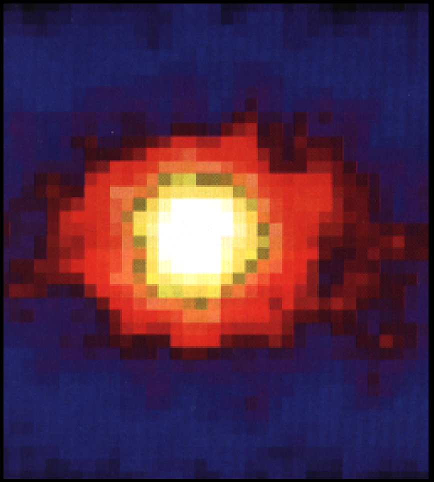
IceCube: A km-scale ν Detector

David Nygren
LBNL
13 July 2006

The observed neutrino sky so far



MeV:
- SUN (Kamiokande, SuperK, SNO)
- SN 1987A (few neutrino events) Kamiokande & IMB
- The neutrino "ground": Geo-ν's in Kamland

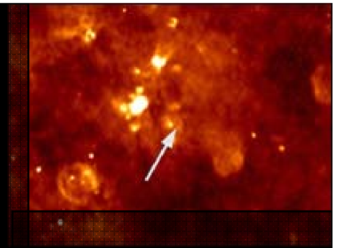
- Atmospheric neutrinos: GeV and above by SuperK, …
- AMANDA, Baikal, IceCube, & km3NeT optimized to detect **High-Energy ν's** from **TeV-PeV and beyond**

$$p + p \rightarrow \pi + \ldots \rightarrow \nu + \ldots \quad \text{or}$$

$$p + \gamma \rightarrow \Delta \rightarrow \pi + n \rightarrow \nu + \ldots$$

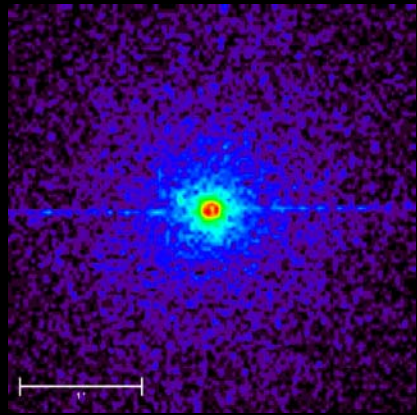
Potential Neutrino Sources

nearby AGN M87 (HST)



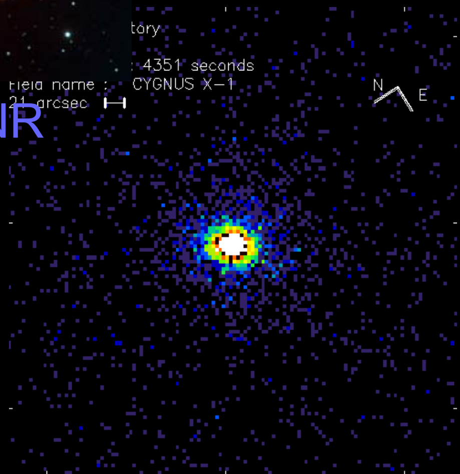
Magnetar SGR 1806-20

Quasar 3C273 Kitt Peak



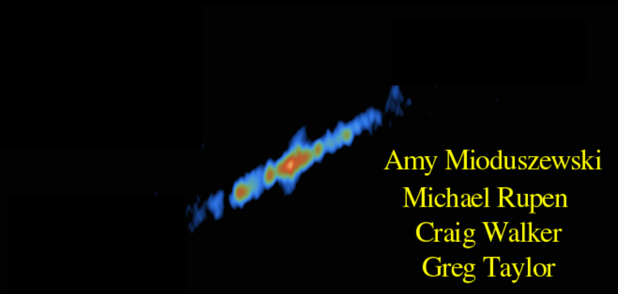
Cygnus X-3 x-ray (Chandra)

Crab nebula SNR



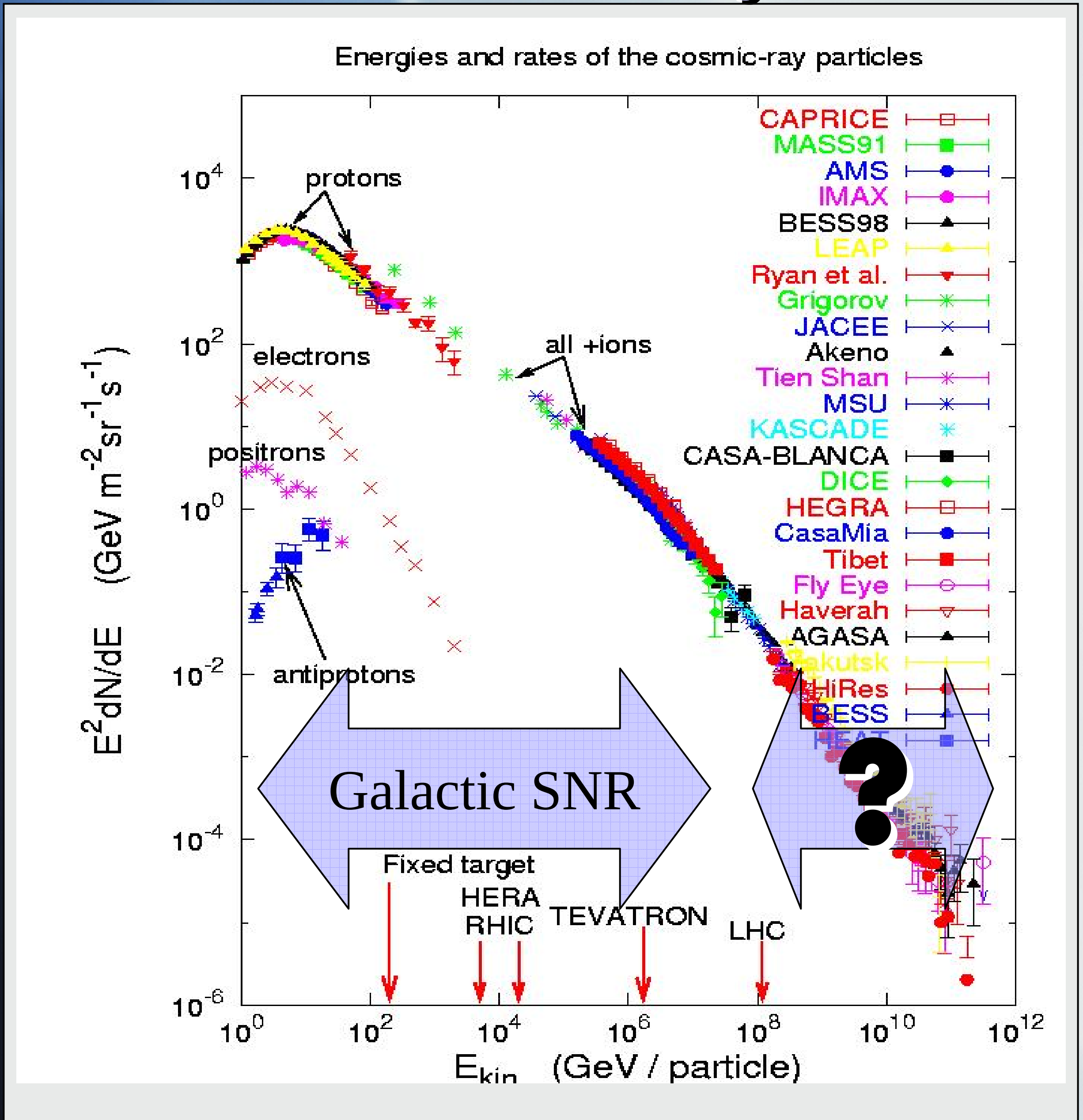
Cygnus X-1

BL Lac Markarian 421



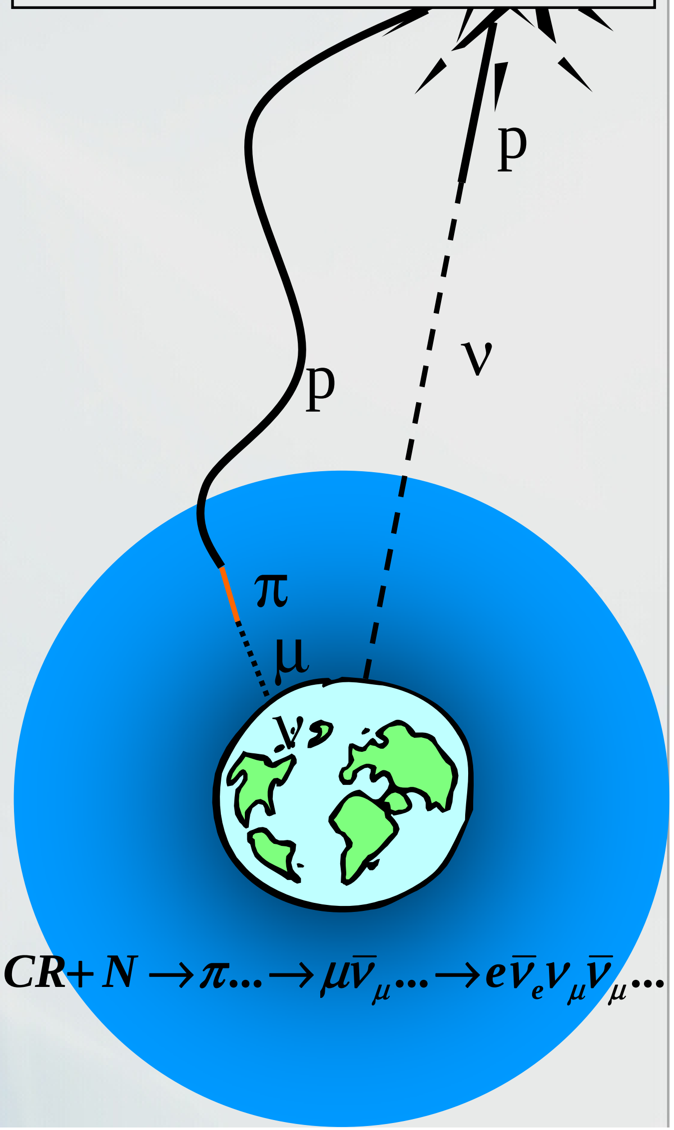
Microquasar SS433 (VLBA)

Cosmic Rays & Neutrinos



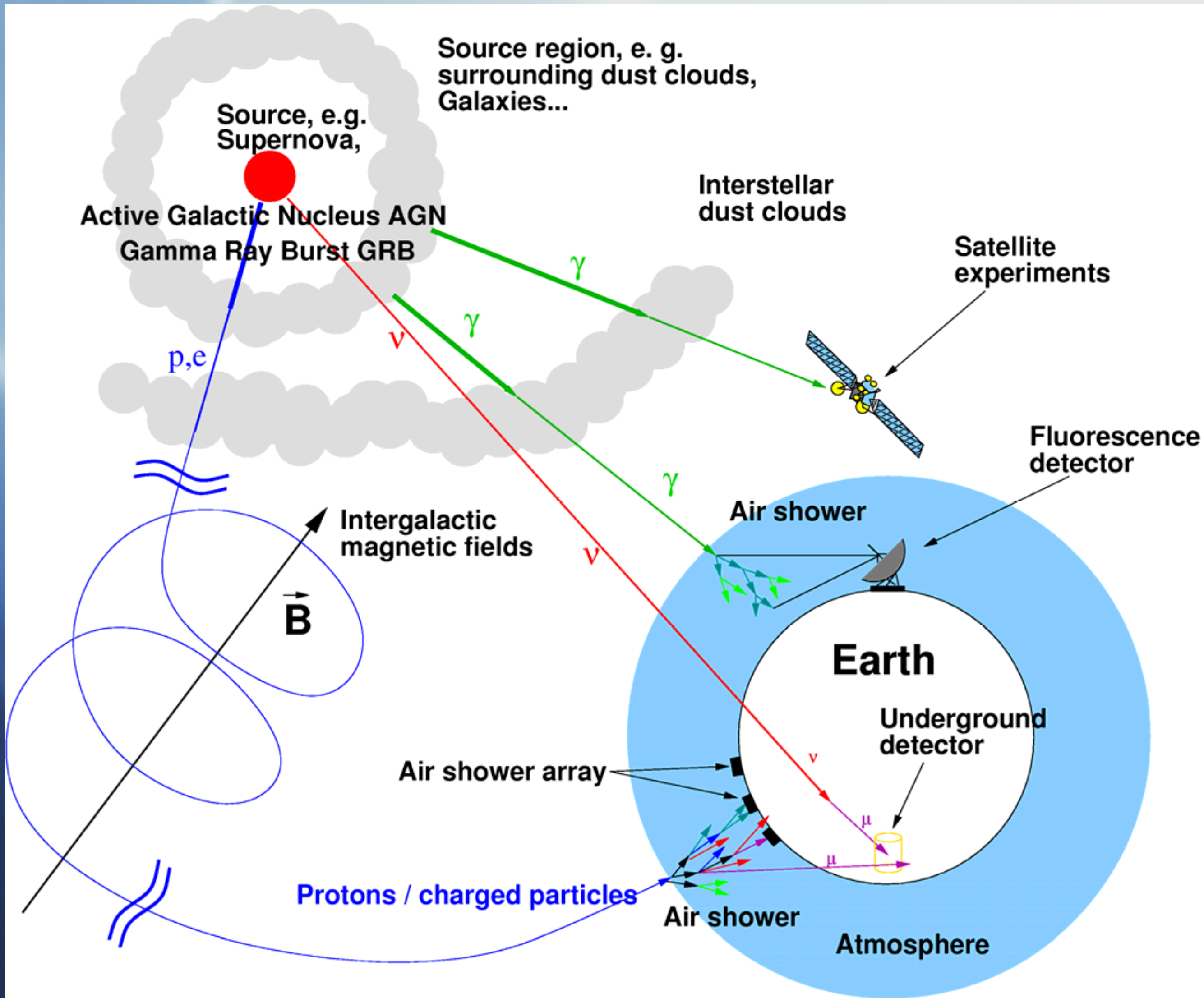
$$p+p \rightarrow \pi + ... \rightarrow \nu + ... \quad \text{or}$$

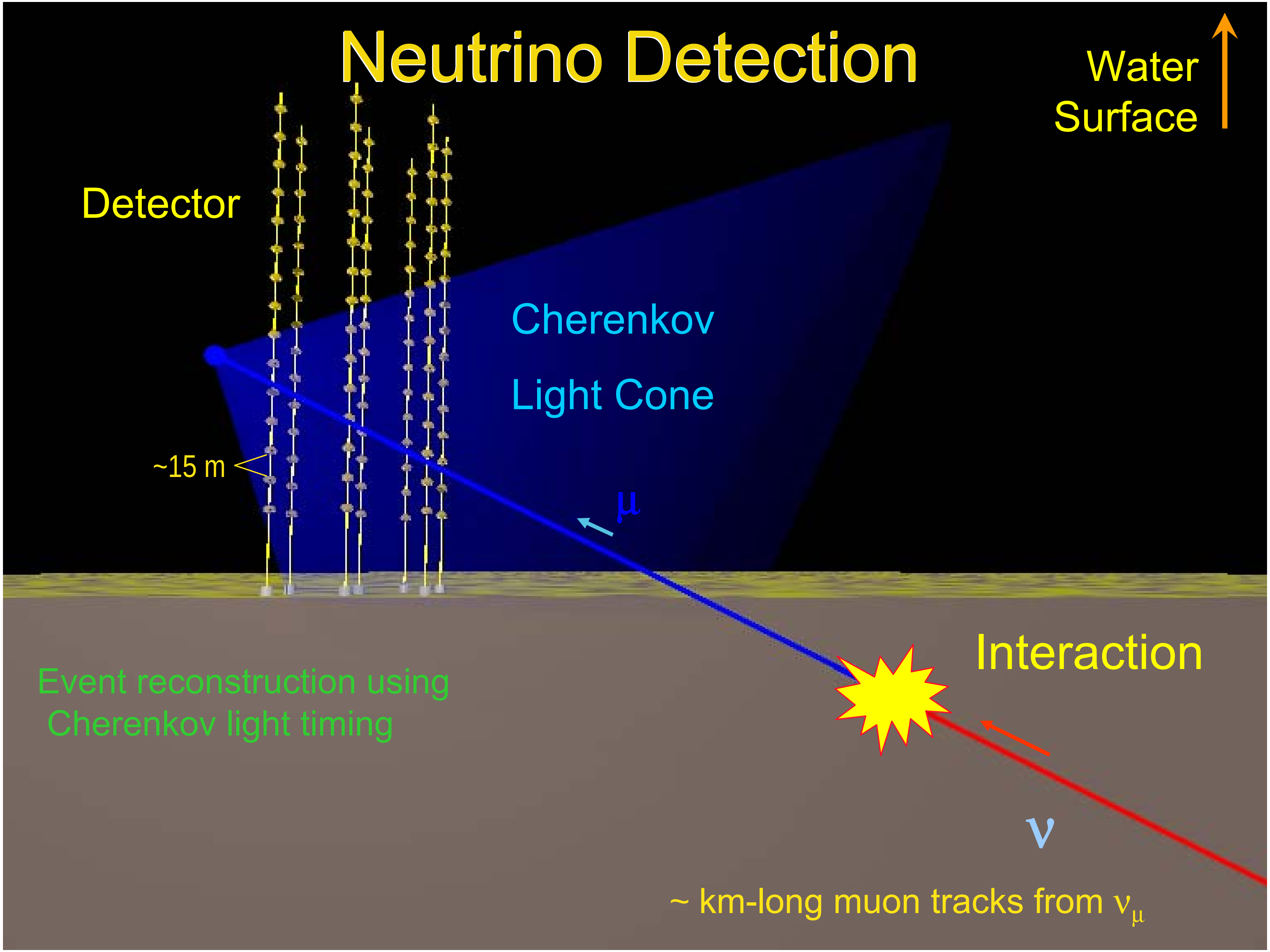
$$p+\gamma \rightarrow \Delta \rightarrow \pi + n \rightarrow \nu + ...$$



$$CR + N \rightarrow \pi ... \rightarrow \mu \bar{\nu}_\mu ... \rightarrow e \bar{\nu}_e \nu_\mu \bar{\nu}_\mu ...$$

