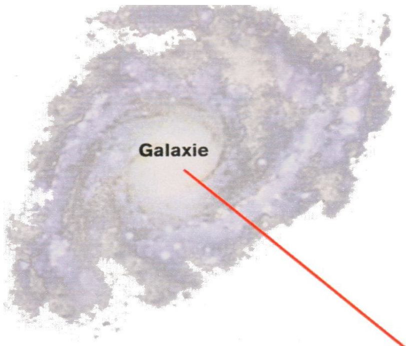
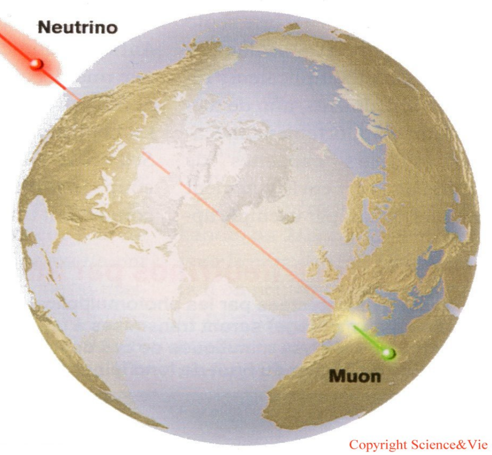
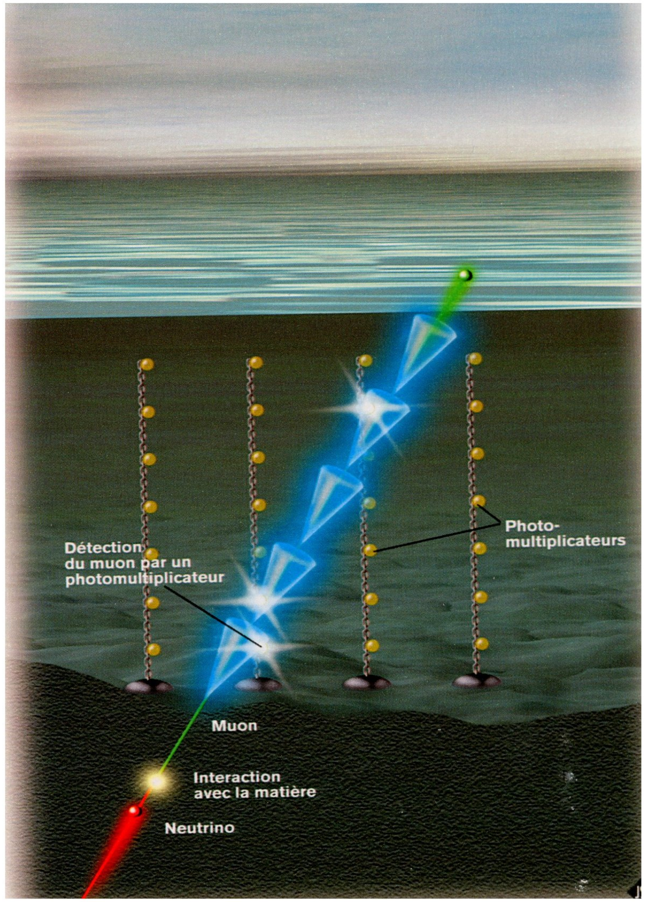
Astrofisica dei neutrini e della radiazione di alta energia

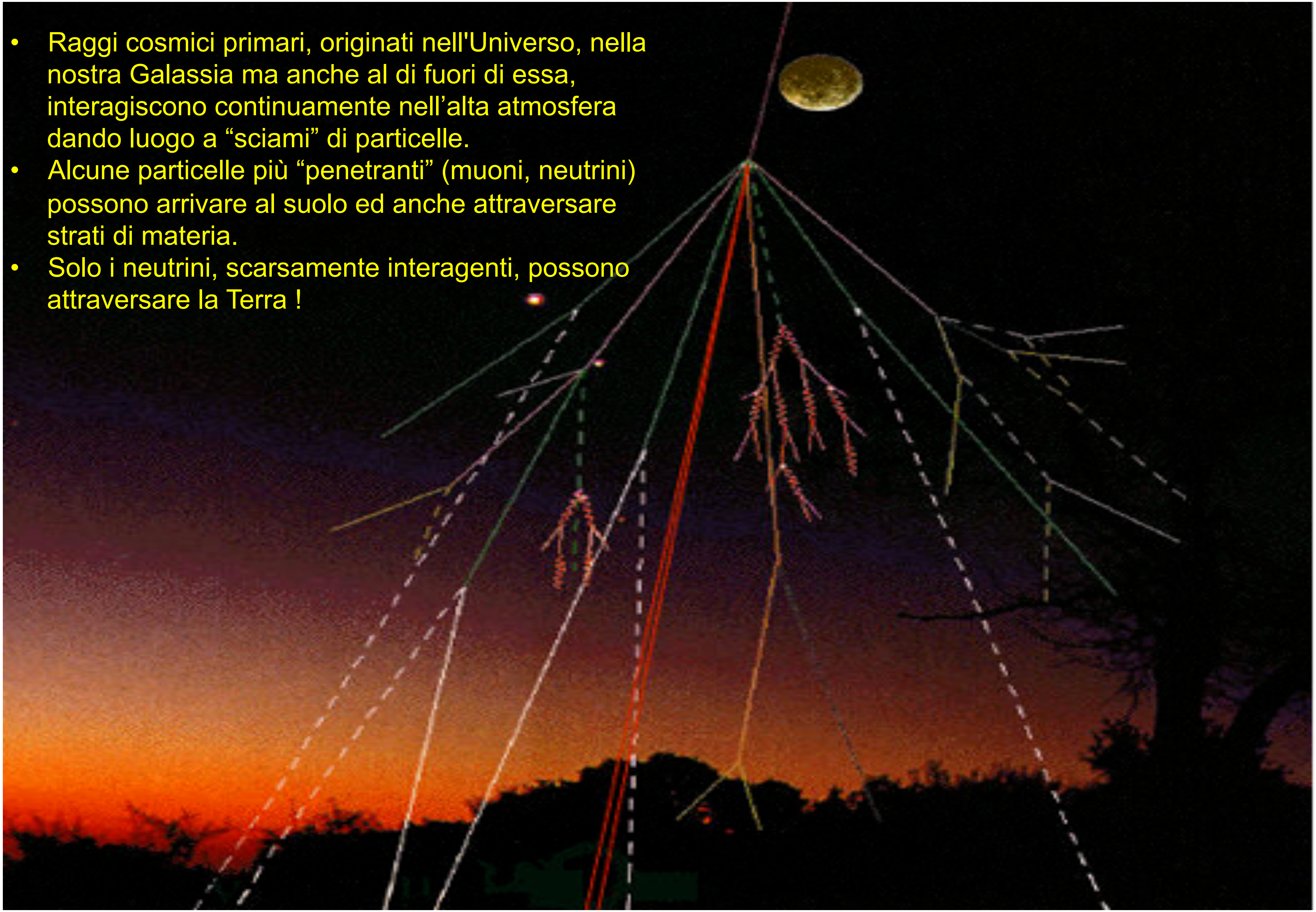


Baikal, AMANDA, IceCube, ANTARES, …

- **Apparati Cherenkov per "osservare" le regioni più attive ed energetiche dell' Universo**
- **Motivazioni scientifiche**
- **Come, dove, quando, …**

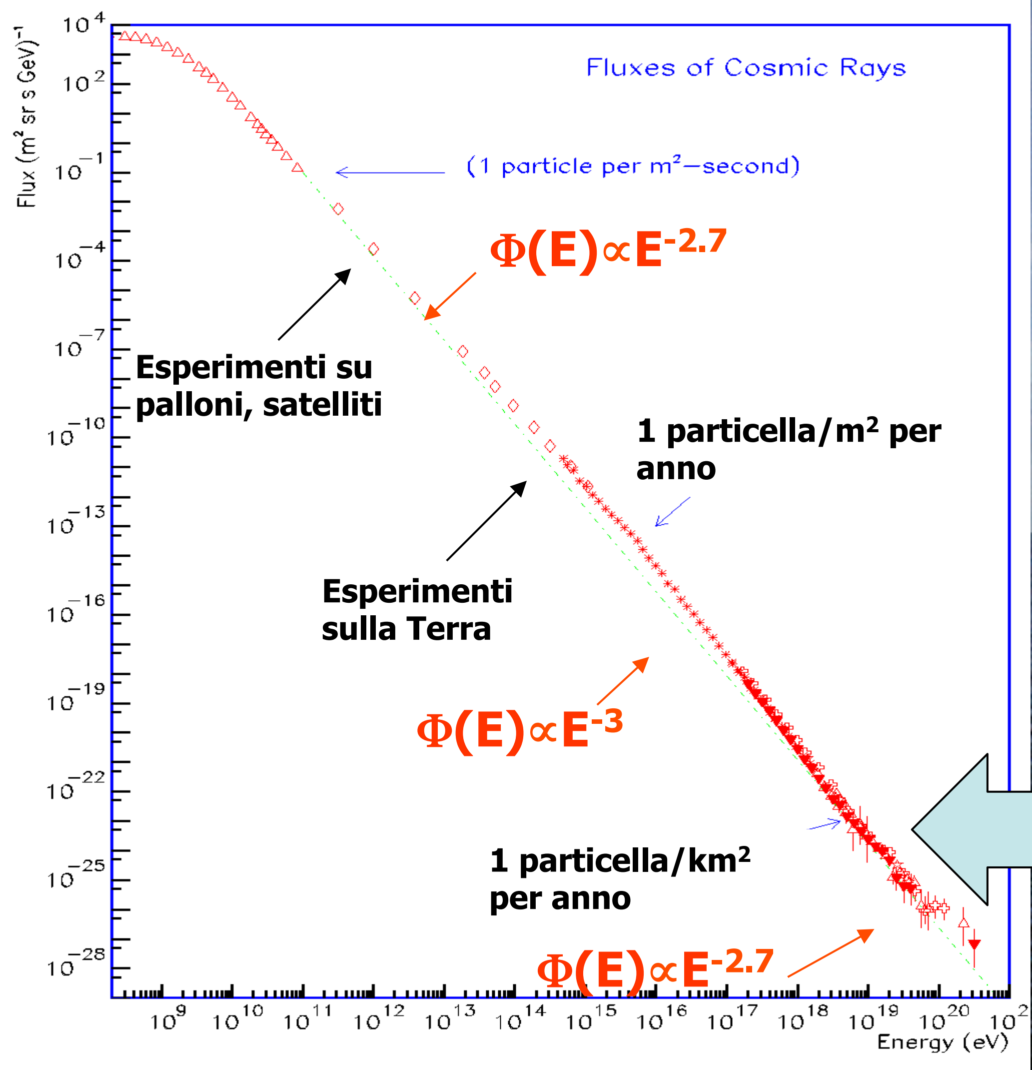






- Raggi cosmici primari, originati nell'Universo, nella nostra Galassia ma anche al di fuori di essa, interagiscono continuamente nell’alta atmosfera dando luogo a “sciami” di particelle.
- Alcune particelle più “penetranti” (muoni, neutrini) possono arrivare al suolo ed anche attraversare strati di materia.
- Solo i neutrini, scarsamente interagenti, possono attraversare la Terra !

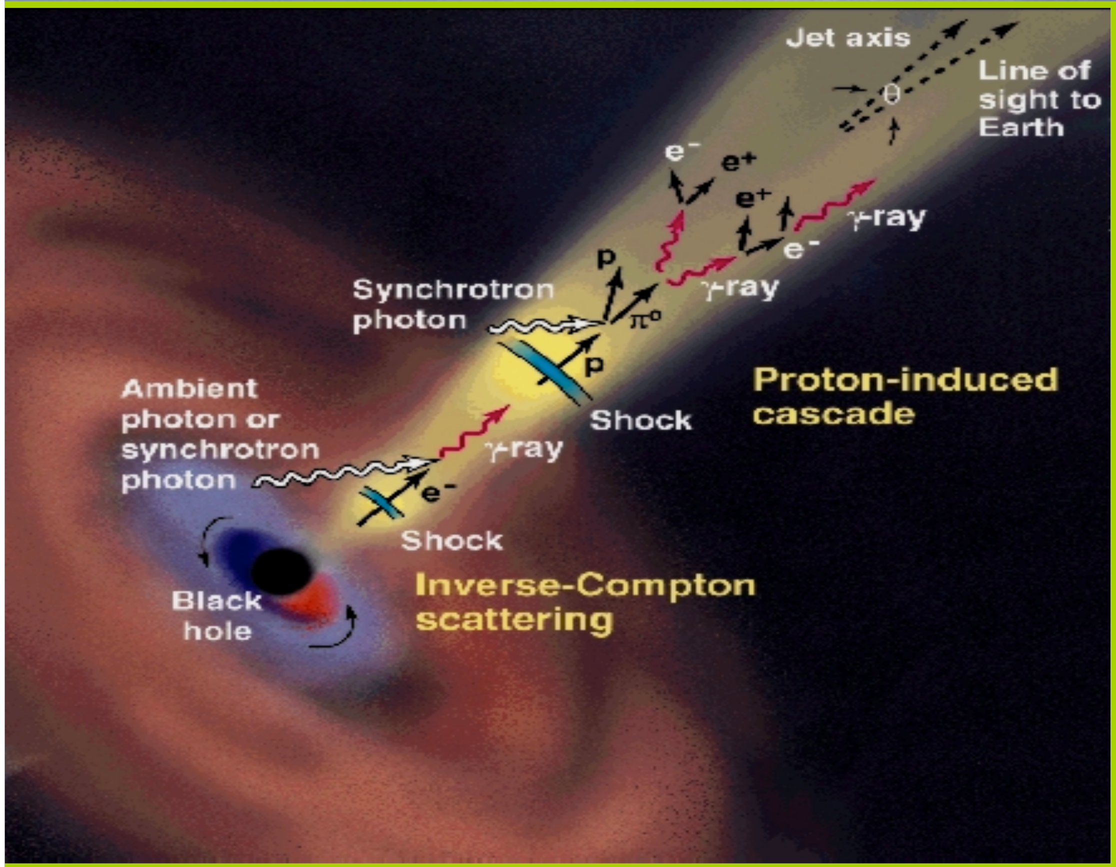
Distribuzione in energia dei raggi cosmici osservati



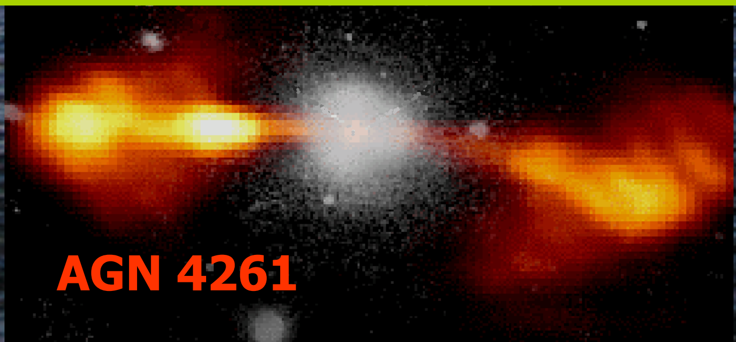
- **Rivelate particelle elementari, protoni, con energia maggiore di 10^{21}eV (come quella di una palla da tennis lanciata in prima battuta da un campione di tennis ~150km/h)**
- Molte domande senza risposta:
  - Da dove vengono ? Dalla nostra Galassia ?
  - Quale meccanismo è capace di accelerarle ?
  - ...

Per rivelare i raggi cosmici di energia più elevata è necessario un rivelatore di grandi superfice: più di 1 km^2

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 ...

Immagini Hubble Space Telescope

Come osservarle ???

