# IceCube
# - construction, performance and operation

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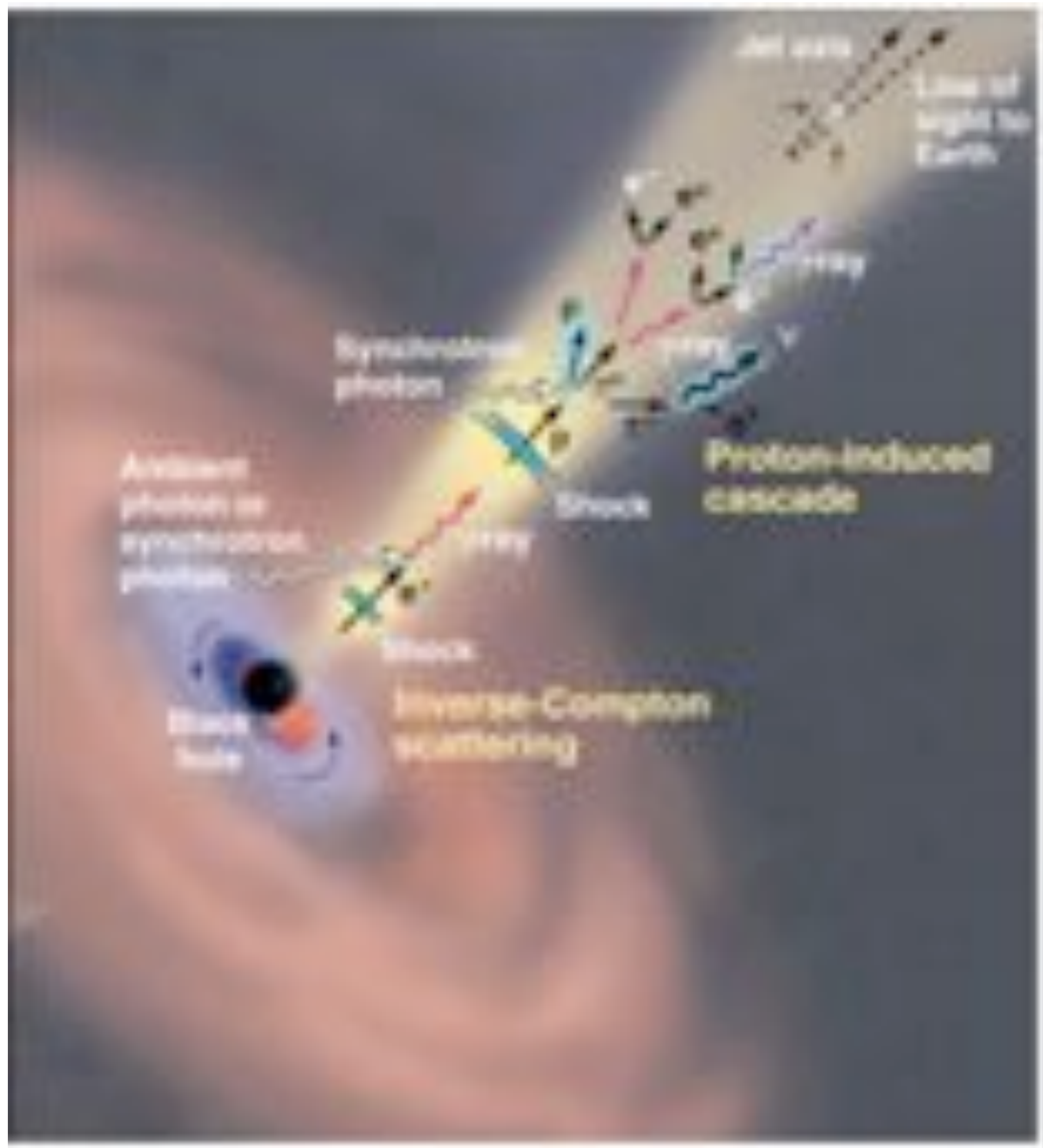
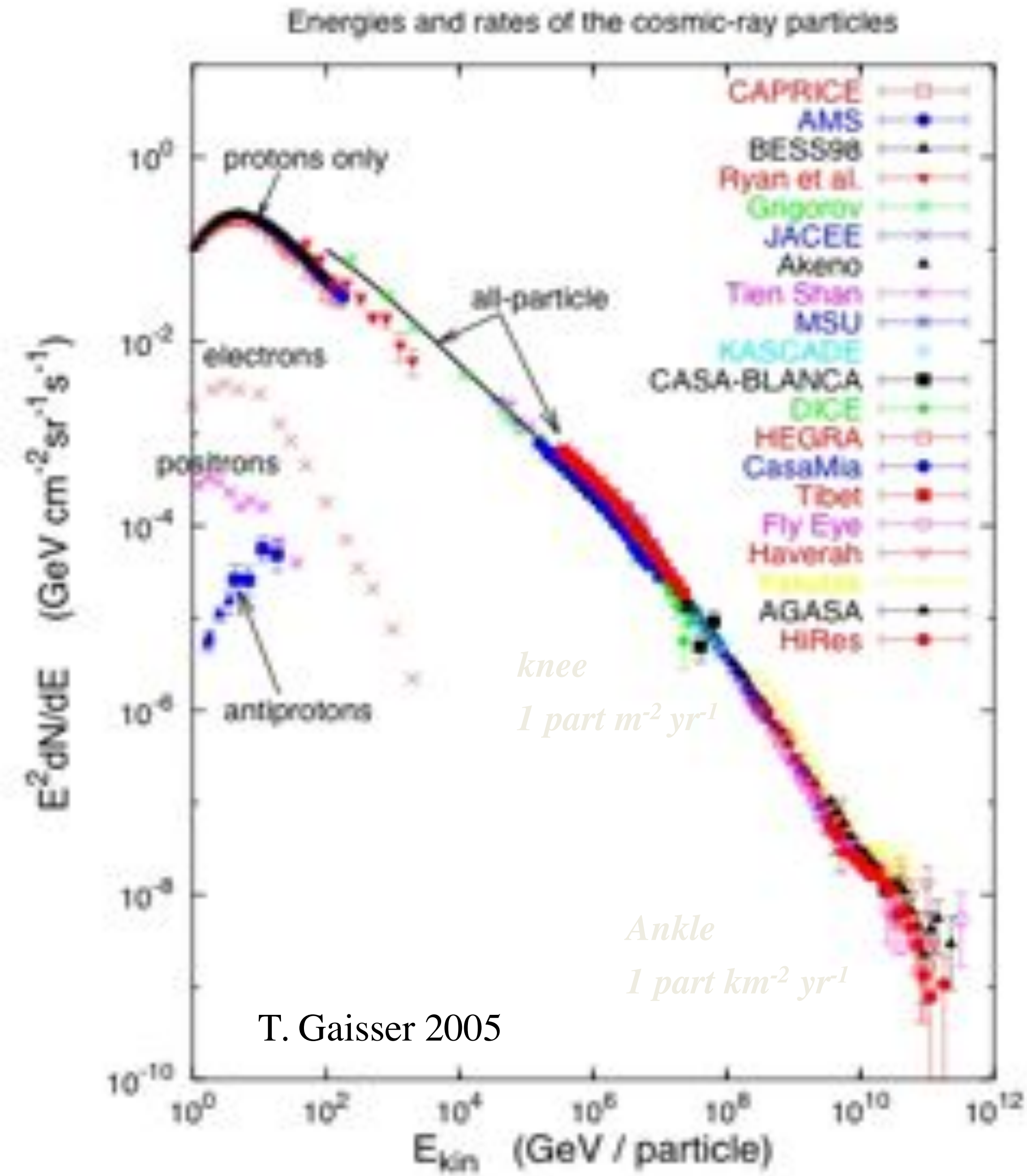
# High energy particles in the Universe

- Cosmic Rays
  - Observed up to 10^21 eV
  - Diffuse, mass composition
- Gamma Rays
  - Observed up to ~100 TeV
  - Numerous TeV point sources resolved
- Neutrinos
  - Atmospheric neutrinos observed up to 300 TeV
  - Solar neutrinos and SN1987a at lower energies

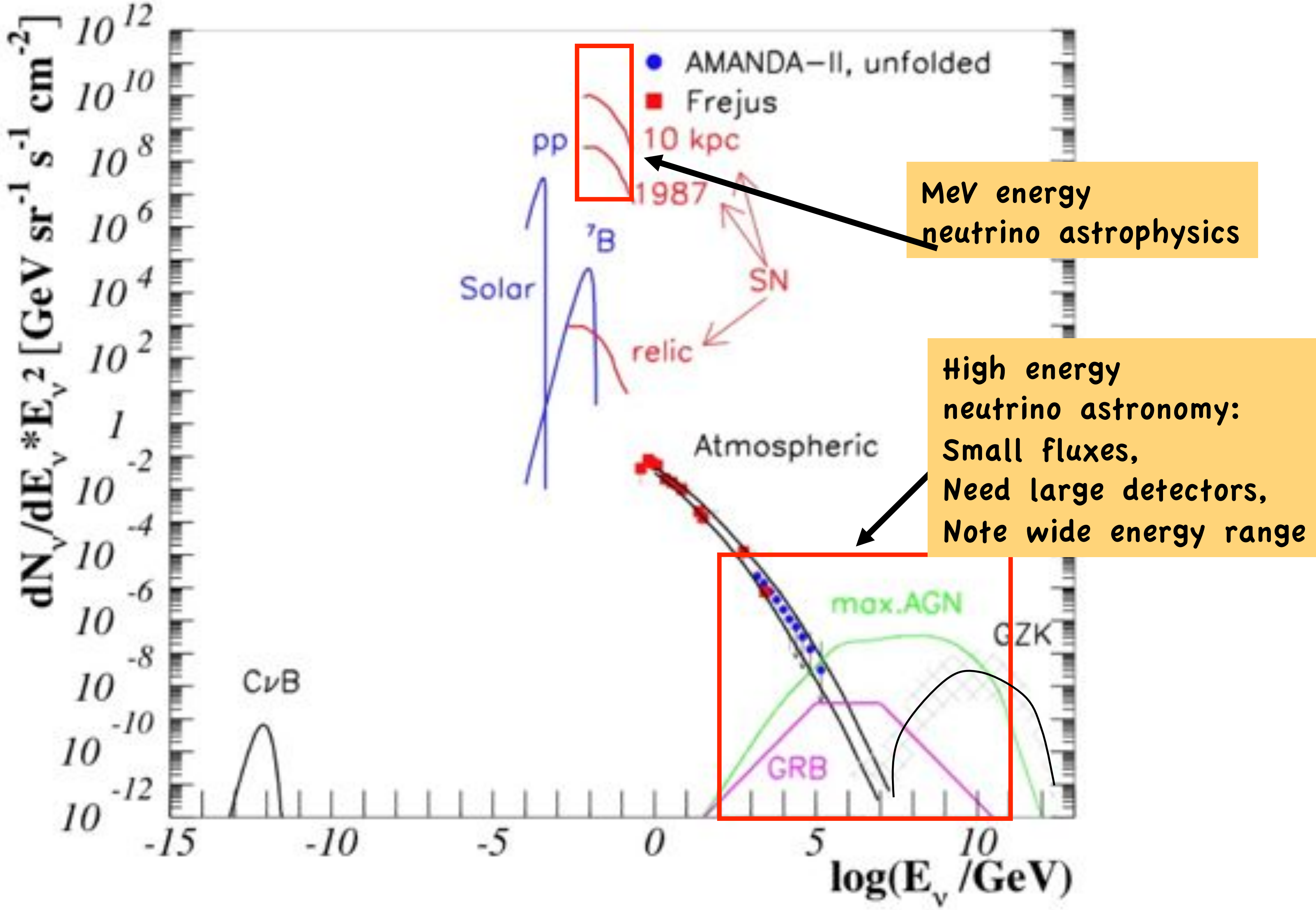


# Cosmic Rays and Neutrino Sources

## Cosmic rays

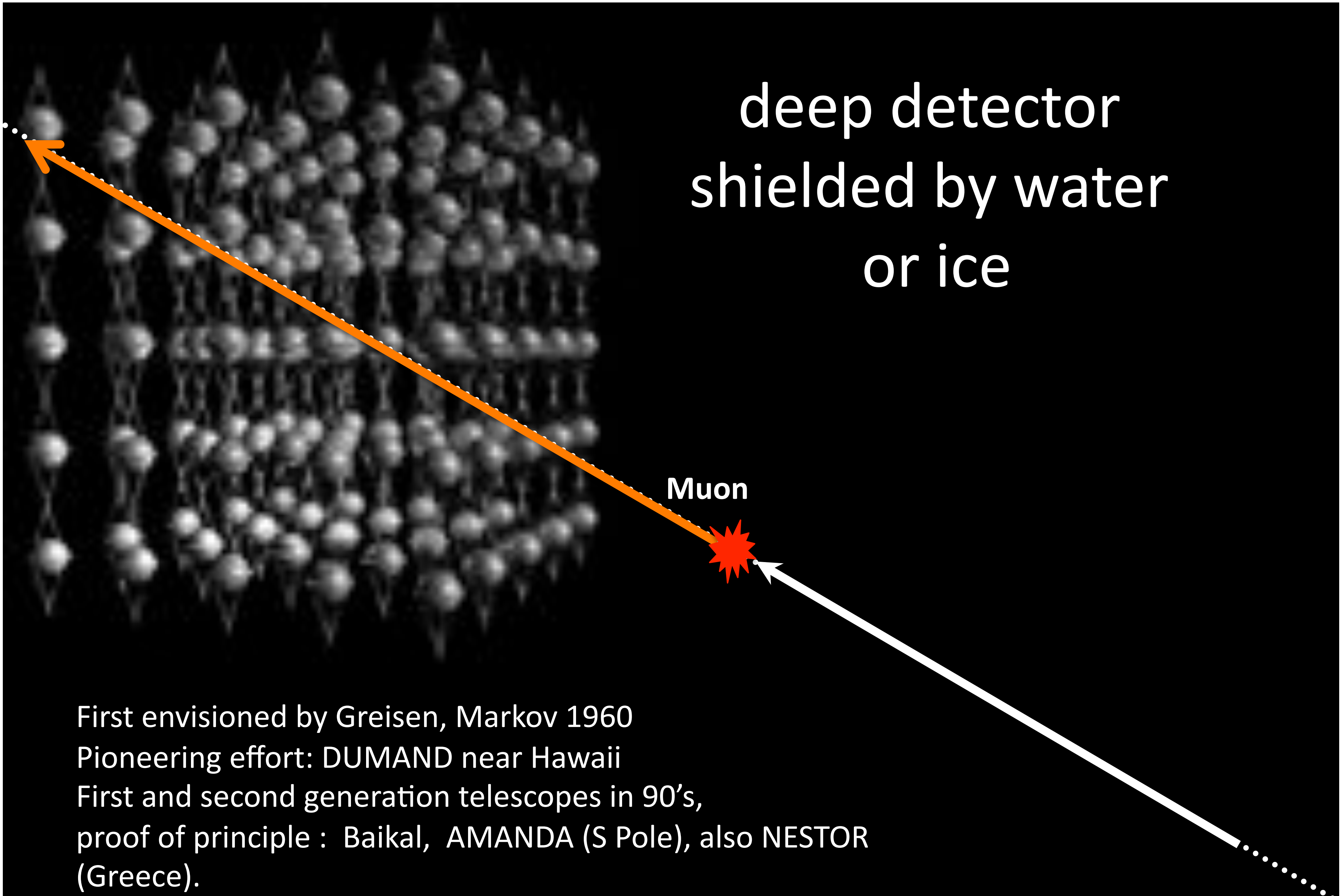


# Neutrinos



AMANDA–II, unfolded
Frejus
10 kpc
1987
SN
relic
pp
Solar
$^7$B
Atmospheric
max.AGN
GZK
GRB
CνB
$dN_\nu/dE_\nu * E_\nu^2$ [GeV sr$^{-1}$ s$^{-1}$ cm$^{-2}$]
log($E_\nu$ /GeV)
MeV energy neutrino astrophysics
High energy neutrino astronomy:
Small fluxes,
Need large detectors,
Note wide energy range

# A few remarks on the beginnings of IceCube



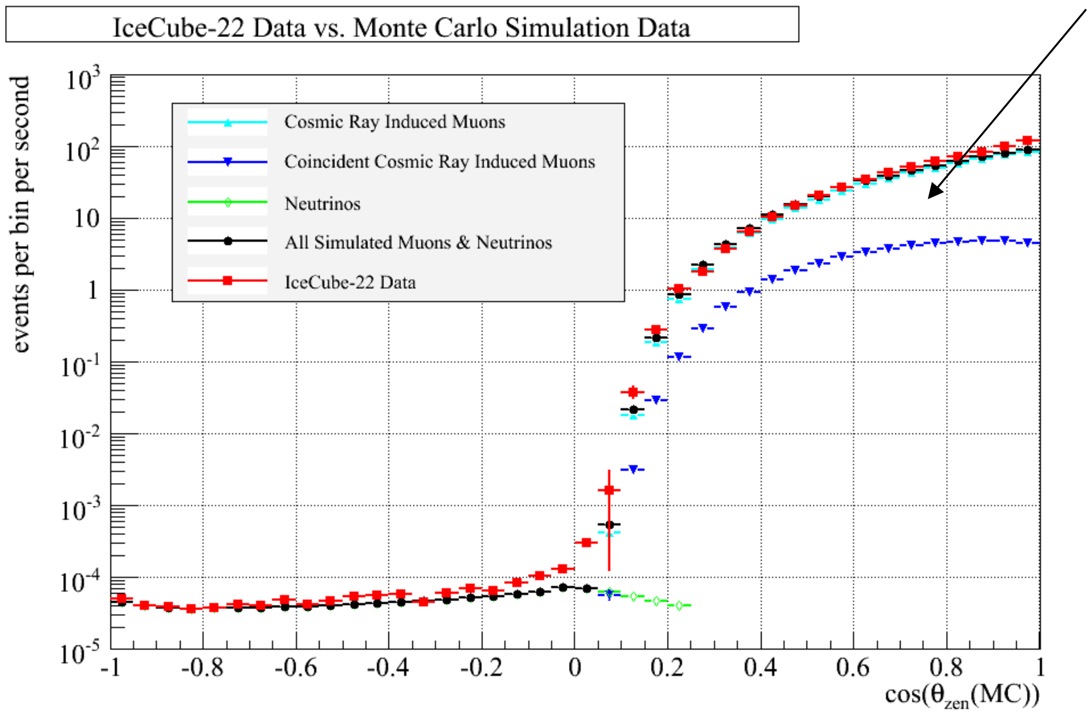

deep detector
shielded by water
or ice

First envisioned by Greisen, Markov 1960
Pioneering effort: DUMAND near Hawaii
First and second generation telescopes in 90's,
proof of principle : Baikal, AMANDA (S Pole), also NESTOR (Greece).