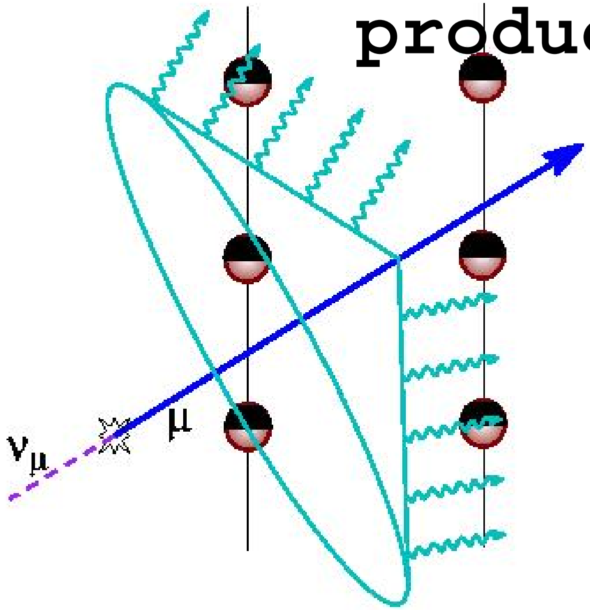
Astroparticle physics

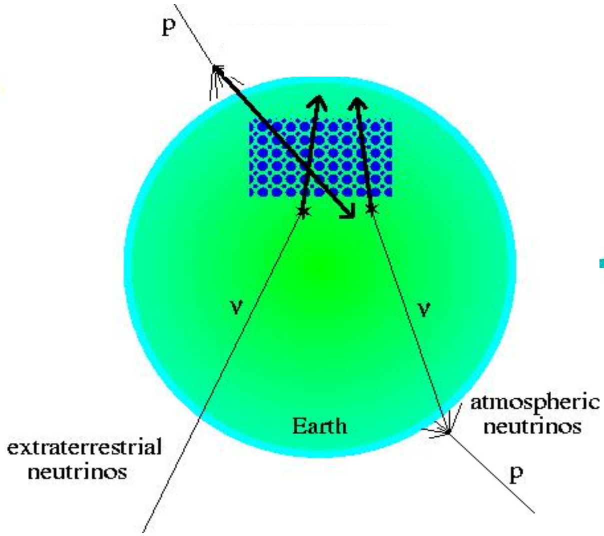


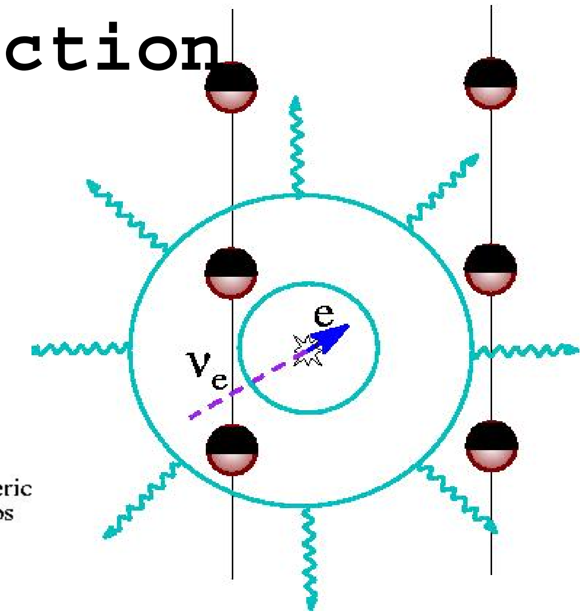


Neutrino Detection
Water
Surface
Detector
Cherenkov
Light Cone
~15 m
μ
Interaction
Event reconstruction using
Cherenkov light timing
ν
~ km-long muon tracks from ν_μ

Neutrino Detection: Cherenkov light from charged products of interaction







Up-going μ tracks (ν_μ)

Cascades ($\nu_{e,\mu,\tau}$ NC, $\nu_{e,\tau}$ CC)

Requires:

Large volumes (small interaction cross sections)

Natural medium (cost)

Very transparent medium (cannot instrument very densely)

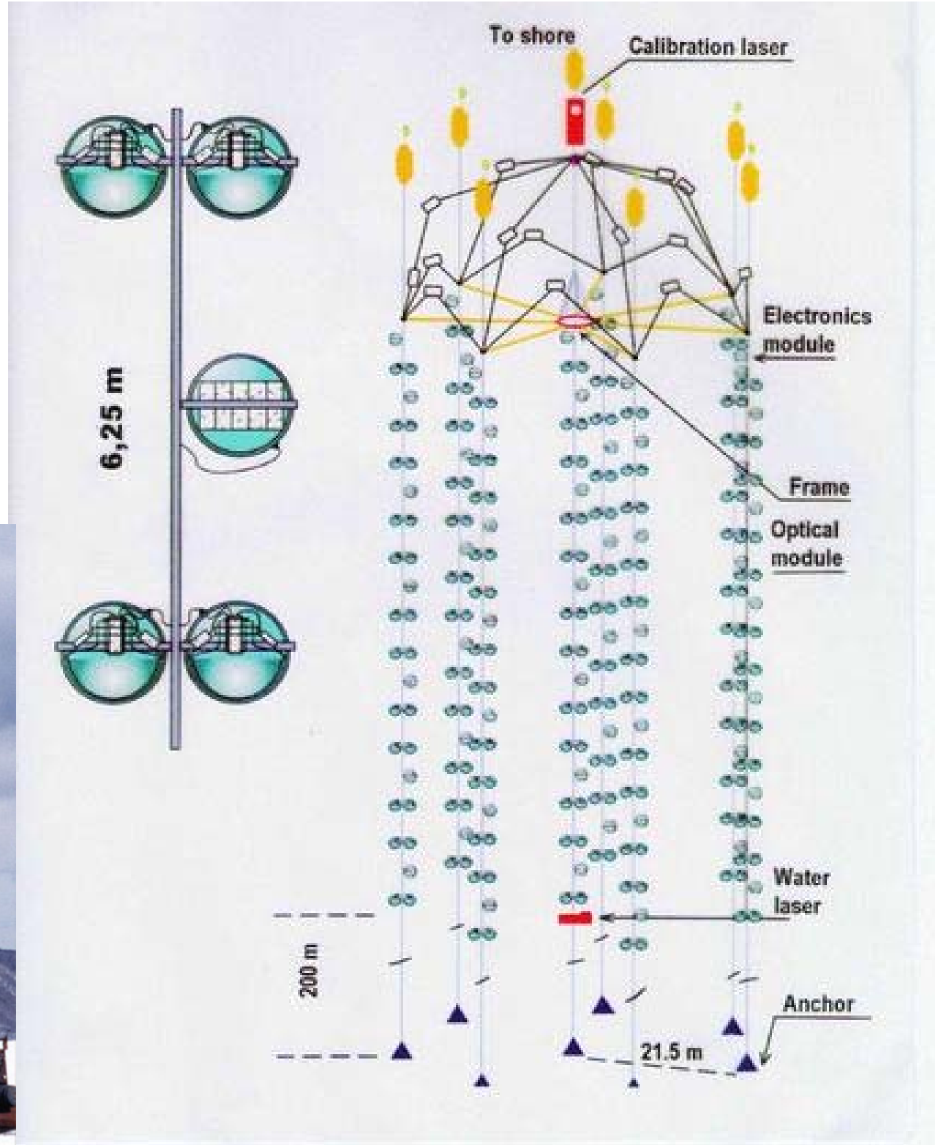
Neutrino Telescopes

BAIKAL NT-200

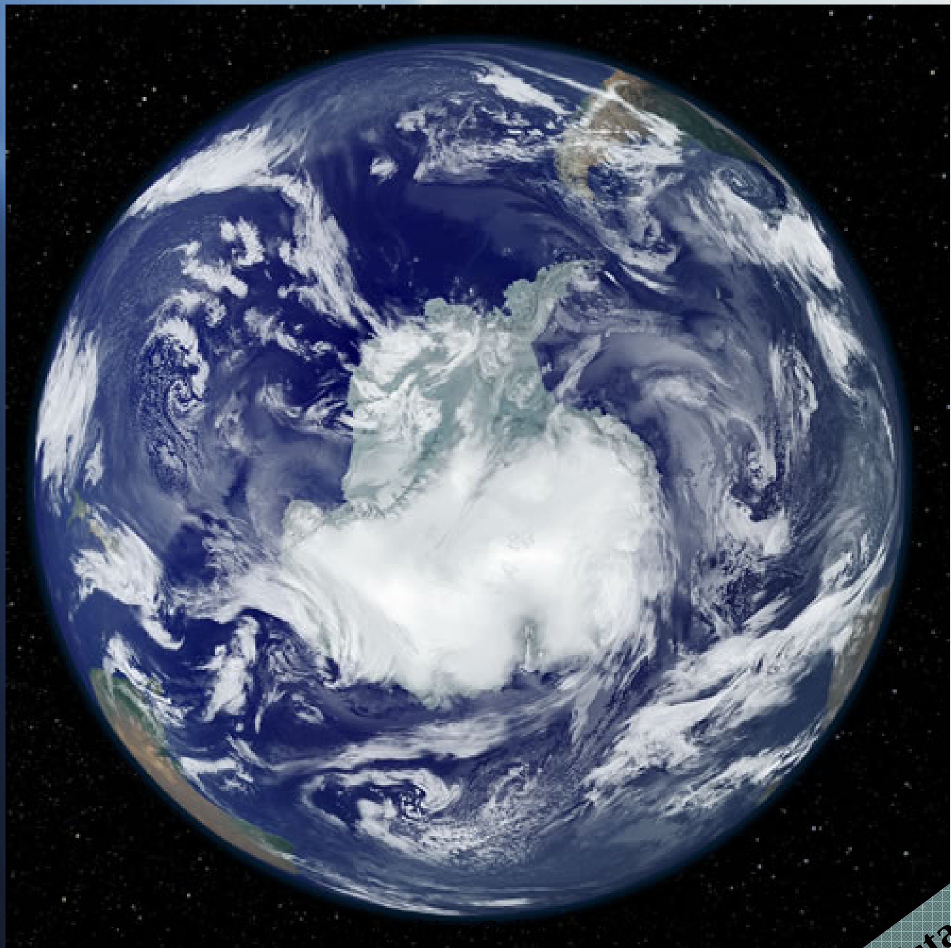
Baikal NT-200

Location: Lake Baikal
Commissioned: 1997
No. of Strings: 8
Optical Sensors: 192
Depth: 1100m
Instrum. Volume/km3: 10^{-4}
μ-Effective area (1 TeV): ≈2000 m^2
Angular resolution (1 TeV): 3°

Deployment and maintenance:
From frozen surface in winter.



The location – at the bottom of the world



Distance from Paris 15440 km

Basic Scientific Goal:
To map the UHE neutrino sky

- Sensitivity adequate to confront estimates for
  - Point sources - AGNs, SNR, μquasars,…
  - Diffuse fluxes - all types
  - Transient events - GRBs, SN, …
  - Energy spectra - atm. neutrinos + …
- Adequate control of systematic effects
  - Confidence in data for unexpected signals

Getting There…

LC-130 Hercules

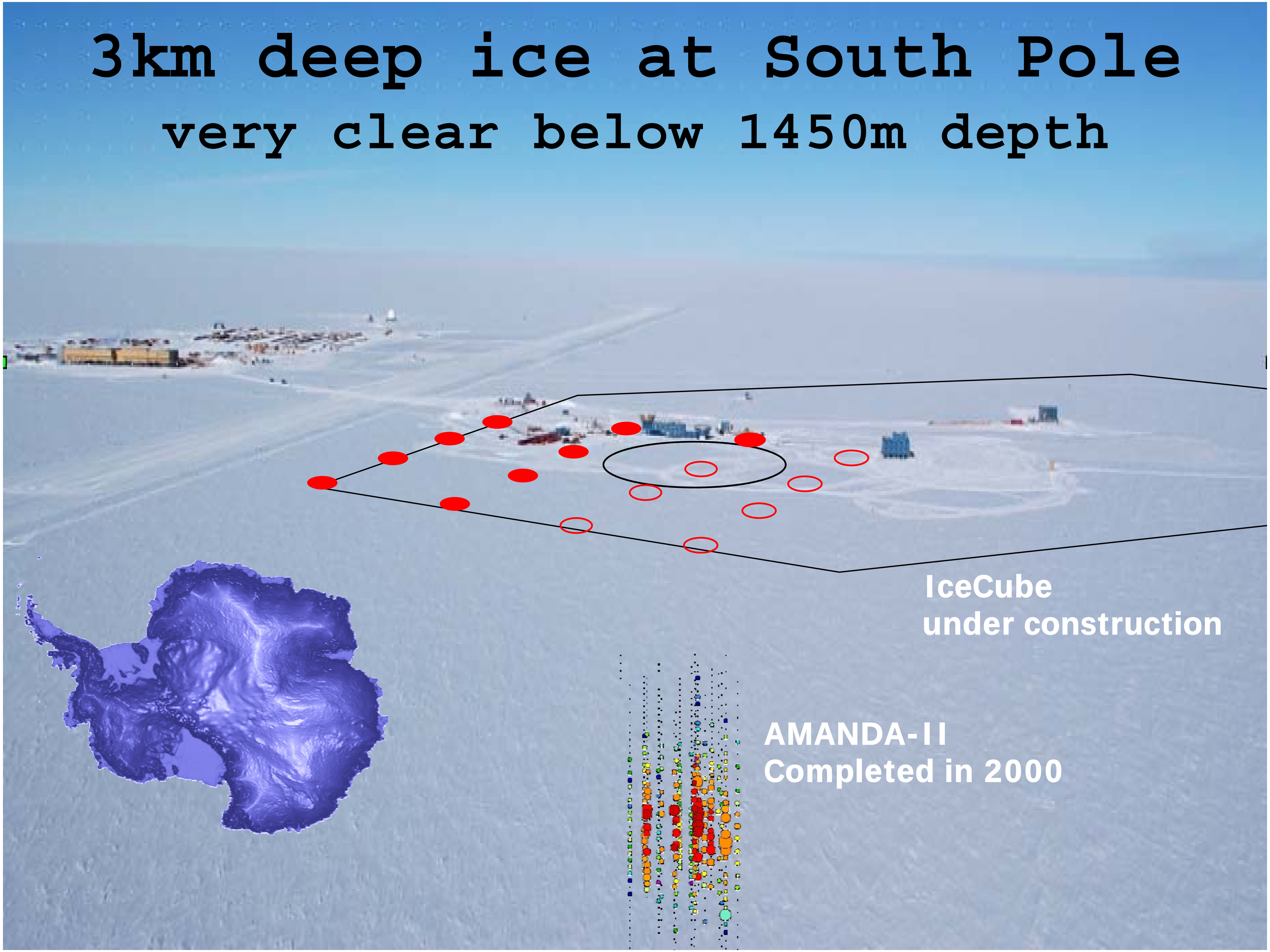
Fuel flown to
South Pole:
To run electrical power plants,
Vehicles, and airplanes

Fuel ship delivers
~7 million Gallons of fuel

LC-130: Cargo from McMurdo to
The Pole. 3 ½ hr for ~ 800 miles

A Hercules plane ready to transport people and goods to Antarctica.

Photo: S. Barwick, UCI


3km deep ice at South Pole
very clear below 1450m depth
IceCube
under construction
AMANDA-II
Completed in 2000

The IceCube collaboration

The South Pole

- Agency: NSF
- Access: ~ 3 summer months
- Altitude: ~ 3000 m (Ice thickness!)
- Temperature: - 30º C (summer)
- Wind: Significant
- Major Activity: Station Modernization
- Population: Limited

$\Rightarrow$ Intense working conditions

Pros of deploying in the Polar Ice

- Deployment from Glacies Firma
- Well established infrastructure provided by South Pole Station

- No radioactivity in ice ⇒ PMT rate ~600 Hz
- Very stable temperature environment once the DOMs are deployed and freeze-back is complete
  - No water trying to leak into the glass sphere

Cons of deploying at the South Pole

- Short deployment season
  - We can only build the experiment at the South Pole for ~ 4 months of each year, during the Austral Summer

AMANDA & IceCube & IceTop

AMANDA-II: 2000-...

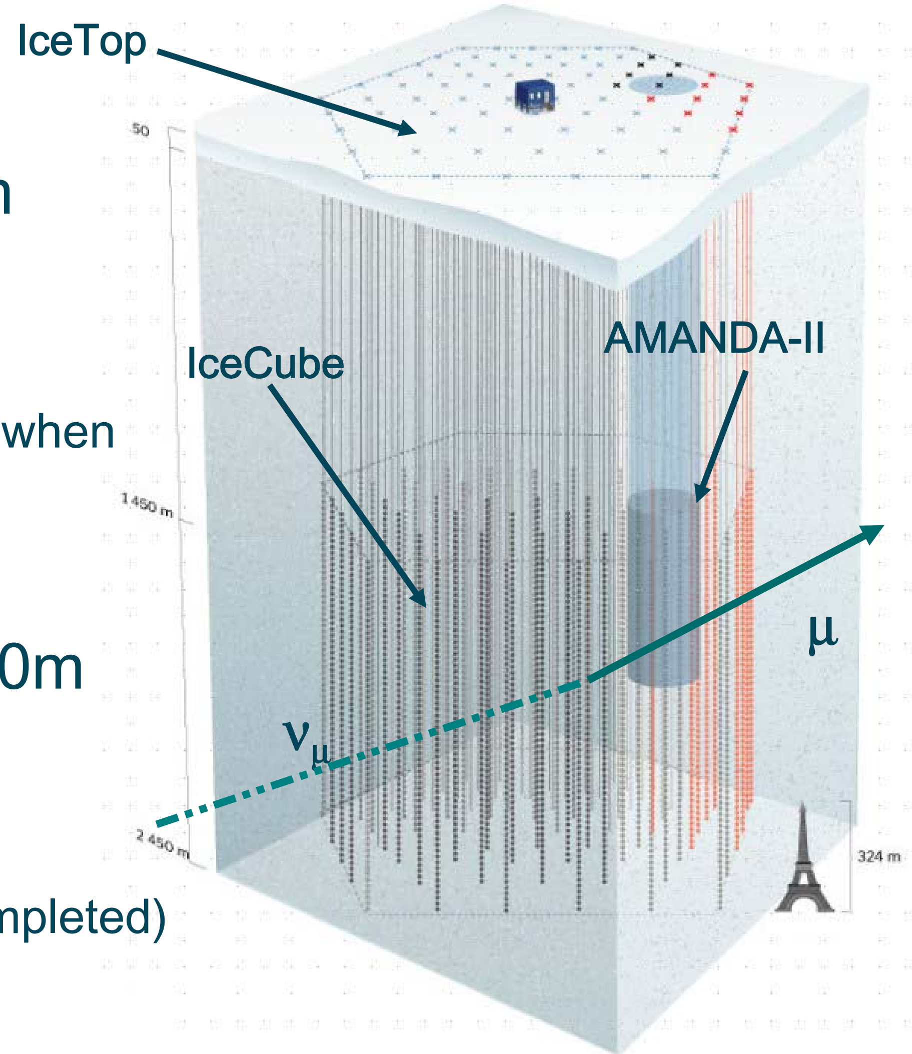
- 677 OMs on 19 strings
- diameter ~200m, height ~500m

IceCube: 2005-...

