Prospects for the detection of high energy neutrinos

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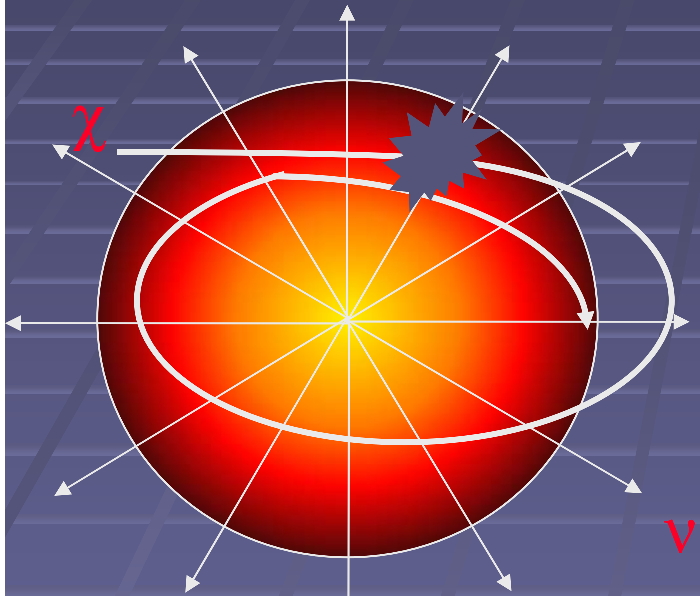
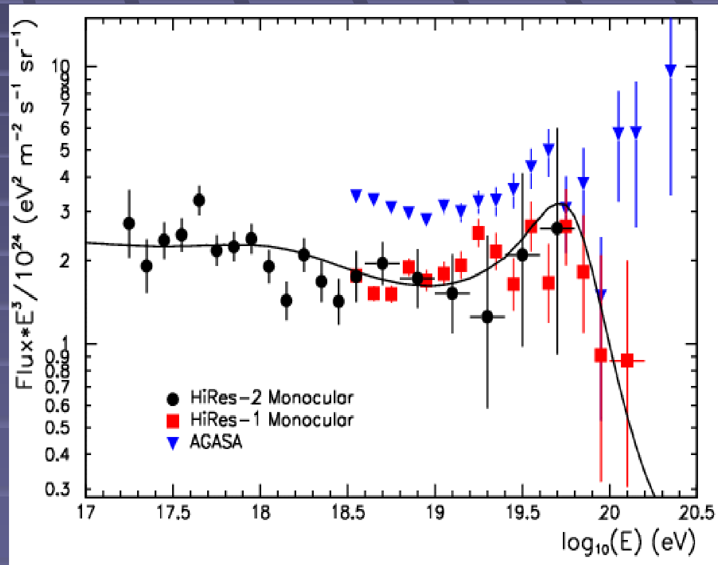
University of Sheffield

Cosmic Particles Workshop
Cosenor's House, Abingdon
18th-20th February 2005

Scientific Programme

>>> Energy >>>





10 GeV | 1 TeV | 10 PeV | 10 ZeV

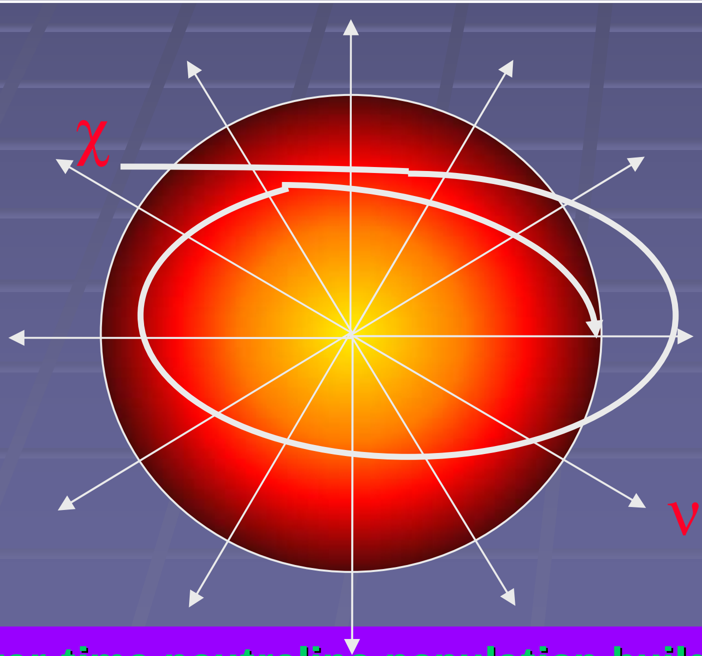
Search for neutralinos via their self-annihilation to products containing neutrinos at the centre of the Earth, Sun and Galaxy

Observation of high-energy neutrinos from (extra-)galactic astrophysical sources such as AGN, SNR, GRB, etc.

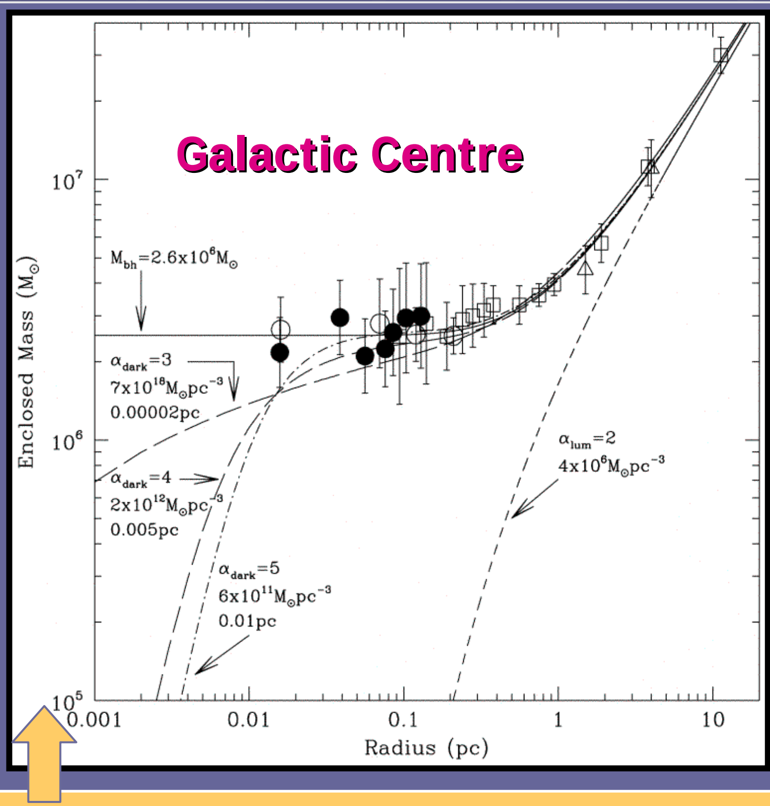
Search for UHE neutrinos from cosmogenic and other possible sources

Indirect Dark Matter Detection

- WIMPs (Neutralinos) become gravitationally trapped in the cores of massive astrophysical objects
- *Neutralinos self-annihilate into fermions or combinations of gauge and Higgs bosons*
- Subsequent decays of c,b and t quarks, τ leptons and Z, W and Higgs bosons can produce a significant flux of high-energy neutrinos.



Sun: over time neutralino population builds up at the core to an equilibrium value



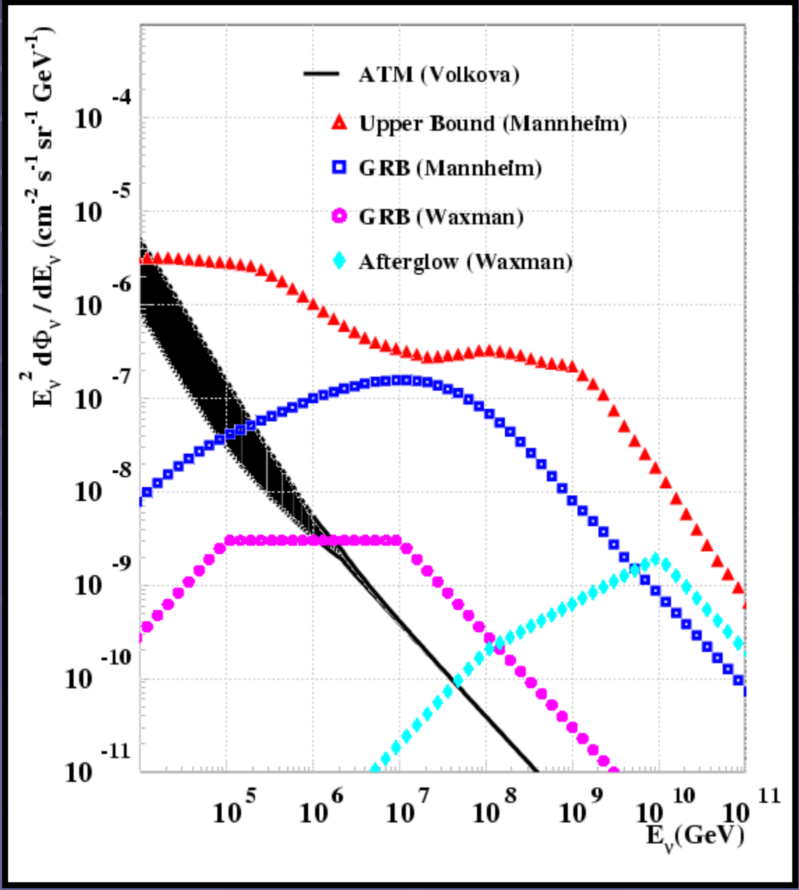
- **There is significant evidence for a 3 million Solar mass black hole at the centre of the galaxy**
- ***Some speculation that we will observe enhancements of neutrinos from neutralino annihilations***
- **Different BH formation models to be investigated**

Astrophysical Neutrinos

- **Galactic and extra-galactic high energy neutrinos are created in cosmic beam dumps**
- **Neutrino fluxes calculable by constraining the parameters of the "accelerator" via known cosmic ray and photon fluxes**
- **2 search strategies: point sources (EGRET, HESS, etc) and diffuse flux**

For example: GRBs

- Waxman-Bahcall, use fireball model, high energy neutrinos created via the photo-pion interaction ($p\gamma \rightarrow \pi \rightarrow \nu$)
- *WB flux gives of the order of a few events in an ANTARES size detector over a 5 year running period with essentially no background*
- There are many other theoretical models including neutron star merger, collapse of a massive star. "collapsar"
- *The latter gives appreciable neutrino fluxes (up to 10^3/km^2/year)*

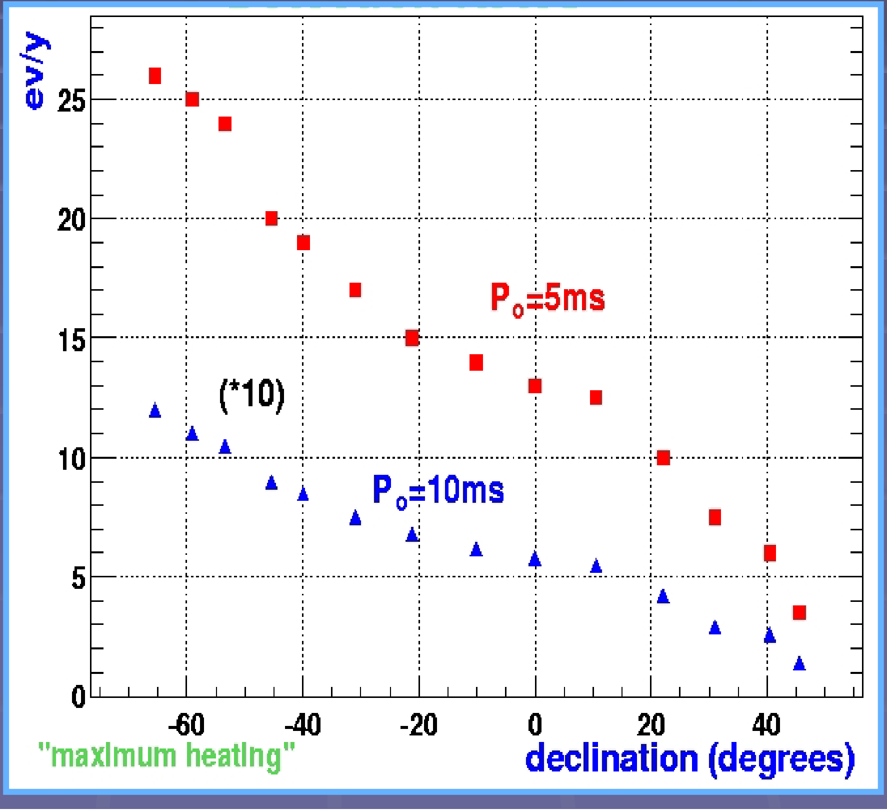


Galactic Sources

- Largest expected rates from galactic sources
- Promising candidates: young SNRs with fast rotating pulsar, magnetic field ~10^{12} G accelerating heavy ions (Protheroe, Bednarek, Luo, 1998) and microquasars (Distefano et al, 2002)

- Largest predictions: GX339-4 and SS433 180-250 ev/yr/km^2

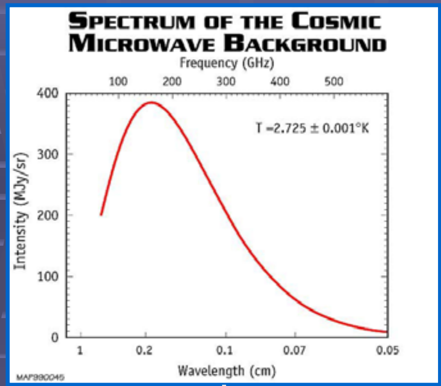
Expected rates in ANTARES
t=0.1 yr after SN explosion
depending on pulsar
rotation period

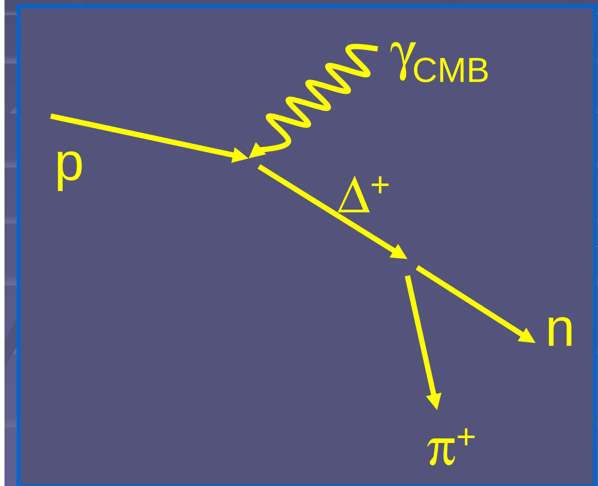


Models in Protheroe, Bednarek, Luo, 1998

UHE neutrinos (I)

- GZK threshold is approx. 5×10^{19} eV
- *Some pion production at lower proton energies due to HE tail of CMB spectrum*





Does the GZK cut-off exist?

