

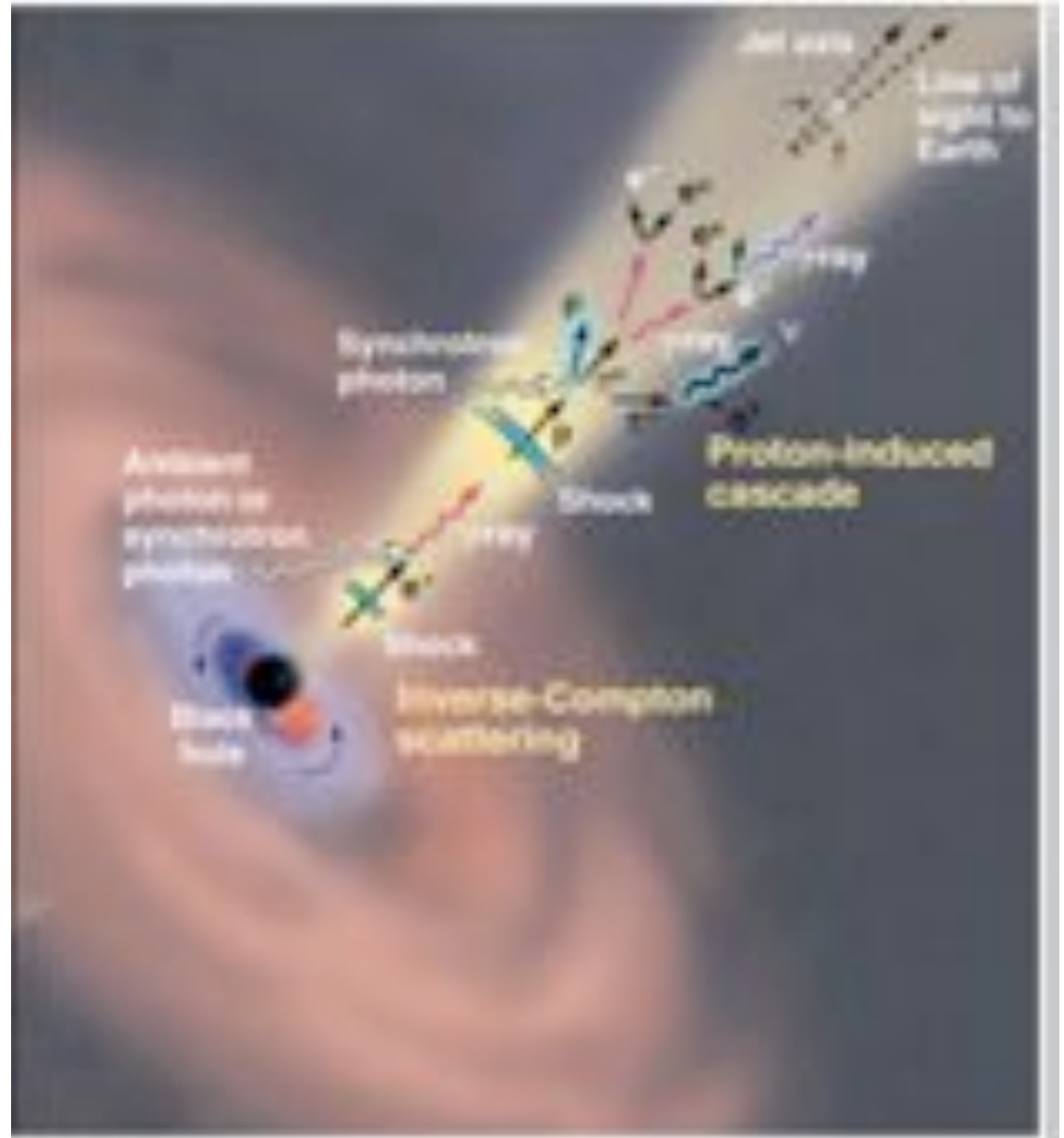
IceCube

- construction, performance and operation

Albrecht Karle
University of Wisconsin-Madison

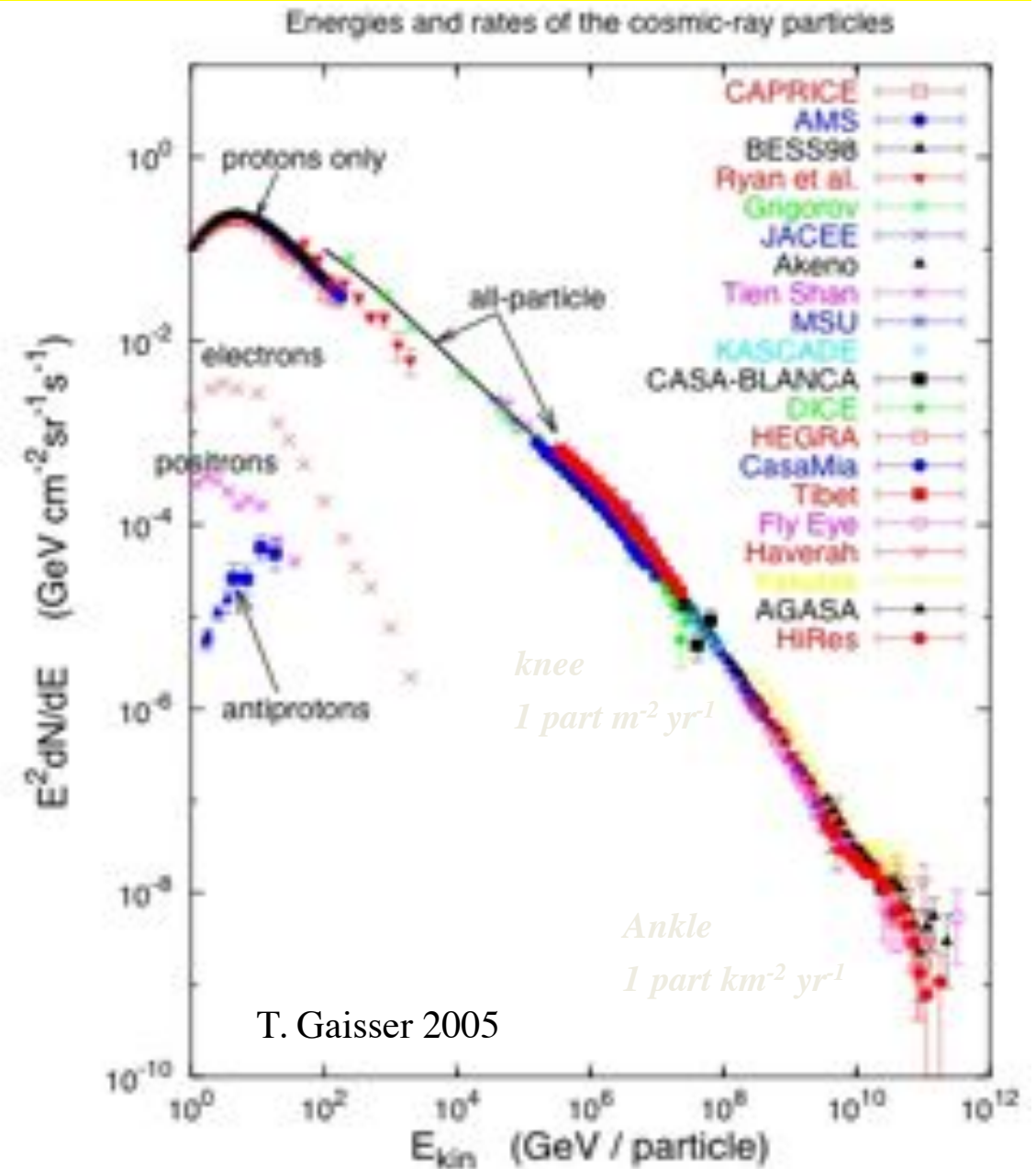
High energy particles in the Universe

- **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

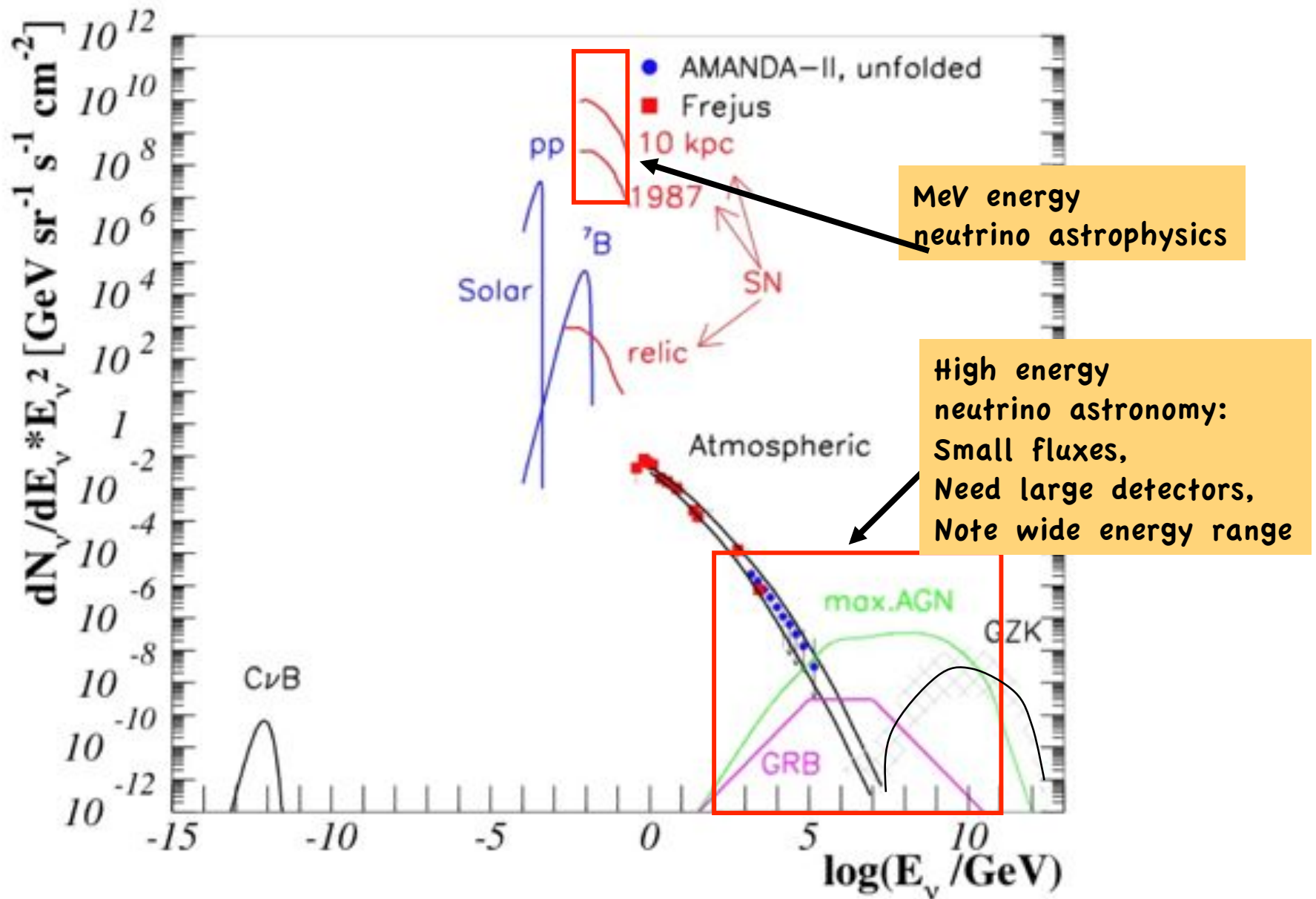


Cosmic Rays and Neutrino Sources

Cosmic rays



Neutrinos

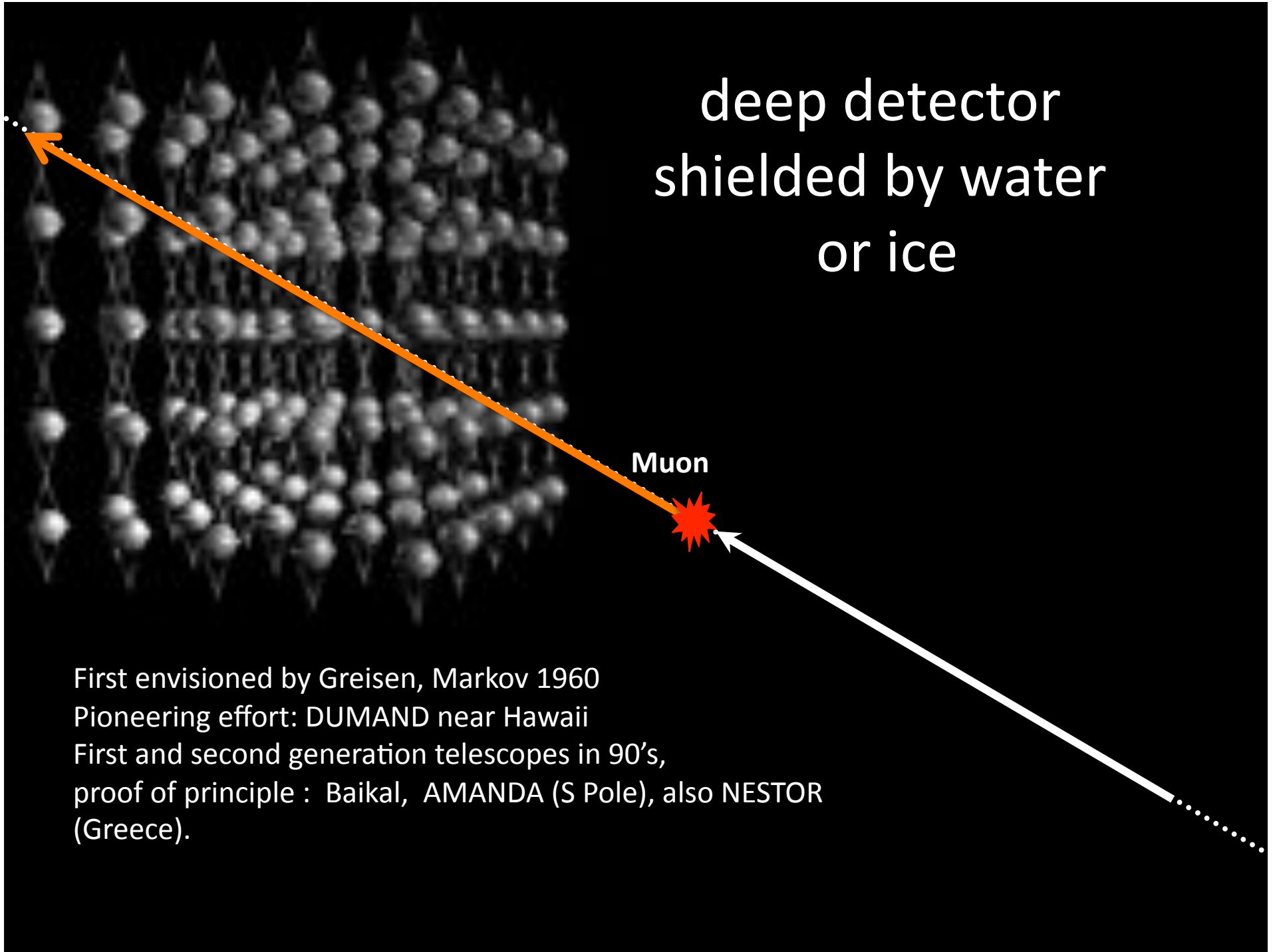


A few remarks on the beginnings of IceCube

deep detector
shielded by water
or ice

Muon

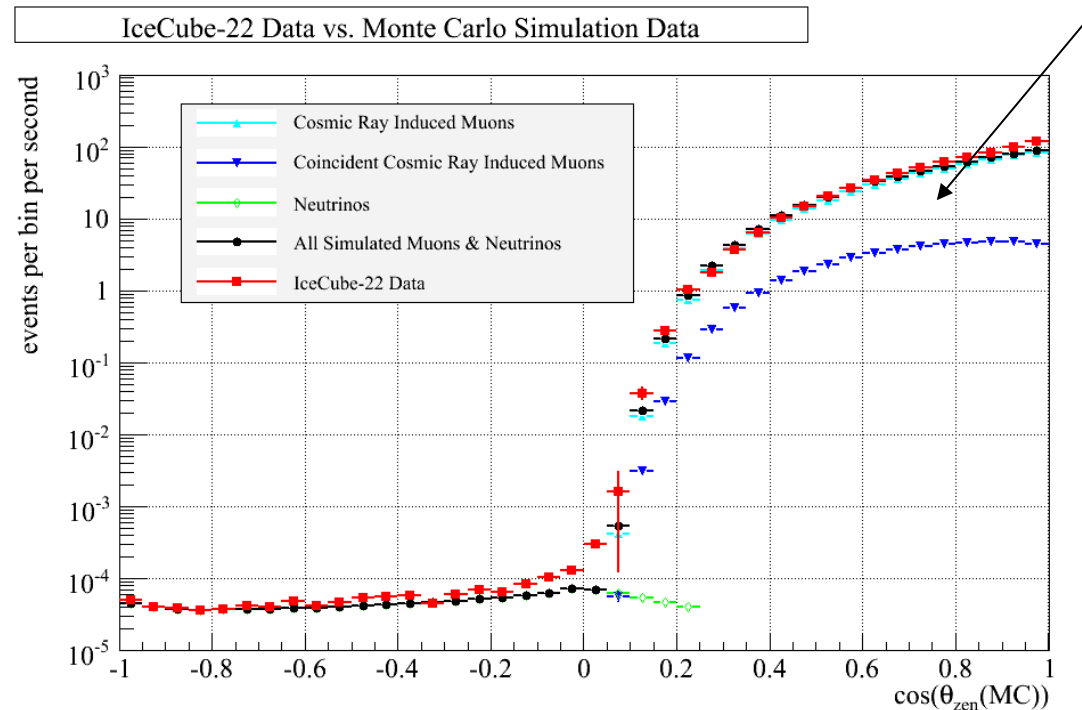
First envisioned by Greisen, Markov 1960
Pioneering effort: DUMAND near Hawaii
First and second generation telescopes in 90's,
proof of principle : Baikal, AMANDA (S Pole), also NESTOR
(Greece).



