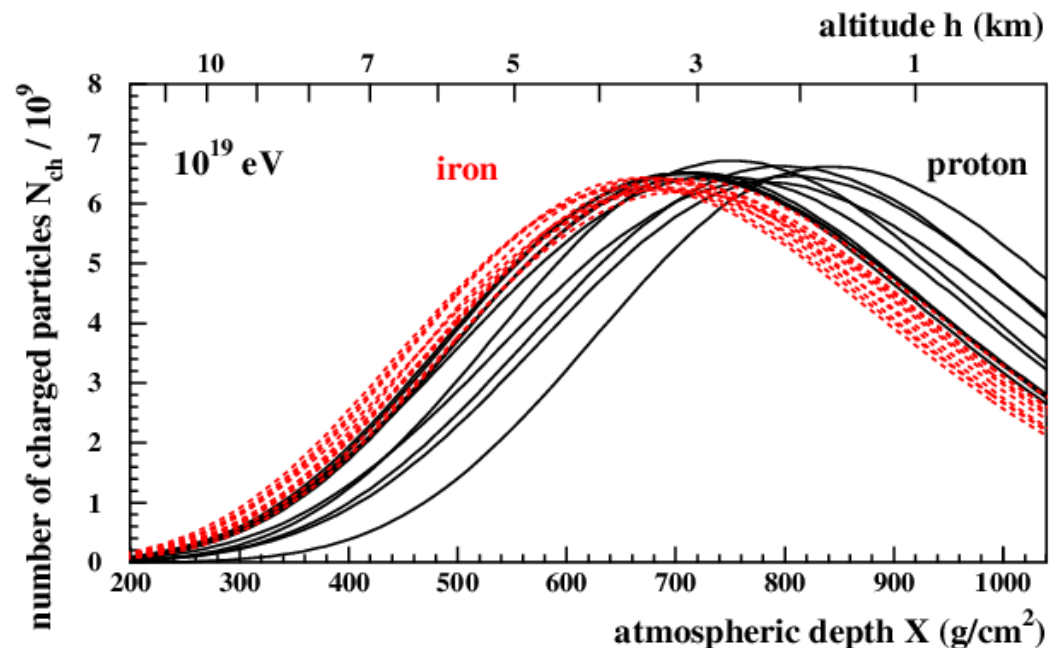


Simulation of the longitudinal profile obtained with the CORSIKA code for 50 **proton-induced (red)** and 50 **iron-induced (blue)** showers. The same total energy of 10^{19} eV is assumed.

Shower by shower fluctuations on N_{\max} and X_{\max} are evident.

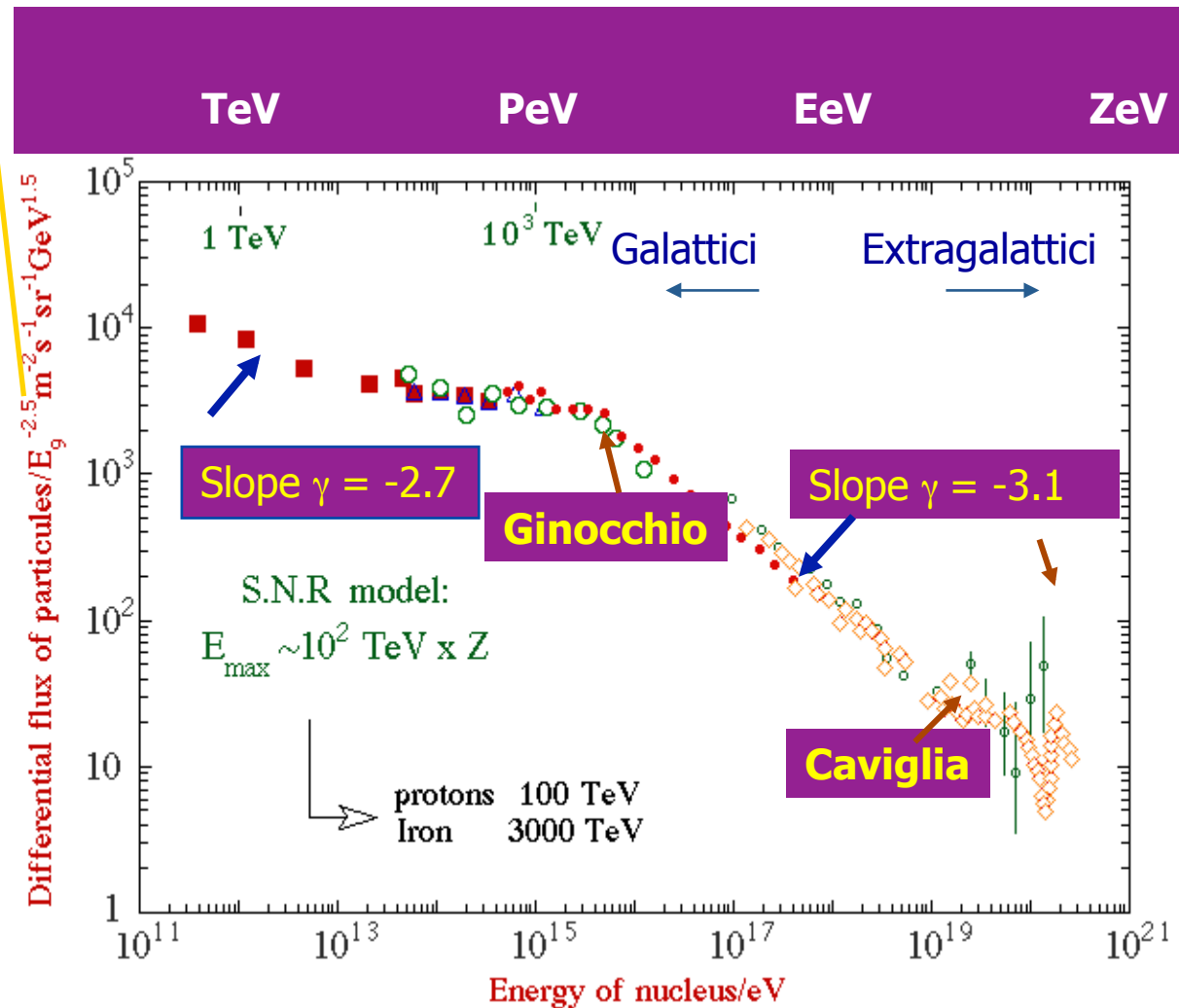
- Il numero di particella al massimo dipende linearmente da E_0
- Solo una frazione ($\sim 1/3$) di E_0 viene convertita nello sciame EM; dalla misura (effettuata a *campionamento* con un rivelatore di sciame estesi) del numero di particella si può risalire tramite MC ad E_0 . In genere: $E_0 = (1.1 \div 1.6) N_{\max} \text{ (GeV)}$.
- La profondità D del massimo dello sciame dipende in maniera logaritmica dall'energia del primario. $D \propto \xi_0 \ln(E_0/E_c)$

Il n. di particelle non alla posizione del massimo D è una funzione più complicata dell'energia (\rightarrow MC).

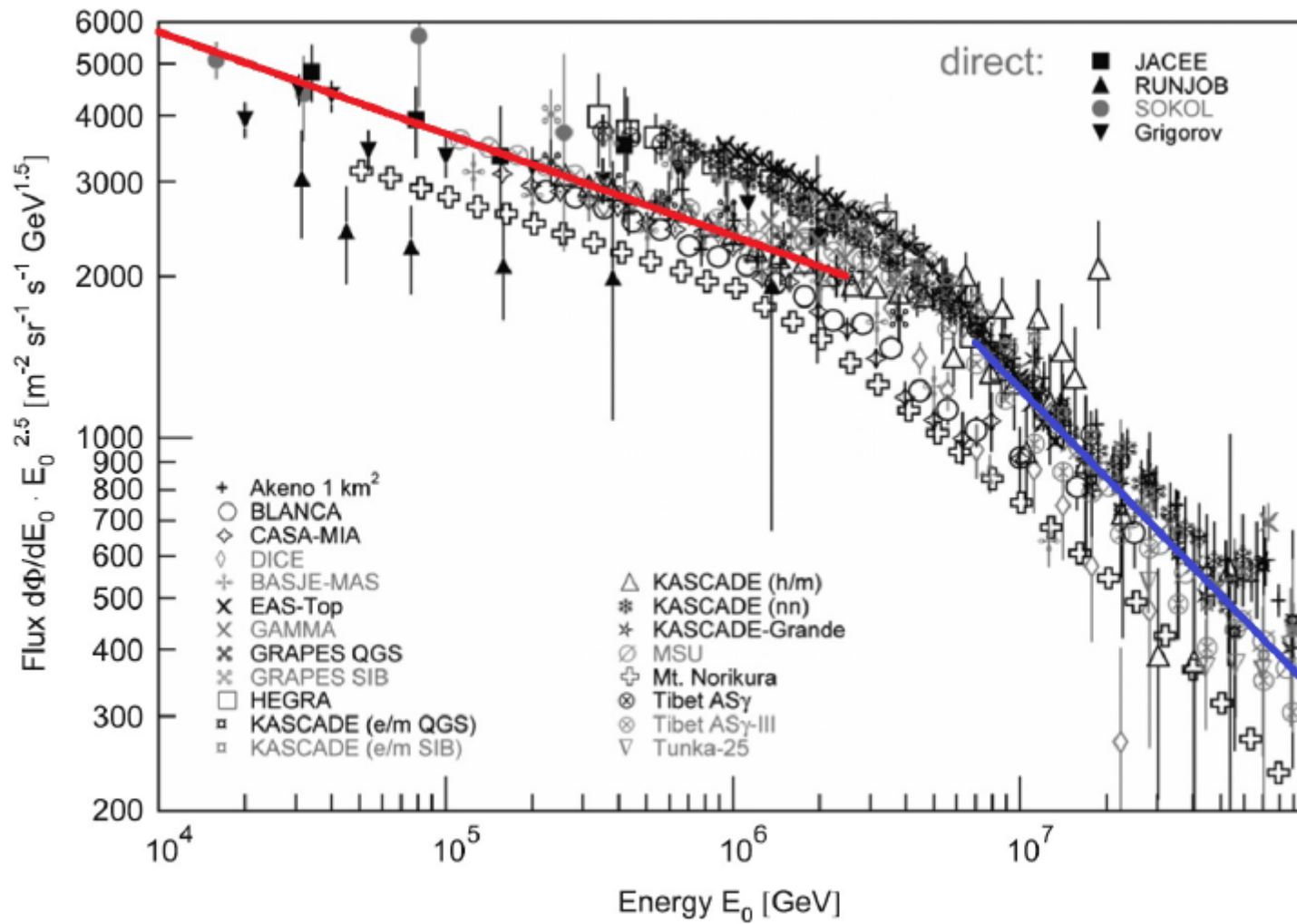


Spettro dei RC ad alta energia

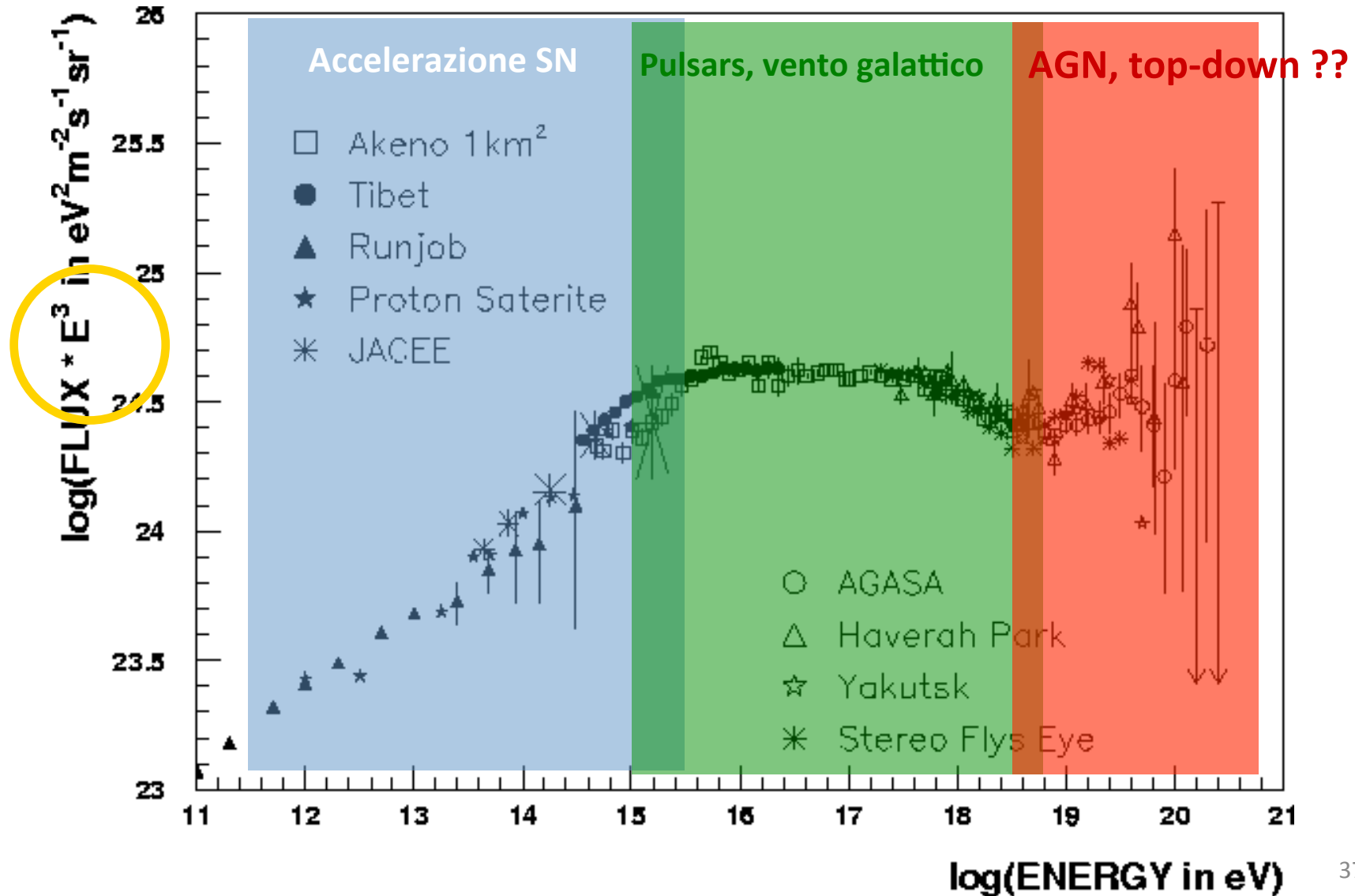
L'asse y viene moltiplicato per $E^{2.5}$, in modo da rendere "più piatta" la figura, ed accentuare il cambiamento di pendenza!



I dati sperimentali

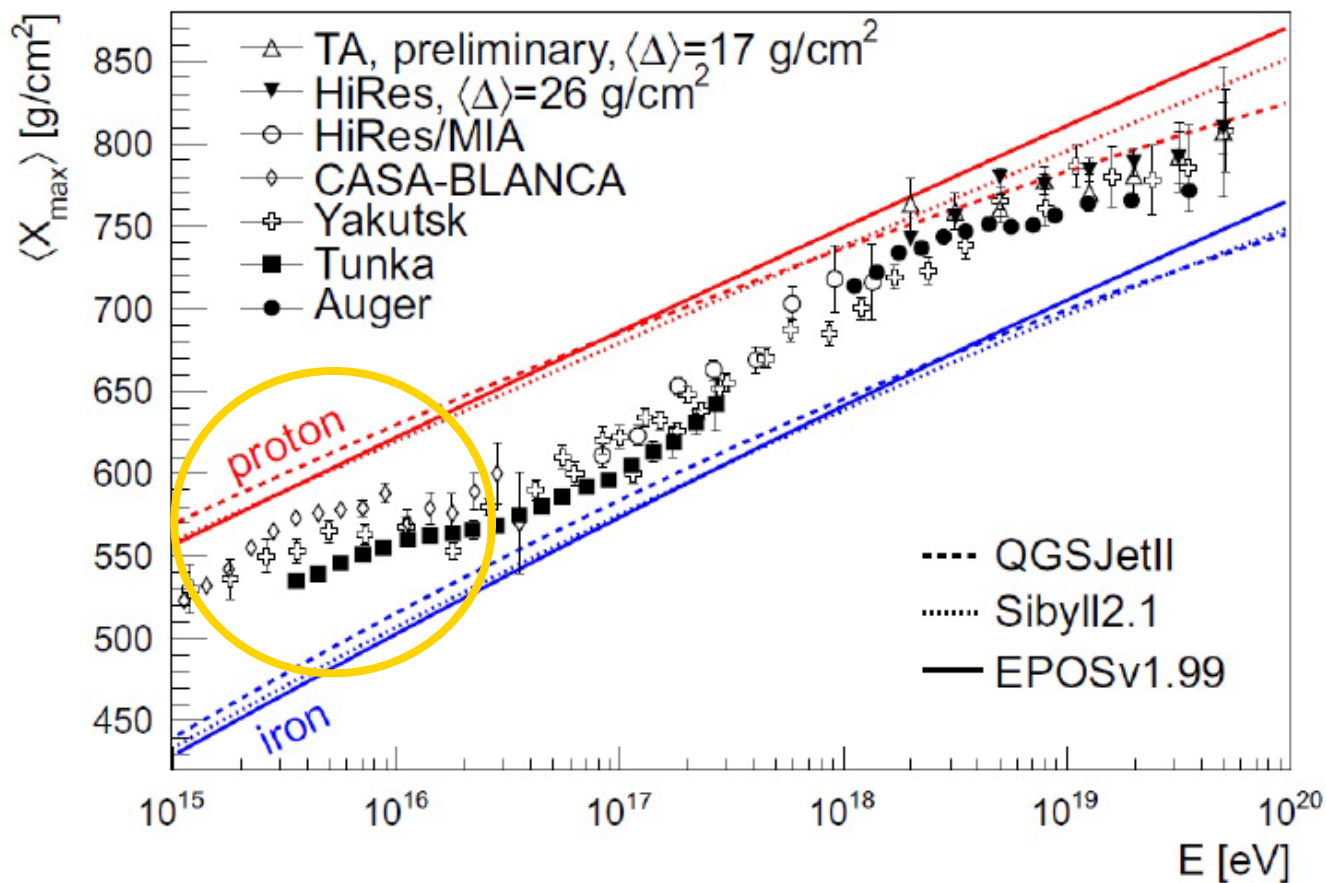


Dati e sorgenti ipotizzate

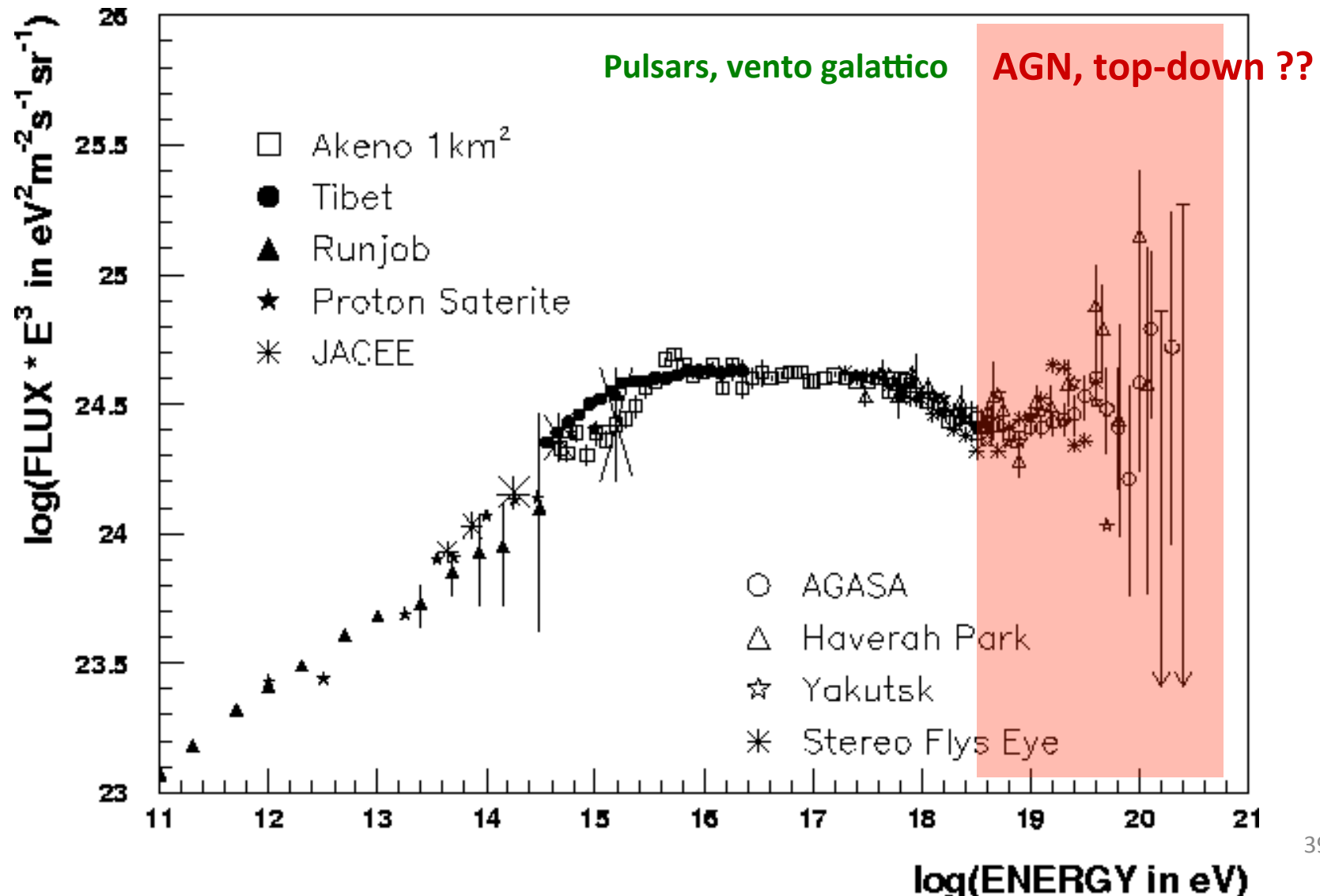


Composizione chimica dei RC nella regione degli EAS

- Il modello del *leaky box* prevede un arricchimento di elementi pesanti nei RC sino al ginocchio.
- Gli EAS possono misurare $\langle A \rangle$ con difficoltà.
- Le misure possono essere poi confrontate con *modelli estremi* (solo p o Fe) via MC



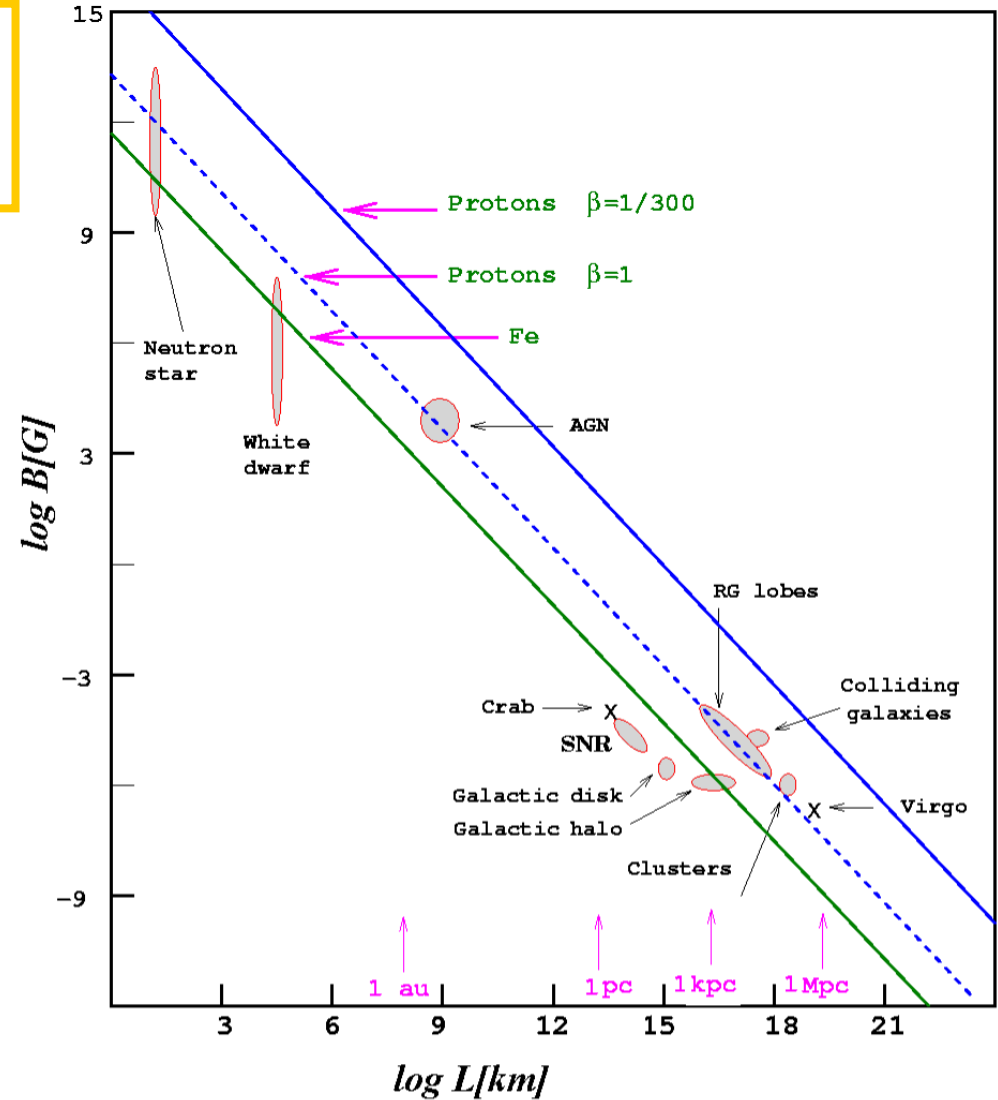
I RC di Energia Estrema $>10^{18}$ Ev (Extragalattici?)



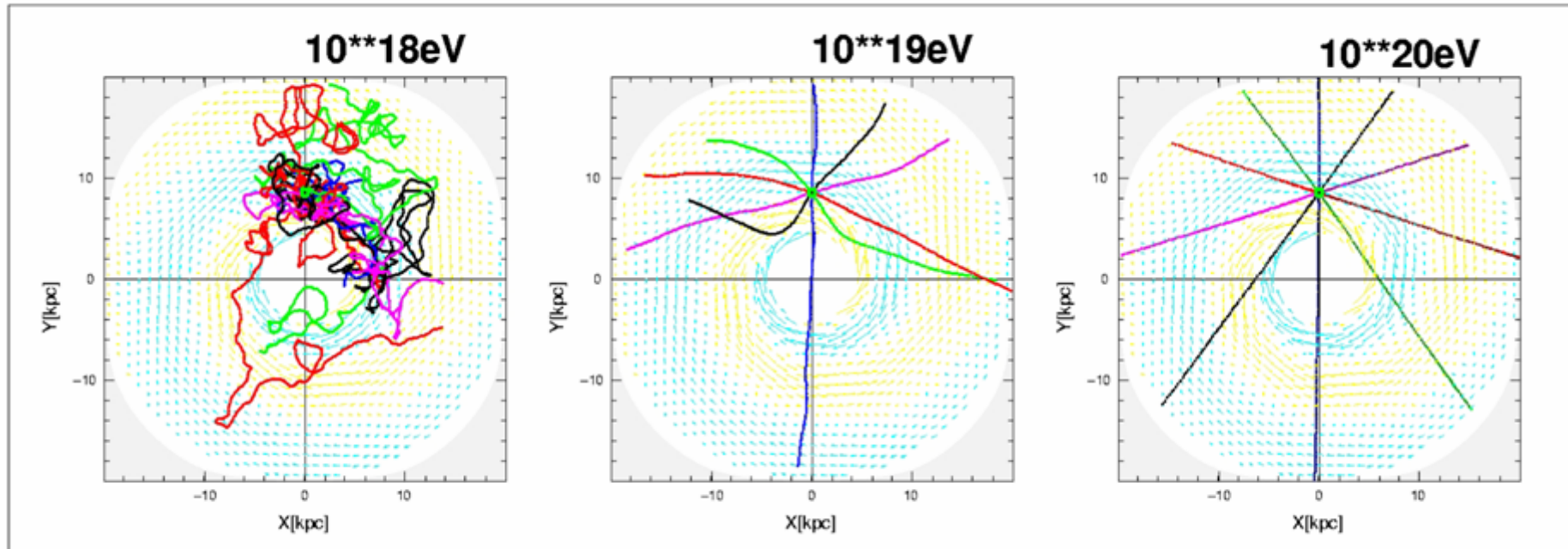
“Hillas Plot”

$$E^{max} \simeq Z\beta \cdot \left(\frac{B}{\mu G}\right) \cdot \left(\frac{L}{kpc}\right) \quad [EeV]$$

Fissata la massima energia (in fig. 10^{20} eV),
 i meccanismi astrofisici candidati
 devono avere campi magnetici intensi
 o grandi regioni di accelerazione.



Confinamento (richiamo)



- $r(kpc) \cong \frac{E(EeV)}{ZB(\mu G)}$
- $\approx 10^{18}$ eV: RC ben confinati nella galassia
 - $\approx 10^{19}$ eV: sorgenti extragalattiche
 - $\approx 10^{20}$ eV la deviazione nella galassia è inferiore ad 1°

La misure del flusso RC con EAS

- Gli EAS sono diversi, ed errori sistematici del 20% sono tipici per la misura dell'energia del primario
- Lo spettro energetico misurato nell'intervallo $10^{16} < E_0 < 10^{19}$ eV è dato dalla funzione:

$$\Phi(E) = K \cdot E^{-3.1} \quad cm^{-2} s^{-1} sr^{-1} GeV^{-1}$$

- La regione tra $10^{14} < E_0 < 10^{15}$ eV è detta *Ginocchio*, a causa del cambiamento di pendenza.
- I RC sono completamente isotropi.
- I RC si arricchiscono di nuclei pesanti nella regione oltre il ginocchio, sino ad energie $E_0 < 10^{19}$.

Come rivelare I RC di alta energia?

Per rivelare I raggi cosmici di energia elevata, occorre:

Una grande area di raccolta, S

Una grande accettazione in angolo solido

Un grande tempo di esposizione T

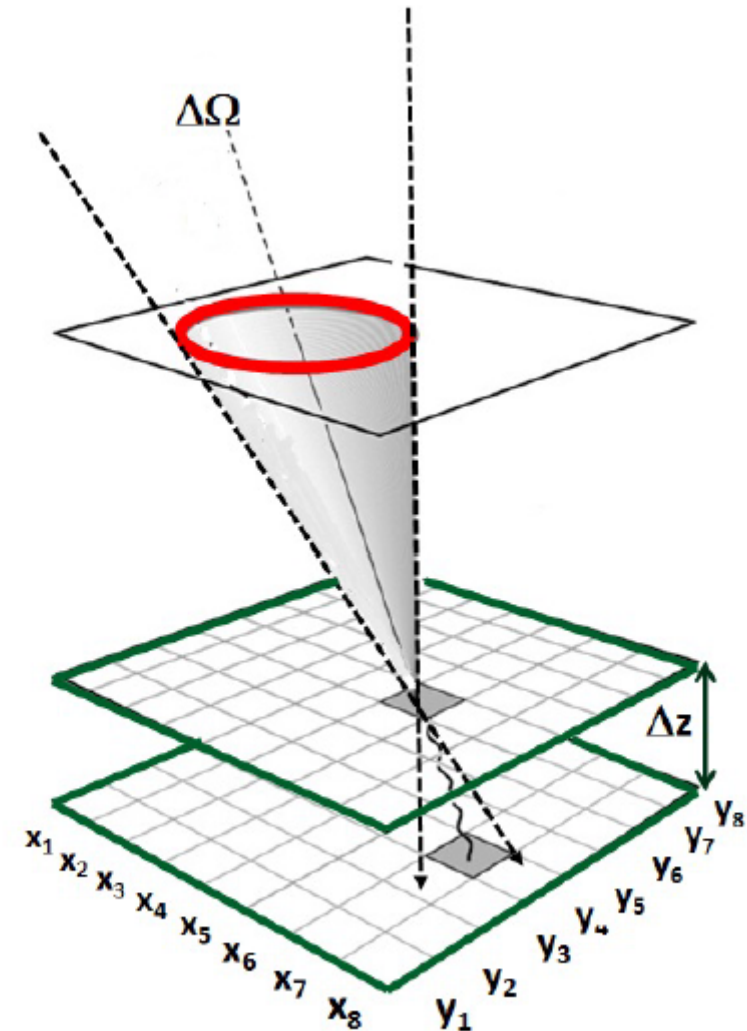
L'esposizione $A \cdot \Delta\Omega \cdot T = \text{cm}^2\text{-sr-s}$

determina il numero di eventi rivelabili.

Il flusso di primari con energia

$E_0 > 10^{19}$ eV è circa:

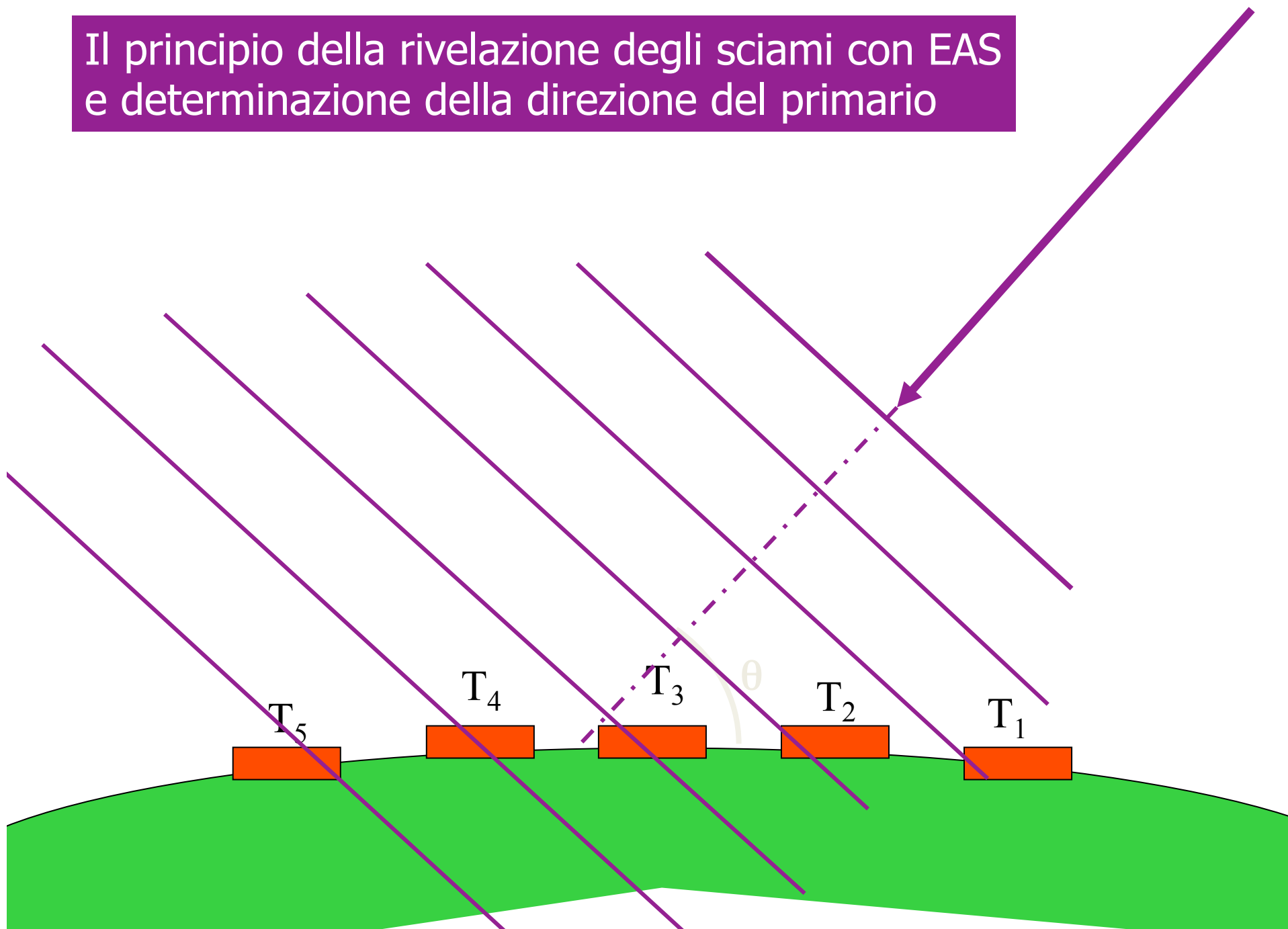
0.5 particelle per $\text{km}^2\text{-sr-year}$



Caratteristiche generali dei rivelatori di sciame

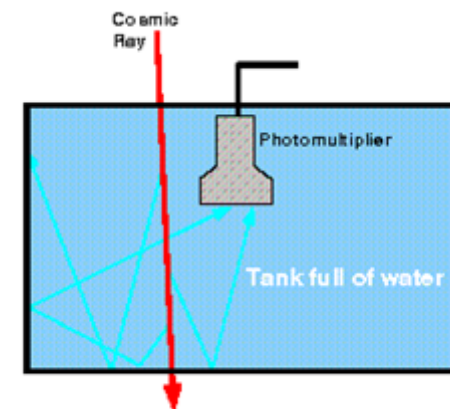
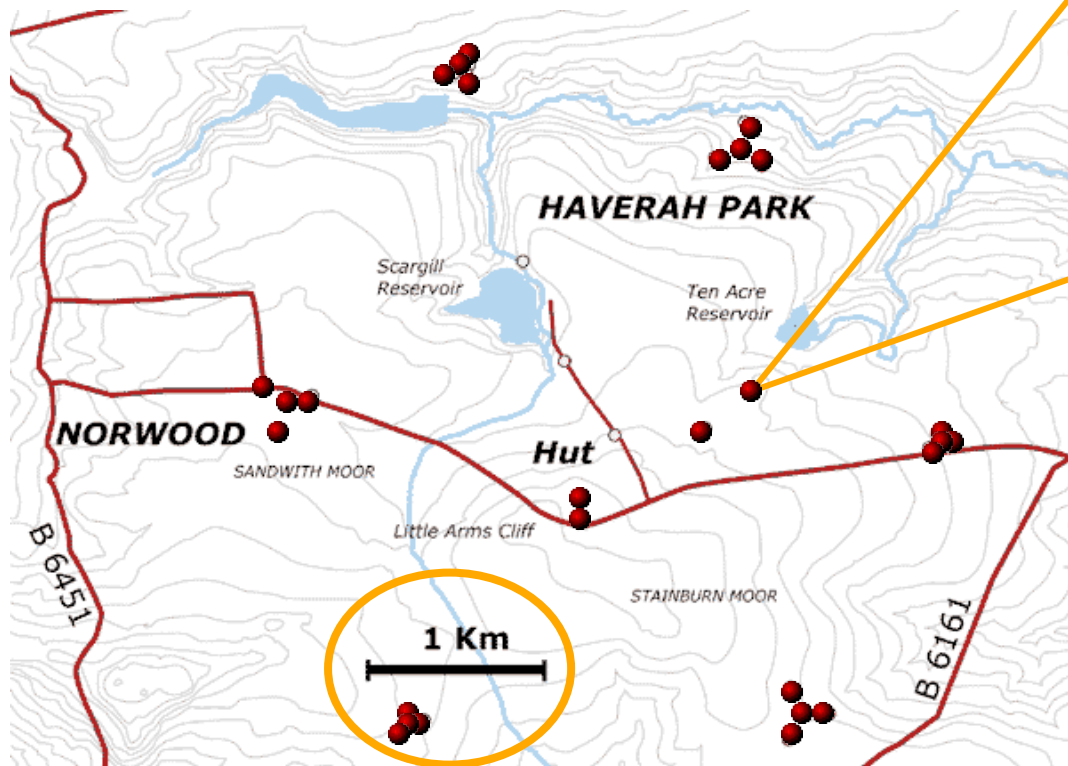
- La distanza media tra i contatori determina la *energia minima* dello sciame rivelabile.
- Il numero dei contatori, la *precisione* della misura
- L'area totale coperta, determina la *massima energia* misurabile.
- Ciascun contatore (*casetta*) misura in modo proporzionale la perdita di energia delle particelle che lo attraversa; da qui, si risale al numero di particelle incidenti
- Dalle misure della densità di particelle in ciascuna casetta dell'array, si risale alla distribuzione laterale $D(r)$.
- Dalla misura di $D(r)$ si risale all'energia del primario, e *dalla frequenza del numero di conteggi* si risale al flusso.
- La direzione dello sciame può essere determinata dalla *misura dei tempi di ritardo temporale* nell'arrivo dello sciame su diverse casette (le particelle dello sciame sono \perp al suo asse)

Il principio della rivelazione degli sciami con EAS e determinazione della direzione del primario

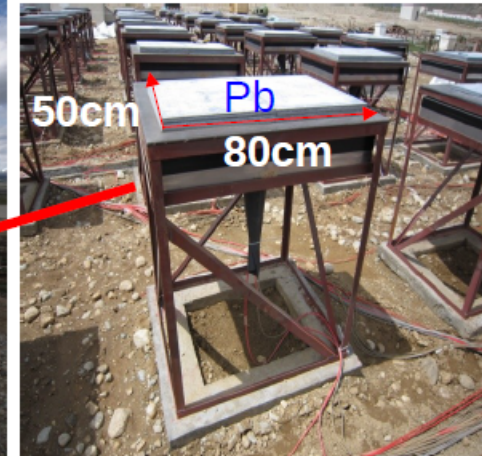
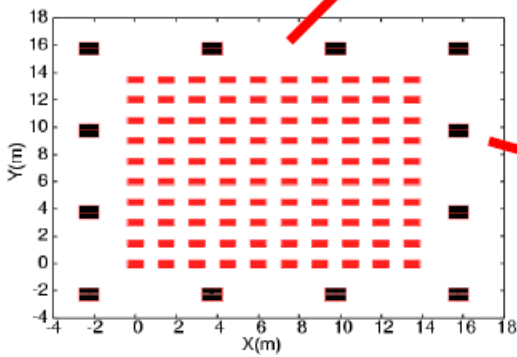
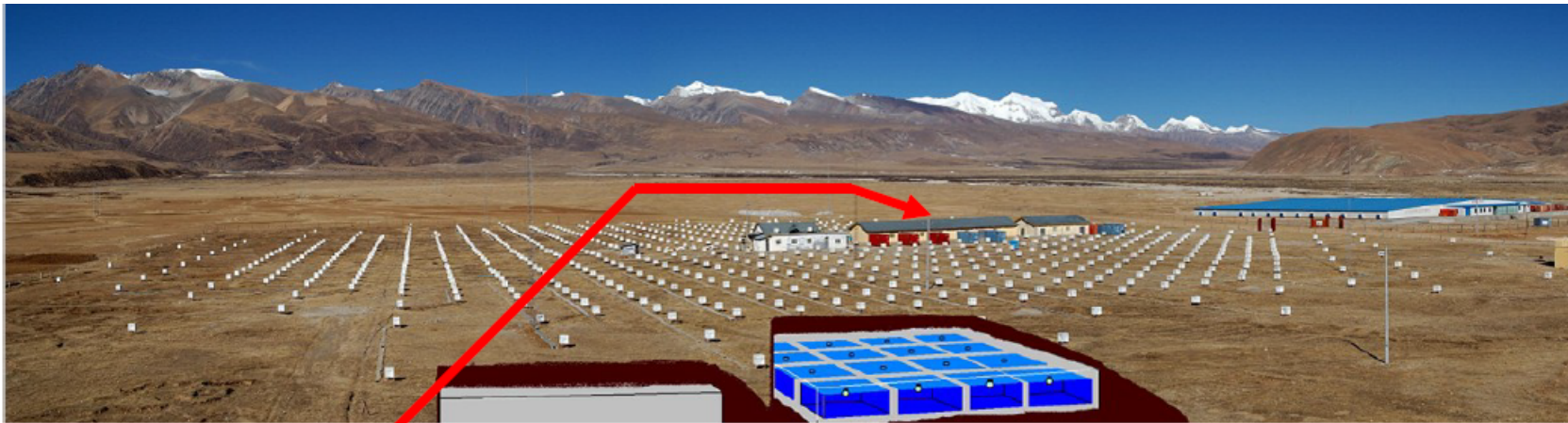


Rivelatori di Sciami

- Apparati sperimentali (Extensive Air Shower Arrays, EAS) che misurano sciame estesi sono in genere situati in alta quota.
- Misurano lo sciame “campionandolo” su una vasta superficie



Tibet



J. Huang (ICRC2011, Beijing, China)

- Il rivelatore di sciame **KASKADE** (**Karlsruhe**) in **Germania**
- Ciascuna casetta contiene un rivelatore
- Distanza media: 13 m. L'edificio centrale contiene l'elettronica necessaria per l'esperimento
- Ottimizzato per lo studio dei RC nella regione del ginocchio. Non deve essere un array di grandissime dimensioni.



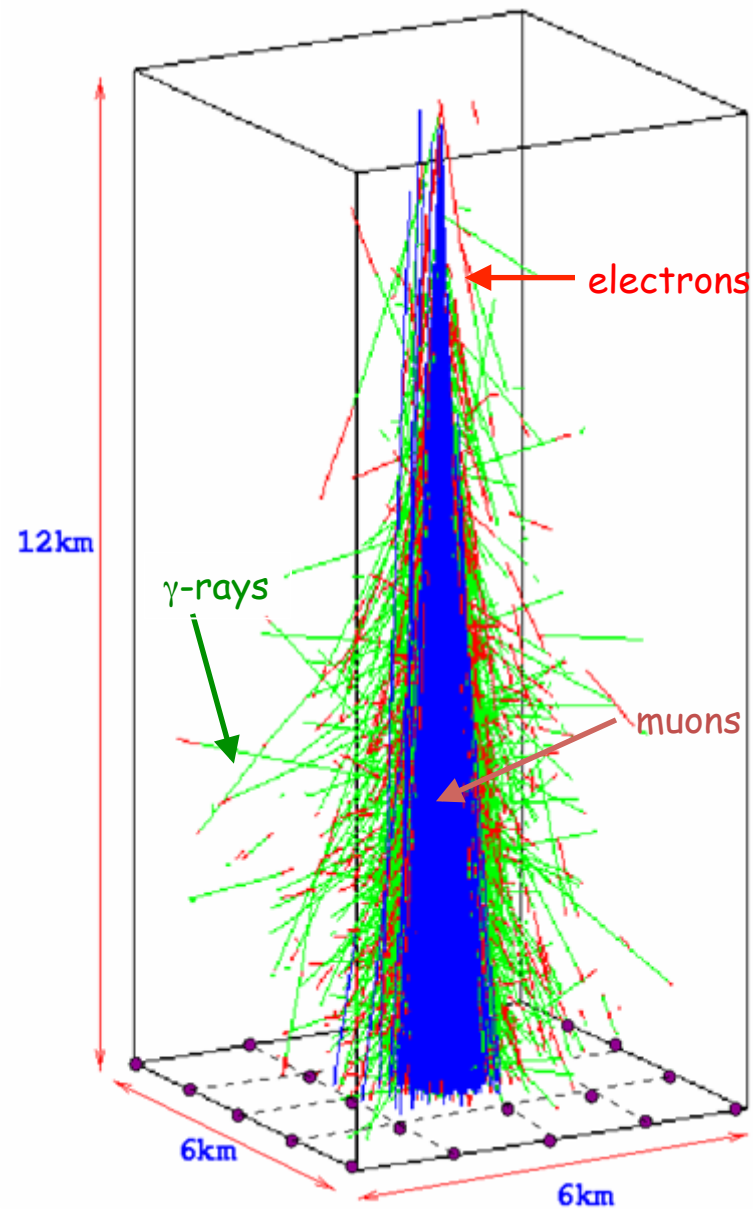
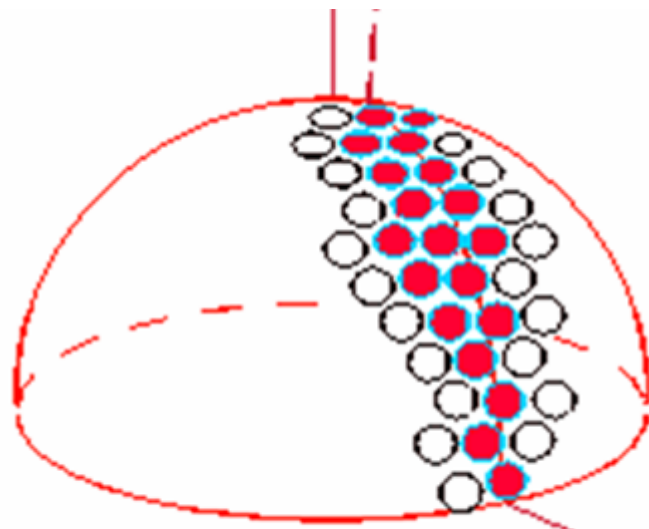
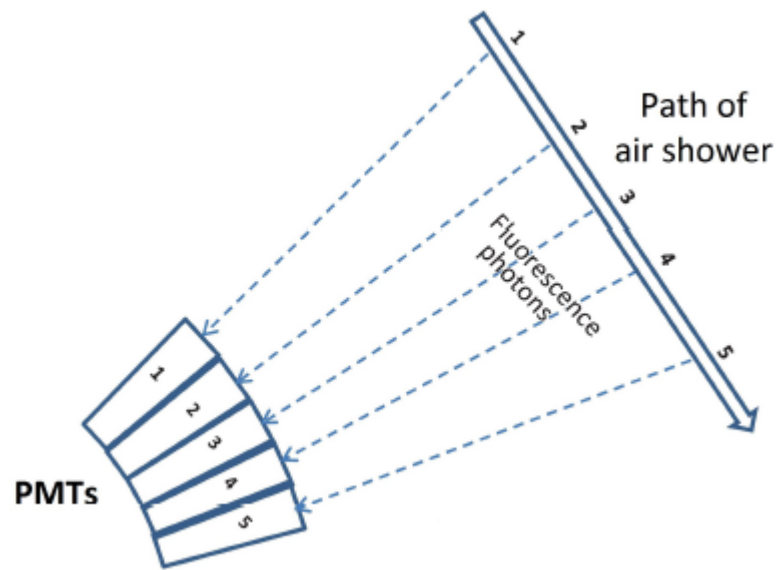
e/ μ



Altri metodi di Rivelazione

- Le particelle cariche dello sciame EM che giungono al suolo possono essere rivelate da rivelatori di sciame estesi
- Gli sciame di particelle producono anche luce nell'atmosfera per effetto Cerenkov (gli elettroni con $E > 20 \div 30$ MeV).
- La luce Cerenkov può venire rivelata (telescopi Cerenkov) nelle notti senza luna da appositi rivelatori al suolo.
- Gli sciame EM inducono anche l'eccitazione dell'azoto atmosferico, che riemette irraggiando luce. Questa fluorescenza può essere rivelata al suolo (Rivelatori fluorescenza).
- La componente di muoni può essere rivelata da rivelatori "underground".