YES

NO

The lack of a GZK cutoff poses problems for astrophysical explanations of UHECR
Need to invoke <u>New Physics</u>

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

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

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

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

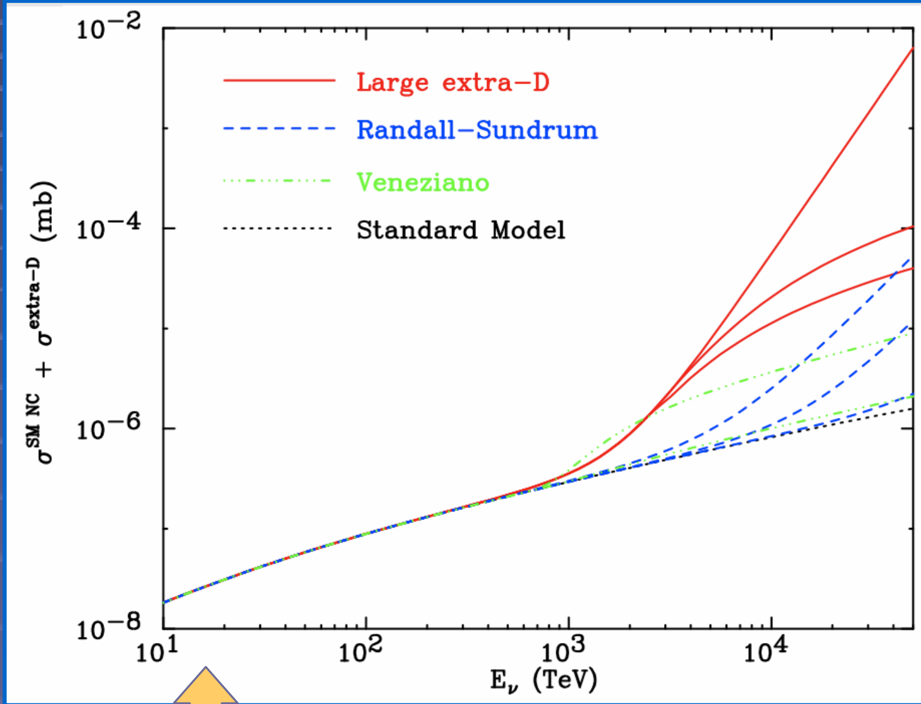
UHE neutrinos from proton interactions with the CMB

UHE neutrinos (II)

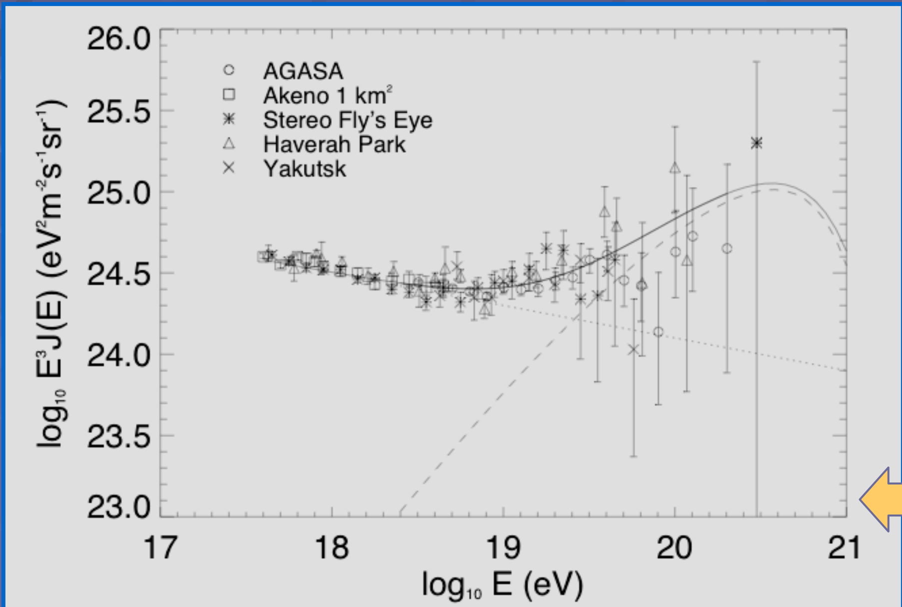
If trans-GZK cosmic rays do exist need some new physics to explain them

Most of these "solutions" predict enhanced fluxes of UHE neutrinos

- Strongly interacting neutrinos
- *New neutral primaries*
- Violation of Lorenz invariance
- *Decaying supermassive dark matter*

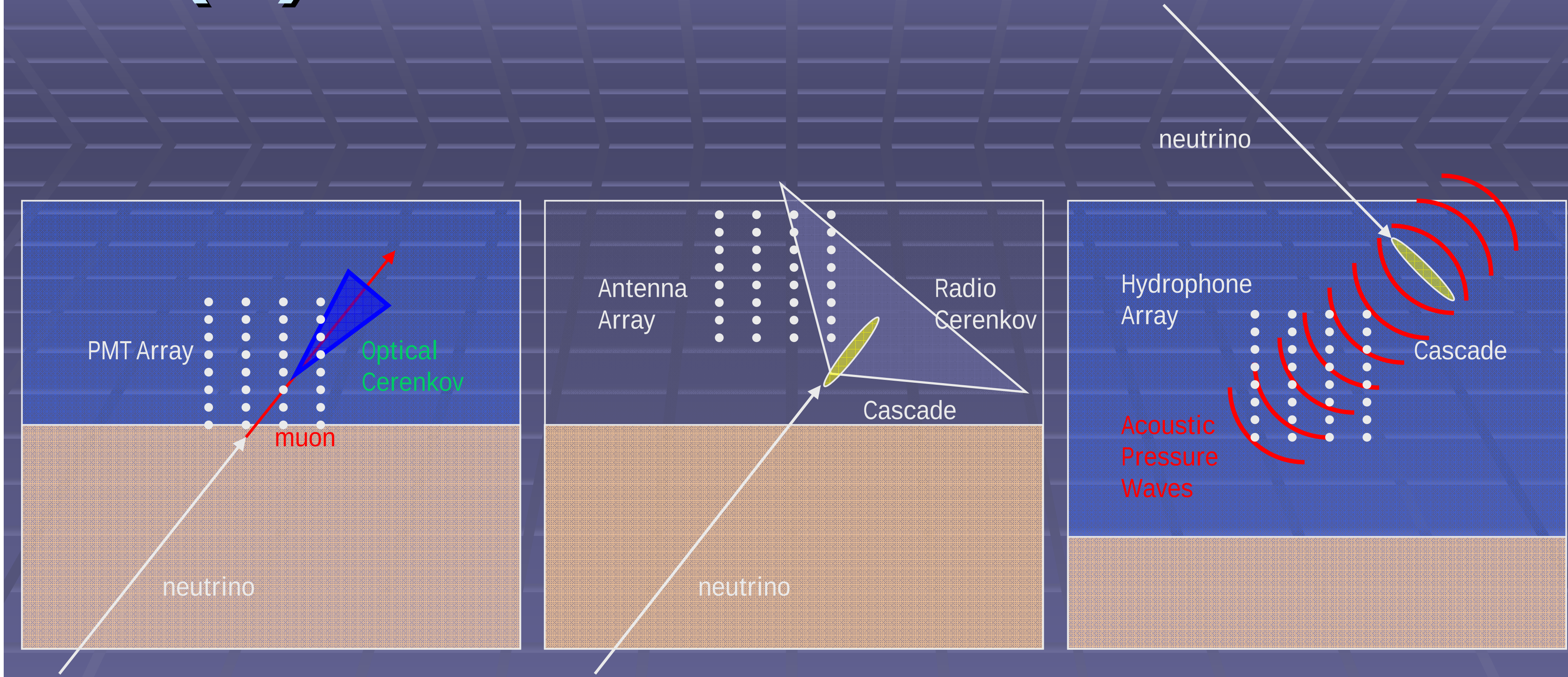


Neutrino-nucleon cross-sections for low-scale models of quantum gravity involving e.g. extra dimensions



Fit to the UHECR spectrum beyond the "ankle" with a decaying supermassive dark matter particle with $m=5\times10^{21}$eV (dashed line)

(U)HE ν Detection Methods



Optical Cerenkov

Works well in water, ice

Attenuation lengths of order 50m to 100m (blue light)

Most advanced technique

Radio Cerenkov

Long (order km) attenuation lengths in ice and salt

First generation experiments proposed

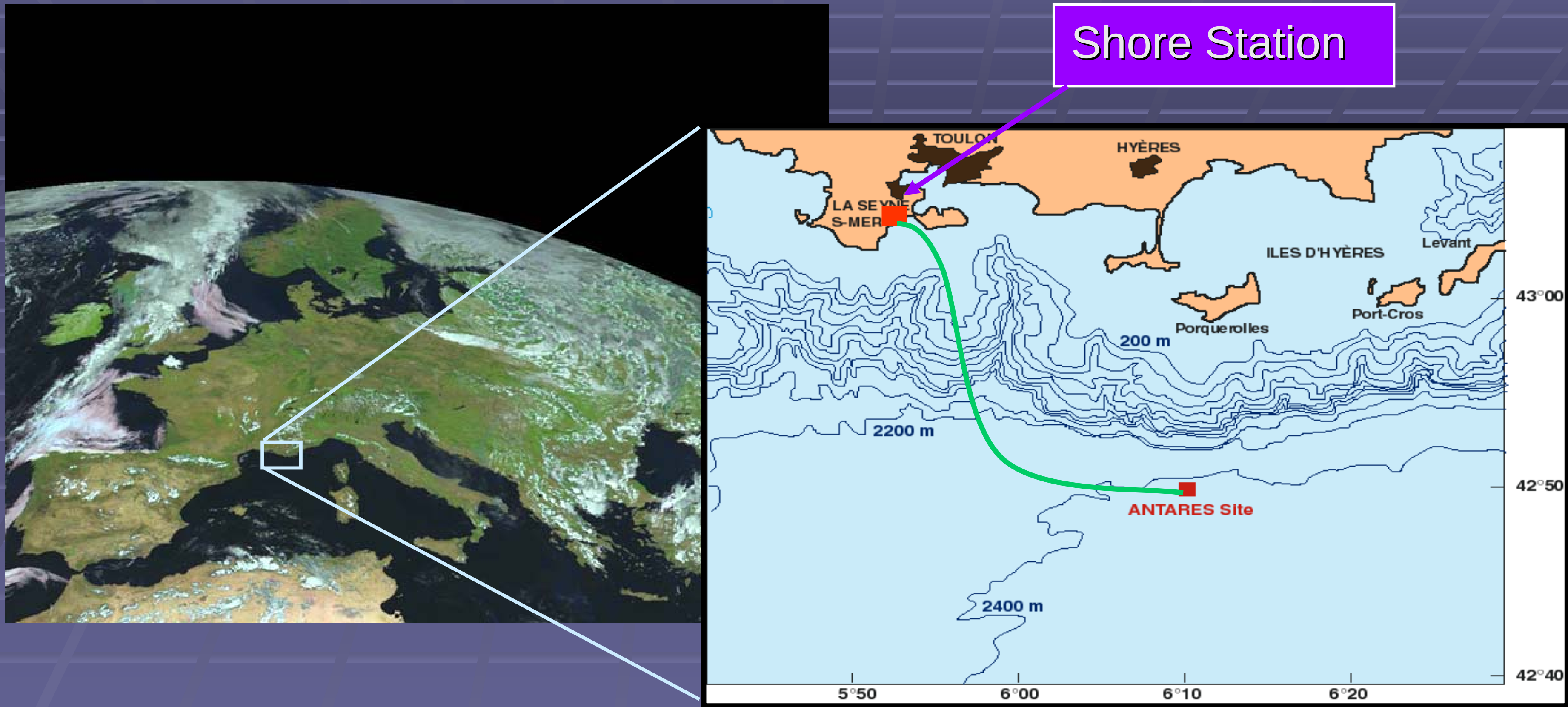
Acoustic Detection

Very long attenuation lengths in water (order 10km), ice and salt

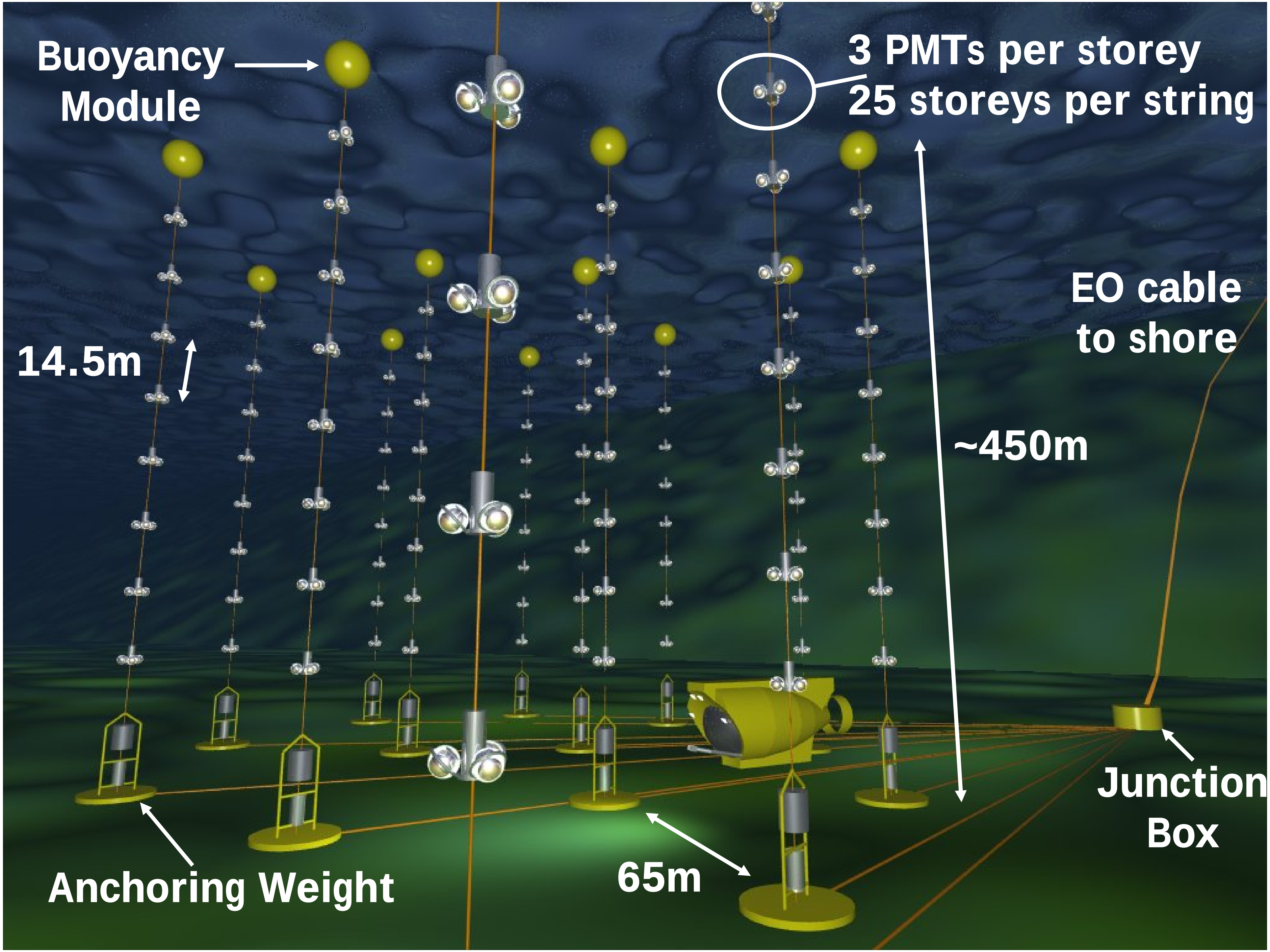
Huge effective volumes may be possible

Optical Cerenkov

ANTARES



- First generation neutrino telescope in Mediterranean Sea
- 2475m below sea level
- 30km off the coast of Toulon in Southern France - close enough to perform return trip and deployment in 1 day
- Deployment of strings will start in 2005, finish 2007


