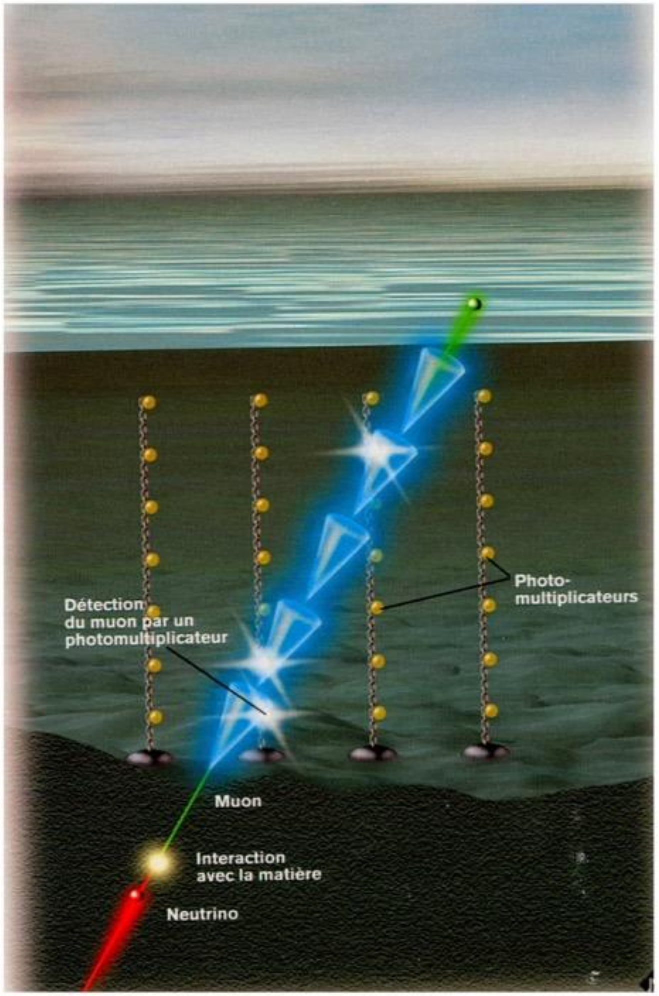
# In quanti modi si può osservare il cielo ? Le stelle ?

**Antonio Capone**

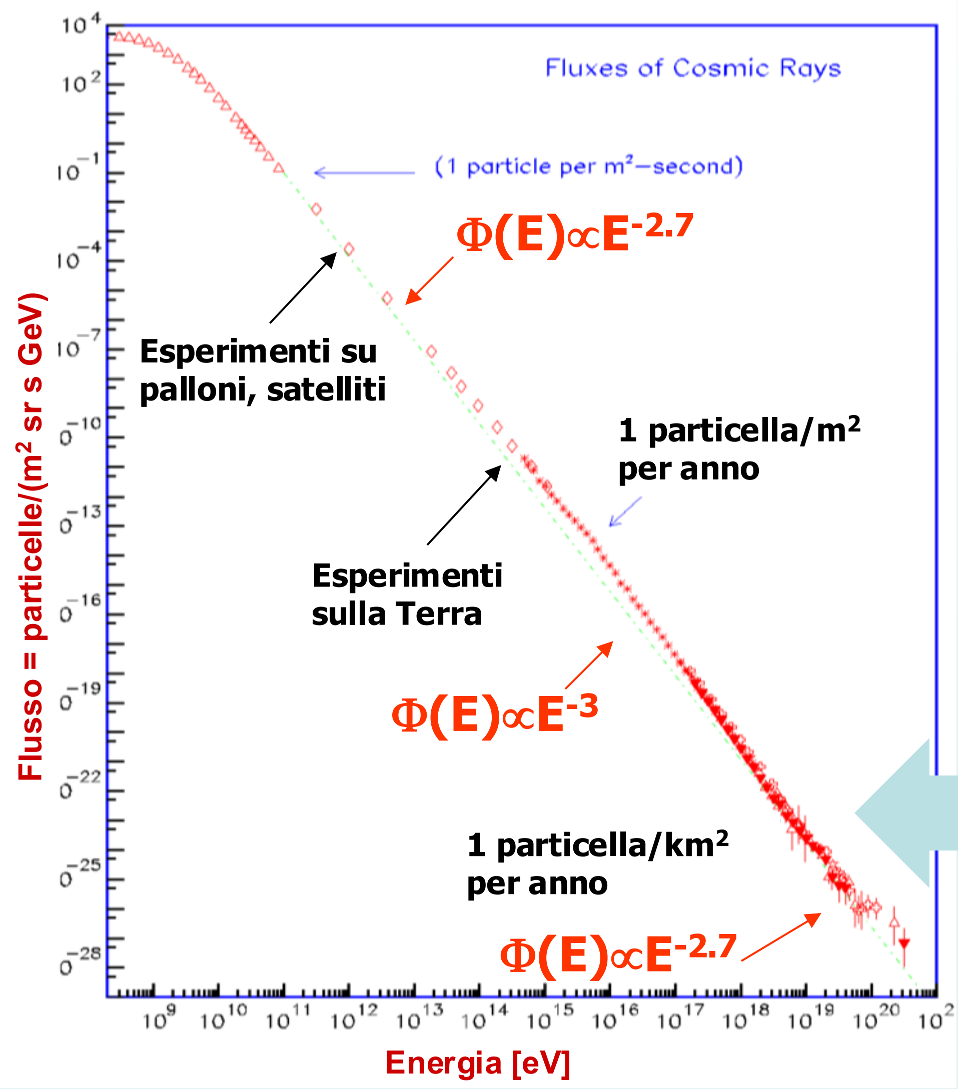
**Università di Roma “La Sapienza”**

- **I Raggi Cosmici: messaggeri da un Universo lontano**
- **Cosa conosciamo, cosa stiamo studiando**
- **Astronomia con neutrini**
- **Apparati sperimentali per “osservare” le regioni più attive ed energetiche dell’Universo**

# Cosa sappiamo oggi dei Raggi Cosmici

**Distribuzione in energia dei R. C.**

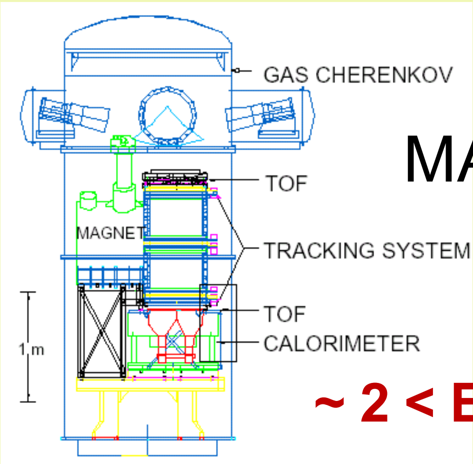



- Rivelate particelle elementari, protoni, con energia maggiore di $10^{21}$eV (come quella di una palla da tennis lanciata in prima battuta da un campione di tennis ~190km/h)
- Molte domande senza risposta:
  - Da dove vengono ? Dalla nostra Galassia ?
  - Quale meccanismo è capace di accelerarle ?
  - …

Per rivelare i raggi cosmici di energia così elevata è necessario un rivelatore di grandi superficie: più di 1 km²

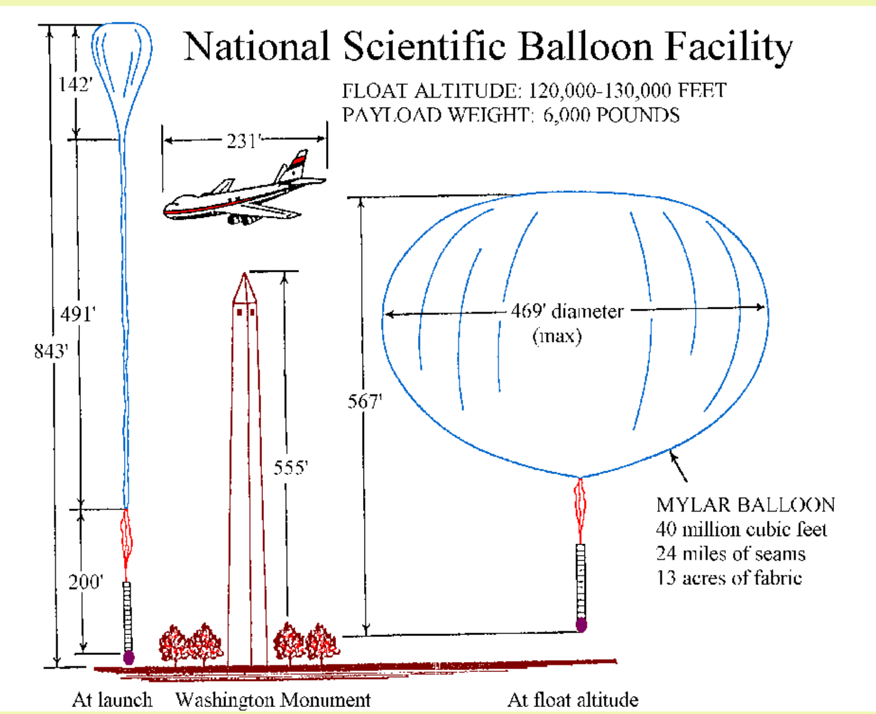
# Rivelatori nell'atmosfera/spazio

Misurano $e, p, \bar{p}$, nuclei, $\gamma$



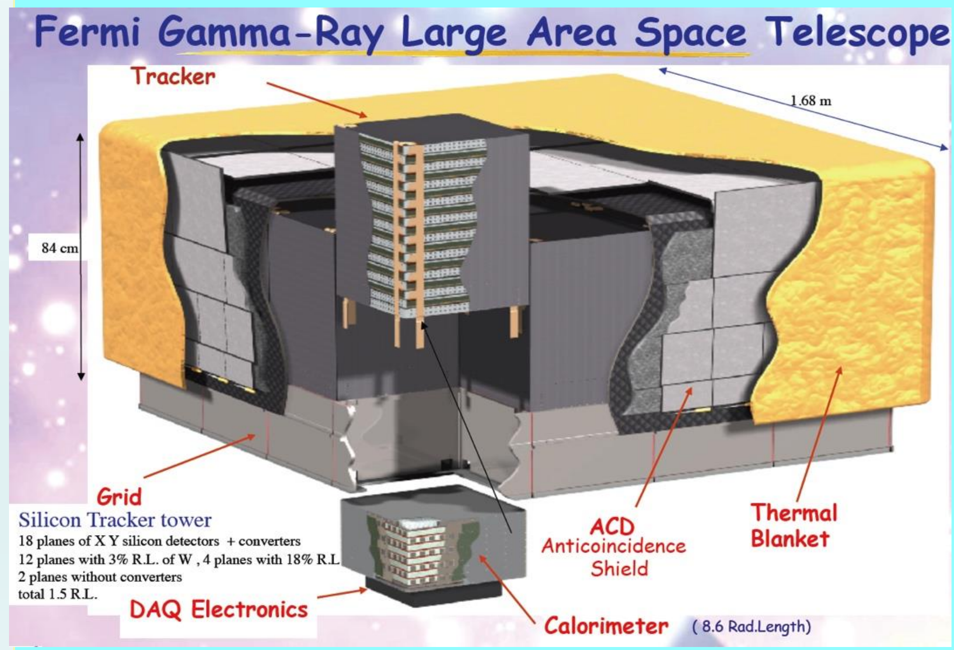

MASS detector

~ 2 < E < ~ 20 GeV




FERMI detector

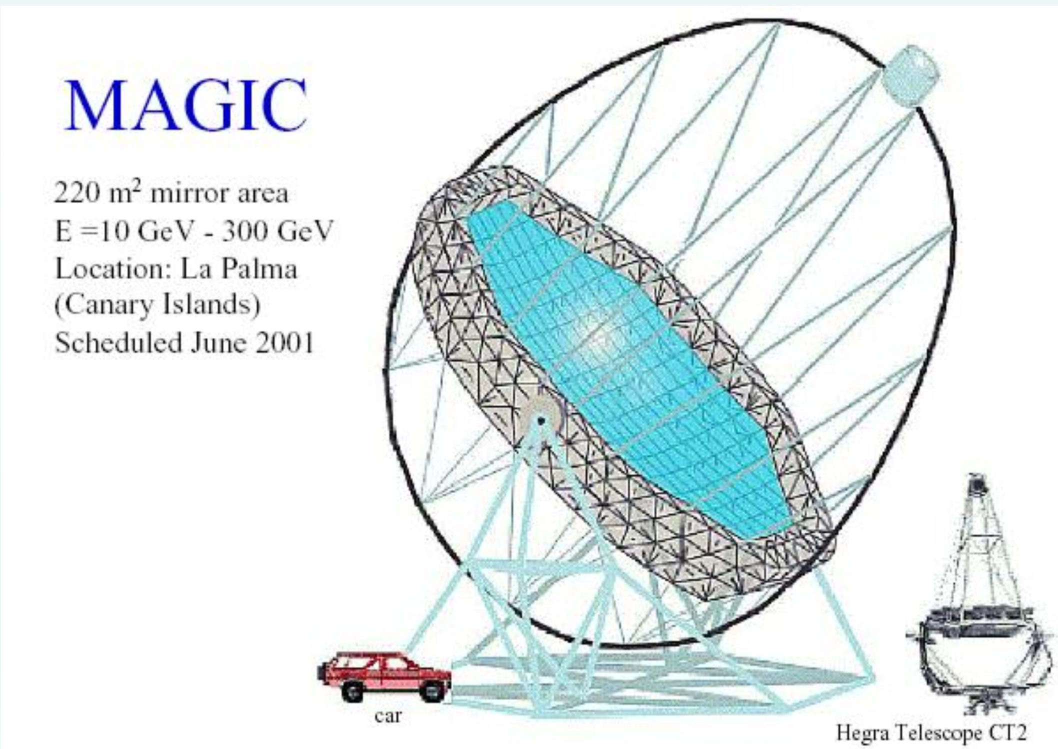
~ 5 < E < ~ 800 GeV

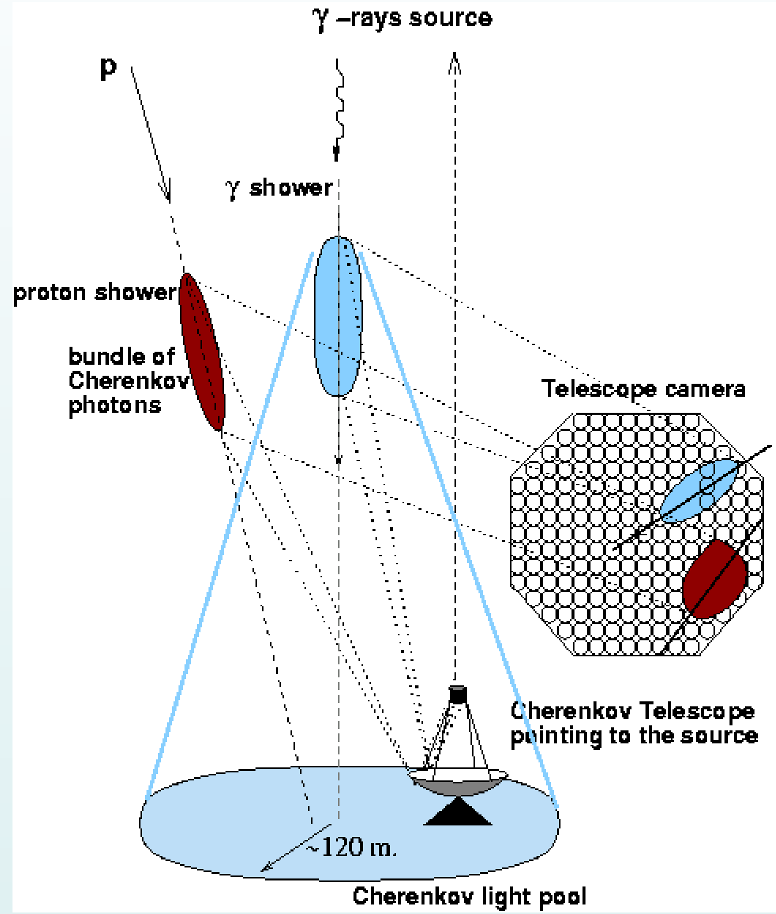


# Telescopi Cherenkov Imaging

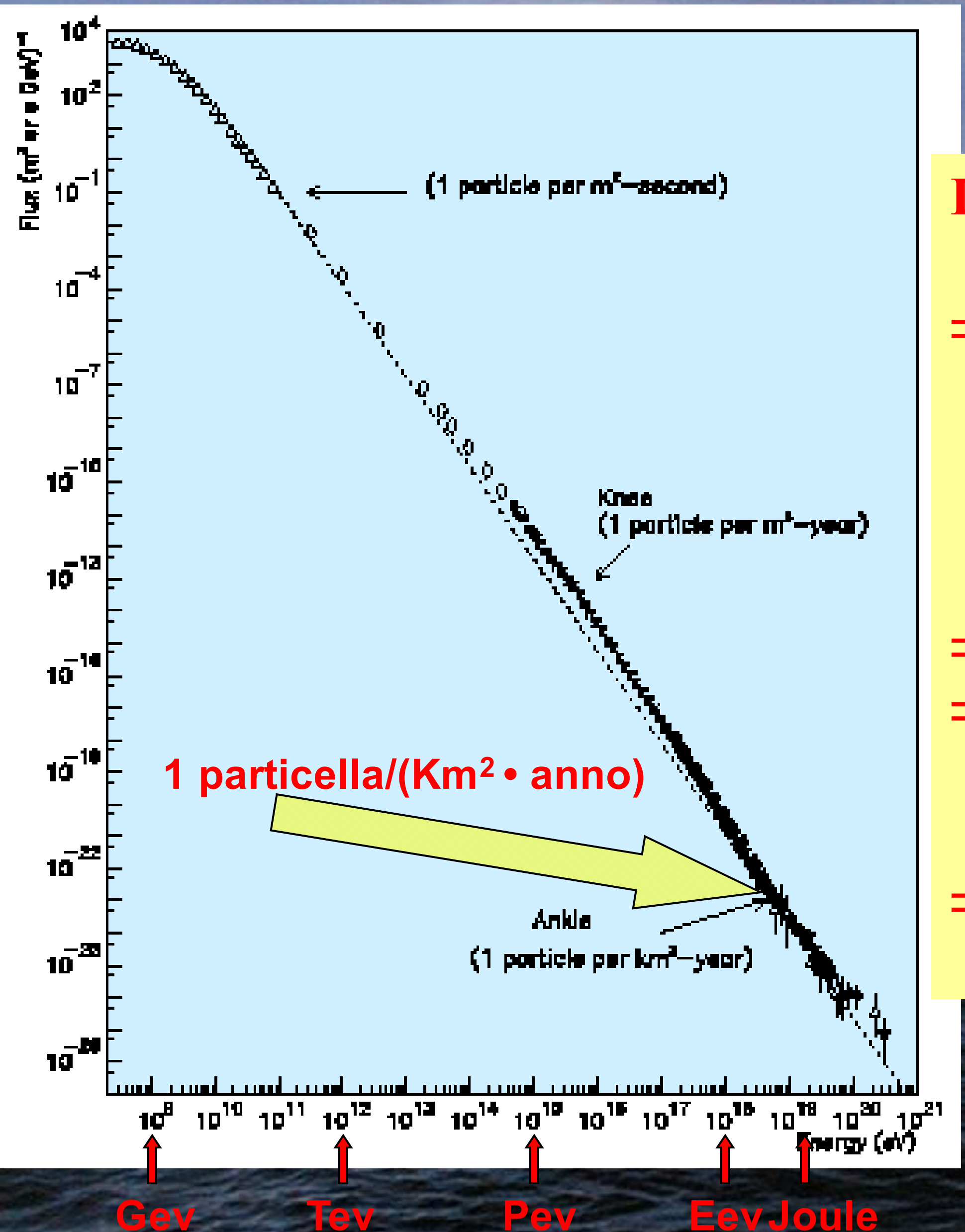
Misurano luce Cherenkov prodotta da sciami atmosferici indotti da p e $\gamma$ con

**~ 30 < E < ~ 300 GeV**



# Rivelazione di raggi cosmici di altissima energia (E > 100TeV)




**Lo studio di raggi cosmici con E> 100TeV richiede:**

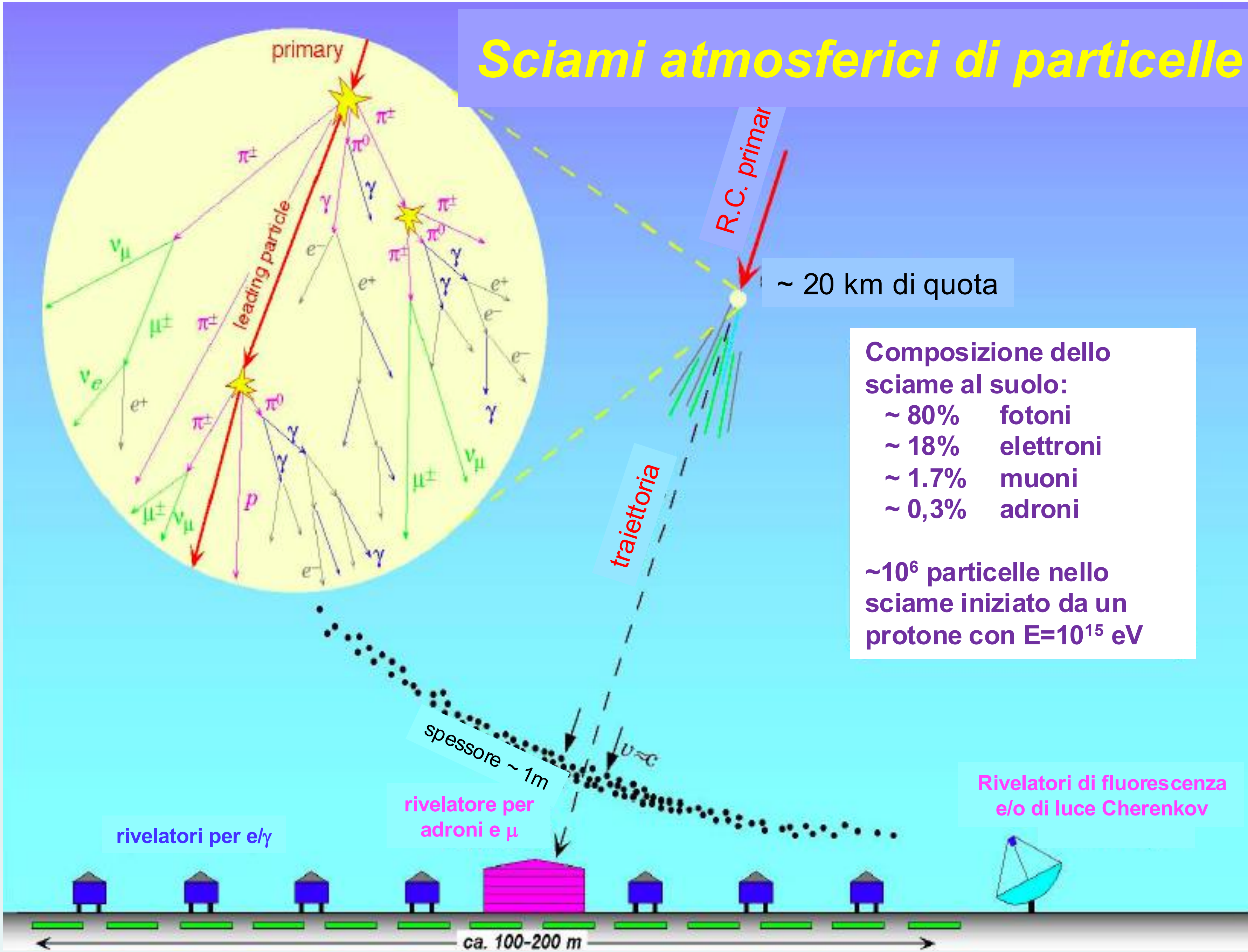
**⇒ Apparati con enormi superfici di rivelazione: $10^3$-$10^4$ km$^2$ (rivelatori "ibridi" composti con apparati a scintillatore, rivelatori di fluorescenza nell'atm., apparati traccianti, ... )**

