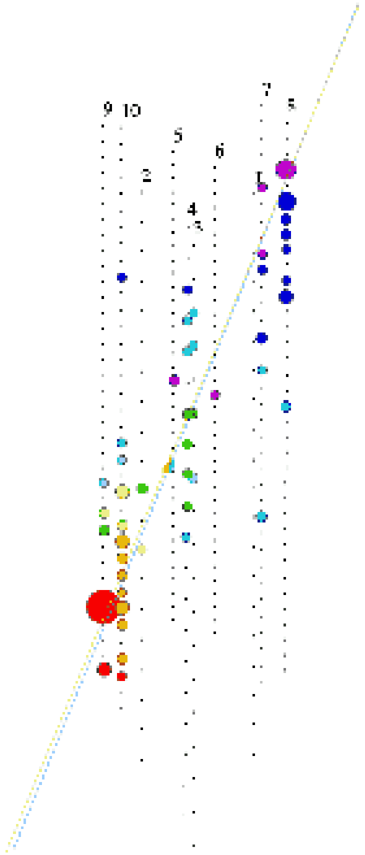
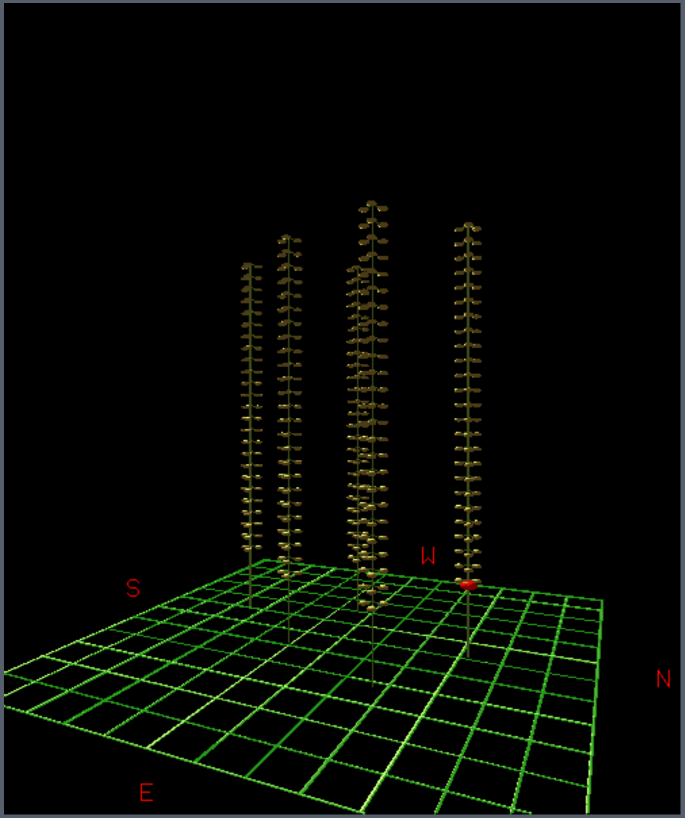


ASTROPARTICLE PHYSICS LECTURE 3

Matthew Malek

University of Sheffield



High Energy Astroparticle Physics

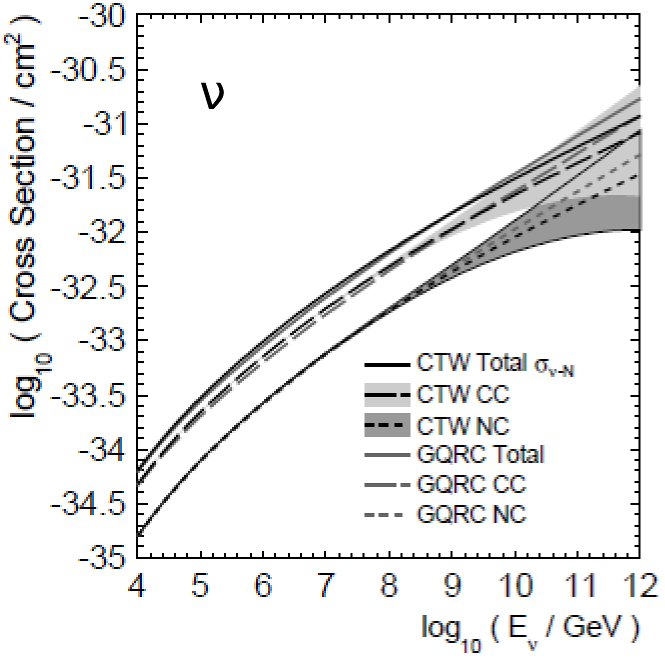
Acceleration Mechanisms

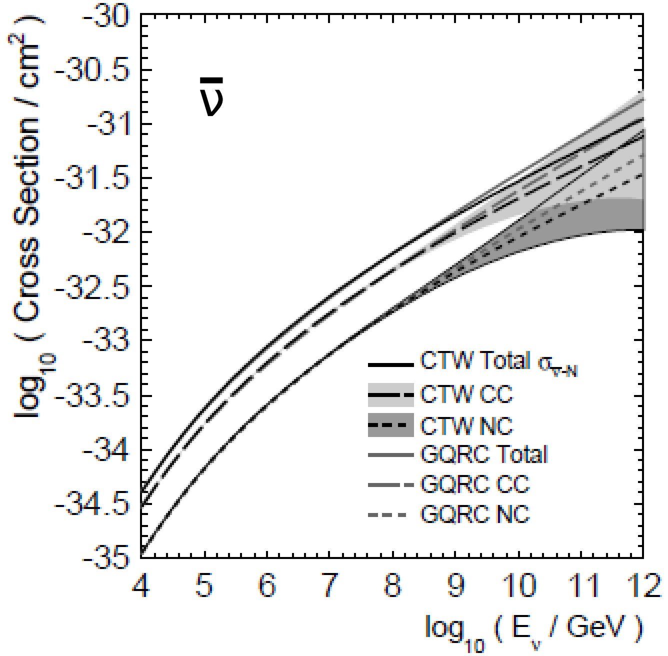
Sources

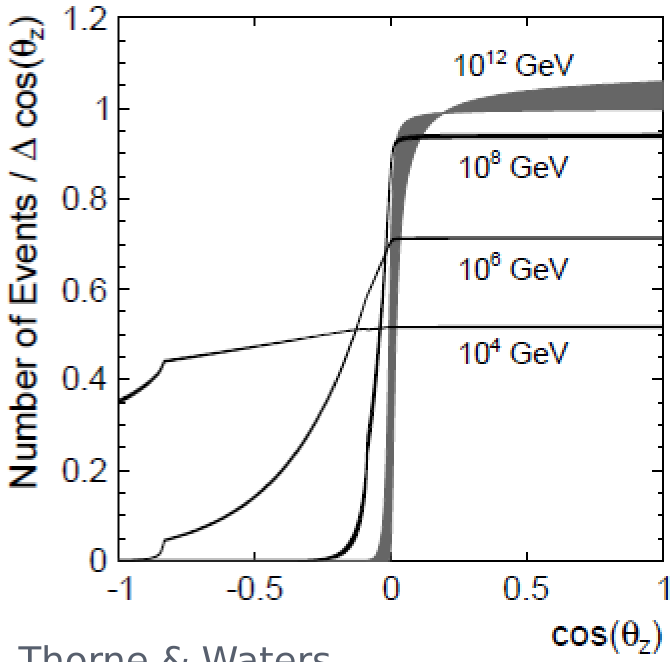
Detection

Neutrino Detection

- Neutrino cross-section rises with energy
- Only UHE neutrinos ($>10^{15}$ eV) interact with reasonably high probability (such that Earth is opaque to them)





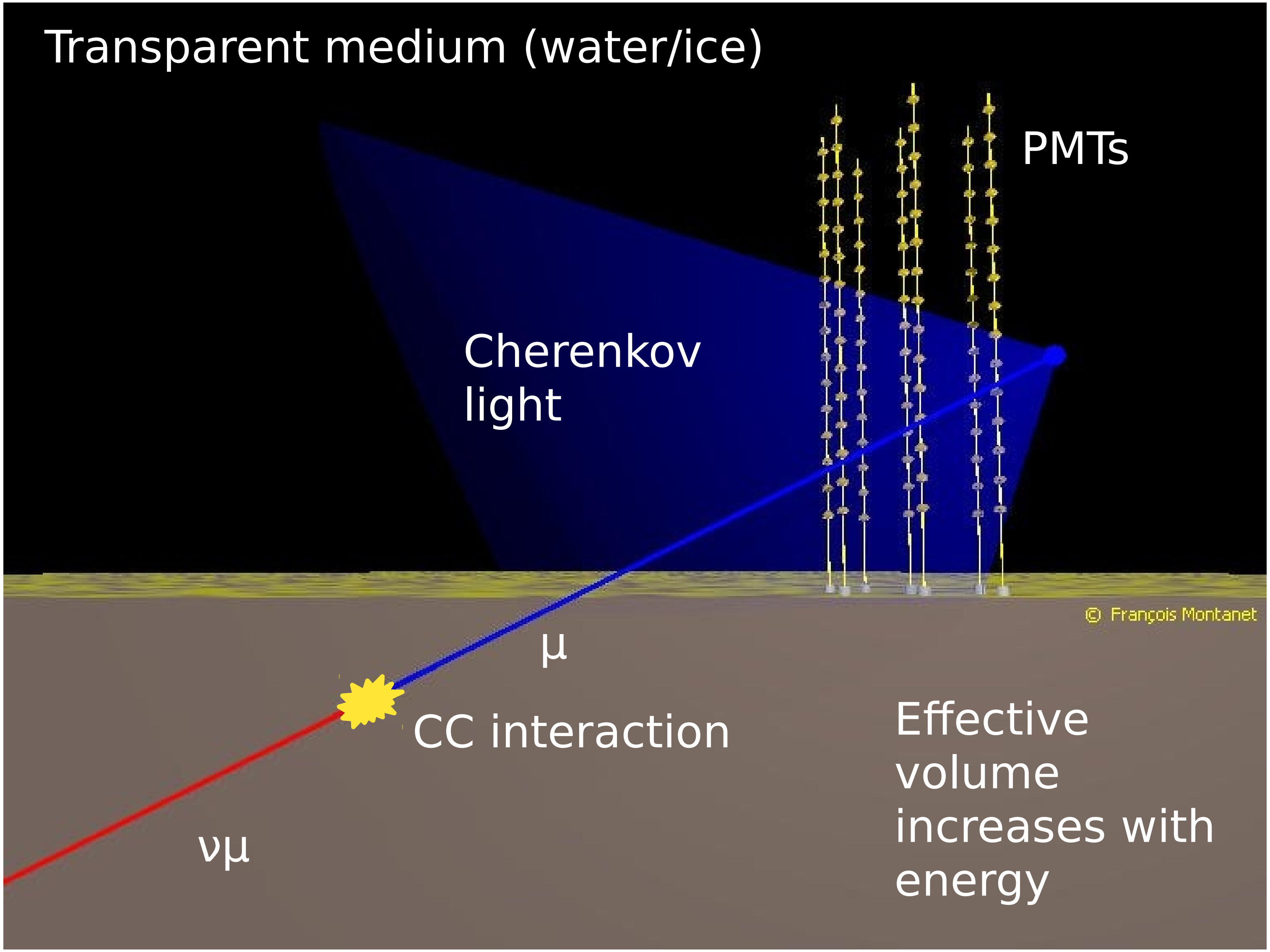


Connolly, Thorne & Waters, hep-ph/1102.0691v1

Neutrino Detection (Penetrating Neutrinos)

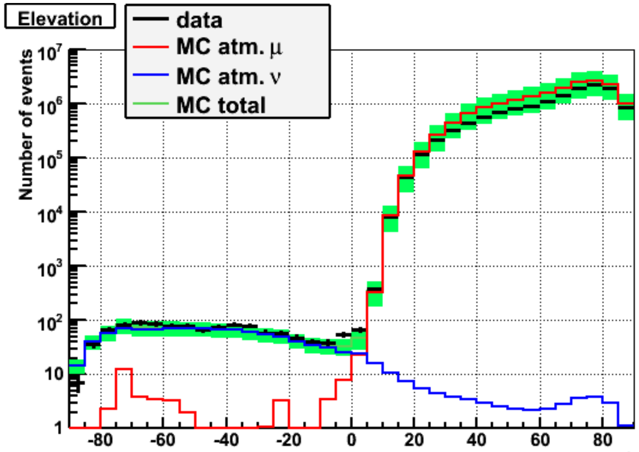
- Mostly rely on detecting the charged lepton produced in CC interactions
  - at lowest energies (solar neutrinos), also elastic scattering ($\nu + e \to \nu + e$) & NC on deuterium ($\nu + d \to \nu + p + n$)
  - note that at solar neutrino energies μ and τ cannot be produced by CC, so ν_μ, ν_τ only seen in NC (*e.g.*, SNO)
- Some early experiments using tracking calorimeters, but water Cherenkovs are now standard practice
  - can obtain large effective volumes by instrumenting *natural* bodies of water/ice
  - particle identification by ring morphology at low energies, shower shape at high energies

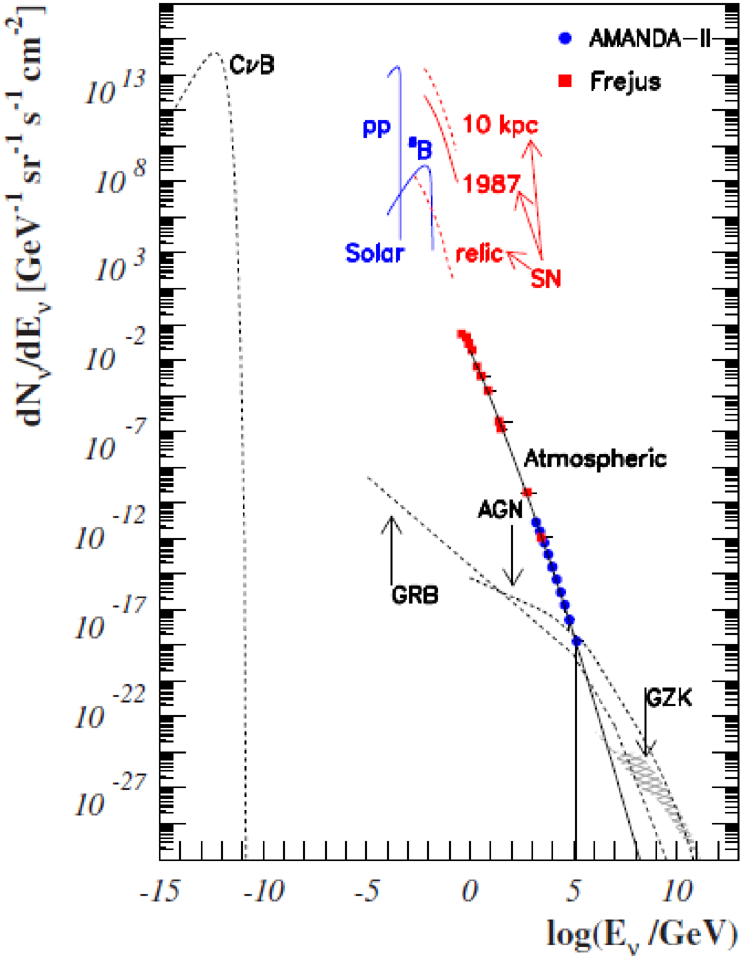
Neutrino Detection by Water Cherenkov



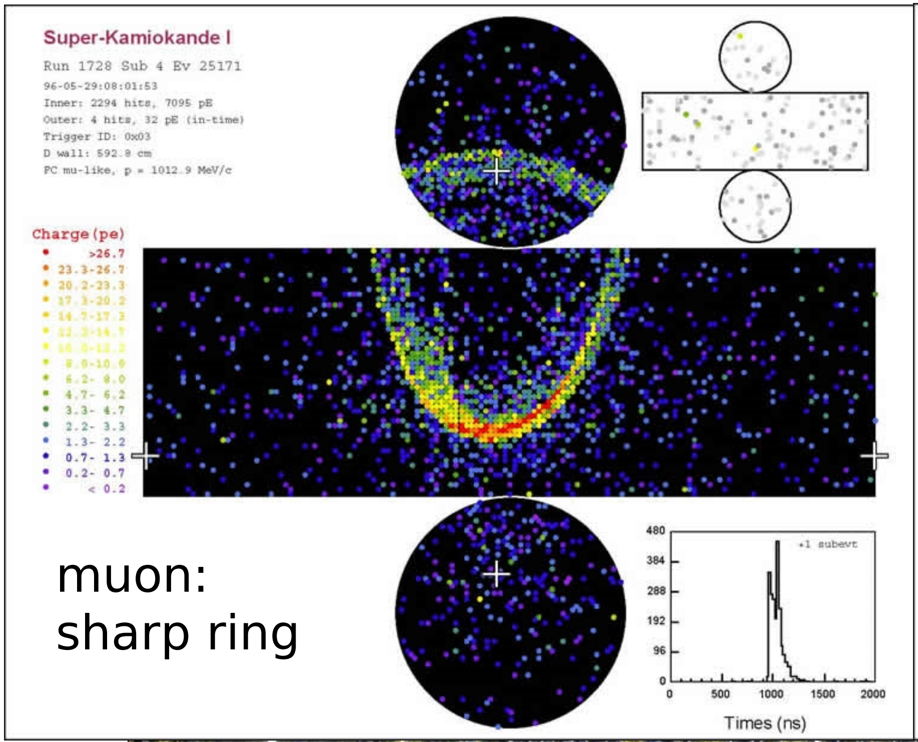
Backgrounds

- Cosmic ray muons
  - Go deep
  - Look down
    - therefore, **northern** hemisphere telescope sees **southern** sky, and vice versa
- Atmospheric neutrinos
  - one person’s signal is another’s background!
  - irreducible, but steeper spectrum than high-energy astrophysical neutrinos

