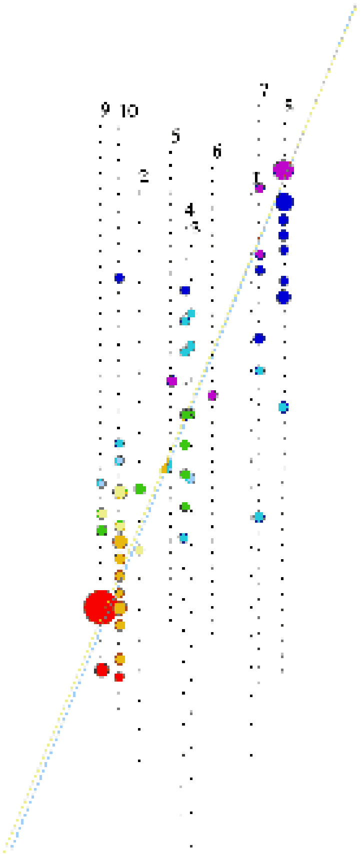
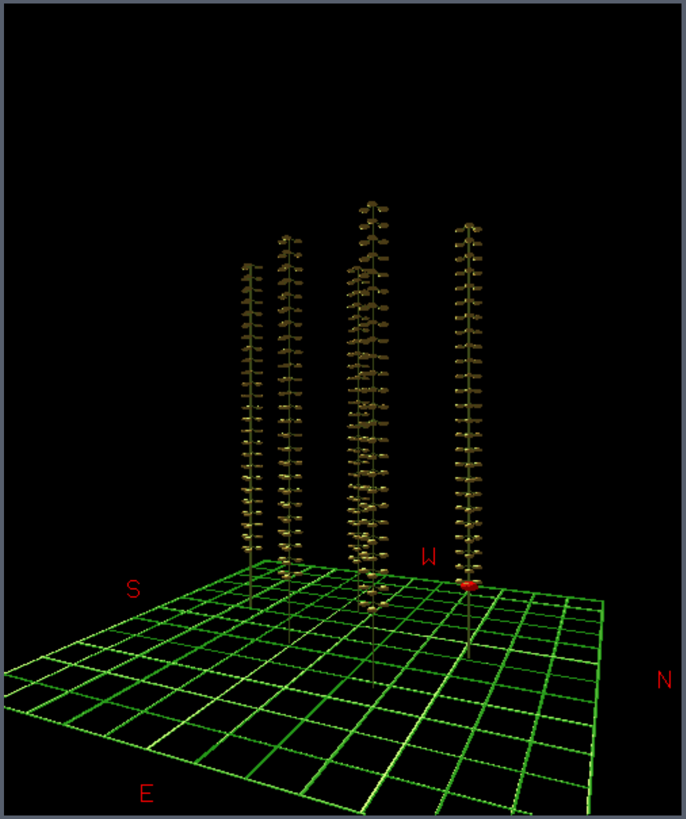
The University Of Sheffield.



# ASTROPARTICLE PHYSICS LECTURE 3


**Matthew Malek**

**University of Sheffield**

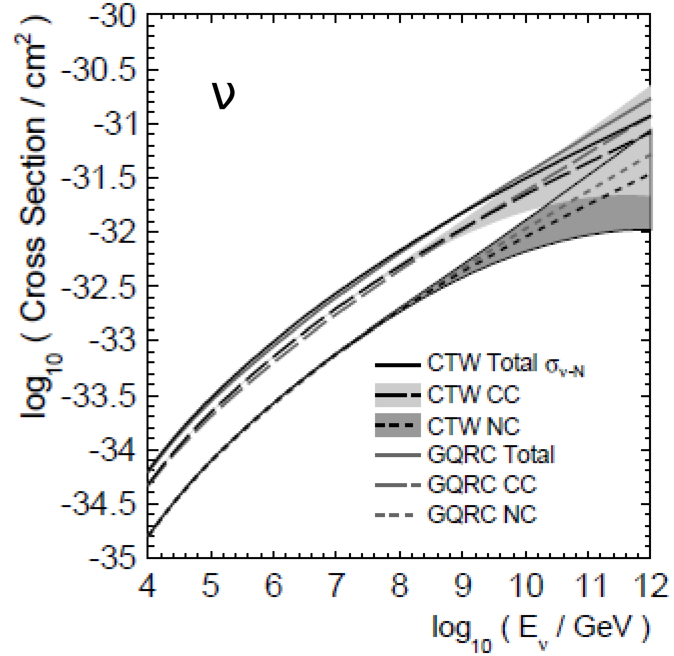


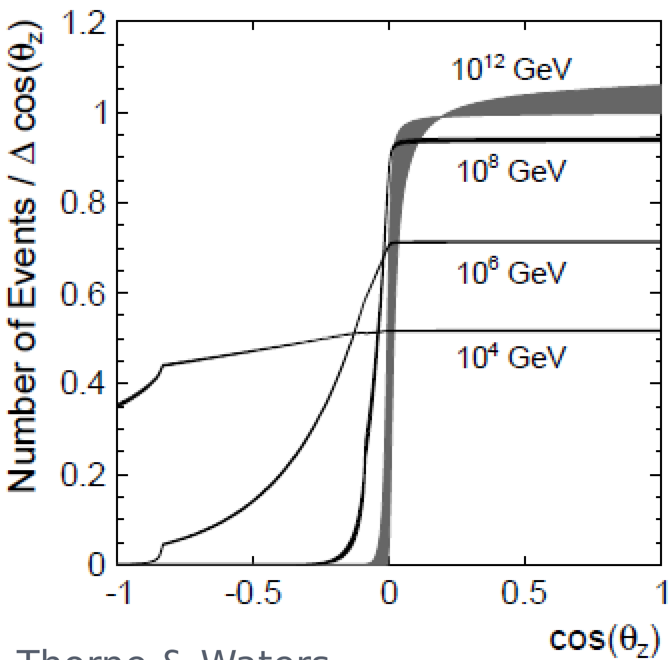

# High Energy Astroparticle Physics

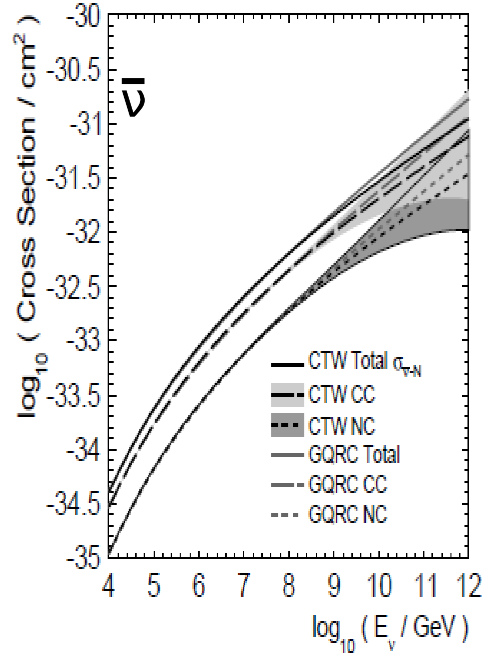
**Acceleration Mechanisms**
**Sources**
**<u>Detection</u>**

# 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)



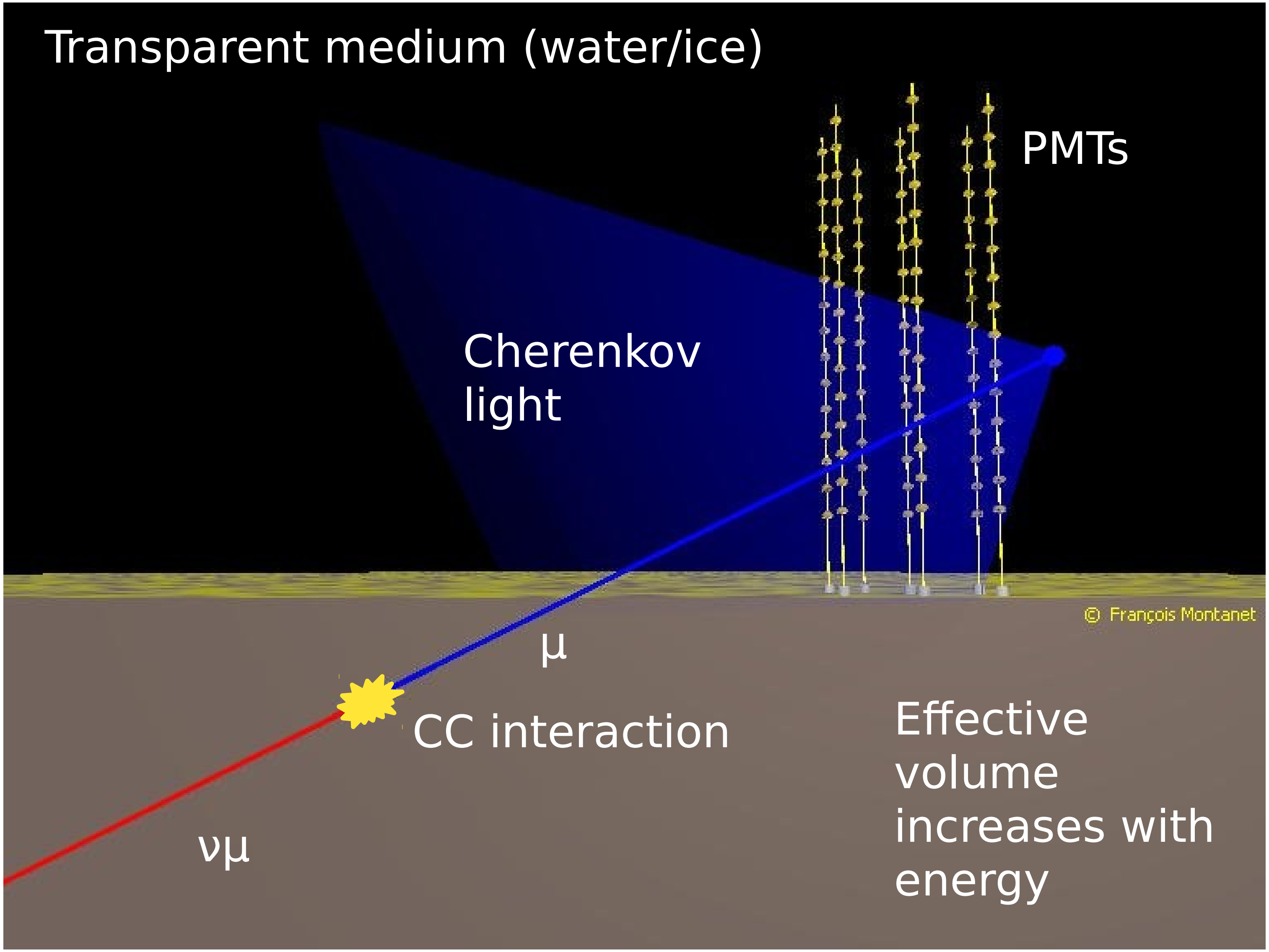




Connolly, Thorne & Waters, hep-ph/1102.0691v1

# Neutrino Detection (Penetrating Neutrinos)

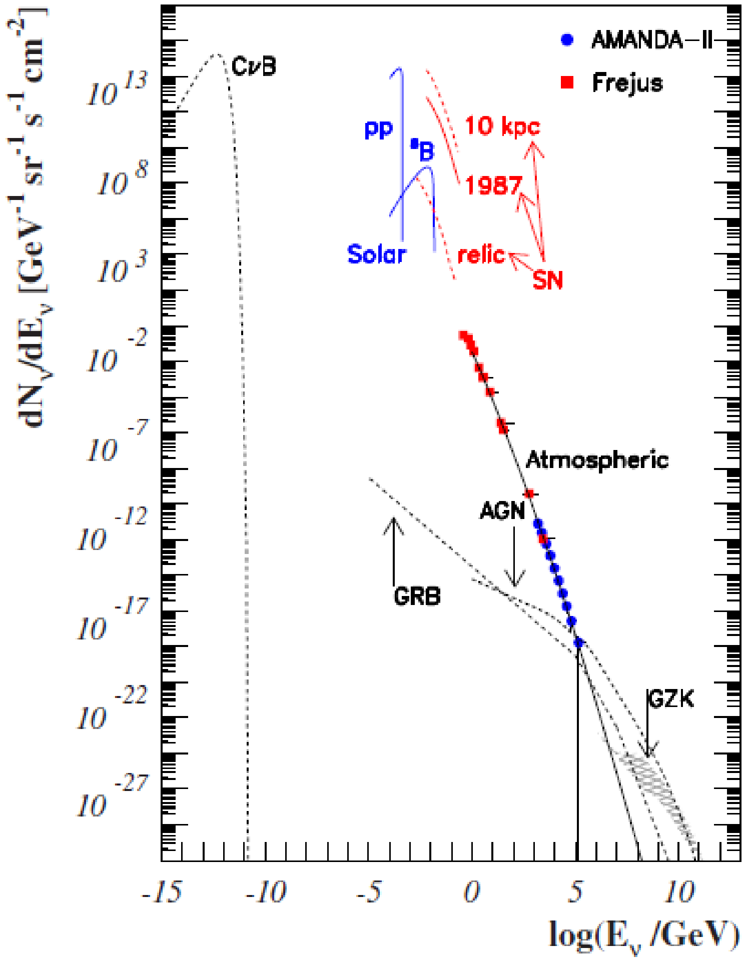
- Mostly rely on detecting the charged lepton produced in CC interactions
- at lowest energies (solar neutrinos), also elastic scattering
  - ($\nu + e \rightarrow \nu + e$) & NC on deuterium ($\nu + d \rightarrow \nu + p + n$)
  - note that at solar neutrino energies $\mu$ and $\tau$ cannot be produced by CC, so $\nu_\mu$, $\nu_\tau$ 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