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

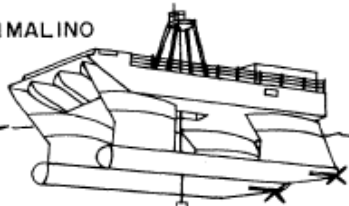
→ Low energies: Use Earth as filter; look for neutrinos from below (GeV to PeV)

→ High energies: Apply energy cut for downgoing atmospheric background (>PeV)

Early Projects in water

DUMAND
(Hawaii)

THE SSP KAIMALINO
FROM BELOW

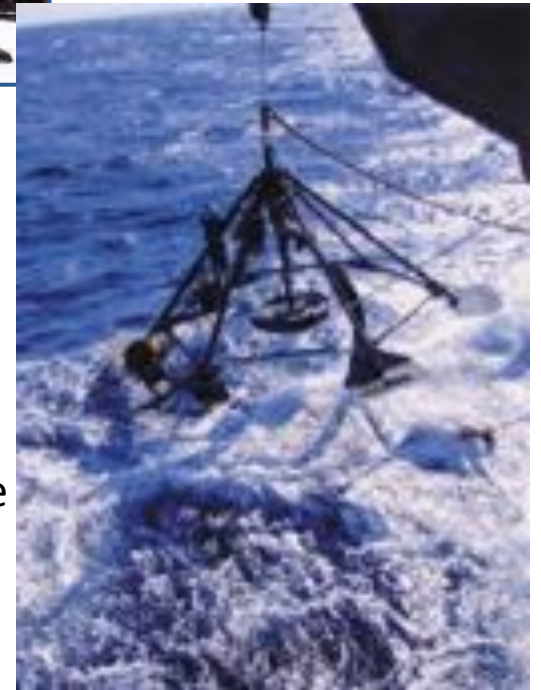


PMT #1 OPTICAL M
PMT #2 CALIBRATIO
PMT #3 MODULE
PMT #4
PMT #5 CALIBRATIO
PMT #6 MODULE
PMT #7
HYDROPHONE #1
HYDROPHONE #2
ENVIRONMENTAL
MODULE
NEAL BROWN
UNIT
STRING BOTTOM
CONTROLLER



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



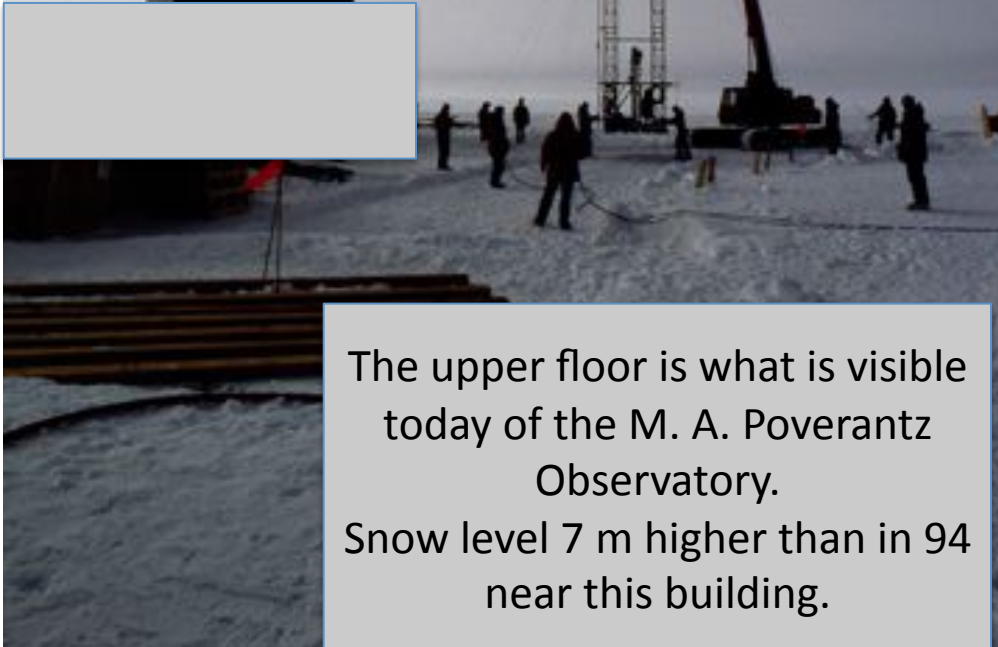
Heaters and pumps
to melt the holes



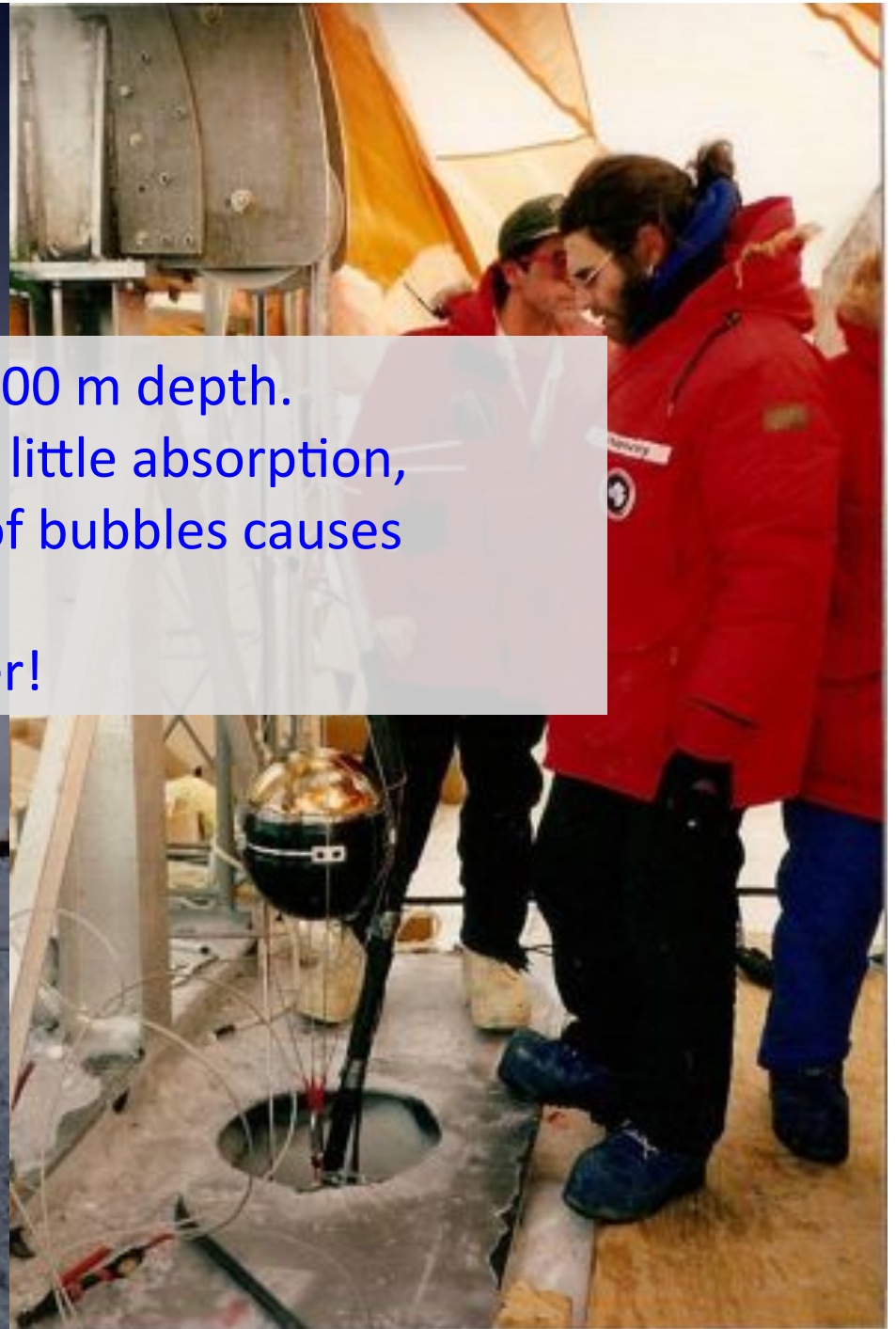
South Pole 93/94

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!

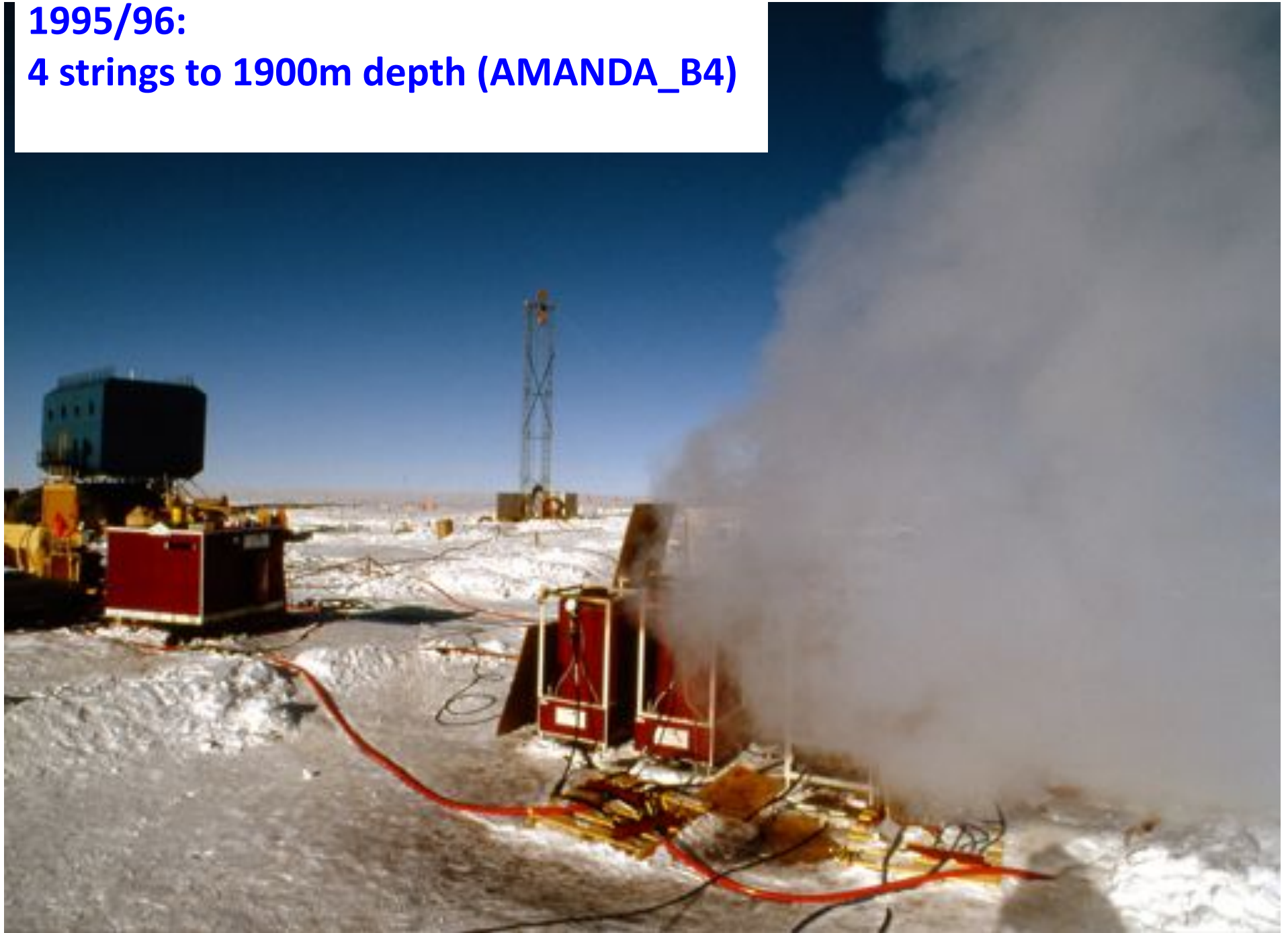


The upper floor is what is visible
today of the M. A. Poverantz
Observatory.
Snow level 7 m higher than in 94
near this building.



