Neutrino Astronomy

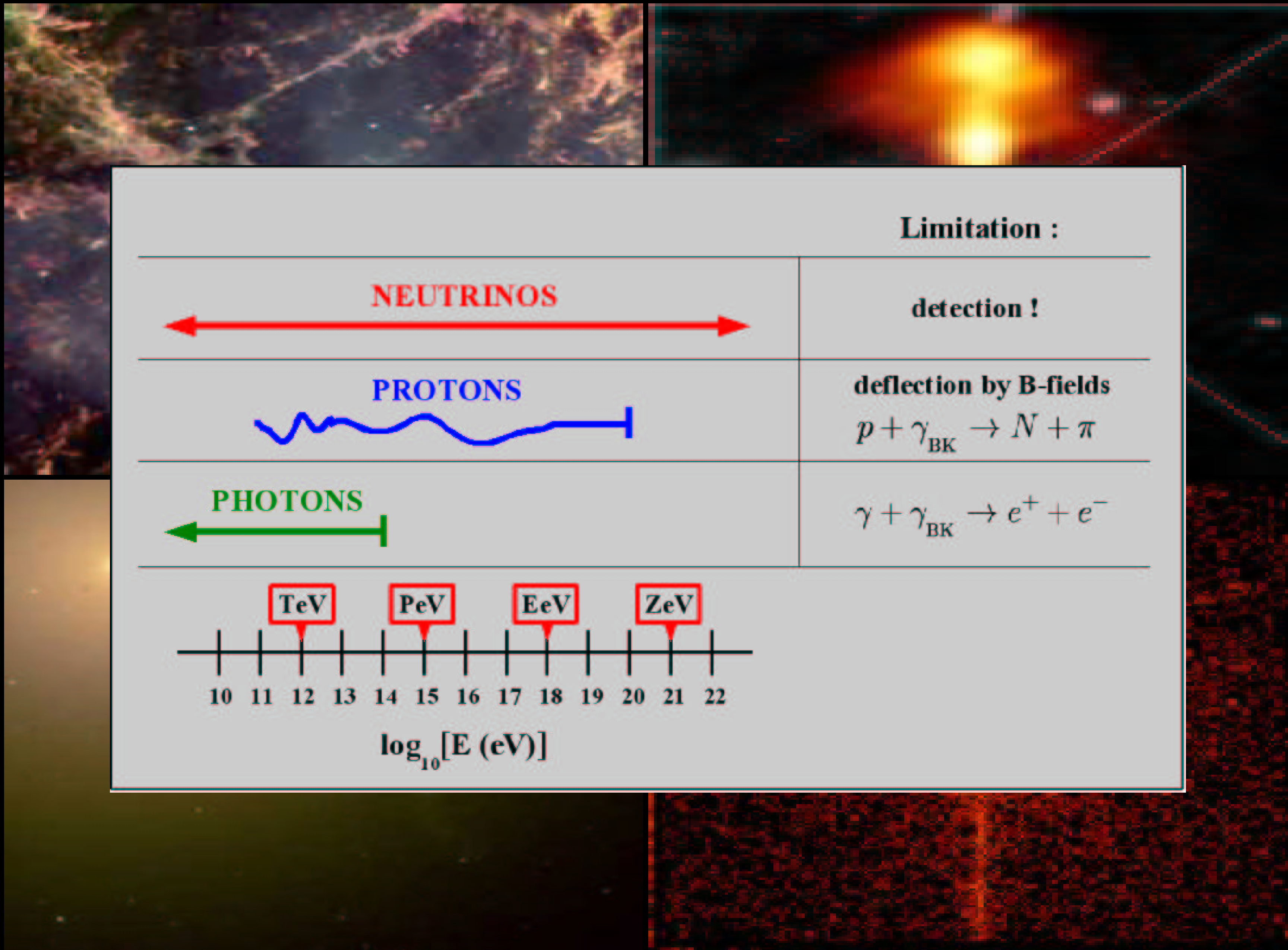
Workshop on Cosmic Particles

February 18th-20th 2005

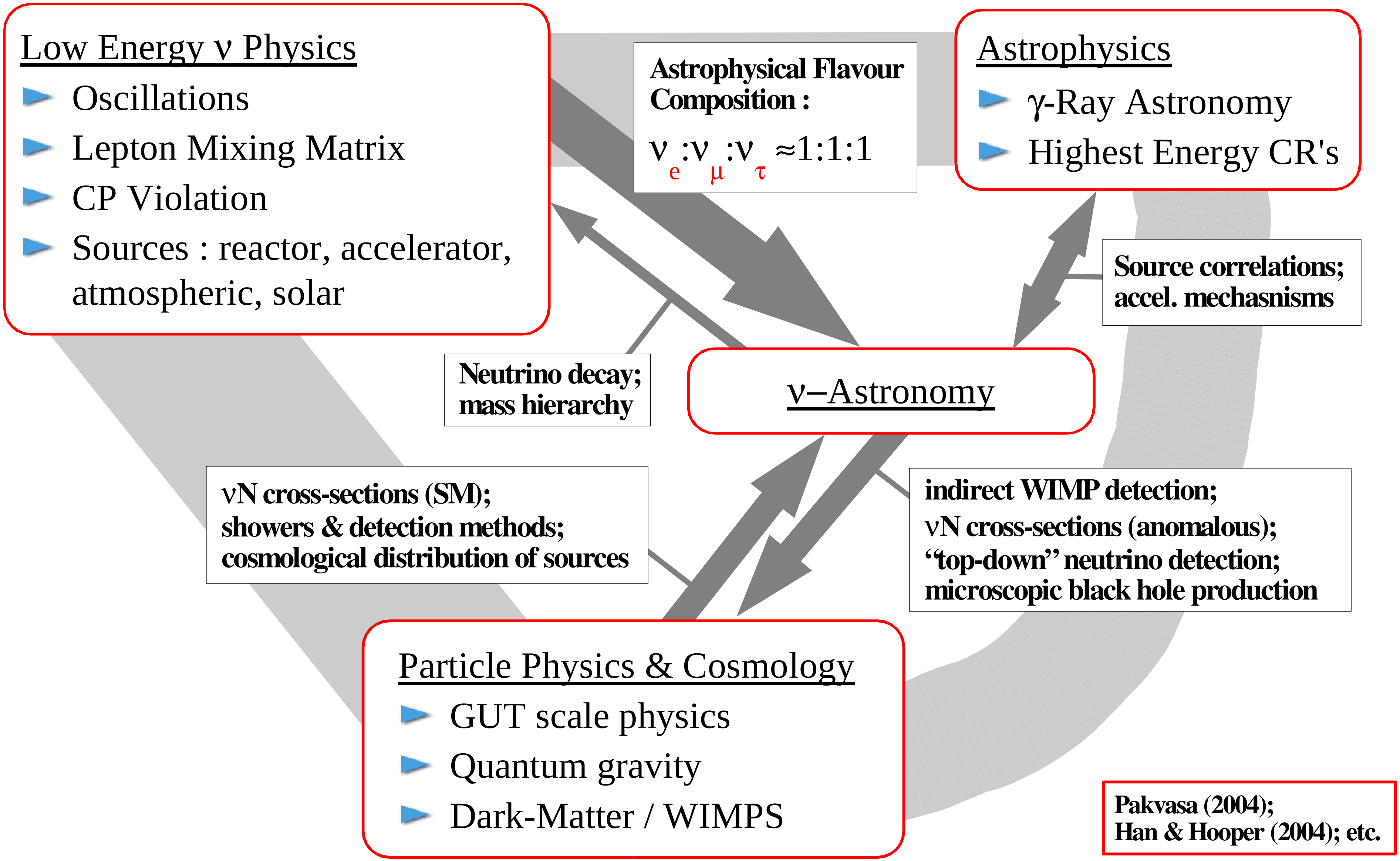
Dave Waters
University College London

- Why Neutrino Astronomy ?
- Connections to Fundamental Physics
- Astrophysical Neutrino Flux Estimates
- Detection Techniques
  - Extensive Air Showers
  - Optical Cerenkov
  - Radio Cerenkov
  - Acoustic
- Comparison & Outlook

Neutrino Astronomy : Why ?



Neutrino Astronomy : Connections



Astrophysical Neutrino Sources : General Bound

<u>Waxman-Bahcall Bound :</u> **Waxman & Bahcall (1998), (1999)**

- $1/E^2$ injection spectrum (Fermi shock).
- Neutrinos from photo-meson interactions in the source.
- Energy in **ν**'s related to energy in **CR**'s :

$$E_\nu^2\,\mathrm{d}N_\nu/\mathrm{d}E_\nu \sim 0.25 \times \epsilon \times t_H \times E_{CR}^2\,\mathrm{d}\dot{N}_{CR}/\mathrm{d}E_{CR}$$

Fraction of CR primary energy converted to neutrinos (ϵ)

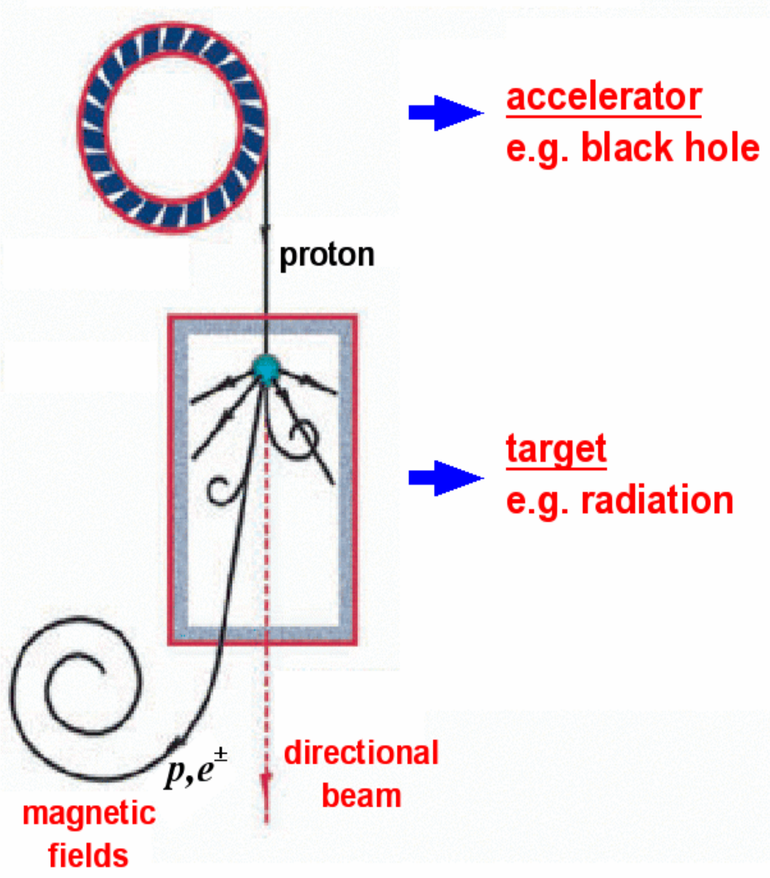
Hubble time (t_H)

From rate of UHE CR's (10^{19}-10^{21} eV)

$$\Rightarrow \quad E_\nu^2\Phi_\nu \lesssim 5\times10^{-8}\ \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

- *Many* qualifications and caveats.
- Can be **evaded** if :
  - sources are optically thick
  - neutrinos from other sources ("top-down")

COSMIC BEAM DUMP : SCHEMATIC



Cosmogenic Neutrinos

GZK mechanism :

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

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

$$\pi^+ \to \mu^+ + \nu_\mu$$

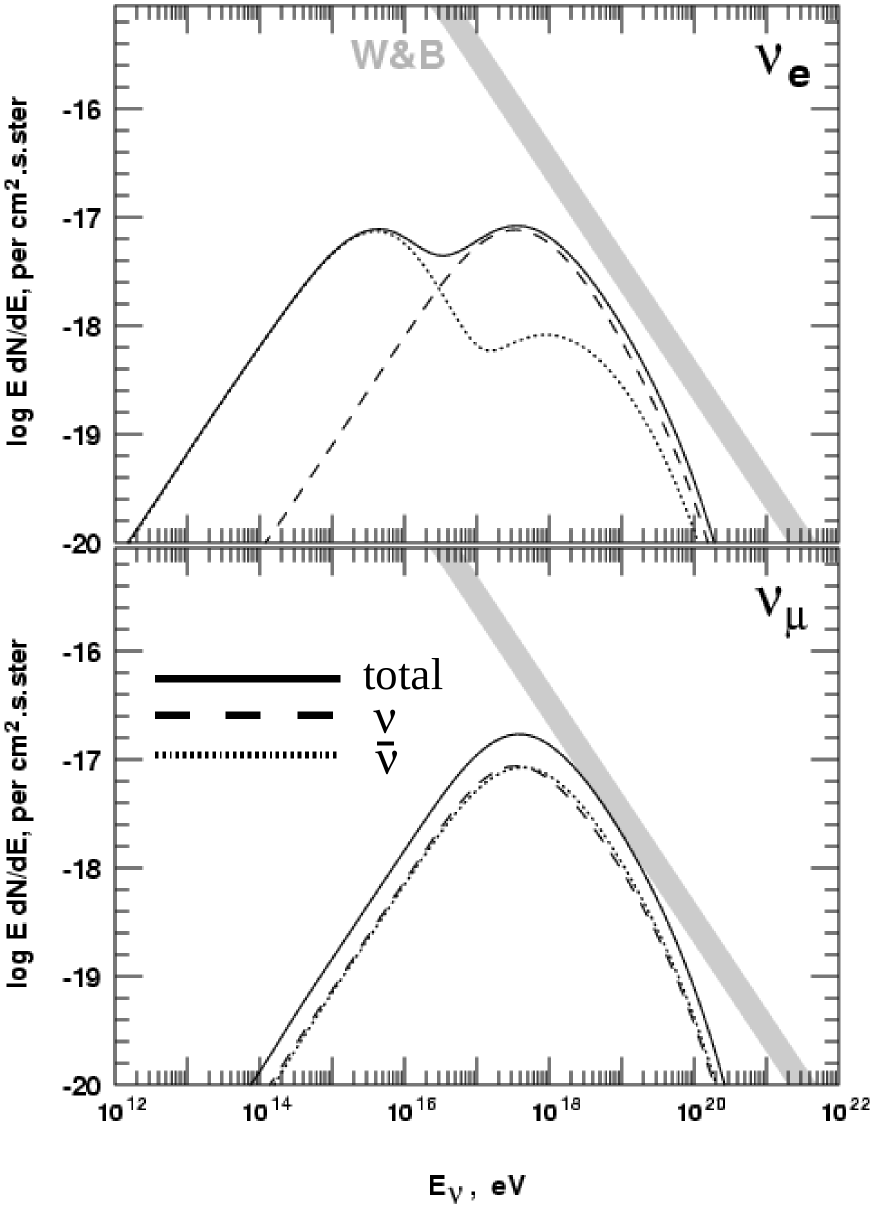
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

$E_{THRESH.} \sim 6 \times 10^{19}$ eV

- Uncertainties in flux calculations :
  - UHECR luminosity; ρ_{CR}(local) $\neq \langle\rho_{CR}\rangle$
  - injection spectrum
  - cosmological evolution of sources
  - IRB & optical density of sources

factors of ~2 uncertainty each;
factor of ~4 overall (?)

Engel, Seckel, Stanev (2001)



Cosmogenic Neutrino Flux : Guaranteed ?

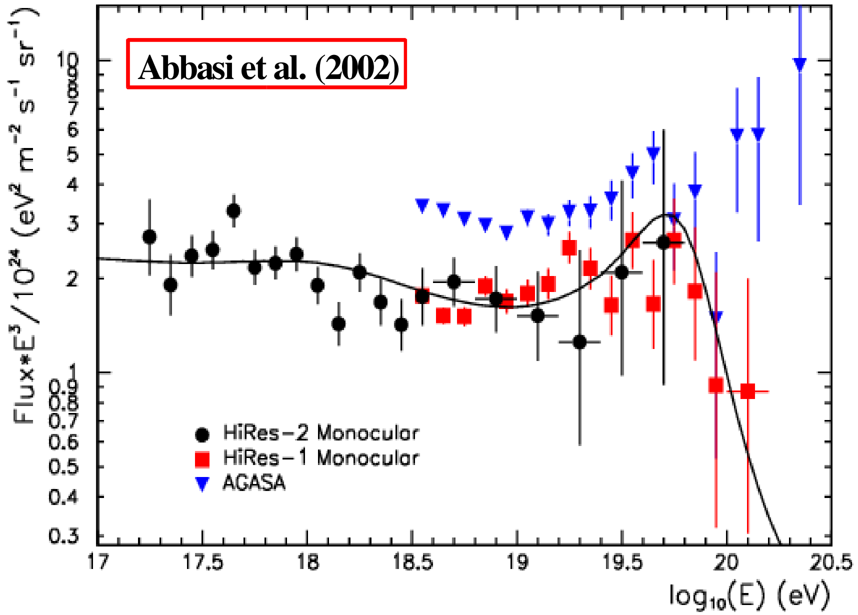
Primary CR spectrum exhibits GZK cut-off ?

