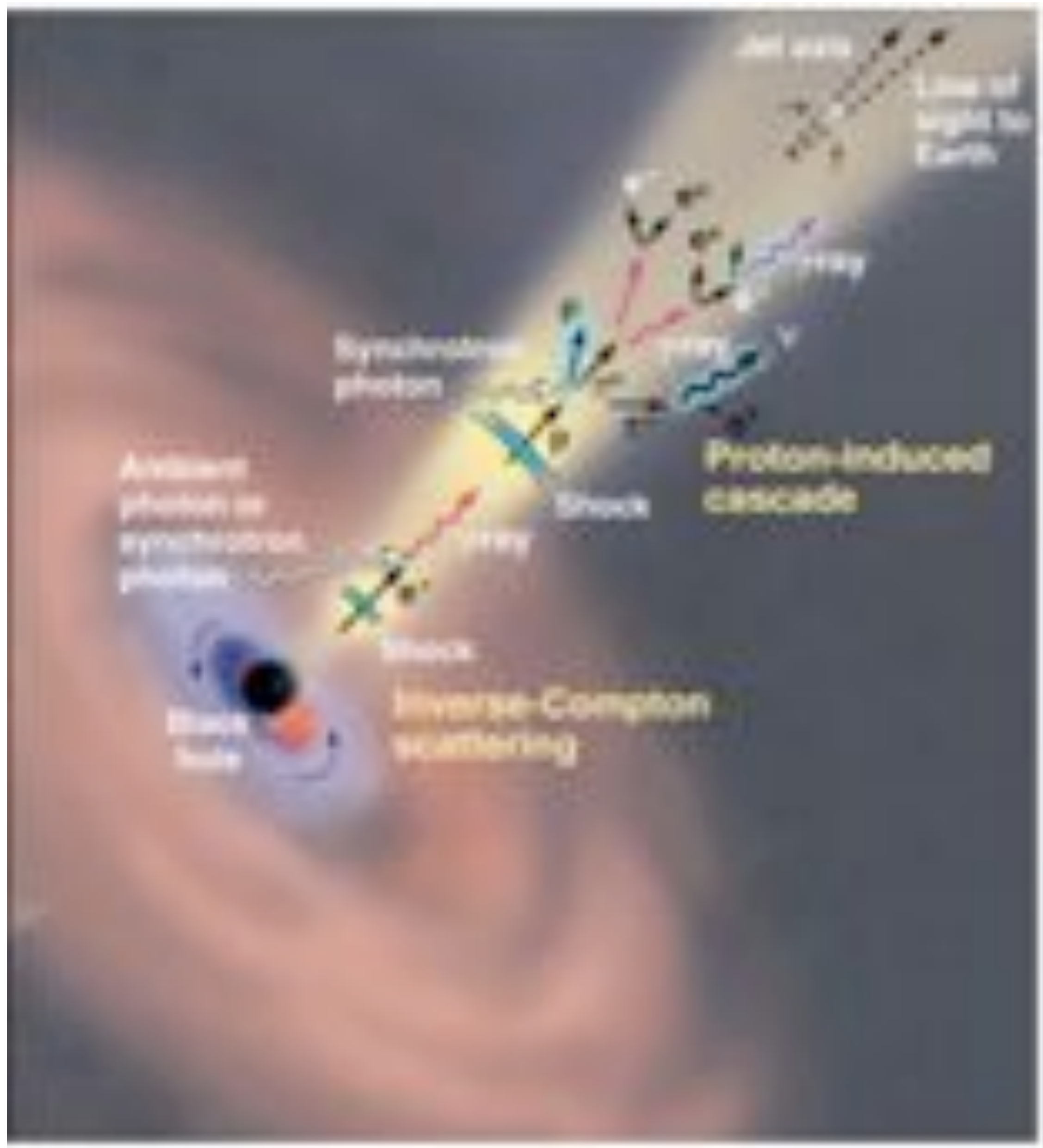
IceCube
- construction, performance and operation

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

Candidate sources (accelerators):

Cosmic ray related:

– SN remnants
– Active Galactic Nuclei
– Gamma Ray Bursts

Other:

– Dark Matter
– Exotics

Guaranteed sources (known targets):

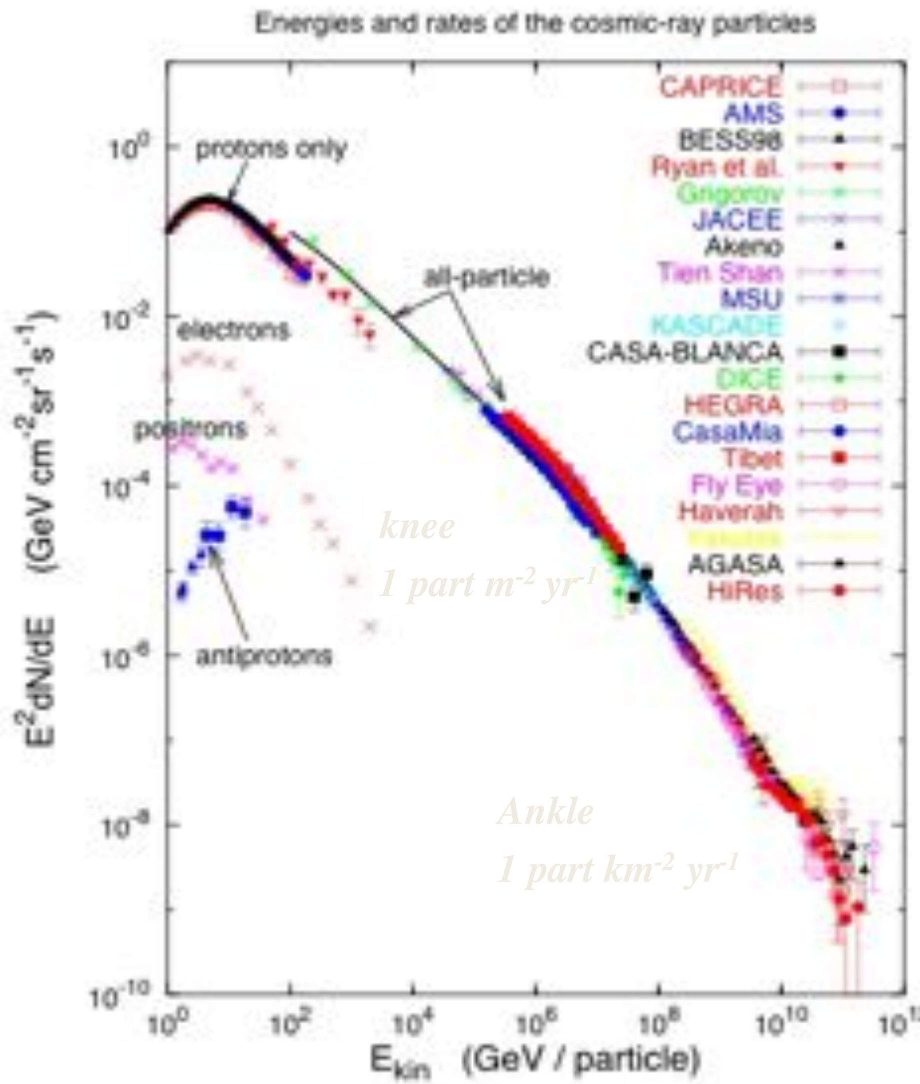
• Atmospheric neutrinos (from π and K decay)

• Galactic plane: CR interacting with ISM, concentrated on the disk

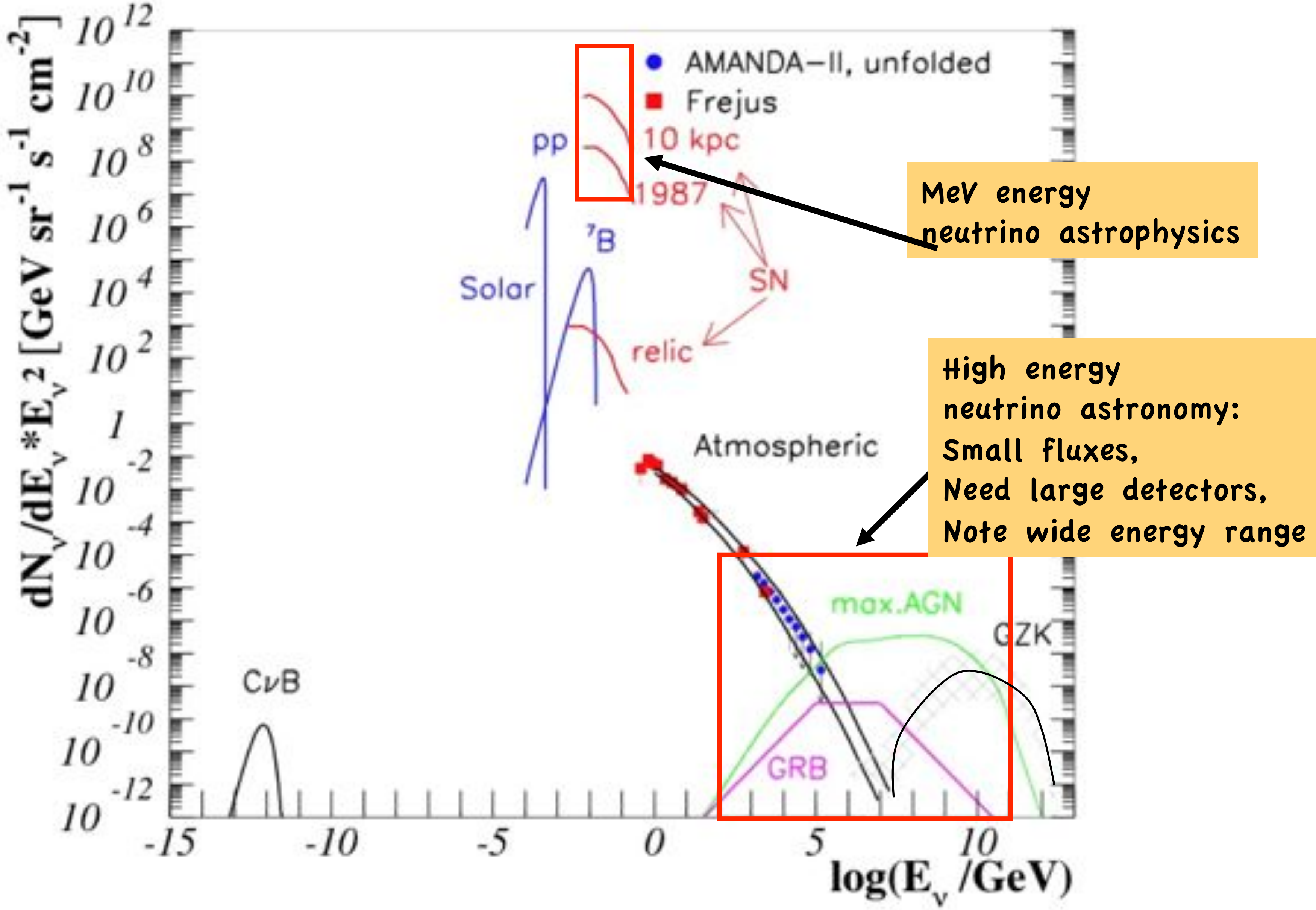
• GZK (cosmogenic neutrinos)

T. Gaisser 2005

Cosmic rays



Neutrinos


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

Neutrinos

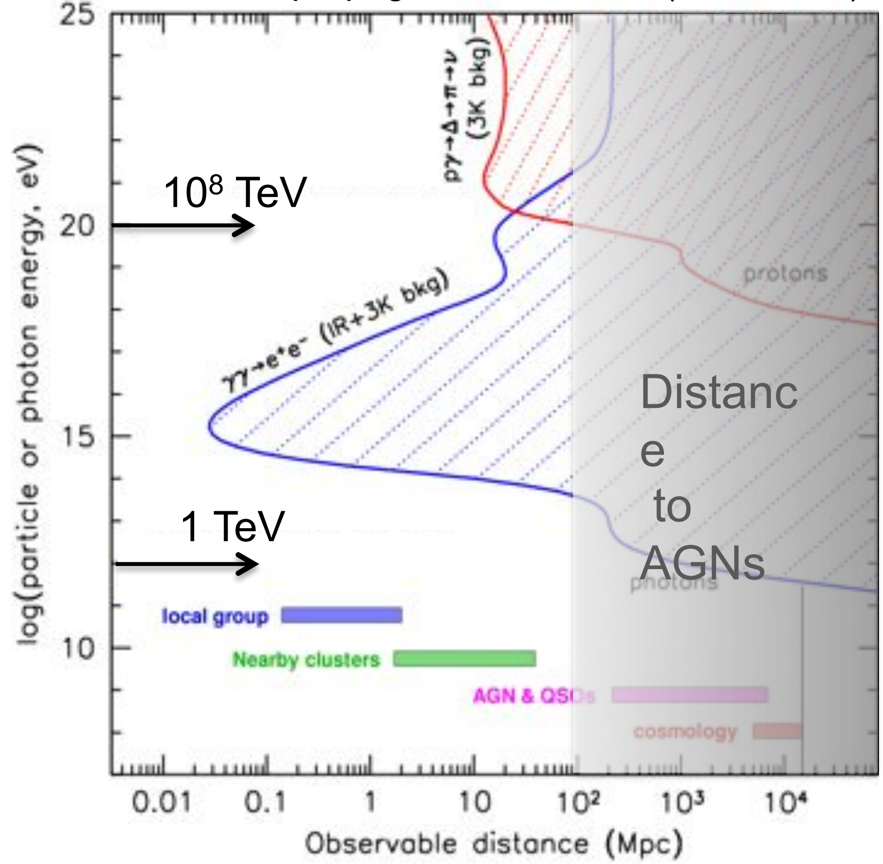
Gamma astronomy limited in energy scale.