- 4800 OMs on 70 - 80 strings (when completed)
- feb 2006: 9 strings deployed
- diameter ~1000m, height ~1000m

IceTop: 2005-…

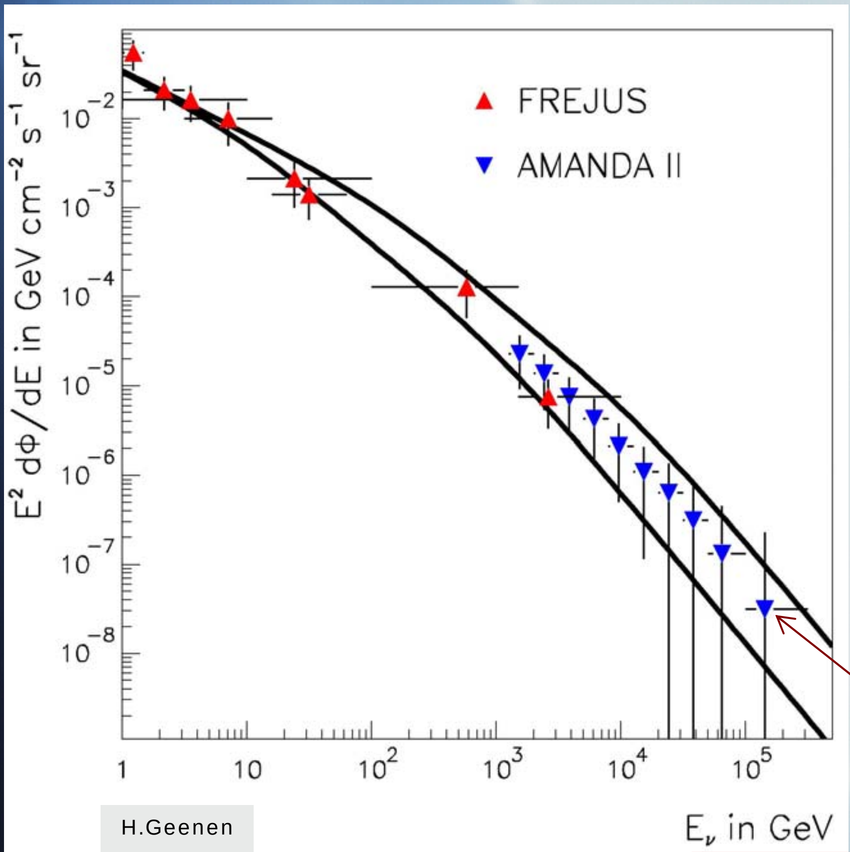
- 320 OMs on 160 tanks (when completed)
- Feb 2006: 32 tanks deployed
- diameter ~1000m



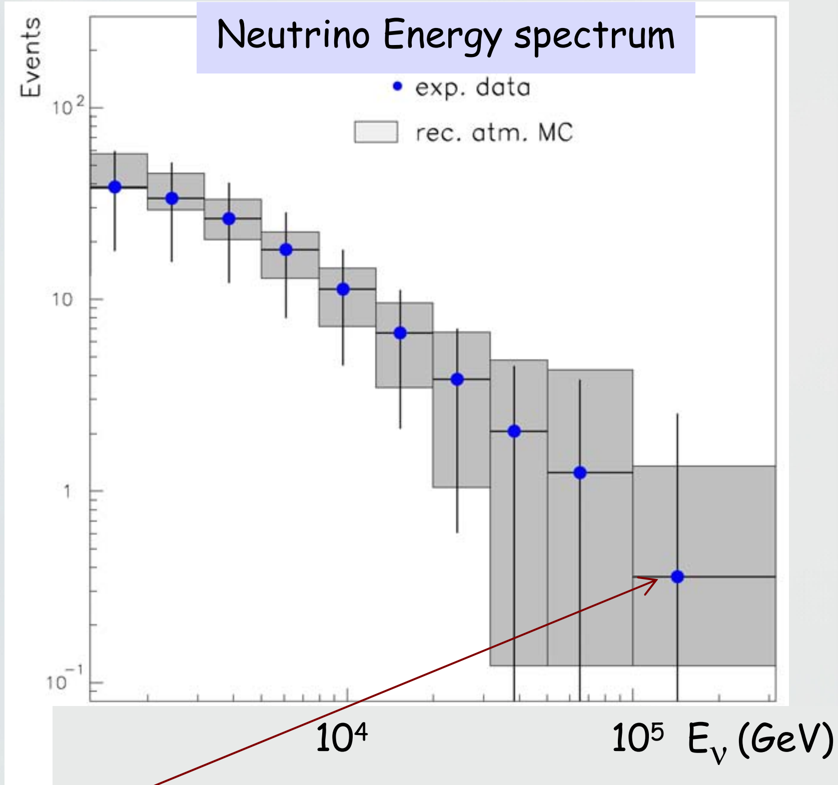
ATMOSPHERIC ν & DIFFUSE FLUX LIMITS [ν_μ]

AMANDA test beams: atmospheric ν and μ

Neutrino fluxes vs. Energy



First spectrum > 1 TeV (up to 100TeV)



Last bin info to calculate the limit to Extraterrestrial E² neutrino flux

Previous analysis publication

Phys. Rev. Lett. 90 251101 (2003)

$$E^2\Phi_{\nu_\mu}(E) < 2.58\cdot10^{-7}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

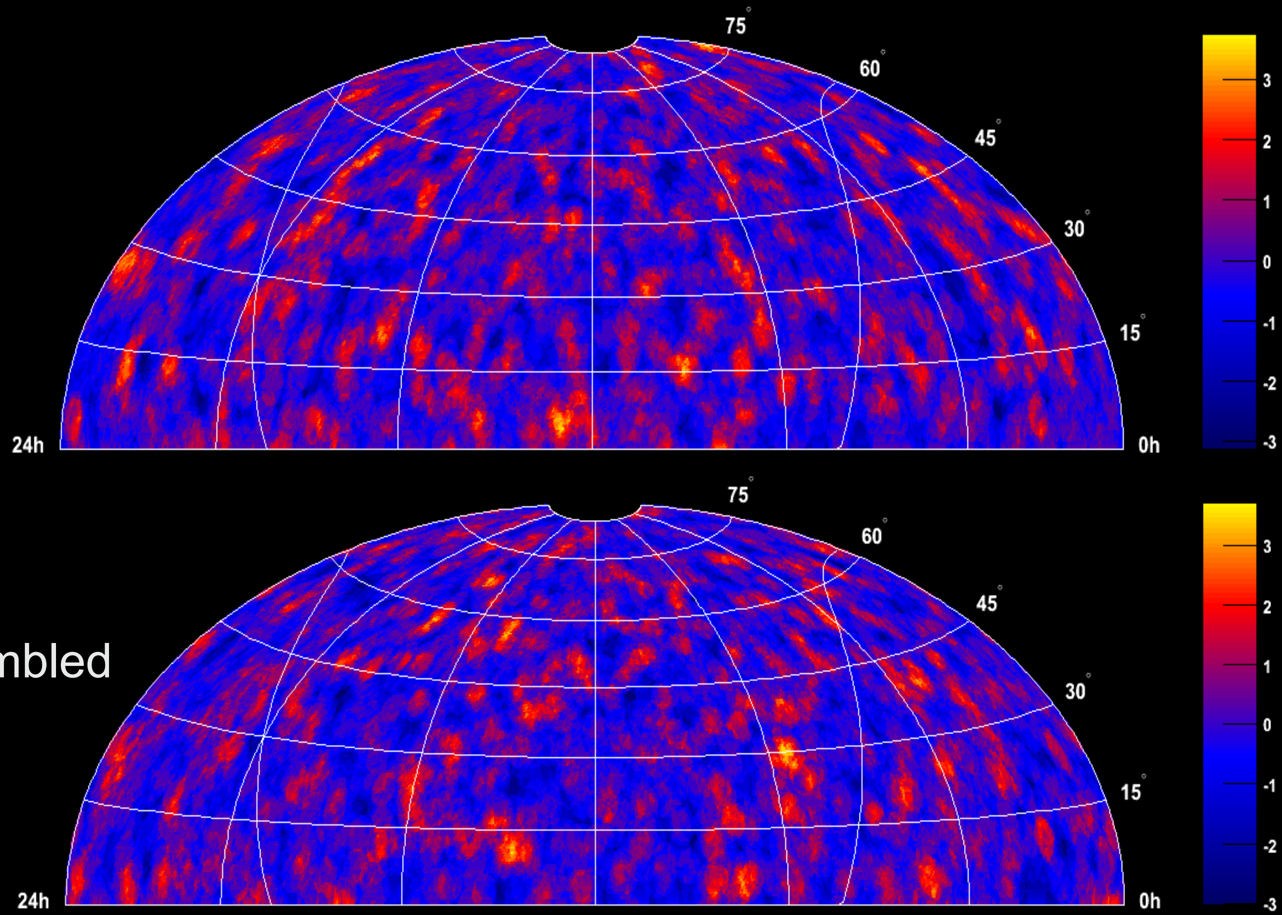
Search for neutrino clusters in the northern sky

event selection optimized for both dN/dE ~ E^{-2} and E^{-3} spectra

significance map

Data

Time scrambled Data

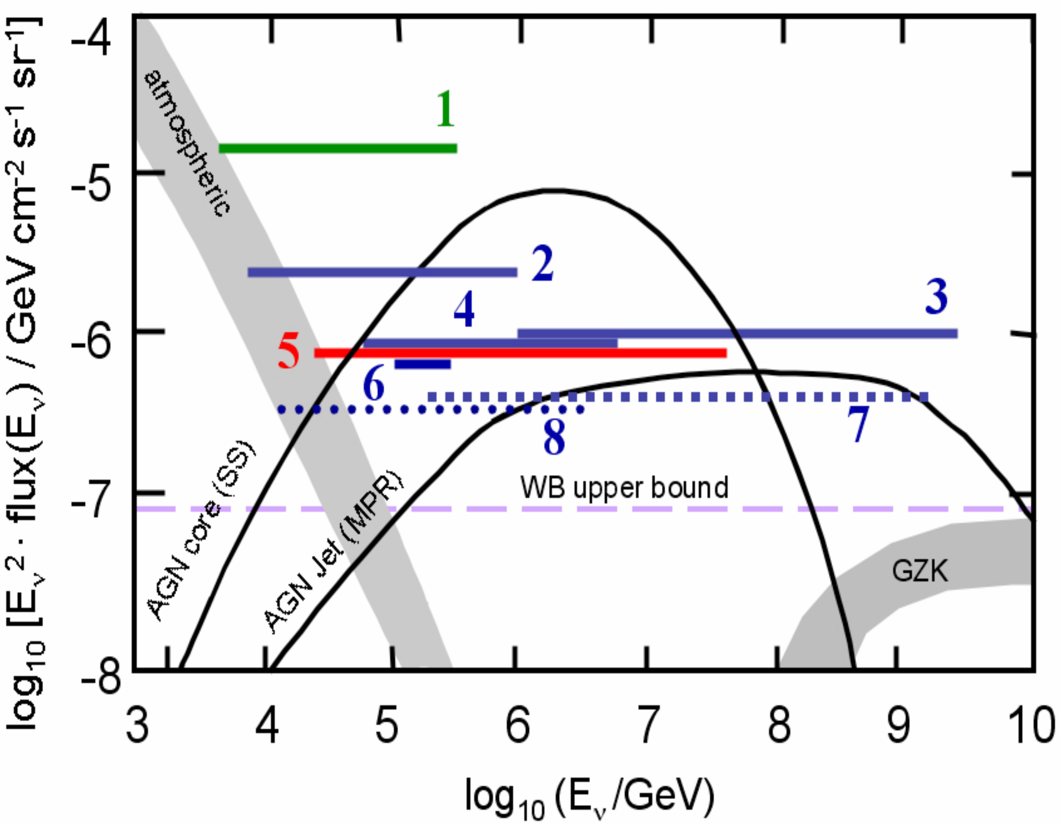


AMANDA II data from 2000-2004 (1001 live days)

4282 ν from northern hemisphere

No signal observed

Diffuse neutrino flux limits



1. MACRO
2. AMANDA B10 ν_μ (1997)
3. AMANDA-B10 UHE (1997)
4. AMANDA-II cascades (2000)
5. Baikal cascades 1998-2002
6. AMANDA-II ν_μ-analysis (2000)
7. AMANDA-II UHE sensitivity !!
8. AMANDA ν_μ-analysis (2000-2003) sensitivity

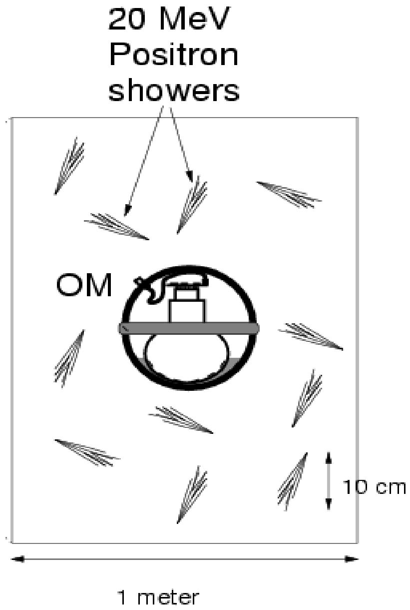
Preliminary!

All limits multiplied by 3 for oscillations!!

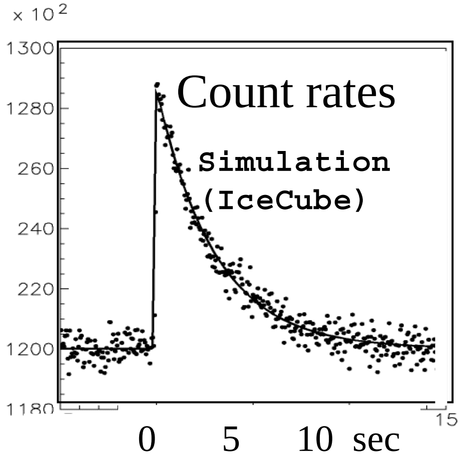
Searches for SN neutrinos

Look for collective rate increase in all PMT's on top of dark noise

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

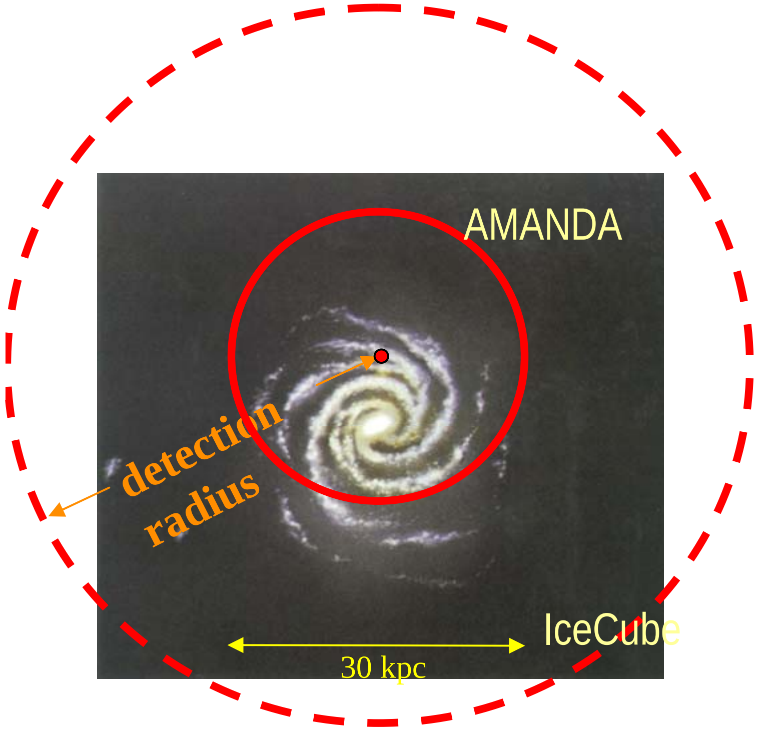


O(10cm) long tracks



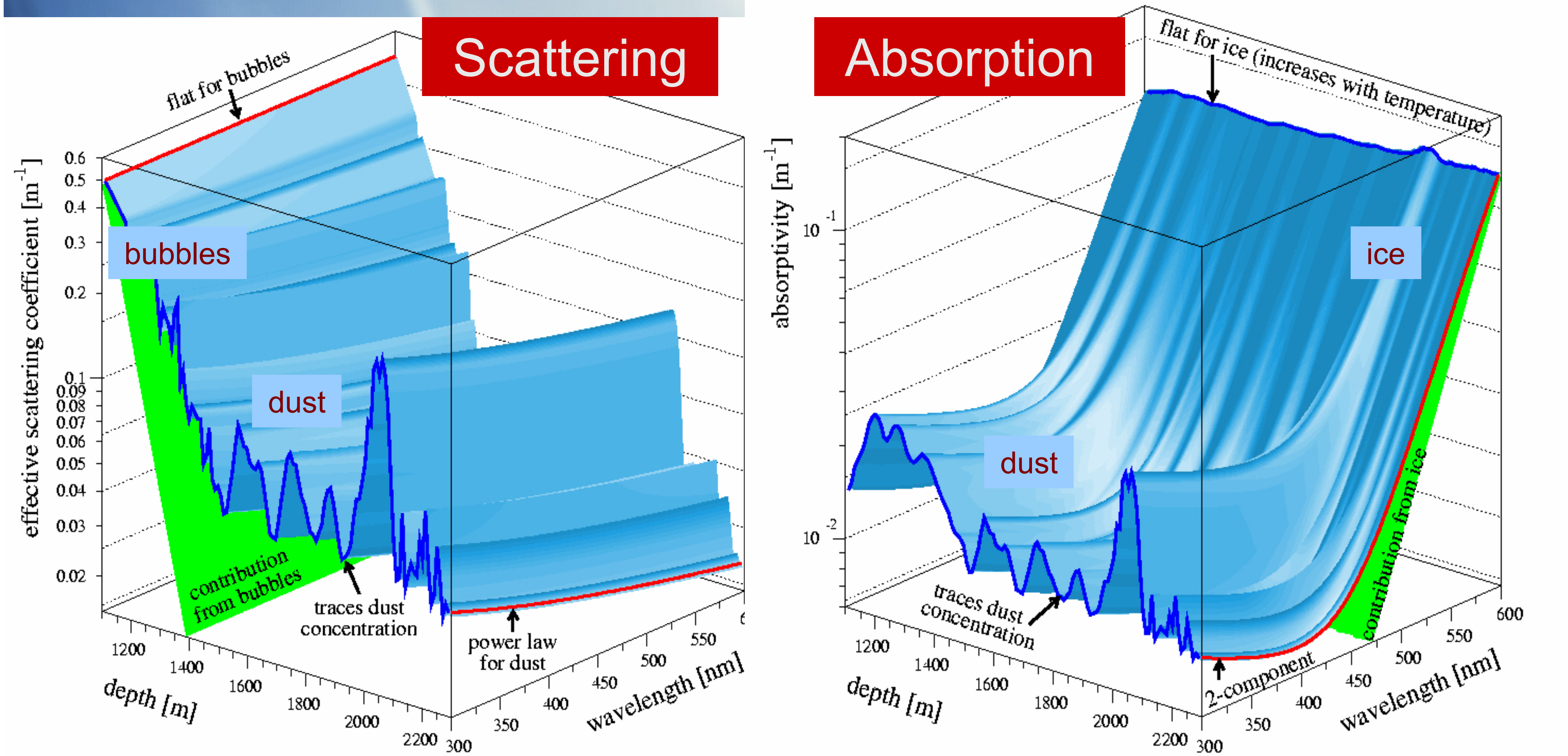
Coverage of our galaxy
B10: 70%
A-II: 95%
IceCube: to LMC

