# Sensitivity Estimates Using a Toy Monte Carlo

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with Sean Danaher, Chris Rhodes, Terry Sloan & Lee Thompson

- Goals of the Study.
- Details of the Toy Monte Carlo.
- Validating the Monte Carlo.
- Generating the Event Ensemble.
- Results.
- Thoughts on Acoustic Array Design.
- Open Questions & Plans

# Goals of the Study

- Get a feeling for the size and shape of acoustic neutrino signals (new to me !).
- Reproduce (in a much simpler fashion) the results of simulations already published.
- Obtain some ball−park flux sensitivity numbers and compare with other UHE neutrino detection techniques and experiments.
- Start to think about possible acoustic detector array designs.

- Everything is based on very simple minded calculations (quick and dirty, for the purposes of writing a funding proposal). We would like to re−do everything with a full blown simulation.
- Noise and backgrounds are not treated at all in this study. We have started thinking about these issues (see talks by Chris Rhodes and Lee Thompson), but these results have not yet been incorporated into our sensitivity estimates.
- Sorry ... nothing presented here is new, but the study has helped us highlight issues that we want to study further.

# Details of the Toy Monte Carlo

- 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>

$\beta$ = coeff. of thermal expansion $\approx 1.2 \times 10^{-3}\,\mathrm{K}^{-1}$

$C_p$ = specific heat capacity $\approx 3.8 \times 10^{3}\,\mathrm{J\,kg^{-1}\,K^{-1}}$

c = speed of sound $\approx 1500\,\mathrm{m\,s^{-1}}$

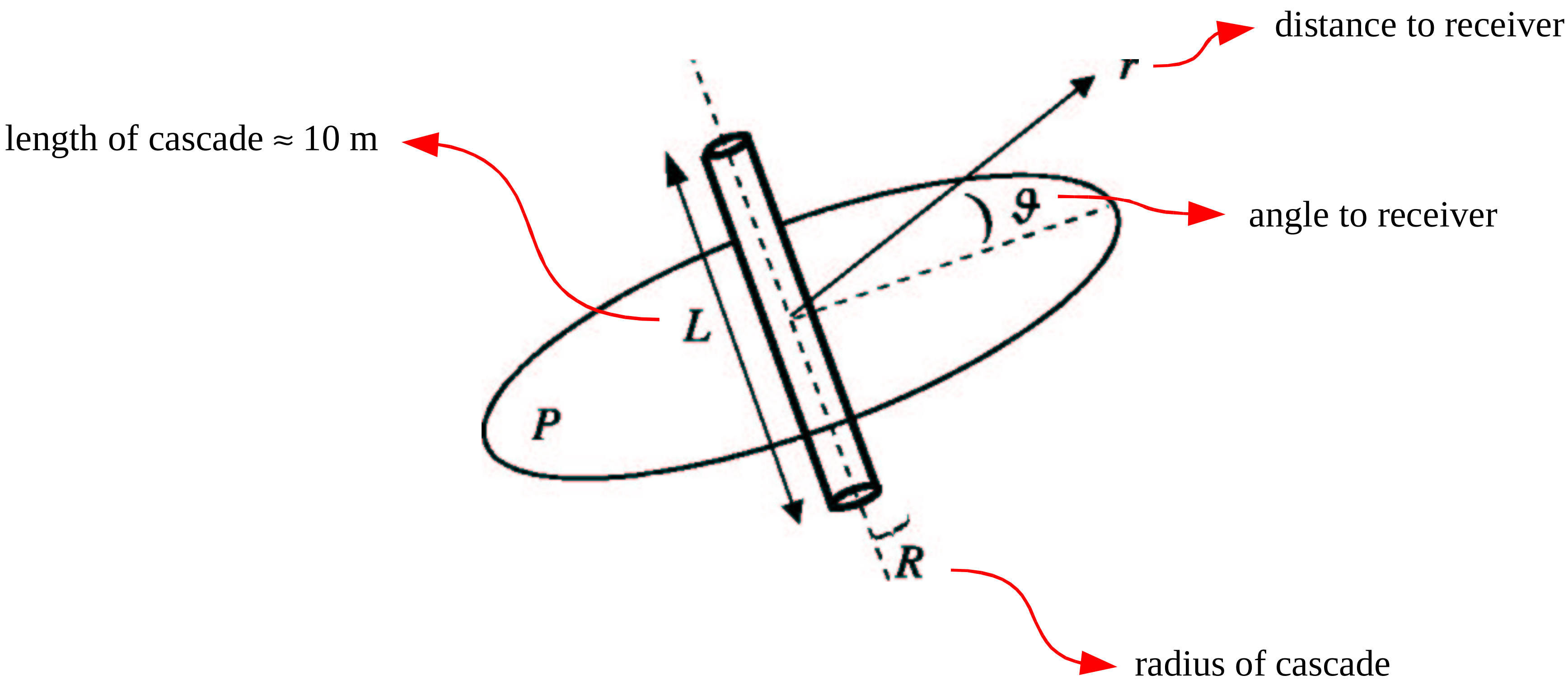
$\omega_0$ = attenuation frequency $\approx 2.5 \times 10^{10}\,\mathrm{s}^{-1}$

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

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

# Details of the Toy Monte Carlo

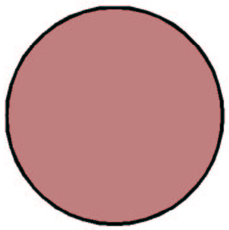
- Use a very naïve cylindrical energy deposition model for hadronic cascades :



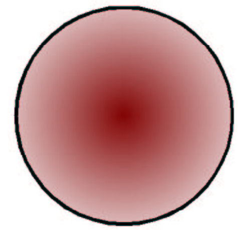
# Details of the Toy Monte Carlo

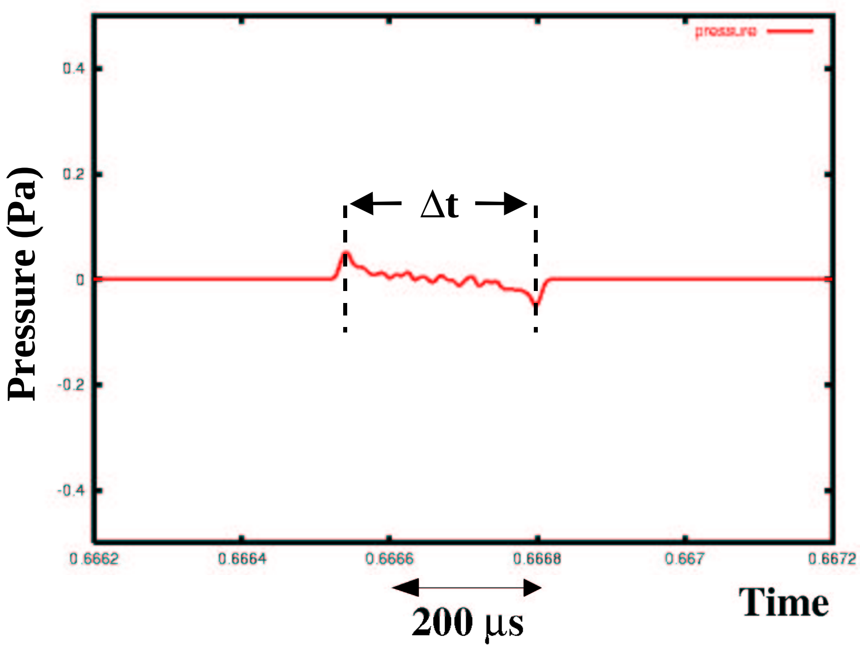
- Simulate hadronic cascades with :
  - Energy = $10^{20}$ eV = 16 Joules.
  - $L$ = 10 m.
  - $R$ = 0.2 m.