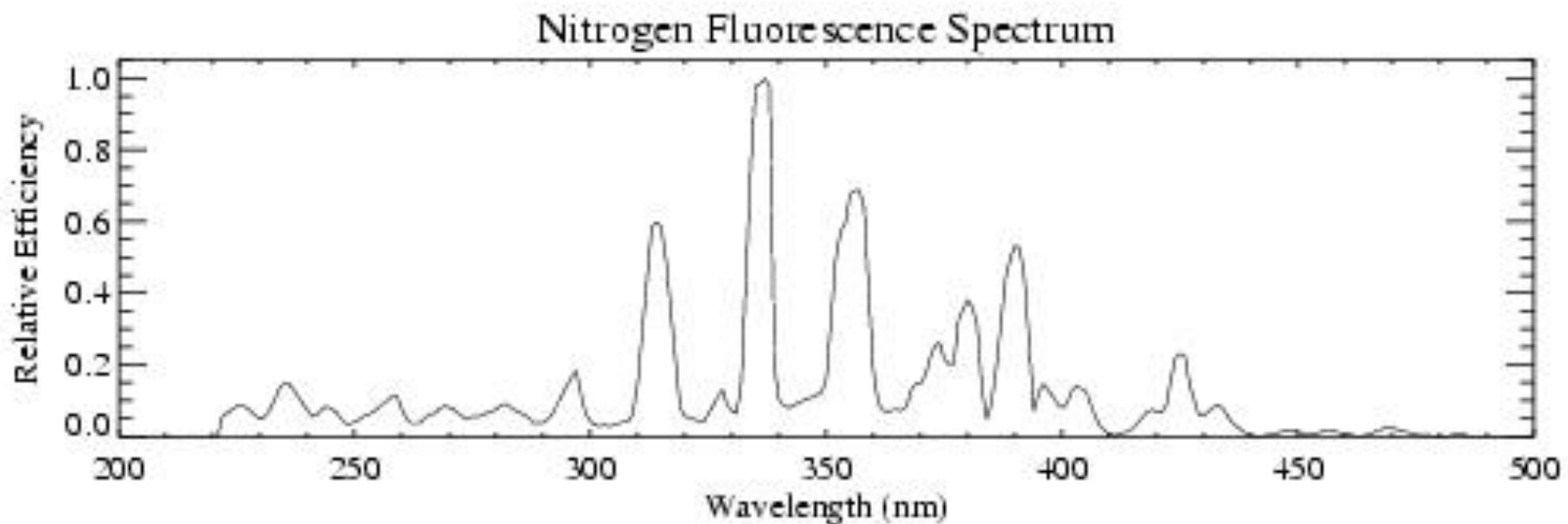
Rivelatori di sciame di alta energia



Il rivelatore Fly's Eye (USA)

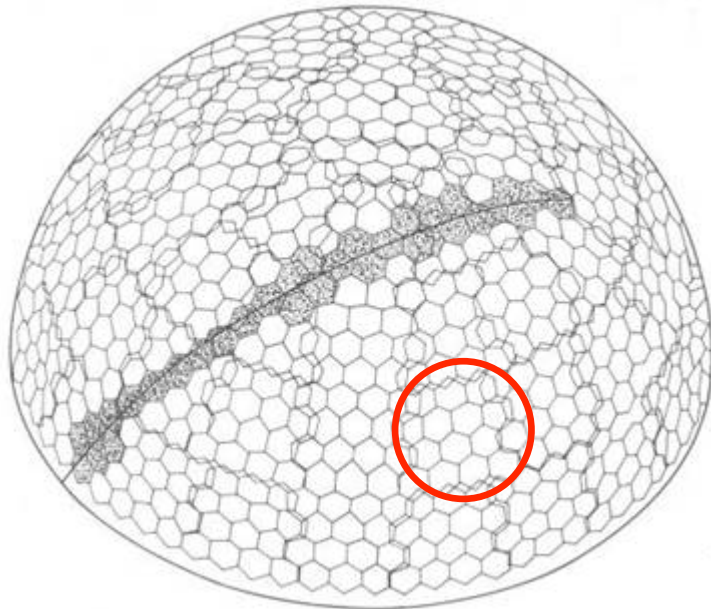


Utah, 160 km da Slat Lake City
Specchi con fotomoltiplicatori
rivelano la fluorescenza (visibile e
UV) di N_2 indotta dalla cascata
Si può quindi studiare lo sviluppo
dello sciame e risalire alla energia
del primario

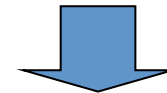


Il rivelatore Fly's Eye - 2

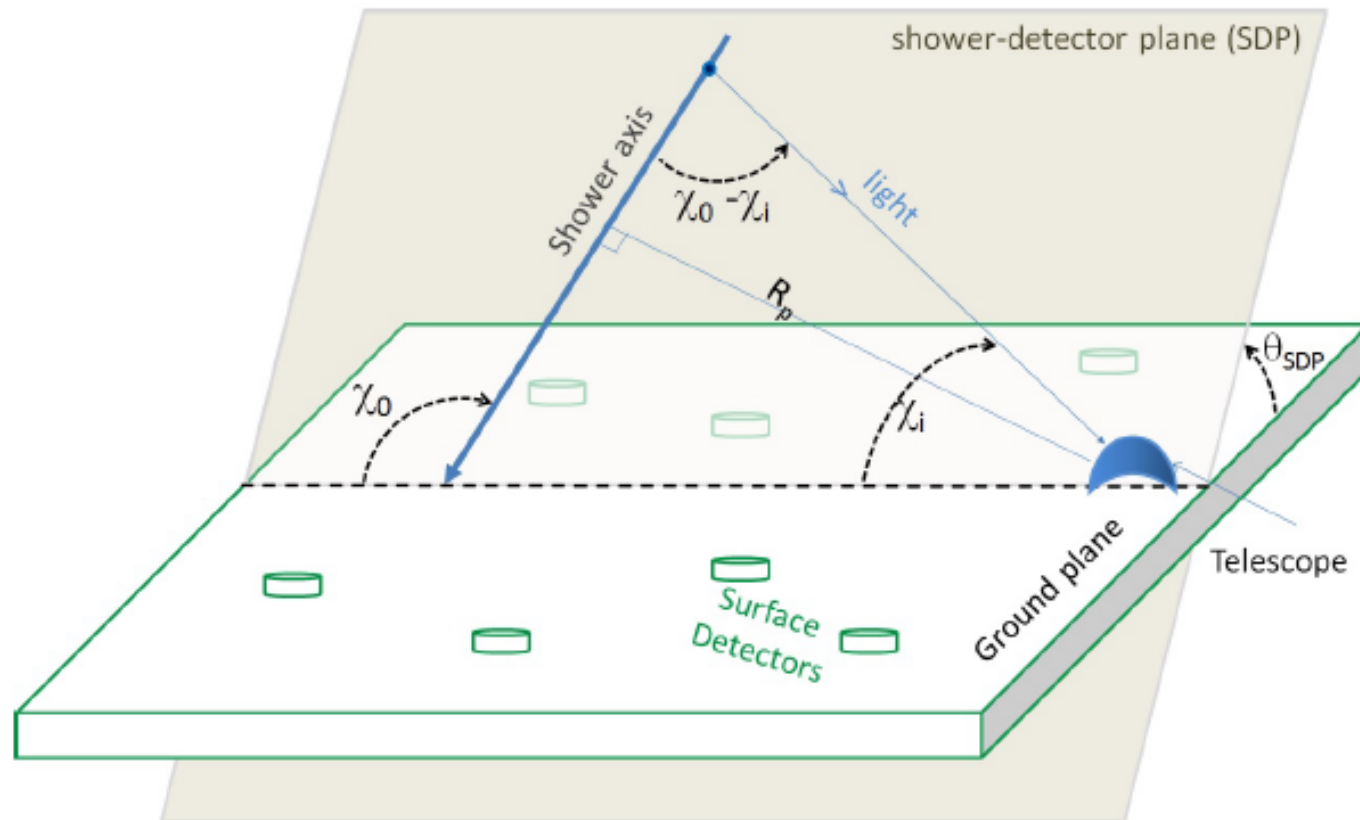
- 67 specchi con PM osservano la volta celeste
- È possibile ricostruire il profilo della cascata



Si misura così energia
(sviluppo shower) e
direzione del primario



FE2: visione stereoscopica

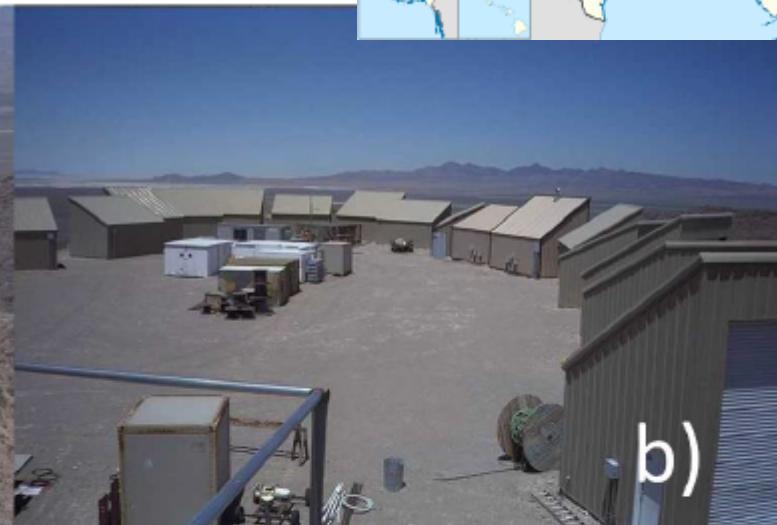


- Sketch of the detection principles of a fluorescent detector.
- The fluorescent light emitted by the EAS is collected on a large mirror and focused onto a camera composed of photomultipliers (PMTs)

HiRes (Utah)



a)



b)



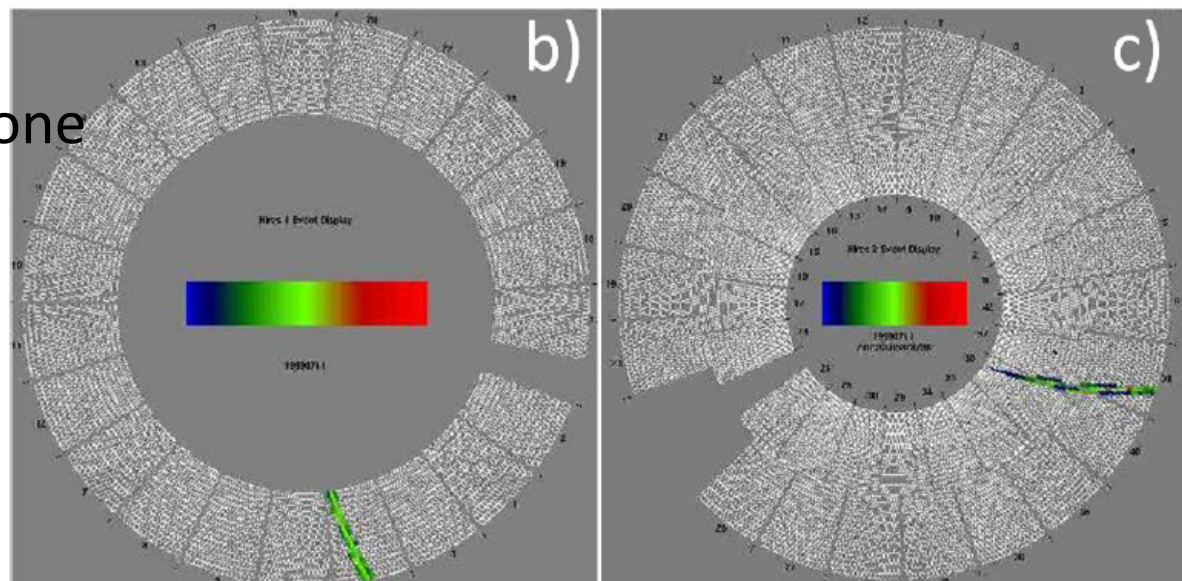
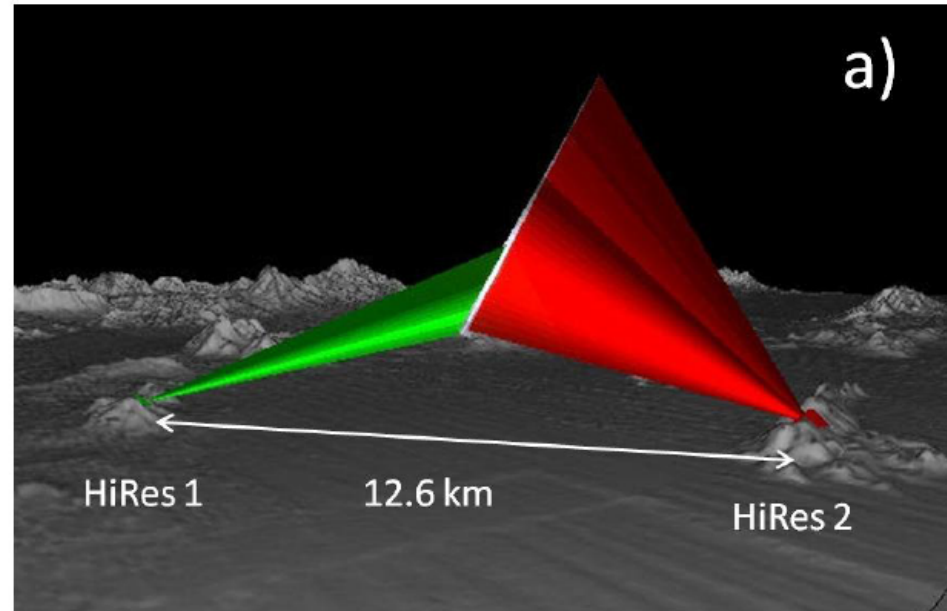
c)



d)

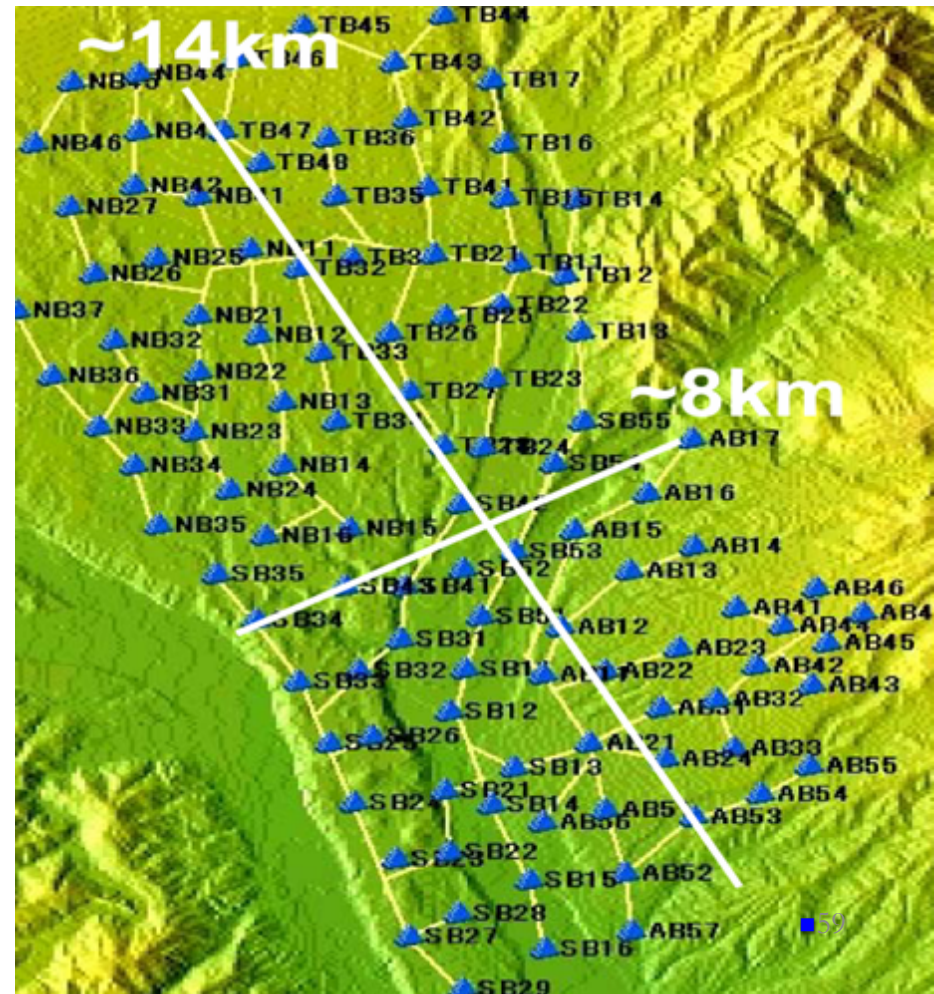
Fly's eye → HiRes

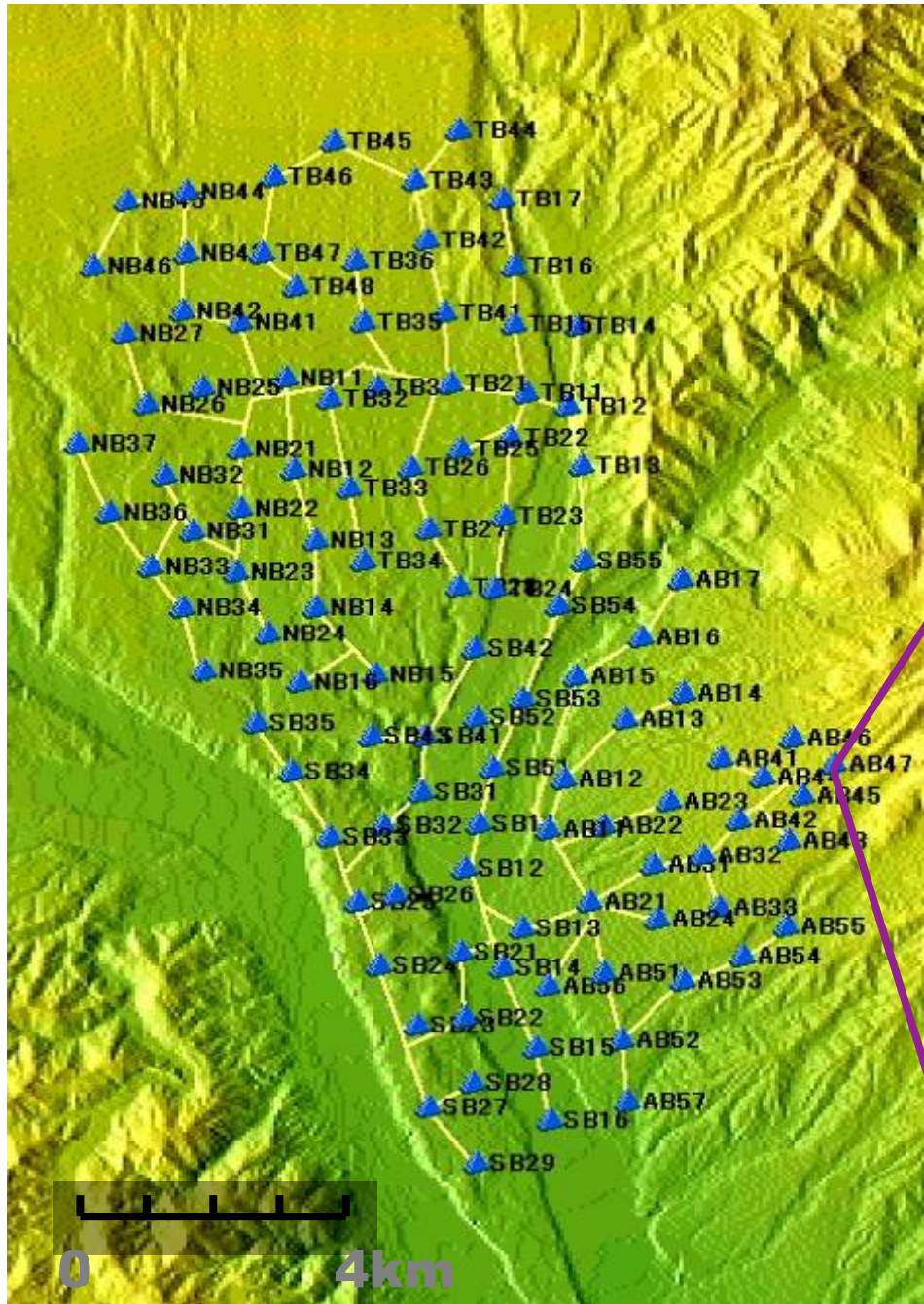
- *Stereo* HiRes: due insiemi di rivelatori per ricostruire in 3D lo sviluppo dello sciame
 - Migliore risoluzione angolare, studio correlazioni a piccoli angoli
 - Migliore comprensione della composizione chimica dei primari



Agasa (Giappone)

- 100 km², 111 rivelatori a scintillazione, 27 per muoni, separazione ~ 1 km – $5 \cdot 10^{16}$ m²s sr per $E > 10^{19}$ eV, $\theta < 45^\circ$





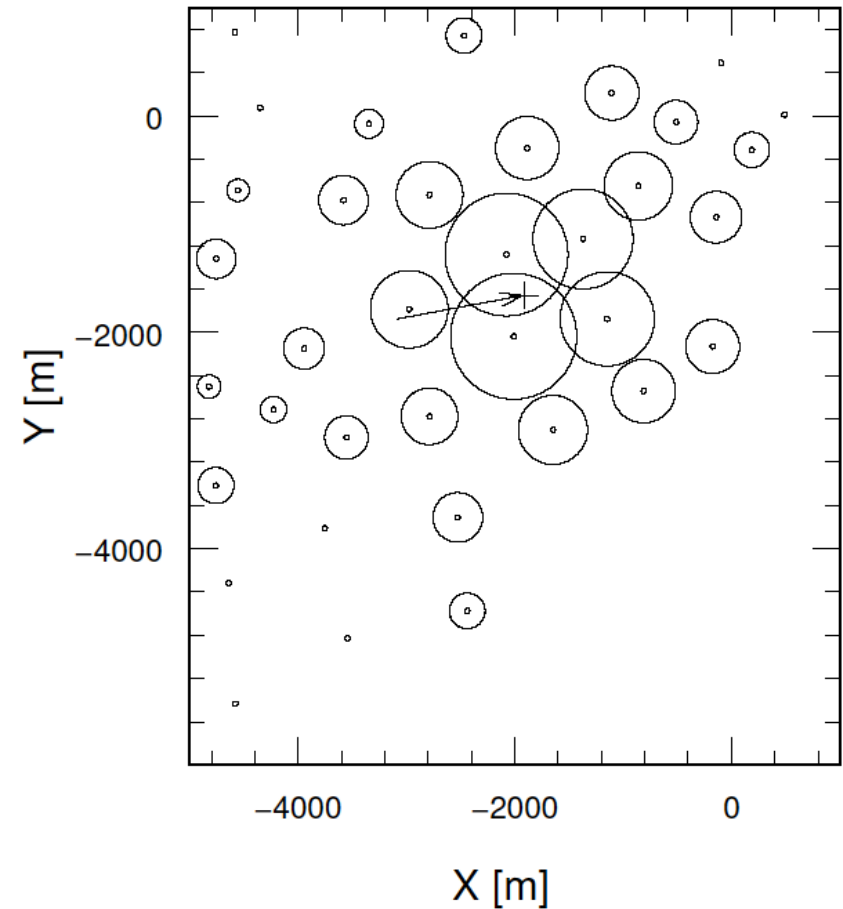
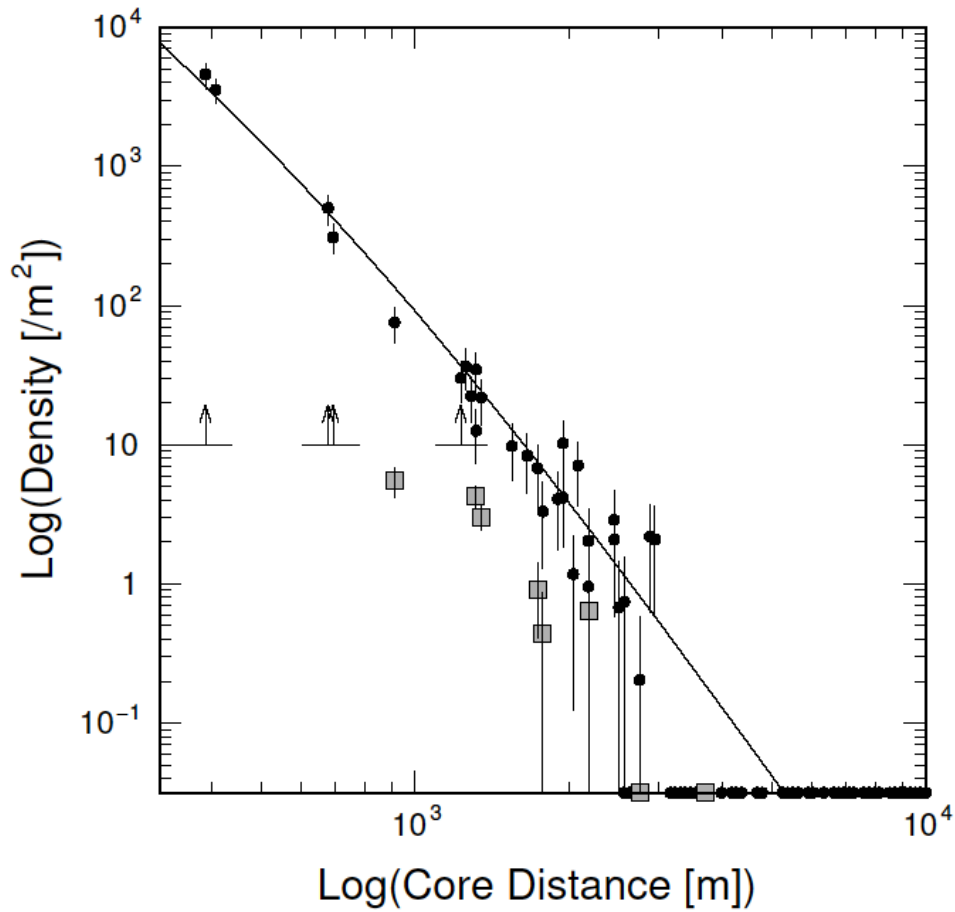
AGASA

Akeno Giant Air Shower Array

111 Electron Det.
27 Muon Det.

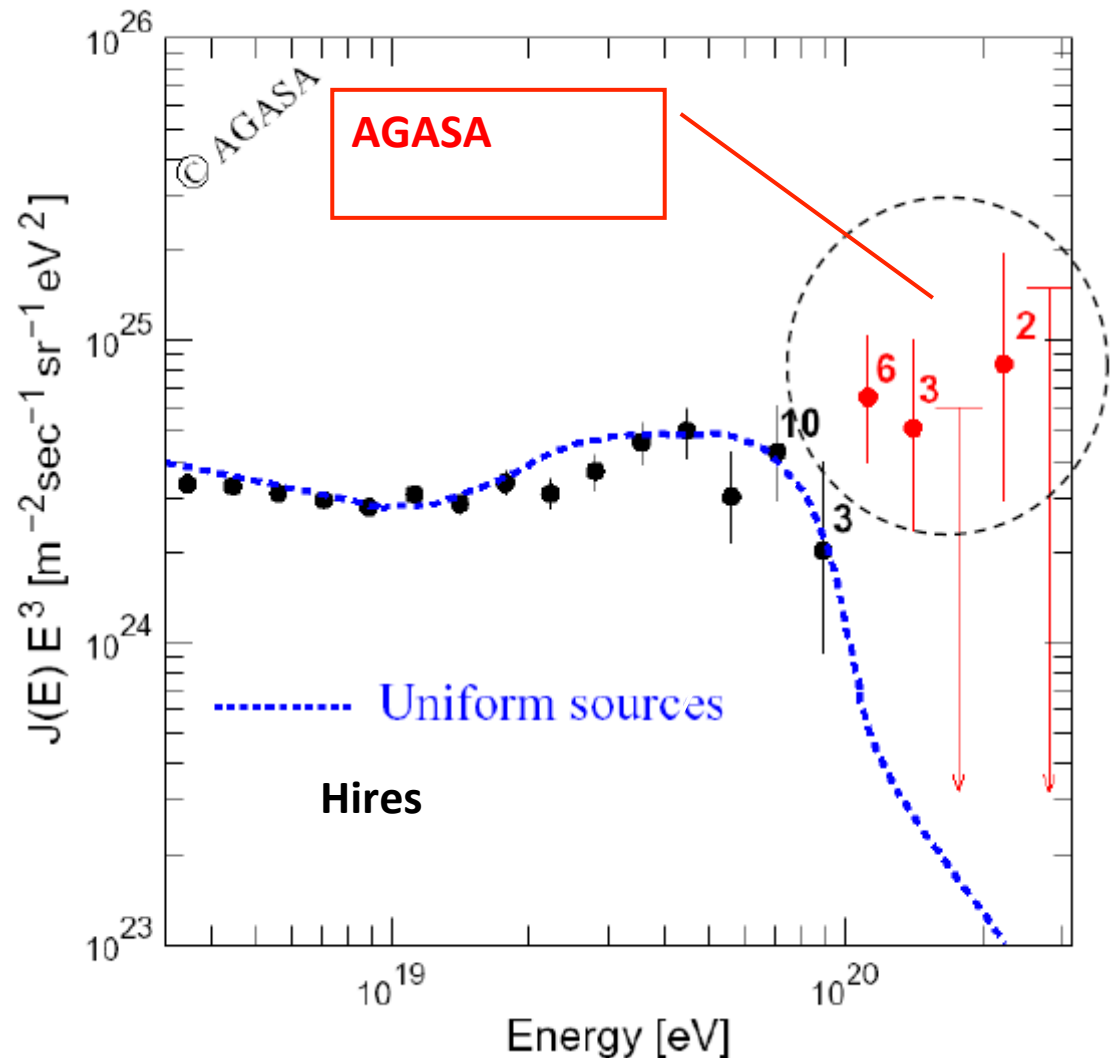


The Highest Energy Event
($2.46 \times 10^{20} \text{eV}$, $E > 1.6 \times 10^{20} \text{eV}$)
on 10 May 2001



Risultati sperimentali per $E > 10^{19}$ eV prima del 2007

- Linea BLU: spettro atteso per distribuzione uniforme di sorgenti e cut-off di GZK.
- AGASA: osservati 11 eventi con $E > 10^{20}$ eV
- Eventi attesi: 1.9 eventi, assumendo cutoff GZK

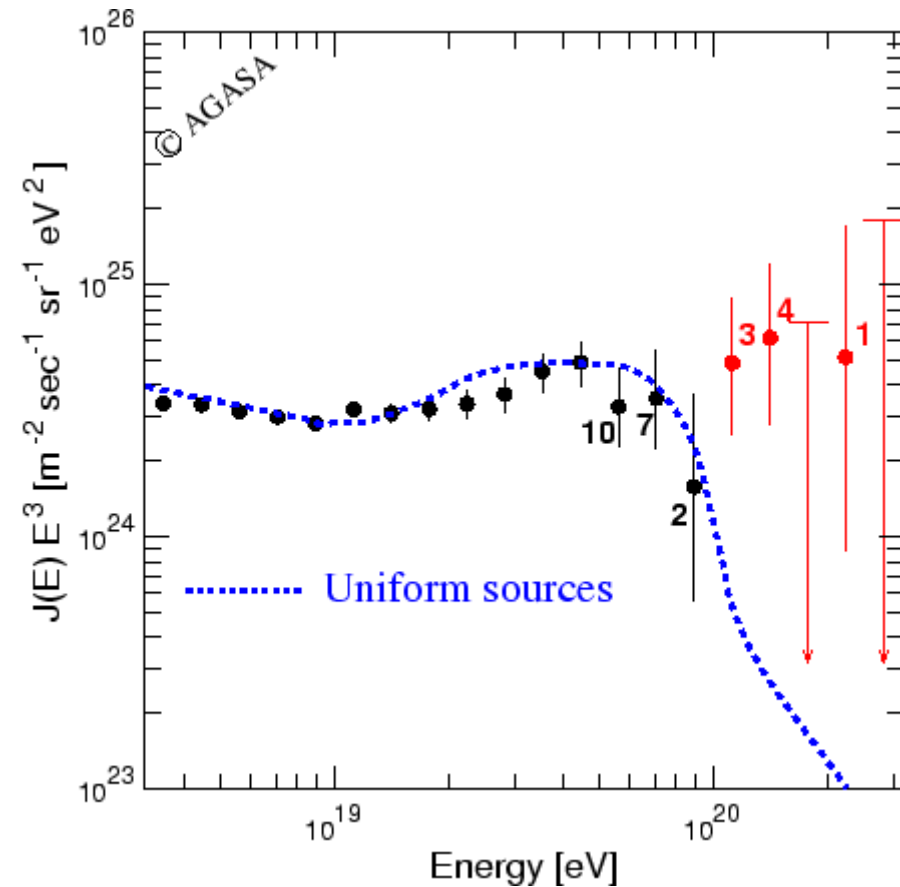


AGASA Results

The dashed curve represents the spectrum expected for extragalactic sources distributed uniformly in the Universe, taking account of the energy determination error.

GZK cut ?

Greisen-Zatsepin-K'uzmin (GZK cut-off predicted at $\sim 6 \times 10^{19}$ eV, which results from photo-pion production in collisions with the cosmic background microwave photons.

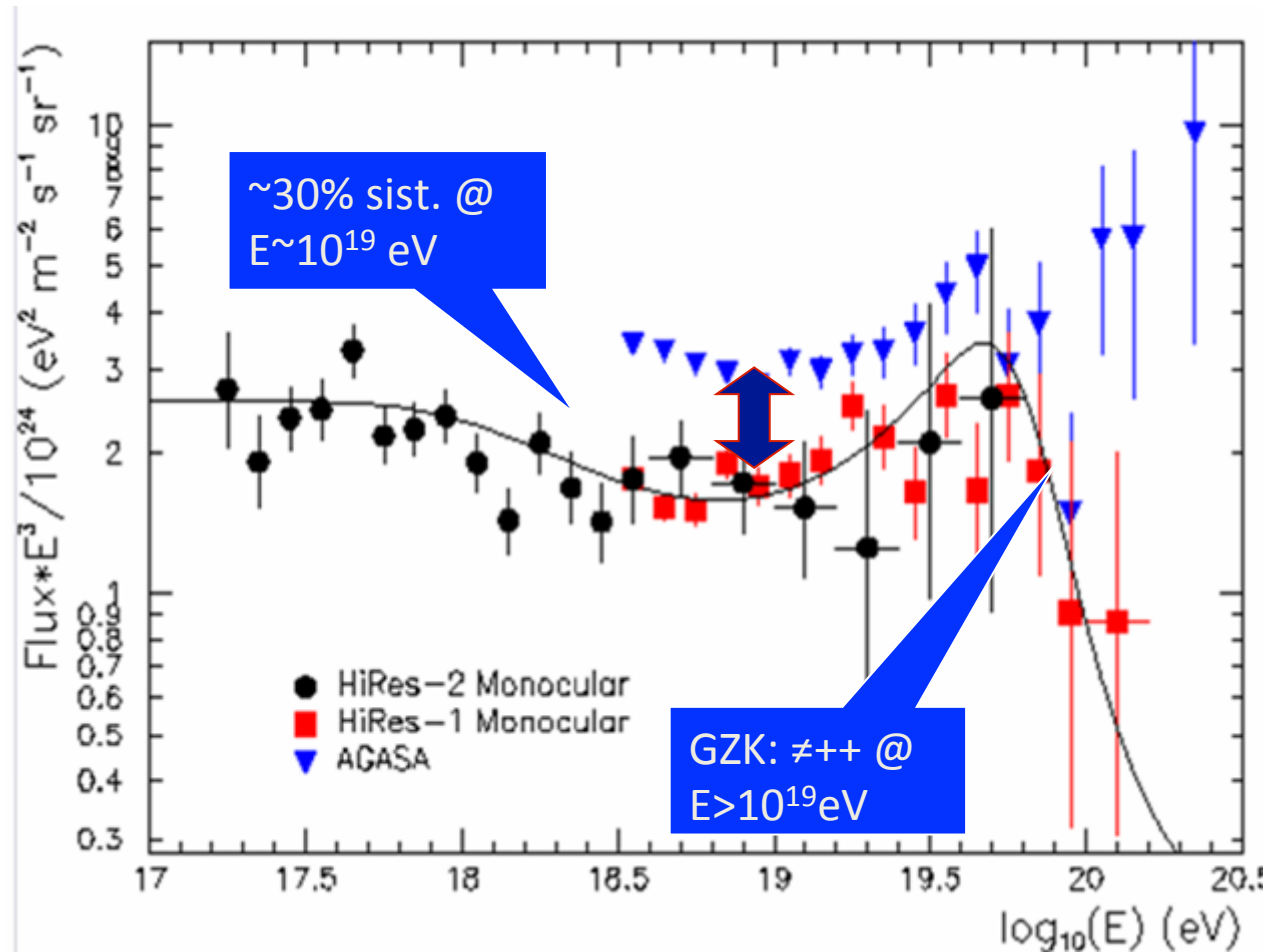


“Conflitto” AGASA-HiRes

Confronto tra dati
Agasa-Hires:
differenza
sistematica del
20-30% per $E <$
 10^{20} eV

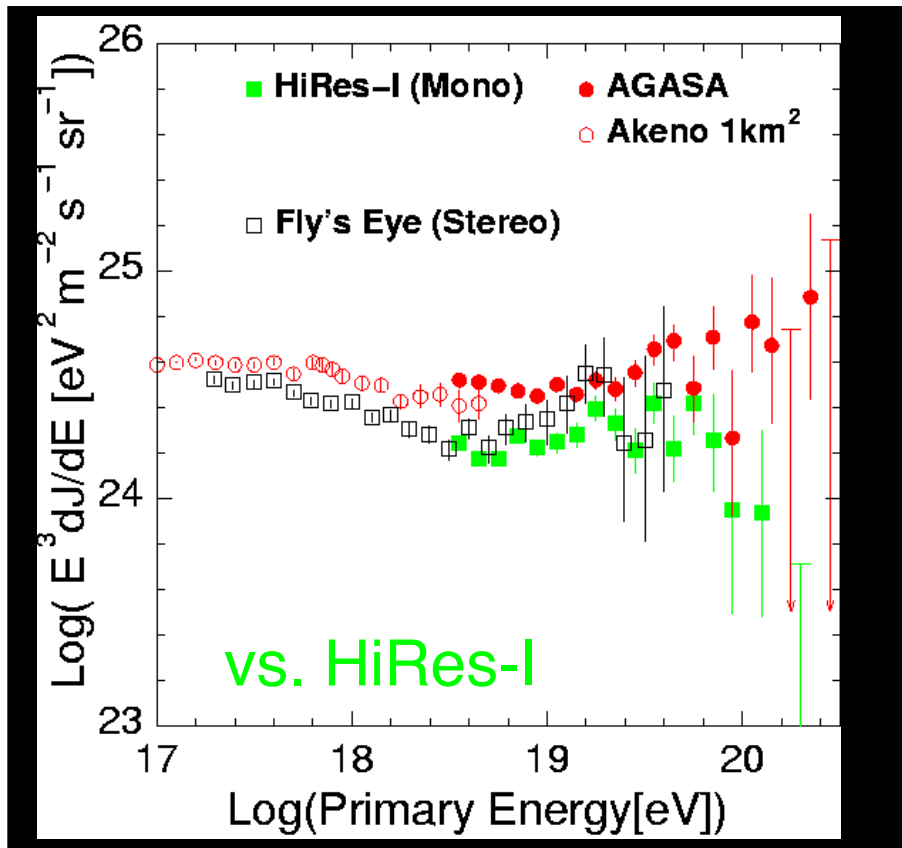
Pur correggendo per
questa differenza, a
 $E > 10^{20}$ eV, i risultati
differiscono per $\sim 2 \sigma$

PROBLEMA: Poca
statistica!

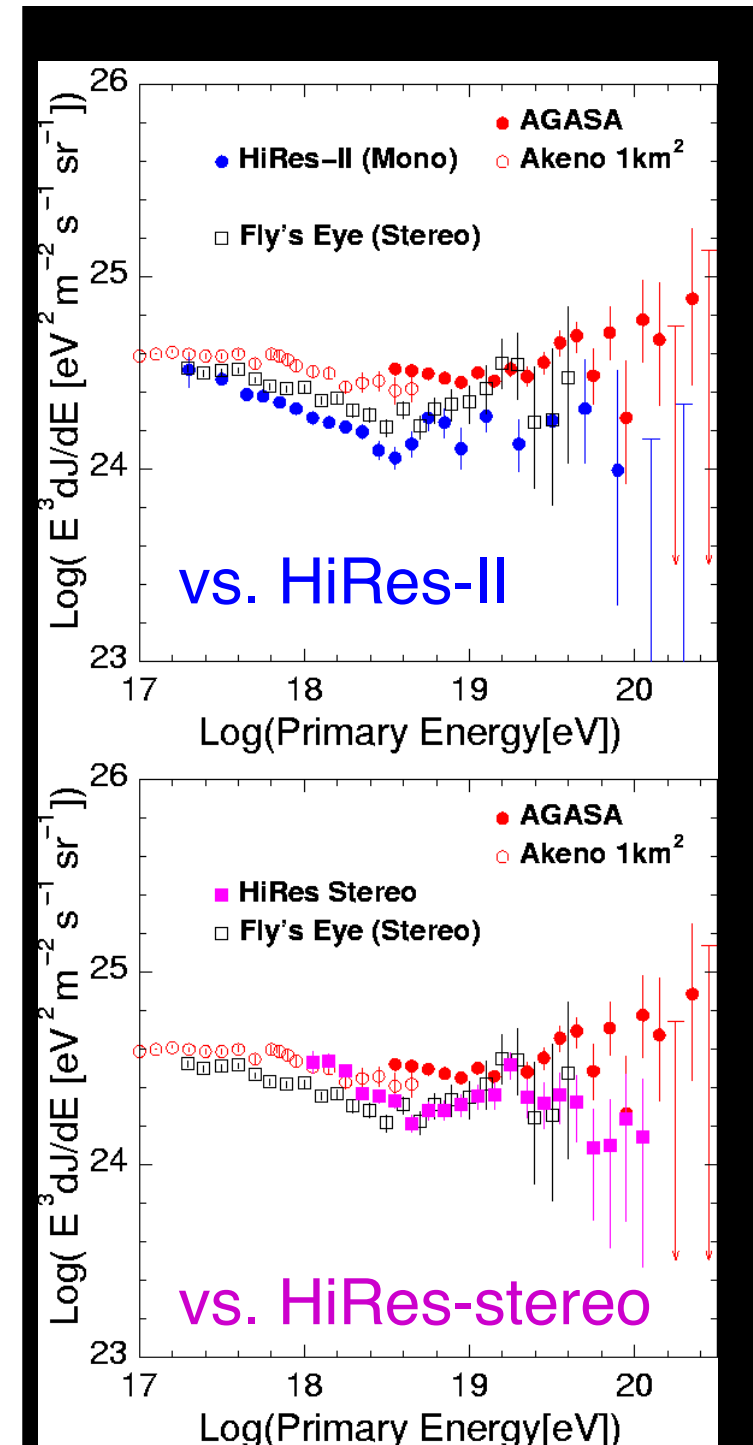


Quale è la natura e la ragione del “conflitto” tra i due esperimenti?

(AGASA vs. HiRes@Tsukuba ICRC)

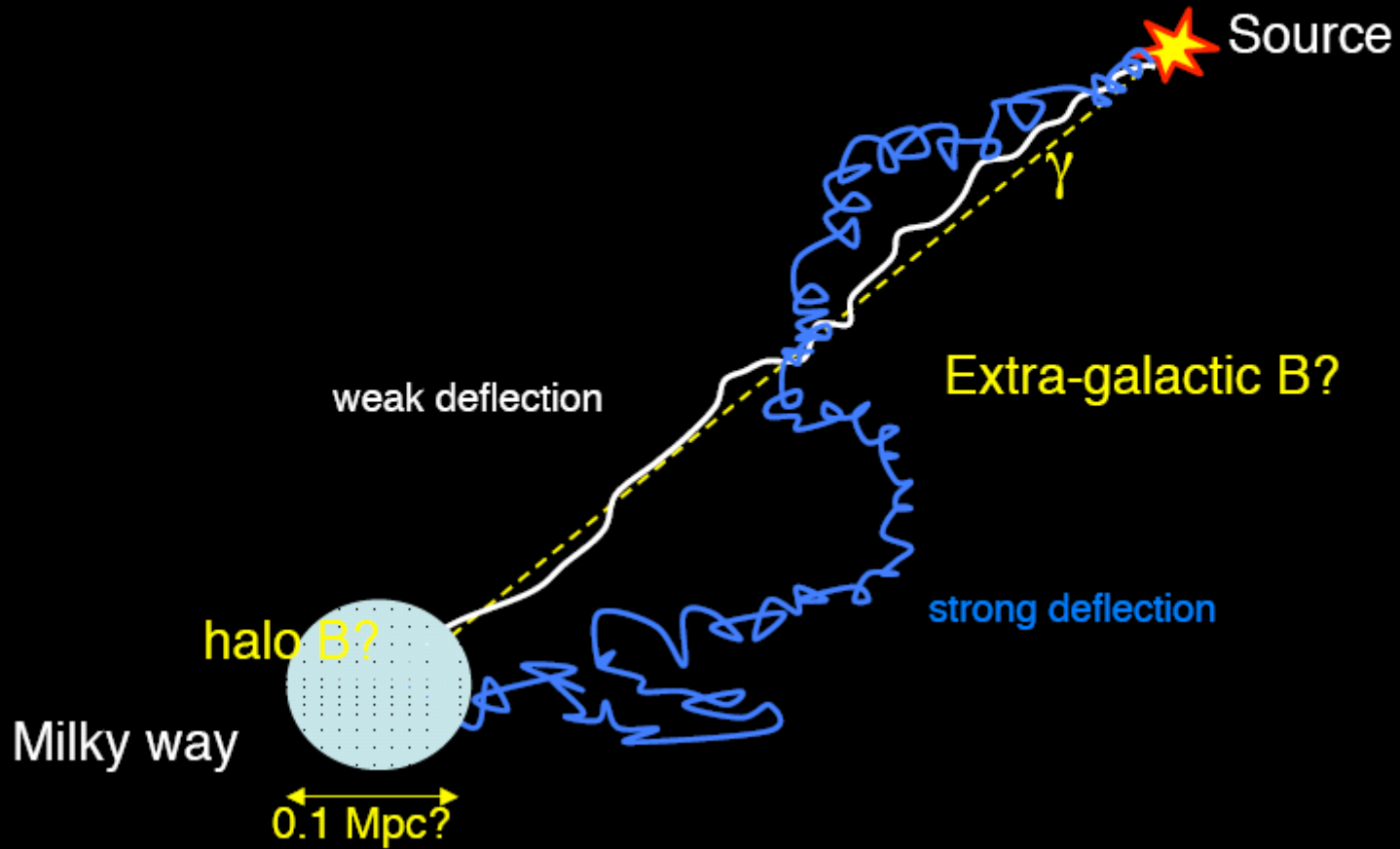


- ~ 2.5 sigma discrepancy between AGASA & HiRes
- Energy scale difference by 25%

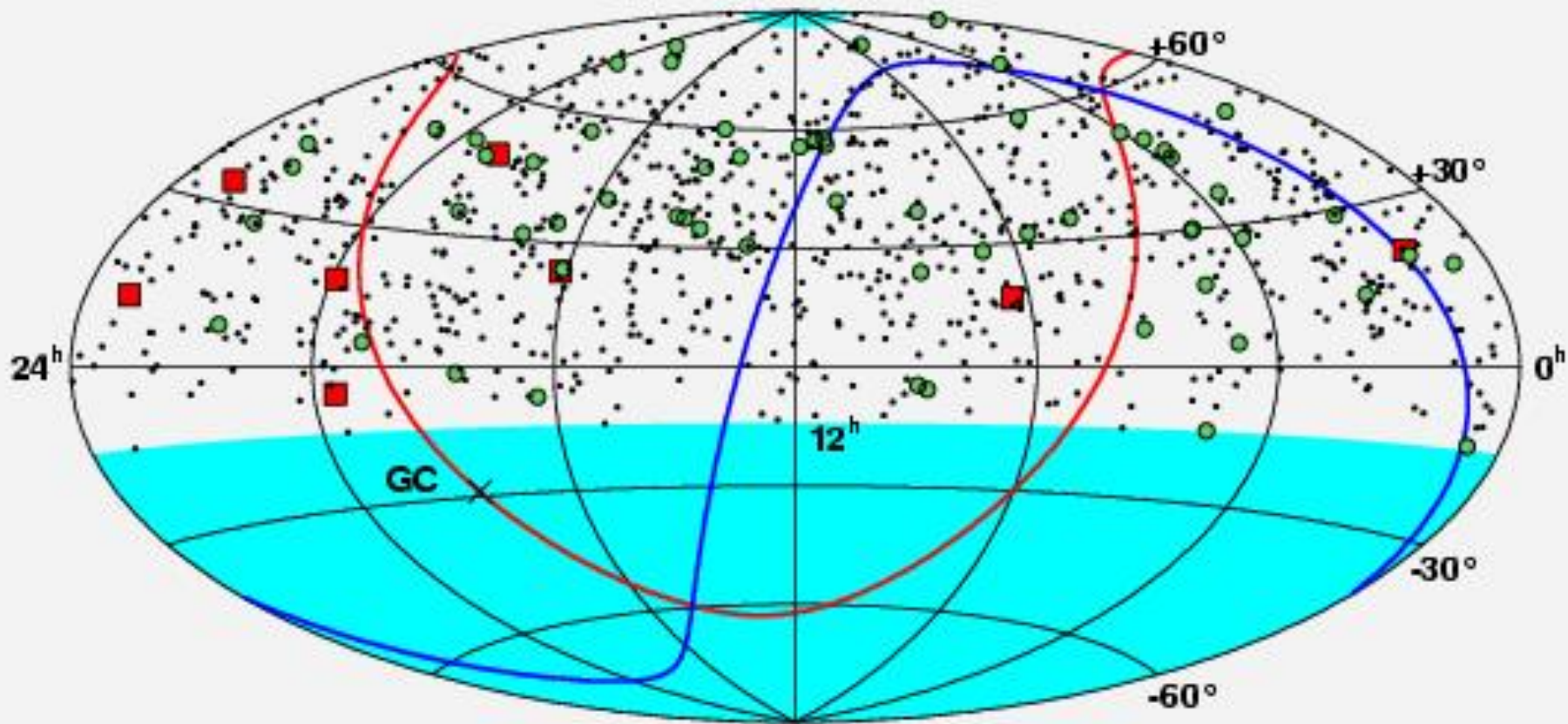


Influence of cosmic magnetic fields

Larmor radius: $r_L = 110 \text{ kpc } Z^{-1} (E / 10^{20} \text{ eV}) (B / 1 \text{ _G})^{-1}$

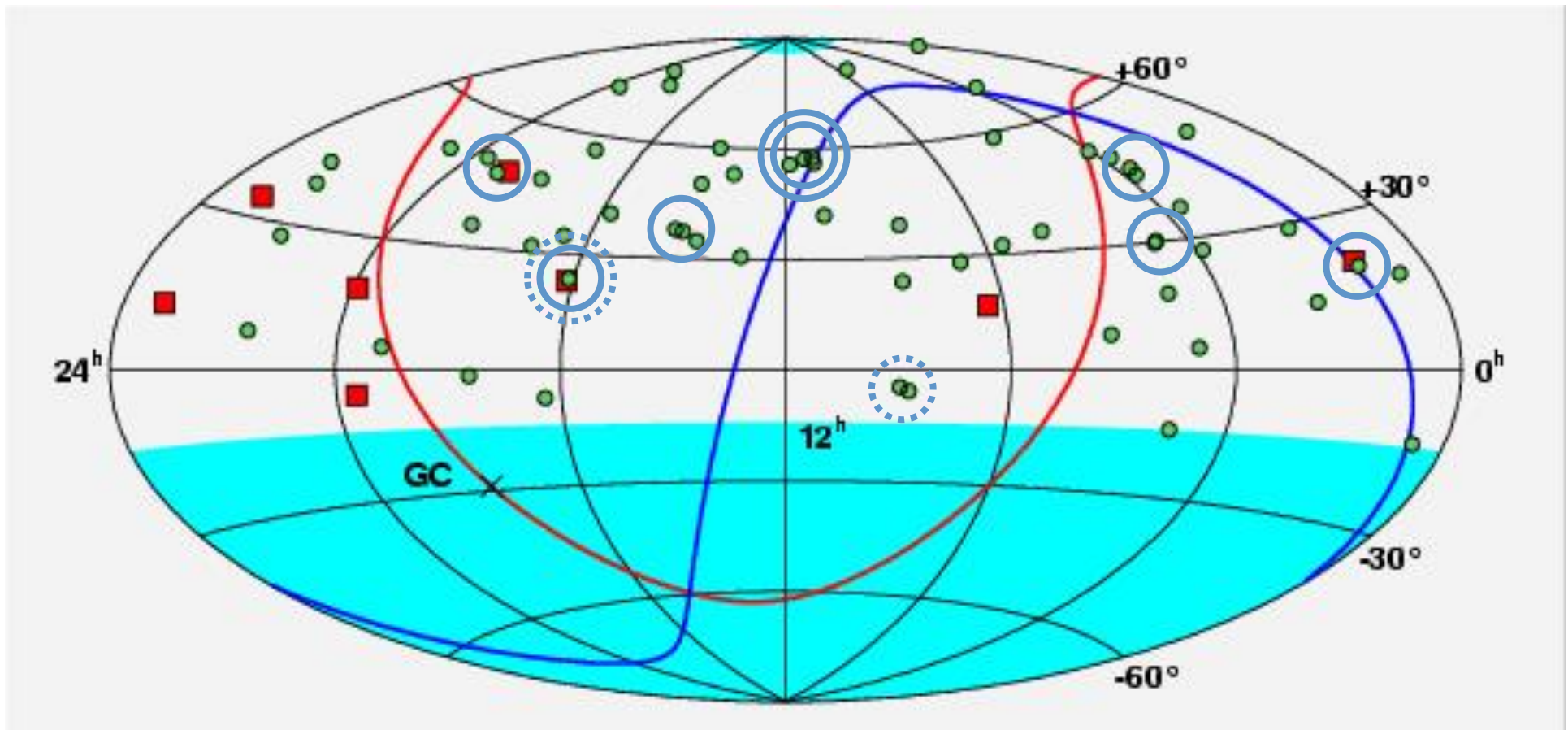


Arrival Direction Distribution $>10^{19}$ eV



Arrival Direction Distribution $>4 \times 10^{19} \text{eV}$ zenith angle $< 50^\circ$.

- Isotropic in large scale \rightarrow Extra-Galactic
- But, Clusters in small scale ($\Delta\theta < 2.5^\circ$)
 - 1 triplet and 6 doublets (2.0 doublets are expected from random)
 - One doublet \rightarrow triplet ($> 3.9 \times 10^{19} \text{eV}$) and a new doublet ($< 2.6^\circ$)

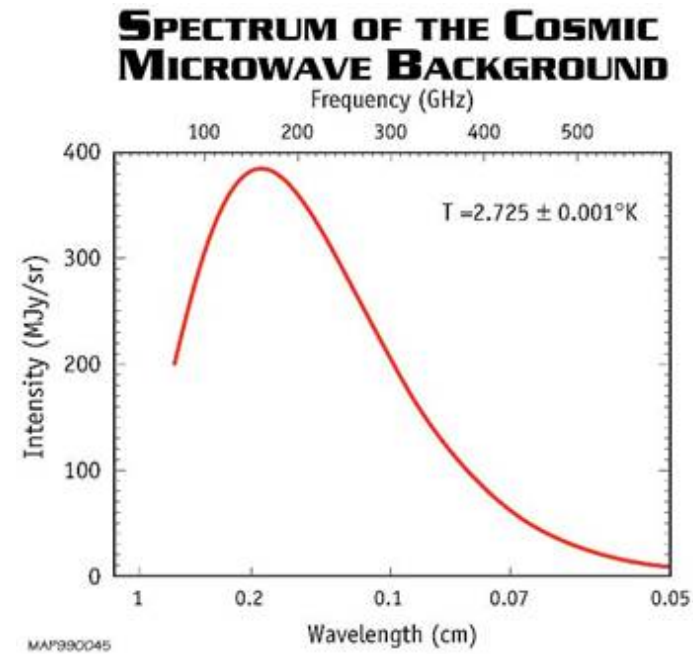


Volume di confinamento dei RC : il cutoff di Greisen-Zatsepin-Kuzmin

- L' universo è permeato dalla Radiazione Cosmica di Fondo a 3° K (CMBR). Frequenza media 280 GHz
- CMBR: fotoni di energia

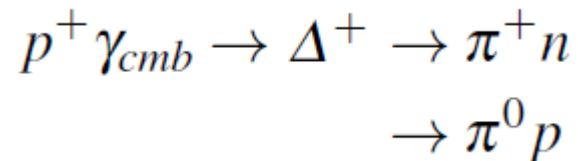
$$E_{cmb} = h\bar{\nu} \simeq 1.2 \times 10^{-3} \text{ eV} .$$

- La densità dei fotoni di fondo è $\sim 400/\text{cm}^3$
- Il fondo di radiazione pone un limite sulla distanza massima da cui i RC possono provenire.