- published 215 live days (AM-B10)
  $\Rightarrow$ no candidate events
- prel. limit 2000-03 < 2.6 SN/year



SNEWS (SuperNova Early Warning System) includes Super-K, SNO, LVD, KamLAND, AMANDA/IceCube, BooNE
http://snews.bnl.gov/

Detector medium: ice optical properties



Measurements:
- in-situ light sources
- atmospheric muons

Average optical ice parameters:
λ_{abs} ~ 110 m @ 400 nm
λ_{sca} ~ 20 m @ 400 nm (eff λ)

Data Quality Issues

- Capture information content of highly variable PMT waveforms
  - Robust operational behavior
  - Very long service life
  - High dynamic range of signals
  - Minimum power dissipation
  - Acceptable cost

Special DAQ Requirements

- High EMI Rejection:
  - Unimpaired by radars, drills, etc.
    - Justification: 100% availability

    ⇒ No low-level analog signals from OMs

- Minimum personnel at pole:

  ⇒ Automated functionality necessary
    - Remote commissioning, setup
    - Automated calibration procedures

IceCube: Technology Transition

Decision

- Digital Optical Module (DOM)
- All-digital copper network: twisted pairs
  - Supplies power to DOM
  - Transmits commands to DOM
  - Transmits timing signal to DOM
  - Receives data from DOM

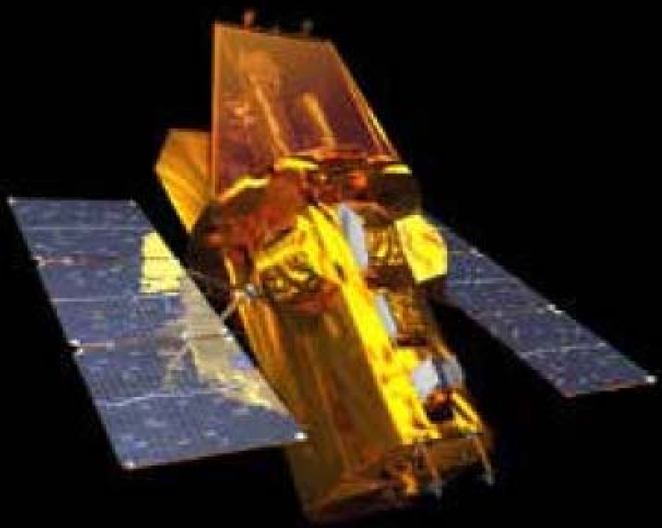
No low-level signals outside of DOM

Fully differential signaling in network

High-Rel Design Challenges

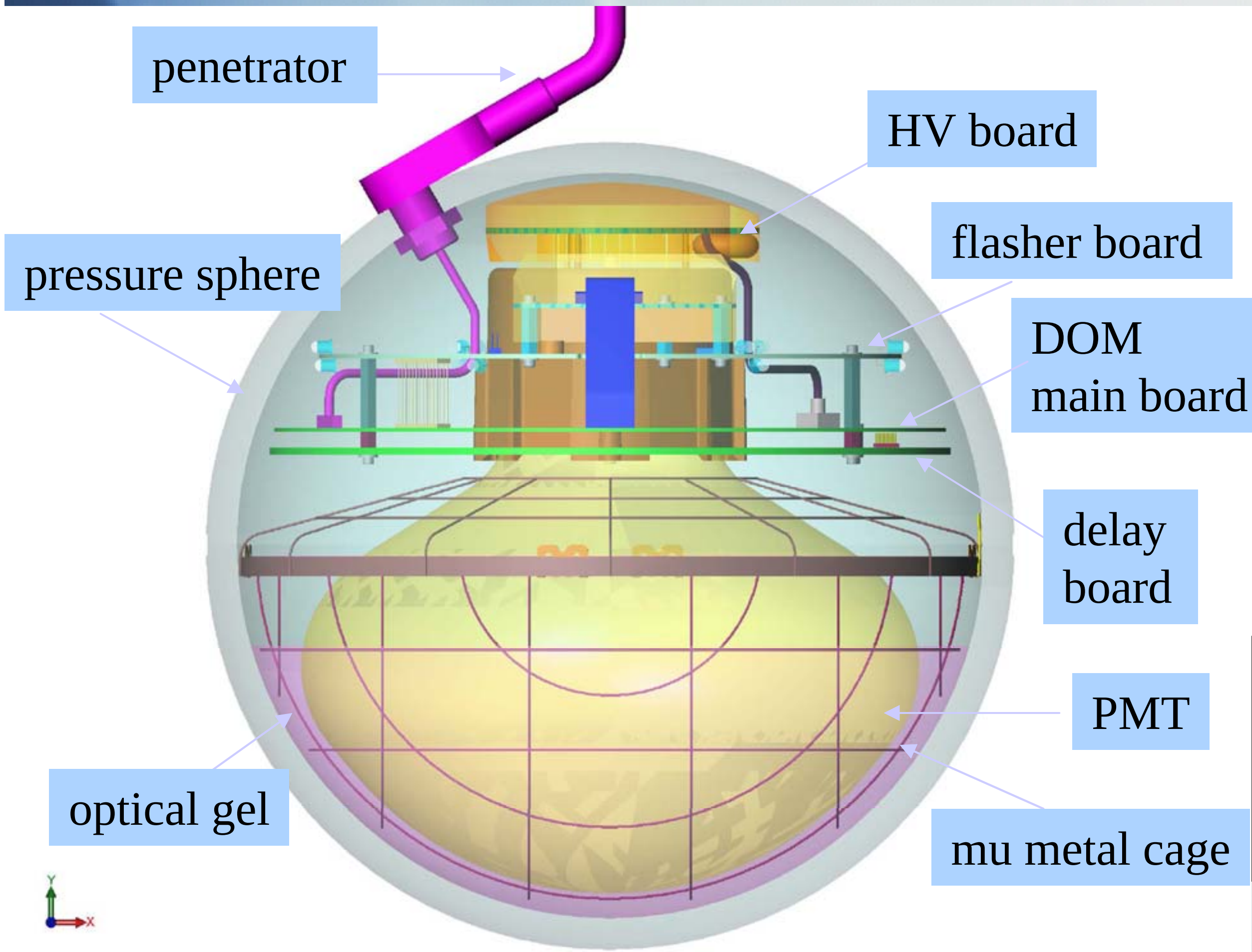
Design for Space application …

on a consumer electronics budget



Digital Optical module (DOM)

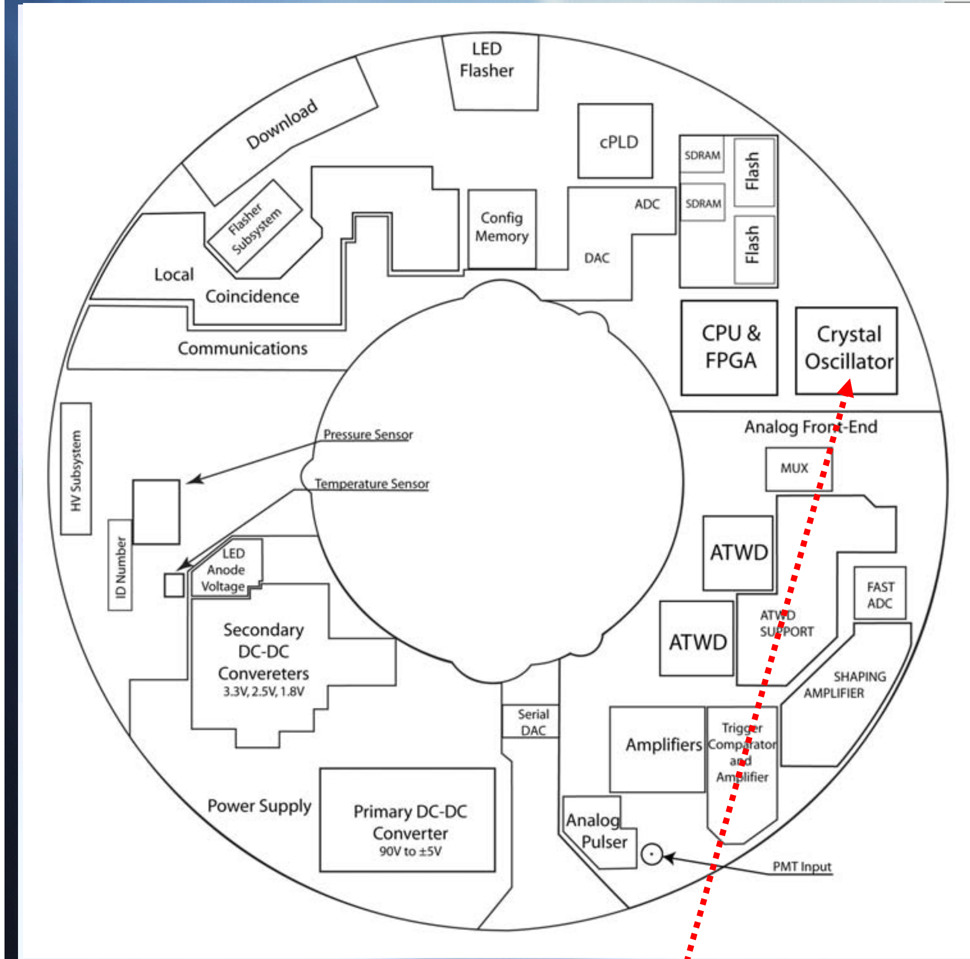
- an optical sensor
10 inch Hamamatsu R-7081



- a semi-autonomous DAQ platform:
  - ✓ records
  - ✓ timestamps
  - ✓ digitizes
  - ✓ stores data
  - ✓ transmits to surface at request

Noise rate ~600 Hz
∴ SN monitoring within our Galaxy

DOM Mainboard



20 MHz quartz oscillator
frequency stability $df/f < 2 \times 10^{-10}$

- 2 four-channel ATWDs
  Analog Transient Waveform Digitizers
  low-power ASICs
  recording at 300 MHz over first 0.4μs
  signal complexity at the start of event

- 10-bit fADC
  recording at 40 MHz
  256 samples → 6.4 μs acquisition

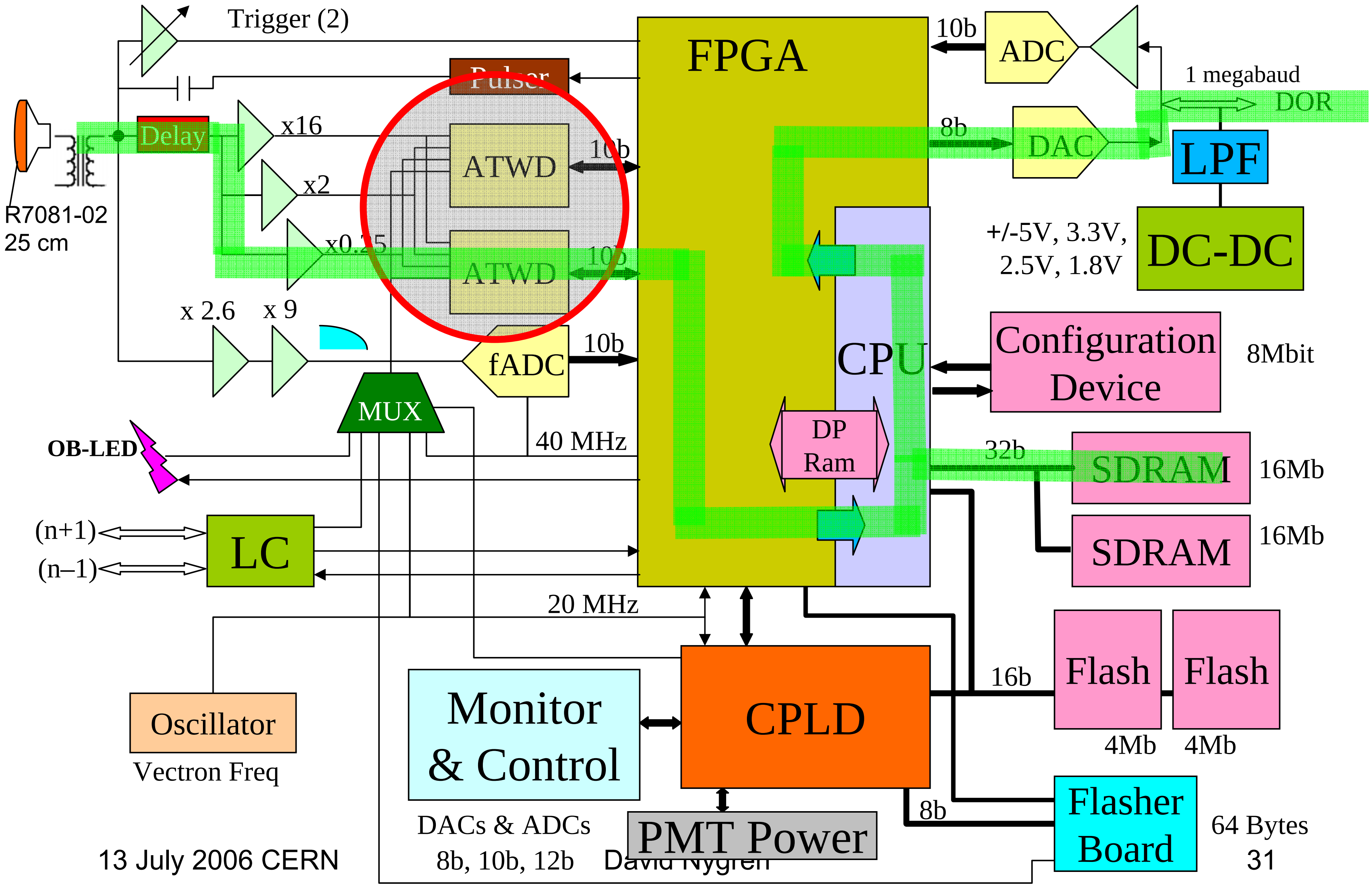
- Dead time <<1%

Dynamic range
- 400 p.e./15 ns (trigger @0.25 p.e.)
- 2000 p.e./5 μs

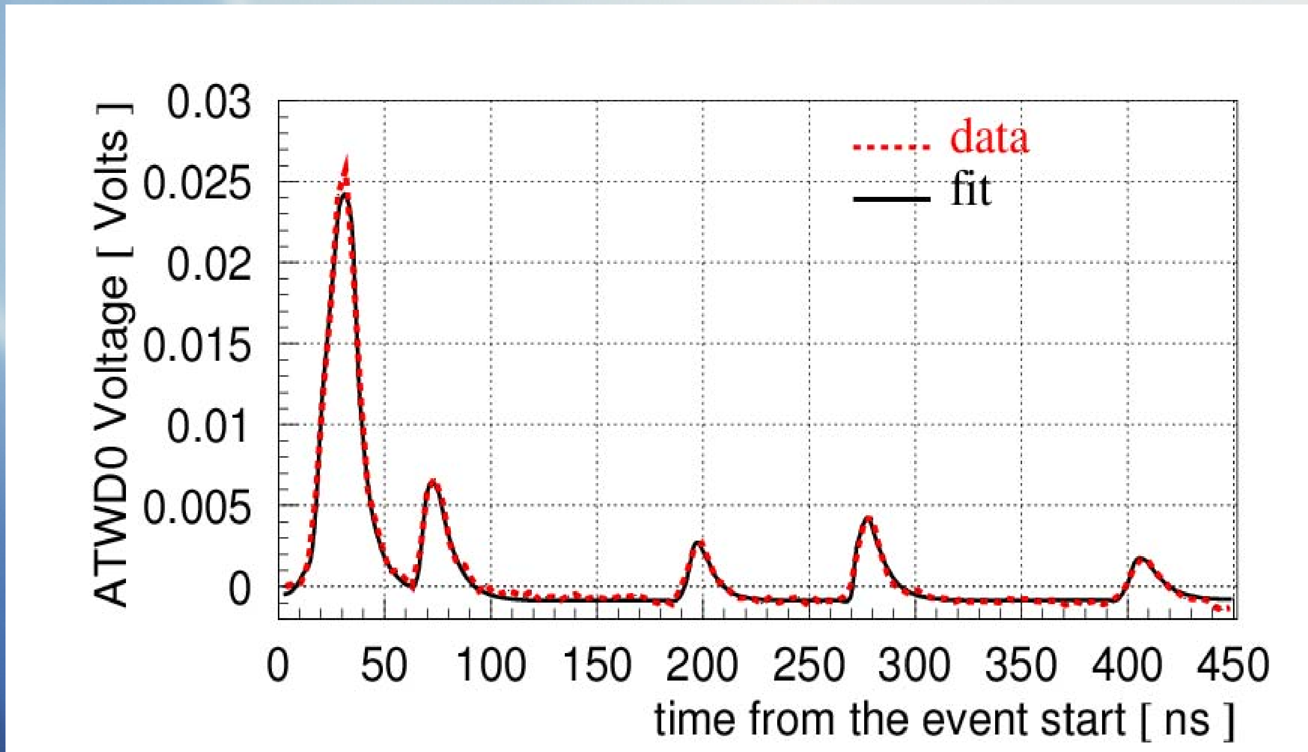
energy measurement (TeV – PeV)