1995/96:

4 strings to 1900m depth (AMANDA_B4)



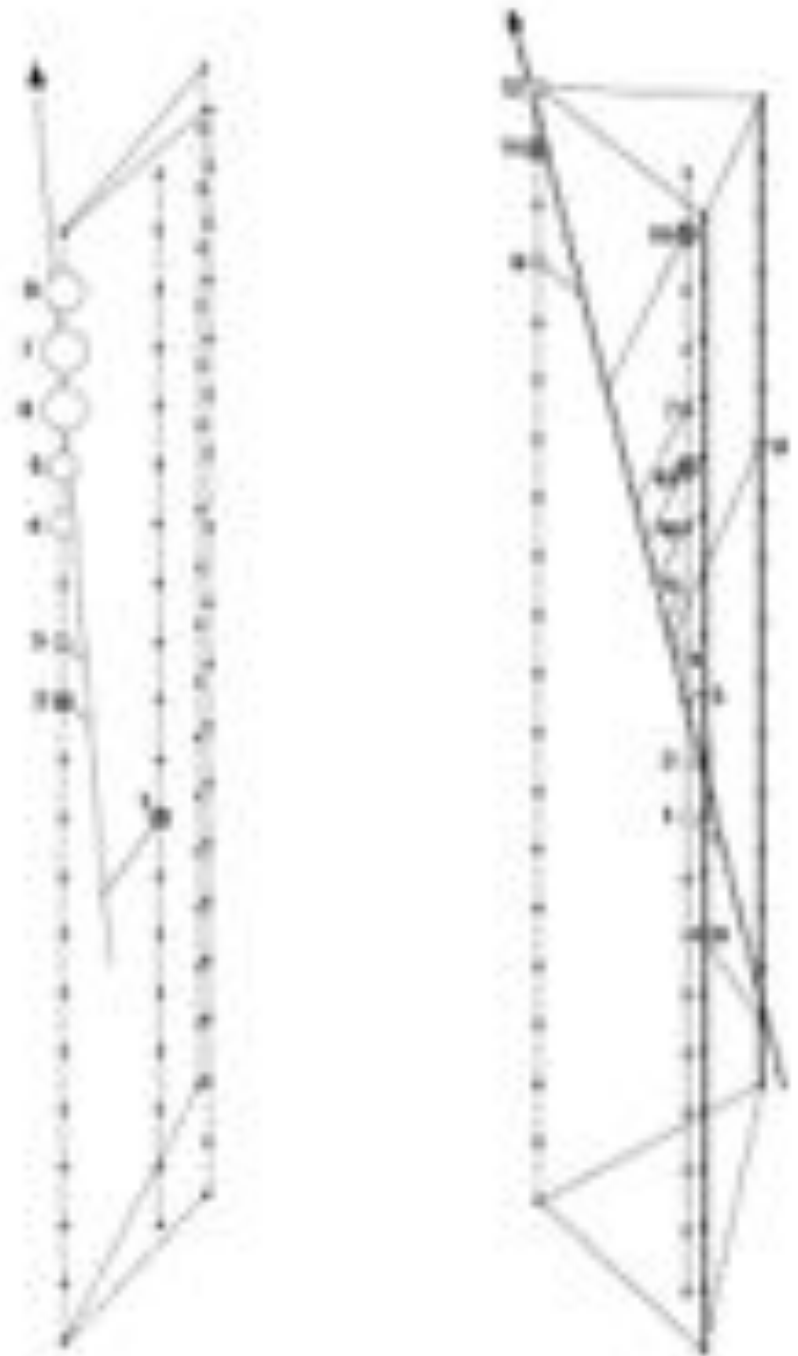
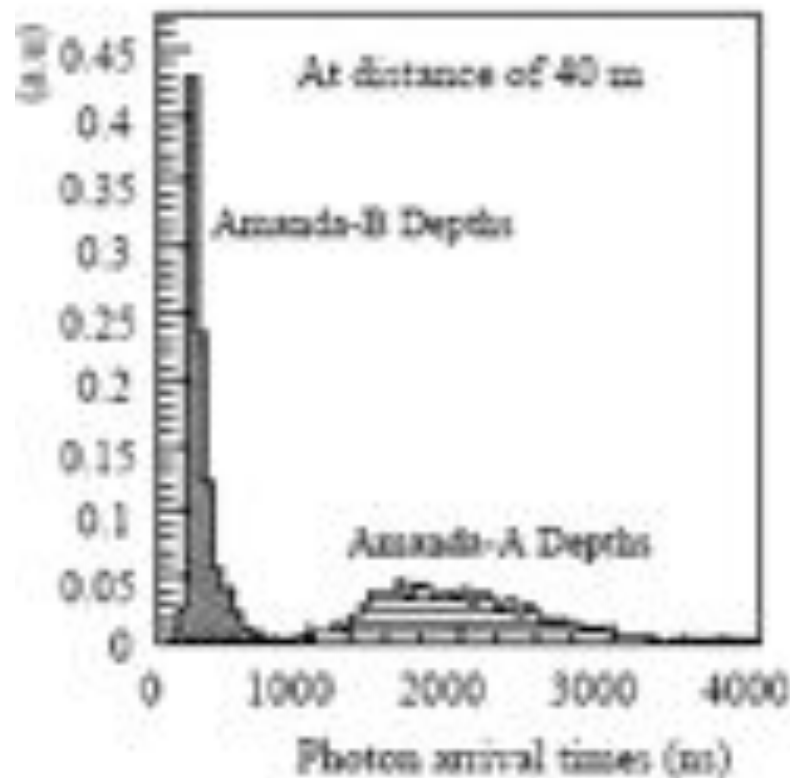
1995/96:

→ 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 →

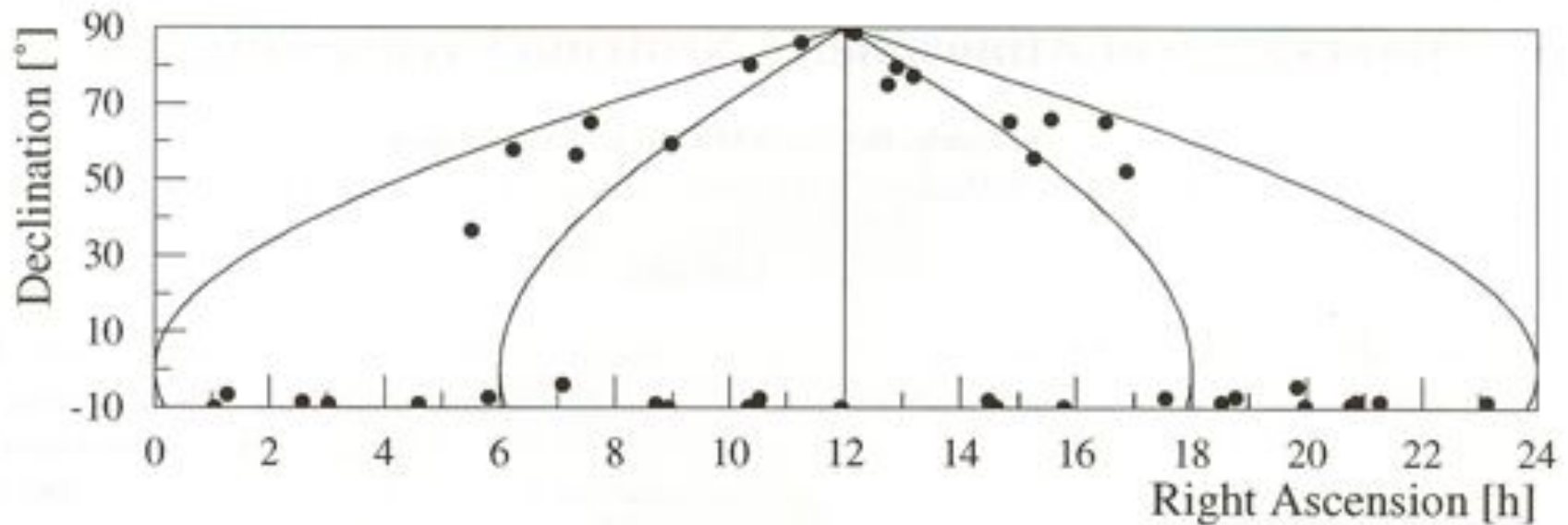


Figure 2: Sky plot of all events that pass level 4 quality cuts.

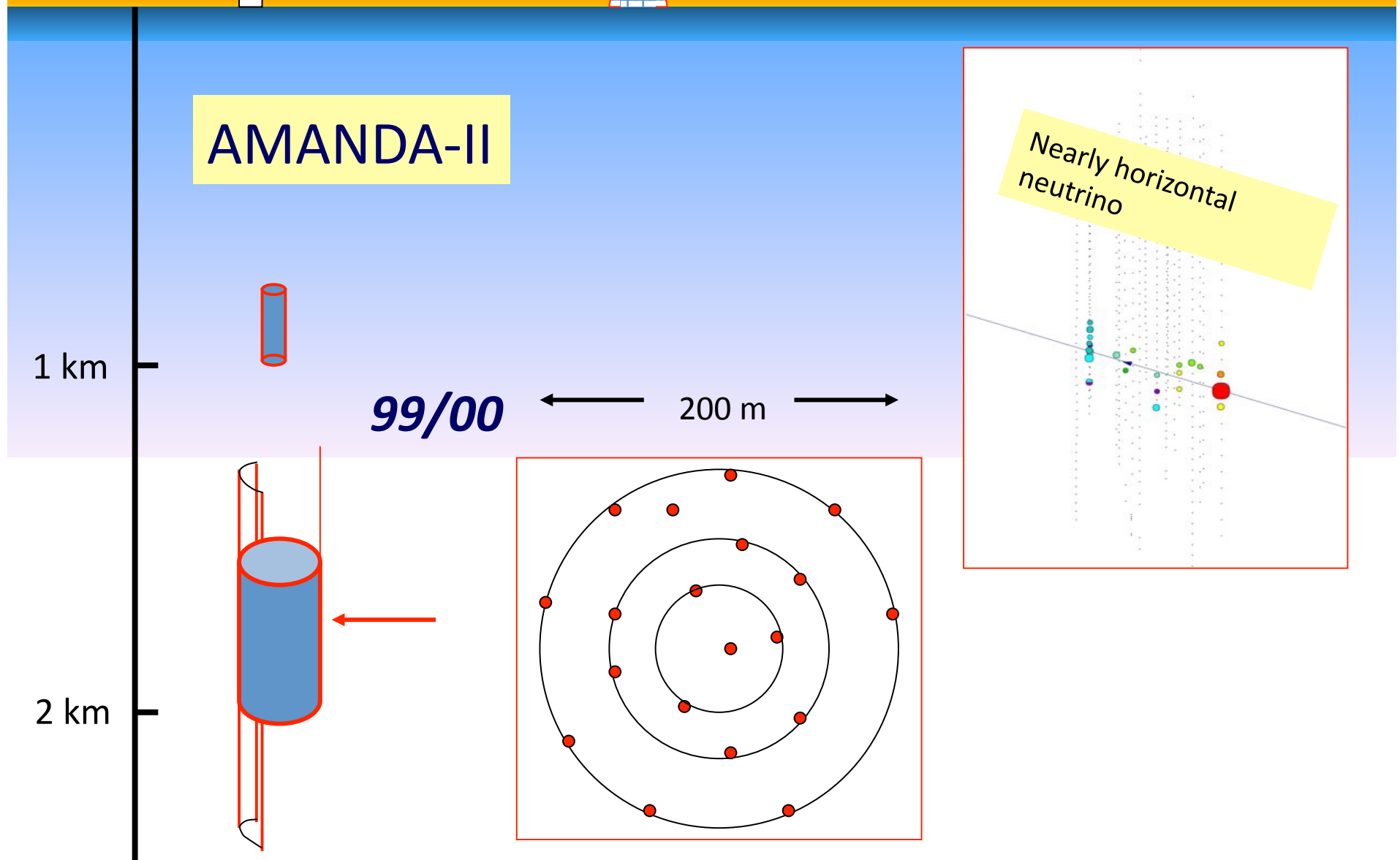
Skyplot of the
very first 17
Nu candidates
in B10

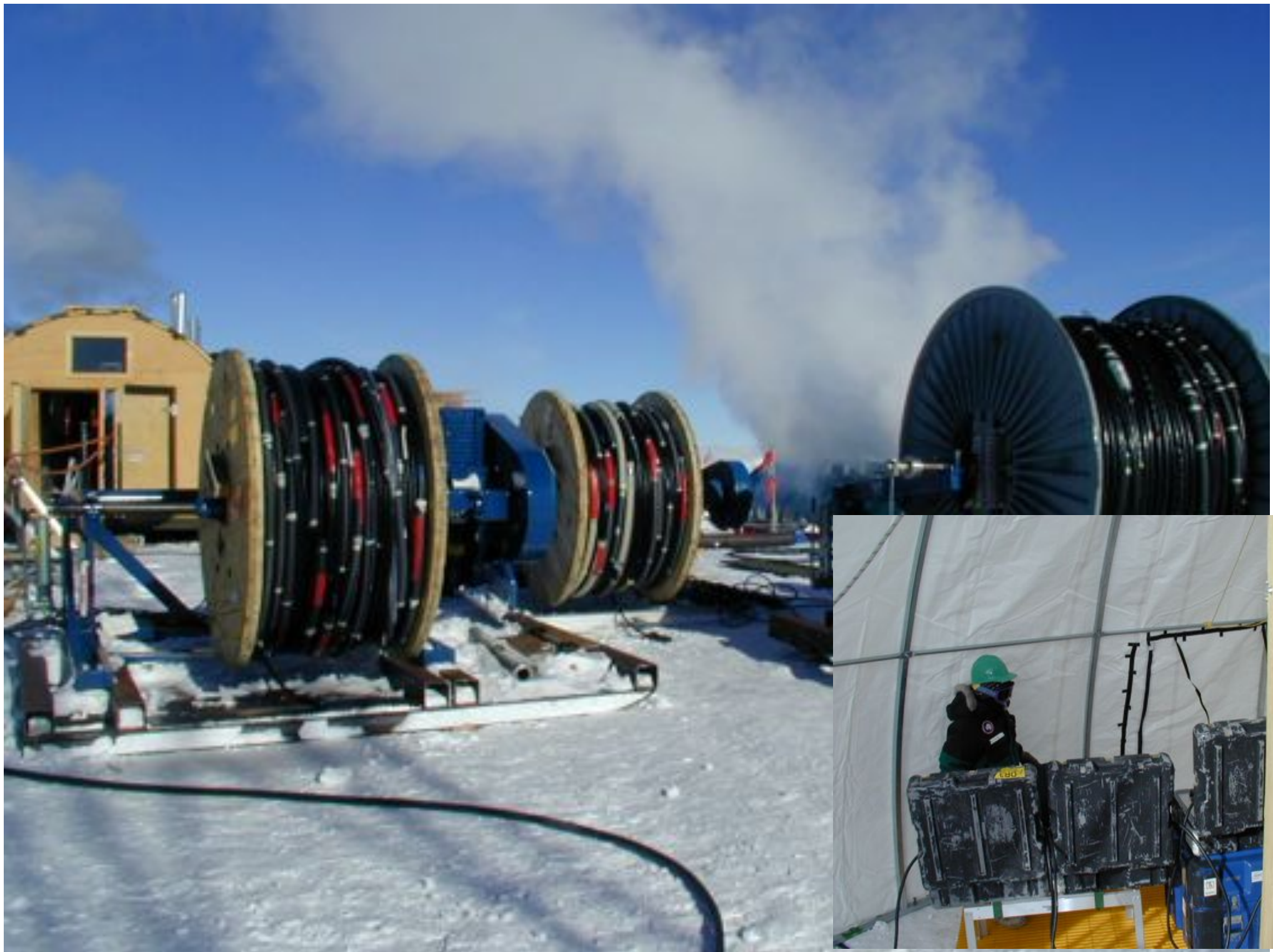


Figure 4 Distribution in declination and right ascension of the upwardly propagating events on the sky. The 263 events shown here are taken from the upward muons contained in both analysis A and analysis B. The median difference between the true and the reconstructed muon angles is about 3 to 4 degrees.

