Acoustic Detection of Ultra−High Energy Neutrinos

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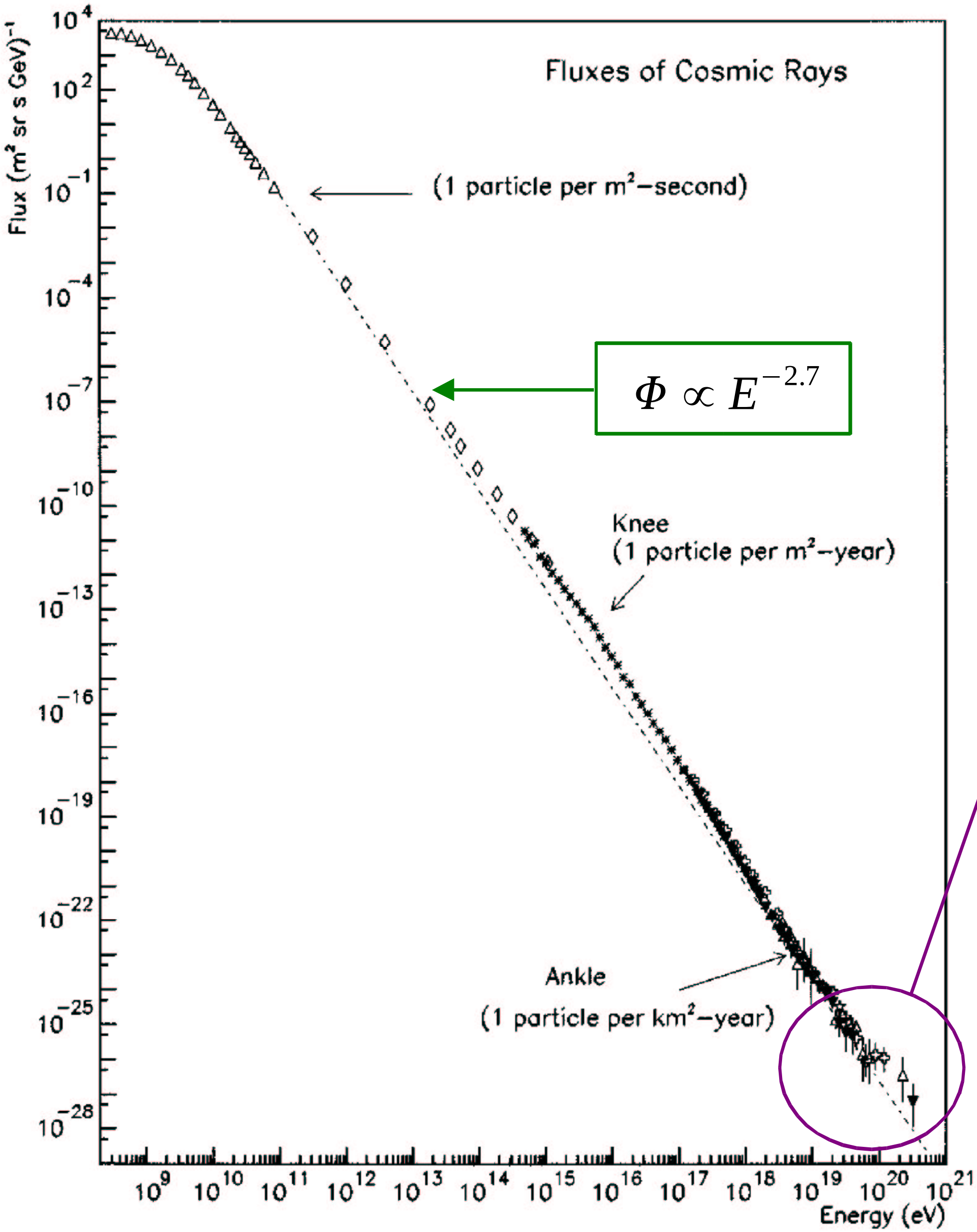
[also : DSTL, Lancaster, Northumbria, Sheffield]

- Ultra−High Energy Cosmic Rays
- UHE Neutrino Sources
- UHE Neutrino Detection
- Acoustic Detection of UHE Neutrinos
- Existing Hydrophone Arrays
- Feasibility Tests of Acoustic Detection
- Summary

IoP HEPP, Birmingham 6th April 2004

Ultra−High Energy (UHE) Cosmic Rays



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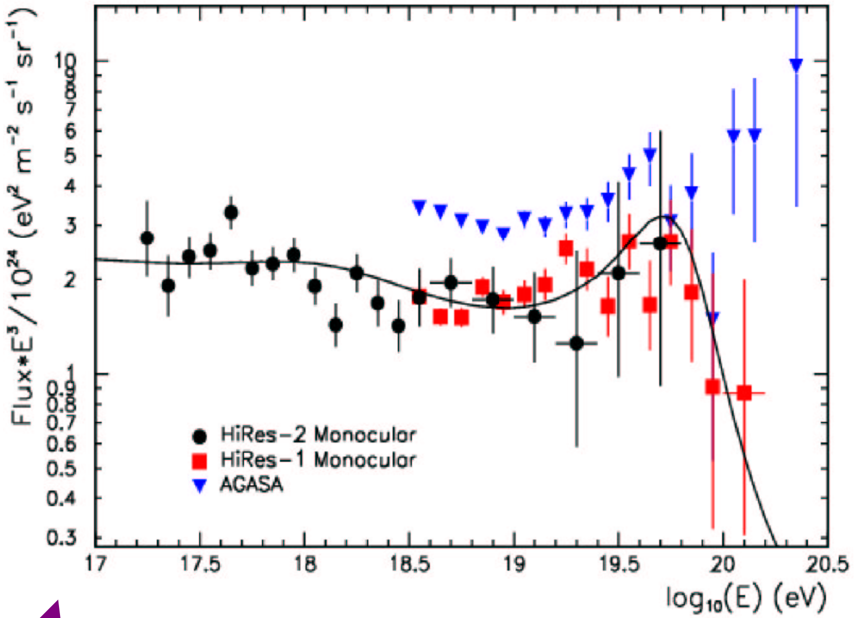


- Existing experiments don’t agree in their measurements of the UHE cosmic ray flux or consistency with "GZK" cut−off :

$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow N + \pi$$

Threshold Energy ≈ 6×10^{19} eV

- Auger experiment will settle this issue definitively in the next few years.

UHE Neutrino Sources

GZK cut−off in primary CR spectrum is confirmed

YES / **NO**

"Guaranteed" flux of cosmogenic neutrinos :

$$p + \gamma_{CMB} \to \Delta^+ \to n + \pi^+$$

$$\hookrightarrow p + e^- + \bar{\nu}_e$$

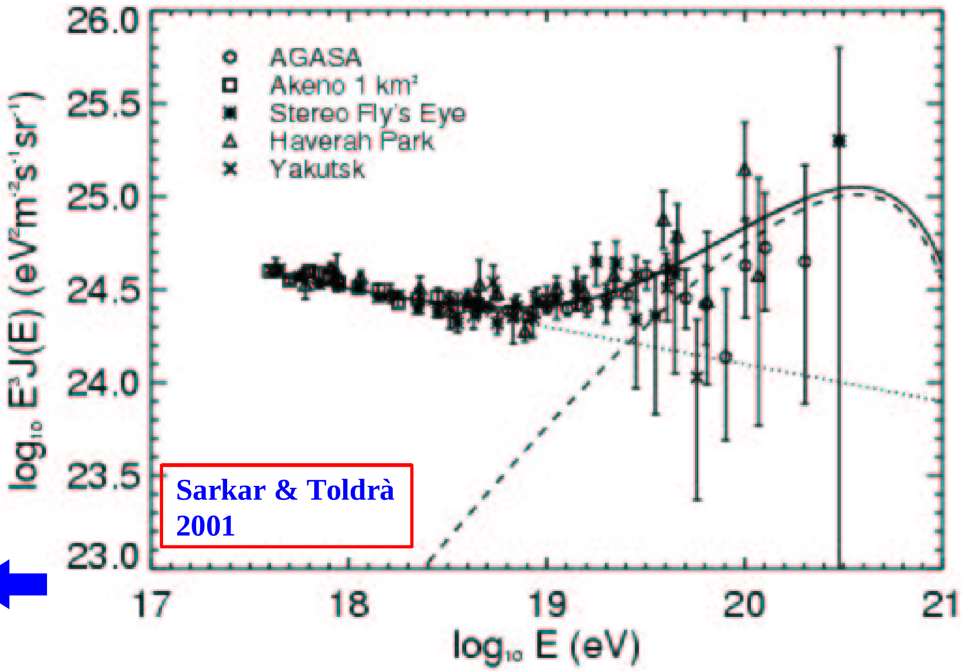
$$\hookrightarrow \mu^+ + \nu_\mu$$

$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Calculable flux with "small" error : factor of ≈ 2