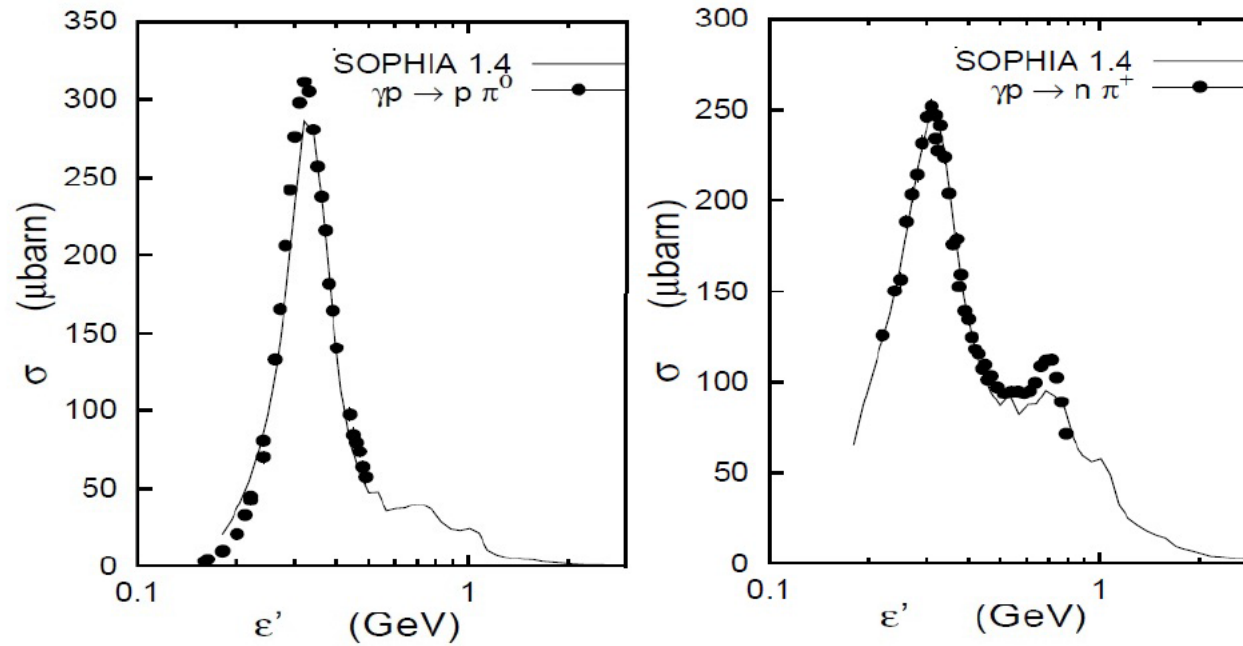
$G_{\text{reisen}} Z_{\text{atsep}} K_{\text{uzmin}}$ cutoff
Soglia per reazioni di fotoproduzione

- **Fotoproduzione:** Protoni di alta energia possono interagire con fotoni, producendo un pione:

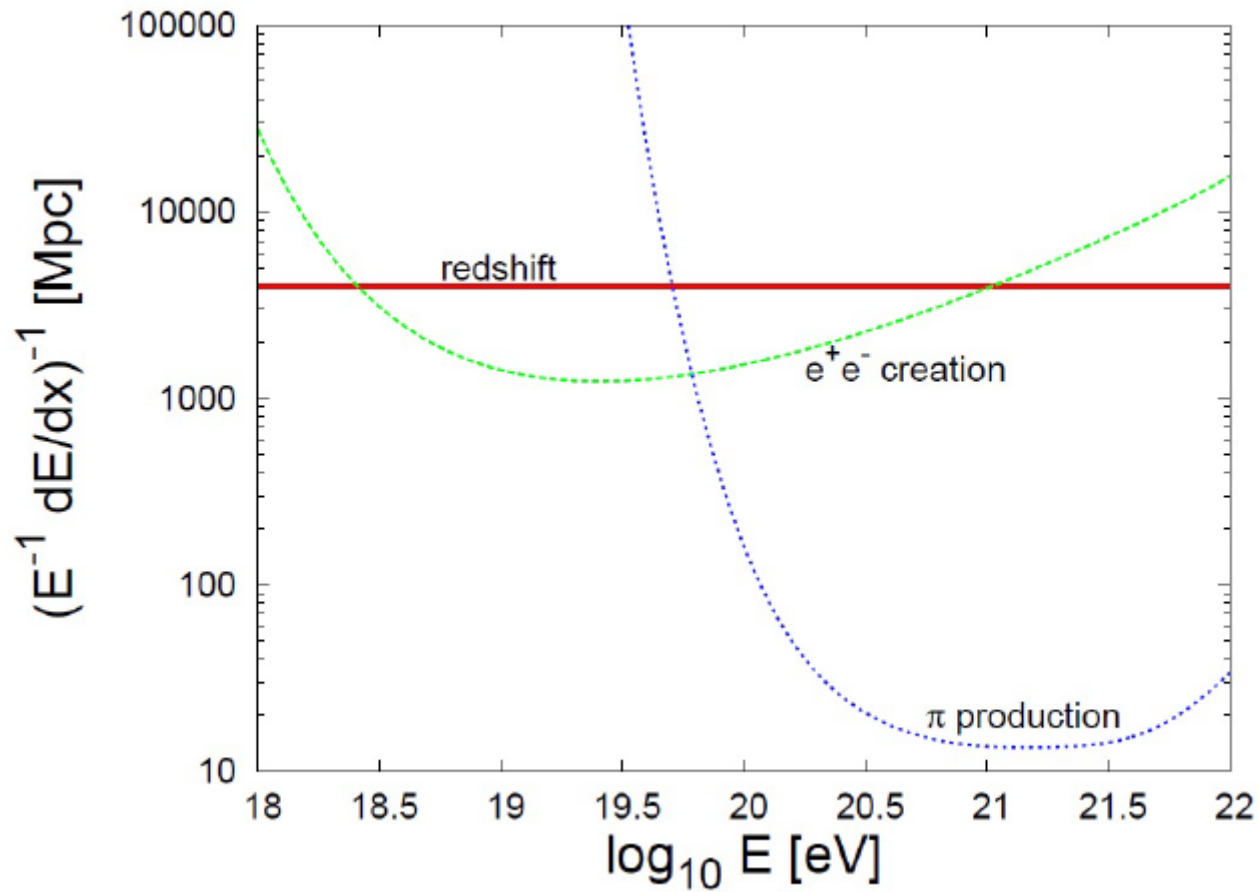


- È necessario essere sopra la soglia di fotoproduzione nel sistema del CM: $E_0^{\text{FP}} \approx 300 \text{ MeV}$
- Il processo ha una sezione d'urto in risonanza $\sigma_0^{\text{P}} \approx 250 \mu\text{b}$
- la densità numerica della CMBR è $n_g = 400 \text{ cm}^{-3}$, da cui si ricava il cammino libero medio del p

Sezione d'urto per la Δ

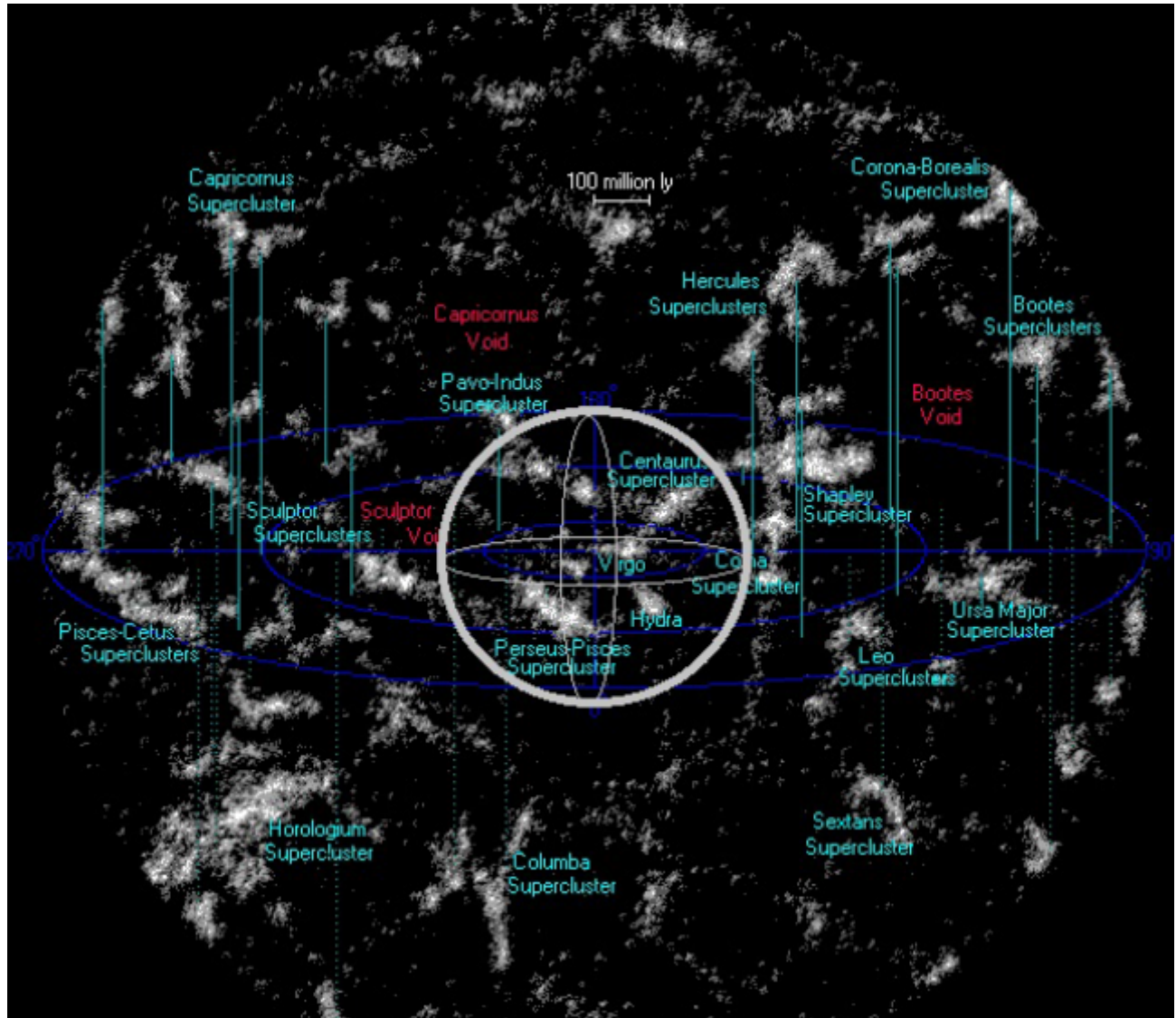


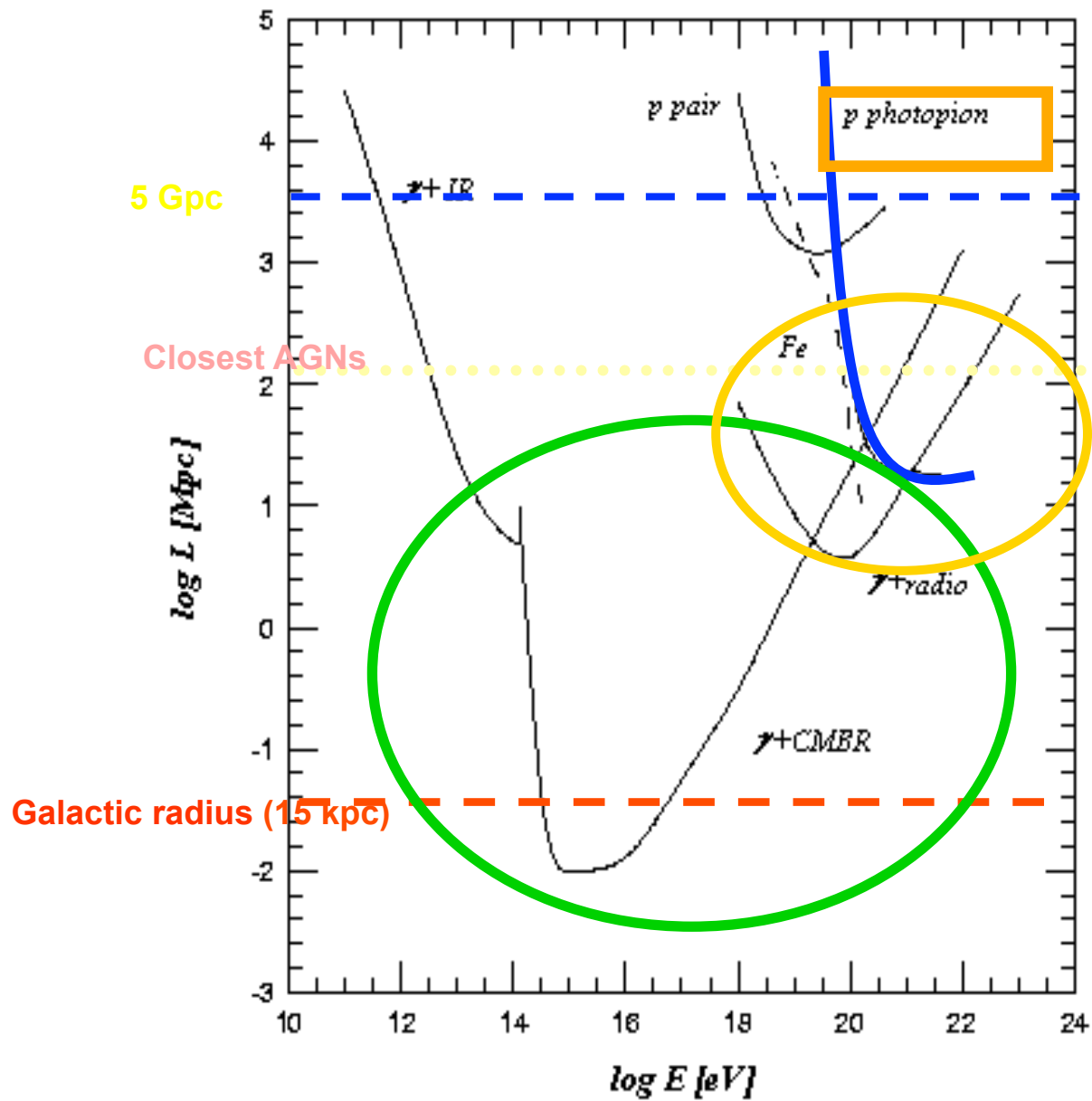
In ogni processo, il p perde circa 1/10 della sua energia
Si può dunque stimare che i p NON possano giungere da distanze superiori a $10 \times 3 \text{ Mpc} = 30 \text{ Mpc}$
Figura: Risultato di calcoli dettagliati.



Orizzonte dell'Universo per p

- The neighboring superclusters of galaxies (<300 Mpc)
- There are about 100 superclusters and about $3 \cdot 10^6$ large galaxies.
- The central sphere corresponds to 100 Mpc (GZK limit)





L'Universo NON è trasparente ai protoni di altissima energia

L'Universo NON è trasparente ai fotoni di alta energia

Ricerca delle sorgenti

- Nella reazione di fotoproduzione (responsabile del cutoff di GZK) sono prodotti π^\pm , π^0 che decadono:

$$\pi^+ \rightarrow \nu_\mu \mu^+ \rightarrow \nu_\mu \nu_\mu \nu_e e^+$$

$$\pi_0 \rightarrow \gamma\gamma$$

- Neutrini e fotoni di altissima energia possono quindi essere studiati per confermare il meccanismo GZK, e per localizzare le sorgenti di RC a $E > 10^{19}$ eV

Il RC di più alta energia osservato: $\geq 3.2 \cdot 10^{20}$ eV (?)

Se le sorgenti **non possono** essere troppo lontane (<30

Mpc), possiamo cercare di localizzarle tramite:

→ Studi di anisotropia con esperimenti di RC

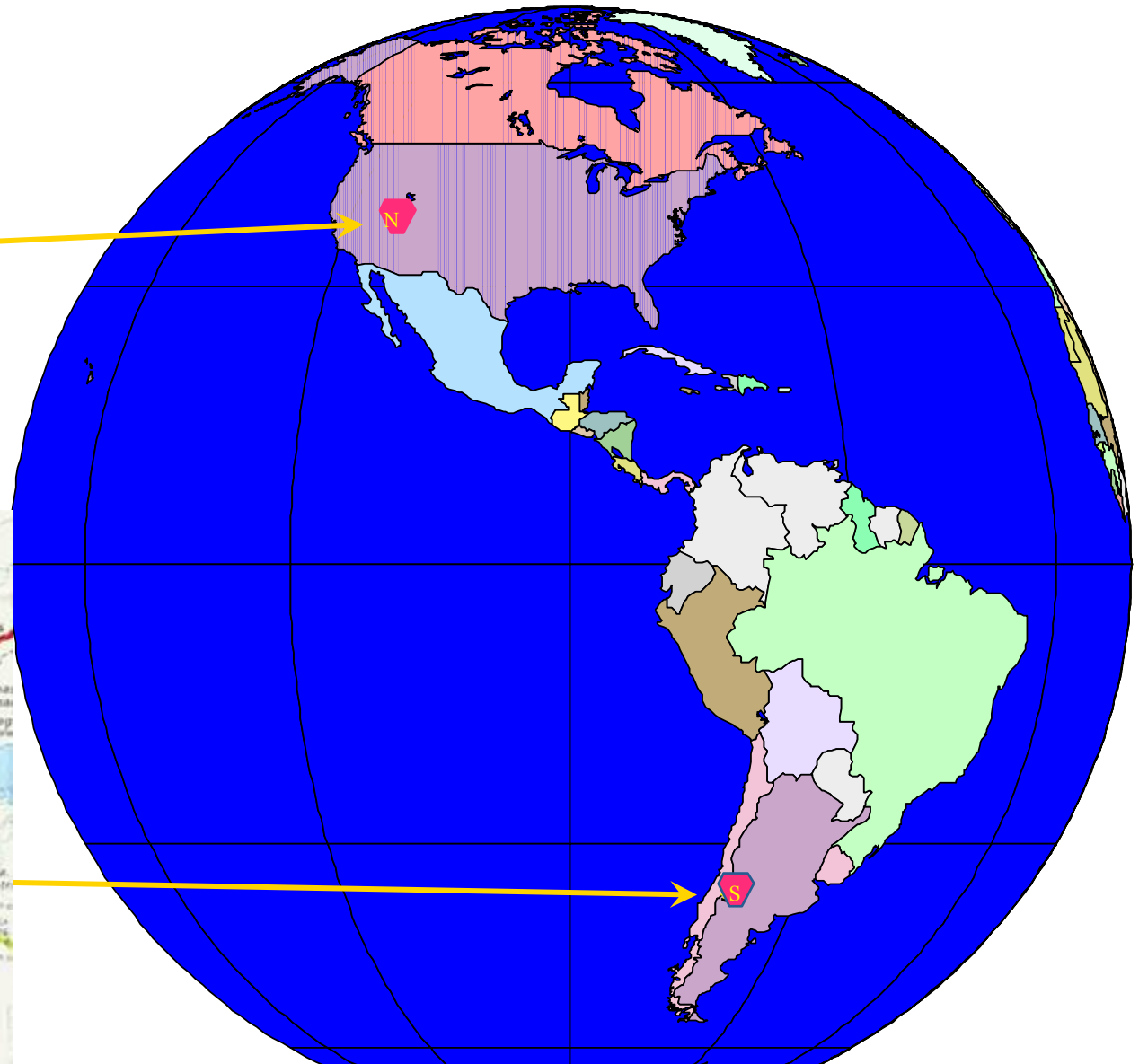
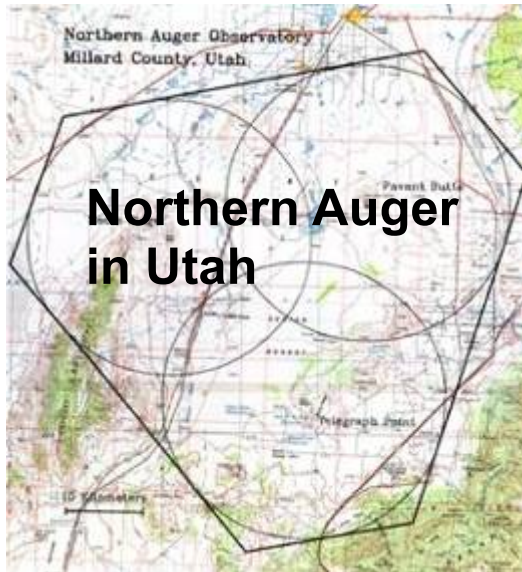
→ Confronto con altre misure astronomiche

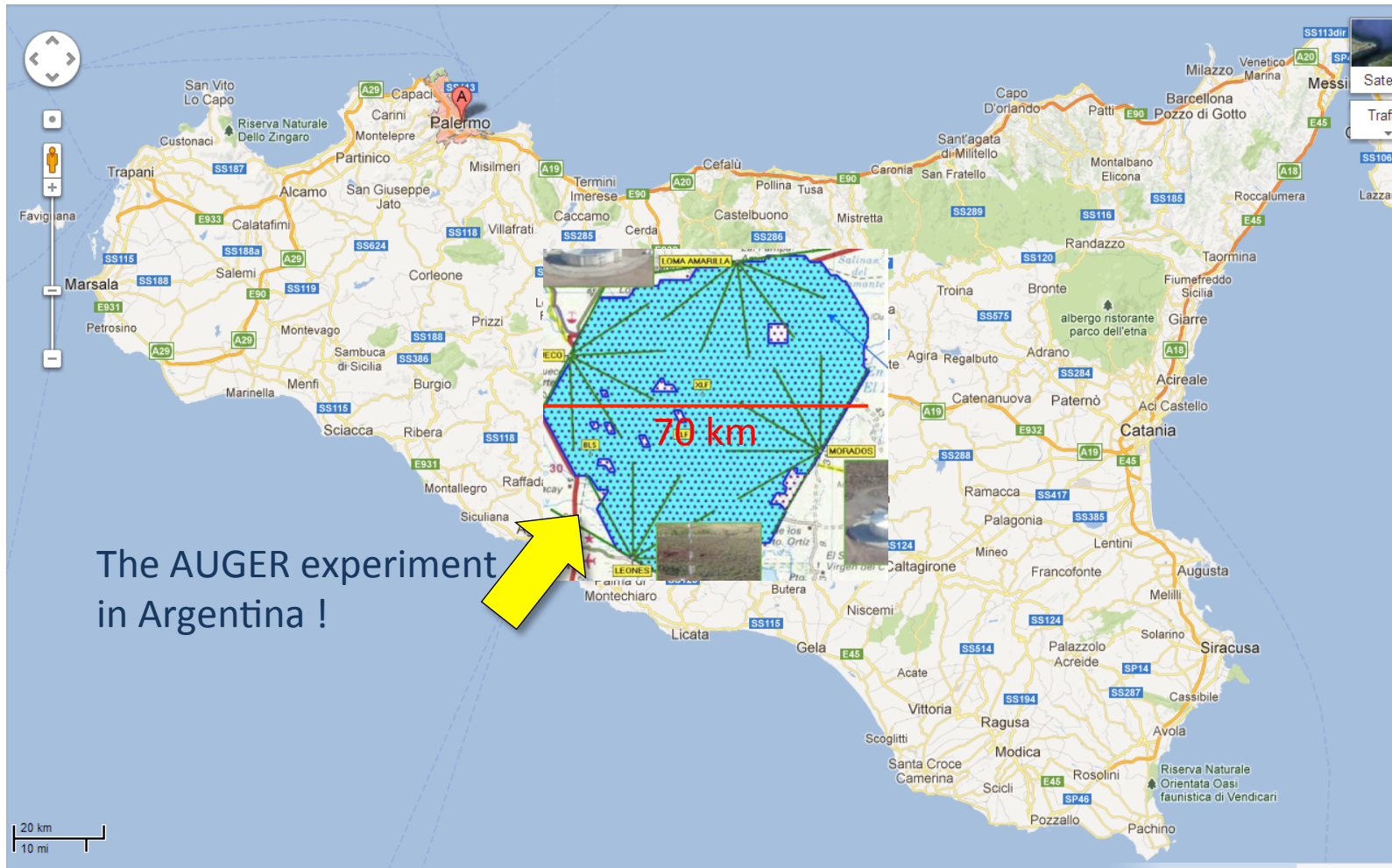
→ Rivelazione gamma e neutrini di fotoproduzione

L'esperimento Auger

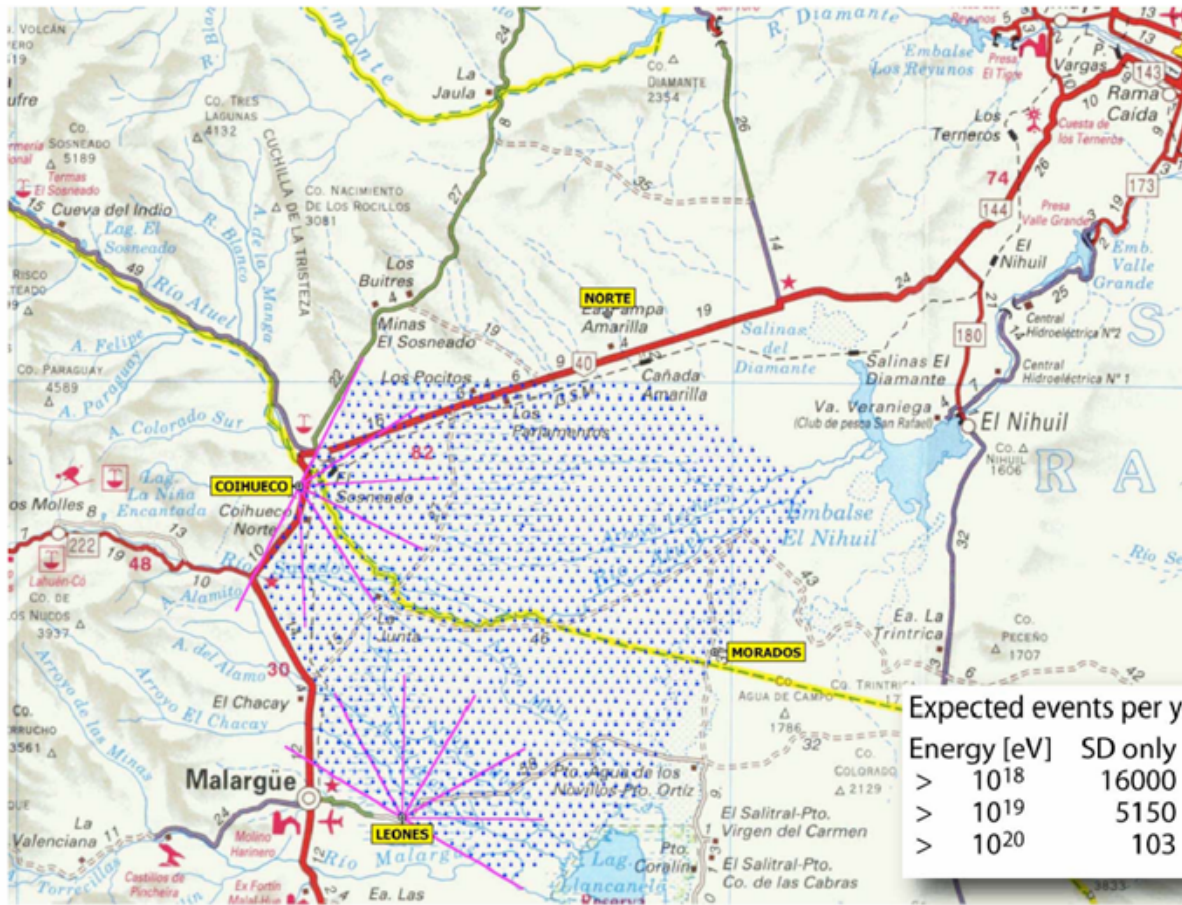
- L'esperimento AUGER è finalizzato a risolvere il problema della bassa statistica di eventi per energie sopra il cutoff GZK, utilizzando ENTRAMBE le tecniche sperimentali di AGASA (EAS) e HiRes (Fluorescenza)
- Due rivelatori simili sono proposti: uno nell'emisfero Australe (Argentina). Quello nel Nord non è stato finanziato
- Per avere statistica sufficiente, i rivelatori sono distribuiti su un'area pari a 3000 km²
- Le differenti tecniche sperimentali permettono una buona risoluzione angolare, sensibilità alla specie del RC che origina la cascata (p o nuclei pesanti), e la possibilità di effettuare calibrazioni energetiche incrociate

Pierre-Auger Observatory



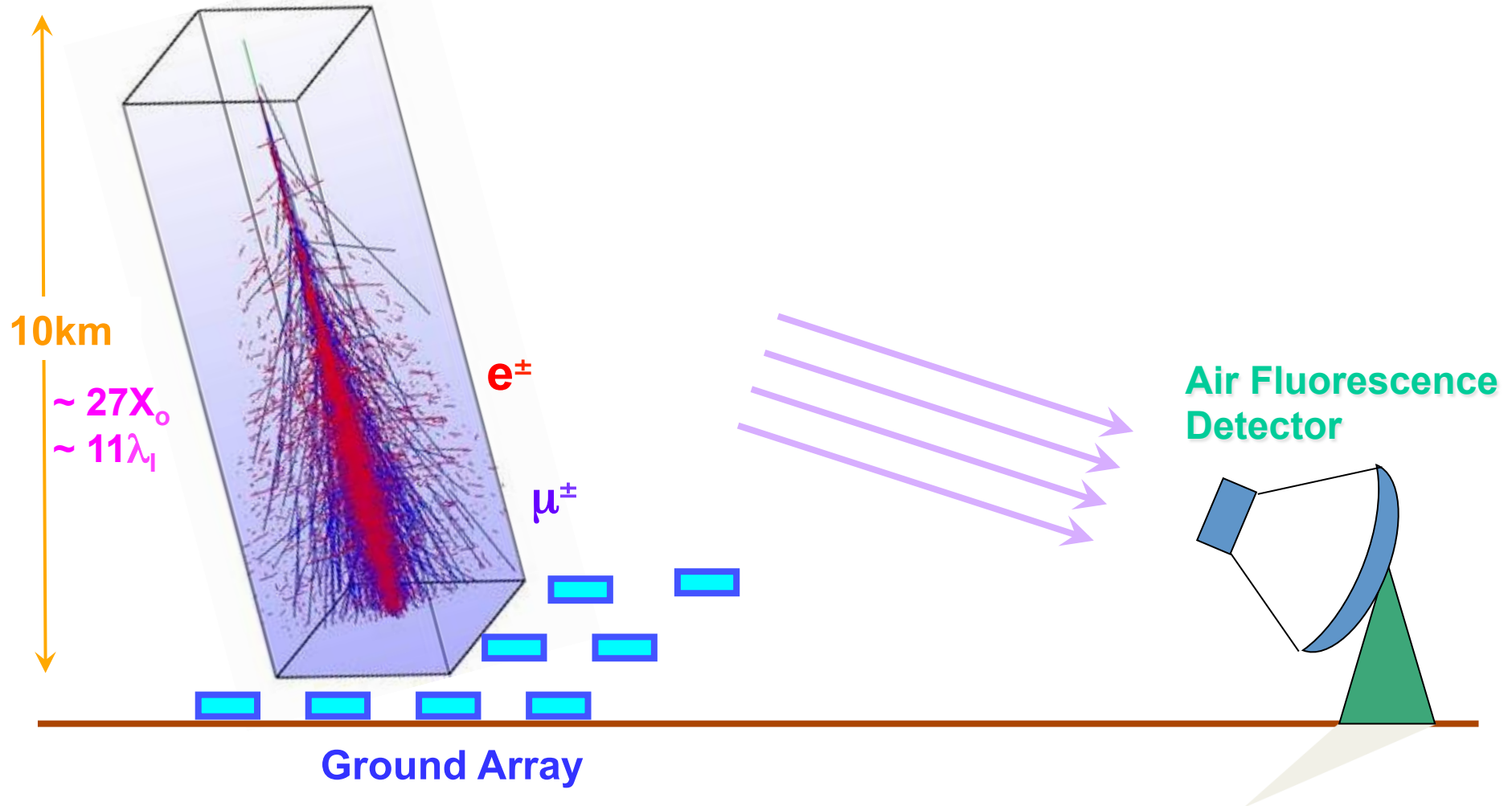


AUGER



Principio della rivelazione ibrida

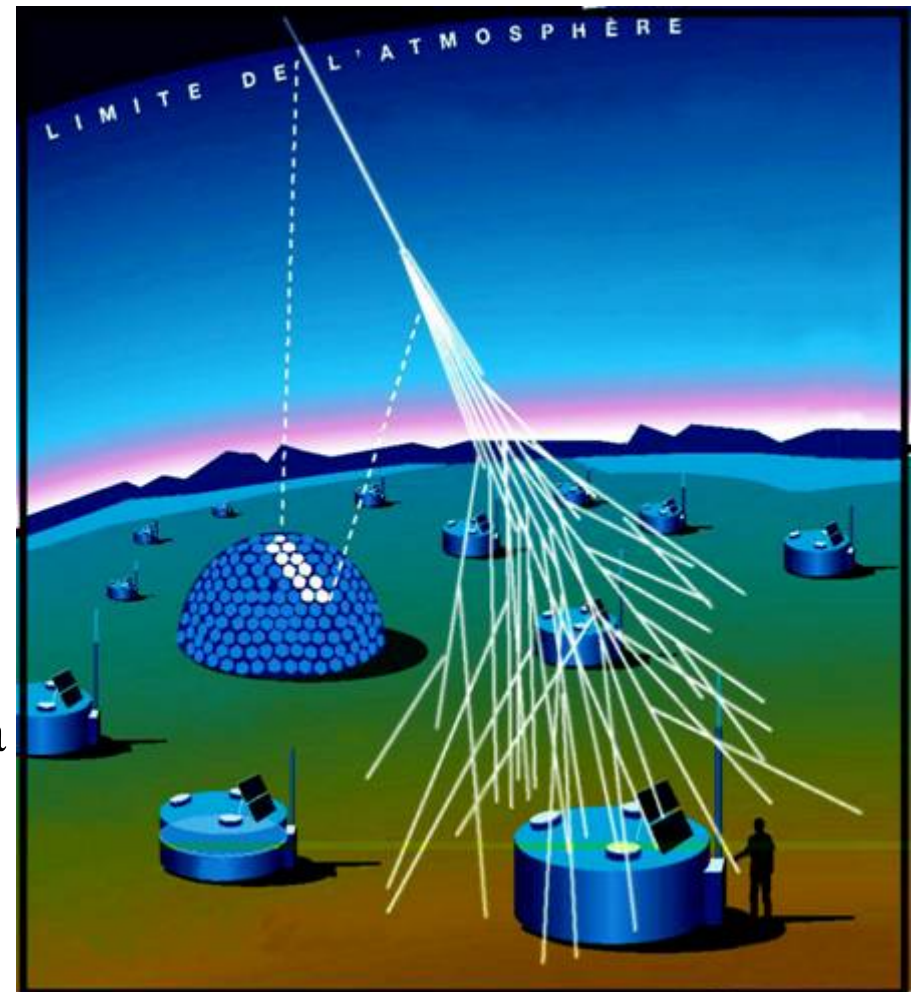
MC Simulation of
 10^{19} eV Proton Shower



AUGER: Un rivelatore ibrido

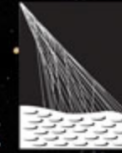
Rivelatore di sciame: 1600 taniche cilindriche (ciascuna di 10 m² ed alte 1.5 m) riempite di acqua, per rivelare gli sciame al suolo tramite la luce Cerenkov emessa dagli elettroni nell'acqua

- Il rivelatore di sciame misura la distribuzione laterale e temporale dello sciame
- Distanza tra taniche: 1.5 km
- Area di forma esagonale, di 60×60 km²
- Rivelatori di fluorescenza: 6 telescopi con ciascuno 4 “occhi” per determinare il profilo longitudinale dello sciame e l'altezza del suo massimo.





PIERRE AUGER OBSERVATORY



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Observatory

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Edu & Outreach

Gallery

Internal

Hybrid Detector



The hybrid nature of the Pierre Auger Observatory provides for two

Time Lapse Video

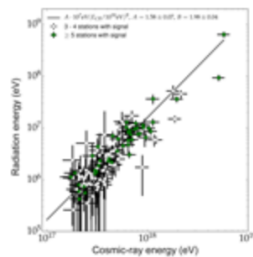


Who Was Pierre Auger?



The Pierre Auger Observatory experiment was named after Pierre

The energy in the radio signal of extensive air showers - a universal estimator for the cosmic-ray energy



One of the biggest challenges in cosmic-ray physics is to accurately pin down the absolute energy of a measured cosmic ray. This is traditionally done with an array of particle detectors deployed on a large grid, which then sample the energetic "air-shower" particles made in atmospheric interactions of the original cosmic particle. This is a tough challenge for particle detectors because the complex interaction physics at the highest energies has to be extrapolated from measurements at collider experiments, which operate at significantly lower energies - even at the Large Hadron Collider (LHC). To accurately set the absolute energy scale, scientists using the

Auger On Site



Tweets by @augerobs



<https://www.auger.org>

Pierre Auger Observatory in Argentina

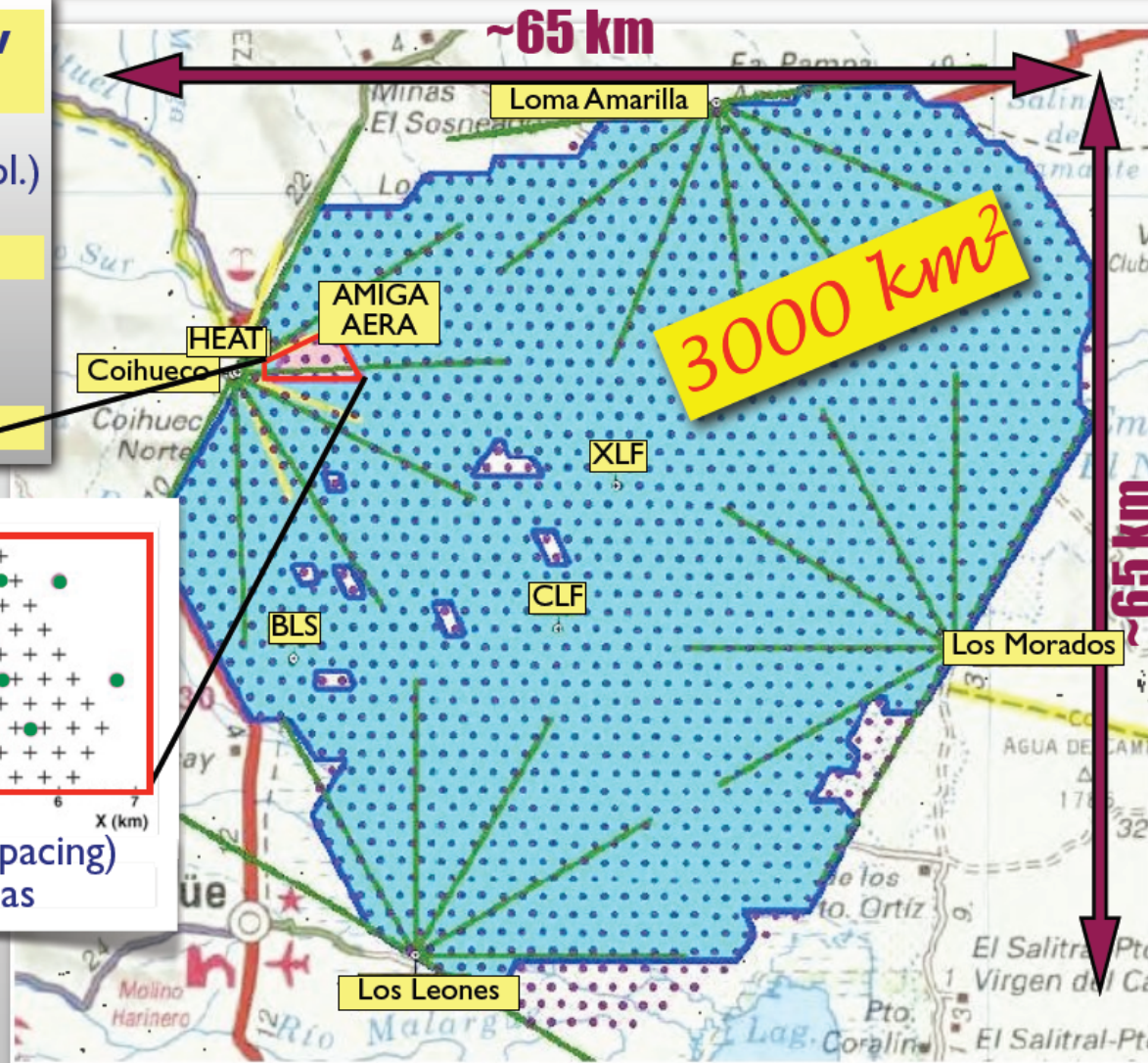
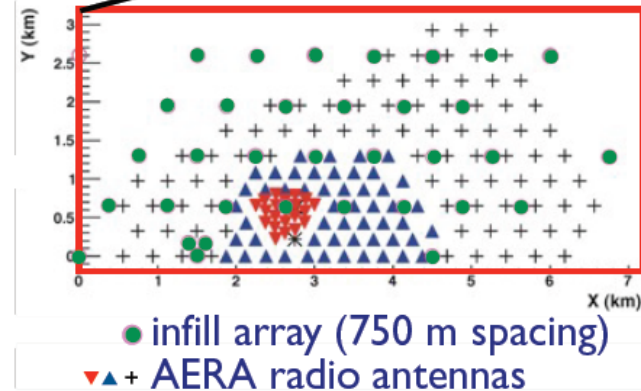
1660 Water-Cherenkov tanks

1.5 km standard grid
0.75 km infill-grid (53/6 l depl.)

27 telescopes

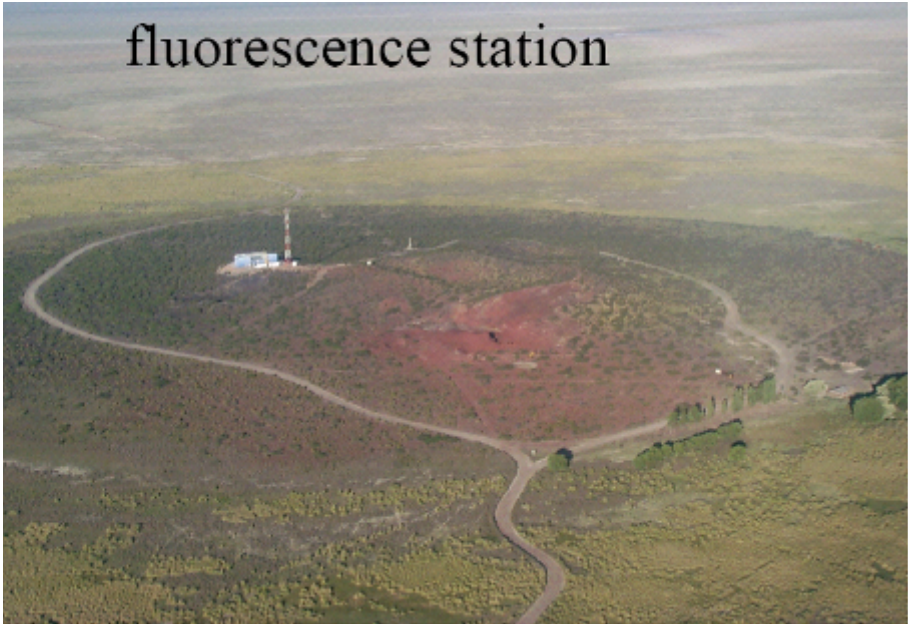
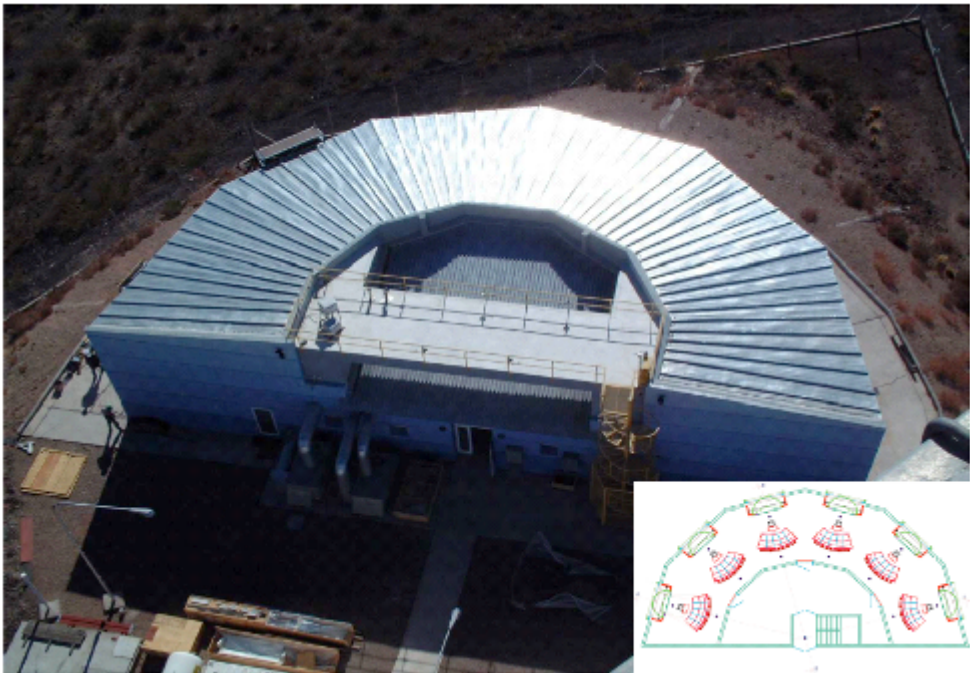
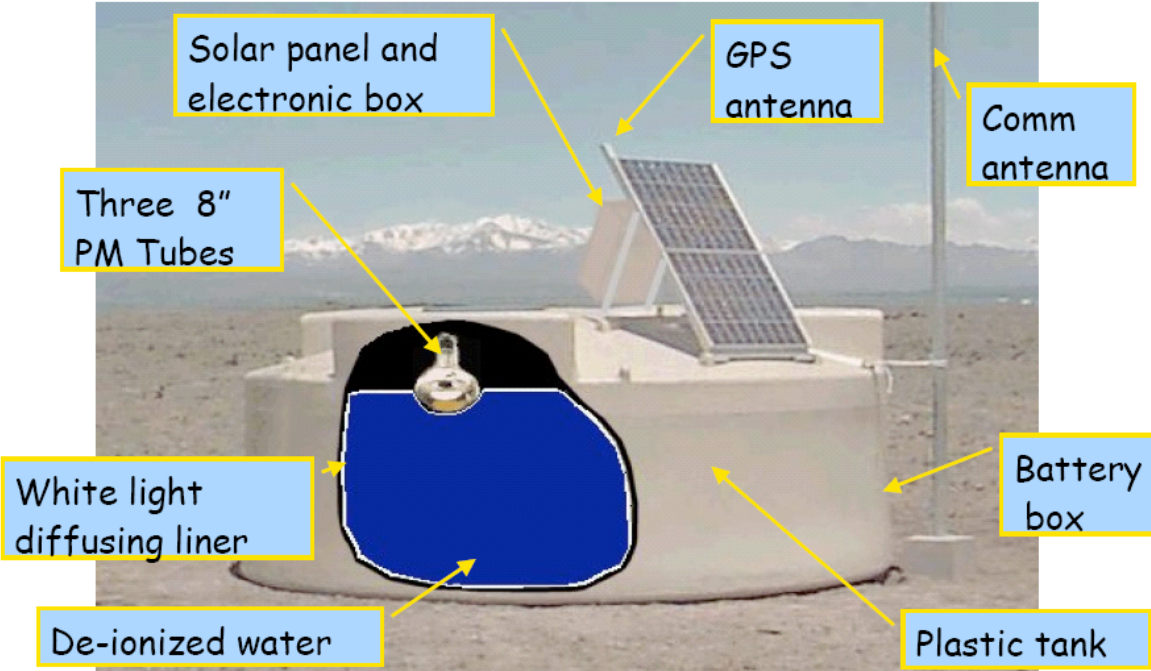
in 4+1 buildings at the periphery

3000 km² area



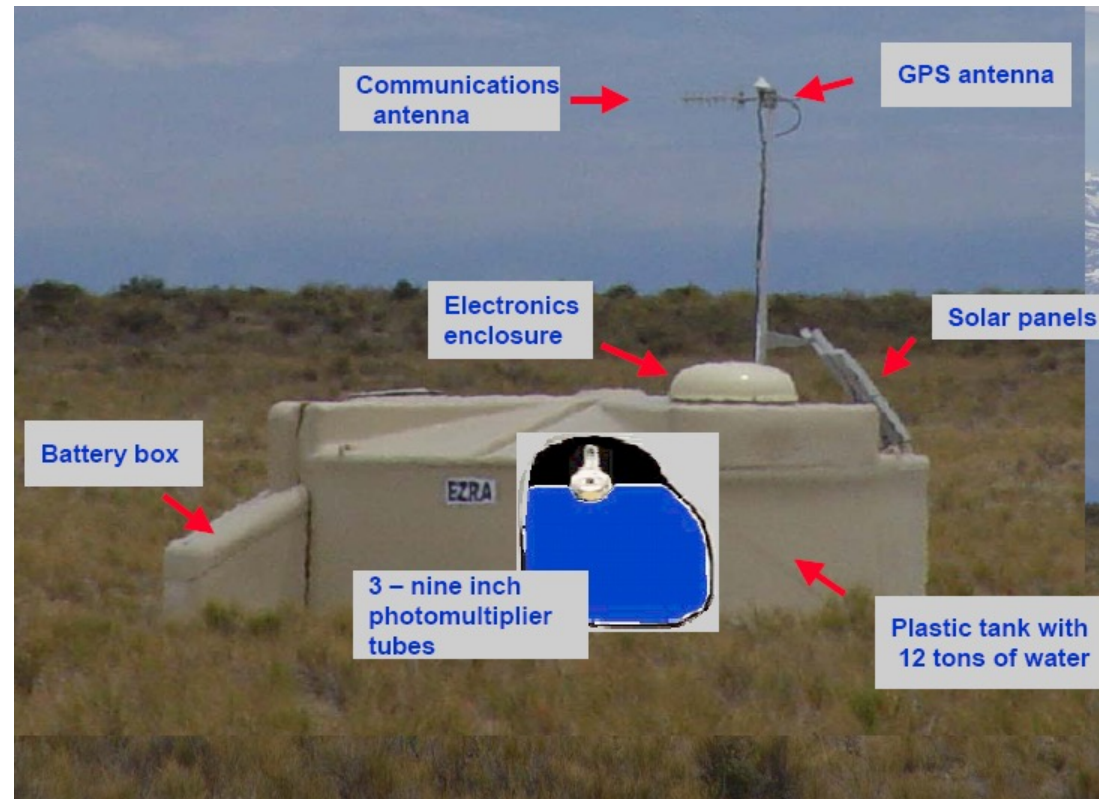
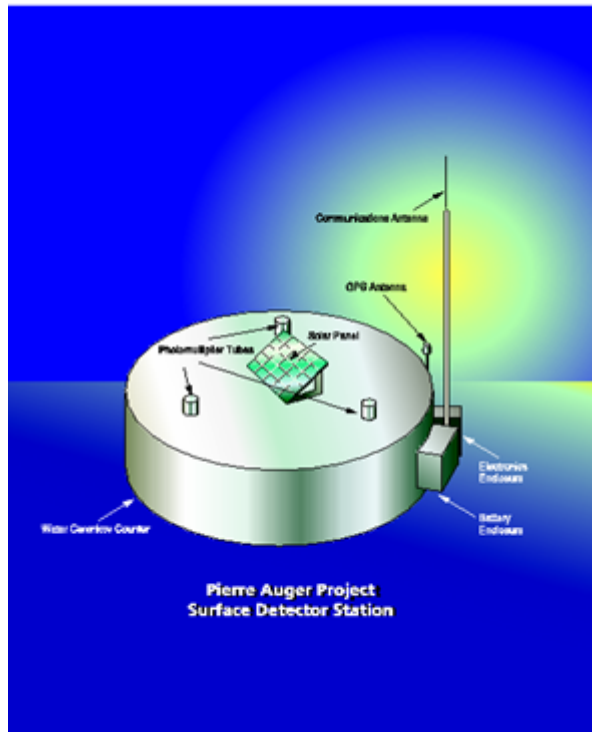