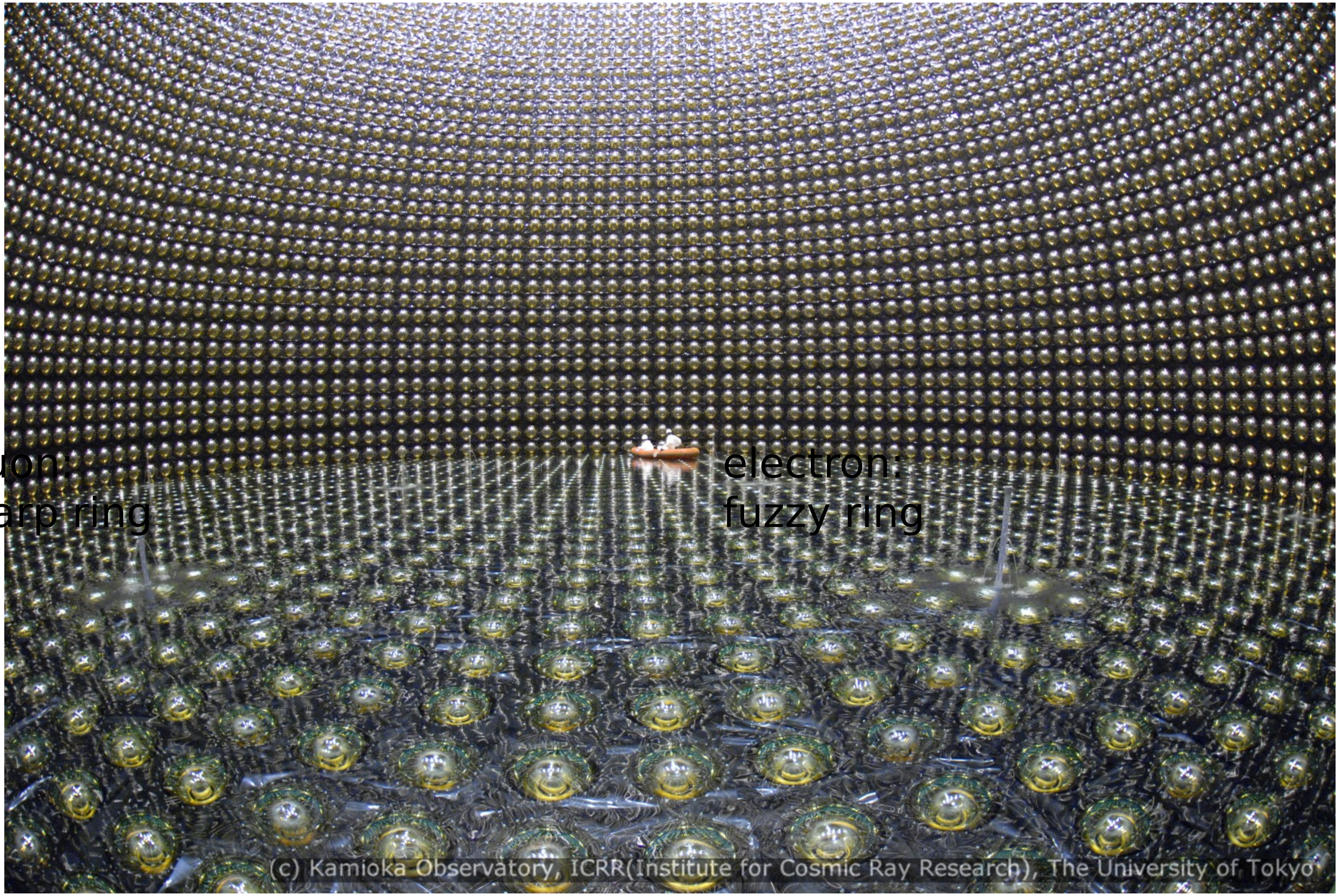


# Backgrounds

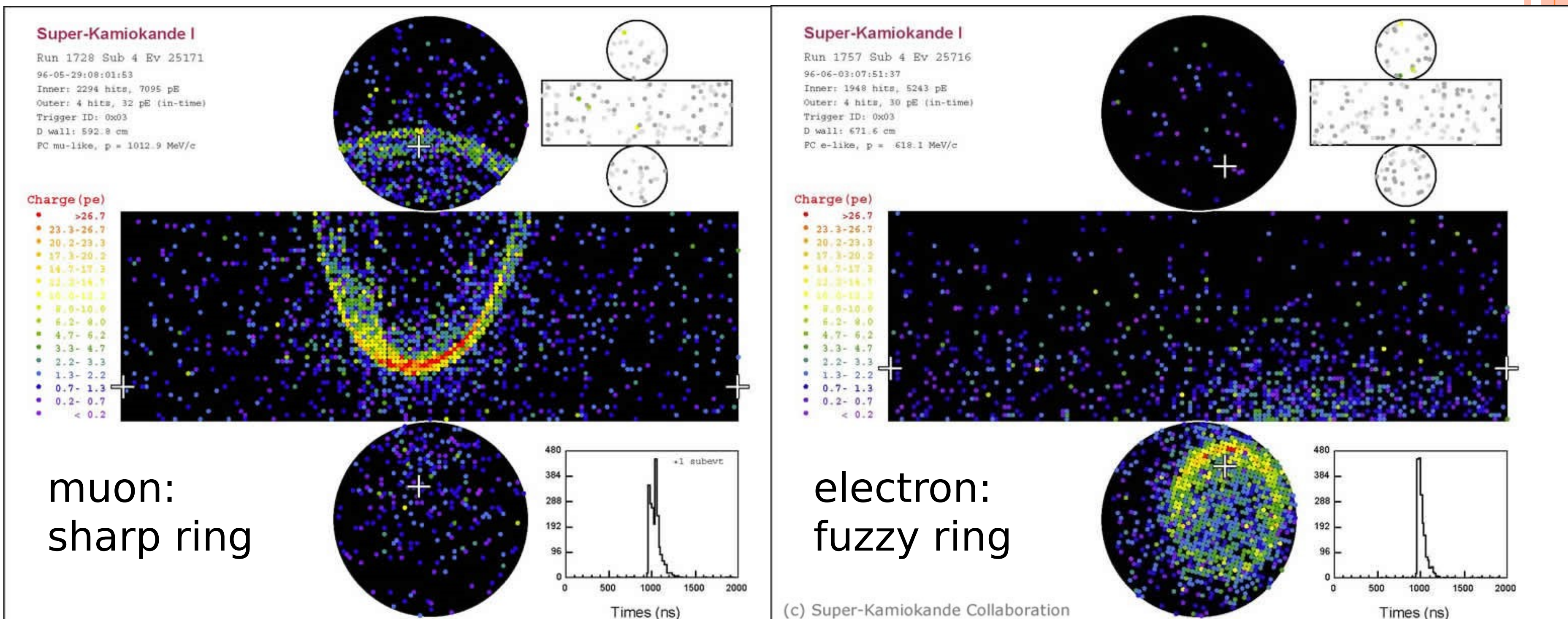
- Cosmic ray muons
  - Go deep
  - Look down
    - therefore, **northern** hemisphere telescope sees **southern** sky, and vice versa
- Atmospheric neutrinos
  - one person’s signal is another’s background!
  - irreducible, but steeper spectrum than high-energy astrophysical neutrinos



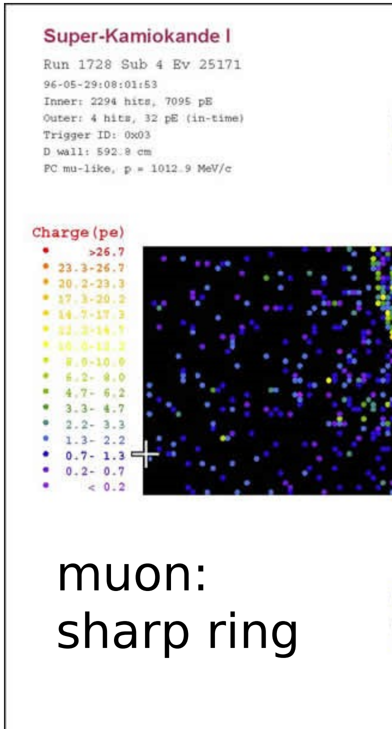
# Particle ID: Super-Kamiokande

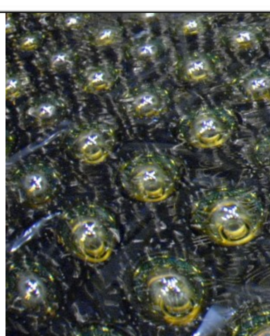


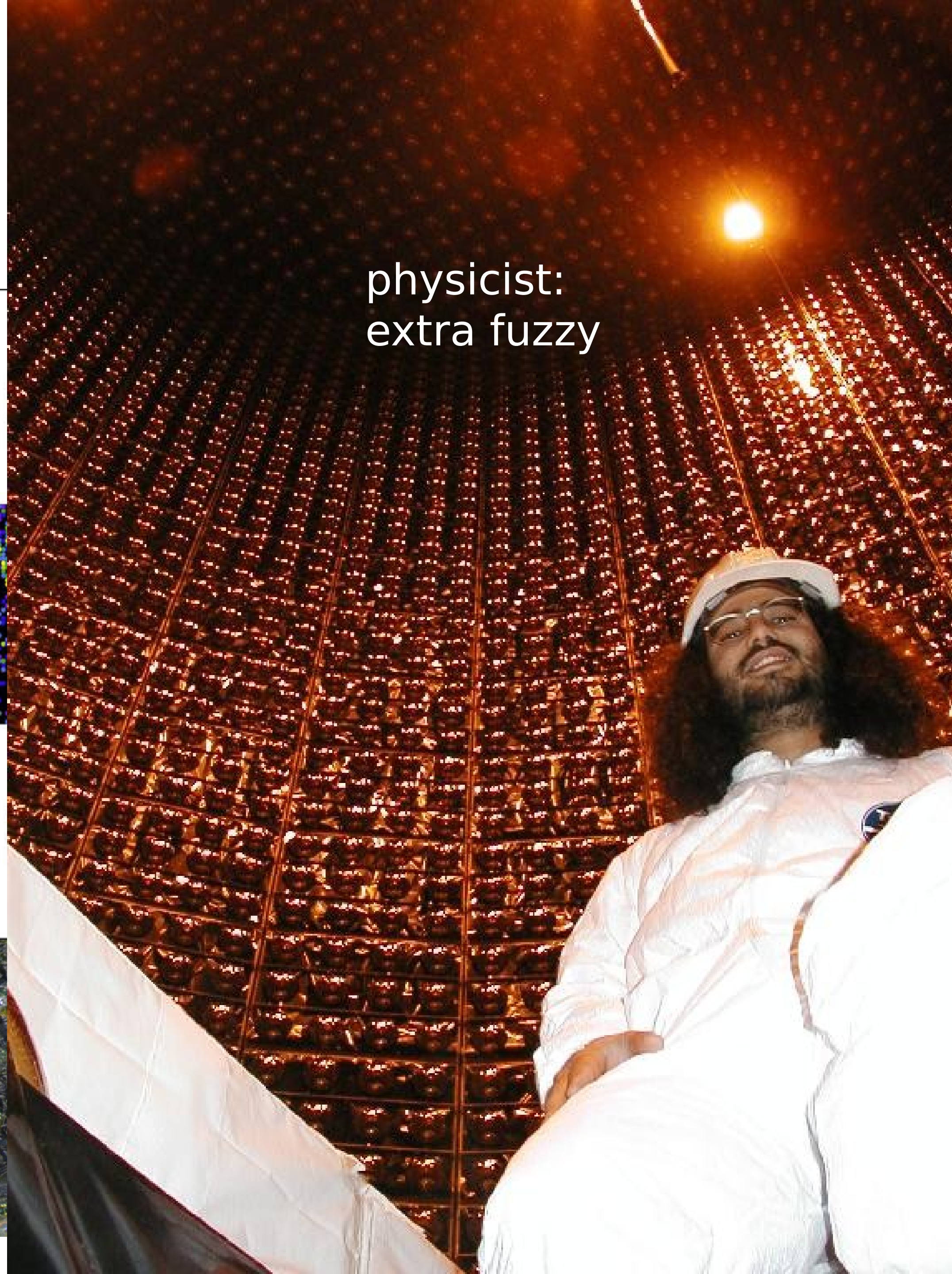
# Particle ID: Super-Kamiokande

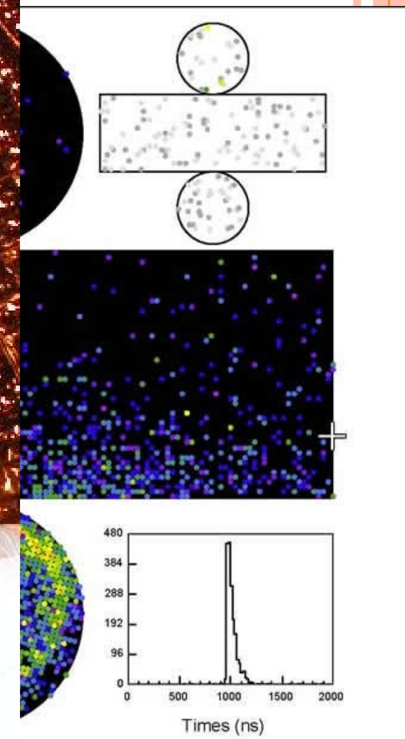


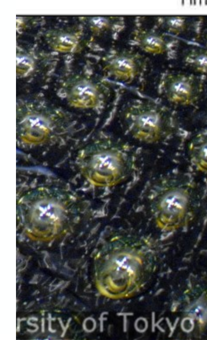

# Particle


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
Charge (pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
muon:
sharp ring

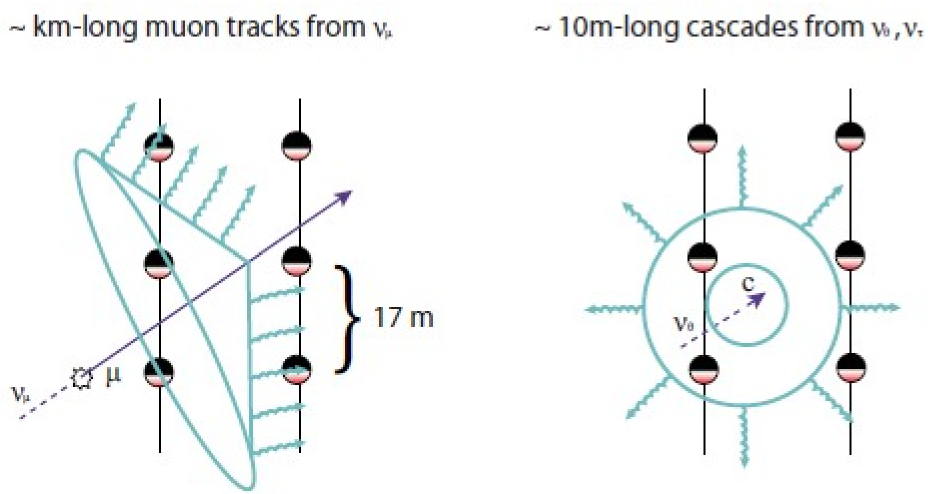


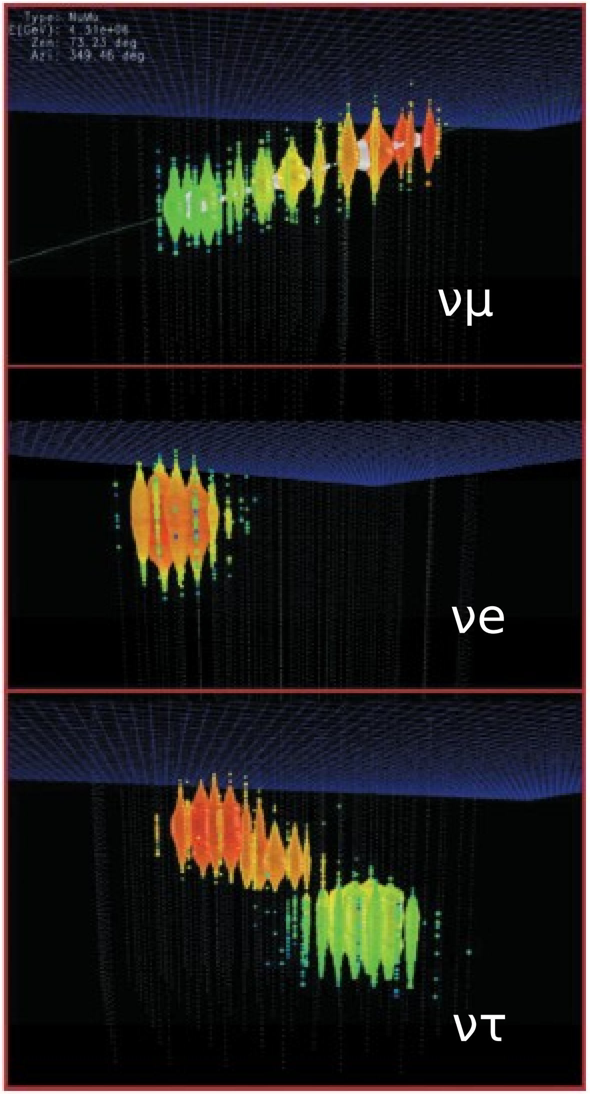

physicist:
extra fuzzy


480
384
288
192
96
0
0
500
1000
1500
2000
Times (ns)


rsity of Tokyo

# Particle ID: IceCube

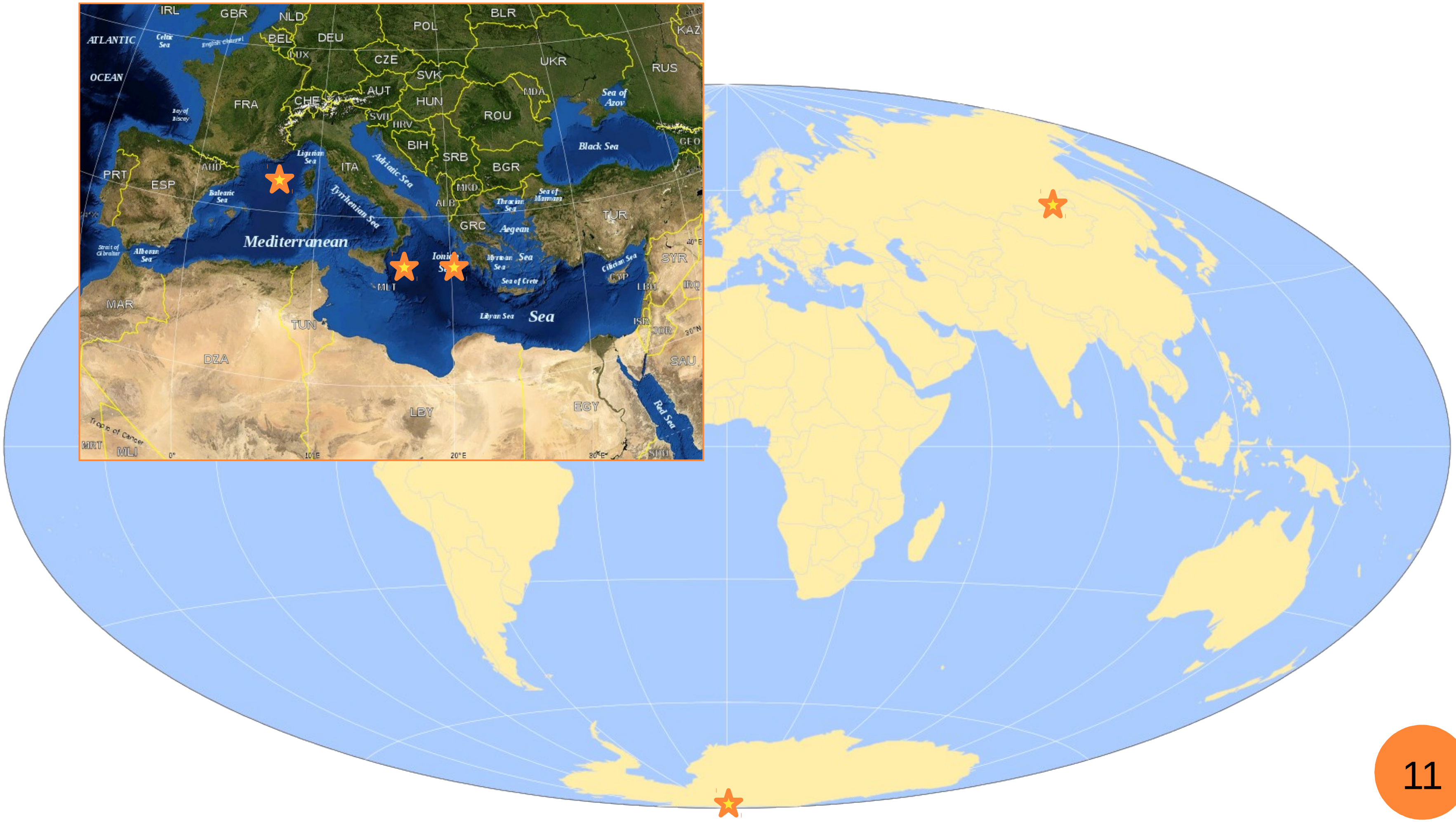



"double-bang" ντ event:
initial signal from CC interaction,
later one from τ decay