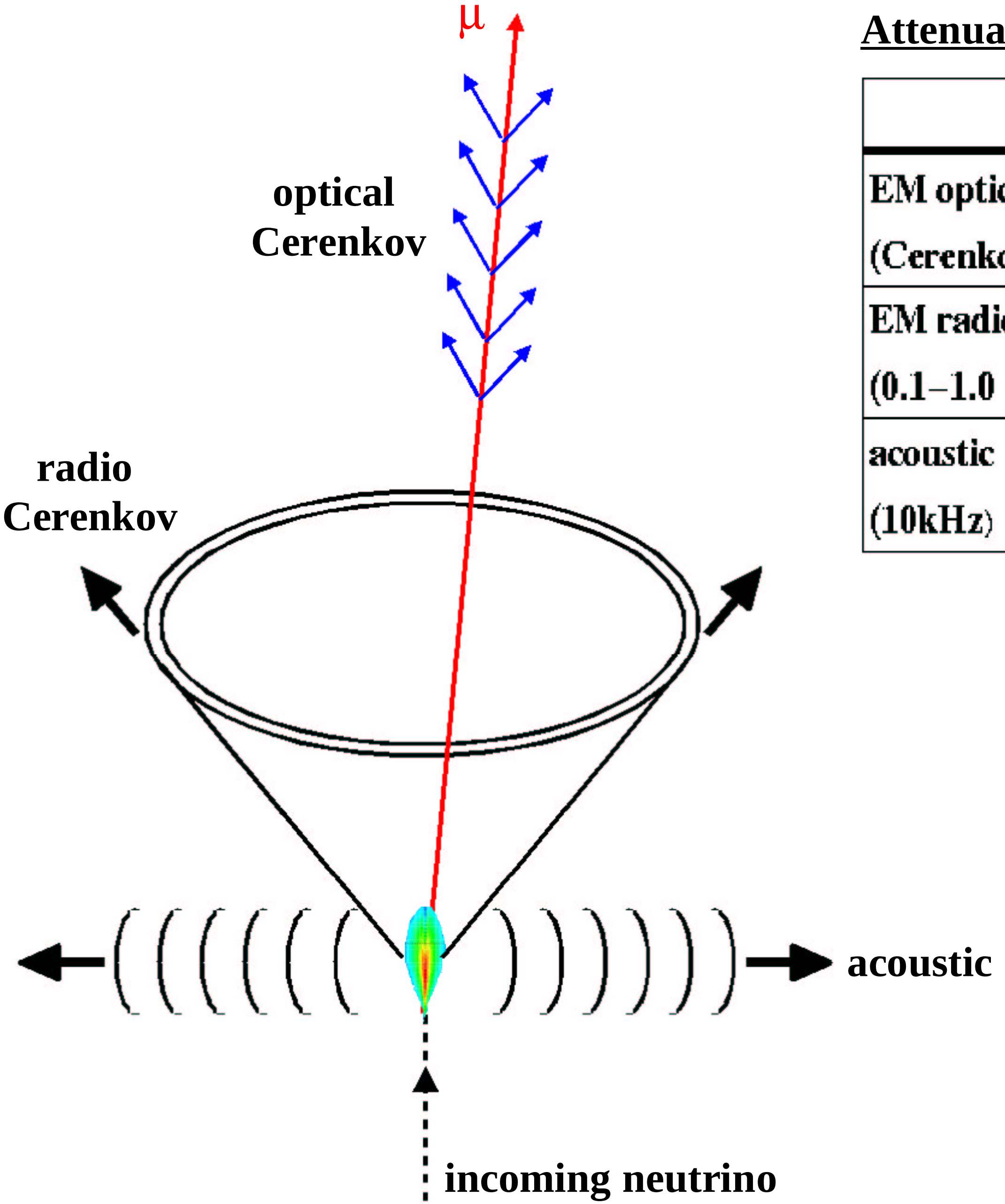
Local source of UHE cosmic rays :

$$X(10^{12}\,\mathrm{GeV}) \to h + X$$



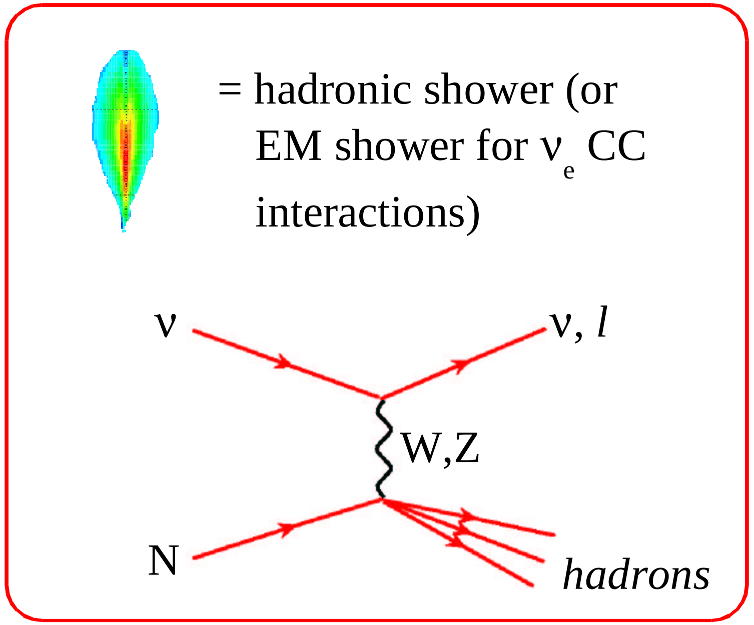
Model dependent, but generally give neutrino fluxes comparable to or $\gg$ cosmogenic flux.