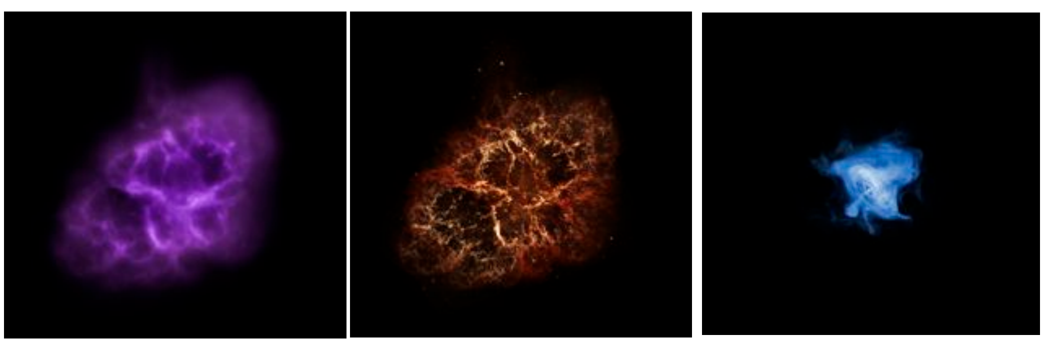
Above 100 TeV, universe is **opaque for photons**, due to pair-production off background radiation fields (CMB, IR)

Cosmic ray sources may be optically thick for gammas but not neutrinos; reveal **“hidden”** sources

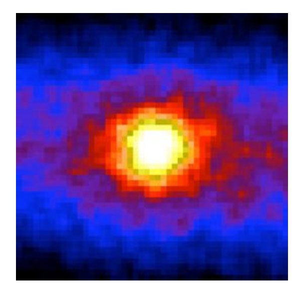
Neutrinos are unique and complementary astrophysical probe

Photon propagation distances (P. Gorham)



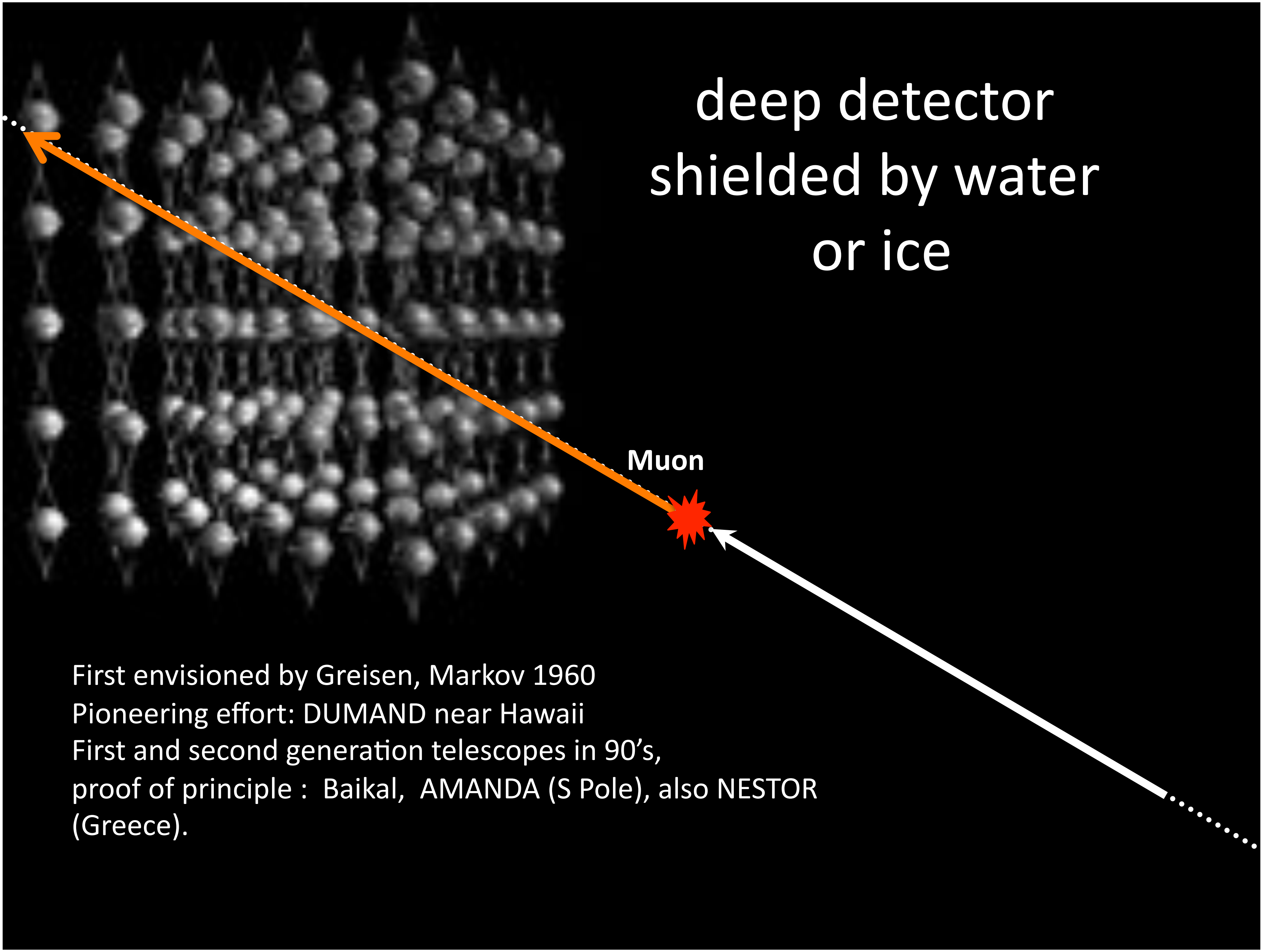


The Crab, in infrared (Spitzer), optical (Hubble), x-ray (Chandra)



The sun, “seen” in MeV neutrinos by Super-Kamiokande

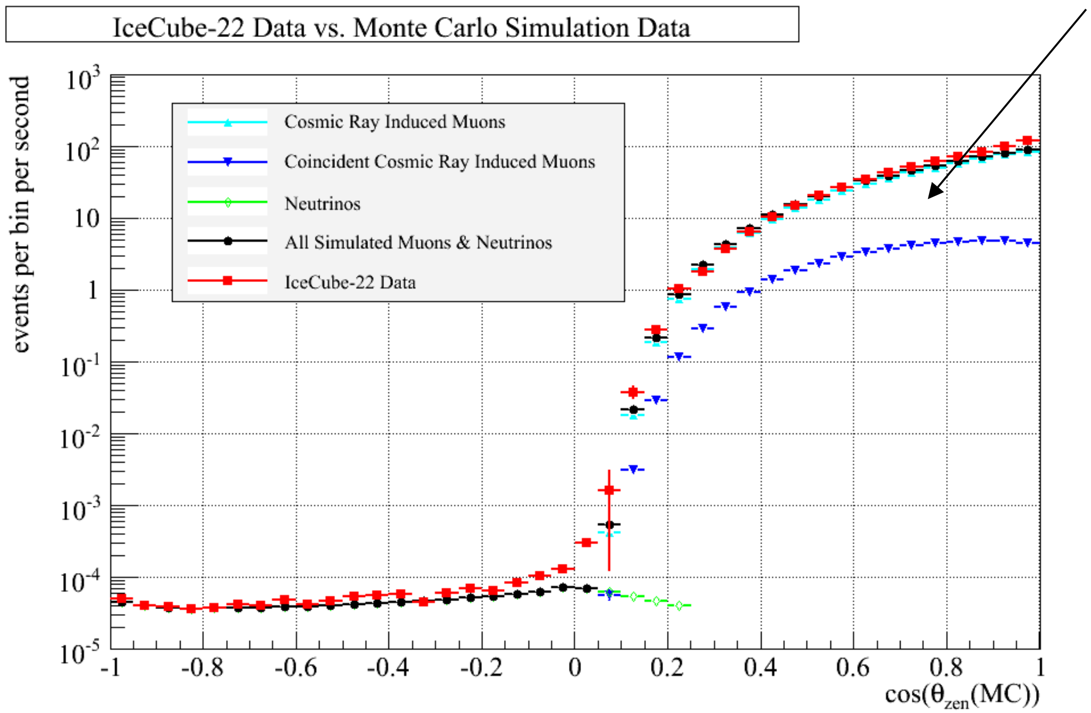
A few remarks on the beginnings of IceCube


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



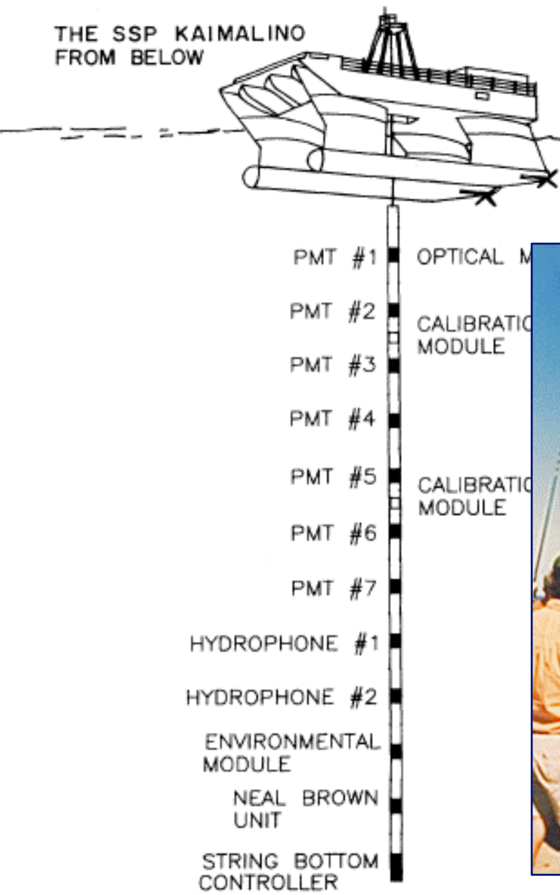
→ *P. Berghaus et al., ISVHECRI-08, also HE1.5*

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

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

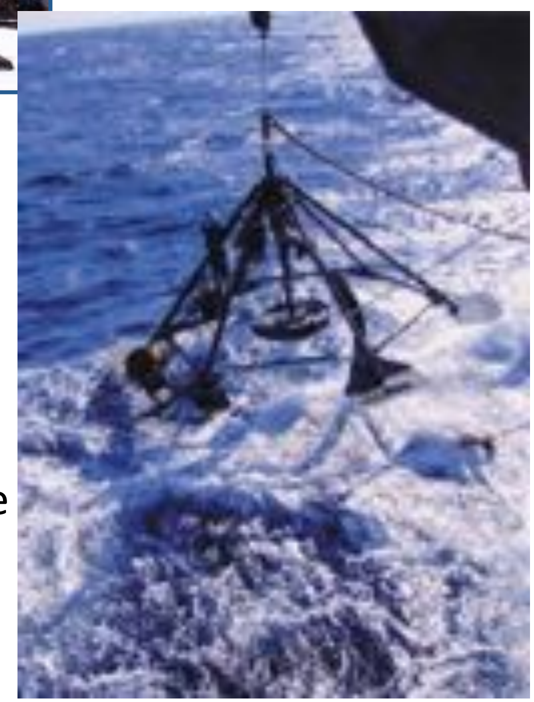
Early Projects in water

DUMAND
(Hawaii)



Baikal

NESTOR
of the shore of Greece



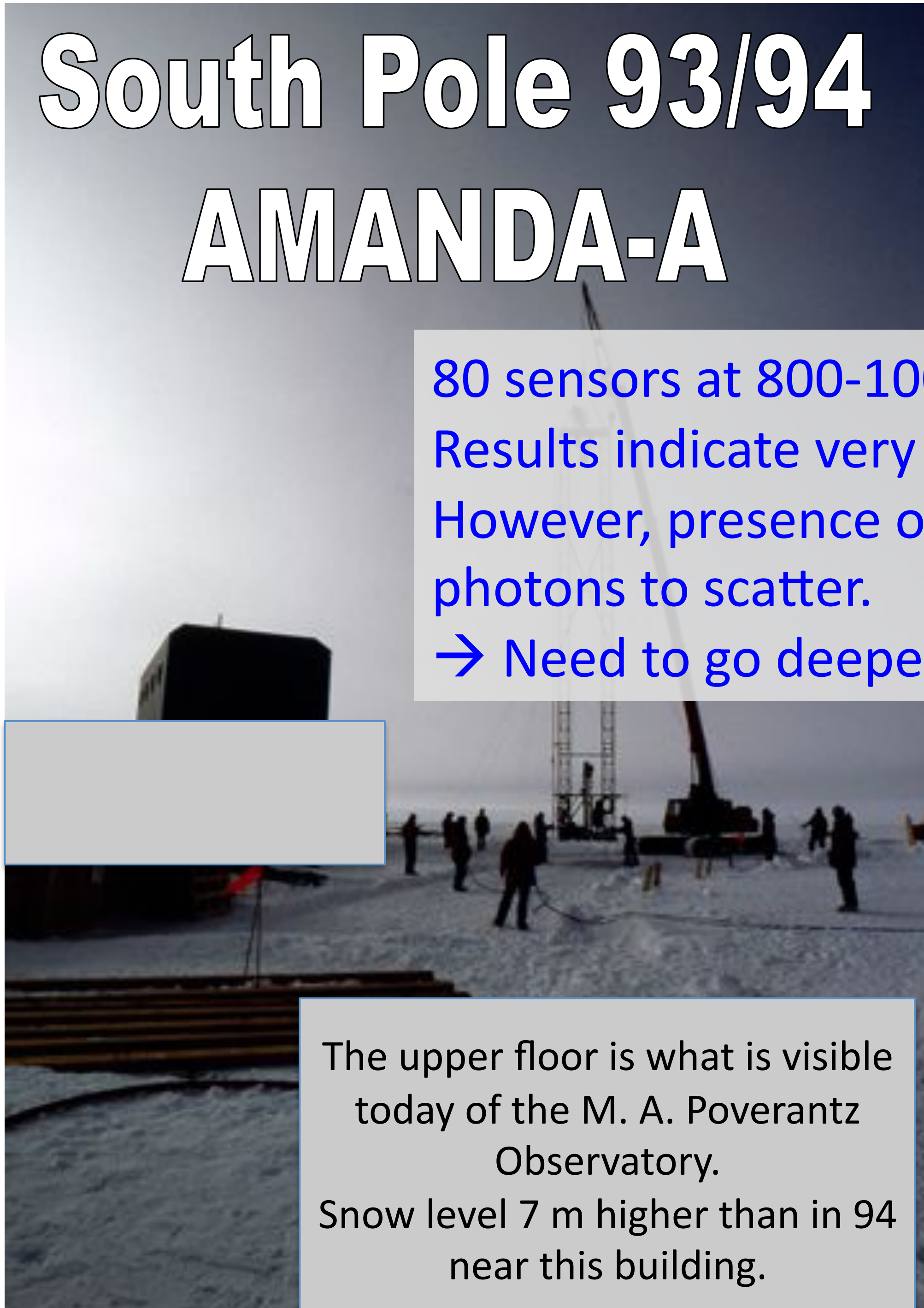
South Pole *- the ice option*

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

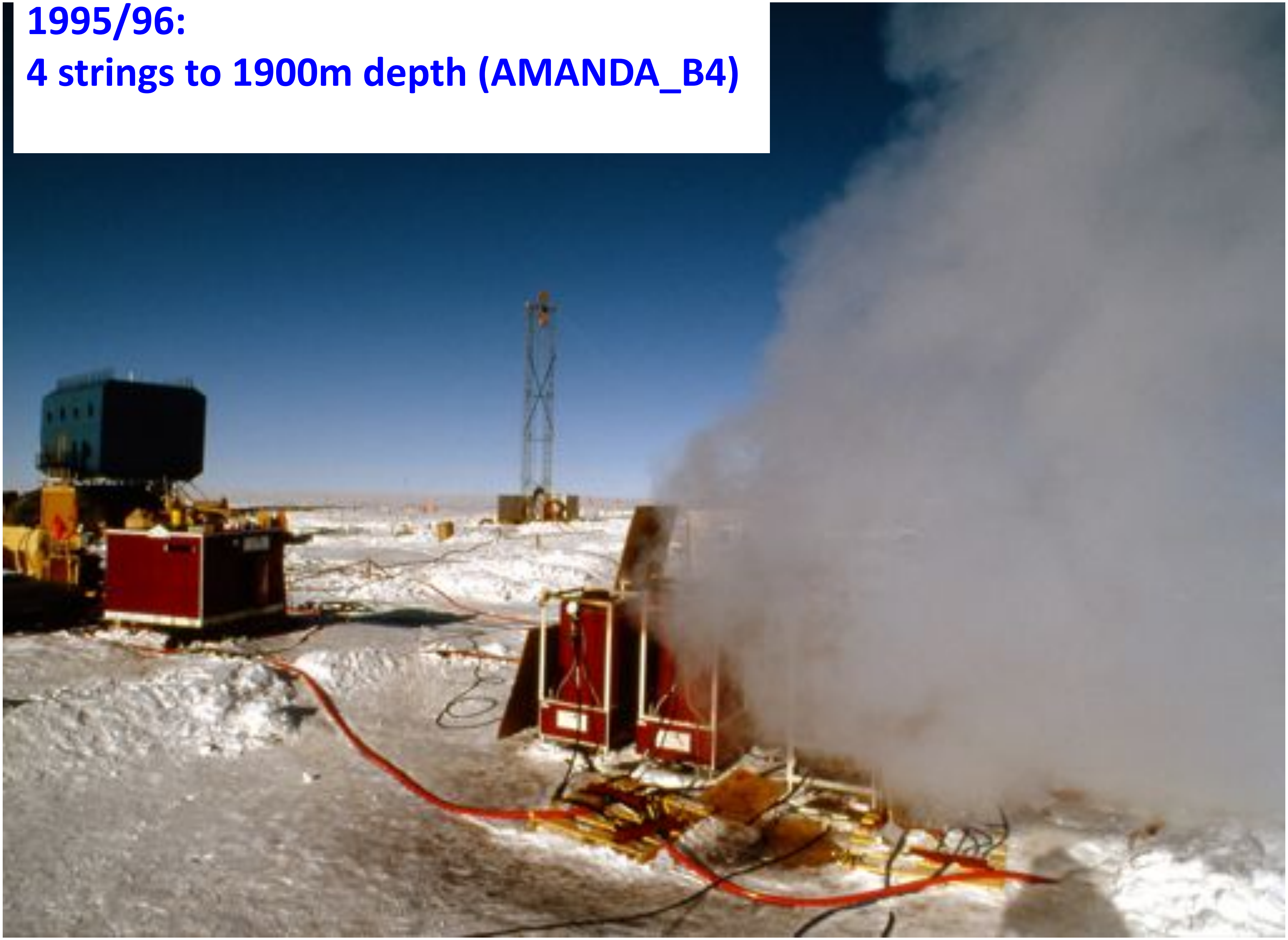


80 sensors at 800-1000 m depth.
Results indicate very little absorption,
However, presence of bubbles causes
photons to scatter.
→ Need to go deeper!