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. Andrieu¹, P. Askarjan¹, E. Ball¹, G. Barabga¹, S. W. Barwick¹, R. C. Bay¹, K.-H. Becker¹, L. Bergström¹, B. Bertrand¹, D. Bilenbaum¹, A. Bion¹, J. Booth¹, D. Bolner¹, A. Boucha¹, M. M. Boyce¹, S. Carls¹, A. Chien¹, B. Chikina¹, J. Conrad¹, J. Cooley¹, C. G. S. Costa¹, D. F. Cowen¹, J. Dailing¹, E. Dalberg¹, T. DeYoung¹, P. Deslafi¹, J.-P. Denault¹, P. Dekus¹, J. Edsjö¹, P. Ekström¹, B. Erlandsson¹, T. Feser¹, M. Gaug¹, A. Goldschmidt¹, A. Goobar¹, L. Gray¹, H. Haase¹, A. Hallgren¹, F. Halzen¹, K. Hanson¹, B. Hardiker¹, Y. D. He¹, M. Hellwig¹, H. Heuvelinkamp¹, G. C. Hill¹, P. O. Hoff¹, S. Hundermark¹, J. Jacobsen¹, V. Kandhadai¹, A. Karle¹, J. Kim¹, S. Koch¹, L. Köpke¹, M. Kowalski¹, H. Leich¹, M. Löffelholz¹, P. Lindahl¹, I. Ljubaric¹, P. Lozza¹, D. M. Lowder¹, J. Ludwig¹, J. Madar¹, P. Marchewski¹, H. S. Marks¹, A. Mikulaj¹, T. Mikulajski¹, T. C. Miller¹, Y. Minowa¹, P. Mironov¹, P. C. Moch¹, R. Morse¹, T. Neuhöffer¹, F. M. Newcomer¹, P. Nesson¹, D. R. Nygren¹, H. Ögelman¹, C. Pérez de los Heros¹, R. Perrata¹, P. B. Price¹, K. Rawlin¹, C. Reed¹, W. Rhode¹, A. Richards¹, S. Richter¹, J. Rodriguez Martinez¹, P. Rommesko¹, D. Ross¹, H. Rubinstein¹, H.-G. Sander¹, T. Schelders¹, T. Schmidt¹, D. Schneider¹, E. Schneider¹, R. Schwarz¹, A. Silvestri¹, M. Solarz¹, G. M. Spiczak¹, C. Spiering¹, N. Starinsky¹, D. Steele¹, P. Steffen¹, R. G. Stokstad¹, G. Streicher¹, B. Sun¹, I. Tabuada¹, L. Thollander¹, T. Thon¹, S. Tilav¹, N. Uchida¹, M. Vanderschueren¹, G. Walck¹, G. Weinheimer¹, G. H. Wiebusch¹, B. Wischmerek¹, H. Wissing¹, K. Wischmerek¹, W. Wu¹, G. Yodanis¹ & S. Young¹

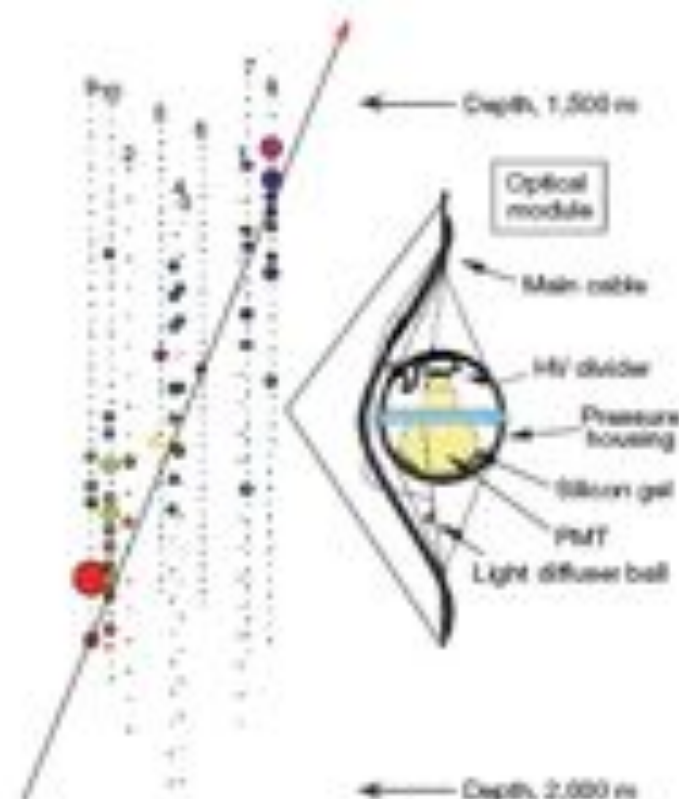


Figure 1 The AMANDA-II detector and a schematic diagram of an optical module. Each dot represents an optical module. The modules are separated by 20 m on the inner strings (1 to 4), and by 10 m on the outer strings (5 to 10). The coloured circles show pulses from the photomultipliers for a particular event; the sizes of the circles indicate the amplitude 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.

NATURE 2001

1999 – IceCube proposal

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

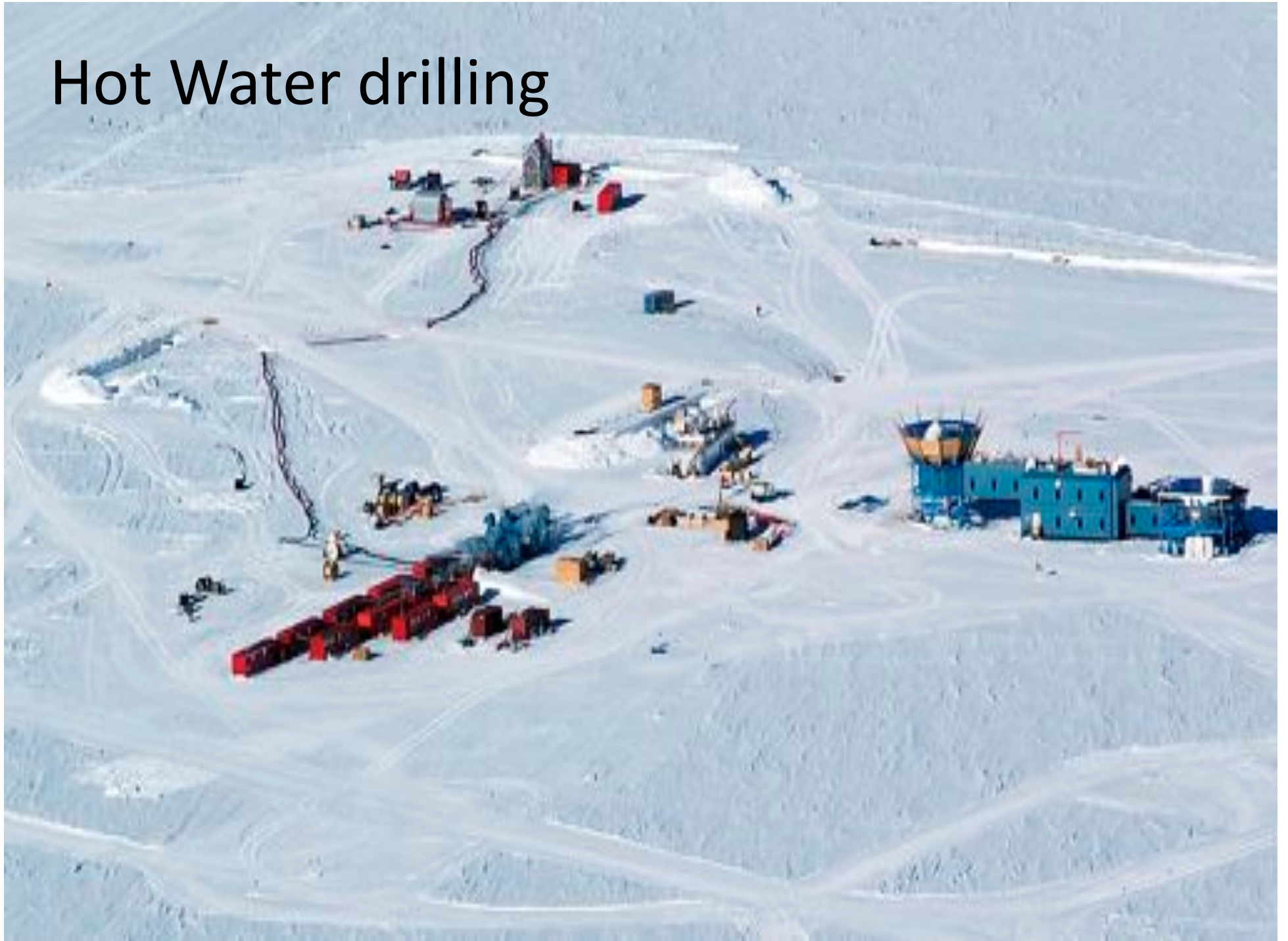
- A strong international collaboration has formed.
- It had been demonstrated that
 - the ice is excellent down to 2500m depth.
 - Drilling technology is established and modeling has improved such that fuel and logistics requirements are solid (they were conservative).
 - The deep Antarctic ice is suitable 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



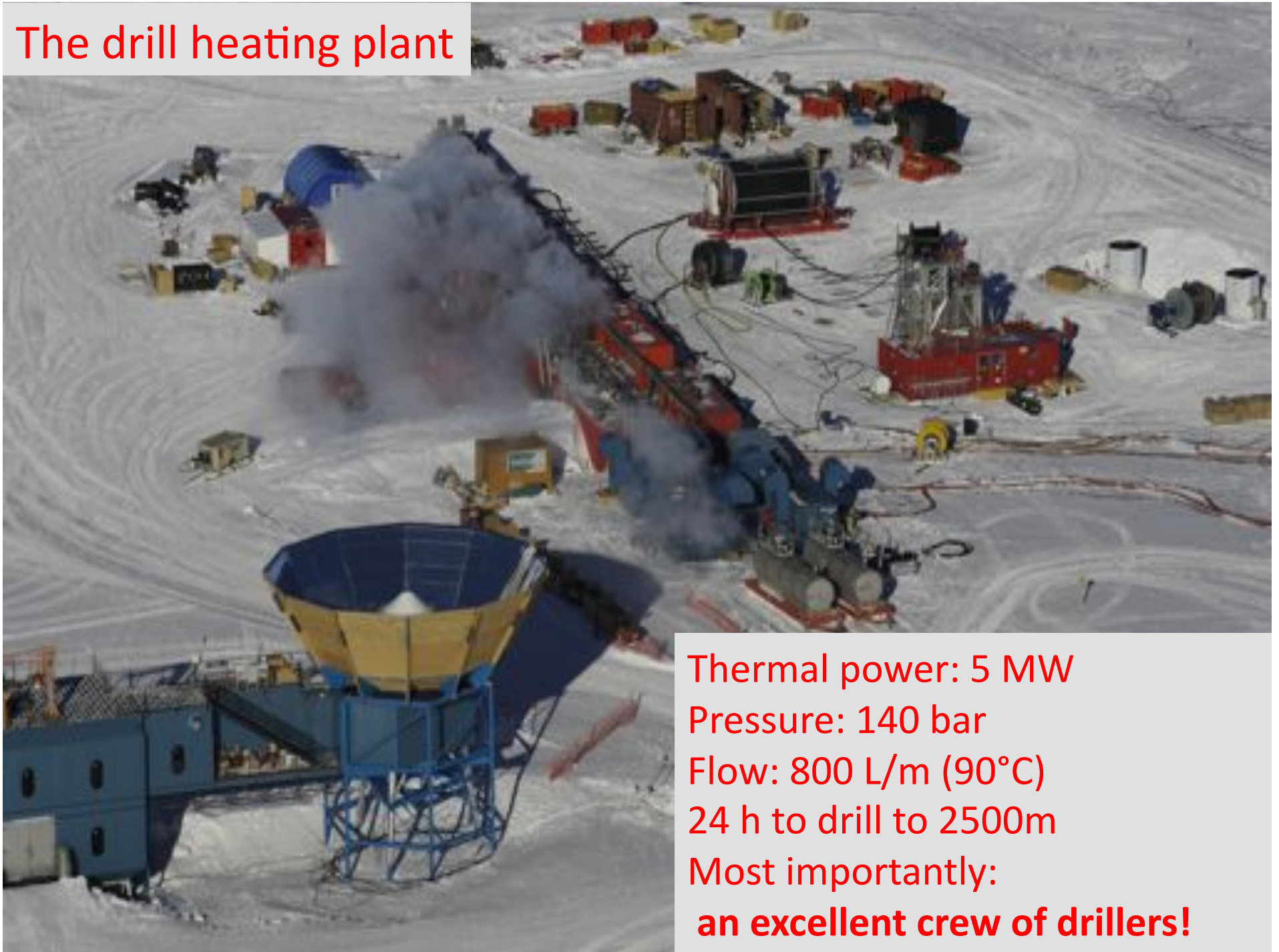
900 tons of Cargo and fuel
300 “Hercules” LC 130 missions (skiers)

Hot Water drilling





The drill heating plant



Thermal power: 5 MW

Pressure: 140 bar

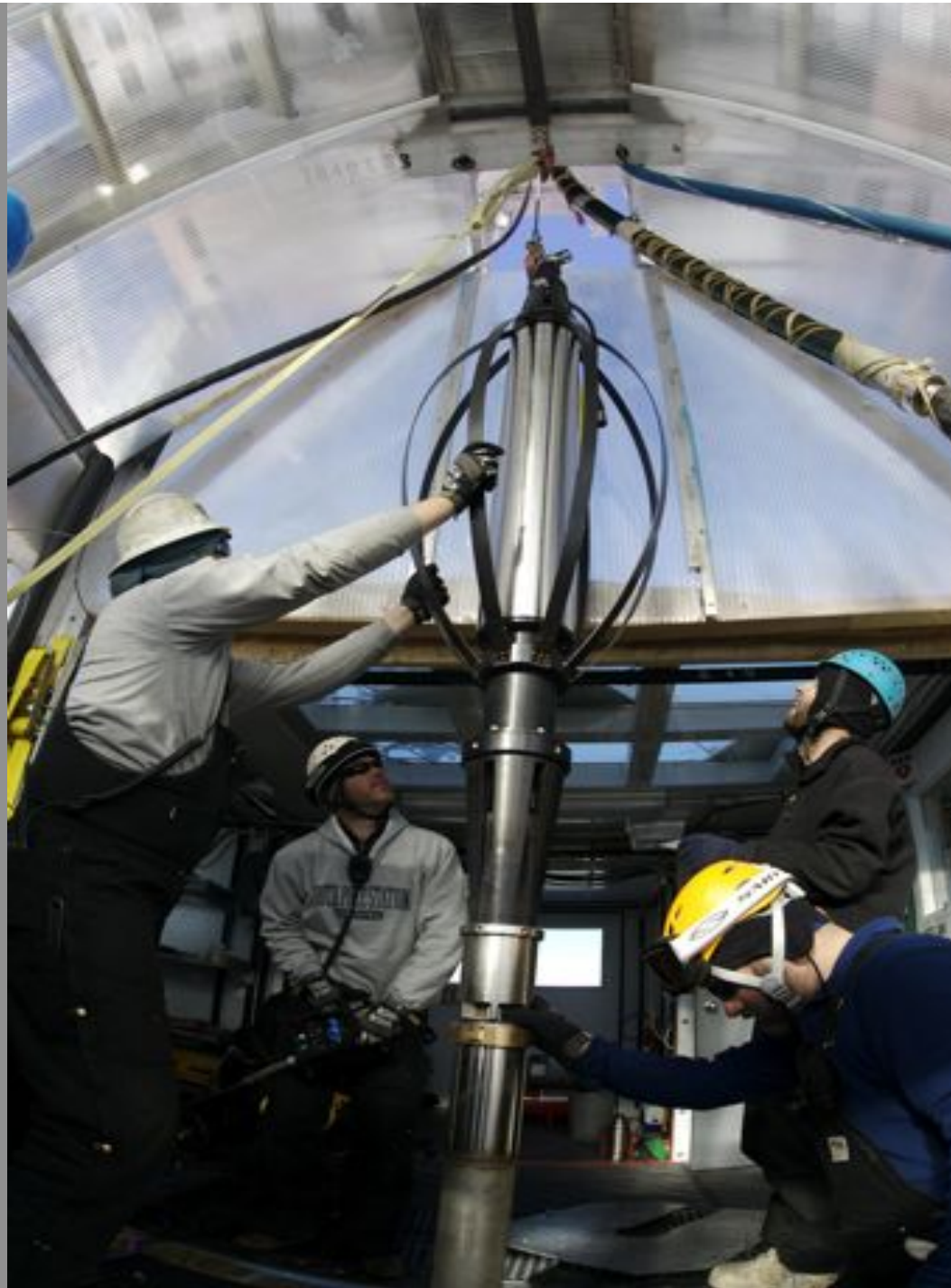
Flow: 800 L/m (90°C)

24 h to drill to 2500m

Most importantly:

an excellent crew of drillers!





Drillers pull out the drillhead.