# Neutrino telescopes, originally primarily thought of as muon detectors

Neutrino-induced muons
from all directions

Downward atmospheric muons

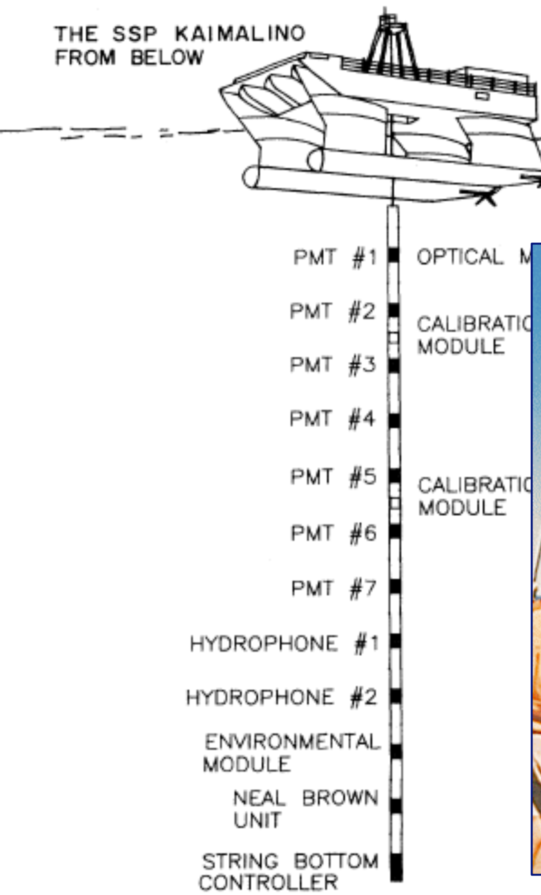



→ *P. Berghaus et al., ISVHECRI-08, also HE1.5*

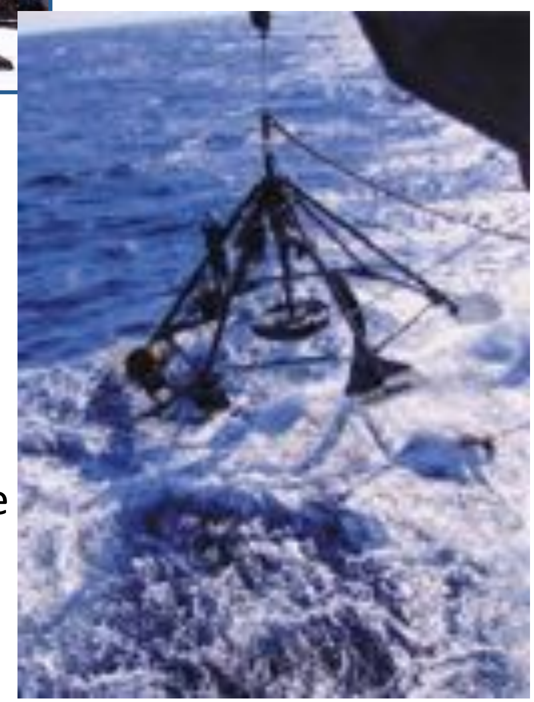
→Low energies: Use Earth as filter; look for neutrinos from below (GeV to PeV)
→High energies: Apply energy cut for downgoing atmospheric background (>PeV)

# Early Projects in water

DUMAND
(Hawaii)




Baikal



NESTOR
of the shore of Greece

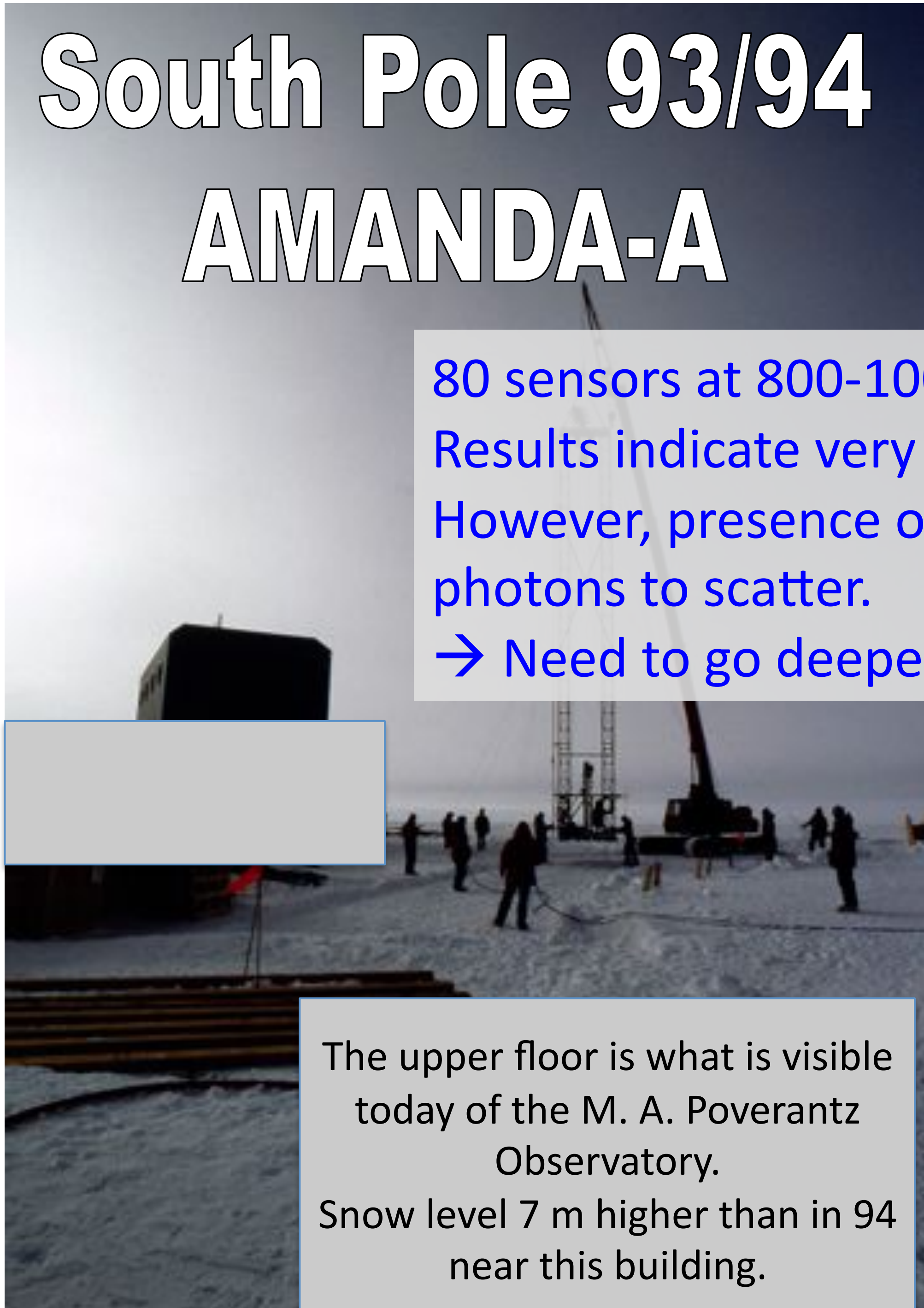
# South Pole *- the ice option*

ICRC1989

- 1991/92 first small PMTs deployed
- Test of hot water drilling at South Pole

Heaters and pumps
to melt the holes

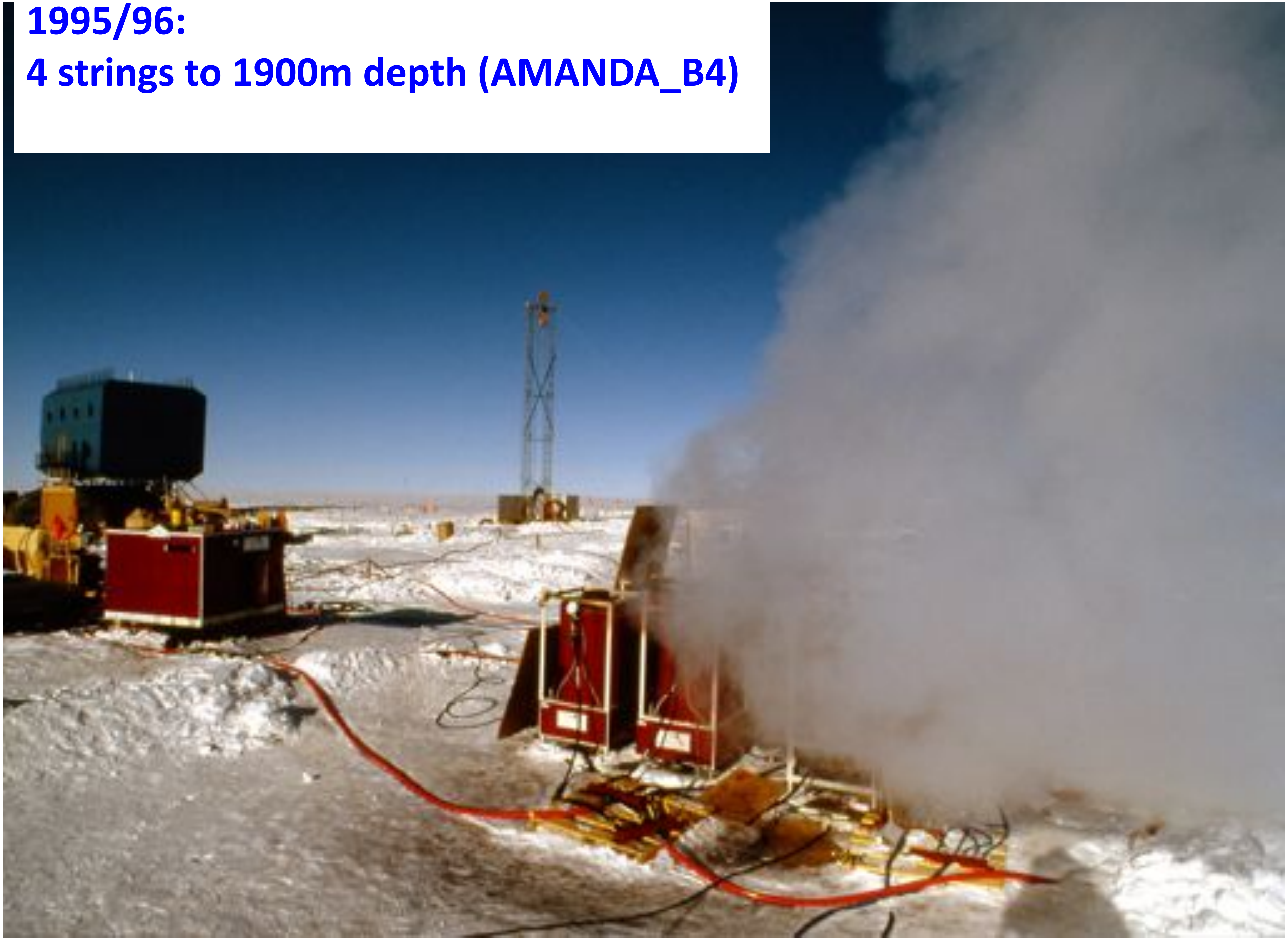
# South Pole 93/94
# AMANDA-A



80 sensors at 800-1000 m depth.
Results indicate very little absorption,
However, presence of bubbles causes
photons to scatter.
→ Need to go deeper!

The upper floor is what is visible today of the M. A. Poverantz Observatory.
Snow level 7 m higher than in 94 near this building.