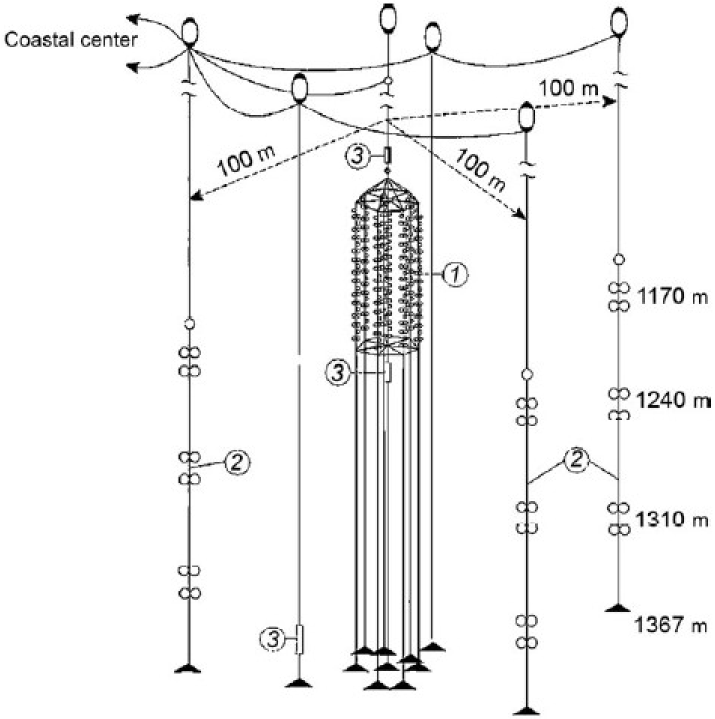
Halzen & Klein, *Rev. Sci. Inst.* **81** (2010) 081101

# 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)

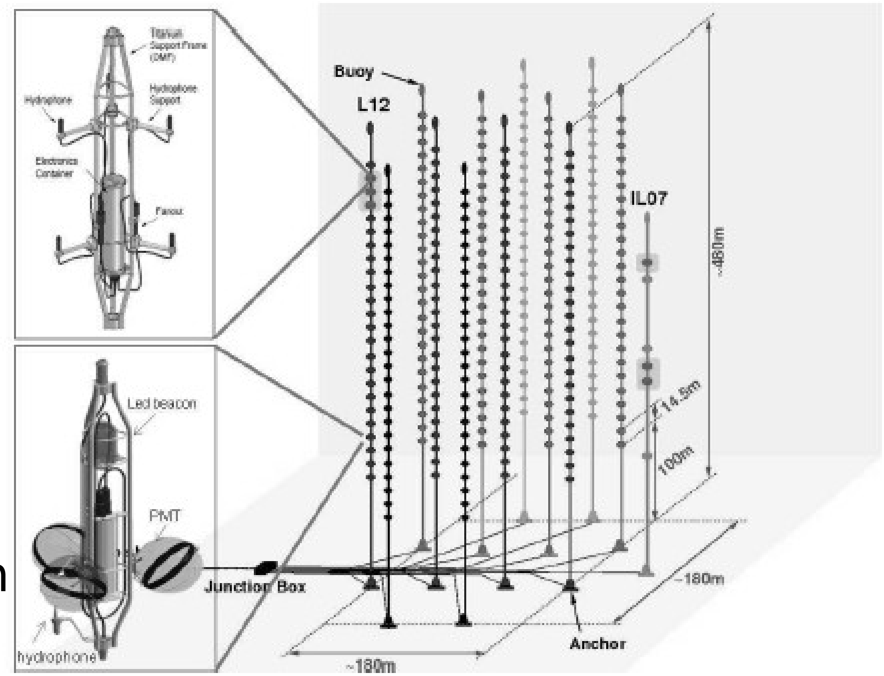
Each OM equipped with 37-cm PMT

# Lake Baikal


**From the New York Times (30th March 2021):**
Upgraded Baikal (called “Baikal-GVD”) now operational.
Volume comprable to IceCube.

# 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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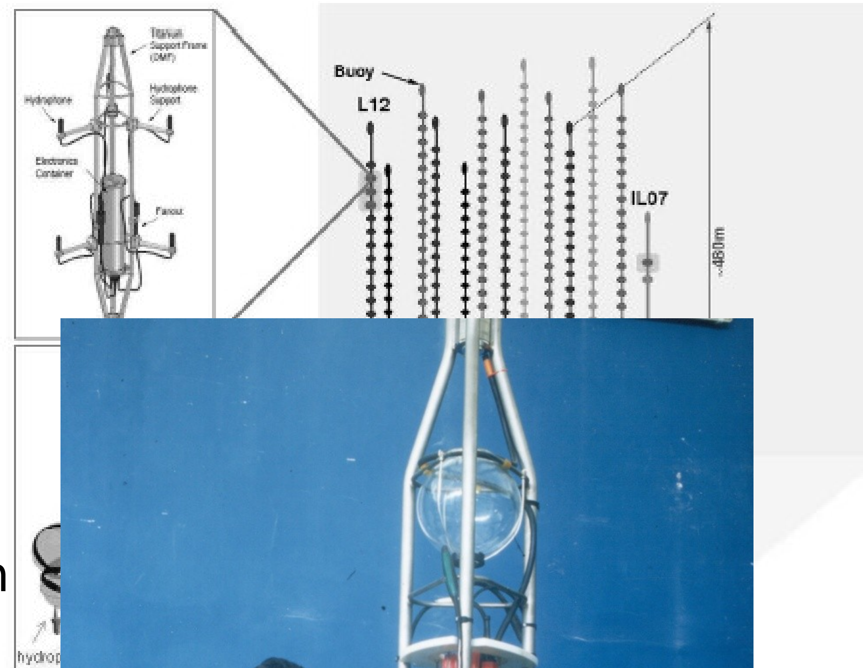


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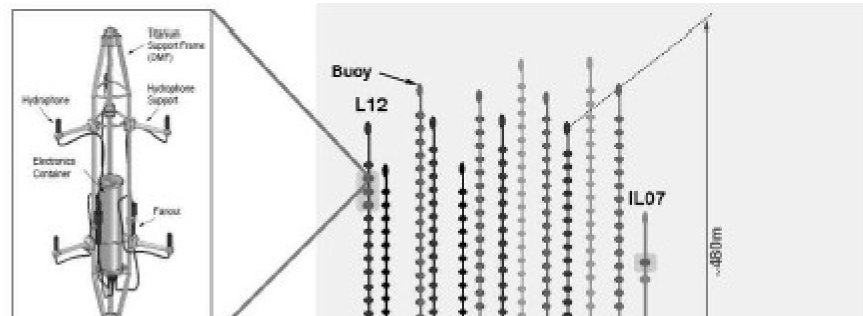
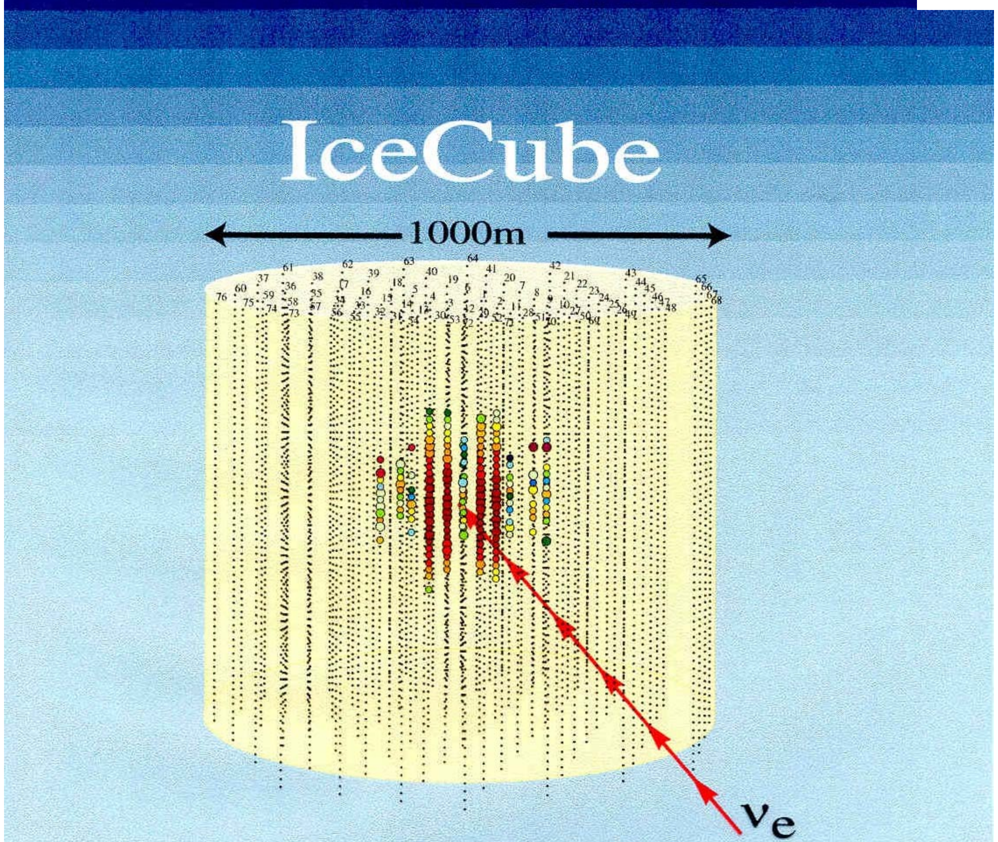
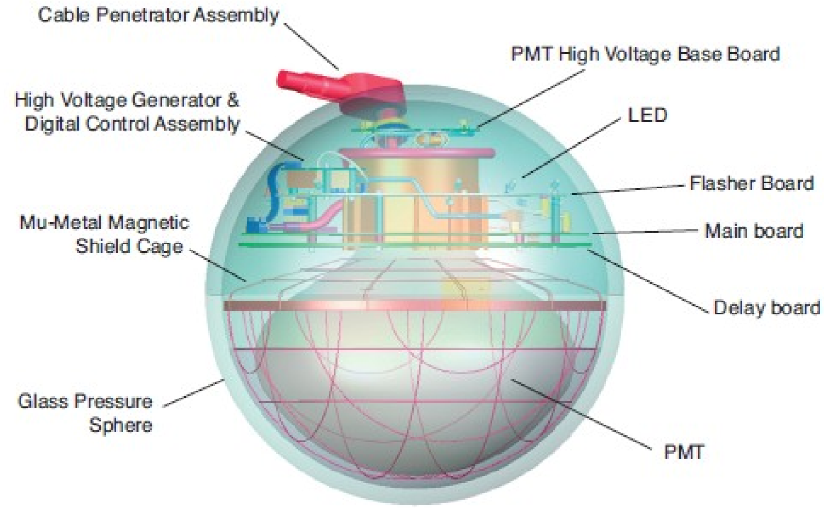



# IceCube



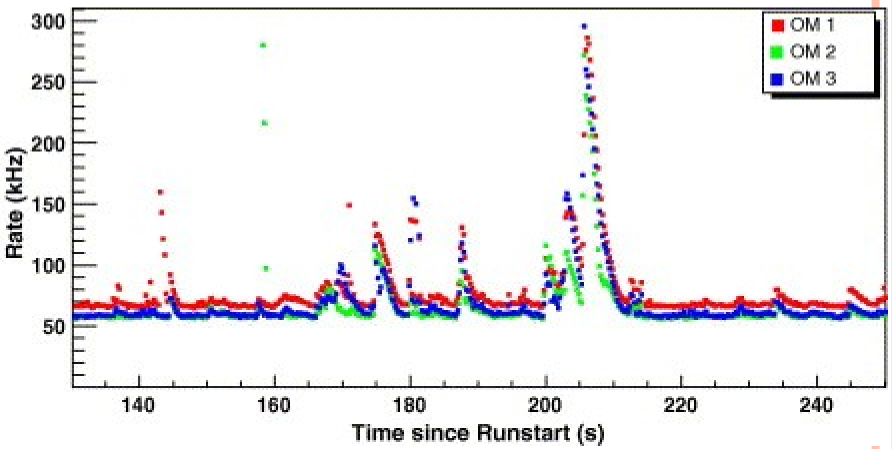

The largest existing detector, instrumenting 1 km$^3$ of Antarctic ice.
Precursor, AMANDA II, very similar to ANTARES in size and sensitivity.

# 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 |

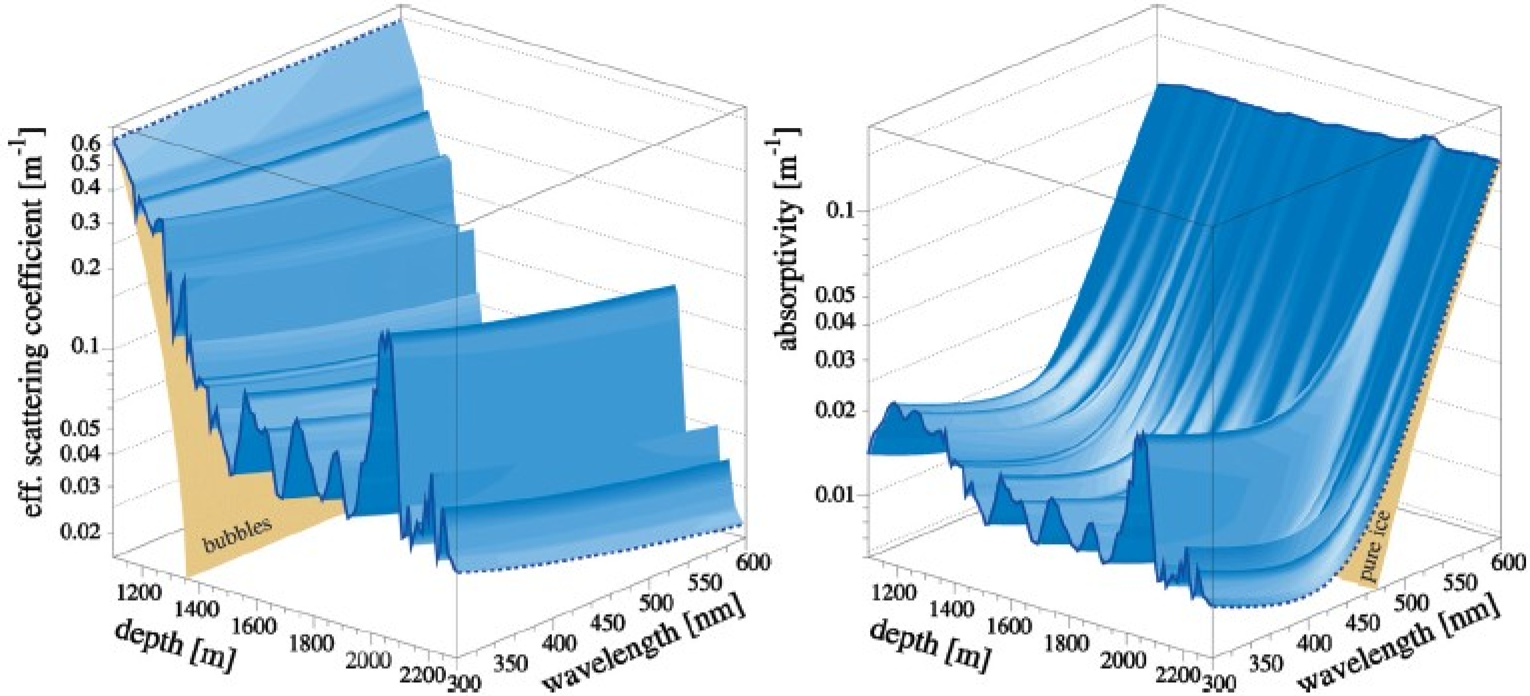
Long scattering length for ANTARES implies better angular resolution; long absorption length for IceCube implies sparser instrumentation. Quiet environments imply potentially useful data from singles rates.

# 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

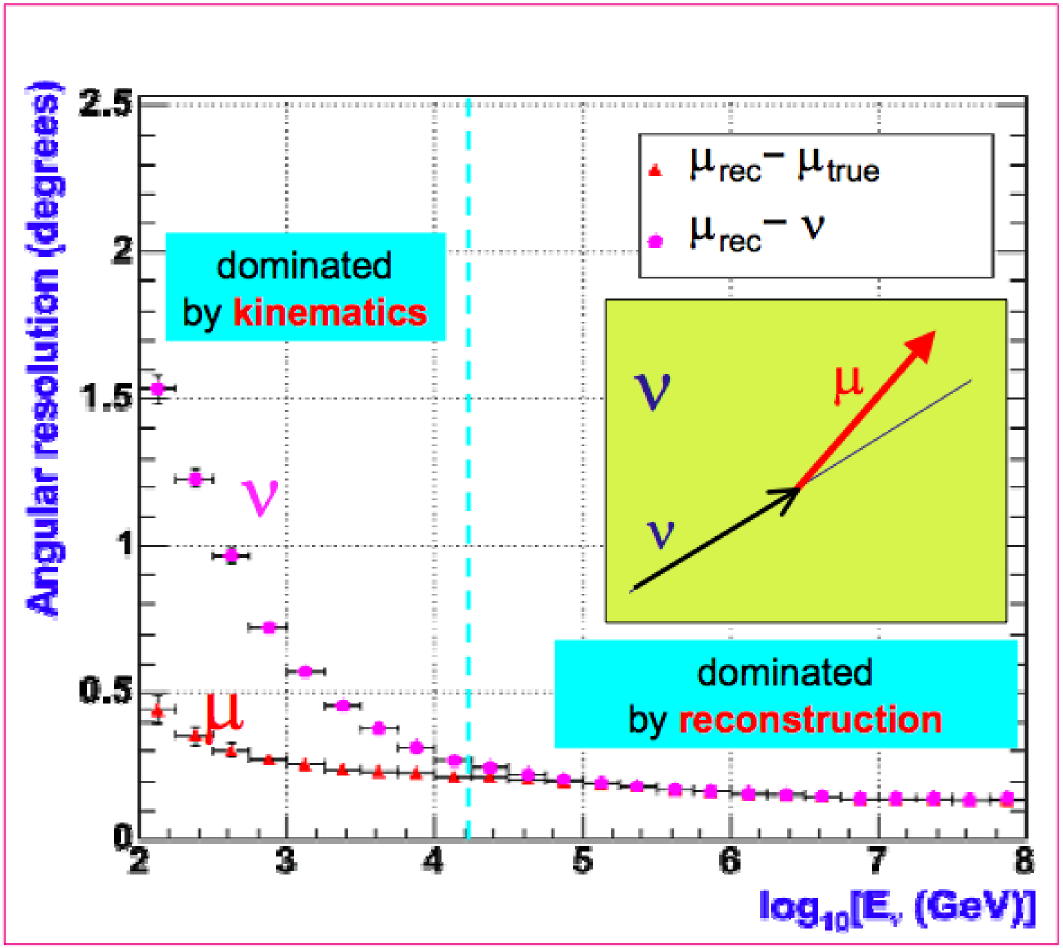



Scattering is a consequence of dust layers in the ice—function of global climate, level of volcanic activity, etc.