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)



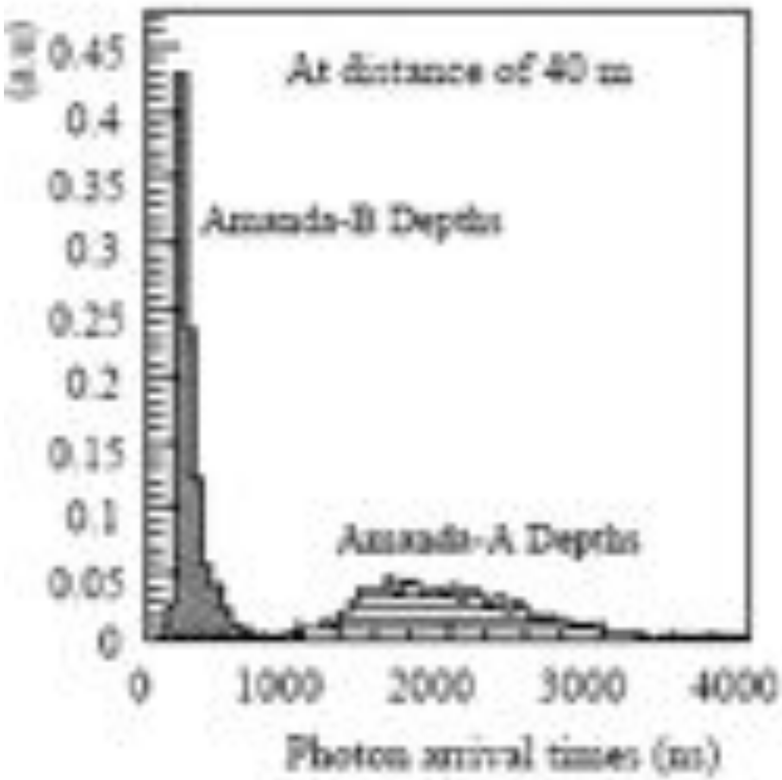
1995/96:

→The ice is clear.

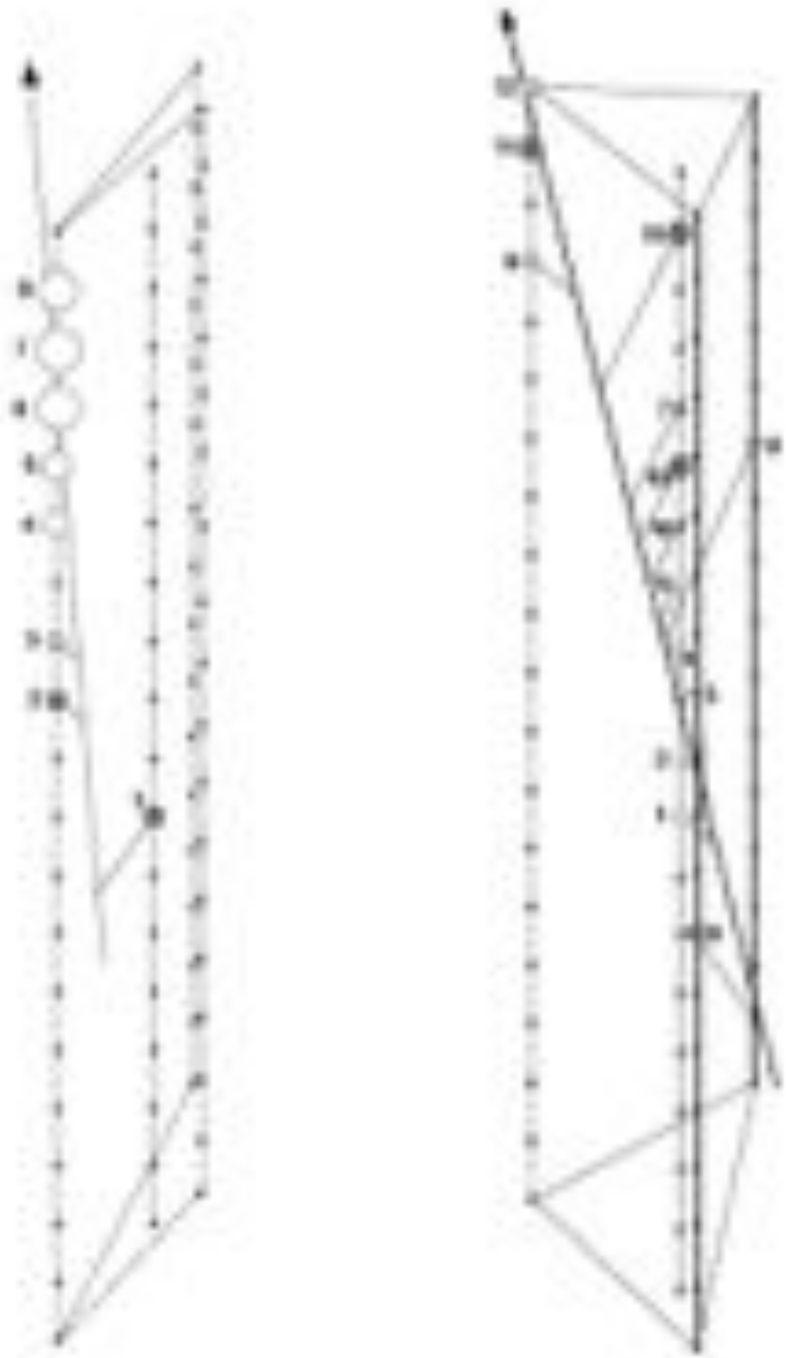
→PMTs work 2000m under ice

→Suitable for a neutrino telescope!

Significant international contributions to instrument hardware.



B4: first 2 neutrino candidates →



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

In the meantime, AMANDA-II WAS DEPLOYED

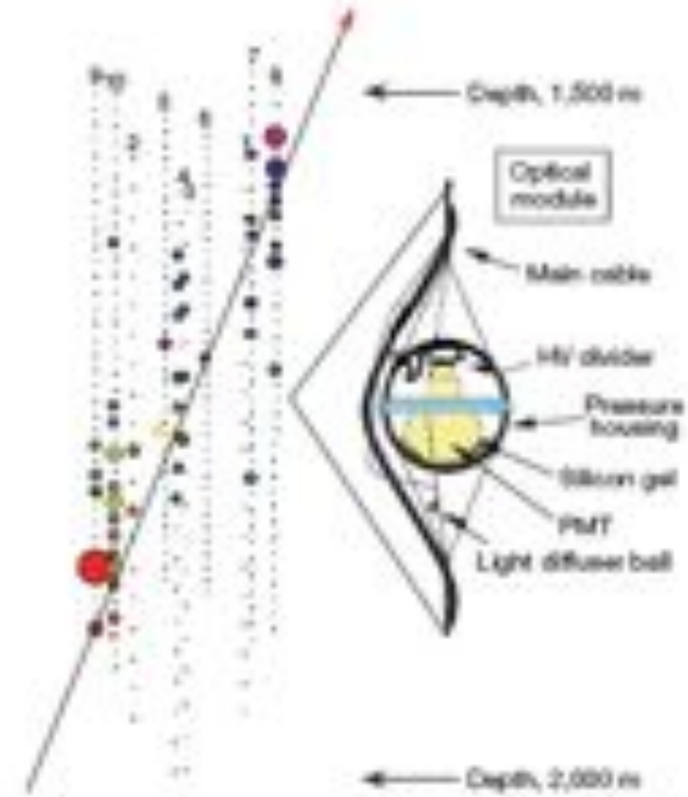


Figure 1 The AMANDA-B10 detector and a schematic diagram of an optical module. Each dot represents an optical module. The modules are separated by 20 m on the inner strings (1 to 4), and by 10 m on the outer strings (5 to 10). The coloured circles show pulses from the photomultipliers for a particular 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.

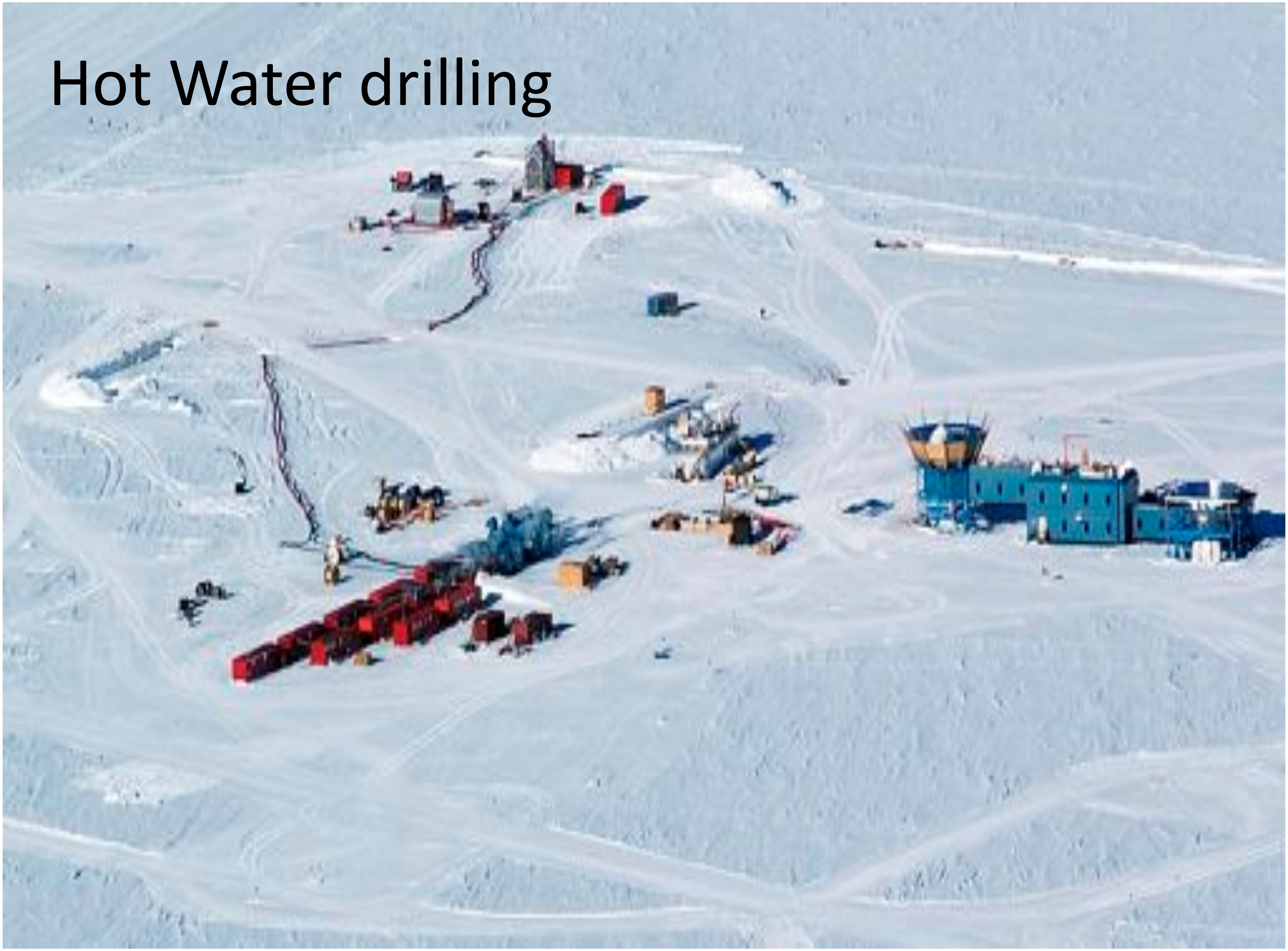
IceCube

start 05-06

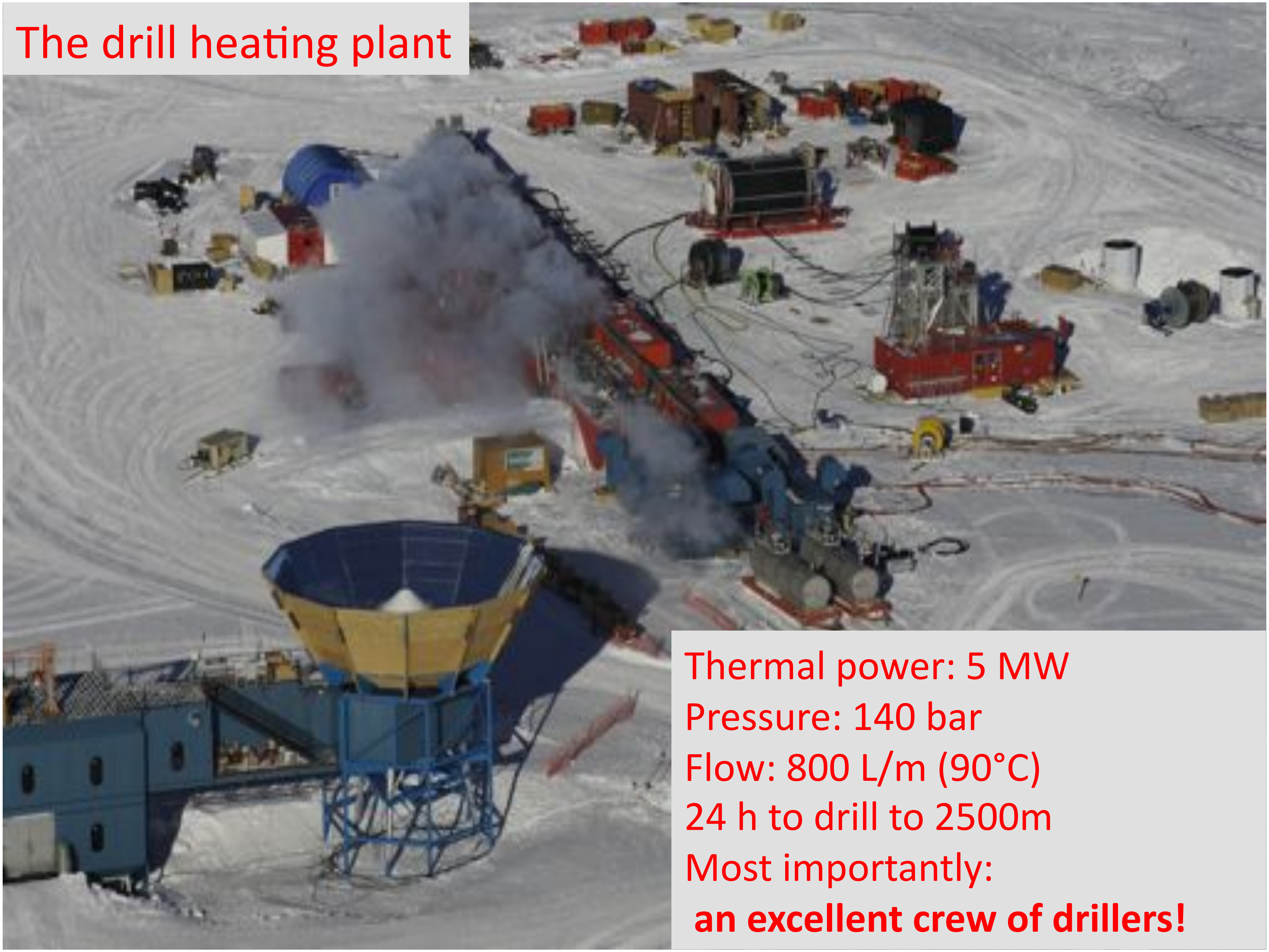
- 1 million pounds of cargo
- C-130 planes: > 50 flights