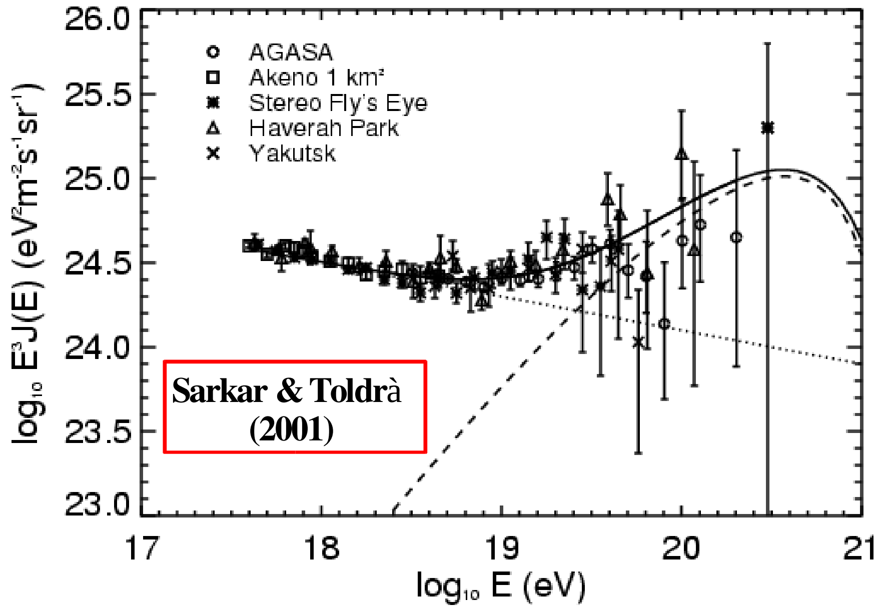
YES → **Confirms basis of GZK neutrino flux calculation.**

NO → **Local source of UHE cosmic rays :**

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

Model dependent, but generally give neutrino fluxes ≥ GZK flux.



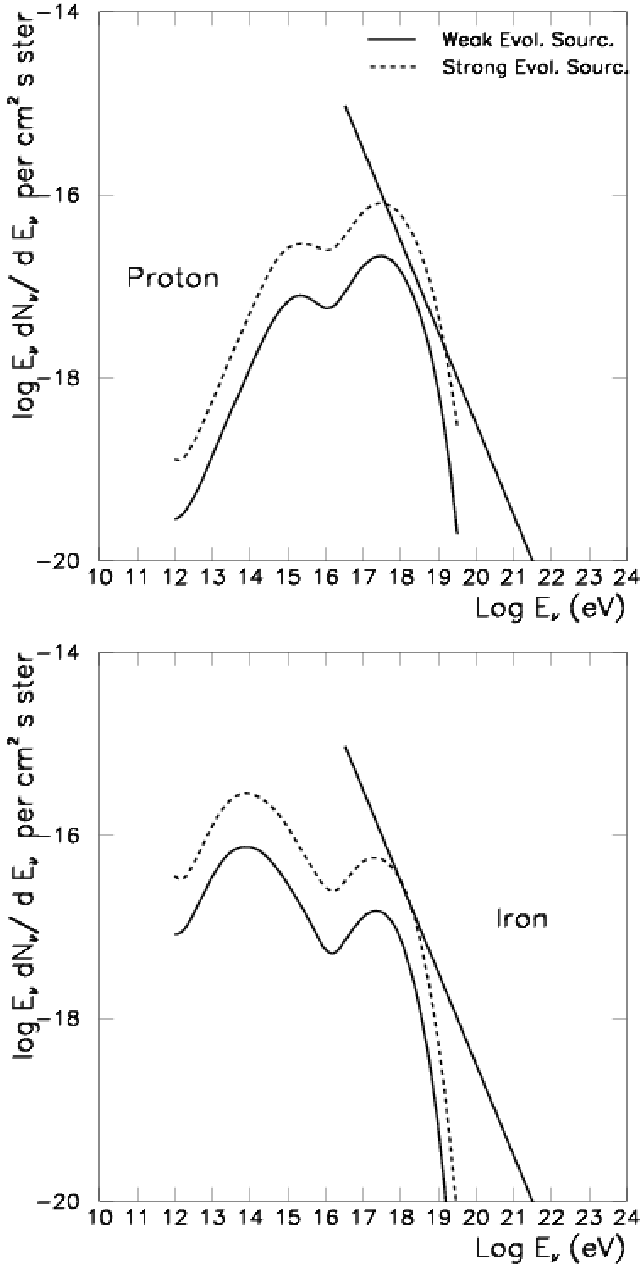


Auger will settle this definitively

Cosmogenic Neutrino Flux : Guaranteed ?

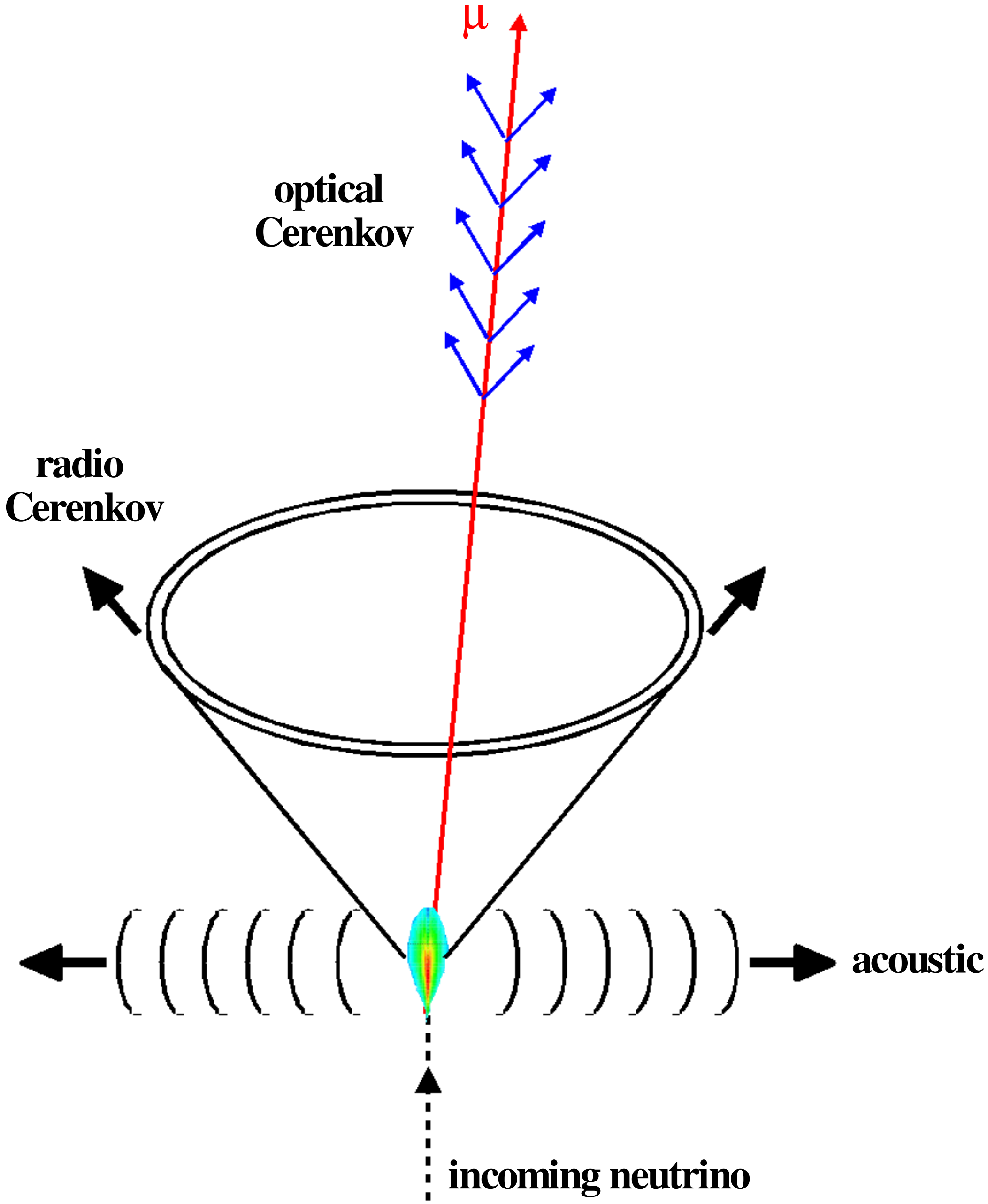
Ave et al. (2004) ; Hooper et al. (2004)

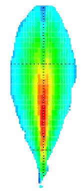
- <u>Remaining caveats :</u>
  - The UHECR primary sources themselves cut-off around the GZK energy : "cosmic conspiracy". Most assume a cut-off substantially higher – 10^{21}-10^{22} eV (Hillas)
  - Composition doubts (Auger also critical)



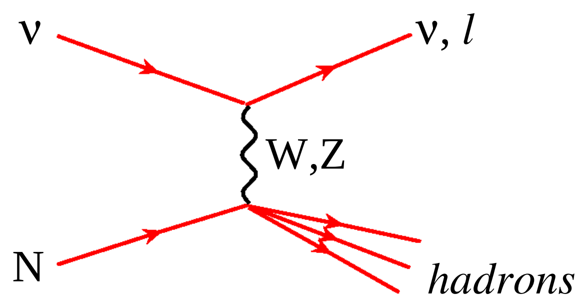
- Nevertheless, GZK neutrinos remain arguably the clearest target for future experiments.

Detection Methods : Summary





= hadronic shower (or EM shower for ν_e CC interactions)

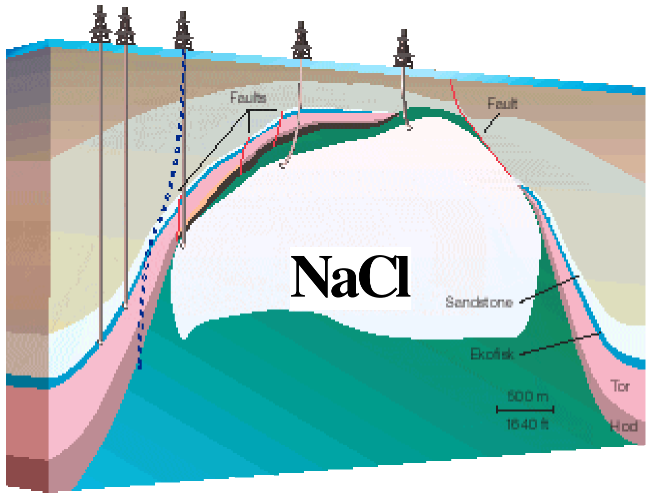


+ extensive air shower (EAS) detection

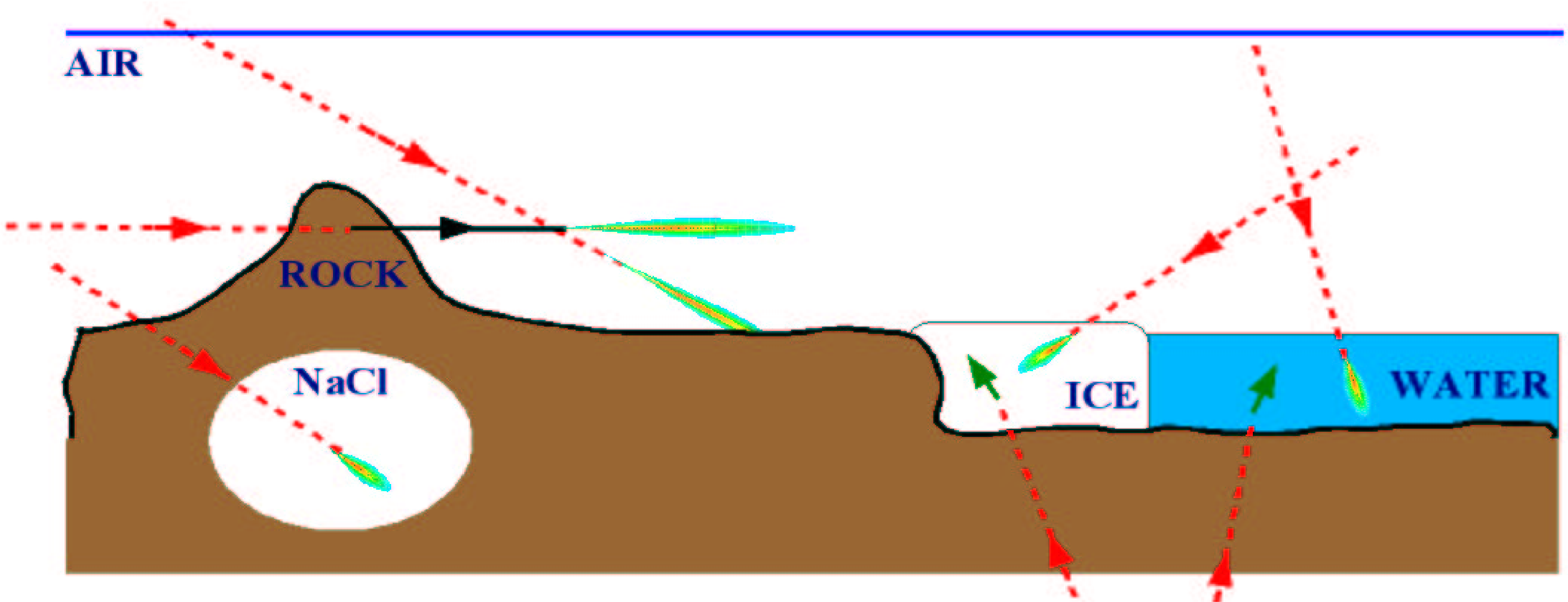
Targets

Targets :

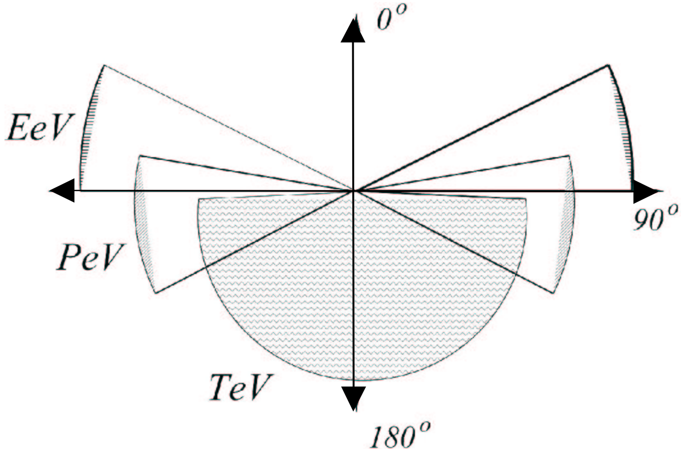
- Ice
- Water
- Salt
- Lunar regolith
- Rock
- Air



Targets

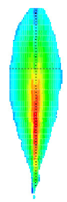


100 TeV : $\lambda_{INTERACTION} \approx D_{EARTH}$



<u>Backgrounds :</u>

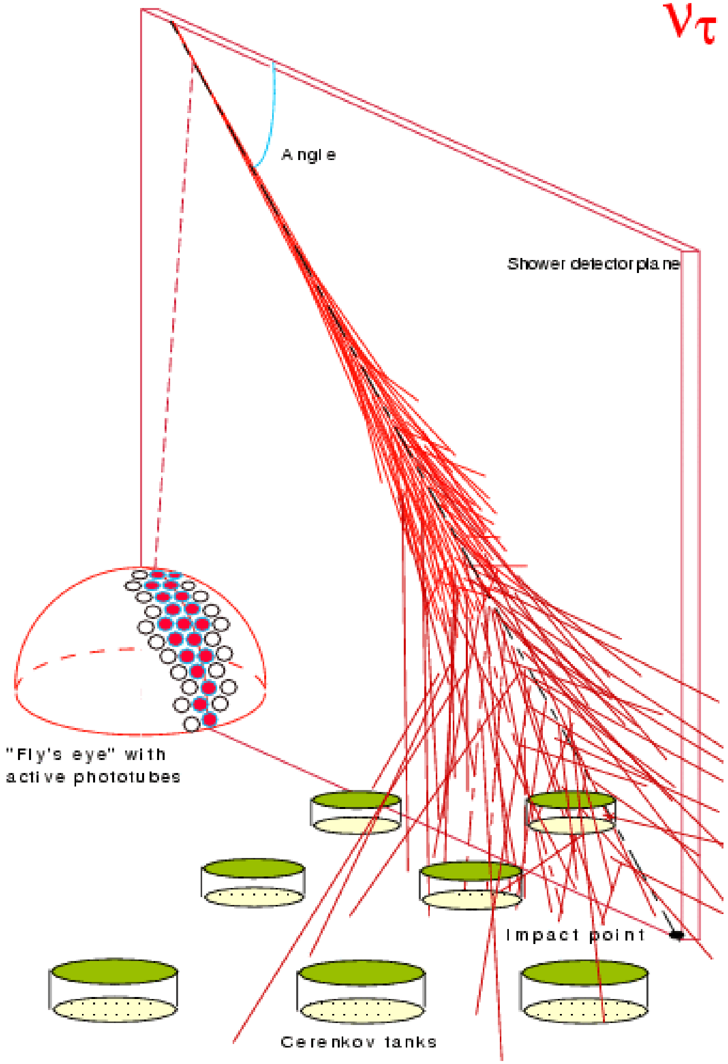
- Downward : CR μ
- Upward : atmospheric ν's

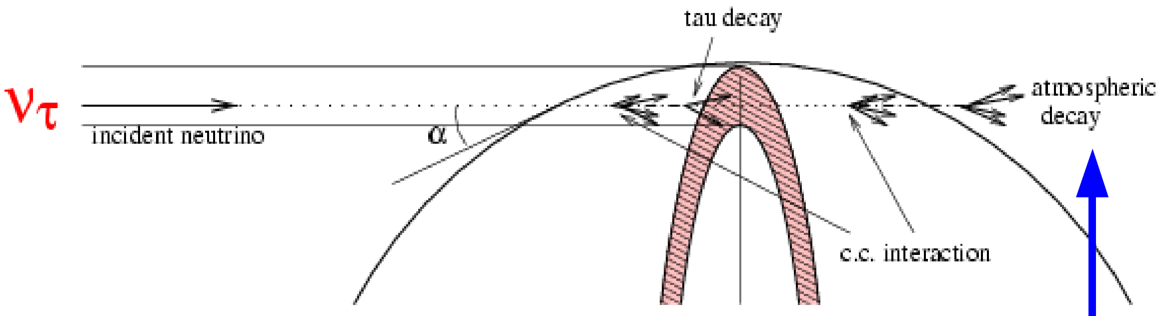


= cascade (hadron, electron, tau)

= μ

Extensive Air Shower





Detect shower from τ decay

Auger :

- sensitivity to ν_τ could dominate
- handfuls of GZK ν events/year.

