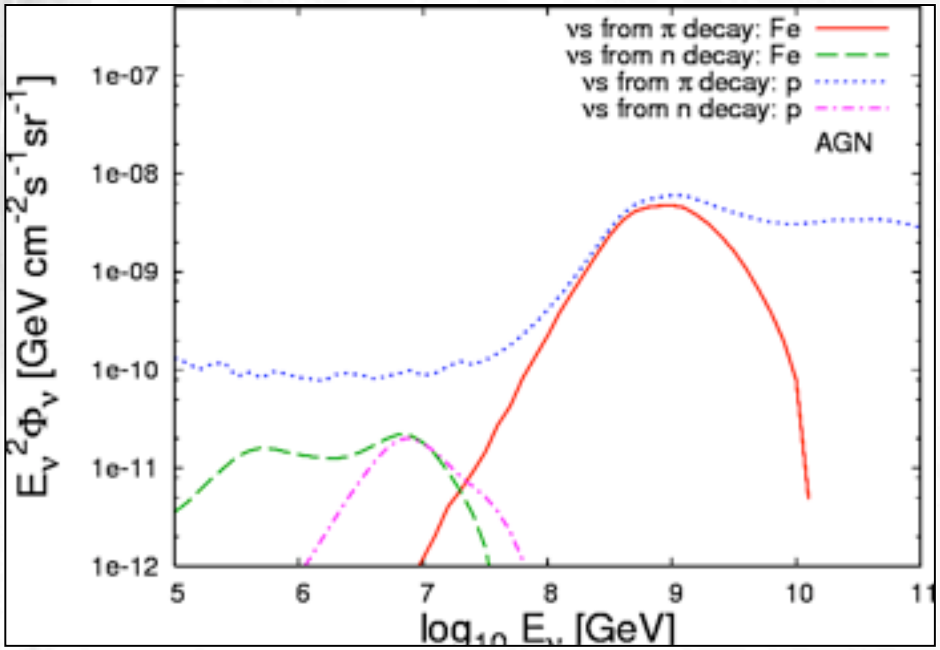
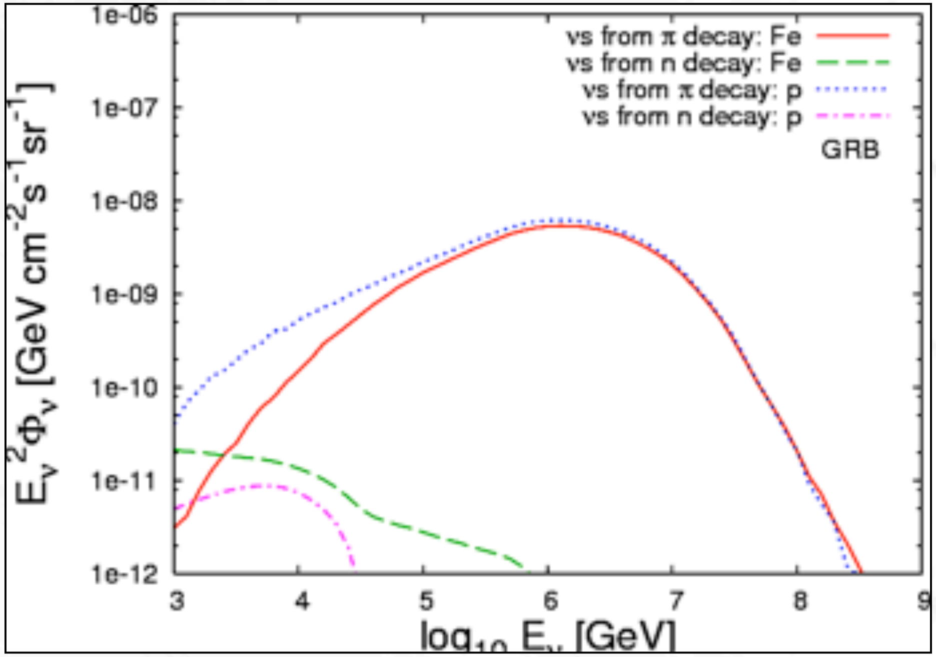
Chemical Composition and Source Contributions to the Ultra-High Energy Neutrino Flux

In AGN sources, nuclei are disintegrated above ~10^{19} eV
In GRB sources, all nuclei are practically disintegrated (compact source)
In starburst galaxy sources, very few nuclei are disintegrated





Anchordoqui, Goldberg, Hooper, Sarkar, Taylor, Phys.Rev. D76 (2007) 123008

Ultra-High Energy Cosmic Rays and the Connection to Diffuse γ-ray and Neutrino Fluxes

accelerated nuclei interact:

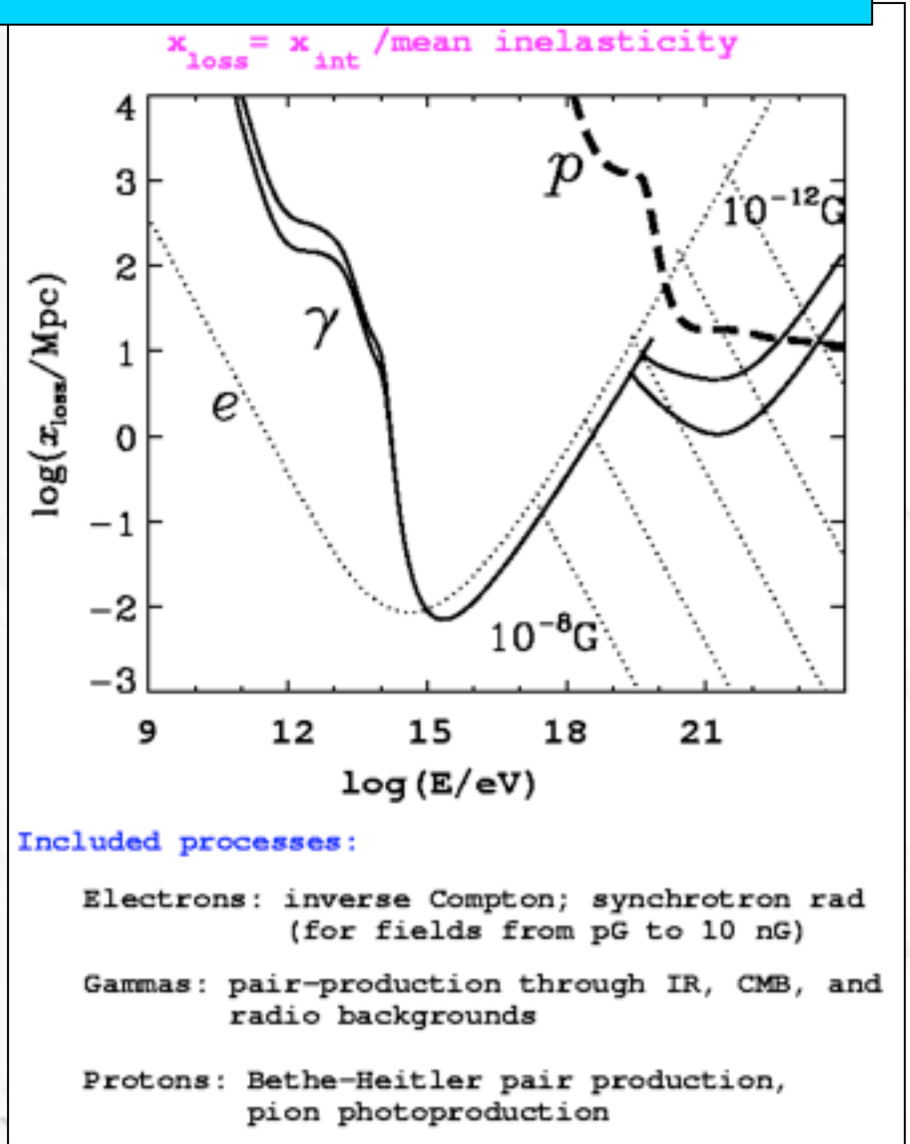
$$^A_Z + N,\gamma \rightarrow X + \begin{cases} \pi^+ & \rightarrow \text{neutrinos} \\ \pi^0 & \rightarrow \gamma - \text{rays} \end{cases}$$

during propagation ("cosmogenic")
or in sources (AGN, GRB, ...)

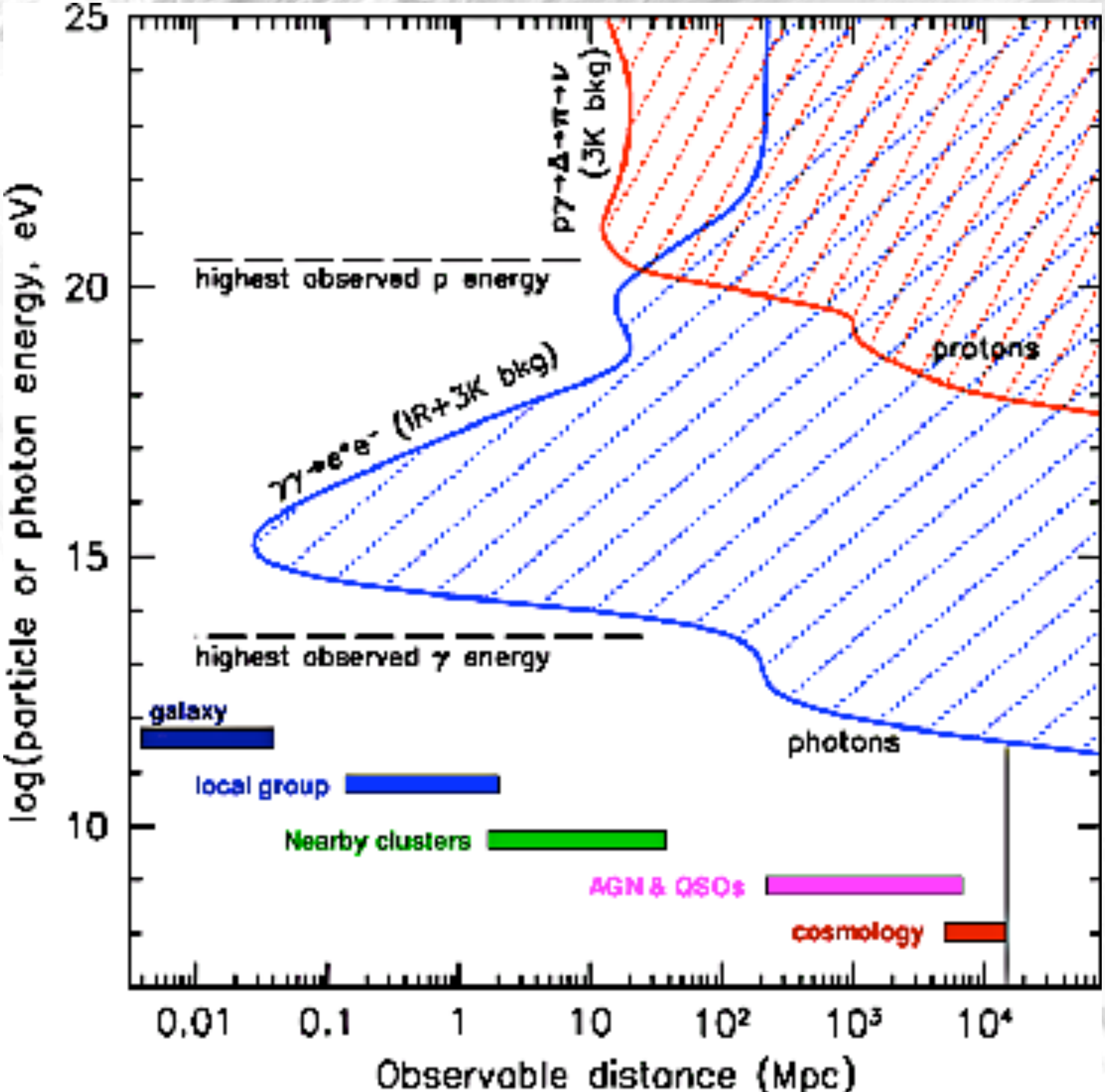
=> energy fluences in γ-rays and neutrinos are comparable due to isospin symmetry.

Neutrino spectrum is unmodified, γ-rays pile up below pair production threshold (on CMB at a few 10^{14} eV)

Universe acts as a calorimeter for total injected electromagnetic energy above the pair threshold.
=> neutrino flux constraints.



Interaction Horizons



Propagation of nucleons, photons, electrons, and neutrinos

In one dimension propagation is governed by Boltzmann equations for differential spectrum of species i, $n_i(E)$:

$$\frac{\partial n_i(E)}{\partial t} = \Phi_i(E) - n_i(E)\int d\varepsilon n_b(\varepsilon)\int_{-1}^{+1} d\mu \frac{1-\mu\beta_b\beta_i}{2}\sum_j \sigma_{i\to j}\Big|_{s=\varepsilon E(1-\mu\beta_b\beta_i)}$$
$$+\int dE'\int d\varepsilon n_b(\varepsilon)\int_{-1}^{+1} d\mu \sum_j \frac{1-\mu\beta_b\beta'_j}{2} n_j(E')\frac{d\sigma_{j\to i}(s,E)}{dE}\Bigg|_{s=\varepsilon E'(1-\mu\beta_b\beta_j)},$$

where:

$\Phi_i(E)$ =injection spectrum,

$n_b(\varepsilon)$ =diffuse background neutrino or photon density at energy ε,

μ = cos(angle between background and in-particle),

β =particle velocities,

$\sigma_{i\to j}$ = cross sections for processes $i \to j$,

s =center of mass energy.

Background spectrum between $\sim 10^{-8}$ eV and ~ 10 eV
propagated particles between 100 MeV and 10^{16} GeV (GUT scale)
transport equations (including cosmology, i.e. redshift-distance relation) solved by implicit methods.