**⇒ sulla superficie terrestre**

**⇒ si studiano i "risultati" delle interazioni dei raggi cosmici primari con l'atmosfera**

**⇒ si risale poi a E, direzione, natura dei "primari"**

# Sciami atmosferici di particelle

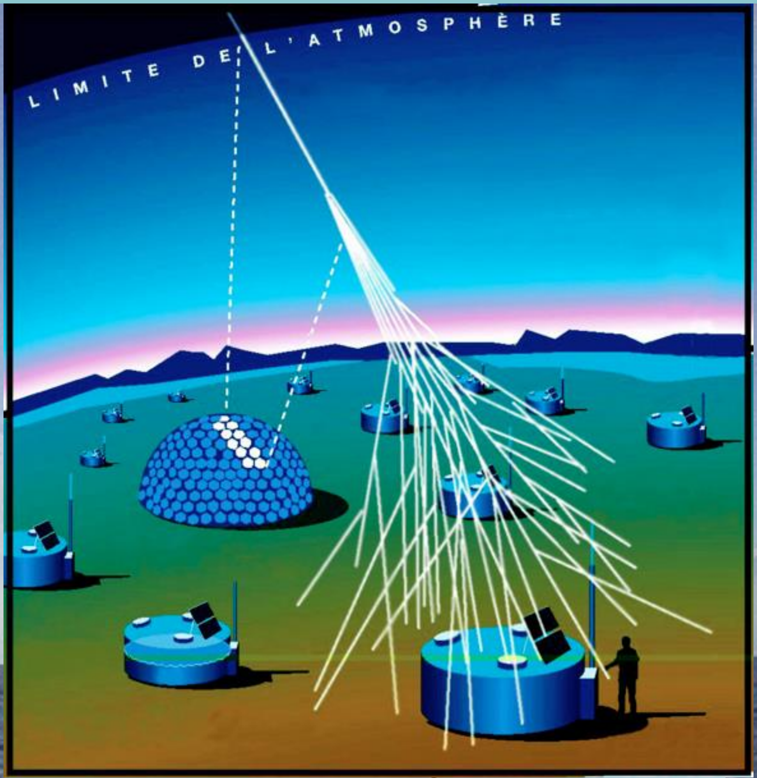


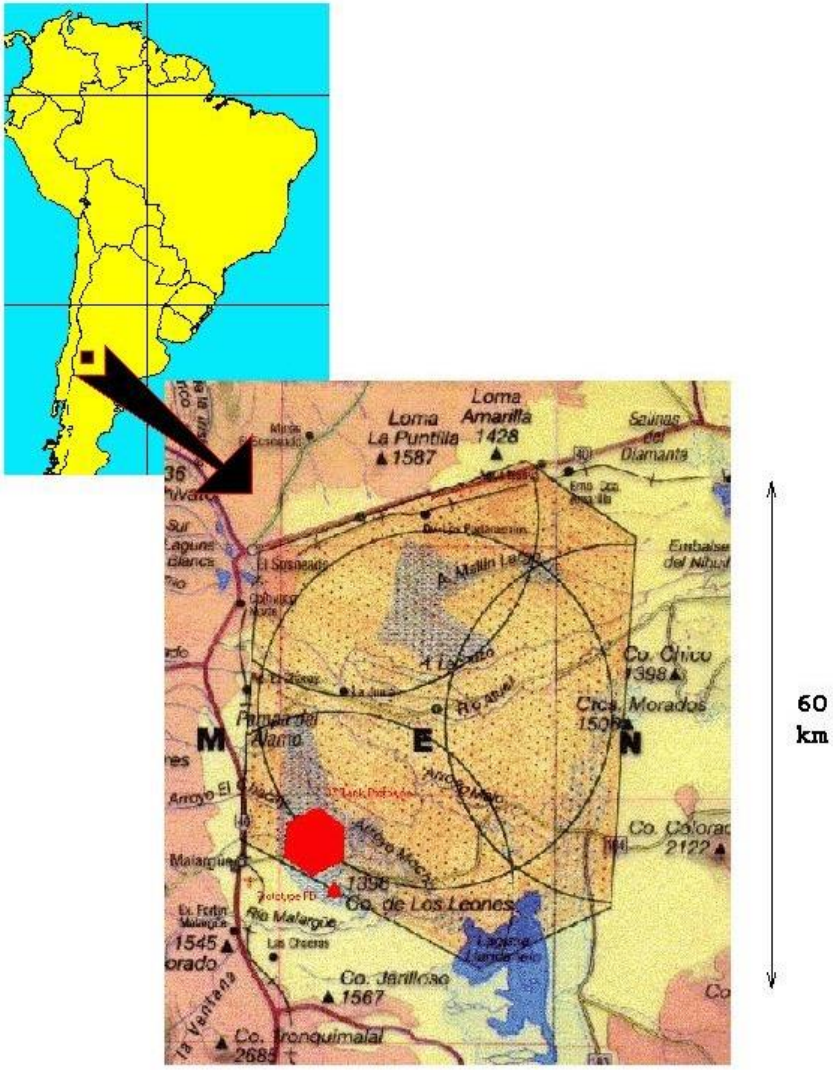

**Composizione dello sciame al suolo:**

- ~ 80% fotoni
- ~ 18% elettroni
- ~ 1.7% muoni
- ~ 0,3% adroni

**~$10^6$ particelle nello sciame iniziato da un protone con E=$10^{15}$ eV**

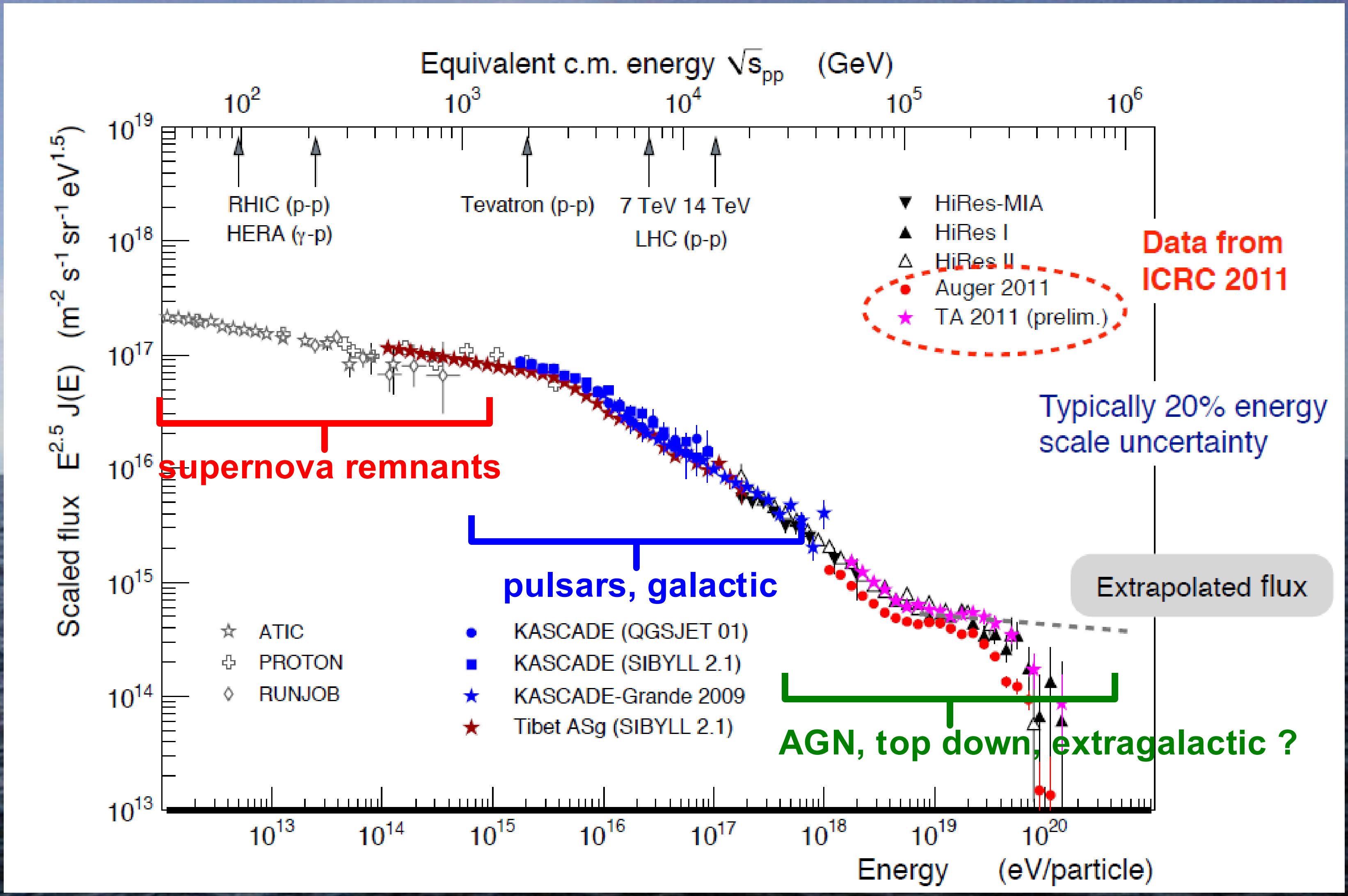
# L'Osservatorio Pierre Auger in Argentina



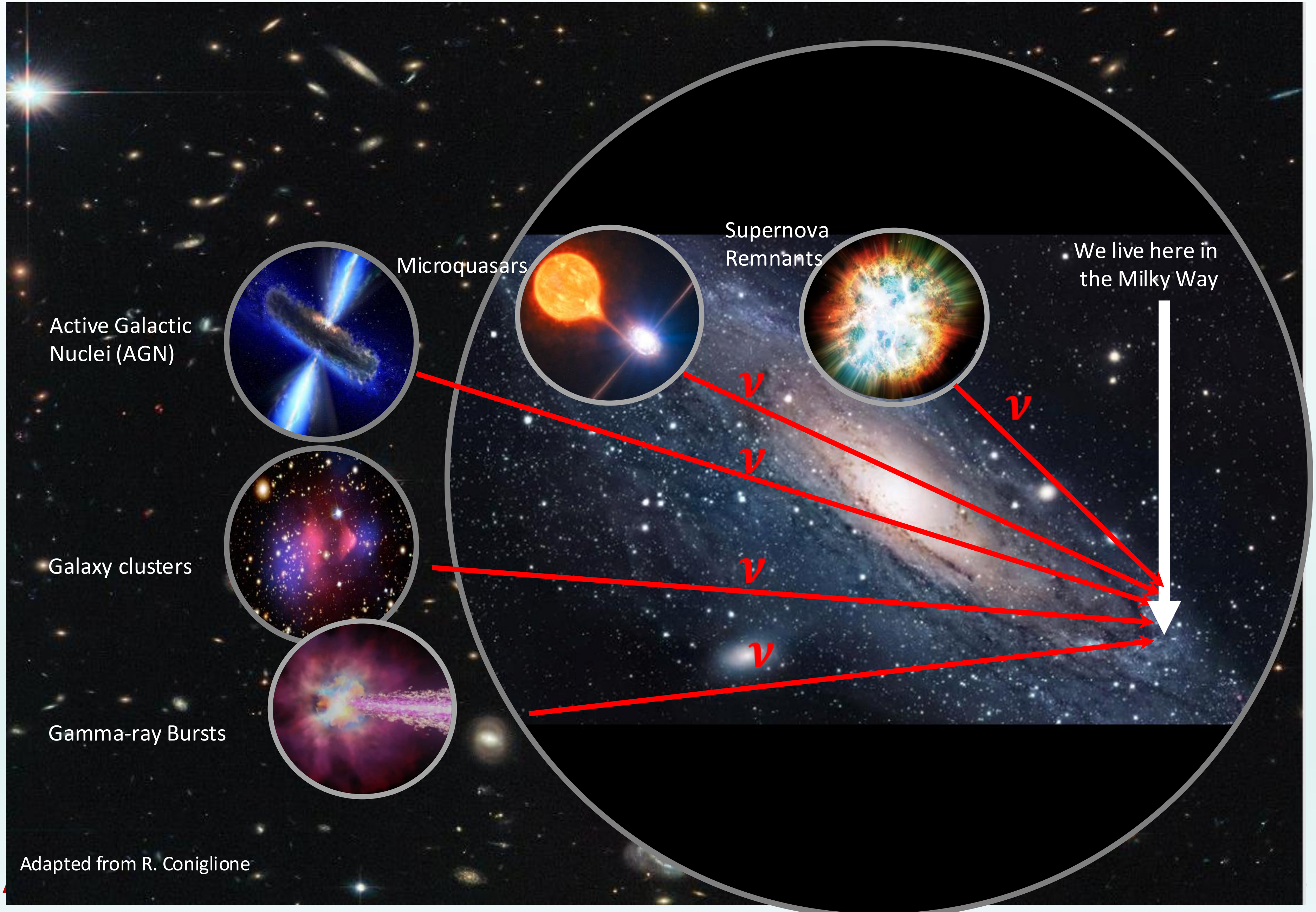




Contour of site (3000 km-sq)
In red: engineering array
Circles: average range of the fluorescence det.
Dots: the 1600 detector stations (tanks)

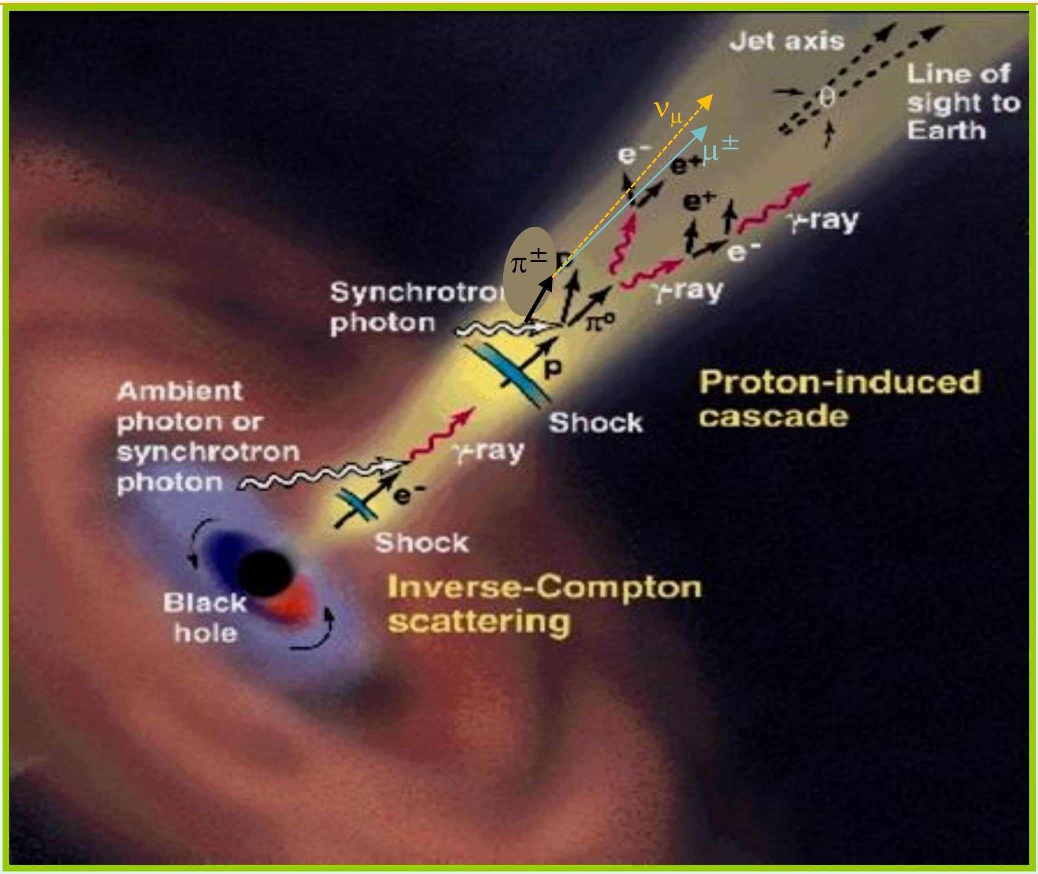
# Pierre Auger: spettro d'energia dei R.C. primari



# Potenziali sorgenti ed acceleratori di Raggi Cosmici



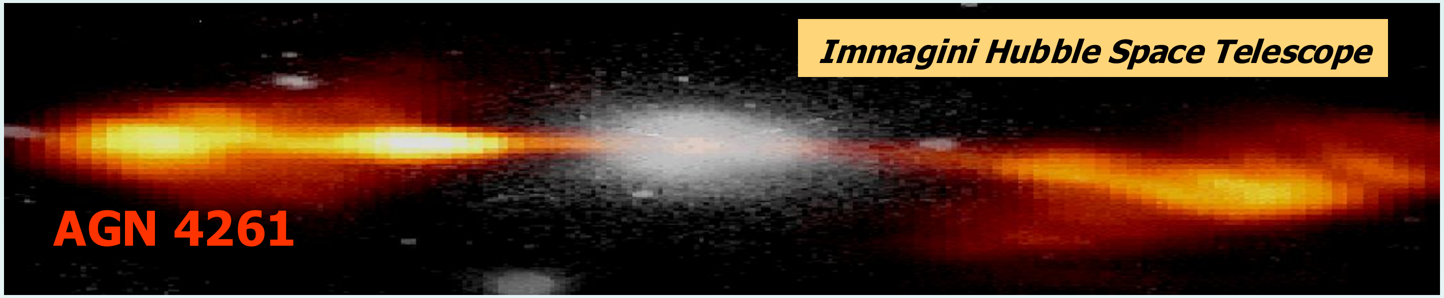
# Quali processi di accelerazione?, Dove ?




**"Acceleratori" di particelle di altissima energia:**
**Nuclei Galattici Attivi (AGN), Gamma Ray Burst (GRB), Micro Quasars ...**

**Sorgenti di particelle di altissima energia che emettono continuamente, molto lontane dalla Terra, al di fuori della nostra Galassia ...**

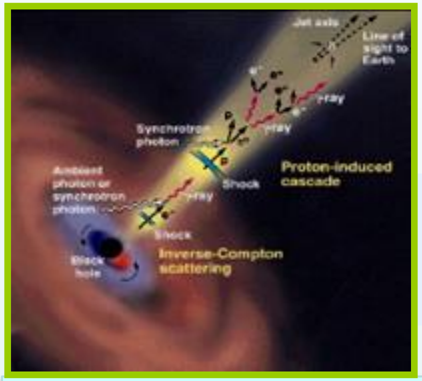
**Come identificarle ???**
**Come capire il meccanismo di accelerazione e la dinamica interna a questi corpi celesti ?**



# Quali processi caratterizzano le sorgenti astrofisiche ?

processi leptonici

Inverse Compton scattering




$e^-$ + radiazione e.m. (sync, MWB, IR) $\longrightarrow e', \gamma$

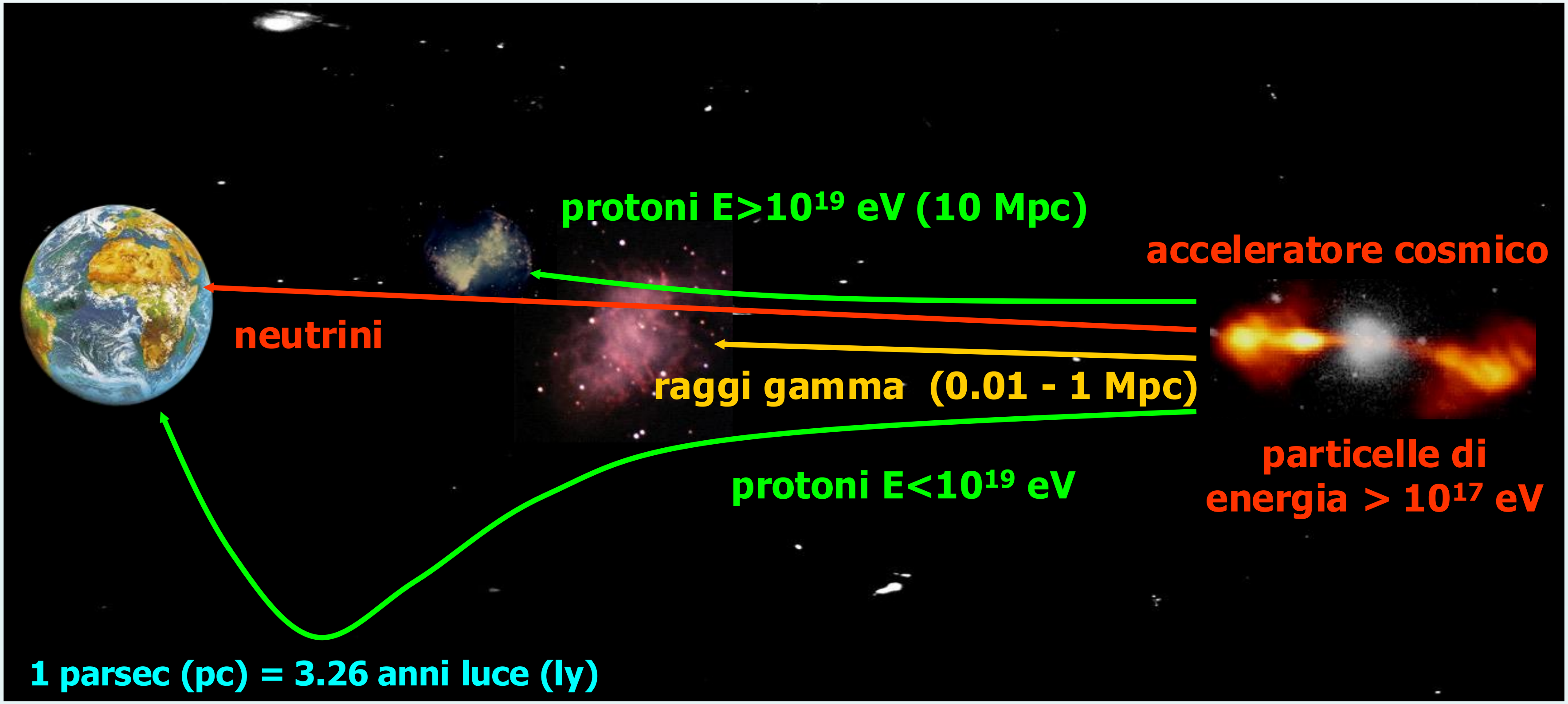
Ma dobbiamo anche considerare processi adronici tipo:

p → materia ambientale / radiazione ambientale → $N, \pi^{\pm}, \pi^{0} \longrightarrow \gamma, \nu$

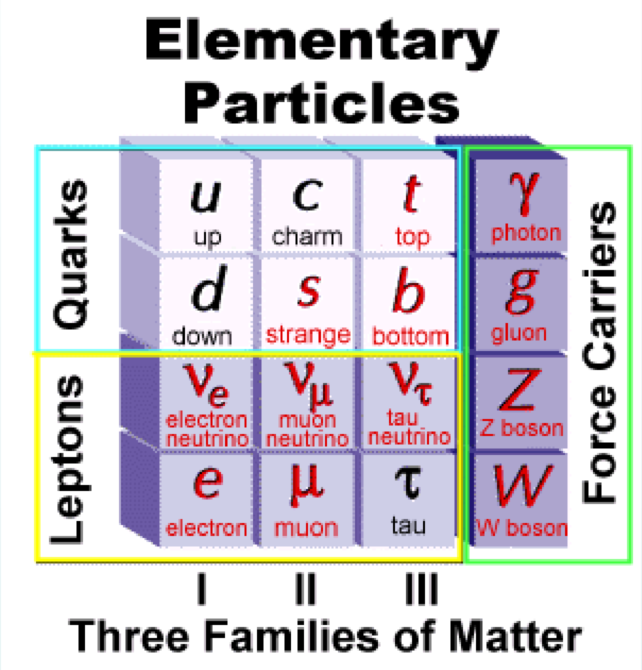
**Solo in questo caso vengono prodotti neutrini !!!**

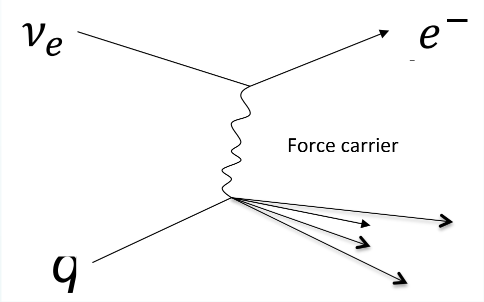
# Diverse particelle, diversi orizzonti ...

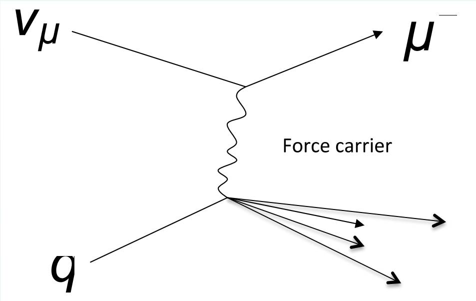
- p e $\gamma$ assorbiti o deviati dalla materia e dalla radiazione interstellare
- **i neutrini ($\nu$):**
  - essendo privi di carica non sono deflessi dai campi magnetici
  - interagiscono debolmente quindi possono attraversare grandi distanze permettendo di osservare l’Universo lontano

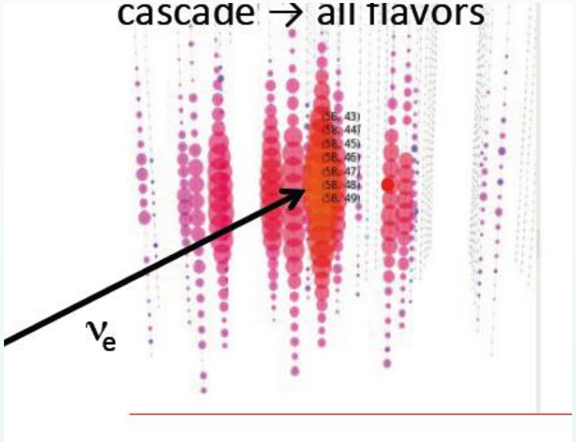


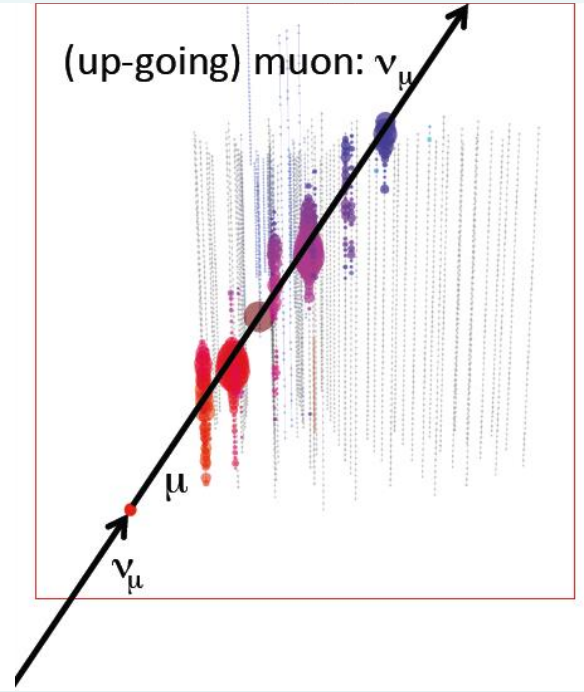
# Come rivelare i neutrini ???



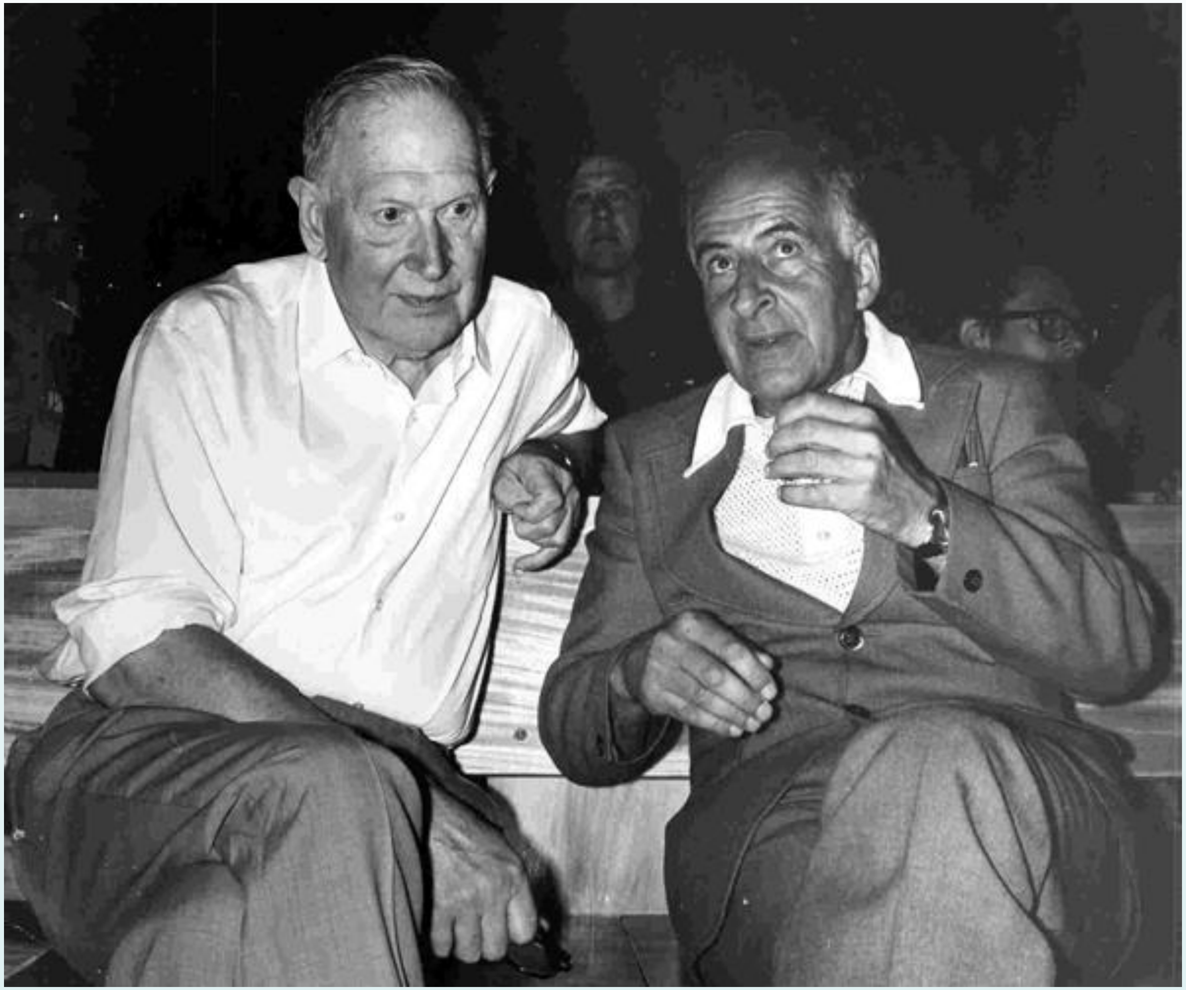




Solo rivelando le particelle cariche prodotte in seguito alla loro interazione con la materia:  i muoni permettono di ricostruire la direzione di volo dei neutrini interagenti e permettono di fare "astronomia"

# ... l'idea geniale …

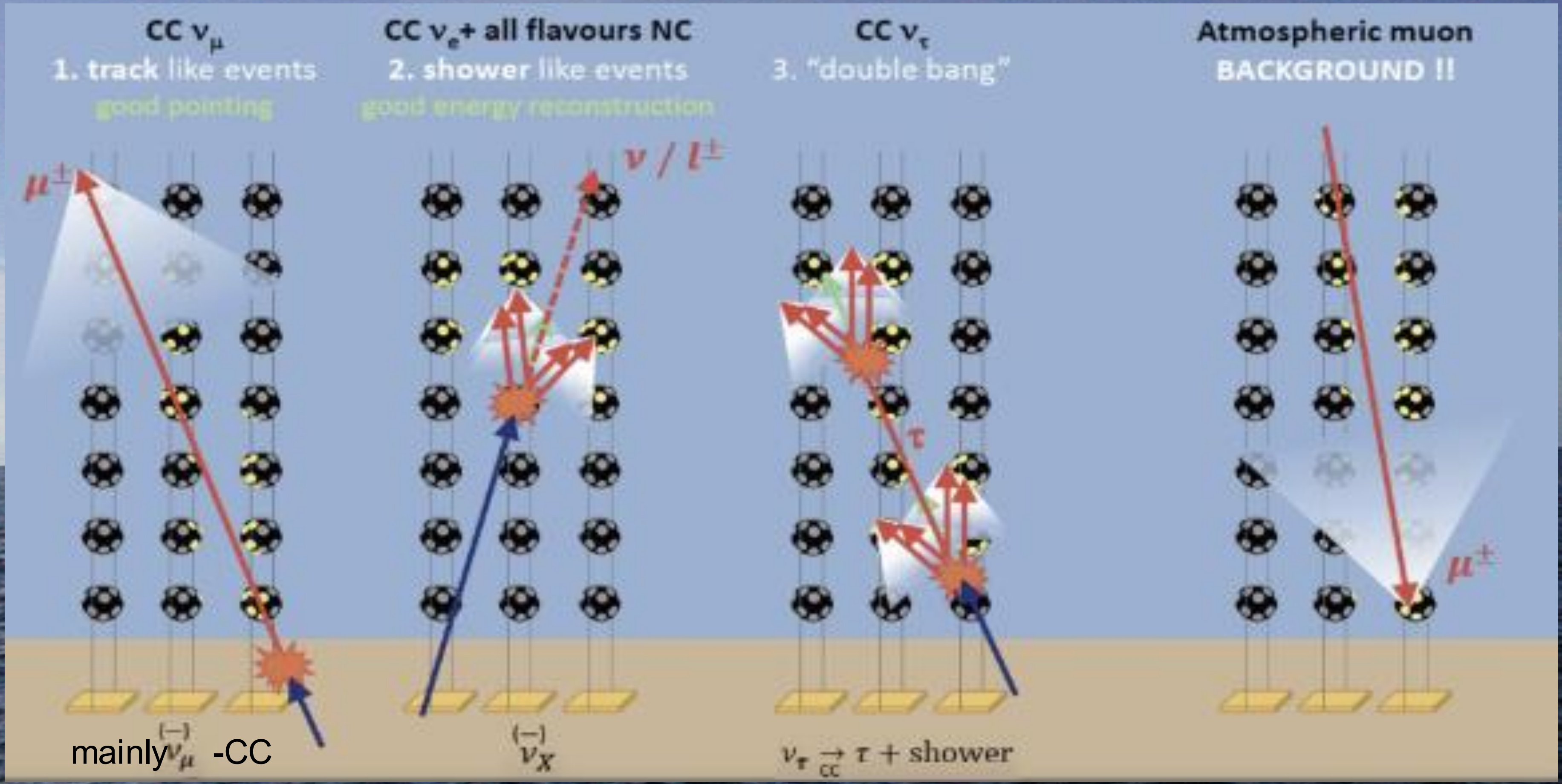


**M. Markov:**
"Proponiamo di installare rivelatori in profondità in un lago o nel mare e di determinare la direzione delle particelle cariche con l'aiuto della radiazione Cherenkov".