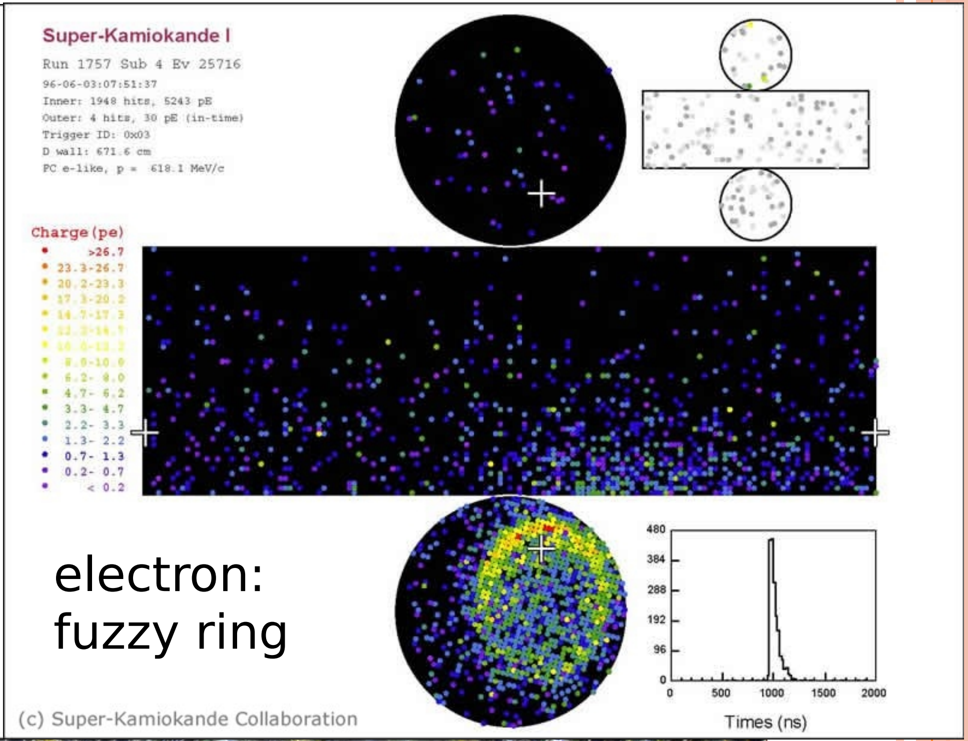




Particle ID: Super-Kamiokande

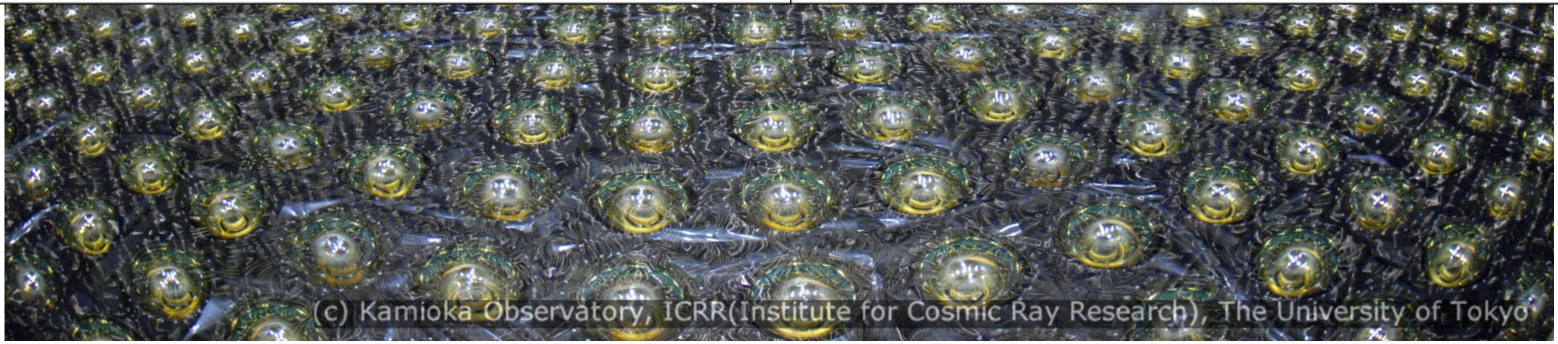


muon:
sharp ring



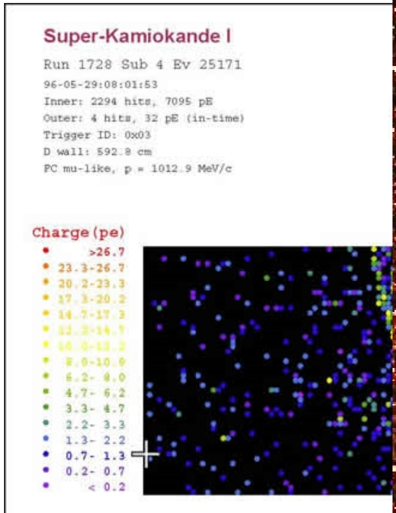
electron:
fuzzy ring

(c) Super-Kamiokande Collaboration



(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

Particle



Super-Kamiokande I

Run 1728 Sub 4 Ev 25171

96-05-29:08:01:53

Inner: 2294 hits, 7095 pE

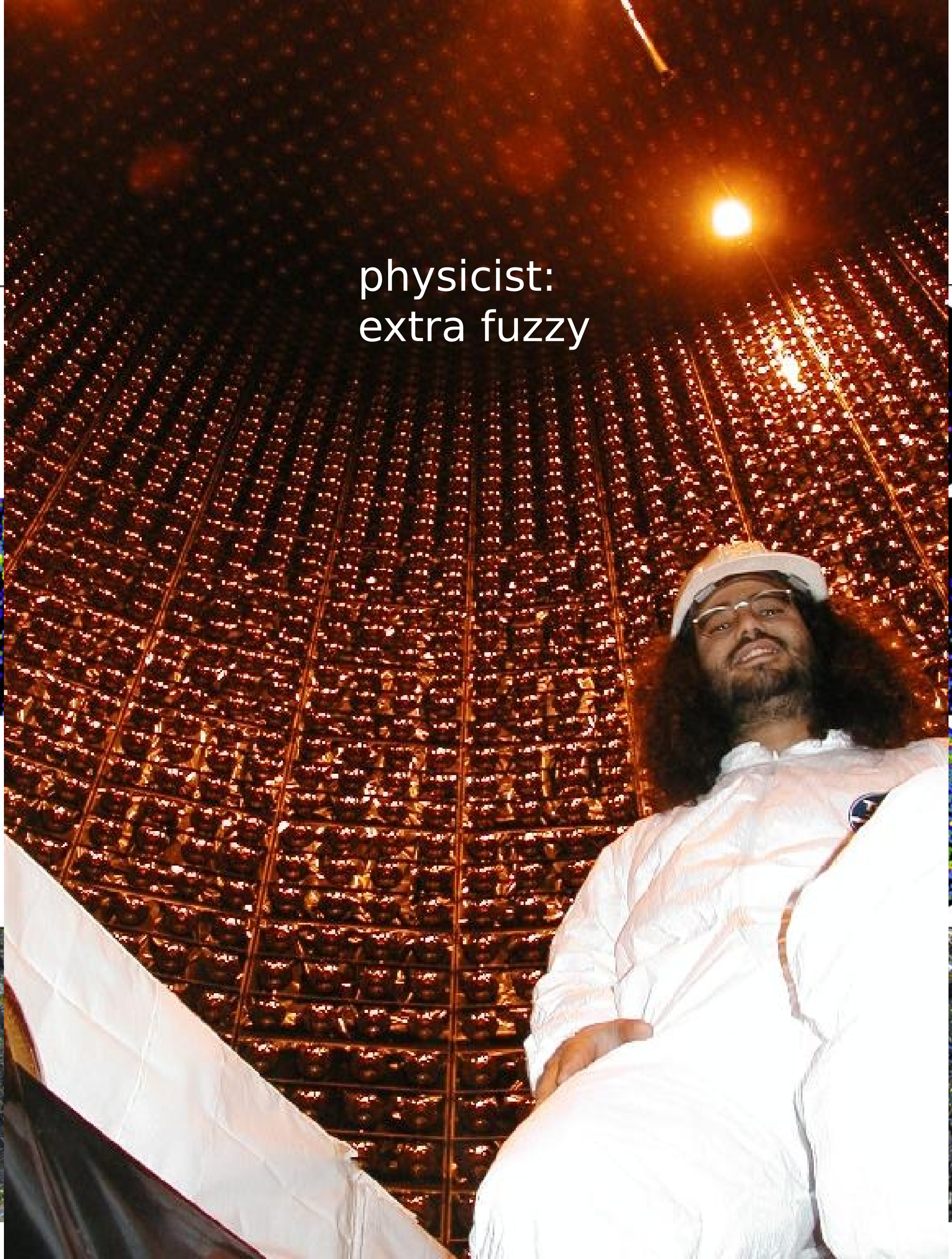
Outer: 4 hits, 32 pE (in-time)

Trigger ID: 0x03

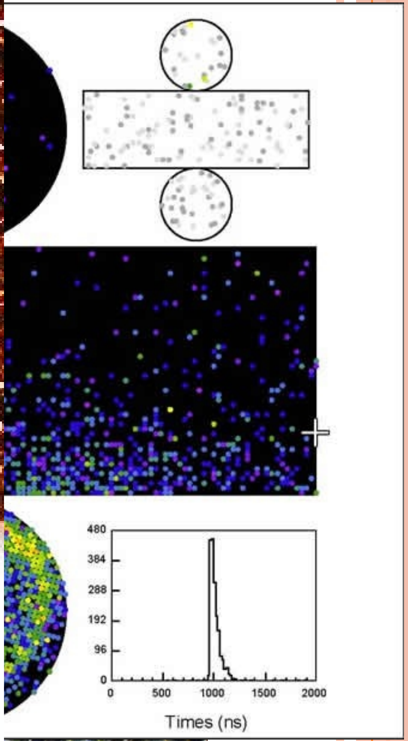
D wall: 592.8 cm

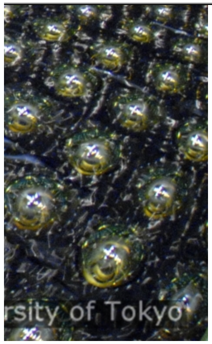
PC mu-like, p = 1012.9 MeV/c

muon:
sharp ring



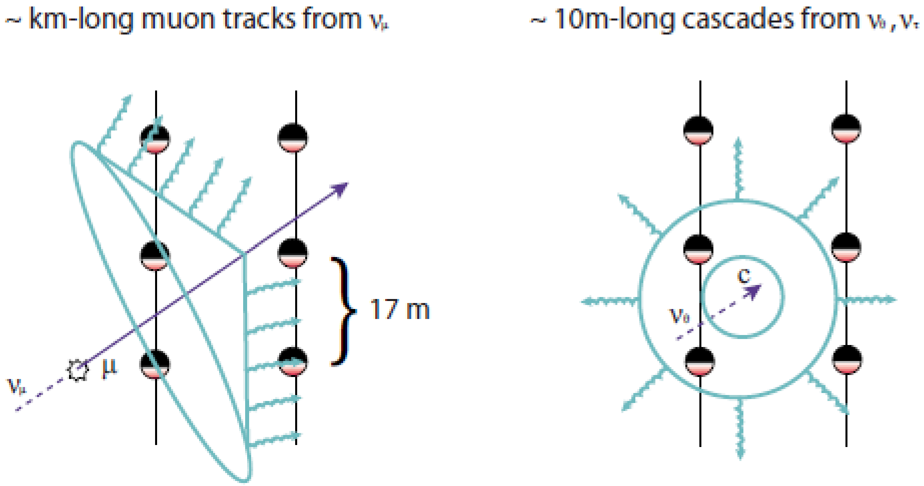
physicist:
extra fuzzy

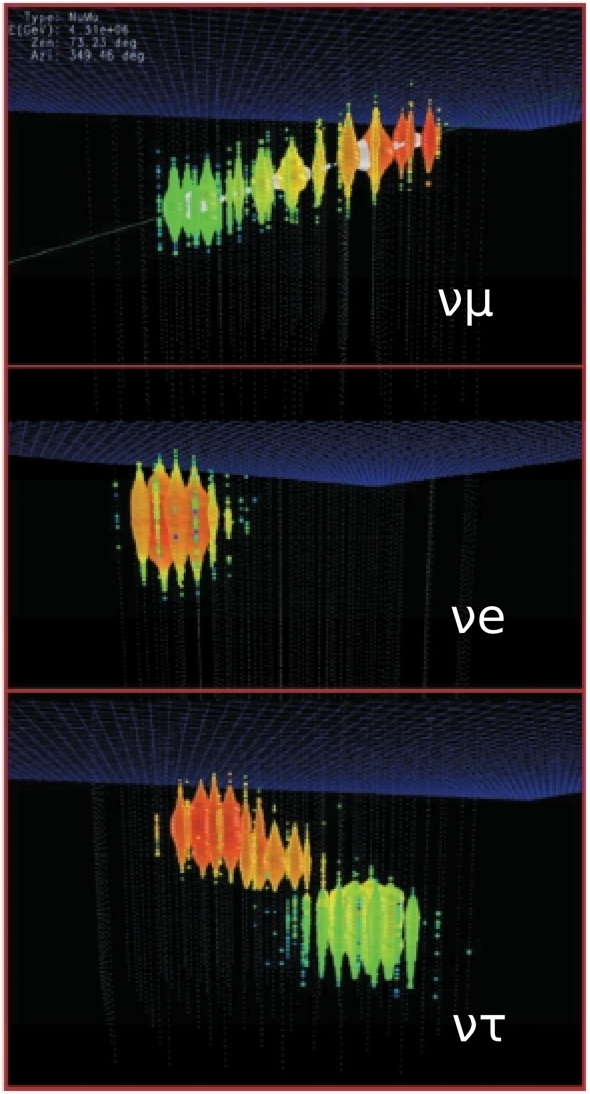




sity of Tokyo

Particle ID: IceCube

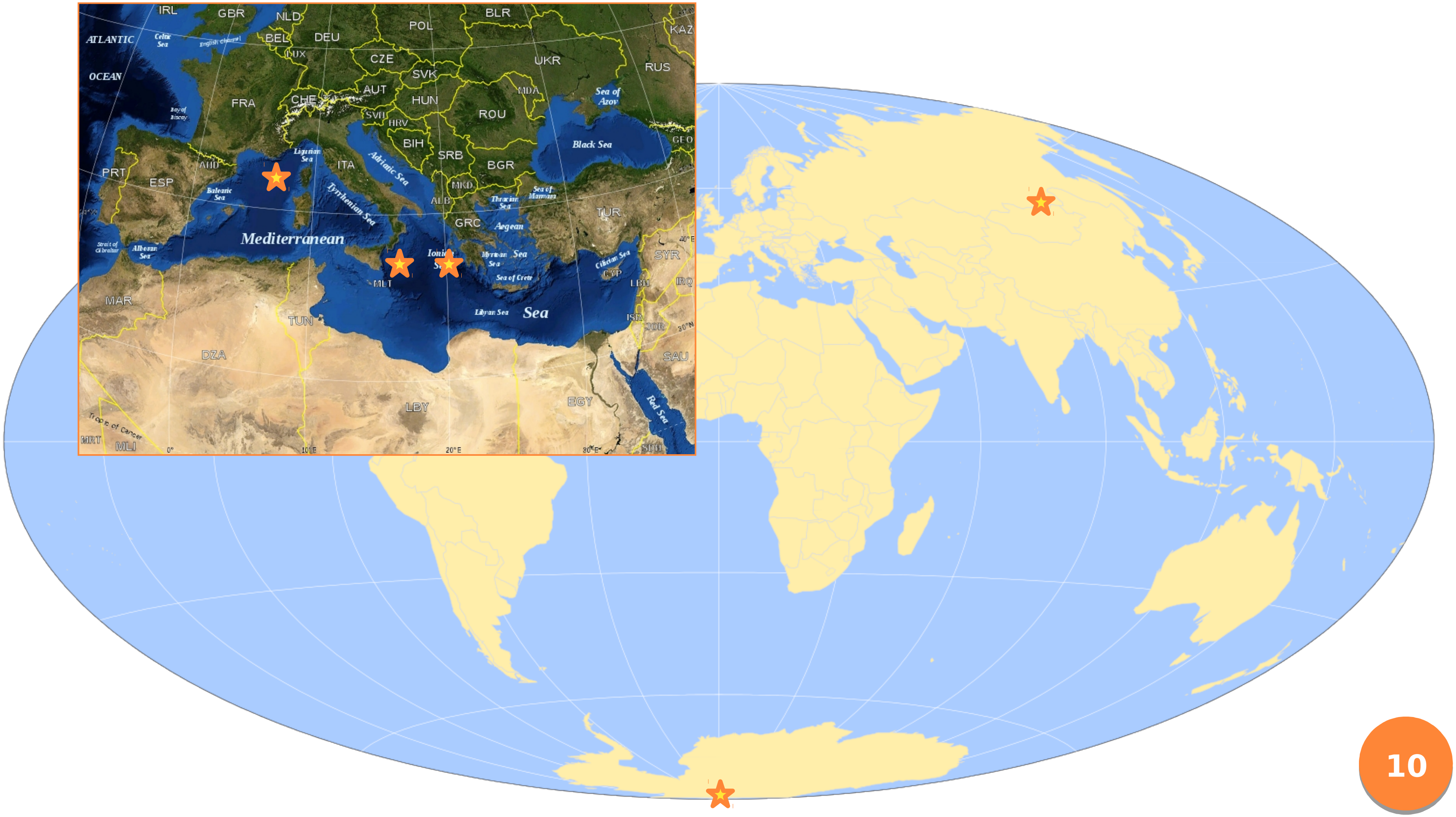




“double-bang” ντ event:
initial signal from CC interaction,
later one from τ decay

