Neutrino 2000 Conference

Sudbury, june 16-22, 2000.

Highest Energy Cosmic Rays

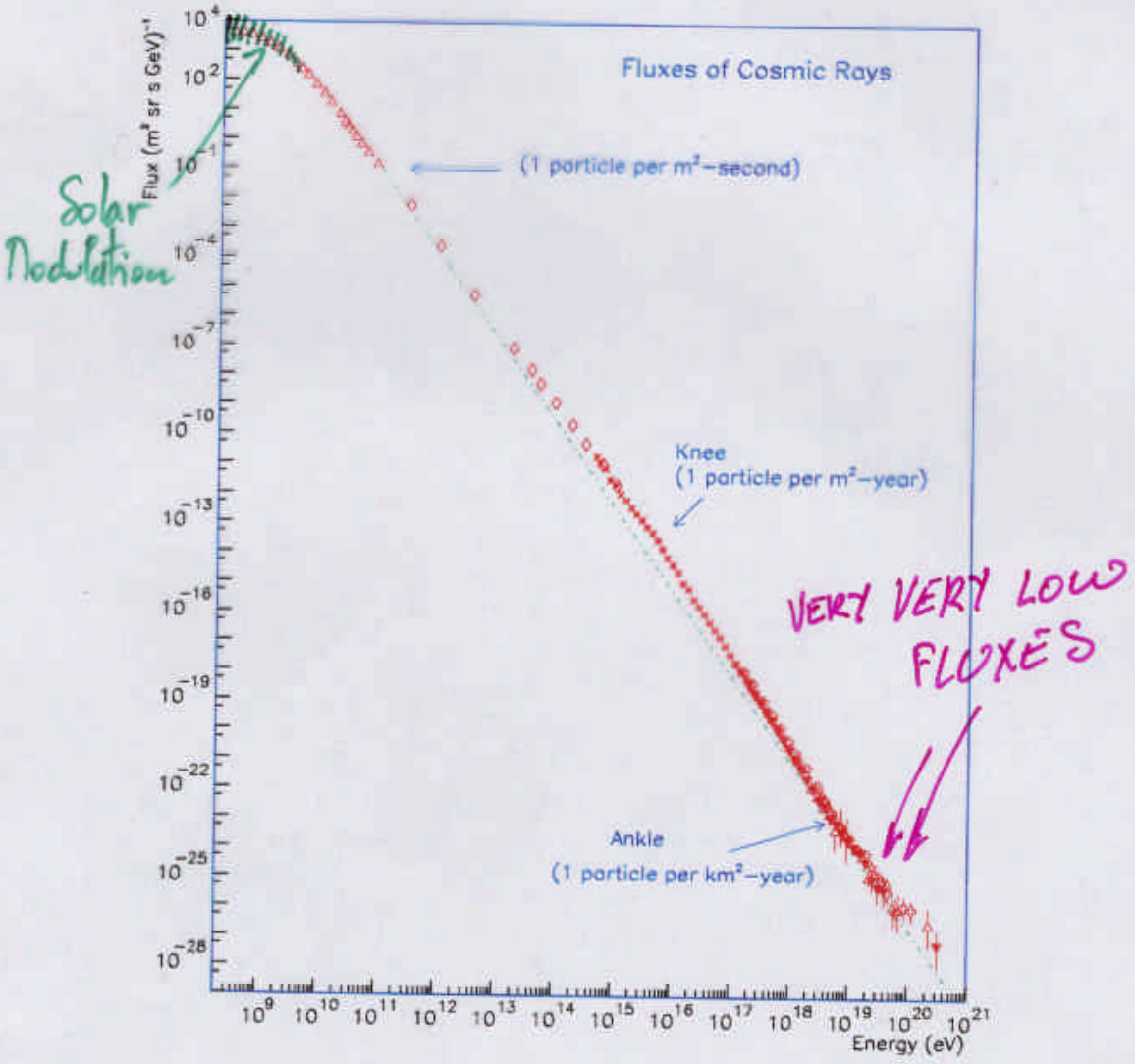
- Observed Spectra
- Transport
- Production or Acceleration ?
- The Auger Detector

Antoine Letessier-Selvon, LPNHE, IN2P3-CNRS,
Universities of Paris VI and VII.

- Victor Hess (1912)
- Showers of secondary particles : Pierre Auger (1938)

Size $\Longrightarrow E > 10^{15} eV$

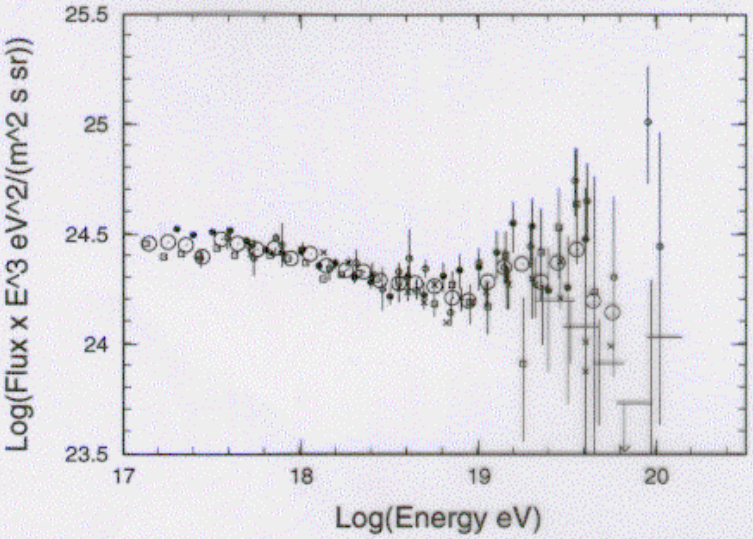
- Around 10^9eV : Galactic origin (strong Solar modulation)
- Between 10^9eV and 10^{15}eV : Galactic origin (SNR)
- Between 10^{15}eV and 10^{18}eV-10^{19}eV : Yet unclear, galactic.
- Above 10^{19}eV : Unknown but likely extra-galactique.



(Part of the).