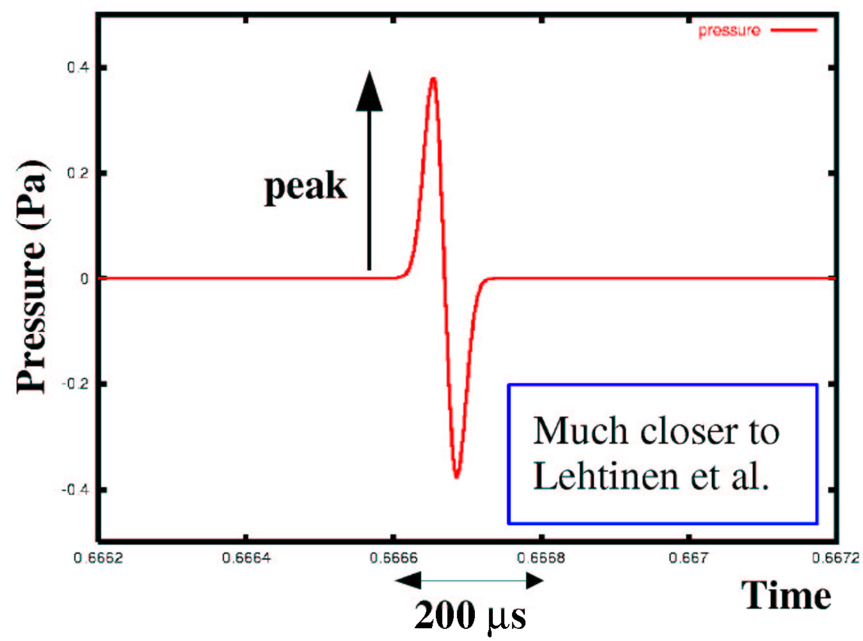
I. uniform energy deposition



II. Gaussian with <r>=few cm.





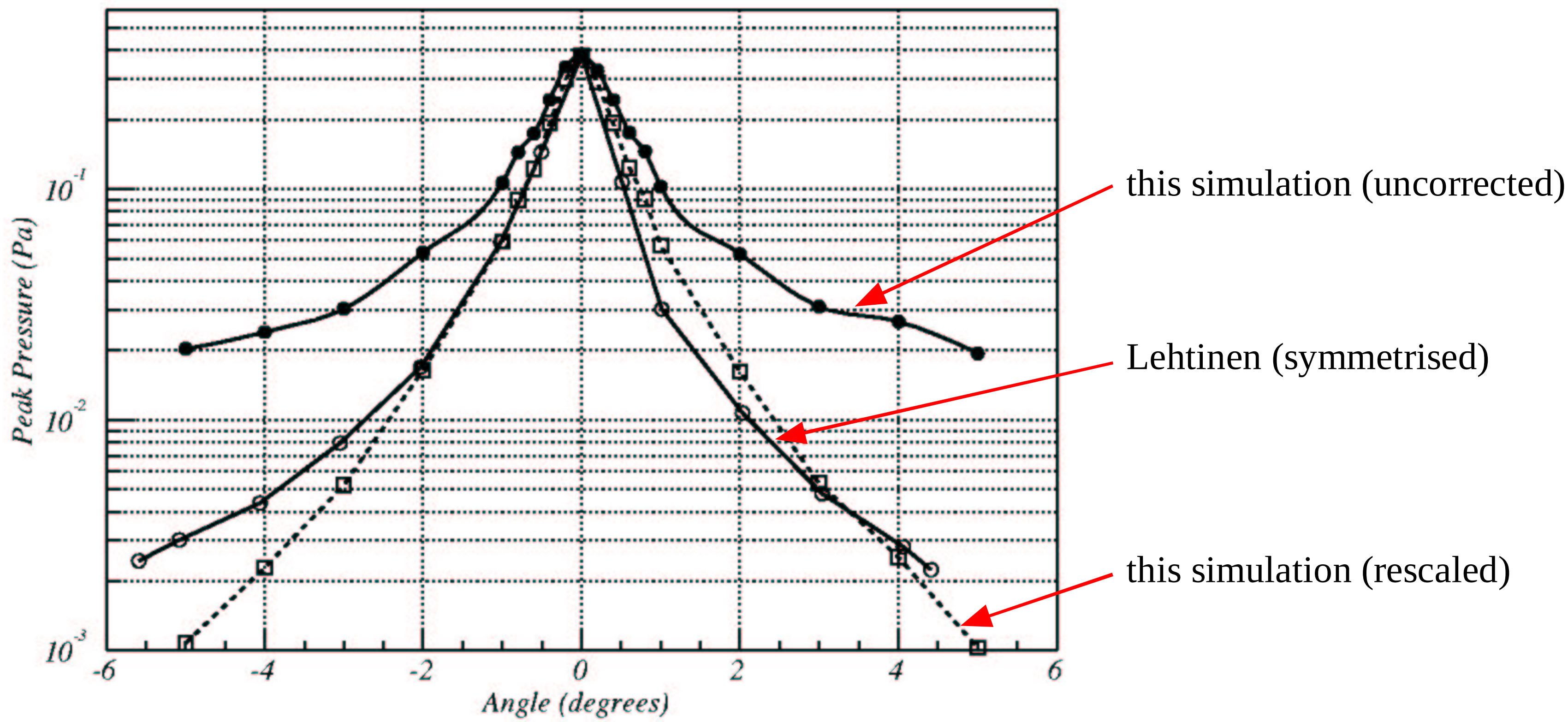




Much closer to Lehtinen et al.

# Details of the Toy Monte Carlo

Angular structure :

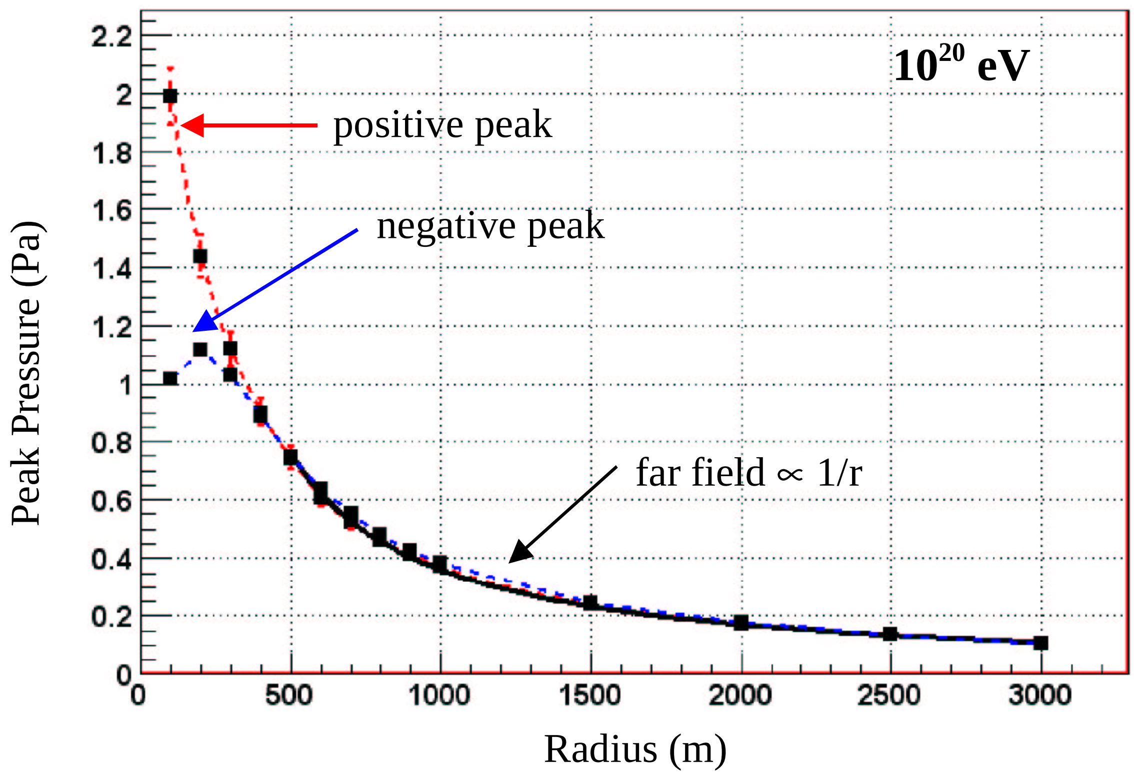
- This simple simulation cannot reproduce the forward−backward asymmetry of Lehtinen.
- The angular structure is also not very well reproduced.
- Scaled peak pressures are used for sensitivity estimates.
- Need full shower simulations (or at least energy dependent average shower dimensions).



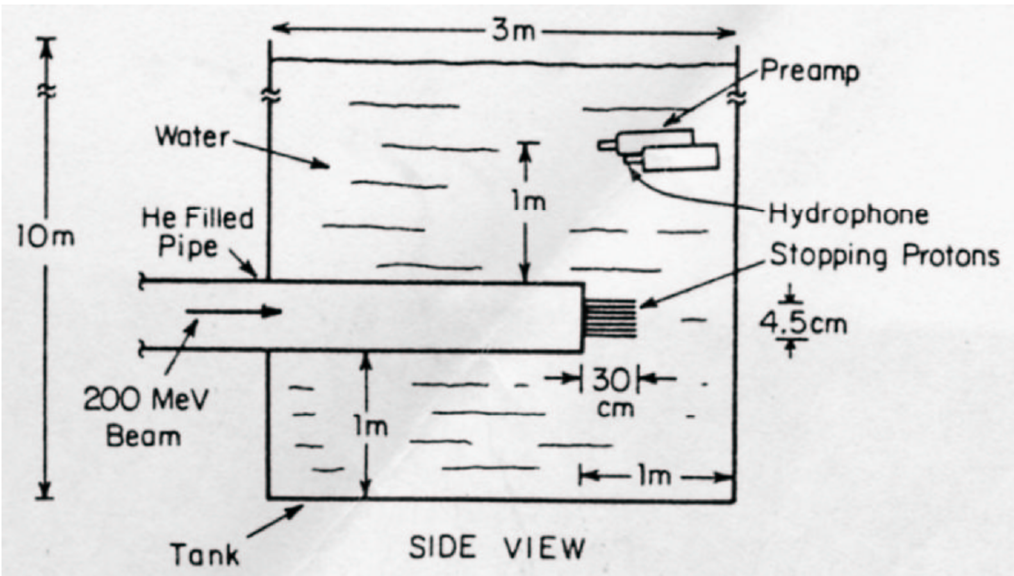
# Details of the Toy Monte Carlo

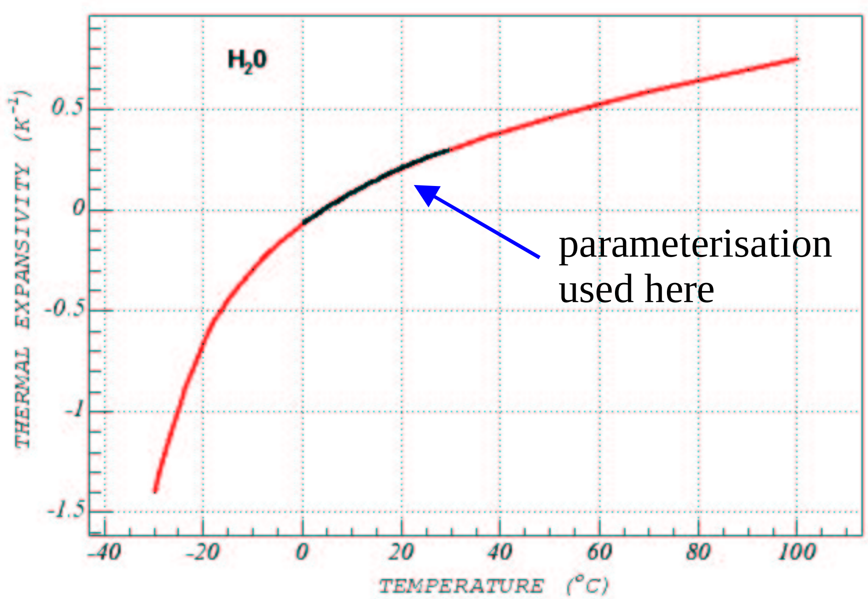
<u>Radial structure :</u>

- Smaller negative peak amplitude described in Lehtinen is reproduced in this simple model.
- Far−field radial dependence described in Learned is reproduced.



