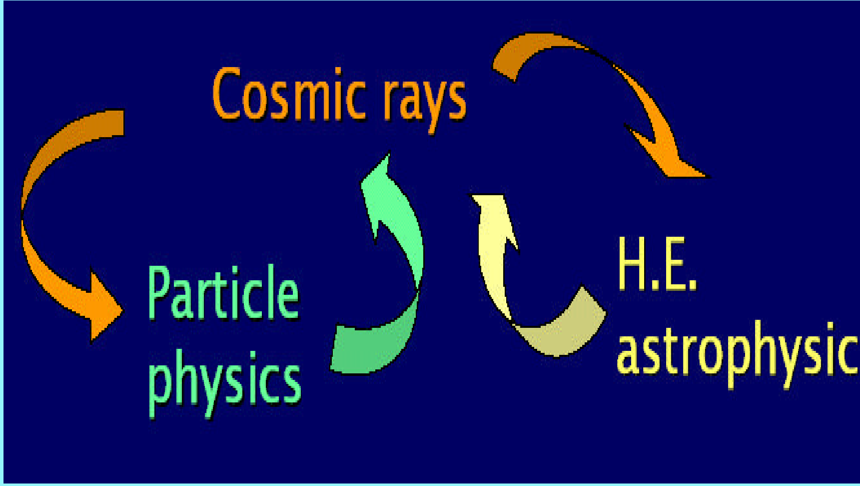
Victor Hess after his 1912 balloon flight, during which he discovered cosmic rays from space. © National Geographic.

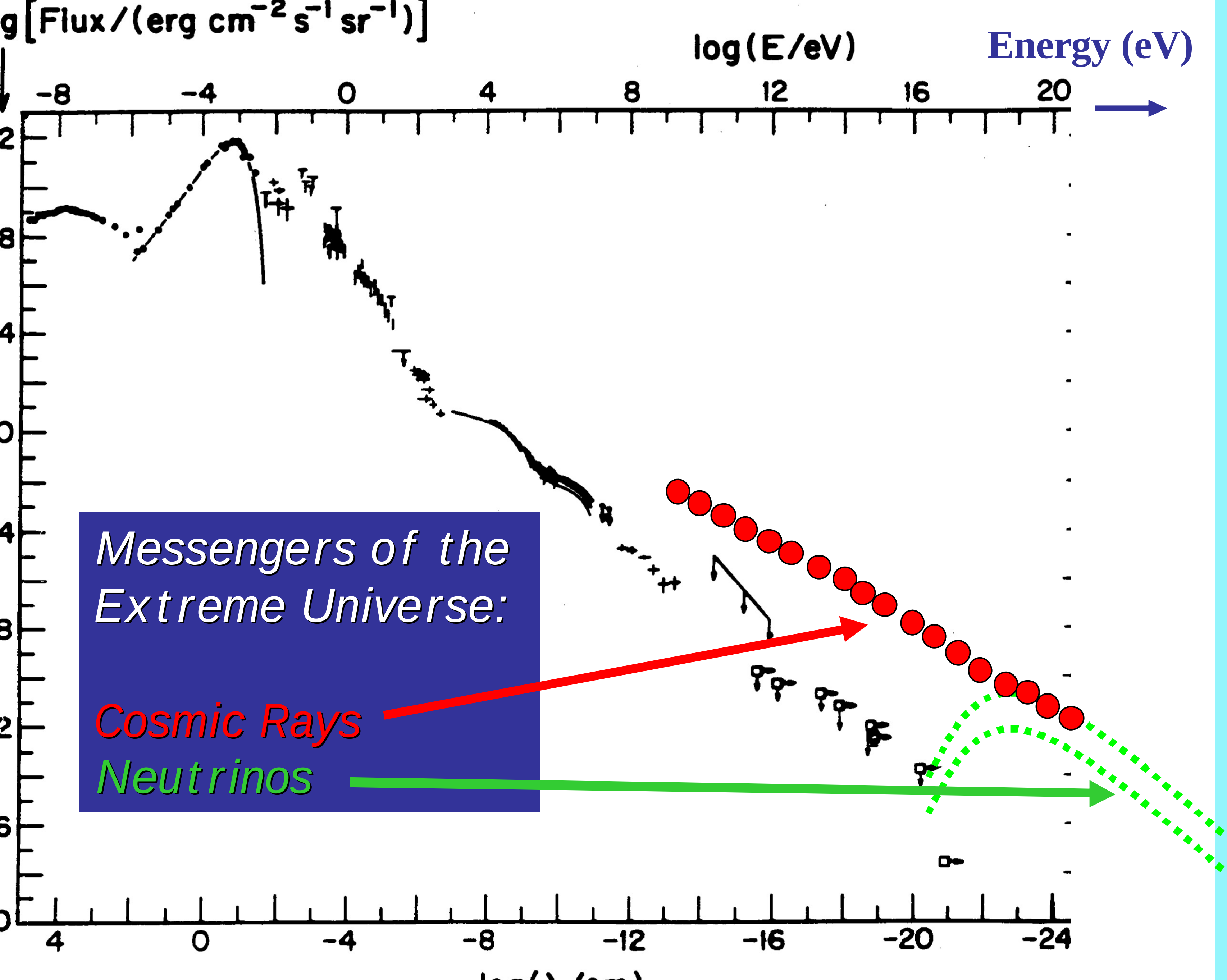


Con lo studio dei raggi cosmici nasce la fisica delle particelle elementari

	1927	Raggi cosmici misurati in camere a bolle
Anderson scopre l'antimateria	**1932**	
	1937	Scoperta del muone
Auger scopre gli sciami estesi	**1938**	
	1946	Primi esperimenti sugli EAS
eoria di Fermi sui raggi cosmici	**1949**	
	1962	Scoperto il primo evento a $E = 10^{20}$ eV
Proposta dell'effetto GZK	**1966**	
	1991	Scoperto il primo evento a Fly's Eye
Eventi EECR visti in Agasa	**1994**	
	1995	Parte il progetto Auger
Parte il progetto EUSO	**1997**	

Table 1. Discovery of elementary particles

Particle	Year	Discoverer (Nobel Prize)	Method
e^-	1897	Thomson (1906)	Discharges in gases
p	1919	Rutherford	Natural radioactivity
n	1932	Chadwik (1935)	Natural radioactivity
e^+	1933	Anderson (1936)	Cosmic Rays
$\mu^\pm$	1937	Neddermeyer, Anderson	Cosmic Rays
$\pi^\pm$	1947	Powell (1950) , Occhialini	Cosmic Rays
$K^\pm$	1949	Powell (1950)	Cosmic Rays
π^0	1949	Bjorklund	Accelerator
K^0	1951	Armenteros	Cosmic Rays
Λ^0	1951	Armenteros	Cosmic Rays
Δ	1932	Anderson	Cosmic Rays
Ξ^-	1932	Armenteros	Cosmic Rays
$\Sigma^\pm$	1953	Bonetti	Cosmic Rays
p^-	1955	Chamberlain, Segre' (1959)	Accelerators
anything else	1955 $\Longrightarrow$ today	various groups	Accelerators
$m_\nu \neq 0$	2000	KAMIOKANDE	Cosmic rays

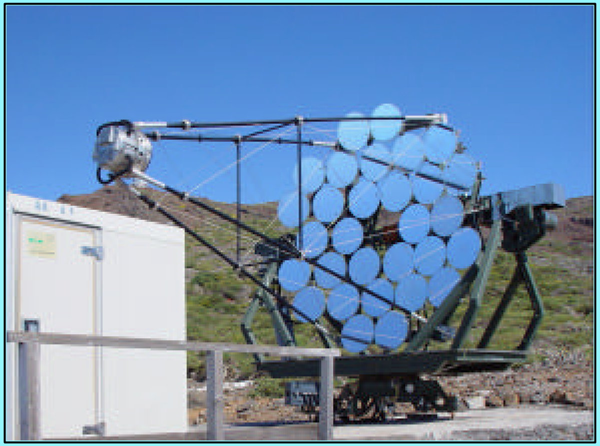

g[Flux/(erg cm^-2 s^-1 sr^-1)]
log(E/eV)
Energy (eV)
-8 -4 0 4 8 12 16 20
4 0 -4 -8 -12 -16 -20 -24
Messengers of the Extreme Universe:
Cosmic Rays
Neutrinos

Progress in Cerenkov technique

Observation time necessary to detect the CRAB Nebula TeV signal:

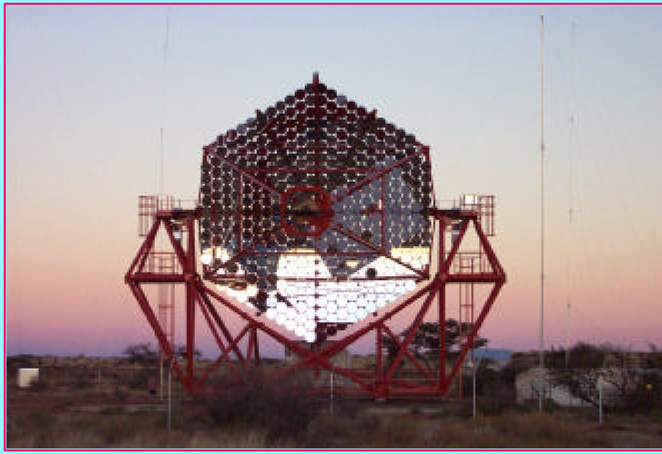
Whipple, 1989

50 h



HEGRA, 1997

15 m



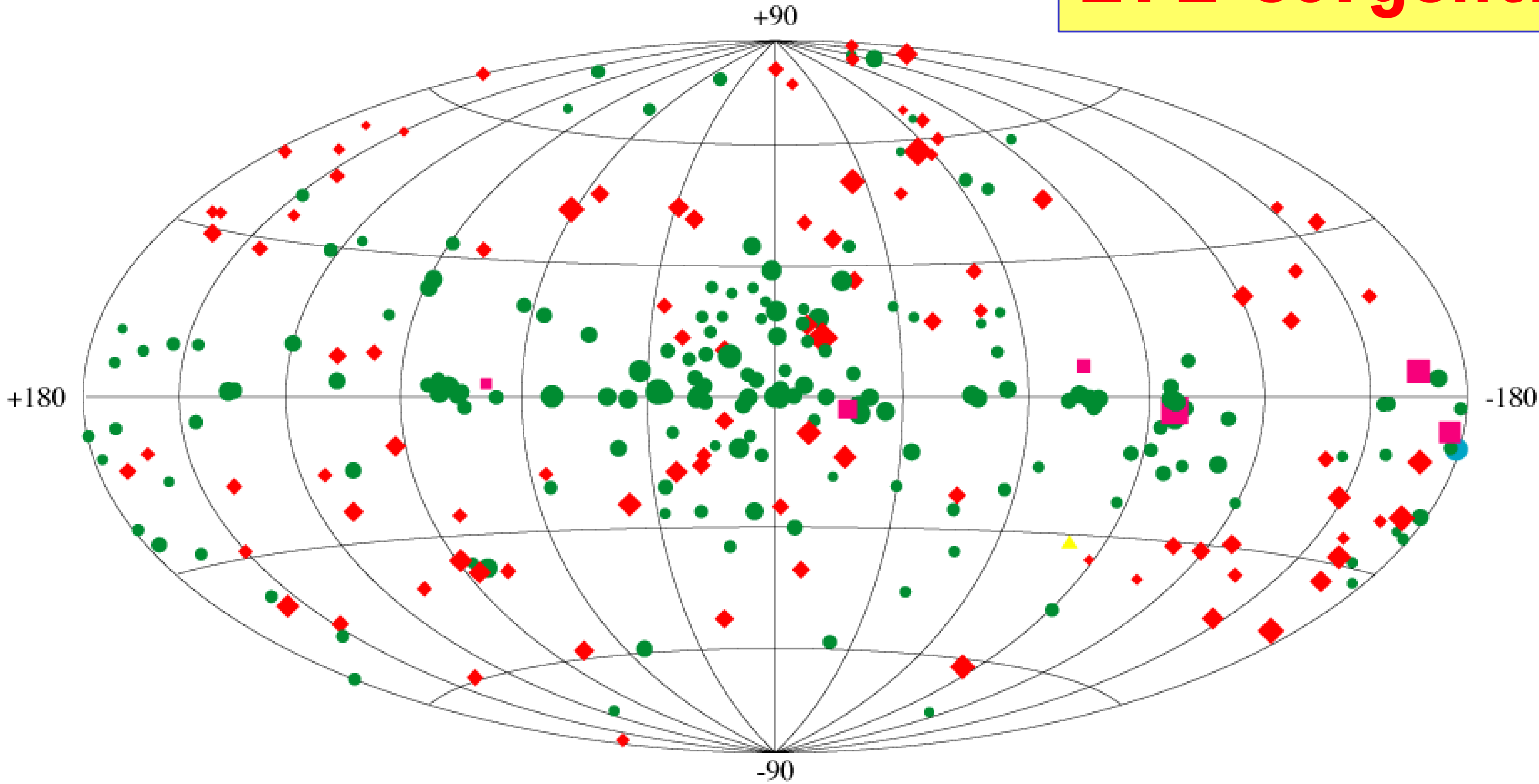
HESS, 2004

30 s !!!!

Third EGRET Catalog

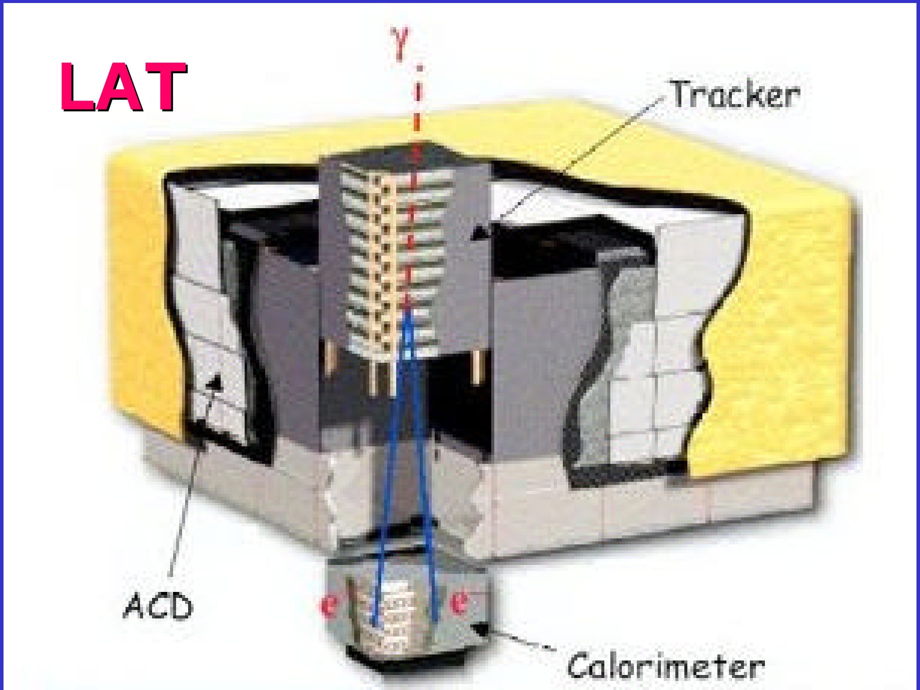
E > 100 MeV

271 sorgenti



- Active Galactic Nuclei **94**
- Unidentified EGRET Sources **170**
- Pulsars **6**
- LMC
- Solar FLare

GLAST
Gamma ray Large Area Space Telescope



50 times more sensitive that EGRET at 100 MeV

Launch in Feb 2007

- **Large Area Telescope (LAT)**
  - 16 Tracker Modules (silicon-strip detector)
  - Calorimeter
  - Anti coicidence detector

  20 MeV < E < 300 GeV

  field of view » 2.5 sr
- **Burst Monitor**

  10 KeV < E < 25 MeV

  field of view: 8 sr

nuove finestre,...nuove scoperte

Telescope	User	date	Intended Use	Actual use
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, noise	3K cosmic background
X-ray	Giacconi …	1965	Sun, moon	neutron stars accreting binaries
Radio	Hewish, Bell	1967	Ionosphere	Pulsars
g-rays	military	1960?	Thermonuclear explosions	Gamma ray bursts

raggi cosmici

Charged particles from the cosmos

- Protons, α-particles, heavier nuclei
- No significant anisotropy seen
  ("well stirred" by Galactic magnetic field)
- Energies above 10^{10} eV are from our Galaxy

(note: TV or PC monitor uses 10^3 eV electron beam)

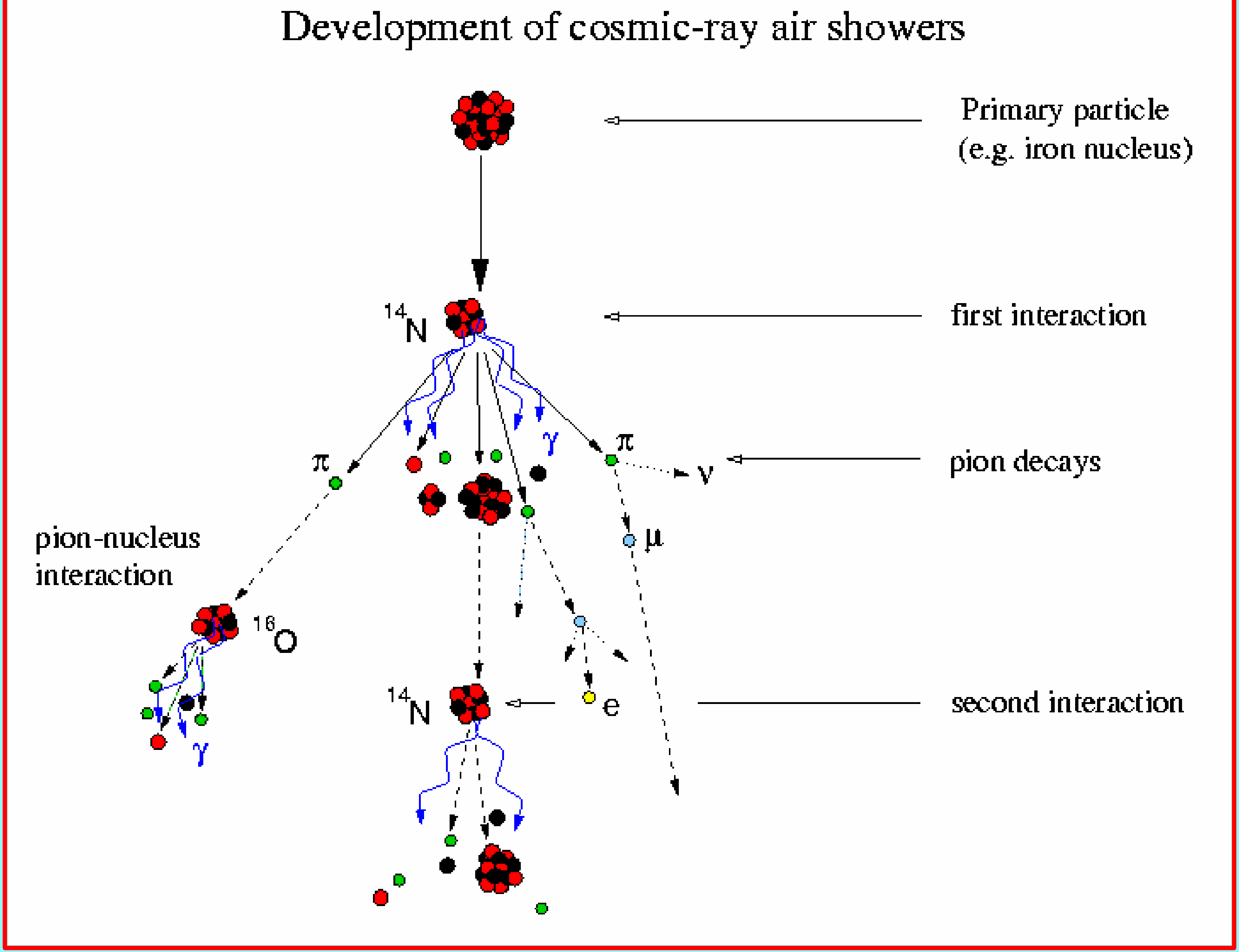
- Energies above 10^{18} eV are extra-galactic
- Intensity drops sharply with E (like $E^{-2.7}$):

Energy	Rate of arrival
10^{10} eV	1000 per m^2 per sec
10^{12} eV	1 per m^2 per sec
10^{15} eV	1000 per m^2 per year
10^{19} eV	1 per kilometer^2 per year

Highest energy seen is ~10^{20} eV, about 50 joules
(energy of a 50 mph baseball in one proton!)

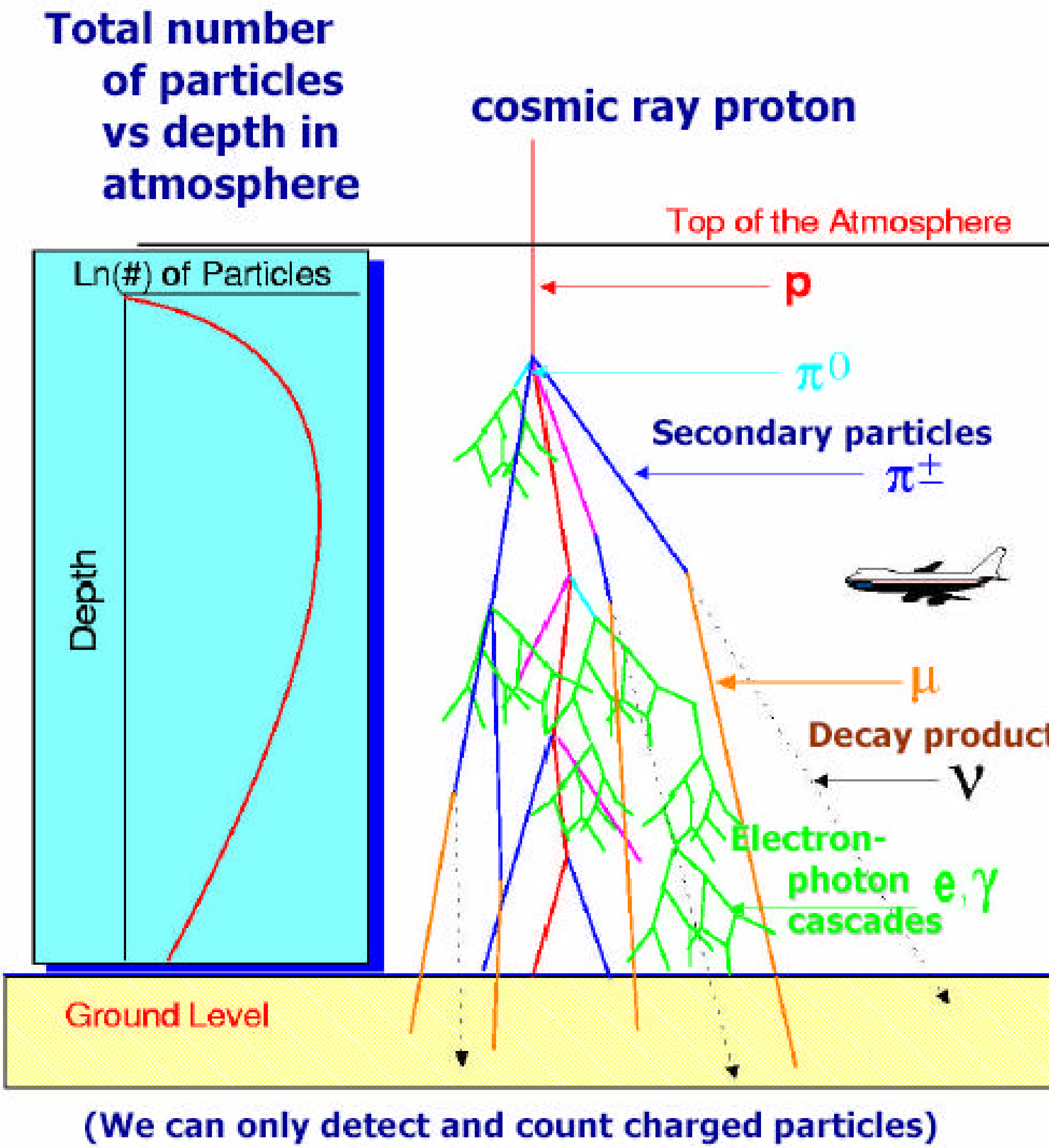
Many open questions:

- How/where are cosmic rays made?
- What process accelerates them to such enormous energies?
  - Supernova shocks?
  - Compact binary systems?
  - Active Galactic Nuclei?
- Why don't the highest energy cosmic ray point back to something interesting?
- Why are there kinks in the cosmic ray energy spectrum?
  - the knee at 10^{15} eV (1 PeV)
  - the ankle at 10^{19} eV (10 EeV)
  - the toe (?) at 10^{21} eV (1 XeV)
- How can the highest energy cosmic rays (>10^{20} eV) ever reach us?
  - GZK cutoff should stop them


Development of cosmic-ray air showers
Primary particle
(e.g. iron nucleus)
14N
first interaction
π
γ
π
ν
pion decays
μ
pion-nucleus
interaction
16O
14N
e
second interaction
γ

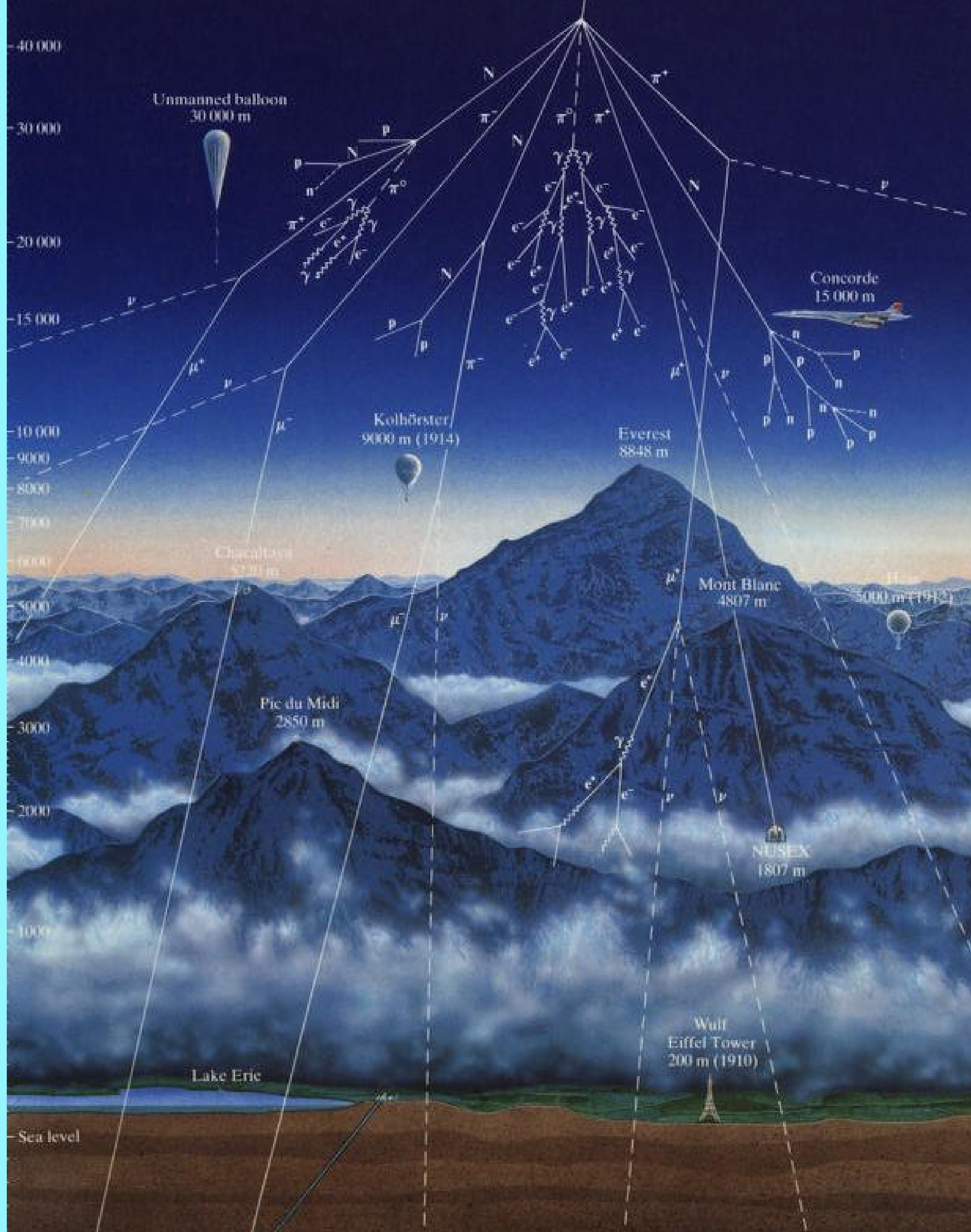
Raggi cosmici:

un legame tra astrofisica, cosmologia e fisica delle particelle elementari



P.Galeotti

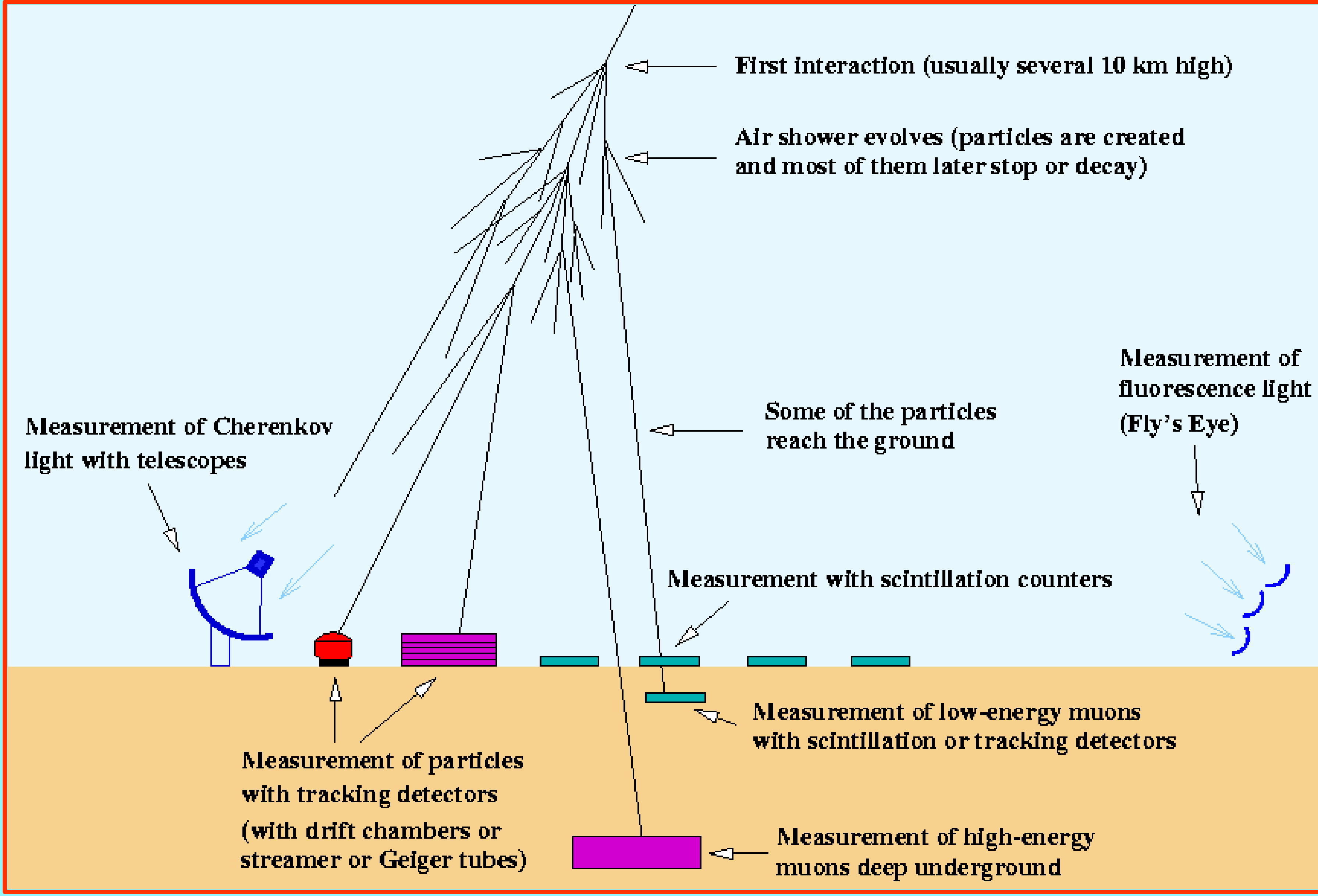
solo m e n riescono a penetrare a grande profondità sotoroccia



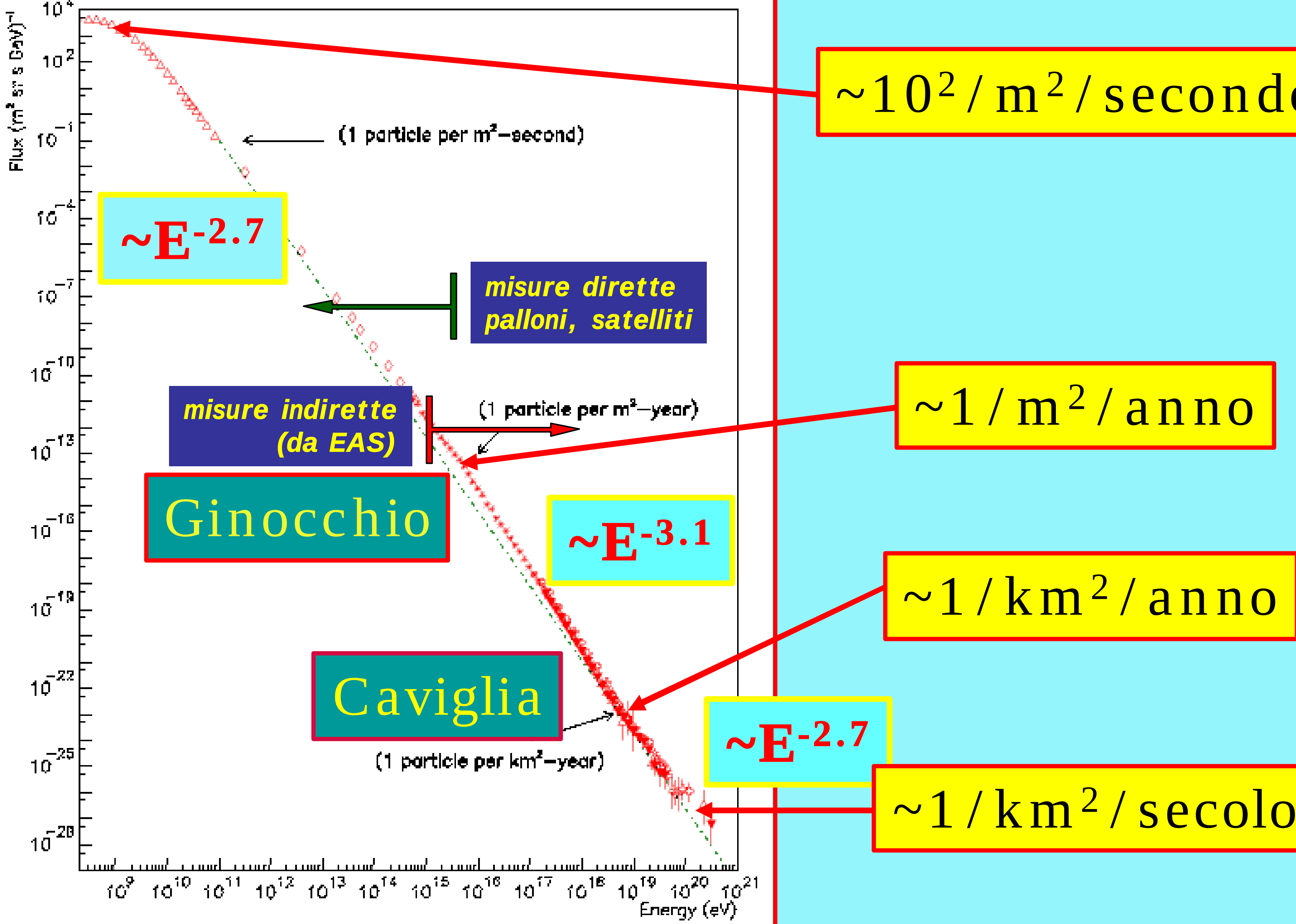
P.Galeotti

Deduce character of the original cosmic ray from shower observations on the ground:

- Number of particles in shower is related to energy of primary cosmic ray
- Average direction of shower particles is direction of primary cosmic ray
- Proportion of muons in the shower is related to type of cosmic ray (proton, nucleus or gamma ray)



First interaction (usually several 10 km high)
Air shower evolves (particles are created and most of them later stop or decay)
Some of the particles reach the ground
Measurement of fluorescence light (Fly's Eye)
Measurement of Cherenkov light with telescopes
Measurement with scintillation counters
Measurement of low-energy muons with scintillation or tracking detectors
Measurement of particles with tracking detectors (with drift chambers or streamer or Geiger tubes)
Measurement of high-energy muons deep underground


~10^2 / m^2 / secondo
(1 particle per m²–second)
~E^-2.7
misure dirette
palloni, satelliti
misure indirette
(da EAS)
~1 / m^2 / anno
(1 particle per m²–year)
Ginocchio
~E^-3.1
~1 / km^2 / anno
Caviglia
(1 particle per km²–year)
~E^-2.7
~1 / km^2 / secolo
Flux (m² sr s GeV)⁻¹
Energy (eV)

Exposure SΩT= m^2-steradian-days

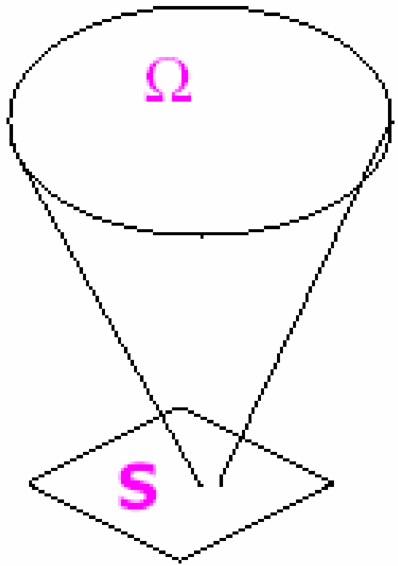
Rate of arrival at highest energies:

about 1 particle per 2 km^2-sr-*year*

for energy > 10^{19} eV

To detect high energy cosmic rays, we need lots of exposure:

- Large collecting area S
- Large solid-angle acceptance Ω
- Large collecting time T

