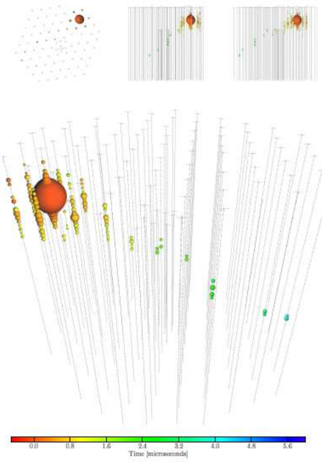
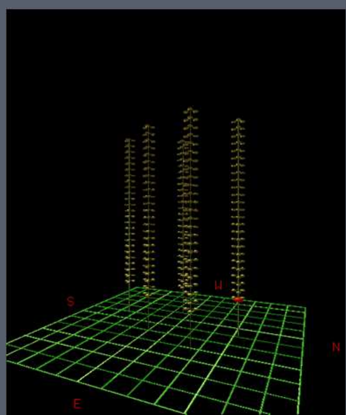
The University Of Sheffield.



ASTROPARTICLE PHYSICS LECTURE 3

Susan Cartwright
University of Sheffield

1



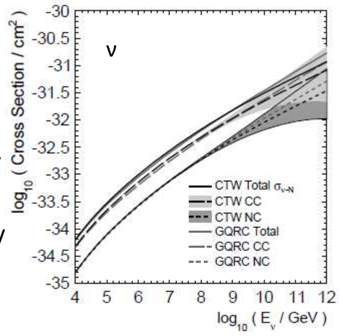
HIGH ENERGY ASTROPARTICLE PHYSICS

Acceleration Mechanisms
Sources
Detection

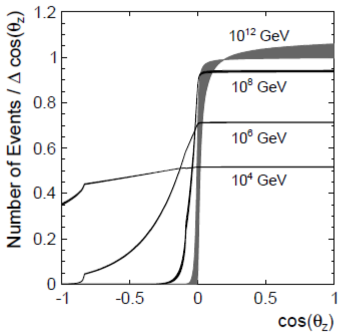
2

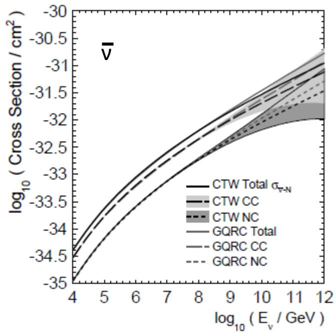
Neutrino Detection

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



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





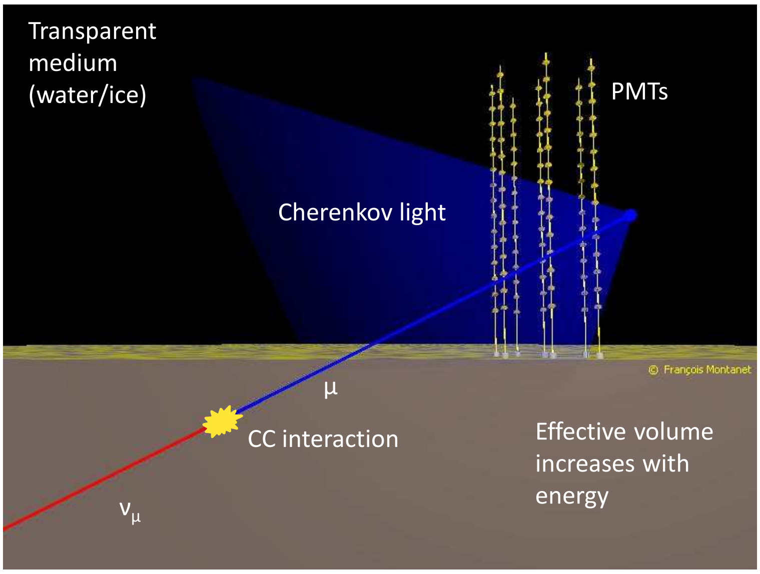
3

Neutrino Detection (Penetrating Neutrinos)

- Mostly rely on detecting the charged lepton produced in CC interactions
  - at lowest energies (solar neutrinos), also elastic scattering ($\nu + e \rightarrow \nu + e$) and NC reaction on deuterium ($\nu + d \rightarrow \nu + p + n$)
  - 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 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