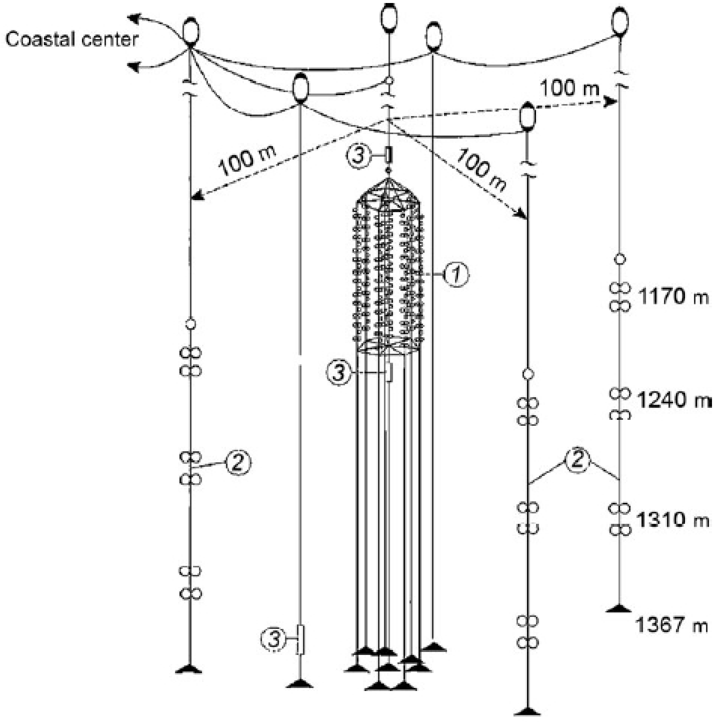
Halzen & Klein, *Rev. Sci. Inst.* **81** (2010) 081101

High-Energy Neutrino Telescopes



Lake Baikal

1. Central core (NT200) with 96 pairs of OMs on 8 strings
2. Outer ring with 3 additional strings each equipped with 6 OM pairs
3. Lasers for calibration

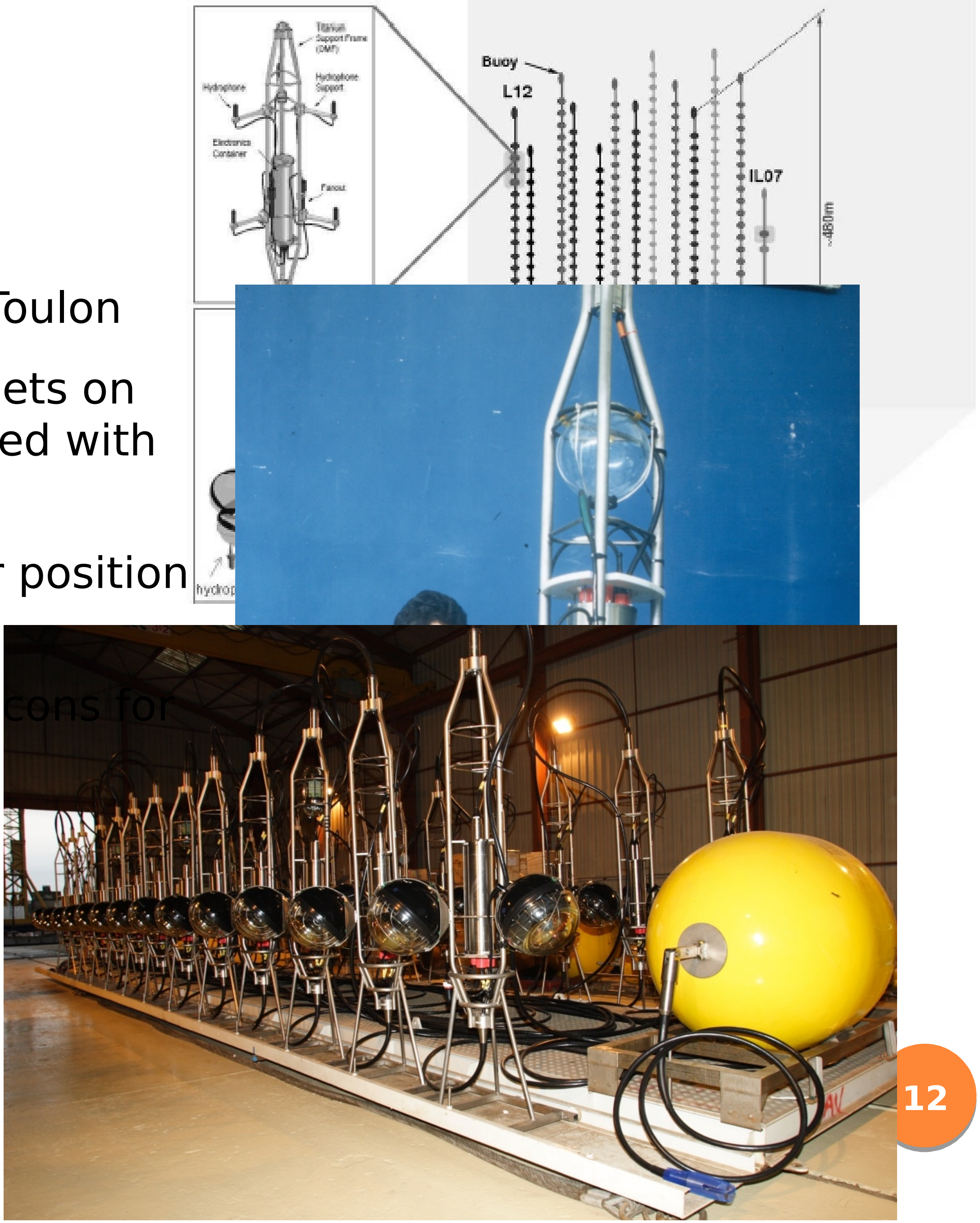



Deployment of the Neutrino Telescope with an electric winch (April, 2004)

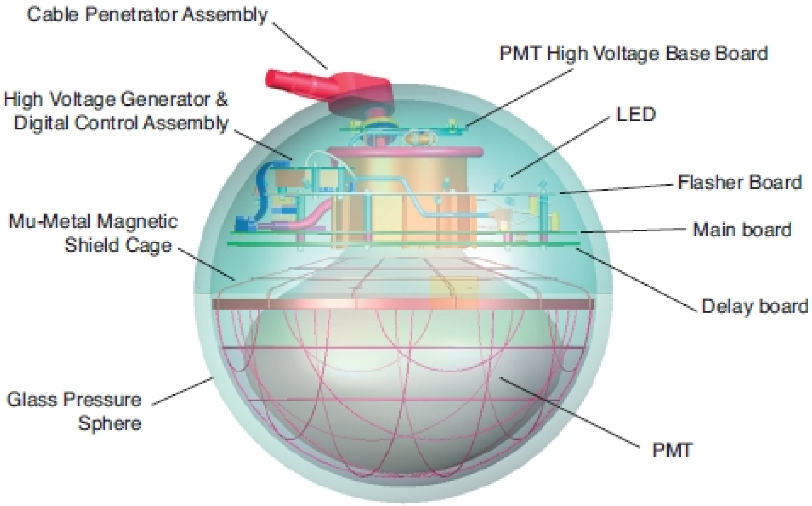
Each OM equipped with 37-cm PMT

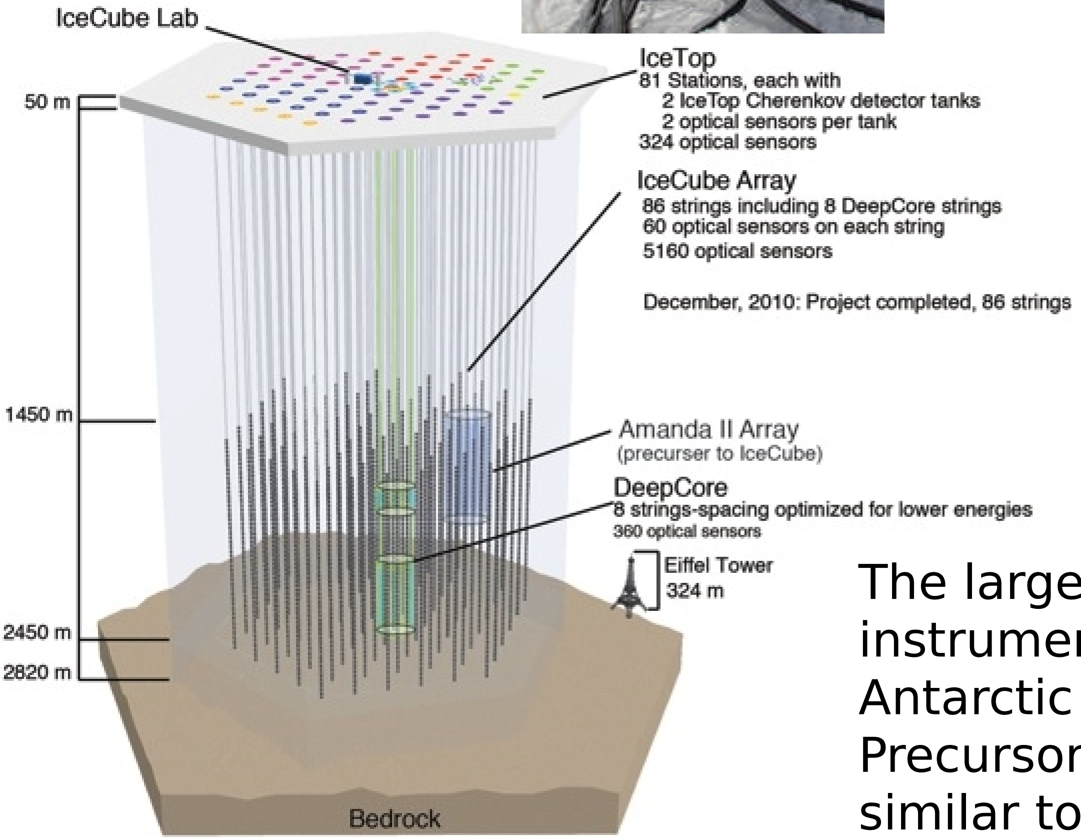
ANTARES

- 2475 m deep, 42 km off Toulon
- 885 OMs arranged in triplets on 12 lines; each OM equipped with 10” PMT
- Acoustic transponders for position monitoring
- LED and laser optical beacons for calibration



IceCube





The largest existing detector, instrumenting 1 km^3 of Antarctic ice.
Precursor, AMANDA II, very similar to ANTARES in size and sensitivity.

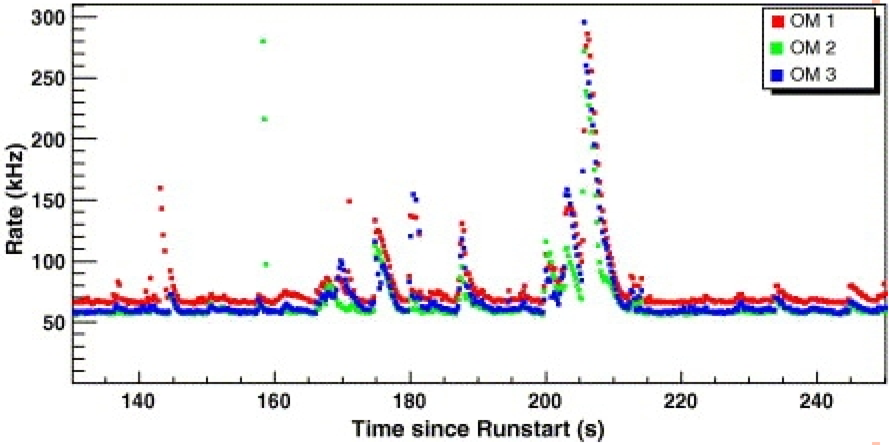
Medium Properties

Property	**Lake Baikal**	**Mediterranean (ANTARES)**	**Antarctic ice**
Absorption length (m)	20−24	50−70 (blue)	~100
Scattering length (m)	30−70	230−300 (blue)	~20
Depth	1370	2475	2450
Noise	Quiet	40K, bioluminescence	Quiet
Retrieve/ redeploy	Yes	Yes	No

Long scattering length for ANTARES implies better angular resolution; long absorption length for IceCube implies sparser instrumentation.

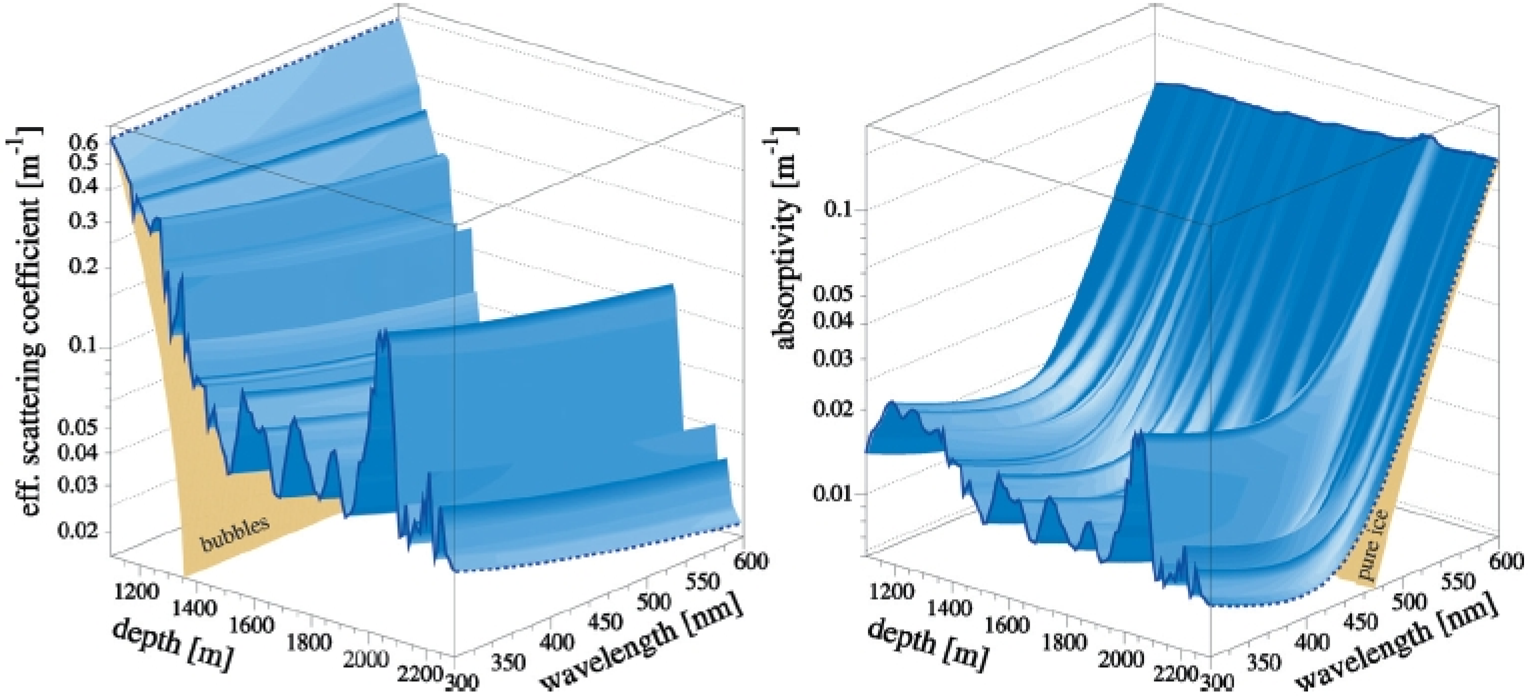
Quiet environments imply potentially useful data from singles rates.