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

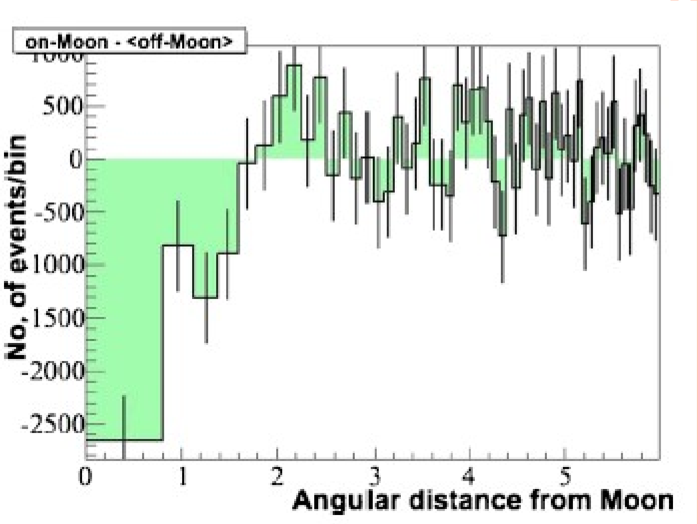
Note additional contribution from bubbles at shallow depths (<1400 m); IceCube deployed below this level.

# Angular Resolution




At 100 TeV: Amanda ~2°

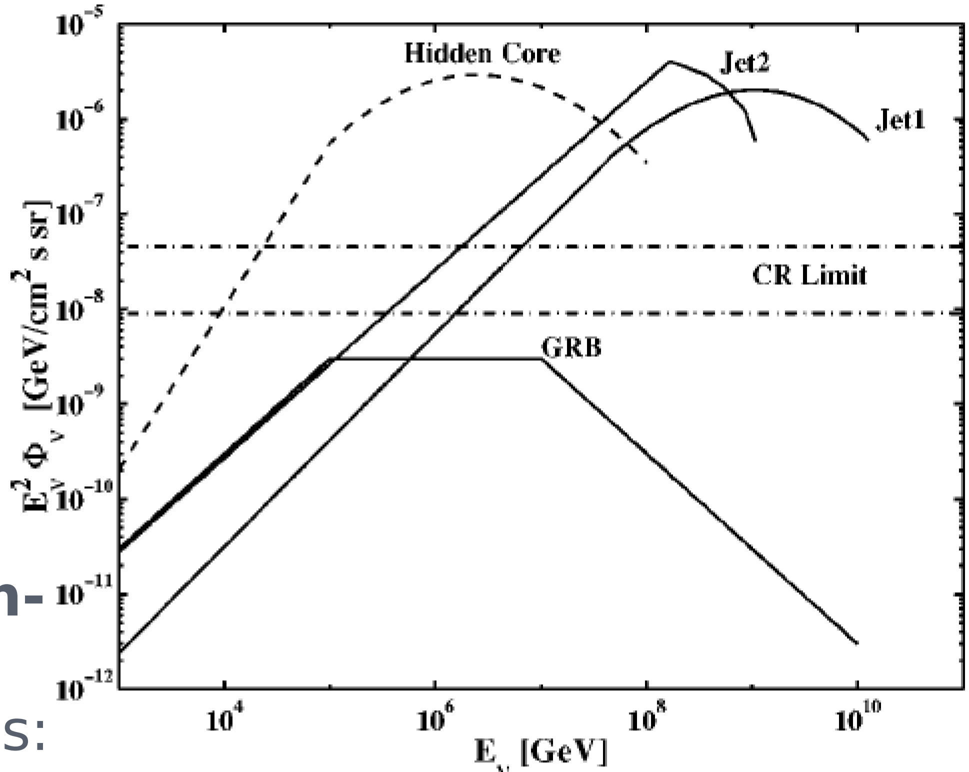
Antares ~ 0.2°




Moon's shadow in CR muons, measured by IceCube

Expected IceCube angular resolution ~0.5°

# Expected Fluxes

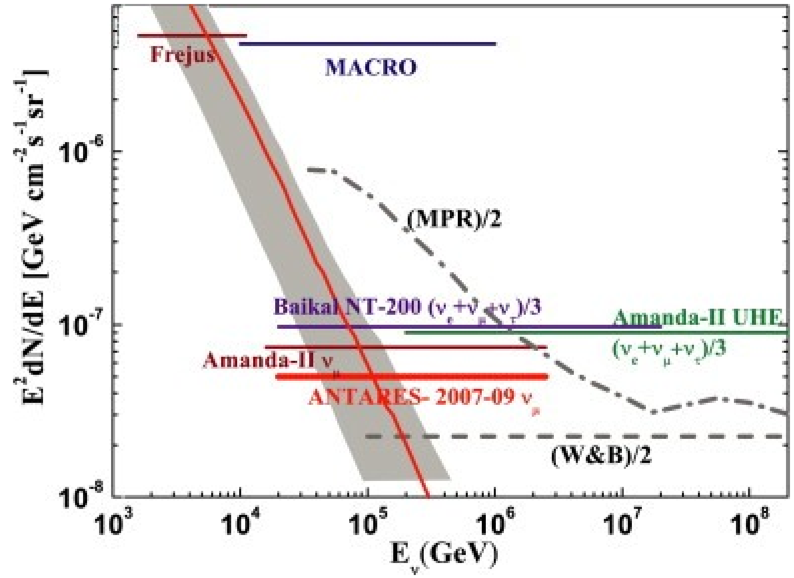


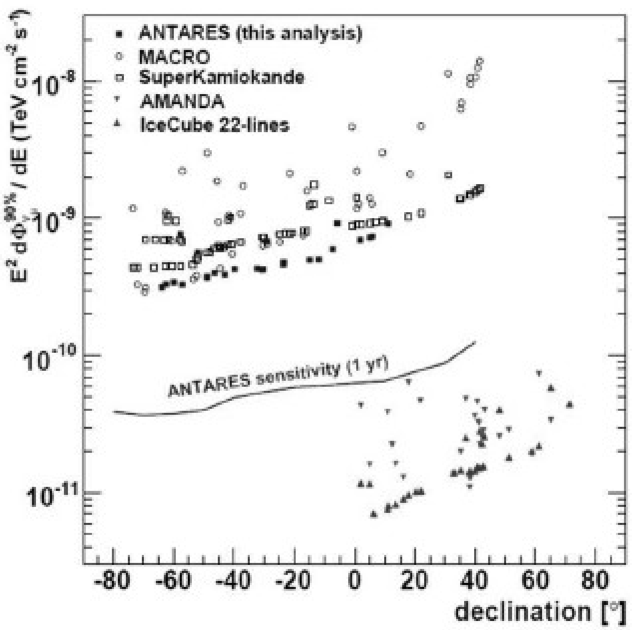

Expect high-energy astrophysical neutrinos to be produced in proton interaction cascades

- therefore, observed CR
- flux implies upper bound
- on neutrino flux (**Waxman-**
  - **Bahcall bound**:
  - 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: Eν2φν < $2\times10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for $10^{14}-10^{16}$ eV ν

# Results

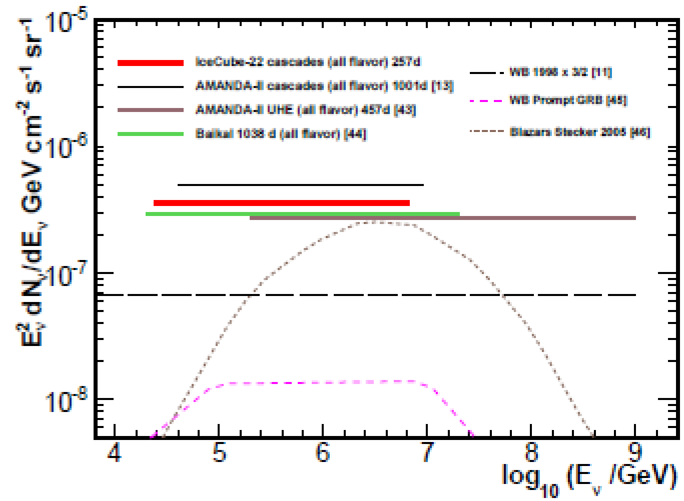
Still very statistics-limited. IceCube should be able to reach Waxman-Bahcall bound.




Point source search

ANTARES astro-ph/1002.0701



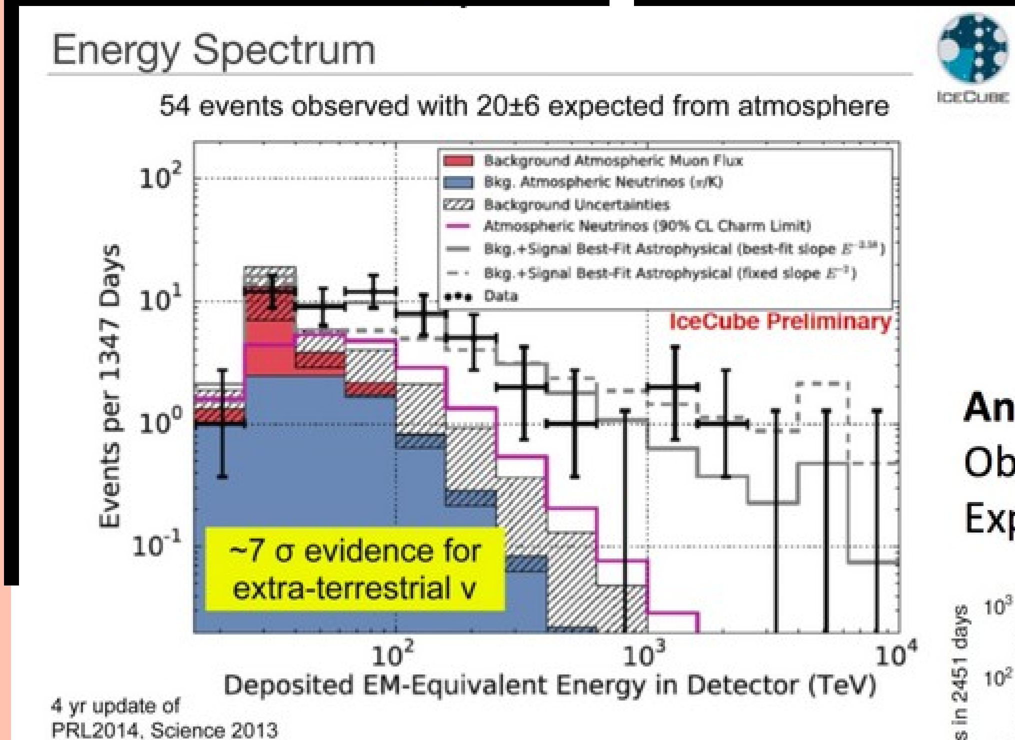

Limits on diffuse fluxes

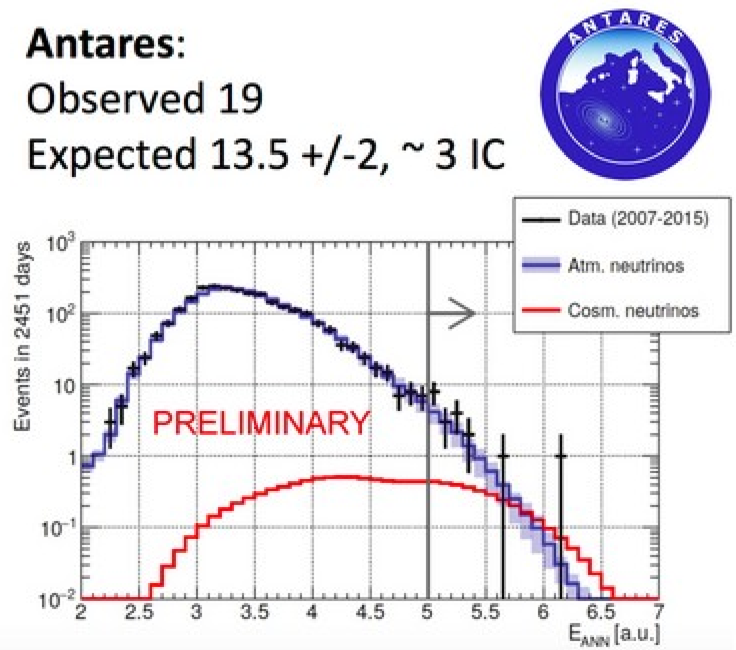
ANTARES, *Phys. Lett.* **B696** (2011) 16

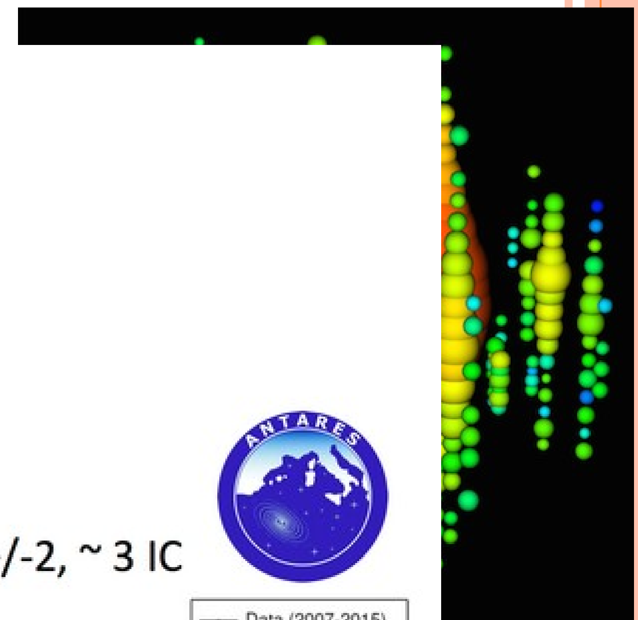
IceCube, astro-ph/1101.1692

# More Results

Statistical evidence for HE astrophysical neutrinos found in IceCube



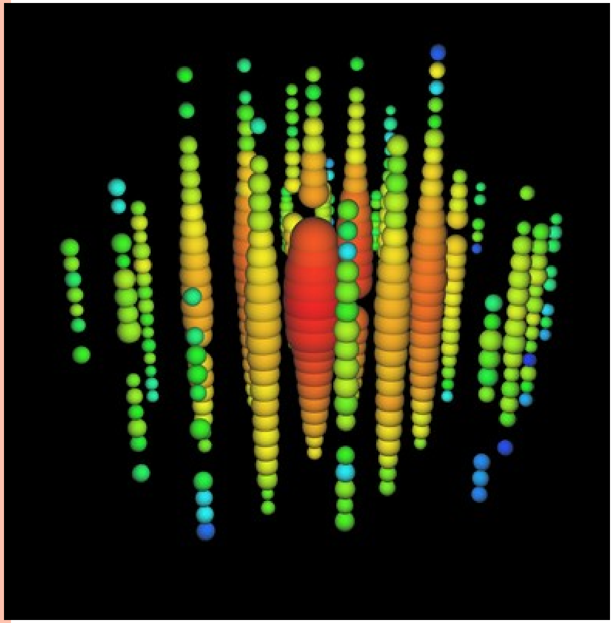



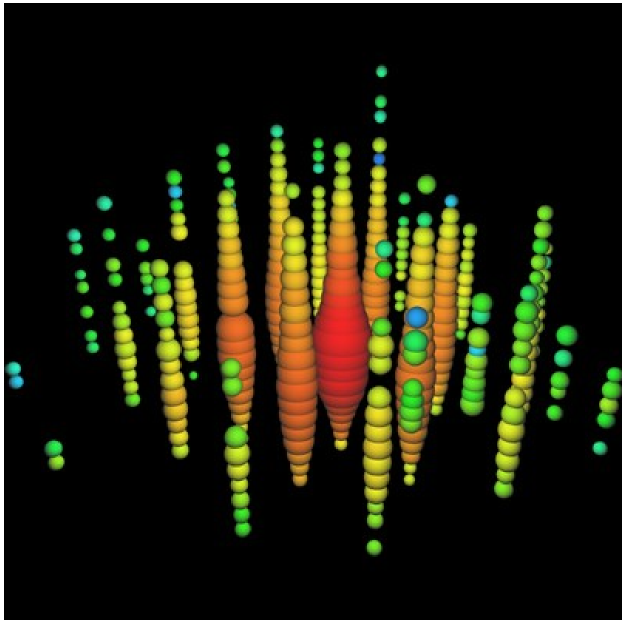
From Neutrino 2016

# More Results

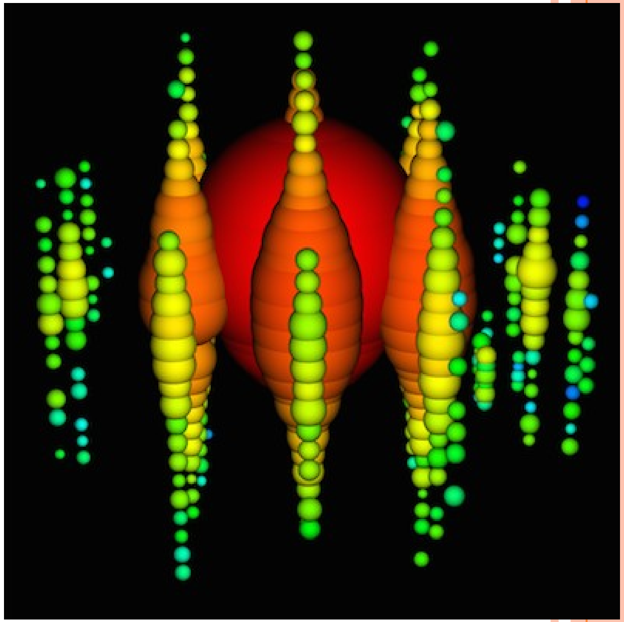
Statistical evidence for HE astrophysical neutrinos found in IceCube