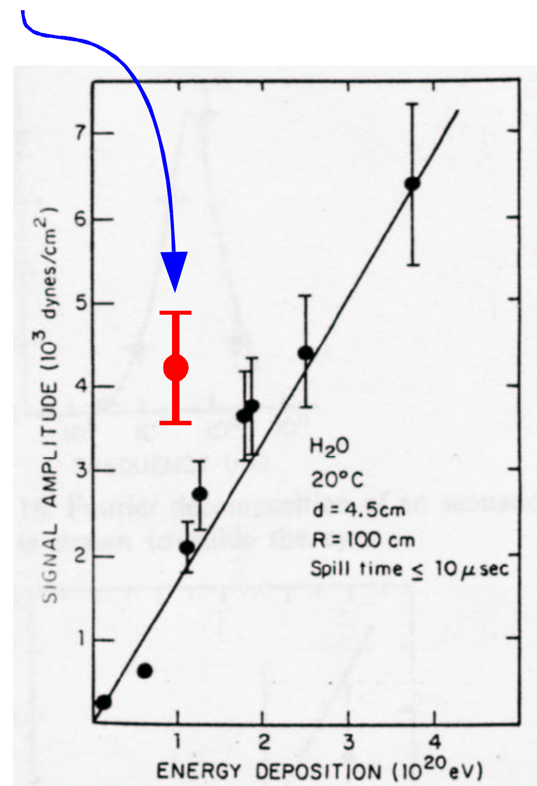
# Validating the Toy Monte Carlo



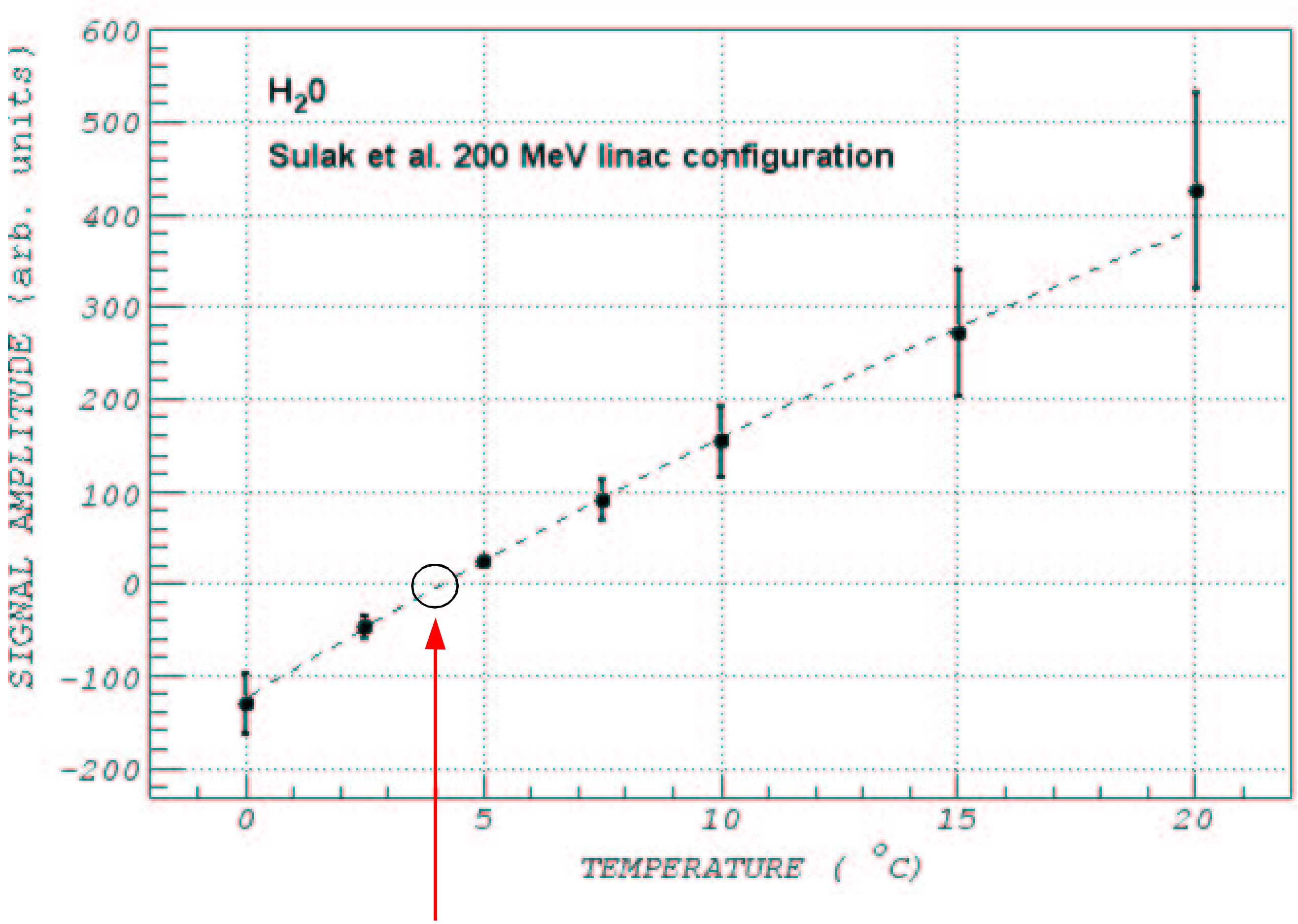




Sulak *et al.*, NIM **161** (1979) 203

- 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.

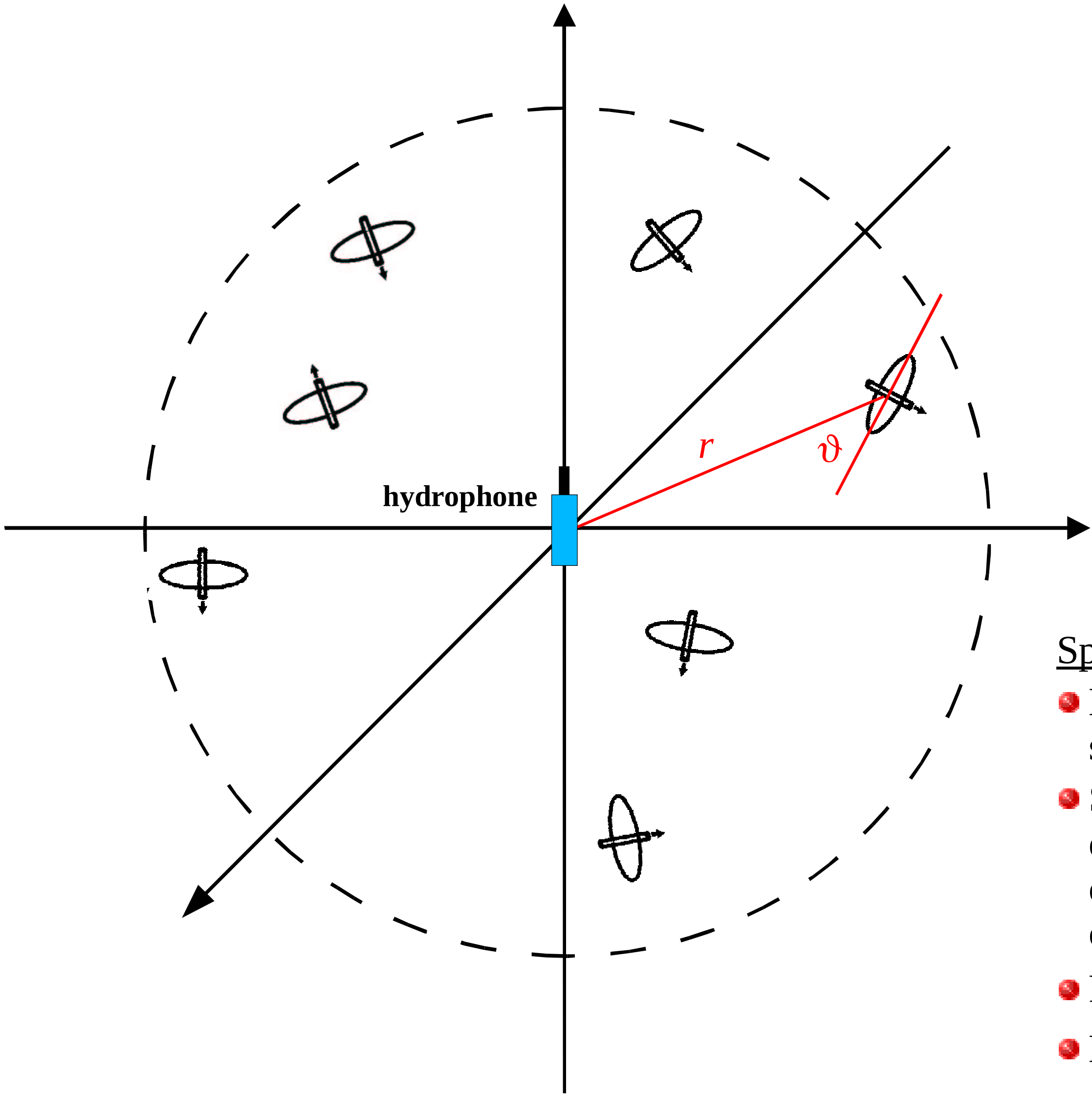


# Validating the Toy Monte Carlo




Agreement with Sulak apart from zero crossing temperature.