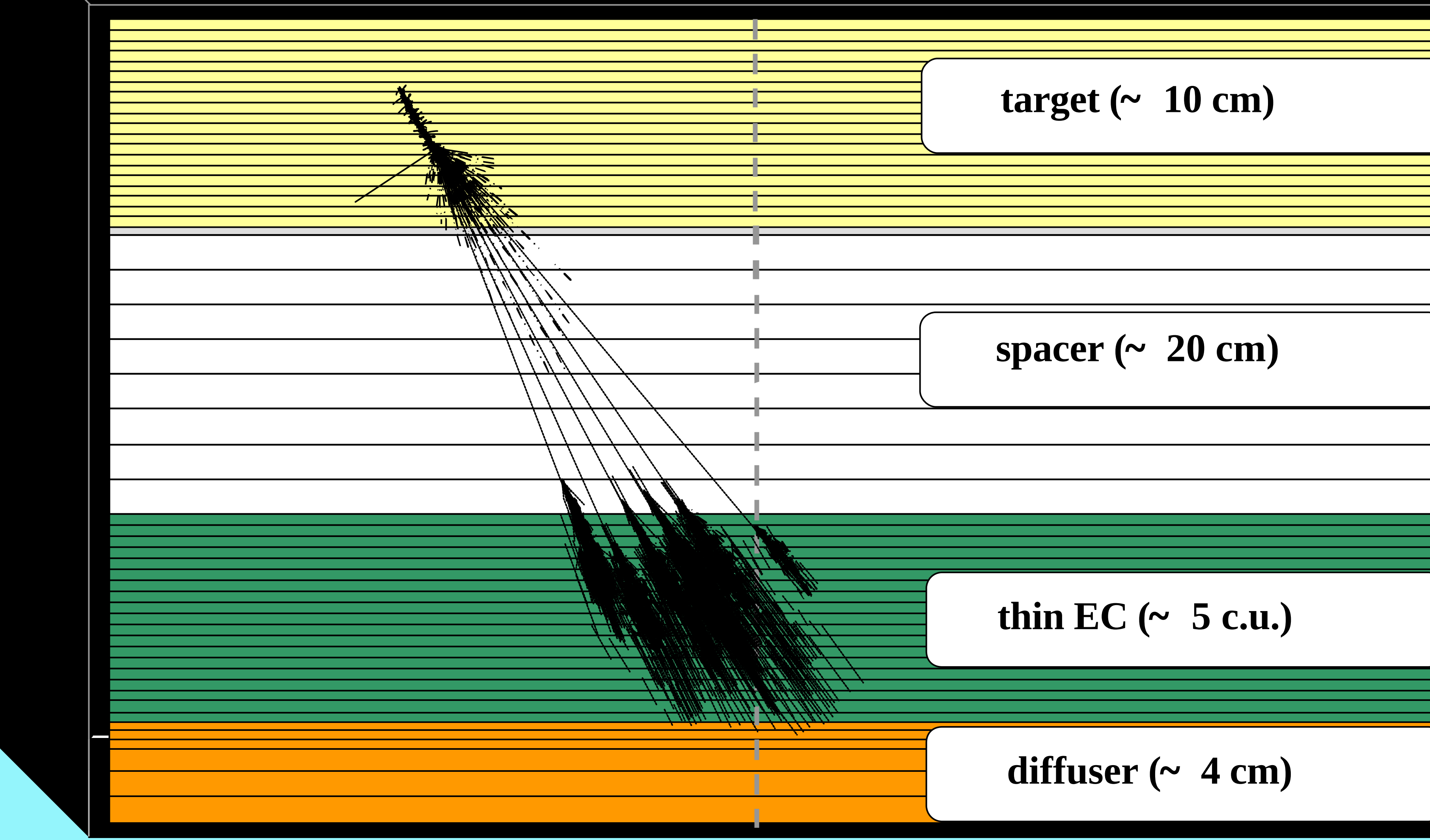


Typical direct observations

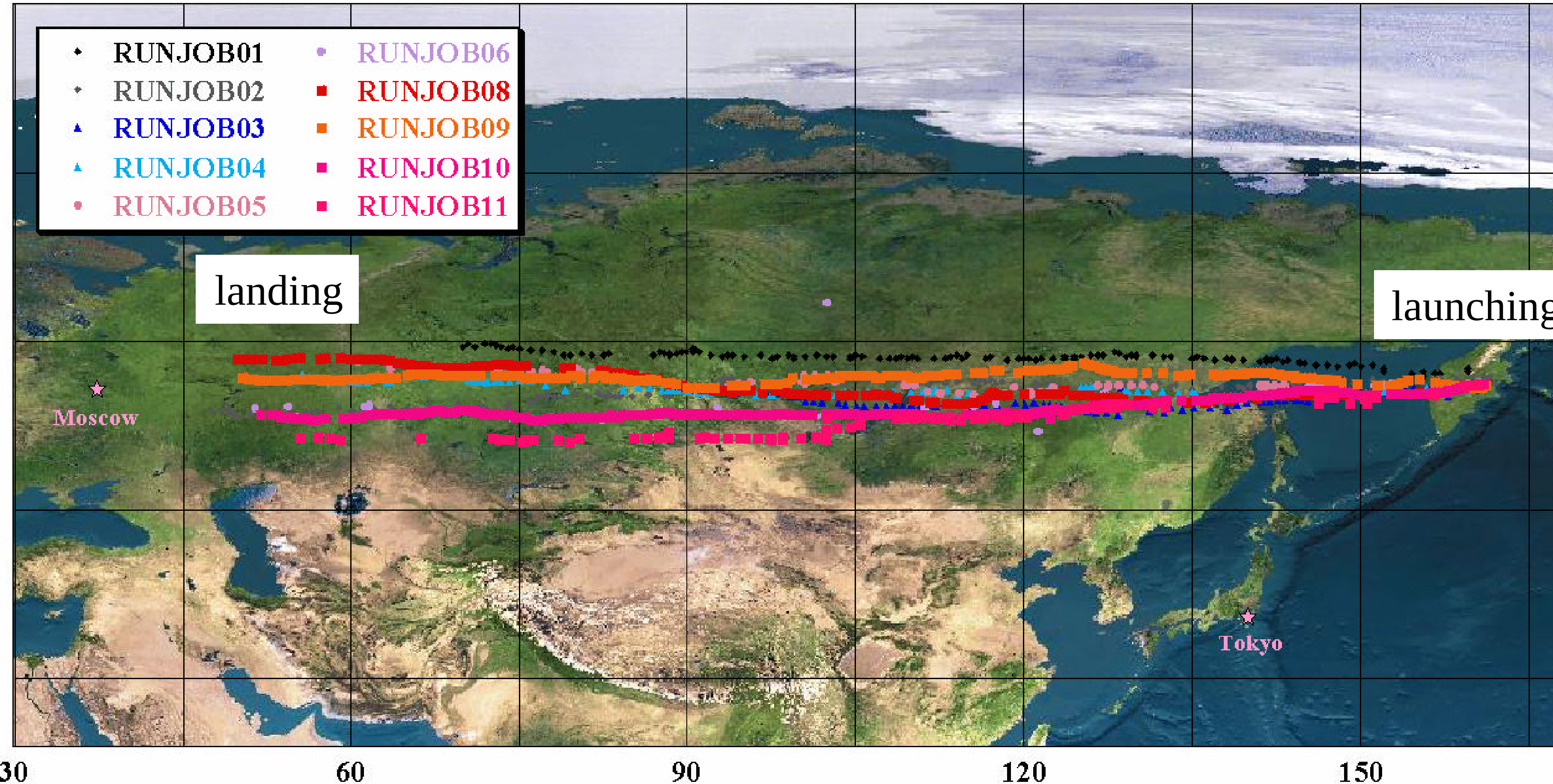
Experiment	Observables	Energy
JACEE(1979-1995)	p, He, …, Fe;	TeV - PeV
RUNJOB(1995-1999)	p, He, …, Fe;	TeV - PeV
	ultra-heavy (Z ? 30);	1-10 GeV/n
ATIC(2001-2002)	p, He, …, Fe;	10 GeV-100 TeV
BESS(1993, -)	p, He;	1-500 GeV
	anti-p, anti-He, $e^{\pm}$;	.1-10 GeV
AMS(1999,..)	p, He, C, …, Fe(?);	1 GeV-1 TeV
	anti-p, anti-He, anti-C, $e^{\pm}$;	.1-10 GeV

RUNJOB experiments

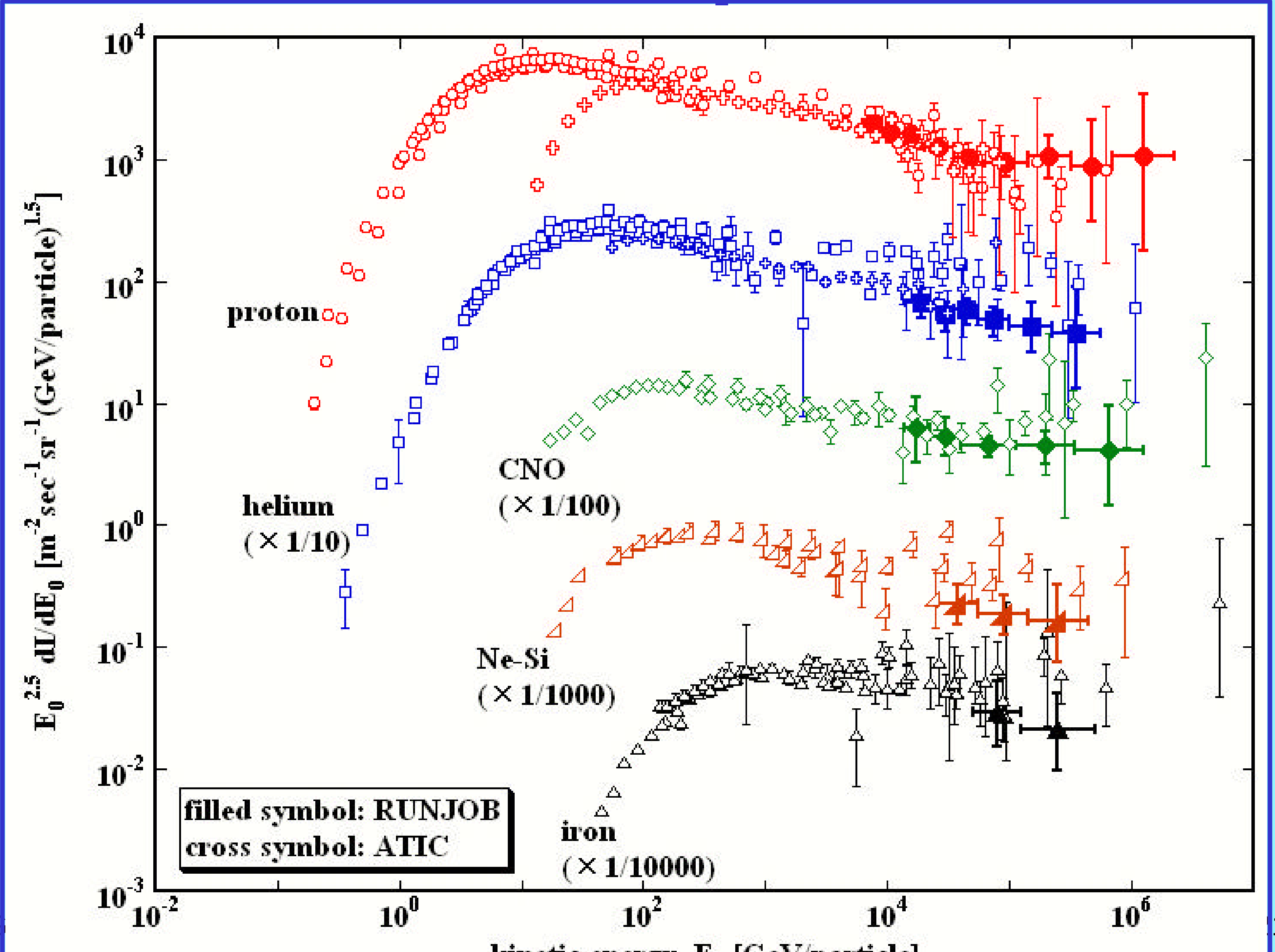
RUNJOB detector



Balloon Trajectory



individual spectra



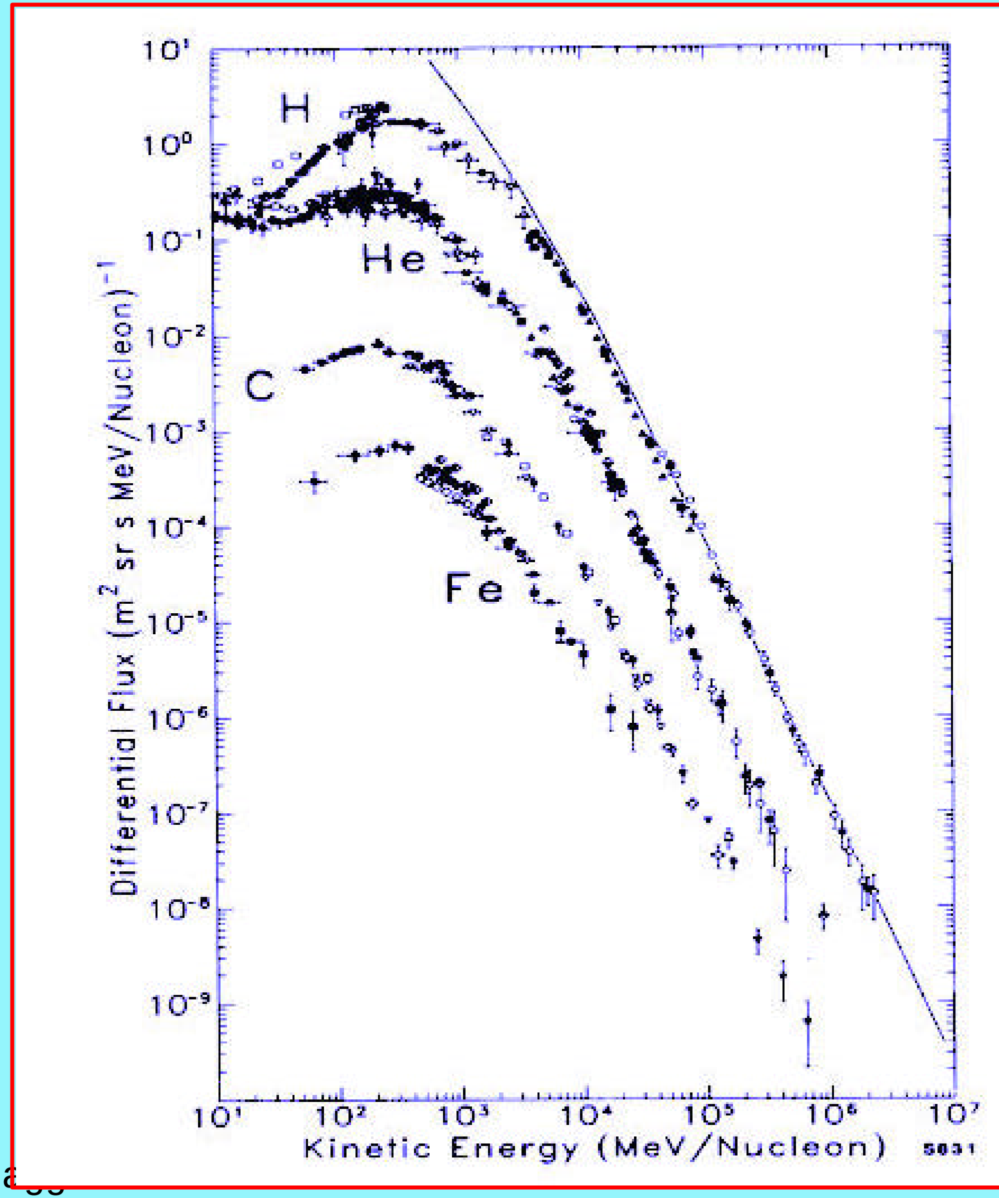
The Primary Cosmic Ray Flux

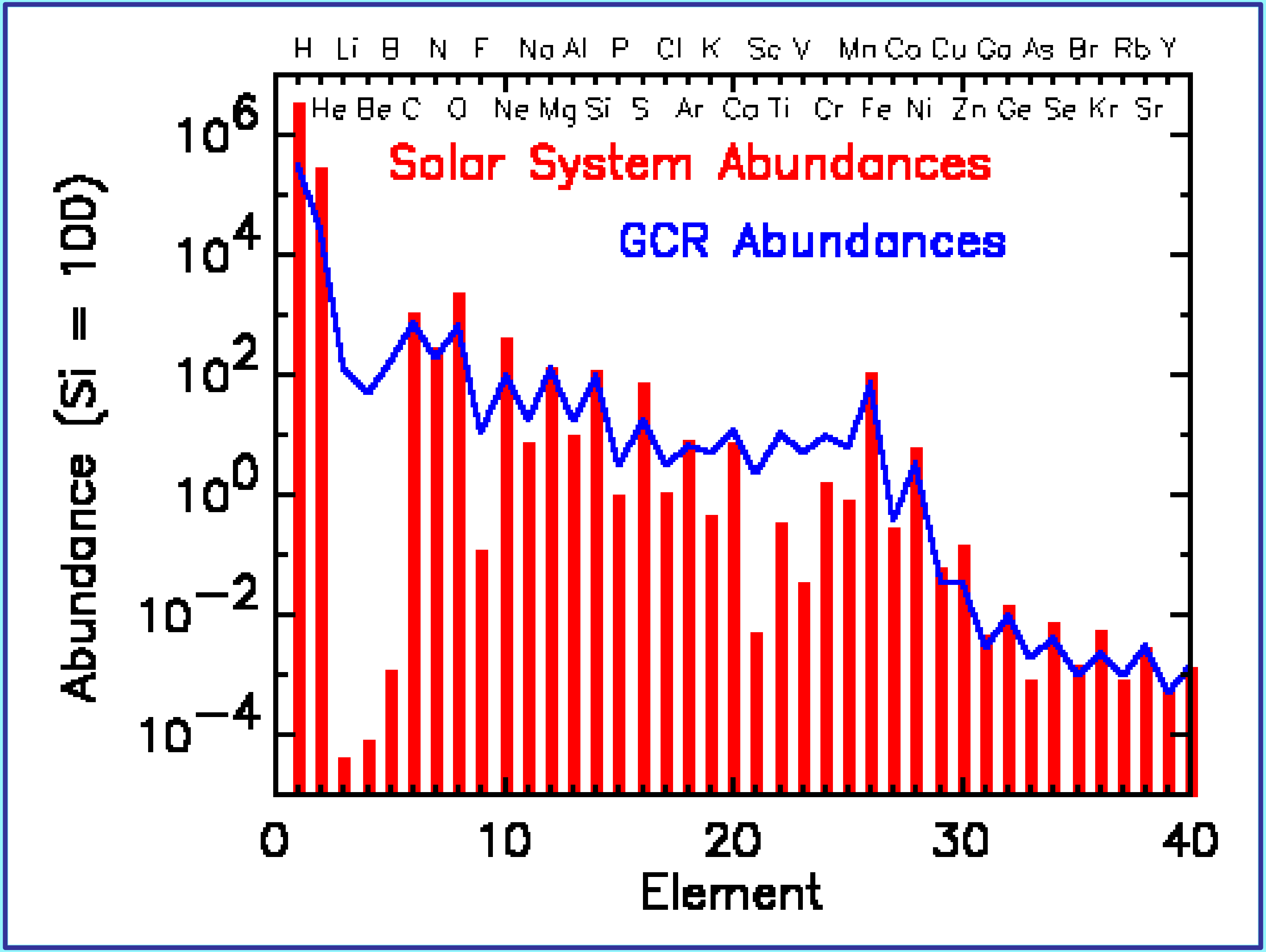
IISURE DIRETTE

nterstellar fluxes

olar modulation

eomagnetic effects

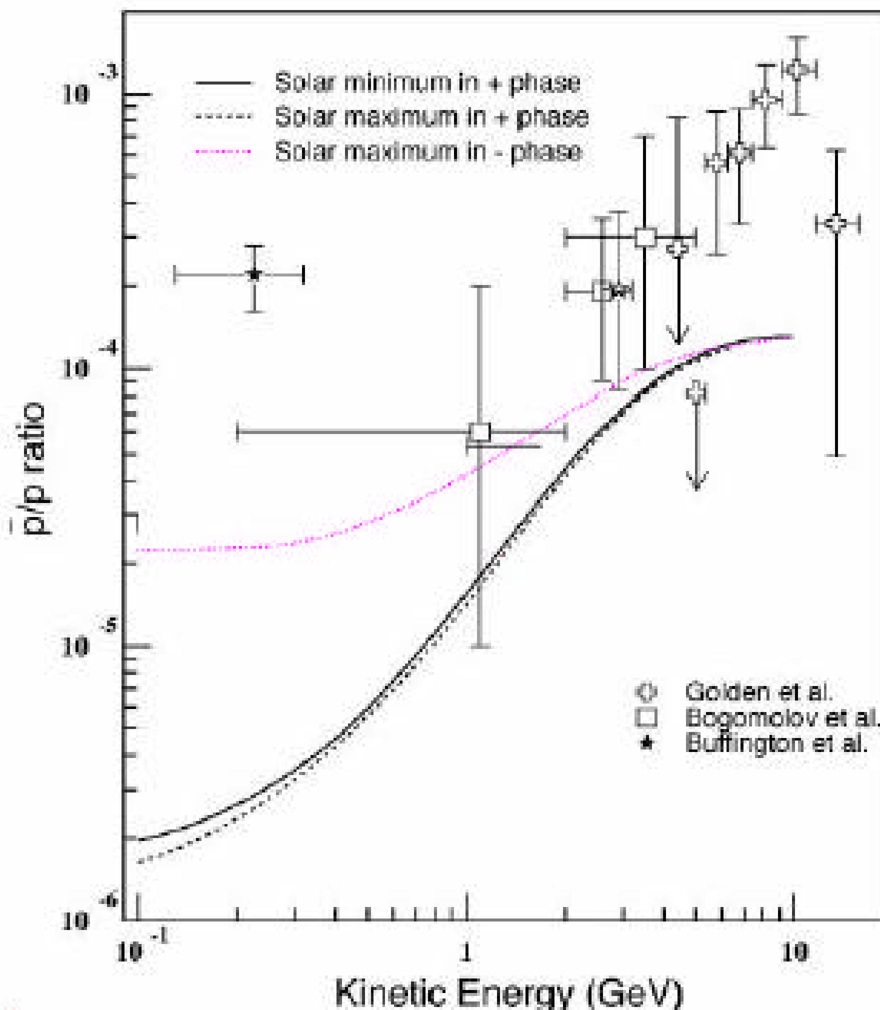



H Li B N F Na Al P Cl K Sc V Mn Co Cu Ga As Br Rb Y
He Be C O Ne Mg Si S Ar Ca Ti Cr Fe Ni Zn Ge Se Kr Sr
Solar System Abundances
GCR Abundances
Abundance (Si = 100)
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
0
10
20
30
40
Element

History of the Search for Cosmic-ray Antiprotons

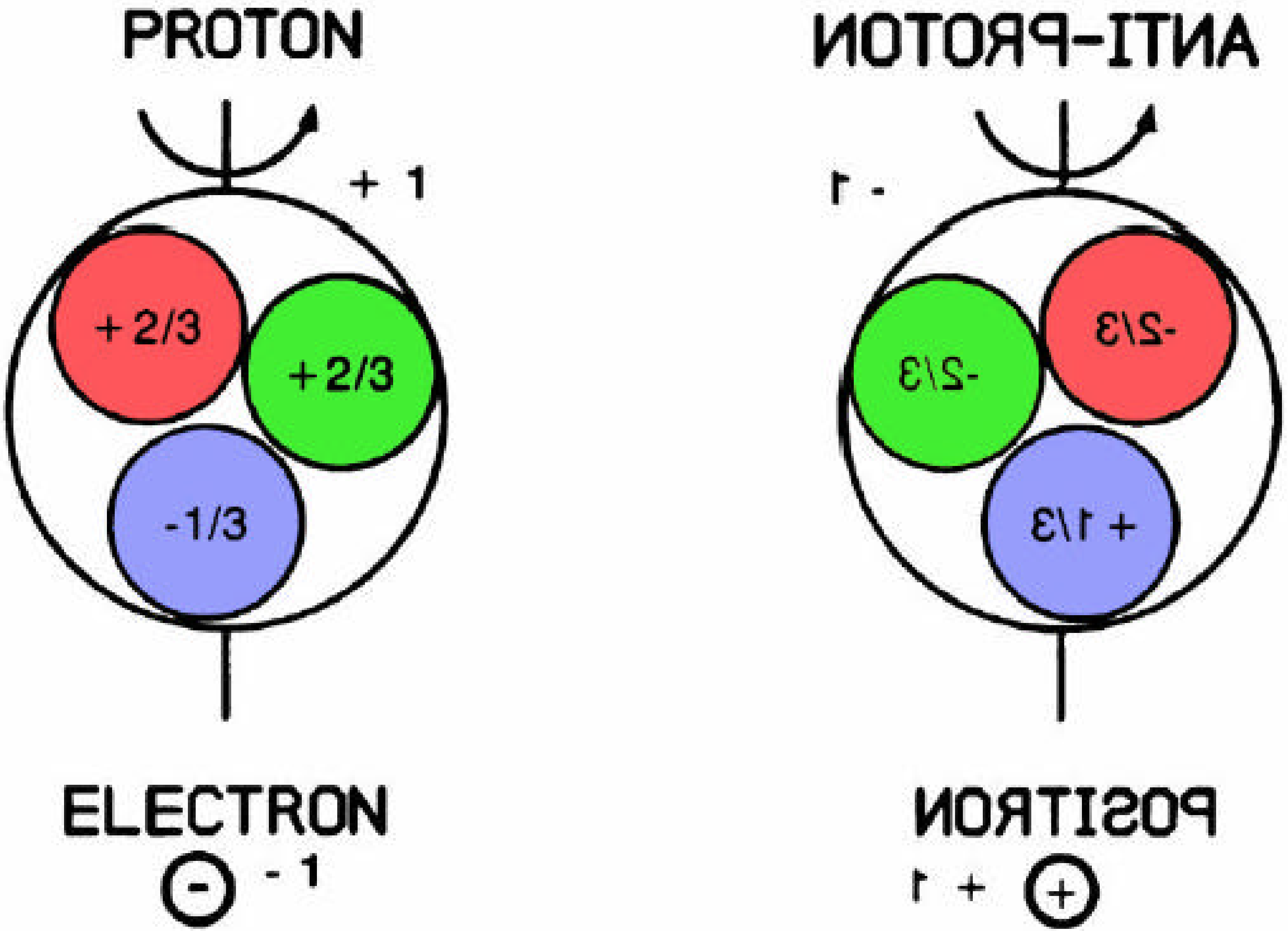
1960s: L. Alvarez et al. Balloons & HEAO
1979: First claimed observations
(Bogomolov et al. and Golden et al.)
1981: Low-energy excess (Buffington et al.)
1985: ASTROMAG Study Started
1987: LEAP, PBAR (upper limits)
1991: MASS
1992: IMAX (16 mass-resolved antiprotons)
1993: BESS (6 antiprotons), TS93
1994: CAPRICE94, HEAT-e±
1996-7: BESS series to Solar minimum
1998: CAPRICE98, AMS-01
2000: BESS 99-00, HEAT-pbar
2004-5: BESS-Polar, PAMELA
2006: BESS-Polar
2007: Solar minimum
2007-8: AMS-02

Antiproton measurements, ca 1980
Disagreement with "theory"

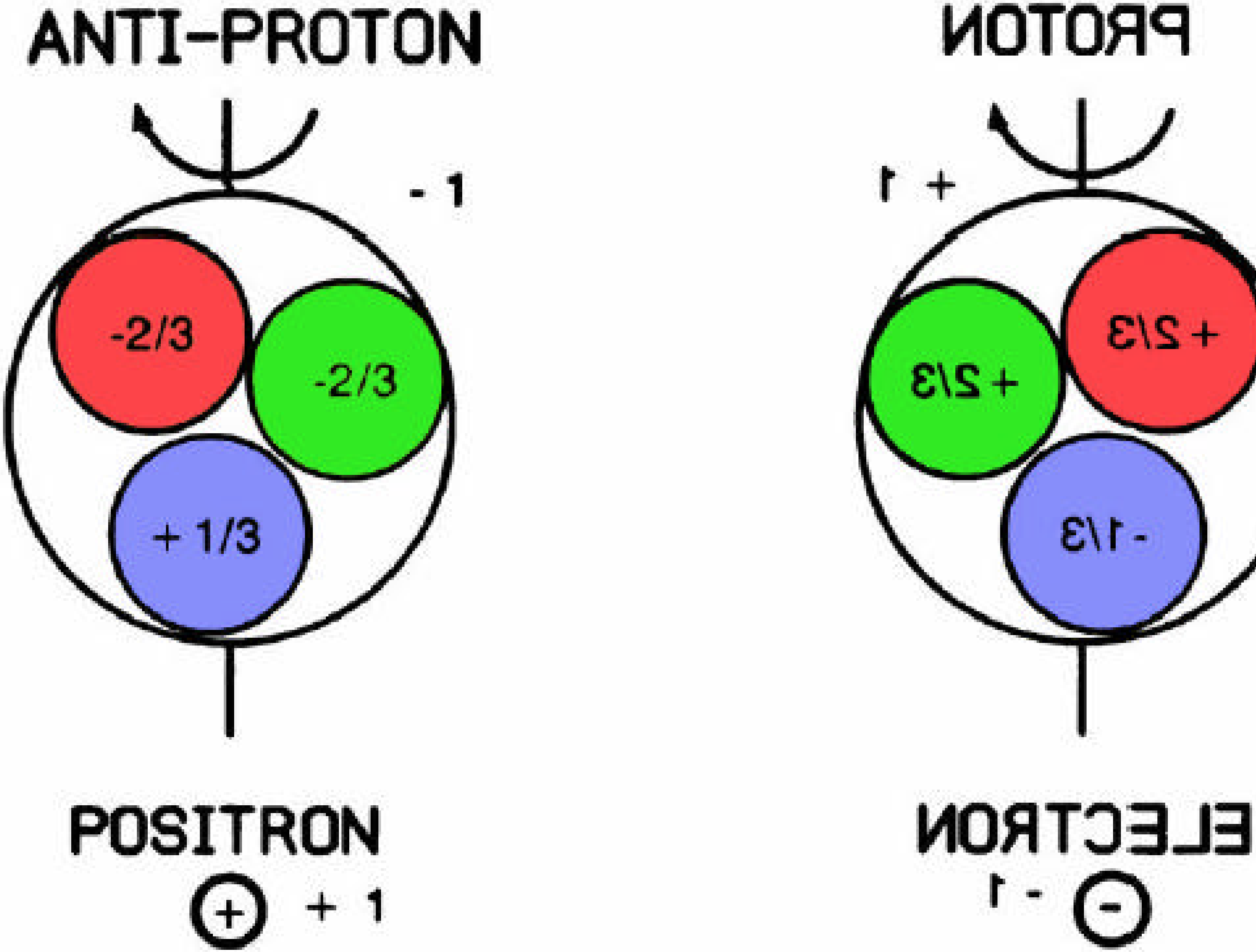


Prepared with R. E. Streitmatter

Matter



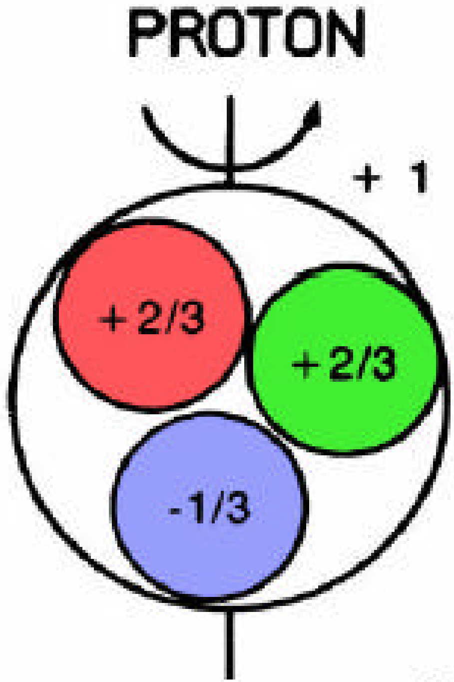
Antimatter



CP violation: BaBar result B^0 and $\overline{B}^0$ mesons

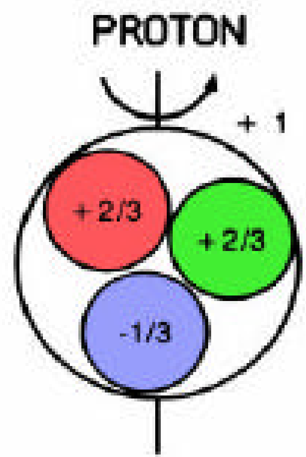
$$B^0 \rightarrow K^+ + \pi^- \qquad 910$$

$$\overline{B}^0 \rightarrow K^- + \pi^+ \qquad 696$$



We still don't understand fully how the matter dominated Universe we live in has evolved. However this new result … greatly advanced our understanding… There is still much to discover and learn on this fundamental issue.

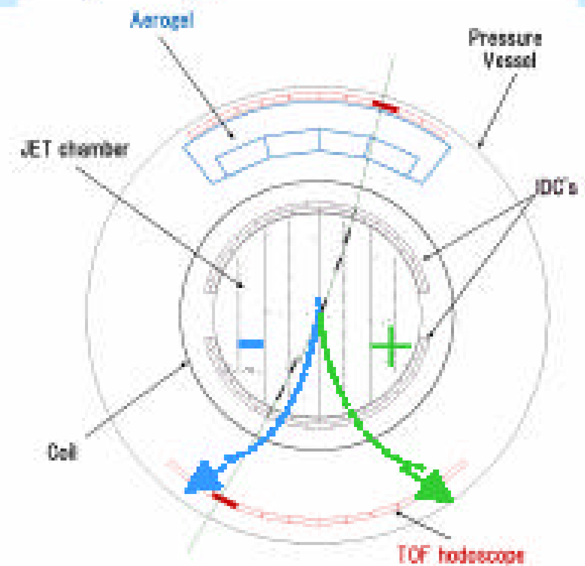
Ian Halliday 2 Aug. 2004



Measurement Technique

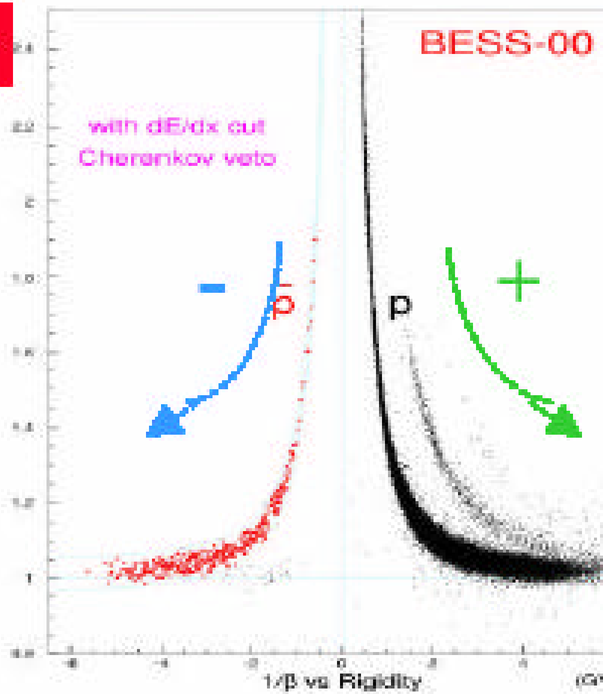
Particle identification by mass and charge

Charge-sign from deflection direction



Warm bore solenoid
B~1 Tesla +/-3%
Drift chambers
dx~150microns

β^{-1}



Rigidity
(R = pA/Ze)

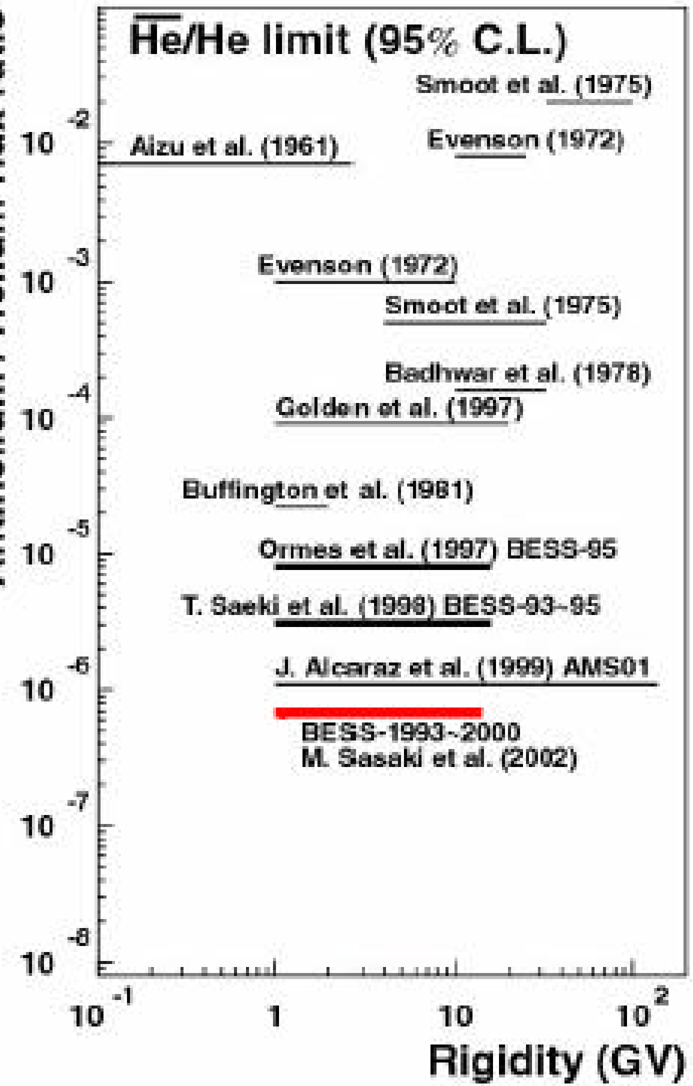
Superconducting magnetic-rigidity spectrometer (B~1Tesla)
- measures momentum per unit charge or rigidity (pA/Ze)

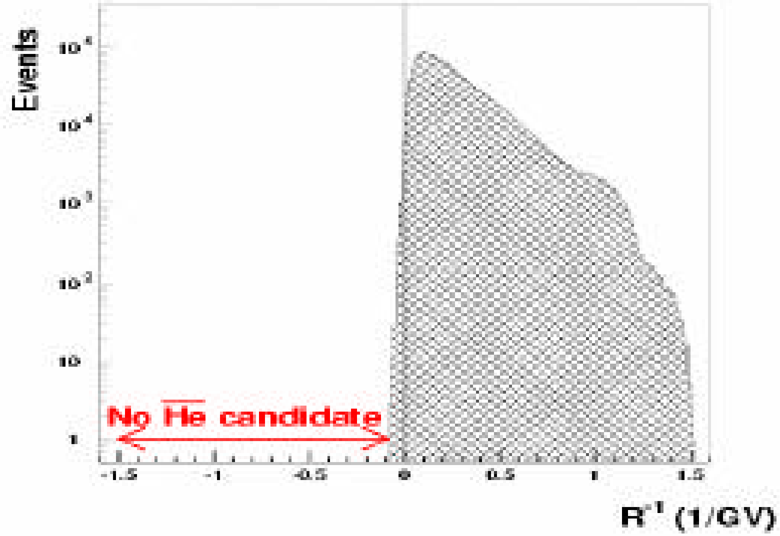
Precision time-of-flight system: measures velocity and charge

Silica-aerogel Cherenkov detector: background rejection

$$m = \frac{RZe}{\gamma\beta c}$$

Searching for antihelium



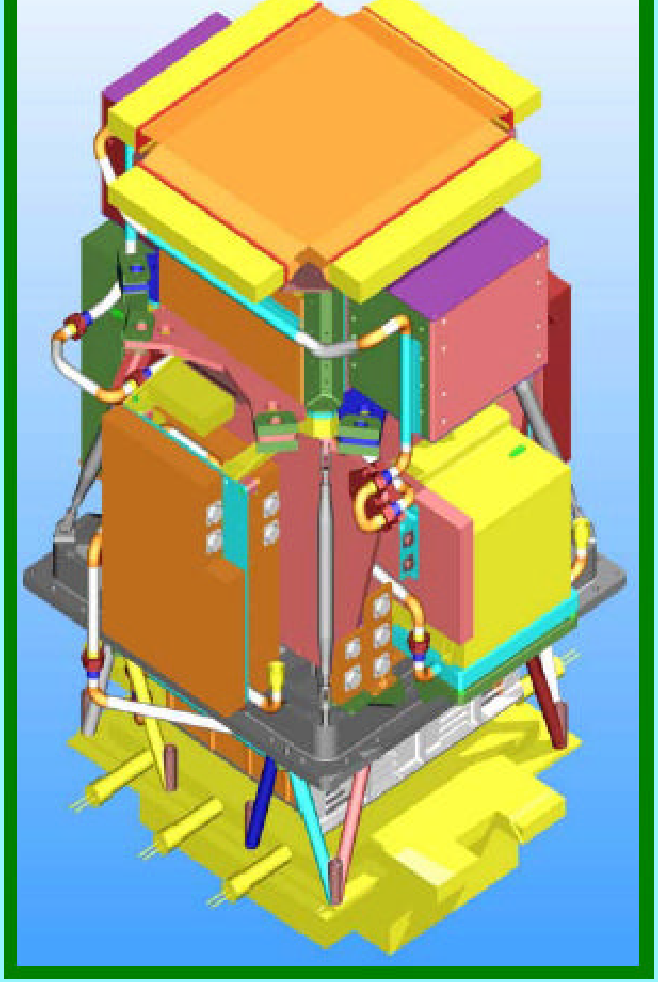


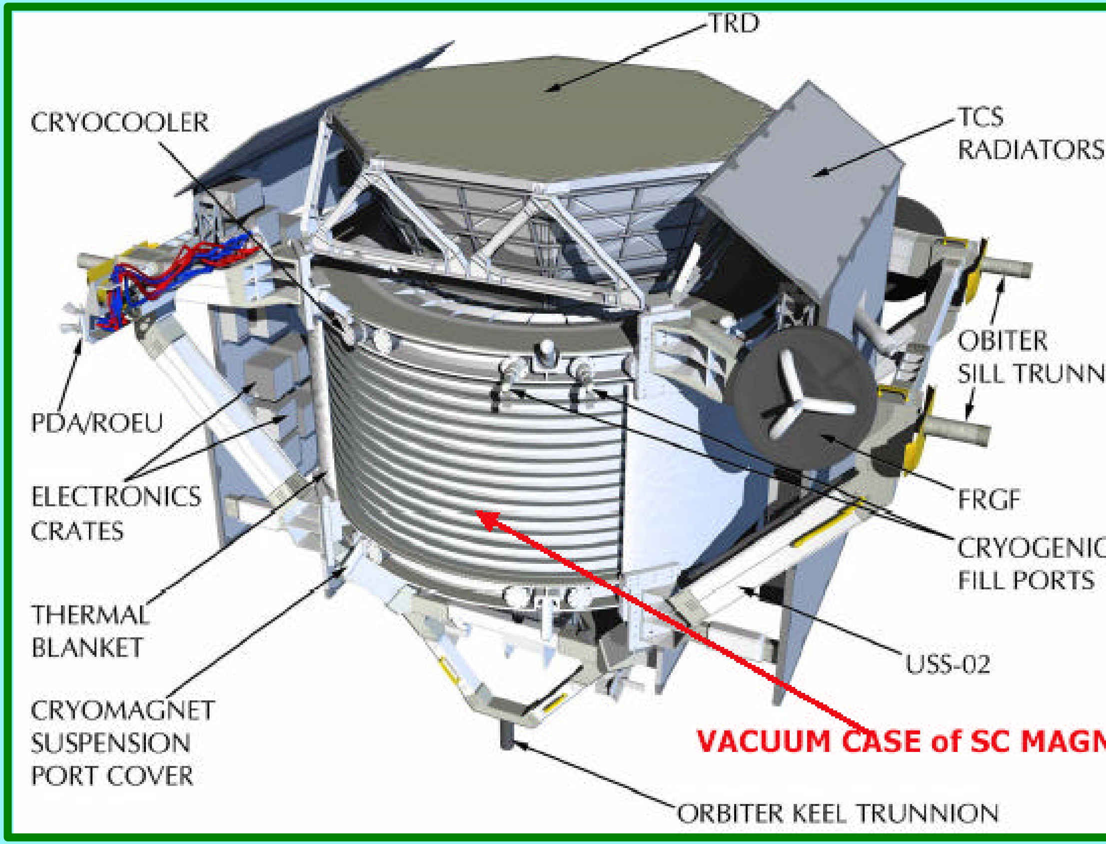
- Unlike antiprotons, anti-helium cannot be produced by collisions in the interstellar gas above the level 10^{-13} or so.

- These 90% confidence limits on the ratio of anti-helium/helium in cosmic rays have been going down by about 2 orders of magnitude pe decade. They are now below 10^{-6} and will be pushed to 10^{-7} by BESS-Polar flights.

- AMS is expected to reach ~ 10^{-9}.