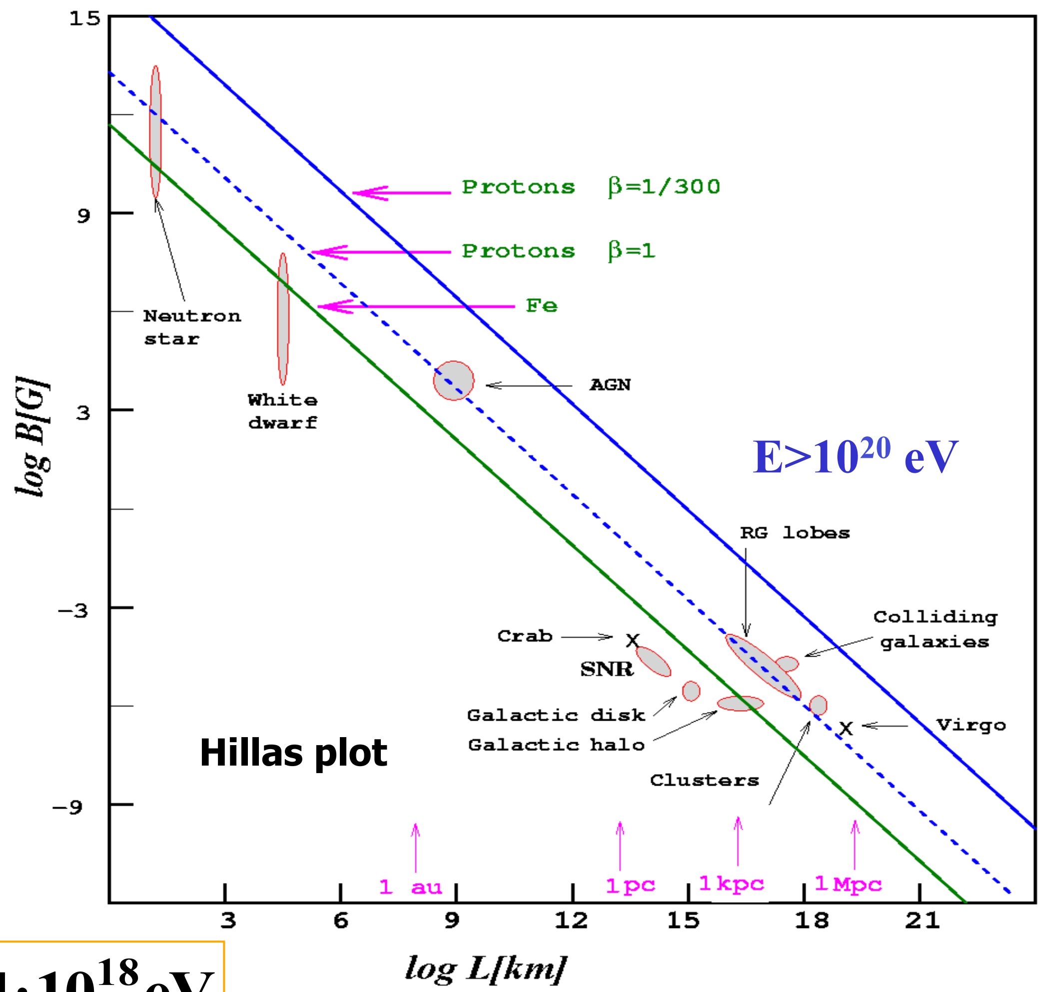
Quali meccanismi di accelerazione ?

Energia:

- **Gravitazionale**
- **Elettromagnetica**

Accelerazione:
meccanismo di Fermi

- **Grandi dimensioni della regione di accelerazione**
- **Grandi campi magnetici**
- **Elevate velocità delle onde d'urto**

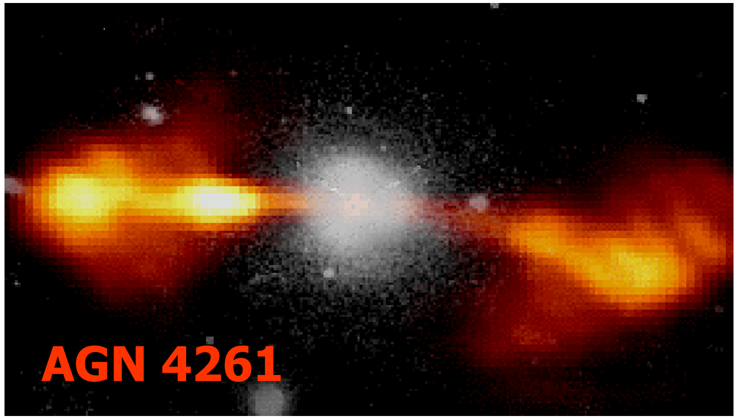


$$E_{max} \approx \beta_{shockwave} Z \cdot B[\mu G] \cdot L[kpc] \cdot 10^{18} eV$$

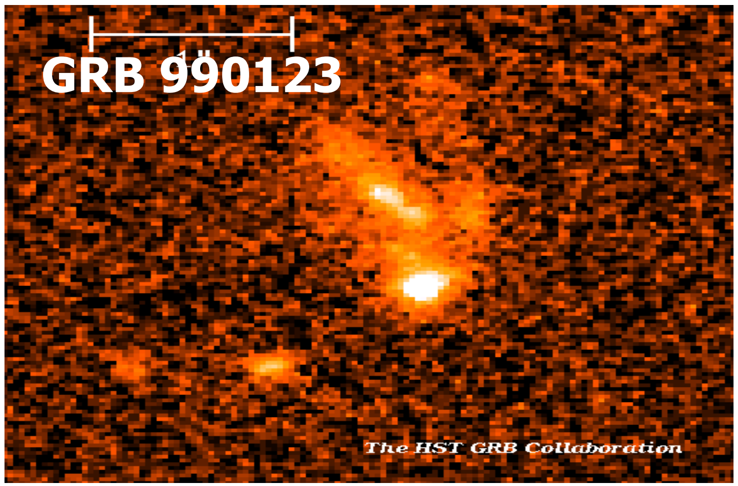
Quali processi di accelerazione?, Dove ?

"Acceleratori" di particelle di altissima energia:

Nuclei Galattici Attivi (AGN), Gamma Ray Burst (GRB), Micro Quasars ...



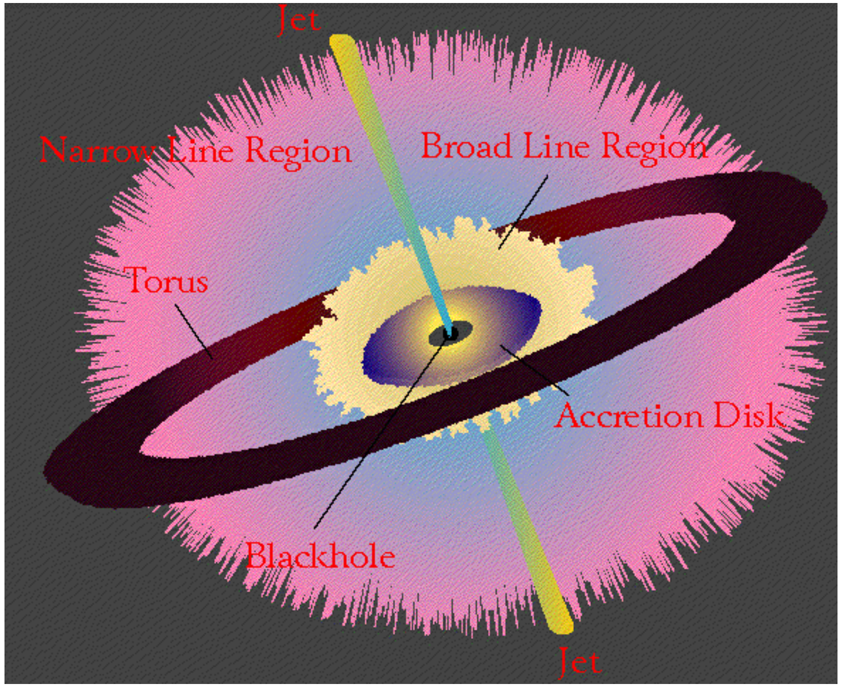
Sorgenti di particelle di altissima energia che emettono continuamente nel tempo



Esplosioni violentissime: GRB990123
E>10^{47} Joules (1 Massa Solare) rilasciati in circa 1 msec

Immagini Hubble Space Telescope

Active Galactic Nuclei



In some galaxies the nucleus far outshines the rest of the galaxy. These are known as "**active galactic nuclei**" (AGN). Perhaps the most popularly known instance of AGN are "quasars" which are AGN that are very distant, up to 60 billion light years away, redshifts typically of 2 to 5.
In some cases, the size of the AGN is smaller than the size of our solar system. There is currently much research going on trying to determine how something smaller than a solar system can outshine entire galaxies. Based on X-ray, radio, and other observations, a good guess is that the power source in AGN is a supermassive **blackhole**.

The blackhole itself is invisible, **the gas accreting**, or falling, onto a blackhole becomes hot and some of this energy escapes for us to observe. The gas and material appear to be confined to orbits in a disk shape which is called an **Accretion Disk**. Many AGN also show evidence for a **huge torus** of gas around the blackhole. There are **two back to back jets** coming out of the black hole region in a direction perpendicular to the Accretion Disk.
There is also a **region around the blackhole and Accretion Disk which emits some radiation** we can observe and it is characterized as **Broad Emission Lines Region**.
Further out there is **a region which emits some radiation** we can observe and it is **characterized as Narrow Emission Lines Region.**

Accelerazione in Nuclei di Galassie Attive

Le sorgenti continue più energetiche hanno Luminosità = 10^{42} erg/sec

Diversi modelli di accelerazione possibili:

Modelli "e.m." ⇒ **produzione di γ**

- **elettroni accelerati producono radiazione di sincrotrone**
- **gli elettroni accelerati nel "jet" producono γ di alta energia interagendo (diffusione Compton inversa e,γ) con la radiazione di sincrotrone**

Modelli "adronici" ⇒ **produzione di γ e di ν**

- **protoni accelerati producono radiazione di sincrotrone**
- **protoni nel "jet" interagiscono con radiazione di sincrotrone e/o con gas (p,p) , (p,γ) → Δ^+ originando γ e ν di alta energia**

"Beam Dump" astrofisico

Fotoni e neutrini possono essere prodotti nella stessa "sorgente" astrofisica se:

$$p + \gamma, p \longrightarrow \Delta^+ + \pi + \ldots$$

$$\pi^o + p \rightarrow \gamma + \gamma$$

$$\pi^+ + n, \quad \pi^+ \rightarrow \nu_\mu + \mu^+, \quad \mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$

BR (π^o) = 2/3

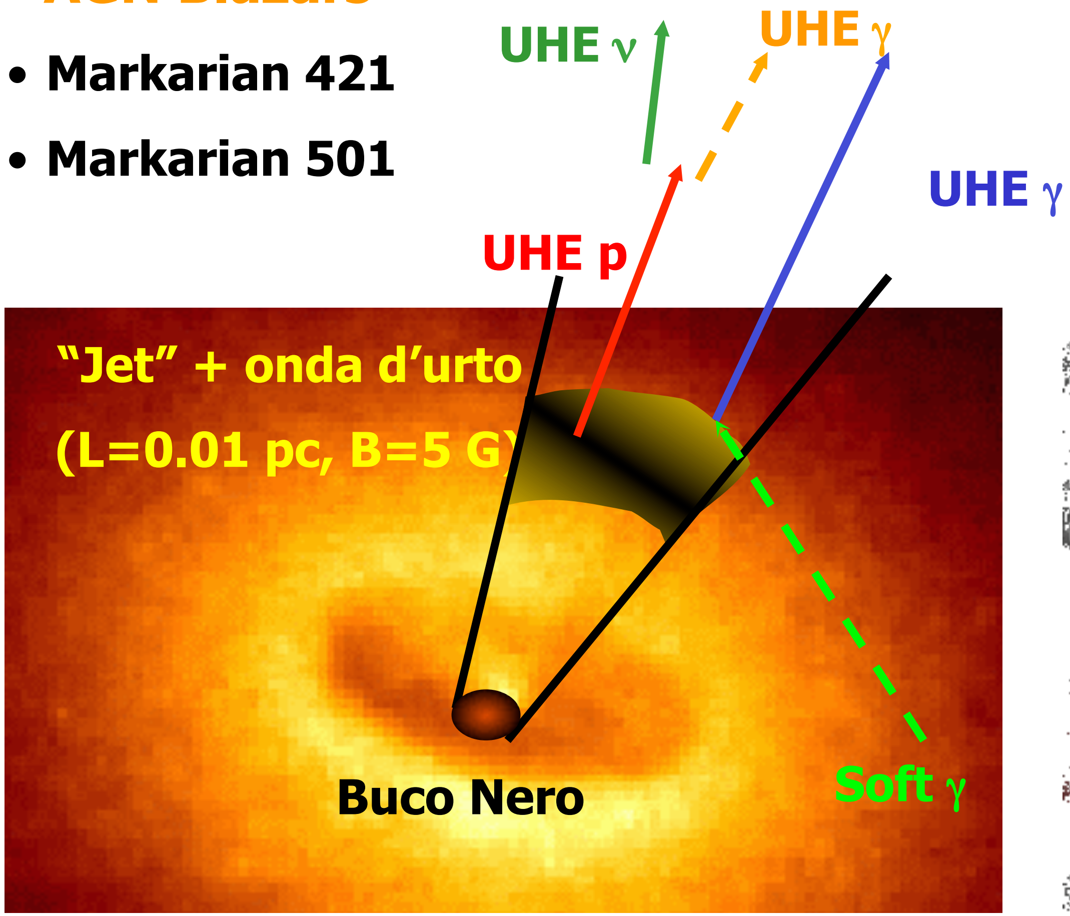
BR (π^+) = 1/3

$$\Phi(\gamma) \sim \Phi(\nu)$$

ν e γ da nuclei di Galassie Attive

AGN Blazars

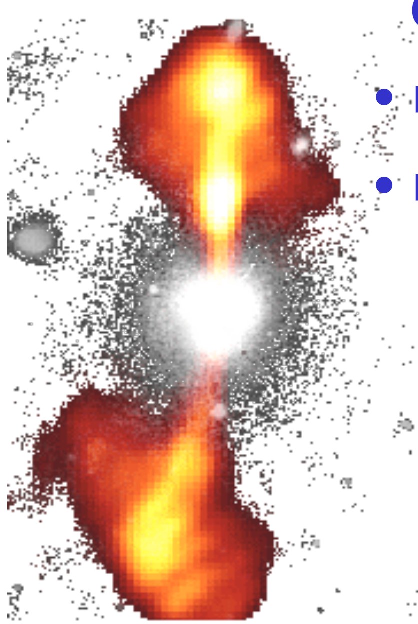
- **Markarian 421**
- **Markarian 501**



Accretion disk

Grazie all' onda d' urto (ed al campo magnetico associato):

accelerazione di Fermi del primo ordine



Onde d' urto:

- **nel centro**
- **nel "jet" Γ=10**

NGC4261 (Hubble Space Telescope)

Accelerazione in sorgenti di Gamma Ray Bursts

Il modello "fireball"

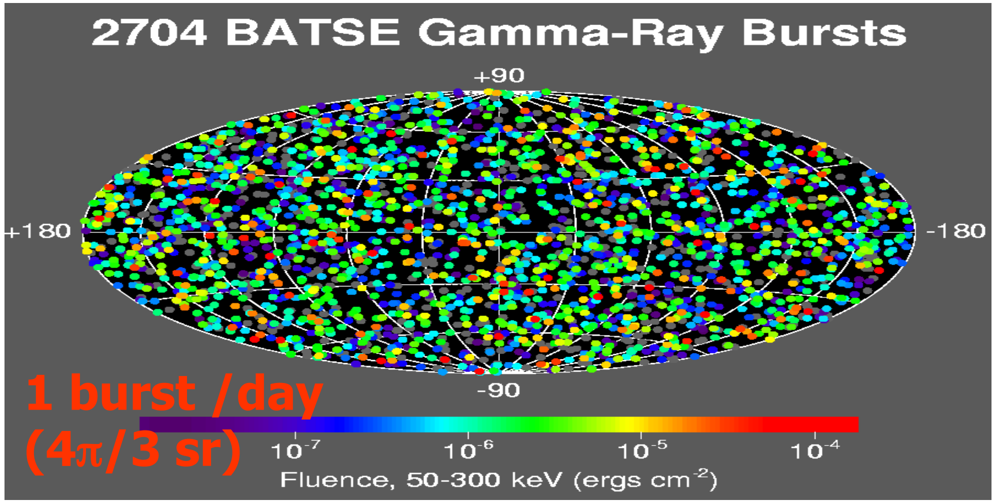
Origine dell'energia:

- coalescenza fra due stelle di neutroni (NS +NS)
- Coalescenza NS e buco nero (NS+BH)