Processes taken into account

Nucleons:

- (multiple) pion production: $N\gamma_b \to N(n\pi)$ with subsequent pion decays: leads to "GZK-effect".
- pair production by protons: $p\gamma_b \to pe^+e^-$: relevant below GZK threshold (similar to triplet pair production below)
- Neutron decay: $n \to pe^-\bar{\nu}_e$

Electromagnetic channel:

- pair production and inverse Compton scattering: $\gamma\gamma_b \to e^+e^-$ and $e\gamma_b \to e\gamma$: leading order processes with

$$\sigma_{\rm PP} \simeq 2\sigma_{\rm ICS} \simeq \frac{3}{2}\sigma_T \frac{m_e^2}{s} \ln\frac{s}{2m_e^2} \quad (s \gg m_e^2)\,.$$

- double pair production: $\gamma\gamma_b \to e^+e^-e^+e^-$: dominates at highest energies with

$$\sigma_{\rm DPP} \simeq \frac{43\alpha^2}{24\pi^2}\sigma_T \quad (s \gg m_e^2)\,.$$

- triplet pair production: $e\gamma_b \to ee^+e^-$: dominant at highest energies with

$$\sigma_{\rm TPP} \simeq \frac{3\alpha}{8\pi}\sigma_T \left(\frac{28}{9}\ln\frac{s}{m_e^2} - \frac{218}{27}\right) \quad (s \gg m_e^2)\,,$$

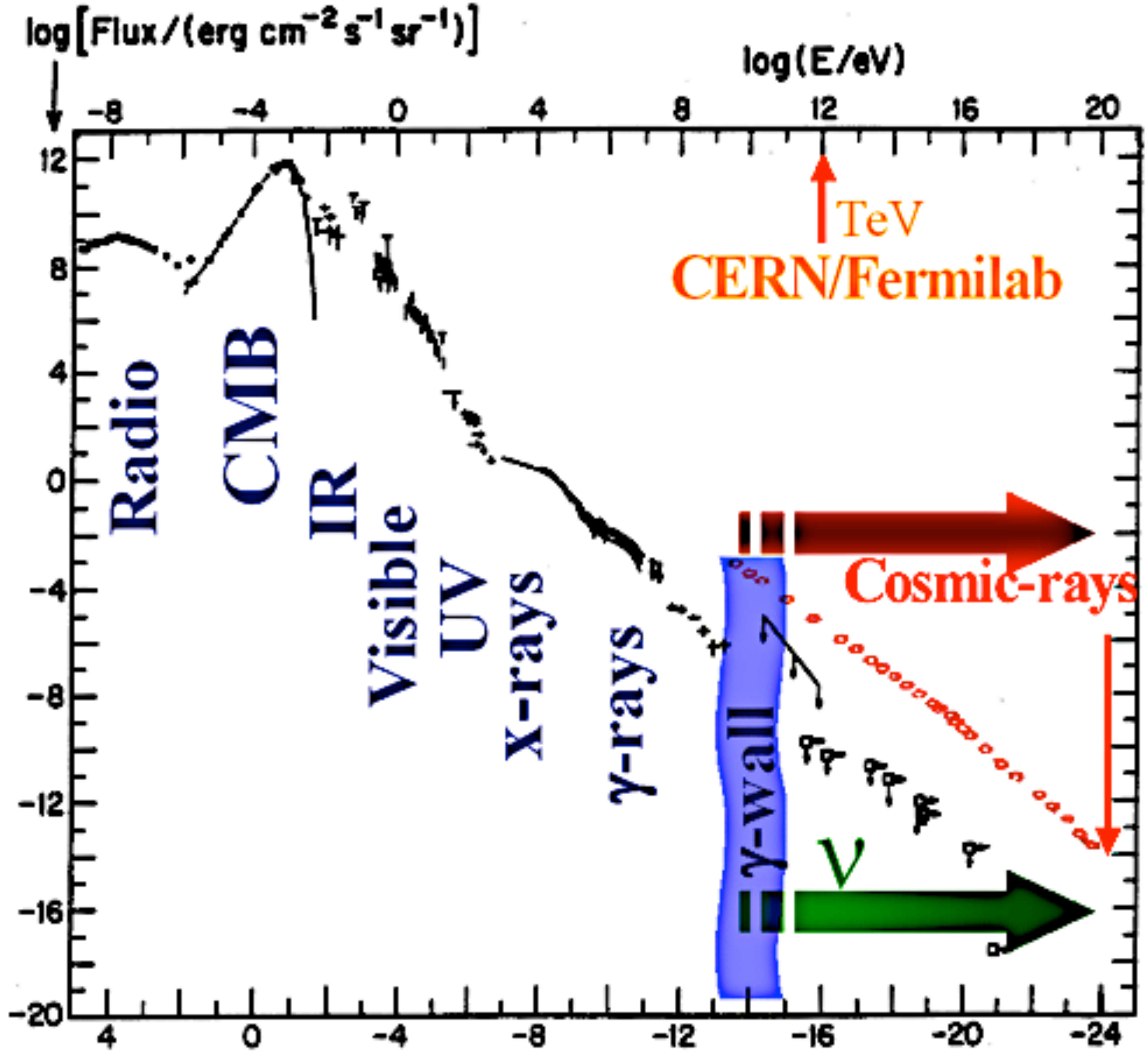
  with fractional energy loss η of leading e

$$\eta \simeq 1.768 \left(\frac{s}{m_e^2}\right)^{-3/4} \quad (s \gg m_e^2)\,.$$

- synchrotron loss of electrons and positrons in cosmic magnetic fields: $eB \to e\gamma$. Energy loss given by

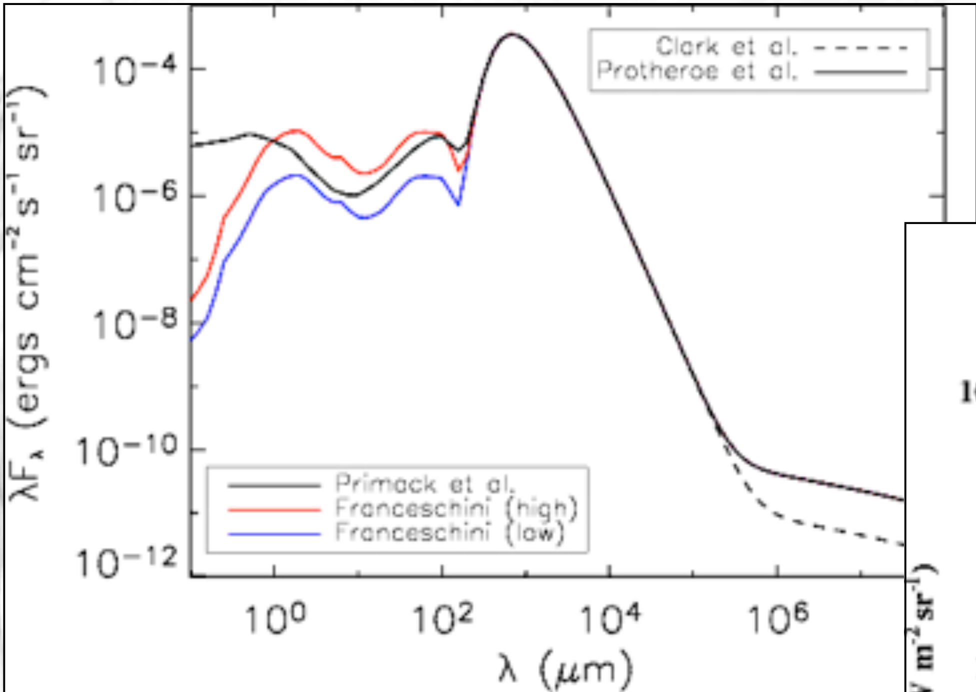
$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T \frac{B^2}{8\pi}\left(\frac{Zm_e}{m}\right)^4 \left(\frac{E}{m_e}\right)^2 .$$

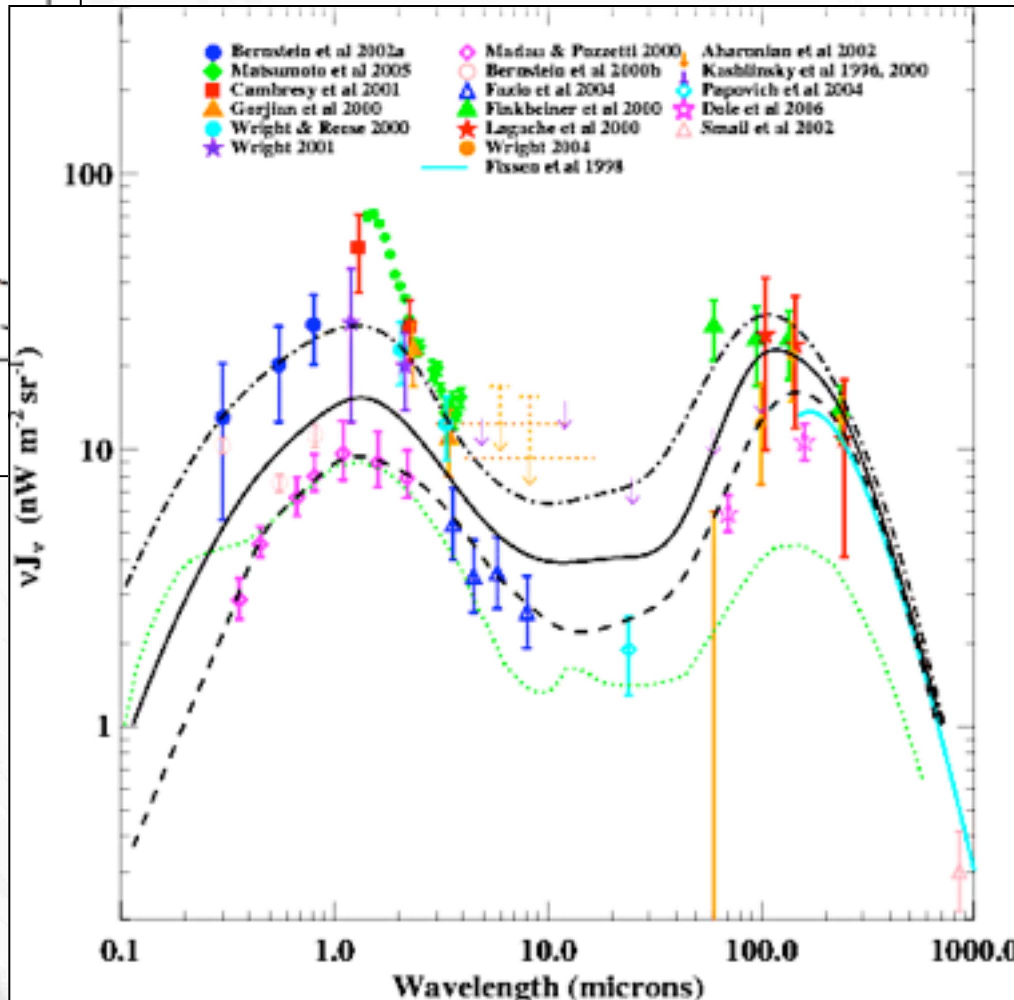
The universal photon spectrum



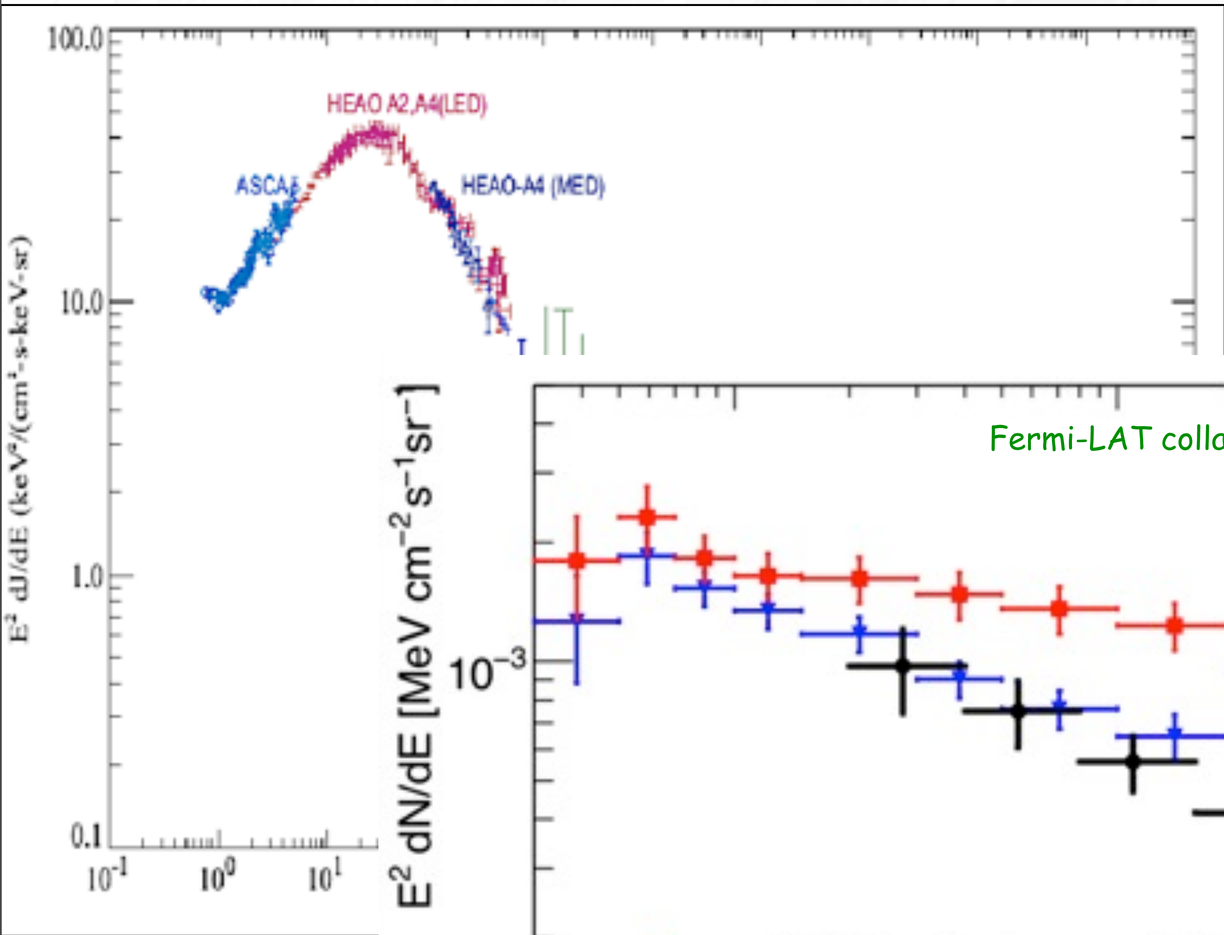
(after Ressell & Turner '90)