- **Ernie (2012)**



- **Bert (2012)**

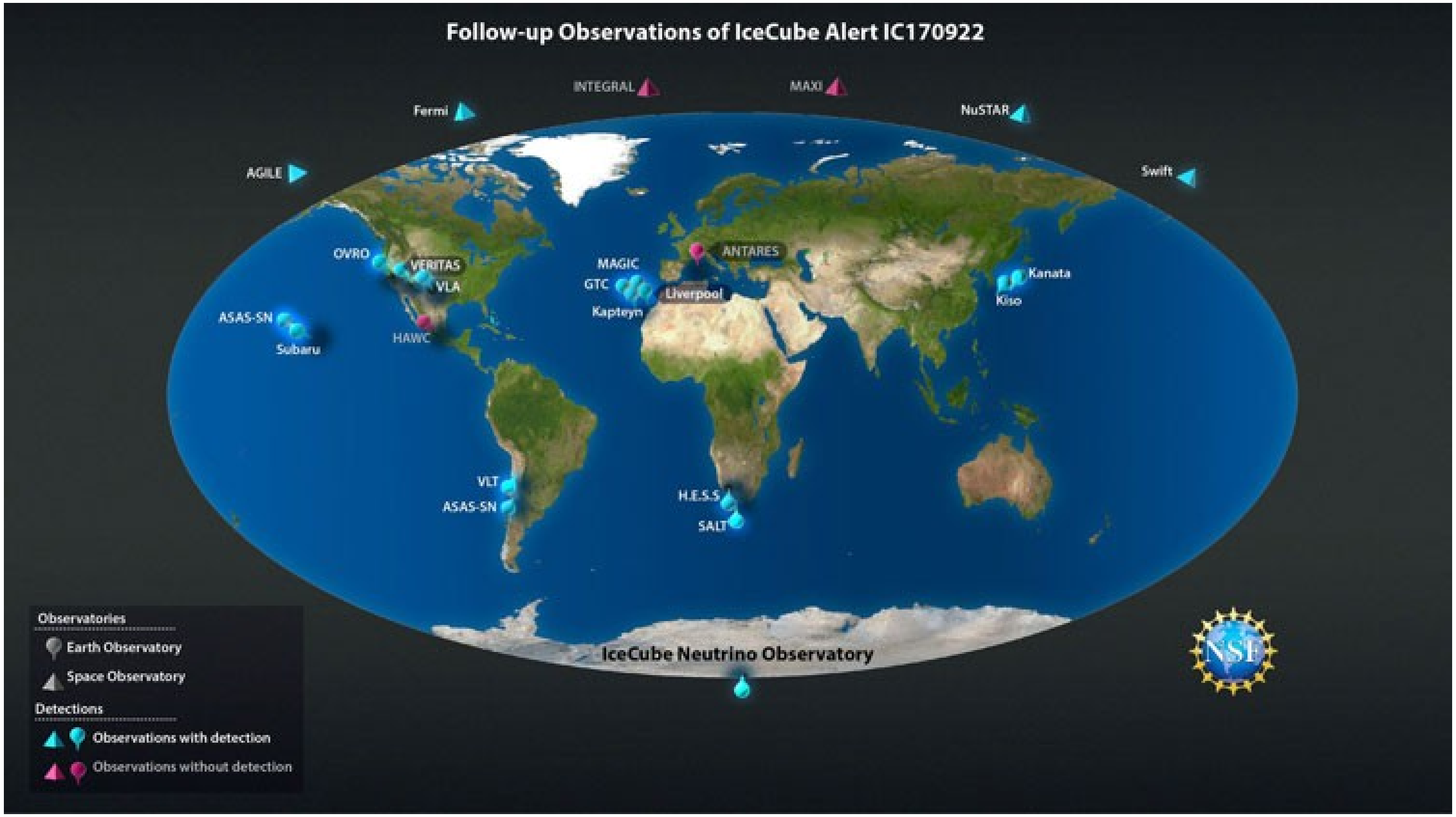


- **Big Bird (2014)**

From Neutrino 2016

# 2018 Breakthrough: First Source!

Statistical evidence for HE astrophysical neutrinos found in IceCube

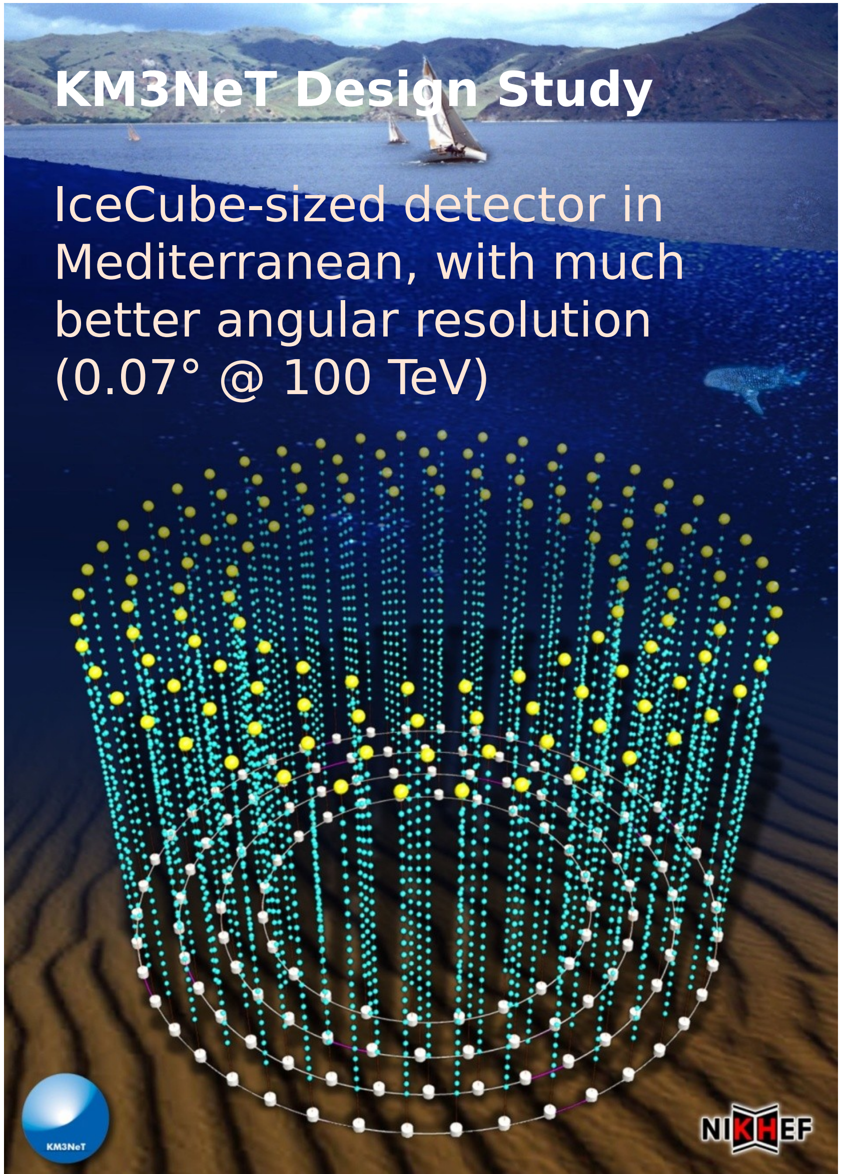


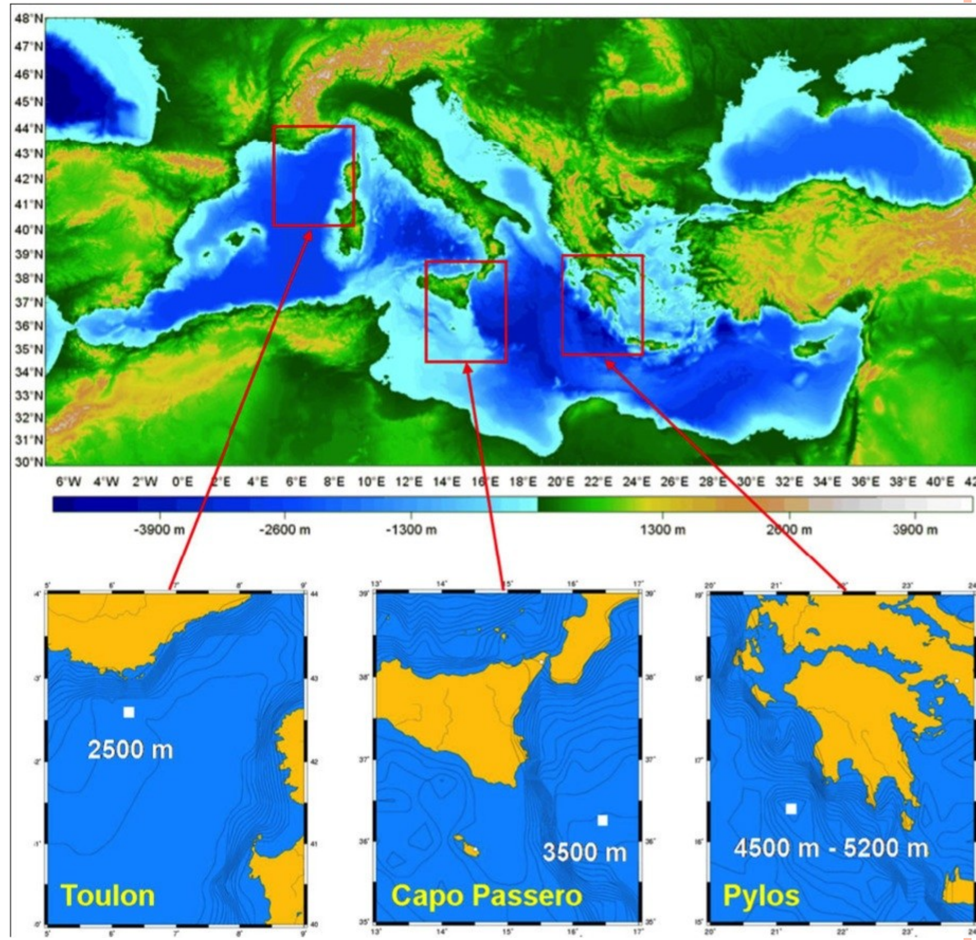

Chasing the ammonia economy p. 120
Time invested matters for mice, rats, and humans pp. 124 & 178
Two spindles are better than one pp. 128 & 189
Science
$15
13 JULY 2018
sciencemag.org
AAAS
NEUTRINOS
FROM A BLAZAR
Multimessenger observations of an astrophysical neutrino source pp. 115, 146, & 147