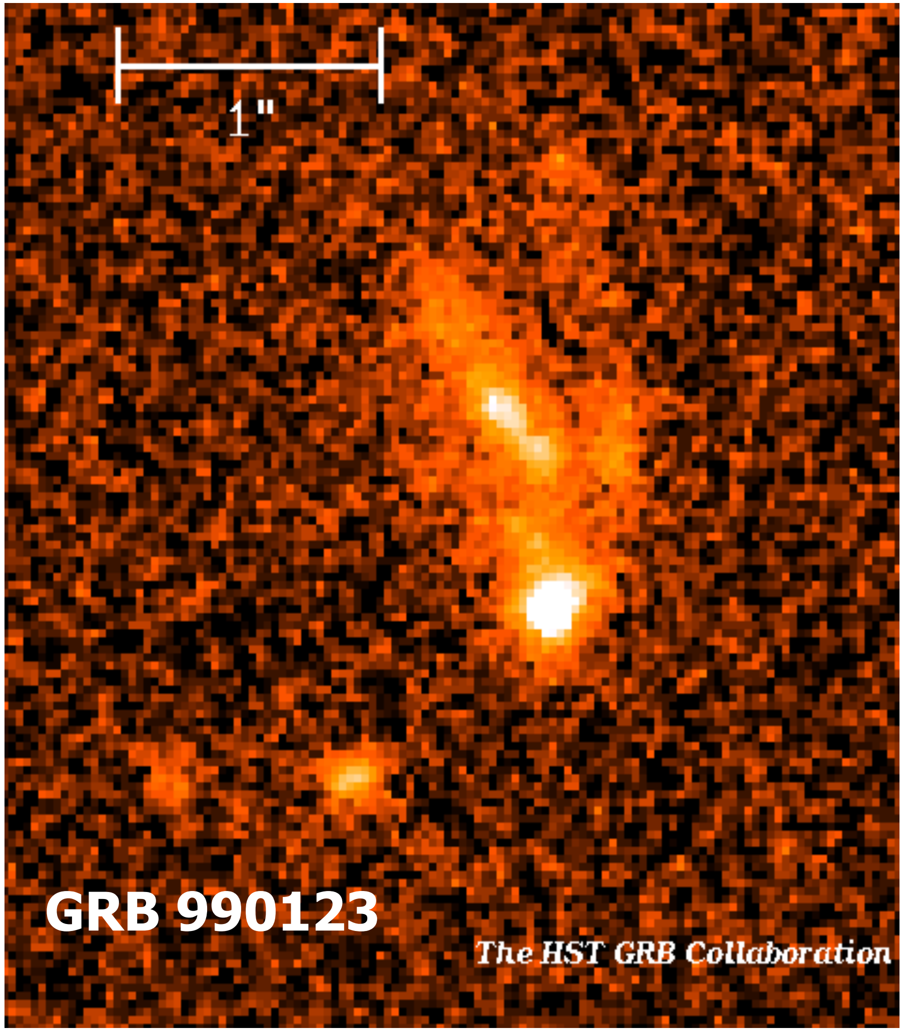
$10^{51} \div 10^{53}$ ergs   in pochi ms

Meccanismo di accelerazione

- interazione fra onda d'urto e "fireball" in espansione ultra-relativistica ($\Gamma \sim 300$)
- Meccanismo di Fermi



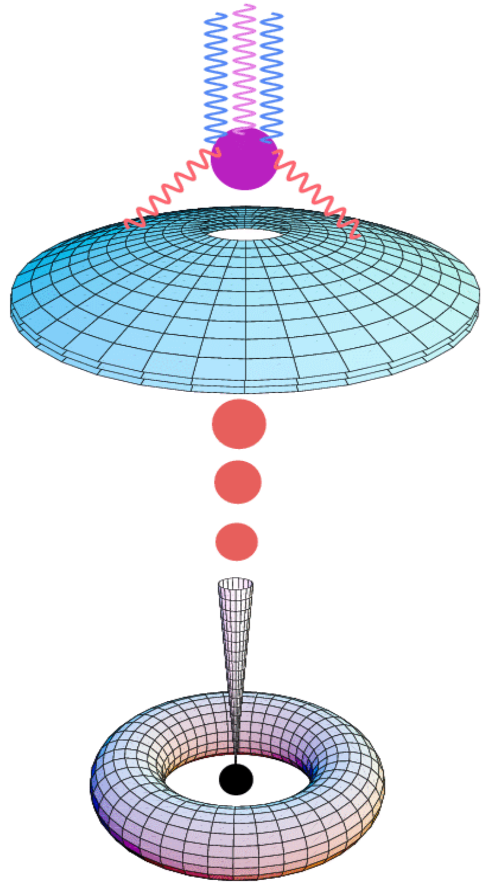
VELA - BATSE Beppo-Sax



GRB : Cannon Ball Model

Dar, DeRujula, et al.

- Dal collasso stellare emessi corpi con massa ~ M_{terra} e $\Gamma \sim 10^{3 \div 4}$.
- L'urto con la shell esterna di gas in espansione porta ad onde d'urto ed accelerazione di particelle.
- Il beam stretto ed intenso spiega i GRB osservati.
- Previsto un intenso flusso di neutrini, osservabili in km^3 (?)



from astro-ph/0105094

Modello molto contestato ma … interessante

Possibili sorgenti galattiche di ν con $E_\nu \sim$ TeV

Supernova Type II

Collisionless Shock Breakout ⇒

$f_\nu(> 1 \text{ TeV}) \approx f_\gamma(> 100 \text{ MeV}) \approx 10^{-4}$ ergs/cm²/s

Ritardo dopo il collasso ~10 ore, durata ~1 ora

$N_\mu \sim 100 / \text{km}^2$

[Waxman&Loeb PRL 01]

Micro-Quasars

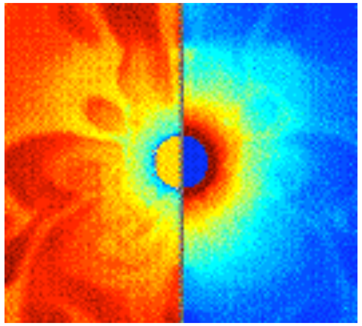
e-p jet ⇒ Getti preceduti da ~ 10 TeV ν

Durata ~1 hour

$$N_\mu \sim 2.\,\Gamma^2 \left[\frac{E}{10^{43}\text{erg}}\right]\left[\frac{D}{3\text{kpc}}\right]^{-2} / \text{km}^2 \qquad \Gamma \sim 10\text{-}100$$

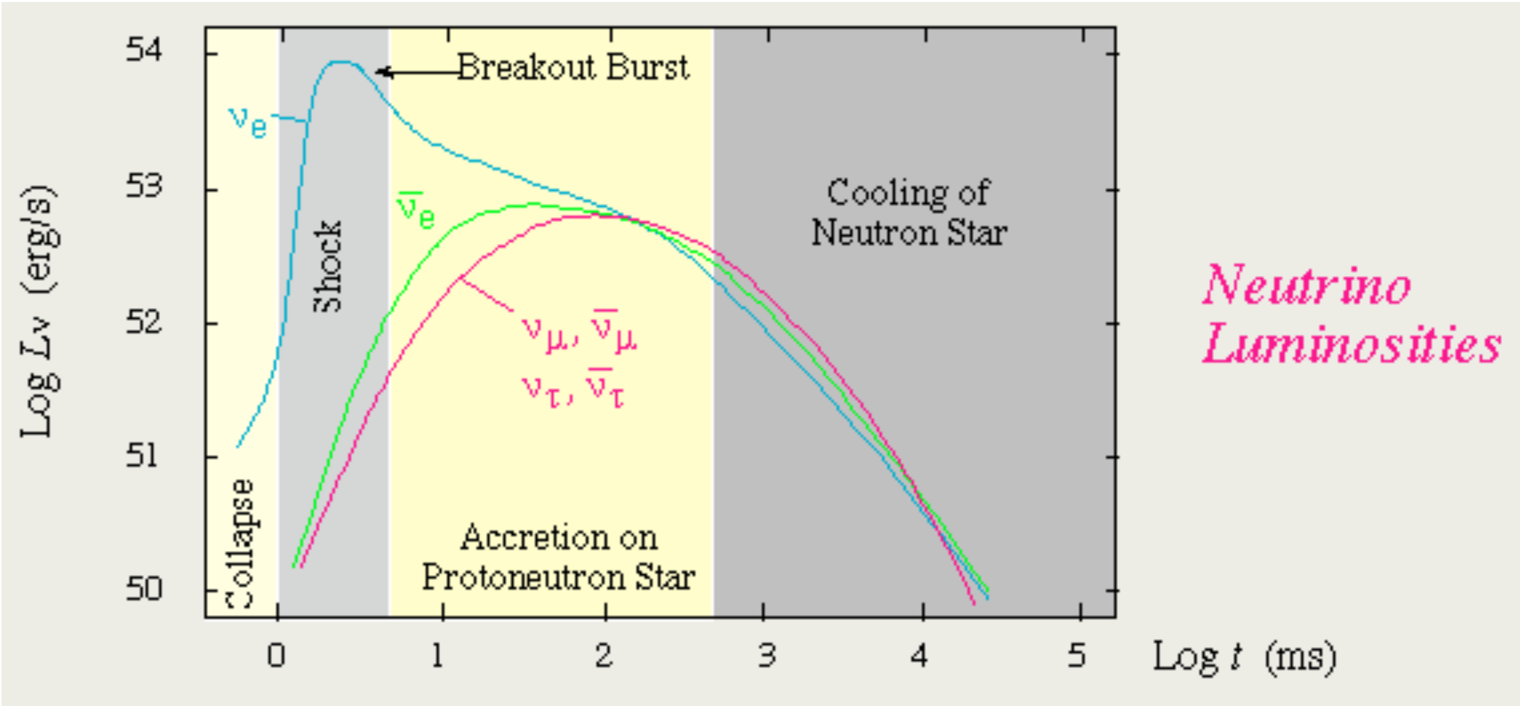
[Levinson&Waxman PRL 01]

Supernovae



Supernovae are some of the most spectacular events in the Universe.
They represent the end stage in the life of a massive star.

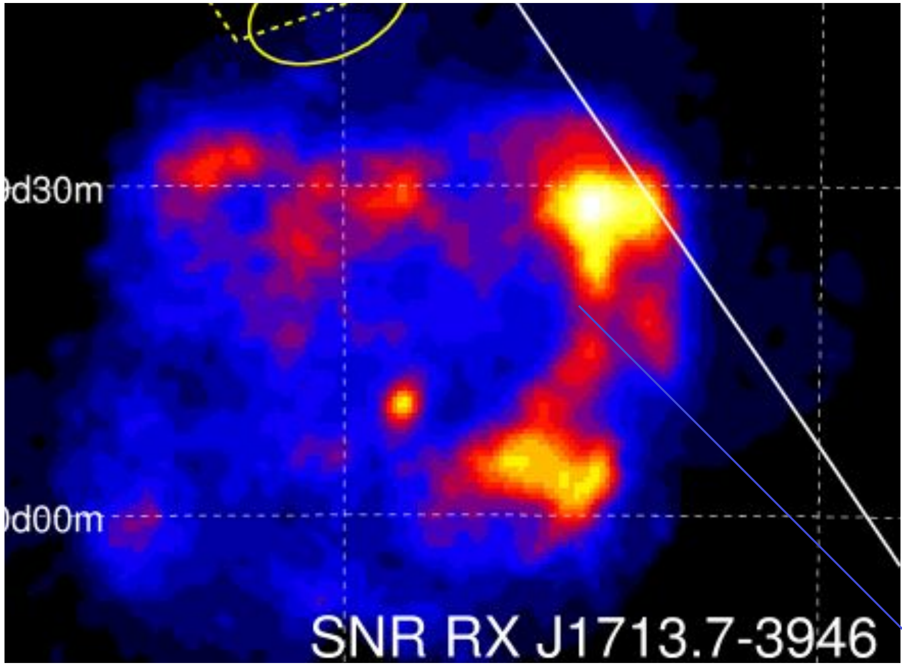
The bulk of the energy output of a Supernova is expected to be in neutrinos.
These neutrinos were first detected for Supernova 1987A.



Supernovae Remnants: Cosmic Ray Accelerators ?

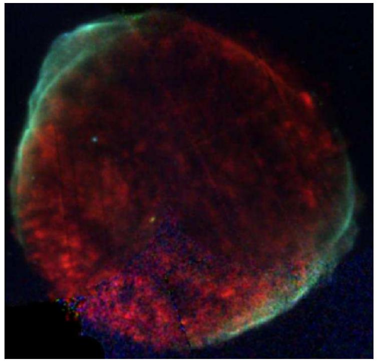
SNRs in our Galaxy: 231 (Green et al. 2001)

with nonthermal X-ray emission - 10 or so

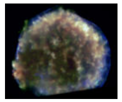


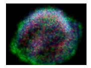
best candidates - young SNRs with nonthermal synchrotron X-rays

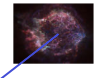
SN1006



Tycho Kepler CasA





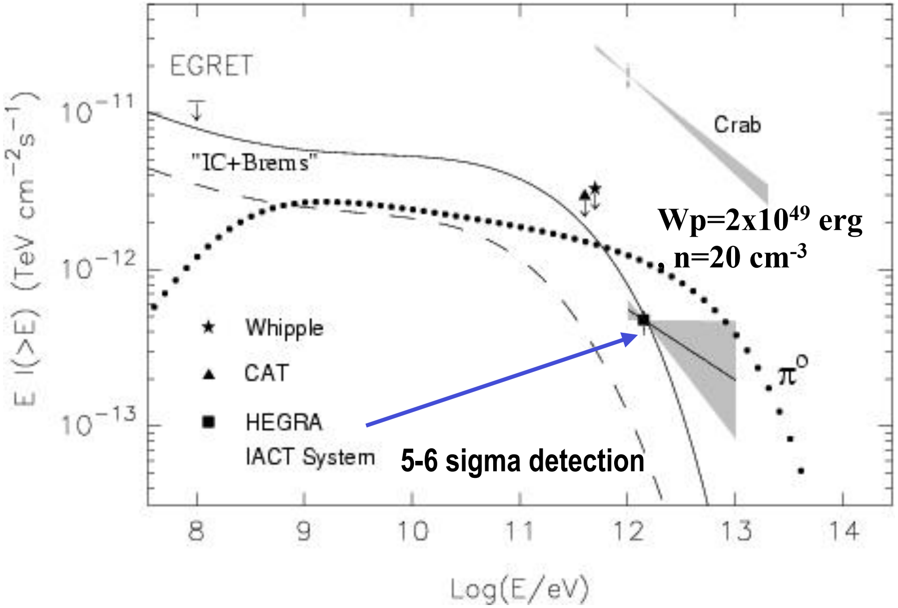


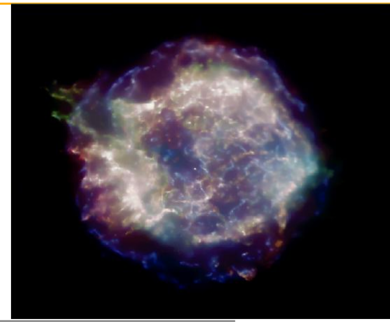
30 arcmin

TeV emission

H.E.S.S. PSF

Cas A – a proton accelerator





$B > 0.1$ mG → IC origin is unlikely;
TeV gamma rays of hadronic origin ?
yes, although Wp $=10^{49}$ erg (only)

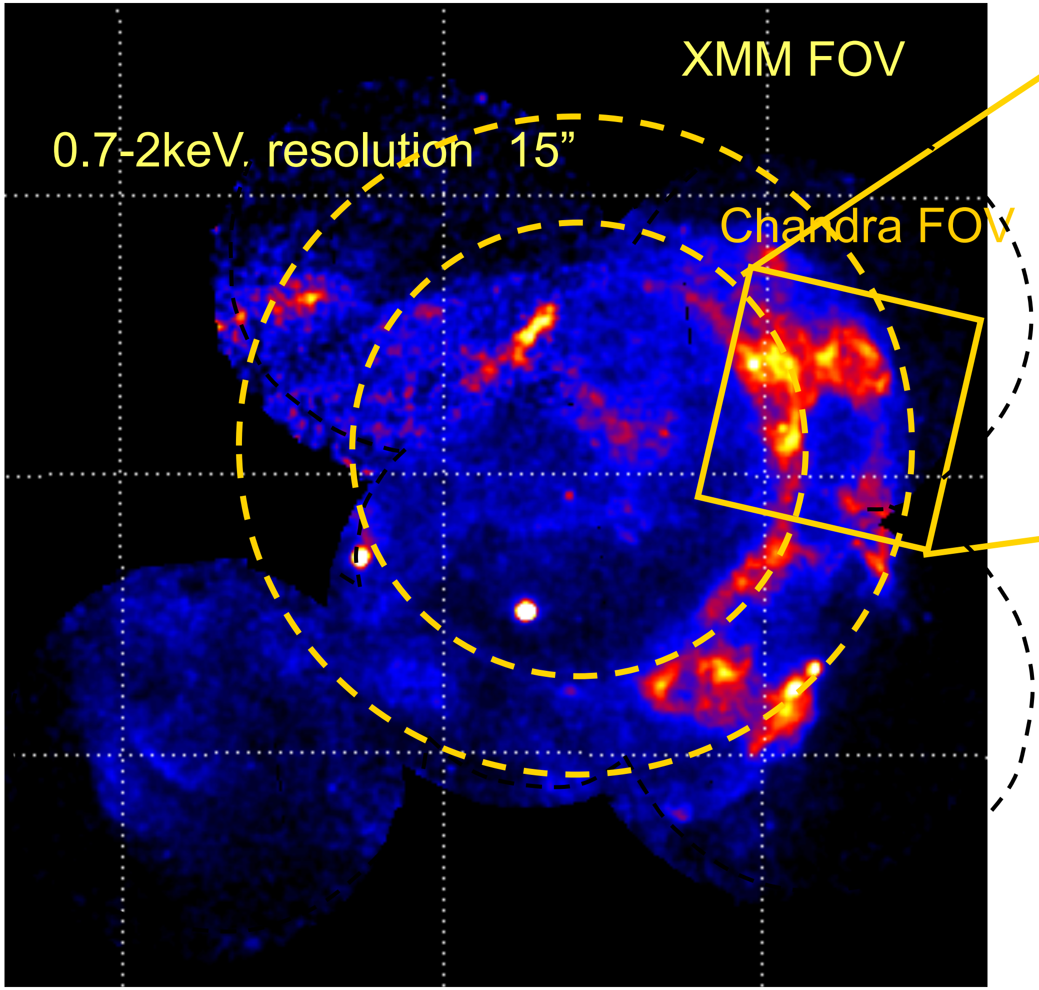
Cas A is well designed to operate as a PeVatron ?