Background in Antares



- Three components
  - steady background of ~60 kHz
  - slowly varying contribution from bioluminescence, probably bacterial
  - short bursts of strong bioluminescence, probably from larger organisms
- Correlated within a single storey, but not over long distances
  - minimal influence on tracking efficiency
  - does probably preclude use of singles rate, e.g. for detection of low energy neutrinos from supernova

Light Transmission in IceCube

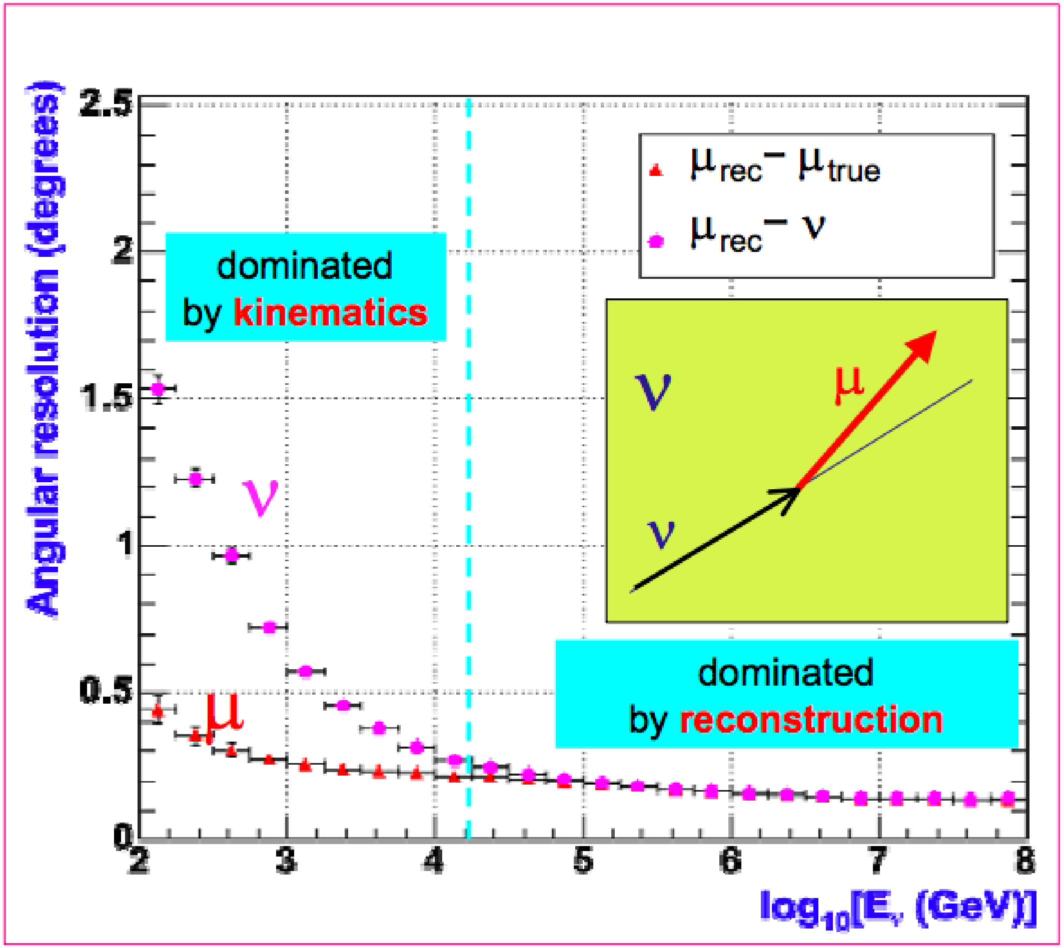


Scattering is a consequence of dust layers in the ice—function of global climate, level of volcanic activity, etc.

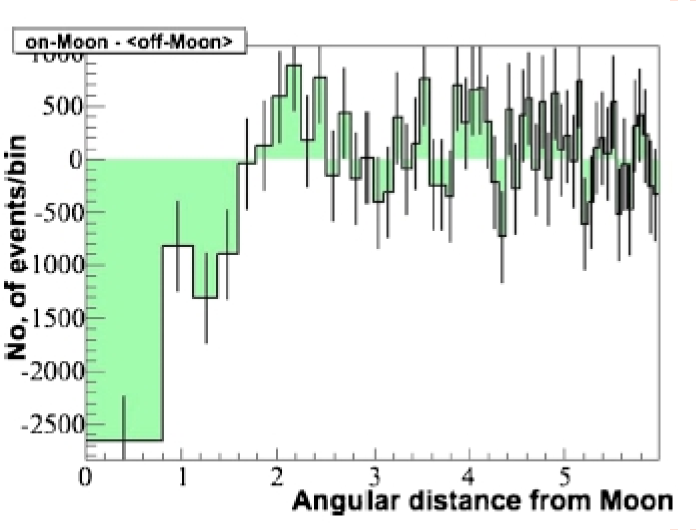
“Dust logger” measures reflected light from artificial light source just after drilling: measure scattering with few mm vertical resolution.

Note additional contribution from bubbles at shallow depths (<1400 m); IceCube deployed below this level.

Angular Resolution



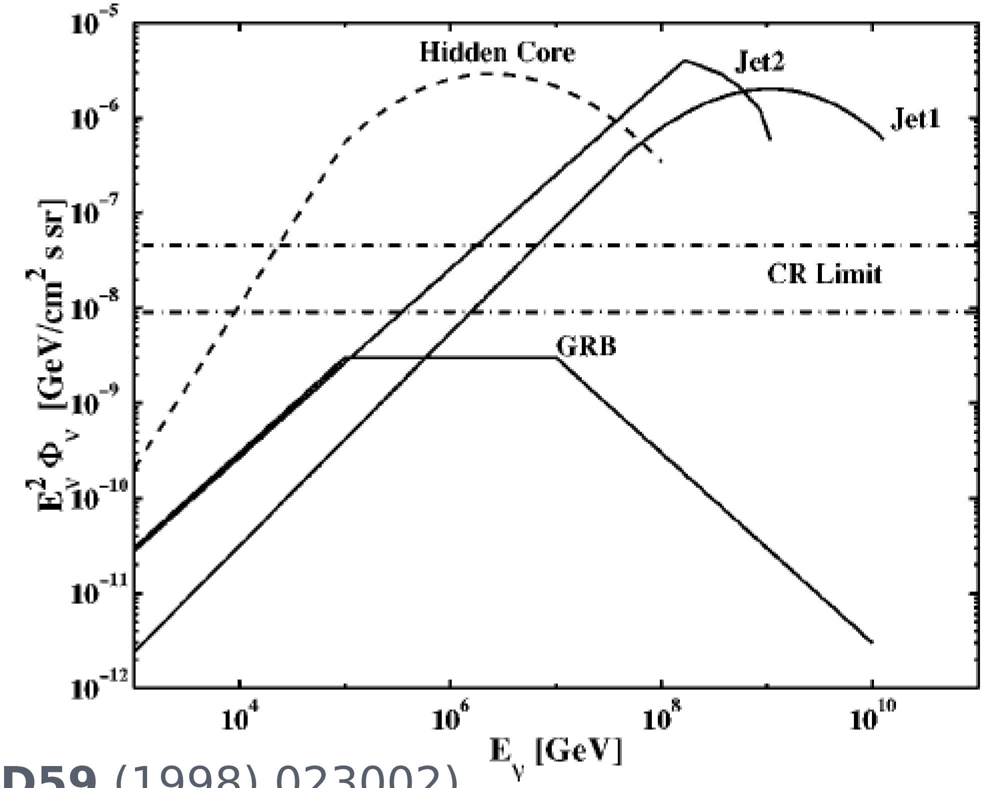
At 100 TeV: Amanda ~2°
Antares ~ 0.2°



Moon's shadow in CR muons, measured by IceCube

Expected IceCube angular resolution ~0.5°

Expected Fluxes

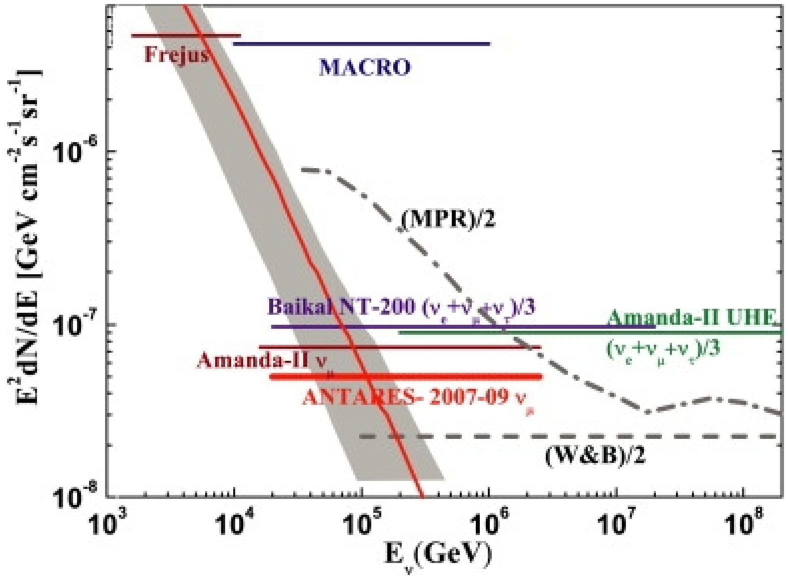


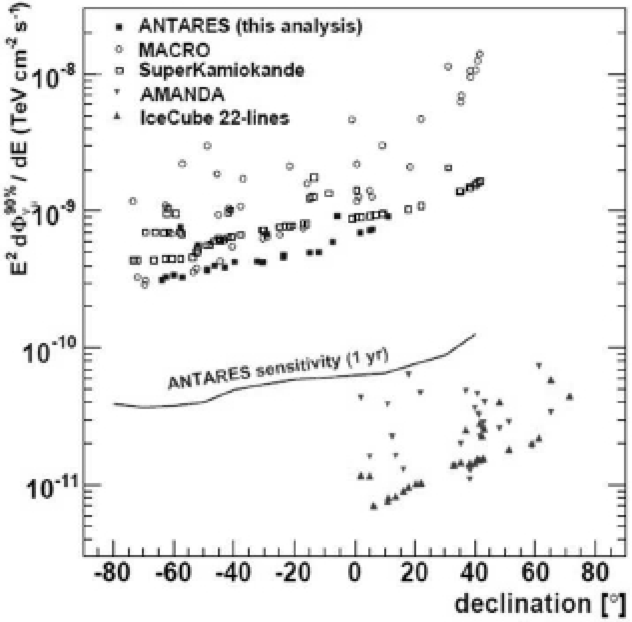
- Expect high-energy astrophysical neutrinos to be produced in proton interaction cascades
  - therefore, observed CR flux implies upper bound on neutrino flux (**Waxman-Bahcall bound**: *Phys. Rev.* **D59** (1998) 023002)
  - argument goes as follows:
  - from observed CR rate, deduce that the amount of energy emitted by astrophysical sources in the form of UHE CRs (10^{19} – 10^{21} eV) is of order 10^{37} J Mpc^{-3} yr^{-1}.
    - assume that CRs lose some fraction ε of their energy through pion photoproduction before escaping the source
    - fraction of proton energy carried by neutrino produced in this way is about 5% independent of proton energy, so neutrino energy spectrum follows scaled-down version of proton spectrum
  - resulting bound: $E\nu 2\varphi\nu < 2\times10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} for 10^{14}—10^{16} eV ν

Results

Still very statistics-limited.

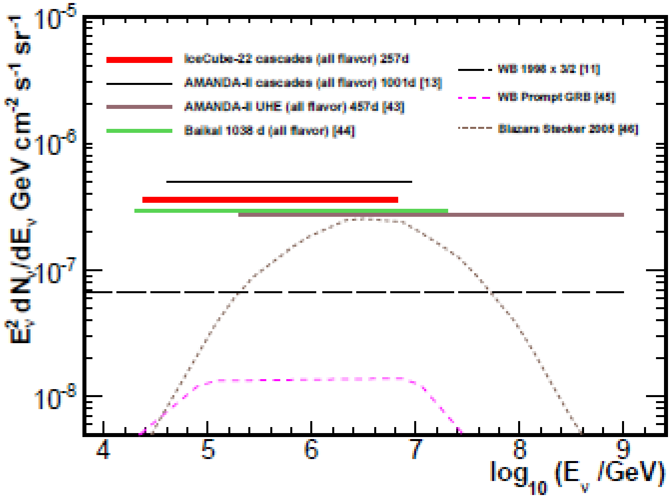
IceCube should be able to reach Waxman-Bahcall bound.





Point source search

ANTARES astro-ph/1002.0701



Limits on diffuse fluxes

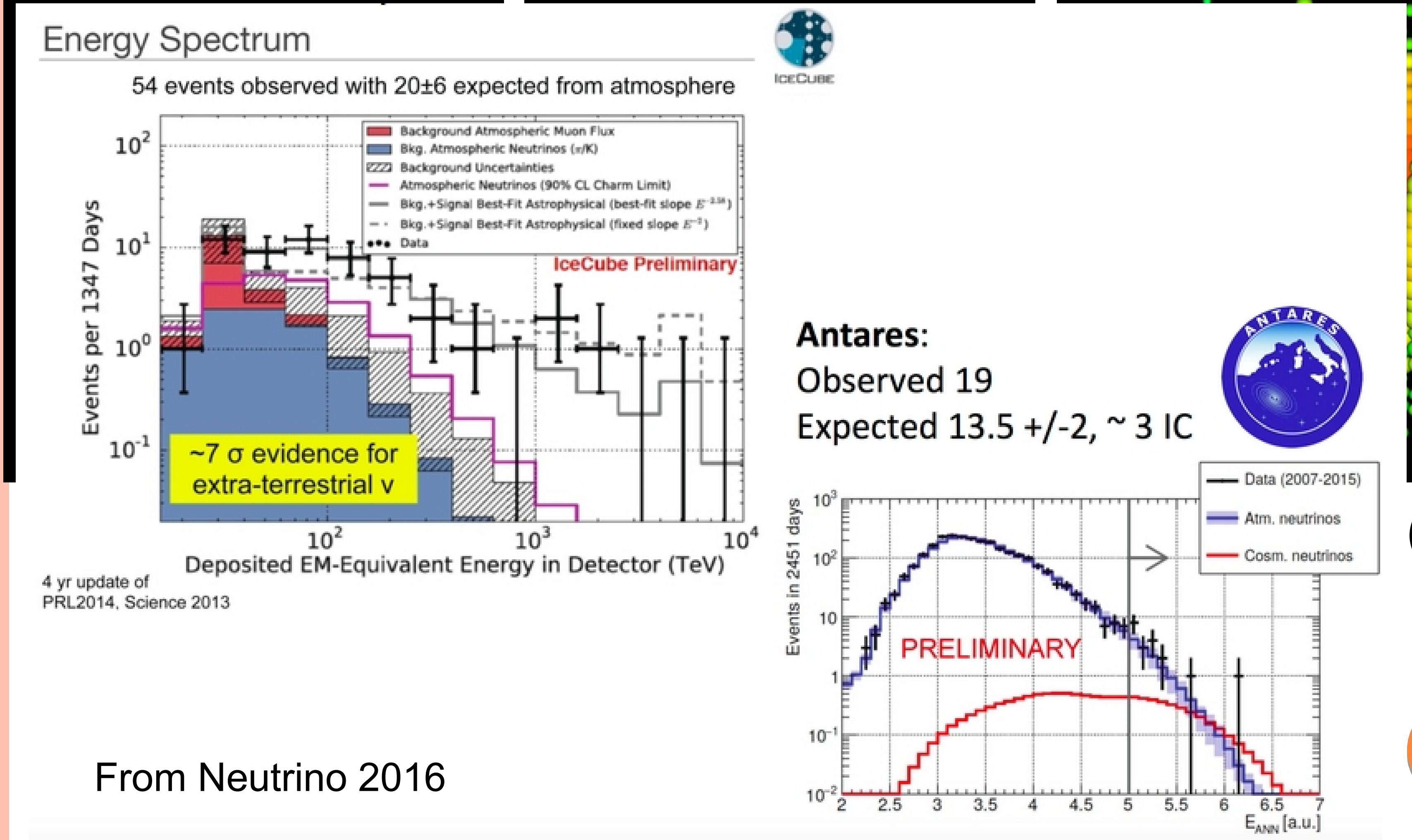
ANTARES, *Phys. Lett.* **B696** (2011) 16