4

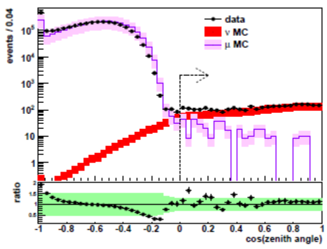
Neutrino Detection by Water Cherenkov

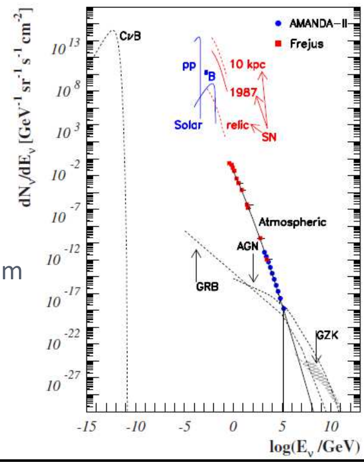


5

Backgrounds

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





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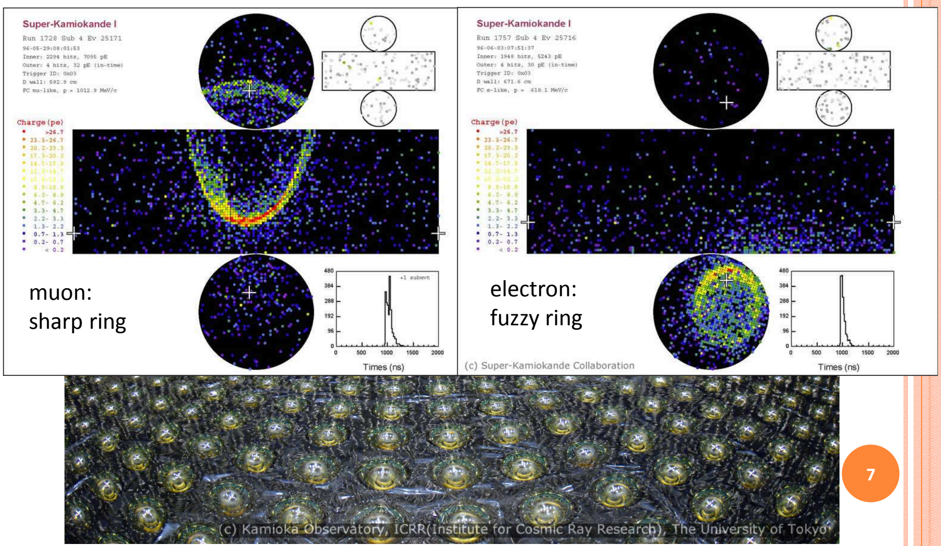
PARTICLE ID: SUPER-KAMIOKANDE



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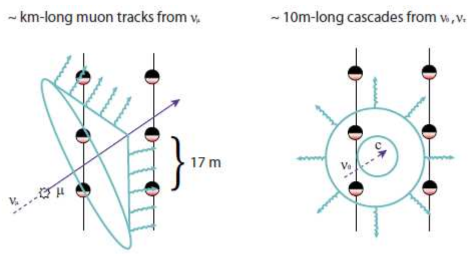
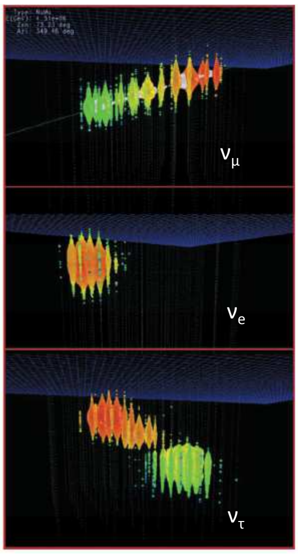
PARTICLE ID: ICECUBE





"double-bang" ν_τ event: initial signal from CC interaction, later one from τ decay

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

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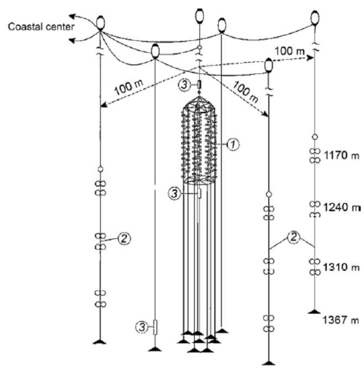
HIGH-ENERGY NEUTRINO TELESCOPES