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

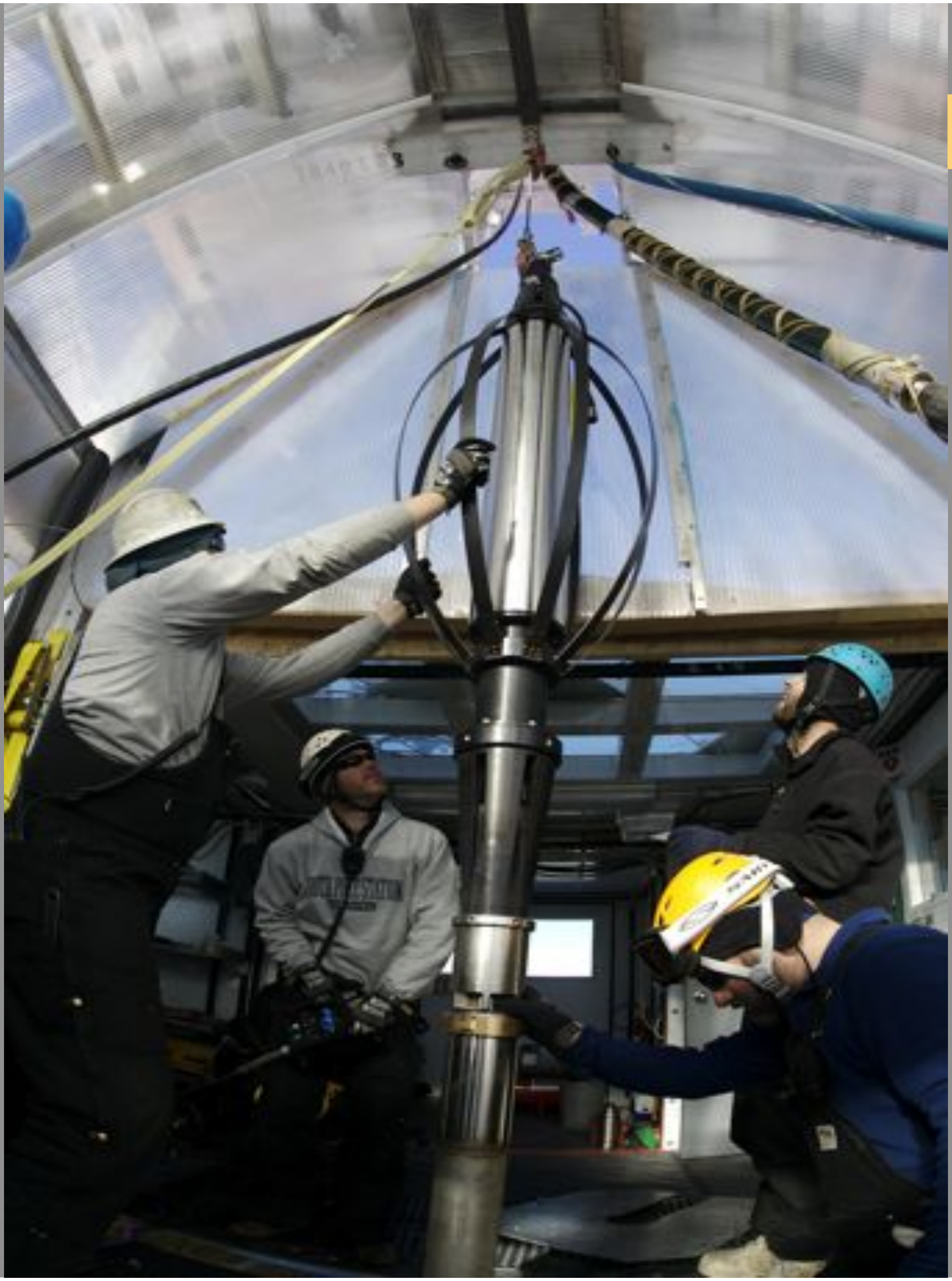
Hot Water drilling



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!

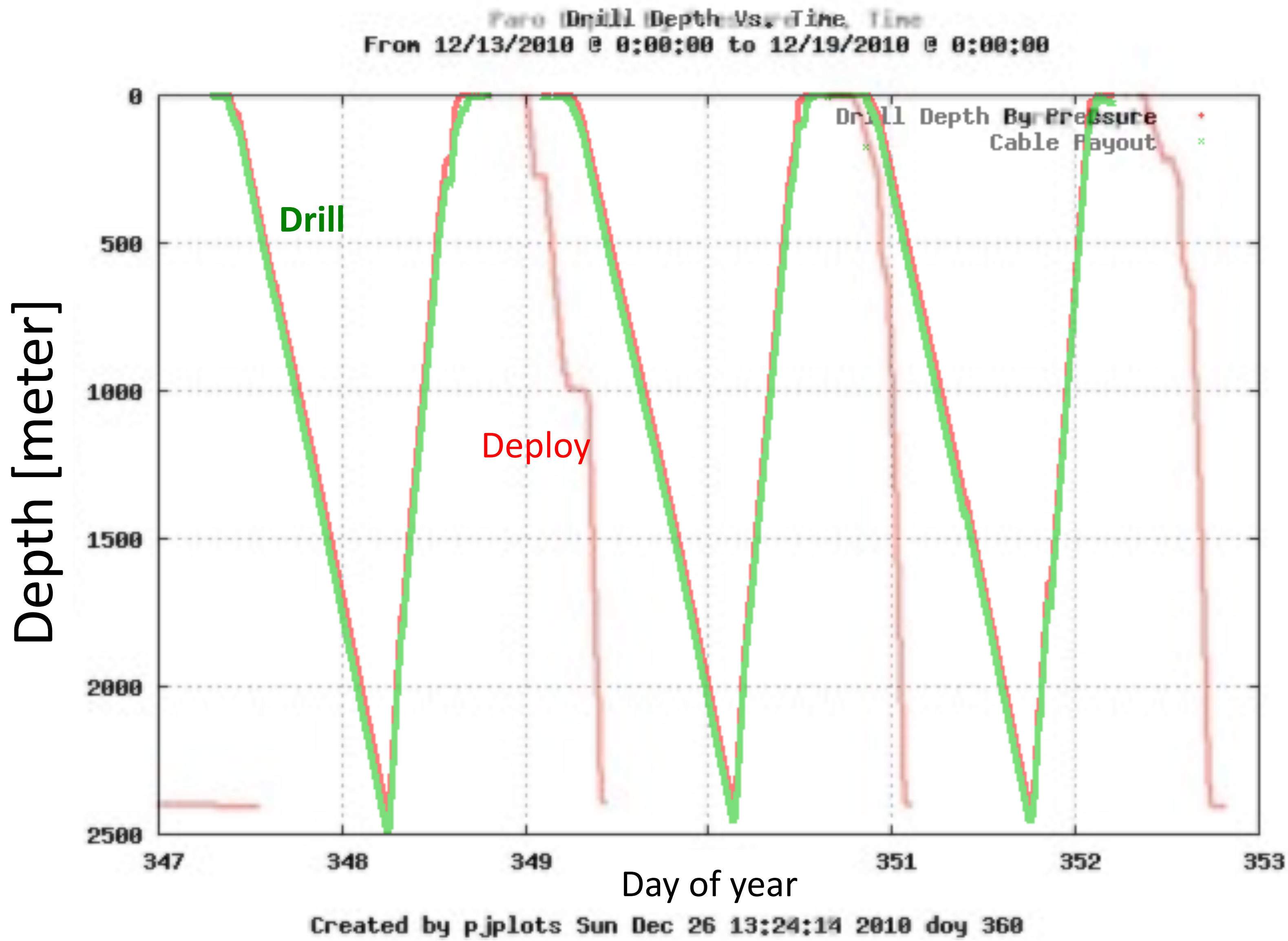


Drillers pull out the drillhead.

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



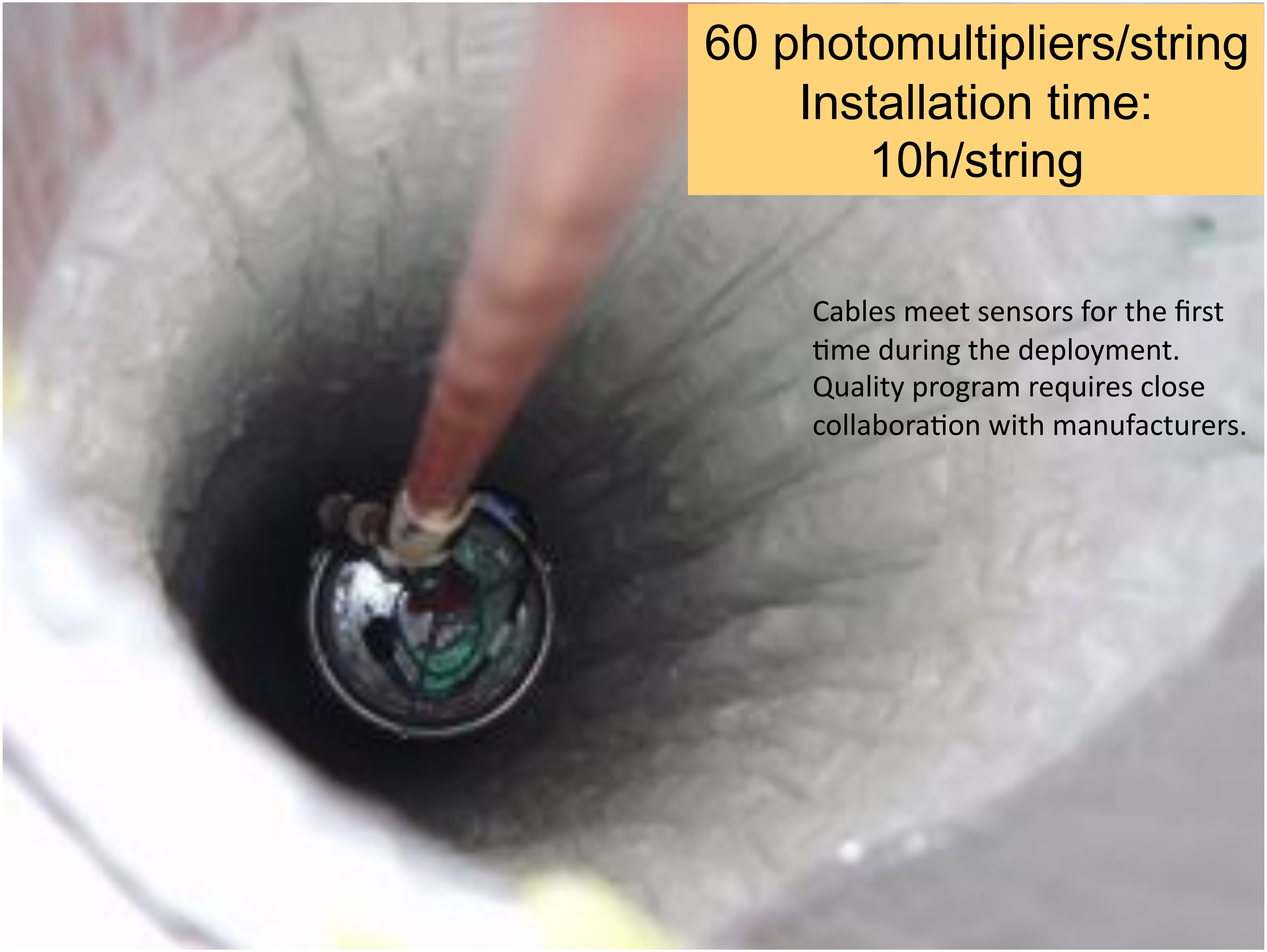
The IceCube Drill in long term storage configuration

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

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

The IceCube Collaboration

USA:

Bartol Re
Universit
Universit
Pennsylv
Clark-Atl
Ohio Sta
Georgia T
Universit
Universit
Universit
Universit
Lawrenc
Universit
Souther
College
Universit

ersity

ury

>33 institutions, >250 members

http://icecube.wisc.edu

AMANDA and IceCube deployments

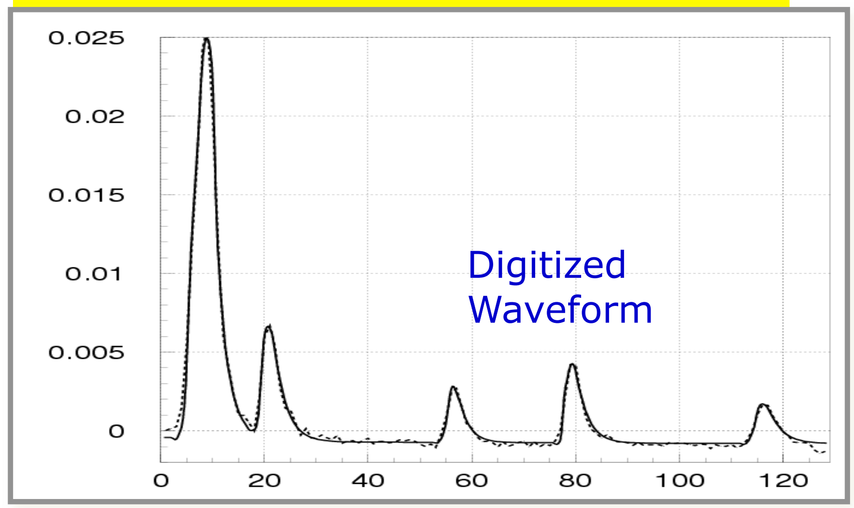
Season	Campaign	Strings deployed	Cumul. Strings	Cum Sensors	Depth		Nu's/yr	resol. [°]
1991/92	exploratory activity			few small PM	shallow depth		0	
1992/93								
1993/94	AMANDA-A	4	4	80	800-1000m		0	
1994/95								
1995/96	AMANDA-B4	4	4	86	1500-1950	one stuck & retrieved	2 (unpubl.)	
1996/97	AMANDA-B10	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	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 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)