Buoyancy Module
3 PMTs per storey
25 storeys per string
EO cable to shore
14.5m
~450m
Junction Box
Anchoring Weight
65m

ANTARES Sky Coverage

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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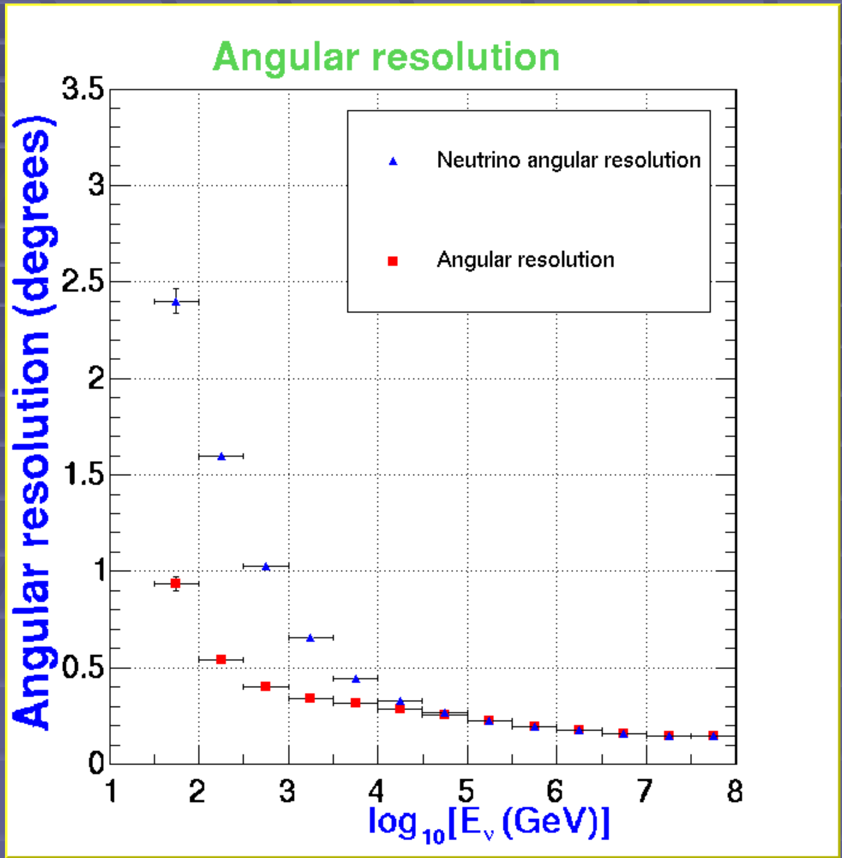
TIFF (Uncompressed) decompressor
are needed to see this picture.

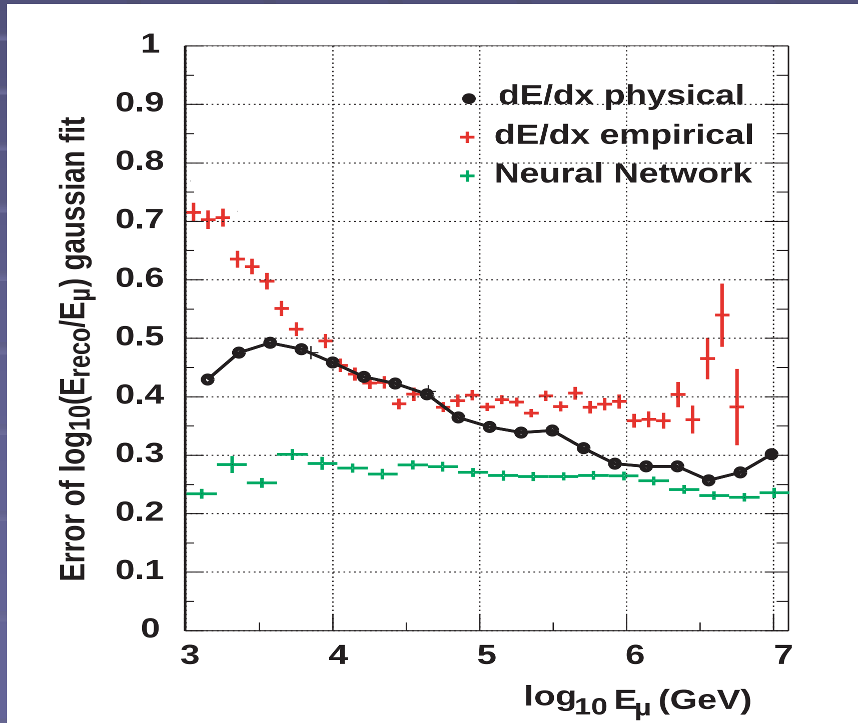
- ANTARES has 3.6π sr coverage
- *ANTARES-AMANDA overlap is 0.6π sr at any one time, 1.6π sr in total - good for systematic studies*
- Need neutrino telescopes in both hemispheres
- ***ANTARES will be the first neutrino telescope to probe the southern hemisphere sky including the Galactic Centre***
- ***Use GRB alerts***

ANTARES Performance

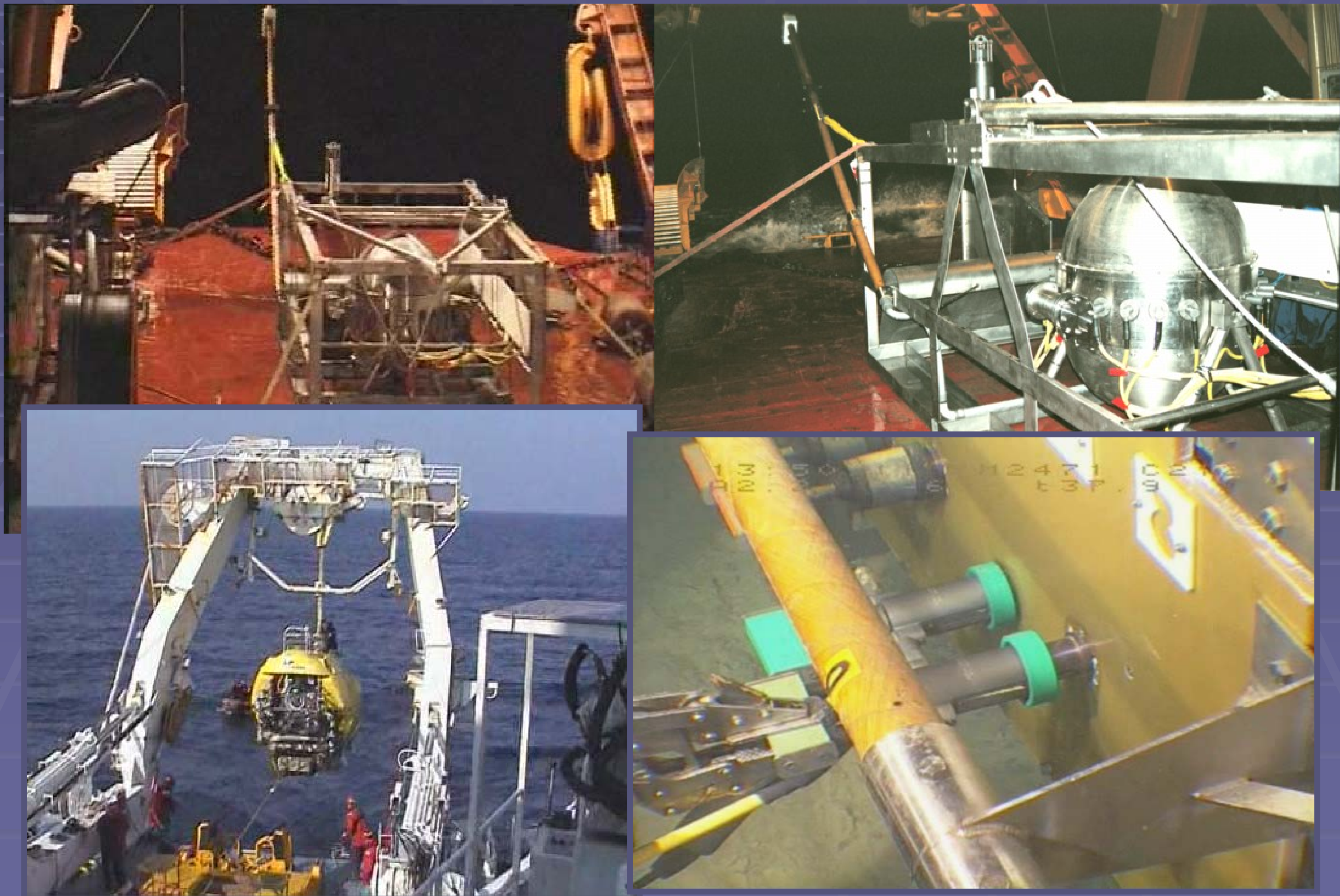


- Angular resolution is dominated at low energies by neutrino-muon angle
- At high energies pointing accuracy is 0.15 degrees

- Energy resolution via different techniques
- Typically a factor of 2-3 at high energies



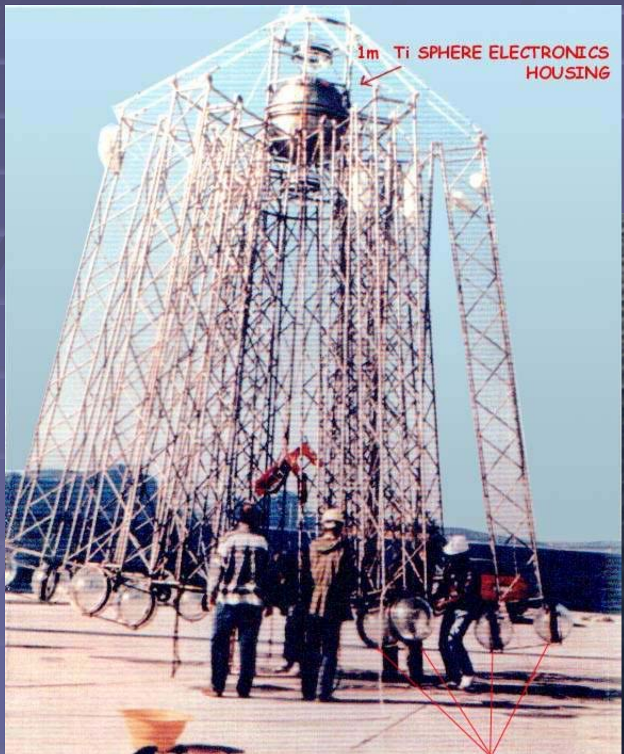
ANTARES deployments (JB)

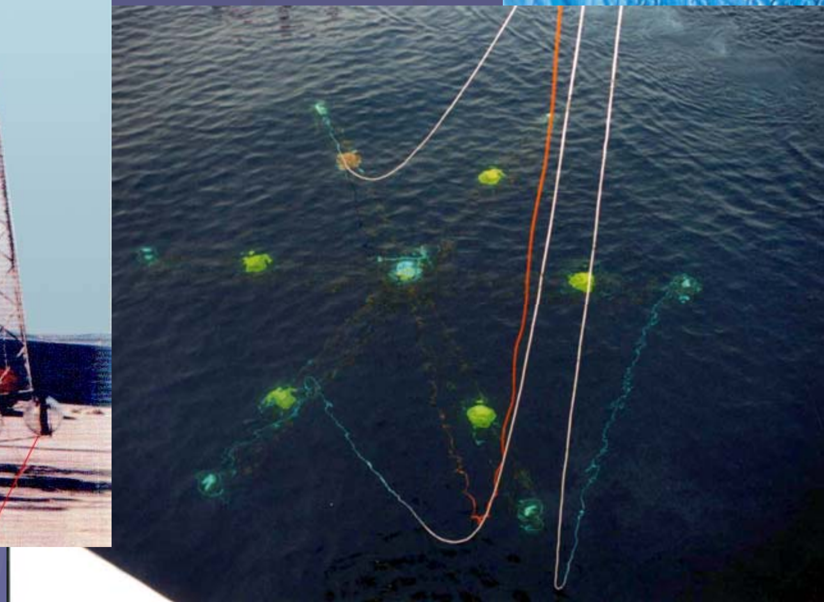


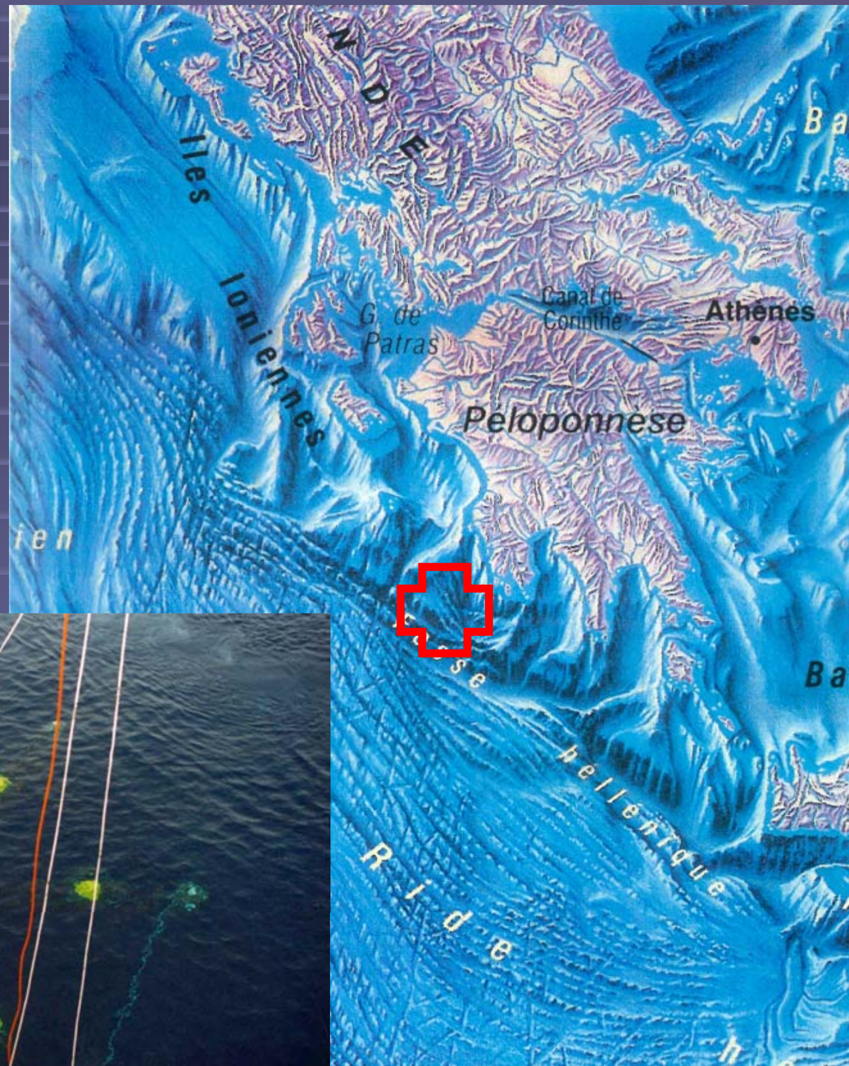
ANTARES deployments (PSL)