UHE Neutrino Detection

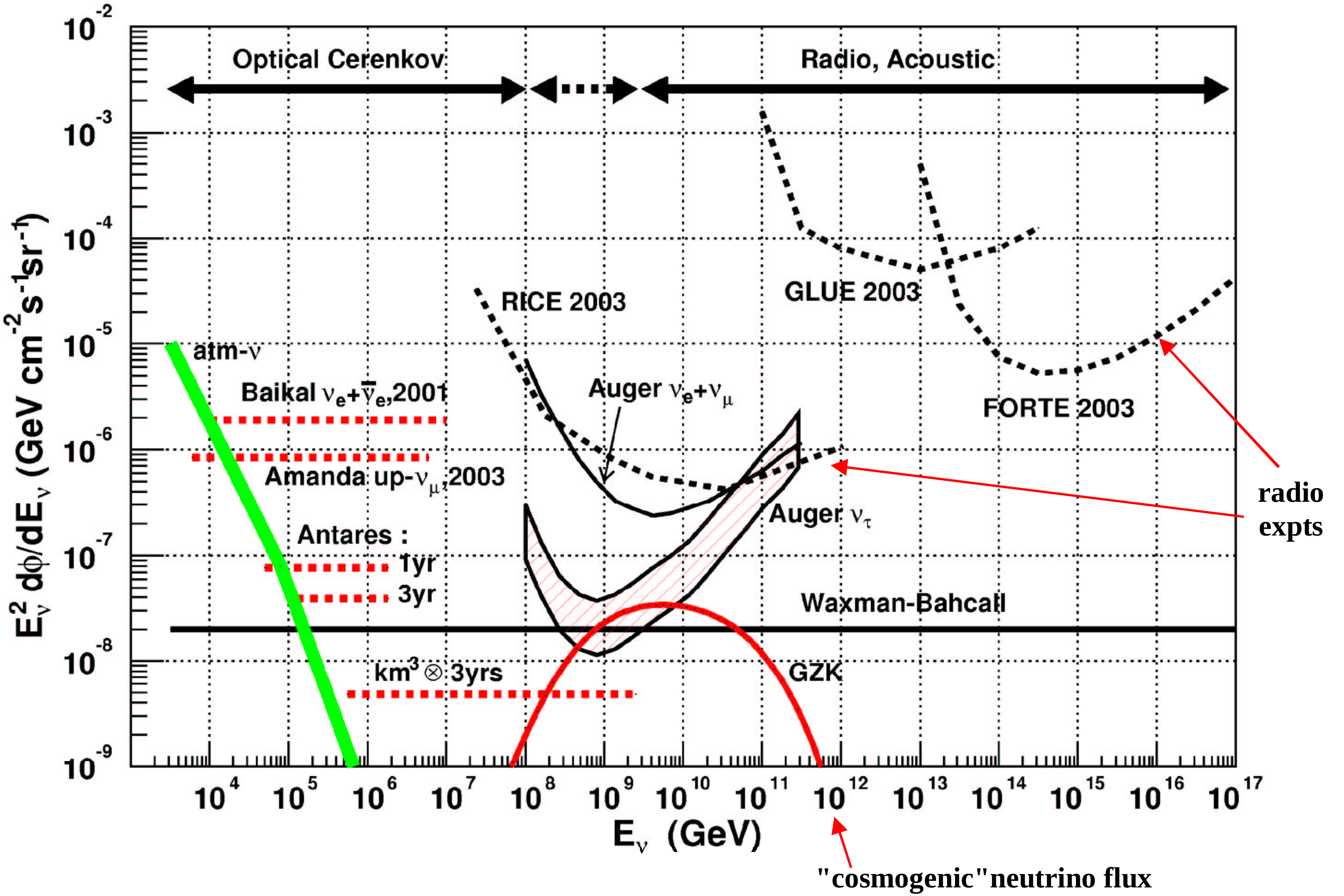


Attenuation Lengths :

	water	ice	salt
EM optical (Cerenkov)	~ 50 m	~ 100 m	~ 0
EM radio (0.1–1.0 GHz)	~ 0	~few km	~1 km (?)
acoustic (10kHz)	~10 km	? (large)	? (large)

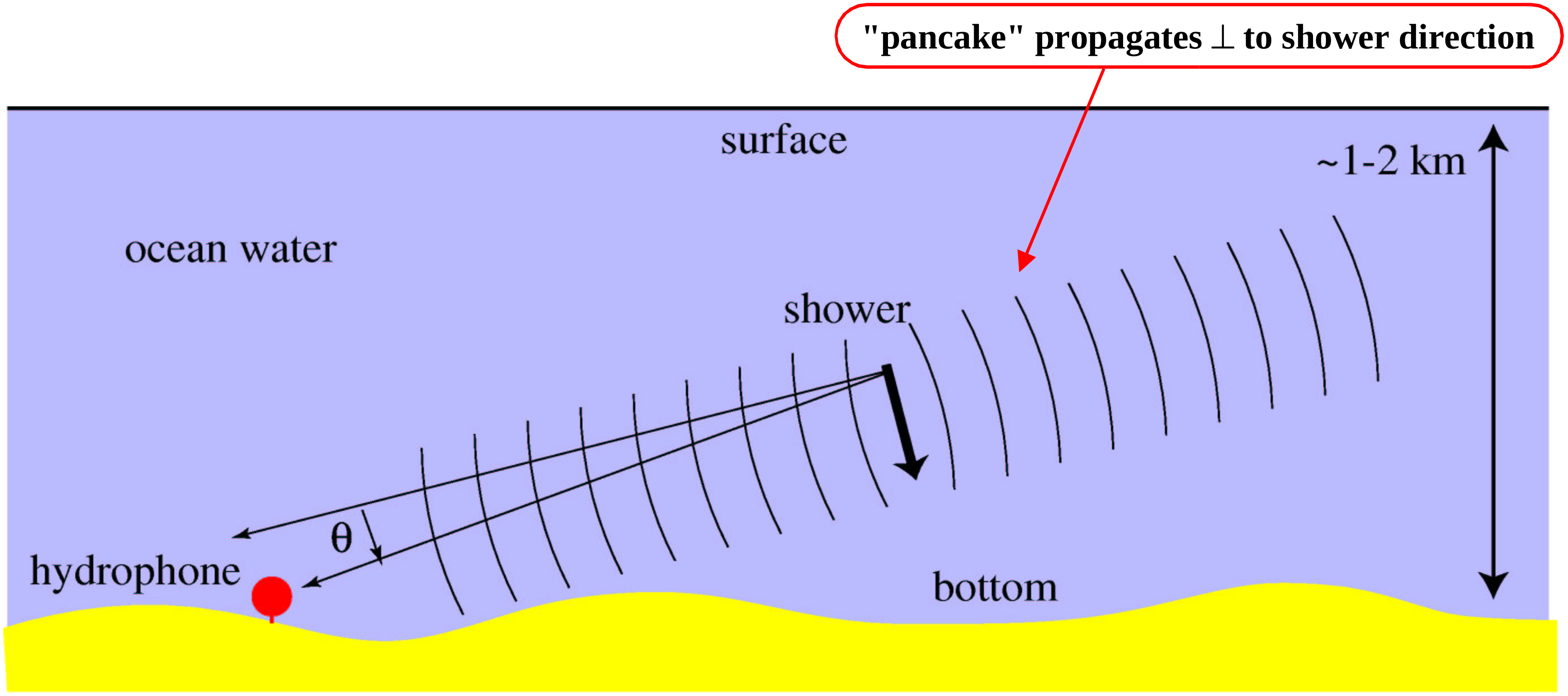


UHE Neutrino Detection



Acoustic Detection of UHE Neutrinos

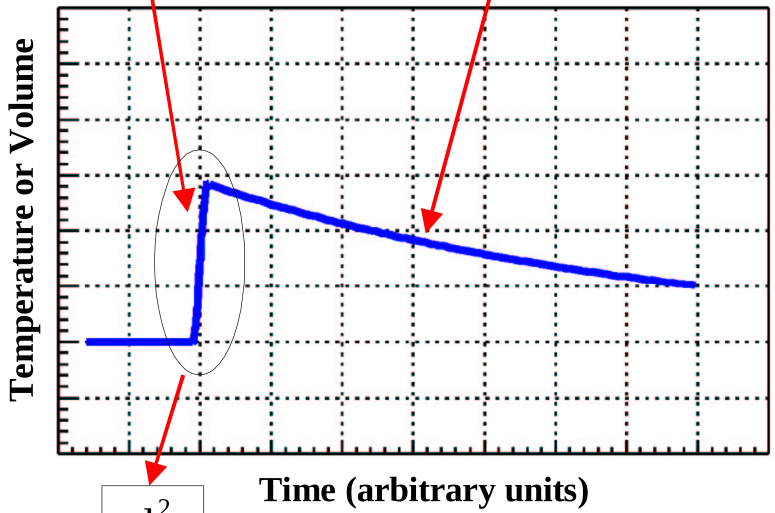
- UHE neutrino induced showers at GZK energies (~10^{19} eV) deposit O(Joules) of ionisation energy in small target volumes.
- The resulting near−instantaneous temperature increase and material expansion gives rise to an "acoustic shock" sound pulse.
- Ionisation−thermo−acoustic coupling has been demonstrated in test beam experiments.
- The shower is an acoustic line−source, with resulting narrow angular spread.