Pamela e AMS

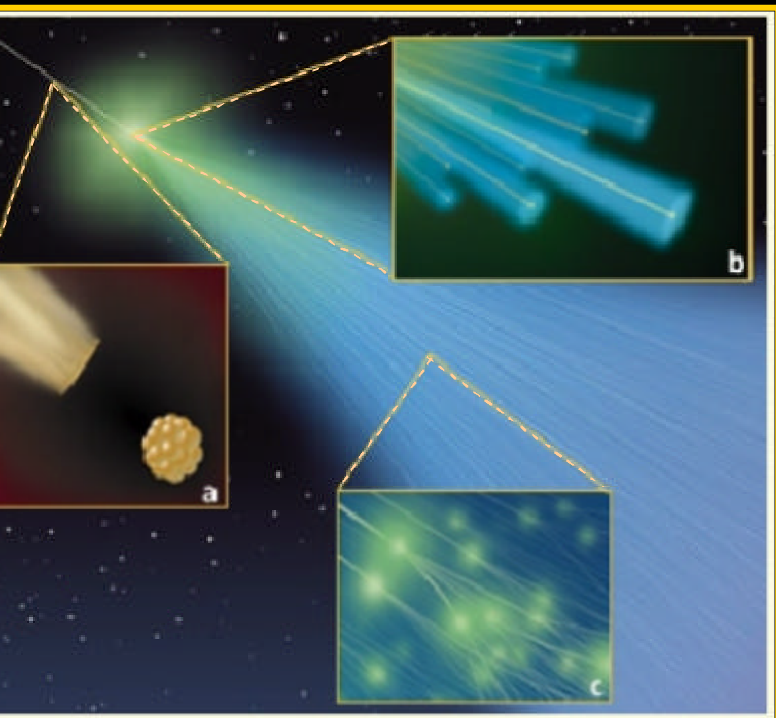




- $\bar{p}$: 80 MeV ÷ 190 GeV
- e^+: 50 MeV ÷ 270 GeV
- $\overline{He}$/He: some unity 10^{-7}
- nuclei spectra (H to O) 100 MeV/n ÷ 200 GeV/n

AMS will search for extraterrestrial p^+,e^-,γ; antimatter nuclei (anti-He, C, 10^{-9}); light isotopes;

… e lo sciame esteso (EAS, Extensive Air Shower) ?



Quando attraversa l'atmosfera terrestre

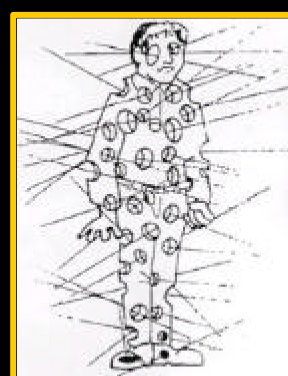
a) il raggio cosmico (particella primaria) collide con i nuclei dell'aria provocando una

b) cascata di particelle secondarie di energia più bassa, che a loro volta

c) subiscono ulteriori collisioni producendo così uno sciame di miliardi e più di particelle che raggiungono il suolo terrestre in un'area la cui estensione può essere anche di diversi chilometri quadrati.

ltre cento particelle secondarie di sciame traversano il nostro corpo ogni secondo ! .. e l'esposizione aumenta con l'altitudine

(i raggi cosmici sono di grande importanza in biologia; ontribuendo, a lungo andare, alle mutazioni genetiche, anno giocato e continuano a giocare un ruolo rilevante nell'evoluzione della vita sulla Terra)



Gli sciami EAS contengono di tutto

- nucleoni, nuclei,
- gamma duri,
- mesoni ($\pi^\pm$,π^0,$K^\pm$, …),
- leptoni carichi ($e^\pm$, $\mu^\pm$, $\tau^\pm$),
- neutrini (ν_e, ν_μ, ν_τ).
- …

MISURE INDIRETTE

Le tecniche indirette misurano i prodotti secondari dell'interazione dei raggi cosmici in atmosfera.

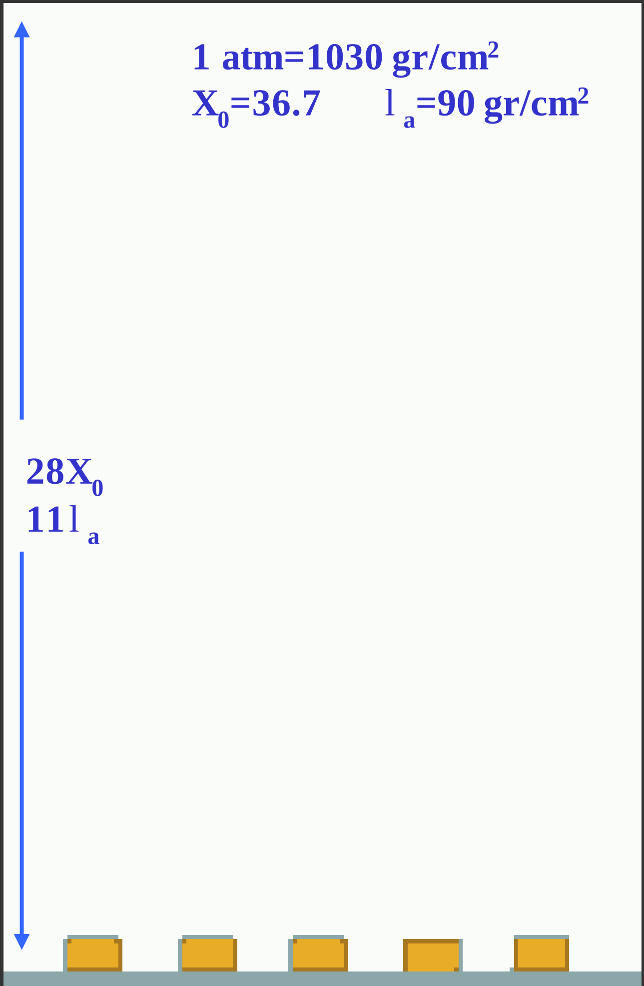
EAS

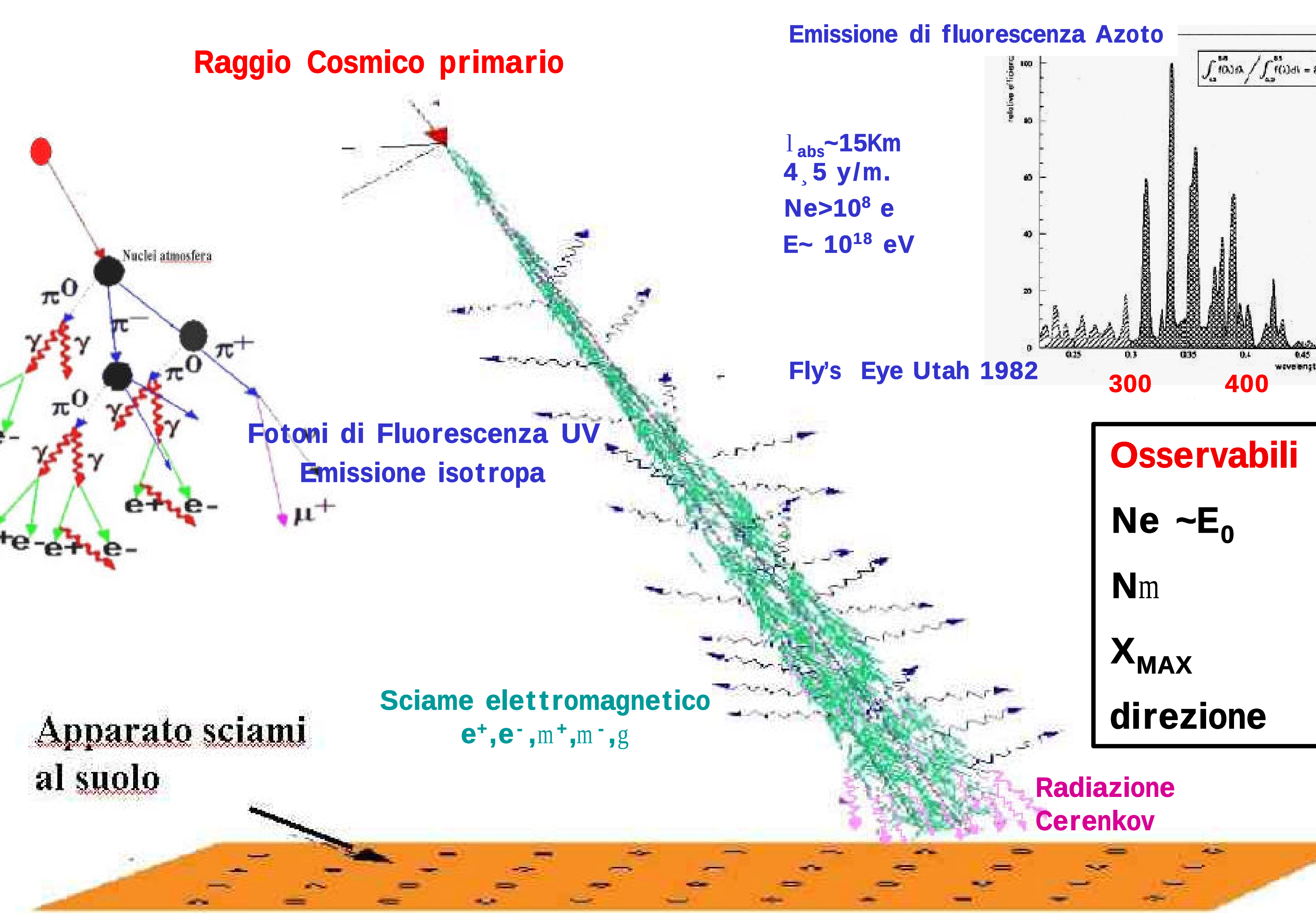
EXTENSIVE AIR SHOWER

Nell' interazione l'identita' del primario e' perduta.

Solo in modo statistico, con analisi multi-parametriche si possono separare gruppi di elementi (p+He, CNO, Fe)

Fondamentale il ricorso alle simulazioni estrapolando alle alte energie i risultati degli acceleratori





Raggio Cosmico primario
Emissione di fluorescenza Azoto
l abs~15Km
4¸5 y/m.
Ne>10^8 e
E~ 10^18 eV
Fly's Eye Utah 1982
300
400
Nuclei atmosfera
Fotoni di Fluorescenza UV
Emissione isotropa
Osservabili
Ne ~E0
Nm
XMAX
direzione
Sciame elettromagnetico
e+,e-,m+,m-,g
Apparato sciami
al suolo
Radiazione
Cerenkov

Towards the Knee...

Measurement of elemental fluxes vs. E

Relevant for:

<u>Astrophysics</u>

Acceleration and confinement of c.r.

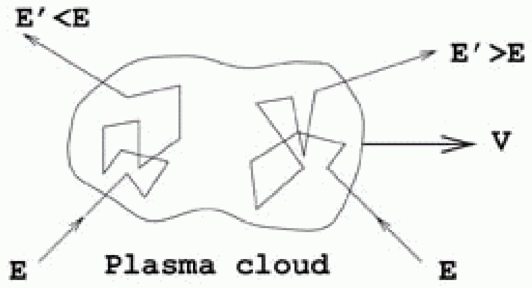
<u>Particle Physics</u>

fluxes of secondaries in atmosphere
Benchmarks for shower/interaction models
input for atmospheric neutrino analysis
(oscillation physics)

Fermi Acceleration Mechanism

Stochastic energy gain in collisions with plasma clouds

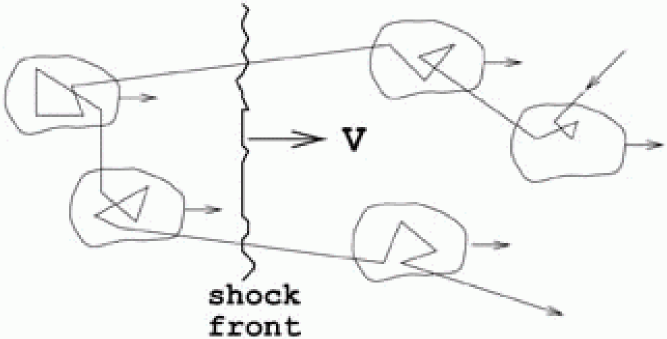
2nd order :
randomly distributed magnetic mirrors



$$\frac{\Delta E}{E} \sim \beta^2 \qquad \beta = \frac{V}{c} \lesssim 10^{-4}$$

[Slow and inefficient]

1st order :
acceleration in strong shock waves
(supernova ejecta, RG hot spots...)



$$\frac{\Delta E}{E} \sim \beta \qquad \beta = \frac{V}{c} \lesssim 10^{-1}$$

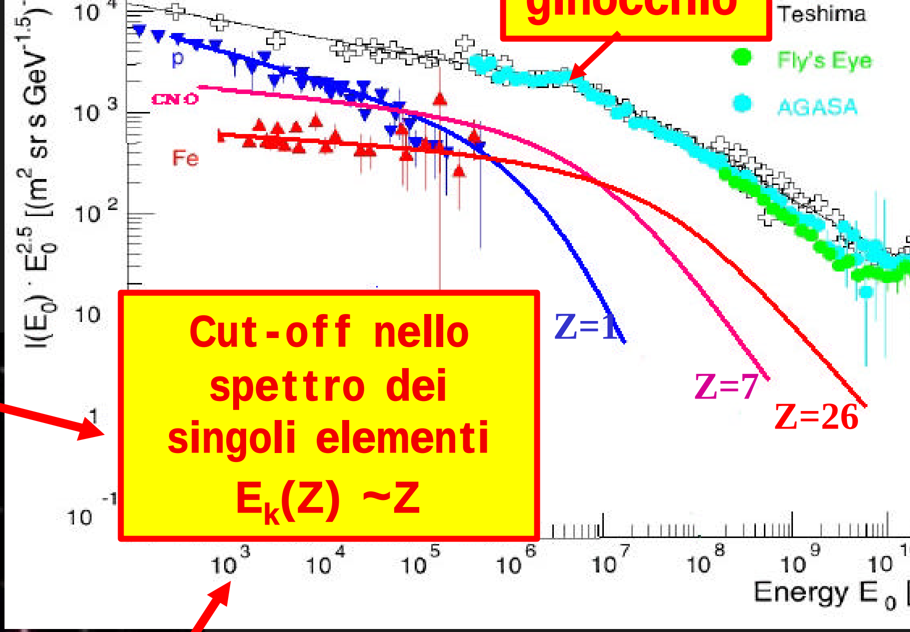
1

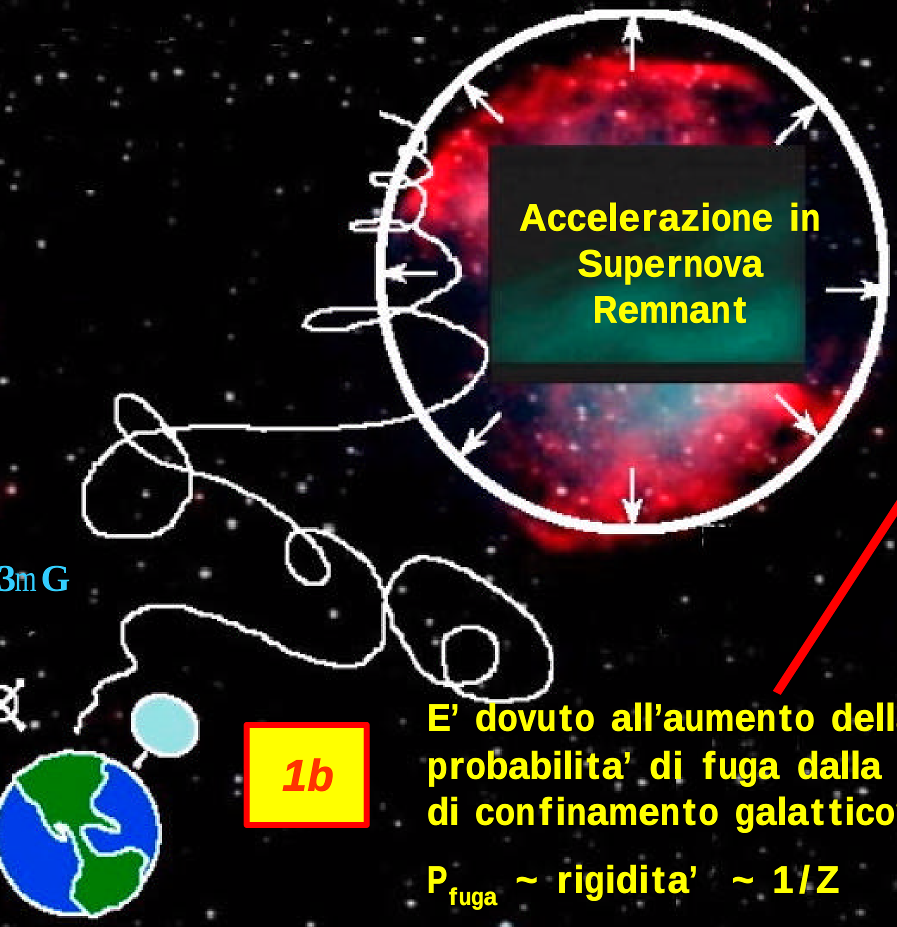
A cosa e' dovuto il ginocchio?

a

E' il limite energetico del meccanismo di accelerazione dei r.c. galattici?

$E_{max} \sim Z \bullet 10^{14}$ eV





1b

E' dovuto all'aumento della probabilita' di fuga dalla regione di confinamento galattico?

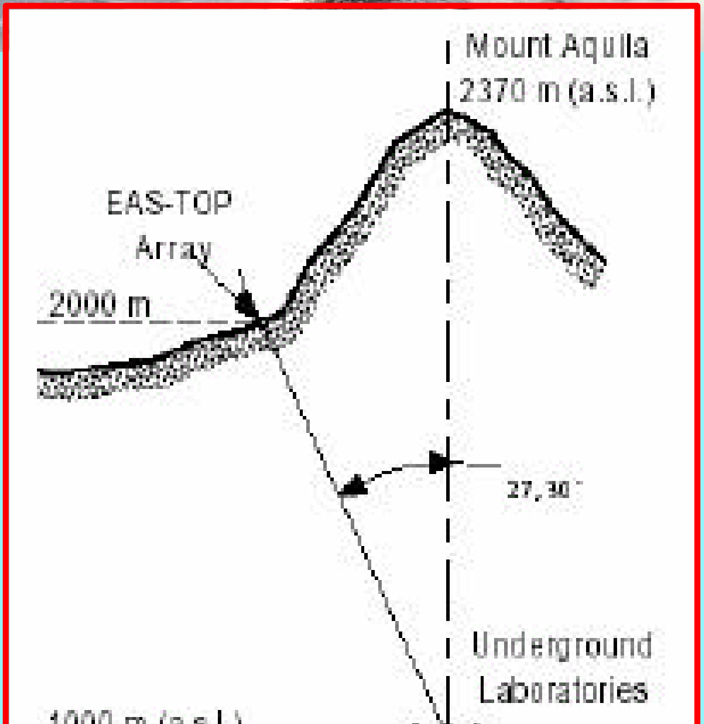
$P_{fuga} \sim$ rigidita' $\sim 1/Z$

BASJE - MAS

E_{th} ~ 6 TeV

Chakaltaya, 5200 m a.s.l.

EAS TOP


Mount Aquila
2370 m (a.s.l.)
EAS-TOP
Array
2000 m
27,30'
Underground
Laboratories

11 esperimenti di fisica astroparticellare: 8 in funzione, 3 in preparazione

4 esperimenti di geofisica

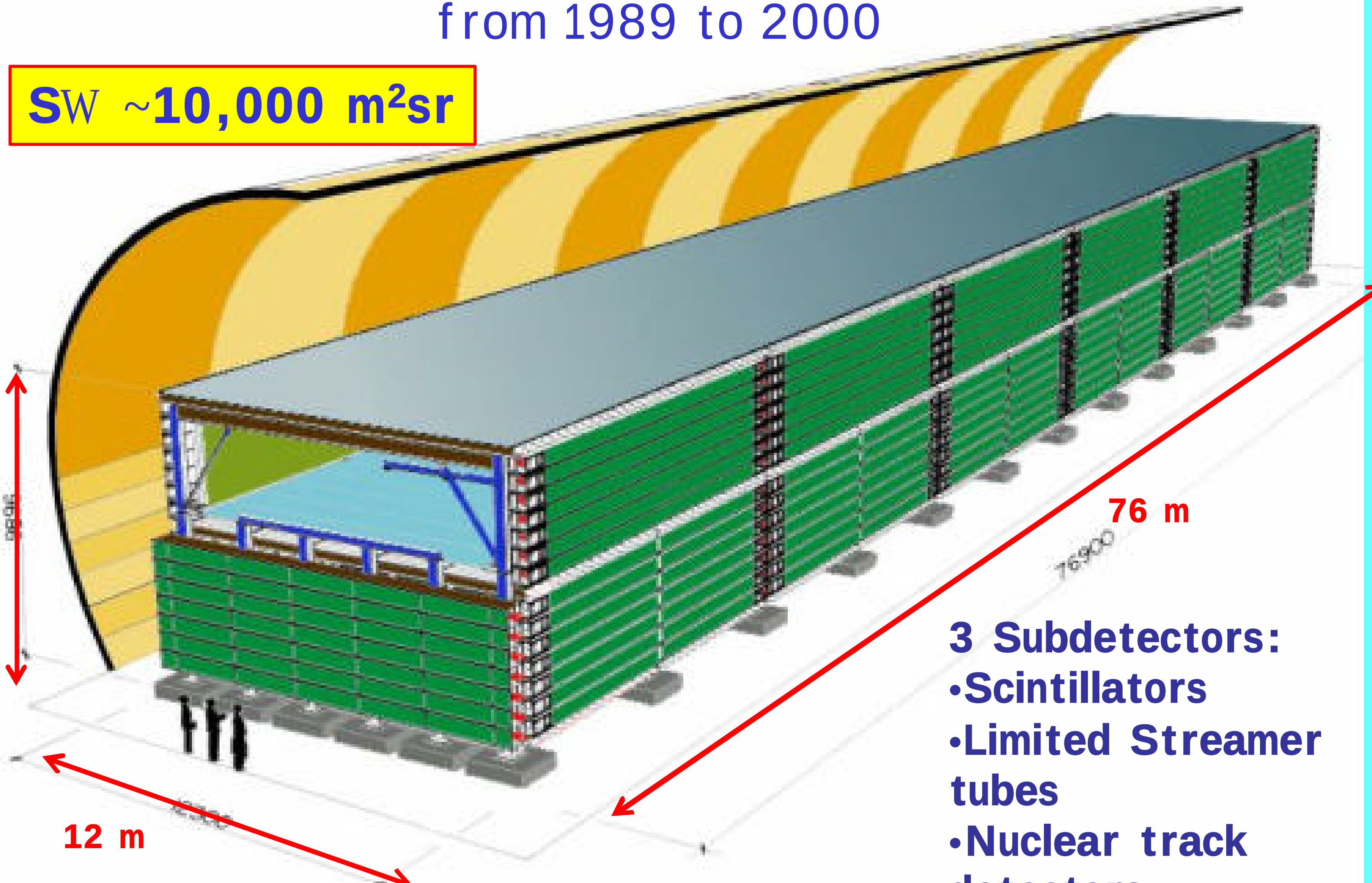
1 esperimento di biologia

4 proposte per esperimenti futuri

The MACRO experiment @ Gran Sasso

from 1989 to 2000

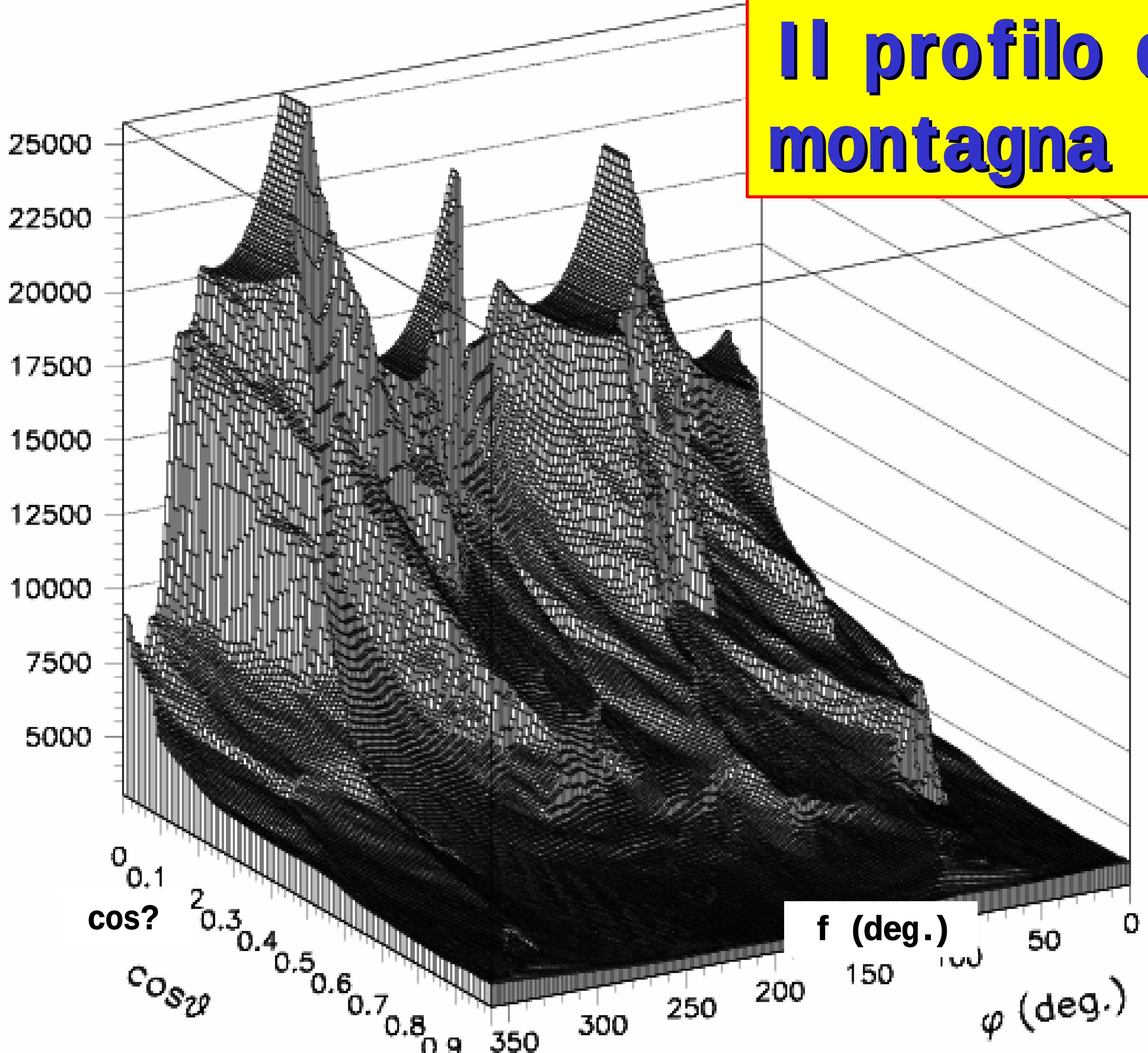
$SW \sim 10{,}000\ m^2sr$



3 Subdetectors:

- **Scintillators**
- **Limited Streamer tubes**
- **Nuclear track detectors**

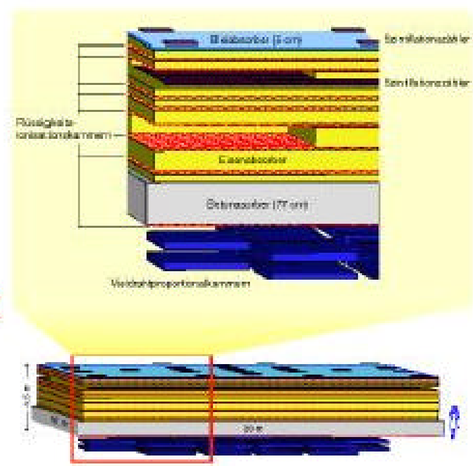
Il profilo della montagna



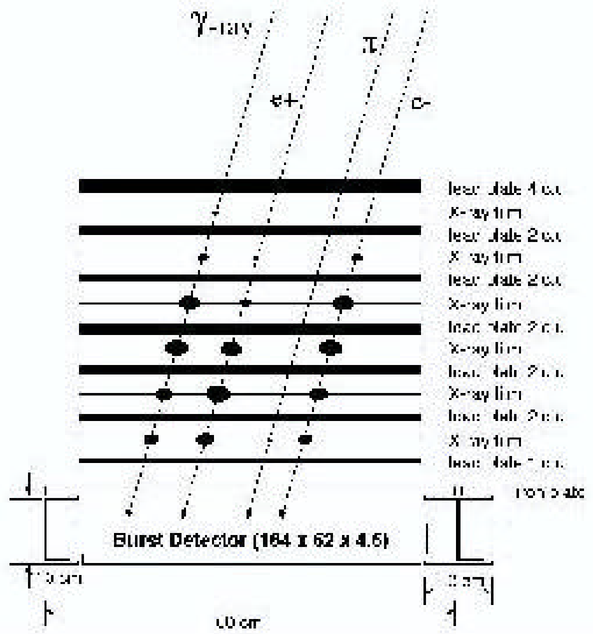
KASCADE

e/μ

Hadron



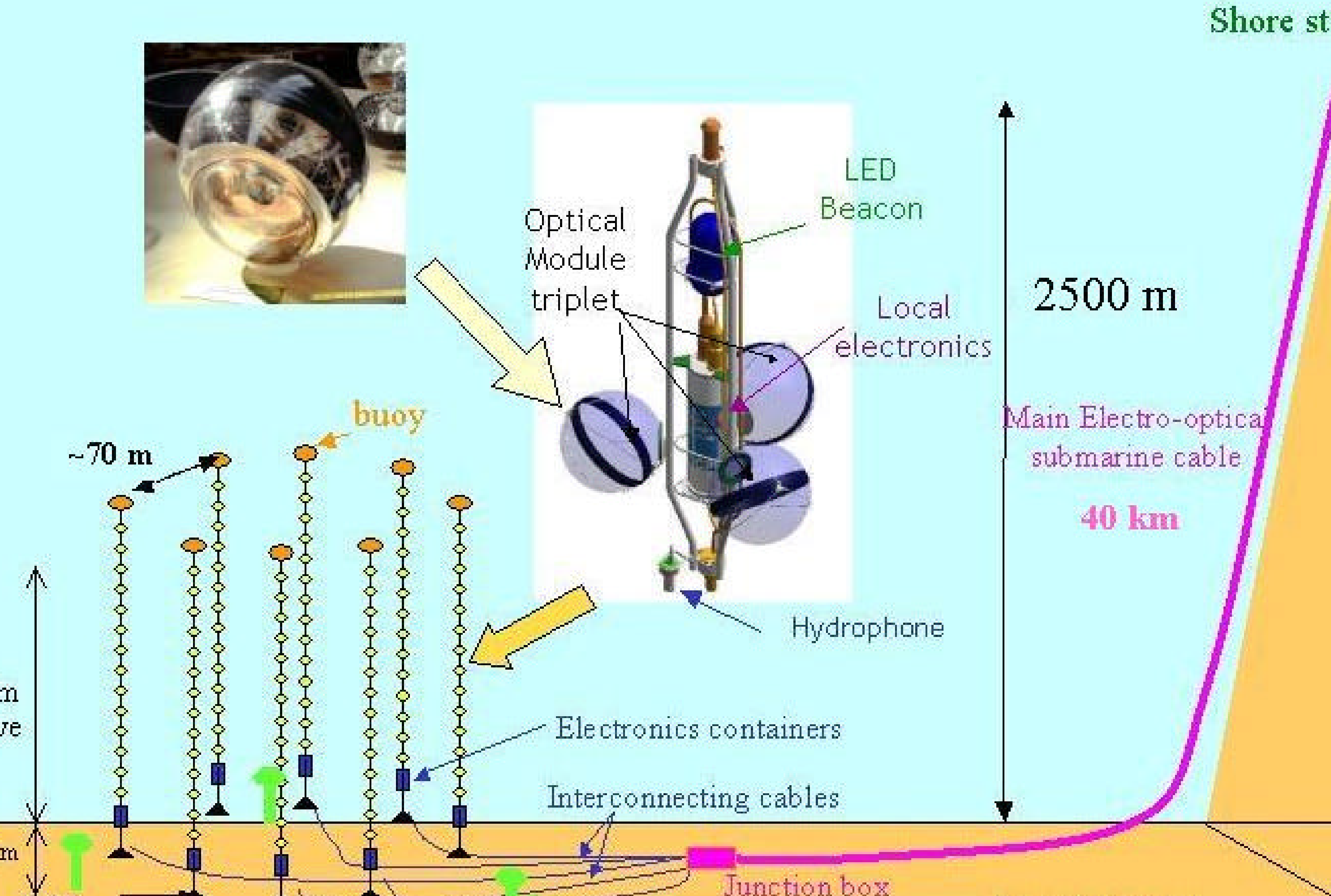
IBET



2 lines of 25 storeys

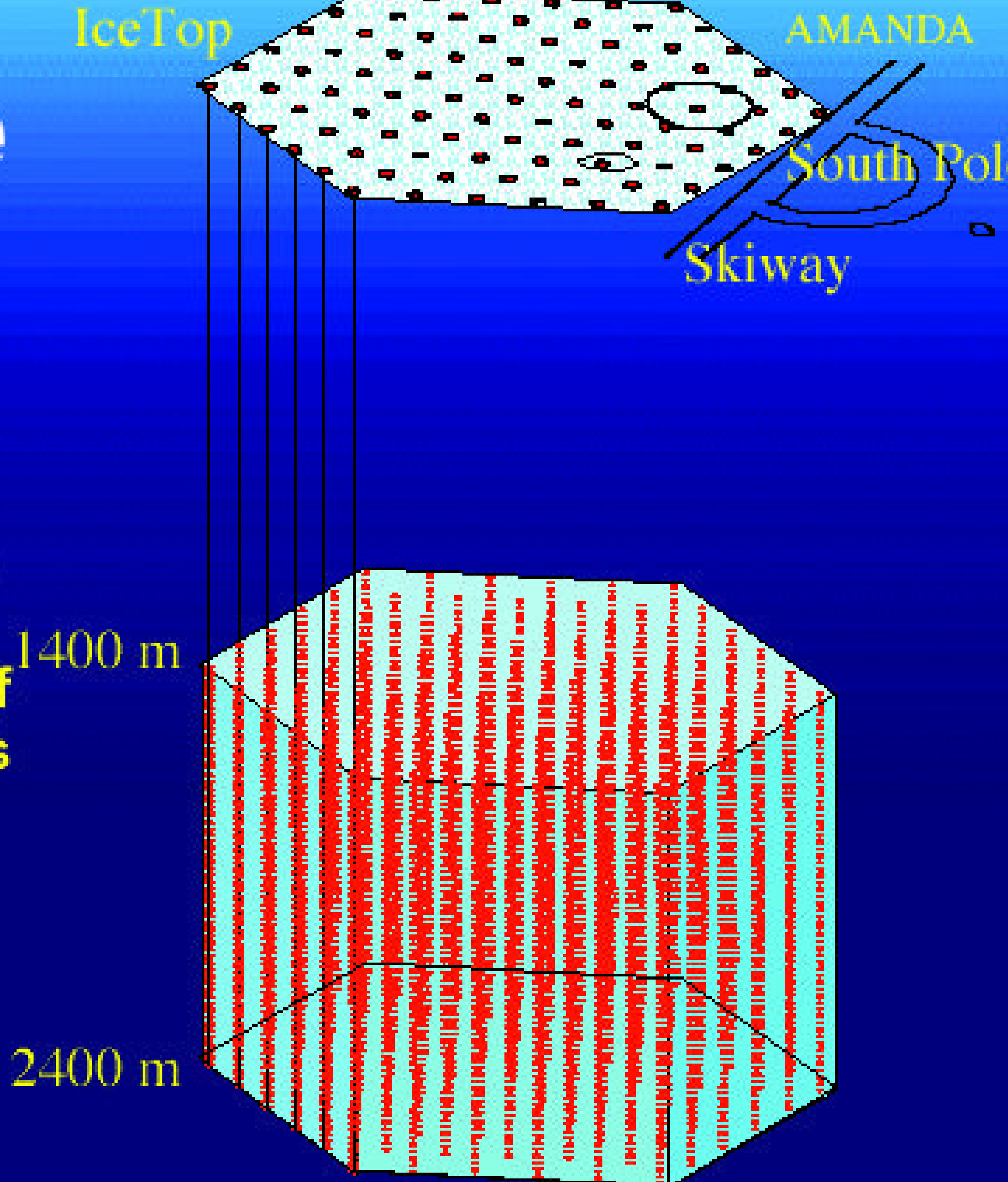
900 PMs

The ANTARES Detector



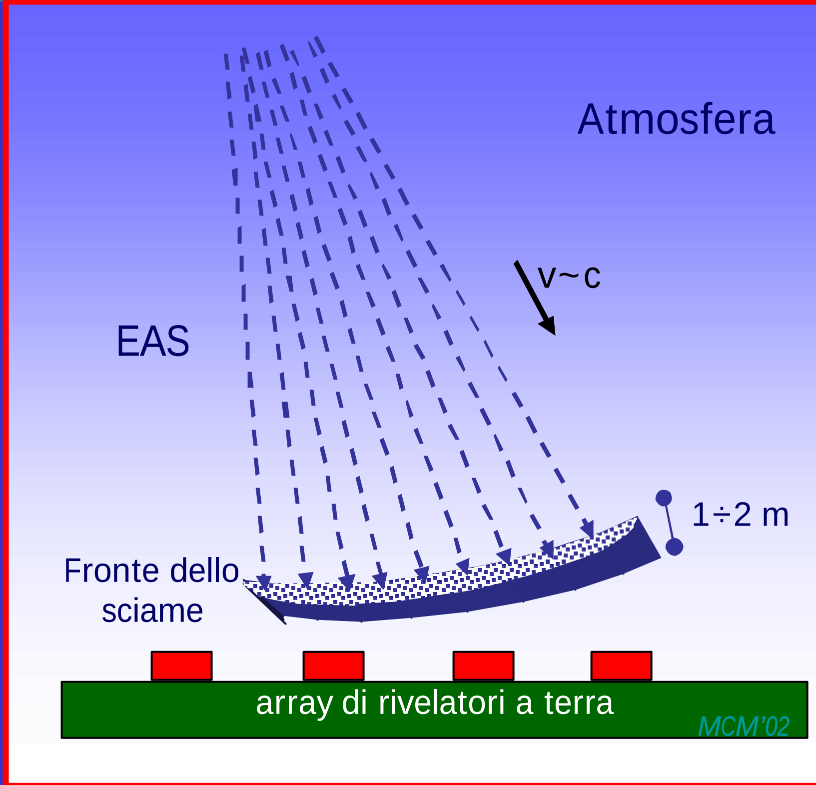
IceCube

- 80 Strings
- 4800 PMT
- Instrumented volume: 1 km3 (1 Gt)
- IceCube is designed to detect neutrinos of all flavors at energies from 10^7 eV (SN) to 10^{20} eV



I metodi "density sampling" e "fast timing"

Il "Gruppo Raggi Cosmici" guidato da Bruno Rossi al M.I.T. mette a punto una nuova tecnica per determinare l'energia e la direzione di arrivo del CR primario che ha originato lo sciame EAS:



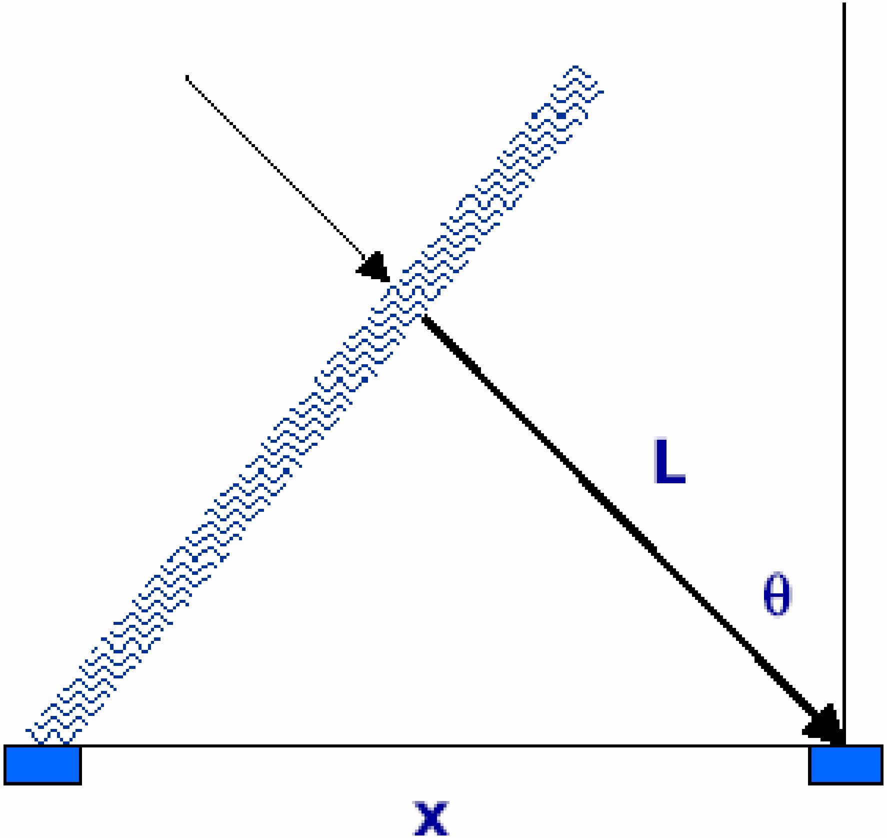
Density sampling": la distribuzione della ensità di particelle secondarie osservate in iverse posizioni in un *array* di contatori è sata per localizzare il centro dello sciame AS, e per risalire all'energia del CR primario.

Fast timing": la direzione d'arrivo del CR primario (assunta coincidente con l'asse lello sciame EAS) è determinata dalle differenze tra i tempi d'arrivo del fronte dello ciame di particelle sui vari contatori.

La tecnica del "density sampling" e del "fast timing" è alla base dei tanti esperimenti con *array* di rivelatori di particelle ...