**1995/96:**
**4 strings to 1900m depth (AMANDA_B4)**



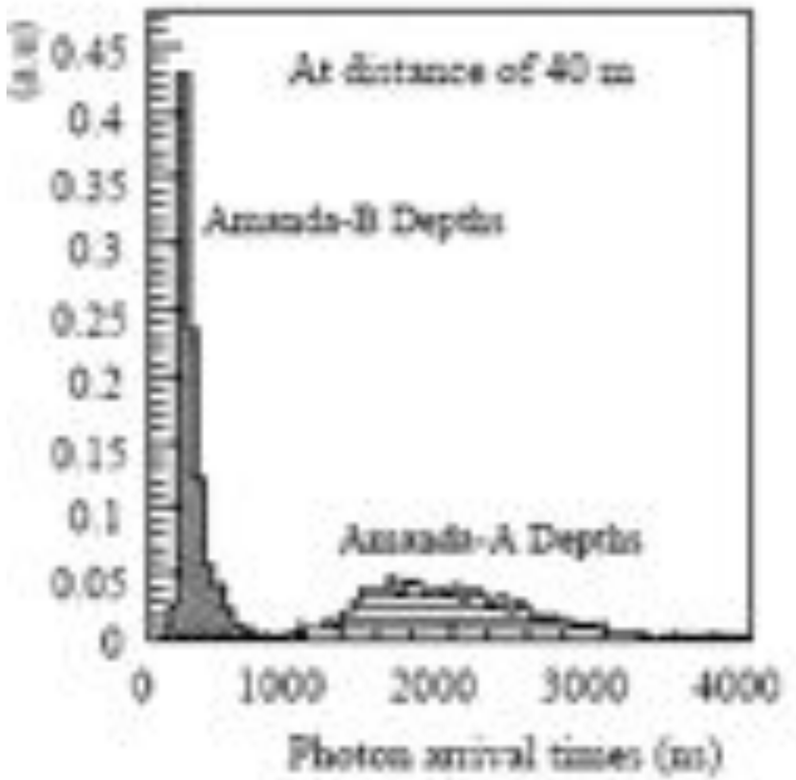
**1995/96:**

**→The ice is clear.**

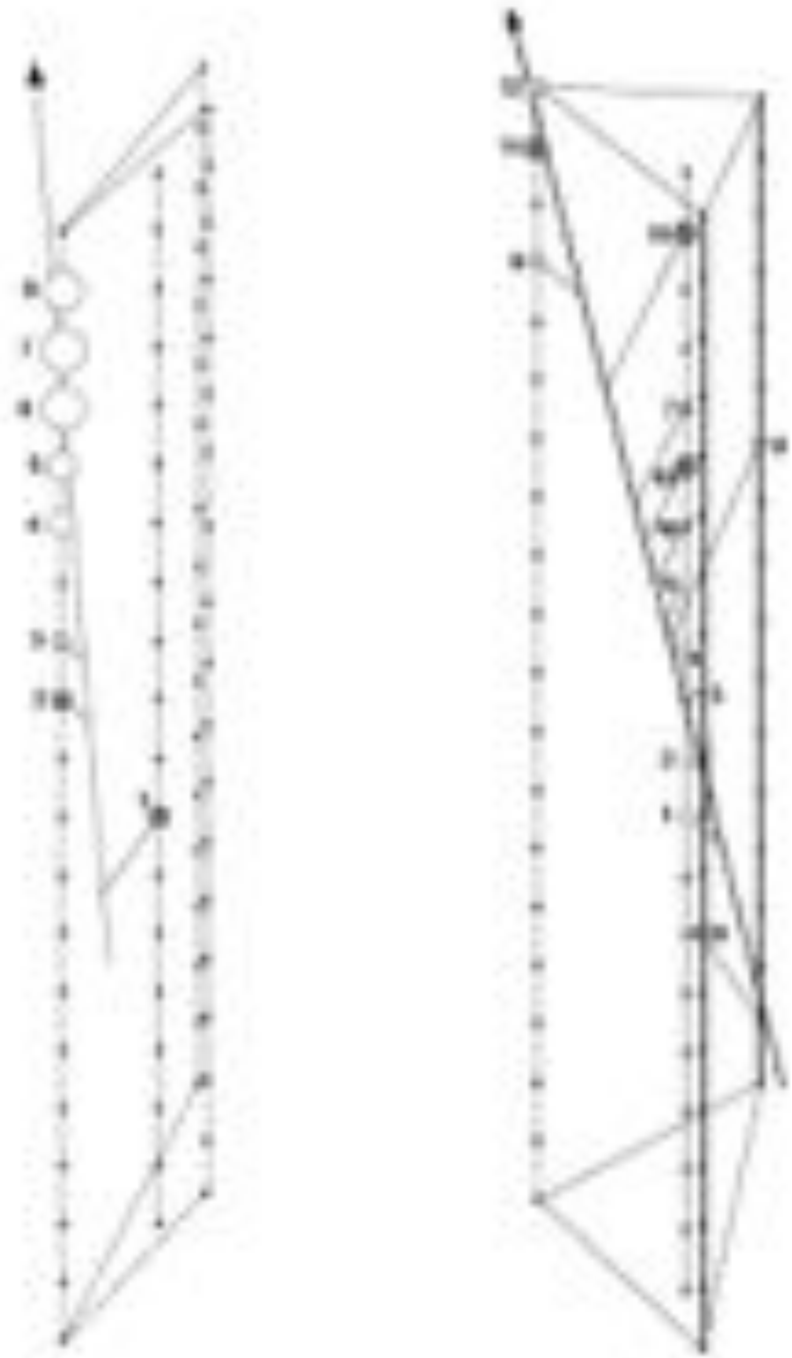
**→PMTs work 2000m under ice**

**→Suitable for a neutrino telescope!**

**Significant international contributions to instrument hardware.**




B4: first 2 neutrino candidates →



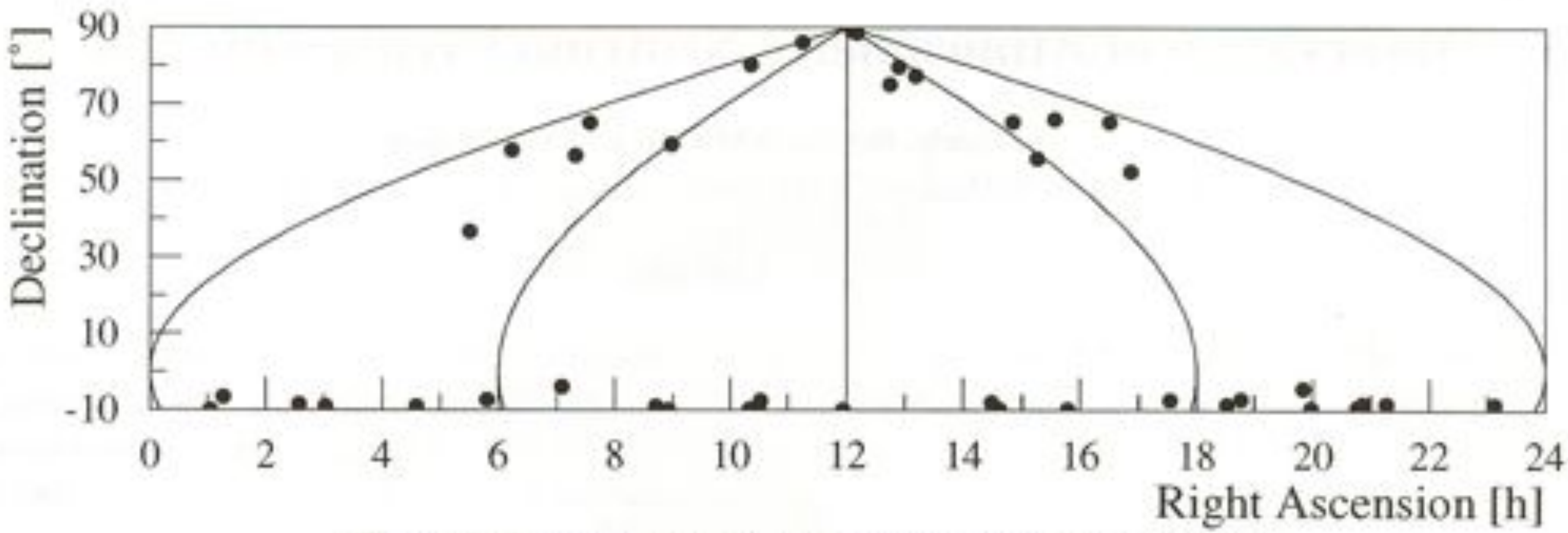


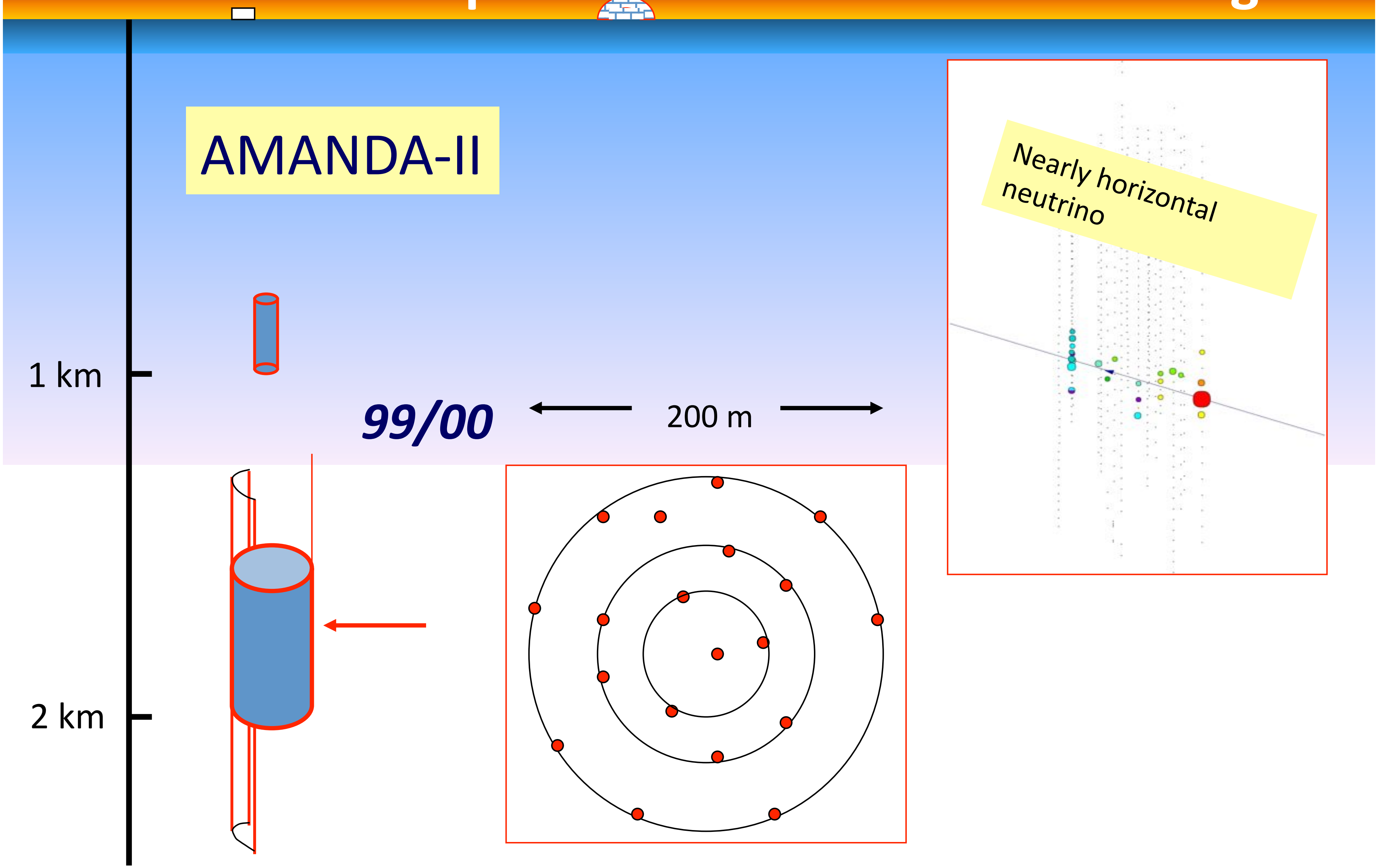

Figure 2: Sky plot of all events that pass level 4 quality cuts.

Skyplot of the very first 17 Nu candidates in B10


Figure 4 Distribution in declination and right ascension of the upwardly propagating events on the sky. The 263 events shown here are taken from the upward muons contained in both analysis A and analysis B. The median difference between the true and the reconstructed muon angles is about 3 to 4 degrees.

B10 skyplot published in Nature 2001

# 1999-2000: add 6 deeper strings to complete AMANDA-II with 19 strings



# Observation of high-energy neutrinos using Čerenkov detectors embedded deep in Antarctic ice

E. Andrés, P. Askebjer, X. Bai, G. Barouch, S. W. Barwick, R. C. Bay, K.-H. Becker, L. Bergström, D. Bertrand, D. Bierenbaum, A. Biron, J. Booth, O. Botner, A. Bouchta, M. M. Boyce, S. Carius, A. Chen, D. Chirkin, J. Conrad, J. Cooley, C. G. S. Costa, D. F. Cowen, J. Dailing, E. Dalberg, T. DeYoung, P. Desiati, J.-P. Dewulf, P. Doksus, J. Edsjö, P. Ekström, B. Erlandsson, T. Feser, M. Gaug, A. Goldschmidt, A. Goobar, L. Gray, H. Haase, A. Hallgren, F. Halzen, K. Hanson, R. Hardtke, Y. D. He, M. Hellwig, H. Heukenkamp, G. C. Hill, P. O. Hulth, S. Hundertmark, J. Jacobsen, V. Kandhadai, A. Karle, J. Kim, B. Koci, L. Köpke, M. Kowalski, H. Leich, M. Leuthold, P. Lindahl, I. Liubarsky, P. Loaiza, D. M. Lowder, J. Ludvig, J. Madsen, P. Marciniewski, H. S. Matis, A. Mihalyi, T. Mikolajski, T. C. Miller, Y. Minaeva, P. Miočinović, P. C. Mock, R. Morse, T. Neunhöffer, F. M. Newcomer, P. Niessen, D. R. Nygren, H. Ögelman, C. Pérez de los Heros, R. Porrata, P. B. Price, K. Rawlins, C. Reed, W. Rhode, A. Richards, S. Richter, J. Rodríguez Martino, P. Romenesko, D. Ross, H. Rubinstein, H.-G. Sander, T. Scheider, T. Schmidt, D. Schneider, E. Schneider, R. Schwarz, A. Silvestri, M. Solarz, G. M. Spiczak, C. Spiering, N. Starinsky, D. Steele, P. Steffen, R. G. Stokstad, O. Streicher, Q. Sun, I. Taboada, L. Thollander, T. Thon, S. Tilav, N. Usechak, M. Vander Donckt, C. Walck, C. Weinheimer, C. H. Wiebusch, R. Wischnewski, H. Wissing, K. Woschnagg, W. Wu, G. Yodh & S. Young

**NATURE 2001**

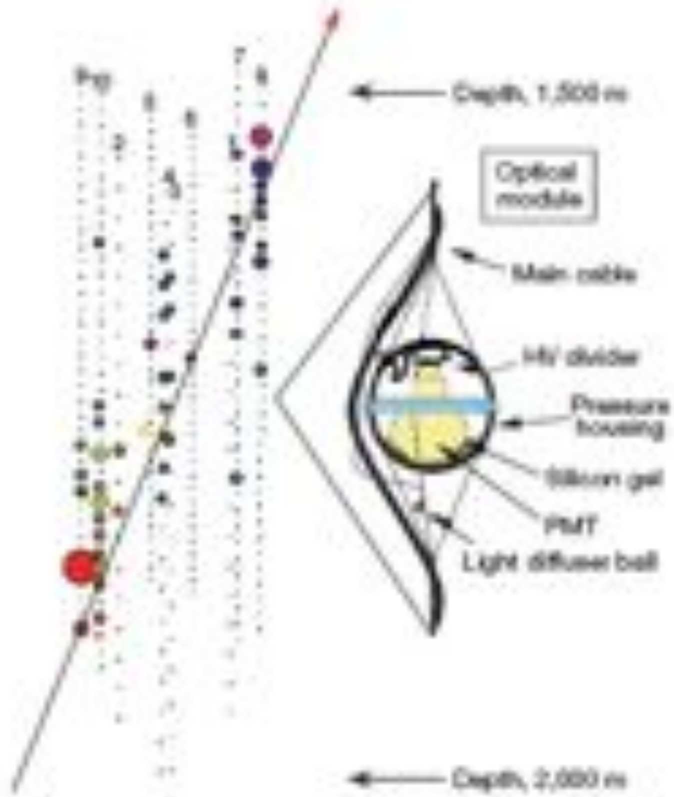


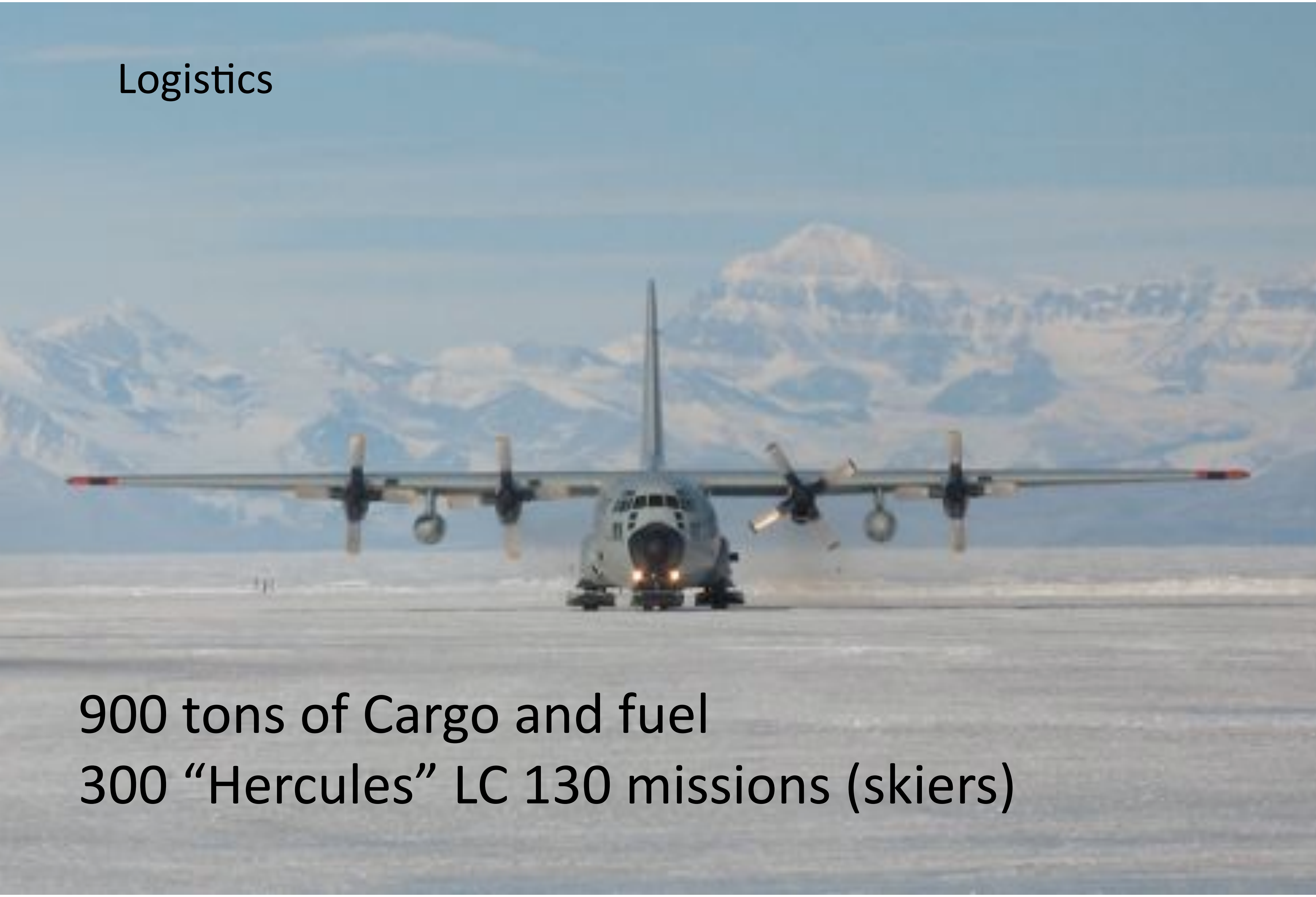

**Figure 1** The AMANDA-B10 detector and a schematic diagram of an optical module. Each dot represents an optical module. The modules are separated by 20 m on the inner strings (1 to 4), and by 10 m on the outer strings (5 to 10). The coloured circles show pulses from the photomultipliers for a particular event; the sizes of the circles indicate the amplitudes of the pulses and the colours correspond to the time of a photon's arrival. Earlier times are in red and later ones in blue. The arrow indicates the reconstructed track of the upwardly propagating muon.

# 1999 – IceCube proposal

By 1999 the following ingredients for a large IceCube proposal were obtained.

- A strong international collaboration has formed.
- It had been demonstrated that
  - the ice is excellent down to 2500m depth.
  - Drilling technology is established and modeling has improved such that fuel and logistics requirements are solid (they were conservative).
  - The deep Antarctic ice is suitable for building a large neutrino telescope. (AMANDA had seen neutrinos consistent with predictions.)
  - A detector technology was demonstrated that would require only limited maintenance and power.
- During the proposal process (2 years) AMANDA-II was completed and the first results solidified the above statements.
  - Challenge that needed to be demonstrated before the final award was given, was that a University based collaborative research effort could make the transition to a very large project with adequate management etc.