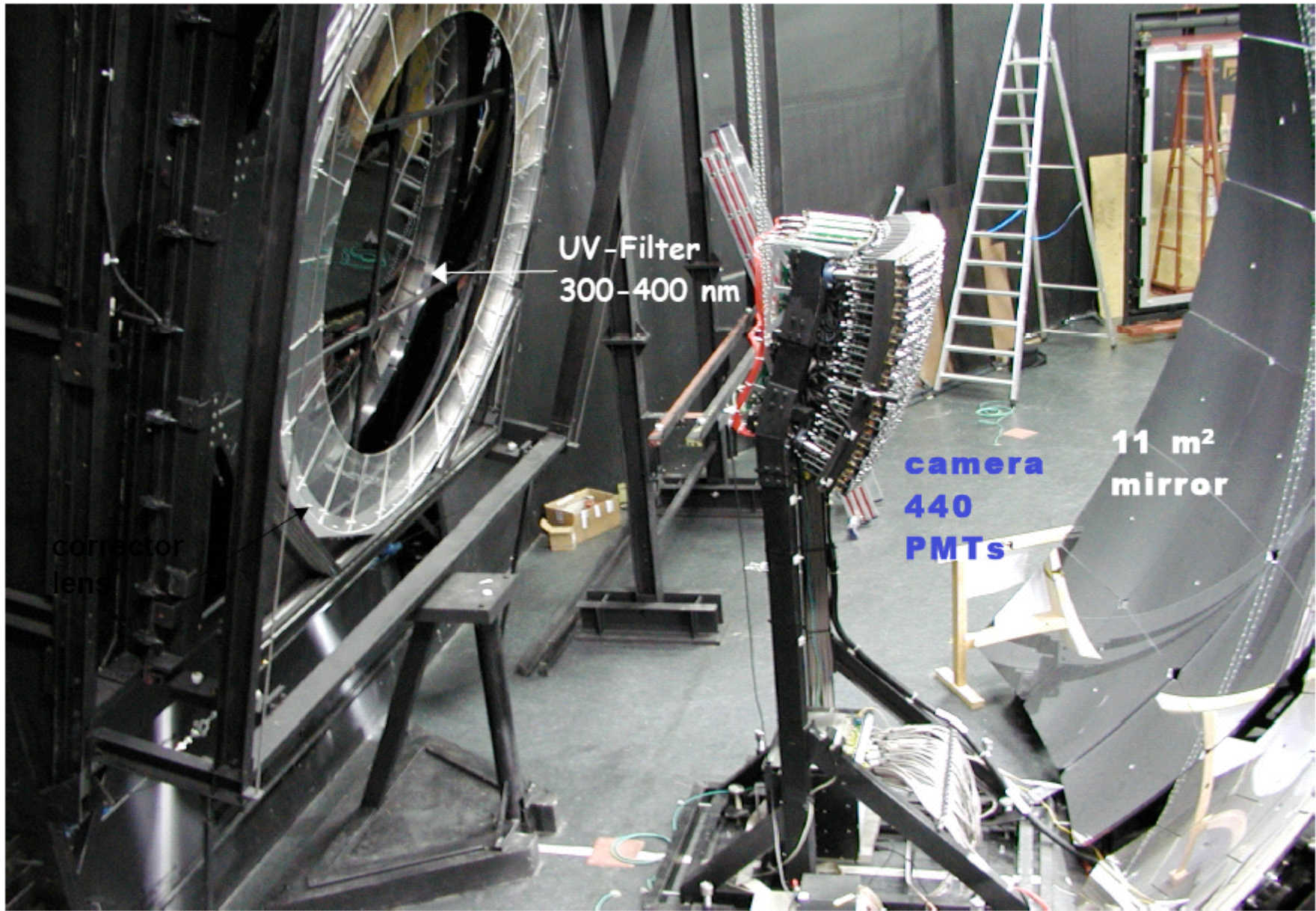
Auger Water Cherenkov Detector



fluorescence station

Uno dei rivelatori Čerenkov di AUGER





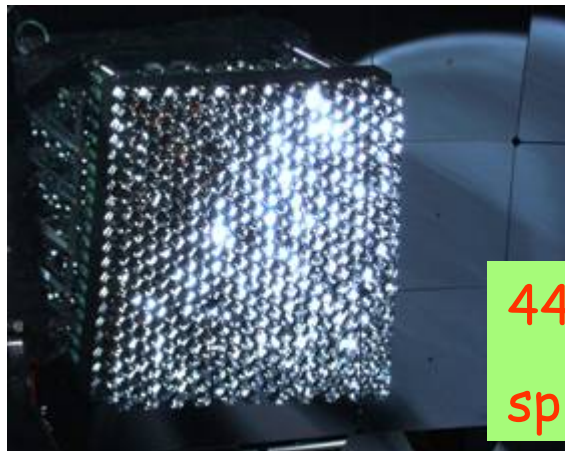
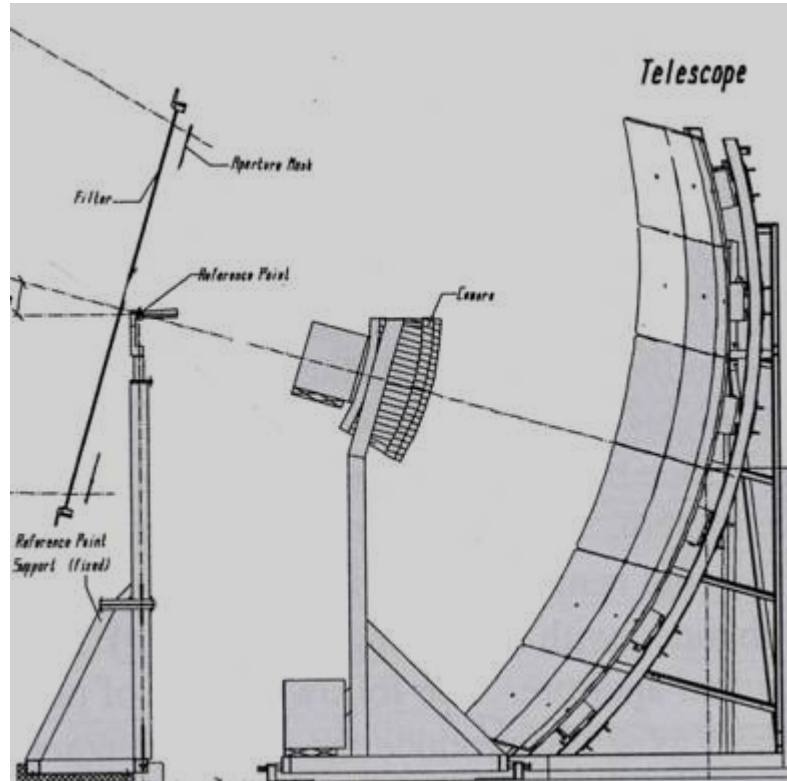
UV-Filter
300-400 nm

corrector
lens

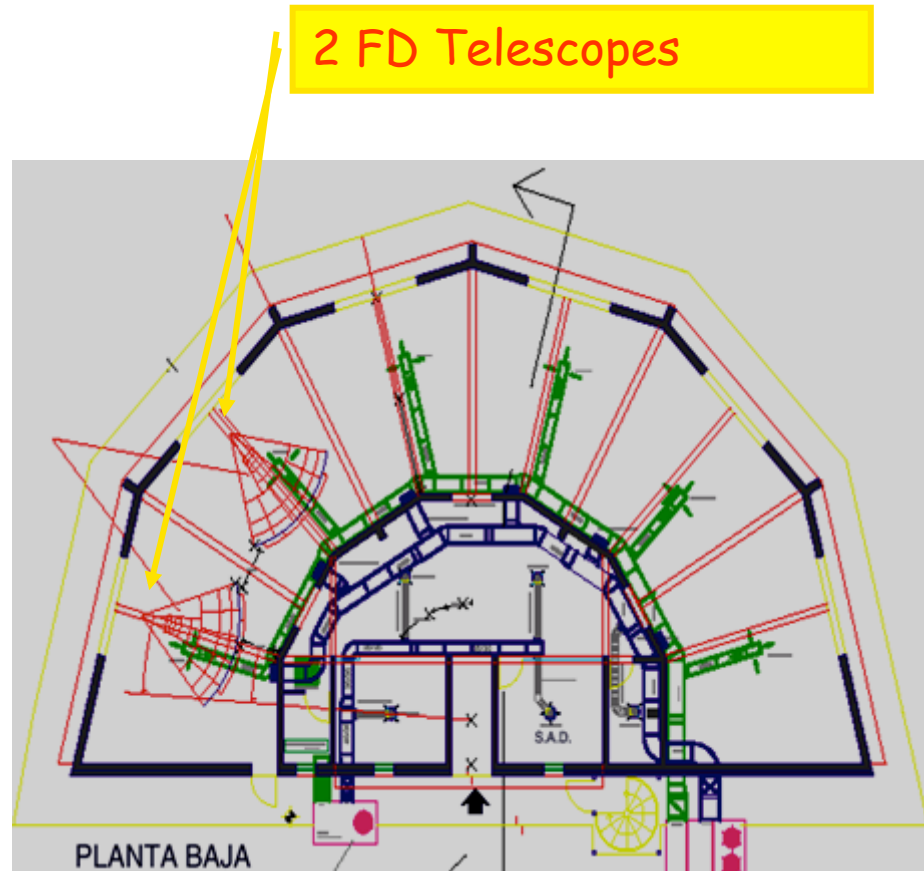
camera
440
PMTs

11 m²
mirror

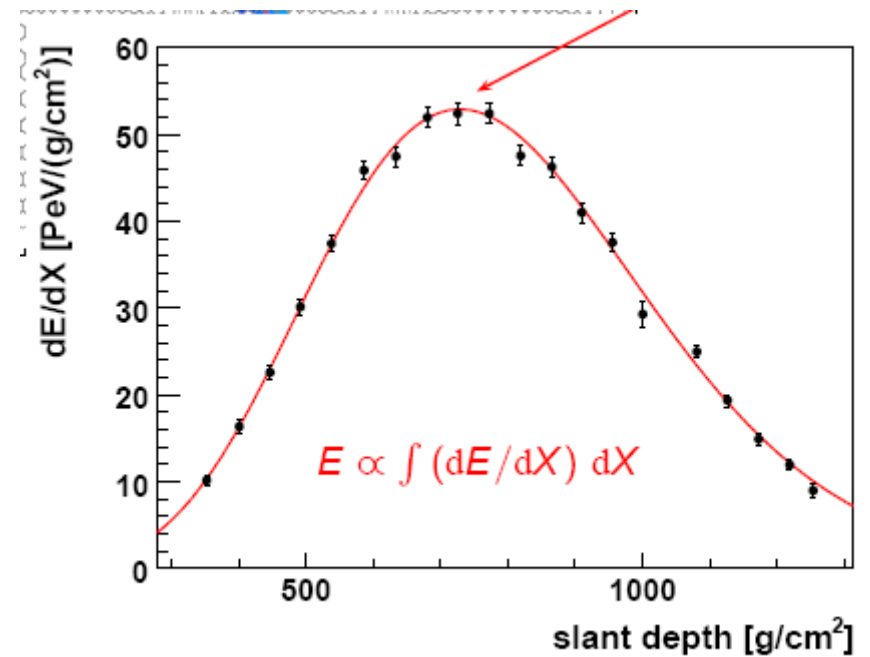
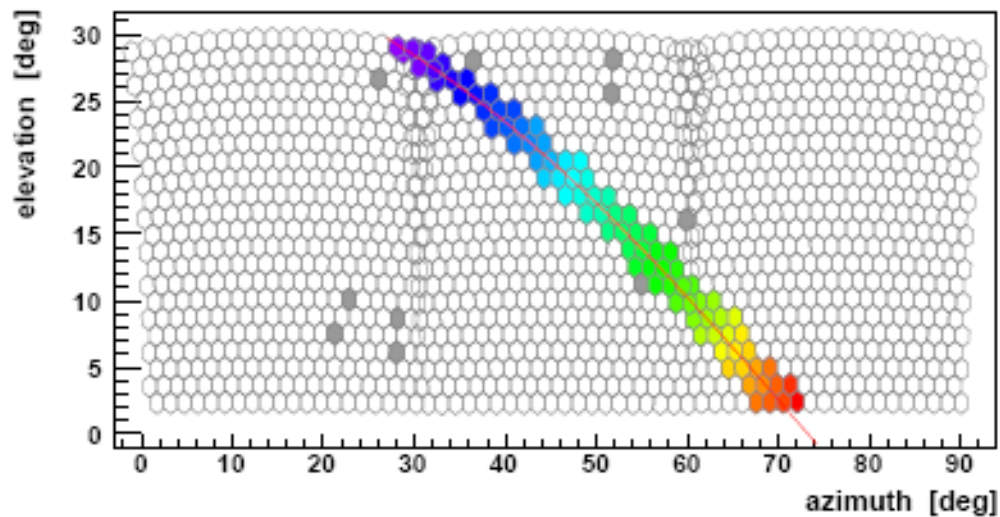
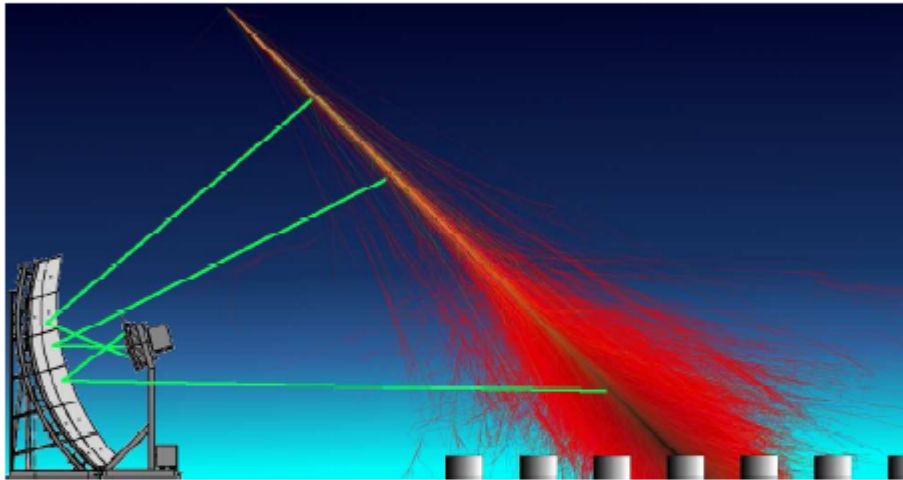
Rivelatori a Fluorescenza

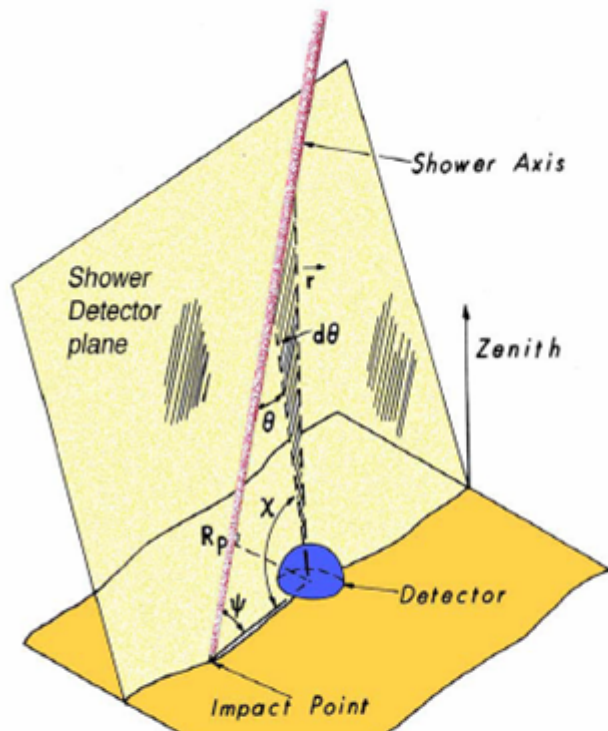


440 photomultipliers upon a spherical cup of 1.741 m ray



Rivelatori di fluorescenza: il profilo longitudinale dello sciame

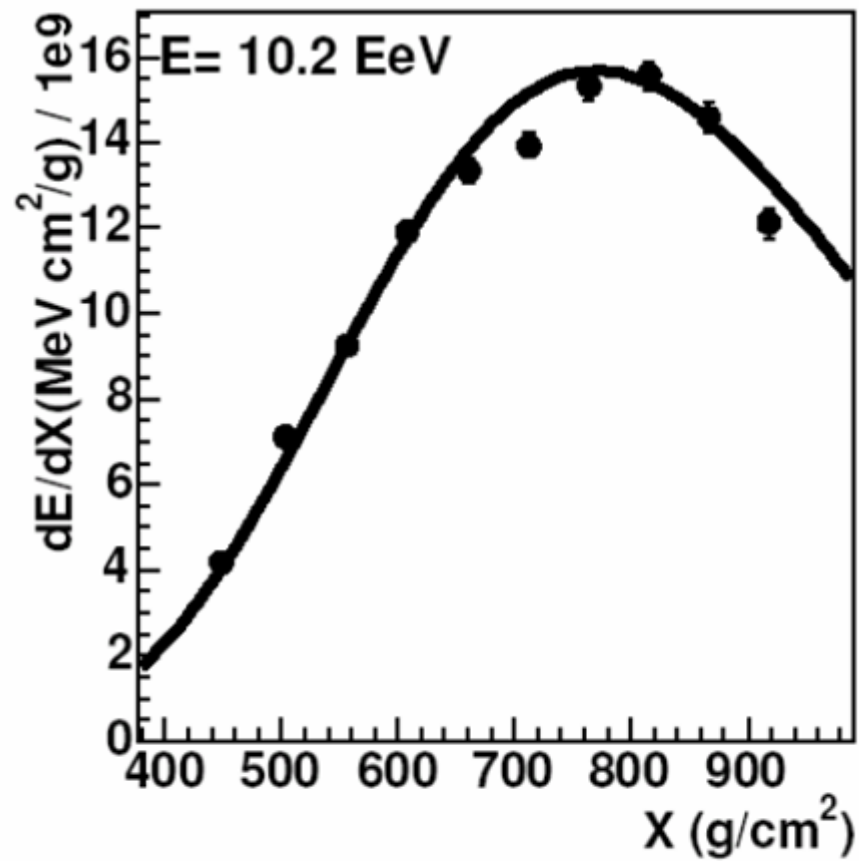
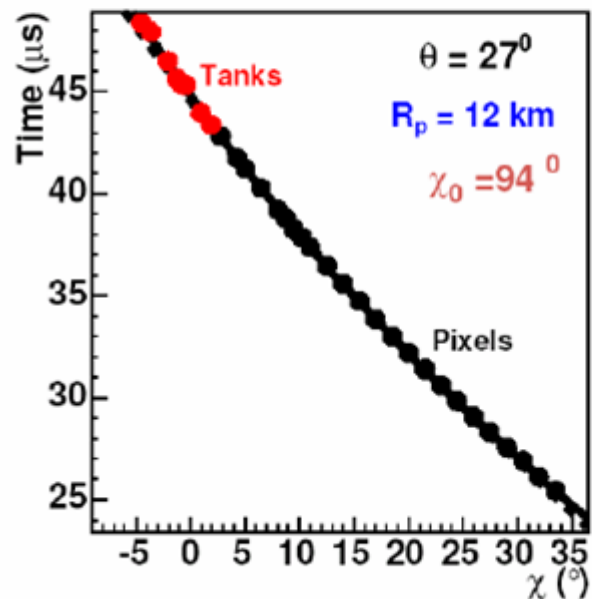




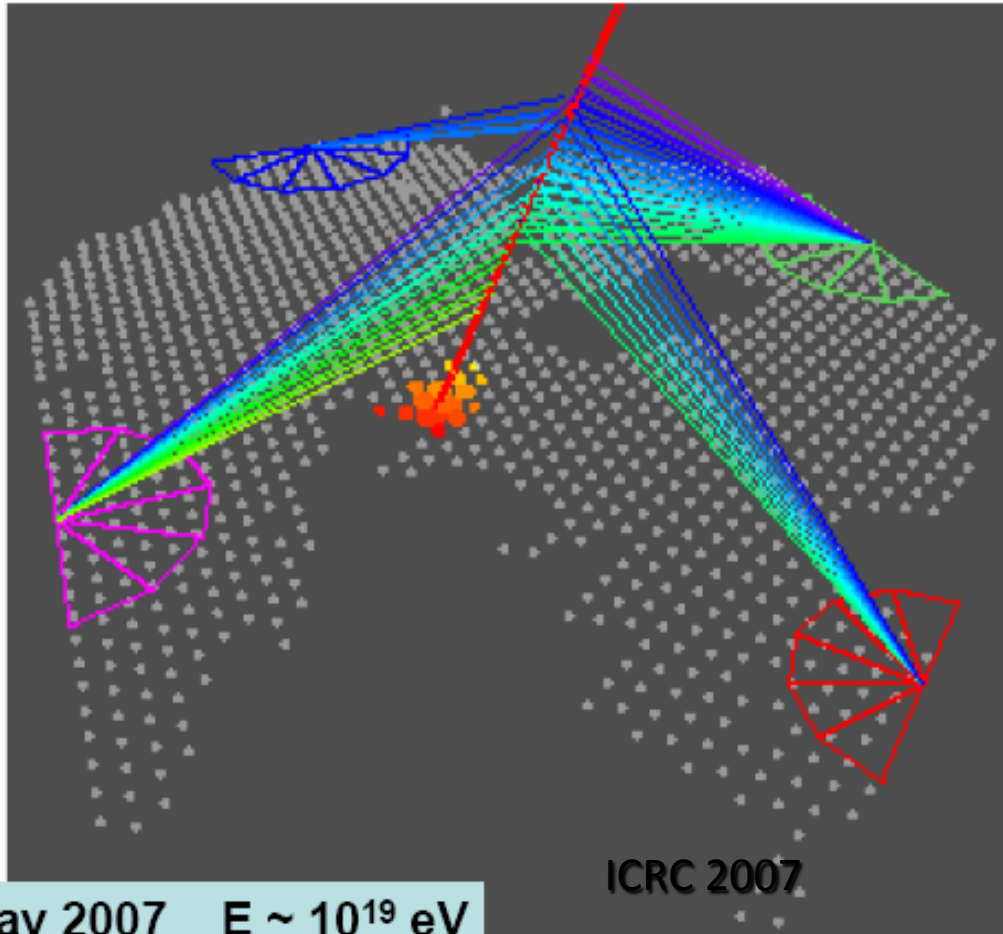
Hybrid Event (FD view)

A hybrid event – 1021302

Zenith angle $\sim 30^\circ$, Energy ~ 10 EeV



from Fly's Eye 1985

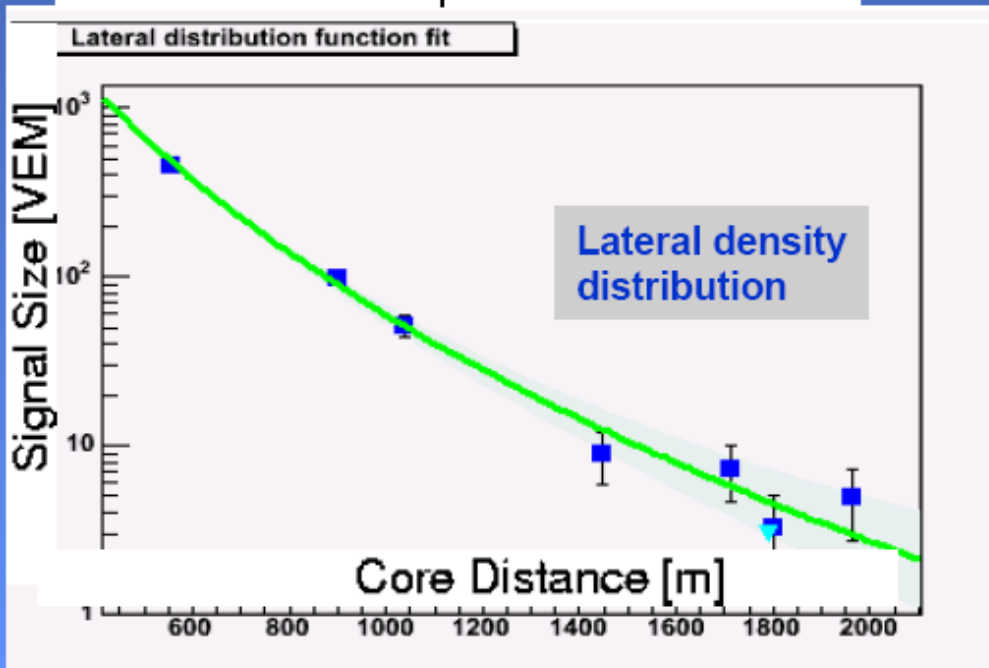
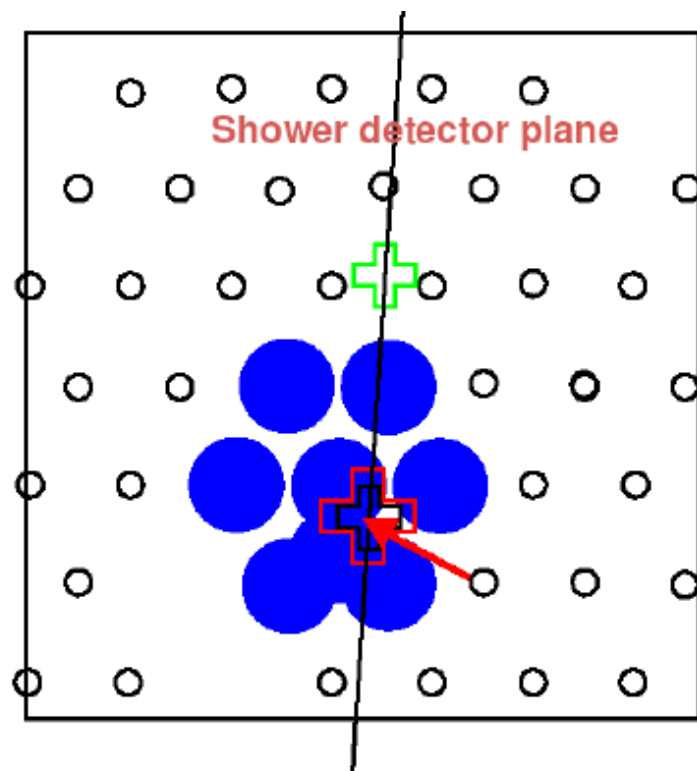
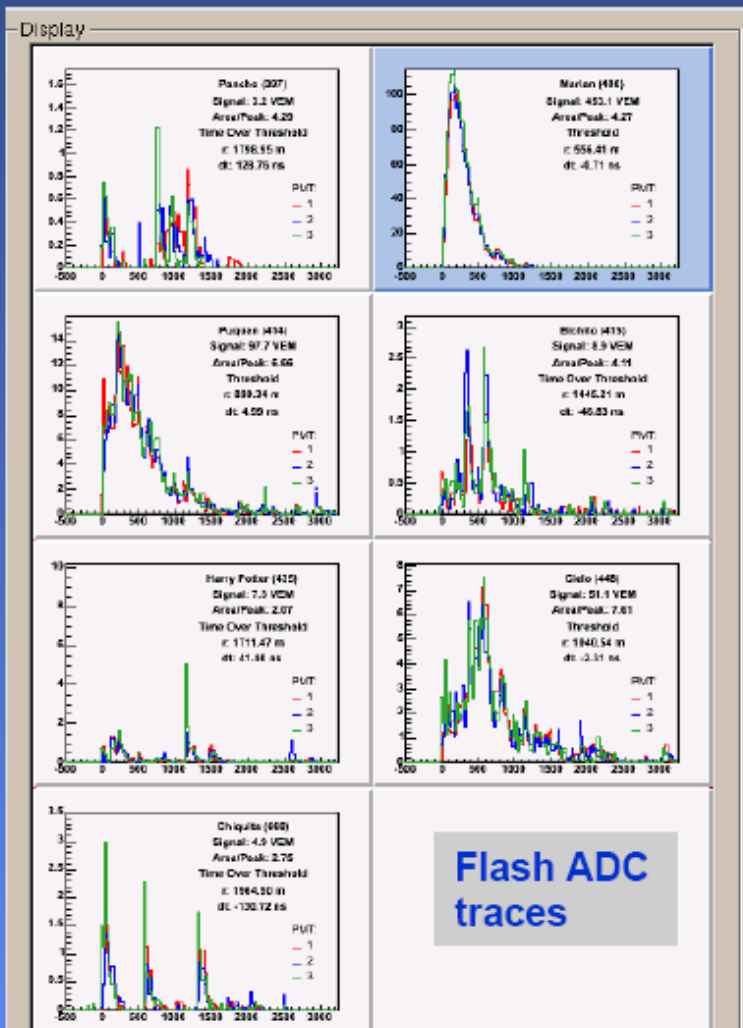


7

<http://www.auger.org/>

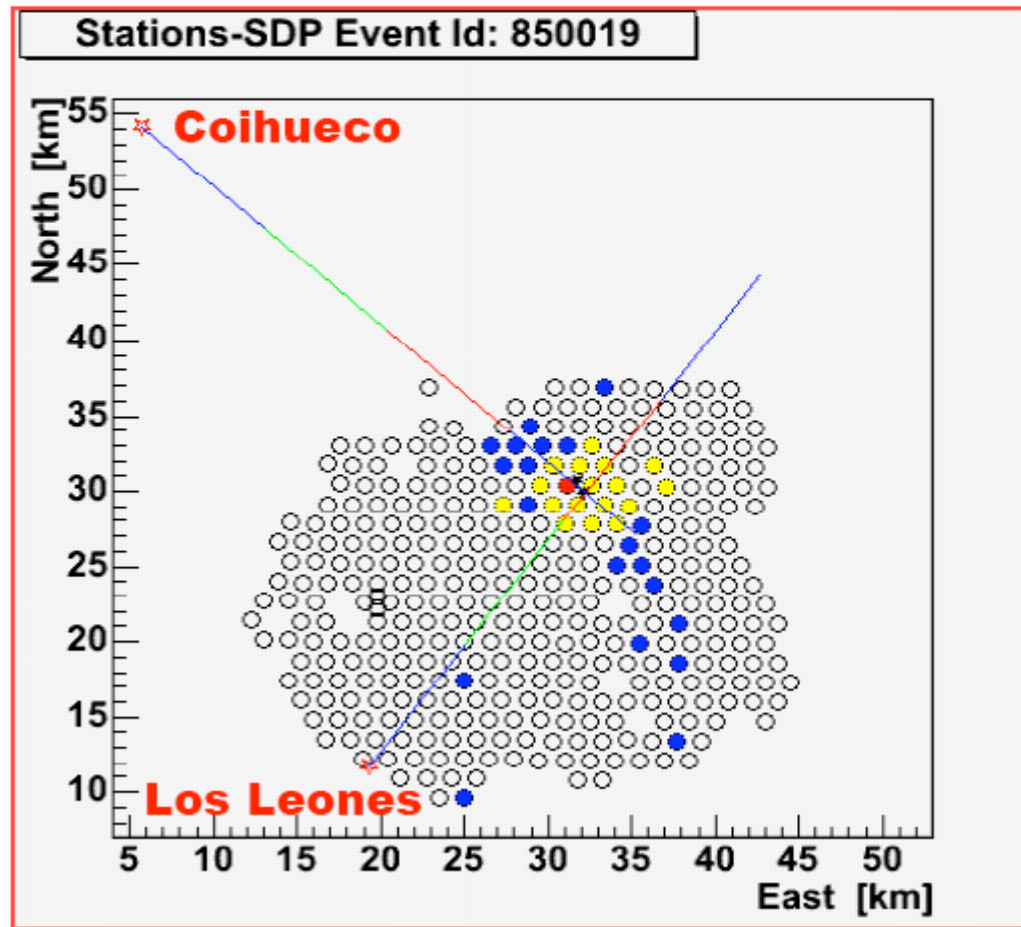
Hybrid Event (SD view)

A hybrid event – 1021302
 Zenith angle ~ 30°, Energy ~ 10 EeV

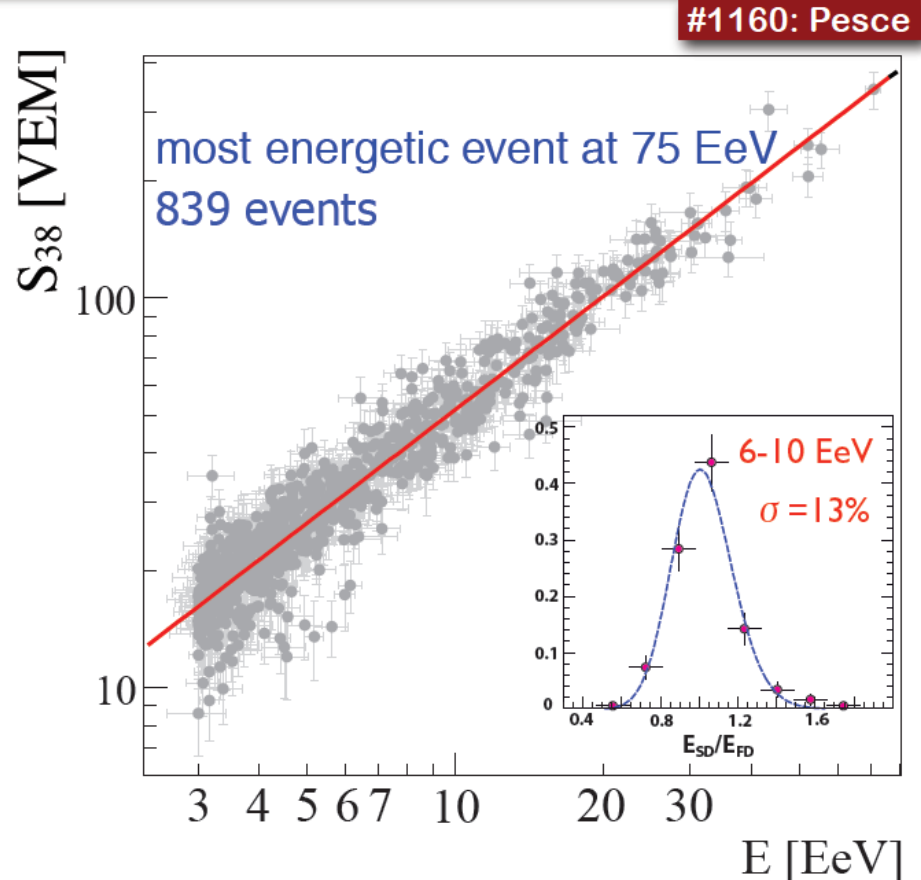
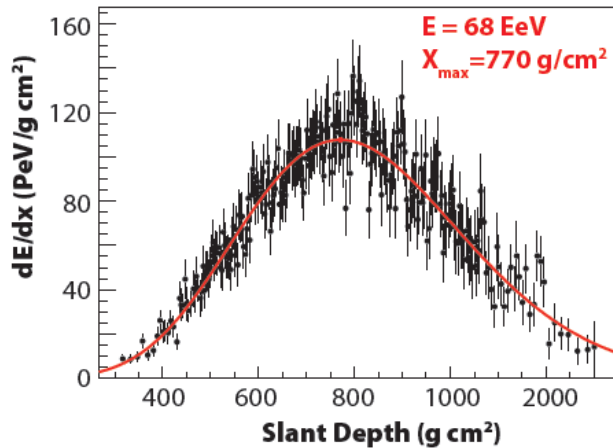
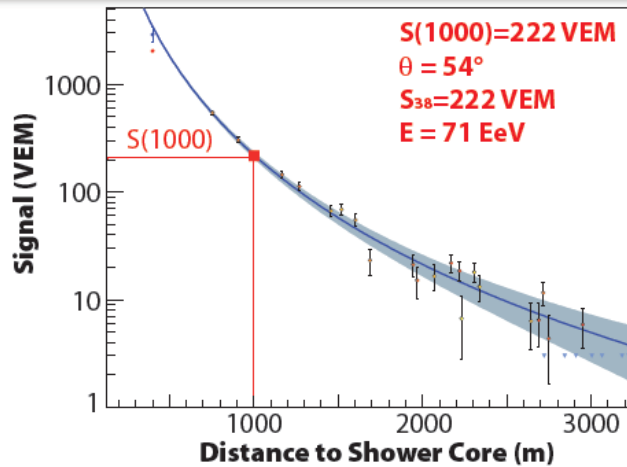


A stereo-hybrid event

- June 26 2004
- An example of an event seen by Los Leones and Coihueco FD eyes, and the SD
- Energy is at least 50 EeV.
- Zenith angle ~ 70 deg.



- L'energia del RC viene misurata con entrambe le tecniche sperimentali
- Vi è correlazione tra le due misure

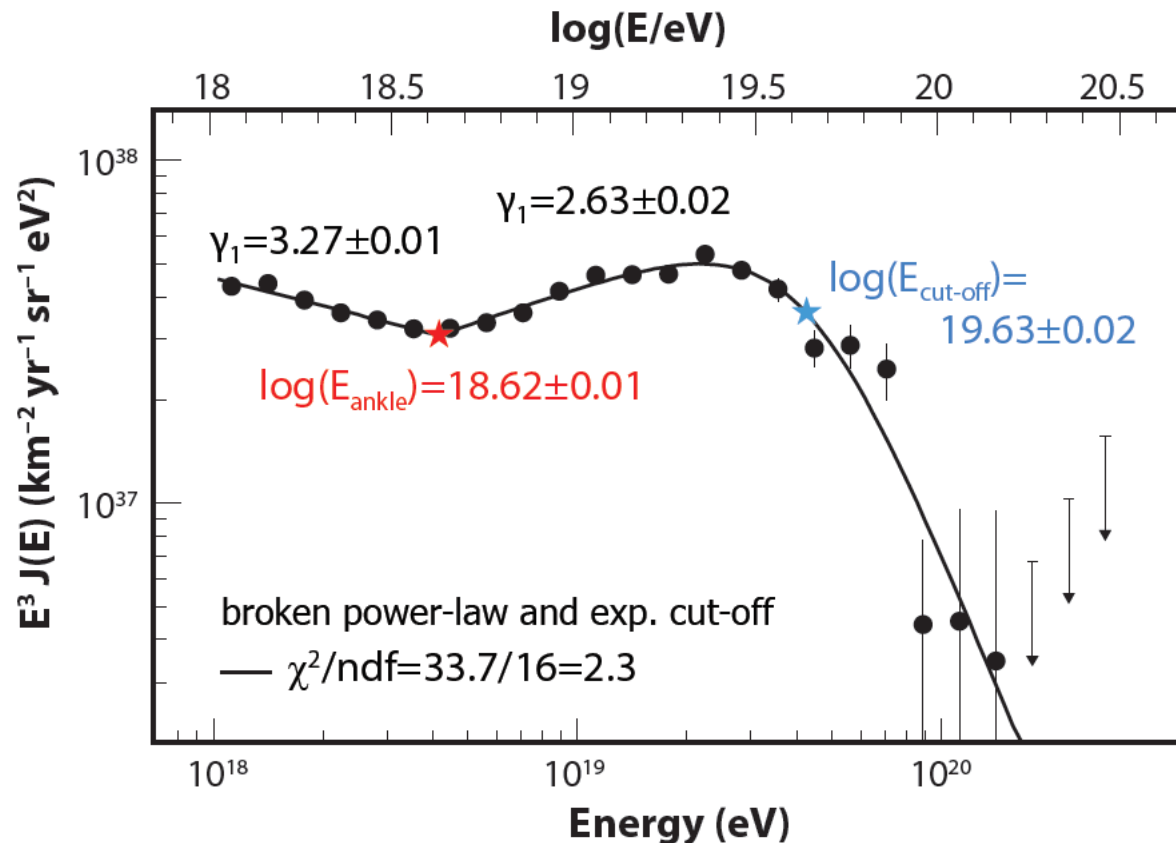


Systematic uncertainty 7% (15%) at 10 EeV (100 EeV)
 Total uncertainty of E-scale: 22% (dominated by Fl.-yield. 14%)

ICRC
 2011

AUGER Energy spectrum

SD+Hybrid Combined Spectrum

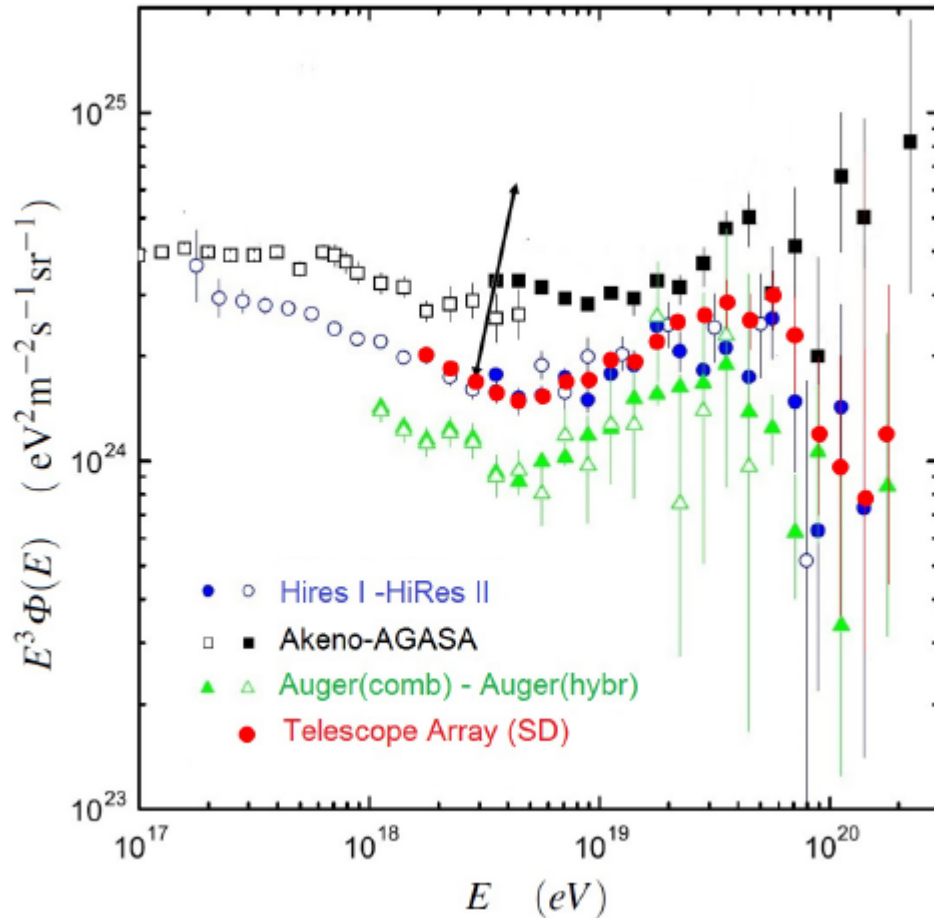


#893:
Salamida

#724:
Dembinsky

Exposure = 20905 km² sr yr (60% increase over PLB 685 (2010) 239)
Inclined showers add another 5300 km² sr yr (→ #724)

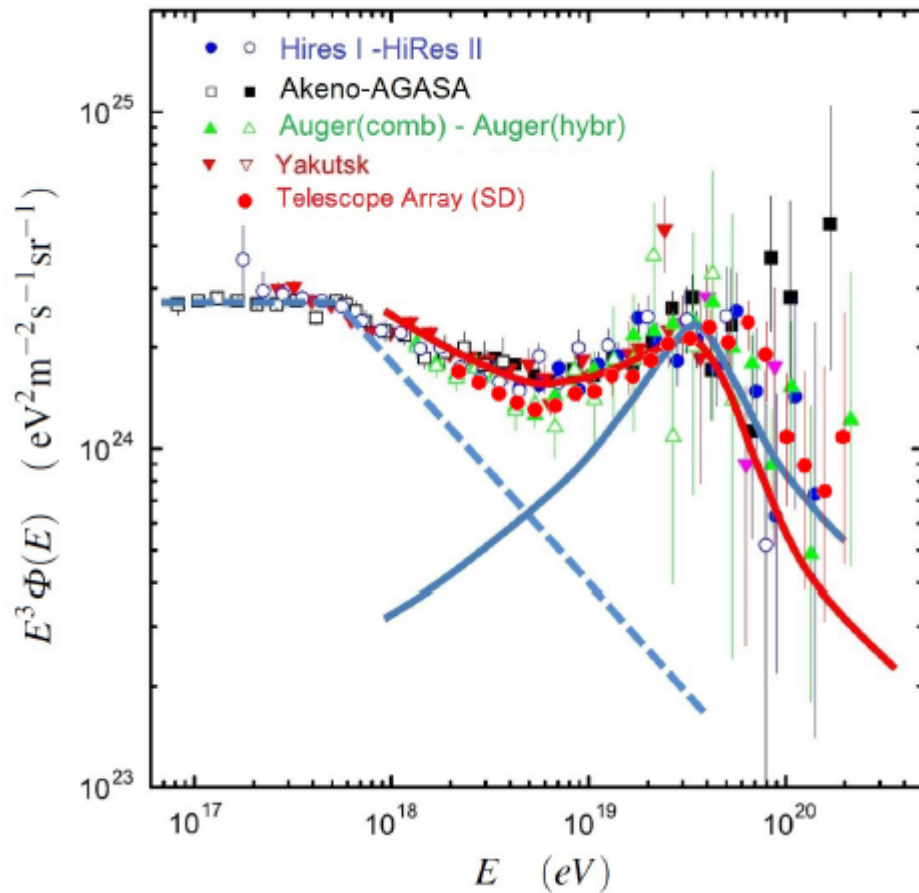
Comparison of Energy Spectra between the largest experiments



Flux of UHECRs multiplied by E^3 as measured by Akeno-AGASA, HiRes, Telescope Array and PAO. The values as published by the Collaborations using the nominal calibration of the detectors are reported.

The end of the arrow on the first point of AGASA indicates the position of the point with a 25% shift in the energy scale

Possible source models



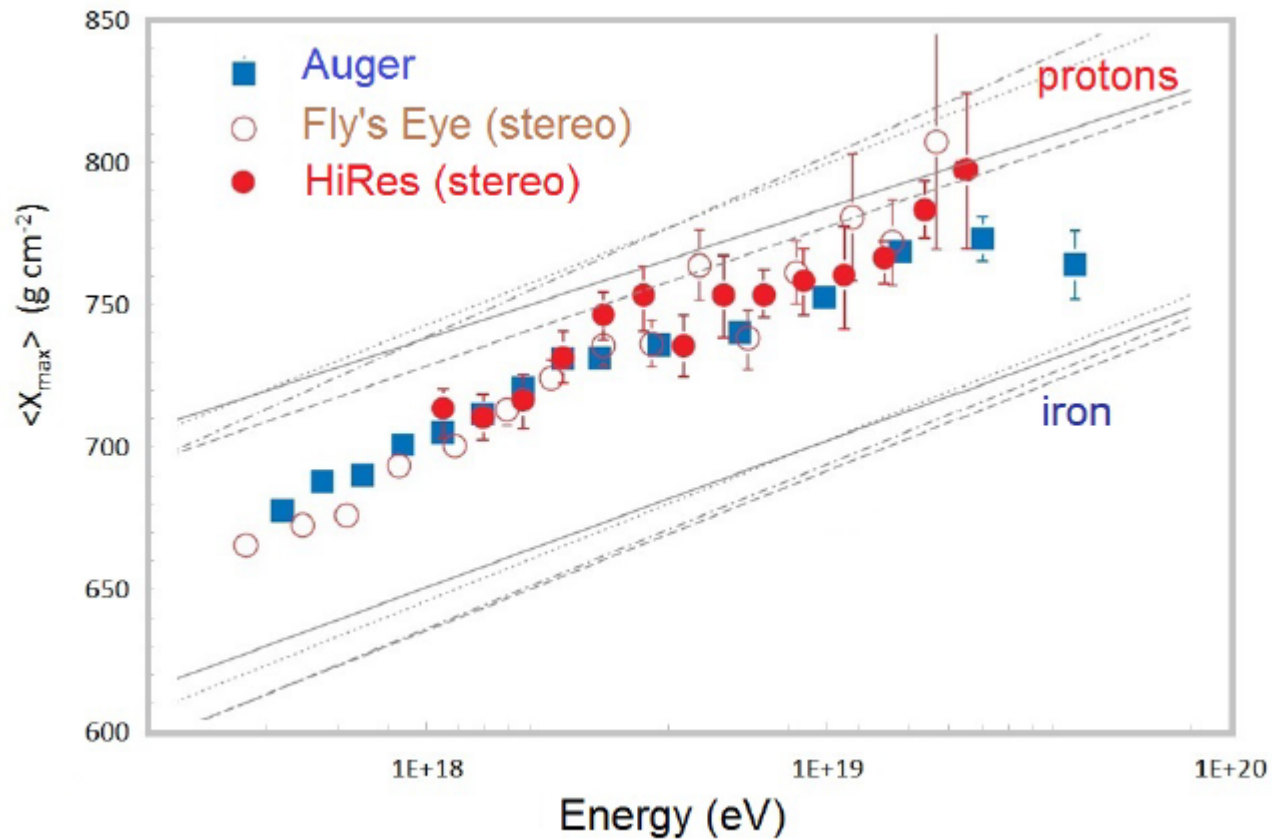
- The same data, after rescaling the energy of the experiments to obtain a common position of the “dip” at 5×10^{18} eV.
- The nominal energy scales multiplied by 1.2 (Auger), 1.0 (HiRes), 0.75 (AGASA), 0.95 (TA) and 0.625 (Yakutsk)

Predictions

- Red line: dip model due to extragalactic protons.
- Blue line: superposition model. A galactic (dashed line) + extragalactic component (full line)

UHE CR chemical composition

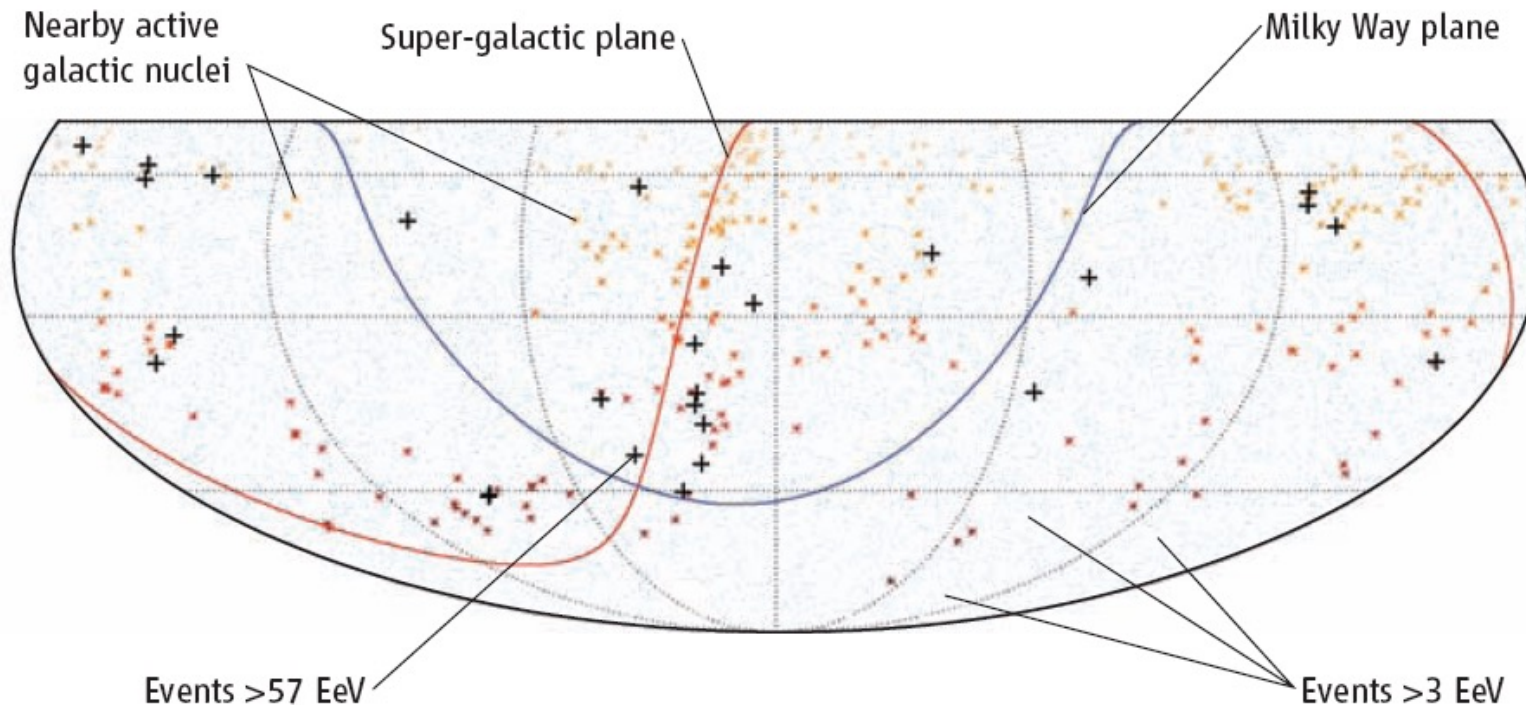
The two largest experiments (AUGER, TA) show discrepancies about the composition at $>10^{19}$ eV



Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects

www.sciencemag.org on November 9, 2007

The Pierre Auger Collaboration*

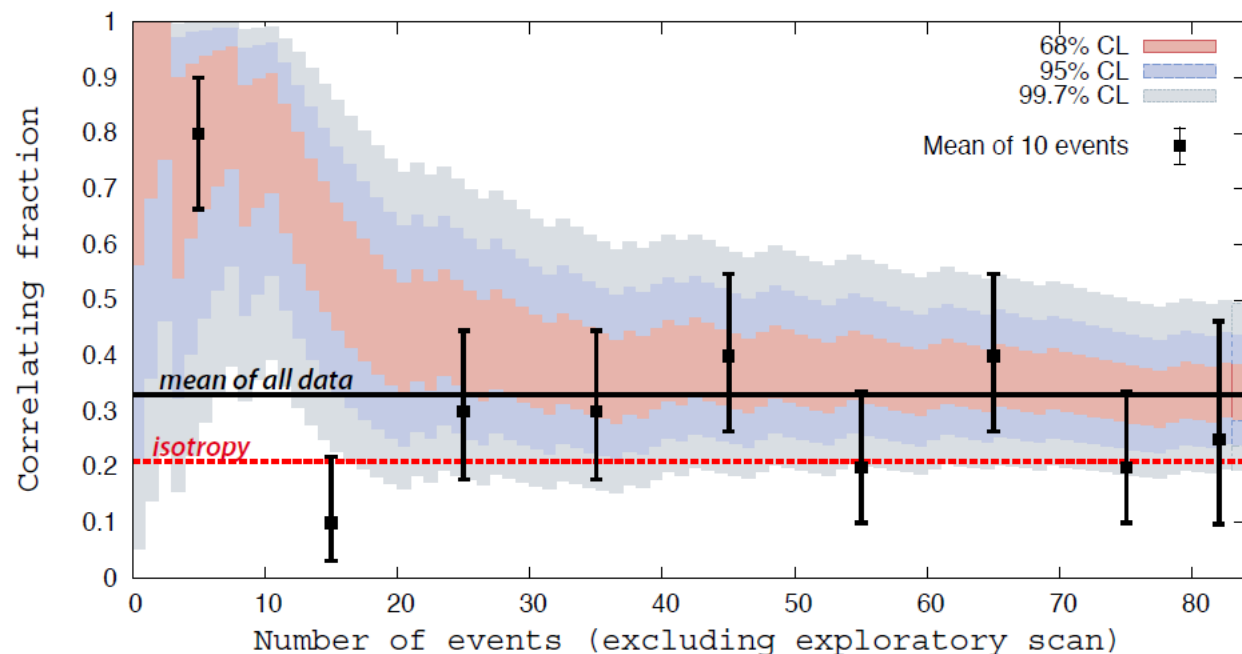


Sky map (2) showing cosmic rays detected by the Pierre Auger Observatory. Low-energy cosmic rays appear to originate from evenly distributed sources (blue dots), but the origins of the highest-energy events (crosses) correlate with the distribution of local matter as represented by nearby active galactic nuclei (red stars). Thus, active galactic nuclei are a likely source of these rare high-energy cosmic rays.

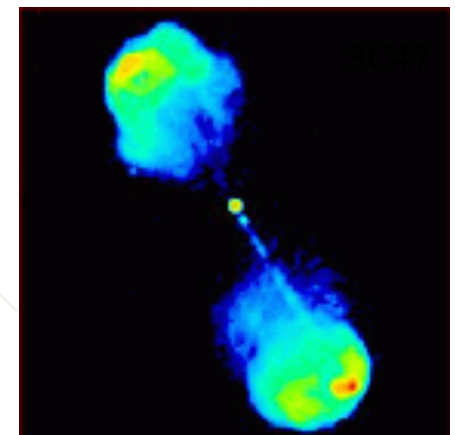
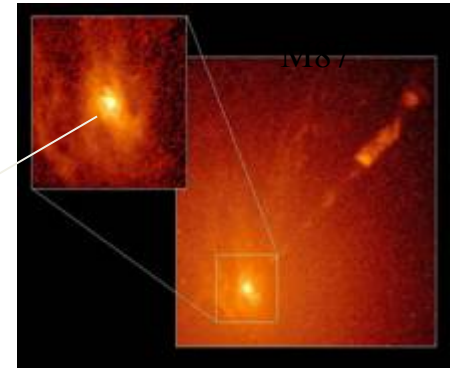
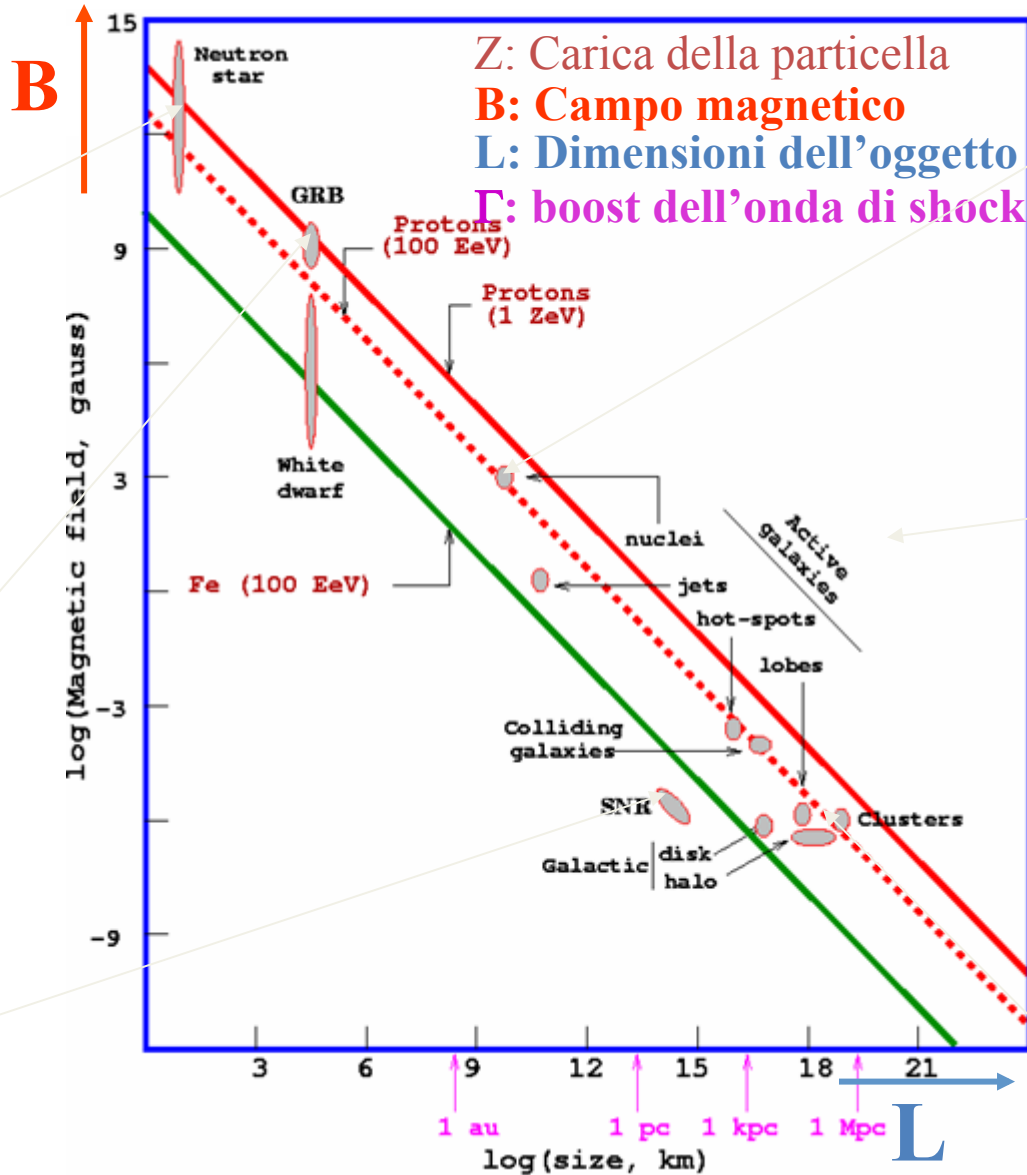
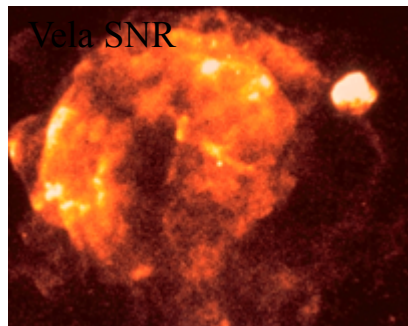
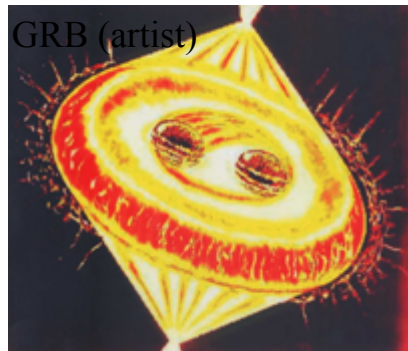
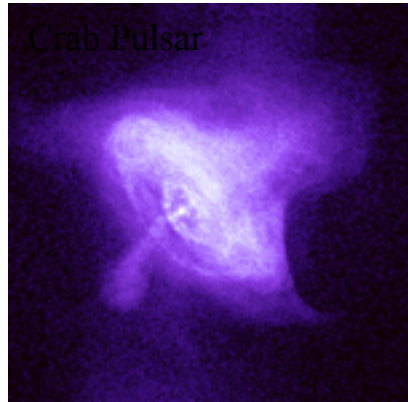
BREAKING NEWS 2009: AUGER trova una correlazione molto meno accentuata tra provenienza dei UHERC AGN

- **2007.** I primi dati di Auger sono in accordo con il cut-off GZK: la diminuzione del flusso di RC sopra 6×10^{19} eV è dovuta all'interazione dei p con la radiazione cosmica di fondo
- La distribuzione di arrivo dei RC più energetici sembra correlata con la distribuzione degli AGN sino a 100 Mpc.
- **2009-2011.** All'aumentare della statistica, la significatività dell'osservazione tende a diminuire

NB: Studiate bene la statistica per l'interpretazione dei dati sperimentali

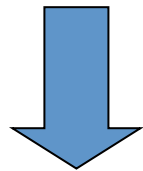


Possibili macchine acceleratrici

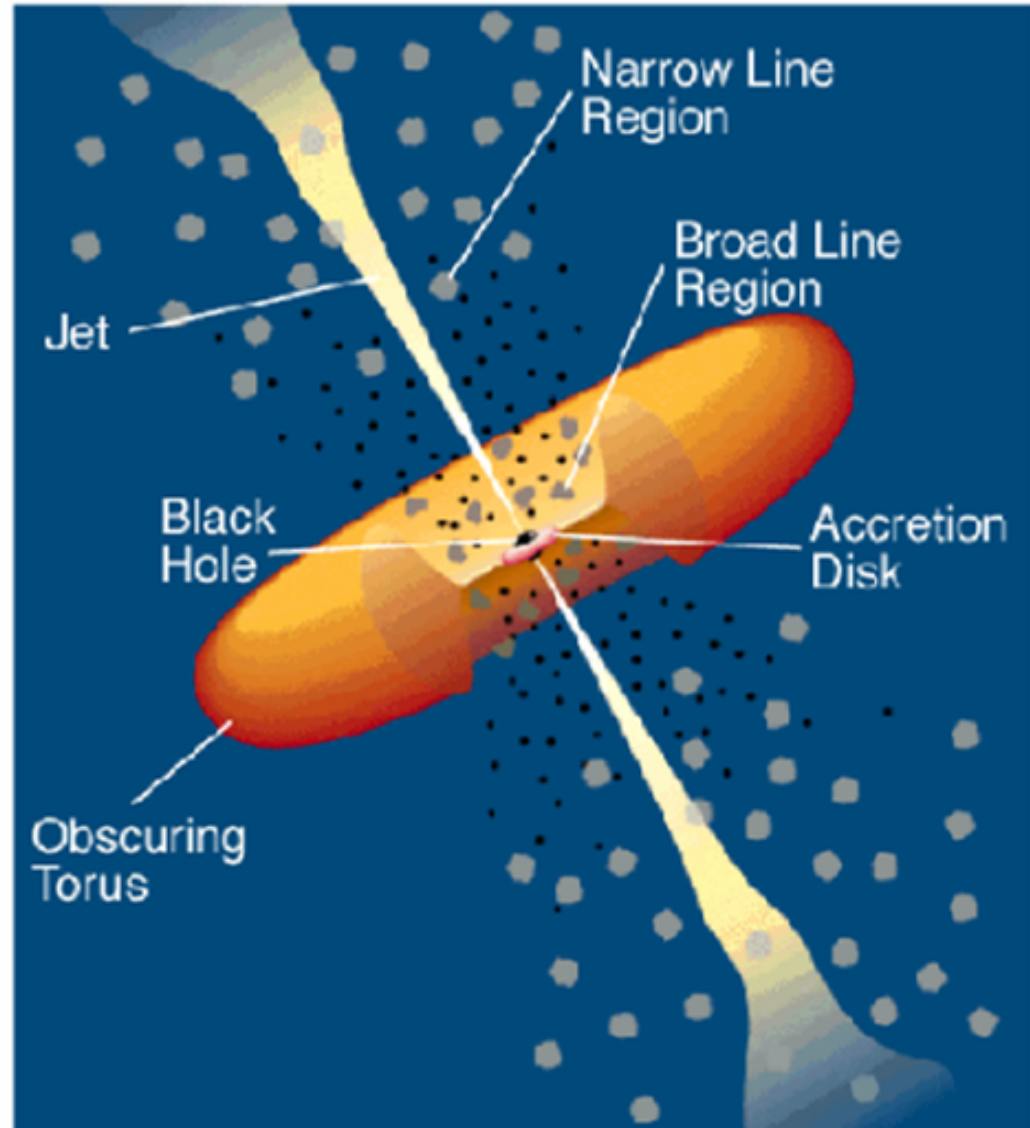


AGNs

- Galassie attive:
 - Buco nero al centro (?)
 - Disco di accrescimento del buco nero
 - Getti ultrarelativistici



Accelerazione da shock ultrarelativistico



Possible Zevatrons (Bottom-up Models)

- Neutron Stars
 - From the Galaxy – inconsistent with isotropic distribution
- AGN- Central Regions
 - Cosmological Distance – GZK cutoff
 - No correlation with Super-GZK events
- AGN- Radio Lobes
 - Cosmological Distance – GZK cutoff
 - M87 + Strong B-Field
- Gamma Ray Bursts
 - Isotropic distribution
 - Energy emission compatible with UHECR
 - Cosmological Distance – GZK cutoff

Top-down Models

(inspired by AGASA spectrum)

- Topological Defects
 - Cosmic Strings, Domain Walls, Magnetic Monopoles...
 - Produce UHE Gamma, Neutrinos
- Super-heavy Relics
 - Trapped in Galactic Halo (like Cold Dark Matter)

Composition and Arrival Direction are the key to distinguish!