9

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

10

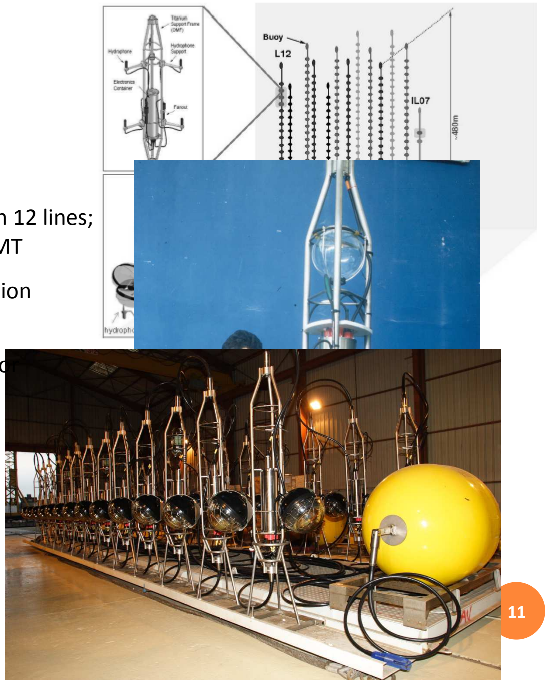
ANTARES

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



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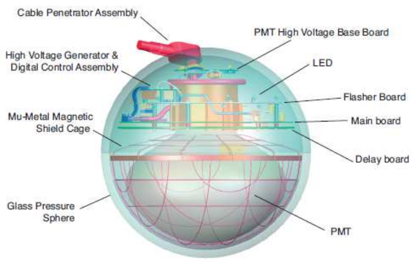
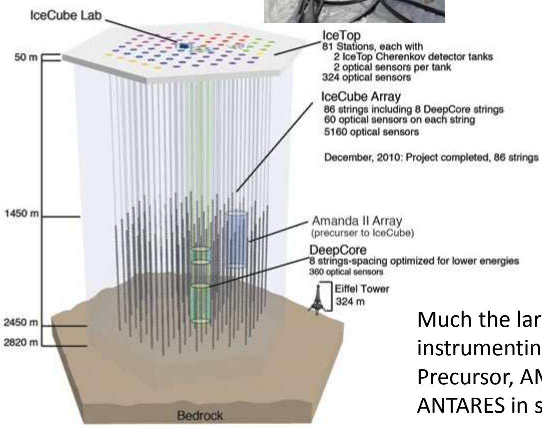
ICECUBE





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

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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	^{40}K, 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.

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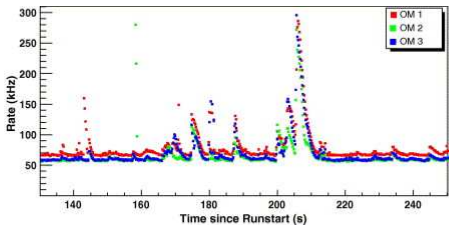
Background in ANTARES



- Three components
  - steady background of ~60 kHz from ^{40}K
  - 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

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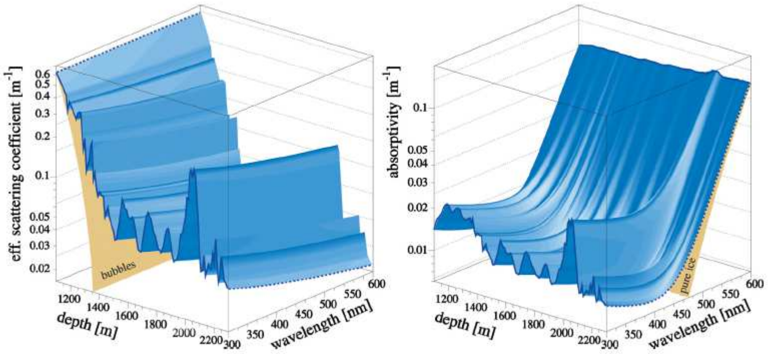
Light Transmission in IceCube



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.

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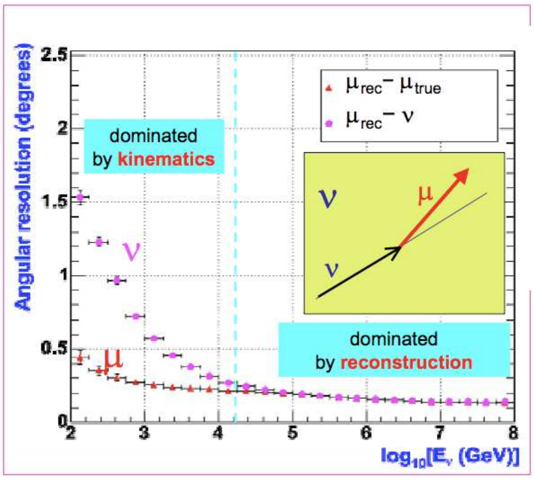
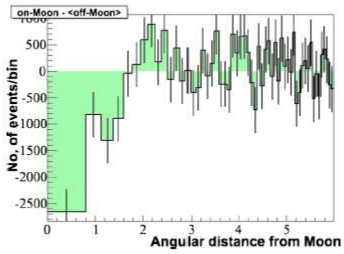
Angular Resolution