**1960, Conf. di Rochester**

M.A. Markov e B.M. Pontecorvo alla conferenza internazionale sulla fisica dei neutrini e l'astrofisica. Canyon di Baksan, Cheget, Caucaso, 1977

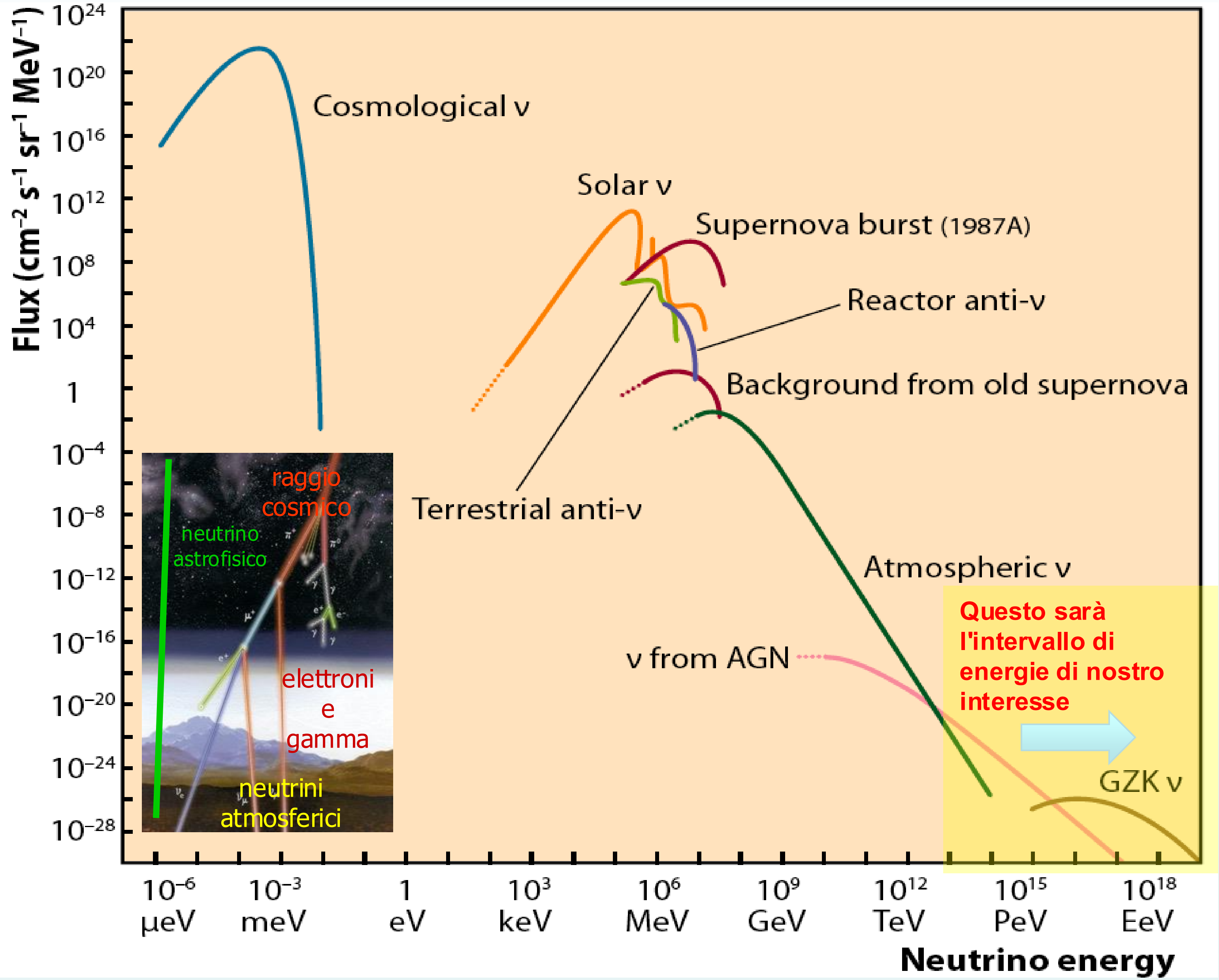
# Interazioni di Neutrino e tipologie di eventi



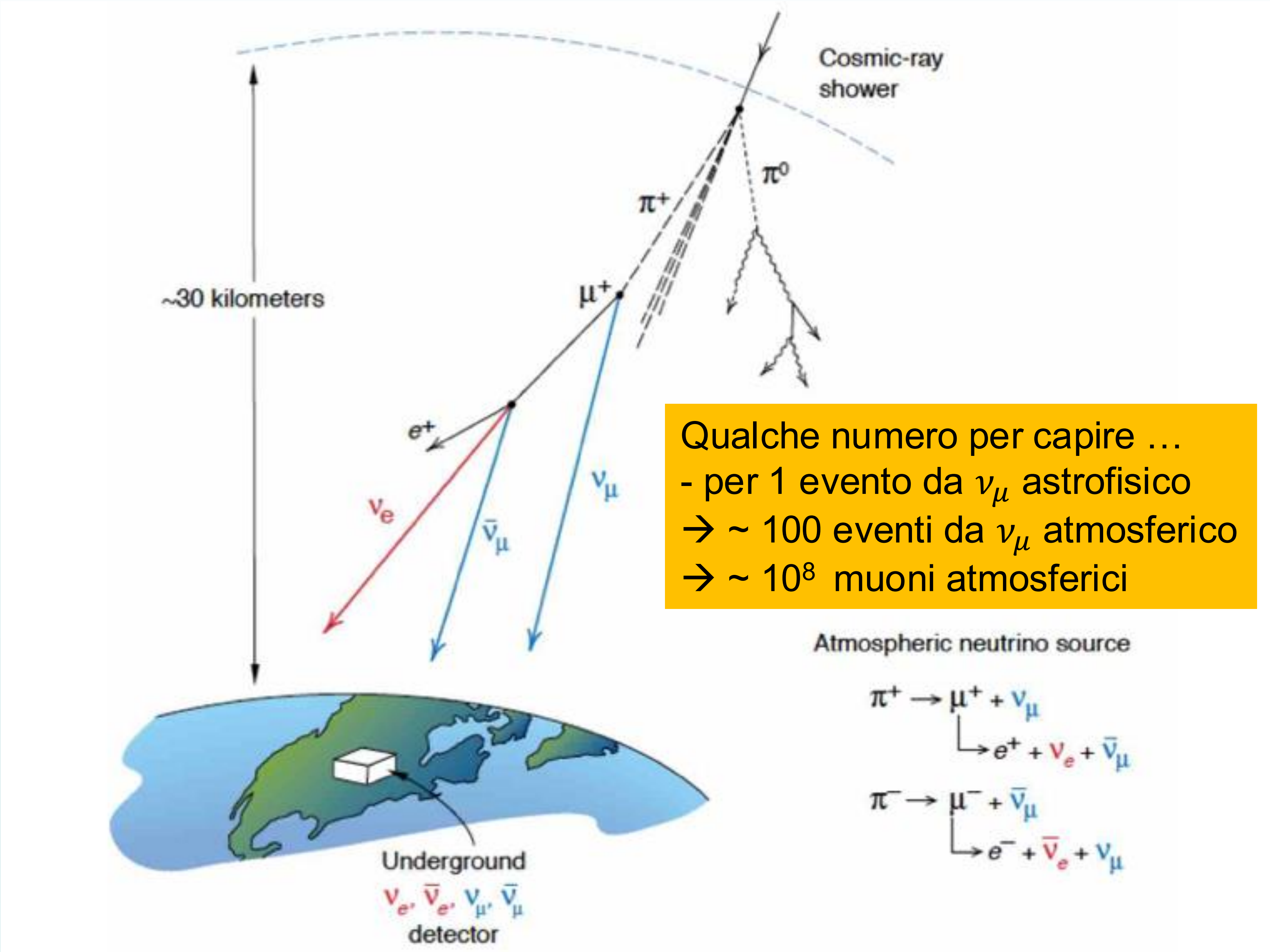

**Traccce** → buona risoluzione angolare: $\leq 0.1^0$ for $E_\nu$ >100 TeV - risoluzione in Energia ~ factor 2

**Sciami** → limitata risoluzione angolare : $\leq 2^0$ for $E_\nu$ >100 TeV - ottima risoluzione in Energia ~6%

# Flussi di neutrini sulla Terra: cosa sappiamo oggi

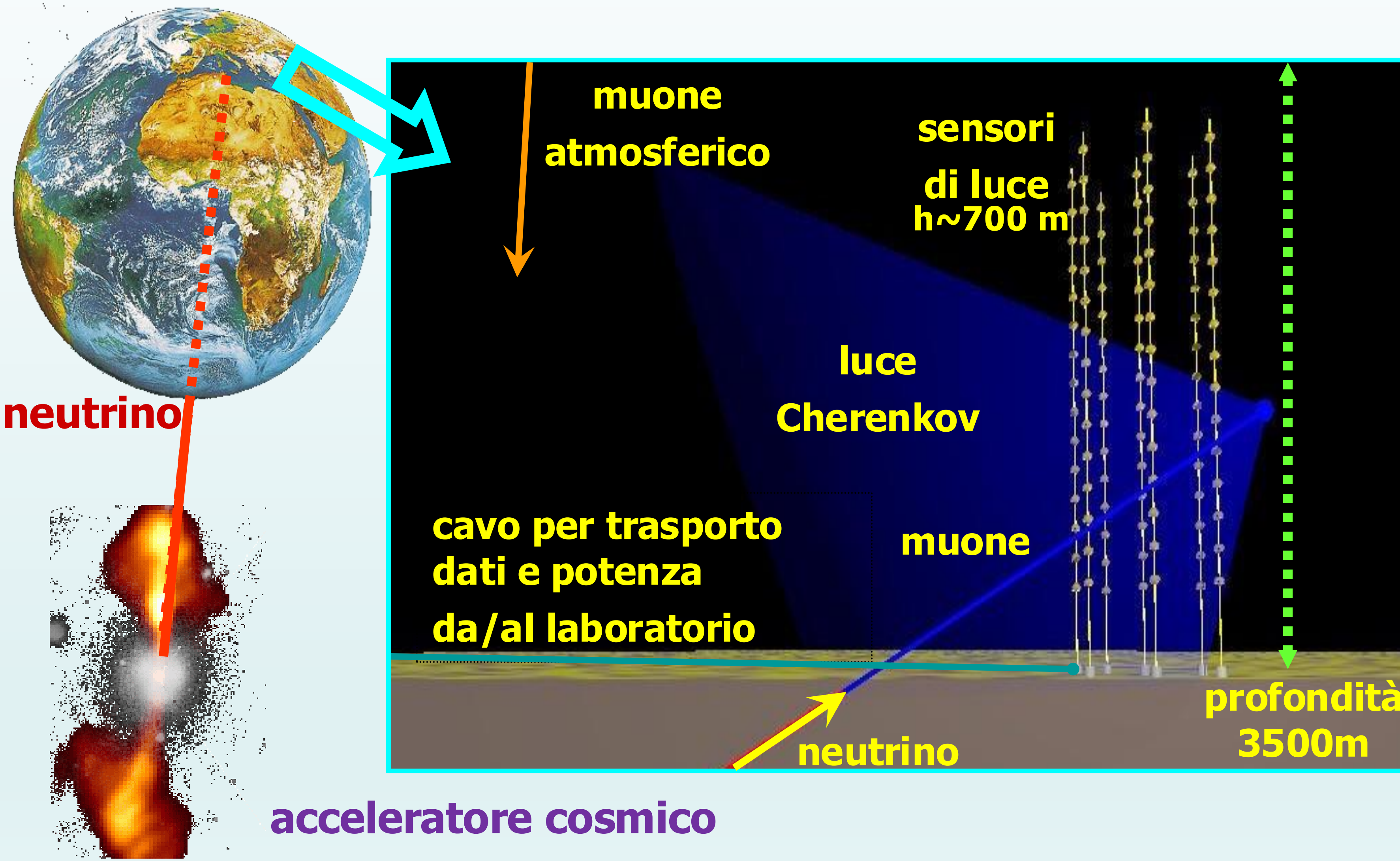


# Intensi flussi di muoni provengono dalla atmosfera …



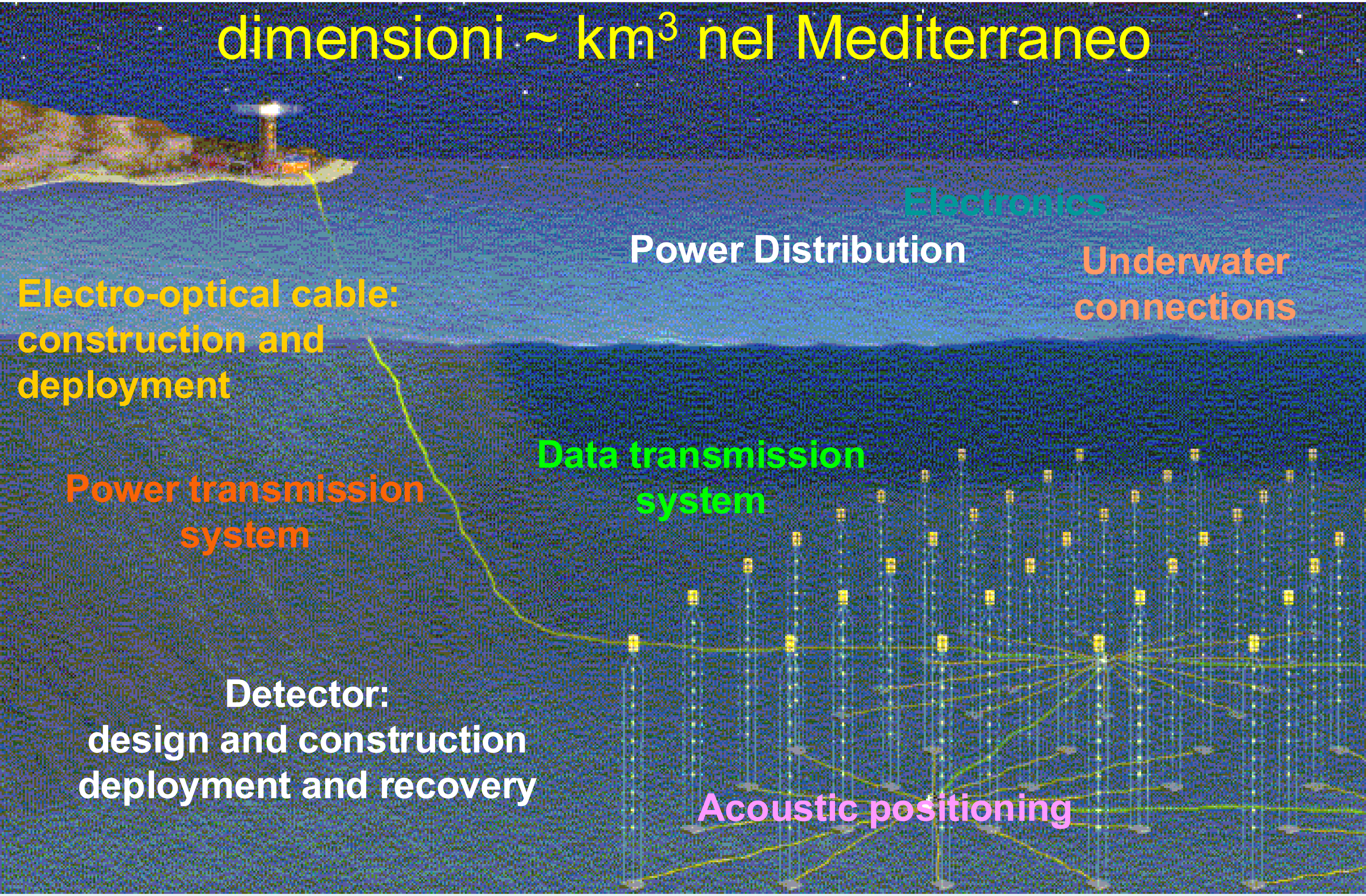

Qualche numero per capire …
- per 1 evento da $\nu_\mu$ astrofisico
→ ~ 100 eventi da $\nu_\mu$ atmosferico
→ ~ $10^8$ muoni atmosferici

# Un rivelatore Cerenkov sottomarino

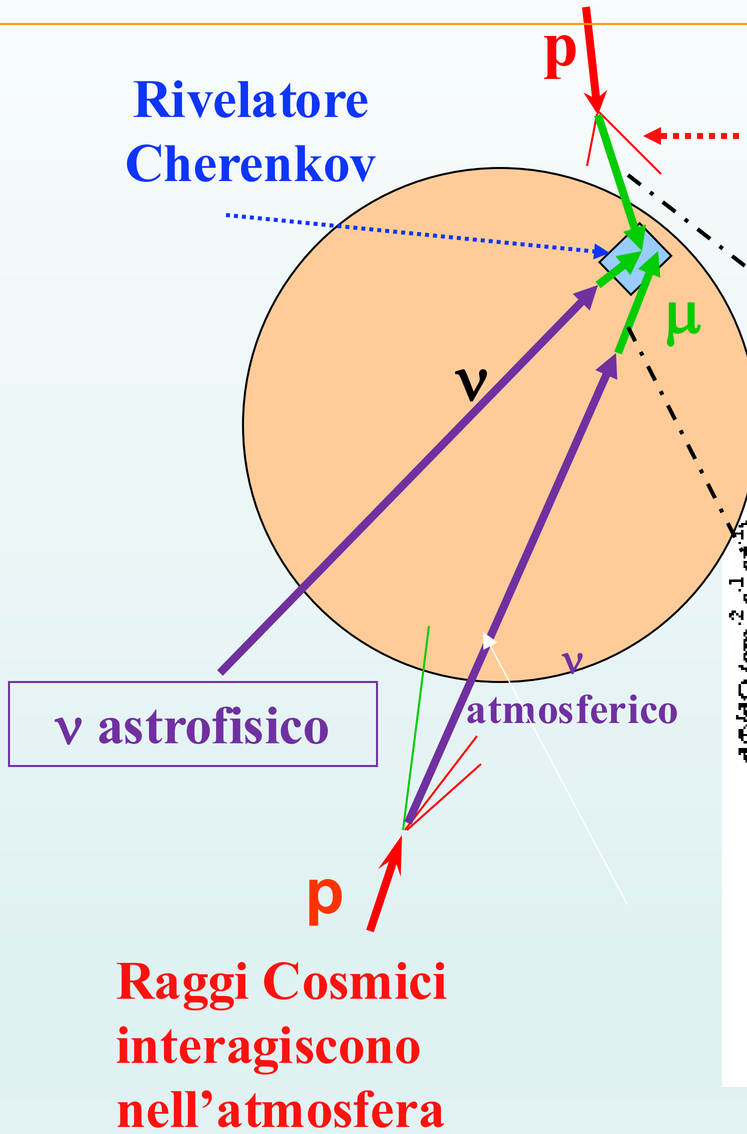


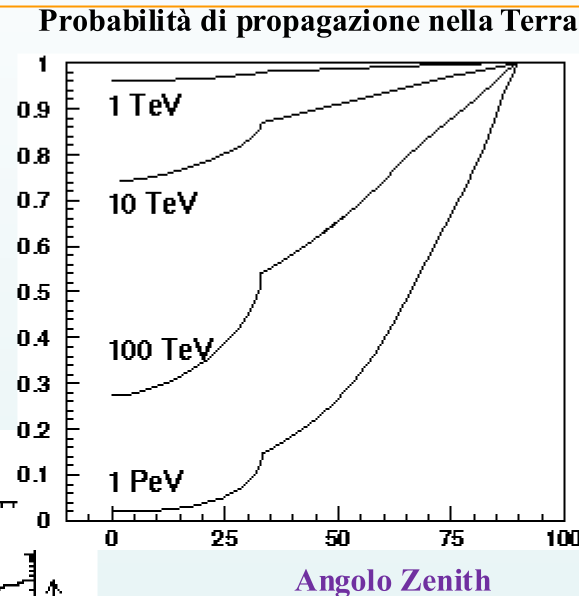

acceleratore cosmico

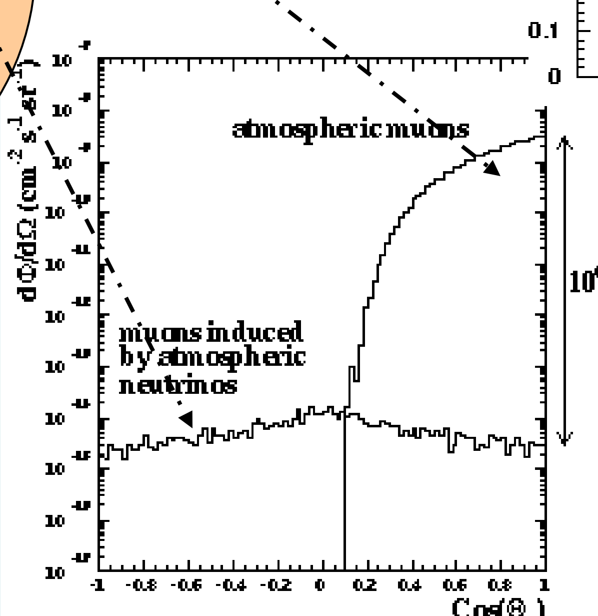
# Un Telescopio Cherenkov sottomarino con dimensioni ~ km$^3$ nel Mediterraneo

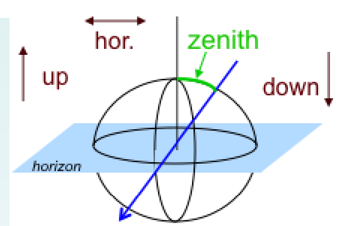


# Vantaggi di un rivelatore sottomarino



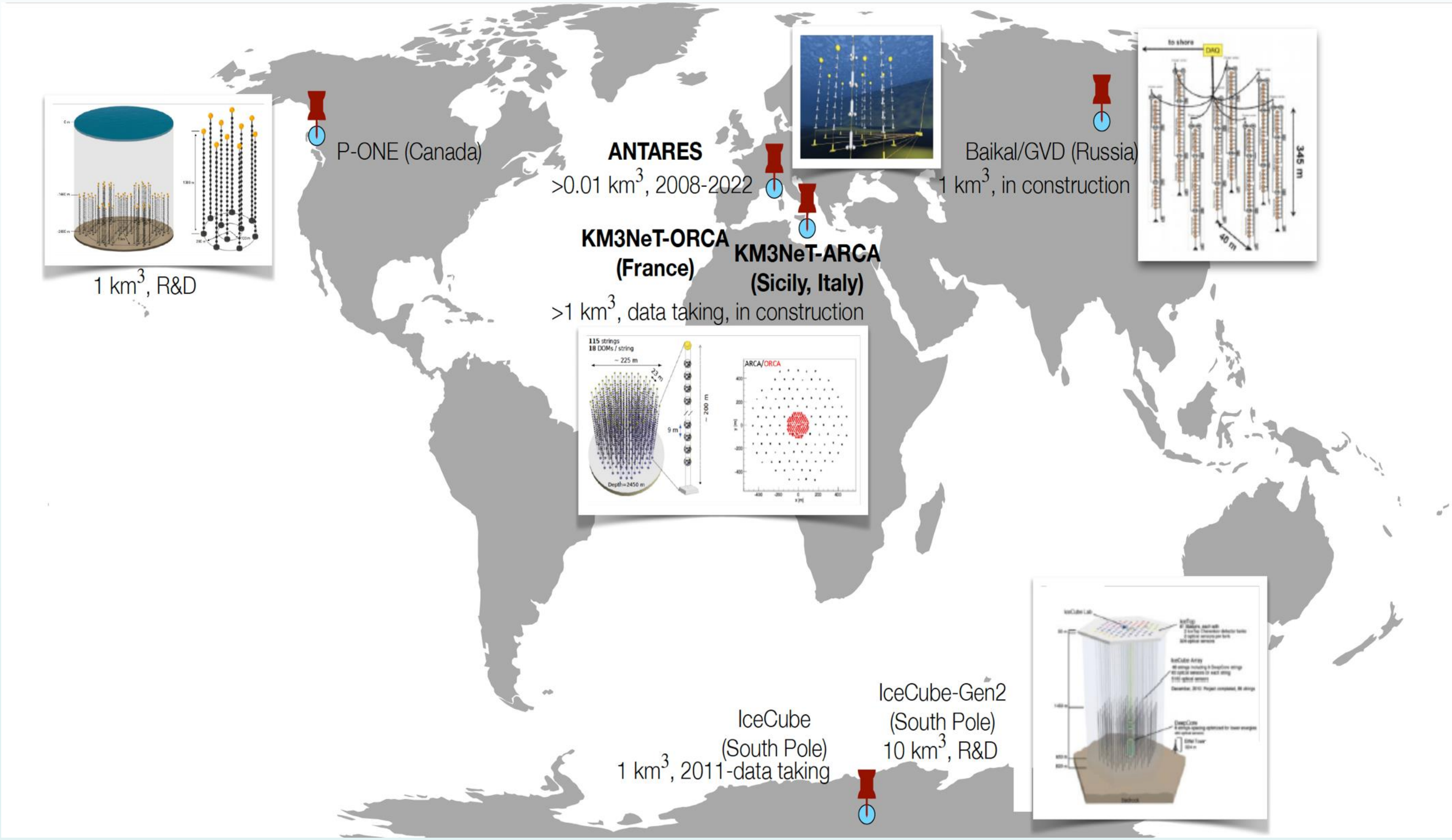




> 1PeV: ν orizzontali o dall'alto

<100 TeV: ν dal basso

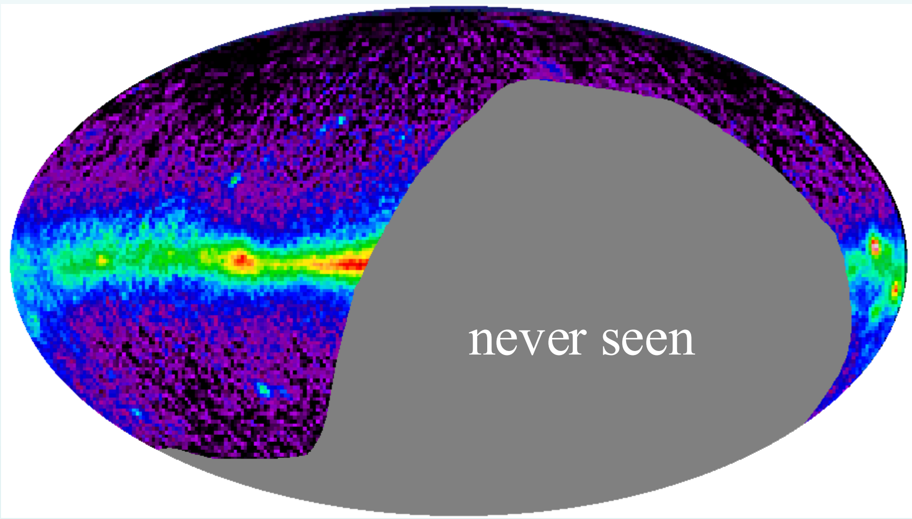
# Mappa mondiale dei Telescopi per  Neutrini