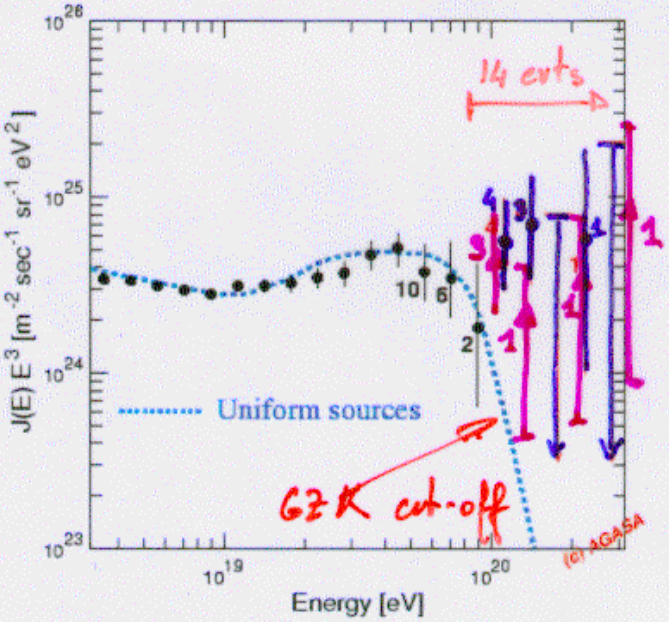
Spectrum above 10^{17}eV : (remarkable agreement of experiments)

Haverah Park
Yakutz
AGASA
Fly's Eye
Volcano Ranch
⋮



Composition (heavy ⟶ light); Origin (galactic ⟶ extra galactic)

Spectrum Above 10^{19}eV :



▲ Hires & F.E.

AGASA
⊕
Fly's Eye
⊕
Hires (Pp 99)
(preliminary)

Production mechanisms ? How to reach this energy ?

Primary mass (Composition) ?

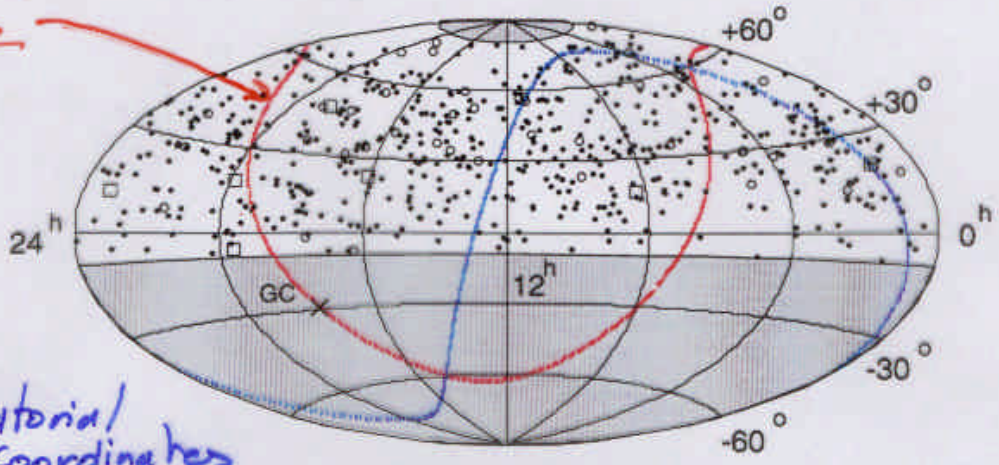
Source distribution and nature? Can those CR reach us ?

Where does the spectrum ends ?

Anisotropy studies :

Galactic plane

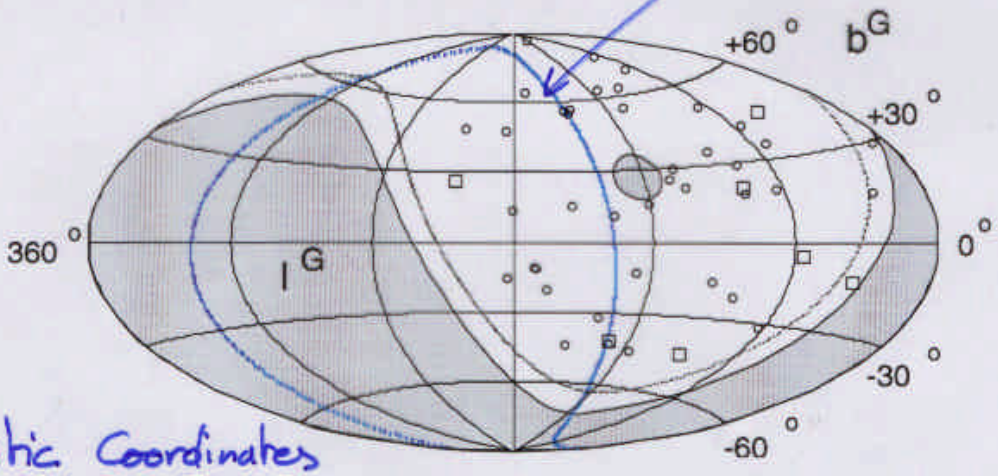
AGASA events above 10^{19}eV



Equatorial Coordinates

Super Galactic plane

AGASA events above 4×10^{19}eV



Galactic Coordinates

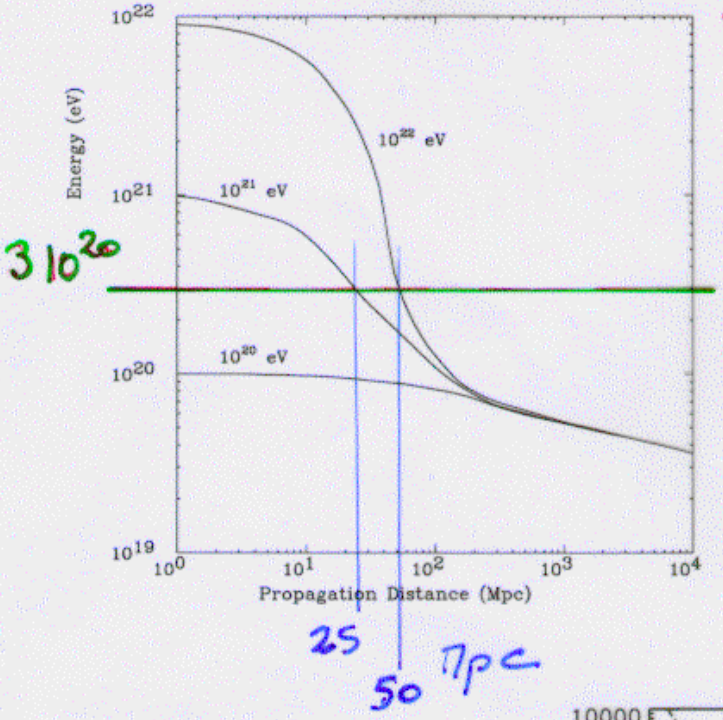
No evidence for anisotropies But poor statistics ...