Distinguish late (ν) from early (**h**) showers for a given atmospheric depth using :

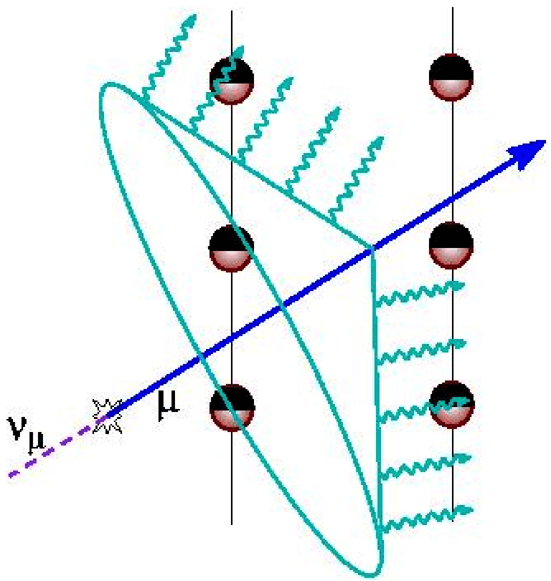
- timing information
- shape information
- composition information

Optical Cerenkov

- Similar to detection techniques used in low-energy experiments (Super-K).
- The only technique employed in currently operational neutrino telescopes.
- The only technique with a proven capacity to detect neutrino events (atmospheric).
- Backgrounds : CR muons (downward); atmospheric neutrinos (upward).

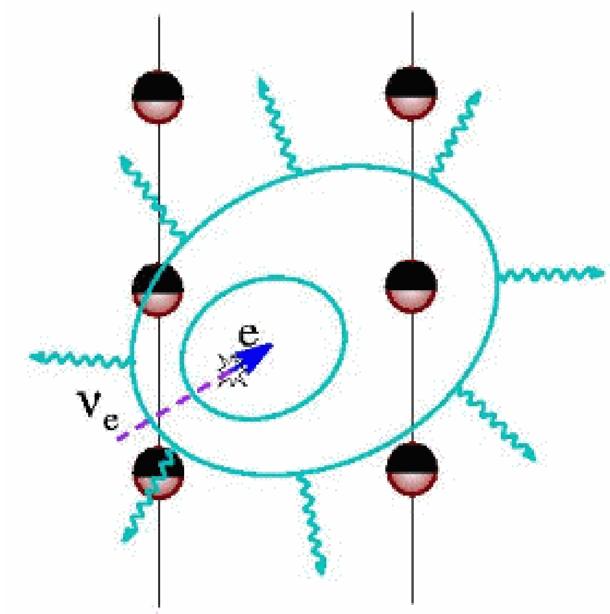
Muon tracking :

- Effective volume >> instrumented volume (@ E such that $R_{\mu} >> S_{detector}$)
- Excellent pointing accuracy.
- Relatively poor energy resolution.

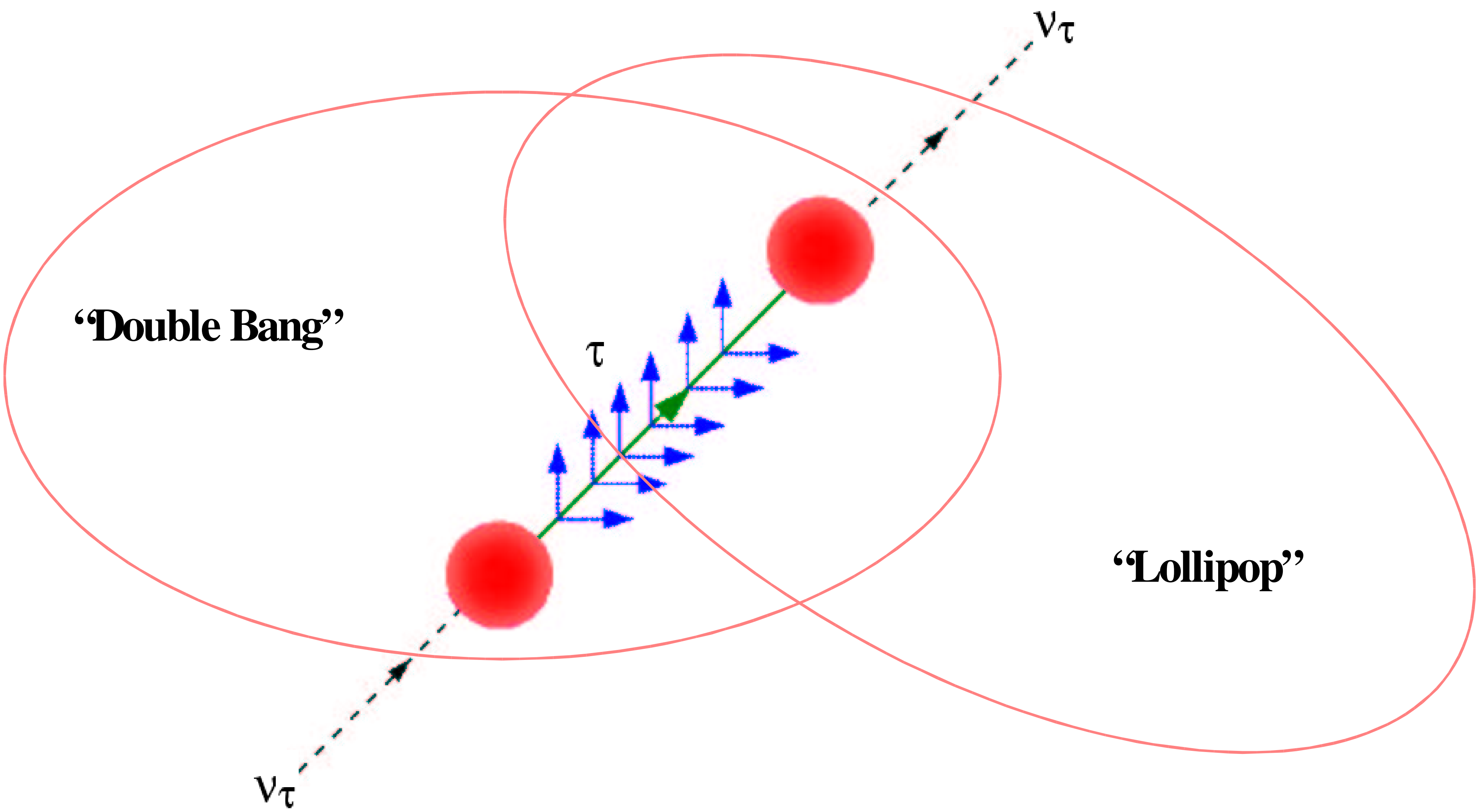


Cascade detection :

- Effective volume = instrumented volume.
- Poor pointing accuracy.
- Relatively good energy resolution.

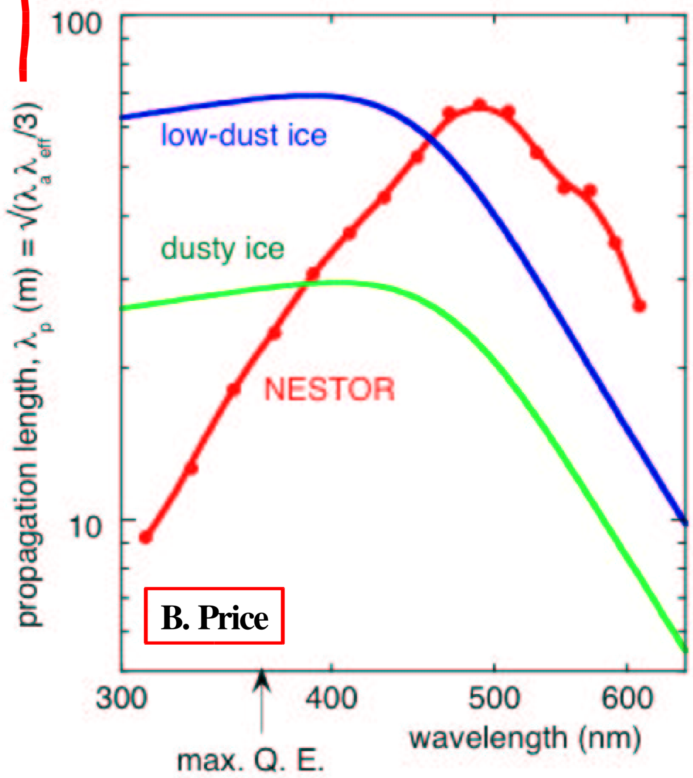


Optical Cerenkov : ν_τ Detection



Optical Cerenkov : Media

figure of merit for **cascade** detection

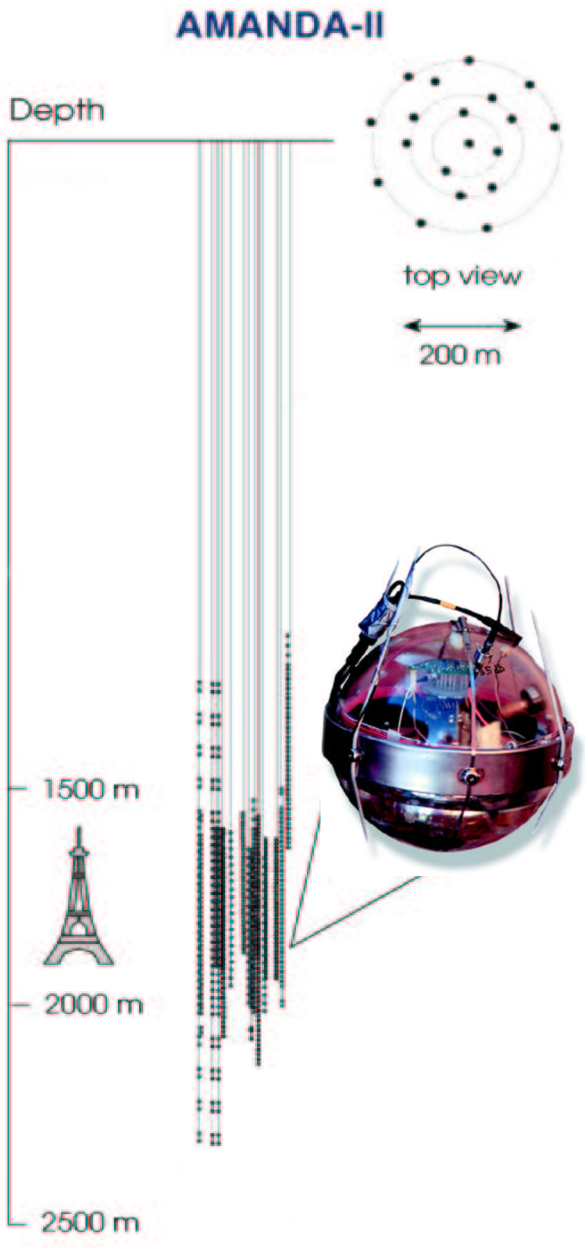


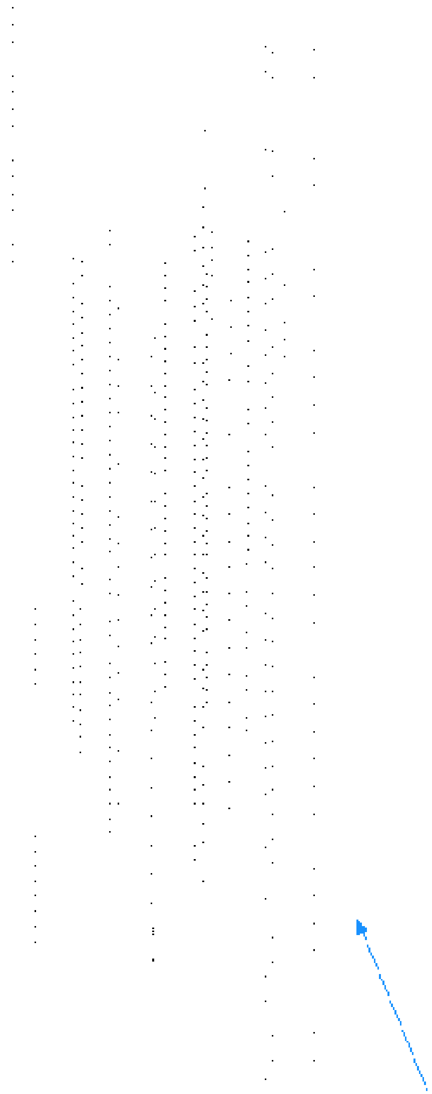
	Water (450-500 nm)	Ice (400 nm)
Absorption Length	~ 50 m	~ 100 m (depth dependent)
Scattering Length	> 100 m (strongly depends on local conditions)	~ 20 m (depth dependent)
Noise	Large (K-40, bio)	Low (SN detection)

Detector capabilities vary but ***broadly*** comparable between ice & water :

- Energy thresholds & ranges
- Pointing resolutions
- Deployment & operational difficulties

Amanda

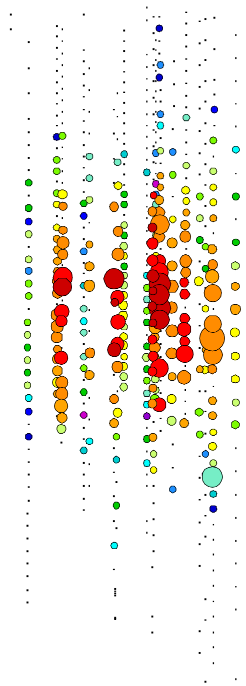




Amanda II (2000)