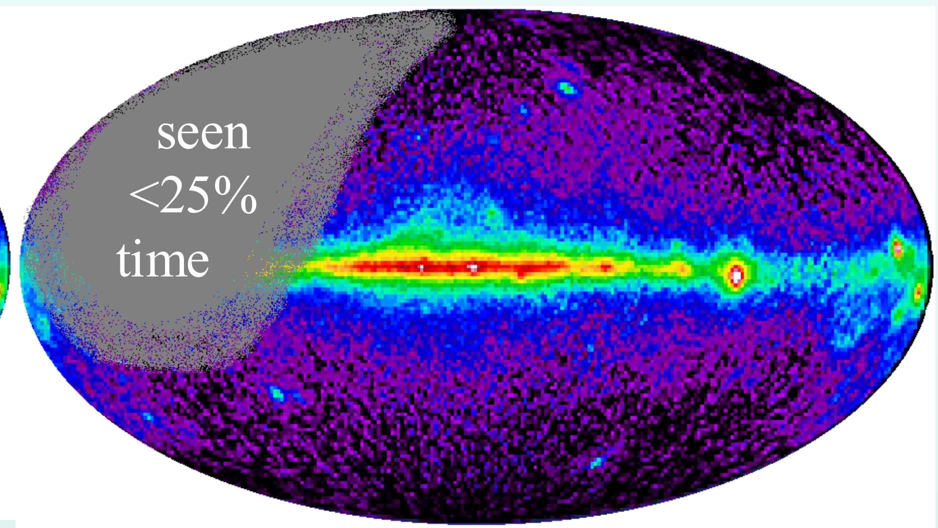


# Quanti Telescopi per neutrini ??

**Sarà importante "osservare" l'Universo in tutto l'angolo solido**

Gamma ray flux >100 MeV observed by EGRET

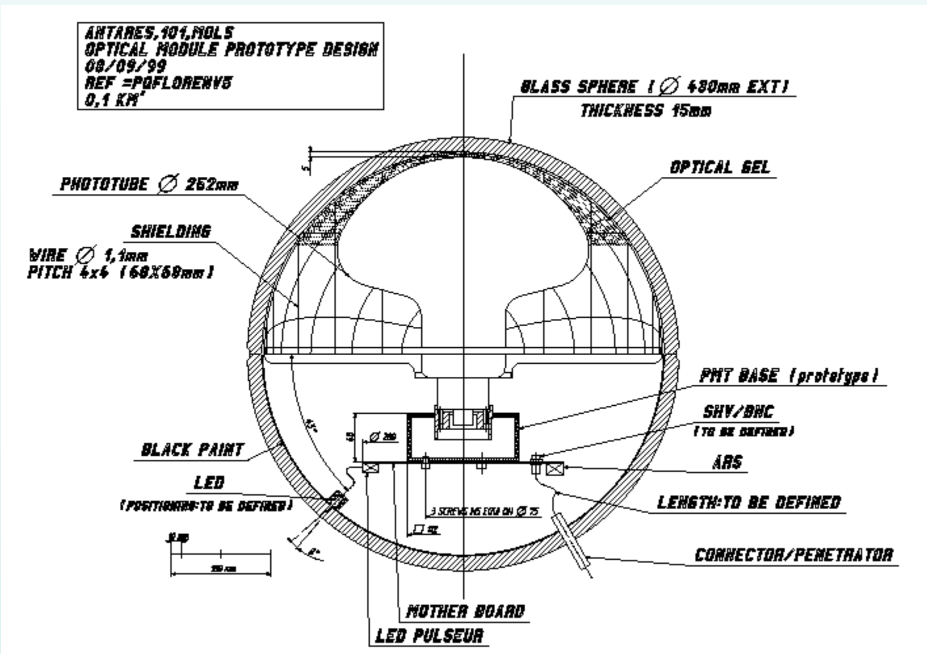


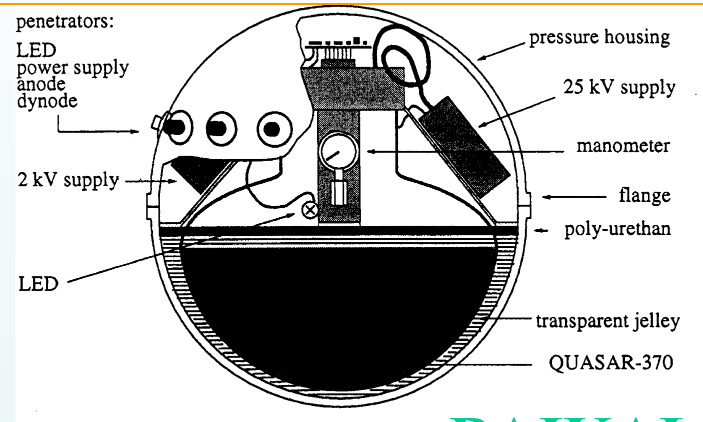

**AMANDA, ICECUBE** | **ANTARES, Baikal, KM3NeT**

# Moduli ottici per telescopi di ν sottomarini

Fotomoltiplicatori da 8÷15″ in sfere di vetro, diametro 13-17″
resistenti alla pressione (300-400 atm)




ANTARES




BAIKAL

# Il Telescopio per  Neutrini IceCube al Polo Sud

## A 3-D cosmic-ray detector:

**Two different kinds of events**

**Closely related scientifically:**

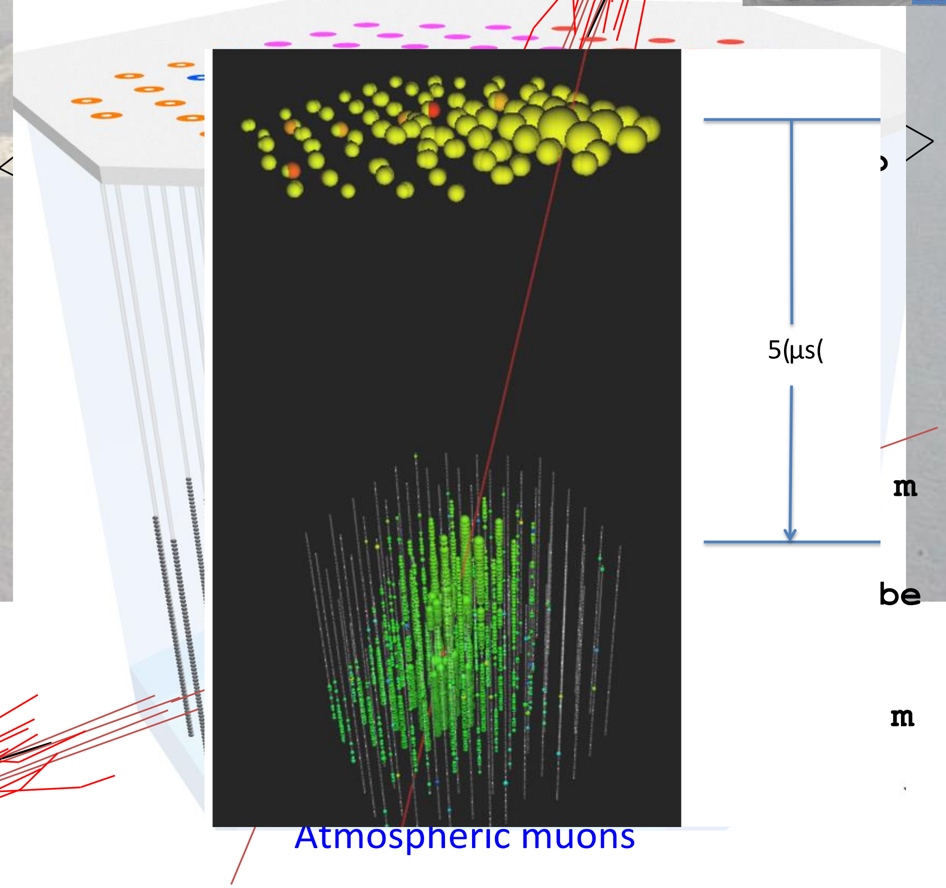
- Cosmic rays after propagation
- Neutrinos from cosmic ray sources
- $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0 → 1:1:1

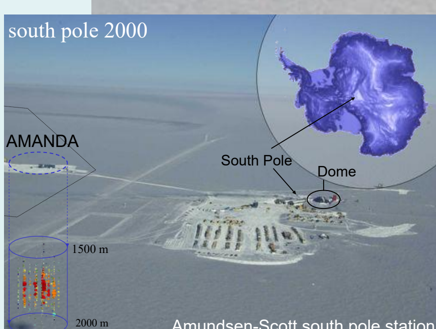
Cosmic ray showers from above

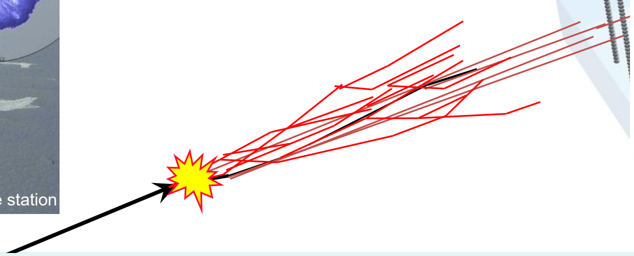

South Pole
2835 m.a.s.l.

Neutrinos from all directions

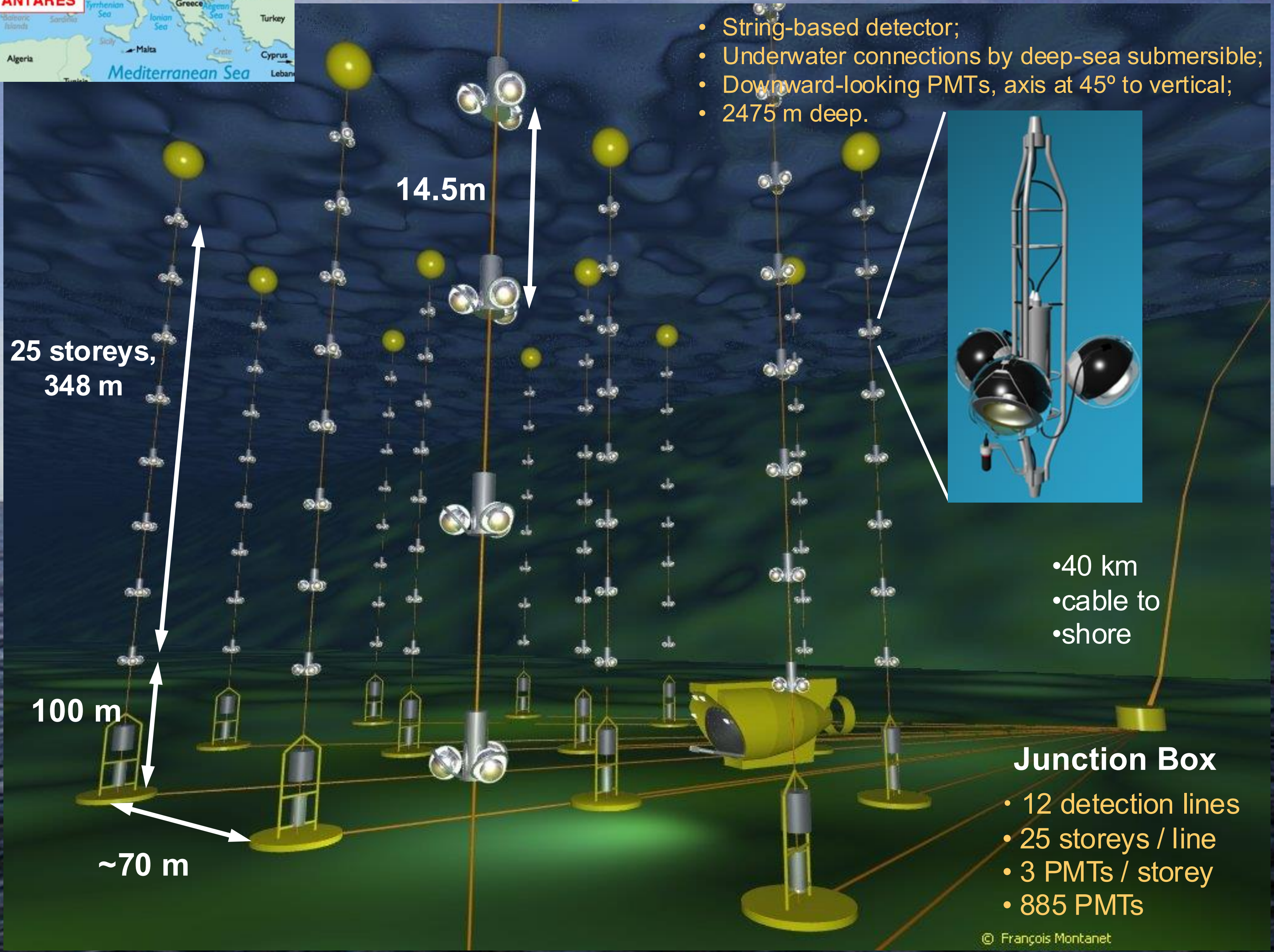
- *$\nu_\mu$-induced $\mu$ (from below)*
- *all flavors starting inside detector*



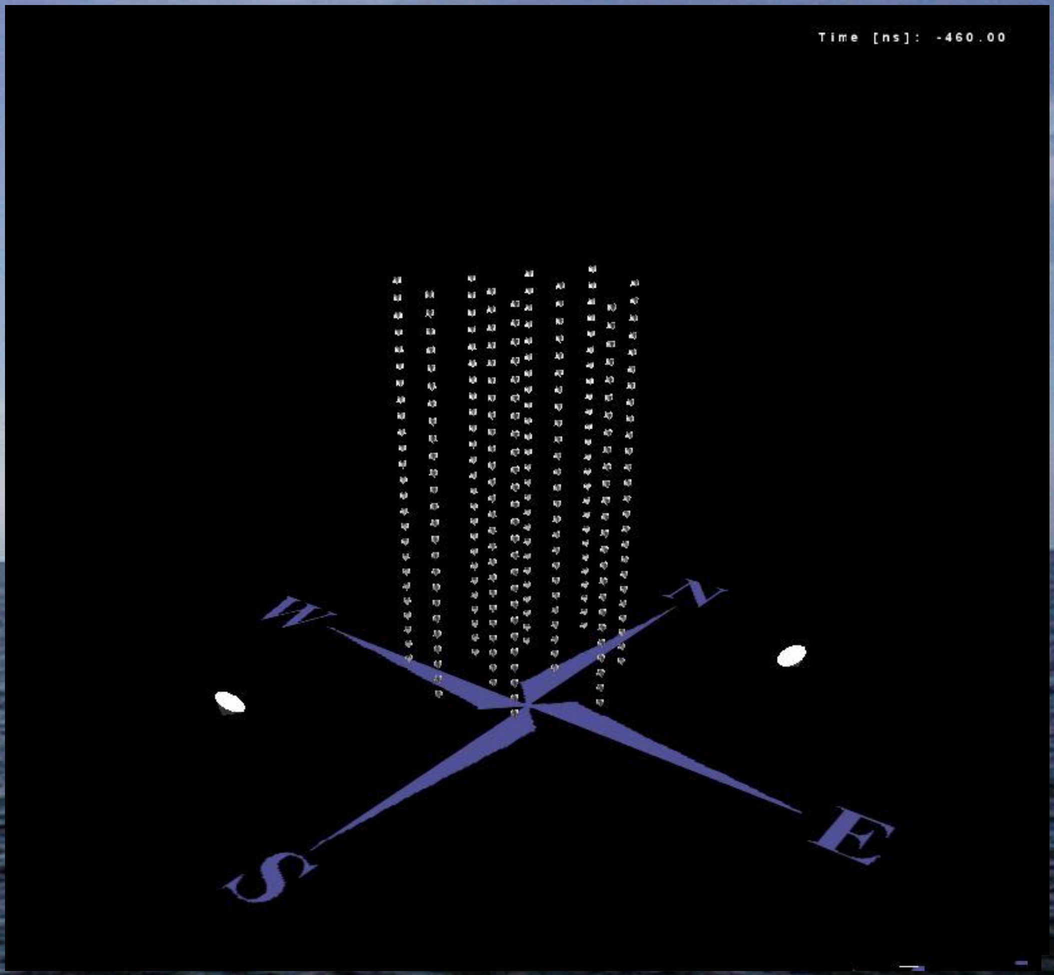



# L'esperimento ANTARES

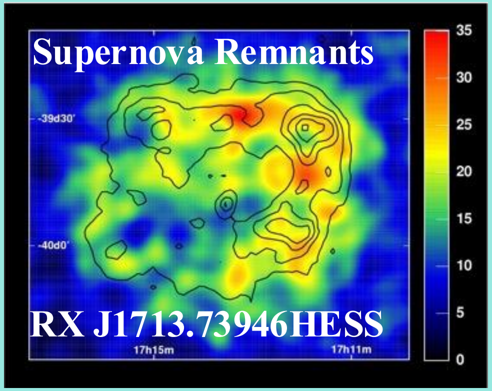
# ANTARES: traccia "dall'alto": un muone atmosferico

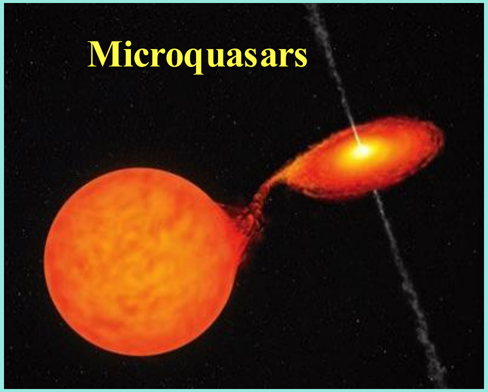
# ANTARES traccia "verso l'alto": un "candidato" neutrino



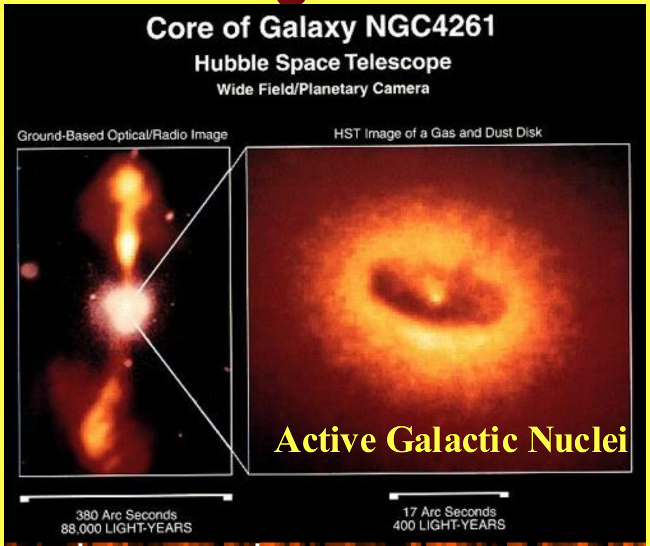
# Obiettivi della ricerca: individuare sorgenti "puntiformi di neutrini"

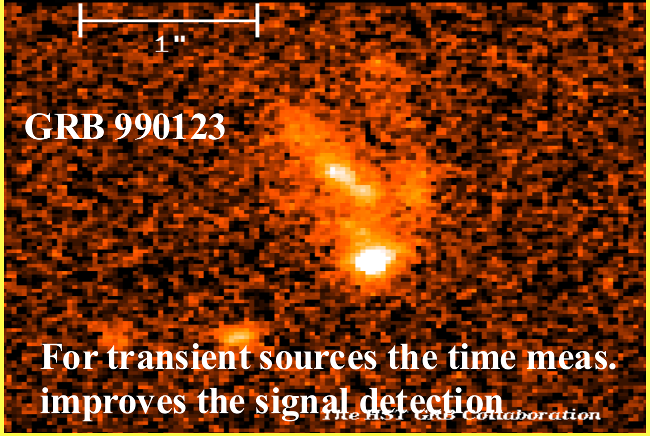
***Galactic***


***Extragalactic***



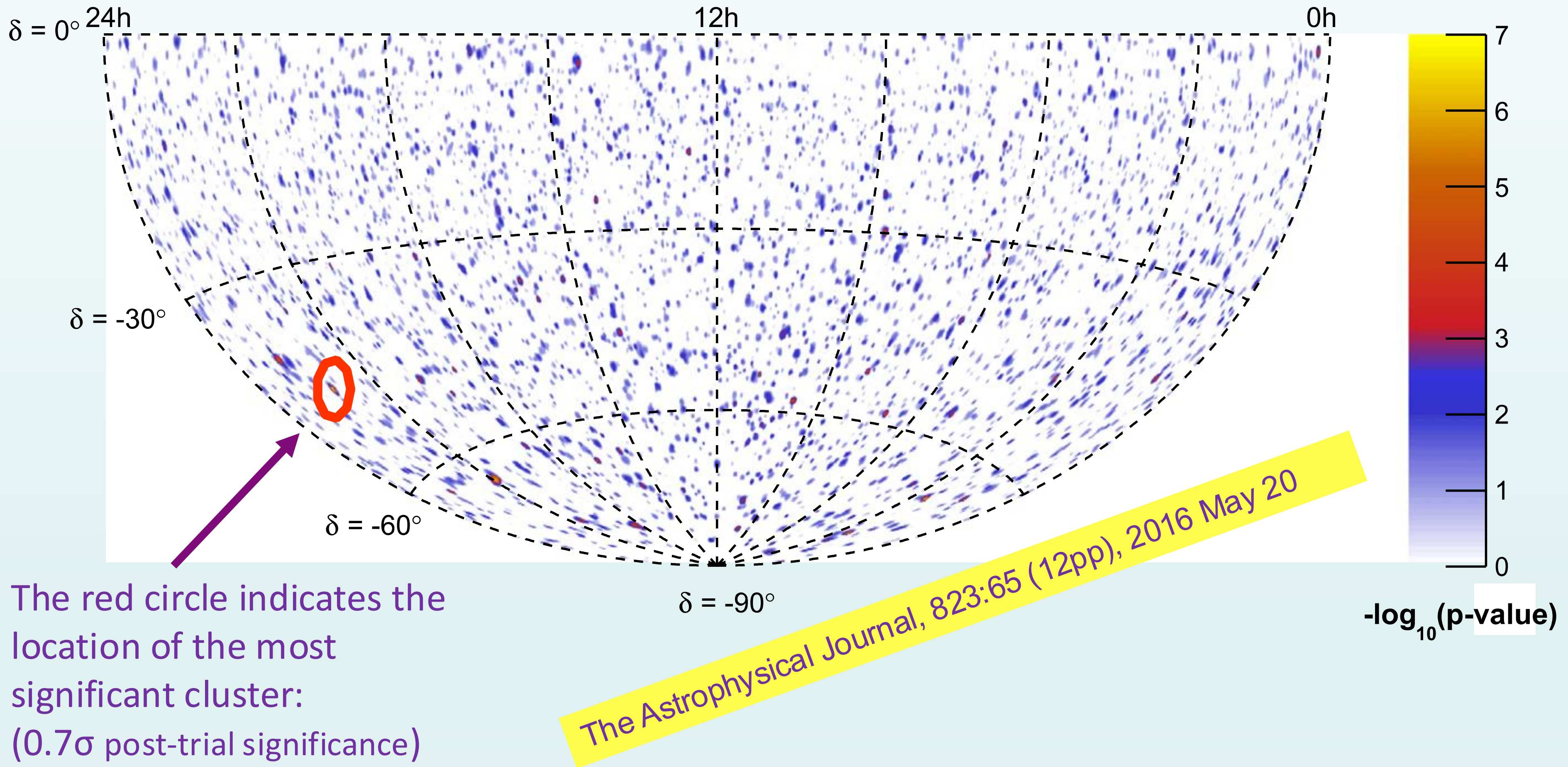




Il segnale cercato: un eccesso di tracce, in un cono centrato attorno ad una posizione nel cielo, rispetto al fondo uniforme dei neutrini atmosferici. Diminuendo l'apertura del "cono di ricerca" si riduce il numero di neutrini atmosferici e si rende più efficiente la ricerca del segnale. Importantissima è la bontà del rivelatore nel ricostruire la direzione delle particelle,

$$\sigma(\vartheta) \leq 0.5^\circ \quad \text{for } E_\nu \geq 1\,\text{TeV}$$

# ANTARES & IceCube: ricerca di sorgenti puntiformi di ν astrofisici

Skymap of pre-trial p-values for the combined
ANTARES 2007/12 and IceCube 40, 59, 79
point-source analyses.