- a FPGA
  reads out the ATWD, fADC
  handles communications
  time stamps waveforms
  system time stamp resolution
  2 ns wrt master clock

DOM MB Block diagram

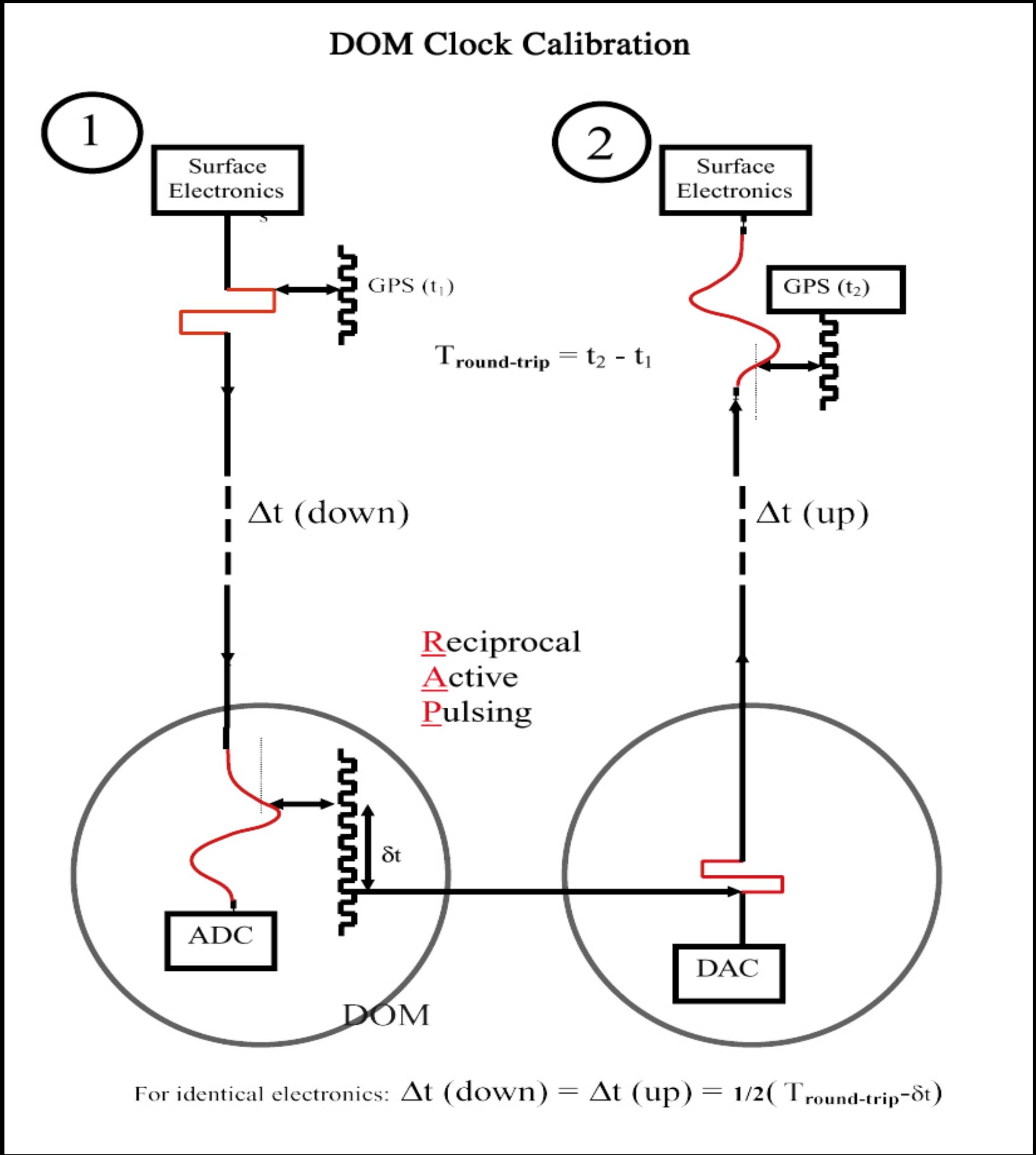


Example of the trace in one DOM, caused by a triggering muon



Acquired and reconstructed waveform

Performance: Reciprocal Active Pulsing

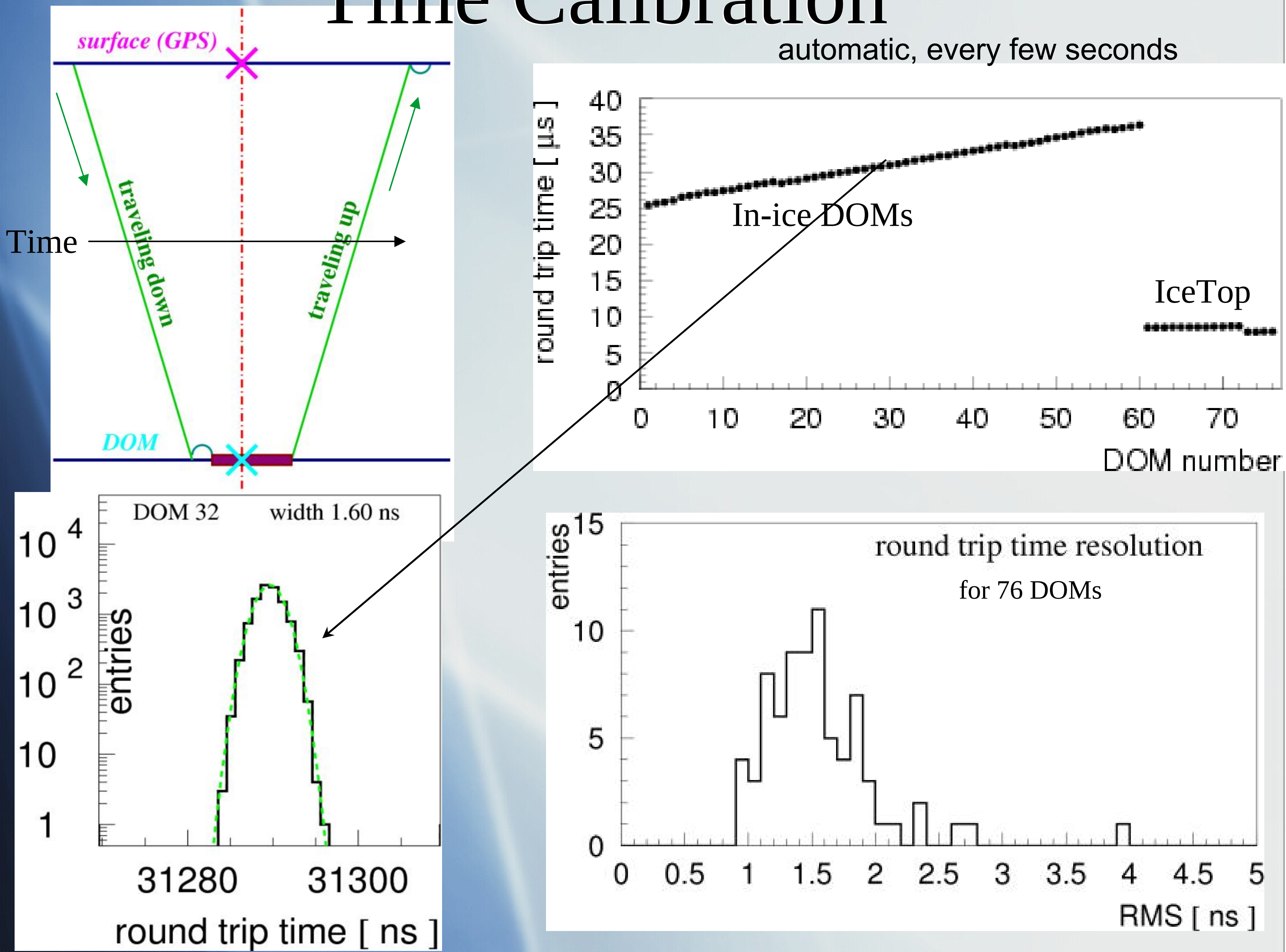


Relates the local free running DOM oscillators to the Universal Time Code standard transmitted by GPS satellites

Makes the 5000 DOMs in the detector and AMANDA look like they are running from a single common clock

Time Calibration

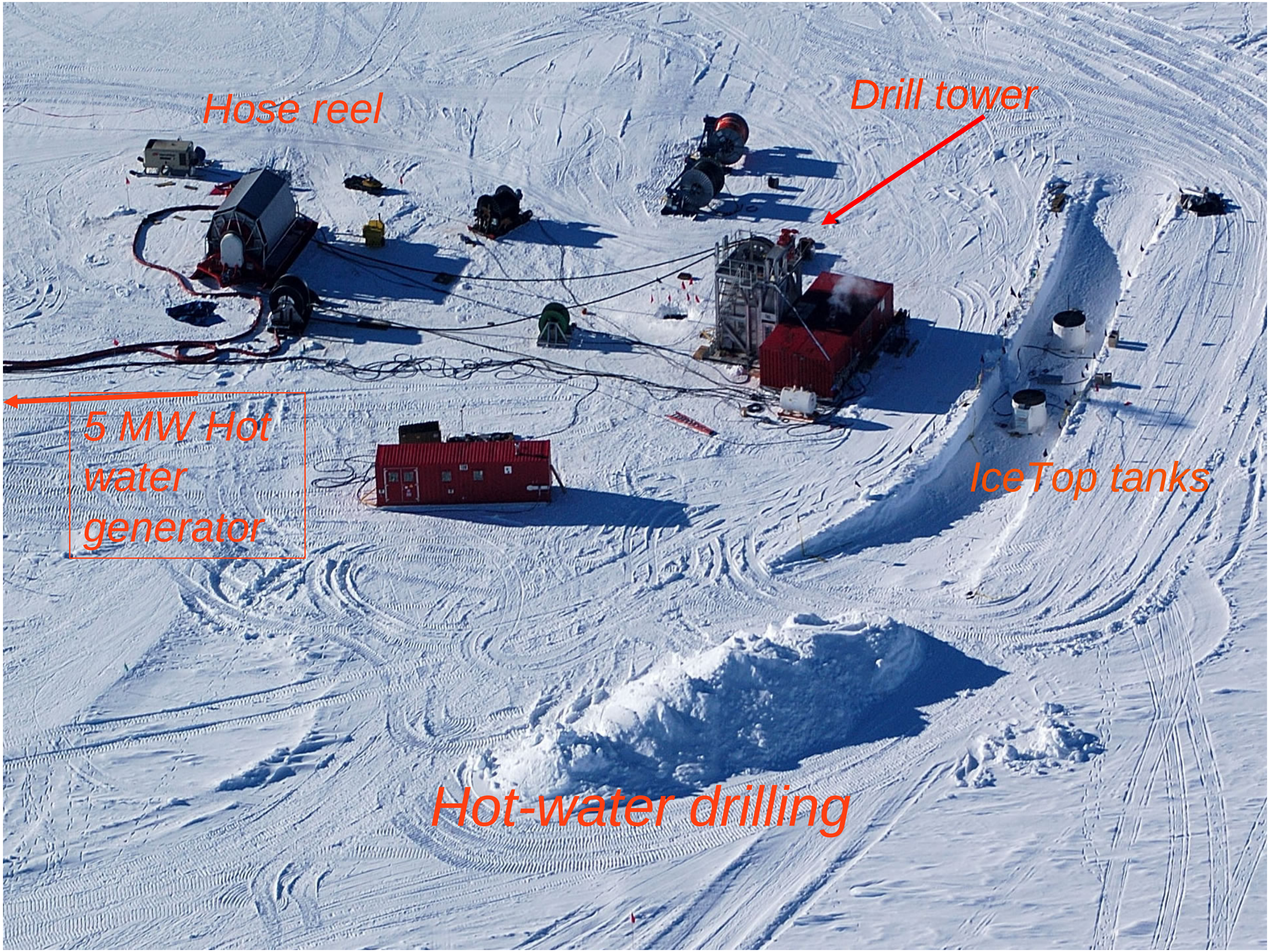
automatic, every few seconds



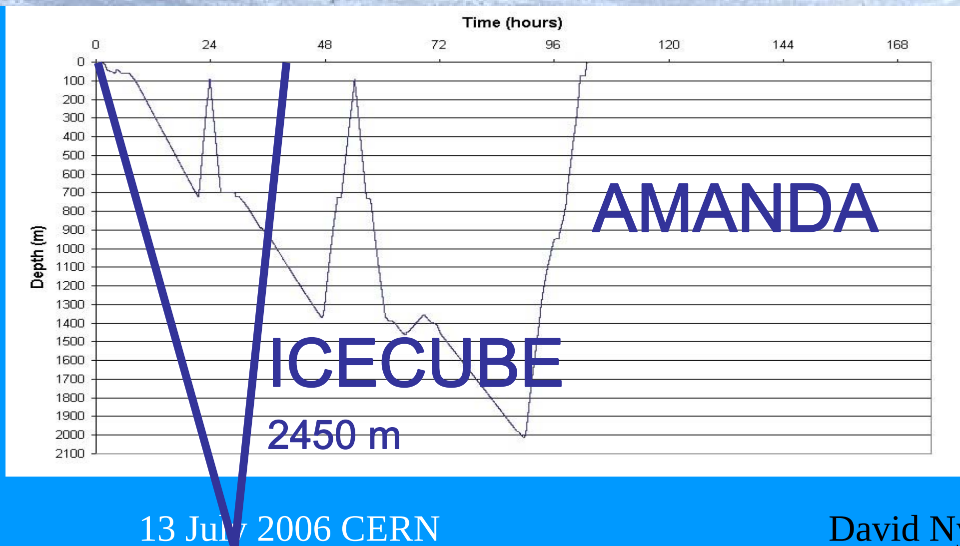
Summary of Technology Impact

- Decentralized architecture preserves data quality through digital messaging
- Innovative timing scheme has negligible impact on bandwidth of network
- Self-calibrating and autonomous behavior permits minimum on-site personnel
- Goal: effective control of systematics