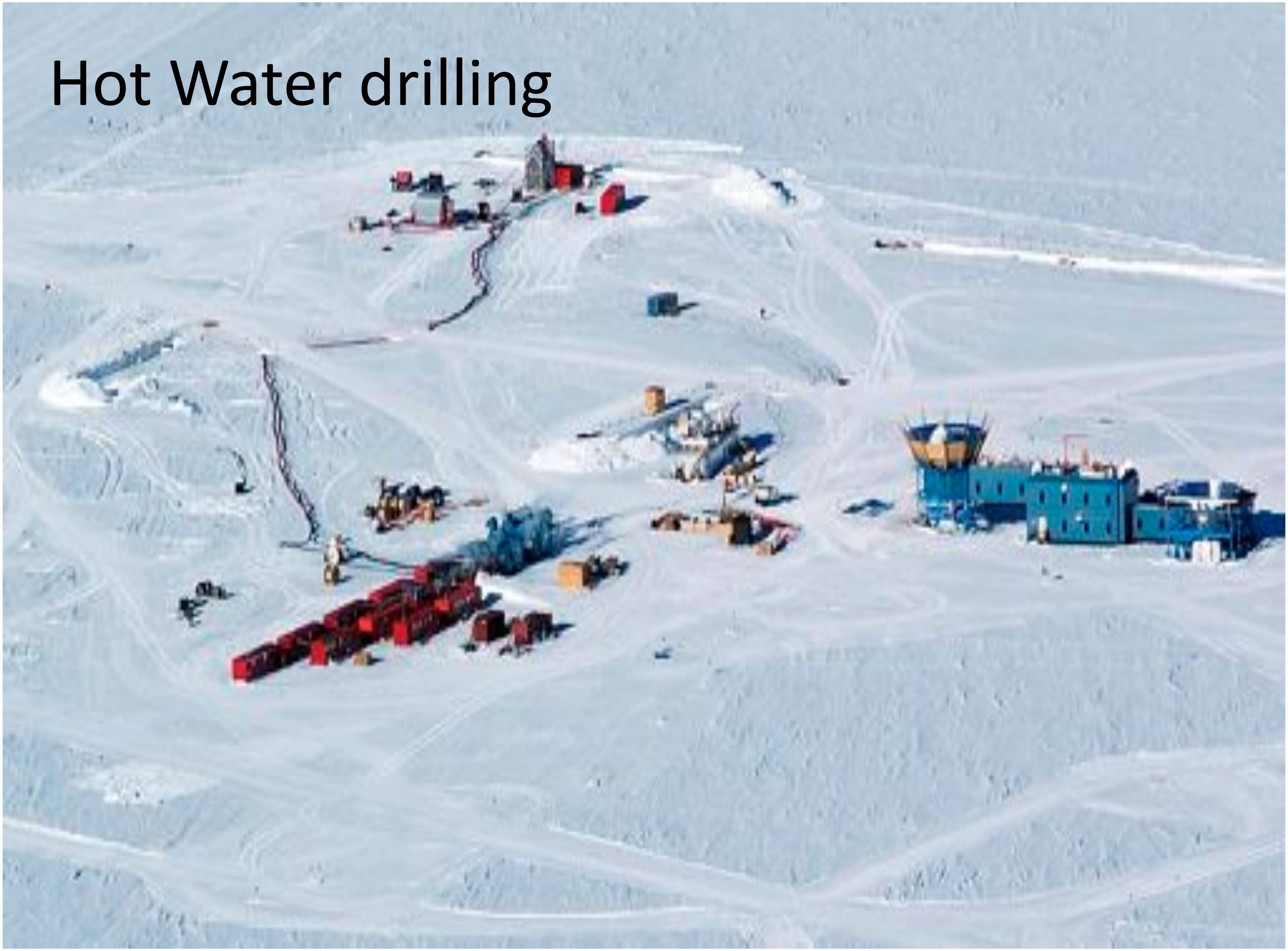
# Logistics



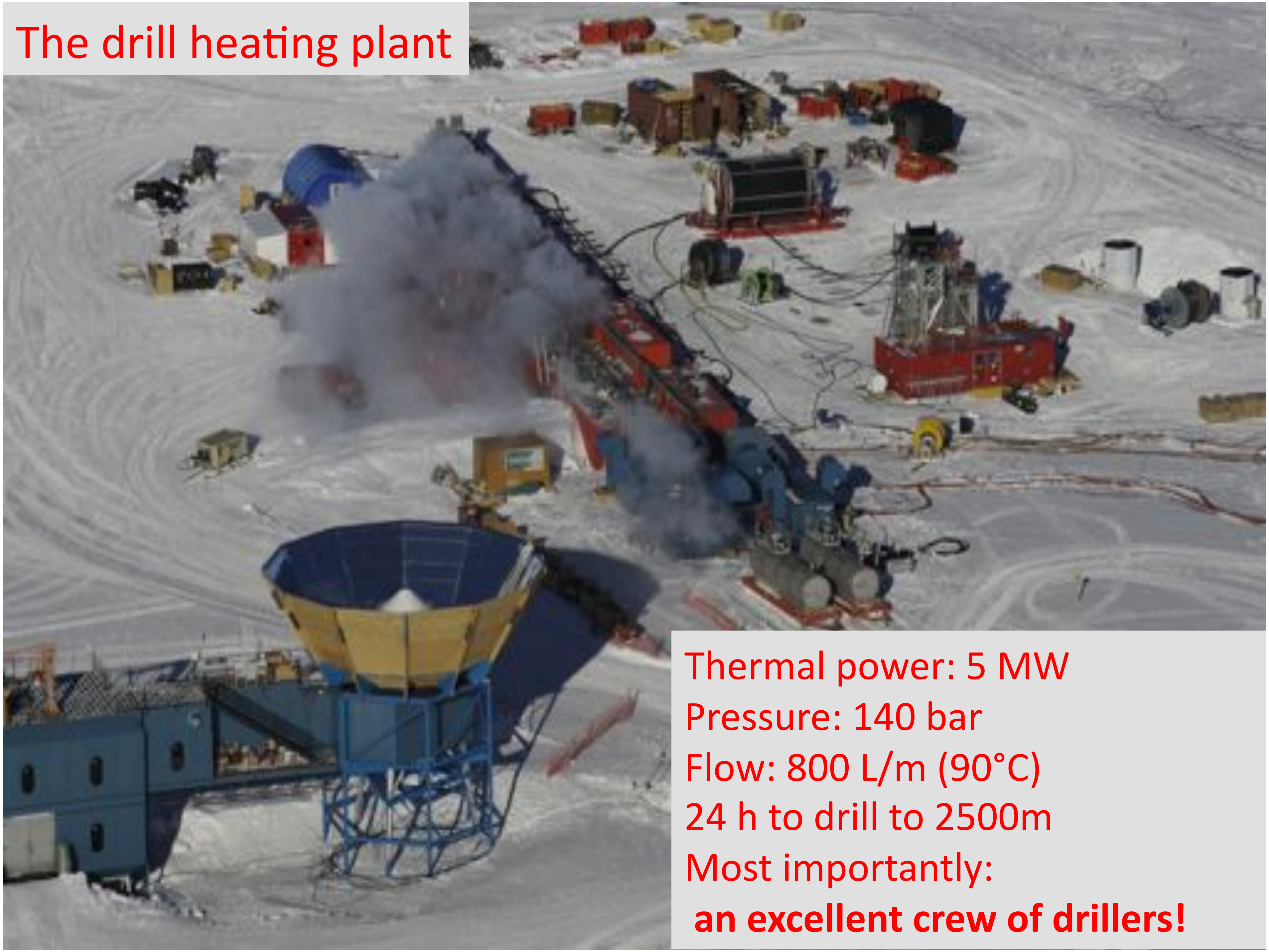
900 tons of Cargo and fuel

300 “Hercules” LC 130 missions (skiers)

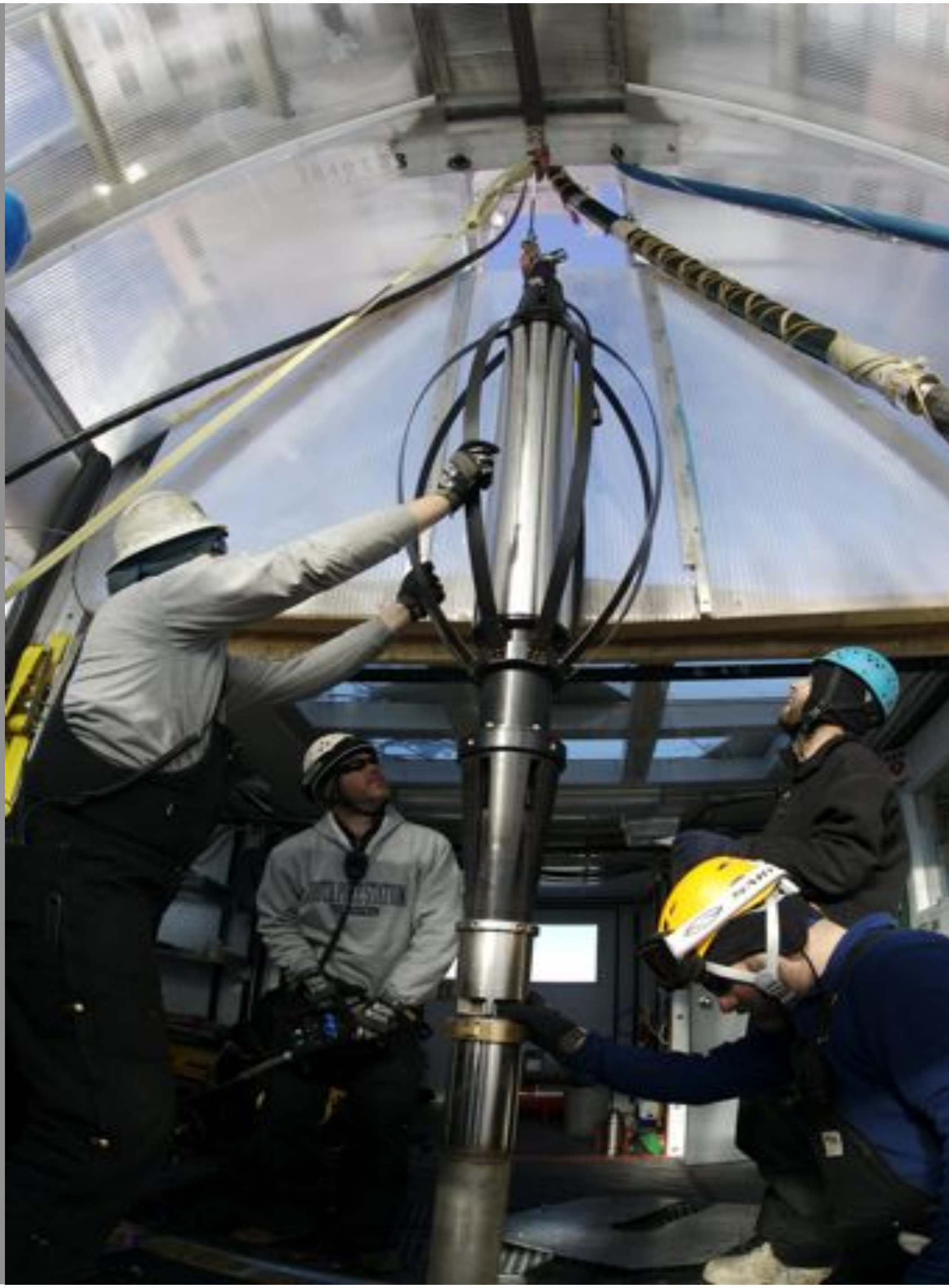
# Hot Water drilling



# The drill heating plant



Thermal power: 5 MW
Pressure: 140 bar
Flow: 800 L/m (90°C)
24 h to drill to 2500m
Most importantly:
**an excellent crew of drillers!**

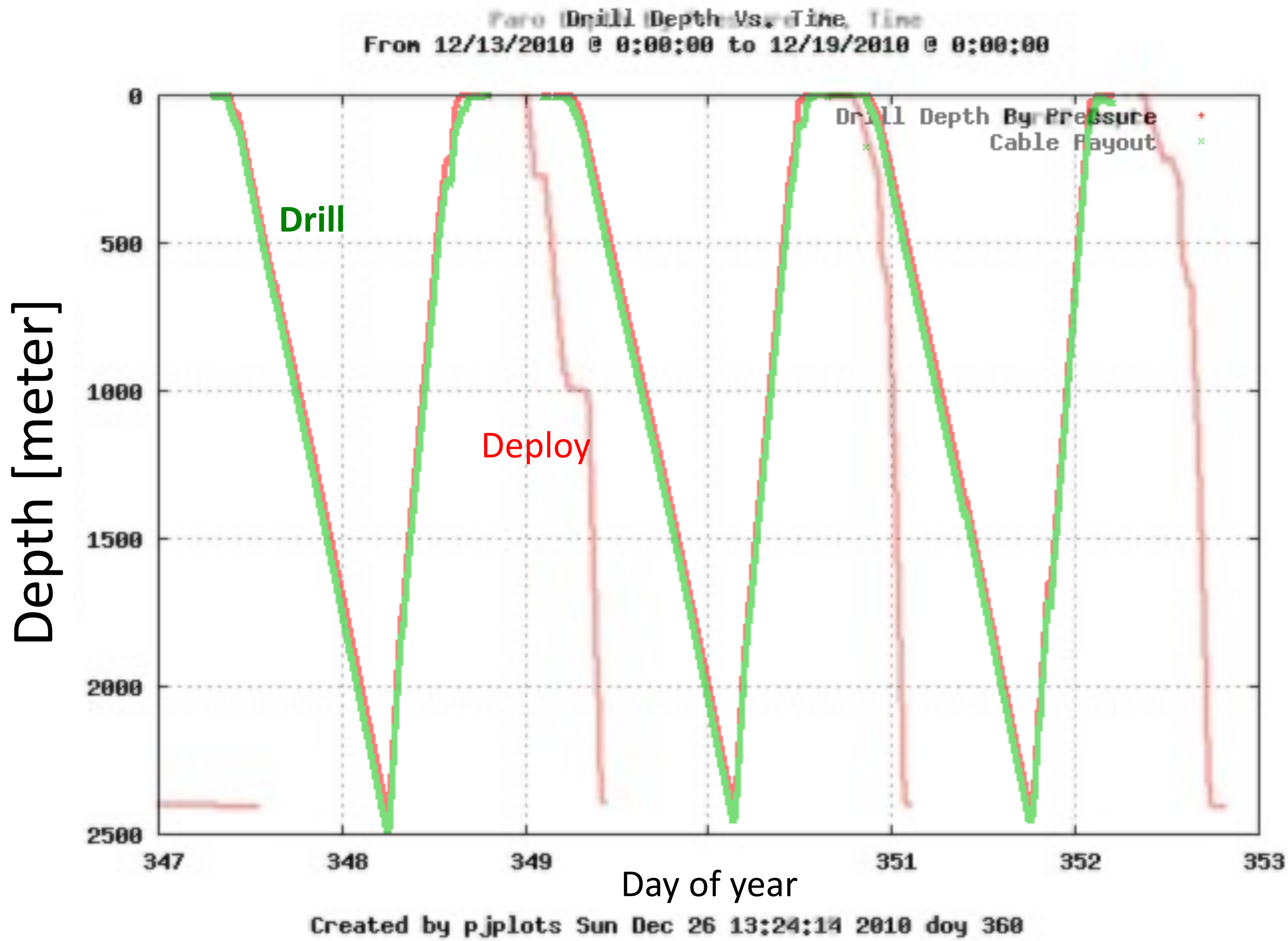


Drillers pull out the drillhead.

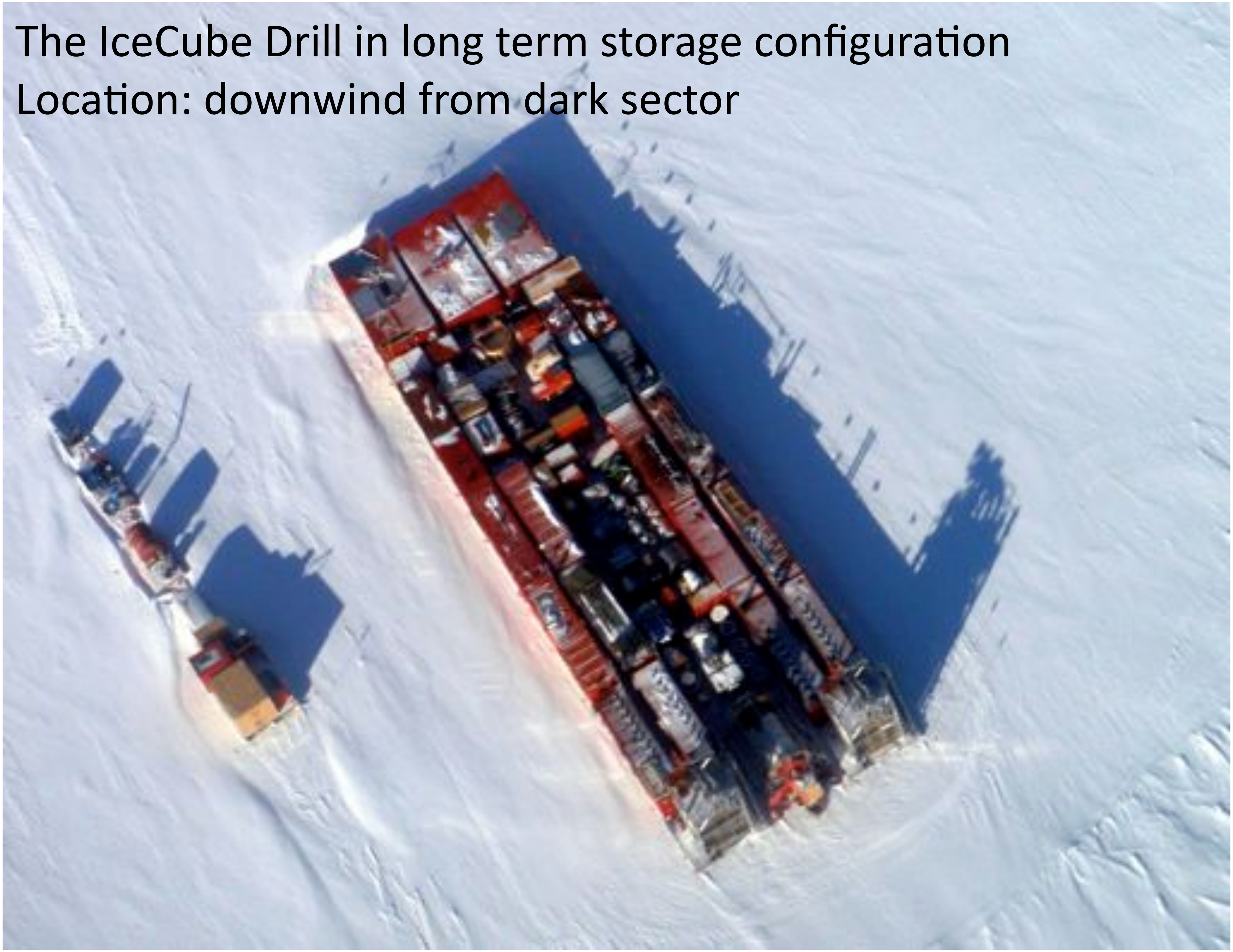
Safety:

A big challenge!
After 7 years, and initial difficulties,
only 3 incidents with loss of time
in >100 person years of work time.
Buy-in in safety culture,
retention of people important.