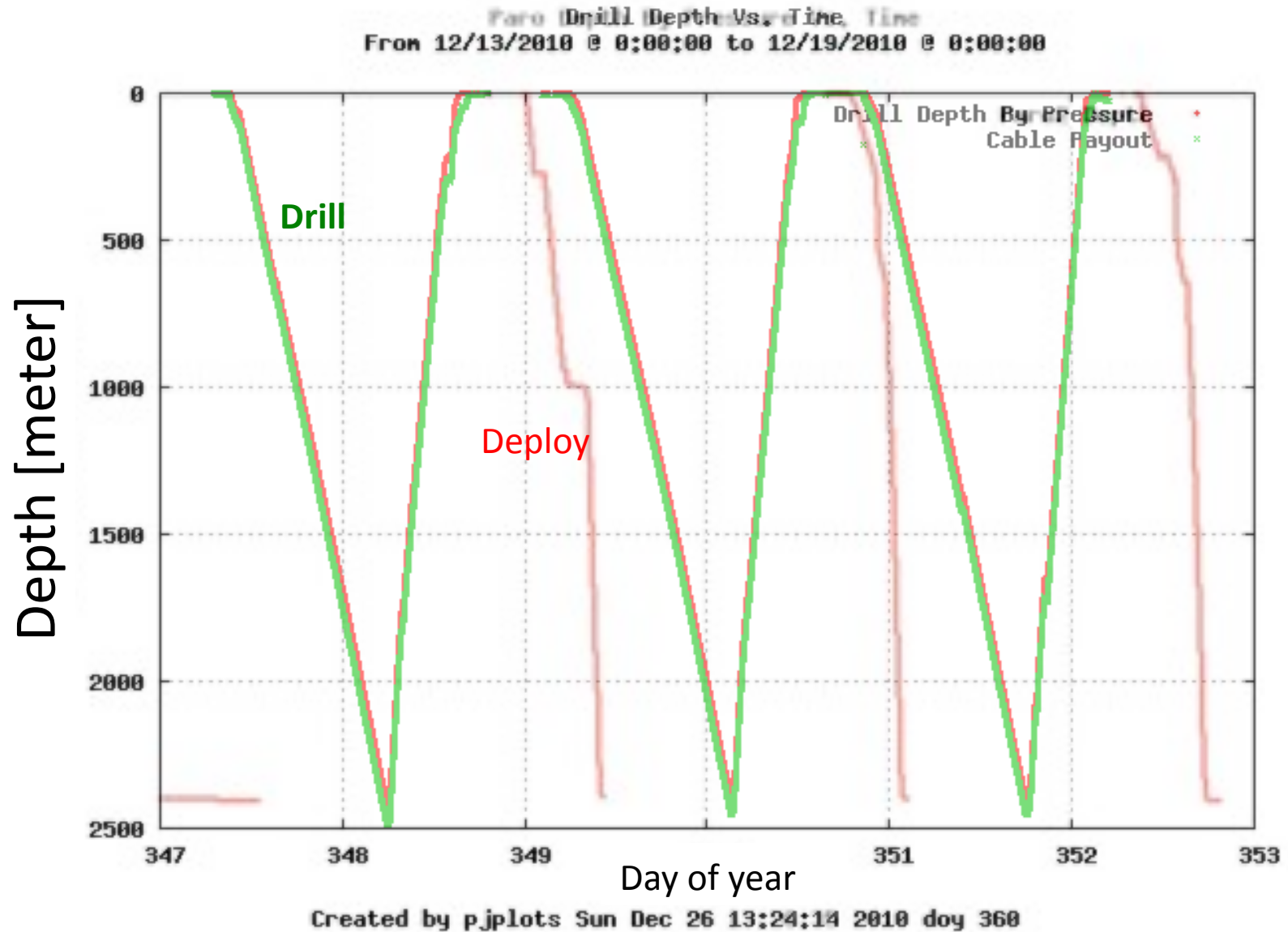
Safety:

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



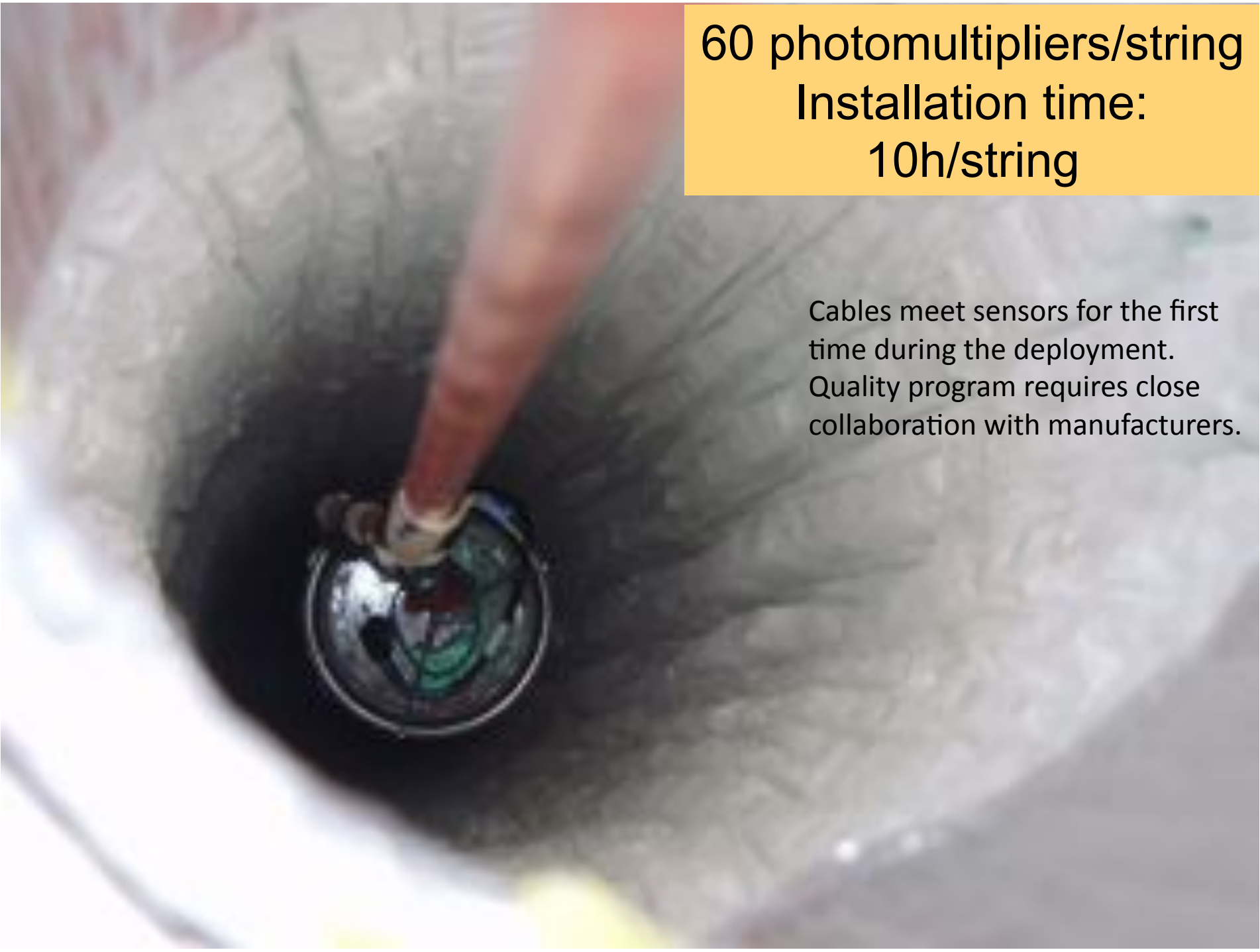
The IceCube Drill in long term storage configuration
Location: downwind from dark sector



ARA drill,
not there now

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

USA:

Bartol Research Institute, Delaware
University of California, Berkeley
University of California, Irvine
Pennsylvania State University
Clark-Atlanta University
Ohio State University
Georgia Tech
University of Maryland
University of Alabama, Tuscaloosa
University of Wisconsin-Madison
University of Wisconsin-River Falls
Lawrence Berkeley National Lab.
University of Kansas
Southern University and A&M
College, Baton Rouge
University of Alaska, Anchorage

Sweden:

Uppsala Universitet
Stockholm Universitet

UK:

Oxford University

Netherlands:

Utrecht University

Switzerland:

EPFL

Germany:

DESY-Zeuthen
Universität Mainz
Universität Dortmund
Universität Wuppertal
Humboldt Universität
MPI Heidelberg
RWTH Aachen

Belgium:

Université Libre de Bruxelles
Vrije Universiteit Brussel
Universiteit Gent
Université de Mons-Hainaut

Japan:

Chiba University

New Zealand:

University of Canterbury

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 stack & 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	1550m	1000	2
2000/2001								
2001/2002								
2002/2003	IceCube				staging			
2003/2004	IceCube	1	1	60	1450-2450m			
2004/2005	IceCube 9	8	9		1450-2450m			
2005/2006	IceCube 22	13	22		1450-2450m			
2006/2007	IceCube 40	18	40	2400	1450-2450m		14000	0.7
2007/2008	IceCube 59	19	59		1450-2450m			
2008/2009	IceCube 79	20	79		1450-2450m			
2009/2010	IceCube 86	7	86	5160	1450-2450m		~30000	0.5

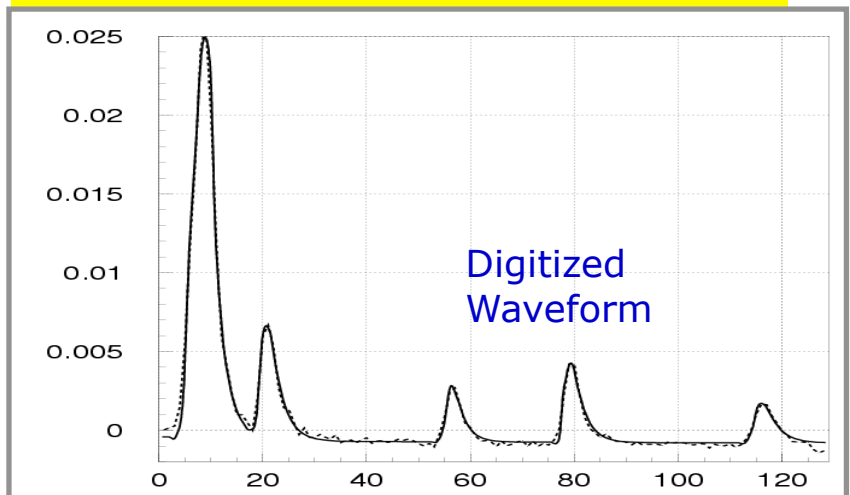
Digital Optical Module (DOM)



PMT: 10 inch Hamamatsu
Power consumption: 3 W
Digitize at 300 MHz for 400 ns with custom chip
40 MHz for 6.4 μ s 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 dynode, are below spe threshold. Gain ratio according to first dynode gain)

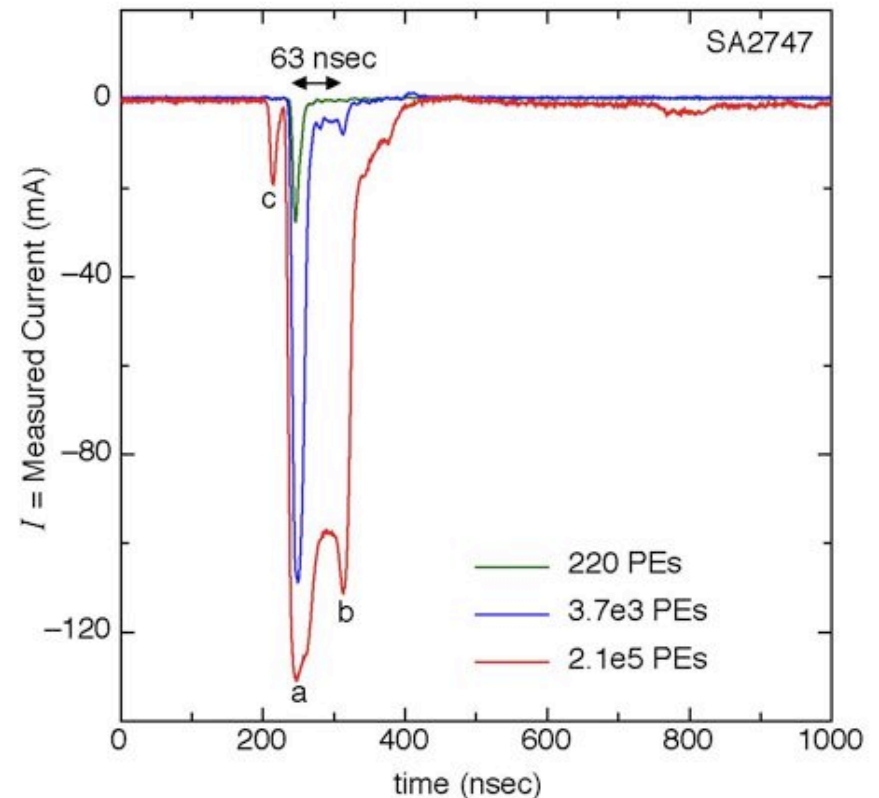
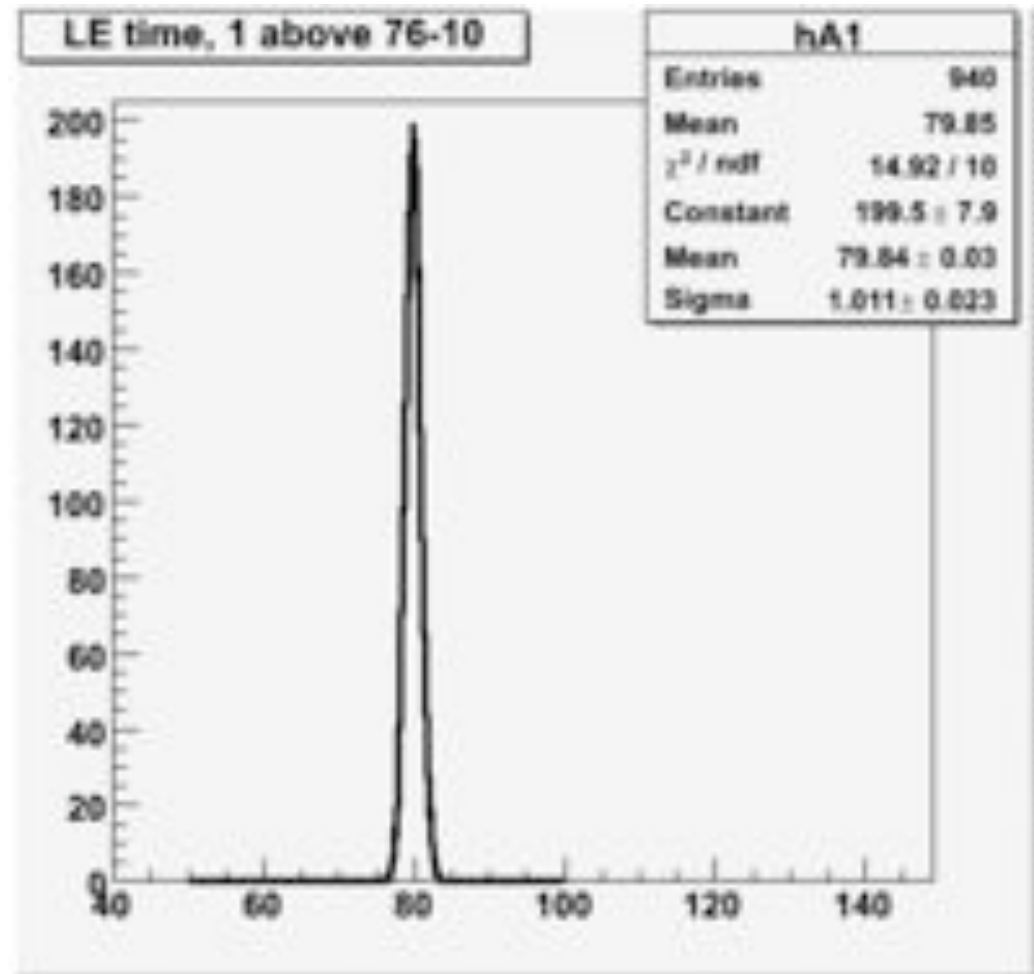


Fig. 16. Response of PMT to 3 ns (FWHM) light pulses with progressively higher-intensity: (a) main peak; (b) secondary peak due to unusual electron trajectories; (c) pre-pulse.