HADRONS : GZK Cut-off

Transport :

Nucleons: GZK cut-off from pion photo-production on the CMB.

$$E_{th} \sim 7 \times 10^{16} (\epsilon/eV)^{-1}\, eV \text{ and } L = (\sigma\rho)^{-1} \simeq 6 Mpc$$



$3\,10^{20}$

25

50 Mpc

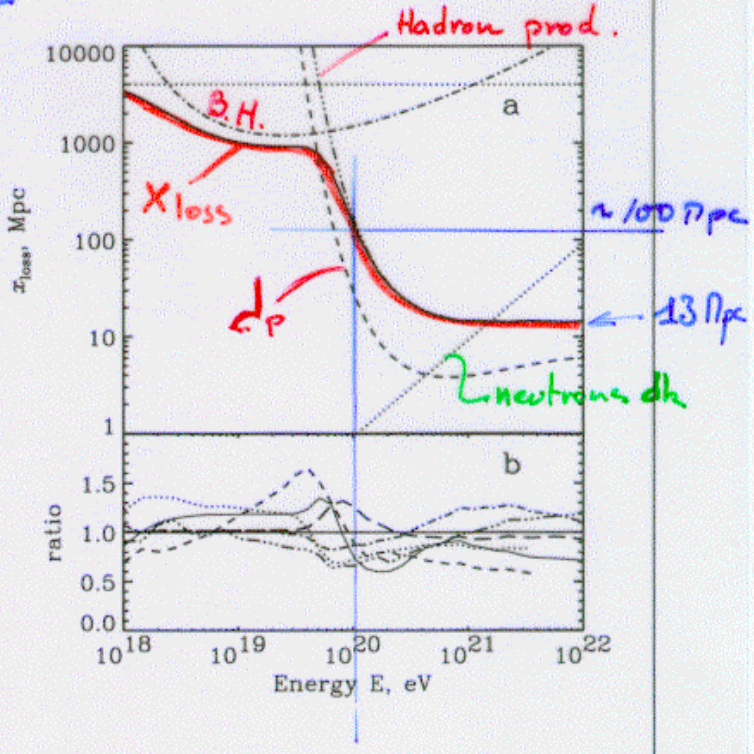
$p + \gamma_{CMB} \rightarrow \Delta^+ \ldots$

Proton energy as a function of source distance.

After 100Mpc the final energy falls below 10^{20}eV

Mean energy loss length of protons as recently calculated with a Monte Carlo [Stanev et al].

$$x_{loss} = \frac{E}{dE/dx} = \frac{E\lambda(E)}{<\Delta E>}$$



A comparision with other calculations.

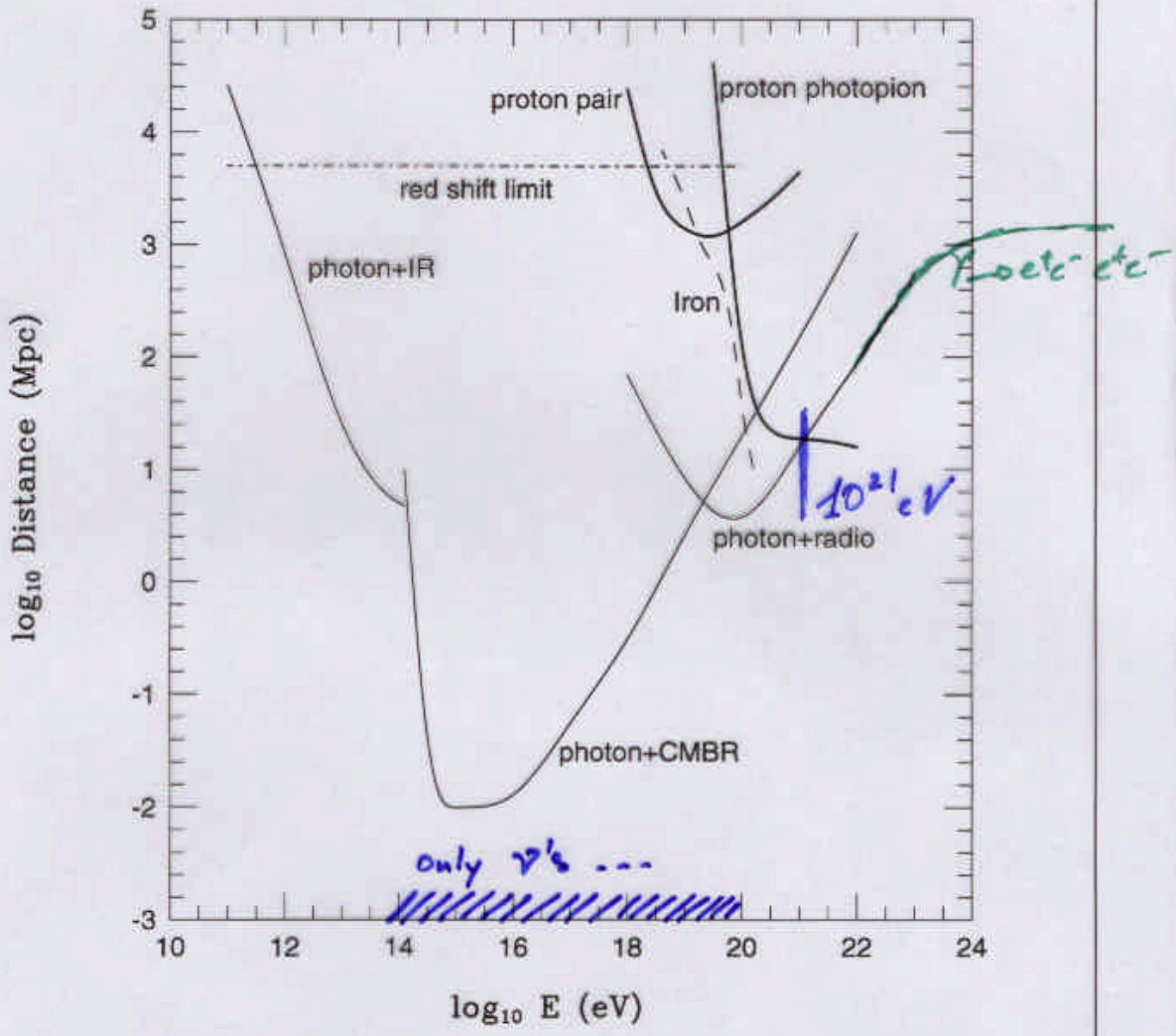
Photons : EM cascades. (Pair production)

Threshold on CMB : $E_{th} \sim 2.5 \times 10^{14} eV$

Targets :

CMB photons, infra-red (IR) and, at very high energy, radio (URB).