Acoustic Detection of UHE Neutrinos

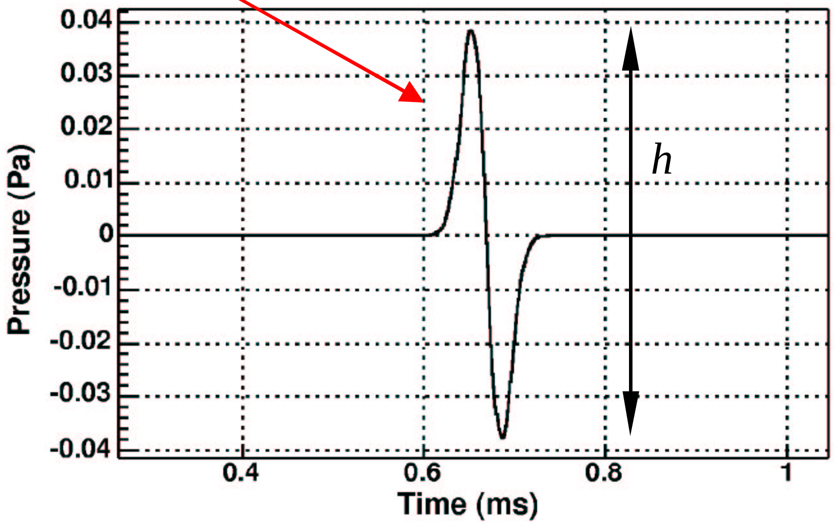
fast thermal energy deposition

slow heat diffusion



$$\frac{d^2}{dt^2}$$

Δt



shower thermal energy density

$$p(\vec{r},t) = \int_V \rho_E(\vec{r}') \, G(\vec{r}-\vec{r}',t) \; d^3\vec{r}'$$

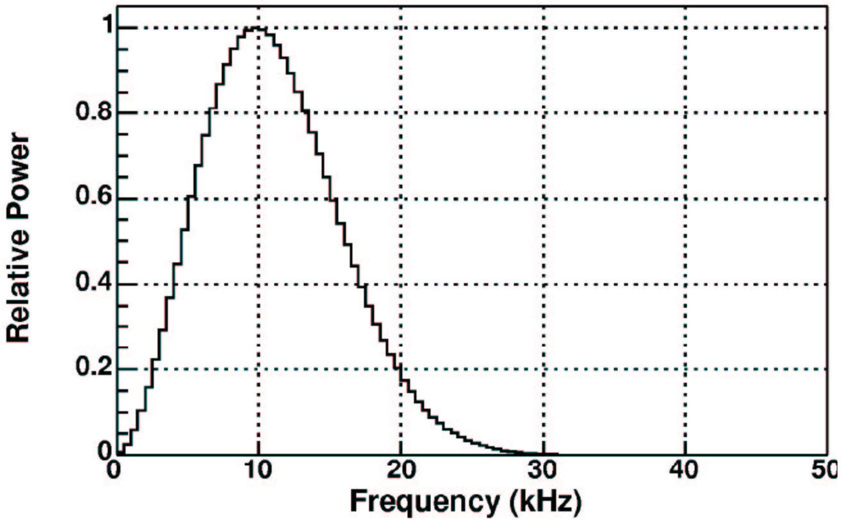
pulse due to a point source

$h \propto \beta / C_P$, where :

β = coefficient of thermal expansivity [$O(10^{-4})\ K^{-1}$ for water]

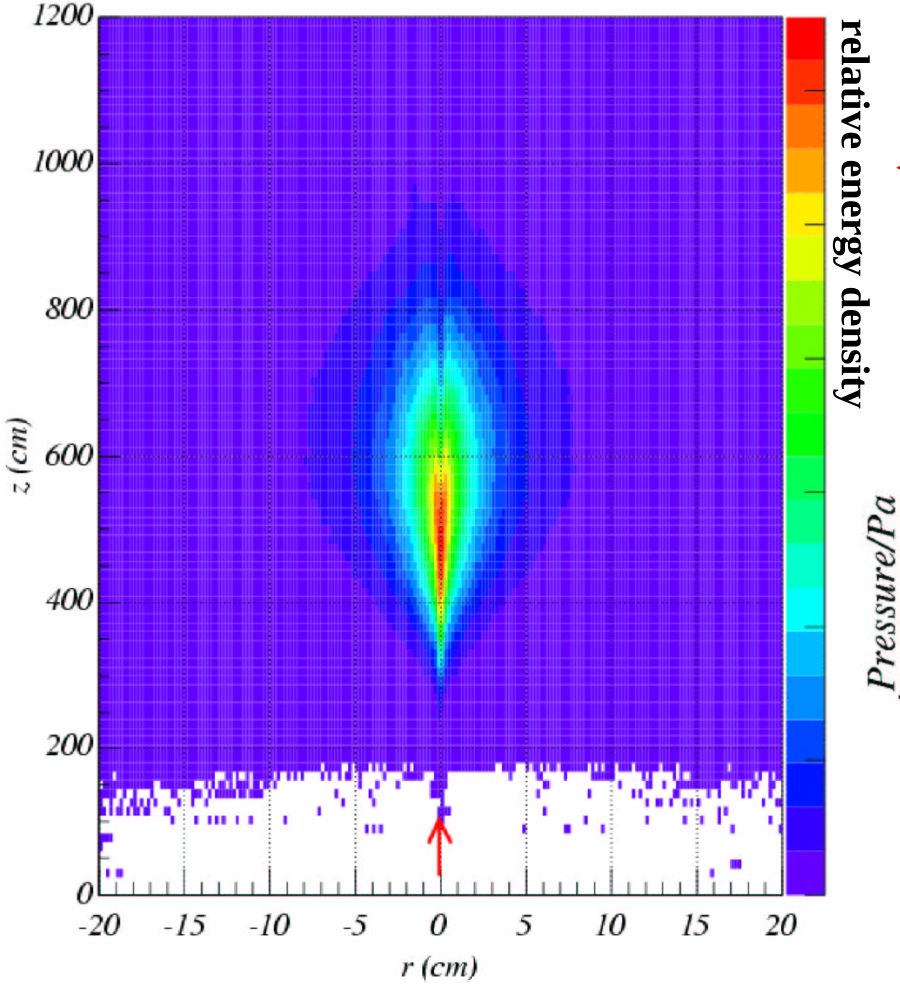
C_P = specific heat capacity [water : $3.8\times10^3\ \mathrm{Jkg^{-1}K^{-1}}$]

$\Delta t \propto$ transverse shower size



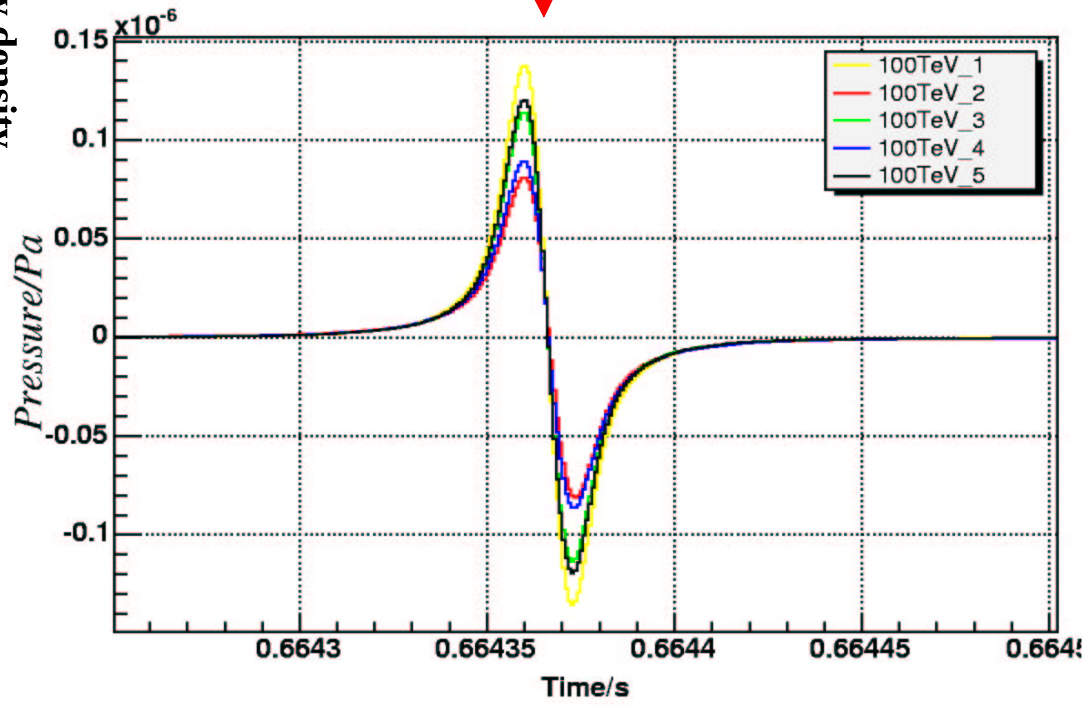
Acoustic Detection of UHE Neutrinos

- Detailed GEANT shower simulations and acoustic signal calculations confirm this basic picture.
- Note small shower−to−shower variations at high energies. This is a calorimetric detection technique that potentially offers very good energy resolution.