# Generating the Event Ensemble




Spatial Distribution :

- Events generated uniformly in a 10km sphere around the hydrophone.
- Shower orientations are random − opacity of earth for upward going neutrinos is taken care of with a factor of 2 in the overall count rate normalisation.
- Pulse only depends on $r$ and $\vartheta$.
- Numerical expediency : events with $\vartheta > 5^o$ are not fully simulated (see later plots).

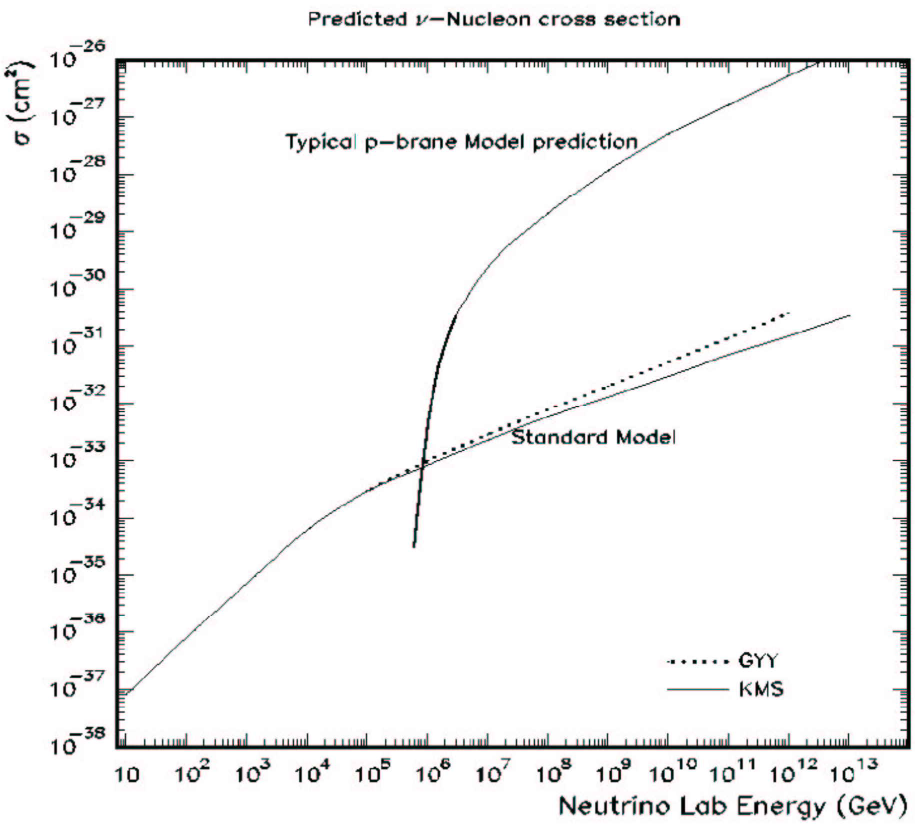
# Generating the Event Ensemble

Energy Distribution :

- Incident flux taken from Waxman−Bahcall :

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

- Convolute with a recent calculation of the neutrino−nucleon interaction cross section at UHE :




half−sky coverage

$10^{10} < E_\nu < 10^{13}$ GeV

$$R = 2\pi V N \times \int_{E_\nu^{min}}^{E_\nu^{max}} \frac{d\phi}{dE_\nu} \sigma_{\nu N}(E)\, dE_\nu$$

10 km sphere; $N \approx 6\times10^{23}$ nucleons/cm$^3$ $H_2 0$

$$R \approx 50\ \text{yr}^{-1}$$

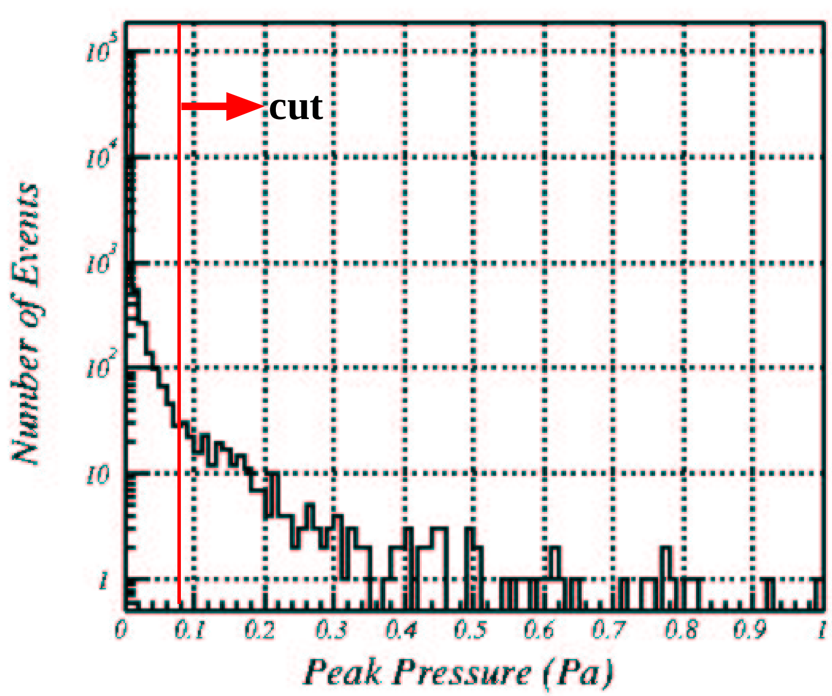
➡ Observed rate = 50 × ε (efficiency from simulation)

Kwiecinski, Martin & Stasto (2000)

# Results

Detector Thresholds :

- Assume that a $2\times10^{10}$ GeV event at 1km and 0° is detectable (Lehtinen) → peak pressure threshold of 0.08 Pa.
- Additional angle dependent scale factor applied (discussed above).
- Additional "fudge factor" of 0.5 applied to peak pressures, to account for "visible energy fraction". This is highly **ad hoc** !



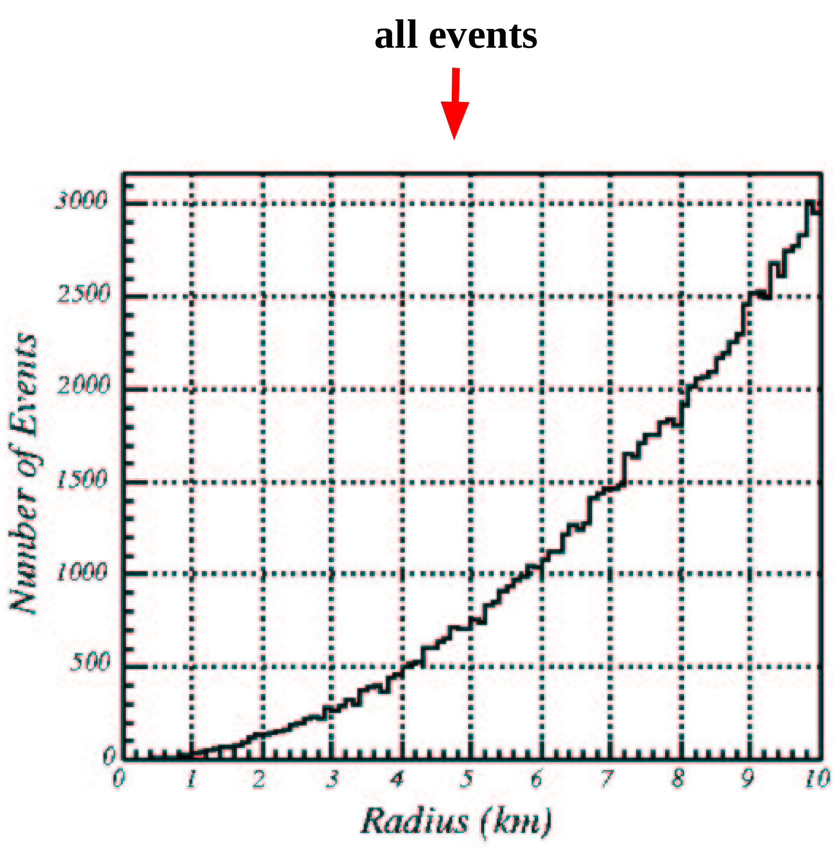

- 68 events out of an initial ensemble of 100k events are above threshold.
- $\varepsilon = O(10^{-3} - 10^{-4})$. Reasonable ?
- This corresponds to a count rate :