NB: IR and URB are not very well known.



- Top-Down UHECR production models give dominantly photons and neutrinos at the sources.
- Gammas, neutrinos (and e^+e^-) are also secondary of the pion photo-production.

Magnetic Fields.

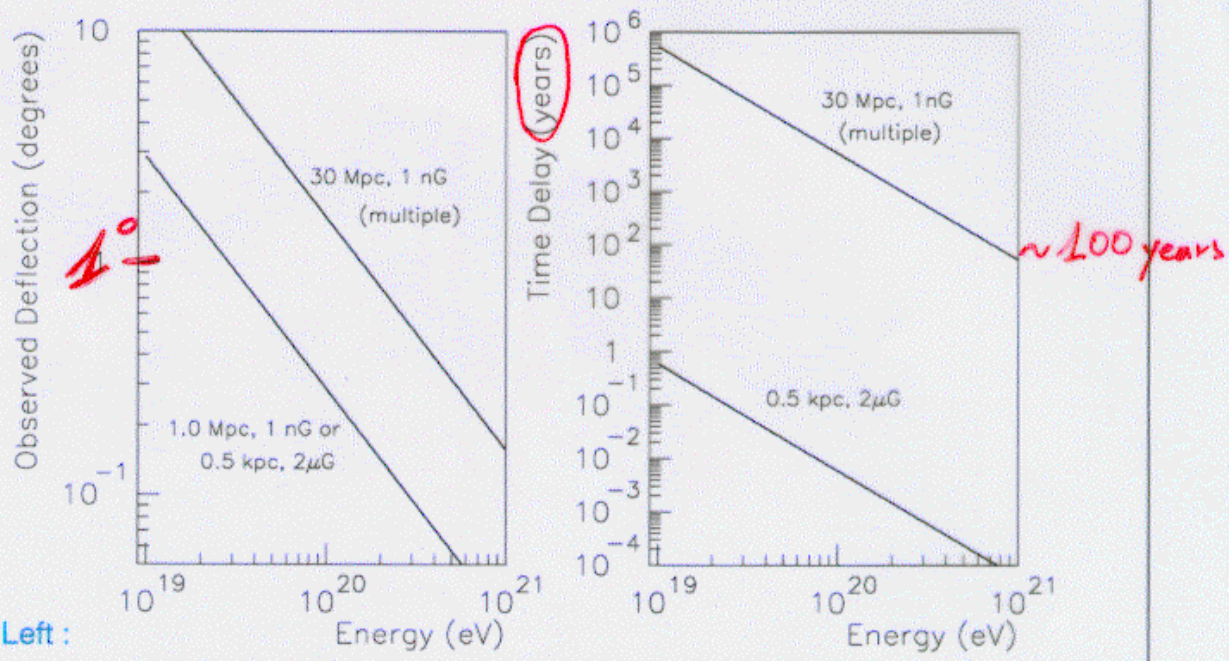
1) Affects the development of EM cascades.

Dominant above :

$$E_{th} \sim 10^{19} \left(\frac{B}{10^{-9} G} \right)^{-1}$$

At threshold (dependent upon the URB density) the loss is about 3×10^{18}eV per 100kpc.

2) Bends and delay charged particles :



Left :

Bottom :0.5 kpc trajectory in the Galactic disk or (equivalently) 1 Mpc in inter-galactic space.

Top : 30 Mpc trajectory in a random field of 1 Mpc coherence length.

Right :

Time delays computed in the same conditions.

Production or Acceleration : How to achieve $E > 10^{20}$eV??

- Acceleration (Bottom-Up) "Classic"
  - Supernova remnants (SNR). Not energetic enough
  - Radio Galaxies (powerful ones!). Ok but rather far away
  - Young neutron stars. Hard to escape, loss at the source
  - GRB. Cosmological distribution

  Sources far away ($> 100 Mpc$) $\longrightarrow$ GZK cut off

  Sources nearby ($< 100 Mpc$) $\longrightarrow$ visible.

- Decay (Top-Down) "Exotic"

  Massive particles or TD are the source of CR (no acceleration)
  - Topological defects collapses, intersections or interactions (strings, Monopoles, super-conducting strings, vortons...)

    Fluxes, constraints from CMB isotropy, EGRET measurements of diffuse gamma rays and ${}^4H_e$ abundance.
  - Massive (M>10^{20}eV) (meta) stable relic particles, (e.g. cryptons).

    Recent decay (<100Mpc) and abundance (flux @10^{20}eV)

    $\Longrightarrow \tau/(t_0 \Omega_X) \sim 10^{11}$: fine tuning

  Cosmological distribution or DM like? Solve Acceleration, power and invisibility, γ and ν are dominant at the source.

- Mixed : e.g. Kaluza-Klein ν interactions (Physics (just) beyond SM)
  - [Nussinov and Shrok (1999), Sigl (2000)] :

    $\sigma_{KK}^{\nu N} \sim \frac{4\pi s}{M^4} \sim 10^{-27} \left(\frac{M}{TeV}\right)^{-4} \left(\frac{E}{10^{20} eV}\right) cm^2$
  - [Kachelrieβ and Plümacher (2000)] :