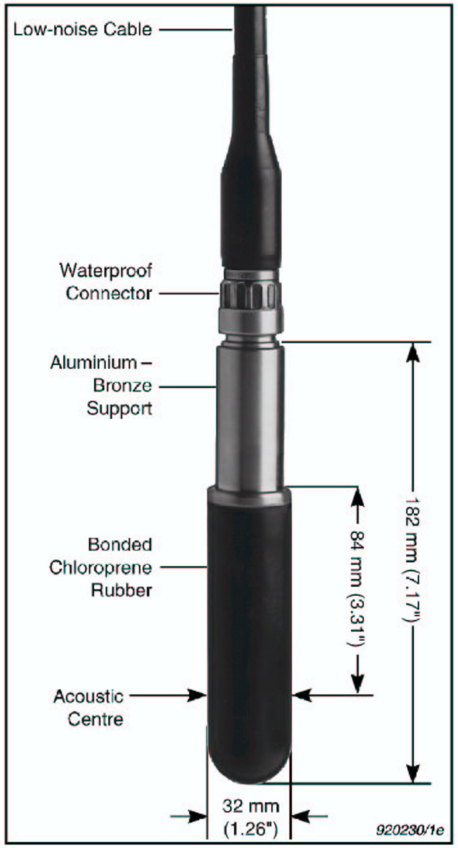


- Our simulations can also reproduce published test beam results.

100 TeV pions in sea−water



Existing Hydrophone Arrays

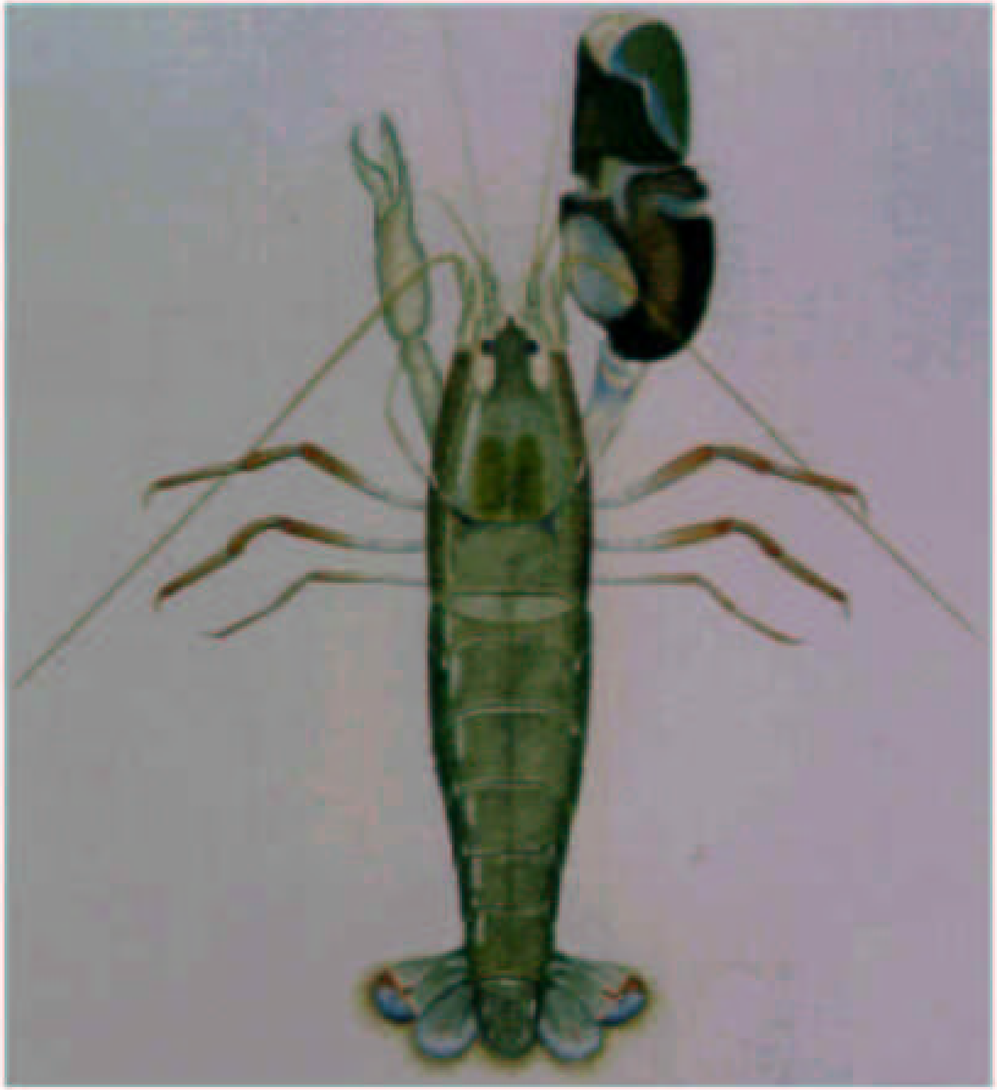


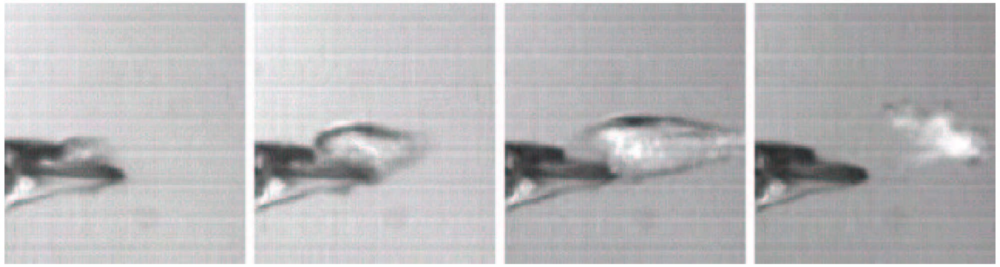
typical ocean hydrophone
[Brüel & Kjær]

- Several hydrophone arrays already exist around the world, including in the UK.
- Used mainly for characterising naval vessels.
- Also sensitive enough to do various studies of the feasibility of acoustic neutrino detection (but not large enough to detect expected fluxes).