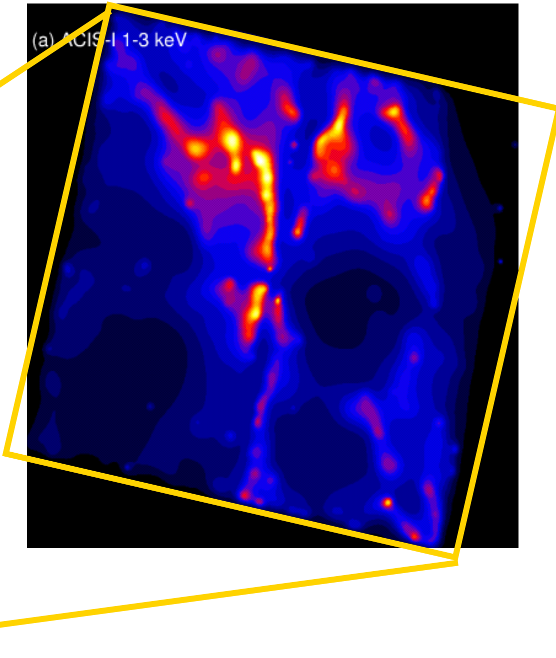
with a "right" combination of B-field, shock speed and age to accelerate and confine particles up to 1 PeV:

a source of >10TeV γ -rays and neutrinos?

An other SNR very active: RX J1713.7-3946

structure of the entire remnant (XMM-*Newton*)

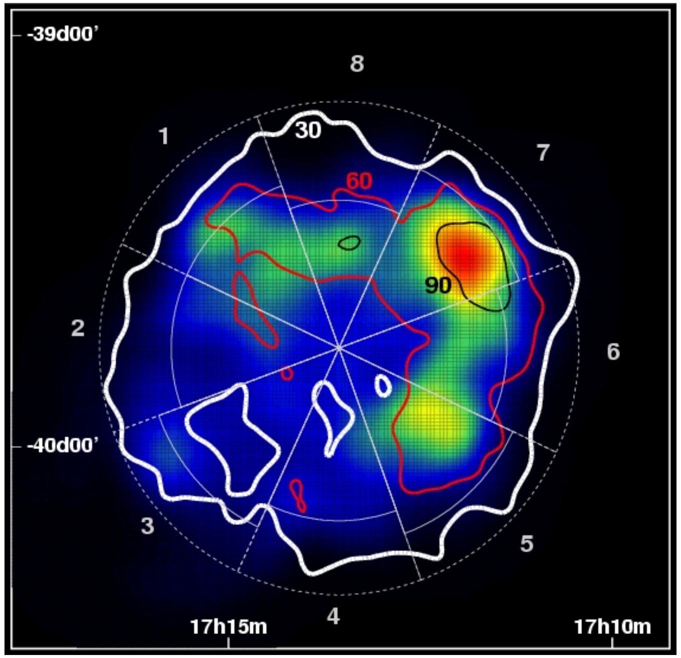




Chandra image

Observed with gamma astronomy in the keV (CHANDRA) and TeV (HESS) spectrum region

RX 1713.7-3946: possible interpretations



TeV-keV correlations …
what this could mean?

the key issue - identification of γ-ray emission mechanisms: – π^0 or IC ?

new! - energy spectra 150GeV-30 TeV
from different parts - ***NW, S W, E,C***

coordinate-independent from 0.2 to 10 TeV
difficult to explain by IC (?)

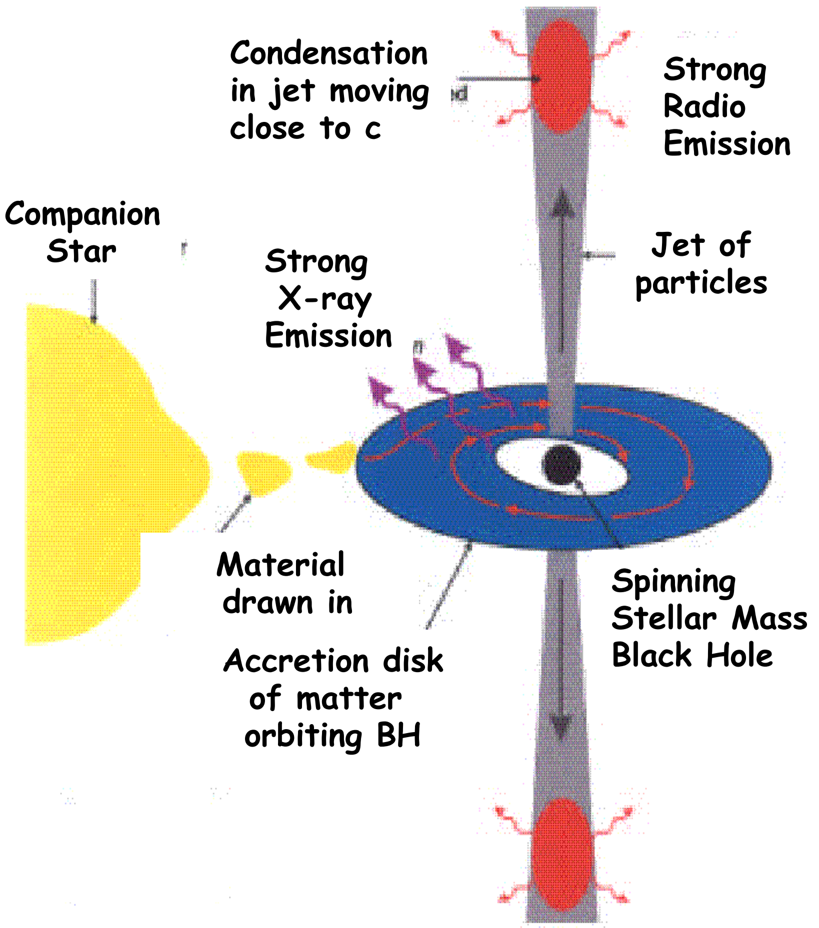
implications ?

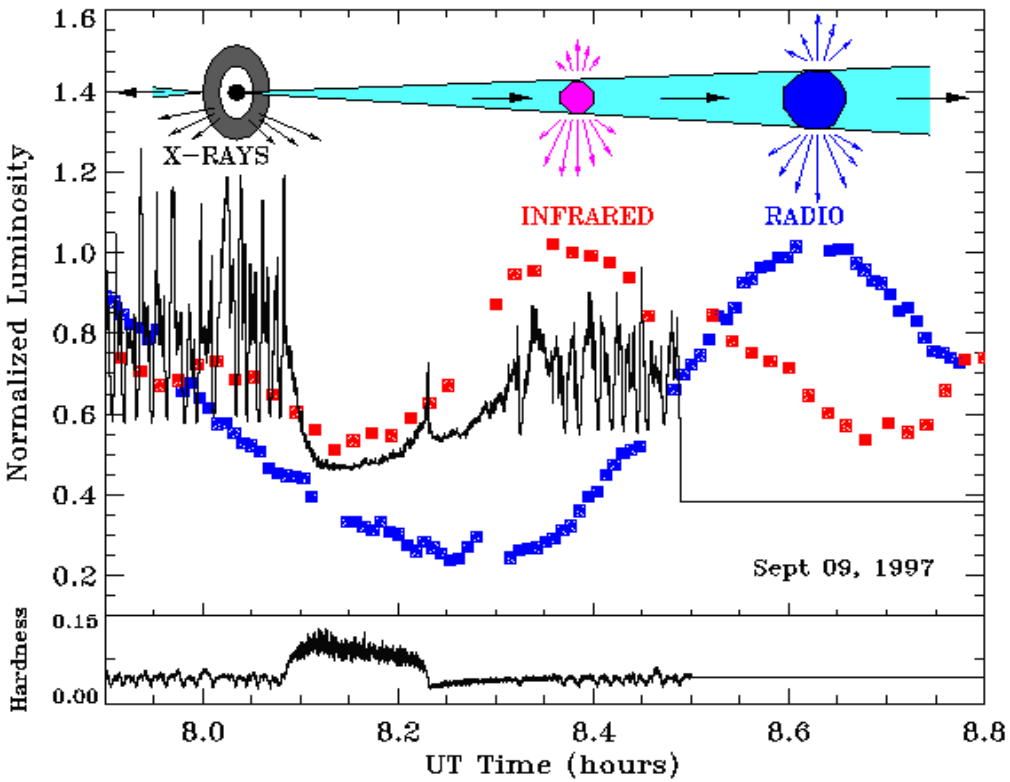
if π^0 - hadronic component is detected !
estimate of Wp (with an uncertainty related to the uncertainty in n/d^2)

if IC - model independent estimate of We (multi-TeV electrons) Le=Lx and model independent map of B-field

MICROQUASARS

~12 microquasars scoperti nella galassia dal 1992,





Jet/cannonball si forma durante la scomparsa del disco di accrescimento interno (R ~ 200 km)

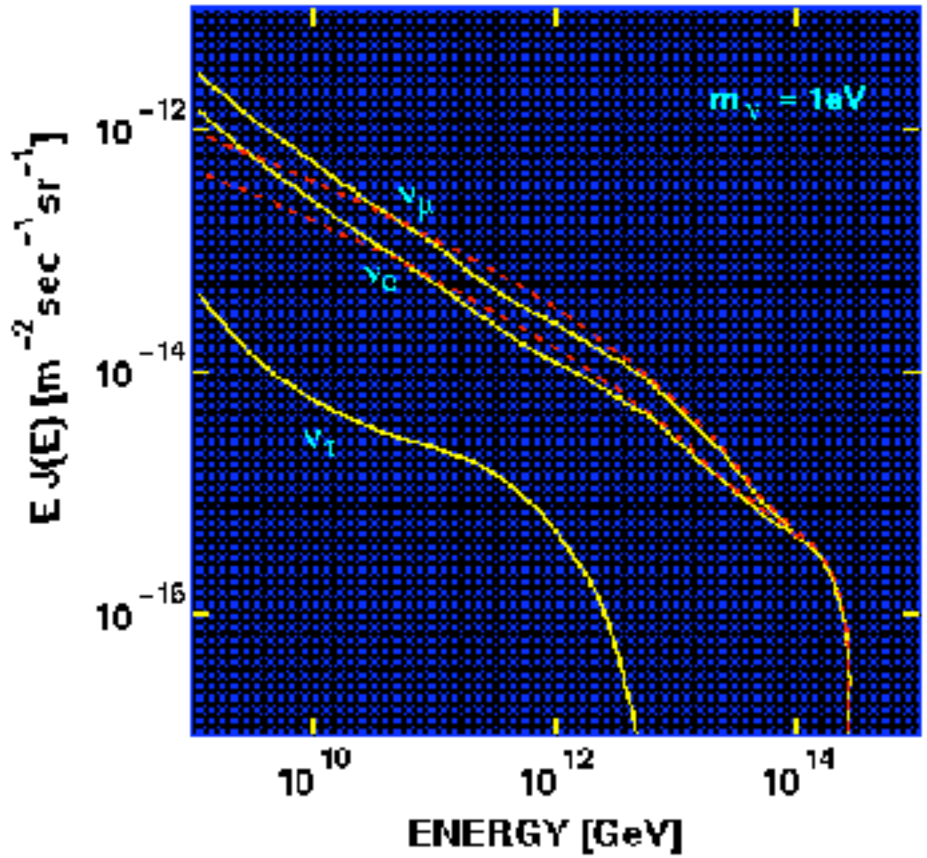
Mirabel/ J. Carr

Altre ipotesi per UHE ν: annichilazione o collasso di “Difetti Topologici”

Il modello Top Down

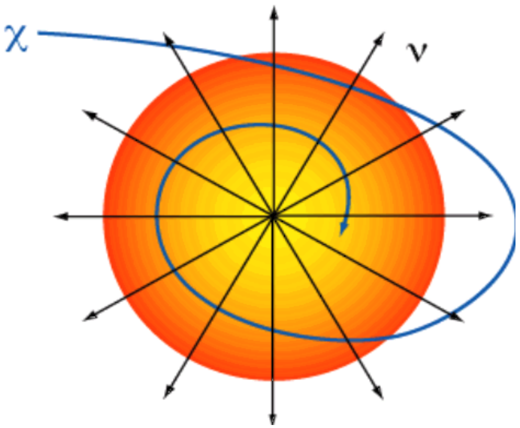
Difetti Topologici (stringhe) e/o Particelle Metastabili originate nell’ Universo primordiale interagiscono/decadono producendo particelle pesanti X dal cui decadimento sarebbero originati leptoni e quarks di altissima energia. Datali particelle sarebbero originati nucleoni EHE, fotoni, neutrini, con energie fino alla scala GUT. Ipotesi:

- **m_X 10^{24}:10^{25} eV**
- **- distanza dalla Terrra < 100 Mpc**



Altre ipotesi per UHE ν

ν da Weak Interacting Massive Particles (WIMPs)