# Next Generation Water Cherenkovs

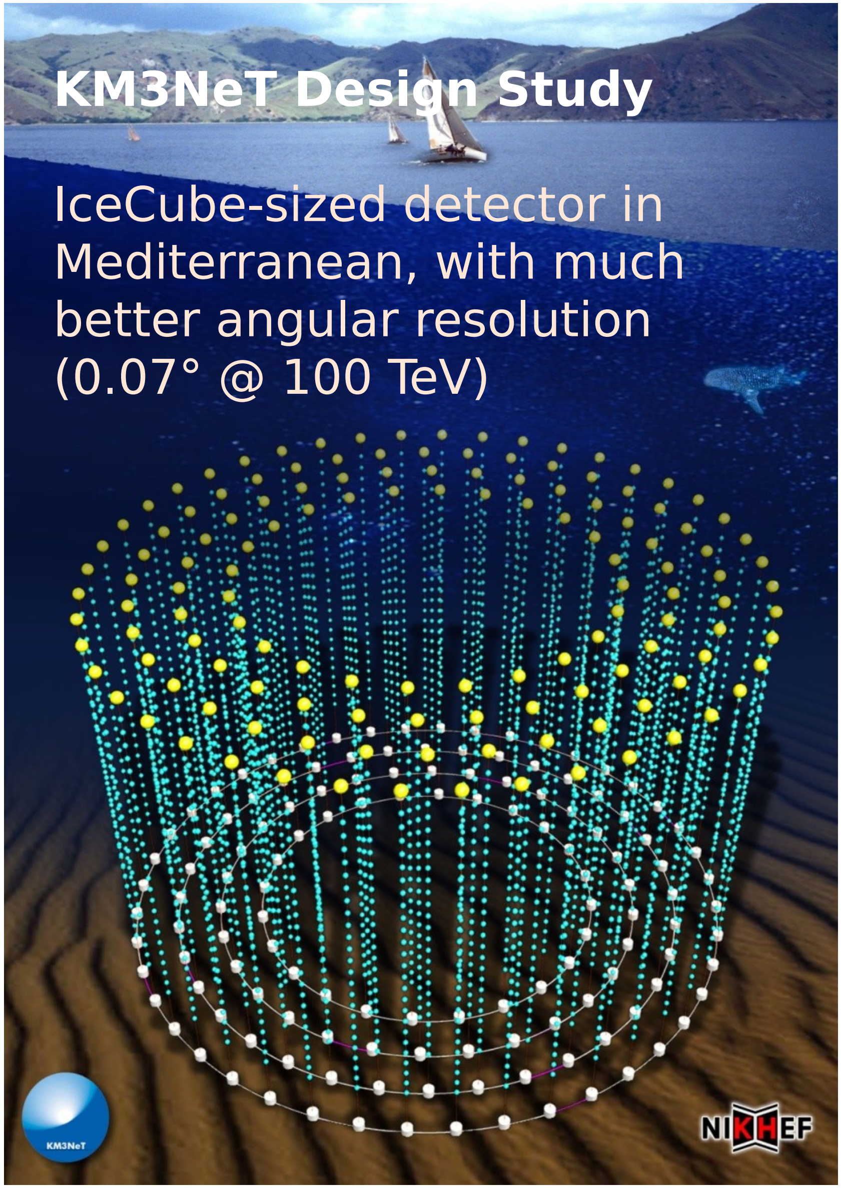
**KM3NeT Design Study**

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

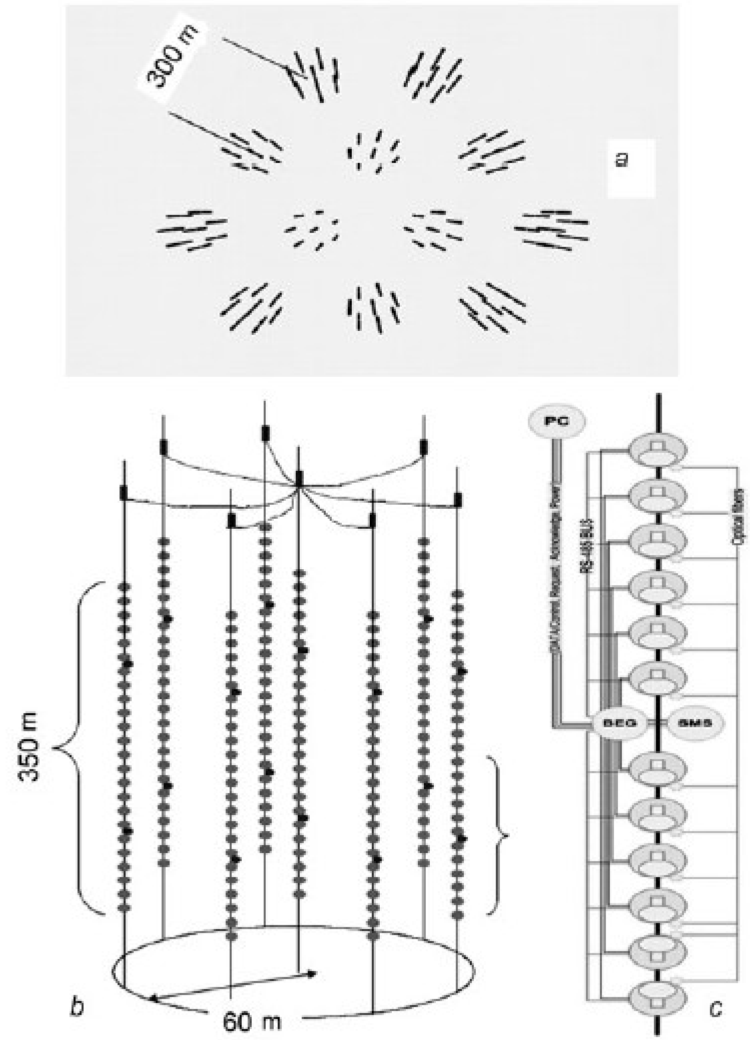




# Next Generation Water Cherenkovs

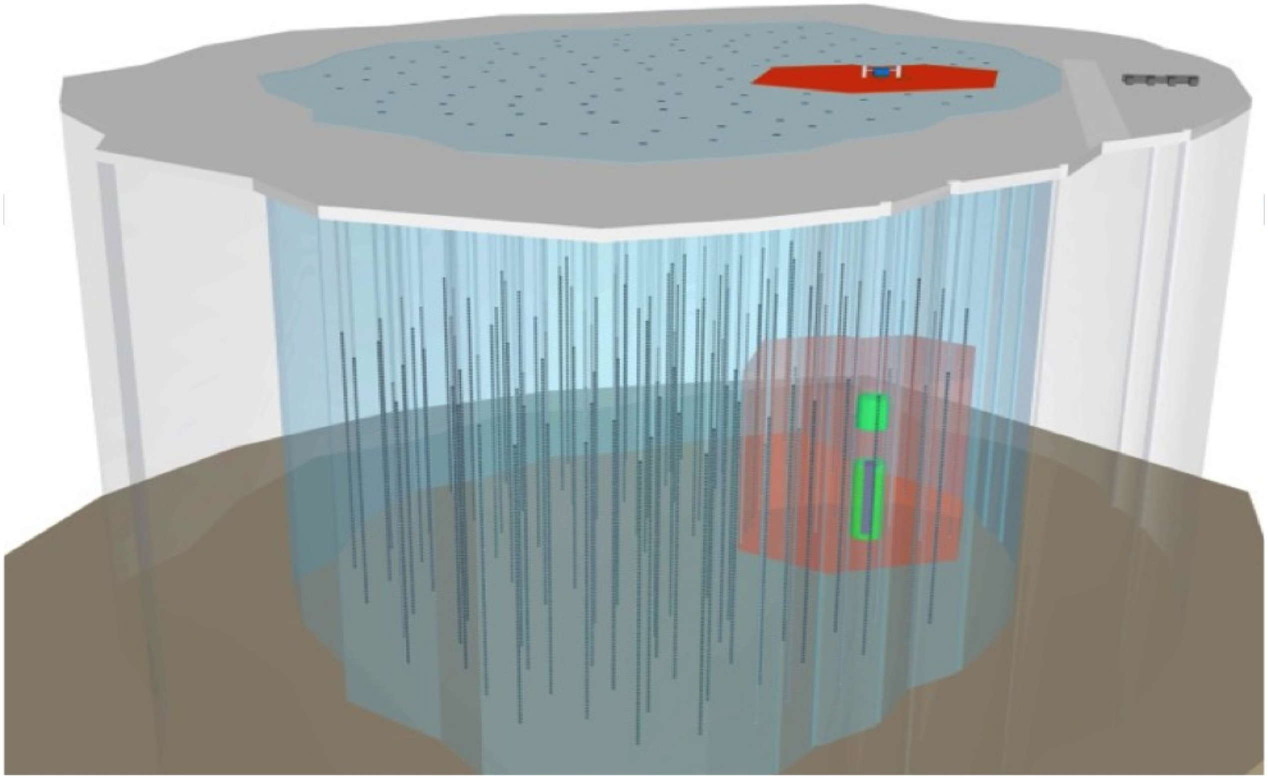



Baikal-1000



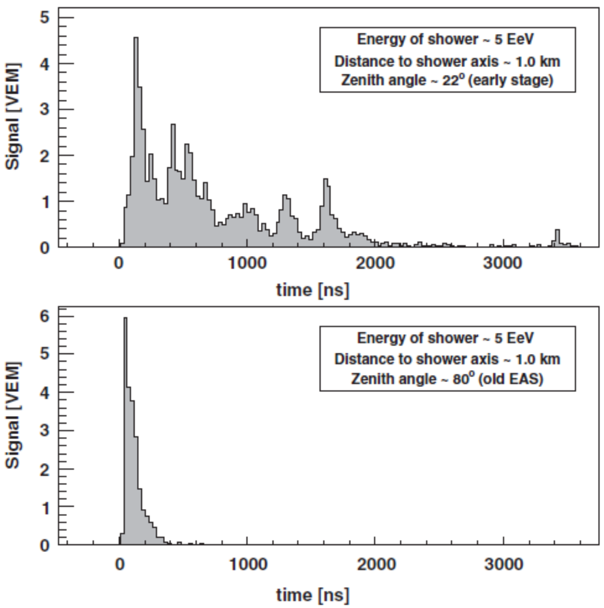
# Next Generation Water Cherenkovs

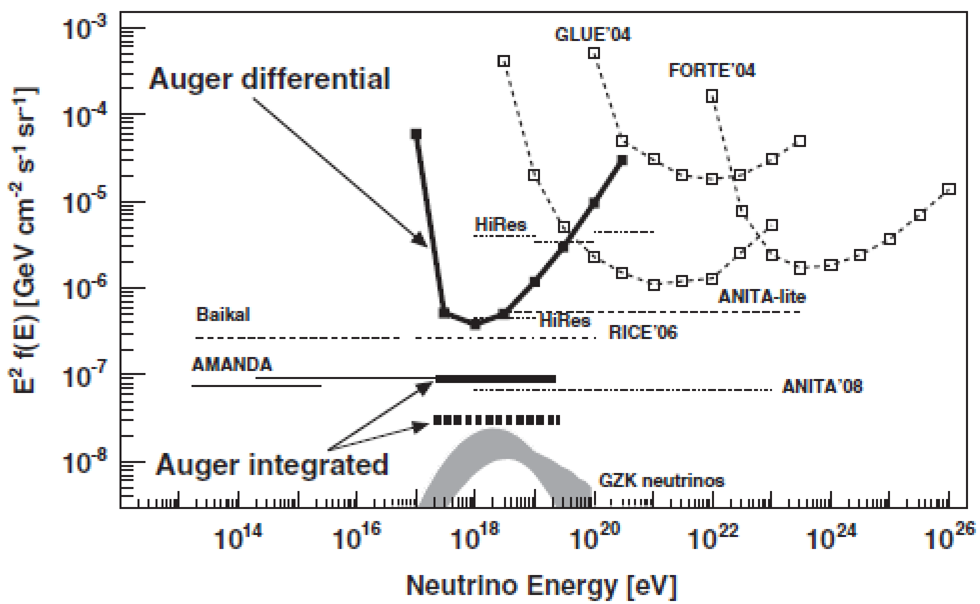
IceCube Gen2:



# Tau-Neutrino Detection By Air Showers

- Earth-skimming $\nu\tau$ interacts in Earth's crust to produce $\tau$
- $\tau$ 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)



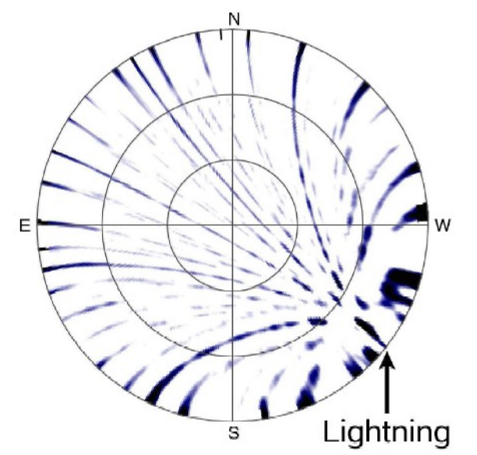



# High Energy Astroparticle Physics

## New Detection Techniques

# Radio-Frequency Detection of Air Showers and Neutrinos

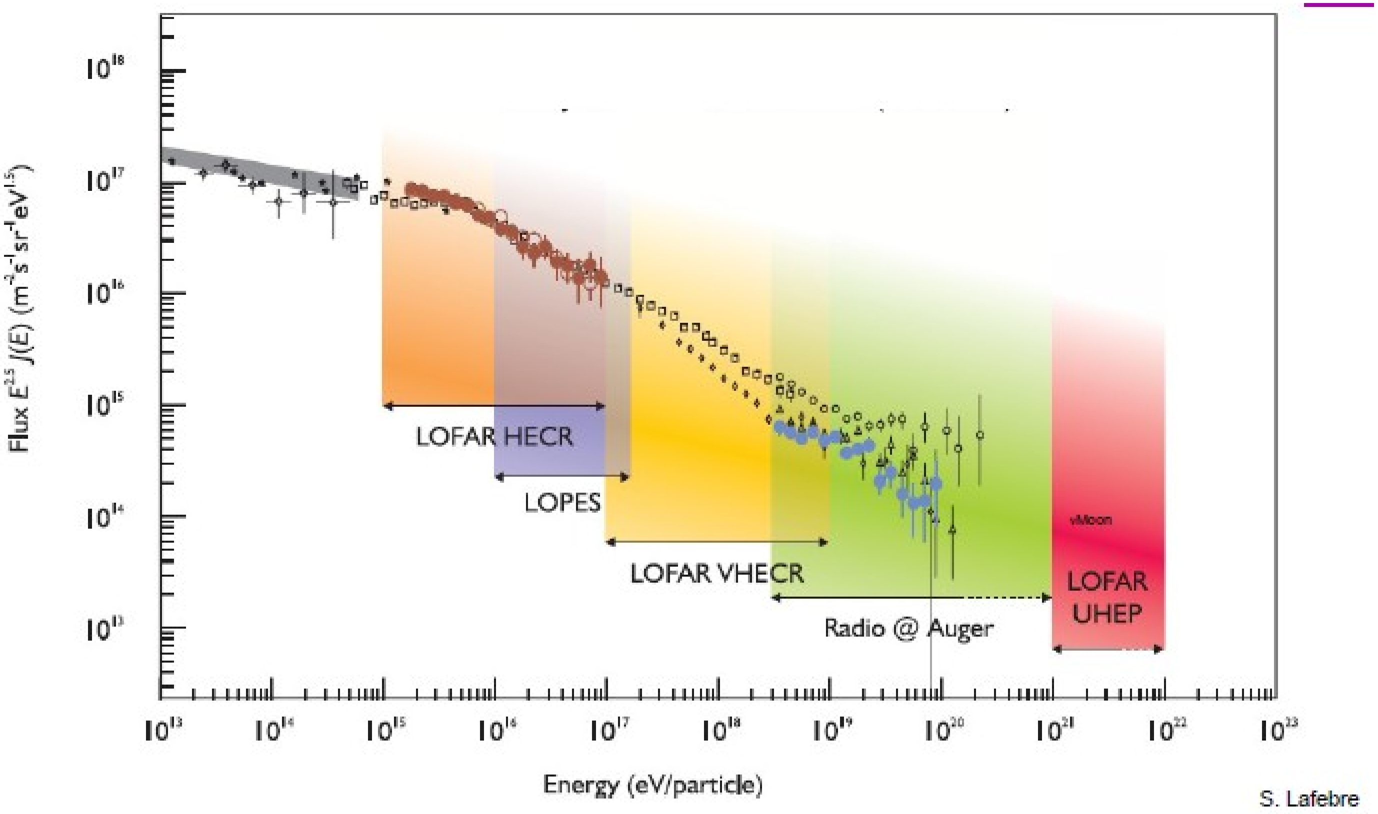
- Geosynchrotron emission (10−100 MHz)
  - synchrotron radiation from air-shower particles gyrating in Earth's magnetic field
  - advantages over fluorescence:
    - very high duty cycle (only wiped out by thundersto
    - low attenuation (so, large effective area)
  - disadvantages:
    - interference (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



# LOFAR

LOw Frequency Array Radio (based in the Netherlands)

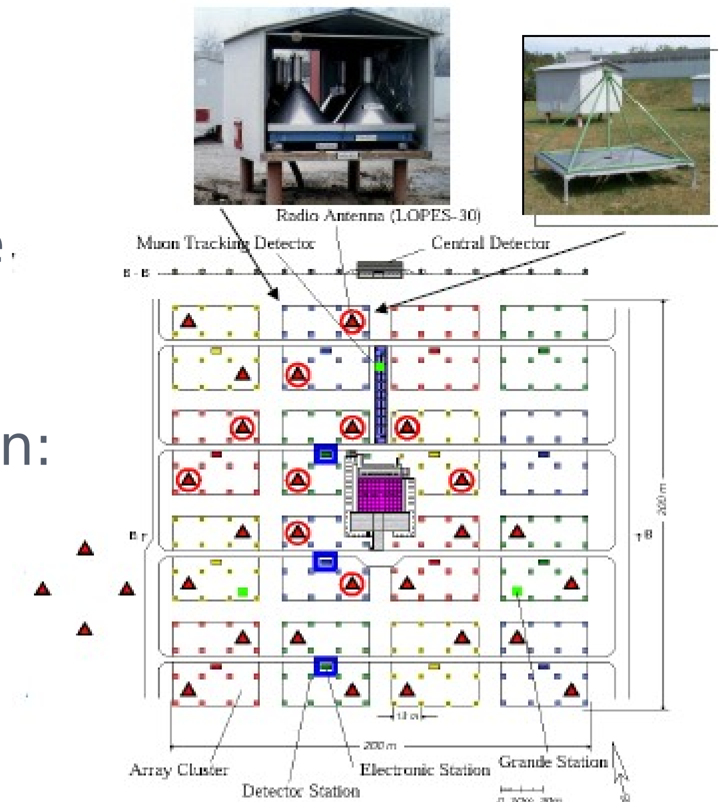
Mostly a radio astronomy facility, but good prospects for radio detection of UHECRs (see LOPES/KASCADE).

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

# LOPES/KASCADE

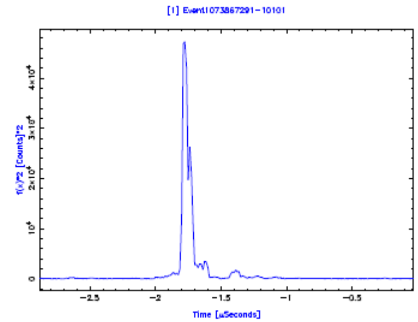
KASCADE: scintillator-based

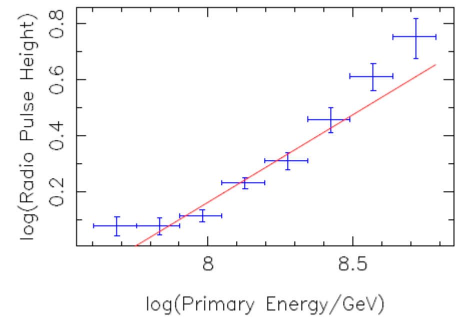
- ground array
- LOPES (LOFAR Prototype Station)
  - initially 10, now 30, low-frequency RF antennas triggered by KASCADE “large event” trigger
  - KASCADE reconstruction
  - provides input to LOPES recon:
    - core position of air shower
    - its direction
    - its size

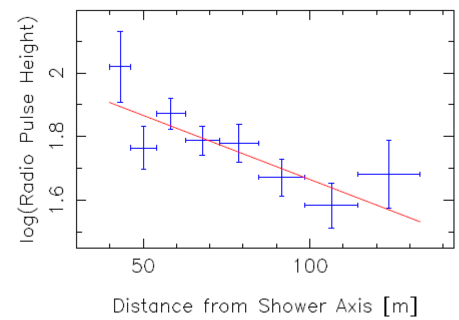


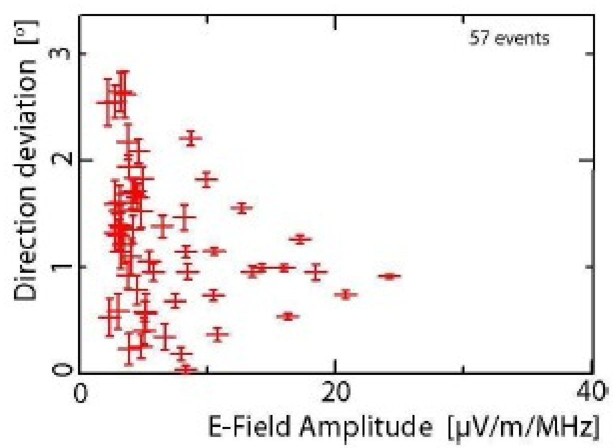
# LOPES/KASCADE

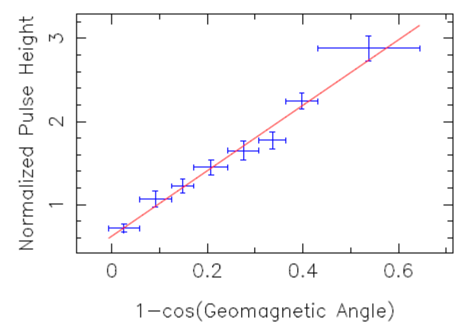
- First detection: January 2004
- strong coherent radio signal
  - coincident with KASCADE shower
  - reconstruction location agreed with KASCADE to 0.5°
- Extensive data sample now accrued
- technique works well and suggested full LOFAR array
- (completed 2012) should be
- excellent
  - CR detector