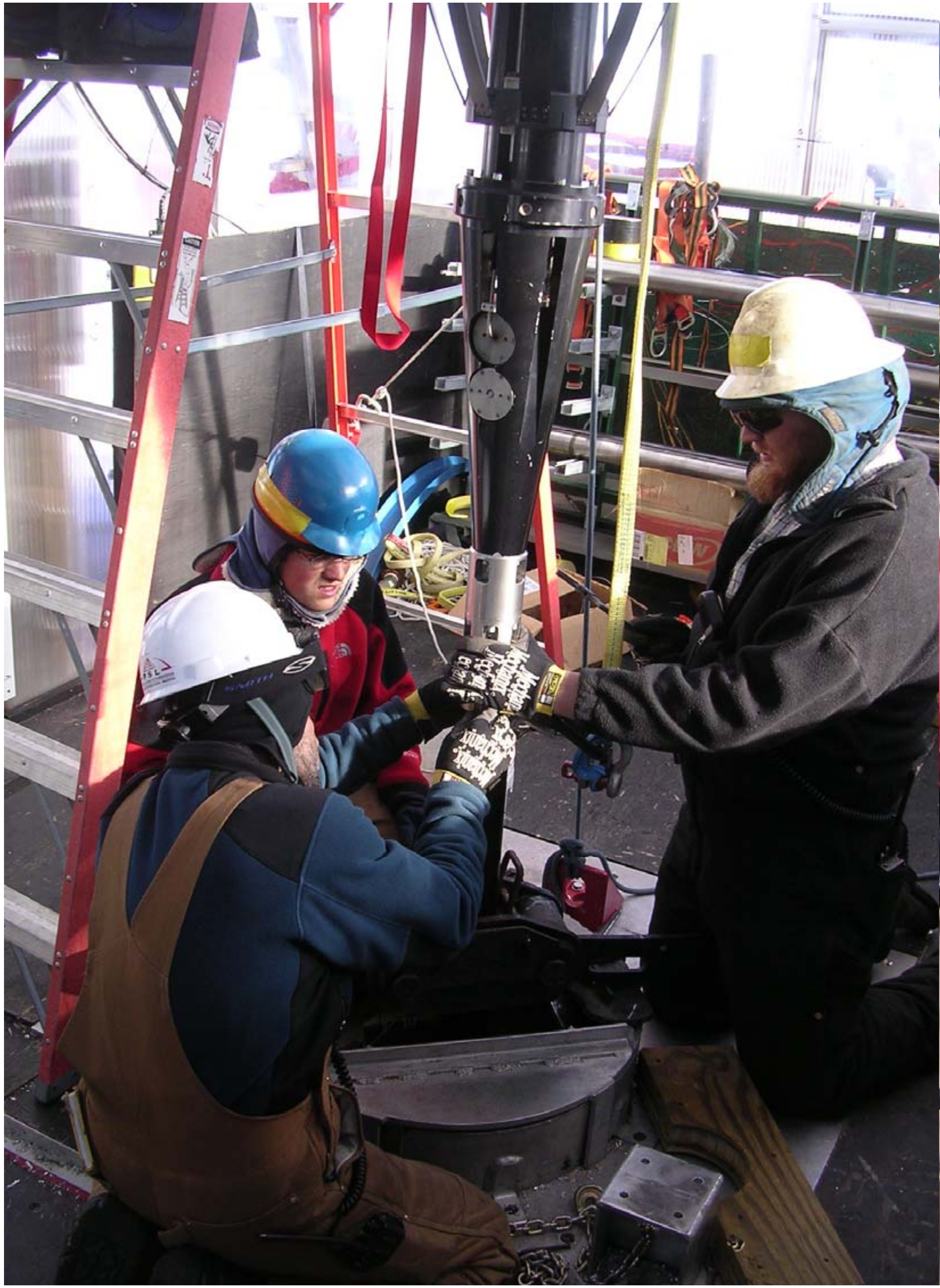
Drill modules at McMurdo


Hose reel
Drill tower
5 MW Hot water generator
IceTop tanks
Hot-water drilling

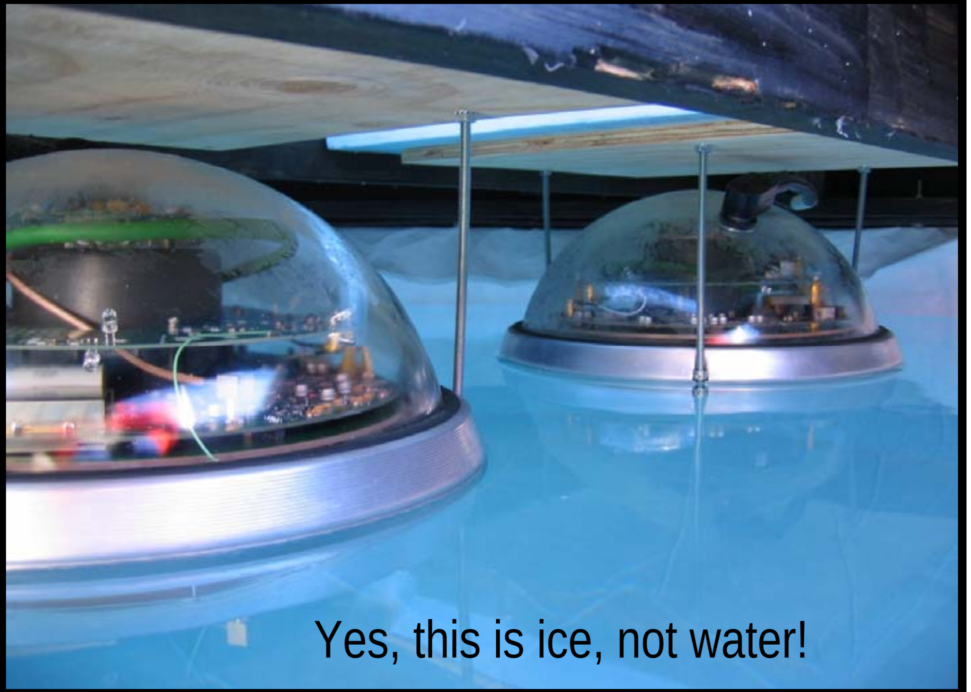
From AMANDA to IceCube…
Hot water drill: major upgrade



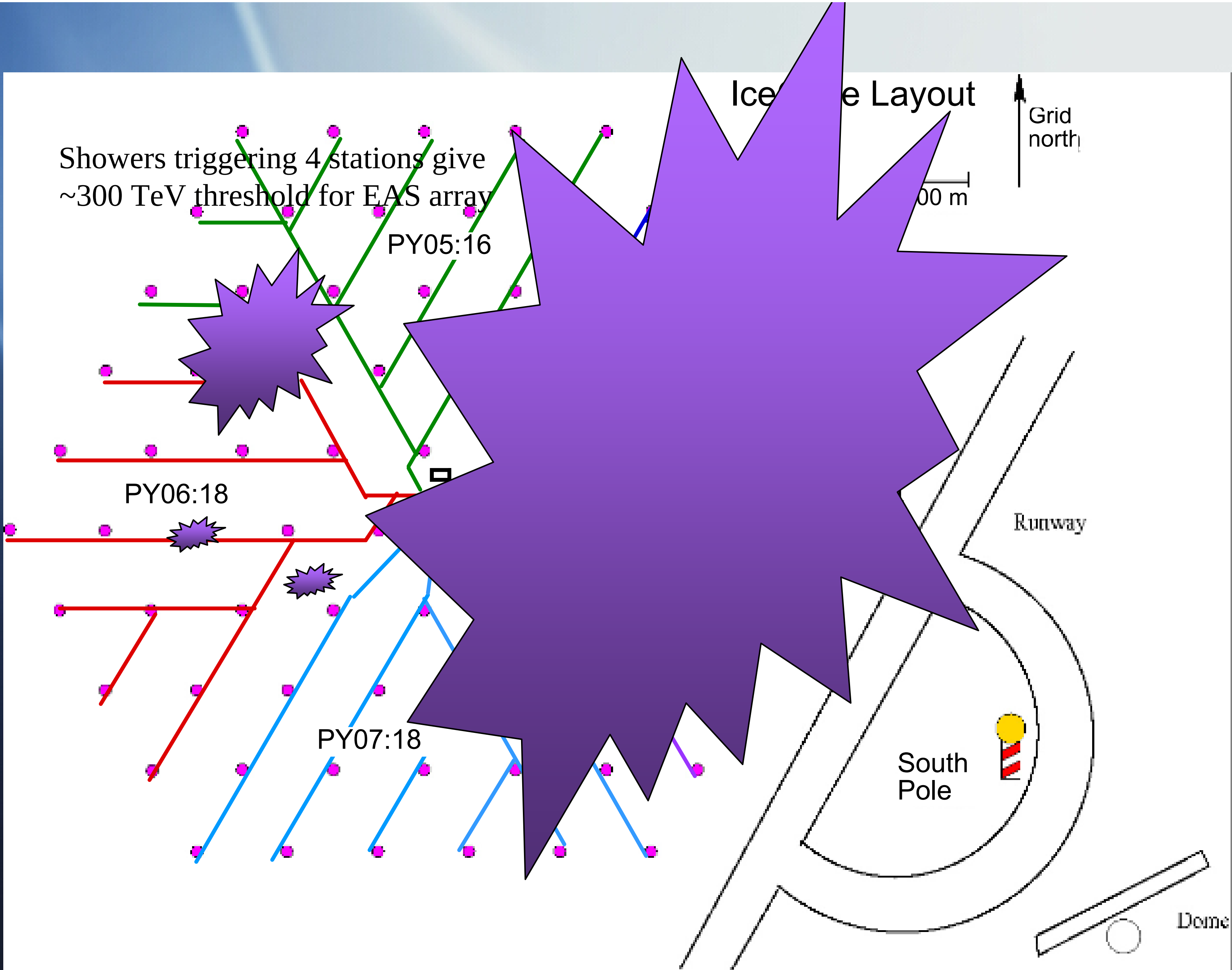
- 5 MW hot water drill
- Single spooled hose
- 60 cm holes
- 2500 m deep
- 40 hours
- DOM deployment: 12 hrs



IceTop Tanks

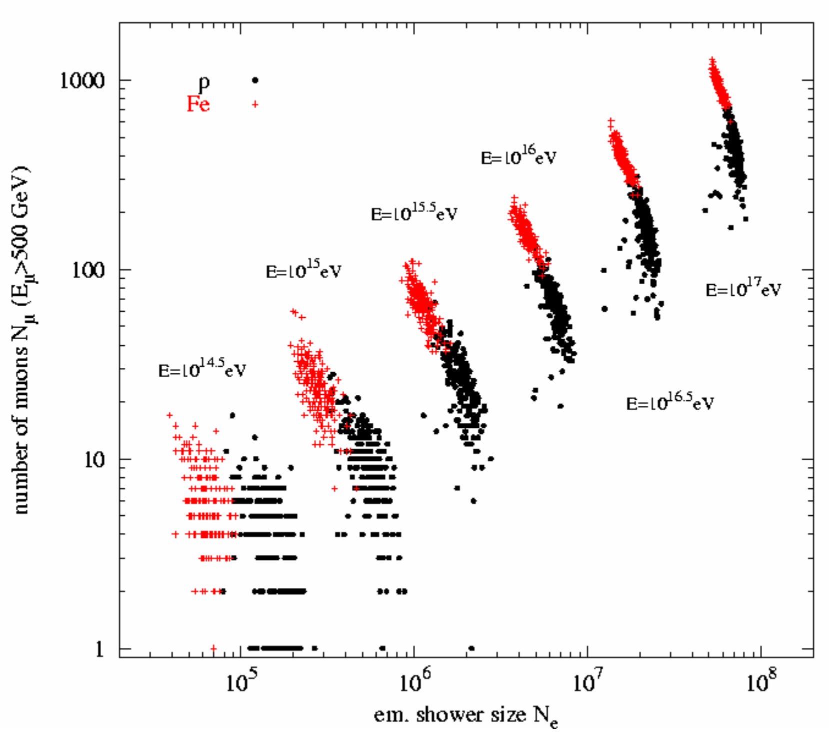


Showers triggering 4 stations give
~300 TeV threshold for EAS array



Primary composition

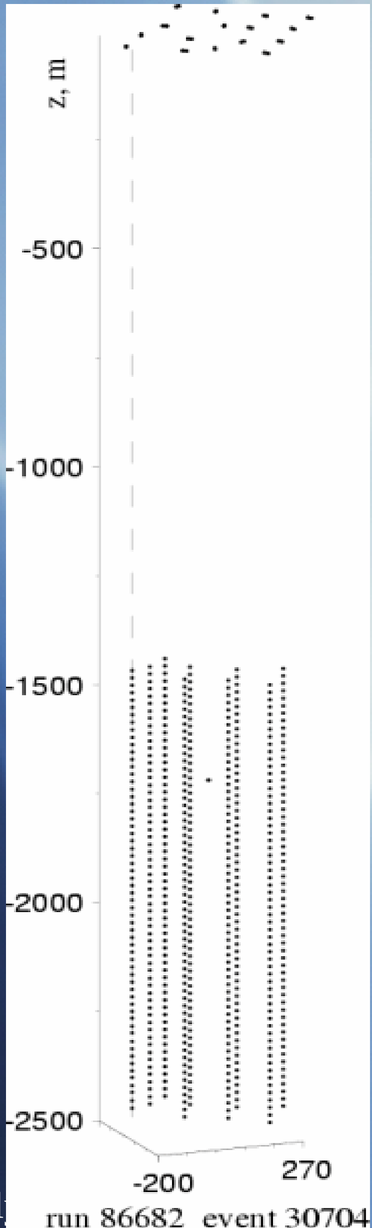
- High altitude allows good energy resolution
- Good mass separation from N_μ/N_e ratio
- PeV to EeV energy range
- Unique IceCube capability

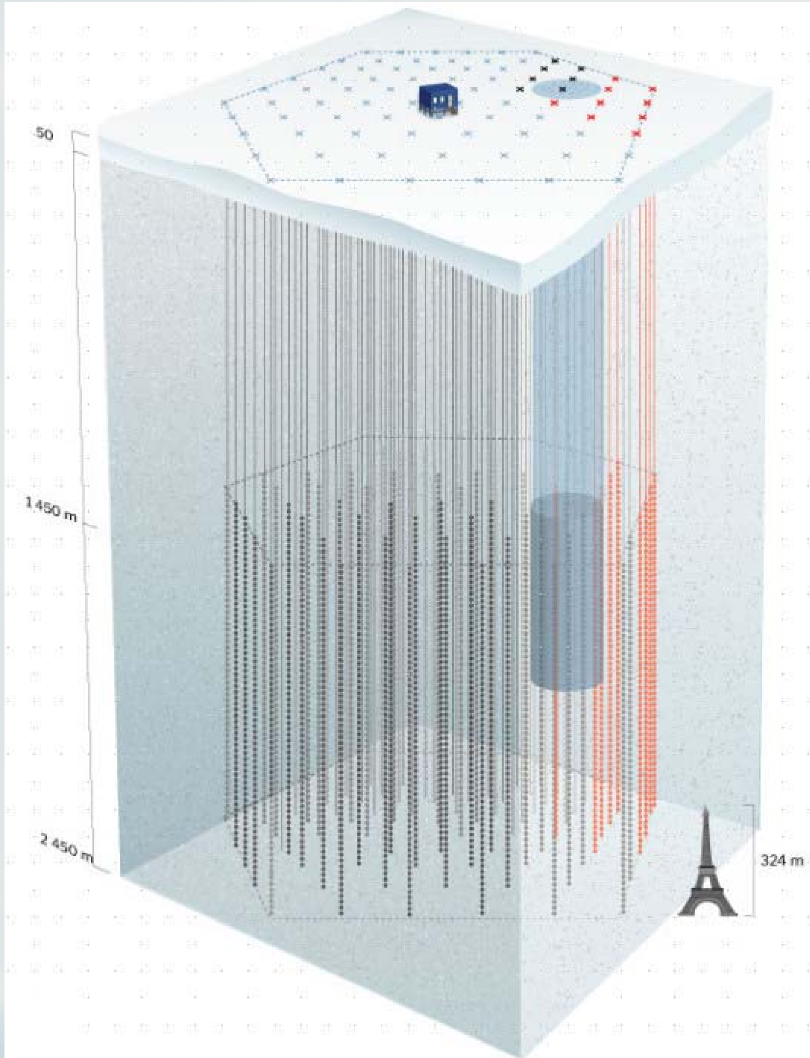


Calibrating Clocks with ns Timing over 3.4km long "phone wires"

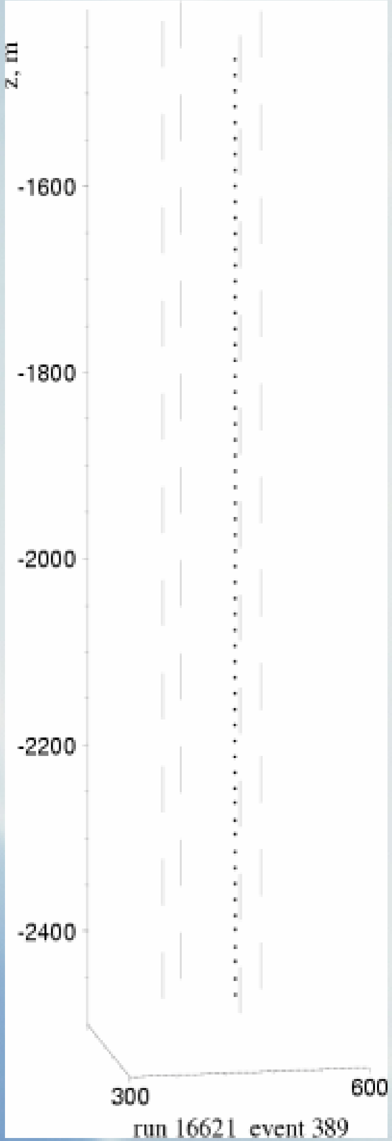
- ~5,000 free running clocks at the end of wires with:
  - Varying cable lengths (depth & position)
  - Transit time for 3.4 km twisted pair: ~17 μs
  - Rise-time after propagation ~ 2 μs (~1/t)
- The solution:
  - High-stability local clock: $\delta f/f \sim 6 \times 10^{-11}$/s !
  - Infrequent, scheduled (1 every 10sec) calibrations
  - Cable delay measurement in situ

an IceCube-IceTop event





an IceCube (1 string) neutrino event

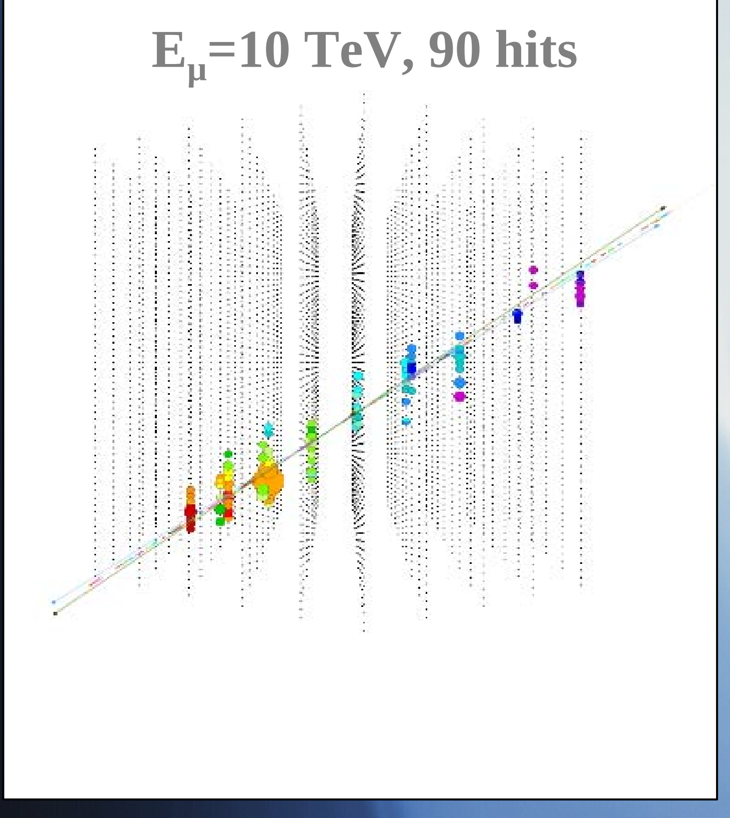


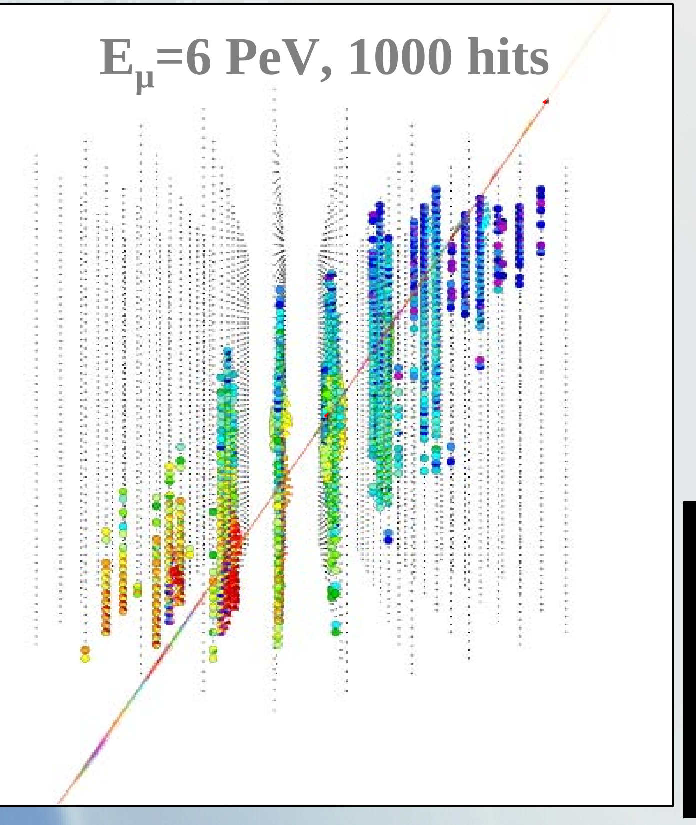
Diffuse ν_μ flux / Point sources

Objective (after removal of atm μ background):