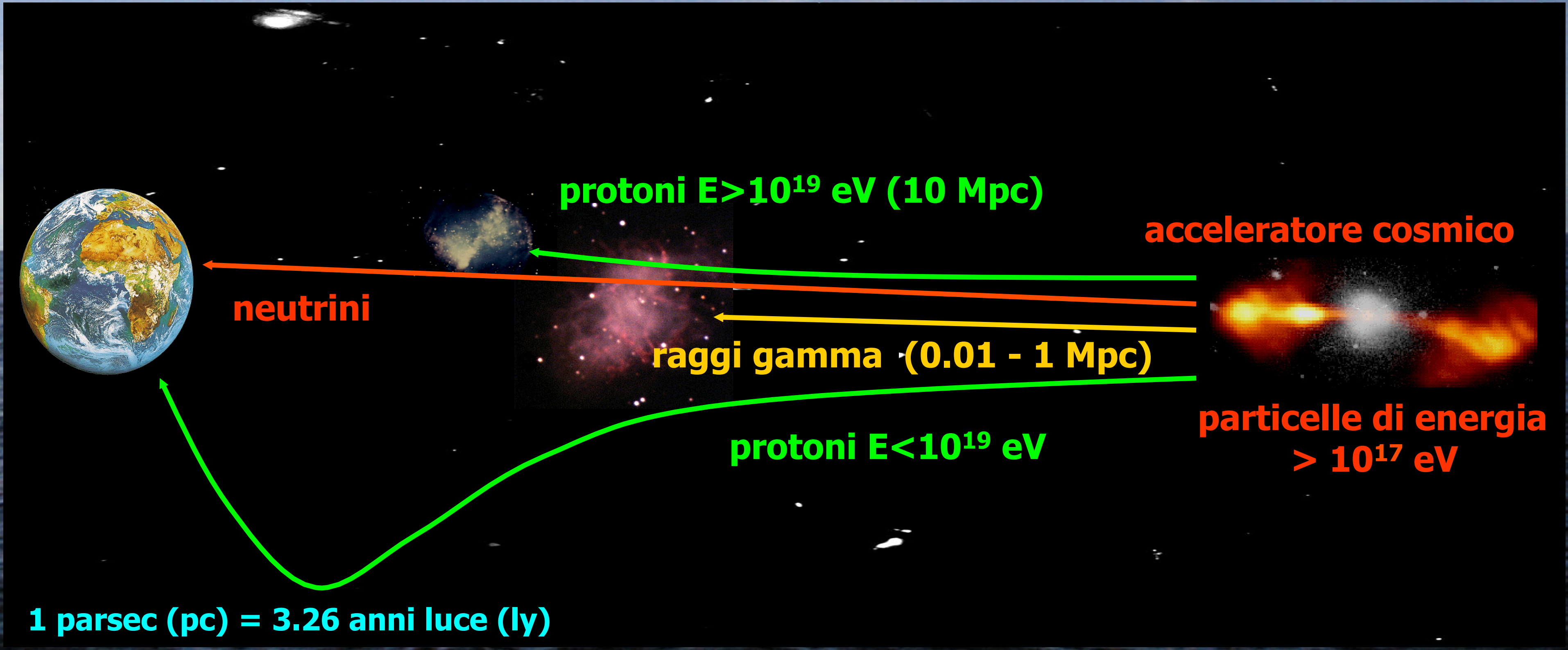
Ad es. Neutralini χ (materia oscura supersimmetrica):

- attratti per gravità al centro di Sole/Terra annichilano → χ χ → quark pesanti → ν + X

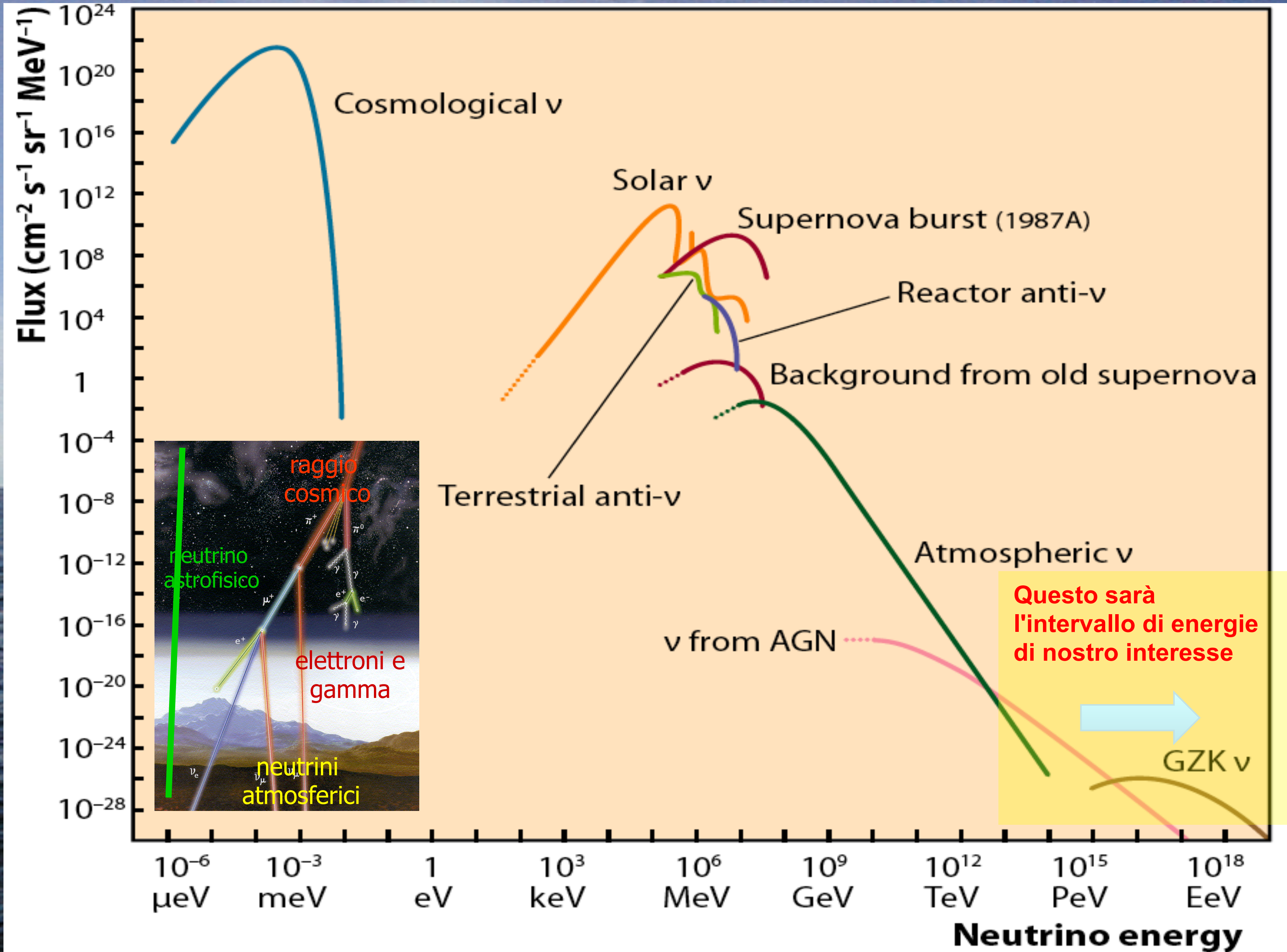
– $E_{\nu} \sim \frac{1}{4} m_{\chi}$

Diverse particelle, diversi orizzonti ...

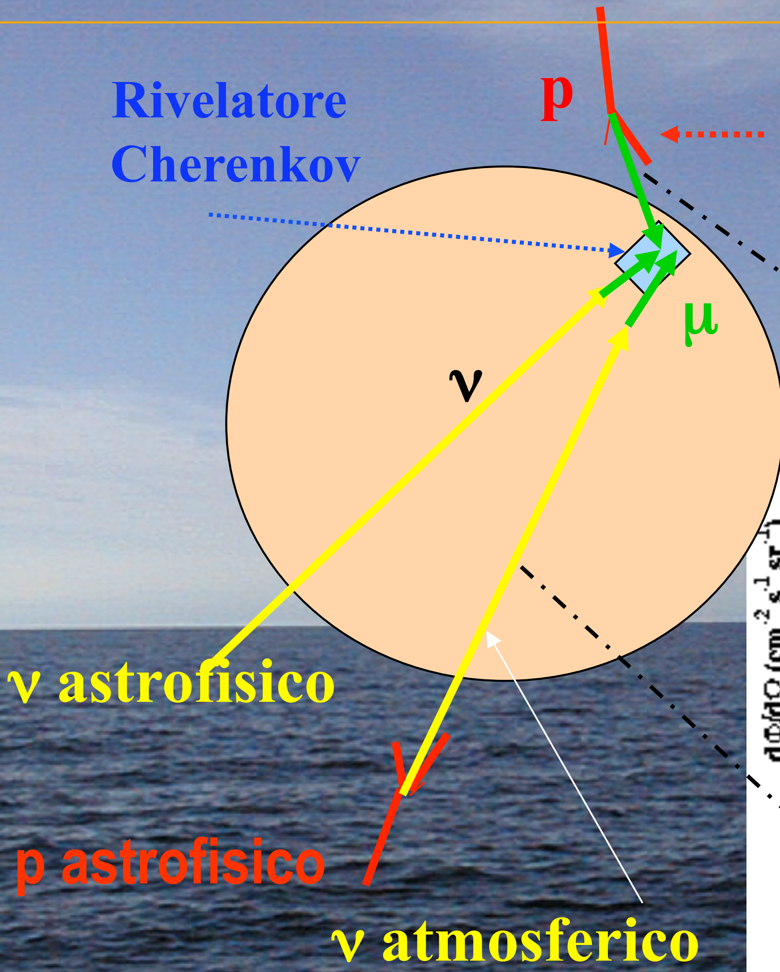
- p e γ assorbiti o deviati dalla materia e dalla radiazione interstellare
- ν interagiscono debolmente: permettono di osservare l'Universo lontano



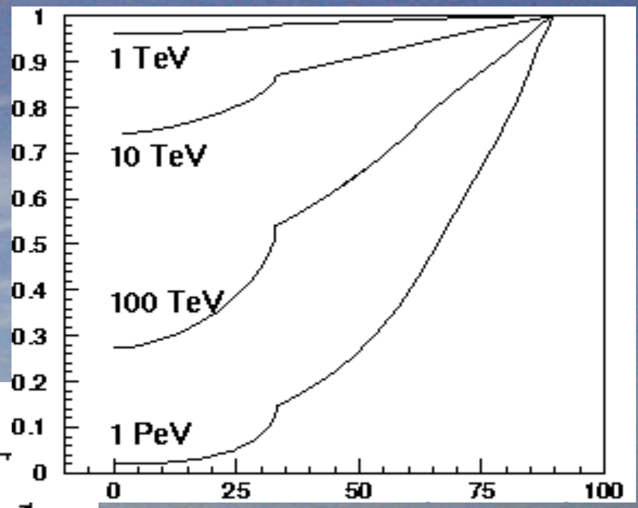
Flussi di neutrini sulla Terra: cosa sappiamo oggi



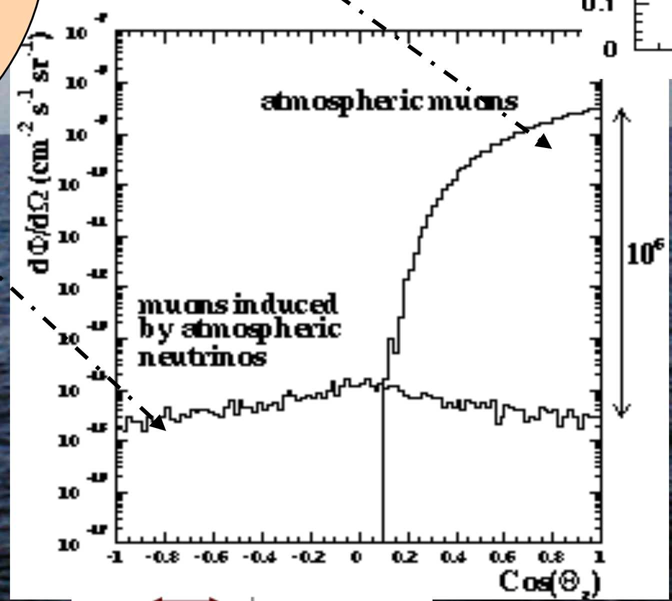
Necessità di un rivelatore sottomarino

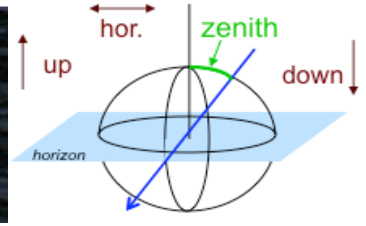


Probabilità di propagazione nella Terra



Angolo Zenith



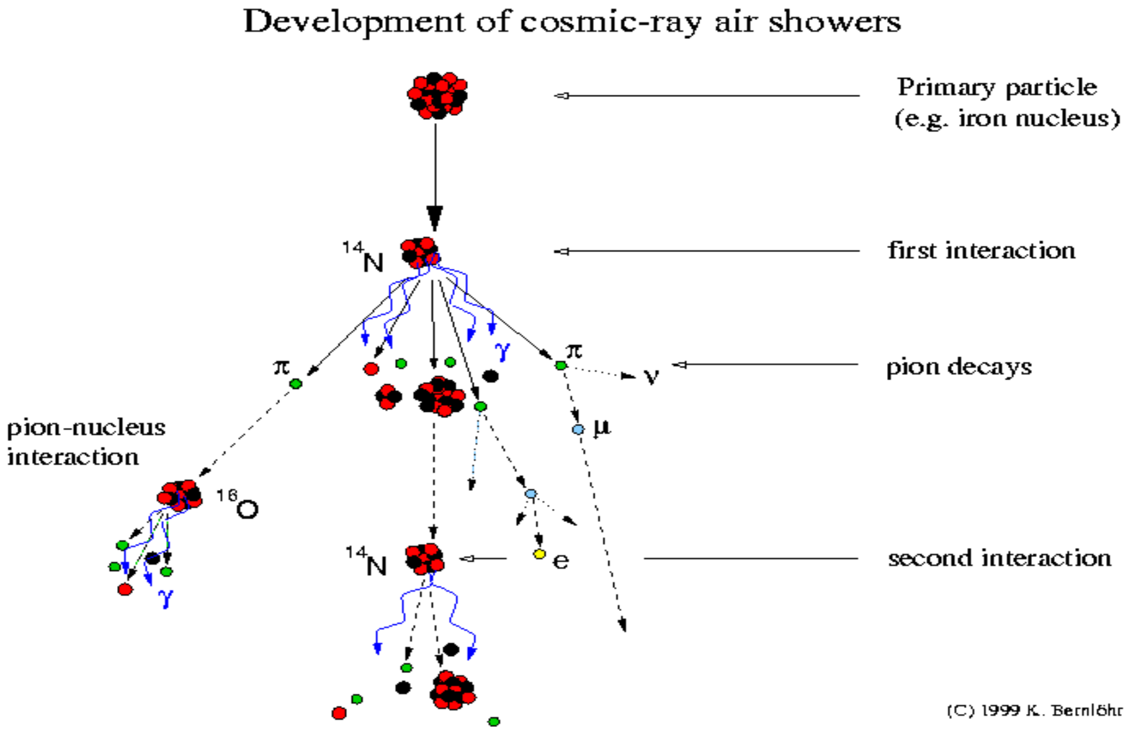


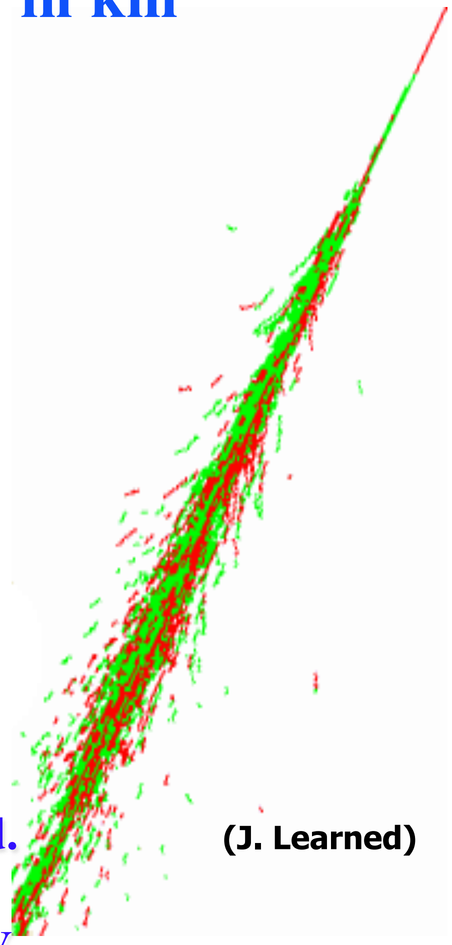
> 1PeV: ν orizzontali o dall'alto

<100 TeV: ν dal basso

Il fondo: neutrini atmosferici

$\langle E_\nu \rangle \sim$1-100 GeV in Macro (Gran Sasso) -> TeV in km^3



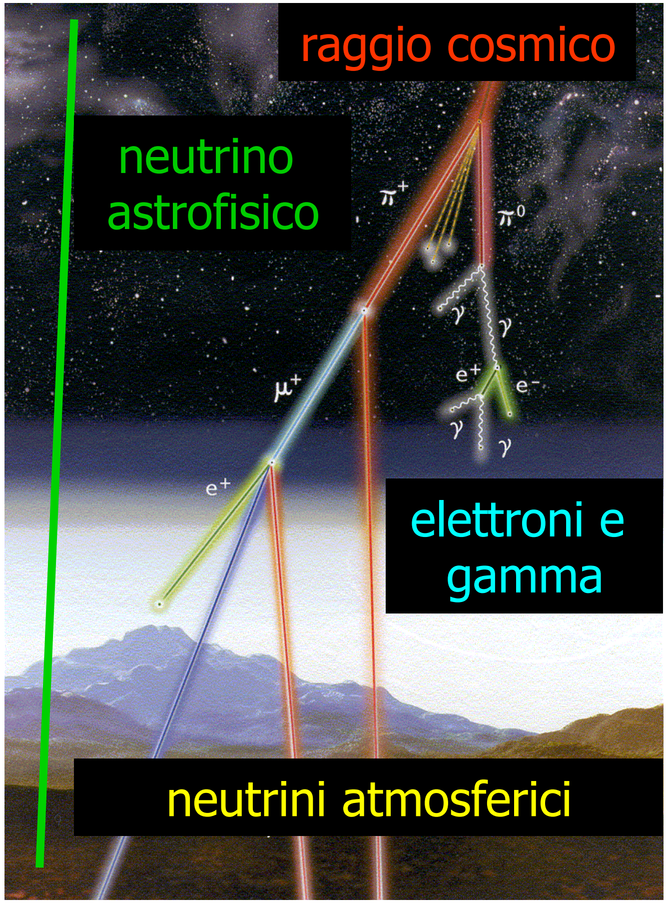


(J. Learned)