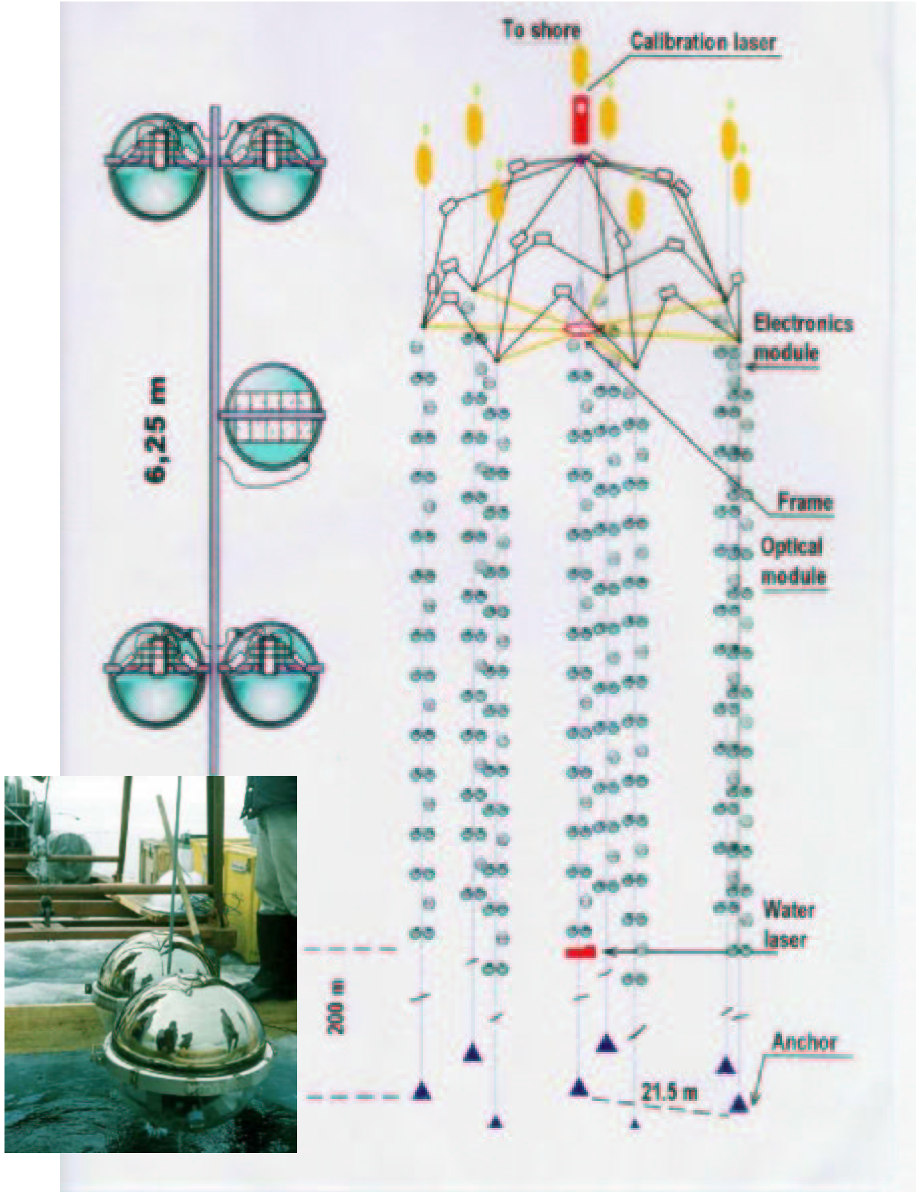
ICE3

- 19 strings
- 677 optical modules
- ~ 400 m high
- ~ 200 m wide
- V_{EFF} ~ O(0.01) km^3 (cascades)
- 8” PMT's



200 TeV ν_e candidate

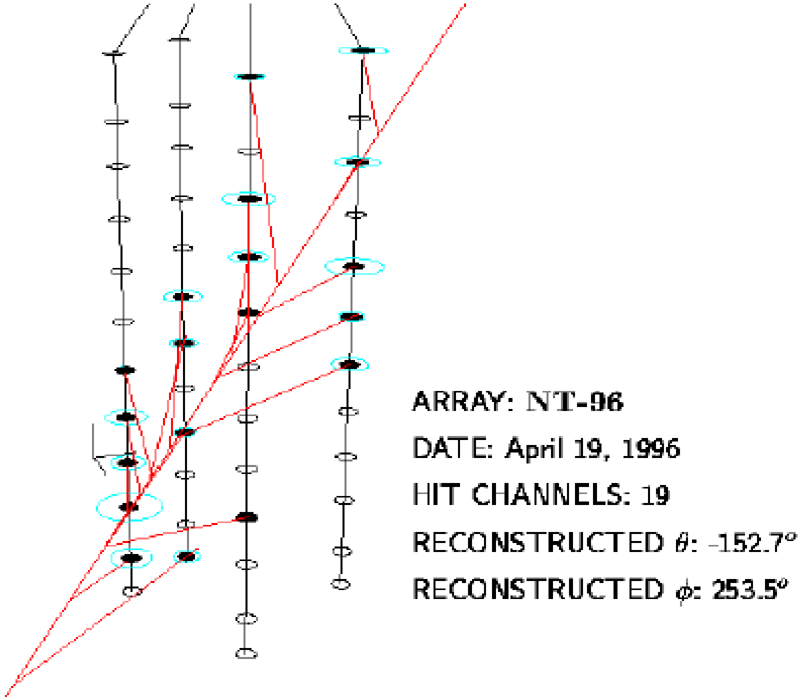
Baikal



Baikal NT-200

- 8 strings
- 192 optical modules
- ~ 70 m high
- ~ 50 m wide
- 1 km deep
- 35 cm diameter PMT
- Effective area **10^4 m^2** (μ)

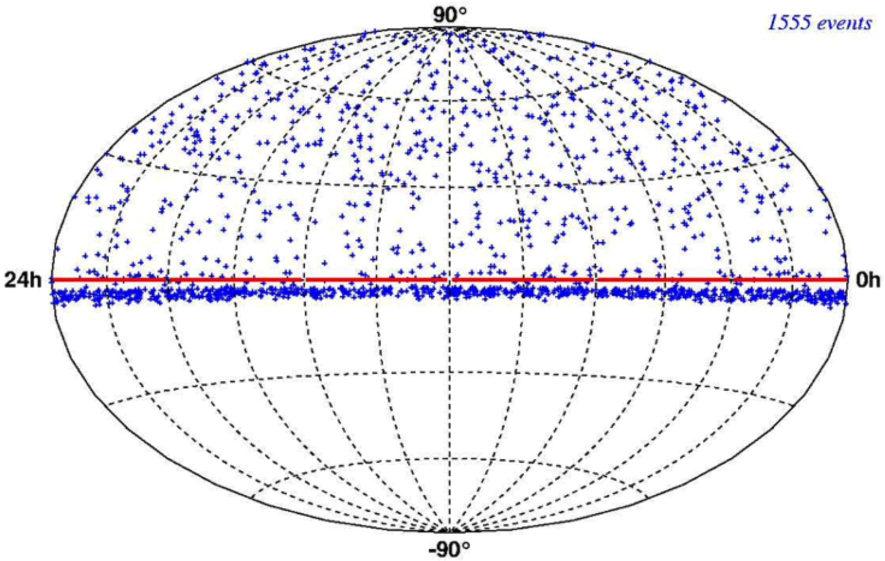
DUMAND
▼
NESTOR
▼
ANTARES
▼
NEMO



Optical Cerenkov : Highlights

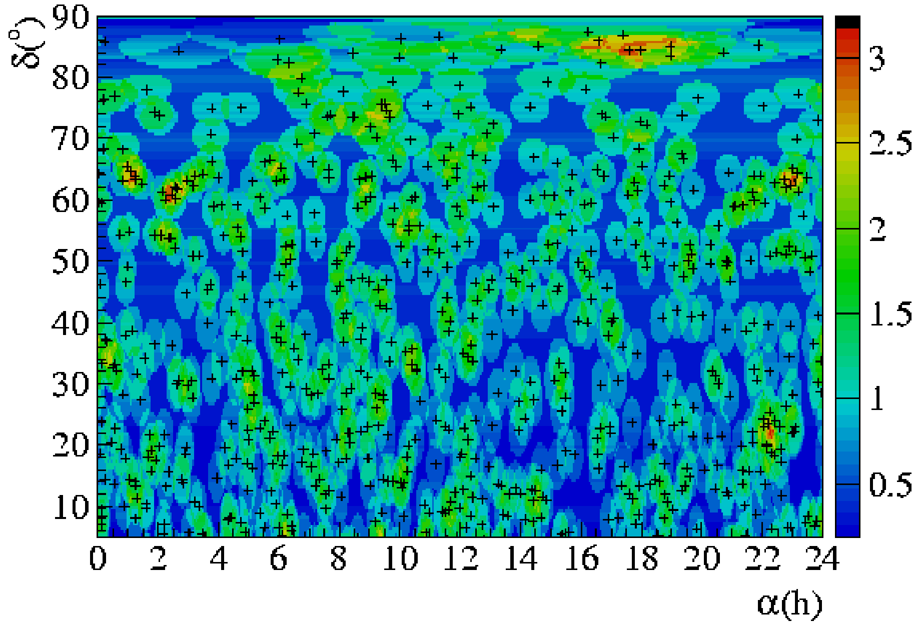
Point Source Search (AMANDA-II, 2003)

197 days, median-$E_\mu \approx 700$ GeV



Point Source Search (AMANDA-II, 2004)

607 days, median-$E_\mu \approx 1.3$ TeV



Plus :

- Diffuse flux limits (upward μ's; cascades).
- Terrestrial WIMP searches.
- Atmospheric neutrino flux measurements out to high energies.
- Cosmic ray composition studies (in conjunction with surface arrays).
- Supernovae.

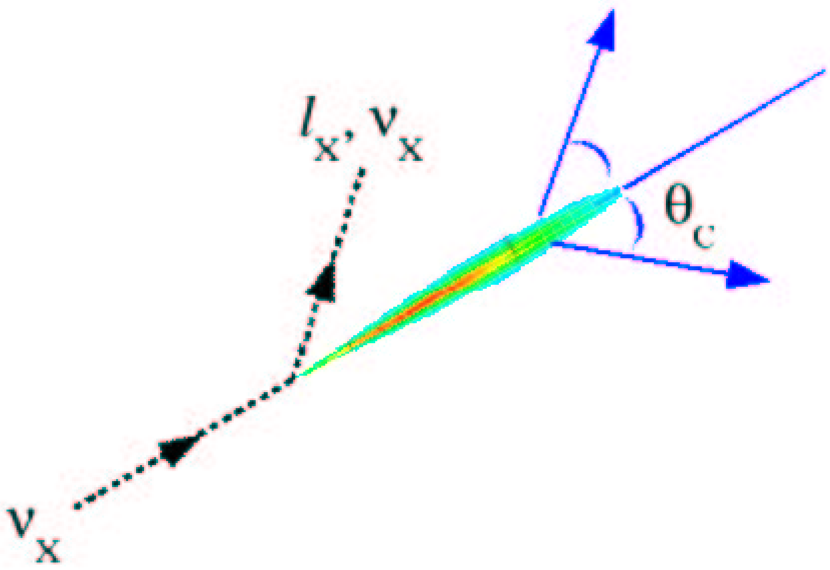
Radio Cerenkov : Mechanism

- First described by Askaryan (1961).
- Expected ~20% net negative co-moving charge excess (Z_{macro}) in UHE shower development due to :
  - Ionisation : $A \rightarrow A^+ + e^-$
  - Annihilation : $e^+ + e^- \rightarrow \gamma$
- Cerenkov radiation from Z_{macro} for $v > c_{local}$.
- Radiation is coherent for :

$$\lambda > D_{shower} \sim O(n\chi_{rad}, n\lambda_{int})$$

↓

f ~ 100 MHz – few GHz

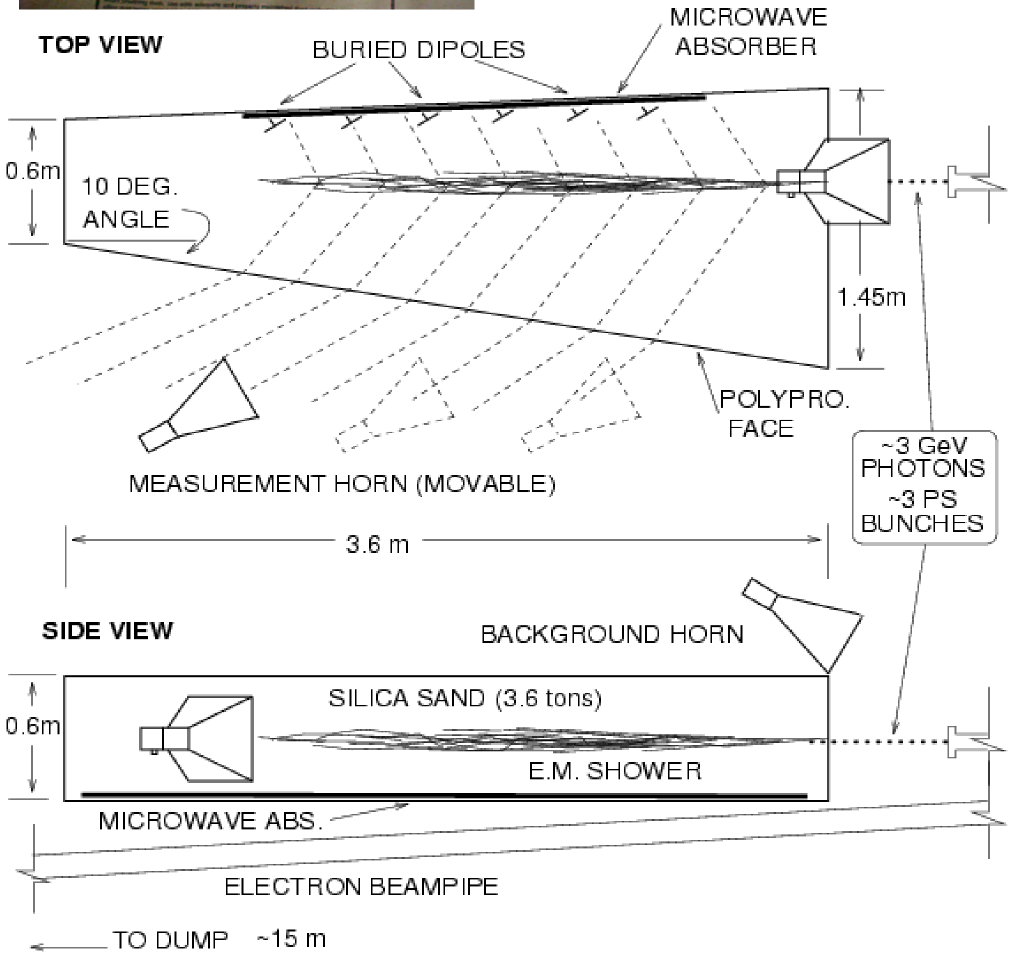


- Target requirements :
  - radio/microwave transparent
  - instrumentable
  - quiet
- Candidates :
  - ice
  - dry salt
  - sand / lunar regolith

<u>N.B.</u> Radio emission from extensive air showers (geo-synchrotron) is a different mechanism – not described here.