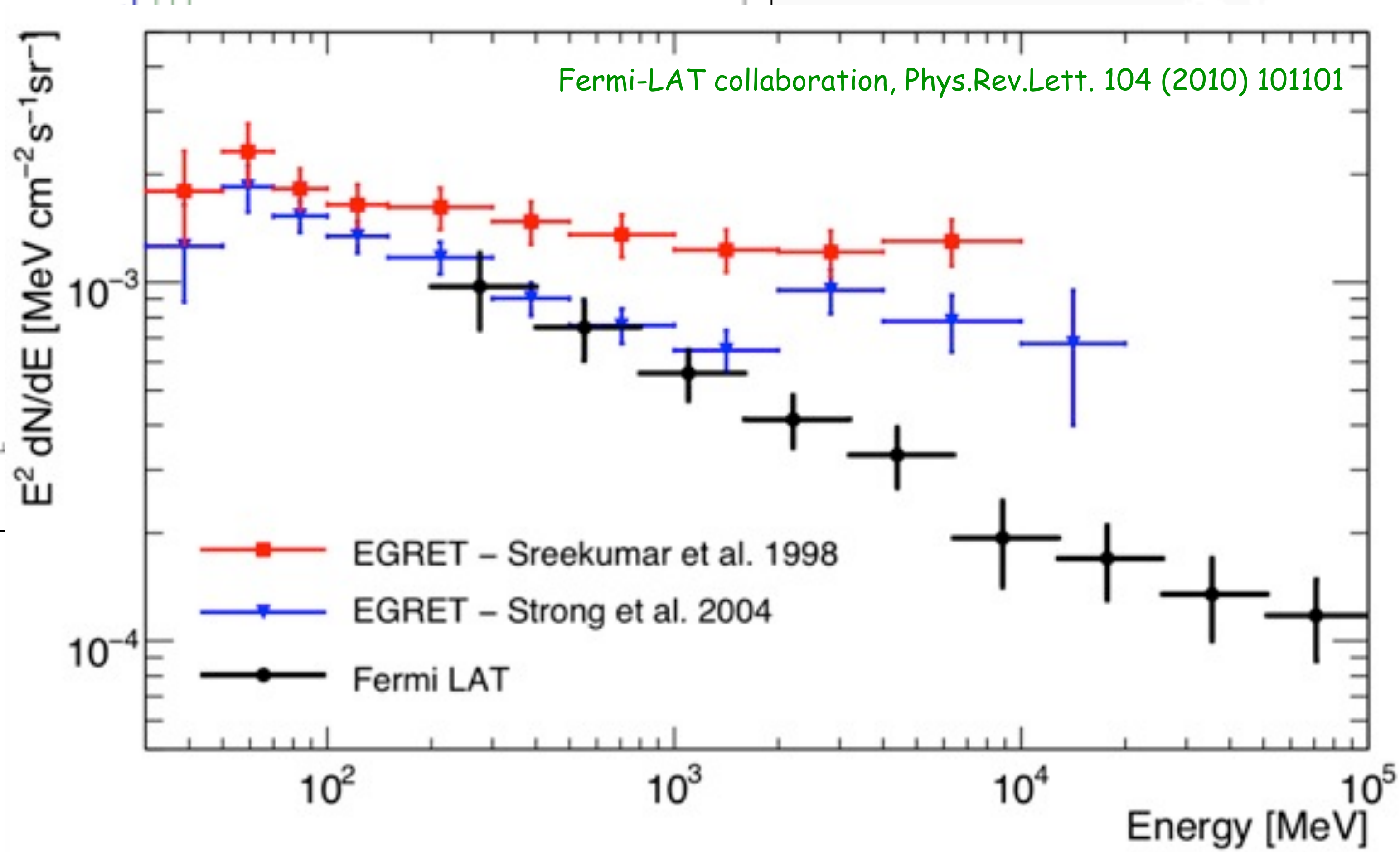
Low energy photon target: Diffuse fluxes



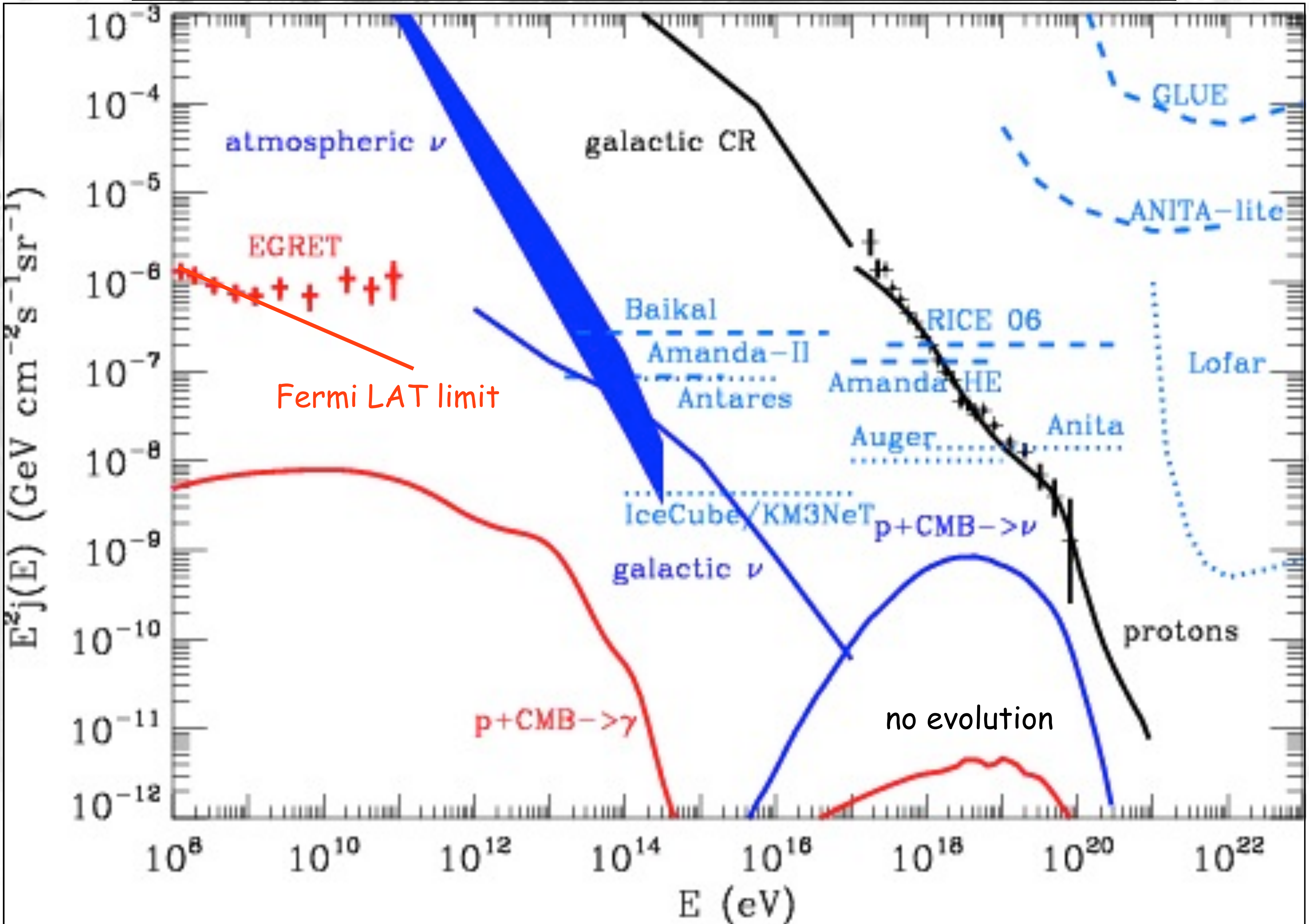


The diffuse photon background from keV to 100 GeV





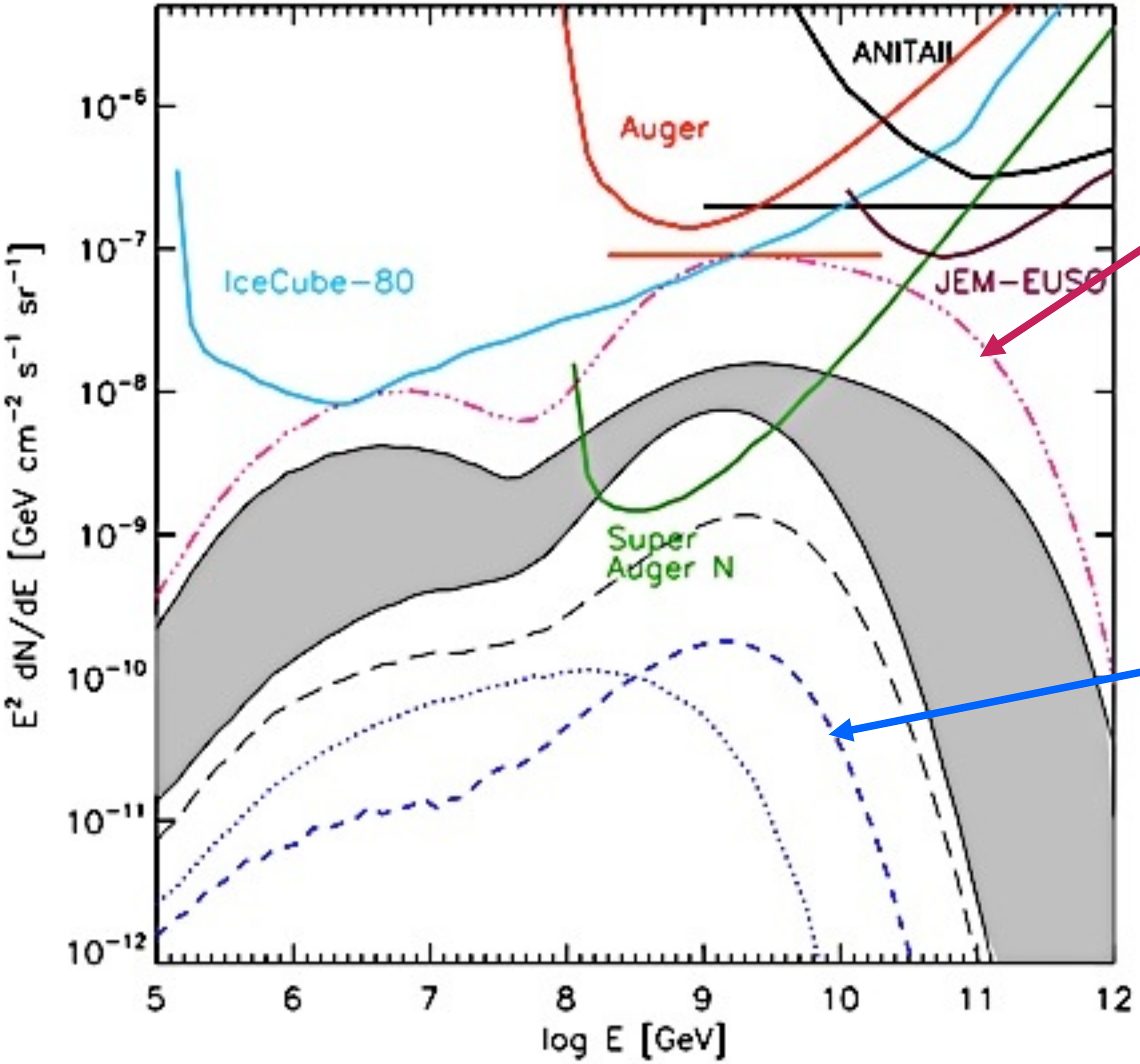
Theoretical Limits, Sensitivities, and "Realistic" Fluxes: A Summary



Physics with Diffuse Cosmogenic Neutrino Fluxes

Cosmogenic neutrino fluxes depend on number of nucleons produced above GZK threshold which is proportional to E_{max}/A