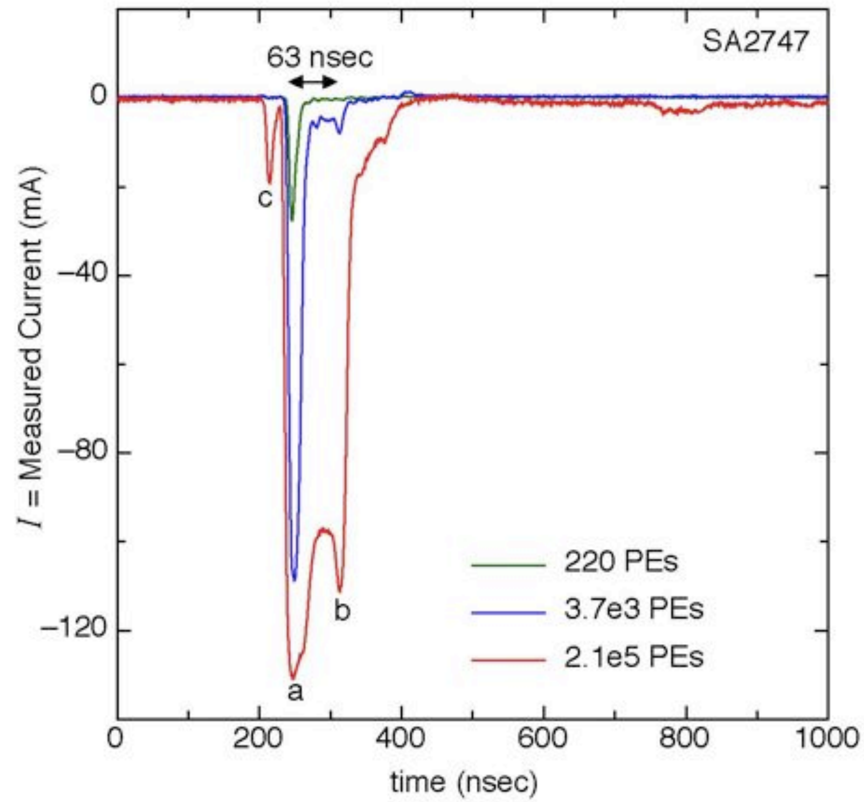
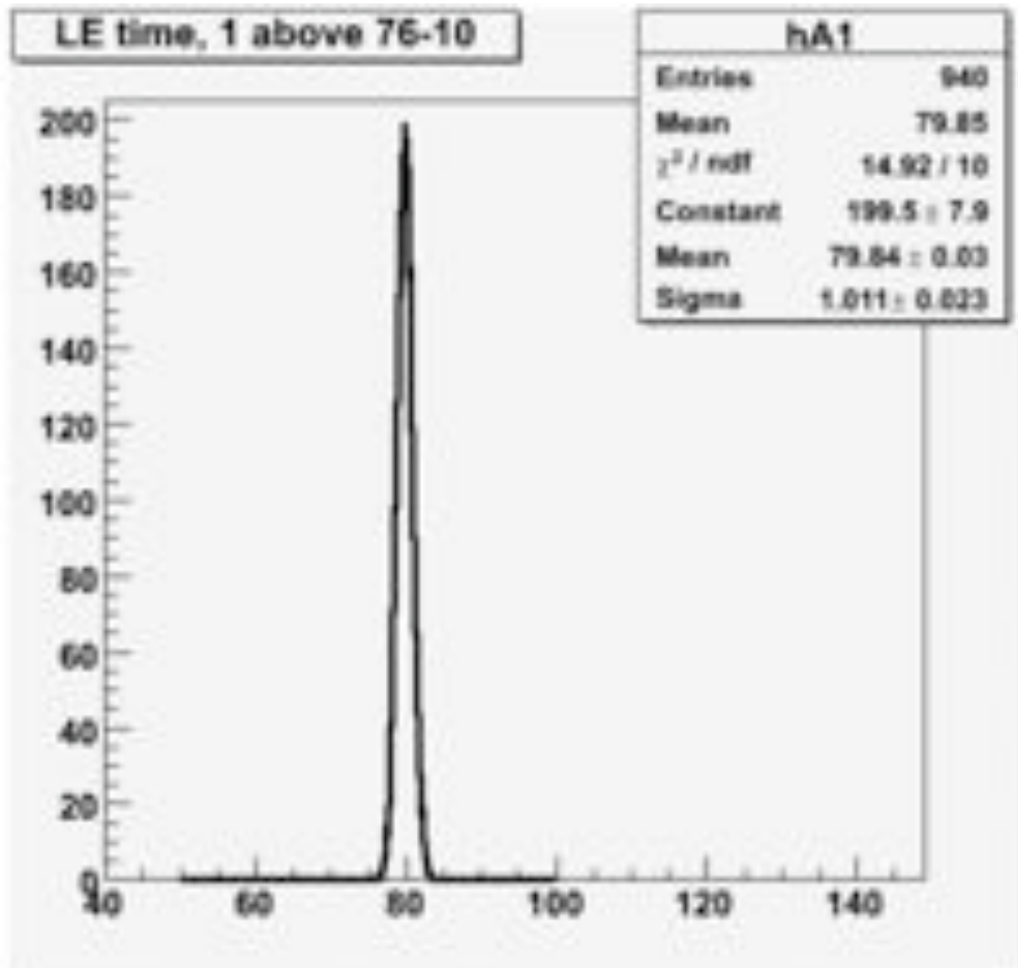


Fig. 16. Response of PMT to 3 ns (FWHM) light pulses with progressively higher-intensity: (a) main peak; (b) secondary peak due to unusual electron trajectories; (c) pre-pulse.

Time resolution:
~1ns for bright pulses

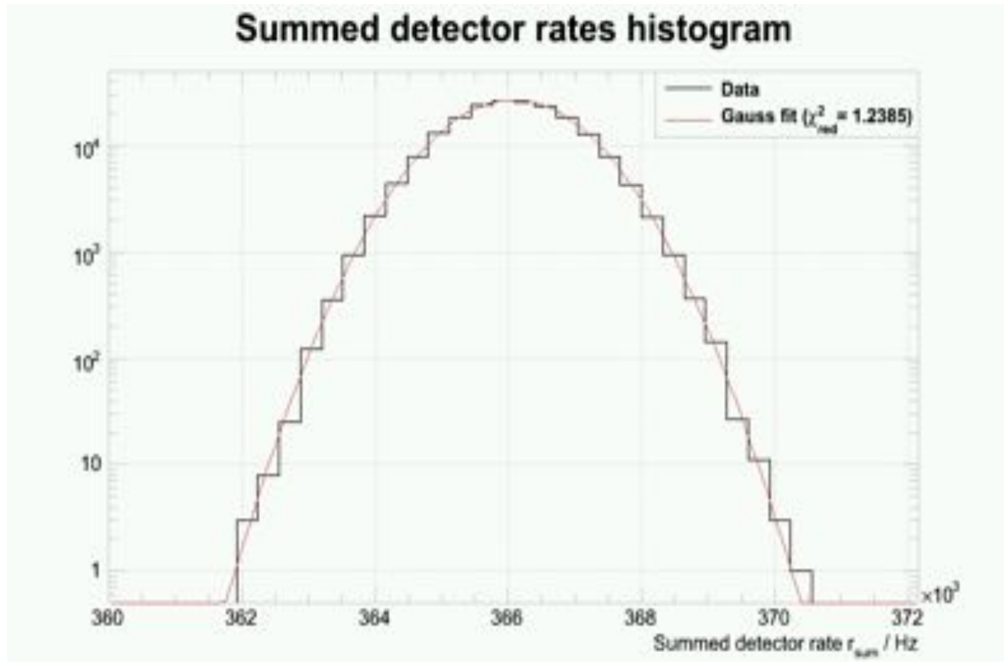
- Time difference between neighboring DOMs fired with (bright) flasher pulses: 1 ns.

- 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 / DOM (w deadtime): 284.9 +/- 26.2 Hz
- DOM noise: stable and as expected.



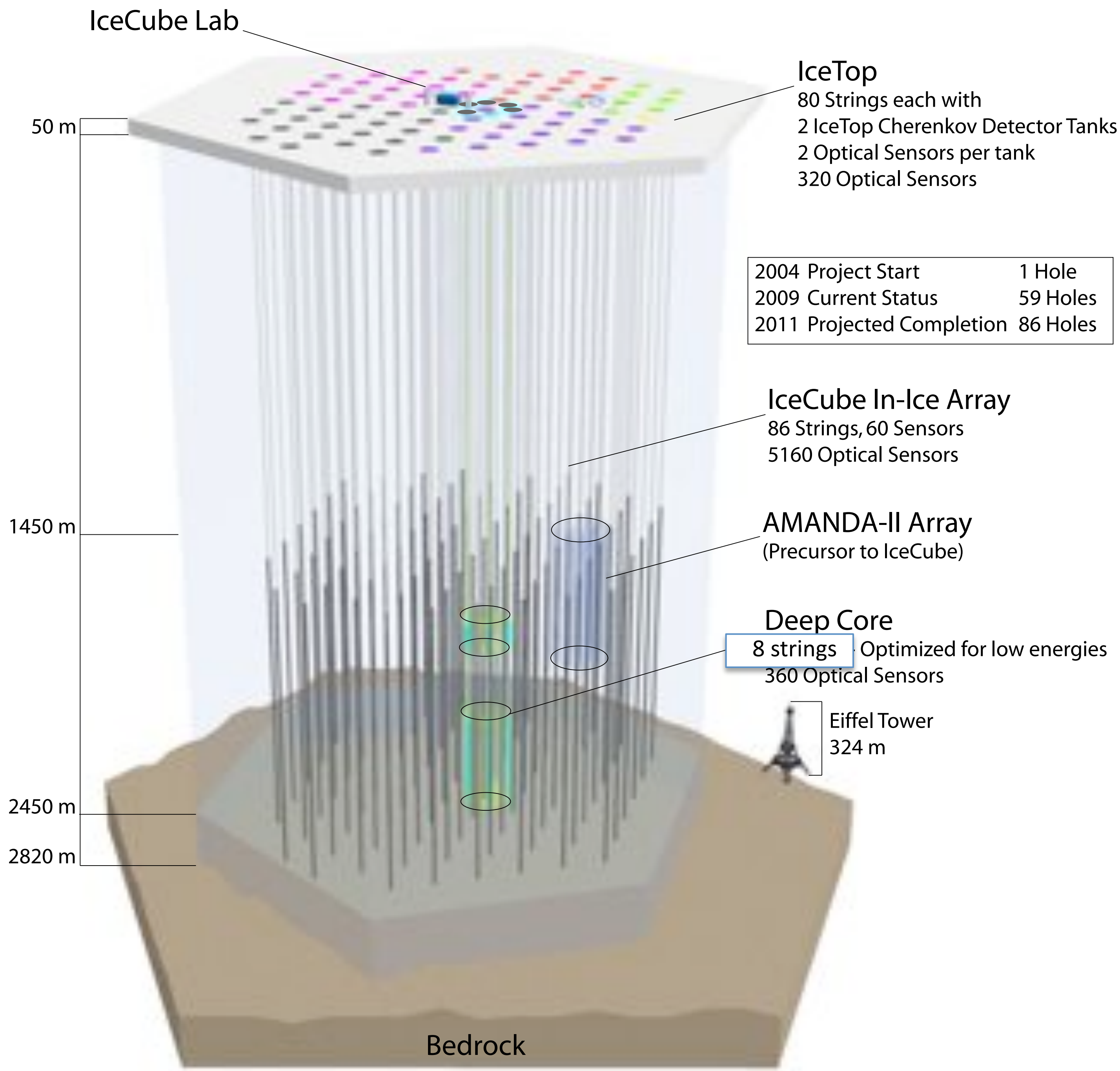
→ msec resolution of neutrino emission profile of galactic supernova core collapse

(Older figure,
When noise was a little higher)