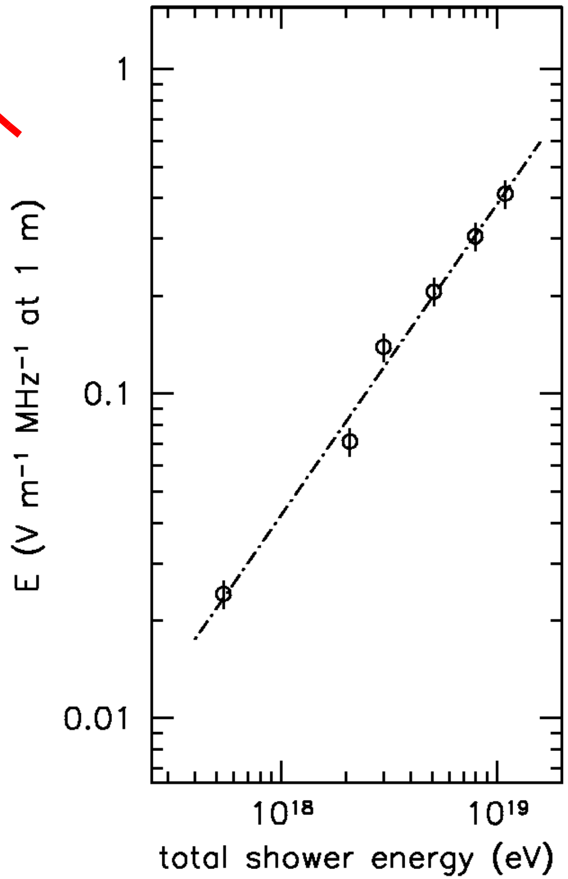
Radio Cerenkov : Test Beam

Saltzberg et al. (2000)



$$\text{Power} \propto (E_{\text{shower}})^2$$

COHERENCE DEMONSTRATED

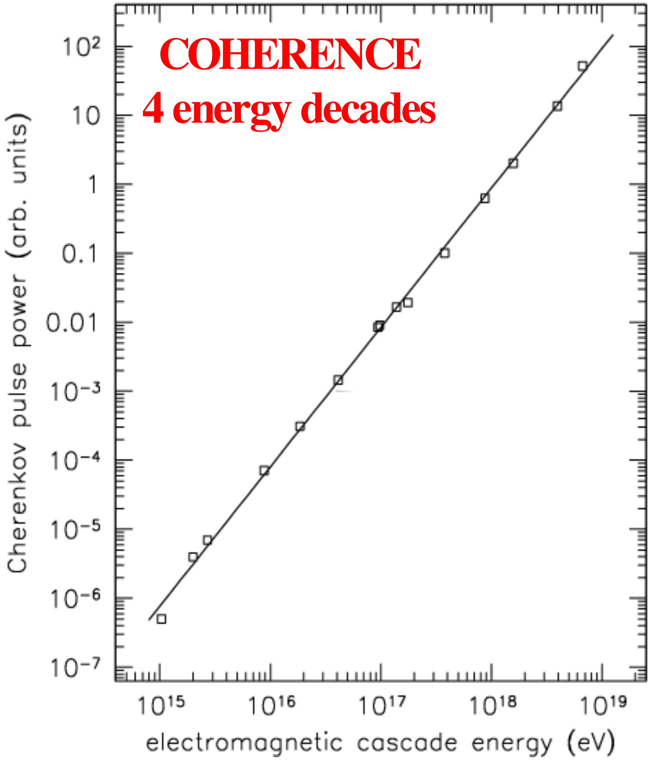


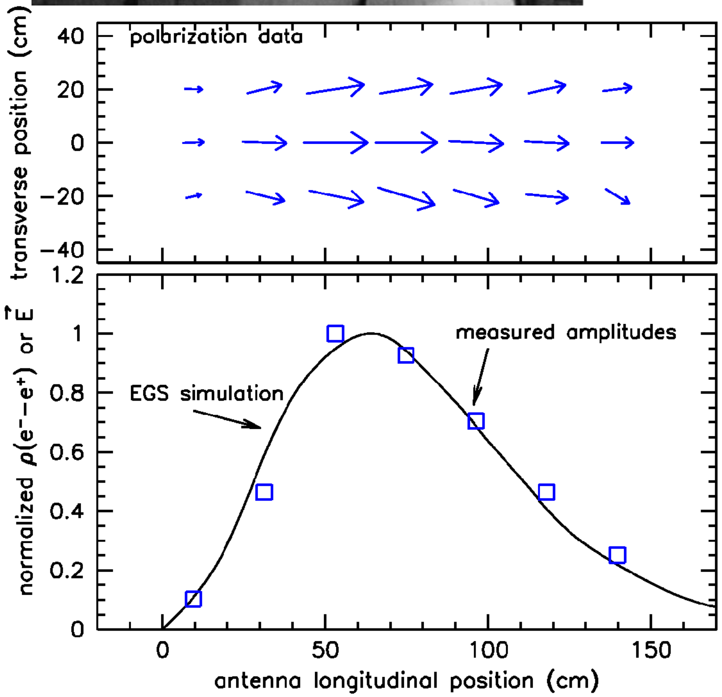
Radio Cerenkov : Test Beam

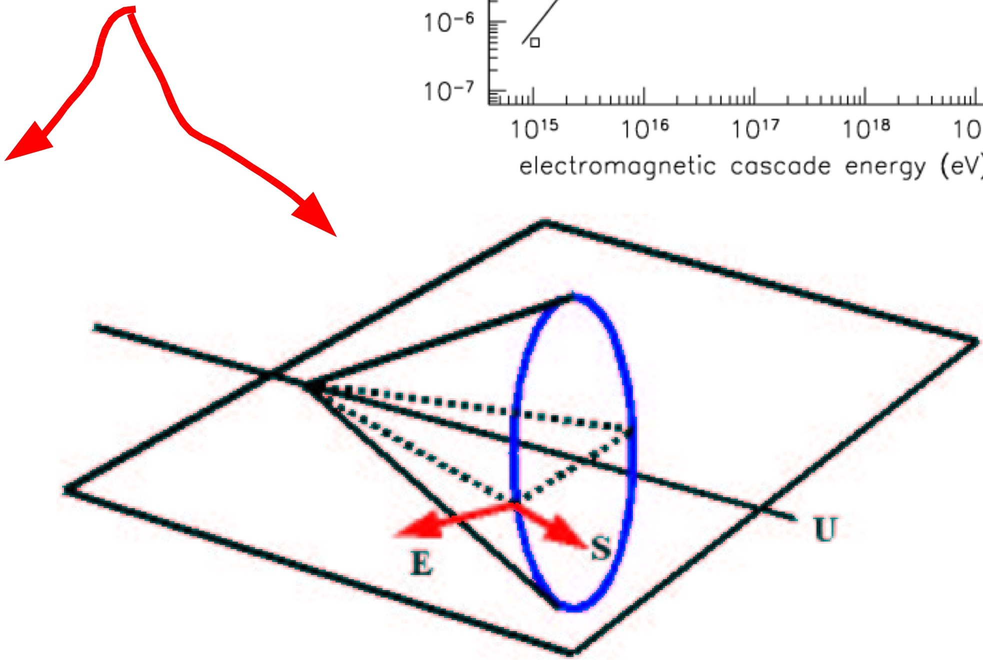
Gorham et al. (2004)

Target : SALT

- Radiation properties
  - polarisation ✔
  - speed ✔
  - long. profile ✔

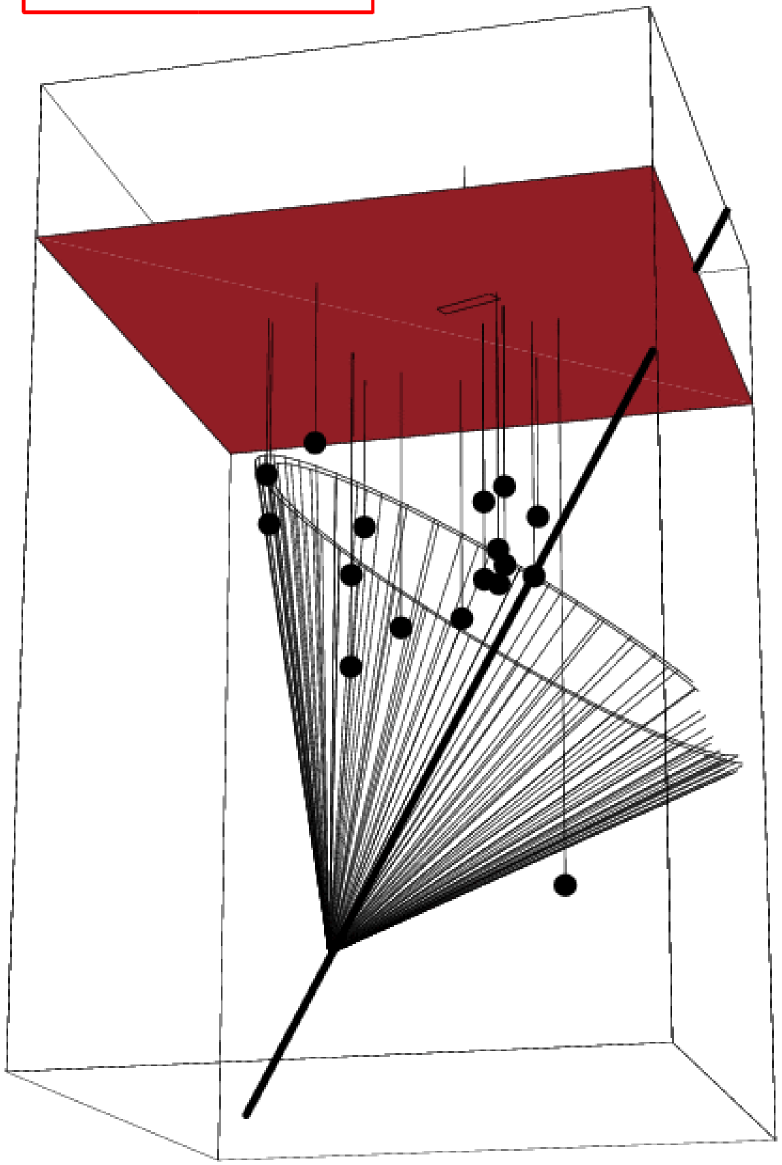




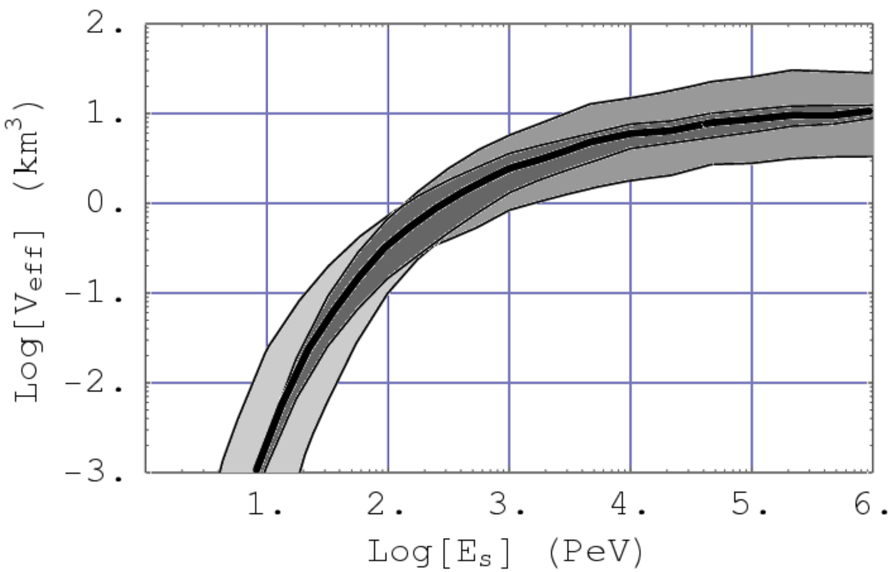


Radio **I**ce **C**erenkov **E**xperiment

Kravchenko et al. (2004)

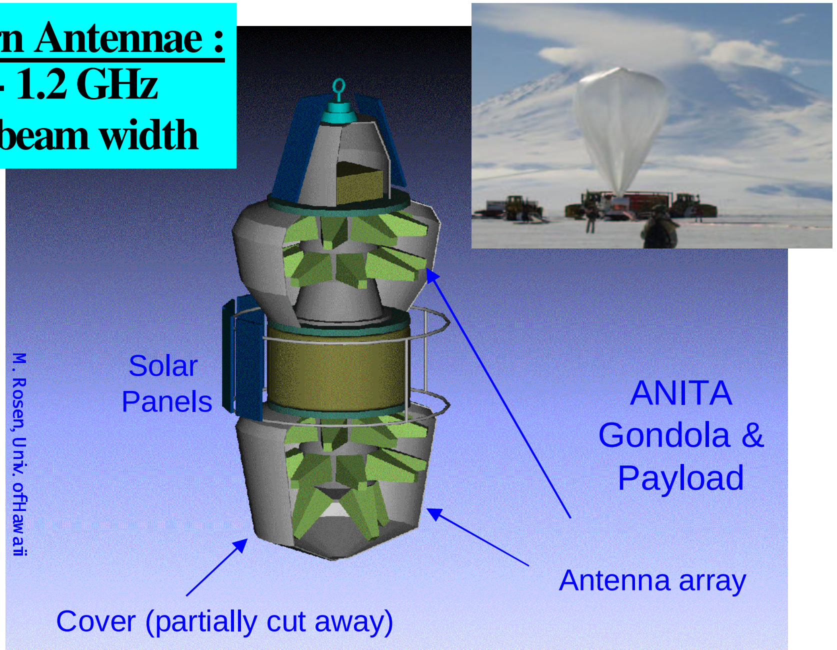


- 20 dipole receivers in South Polar ice.
- Scattered within 200m × 200m × 200m cube.
- Threshold ~ **10^{16} eV**
- Effective volume ~ **1 km^3 @ 10^{18} eV**
- Anthropogenic noise reduction through event reconstruction.
- Refractive effects measured in situ.
- Attenuation length > array size.
- Currently sets the best limits on neutrino fluxes at GZK energies.

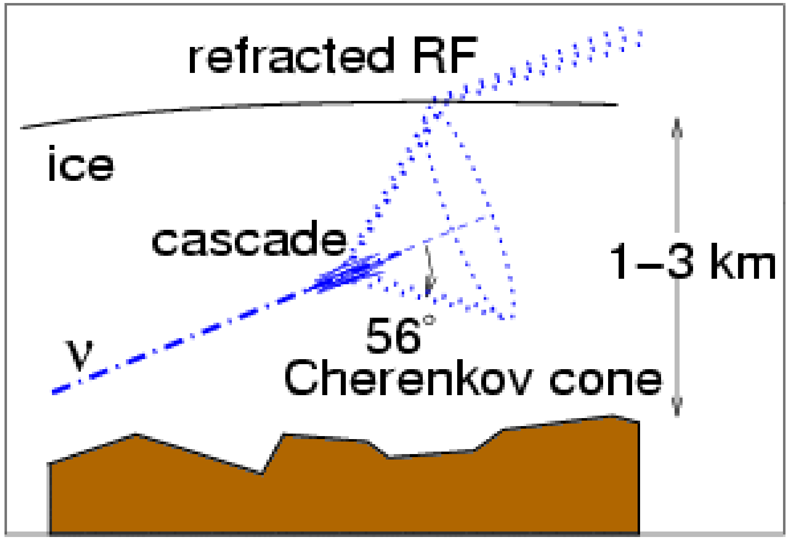


ANtarctic Impulsive Transient Antenna

Horn Antennae :
0.2 - 1.2 GHz
60° beam width



Barwick et al.



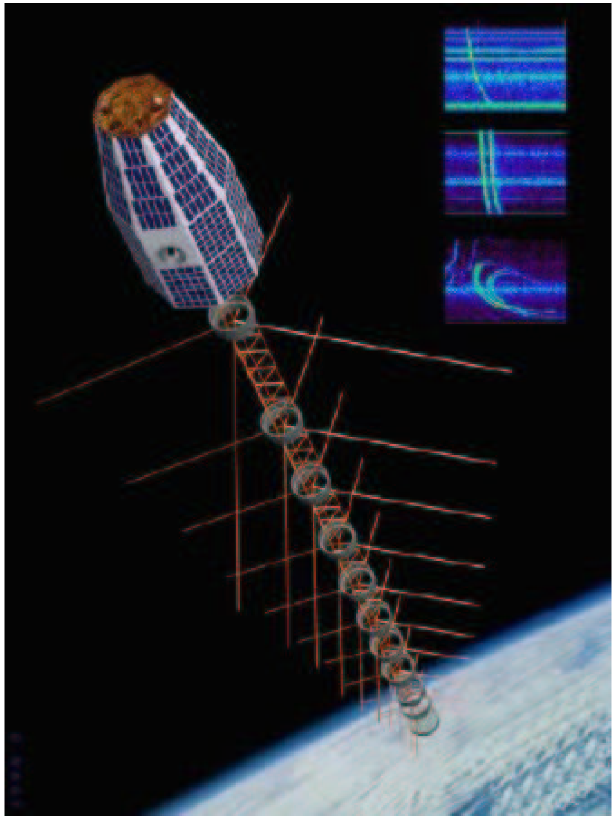
ANITA-LITE flew in 2003/2004 :

- Radio noise (solar, galactic, cosmic, thermal) understood.
- Impulsive backgrounds could be identified & rejected.
- Projections for ANITA resolutions (~0.5° zenith angle) are realistic.
- Other measurements indicate $\lambda_{ATTEN.}$ **> 1 km**.