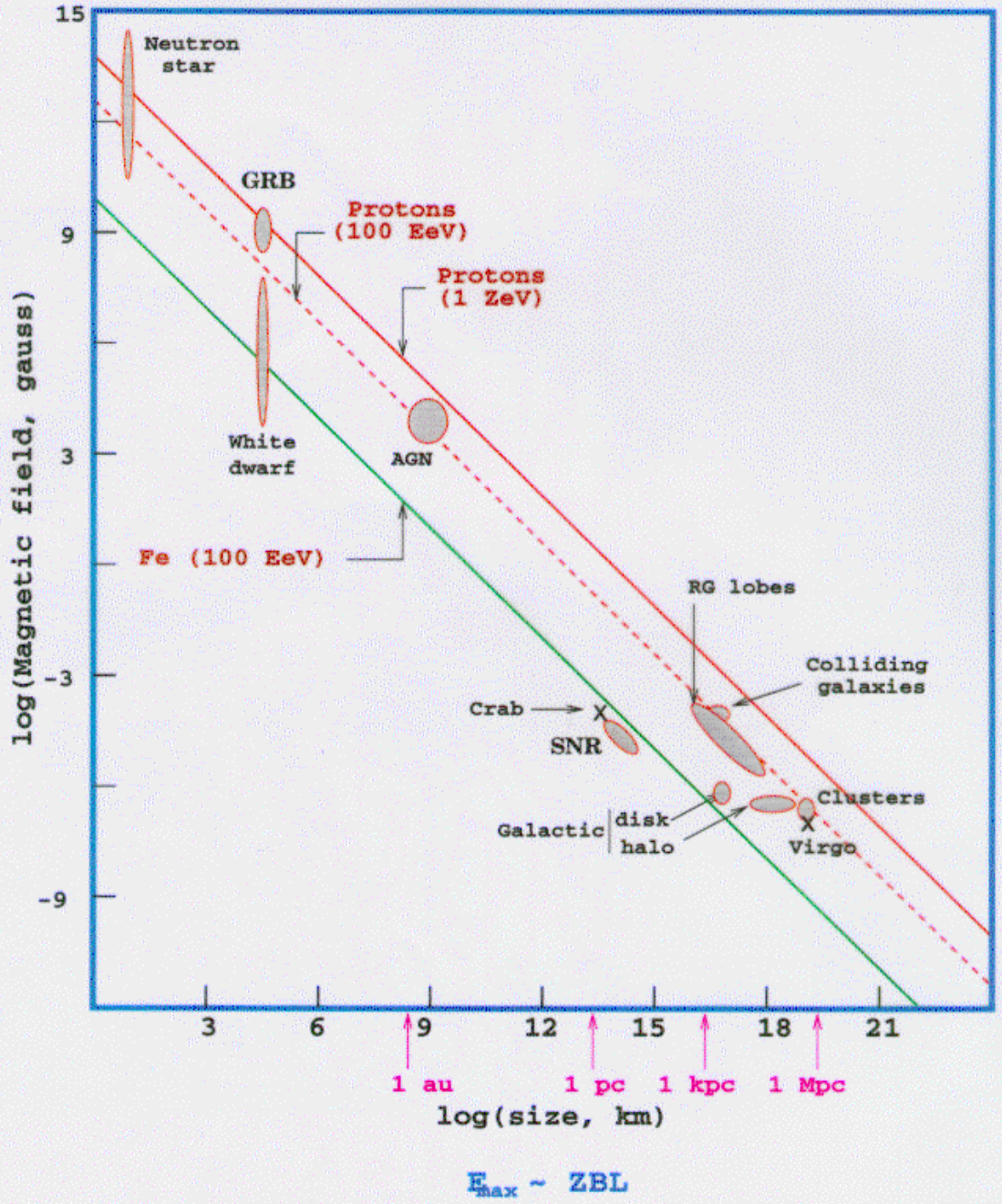
    $\sigma_{tot} \sim \sigma_{KK}^{\nu N}(M^2) ln^2(s/M^2) \left(\frac{s}{M^2}\right)^{0.363} \sim 5\, 10^{-29} cm^2$

    ($M = 1$Tev, E=10^{20}eV) and ($y < 0.1$)

$$E_{max}[10^{n}eV] = Z\ B[\mu G]\ R[kpc]$$

Hillas-plot

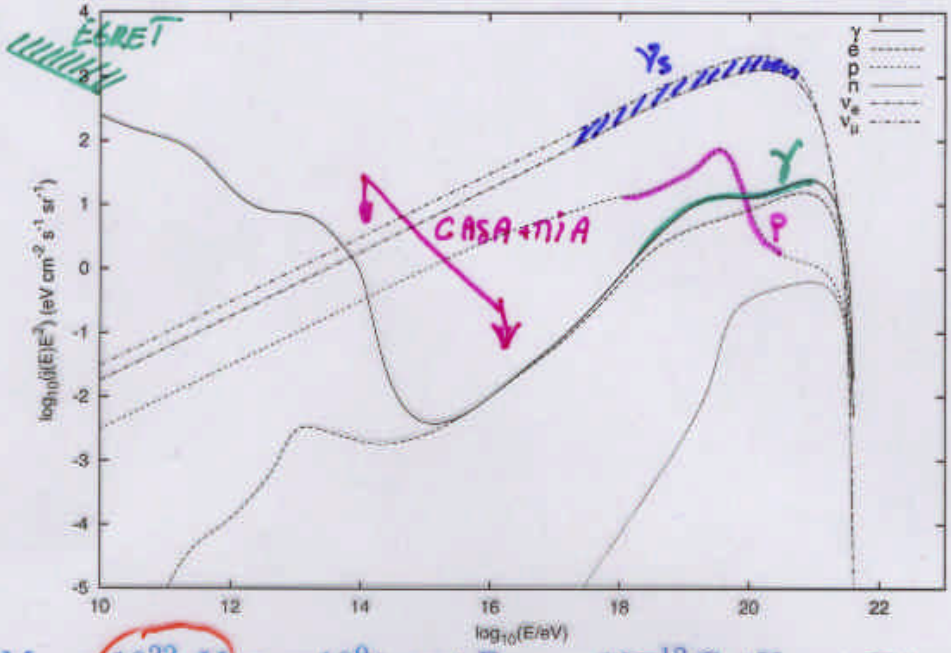
(candidate sites for E=100 EeV and E=1 ZeV)