Time resolution:
~1ns for bright pulses

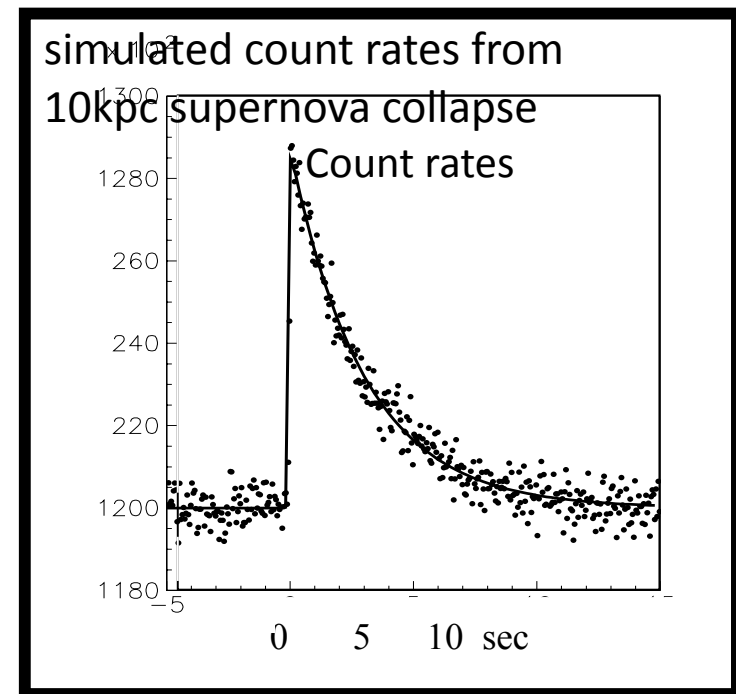
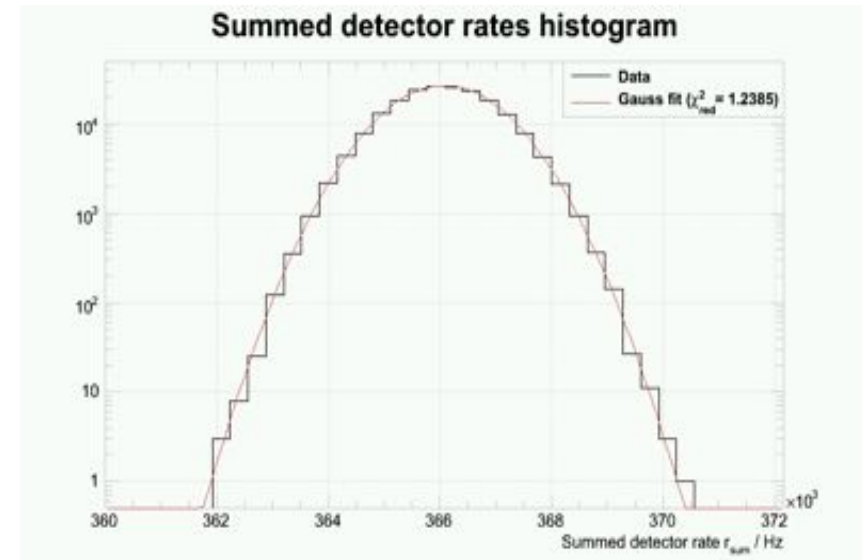
- Time difference between neighboring DOMs fired with (bright) flasher pulses: 1 ns.
- For SPE pulses add jitter (3 nsec)



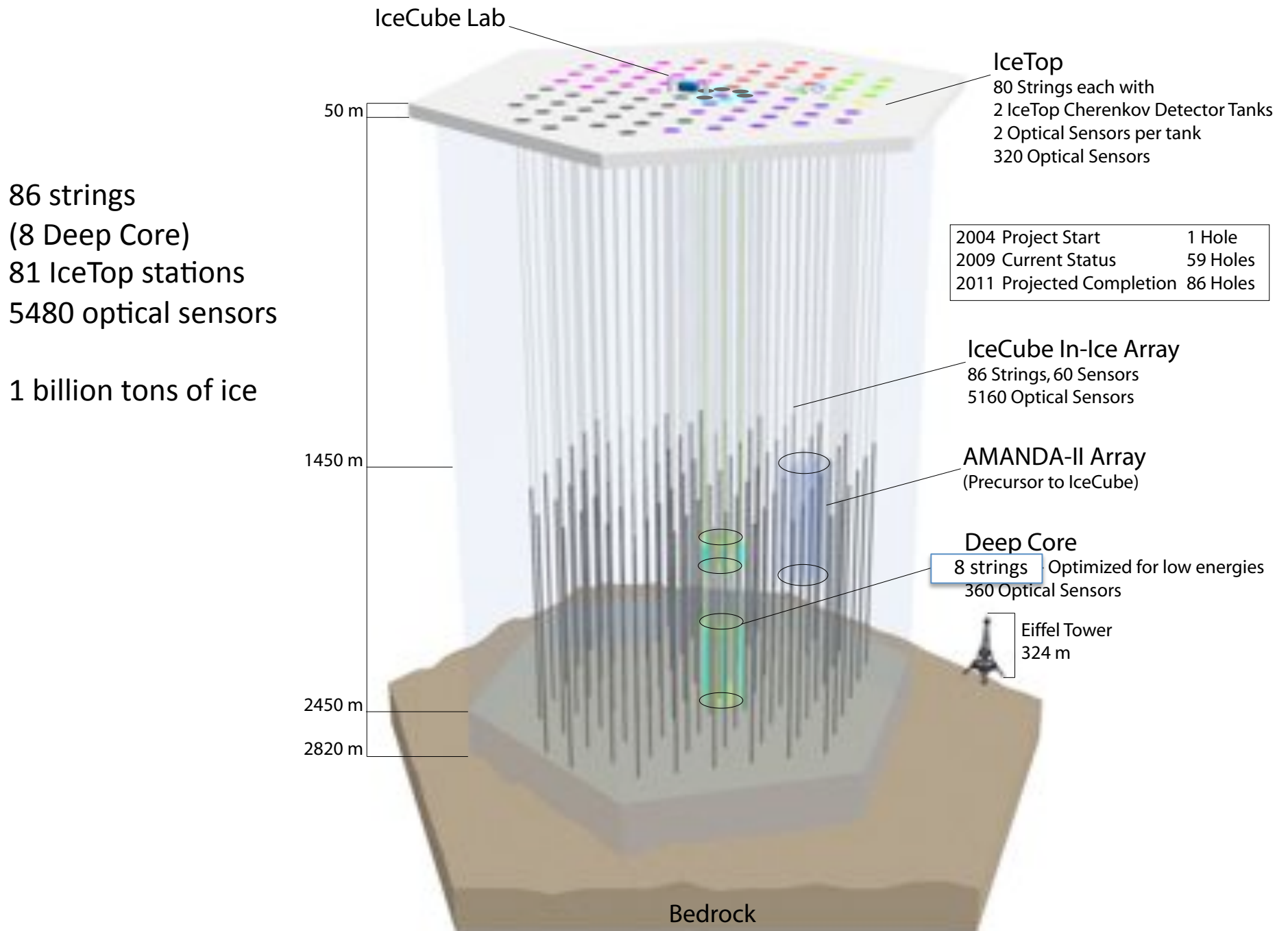
Noise behavior

- 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



IceCube

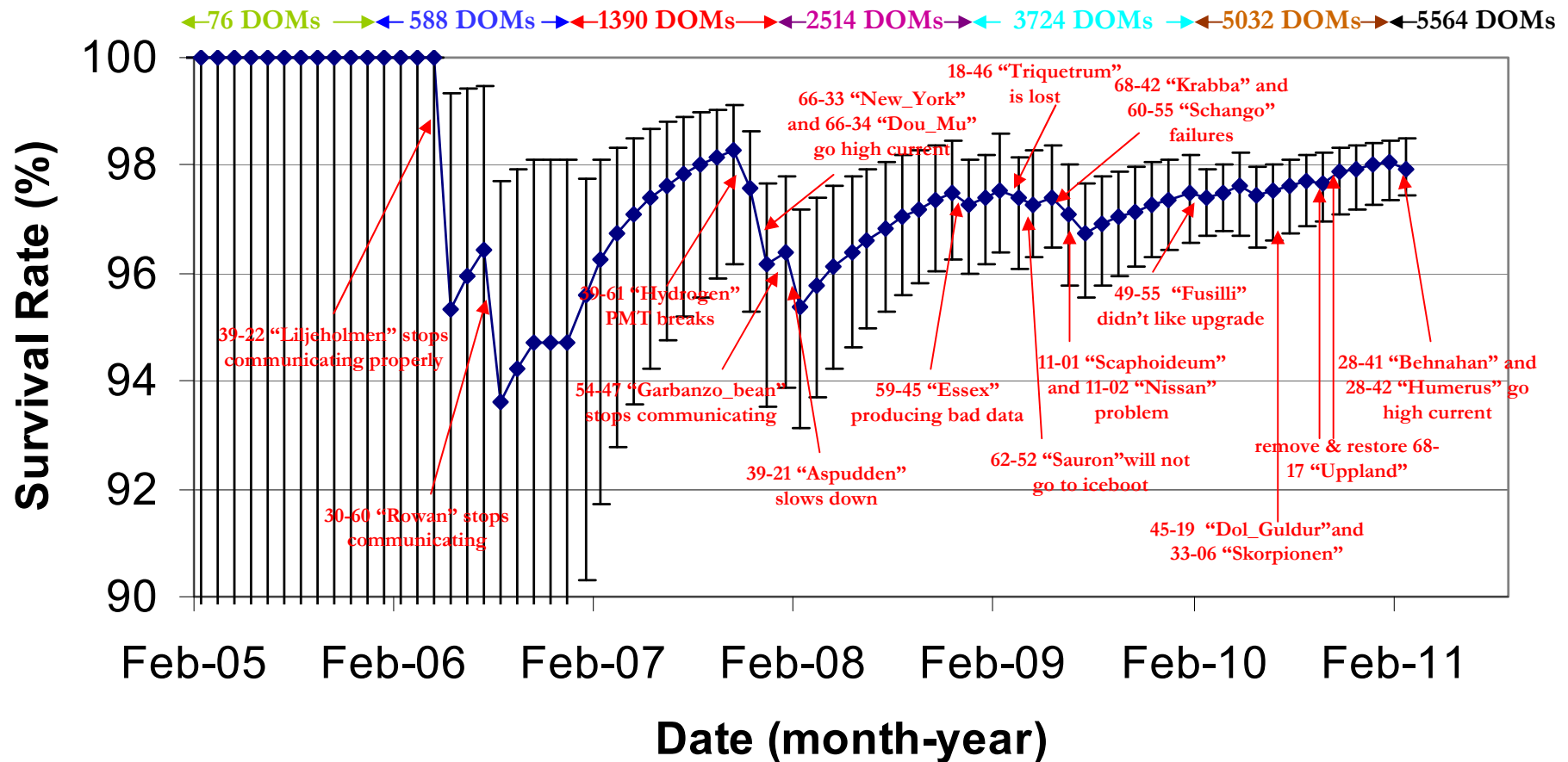


Reliability of sensors

- 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)





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 $\sim 3E17$ eV
Observed by IceTop,
Then by Deep detector strings**

2000 μ >400GeV

Ice

cosmic ray physics

mass independent

energy resolution,

composition

veto

calibration

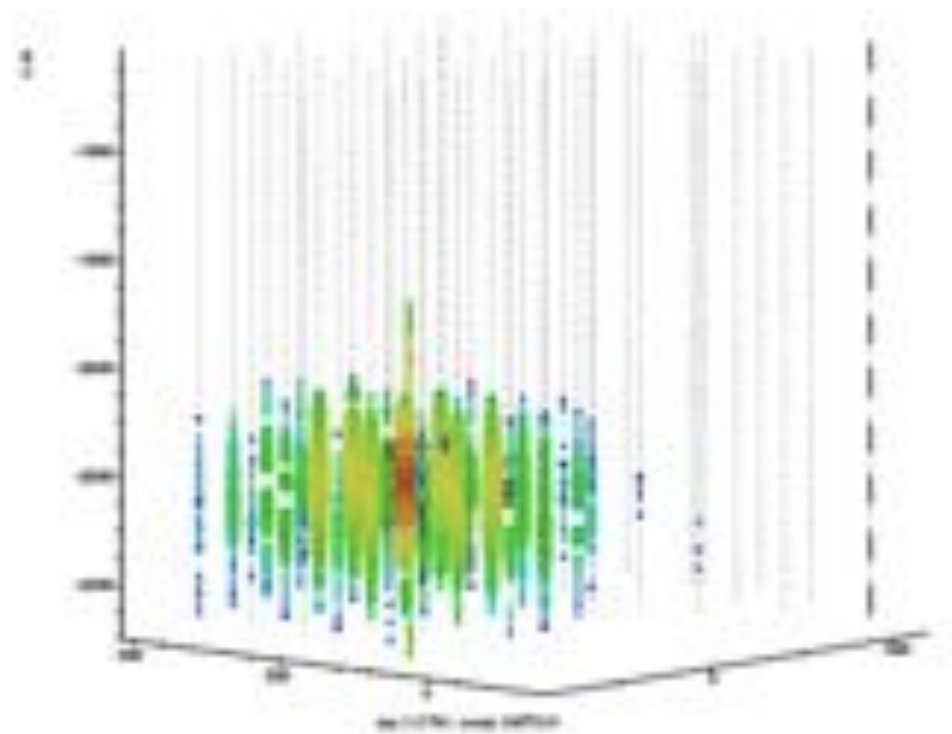
Run 110890 Event 19718500 [9000ns 9000ns]

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

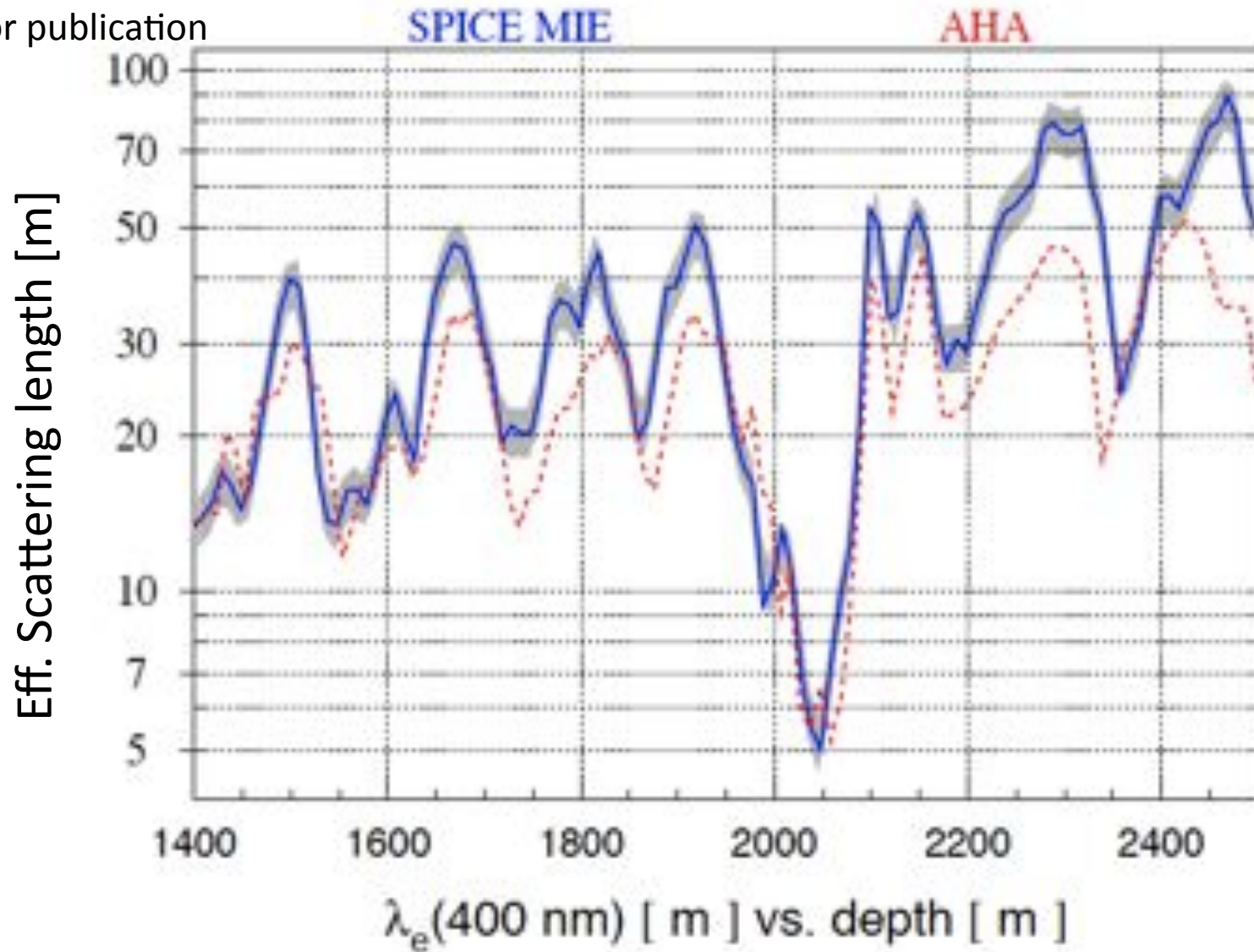
- time
- geometry
- optical properties of the ice