Fast **O**n-orbit **R**ecording of **T**ransient **E**vents

Lehtinen et al. (2003)

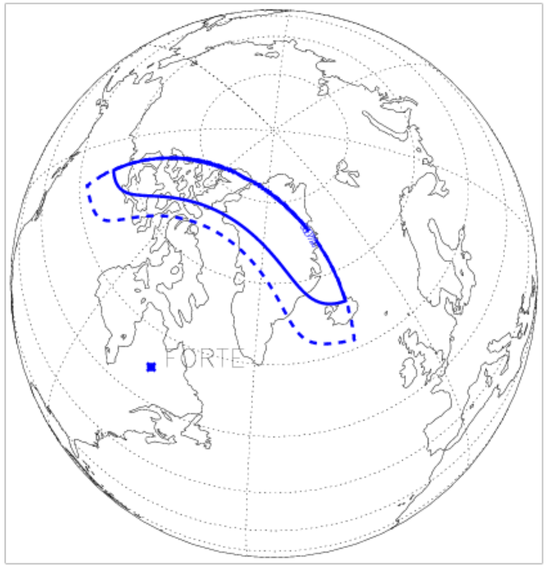
- Satellite radio antennae.
- 22 MHz bandwidth tunable [20-300 MHz]
- Search for impulsive events originating in Greenland ice.
- Very high threshold : **10^{13} GeV**
- Few day effective exposure (now defunct)

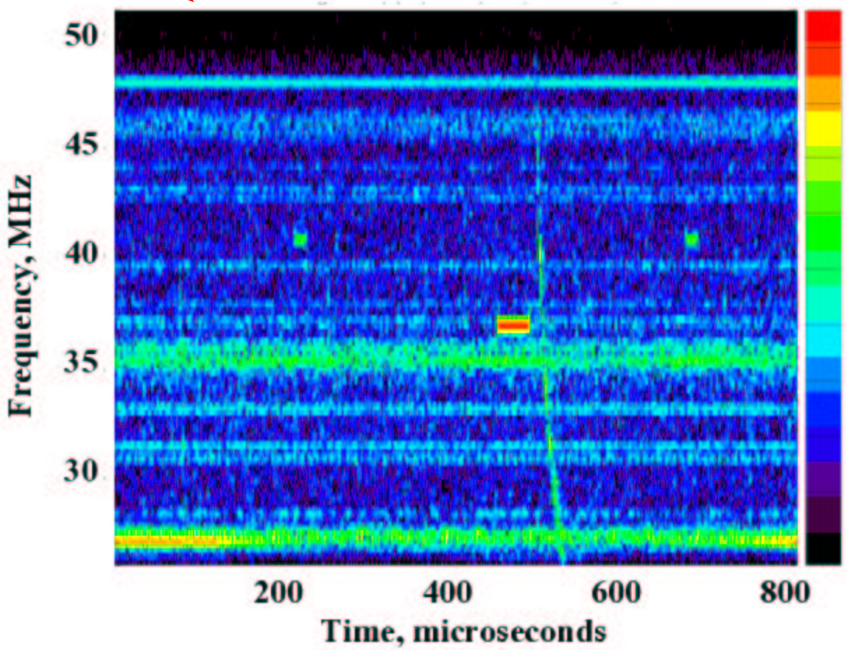


ν-candidate

Backgrounds :

- lightening
- anthropogenic

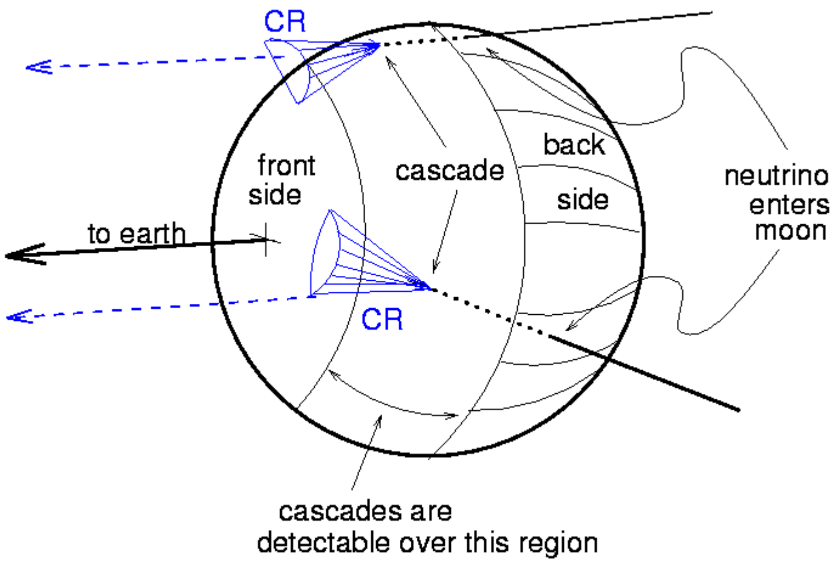


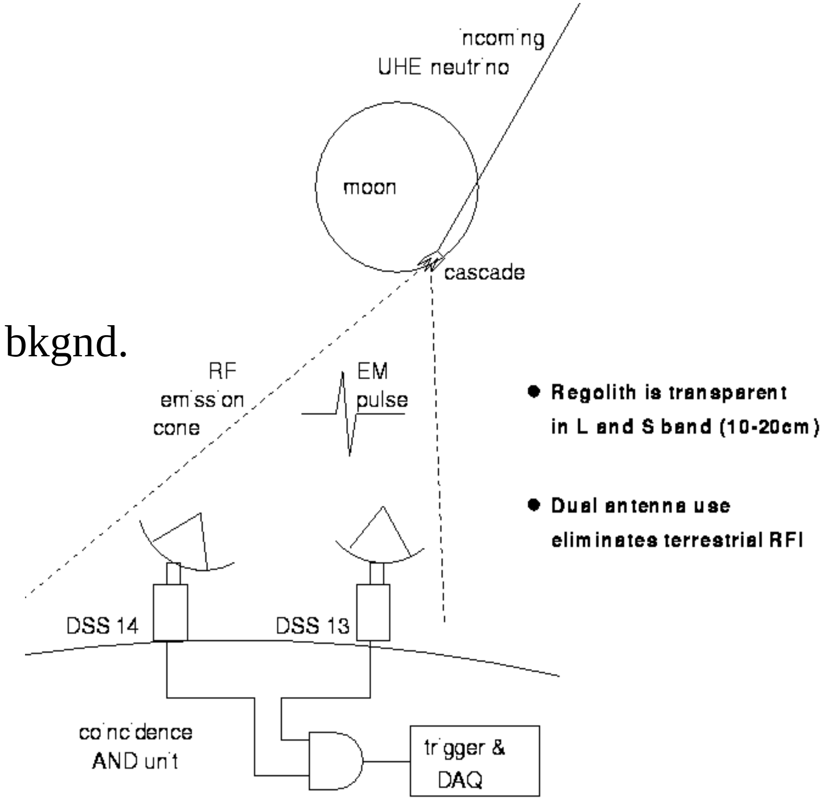


Goldstone Lunar Ultra-high energy neutrino Experiment

Gorham et al. (2003)

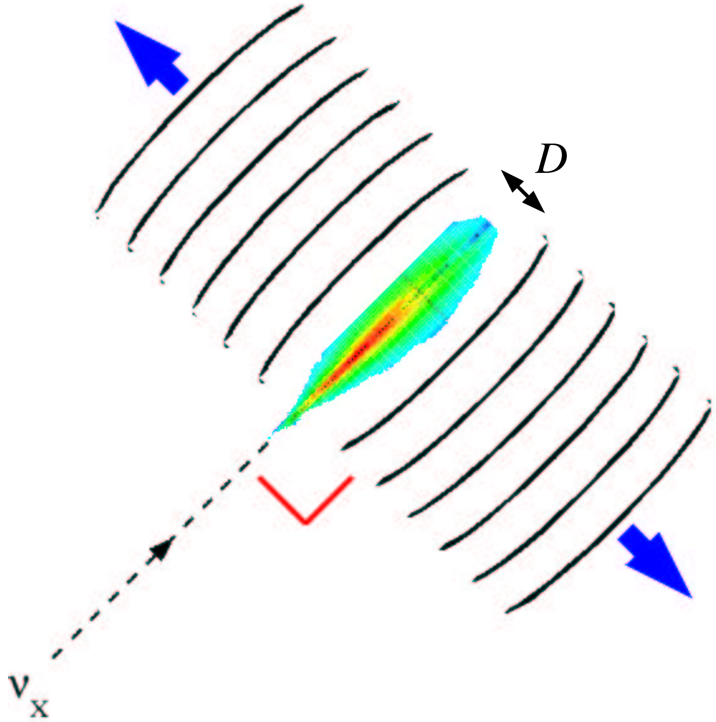
- Ground-based radio experiment.
- Detect radio emission from grazing ν's.
- Effective volume100,000 km^3 (!)
- Coincidence requirement removes anthropogenic bkgnd.
- High threshold : ~**10^{11} GeV**

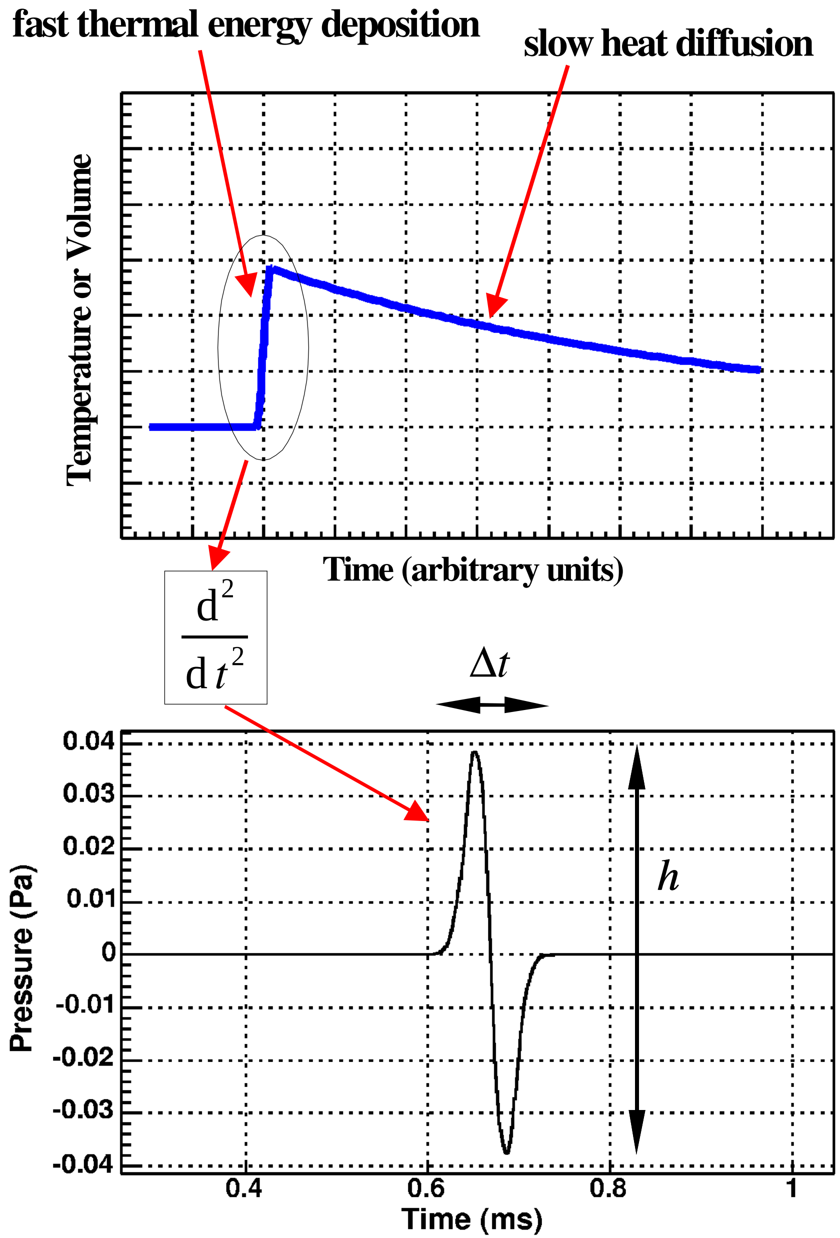




Acoustic

- Mechanism first described by Askaryan (1957) : "Hydrodynamical emission of tracks of ionising particles in stable liquids".





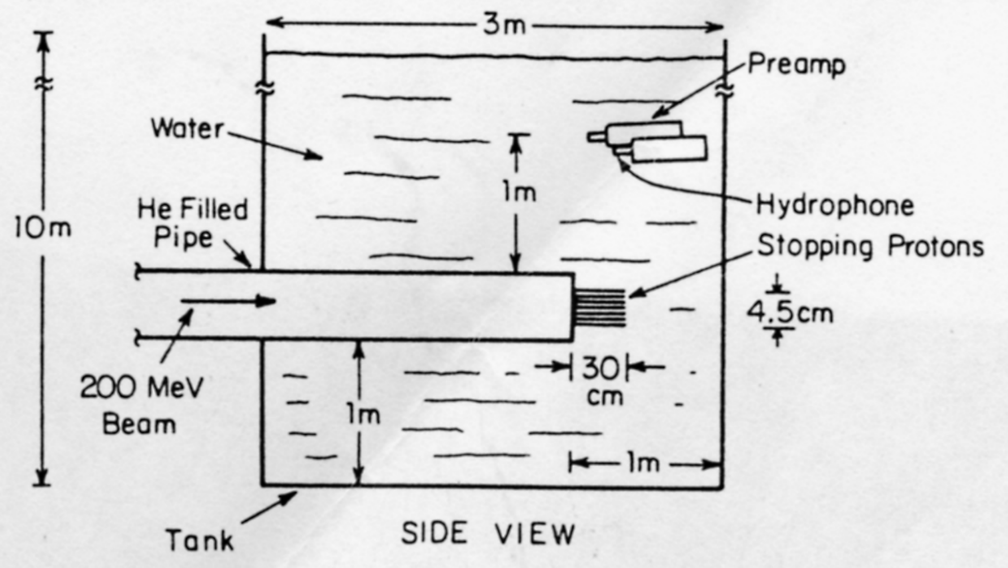
$f \propto 1/\Delta t \propto c/D$ (10-20 kHz for water)

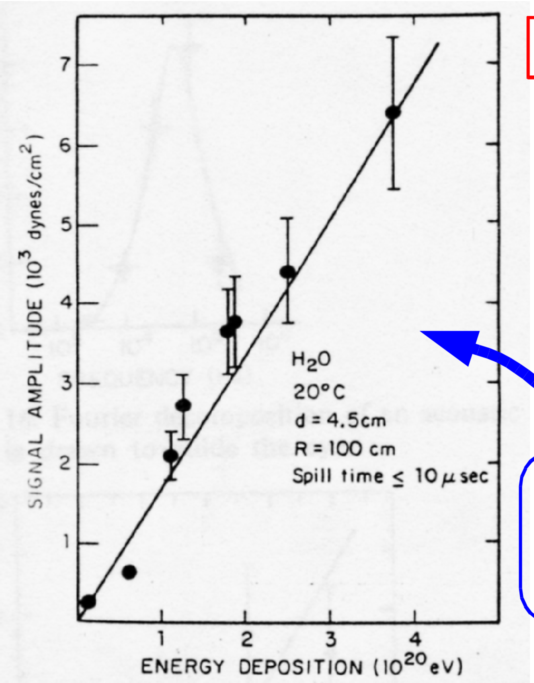
$h \propto \beta/C_P$:

β = coefficient of thermal expansivity

C_P = specific heat capacity

Acoustic : Test Beam





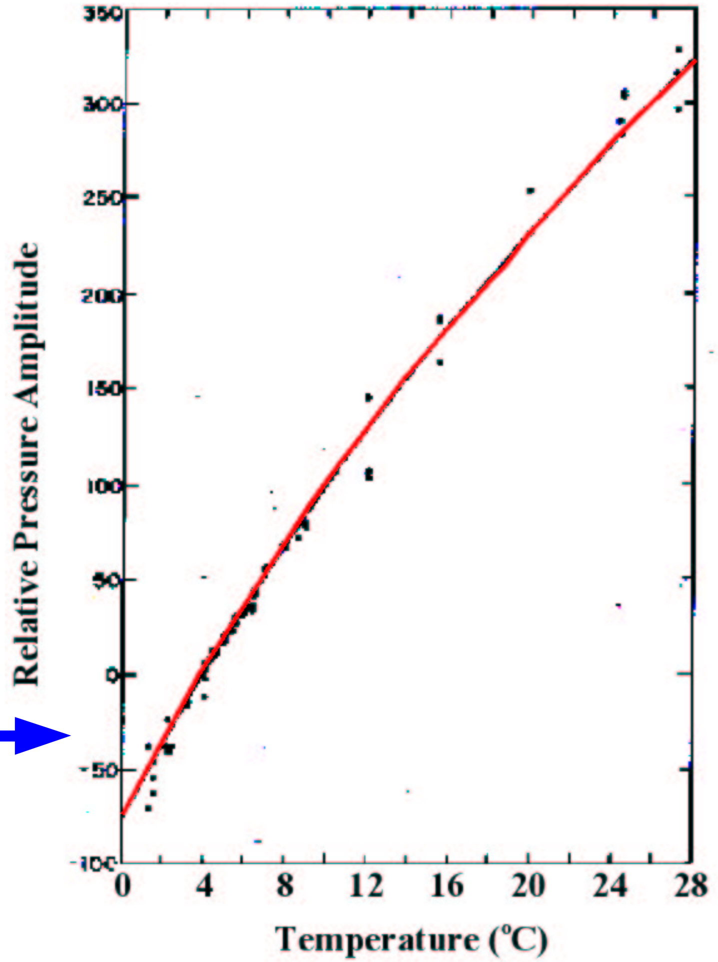
Sulak et al. (1979)