Further suppressed for heavy nuclei due to increased pair production

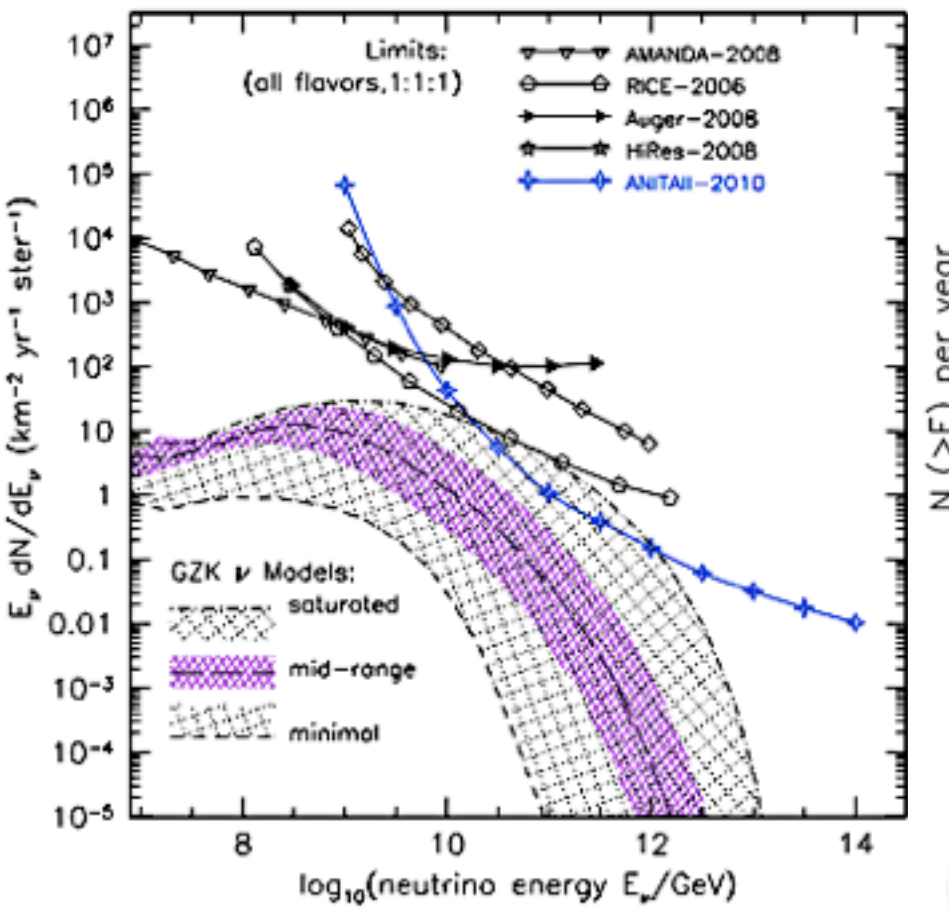


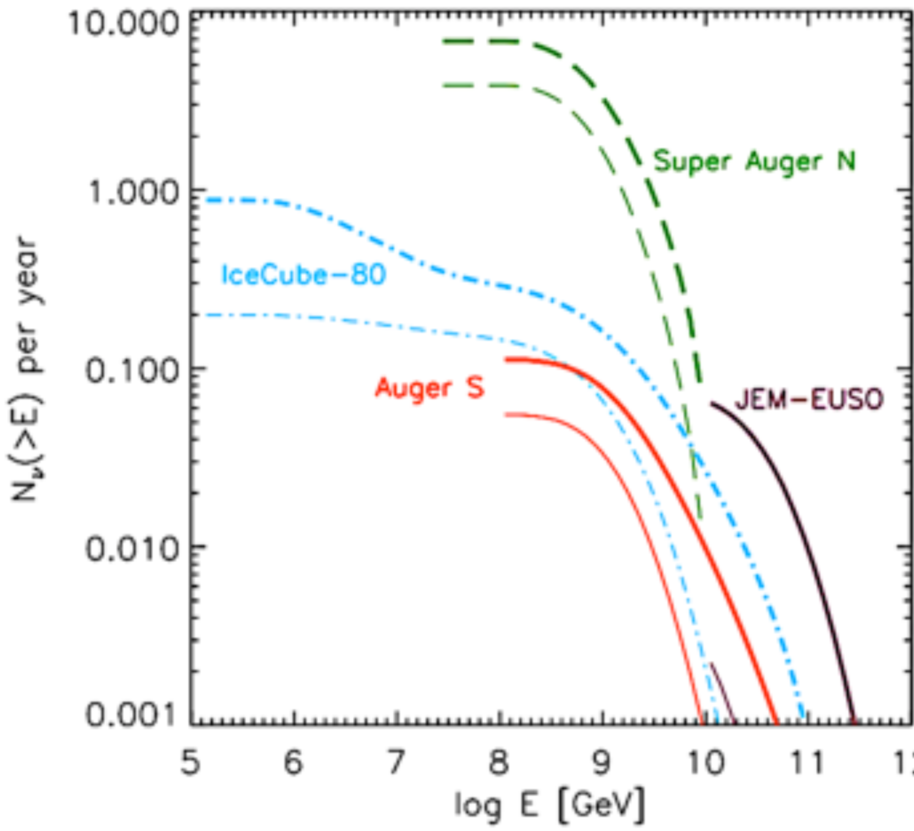
Pure protons, E_{max}=3 10^{21} eV, strong evolution

Pure iron, E_{max}= 10^{20}/26 eV, no evolution

Kotera, Allard, Olinto, arXiv:1009.1382

Expected Sensitivities to/Rates of UHE neutrino fluxes





Rates for intermediate fluxes

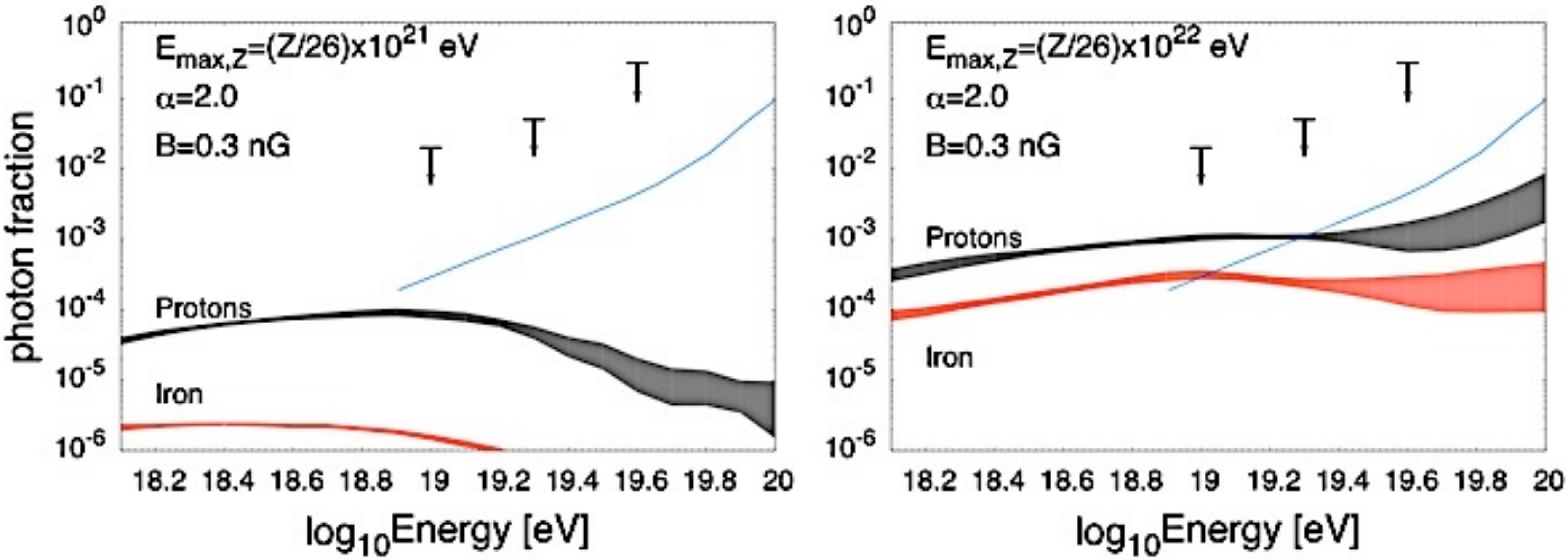
P. Gorham et al, arXiv:1003.2961

Kotera, Allard, Olinto, arXiv:1009.1382

Physics with Diffuse Secondary Gamma-Ray Fluxes

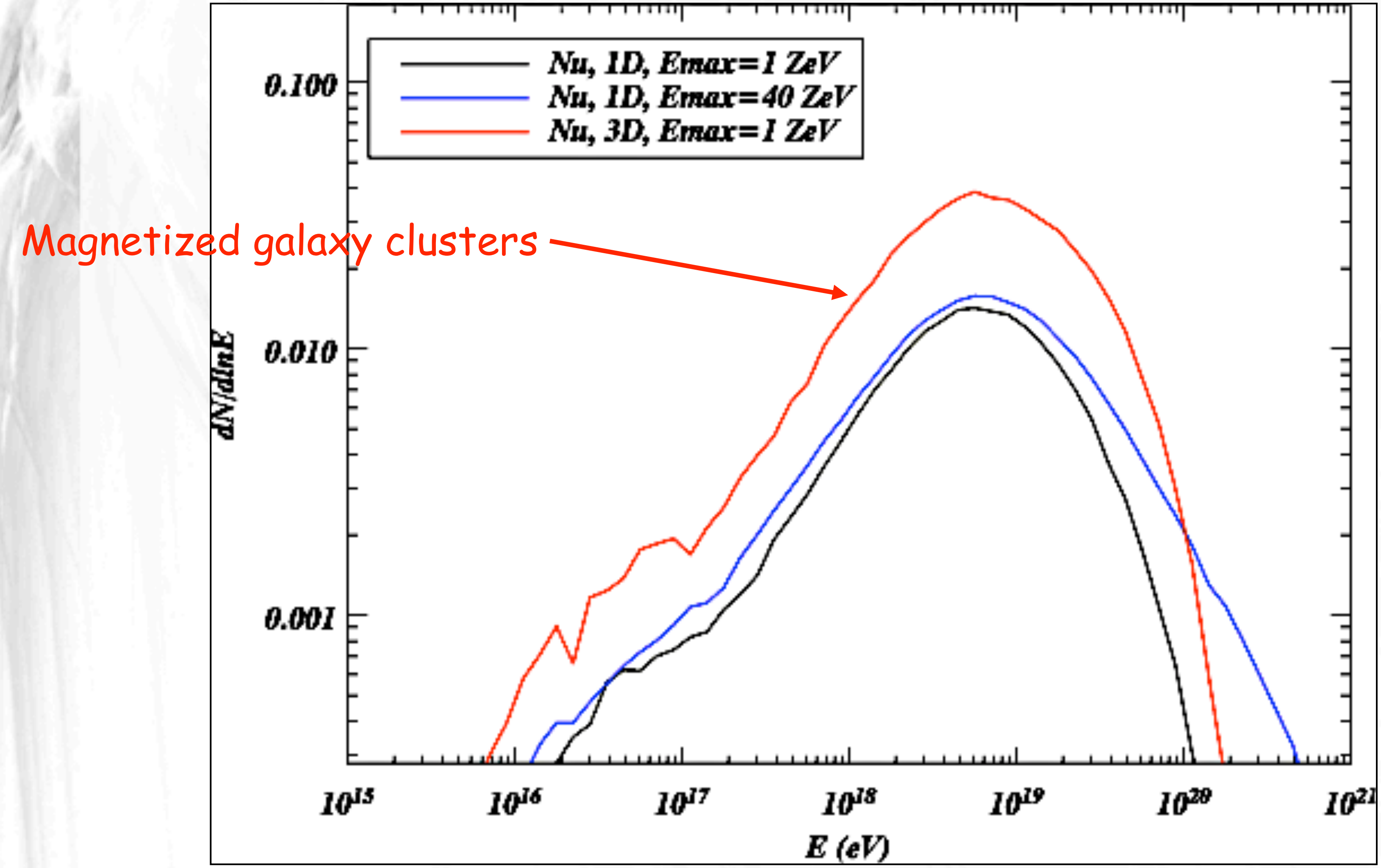
UHE gamma-ray fluxes depend on number of nucleons locally produced above GZK threshold which is proportional to E_{max}/A

Further suppressed for heavy nuclei due to increased pair production



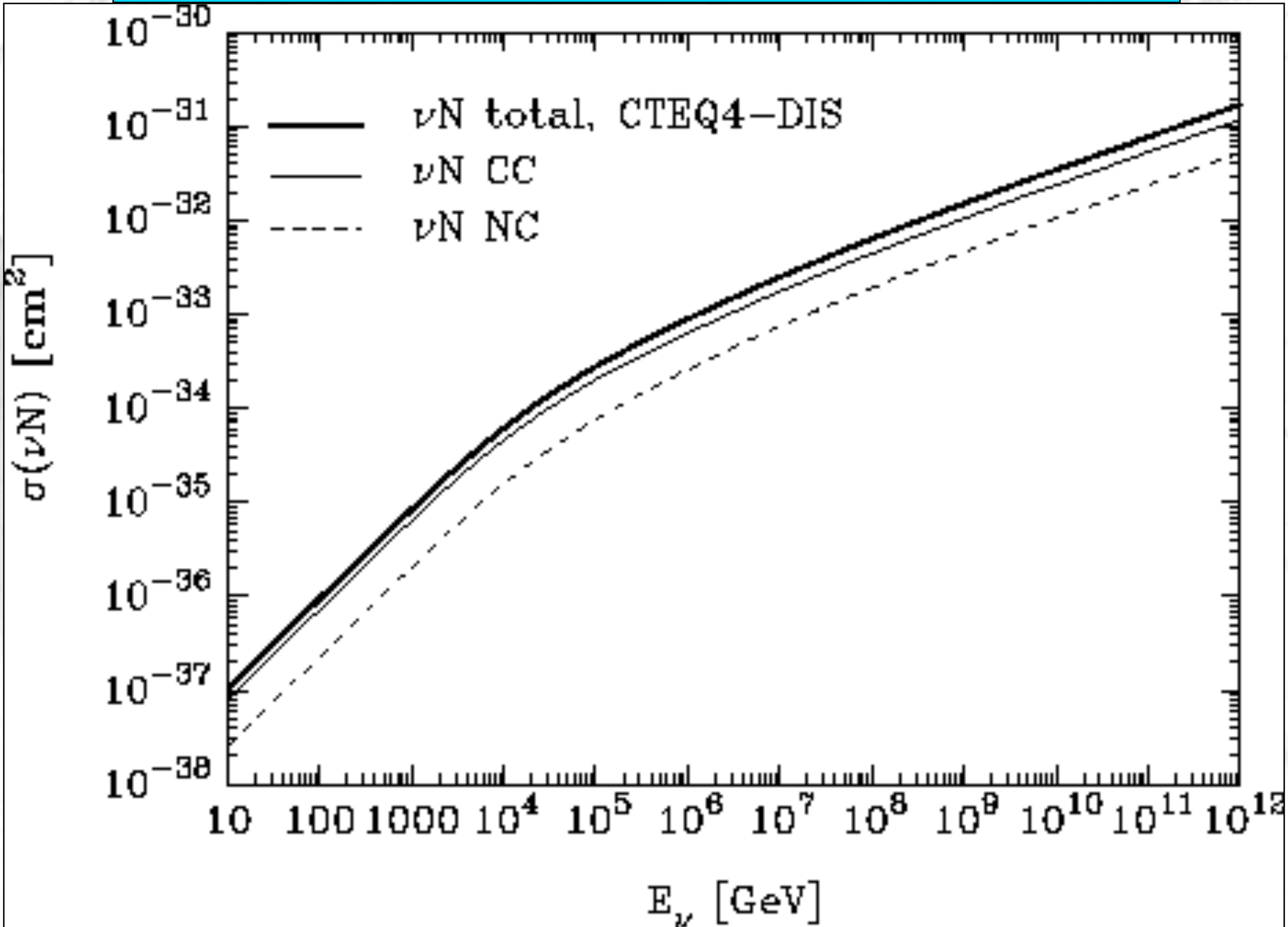
Hooper, Taylor, Sarkar, arXiv:1007.1306

The GZK neutrino flux can also be enhanced by magnetic fields surrounding the sources



Armengaud and Sigl

Neutrino-Nucleon Cross Section and Required Detector Size



Ultra-High Energy Neutrino Detection: Traditional and New Ideas

Mostly uses the charged-current reactions: $\nu_i + N$ ® $l_i + N\,, \quad i = e, \mu, \tau$

1.) detect Cherenkov radiation from muons in deep sea or ice

AMANDA, ANTARES, BAIKAL, NESTOR

aims at 1 km^3 for E> 100 GeV to 1 TeV

2.) horizontal air showers for electron and τ-neutrinos

PIERRE AUGER, MOUNT

for E> 10^{18} eV, increased efficiency for τ-neutrinos if surrounded by mountains on 100 km scale which is decay length of produced taus.