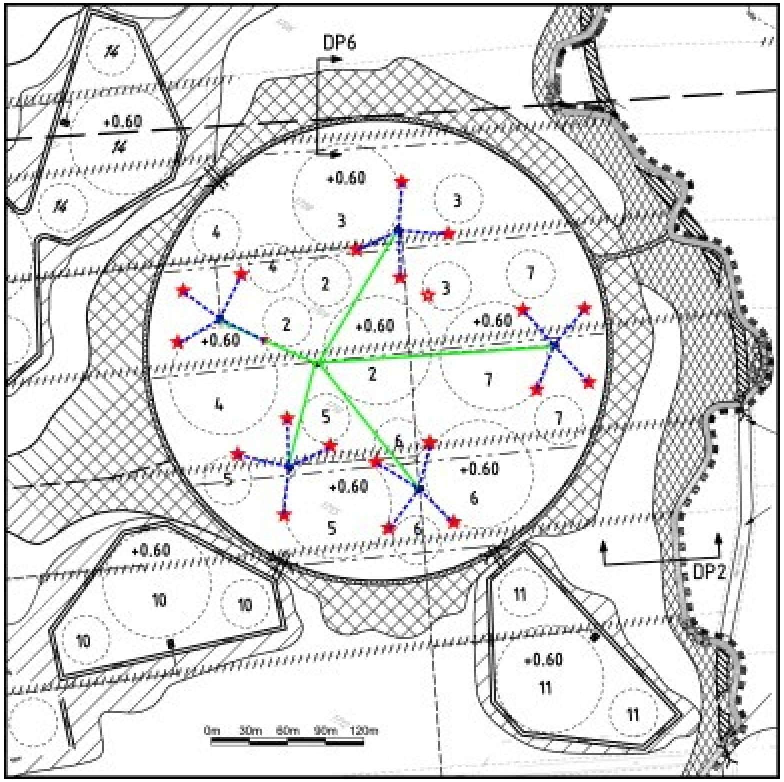



# LOFAR as a cosmic ray detector

- 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

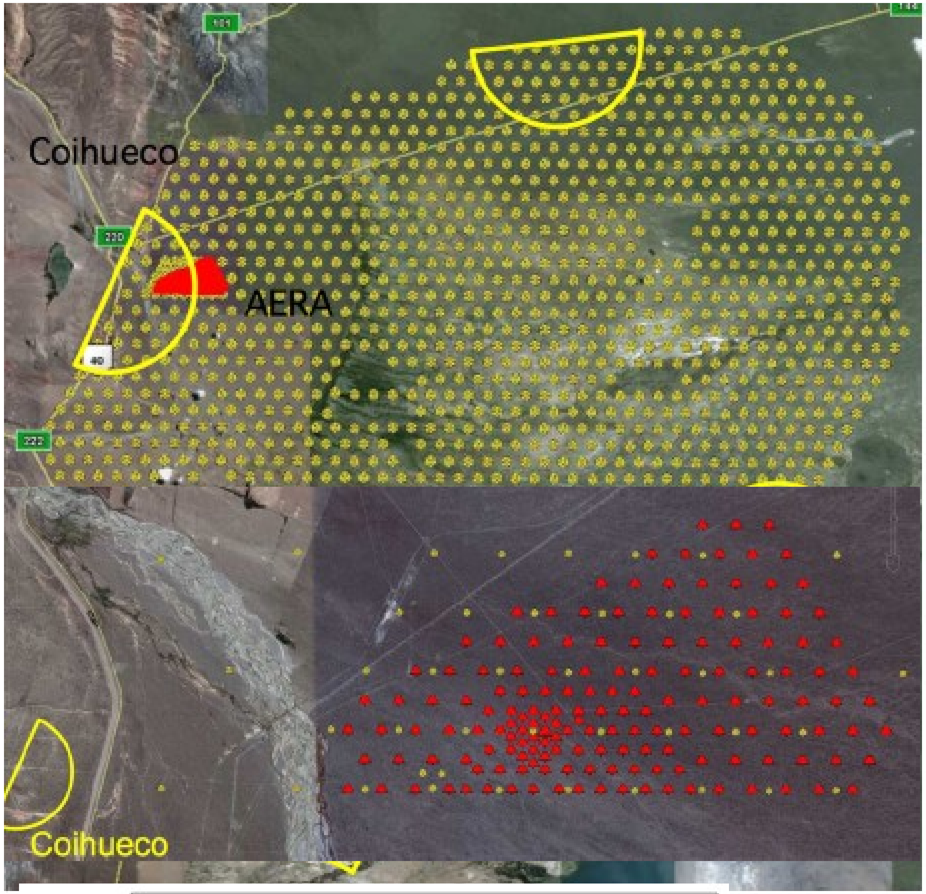


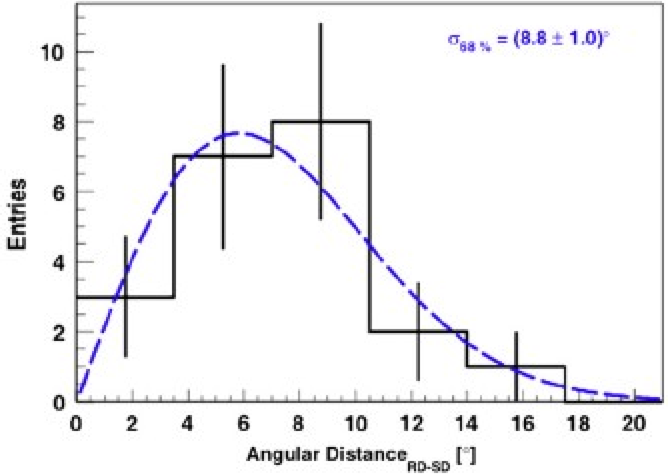

Thoudam et al., astro-ph/1102.0946v1

# 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

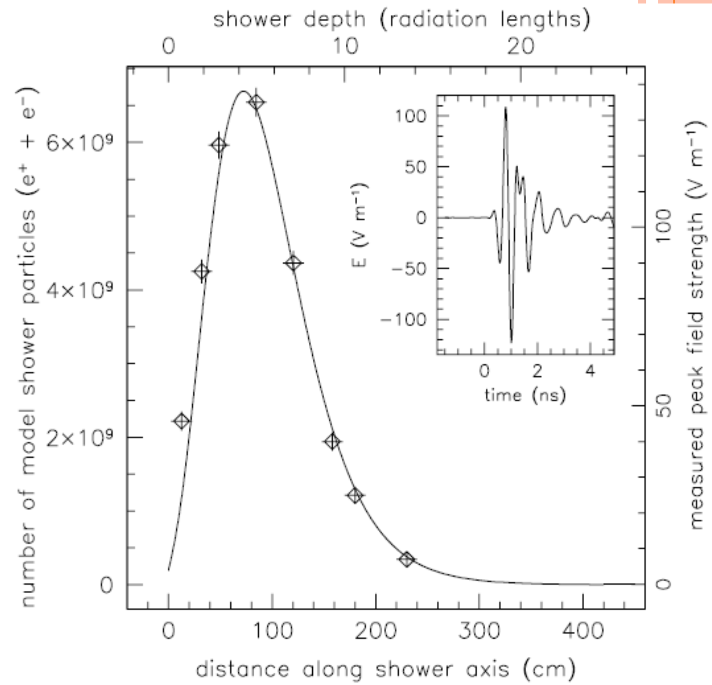


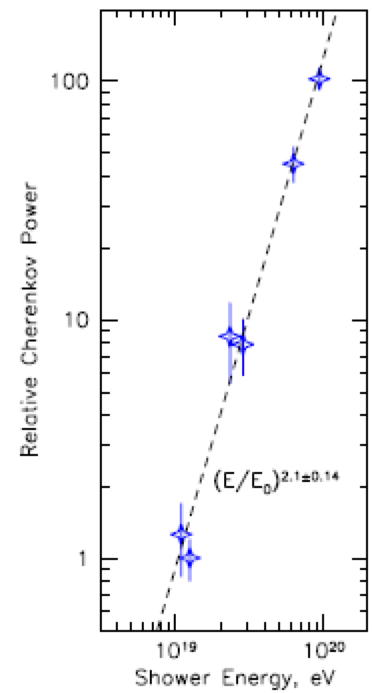



# Askaryan Effect

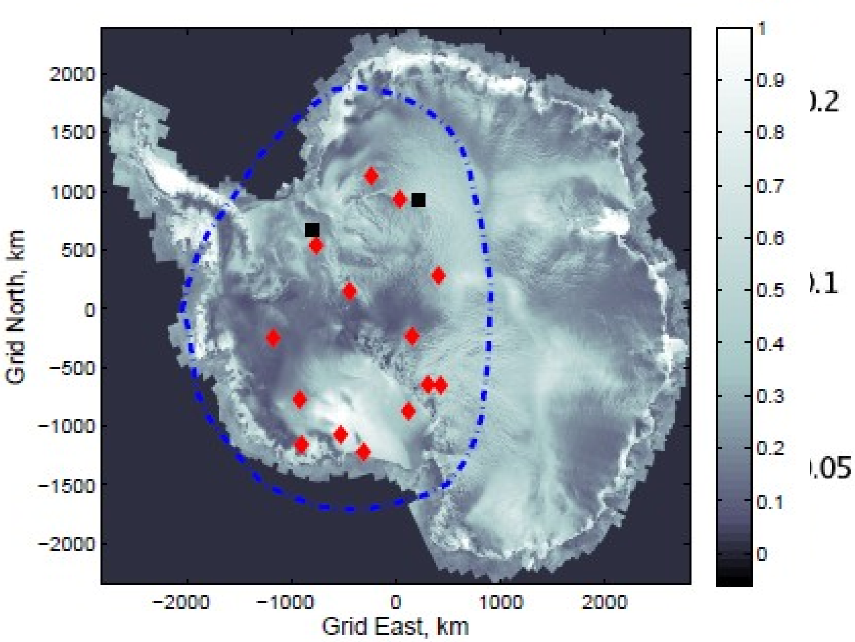
Effect demonstrated in sand(2000),

- 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)



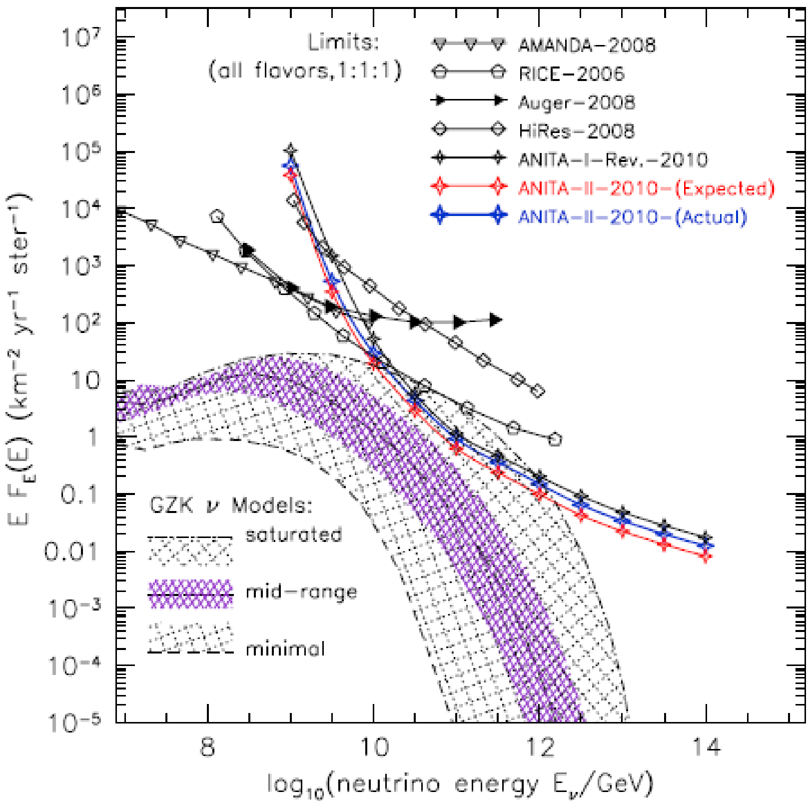
# Askaryan Effect: ANITA

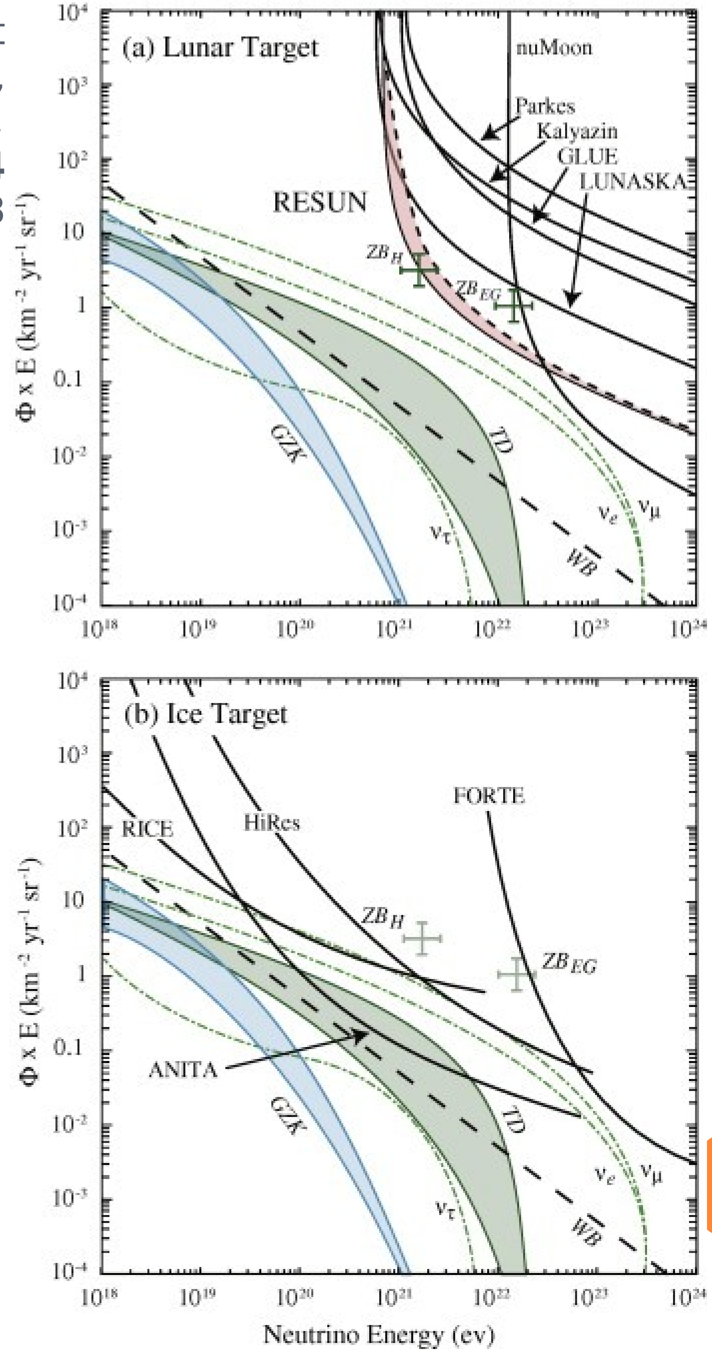



# Askaryan Effect

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

- ANITA observed UHECRs (geosynchrotron signal)
- First possible signal (2017)