NESTOR

- Deep site in Peloponnese (~4000m)
- Deployed and operated one NESTOR “star” in 2003
- Muon co-incidences recorded

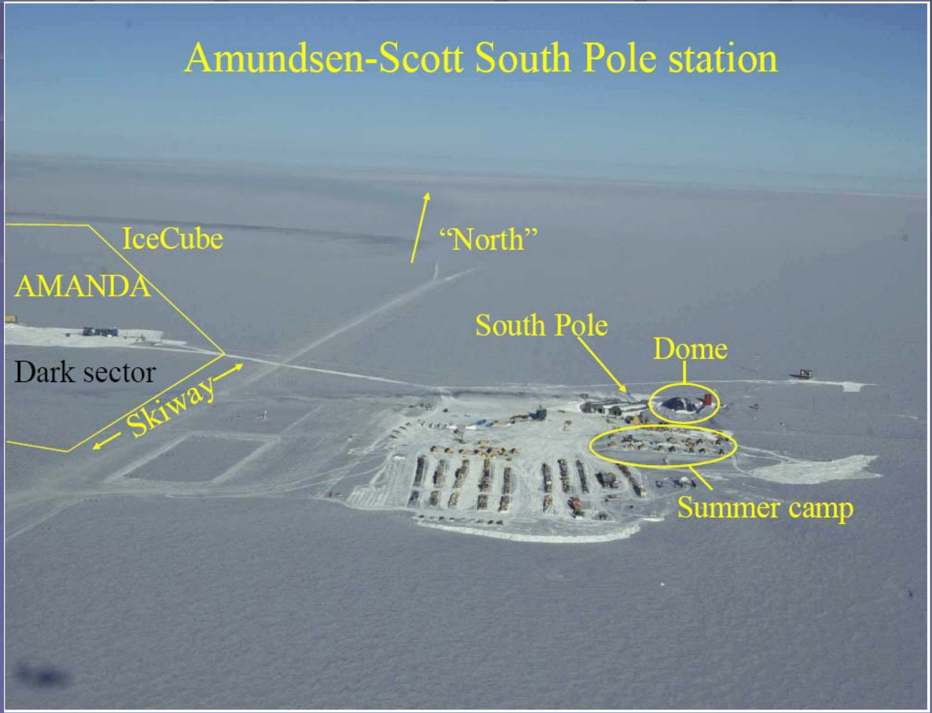


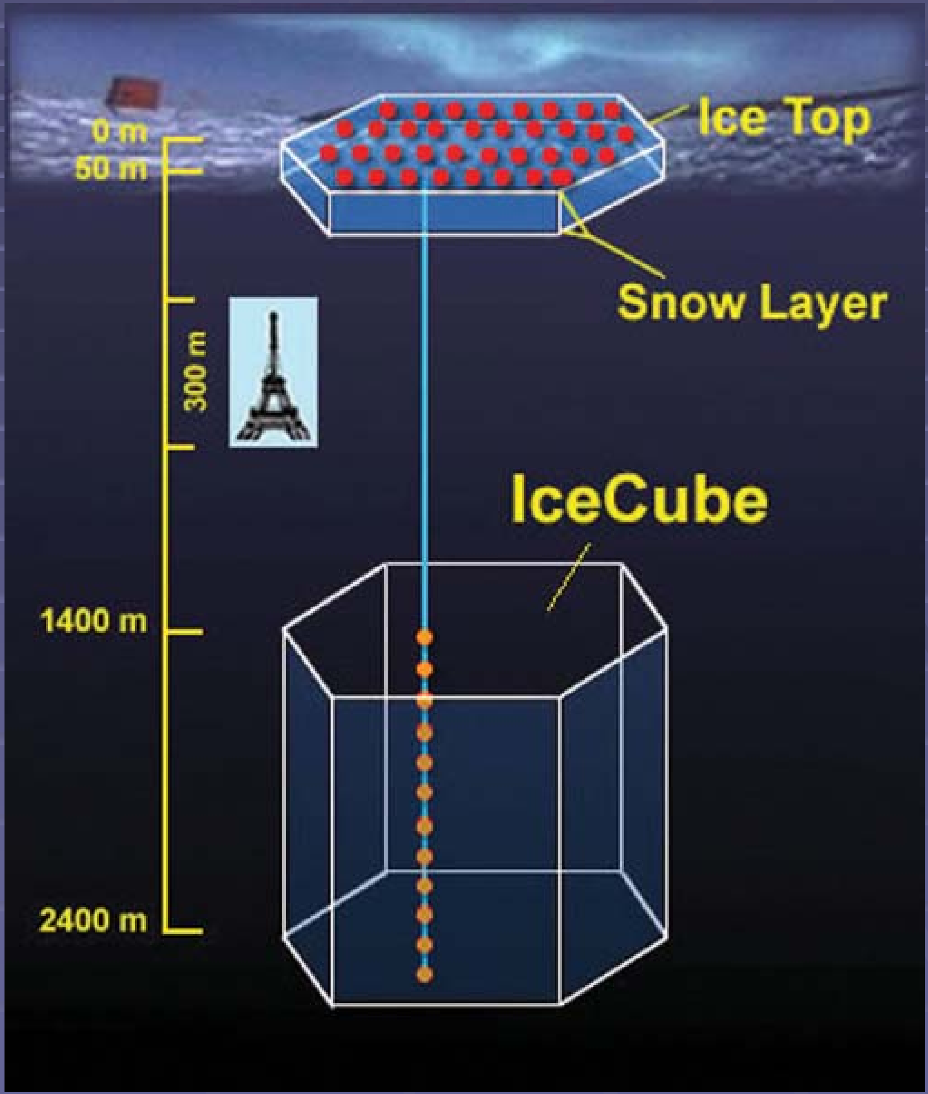




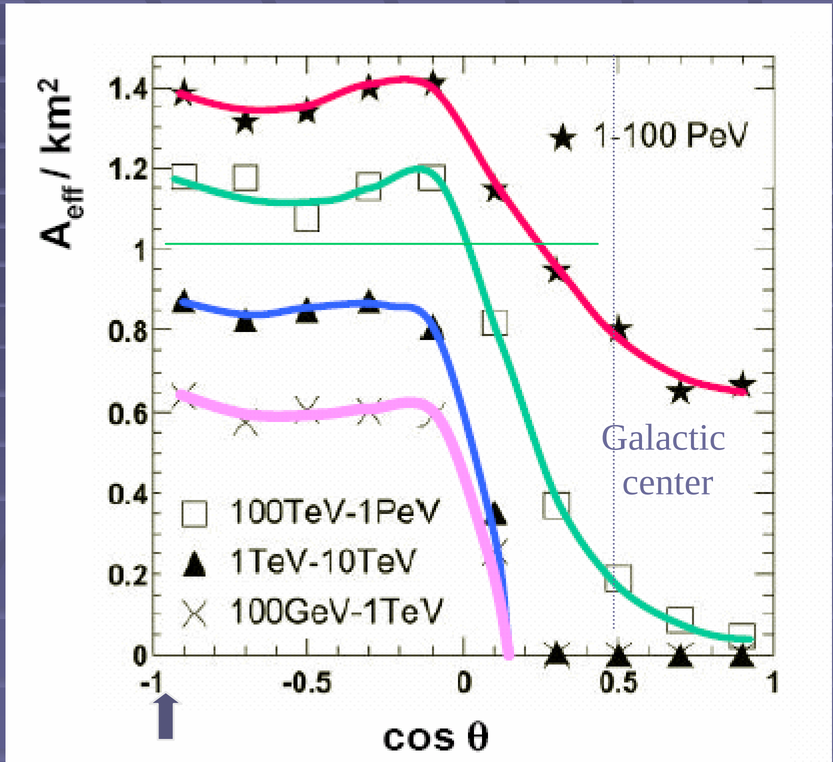
ICECUBE

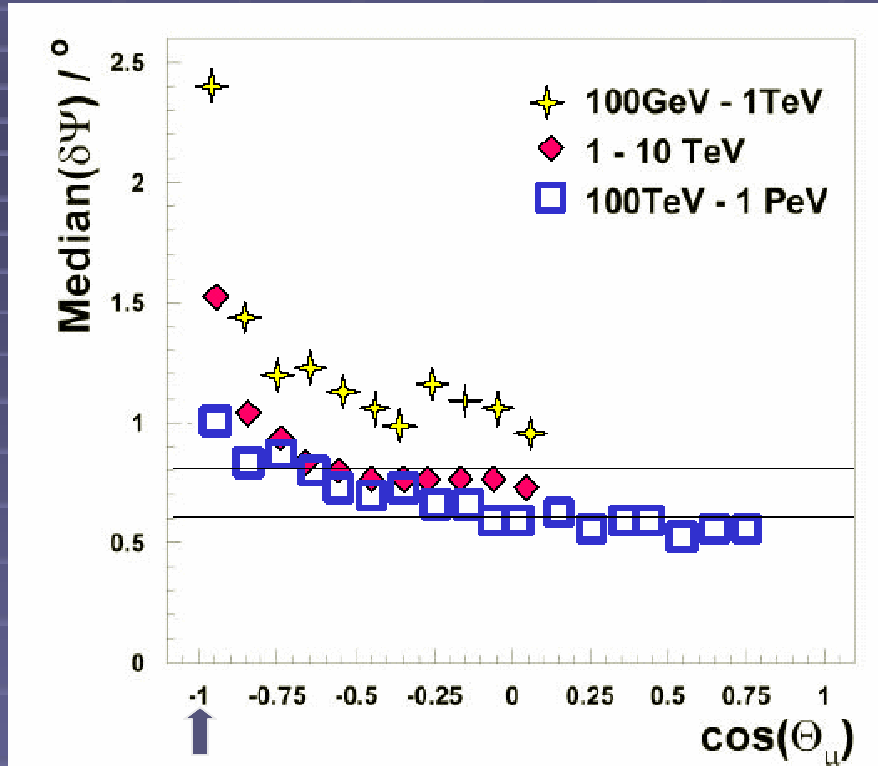
- "Second generation" neutrino telescope
- *Extension of existing AMANDA neutrino telescope in Antarctica*
- 4800 PMTs in ice
- *Aim is order 1 km^3 active volume*
- 80 strings of 60 PMTs





ICECUBE Performance





Muon effective area vs. zenith angle for different muon energy ranges

- Pointing accuracy vs. zenith angle
- Further improvement expected using waveform information
- NB Ice worse than water for pointing

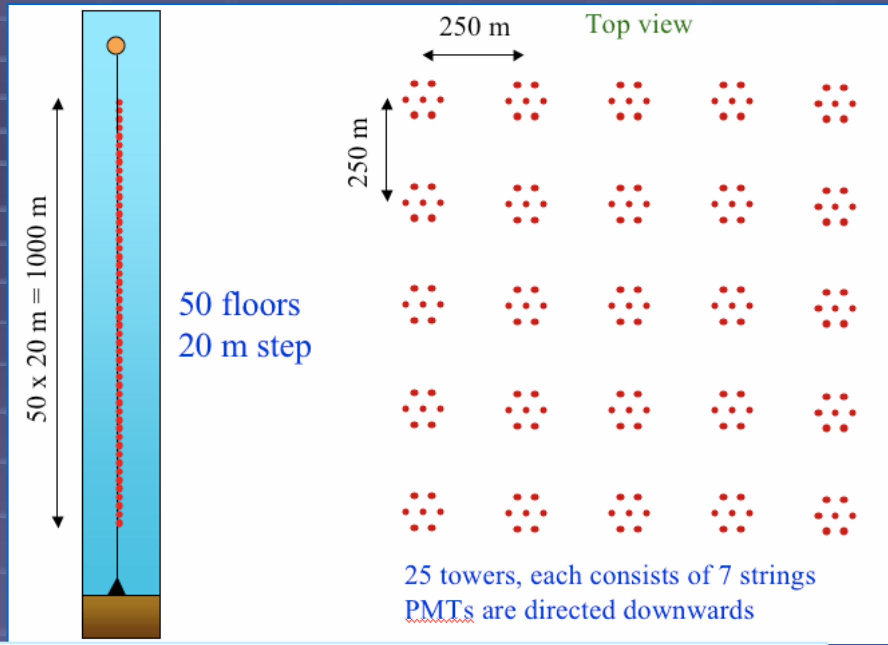
ICECUBE Plans

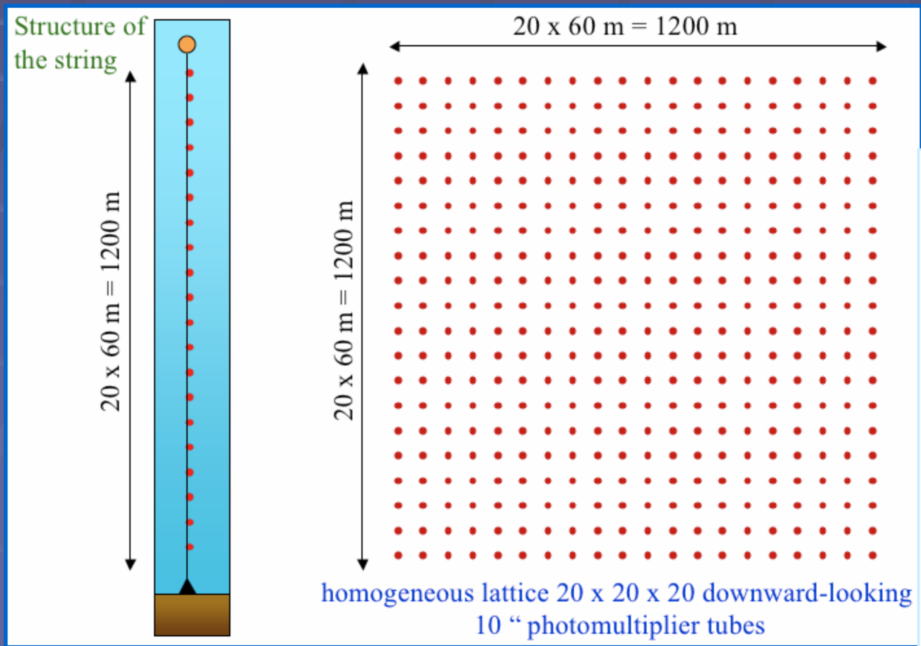
- Basically fully funded from US
- Also funding from Belgium, Germany, Sweden
- Deployment programme lasts for 6 years starting now
- First string installed Jan/Feb 2005!