# Drilling and deployment Dec. 13-18, 2010

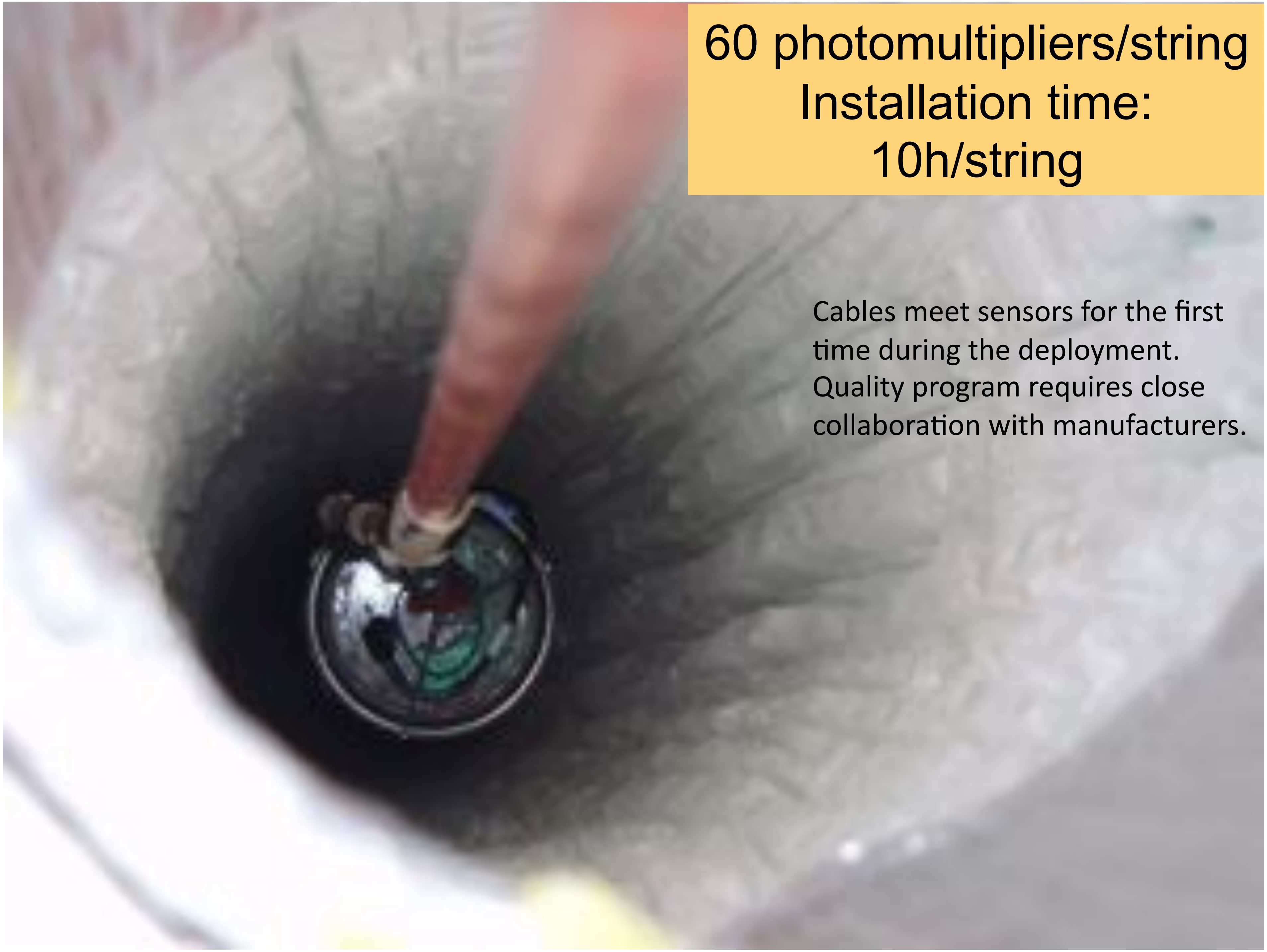


The IceCube Drill in long term storage configuration
Location: downwind from dark sector



# Comment on possible future drill mobilization

- Most drill equipment is at South Pole
- Exceptions:
  - drill hose (McMurdo, warmer),
  - drill heads, motor drives, computers (Wisconsin)
  - one generator (ConUS for refurbishment)
- Mobilization:
  - takes 4 weeks longer than usual IceCube season (start drilling second half of December)
- Drill is complex system, removing pieces will likely result in substantial redesign, rebuild efforts.



60 photomultipliers/string
Installation time:
10h/string

Cables meet sensors for the first time during the deployment. Quality program requires close collaboration with manufacturers.

# Dec 18, 2010 Last DOM deployed.

# The IceCube Collaboration


**33 institutions, ~250 members**

**http://icecube.wisc.edu**

# AMANDA and IceCube deployments

| Season | Campaign | Strings deployed | Cumul. Strings | Cum Sensors | Depth | | Nu's/yr | resol. [°] |
|---|---|---|---|---|---|---|---|---|
| 1991/92 | exploratory activity | | | few small PM | shallow depth | | 0 | |
| 1992/93 | | | | | | | | |
| 1993/94 | AMANDA-A | 4 | 4 | 80 | 800-1000m | | 0 | |
| 1994/95 | | | | | | | | |
| 1995/96 | AMANDA-B4 | 4 | 4 | 86 | 1500-1950 | one stuck & retrieved | 2 (unpubl.) | |
| 1996/97 | AMANDA-B10 | 6 | 10 | 206 | 1500-1950 | | 100 | 4 |
| 1997/98 | | | | | | | | |
| 1998/99 | AMANDA-II | 3 | 13 | 306 | 1500-1950 | | | |
| 1999/2000 | AMANDA-II | 6 | 19 | 677 | 1500-1950 | one stuck at 1550m | 1000 | 2 |
| 2000/2001 | | | | | | | | |
| 2001/2002 | | | | | | | | |
| 2002/2003 | | | | | | | | |
| 2003/2004 | IceCube | | | staging | | | | |
| 2004/2005 | IceCube | 1 | 1 | 60 | 1450-2450m | | | |
| 2005/2006 | IceCube 9 | 8 | 9 | | 1450-2450m | | | |
| 2006/2007 | IceCube 22 | 13 | 22 | | 1450-2450m | | | |
| 2007/2008 | IceCube 40 | 18 | 40 | 2400 | 1450-2450m | | 14000 | 0.7 |
| 2008/2009 | IceCube 59 | 19 | 59 | | 1450-2450m | | 43000 | |
| 2009/2010 | IceCube 79 | 20 | 79 | | 1450-2450m | | | |
| 2010/2011 | IceCube 86 | 7 | 86 | 5160 | 1450-2450m | | 100k? | 0.5 |

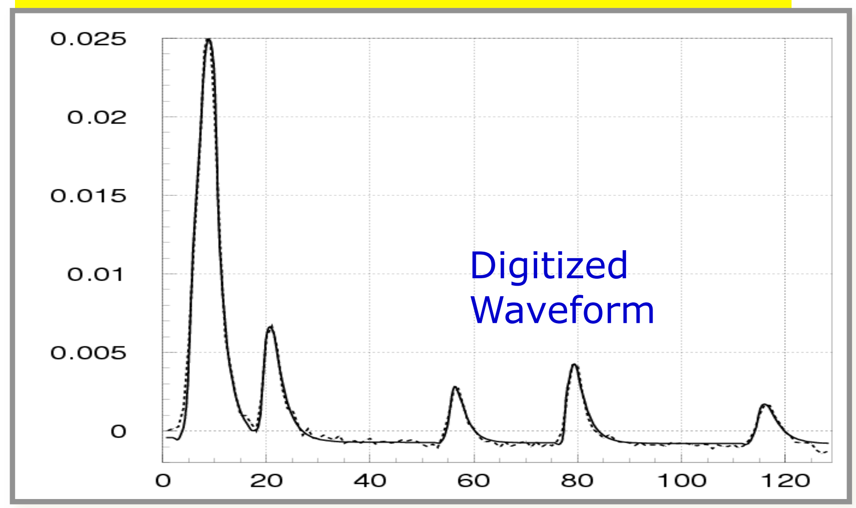
IceTop tanks not inlcuded in table

# Digital Optical Module (DOM)

PMT: 10 inch Hamamatsu
Power consumption: 3 W
Digitize at 300 MHz for 400 ns with custom chip
40 MHz for 6.4 μs with fast ADC
Dynamic  range 500pe/15 nsec

Flasherboard with 12 LEDs
Local HV

*Clock stability: $10^{-10} \approx 0.1$ nsec / sec*
*Synchronized to GPS time every ≈10 sec*
*Time calibration resolution = 2 nsec*



# PMT response -
# Optical characteristics of DOM

- Detailed measurements in lab and analysis of test data.
- **Calibration and Characterization of the IceCube Photomultiplier Tube.**
  ***R. Abbasi** et al.**, Feb 2010. 40pp.***
  ***e-Print: arXiv:1002.2442 [astro-ph.IM]***

Example:

PMT response to high amplitude pulses

a) Main pulse
b) Secondary peak due to unusual electron trajectories
c) Pre-pulse (from first dynaode, are below spe threshold. Gain ratio accordiing to first dynode gain)

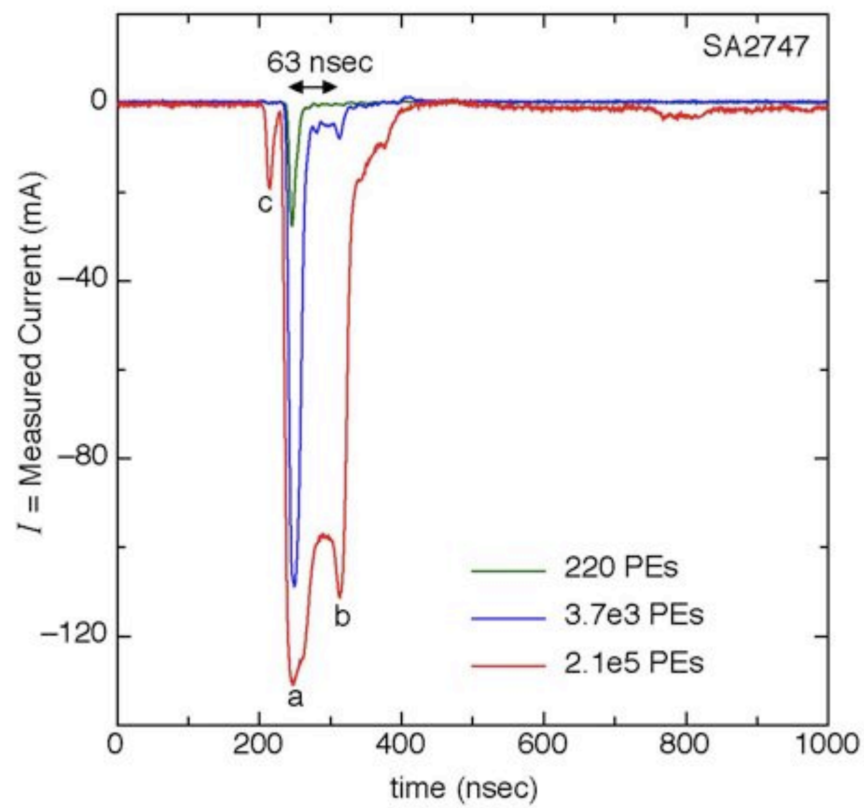
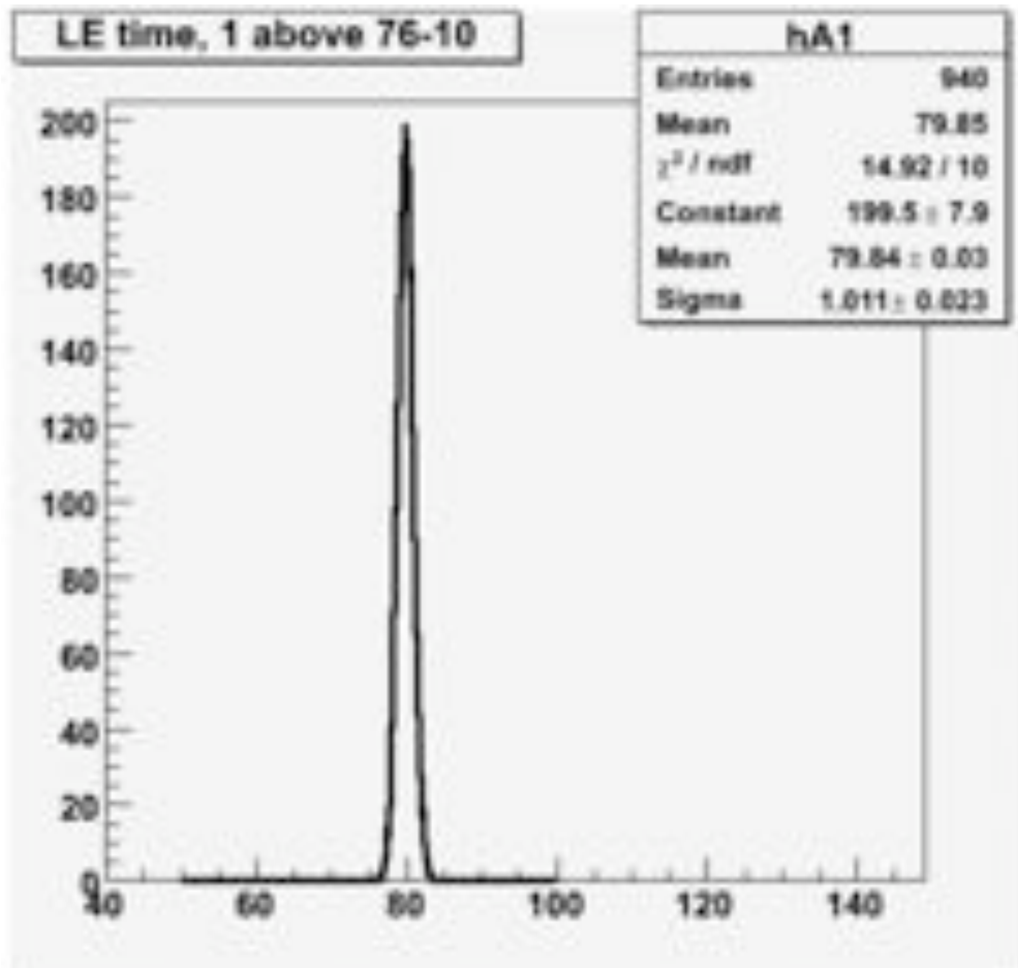



Fig. 16. Response of PMT to 3 ns (FWHM) light pulses with progressively higher-intensity: (a) main peak; (b) secondary peak due to unusual electron trajectories; (c) pre-pulse.

# Time resolution:
# ~1ns for bright pulses

- Time difference between neighboring DOMs fired with (bright) flasher pulses: 1 ns.

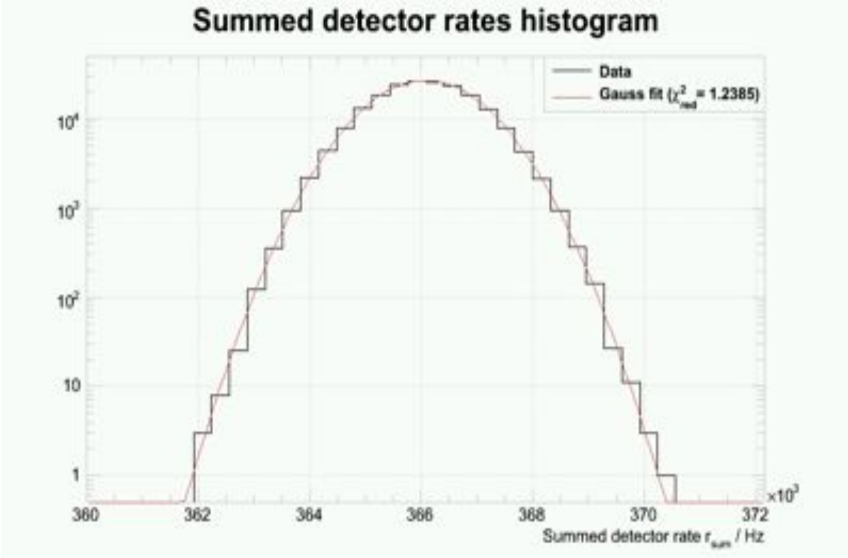
- For SPE pulses add jitter (3 nsec)