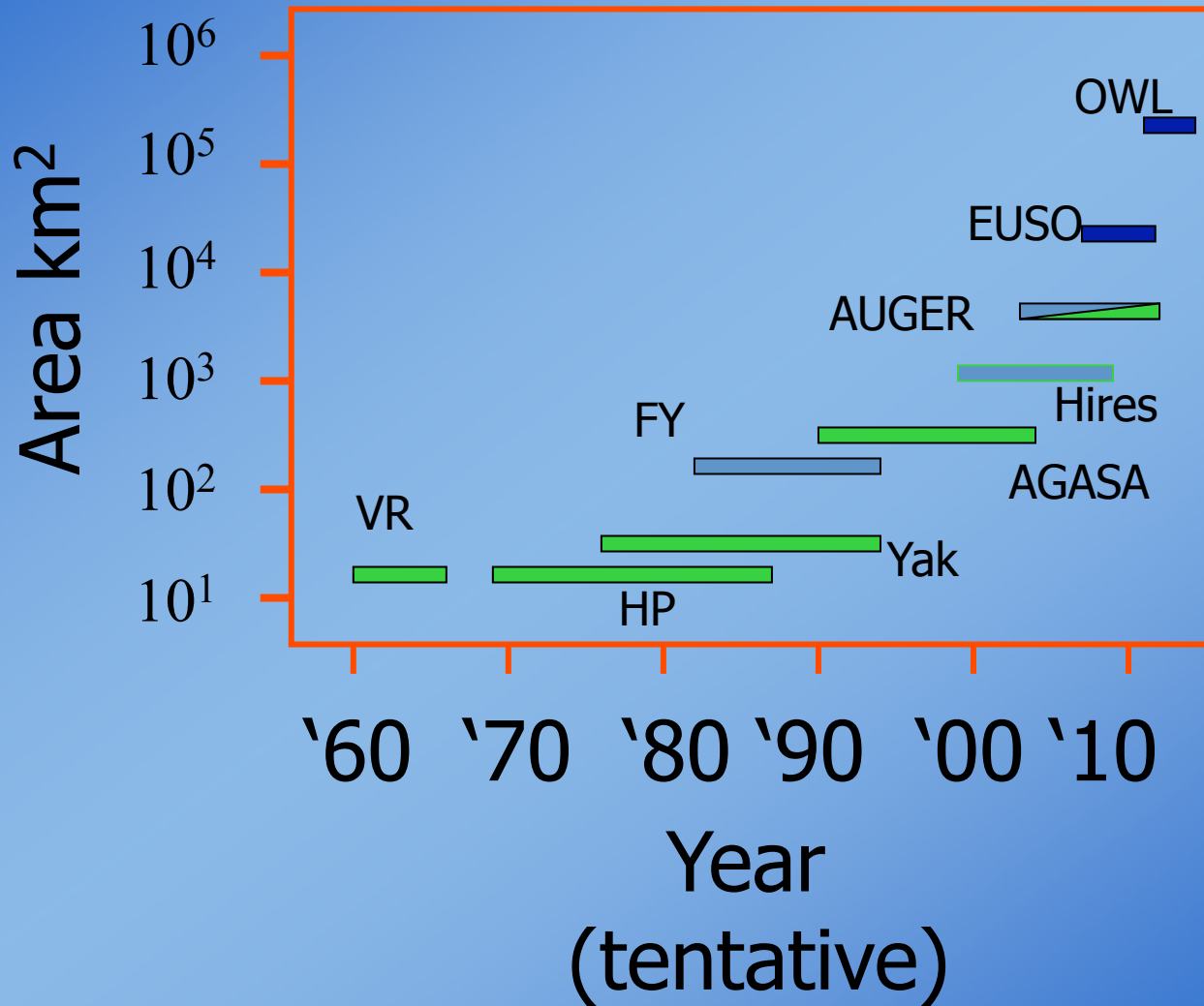
Ultimate Goals

- Energy Frontier of Particle Physics, Cosmology and Astronomy
 - Earliest Universe: GUT, Planck Scale ...
 - Extreme Universe: AGN, GRB ...
- Charged-Particle Astronomy
- Need for Multi-Messenger Approach
 - Gamma ray Veritas, Fermi ...
 - Charged Particle Auger, EUSO , OWL...
 - Neutrino Icecube, Auger ...
 - Gravitational Wave LIGO, LISA ...

Astrofisica Nucleare e Subnucleare

Rivelatori futuri per UHECR

Detectors for UHECR





JEM-EUSO Program

Extreme Universe Space Observatory



[HOME](#) [THE PROGRAM](#) [SCIENCE CASE](#) [OBSERVATIONAL PRINCIPLE](#) [MISSIONS »](#) [PUBLICATIONS](#) [JEM-EUSO COLLABORATION »](#) [TECHNICAL PAGE](#)



The origin and nature of Ultra-High Energy Cosmic Rays (UHECRs) remain unsolved in contemporary astroparticle physics. A cutoff in the cosmic ray energy spectrum clearly appears at $\sim 10^{20}$ eV in the data of Hires, Telescope Array and Auger on ground experiments. It is well known that the detection of events with energy $\geq 10^{20}$ eV is challenged by the GZK effect, which limits the highest detectable energy at $\sim 10^{20}$ eV due to photopion production in the interaction of UHECR on the microwave fossil radiation of the Big Bang, as suggested also by the Hires and Telescope Array data, or by nuclei photodisintegration as indicated by the Auger

results. However, the possibility that the cutoff at $\sim 10^{20}$ eV can be intrinsic to the acceleration power of the astrophysics cosmic ray sources remains alive. Moreover, indications of sources or excesses in the arrival direction distribution of UHECRs have been claimed by Telescope Array, in the North Emisphere, and by Auger, in the South Emisphere. To give an answer to these questions is rather challenging because of the extremely low flux of a few per km² per century at extreme energies such as $E > 5 \times 10^{19}$ eV.

The objective of the **JEM-EUSO program**, **Extreme Universe Space Observatory**, is the realization of a space mission devoted to scientific research of cosmic rays of highest energies. Its super-wide-field telescope will look down from space onto the night sky to detect UV photons emitted from air showers generated by UHECRs in the atmosphere.

<http://jem-euso.roma2.infn.it>

► PHOTO GALLERY

NEWS

New Publication

Special Issue on the JEM-EUSO Mission, The Experimental Astronomy, vol. 40, 2015.

EUSO-SPB

NASA Program Initiation Conference (PIC) carried out on March 11, 2016.

Flight confirmed for April 2017.

Mini-EUSO

Approved by Roscosmos and ASI. Meeting ASI-Roscosmos on March 22, 2016.

K-EUSO

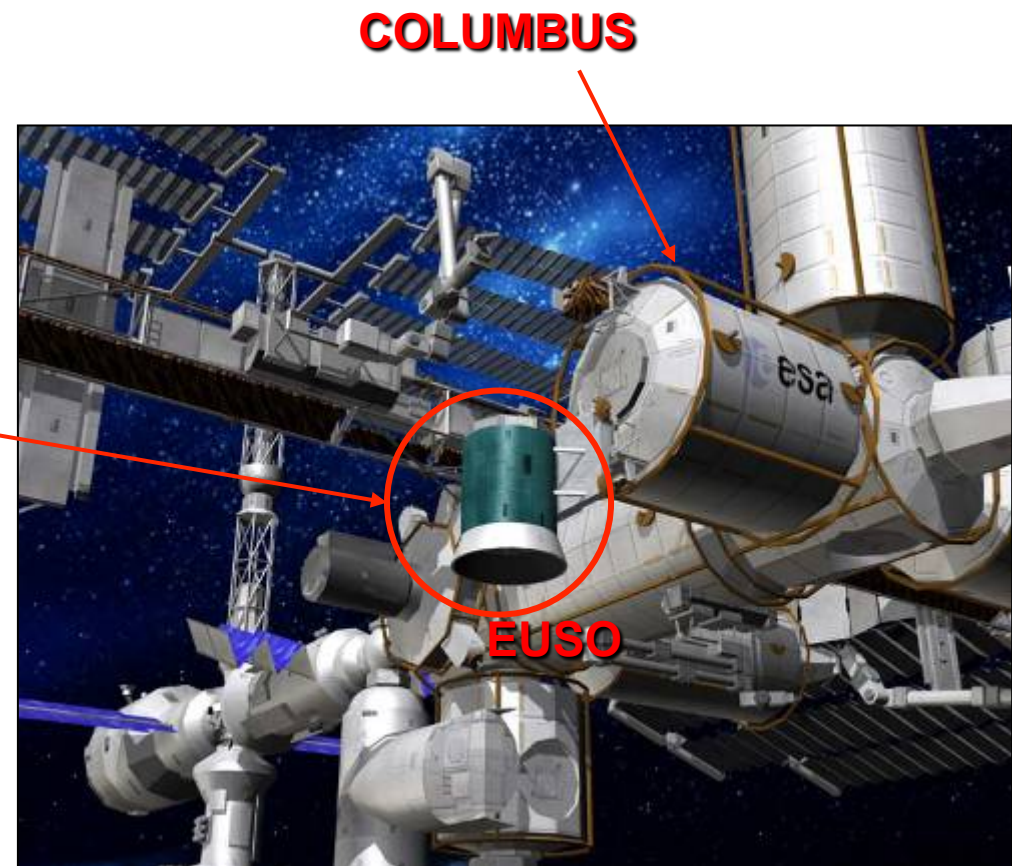
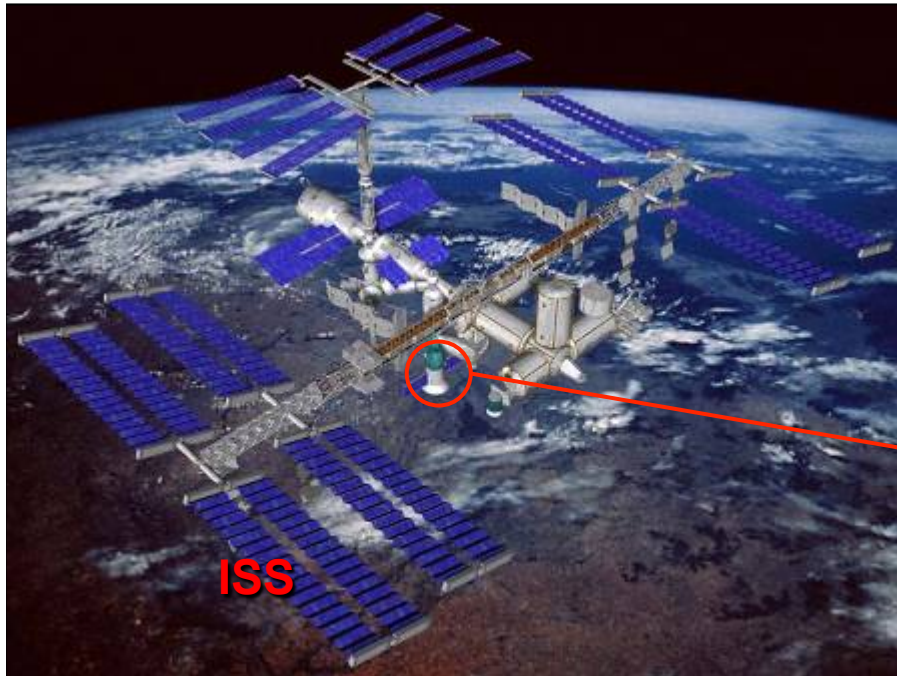
Conceptual design stage.

EUSO-Balloon

Soluzione: EUSO

(**Extreme Universe Space Observatory**)

Da installare sul modulo europeo Columbus dell'International Space Station (ISS), orbitante a 500 Km di altitudine





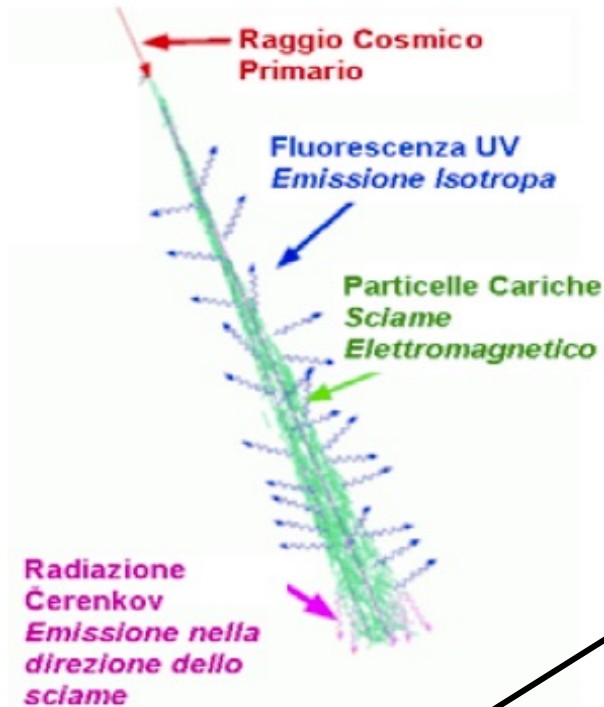
EUSO FoV

**Confronto Area effettiva di EUSO con
esperimenti al suolo**

TECNICHE DI RIVELAZIONE PER EUSO

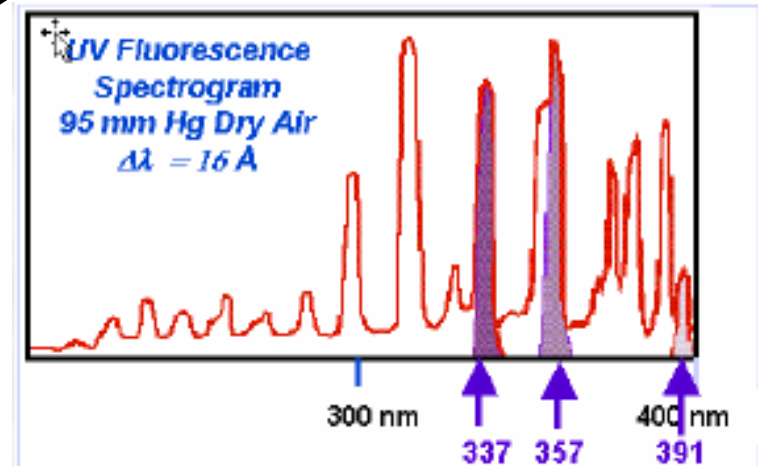
Luce di fluorescenza

Sciame atmosferico esteso → eccitazione e ionizzazione dei livelli metastabili delle molecole d'aria (prevalentemente N₂)



↓
diseccitazione dei livelli

Emissione di fotoni con picchi caratteristici (fluorescenza)





The Concept

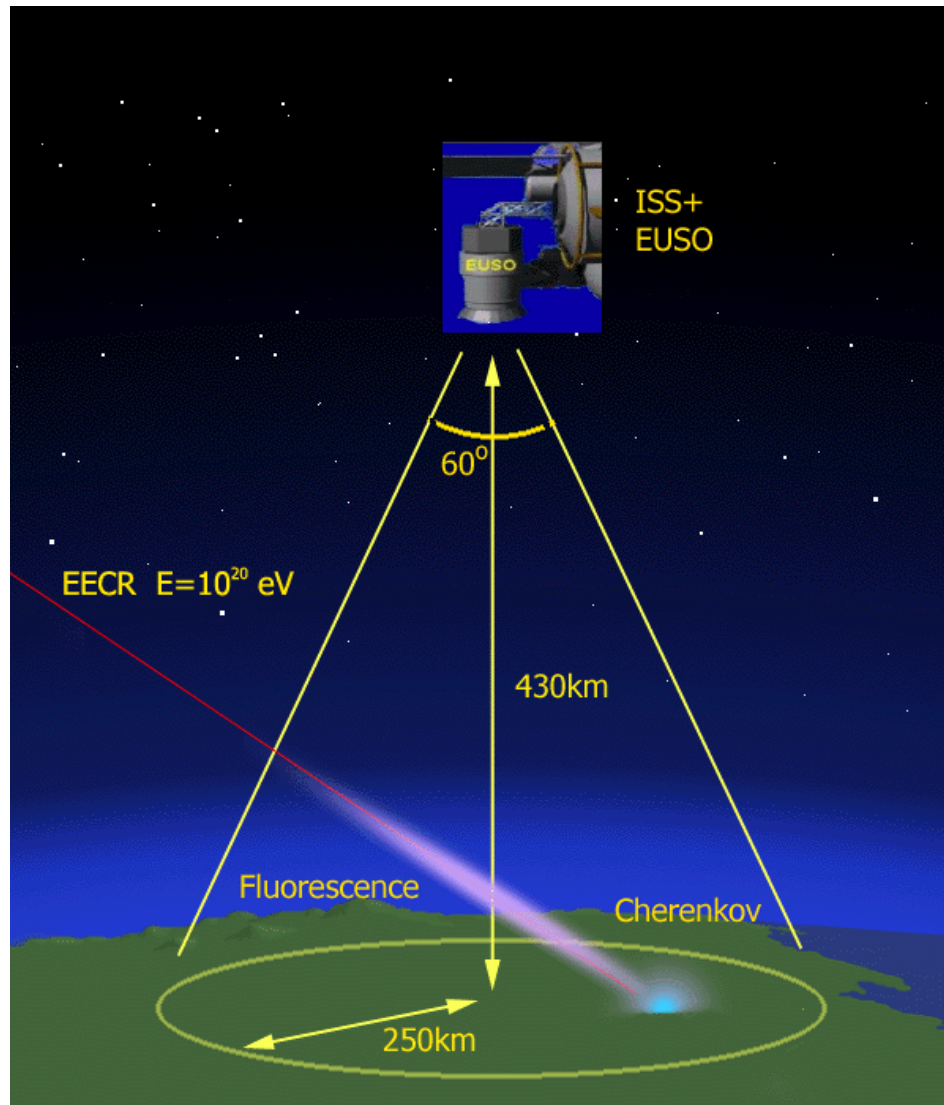


Extreme Universe Space Observatory

'Space-telescope using entire Earth atmosphere as CR & ν detector.'

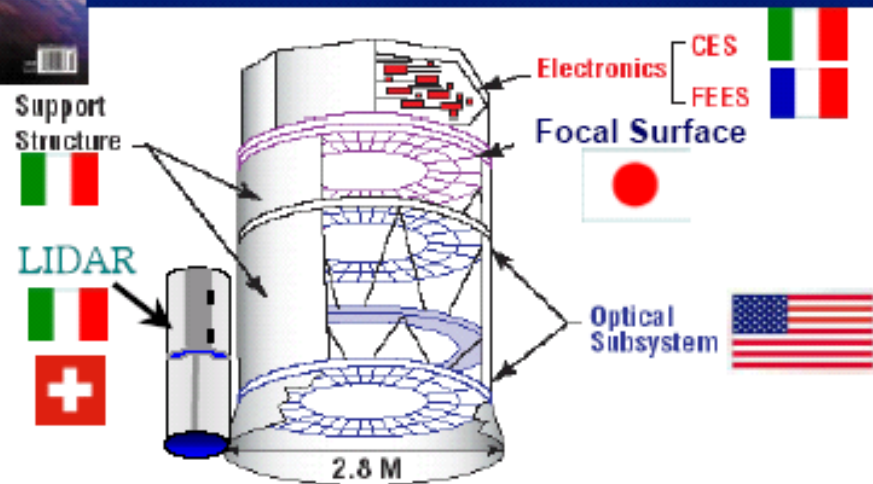
- CR detector $\sim 200.000 \text{ km}^2 \text{ sr}$.
- Neutrino detector $\sim 10^{12} \text{ tons air}$.
- N_2 fluorescence & Cherenkov

International Space Station L.E.O

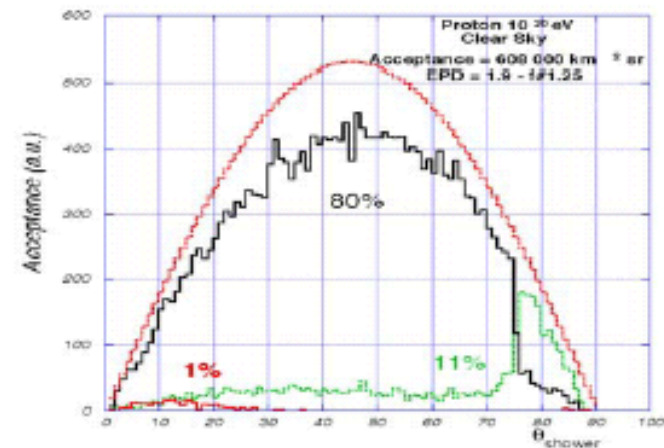
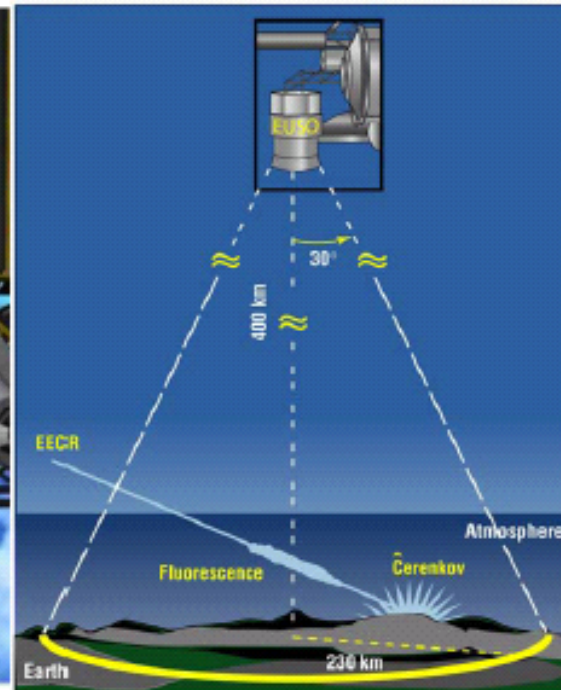
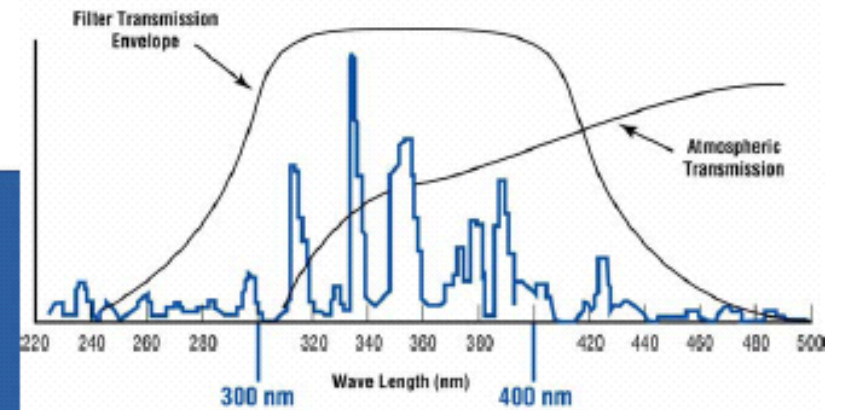




EUSO Instrument



Fluorescence Spectrum

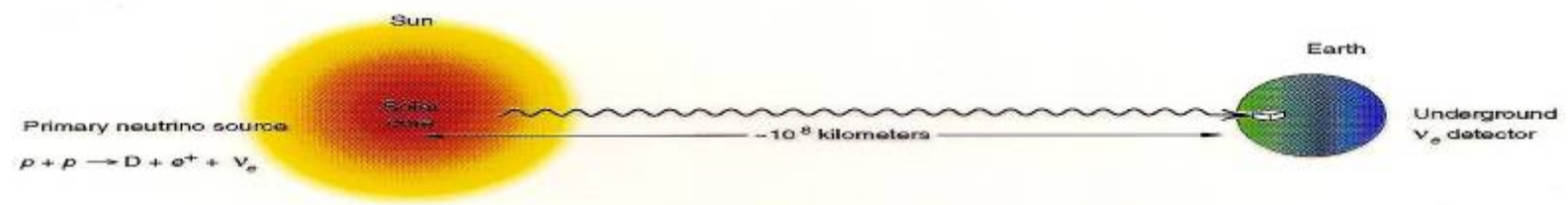


Astrofisica Nucleare e Subnucleare

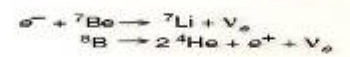
Astrophysical Neutrinos

NEUTRINO SOURCES

SOLAR ν : (ν_e)

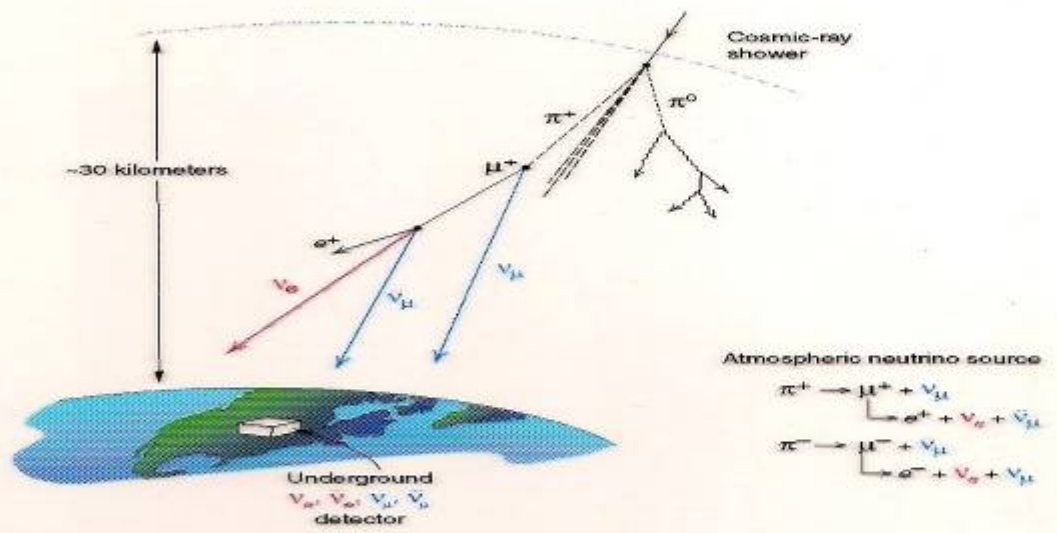


Other sources of neutrinos:



SUPERNOVA ($\nu_x, \bar{\nu}_x$)

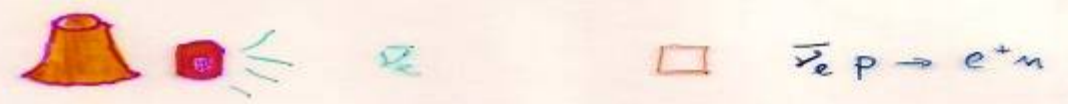
ATMOSPHERIC ν :
($\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$)



ACCELERATOR ν :
($\nu_\mu, \bar{\nu}_\mu, \nu_e$)

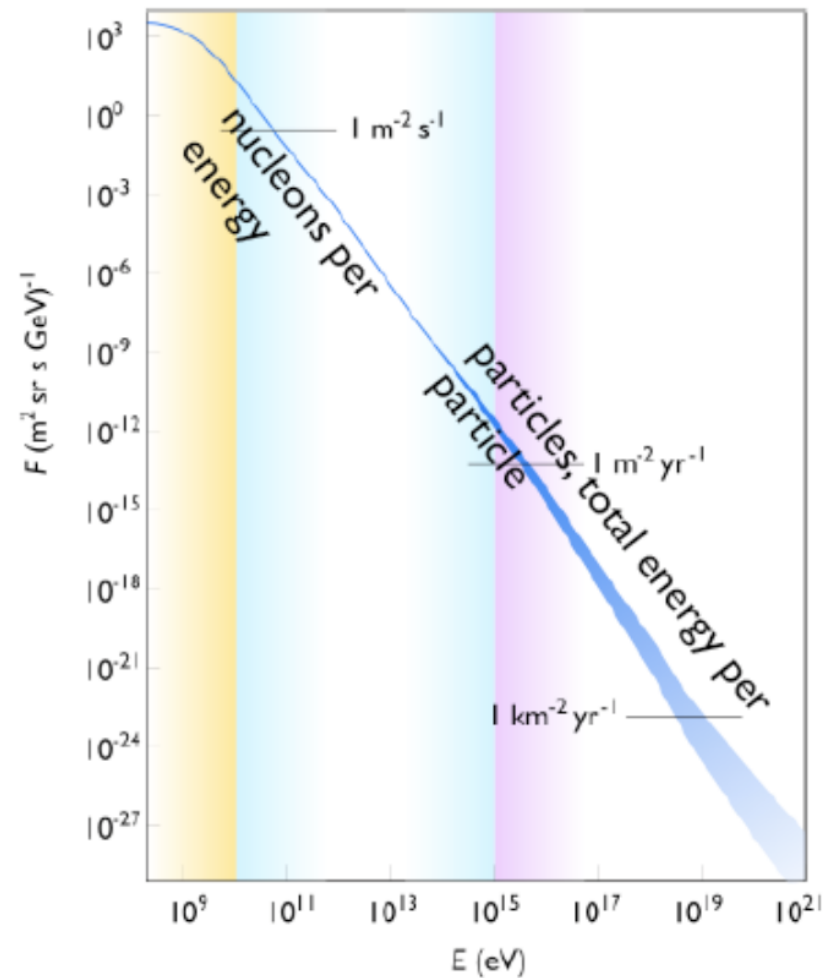


REACTOR ν :
($\bar{\nu}_e$)



Cosmic rays

- The primary cosmic ray *differential energy spectrum* shows:
 - A cut-off at energies $<$ few GeV
 - A power-law: $N(E)dE = K \cdot E^{-\gamma}dE$
- Spectral indices:
 - $\gamma = 2.7$ $E < 10^{15}$ eV
 - $\gamma = 3$ $10^{15} < E < 10^{18}$ eV
 - somewhat flatter $E > 10^{18}$ eV

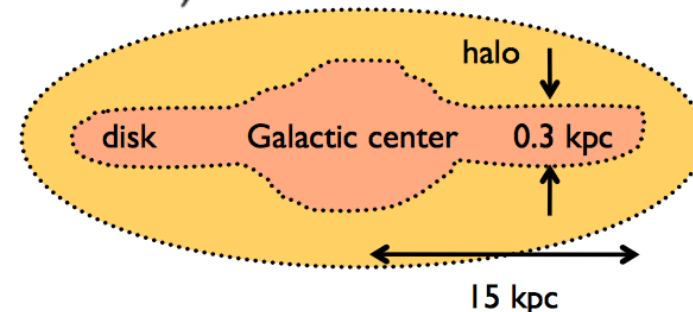


Propagation of cosmic rays in the Galaxy

- The typical galactic magnetic field is $3 \mu\text{G}$ (energy density of $0.2 \text{ eV}/\text{cm}^3$)

$$ze|\vec{B} \times \vec{v}| = \frac{mv^2}{R} \quad r(\text{kpc}) \cong \frac{E(\text{EeV})}{ZB(\mu\text{G})}$$

- E.g. protons with energy 10^{14} eV have a curvature radius of $\sim 10^{16} \text{ m}$
- 1 pc = $3 \cdot 10^{16} \text{ m}$, distance to the Crab Nebula**
- The *directionality* of Cosmic Rays is smeared out by the magnetic field!
- The higher the energy, the more preserved in the directionality
- Can we *find the sources of Cosmic Rays*?
- For a proton at $E \sim 10^{19} \text{ eV}$
- $r \sim 3.3 \text{ kpc}$ ($\sim 10 \cdot$ thickness of galactic disk)
- Fe could be confined at 10^{19} eV
- $r = 10(E\text{eV})/26 \cdot 3(\mu\text{G}) \approx 100 \text{ pc}$

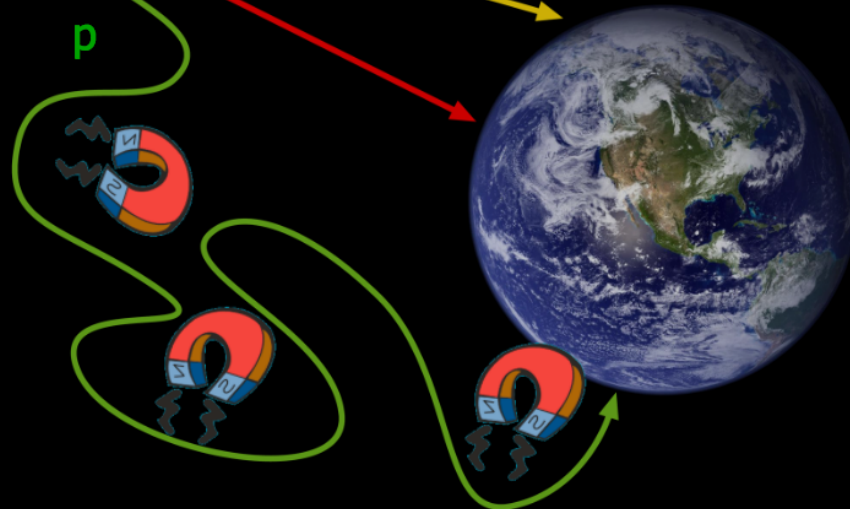


Identification of cosmic sources

- Charged particle tracks do not point to their source: Larmor radius \ll diameter of galaxy



*γ -rays and neutrinos
provide new
observational windows:
might reveal unknown
truths!*

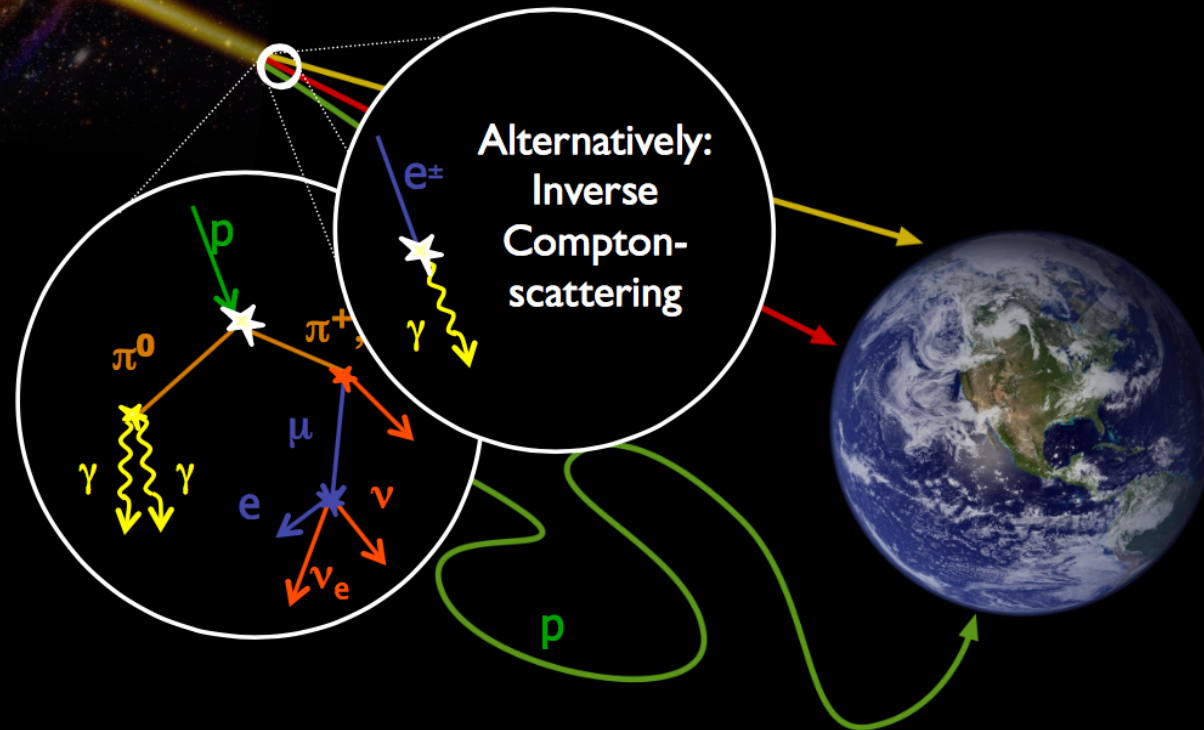


Identification of cosmic sources

- Source identification by detection of neutral secondaries from inelastic scattering of cosmic rays with photons and matter close to their source

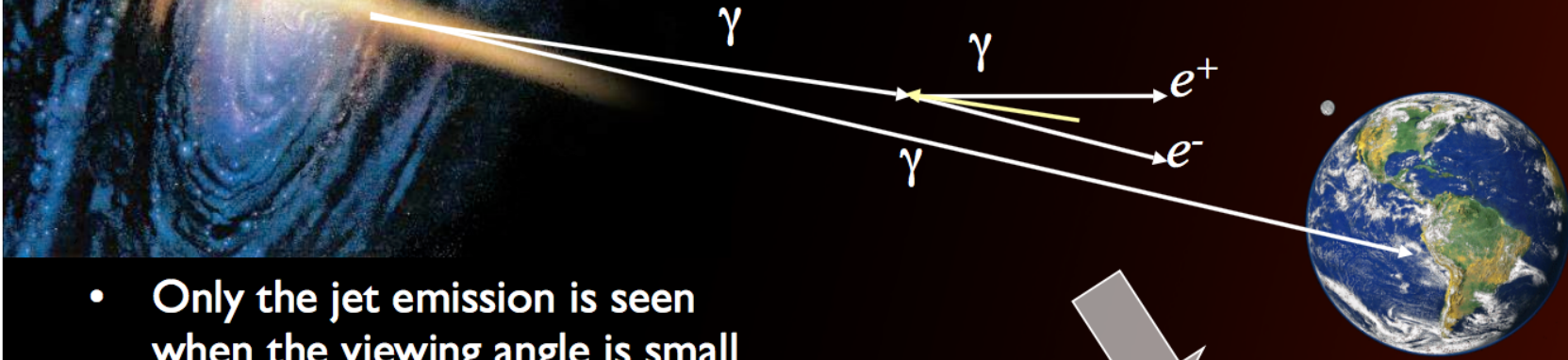


Astrophysical beam dump

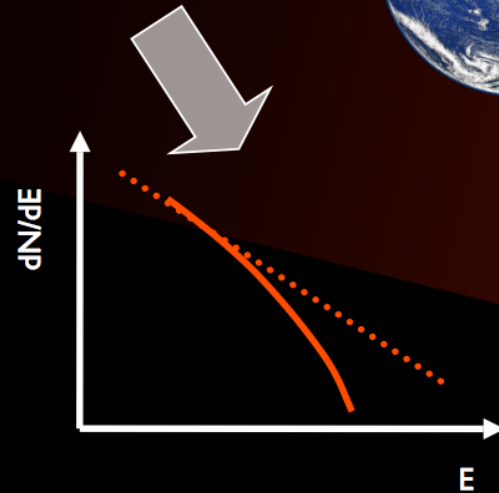


AGNs and extragalactic background light

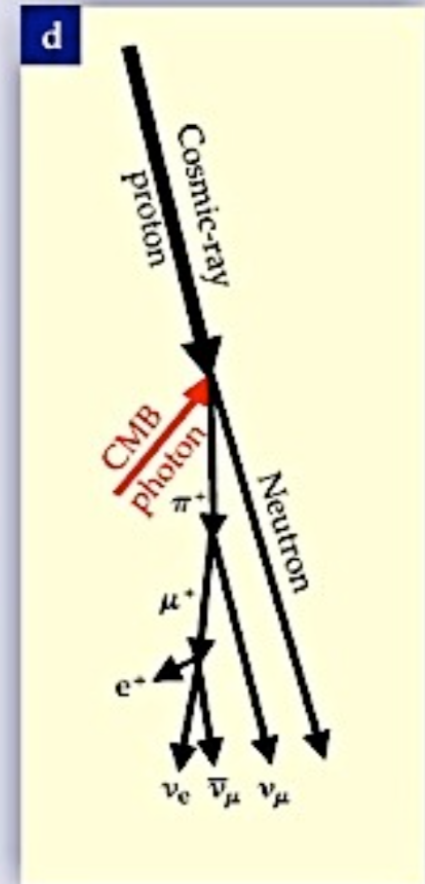
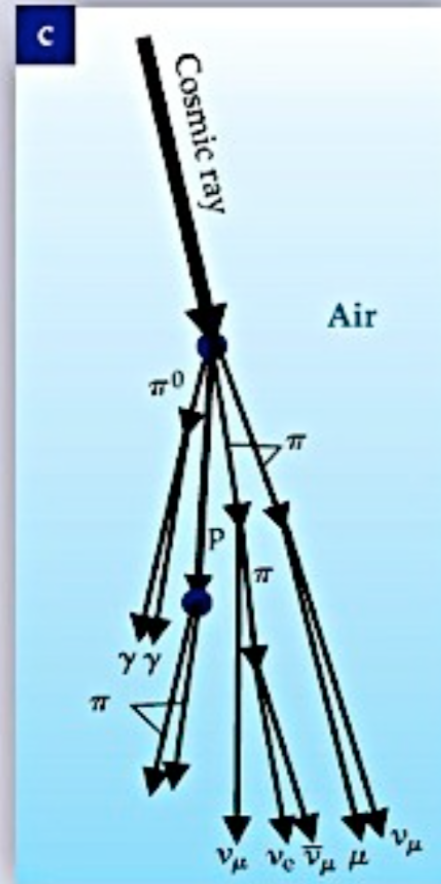
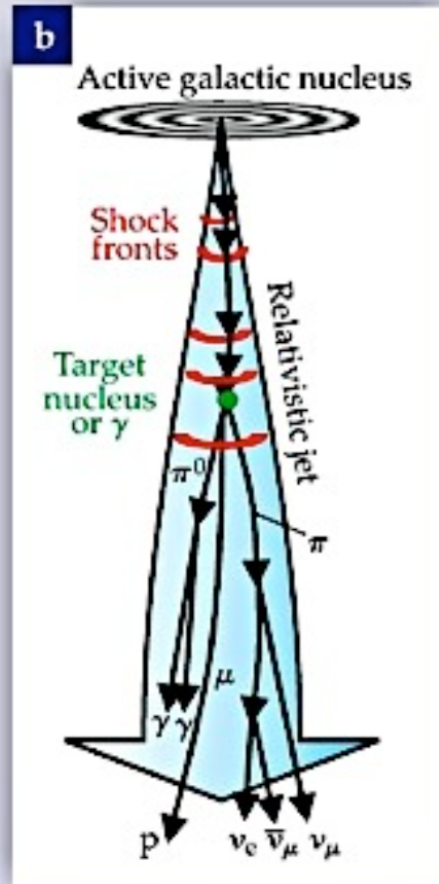
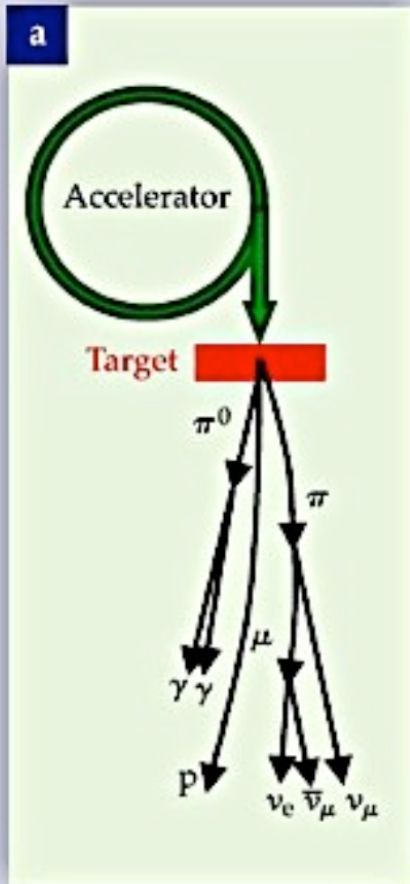
Absorption in (infrared) extragalactic background light (EBL):
 $\gamma(\text{TeV}) + \gamma(\text{EBL}) \rightarrow e^+e^-$

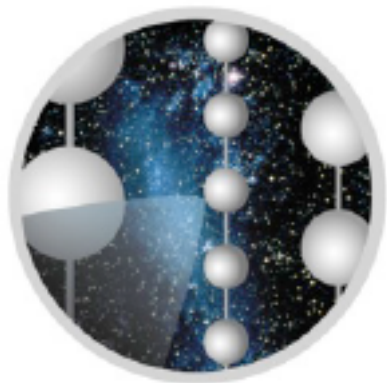


- Only the jet emission is seen when the viewing angle is small
- The luminosity of the jet depends on the *Lorentz factors* of the plasma in the jets



Summary of neutrino production modes





ICECUBE

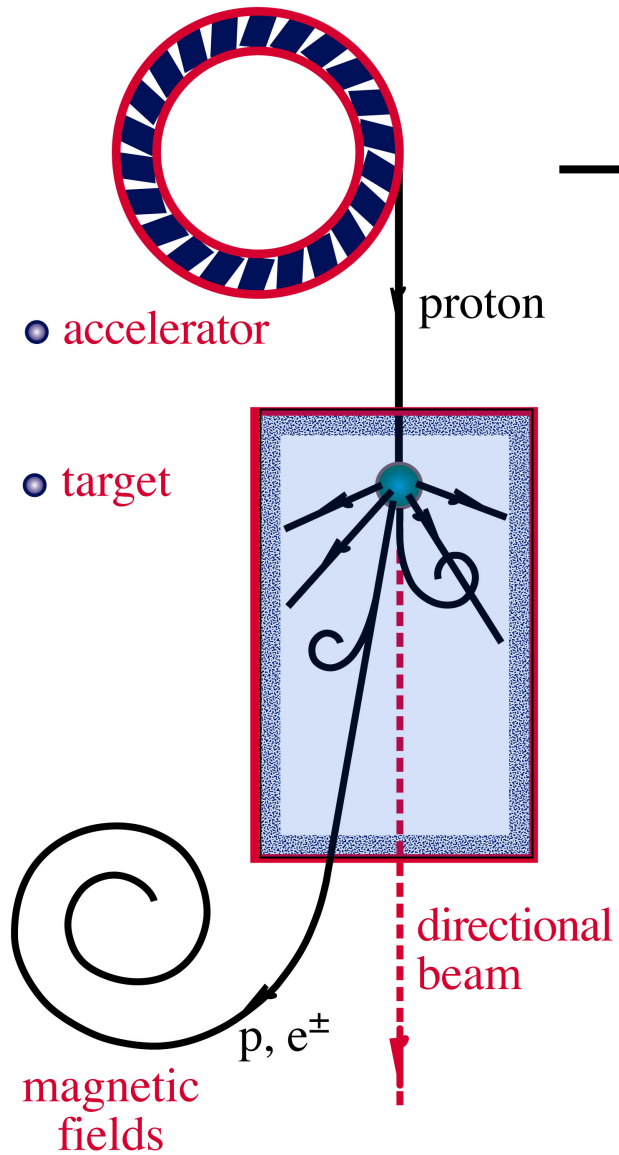


IceCube

francis halzen

- IceCube: a cubic kilometer detector
- the discovery (and confirmation) of cosmic neutrinos
- from discovery to astronomy
- and there is more

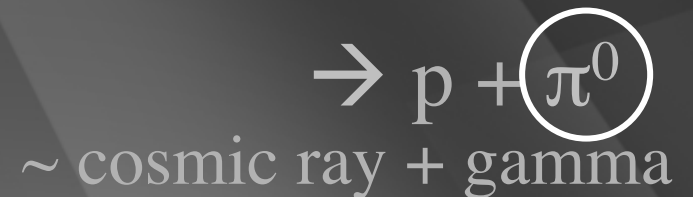
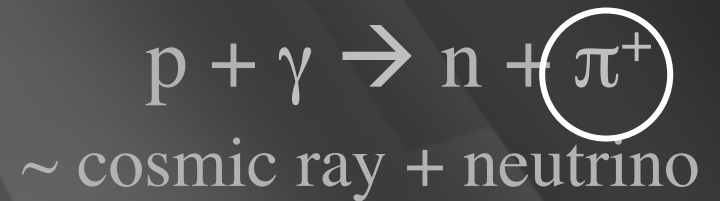
ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

**black hole
neutron star**

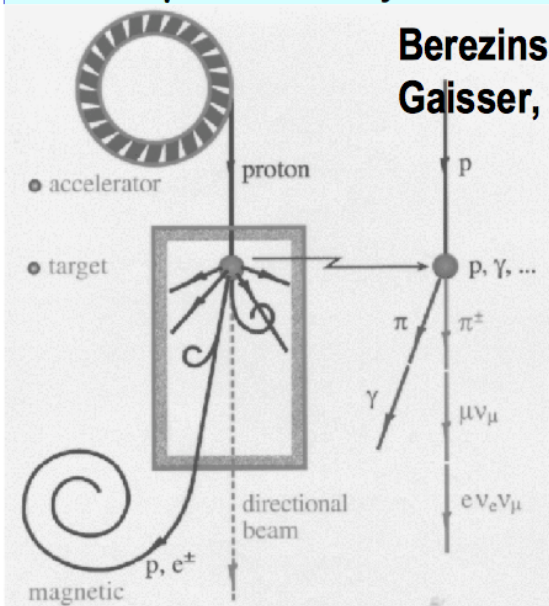
**radiation
and dust
molecular cloud**



ν production

Bottom-up (beam-dump model): cosmic accelerator + interaction on matter or photons:

$\pi^0 \rightarrow \gamma$ -astronomy $\pi^\pm \rightarrow \nu$ -astronomy



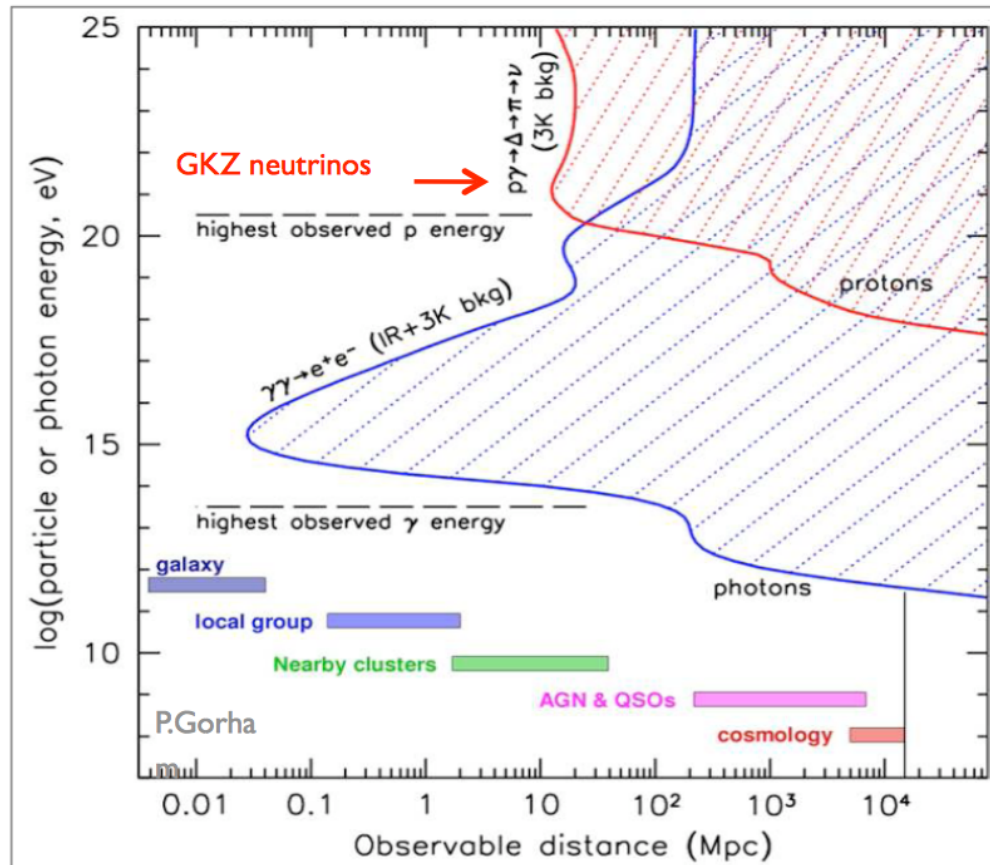
Neglecting γ absorption (uncertain) $\Phi_\nu \sim \Phi_\gamma$
1st order Fermi acceleration mechanism:
harder spectra than atm ν 's ($\sim E^{-2}$ - $E^{-2.5}$)