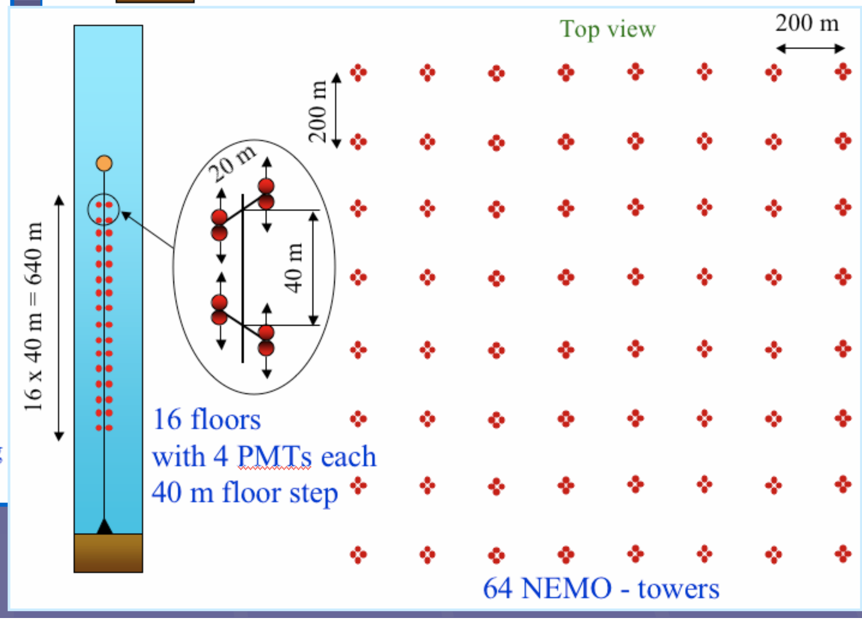
IceCube strings	IceTop tanks	
4	8	Jan 2005
16	32	Jan 2006
32	64	Jan 2007
50	100	Jan 2008
68	136	Jan 2009
80	160	Jan 2010

Km3 Detector in the Med

- Recently groups from ANTARES, NESTOR and NEMO have come together to consider building a cubic kilometre neutrino telescope in the Mediterranean
- First workshop in Amsterdam, late 2003

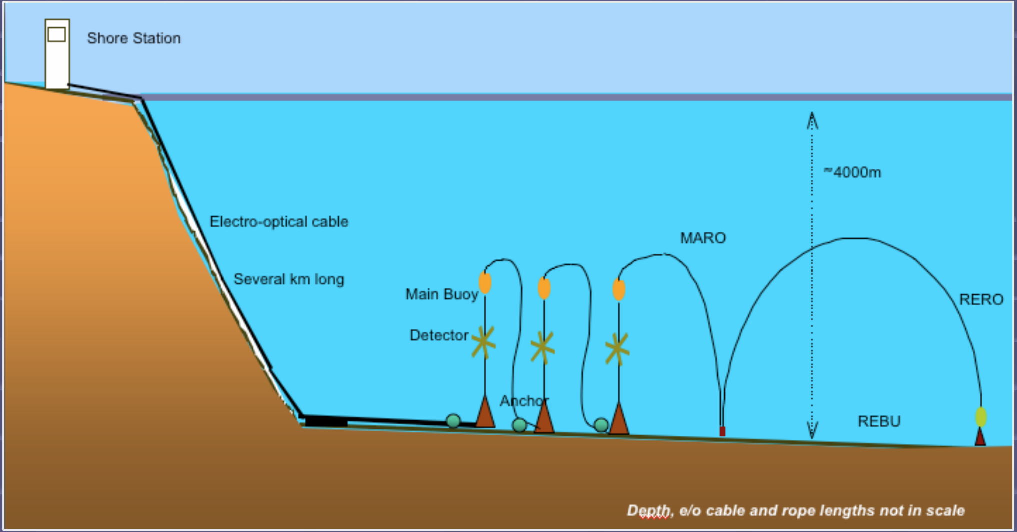




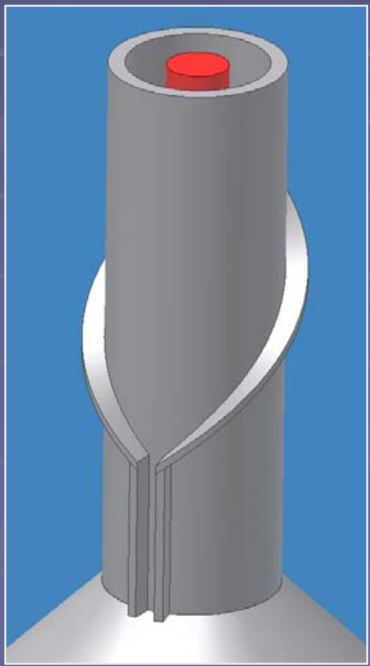


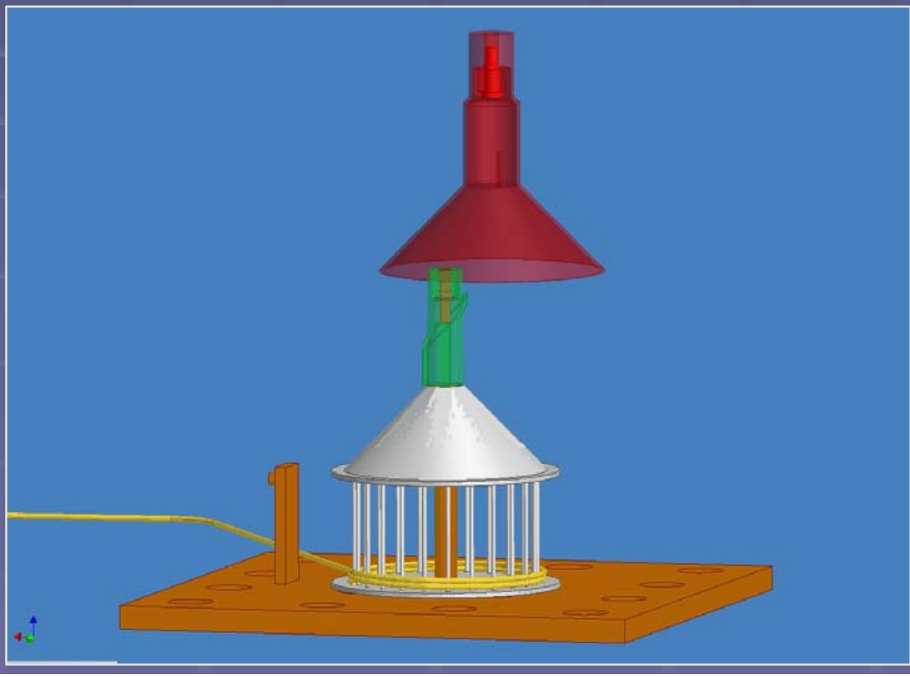
Example of discussions on detector architecture

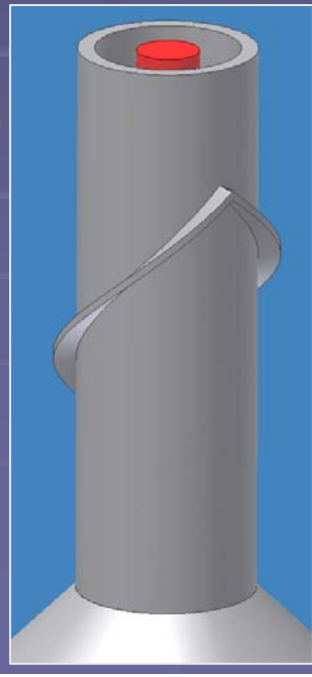
Km3 in the Med: Sea Operations



- Different deployment strategies, central “star” arrangement vs linear (surface connected) topology a la NESTOR
- Possible “self connecting” systems that obviate the need for ROVs/submarines







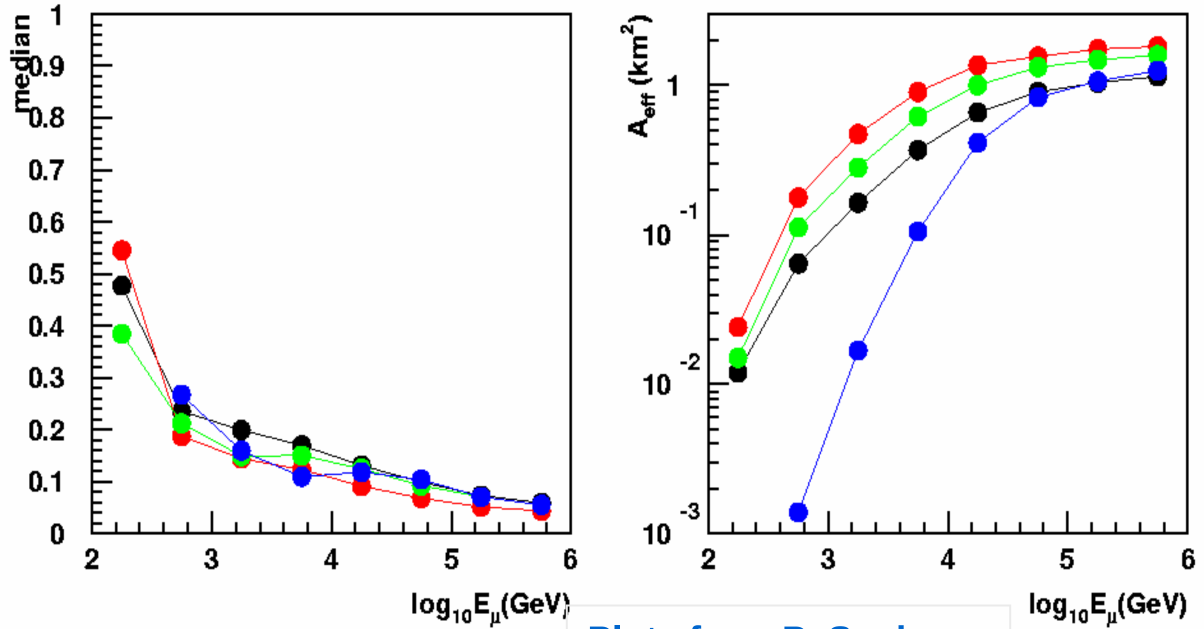
Km3 in the Med: Performance

- Very many parameters - some well known, some less well known, e.g.:
  - Detector layout
  - Water properties (absorption, scattering, dispersion)
  - Optical backgrounds
  - Currents
  - Sedimentation

- Want to determine
  - Effective area/volume
  - Angular resolution
  - Energy resolution
  - Sensitivity to cascades

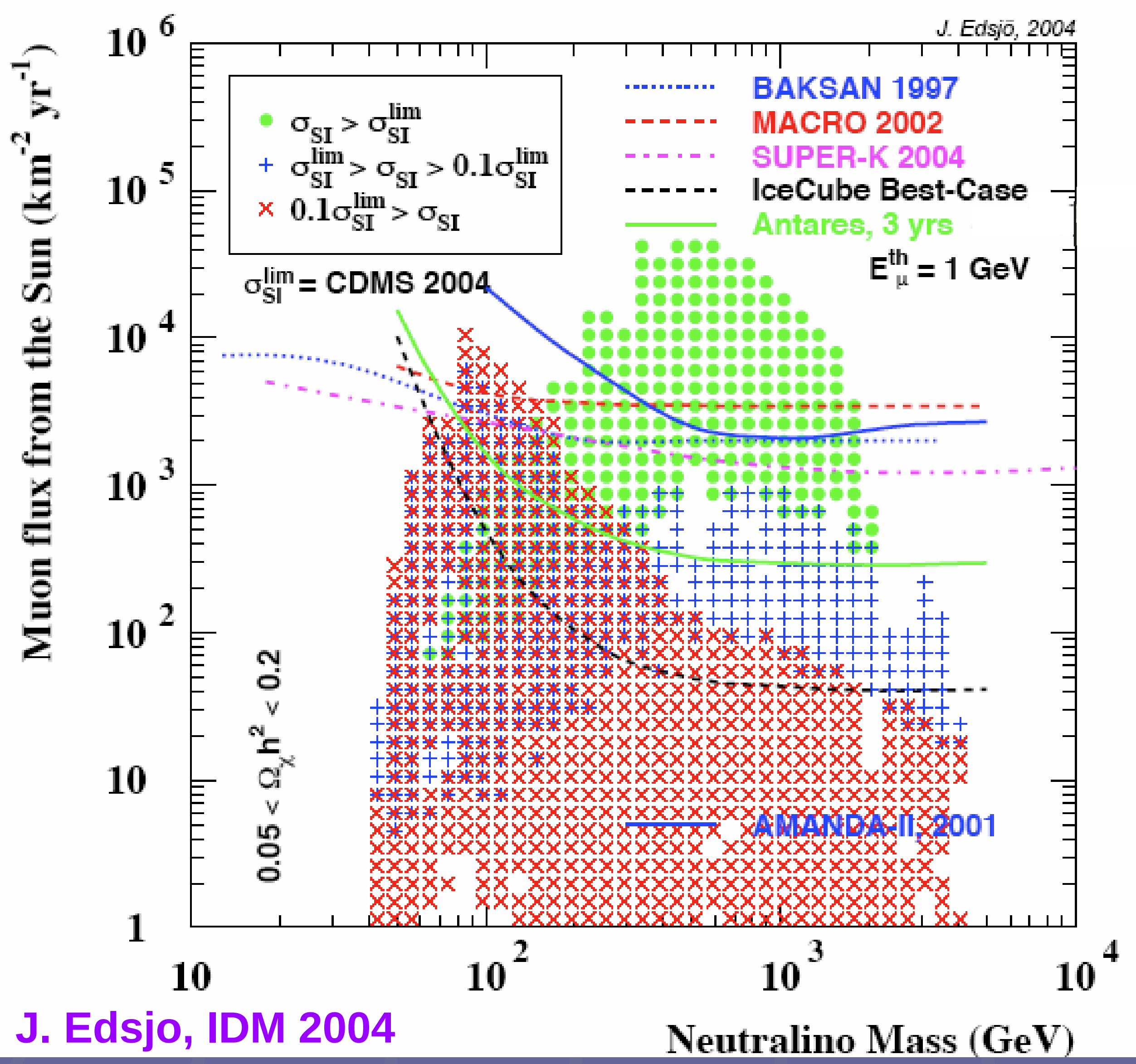
as a function of cost

Example of types of calculations being made:
Effective area and angular resolution for a 5600 PMT detector with different levels of ^{40}K backgrounds