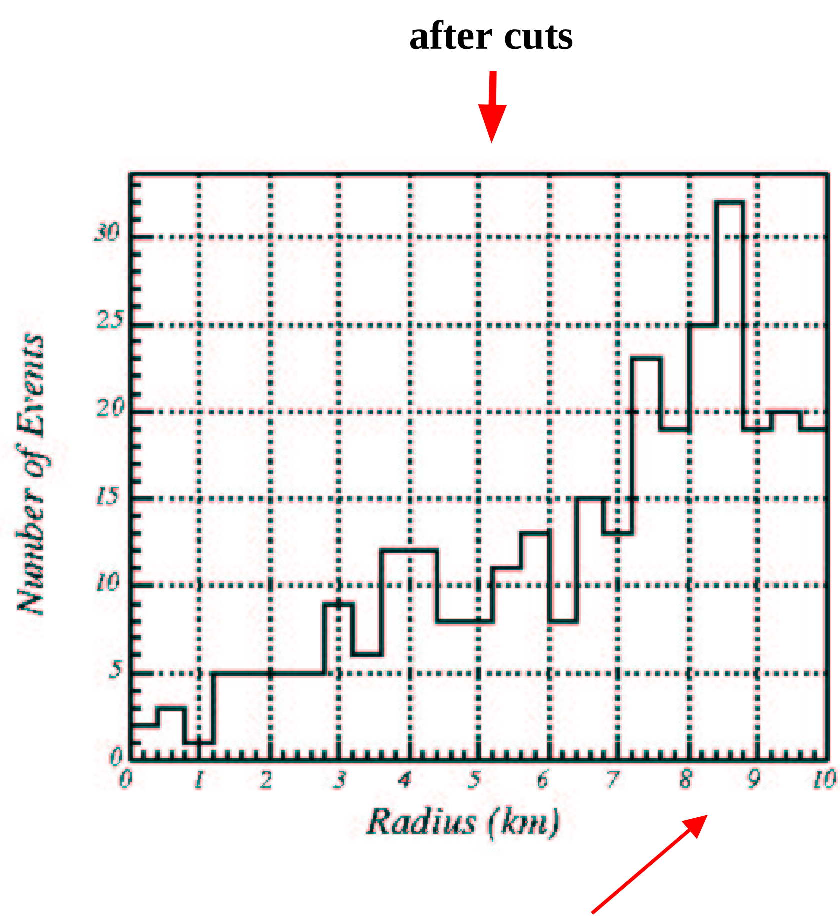
$O(10^{-2})$ events/yr

Reminder of key assumptions :

- Single hydrophone
- Waxman−Bahcall $1/E^2$ incident flux
- Energy range $10^{10} < E_\nu < 10^{13}$ GeV

# Results

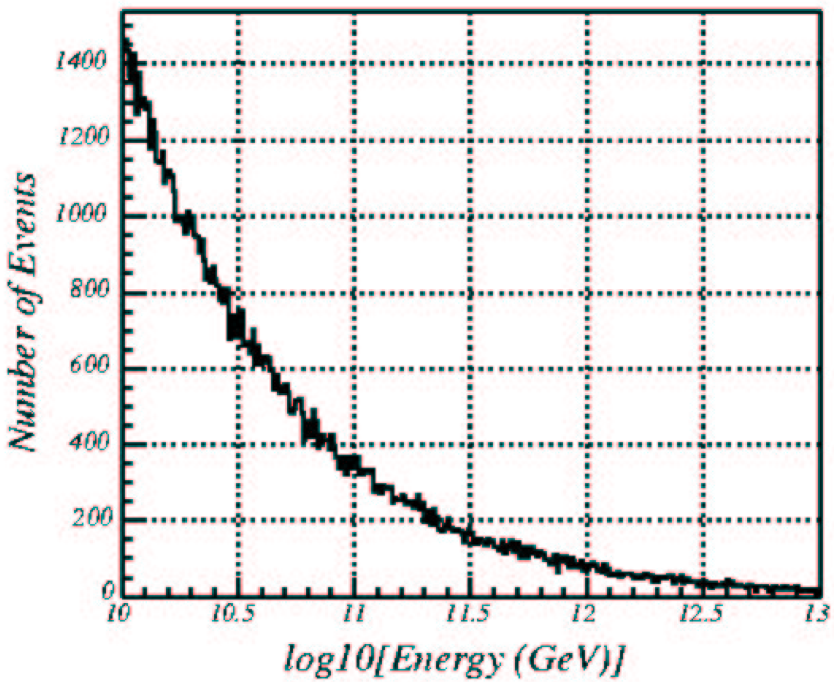


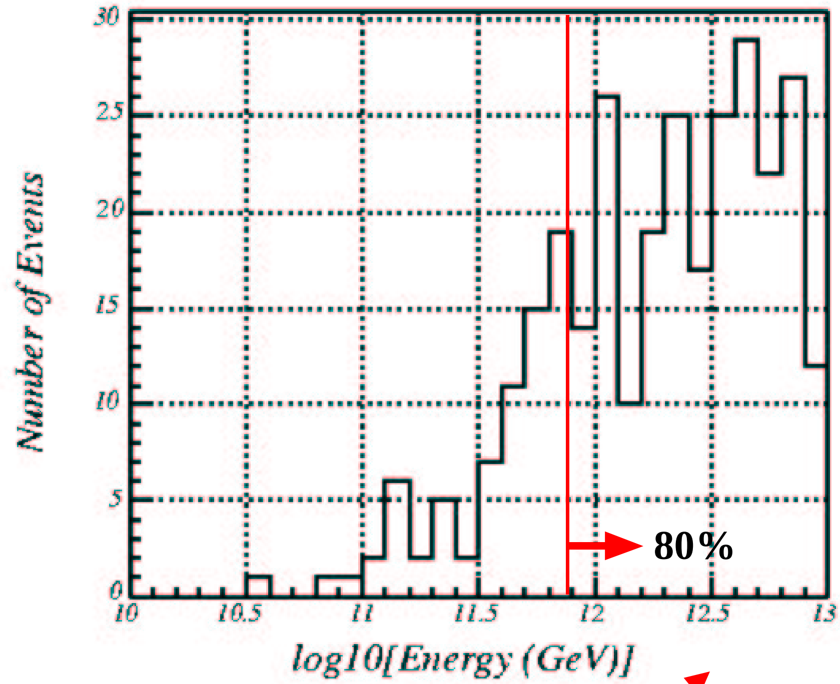

- Possibly some sensitivity beyond 10km.
- Need to take care that attenuation correctly taken into account in this region.

# Results

all events



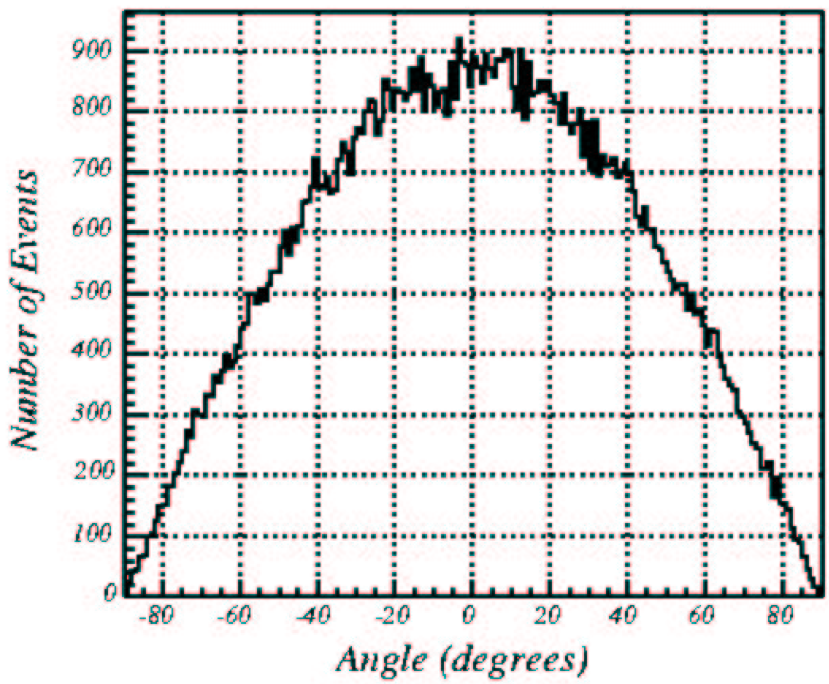

after cuts



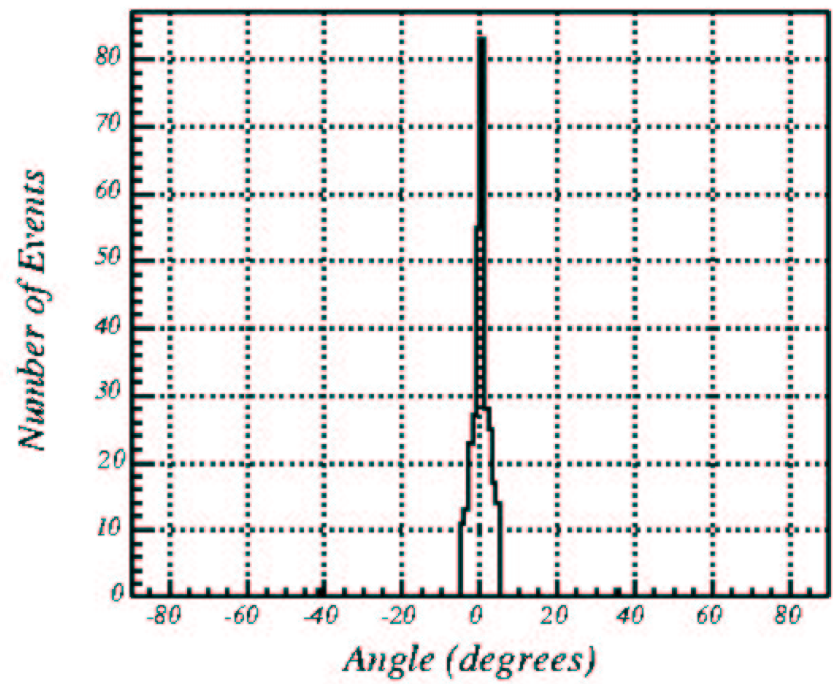

- Effective range increases with energy − enough to overcome the steeply falling prior distribution.