- reject the steep energy spectrum of atm ν
- retain as much signal as possible from a (generic) E^{-2} spectrum

Use optimized energy cut $E_\mu \leftrightarrow$ number of hit OM's

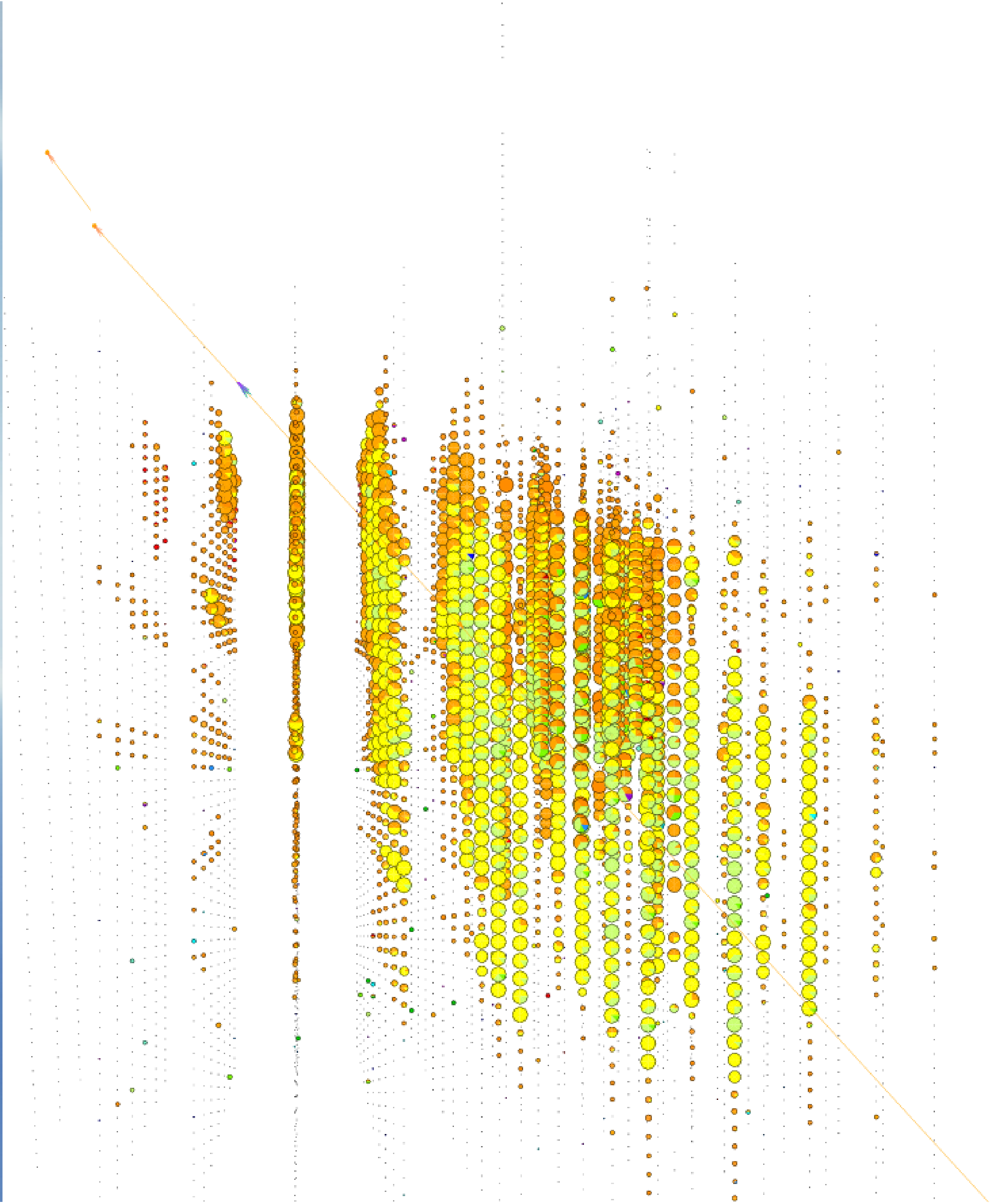




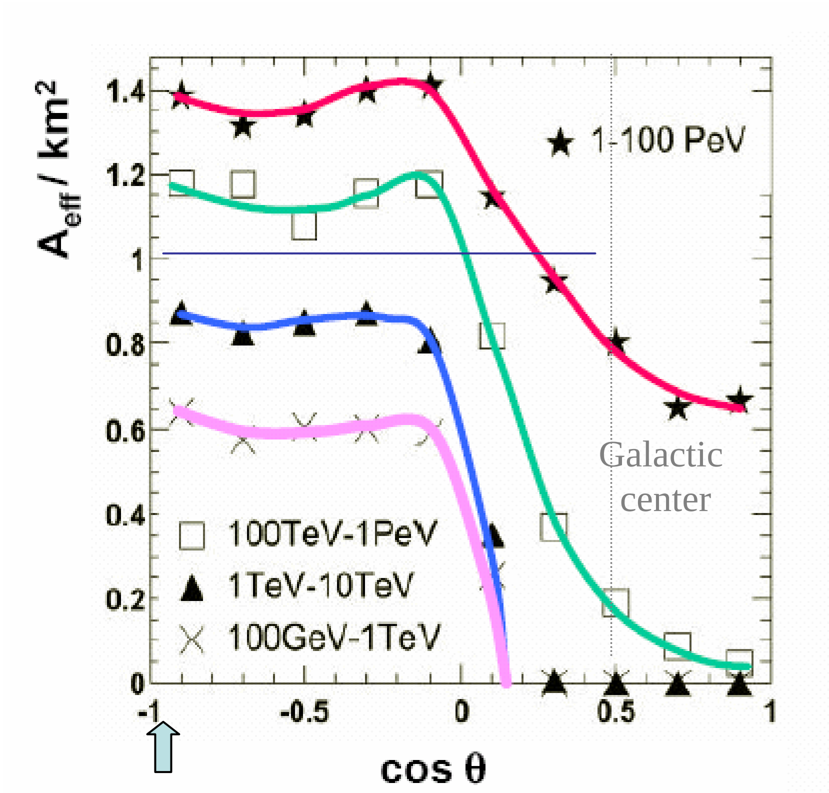
Diffuse $\leftrightarrow$ hard E_μ cut E_μ > 100 TeV

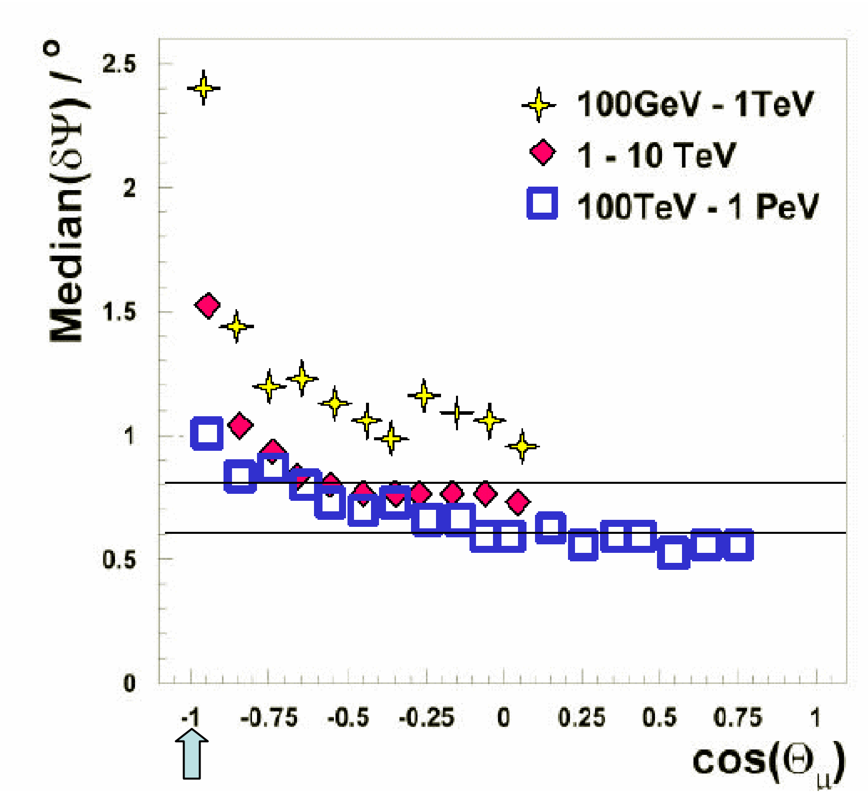
Point sources $\leftrightarrow$ softer E_μ cut + spatial correlation

UHE ν in AMANDA And IceCube



IceCube effective area and angular resolution for muons



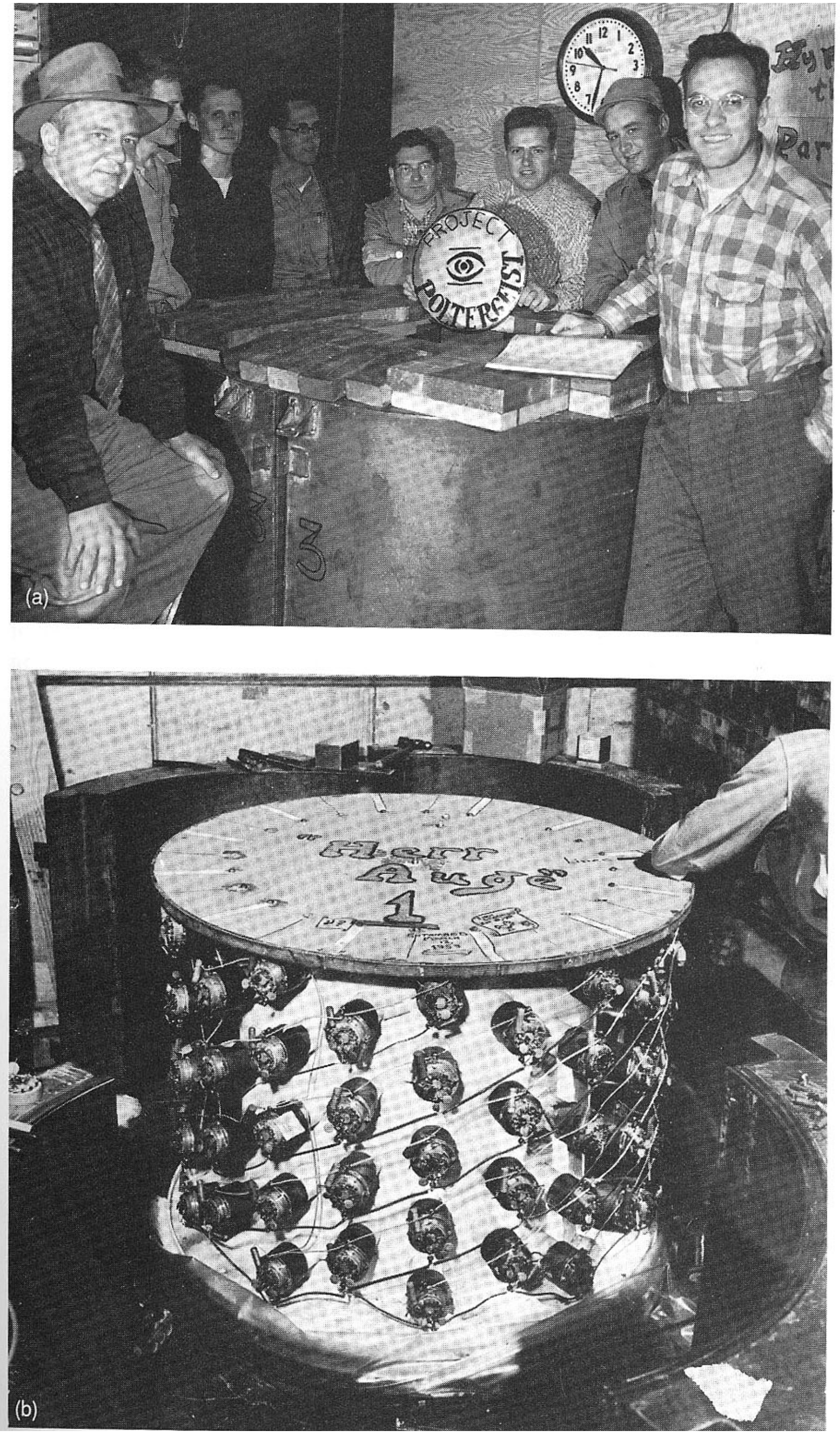


- E^{-2} ν_μ spectrum
- quality cuts and bkgr suppression
- (atm μ reduction by ~10^6)

Median angular reconstruction uncertainty ~ 0.8°

Perspective:

in ~50 years, the physical scale & energy scale have increased by 10^9



From an “undetectable particle” to a messenger from distant galaxies!

Telescope	User	date	Intended Use	Actual use
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, noise	3K cosmic background
X-ray	Giacconi …	1965	Sun, moon	neutron stars accreting binaries
Radio	Hewish, Bell	1967	Ionosphere	Pulsars
γ-rays	military	1960?	Thermonuclear explosions	Gamma ray bursts

New Window on Universe?
Expect Surprises

Conclusions

- IceCube will reach a sensitivity where signals beyond the atmospheric v spectrum can be reasonably expected
- ...

Conclusions

- IceCube will reach a sensitivity where signals beyond the atmospheric *ν* spectrum can be reasonably expected
- High quality data will aid in the perception of new unexpected signals
- …

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- IceCube will reach a sensitivity where signals beyond the atmospheric *ν* spectrum can be reasonably expected
- High quality data will aid in the perception of new unexpected signals
- If so, IceCube will open, for the first time, a **new tunnel** into the universe.

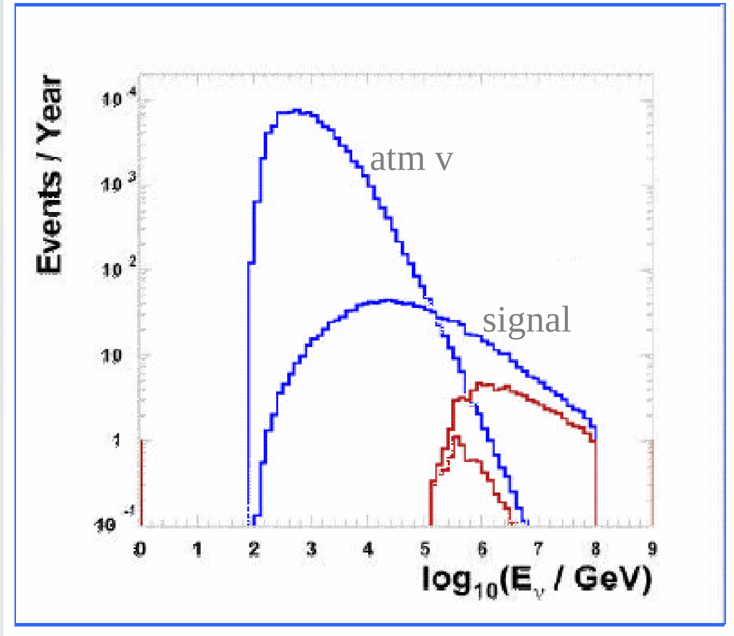
Assume generic flux $dN/dE = 10^{-7} E^{-2}$ $(cm^{-2}s^{-1}sr^{-1}GeV)$