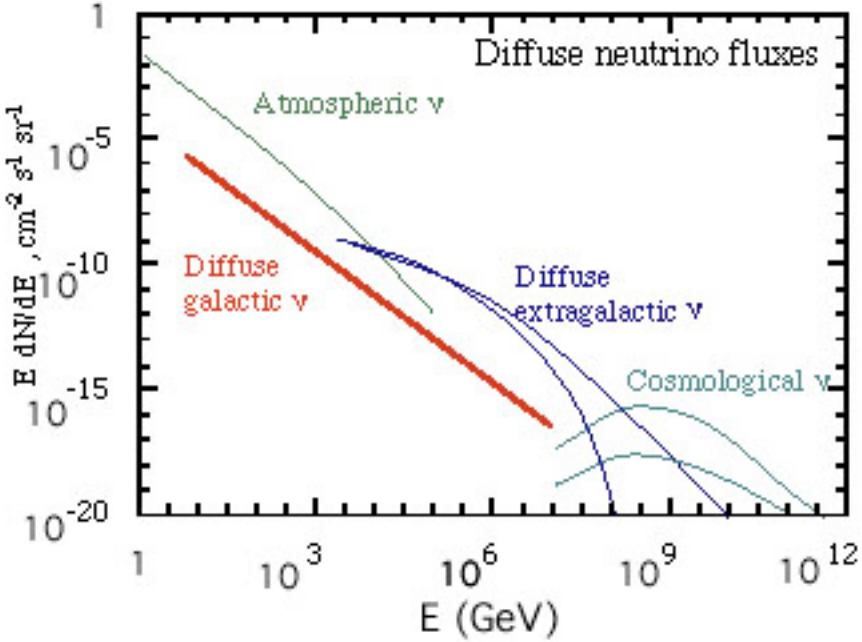
	$\pi \to \nu_\mu \mu \to \nu_\mu \nu_e\, e$			$\pi \to \nu_\mu \mu$		Dir. Prod.
$\nu_\mu / \nu_e / \nu_\tau$ =	(2/1/0)	1/1/1	$\to$	1/0.01/0.01	$\to$	1/1/1
	(no-osc)	osc	GeV	TeV		10-100 TeV

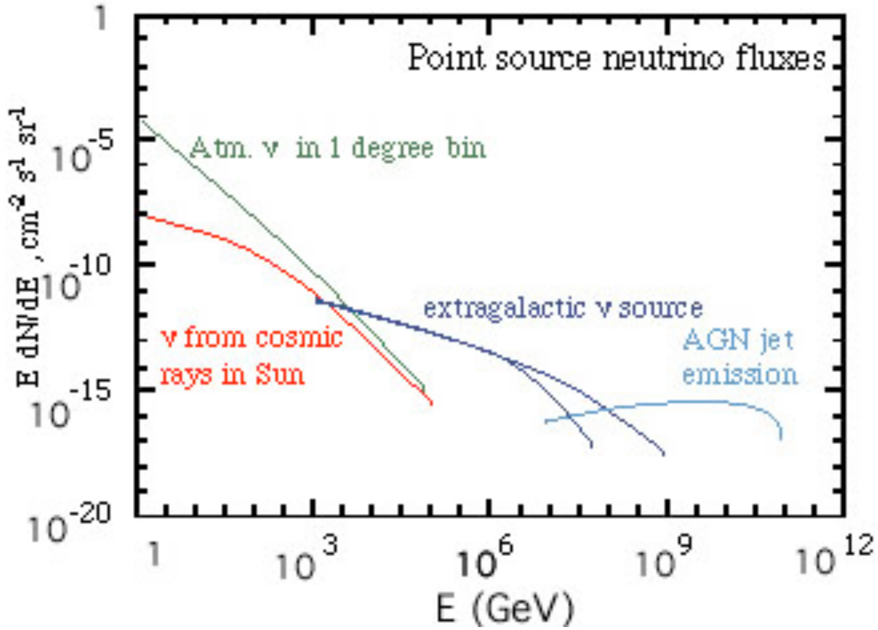
Flussi di neutrini sulla Terra

ν atmosferici, da sorgenti astrofisiche,

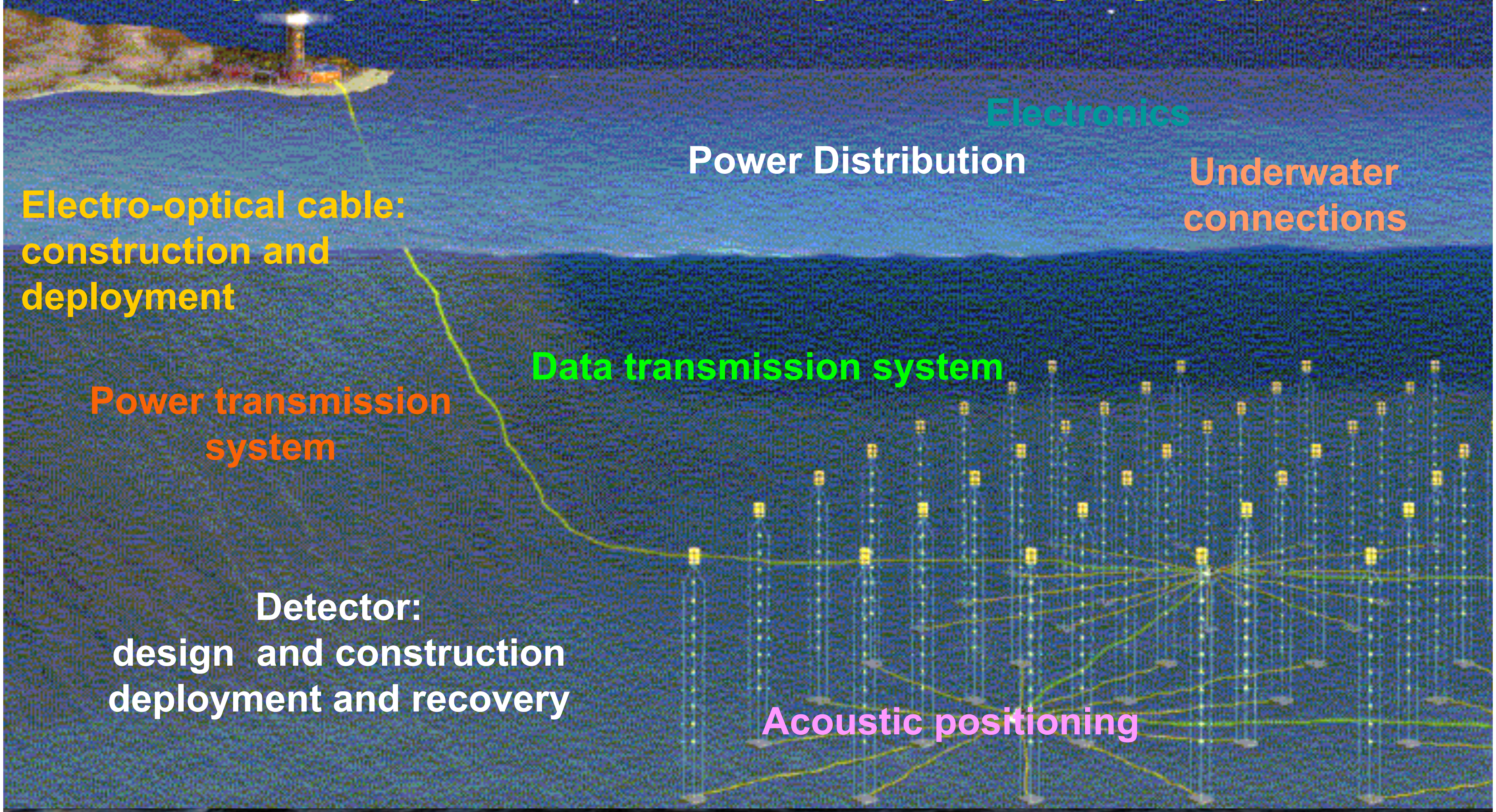


E dΦ/dE cm^{-2} s^{-1} sr^{-1}





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



Telescopi per neutrini: programma scientifico

- **Astrofisica con ν di alta energia:**
  - ν da sorgenti diffuse nell'Universo
    - ν da collassi stellari, AGN, GRB,
    - … sorgenti non altrimenti note

Misura di energia e flusso dei neutrini

  - ν da sorgenti puntiformi galattiche/extra-galattiche
    - Stelle binarie X , Resti di SuperNovae (SNR), Nuclei di Galassie Attive (AGN), Micro-Quasars, sorgenti di Gamma Ray Bursts (GRB), SN, …

Misura di direzione, energia e flusso di ν

Importante: osservare l' angolo solido più vasto includendo il Centro della Galassia

Misura di direzione, energia e flusso di ν

- **Fisica delle alte energie:**
  - ricerca indiretta di materia oscura (WIMPs), di Monopoli magnetici, oscillazioni di neutrino, rivelazione della "risonanza di Glashow (6,3 PeV), …

- **Interdisciplinarietà**

Interazioni di ν astrofisici

All' aumentare dell' energia del ν:
- **aumenta la σ aumenta → il numero di interaz.**
- **aumenta la probabilità di rivelazione (aumenta Eμ)**
- **diminuisce il fondo (μ atmosferici)**
- **diminuisce il flusso dei neutrini astrofisici**

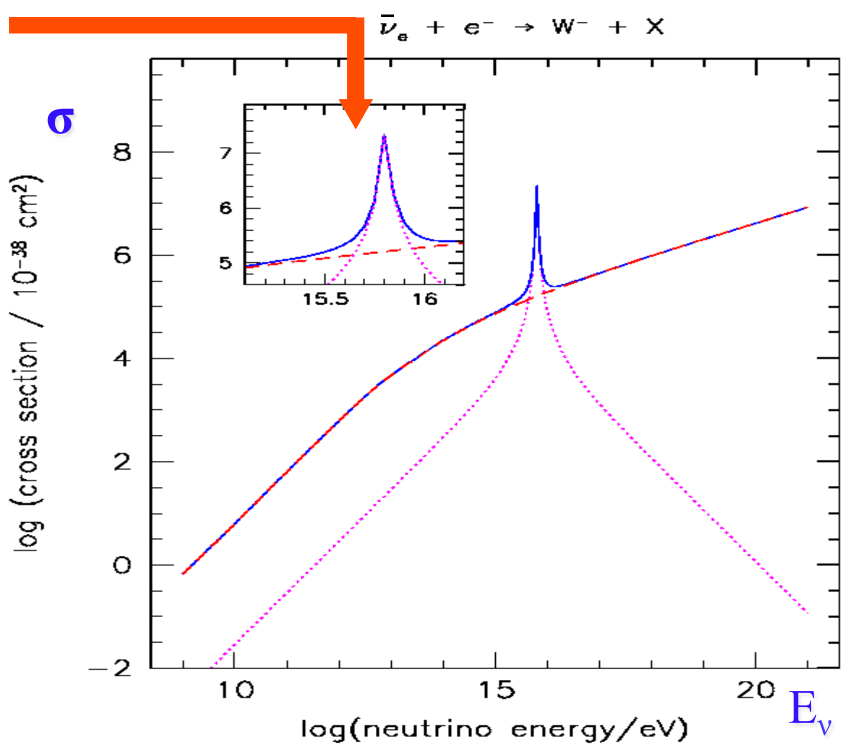
La ricerca di sorgenti astrofisiche con ν_μ O.K. per E_{ν_μ} > 10TeV

Il fondo di μ atmosferici non permette di realizzare apparati a livello del mare

Per E_ν > 10TeV i flussi di ν astrofisici stimati sono tali che il rivelatore deve essere esteso per ~ 1km³

Il km³ apparato sottomarino e/o in Antardide

6.4 PeV risonanza di Glashow



I primi tentativi di misurare ν astrofisici

Fine tracking calorimeters:

- Kolar Gold Fields: proportional counters and Fe absorber, 350 ton, S = 36 m^2, 6045 m.w.e. depth, intrinsic angular resolution $\sim 2.5°$, source search in 5°, 188 $\mu\uparrow$ $(\theta > 60°)$
  (H. Adarkar et al, 24^{th} ICRC in Rome (1995))

- Frejus: flash chambers, Geiger tubes and Fe planes, 900 ton, S = 36 m^2, 4000 m.w.e. Horizontal and upward stopping μs (0 events with > 140 MeV per radiation length) $\Longrightarrow$ Upper limit (isotropic flux of νs)
  (Astropart. Phys. **4** (1996) 217):

$$\frac{d\Phi_{\nu_\mu}}{dE_\nu}(2.6TeV) < 7\cdot 10^{-13}GeV^{-1}cm^{-2}s^{-1}sr^{-1}(90\%c.l.)$$

Water Cherenkov technique (development of Cherenkov cone seen by an array of 1000-2000 PMTs):

- IMB: 3.3 kton of water, $S_{eff} = 390$ m^2, 1570 m.w.e., Gaussian point spread function $\sigma = 3.4° - 4.5°$, 624 $\mu\uparrow$
  (Nucl. Phys. **B** (Proc. Suppl.) **38** (1995) 331)
- Kamiokande: 2.3 kton of water, $S_{eff} \sim 150$ m^2, 2700 m.w.e., 2.5° includes 68% events from point source, 252 $\mu\uparrow$ (PRD**39** (1989) 1481)

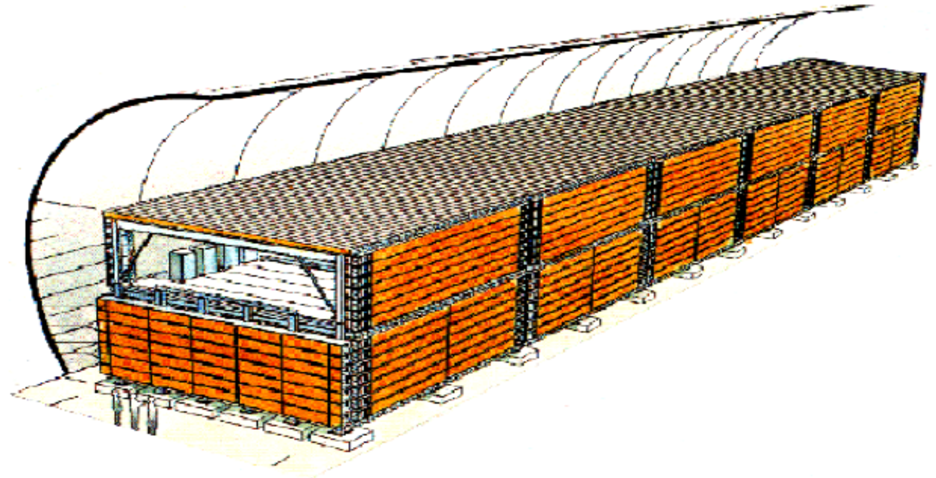
- Baksan: T.o.F. (res. 5 ns) with liquid scintillators $(\theta > 80°$ at trigger level), S $\sim$ 290 m^2, 850 m.w.e., angular res. $\sim° 2$, source search in 5°, 682 $\mu\uparrow$, (Proc. of 24^{th} ICRC, Rome (1995))

rivelatori di "I generazione"

rivelatori di "II generazione"