Angular vs timing accuracy

Error of 65 nsec in timing causes ~ 2 deg error in direction estimate for shower at 45 deg and array with 1 km spacing:



Zenith angle θ=45.00 deg

X=1000m,   L=707m

Δt=L/c=2.36 μsec

With timing error:

Δt+65 nsec=2.42 μsec

- **apparent L = 727 m**
- **apparent θ = 43.4 deg**
- **Δθ = 1.6 deg**

li apparati sciami e.m. misurano densita' e tempo di arriv
elle particelle (e,μ,γ) su di una matrice di rivelatori al
uolo.

$T_1<T_2<T_3... \rightarrow$ direzione

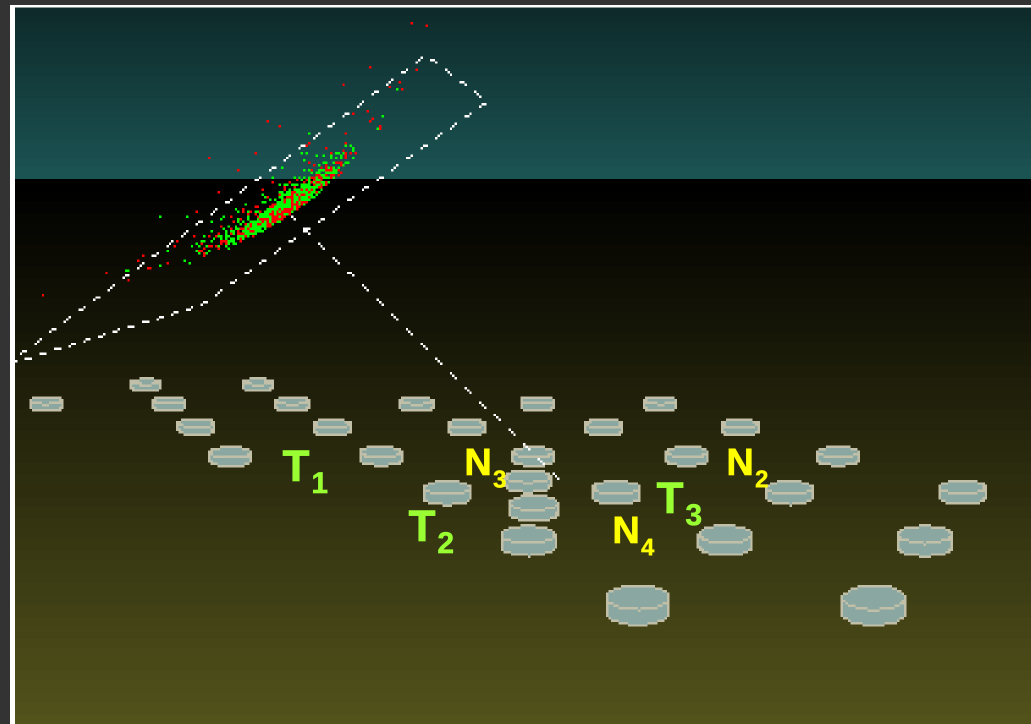
$N_3>N_4>N_2... \rightarrow$ d.l.

↓

e numero totale di particelle

↓

Energia primario



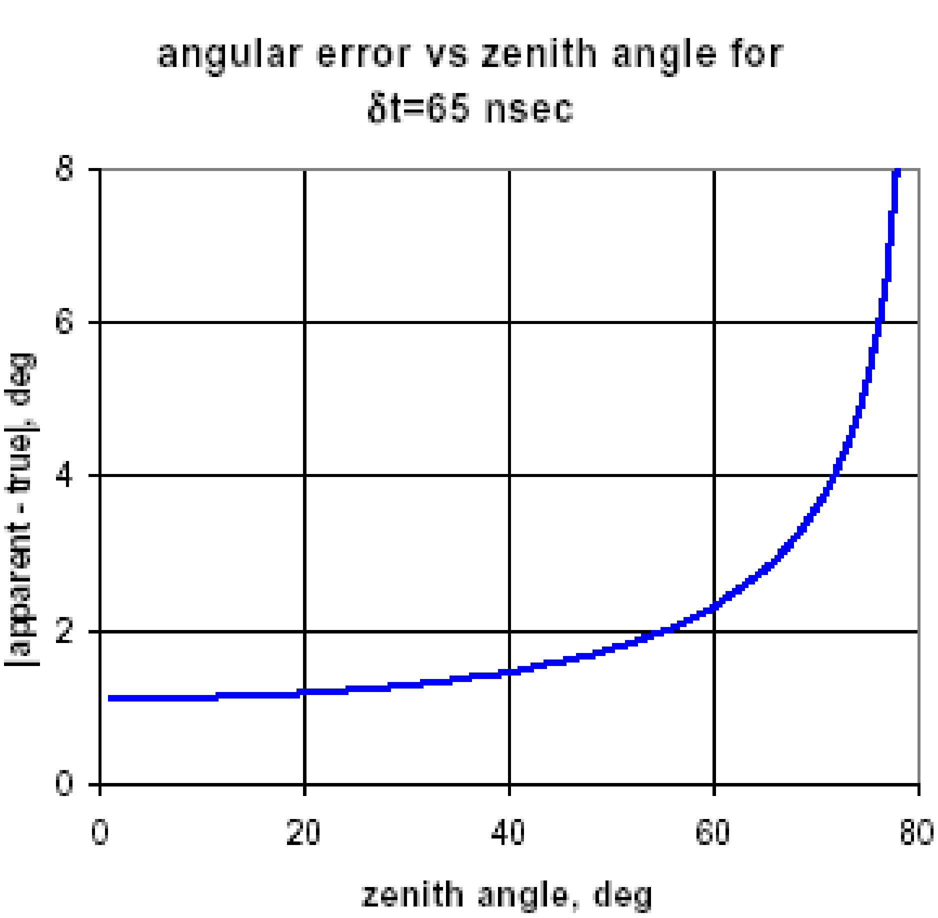
2 parametri dello sciame e.m. permettono di separare
nuclei leggeri da nuclei pesanti

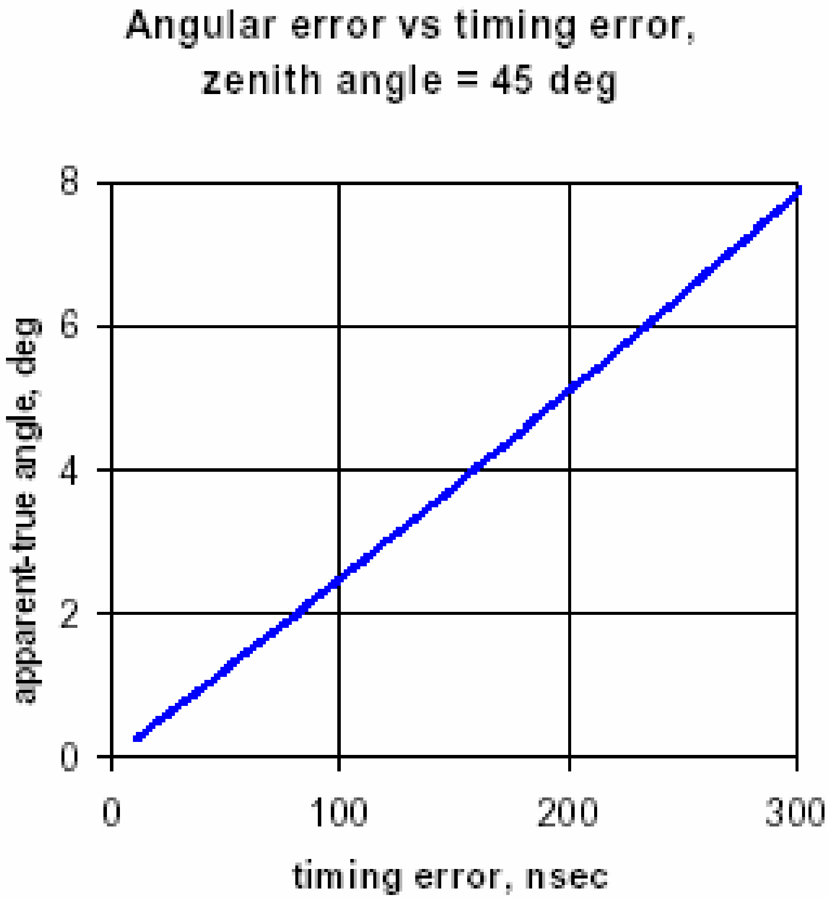
N_μ / N_e

$X(Ne_{max})$ altezza del massim

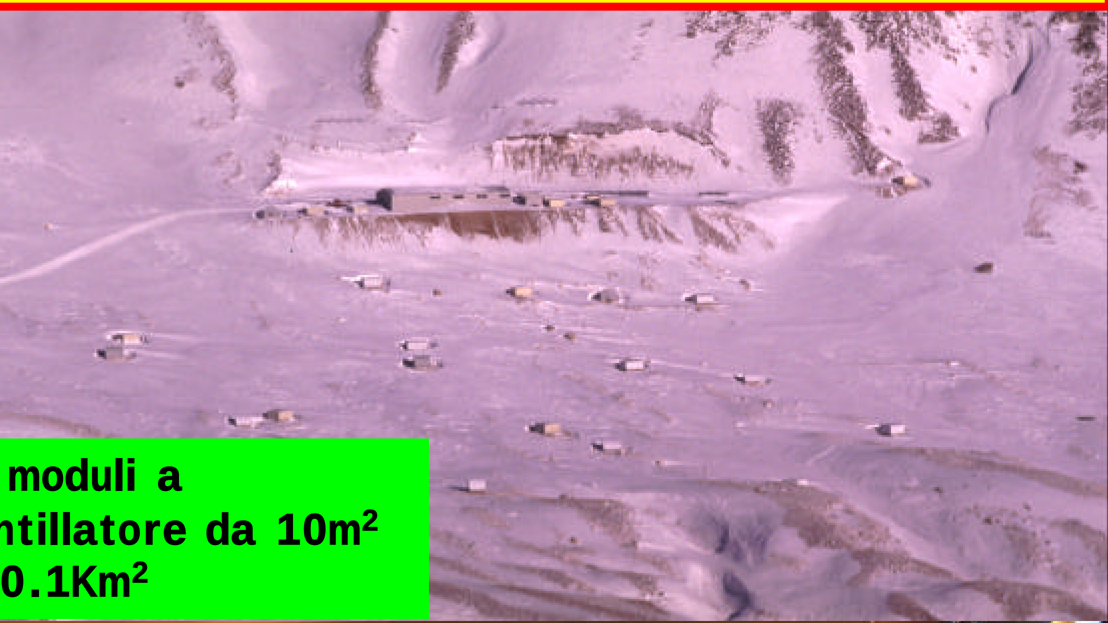
$(N_\mu / N_e)_{Fe} > (N_\mu / N_e)_p$

$X(Ne_{max})_{Fe} > X(Ne_{max})_p$

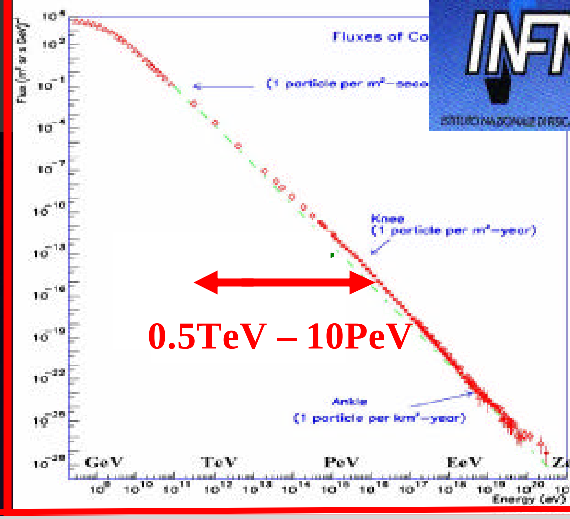

angular error vs zenith angle for
δt=65 nsec
|apparent - true|, deg
zenith angle, deg
0
2
4
6
8
0
20
40
60
80


Angular error vs timing error,
zenith angle = 45 deg
apparent-true angle, deg
timing error, nsec
0
2
4
6
8
0
100
200
300

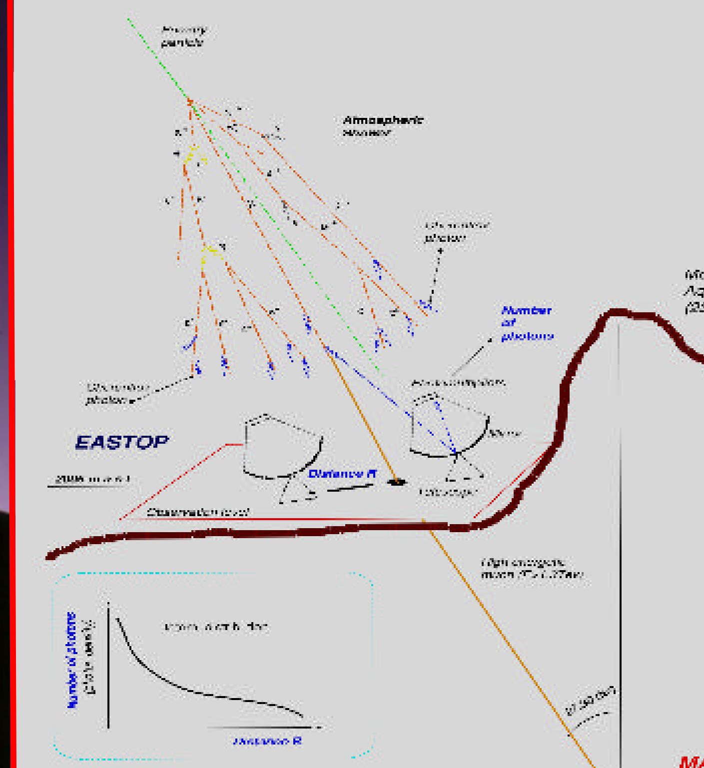
AS-TOP Campo Imperatore 1989-2000



moduli a
ntillatore da 10m²
0.1Km²

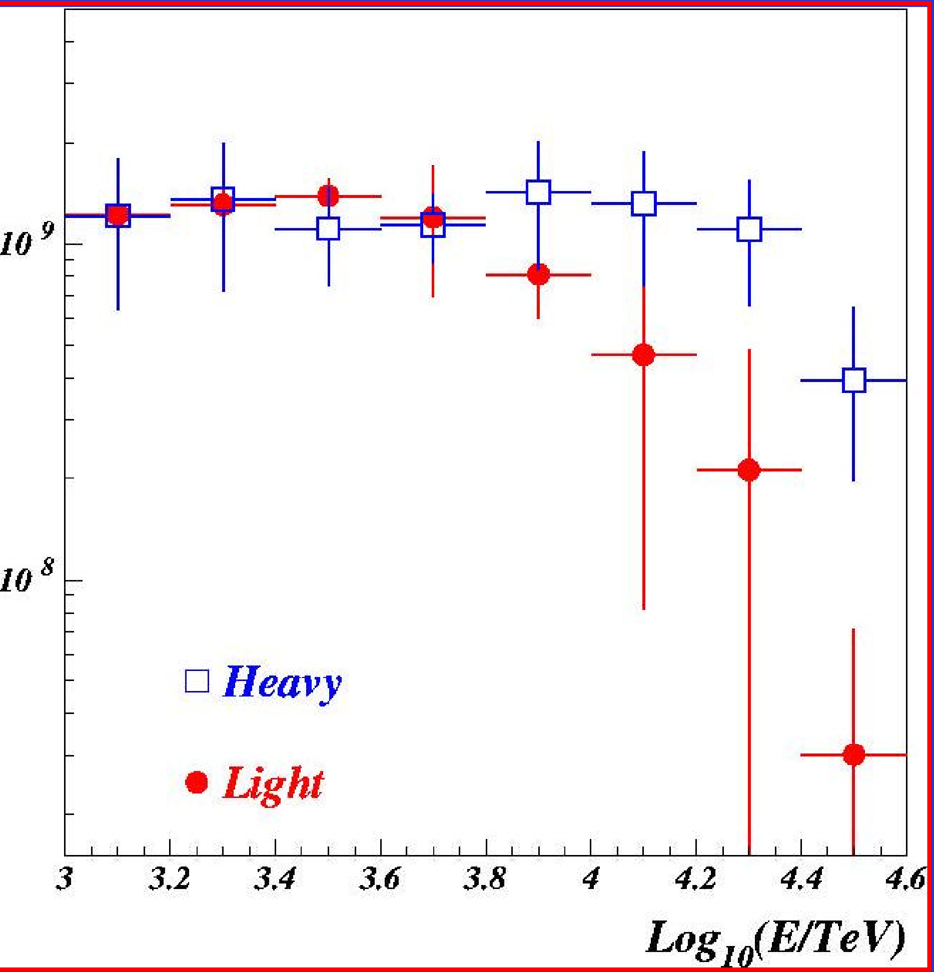


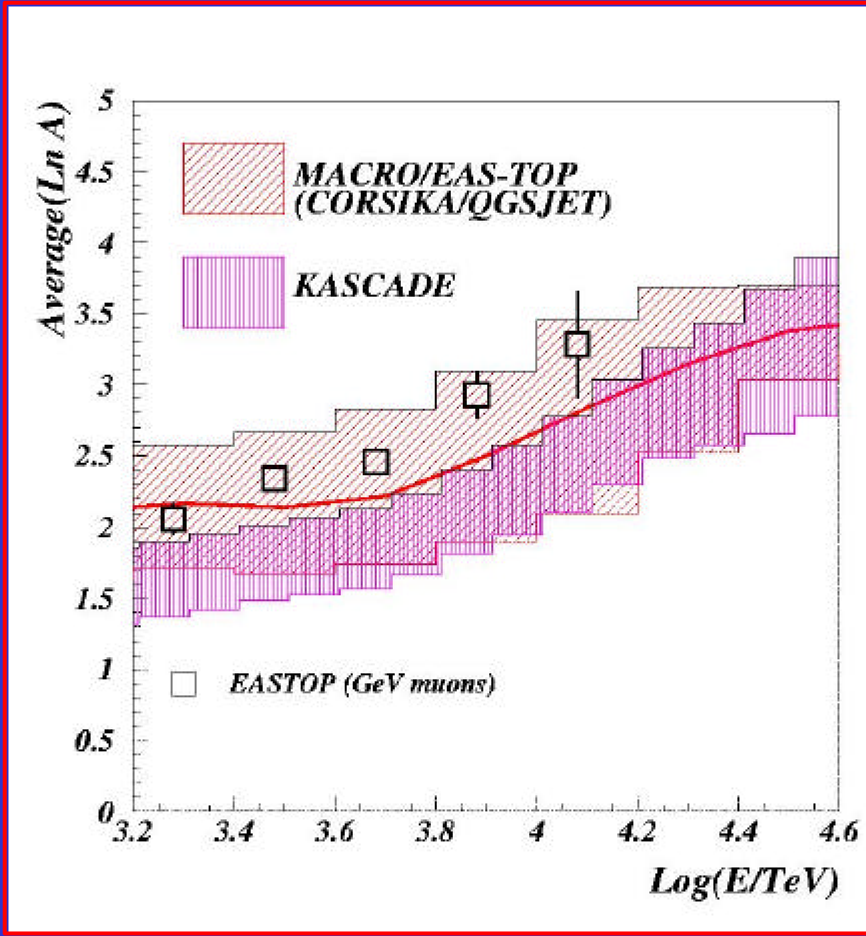
E_0 ~ 100 TeV



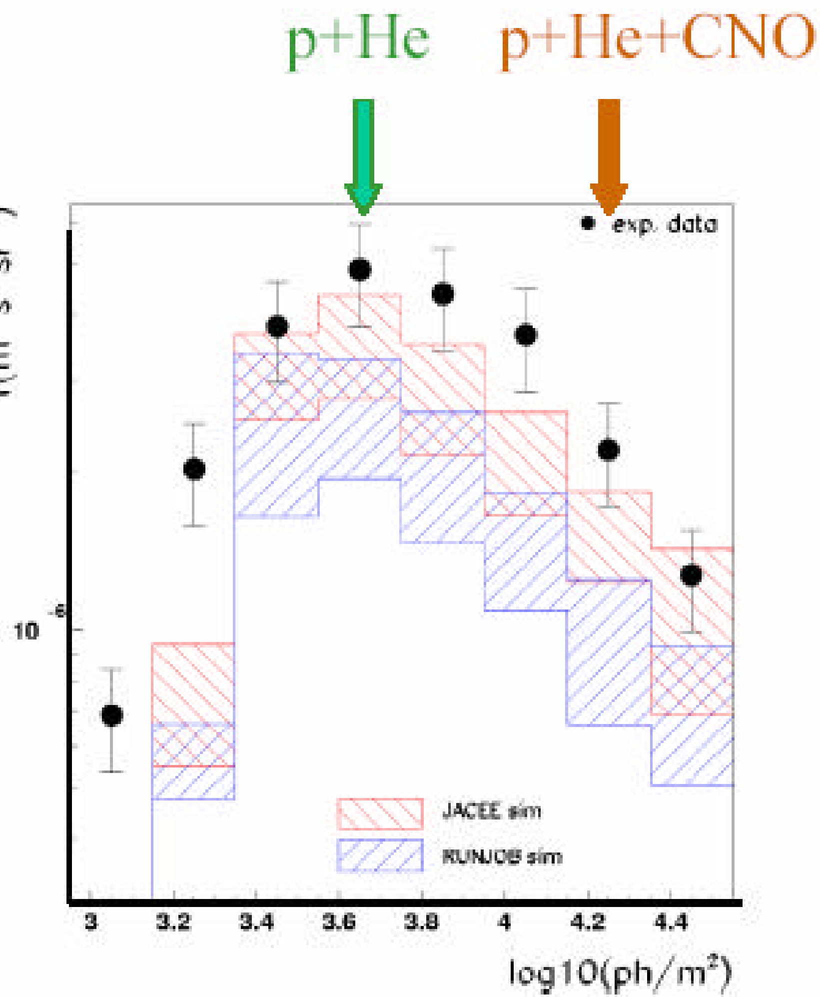
orimetro adronico

MACRO / EAS - TOP Coincidences





p, He, CNO @ ~ 100 TeV



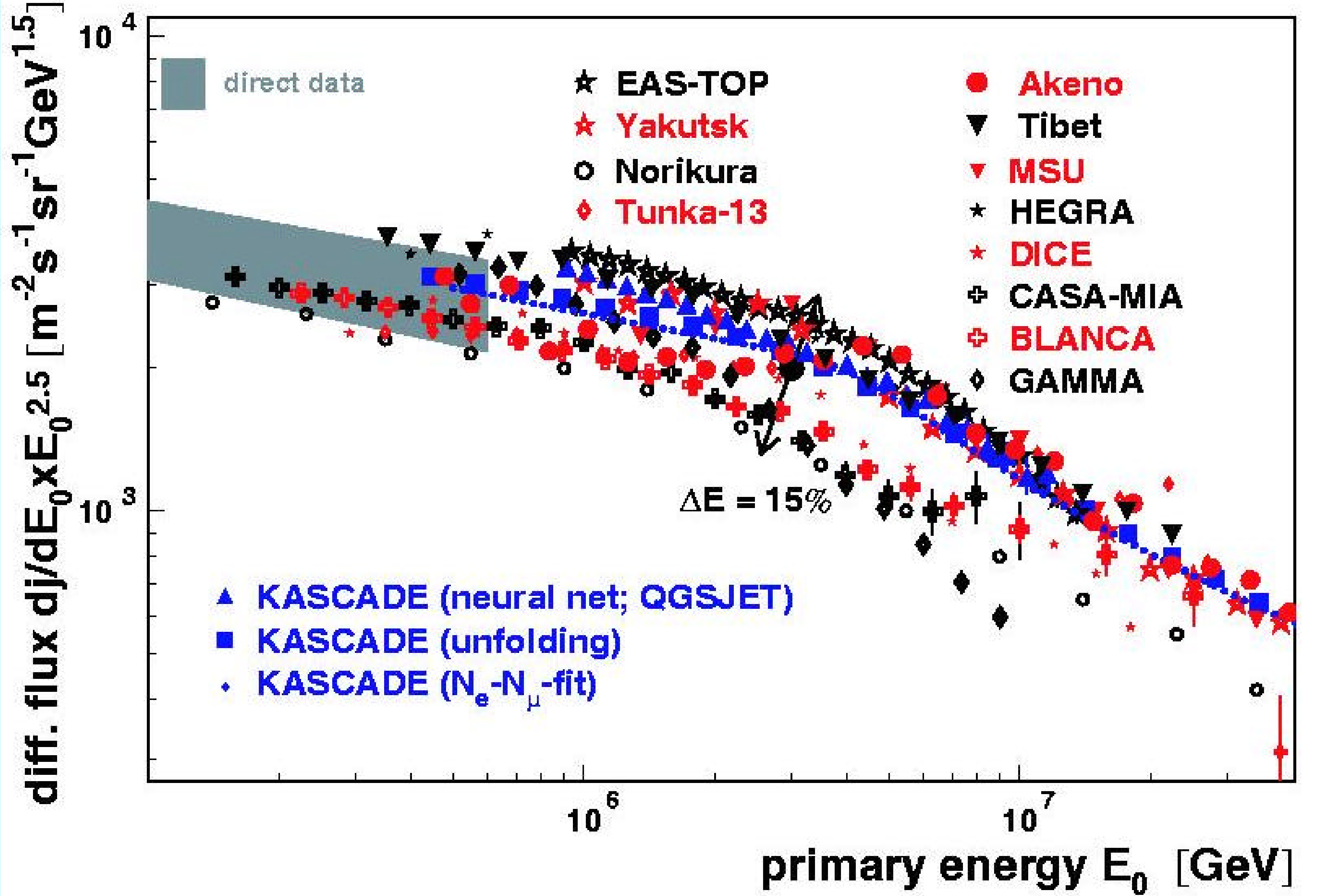
Information	EAS-TOP & MACRO	JACEE	RUNJOB
J_{p+He} (80 TeV)	18 ± 4	12 ± 3	8 ± 2
$J_{p+He+CNO}$ (250 TeV)	1.1 ± 0.3	0.7 ± 0.2	0.5 ± 0.1
J_p / J_{p+He} (80 TeV)	0.29 ± 0.09	0.45 ± 0.12	0.63 ± 0.2
$J_{p+He} / J_{p+He+CNO}$ (250 TeV)	0.78 ± 0.17	0.70 ± 0.20	0.76 ± 0.2
J_{He} (80 TeV)	12.7 ± 4.4	6.4 ± 1.4	3.1 ± 0.7

x 10^{-7} $m^{-2}s^{-1}sr^{-1}TeV^{-1}$

EAS-TOP & MACRO data

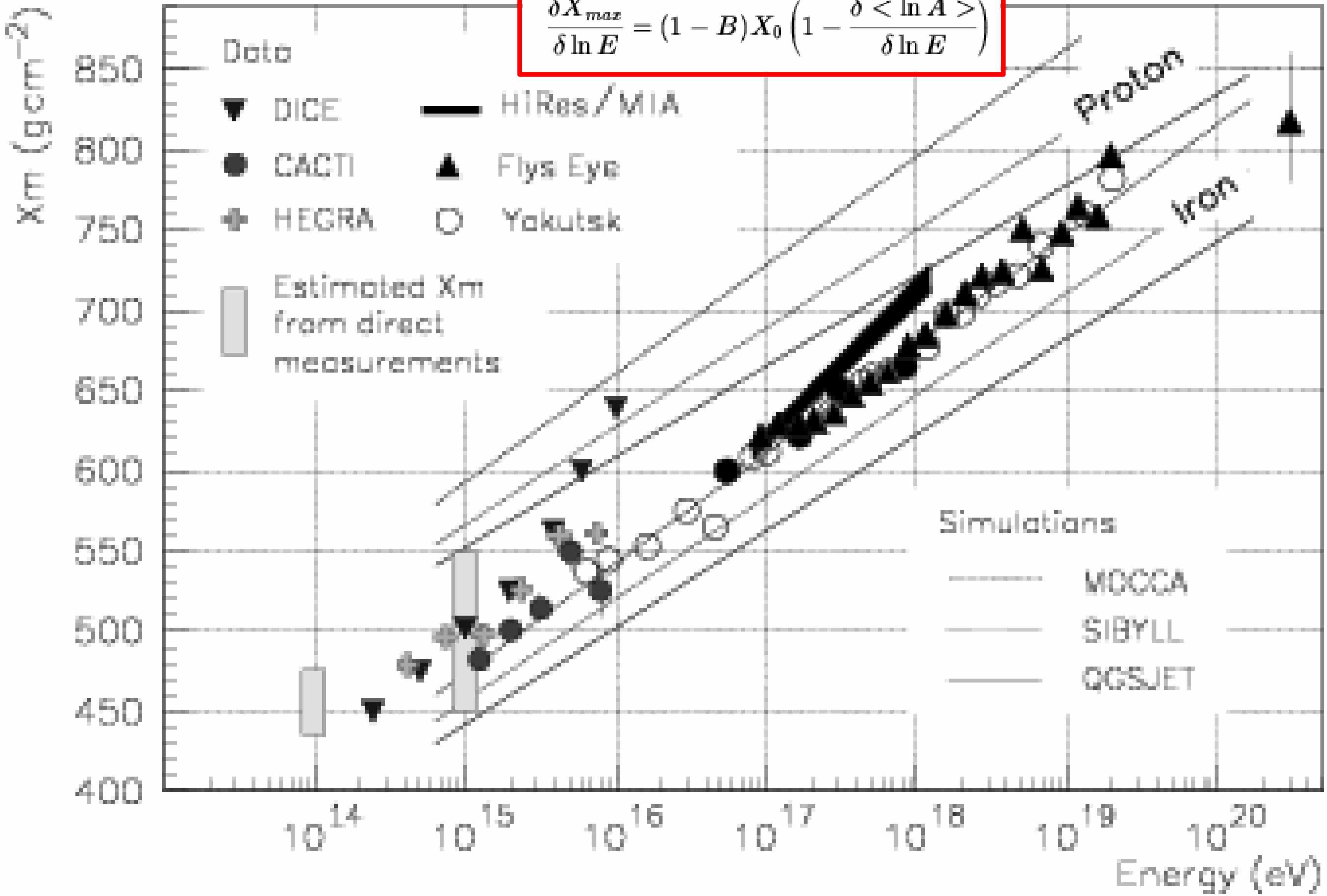
EAS-TOP & MACRO data + p-flux

The All Particle Spectrum



$$X_{max} = (1-B)X_0\left(\ln\frac{E}{\epsilon} - <\ln A>\right)$$

$$\frac{\delta X_{max}}{\delta \ln E} = (1-B)X_0\left(1 - \frac{\delta <\ln A>}{\delta \ln E}\right)$$



The connection between All-particle flux and All-nucleon flux

$$\frac{d\phi(E_0)}{dE_0} = \sum_i K_i {E_0}^{-\gamma}$$

$$E_{nuc} = E_0/A$$

$$\frac{d\phi(E_{nuc})}{E_{nuc}} = \frac{d\phi(E_0)}{dE_0}\frac{dE_0}{dE_{nuc}}$$

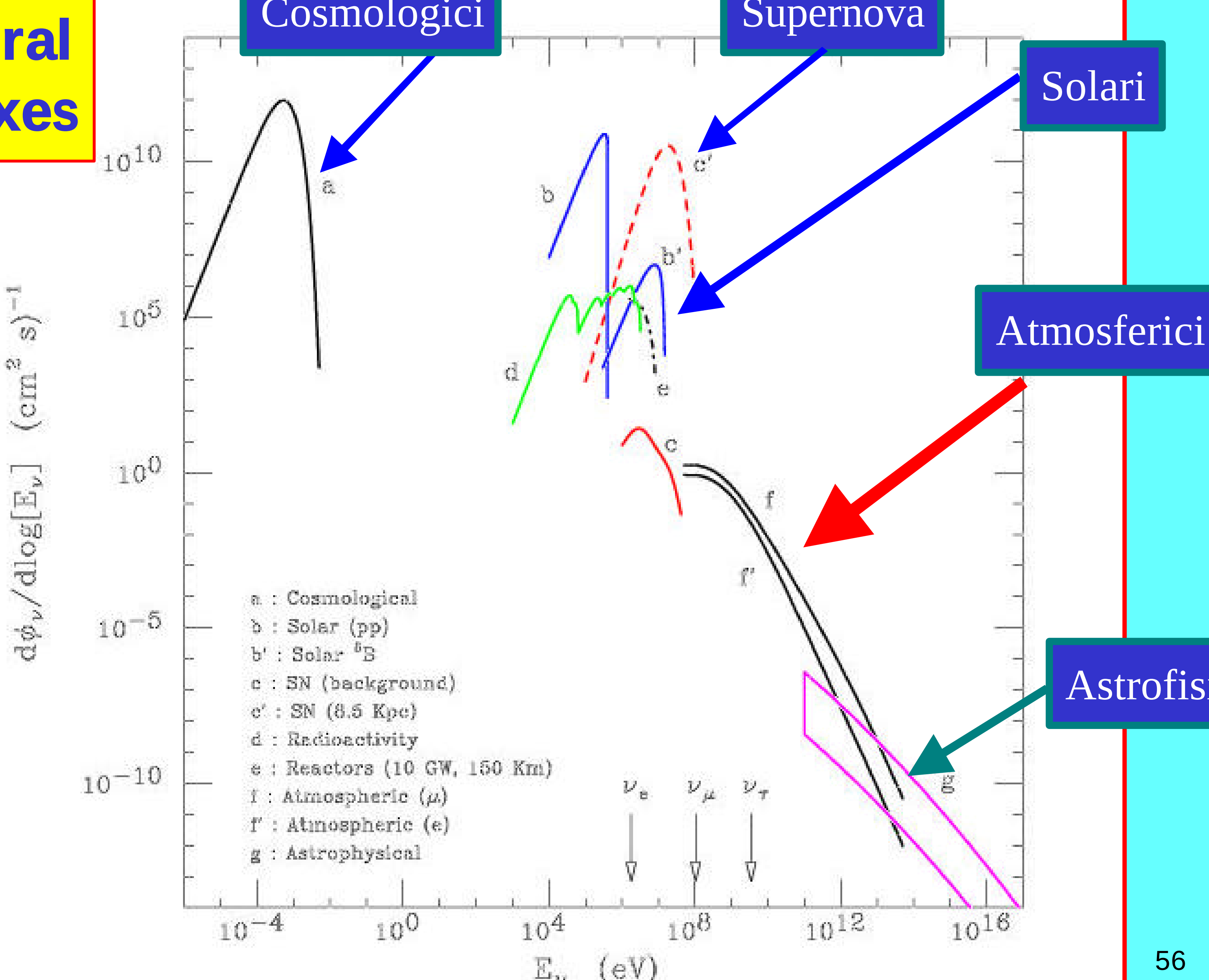
$$\frac{d\phi(E_{nuc})}{E_{nuc}} = \sum_i K_i (A_i E_{nuc})^{-\gamma} A_i$$

$$\frac{d\phi(E_{nuc})}{E_{nuc}} = \sum_i K_i A_i^{\gamma-1} {E_{nuc}}^{-\gamma}$$

sum running on different mass groups

(A = mass number)

Natural Fluxes



OSCILLAZIONI DI NEUTRINO

nel vuoto:

$$P(n_m \rightarrow n_t) \approx \sin^2(2J)\sin^2\left(1.27\frac{\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

1. **neutrini solari**

   $L = 1.5\ 10^{11}$ m, E ~ 10 MeV.

   da cui: L/E ~ 10^{10} km/GeV.

   $$n_e \rightarrow n_x$$

2. **neutrini atmosferici** (eventi confinati)

   L = 30 km (dall'alto), E ~ 10 GeV

   $L = 10^4$ km (dal basso), E ~ 10 GeV

   da cui: L/E varia da ~ 1 a 10^4 km/GeV.

   $$n_m \leftrightarrow n_t$$

3. **neutrini da sorgenti astrofisiche**

   $L = 3{\cdot}10^{21}$ km (100 Mpc), E > 10^7 GeV

   Sorgenti localizzate rispetto al fondo dei neutrini atmosferici

HADRONIC INTERACTIONS

$$p + A_{\mathrm{Air}} \quad \rightarrow \quad p, n, \quad \pi^{\circ}, \quad \pi^{\pm}, \quad K^{\pm}, K_L \ldots$$

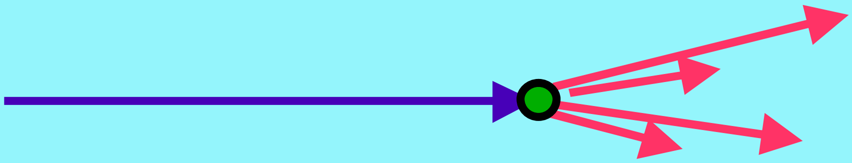
Leading nucleon
~ 50% of energy

π^{o} ® $\gamma\,\gamma$
Electromagnetic
Shower

Decadimento

$$\pi^+ \rightarrow \quad \mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \overline{\nu}_\mu$$

Interazione



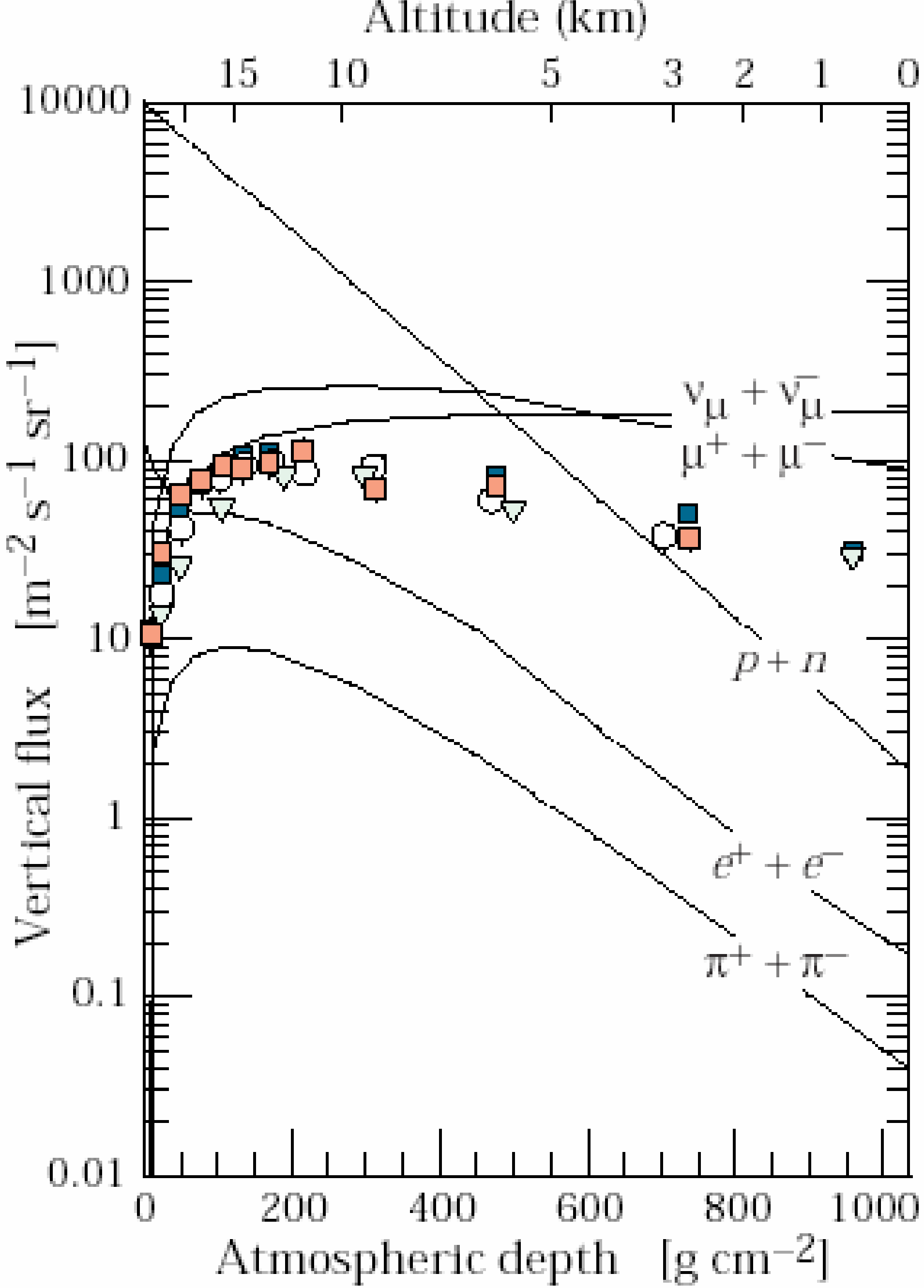
Caratteristiche del flusso di neutrini atmosferici