- **Extra-galactic:**
jets of AGNs, GRB fireballs
accretion shocks in galaxy clusters, galaxy mergers
- **Galactic:** young SNR (p or heavy ion acceleration), pulsars, magnetars, micro-quasars (binaries with jets in radio)

Top-down: decays of particles produced by topological defects or relic particles
Z decays due to UHE ν interaction on relic ν 's (Weiler, 1982)

GZK ν s: UHECR photopion production on CMB (Berezhinsky & Zatsepin, 1970, Yoshida & Teshima, 1993 Engel, Sekel, Stanev, 2001)

Rationale for neutrino astrophysics



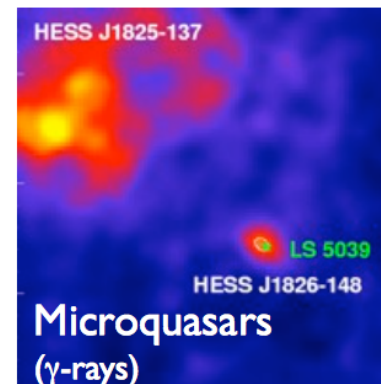
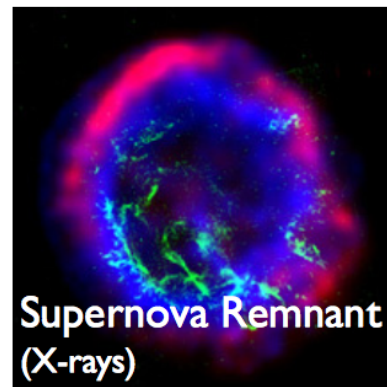
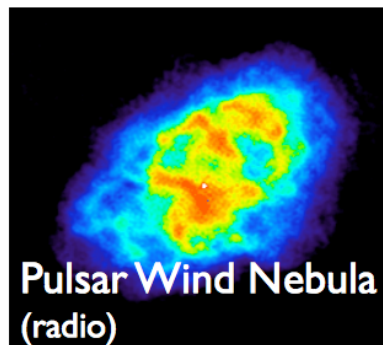
- While protons and photons interact, neutrinos survive
- Guaranteed neutrino source from interaction of cosmic rays of highest energies (GKZ) with microwave background

Candidate cosmic accelerators

Source classes show clear evidence of non-thermal emission

Galactic Sources:

- Supernova Remnants, Pulsars, Supernova Wind Nebulae, binary systems, small mass black holes (e.g. Microquasars) ...
- Lower luminosities are enough to give detectable fluxes

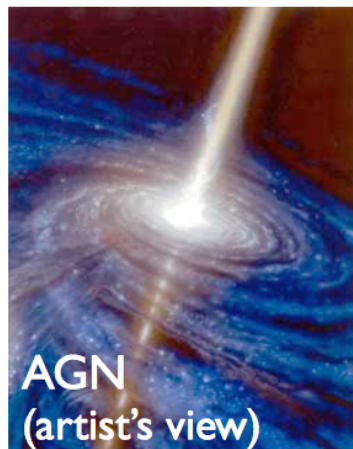
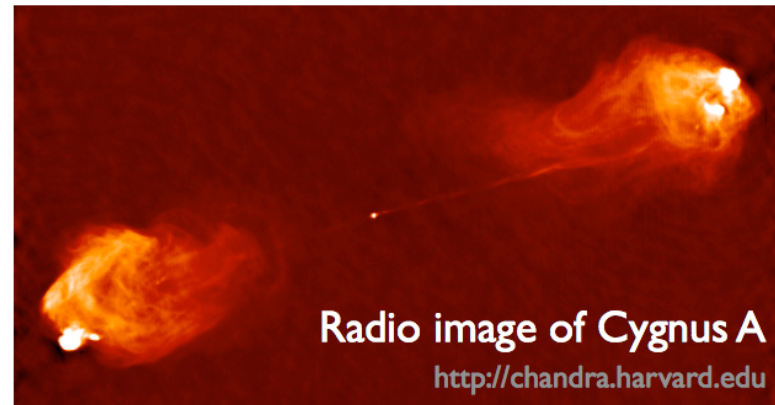


Candidate cosmic accelerators

Source classes show clear evidence of non-thermal emission

Extragalactic Sources:

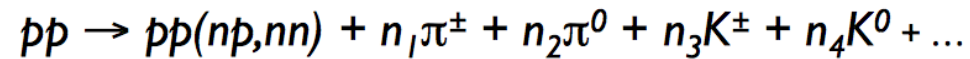
- Active Galactic Nuclei (AGN), Gamma Ray Burst (GRB) ...
- Higher luminosities required but are massive objects with highly variable engines



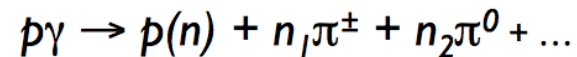
Astrophysical neutrinos: production

- Production:

- Nucleon interactions:



- Photonuclear interaction of very high energy protons:



- Power law of cosmic rays at the source \Rightarrow the energy spectrum of neutrinos is also a power law

- Relation neutrinos/photons:

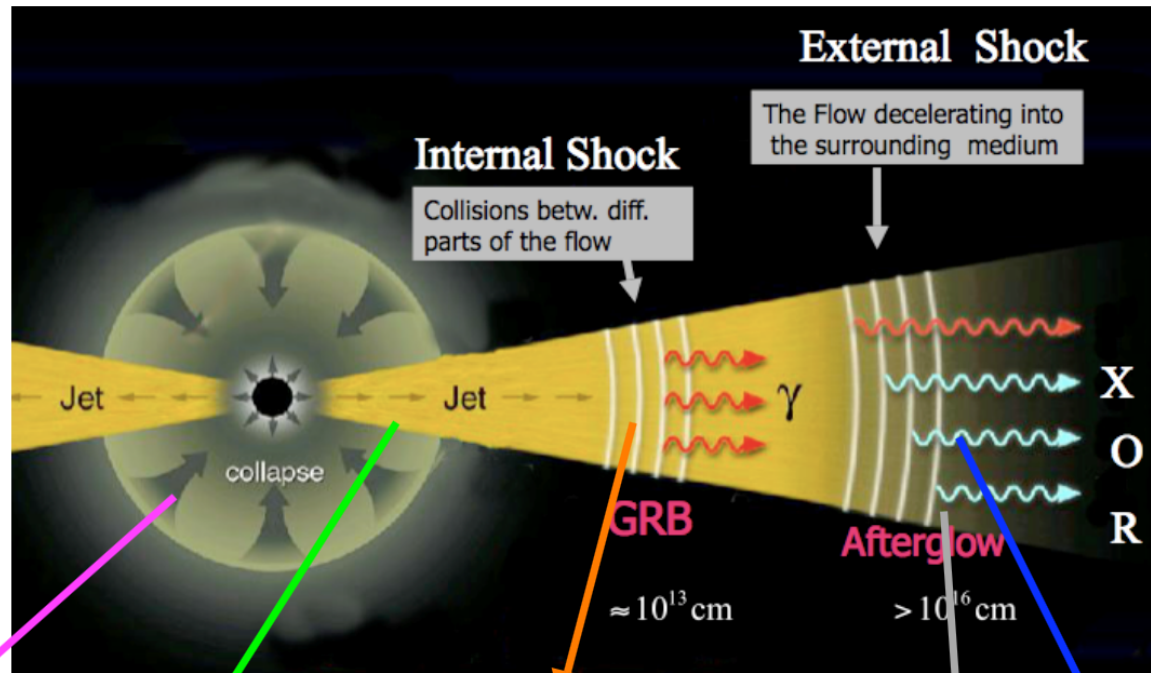
- Assuming hadronic origin of photons
- No absorption

$$\frac{\Phi_\gamma}{\Phi_\nu} \simeq 1$$

GRBs as sources of high-energy neutrinos

Fireball model for long GRBs:

Credit:
Meszaros & Murase



MeV neutrinos at collapse

TeV neutrinos from inside the star
[Meszaros & Waxman, 2001]
[Razzaque et al. 2003]

PeV neutrinos from internal shock

[Waxman & Bahcall 1997]
[Gupta & Zhang, 2006]
[Murase & Nagataki 2006]

EeV neutrinos from external shocks

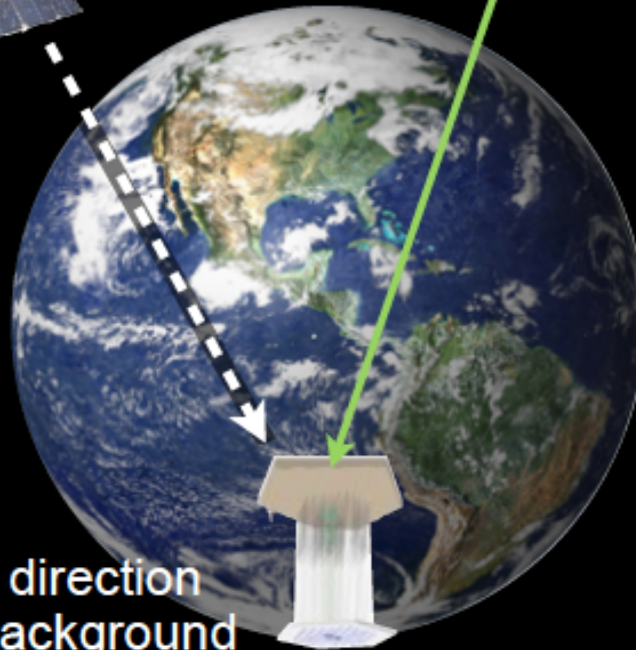
[Dermer 2001]
[Waxman & Bahcall 2000]

PeV-EeV neutrinos from flares
[Murase & Nagataki 2006]

flux < 1% of astrophysical
neutrino flux observed
Nature 484 (2012) 351-353

timing/localization
from satellites

timing + direction
→ low background

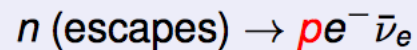
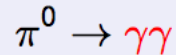
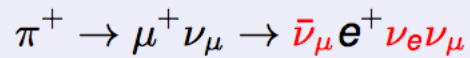
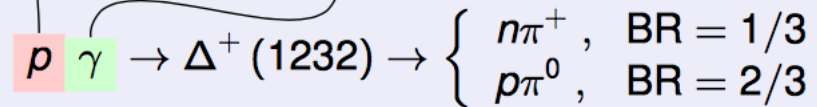


Producing the UHE ν 's, CRs, γ rays – a first look

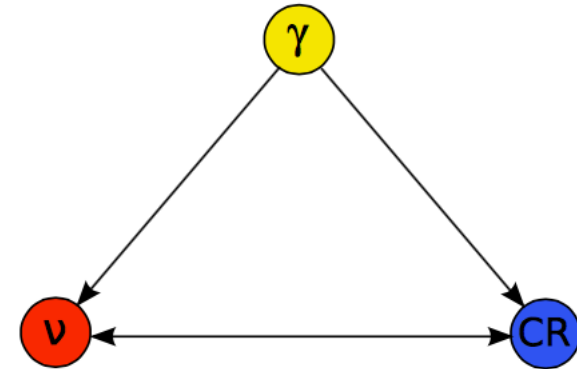
Joint production of UHECRs, ν 's, and γ 's:

power law $\sim E^{-\alpha p}$

broken power law



(Δ^+ : $\sim 50\%$ of all $p\gamma$ interactions)



After propagation, with flavor mixing:

$$\nu_e : \nu_\mu : \nu_\tau : p = 1 : 1 : 1 : 1$$

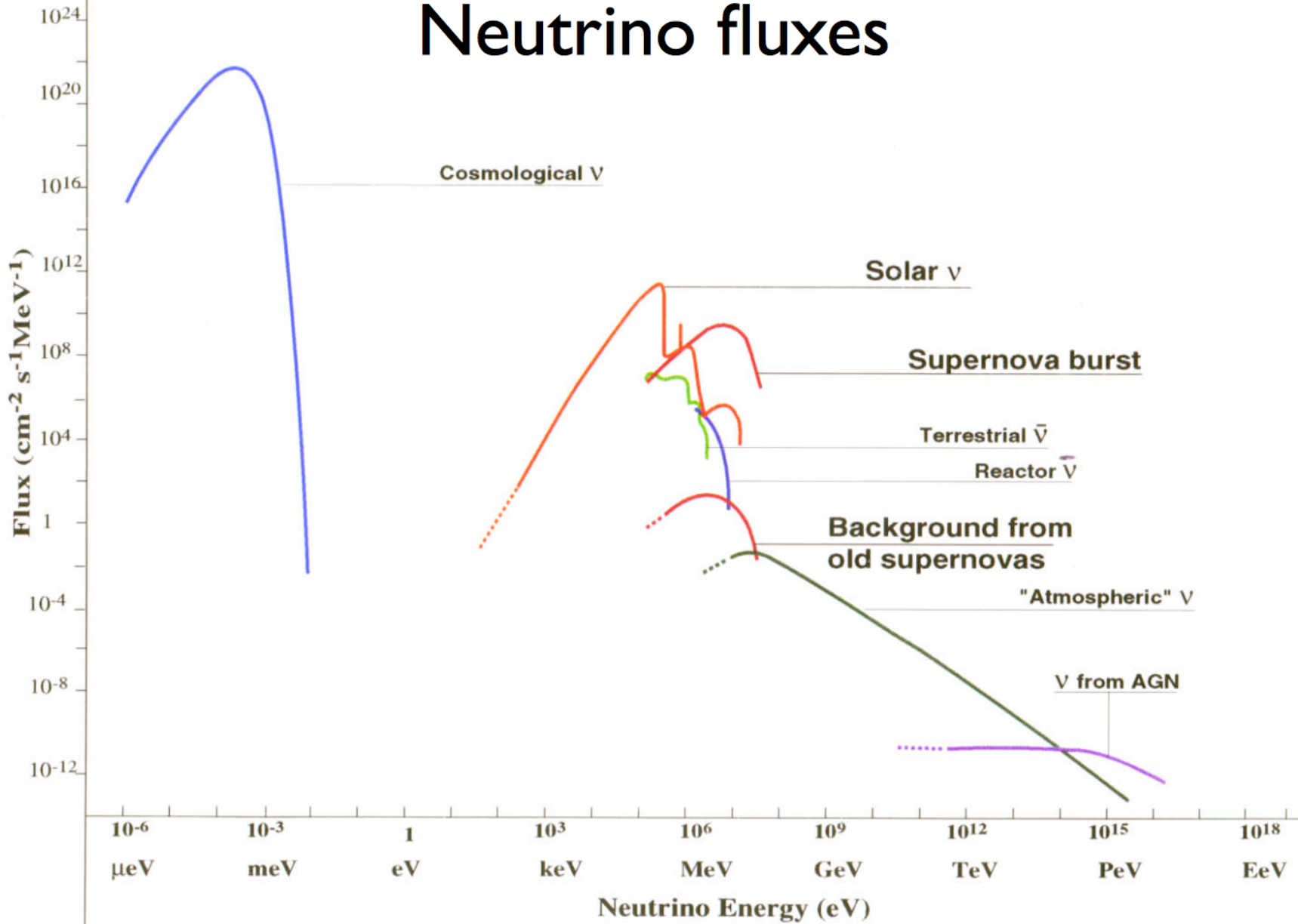
("one ν_μ per cosmic ray")

This **neutron model** of CR emission is now strongly disfavoured

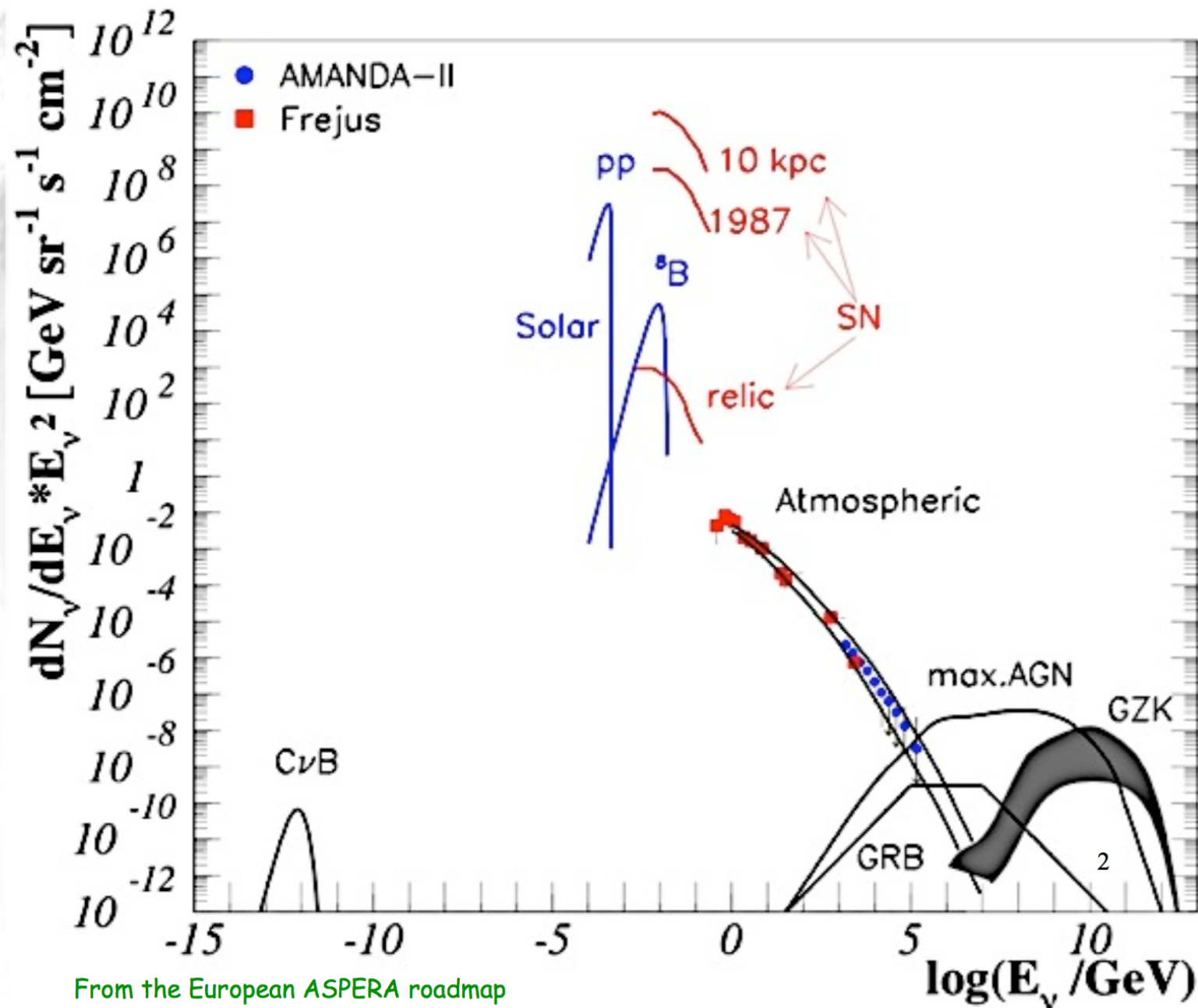
ICECUBE, *Nature* **484**, 351 (2012)

M. AHLERS *et al.* *Astropart. Phys.* **35**, 87 (2011)

Neutrino fluxes

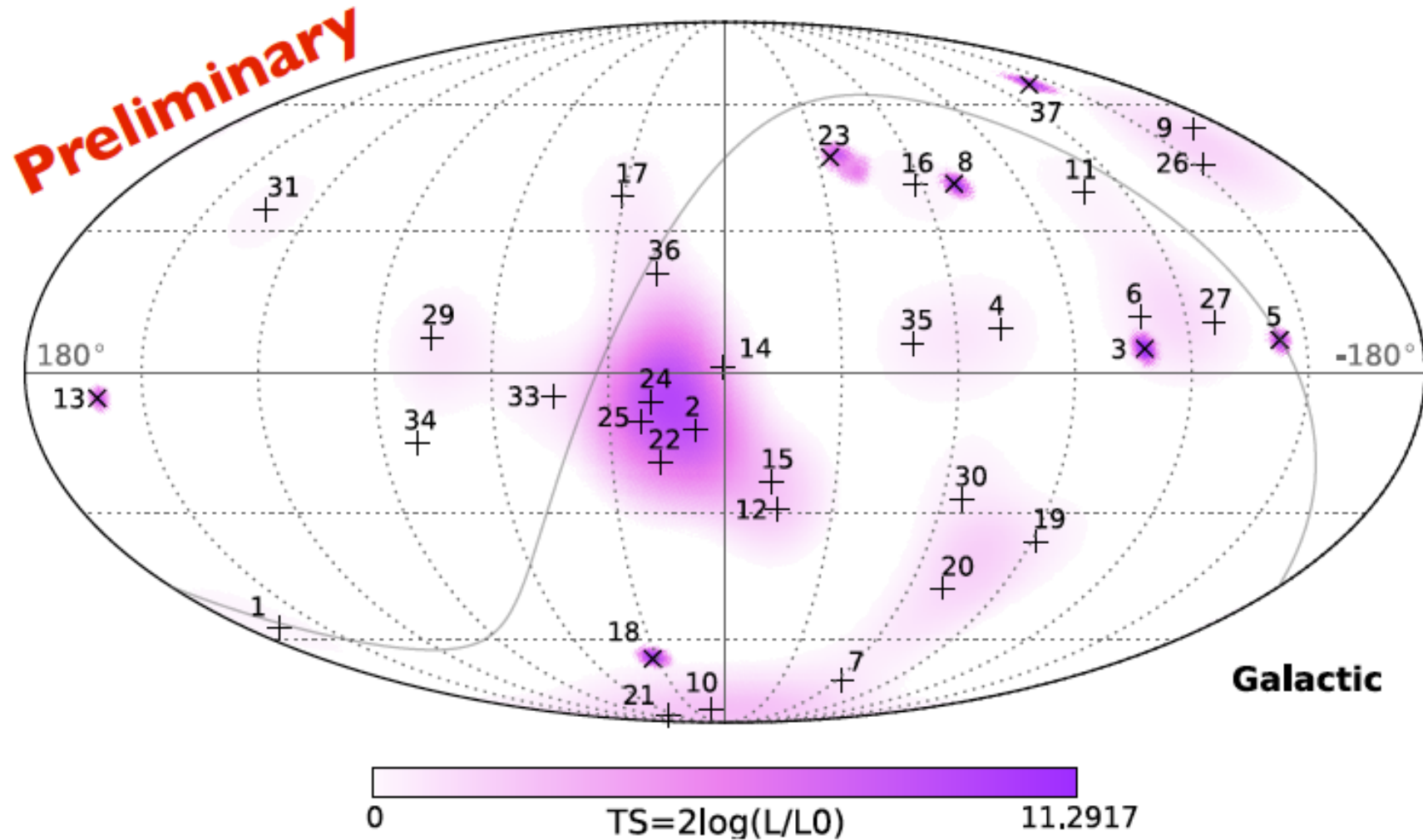


The „grand unified“ neutrino energy flux spectrum



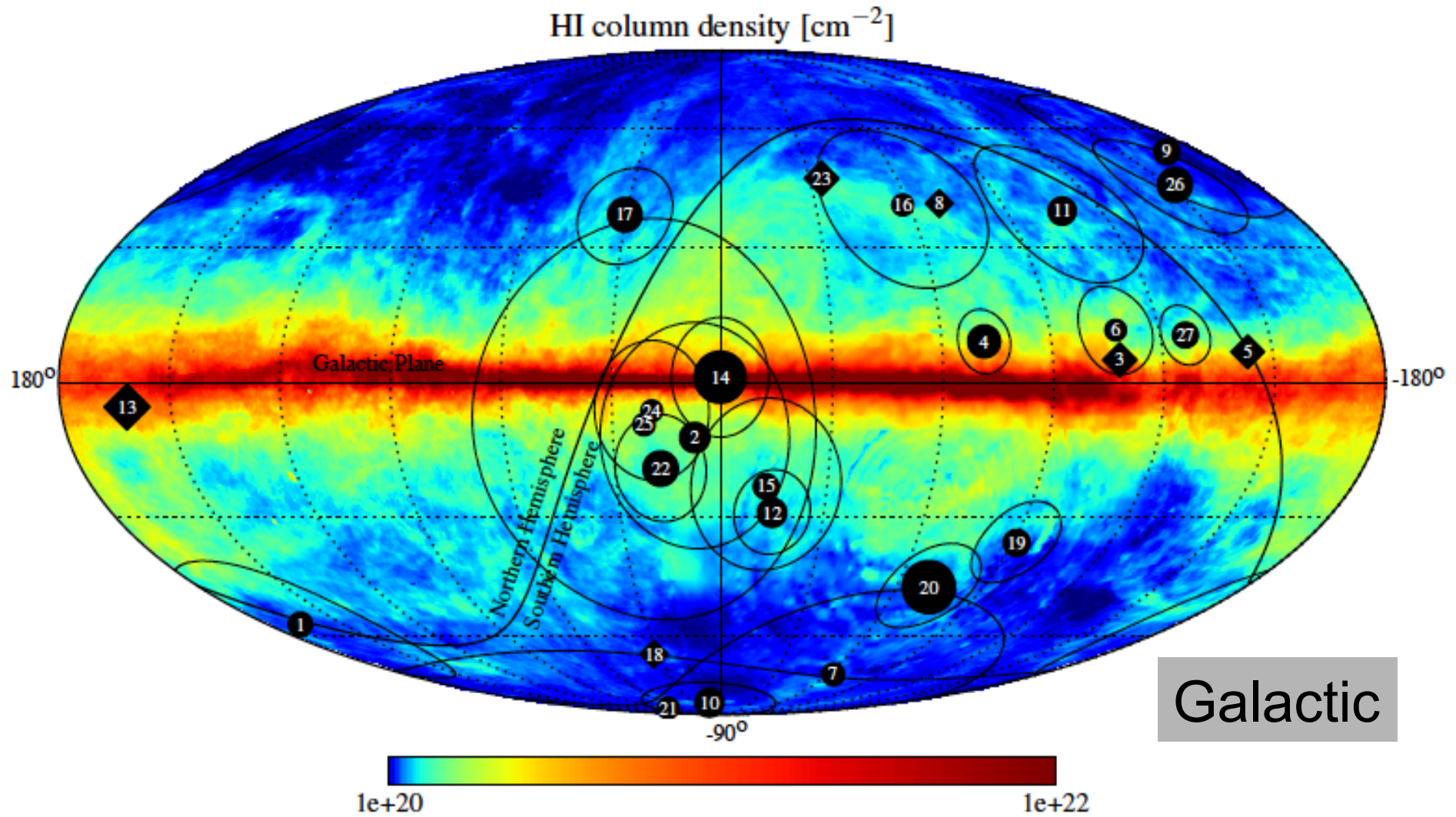
From the European ASPERA roadmap

where do they come from (3 year data)?



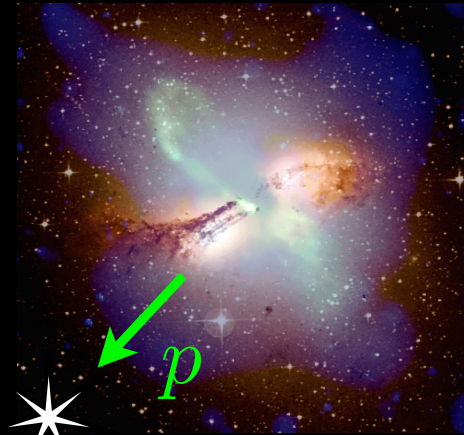
hottest spot 7.2%: consistent with diffuse flux with flavor 1:1:1

correlation with Galactic plane: TS of 2.8% for a width of 7.5 deg



hadronic gamma rays ?

$$\pi^+ = \pi^- = \pi^0$$

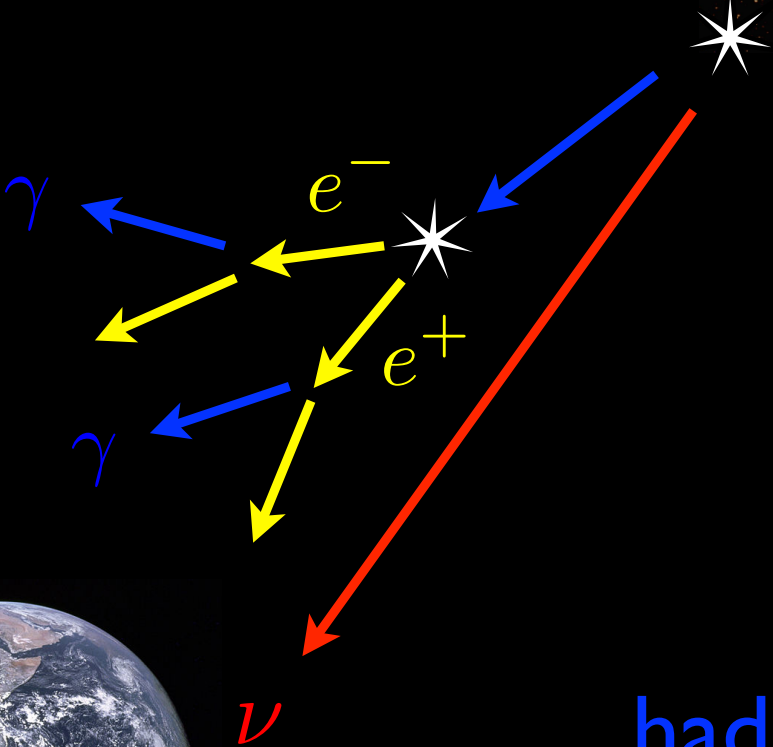
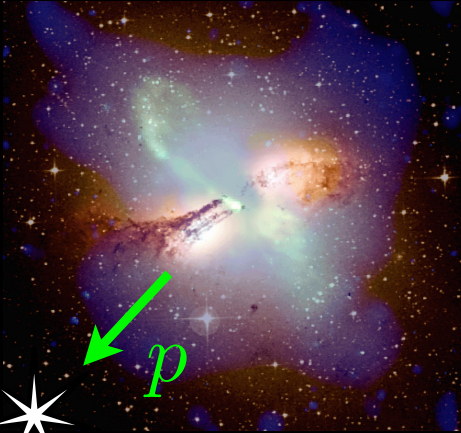


γ

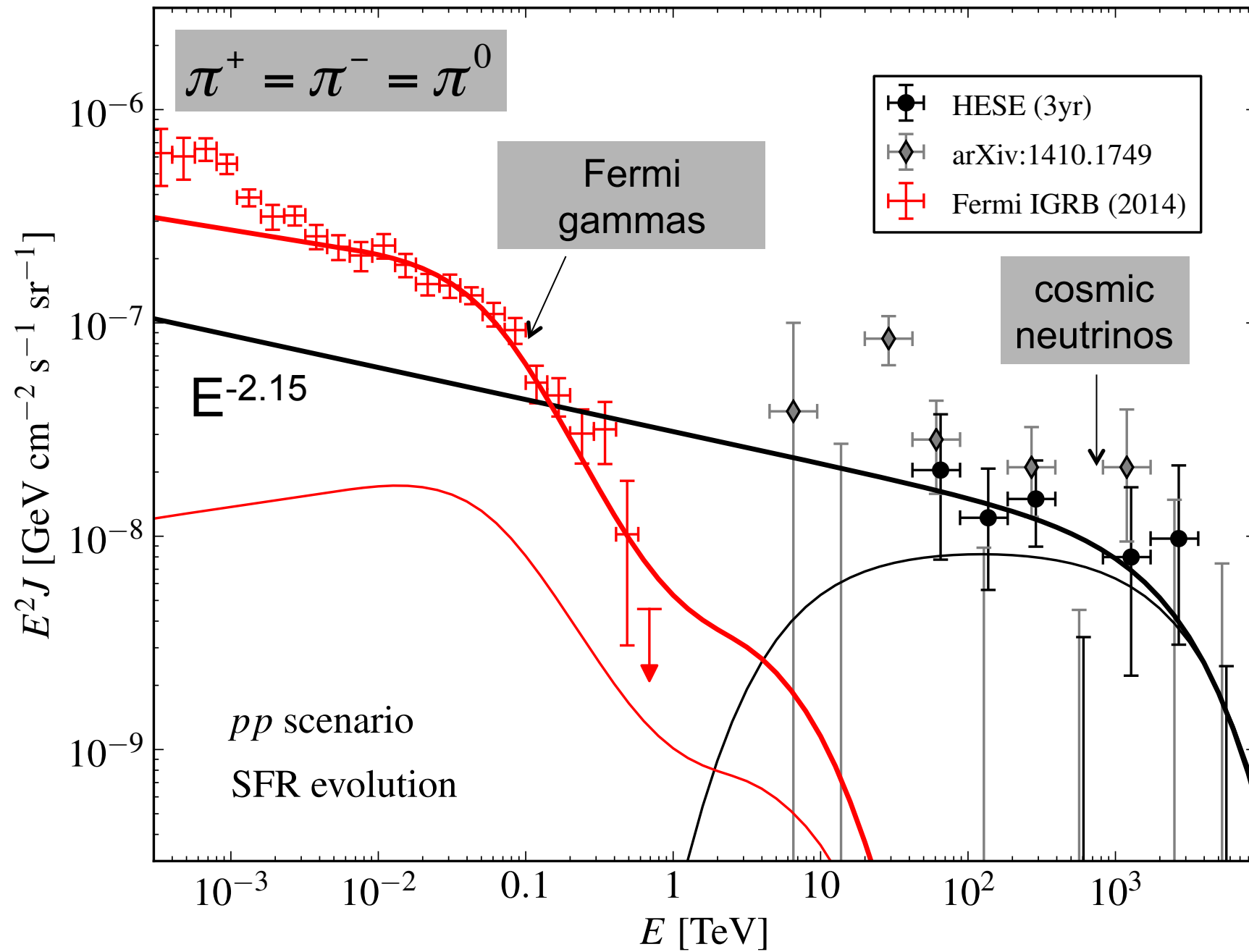
ν

hadronic
gamma rays

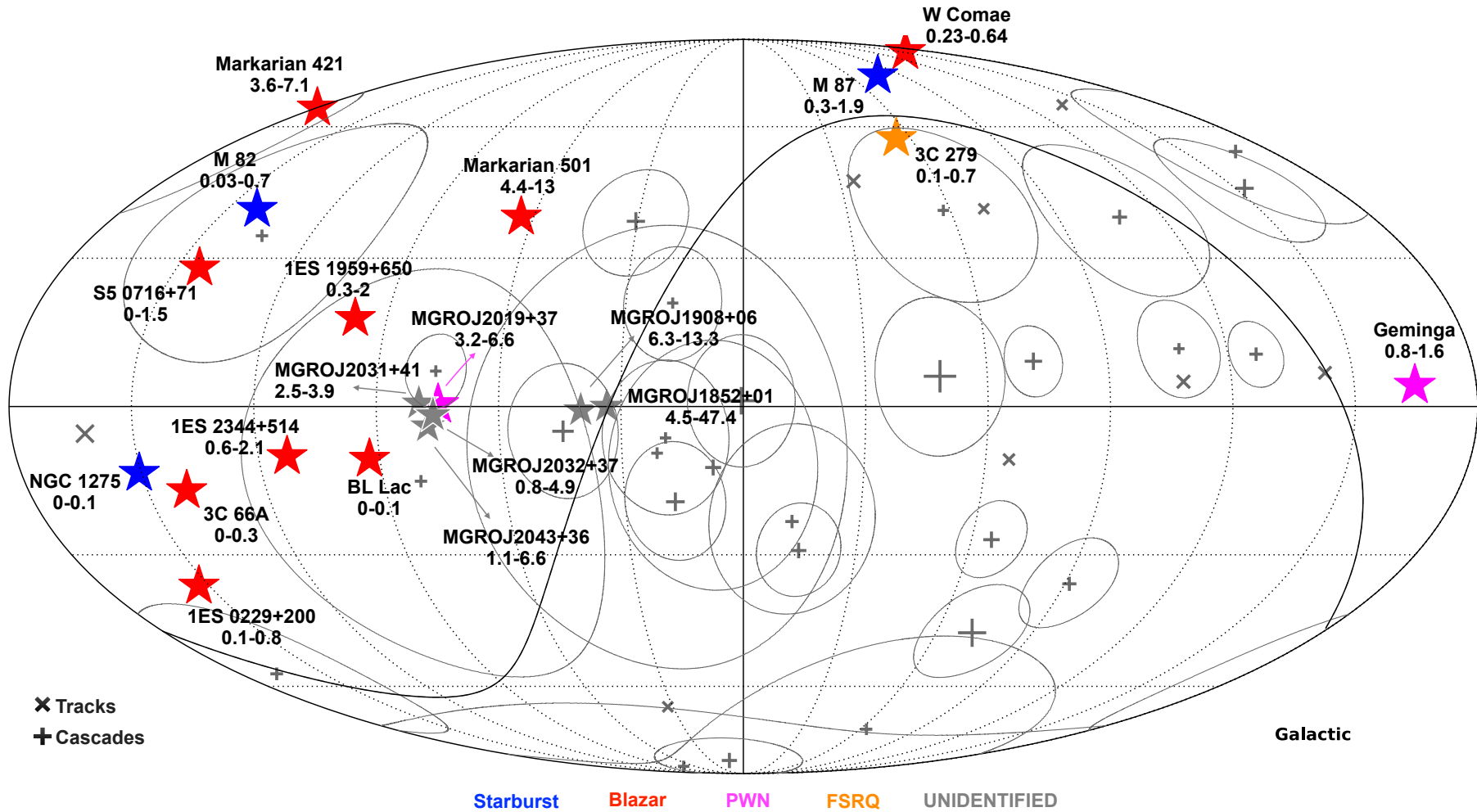
electromagnetic
cascades in CMB



hadronic
gamma rays



number of neutrino events from gamma ray sources in 5 years





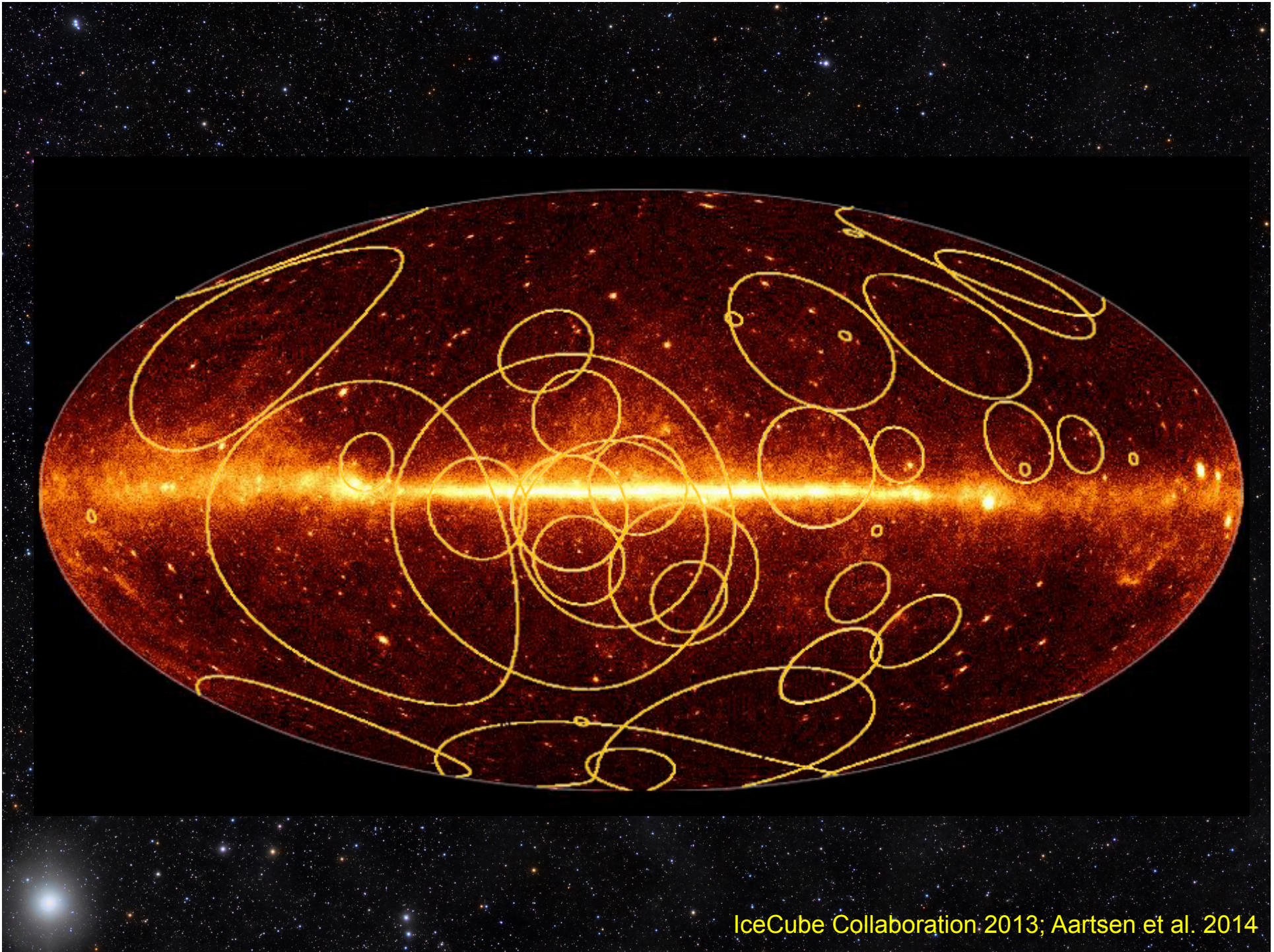
High-Fluence Blazars as Possible Counterparts to PeV Neutrinos

Matthias Kadler

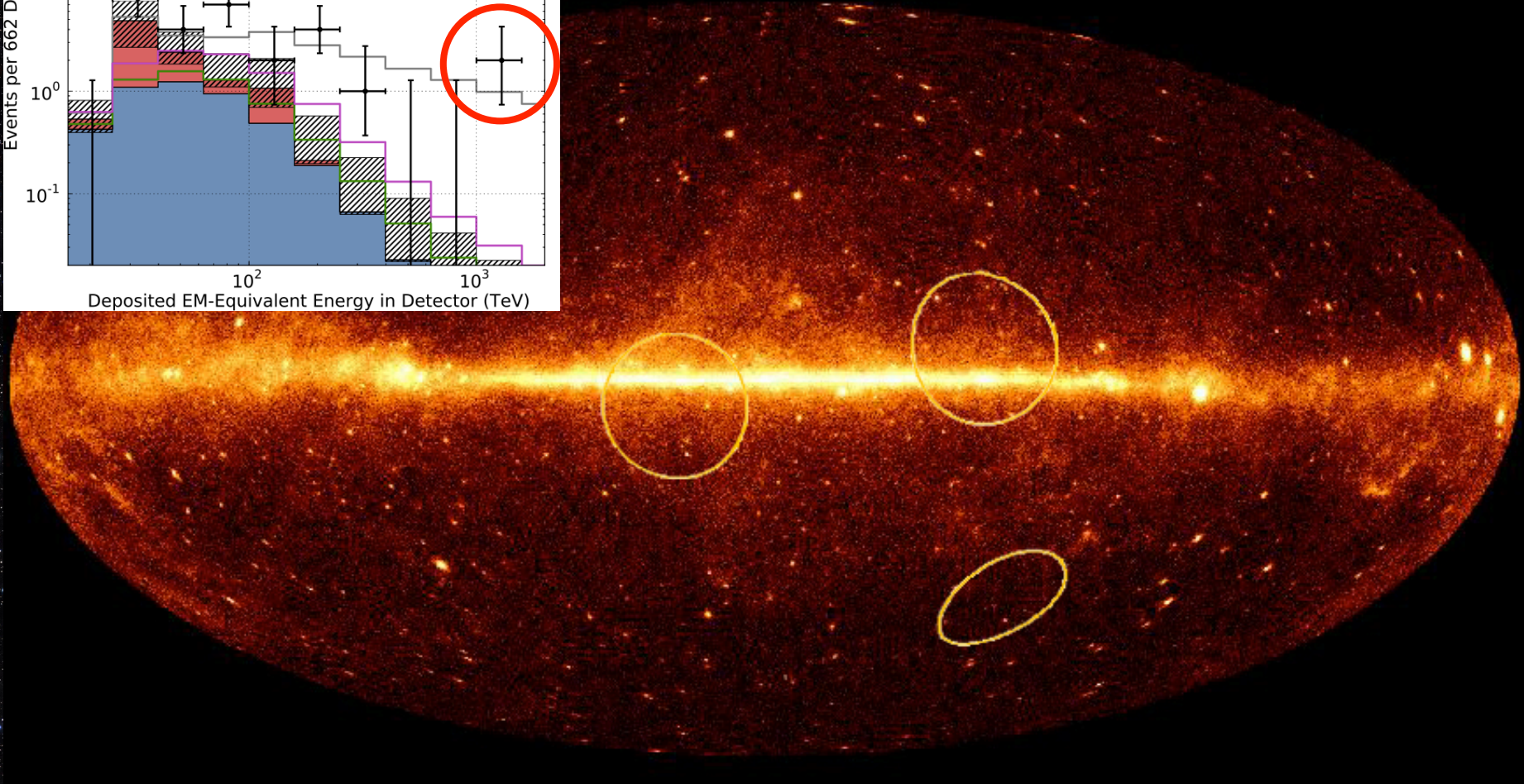
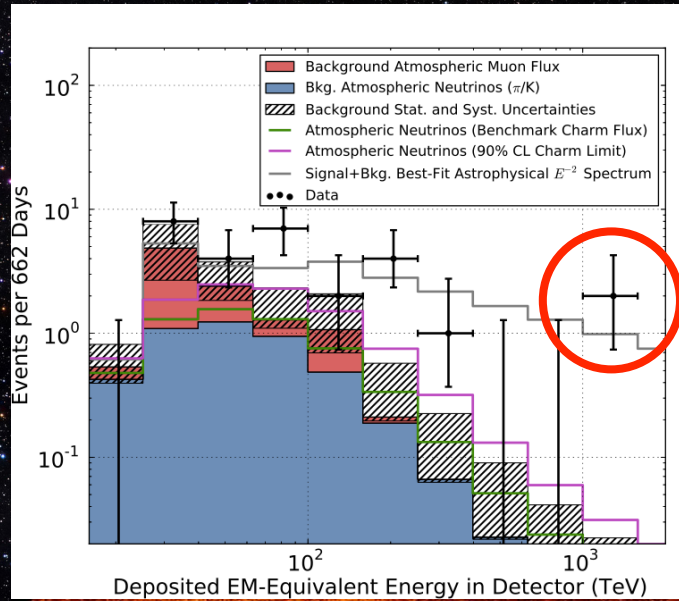
F. Krauß, K. Mannheim, R. Ojha



Perspectives on the Extragalactic Frontier, Trieste, May 6, 2016



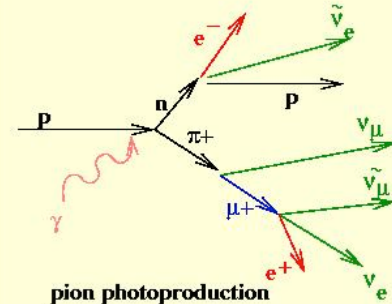
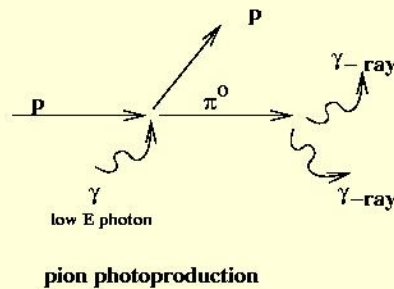
IceCube Collaboration 2013; Aartsen et al. 2014



Ansatz: p- γ in blazar jets

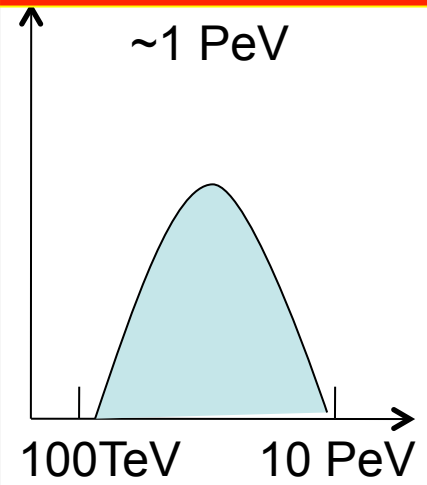
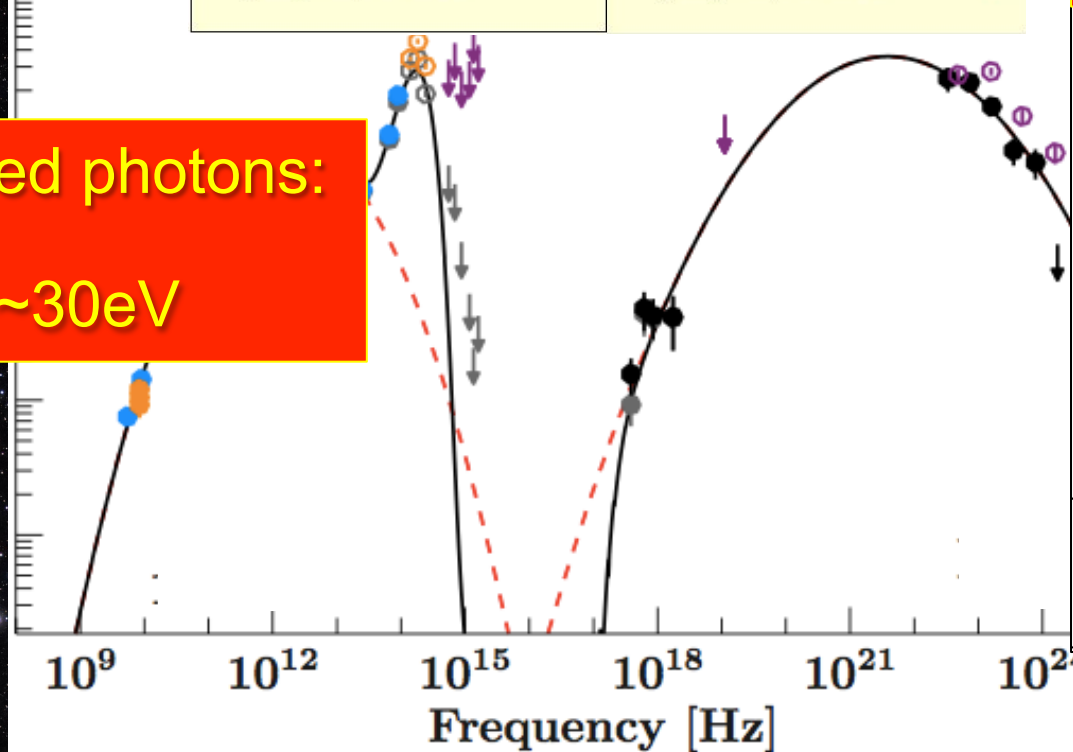
Rel. protons
(jet)

Energy threshold: \sim PeV



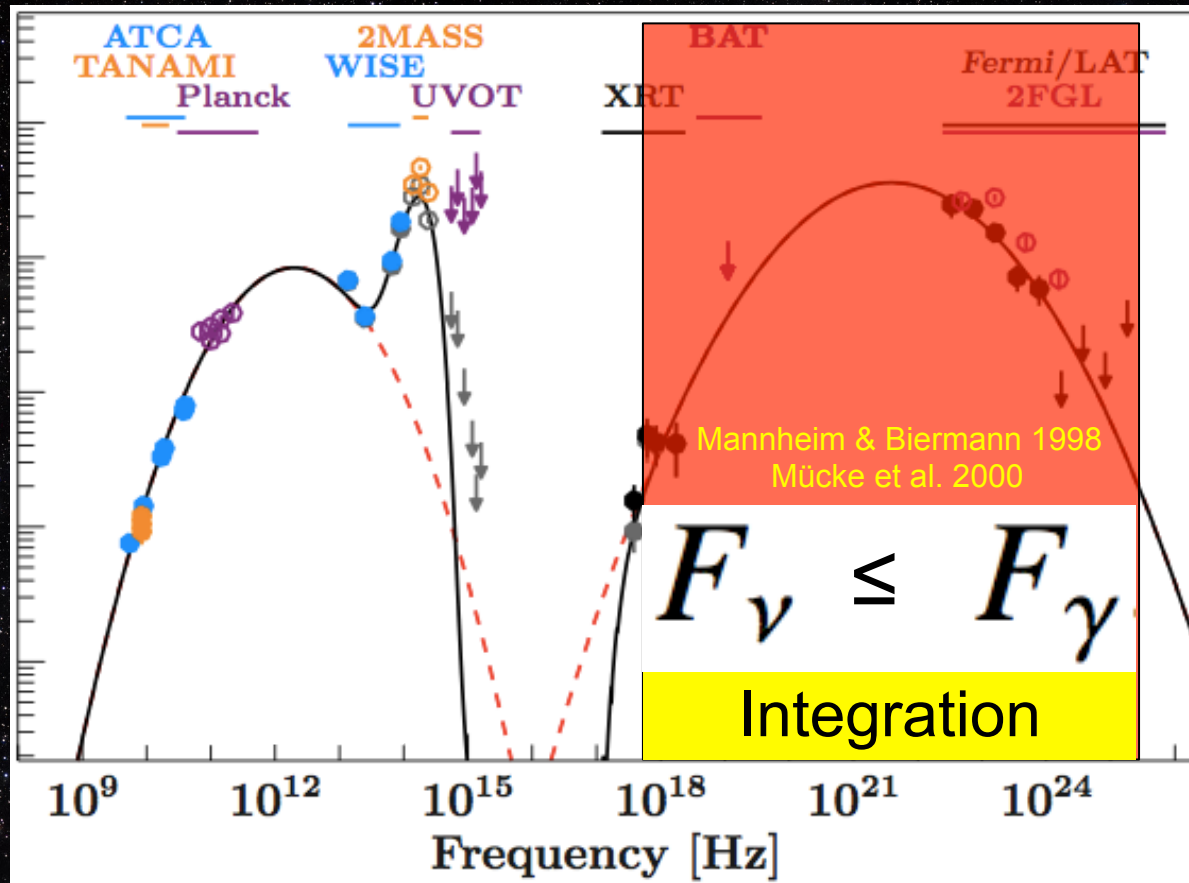
Neutrino
Spectrum
($\Gamma \sim 10$, θ varies)