$P \propto \beta(T)$

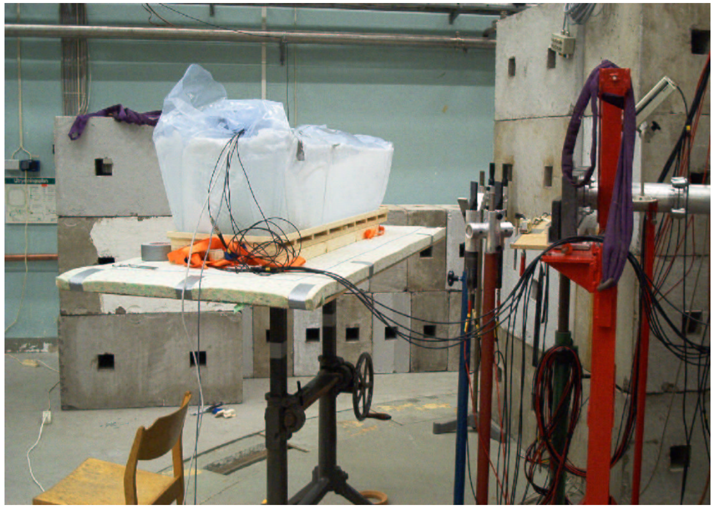
THERMO-ACOUSTIC ORIGIN

$\text{Pressure} \propto E_{\text{shower}}$

COHERENCE

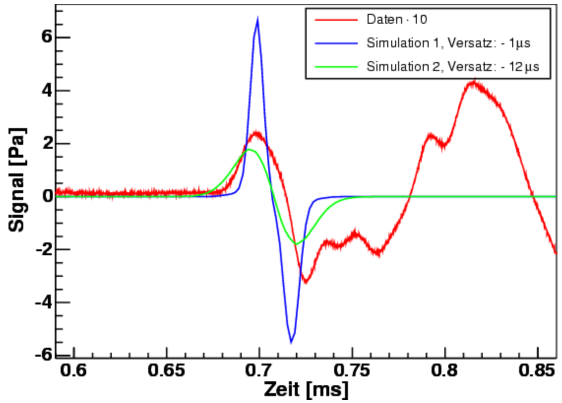


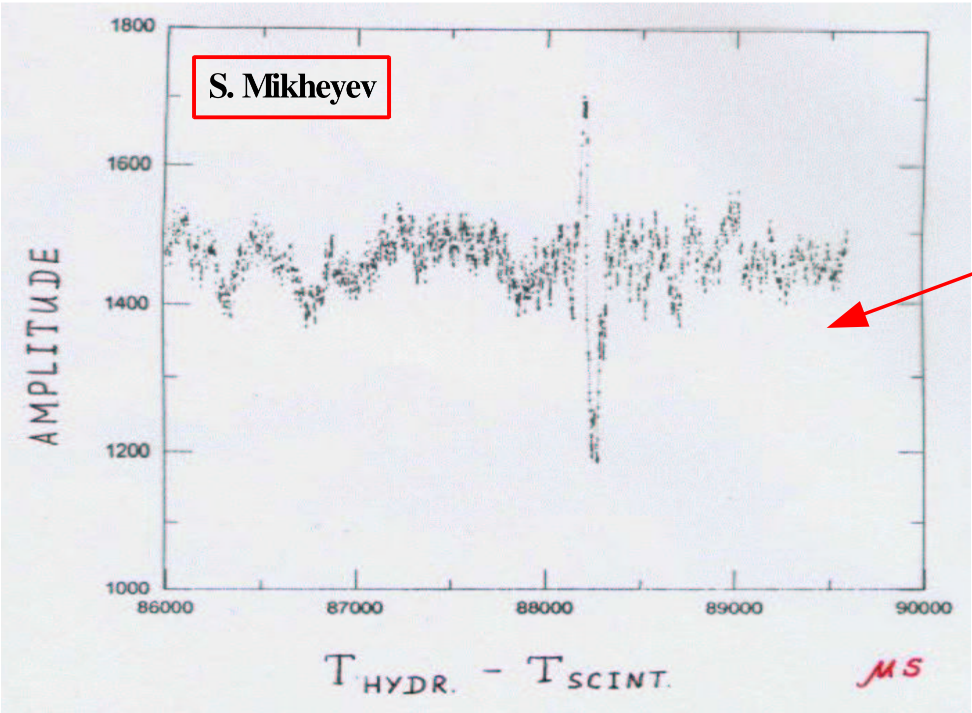
Acoustic : Recent R&D



Acoustic test-beam work : [Erlangen, Zeuthen]

- Proton beams & lasers in ice & water.
- Thermo-acoustic mechanism confirmed.
- Hydrophone response, reflections etc. complicate the picture.





Lake Baikal acoustic tests :

- Signal-like bipolar pulses observed.
- Some hint of a correlation with EAS measurements in surface scintillator array.

Hydrophone tests : [Erlangen, Marseille, ...]

- Development of cheap receivers with characteristics optimised for neutrino detection.

Acoustic Media : Comparison

Acoustic Figure-of-Merit $\frac{c^2\beta}{C_P} \times \rho\frac{dE}{dx}$

~ peak pressure ($\frac{c^2\beta}{C_P}$)

~ thermal energy density ($\rho\frac{dE}{dx}$)

c = *sound speed*

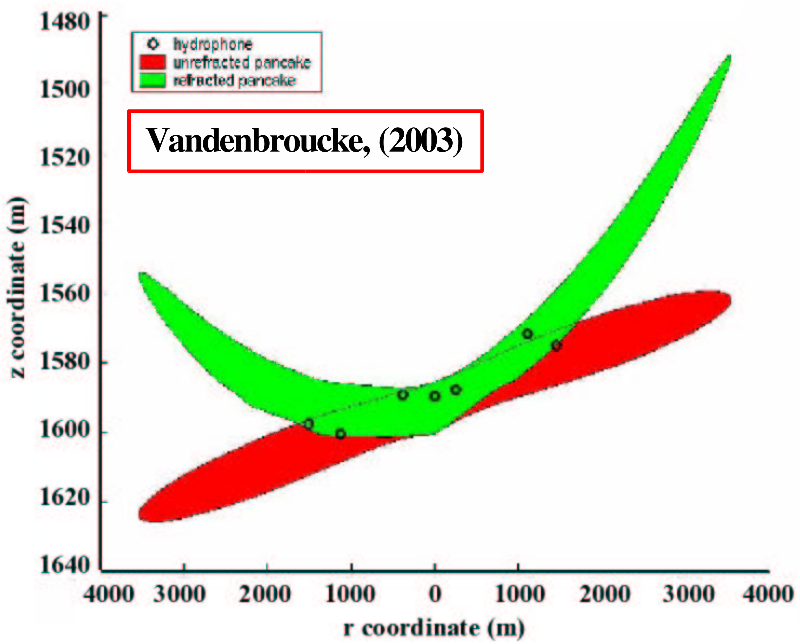
β = *coefficient of thermal expansivity*

C_P = *specific heat capacity*

ρ = *density*

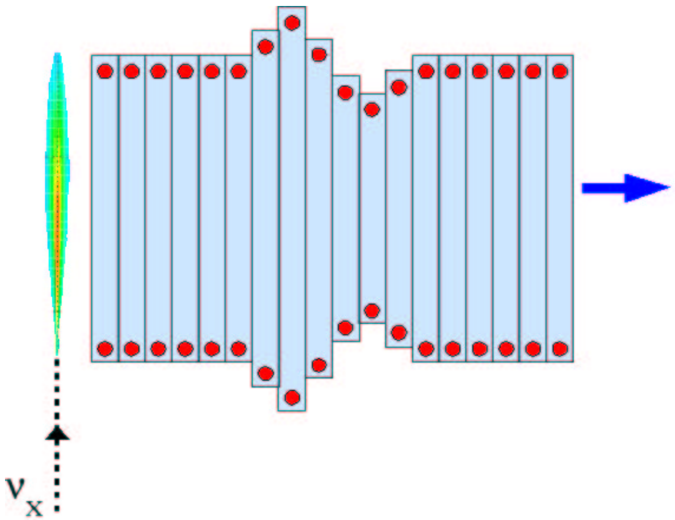
$\frac{dE}{dx}$ = *ionisation energy loss*

	FoM (relative)	Attenuation Length	Scattering Length	Noisy ?
Water	1	~ 10 km	N/A	Yes
Ice	~ 5-10	? (large)	? (large at depth)	? (creaking)
Salt	~ 100	? (large)	?	No



Refractive effects in water :

- Significantly complicates (compromises ?) acoustic reconstruction.
- May make the deep oceans very quiet.



Shear wave modes in solids

$$v_{\text{shear}} \sim \frac{1}{2} \times v_{\text{compression}}$$

$\Rightarrow$ Ranging

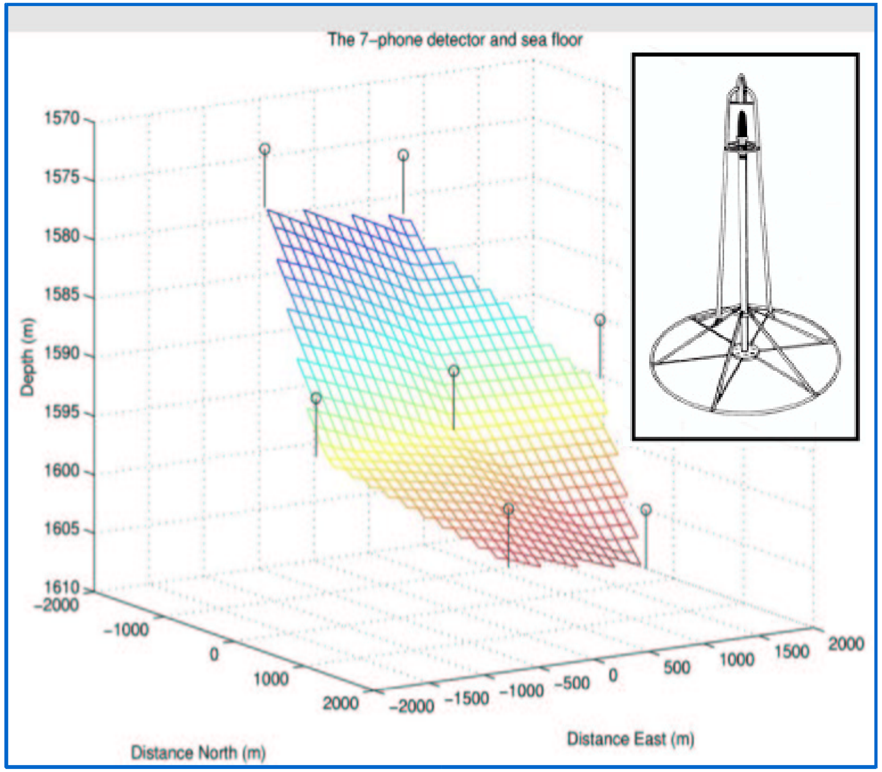
Practical considerations :

- existing infrastructure
- receiver technology
- acoustic characterisation

are *far* more advanced for water than any other medium.

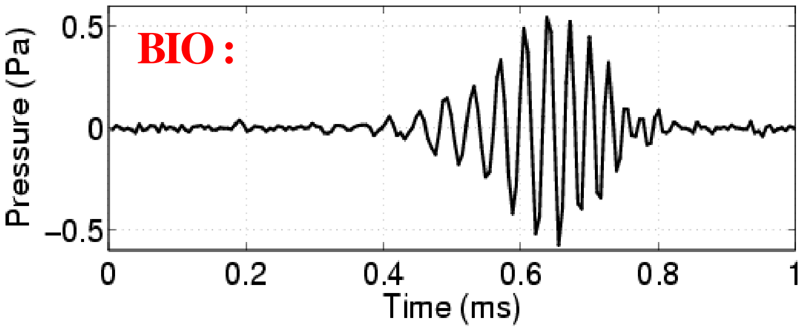
Study of Acoustic Ultrahigh-energy Neutrino Detection

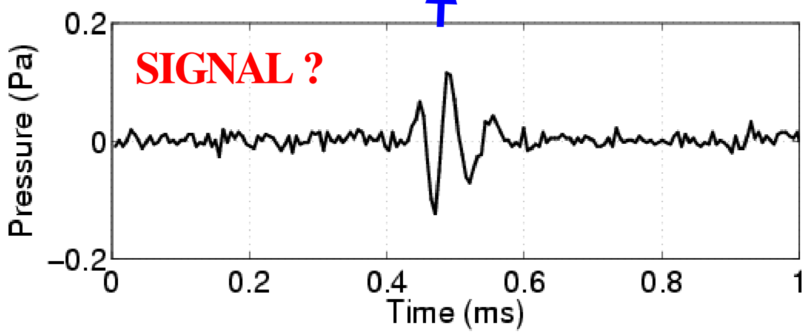
Vandenbroucke et al. (2004)

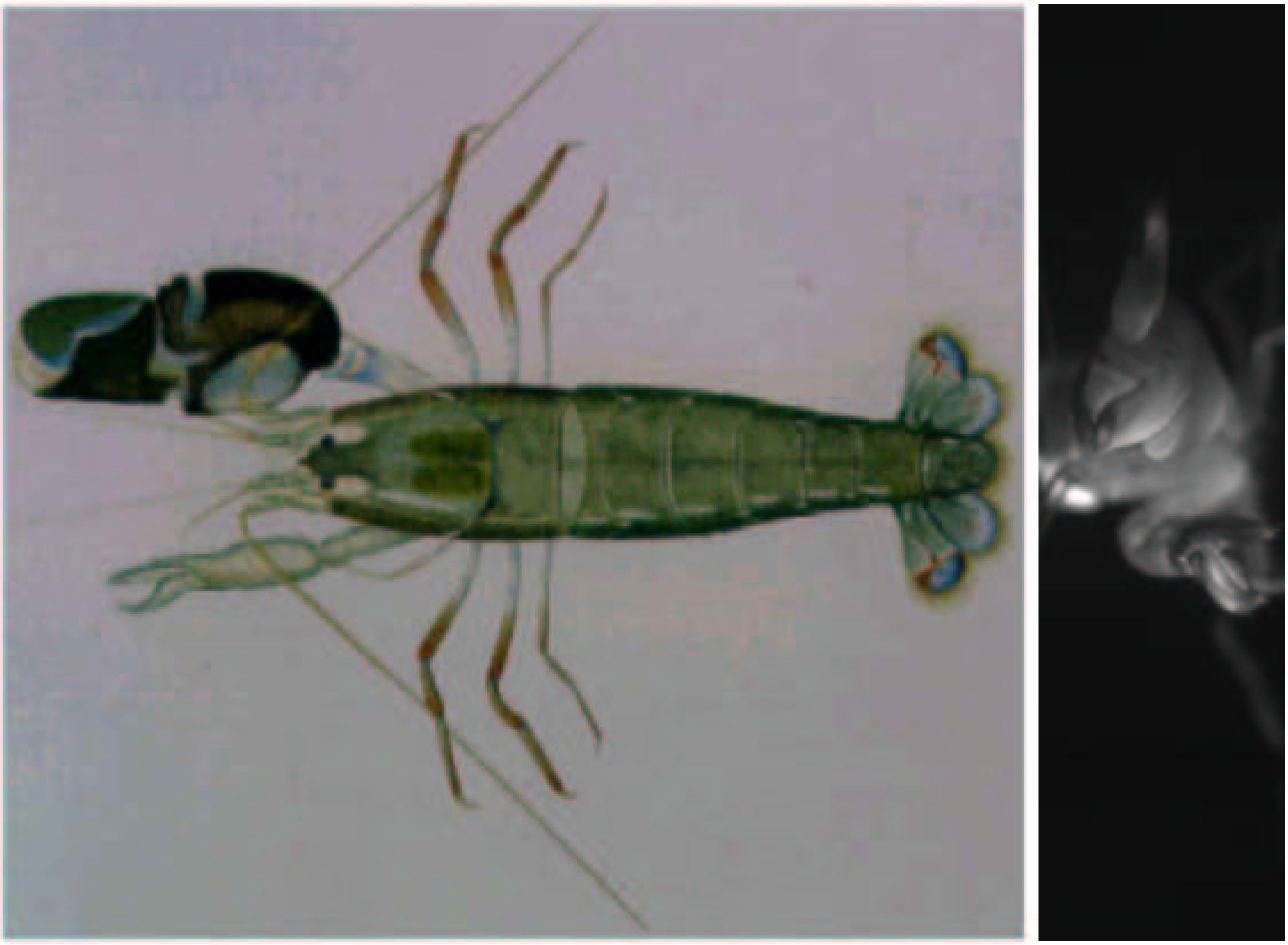


- 7 hydrophones in a larger US navy array instrumented with 180 kHz ADC's.
- Warm water : expansive but noisy :