At 100 TeV: Amanda ~2°

Antares ~ 0.2°



Moon's shadow in CR muons, measured by IceCube

Expected IceCube angular resolution ~0.5°

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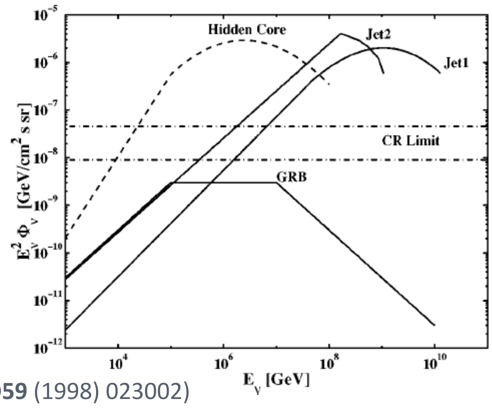
Expected Fluxes



- 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 is $E_\nu^2\phi_\nu < 2\times10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} for 10^{14}–10^{16} eV ν

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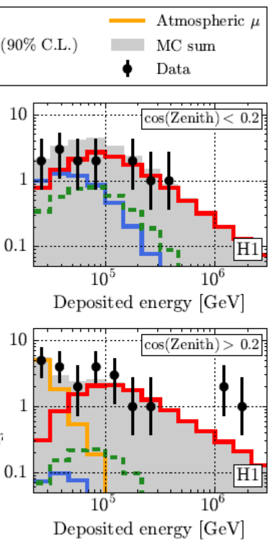
Results

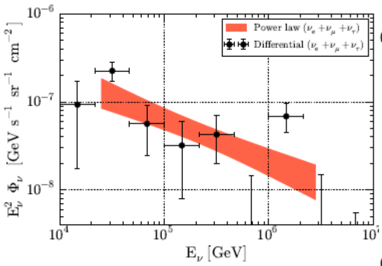
For 3 years of data-taking: 37 events above 100 TeV, on background of about 15

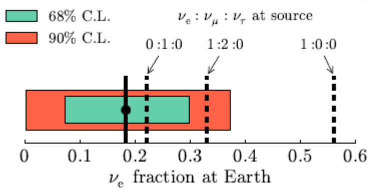
Flux at 100 TeV: $(6.7\pm1.2)\times10^{-18}$ GeV^{-1} s^{-1} sr^{-1} cm^{-2}

Spectral index 2.50±0.09

No significant point sources or correlations with other data







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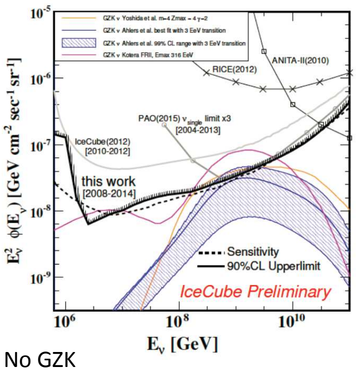
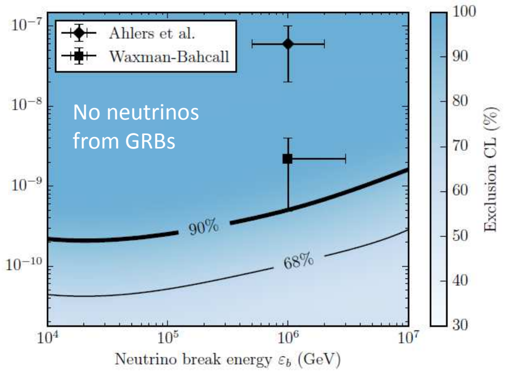
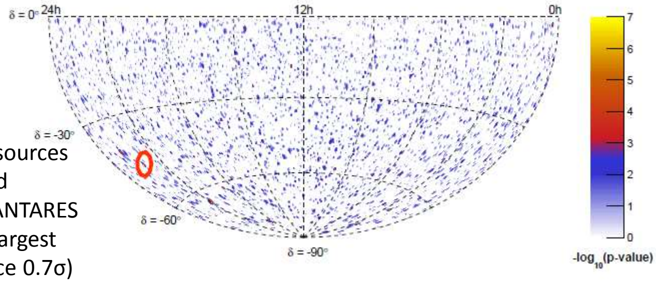