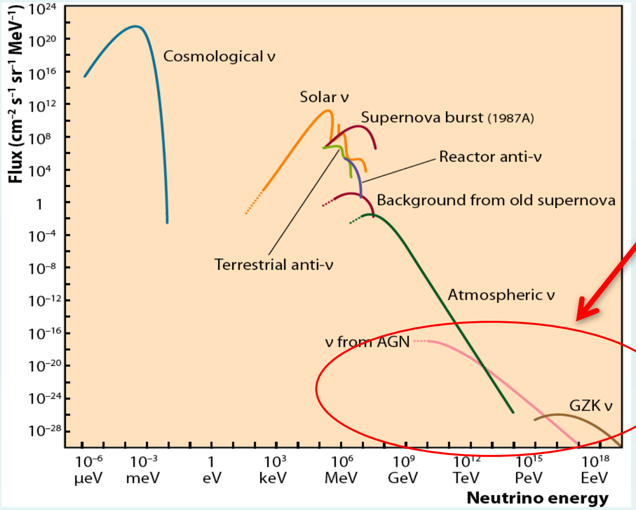



The red circle indicates the location of the most significant cluster:
(0.7σ post-trial significance)

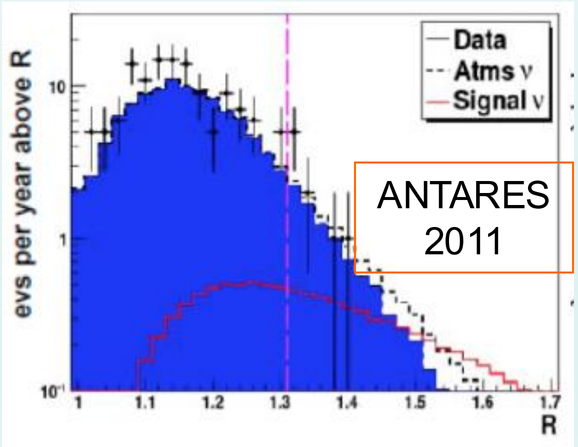
# Un altro obiettivo: identificare un flusso di neutrini oltre quello di origine atmosferica

- **Unresolved Active Galactic Nuclei**
- **Neutrinos from "Z-bursts"**
- **Neutrinos from "GZK like" p-CMB interactions**
- **Neutrinos foreseen by Top-Down models**
- **….**

**Their identification out of the more intense background of atmospheric neutrinos (and muons) is possible at very high energies (E > TeV) and implies accurate energy reconstruction.**

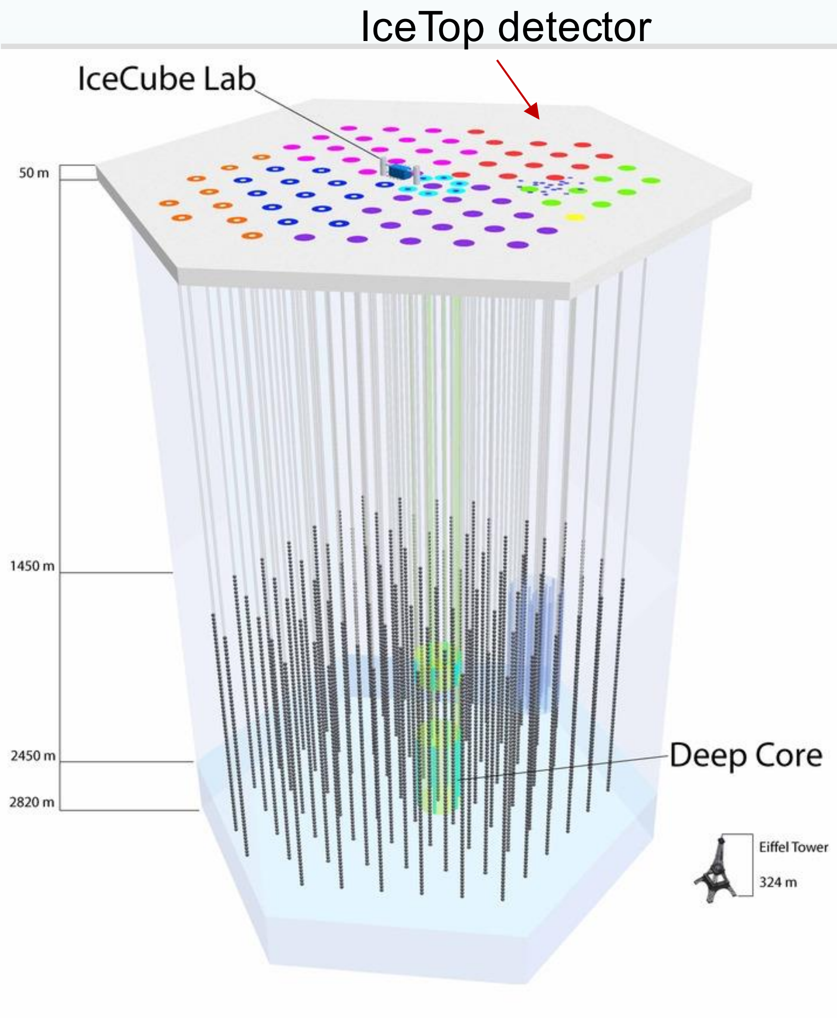


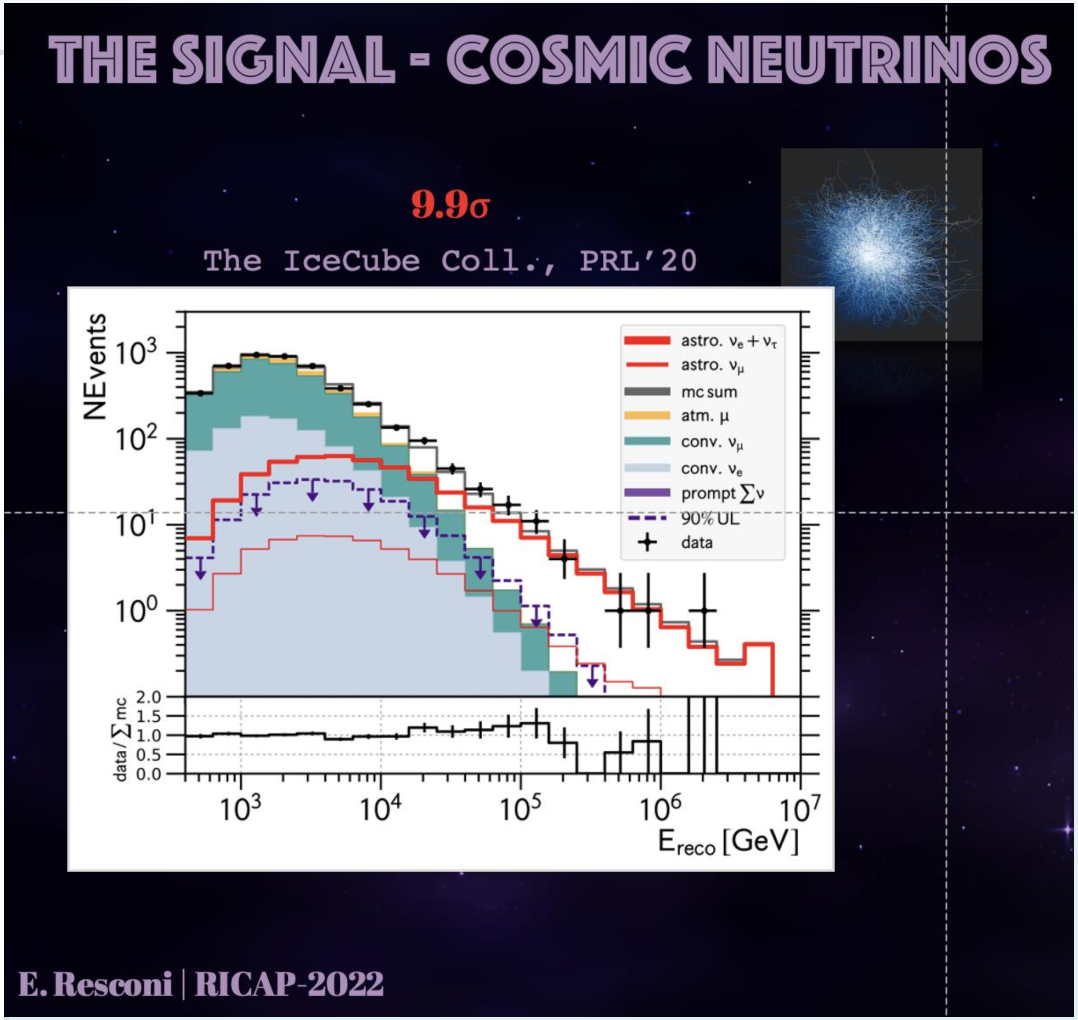

Search here !!!




ANTARES 2011

# IceCube: misurato un flusso "diffuso" di neutrini astrofisici sin dal 2013

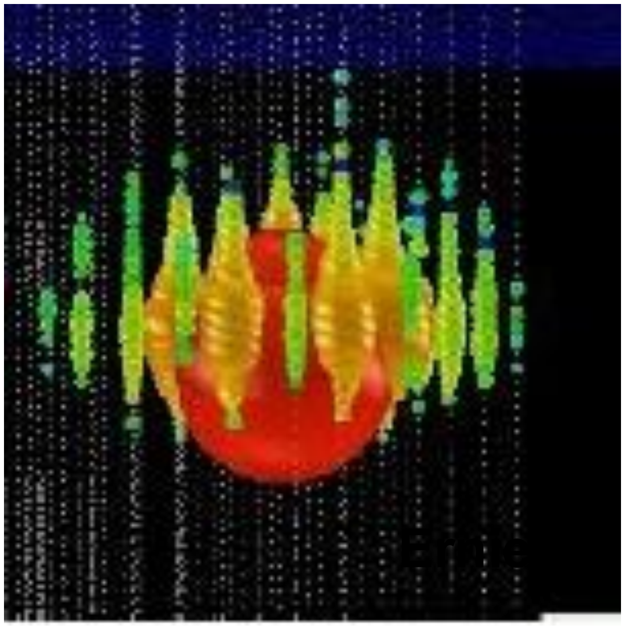


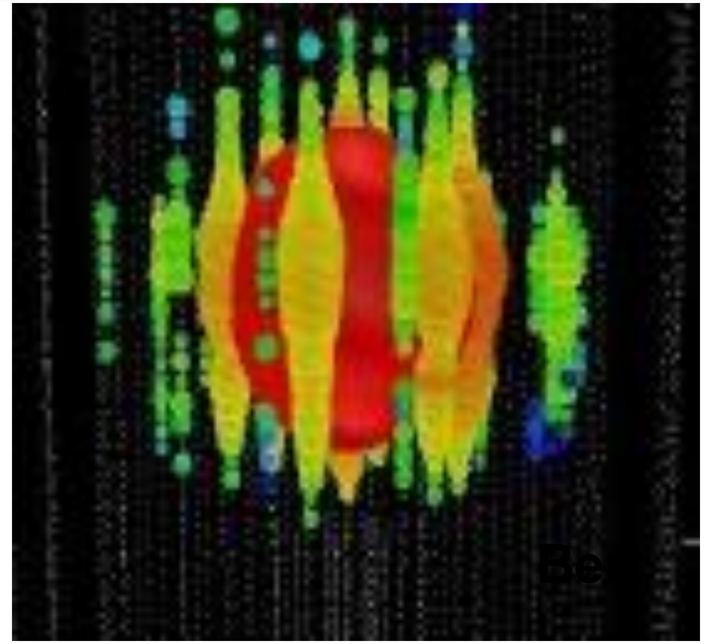

In operation at the South Pole since 2010
Sensitive to TeV – PeV neutrinos

$$\frac{d\phi}{dE} = 6.45\left(\frac{E_\nu}{100TeV}\right)^{-2.89} 10^{-18}[GeV^{-1}cm^{-2}\ s^{-1}\ sr^{-1}]$$

# SCOPERTA !!!: i primi due eventi di neutrini astrofisici di altissima energia identificati da IceCube (2012) !!!



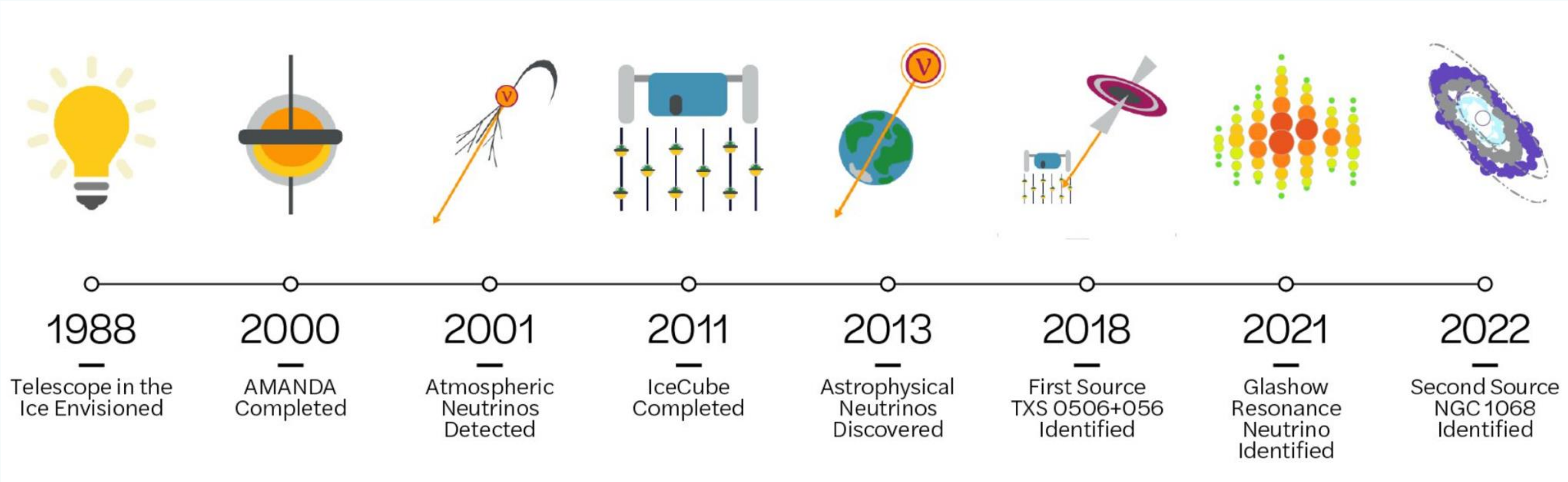
312 DOMs

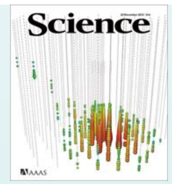


354 DOMs

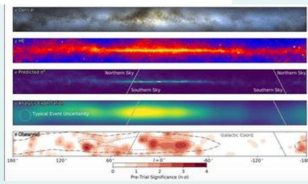
**Two neutrino events of energy above $10^{15}$ eV detected in IceCube were reported on Neutrino 2012 Conference.**
**T. Stanev @ Now 2012 Conference: "The first thought was that these events are produced by electron antineutrinos generating the Glashow resonance."**

# IceCube: altri risultati interessanti ....



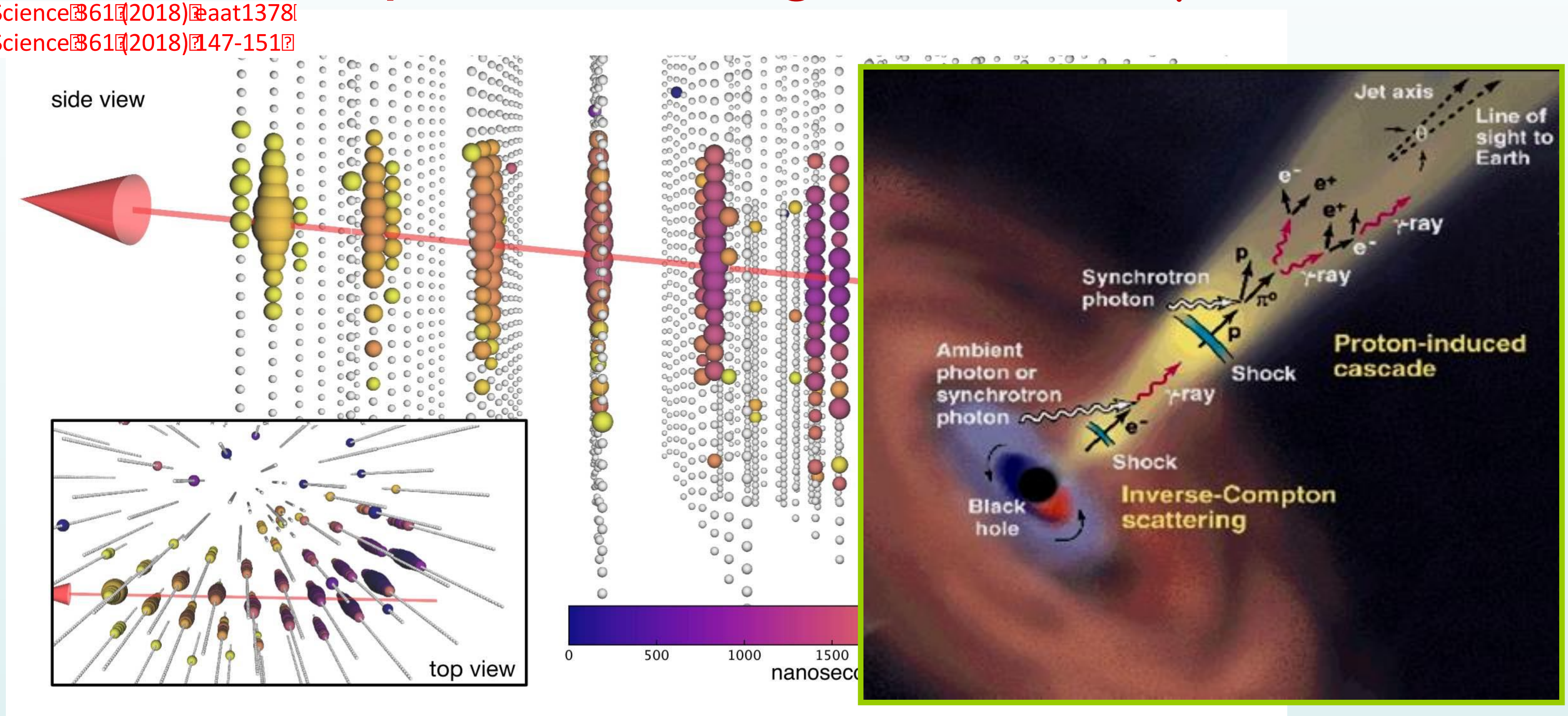




... l'astronomia con neutrini necessita di apparati più sensibili ...
ma può trarre vantaggio da misure fatte con altri strumenti:
nasce la "**astronomia a molti messaggeri**"

# IceCube e FERMI: la scoperta di una possibile sorgente di $\nu$ e $\gamma$

Science 361 (2018) eaat1378
Science 361 (2018) 147-151




All'annuncio di IceCube di aver osservato questo evento di altissima energia FERMI e MAGIC hanno replicato annunciando di aver osservato "in coincidenza" spaziale e temporale un "getto di fotoni" dalla stessa sorgente: il Blazar TXS 0506+056

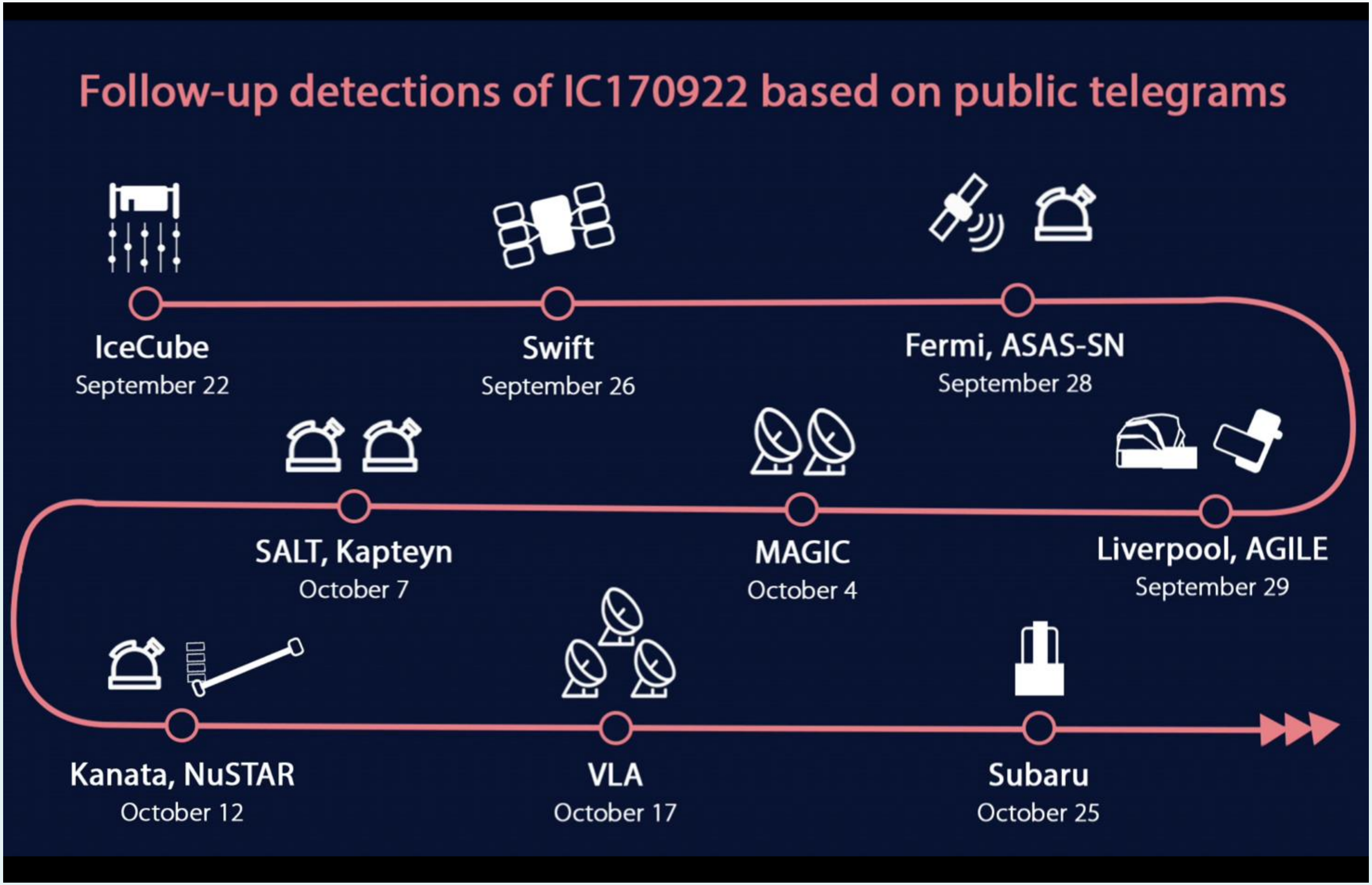
# 22 settembre 2017: IceCube annuncia l'evento osservato

## IceCube Trigger

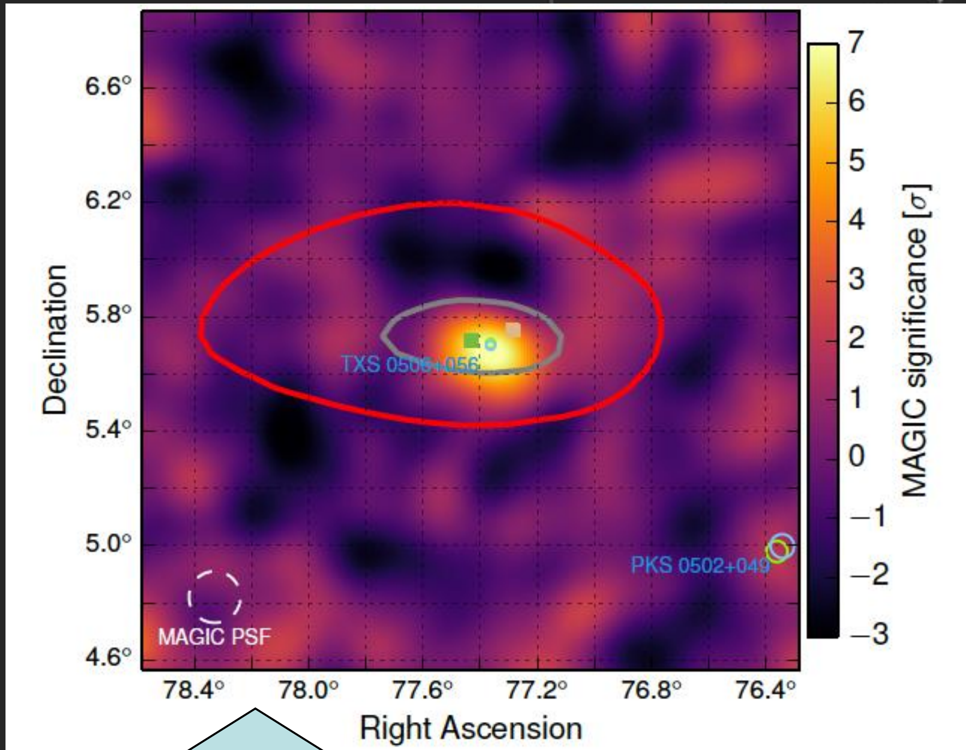
43 seconds after trigger, GCN notice was sent

```
//////////////////////////////////////////////////////////////////////
TITLE:                 GCN/AMON NOTICE
NOTICE_DATE:           Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:           AMON ICECUBE EHE
RUN_NUM:               130033
EVENT_NUM:             50579430
SRC_RA:                 77.2853d {+05h 09m 08s} (J2000),
                        77.5221d {+05h 10m 05s} (current),
                        76.6176d {+05h 06m 28s} (1950)
SRC_DEC:                +5.7517d {+05d 45' 06"} (J2000),
                        +5.7732d {+05d 46' 24"} (current),
                        +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:             14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:        18018 TJD;    265 DOY;    17/09/22 (yy/mm/dd)
DISCOVERY_TIME:        75270 SOD {20:54:30.43} UT
REVISION:              0
N_EVENTS:              1 [number of neutrinos]
STREAM:                2
DELTA_T:               0.0000 [sec]
SIGMA_T:               0.0000e+00 [dn]
ENERGY :               1.1998e+02 [TeV]
SIGNALNESS:            5.6507e-01 [dn]
CHARGE:                5784.9552 [pe]
```

# Immediata reazione dei vari telescopi/esperimenti in funzione: ricerca a "*molti messaggeri*"

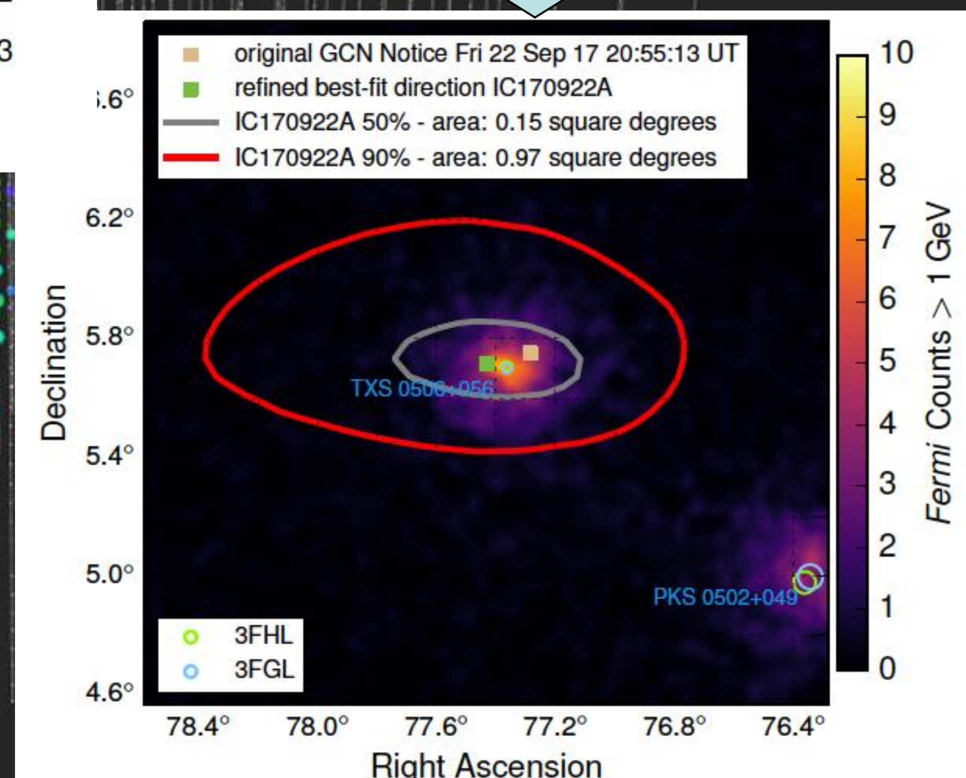


# IceCube 170922

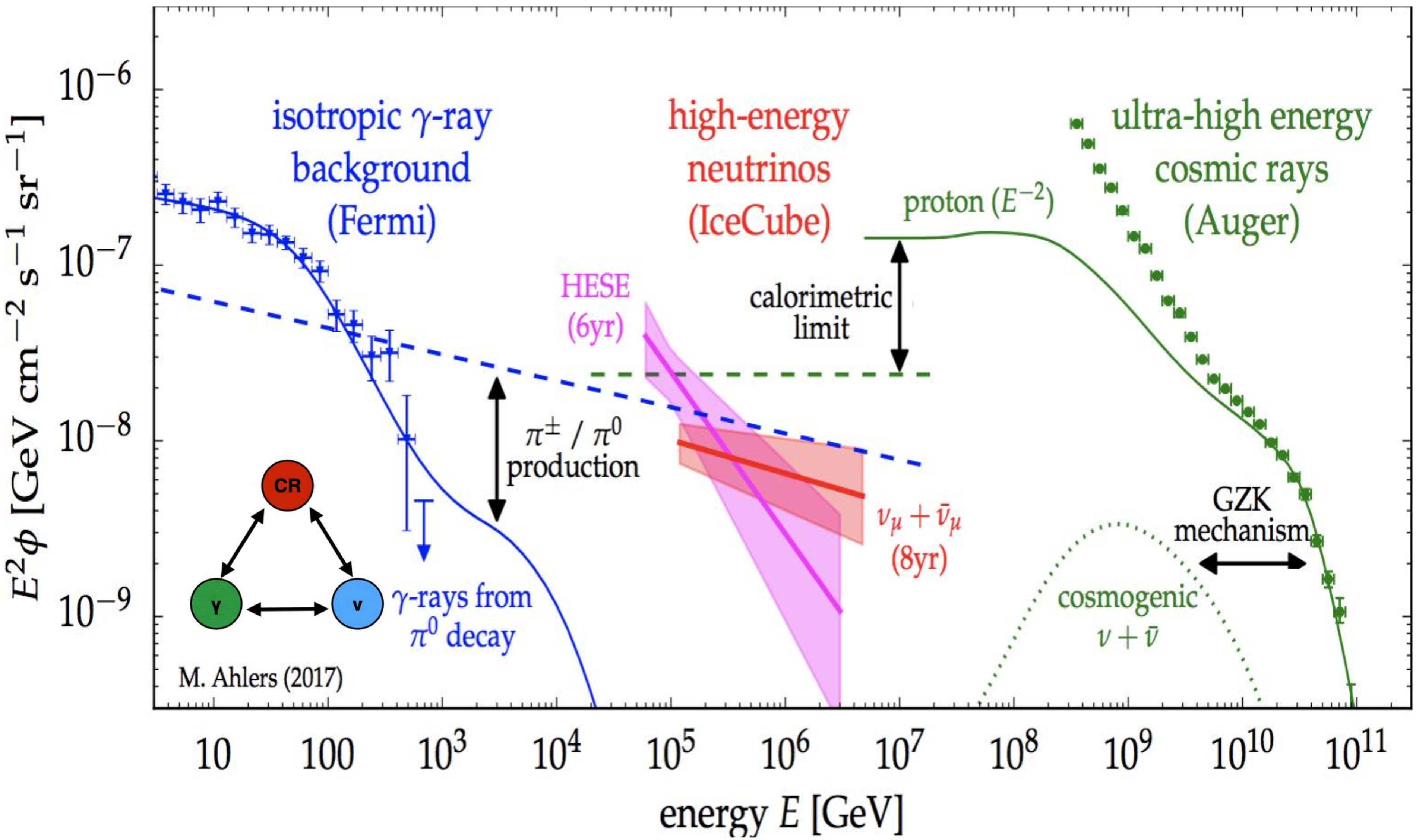



**MAGIC**
rivelati fotoni, in coincidenza temporale, con E> 100 GeV

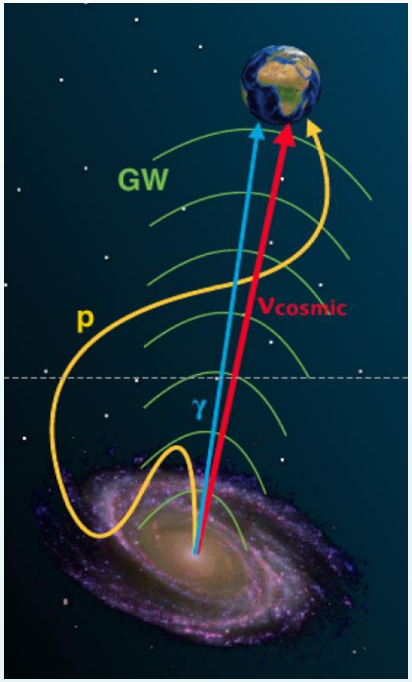
**Fermi**
rivelato un "blazar" molto vicino $\Delta\theta \sim 0.06^o$