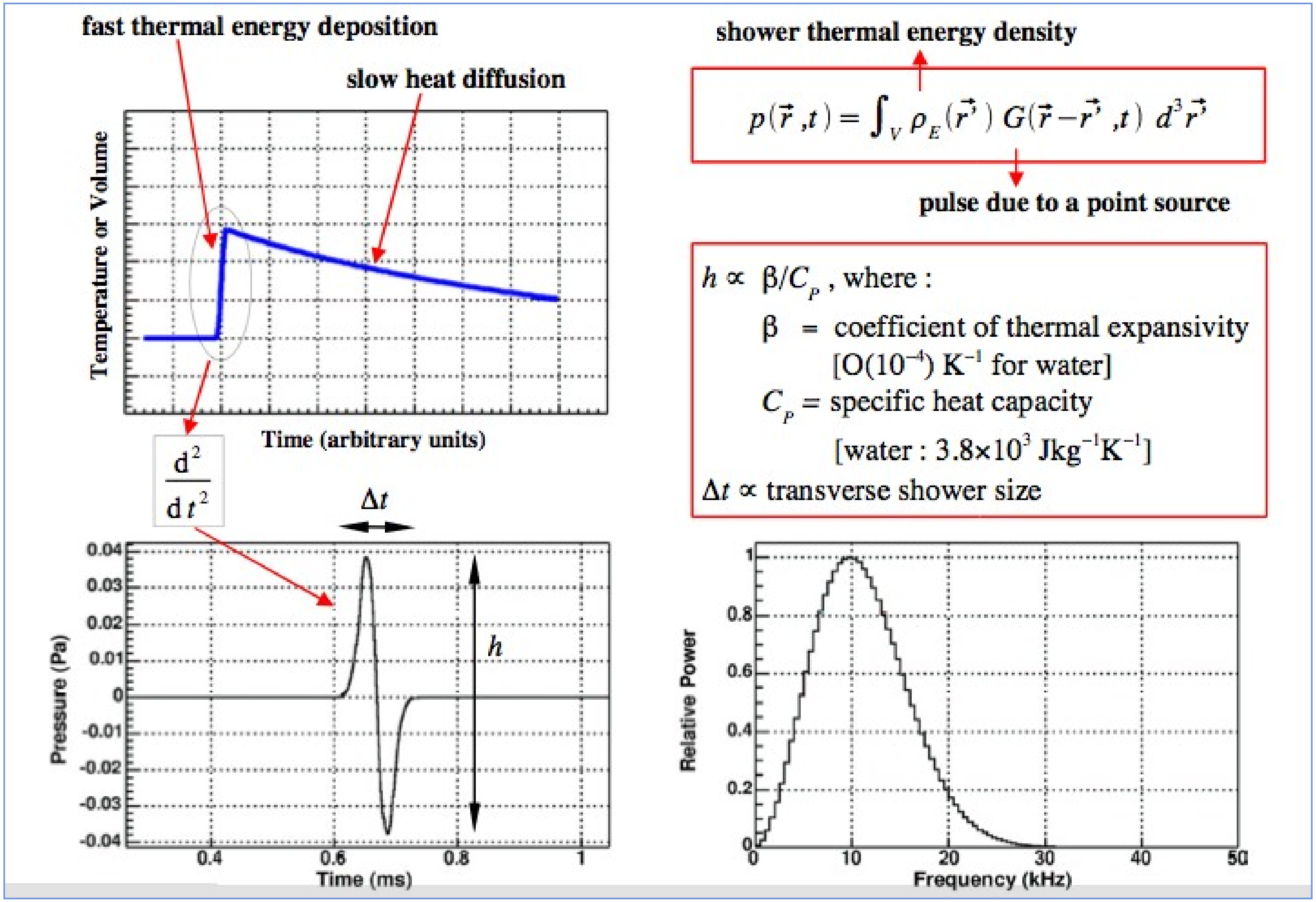


# Acoustic Detection (Showering Neutrinos)

- 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

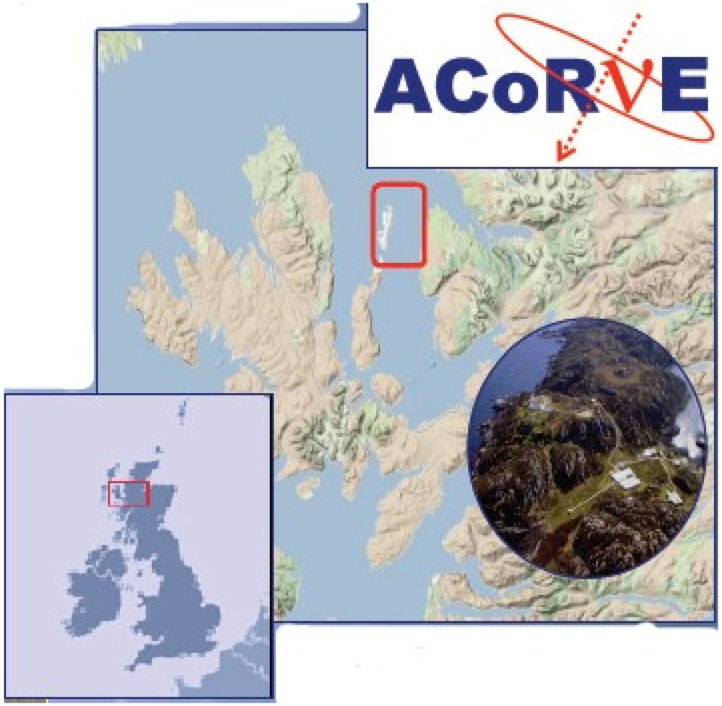

fast thermal energy deposition
slow heat diffusion
Temperature or Volume
Time (arbitrary units)
$\frac{d^2}{dt^2}$
$\Delta t$
$h$
Pressure (Pa)
Time (ms)
shower thermal energy density
$p(\vec{r},t) = \int_V \rho_E(\vec{r}') \, G(\vec{r}-\vec{r}',t) \, d^3\vec{r}'$
pulse due to a point source
$h \propto \beta/C_p$, where :
$\beta$ = coefficient of thermal expansivity
[$O(10^{-4})$ $K^{-1}$ for water]
$C_p$ = specific heat capacity
[water : $3.8\times10^3$ $Jkg^{-1}K^{-1}$]
$\Delta t \propto$ transverse shower size
Relative Power
Frequency (kHz)

# Experiments

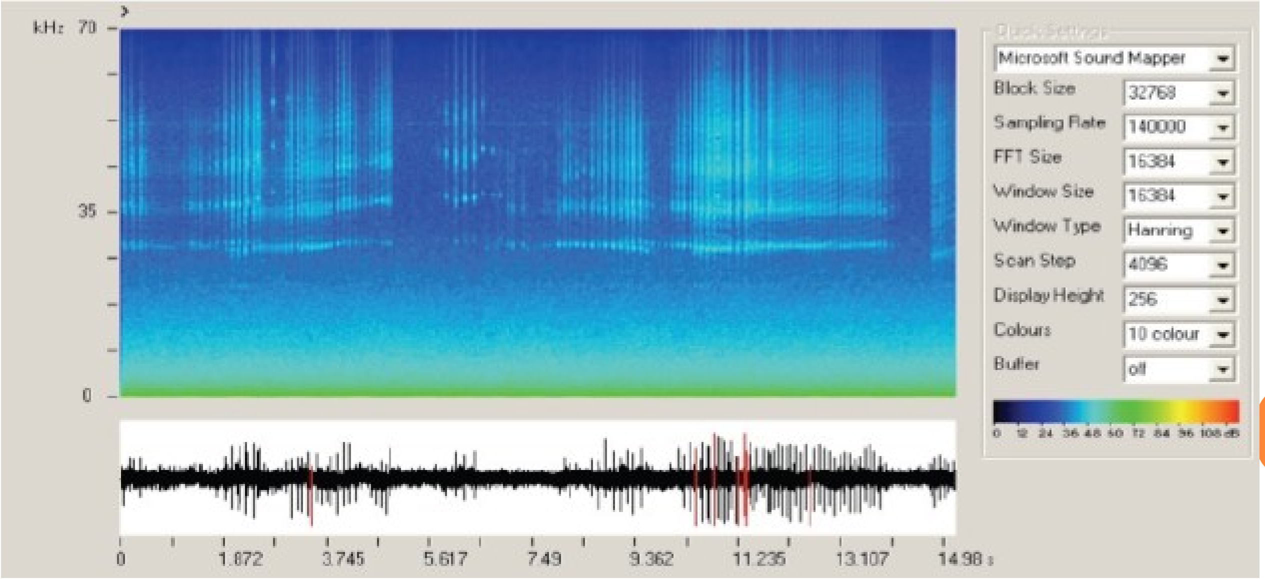
- ACORnE
  - UK feasibility study using military hydrophone array off Rona
- AMADEUS
  - co-deployed with ANTARES
- Lake Baikal
  - co-deployed with Baikal-200
- ONDE
  - part of NEMO (NEutrino Mediterranean Observatory)
  - NB: <u>NOT</u> Neutrino Ettore Majorana Observatory!
- SAUND-I and SAUND-II
  - 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!)

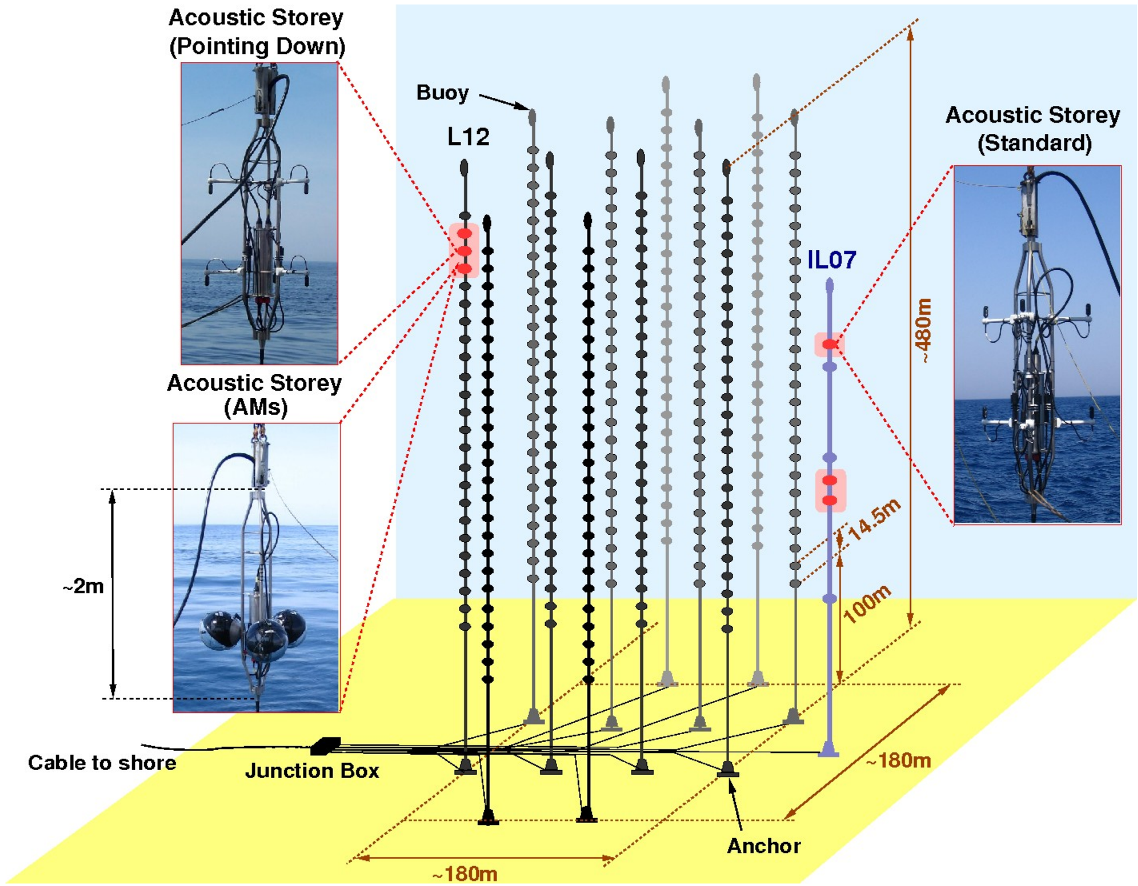


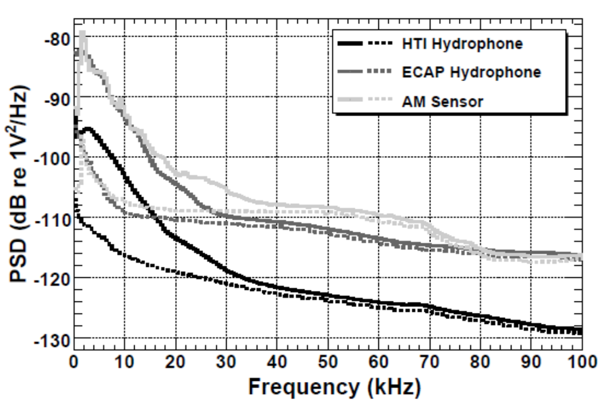

Example of background source—dolphin clicks!

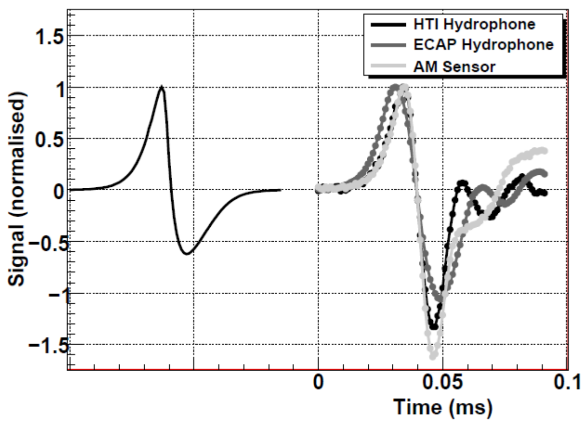


# AMADEUS

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

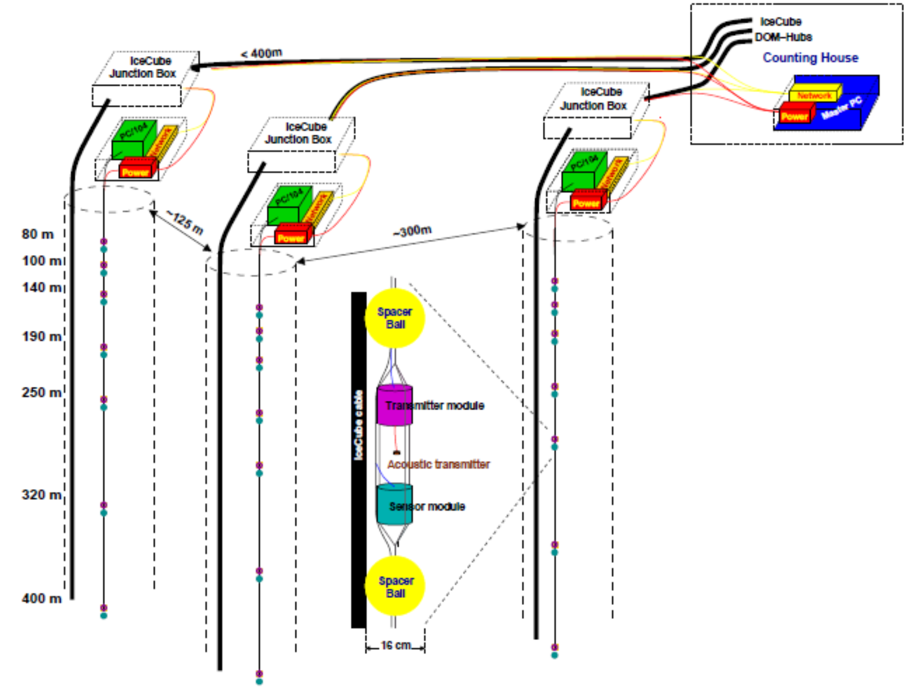


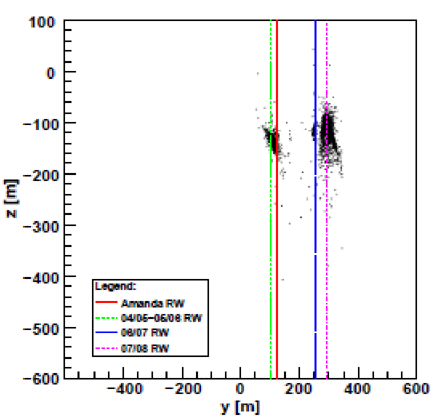



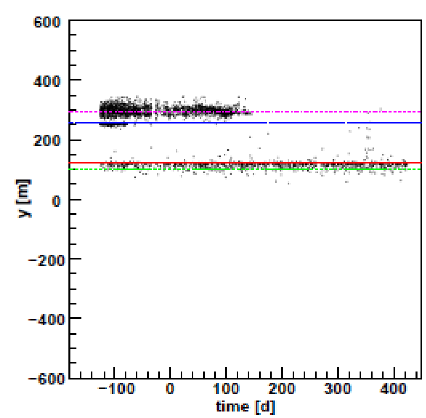



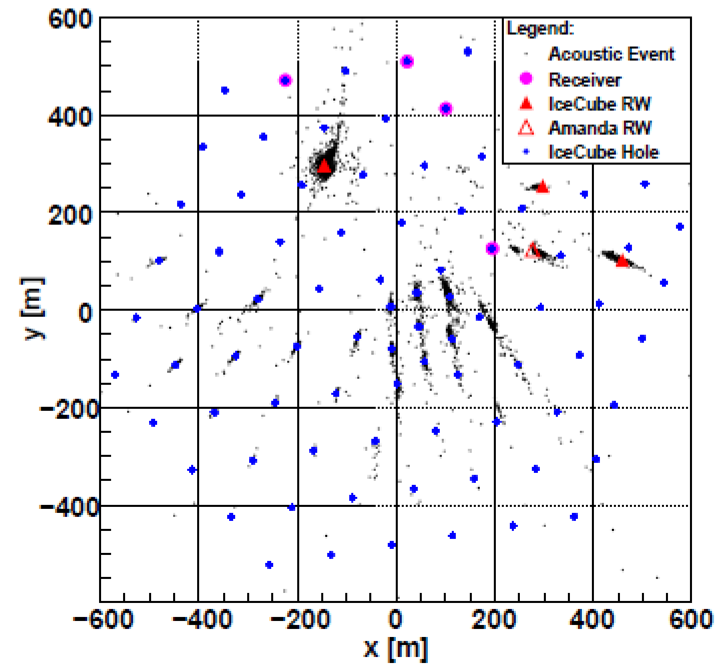
# SPATS

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

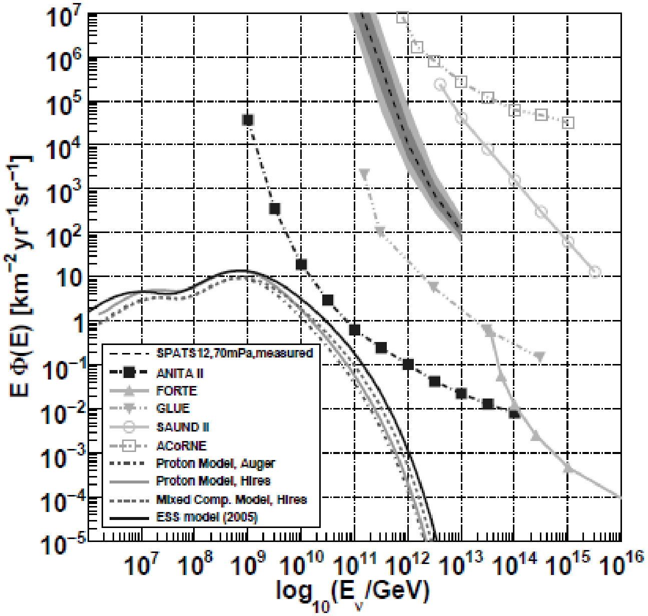


# Acoustic Detection: Summary




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