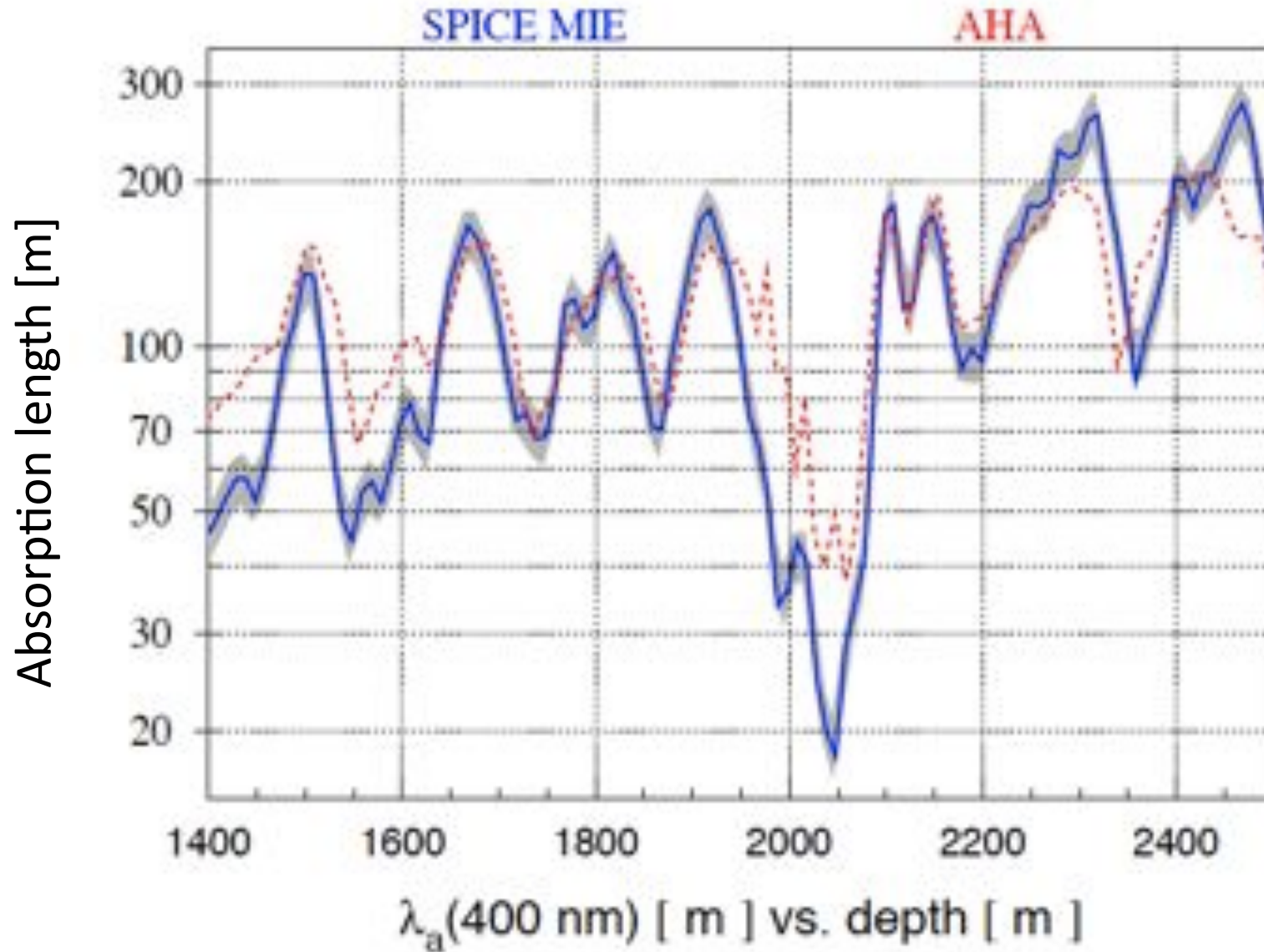
The Ice is very clear

Effective scattering length vs Depth

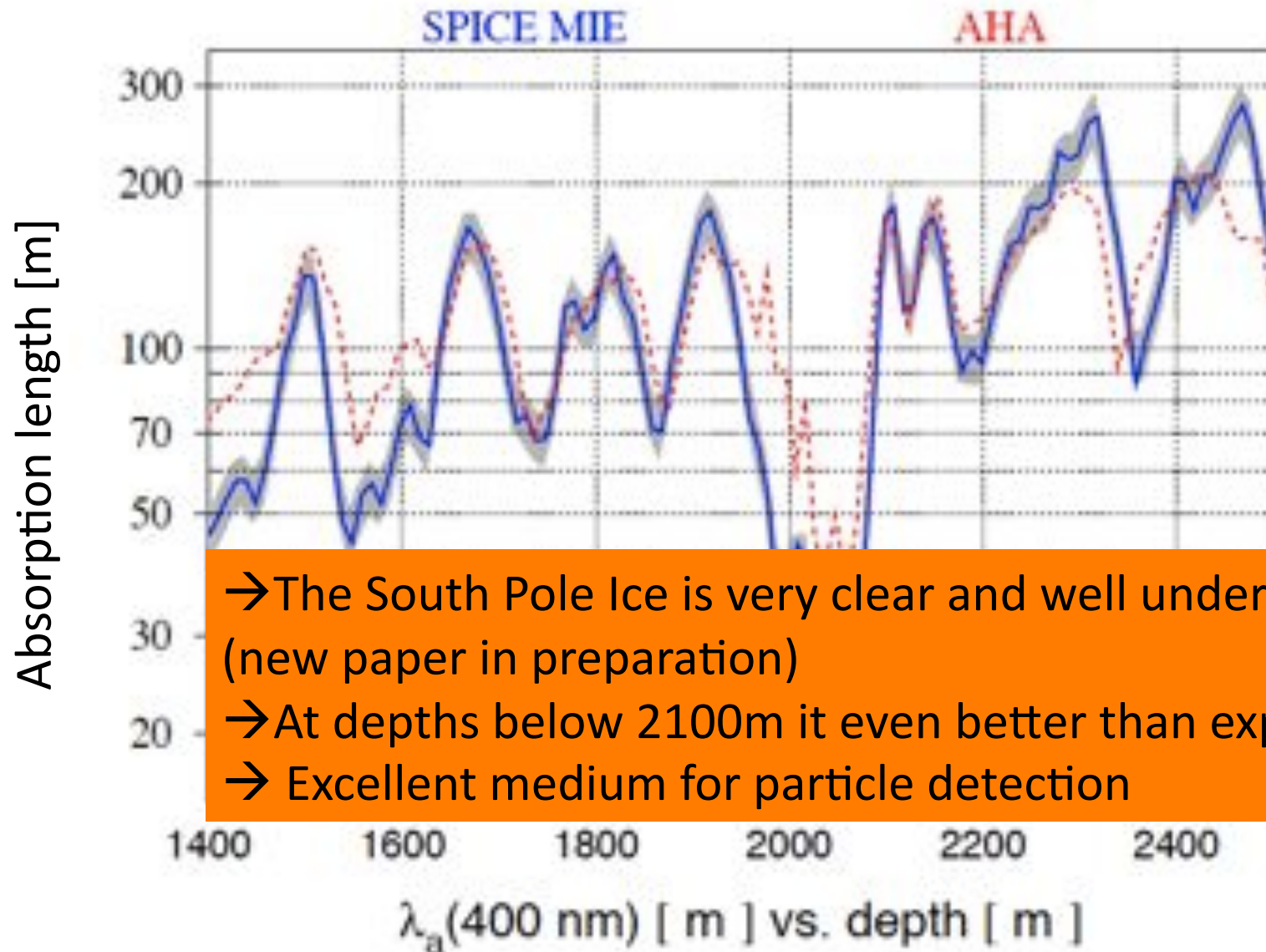
in internal review
for publication



Absorption length vs Depth



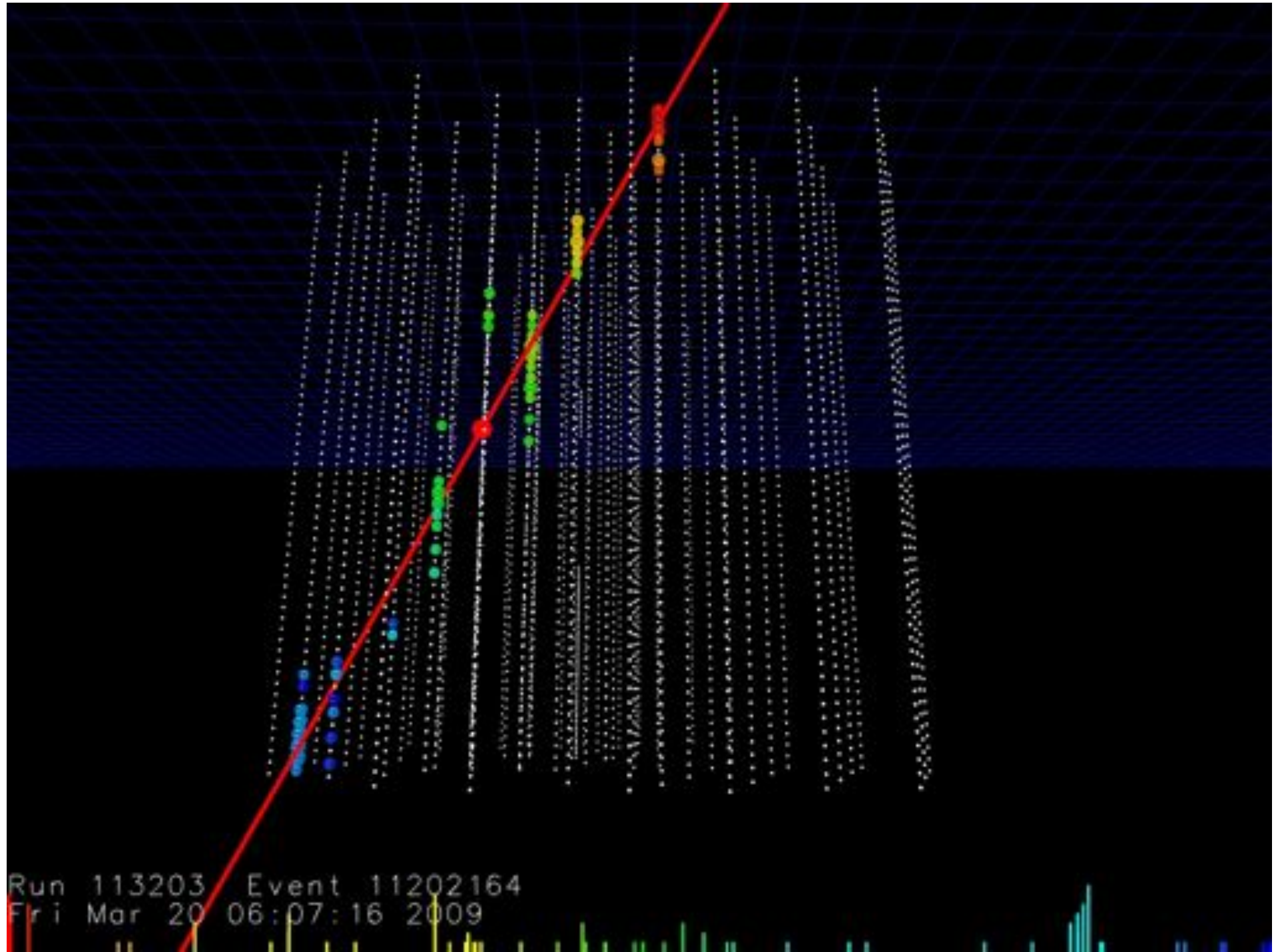
Absorption length vs Depth



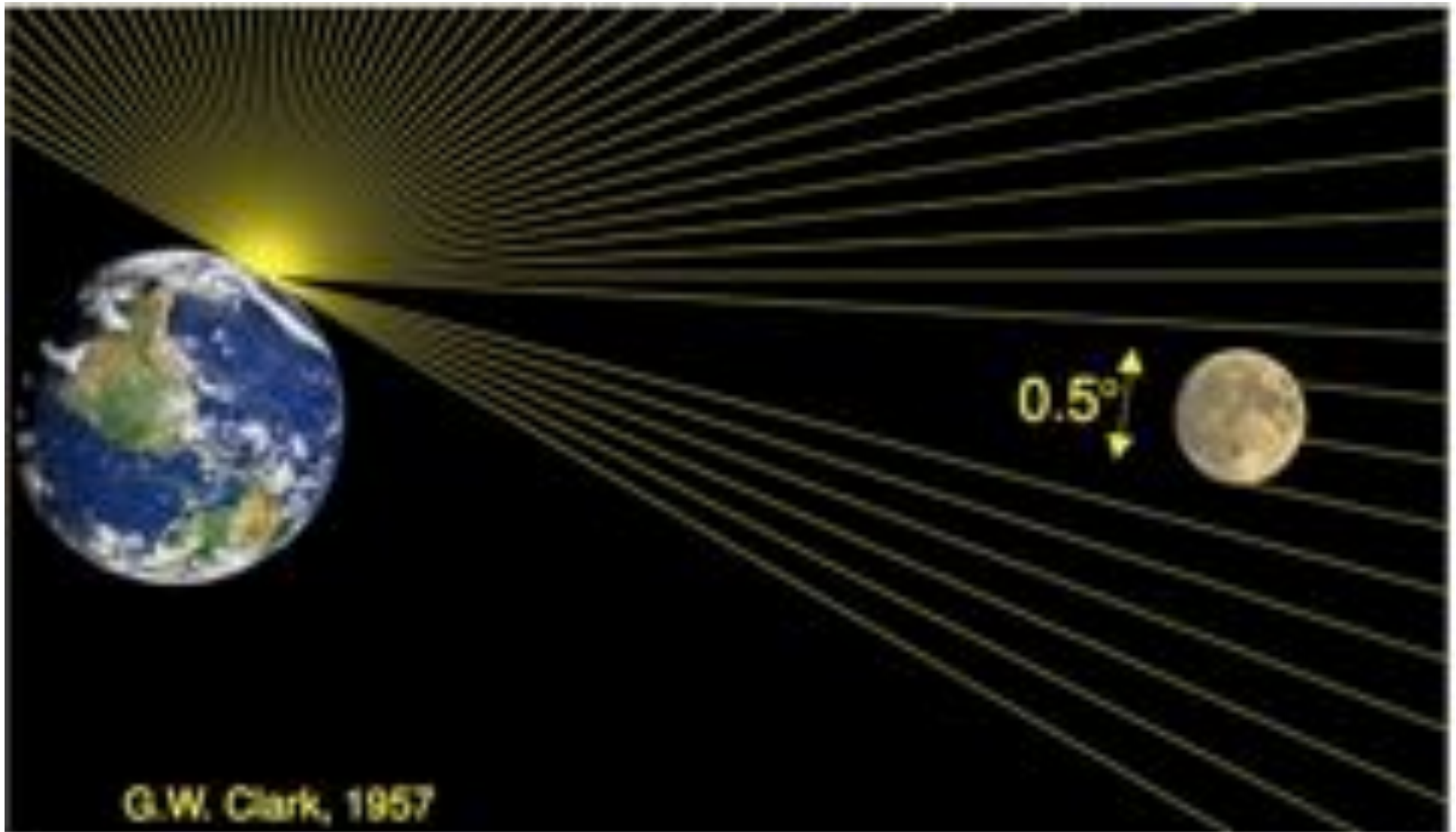
→ The South Pole Ice is very clear and well understood.
(new paper in preparation)