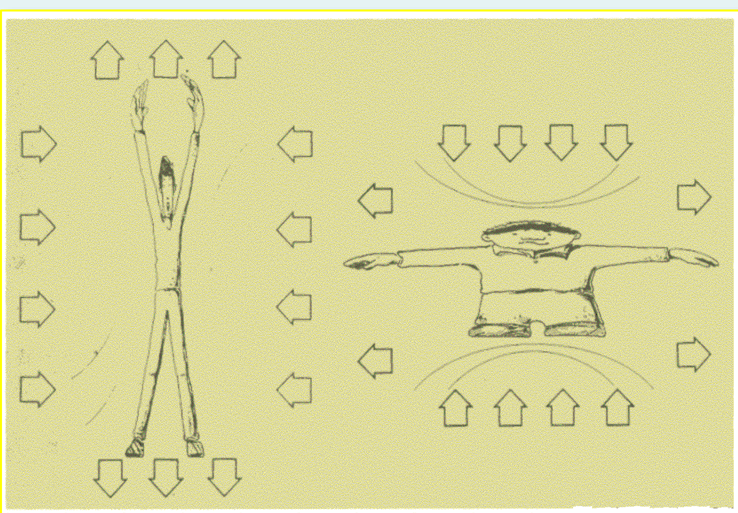
# I flussi di ν-γ-CR "diffusi" sono fortemente correlati



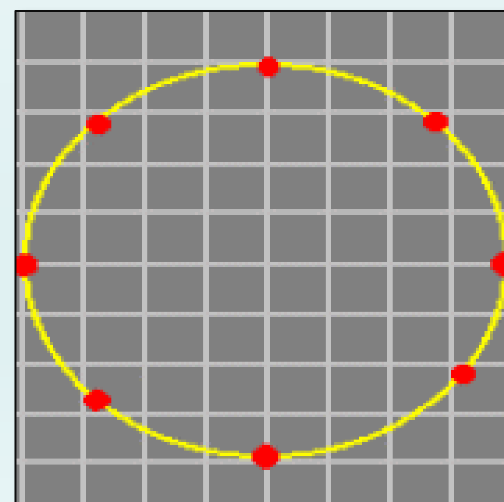
# anche ν-γ-GW possono essere correlati



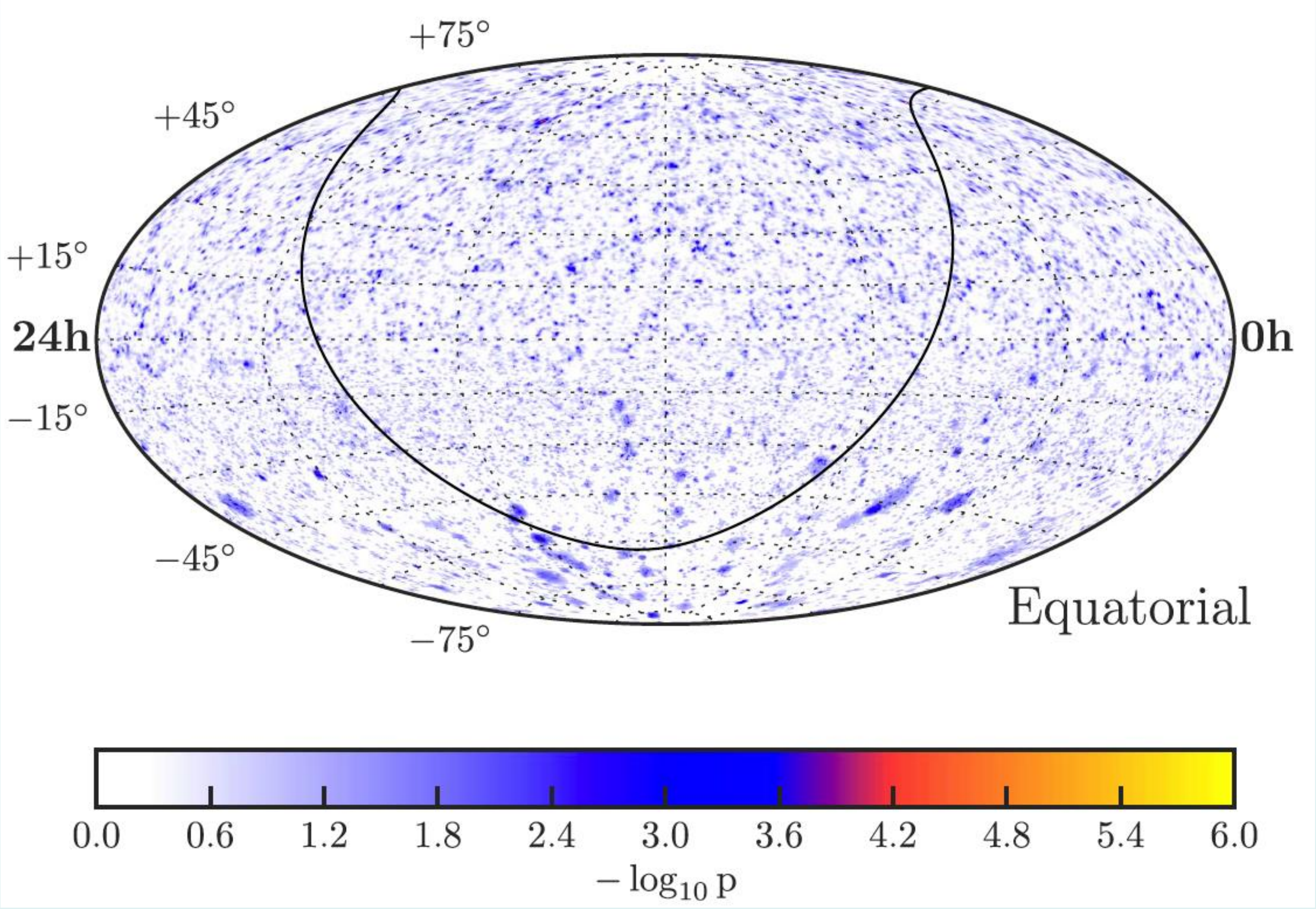

2017: coalescenza fra due stelle di neutroni



La deformazione potrebbe essere molto piccola $\Delta L/L \sim 10^{-23}$ !

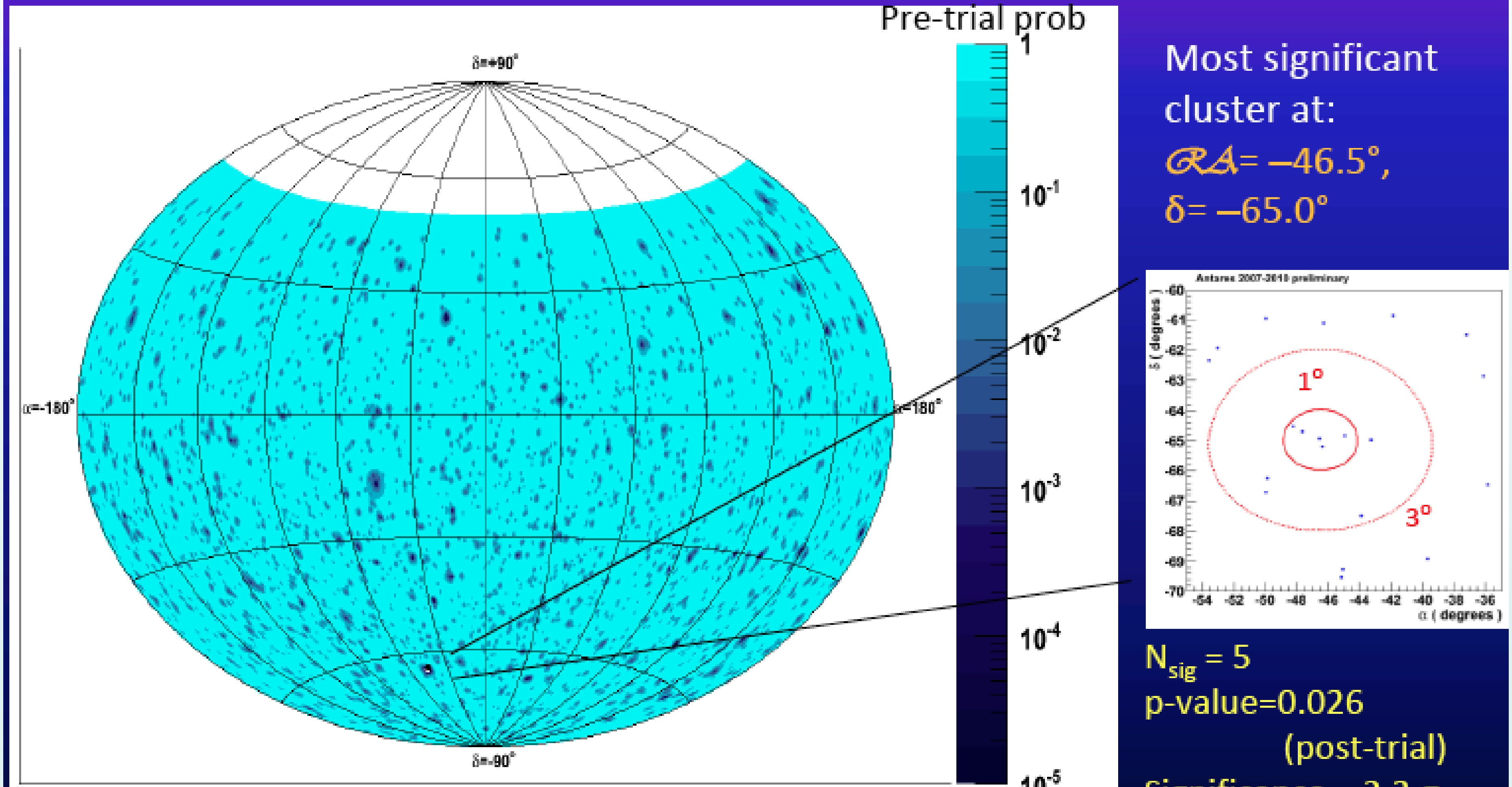


# Astronomia a molti messaggeri:
# ricerca di "sorgenti astrofisiche puntiformi di neutrini"




Moltissimi i neutrini rivelati, alcuni sembrano "addensarsi" in particolari posizioni nel cielo ma ancora la probabilità che non siano "da sorgente puntiforme" è alta.
→ Si ricorre alla rivelazione a molti-messaggeri: si cercano direzioni nel cielo da cui provengono  neutrini, raggi gamma, protoni etc…

# Un esempio: la ricerca di sorgenti puntiformi dell'esperimento ANTARES



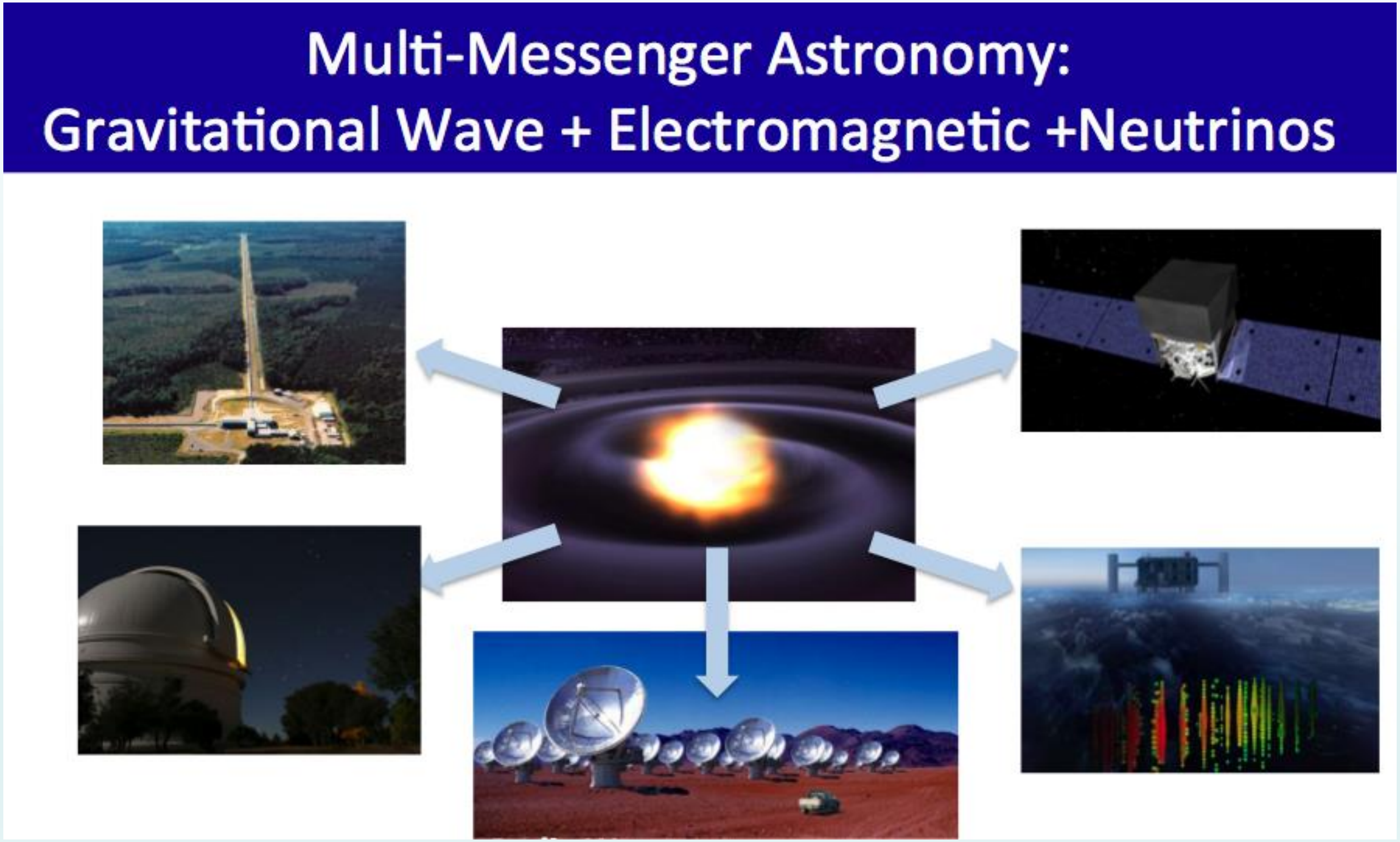

Most significant cluster at:
RA= –46.5°,
δ= –65.0°

$N_{sig}$ = 5
p-value=0.026 (post-trial)
Significance = 2.2 σ

Results compatible with the background hypothesis

# Il futuro ???

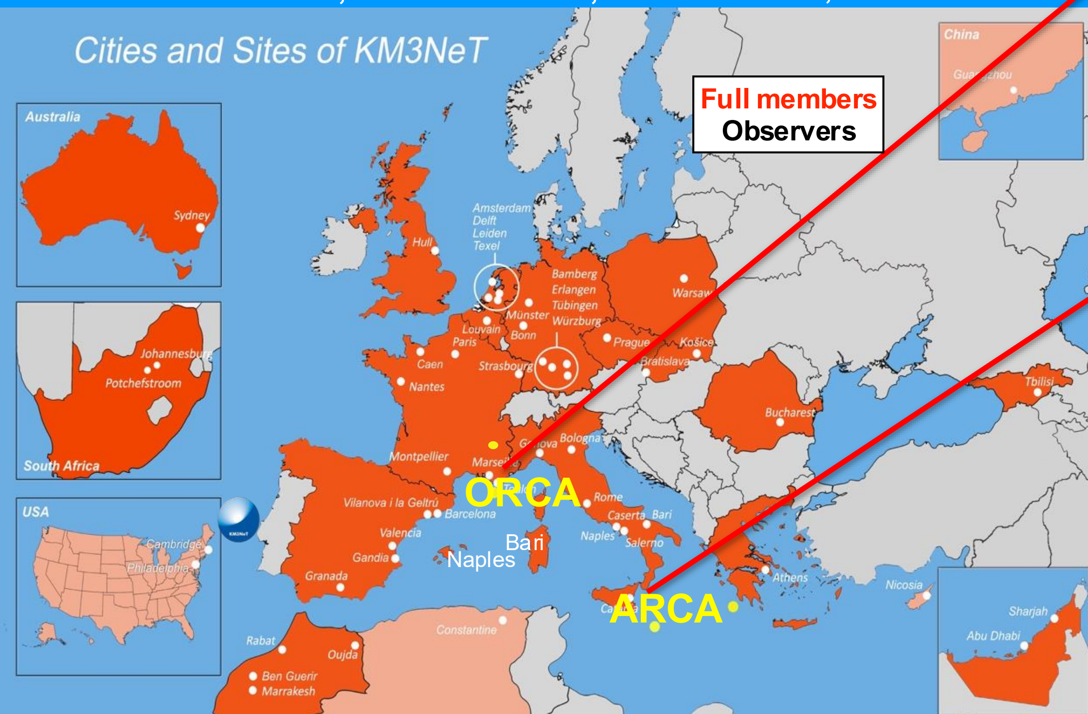
# L'astronomia Multi-Messenger !!!

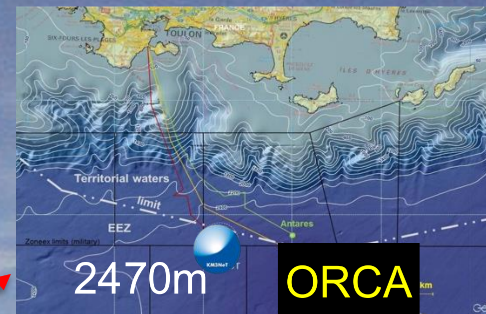


# KM3NeT: il futuro della astronomia con $\nu$ nel Mediterraneo

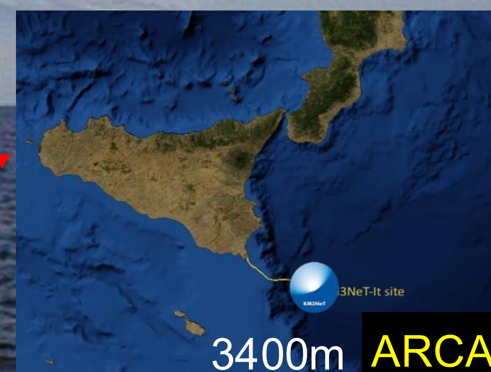
- Multi-sito, telescopio per neutrini abissale
- Selezionato e finanziato ESFRI (EU)
- Una collaborazione, una tecnologia
- Duplice programma scientifico

>250 scientists, 63 institutes, 22 countries, 5 continents



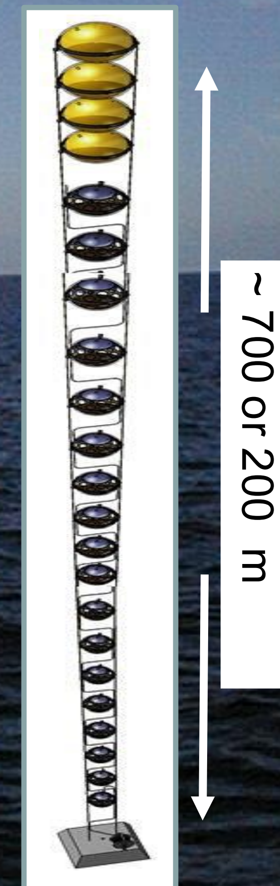




**O**scillation **R**esearch with **C**osmics In the **A**byss



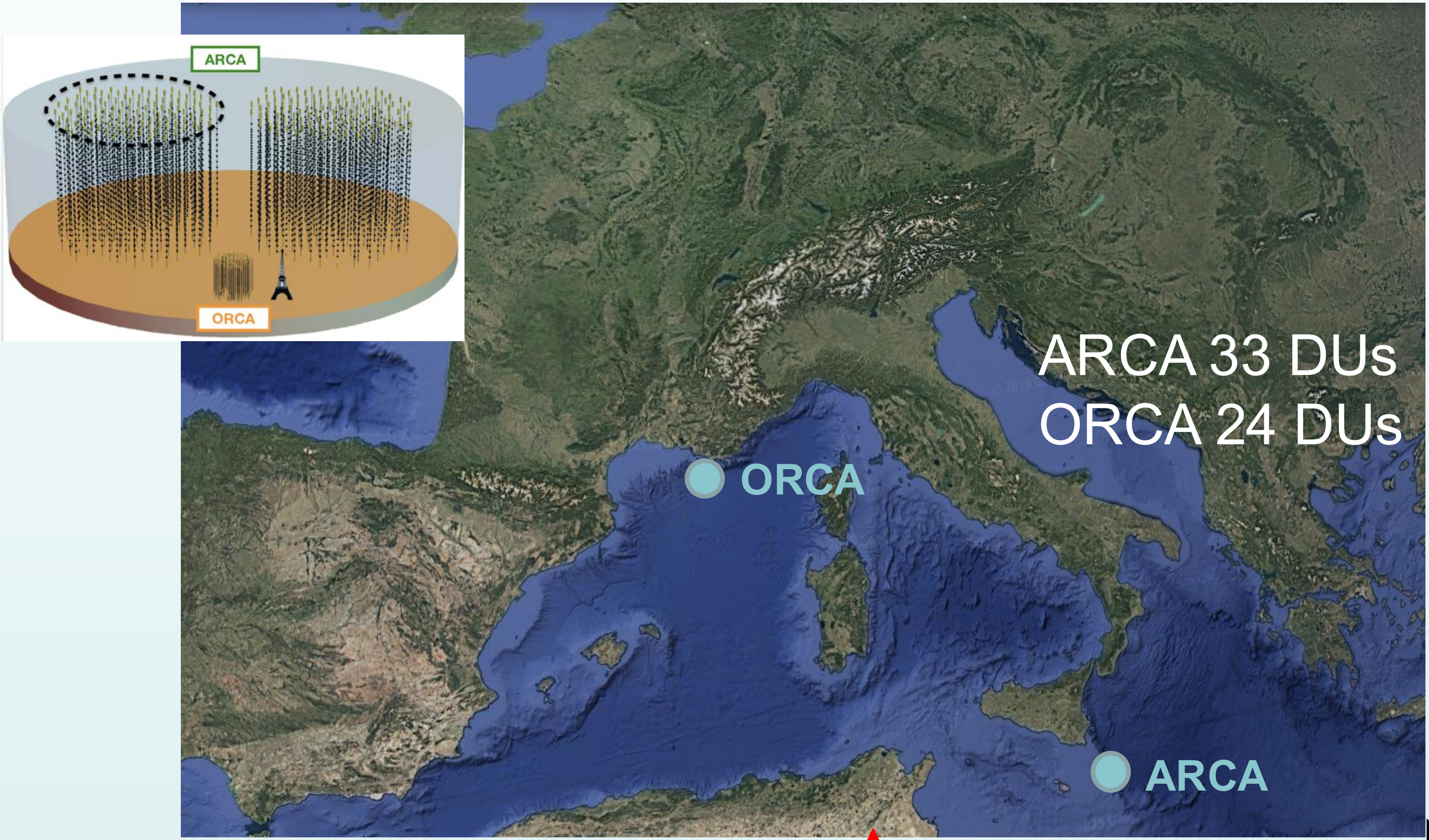

**A**stroparticle **R**esearch with **C**osmics in the **A**byss

Connection nodes of european multidisciplinary seafloor & water column observatory emso




[KM3NeT 2.0: Letter of Intent]
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

# KM3NeT: in costruzione ed in misura !!!




2020 2021 2022 2023 2024 2025 2026 2027 2028 2029

**ANTARES**
**Termine operazioni**

**ANTARES**
**Ultimi articoli**

**ORCA & ARCA**
**Completamento apparato**

# KM3NeT: gli elementi basilari

## Il Modulo Ottico Digitale (DOM)

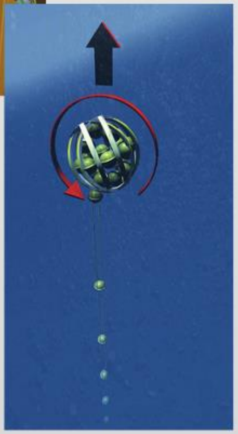
Multi-PMT DOM

- 31 PMTs
- Cost effective sensor Area
- Photon counting
- Directional sensitivity