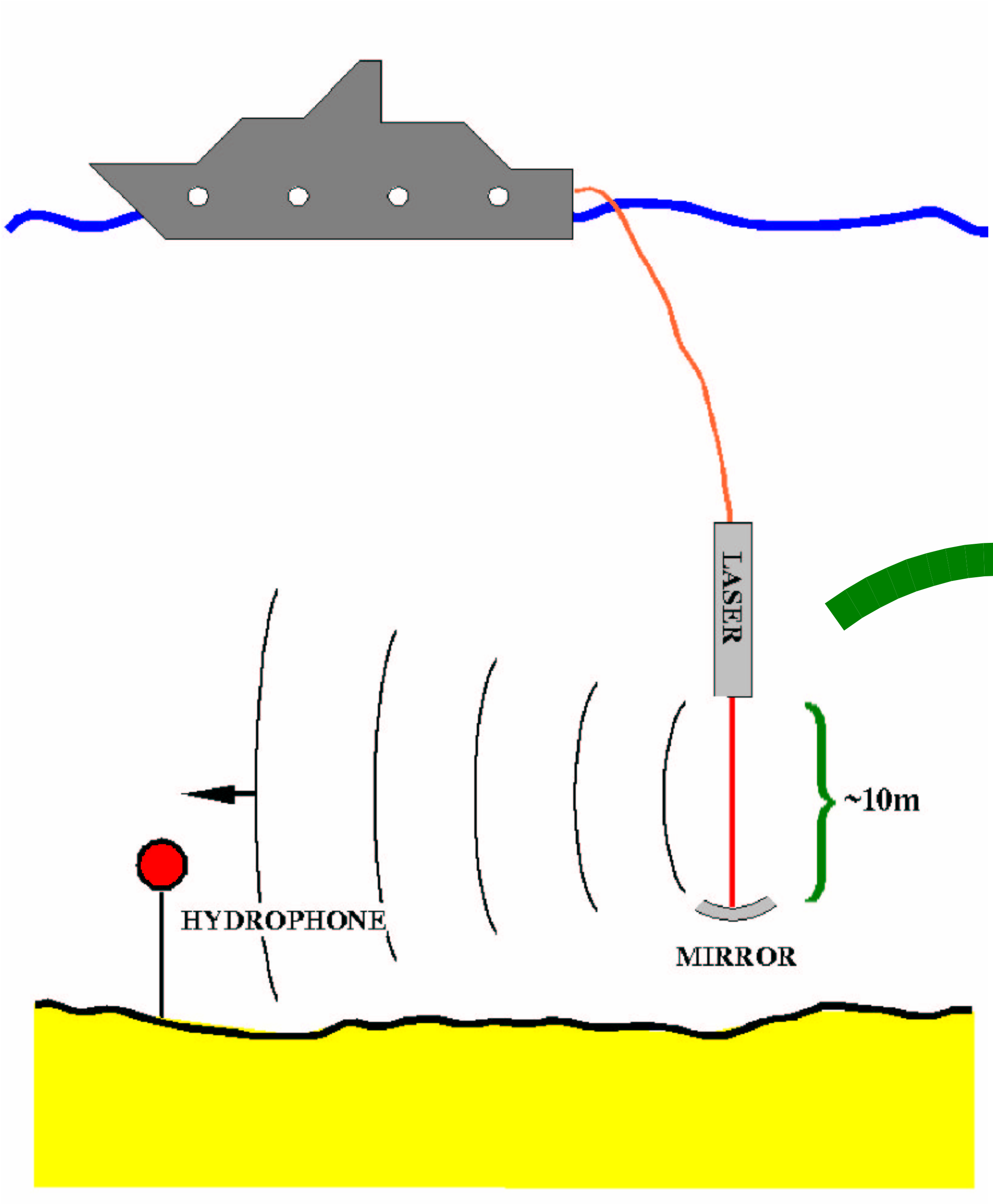
The Enemy

- Weather
- Critters
- Traffic

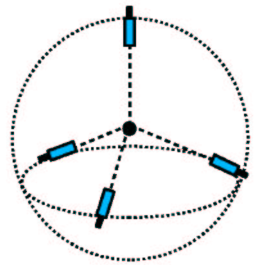




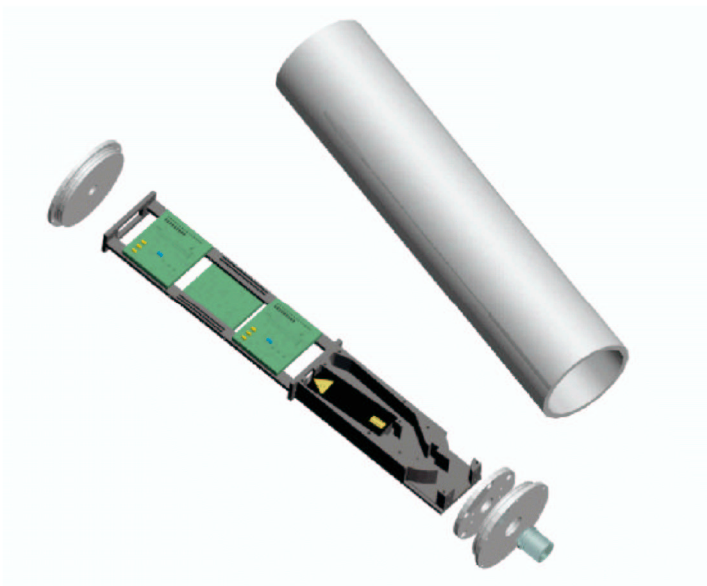
Feasibility Tests of Acoustic Detection



- Interesting to try directional hydrophone arrays also :



underwater laser beacon



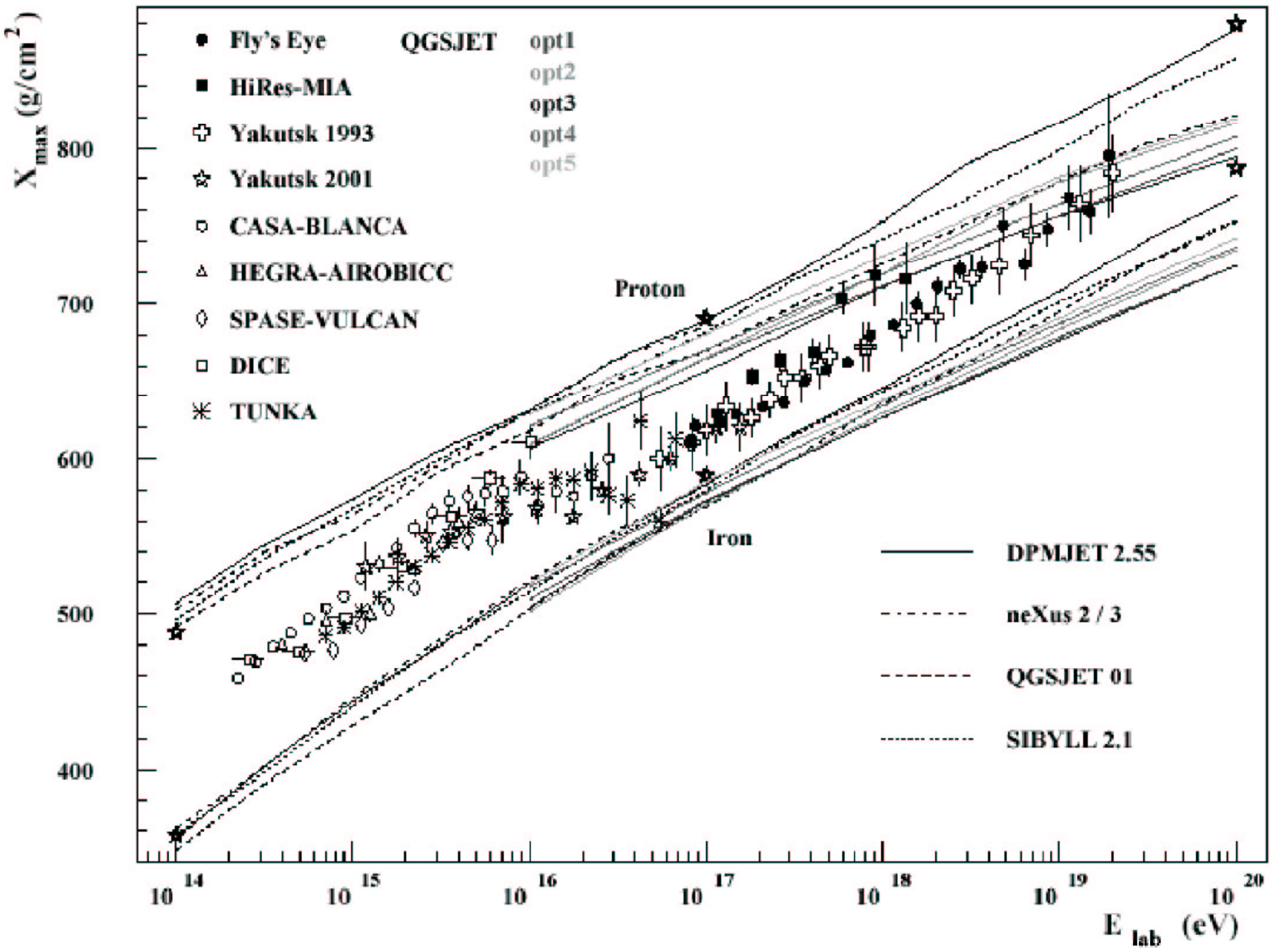
Summary

- There is currently huge interest in experiments and detection techniques that could be sensitive to UHE neutrinos (GZK energies and beyond).
- GZK neutrinos are probably our best understood astrophysical source of UHE neutrinos and provide a target for future experiments.
- Observing UHE neutrinos would shed light on the mystery of the origin of UHE cosmic rays.
- The detection volumes required are huge : 10’s to 100’s of km^3.
- Detection of the ionisation−thermo−acoustic pulses generated by UHE neutrino induced showers is a promising technique due to the very long attenuation lengths for sound in water.
- Overcoming noise and backgrounds and constructing an array capable of reconstructing shower positions and directions presents formidable obstacles.
- Further experiments are required to establish the feasibility of acoustic detection.