# Results

**all events**

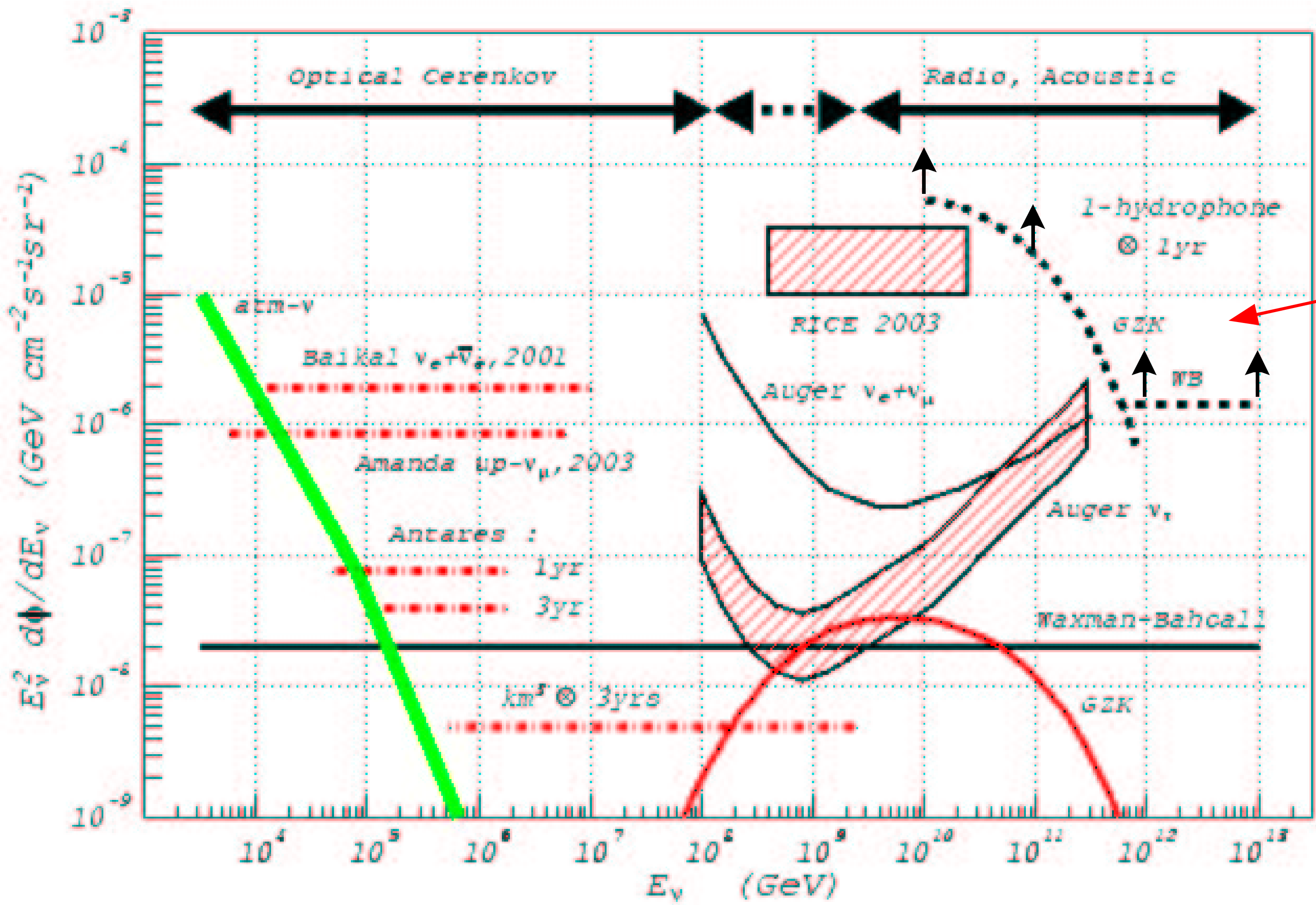



**after cuts**




- no sensitivty beyond 5$^o$
- 5$^o$ pre−simulation cut safe

# Results



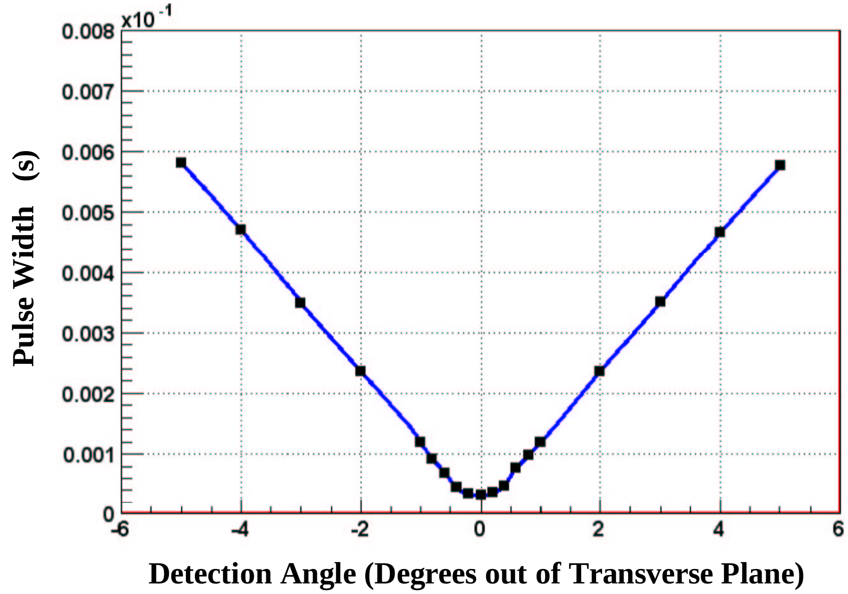

**Perfect hydrophone**
90% CL limits based on MC estimated sensitivities and assumed non−observation of a signal.

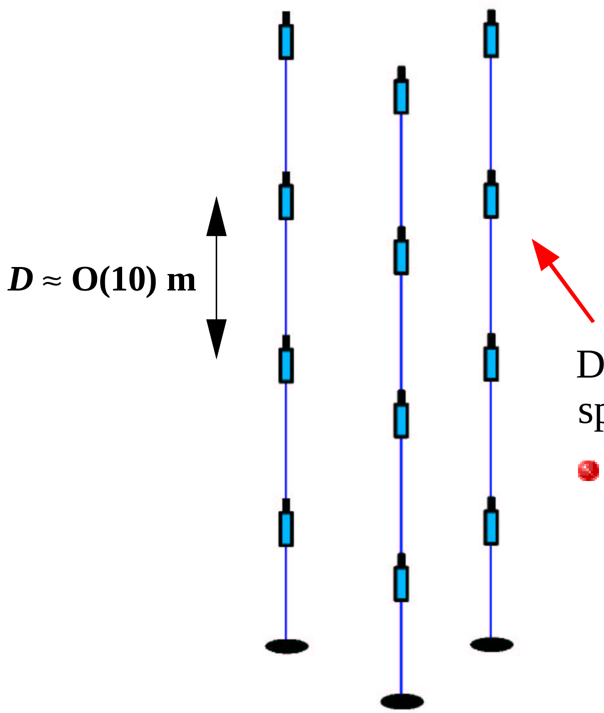
Coincidence requirements and noise considerations will **worsen limits by orders of magnitude**.

**Not a RONA expected limit !**

# Thoughts on Acoustic Array Design

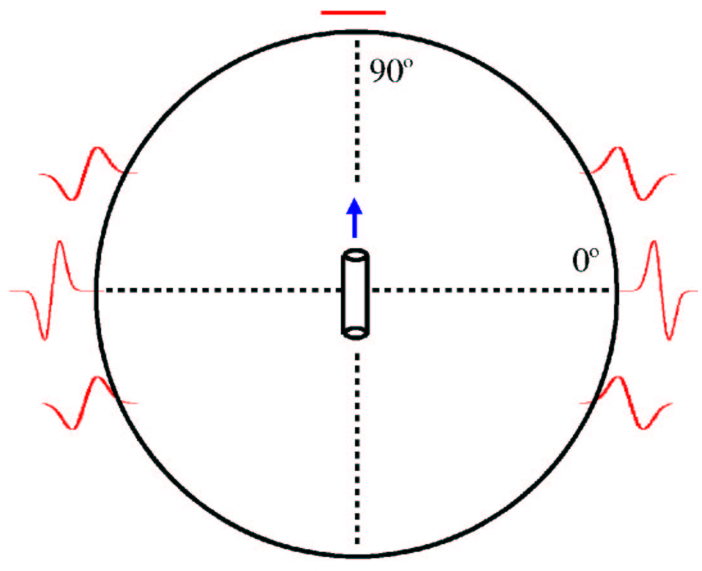
- Goal : combine information from multiple hydrophones to meaure energy and direction of UHE neutrino cascade.
- Directional information can in principle be extracted from each pulse ⇒
- Will be more difficult for realistic pulses.