- MACRO
- Super-Kamiokande: 50,000 ton water Cherenkov (22.5 kton fiducial volume) with 20-inch 11146 PMTs and 1885 8-inch for veto, 2700 m.w.e., 1028 throughgoing $\mu\uparrow$/923 d, no results on ν sources yet

I primi tentativi di misurare ν astrofisici: MACRO



6 supermodules of total dimension $12 \times 76.6 \times 9\ m^3$
μ-flux at ~ 3700 mwe $\sim 10^{-6}$ surface flux
3 sensitive elements:

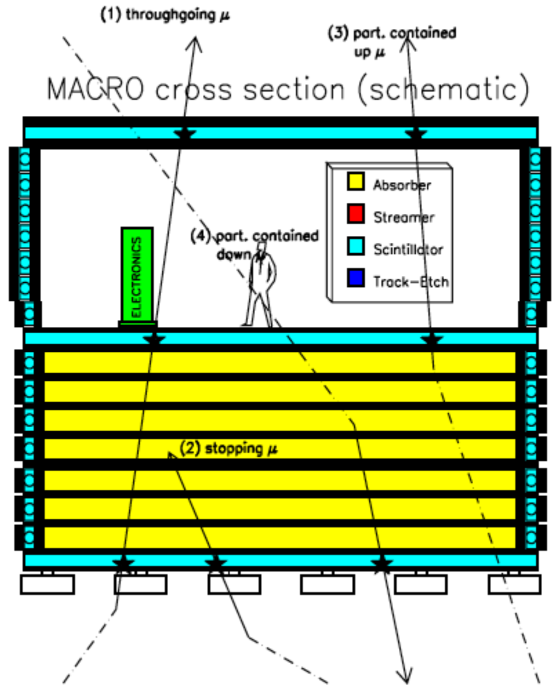
1. $1263\ m^2$ track-etch (CR39+Lexan) in the middle of lower part, vertical E and N walls in "wagons" of $\sim 25 \times 25\ cm^2$ (etched $227\ m^2$, exposure 7.6 yr)
2. ~ 600 tons liquid scintillators (time resolution ~ 500 psec
3. $\sim 20{,}000\ m^2$ limited ST for tracking (angular resolution $< 1°$, pointing capability checked with Moon shadow, PRD59 (1999) 012003)

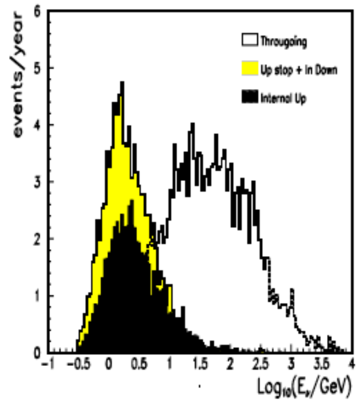
Minimum E_{th} set by rock absorber = 1 GeV for vertical μs

Neutrino measurement in MACRO @ LNGS

3 Topologies of neutrinos detected:

- Upward Throughgoing μs ($\langle E_\nu \rangle \sim 100$ GeV): T.o.F. ($\sim 50\%$ through 3 scintillator planes)
- IUμ ≡ Internal Upgoing μs ($\langle E_\nu \rangle \sim 4$ GeV): T.o.F.
- IDμ ≡ Internal Downgoing μs + UGSμ ≡ UpwardGoing Stopping μs ($\langle E_\nu \rangle \sim 4$ GeV): topological constraints

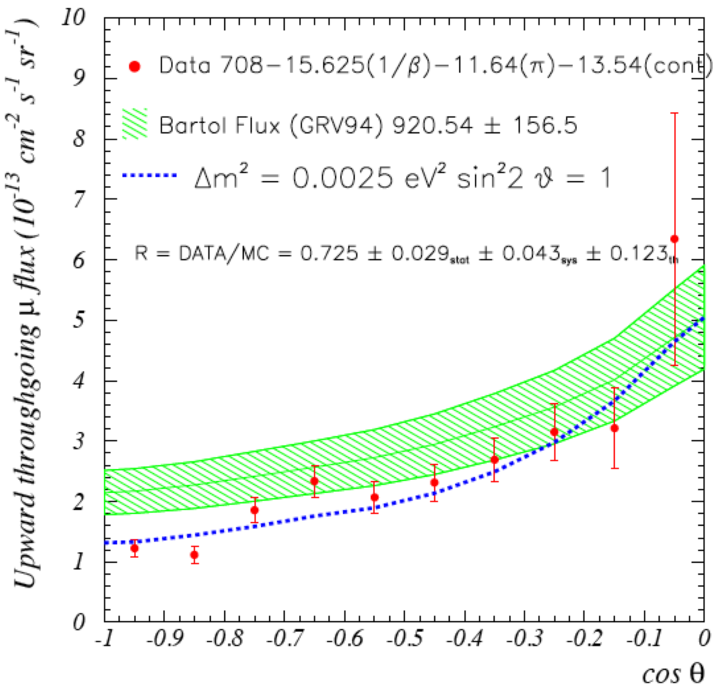




MACRO: alcuni risultati

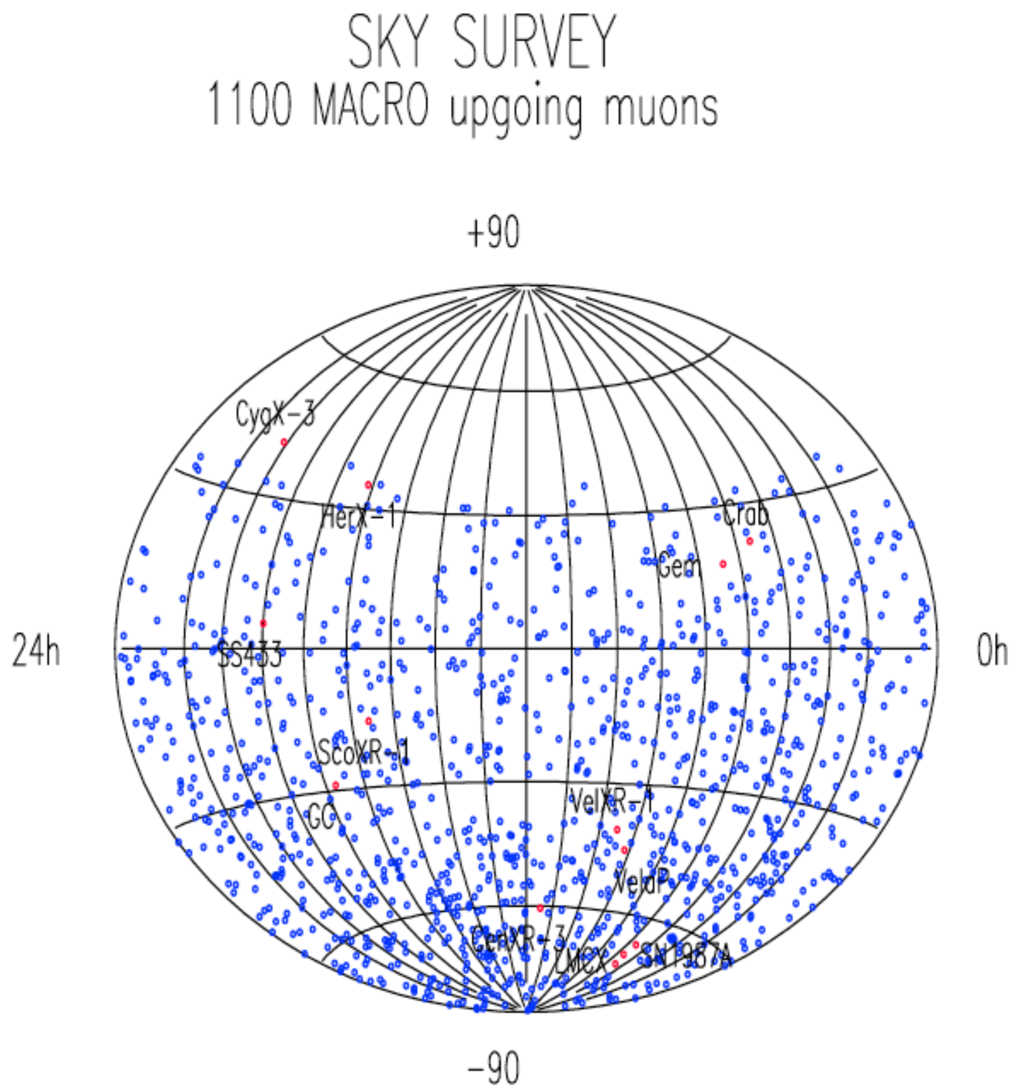
The Atmospheric Neutrino Background

708 events used for oscillation analysis



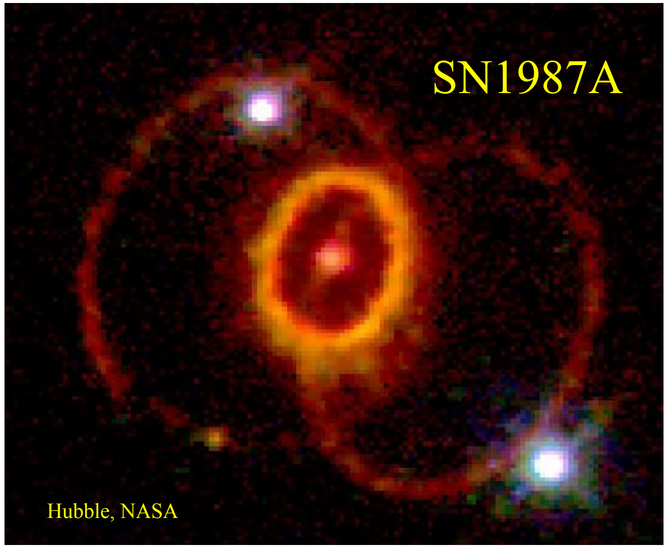
MACRO data favor $\nu_\mu \to \nu_\tau$ oscillation analysis with maximum mixing and $\Delta m^2 \sim 2.5 \cdot 10^{-3}$ eV^2 ($P(\chi^2) = 36\%$) with respect to the no oscillation case ($P(\chi^2) = 0.36\%$)

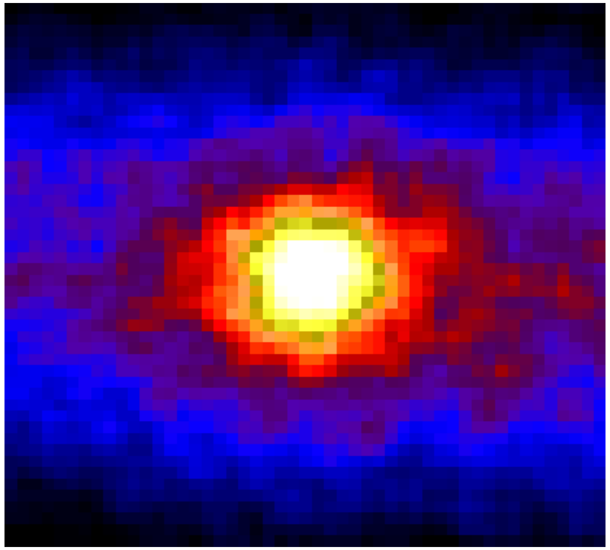
MACRO search for point like ν sources



L’astronomia con ν è già cominciata …

1987: rivelati ν prodotti da una SuperNovae

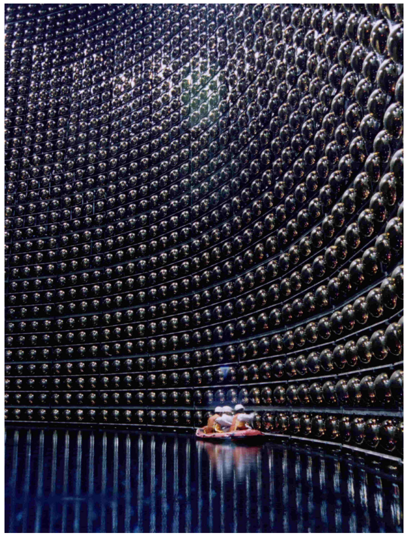


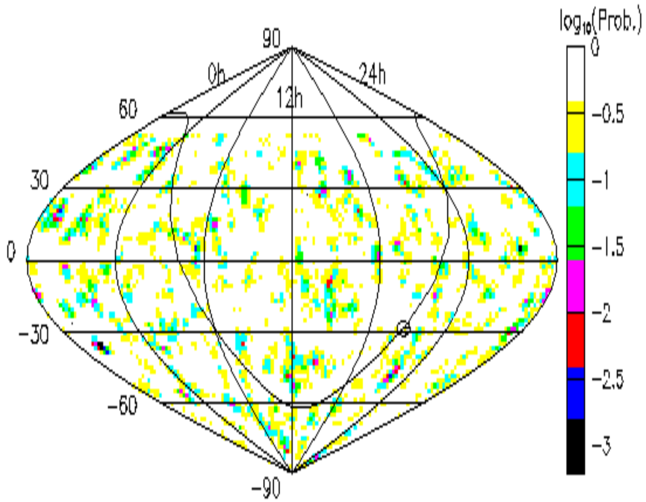


SuperKamiokande ν prodotti dal Sole

SuperKamiokande

- Realizzato in una caverna
- 50,000 T di acqua ultra-pura
- 22.500 T fiduciali
- 40m altezza
- 40 m di diametro
- PMT semisferici
- 1200 m^2 di area eff. per μ (4MeV- 200GeV)
- → >2000 μ dal basso
- Nessun "segnale" di ν astrofisici !

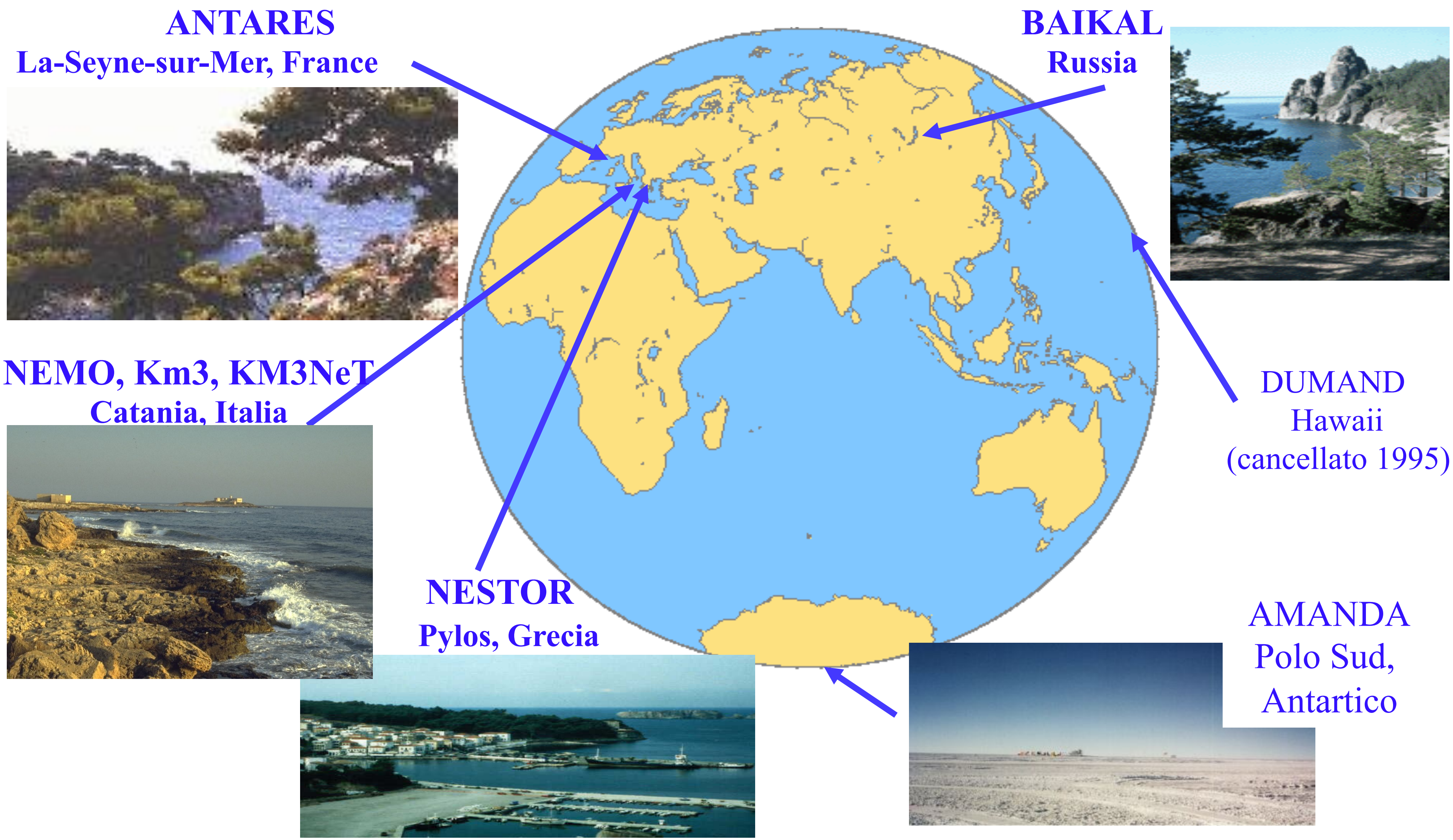




Source name	upmu observed (in 4° cone)	noise expected	Accept. (cm^2)	Flux Limit ($cm^{-2}s^{-1}$)
Cyg X−1	6	2.0	4.1×10^6	2.4×10^{-14}
Cyg X−3	1	1.8	3.5×10^6	1.03×10^{-14}
Her X−1	1	1.7	4.1×10^6	8.7×10^{-15}
Sco X−1	2	2.6	6.9×10^6	7.0×10^{-15}
Vela X−1	5	2.9	8.6×10^6	9.9×10^{-15}
Crab N.	0	1.8	5.1×10^6	4.1×10^{-15}
3C273	6	2.4	6.2×10^6	1.6×10^{-14}
Per A	1	1.9	3.4×10^6	1.05×10^{-14}
Vir A	1	1.7	5.7×10^6	6.3×10^{-15}
Coma cl.	2	1.7	4.7×10^6	1.03×10^{-14}
Gemminga	3	2.0	5.4×10^6	1.14×10^{-14}
G.C.	3	2.2	7.6×10^6	8.0×10^{-15}
Mrk 421	2	1.9	3.8×10^6	1.28×10^{-14}
Mrk 501	1	1.9	3.6×10^6	9.9×10^{-15}