BACKUP SLIDES

Ultra−High Energy Cosmic Rays : Composition

astro−ph/0312475

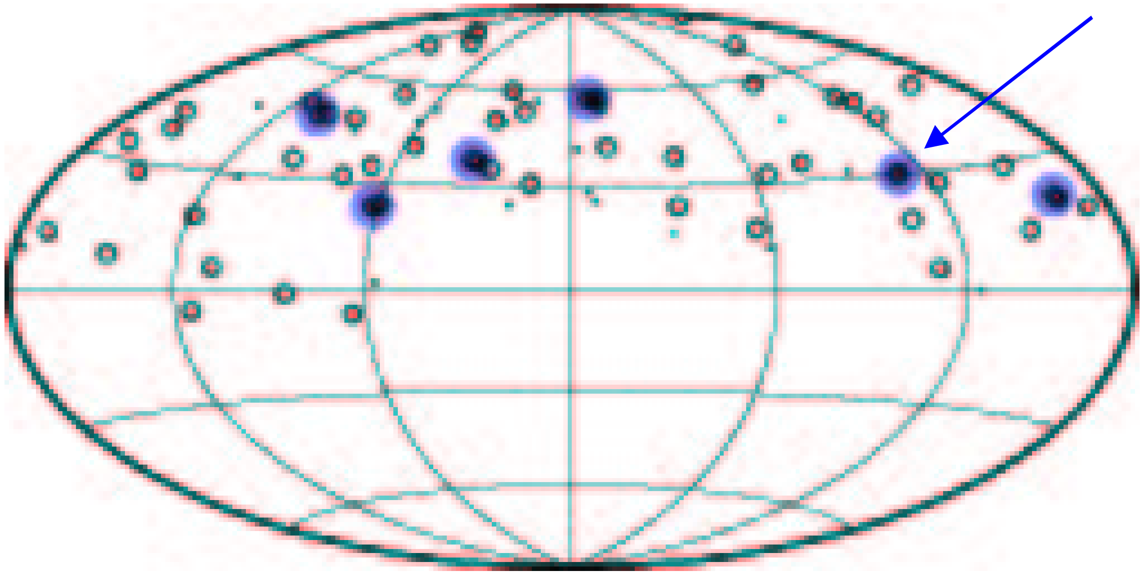


Ultra−High Energy Cosmic Rays : Clustering ?

Clustering of AGASA events with $E > 4\times10^{19}$ eV :

Wyn−Evans, Ferrer, Sarkar 2003

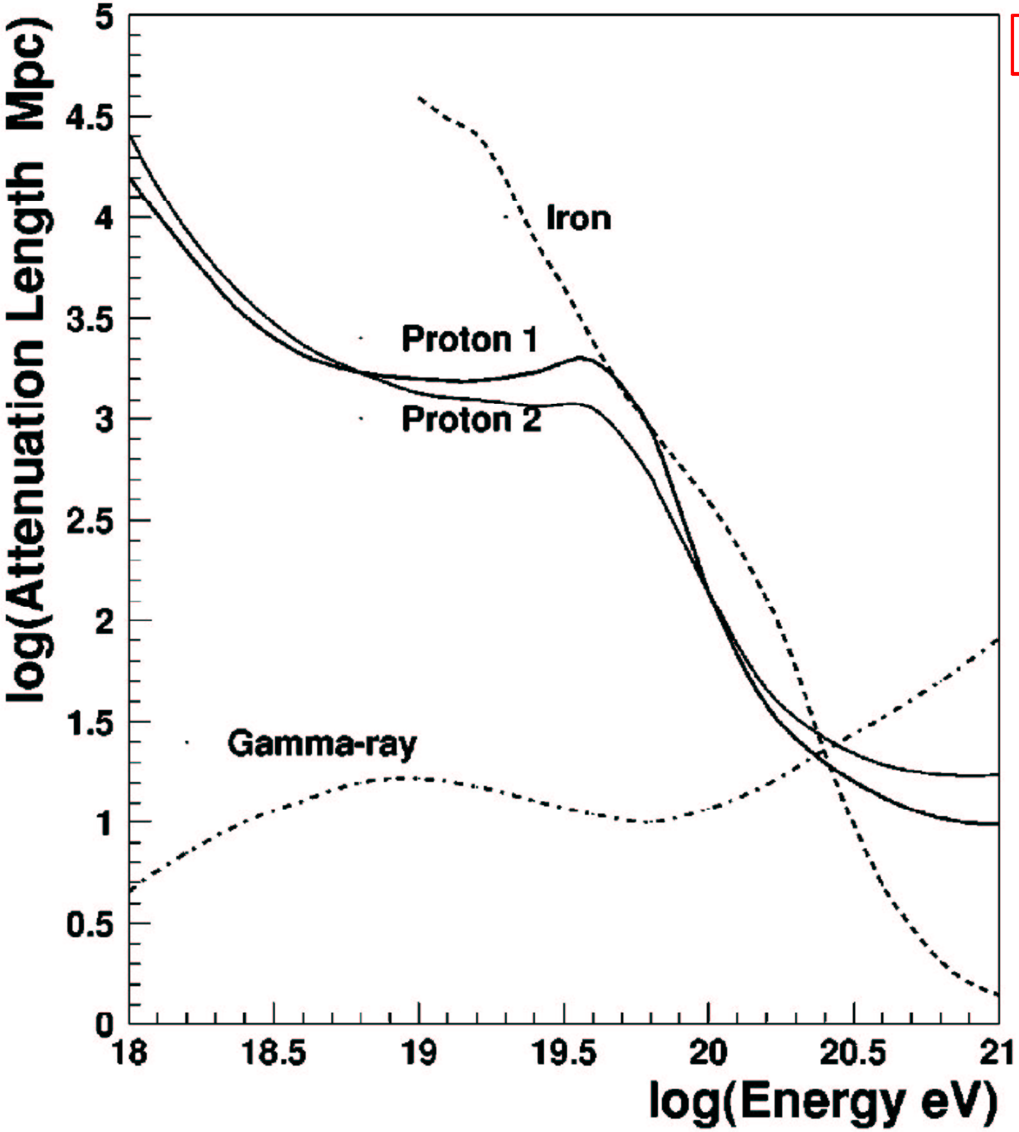
5 doublets, 1 triplet with < 2.5° spacing



Conclusions :

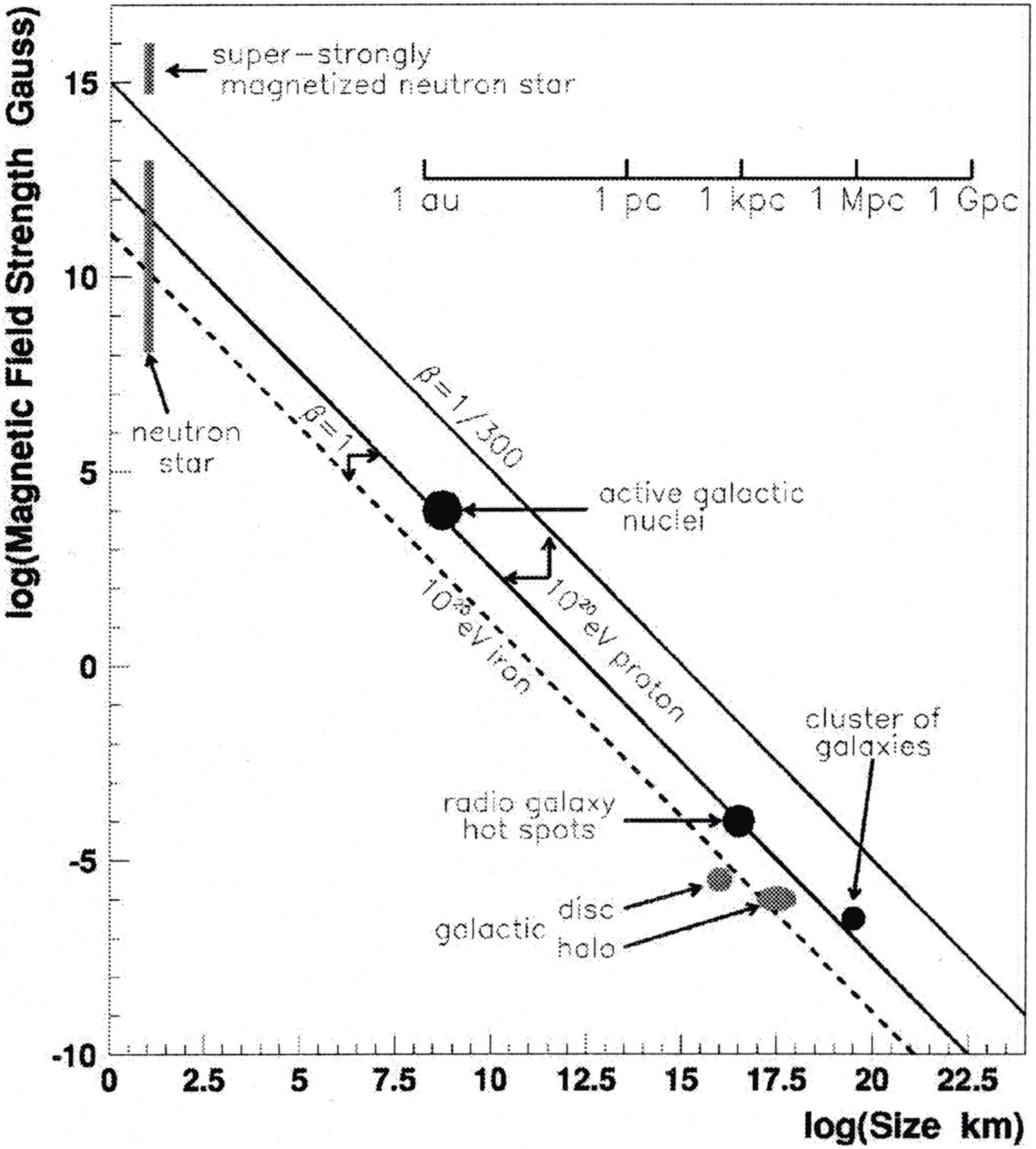
- No strong statistical claim for clustering or anisotropy.
- No clear correlation with sky positions of other astrophysical objects.