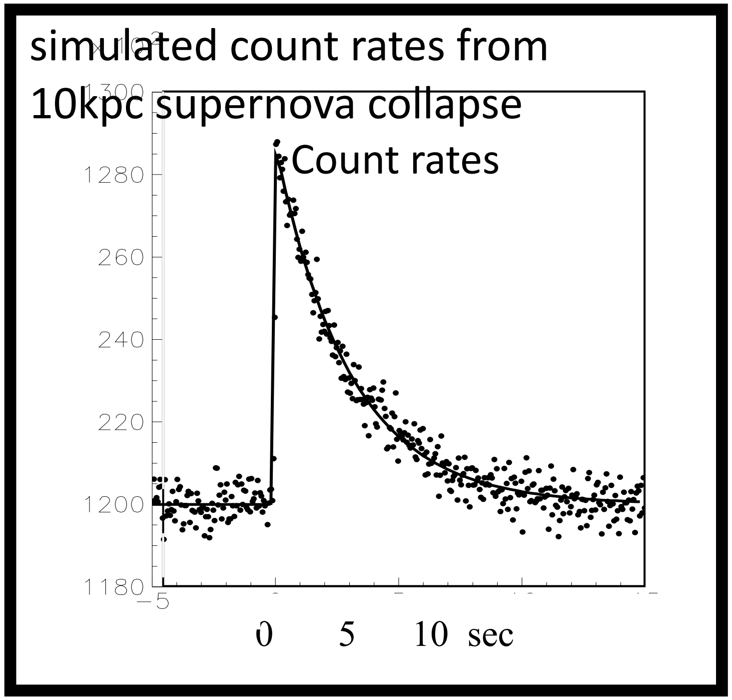


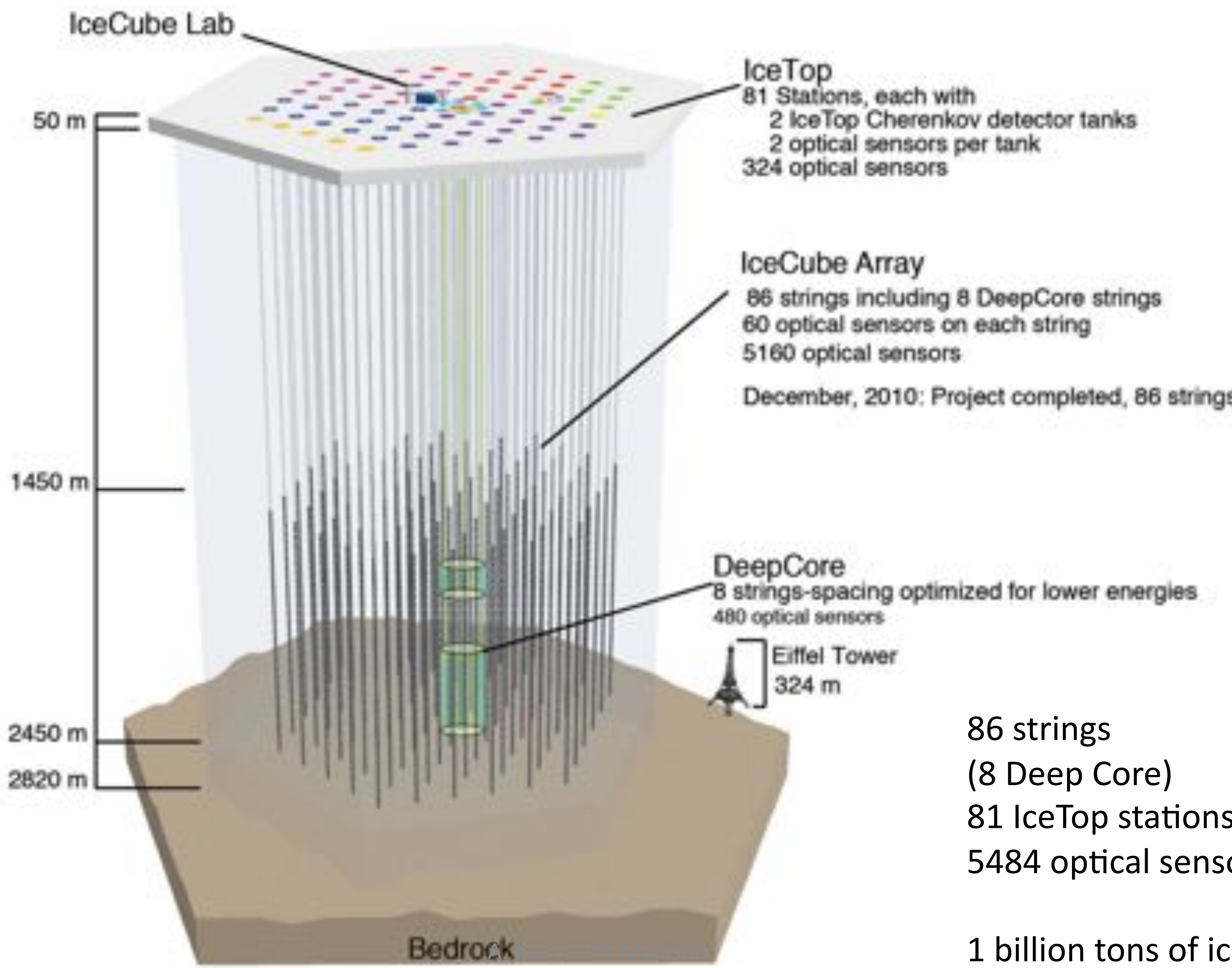
# Noise behavior

- Very low noise rate due use of low radioactivity glass and good PMT characteristics.
- Average rate / sensor (w deadtime):
  284.9 +/- 26.2 Hz
- sensor noise: stable and as expected.

**→ msec resolution of neutrino emission profile of galactic supernova core collapse**



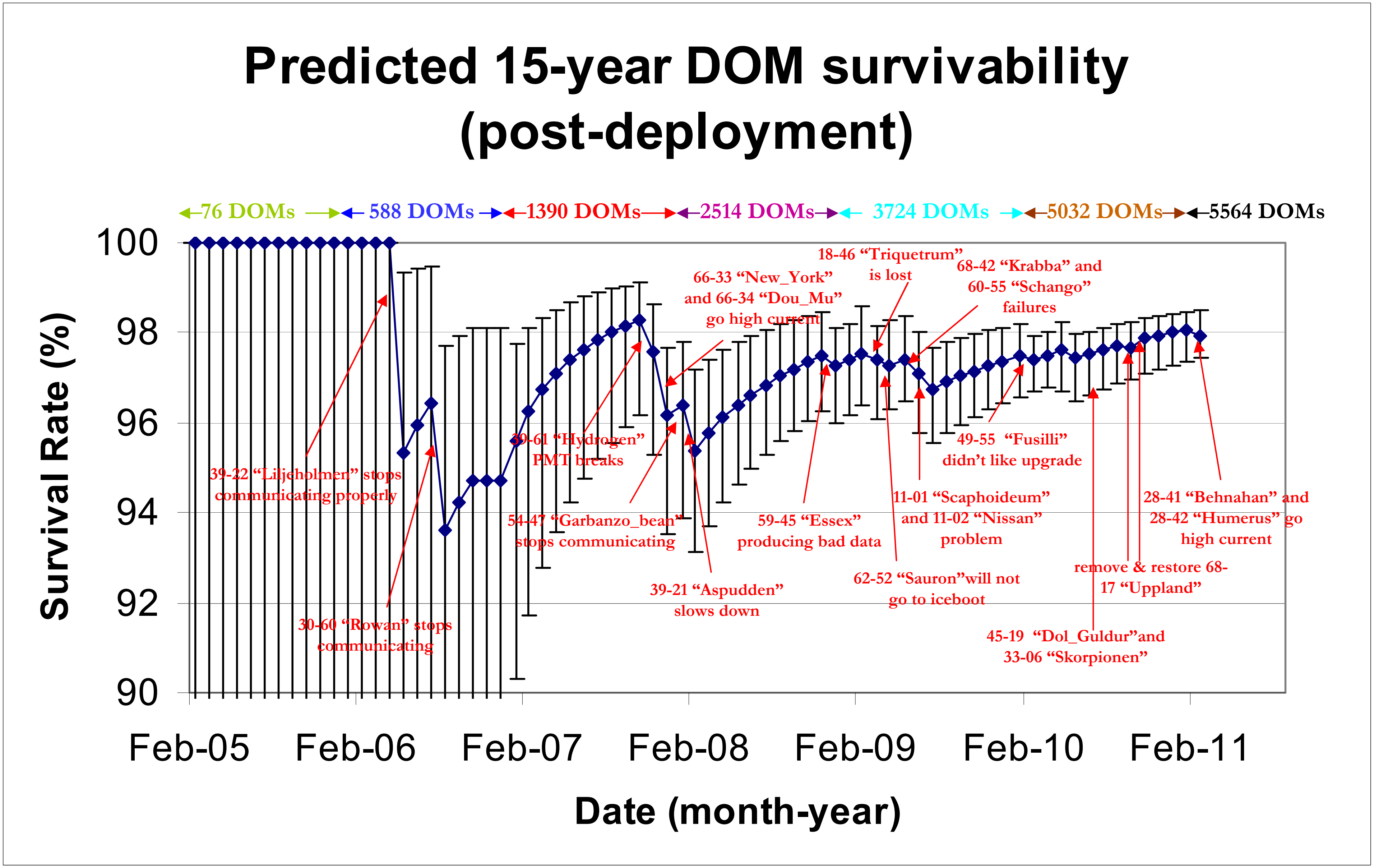



86 strings
(8 Deep Core)
81 IceTop stations
5484 optical sensors

1 billion tons of ice

# Reliability of sensors
# - survival rates before and after commissioning

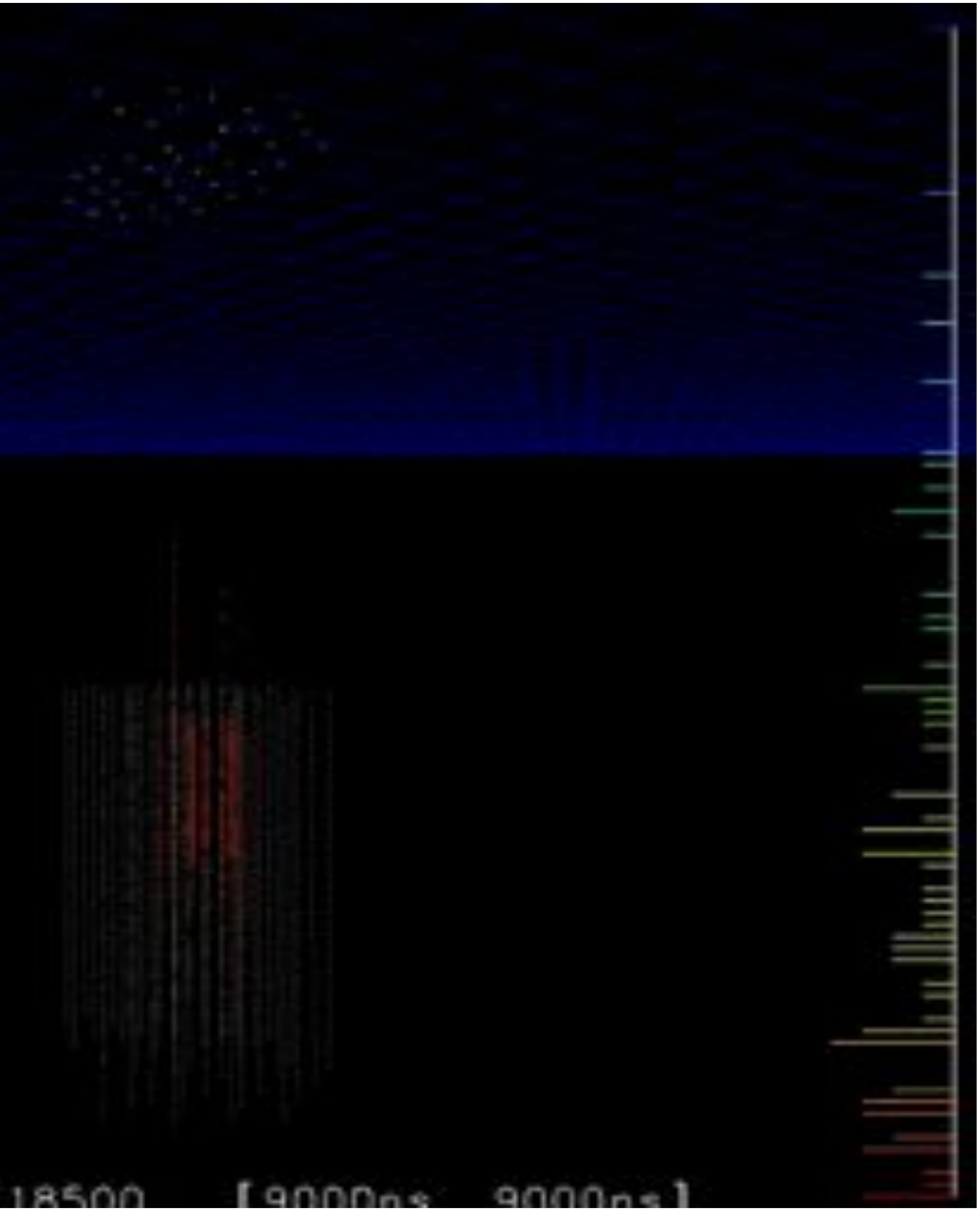
- Some numbers regarding reliability:
- Accumulated lifetime as of April 1, 2011: 13,400 DOM years
- Lost DOMs during deployment and freeze-in (fail commissioning): 127
- Lost DOMs after successful freeze-in and commissioning: 18
  - Assuming constant failure rate: The IceCube sensors would live for about 740 years (MTBF).



Predicted 15-year DOM survivability (post-deployment)
76 DOMs
588 DOMs
1390 DOMs
2514 DOMs
3724 DOMs
5032 DOMs
5564 DOMs
Survival Rate (%)
100
98
96
94
92
90
Feb-05
Feb-06
Feb-07
Feb-08
Feb-09
Feb-10
Feb-11
Date (month-year)
39-22 "Liljeholmen" stops communicating properly
30-60 "Rowan" stops communicating
39-61 "Hydrogen" PMT breaks
54-47 "Garbanzo_bean" stops communicating
66-33 "New_York" and 66-34 "Dou_Mu" go high current
39-21 "Aspudden" slows down
59-45 "Essex" producing bad data
18-46 "Triquetrum" is lost
62-52 "Sauron" will not go to iceboot
68-42 "Krabba" and 60-55 "Schango" failures
11-01 "Scaphoideum" and 11-02 "Nissan" problem
49-55 "Fusilli" didn't like upgrade
45-19 "Dol_Guldur" and 33-06 "Skorpionen"
remove & restore 68-17 "Uppland"
28-41 "Behnahan" and 28-42 "Humerus" go high current

Operational support:
ICL maintenance
~60 kW power to electronics
90 GB/day
2 winterovers
summer population (around 5-7 pop Dec - Jan)

**Air shower of ~3E17 eV**
**Observed by IceTop,**
**Then by Deep detector strings**




2000μ >400GeV

Ice

cosmic ray physics

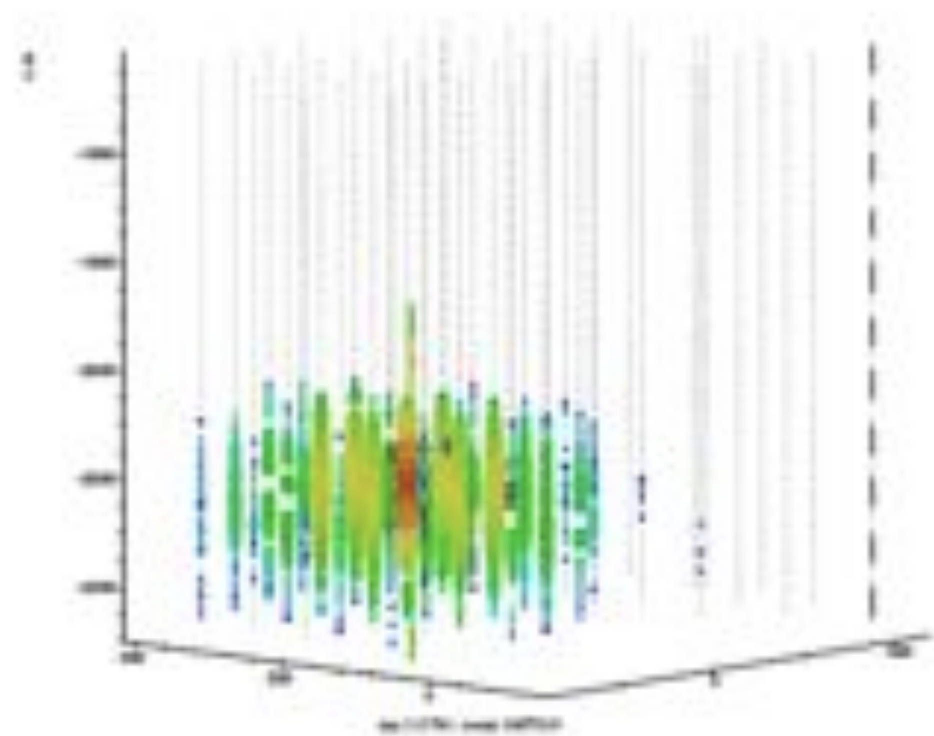
- mass independent
- energy resolution,
- composition

veto

calibration

# Flasher events used for calibration

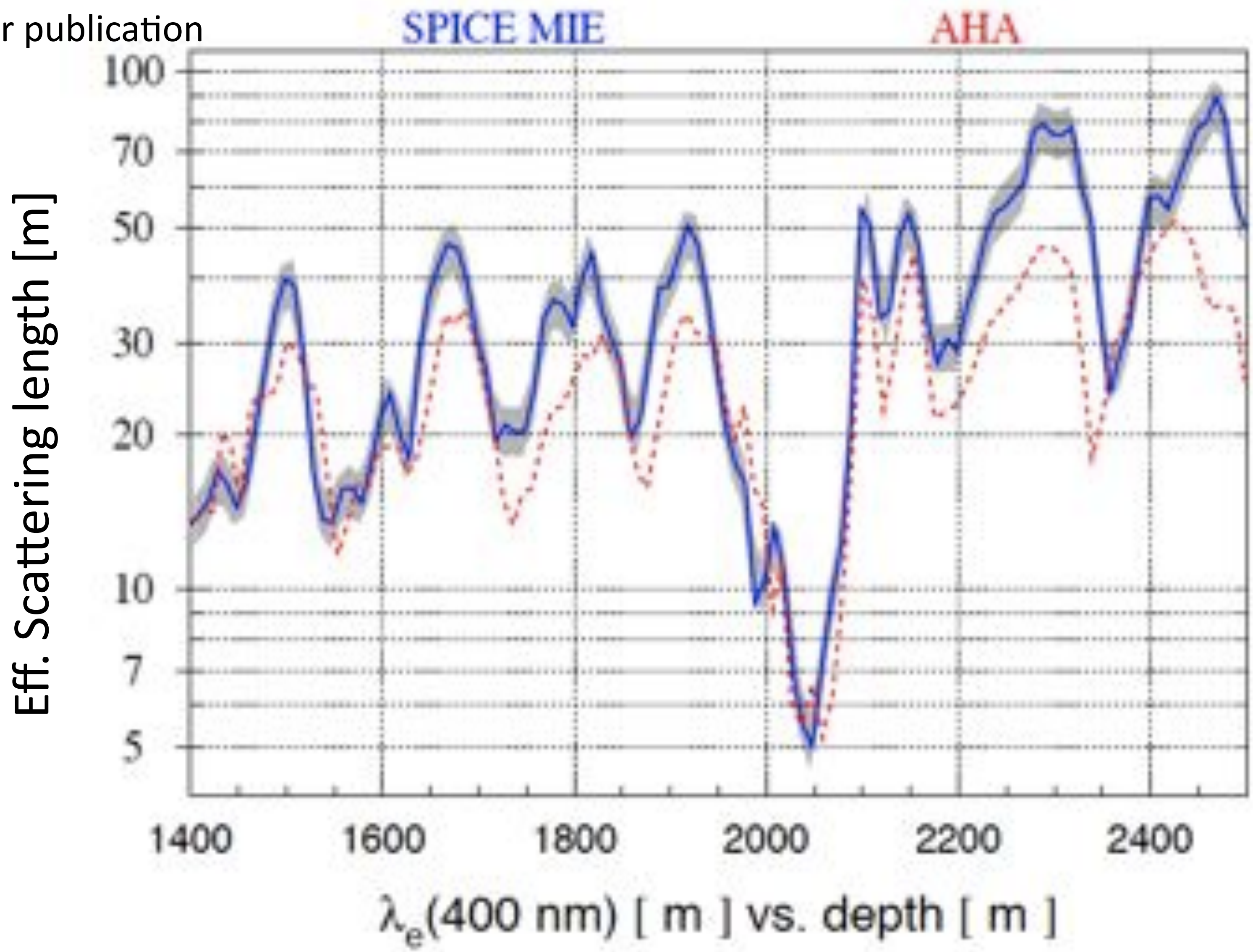
All sensors are equipped
with a set of 12 LED flashers.
A 30 ns pulse of only
10 billion photons (400nm)
is visible to a distance of 600m.