Flussi dei diversi flavor di neutrini

$$\frac{\nu_\mu + \overline{\nu}_\mu}{\nu_e + \overline{\nu}_e} \simeq 2$$

Simmetria Up-Down dei flussi di neutrini

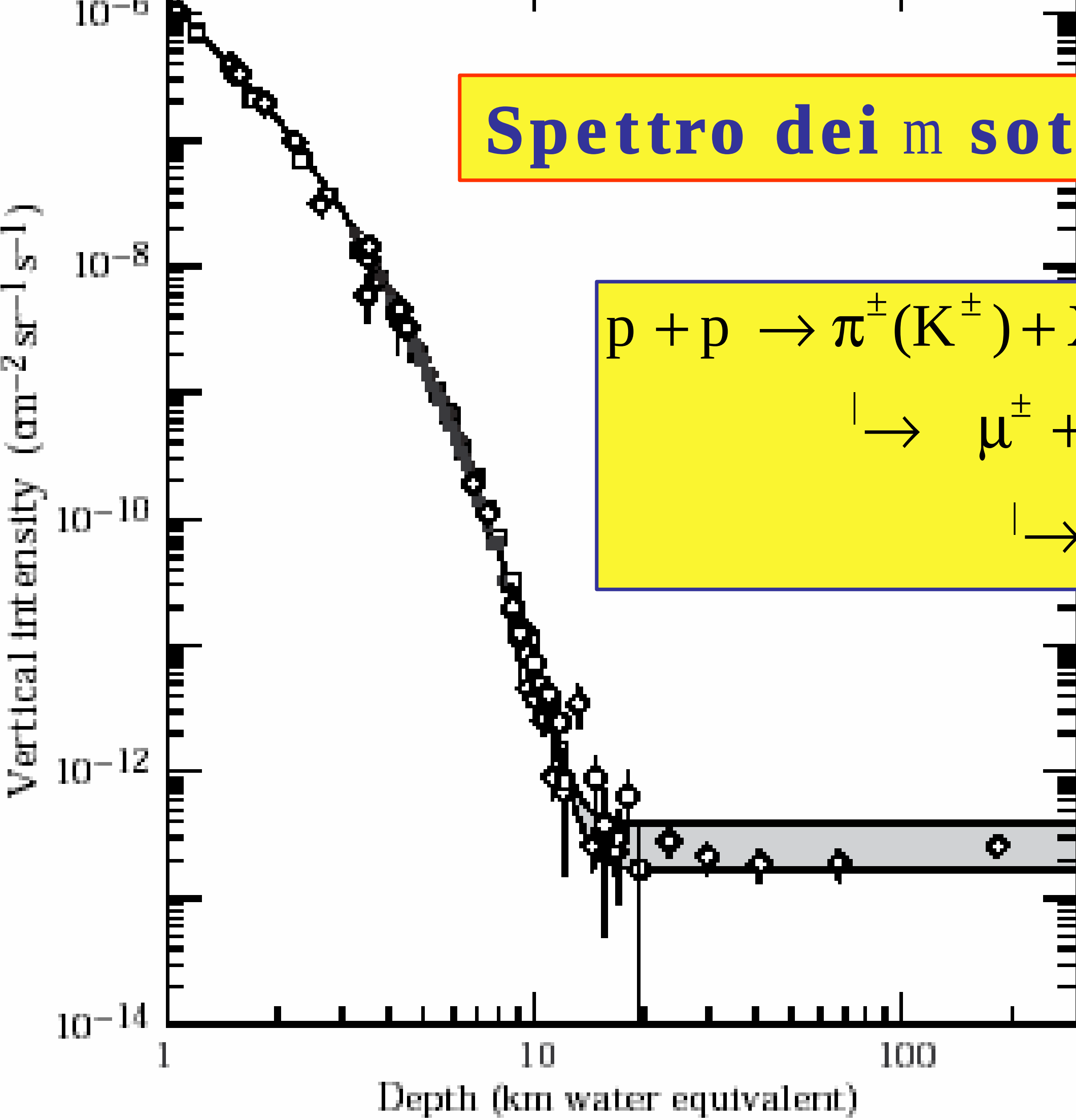
$$\phi_{\nu_\alpha}(E, \theta) = \phi_{\nu_\alpha}(E, \pi - \theta)$$



Altitude (km)
15
10
5
3
2
1
0
10000
1000
100
10
1
0.1
0.01
Vertical flux [m^-2 s^-1 sr^-1]
$\nu_\mu + \bar{\nu}_\mu$
$\mu^+ + \mu^-$
$p + n$
$e^+ + e^-$
$\pi^+ + \pi^-$
0
200
400
600
800
1000
Atmospheric depth [g cm^-2]

Spettro dei m sottoterra

LVD



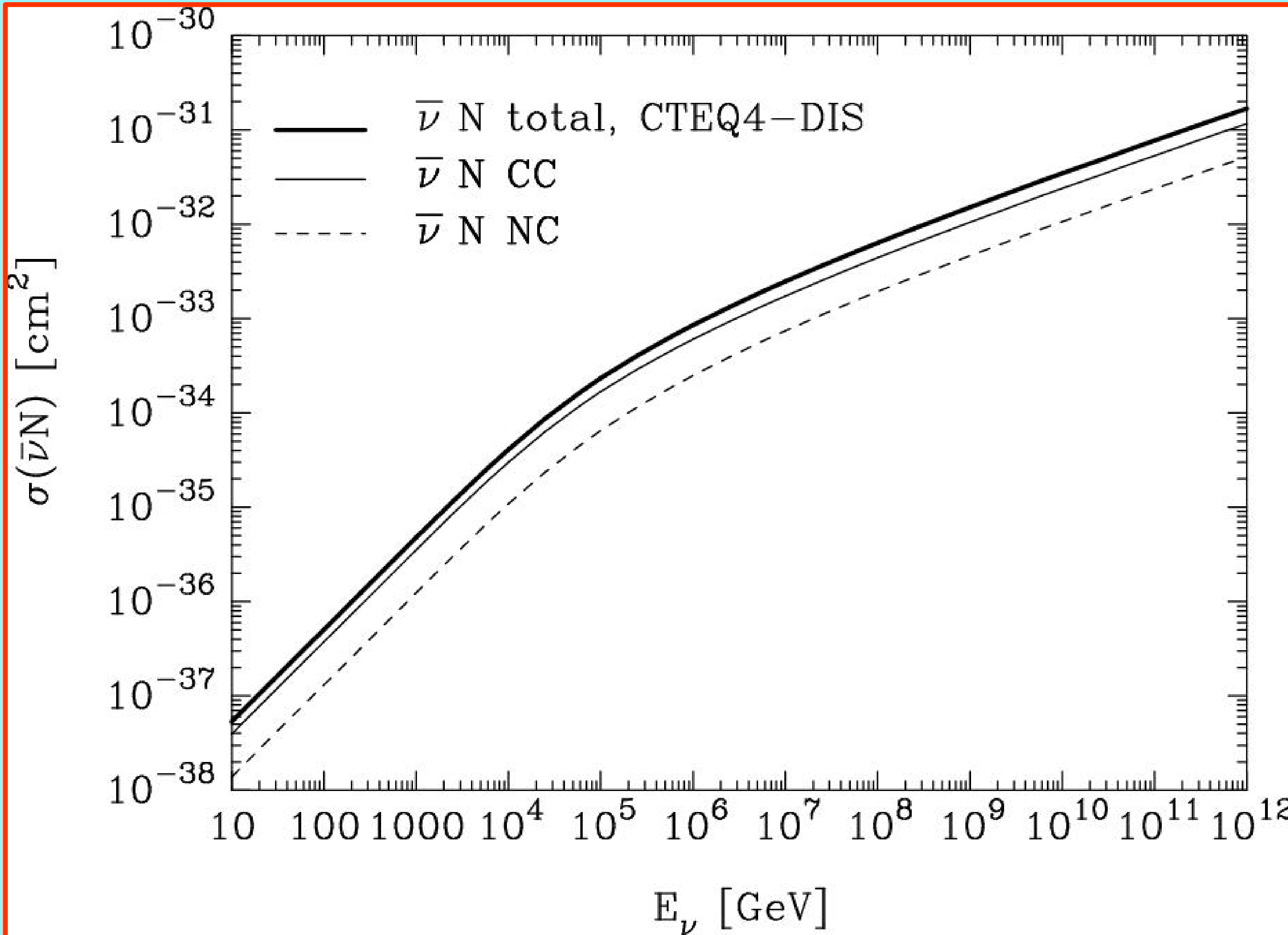
$$p + p \rightarrow \pi^{\pm}(K^{\pm}) + X$$

$$\hookrightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

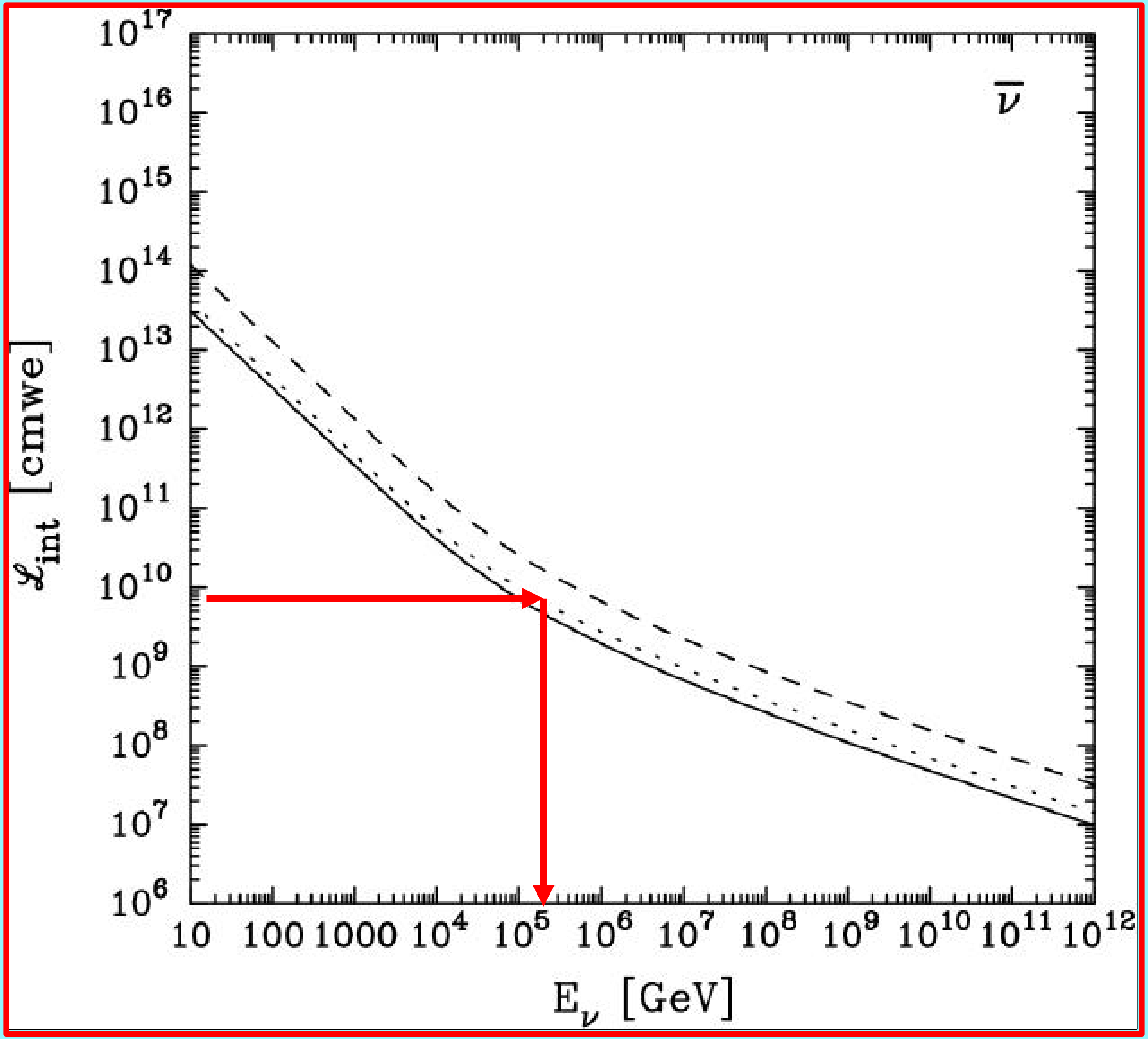
$$\hookrightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_e(\bar{\nu}_e$$

$$n_m + N \rightarrow m + X$$

s(p-air) = 3x10 cm

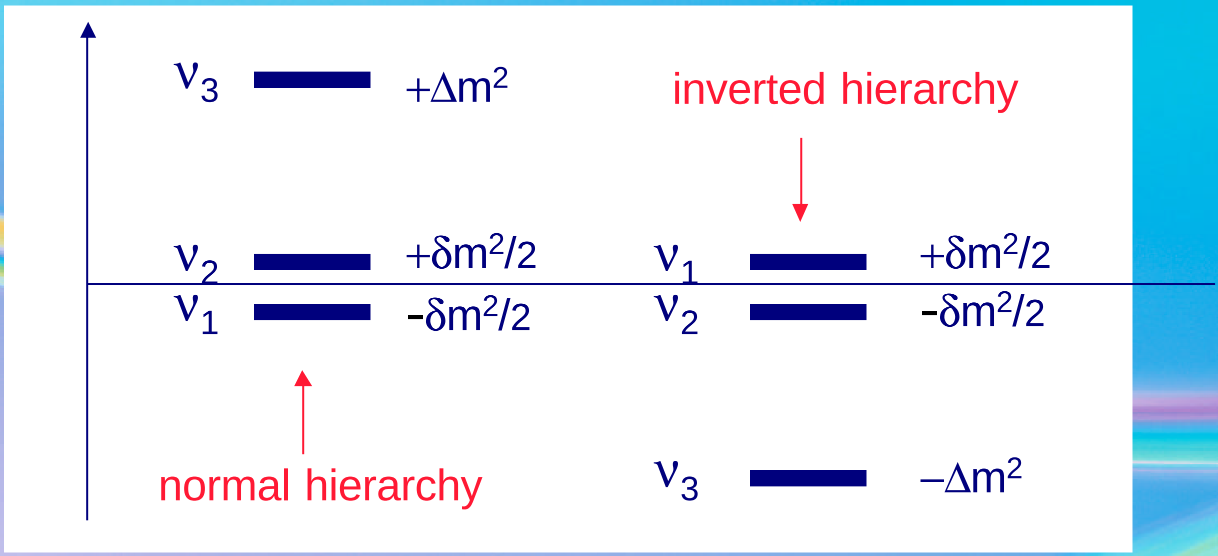


"Upward muons" sono limitati dall'assorbimento dei neutrini nella Terra



- Mass-gap parameters: $M^2 = \left[-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}, \pm \Delta m^2 \right]$

"solar" "atmospheric"



conventional zero

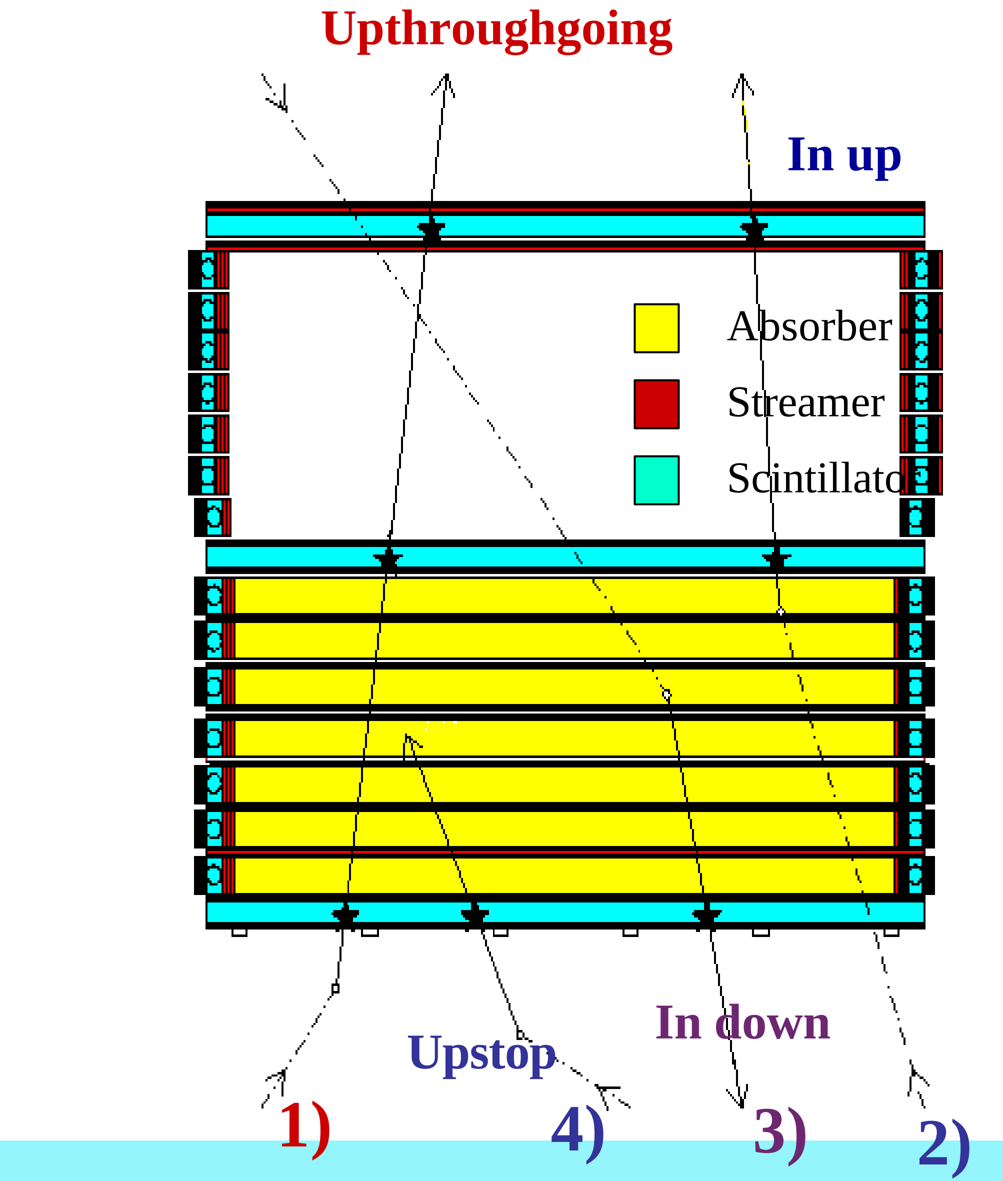
Should be set only by observables sensitive to absolute n mass:

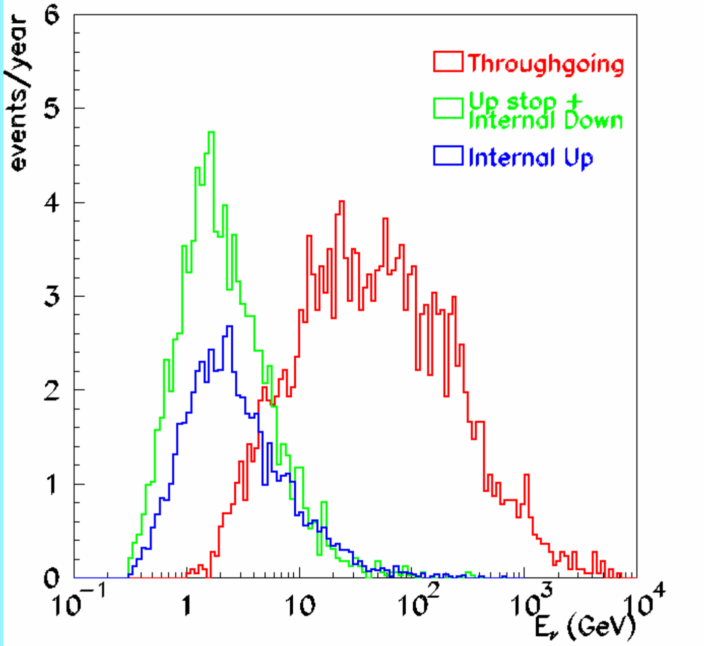
- β-decay
- 0ν2β-decay
- cosmology

- Dynamical term (MSW): $\begin{pmatrix} \pm 2^{1/2} G_F N_e E_\nu & & \\ & 0 & \\ & & 0 \end{pmatrix}$

induced by the CC interactio of ν_e in matter (with electro density N_e)

MACRO





DATA SAMPLES(measured

(Bartol96 expected

Upthrough(1) 857

1169

In up(2) 157

285

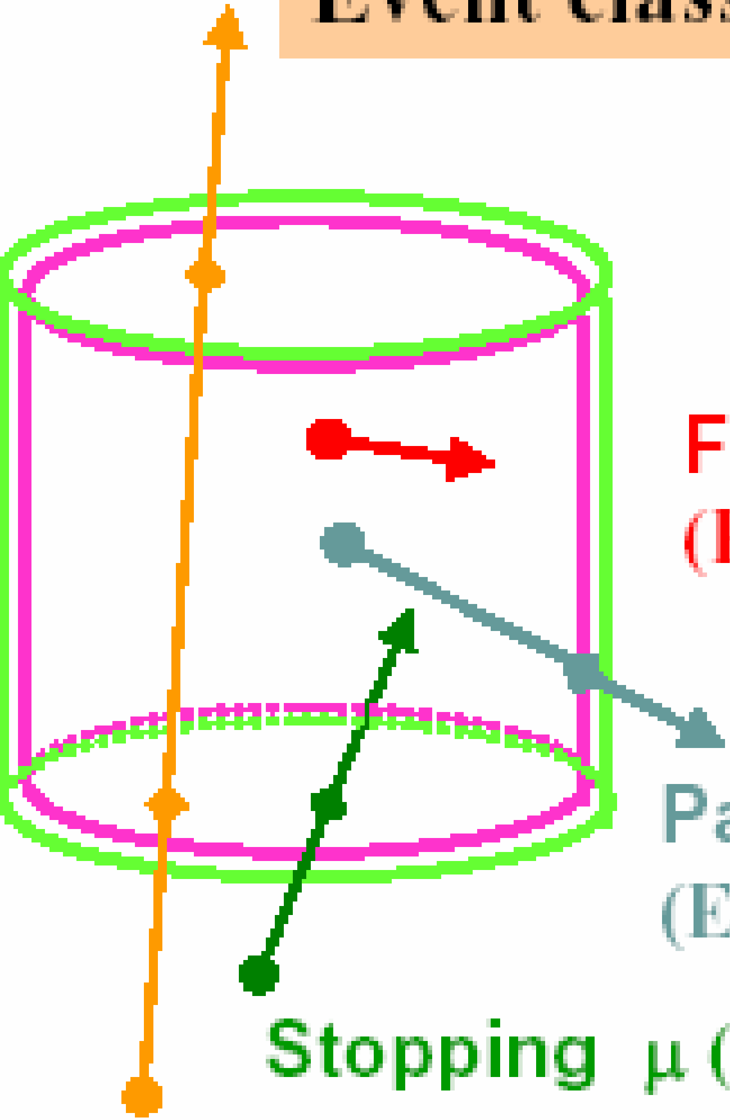
In down(3)+

Up stop(4) 262

Event classification

SuperK

$$n_m(\bar{n}_m) + N \rightarrow m^-(m^+) + X$$



Fully Contained
(E_ν ~1GeV)

$$\sigma_\nu(E_\nu) \sim \frac{\alpha^2}{M_W^4} M_p\, E_\nu\, (\hbar\, c)^2 \sim 10^{-38}\, E(\mathrm{GeV})\, \mathrm{c}$$

Partially Contained
(E_ν ~10GeV)

Stopping μ (E_ν ~10GeV)

Through-going μ (E_ν ~100GeV)

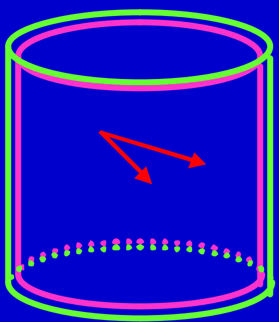
$$\vartheta_{\nu\mu} \approx 2{,}6 \left(\frac{100\ \mathrm{GeV}}{\mathrm{E}_\nu} \right)^{1/2}$$

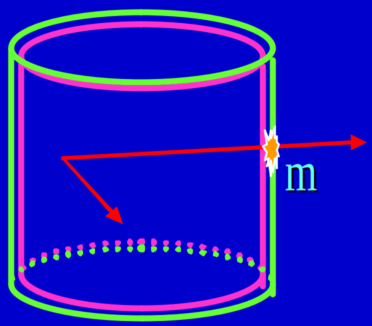
Neutrino events in Super-K

Contained events:

All have to be separate from „cosmic” muons (3Hz)

ully contained FC	Partially contained PC



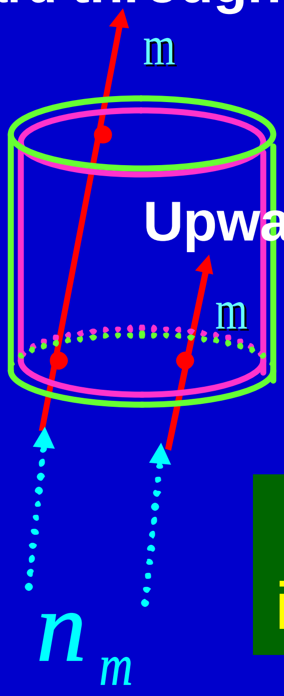


e/m identification

all assumed to be m

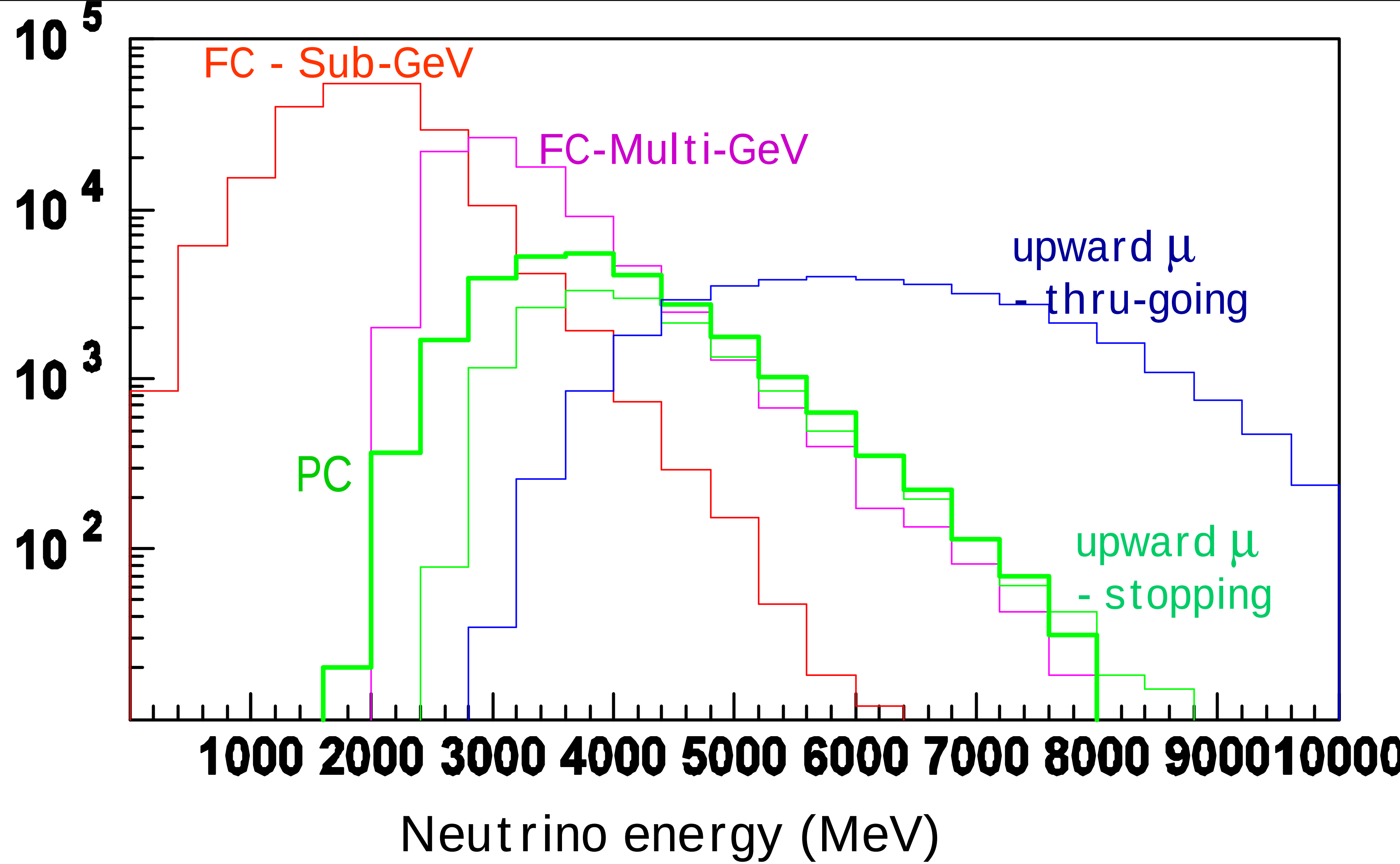
- different energy scale
- different analysis technique
- different systematics

Upward through-going m



Interaction in rocks

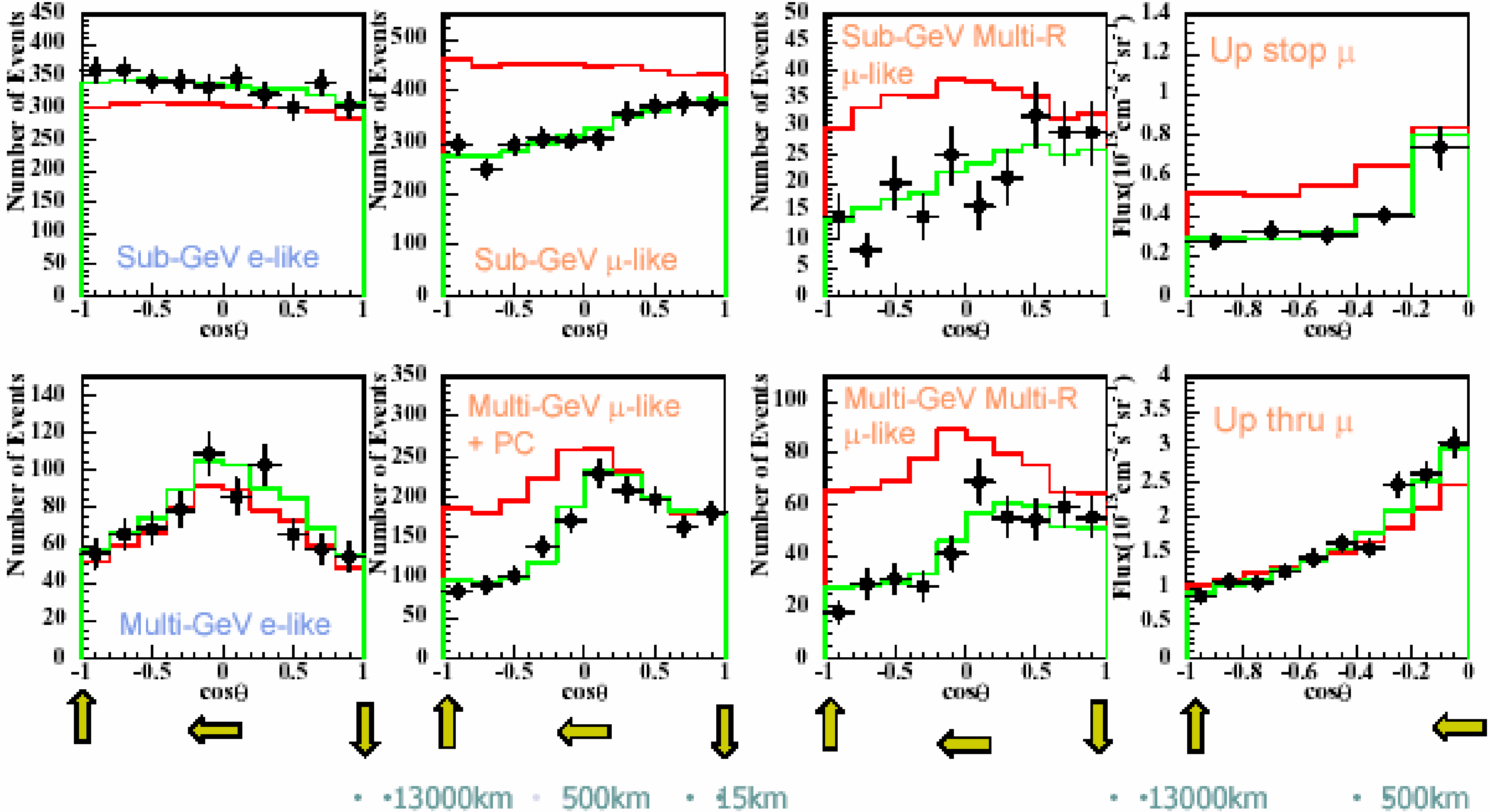
Neutrino energy spectra



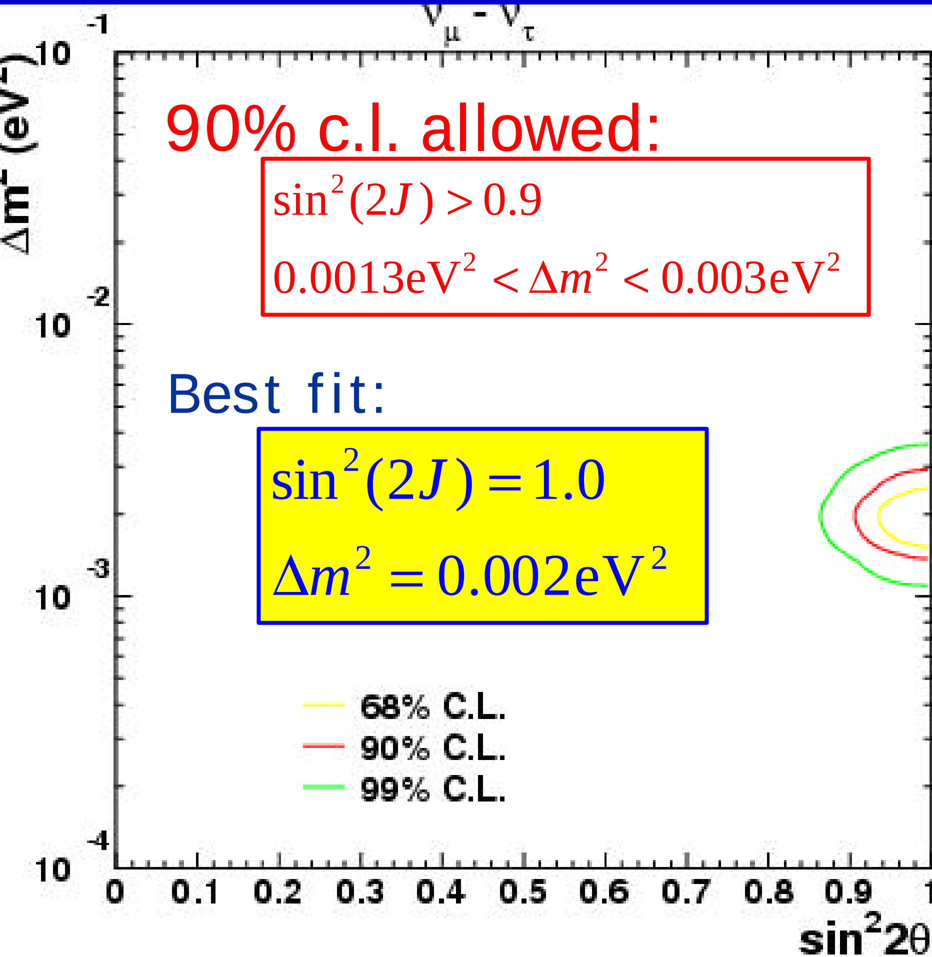
Zenith angle distributions

$\nu_\mu \leftrightarrow \nu_\tau$
2-flavor oscillations

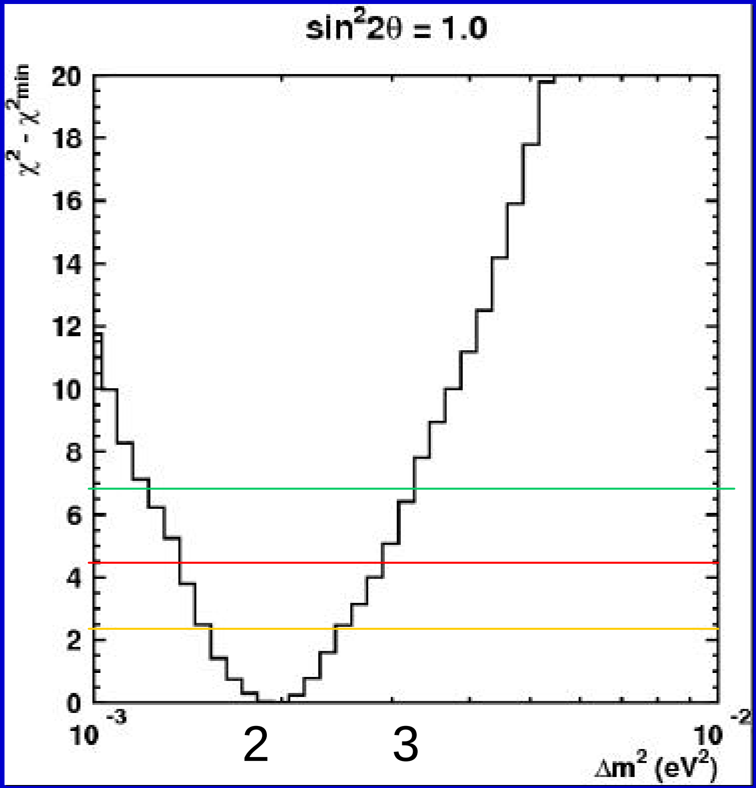
Best fit
$\sin^2(2\theta)=1.0$, $\Delta m^2=2.0\times10^{-3}$ eV^2
Null oscillation