Ultra−High Energy Cosmic Rays : Cosmic Attenuation



Nagano & Watson, 2000

Ultra−High Energy Cosmic Rays : Sources

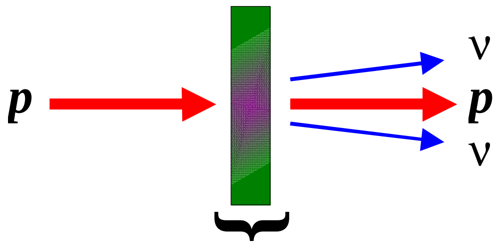


Nagano & Watson, 2000

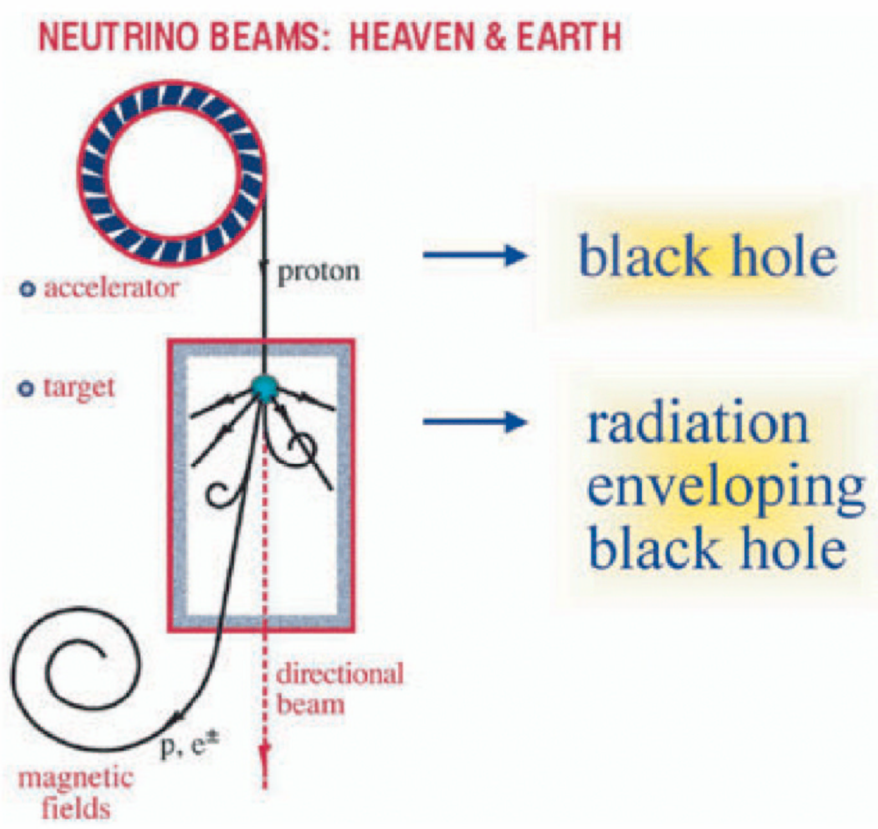
Sources of UHE Neutrinos

- Possible astrophysical acceleration sites :
  - Gamma−ray bursts ?
  - Active galactic nuclei ?

- Benchmark flux estimate : Waxman−Bahcall.



- Protons produce neutrinos (and gamma rays) in cosmic "beam dumps".
- Assume "optically thin" targets such that the observed proton cosmic ray energy density is a good measure of source activity. **If this isn't the case, the WB bounds could be exceeded.**
- Then by considering the amount of energy that can be converted into neutrinos :



Halzen & Hooper, 2002

$$E_\nu^2 \frac{d\Phi_\nu}{dE_\nu} \leq 2\times10^{-8} \quad \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

Simulating Acoustic Pulses

- Use the propagation model described in Lehtinen *et al.* (Astropart. Phys. **17** (2002) 279), which in turn relies on the formalism developed in Learned (Phys. Rev. **D19** (1979) 3293).

$$p(\vec{r},t) = \int_V \rho_E(\vec{r}\,') \, G(|\vec{r}-\vec{r}\,'|,t) \; d^3\vec{r}\,'$$

thermal energy density — **pulse due to point−like energy deposition**

<u>Caribbean, not Scottish water !</u>

β = coeff. of thermal expansion $\approx$ **1.2×10^{-3} K^{-1}**

C_P = specific heat capacity $\approx 3.8 \times$ **10^3 J kg^{-1} K^{-1}**

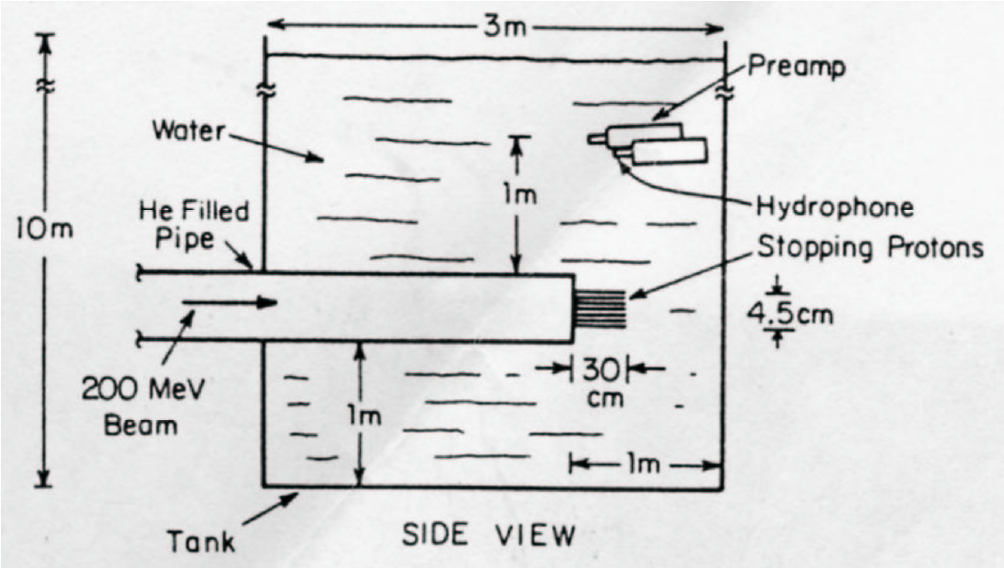
c = speed of sound ≈ 1500 **m s^{-1}**

ω_0 = attenuation frequency $\approx 2.5 \times$ **10^{10} s^{-1}**

$$G(r,t) = -\frac{\beta}{4\pi C_P} \frac{(t-r/c)}{r\sqrt{2\pi\tau^3}} \exp(-(t-r/c)^2/(2\tau^2))$$

$$\tau = \sqrt{r/(\omega_0 c)}$$

Test Beam Results



<u>Sulak *et al*., NIM **161** (1979) 203</u>

- Results of this simulation agree within a factor of 2.
- Inhomogeneities in energy deposition not taken into account.
- Other details of the experimental arrangement not known.
- Probably OK.