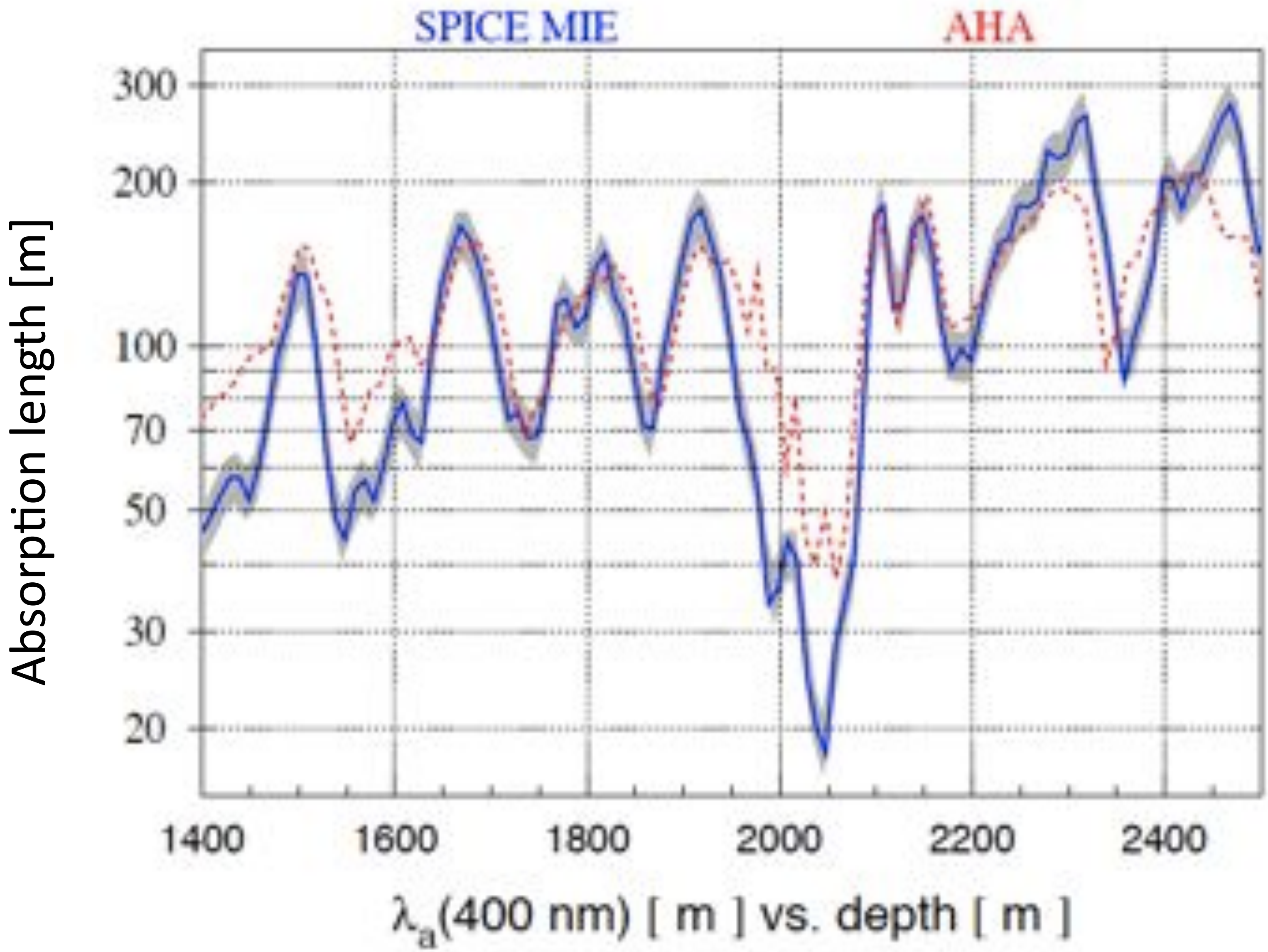
These measurements are used
to calibrate the detector
- time
- geometry
- optical properties of the ice

# The Ice is very clear
# Effective scattering length vs Depth

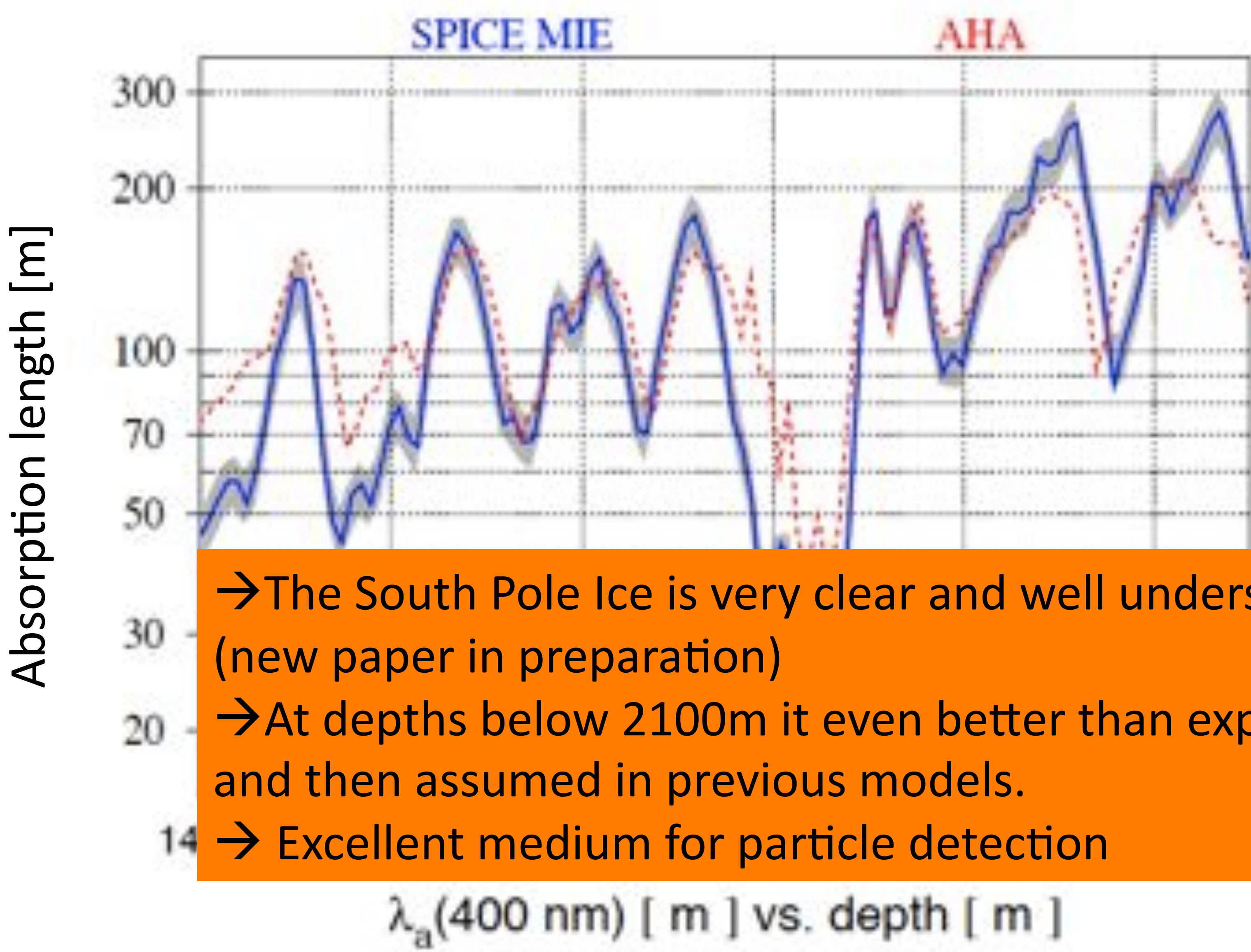
in internal review
for publication



# Absorption length vs Depth



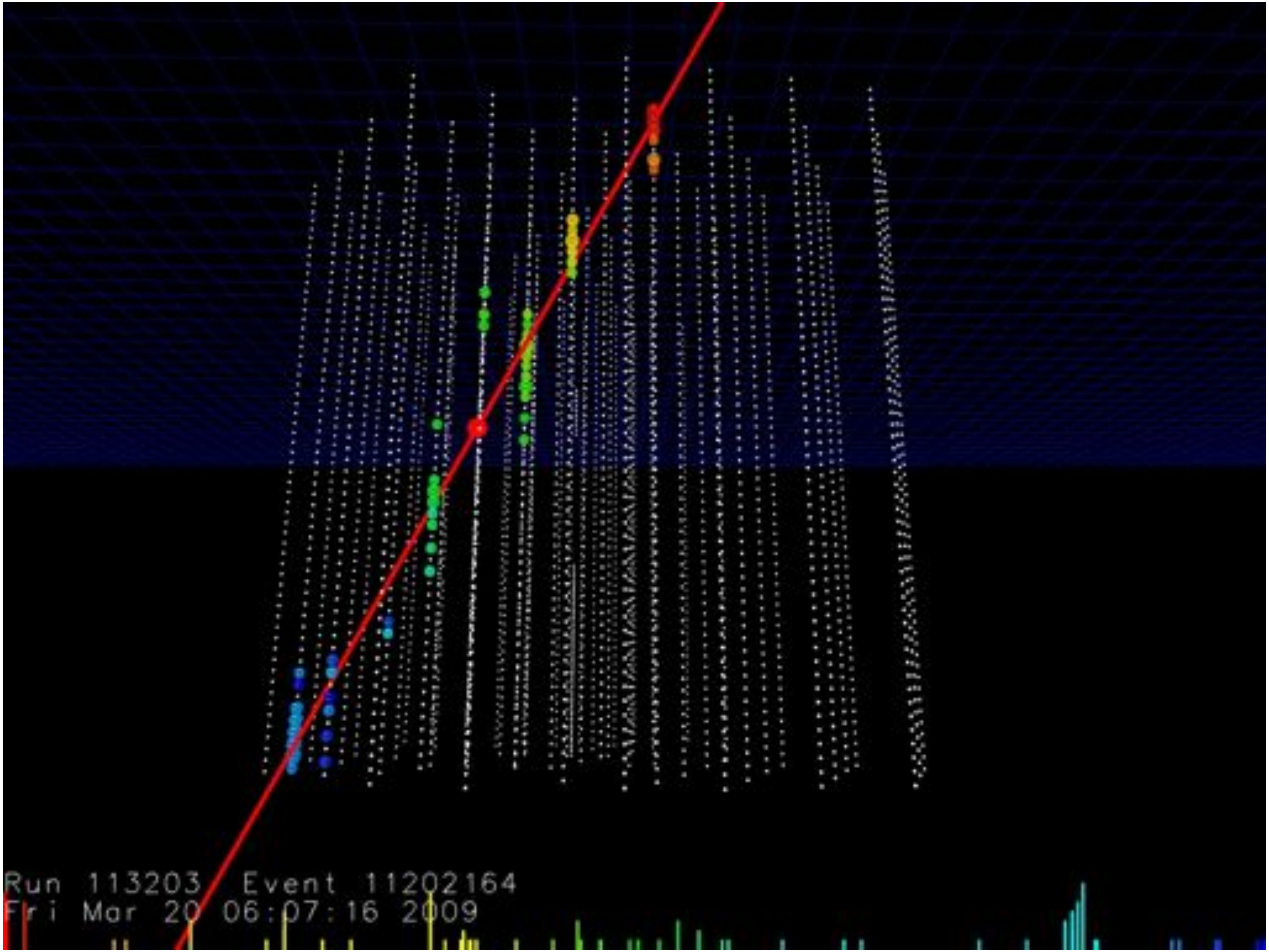
# Absorption length vs Depth



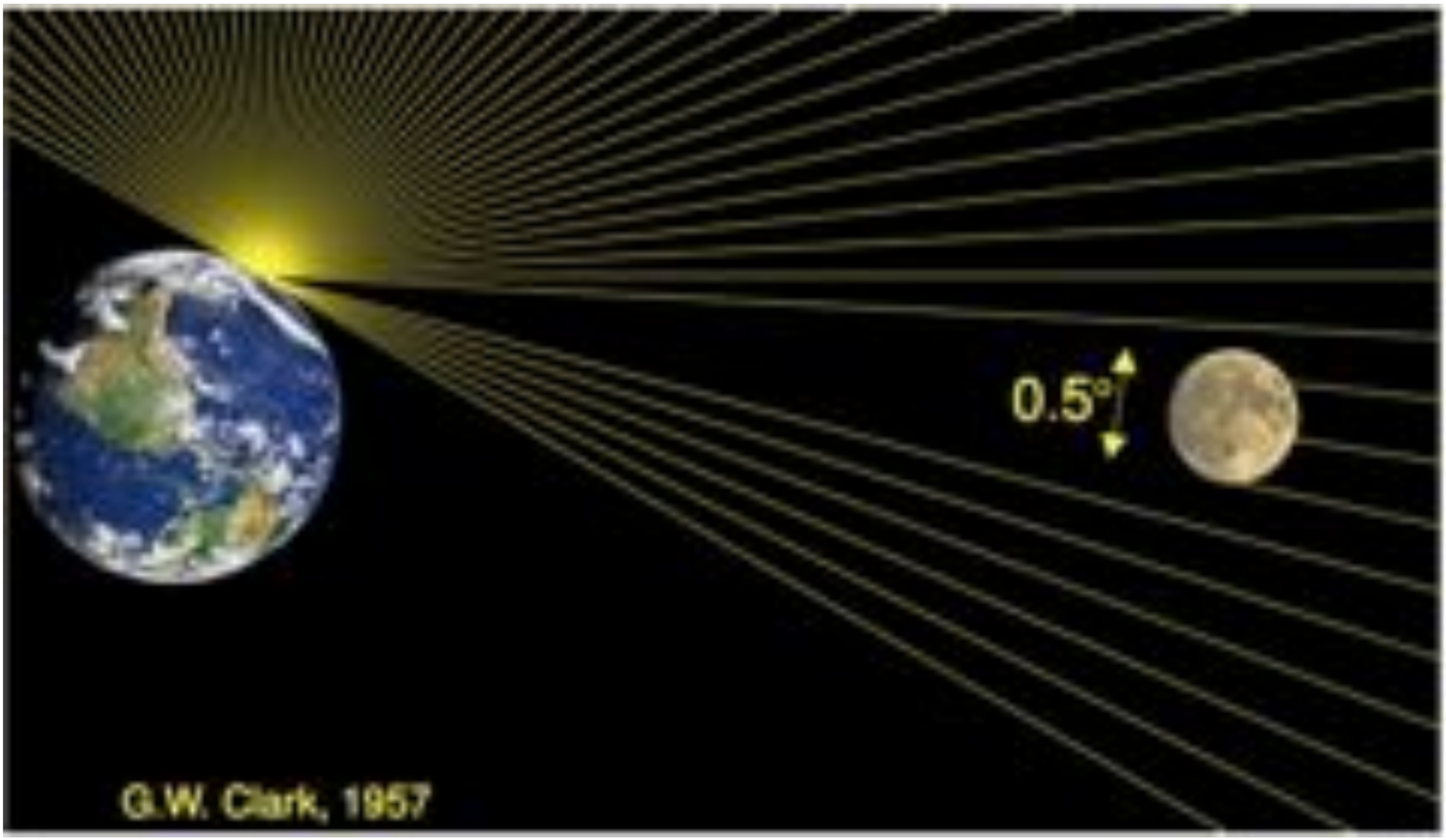

→The South Pole Ice is very clear and well understood. (new paper in preparation)

→At depths below 2100m it even better than expected and then assumed in previous models.