IceCube

86 strings
81 IceTop stations
5480 optical sensors

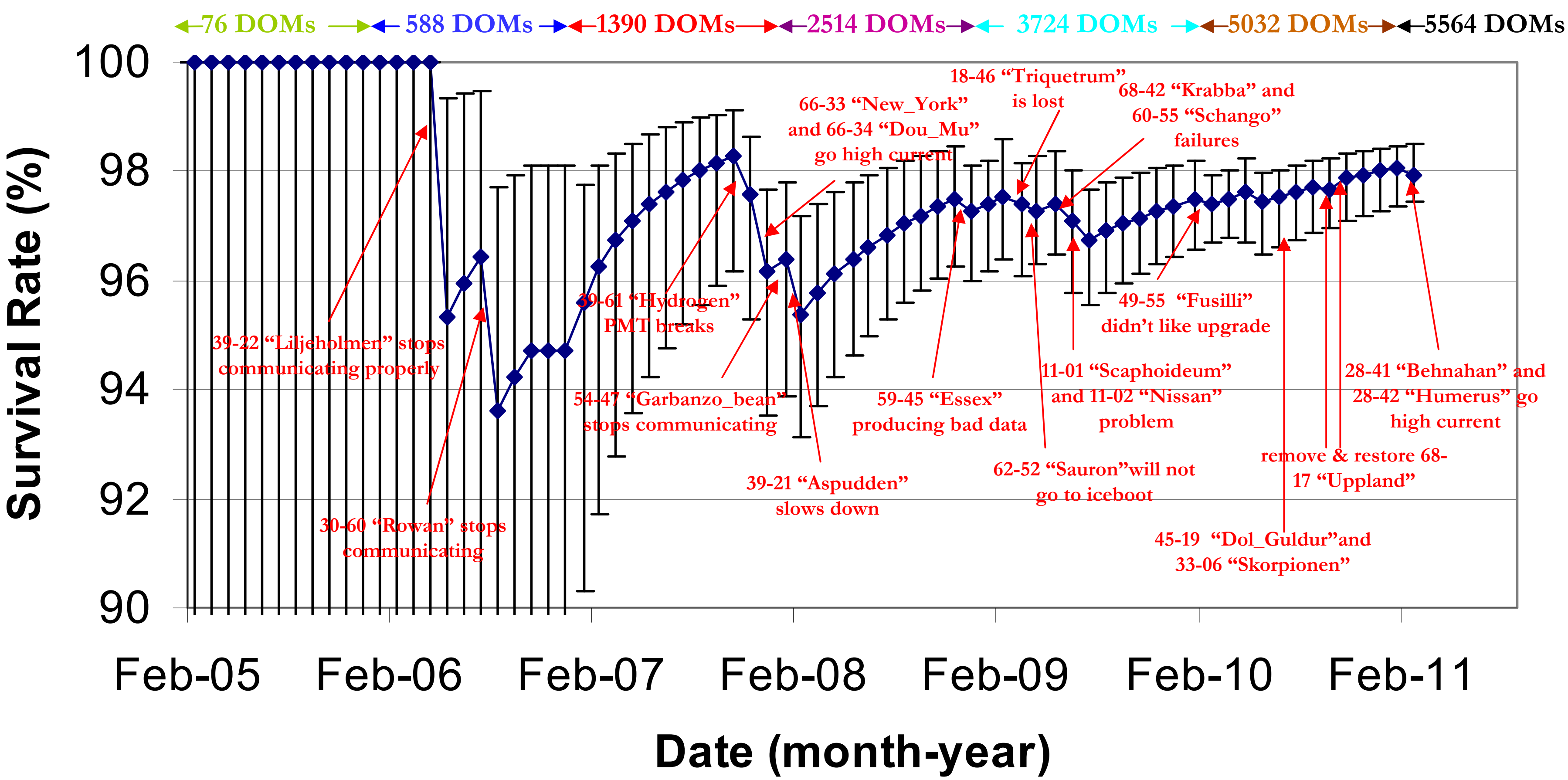
1 billion tons of ice



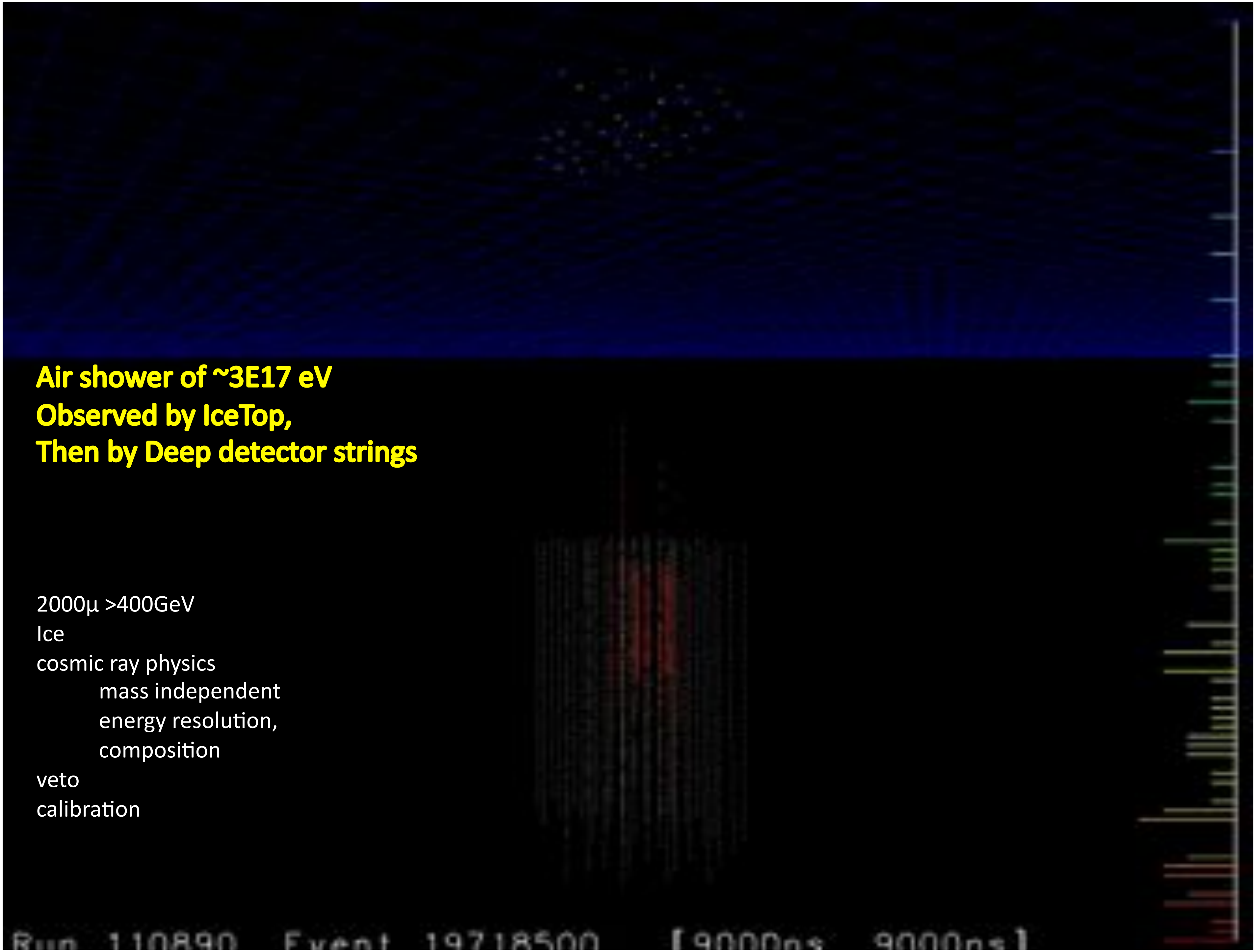
Reliability of sensors
- survival rates before and after commissioning

- 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)



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



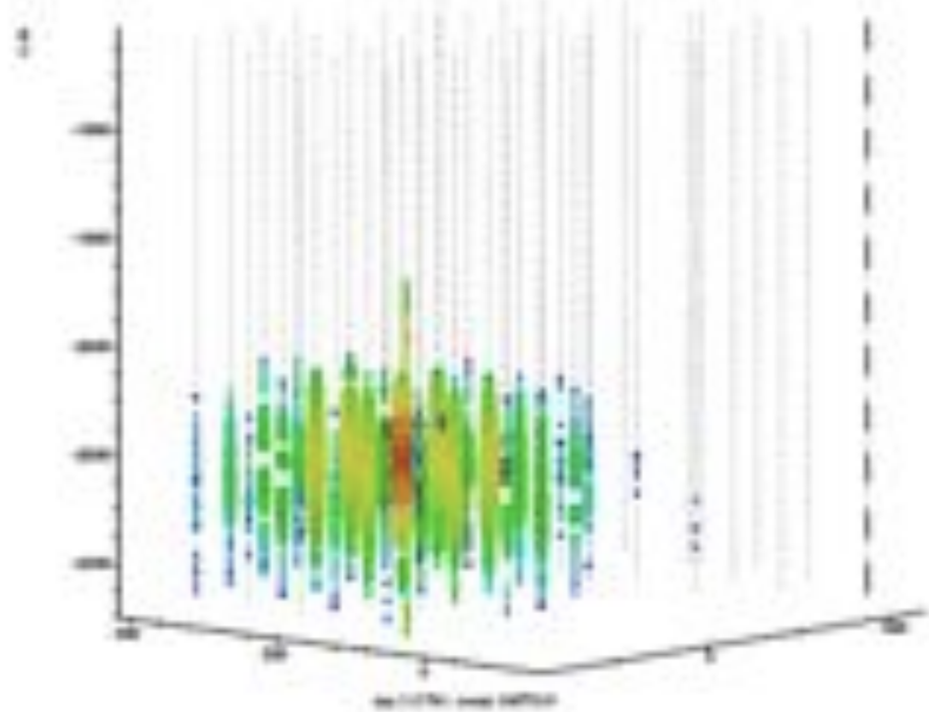
2000μ >400GeV
Ice
cosmic ray physics
- mass independent
- energy resolution,
- composition

veto
calibration

Flasher events used for calibration

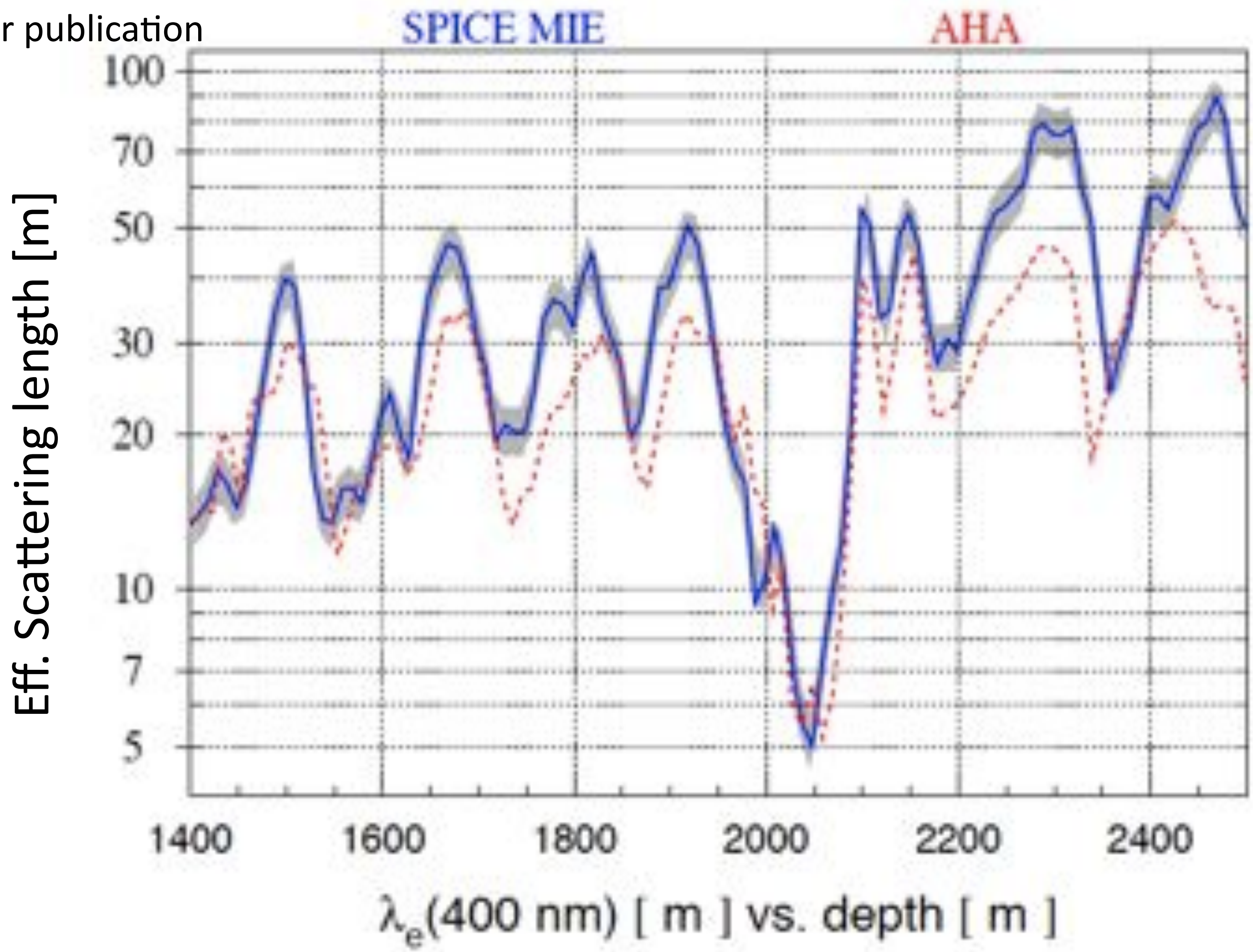
All sensors are equipped
with a set of 12 LED flashers.
A 30 ns pulse of only
10 billion photons (400nm)
is visible to a distance of 600m.