Results of combined fit (2 flavors)
FC + PC + Up-m + Multi-ring

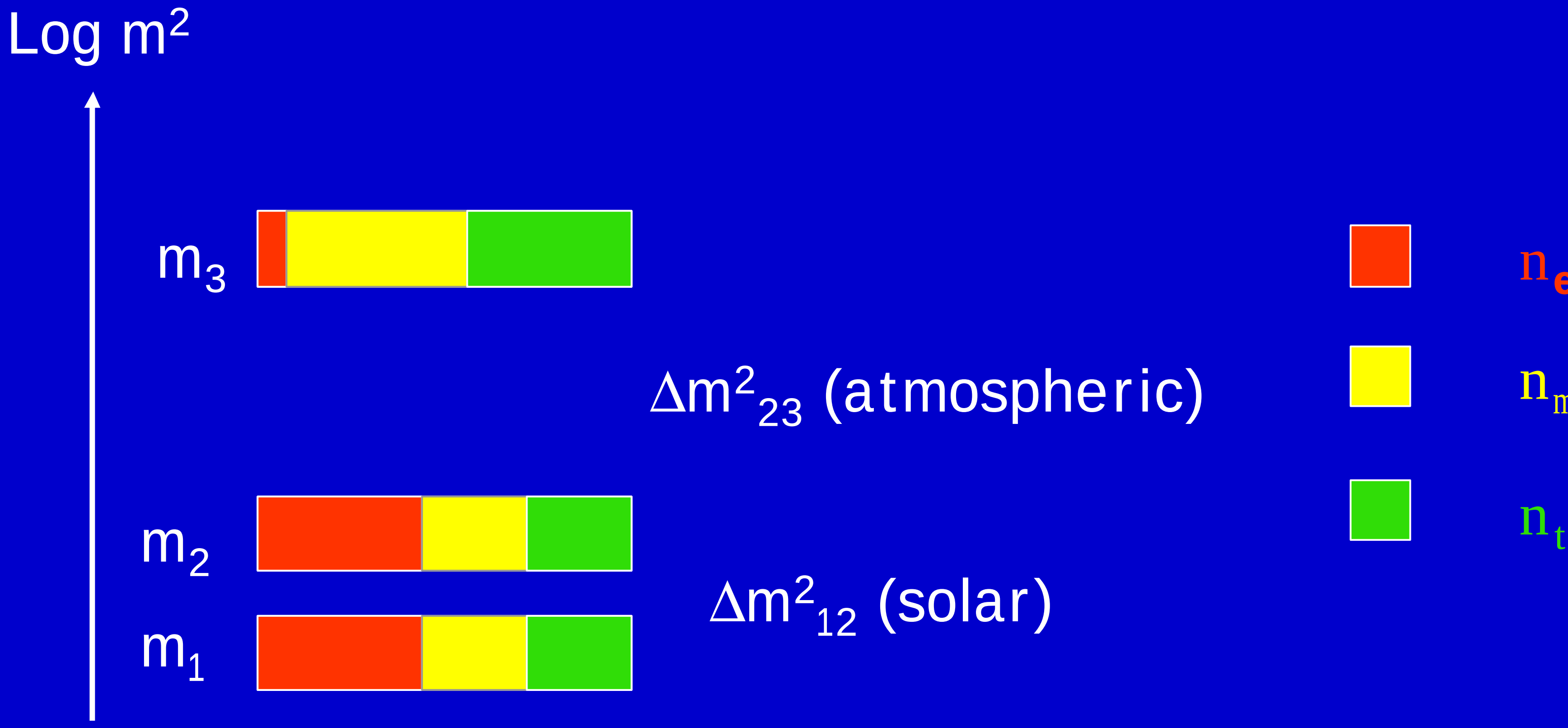


c^2 vs Dm^2



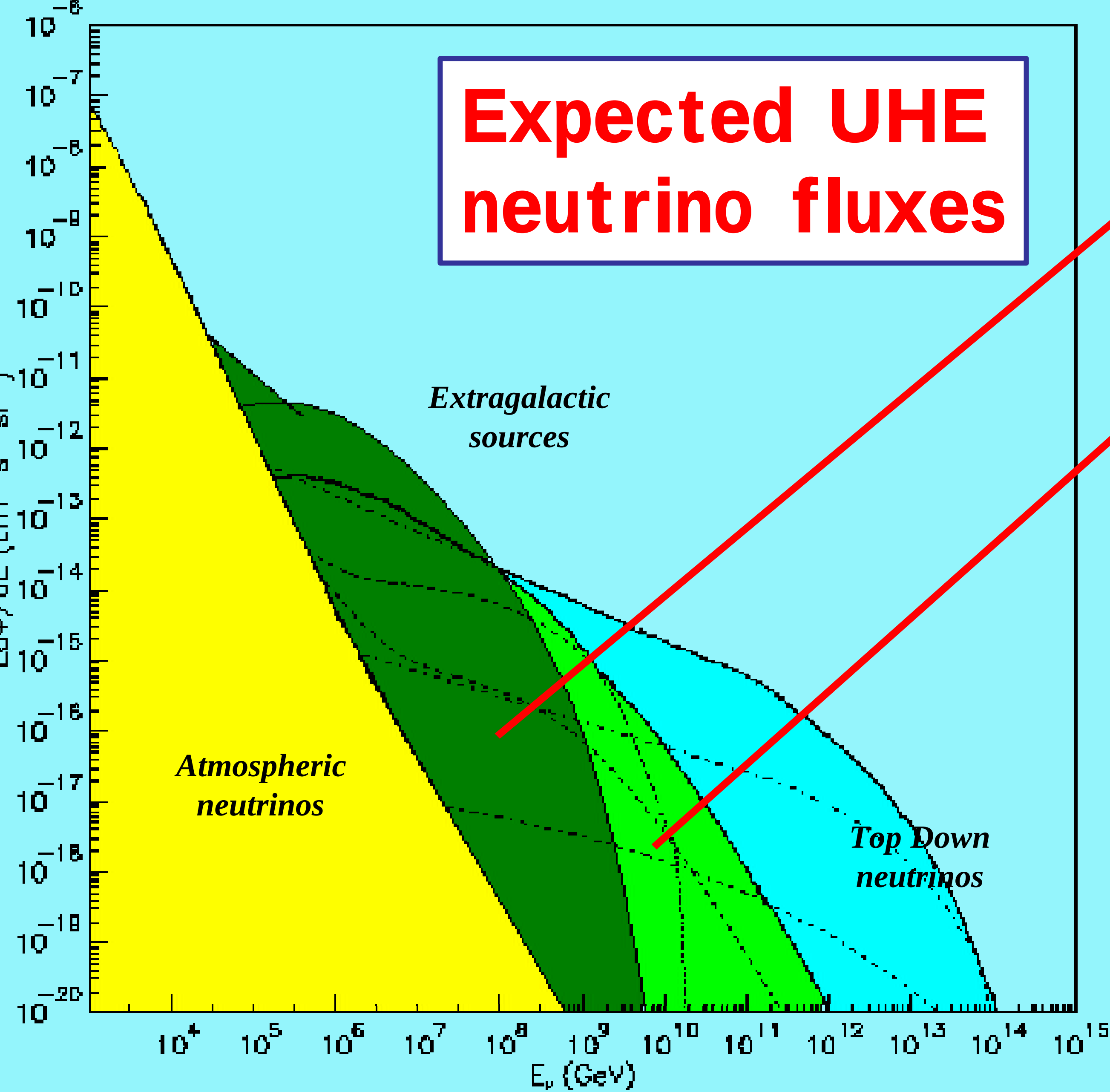
1489 days – updated Nov 2003

A plausible neutrino mass hierarch



Describes well solar and atmospheric neutrino oscillations, ignores LSND result

Expected UHE neutrino fluxes

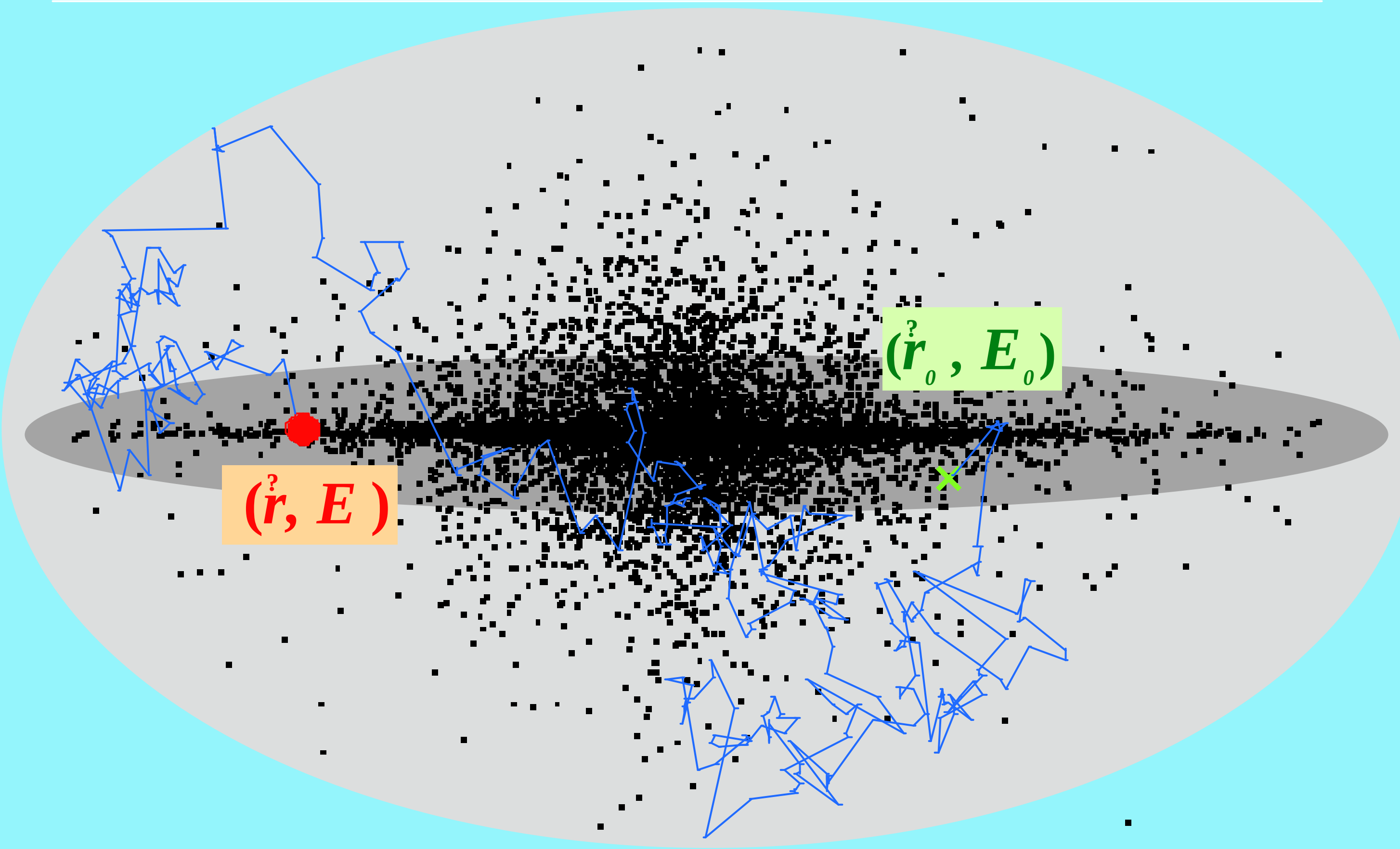


AGN Model Stecker

AGN Models Protheroe, Mannheim

GRB (fireball model) good candidates bu big variability in flux calculations depending on GRB distance

$F\ (r, E; r_0, E_0)$: structure function

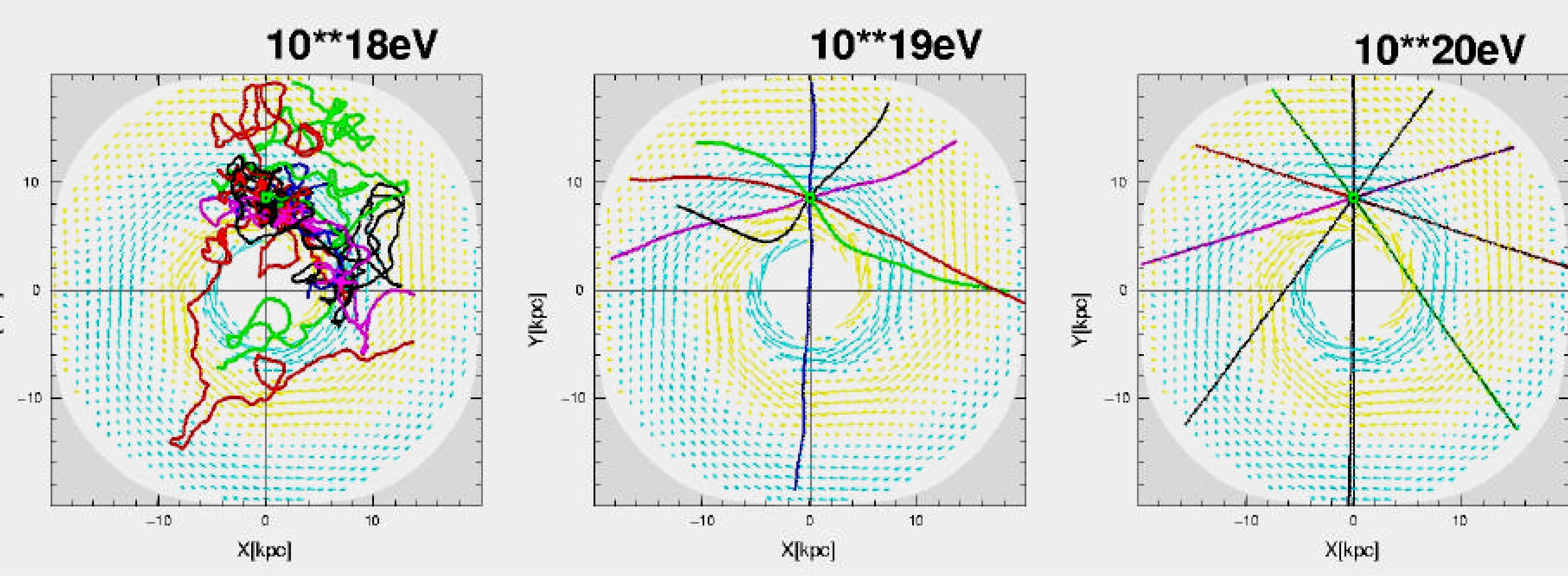


● : solar system $\vec{r}\ (r \sim 10\text{kpc}, z \sim 0)$

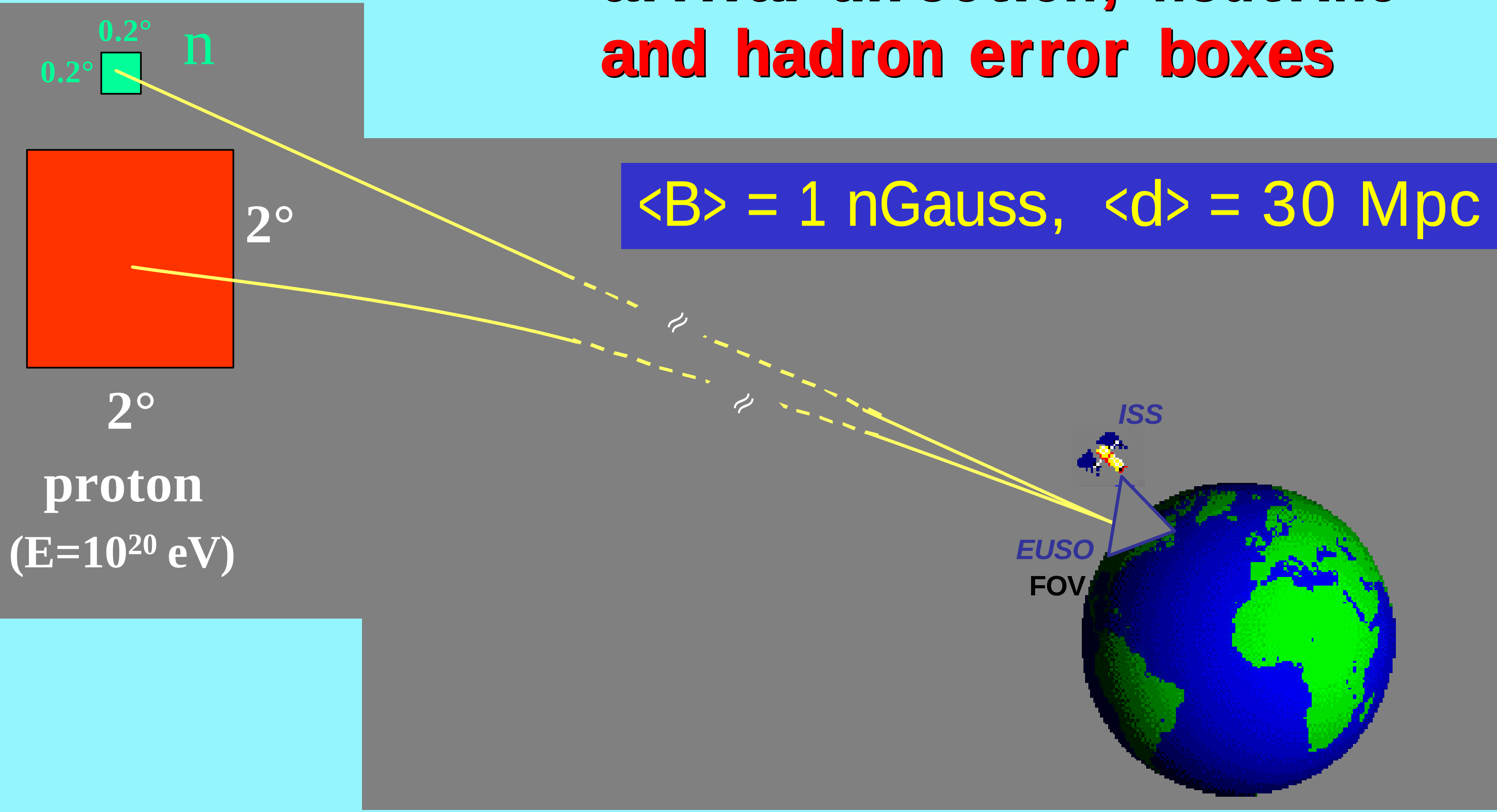
× : source $\vec{r}_0\ (r_0\ , z_0)$

Cosmic Ray Propagation in our Galaxy

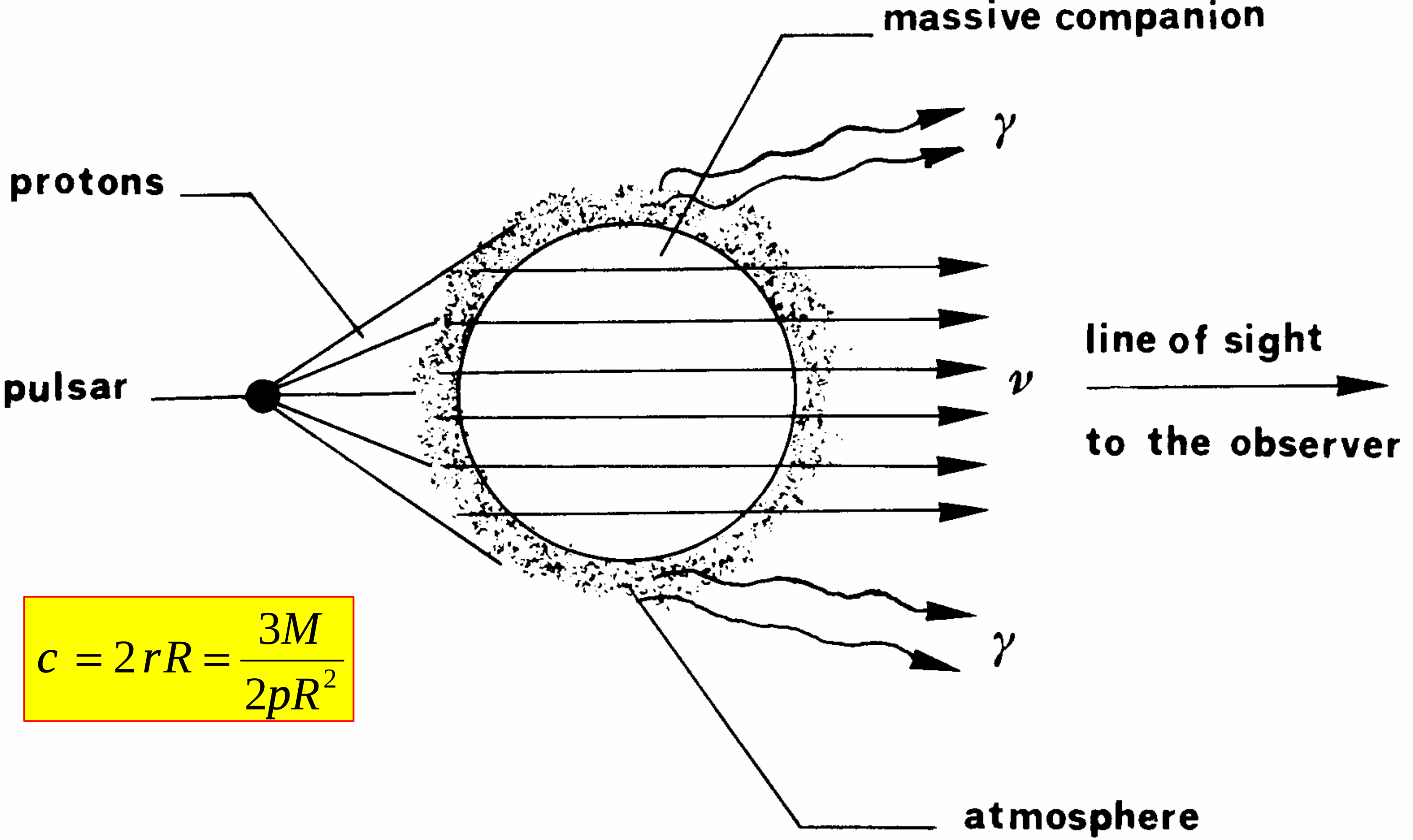
- Deflection angle < 1 degree at 10^{20}eV



arrival direction, neutrino and hadron error boxes



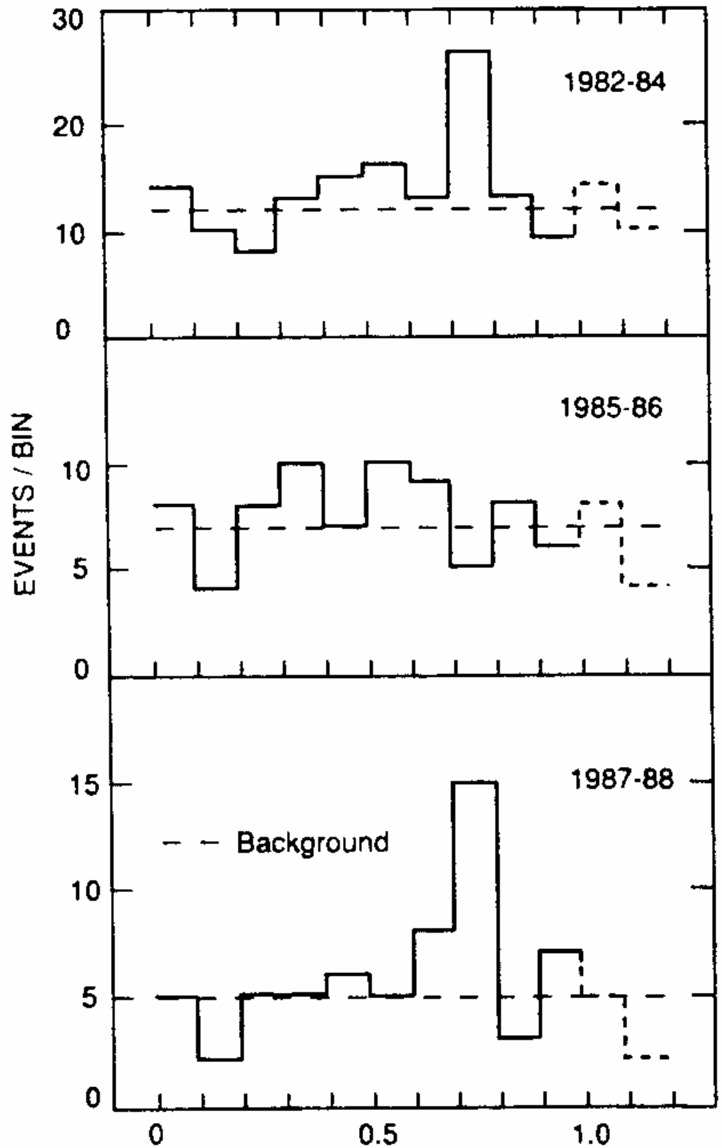
The neutrino error box is limited only by the instrument angular resolution, the proton error box is dominated by the intergalactic magnetic fields.



$$c = 2 r R = \frac{3M}{2pR^2}$$

$$s(n_m) = 0{,}6 \cdot 10^{-38} E_n \ \text{cm}^2$$
$$s(\bar{n}_m) = 0{,}3 \cdot 10^{-38} E_n \ \text{cm}^2$$

$$\vartheta_{\nu\mu} \approx 2{,}6 \left(\frac{100 \ \text{GeV}}{\text{E}_\nu} \right)^{1/2}$$



30
20
10
0
1982-84
1985-86
EVENTS / BIN
10
5
0
1987-88
15
Background
10
5
0
0
0.5
1.0

Cyg X-3 Nusex

AGN Unified Model

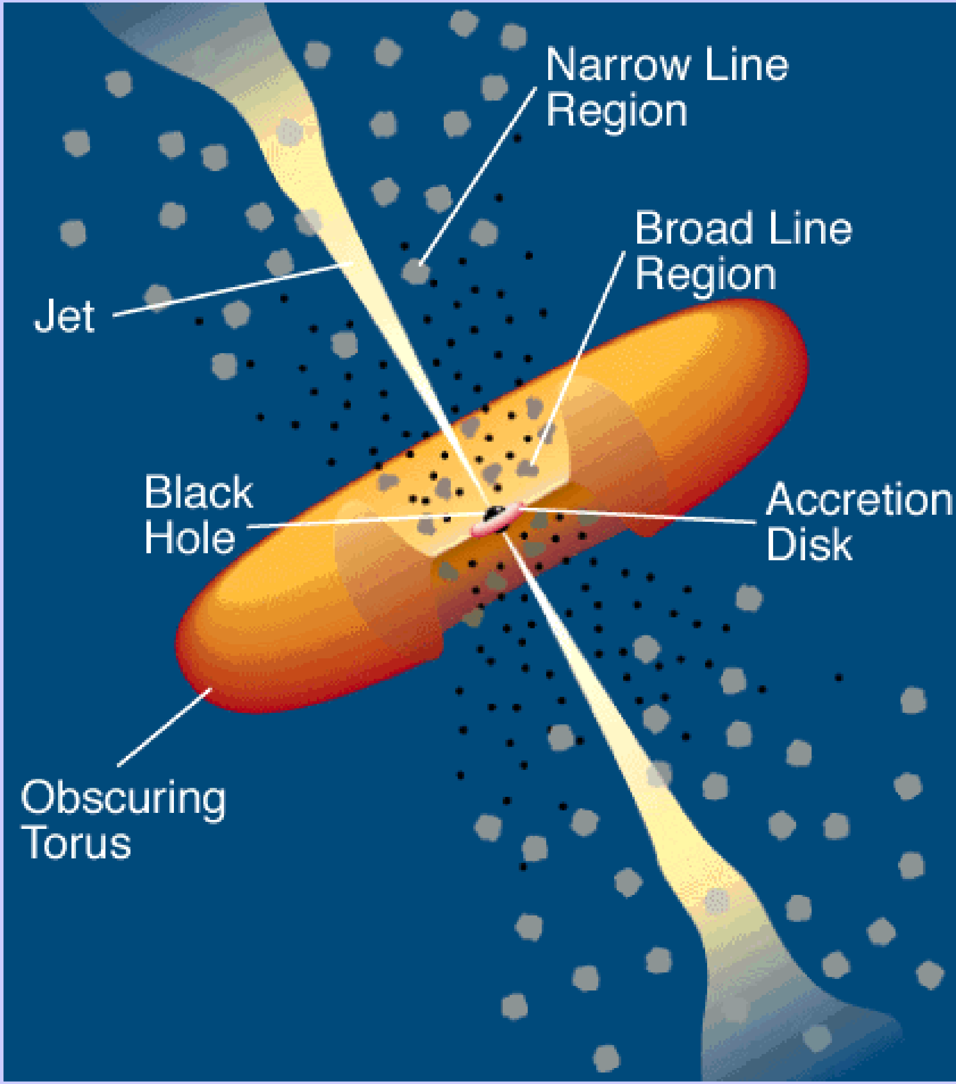
According to the Unified Model all AGNs share the same fundamental mechanism.

Source of energy:

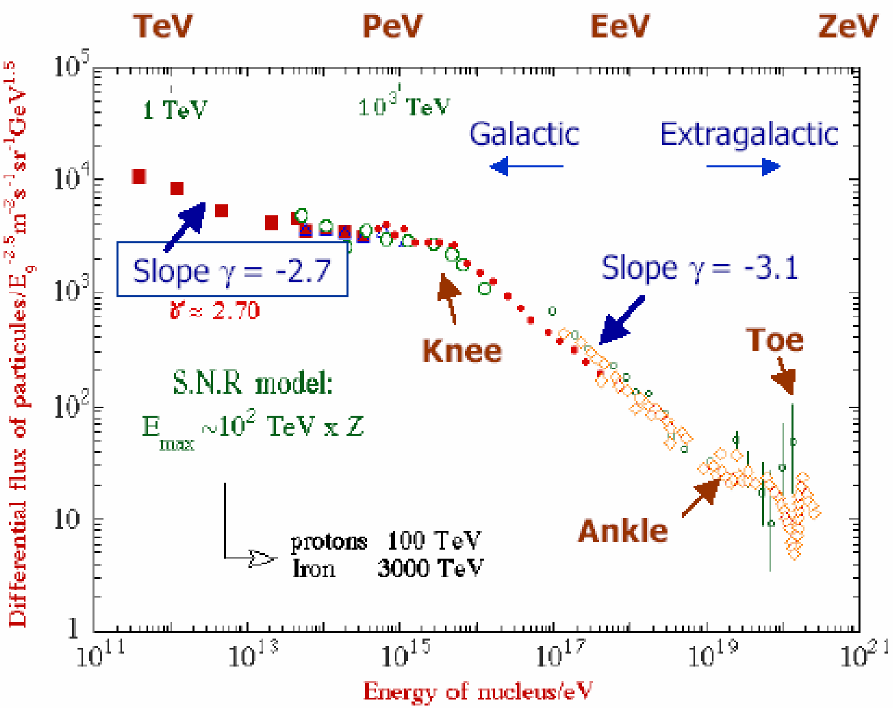
super massive black hole ~10^6-10^9 solar masses

+ accretion disk

Fuel: 1-10 solar masses /year



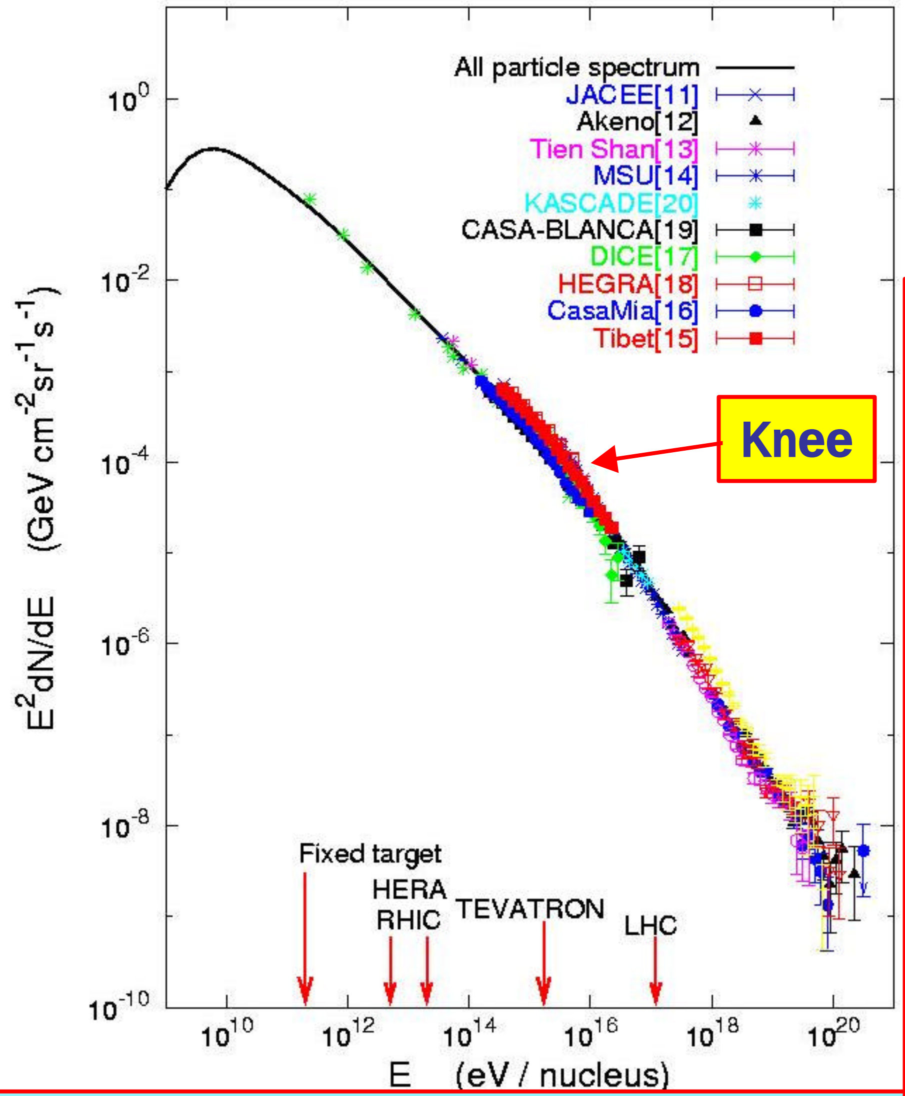
The Cosmic Ray Spectrum

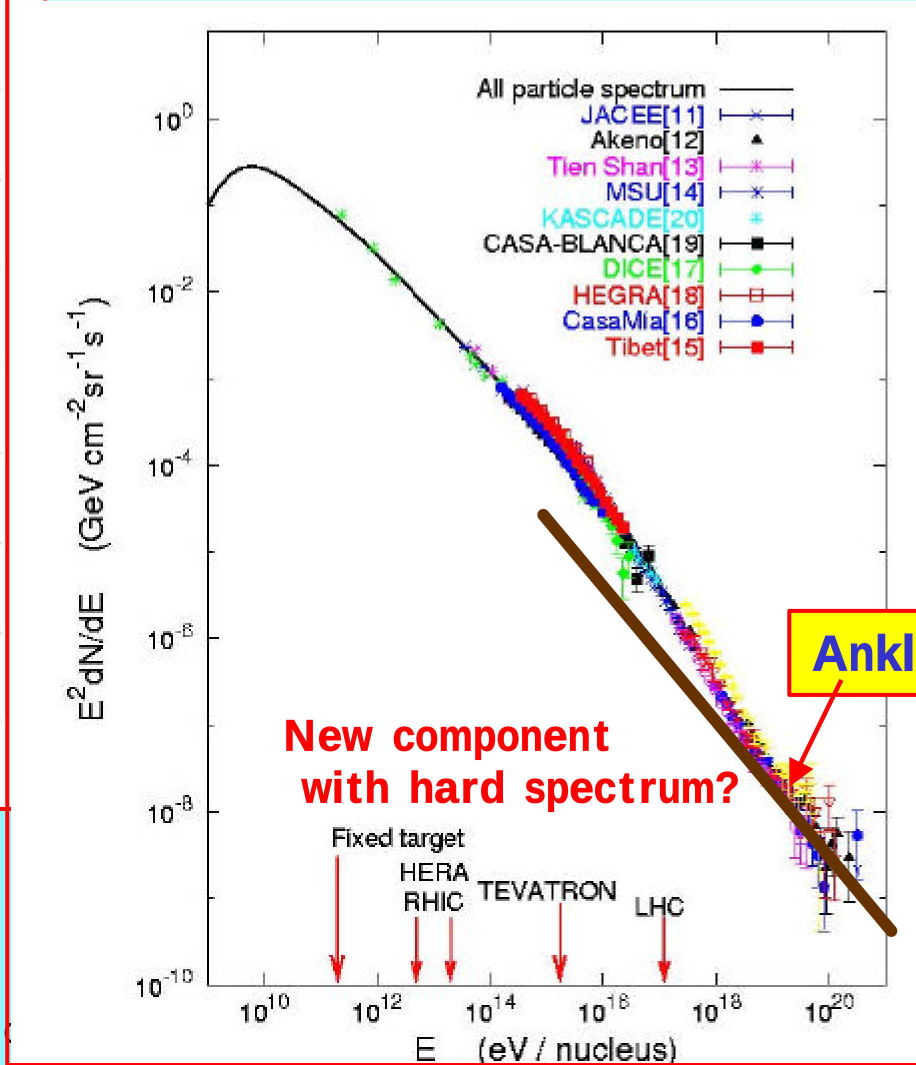


All-charged-particle spectrum plotted to make it easier to see slope changes (flux is scaled by $E^{2.5}$)

PS: Need to know prefixes for really big powers of 10!

- TeV = Tera-electron-volt (10^{12} eV)
- PeV = Peta-electron-volt (10^{15} eV)
- EeV = Exa-electron-volt (10^{18} eV)
- ZeV = Zetta-electron-volt (10^{21} eV)


All particle spectrum
JACEE[11]
Akeno[12]
Tien Shan[13]
MSU[14]
KASCADE[20]
CASA-BLANCA[19]
DICE[17]
HEGRA[18]
CasaMia[16]
Tibet[15]
Knee
Fixed target
HERA
RHIC
TEVATRON
LHC
$E^2dN/dE \quad (GeV\ cm^{-2}sr^{-1}s^{-1})$
$E \quad (eV / nucleus)$


All particle spectrum
JACEE[11]
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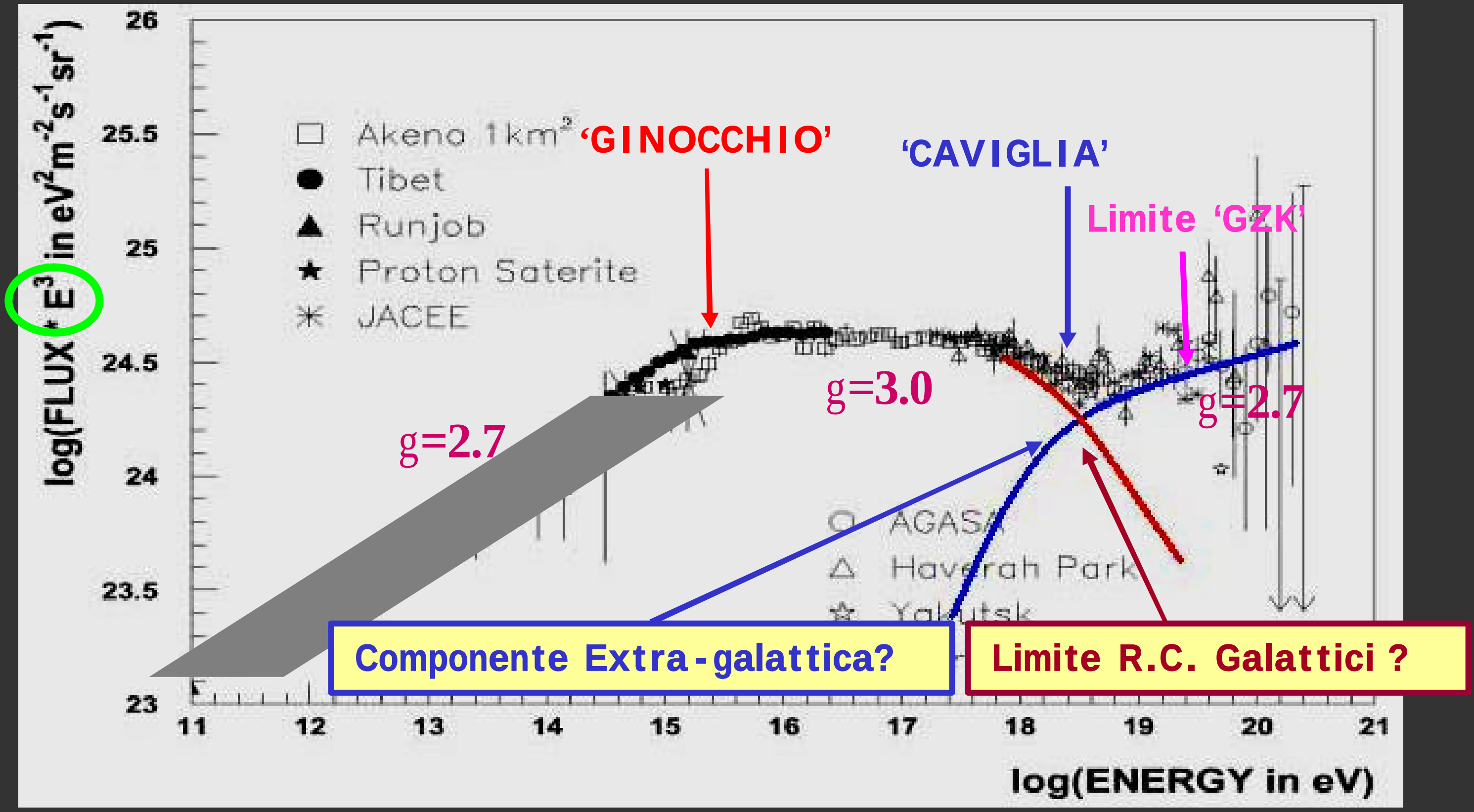
MSU[14]
KASCADE[20]
CASA-BLANCA[19]
DICE[17]
HEGRA[18]
CasaMia[16]
Tibet[15]
Ankl
New component
with hard spectrum?
Fixed target
HERA
RHIC
TEVATRON
LHC
$E^2dN/dE \quad (GeV\ cm^{-2}sr^{-1}s^{-1})$
$E \quad (eV / nucleus)$

…la caviglia segna il passaggio tra r.c. galattici ed extra galattici ?



Sull'origine dei raggi cosmici (entro il limite GZK)

L'identificazione delle sorgenti di origine è legata all'energia dei raggi cosmici stessi.

Per energie entro il limite GZK, i raggi cosmici sono prodotti in sistemi celesti dotati di intensi campi magnetici che riescono ad accelerare i nuclei ad alte energie o sono prodotti durante l'esplosione di una stella.

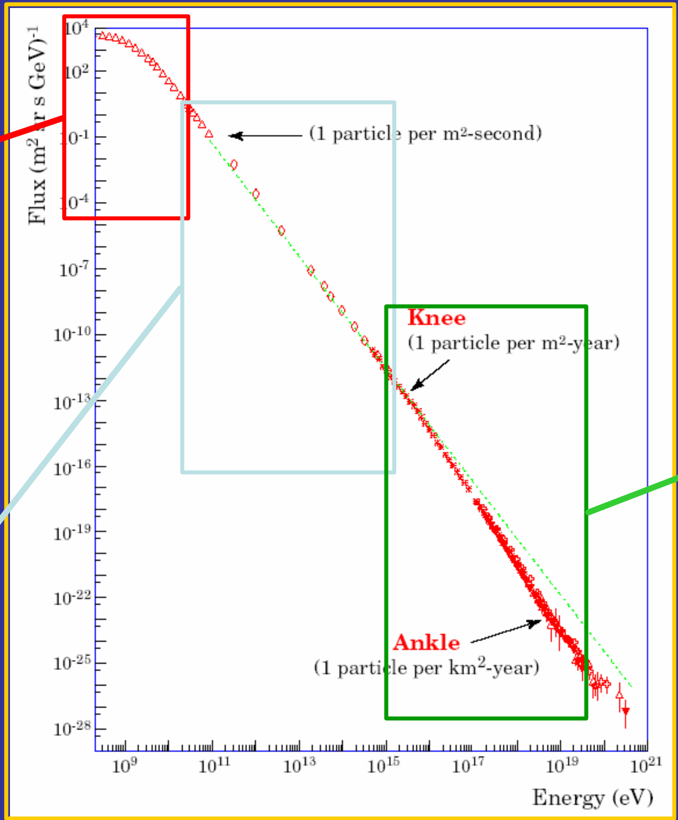
$10^9 \div 10^{10}$ eV:

origine solare

$10^{10} \div 10^{15}$ eV:

origine galattica

(esplosioni di SuperNovae)



$10^{15} \div 5\times10^{19}$ eV (limite GZK):

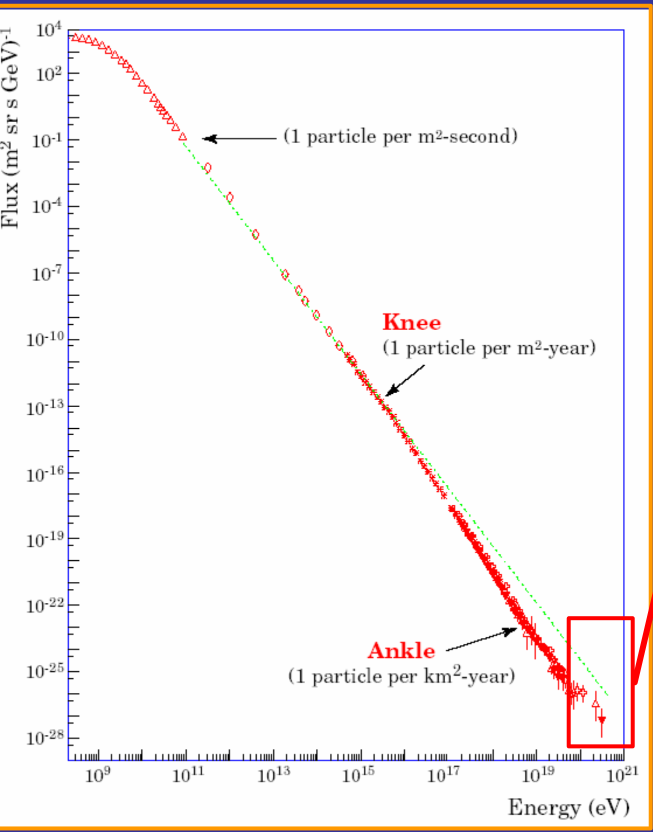
origine extragalattica

(esplosioni di Super Novae, pulsar con intensi campi magnetici, buchi neri nuclei galattici attivi)

Sull'origine dei raggi cosmici (oltre il limite GZK)

Per energie E_0 >~ 5×10^{19} eV l'origine dei raggi cosmici primari diventa un mistero.