IceCube, astro-ph/1101.1692

More Results

Statistical evidence for HE astrophysical neutrinos found in IceCube

Sources not yet identified…

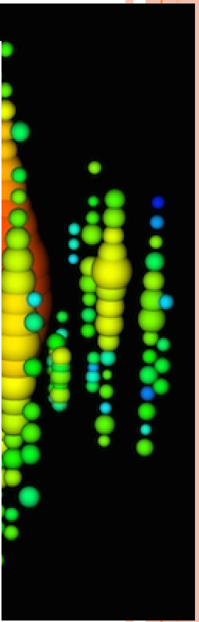


Energy Spectrum

54 events observed with 20±6 expected from atmosphere

4 yr update of
PRL2014, Science 2013

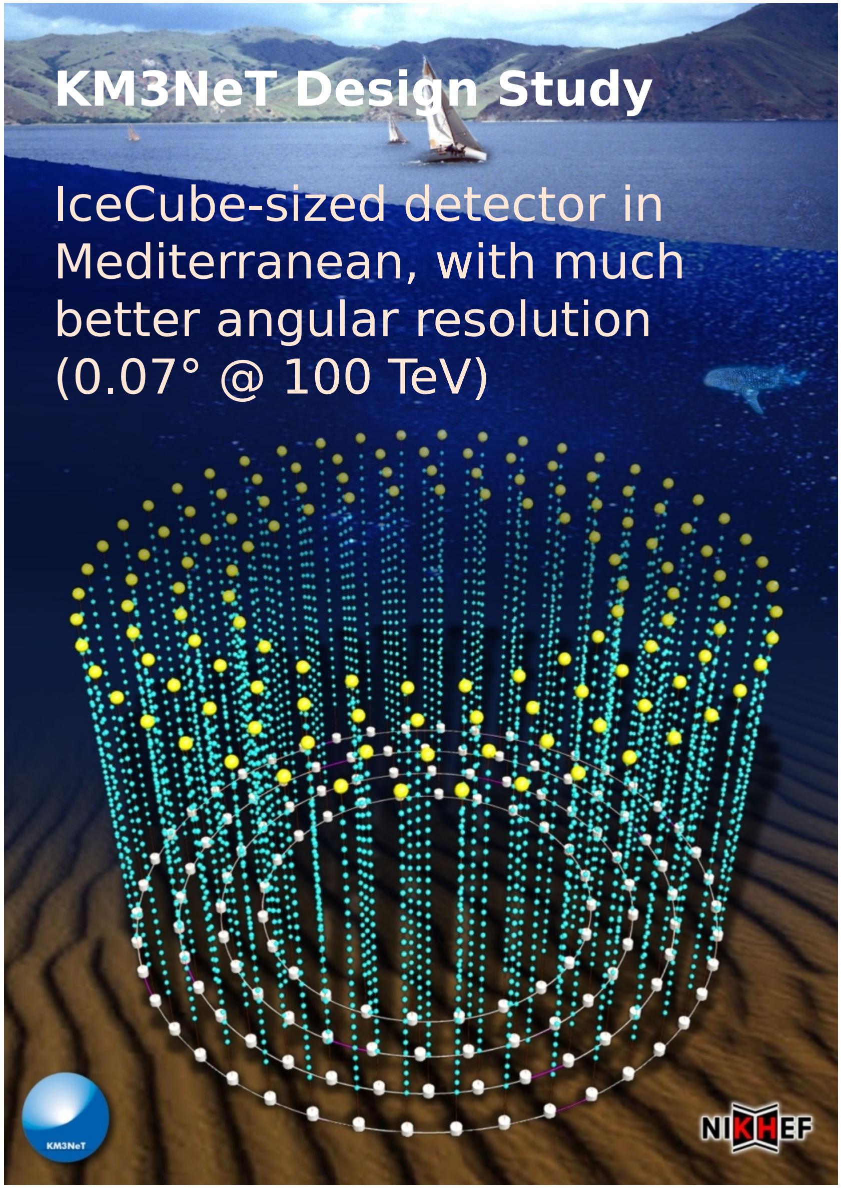
Antares:
Observed 19
Expected 13.5 +/-2, ~ 3 IC



(2014)

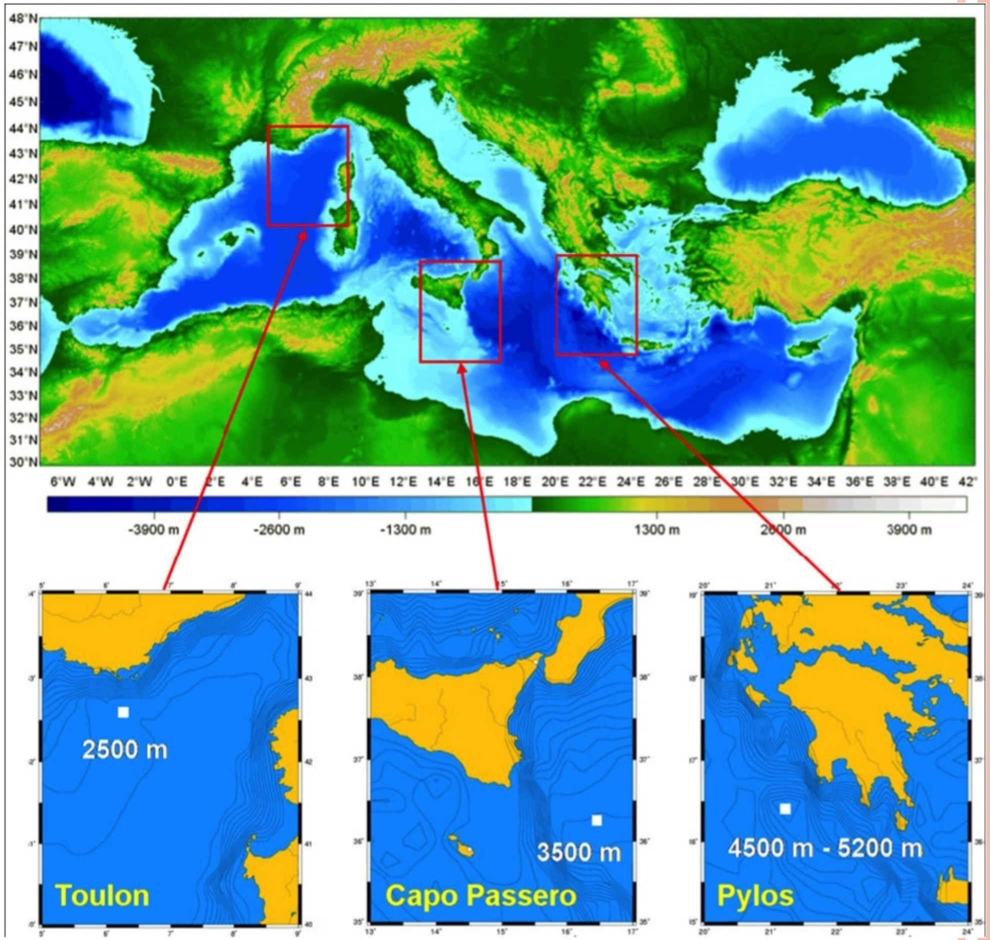
From Neutrino 2016

Next Generation Water Cherenkovs

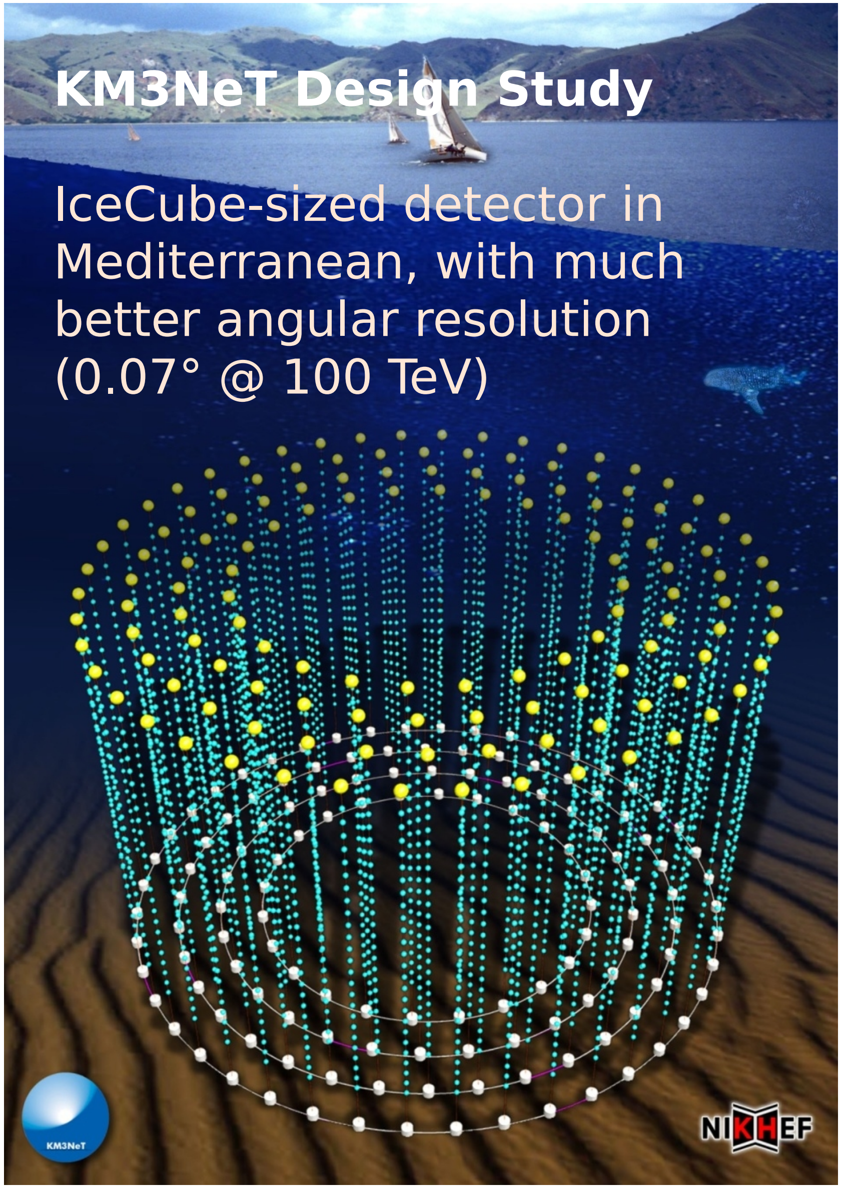


KM3NeT Design Study

IceCube-sized detector in Mediterranean, with much better angular resolution (0.07° @ 100 TeV)



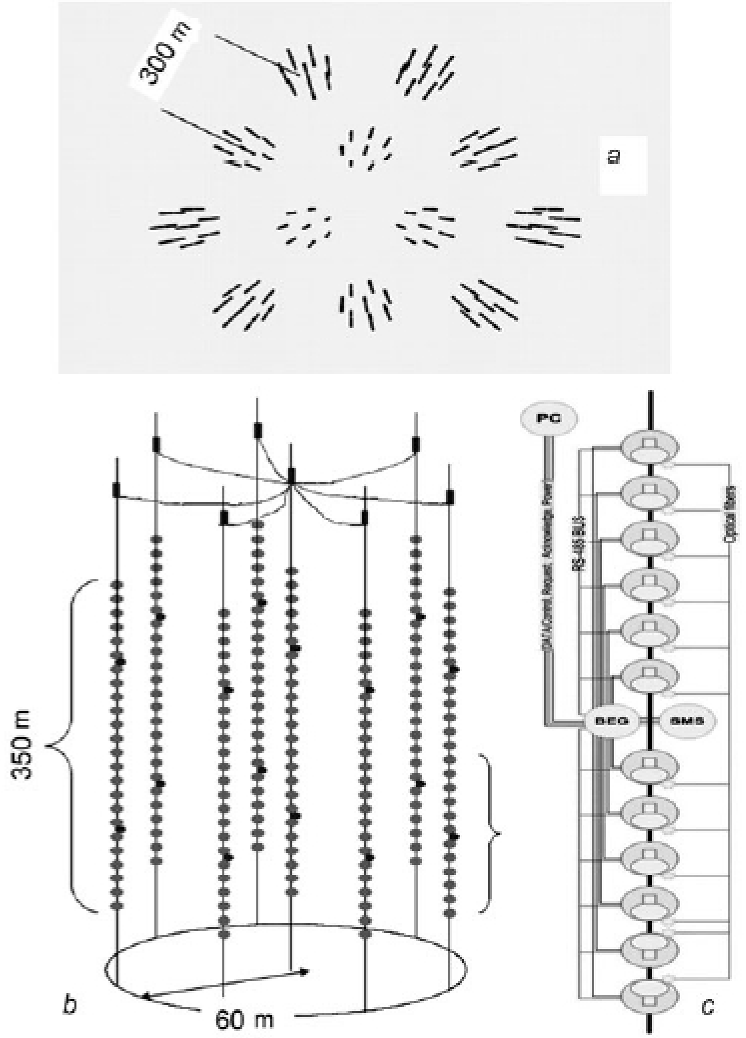
Next Generation Water Cherenkovs



KM3NeT Design Study

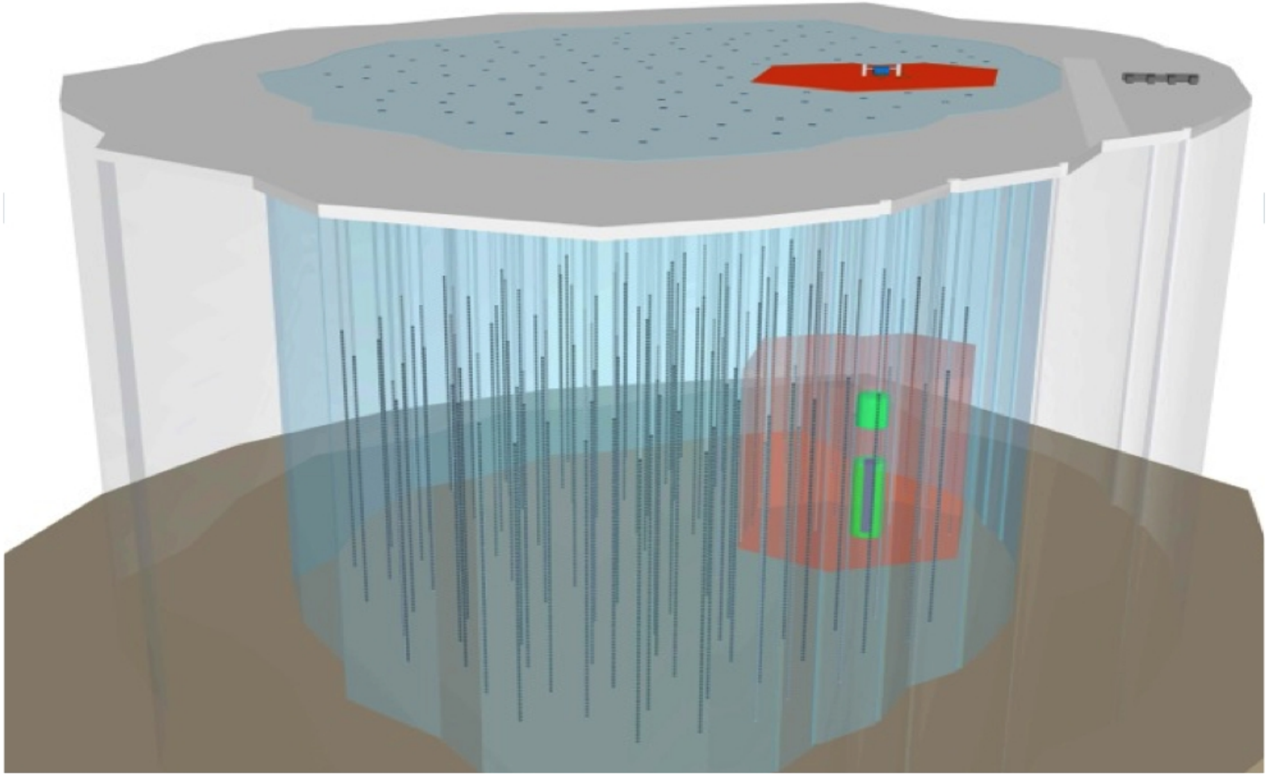
IceCube-sized detector in Mediterranean, with much better angular resolution (0.07° @ 100 TeV)