Analoghi "limiti" anche da MACRO, IMB, BAIKAL, Frejus, BAKSAN ,…

“Telescopi” Cherenkov per neutrini



From Neutrinos to detectable muons

ν detected through CC interactions with rock surrounding detectors as upward-going μs (to discriminate atmospheric μs):

$$\nu_\mu(\bar{\nu}_\mu) + N \to \mu^-(\mu^+) + X$$

Measurement of structure functions at HERA improved estimation of VHE ν σs (we use CTEQ3-DIS available in PDFLIB, see Gandhi et al, hep-ph/9807264)

Probability that a ν with E_ν crossing the detector produces a μ with $E_\mu \geq E^\mu_{th} = 1$ GeV:

$$P_\nu(E_\nu, E^\mu_{th}) = N_A \int_0^{E_\nu} dE'_\mu \frac{d\sigma_\nu}{dE'_\mu}(E'_\mu, E_\nu) R_{eff}(E'_\mu, E^\mu_{th})$$

where μ effective range is the probability a μ with E_μ survives with $E_\mu \geq E^\mu_{th}$:

$$R_{eff}(E_\mu, E^\mu_{th}) = \int_0^\infty dX \, P_{surv}(E'_\mu, E^{th}_\mu, X)$$

evaluated from the μ energy loss

$$\frac{dE_\mu}{dX} = \alpha(E_\mu) + \beta(E_\mu) E_\mu$$

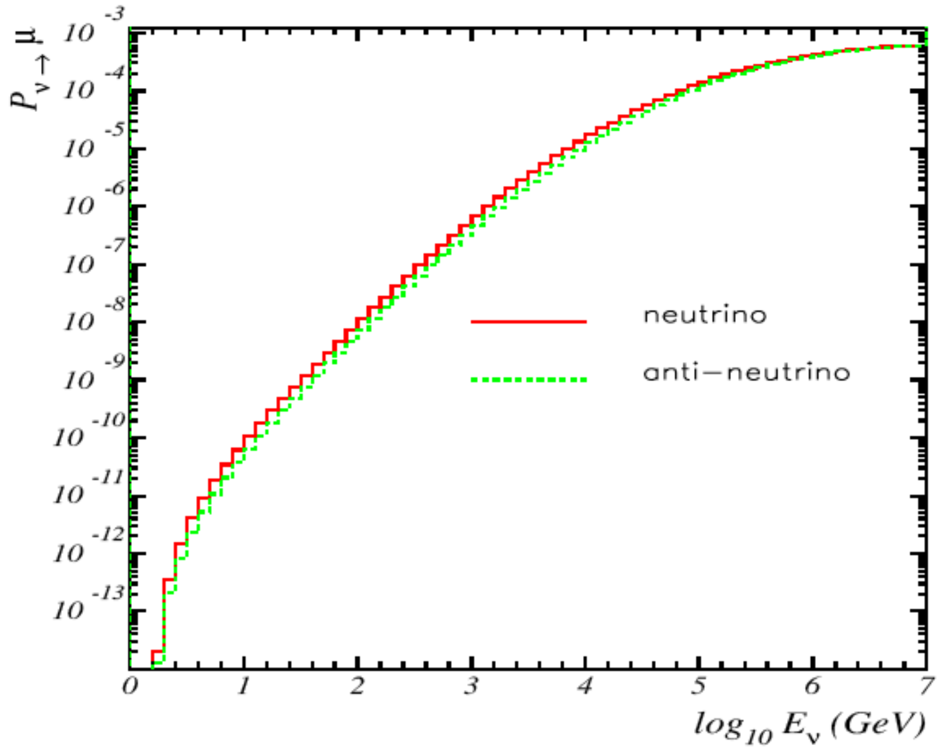
$\alpha \equiv$ ionization losses ~ 2 MeV g^{-1} cm^2
$\beta \equiv$ bremsstrahlung, pair production, nuclear interactions $\sim 4 \cdot 10^{-6}$ g^{-1} cm^2

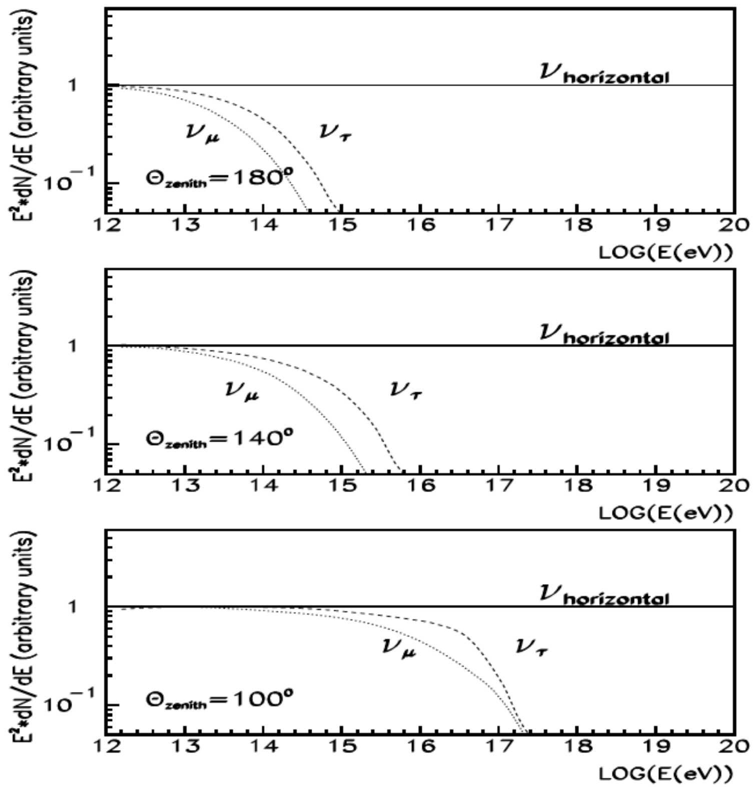
From Neutrinos to detectable muons

From Neutrinos to Detectable Muons

$E_\nu \lesssim 1$ TeV: $\sigma_\nu \sim E_\nu$ and $R_{eff} \sim E_\mu$
$E_\nu \gtrsim 1$ TeV: σ_ν dumped by W propagator and $R_{eff} \sim \ln(E_\mu)$

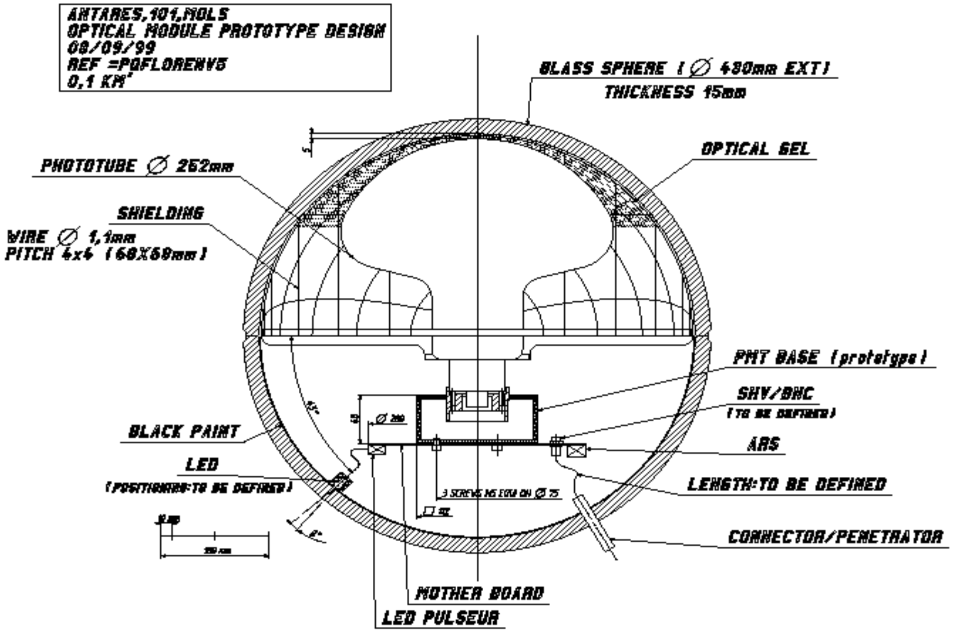
E_ν	$P_{\nu\to\mu^-}$	$P_{\bar{\nu}\to\mu^+}$
10	8.15×10^{-11}	4.88×10^{-11}
10^2	9.05×10^{-9}	5.87×10^{-9}
10^3	5.79×10^{-7}	3.86×10^{-7}
10^4	1.52×10^{-5}	1.09×10^{-5}
10^5	1.35×10^{-4}	1.17×10^{-4}



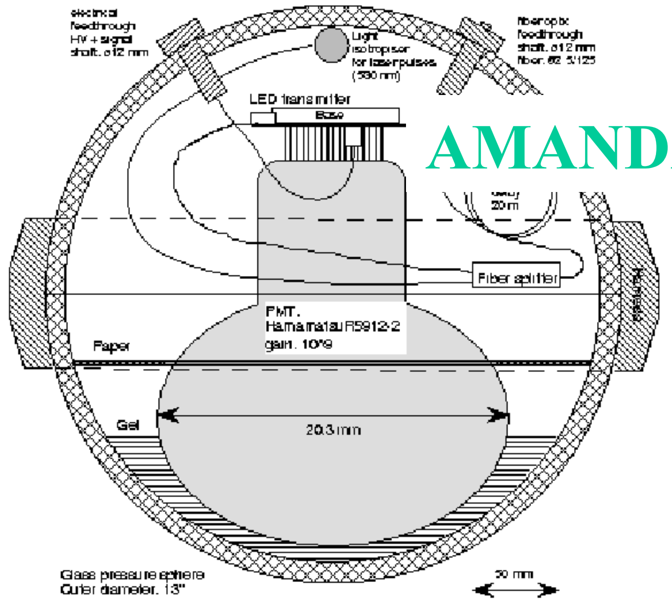


Moduli ottici per telescopi di ν sottomarini

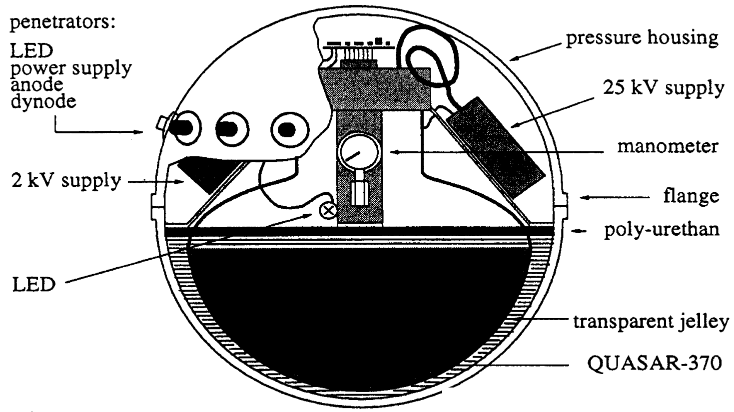
Fotomoltiplicatori da 8÷15” in sfere di vetro, diametro 13-17”
resistenti alla pressione (300-400 atm)



ANTARES



AMANDA



BAIKAL

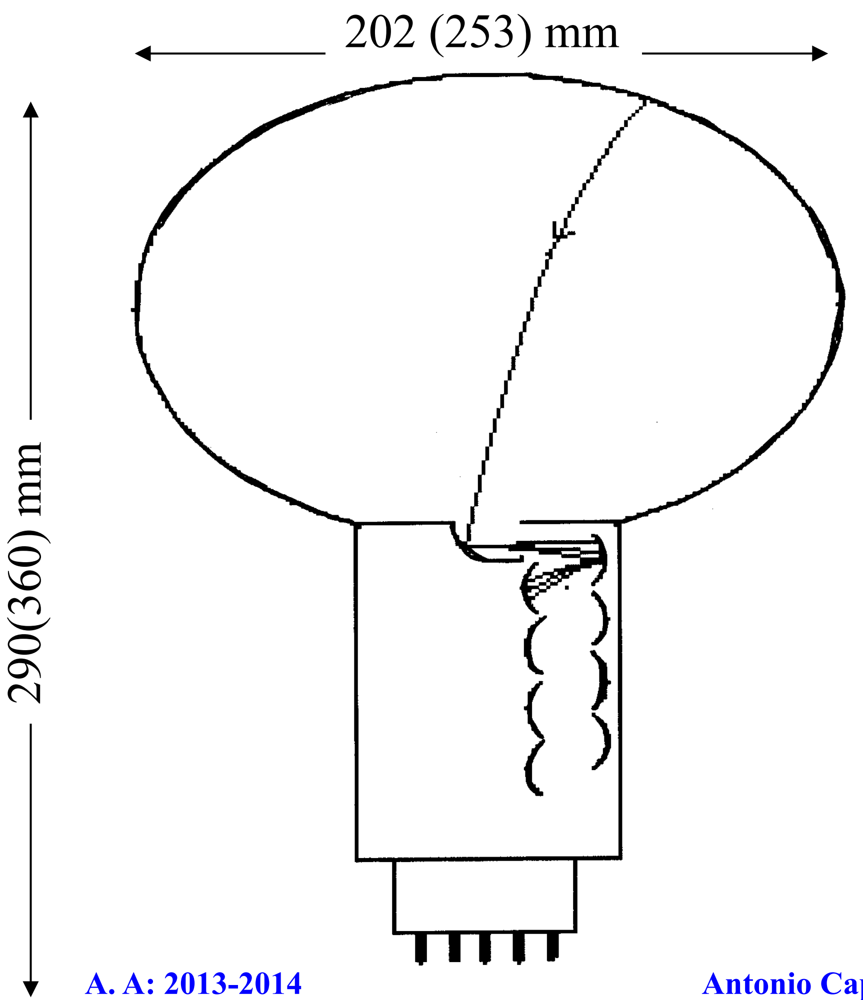
Fotomoltiplicatori

AMANDA, ANTARES

Use Hamamatsu: R5912-02, (P7081-20)

Developments by Photonis (ex Philips)

ETL (ex EMI)



BAIKAL

Use EKRAN Quasar-370

(original idea from Philips)