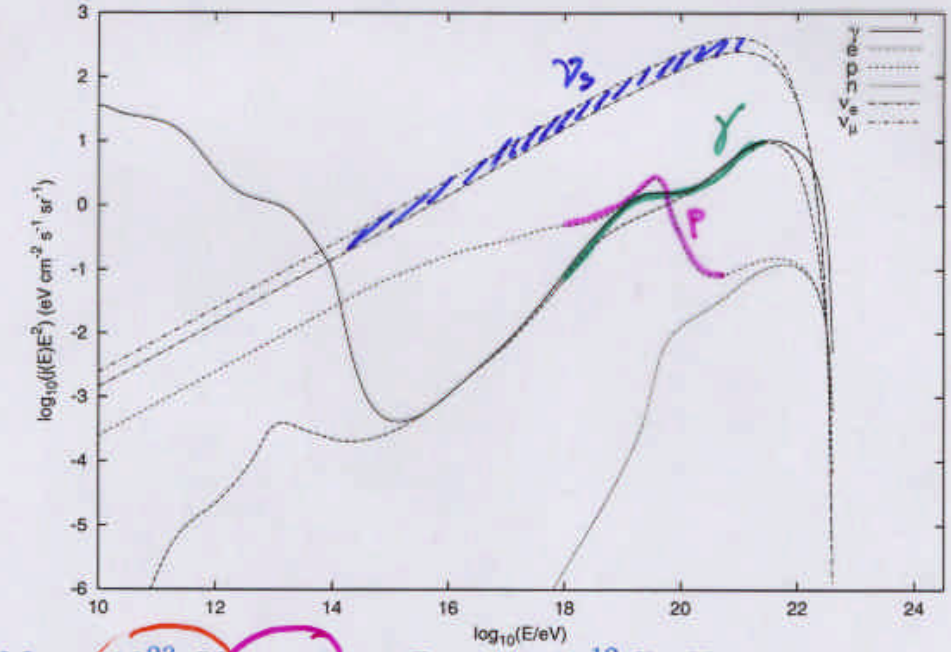
$E_{max} \sim ZBL$

Some Top-down predictions

Kalashev, Kuzmin and Semikoz [1999].



$M_X = 10^{22} eV$, $\tau = 10^9 t_0$ and $B_{EG} = 10^{-12} G$. $(X \longrightarrow \bar{q}q)$



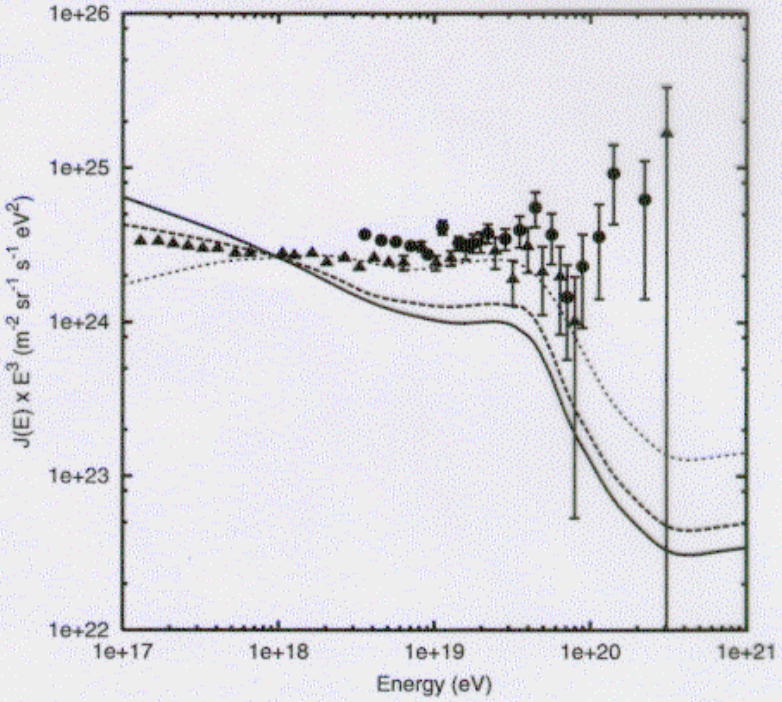
$\dot{n}_X(t) \propto \left(\frac{E}{E_0}\right)^{-q+p}$

$M_X = 10^{23} eV$, $p = 1$ and $B_{EG} = 10^{-12} G$. $(X \longrightarrow \bar{q}q)$

Gamma Ray Burst : [Rees & Meszaros]

- Expanding fireball model : [Waxman] Engine?
- Distribution : very likely cosmological (after glow). High luminosity (energy output)10^{52} ergs/sec (10^{53} ergs).
- Time delays: cosmological distribution $\Rightarrow$ a few local events. At most 1 every 50 years within 100 Mpc.

2 UHECR events (AGASA and FE) within 26 months and with $\Delta\Omega$ too large for a single source $\Longrightarrow \Delta t \sim 100yr \Longrightarrow$ EGMF $< 10^{-12}G$



UHECR fluxes from GRB [Scully and Stecker 2000].

3 redshift dependence of the GRB density:

- Solid strong ($q = 3.6, z_{max} = 3.6$) from [Fenimore and Ramires-Ruiz]
- Dashed same as star formation rate ($q = 3.0, z_{max} = 2.5$)
- Dotted no redshift dependence

The GZK cut-off is always visible.

Experimental Techniques :

To be measured :

1 Primary direction $\equiv$ shower axis

2 Primary Energy

3 Primary nature (mass)

Primary Direction (Origin) :

A) On the ground using a lateral time and density distribution .

B) With the fluorescence using the longitudinal profile

Primary Energy (Spectrum):

A) On the ground with $\rho(r)$
This estimate depends only weakly on the physics of first interactions and on the primary nature.

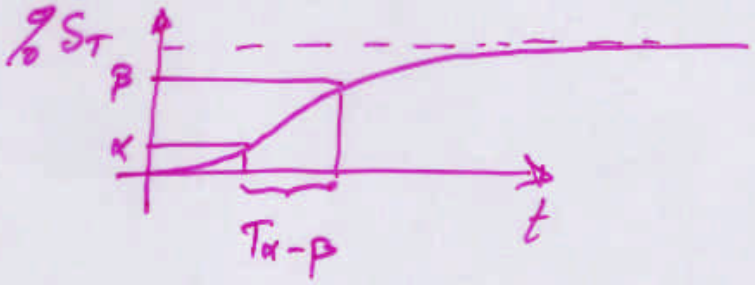
B) With the fluorescence $N_\gamma \propto N_e$ along the longitudinal profile.

Primary Mass(Composition) :

1) ρ_μ is a good estimator (also ρ_μ/ρ_{em}).

2) Rise time $T_{\alpha-\beta}$

3) X_{max}position



Auger

- Large detection surface.

  6000 km^2 (2 sites), 1600 ground detector stations, 3 Fly's Eyes.

- Uniform sky coverage.

  Two sites, Argentina being installed, one foreseen in Utah, USA.