Baikal-1000



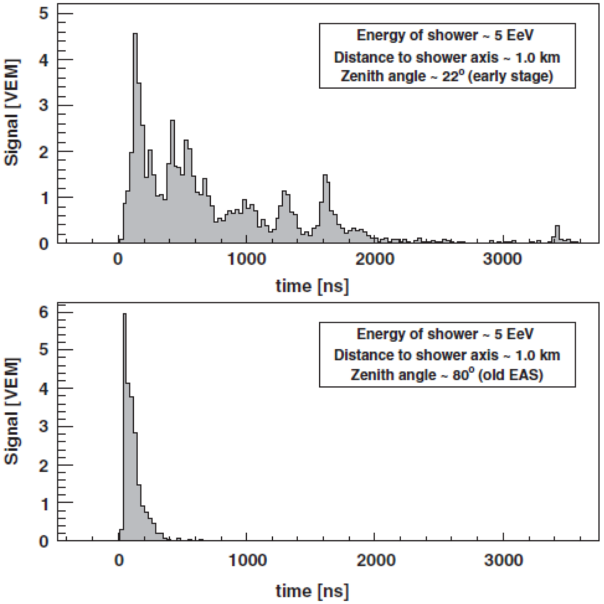
Next Generation Water Cherenkovs

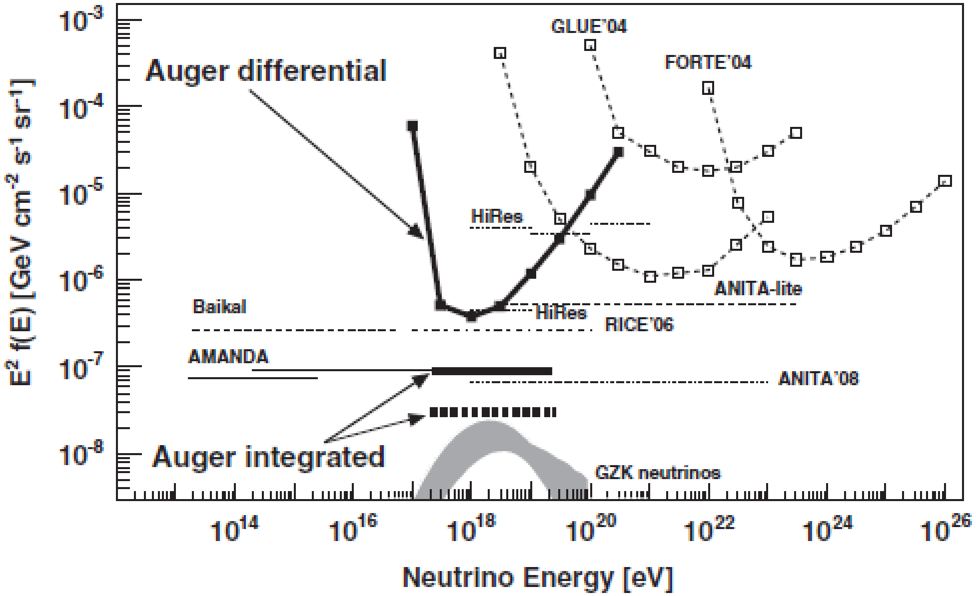
IceCube Gen2:



Tau-Neutrino Detection By Air Showers

- Earth-skimming ντ interacts in Earth’s crust to produce τ
- τ decay in atmosphere initiates characteristic air shower
  - shower appears to be in early stage of development—typical horizontal shower is “old”
  - searched for by Auger—no signal (*PRD* **79** (2009) 102001)



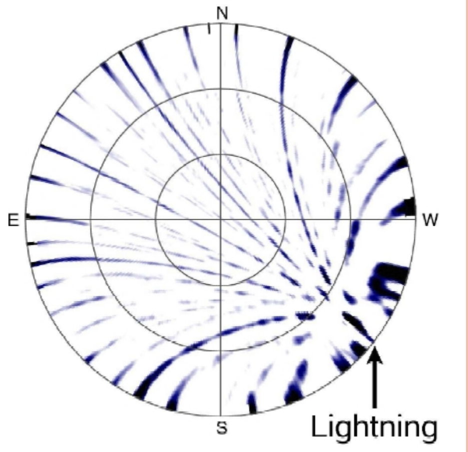


High Energy Astroparticle Physics

New Detection Techniques

Radio-Frequency Detection of Air Showers and Neutrinos

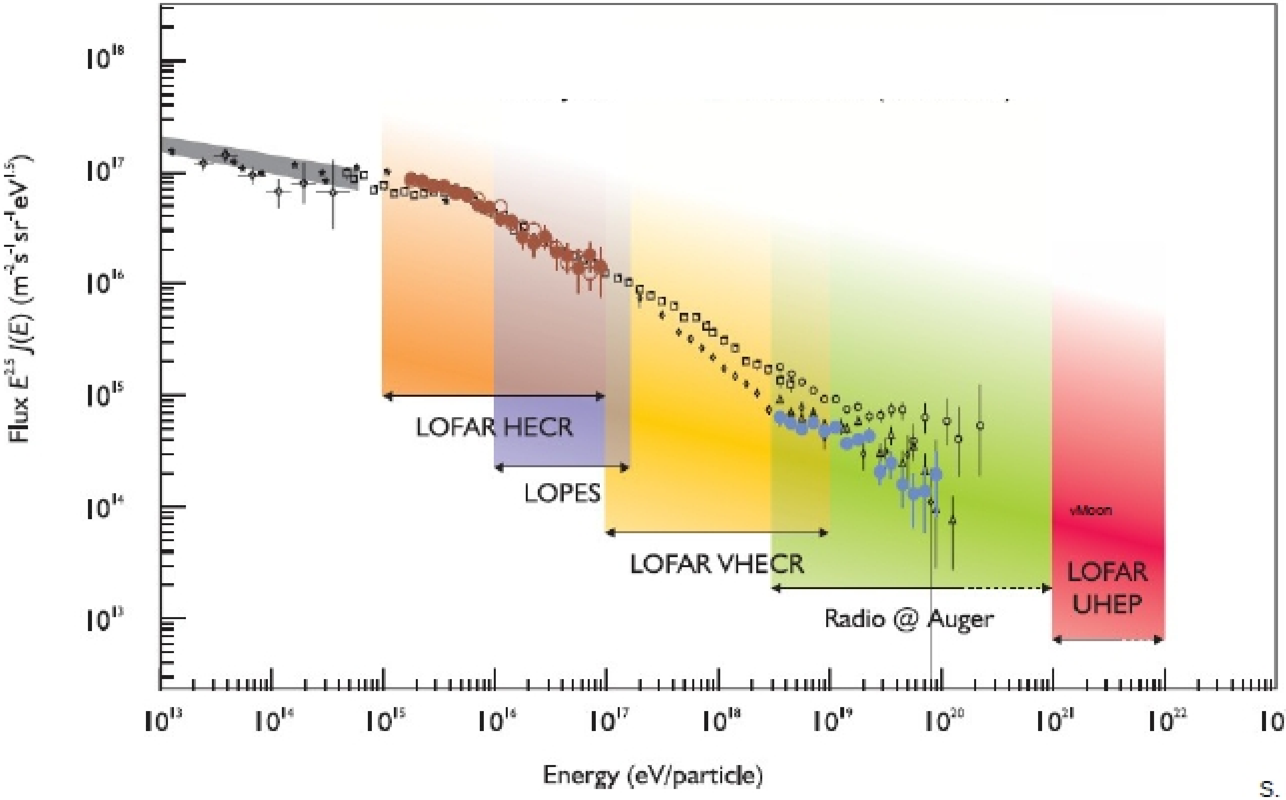
- Geosynchrotron emission (10−100 MHz)
  - synchrotron radiation from air-shower particles gyrating in Earth’s magnetic field
  - advantages over fluorescence:
    - very high duty cycle (only wiped out by thunderstorms)
    - low attenuation (so, large effective area)
  - disadvantages:
    - interference (need radio-quiet sites)
    - high threshold (10^{17} eV)



- Radio Cherenkov (Askaryan effect) (0.1−2 GHz)
  - Cherenkov emission from neutrino-induced showers because of net negative charge
    - initially neutral shower develops ~20% negative bias because of annihilation of e^+ and additional e^- from Compton scattering etc.
    - requires dense, radio-transparent medium
      - not air, not water

Geosynchrotron Emission

- Studies run in association with Auger and KASCADE CR ground arrays
- A declared key science goal of LOFAR Collaboration



S. Lafebre

LOFAR

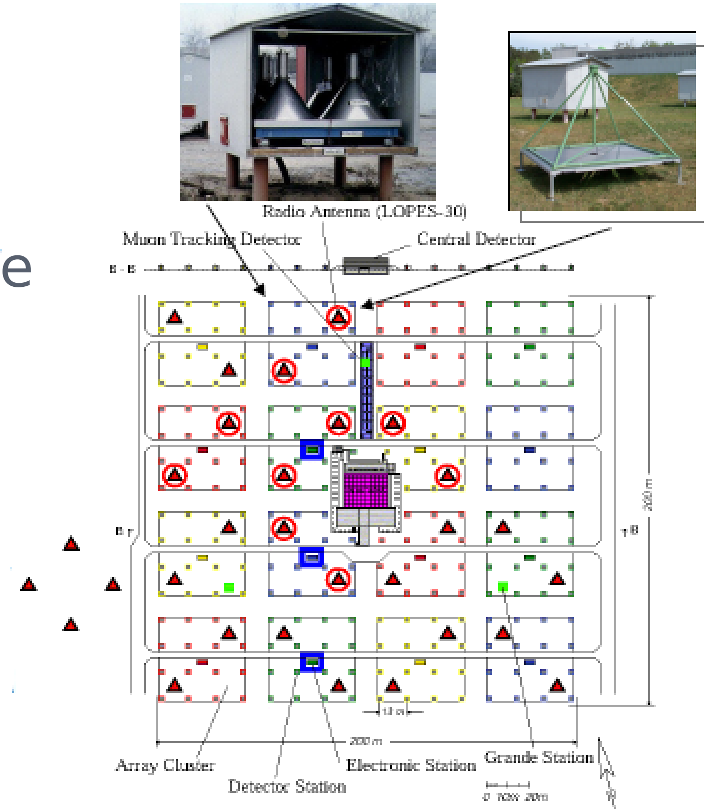
LOw Frequency Array Radio (based in the Netherlands)

Mostly a radio astronomy facility, but good prospects for radio detection of UHECRs (see LOPES/KASCADE).

Also good for gravitational wave follow-up (excellent wide-field coverage)

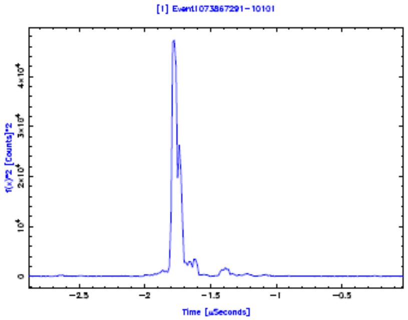
LOPES/KASCADE

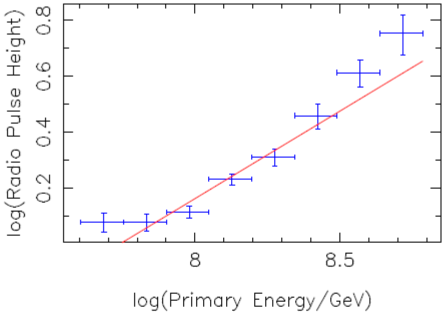
- KASCADE: scintillator-based ground array
- LOPES (LOFAR PrototypE Station)
  - initially 10, now 30, low-frequency RF antennas triggered by KASCADE “large event” trigger
  - KASCADE reconstruction provides input to LOPES recon:
    - core position of air shower
    - its direction
    - its size

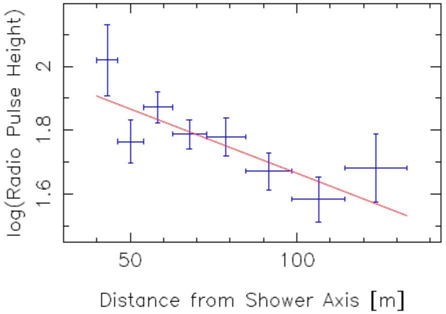


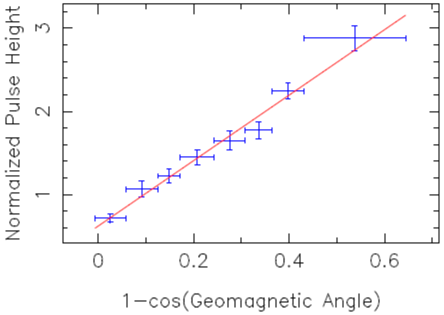
LOPES/KASCADE

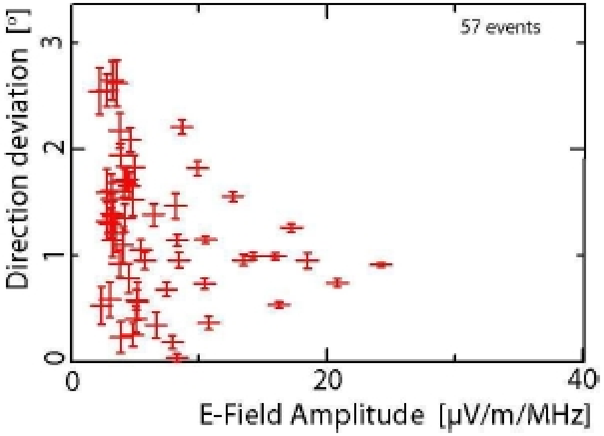
- First detection: January 2004
  - strong coherent radio signal coincident with KASCADE shower
  - reconstruction location agreed with KASCADE to 0.5°
- Extensive data sample now accrued
  - technique works well and suggested full LOFAR array (completed 2012) should be excellent CR detector





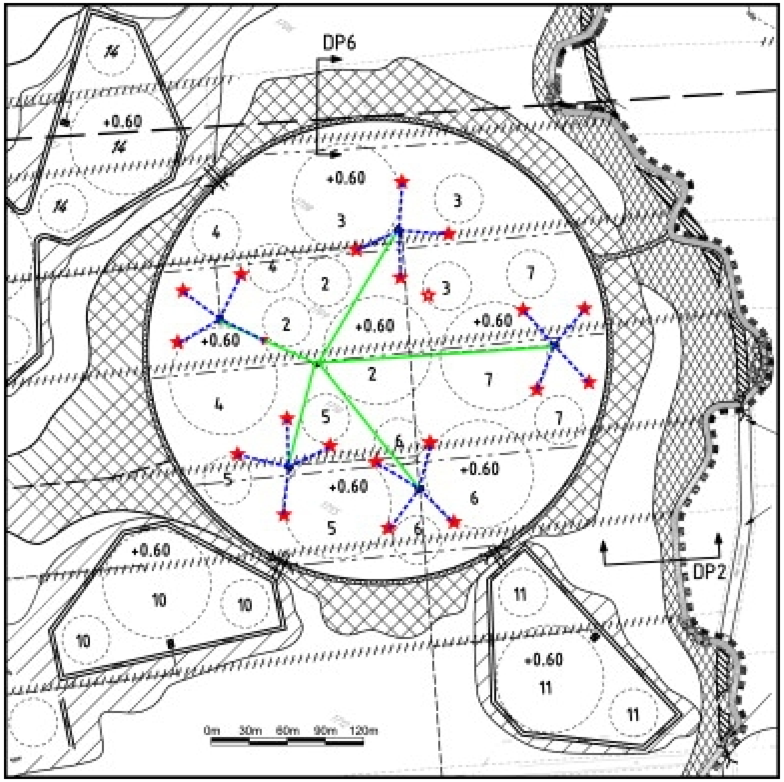






LOFAR as a cosmic ray detector

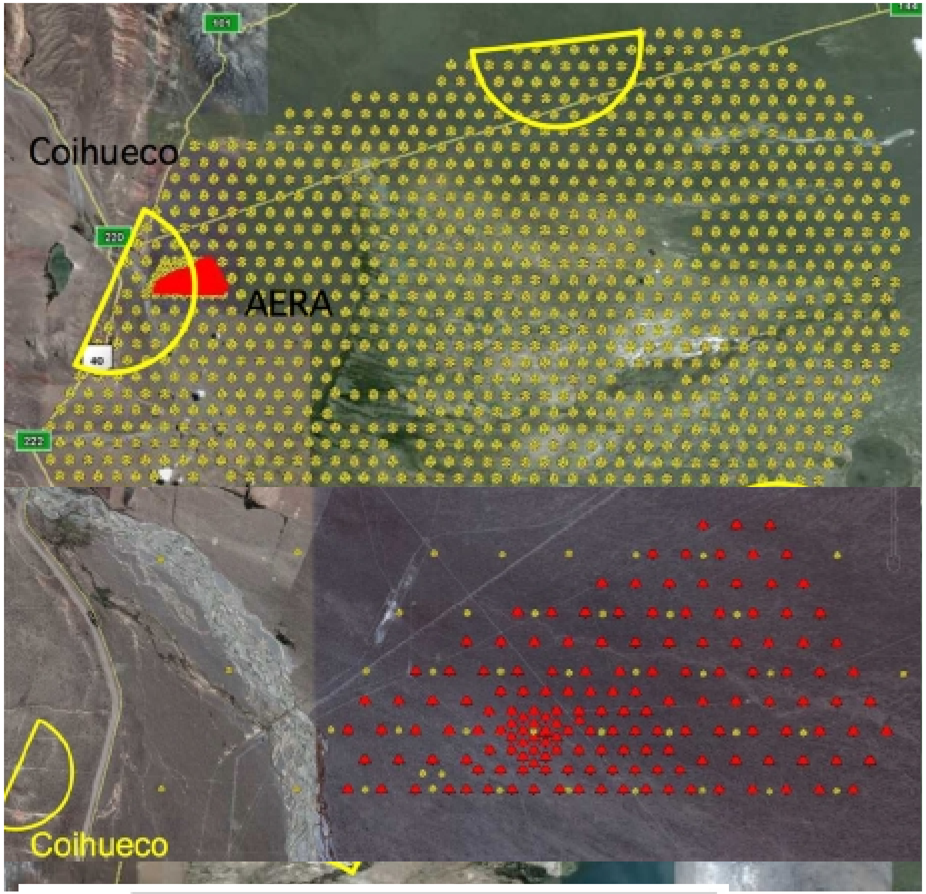
- Small scintillator-based air-shower array (LORA) set up in LOFAR core
  - plastic scintillator detectors from KASCADE, set up in 5 sets of 4
  - estimated energy resolution ~30%, angular resolution ~1%
  - combined running with LOFAR radio signals