## La Unità di Rivelazione (DU)

The Detection Unit



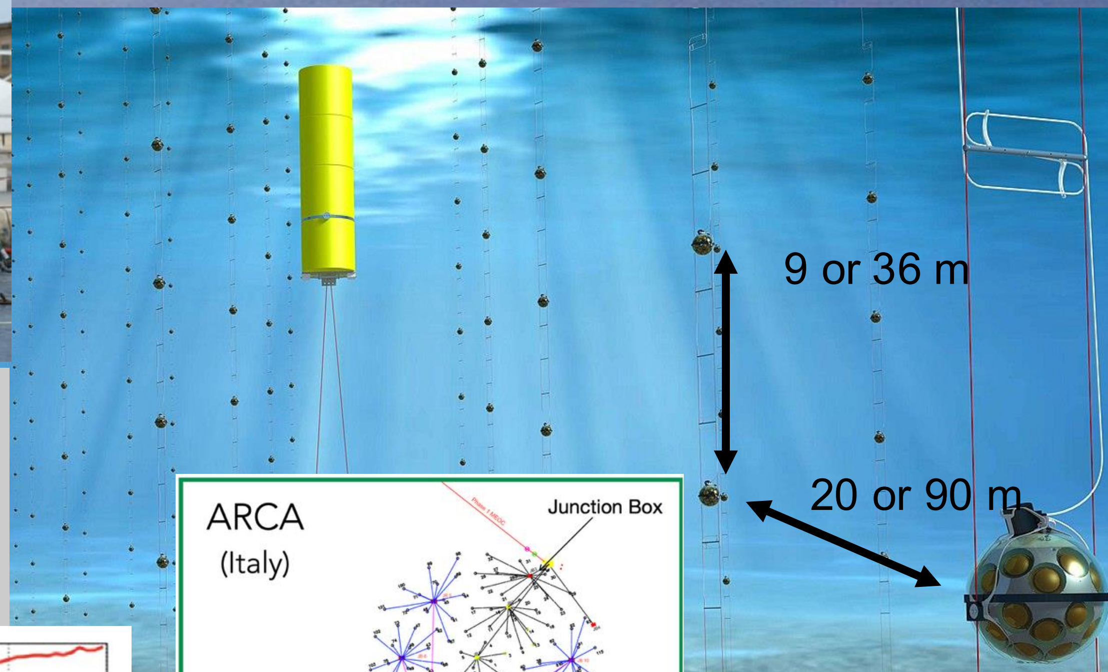


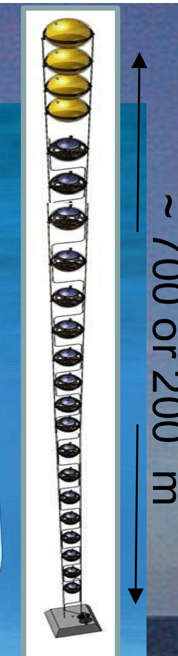
18 DOMs in a DU

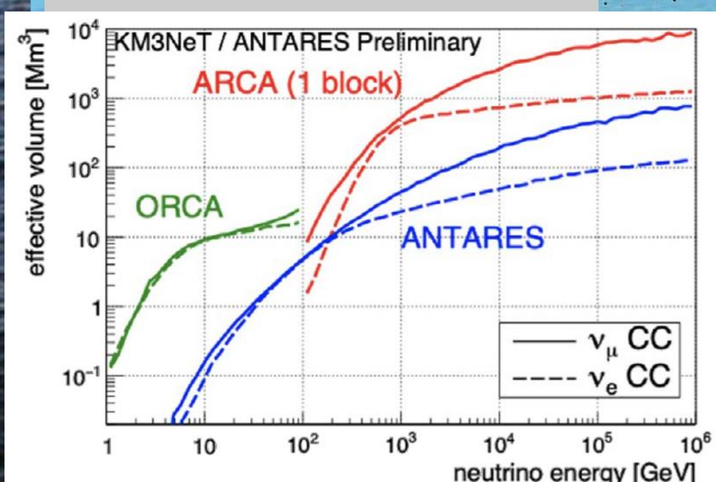
DU

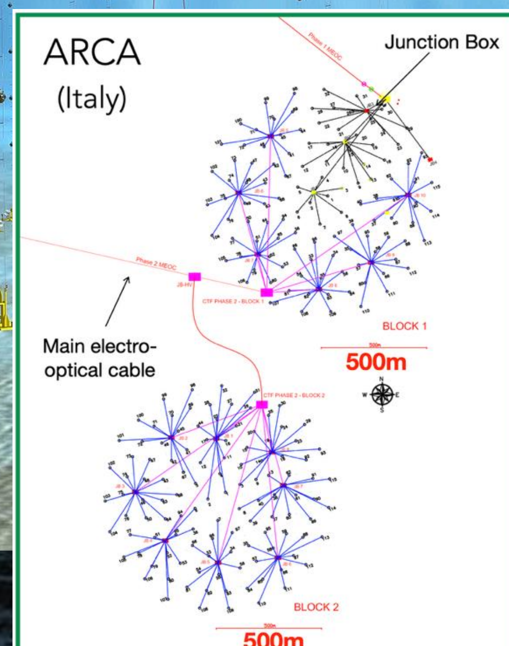
# ORCA ed ARCA: una vista schematica

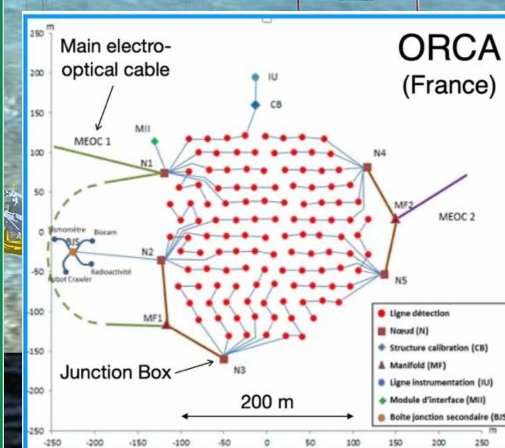
- Posizionamento rapido
- Più stringhe posizionate ogni campagna marina
- "apertura" con ROV
- Moduli riutilizzabili



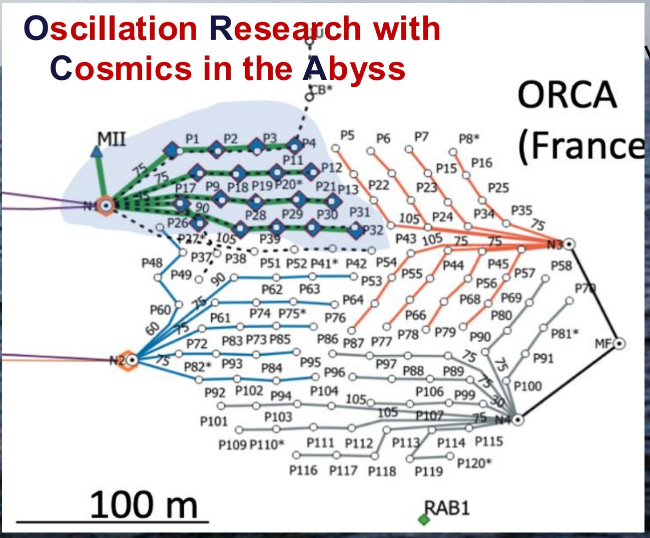



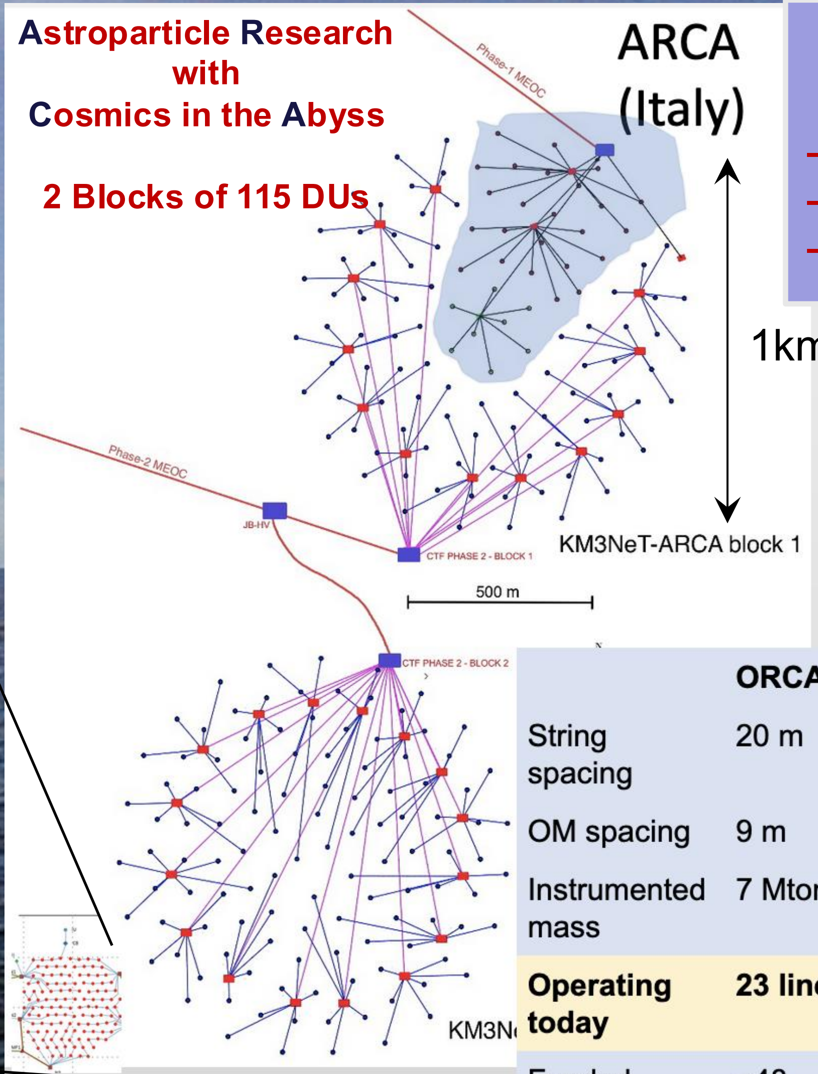
# Costruzione di KM3NeT e della infrastruttura di fondo

ARCA Current status:
- 2 long cables
- 3 Junction Boxes
- 28 DUs operating

ORCA Current status:
- First node completed ! (Oct. 2024)
- 24 DUs operating (20% full detector)

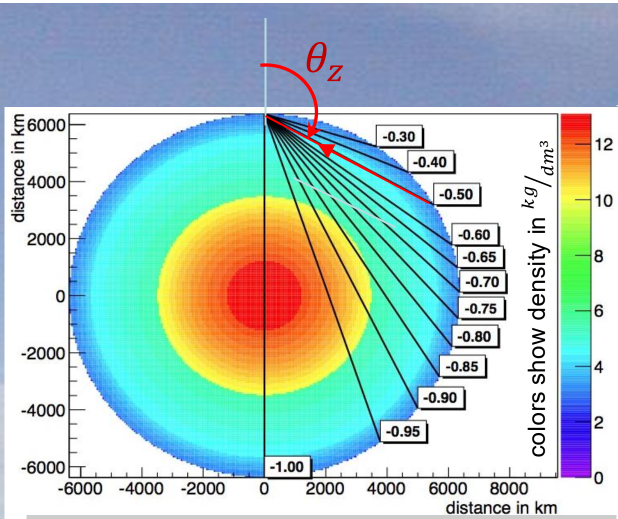
**One block of 115 DUs**



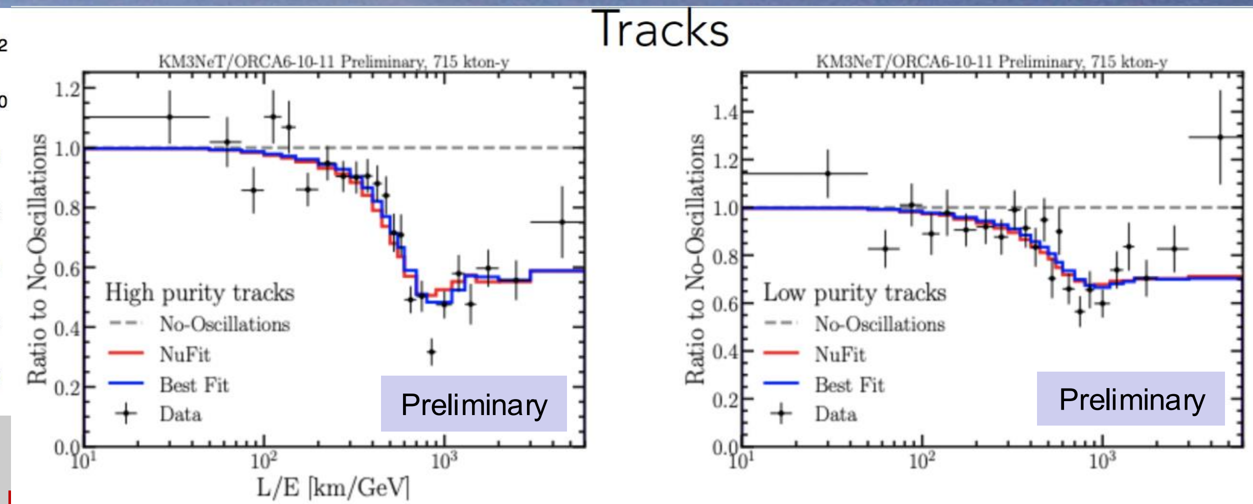



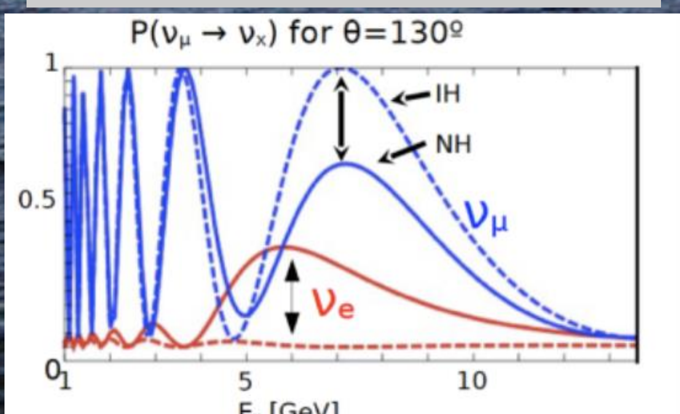

| | ORCA | ARCA |
|---|---|---|
| String spacing | 20 m | 90 m |
| OM spacing | 9 m | 36 m |
| Instrumented mass | 7 Mton | 500*2 Mton |
| **Operating today** | **23 lines** | **28 lines** |
| Funded | ~48 lines | ~130 lines |

# oscillazioni di $\nu$ e gerarchia di massa di $\nu$ con ORCA




Event measurements
→ $\theta_z$ → path into the Earth L
→ $E_\nu$ → evaluate **L/ $E_\nu$**

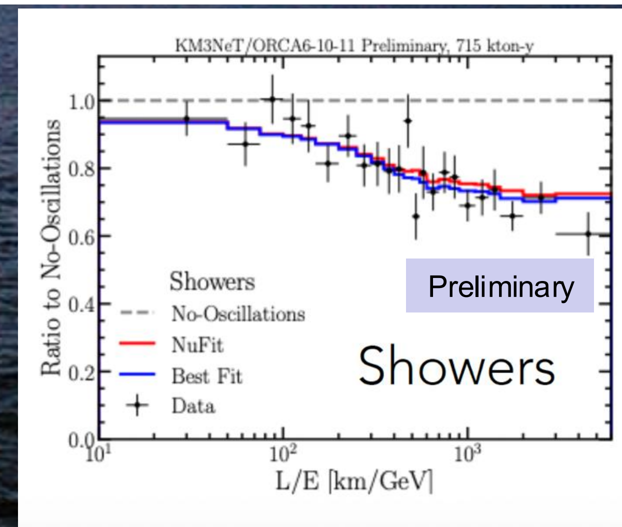



$(\sim 5 \leq E_\nu \leq \sim 15)\ GeV$

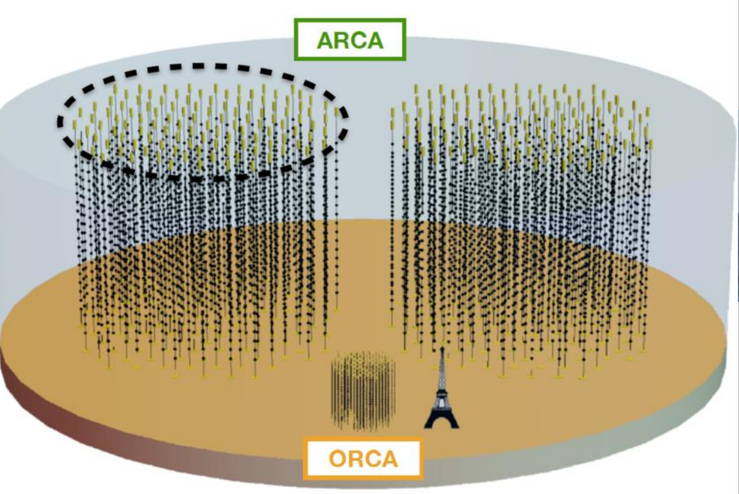
**Neutrino oscillation clearly Indicated both in track and shower events**

Data collected with ORCA 6 – 7 -11 Dus (715 kto/y) Preliminary Results



# KM3NeT: programma di ricerca a Molti-Messaggeri

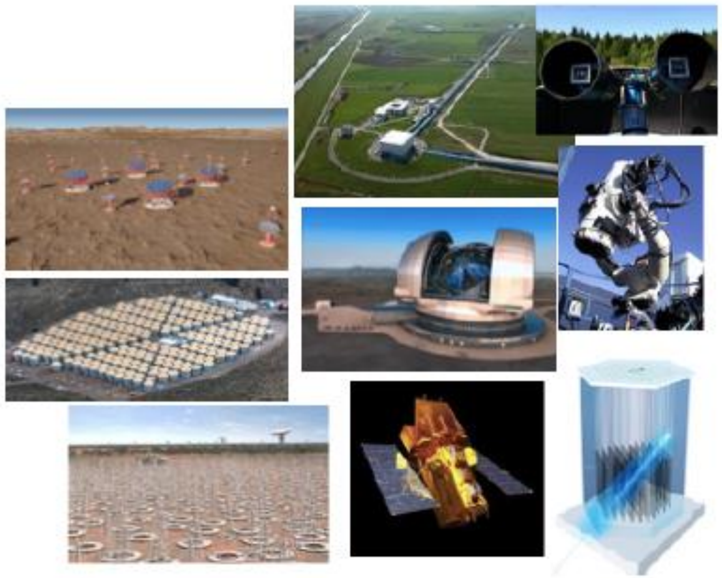
Presso i laboratori a riva di ARCA/ORCA Analisi Dati in tempo reale & comunicazione di segnali di "allerta"




Invio di "allerte" da neutrino alla comunità esterna

Ricezione di "allerte" dalla comunità esterna ➢ analisi dati in tempo reale, osservazione della evoluzione della sorgente

EM/MM external communities



Ricezione di "allerte" operativa sin da novembre 2022 in ARCA and ORCA.
Invio di "allerte" per eventi High-energy neutrino ~ finalizzato

# KM3-230213A ... una esaltante sorpresa


Article

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

https://doi.org/10.1038/s41586-024-08543-1

Received: 19 August 2024

Accepted: 18 December 2024

Check for updates

The KM3NeT Collaboration*[⊠]

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

Cosmic neutrinos may be produced either in the vicinity of the cosmic-ray source or along the cosmic-ray propagation path, leading to the production of secondary unstable particles, which subsequently decay into neutrinos. Cosmic rays interacting in the Earth's atmosphere produce atmospheric neutrinos, which form an experimental background to cosmic neutrinos. To detect cosmic neutrinos, very-large-volume neutrino observatories monitor natural bodies of water or ice for the Cherenkov light induced by the passage of the charged particles that result from neutrino interactions in or near the detector. The KM3NeT research infrastructure comprises two detector arrays of optical sensors deep in the Mediterranean Sea[4]. The ARCA detector is located offshore Portopalo di Capo Passero, Sicily, Italy, at a depth of about 3,450 m and connected by means of an electro-optical cable to the shore station of the INFN, Laboratori Nazionali del Sud (LNS). The geometry of ARCA is optimized for the study of high-energy cosmic neutrinos. The ORCA detector is located at a depth of about 2,450 m, offshore Toulon, France, and is optimized for the study of neutrino oscillations. Both detectors are under construction but already operational. Once completed, they will comprise 345 (230 for ARCA and 115 for ORCA) vertical detection lines, each holding 18 optical modules. Each module hosts 31 3-inch photomultiplier tubes (PMTs) pointing in all directions and ensuring 4π coverage[9]. Both detectors can identify all flavours of neutrino interactions: those producing long-lived muons, denominated 'tracks', and those producing electromagnetic and hadronic cascades at the neutrino interaction vertex, denominated 'showers'.

Of interest in this article are neutrino interactions that produce high-energy muons, which can travel several kilometres in seawater before being absorbed. These muons lose energy as they propagate mainly because of stochastic radiative processes such as bremsstrahlung, pair production and photonuclear reactions. The average energy loss per unit path length is proportional to the muon energy. Electromagnetic cascades arise from these stochastic energy losses; the number of charged particles that produce Cherenkov radiation in the cascades is proportional to the amount of energy lost by the muon in the process. The recorded time of arrival and time-over-threshold of the signals on the PMTs (denoted as 'hits') are used to reconstruct the muon direction and energy.

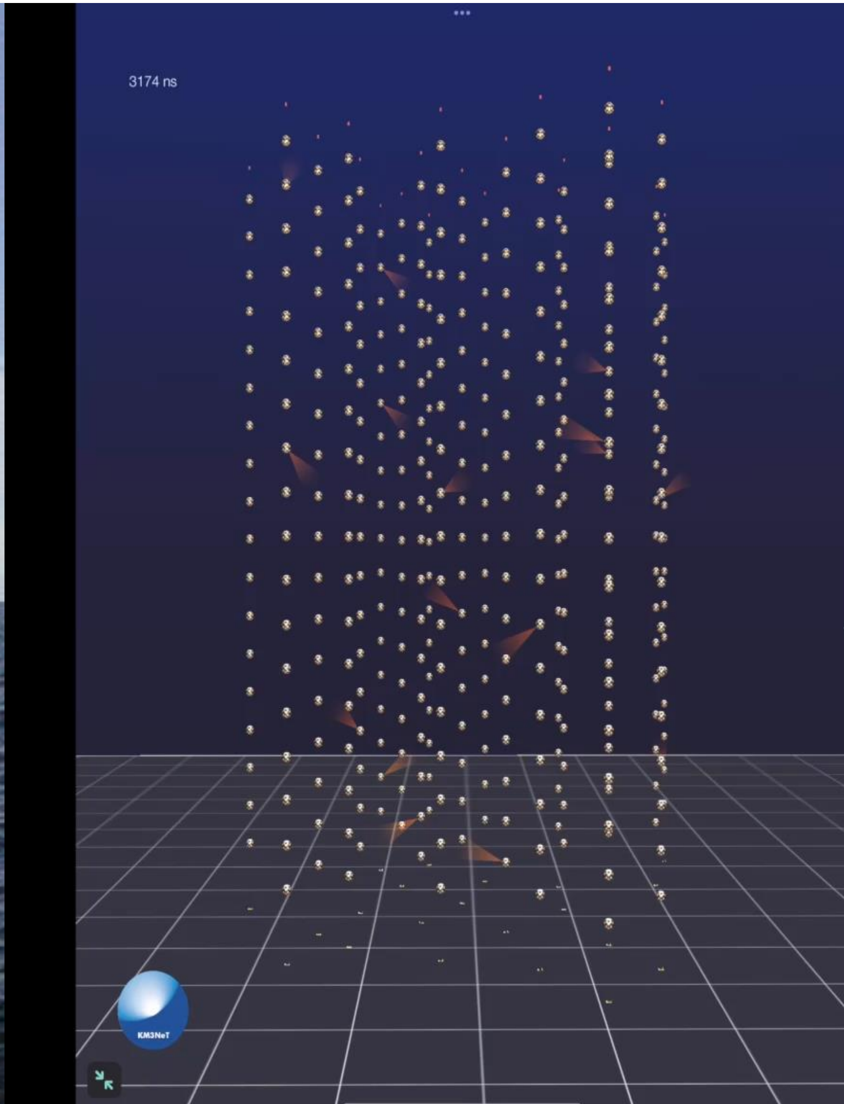
Although atmospheric neutrinos are more abundant at lower energies (≈TeV), cosmic neutrinos should become dominant at energies above 100 TeV. The neutrino energy is thus a crucial parameter for establishing a cosmic origin. The IceCube Collaboration announced the discovery of PeV cosmic neutrinos in 2013 (ref. 10). The most energetic neutrinos reported so far are a $6.05 \pm 0.72$ PeV electron antineutrino observed at the energy of the Glashow resonance[11] and a muon neutrino above 10 PeV from the observation of a 4.4-PeV muon[5].

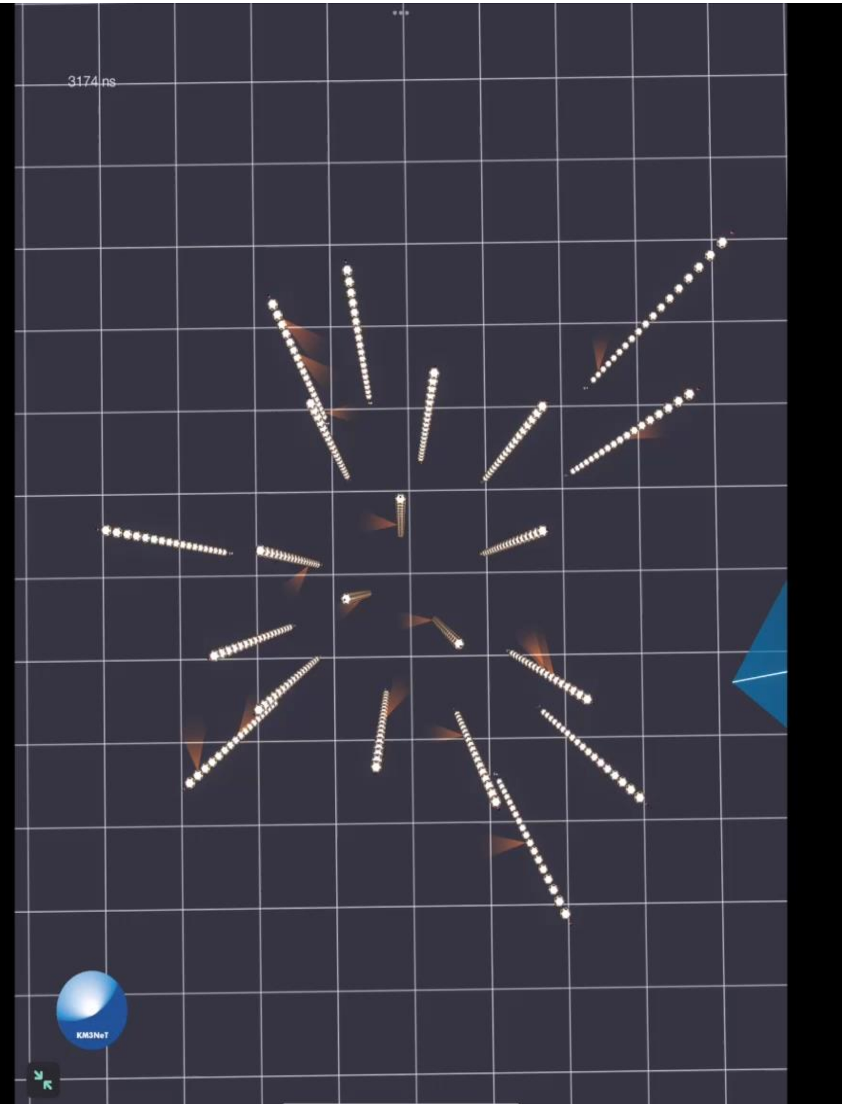
### The neutrino event KM3-230213A

An extremely high-energy muon traversing the ARCA detector was observed on 13 February 2023 at 01:16:47 UTC. This event is referred to here as KM3-230213A. At that time, 21 detection lines were in operation.

*A list of authors and their affiliations appears at the end of the paper.