Need well calibrated phase response

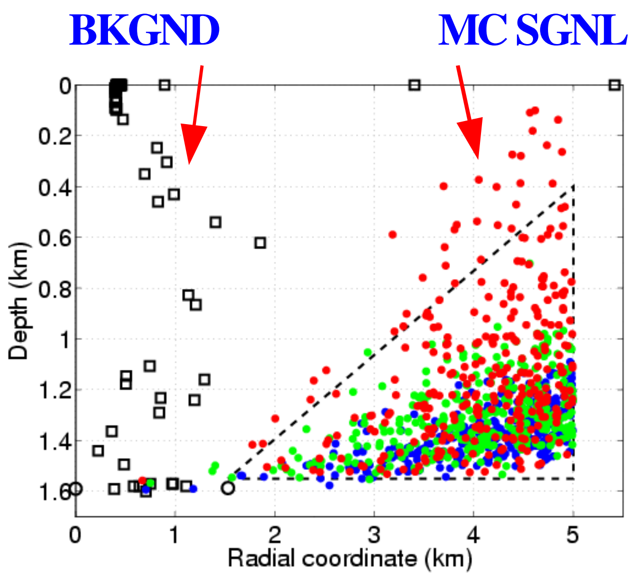




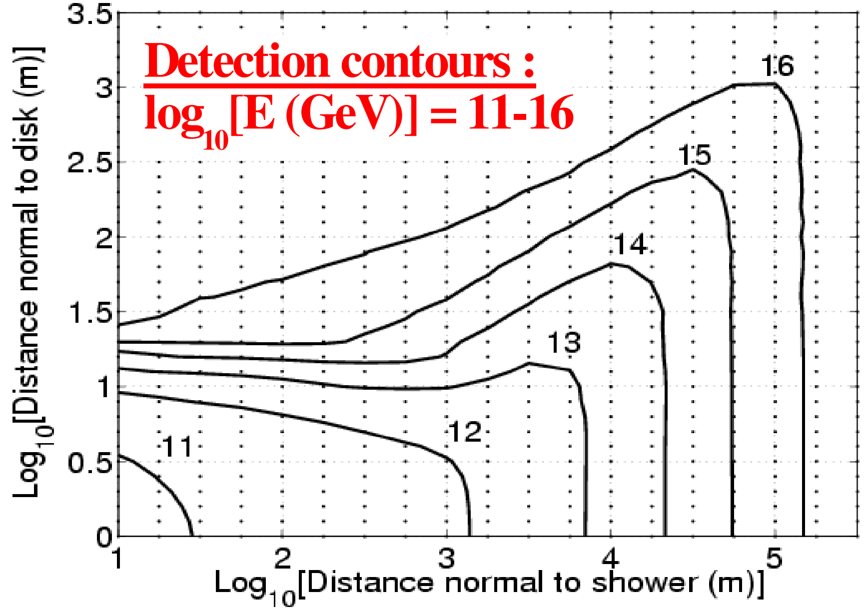


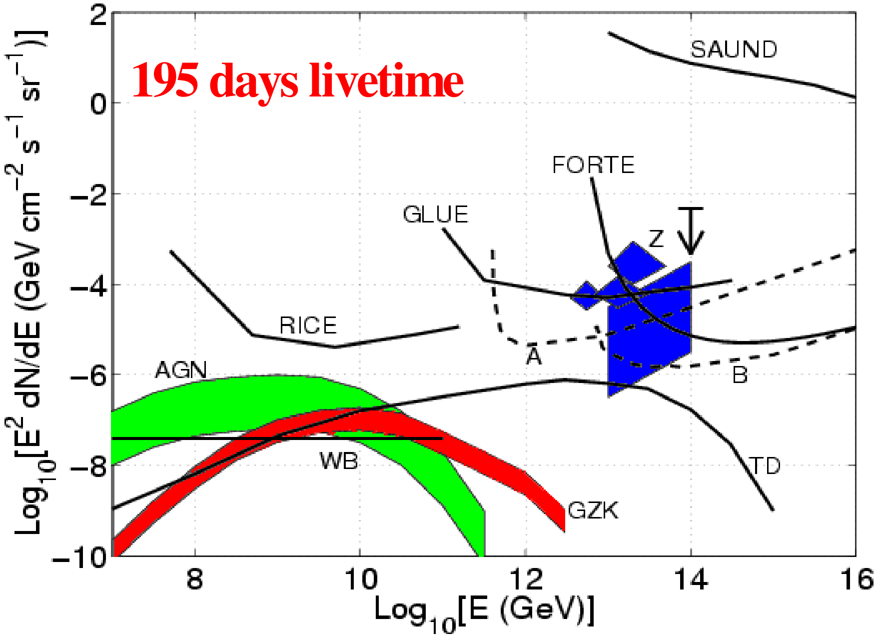
Study of Acoustic Ultrahigh-energy Neutrino Detection

- Multi-phone coincidence requirements and fiducial volume cuts remove the remaining multi-polar background.

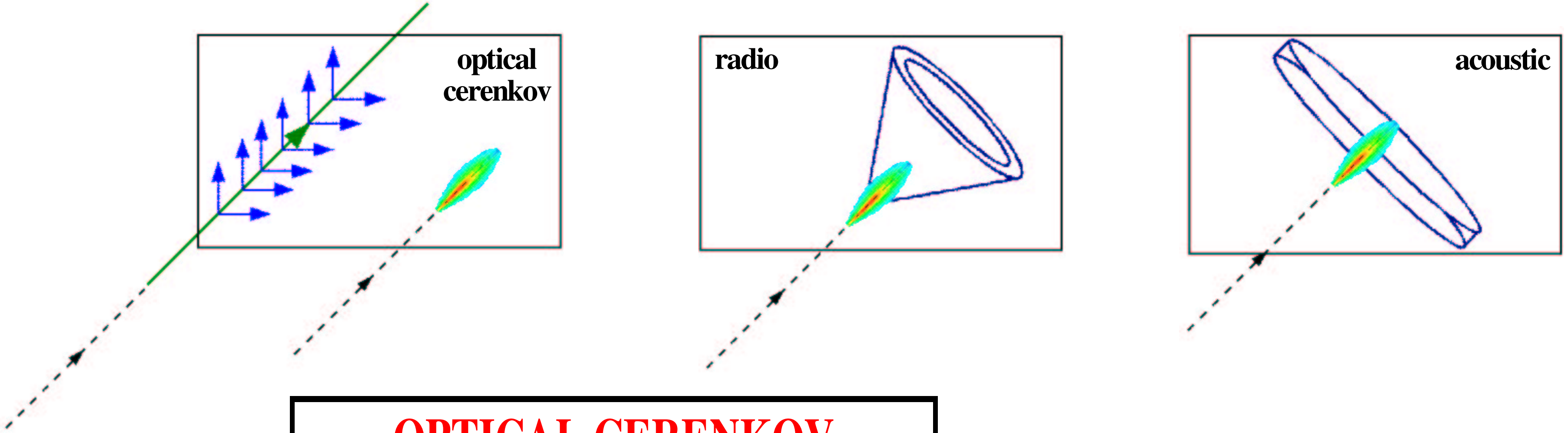


- Thresholds too high – small effective volumes at GZK energies.
- Fundamental limits (hydrophone sensitivity, noise floors) ***not*** yet reached.
- A lot of scope for :
  - finding quieter ocean volumes
  - optimal hydrophone arrangement
  - far larger hydrophone arrays



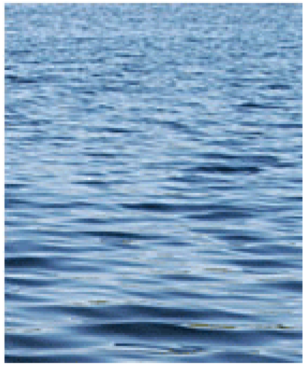


Detection Techniqes : Overview



	OPTICAL CERENKOV			
	MUON	CASCADE	RADIO	ACOUSTIC
Type	tracking	calorimetric	calorimetric	calorimetric
Channels	$\nu_\mu\ CC$	$\nu_X\ \ NC + CC$	$\nu_X\ \ NC + CC$	$\nu_X\ \ NC + CC$
Energy Dependence	$E_\mu \propto E_\nu$	$E_{\mathrm{cascade}} \propto E_\nu$	$E_{\mathrm{radio}} \propto E_\nu^2$	$E_{\mathrm{acoustic}} \propto E_\nu^2$
Effective Volume	$V_{\mathrm{eff}} \propto E_\nu$	$V_{\mathrm{eff}} \approx$ fixed	$V_{\mathrm{eff}} \propto E_\nu^3$	$V_{\mathrm{eff}} \propto E_\nu^{2-3}$

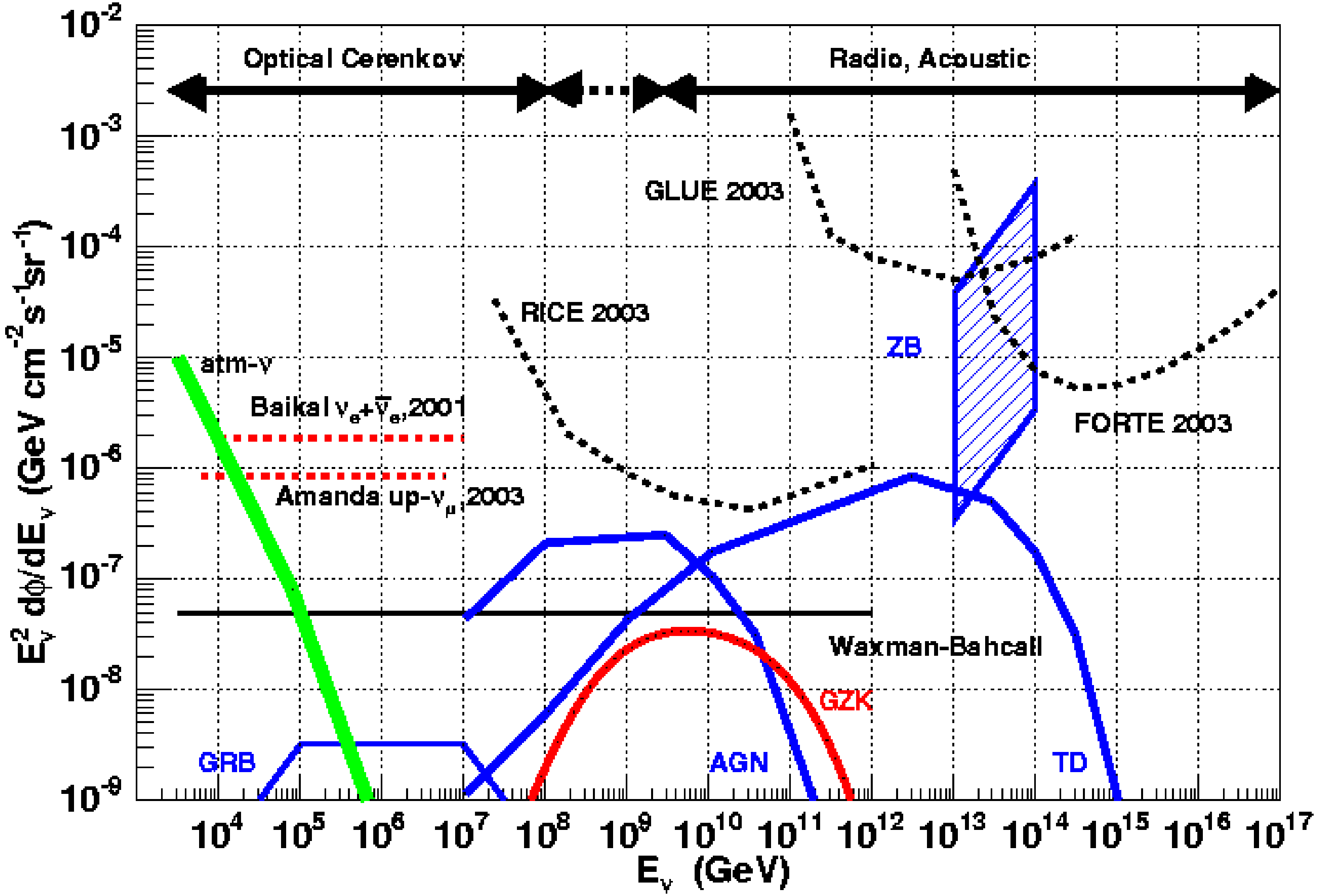
Target Media : Overview



† : ρ(NaCL) ~ 2 × ρ(H_2O)

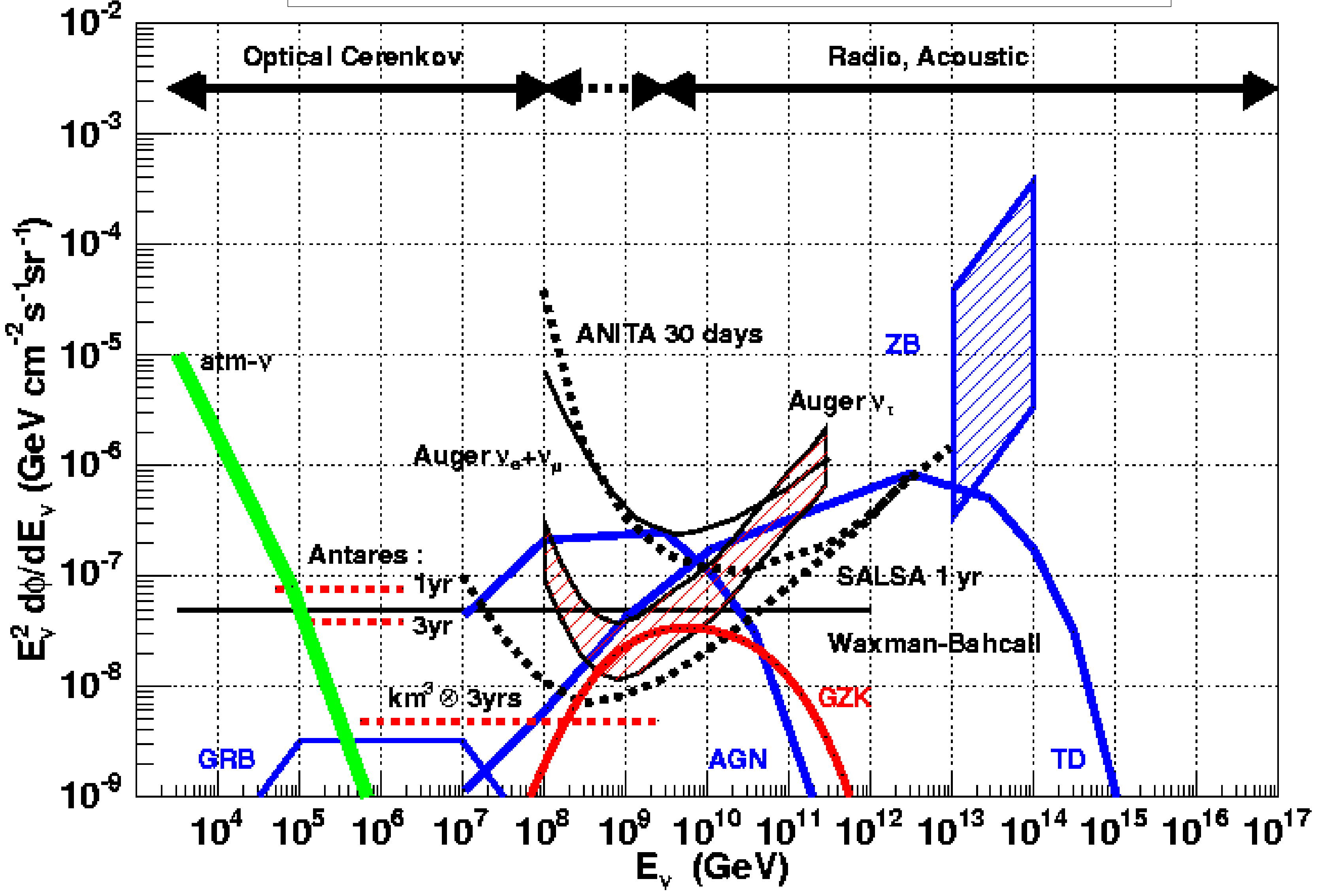
	Attenuation Length		
	water	ice	salt†
EM optical (Cerenkov)	~ 50 m	~ 100 m	?!?!
EM radio (0.1-1.0 GHz)	~ 0	~ few km	~ 1 km
Acoustic (10 kHz)	~ 10 km	? (large)	? (large)

Some Existing Limits



Some Future Limits

GZK : ICE3 (few/year) SALSA (few 10's / year)



Summary

- Neutrino astronomy holds the promise of :
  - opening a new observational window on the universe at very high energies & distances.
  - telling us about fundamental physics at very high energy scales.
- **Optical** Cerenkov detectors are the only ones so far constructed that have unambiguously detected (atmospheric) neutrino signals.
- **Radio** detection has been demonstrated in the lab and in first generation experiments. It is the most promising technique for discovering a GZK flux of neutrinos.
- **Acoustic** detection is less well advanced but holds out much promise due to potentially vast detection volumes.
- EAS detectors – especially Auger – will be viable neutrino detectors.
- Many very interesting experiments on the horizon ➡ **Lee**