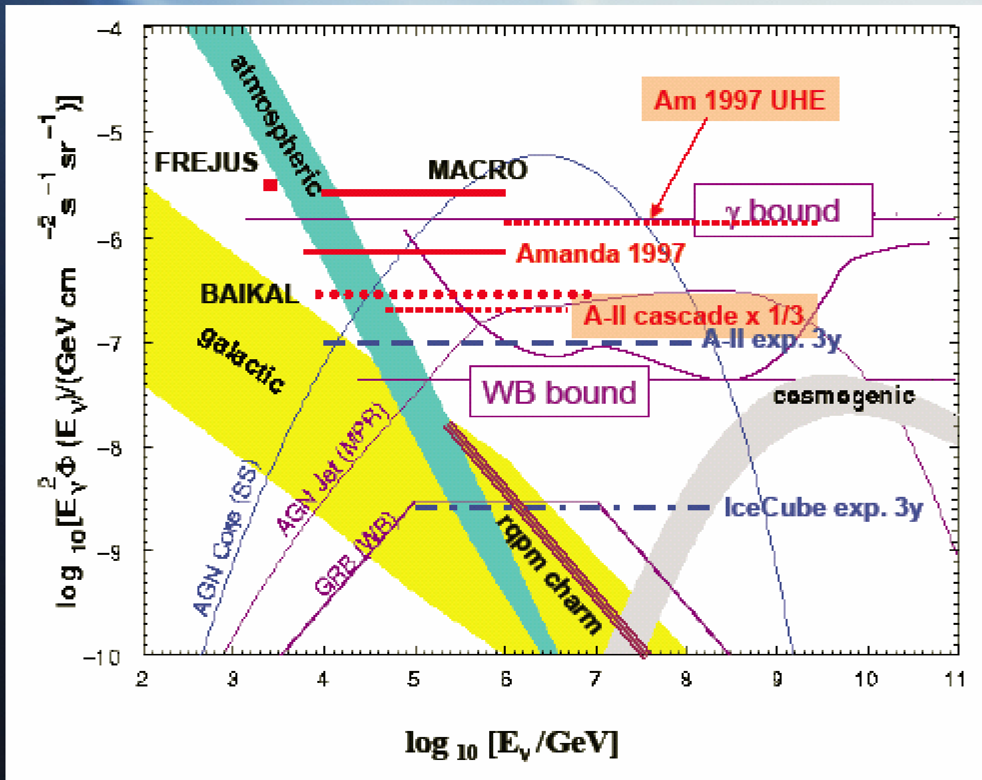
Expect

~10^3 events/year after atm μ rejection

~75 events/year after energy cut

cf background 8 atm ν





blue: after atm μ rejection
red: after E_μ cut

Sensitivity (1 y): $8.1 \cdot 10^{-9} E^{-2}$ $(cm^{-2}s^{-1}sr^{-1}GeV)$

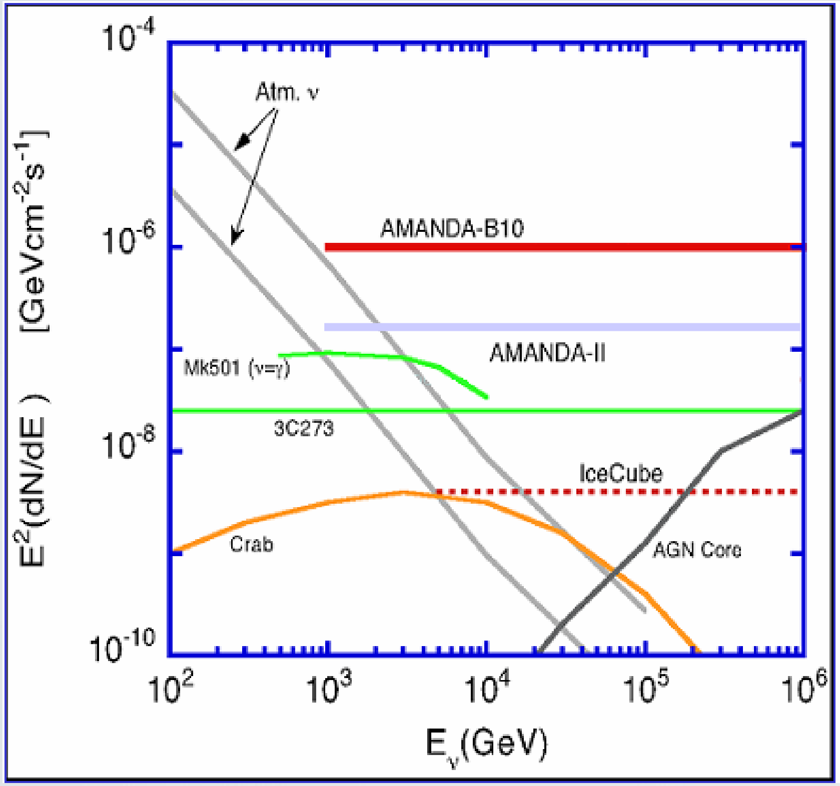
Diffuse ν_μ flux

Steady point sources

Search cone 1° opening half-angle
+ "soft" energy cut (< 1 TeV)

Sensitivity point sources (1 y):

$5.5 \cdot 10^{-9}\ E^{-2}\ (cm^{-2}s^{-1}GeV)$



Transient point sources – eg GRB

Essentially background-free search energy, spatial and temporal correlation with independent observation

For ~1000 GRB's observed/year expect (looking in Northern sky only)

- signal: 12 ν
- background (atm ν): 0.1

Sensitivity GRB (1 y):
$\sim 0.2\ \phi_{WB}$

Neutrino Telescopes	ANTARES

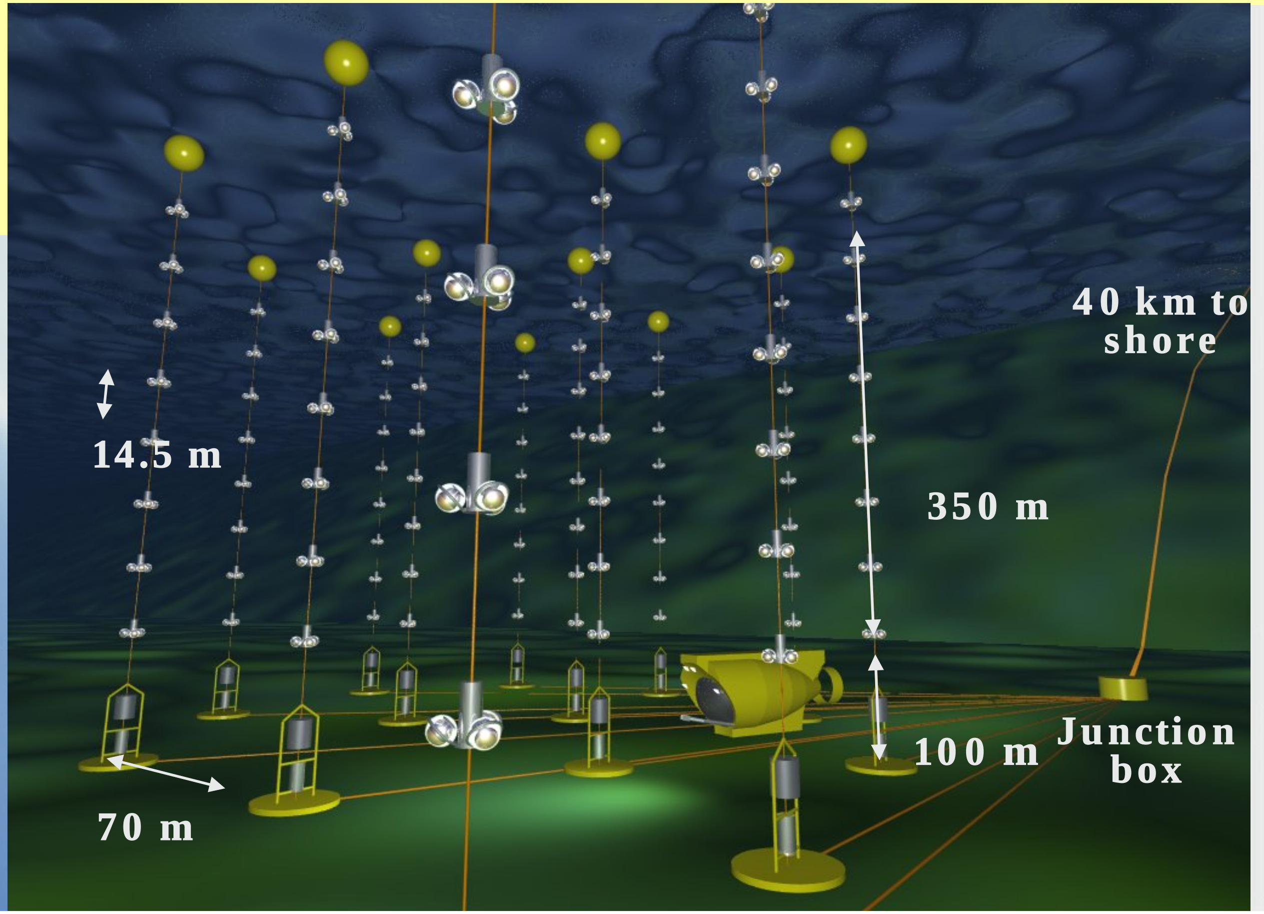
Location: Mediterranean Sea, 40 km off shore

Construction schedule:	2005 - 2007
No. of Strings:	12
Optical Sensors:	900
Depth:	2100-2400m
Instrum. Volume/km3:	0.011

μ-Effective area (1 TeV): 0.016 km^2

Angular resolution (>10 TeV): <0.3°

Architecture: local digitization, transmission of all data to shore.



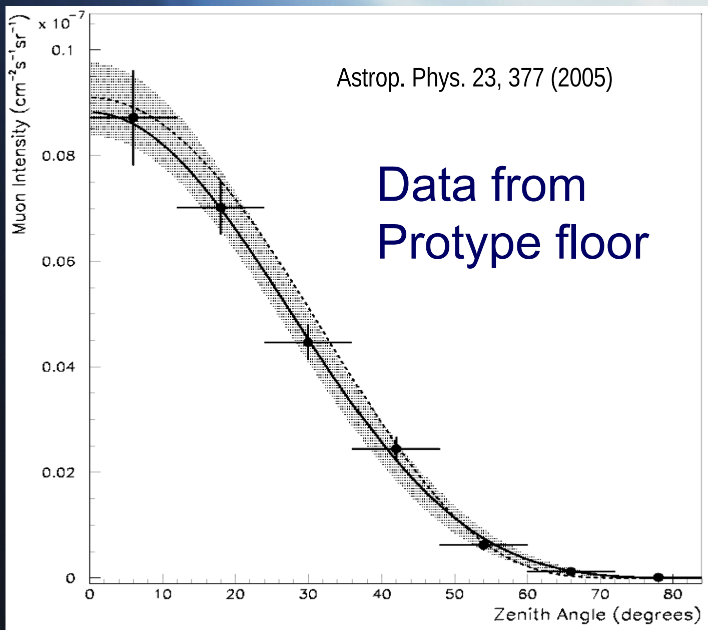
Neutrino Telescopes — NESTOR

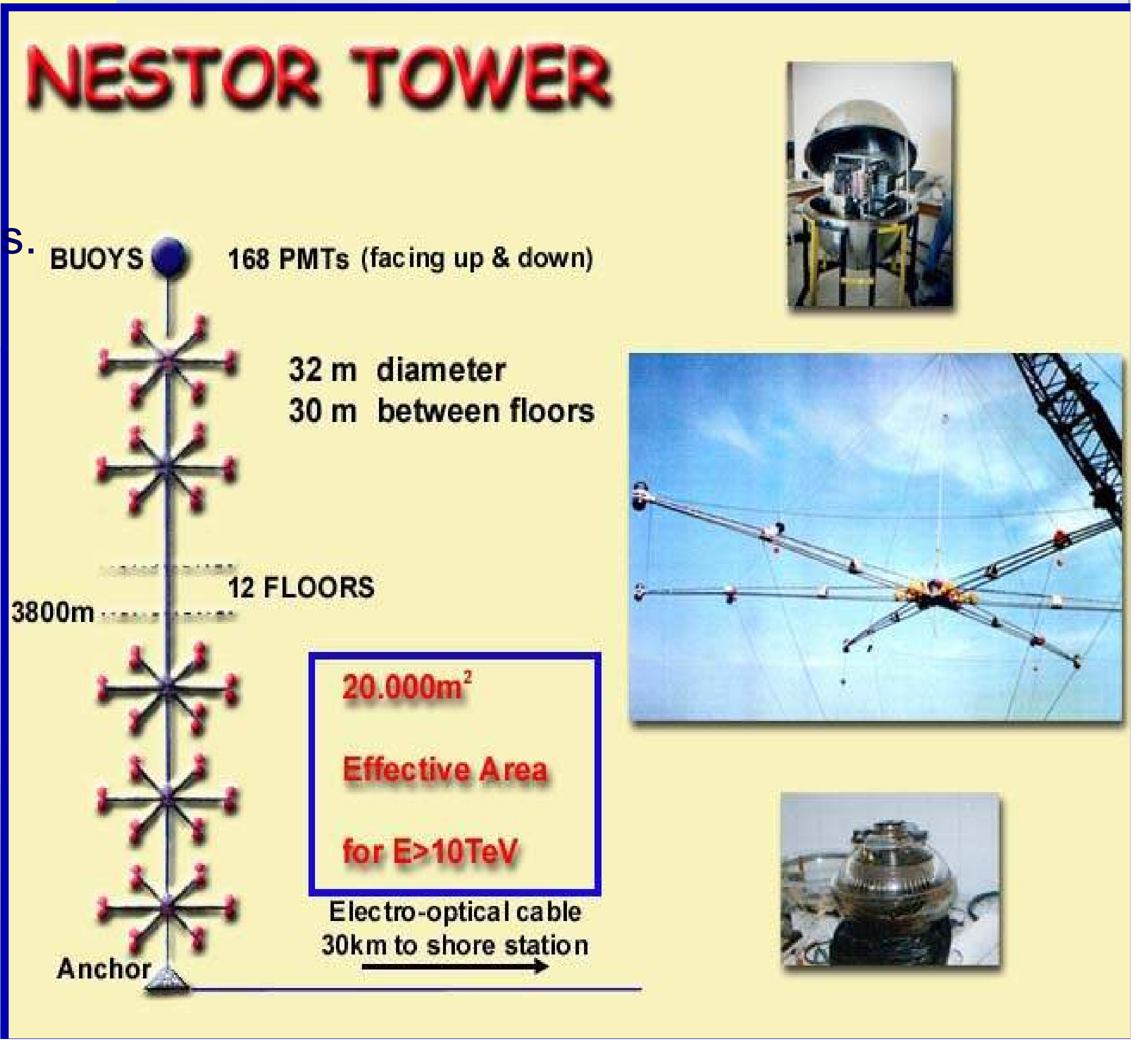
Location: Mediterranean Sea, Pylos
Construction schedule: 2005 - 2007
No. of sensors/floor: 12
Optical Sensors: 168
Pairs facing up and down

Depth (sea floor): 5200 m

Measured very good water properties.
Reconstructed events.

First floor (reduced size) with
12 PMTs deployed and operated
in 2003
Goal to deploy 4 more floors in spring 2006.





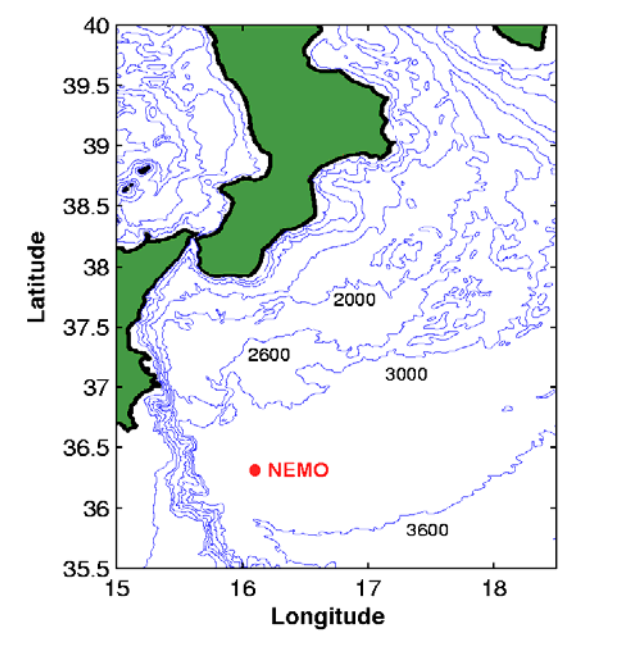
Neutrino Telescopes | NEMO

NEMO in R & D, Phase 1 (to 2006)
Location: (≈80 km) off the coast of Sicily (Capo Passero)

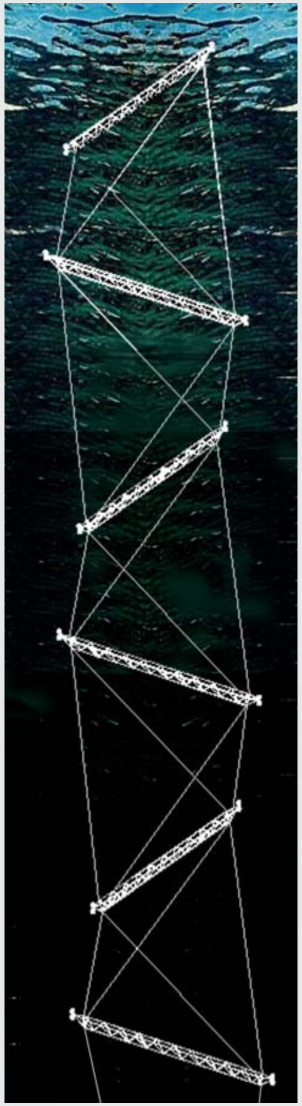
Optical Sensors:	5600
Depth:	≈2800 m - 3400 m
Instrum. Volume/km3:	1

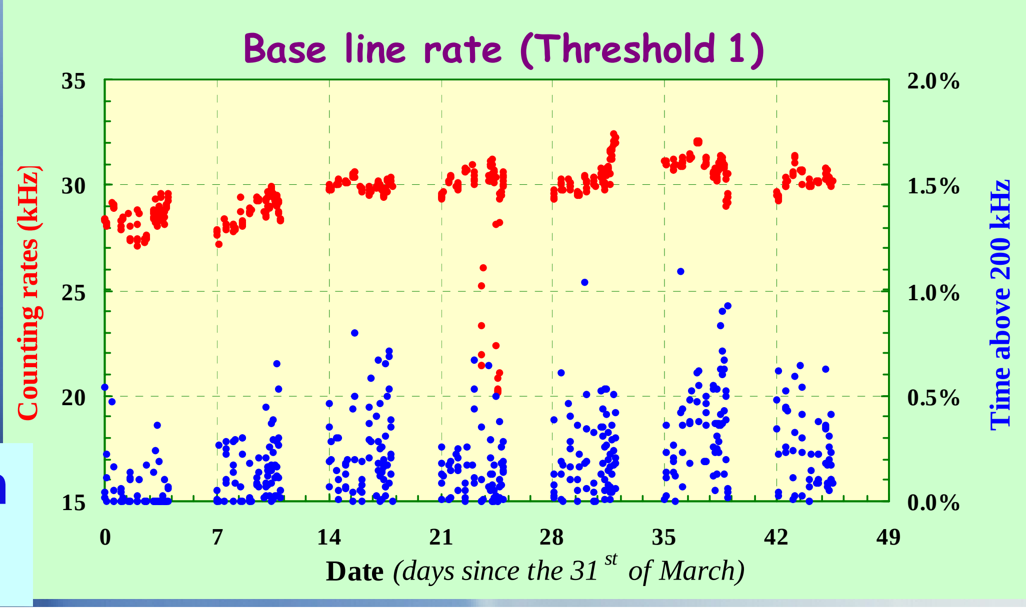
Detailed measurements and studies of water and other site parameters.

Medium is found excellent.



Tower structure





Baseline rate ~ 30 kHz

Burst fraction ~ 0.2 %