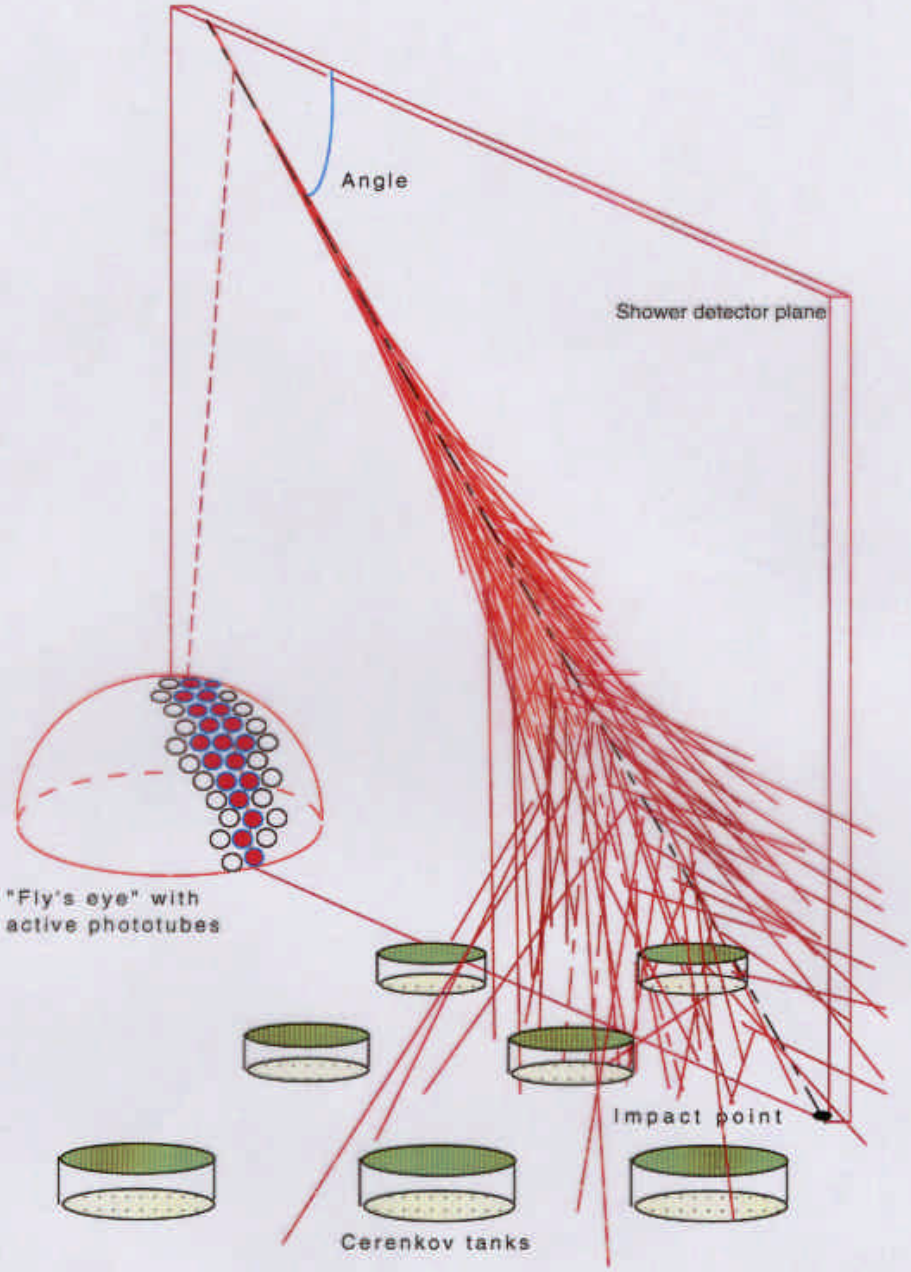
- Combined detector.

  Use two detection techniques for cross calibrations, hybrid operation.

Performances

- Duty Cycle : 100 % Array, 10% Fluorescence
- Efficiency : > 90 % above 10^{19}eV
- Resolutions:
  - Energy (array) : 15% (10^{20}eV) & 30% (10^{19}eV)
  - Energy (hybrid) : 10% (10^{20}eV) & 20% (10^{19}eV)
  - Angle (array) : 1^o (10^{20}eV) & 2^o (10^{19}eV)
  - Angle (hybrid) : 0.2^o (10^{20}eV) & 0.35^o (10^{19}eV)
  - Statistics : $30 > 10^{20}$eV per year (today 20)
  - Identification:
    - statistical for ^{56}Fe
    - shower by shower ID for neutrino and gamma.

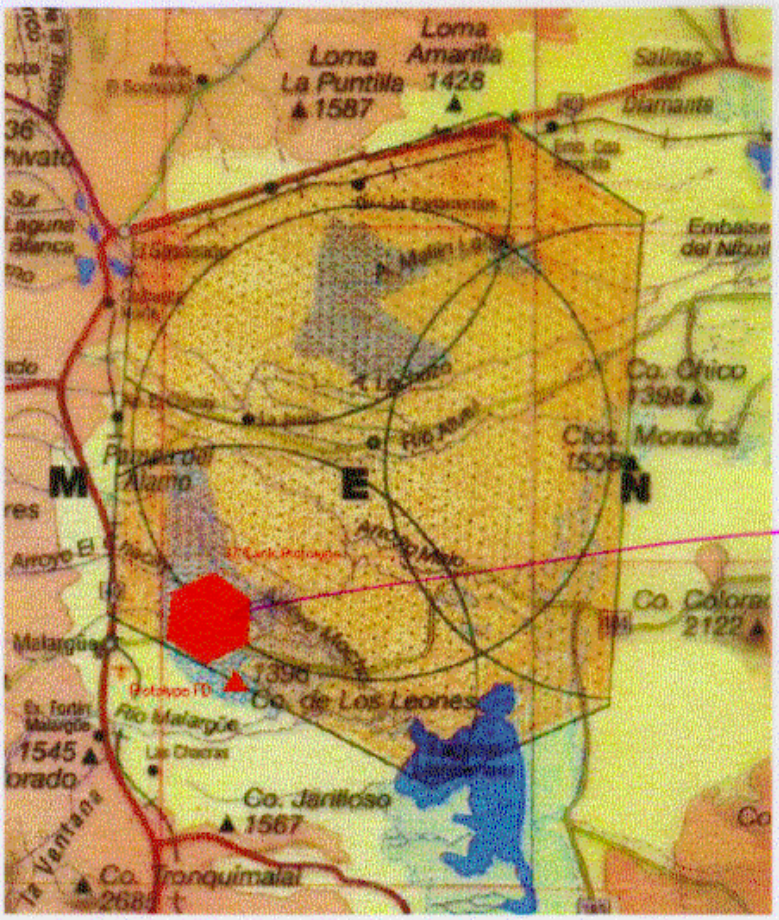
Hybrid operation mode :



Southern site :

Foreseen US site.