No GZK neutrinos





No point sources (combined IceCube/ANTARES analysis: largest significance 0.7σ)

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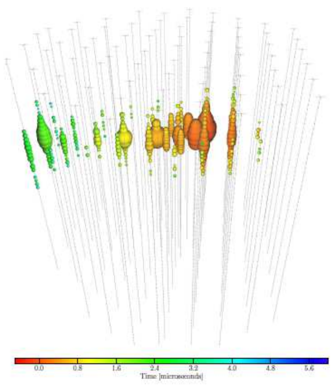
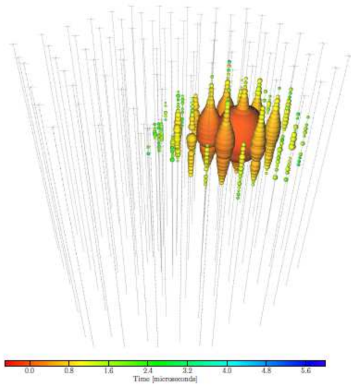


Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$71.4^{+9.0}_{-9.0}$	55512.5516214	−0.4	110.6	$\lesssim 1.2$	Track



Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$1040.7^{+131.6}_{-144.4}$	55782.5161816	−27.9	265.6	13.2	Shower

Example IceCube events

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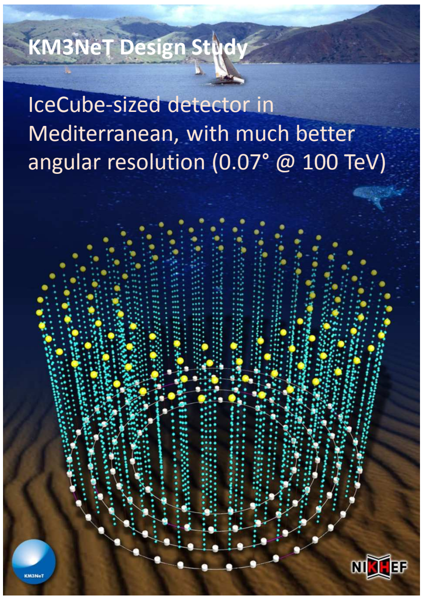
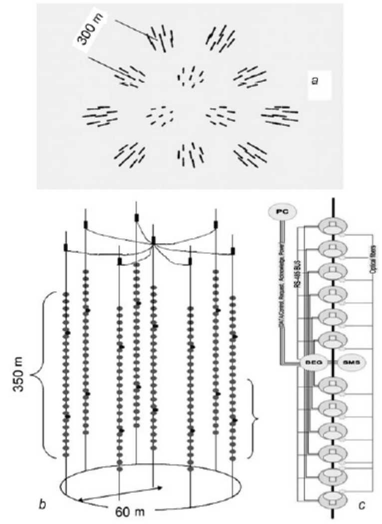
NEXT GENERATION WATER CHERENKOVS

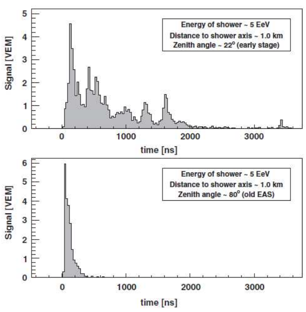


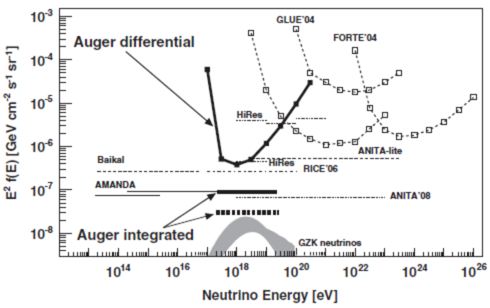
Baikal-1000



TAU-NEUTRINO DETECTION BY AIR SHOWERS

- Earth-skimming ν_τ 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)





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High Energy Astroparticle Physics

New Detection Techniques

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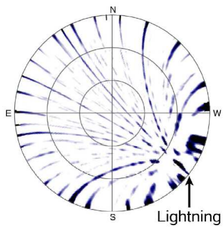
Radio-Frequency Detection of Air Showers and Neutrinos