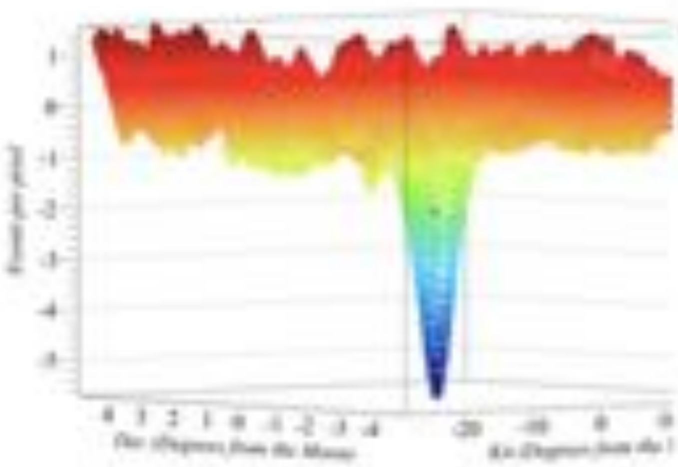
→ Excellent medium for particle detection

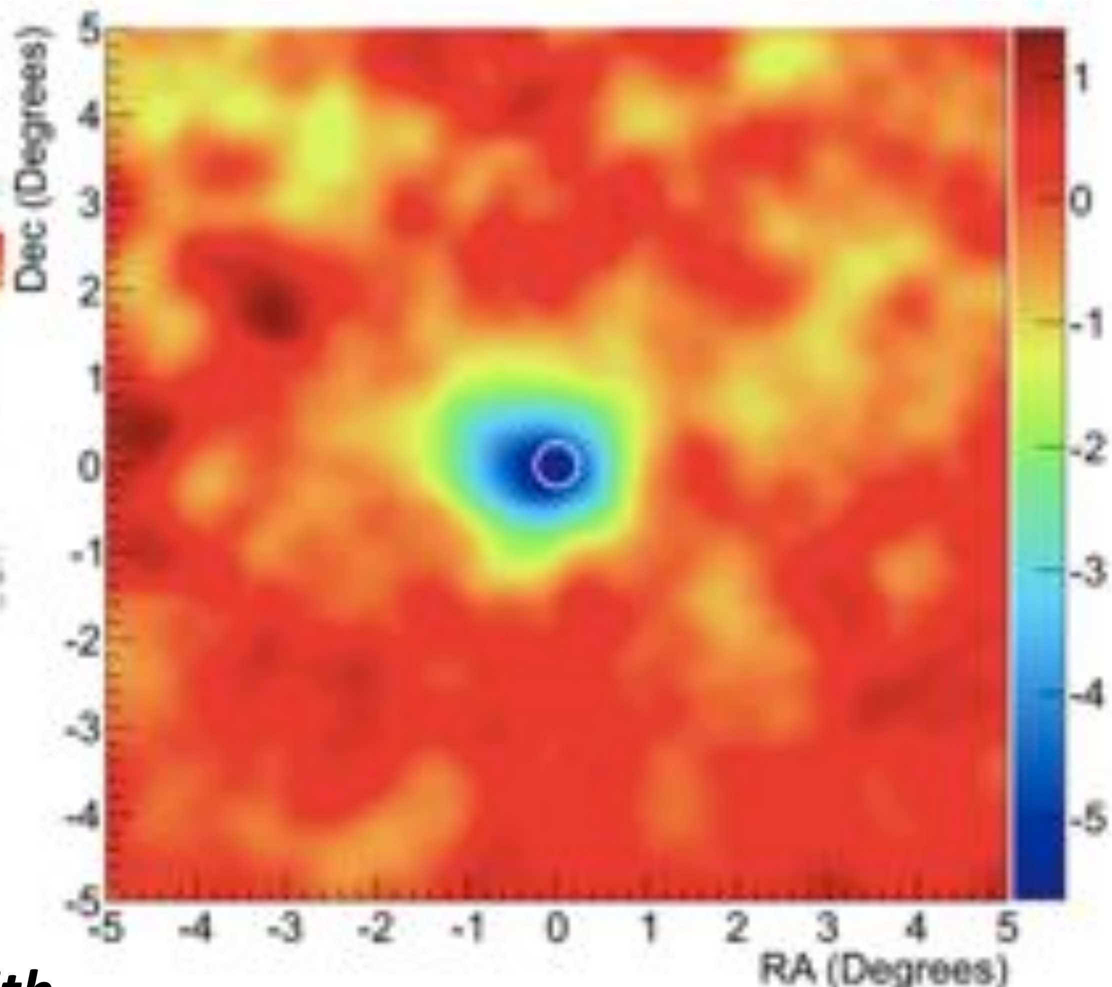

Run 113203 Event 11202164
Fri Mar 20 06:07:16 2009

# Cosmic rays get stuck in the Moon – Does IceCube see the moon (shadow)?



# Moon shadow observed in muons – IceCube points in the right direction!






Center of moon is spot on
to a precision of <0.1 degrees.

***Statistical significance with IC 59: > 10 sigma***

# Detector operation, rates

- Detector performance parameters increase faster than the number of strings
  - Longer muon tracks (km scale)
  - Improved analysis techniques

| Strings | Year | Livetime | μ rate (Hz) | ν rate (/ day) | angular resol./° |
|---|---|---|---|---|---|
| AMANDAII (19) | 2000-2006 | 3.8 years | 100 | 5 / day | 2.4 |
| IC22 | 2007 | 275 days | 550 | 18 / day | 1.4 |
| IC40 | 2008 | 375 days | 1100 | 38 / day | 0.75 |
| IC59 | 2009 | 360 days | 1900 | 129 / day | |
| IC86test | 2011 | 1 day | 2650 | | 0.5 |

# Detector operation, rates

- Detector performance parameters increase faster than the number of strings
  - Longer muon tracks (km scale)
  - Improved analysis techniques

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strings
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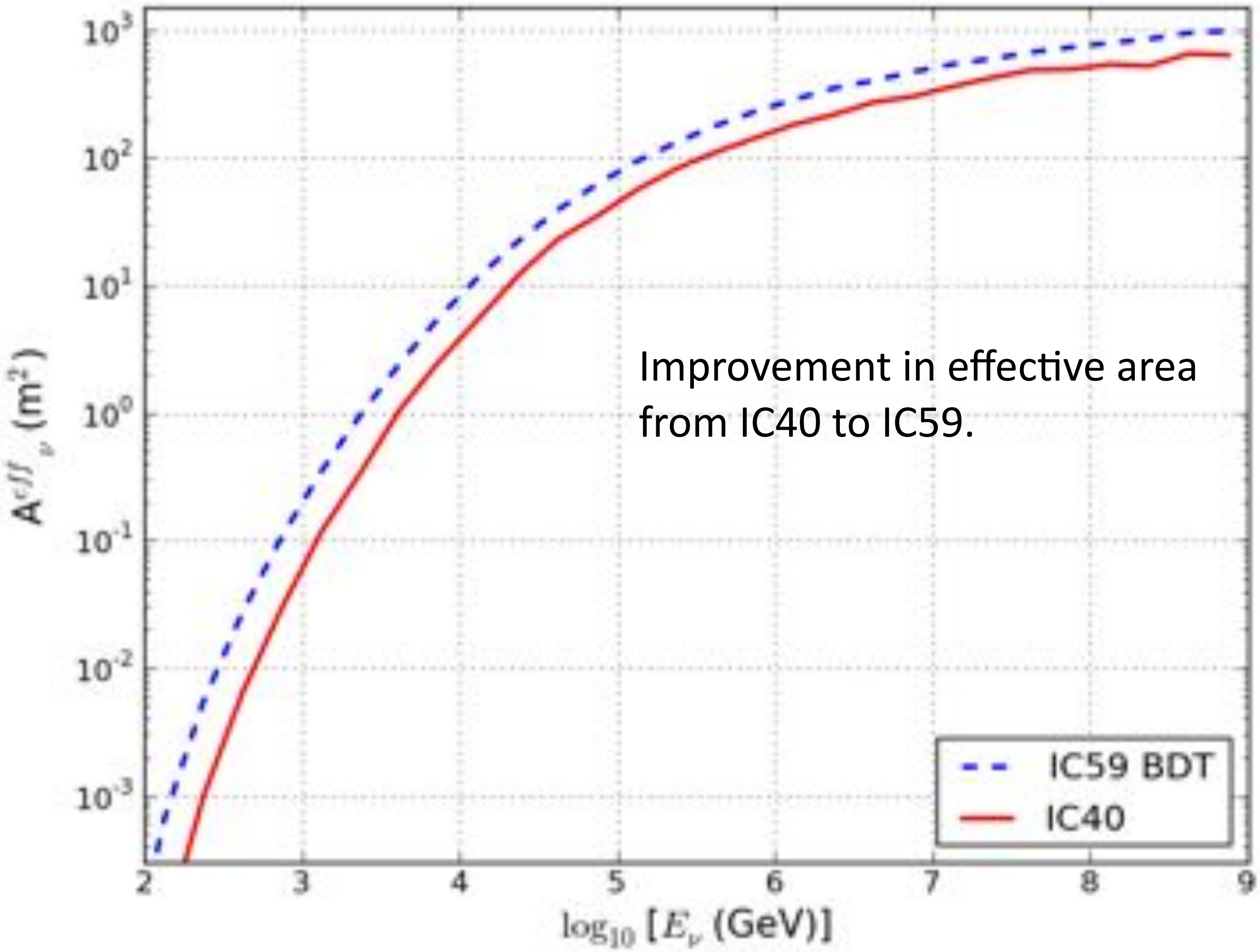
| Strings |
| --- |
| AMANDAII (19) |
| IC22 |
| IC40 |
| IC59 |
| IC86test |




Improvement in effective area from IC40 to IC59.

# Detector operation, rates

- Detector performance parameters increase faster than the number of strings
  - Longer muon tracks (km scale)
  - Improved analysis techniques (expect still significant improvement in the future still)

| Strings | Year | Livetime | μ rate (Hz) | ν rate (/ day) | angular resol./° |
|---|---|---|---|---|---|
| AMANDAII (19) | 2000-2006 | 3.8 years | 100 | 5 / day | 2.4 |
| IceCube 22 | 2007 | 275 days | 550 | 18 / day | 1.4 |
| IceCube 40 | 2008 | 375 days | 1100 | 38 / day | 0.75 |
| IceCube 59 | 2009 | 360 days | 1900 | 129 / day | |
| IceCube 86 test | 2011 | 1 day | 2650 | | 0.5 (est) |

Angular resolution at high energies has still much potential to improve. Current resolution still far from statistical limit.

# Angular resolution

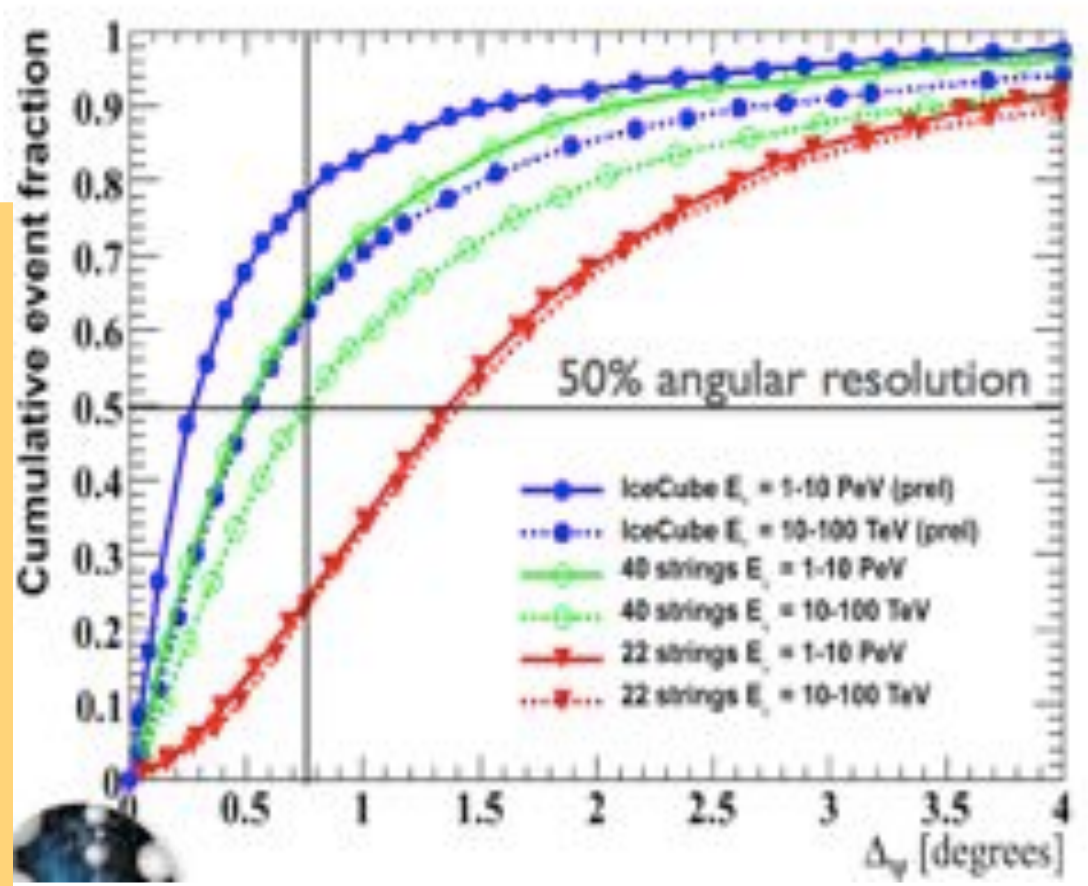
**Median angular resolution**

**10 – 100 TeV (1 – 10 PeV)**

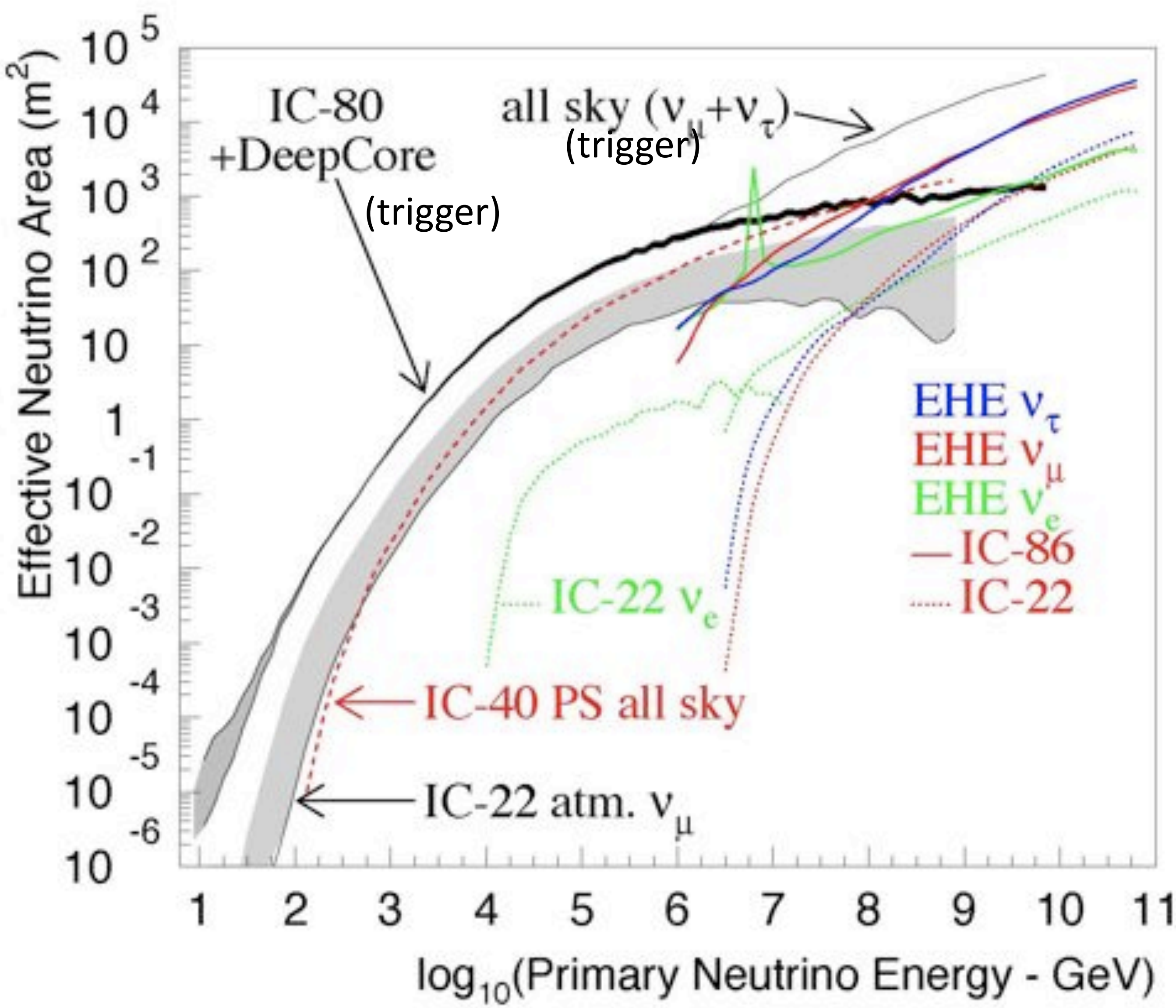
- IC40: 0.76° (0.5°)
- **IceCube: 0.5° (0.3°)**

Design expectation 2005: 0.75°

Improved algorithms: better resolution, and resolution improves with energy. (original performance projection: Astropart.Phys. 20:507-532,2004, **astro-ph/0305196**)



# Neutrino effective areas
# - Why neutrino telescopes can be used over a wide energy range.




Area at 100 TeV (1TeV)
AMANDA-II: 3m$^2$ (0.005)
IceCube 86: 100m$^2$ (0.3)

Deep Core lowers threshold from 100 GeV to 10 GeV.

Effective area for $n_m$

Strong rise with energy:

- $\sigma \propto E_\nu$
- Increase of muon range with energy up to PeV

# Outlook

New projects in consideration or prototype phase will be discussed in other talks in this session:

- DM-ICE: A new direct dark matter detector in the center of IceCube
- ARA, a large radio array (100km^2) for highest energy (GZK) neutrinos
- Deep Core upgrade by 18 strings for dark matter and neutrino physics and supernova detection beyond the galaxy
  - Visions of extremely dense array inside IceCube to solve precision particle physics questions (eg proton decay)
- Also in consideration, a full air shower veto using a surface radio component / basically an extension of IceTop

# Summary

- Major construction of IceCube has been completed in December 2010, on budget and on schedule.
- IceCube drill currently in storage at Pole
- High reliability and operational stability
- Performance characteristics meet or exceed design goals.