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

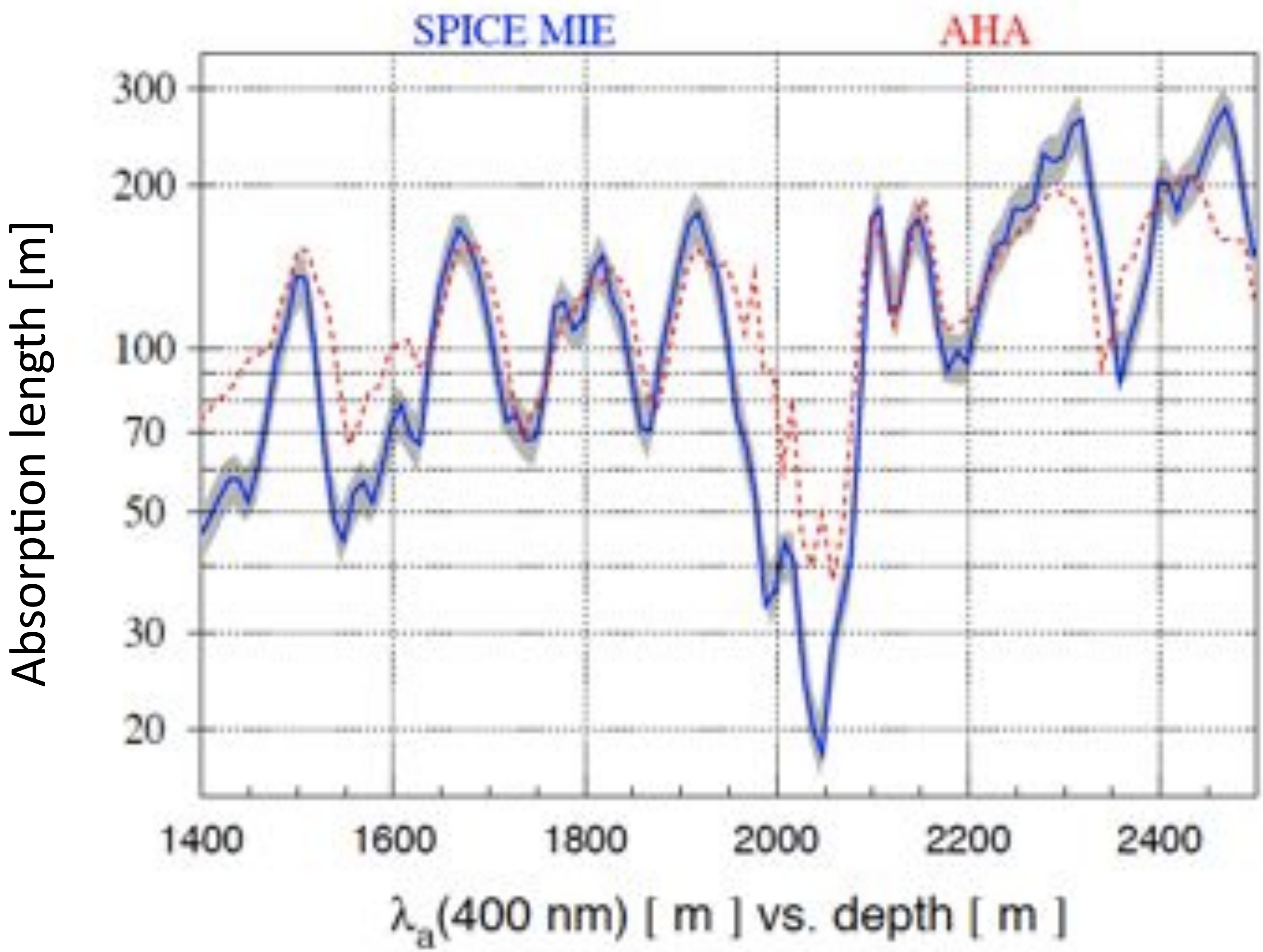


The Ice is very clear
Effective scattering length vs Depth

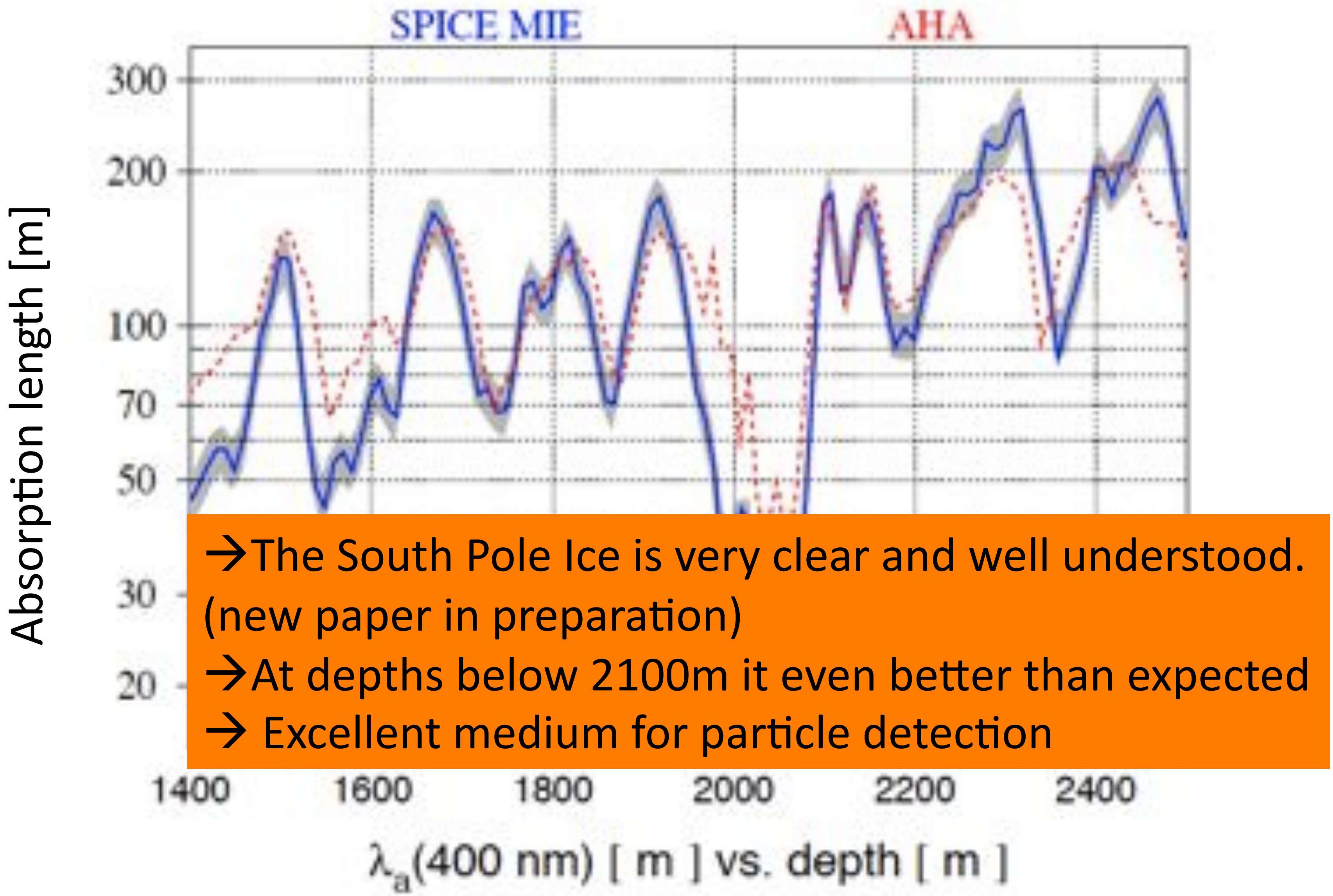
in internal review
for publication



Absorption length vs Depth



Absorption length vs Depth

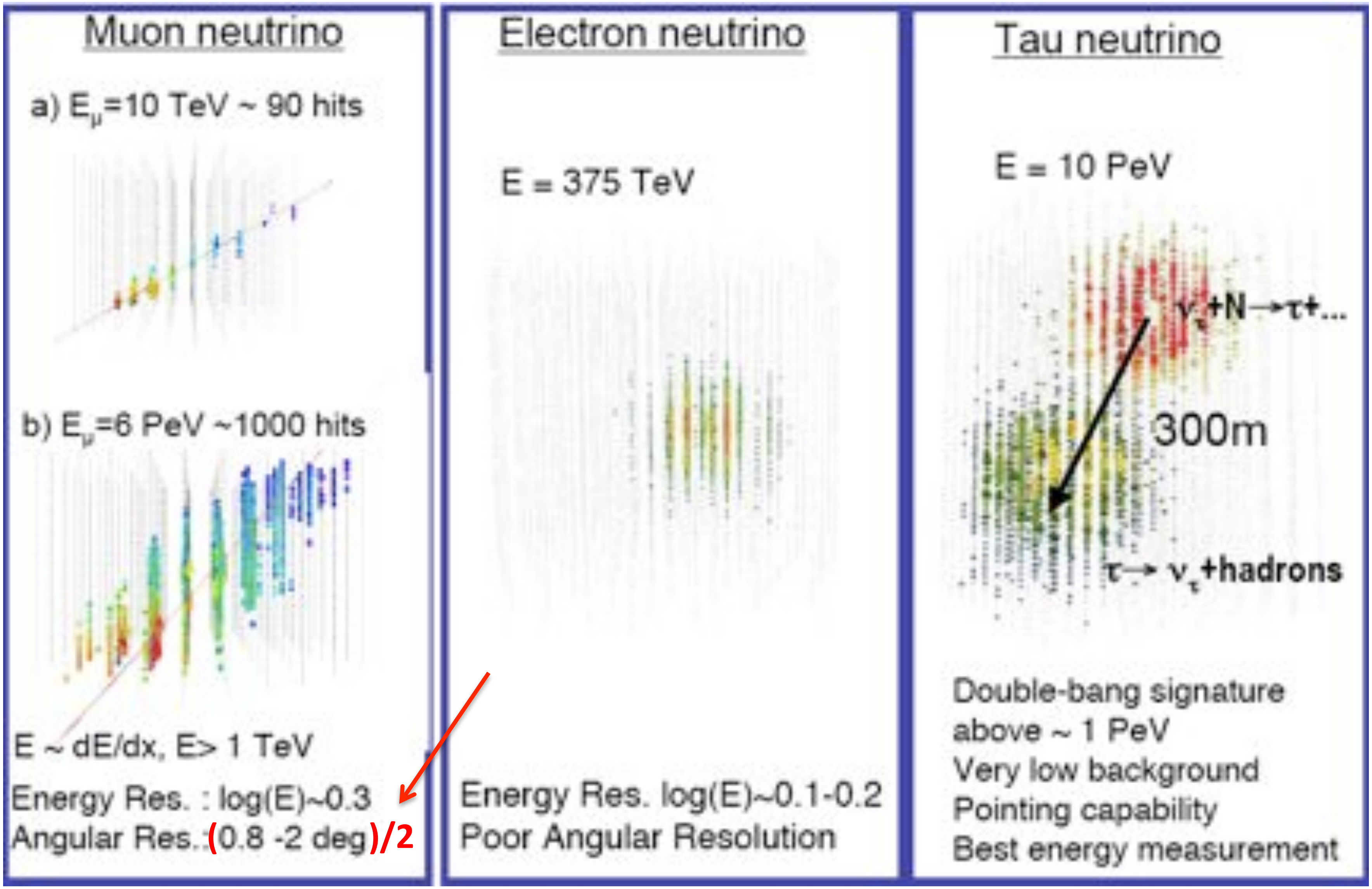


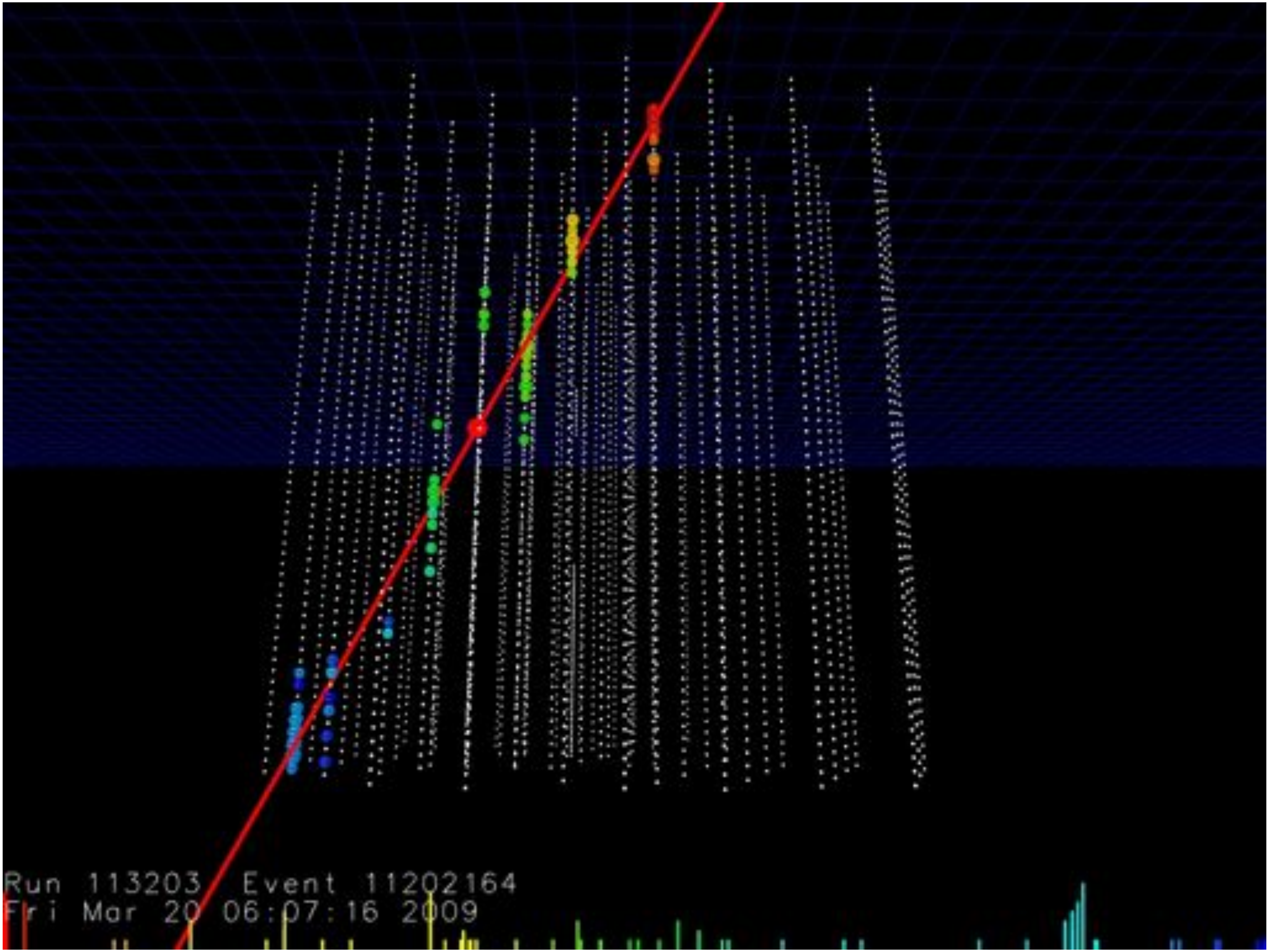
→The South Pole Ice is very clear and well understood. (new paper in preparation)

→At depths below 2100m it even better than expected

→ Excellent medium for particle detection

Neutrino Topologies




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

Angular resolution

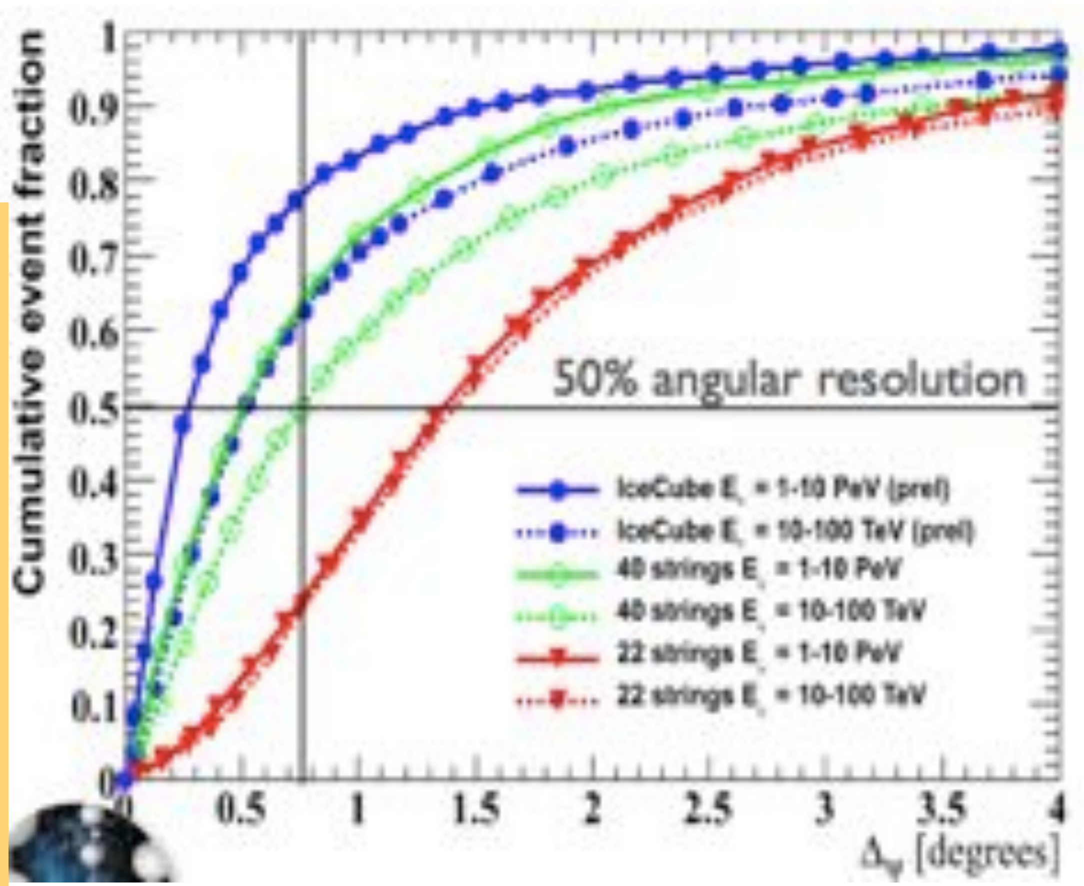
Median angular resolution

10 – 100 TeV (1 – 10 PeV)

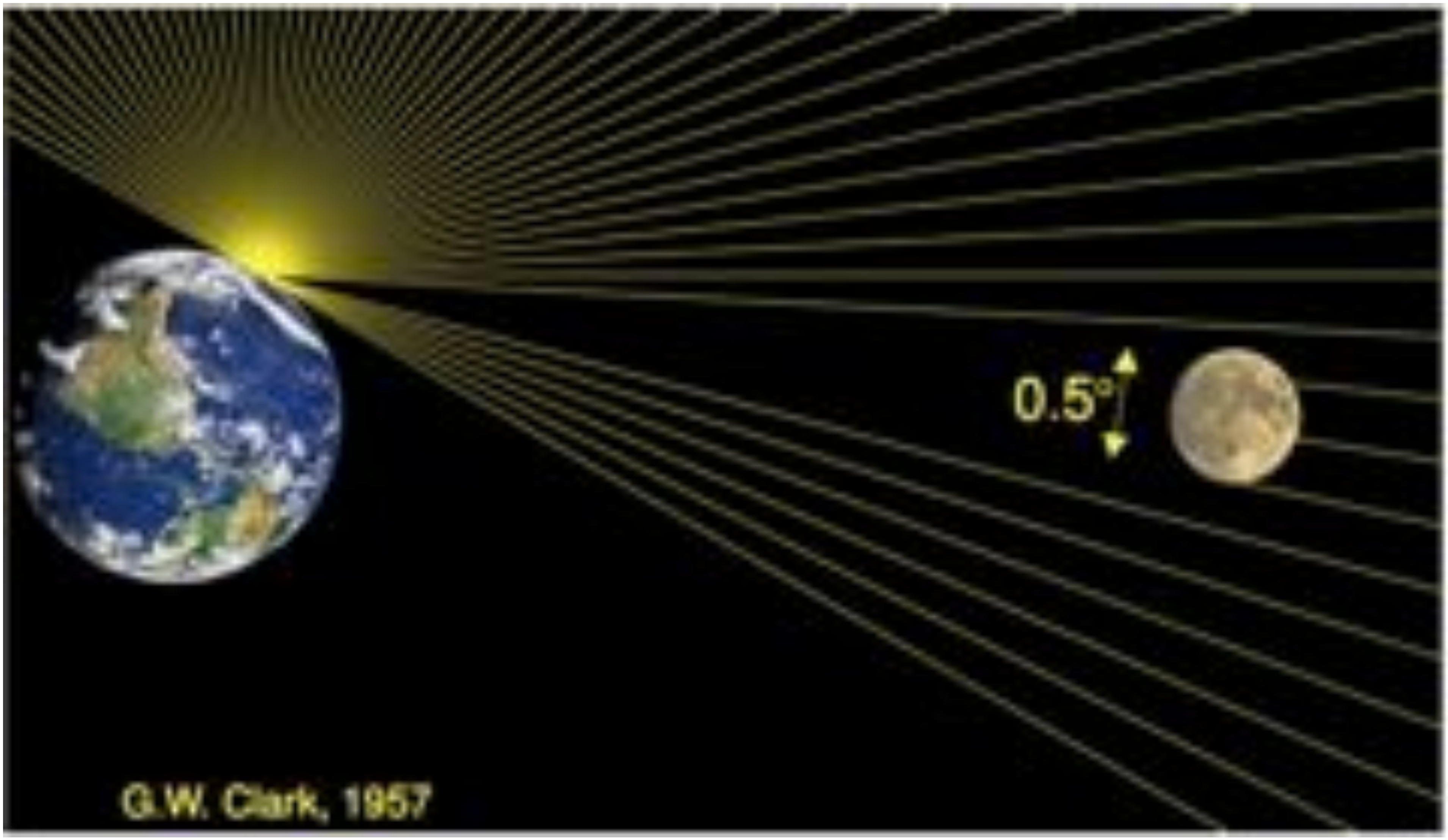
- IC40: 0.76° (0.5°)
- **IceCube: 0.5° (0.3°)**