Plots from P. Sapienza

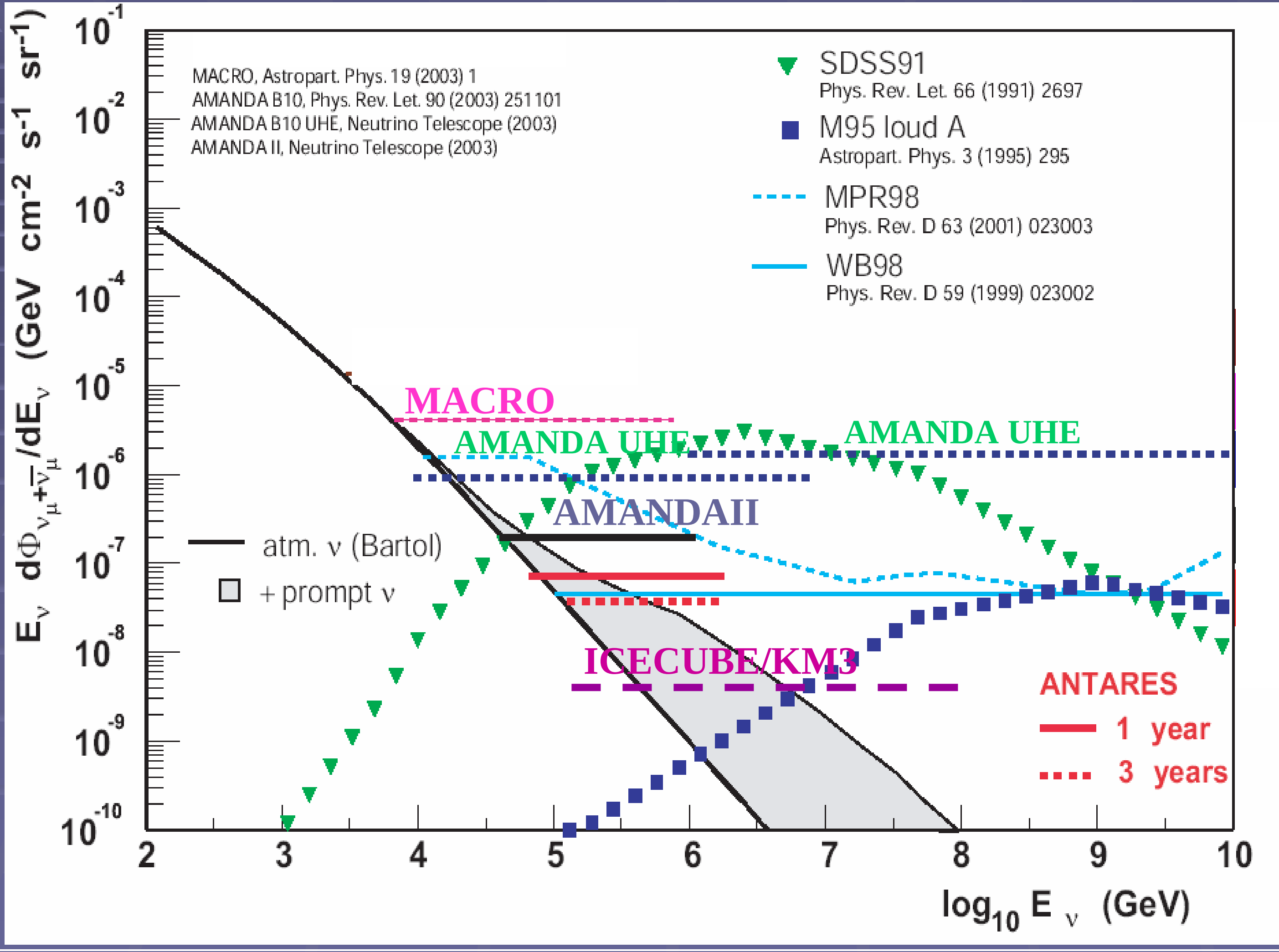
Neutralino Sensitivities



J. Edsjo, IDM 2004

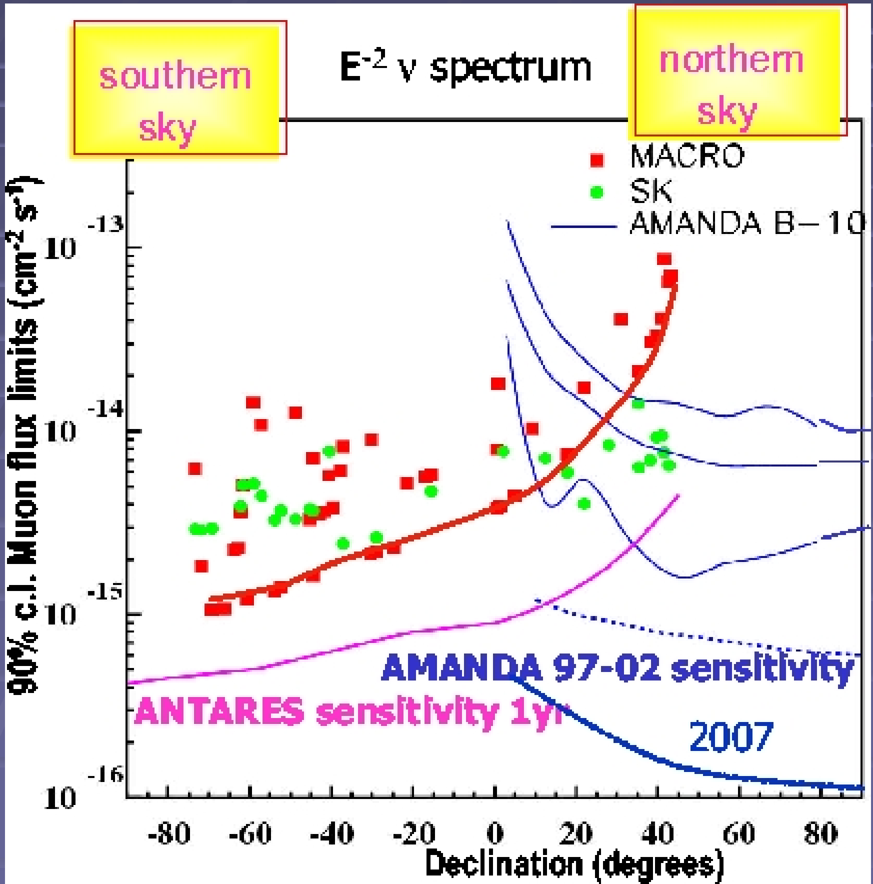
- Comparison of muon flux sensitivities from neutralino annihilations at the centre of the Sun
- Points correspond to specific SUSY models in so-called mSUGRA space
- Colour coding represents sensitivities of direct detection experiments
- The two techniques are complementary

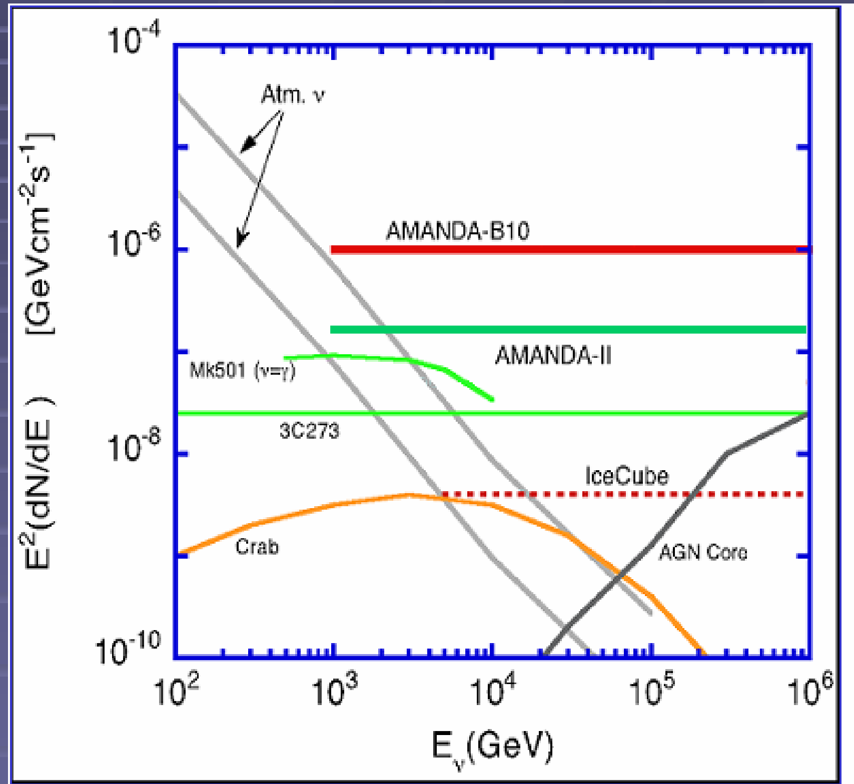
Diffuse Flux Sensitivities



- Diffuse flux limits assuming an E^{-2} spectrum
- Plot shows atmospheric neutrino background plus various theoretical predictions

Point Source Sensitivities





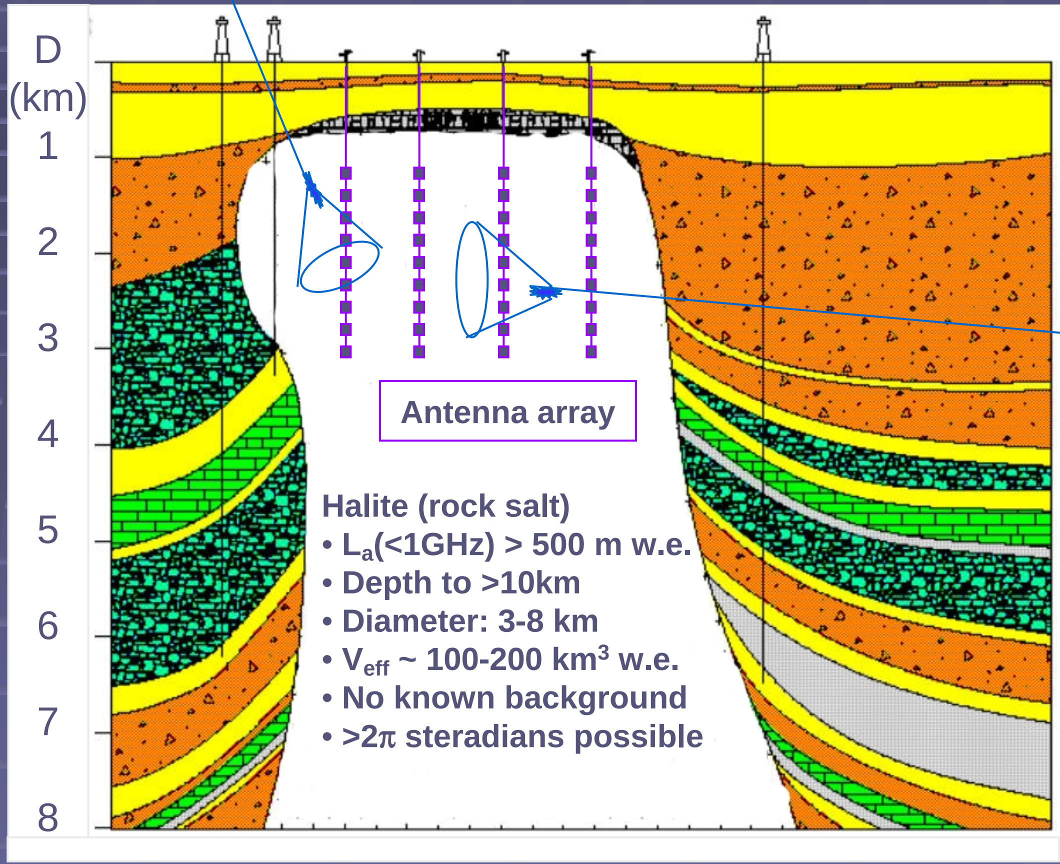
ICECUBE Sensitivity to point sources (1 y):

5.5·10^{-9} E^{-2} (cm^{-2}s^{-1}GeV)

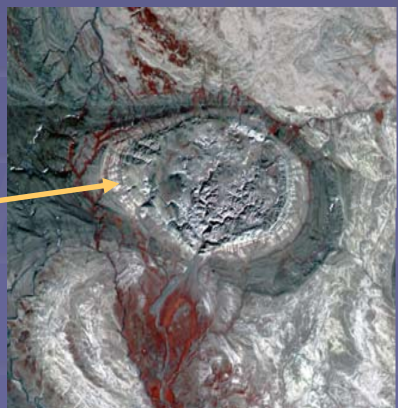
Radio Cerenkov

SALSA: SALtbed Shower Array

- The concept:
- Exploits radio Cerenkov effect
- Instrument natural "salt domes" with antennae
- RF losses in salt are very low
- As radio clear as Antarctic ice but 2-3 times as dense