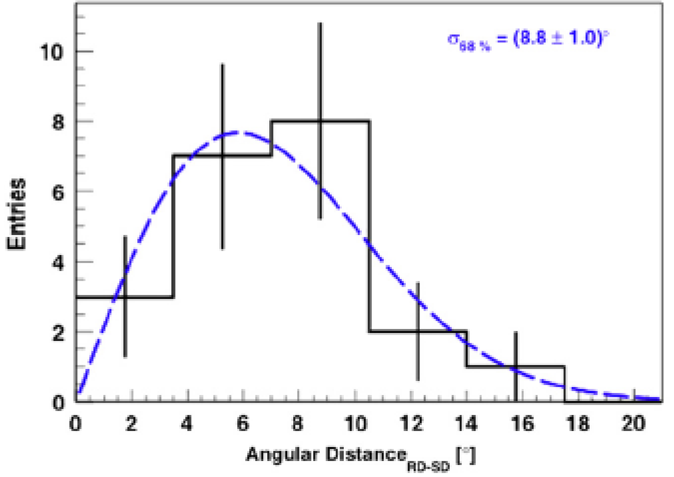


Thoudam et al., astro-ph/1102.0946v1

Auger/AERA

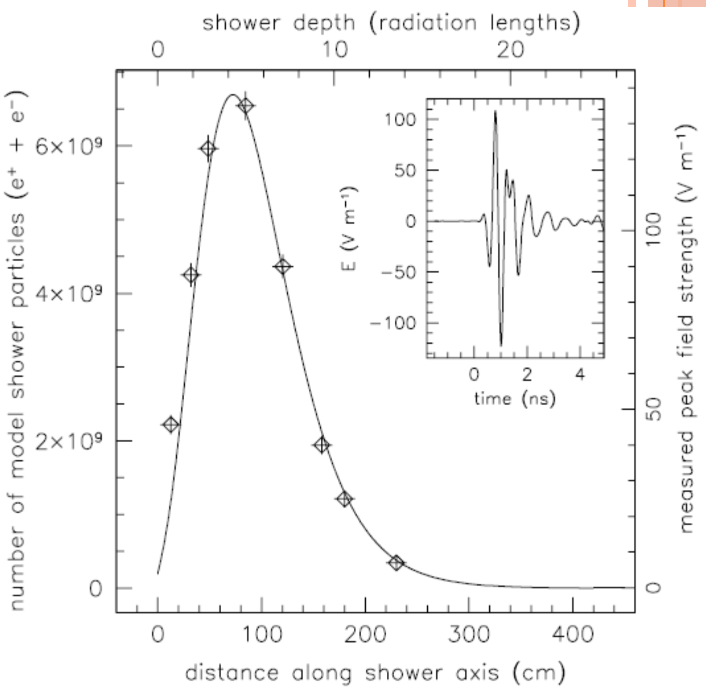
- Preliminary studies using a few radio antennas at the Auger site gave promising results
- Plan to instrument 20 km^2 near Coihueco fluorescence telescope with 150 autonomous self-triggering radio antennas
    - 5000 events/year expected, 1000 above 10^{18} eV
- Currently 124 radio stations covering 6 km^2 aperture

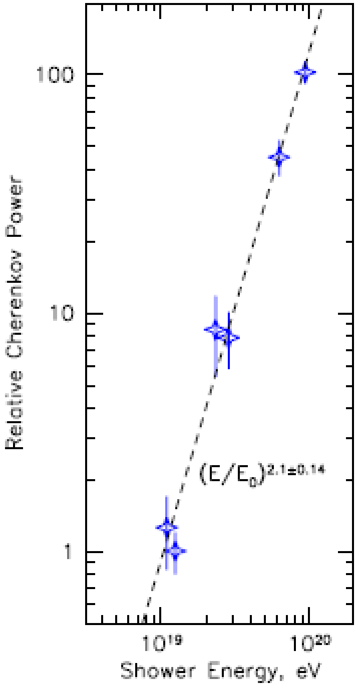




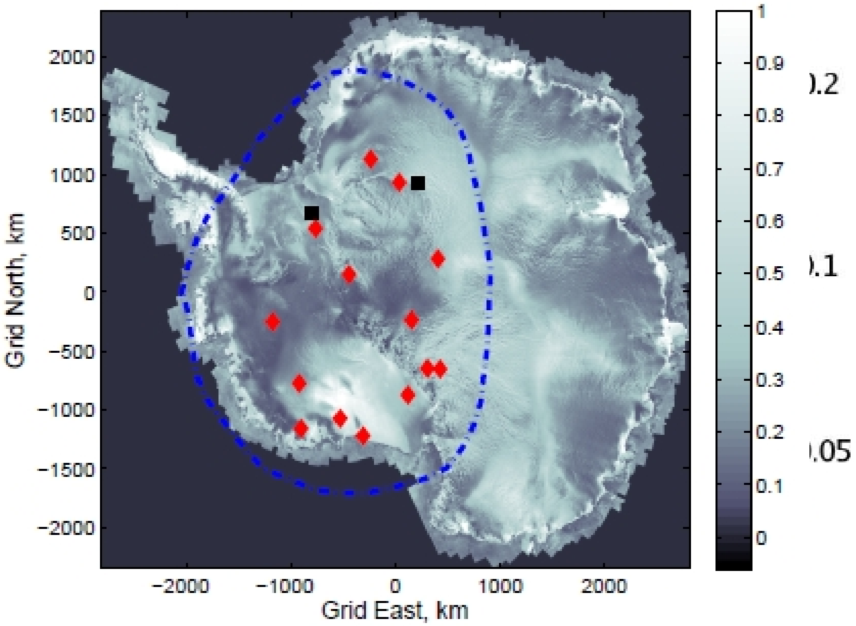
Askaryan Effect

- Effect demonstrated in sand(2000) rock salt (2004) and ice (2006)
  - all done in laboratory at SLAC
- Applications to neutrino detection
  - using the Moon as target
    - GLUE (detectors are Goldstone RTs)
    - NuMoon (Westerbork array; LOFAR)
    - RESUN (EVLA)
  - using ice as target
    - FORTE (satellite observing Greenland ice sheet)
    - RICE (co-deployed on AMANDA strings, viewing Antarctic ice)
    - ANITA (balloon-borne over Antarctica, viewing Antarctic ice)





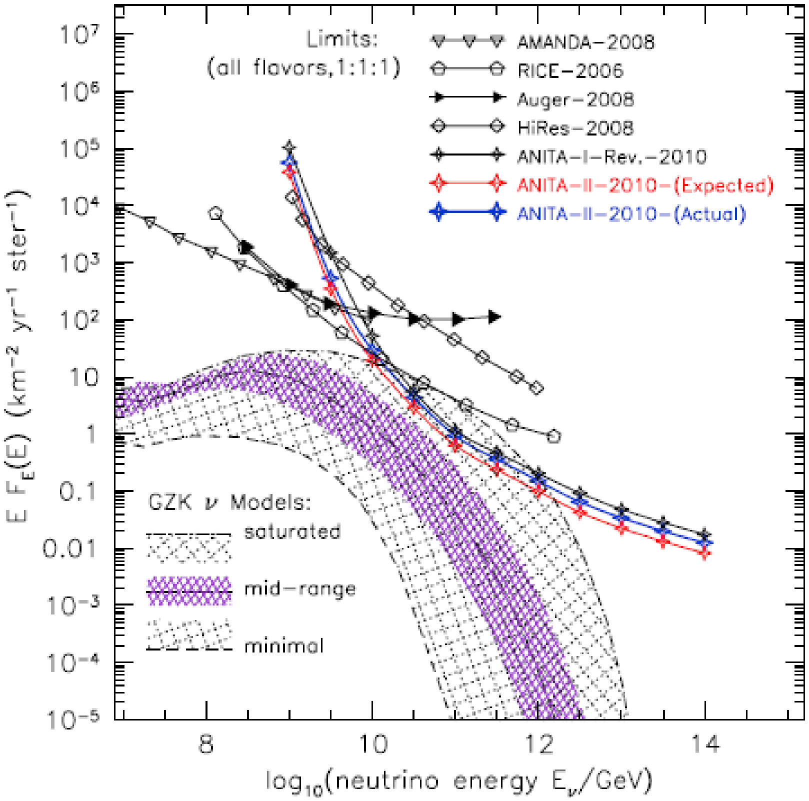
Askaryan Effect: ANITA

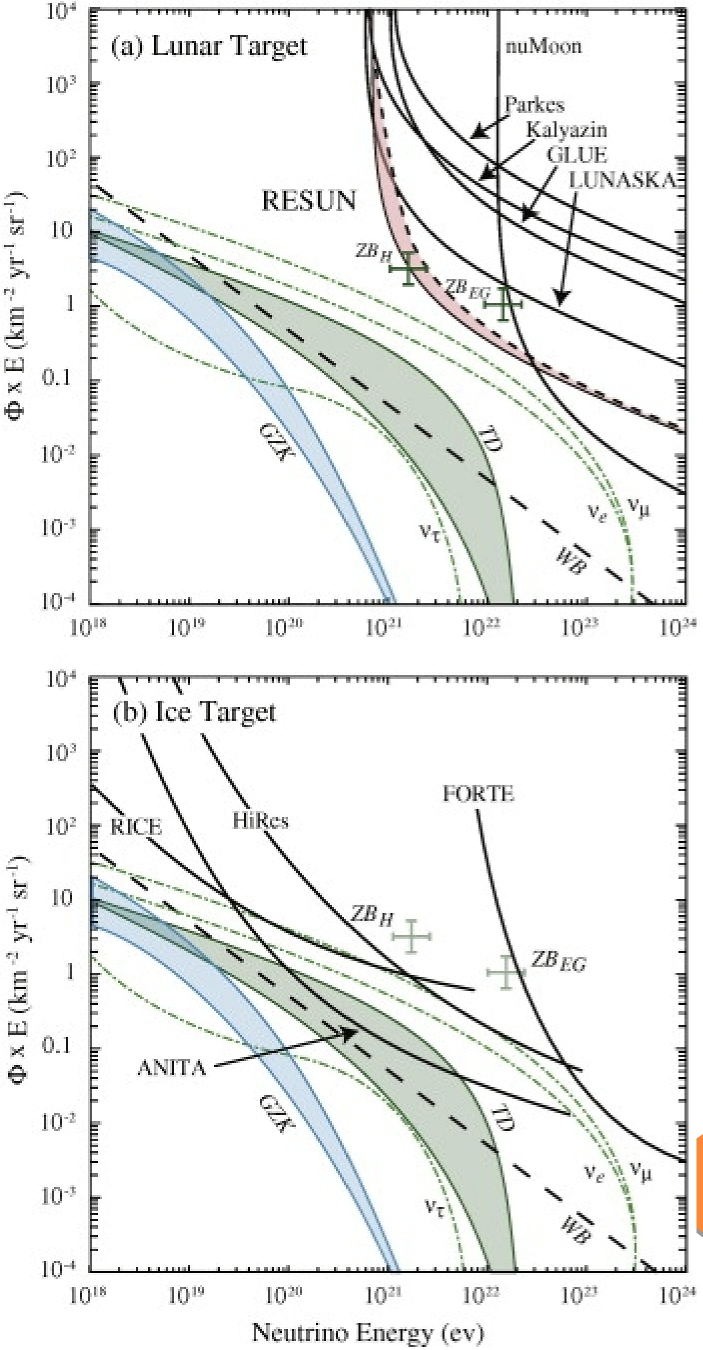


Askaryan Effect

Jaeger et al., *Astropart. Phys.* **34** (2010) 293

- ANITA observed UHECRs (geosynchrotron signal)
- Nobody saw neutrinos (sadly)

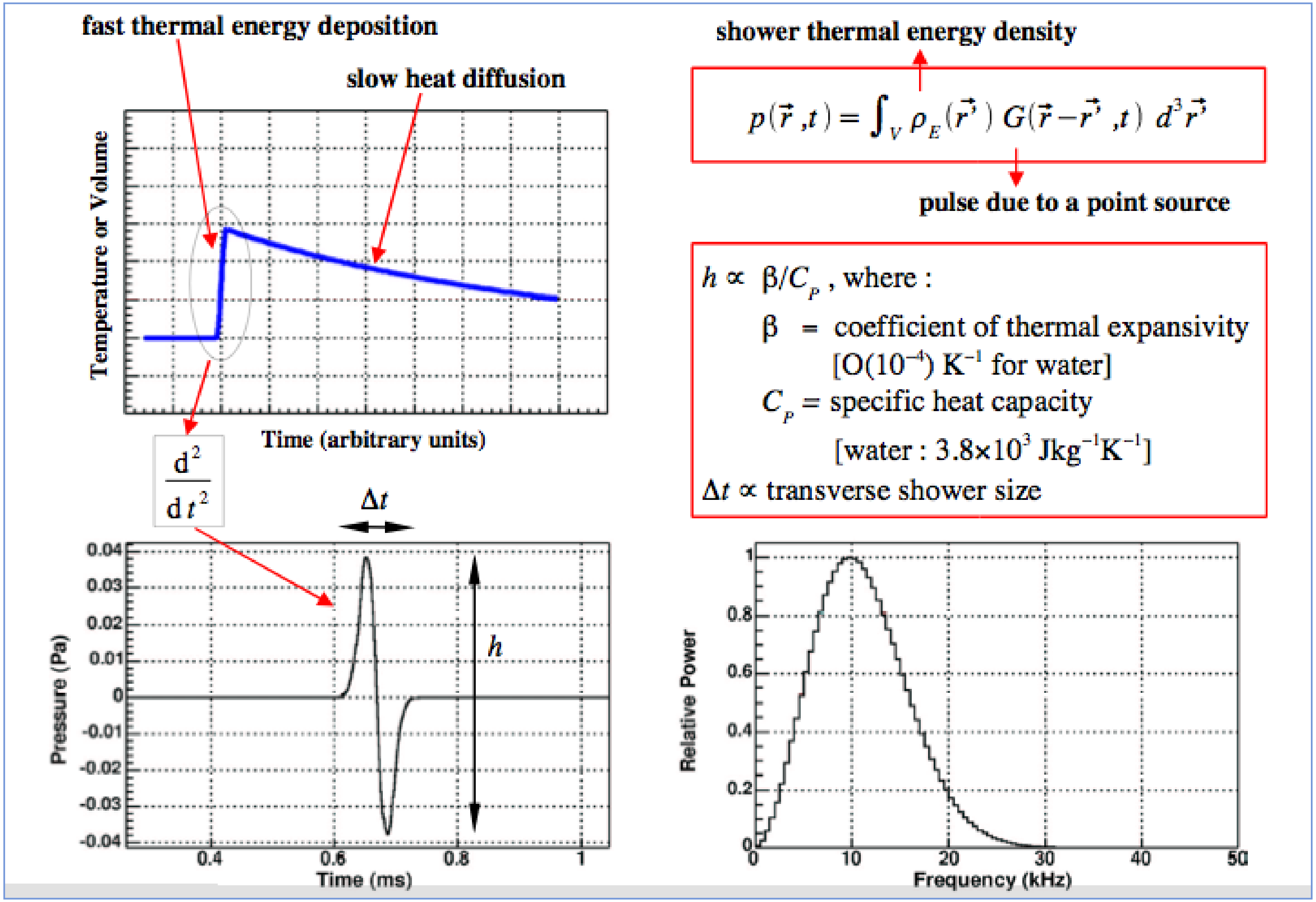




Acoustic Detection (Showering Neutrinos)

- UHE (>1 PeV) neutrinos interact fairly readily
  - on entering dense medium (water) they will initiate shower
    - this dumps energy in a thin cylinder (~20 m × 20 cm)
    - resulting pressure pulse spreads out from this cylinder in thin “pancake” perpendicular to incoming neutrino direction
    - produces characteristic bipolar acoustic pulse which can be detected by hydrophone array
  - advantages
    - extremely long attenuation length (several km)
      - very large volume can in principle be instrumented with relatively small number of hydrophones
    - hydrophone technology well established in underwater applications
      - can use off-the-shelf hardware
  - disadvantages
    - the sea is a very noisy place
      - identifying signal very challenging