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**)

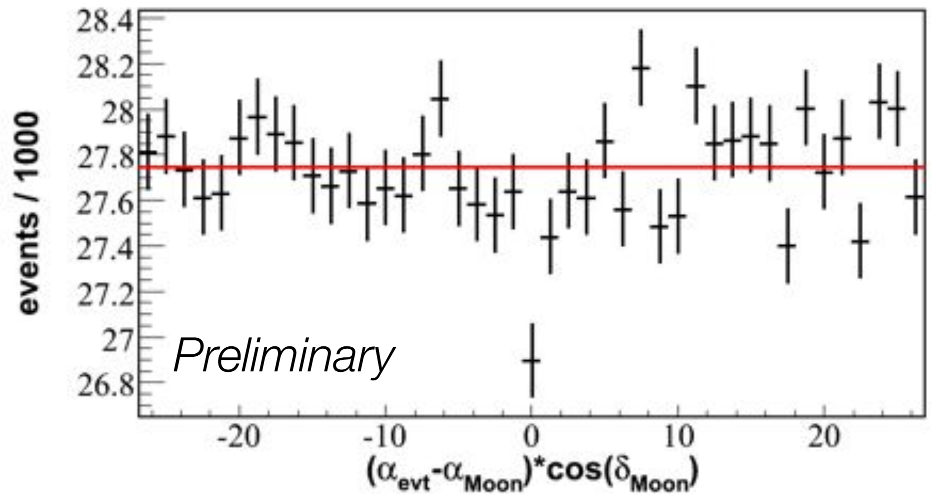


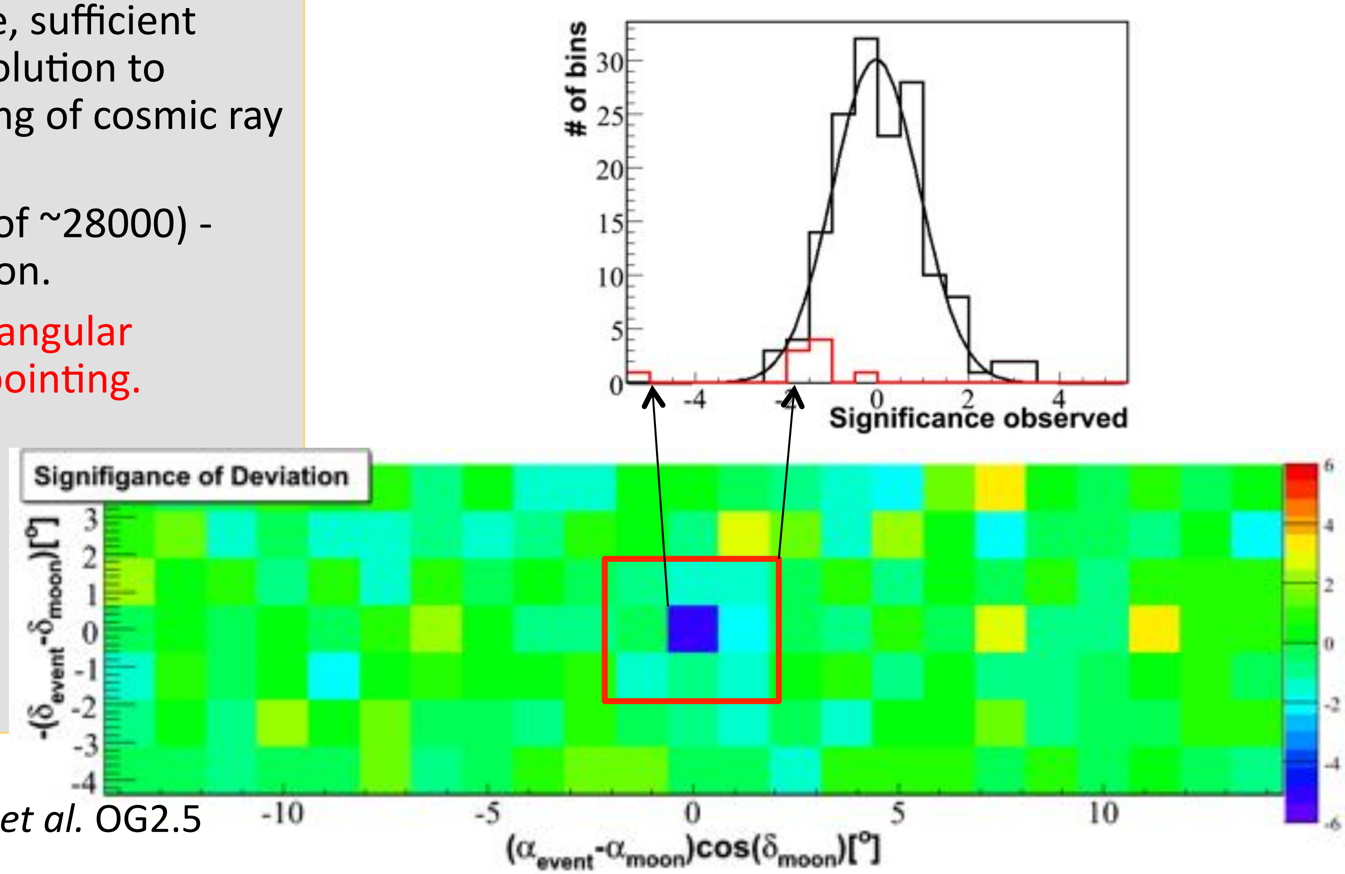
Cosmic rays get stuck in the Moon – Does IceCube see the moon (shadow)?



Moon shadow observed in muons

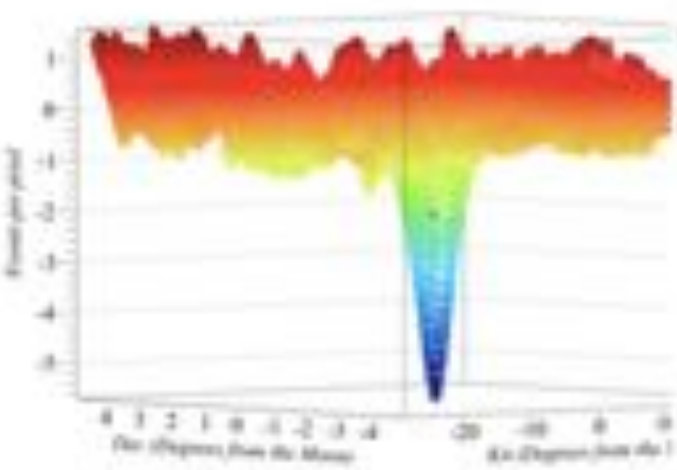
- Moon reaches an altitude of 28° at the South Pole (2008)
- Energy of parent air shower primary ~30TeV (median)
- Despite large zenith angle, sufficient statistics and angular resolution to analyze data for shadowing of cosmic ray primaries.
- Deficit: 5 s (~900 events of ~28000) - consistent with expectation.
- Important verification of angular resolution and absolute pointing.
- More statistics will allow study of angular response function

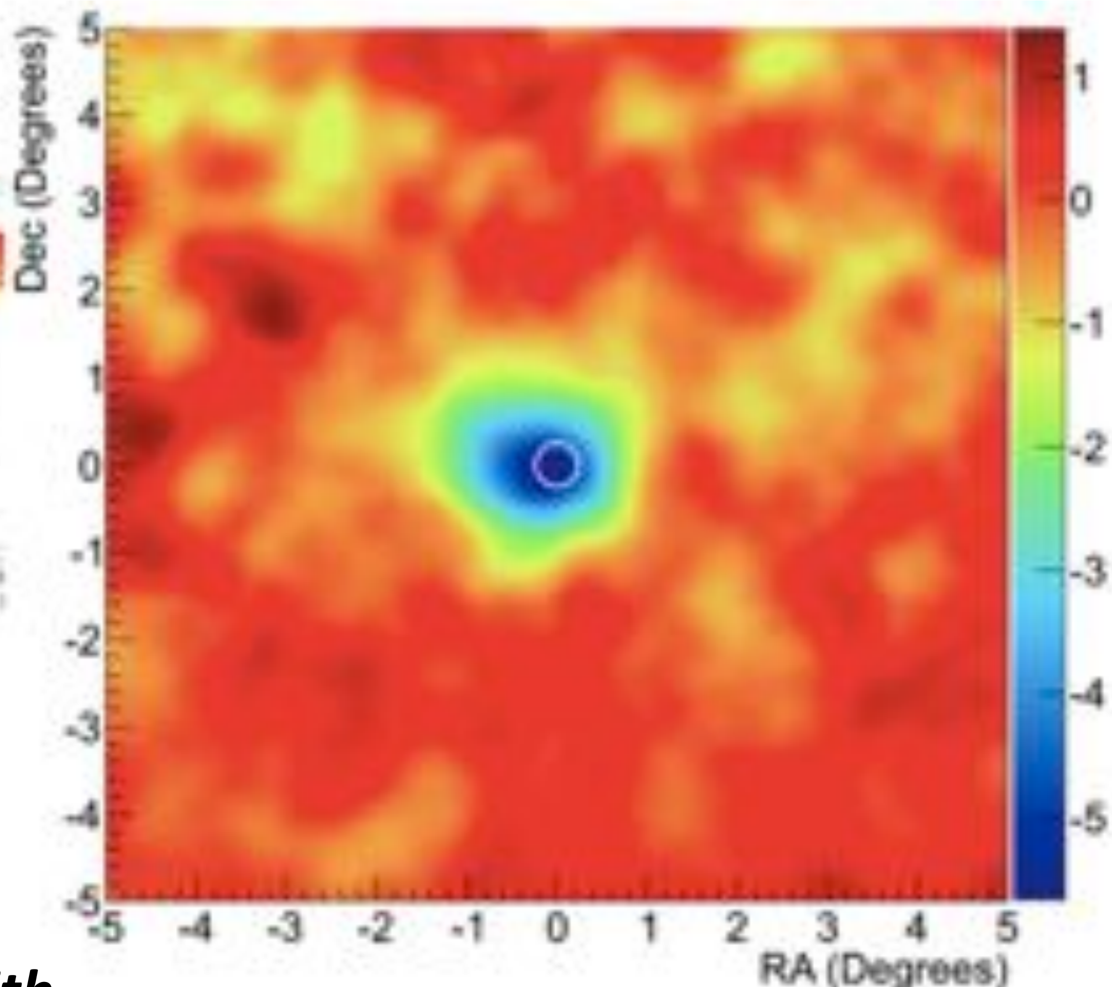




→ *Talk by Boersma, Gladstone et al.* OG2.5

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	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

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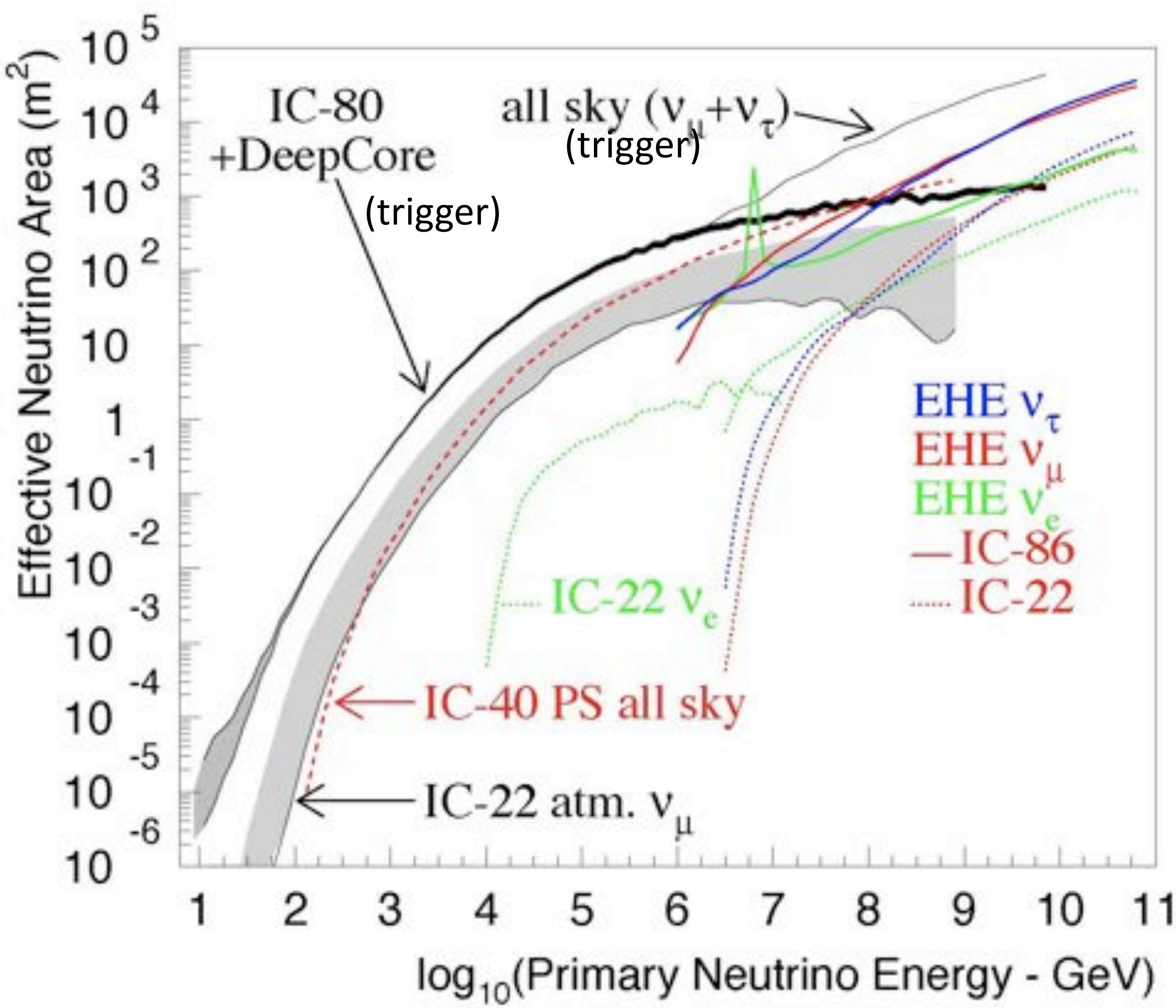
Detector operation, rates

- 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)

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

Conclusion

- 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.