→ At depths below 2100m it even better than expected

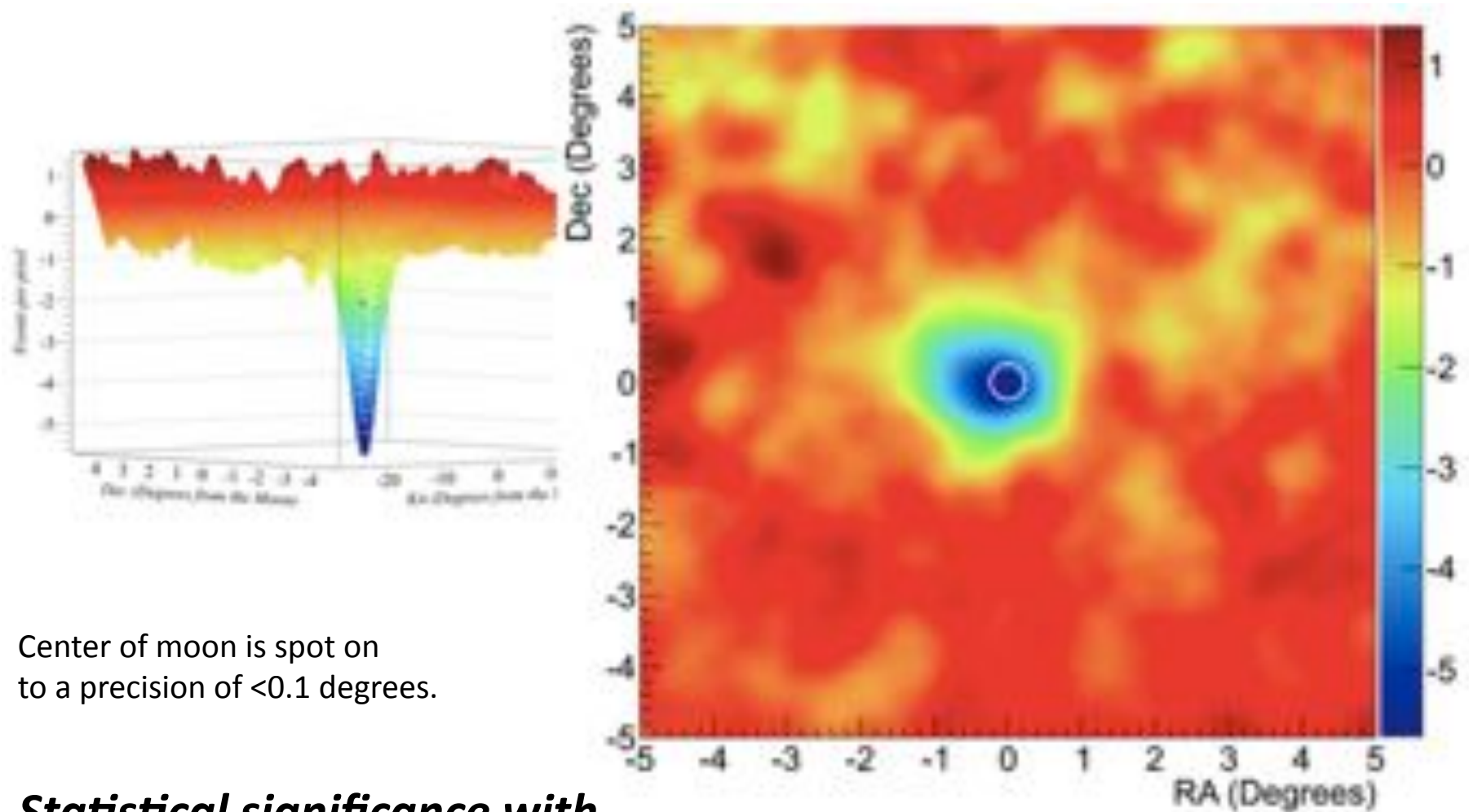
→ Excellent medium for particle detection



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

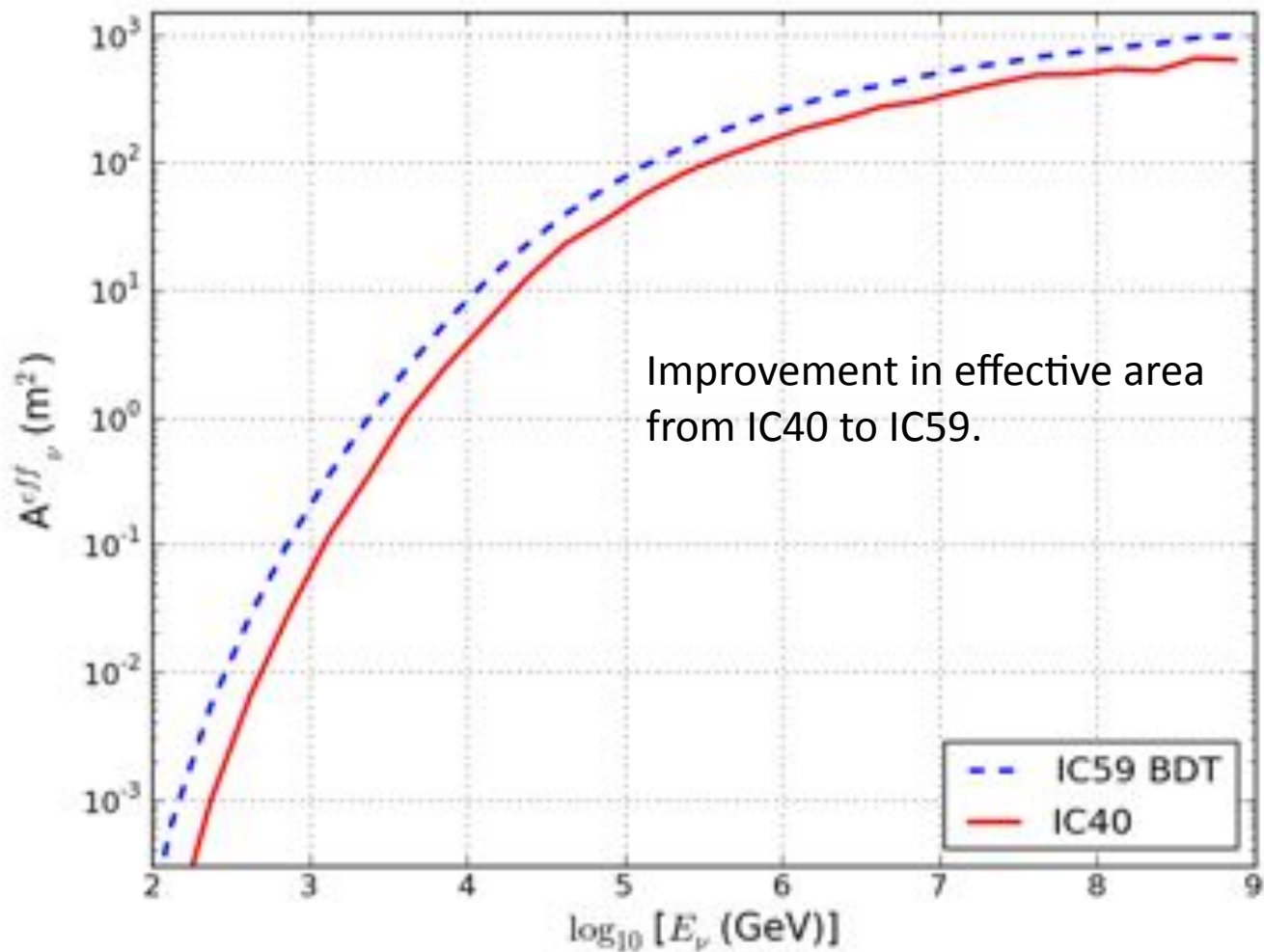
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Detector operation. rates

- Detector performance strings
 - Longer muon track
 - Improved analysis

Strings
AMANDAII (I9)
IC22
IC40
IC59
IC86test



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.

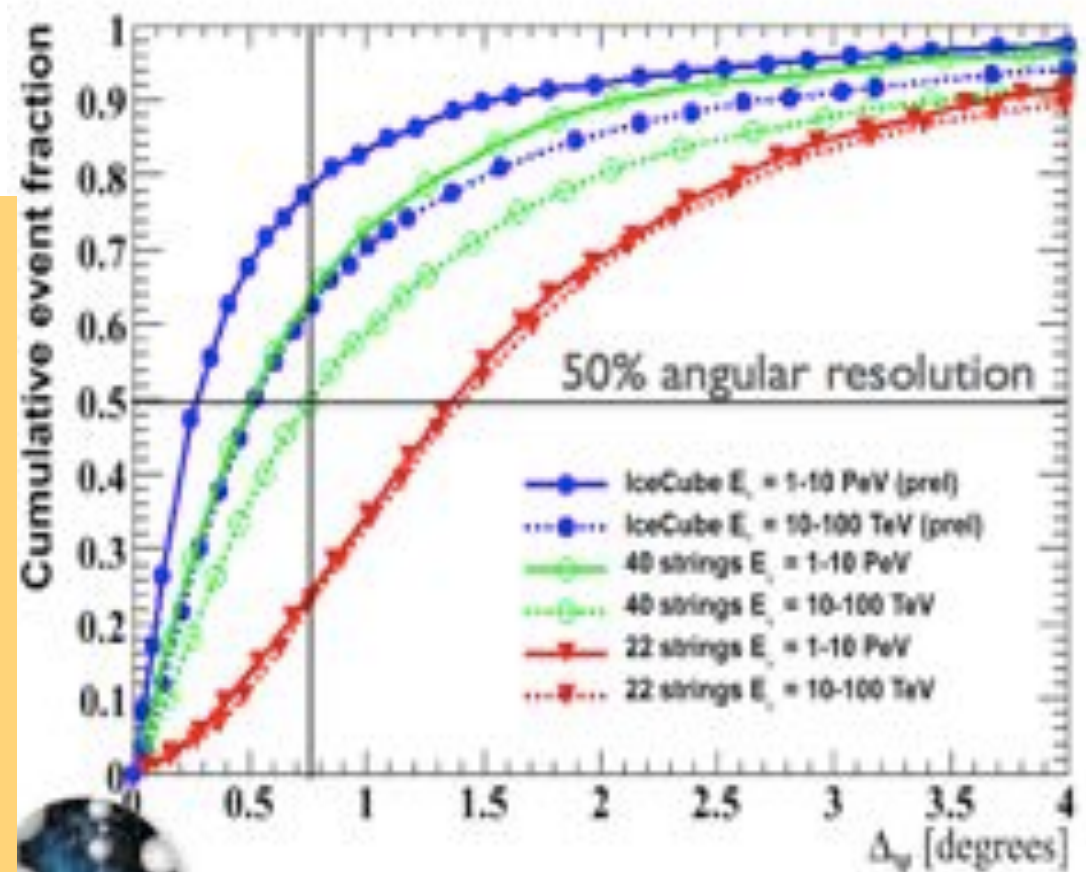
Angular resolution

Median angular resolution
10 – 100 TeV (1 – 10 PeV)

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

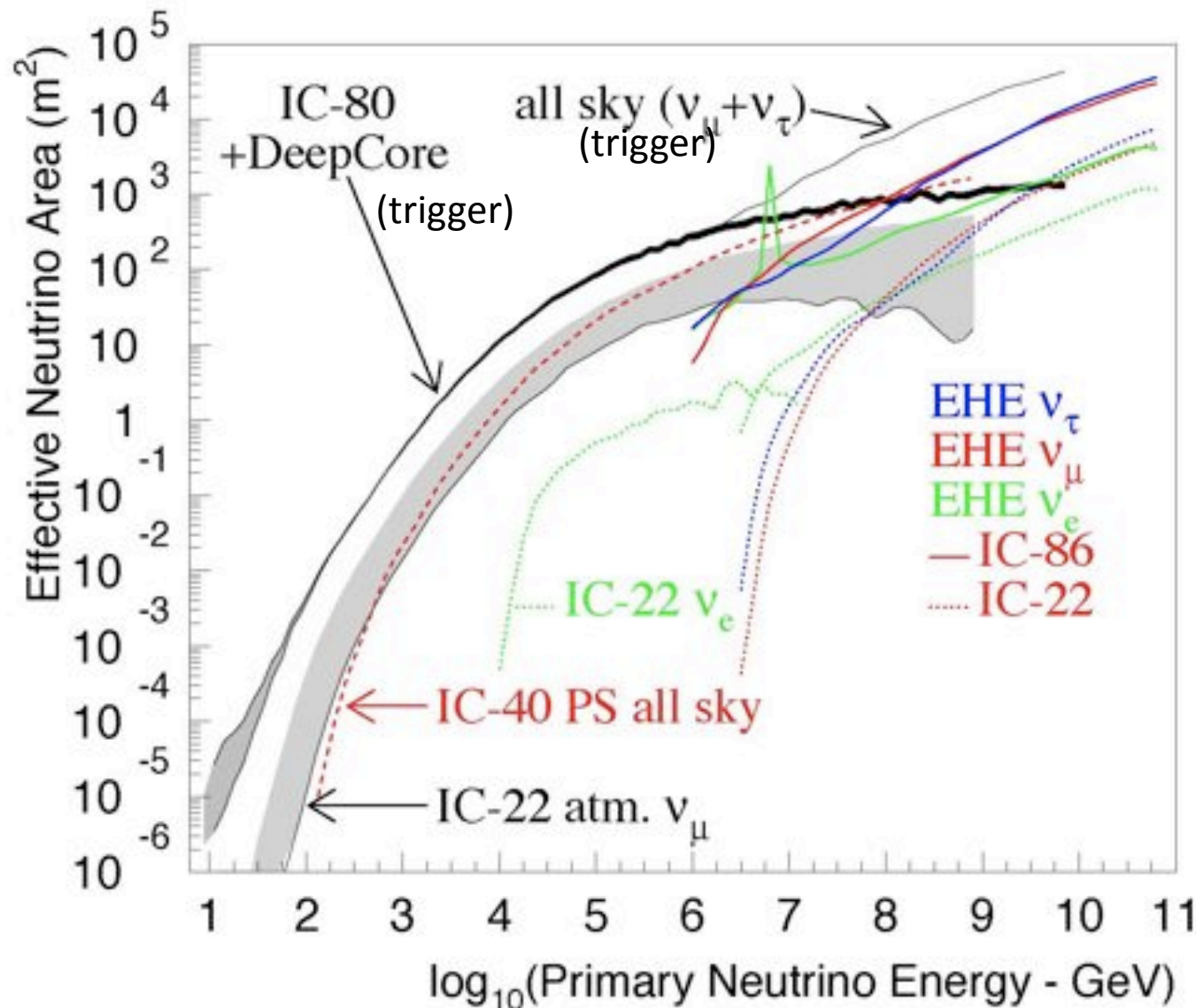
Design expectation 2005: 0.75°

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 2011, on budget and on schedule
- IceCube drill currently in storage at Pole
- High reliability and operational stability
- Performance characteristics meet or exceed design goals.