Potenziali sorgenti sono:



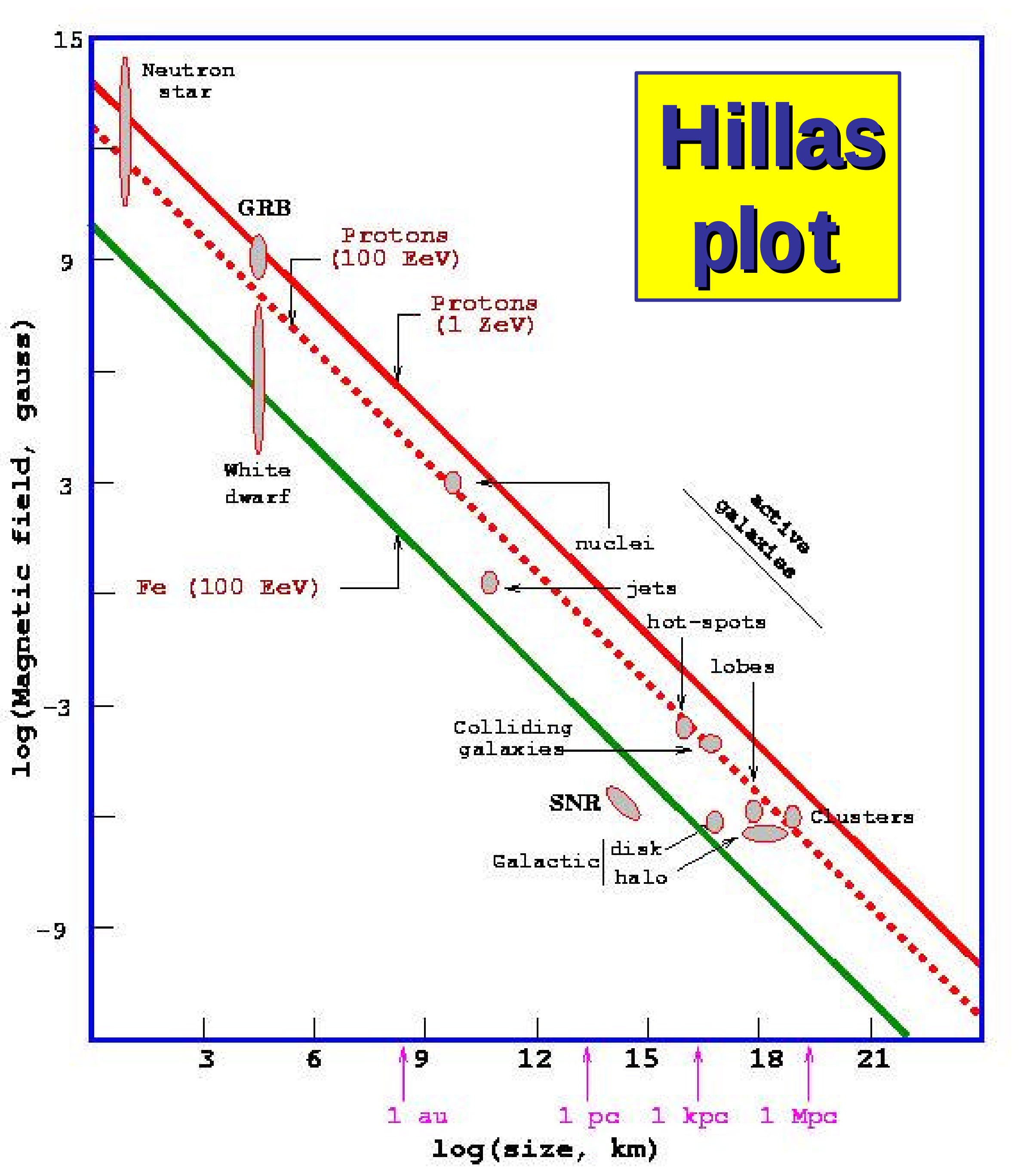
- Collisioni tra galassie o ammassi di galassie, radio galassie. Ma la presenza della radiazione di fondo cosmico (CMB) impedisce che particelle di altissima energia possano percorrere distanze cosmologiche (effetto GZK); la massima distanza da cui possono provenire è quella dell'ammasso della Vergine (M87). Ma questo contraddice con la isotropia del fenomeno EHECR. Infatti, mentre i CR di energia inferiore a 10^{18} eV mostrano una piccola ma significativa anisotropia verso il centro galattico, la distribuzione delle direzion di arrivo degli EHECR è apparentemente isotropa su larga scala, con una indicazione di raggruppamenti su piccola scala (doppiette, triplette) che suggeriscono la possibile esistenza di sorgenti compatte.
- Decadimento di particelle createsi subito dopo il Big Bang. In questo caso molti dei Raggi Cosmici EHECR dovrebbero essere neutrini.

Poche sorgenti sopravvivono al criterio

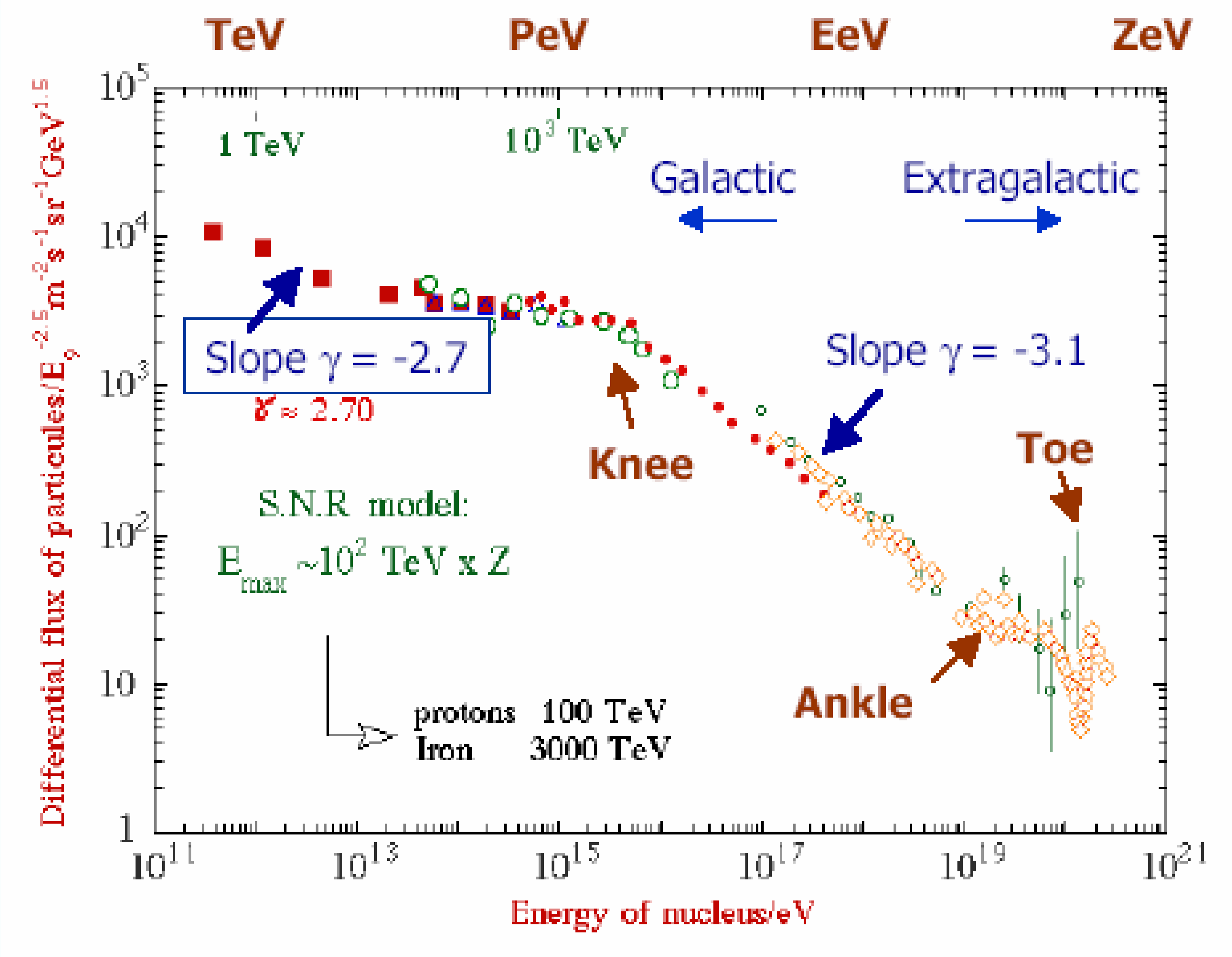
B x L > E/Z

- Stelle di neutroni
- GRB
- AGN
- Radio lobi
- Ammassi
- collisioni di Galassie/Ammassi

$$E_{MAX} \propto gZBL$$

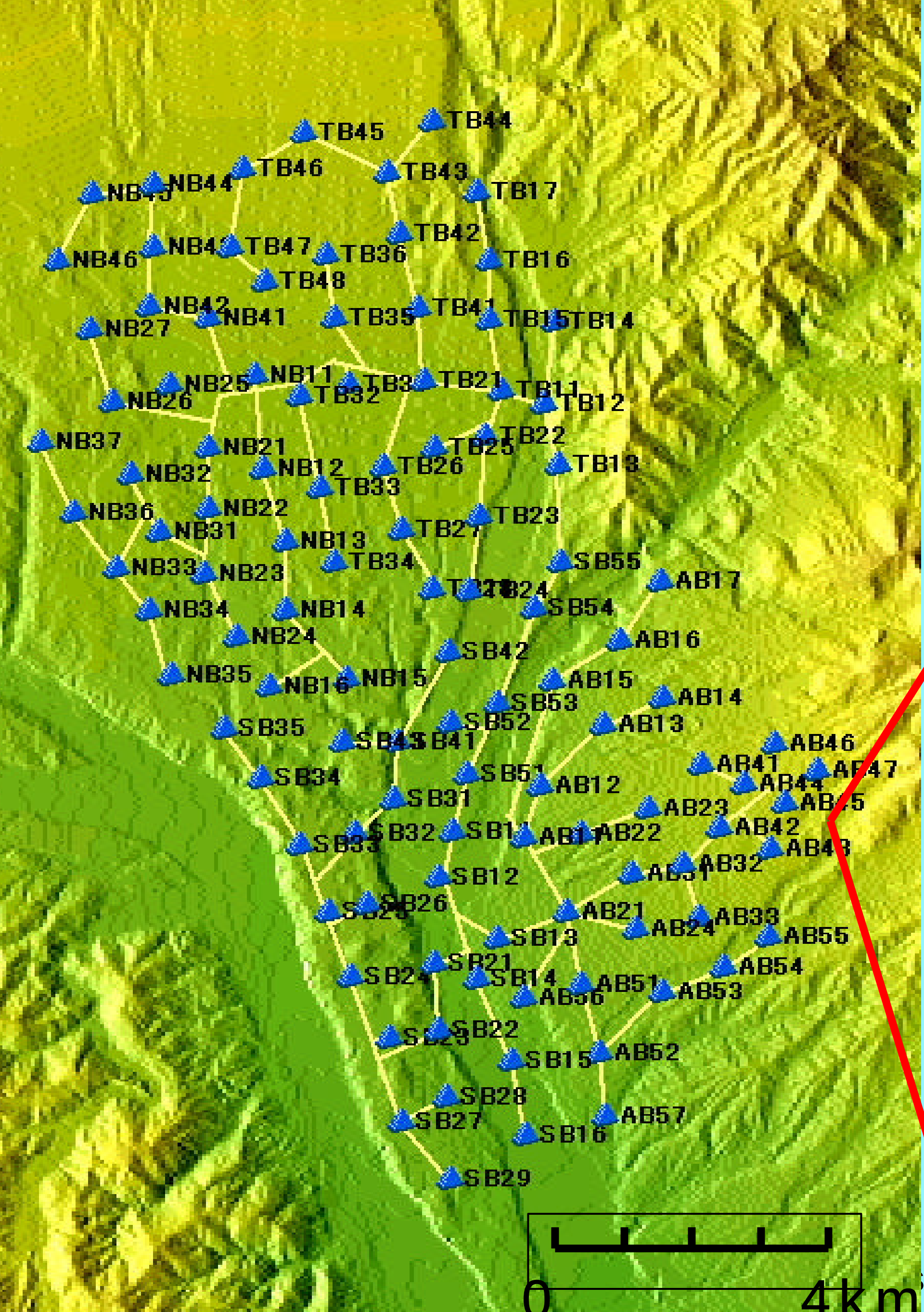


- **Atmosphere is required for the primary particle to interact and develop shower with a production of :**
  - **Cherenkov light**
  - **fluorescence light**
- **Details of the UV light production yield details of the primary particle :**
  - **the amount of UV light produced is proportional to the particle's energy**
  - **the shape of the shower profile and the atmospheric depth of the shower maximum contain information about particle mass composition**


TeV
PeV
EeV
ZeV
1 TeV
10^3 TeV
Galactic
Extragalactic
Slope γ = -2.7
γ ≈ 2.70
Knee
Slope γ = -3.1
Toe
S.N.R model:
E_{max} ~10^2 TeV x Z
protons 100 TeV
Iron 3000 TeV
Ankle
Differential flux of particules/$E_9^{-2.5}$ $m^{-2}s^{-1}sr^{-1}GeV^{1.5}$
Energy of nucleus/eV
10^5
10^4
10^3
10^2
10
1
10^{11}
10^{13}
10^{15}
10^{17}
10^{19}
10^{21}

AGASA

Akeno Giant Air Shower Array

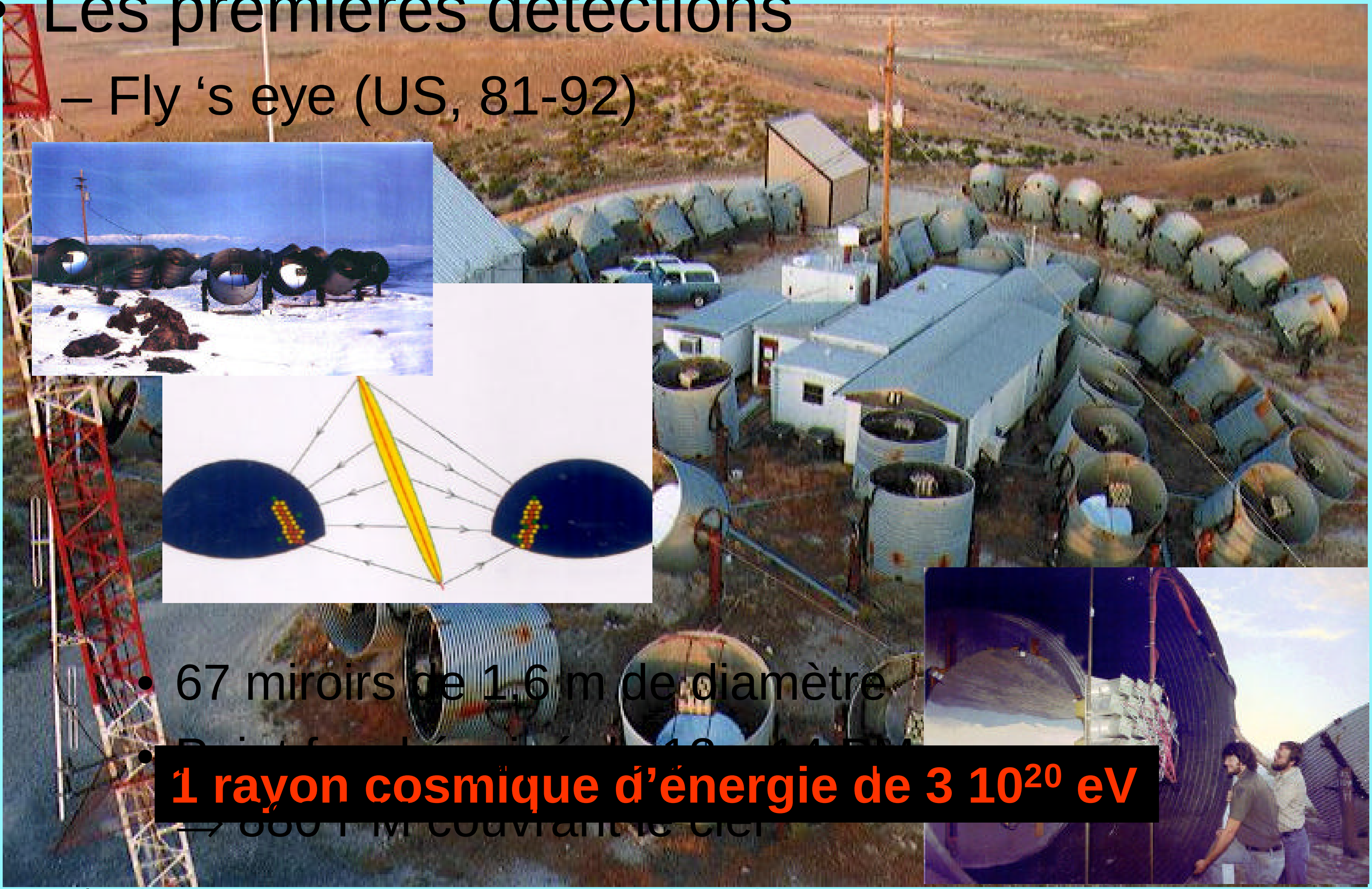


111 Electron Det

27 Muon Det.

• Les premières détections

– Fly 's eye (US, 81-92)



• 67 miroirs de 1,6 m de diamètre

1 rayon cosmique d'énergie de 3 10^{20} eV

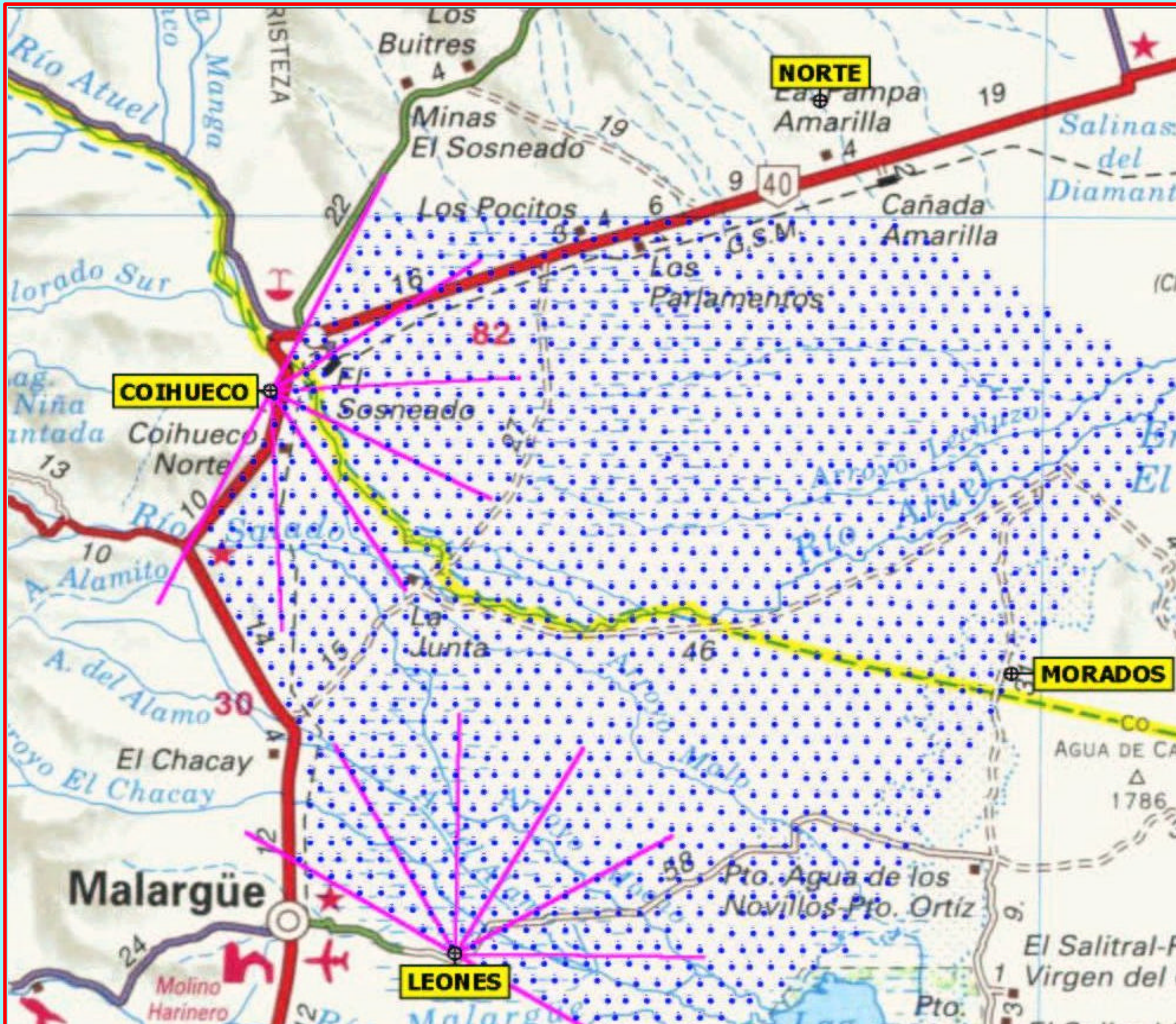
⇒ 880 PM couvrant le ciel

The Auger Observatory

Area ~ 3000 km² Aperture ~ 7400 km² sr

SD Array 1600
herenkov tanks
1.5 km spacing

FD 24
uorescence
lescopes
4 buildings



P.Galeotti


EUSO
esa
EUSO


Gravitational Wave Detectors
Interferometric
Resonant-Mass
LISA
GEO
AURIGA
EXPLORER
VIRGO
NAUTILUS
TAMA
LIGO
LIGO
ALLEGRO
NIOBE

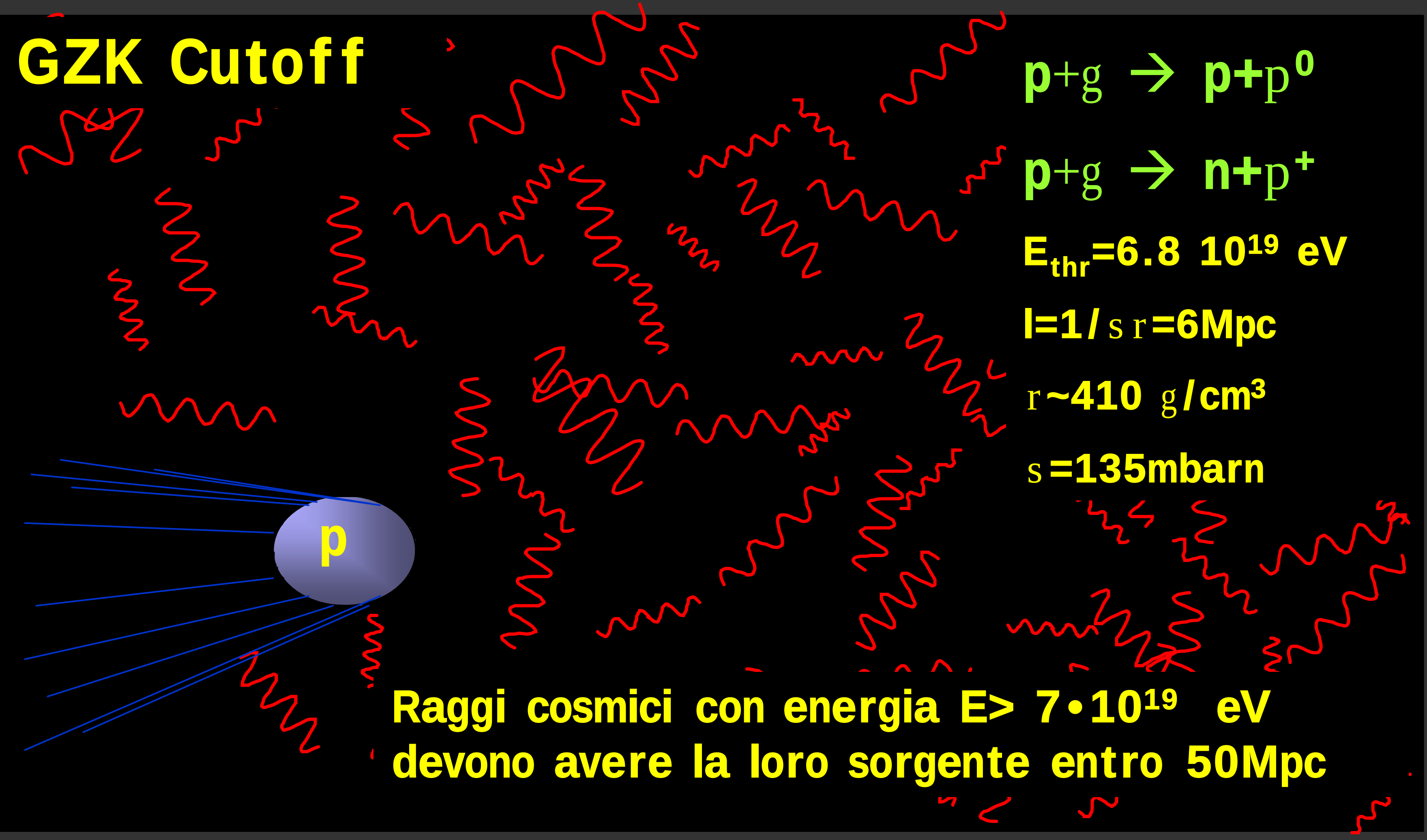
Greisen, Zatsepin and Kuzmin (1960) pointed out that there ought to be a "cutoff" in the cosmic ray spectrum around 10^{20} eV:

- The universe is filled with Cosmic Background Radiation (CBR), relic photons from the Big Bang
- CBR photons have an energy spectrum characteristic of a blackbody at ~3K, so they are in the ~0.001 eV (microwave) energy range
- But in the rest frame of a 10^{20} eV proton, they look like high energy (10^9 eV) gamma rays!
- Protons and nuclei have a high probability (cross section) for interacting with GeV gamma rays and getting smashed into other (lower energy) particles

Many hypotheses have been offered, suggesting UHE CRs are due to:

- Bottom-up models: some variant of the same mechanism valid for lower energies
- Top-down models: created at UHE - due to decay of a very heavy parent particle (GUT or supersymmetry models), or perhaps due to topological defects in the Universe
- Neutrino interactions in intergalactic space
- Exotic astrophysics: AGNs, , jets, GRBs - little is known about gamma ray bursters or UHE CRs, so maybe there is a connection!
- Magnetic field models: maybe intergalactic space has a larger magnetic field than expected, so charged particles do not point back to sources even at UHE
- Violation of Lorentz invariance - would solve the GZK puzzle

a radiazione cosmica di fondo a 3 ^{0}K rende l'Universo
paco ai raggi cosmici di energia molto elevata
. Greisen - G.T.Zatsepin & V.A.Kuz'min (1966)



Propagation : interaction des RC avec le CMB

- **Ces photons sont inoffensifs, car d'énergie très faible…**
  ... à moins de se jeter sur eux à toute allure !!!

	proton	photon
Système du laboratoire	10^{20} eV	0.5 meV
Référentiel du proton	$E_{cin}=0$	300 MeV

Interaction des RC avec le CMB

Interaction des protons

- photoproduction de pions :

$$p+\gamma_{2,7K} \rightarrow \Delta \rightarrow n+\pi^{+}$$
$$p+\gamma_{2,7K} \rightarrow \Delta \rightarrow p+\pi^{0}$$
$$p+\gamma_{2,7K} \rightarrow \Delta \rightarrow p+e^{+}+e^{-}$$

- À chaque interaction, perte d'environ 22% d'énergie
- Processus se répète jusqu'à ce que l'énergie totale p–γ dans leur centre de masse soit inférieure au seuil de production de la résonance Δ :

c'est **l'effet Greisen-Zatsepin-Kuzmin (1966)**
ou effet GZK

Propagation : interaction des RC avec le CMB

- **Les noyaux ultra-énergétiques se brisent sur les photons du rayonnement fossile**

$$A + g_{2,7K} \rightarrow (A-1) + N$$
$$A + g_{2,7K} \rightarrow (A-2) + 2N$$
$$A + g_{2,7K} \rightarrow A + e^{+} + e^{-}$$

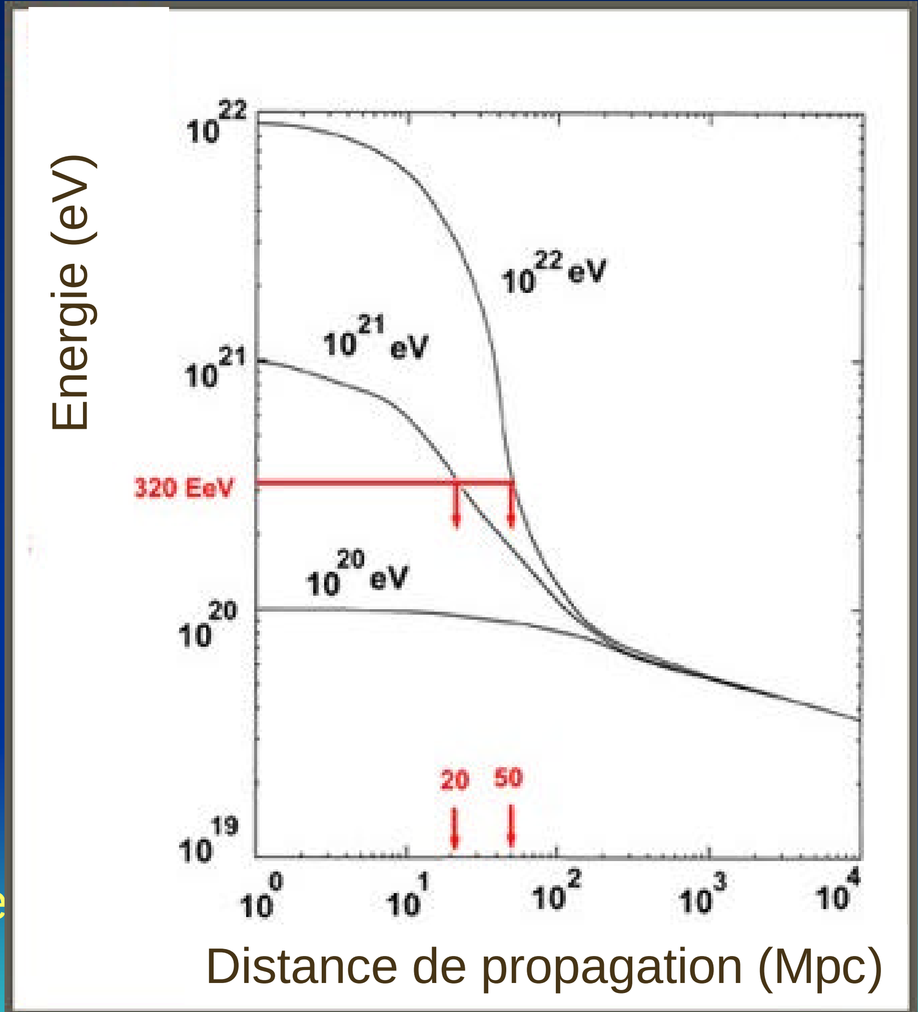
  - Energie d'excitation plus faible, mais sont les noyaux les plus stables $\Rightarrow$ étapes moins connues

- **Photons**
  - Seuil de création de paires $e^{+}e^{-}$ atteint rapidement. Coupure GZK vers $10^{12\text{-}13}$eV

- **Neutrinos**
  - Parfaitement insensible à tous les obstacles : sondes idéales… oui, mais extrêmement difficile de les détecter

Conséquences de l'effet GZK sur les protons

- **Libre parcours moyen**
  - Au dessus de 5.10^{19} eV : 10Mpc.
    (1 pc = 3.09 10^{16} m)
- **Brutalité de la coupure GZK:**
  - à partir de 100Mpc, toutes les énergies sont ramenées sous 10^{20} eV
  - record à 3 10^{20} eV $\Rightarrow$
    - Source dépassant largement cette énergie
    - Ou située à quelques dizaines de Mpc
  - Problème : on ne connaît pas de telle source !!!



THE GZK EFFECT

p + hn ® D$^+$ ® N + p

Energy and attenuation factor ($e^{-x/l}$ $_{GZK}$) are:

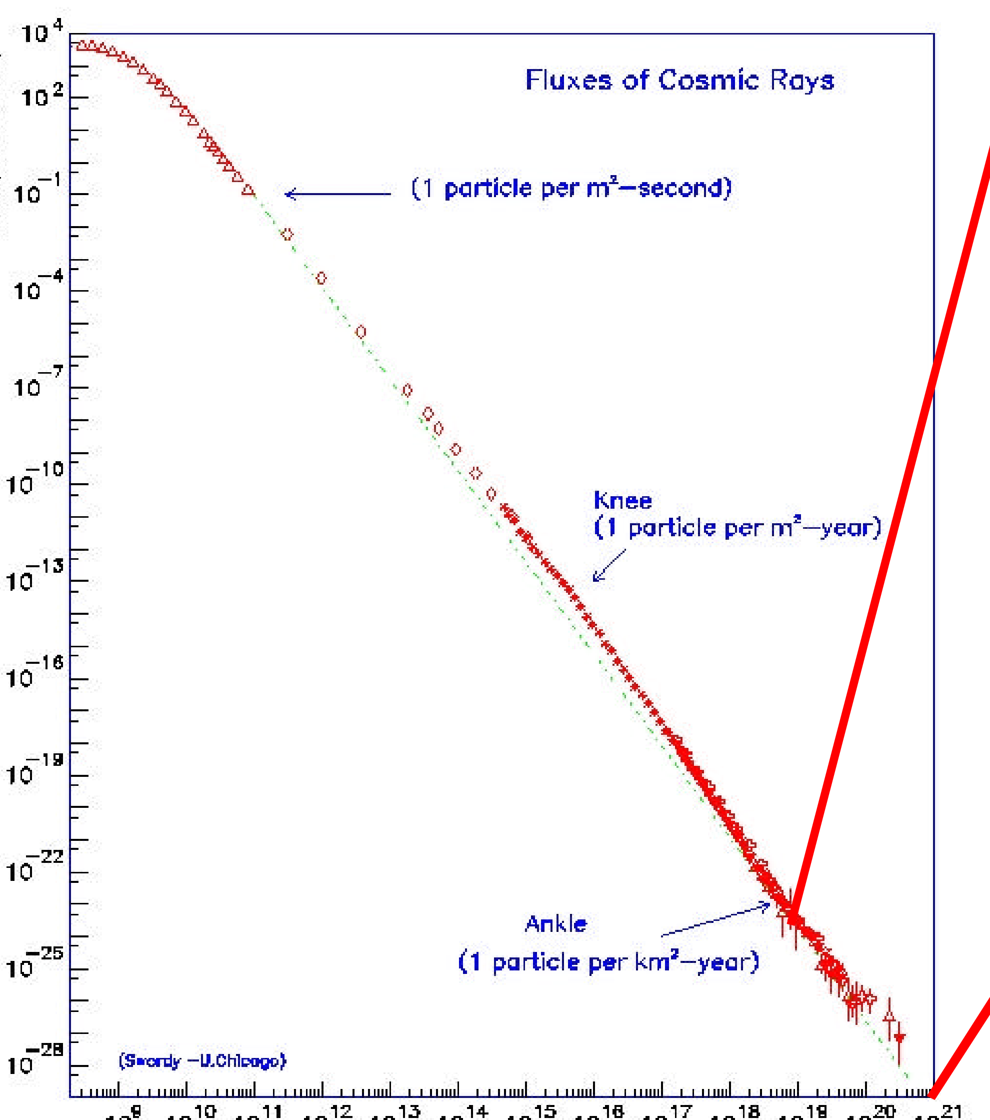
$$E_{GZK} \sim 5 \bullet 10^{19}\ \text{eV}$$

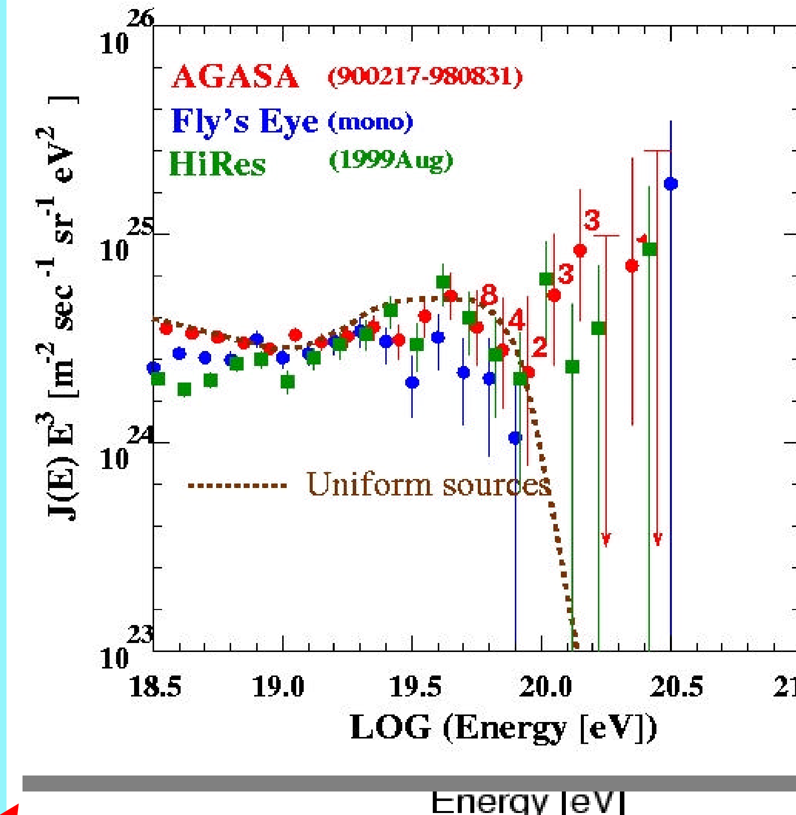
$$\lambda_{GZK} \sim 30\ \text{Mpc}$$

•Super-GZK hadrons from distant sources will lose energy and pile-up at sub-GZK energies.

•If UHE CR are protons, they show the highest value for the Lorentz factor ($\gamma \sim 10^{11}$) observed in nature.