3.) detection of inclined showers from space for E>10^{20} eV

EUSO, OWL

4.) detection of radio emission from negative charge excess of showers produced in air, water, ice, or in skimming rock.

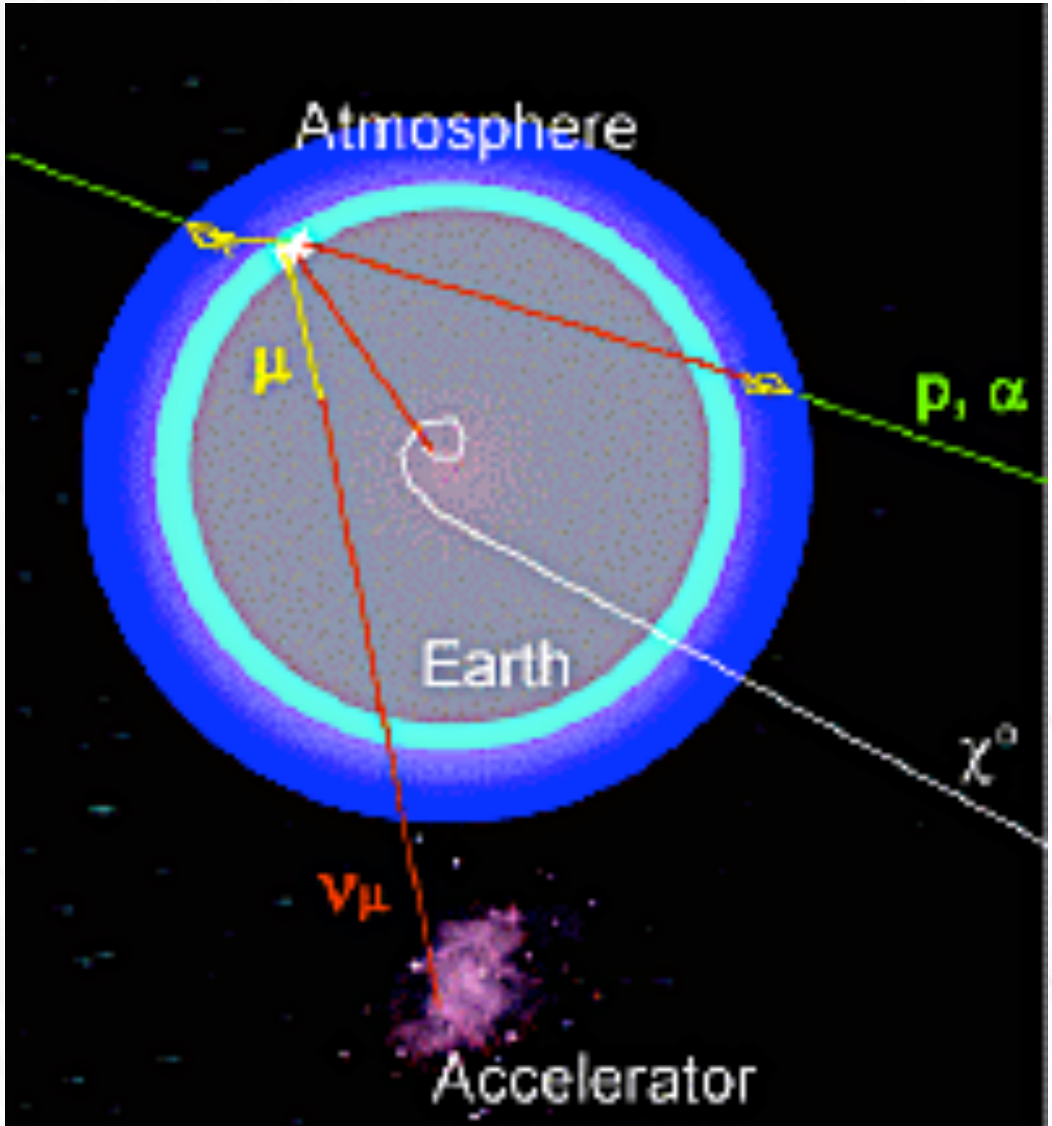
RICE (in South-pole ice), GLUE (radio-telescope observing the moons rim)

5.) acoustic detection in water: hydrophonic arrays

6.) Earth-skimming events in ground arrays or fluorescence detectors.

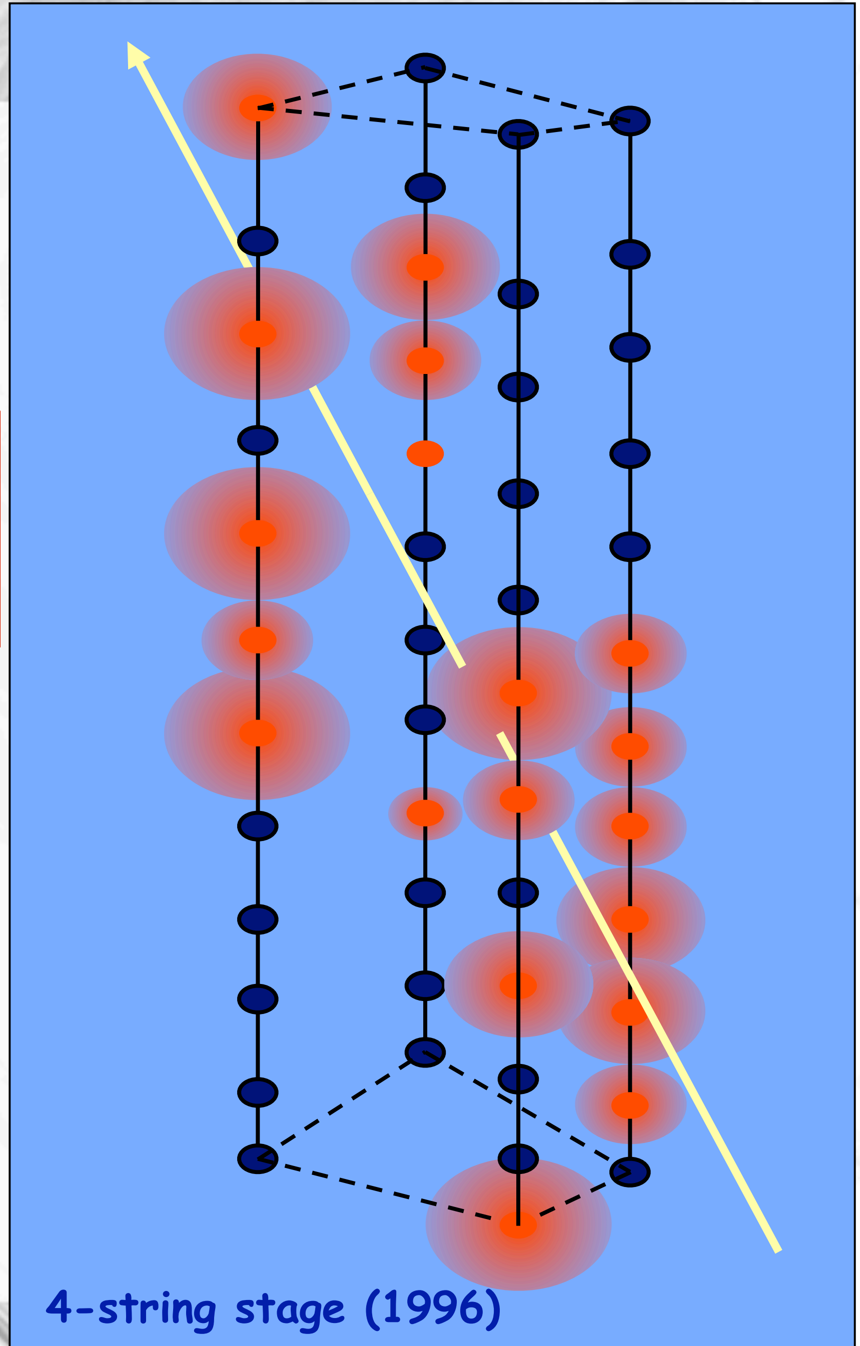
Experimental Detection of E<10^{17}eV Neutrinos

- Neutrinos coming from above are secondary from cosmic rays
- Neutrino coming from below are mixture of atmospheric neutrinos and HE neutrinos from space
- Earth is not transparent for neutrinos E>10^{15}eV
- Former/current experiments: MACRO, Baikal, AMANDA
- Future experiments:



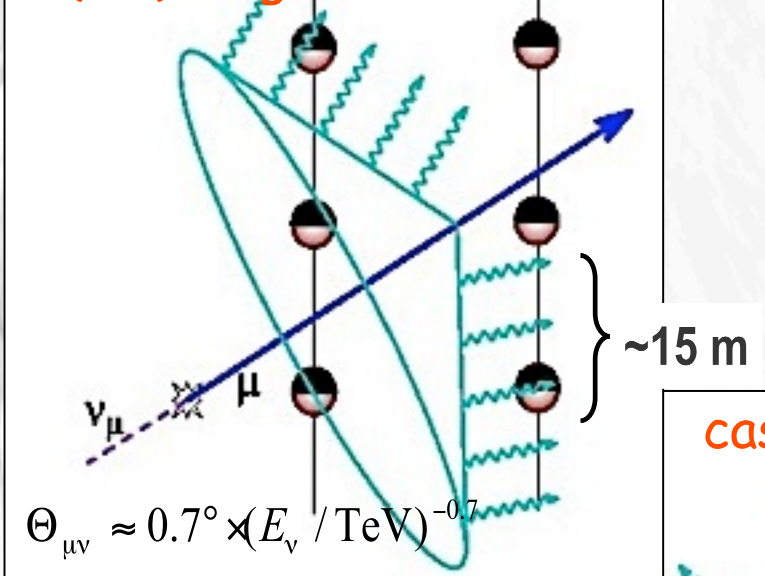
Lake

First underwater telescope
First neutrinos underwater



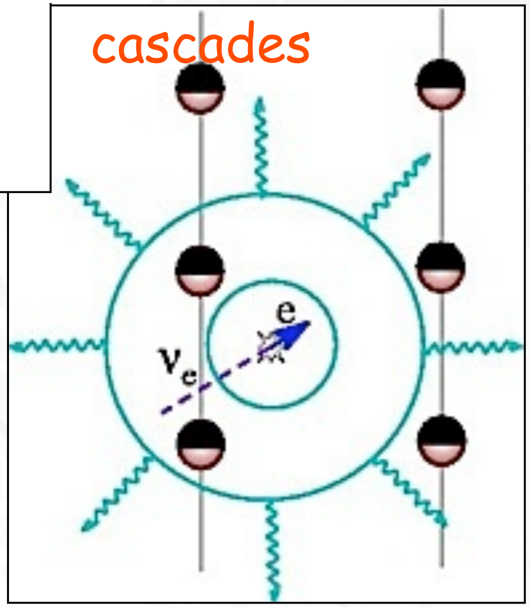
Neutrino detection in polar ice

O(km) long muon tracks

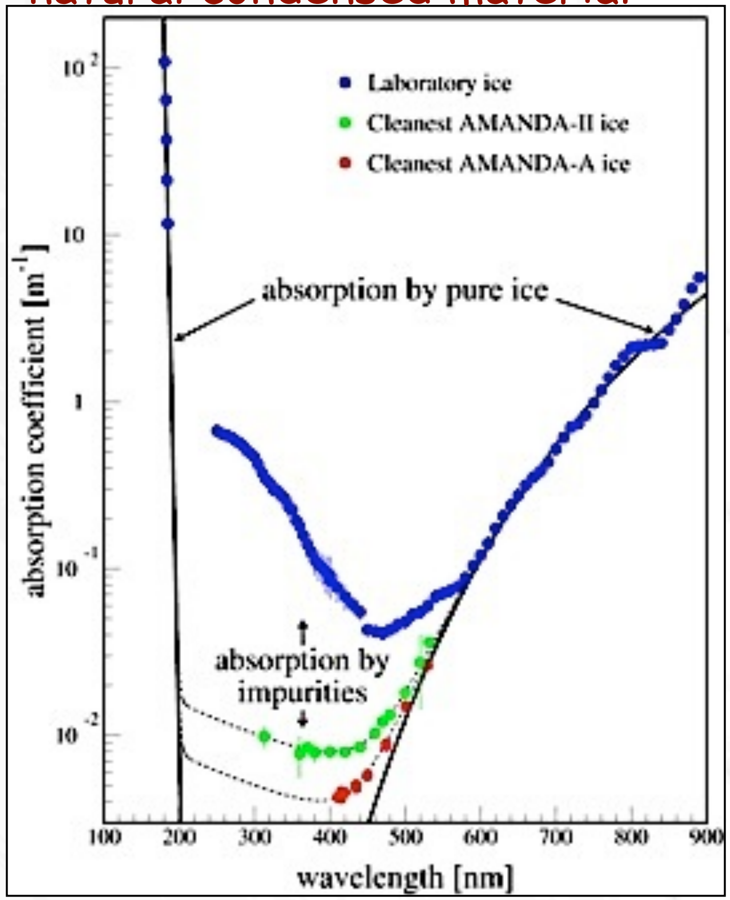


$\Theta_{\mu\nu} \approx 0.7° \times (E_\nu / \mathrm{TeV})^{-0.7}$

cascades



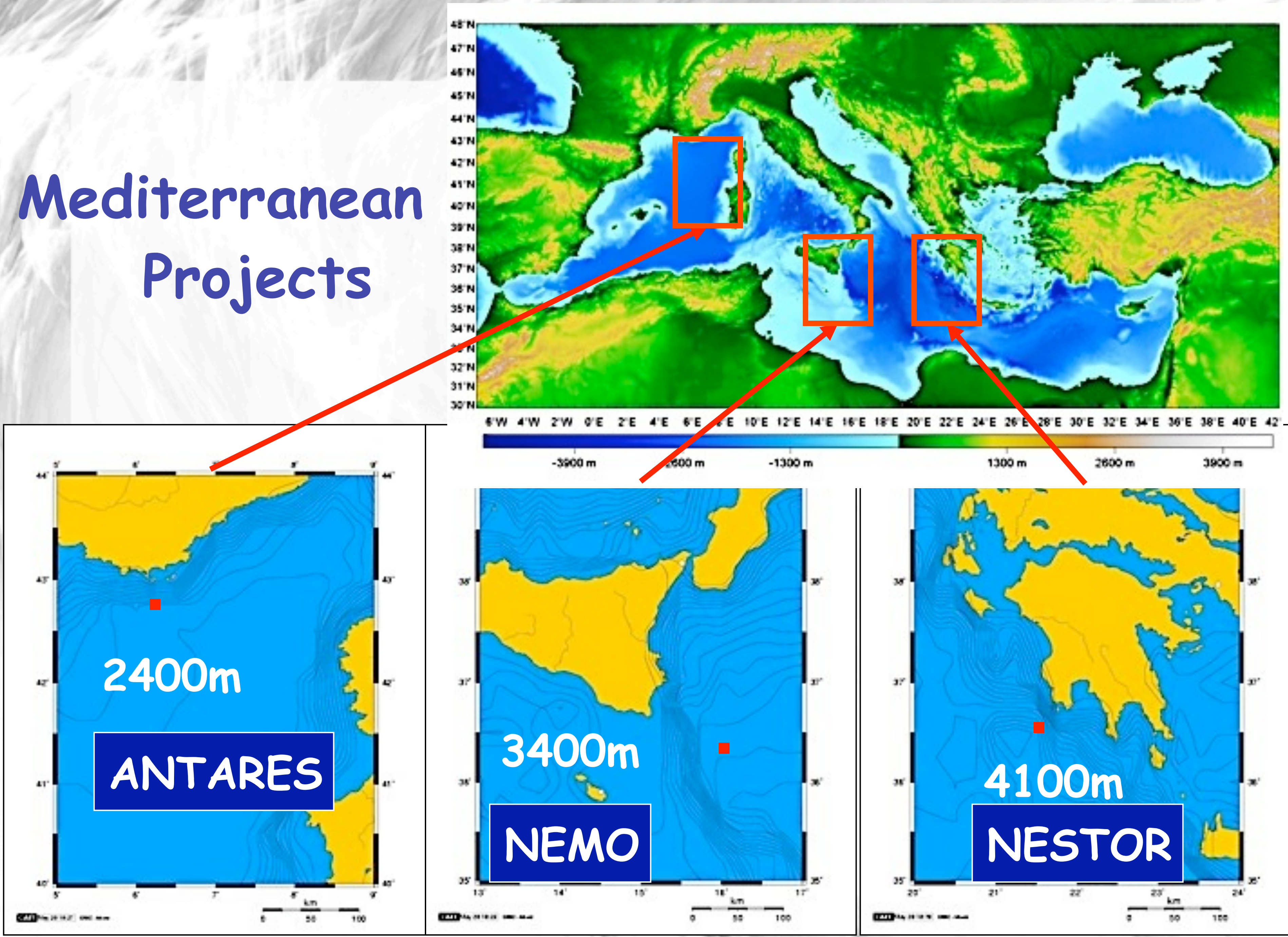
South Pole ice:
(most?) transparent
natural condensed material



event reconstruction by
Cherenkov light timing

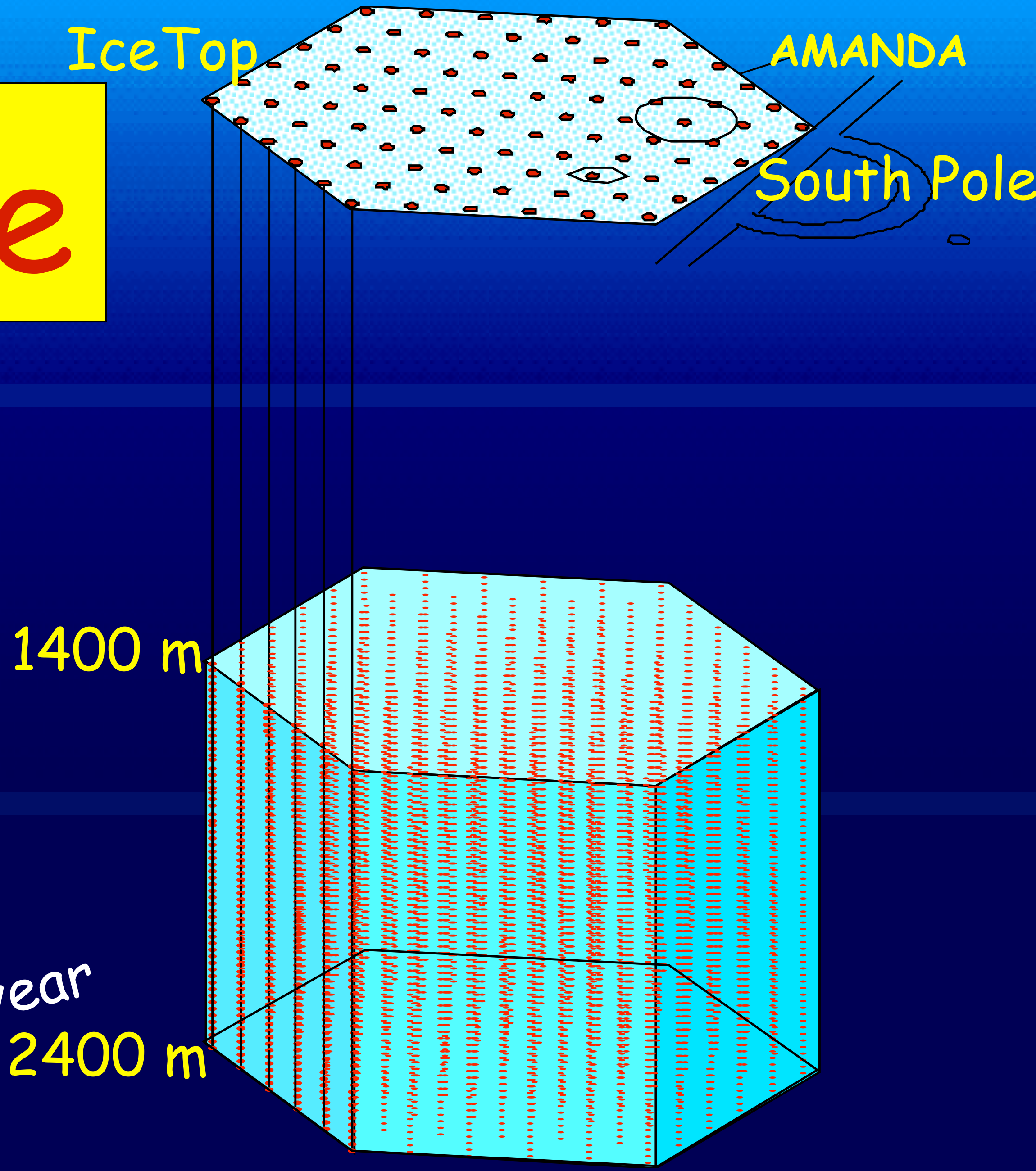
Longer absorption length → larger effective volume

Mediterranean Projects



IceCube

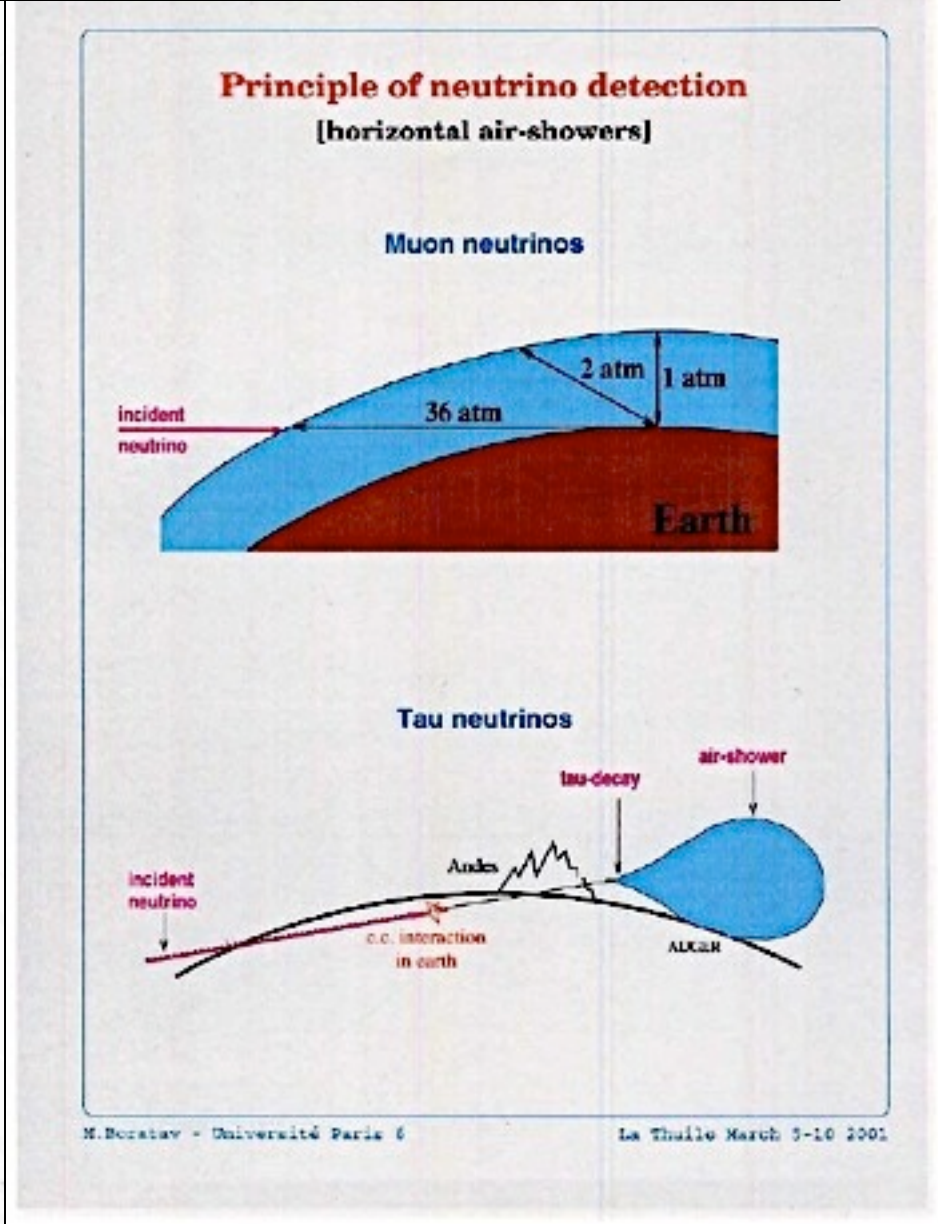
- 80 Strings
- 4800 PMT
- Instrumented volume: 1 km^3
- Installation:



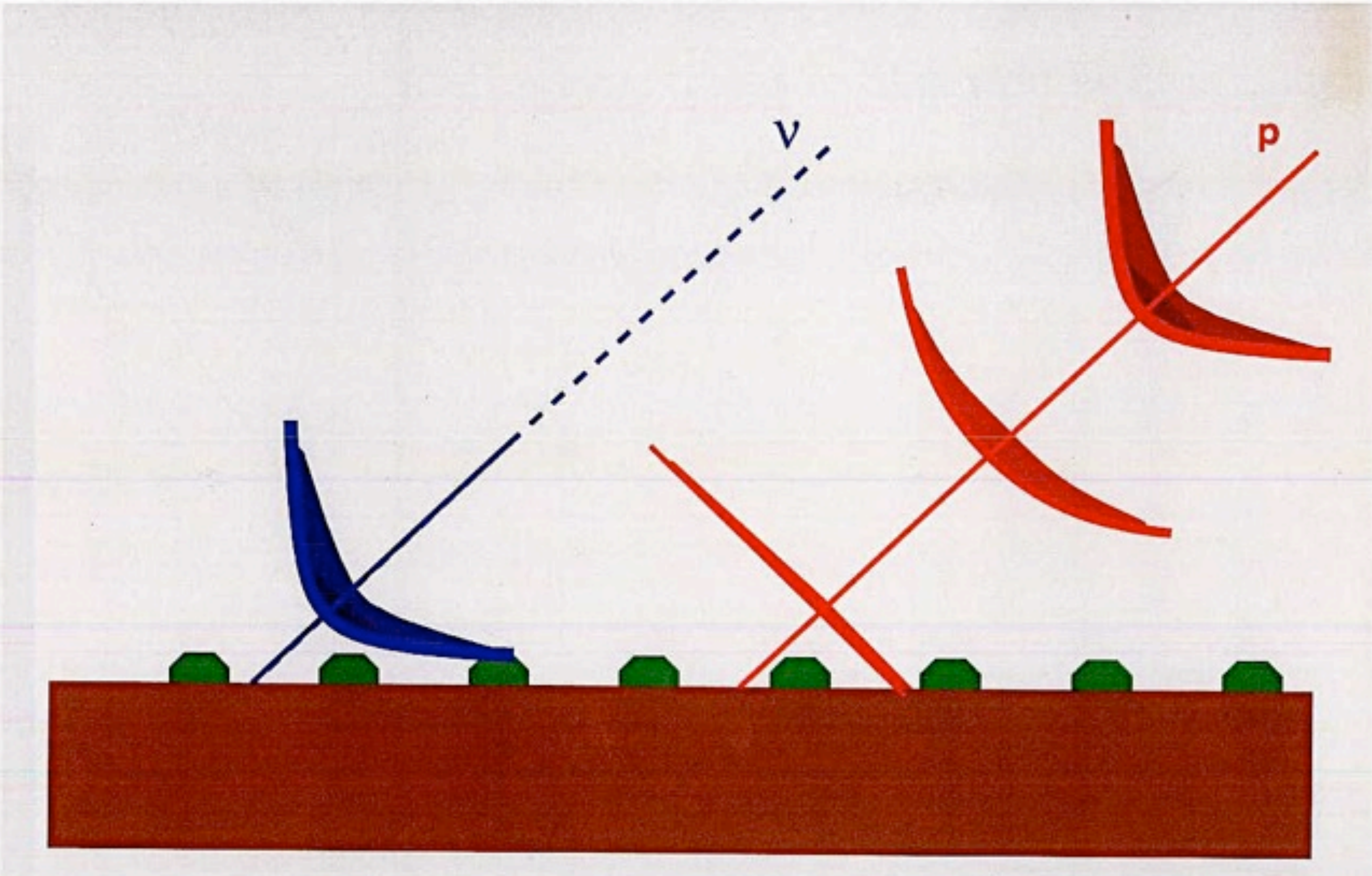
~ 80.000 atm.ν per year

Air Shower Detection of UHE ($E>10^{17}$eV)

- Neutrinos are not primary UHECR
- Horizontal or Earth-skimming air showers – easy way to detect neutrinos
- Former/current experiments: Fly's Eye, AGASA
- Future experiments: Pierre Auger, OWL/EUSO…

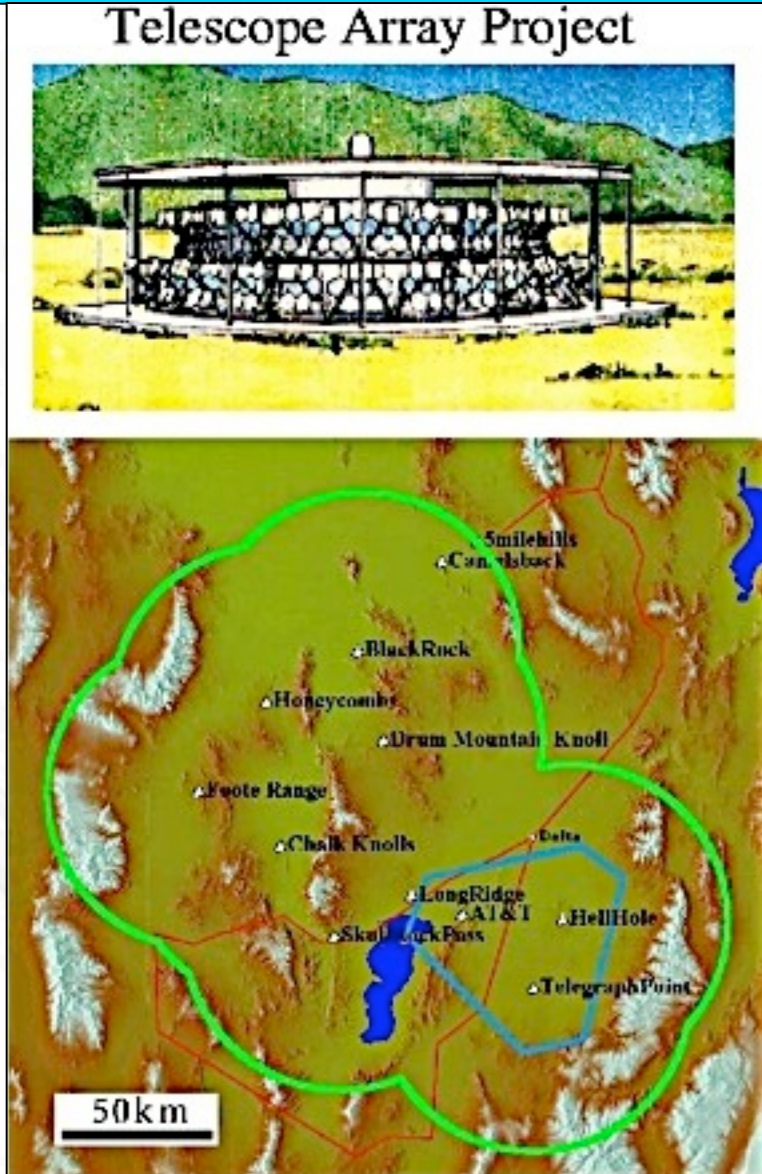


Neutrino penetration depth

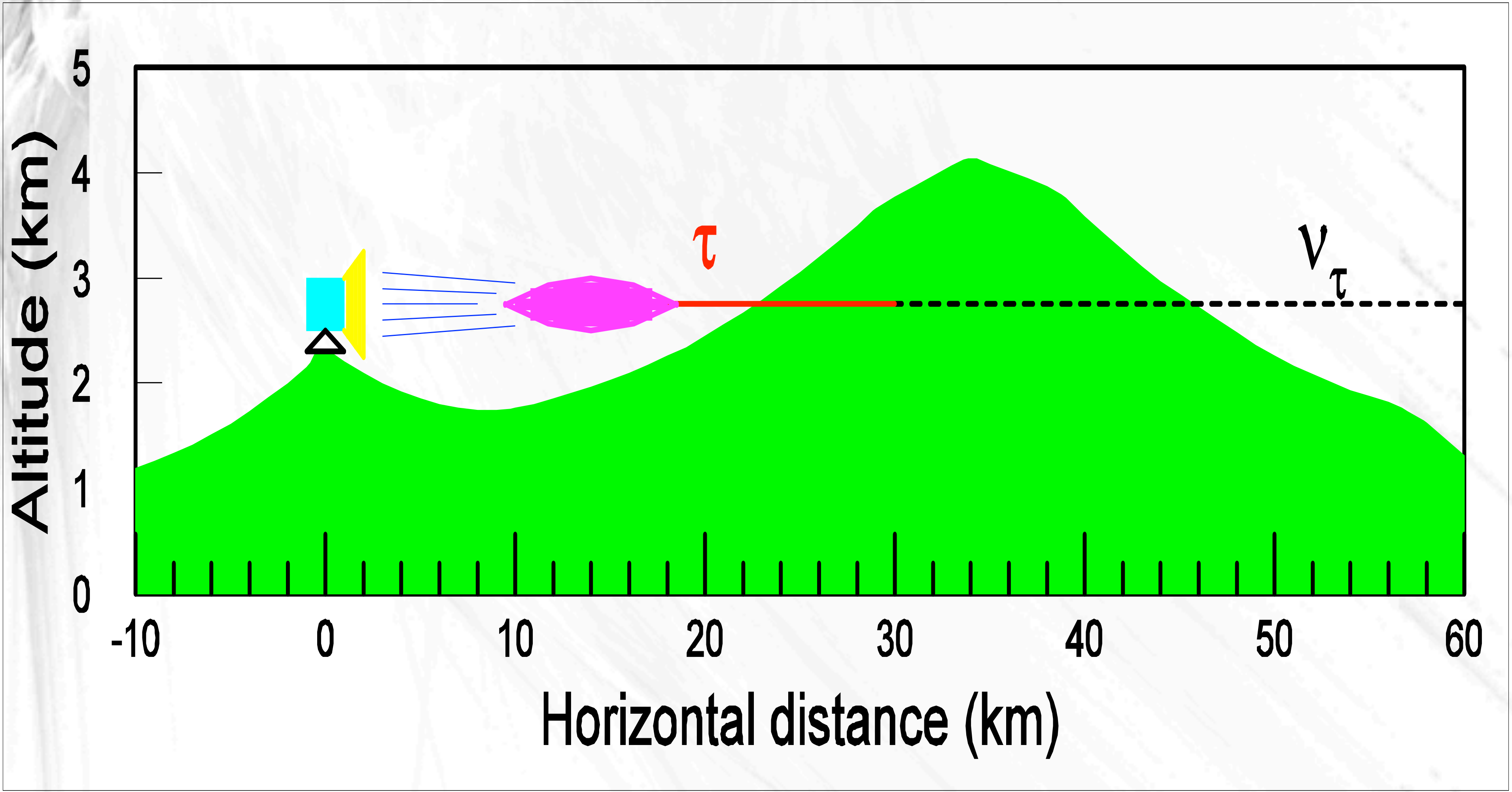


Curved "young" shower => neutrino
Flat "old" shower => hadron

Telescope

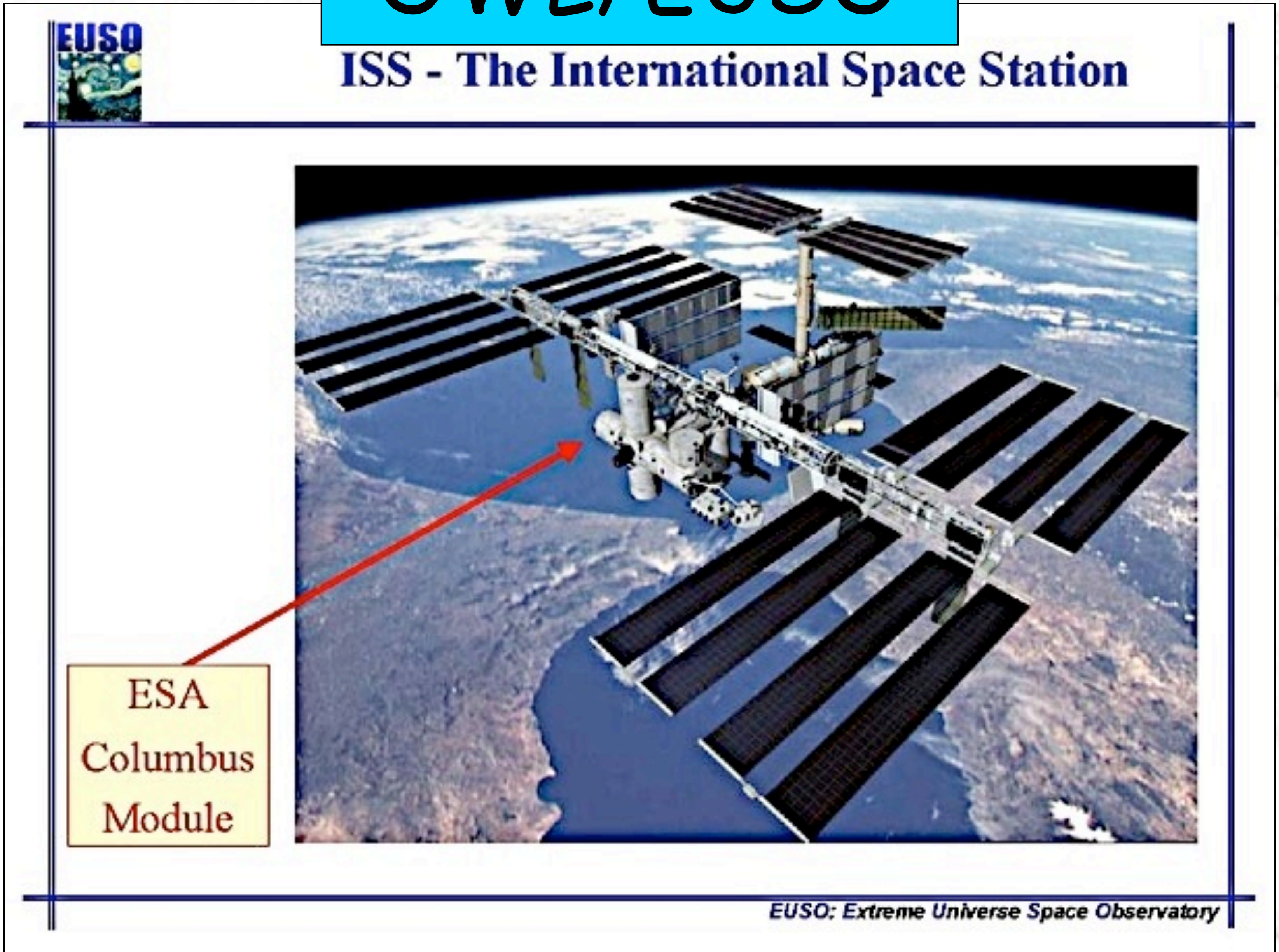

Telescope Array Project
5milehills
BlackRock
Honeycombs
Drum Mountain Knoll
Foote Range
Chalk Knolls
Delta
LongRidge
AT&T
HellHole
TelegraphPoint
50km

MOUNT/ASHRA



Altitude (km)
0
1
2
3
4
5
τ
ν_τ
-10
0
10
20
30
40
50
60
Horizontal distance (km)

OWL/EUSO


EUSO
ISS - The International Space Station
ESA Columbus Module
EUSO: Extreme Universe Space Observatory

Radio Detection of Neutrinos

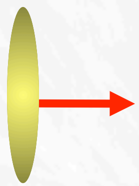
$\nu_e + n \rightarrow p + e^-$

$e^- \rightarrow$ ... cascade

negative charge is sweeped into developing shower, which acquires a negative ne

$Q_{net} \sim 0.25\ E_{cascade}$ (GeV).