UV seed photons:
 $\epsilon \sim 30$ eV

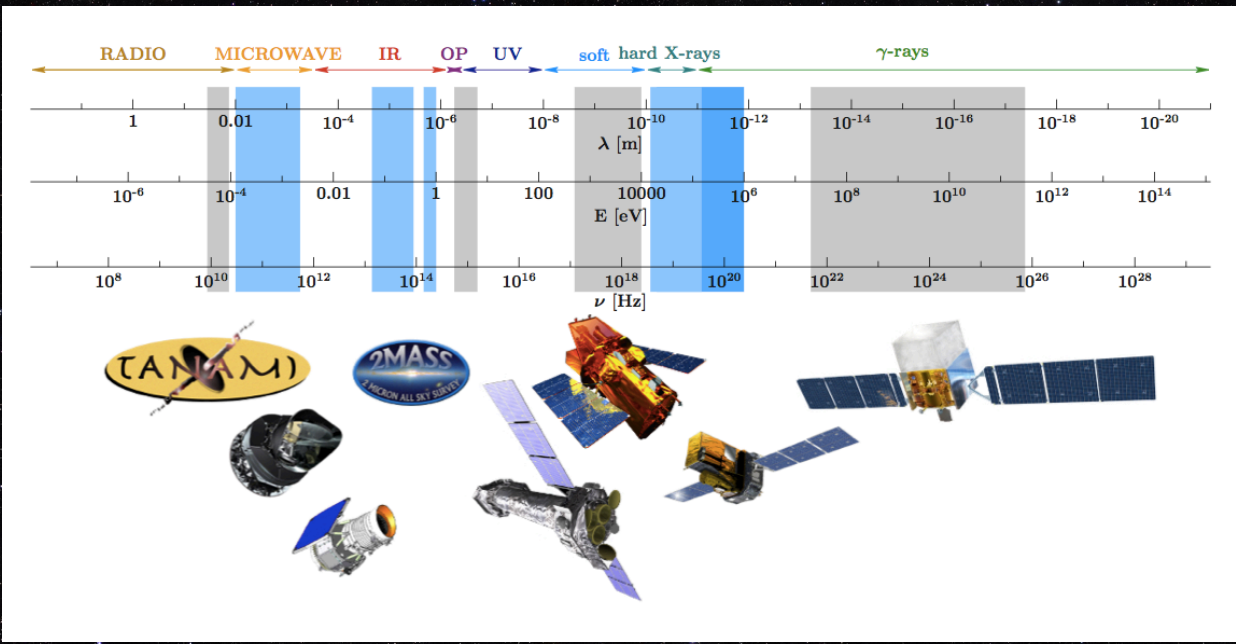


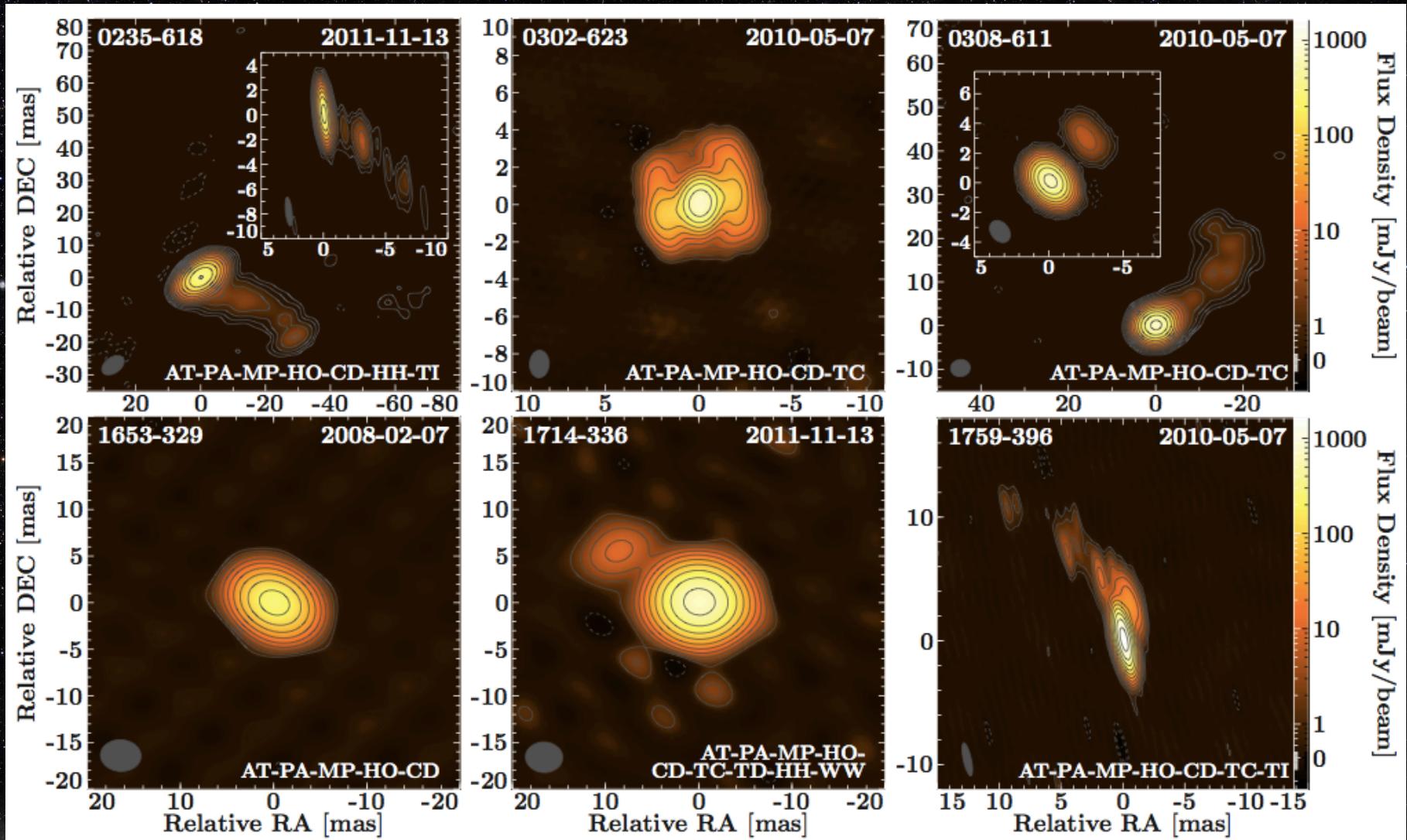
For details, see
Krauß et al. 2014

Ansatz: p- γ in blazar jets



$$N_{\nu, \text{PeV}}^{\text{max}}(\Omega) = A_{\text{eff}, \nu_e} \cdot \left(\frac{F_\gamma}{E_\nu} \right) \cdot \Delta t \rightarrow \underline{\text{need high-fluence FSRQs!}}$$



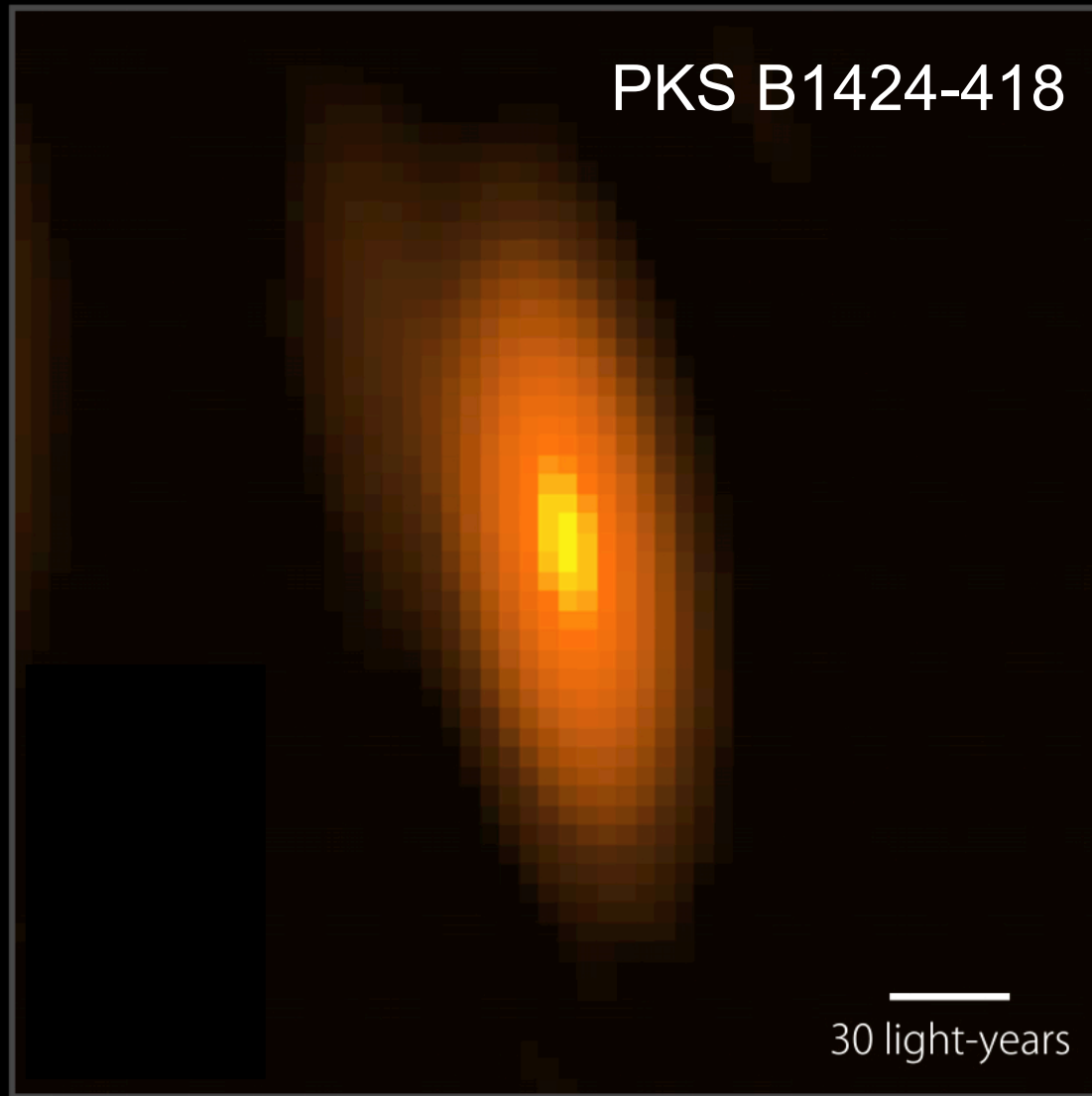




**Most individual blazars have very low
neutrino expectation values!**

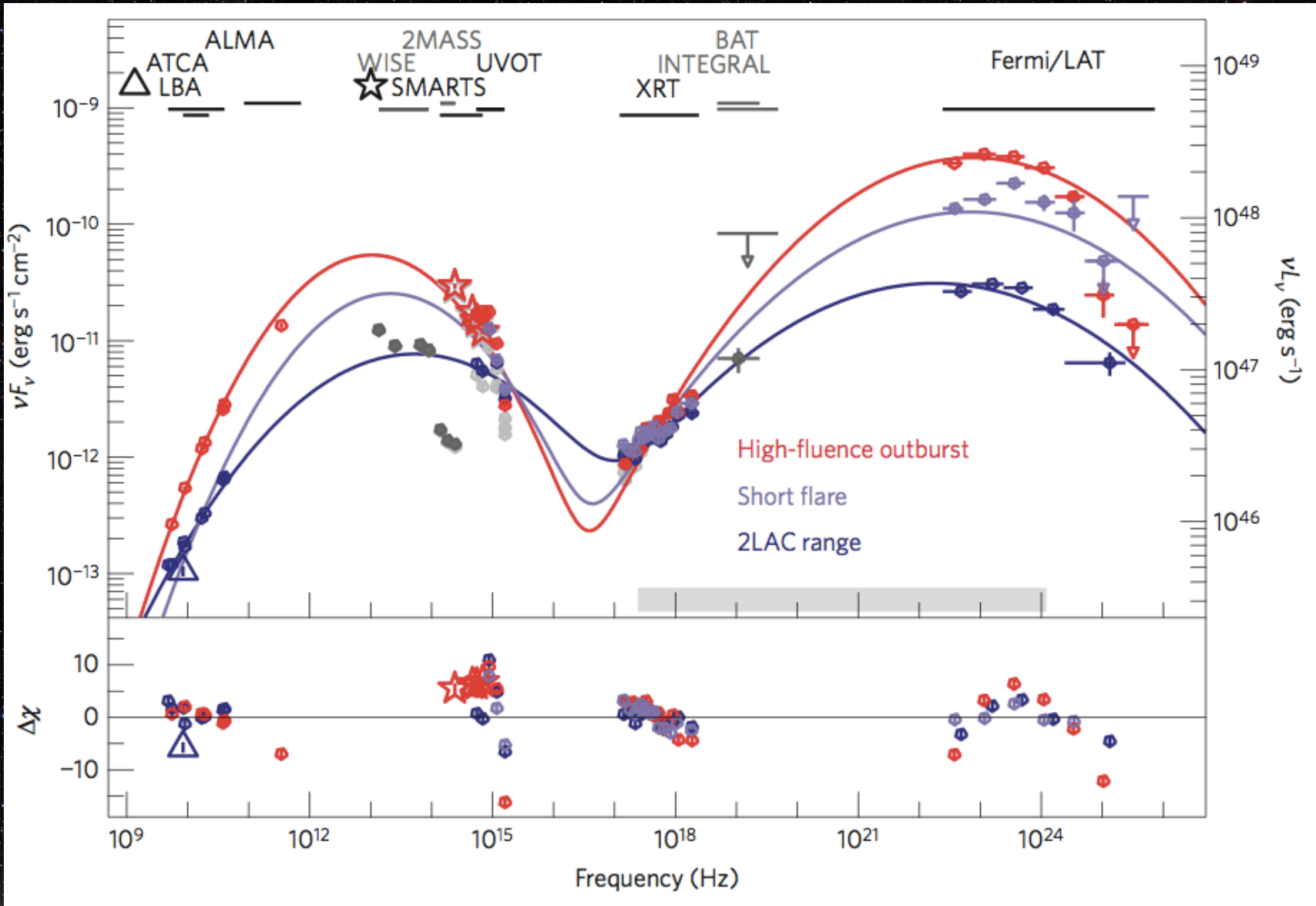
**Look at the very brightest blazars during
major outbursts**

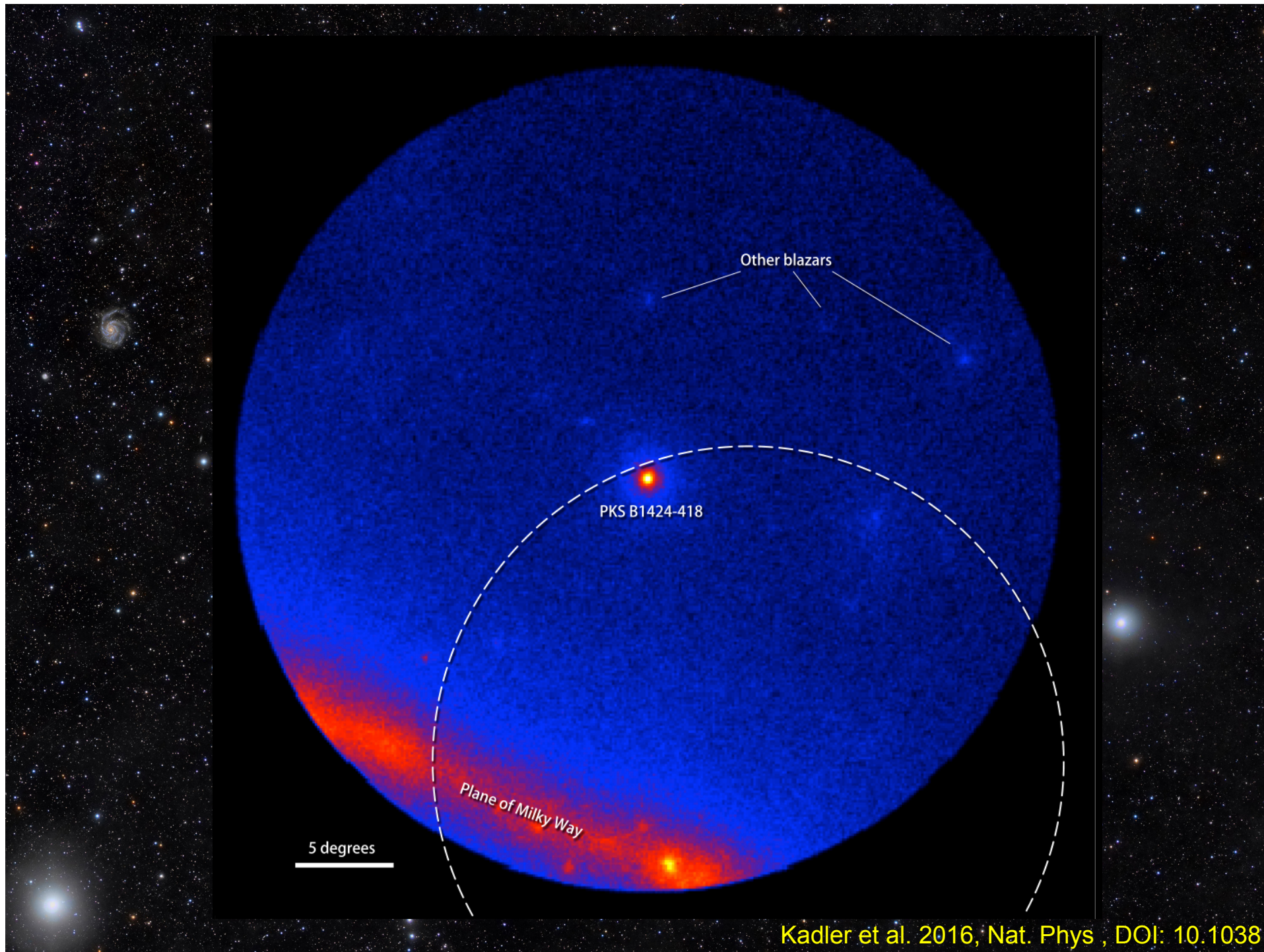
PKS B1424-418

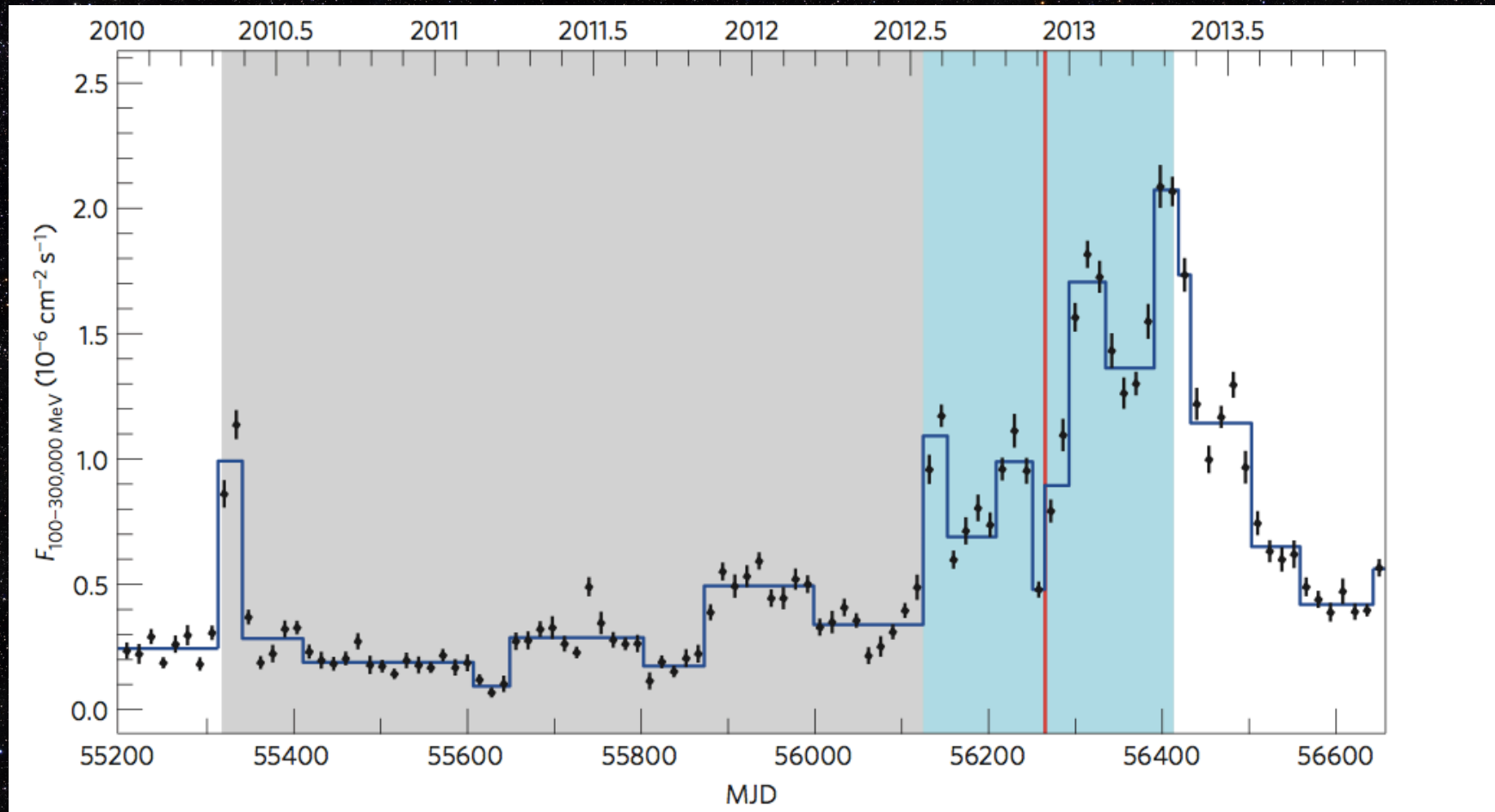


30 light-years

Nov. 13, 2011







$$N_{\nu, \text{PeV}}^{\text{max}}(\Omega) = 1.2$$

$$N_{\nu, \text{PeV}}^{\text{max}}(\Omega) = 4.5$$

Astrofisica Nucleare e Subnucleare

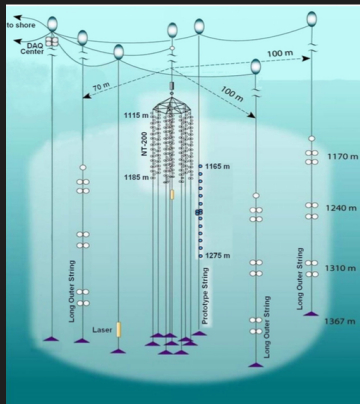
Rivelatori per Neutrini Astrofisici



THE WORLD'S NEUTRINO TELESCOPES

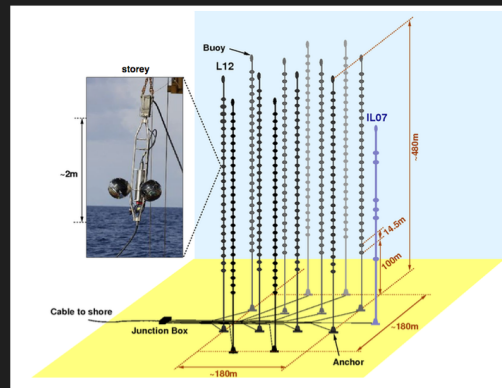
lakes, sea, glaciers

NT-200+



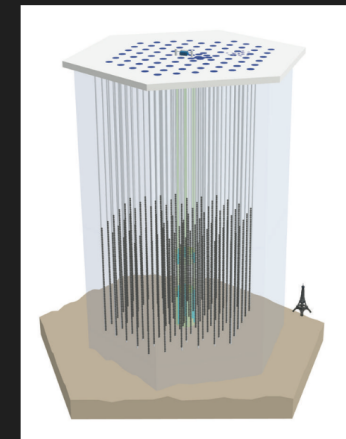
Lake Baikal
 $1/2000 \text{ km}^3$
228 PMTs

Antares



Mediterranean Sea
 $1/100 \text{ km}^3$
885 PMTs

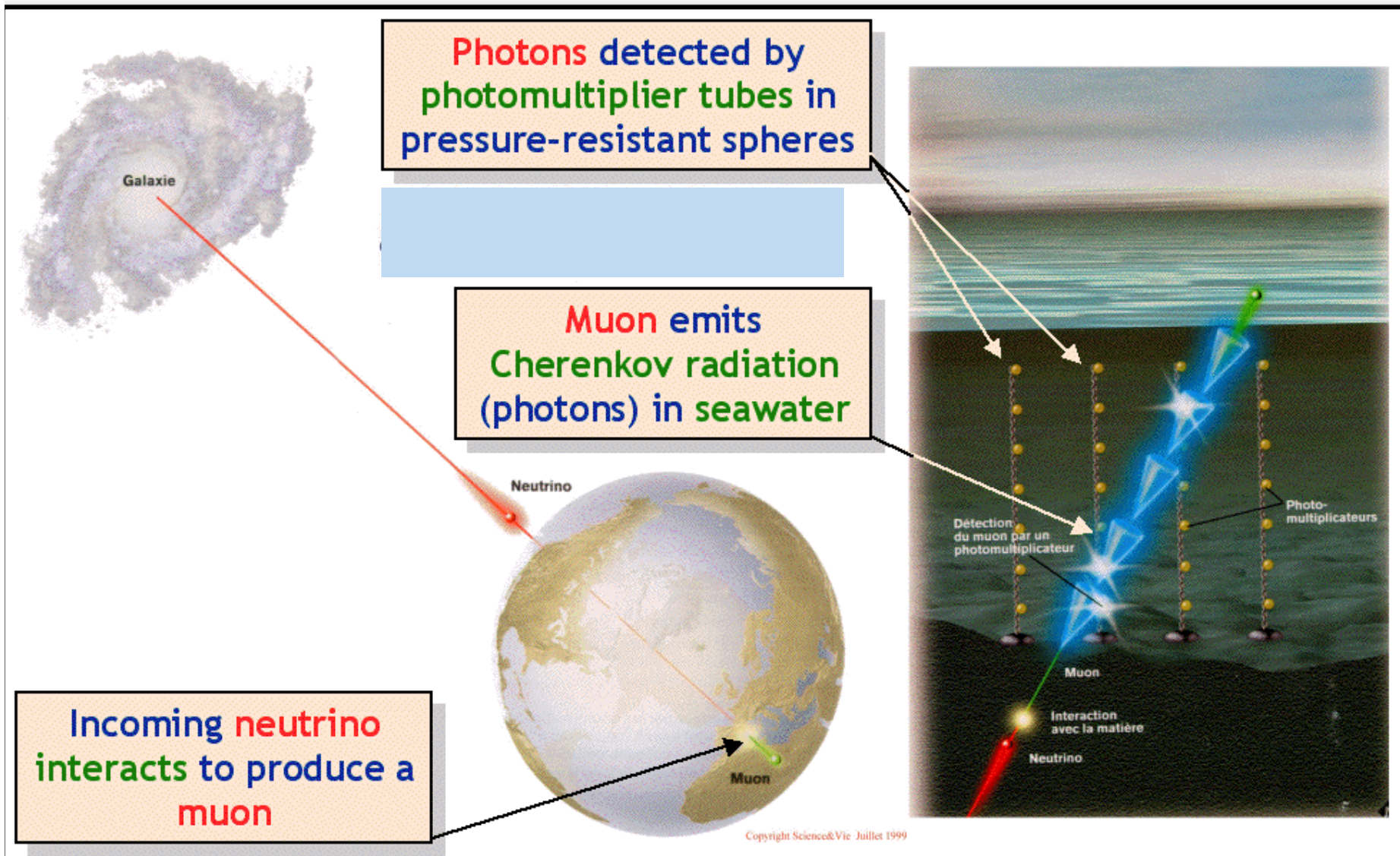
IceCube



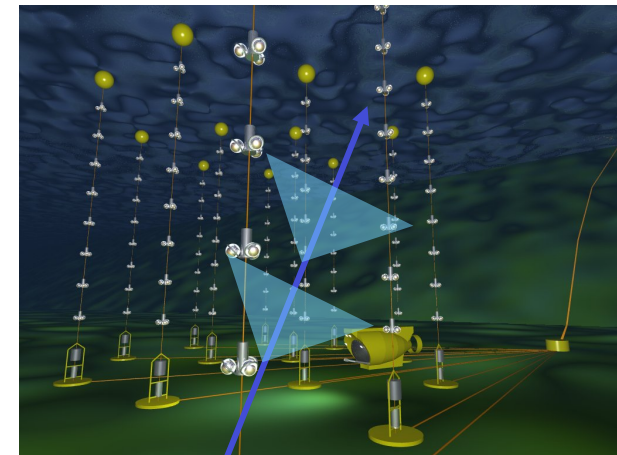
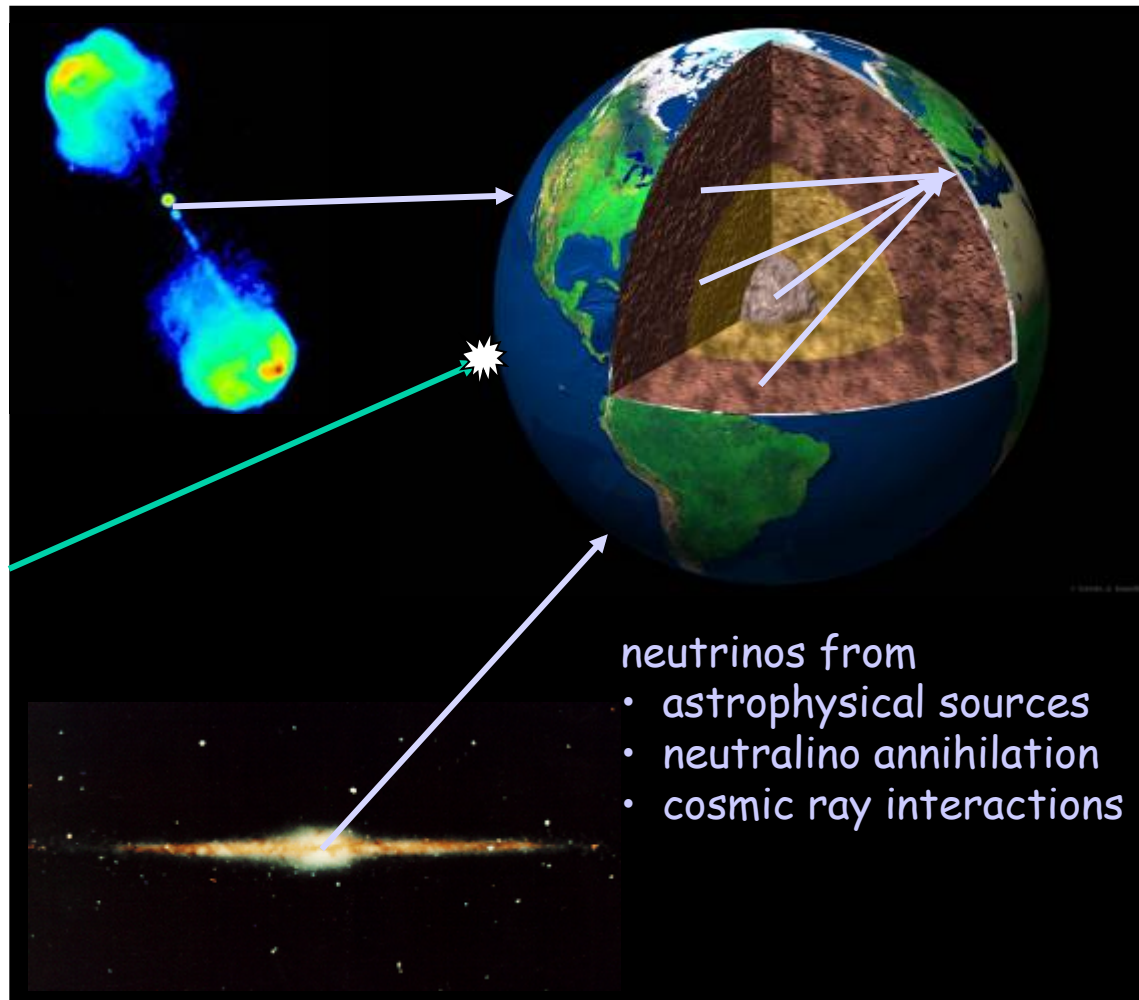
South Pole glacier
 1 km^3
5160 PMTs

—————>
Larger, sparser → higher energies

NEUTRINO ASTRONOMY: Detecting High Energy Neutrinos



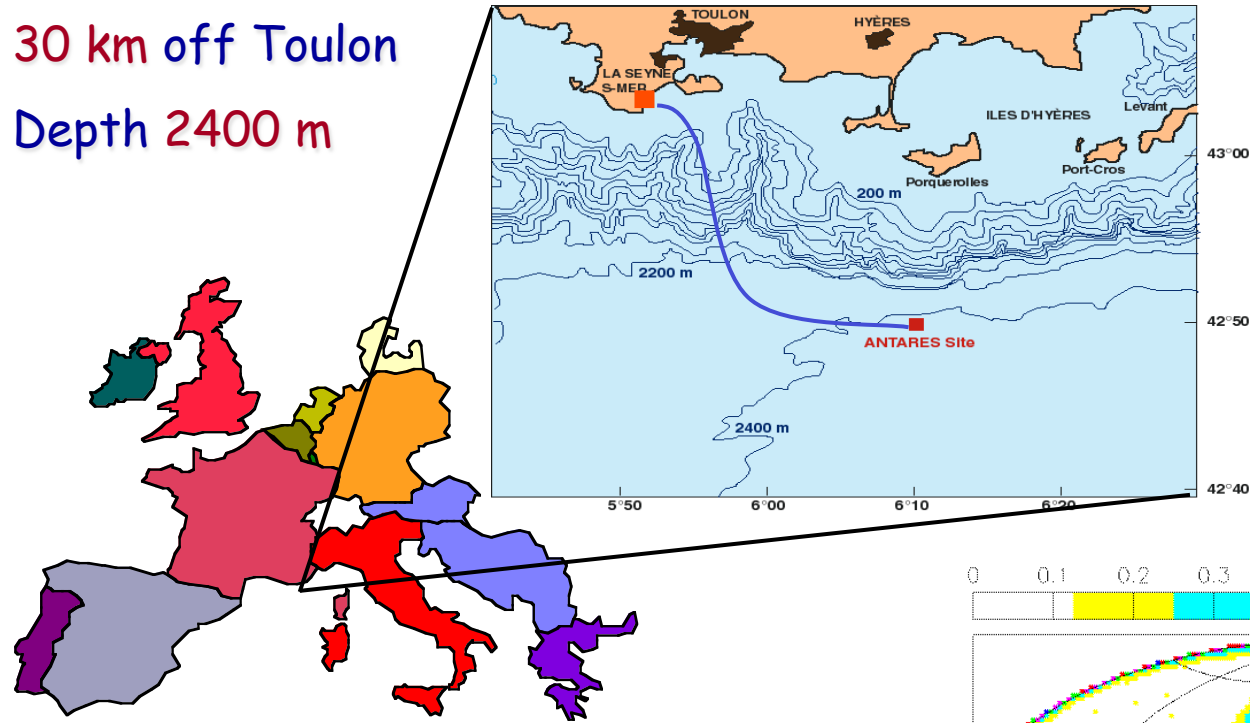
Principles



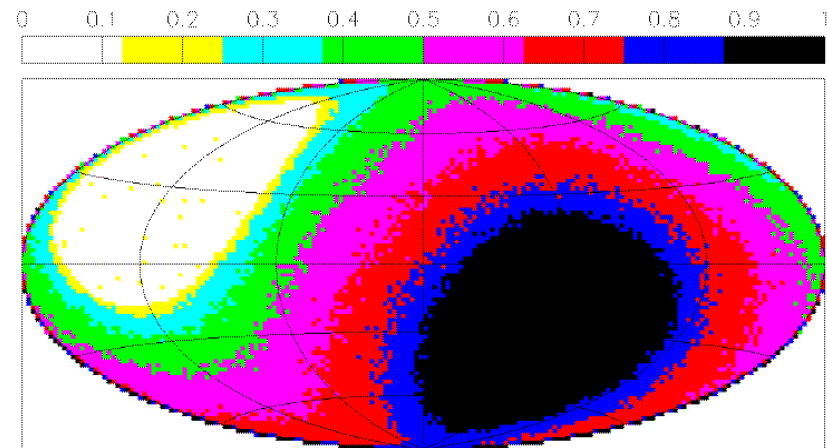
detected and reconstructed via Cerenkov radiation from produced muon

Antares Site

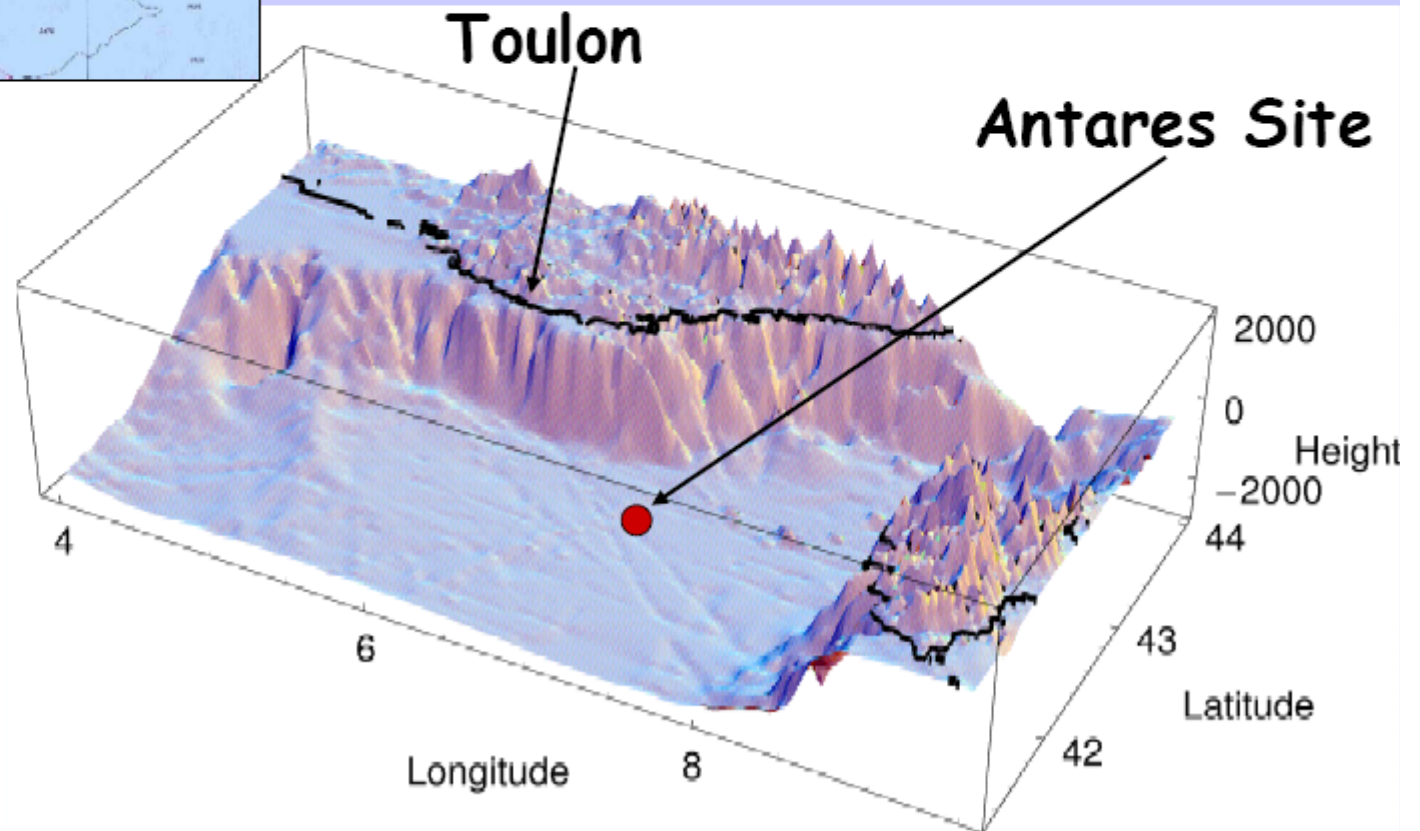
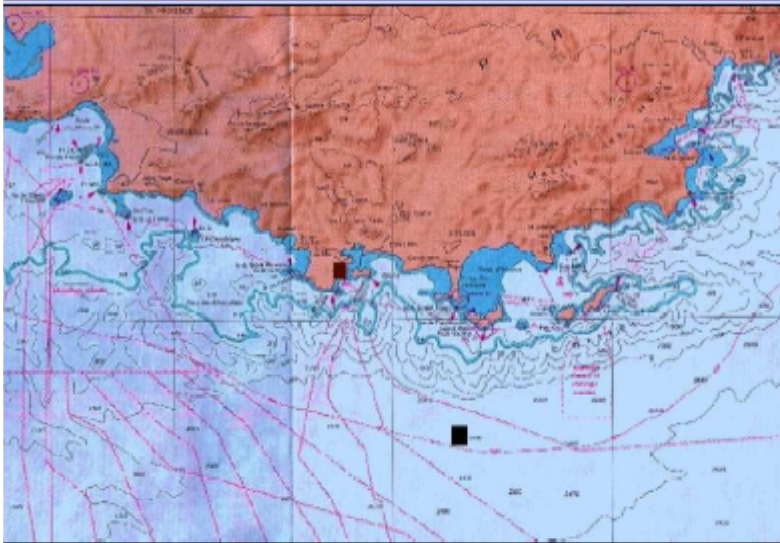
30 km off Toulon
Depth 2400 m



sky coverage 3.6π sr
overlap with AMANDA 0.6π sr



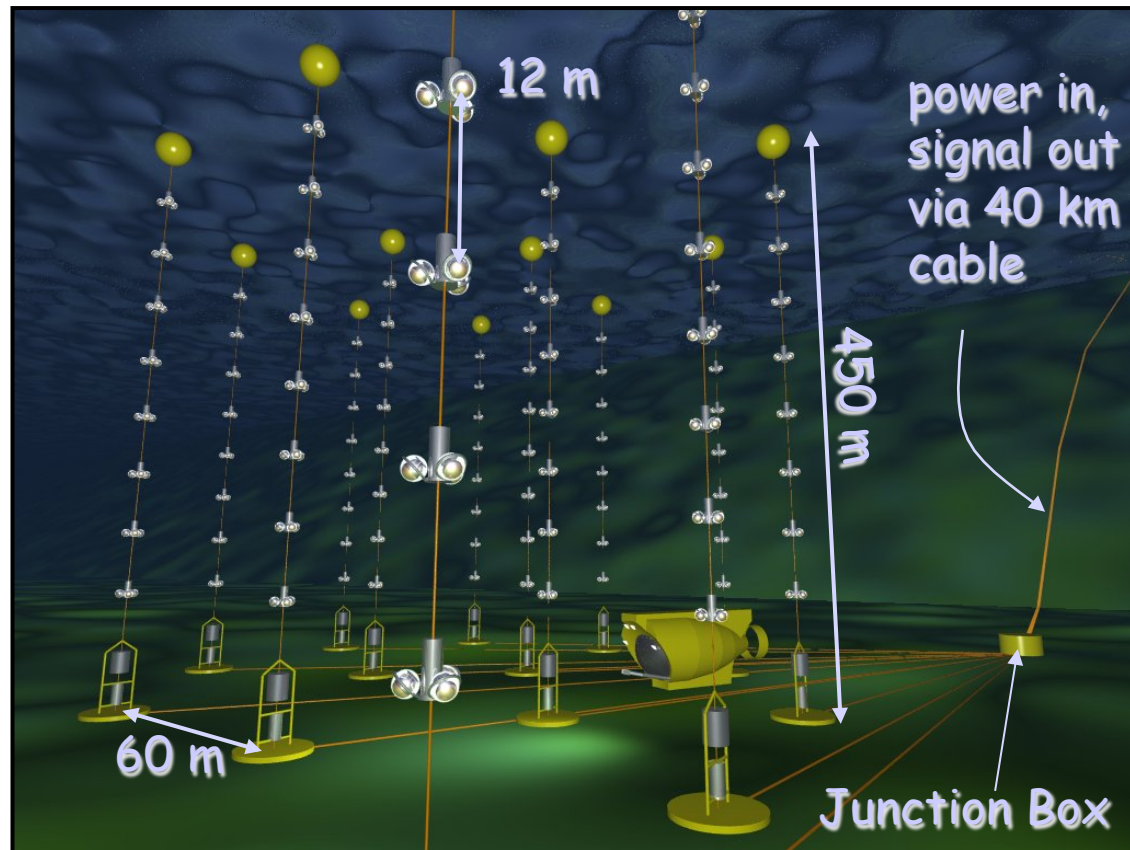
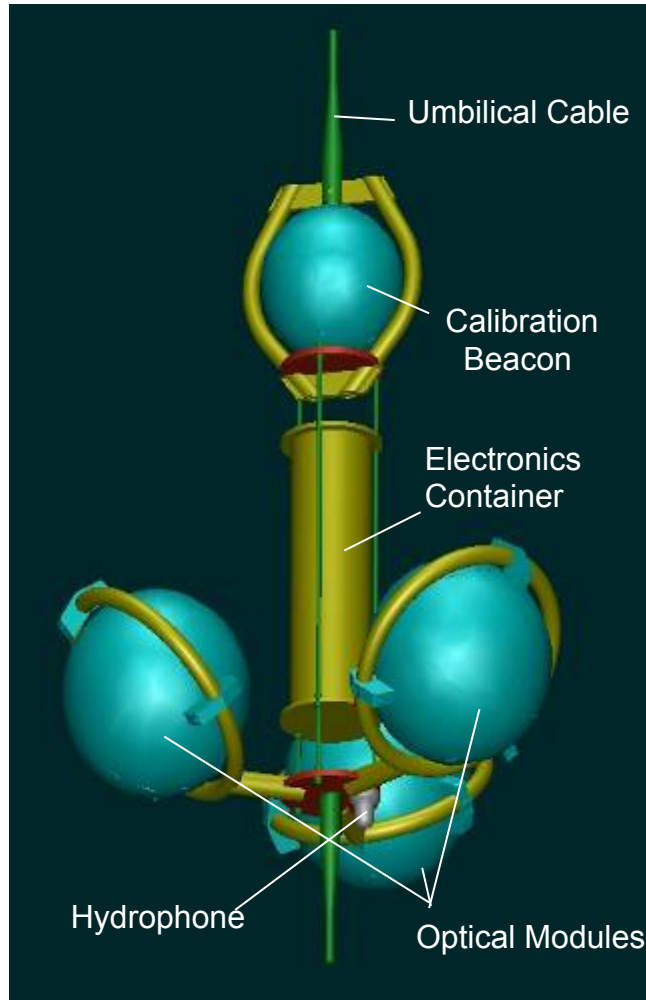
Antares Site



Site Location
42°30' N, 07°00' E

Average Deep
~2600 m
(2685 m in our
simulation)

Detector design

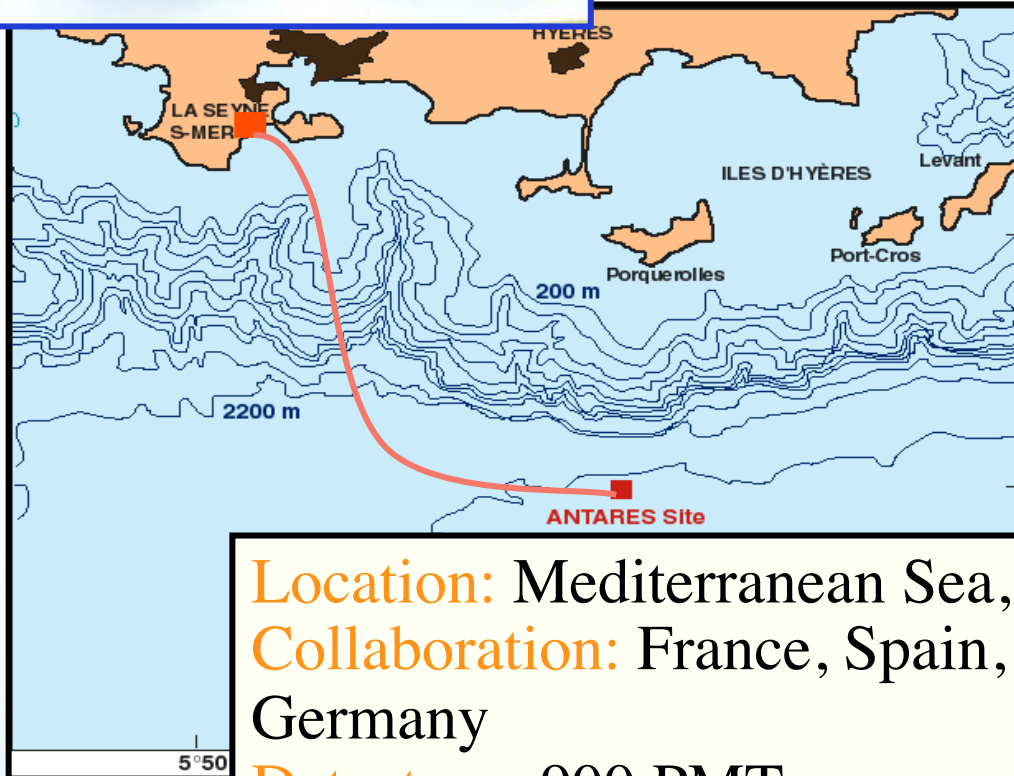
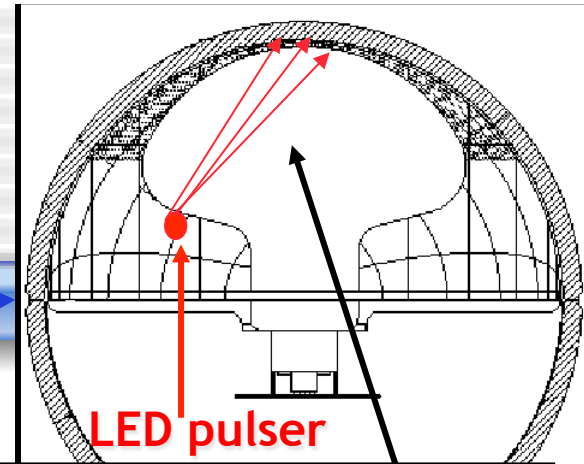


13 strings, 30 storeys/string, 3 OM/storey;
first 100 m uninstrumented

Glass sphere (Nautilus)



ANTARES



Large area photocathode



Location: Mediterranean Sea, off the southern French coast

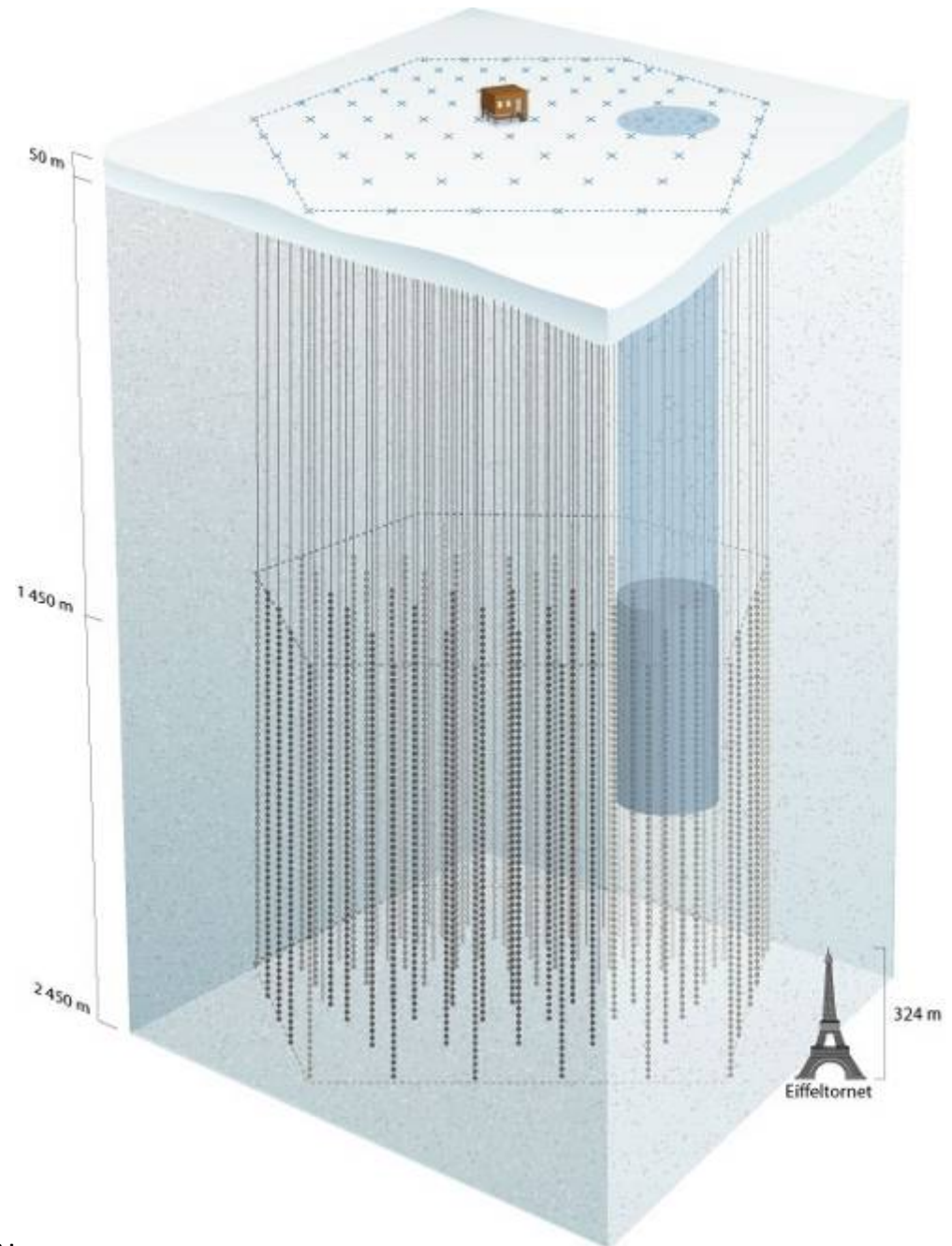
Collaboration: France, Spain, UK, Russia, Holland, Italy, Germany