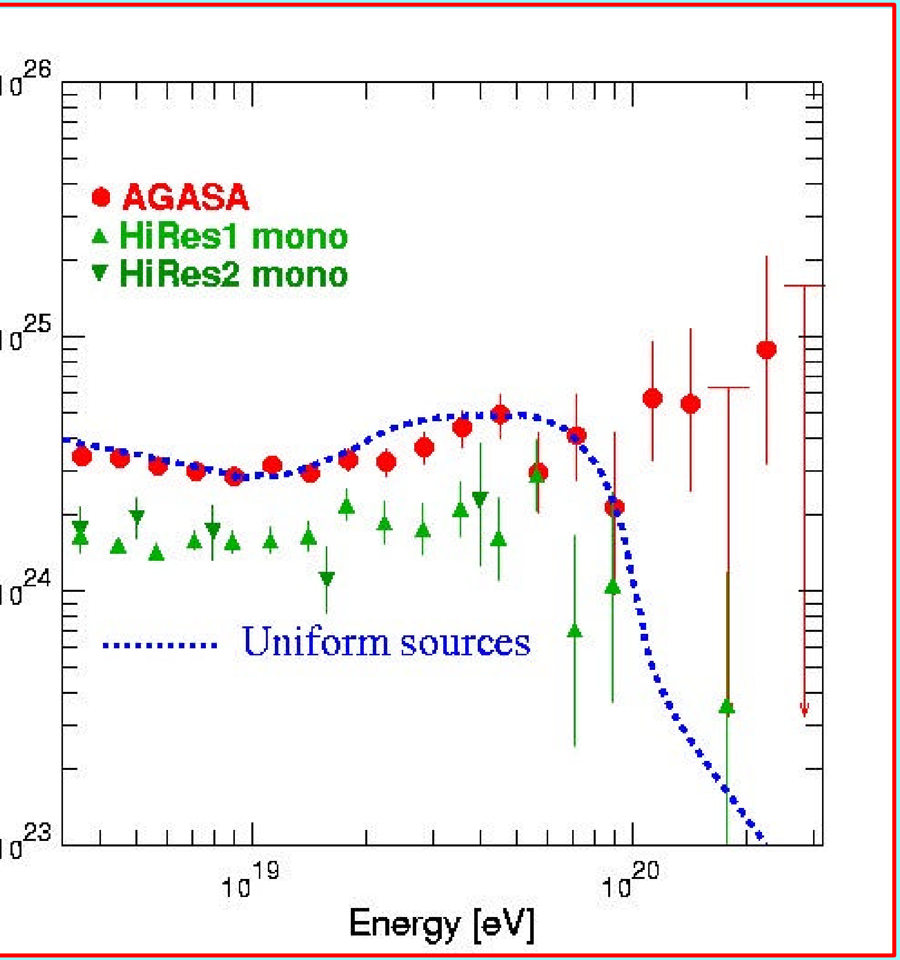
EECRs → E > 5*10^{19} eV

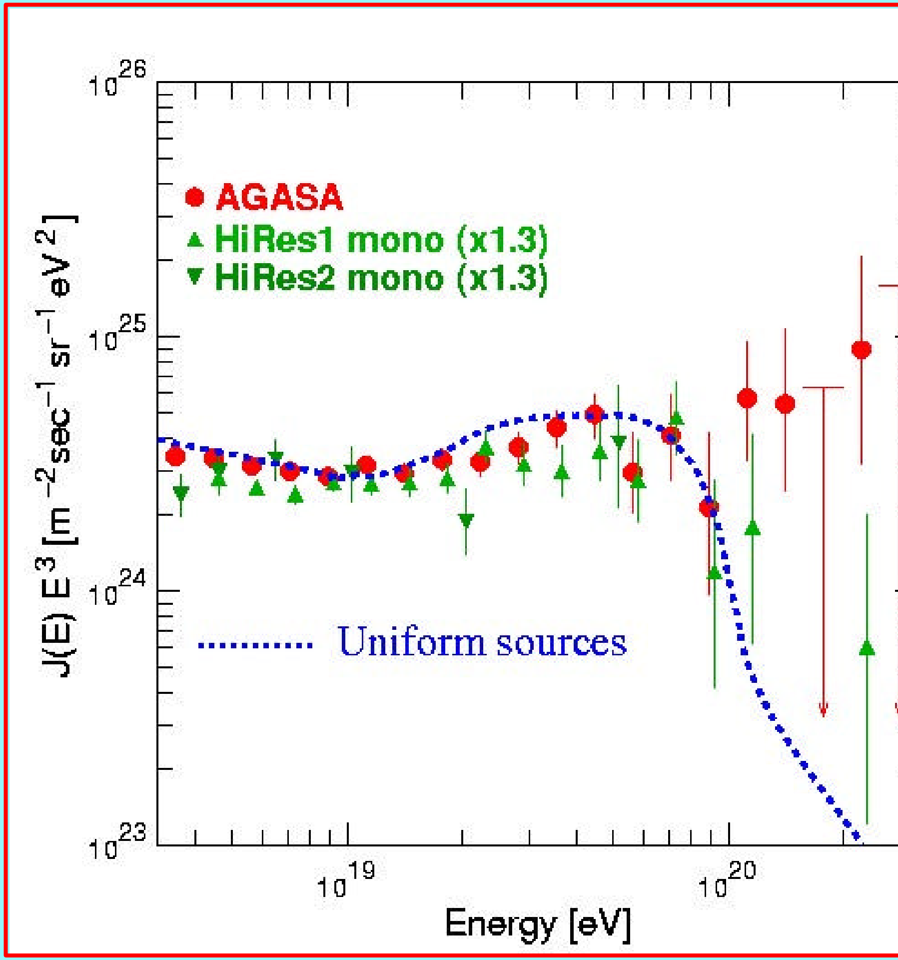


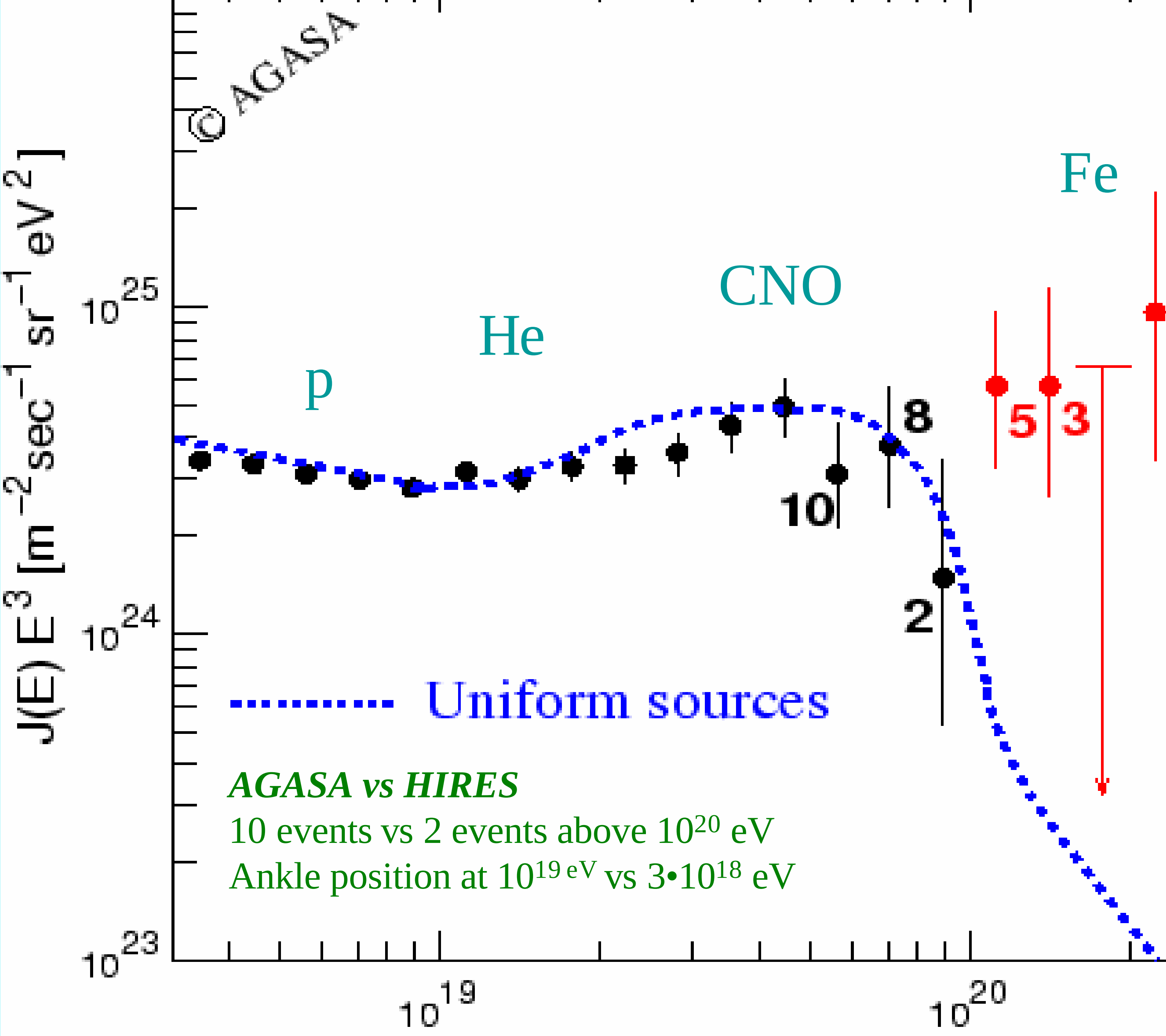


Their existence and their route to the Earth presents

AGASA vs HiRes



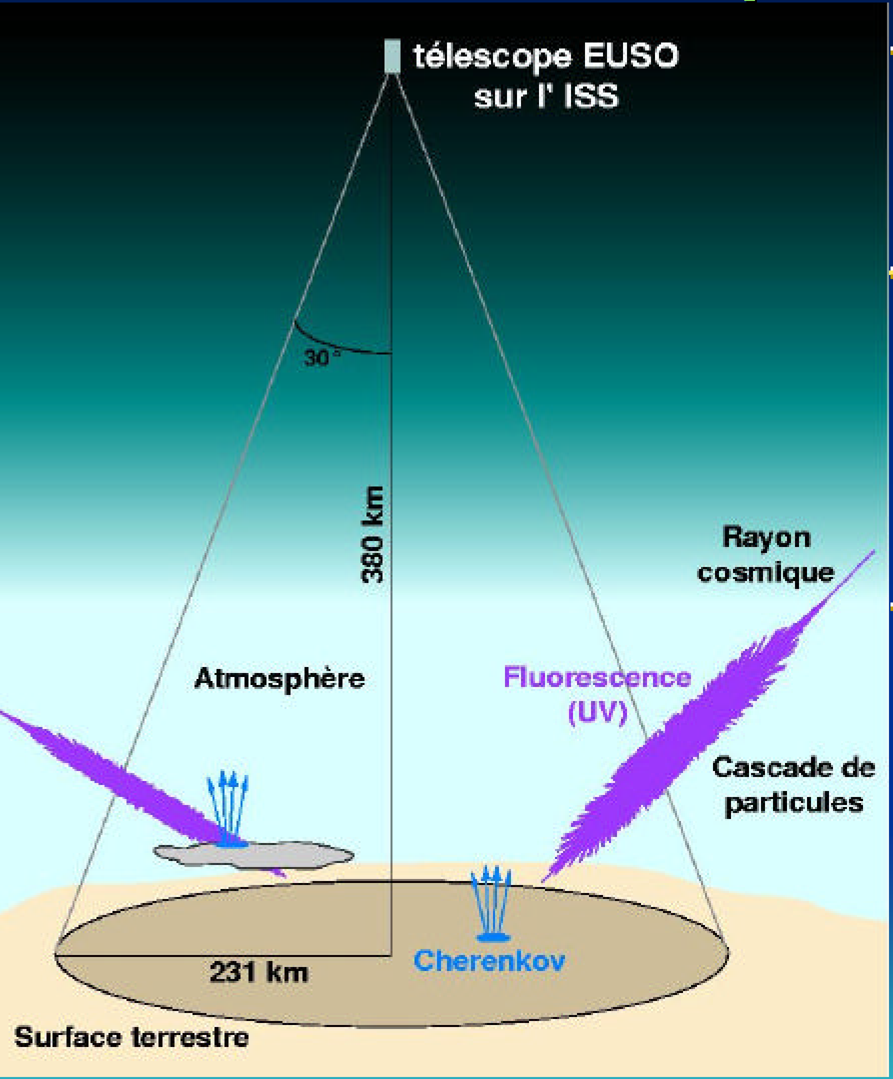




© AGASA
J(E) E³ [m⁻² sec⁻¹ sr⁻¹ eV²]
10^{25}
10^{24}
10^{23}
10^{19}
10^{20}
p
He
CNO
Fe
10
8
2
5
3
Uniform sources
AGASA vs HIRES
10 events vs 2 events above 10^{20} eV
Ankle position at 10^{19} eV vs $3 \cdot 10^{18}$ eV

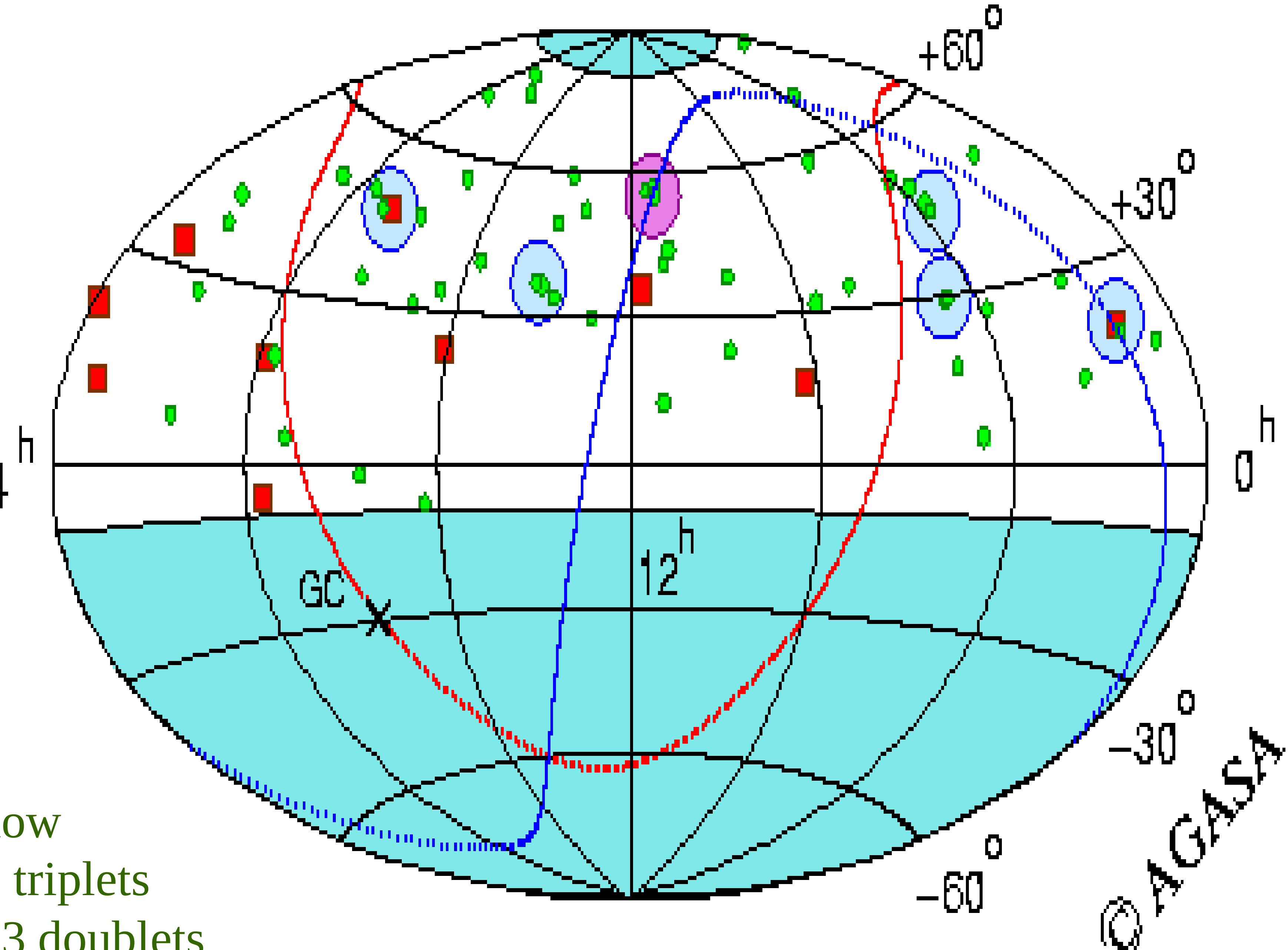
P.Galeotti

Le Principe de détection



- **Grandes surface d'observation e[...] masse de cible**
- **Mesure de la fluorescence** produite par les molécules d'azote excitées par les particules chargées de la gerbe
- **Détection du Cherenkov** produit par les particules chargées relativistes et réfléchi (sol, nuages)

→ **détection de photons dans l'UV (300-400nm)** rrival direction of 59 events (E > 4 10 eV)



ow
triplets
3 doublets

BOTTOM - UP PROCESSES

Here acceleration of low energy particles occurs in objects such as AGN and their radio lobes, interacting galaxies or highly magnetized neutron stars (an extreme case in this class are GRBs).

The observation of a direction of arrival and time coincidence of a GRB and an extreme energy neutrino ($E > 10^{19}$ eV) would provide a crucial test for the identification of GRBs as the UHE CR sources, in spite of their location at distances well beyond the GZK limit.

Other Bottom-Up Hyp.

Cosmological and Low lumininosity Gamma-Ray Bursts

Heavy Nuclei from astrophysical sources With heavy composition and accelerated under conditions preventing dissociation.

Fe could have a cutoff ~200 EeV instead of the ~60 for protons

TOP - DOWN PROCESSES

One way to overcome the many difficulties with the acceleration of EECR is to introduce a new, unstable supermassive particle called the X-particle. The decay of these particles is thought to produce copious amounts of photons, neutrinos and leptons, and a smaller fraction of protons and neutrons which could be detected as UHE CR.

The X-particles themselves could be produced by the decay of topological defects or supermassive relic particles produced at the end of the GUT phase transition stage of the universe.

The “Top-Down” alternatives

– Relics of GU Era: Topological Defects

Localized regions where extreme densities of mass-energy are trapped. $M>10^{23}$ eV decaying into GUT Higgs, superheavy fermions or leptoquarks

– “Z-bursts”

UHE neutrinos could produce interacting with relic neutrinos, particles fragmenting into burst of Z^0. Does a halo of neutrinos exist? (there are problems anyway)

– UltraHeavy Dark Matter Particles

UHE CR PRODUCTION MECHANISMS

Observations and Experiments are needed to answer to the questions remaining open

Bottom – up signatures

- Protons/nuclei
- Power law spectrum
- counterparts

Top – down signatures

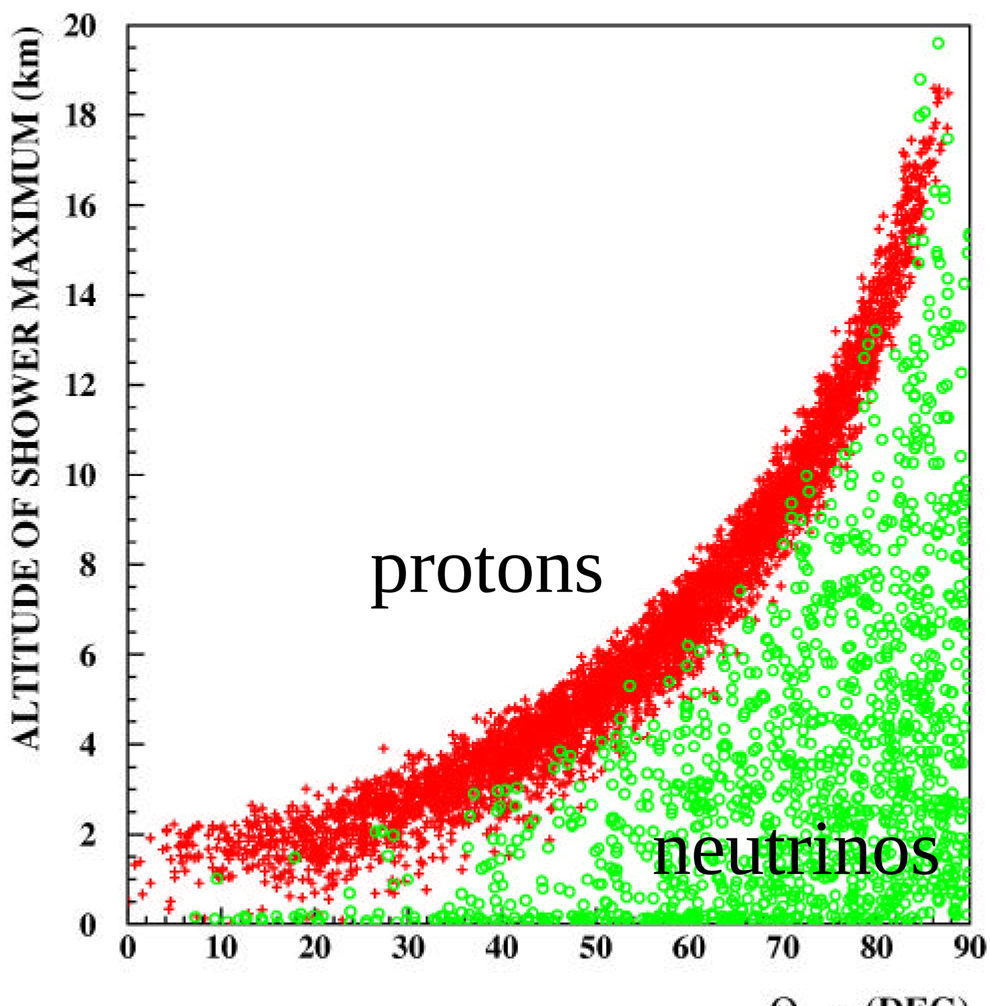
- Photons/neutrinos
- Non-power law spectrum
- No counterparts/repeats
- Halo distribution

Proton – neutrino discrimination

Proton spectrum according to $E^{-2.7}$, 3 years of data taking

Neutrino spectrum : E^{-1} $3*10^{19} – 10^{21}$ (arbitrary large statistics

The probability of neutrino interaction in atmosphere is proportional to the atmospheric density.



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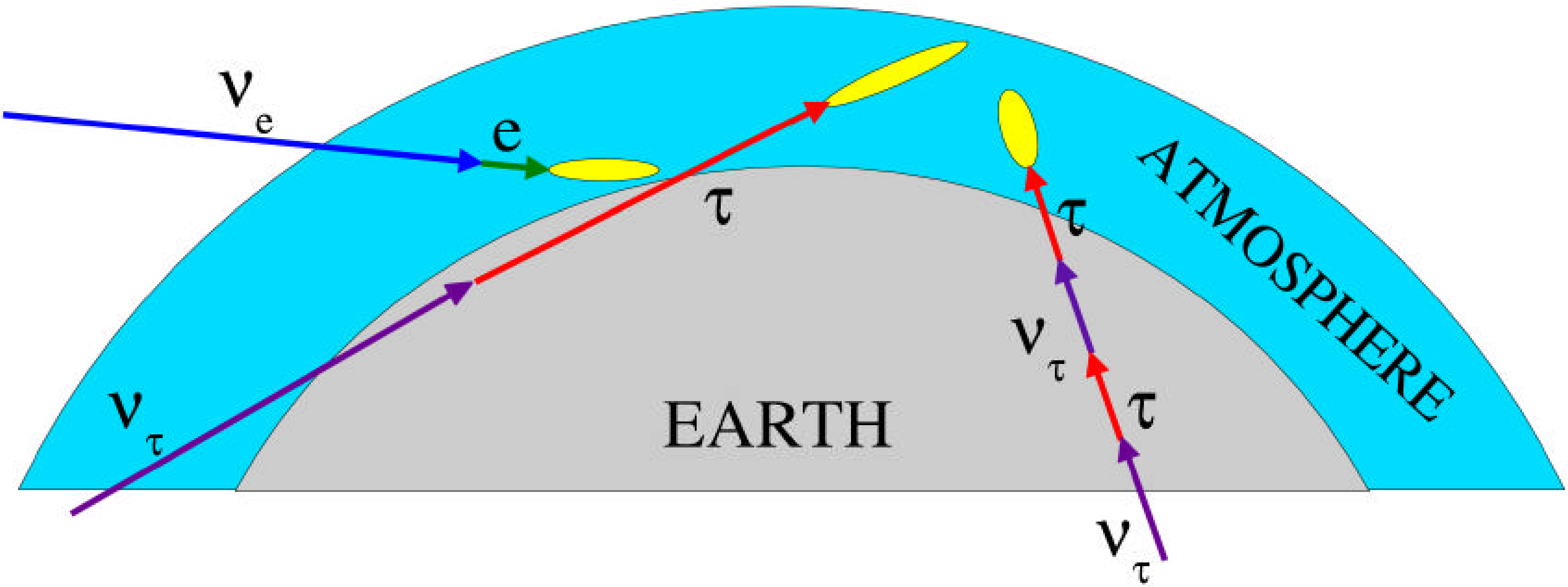
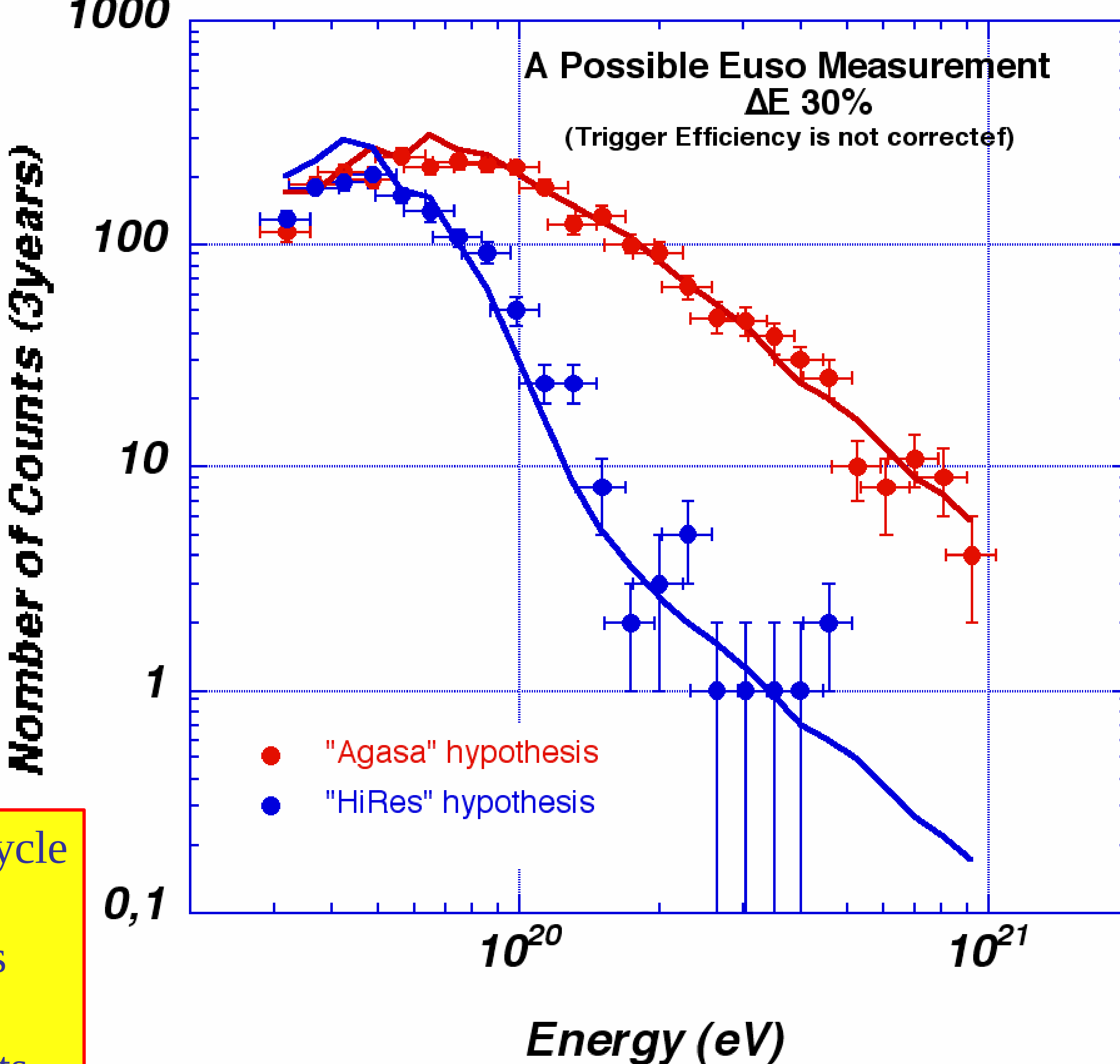
Rigenerazione e sciami EAS

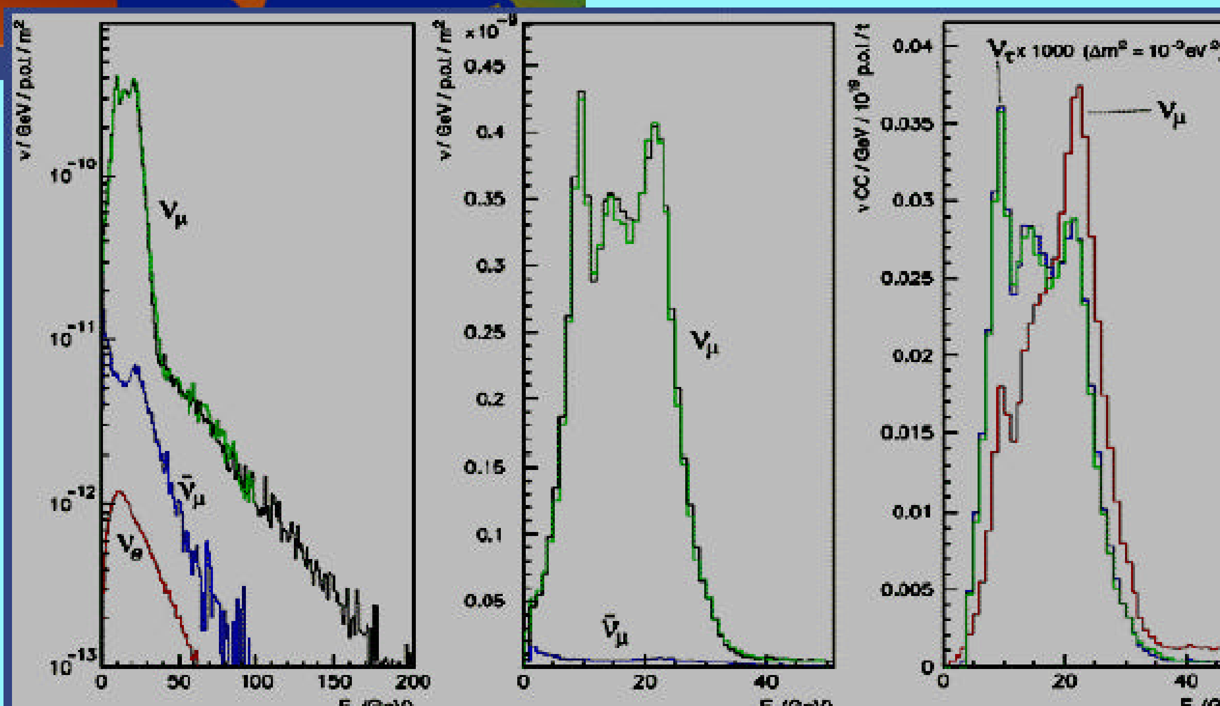


Interazioni di neutrino (CC e NC)
Perdita di energia del tau
Decadimento del tau



With a 12% Duty Cycle
? E of 30%
Statistical error bars
Above 10^{20}eV
Agasa > 1000 events
Hires > 78 events

A ν_τ appearance program



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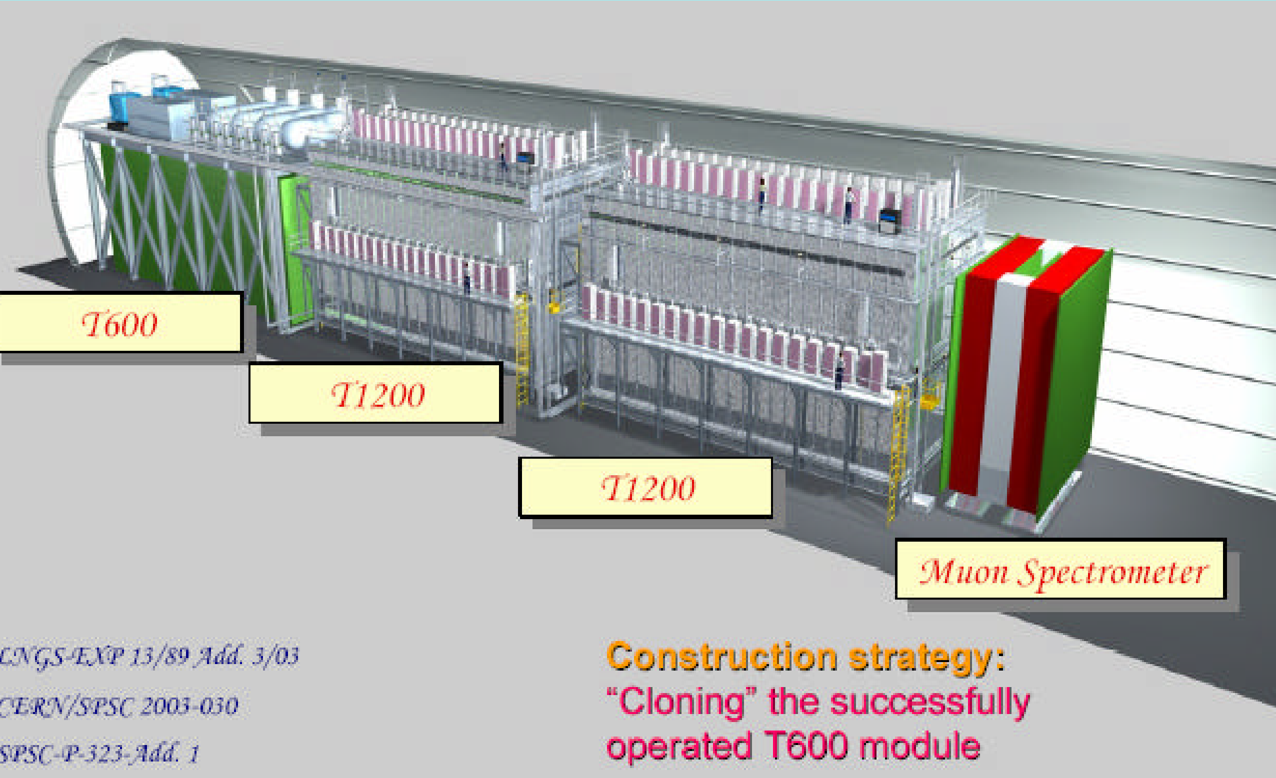
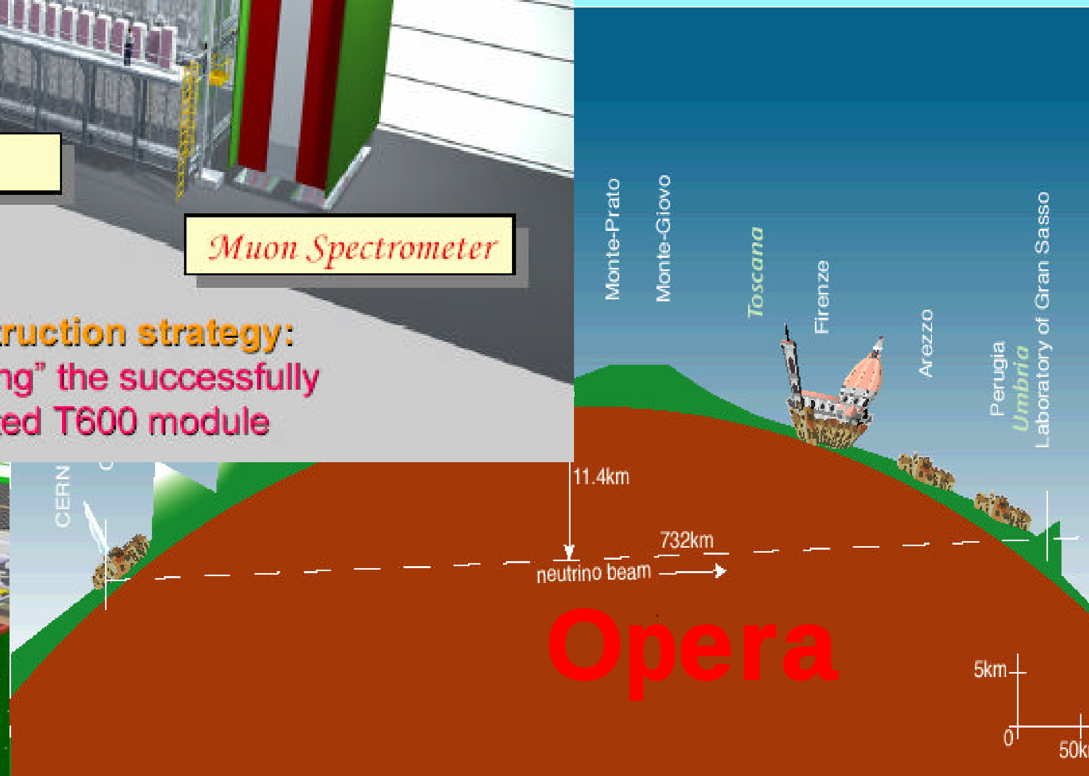
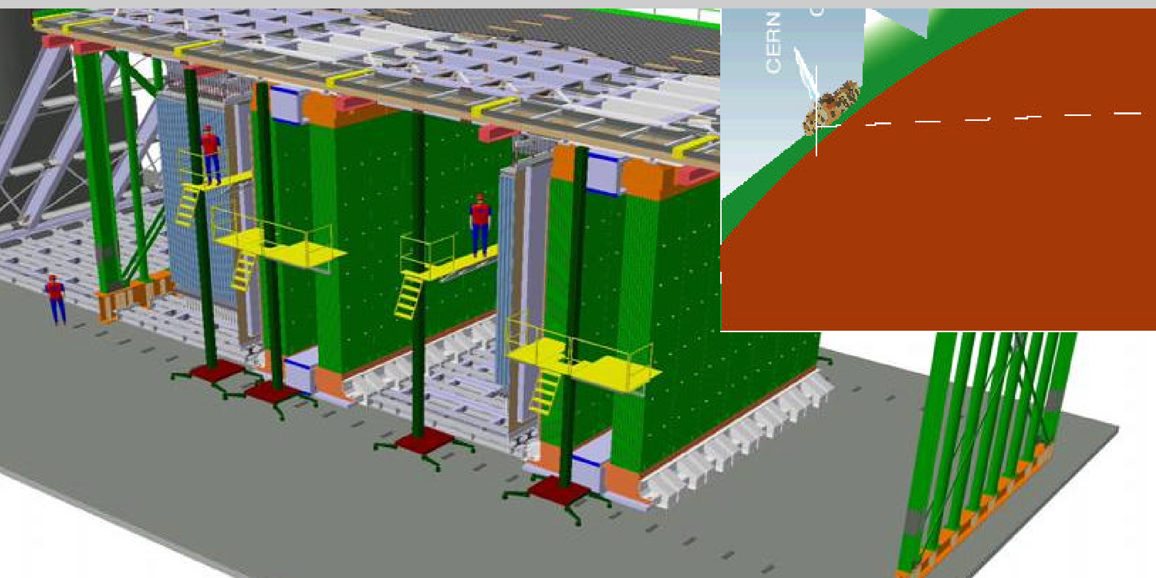
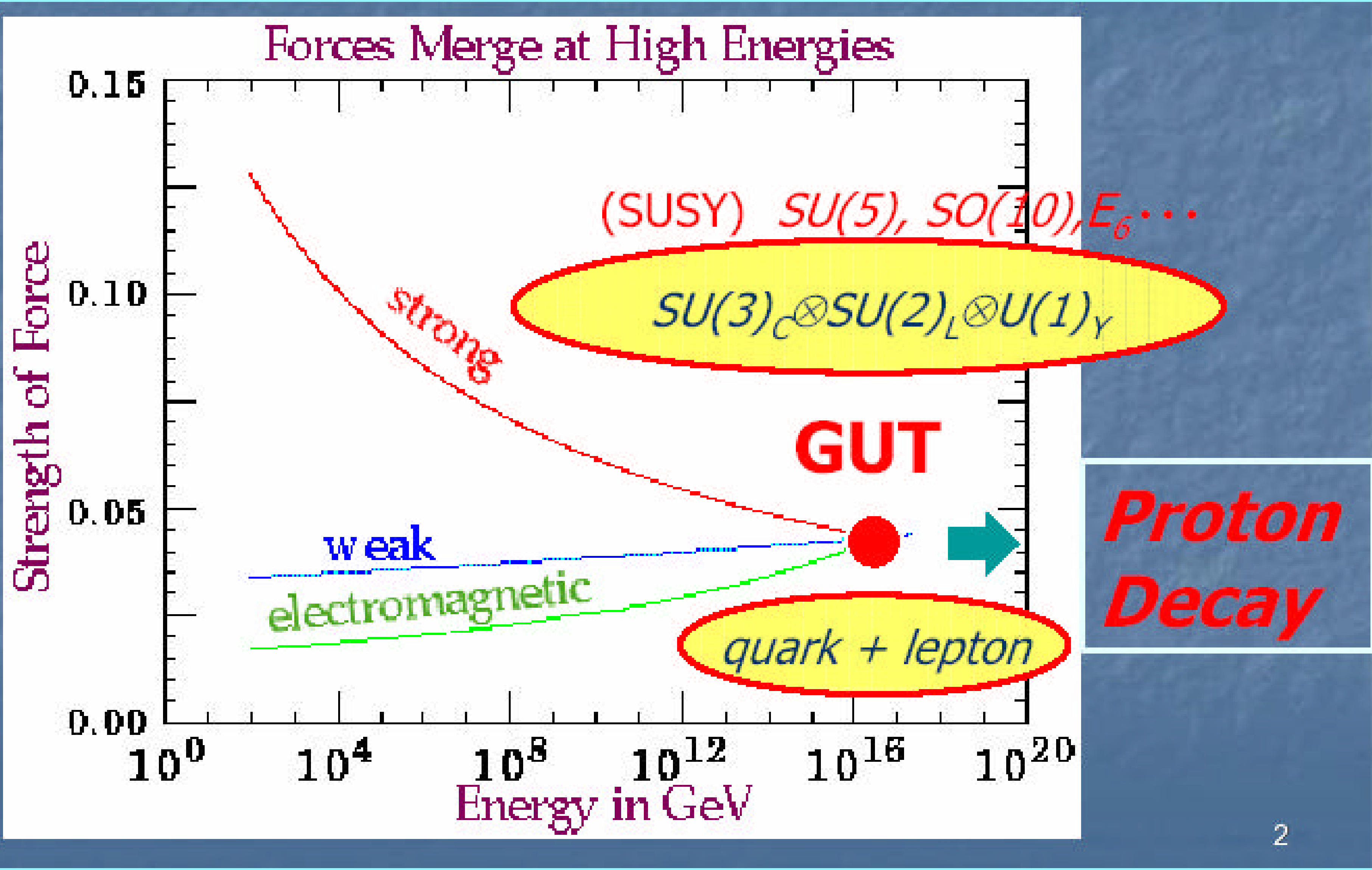

T600
T1200
T1200
Muon Spectrometer
LNGS-EXP 13/89 Add. 3/03
CERN/SPSC 2003-030
SPSC-P-323-Add. 1
Construction strategy:
"Cloning" the successfully
operated T600 module


Monte-Prato
Monte-Giovo
Toscana
Firenze
Arezzo
Perugia
Umbria
Laboratory of Gran Sasso
CERN
11.4km
732km
neutrino beam
Opera
5km
0
50km




Forces Merge at High Energies
Strength of Force
0.15
0.10
0.05
0.00
10^0 10^4 10^8 10^{12} 10^{16} 10^{20}
Energy in GeV
strong
weak
electromagnetic
(SUSY) $SU(5), SO(10), E_6 \cdots$
$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
GUT
quark + lepton
Proton Decay
2

Summary of Super-K nucleon decay searches

mode	exposure (kt• yr)	εB_m (%)	observed event	B.G.	τ/B limit (10^{32} yrs)
$p \rightarrow e^+ + \pi^0$	92	40	0	0.2	54
$p \rightarrow \mu^+ + \pi^0$	92	32	0	0.2	43
$p \rightarrow e^+ + \eta$	92	17	0	0.2	23
$p \rightarrow \mu^+ + \eta$	92	9	0	0.2	13
$n \rightarrow \bar{\nu} + \eta$	45	21	5	9	5.6
$p \rightarrow e^+ + \rho$	92	4.2	0	0.4	5.6
$p \rightarrow e^+ + \omega$	92	2.9	0	0.5	3.8
$p \rightarrow e^+ + \gamma$	92	73	0	0.1	98
$p \rightarrow \mu^+ + \gamma$	92	61	0	0.2	82
$p \rightarrow \bar{\nu} + K^+$	92				22
$K^+ \rightarrow \nu\mu^+$ (spectrum)		34	--	--	3.8
prompt $\gamma + \mu^+$		8.6	0	0.7	11
$K^+ \rightarrow \pi^+\pi^0$		6.0	0	0.6	7.9
$n \rightarrow \bar{\nu} + K^0$	92				2.0
$K^0 \rightarrow \pi^0\pi^0$		6.9	14	19.2	3.0
$K^0 \rightarrow \pi^+\pi^-$		5.5	20	11.2	0.8
$p \rightarrow e^+ + K^0$	92				10.7
$K^0 \rightarrow \pi^0\pi^0$		9.2	1	1.1	8.7
$K^0 \rightarrow \pi^+\pi^-$					
2-ring		7.9	5	3.6	4.0
3-ring		1.3	0	0.1	1.7
$p \rightarrow \mu^+ + K^0$	92				13.9
$K^0 \rightarrow \pi^0\pi^0$		5.4	0	0.4	7.1
$K^0 \rightarrow \pi^+\pi^-$					
2-ring		7.0	3	3.2	4.9
3-ring		2.8	0	0.3	3.7