⇒ relativist. pancake
~ 1cm thick, ∅ ~10cm

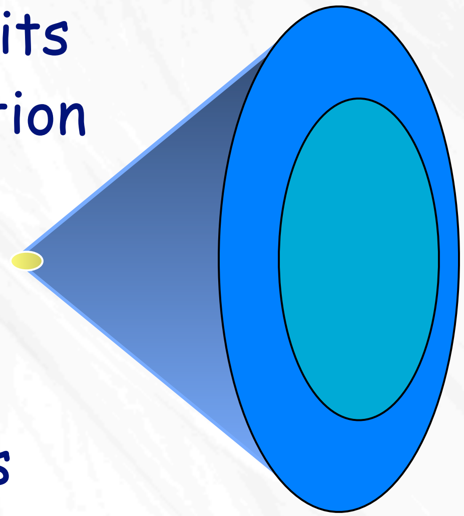


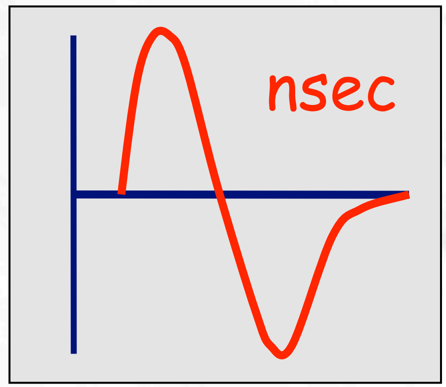
⇒ for λ >> 10 cm (radio)
coherence

⇒ each particle emits Cherenkov radiation

⇒ C-signal ~ E^2

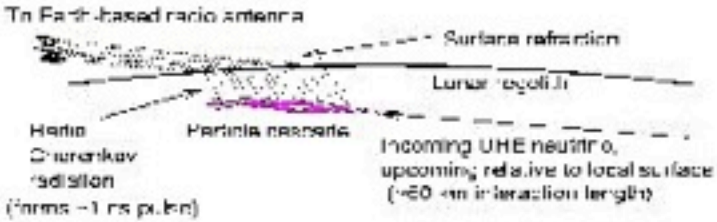
⇒ C signal is resultant of overlapping Cherenkov cones

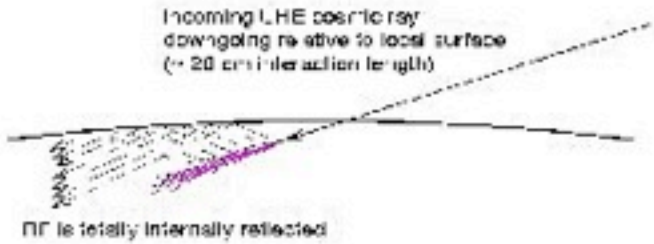


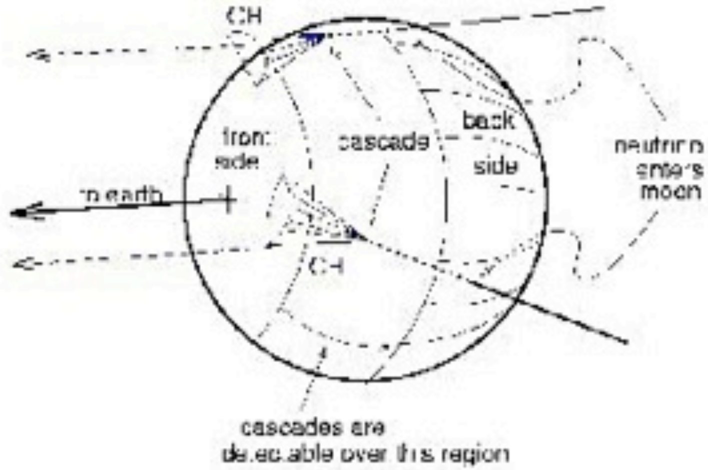


Threshold > 10^{16} eV

Lunar Regolith Interactions & RF Cherenkov radiation



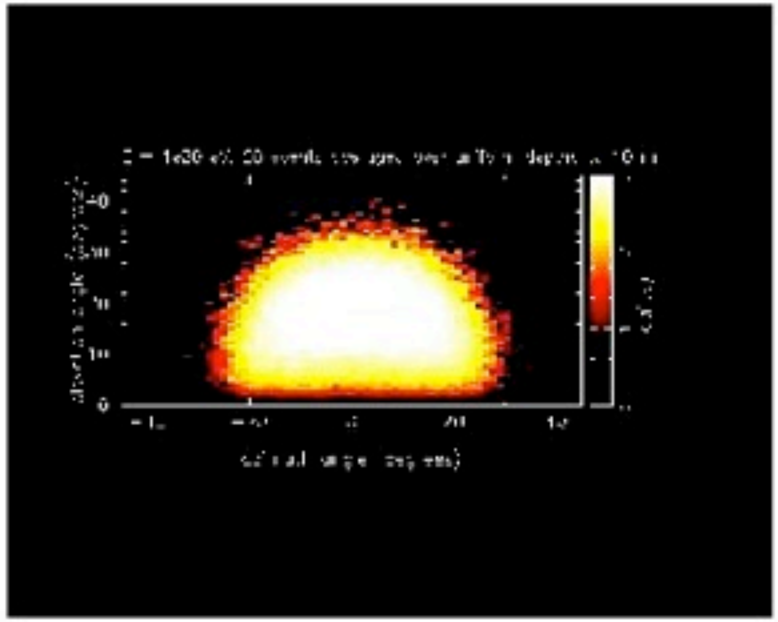




• At ~100 EeV energies, neutrino interaction length in lunar material is ~60km

• Rmoon ~ 1740 km, so most detectable interactions are grazing rays, but detection not limited to just limb

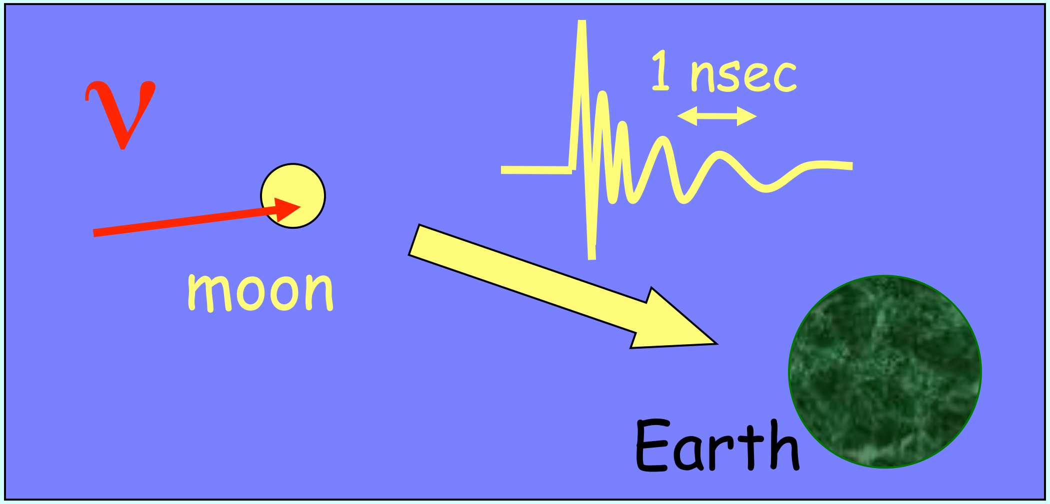
• Refraction of Cherenkov cone at regolith surface “fills in” the pattern, so acceptance solid angle is ~50 times larger than apparent solid angle of moon



GLUE Goldstone Lunar Ultra-high Energy

Lunar Radio Emissions from Interactions of ν and CR with > 10^{19} eV

Gorham et al. (1999), 30 hr NASA Goldstone 70 m antenna + DSS 34 m antenna



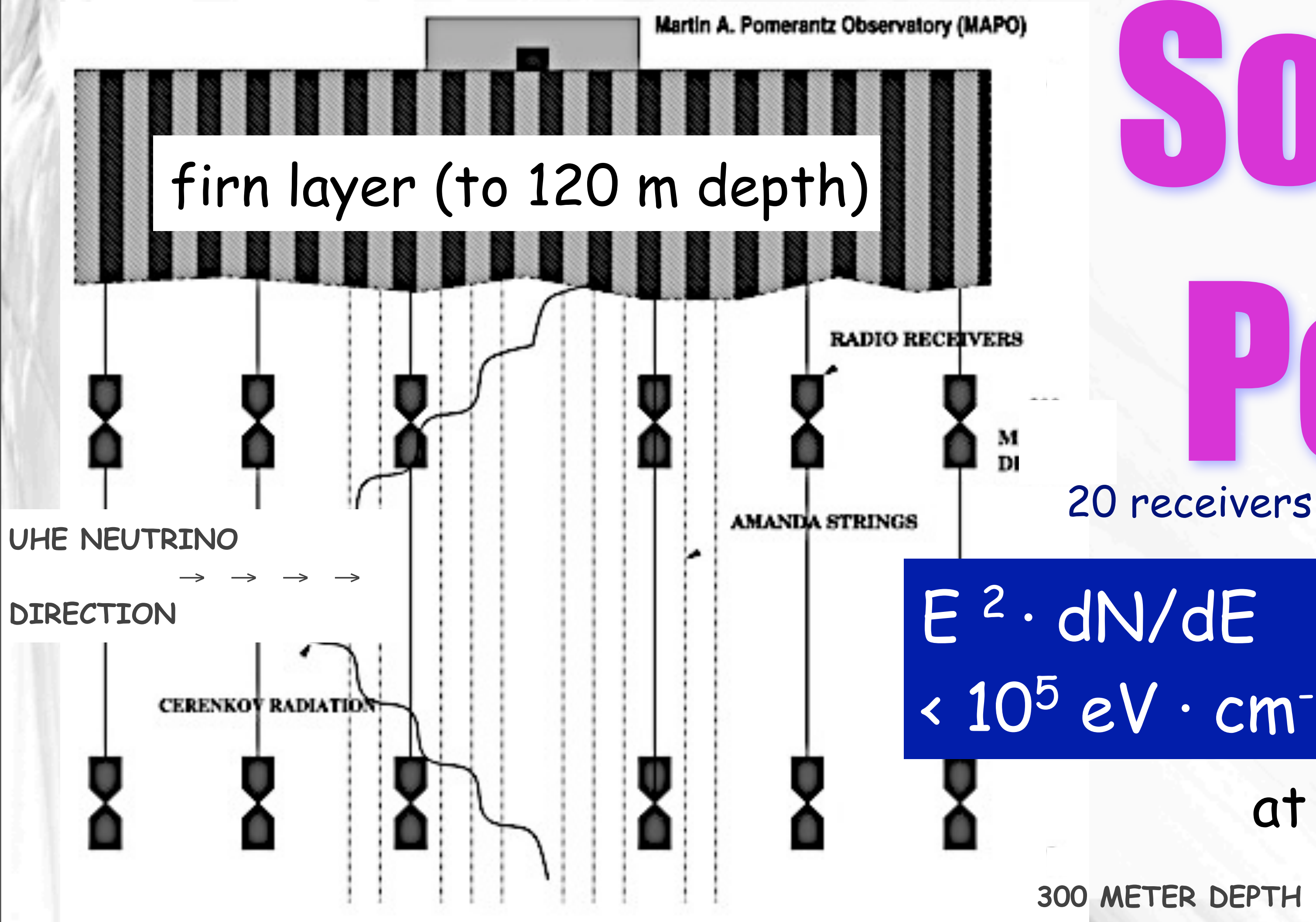
→ $E^2 \cdot dN/dE < 10^5$ eV·cm^{-2}·s^{-1}·sr^{-1}

at 10^{20} eV

Effective target volume
~ antenna beam (0.3°)
× 10 m layer

→ 10^5 km^3

RICE Radio Ice Cherenkov Experiment



South Pole

20 receivers +transmitters

$E^2 \cdot dN/dE$

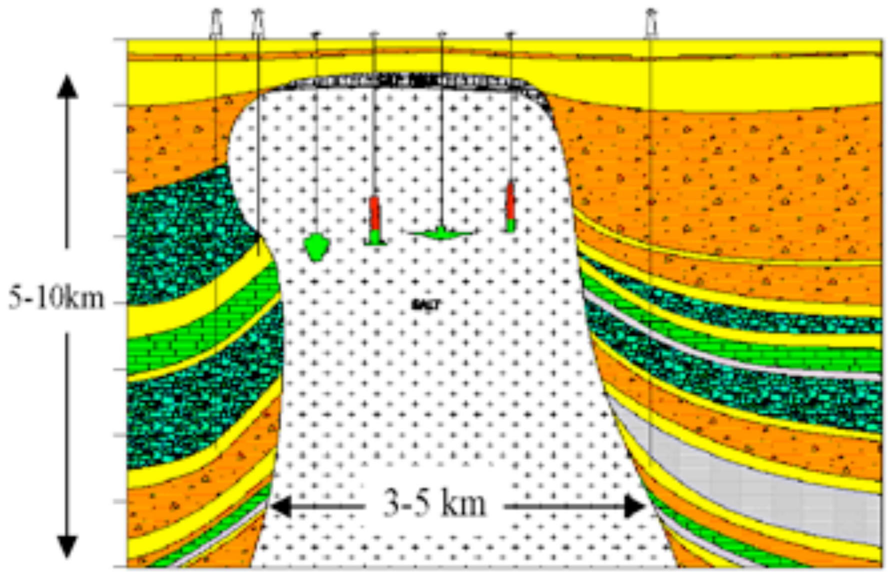
$< 10^5\ eV \cdot cm^{-2} \cdot s^{-1} \cdot sr^{-1}$

at 10^{17} eV

Natural Salt Domes: Potential PeV-EeV Neutrino Detectors

- Natural salt can be extremely low RF loss: ~ as clear as very cold ice, 2.4 times as dense

- Typical salt dome halite is comparable to ice at -40C for RF clarity



SalSA

Salt **D**ome

Shower

Array