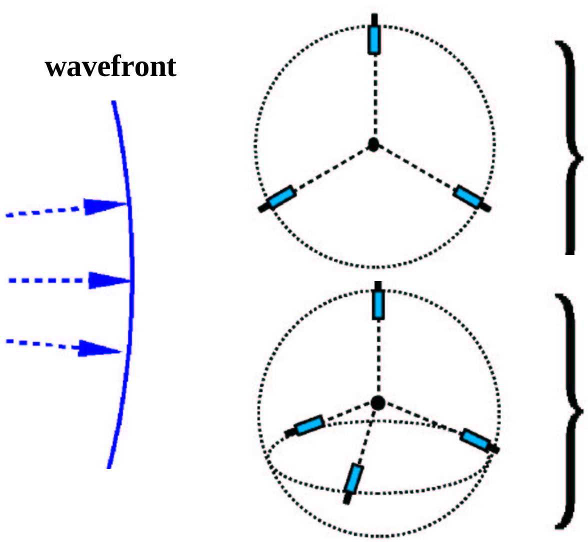

Detector comprising equally spaced single hydrophones.

- Vertical spacing will have to be relatively dense to ensure string hits.



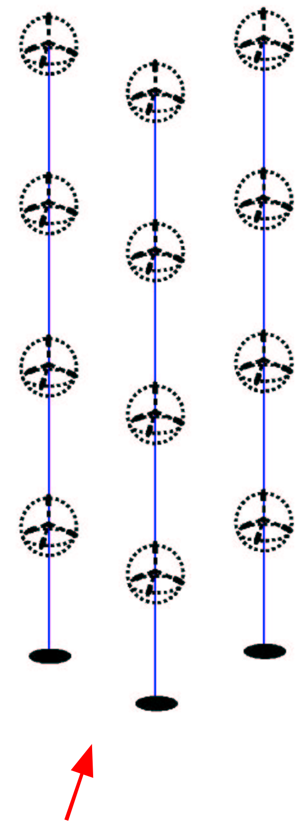
# Thoughts on Acoustic Array Design

- Measurements from multiple hydrophones could in principle be used to determine wavefront direction and curvature (range).
- Perhaps better to ensure multiple hits by clustering hydrophones.
- Assuming a timing resolution of $10^{-5}$ s (given a typical sampling frequency of O(100) kHz), then the pointing requirements might be something like :




$L \approx$ O(1) m for O(1) degree pointing resolution

$L \approx$ O(10) m for measuring range out to O(1) km. Combine range and pulse height to determine energy.



Detector composed of multiple pointing elements.

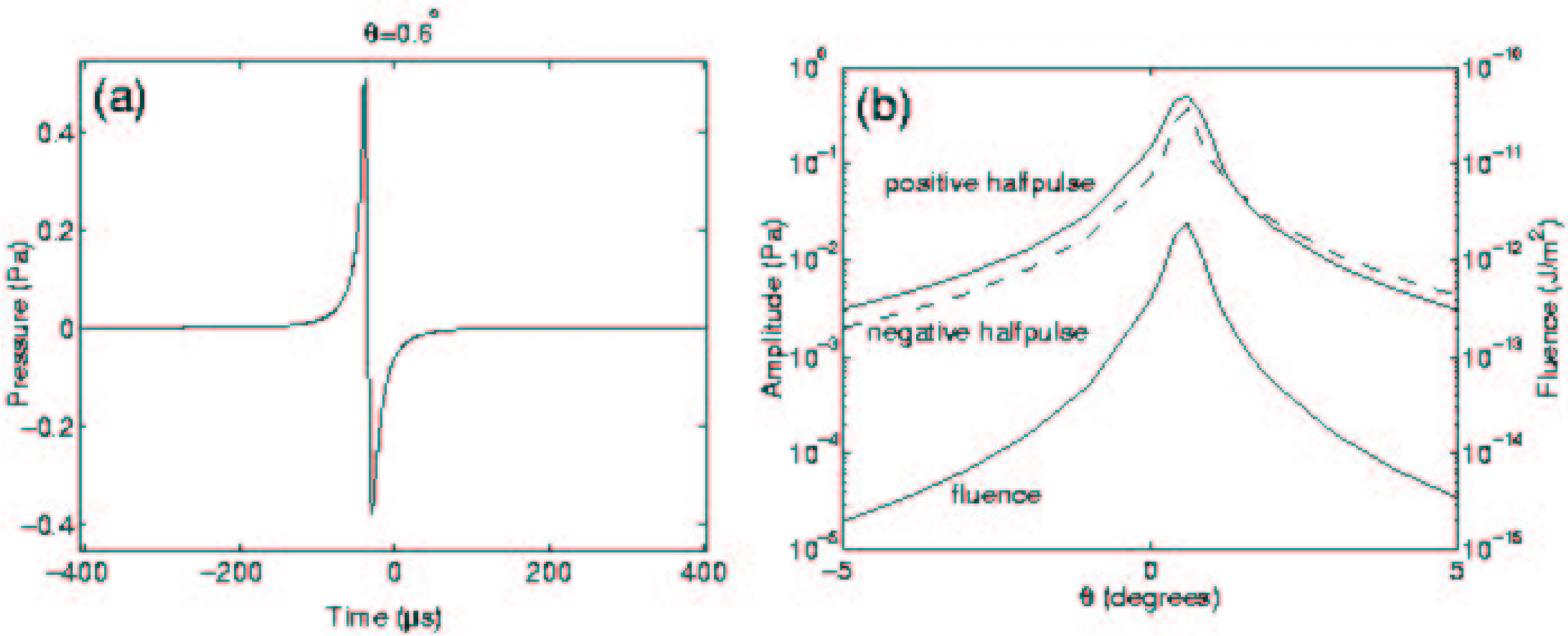
# Open Questions & Plans

- Thermo−acoustic coupling mechanisms (Sulak temperature dependence problem) − what further studies could/should be done ?
- Robustness of sensitivity estimates : realistic shower modelling required (LPM, stochastic effects, etc.); realistic signal attenuation in sea water.
- Feasibility of a counting experiment : fake rates (physical & biological noise sources),
- Feasibility of a telescope with finite pointing and energy resolutions. Investigate optimal hydrophone arrangement and number of elements required to reach certain flux sensitivity levels.
- How can we calibrate such a hydrophone array ?
- What is the lower energy limit of acoustic detection − smart ways to reduce the threshold ?

- ..... need data from RONA, a calibration system and lots of simulation work.

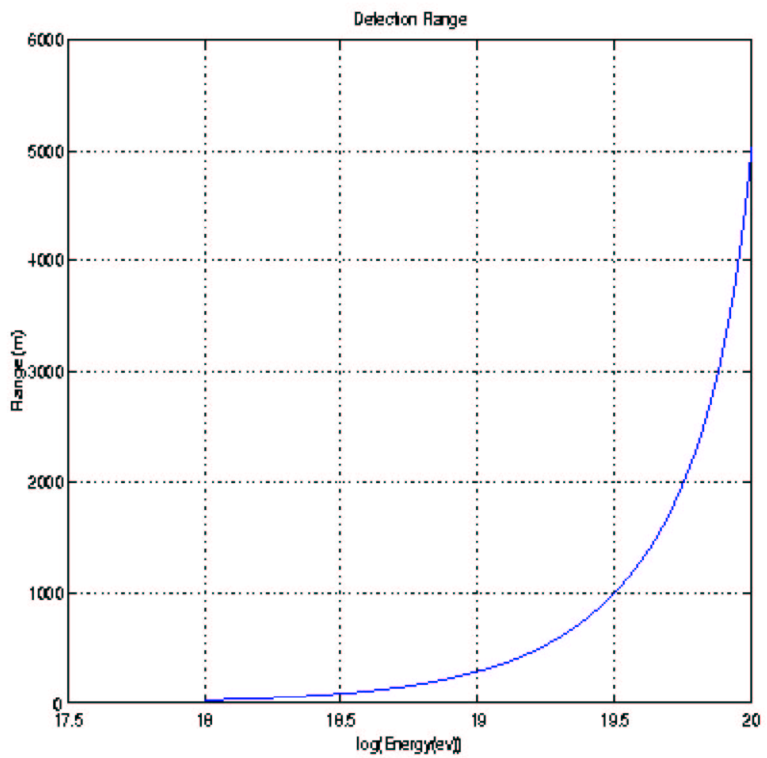
# Backup Slides

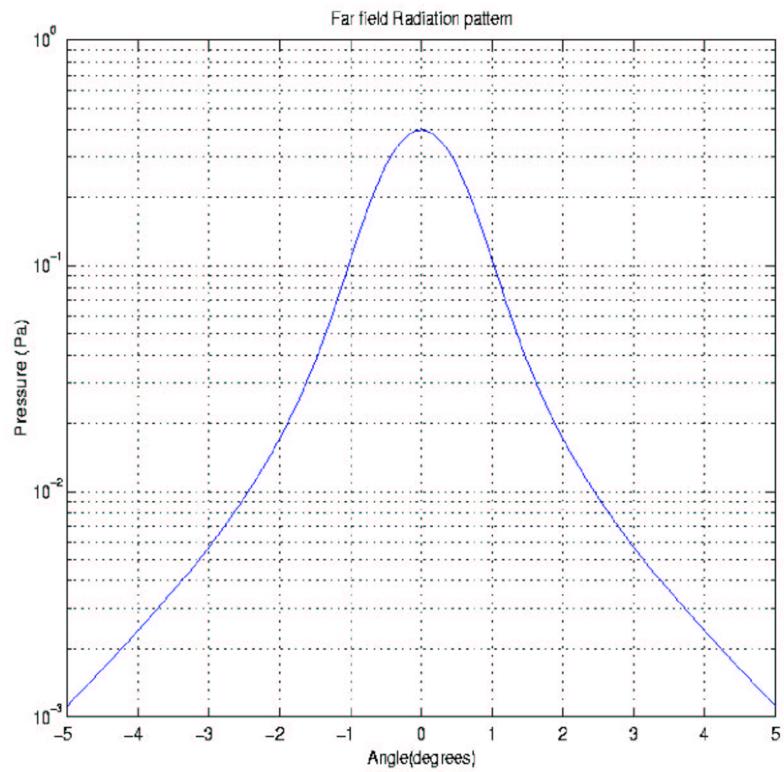
- Lehtinen amplitudes :