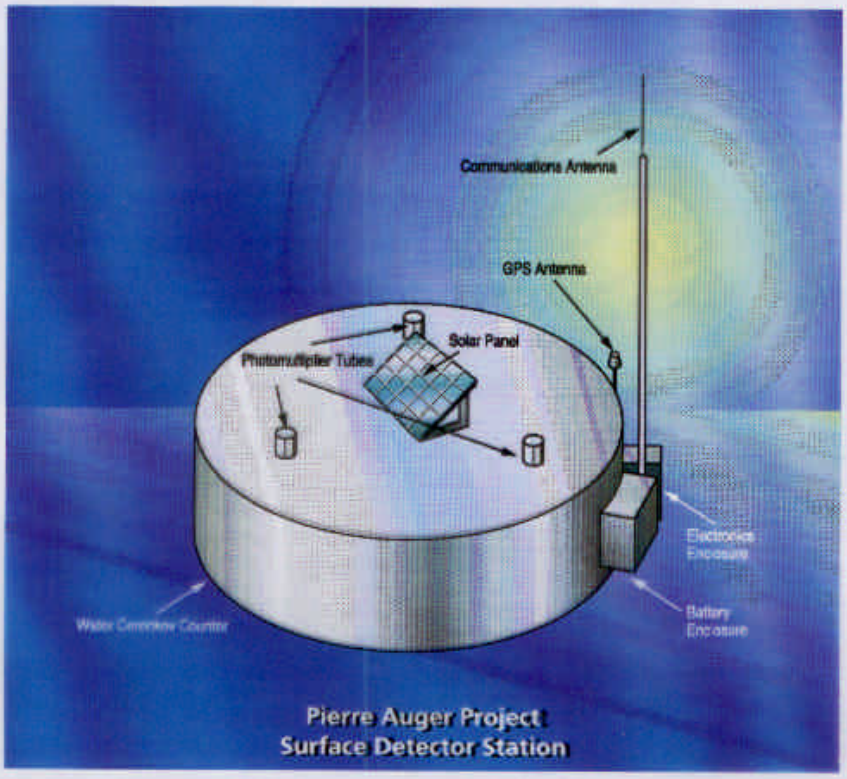
We are Here



prototype array 40 stations 1/6 eye. 2001

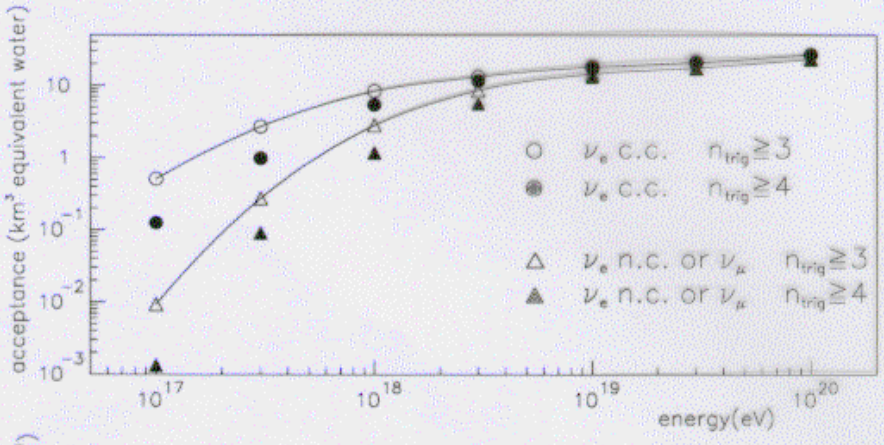
Full array 2003-2004.

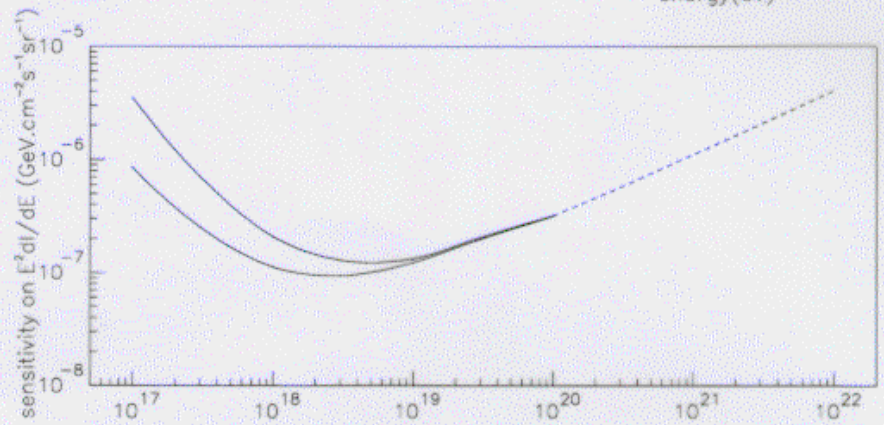
A surface Detector Element :



Conclusions with neutrinos . . .

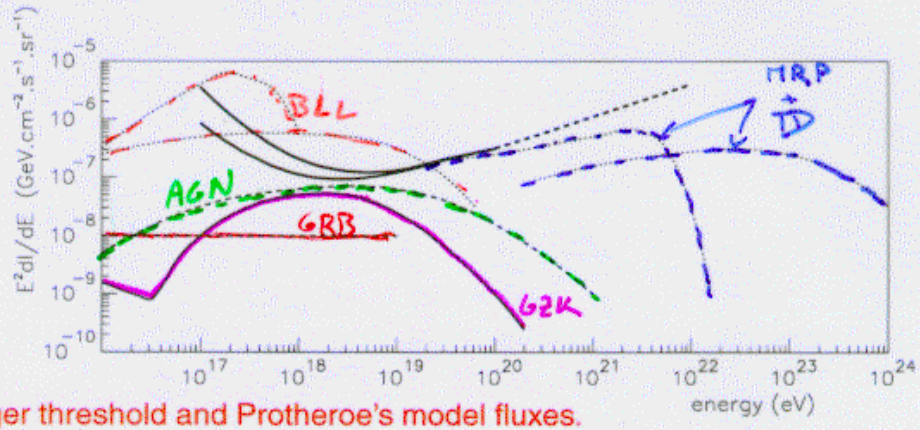
P.Billoir et al.





Sensitivity threshold of 0.3 evt/year/decade

E (eV)



ν_τ ?

Auger threshold and Protheroe's model fluxes.

Dot : speculative, Dash : probable, Solid : certain