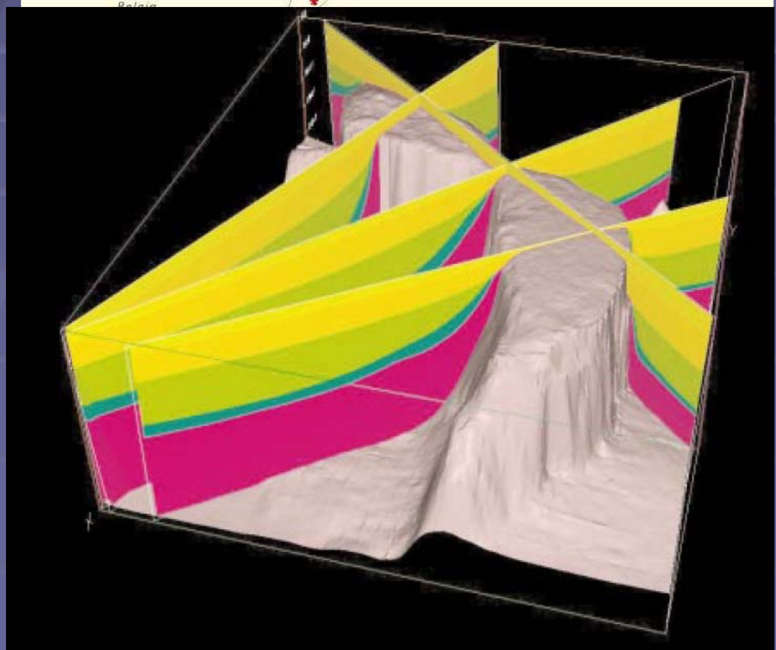
Isacksen salt dome, Elf Ringnes Island, Canada 8 by 5km



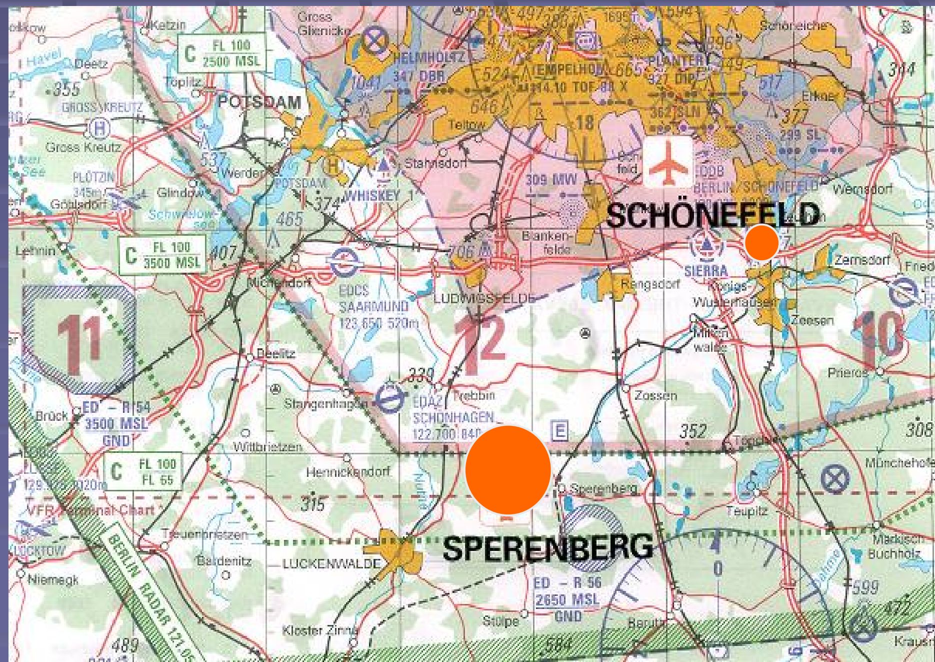
Programme underway to identify potential sites in the US (e.g: Gulf coast states

Plans to deploy by 2007-8

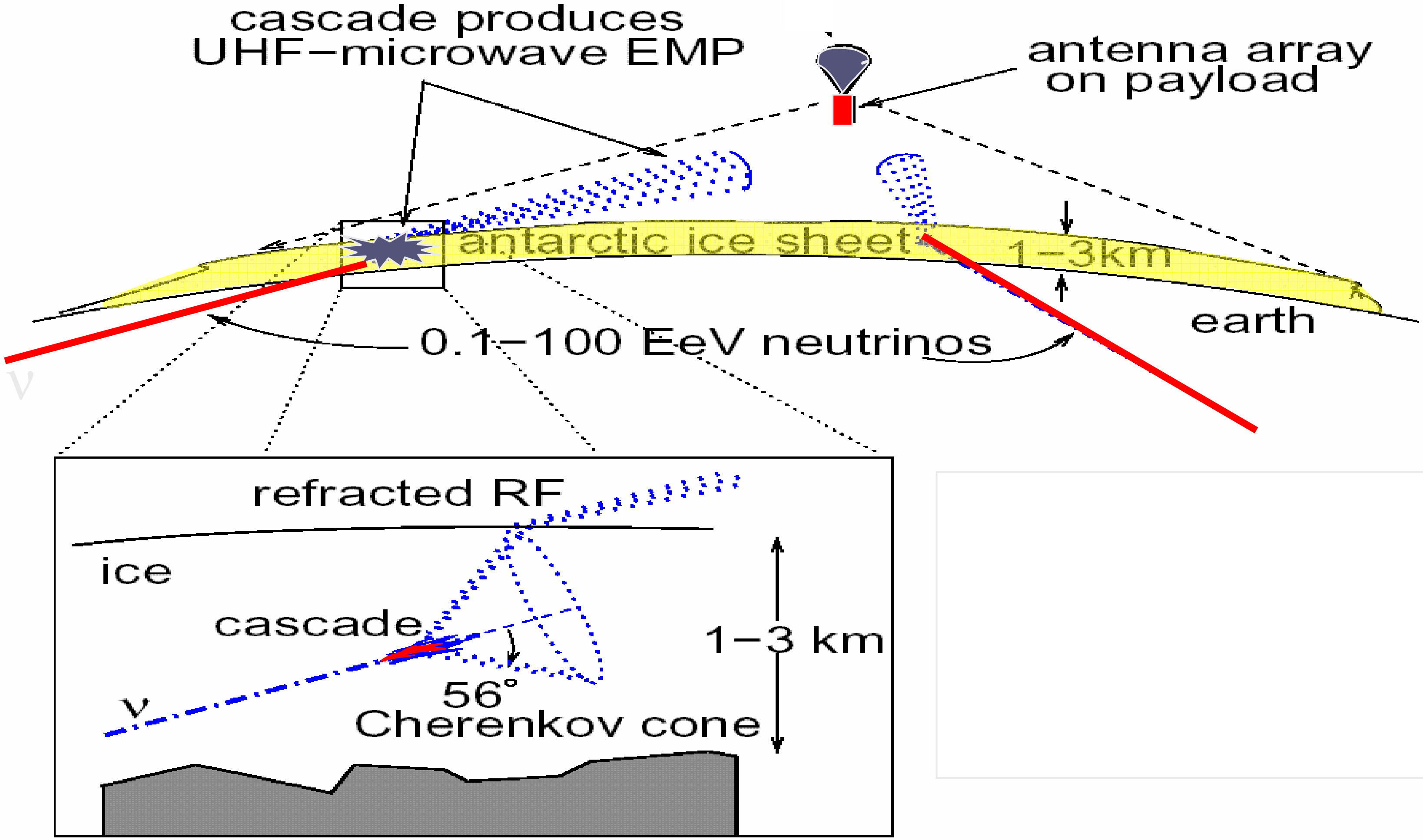
SALSA in EU?



- Recently been observed that salt domes exist in Europe also in particular
  - Under the LOFAR array
  - Close to DESY (Zeuthen)
- Preliminary studies underway

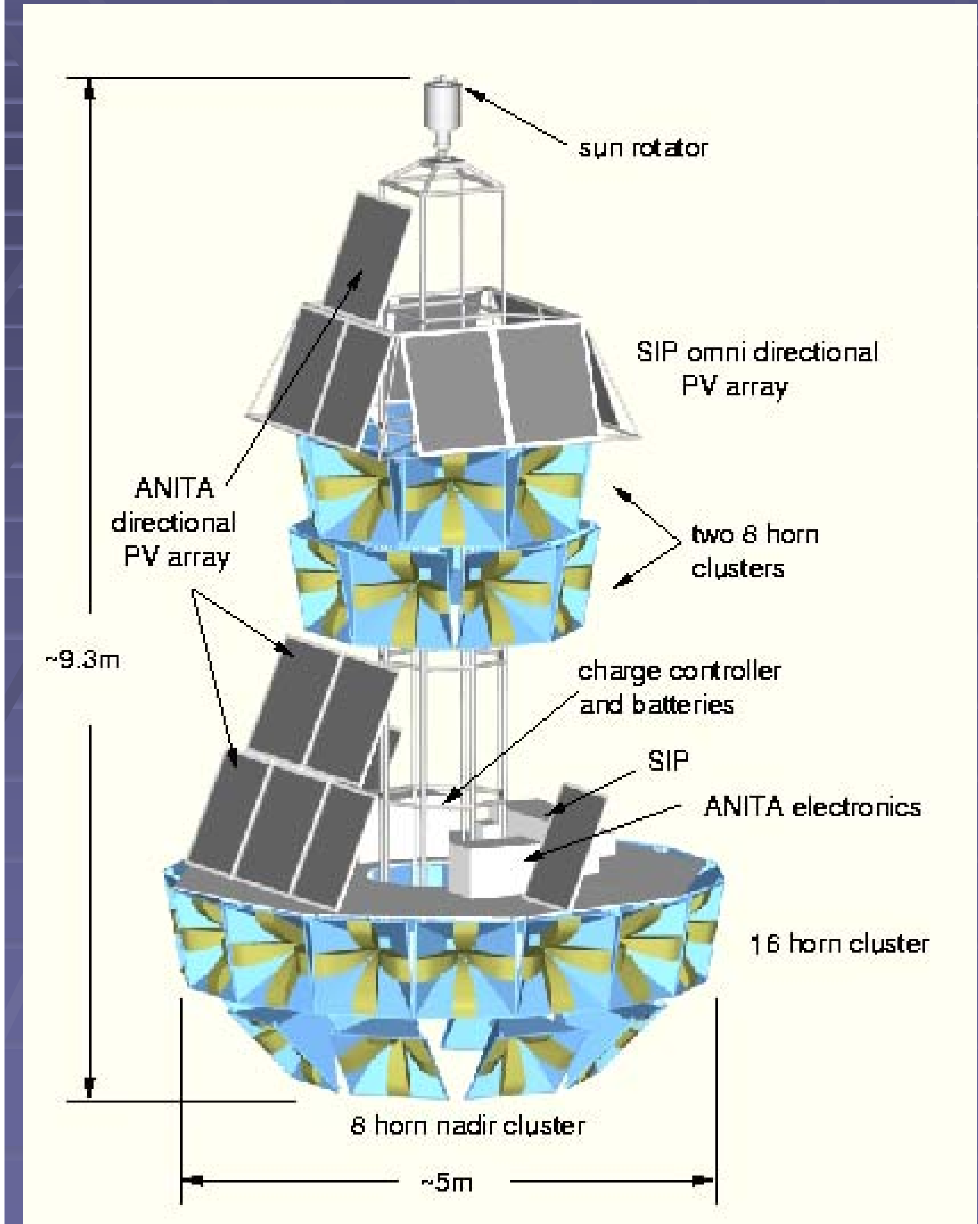


ANITA



cascade produces
UHF−microwave EMP
antenna array
on payload
antarctic ice sheet
1−3km
earth
0.1−100 EeV neutrinos
ν
refracted RF
ice
cascade
1−3 km
ν
56°
Cherenkov cone

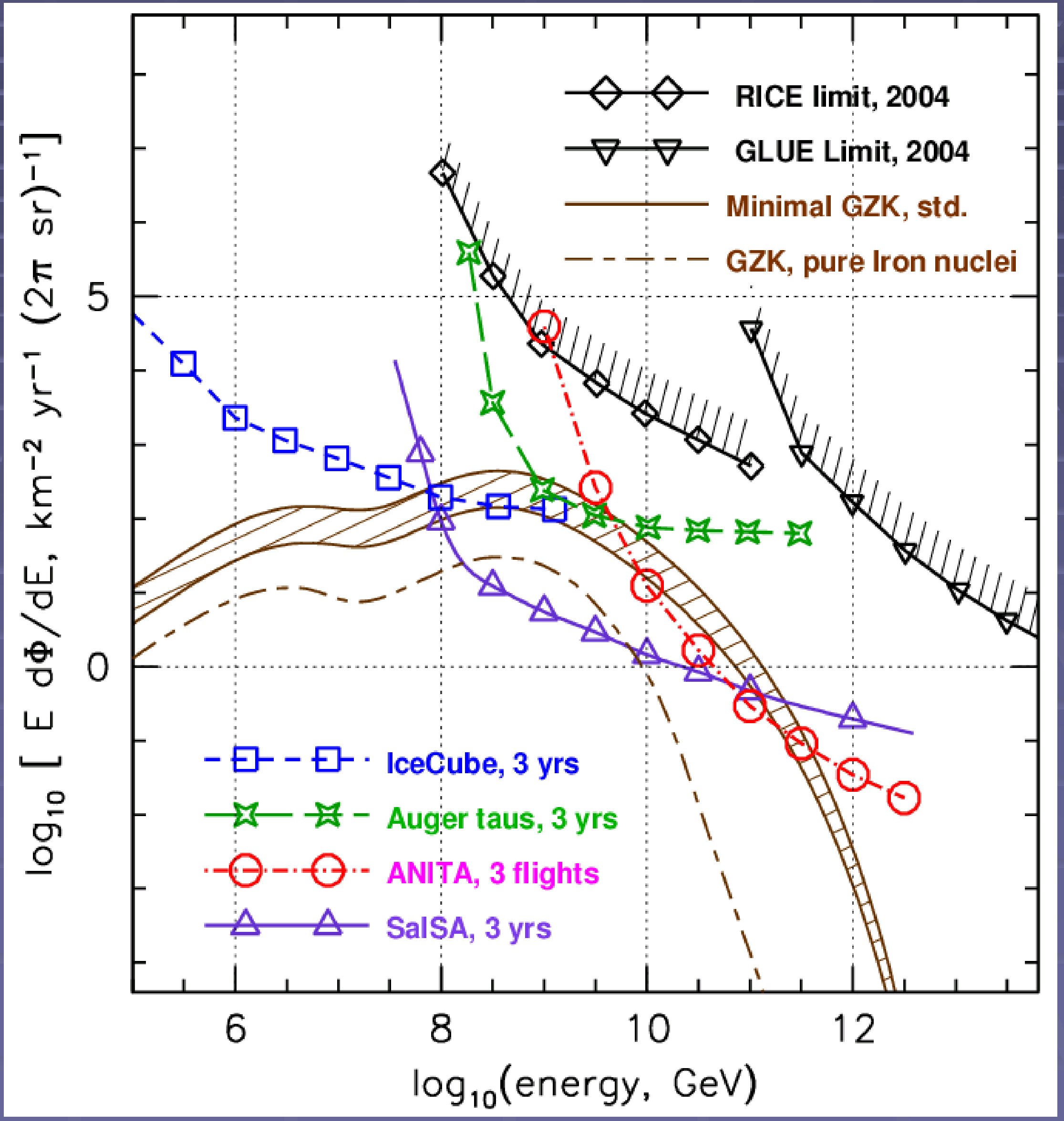
ANITA



- **Test flight (ANITA-lite) in 2004**
- **Fully funded US-NASA**
- **First flight due 2006**
- **Effective area ~ 10^6 km^2**
- **~10^0 azimuth resolution via antenna beam gradiometry within antenna clusters**
- **• ~3^0 elevation resolution by interferometry between top & bottom antenna clusters**