Detector: ~900 PMTs

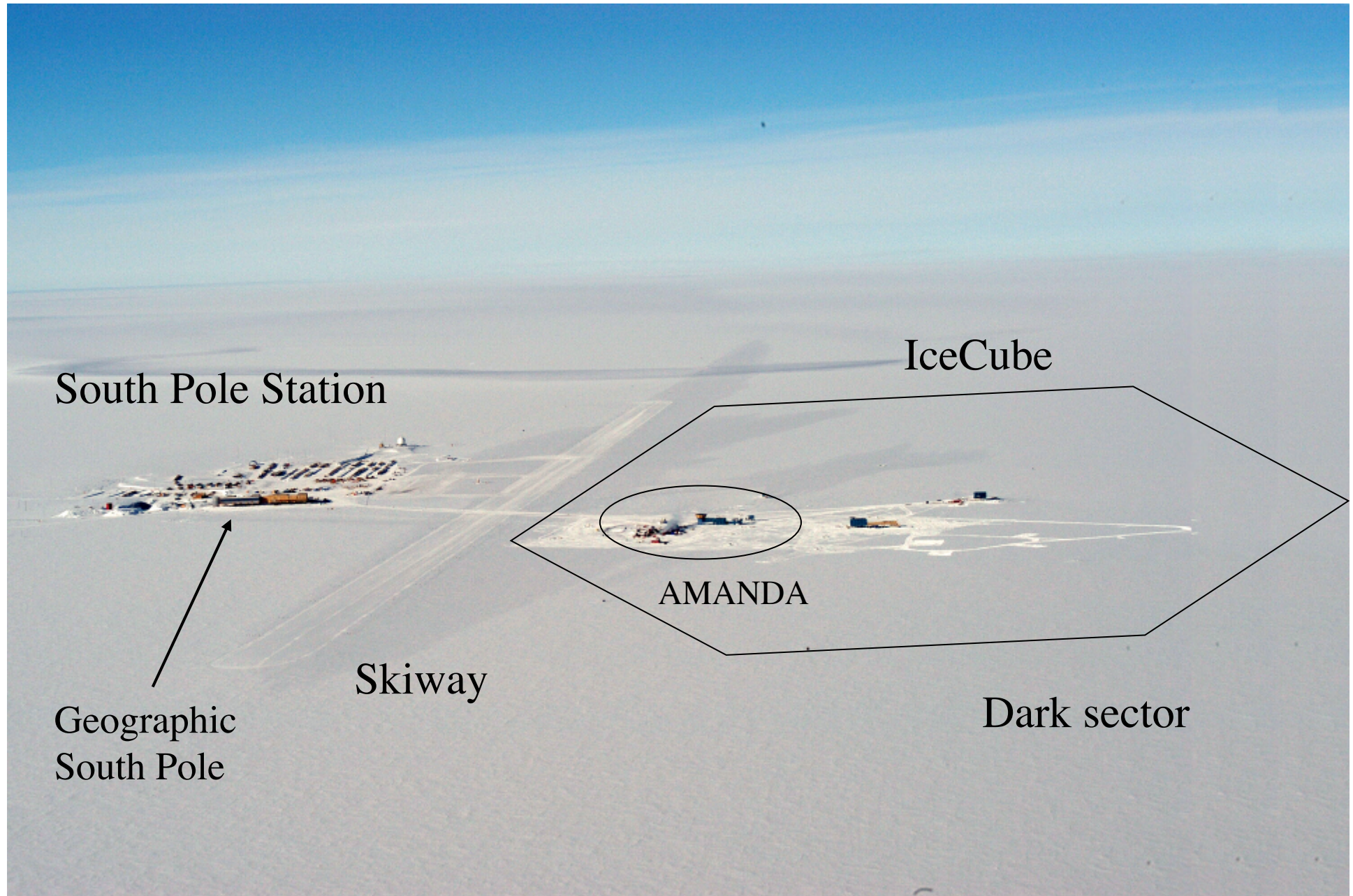
Status: Under construction, full deployment by 2005

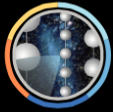
IceCube

- 4800 Digital Optical modules on 80 strings
- 160 Ice-Cherenkov tank surface array (IceTop)
- Instrumenting 1 km³ of Antarctic Ice
- Surrounding existing AMANDA detector
 - 677 Optical Modules
- Just completed 3rd construction season



IceCube at the South Pole





THE ICECUBE NEUTRINO OBSERVATORY

Deployed in the deep glacial ice at the South Pole

11

5160 PMTs

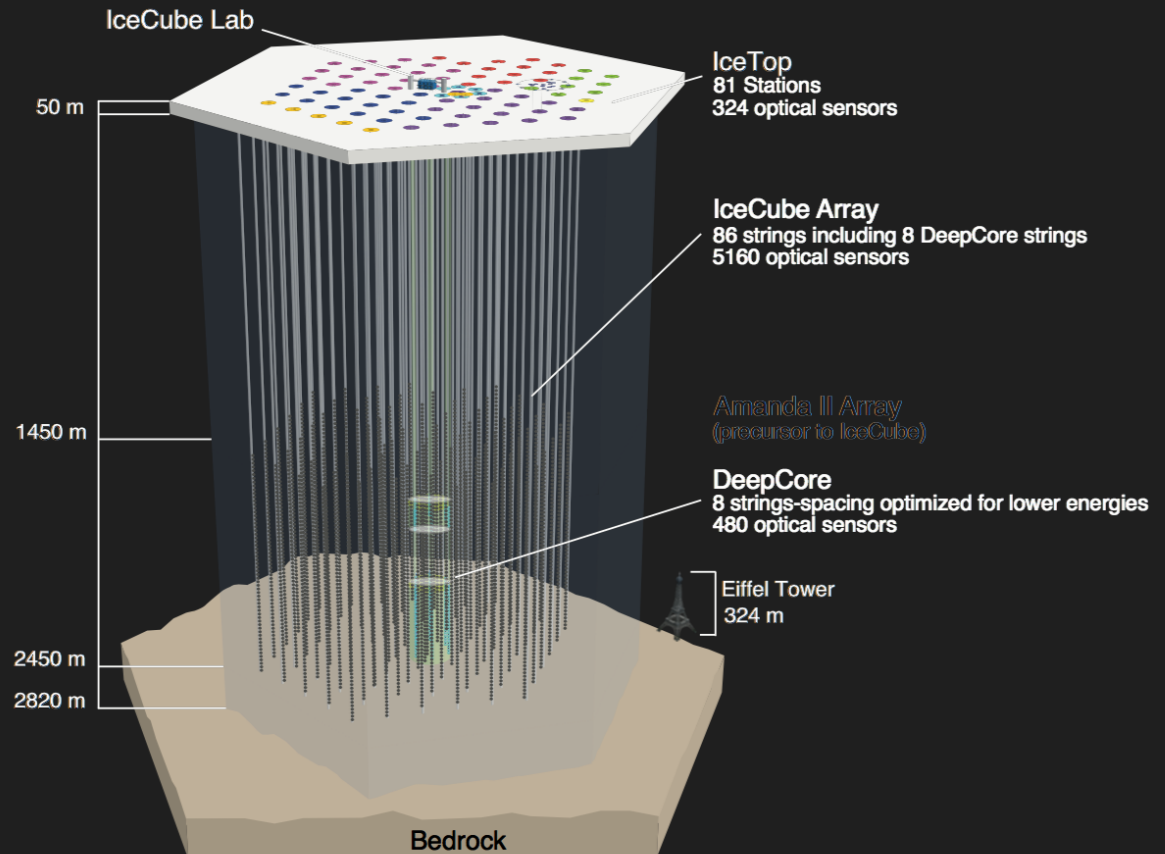
1 km³ volume

86 strings

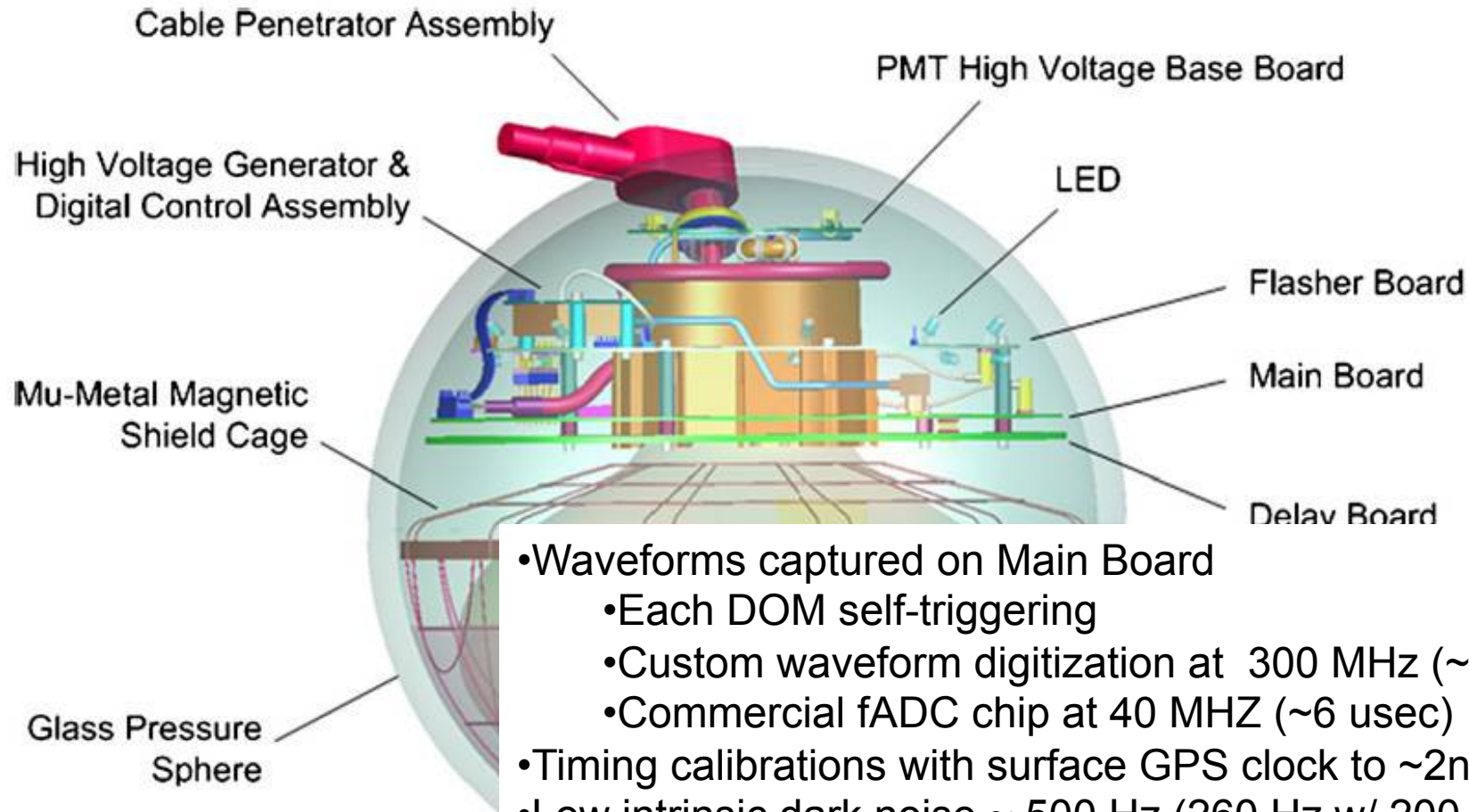
17 m vertical spacing

125 m string spacing

Completed **2010**



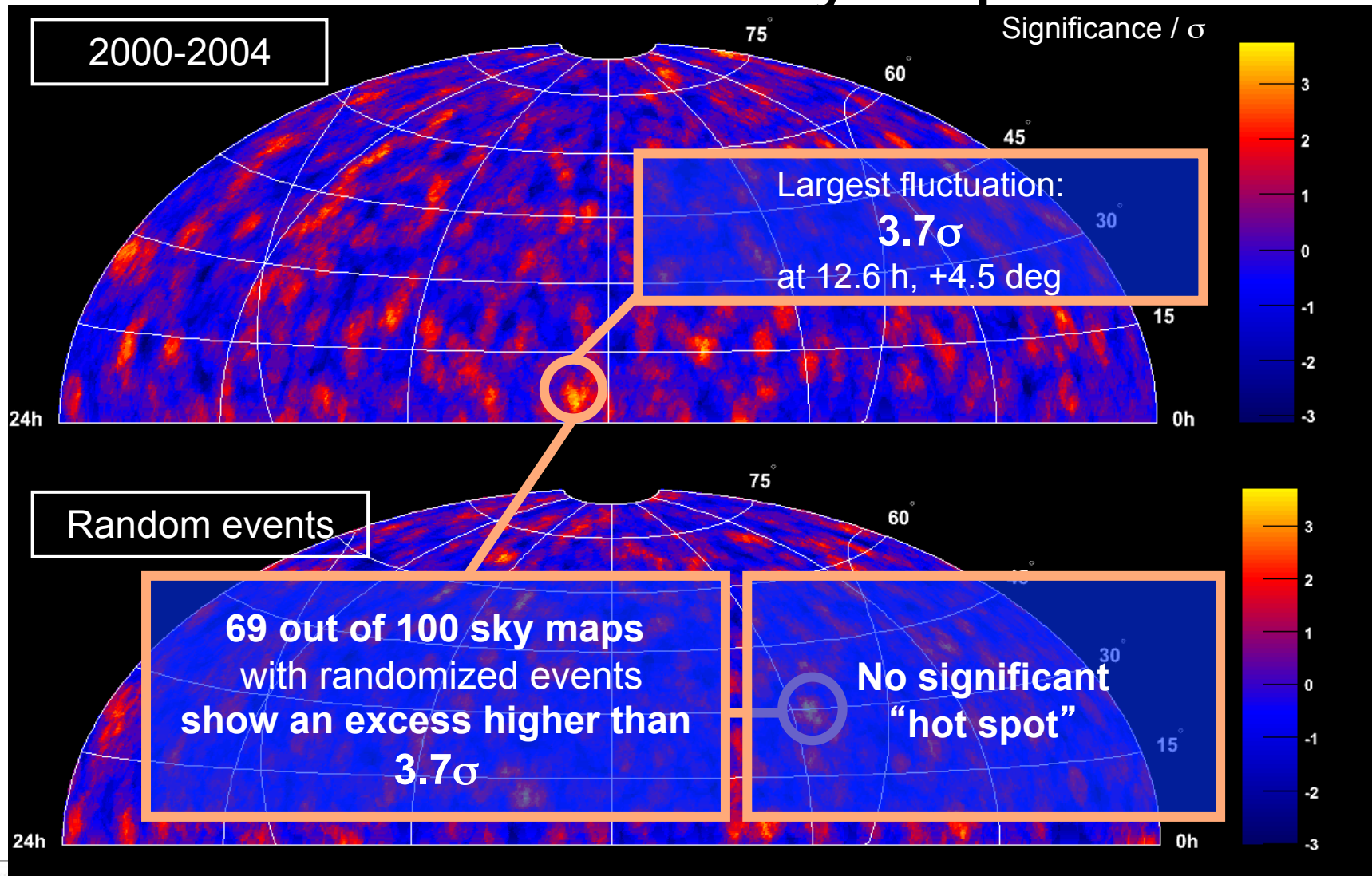
The Digital Optical Module (DOM)



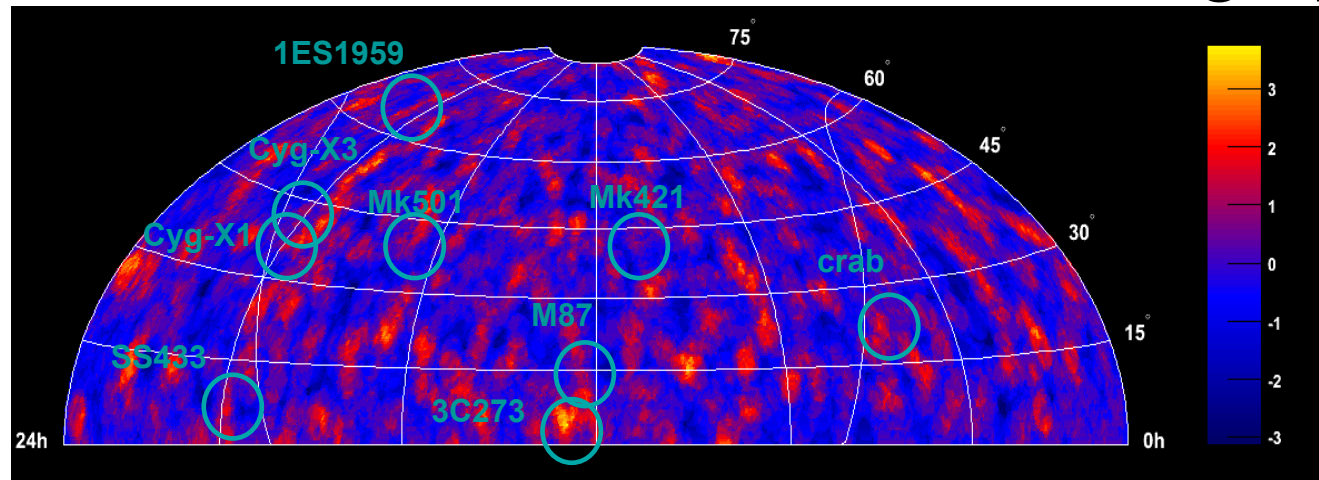
- Waveforms captured on Main Board
 - Each DOM self-triggering
 - Custom waveform digitization at 300 MHz (~425ns)
 - Commercial fADC chip at 40 MHz (~6 usec)
- Timing calibrations with surface GPS clock to ~2ns
- Low intrinsic dark noise ~ 500 Hz (260 Hz w/ 200 μ sec)
- Low Power consumption: <5 W per DOM
- Large dynamic range (~1000pe/10ns)
- Main board software is reprogrammable
- Self calibrating
- Very robust design: Failure rate <1%



AMANDA Skymap



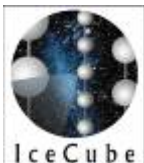
Search for neutrinos from interesting spots



event selection optimized for both $dN/dE \sim E^{-2}$ and E^{-3} spectra

source	nr. of ν events (5 years)	expected background (5 years)	flux upper limit $\Phi_{90\%}(E_\nu > 10 \text{ GeV})$ [$10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$]
Markarian 421	6	7.37	0.43
M87	6	6.08	0.50
1ES1959+650	5	4.77	0.78
SS433	4	6.14	0.27
Cygnus X-3	7	6.48	0.67
Cygnus X-1	8	7.01	0.76
Crab Nebula	10	6.74	1.01
3C273	8(1yr)	4.72(1yr)	0.99

No significant excess observed



E. Blaufuss - Neutrino Physics with IceCube





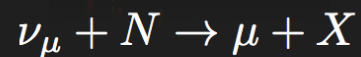
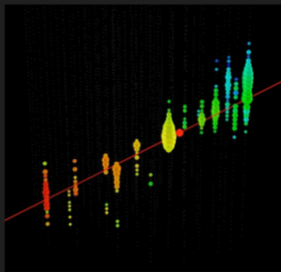
NEUTRINO EVENT SIGNATURES

Signatures of signal events

12



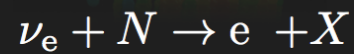
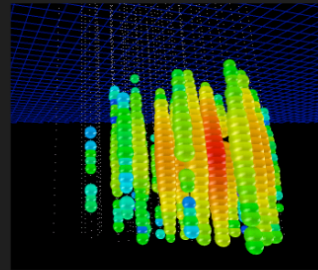
CC Muon Neutrino



track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies

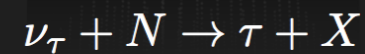
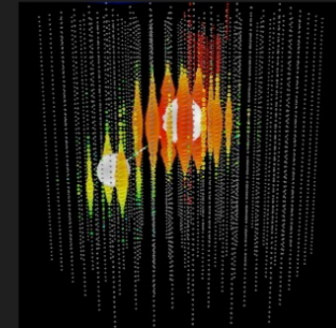
Neutral Current / Electron Neutrino



cascade (data)

$\approx \pm 15\%$ deposited energy resolution
 $\approx 10^{\circ}$ angular resolution (in IceCube)
(at energies ≈ 100 TeV)

CC Tau Neutrino



"double-bang" (≈ 10 PeV) and other signatures (simulation)

(not observed yet: τ decay length is 50 m/PeV)



“HISTORY”

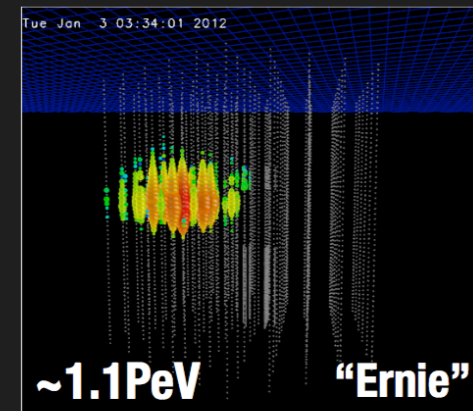
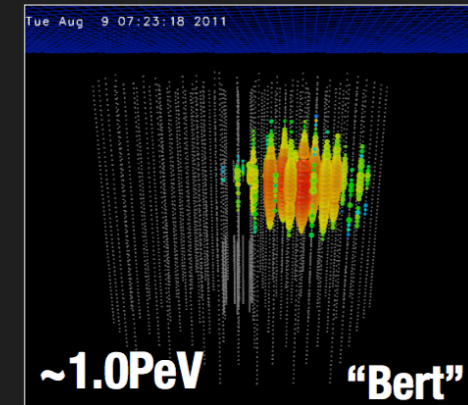
Appearance of ~ 1 PeV cascades as an at-threshold background

Two very interesting events in IceCube (between May 2010 and May 2012)

2.8σ excess over expected background in GZK analysis (PRL 111, 021103 (2013))

There should be more

GZK analysis is only sensitive to very specific event topologies at these energies





WHAT DID ICECUBE FIND? (4 YEARS)

54 events!

53(+1) events observed!

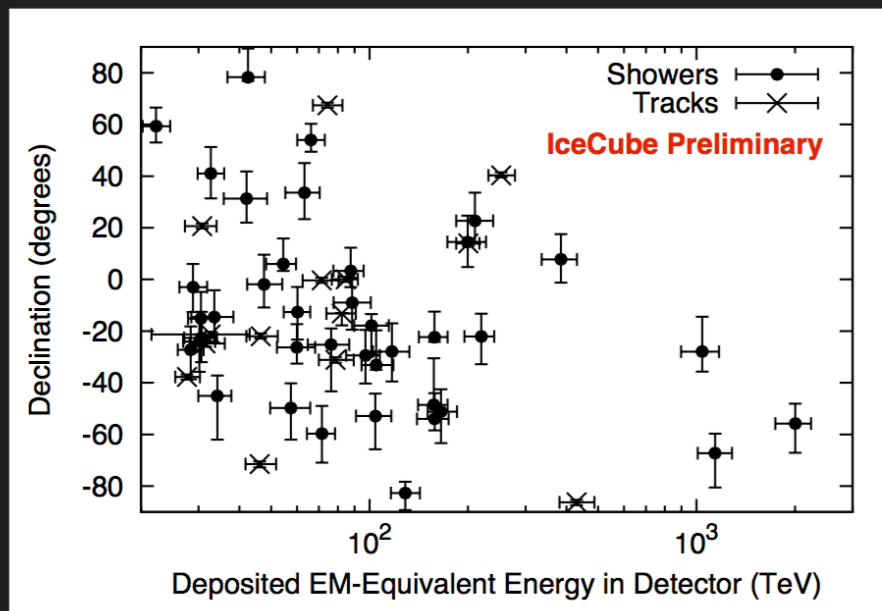
Estimated background:

$9.0^{+8.0}_{-2.2}$ atm. neutrinos

12.6 ± 5.1 atm. muons

One of them is an obvious (but expected) background

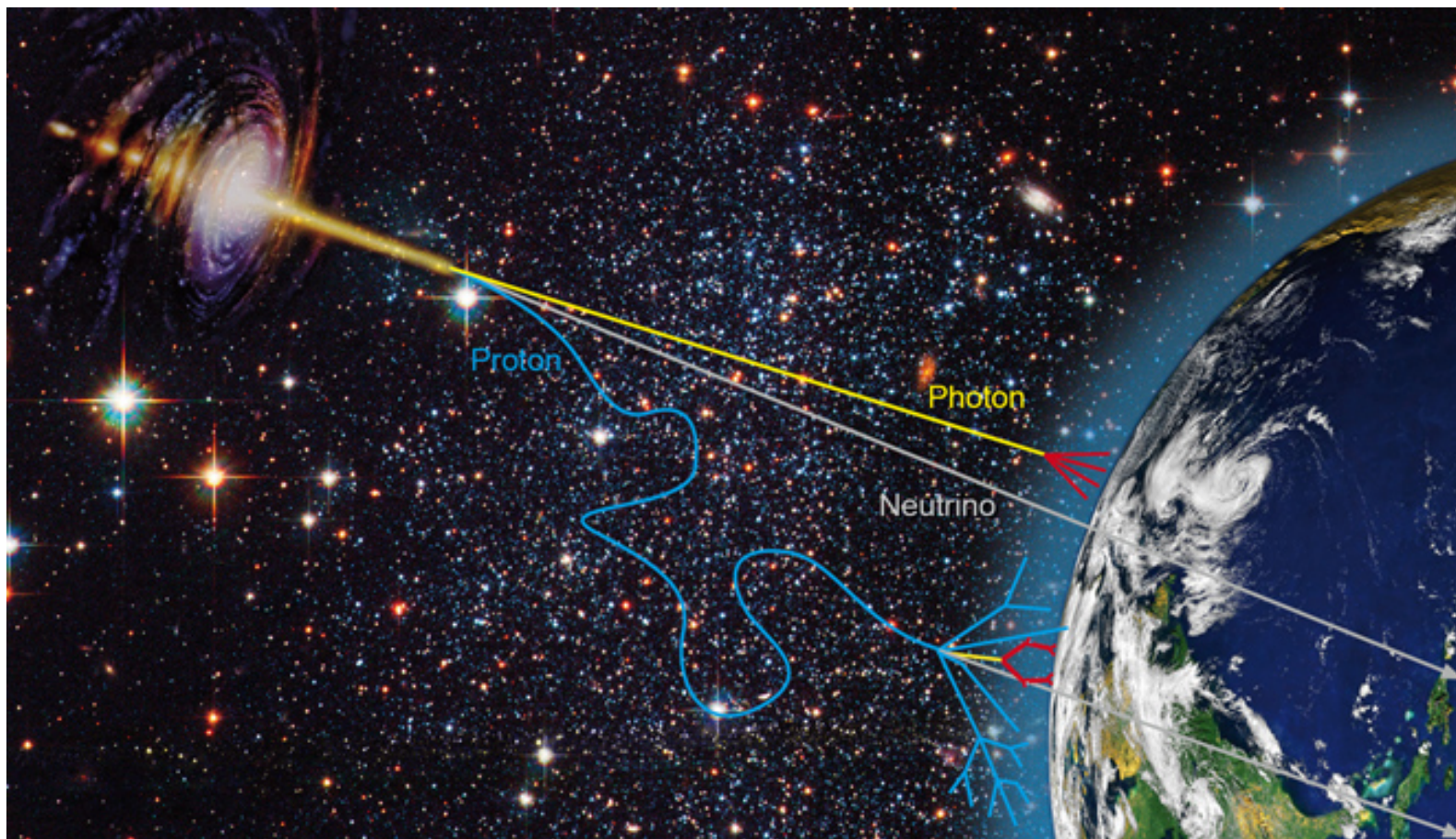
coincident muons from two CR air showers



full likelihood fit of all components:
 6.5σ for 53(+1) events

presented at ICRC2015 / PoS(ICRC2015)1081

Astrophysical Neutrinos





ENERGY SPECTRUM (4 YEARS)

energy deposited in the detector (lower limit on neutrino-energy)

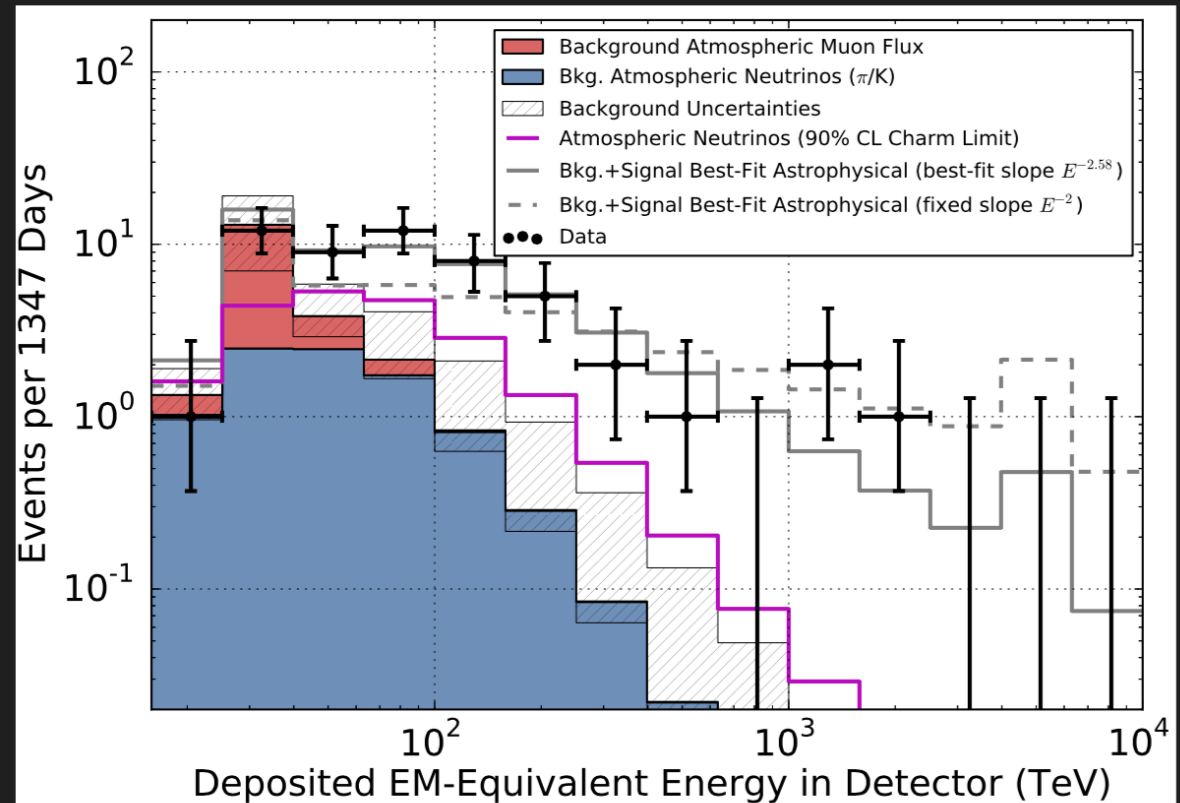
26

Somewhat compatible with benchmark E^{-2} astrophysical model or single power-law model, but looks like things are more complicated

Best fit assuming E^{-2} (not a very good fit anymore):

$$0.84 \pm 0.3 \cdot 10^{-8} E^{-2} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

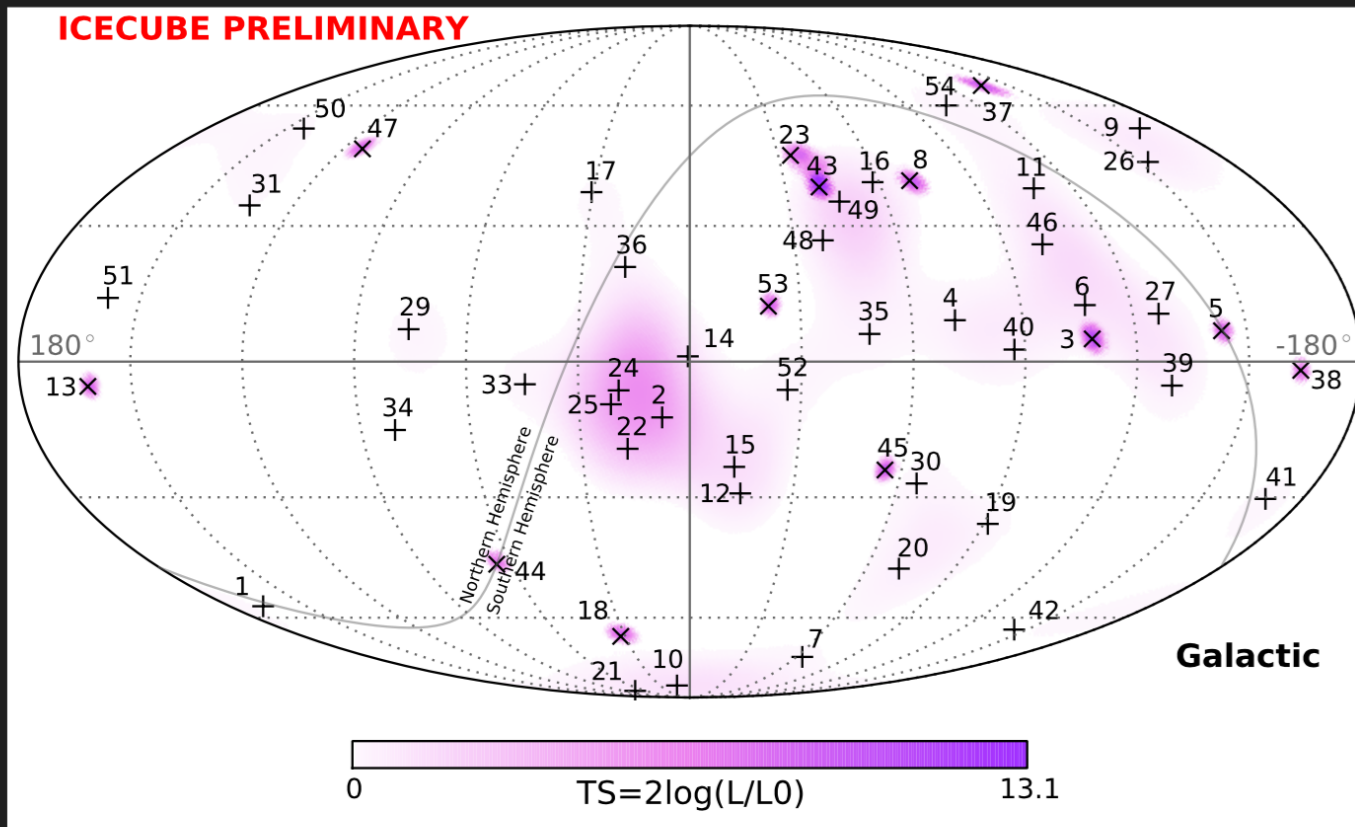
Best fit spectral index: $E^{-2.58}$





SKYMAP / CLUSTERING

No significant clustering observed (four years)



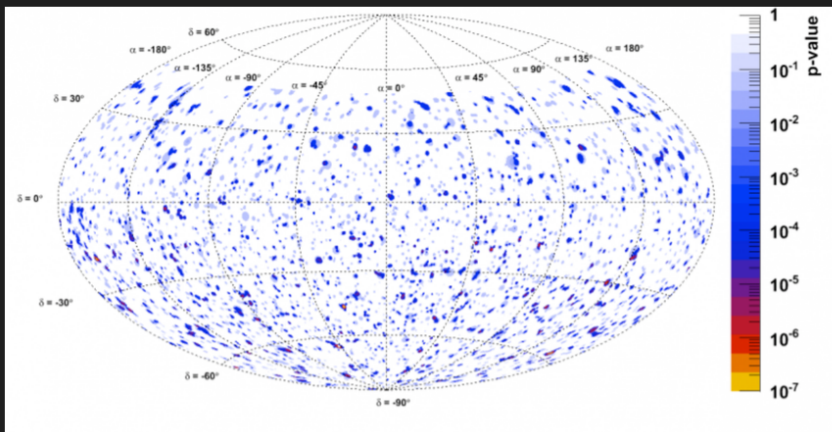
(all p-values are post-trial)



WHERE ARE THE SOURCES?

There is still no evidence for point sources of high-energy neutrinos.

30



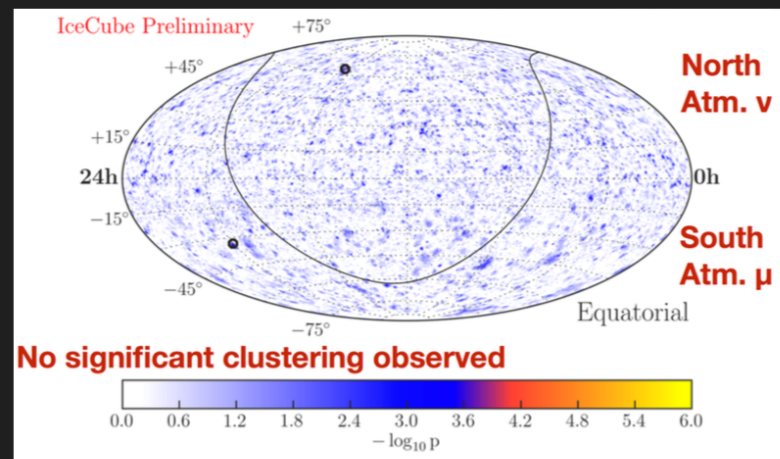
IceCube 6-year through-going muon point source search

Northern-sky muons: **35%** chance probability
> PeV southern-sky muons: **87%**

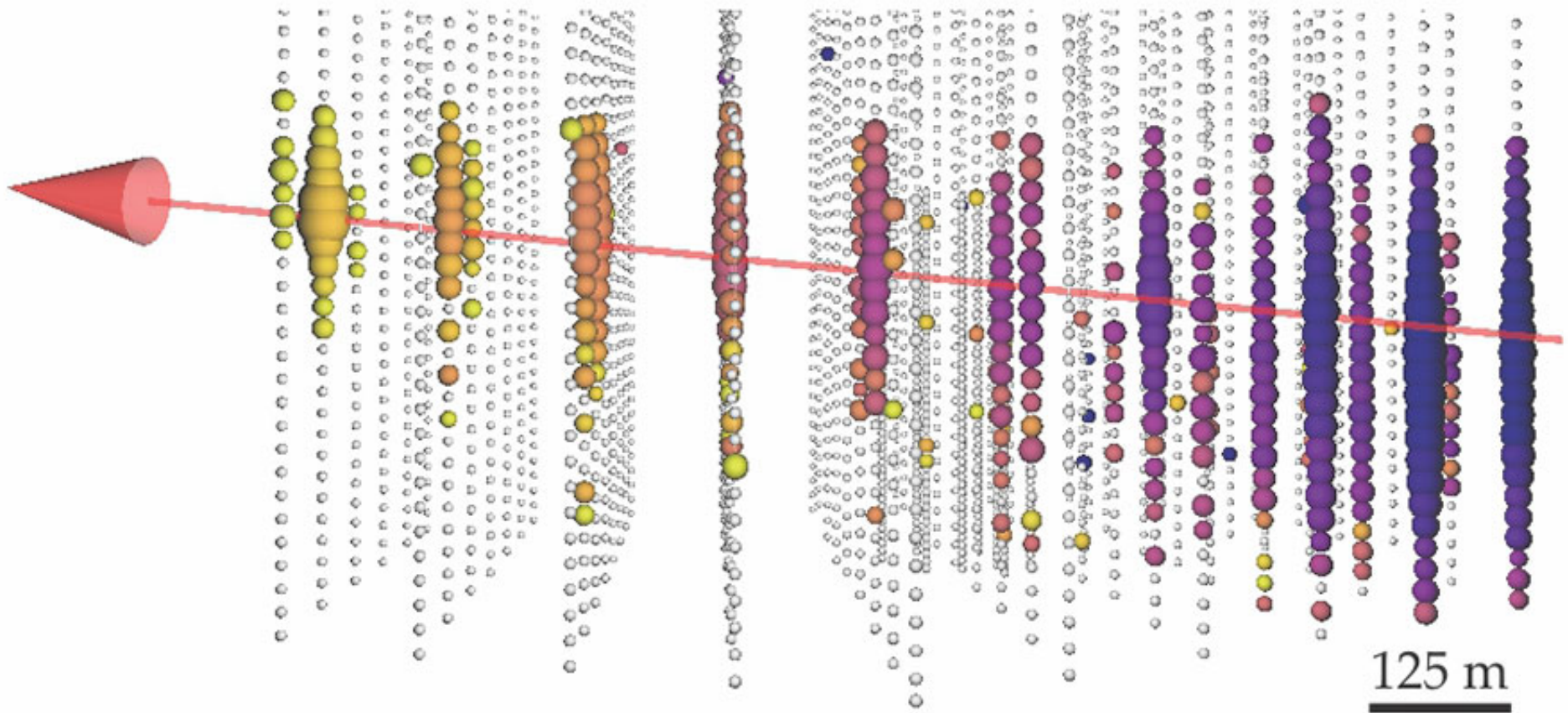
PoS(ICRC2015)1047

ApJ Lett, 786, L5 (2014)

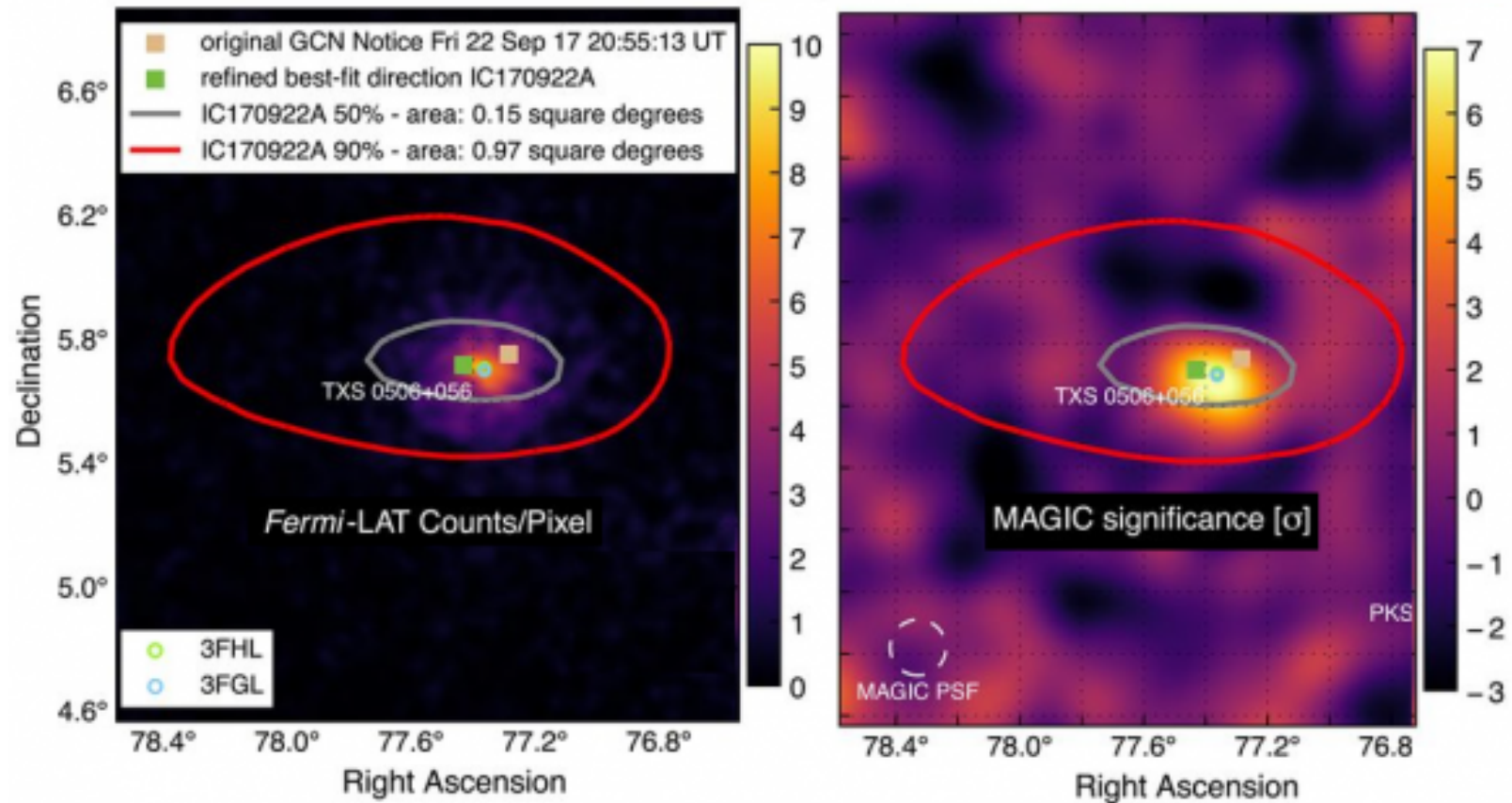
ANTARES 4-year up-going muon point source search: **~2%** chance probability (post-trial)



“The” neutrino ...



TXS 0506+056



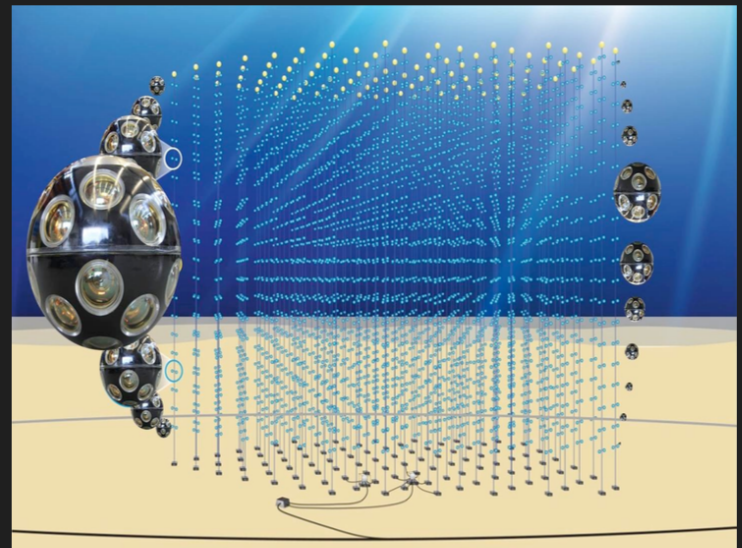
Astrofisica Nucleare e Subnucleare

Future Detectors

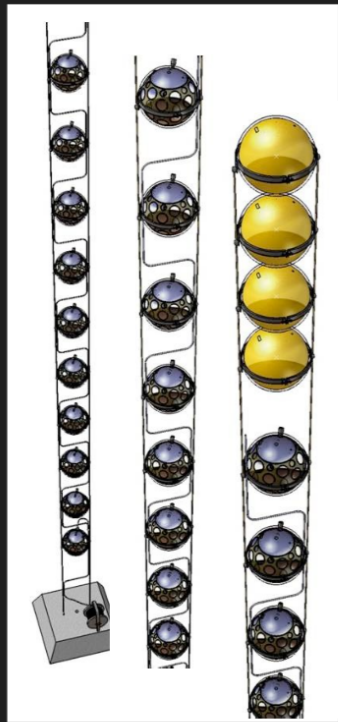


THE KM3NET NEUTRINO TELESCOPE

Multi-site installation in the Mediterranean Sea (France, Italy), instrumented in “building blocks”, started construction



KM3NeT “building block”



string with OMs



Multi-PMT digital optical module (“DOM”)



THE KM3NET NEUTRINO TELESCOPE

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Multi-site installation in the Mediterranean Sea (France, Italy), instrumented in “building blocks”, started construction

31 x 3” PMTs

Hamamatsu, ETL, HZC

Light collection ring

20–40% gain in PC for free

Low power

<10 W / DOM

FPGA readout

sub-ns time stamping
time over threshold

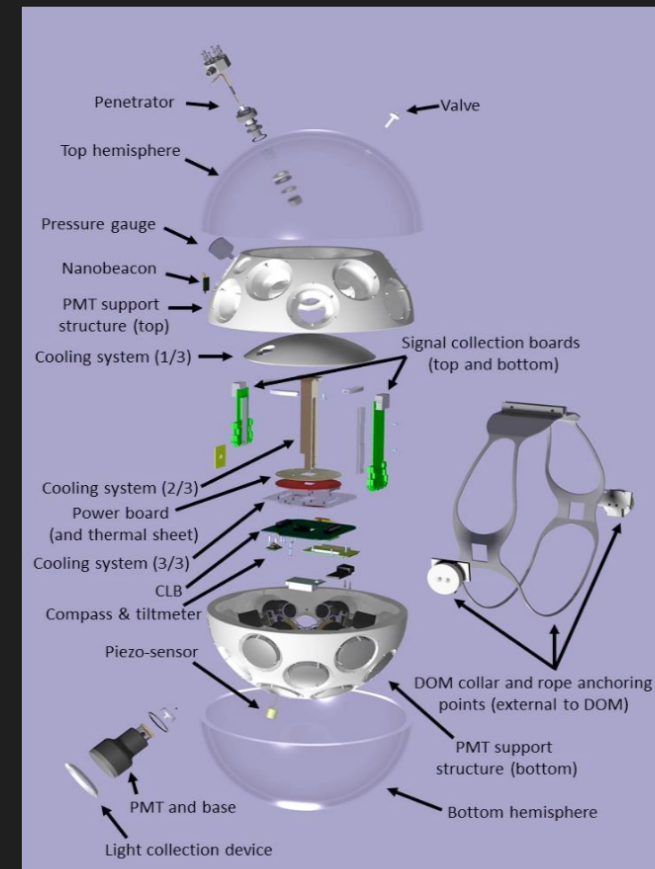
Calibration

LED & acoustic piezo

Optical fibre data transmission

DWDM with 80 wavelengths
Gb/s readout

multiPMT optical module





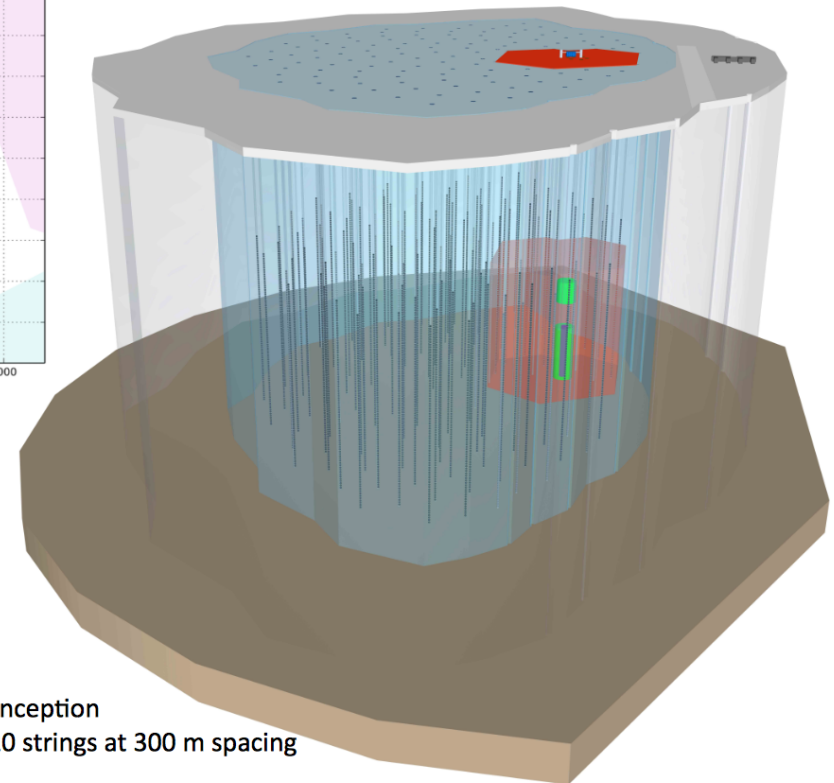
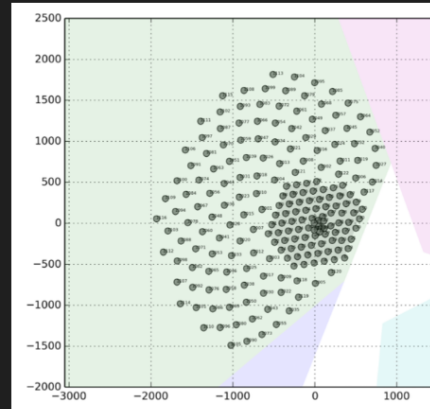
ICECUBE-GEN2: HIGH-ENERGY

65

IceCube has provided an amazing sample of events, but is still limited by the small number of events

few 10's of astrophysical neutrinos per year

The IceCube-Gen2 High-Energy Array will instrument a significantly larger volume ($\sim 10\text{km}^3$)



Artist conception
Here: 120 strings at 300 m spacing



ICECUBE-GEN2: PINGU

measuring the mass hierarchy using atmospheric neutrinos

67

cover energies down to a **few GeV**

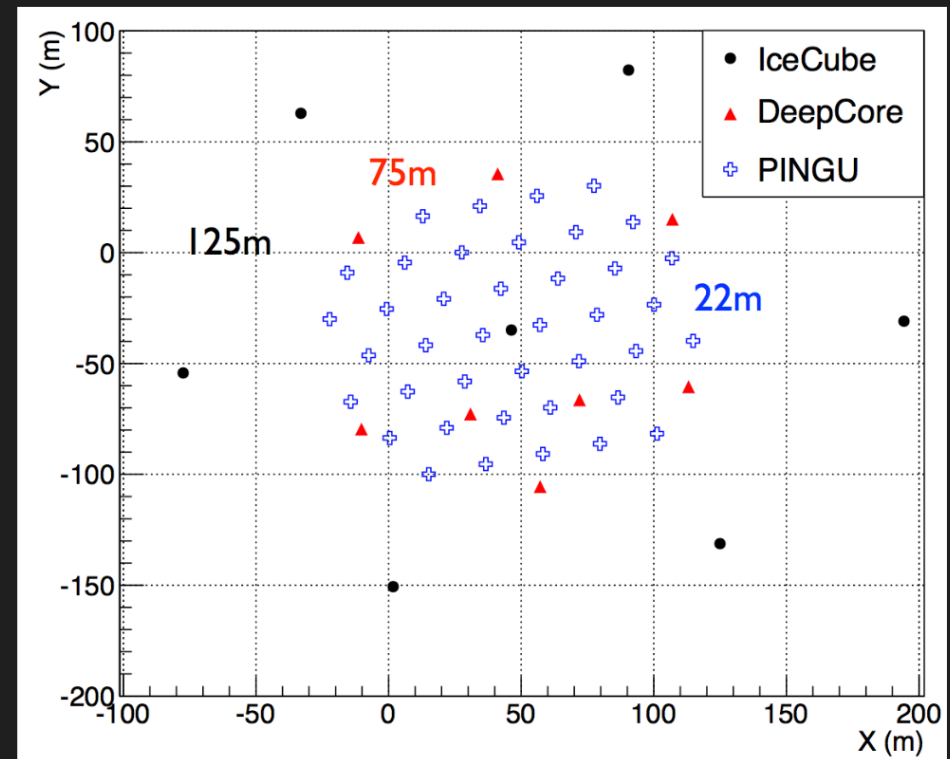
add **40** strings to IceCube/DeepCore

22m string spacing

2m DOM spacing

use the difference in MSW effect for ν and anti- ν

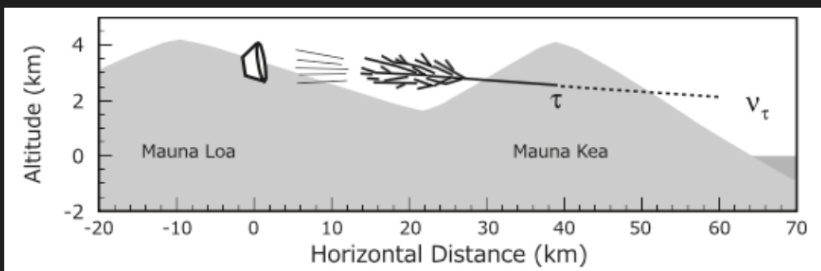
combine with difference in ν and anti- ν cross-section





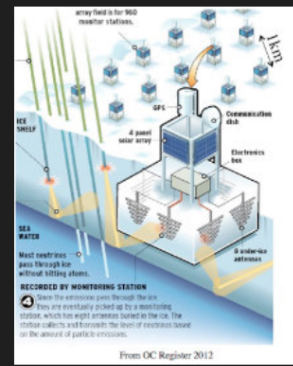
MORE DETECTORS / METHODS

non-water detectors and radio detectors

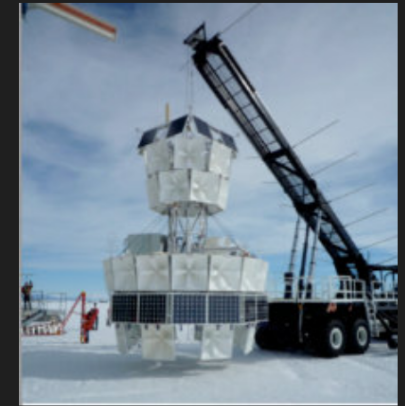


earth skimming tau Cherenkov shower detection (arXiv:1202.5656) - can be deployed on land!

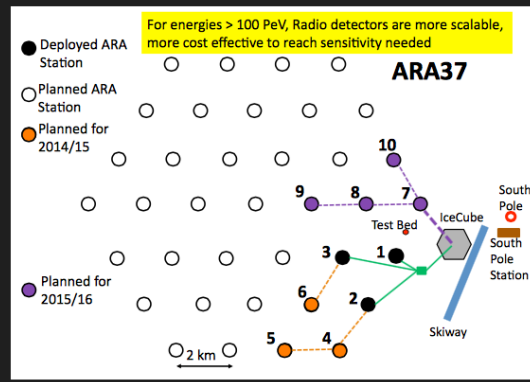
radio detectors for energy range above ~10 PeV (Askaryan effect)



ARIANNA



ANITA



ARA