# Backup Slides

- Signal & background analysis (Danaher & Rhodes) :

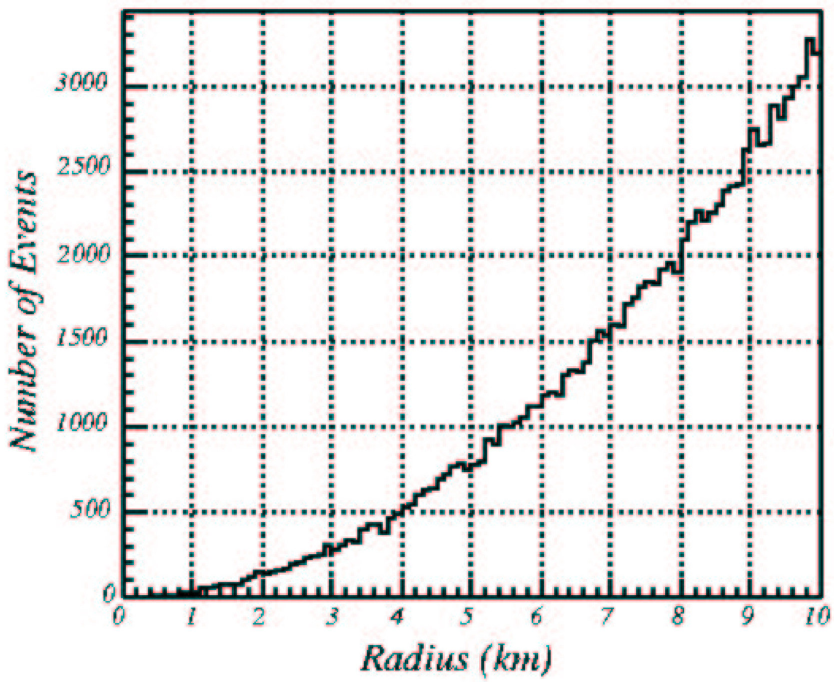


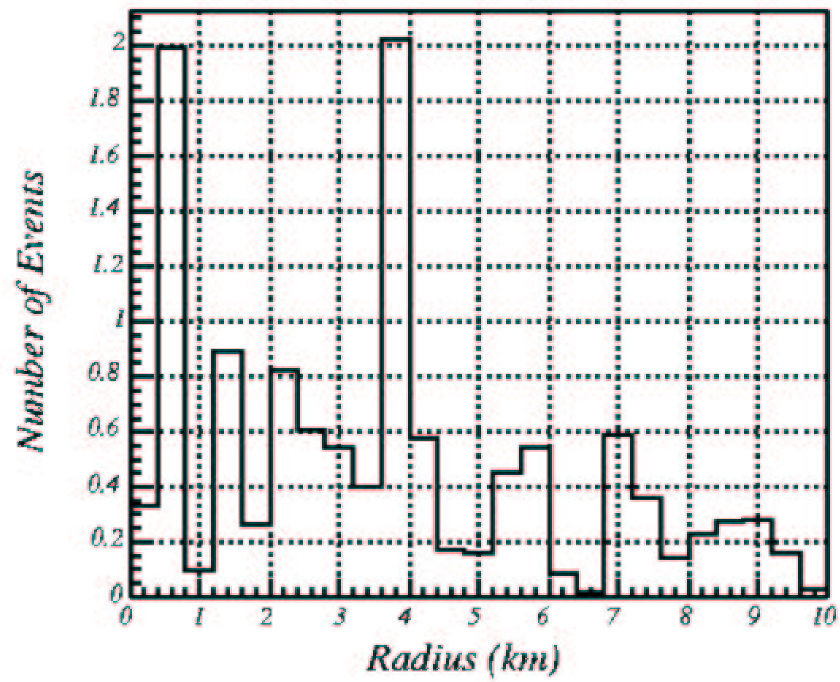
# Backup Slides

- GZK (ESS) reweighted distributions :

**all events**




**after cuts**



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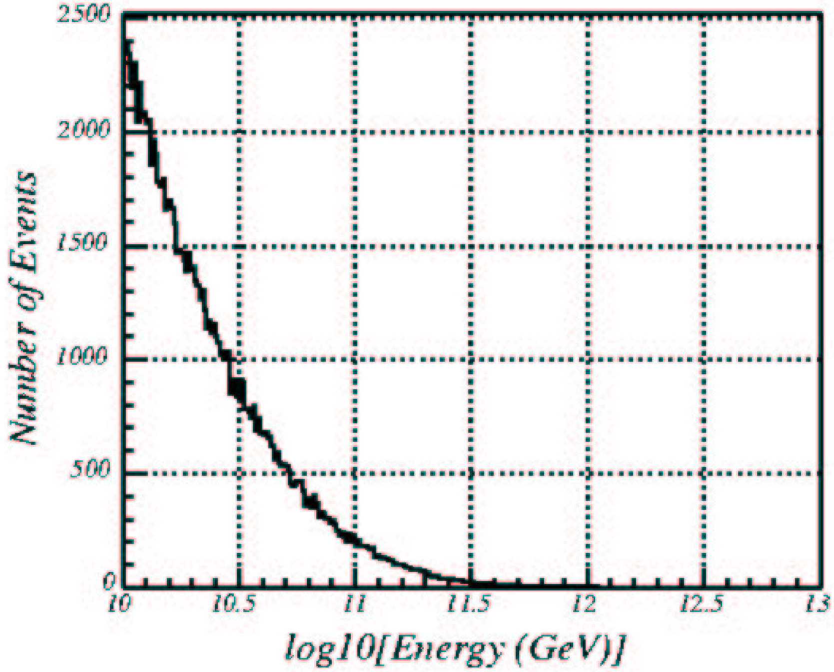


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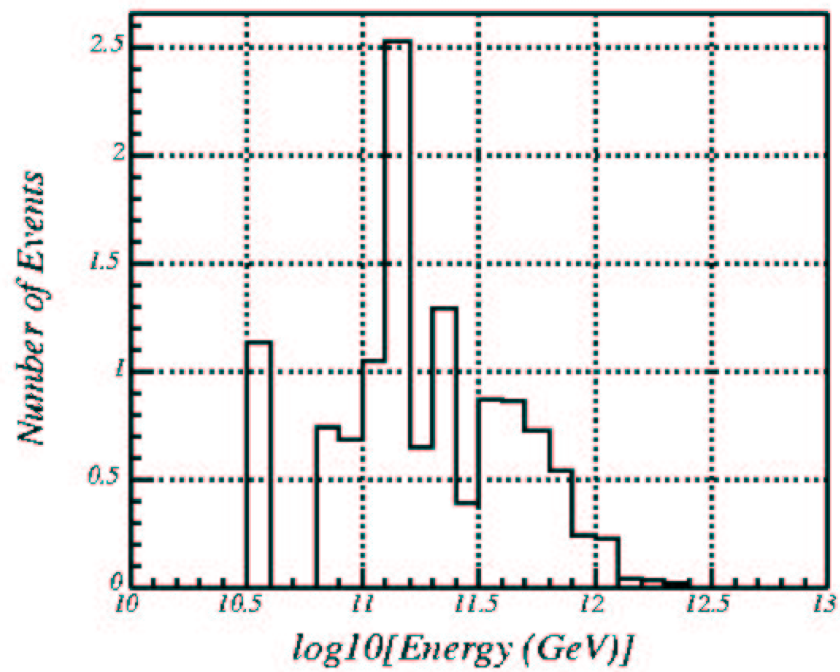

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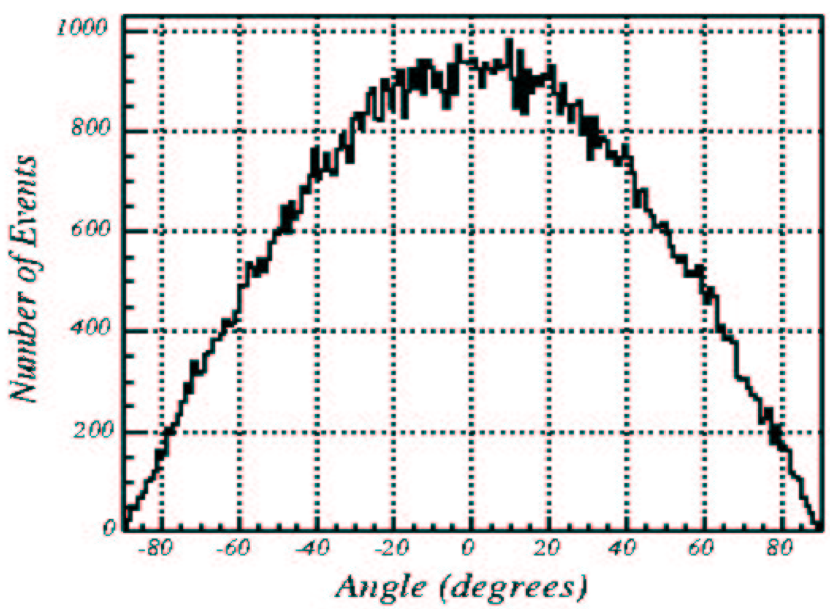


**after cuts**