Principles



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

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

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

C_p = specific heat capacity
[water : 3.8×10^3 $\mathrm{Jkg^{-1}K^{-1}}$]

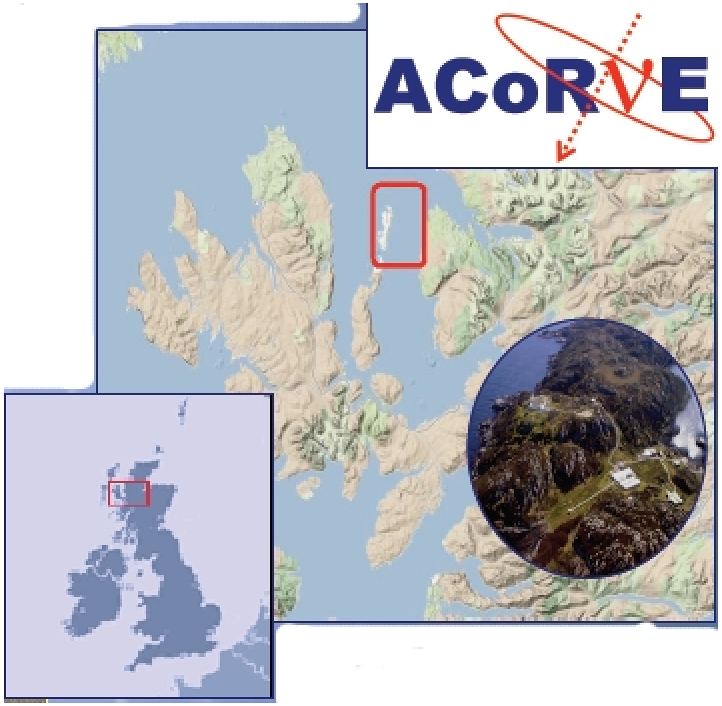
$\Delta t \propto$ transverse shower size

Experiments

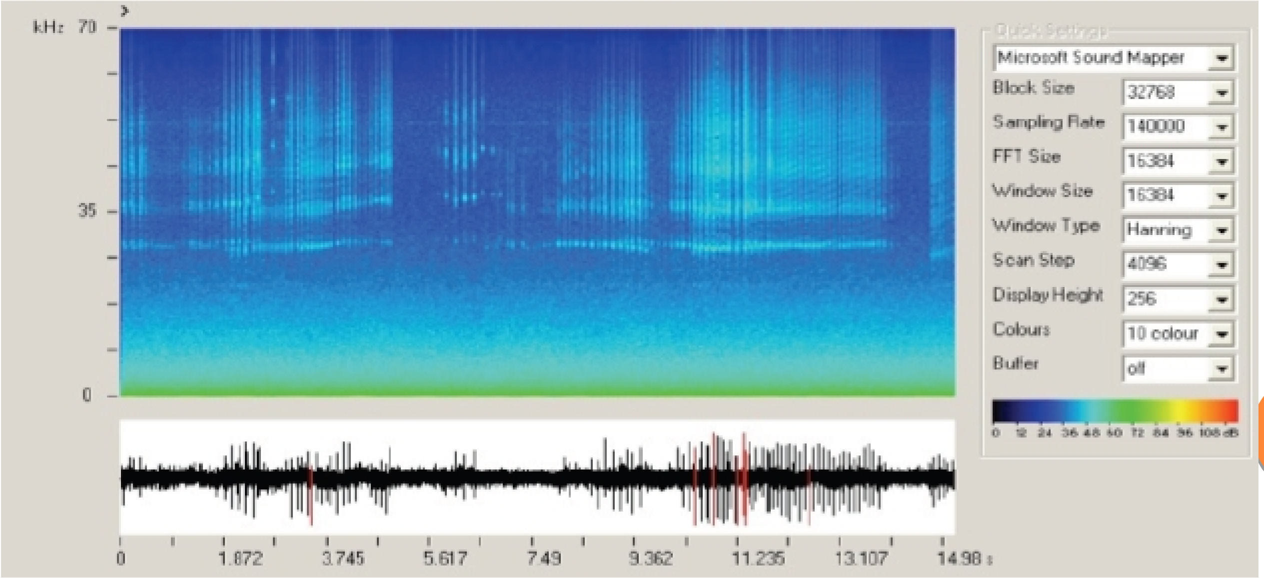
- ACORνE
  - UK feasibility study using military hydrophone array off Rona
- AMADEUS
  - co-deployed with ANTARES
- Lake Baikal
  - co-deployed with Baikal-200
- ONDE
  - part of NEMO (NEutrino Mediterranean Observatory)
  - NB: NOT Neutrino Ettore Majorana Observatory!
- SAUND-I and SAUND-II
  - in Bahamas, originally using military array, now extended
- SPATS
  - at South Pole, associated with IceCube

ACORνE

- MoD hydrophone array off NW coast of Scotland
  - successful R&D project showing feasibility of technique
  - array geometry not optimal (not designed for neutrinos!)



Example of background source—dolphin clicks!



Quick Settings

Microsoft Sound Mapper

Block Size: 32768

Sampling Rate: 140000

FFT Size: 16384

Window Size: 16384

Window Type: Hanning

Scan Step: 4096

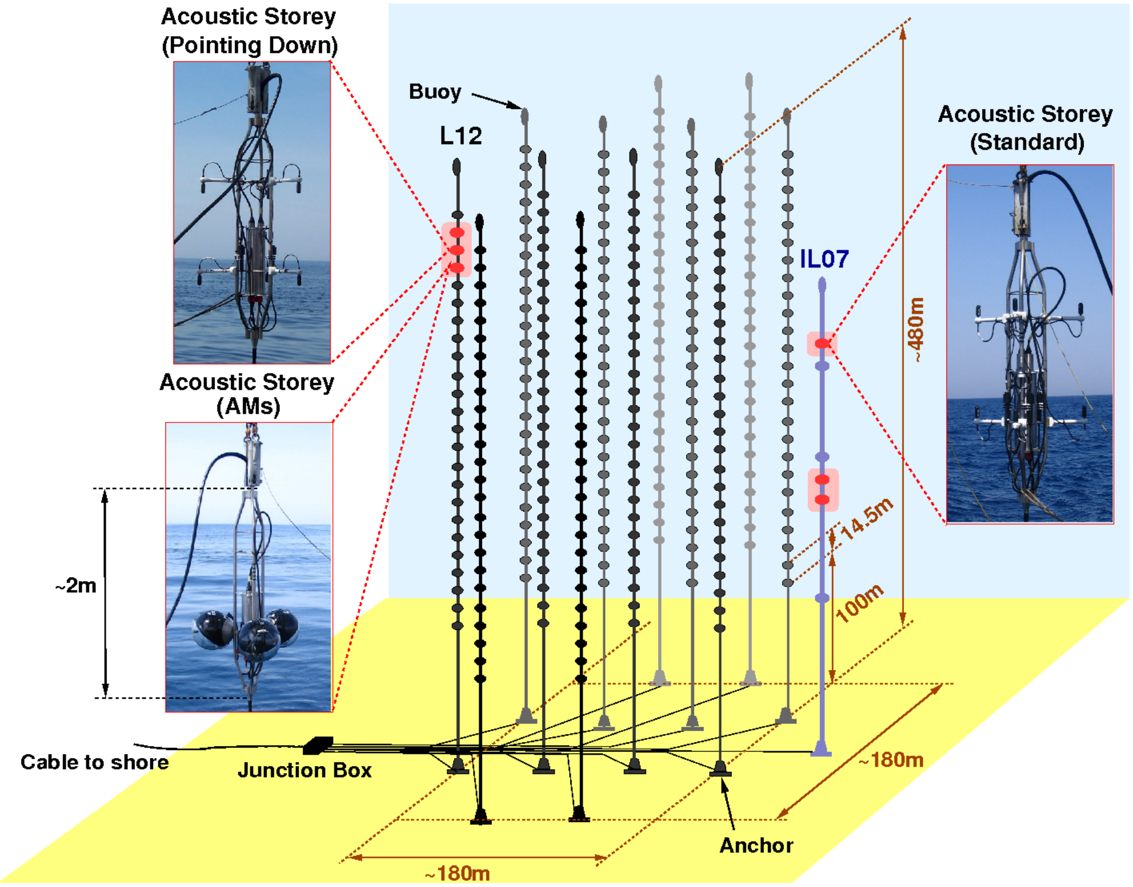
Display Height: 256

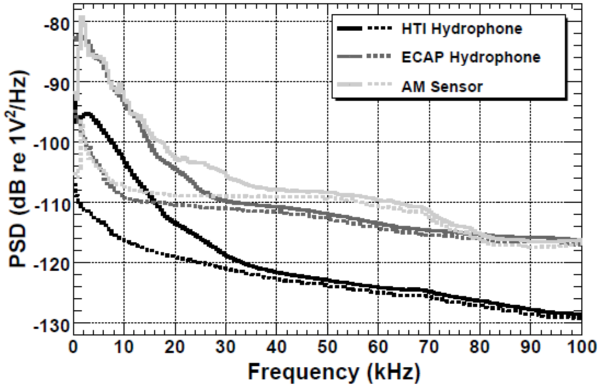
Colours: 10 colour

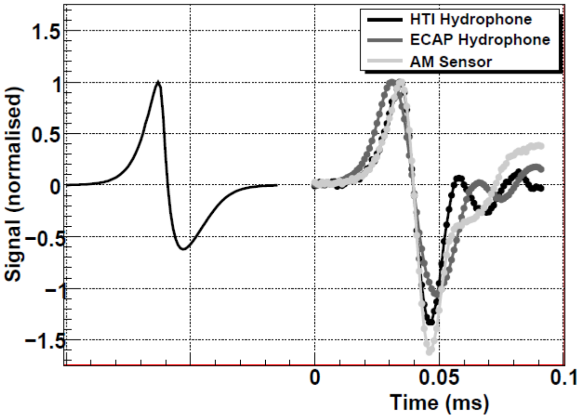
Buffer: off

AMADEUS

- Acoustic storeys added to ANTARES strings
  - R&D project comparing different hydrophones
  - feasibility study for KM3NeT

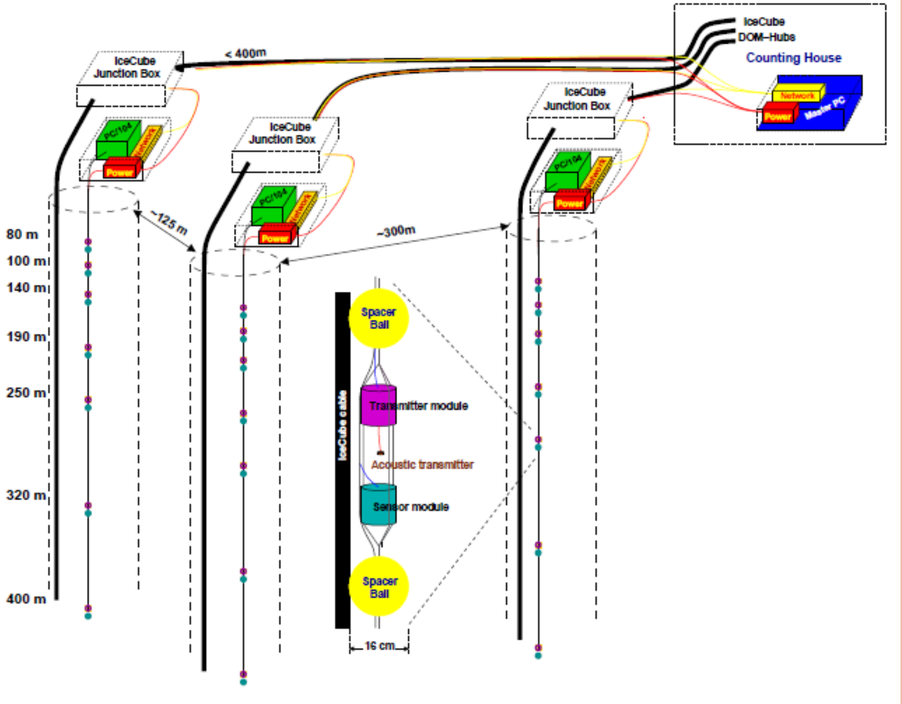


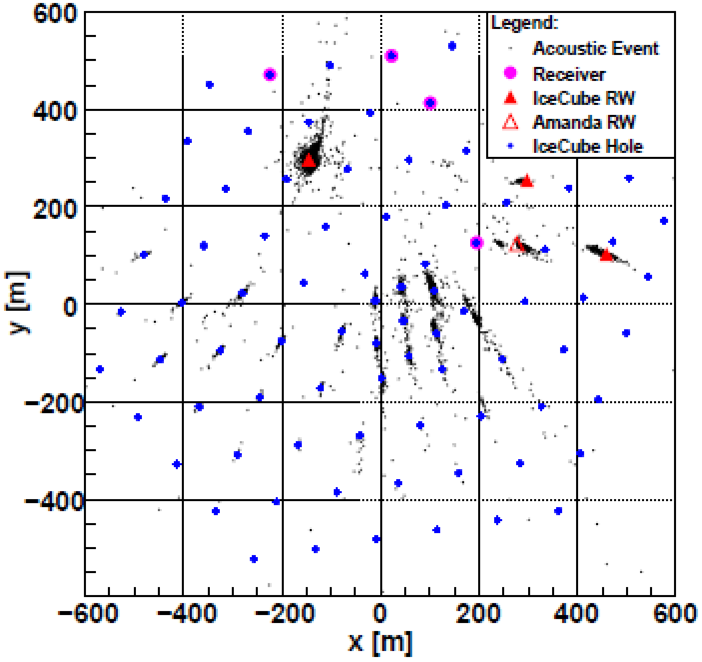


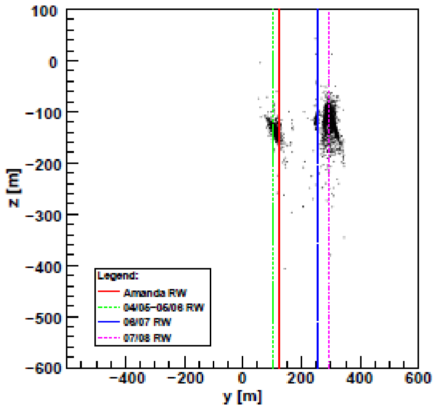


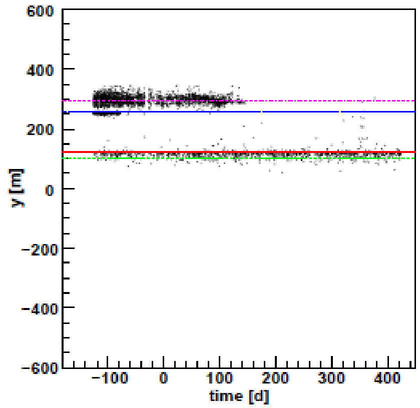
SPATS

- Acoustic sensors on strings deployed in association with IceCube
  - very good at detecting IceCube drilling and water storage activities!

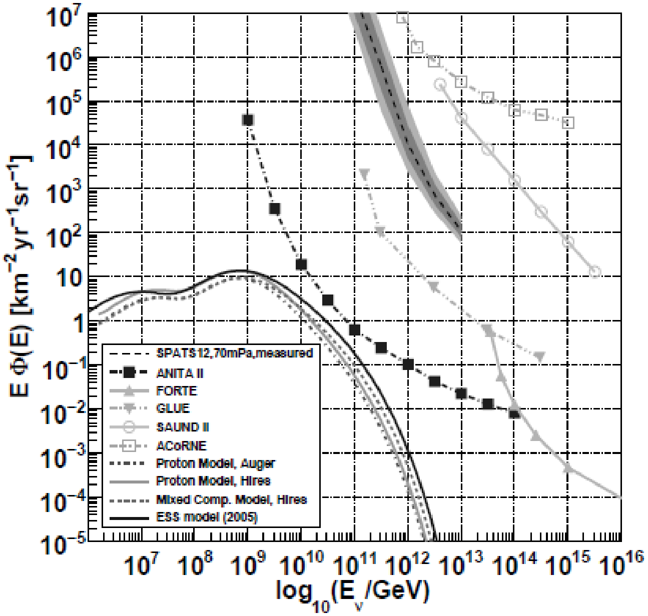








Acoustic Detection: Summary



- Experiments so far are R&D projects/feasibility studies
  - limits not competitive with radio at present
- Future strategy mostly co-deployment with large optical Cherenkovs
  - improves high-energy sensitivity
  - likely future direction: super-hybrid experiments with optical Cherenkov, acoustic and radio elements, plus air-shower array if appropriate
    - most nearly realised at South Pole with IceCube/IceTop/RICE/SPATS

Neutrino Detection: Summary

- High-energy neutrinos could provide information on
  - acceleration processes in high-energy astrophysics
  - GZK cut-off in cosmic rays
  - dark matter (see next lecture)
- Detection still in infancy
  - only IceCube has been large enough
- Various promising techniques
  - water Cherenkov at lower energies
  - radio and possibly acoustic at high end
- Hybrid experiments feasible at many sites