- 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

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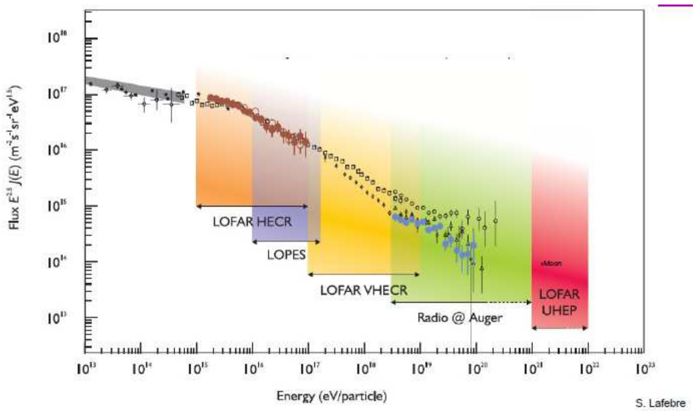
Geosynchrotron Emission

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



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LOFAR

Low frequency radio array 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)

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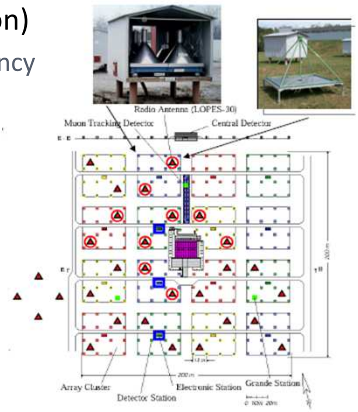
LOPES/KASCADE

- 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



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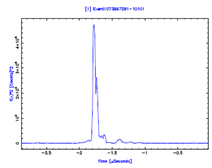
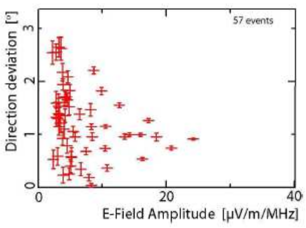
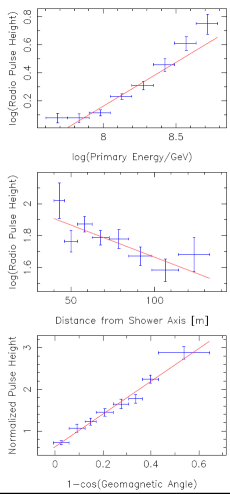
LOPES/KASCADE



- 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 suggests full LOFAR array should be excellent CR detector





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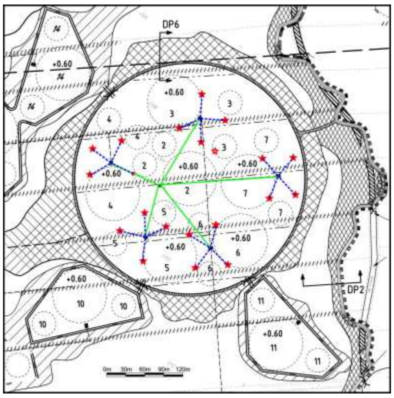
LOFAR AS A COSMIC RAY DETECTOR

- 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



Thoudam et al., astro-ph/1102.0946v1

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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 160 autonomous self-triggering radio antennas
  - 5000 events/year expected, 1000 above 10^{18} eV
  - 124 stations deployed so far

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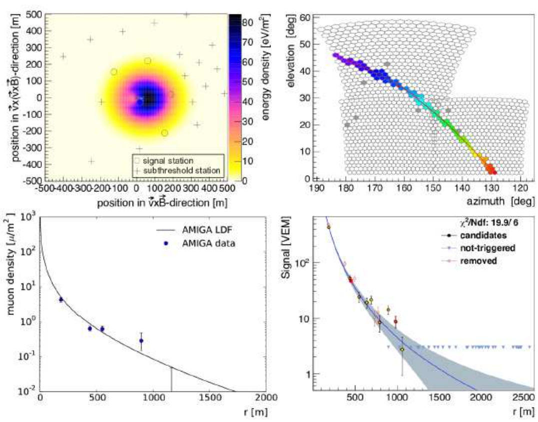
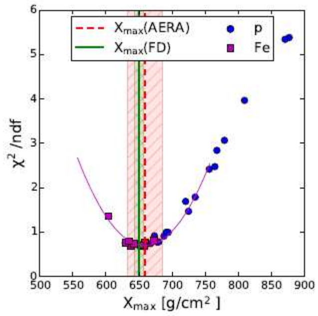
AUGER/AERA/AMIGA EVENT DETECTION