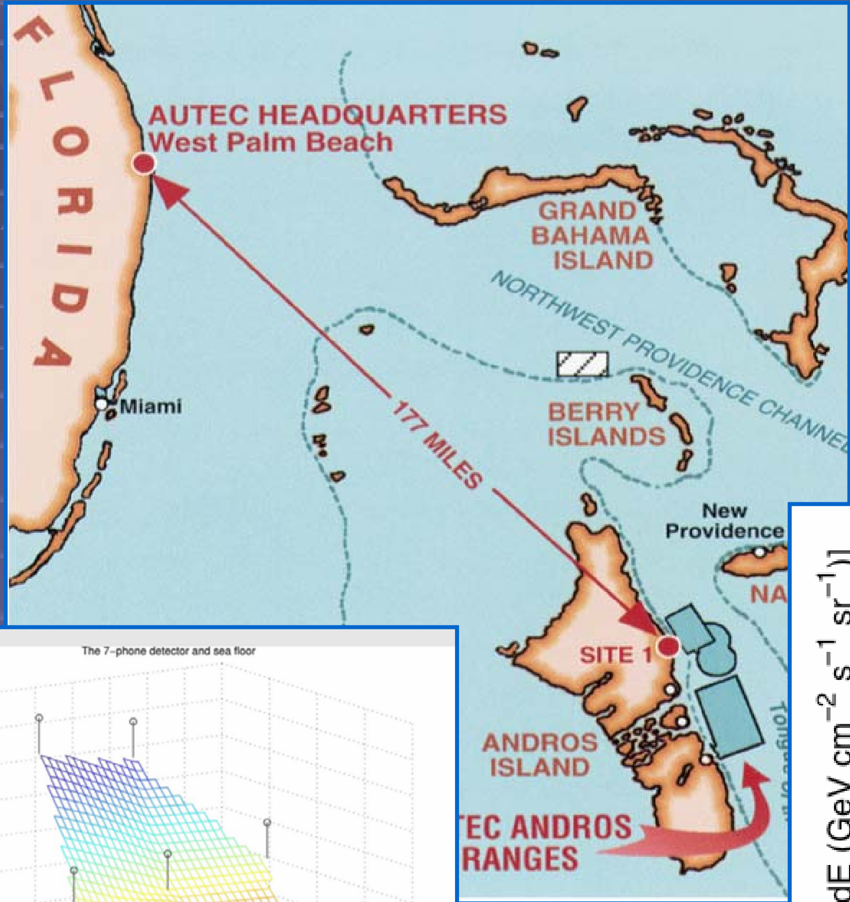
ANITA, SALSA sensitivities

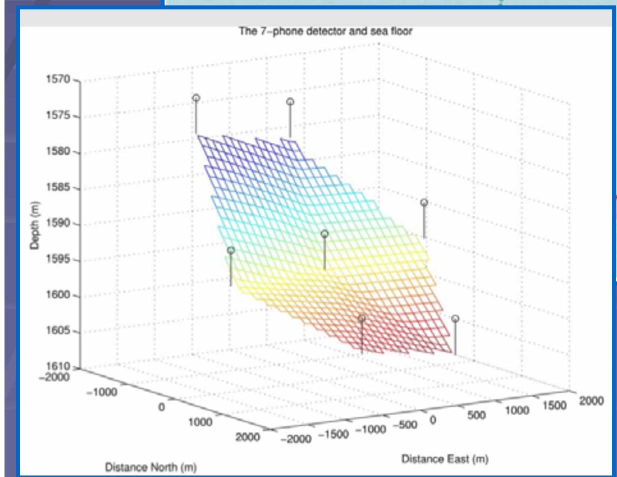
- Predicted sensitivity of SALSA (3 years)
- Based upon a 2.5 km^3 array with 225m spacing, 12^2=144 strings, 12^3=1728 antenna nodes, 12 antennas per node, dual polarization
- 290 km^3 sr at 1 EeV
- Threshold 10^{17} eV
- A few hundred antennas hit at 1 EeV, >1000 hits at 10 EeV
- Expect 70-230 events over 3 year period



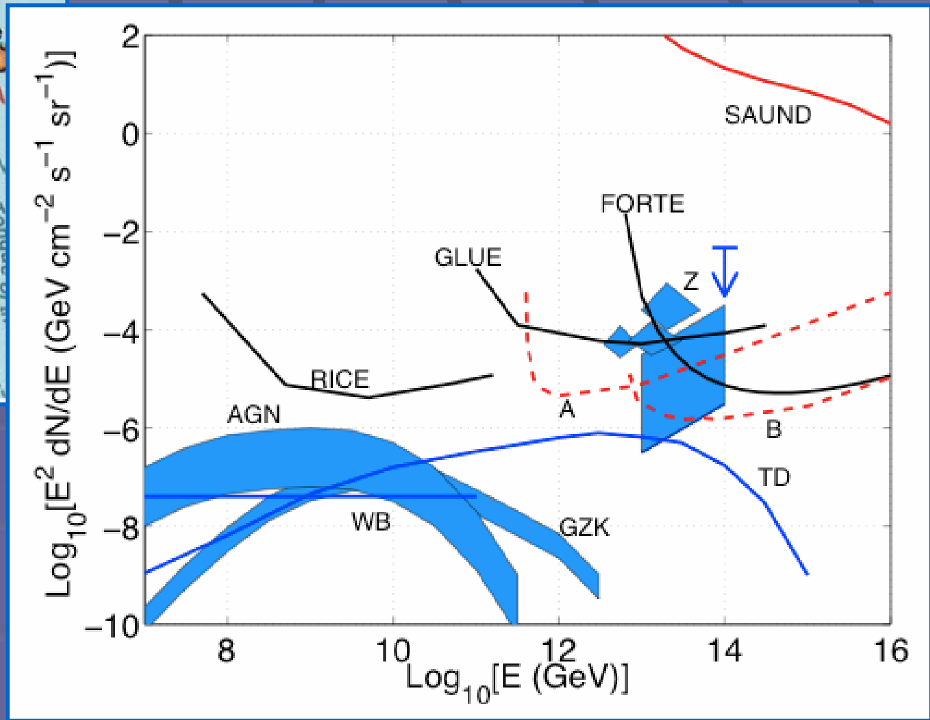
Acoustic Detection

SAUND II





- SAUND have submitted a proposal to the NSF for funding to extend the number of hydrophones read out from 7 to ~30



ACoRNE and UK interests

- A collaboration between
  - DSTL (Ministry of Defence)
  - University College London
  - University of Lancaster
  - University of Northumbria (School of Engineering)
  - University of Sheffield
- Recently awarded ~280k of joint funding from PPARC (PPRP Seedcorn Fund) and the MoD
- Collaborations interests focus on
  - Computer simulation of large scale (~1000) hydrophone arrays to assess the potential sensitivity of the technique
  - Energy calibration via a "simulator"
  - Operations at Rona
  - DAQ upgrade at Rona
  - Developing refined signal processing techniques

The RONA Hydrophone Array

- MoD facility in North West Scotland
- *An array of high sensitivity hydrophones with a frequency response appropriate to acoustic detection studies*
- Existing large-scale infrastructure including DAQ, data transmission, buildings, anchorage
- *PPARC/MoD funding permits us to upgrade Data Acquisition system there to facilitate several weeks' worth of <u>unfiltered</u> data to be recorded*
- Provides an excellent testbed for the "simulators"
- *Expect to also make use of a NATO "line array", enables phases to be tuned so that response in non-isotropic (well matched to "pancake" nature of expected signal)*

Simulations and Sensitivity Studies

Basic approach:

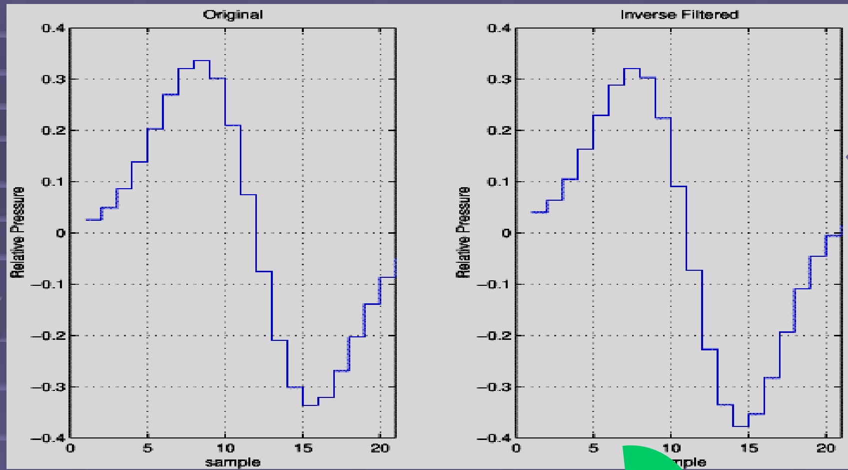
- Take a parametrised acoustic signal - amplitude is a function of incoming neutrino energy and direction
- **Calculate the expected signal at each hydrophone in the array taking into account attenuation, etc.**
- Place cuts at each hydrophone at a very conservative threshold that corresponds to **one false alarm per 10 years** according to the known sea state
- **Record only those hydrophones above threshold and within the plane of the acoustic "pancake"**
- NB: results of parametric simulation have been cross-checked against, e.g. GEANT, in appropriate energy domains

QuickTime™ and a
Video decompressor
are needed to see this picture.

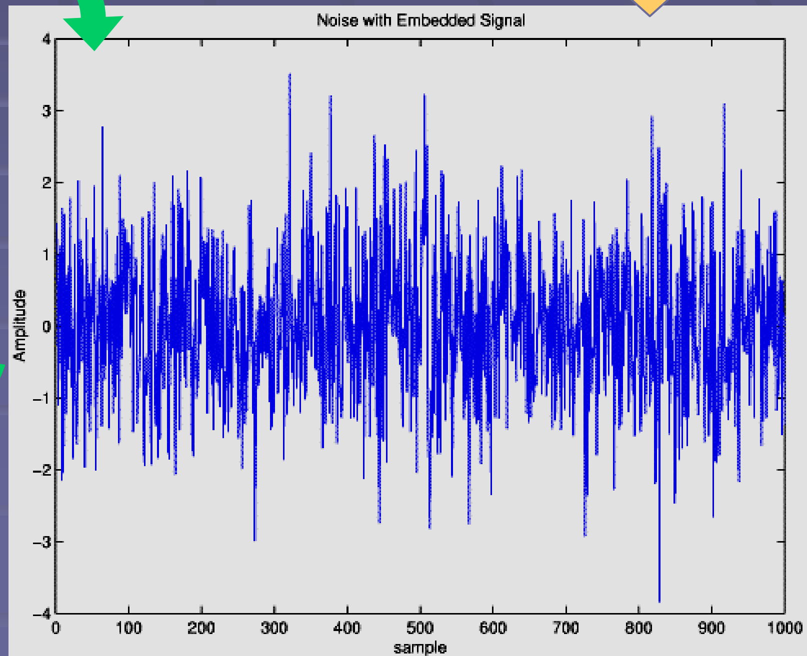
Example simulated event in a 1000 hydrophone array

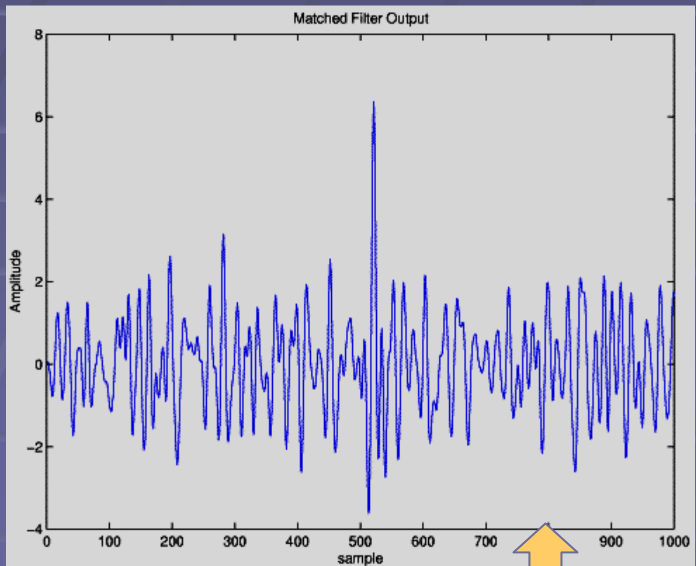
Signal processing studies

Work carried out at University of Northumbria



1. **Take original signal pulse and apply inverse filter**
2. **Add noise according to known sea state**





3. **Apply matched filter algorithm to search for signal**

UK Involvement in (U)HE Projects

- ANTARES
  - *Leeds, Sheffield (members '96-'04, withdrawn since 11/04)*
- ICECUBE
  - *Imperial, Oxford*
- KM3
  - *EU Design Study proposal under FP6 submitted April 2004*
  - *9 countries (Cyprus, Greece, France, Italy, Holland, Spain, Germany, UK)*
  - *Leeds, Liverpool, LJMU, Sheffield in UK*
  - *Proposal is accepted - awaiting final word on amount*
- NESTOR, ANITA, SALSA
  - *None*
- Acoustic (ACORNE)
  - *DSTL (MoD), Lancaster, Northumbria, Sheffield, UCL*
  - *Currently EU FP6 I3 (N/W+JRA+TA) Acoustic Detection JRA (LT co-ordinator) IT+DE+SP+FR+UK, may wait for FP7 …*

Summary

- Neutrinos are a unique probe of high energy phenomena in the Universe
- *Optical Cerenkov telescopes such as ANTARES, AMANDA and their successors - ICECUBE, KM3, will probe numerous astrophysical sources such as AGN, GRB, SN remnants, etc. as well as being sensitive to the annihilation of neutralino-type dark matter*
- UHE neutrinos, if detected, may give important information on the source of the highest energy cosmic rays
- *UK has an interest in both of these areas through KM3, ICECUBE and ACORNE*