# $\nu$ cosmico "Very High Energy" rivelato in ARCA21

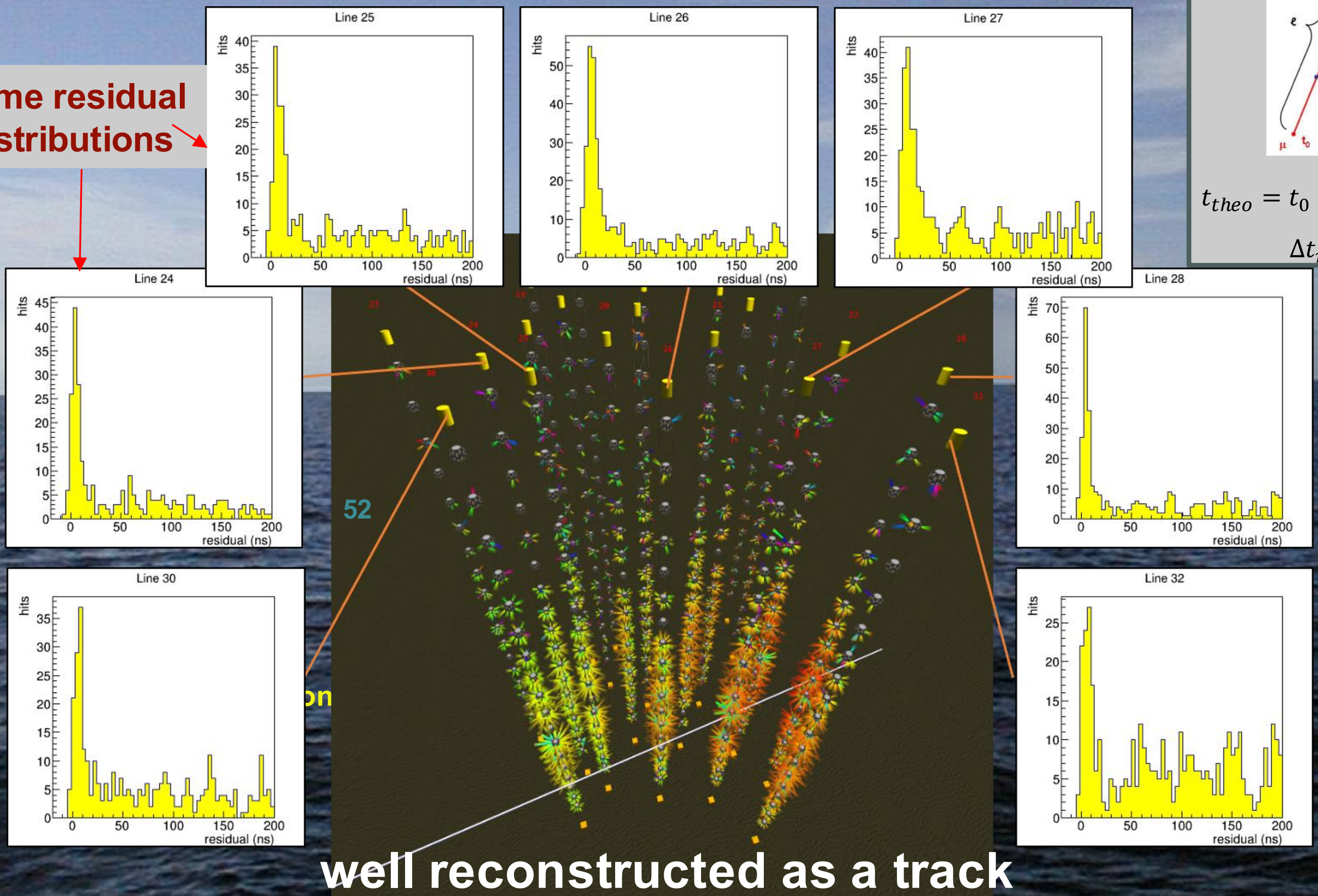


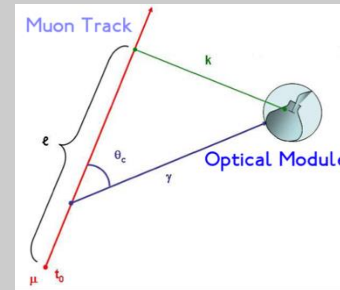



# ν cosmico "Very High Energy" rivelato in ARCA21

**Febbaio 2023**

**Time residual distributions**

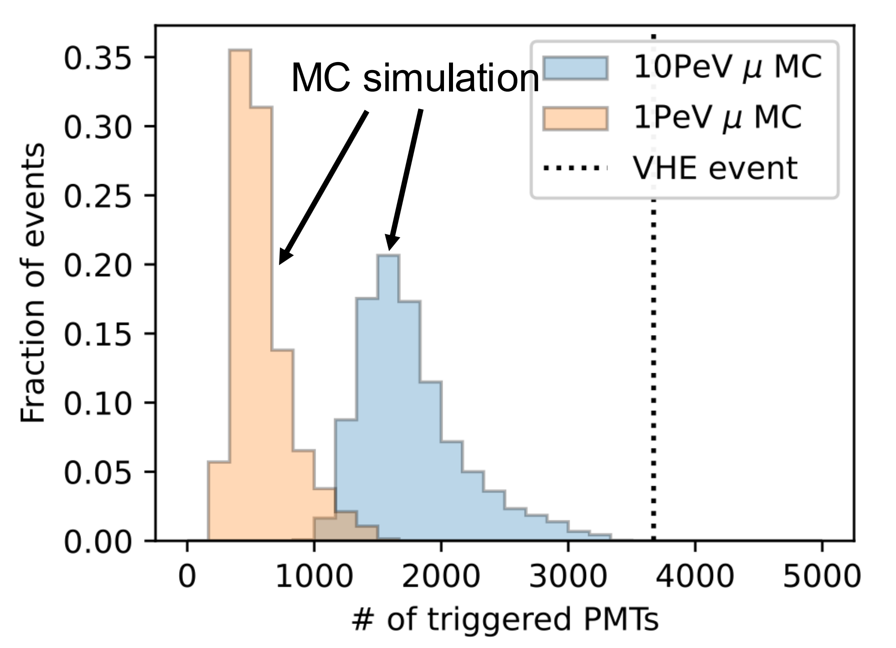


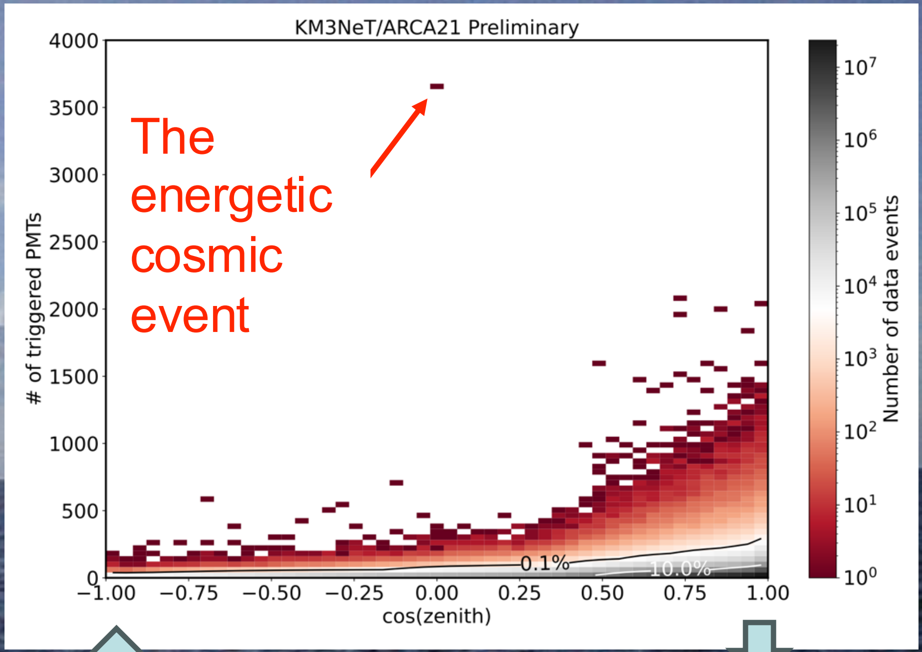




$$t_{theo} = t_0 + \frac{1}{c}\left(l - \frac{k}{tan\theta_c}\right) + \frac{1}{v_g}\left(\frac{k}{sin\theta_c}\right)$$

$$\Delta t_{residual} = t_{theo} - t_{exp}$$

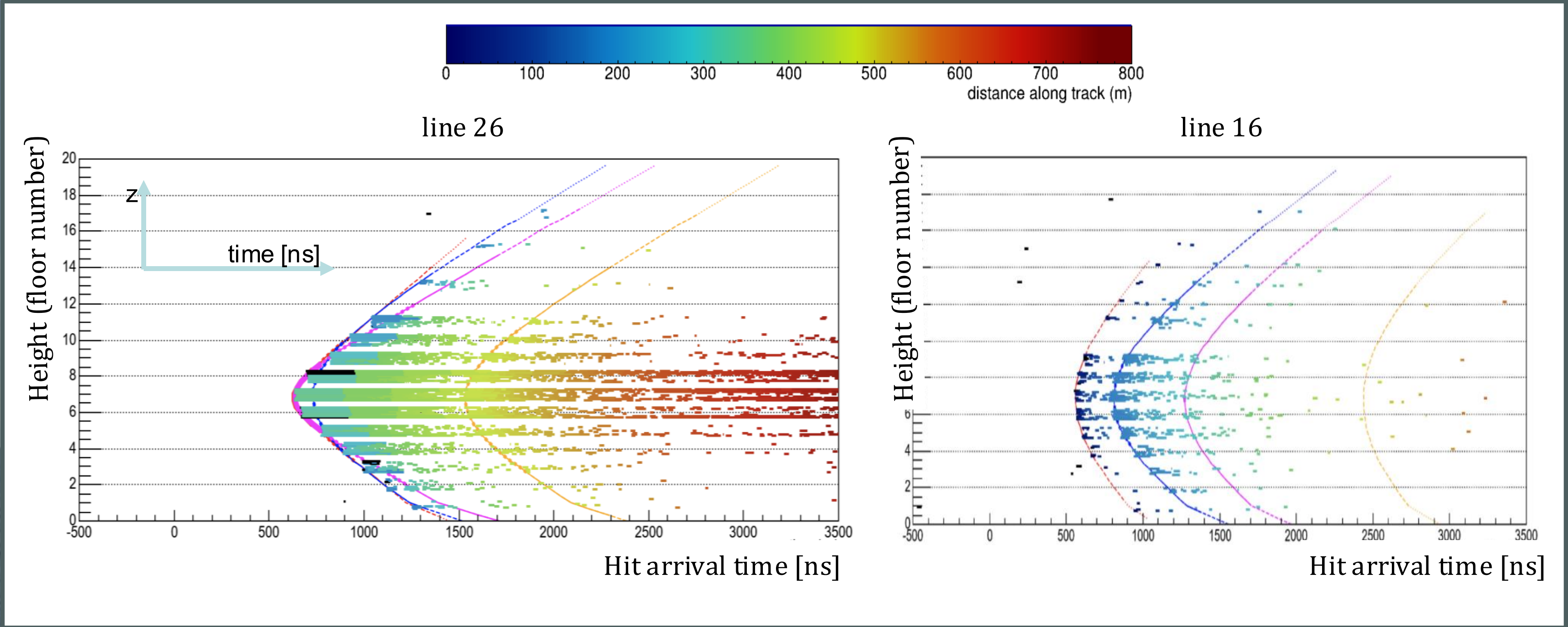
# ν cosmico "Very High Energy" rivelato in ARCA21




**Evento orizzontale (1 sopra l'orizzonte) con E ~ $10^{17}$ eV**
**Elevatissimo numero di fotoni Cherenkov emessi**
**⇛ 35% del totale dei fotomoltiplicatori con segnali**

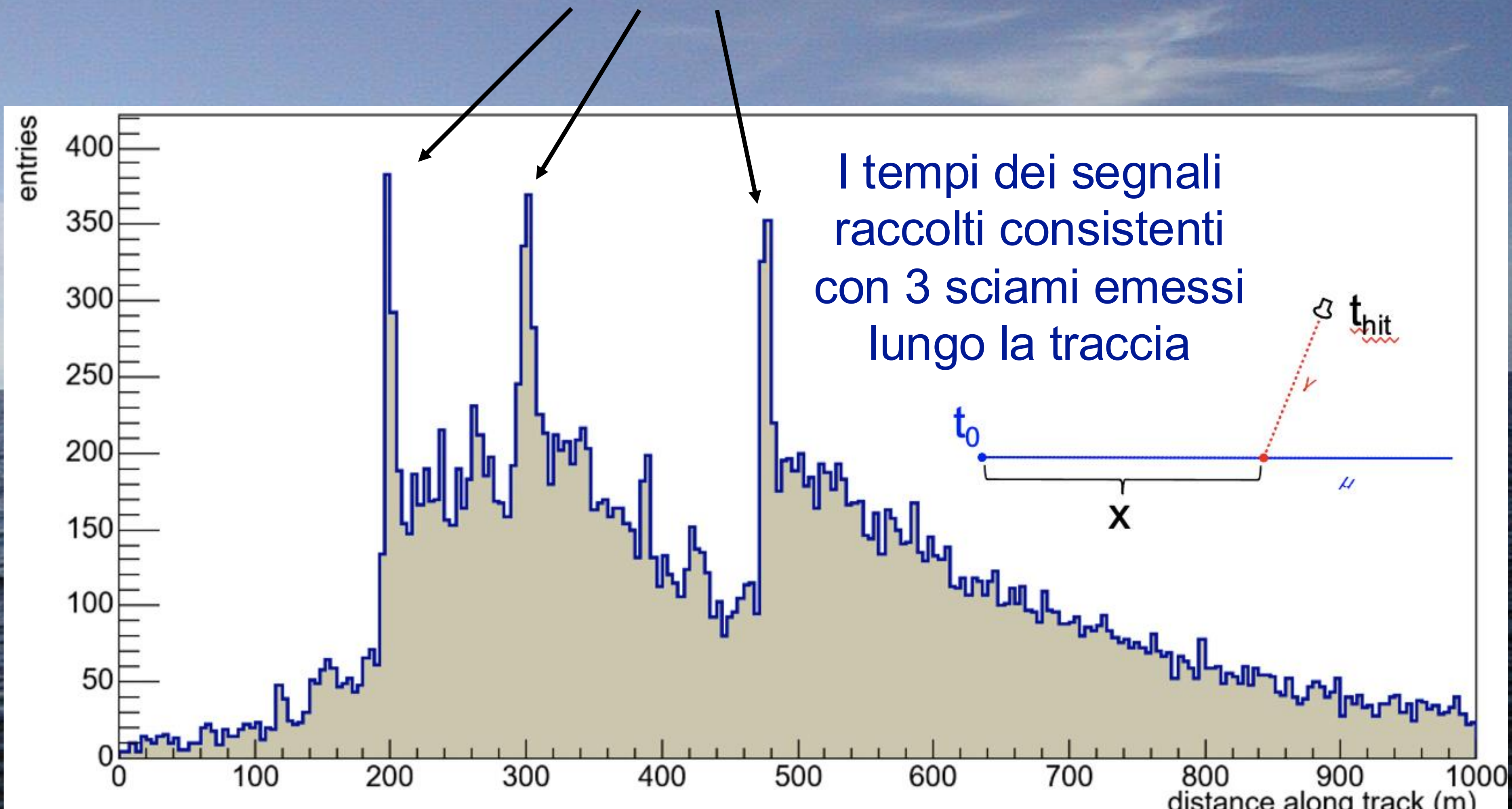
# ν cosmico "Very High Energy" rivelato in ARCA21




I "tempi dei segnali" consistenti con fotoni Cherenkov da traccia

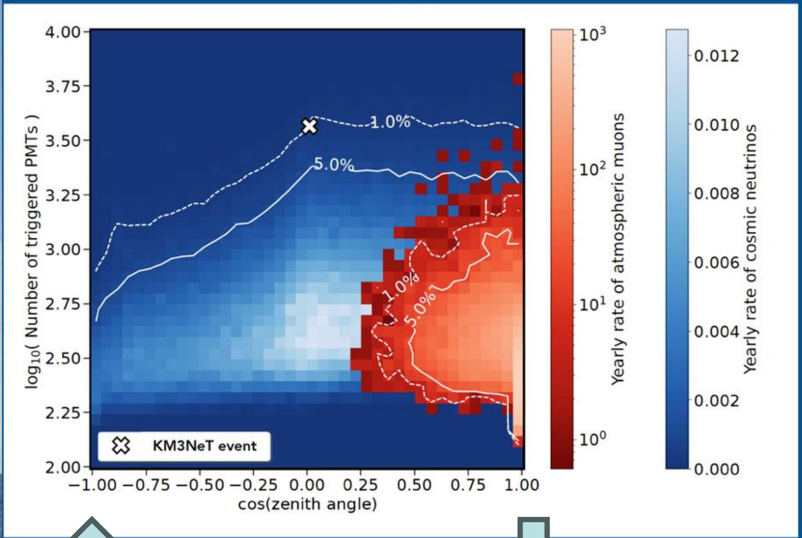
Evento compatibile con singola traccia e tre sciami

# ν cosmico "Very High Energy" rivelato in ARCA21



# ν cosmico "Very High Energy" rivelato in ARCA21

## Is it background ?

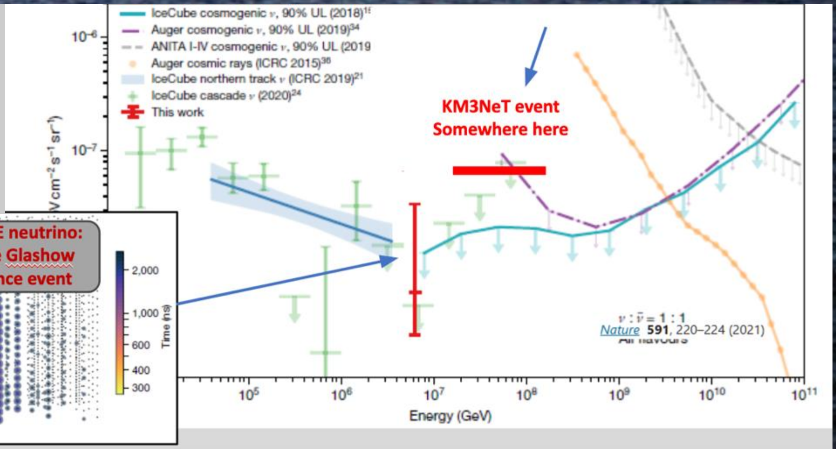



Given the detected energy and direction the expected rate of atmospheric muon reaching the detector is very low

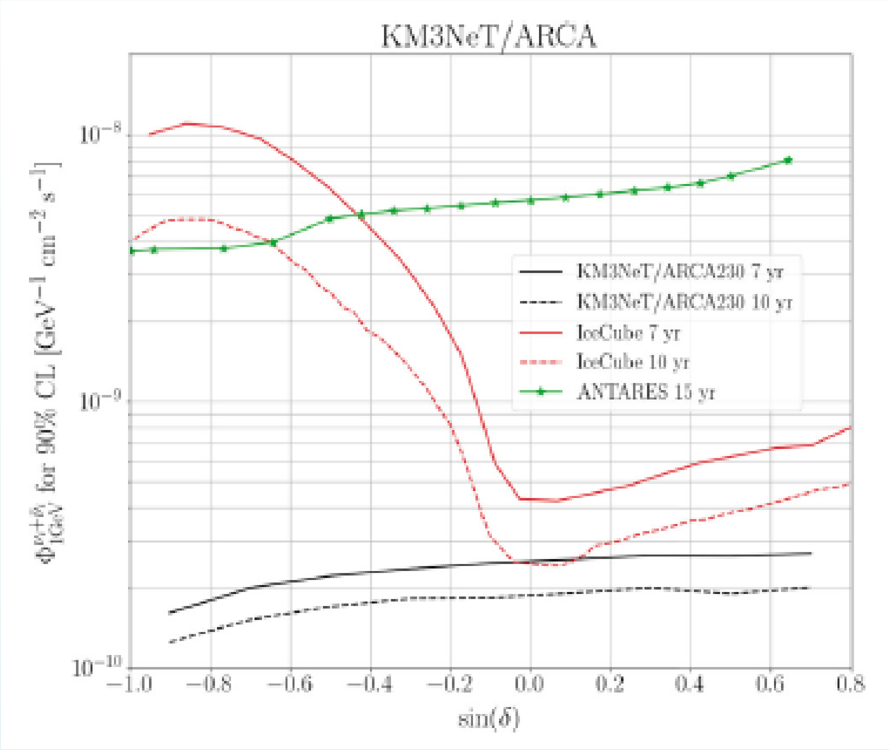
- The amount of material traversed along the event direction is >100km of water equivalent (uncertainties included)

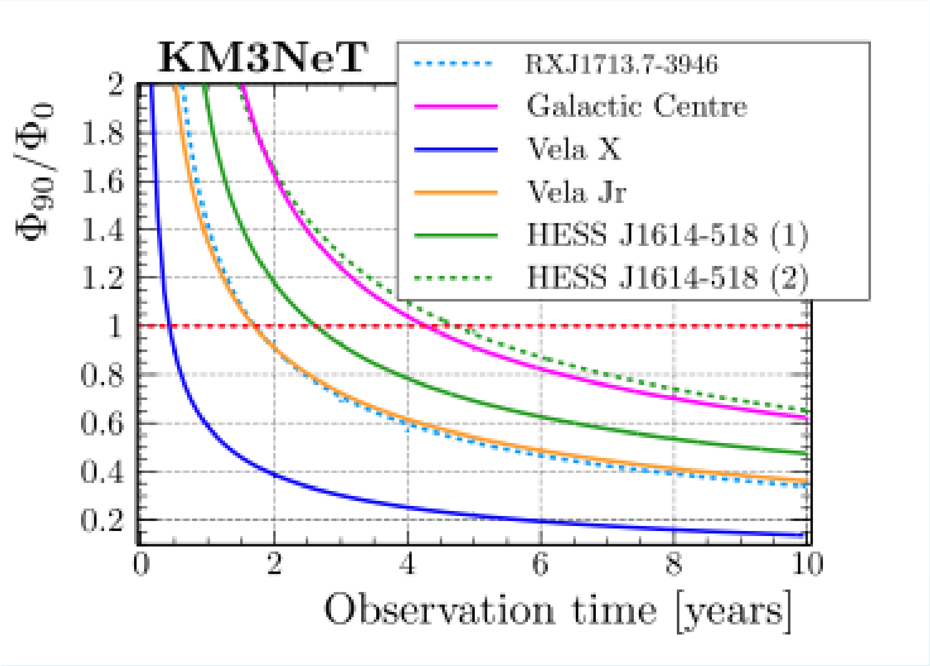
At this energies the expected rate of an atmospheric neutrino (prompt component) is about $10^{-5}$ events per year

New energy frontier



# KM3NeT-ARCA: sensibilità aspettata




Astroparticle Physics 111 (2019) 100–110

Sensibilità (90% CL) calcolata per un flusso di neutrini con dipendenza $\Phi(E) \sim E^{-2}$

Sensibilità (90% CL) per alcune candidate sorgenti galattiche

Sensibilità migliorata per più di un ordine di grandezza

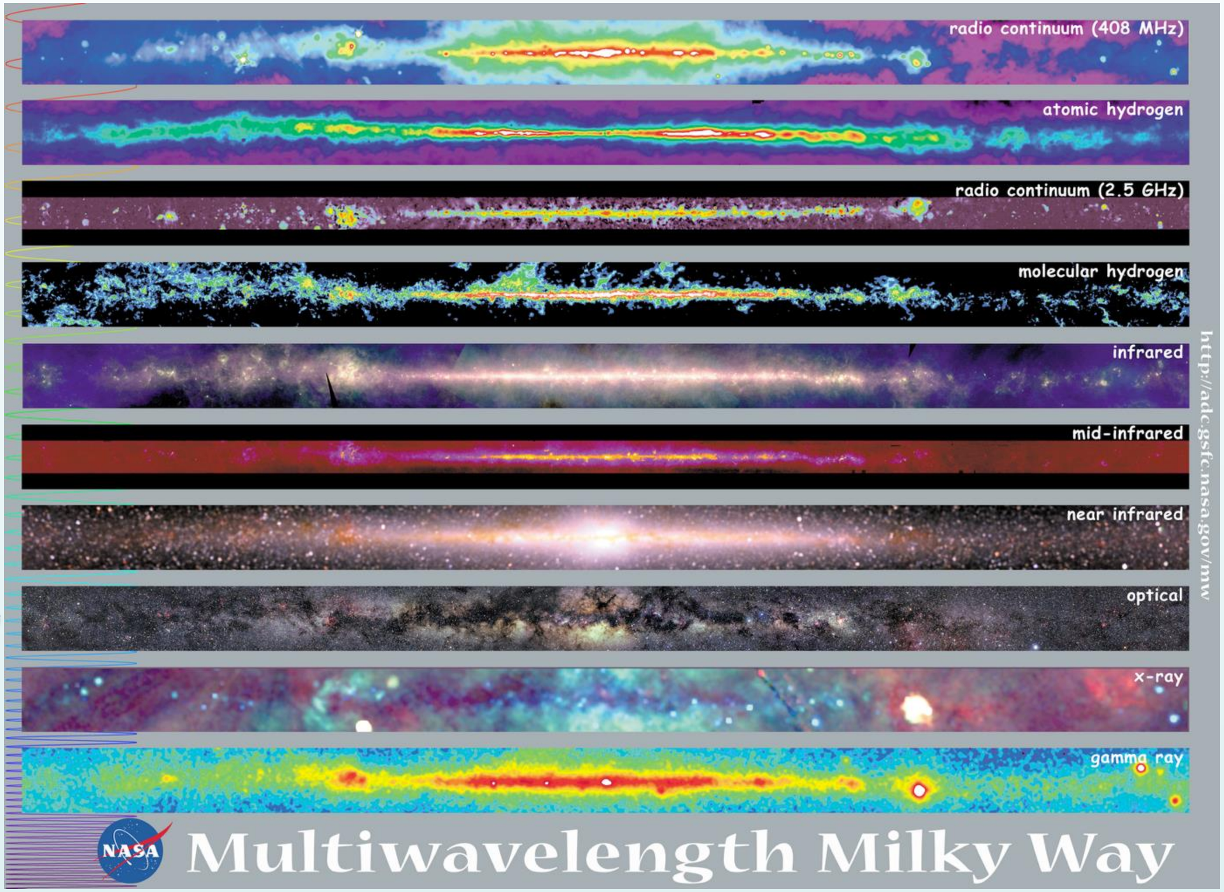
Possibilità di confermare o confutare l'accelerazione di protoni in alcune sorgenti galattiche

# L'evoluzione dell'astronomia: da Galileo ad oggi

## Dalla tradizionale astronomia "ottica" alla "multi-messengers"

L'osservazione della luce nella banda visibile è affiancata e completata con misure "radio", raggi X, raggi $\gamma$

*Galileo Galilei mostra al Doge di Venezia come usare il telescopio (1858), affresco di Giuseppe Bertini (1825–1898)*




**http://mwmw.gsfc.nasa.gov/**

…e l'Astronomia Multi-Messengers: Raggi Cosmici di altissima energia, fotoni, neutrini, onde gravitazionali …

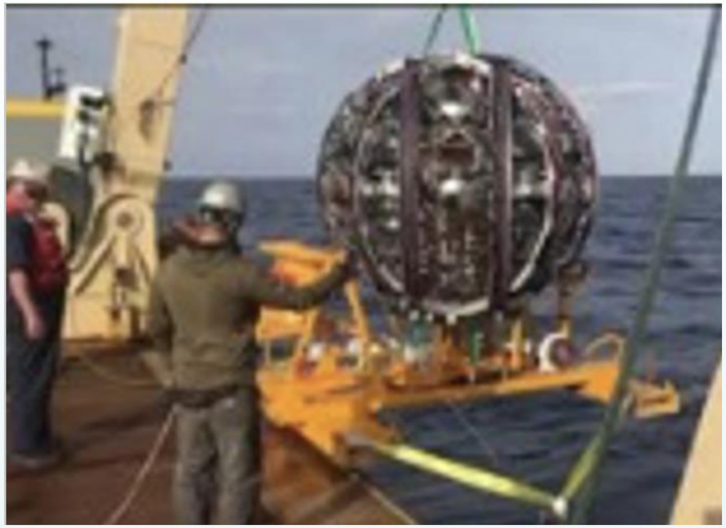
La nostra conoscenza del cosmo, della evoluzione dell'Universo è ancora molto limitata

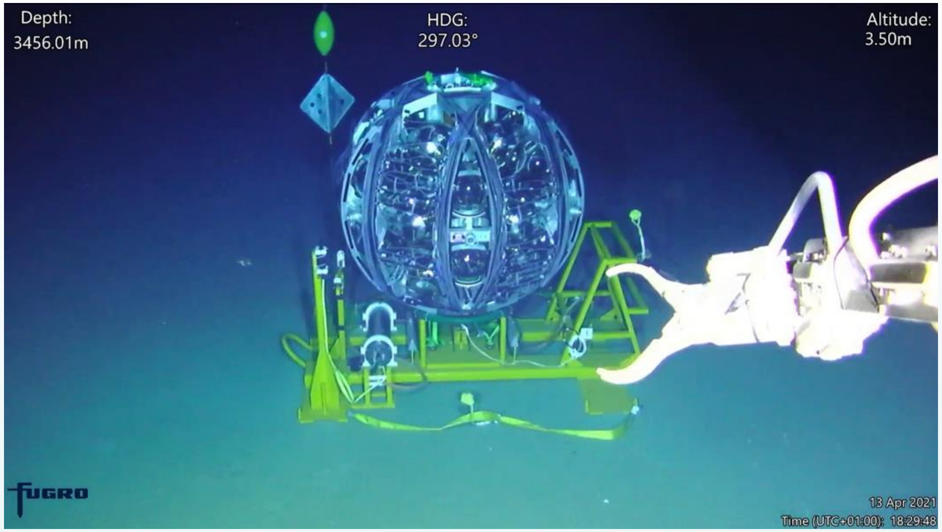
Ogni misura, ogni risultato, ci fornisce una tessera di un grande mosaico

L'Astronomia a Molti Messaggeri permetterà una visione d'insieme del Cosmo, della sua evoluzione, della dinamica che caratterizza ogni sua parte

Ruolo primario dei "Telescopi per neutrini"

Molti altri risultati interessanti attesi per il prossimo futuro ...






KM3NeT: posizionamento di una D.U.