Event detected by all four Auger subdetectors



Shower depth determination by AERA and fluorescence

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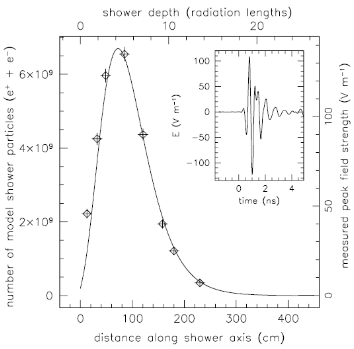
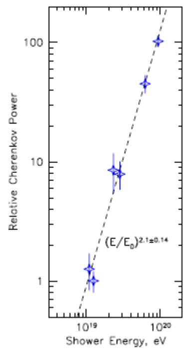
ASKARYAN EFFECT

- 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)





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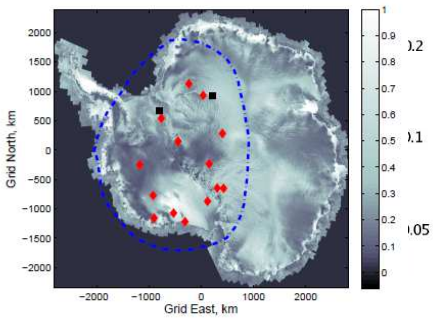
ASKARYAN EFFECT: ANITA



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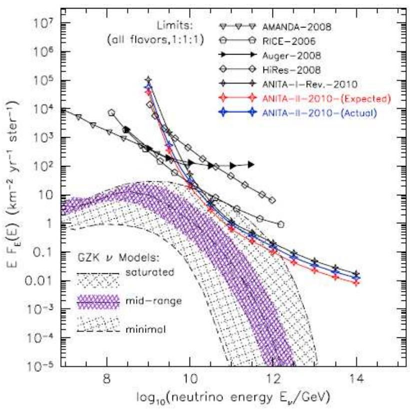
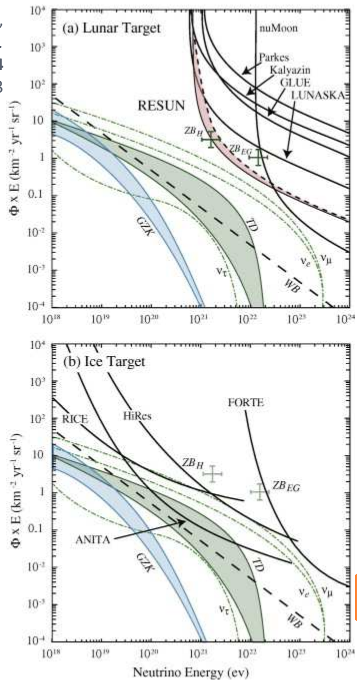
ASKARYAN EFFECT

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

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





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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

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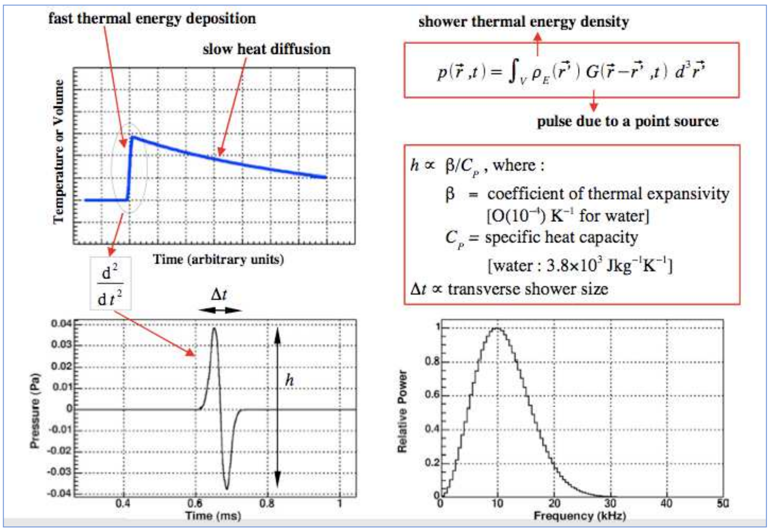
PRINCIPLES



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EXPERIMENTS

- ACORNE
  - UK feasibility study using military hydrophone array off Rona
- AMADEUS
  - codeployed with ANTARES
- Lake Baikal
  - codeployed with Baikal-200
- ONDE
  - part of NEMO (NEutrino Mediterranean Observatory, 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

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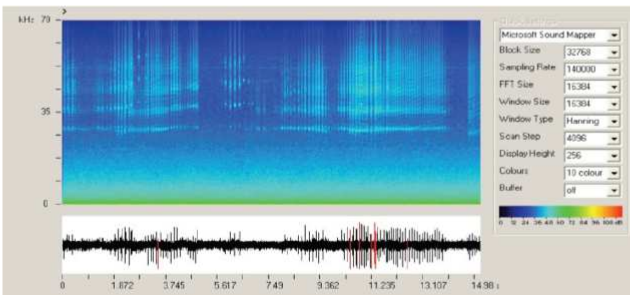
ACORNE

- 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!

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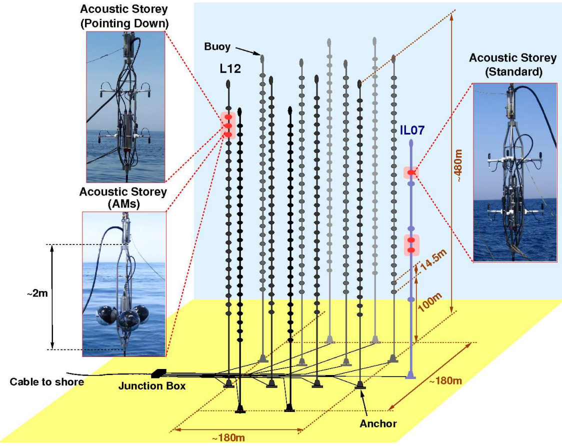
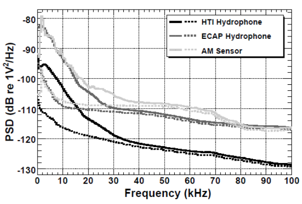
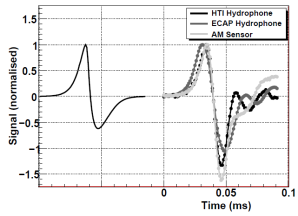
AMADEUS

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







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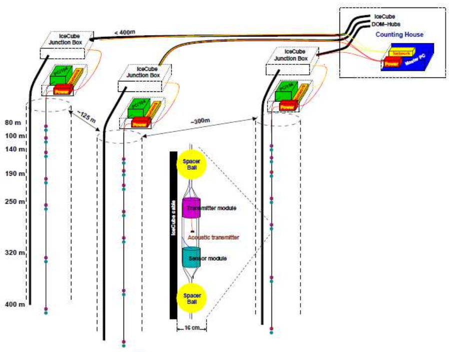
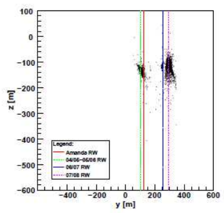
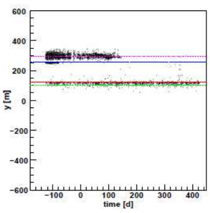
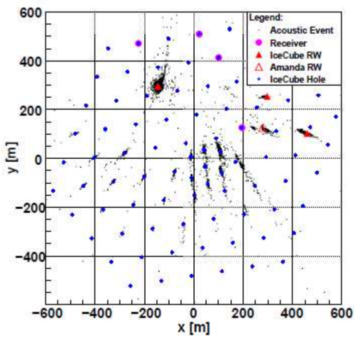
SPATS

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



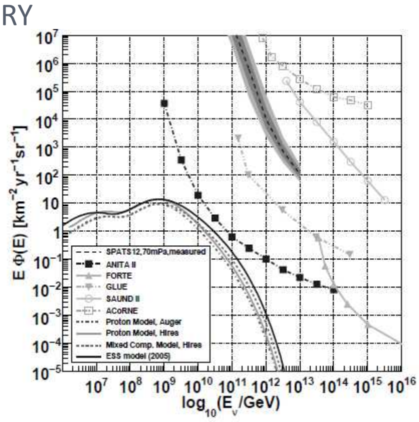






Acoustic Detection: Summary

- 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



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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 probably large enough to collect statistics
- Various promising techniques
  - water Cherenkov at lower energies
  - radio and possibly acoustic at high end
- Hybrid experiments feasible at many sites

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